Elementary Particles

and their

Interactions

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DEUTSCHES ELEKTRONEN-SYNCHROTRON

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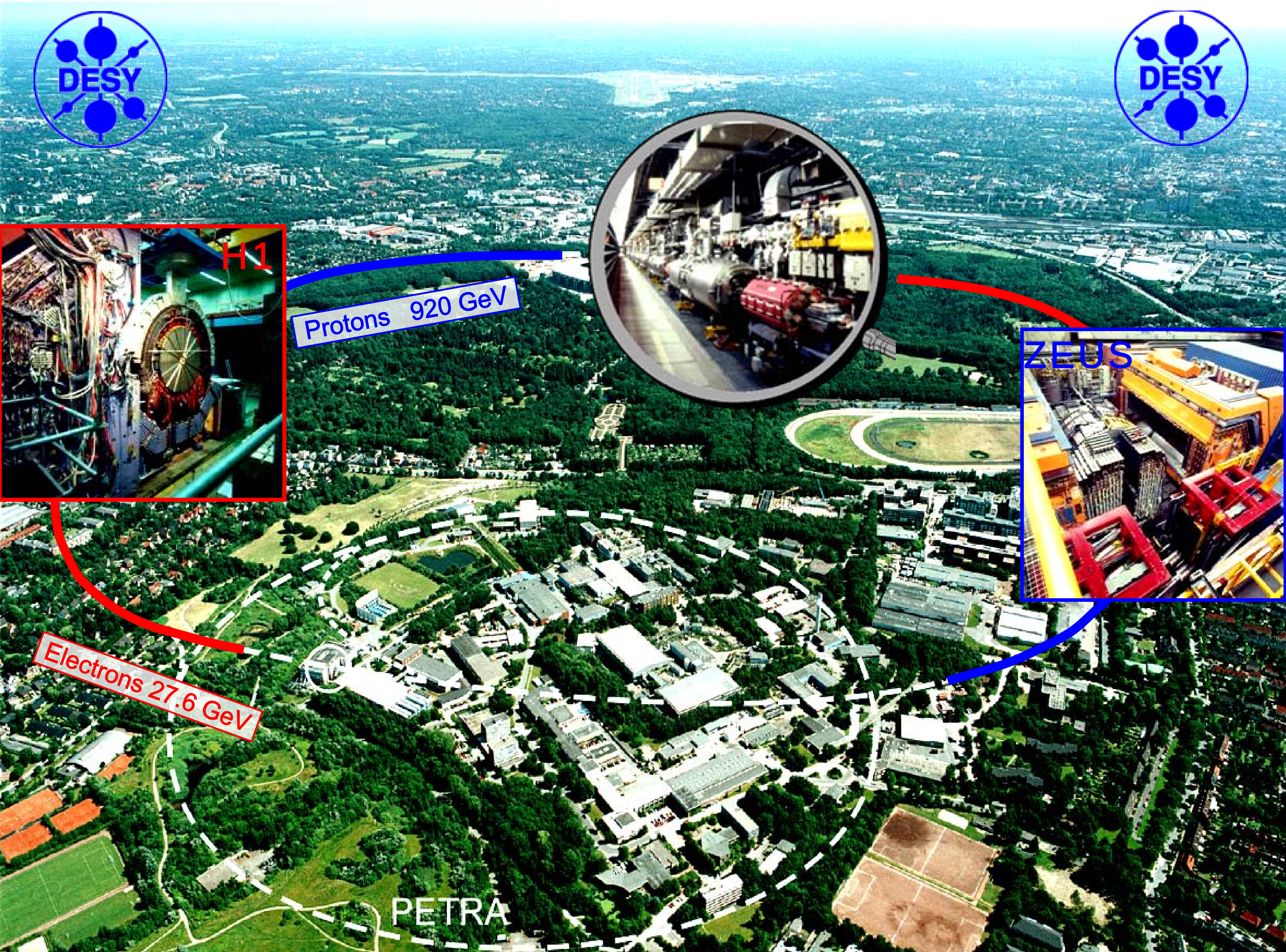
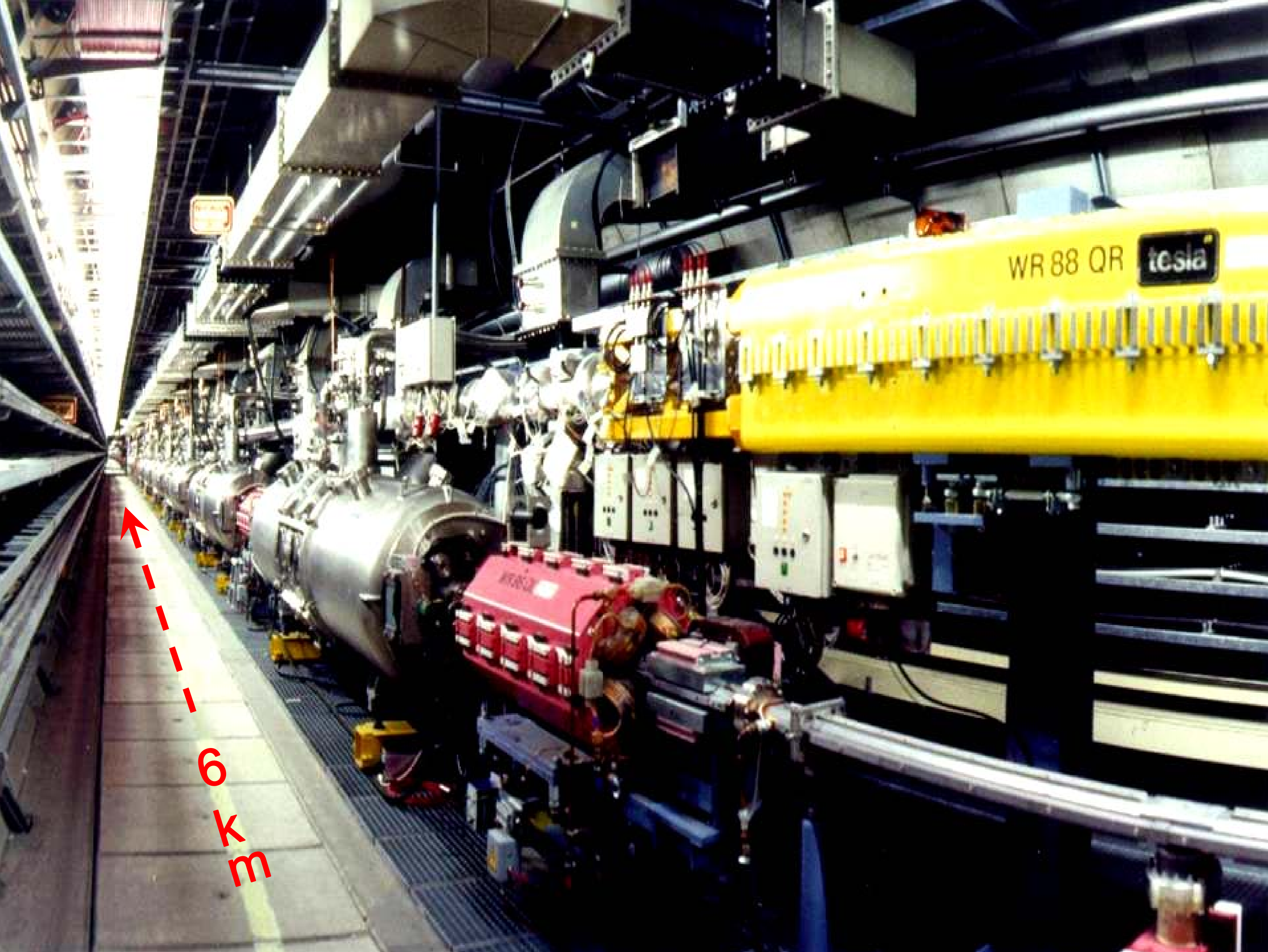
http://www-zeuthen.desy.de/~naumann/lectures/summer_lecture.pdf



DESY
DESY
H1
Protons 920 GeV
ZEUS
Electrons 27.6 GeV
PETRA


WR 88 QR
tesla
6 km

1. Introduction

1. Leptons
2. Hadrons

2. The Quark Model

1. Isospin
2. Multiplets and SU(N)
3. Spectroscopy of Light Quarks
4. Spectroscopy of Heavy Quarks
5. Measurement of Quark Charges

3. Symmetries and Conservation Laws

1. Charge Conjugation C
2. Parity P
3. *CP Violation*

4. Phenomenology of Weak Interactions

1. Neutral and Charged Currents
2. Neutrino Physics
3. Cross section and Fermi Constant
4. W- and Z-Bosons

5. Gauge Theory of Weak Interactions **(W. Lohmann)**

1. Gauge Theories
2. Spontaneous Symmetry Breaking and Higgs Mechanism
3. Lagrangian of Weak Interactions
4. Experimental Tests of the Standard Model
5. Higgs Search **(Th. Naumann)**

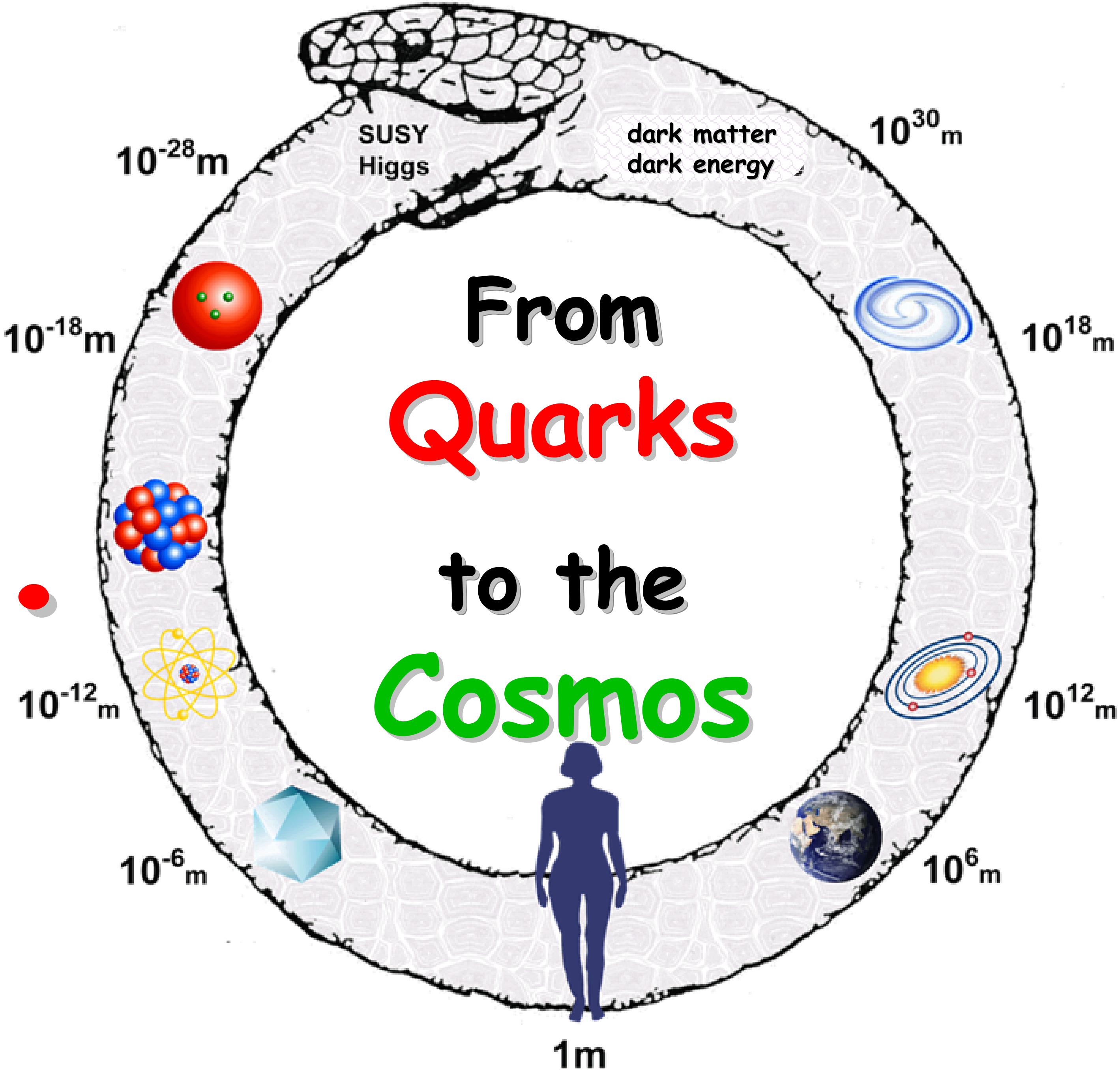
6. Gauge Theory of Strong Interactions **(J. Blümlein)**

1. Quantum Chromodynamics
2. Hadron Structure

7. Grand Unification and Cosmology

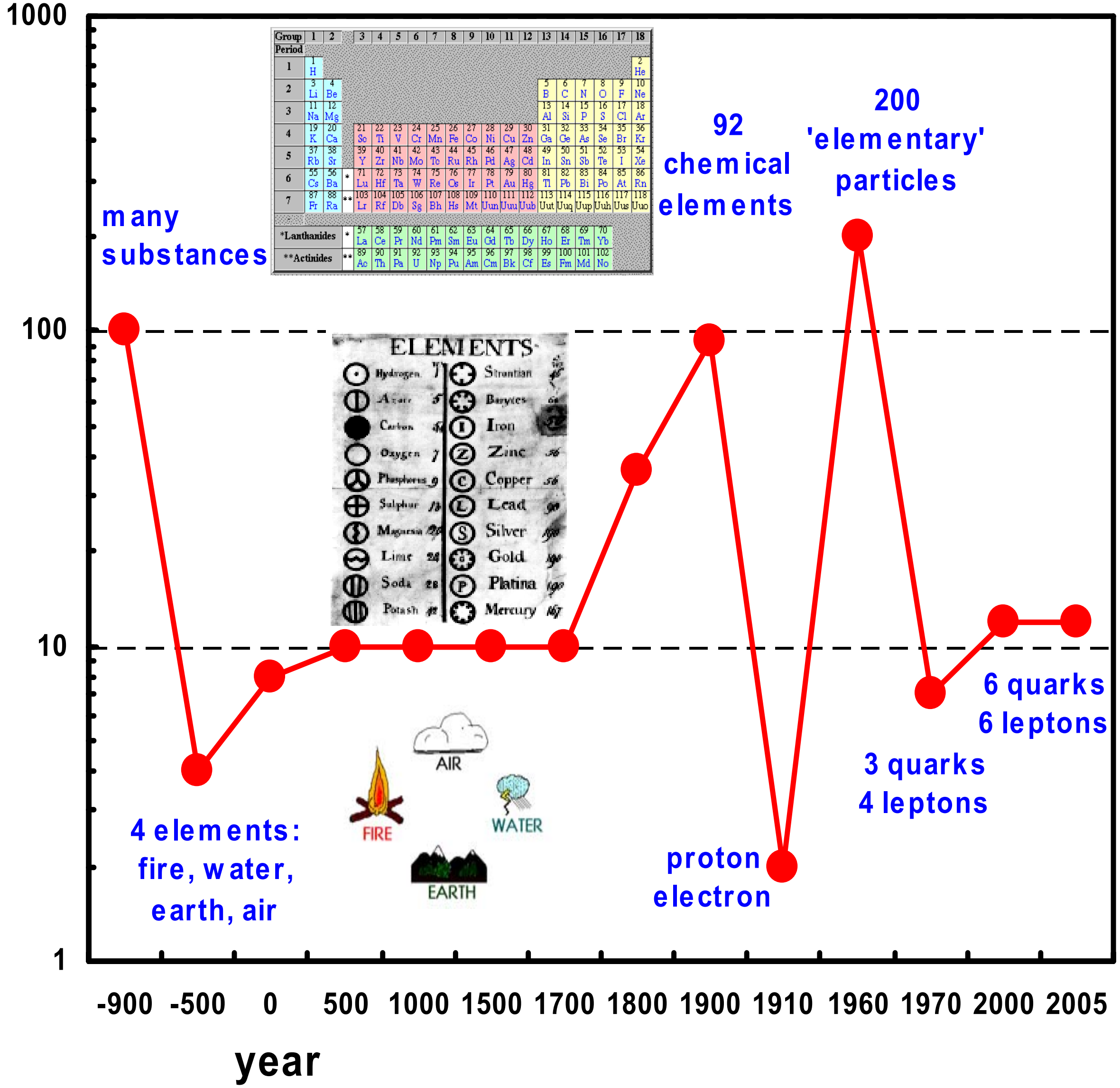
1. Unified Gauge Theories
2. Proton Decay and Baryon Asymmetry of the Universe
3. Supersymmetry and Superstrings **(H. Nowak)**
4. Cosmology and Particle Physics

1.



From
Quarks
to the
Cosmos
SUSY
Higgs
dark matter
dark energy
10^-28m
10^-18m
10^-12m
10^-6m
1m
10^6m
10^12m
10^18m
10^30m

The Building Blocks of Matter



Structure of Matter

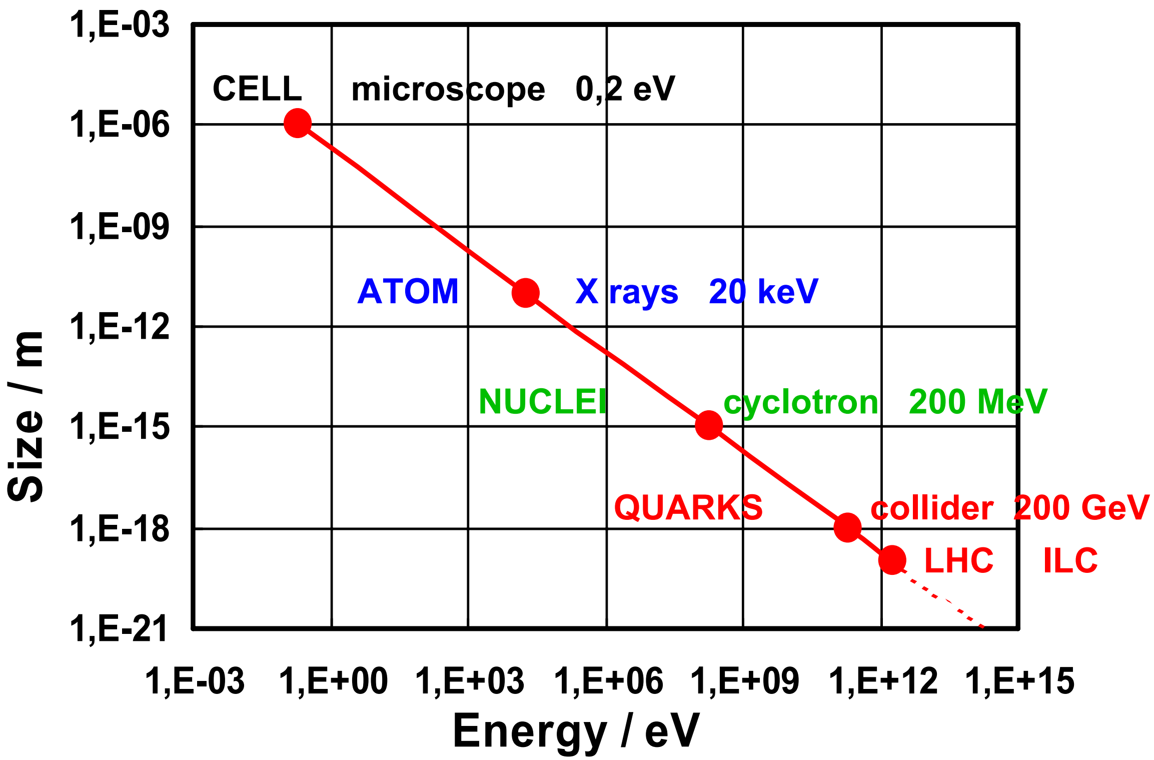
subatomic units:
electron-volt

uncertainty
relation

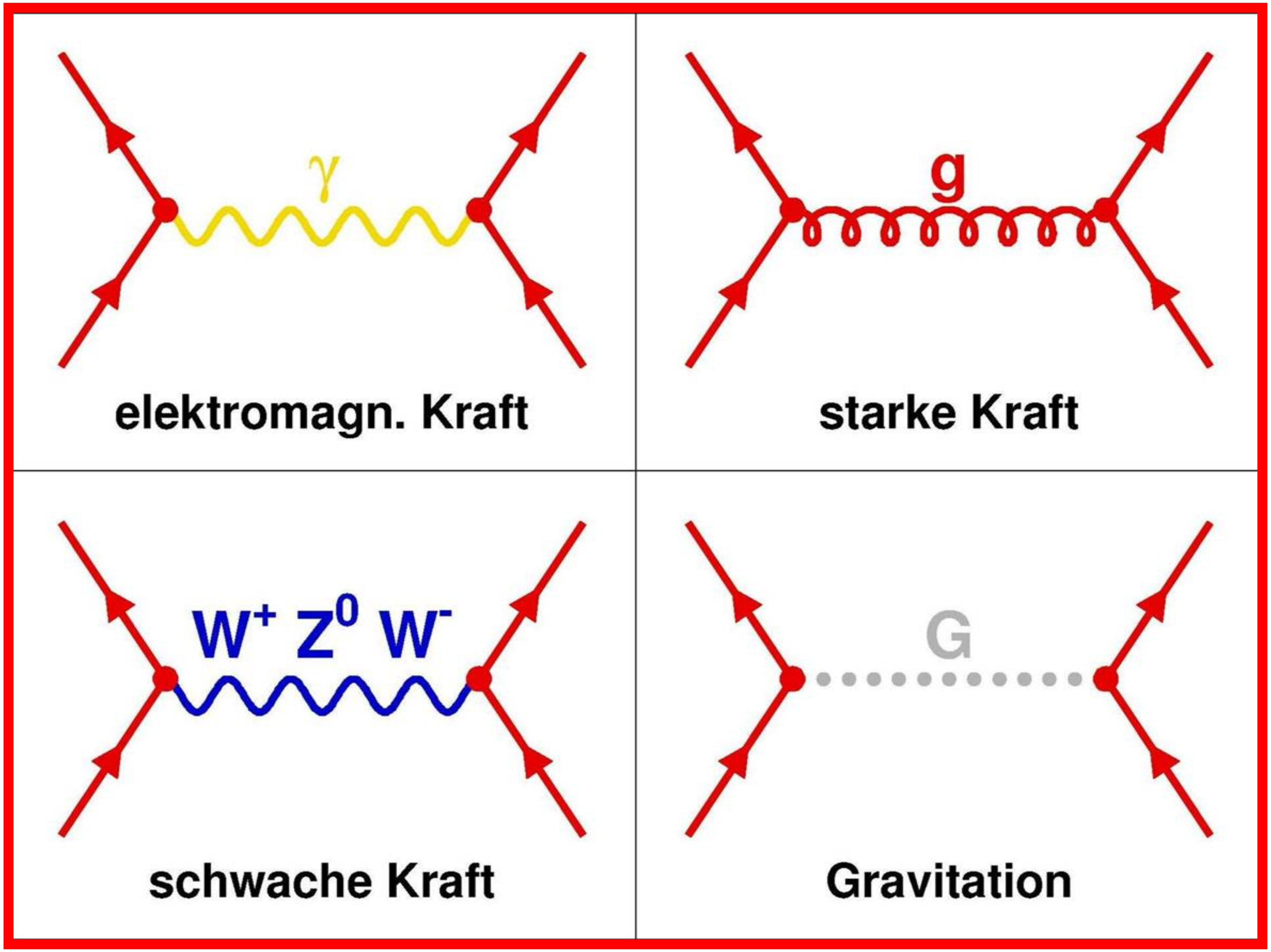
1 eV ≈ k·10.000 K

$\Delta E\ \Delta x = \hbar\ c$
≈ 200 MeV fm

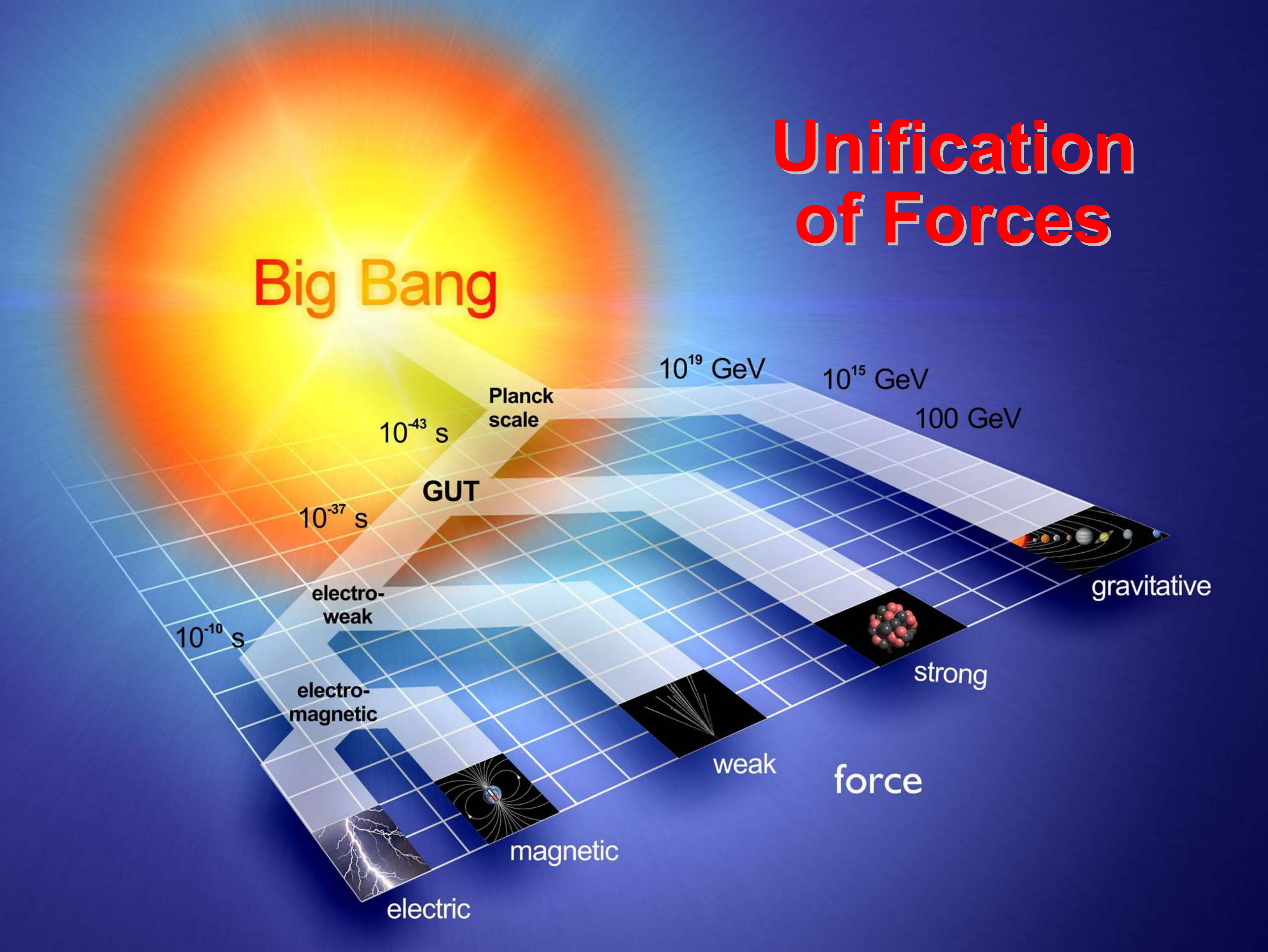
Energy	Size	Device	Object	Year
0.2 eV	10^{-6} m	microscope	cell	1600
20 keV	10^{-11} m	X rays	atom	1910
200 MeV	10^{-15} m	cyclotron	nuclei	1946
200 GeV	10^{-18} m	collider	quarks	1998



The Forces

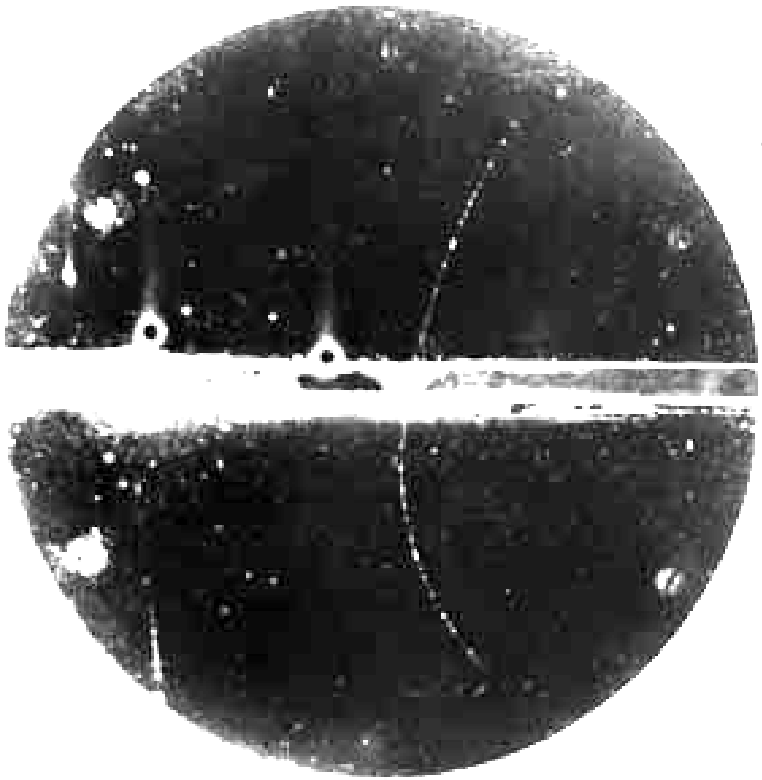

γ
elektromagn. Kraft
g
starke Kraft
W+ Z0 W-
schwache Kraft
G
Gravitation

Unification of Forces



The Positron

- curvature R in magnetic field B: $R \sim p \sim 1/B$
- ionization $I \sim$ velocity $\beta = v/c$: $I \sim 1/\beta \sim 1/(p/m)$

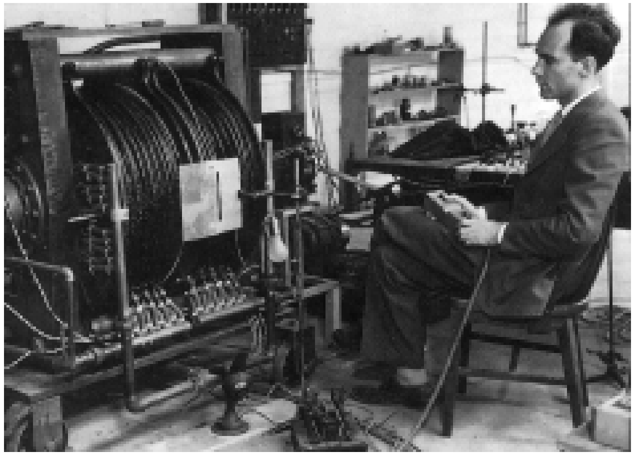


C. Anderson,

The Positive Electron

Phys.Rev. 43, 491 (1933)

Wilson's cloud chamber



Nobel prize 1936 C. Anderson for the discovery of the positron

Nobel prize 1927 Ch. Wilson for the cloud chamber

The Muon

1935: H.Yukawa:
carrier of nuclear force
mass ~200 MeV (between e + p)

Nobel prize 1949

J.C. Street, E.C. Stevenson,

New Evidence for the Existence of a Particle of Mass Intermediate between the Proton and the Electron, Phys. Rev. 52, 1003 (1937).

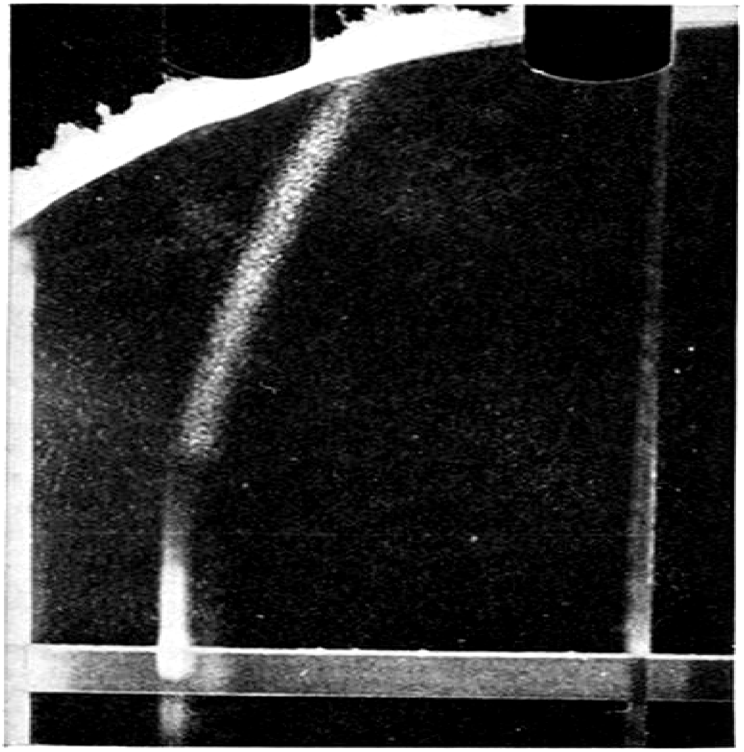
Too penetrating - NOT the Yukawa particle !

I.I. Rabi  Nobel 1944

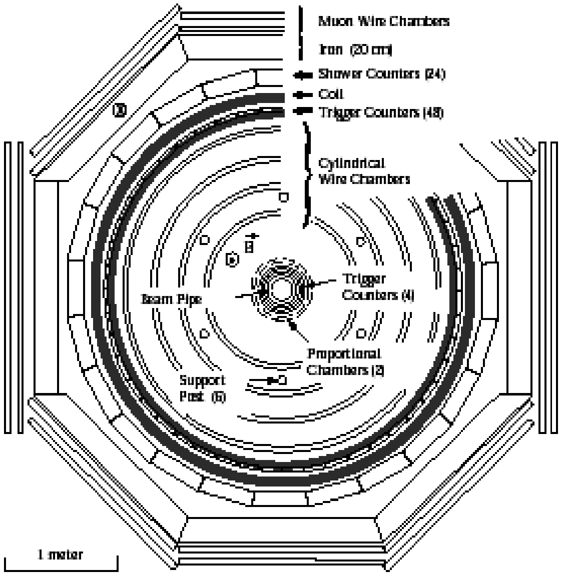
Who ordered that ?

curvature R in magnetic field B:
$R \sim p \sim 1/B$

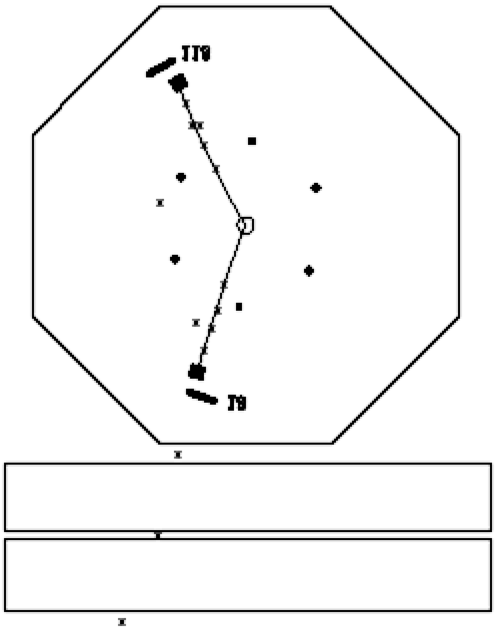
ionization I ~ velocity $\beta = v/c$:
$I \sim 1/\beta \sim 1/(p/m)$



τ lepton



MARK-I detector
at SPEAR $e^+ e^-$ ring
SLAC, USA.



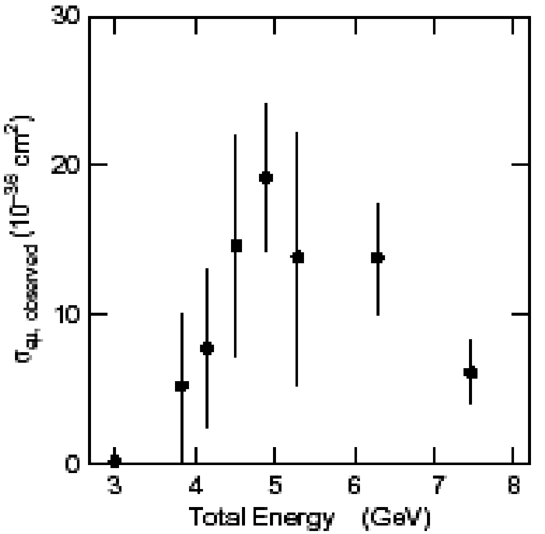


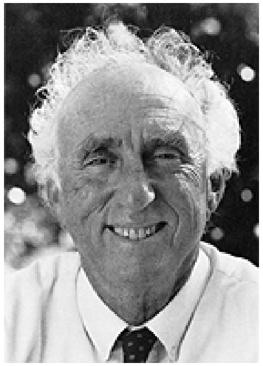
FIG. 2. The *observed* cross section for the signature e-μ events.

M. Perl et al., 1975-77:

$$e^+ e^- \rightarrow L^+ L^-$$

above 3.5 GeV threshold: unlike lepton pair production:

$L^+ \rightarrow e^+$ + unseen ν's carrying off energy + L_e
$L^- \rightarrow \mu^-$ + unseen ν's carrying off energy + L_μ

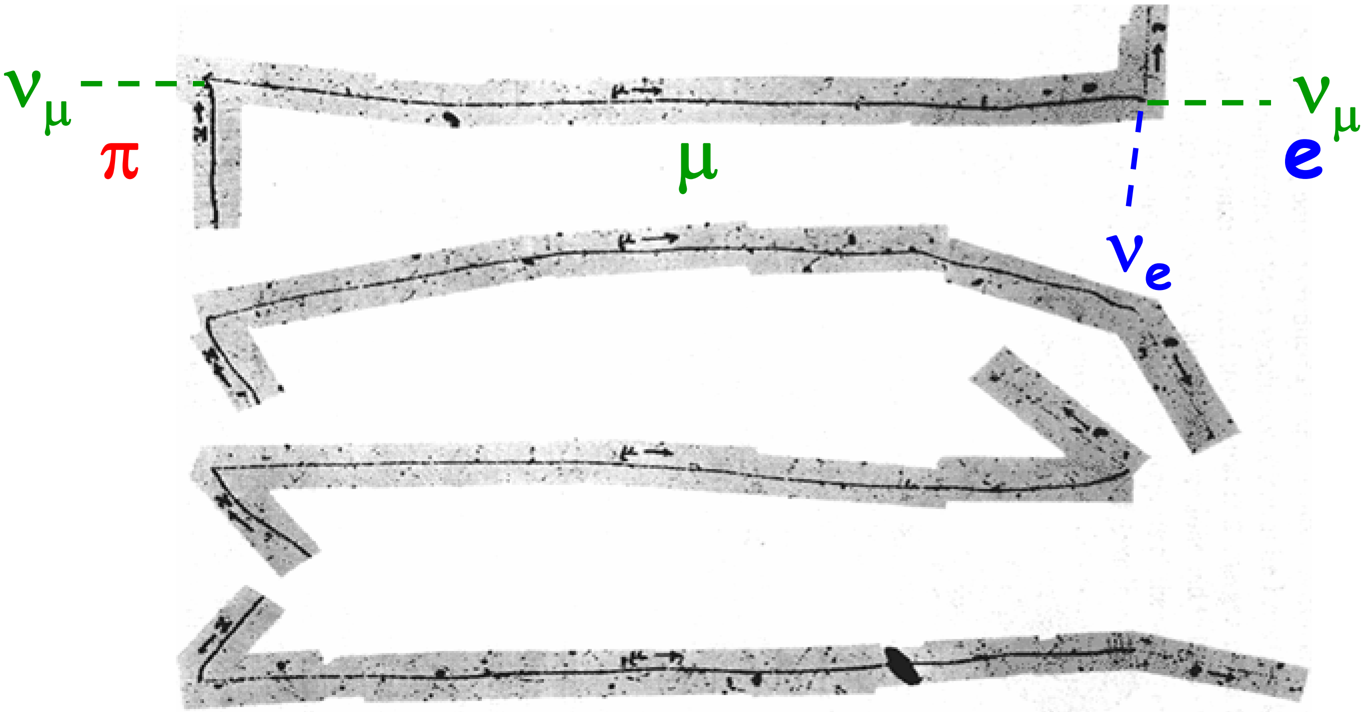


Nobel prize

1995

The Pion

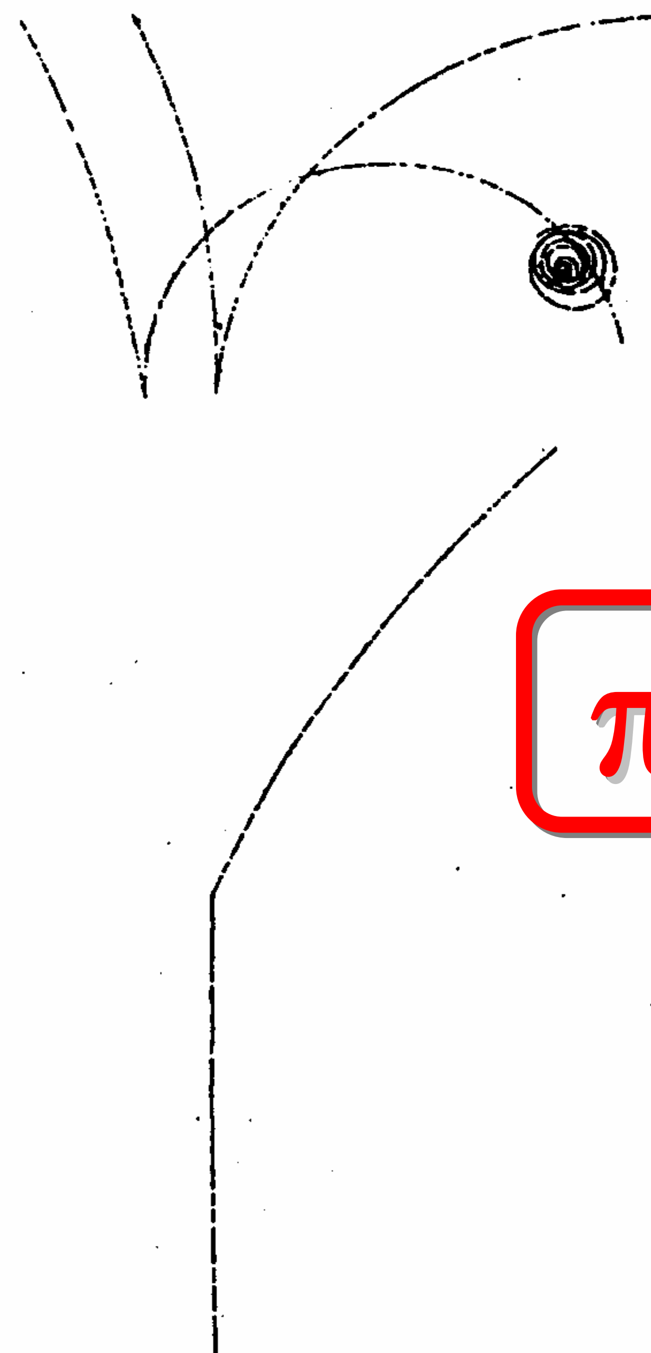
- stopping track + typical decay cascade
- decay product fixed range in nuclear emulsion = always same E
- two body decay to muon + neutrino



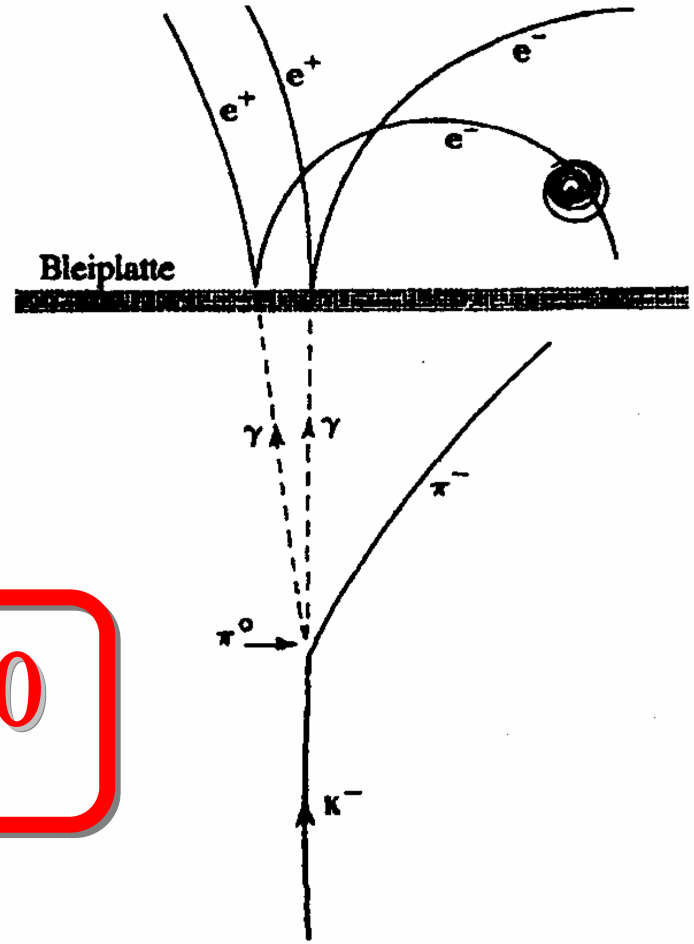
Nobel prize 1948:  P. Blackett, Use of cloud chambers in cosmic radiation

Nobel prize 1950: C.F. Powell, Discoveries on mesons with emulsions

(still used, τ in OPERA, Gran Sasso)



π^0

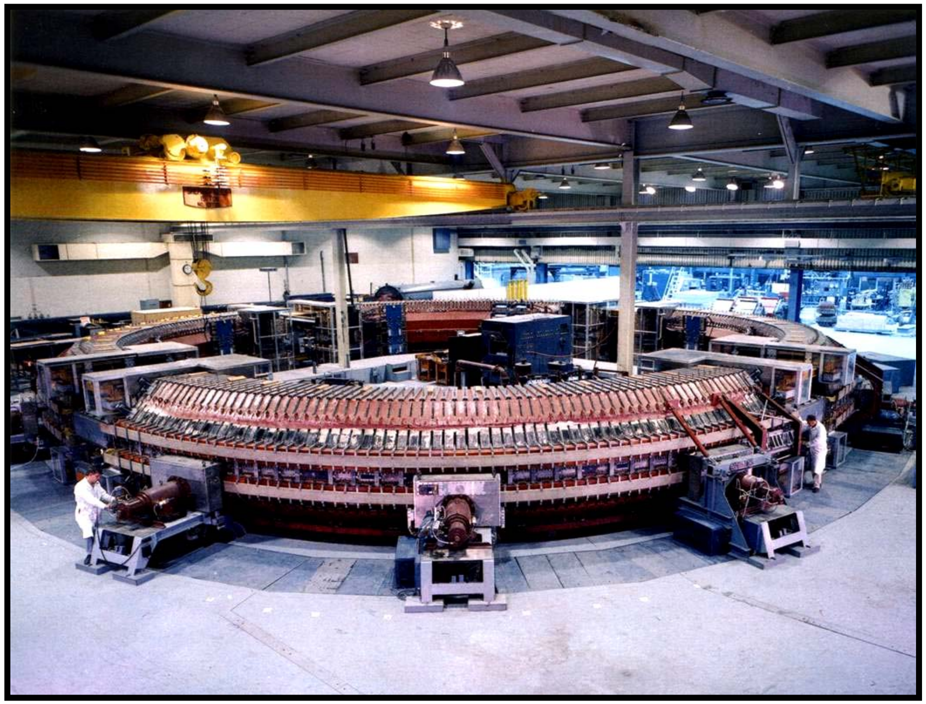


Die beiden Bilder zeigen eine Fotografie (bei der alle für den Vorgang unwichtigen Linien gelöscht wurde) und eine Zeichnung zur Erklärung des Zerfalls eines negativen Kaons in ein negatives und ein neutrales Pion. Die enge Spirale rechts oben stammt von einem Elektron, das aus einem Atom der Blasenkammerflüssigkeit herausgeschlagen wurde. Die Aufnahme stammt aus der Blasenkammer des LBL.

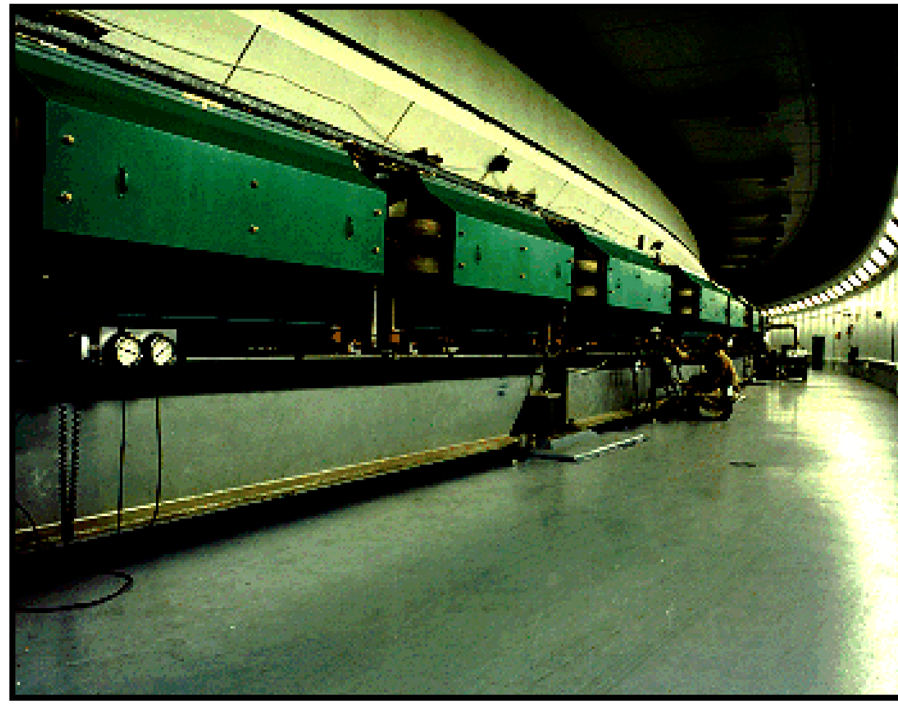
Accelerators

find particle zoo:

BNL Brookhaven National Lab., USA

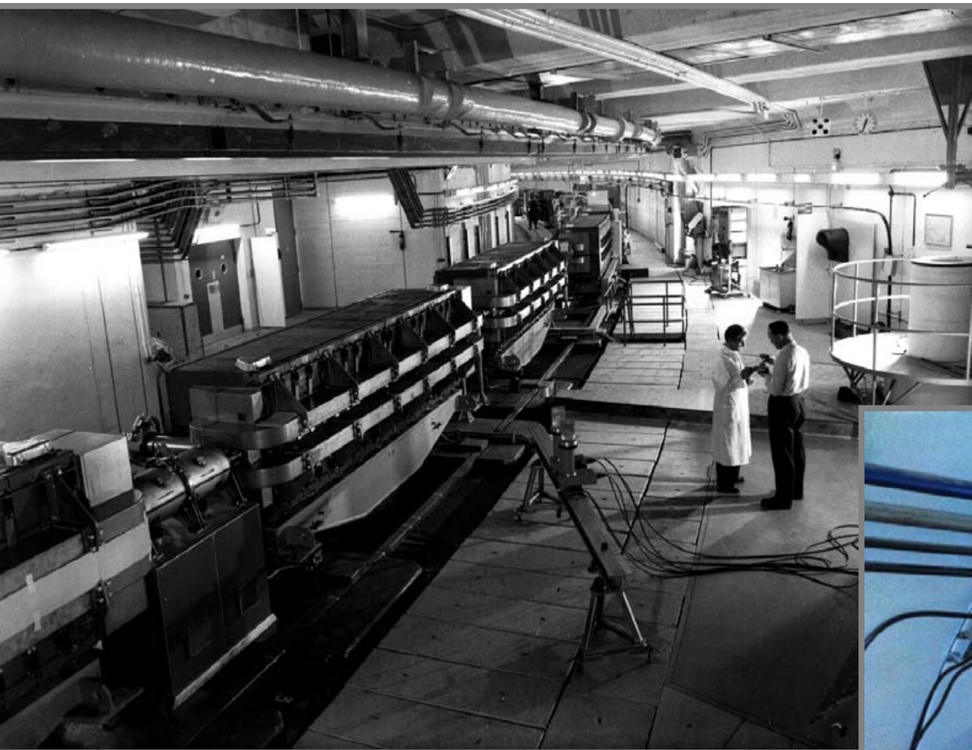


Cosmotron: 1st proton synchrotron.
1953: 3.3 GeV



AGS: Alternating Gradient Synchrotron
1960: 33 GeV

CERN Accelerators



CERN 1959:

26 GeV

Proton Synchrotron

CERN 1976:

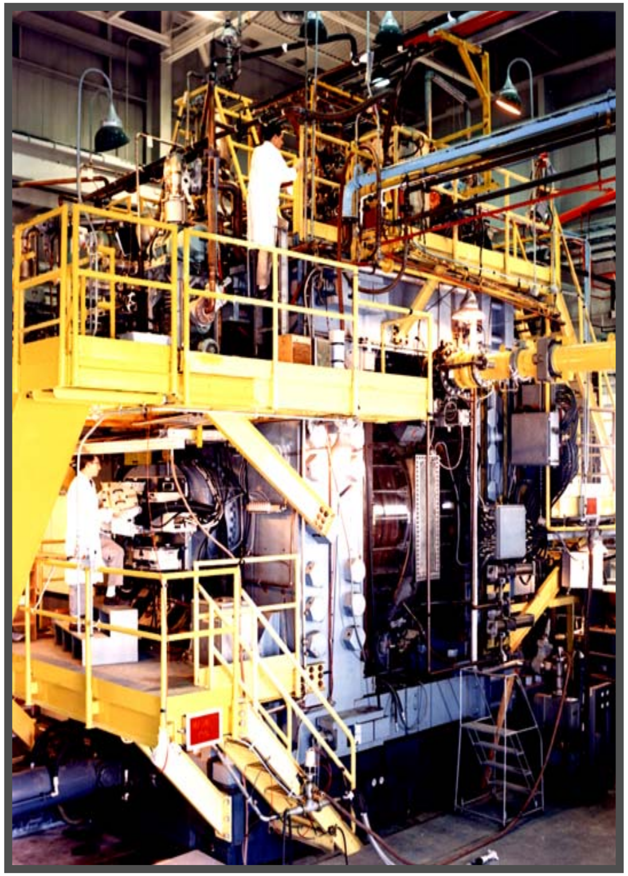
400 GeV

Super Proton Synchrotron

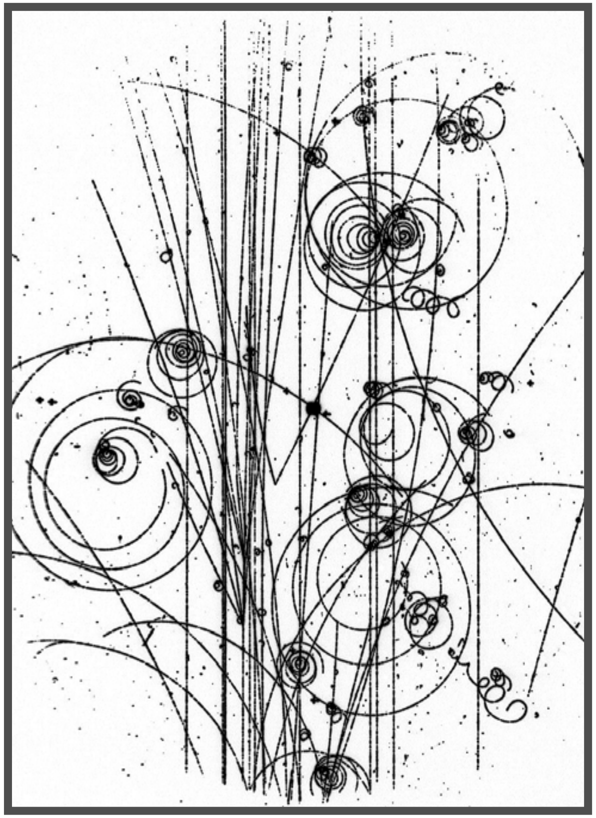
7 km

Bubble Chambers

Particle



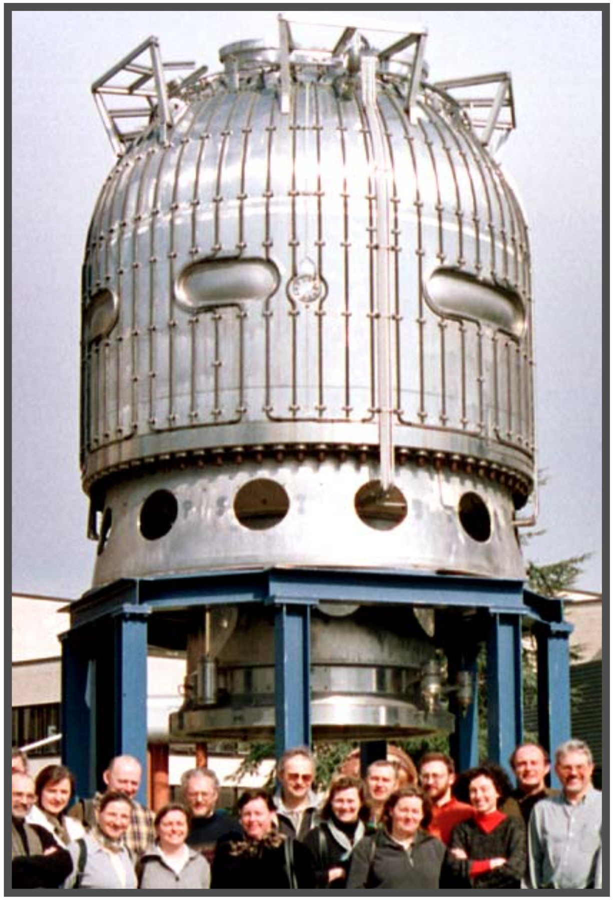
BNL 80" Bubble Chamber
1963-74
1964 Ω^-
Nobel prize



Zoo

Quark model !

~100 million photos
US + EU



CERN: BEBC
Big European Bubble Chamber
3.7 m, 20 m^3, 3.5 T
6 million photos 1974-84

Strangeness

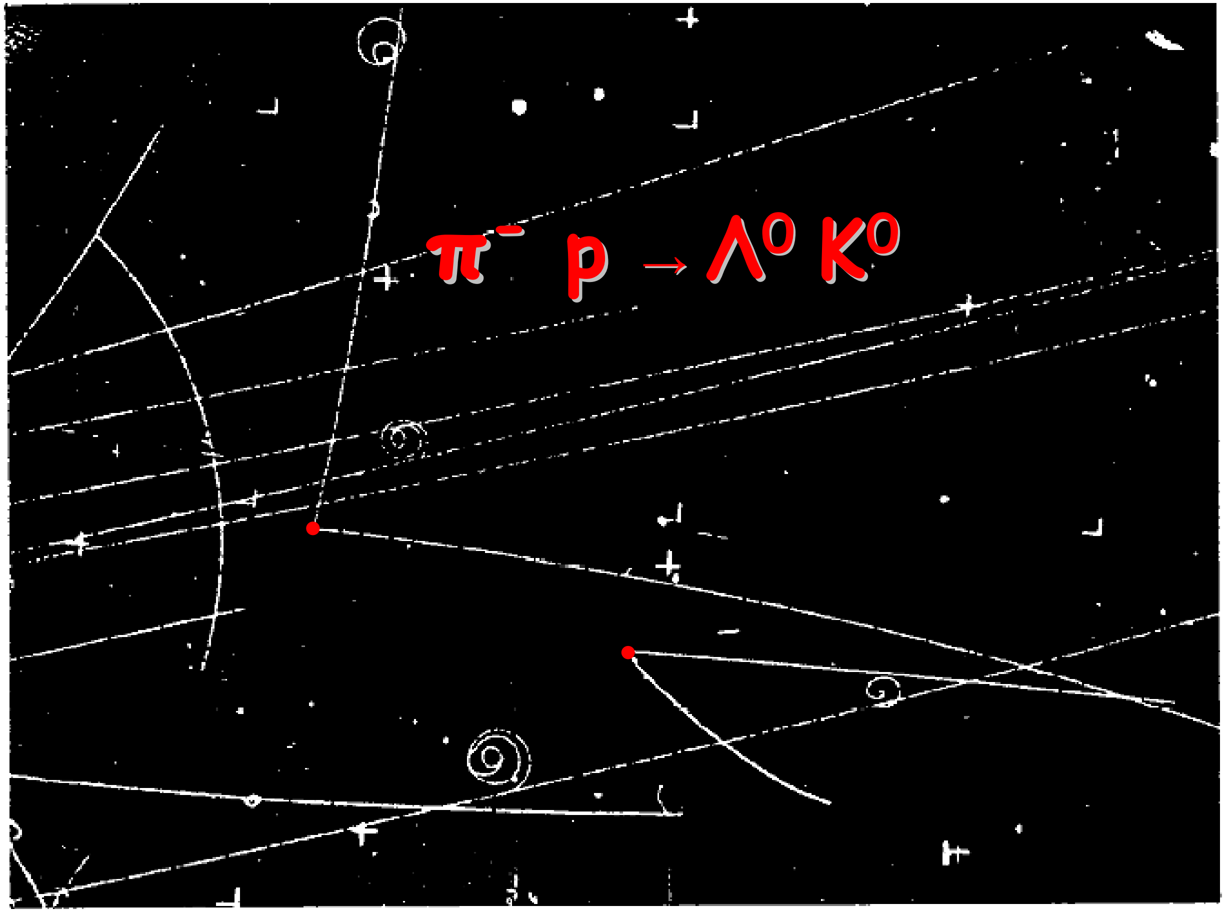


Fig. 12. Associated production, $\pi^- + p \rightarrow \Lambda^\circ + K^\circ$ at about 1 GeV with subsequent decays in Alvarez's hydrogen bubble chamber.

Strange particles:

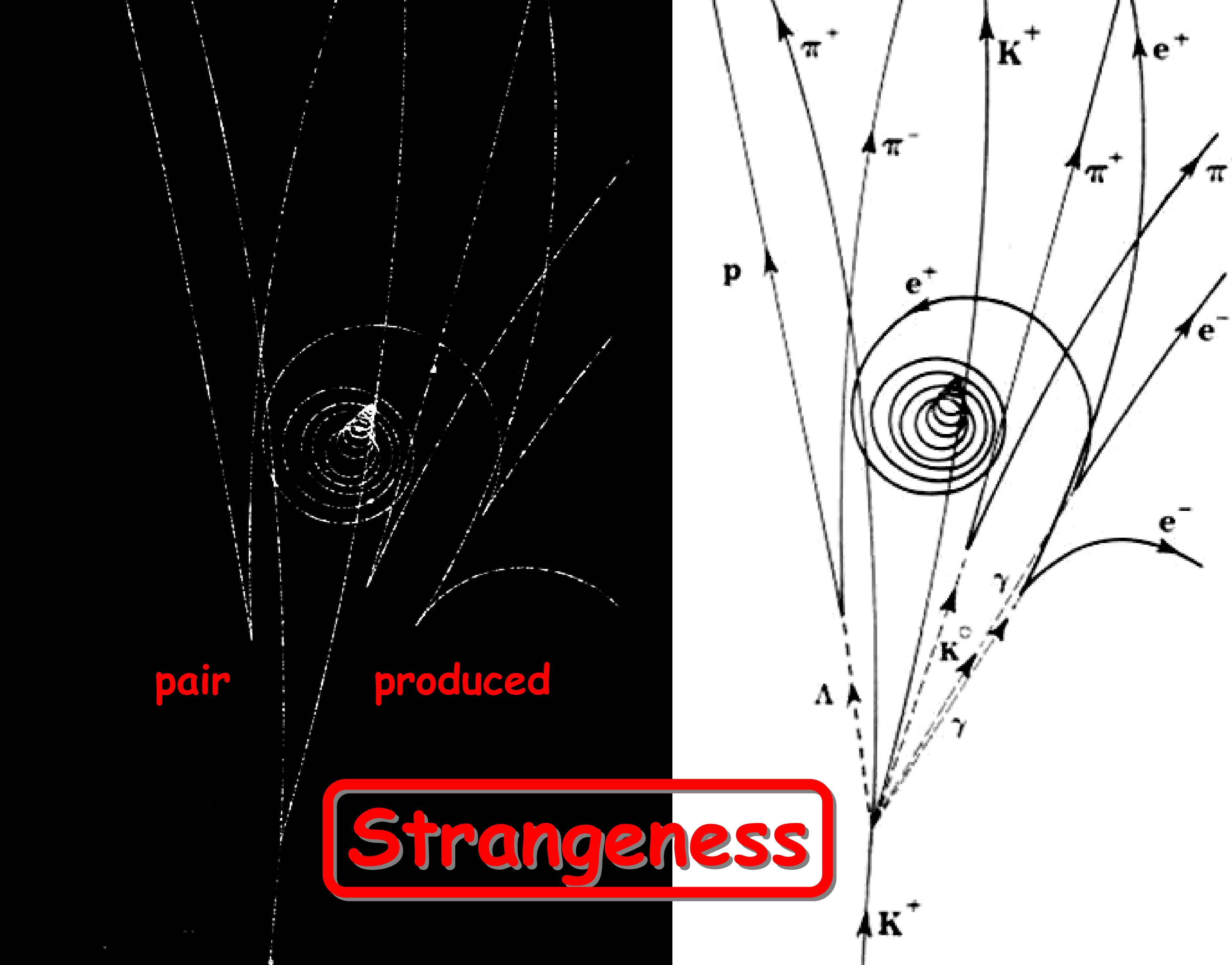
always
pair produced
in strong interactions:

new
conservation law !

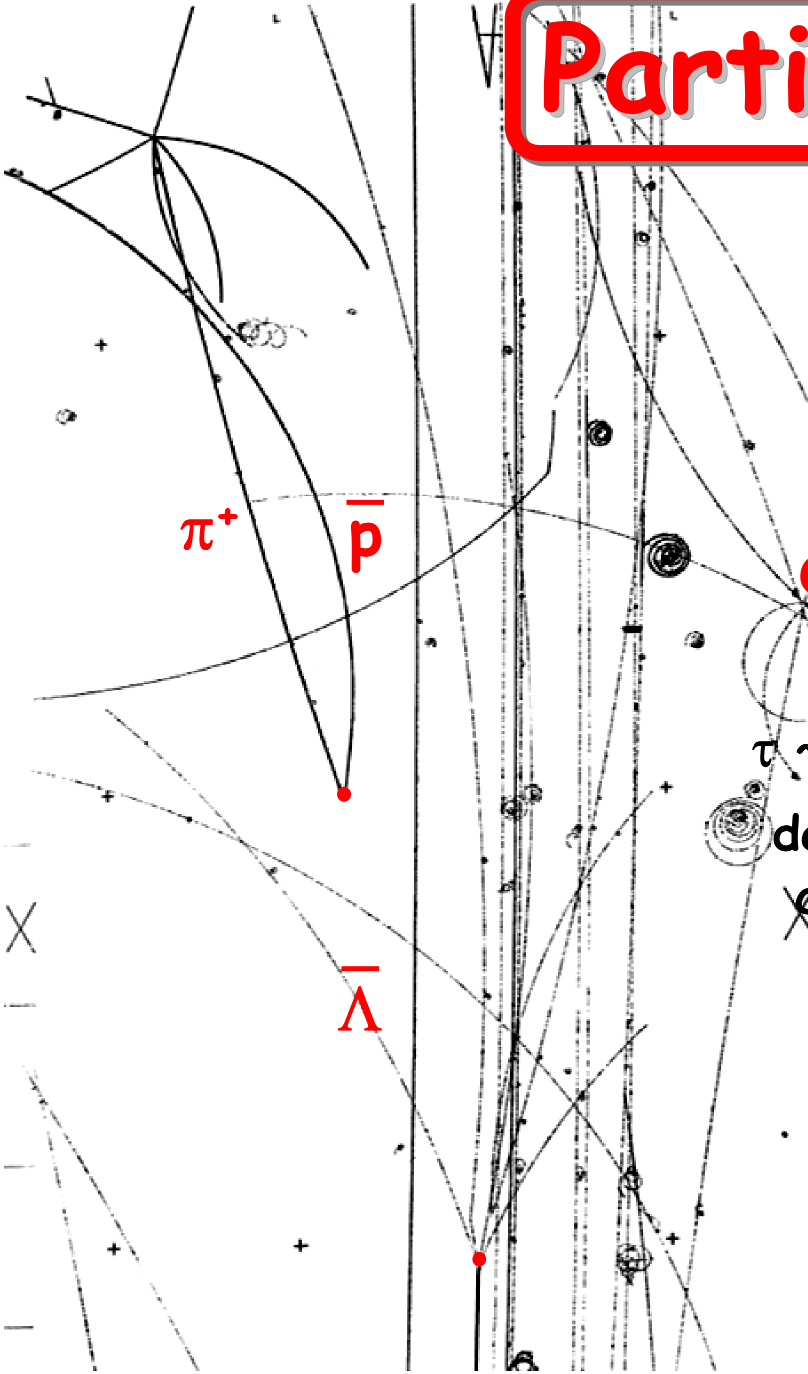
life time $\tau \sim 10^{-8 \ldots -10}$ s
decay length $c\tau \sim$ cm…m

D. Glaser, Nobel prize 1960 — invention of bubble chambers
L. Alvarez, 1968 — use of bubble chambers

Strangeness



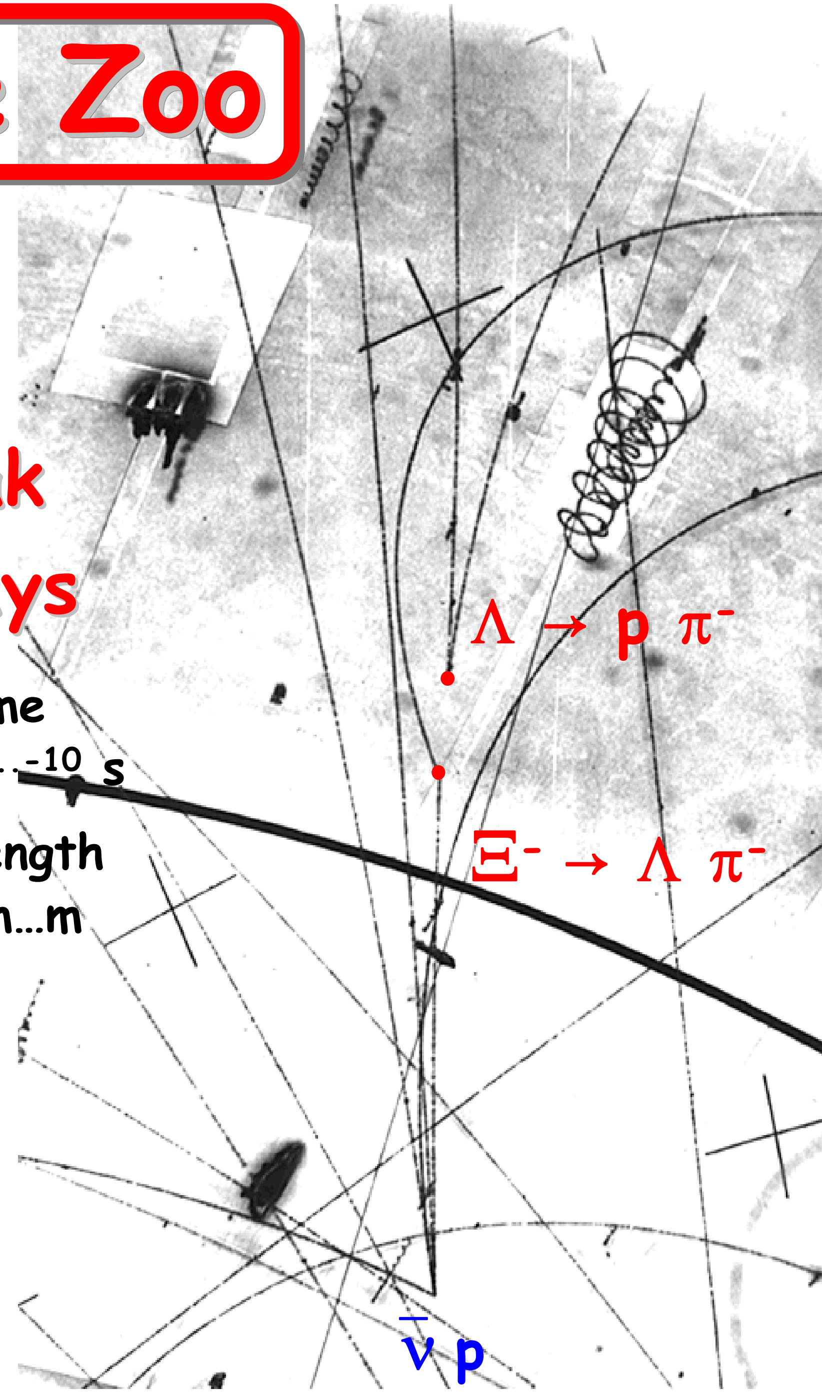
Particle Zoo



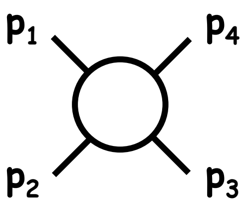
weak decays

lifetime
$\tau \sim 10^{-8...-10}$ s

decay length
$c\tau \sim$ cm…m



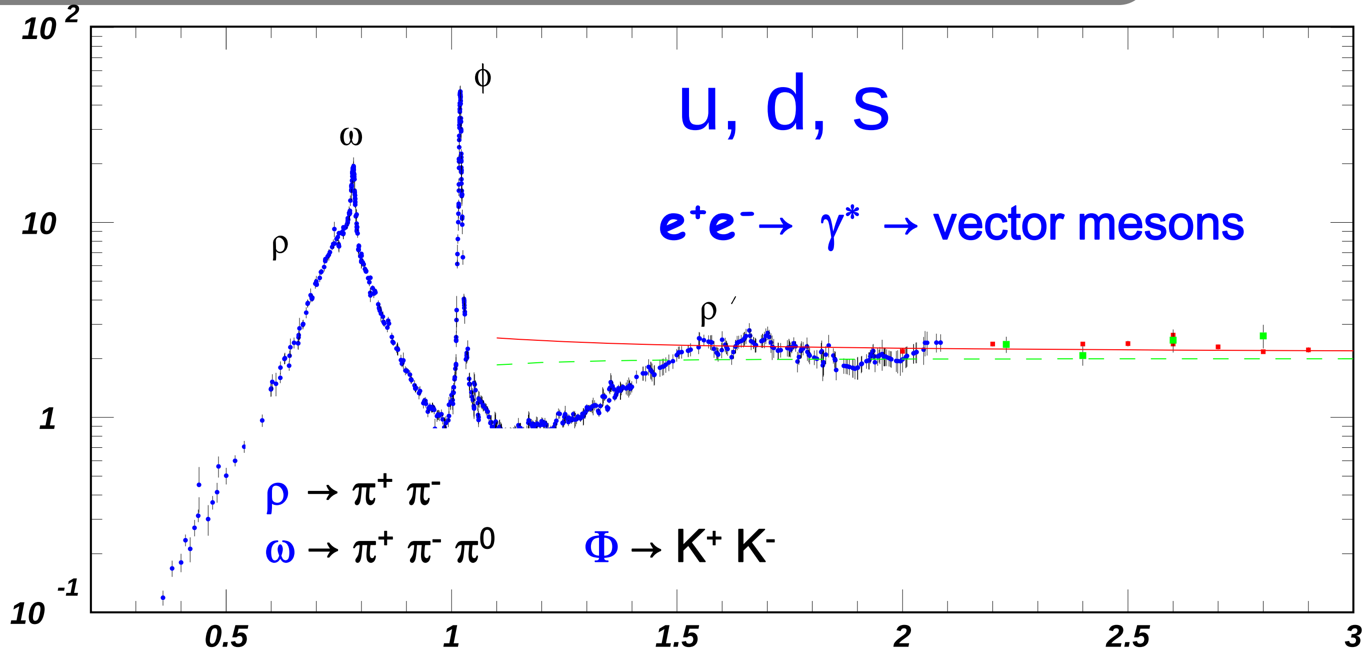
Strongly bound hadrons



four-momentum
$p_i = (E_i, \vec{p}_i)$

invariant mass of a particle:

$m^2 = p^2 = s = (p_1+p_2)^2$



width:

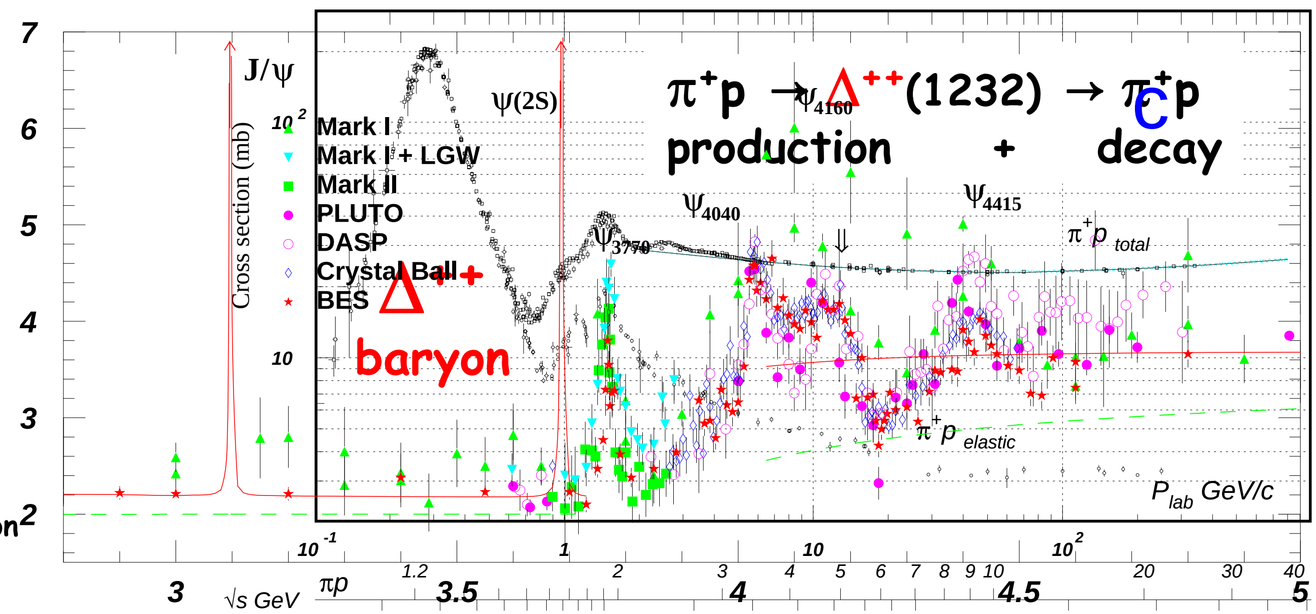
$\Gamma \sim 120$ MeV

lifetime:

$\tau \sim 10^{-23}$ s

decay length:

$c\tau \sim$ fm $\sim r_{proton}$



The Particle Zoo

Light Mesons

$n\,^{2s+1}\ell_J$	J^{PC}	I = 1 $u\bar{d}$, $\bar{u}d$, $\frac{1}{\sqrt{2}}(d\bar{d}-u\bar{u})$	I = $\frac{1}{2}$ $u\bar{s}$, $d\bar{s}$; $\bar{d}s$, $-\bar{u}s$	I = 0 f'	I = 0 f	$\theta_{\rm quad}$ [°]	$\theta_{\rm lin}$ [°]
$1\,^1S_0$	0^{-+}	π	K	η	$\eta'(958)$	−11.5	−24.6
$1\,^3S_1$	1^{--}	$\rho(770)$	$K^*(892)$	$\phi(1020)$	$\omega(782)$	38.7	36.0
$1\,^1P_1$	1^{+-}	$b_1(1235)$	$K_{1B}{}^\dagger$	$h_1(1380)$	$h_1(1170)$		
$1\,^3P_0$	0^{++}	$a_0(1450)$	$K_0^*(1430)$	$f_0(1710)$	$f_0(1370)$		
$1\,^3P_1$	1^{++}	$a_1(1260)$	$K_{1A}{}^\dagger$	$f_1(1420)$	$f_1(1285)$		
$1\,^3P_2$	2^{++}	$a_2(1320)$	$K_2^*(1430)$	$f_2'(1525)$	$f_2(1270)$	29.6	28.0
$1\,^1D_2$	2^{-+}	$\pi_2(1670)$	$K_2(1770)^\dagger$	$\eta_2(1870)$	$\eta_2(1645)$		
$1\,^3D_1$	1^{--}	$\rho(1700)$	$K^*(1680)^\ddagger$		$\omega(1650)$		
$1\,^3D_2$	2^{--}		$K_2(1820)^\ddagger$				
$1\,^3D_3$	3^{--}	$\rho_3(1690)$	$K_3^*(1780)$	$\phi_3(1850)$	$\omega_3(1670)$	32.0	31.0
$1\,^3F_4$	4^{++}	$a_4(2040)$	$K_4^*(2045)$		$f_4(2050)$		
$1\,^3G_5$	5^{--}	$\rho_5(2350)$					
$1\,^3H_6$	6^{++}	$a_6(2450)$			$f_6(2510)$		
$2\,^1S_0$	0^{-+}	$\pi(1300)$	$K(1460)$	$\eta(1475)$	$\eta(1295)$	−22.4	−22.6
$2\,^3S_1$	1^{--}	$\rho(1450)$	$K^*(1410)^\ddagger$	$\phi(1680)$	$\omega(1420)$		

LIGHT UNFLAVORED ($S = C = B = 0$)

	$I^G(J^{PC})$		$I^G(J^{PC})$
• $\pi^\pm$	$1^-(0^-)$	• $\pi_2(1670)$	$1^-(2^{-+})$
• π^0	$1^-(0^{-+})$	• $\phi(1680)$	$0^-(1^{--})$
• η	$0^+(0^{-+})$	• $\rho_3(1690)$	$1^+(3^{--})$
• $f_0(600)$	$0^+(0^{++})$	• $\rho(1700)$	$1^+(1^{--})$
• $\rho(770)$	$1^+(1^{--})$	$a_2(1700)$	$1^-(2^{++})$
• $\omega(782)$	$0^-(1^{--})$	• $f_0(1710)$	$0^+(0^{++})$
• $\eta'(958)$	$0^+(0^{-+})$	$\eta(1760)$	$0^+(0^{-+})$
• $f_0(980)$	$0^+(0^{++})$	• $\pi(1800)$	$1^-(0^{-+})$
• $a_0(980)$	$1^-(0^{++})$	$f_2(1810)$	$0^+(2^{++})$
• $\phi(1020)$	$0^-(1^{--})$	• $\phi_3(1850)$	$0^-(3^{--})$
• $h_1(1170)$	$0^-(1^{+-})$	$\eta_2(1870)$	$0^+(2^{-+})$
• $b_1(1235)$	$1^+(1^{+-})$	$\rho(1900)$	$1^+(1^{--})$
• $a_1(1260)$	$1^-(1^{++})$	$f_2(1910)$	$0^+(2^{++})$
• $f_2(1270)$	$0^+(2^{++})$	• $f_2(1950)$	$0^+(2^{++})$
• $f_1(1285)$	$0^+(1^{++})$	$\rho_3(1990)$	$1^+(3^{--})$
• $\eta(1295)$	$0^+(0^{-+})$	• $f_2(2010)$	$0^+(2^{++})$
• $\pi(1300)$	$1^-(0^{-+})$	$f_0(2020)$	$0^+(0^{++})$
• $a_2(1320)$	$1^-(2^{++})$	• $a_4(2040)$	$1^-(4^{++})$
• $f_0(1370)$	$0^+(0^{++})$	• $f_4(2050)$	$0^+(4^{++})$
$h_1(1380)$	$?^-(1^{+-})$	$\pi_2(2100)$	$1^-(2^{-+})$
• $\pi_1(1400)$	$1^-(1^{-+})$	$f_0(2100)$	$0^+(0^{++})$
• $\eta(1405)$	$0^+(0^{-+})$	$f_2(2150)$	$0^+(2^{++})$
• $f_1(1420)$	$0^+(1^{++})$	$\rho(2150)$	$1^+(1^{--})$
• $\omega(1420)$	$0^-(1^{--})$	$f_0(2200)$	$0^+(0^{++})$
$f_2(1430)$	$0^+(2^{++})$	$f_J(2220)$	$0^+(2^{++}$ or $4^{++})$
• $a_0(1450)$	$1^-(0^{++})$		
• $\rho(1450)$	$1^+(1^{--})$	$\eta(2225)$	$0^+(0^{-+})$
• $\eta(1475)$	$0^+(0^{-+})$	$\rho_3(2250)$	$1^+(3^{--})$
• $f_0(1500)$	$0^+(0^{++})$	• $f_2(2300)$	$0^+(2^{++})$
$f_1(1510)$	$0^+(1^{++})$	$f_4(2300)$	$0^+(4^{++})$
• $f_2'(1525)$	$0^+(2^{++})$	• $f_2(2340)$	$0^+(2^{++})$
$f_2(1565)$	$0^+(2^{++})$	$\rho_5(2350)$	$1^+(5^{--})$
$h_1(1595)$	$0^-(1^{+-})$	$a_6(2450)$	$1^-(6^{++})$
• $\pi_1(1600)$	$1^-(1^{-+})$	$f_6(2510)$	$0^+(6^{++})$
$a_1(1640)$	$1^-(1^{++})$		
$f_2(1640)$	$0^+(2^{++})$		
• $\eta_2(1645)$	$0^+(2^{-+})$		
• $\omega(1650)$	$0^-(1^{--})$		
• $\omega_3(1670)$	$0^-(3^{--})$		

OTHER LIGHT

Further States

STRANGE ($S = \pm1$, $C = B = 0$)

	$I(J^P)$
• $K^\pm$	$1/2(0^-)$
• K^0	$1/2(0^-)$
• K_S^0	$1/2(0^-)$
• K_L^0	$1/2(0^-)$
$K_0^*(800)$	$1/2(0^+)$
• $K^*(892)$	$1/2(1^-)$
• $K_1(1270)$	$1/2(1^+)$
• $K_1(1400)$	$1/2(1^+)$
• $K^*(1410)$	$1/2(1^-)$
• $K_0^*(1430)$	$1/2(0^+)$
• $K_2^*(1430)$	$1/2(2^+)$
$K(1460)$	$1/2(0^-)$
$K_2(1580)$	$1/2(2^-)$
$K(1630)$	$1/2(?^?)$
$K_1(1650)$	$1/2(1^+)$
• $K^*(1680)$	$1/2(1^-)$
• $K_2(1770)$	$1/2(2^-)$
• $K_3^*(1780)$	$1/2(3^-)$
• $K_2(1820)$	$1/2(2^-)$
$K(1830)$	$1/2(0^-)$
$K_0^*(1950)$	$1/2(0^+)$
$K_2^*(1980)$	$1/2(2^+)$
• $K_4^*(2045)$	$1/2(4^+)$
$K_2(2250)$	$1/2(2^-)$
$K_3(2320)$	$1/2(3^+)$
$K_5^*(2380)$	$1/2(5^-)$
$K_4(2500)$	$1/2(4^-)$
$K(3100)$	$?^?(?^{??})$

CHARMED ($C = \pm1$)

• $D^\pm$	$1/2(0^-)$
• D^0	$1/2(0^-)$
• $D^*(2007)^0$	$1/2(1^-)$
• $D^*(2010)^\pm$	$1/2(1^-)$
• $D_1(2420)^0$	$1/2(1^+)$
$D_1(2420)^\pm$	$1/2(?^?)$
• $D_2^*(2460)^0$	$1/2(2^+)$
• $D_2^*(2460)^\pm$	$1/2(2^+)$
$D^*(2640)^\pm$	$1/2(?^?)$

CHARMED, STRANGE ($C = S = \pm1$)

• $D_s^\pm$	$0(0^-)$
• $D_s^{*\pm}$	$0(?^?)$
• $D_{sJ}^*(2317)^\pm$	$0(0^+)$
• $D_{sJ}(2460)^\pm$	$0(1^+)$
• $D_{s1}(2536)^\pm$	$0(1^+)$
• $D_{s2}(2573)^\pm$	$0(?^?)$

BOTTOM ($B = \pm1$)

	$I^G(J^{PC})$
• $B^\pm$	$1/2(0^-)$
• B^0	$1/2(0^-)$
• $B^\pm/B^0$ ADMIXTURE	
• $B^\pm/B^0/B_s^0/b$-baryon ADMIXTURE	
V_{cb} and V_{ub} CKM Matrix Elements	
• B^*	$1/2(1^-)$
$B_J^*(5732)$	$?(?^?)$

BOTTOM, STRANGE ($B = \pm1$, $S = \mp1$)

• B_s^0	$0(0^-)$
B_s^*	$0(1^-)$
$B_{sJ}^*(5850)$	$?(?^?)$

BOTTOM, CHARMED ($B = C = \pm1$)

• $B_c^\pm$	$0(0^-)$

$c\bar{c}$

• $\eta_c(1S)$	$0^+(0^{-+})$
• $J/\psi(1S)$	$0^-(1^{--})$
• $\chi_{c0}(1P)$	$0^+(0^{++})$
• $\chi_{c1}(1P)$	$0^+(1^{++})$
$h_c(1P)$	$?^?(?^{??})$
• $\chi_{c2}(1P)$	$0^+(2^{++})$
$\eta_c(2S)$	$0^+(0^{-+})$
• $\psi(2S)$	$0^-(1^{--})$
• $\psi(3770)$	$0^-(1^{--})$
$\psi(3836)$	$0^-(2^{--})$
$X(3872)$	$?^?(?^?)$
• $\psi(4040)$	$0^-(1^{--})$
• $\psi(4160)$	$0^-(1^{--})$
• $\psi(4415)$	$0^-(1^{--})$

$b\bar{b}$

$\eta_b(1S)$	$0^+(0^{-+})$
• $\Upsilon(1S)$	$0^-(1^{--})$
• $\chi_{b0}(1P)$	$0^+(0^{++})$
• $\chi_{b1}(1P)$	$0^+(1^{++})$
• $\chi_{b2}(1P)$	$0^+(2^{++})$
• $\Upsilon(2S)$	$0^-(1^{--})$
• $\chi_{b0}(2P)$	$0^+(0^{++})$
• $\chi_{b1}(2P)$	$0^+(1^{++})$
• $\chi_{b2}(2P)$	$0^+(2^{++})$
• $\Upsilon(3S)$	$0^-(1^{--})$
• $\Upsilon(4S)$	$0^-(1^{--})$
• $\Upsilon(10860)$	$0^-(1^{--})$
• $\Upsilon(11020)$	$0^-(1^{--})$

NON-$q\bar{q}$ CANDIDATES

NON-$q\bar{q}$ CANDIDATES

Particle Types

LEPTONS
B=0 L=1

fundamental fermions
no strong interaction
no substructure
spin = 1/2

ELECTRONS
Q=1

e m = 511 keV
μ 106 MeV
τ 1.8 GeV

NEUTRINOS
Q=0

ν_e m $\lesssim$ 1 eV
ν_μ
ν_τ

HADRONS
L=0

B baryon nr
L lepton nr
S strangeness

BARYONS
B=1

NUCLEONS
S=0

N = (n, p)

m_p = 938 MeV
$m_n - m_p$ = 1 MeV

p stable
$n \to p\, e^- \bar{\nu}_e$ τ = 886 s

HYPERONS
S=1

Σ^+ (1189) $\to N\, \pi$
Λ^0 (1116) $\to p\, \pi^-$
Ξ^- (1321) $\to \Lambda\, \pi^-$

$\tau \approx 10^{-10}$ s $c\tau \approx$ cm

MESONS
B=0

Pions = ($\pi^+\ \pi^0\ \pi^-$) **S=0**
$m(\pi^\pm)$ = 140 MeV
$m(\pi^0)$ = 135 MeV
$\pi^+ \to \mu^+\, \nu_\mu$ τ = 26 ns $c\tau$ = 8 m

Kaons = ($K^+\ K^0$) , ($K^-\ \bar{K}^0$) **S=1**

$m(K^\pm)$ = 494 MeV
$m(K^0)$ = 498 MeV
$K^+ \to \mu^+\, \nu_\mu$ τ = 12 ns $c\tau$ = 3 m

2.
Quark Model

Iso-Spin

- **observation:** level scheme of **mirror nuclei** similar:

  $^{15}_{7}N \equiv {}^{15}_{8}O \qquad {}^{14}_{6}C \; {}^{14}_{7}N \; {}^{14}_{8}O \qquad {}^{13}_{7}N \equiv {}^{13}_{6}C$

- **strong interactions symmetric** w.r.t. exchange $n \leftrightarrow p$?

  can we say: $n \equiv p$???

- **but:** $^{3}_{1}H \neq {}^{3}_{2}He$

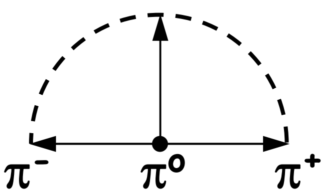
nn	≠	np = $^{2}_{1}H$	≠	pp
not binding		deuterium		repulsive

- **symmetry broken** by electromagnetic interaction:
  $(m_n - m_p) / m_p$ = 1 MeV / 1 GeV = 1 ‰ small
  p e = H atom bound system
  n e = not bound

- and by weak interaction: $n \rightarrow p \, e^- \, \nu_e$

- **Heisenberg 1932:** isotopic spin:
  rotations in 3D real vector space **SO(3)** (spin algebra) isomorphic to
  rotations in 2D complex vector space **SU(2)** (isospin algebra)

- **nucleons (n, p) I = 1/2 (2I+1) = 2 iso-doublet**
- **deuterium (n p) I = 0 (2I+1) = 1 iso-singlet**
- **pions (π^+ π^o π^-) I = 1 (2I+1) = 3 iso-triplet**



$I_3 = Q$

$I_3 = Q - B/2$ incl. nucleon baryon nr

- same **algebra** as for spin:

  Clebsch-Gordon coefficients give
  cross section and decay branching ratios. See exercises !

Clebsch-Gordon coefficients

- Quantum Mechanics: vector addition of angular momenta $j_1 \oplus j_2$:
- triangular condition: $|j_1 - j_2| < J < j_1 + j_2$ $M = m_1 + m_2$

$$|JM\rangle = \sum_{m_1, m_2} |j_1\, m_1\, j_2\, m_2\rangle \langle j_1\, m_1\, j_2\, m_2\, |JM\rangle$$

- multiplicity: $\sum_{j=|j_1-j_2|}^{j_1+j_2} (2j+1) = (2j_1+1)(2j_2+1)$
- normalization: $\sum_{m_1, m_2} |\langle j_1\, m_1\, j_2\, m_2\, |JM\rangle|^2 = 1$ =>

$$\langle j_1 m_1 j_2 m_2 | jm \rangle = \delta_{m_1+m_2,m} \sqrt{\frac{(j_1+j_2-j)!(j+j_1-j_2)!(j+j_2-j_1)!(2j+1)}{(j+j_1+j_2+1)!}}$$
$$\times \sum_k \frac{(-1)^k \sqrt{(j_1+m_1)!(j_1-m_1)!(j_2+m_2)!(j_2-m_2)!(j+m)!(j-m)!}}{k!(j_1+j_2-j-k)!(j_1-m_1-k)!(j_2+m_2-k)!(j-j_2+m_1+k)!(j-j_1-m_2+k)!}$$

Wigner 1931
Racah 1942

- Abramowitz, M. and Stegun, I.A. (Eds.). "Vector-Addition Coefficients." § 27.9 in "Handbook of Mathematical Functions with Formulas, Graphs, and Mathematical Tables", 9th printing. New York: Dover, pp. 1006-1010, 1972.
- Condon, E.U. and Shortley, G. § 3.6-3.14 in "The Theory of Atomic Spectra." Cambridge, England: Cambridge University Press, pp. 56-78, 1951.
- Messiah, A. "Clebsch-Gordan Coefficients and 3j Symbols." Appendix C.I in "Quantum Mechanics", Vol. 2. Amsterdam, Netherlands: North-Holland, pp. 1054-1060, 1962.

Clebsch-Gordon coefficients

$J_1 x J_2$

$J = J_1 \otimes J_2$

$M = m_1 + m_2$

Notation:

m_1	m_2	J M	J M	...
m_1	m_2	Coefficients		
.	.			

1/2×1/2

m_1	m_2	J=1, M=+1
+1/2	+1/2	1

m_1	m_2	J=1, M=0	J=0, M=0
+1/2	−1/2	1/2	1/2
−1/2	+1/2	1/2	−1/2

m_1	m_2	J=1, M=−1
−1/2	−1/2	1

1×1/2

m_1	m_2	J=3/2, M=+3/2
+1	+1/2	1

m_1	m_2	J=3/2, M=+1/2	J=1/2, M=+1/2
+1	−1/2	1/3	2/3
0	+1/2	2/3	−1/3

m_1	m_2	J=3/2, M=−1/2	J=1/2, M=−1/2
0	−1/2	2/3	1/3
−1	+1/2	1/3	−2/3

m_1	m_2	J=3/2, M=−3/2
−1	−1/2	1

2×1

m_1	m_2	J=3, M=+3
+2	+1	1

m_1	m_2	J=3, M=+2	J=2, M=+2
+2	0	1/3	2/3
+1	+1	2/3	−1/3

m_1	m_2	J=3, M=+1	J=2, M=+1	J=1, M=+1
+2	−1	1/15	1/3	3/5
+1	0	8/15	1/6	−3/10
0	+1	6/15	−1/2	1/10

m_1	m_2	J=3, M=0	J=2, M=0	J=1, M=0
+1	−1	1/5	1/2	3/10
0	0	3/5	0	−2/5
−1	+1	1/5	−1/2	3/10

m_1	m_2	J=3, M=−1	J=2, M=−1	J=1, M=−1
0	−1	6/15	1/2	1/10
−1	0	8/15	−1/6	−3/10
−2	+1	1/15	−1/3	3/5

m_1	m_2	J=3, M=−2	J=2, M=−2
−1	−1	2/3	1/3
−2	0	1/3	−2/3

m_1	m_2	J=3, M=−3
−2	−1	1

1×1

m_1	m_2	J=2, M=+2
+1	+1	1

m_1	m_2	J=2, M=+1	J=1, M=+1
+1	0	1/2	1/2
0	+1	1/2	−1/2

m_1	m_2	J=2, M=0	J=1, M=0	J=0, M=0
+1	−1	1/6	1/2	1/3
0	0	2/3	0	−1/3
−1	+1	1/6	−1/2	1/3

m_1	m_2	J=2, M=−1	J=1, M=−1
0	−1	1/2	1/2
−1	0	1/2	−1/2

m_1	m_2	J=2, M=−2
−1	−1	1

2×1/2

m_1	m_2	J=5/2, M=+5/2
+2	1/2	1

m_1	m_2	J=5/2, M=+3/2	J=3/2, M=+3/2
+2	−1/2	1/5	4/5
+1	+1/2	4/5	−1/5

m_1	m_2	J=5/2, M=+1/2	J=3/2, M=+1/2
+1	−1/2	2/5	3/5
0	+1/2	3/5	−2/5

m_1	m_2	J=5/2, M=−1/2	J=3/2, M=−1/2
0	−1/2	3/5	2/5
−1	+1/2	2/5	−3/5

m_1	m_2	J=5/2, M=−3/2	J=3/2, M=−3/2
−1	−1/2	4/5	1/5
−2	+1/2	1/5	−4/5

m_1	m_2	J=5/2, M=−5/2
−2	−1/2	1

3/2×1/2

m_1	m_2	J=2, M=+2
+3/2	+1/2	1

m_1	m_2	J=2, M=+1	J=1, M=+1
+3/2	−1/2	1/4	3/4
+1/2	+1/2	3/4	−1/4

m_1	m_2	J=2, M=0	J=1, M=0
+1/2	−1/2	1/2	1/2
−1/2	+1/2	1/2	−1/2

m_1	m_2	J=2, M=−1	J=1, M=−1
−1/2	−1/2	3/4	1/4
−3/2	+1/2	1/4	−3/4

m_1	m_2	J=2, M=−2
−3/2	−1/2	1

3/2×1

m_1	m_2	J=5/2, M=+5/2
+3/2	+1	1

m_1	m_2	J=5/2, M=+3/2	J=3/2, M=+3/2
+3/2	0	2/5	3/5
+1/2	+1	3/5	−2/5

m_1	m_2	J=5/2, M=+1/2	J=3/2, M=+1/2	J=1/2, M=+1/2
+3/2	−1	1/10	2/5	1/2
+1/2	0	3/5	1/15	−1/3
−1/2	+1	3/10	−8/15	1/6

m_1	m_2	J=5/2, M=−1/2	J=3/2, M=−1/2	J=1/2, M=−1/2
+1/2	−1	3/10	8/15	1/6
−1/2	0	3/5	−1/15	−1/3
−3/2	+1	1/10	−2/5	1/2

m_1	m_2	J=5/2, M=−3/2	J=3/2, M=−3/2
−1/2	−1	3/5	2/5
−3/2	0	2/5	−3/5

m_1	m_2	J=5/2, M=−5/2
−3/2	−1	1

3/2×3/2

m_1	m_2	J=3, M=+3
+3/2	+3/2	1

m_1	m_2	J=3, M=+2	J=2, M=+2
+3/2	+1/2	1/2	1/2
+1/2	+3/2	1/2	−1/2

m_1	m_2	J=3, M=+1	J=2, M=+1	J=1, M=+1
+3/2	−1/2	1/5	1/2	3/10
+1/2	+1/2	3/5	0	−2/5
[cut off]				

		J=3	J=2	J=1	J=0
[cut off]					

2×3/2

m_1	m_2	J=7/2, M=+7/2
+2	+3/2	1

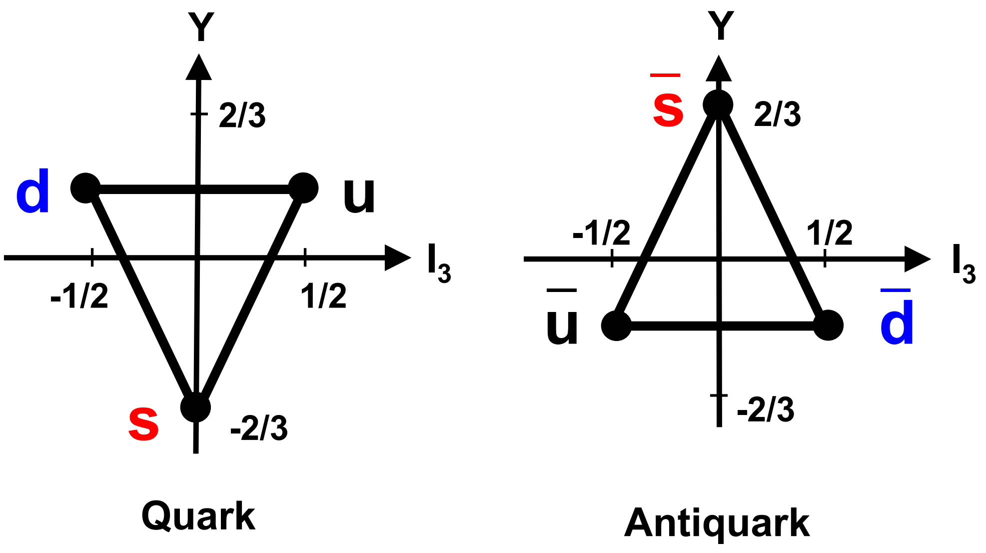
m_1	m_2	J=7/2, M=+5/2	J=5/2, M=+5/2
+2	+1/2	3/7	4/7
[cut off]			

		J=7/2	J=5/2	J=3/2
[cut off]				

Quarks

Quark	Q	I_3	B	S	Y
u	+2/3	+1/2		0	+1/3
d	-1/3	- 1/2	1/3	0	+1/3
s	-1/3	0		-1	-2/3

spin
$J = 1/2$



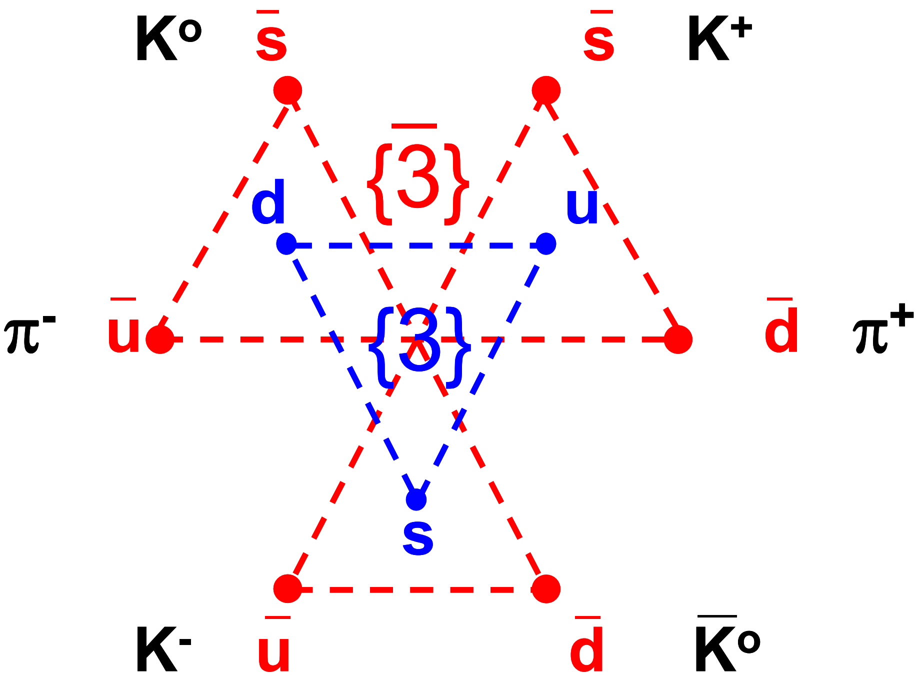
$Y = B + S$ hypercharge

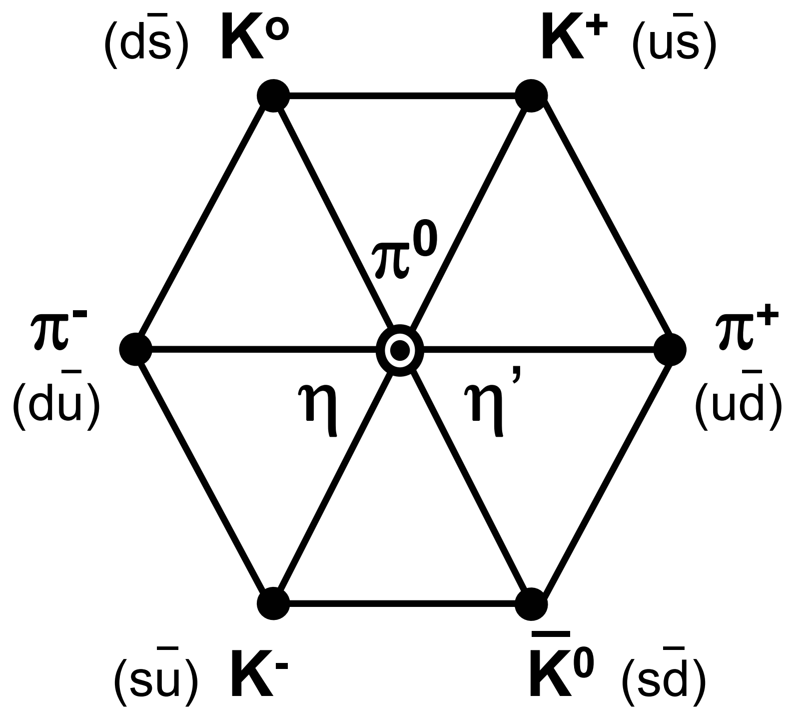
$I_3 = Q - Y/2$ Gell-Mann - Nishijima rule

Meson Octet

$$\{q\} \otimes \{\bar{q}\} = \nabla \otimes \Delta = \{2\} \otimes \{\bar{2}\} = \{1\} \oplus \{3\} \quad \text{in SU(2)}$$

$$= \{3\} \otimes \{\bar{3}\} = \{1\} \oplus \{8\} \quad \text{in SU(3)}$$

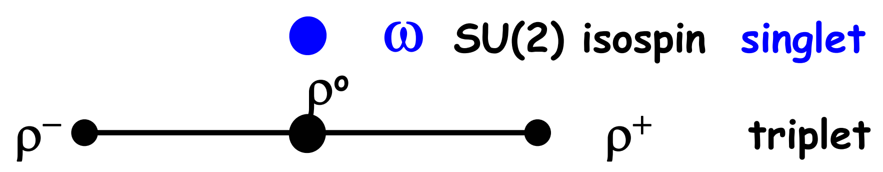




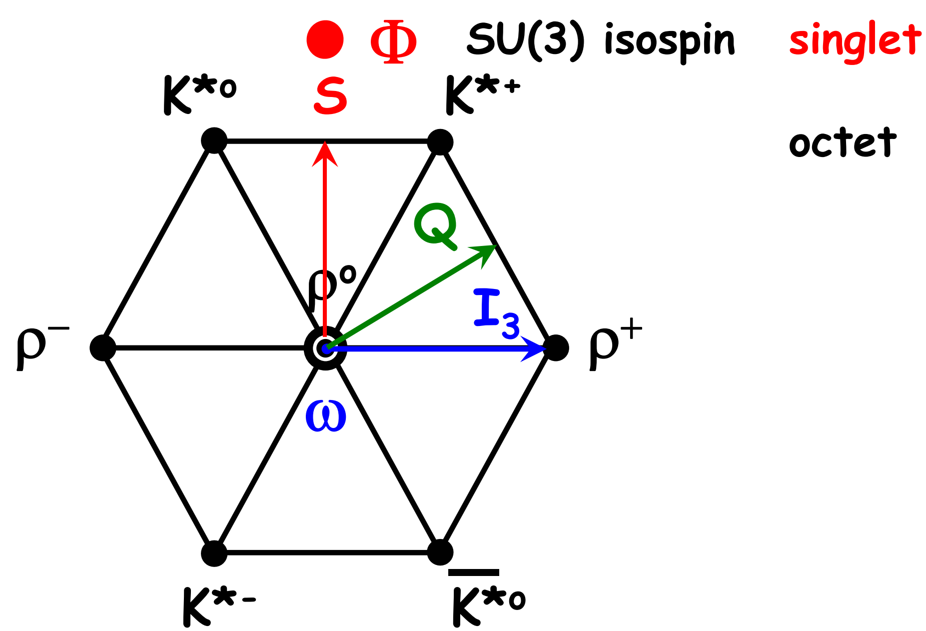
Meson Octet

$= \{q\} \otimes \{\bar{q}\} = \nabla \otimes \Delta$

$= \{2\} \otimes \{\bar{2}\} = \{1\} \oplus \{3\}$ in **SU(2)**



$= \{3\} \otimes \{\bar{3}\} = \{1\} \oplus \{8\}$ in **SU(3)**



hyper-charge
$Y = B + S$

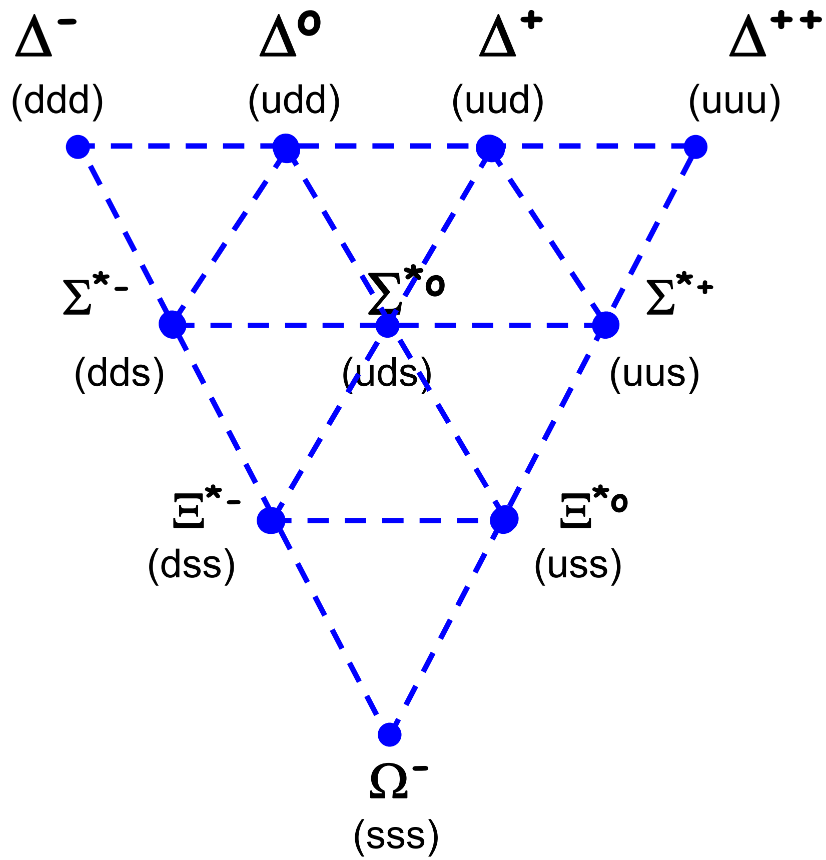
Gell-Mann - Nishijima:
$I_3 = Q - Y/2$

Baryon Decuplet

$= \{q\} \otimes \{q\} \otimes \{q\} = \nabla \otimes \nabla \otimes \nabla$

$= \{2\} \otimes \{2\} \otimes \{2\} = \{2\} \oplus \{2\} \oplus \{4\}$ in SU(2)

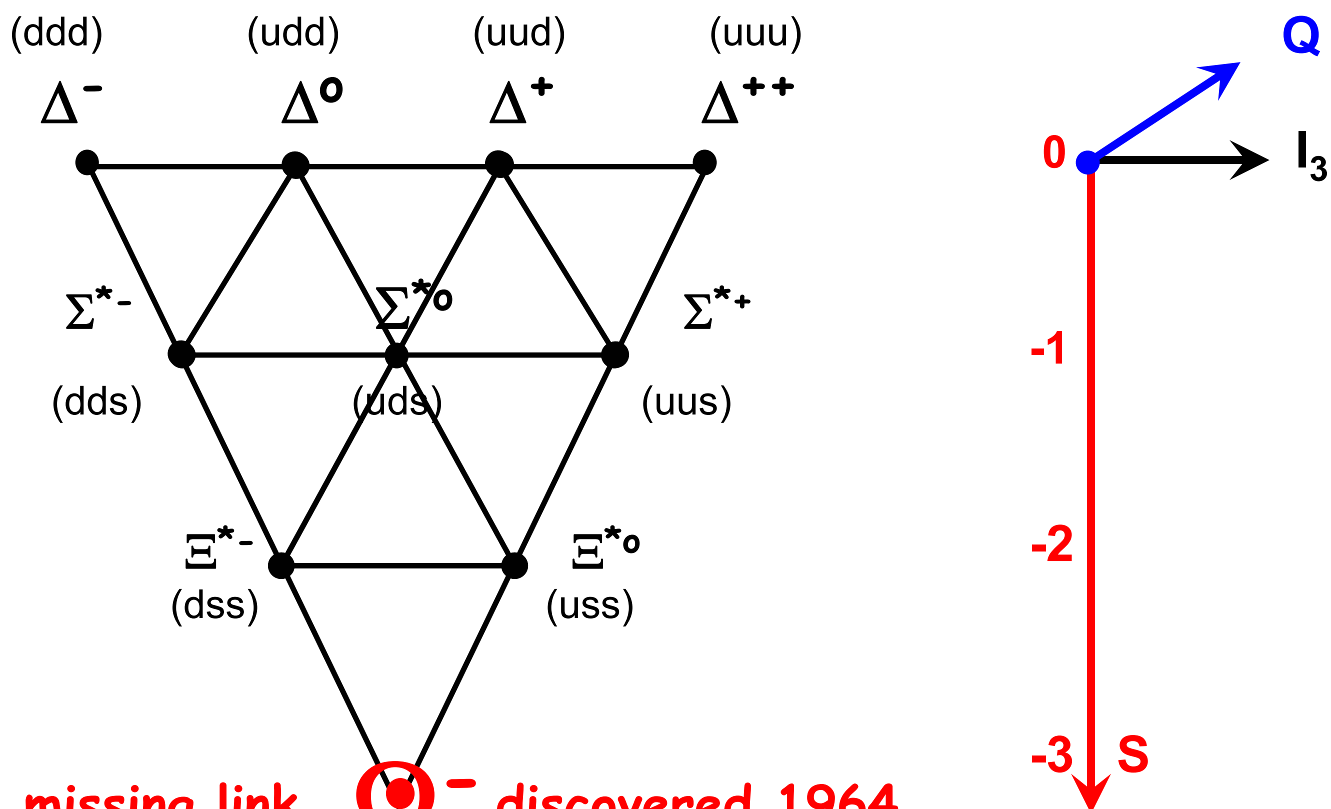
$= \{3\} \otimes \{3\} \otimes \{3\} = \{1\} \oplus \{8\} \oplus \{8\} \oplus \{10\}$ in SU(3)



{4} in SU(2)

{10} in SU(3)

Baryon Decuplet



the missing link Ω^- discovered 1964

(sss)

in Brookhaven 80 inch bubble chamber

Nobel prizes:

1968 Alvarez for bubble chamber
1969 Gell-Mann for quark model

Quarks

Three quarks for Muster Mark!
Sure he hasn't got much of a bark
And sure any he has it's all beside the mark.

James Joyce, Finnegan's Wake, Book 2, Episode 4, Page 383.
Poem against King Mark, cuckolded husband in the Tristan legend.

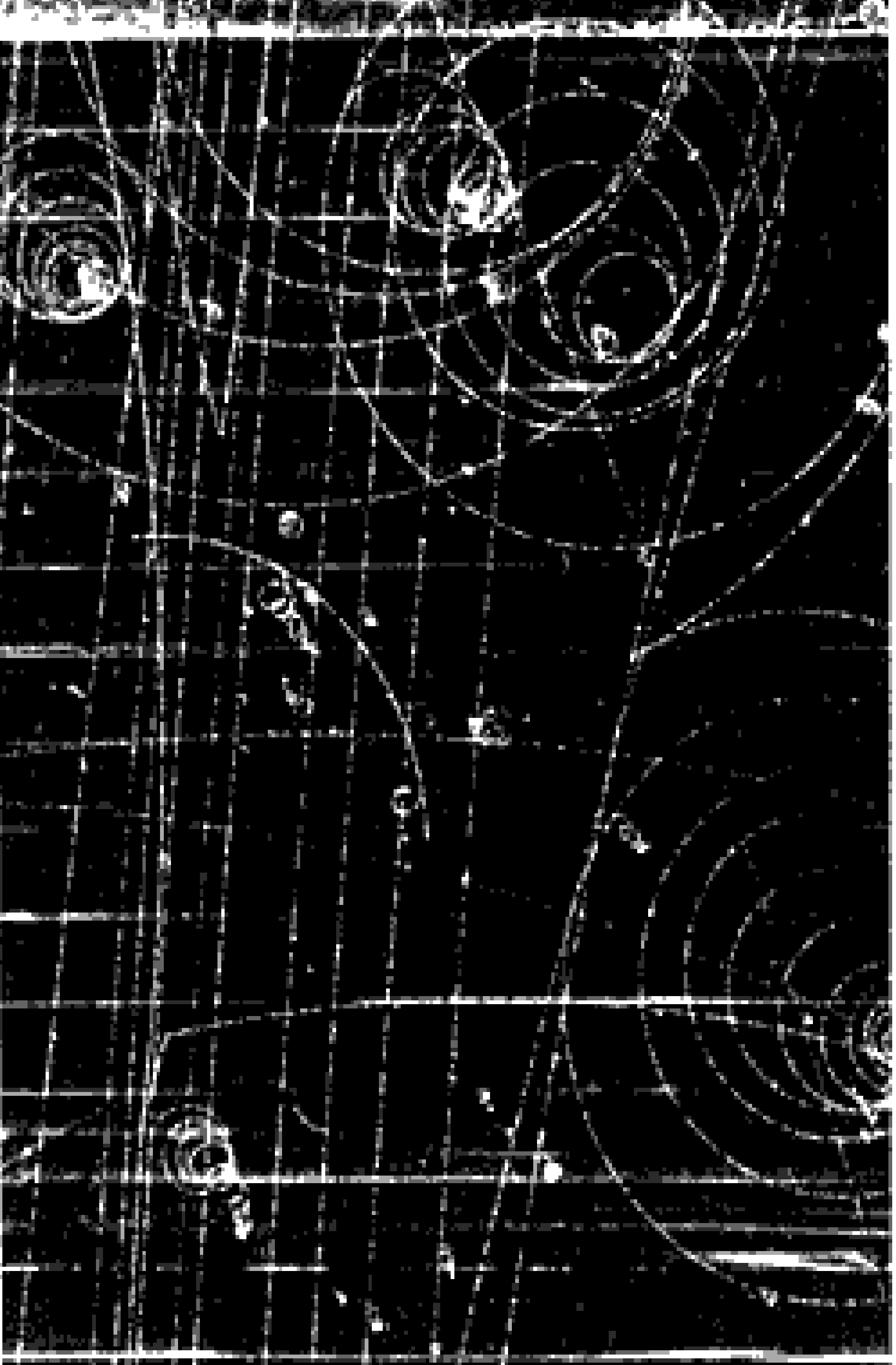
Nobel prize 1969

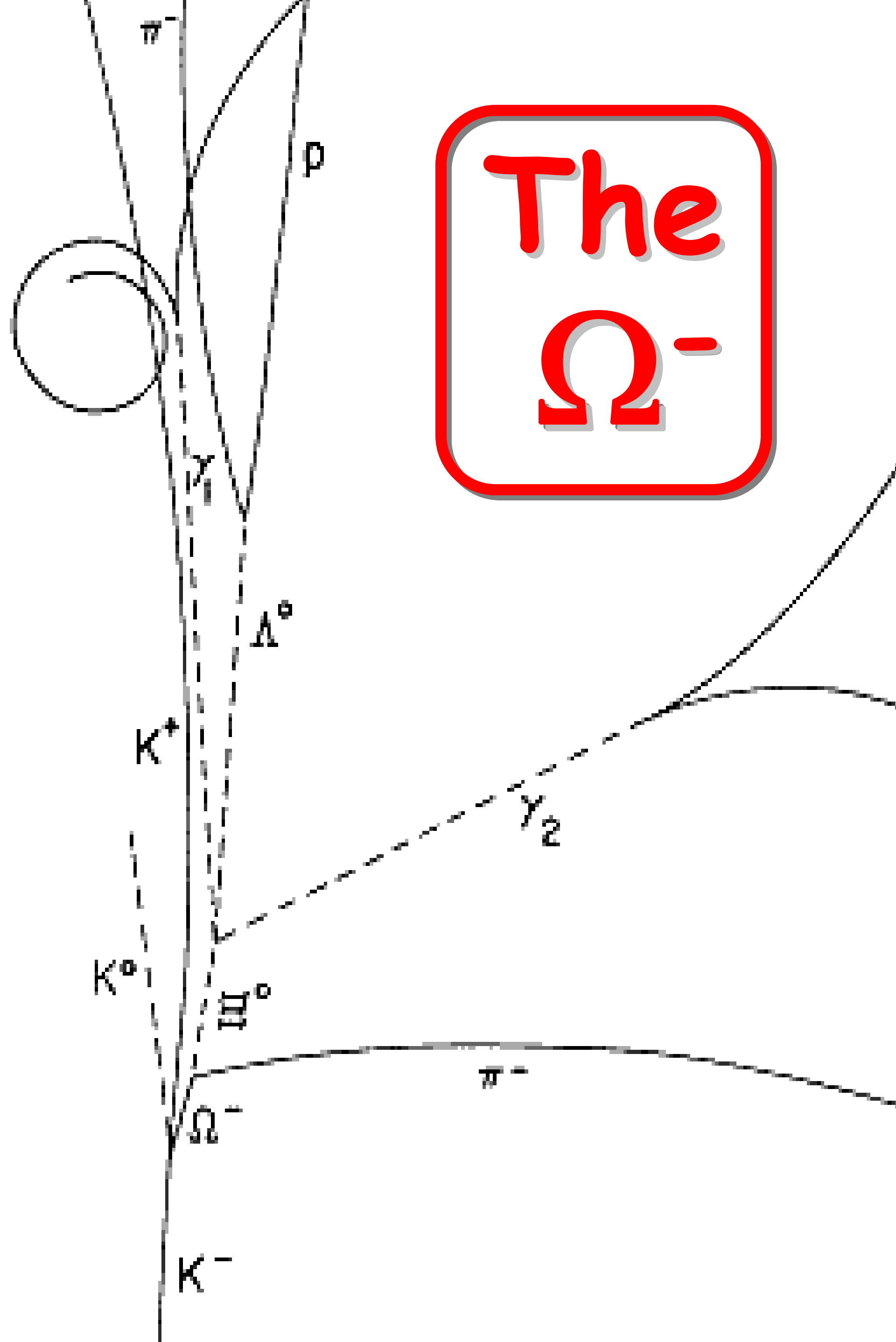
The allusion to three quarks seemed perfect ...
by supposing that one ingredient of the line
'Three quarks for Muster Mark'
was a cry of 'Three quarts for Mister Mark'
heard in H.C. Earwicker's pub.

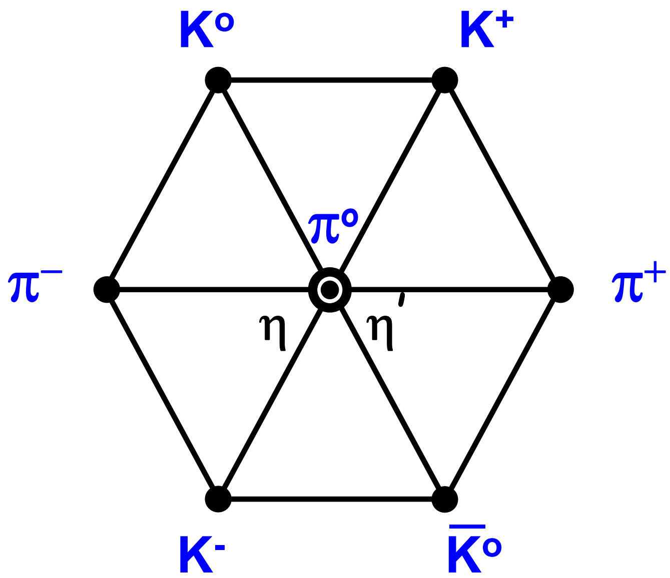
M. Gell-Mann
for quark model

Murray Gell-Mann, private Letter to the Editor
of the Oxford English Dictionary, June 27, 1978 .

The Ω^-





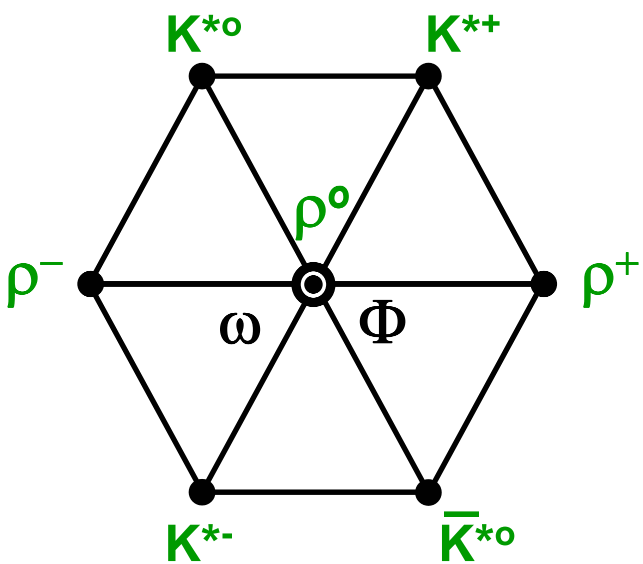


PSEUDO-SCALAR

↑ ↓ $J^P = 0^{-+}$

weak / elm. decay

The Spin



VECTOR

↑ ↑ $J^P = 1^-$

strong decay

The Quark Model

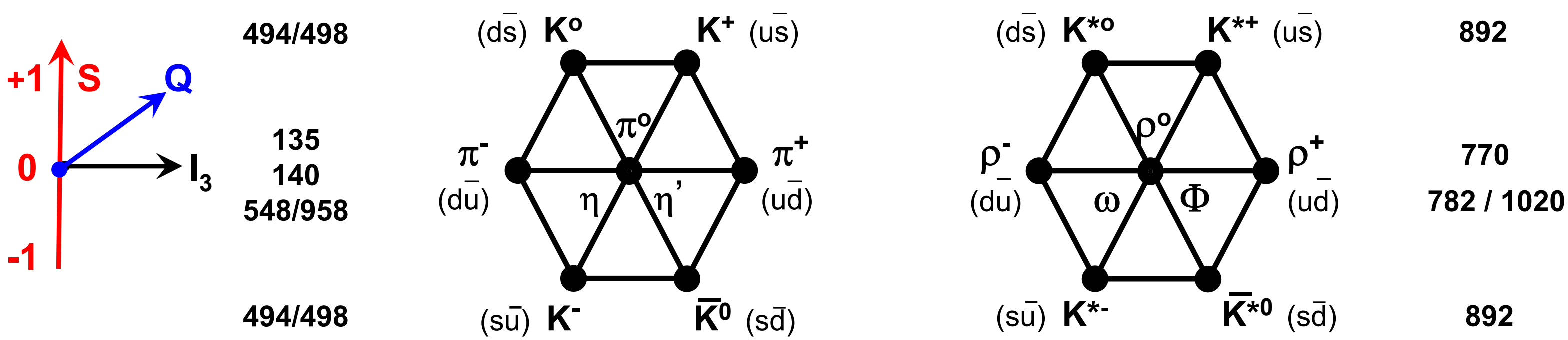
MESONS

Mass MeV

$J^P = 0^-$ (↑↓)

$J^P = 1^-$ (↑↑)

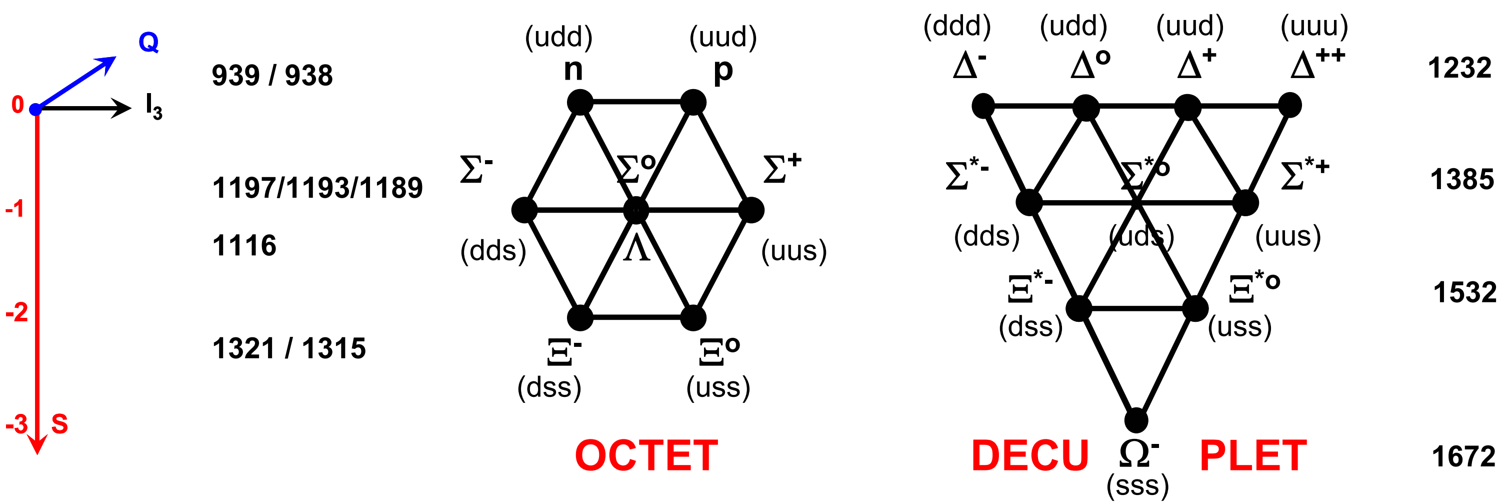
Mass MeV



BARYONS

$J^P = 1/2^+$ (↑↓↑)

$J^P = 3/2^+$ (↑↑↑)

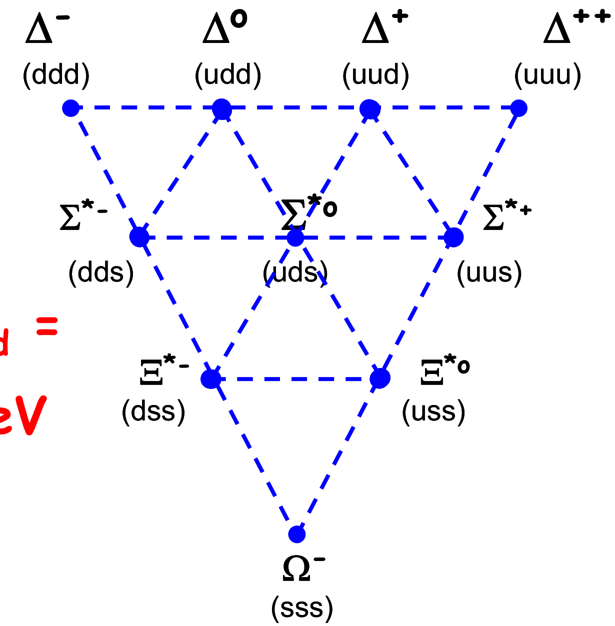


Quark Masses

1. $M_{\Sigma^-} + M_{\Sigma^\circ} - 2\ M_{\Sigma^+} = 3m_d - 3m_u = 11$ MeV

   (dds) + (uds) - 2 (uus) = 3 d - 3 u

   $m_d - m_u \sim$ MeV



2. decuplet equal spacing rule:

   $M_{\Omega} - M_{\Xi^*} = M_{\Xi^*} - M_{\Sigma^*} = M_{\Sigma^*} - M_{\Delta} = m_s - m_d =$

   142 ~ 145 ~ 153 ~ 145 MeV

3. Gell-Mann–Okubo mass relation:

   $3\ M_{\Lambda} + M_{\Sigma} = 2\ (M_N + M_{\Xi})$

   3 (uds) + (uds) = 2 [(uud) + (dss)]

Hadron Spectroscopy

$SU(N)_F \otimes O(3)$: N flavors ⊗ spatial excitations

1. S hyperfine splitting: energy of spin flip:

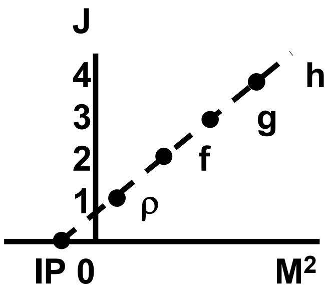
↑↑		↑↓	mass split / GeV
K^*	-	K	~ 0.4
↑↑↑		↑↓↑	
Δ	-	N	~ 0.3
Σ^*	-	Σ	~ 0.2 ~ Ξ^* - Ξ

$$M_{\Sigma*} - M_{\Sigma} = M_{\Xi*} - M_{\Xi} = M_{\Delta} - M_N$$

196 ~ 214 ~ 294 MeV

2. L orbital momentum: $J = L + S \sim M^2$

Regge theory:



3. N radial excitations:

$\rho' - \rho$ dm ~ 0.5 GeV

heavy quarks: non-relativistic potential: harmonic oscillator:

$\Psi' - \Psi$ dm ~ 0.6 GeV

$\Psi'' - \Psi'$

$\Upsilon' - \Upsilon$

Spectroscopy of light mesons

$n\,^{2s+1}\ell_J$	J^{PC}	I = 1 $ud,\ \bar{u}d,\ \frac{1}{\sqrt{2}}(d\bar{d}-u\bar{u})$	I = $\frac{1}{2}$ $u\bar{s},\ d\bar{s};\ \bar{d}s,\ -\bar{u}s$	I = 0 f'	I = 0 f	$\theta_{\rm quad}$ [°]	$\theta_{\rm lin}$ [°]
$1\,^1S_0$	0^{-+}	π	K	η	$\eta'(958)$	−11.5	−24.6
$1\,^3S_1$	1^{--}	$\rho(770)$	$K^*(892)$	$\phi(1020)$	$\omega(782)$	38.7	36.0
$1\,^1P_1$	1^{+-}	$b_1(1235)$	$K_{1B}{}^\dagger$	$h_1(1380)$	$h_1(1170)$		
$1\,^3P_0$	0^{++}	$a_0(1450)$	$K_0^*(1430)$	$f_0(1710)$	$f_0(1370)$		
$1\,^3P_1$	1^{++}	$a_1(1260)$	$K_{1A}{}^\dagger$	$f_1(1420)$	$f_1(1285)$		
$1\,^3P_2$	2^{++}	$a_2(1320)$	$K_2^*(1430)$	$f_2'(1525)$	$f_2(1270)$	29.6	28.0
$1\,^1D_2$	2^{-+}	$\pi_2(1670)$	$K_2(1770)^\dagger$	$\eta_2(1870)$	$\eta_2(1645)$		
$1\,^3D_1$	1^{--}	$\rho(1700)$	$K^*(1680)^\ddagger$		$\omega(1650)$		
$1\,^3D_2$	2^{--}		$K_2(1820)^\ddagger$				
$1\,^3D_3$	3^{--}	$\rho_3(1690)$	$K_3^*(1780)$	$\phi_3(1850)$	$\omega_3(1670)$	32.0	31.0
$1\,^3F_4$	4^{++}	$a_4(2040)$	$K_4^*(2045)$		$f_4(2050)$		
$1\,^3G_5$	5^{--}	$\rho_5(2350)$					
$1\,^3H_6$	6^{++}	$a_6(2450)$			$f_6(2510)$		
$2\,^1S_0$	0^{-+}	$\pi(1300)$	$K(1460)$	$\eta(1475)$	$\eta(1295)$	−22.4	−22.6
$2\,^3S_1$	1^{--}	$\rho(1450)$	$K^*(1410)^\ddagger$	$\phi(1680)$	$\omega(1420)$		

Heavy Quarks

flavor =

property to be up, down, strange, … quark

N flavors

SU(N) flavor space =

unitary N-dim. complex vector space

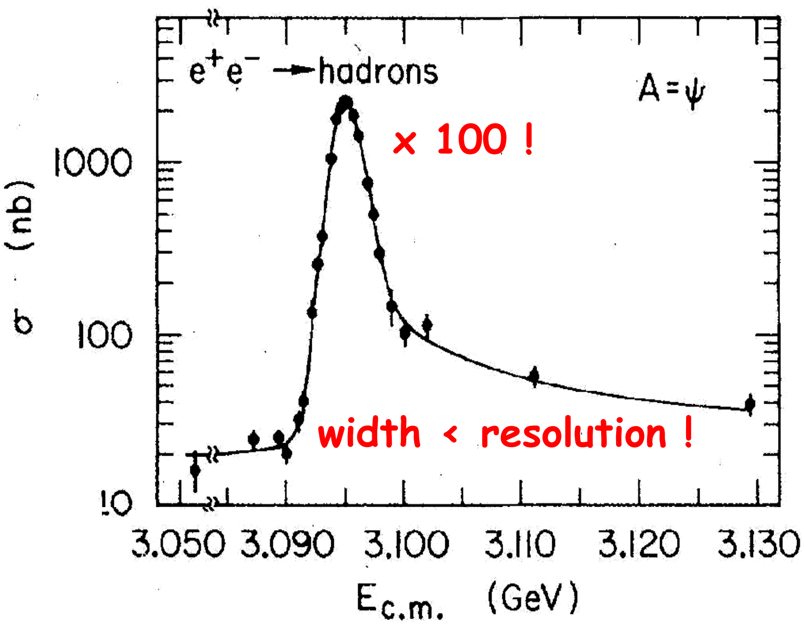
from SU(3) to SU(N):

Charm

discovered
1974

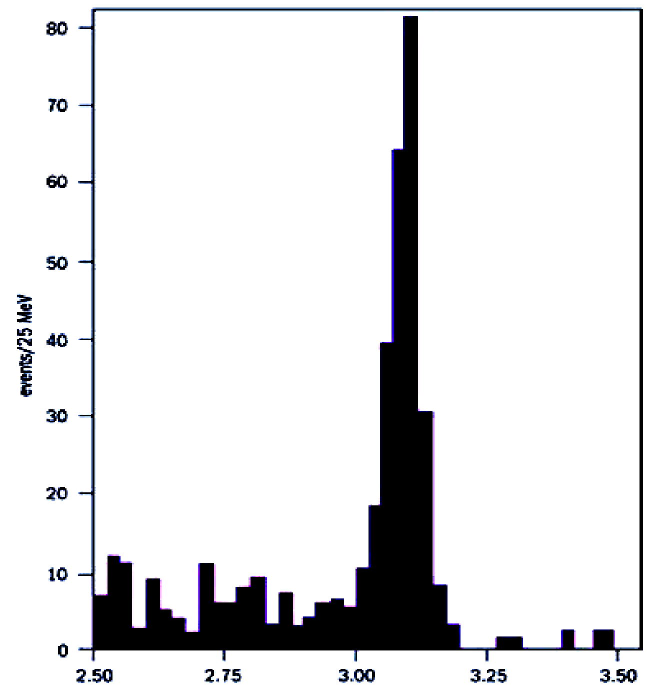
B. Richter

S. Ting



Nobel

Prize
1976



$e^+ e^- \rightarrow \Psi \rightarrow$ hadrons

3.1 GeV

MARK-I @ SPEAR

Stanford Linear Accelerator Lab.

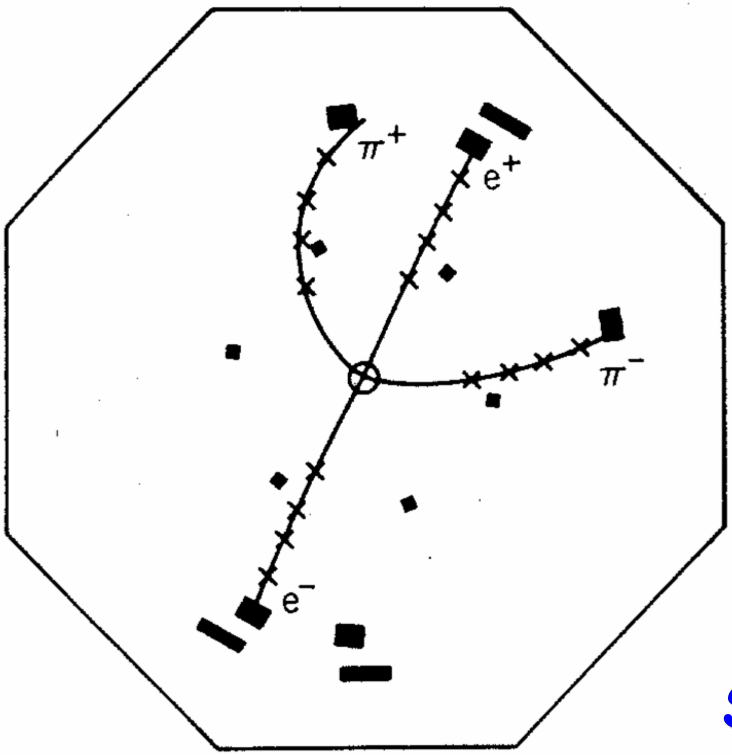
$p\,Be \rightarrow J\,X \rightarrow e^+ e^- X$

28.5 GeV

double arm spectrometer @ AGS

Brookhaven National Lab.

Charmonium



$e^+e^- \rightarrow \Psi' \rightarrow \Psi\ \pi^+\ \pi^-$

$\quad\quad\quad\quad\quad\quad \hookrightarrow e^+\ e^-$

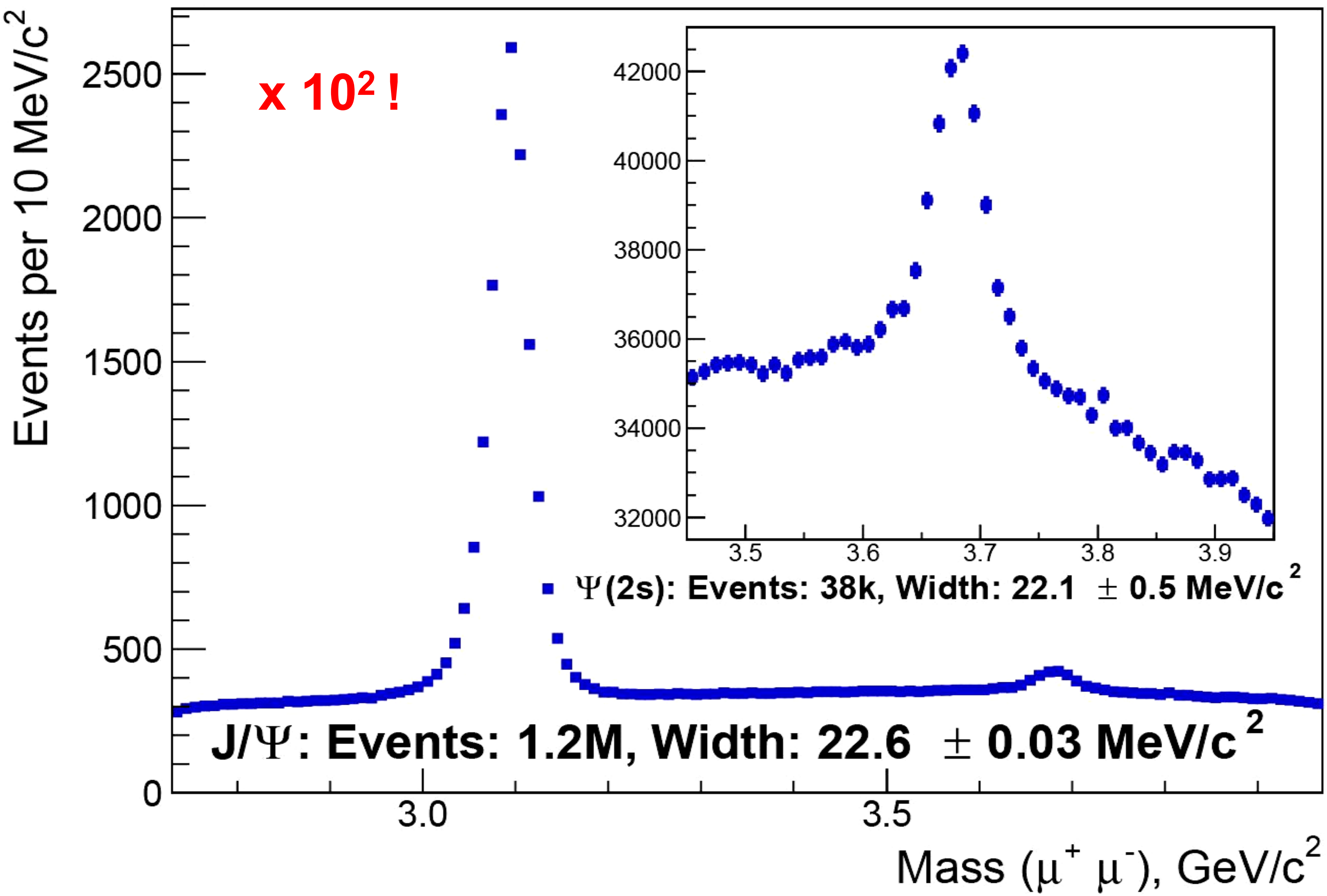
m_Ψ = 3.1 GeV

m_c = 1.5 GeV

MARK-I @ SPEAR 1975

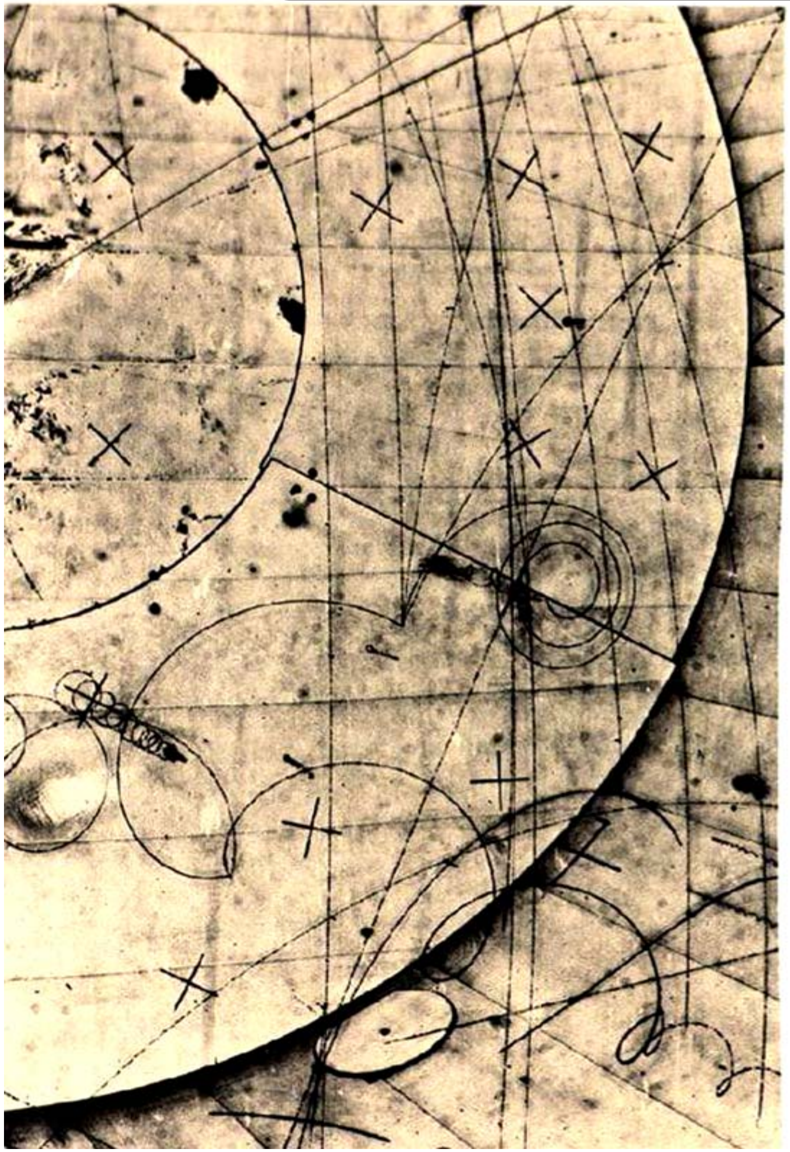
Stanford Linear Accelerator Lab.

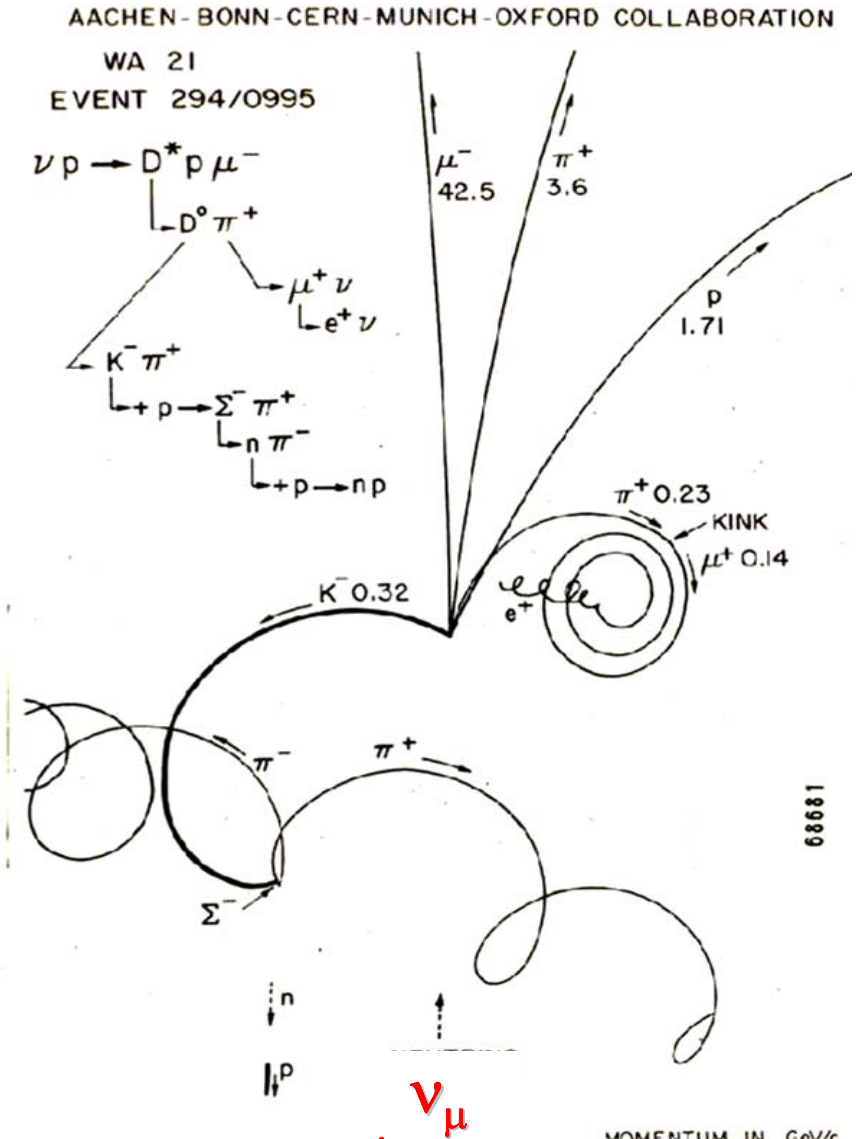
Charm



x 10² !
Events per 10 MeV/c²
2500
2000
1500
1000
500
0
3.0
3.5
Mass (μ⁺ μ⁻), GeV/c²
42000
40000
38000
36000
34000
32000
3.5
3.6
3.7
3.8
3.9
Ψ(2s): Events: 38k, Width: 22.1 ± 0.5 MeV/c²
J/Ψ: Events: 1.2M, Width: 22.6 ± 0.03 MeV/c²

Open Charm Decay





ν_{μ} beam

production flavor violating = weak

Open Charm Decay

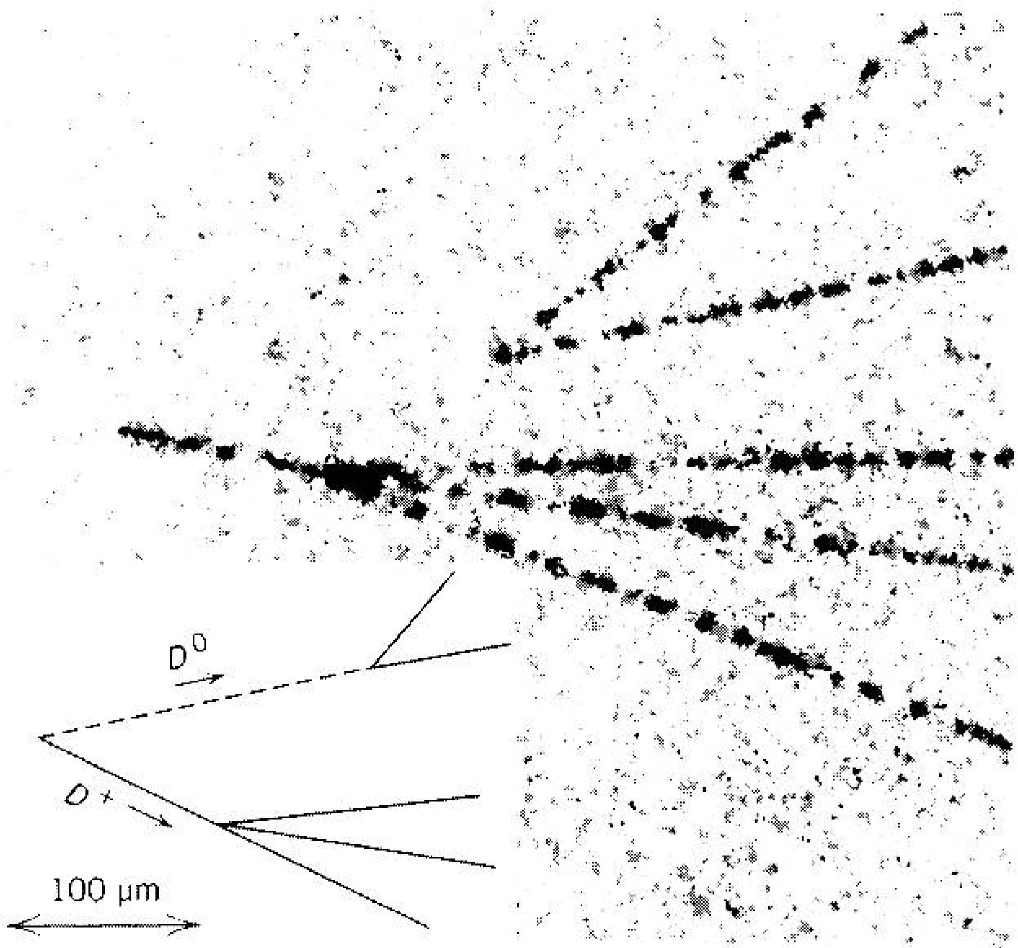


FIGURE 18-11 Example of *D* meson decays observed in a bubble chamber.
From K. Abe et al., *Phys. Rev. Lett.* **48**, 1526 (1982).

$D^0 \rightarrow K^- \ \pi^+$

τ = 0.4 ps

$c\tau$ = 123 μm

$D^+ \rightarrow K^+ \pi^+ \pi^-$

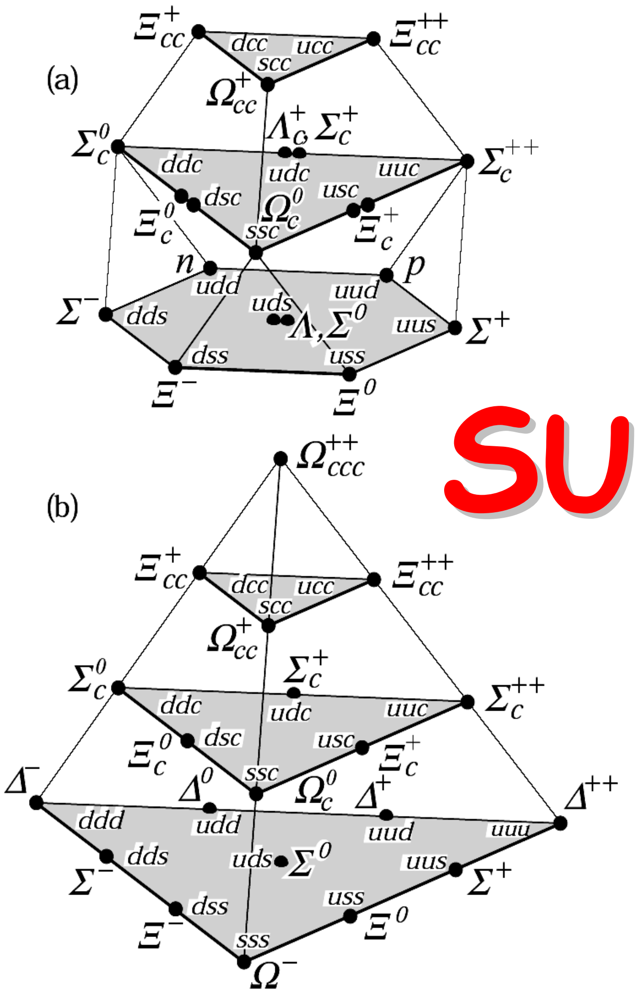
τ = 1.0 ps

$c\tau$ = 315 μm

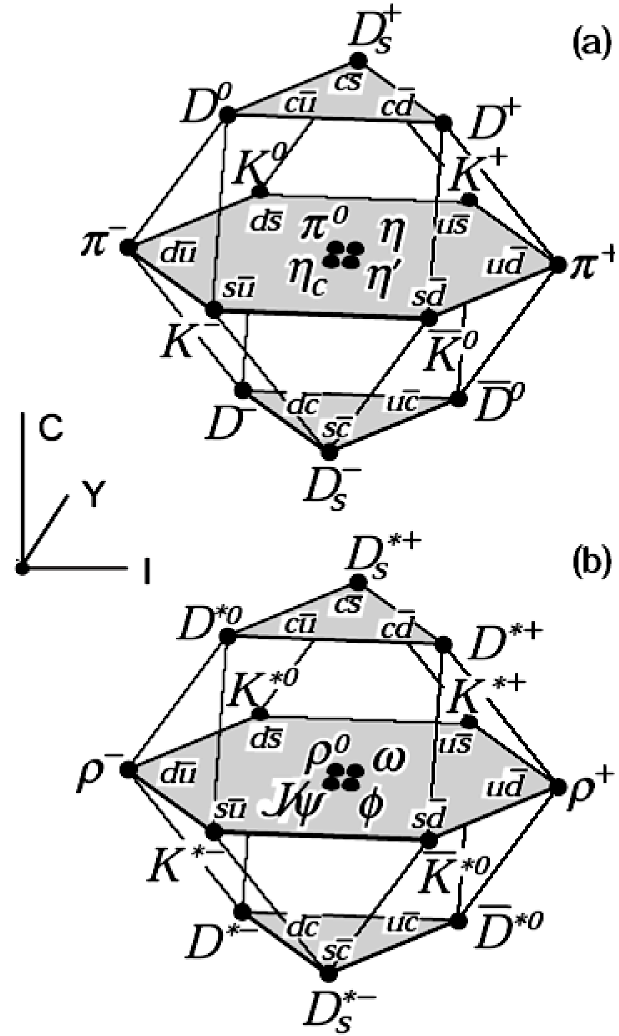
Charm Spectroscopy

J=1/2
↑ ↓ ↑

J=3/2
↑ ↑ ↑



SU(4)



J=0
↑ ↓

J=1
↑ ↑

Baryons

Mesons

Beauty

discovered 1977 by

L. Lederman et al.

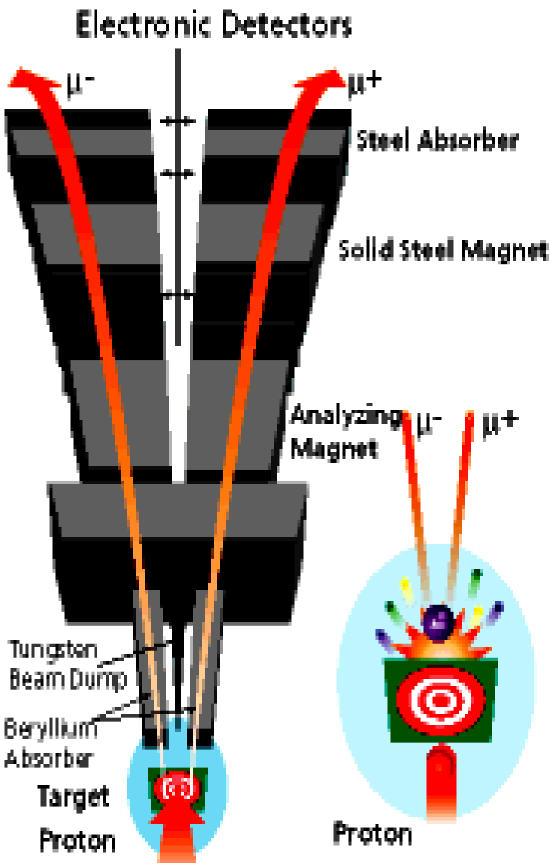
$p\,N \rightarrow \mu^+\mu^-\,X$

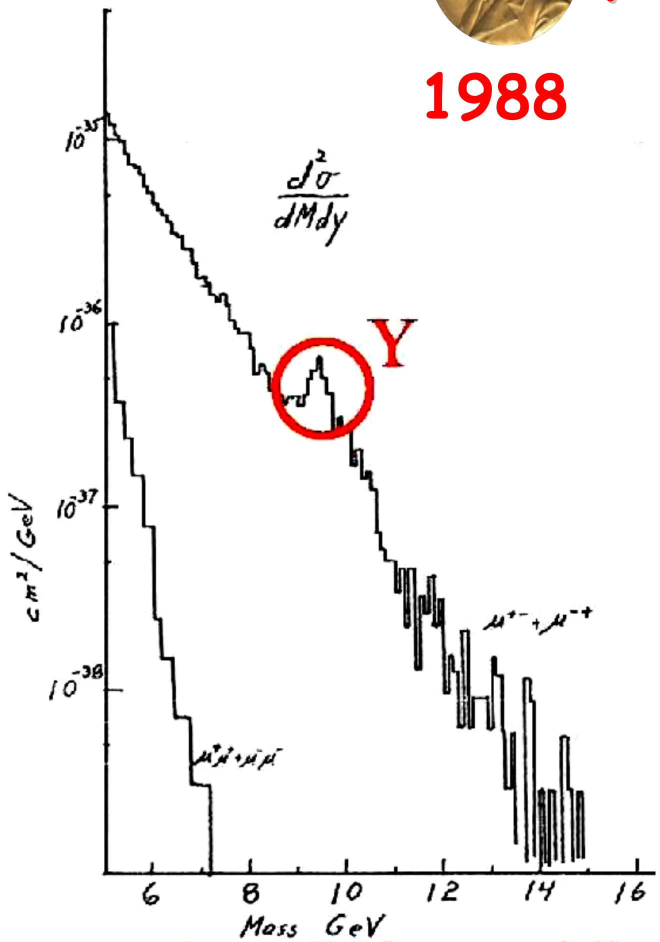
Fermilab, USA

Nobel  prize

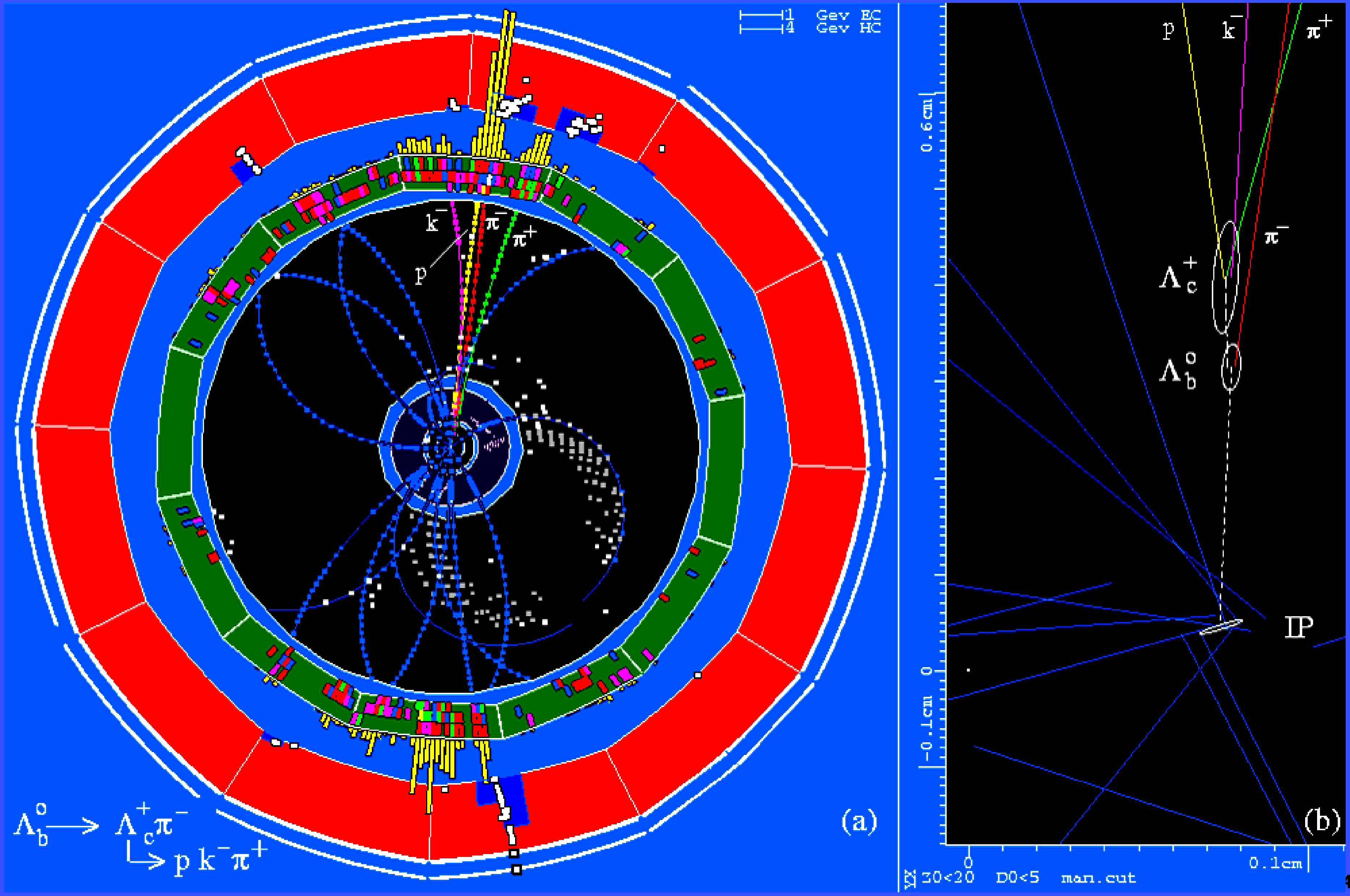
1988

L.Lederman





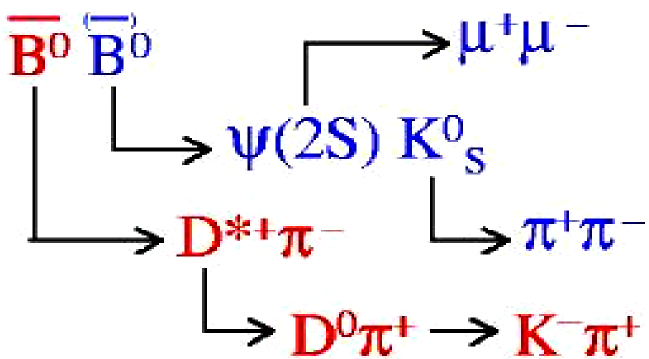
Heavy Quark Decays

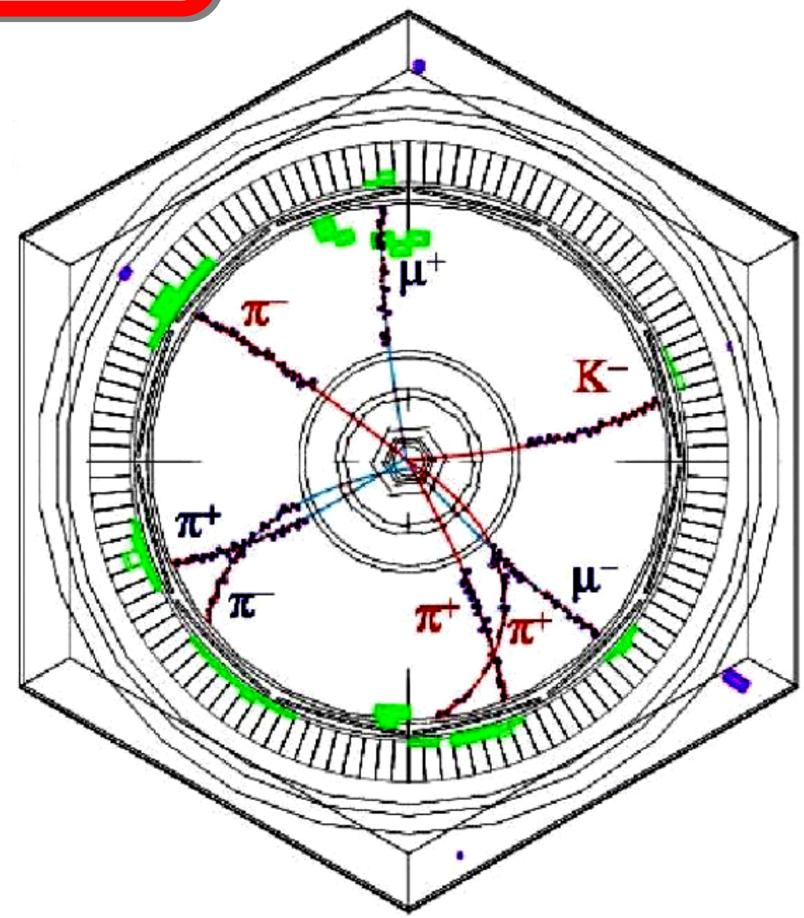


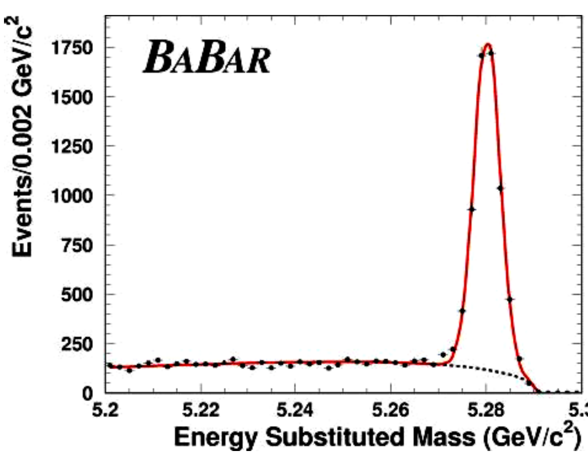
Bottom quark

BaBar @ PEP, SLAC: $e^+e^- \rightarrow$

$\Upsilon(4S, \bar{b}b) \rightarrow$



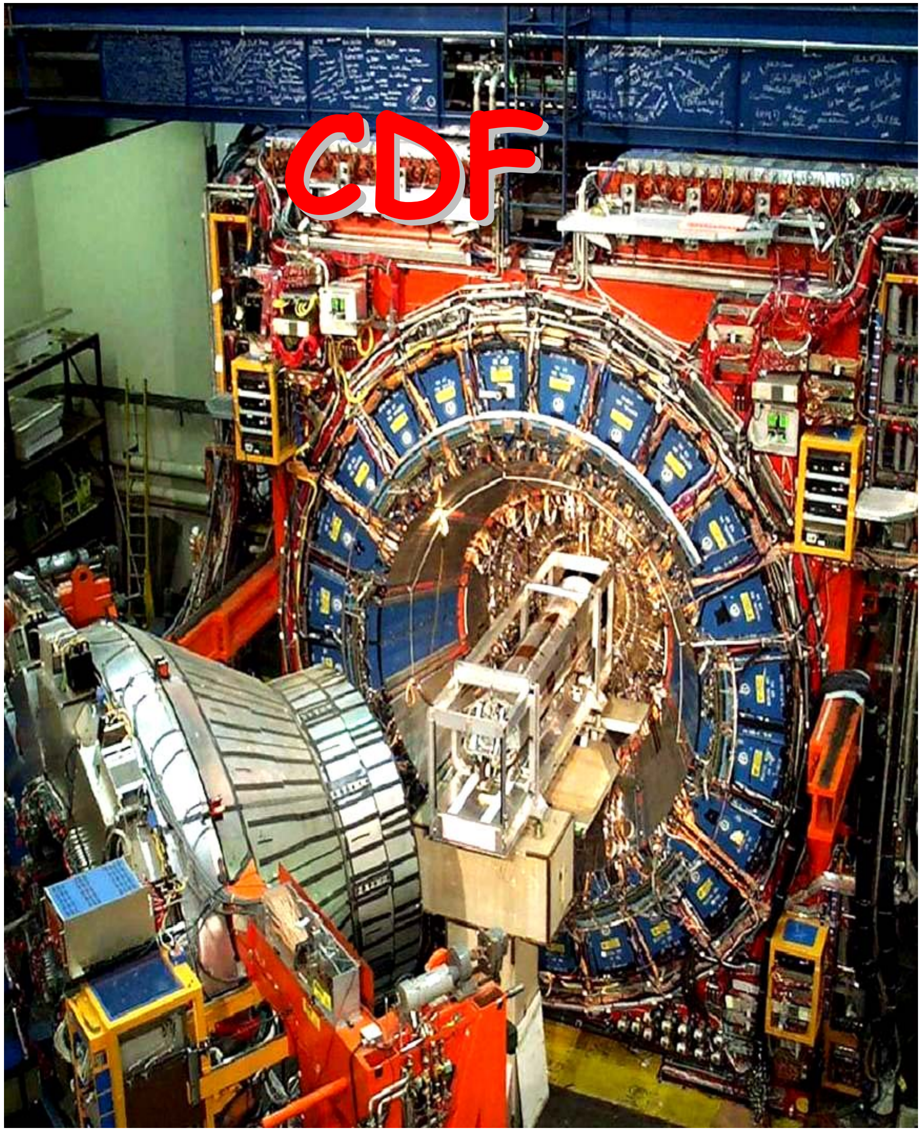


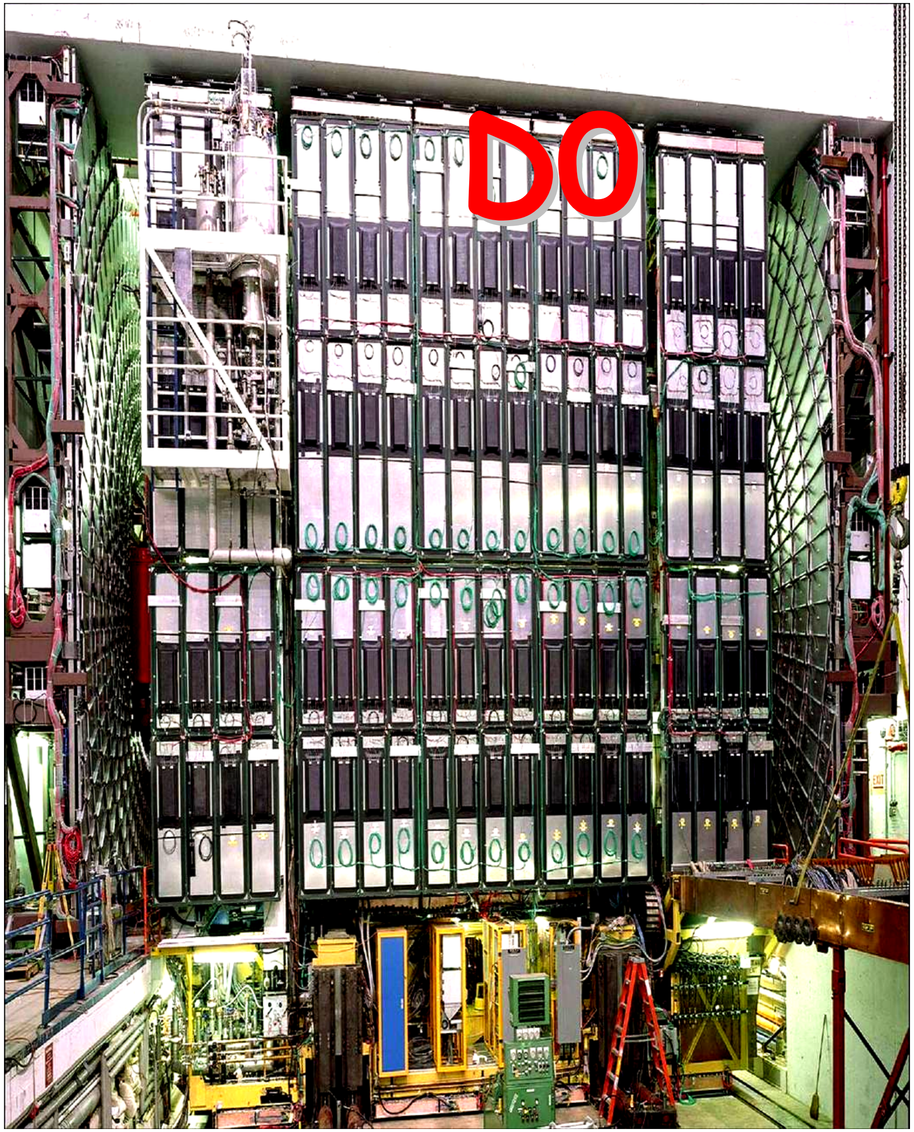


BaBar @ PEP, SLAC, Stanford, USA
Belle @ KEK, Tsukuba, Japan:

Belle: 500 million $\bar{B}B$ pairs in 500 fb^{-1} in 6 years

Tevatron

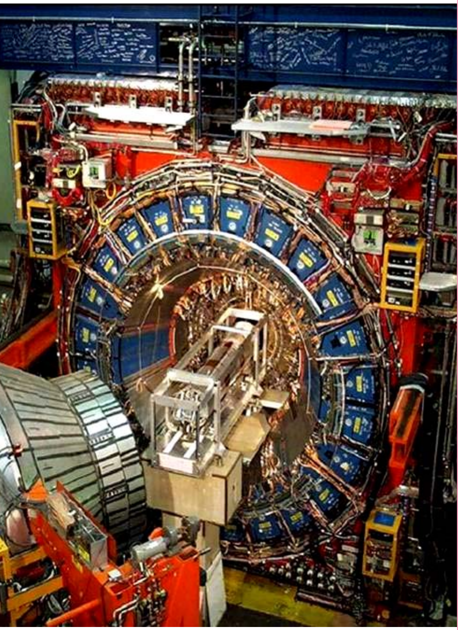




Fermi National Lab., Chicago: $\bar{p}\,p$ @ 1x1 TeV

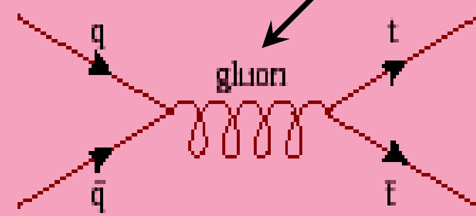
Top

discovered
1994
CDF + D0

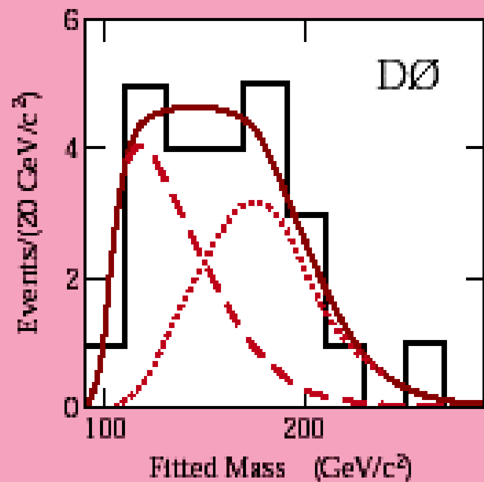


Tevatron
p p @ 2x1 TeV
Fermi Natl. Lab.
USA

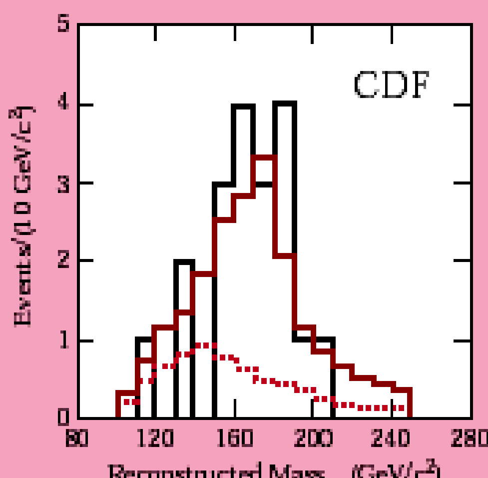
quantum of
strong int.

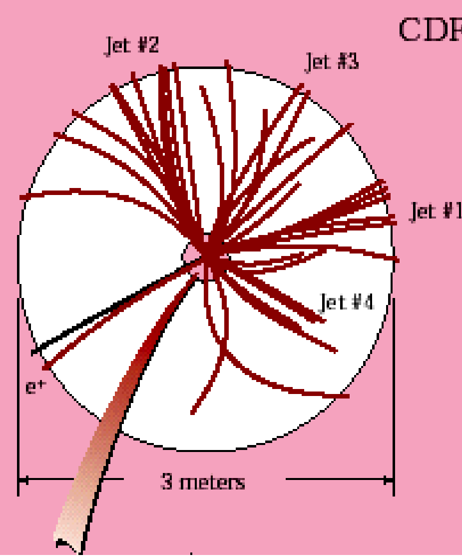


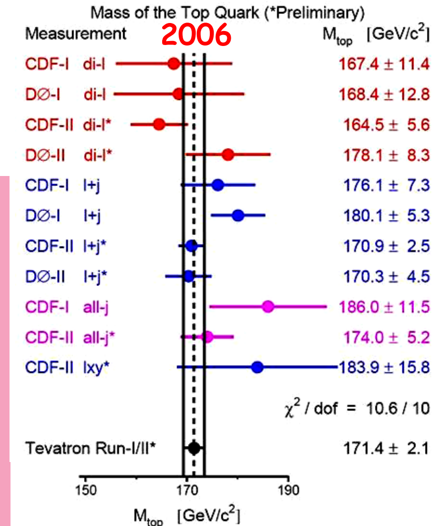
Top Mass Distribution



Dilepton channel:
$t\bar{t} \to W^+bW^-\bar{b} \to l^+l^-\nu\nu b\bar{b}$
Single lepton channel:
$t\bar{t} \to W^+bW^-\bar{b} \to l^+\nu q\bar{q}b\bar{b}$
or $l^-\bar{\nu}q\bar{q}b\bar{b}$







m_t = 172 ± 2 GeV !

prediction
from
radiative corrections
to Z mass + width:
172 ± 4 GeV !

weak decay
within 10^{-26} s -
faster than
hadronic time scale

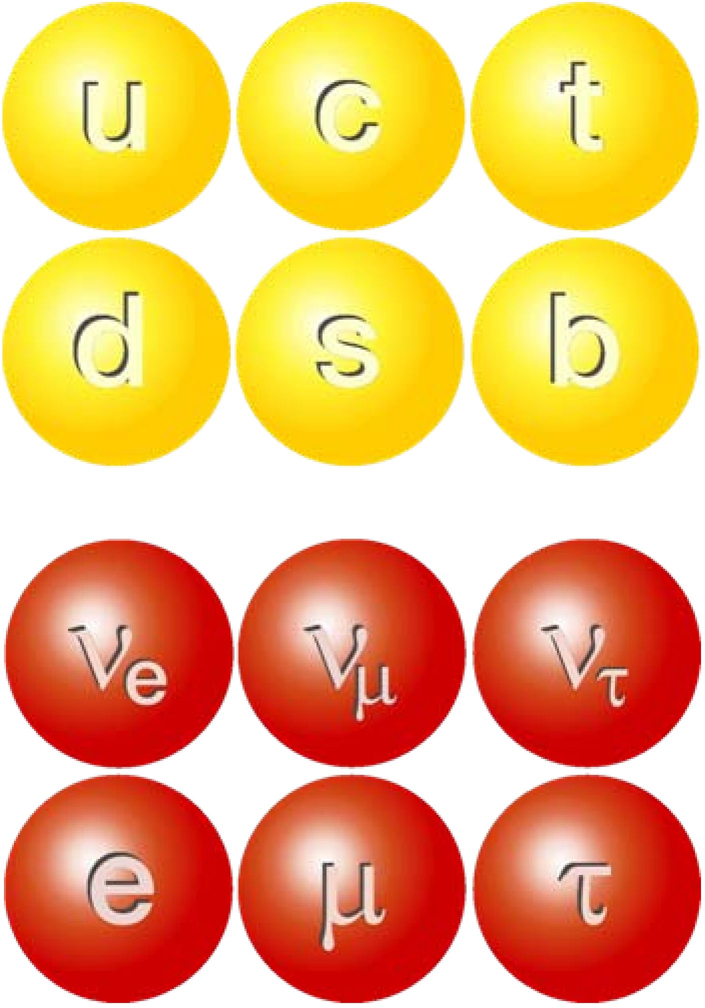
too fast
to find a partner -

top quark
never becomes
a dressed hadron

The Building Blocks

Quarks

Leptons



Fermions

QUARKS			Q	I_3	B	L
u	c	t	+2/3	+1/2	1/3	0
d	s	b	-1/3	- 1/2		
LEPTONS						
e^-	μ^-	τ^-	-1	- 1/2	0	1
ν_e	ν_μ	ν_τ	0	+1/2		

Spin
J=1/2

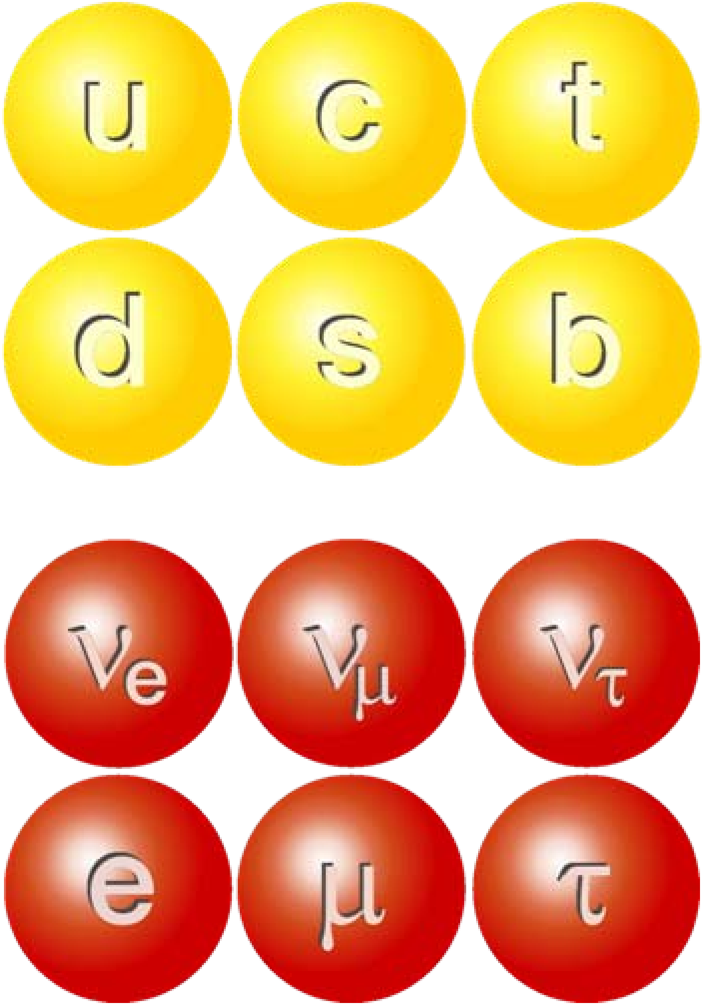
Questions:

- why no free quarks ?
  => confinement, QCD
- fractional charge 1/3 ?

Masses

u	c	t	e^-	μ^-	τ^-
2-5 MeV	1.25 GeV	172 GeV	511 keV	106 MeV	1.78 GeV
d	s	b	ν_e	ν_μ	ν_τ
5-8 MeV	120 MeV	4.25 GeV	<2 eV	<190 keV	<18.2 MeV

The Building Blocks



Great scheme,

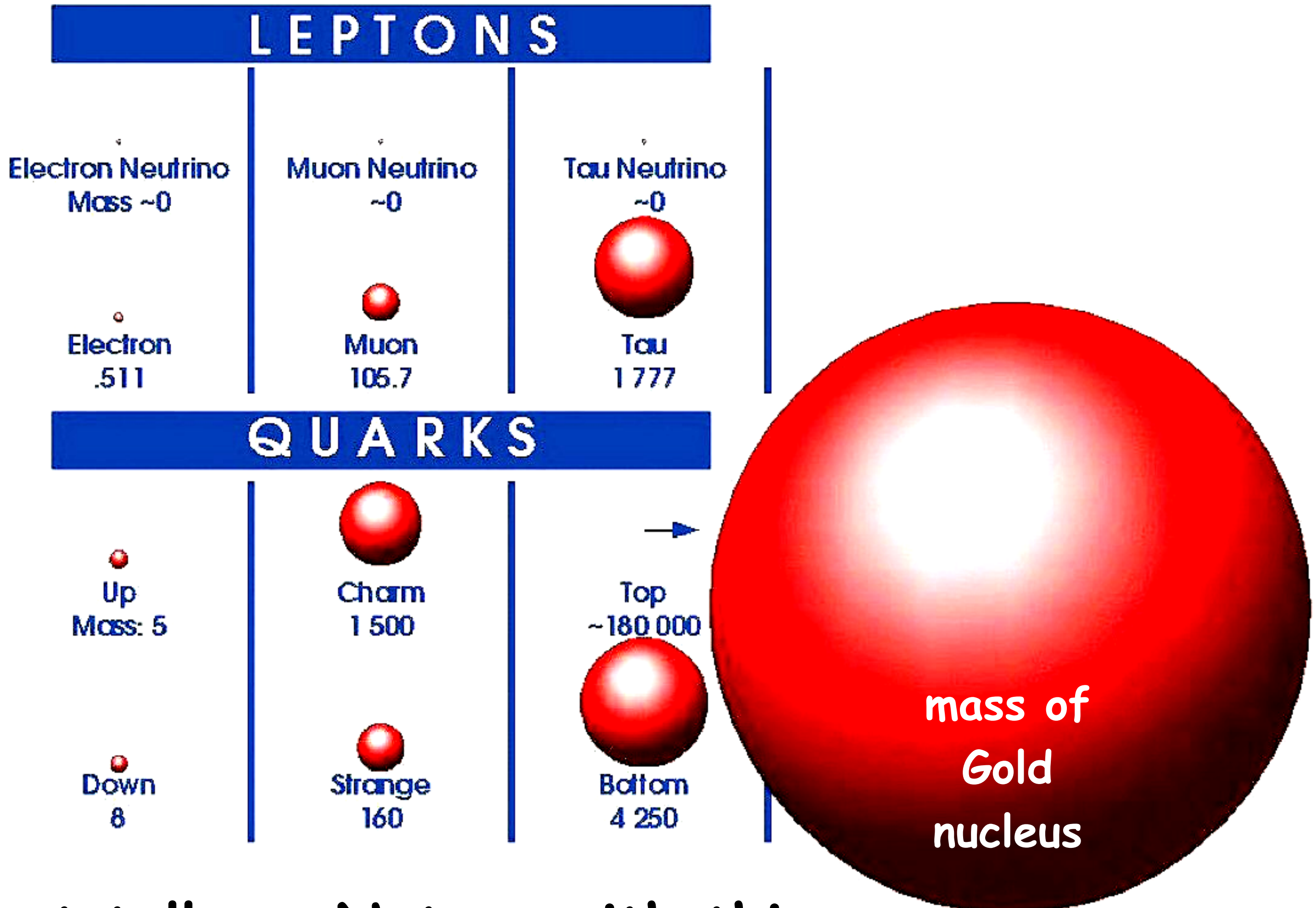
BUT:

all 3 symmetries mysterious:

- **up-down** ((weak) isospin)
- **lepton-quark**
- **3 families**

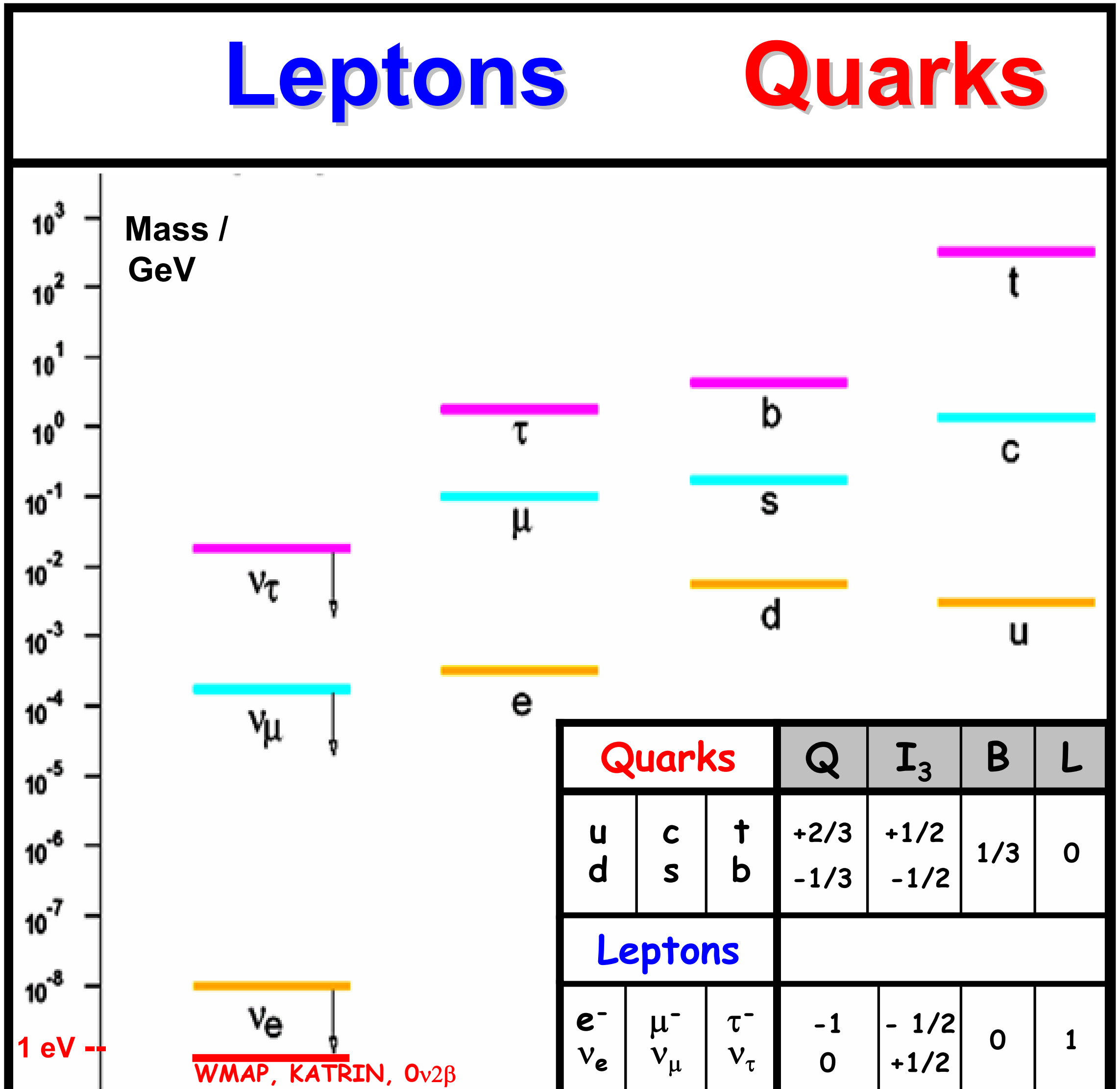
PARTICLES					**FORCES**			
					Electro-Magnet.	Weak	Nuclear	Gravi-tation
		Charge			Electric	Weak	Color	Mass
		Symmetry			U(1)	SU(2)	SU(3)	
Matter Particles		Fermions J=1/2						
Quarks	Up	u	c	t	+2/3	I_W, Y_W	r g b	
	Down	d	s	b	-1/3			
Leptons	Electrons	e	μ	τ	-1	I_W, Y_W		
	Neutrinos	ν_e	ν_μ	ν_τ	0			
Force Particles		Bosons J=1						
Photon		γ						
Weak Bosons		W^+, Z^0, W^-						
Gluons		$8\ g_{ij}$						
Graviton (J=2)		G						

Fermion Mass Spectrum



What tells us Nature with this **new spectroscopy ?**

Fermion Mass Spectrum



Quarks			Q	I_3	B	L
u d	c s	t b	+2/3 -1/3	+1/2 -1/2	1/3	0
Leptons						
e^- ν_e	μ^- ν_μ	τ^- ν_τ	-1 0	- 1/2 +1/2	0	1

What tells us **Nature** with this **spectrum** ?

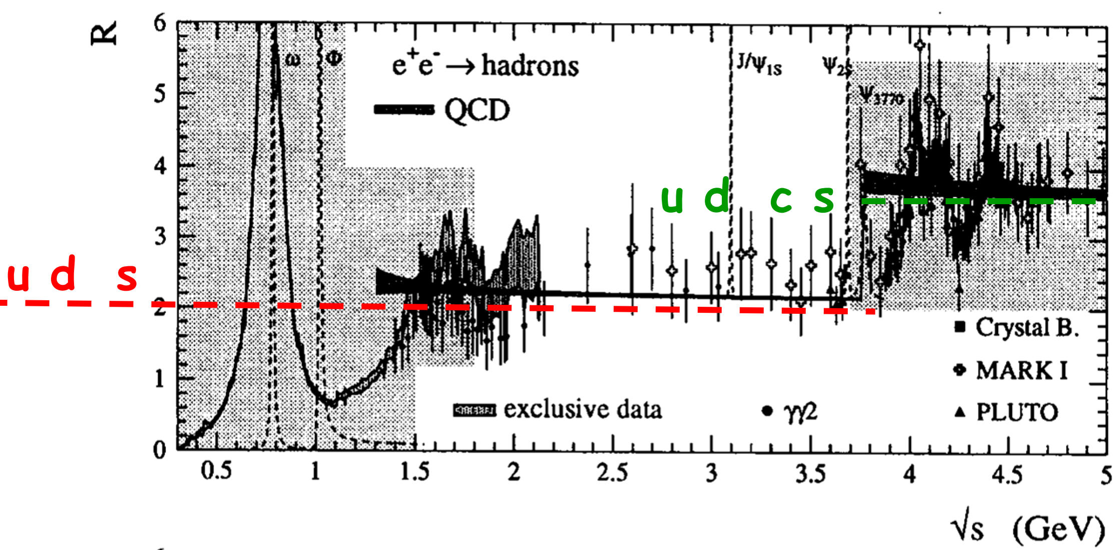
Hadron

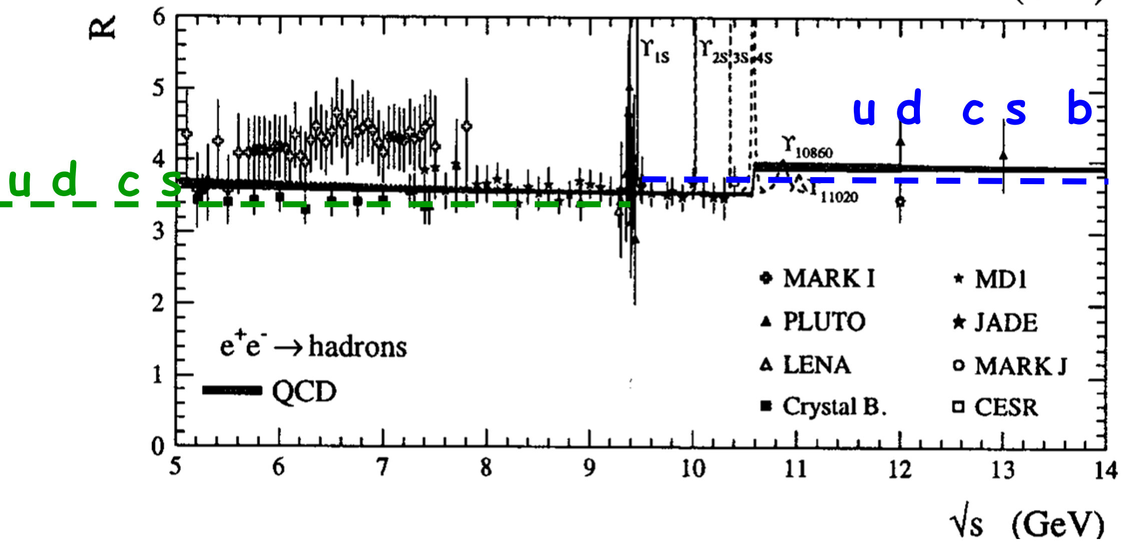
spectroscopy

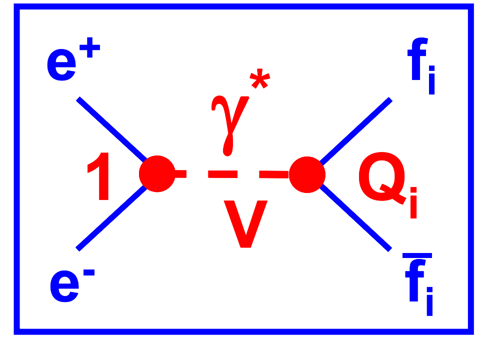
+

mixing

Quark Charge





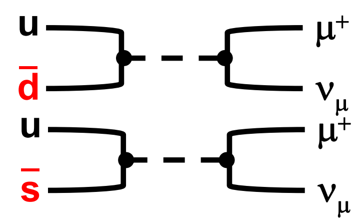


$$R = \frac{\sigma(e^+e^- \to q\ \bar{q} \to \text{hadrons})}{\sigma(e^+e^- \to \mu^+\mu^-)} = \sum_{\substack{\text{flavors}\\ \text{colors}}} Q_i^2 =$$

N_F	Q_i^2		
3	$\left(\frac{2}{3}\right)^2 + \left(\frac{1}{3}\right)^2 + \left(\frac{1}{3}\right)^2$	$= \frac{6}{9} * 3 = \frac{6}{3}$	$\binom{u}{d}\binom{}{s}$
4	$\left(\frac{2}{3}\right)^2 + \left(\frac{1}{3}\right)^2 + \left(\frac{2}{3}\right)^2 + \left(\frac{1}{3}\right)^2$	$= \frac{10}{9} * 3 = \frac{10}{3}$	$\binom{u}{d}\binom{c}{s}$
5	$\left(\frac{2}{3}\right)^2 + \left(\frac{1}{3}\right)^2 + \left(\frac{2}{3}\right)^2 + \left(\frac{1}{3}\right)^2 + \left(\frac{1}{3}\right)^2$	$= \frac{11}{9} * 3 = \frac{11}{3}$	$\binom{u}{d}\binom{c}{s}\binom{}{b}$

Quark Mixing

Decay	ΔM/MeV	τ/ns
$\pi^+ \rightarrow \mu^+ \nu_\mu$	139-105 = 34	26
$K^+ \rightarrow \mu^+ \nu_\mu$	494-105 = 389	8



- coupling to d,s could be identical or zero, but different ?
- N.Cabbibo 1963:
  universal couplings, but weak interaction
  does not see eigenstates d and s of mass + strong interaction,
  but mixed states d', s' with mixing angle θ_C :

$$d' = d \cos\theta_C + s \sin\theta_C$$
$$s' = -d \sin\theta_C + s \cos\theta_C$$

with **Cabbibo angle:** $\sin\theta_C = 0.220 \pm 0.002$

- $\sin\theta_C$: mixing strange - normal world or probability of family change
- SU(2) doublet: (u d') , $\Gamma(K^+\rightarrow\mu^+ \nu_\mu)/\Gamma(\pi^+\rightarrow\mu^+ \nu_\mu) \sim \sin^2\theta_C / \cos^2\theta_C$

GIM Mechanism

Decay	Current	Γ_i / Γ
$K^+ \rightarrow \mu^+ \nu_\mu$	charged	60 %
$K^+ \rightarrow \pi^+ \nu \bar{\nu}$	neutral	$< 10^{-9}$
$K^0 \rightarrow l^+ l^-$	neutral	$< 10^{-8}$

- **Cabbibo theory:** weak neutral current

$$= (ud')(ud')^T = u\bar{u} + d'\bar{d}' =$$

$$= u\bar{u} + \cos^2\theta_C \, d\bar{d} + \sin^2\theta_C \, s\bar{s} + \ldots \qquad \Delta S = 0$$

$$\sin\theta_C \cos\theta_C \, (s\bar{d} + d\bar{s}) \qquad \Delta S = 1$$

- $\Delta S = 1$ flavor changing neutral current not observed
- 1970: Glashow, Iliopoulos, Maiani: 2. quark doublet

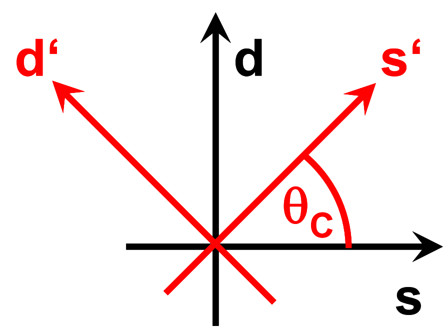
$$d' = d\cos\theta_C + s\sin\theta_C$$

$$s' = -d\sin\theta_C + s\cos\theta_C$$

$$\begin{pmatrix} u \\ d' \end{pmatrix} \quad \begin{pmatrix} c \\ s' \end{pmatrix}$$

neutral current $= u\bar{u} + d'\bar{d}' + c\bar{c} + s'\bar{s}'$

$$= u\bar{u} + d\,\bar{d} + c\bar{c} + s\,\bar{s} \qquad \Delta S = 0$$



- **1974: Charm discovered** by S.Ting (SLAC) and B.Richter (BNL)
- **1973:** Kobayashi + Maskawa postulate 3rd quark family
  mixing matrix with 1 complex phase -> CP violation

Quark Mixing

1973: Cabbibo-Kobayashi-Maskawa postulate 3rd quark family

CKM matrix V_{CKM} transforms
mass eigen states (d s b) to
weak eigen states (d's'b')

$$\begin{pmatrix} d' \\ s' \\ b' \end{pmatrix} = \begin{pmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{pmatrix} \begin{pmatrix} d \\ s \\ b \end{pmatrix} \equiv \hat{V}_{\mathrm{CKM}} \begin{pmatrix} d \\ s \\ b \end{pmatrix}$$

represent by 3 Euler angles in (dsb) space

$c_{ij} = \cos\theta_{ij}$, $s_{ij} = \sin\theta_{ij}$:

$$\hat{V}_{CKM} = \begin{pmatrix} c_{12} & s_{12} & 0 \\ -s_{12} & c_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix} \cdot \begin{pmatrix} 1 & 0 & 0 \\ 0 & c_{23} & s_{23} \\ 0 & -s_{23} & c_{23} \end{pmatrix} \cdot \begin{pmatrix} 1 & 0 & 0 \\ 0 & 1 & 0 \\ 0 & 0 & e^{i\delta} \end{pmatrix} \cdot \begin{pmatrix} c_{13} & 0 & s_{13} \\ 0 & 1 & 0 \\ -s_{13} & 0 & c_{13} \end{pmatrix}$$

+ complex phase δ (allows CP violation)

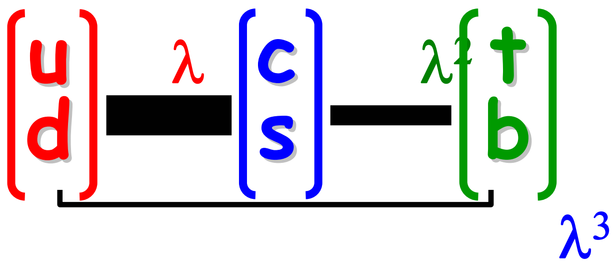
$$\hat{V}_{\mathrm{CKM}} = \begin{pmatrix} c_{12}c_{13} & s_{12}c_{13} & s_{13}e^{-i\delta} \\ -s_{12}c_{23} - c_{12}s_{23}s_{13}e^{i\delta} & c_{12}c_{23} - s_{12}s_{23}s_{13}e^{i\delta} & s_{23}c_{13} \\ s_{12}s_{23} - c_{12}c_{23}s_{13}e^{i\delta} & -s_{23}c_{12} - s_{12}c_{23}s_{13}e^{i\delta} & c_{23}c_{13} \end{pmatrix}$$

Quark Mixing

Experiment:

$$\begin{pmatrix} 0.9741 \text{ to } 0.9756 & 0.219 \text{ to } 0.226 & 0.0025 \text{ to } 0.0048 \\ 0.219 \text{ to } 0.226 & 0.9732 \text{ to } 0.9748 & 0.038 \text{ to } 0.044 \\ 0.004 \text{ to } 0.014 & 0.037 \text{ to } 0.044 & 0.9990 \text{ to } 0.9993 \end{pmatrix}$$

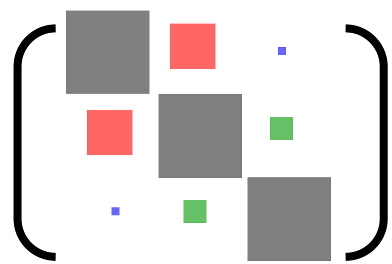
hierarchic suppression of family change :



why ?

Wolfenstein parameterization :

$$V_{CKM} = \begin{pmatrix} 1-\lambda^2/2 & \lambda & A\lambda^3(\rho - i\eta) \\ -\lambda & 1-\lambda^2/2 & A\lambda^2 \\ A\lambda^3(1-\rho-i\eta) & -A\lambda^2 & 1 \end{pmatrix} =$$



mixing angles:

$s_{12} = V_{us} = \lambda = 0.223 \pm 0.003$ Cabbibo

$s_{23} = V_{cb} = A\lambda^2 = 0.041 \pm 0.002$

$s_{13} = V_{ub}\, e^{i\delta} = A\lambda^3 (\ldots) = 0.004 \pm 0.001 \pm 0.001$

$A = 0.83 \pm 0.02$

3. C+P Symmetries

C Parity

Dirac, QFT:

matter-antimatter: each particle has antiparticle !

C operator

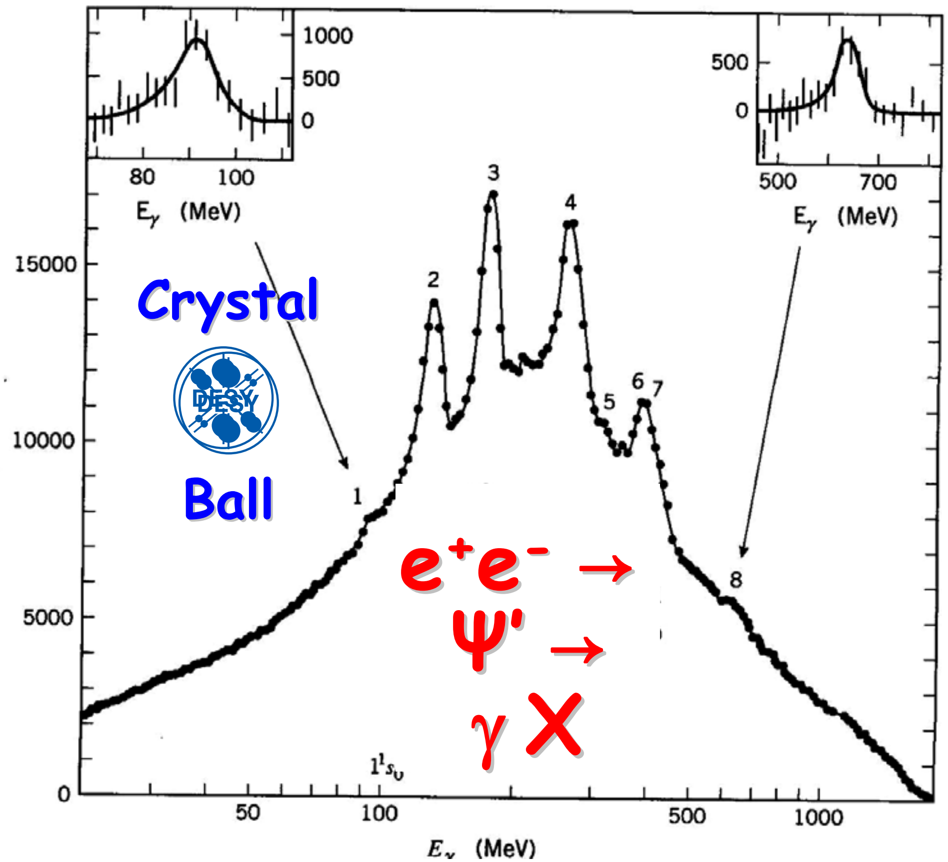
inverts all charge like additive quantum numbers:

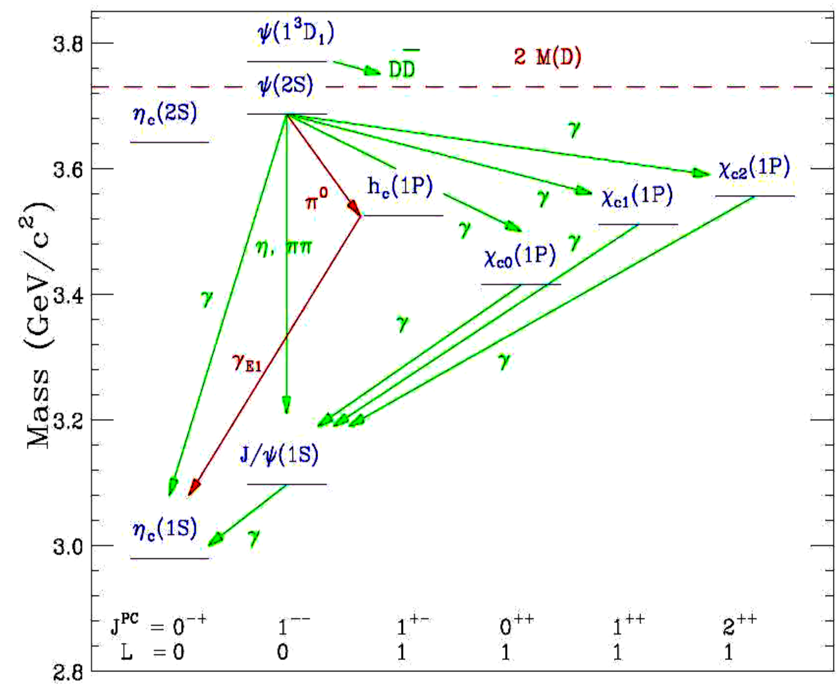
	$\xrightarrow{C}$		
L,B	$\rightarrow$	-L, -B	lepton + baryon nr.
F	$\rightarrow$	-F	flavor: F = u, d, s, c, b, t
Y,Q	$\rightarrow$	-Y, -Q	((weak) hyper) charge
$\mathbf{E},\mathbf{B}$	$\rightarrow$	$-\mathbf{E}$, $-\mathbf{B}$	electric + magnetic field

=> $C\,|\gamma\rangle = -|\gamma\rangle$

C: multiplicative, not charge like

Charmonium Spectrum





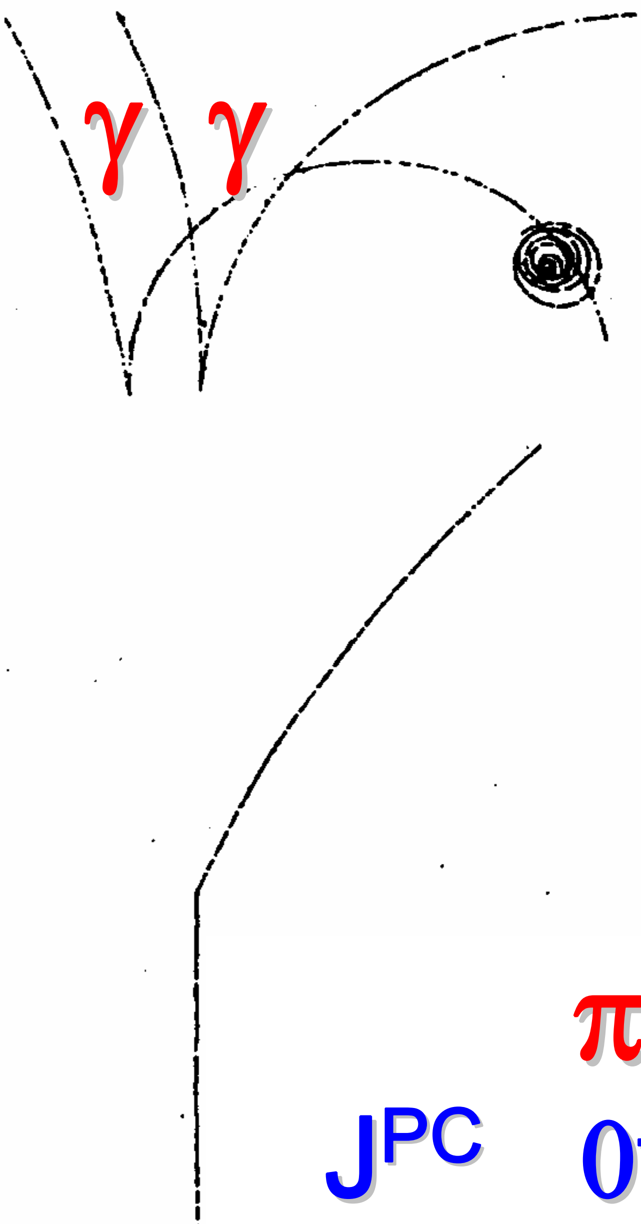
$N^{2S+1}\ L_{J=L+S}$

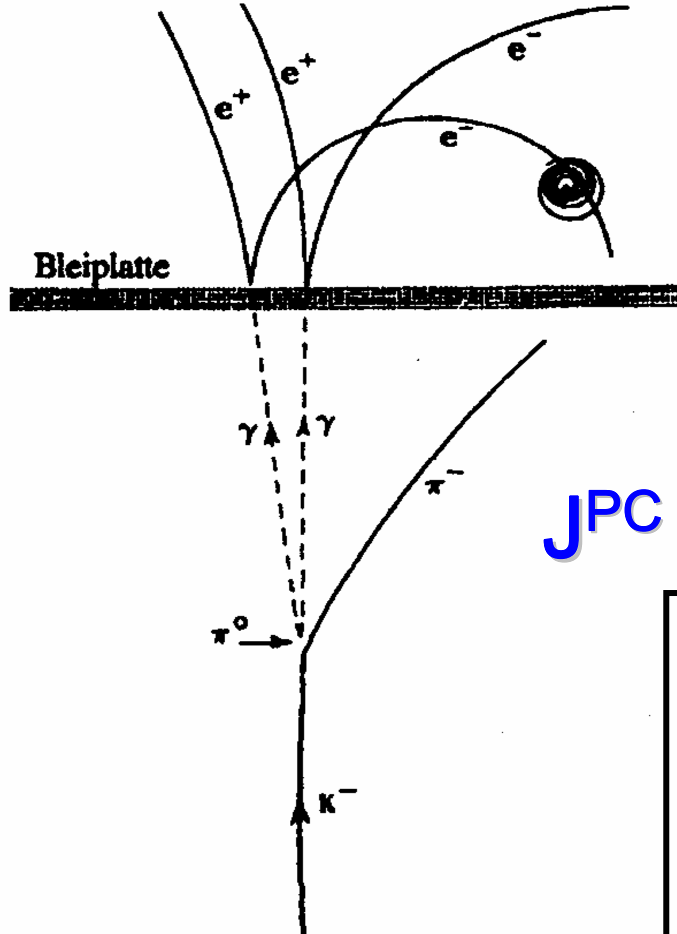
Ψ'-Ψ	radial	N
Ψ-η	↑↑- ↑↓	S
Ψ-χ	orbital	L

- input state fixed by Ψ', measure γ in NaI (Tl) crystals =>
- missing mass spectrum
- $^1S_0$ and ^3P states η and χ only in Ψ(') decays, not in e^+e^-
- Ψ' ↛ Ψ γ : $1^{--} \nrightarrow 1^{--}\ 1^{--}$ (C violated)

C Parity

$\gamma \quad \gamma$



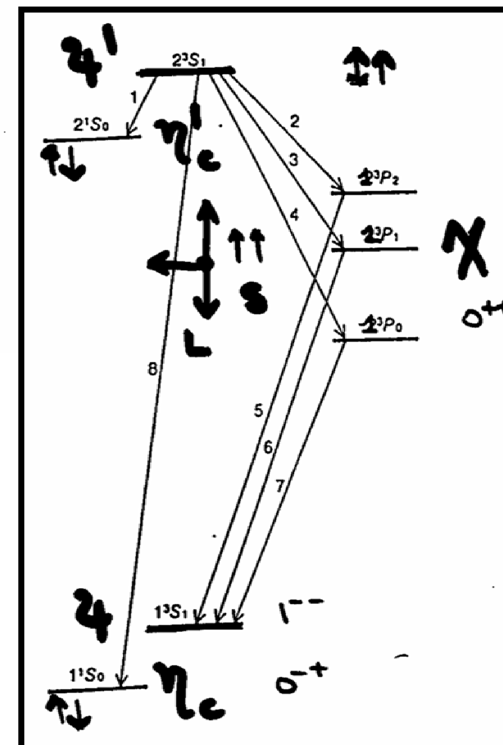


$\pi^0 \rightarrow \gamma \quad \gamma$

$J^{PC} \quad 0^{-+} \rightarrow 1^{--}\ 1^{--}$

$\Psi' \not\rightarrow \Psi\ \gamma$

$J^{PC} \quad 1^{--} \not\rightarrow 1^{--}\ 1^{--}$



C Parity

$\pi^0 \nrightarrow \gamma\gamma\gamma$ $\Gamma(\pi^0 \to 3\gamma)/\Gamma(\pi^0 \to 2\gamma) < 3\ 10^{-8} \ll \alpha = 1/137$

$\pi^0 \to \gamma\gamma$

$C\,|\pi^0\rangle = C_\gamma^{\,2}\,|\pi^0\rangle = +\,|\pi^0\rangle$ $J^{PC} = 0^{-+}$ pseudo-scalar mesons

$V \to P\,\gamma$

$\rho^0 \to \pi^0\,\gamma$

$\rho^0 \nrightarrow$ 2 identical particles :

$\rho^0 \nrightarrow \pi^0\,\pi^0$

$\rho^0 \nrightarrow \gamma\gamma$

$C\,|\rho^0\rangle = +C\,|\gamma\rangle = -\,|\rho^0\rangle$ $J^{PC} = 1^{--}$ vector mesons

quarkonium spectroscopy:

$\Psi' \nrightarrow \Psi\ \gamma$ $1^{--} \nrightarrow 1^{--}\,1^{--}$

$\to \eta_C\,\gamma$ $1^{--} \to 1^{--}\,0^{-+}$

$\to \chi\ \ \gamma$ $1^{--} \to 1^{--}\ 0,1,2^{++}$

$\Phi, \Psi, \Upsilon \nrightarrow$ 2 gluons OZI rule

$\to$ 3 gluons

C Parity

- not eigenstates of C operator !
  only eigenstates have eigenvalue !

$C\ |\pi^+\rangle = |\pi^-\rangle$ (Q)
$C\ |n\rangle = |\bar{n}\rangle$ (B)
$C\ |K^0\rangle = |\bar{K}^0\rangle$ (S)
$C\ |\nu\rangle = |\bar{\nu}\rangle$ (L)

- only totally neutral states with all additive quantum numbers zero:
  Q, B, L, S, C = 0

  $\gamma,\ \pi^0,\ \eta^0,\ \rho^0,\ \omega^0,\ \Phi^0,\ \Psi,\ Y,\ Z$

  are eigenstates of C operator !

- spin like magnetic field = rotating charge:
  negative C parity

$$C\ |f\ \bar{f}\rangle = C\ |\text{Meson}\rangle = |f\ \bar{f}\rangle\ (-1)^{L+S}$$

L	S	J	C	Multiplet	Expl.
L=S			+		
0	0	0	+	Pseudo-Scalar	π^0
0	0	0	-	FORBIDDEN !	
0	1	1	-	Vector (like γ)	ρ^0
1	1	0	+	Scalar L=1 rare	A_0
1	1	1	+	Axial-Vector	A_1
1	1	2	+	Tensor	f^0

P Parity

P Operation	Type	Dirac	J^P	Example
$P\,\lvert\vec{r}\rangle = -\,\lvert\vec{r}\rangle$	vector	γ_μ	1^-	
$P\,\lvert\vec{p}\rangle = -\,\lvert\vec{p}\rangle$	vector	γ_μ	1^-	$\vec{p} = d\vec{r}\,/\,dt$
$P\,\lvert t\rangle = \lvert t\rangle$	scalar	1	0^+	
$P\,\lvert E\rangle = \lvert E\rangle$	scalar	1	0^+	
$P\,\lvert\vec{B}\rangle = \lvert\vec{B}\rangle$	axialvecto r	$\gamma_5\gamma_\mu$	1^+	$\vec{B} = \vec{v}\times\vec{E} = \vec{\nabla}\times\vec{A}$
$P\,\lvert\vec{\sigma}\rangle = \lvert\vec{\sigma}\rangle$	axialvecto r	$\gamma_5\gamma_\mu$	1^+	$\vec{L} = \vec{v}\times\vec{r}$
$P\,\lvert\vec{p}\,\vec{\sigma}\rangle = -\,\lvert\vec{p}\,\vec{\sigma}\rangle$	pseudoscal ar	γ_5	0^-	$H = \vec{p}\vec{\sigma}\,/\,\lvert\vec{p}\rvert\lvert\vec{\sigma}\rvert$
$P\,\lvert F_{\mu\upsilon}\rangle = \lvert F_{\mu\nu}\rangle$	tensor	$\gamma_\mu\gamma_\nu$	2^+	$F_{\mu\nu} = \partial_\mu A_\nu - \partial_\nu A_\mu$
$T\,\lvert t\rangle = -\,\lvert t\rangle$	time reversal			

H = helicity
helix = screw

$P^2 = 1$ P ... unitary

combined CPT conserved in field theory

θ-τ paradox

1955: $P\,|\pi\rangle = -|\pi\rangle$

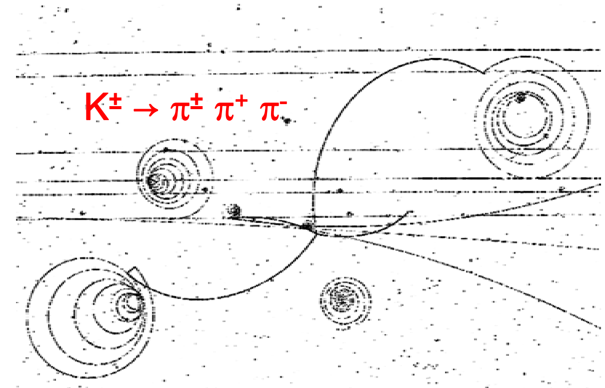
τ: $K^{\pm} \rightarrow \pi^{\pm}\pi^{+}\pi^{-}$ $P\,|3\pi\rangle = -|3\pi\rangle$

θ: $K^{\pm} \rightarrow \pi^{\pm}\pi^{0}$ $P\,|2\pi\rangle = +|2\pi\rangle$

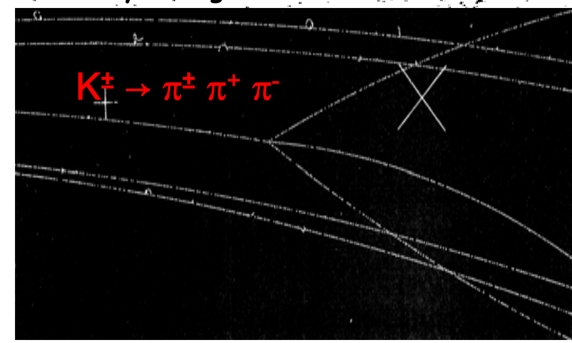
Are θ and τ different ?
But their masses are equal !

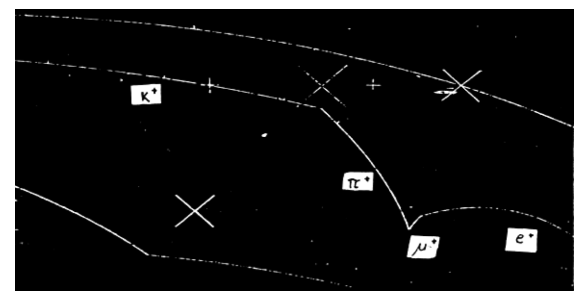
Solution: $\theta = \tau$

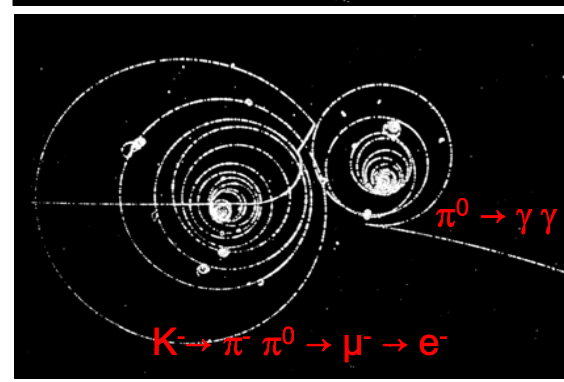
Parity VIOLATED in weak decays !



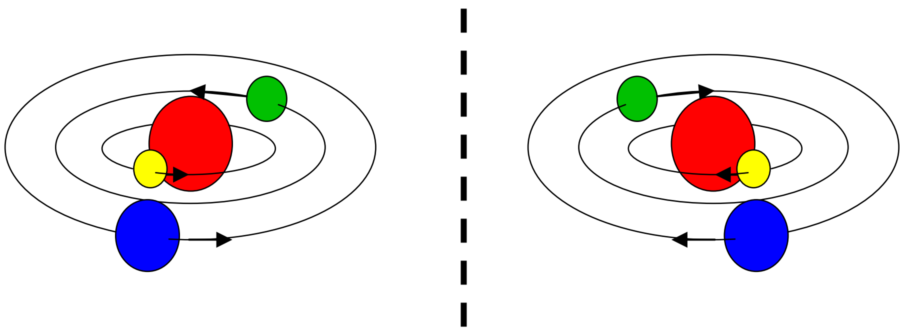
decay in flight: uneven nr of tracks!







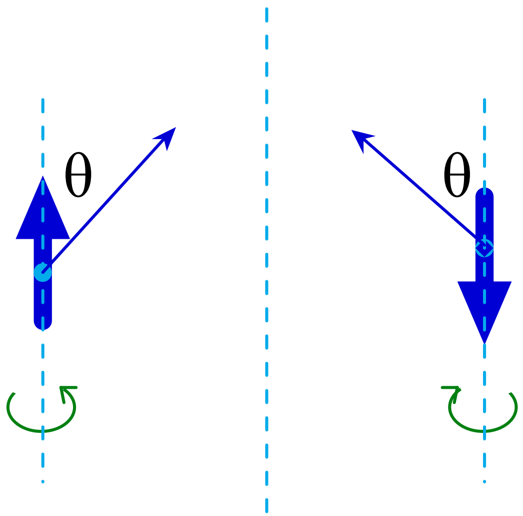
Parity violation



Gravitation + electromagnetism:

same physical laws
in mirror system,
e.g. planetary motion

parity conserved.



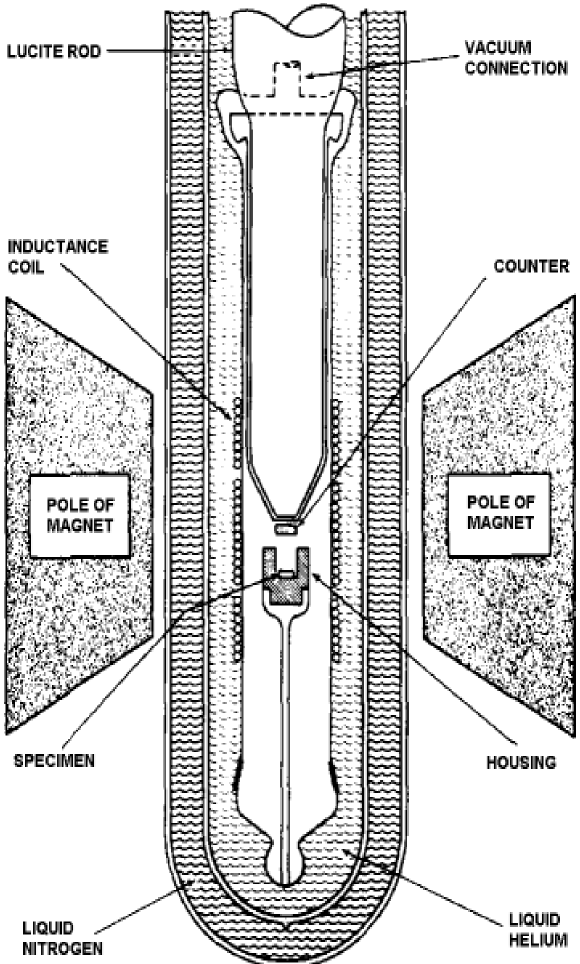
Weak interaction:

β-decay
of polarized ^{60}Co
violates parity !

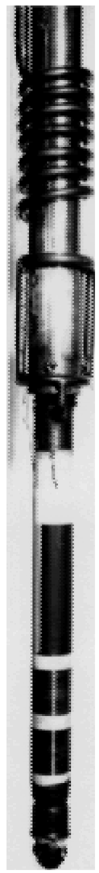
discovered 1956

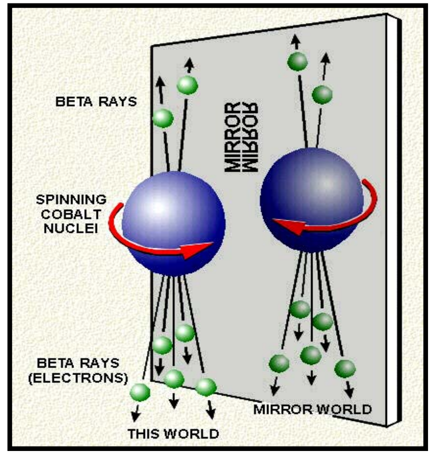
Parity violation

cool to 10 mK

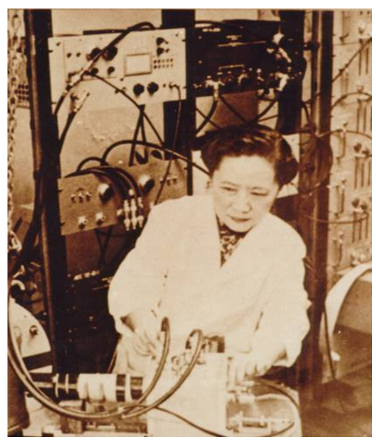


polarize nuclear spins along magnetic field





C.S. Wu et al.,



Columbia Univ., USA 1957

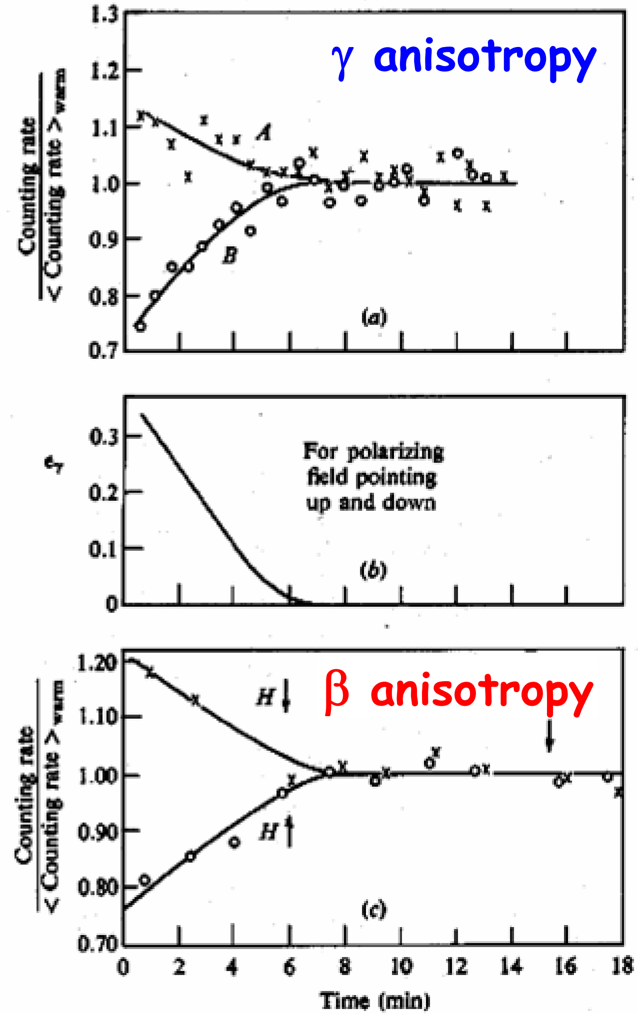


FIG. 8.37 The results obtained by Wu, *et al.* by using the apparatus shown in Fig. 8.36. [From Wu., *et al.*, *Phys. Rev.*, **105**, 1413, (1957).] (a) gamma-anisotropy obtained by equatorial counter (*A*) and polar counter (*B*). (b) gamma-anisotropy calculated from (a). (c) beta-asymmetry.

Parity Violation

nuclear β decay:

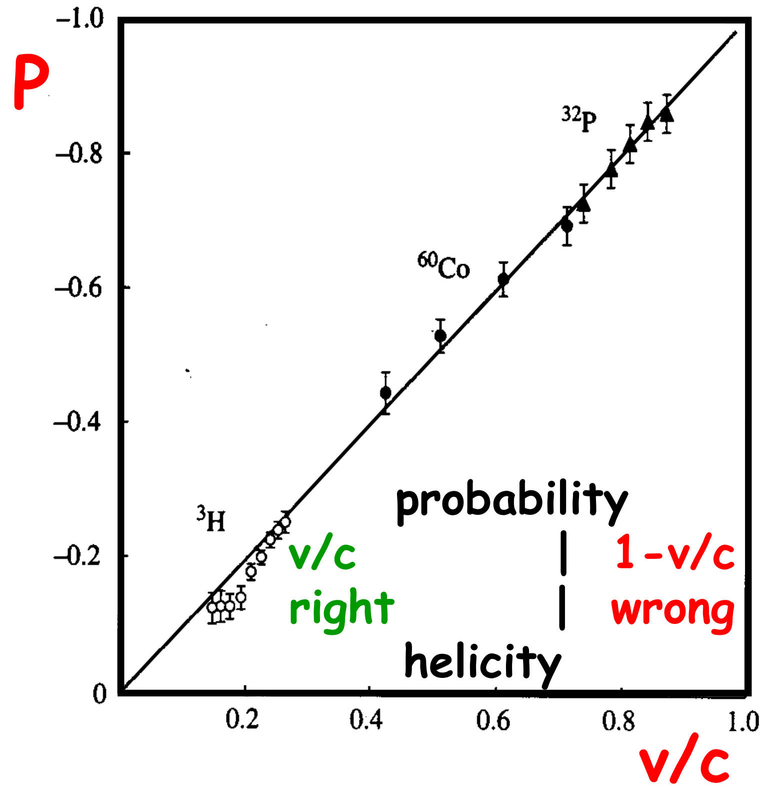
helicity $H = (\vec{\sigma}\cdot\vec{p})/|p|$

in a system with c>v'>v
momentum p and helicity H
are inverted:

probability of 'wrong' helicity 1-v/c

polarization $P = (N^+ - N^-)/(N^+ + N^-)$
$= \sigma \cdot pc / E = H\, v/c$

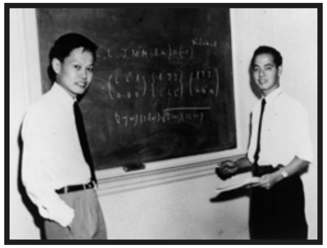
longitudinal polarization P
vs. electron velocity v/c:



(V-A) Theory

$\vec{\sigma}$ ... unit vector in spin direction
helicity operator H:

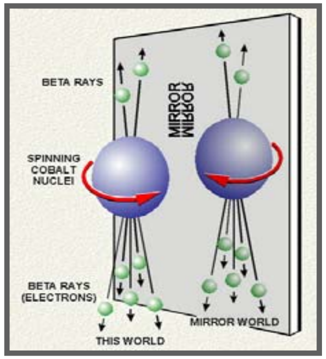
$$H = \frac{\vec{\sigma}\ \vec{p}}{|\vec{p}|} \qquad H\,|\psi\rangle = \pm\,|\psi\rangle$$



projection operator L / R left / right:

$L = (1-H)\,/\,2 = 0,1$ for $H = \pm 1$ or $(1 \pm \gamma_5)/2$
$R = (1+H)\,/\,2 = 1,0$

chirality = handiness



$L = (1-H)\,/\,2$ particle: left handed
$L = (S-P)\,/\,2$ space structure: (Scalar-Pseudoscalar)

all interactions via vector bosons V :
$L = V\,(S-P)\,/\,2$
$L = (V-A)\,/\,2$
$L = \gamma^{\mu}(1-\gamma^{5})\,/\,2$

space structure of weak force :

(V–A) why ?

maximum parity violation !

Helicity + Chirality

ν_L :	FERMIONS	are	LEFT	handed
$\bar{\nu}_R$:	ANTI-FERMIONS		RIGHT	handed

$P \, | \nu_L \rangle = | \nu_R \rangle$ (crossed out)	P violated
$C \, | \nu_L \rangle = | \bar{\nu}_L \rangle$ (crossed out)	C violated
$CP \, | \nu_L \rangle = | \bar{\nu}_R \rangle$	CP conserved

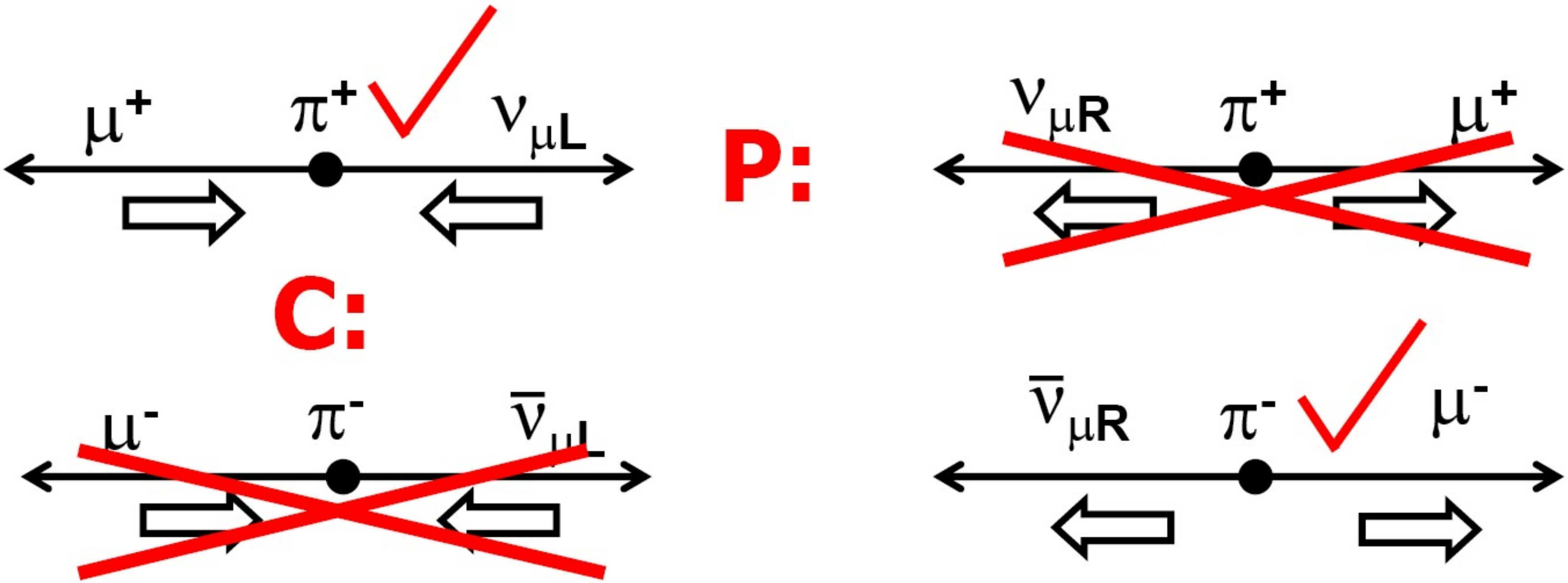
Manche meinen,
lechts und rinks
kann man nicht
velwechsern.

Werch ein Illtum !

E.Jandl

C,P violation - CP conservation

only left-handed neutrinos exist
weak interaction violates C+P separately:



Only combined CP operation
gives right-handed antineutrino, which exists:

CP conserved !

4. Weak Interaction

Neutrinos, they are very small.
They have no charge and have no mass
And do not interact at all.

The earth is just a silly ball
To them, through which they simply pass.

John Updike

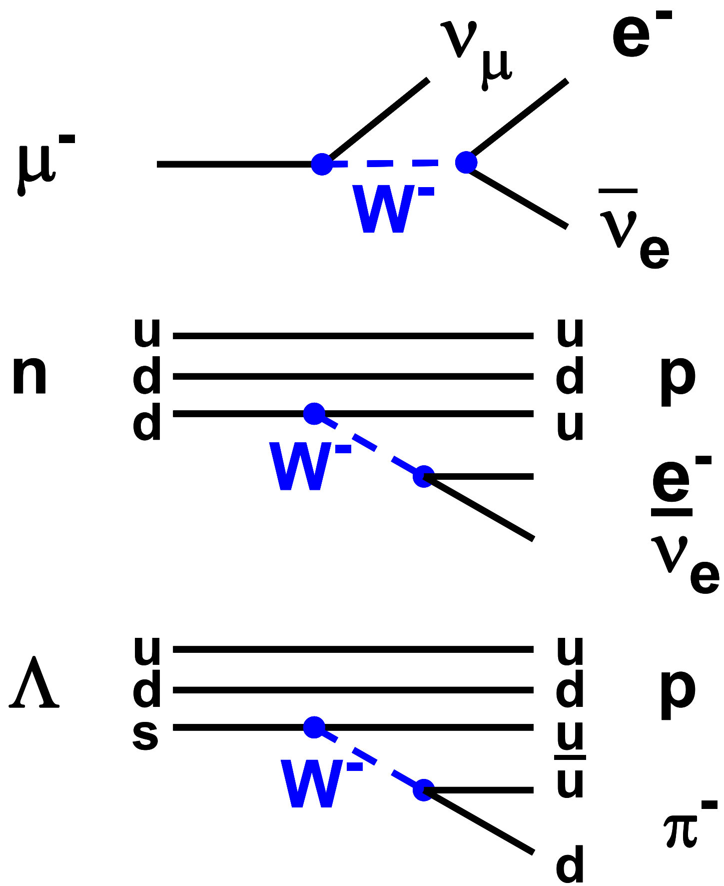
Weak Decays

DECAYS

leptonic

semi-leptonic

non-leptonic

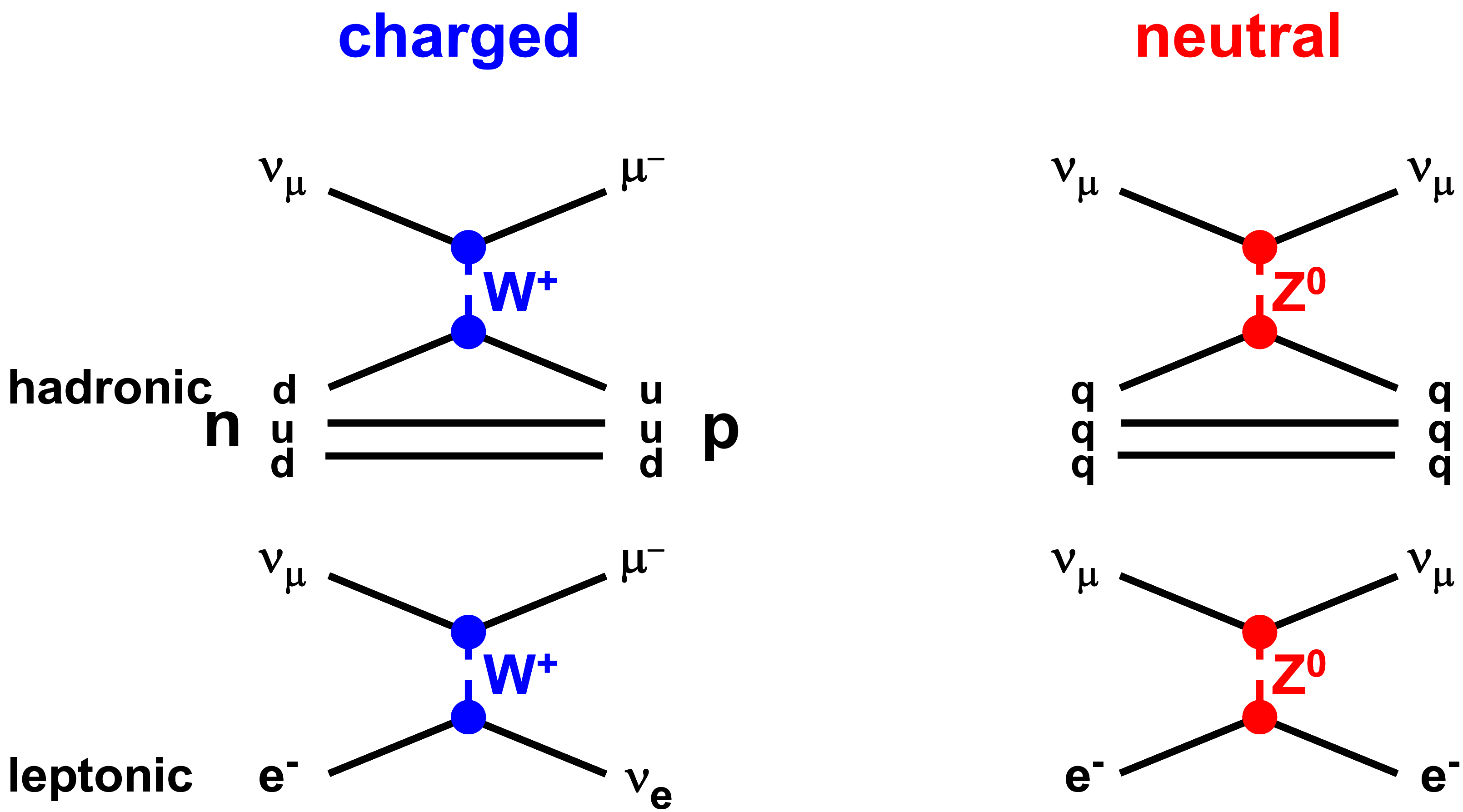


μ decay

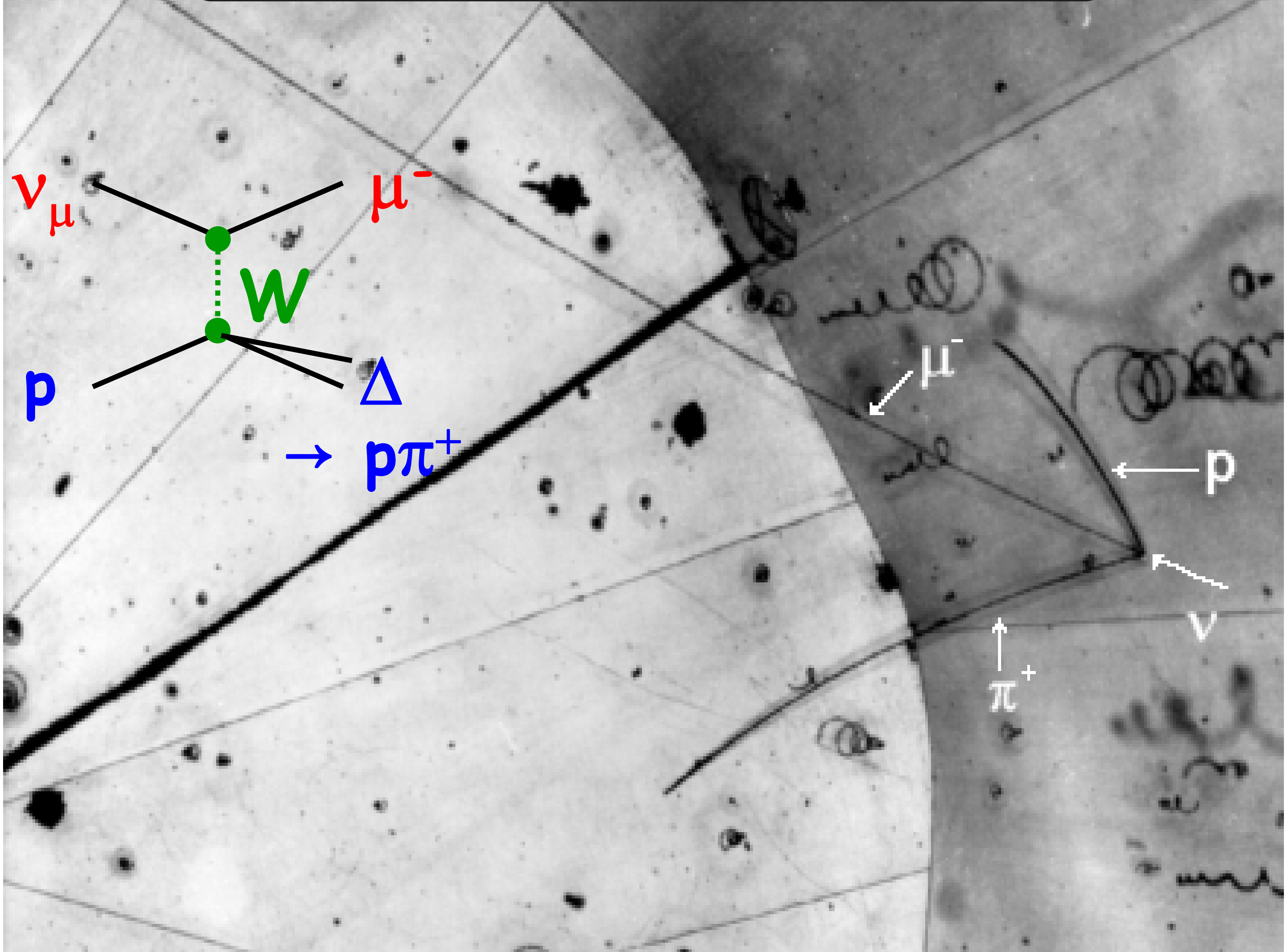
β decay

Weak Reactions

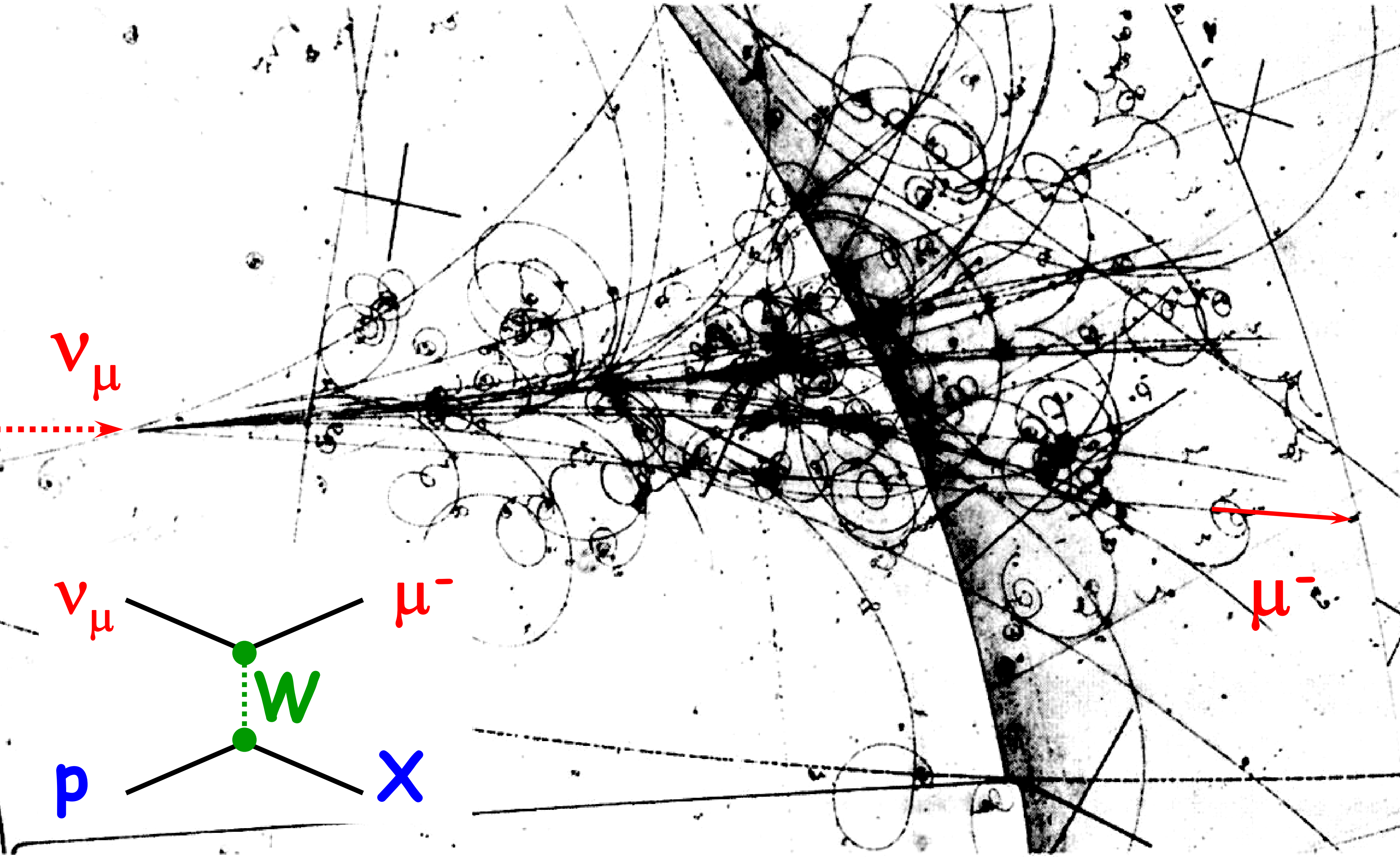
current



Charged Weak Current



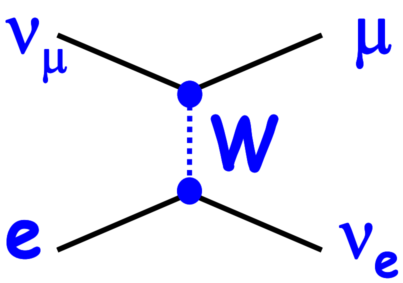
Charged Weak Current



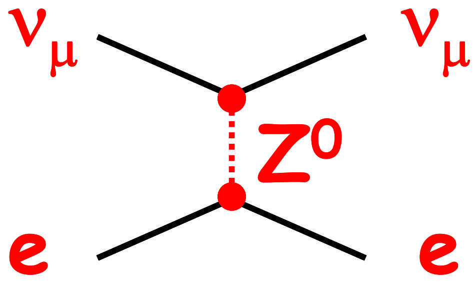
CERN **1984:** Big European Bubble Chamber BEBC

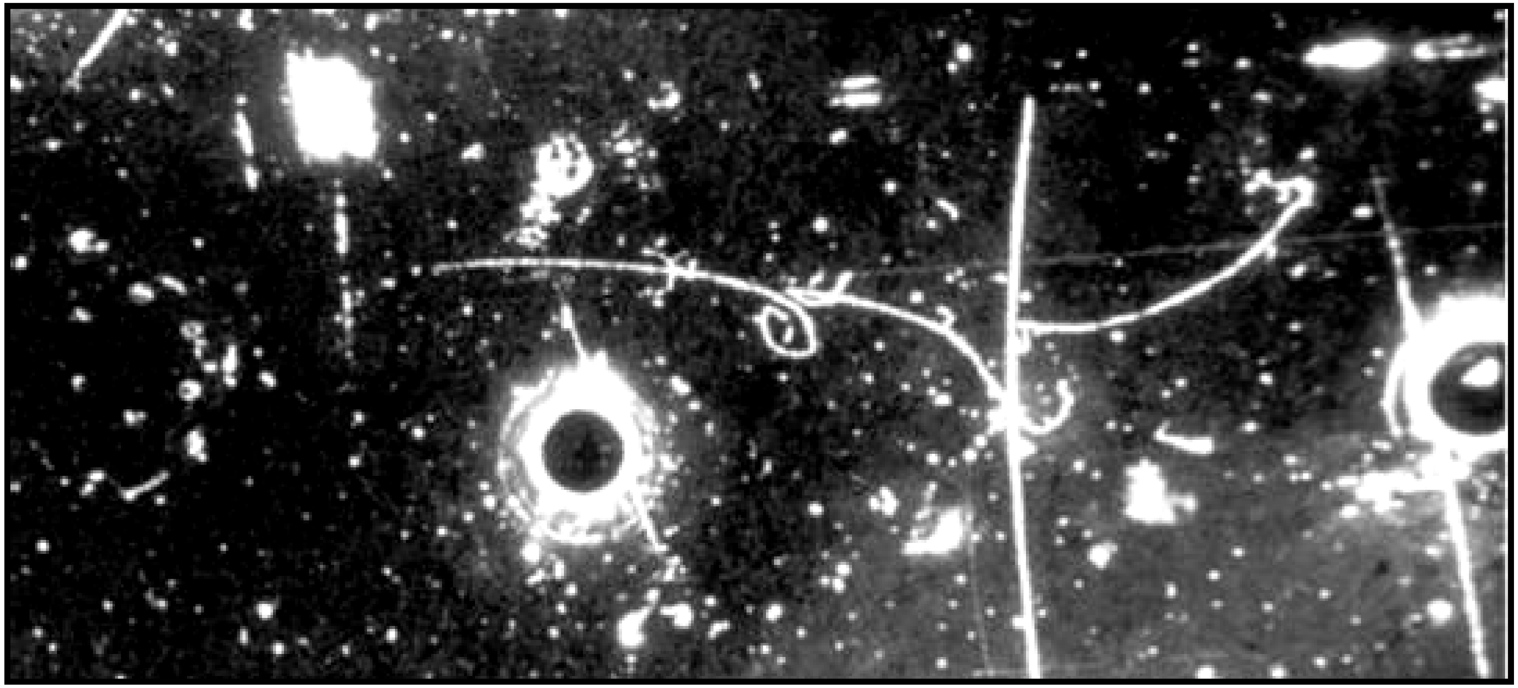
Neutral Weak Current

charged current



neutral current



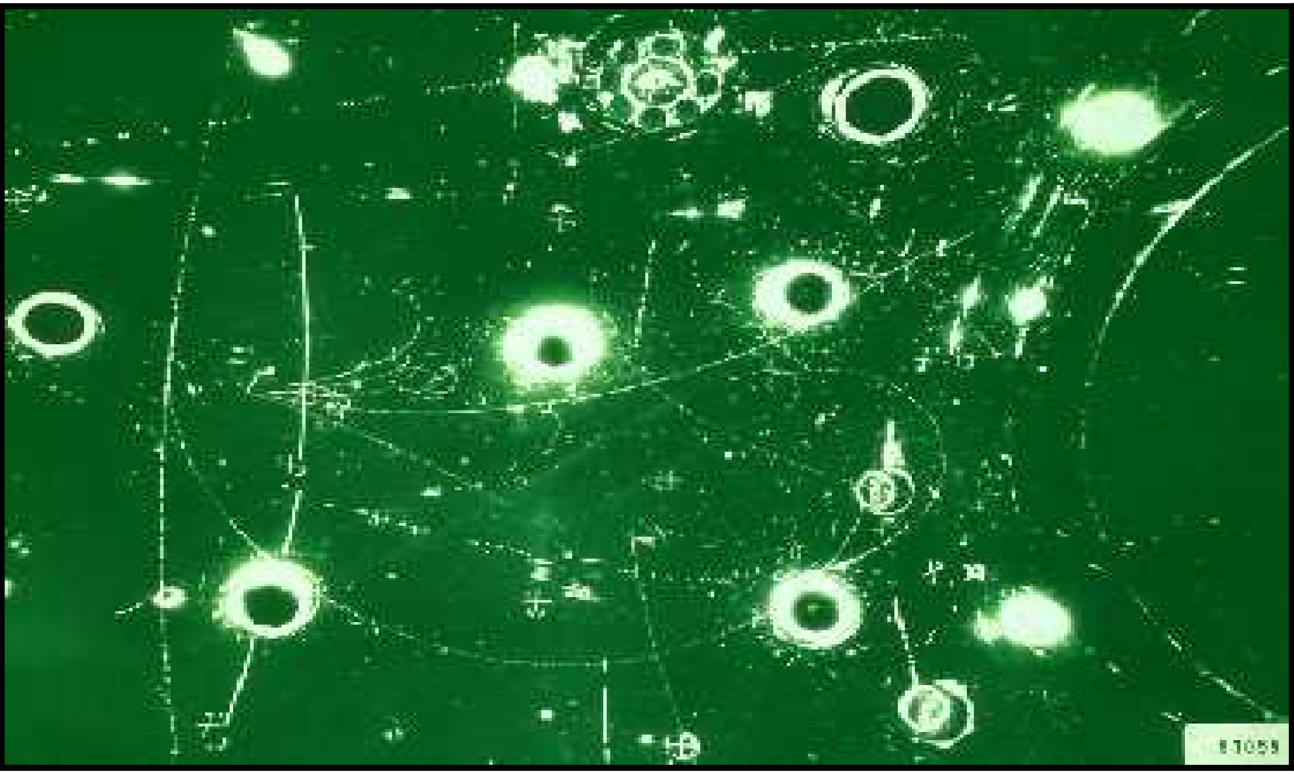


CERN 1973 : Gargamelle Heavy Liquid Bubble Chamber

Neutral Weak Current

$$\nu_\mu \, N \rightarrow \nu_\mu \, X$$

CERN 1973 : Gargamelle Heavy Liquid Bubble Chamber



Neutrinos

Neutrinos, they are very small
They have no charge and have no mass
And do not interact at all.
The earth is just a silly ball
To them, through which they simply pass,
Like dustmaids down a drafty hall
Or photons through a sheet of glass.

They snub the most exquisite gas,
Ignore the most substantial wall,
Cold-shoulder steel and sounding brass,
Insult the stallion in his stall,
And, scorning barriers of class,
Infiltrate you and me! Like tall
And painless guillotines, they fall
Down through our heads into the grass.

At night, they enter at Nepal
And pierce the lover and his lass
From underneath the bed. You call
It wonderful; I call it crass.

John Updike

Neutrinos

- pure sources + pure probes of weak interaction
- extremely penetrating !
- omnipresent:
  - solar neutrino flux: $6 \cdot 10^{10}\ m^{-2}\ s^{-1}$
  - atmospheric neutrino flux: $10^{4}\ m^{-2}\ s^{-1}$
  - supernova SN 1987A flux: $10^{15}\ m^{-2}$
  - cosmic relic neutrinos: $335\ cm^{-3}$

$\begin{pmatrix} u \\ d \end{pmatrix}$ strong, electromagnetic, weak

$\begin{pmatrix} e \\ \nu_e \end{pmatrix}$ e: electromagnetic, weak; ν_e: weak

- charged leptons have mass :

511 keV	106 MeV	1.8 GeV
$\begin{pmatrix} e \\ \nu_e \end{pmatrix}$	$\begin{pmatrix} \mu \\ \nu_\mu \end{pmatrix}$	$\begin{pmatrix} \tau \\ \nu_\tau \end{pmatrix}$
<2 eV	<190 keV	<18 MeV
$H \rightarrow He\ e\ \bar{\nu}_e$	$\pi \rightarrow \mu\ \nu_\mu$	$\tau \rightarrow 5\pi\ \nu_\tau$

NEUTRINO MASS

?

Pauli's Neutrino hypothesis

$n \rightarrow p\, e^-$?   continuous β spectrum
E conservation violated ?

Offener Brief an die Gruppe der Radioaktiven bei der Gauvereins-Tagung zu Tübingen.

Abschrift

Physikalisches Institut
der Eidg. Technischen Hochschule
Zürich

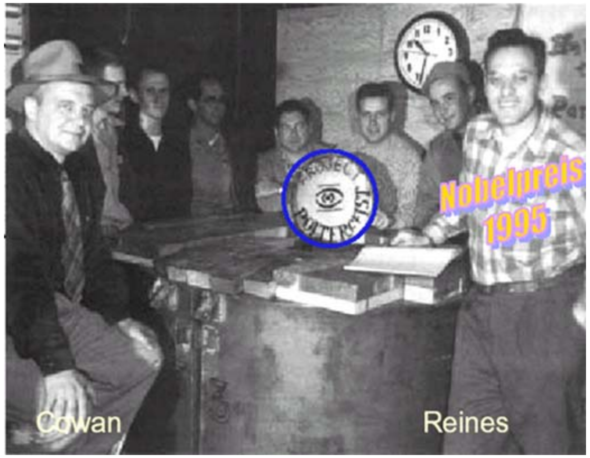
Zürich, 4. Dez. 1930
Gloriastrasse

Liebe Radioaktive Damen und Herren,

Wie der Ueberbringer dieser Zeilen, den ich huldvollst anzuhören bitte, Ihnen des näheren auseinandersetzen wird, bin ich angesichts der "falschen" Statistik der N- und Li-6 Kerne, sowie des kontinuierlichen beta-Spektrums auf einen verzweifelten Ausweg verfallen um den "Wechselsatz" (1) der Statistik und den Energiesatz zu retten. Nämlich die Möglichkeit, es könnten elektrisch neutrale Teilchen, die ich Neutronen nennen will, in den Kernen existieren, welche den Spin 1/2 haben und das Ausschliessungsprinzip befolgen und sich von Lichtquanten ausserdem noch dadurch unterscheiden, dass sie nicht mit Lichtgeschwindigkeit laufen. Die Masse der Neutronen müsste von derselben Grössenordnung wie die Elektronenmasse sein und jedenfalls nicht grösser als 0,01 Protonenmasse.- Das kontinuierliche beta- Spektrum wäre dann verständlich unter der Annahme, dass beim beta-Zerfall mit dem Elektron jeweils noch ein Neutron emittiert wird, derart, dass die Summe der Energien von Neutron und Elektron konstant ist.

$n \rightarrow p\, e^- \bar{\nu}_e$

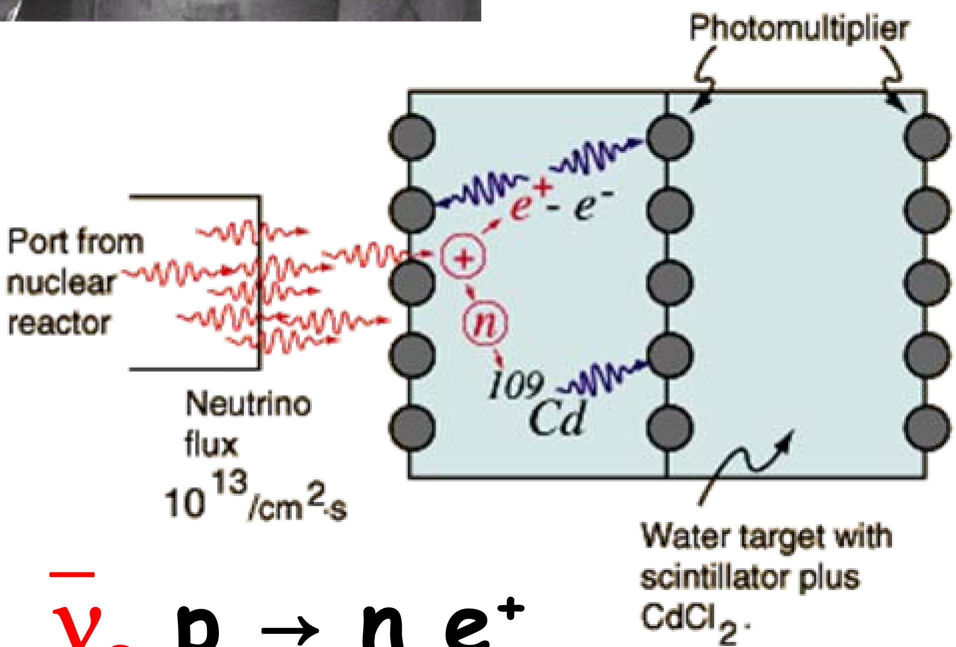
renamed
Neutrino
1933 by E. Fermi
after neutron
discovery



Neutrino Discovery

25 years later: Project Poltergeist:

C.Cowan and F.Reines, 1956 :
Savannah river reactor, USA



Delayed coincident detection of γ from ^{109}Cd with pair of γ's from $e^+ - e^-$ annihilation.

Reines:
Nobel prize

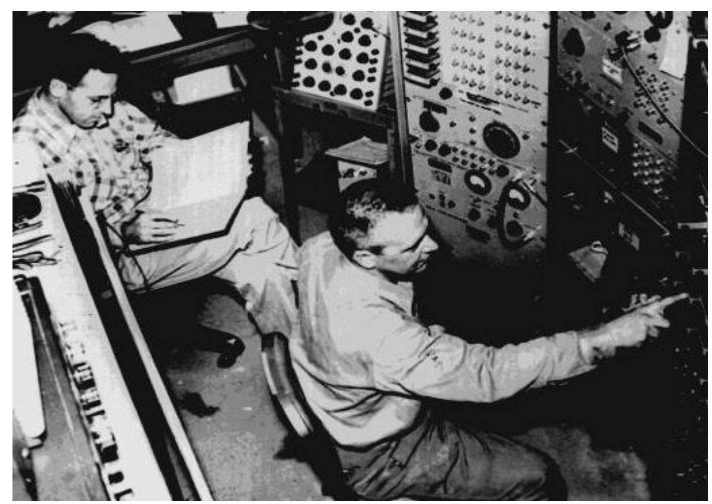
1995

$$\bar{\nu}_e \; p \rightarrow n \; e^+$$

$$e^+ e^- \rightarrow \gamma \gamma \qquad E_\gamma = m_e$$

$$n \; Cd \rightarrow Cd^* \; \gamma$$

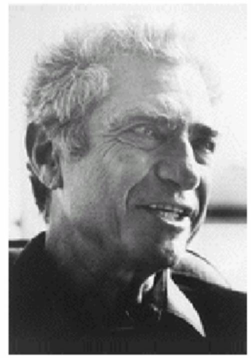
$\gamma_n \gamma_e$-coincidences $\quad \delta t \sim \mu s$



Discovery of muon neutrino

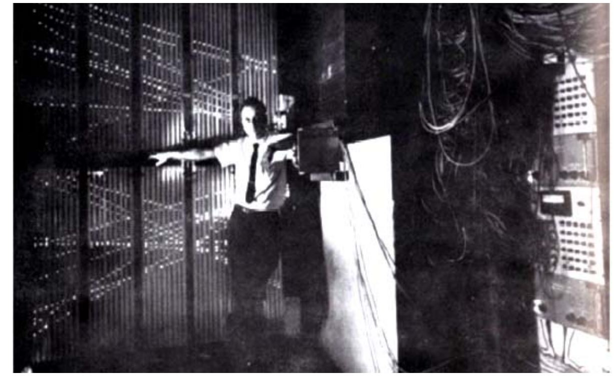

L.Lederman

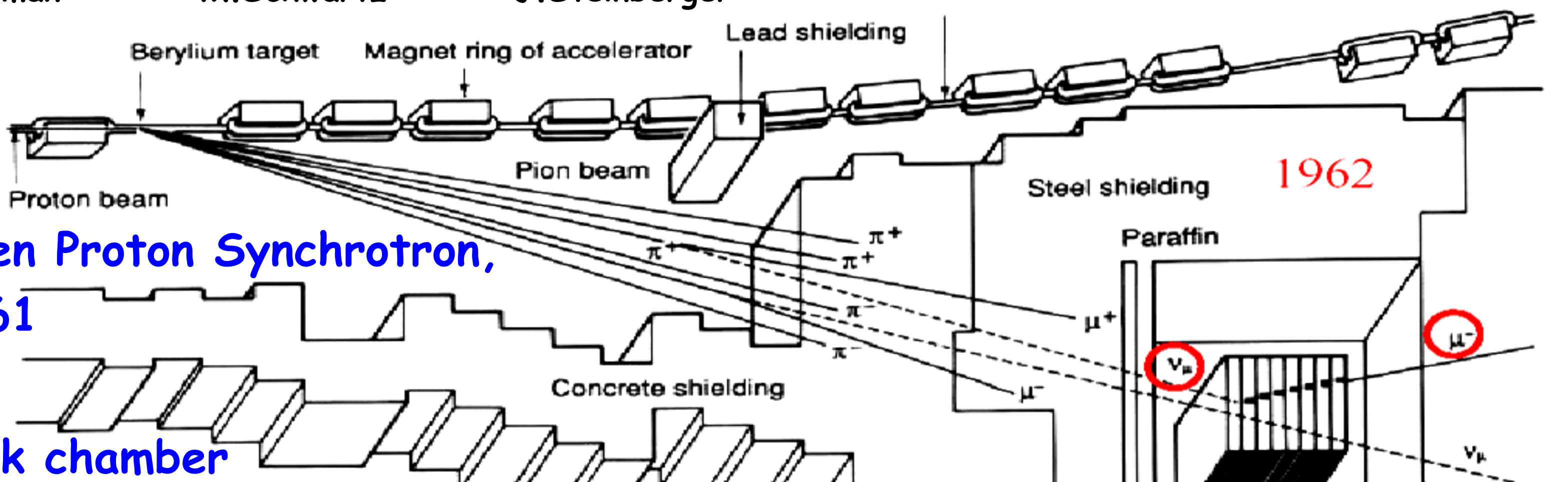

M.Schwartz


J.Steinberger

Nobel

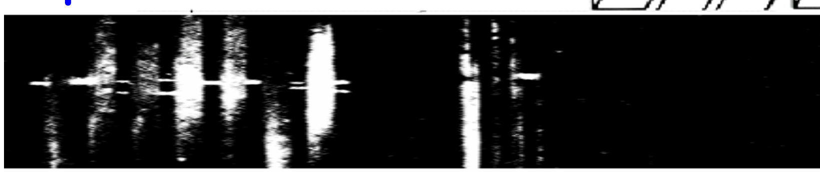
prize
1988



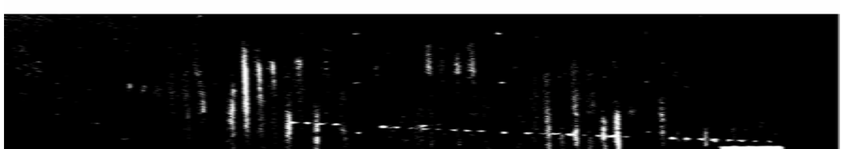


Brookhaven Proton Synchrotron,
USA, 1961

10 t spark chamber



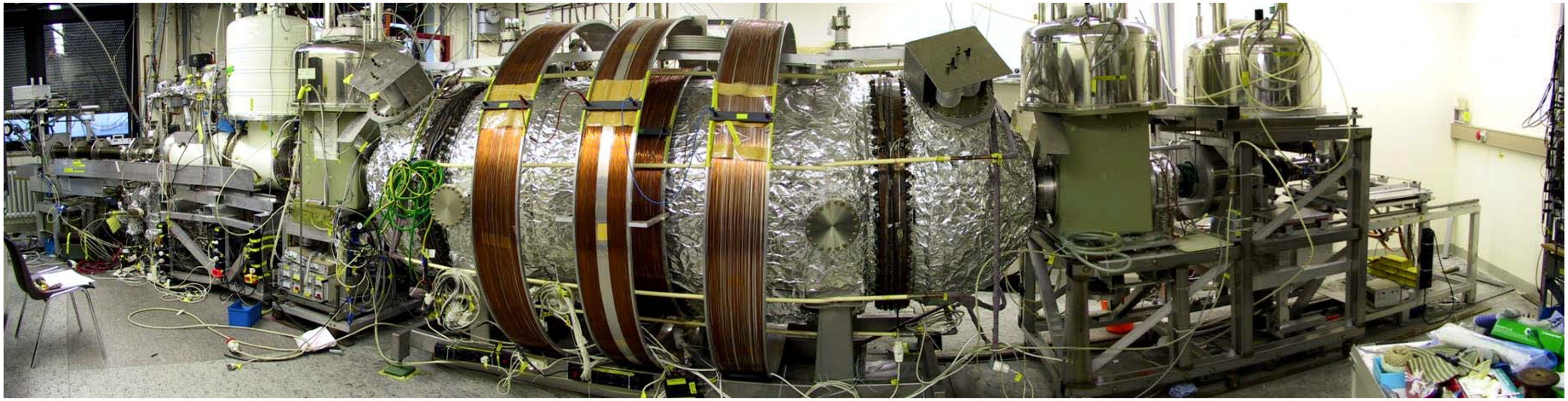
ν_μ



μ

$\nu_\mu \neq \nu_e$

Neutrino mass



Mainz experiment:

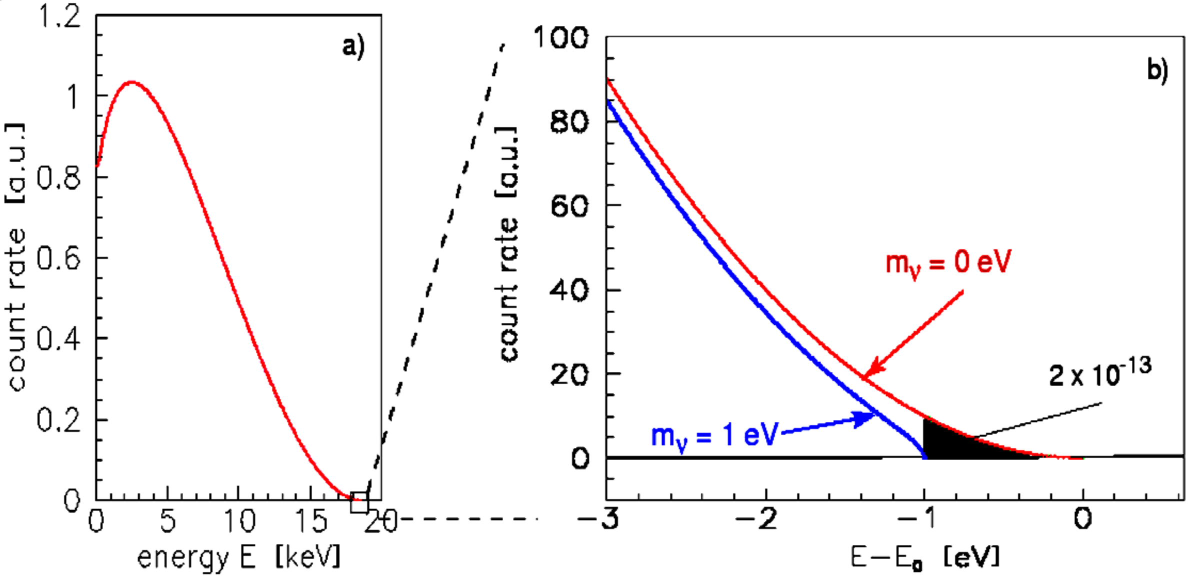
Kurie plot: end point of Tritium β spectrum

$H^3 \rightarrow He^3 \, e^- \, \bar{\nu}_e$

$m(\nu_e) < 2.3$ eV

(95% CL)

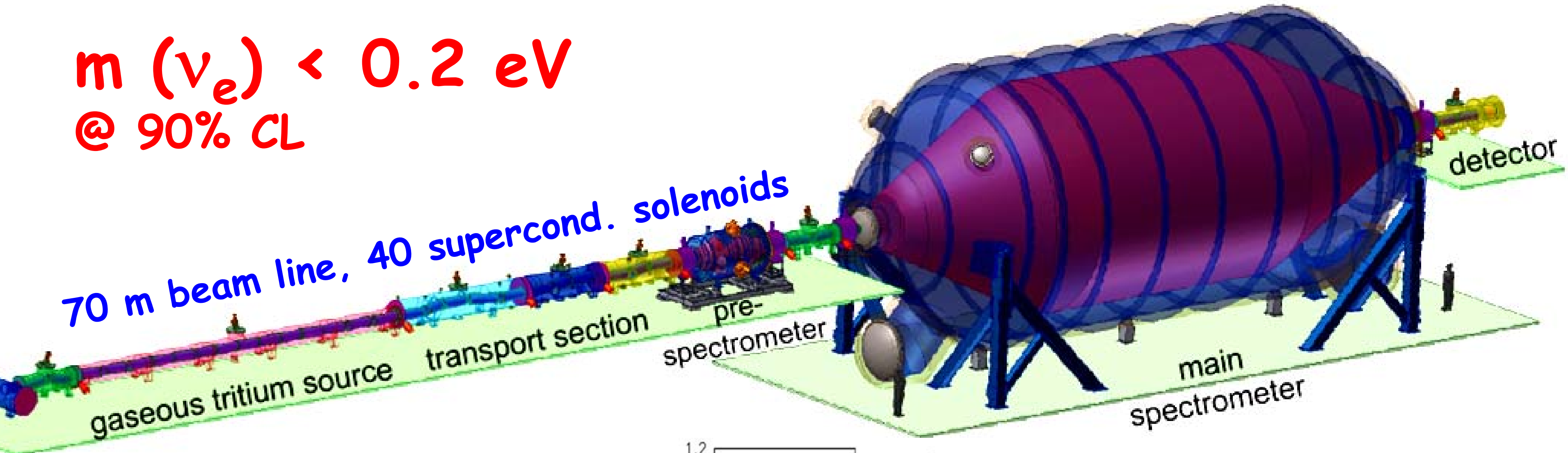
problem: nuclear models



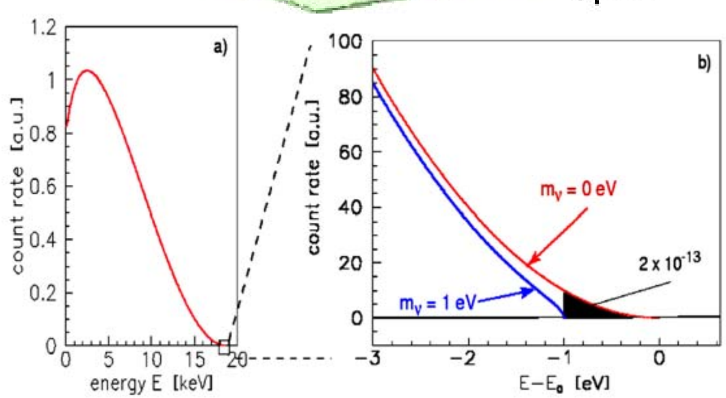
Neutrino Mass

KATRIN: KArlsruhe TRItium Neutrino Experiment

$m(\nu_e) < 0.2$ eV
@ 90% CL

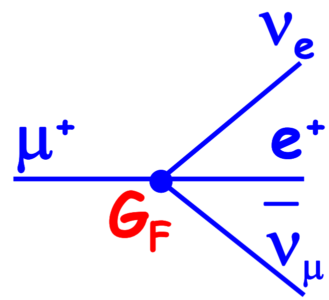


> 2008:
measure end point
of tritium β spectrum:



Fermi Constant

4 Fermion theory of weak interaction with coupling constant



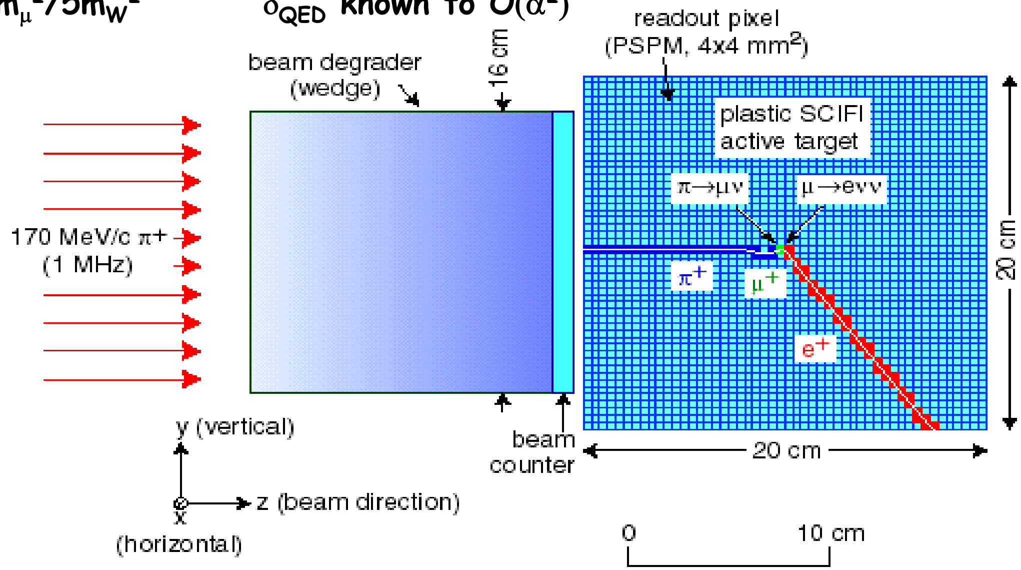
$G_F = (1.16637 \pm 0.00001) \times 10^{-5}\ \mathrm{GeV}^{-2}$

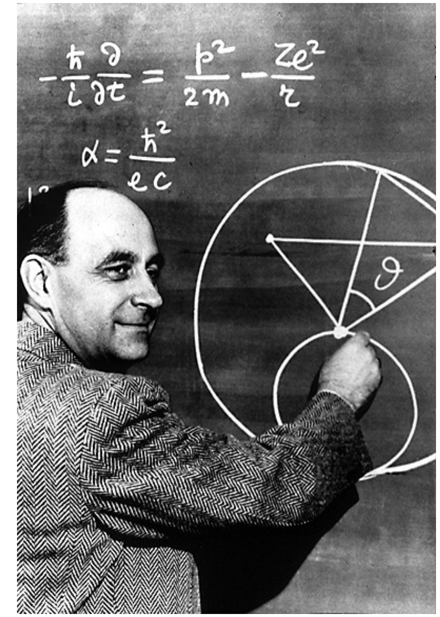
determined from muon lifetime

$$\tau_\mu = 192\pi^3/(G_F^2 m_\mu^5)\ (1+\delta_{kin})(1+\delta_{weak})(1+\delta_{QED})$$

$\delta_{kin} = -8x+8x^3-x^4-12x^2\ln x$ with $x = m_e^2/m_\mu^2 = 2\ 10^{-5}$

$\delta_{weak} = 3m_\mu^2/5m_W^2$ δ_{QED} known to $O(\alpha^2)$





E. Fermi

Nobel  prize

1938

FAST at CERN

get G_F to 1 ppm
with $>10^{12}$ μ decays

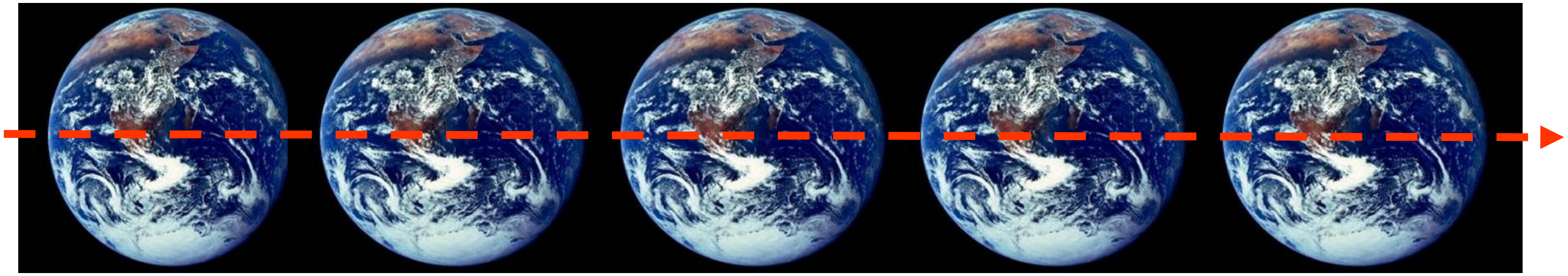
Neutrino interactions

only 1 solar neutrino/person/human life reacts !

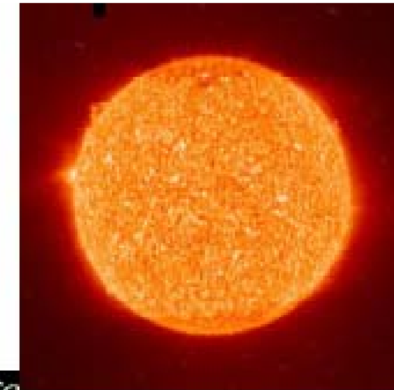
can a solar neutrino penetrate the Earth?

$$L_{reaction} = \frac{\text{atomic weight}}{\text{density} \times \text{cross section} \times N_{Avogadro}} = \frac{40\,\text{g/mol}}{5.5\text{g/cm}^3 \times 0.7 \times 10^{-38}(E/\text{GeV})\,\text{cm}^2 \times 6.023 \times 10^{23}\,/\text{mol}}$$

mean free path 2×10^{13} km = 2 light years :



1 billion earths or 10 million suns



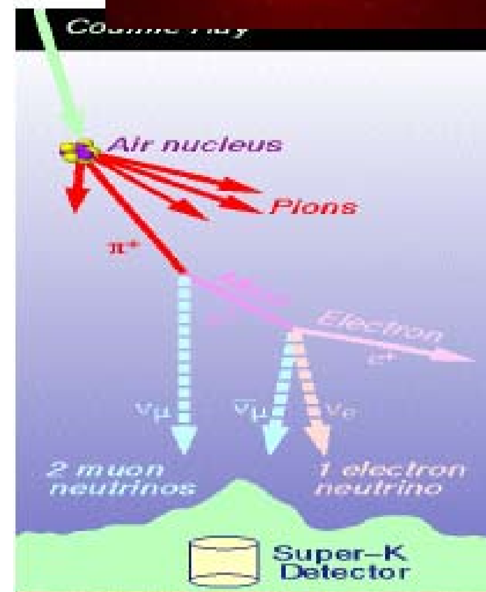
Neutrinos

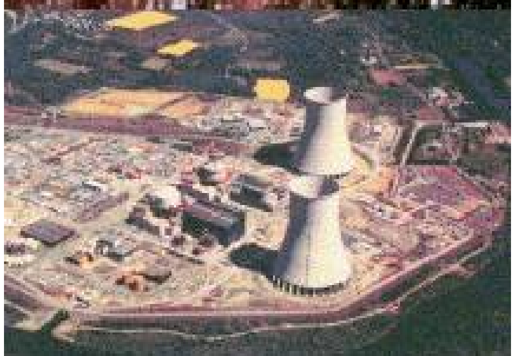
Supernovae

SN 1987A: 10^{15} m^{-2}

Sun

$6 \cdot 10^{10}$ m^{-2} s^{-1}





Reactors

$2 \cdot 10^{20}$ /GW s

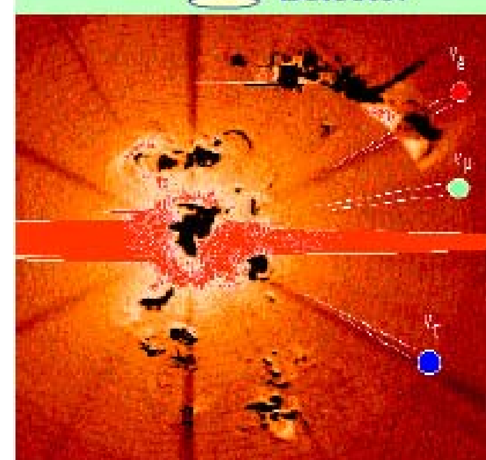
Cosmic radiation - Atmosphere

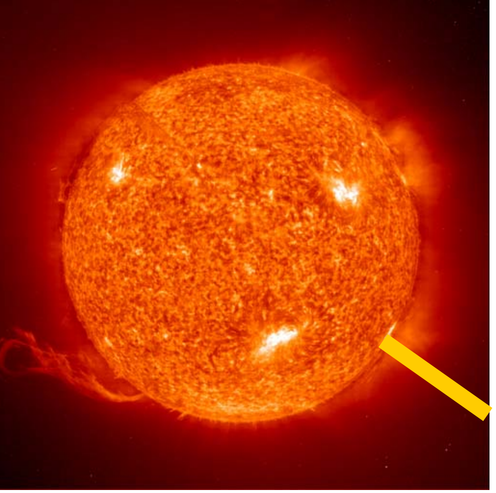
10^4 m^{-2} s^{-1}

Accelerators

Big Bang

335 cm^{-3}





Solar Neutrinos

Homestake Gold mine

ν_e

$6\text{x}10^{10}$ $m^{-2}s^{-1}$

nuclear fusion in the Sun :

pppp → ppnn = He

p → n e^+ ν_e

micro-chemistry: detect single atoms

ν_e Cl^{37} → Ar^{37} e^-

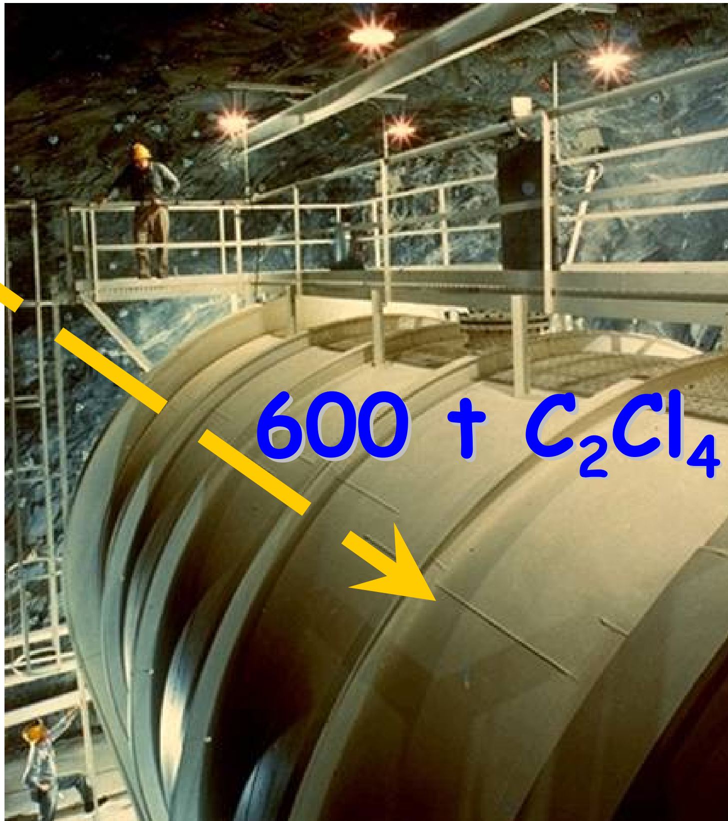
ν_e n → p e^-

1967-94: ~ 2/3 neutrinos missing !

nuclear fission in reactors produces $\bar{\nu}_e$

$\bar{\nu}_e$ Cl^{37} ↛ Ar^{37} e^- no signal =>

$$\nu \neq \bar{\nu}$$



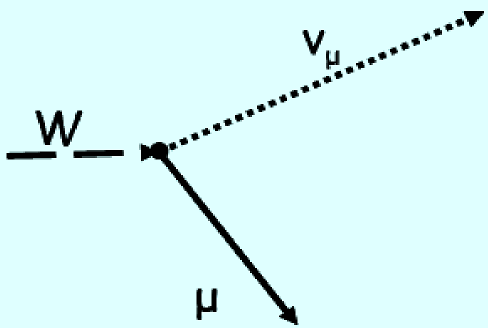
Neutrino oscillations

Flavor eigenstates
ν_μ, ν_τ

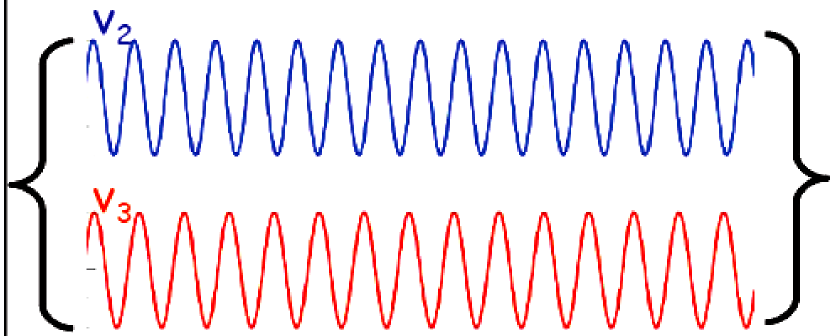
$$\begin{pmatrix} \nu_\mu \\ \nu_\tau \end{pmatrix} = \begin{pmatrix} \cos\theta_{23} & \sin\theta_{23} \\ -\sin\theta_{23} & \cos\theta_{23} \end{pmatrix} \begin{pmatrix} \nu_2 \\ \nu_3 \end{pmatrix}$$

Mass eigenstates
ν_2, ν_3 with m_2, m_3

source creates flavor-eigenstates



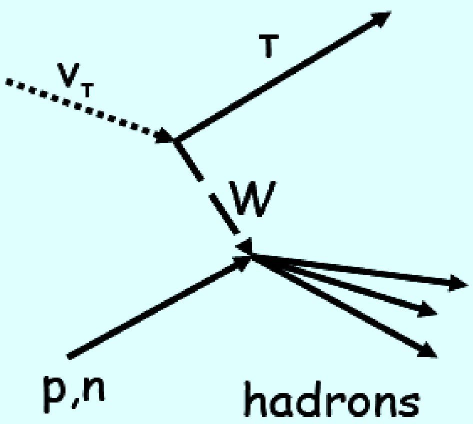
propagation determined by mass-eigenstates



$$\omega_{2,3} = E_{2,3} = \sqrt{p^2 + m_{2,3}^2}$$

slightly different frequencies
→ phase difference changes

detector sees flavor-eigenstates

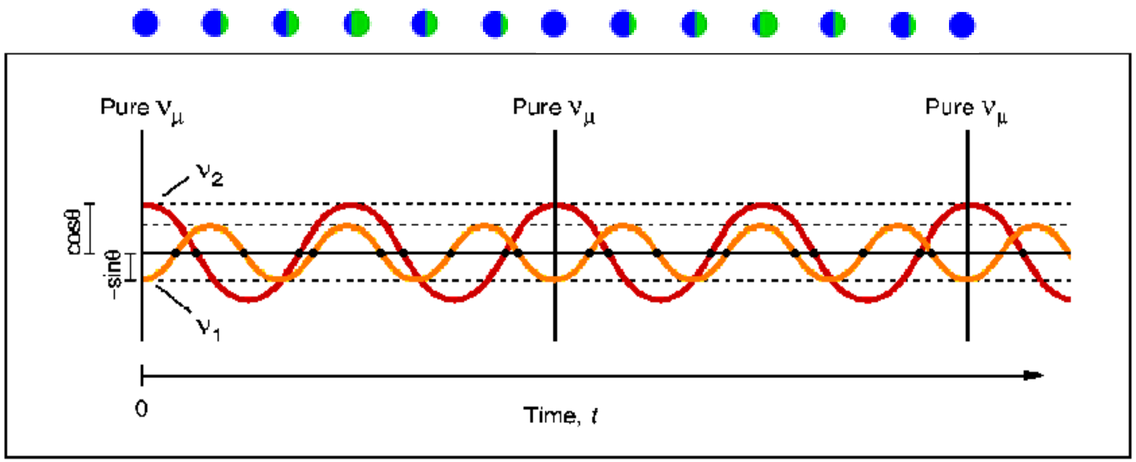


θ=45° max. mixing: $\nu_e = \nu_1 - \nu_2$ $\nu_\mu = \nu_1 + \nu_2$

Neutrino oscillations

2 Neutrinos: ν_e, ν_μ

$$|\nu_e(0)\rangle = \cos\theta\,|\nu_1\rangle + \sin\theta\,|\nu_2\rangle$$
$$|\nu_\mu(0)\rangle = -\sin\theta\,|\nu_1\rangle + \cos\theta\,|\nu_2\rangle$$



$$|\nu_\mu(t)\rangle = -\sin\theta\ \exp[-\frac{iE_1 t}{\hbar}]\ |\nu_1\rangle + \cos\theta\ \exp[-\frac{iE_2 t}{\hbar}]\ |\nu_2\rangle$$

$$E_i = \sqrt{p_i^2 + m_i^2} \xrightarrow{p_i = p \gg m_i} \simeq p + \frac{m_i^2}{2p} \simeq p + \frac{m_i^2}{2E}$$

$$L = c \cdot t \qquad \Delta m^2 = m_2^2 - m_1^2 \Rightarrow E_2 - E_1 = \frac{\Delta m^2}{2E}$$

2ν-transition-probability:

$$P(\nu_\mu \to \nu_e) = |\langle\nu_\mu(t)|\nu_e(0)\rangle|^2 = \sin^2 2\theta \cdot \sin^2\left(\frac{\Delta m^2 L}{4E}\right)$$

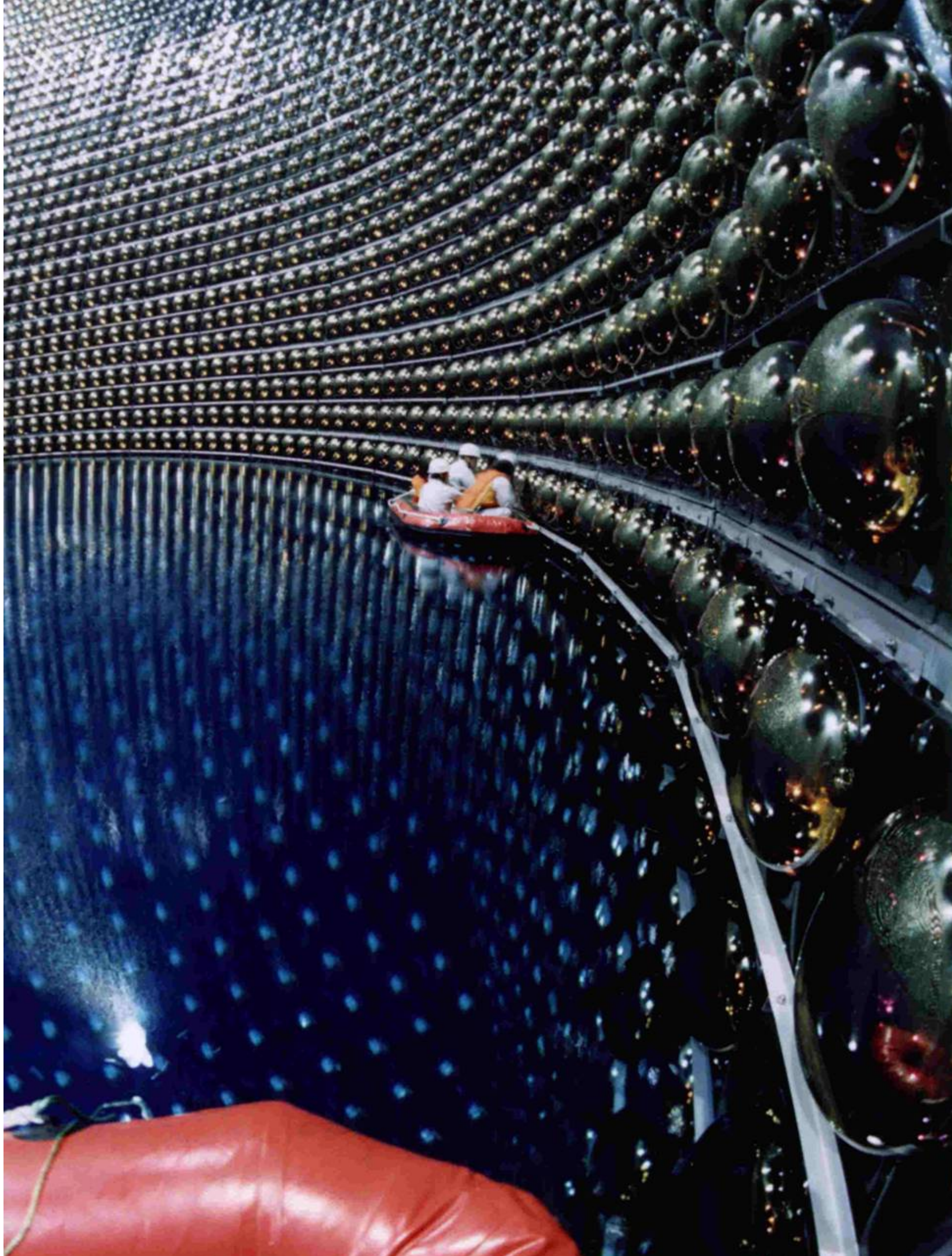
$$= \sin^2 2\theta \cdot \sin^2 (1.27\ [\Delta m^2/eV^2]\ [L/km]\ /\ [E/GeV])$$

Super-Kamiokande

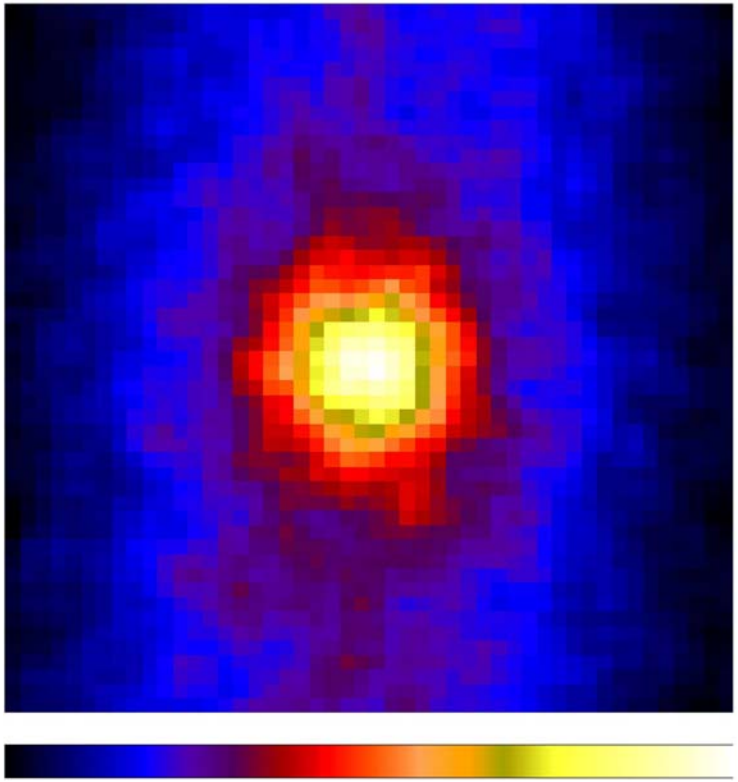
Kamioka mine
Japan :

detect Cerenkov light
in 50.000 t water
12.000 photomultipliers
1000 m underground

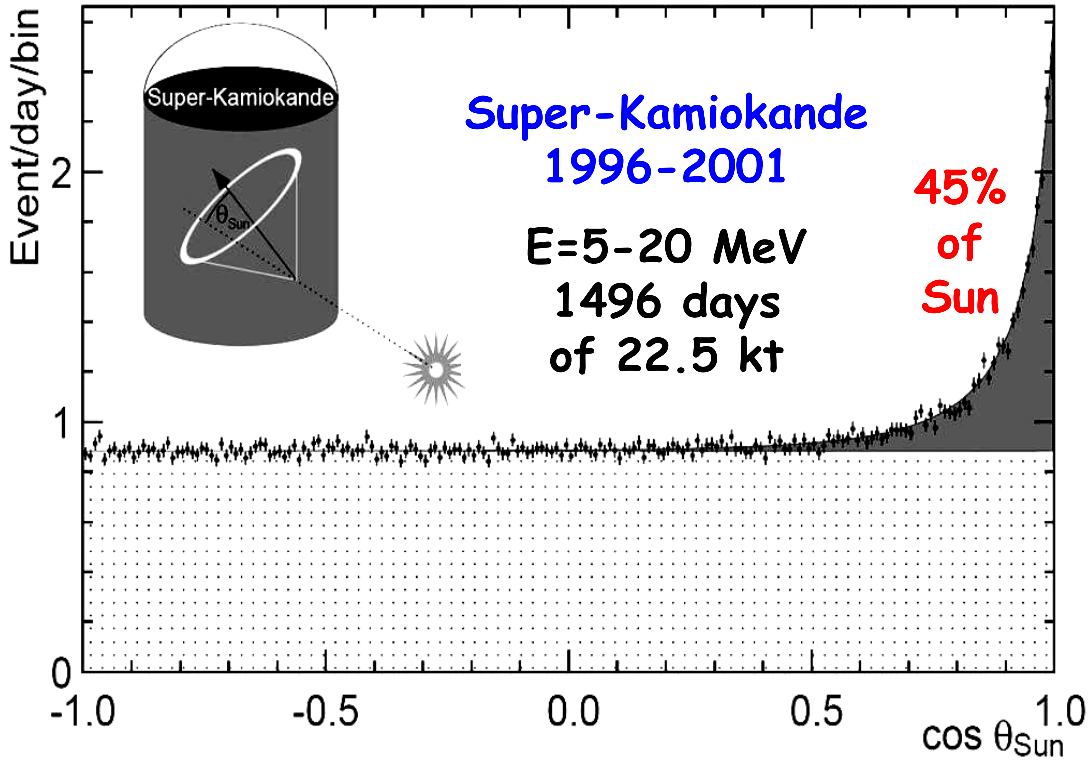
built for p decay
1989:
$\tau\,(p \to \pi^0 e^+) > 10^{33}$ a



Solar Neutrinos



First Sun neutrino-graphy.
$90^0 \times 90^0$.
SuperKamiokande 1998.



45±2% of Bahcall solar model

where are the solar neutrinos?

Atmospheric Neutrinos

Super-Kamiokande:

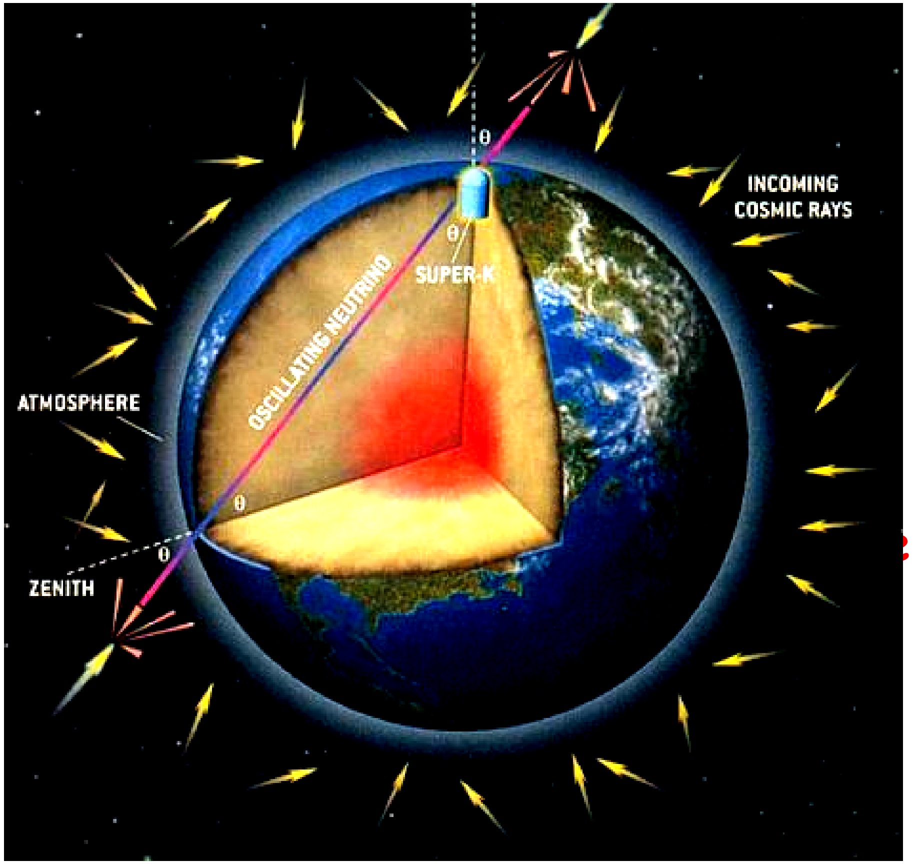
cosmic protons
react in atmosphere:

$pA \rightarrow n\ \pi$

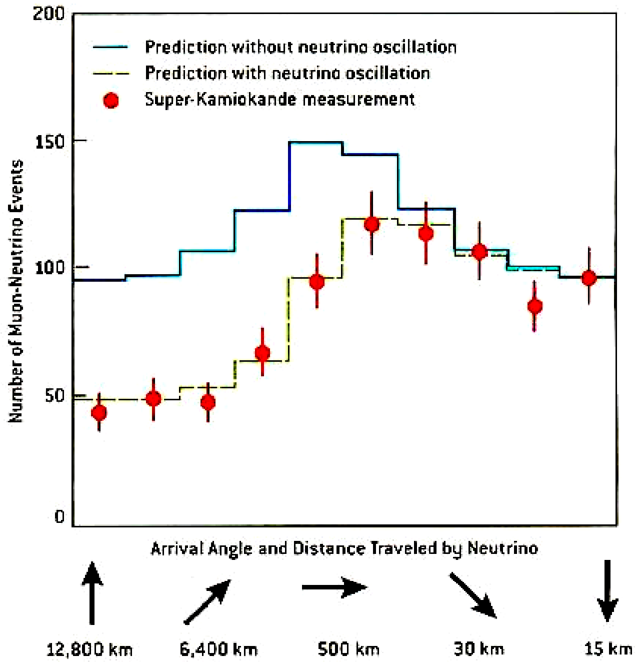
$\pi \rightarrow \mu\ \nu_\mu$ $\mu \rightarrow \nu_\mu\ e\ \nu_e$

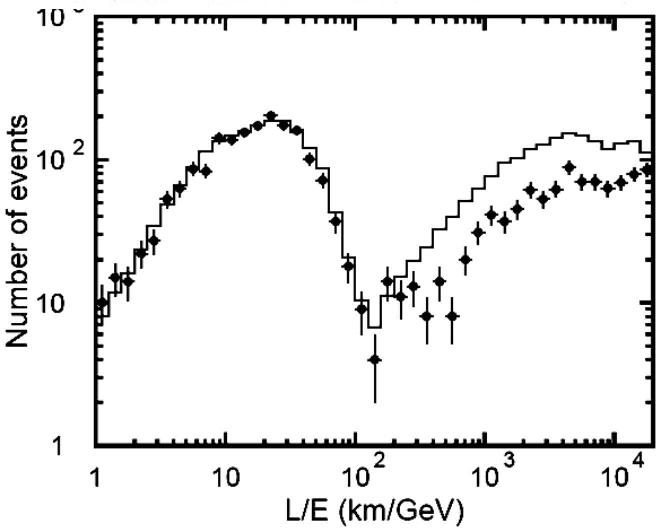
expect $\nu_\mu / \nu_e \sim 2/1$
observe $\sim 1/1$

$\nu_\mu \rightarrow \nu_e$ disappear ?!
detect Cerenkov rings
from $\nu_e \rightarrow e$ and $\nu_\mu \rightarrow \mu$



Atmospheric Neutrinos





Super Kamiokande 2004:

rate too small as f (θ, E) !

ν_μ disappear !

ν oscillation with mass difference

$\Delta m_{23}^2 = 2.4 \pm 0.4 \cdot 10^{-3}$ eV^2

and max. mixing angle:

$\sin^2 2\theta_{23} > 0.92$ @ 90% CL

$\theta_{23} \sim 45°$ max. mixing !

Neutrino Mixing

$$\begin{pmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \end{pmatrix} = \begin{pmatrix} 1 & 0 & 0 \\ 0 & c_{23} & s_{23} \\ 0 & -s_{23} & c_{23} \end{pmatrix} \begin{pmatrix} c_{13} & 0 & s_{13}e^{-i\delta} \\ 0 & 1 & 0 \\ -s_{13}e^{i\delta} & 0 & c_{13} \end{pmatrix} \begin{pmatrix} c_{12} & s_{12} & 0 \\ -s_{12} & c_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix} \begin{pmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \end{pmatrix}$$

θ_{23}: 34° - 58°

θ_{13}<13°, δ ?

θ_{12}: 29° - 39°

Atmospheric + accelerator
- MINOS (precision)
- OPERA (ν_τ appearance)

Reactor (CHOOZ)
- Super+Beta-Beams
- Neutrino factory

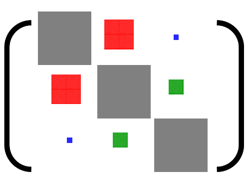
Solar + reactor

- Is θ_{23} exactly maximal?
- sign of Δm^2_{23}?

- how small is θ_{13} ?
- CP-violation Dirac CP-phase?

- θ_{12} how far from max.?
- test MSW effect

Quarks: $V_{CKM} = \begin{pmatrix} 1.0 & 0.2 & 0.001 \\ 0.2 & 1.0 & 0.01 \\ 0.001 & 0.01 & 1.0 \end{pmatrix}$



Neutrinos: $V_{MNS} = \begin{pmatrix} 0.8 & 0.5 & 0.2 \\ 0.4 & 0.6 & 0.7 \\ 0.4 & 0.6 & 0.7 \end{pmatrix}$

Why so different ?

Solar neutrinos: SNO

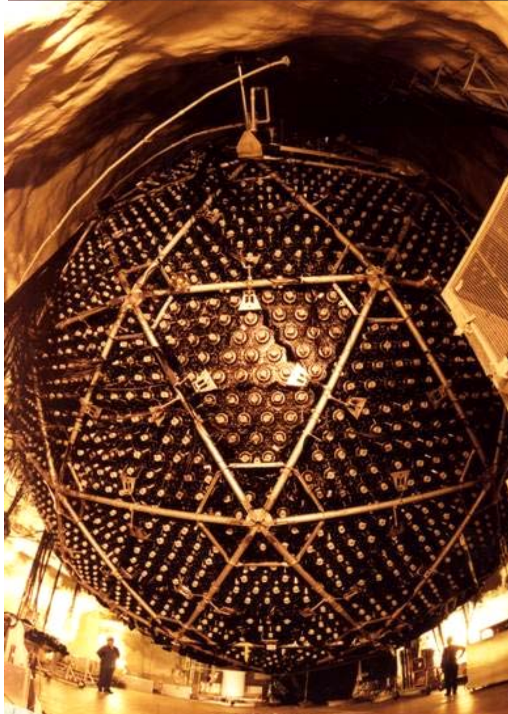
Sudbury **N**eutrino **O**bservatory, Canada

lend ~1 reactor load ~ 1000 t heavy water ~ 100 M$

CC: ν_e d -> p p e   get ν_e flux + see difference
NC: ν d -> p n ν get ν_{total} flux + verify solar models

CC: e in water Cerenkov, detect by photomultipliers
NC: n capture in salt: n ^{35}Cl -> ^{36}Cl -> Cl + γ's (8MeV)

~10 evts/s   radioactive background
~30 evts/day solar neutrinos



2002-4: Sun ok , but

$\nu_e \sim \nu_{all}/3$

Neutrino oscillation results

solar + reactor neutrinos (low E):

$\Delta m_{12}^2 = 8.0 \pm 0.5 \cdot 10^{-5}\ eV^2$

$m(\nu_\mu) = 9$ meV ~ 10^{-7} $m(\mu)$ in simplest mass hierarchy

large mixing angle $\tan^2\theta_{12} = 0.4 \pm 0.1$

atmospheric + accelerator neutrinos (high E): ν_μ disappear

$\Delta m_{23}^2 = 2.4 \pm 0.4 \cdot 10^{-3}\ eV^2$

max. mixing angle $\sin^2 2\theta_{23} > 0.92$ @ 90% CL

min. mixing angle $\sin^2 2\theta_{13} < 0.09$ @ 90% CL fitted

quark mixing: CKM matrix - lepton mixing matrix

more expts:

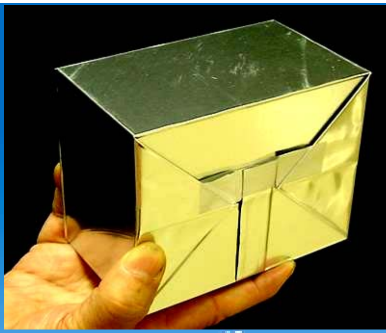
FermiLab, USA:	MiniBoonE, MINOS
KEK, Japan:	K2K, KamLand (reactor)
France:	Double-CHOOZ (reactor) θ_{13}
CERN, Geneva:	CERN-Gran Sasso OPERA $\nu_\mu - \nu_\tau$ appearance

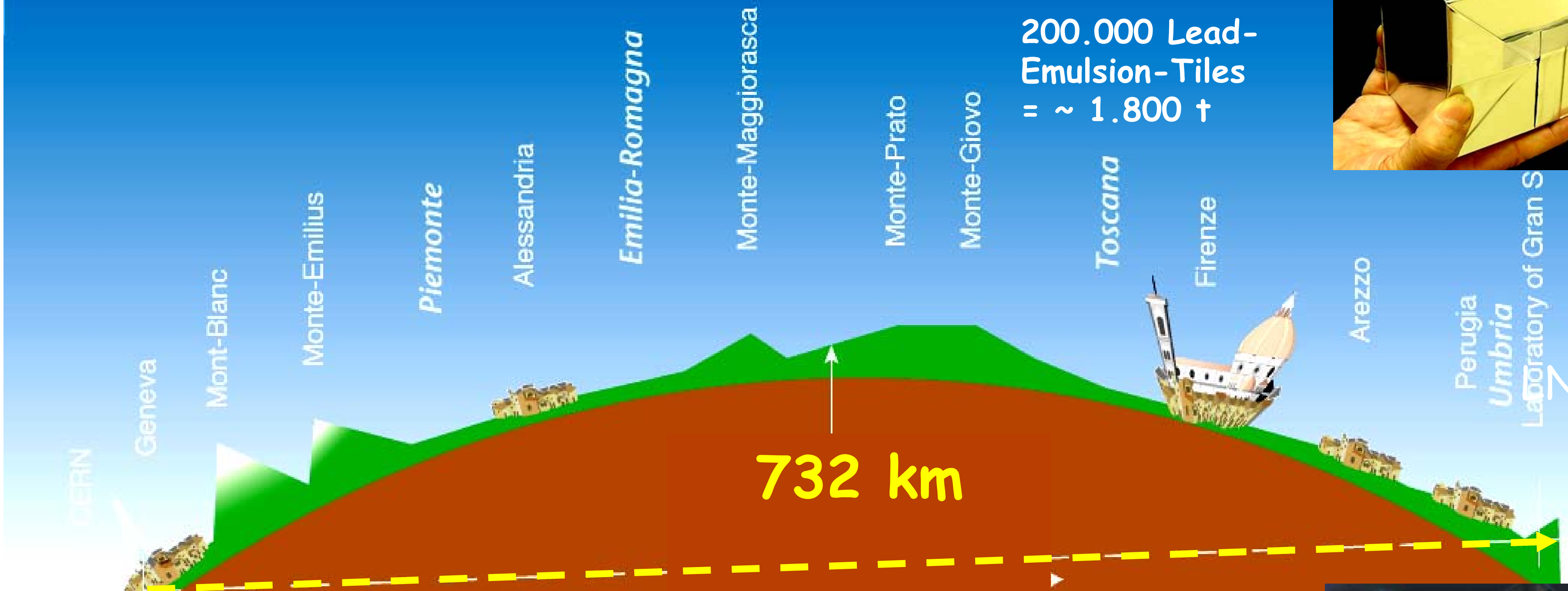
ν_τ appearance: CNGS+OPERA

CERN **N**eutrino ν_μ beam to **G**ran **S**asso Underground Lab near Rome

Detect τ leptons in Active Target:

200.000 Lead-Emulsion-Tiles = ~ 1.800 t





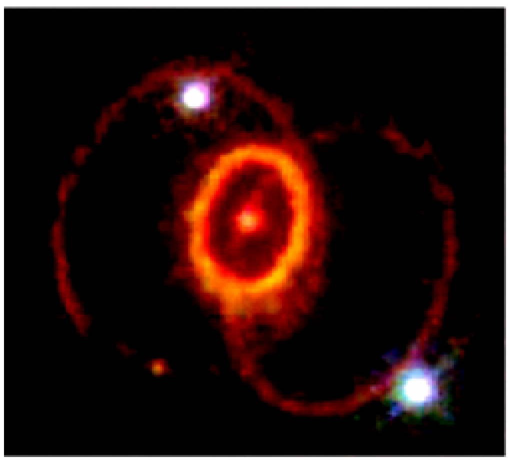
$\nu_\mu \rightarrow \nu_\tau$ $\nu_\tau N \rightarrow \tau X$

high E ! start 2006 $\sin^2(2\theta_{13}) < 0.06$

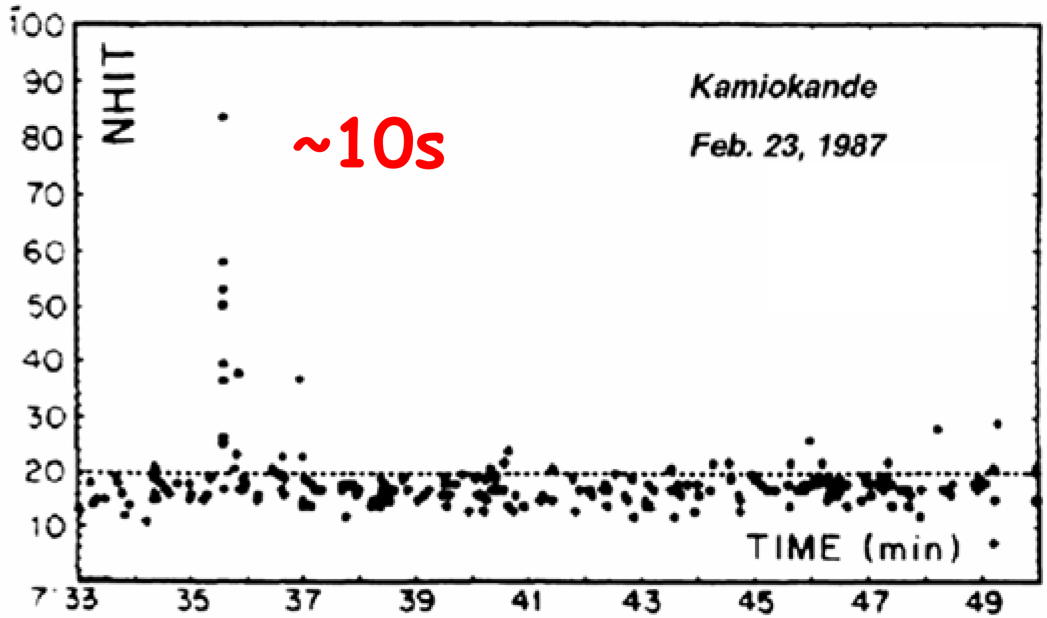
Cosmic Neutrinos

Supernova SN 1987A: Magellan cloud, 150 million ly

10^{57} ν total, 10^{15} ν/m^2

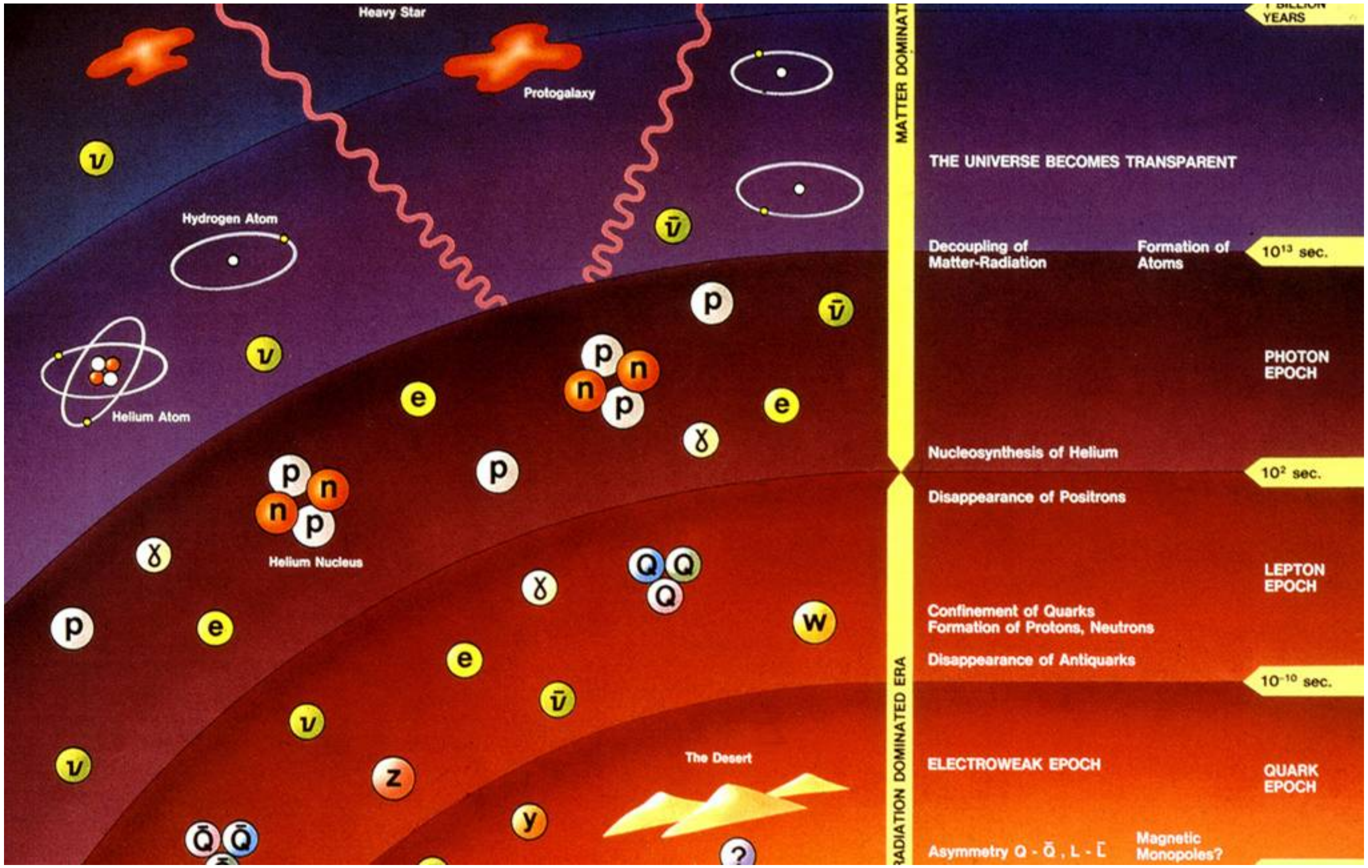


2002



First Supernova visible by naked eye since Kepler 1604 !

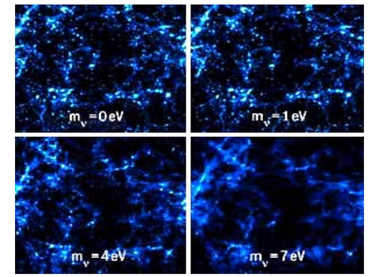
Big Bang Neutrinos



$\bar{\nu}\,\nu \nrightarrow e^+ e^-$

decoupling:

γ 380.000 a



hot ν's m>1eV wipe out cosmic structures

ν 1 s

equilibrium

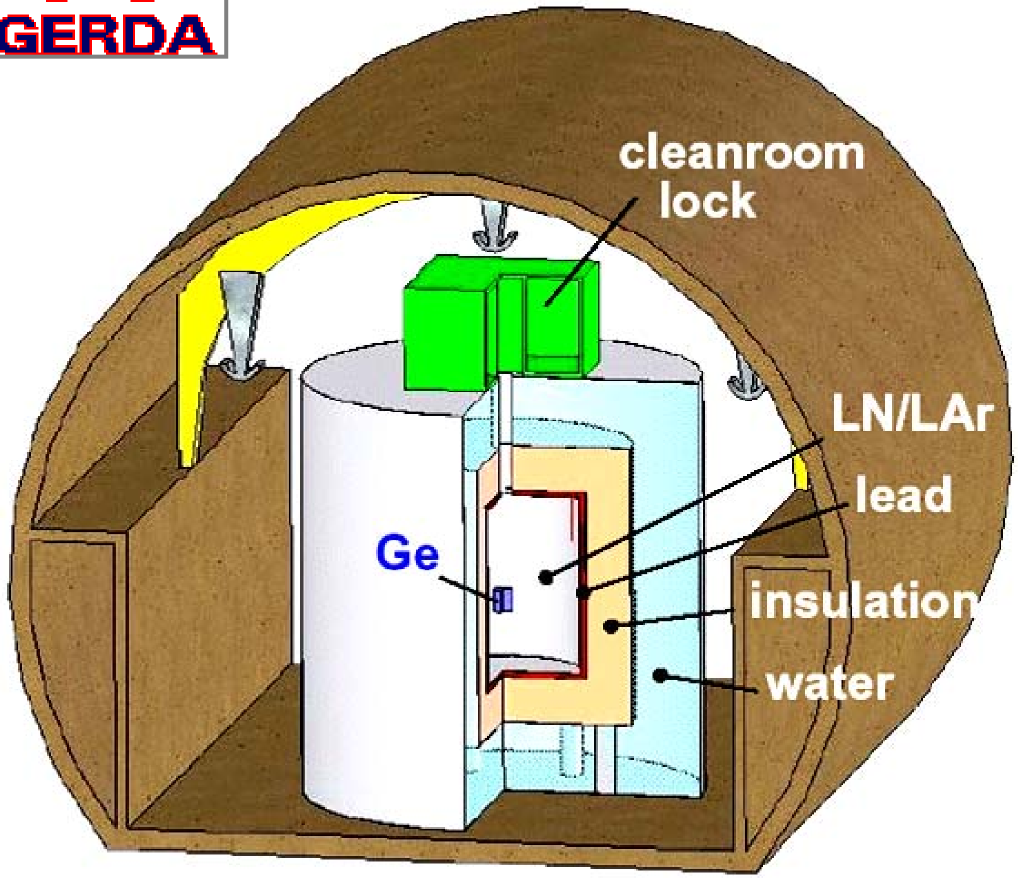
$\bar{\nu}_e\, p \to n\, e^+$

$n \to p\, e^-\, \bar{\nu}_e$

now: γ: 2.7 K background radiation 410/cm^3 Penzias, Wilson 1964

ν: 1.9 K background radiation 335/cm^3 Nobel  1978

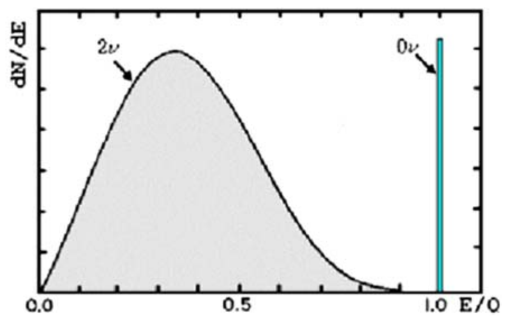
GERmanium Detector Array

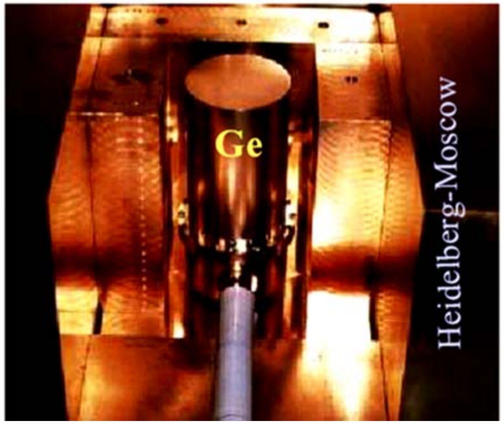


phase 1: 40 kg
phase 2: 500 kg

high purity
86% enriched ^{76}Ge diodes
in cryogenic fluid shield

$Q_{\beta\beta}$ = 2039 keV:



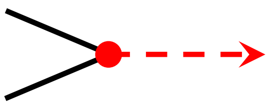


Heidelberg-Moscow expt.

Weak Interactions

Kinematics

- four-momentum : $p = (E, \mathbf{p})$ $c=1$
- four-momentum^2 : relativistic invariant
- effective mass^2 : $m^2 := p^2 = E^2 - \mathbf{p}^2$
- ultra-relativist.: $m \ll E$ $E = p$
- classic: $p \ll m$ $E = m$
- s = invariant reaction energy^2



$\mathbf{s} = (p_1+p_2)^2$

omit $p_x=p_y=0$

- **Center-of-Mass System :** e^- -------><------- e^+

$(E, \mathbf{p})$ $(E, -\mathbf{p})$

$p_1+p_2 = (2E, 0)$

$s = 4E^2$

- **Lab system :** 1 --------> • 2

$m_{1,2} \ll E_1$

$(E_1,\mathbf{p}_1)$ $(m_2,0)$

$p_1+p_2 = (E_1+m_2, E_1)$

$s = 2\, m_2 E_1$

target mass effect: $m_p = 2000\, m_e$

Weak Interaction

$$\sigma(\nu_\mu e^- \to \nu_e \mu^-) = G_F^2\, s / \pi$$

$$G_F = 1.2 \times 10^{-5}\ \mathrm{GeV}^{-2}$$

$s = 2\, m_e\, E_\nu = 1\ \mathrm{MeV}\ E_\nu = 10^{-3}\ \mathrm{GeV}^2\ [E_\nu/\mathrm{GeV}]$

$\sigma = 4 \times 10^{-14}\ \mathrm{GeV}^{-2}\ [E_\nu/\mathrm{GeV}]$

$\hbar c = 1 = 0.2\ \mathrm{GeV\ fm}$

$(\hbar c)^2 = 1 = 0.04\ \mathrm{GeV}^2\ \mathrm{fm}^2 = 0.4\ \mathrm{mb\ GeV}^2$

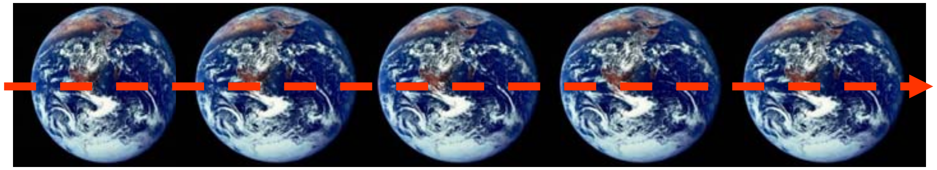
$\sigma = 1.6 \times 10^{-14}\ \mathrm{mb}\ [E_\nu/\mathrm{GeV}] = 10^{-16}\ \sigma\,(\text{strong: } \pi p \to \Delta)$

$\sigma = 1.6 \times 10^{-15}\ \mathrm{fm}^2\ [E_\nu/\mathrm{GeV}]$

$\sigma = 1.6 \times 10^{-45}\ \mathrm{m}^2\ [E_\nu/\mathrm{GeV}]$ = extremely weak !

$m_N / m_e = 2.000$ => target mass effect !

mean free path $\sim 10^{13}$ km ~ light years:



1 billion earths or 10 million suns

Weak Interaction

$[G_F] = GeV^{-2}$

Which energy scale hidden in G_F ?

$$G_F^2\, s / \pi = \sigma = \pi R^2$$

$R \sqrt{s} = \hbar c = 1$ Uncertainty relation

$G_F^2 s/\pi = \sigma = \pi/s$ $1/s$: point like interaction

$$s^2 = \pi^2 / G_F^2$$

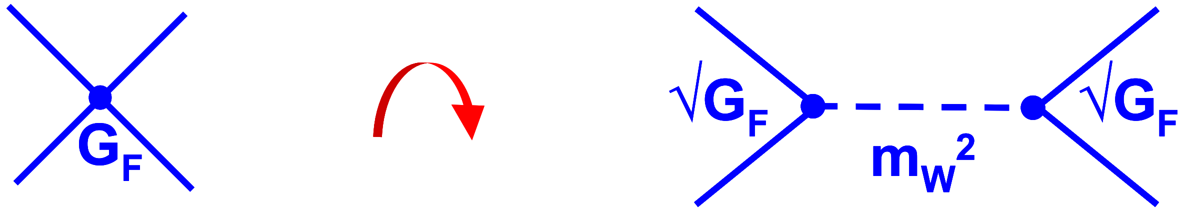
$\sqrt{G_F^{-1}} \sim \sqrt{10^5\ GeV} \sim 300\ GeV$

collapse of Fermi theory

transition to

massive exchange boson W

Weak Interaction



$G_F \quad \rightarrow \quad e'^2 / (m_W^2 - s)$

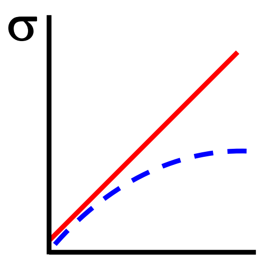
e' ... weak charge, dimensionless
massive W boson, correct s dependence.

- $s \rightarrow 0$: $e'^2 = m_W^2 G_F \; = \; e^2 = 4\pi\,\alpha \sim 0.1$

weak ~ electric force !

$m_W^2 = 4\pi\alpha \,/\, G_F$ $\quad m_W \sim 90$ GeV

- $s \gg m_W^2$: $\sigma \sim e'^4 / s$ scatter on pointlike charge

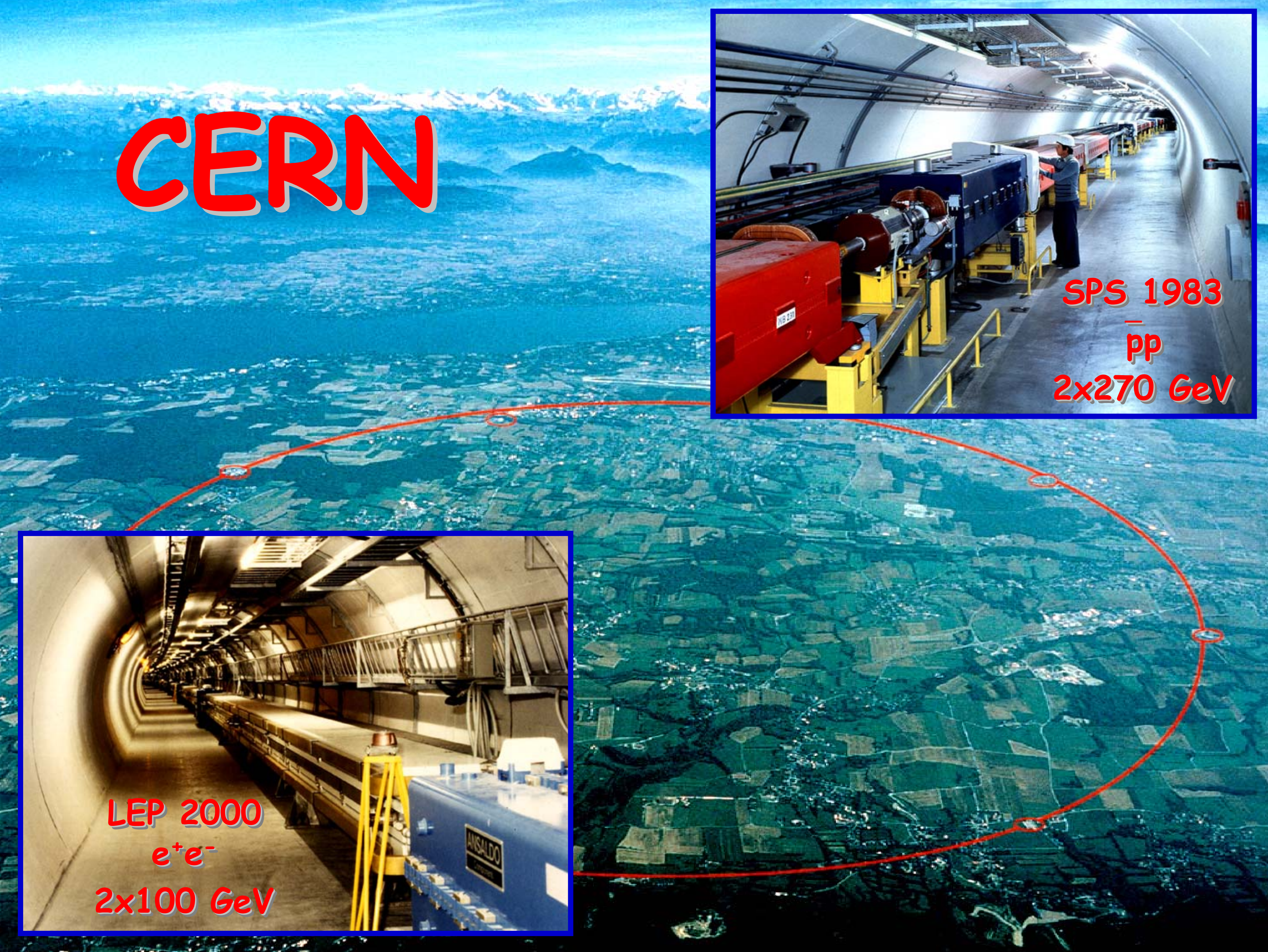


$G_F^2\, s$ $\quad s \rightarrow \infty \; => \; s \rightarrow \infty$ unitarity violated !

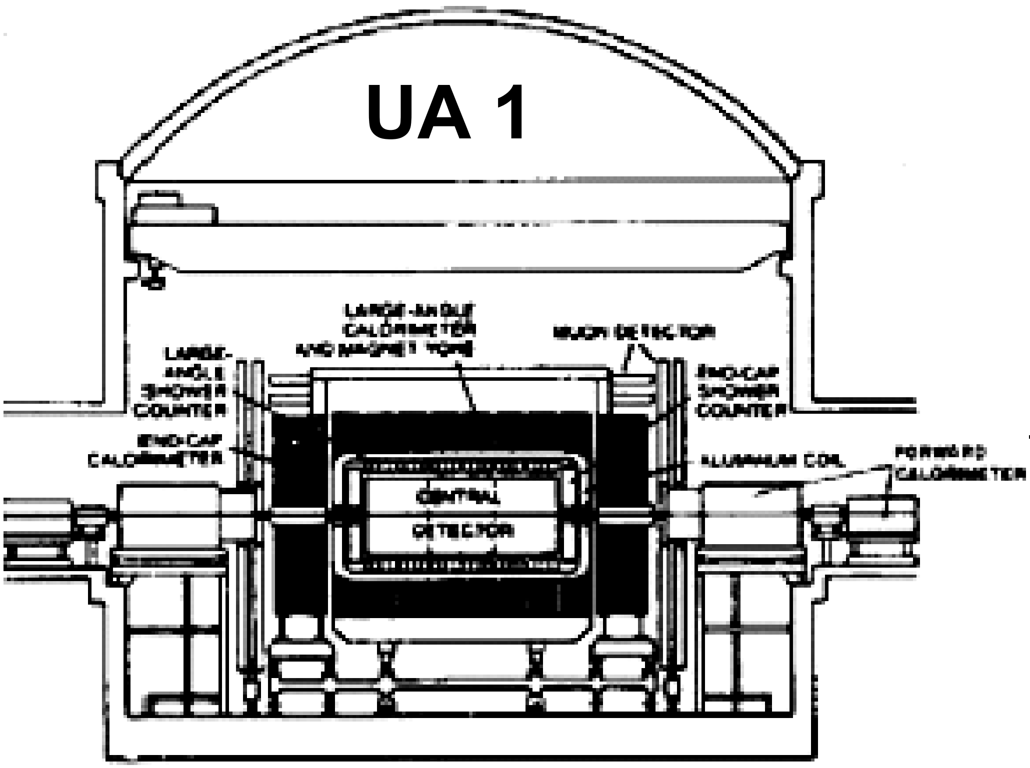
$\dfrac{e'^4\, s}{(m_W^2 - s)^2}$ weak charge, dimensionless
massive W boson
correct s dependence

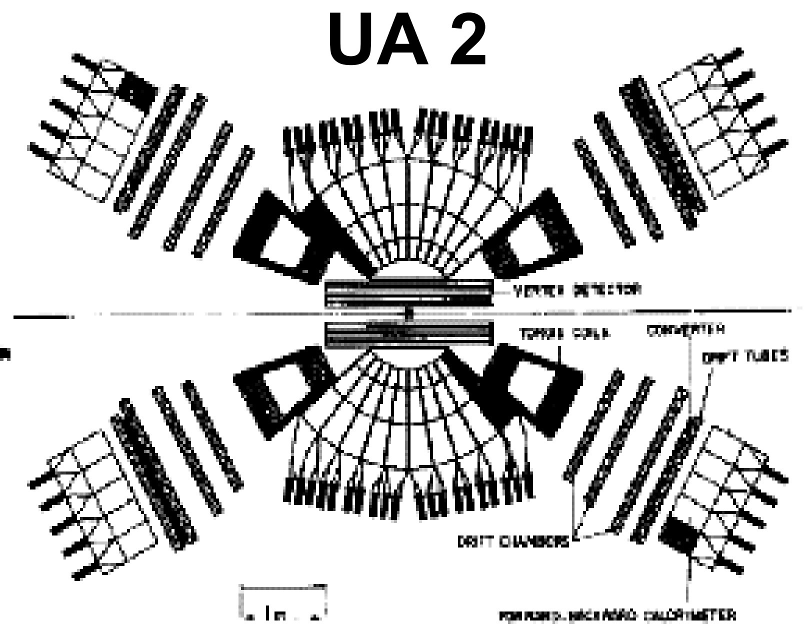
s

~1970: find the $W^\pm + Z^0$ bosons !


CERN
SPS 1983
$\bar{p}p$
2x270 GeV
LEP 2000
e^+e^-
2x100 GeV

W+Z Discovery





Expts. UA1+UA2 1983

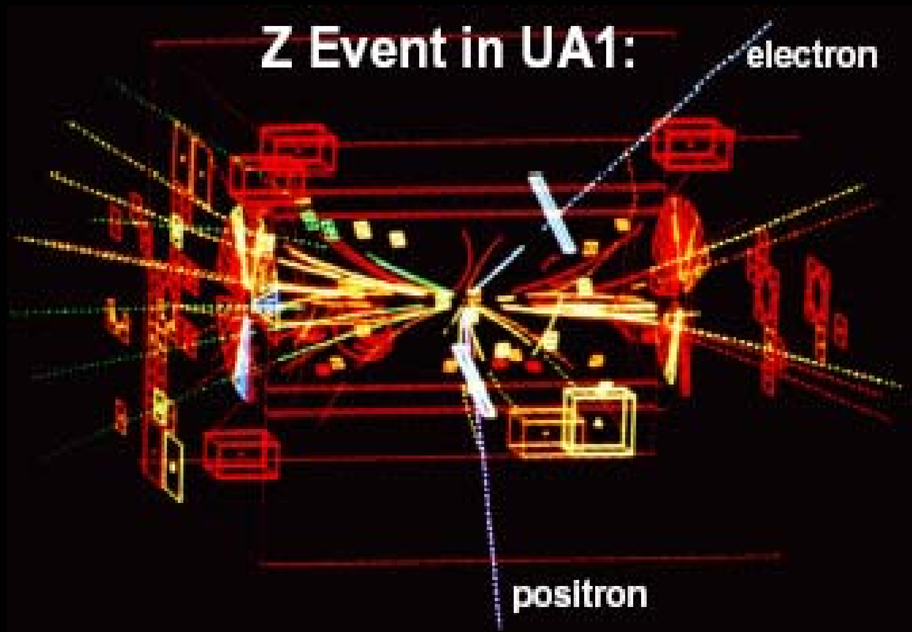
C. Rubbia

SPS $p\ \bar{p}$ collider at CERN

S. van der Meer

Nobel prize 1984

W+Z Discovery



$u\,\bar{d} \rightarrow W^{+} \rightarrow e^{+}\,\nu_e$

$q\,\bar{q} \rightarrow Z^{0} \rightarrow e^{+}e^{-}$

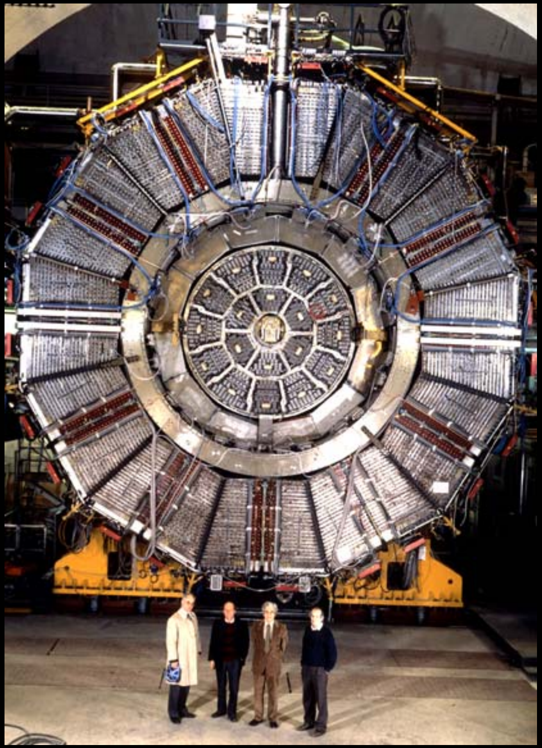
Expts. UA1+UA2 1983

C. Rubbia

SPS $p\,\bar{p}$ collider at CERN

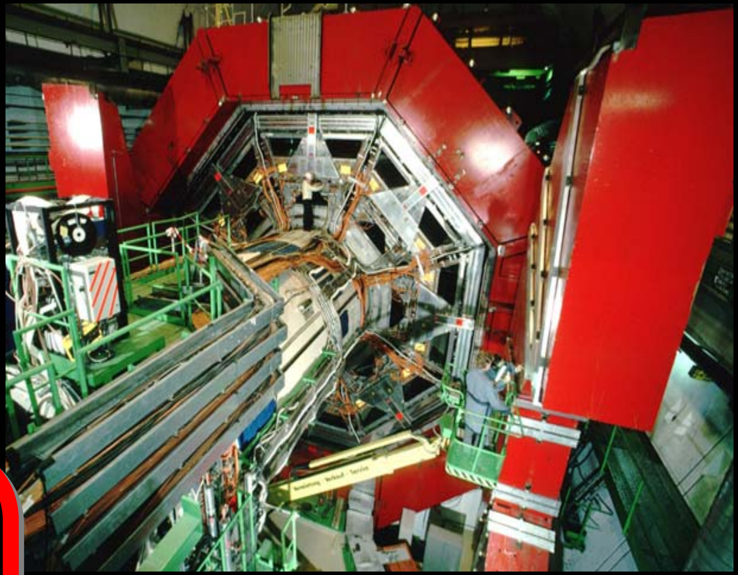
S. van der Meer

Nobel prize 1984



ALEPH

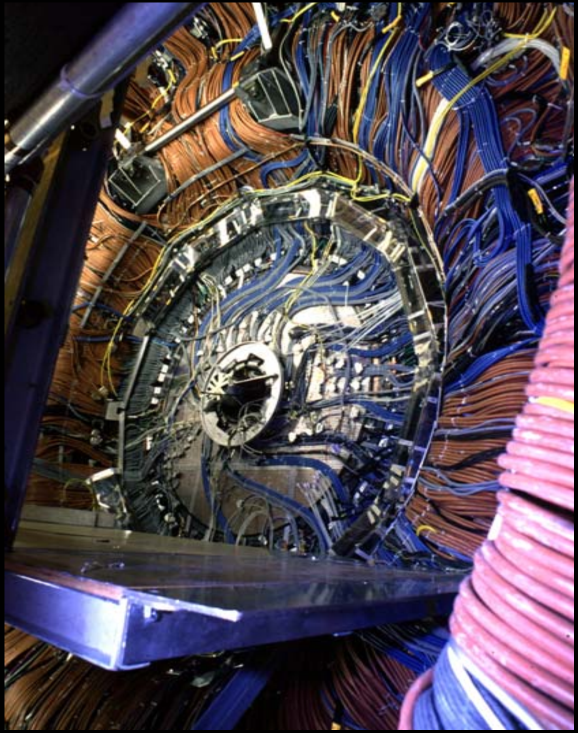
L3



LEP detect ors

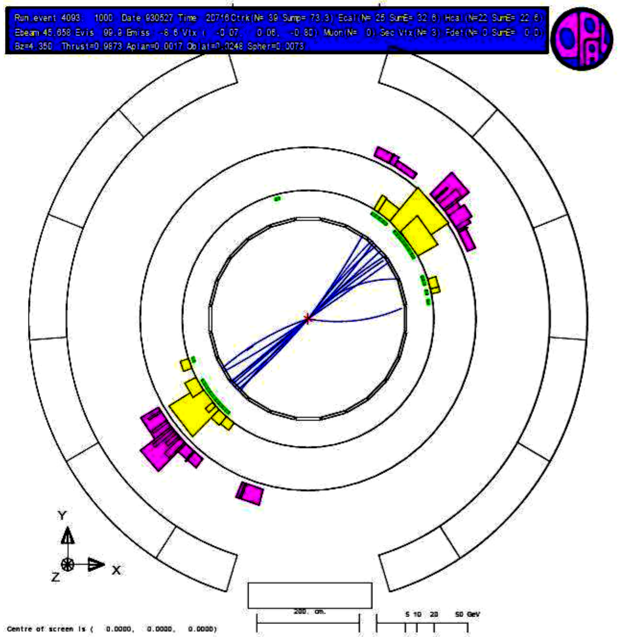
OPAL

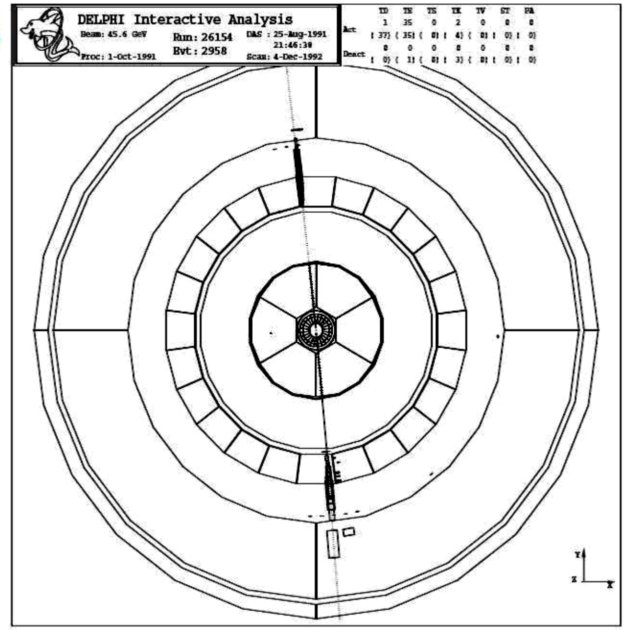
DELPHI



$q\bar{q}$

OPAL





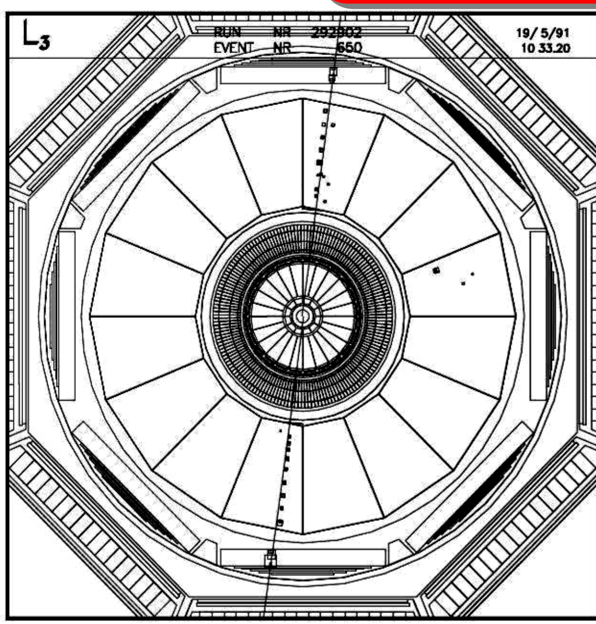
e^+e^-

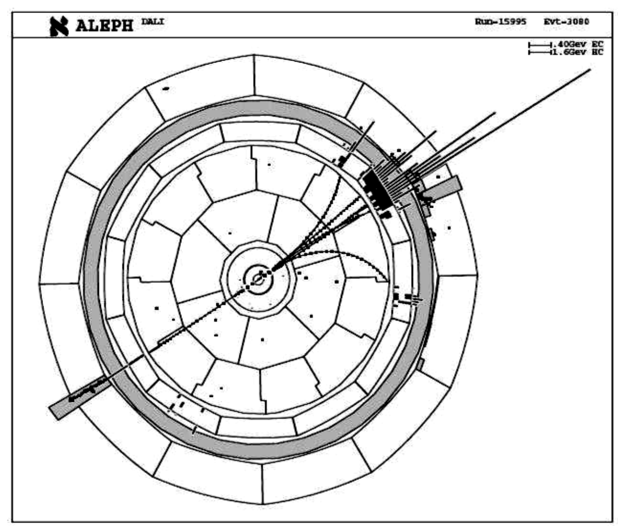
DELPHI

LEP **Z decays** CERN

L3

$\mu^+\mu^-$



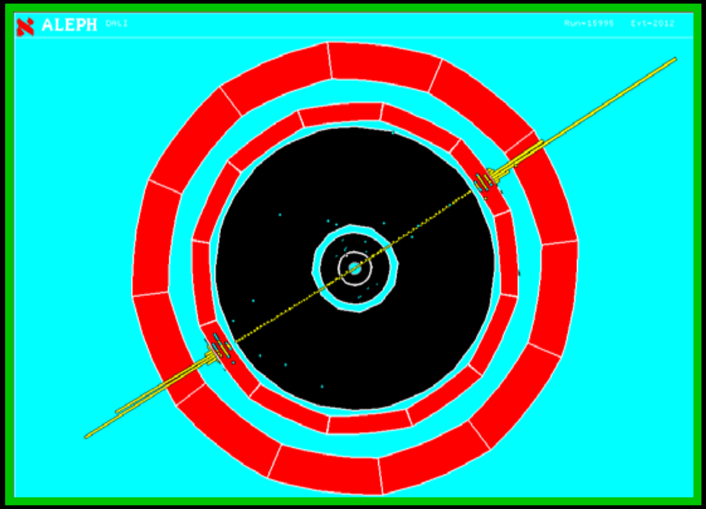


ALEPH

$\tau^+\tau^-$

Z decays

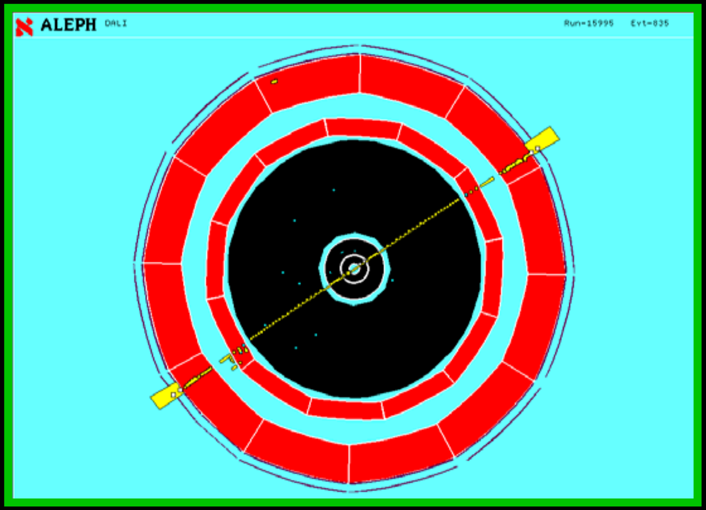
ALEPH @ LEP



$Z^0 \rightarrow e^+ e^-$

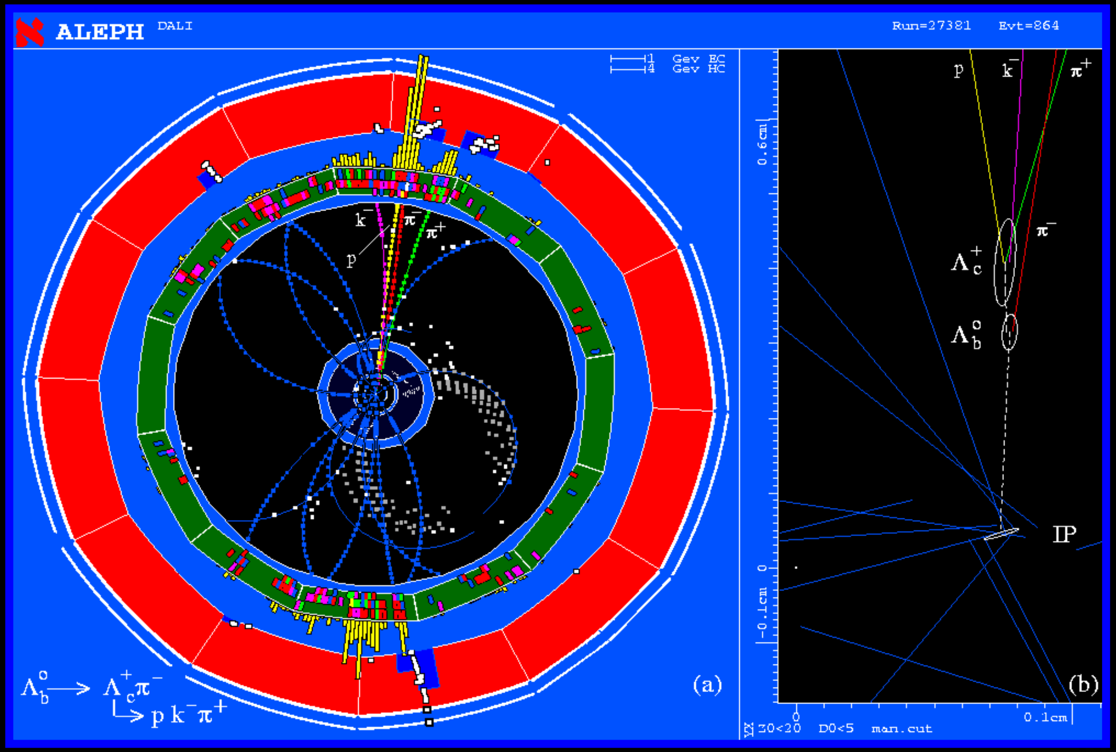
leptonic

$Z^0 \rightarrow \mu^+ \mu^-$

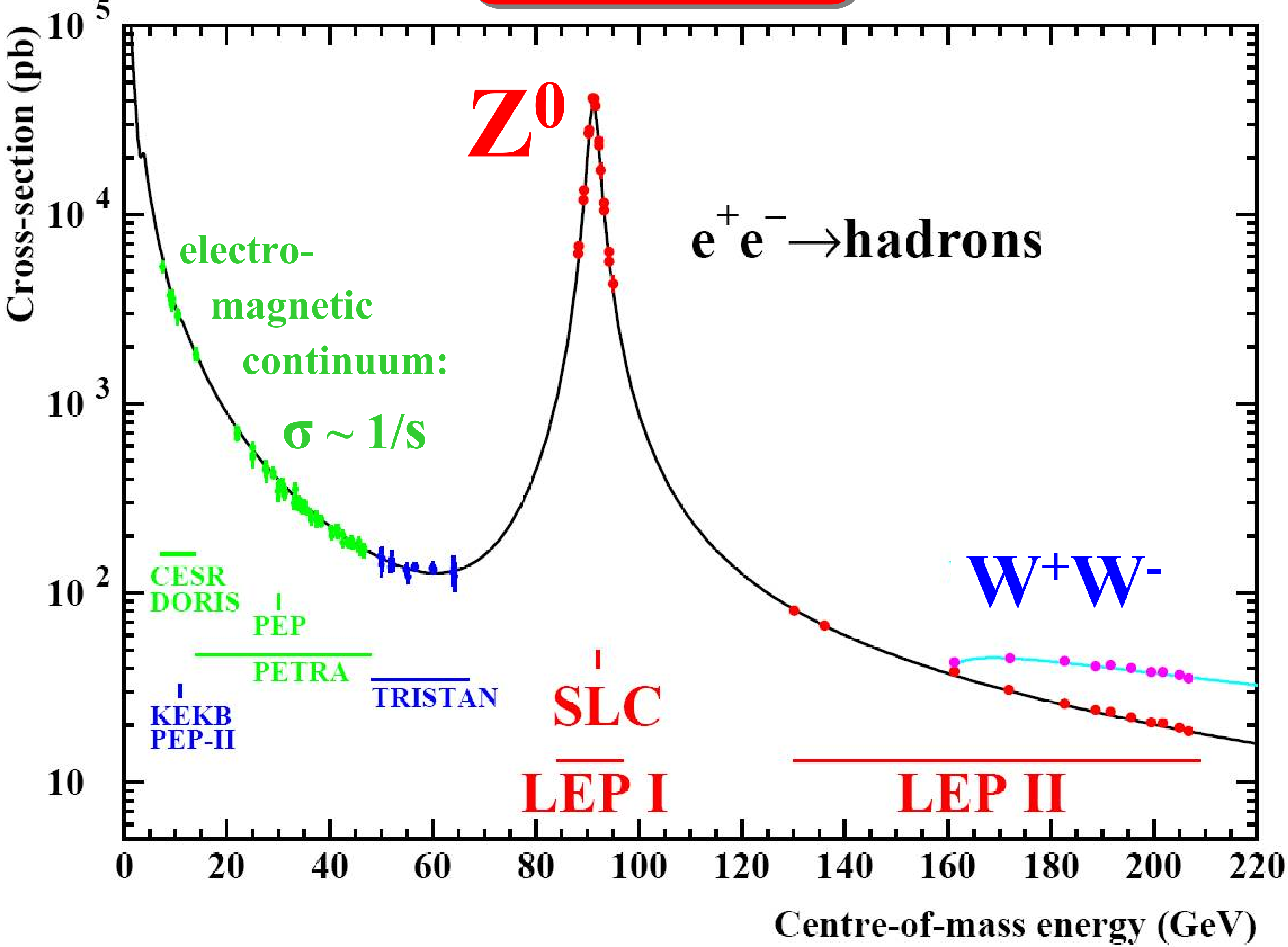


hadronic

$Z^0 \rightarrow b\bar{b}$



Z peak



Cross-section (pb)
10^5
10^4
10^3
10^2
10
Z^0
e^+e^- →hadrons
electro-
magnetic
continuum:
σ ~ 1/s
W^+W^-
CESR
DORIS
PEP
PETRA
KEKB
PEP-II
TRISTAN
SLC
LEP I
LEP II
0
20
40
60
80
100
120
140
160
180
200
220
Centre-of-mass energy (GeV)

5. Gauge Theories

for an overview, see e.g.:
A. Pich, The Standard Model of Electroweak Interactions, http://arxiv.org/pdf/hep-ph/0502010
The LEP Electroweak Working Group, http://arxiv.org/pdf/hep-ex/0511027 , http://arxiv.org/pdf/hep-ex/0509008

Higgs Mechanism

- **Fermion mass term gauge invariant :**

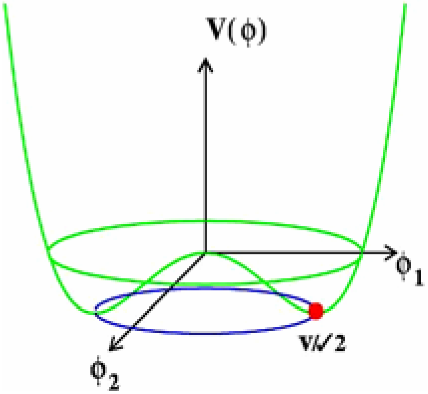
$$m\,\psi'^{*}\,\psi' = m\,\psi^{*}\,\psi$$

- **Boson mass term gauge violating :**

$$m^2 A'_\mu A'^\mu = m^2 (A_\mu + \partial_\mu\alpha)(A^\mu + \partial^\mu\alpha) =$$
$$m^2 (A_\mu A^\mu + \ldots)$$

- introduce auxiliary scalar boson field:

$$\Phi = v\ \exp(i\,\xi(x_\mu))$$



- specify gauge transformation:

$$A'_\mu = A_\mu + 1/gv\ \partial_\mu\,\xi(x_\mu)$$

now :

- cancel gauge viol. terms of vector boson mass term (long. polar.) with ξ degrees of freedom of Higgs field :
- **vector boson mass term gauge invariant !**
- **Higgs boson mass term: witness of trick !**

Higgs in SU(2)

- Higgs produces BOSON masses:

mass term for 2 W bosons in Lagrangian:

$$g^2v^2/2 \; A_\mu A^\mu = (2m_W)^2/2 \; A_\mu A^\mu$$

$$v = 2m_W/g = (\sqrt{2}\, G_F)^{-1/2} = 246 \text{ GeV}$$

v … 1 parameter of Higgs potential = scale of electroweak unification !

U(1) toy model -> SU(2) electroweak Higgs doublet (Φ^+, Φ^0)

$$\mathcal{L}_H = G_e \left\{ (\bar{\nu}_e, e^+)_L \begin{pmatrix} \Phi^+ \\ \Phi^0 \end{pmatrix} e^-_R + e^+_R (\Phi^-, \Phi^0) \begin{pmatrix} \nu_e \\ e^- \end{pmatrix}_L \right\}$$

(P violation, no ν_R)

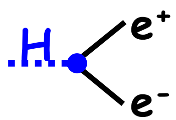
spontaneous symmetry breaking – only 1 real excitation remains:

$$\Phi = \begin{pmatrix} 0 \\ v+\eta(x) \end{pmatrix} e^{i\xi(x))}$$

(no neutrino mass)

$$\mathcal{L}_H = G_e v \;\; e^-e^+ + G_e \;\; e^- \eta\, e^+$$

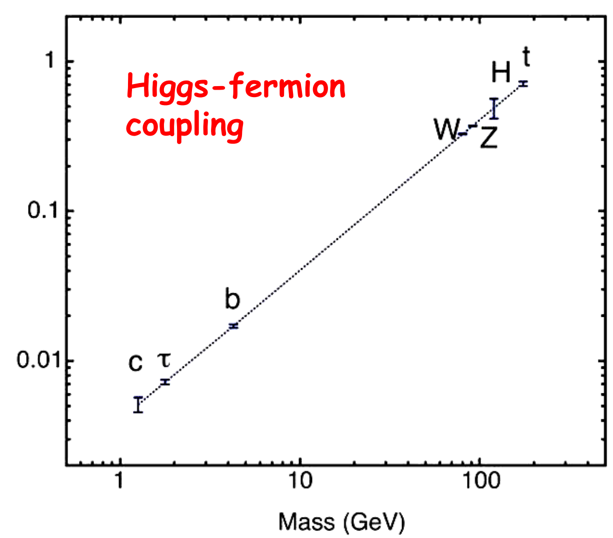
$G_e v := m_e$



$$= m_e \;\; e^-e^+ + m_e/v \;\; e^- \eta\, e^+$$

- Higgs produces FERMION masses !
- Higgs-fermion coupling ~ fermion masses:

$$m_e/v = 511 \text{ keV} / 246 \text{ GeV} \sim 10^{-6}$$
$$m_t/v = 172 \text{ GeV} / 246 \text{ GeV} \sim 1$$



Higgs boson

The discovery of a Higgs boson will be of profound importance.
It is one of the most important experimental results of all time.

The Higgs boson is a new kind of matter:

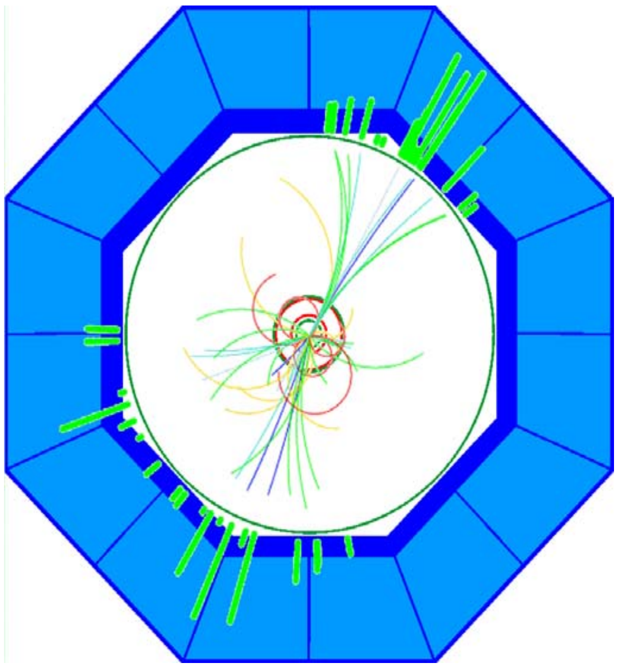
New quarks and leptons have been found, but they are all particles like the electron that carry charges.

New force-mediating bosons have been found but they are all quanta like the photon.

The Higgs boson is the quantum of a new kind of field,

for which the energy density of the universe is lower when the field has a non-zero value, and who

gives mass to bosons and fermions through its interactions.



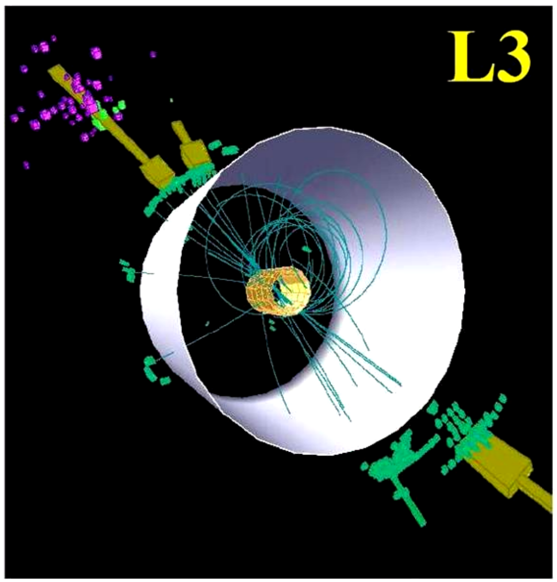
simulated Higgs decays

Kane, King, Wang, hep-ph/0010312.

LEP Higgs candidates

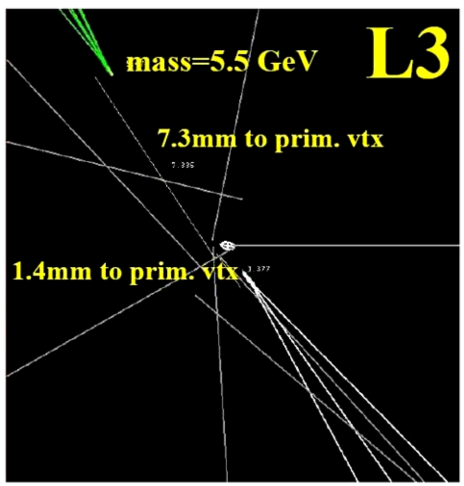
$e^+e^- \rightarrow$ H Z

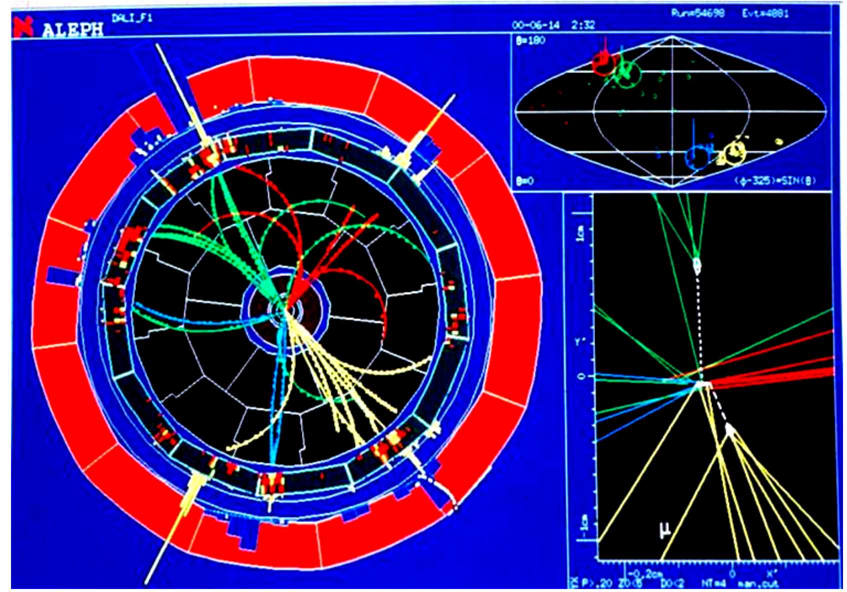
H $\rightarrow$ bb
Z $\rightarrow \nu\nu$



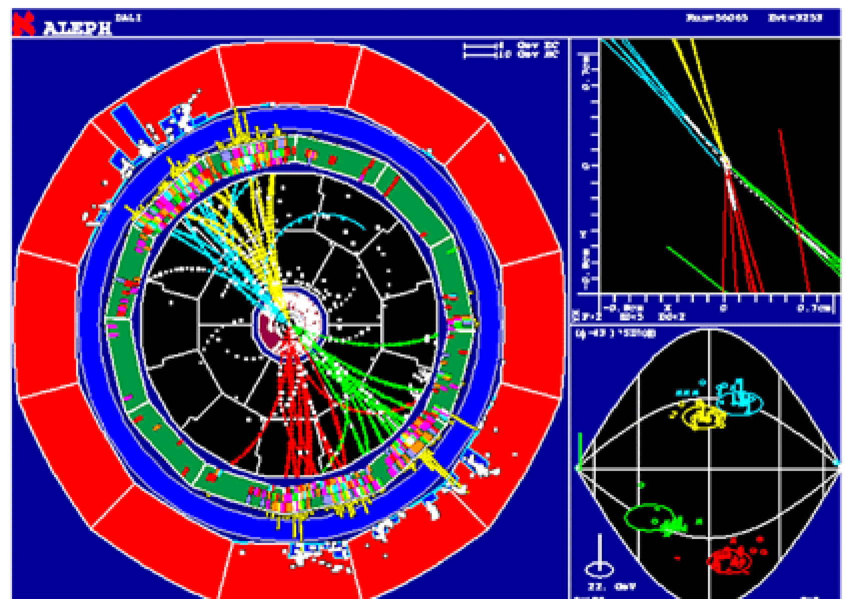
measured H mass=115 GeV
H mass resolution ~3 GeV

Secondary vtx's view



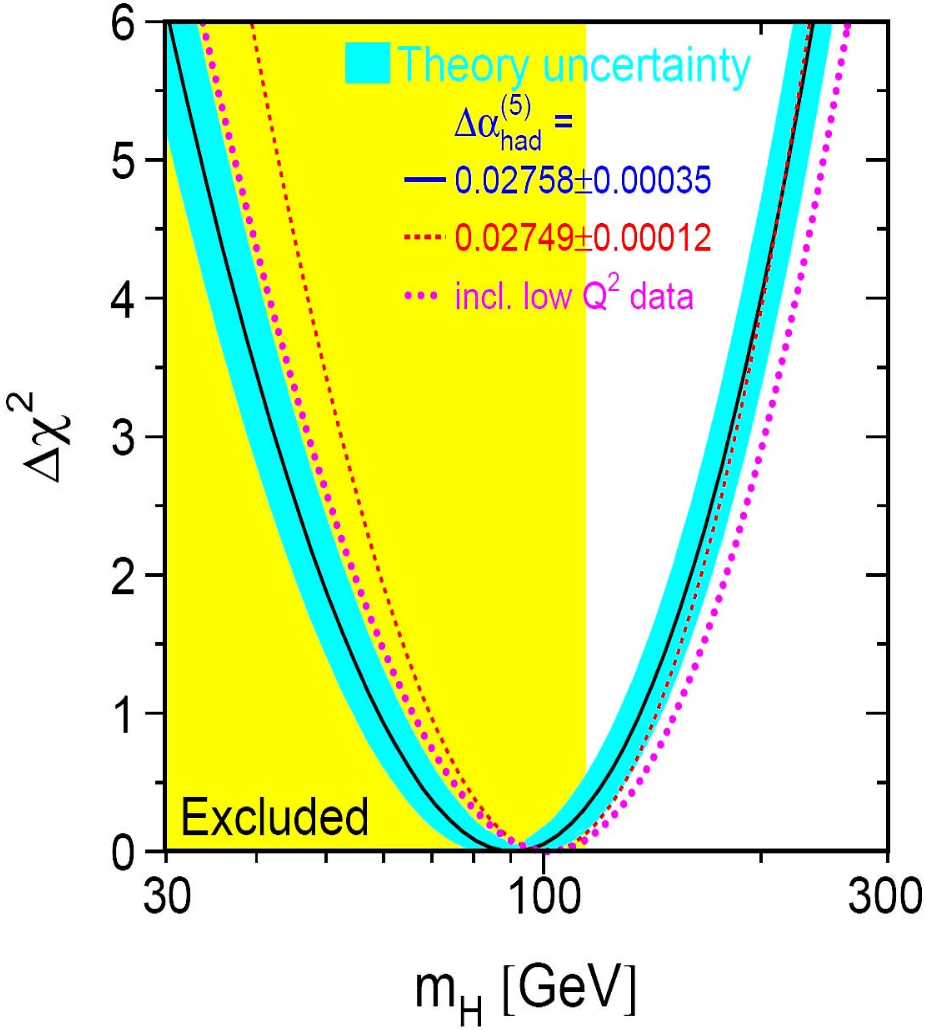


H $\rightarrow$ 4 jets, 2 b tags, m_H=114.3 GeV



H $\rightarrow$ 4 jets, 2+2 jets back-to-back

Higgs Search @ LEP



LEP direct search:

$m_H > 114.4$ GeV

Standard Model fits 2006:

$m_H < 194$ GeV @ 95% CL

$m_H = 89^{+38}_{-28}$ GeV

Higgs production

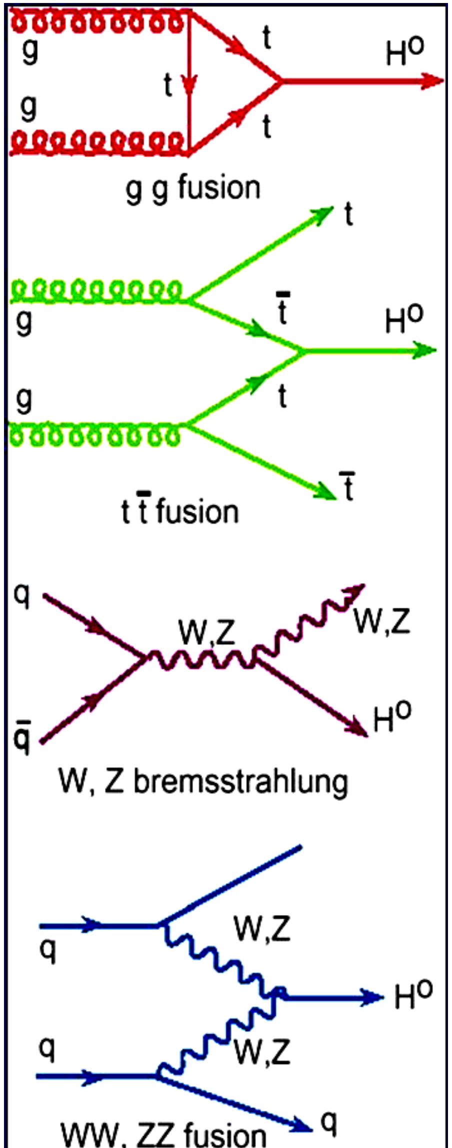
ILC	LHC
$e^+ e^-$	p p
2x0.5-1	2x7 TeV

γ
γ

γ
γ

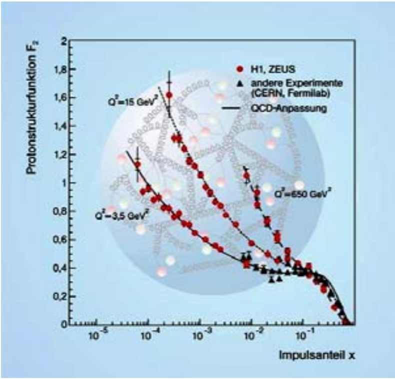
e^+
e^-

e^+
e^-



HERA

p structure function:



gluon + sea quark
distributions very soft
$x^2_{g,sea} \ll 1$

weak:

$\sim G_F \sim g^2/m_W^2$

superweak:

$\sim G_F^2 \sim g^4/m_W^4$

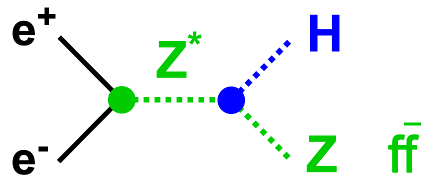
but valence quarks: ud -> W^+W^- or qq -> ZZ

Higgs Production

Higgs couples to heaviest possible particle !

Higgs coupling $h = m_f$ / (v=246 GeV) h_Z = 91/246 ~ 0.4 h_t = 172/246 ~ 0.7

1. e^+e^-: Higgs-strahlung:



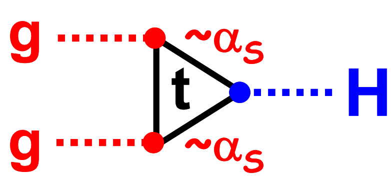
detect Higgs in missing mass: $m_H < \sqrt{s} - m_Z$

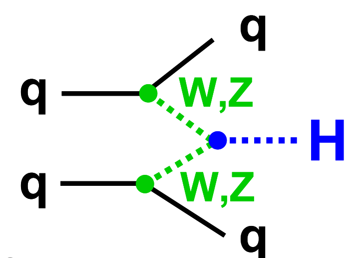
- Higgs coupling
- strong coupling
- weak coupling

LEP: $m_H < \sqrt{s} - m_Z$ = 2x102-91 GeV = 114 GeV 1997-2000

ILC: $m_H < \sqrt{s} - m_Z$ = 2x250-91 GeV = 400 GeV 2015-

2. pp: boson fusion:





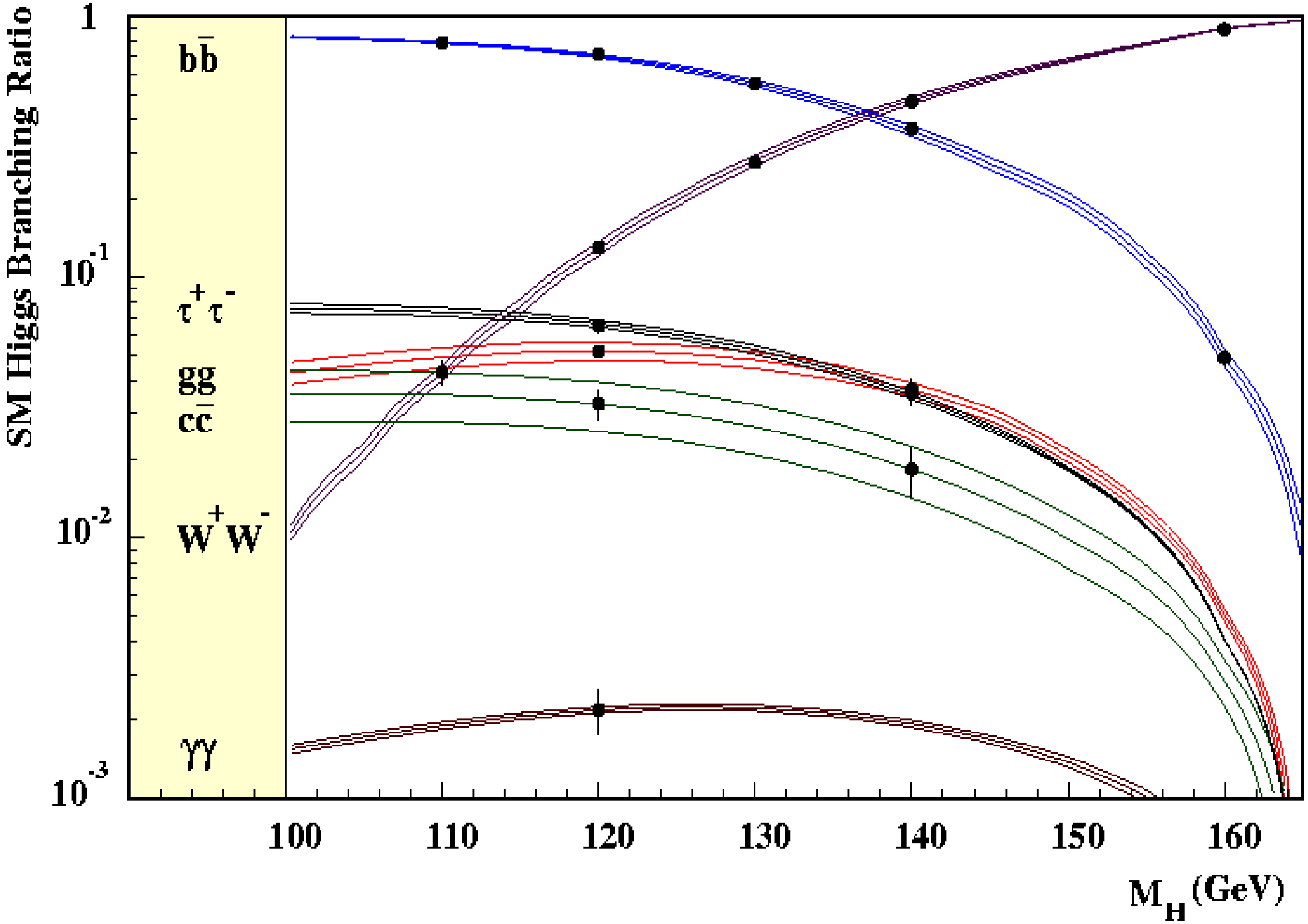
Tevatron, FNAL, USA: 2x1 TeV, 1996-2008

Large Hadron Collider LHC, CERN: 2x7 TeV, 2008-

gluon carries only tiny fraction of p momentum

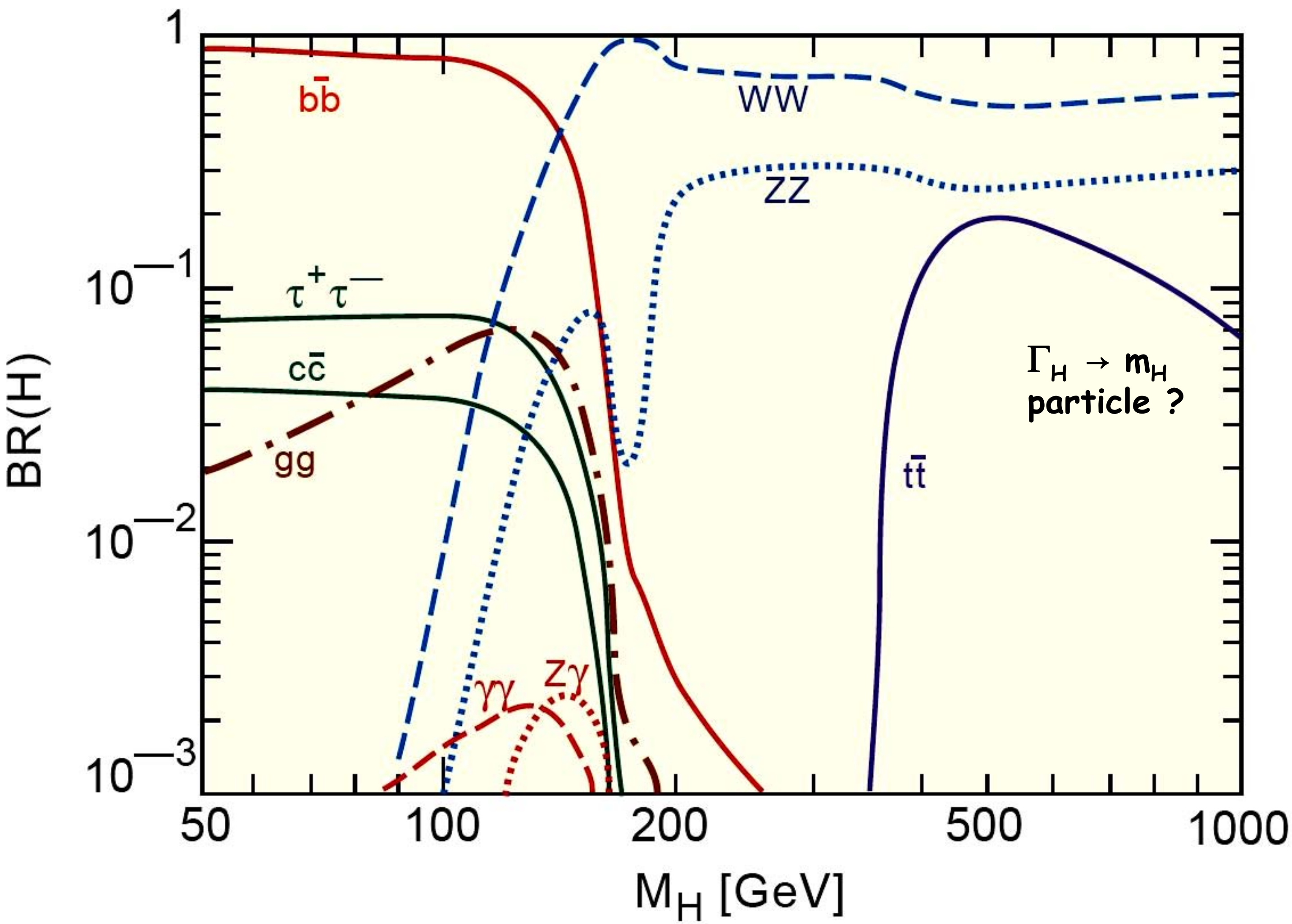
quark carries ~1/6 of p momentum: ~1 TeV /7 TeV @ LHC

Higgs Decay



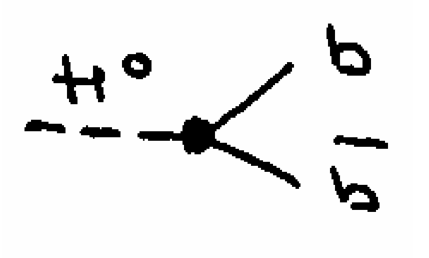
- **Higgs** = origin of mass in physics
- **Higgs** coupling = Yukawa coupling ~ mass of reaction partner

Higgs Decay



- Higgs = origin of mass in physics
- Higgs coupling = Yukawa coupling ~ mass of reaction partner

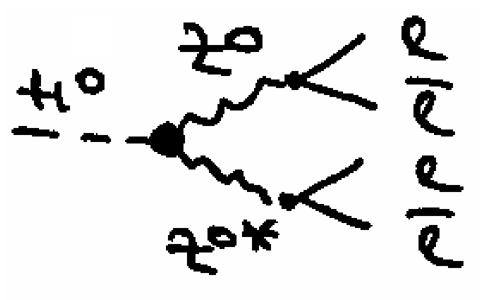
Higgs Decay



$m_b \sim 4.5$ GeV

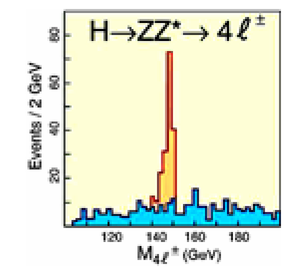
dominant for light Higgs $m_H < 2m_{W,Z}$

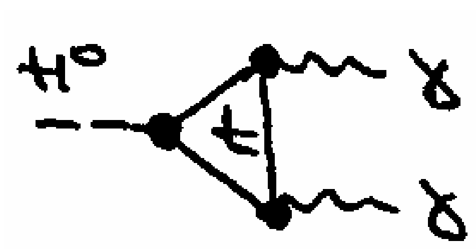
identify **2 b jets !**



good to detect: find **4 leptons**

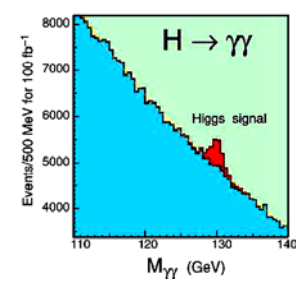
rare: $(\Gamma_l/\Gamma_Z)^2 \sim (3\%)^2 \sim 10^{-3}$

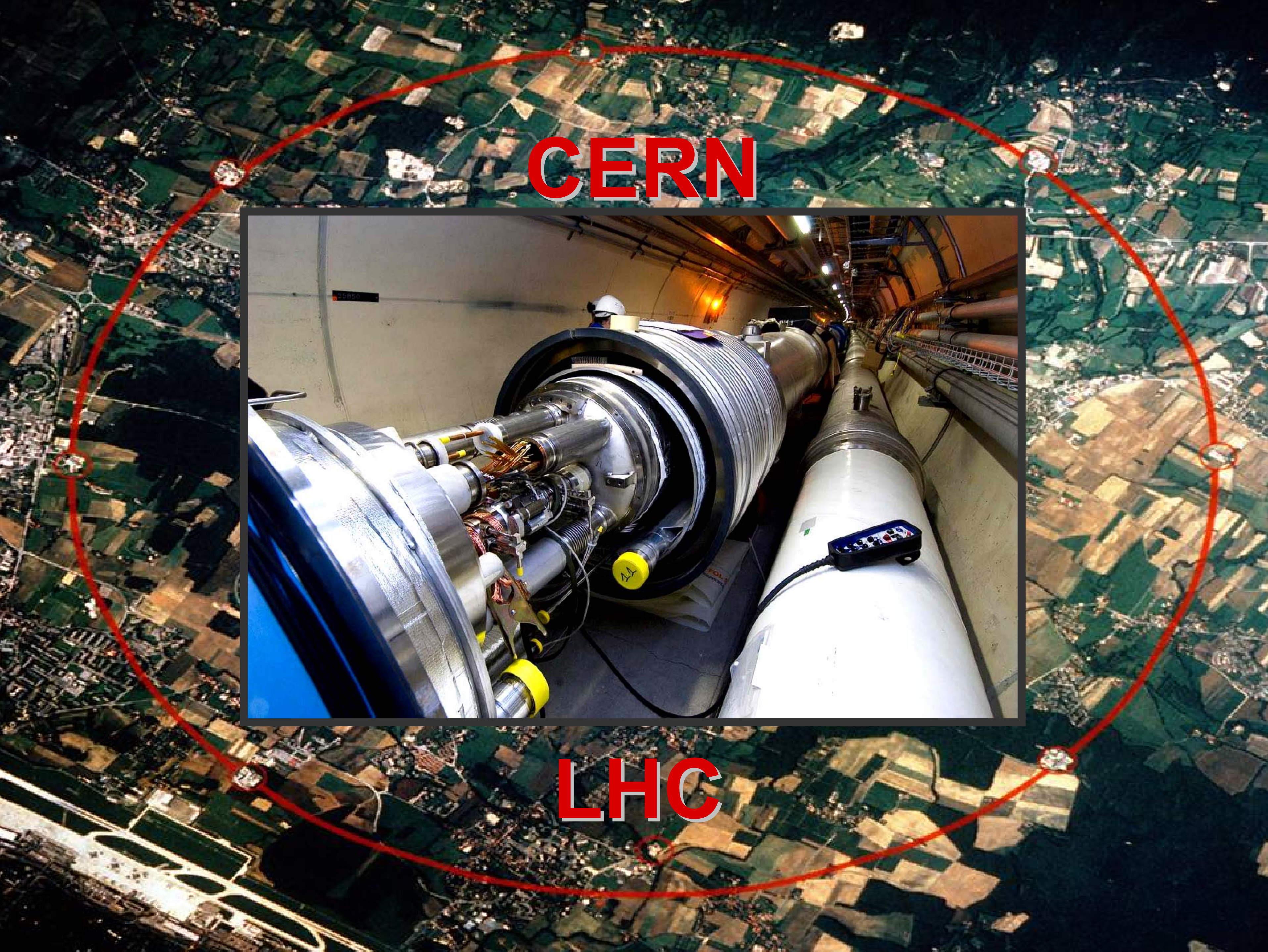




good to detect: find **2 photons**

rare: $\sim \alpha^2 < 10^{-4}$

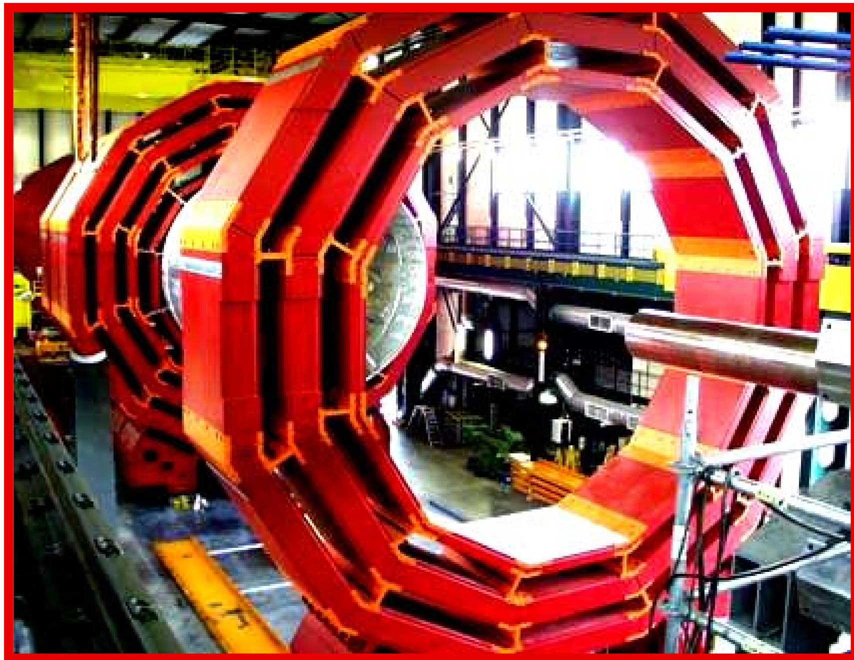



CERN
LHC

LHC @ CERN

Large Hadron Collider
at CERN in Geneva :

27 km long
8 T superconducting magnets
7x7 TeV proton-proton collisions



> 2007 search for :

Higgs particle
Super-Symmetry
...

LHC parameters

	LHC pp	HERA ep
beam energy	7 TeV x 7 TeV	27 GeV x 920 GeV
luminosity	10^{32-34} $cm^{-2}s^{-1}$	10^{31} $cm^{-2}s^{-1}$
nr of bunches	2800	180
protons / bunch	10^{10}	10^{11}
bunch crossing rate	25 ns / 40 MHz	96 ns / 10 MHz
beam current	0.5 A	40x100 mA^2

LHC beam + magnets

CMS magnet: world's largest SC magnet!

- 6x12.5 m @ 4T = 2.6 GJ

  = enough to melt 18 t of gold!

LHC magnets: world's largest superfluid cryosystem !

- 27 km or 96 t He @ 8.4 T and 1.8 K
- energy stored 10 GJ

  = airbus A380 @ 700 km/h

  = enough to melt 50 t of copper!

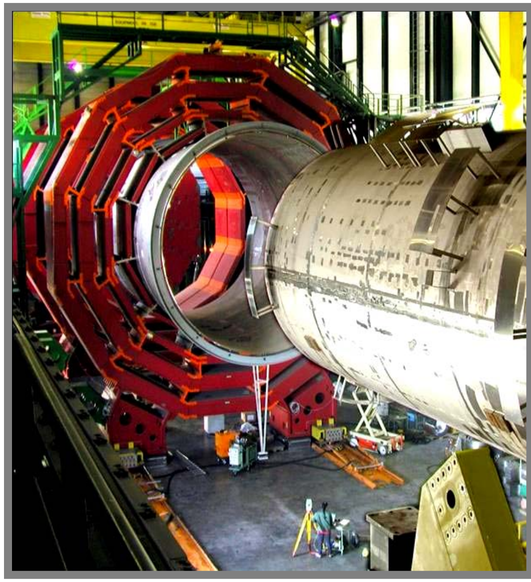
LHC beam:

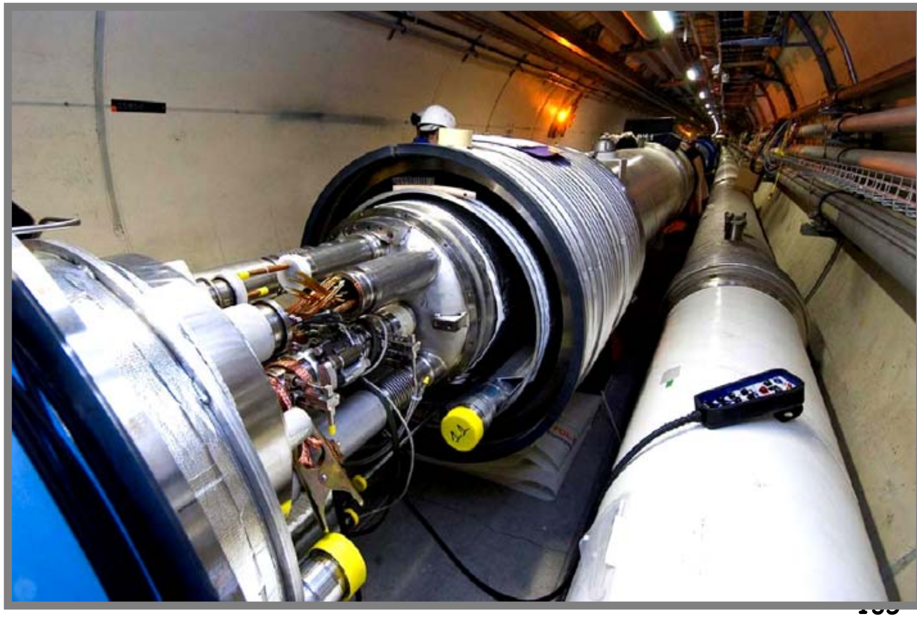
- 0.5 A @ 7 TeV: E = 362 MJ

  = 120 kg TNT

  = 200 t train locomotive @ 200 km/h

  = melt 25 m deep in Cu beam dump

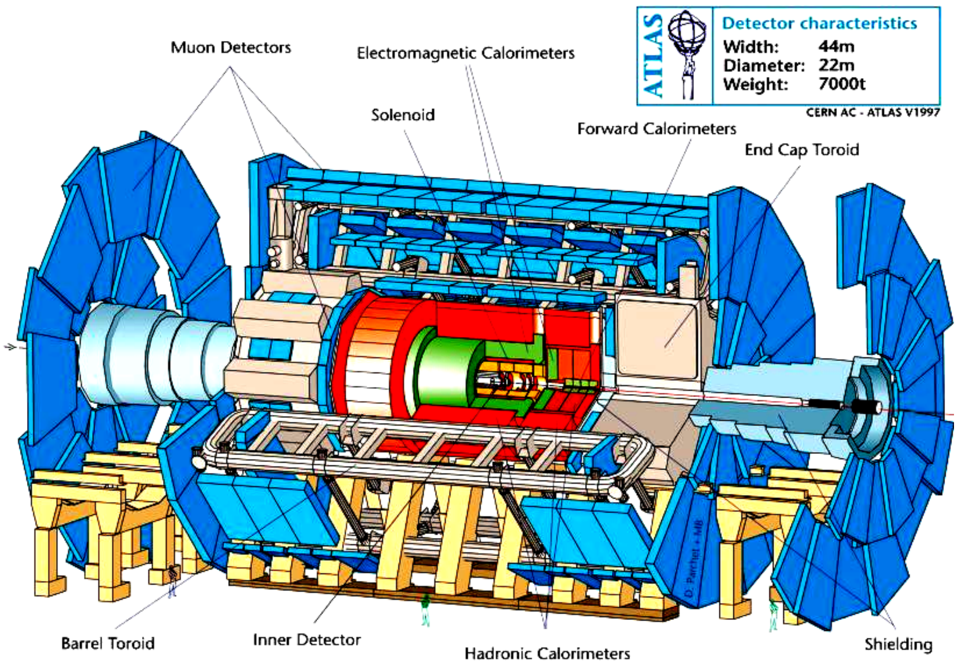




LHC experiments

Liquid Argon Calorimeter

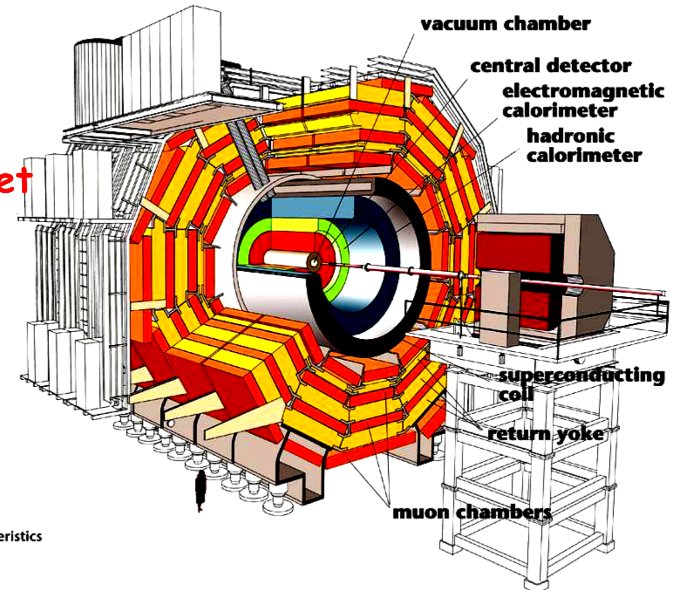
83 m^3



SC magnet

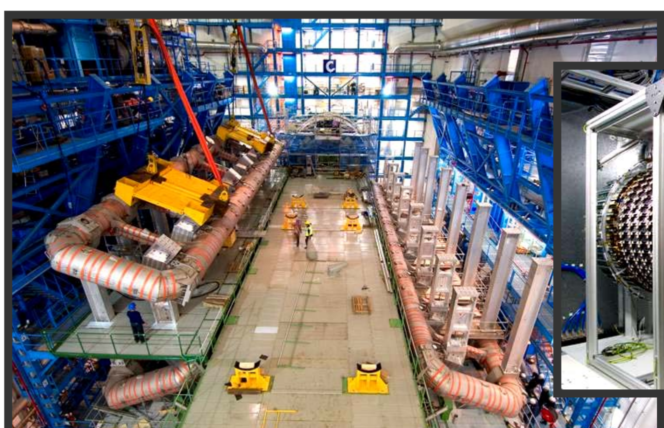
6x12 m
20 kA
4 T
2.6 GJ

world record

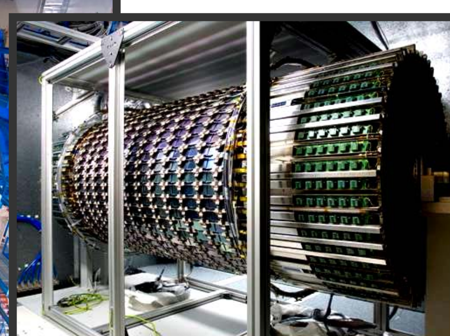


Detector characteristics

Width: 22m
Diameter: 15m
Weight: 14'500t



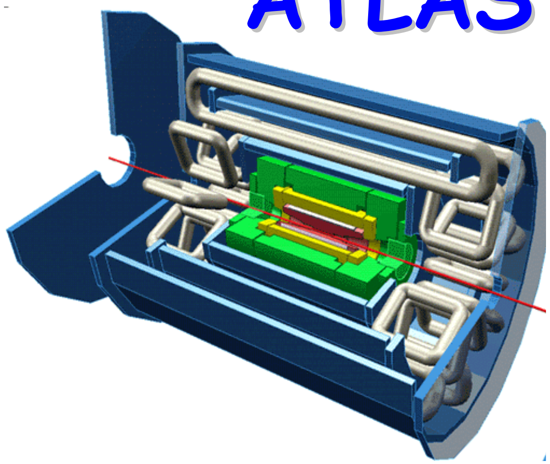
Si pixel tracker



>100 million channels

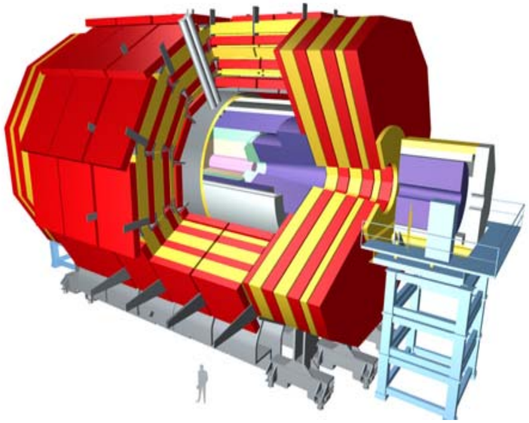
LHC experiments

ATLAS

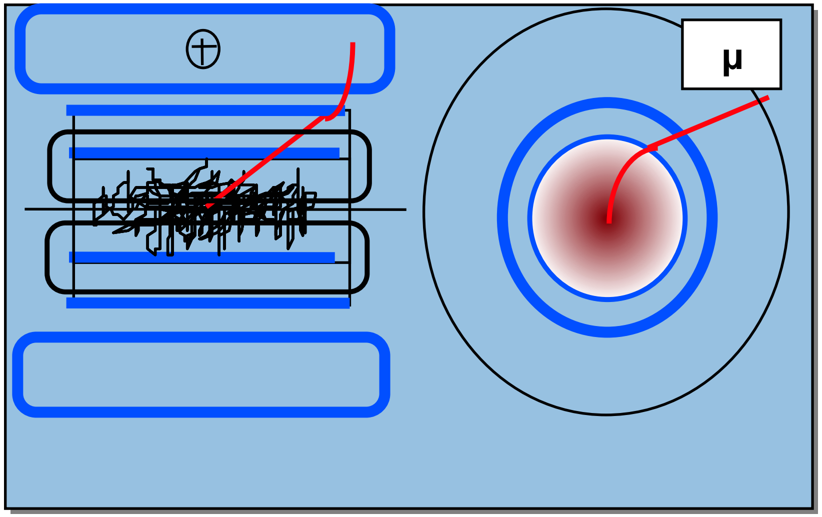


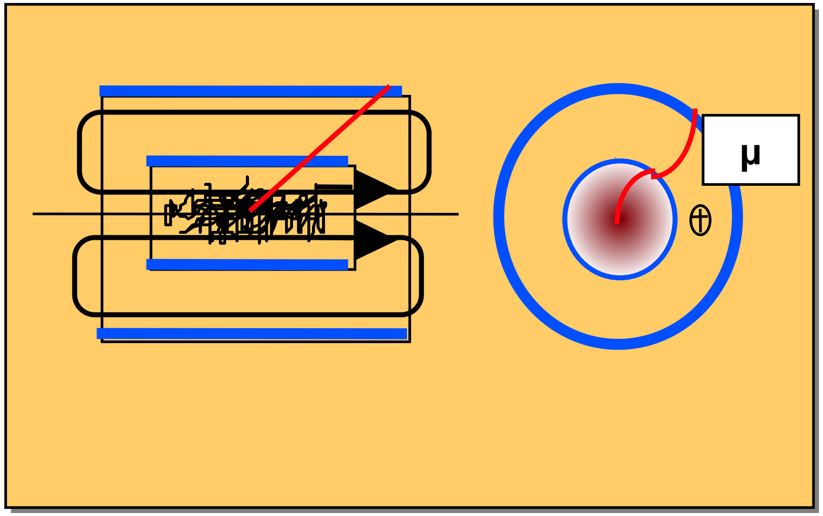
A Toroidal LHC ApparatuS

CMS

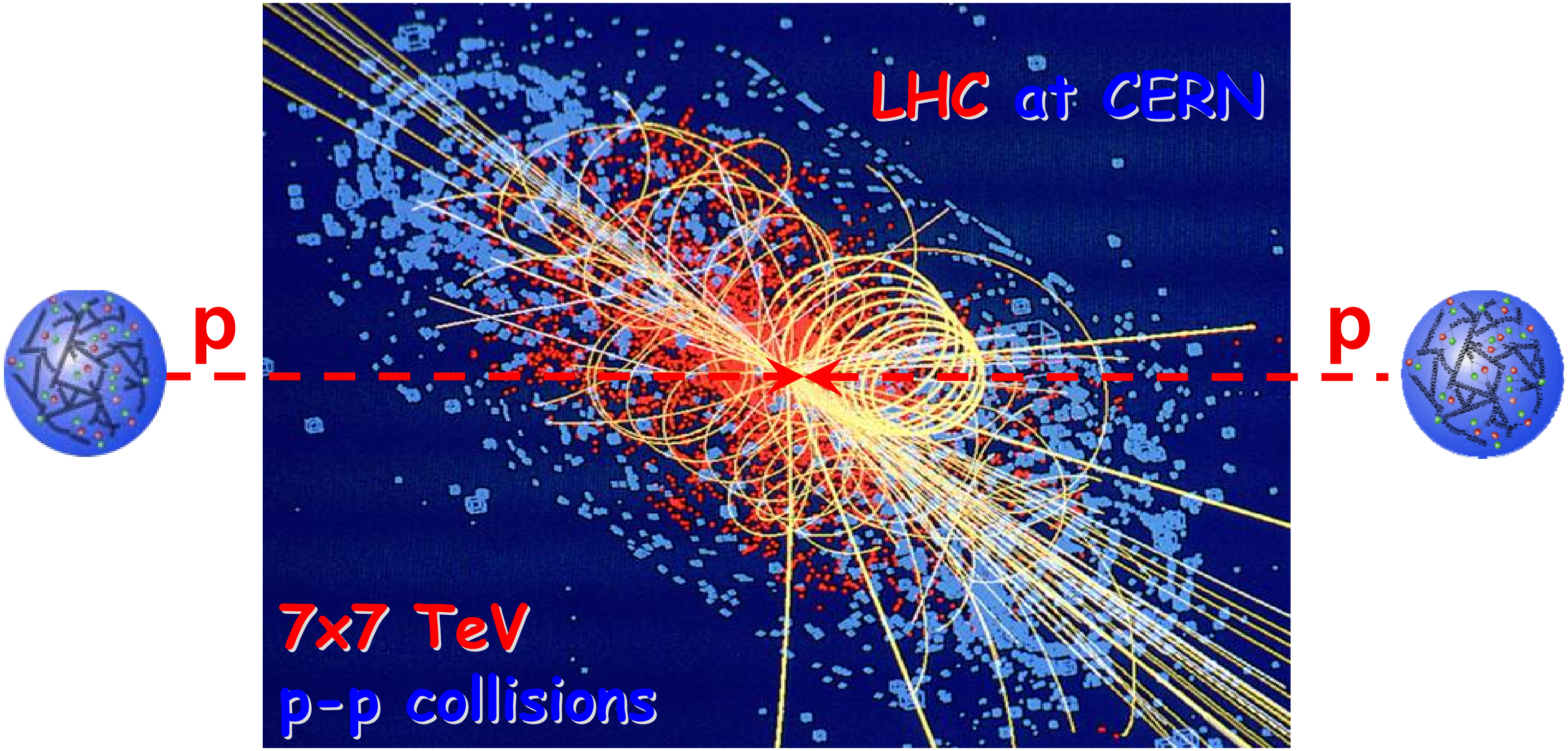


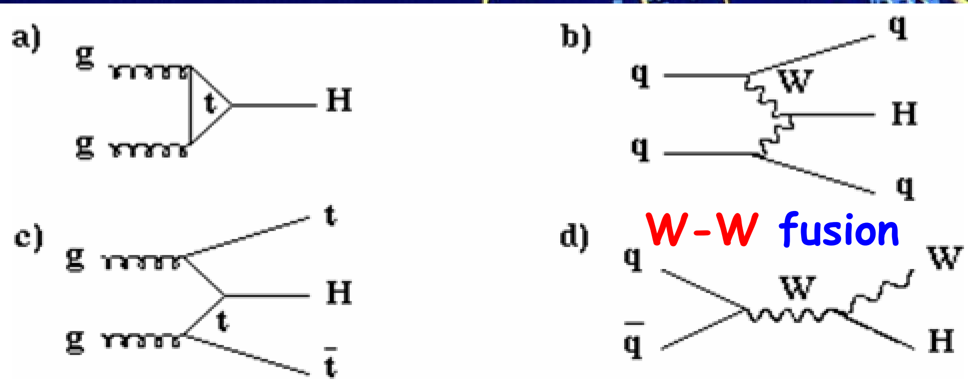
Compact Muon Solenoid





LHC Higgs production





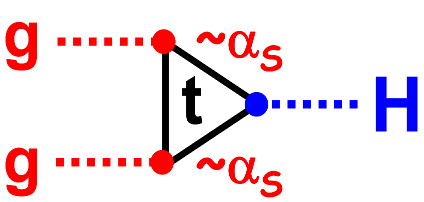
W-W fusion

gluon-gluon fusion

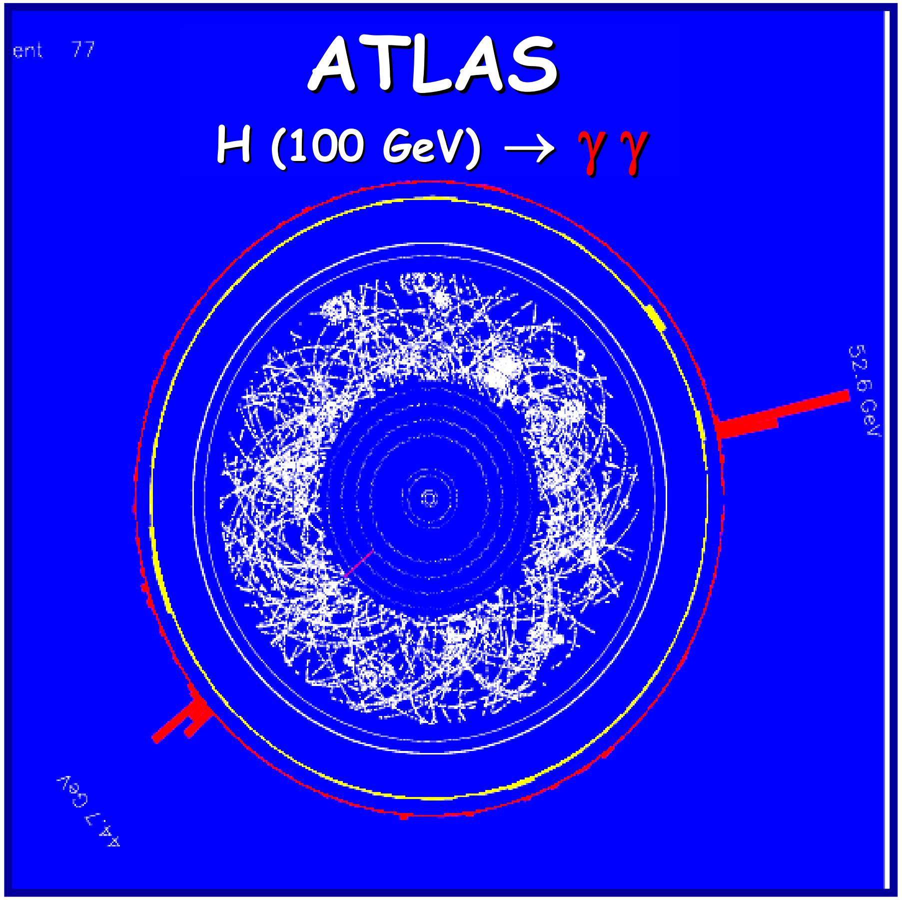
Higgs radiation

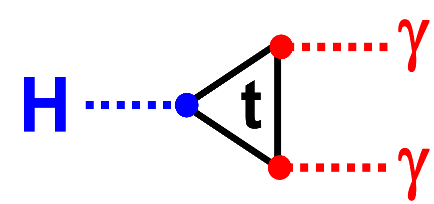
Higgs Search

$pp \rightarrow H \rightarrow \gamma\gamma$



production

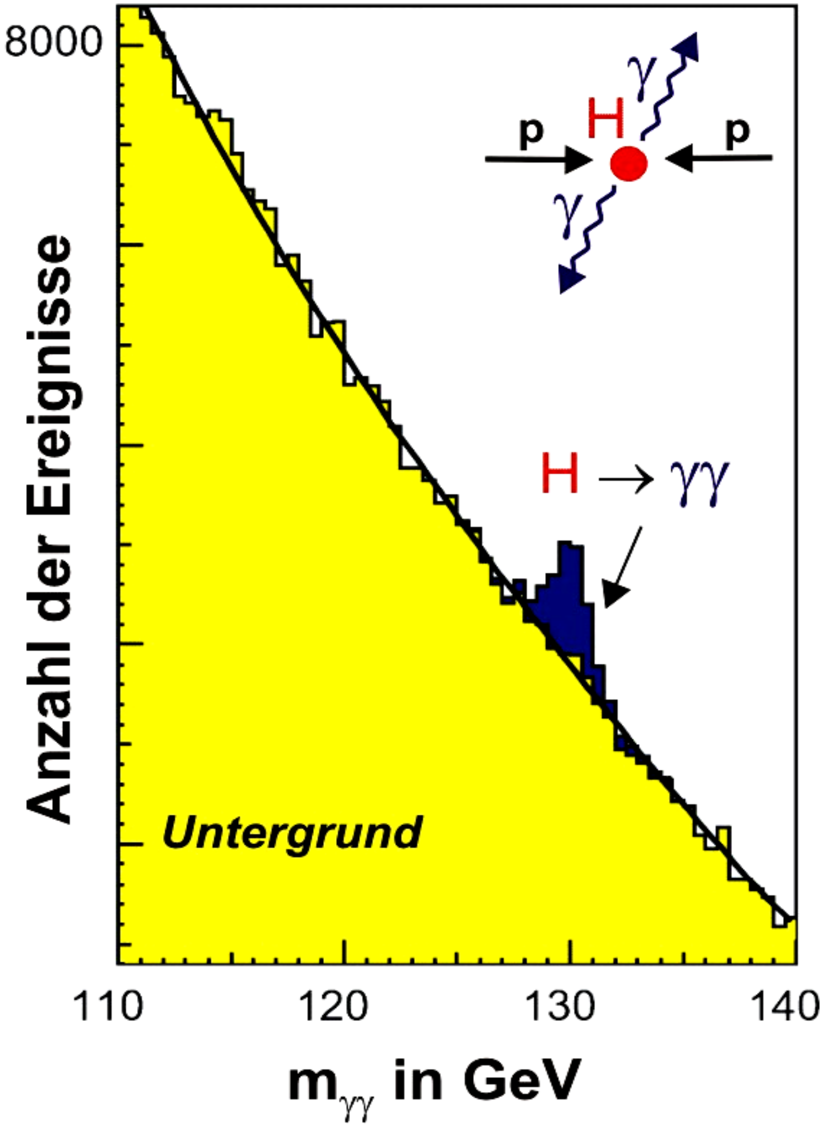


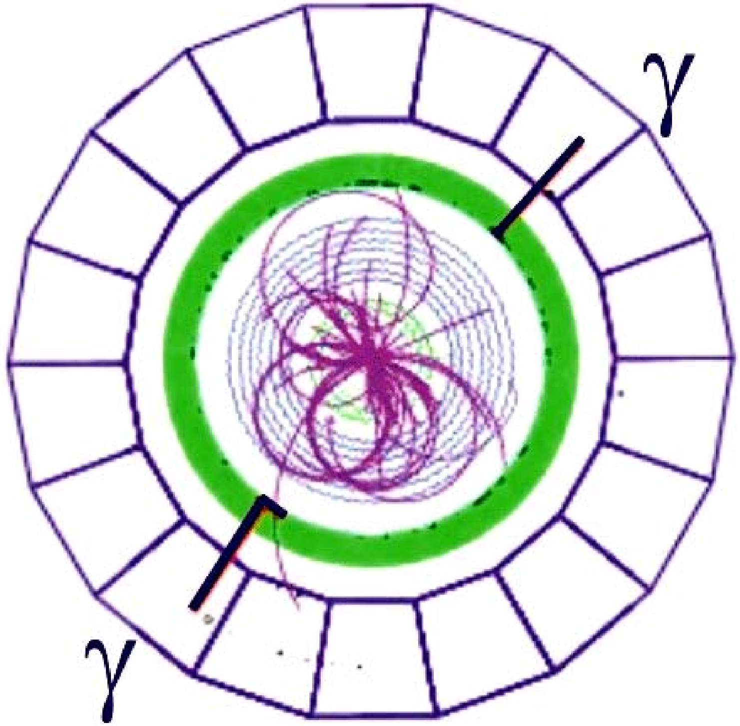


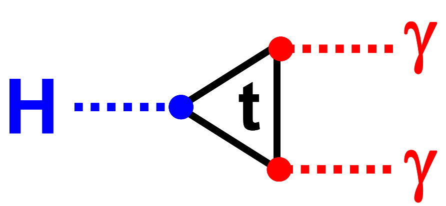
decay

simulation in the ATLAS detector at the LHC at CERN

Higgs → γ γ

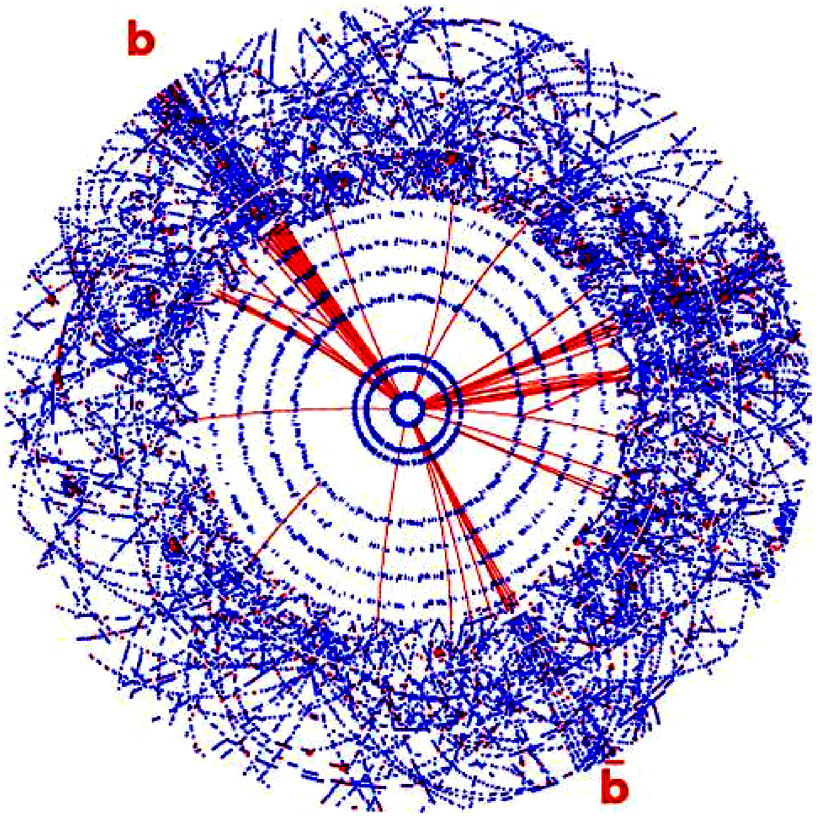

8000
Anzahl der Ereignisse
p
H
p
γ
γ
H → γγ
Untergrund
110
120
130
140
m_γγ in GeV

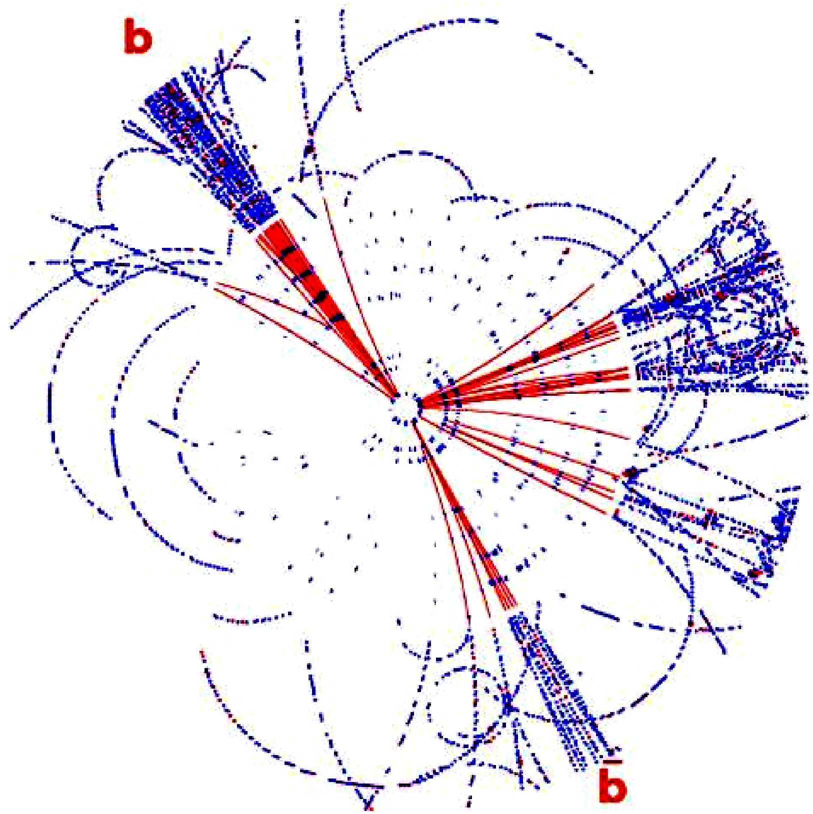

γ
γ


H
t
γ
γ

Higgs Search

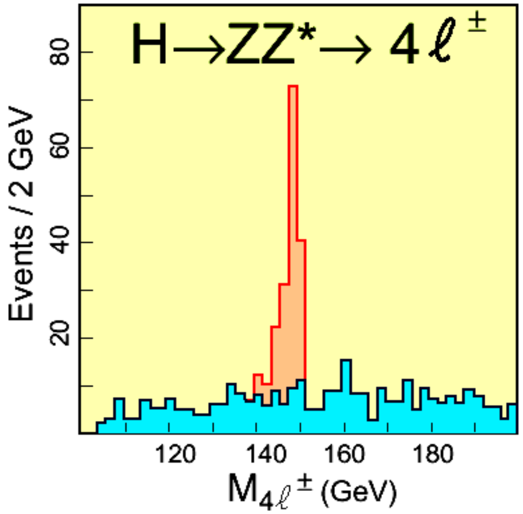
$$pp \to H\ X \to b\ b\ X$$

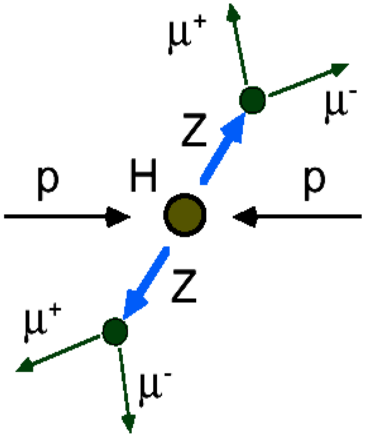




simulation in the ATLAS barrel inner detector

Higgs Search

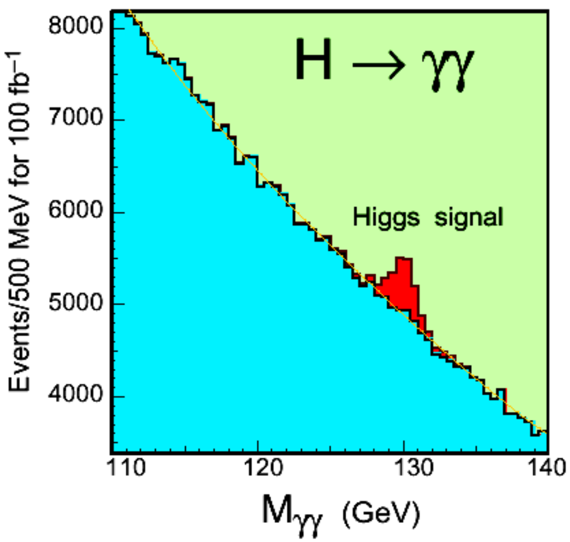


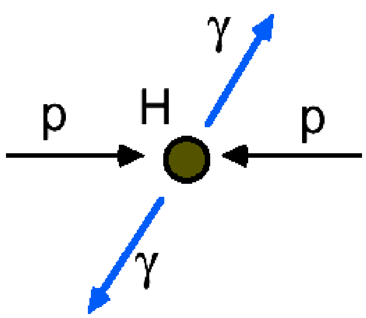


golden decay:

little background

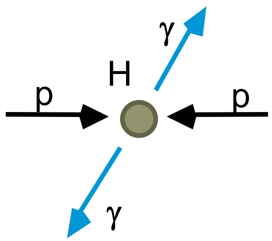
$H \to Z\,Z \to \mu^+\mu^-\ \mu^+\mu^-$

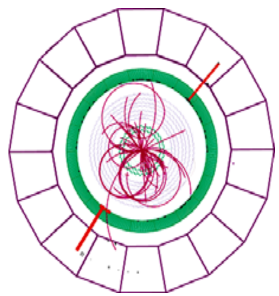




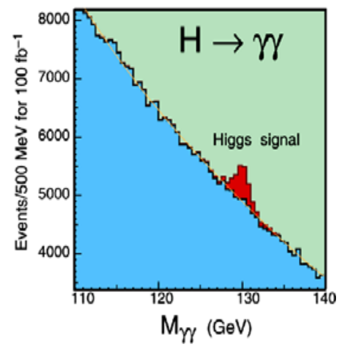
$H \to \gamma\,\gamma$

LHC physics: Higgs

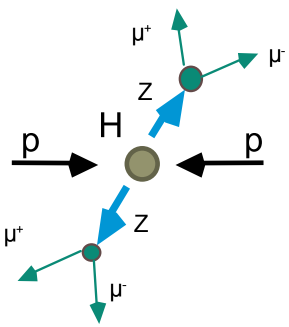


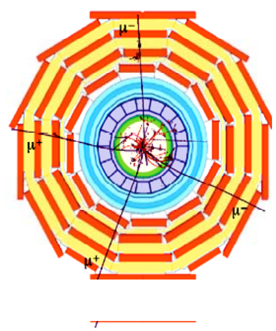


M_{Higgs}= 100 GeV

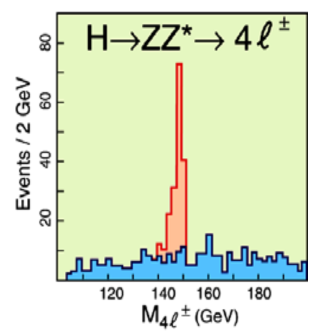


Higgs to 2 photons (M_H< 140 GeV) .
$H^0 \rightarrow \gamma\gamma$ is the most promising channel if M_H is in the range 80 – 140 GeV. The high performance $PbWO_4$ crystal electromagnetic calorimeter in CMS has been optimized for this search.
The $\gamma\gamma$ mass resolution at $M_{\gamma\gamma}$ ~ 100 GeV is better than 1%, resulting in a S/B of -1/20

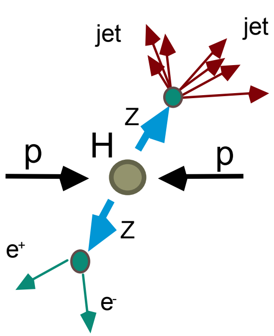


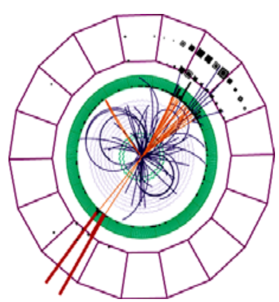


M_{Higgs}= 150 GeV

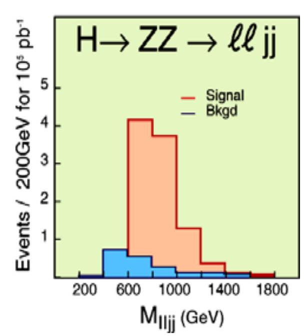


Higgs to 4 leptons (140 < M_H< 700 GeV). In the M_H range 130 - 700 GeV the most promising channel is $H^0 \rightarrow ZZ^* \rightarrow$ 2, + 2, − or $H^0 \rightarrow ZZ \rightarrow$ 2, + 2, −. The detection relies on the excellent performance of the muon chambers, the tracker and the electromagnetic calorimeter. For M_H Š 170 GeV a mass resolution of ~1 GeV should be achieved with the combination of the 4 Tesla magnetic field and the high resolution of the crystal calorimeter





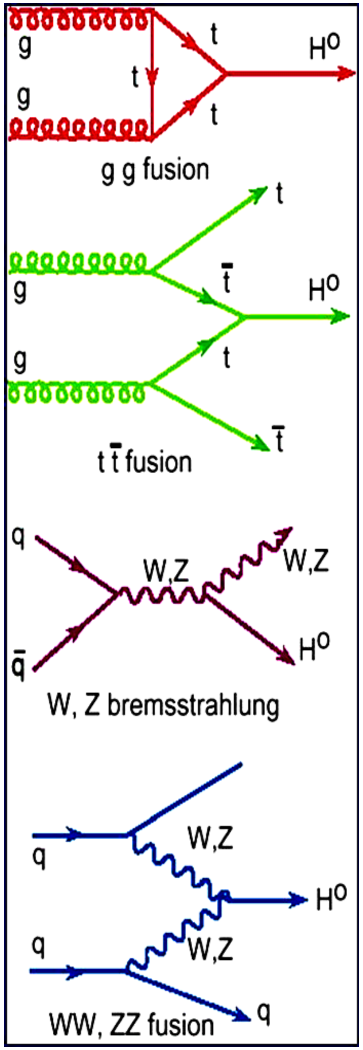
M_{Higgs}= 800 GeV



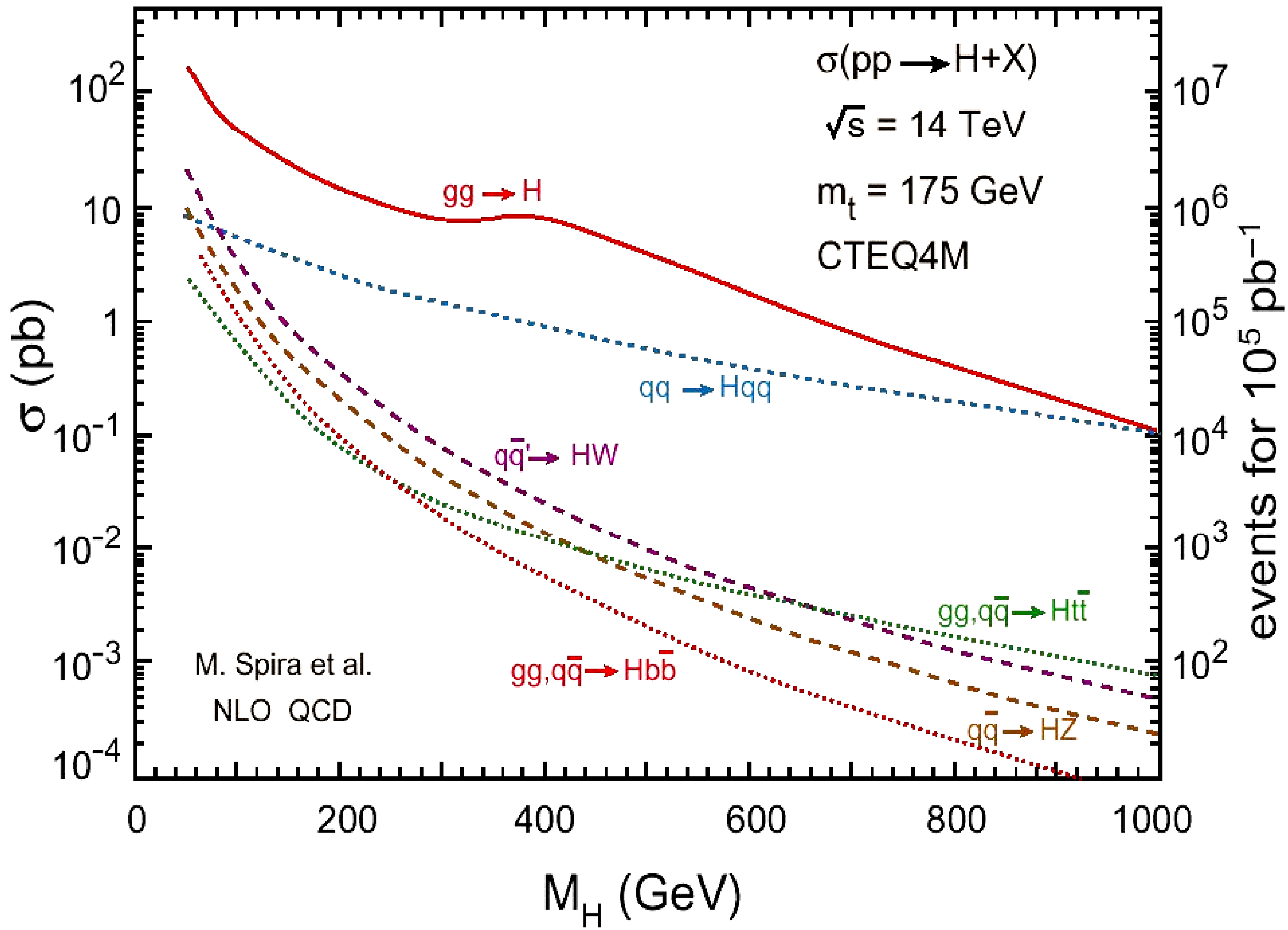
Higgs to 2 leptons+2 jets (M_H > 500 GeV). For the highest M_H, in the range 0.5 - 1 TeV, the promising channels for one year at high luminosity are $H^0 \rightarrow ZZ \rightarrow$, + , − $\nu\nu$, $H^0 \rightarrow ZZ \rightarrow$, + , − jj and $H^0 \rightarrow W^+W^- \rightarrow$, ± ν jj .
Detection relies on leptons, jets and missing transverse energy (E_t^{miss}), for which the hadronic calorimeter (HCAL) performance is very important

Higgs cross sections

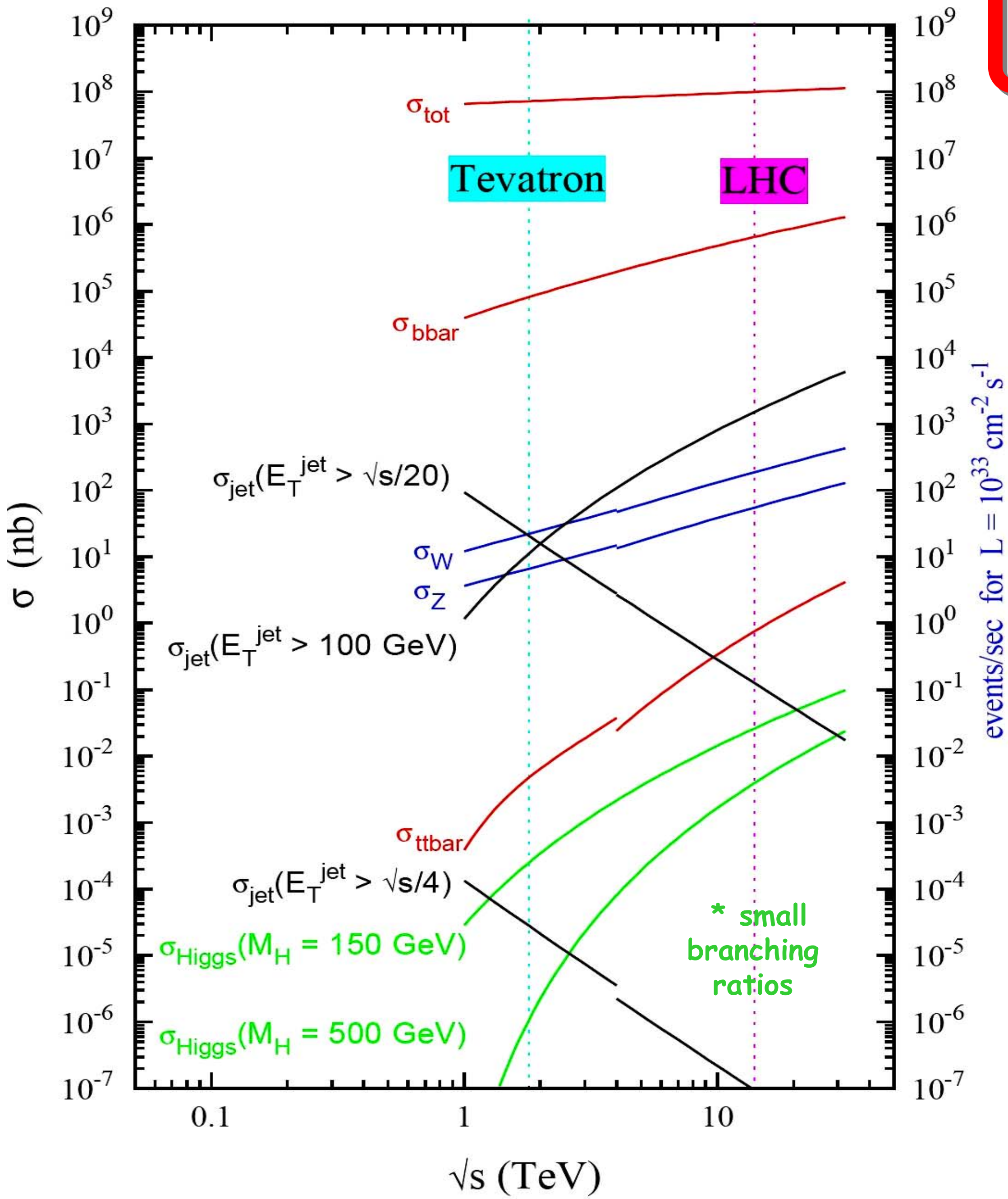
dominant



No color exchange:
2 clear forward jets



pp cross sections

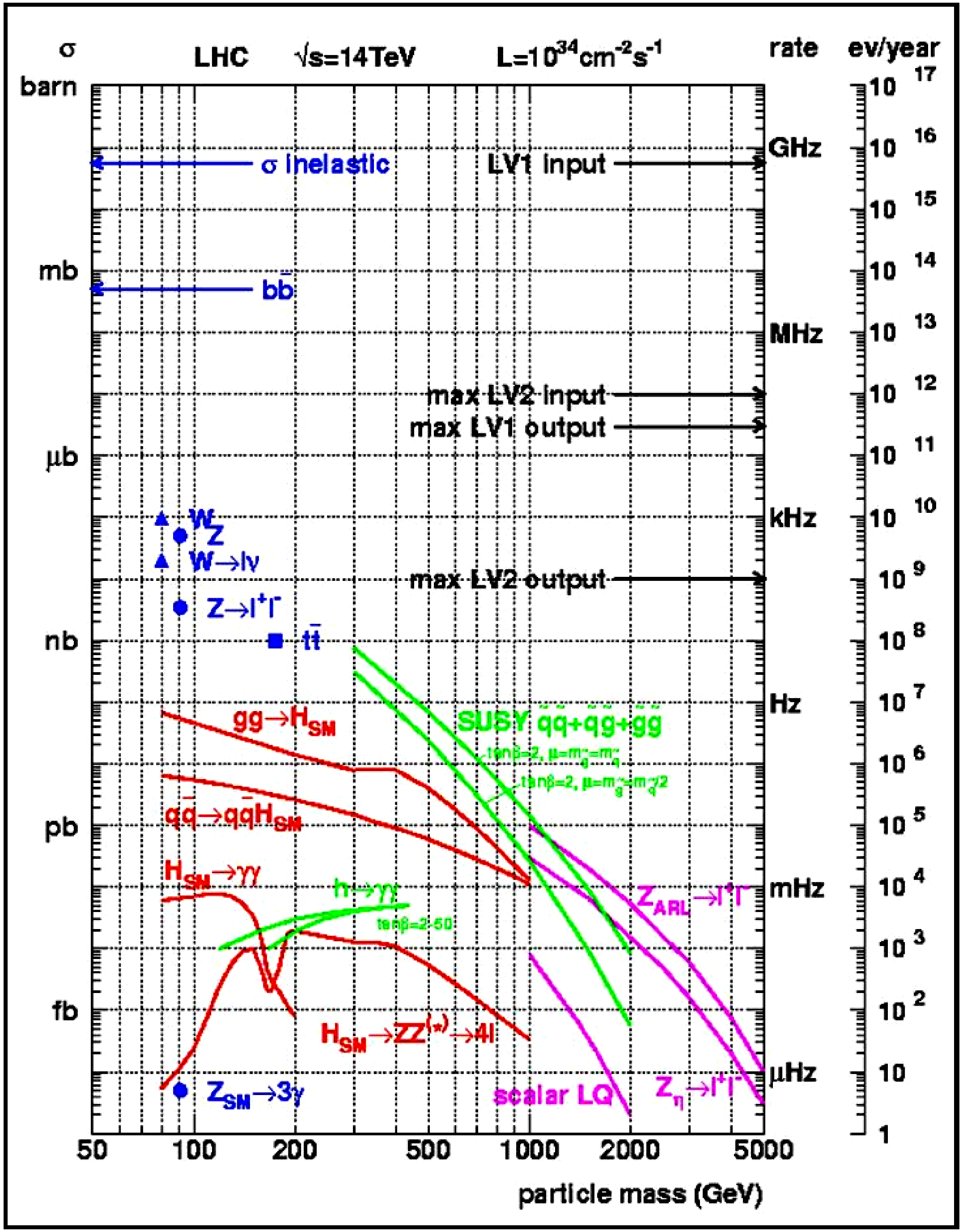


σ_{tot} ~ 100 mb:
gigantic soft hadronic background

E_T^{jet}>100 GeV:
huge hard QCD backgr.

hadronic H decays
swamped by backgr.
need leptonic decays:
H -> $\gamma\gamma$,
H -> ZZ -> 4l

look for weak signal
in a strong int. machine !



design luminosity

10^9 evts/s * 10 MB = 10 PB/s

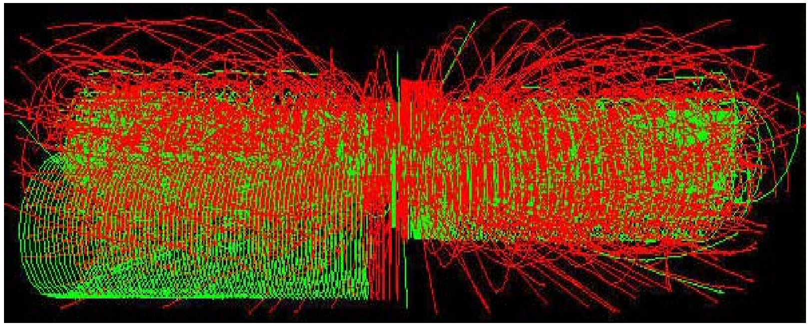
LHC event rates

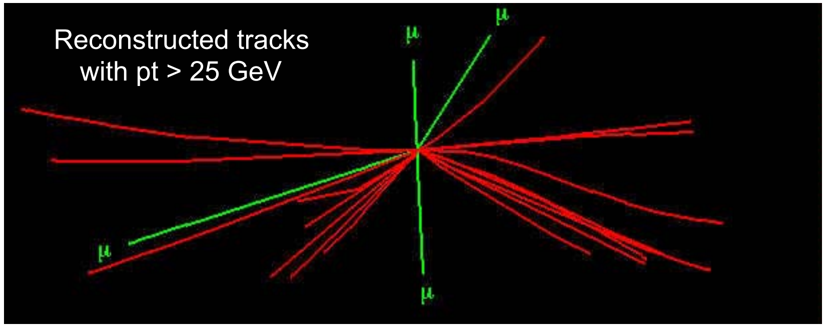
10^9 evts/a * 2 MB = 2 PB/a

10^3 evts/a * efficiency*acceptance

LHC rates

Process	evts/s @ 10^{34} $cm^{-2}s^{-1}$	evts/10 fb^{-1} ~1/2 y @ 10^{33} $cm^{-2}s^{-1}$	before LHC
• Inelastic p-p reactions	10^9		
• q-q/g interactions, p_t>20 GeV	10^8		
• $b\bar{b}$ pairs	5 10^6	10^{12-13}	10^9 BaBar/Belle
• $t\bar{t}$ pairs	8	10^7	10^4 FNAL
• $W \rightarrow e\,\nu$	150	10^8	10^4 LEP, 10^6 FNAL
• $Z \rightarrow e\,e$	15	10^7	10^6 LEP
• Higgs (150 GeV)	0.2	10^5	
• SUSY: Gluino, Squarks (1 TeV)	0.03	10^4	
• Black Holes m_D=3 TeV n=4	0.001	10^3	

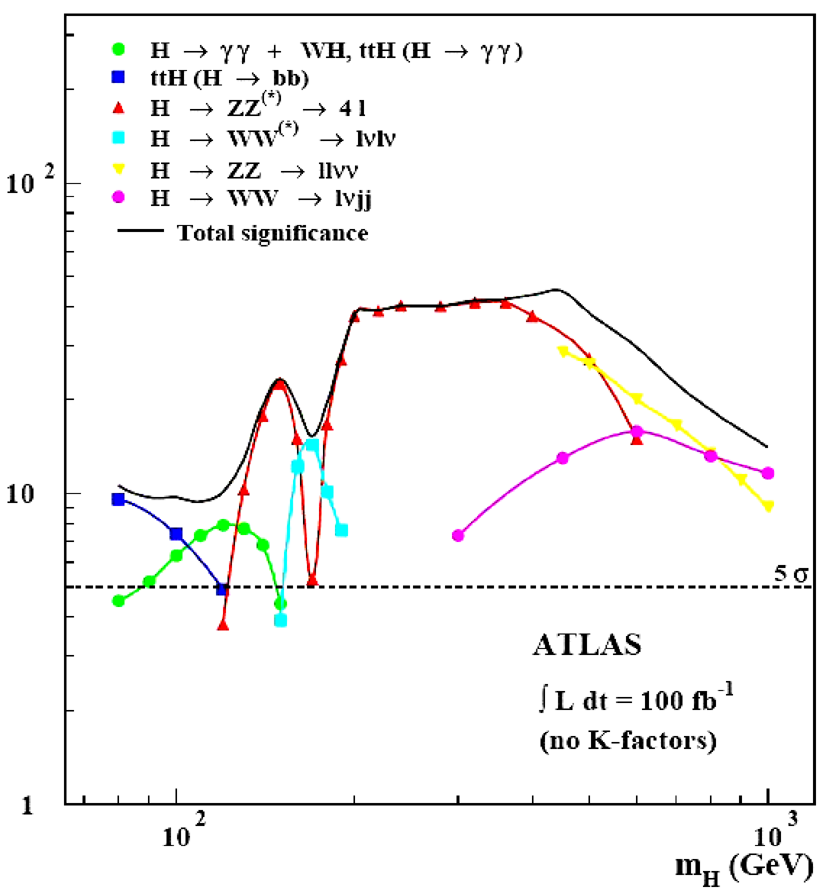


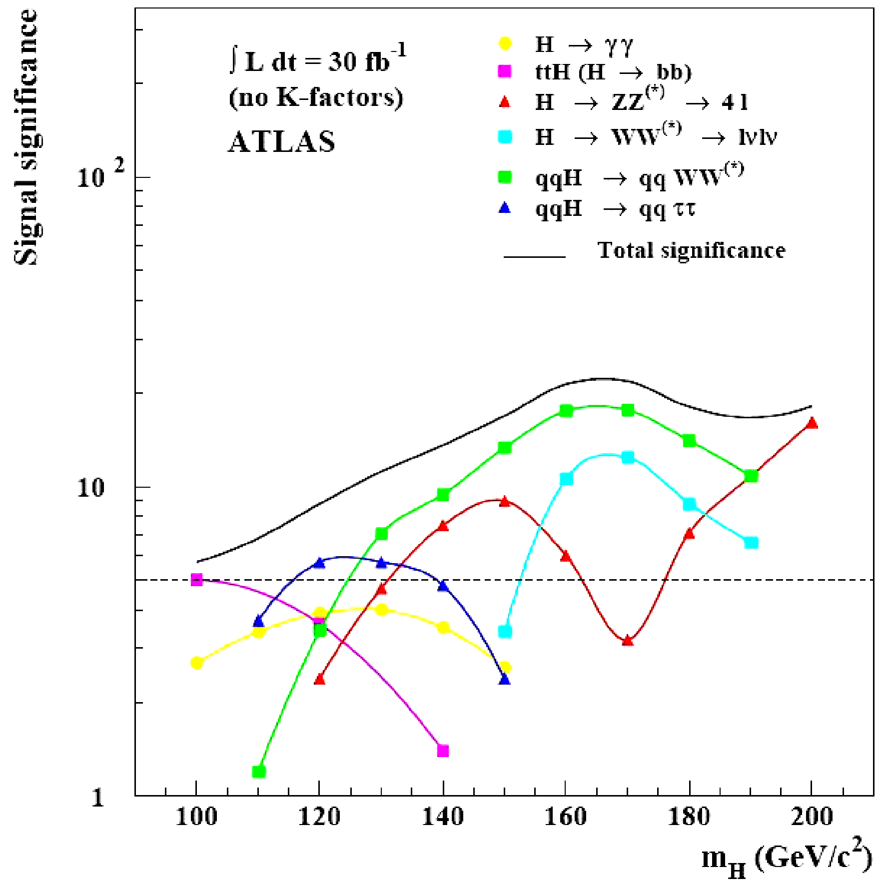


Find a needle in a haystack:

- high luminosity L ~ 10^{34} cm^{-2} s^{-1} , 40 MHz event rate , 100 GB/s data
- excellent detector , excellent trigger

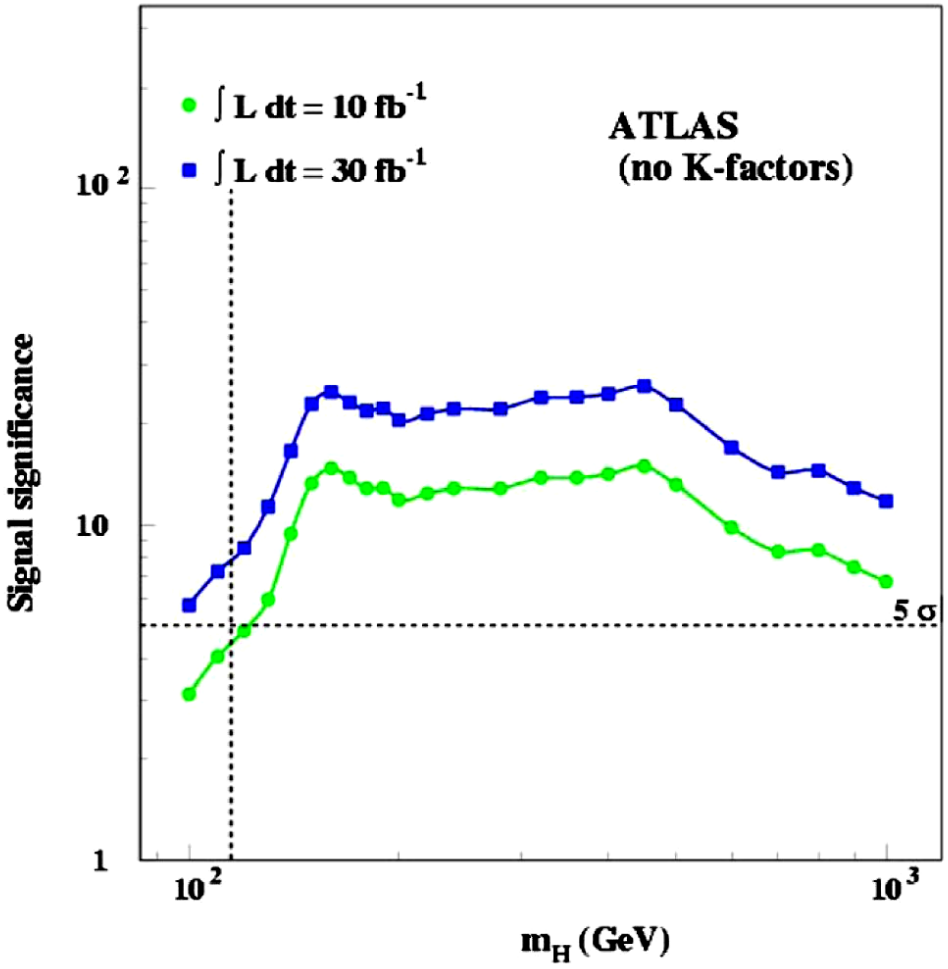
Higgs Significance





- m_H <150 GeV: H -> γγ
- m_H >150 GeV: H -> ZZ -> 4l

Higgs Significance



1 y @ 10^{33} $cm^{-2}s^{-1}$:

10 fb^{-1} (≥2008)

1 y @ 10^{34} $cm^{-2}s^{-1}$:

100 fb^{-1} (≥2010)

discovery vs precision

SPS 2 x 270 GeV

1983 W,Z discovery
1984 Nobel prize

LEP 2 x 50-100 GeV

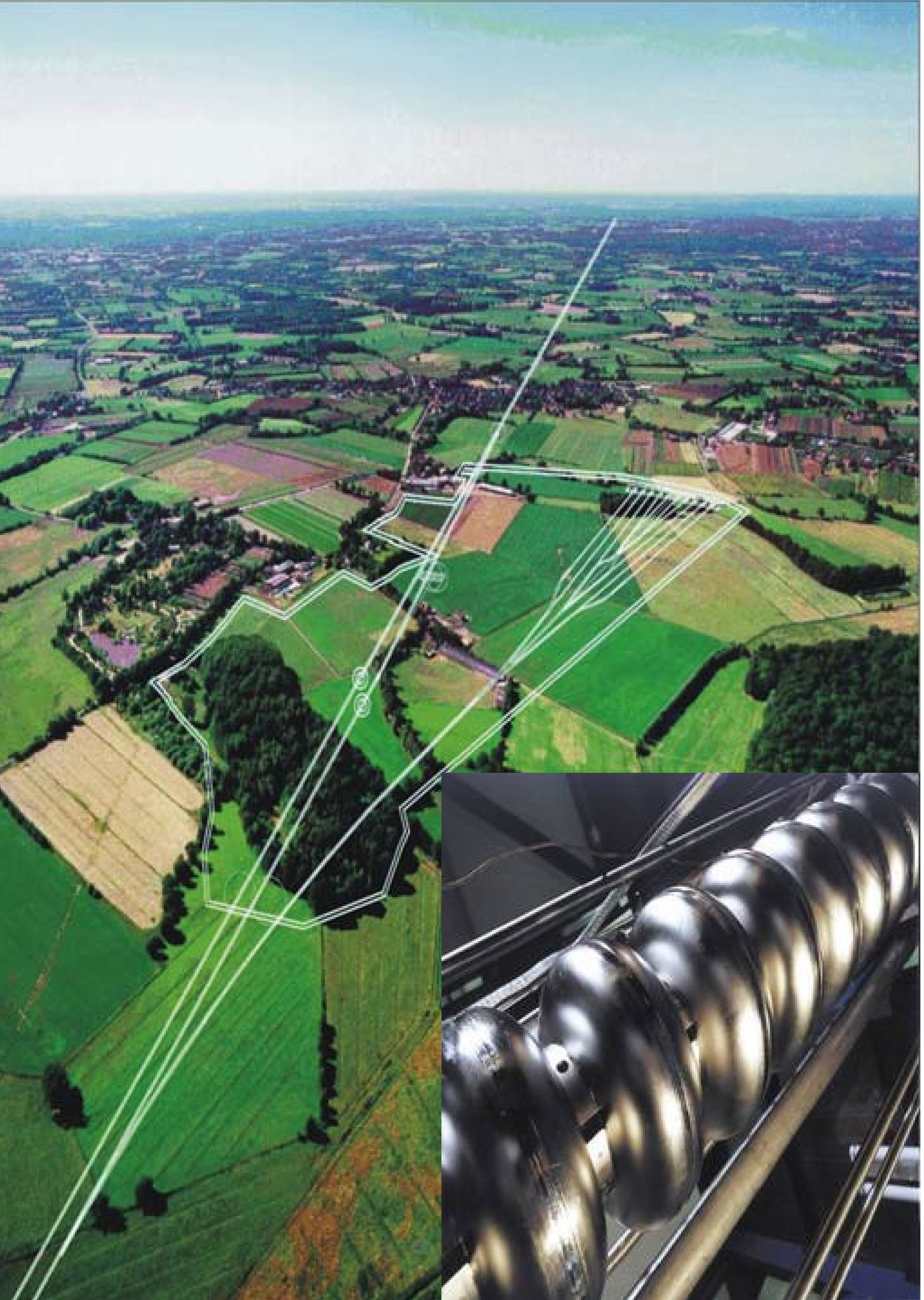
1992-2000 establish Standard Model to 10^{-3}

LHC 2 x 7 TeV

>2007 Higgs, SUSY discovery ?

ILC 2 x 500 GeV – 1 TeV

>2015 establish Higgs + SUSY ?



ILC

International
Electron-Positron-
Linear Collider

Superconducting
500-800 GeV
30 km long

Aim:

Higgs- and SUSY-
precision physics

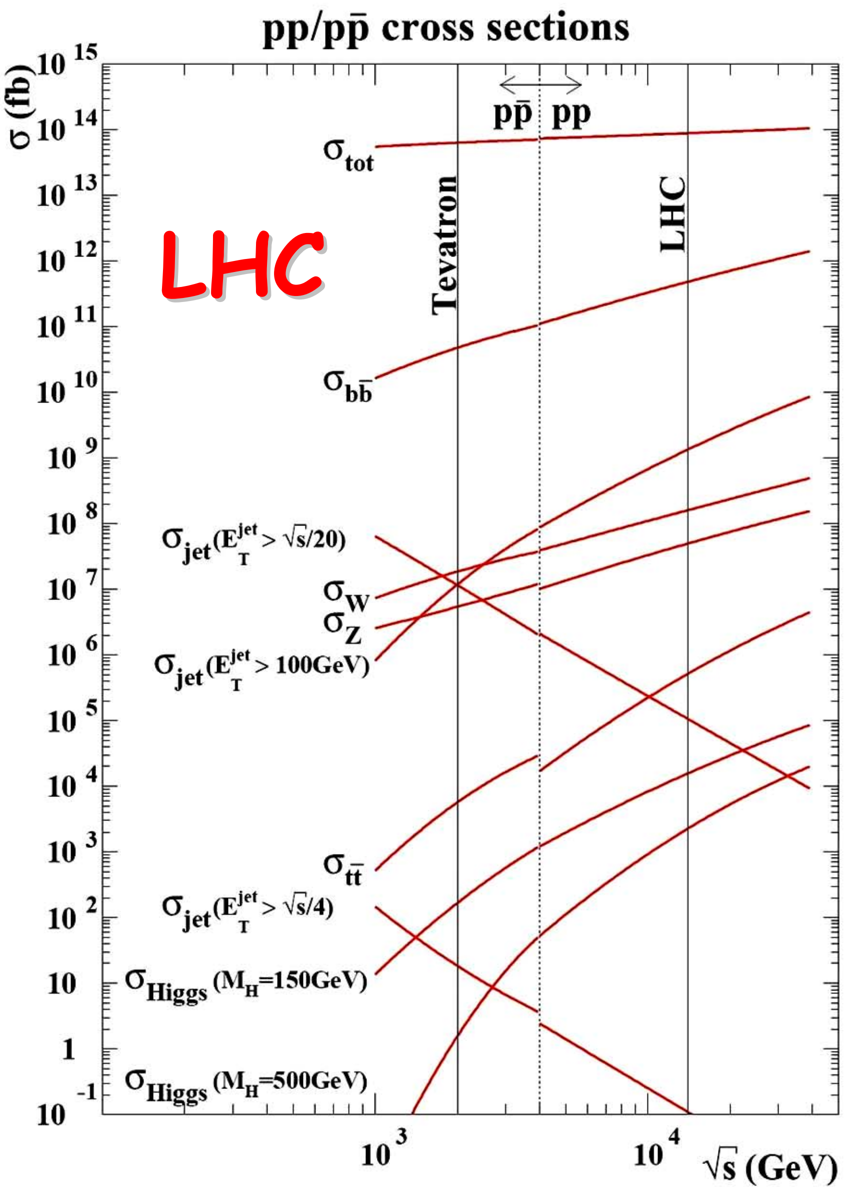
> 2015

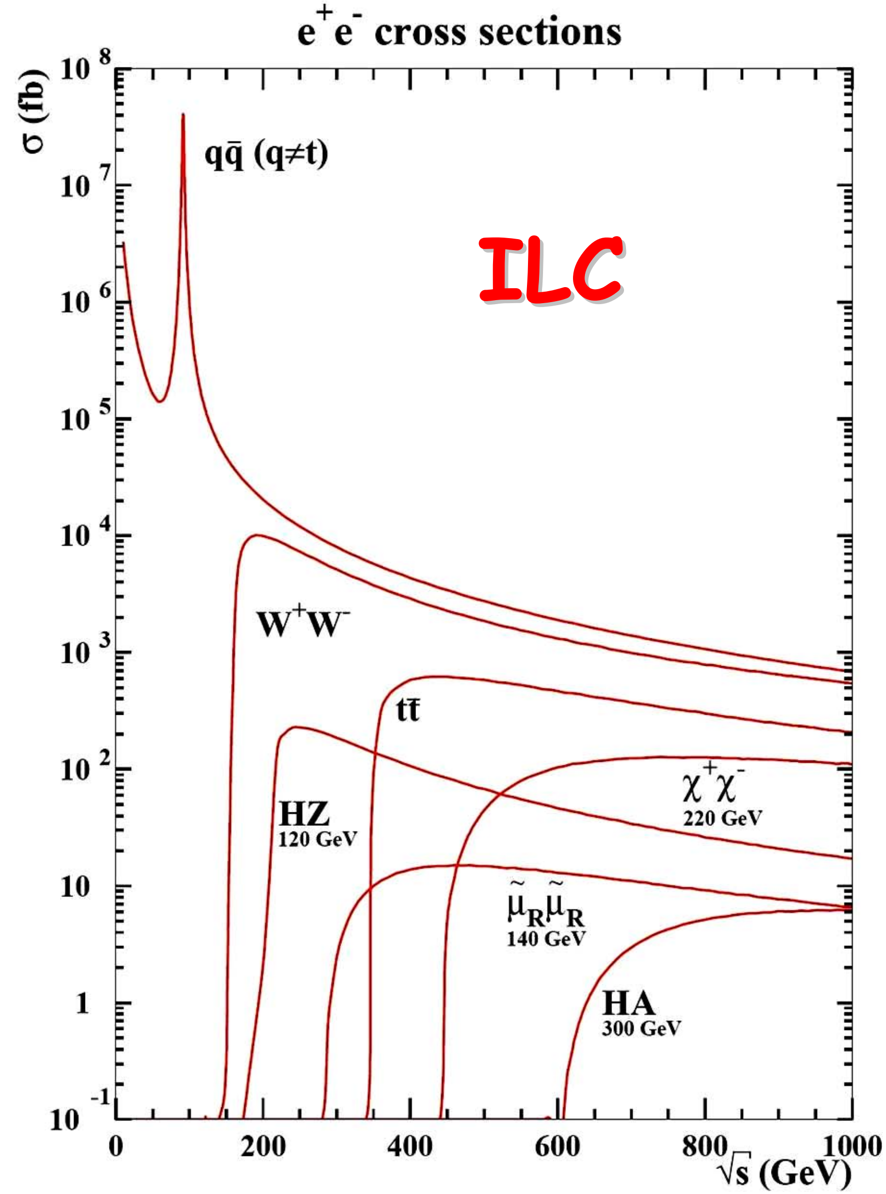
http://www.interactions.org/linearcollider/gde

LHC vs ILC

- signal ~ 10^4 fb
- background ~ 10^{10} x signal

- signal ~ 10^2 fb
- background ~ 10^2 x signal





6. QCD

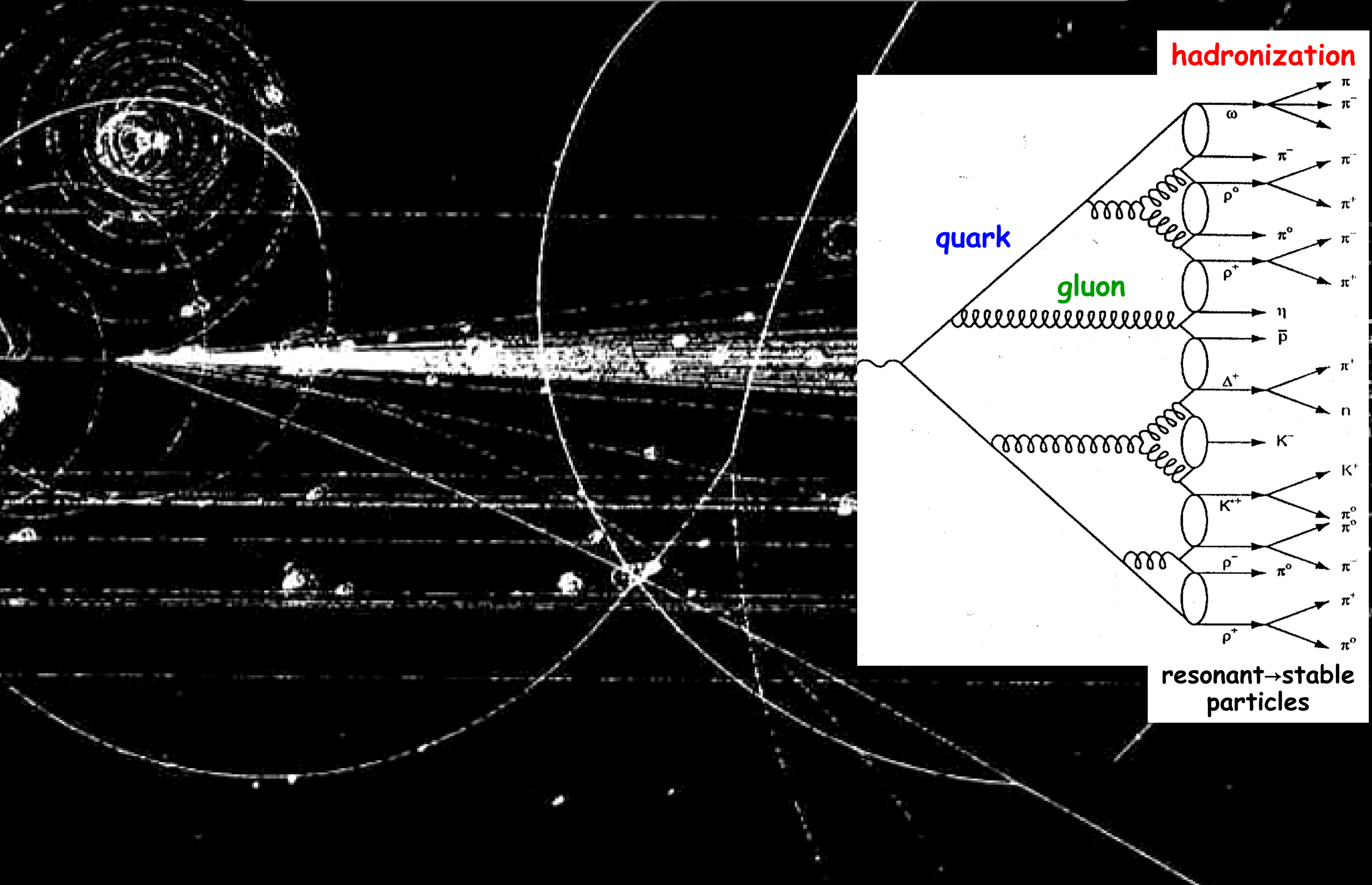
Quantum Chromo-Dynamics

Gauge field theory of strong interactions

in $SU(3)_{COLOR}$

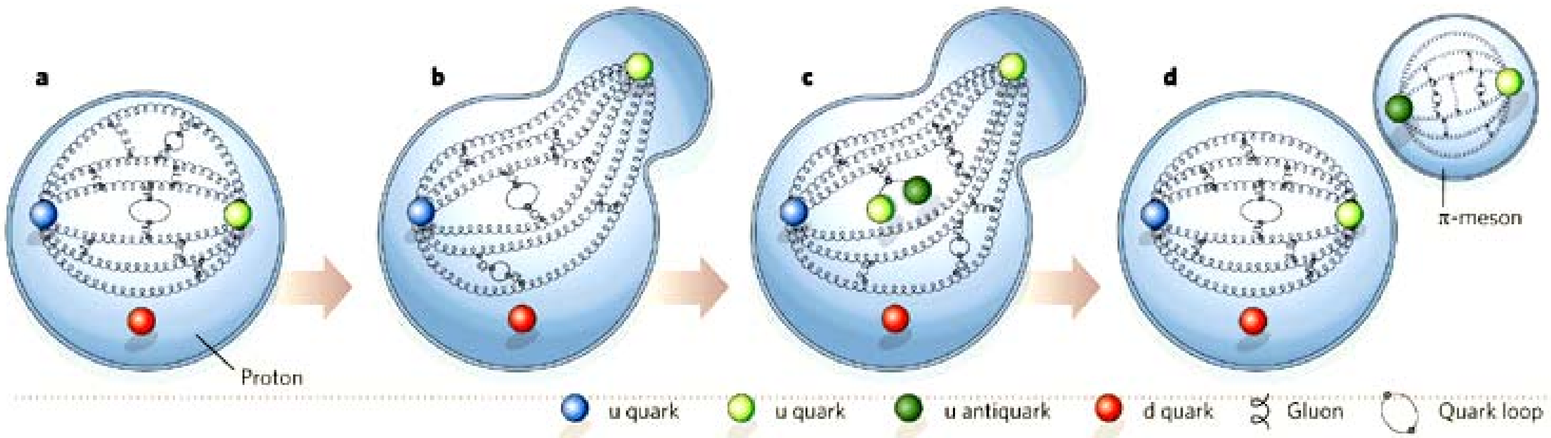
1. Color
2. Gluons
3. Quarks
4. Confinement + asymptotic freedom
5. Running coupling constant

Hadronic interactions

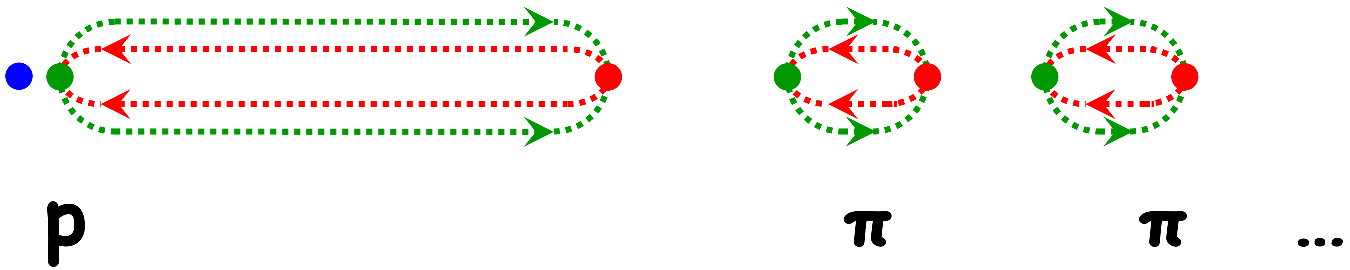


Confinement

Why no free quarks, no fractional charge observed ?!



color string: tension 200 MeV/fm ~ m_π



Color

1. Confinement:

no free quarks, no 1/3 charge observed !

which law forbids that + enforces trinity (qqq) ?

Color: hadrons have to be color singlets

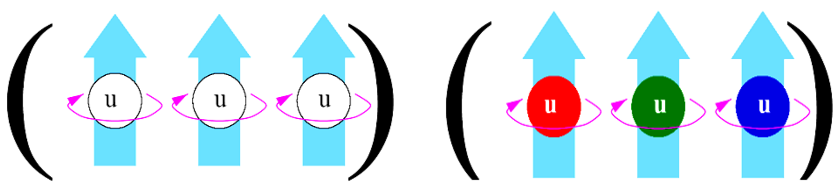
Mesons: $\{N\} \otimes \{\overline{N}\} = \{1\} \oplus \{N^2-1\}$

Baryons: $\{3\} \otimes \{3\} \otimes \{3\} = \{1\} \oplus \ldots$

2. Spin-Statistics problem (Nambu 1964)

baryon decuplet $J^P = 3/2^+$

Δ^{++} :



also $\Omega^- =$ (sss)

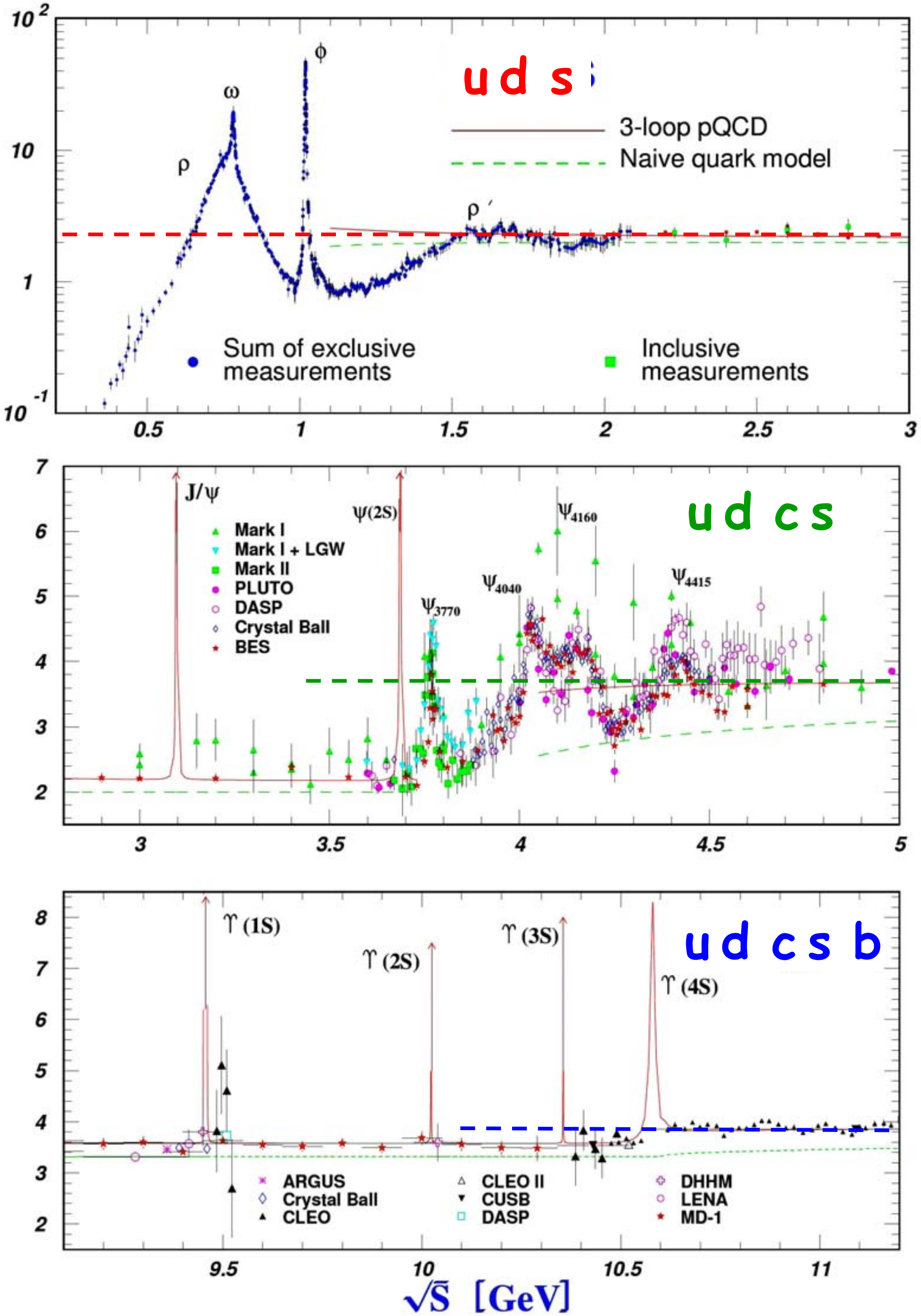
$\Psi(qqq) = \Psi(\text{space})\ \Psi(\text{spin})\ \Psi(\text{flavor})\ \Psi(\text{color})$

asy = sym × sym × sym × asy

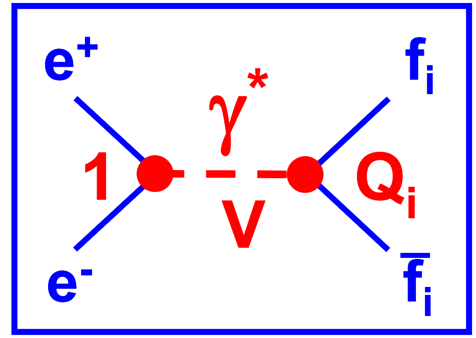
$\Psi_C(q\bar{q}) = (r\bar{r}+g\bar{g}+b\bar{b})/\sqrt{3}$

$\Psi_C(qqq) = (rgb-grb+rbg-gbr+brg-bgr)/\sqrt{6}$ asym. color wave fct.!

3. $R_{QCD} = \sigma(e^+e^- \rightarrow q\bar{q}) / \sigma(e^+e^- \rightarrow \mu^+\mu^-) \sim N_C$:



Color counting



$$R = \frac{\sigma(e^+e^- \to q\ \overline{q} \to \text{hadrons})}{\sigma(e^+e^- \to \mu^+\mu^-)}$$

$$= \sum_{\substack{\text{flavors}\\\text{colors}}} Q_i^2 \quad =$$

N_F	Q_i^2		N_C		
3	$\left(\frac{2}{3}\right)^2 + \left(\frac{1}{3}\right)^2 + \left(\frac{1}{3}\right)^2$	$= \frac{6}{9}$	$\cdot 3$	$= \frac{6}{3}$	$\binom{u}{d}\binom{}{s}$
4	$\left(\frac{2}{3}\right)^2 + \left(\frac{1}{3}\right)^2 + \left(\frac{2}{3}\right)^2 + \left(\frac{1}{3}\right)^2$	$= \frac{10}{9}$	$\cdot 3$	$= \frac{10}{3}$	$\binom{u}{d}\binom{c}{s}$
5	$\left(\frac{2}{3}\right)^2 + \left(\frac{1}{3}\right)^2 + \left(\frac{2}{3}\right)^2 + \left(\frac{1}{3}\right)^2 + \left(\frac{1}{3}\right)^2$	$= \frac{11}{9}$	$\cdot 3$	$= \frac{11}{3}$	$\binom{u}{d}\binom{c}{s}\binom{}{b}$

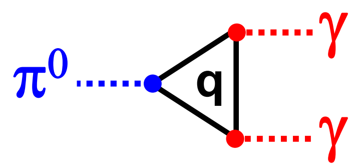
4. OZI rule:

Why are $\Phi(s\bar{s})$, $\Psi(c\bar{c})$, … so narrow? Why is

suppressed ?

5. Triangle anomaly (Adler,Bell,Jackiw 1969)

$\Gamma\,(\pi^0 \to \gamma\gamma) = (\alpha/2\pi)^2\,(Q_u^2 - Q_d^2)\,N_C^2\;\; m_\pi^2/(8\pi\, f_\pi)$



Γ = 0.86 eV	THEORY	N_C=1
Γ = 7.8±0.5 eV	EXPT.	
Γ = 7.75 eV	THEORY	N_C=3

6. τ branching ratios

$$\frac{\Gamma\,(\tau^- \to e^-\, \nu_e \nu_\tau)}{\Gamma_{tot}} = \frac{\Gamma_e}{\Gamma_e + \Gamma_\mu + \Gamma_{had}\cdot N_C} = \frac{1}{1+1+3} = \frac{1}{5} = (17.8 \pm 0.1)\ \%$$

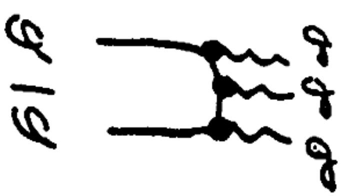
Vector Mesons

$J^{PC}=1^{--}$

OZI rule

α_s^1 forbidden: free color !

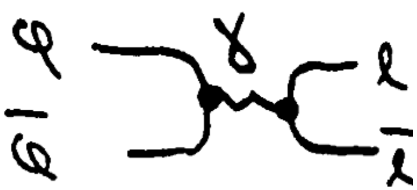
α_s^2 forbidden: $1^{--} \neq (\ldots)^2$



α_s^3 ok: measure α_s

$\Upsilon \to ggg \to$ 3 gluon jets

$$\frac{\Gamma(V \to 3g \to \text{hadrons})}{\Gamma(V \to \gamma \to l^+l^-)} = \frac{\alpha_s^3(m_V)}{\alpha^2 q_i^2} \frac{10(\pi^2-9)}{81\pi}(1+\ldots)$$

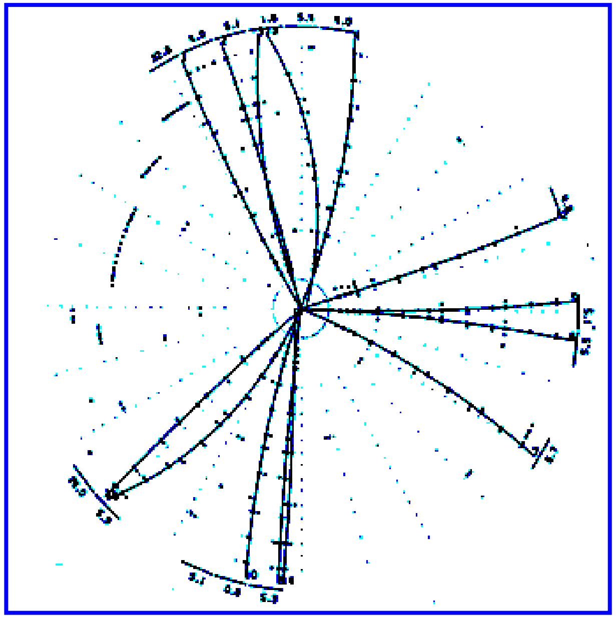


$\alpha^2 q_i^2$ measure quark charges q_i

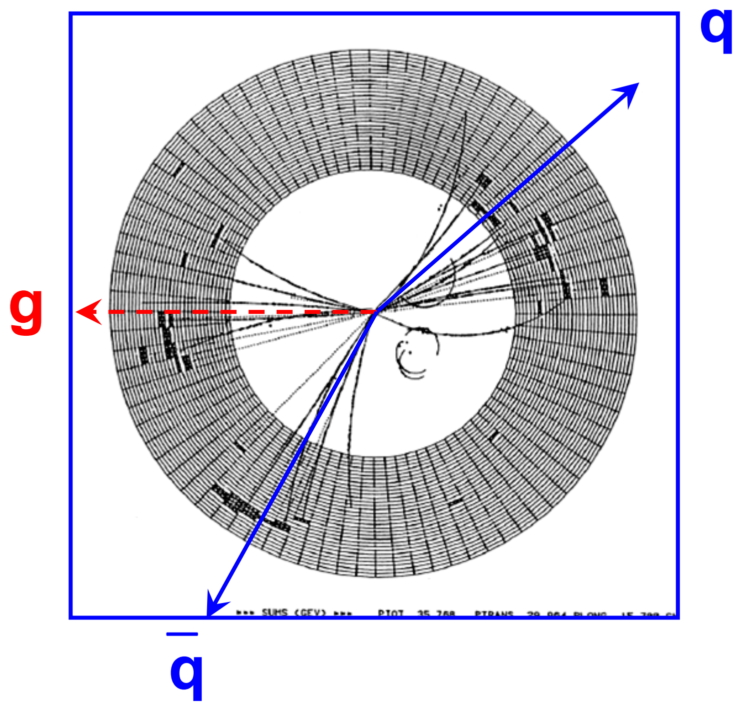
Gluon

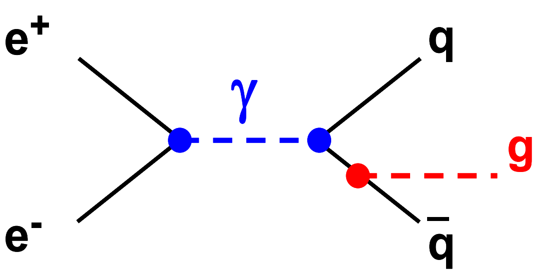
discovered 1979 at PETRA at DESY in

TASSO



JADE

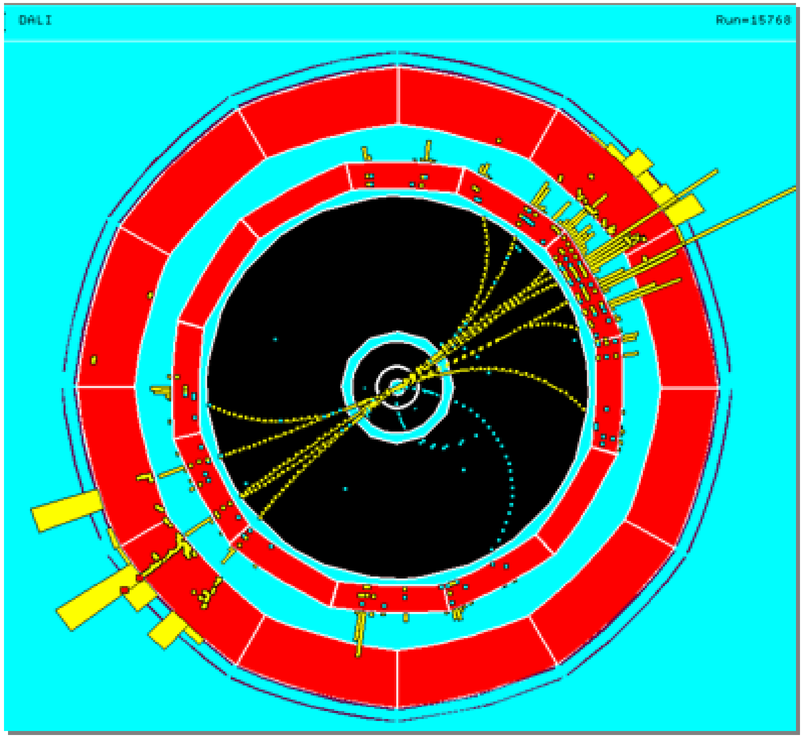




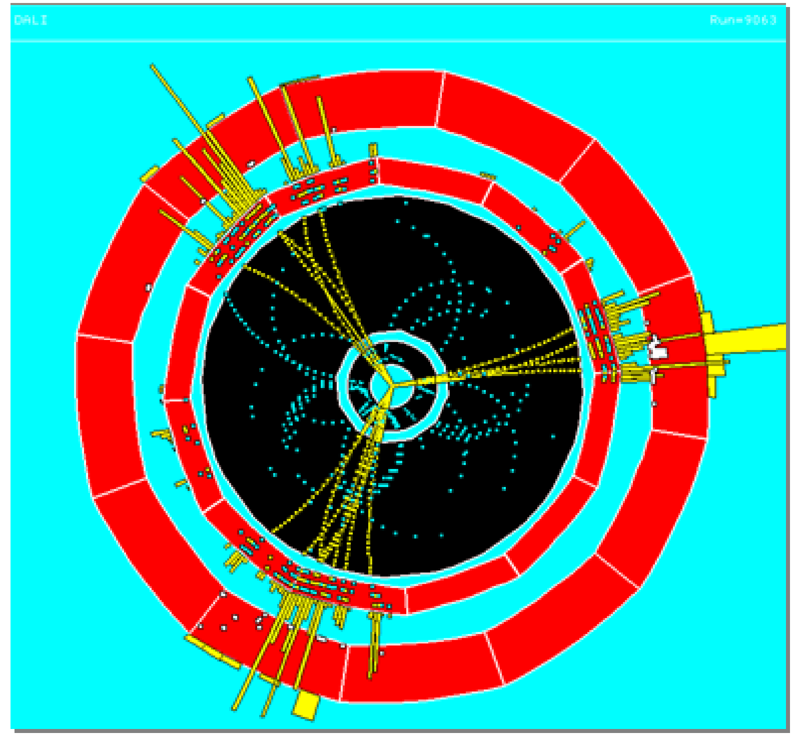
$$e^+ e^- \rightarrow q\ \bar{q}\ g$$

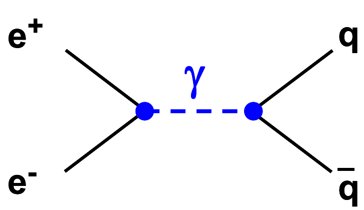
Europhysics Prize 1995

Gluon



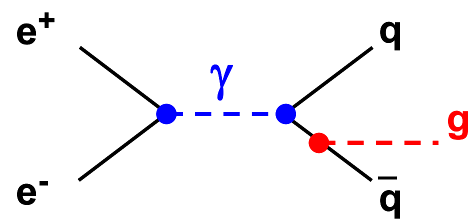
ALEPH





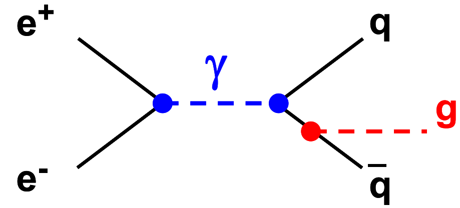
$$e^+ e^- \rightarrow q \; \bar{q}$$

LEP



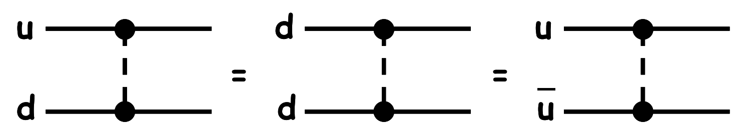
$$e^+ e^- \rightarrow q \; \bar{q} \;\; g$$

Gluons

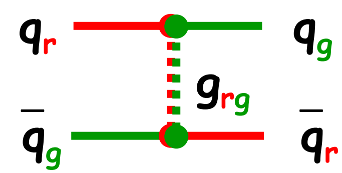


1. Existence: DESY PETRA 1978: 3 jet events

2. Couplings



SU(3): N=3 color charges
group has N^2-1 = 8 generators



$\{3\} \otimes \{\bar{3}\} = \{1\} \oplus \{8\}$

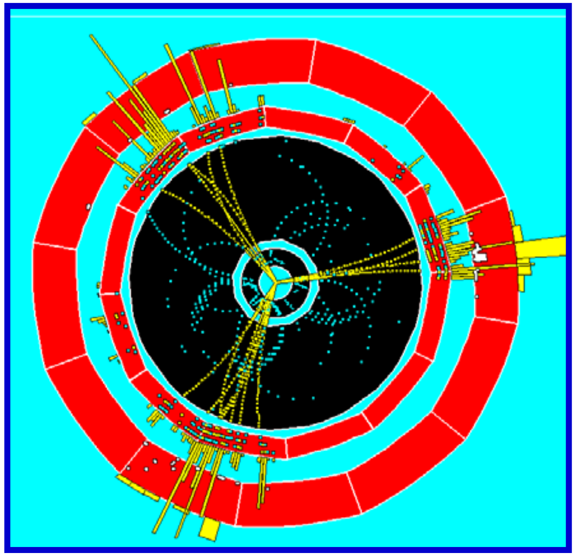
strong int. conserves isospin,
not flavor dependent

$\{1\} = (r\bar{r}+g\bar{g}+b\bar{b})/\sqrt{3}$ color singlet, meson, color blind

$\{8\} = r\bar{g}+r\bar{b}+b\bar{g}+b\bar{r}+g\bar{b}+g\bar{r} + (r\bar{r}-g\bar{g}) + (r\bar{r}+g\bar{g}-2b\bar{b})$
8 colored gluons

3. Spin: jet-jet angle => $J^P=1^-$

CERN LEP ALEPH 200 GeV



Gluon spin

LEP

$e^+ e^- \rightarrow$ 3 jets:

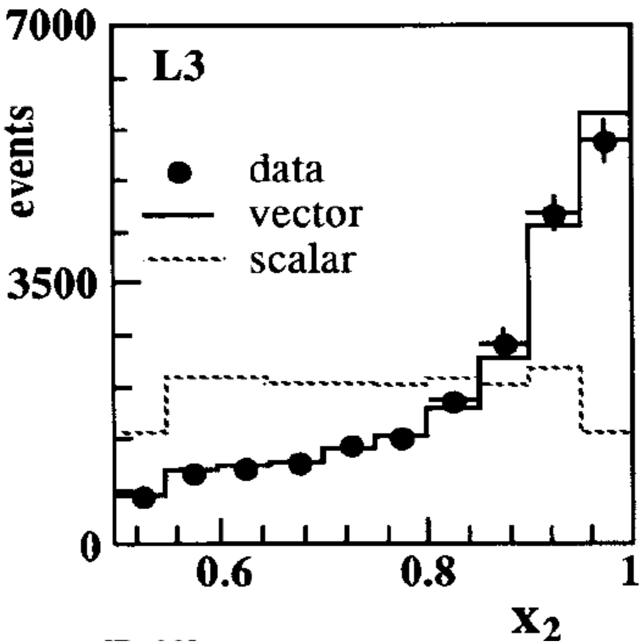
order the scaled

jet energies x_i:

$$x_i = 2E_i / \sqrt{s}$$

$$x_1 > x_2 > x_3$$

collinearity of 2nd energetic jet:



infrared collinear singularity
of gluon bremsstrahlung

S.Bethke, J.Pilcher, Ann.Rev.Nucl.Part.Sci. 42 (1992) 251.

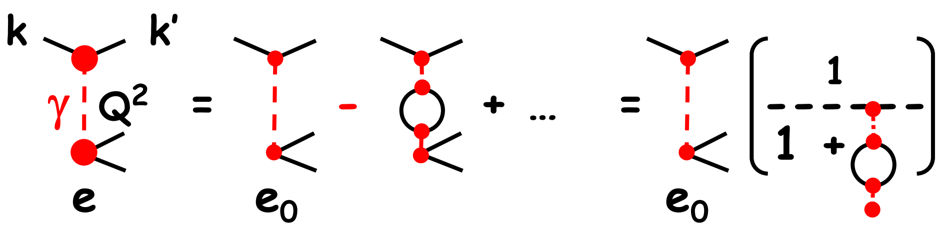
Running coupling constant

A constant is not constant:

- running coupling constant
- asymptotic freedom
- confinement

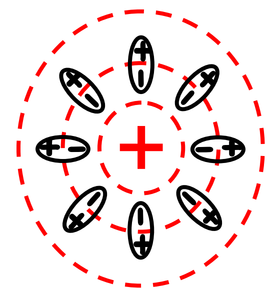
QED

Vacuum polarization in e-e scattering:



physical charge | naked charge | vacuum polarization | $Q^2 = -(k^2-k')^2$

dielectric screening:



- coupling ~ charge^2: $F = \alpha/r^2$ $\alpha = e^2/4\pi$
- infrared stable: $\alpha = 1/137$
  ultraviolet divergent - naked charge infinite !?
- Cutoff at arbitrary scale: renormalization !
  energy scale: $Q^2 = -(k-k')^2$
- consider only evolution from energy scale Q to scale μ
  UV divergences cancel

classical electron radius
$r = \alpha/m_e \sim 3$ fm

Compton wavelength
$\lambda_C = 1/m_e$

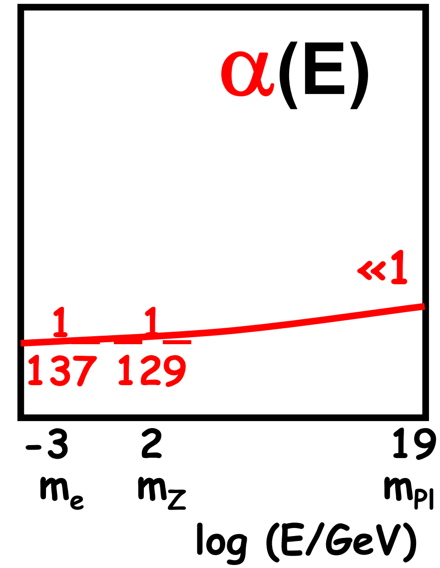
Running coupling

$\alpha = e^2/4\pi$ charge ~ coupling = fine structure constant

constant **not constant:**

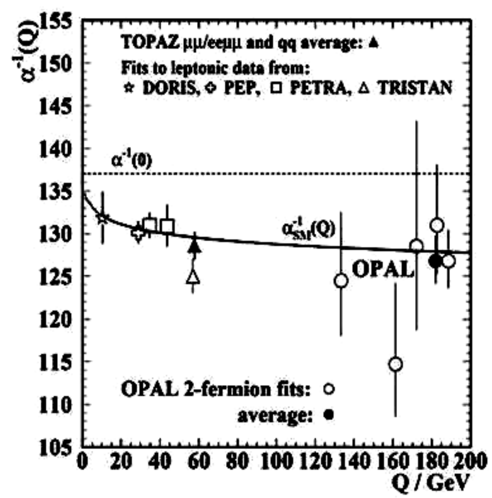
$$2\beta = \partial\,\alpha(\mu)/\partial \ln \mu = \frac{2}{3\pi}\alpha^2 + \ldots$$

$$\alpha(Q^2) = \frac{\alpha(\mu^2)}{1 - \frac{\alpha(\mu^2)}{3\pi}\log\frac{Q^2}{\mu^2}}$$



α (E) running (or crawling):

$$\partial\ \alpha(Q^2)\ /\ \partial Q^2 > 0$$



α (m_e = 0.5 MeV) = 1/137

α (m_Z = 91 GeV) = 1/128.9 CERN LEP

α (m_{Pl} = 10^{19} GeV) « 1 more Fermion-Loops

α (∞) undefined no electric point interaction ?!

QCD: the Lagrangian

$$\mathcal{L} = \frac{1}{4g^2} G^a_{\mu\nu} G^a_{\mu\nu} + \sum_j \bar{q}_j \left(i\gamma^\mu D_\mu + m_j \right) q_j$$

where $G^a_{\mu\nu} \equiv \partial_\mu A^a_\nu - \partial_\nu A^a_\mu + i f^a_{bc} A^b_\mu A^c_\nu$

and $D_\mu \equiv \partial_\mu + i t^a A^a_\mu$

<u>That's it!</u>

j … quark flavors

a,b,c … 3 colors

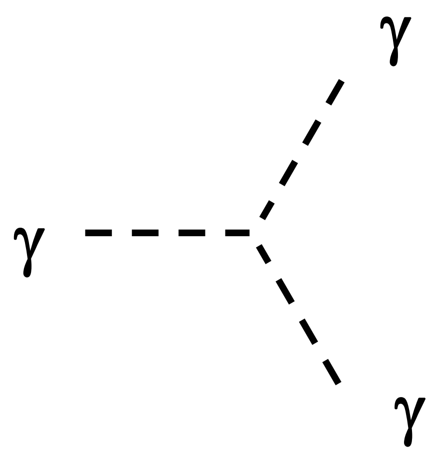
μ,ν … space-time

F.Wilczek, Physics Today, August 2000.

Quantum Chromo-Dynamics

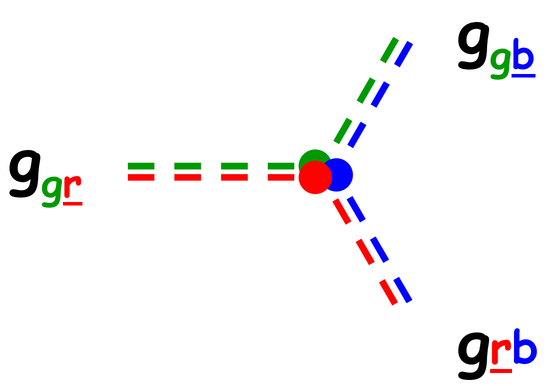
QED

- U(1), abelian
- 1 charge type
- 1 photon:
- electric neutral
- no photon-photon coupling:
  - light does not clump !



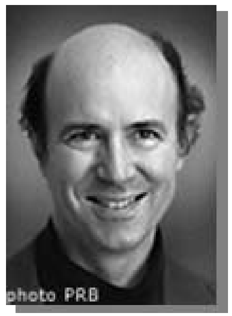
QCD

- $SU(3)_{COLOR}$, non-abelian
- 3 charge types: r,g,b
- $\{3\}\otimes\{\bar{3}\} = \{1\}\oplus\{8\}$: 8 gluons:
- carry color charges
- gluon-gluon self-coupling
  - gluonium, glue balls

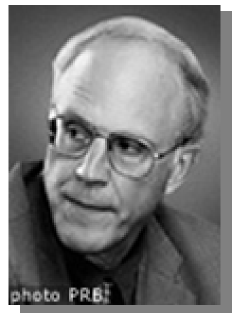


Nobel prize 2004

for the discovery of asymptotic freedom
in Quantum Chromo-Dynamics



D. Gross



D. Politzer

F. Wilczek

The most dramatic of these [consequences],
that protons viewed at ever higher resolution
would appear more and more as field energy (soft glue),
was only clearly verified at

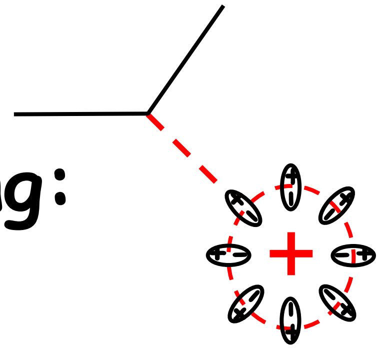
HERA

twenty years later.

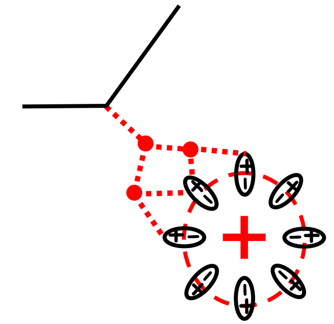
F. Wilczek, 2001

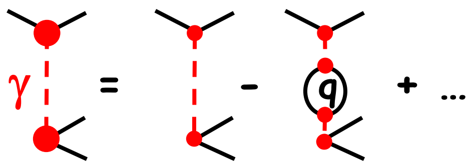
QED and QCD

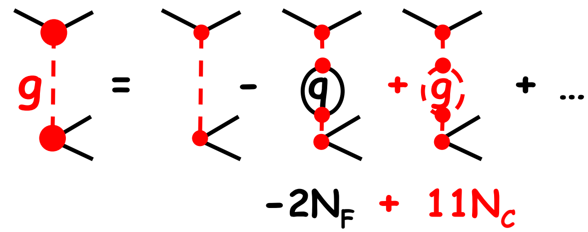
Screening:



Anti-Screening:







$$\alpha(Q^2) = \frac{\alpha(\mu^2)}{1 + b_0 / 4\pi \; \alpha(\mu^2) \log(Q^2/\mu^2)}$$

$b_0 = -4/3$

$\partial\, \alpha(Q^2) / \partial Q^2 > 0$

$b_0 = (-2N_F + 11N_C)/3$

$\partial\, \alpha(Q^2) / \partial Q^2 < 0$

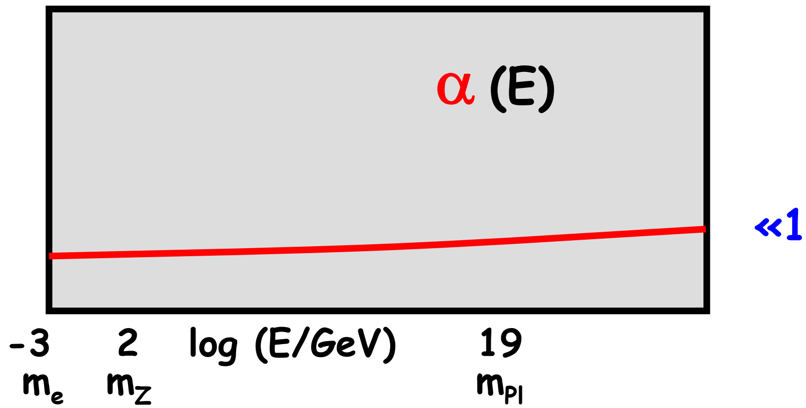
gluon massless ! SU(2)$_W$: $m_W > 10^5\, m_e$

QED and QCD

QED: $\partial\, \alpha(\mu^2) / \partial \mu^2 > 0$ **screening**

IR:

α = 1/137



UV:

Landau Singularity

QCD: $\partial\, \alpha(\mu^2) / \partial \mu^2 < 0$ **anti-screening**

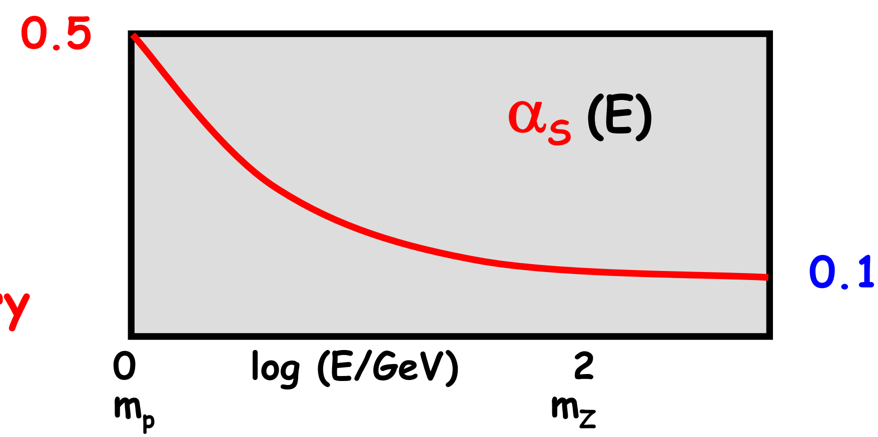
IR:

$\alpha_s \to \infty$

collapse of perturbation theory

infrared slavery

confinement



UV:

$\alpha_s \to 0$

asymptotic freedom

Confinement

instead of $\alpha_s(\mu^2)$ define

$$\Lambda = \mu \exp [-2\pi/(b_0\alpha_s(\mu^2))]$$

$$\alpha_s (Q^2) = \frac{4\pi}{9 \ln (Q^2/\Lambda^2)} + \ldots \quad (N_F=3)$$

$$\alpha_s (Q^2 \rightarrow \Lambda^2) \rightarrow \infty$$

collapse of perturbation theory
nuclear force confines - infrared slavery:
no free quarks !

$\hbar c \approx$ 200 MeV • fm
QCD scale • proton radius

proton = 'QCD black hole'

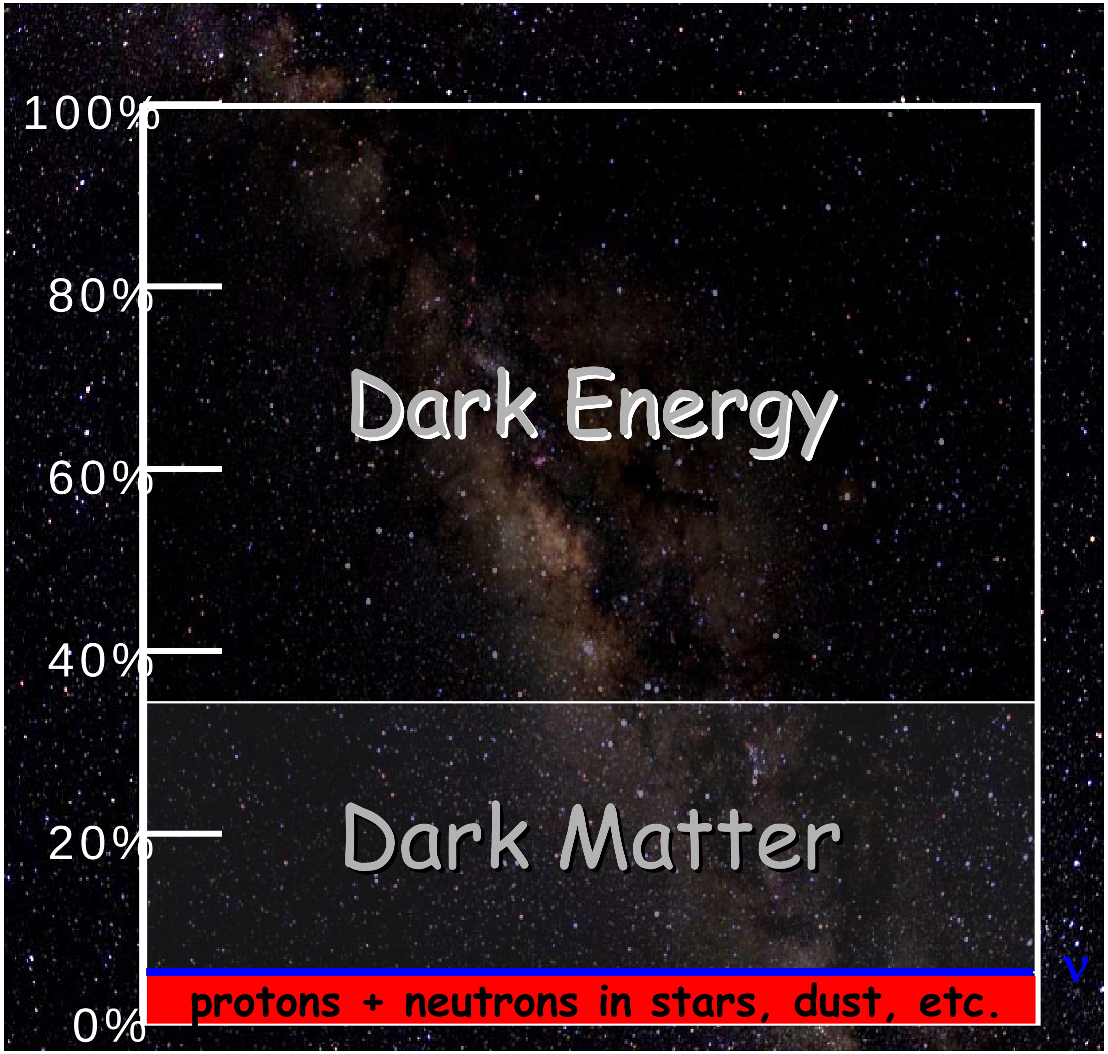
From asymptotic freedom to infrared slavery

Quarks are
born free,
but everywhere
they are
in chains.

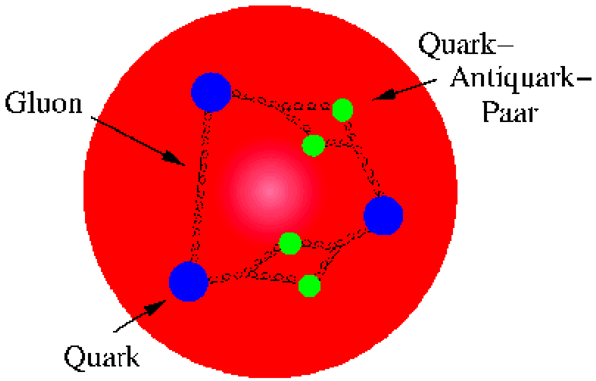
F.Wilczek, Nobel talk, 2004.

J.J. Rousseau, Du Contrat Social, 1762:
«L'homme est né libre et partout il est dans les fers.»

Mass vs Energy



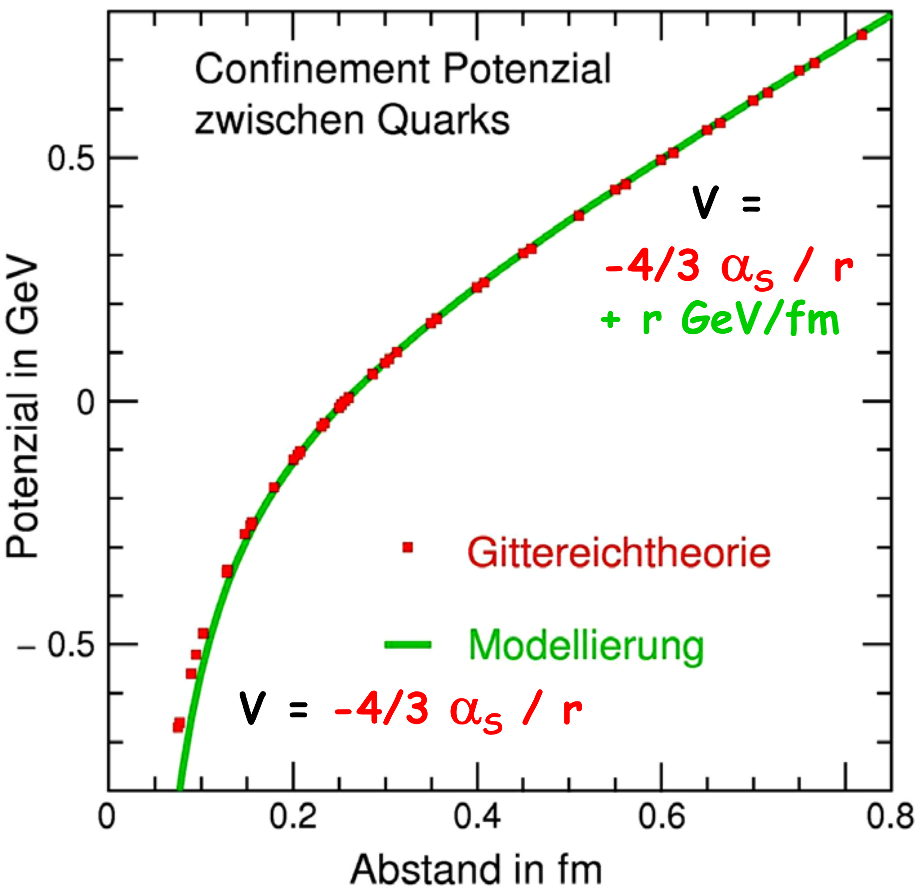
Nucleon mass



~ % due to
quark masses

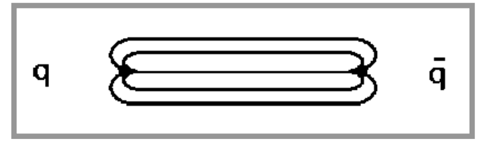
rest:
binding energy
of partons

Confinement



hadron radius:

confinement



color string: constant force = energy/length: k = 1 GeV / fm

describes spectroscopy of heavy quark bound states:

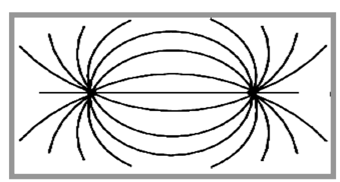
$\Psi, \Psi', \Psi'', \ldots = (c\ \bar{c})$

$\Upsilon, \Upsilon', \Upsilon'', \ldots = (b\ \bar{b})$

like positronium $= (e\ \bar{e})$

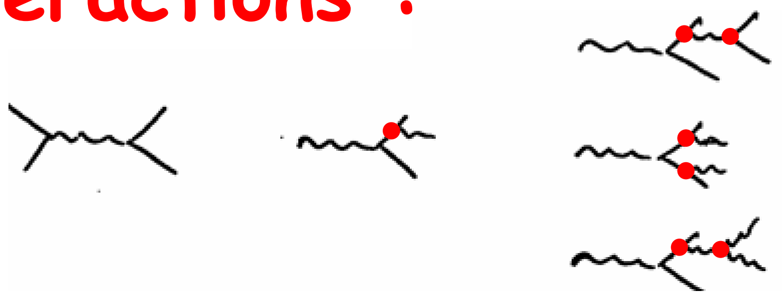
asymptotic freedom

at short distances = high energies:
Coulomb law



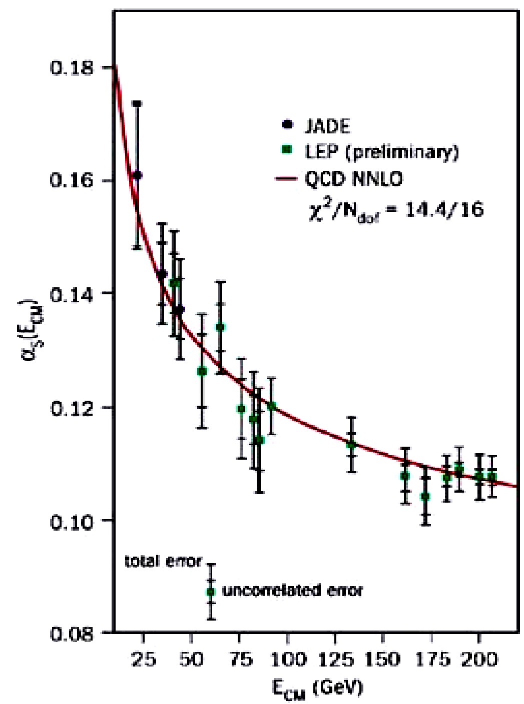
α_s measurement

e^+e^- interactions :



2+0 2+1 2+2 jets

$$R = \Gamma_h/\Gamma_l = R_0\,[1^0 + (\alpha_s/\pi)^1 + 1.4(\alpha_s/\pi)^2 + \ldots]$$



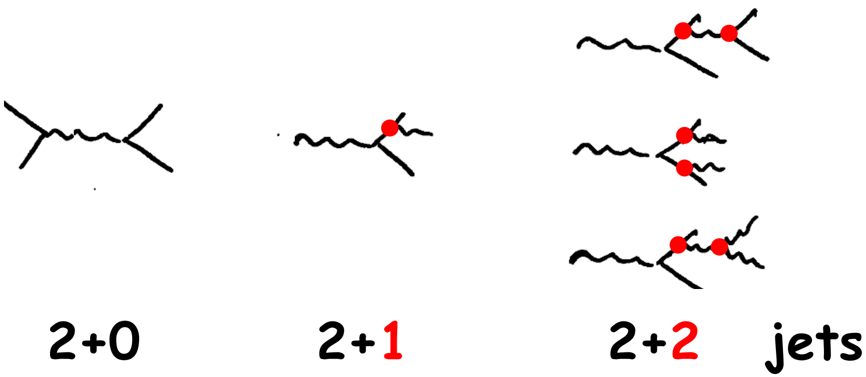
$\delta R/R \sim 10^{-3}$ syst. errors cancel: luminosity, …

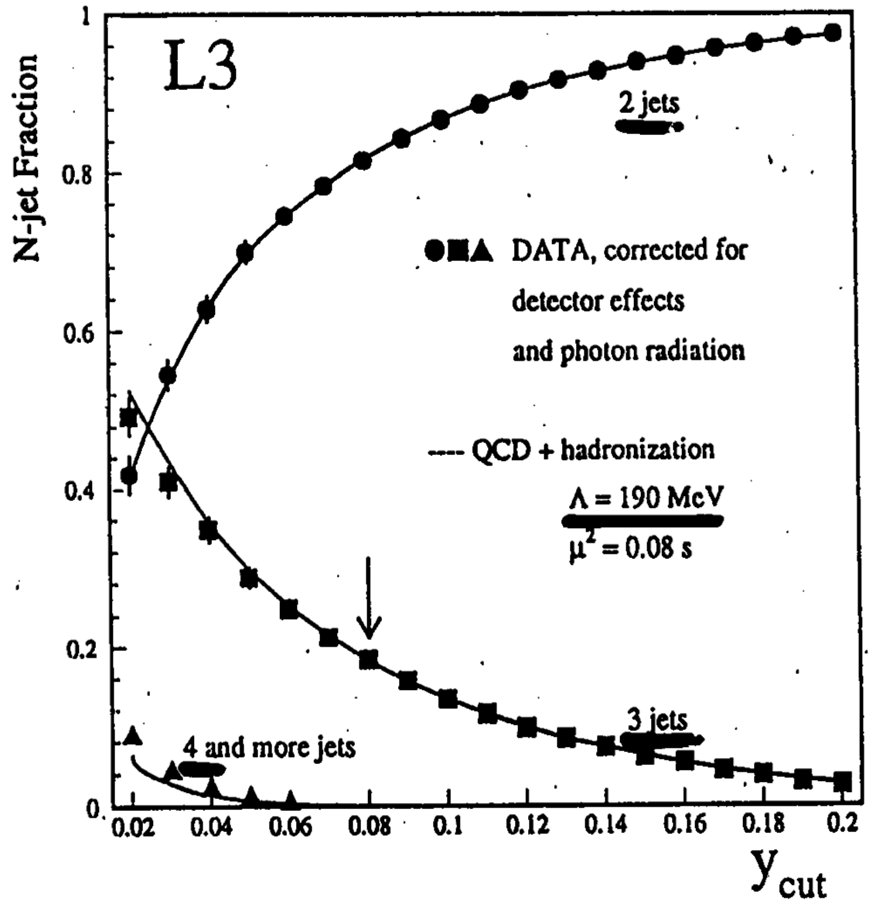
$\delta\alpha_s/\alpha_s = \pi/\alpha_s\ \delta R/R \sim 25\ \delta R/R$

- CLEO, PEP,PETRA, TRISTAN: α_s (34 GeV) = 0.15 ± 0.03
- LEP,SLC @ Z pole: α_s (91 GeV) = 0.120 ± 0.003 (exp) ± 0.002 (th)
- LEP2: α_s (172 GeV) = 0.102 ± 0.006

α_s from jets

$e^+e^- \to$ 2+n jets



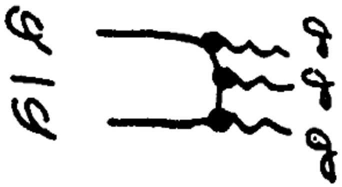


Heavy Vector Mesons

α_s in Quarkonium

α_s^1 forbidden: free color !

α_s^2 forbidden: $1^{--} \neq (...)^2$



α_s^3 ok: measure α_s

$\Upsilon \rightarrow ggg \rightarrow$ 3 gluon jets: $R = \dfrac{\Gamma\,(V \rightarrow 3g \rightarrow \text{hadrons})}{\Gamma\,(V \rightarrow \gamma \rightarrow l^+l^-)} = \dfrac{\alpha_s^3(m_V)}{\alpha^2\, q_i^2}\ \dfrac{10(\pi^2-9)}{81\pi}\ (1+\alpha_s/\pi\ [...])$

$\alpha^2\, q_i^2$ measure quark charges q_i

$\alpha_s\ (m_b=4.25\ \text{GeV}) = 0.18 \pm 0.01$

$\alpha_s\ (m_c=1.25\ \text{GeV}) \sim 0.4$

Running coupling

$$\alpha_s(Q^2) = \frac{4\pi}{9\ \ln(Q^2/\Lambda^2)} + \ldots$$

$\alpha_s(M_Z) = 0.1182 \pm 0.0027$

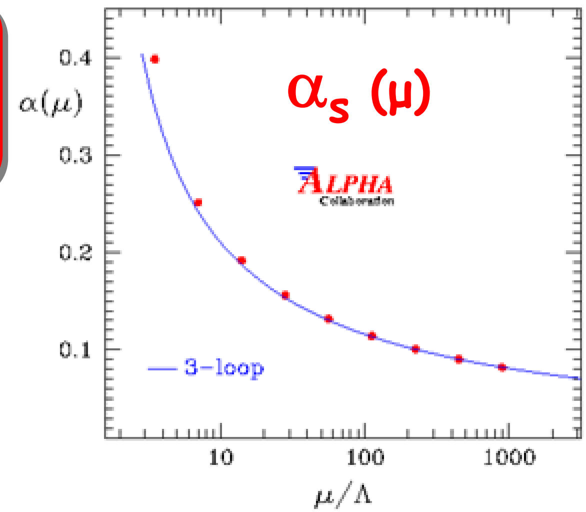
QCD scale:

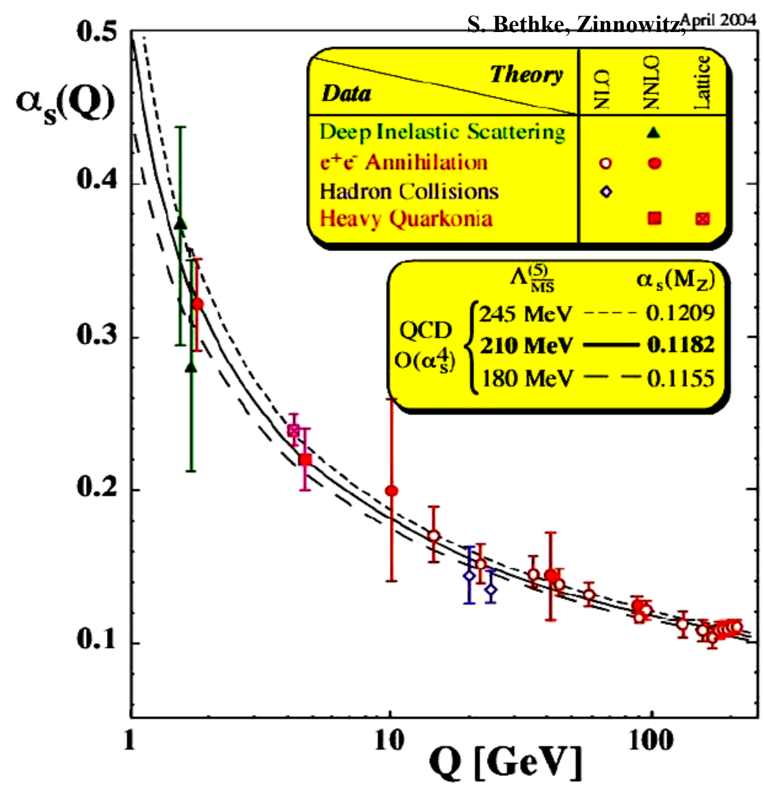
$\Lambda = 210 \pm 30$ MeV (MS, N_F=5)

$\hbar c \approx$ 200 MeV • fm

QCD scale • proton radius

QCD on a 3D discrete lattice:

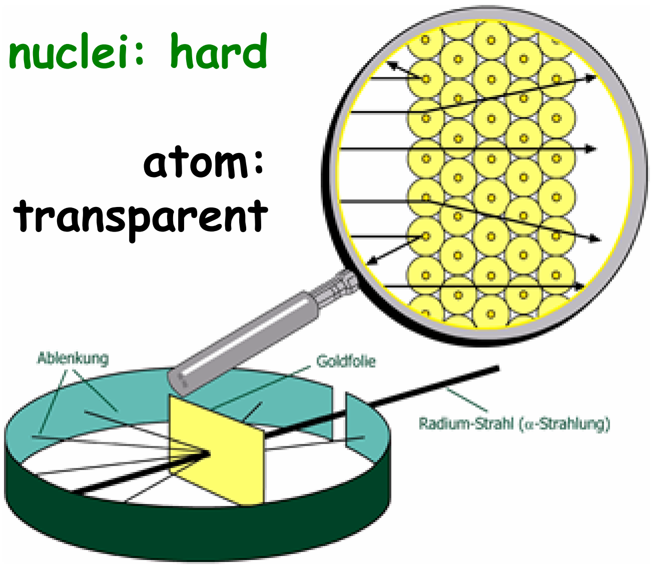


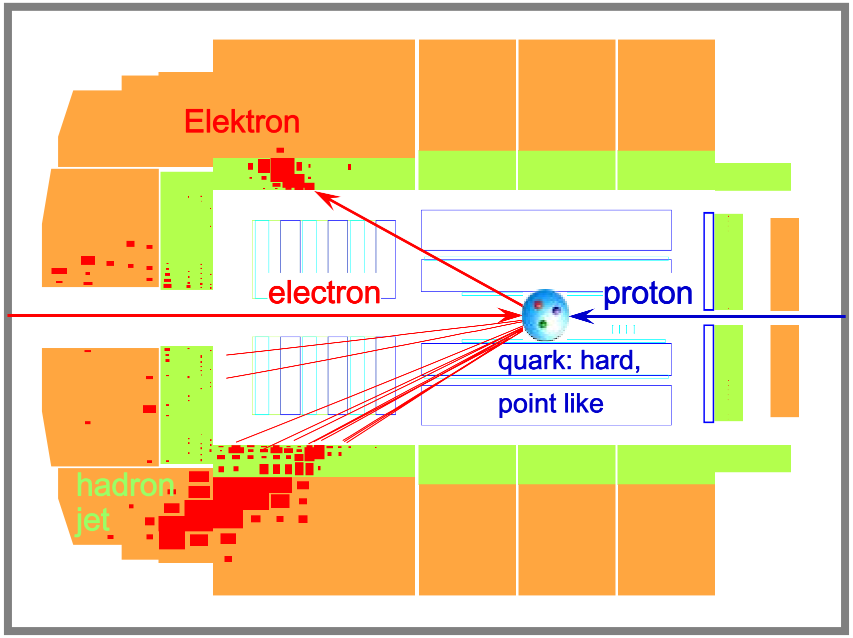


Structure of Matter

Rutherford 1910
atomic nucleus

HERA 2000
proton structure

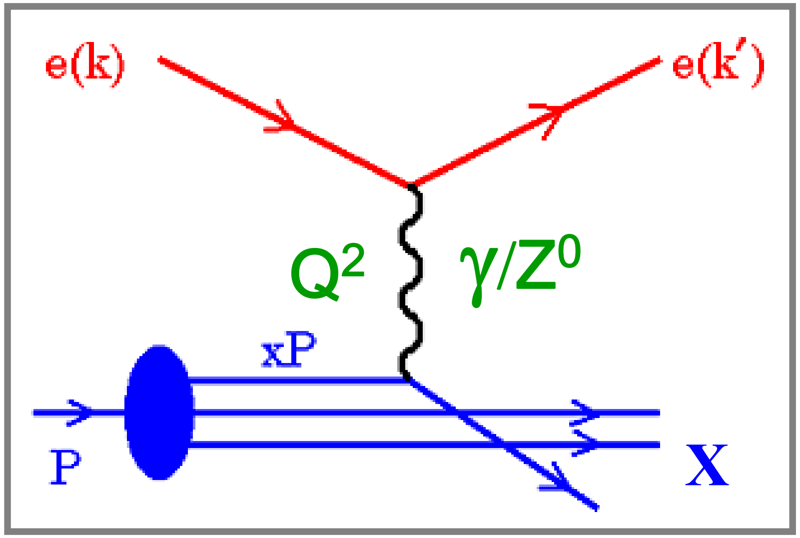




DIS Kinematics

$s = (k+P)^2 = 4\, E_e\, E_p$ center-of-mass energy^2 ($m^2 \ll s$)

$s = 4 \cdot 27.6$ GeV $\cdot$ 920 GeV = (319 GeV)^2 @ HERA



$Q^2 = -q^2 = -(k-k')^2$

four-momentum transfer^2

Rutherford 1911:
photon propagator

$d\sigma / dQ^2 = 4\pi\alpha^2 / Q^4$

$d\sigma / d\cos(\theta) = \pi\alpha^2 / 2E^2 \sin^4(\theta/2)$

Mott 1929, electron spin:

$\sigma_{Mott} = \cos^2(\theta/2)\, \sigma_{Ruth}$

$x = Q^2 / (2P\cdot q)$ Bjorken-x

parton momentum fraction in proton (quark, gluon)

$W^2 = (P+Q)^2$

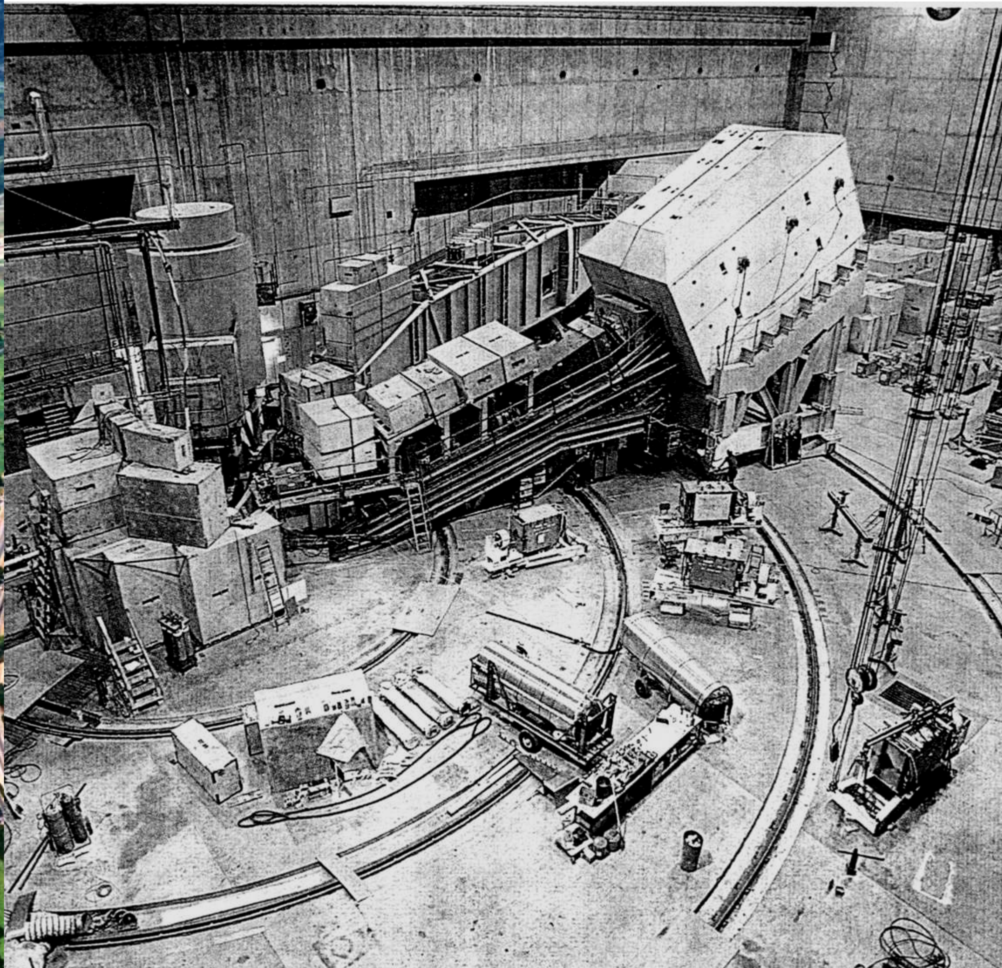
mass^2 of the hadronic system X

$s = x\, y\, Q^2$

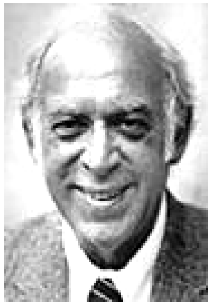
SLAC - Stanford Linear Accelerator

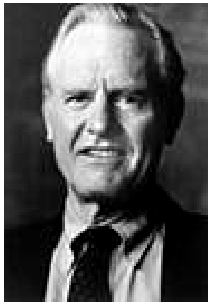
SLAC-MIT expt.

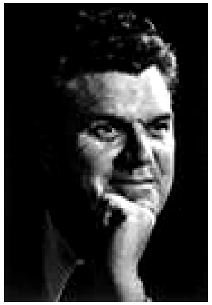
$E = 1.5\text{-}20$ GeV $\theta = 6°\text{-}26°$
$Q^2 = 1\text{-}7$ GeV^2



Quark Discovery


Friedman


Kendall


Taylor

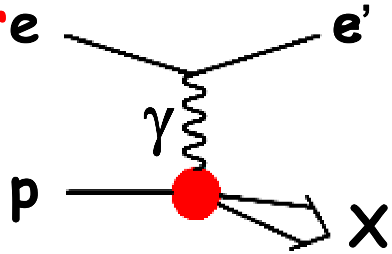
Nobel prize

1990

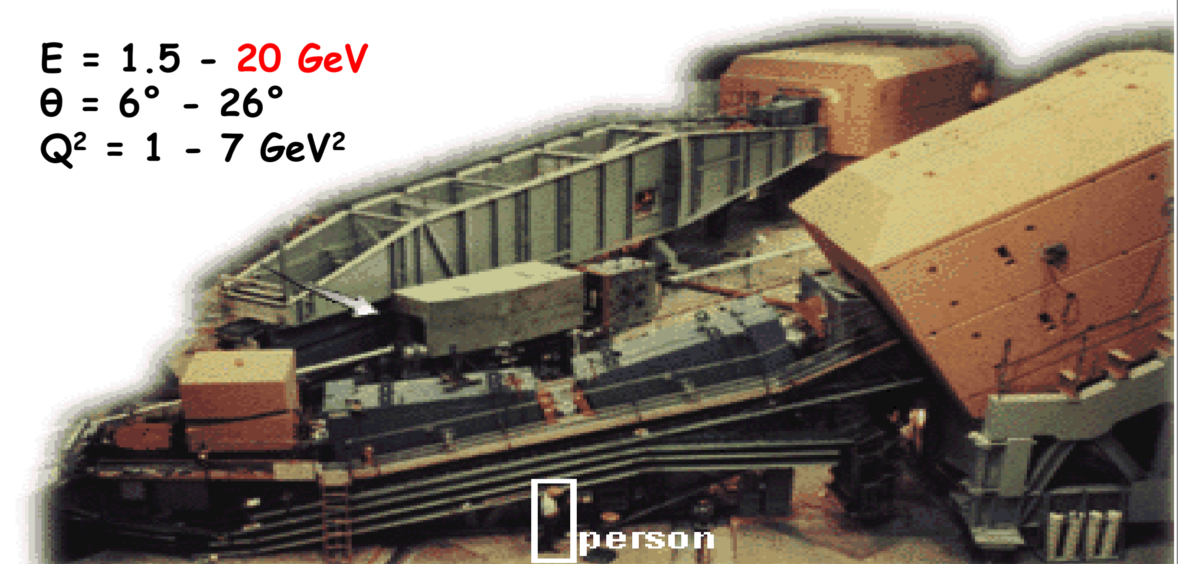
Stanford Linear Accelerator

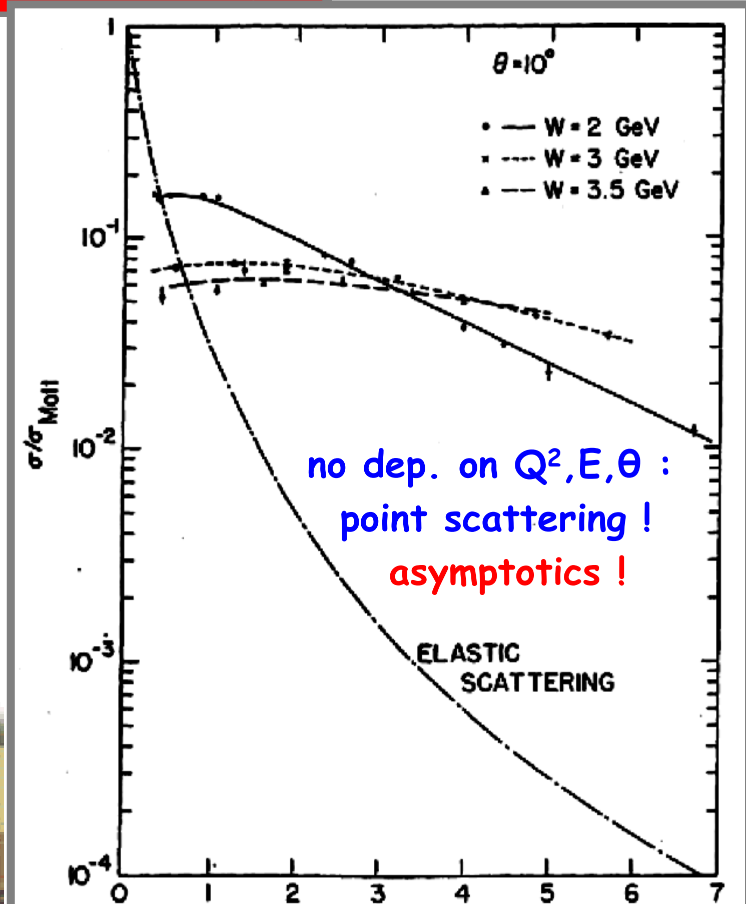
USA, 1968-71:

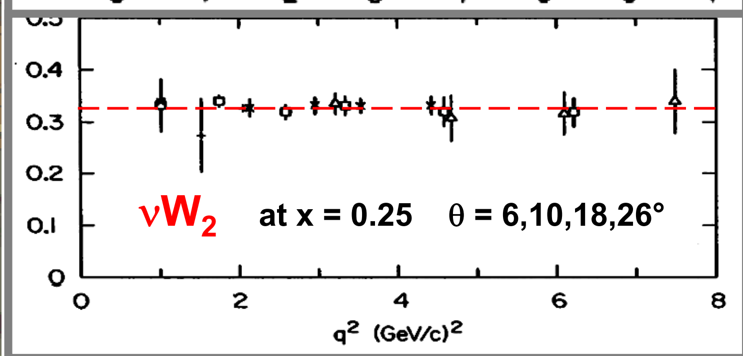
electron-proton
deep inelastic scattering

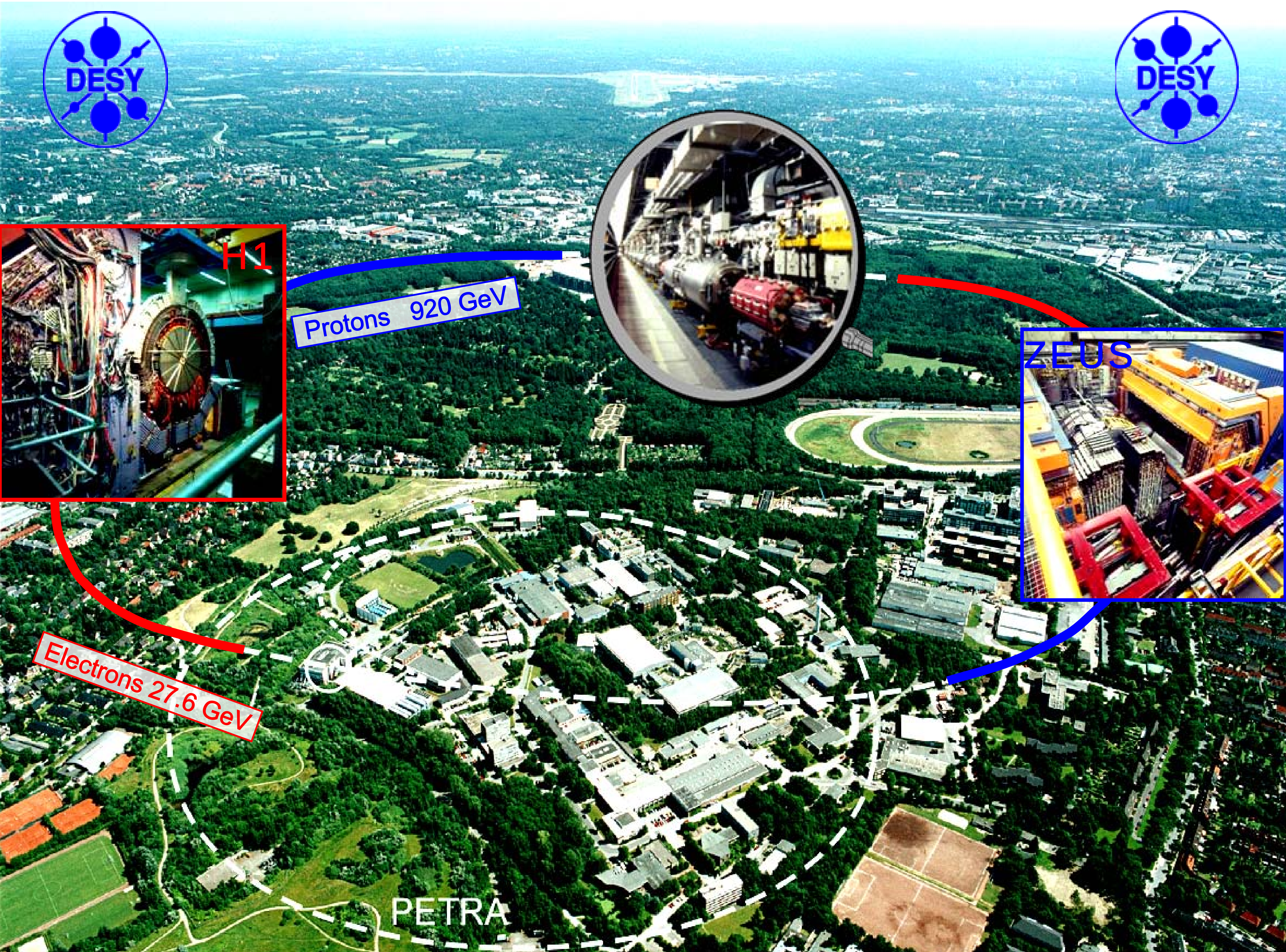


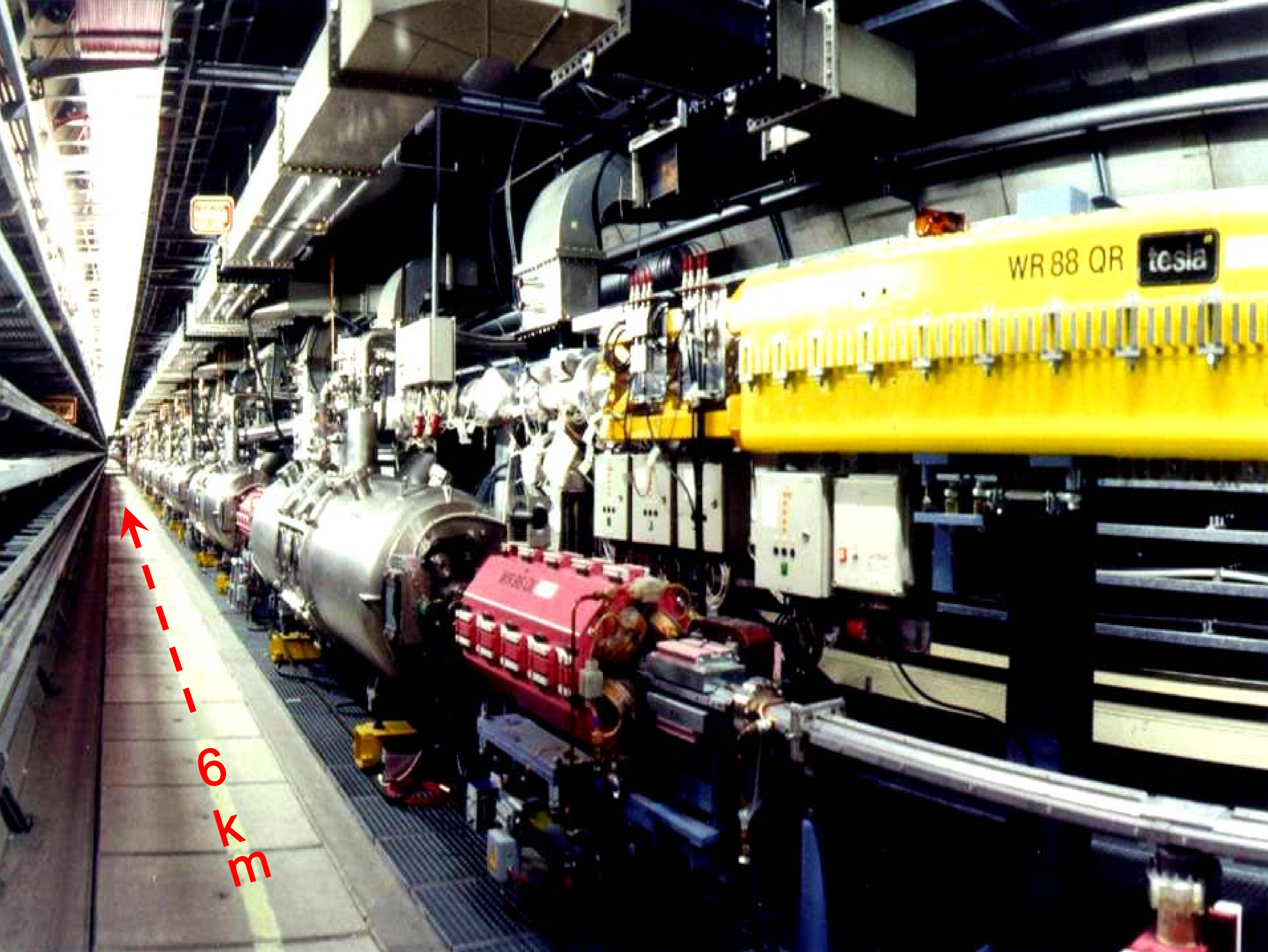
E = 1.5 - 20 GeV
θ = 6° - 26°
Q^2 = 1 - 7 GeV^2







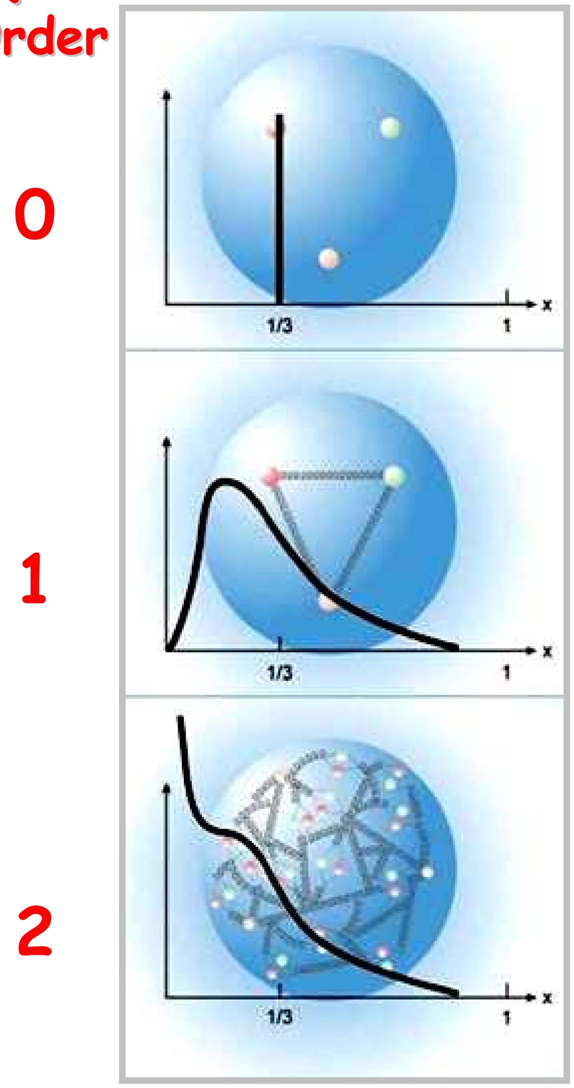

DESY
DESY
H1
Protons 920 GeV
ZEUS
Electrons 27.6 GeV
PETRA


WR 88 QR
tesla
6 km


ZEUS

Proton Structure

QCD Order

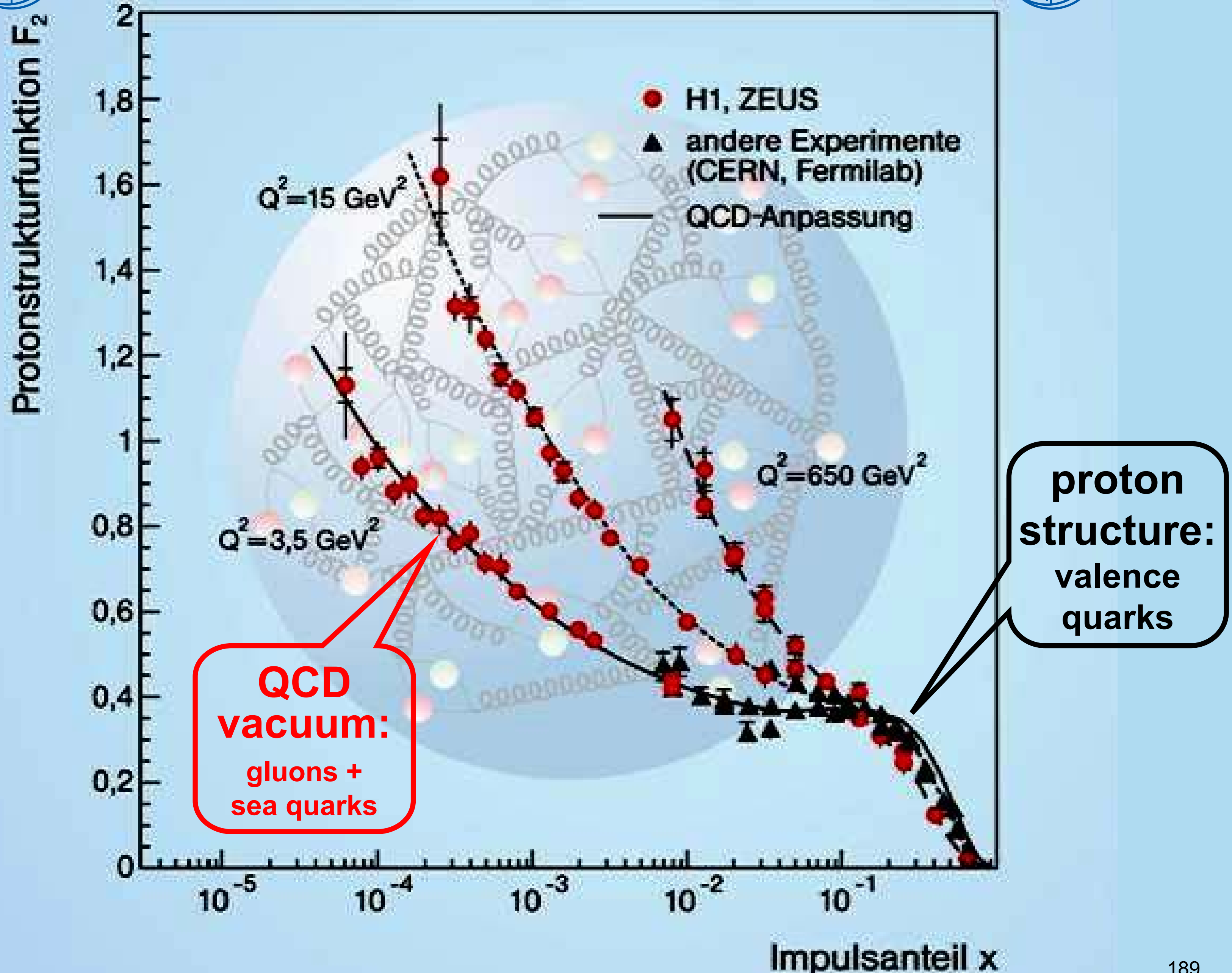


- **SLAC 1968:**
  3 valence quarks:
  x = 1/3

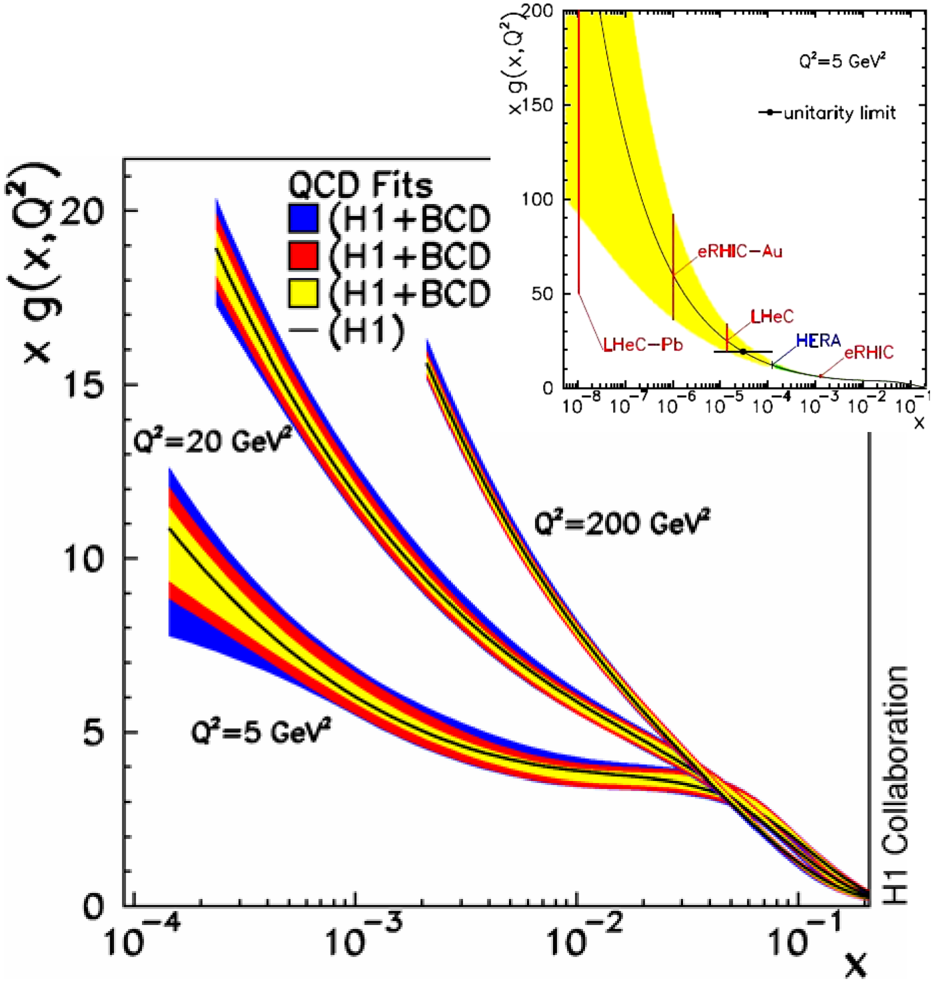
- 3 bound quarks:
  ~ 50% of p in 3 quarks +
  ~ 50% of p in N gluons
  quark momentum fraction in hadron:
  x ~ 1/6

- **HERA 1994:**
  $x > 0.1$: valence quarks
  $x \ll 0.1$: sea quarks + gluons :
  pure QCD !

Proton Structure



gluon density



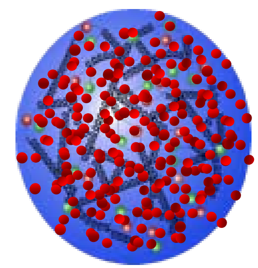
gluon self coupling

drives proton structure + $\alpha_S(Q^2)$

$\partial\, \sigma(x,Q^2) / \partial \ln Q^2 \sim \alpha_S(Q^2)\, xg(x,Q^2)$

test non-abelian QCD :

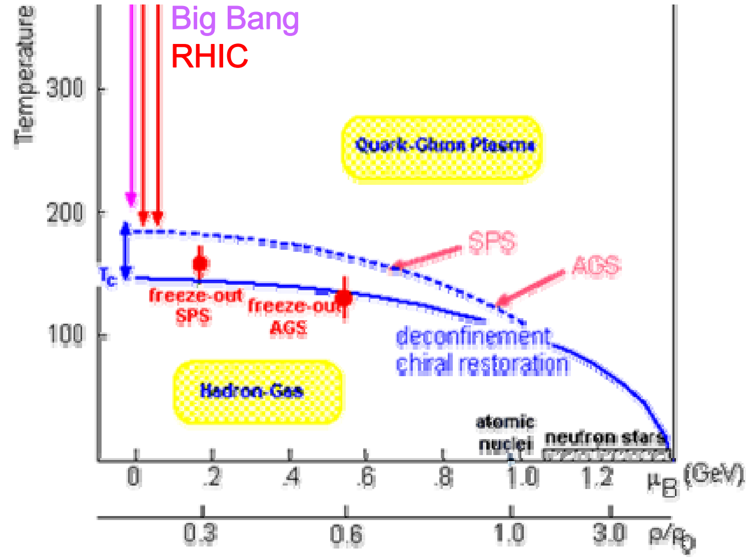
boil up QCD vacuum:

$Q^2 \uparrow$  $x \downarrow$

$\alpha_S \to 1$: end of perturbation theory?

- gluons = bosons !
  gluon saturation ? shadowing ?
- gluonium, glue-balls ?
- quark-gluon plasma ?

Quark-Gluon Plasma

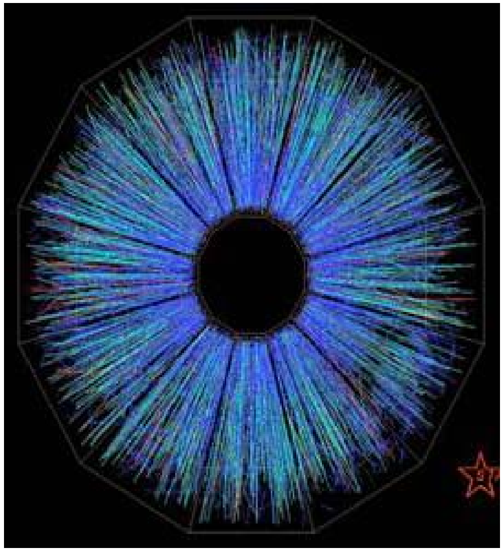


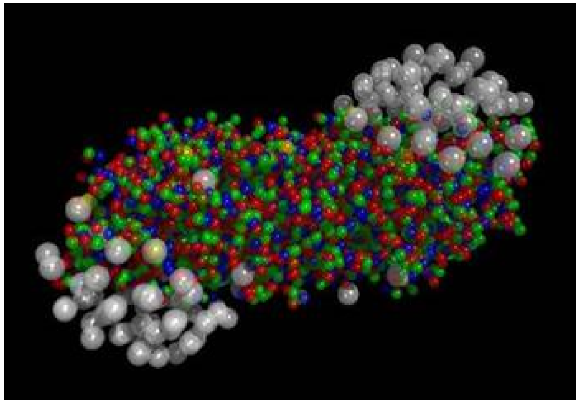
Big Bang: quarks are born free

after μs: QCD confinement:

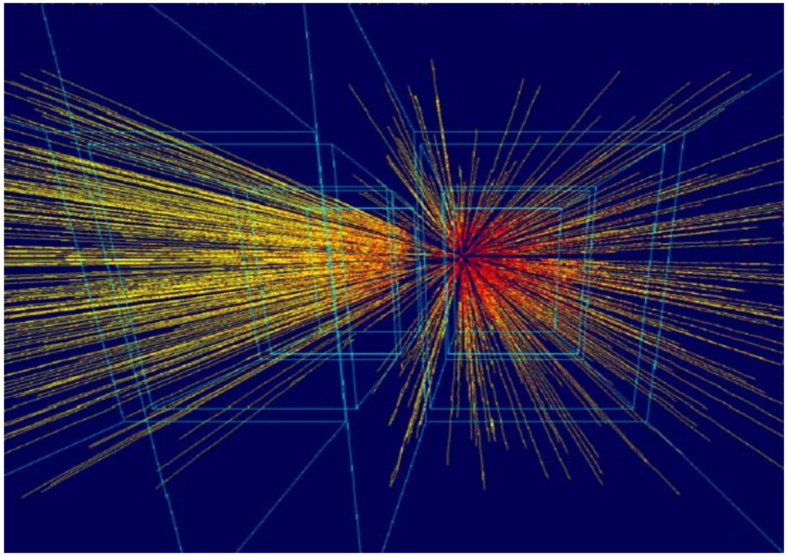
phase transition quagma-hadron gas

nucleons freeze out at T_C =173±15 MeV (lattice)





>1000 quarks: thermalisation



RHIC at BNL Brookhaven:

- Au-Au collisions at 100 GeV/nucleon

ALICE at CERN LHC >2008:

- Pb-Pb at 3 TeV/nucleon

Quarks + Hadrons

HADRONS consist of :

- point like partons
  - with spin 1/2
  - with charges +2/3, -1/3
- 3 valence quarks
  - \+ sea quarks carry ~ p/2
  - \+ gluons carry ~ p/2

QUARKS are

- colored
- confined in the hadrons
- asymptotically ($Q^2 \gg \Lambda^2$) free

QCD violates scaling:

- $\partial F_2(x,Q^2) / \partial \log Q^2$
- $F_2 \neq 2x F_1$

7. Unification

PARTICLES | FORCES

					Electro-Magnet.	Weak	Nuclear	Gravi-tation
		Charge			Electric	Weak	Color	Mass
		Symmetry			U(1)	SU(2)	SU(3)	
Matter Particles	Fermions J=1/2							
Quarks	Up	u	c	t	+2/3	I_W, Y_W	r g b	
	Down	d	s	b	-1/3			
Leptons	Electrons	e	μ	τ	-1	I_W, Y_W		
	Neutrinos	ν_e	ν_μ	ν_τ	0			
Force Particles	Bosons J=1							
Photon		γ						
Weak Bosons		W^+, Z^0, W^-						
Gluons		8 g_{ij}						
Graviton	(J=2)	G						

The Standard Model

- predictive power: c, b, t, ... ok
- Higgs, SUSY to be discovered !
- theory + experiment agree to 10^{-3}
  with 3^{rd} order radiative corr.: test of theory
- consistency of all parameters
- no new building blocks :
  - quarks
  - leptons
  - bosons: W´ , Z´
- no new structure level :
  - composite leptons: e*, ...
  - quarks: q*
  - bosons: W*, Z*
  - lepto-quarks
- no new couplings:
  lepton-quark universality
- no proton decay: baryon nr ok
- neutrino oscillations: lepton nr violated NEW PHYSICS !!!
- no magnetic monopole

The Standard Model

DESCRIBES THE PROPERTIES OF

ELEMENTARY PARTICLES

AND THEIR

- WEAK
- ELEKTRO-MAGNETIC
- STRONG

INTERACTIONS

PRECISELY + COMPLETELY.

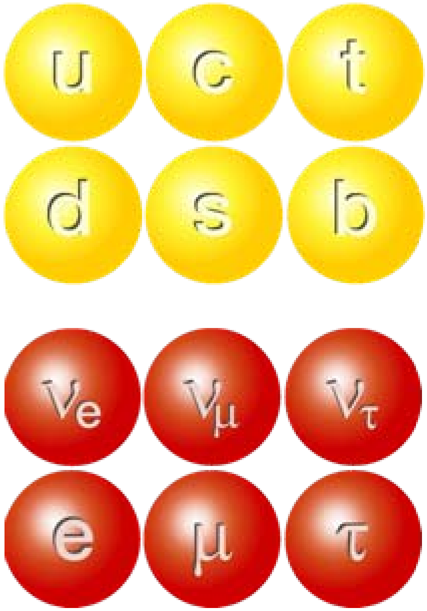
HOWEVER ,

MANY QUESTIONS REMAIN OPEN ...

PARTICLES:

- NR OF FAMILIES ?
- LEPTON-QUARK SYMMETRY ?
- SUBSTRUCTURE of Quarks + Leptons ?
- MASS: Higgs Mechanism ?
  Quark + Lepton Masses ?
- NEUTRINO: Dirac or Majorana ?
- MIXING ANGLES of Quarks + Neutrinos ?
- SUSY ?

Questions



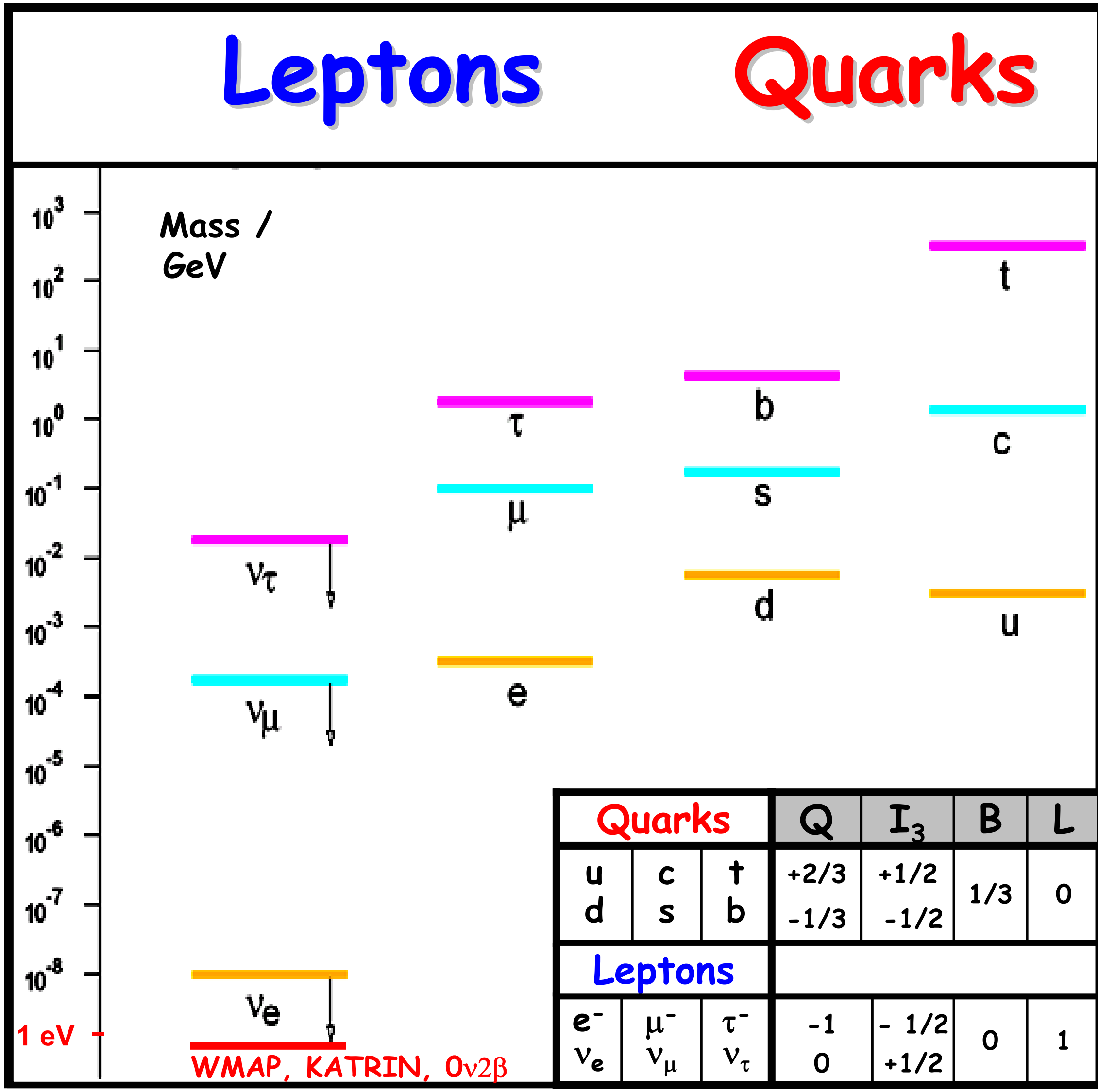
FORCES:

- STRUCTURE: $U(1) \otimes SU(2) \otimes SU(3)$?
- COUPLINGS: Values ?
- GRAND UNIFICATION: Scale + Scheme ?
- GRAVITATION AND SUPER-STRINGS ?
- EXTRA DIMENSIONS ?

SYMMETRIES:

- P-VIOLATION ?
- CP-VIOLATION ?
- BARYON-NR ? Baryon Asymmetry of Universe ?
- LEPTON-NR ? Neutrino Oscillations !
- MAGNETIC MONOPOLES ?
- SYMMETRY BREAKING: HOW ?
- SUPER-SYMMETRY ?

Fermion Masses

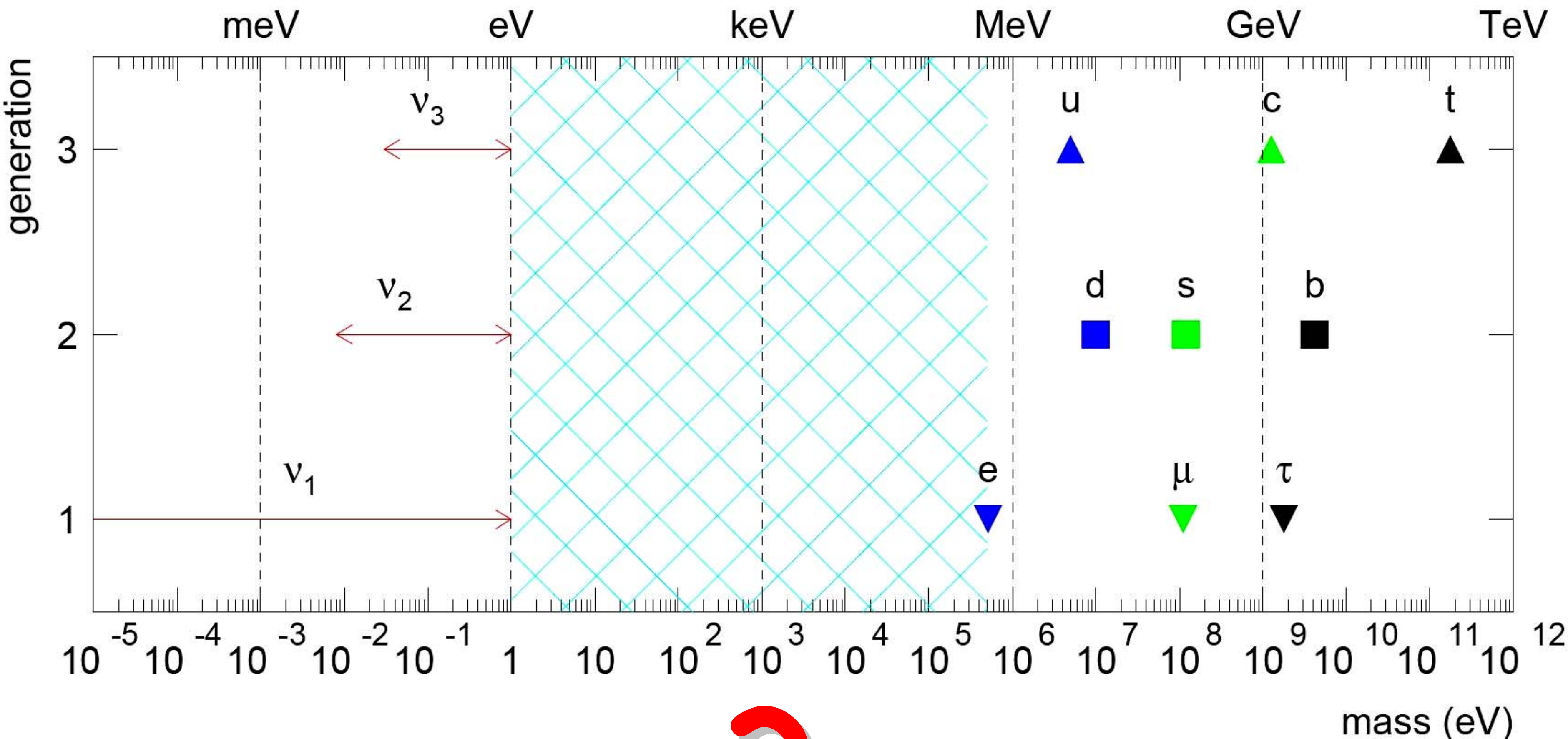


Quarks			Q	I_3	B	L
u d	c s	t b	+2/3 -1/3	+1/2 -1/2	1/3	0
Leptons						
e^- ν_e	μ^- ν_μ	τ^- ν_τ	-1 0	- 1/2 +1/2	0	1

explained by **Higgs** mechanism

?

Neutrino masses



?

What tells us Nature with this mass spectrum

Cosmology

Natural Units

M.Planck, 1899:

besides speed of light c and
Newton's constant G
find a third quantity b=h that allows

„Einheiten für Länge, Masse, Zeit und Temperatur aufzustellen, welche ... ihre Bedeutung für alle Zeiten und für alle, auch außerirdischen und außermenschlichen Culturen nothwendig behalten.“

one year before Planck's law !

Planck

$$\text{mass} = (\hbar c/G_N)^{1/2} = 1.2\cdot 10^{19}\ \text{GeV}/c^2$$

$$\text{time} = (\hbar G_N/c^5)^{1/2} = 5.4\cdot 10^{-44}\ \text{s}$$

$$\text{length} = (\hbar G_N/c^3)^{1/2} = 1.6\cdot 10^{-35}\ \text{m}$$

Die Mittel zur Festsetzung der vier Einheiten für Länge, Masse, Zeit und Temperatur werden gegeben durch die beiden erwähnten Constanten a und b, ferner durch die Grösse der Lichtfortpflanzungsgeschwindigkeit c im Vacuum und durch die der Gravitationsconstante f. Bezogen auf Centimeter, Gramm, Secunde und Celsiusgrad sind die Zahlenwerthe dieser vier Constanten die folgenden:

$$a = 0.4818\cdot 10^{-10}[\text{sec}\times\text{Celsiusgrad}]$$

$$b = 6.885\cdot 10^{-27}\left[\frac{\text{cm}^2\text{gr}}{\text{sec}}\right] \quad = \hbar$$

$$c = 3.00\cdot 10^{10}\left[\frac{\text{cm}}{\text{sec}}\right]$$

$$f = 6.685\cdot 10^{-8}\left[\frac{\text{cm}^3}{\text{gr. sec}^2}\right]$$ [1].

Wählt man nun die »natürlichen Einheiten« so, dass in dem neuen Maasssystem jede der vorstehenden vier Constanten den Werth 1 annimmt, so erhält man als Einheit der Länge die Grösse:

$$\sqrt{\frac{bf}{c^3}} = 4.13\cdot 10^{-33}\,\text{cm},$$

als Einheit der Masse:

$$\sqrt{\frac{bc}{f}} = 5.56\cdot 10^{-5}\,\text{gr},$$

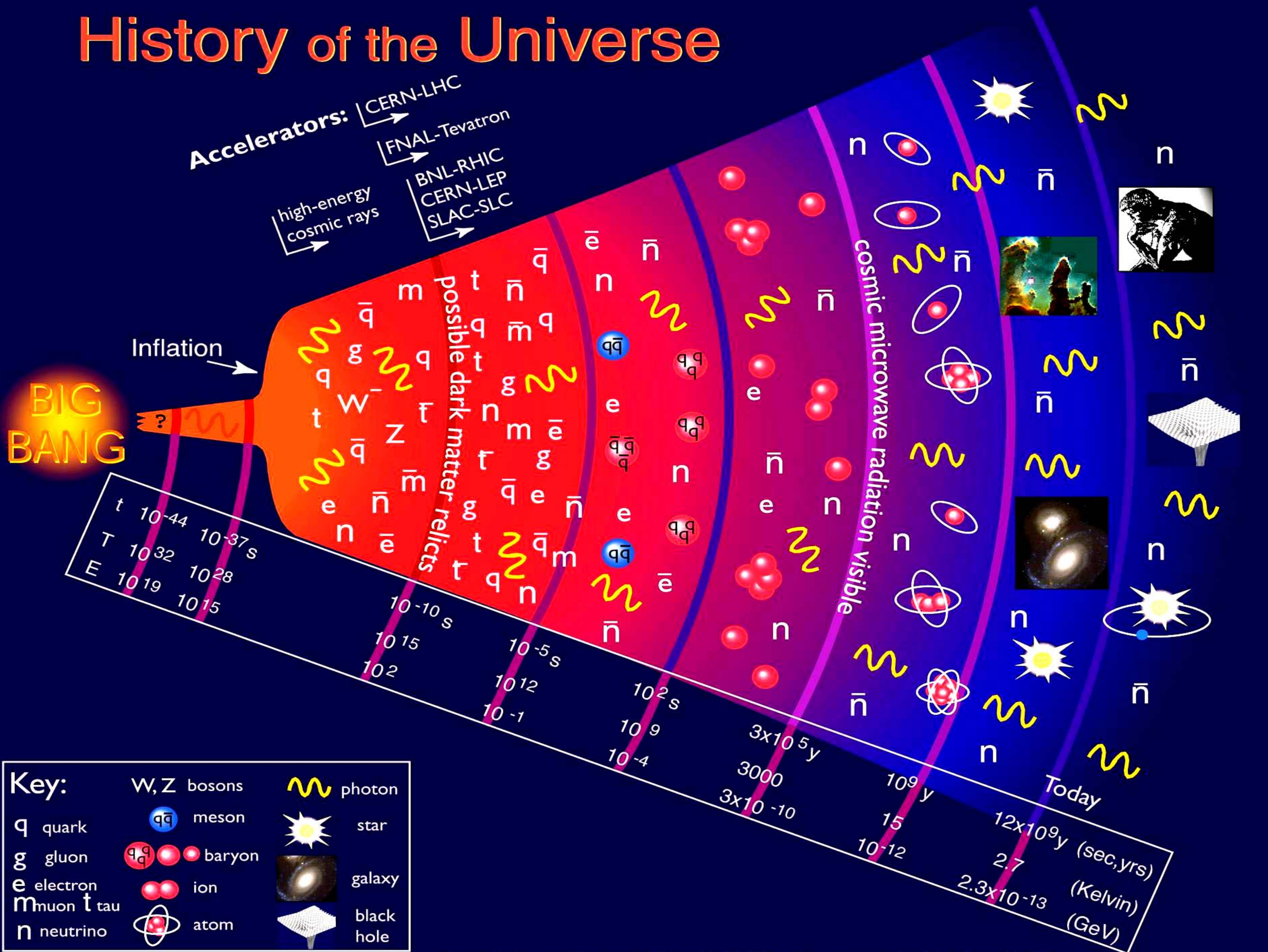
als Einheit der Zeit:

$$\sqrt{\frac{bf}{c^5}} = 1.38\cdot 10^{-43}\,\text{sec},$$

als Einheit der Temperatur:

$$a\sqrt{\frac{c^5}{bf}} = 3.50\cdot 10^{32}\,{}^\circ\text{Cels.}$$

Diese Grössen behalten ihre natürliche Bedeutung so lange bei, als die Gesetze der Gravitation, der Lichtfortpflanzung im Vacuum und die beiden Hauptsätze der Wärmetheorie in Gültigkeit bleiben, sie müssen also, von den verschiedensten Intelligenzen nach den verschiedensten Methoden gemessen, sich immer wieder als die nämlichen ergeben.


History of the Universe
Acceleratorss:
CERN-LHC
FNAL-Tevatron
BNL-RHIC
CERN-LEP
SLAC-SLC
high-energy cosmic rays
Inflation
BIG BANG
possible dark matter relicts
cosmic microwave radiation visible
t 10-44 10-37 s
T 1032 1028
E 1019 1015
10-10 s
1015
102
10-5 s
1012
10-1
102 s
109
10-4
3x105 y
3000
3x10-10
109 y
15
10-12
Today
12x109 y (sec,yrs)
2.7 (Kelvin)
2.3x10-13 (GeV)
Key:
q quark
g gluon
e electron
m muon t tau
n neutrino
W, Z bosons
meson
baryon
ion
atom
photon
star
galaxy
black hole

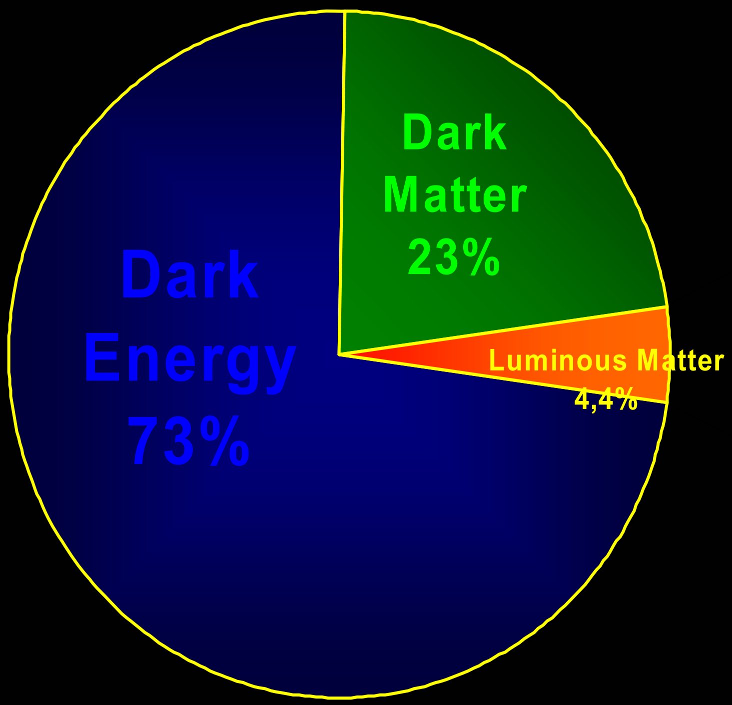
Big Bang Cosmology

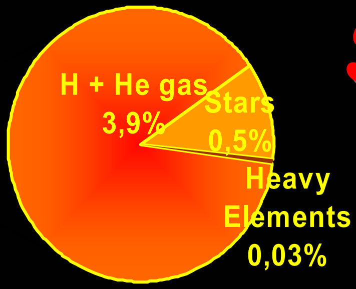
	time/s	E/GeV	T/K	R/m
Planck time	10^{-44}	10^{19}	10^{32}	$10^{-5/-35}$
Grand Unification	10^{-37}	10^{16}	10^{29}	10^{-2}
electroweak unification	10^{-10}	10^{2}	10^{15}	10^{12}
quark confinement	10^{-5}	10^{-1}	10^{12}	10^{15}
ν decouple, e^+e^- annihilate	1	10^{-3}	10^{10}	10^{17}
light nuclei form	10^{2}	10^{-4}	10^{9}	10^{18}
from radiation to matter dom.	10^{11} = 10 ky	10^{-8}	10^{4}	10^{22}
atoms form, γ decouple	10^{13} =379 ky	10^{-9}	3000	10^{23}
now	10^{17} = 13 Gy	10^{-13}	2.73	10^{26}

$\rho \sim T^4$ radiation, $\sim T^3$ matter dominated universe

inflation !

Microcosm - Macrocosm



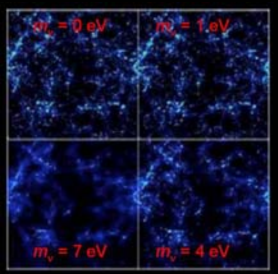


Motion in galaxies + clusters, gravit. lenses:

- WIMPs = Weakly Interacting Massive Particles =

SUSY ?

ν density



<5% dark matter !

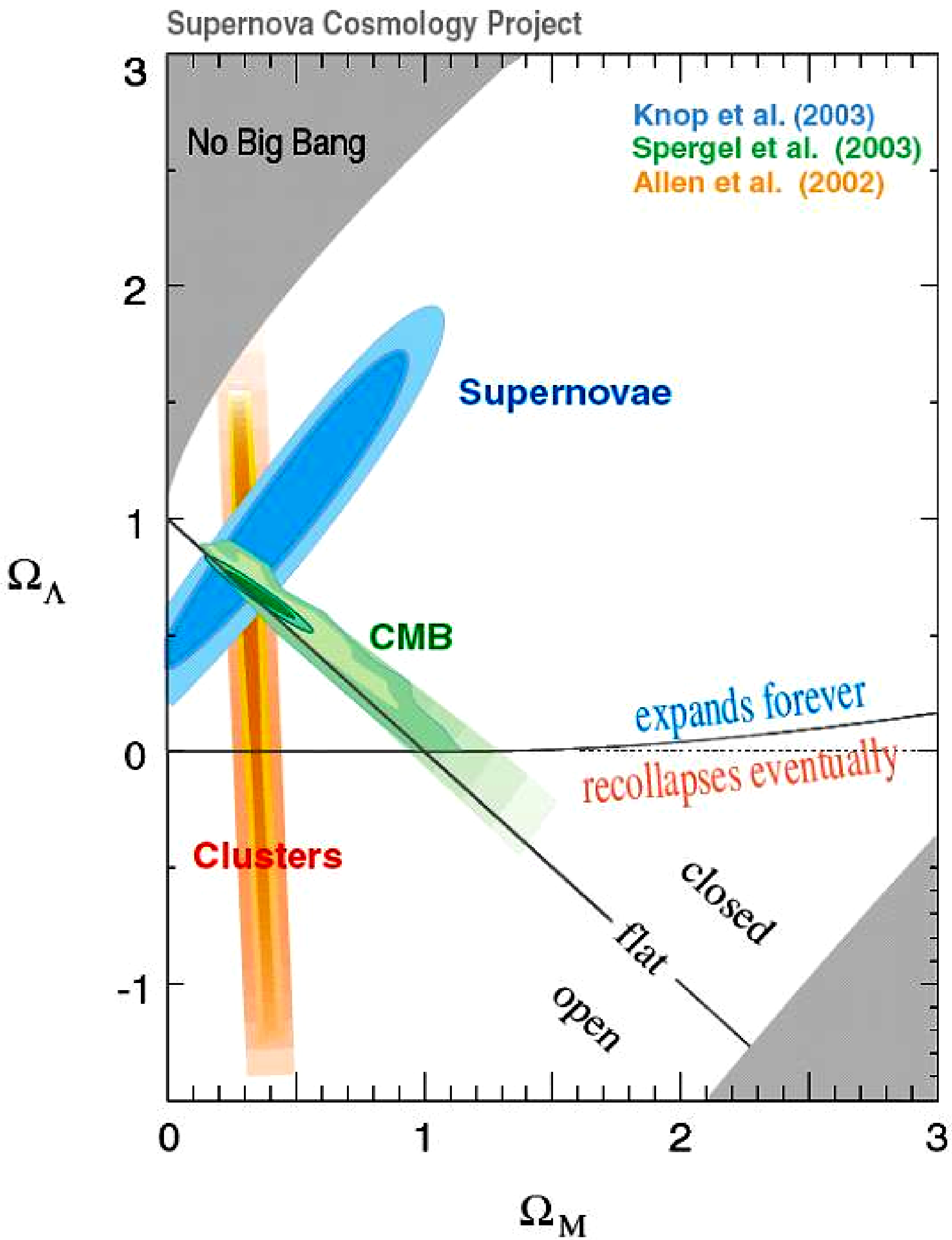
Supernovae Type Ia accelerated expansion:

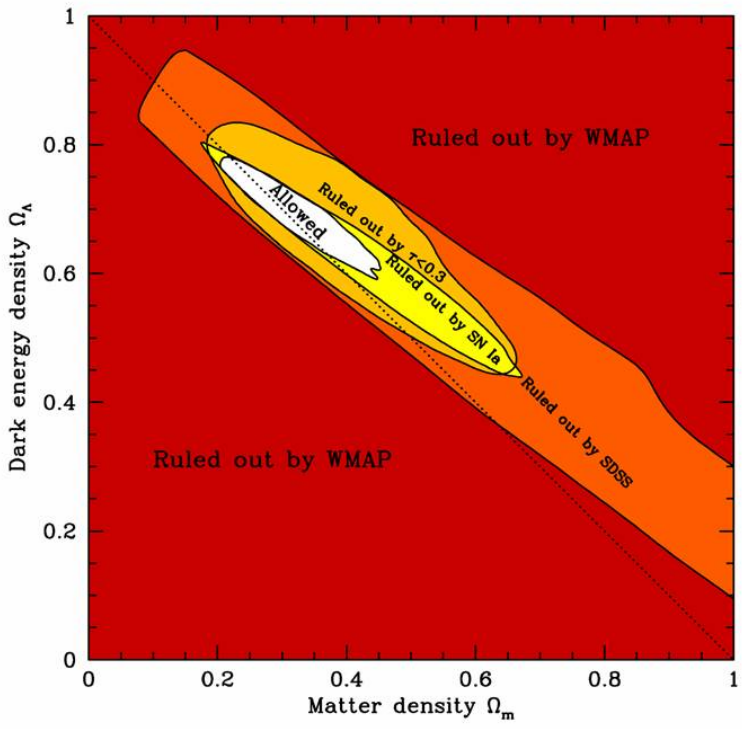
- Newton's law ?
- Einstein's cosmological constant Λ ?
- quintessence ?

HIGGS ?

Quantity	Symbol	Value	Comment
Total density	Ω_{tot}	1.02 ± 0.02	why = 1 ?
Dark energy density	Ω_Λ	0.73 ± 0.04	what is dark energy ?
Matter density	Ω_m	0.27 ± 0.04	
Baryon density	Ω_b	0.041 ± 0.002	
Dark matter fraction	$1-\Omega_b / \Omega_m$	0.83 ± 0.01	what is dark matter ?
Baryon-to-photon ratio	η	$(6.1 \pm 0.3) \cdot 10^{-10}$	why >0 + so small ?
CMB temperature / K	T_{CMB}	2.725 ± 0.002	
CMB photon density / cm^{-3}	n_γ	410.4 ± 0.9	
Age at decoupling / kyr	t_{dec}	379 ± 8	causal horizon 2°
Age of the Universe / Gyr	t_0	13.7 ± 0.02	very precise !

Dark Energy Dark Matter

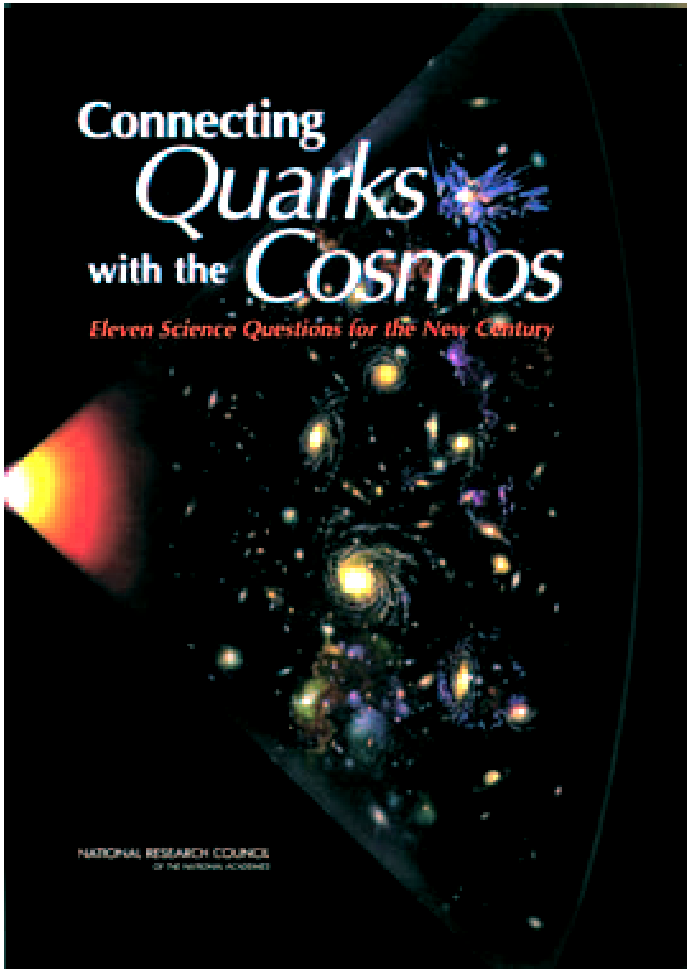




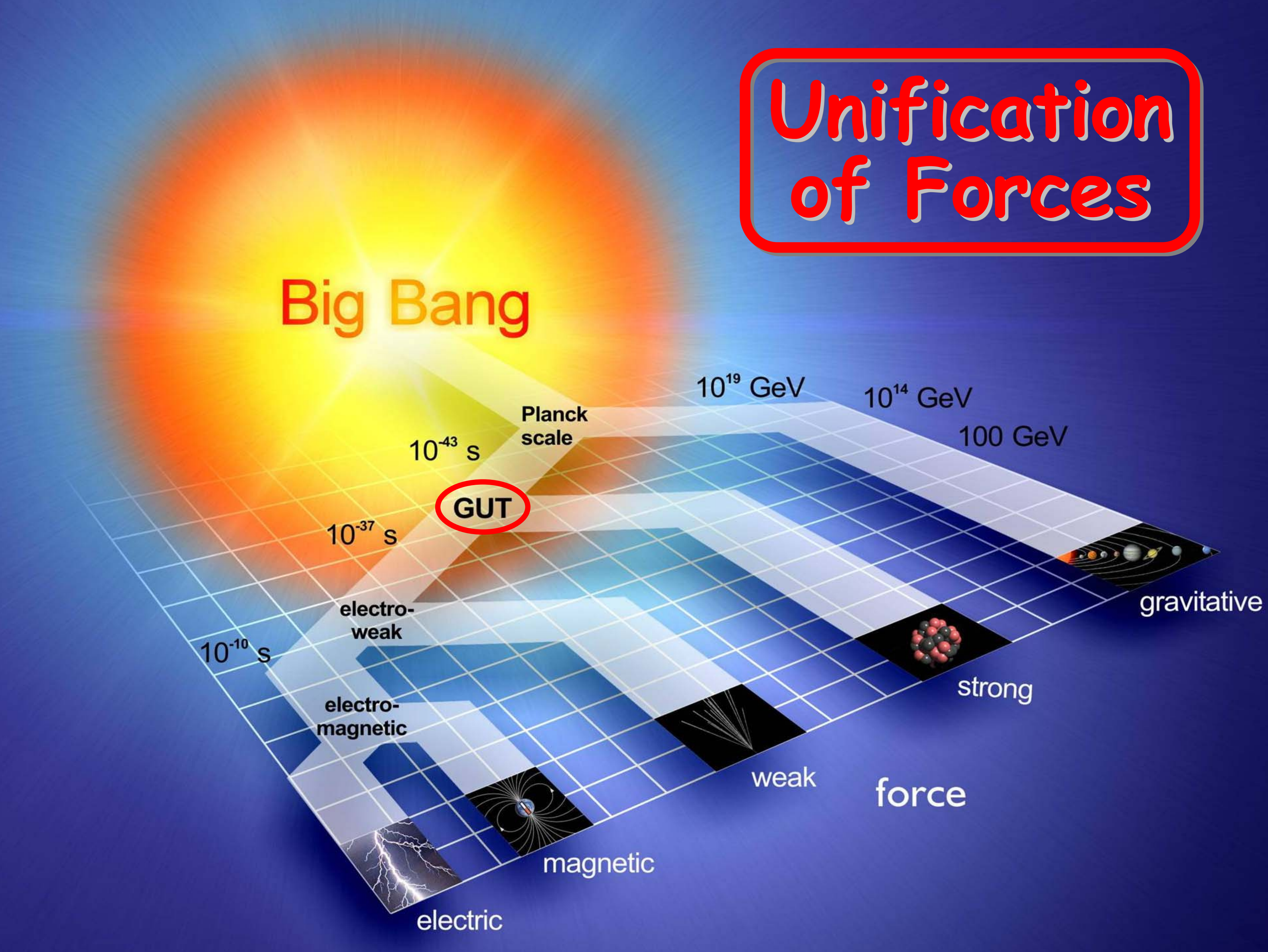
Connecting Quarks with the Cosmos:

Eleven Science Questions for the New Century

The US National Research Council, 2001.



1. What is Dark Matter?
2. What is the Nature of Dark Energy?
3. How Did the Universe Begin?
4. Did Einstein Have the Last Word on Gravity?
5. What are the Masses of the Neutrinos and How Have They Shaped the Evolution of the Universe?
6. How do Cosmic Accelerators Work and What are They Accelerating?
7. Are Protons Unstable?
8. What Are the New States of Matter at Exceedingly High Density and Temperature?
9. Are There Additional Space-Time Dimensions?
10. How Were the Elements from Iron to Uranium Made?
11. Is a New Theory of Light and Matter Needed at the Highest Energies?


Unification of Forces
Big Bang
10^{19} GeV
10^{14} GeV
100 GeV
Planck scale
10^{-43} s
GUT
10^{-37} s
electro-weak
10^{-10} s
electro-magnetic
gravitative
strong
weak
force
magnetic
electric

Grand Unification

elm.	weak	strong			
$U(1) \otimes$	$SU(2) \otimes$	$SU(3)$	$\subset$	$SU(5)$	SYMMETRIES

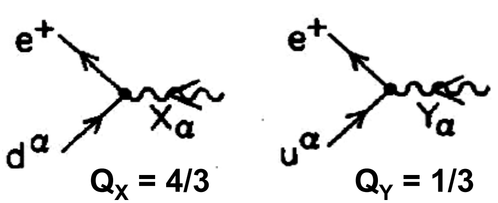
$$\{ e^- \ \nu_e \ , \ \bar{d}_r \ \bar{d}_g \ \bar{d}_b \}_L \qquad \{\bar{5}\}$$

MULTIPLETS

γ $W^{\pm 0}$ g_{ij} BOSONS

X,Y

Lepton



Lepto-
Quark

Quark

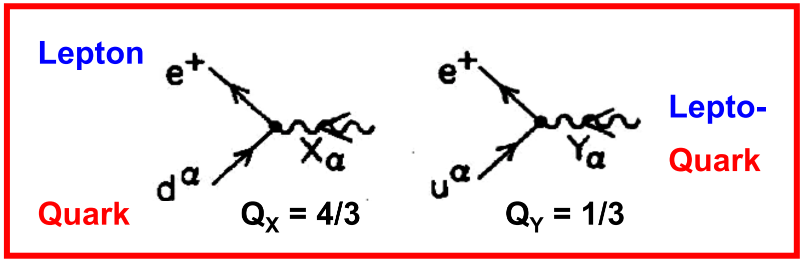
HERA: e p -> LQ m>300 GeV

proton decay: p -> e π $\tau > 5 \cdot 10^{33}$ a

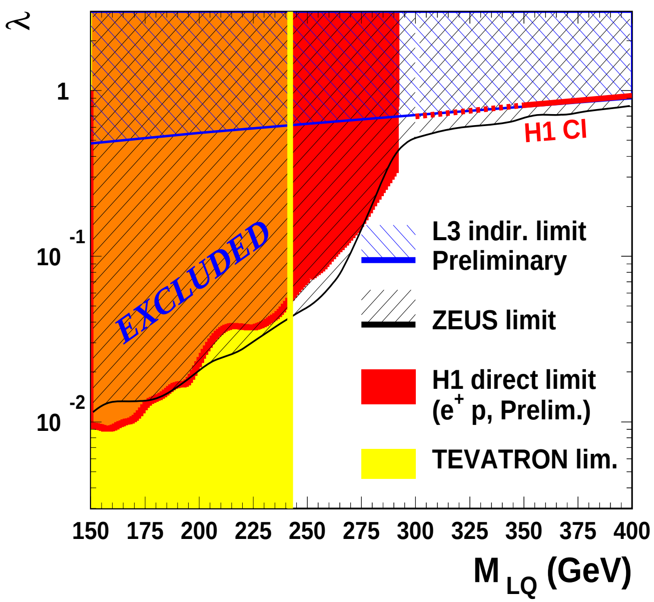
Grand Unification

SU(N)	N^2-1	gauge bosons
SU(5)	25-1 =	24
SU(3)	9-1 =	-8 gluons
SU(2)	4-1 =	-3 Z,W
U(1)	1 =	-1 photon
	6 (X+Y) =	12 X,Y bosons

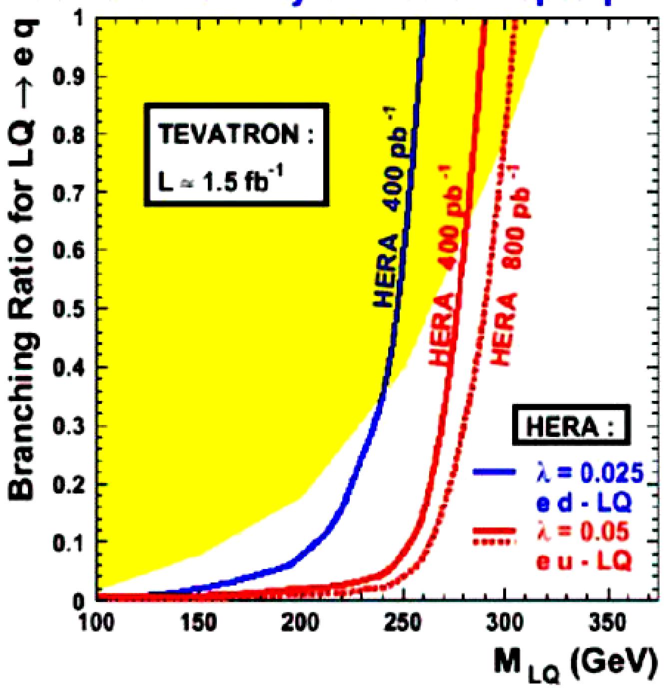
Leptoquarks @ HERA



SCALAR LEPTOQUARKS WITH F=0 ($\tilde{S}_{1/2,L}$)



Future Sensitivity on Scalar Leptoquarks



LQ (RPV q)	H1 M_{LQ}	LEP GeV/g
S_0L	710	2150
S_0R	640	1700
$\check{S}_0R$	330	660
$S_{1/2}L$	850	590
$S_{1/2}R$	370	770
$\check{S}_{1/2}L$	430	-
S_1L	490	1190
V_0L	730	3030
V_0R	580	540
$V\sim_0R$	990	1610
$V_{1/2}L$	420	1000
$V_{1/2}R$	950	750
$V\sim_{1/2}L$	1020	580
V_1L	1360	2170

HERA competitive with LEP and Tevatron for small branching ratios

Charge quantization + $\sin^2 \theta_W$

- U(1)xSU(2):

Q not conserved, def. $Q = I_3^w + Y^W/2$

$Tr_2 (I_3^w) = 0$

- SU(5):

$Tr_5 (Q) = N_C Q_d - Q_e = 0 \quad =>$

$Q_d = e/N_C \quad$ or $\quad Q_p = -Q_e$

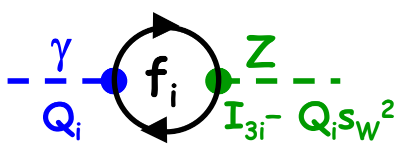
'explain' fractional quark charges from nr. of colors !

	I_3	Q
ν_e	+1/2	0
e^-	-1/2	-1
$\bar{d}_r$	0	1/3
$\bar{d}_g$	0	1/3
$\bar{d}_b$	0	1/3

$\bar{d}_L$ ... $\{1\}_{SU(2)}$

- prediction of electroweak mixing angle:

γ,Z orthogonal => no coupling, but:



$$\Sigma_i Q_i (I_{3i} - Q_i s_W^2) = 0$$

$s_W^2 = \Sigma_i Q_i I_{3i} / \Sigma_i Q_i^2$ = "SU(2)/U(1)" = 3/8 @ true unification point m_{GUT}

Grand Unification

- quark-lepton symmetry:

  quarks + leptons in one multiplet

$$\{e^- \ \nu_e \ , \ \bar{d}_r \ \bar{d}_g \ \bar{d}_b\}_L$$

- quantization of electric charge:

  $N_C \, Q_q - Q_e = 0 \;=\; 3 \times 1/3 - 1$

  or $\quad Q_p = Q_e$

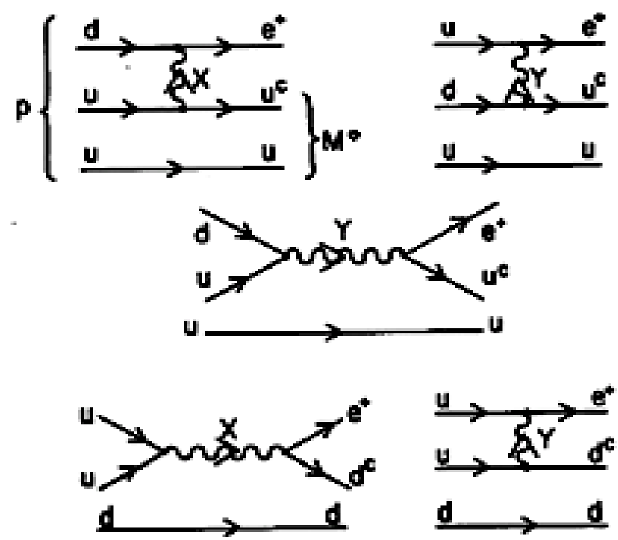
- prediction for electro-weak mixing angle:
  - $\sin^2\theta_W\,(M_X) \;=\; g'^2 / (g^2+g'^2) \;=\; 3/5 \,/\, (1+3/5) \;=\; 3/8$
  - $\sin^2\theta_W\,(M_Z) \;=\; 0.20$ GUT $\quad (M_X \to M_Z)$
  - $\sin^2\theta_W\,(M_Z) \;=\; 0.22$ expt.

- lepton number violation:

  neutrino masses + oscillations

- baryon number violation: proton decay: $\tau_p \sim M_X^4 / g^4 \, m_p^5$

  baryon asymmetry of universe: $N_p / N_\gamma = 10^{-10}$



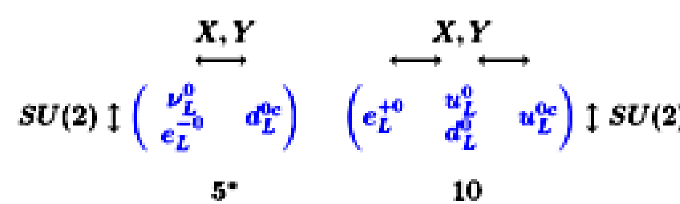
- SU(5) GUT: $\quad M_X \sim 10^{15}$ GeV $\quad \tau \sim 10^{29\pm2}$ a

  Super-K 1998: $\quad \tau\,(p \to e^+\pi^0) > 5 \cdot 10^{33}$ a $\quad \tau\,(p \to K^+\nu) > 2 \cdot 10^{33}$ a

- SUSY GUT: $\quad M_X \sim 10^{16}$ GeV :

  $\tau\,(p \to e^+\pi^0) \sim 10^{35\pm1}$ a $\quad \tau\,(p \to K^+\nu) \sim 10^{32\pm3}$ a

  Hyper-K 201x+10: $\quad \tau\,(p \to e^+\pi^0) > 10^{35}$ a $\quad \tau\,(p \to K^+\nu) > 3 \cdot 10^{34}$ a

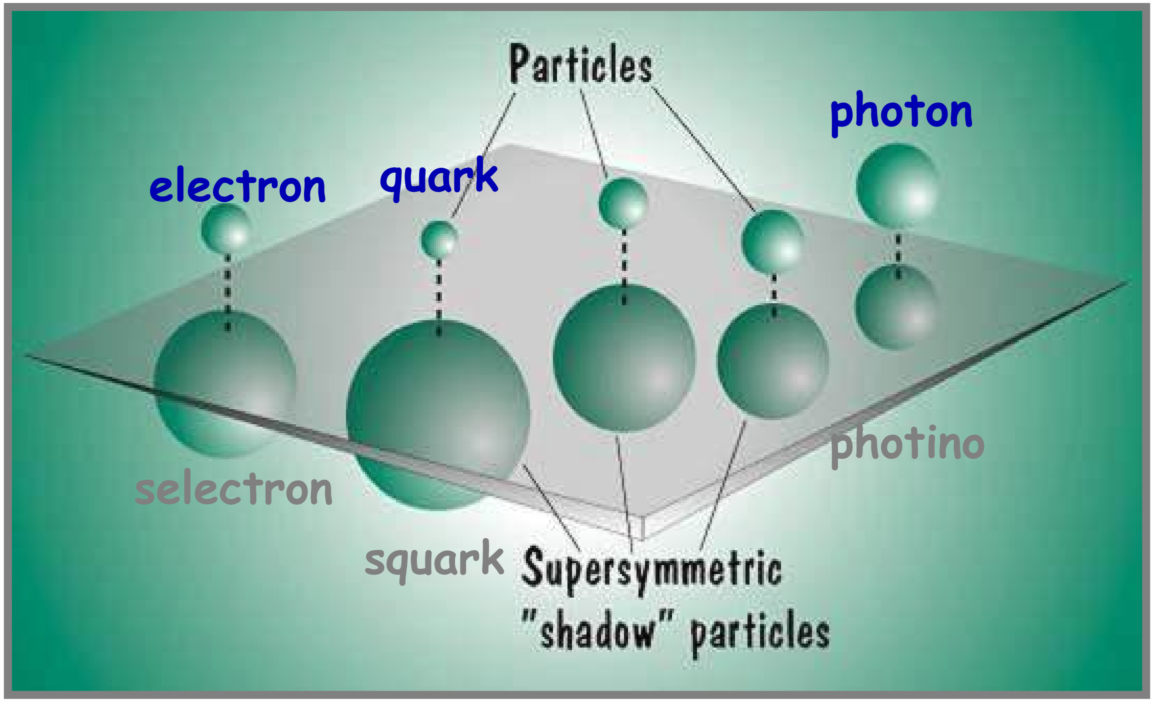


- GUT magnetic monopoles

Super-Symmetry

Fermion

Boson



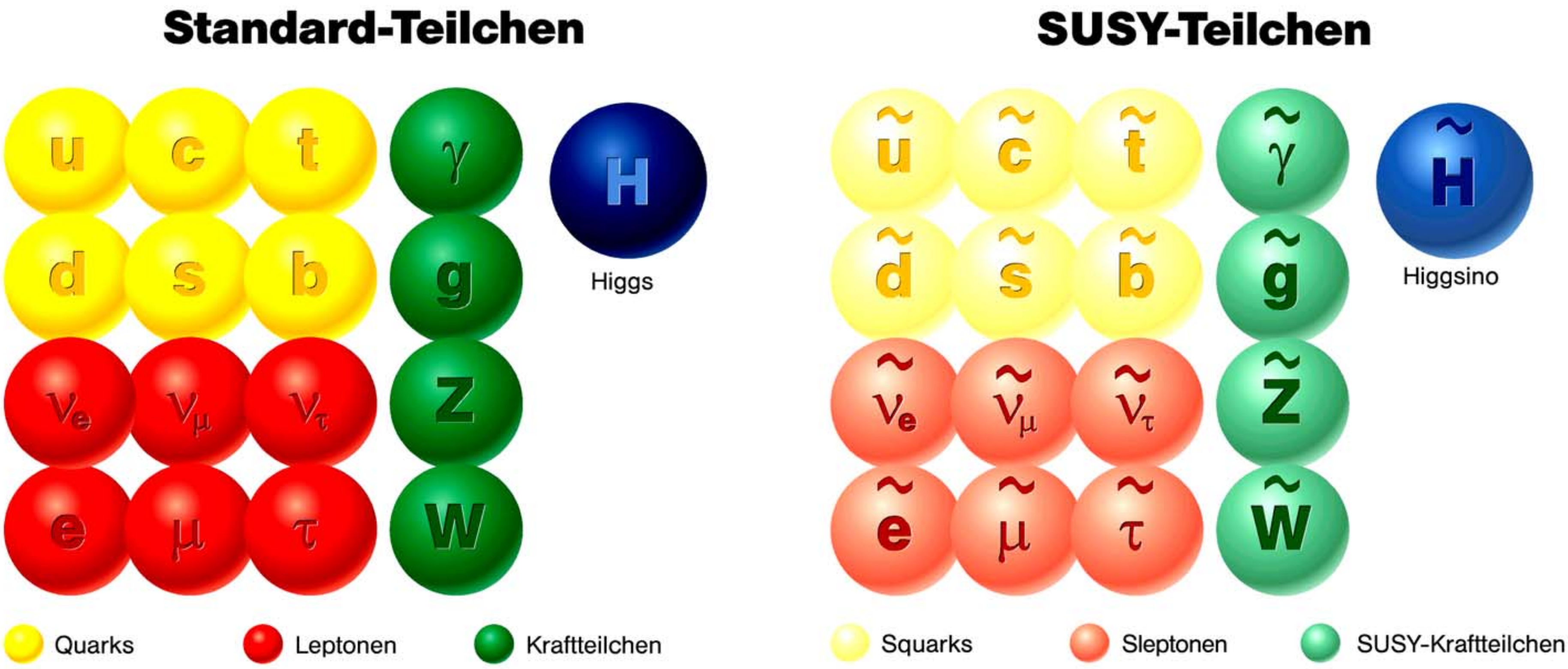
Boson

Fermion

Super - Symmetry

mirror world
unifies
bosons with fermions
force with matter

Super-Symmetry



Super-Symmetry

Neveu, Schwarz, Ramond 1971
Wess, Zumino 1974
Fayet, Farrar 1976

SUSY transformation:

turn boson to fermion state + vice versa:

$Q\,|\text{Boson}\rangle = |\text{Fermion}\rangle$ $\qquad$ $Q\,|\text{Fermion}\rangle = |\text{Boson}\rangle$

Q ... anticommuting Weyl spinor (spin ½) operator

P^μ ... 4-momentum generator of space-time translations
vector (spin 1) under Lorentz trafo.

$\{Q,Q^\dagger\} = 2\,\sigma^\mu P_\mu$ $\qquad$ σ^μ ... Pauli matrices

$\{Q,Q\} = 0$

$\{P^\mu,Q\} = 0$

SUSY: connects space-time with statistics properties

local SUSY needs metric tensor: $g_{\mu\nu}(x)\,P^\mu$

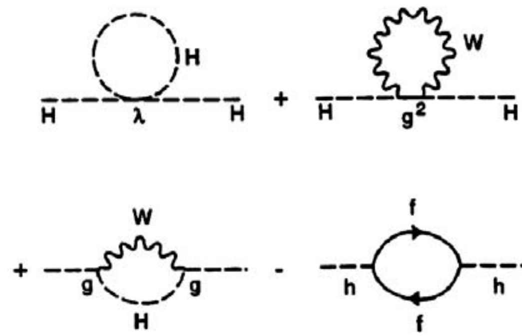
J=2 graviton , J=3/2 gravitino: gauge fields of local SUSY

general relativity from local SUSY =>

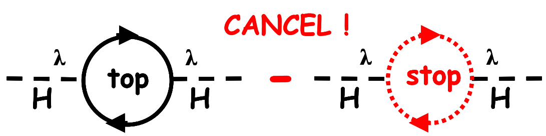
SUperGRAvitation => Superstrings !

Super-Symmetry

- Higgs mass terms divergent:

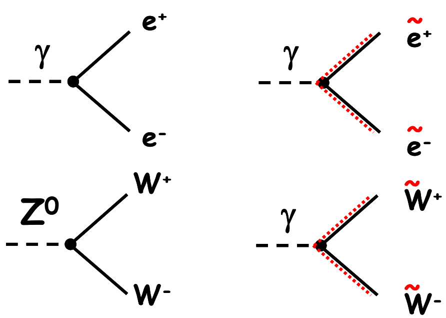


- cancel divergences by
  a mirror world:



n (bosons) = n (fermions)

- SUSY adds new decay channels:



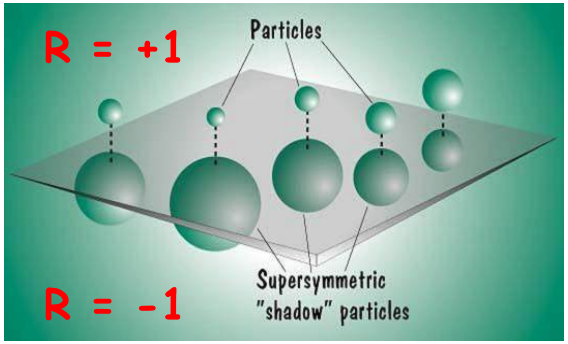
changes coeff. b_N of renorm. group equ.
changes evolution of coupling constants:
evolution of weak coupling changes sign !
changes Grand Unification scale !

particle		spin	sparticle		spin
bosons		int.	fermions		I/2
photon	γ	1	photino	$\tilde{\gamma}$	1/2
gluon	g	1	gluino	$\tilde{g}$	1/2
W,Z boson	W,Z	1	wino, zino	$\tilde{W},\tilde{Z}$	1/2
graviton	G	2	gravitino	$\tilde{G}$	3/2
higgs	H	0	higgsino	$\tilde{H}$	1/2
			neutralino	$\tilde{\gamma}$, Z, H	1/2
fermions		1/2	bosons		int.
lepton	l	1/2	slepton	$\tilde{l}$	0
quark	q	1/2	squark	$\tilde{q}$	0

R parity

conserved multiplicative quantum number:

$$R = (-1)^{3B+L+2S}$$

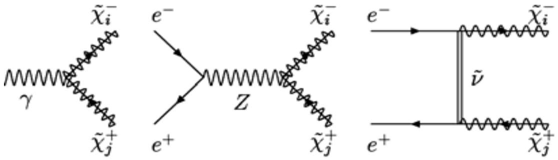


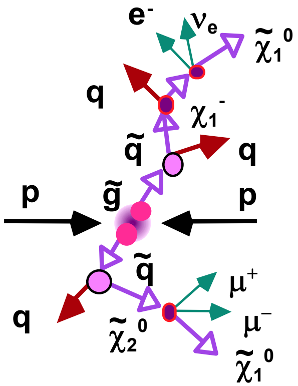
B,L: baryon+lepton nr, S: spin

particles: R=+1 sparticles: R=-1

- sparticles produced in pairs: $pp \rightarrow \tilde{q}\tilde{q}\,X$, $e^+e^- \rightarrow \tilde{\mu}^+\,\tilde{\mu}^-$
- heavier sparticles decay to lighter ones: $\tilde{q} \rightarrow q\,\tilde{g}$, $\tilde{\mu} \rightarrow \mu\,\tilde{\gamma}$
- the lightest particle is stable – it has to conserve R parity !

  not seen in universe => no electric + strong charge
- neutralino $\tilde{\chi} = (\tilde{\gamma}, \tilde{Z}, \tilde{H}_{1,2})$!?





Experiment:

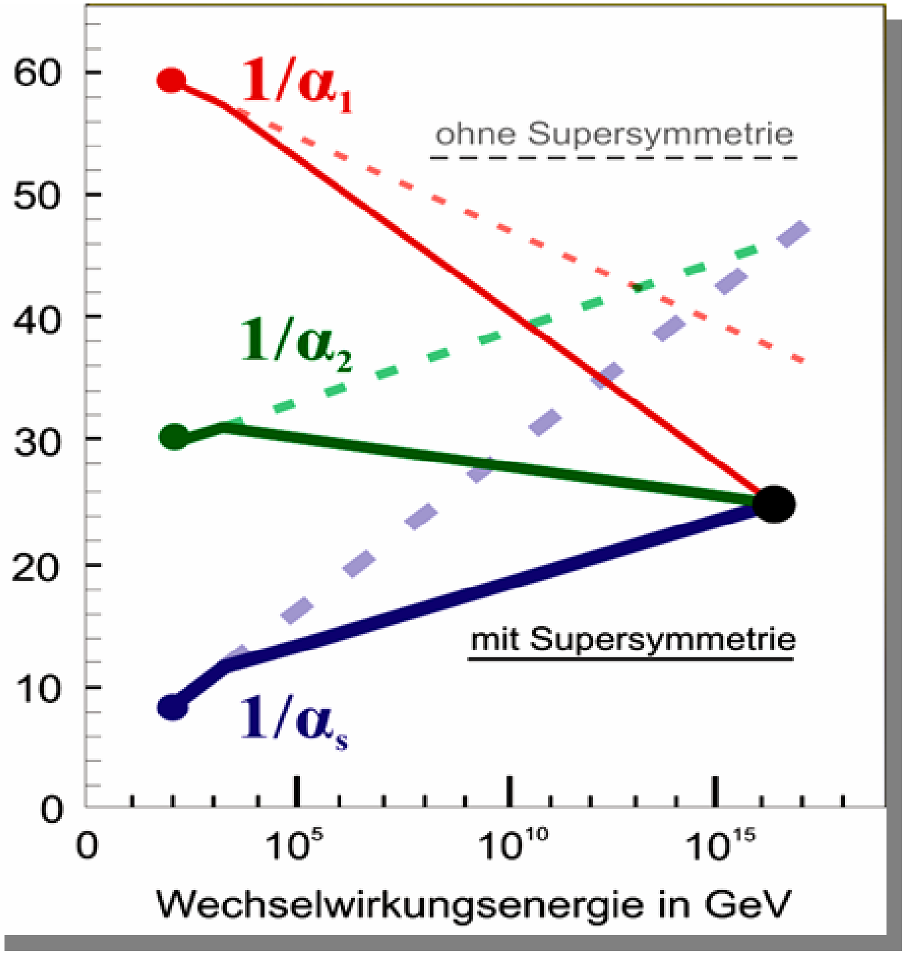
- 2 neutralinos end all SUSY decay chains
- interact only weakly + escape => large missing E_T = SUSY signature !

SUSY + Grand Unification

elm.

weak

strong

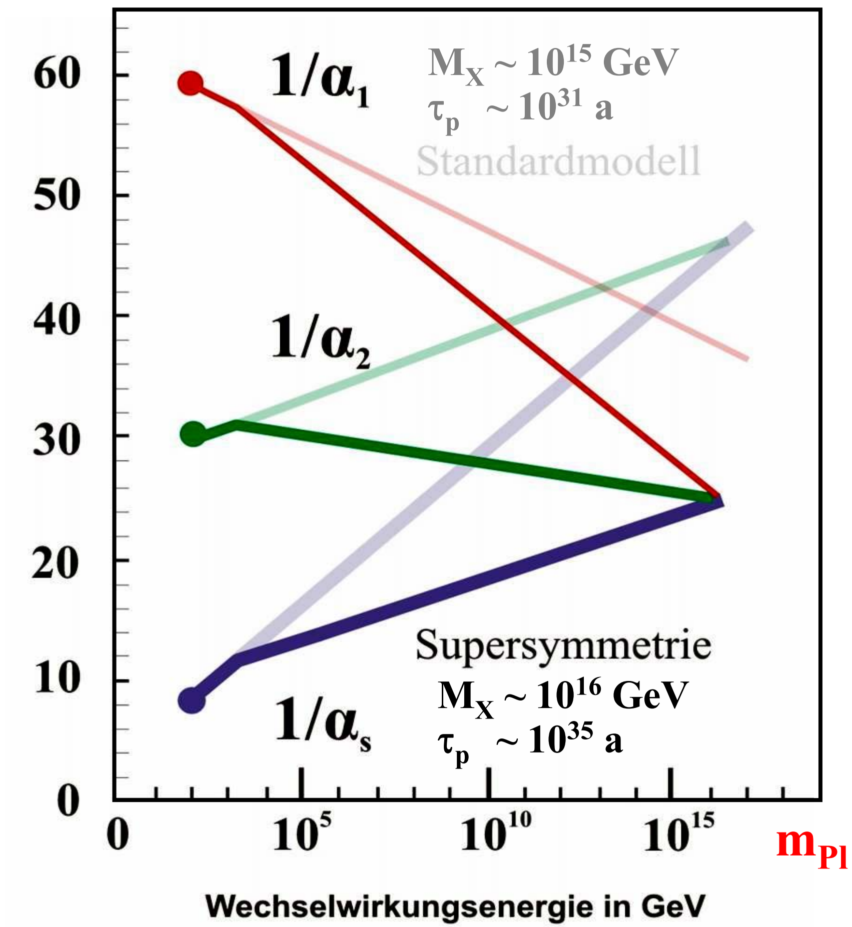


U(1) $\otimes$ SU(2) $\otimes$ SU(3) $\subset$ SU(5), SO(10) ...

unified at the Planck scale ?

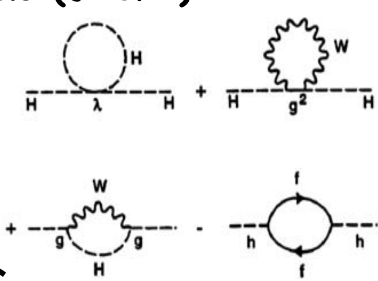
Super-Symmetry

unifies forces + couplings

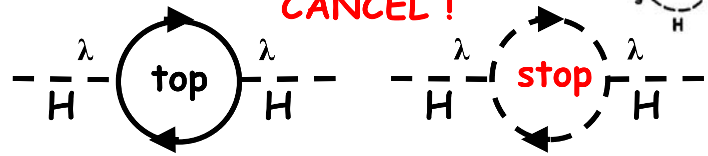


- changes energy dependence of couplings:
- one unification point at $M_X = 2 \cdot 10^{16}$ GeV !
- proton lifetime > exptl. limit
- Neutralino ($\tilde{\gamma}, \tilde{Z}, \tilde{H}_{1,2}$): lightest SUSY particle
  Dark Matter in the Universe !

- connects continuous space-time symmetry
  with spin-statistics + symmetries
  $U(1) \otimes SU(2) \otimes SU(3) \supset SU(5), SO(10), E(6), \ldots$
- gauge fields of local SUSY:
  Graviton (J=2) + Gravitino (J=3/2)
  Super-Gravity !
- Higgs radiative corrections
  stable:

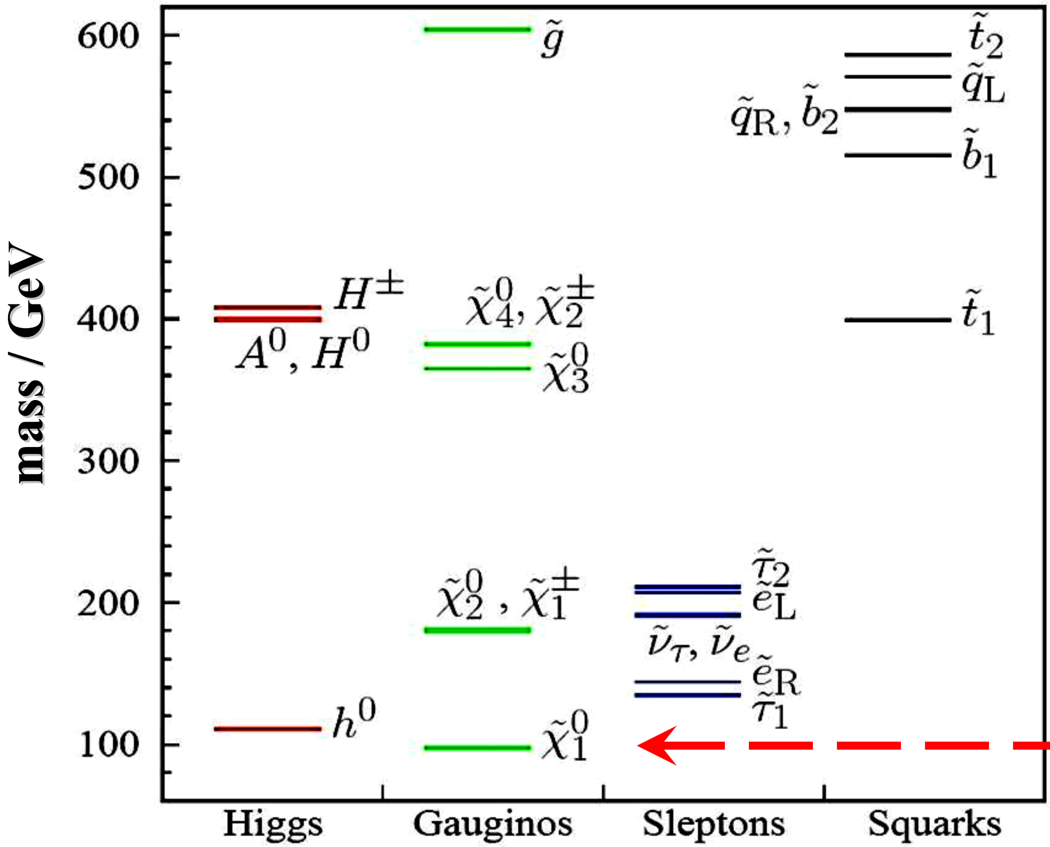


CANCEL !



SUSY mass spectrum

minimum Super-Gravity



SUSY WIMP:

dark matter candidate !

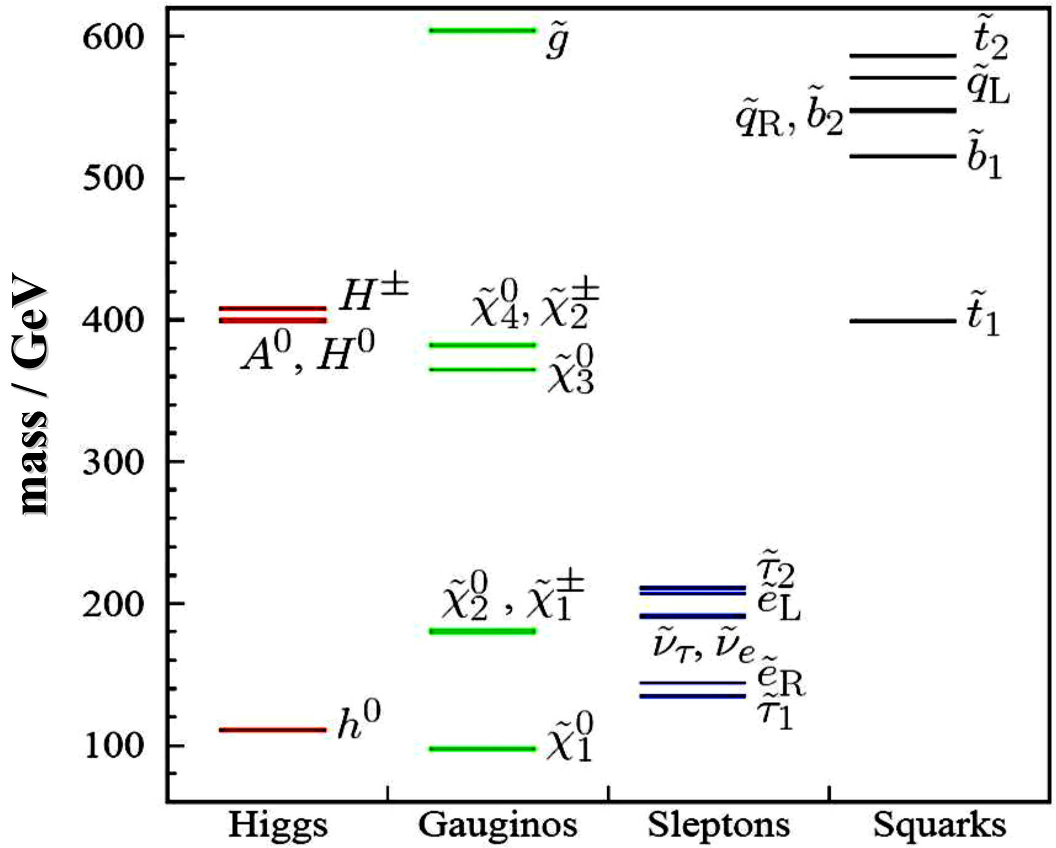
lightest neutral SUSY particles mix -

Neutralino

=

Higgsino+Photino+Zino

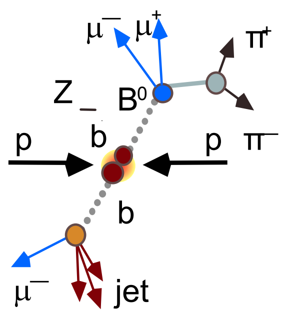
SUSY mass limits

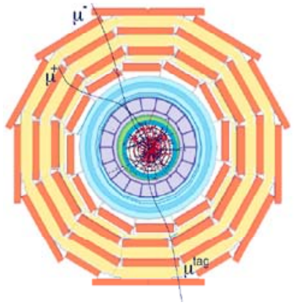


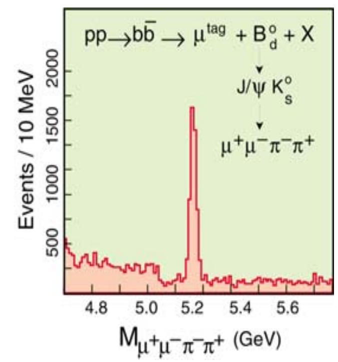
sparticle	mass limit
slepton	≳ 80 GeV
sneutrino	≳ 40 GeV
neutralino	≳ 30 GeV
gaugino	≳ 50 GeV
higgsino	≳ 100 GeV
gluino	≳ 200 GeV
squarks	≳ 300 GeV

lowest limit + prediction for neutralino = WIMP/dark matter candidate

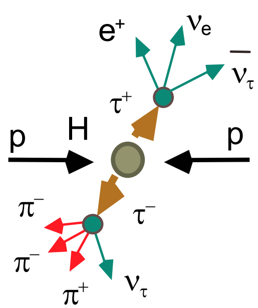
LHC physics: Supersymmetry

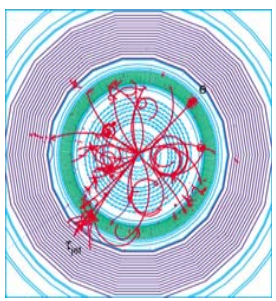




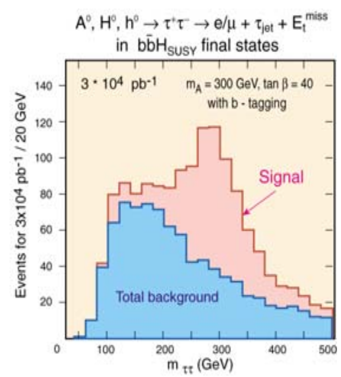


The decay B^0 or $B^0 \rightarrow J/\psi\ K^0_S$ presents a very clean experimental signature. The particle content (B^0 or B^0 meson) that gave the decay can be determined from a muon from the second b-flavored hadron in the event. An asymmetry in the two rates (B^0 vs B^0) would signal CP violation. This would be the first time that CP violation is observed outside the neutral kaon system

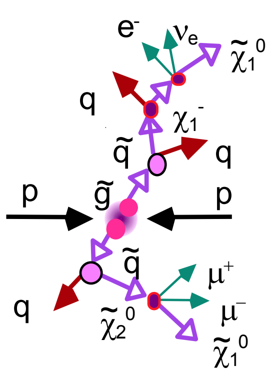


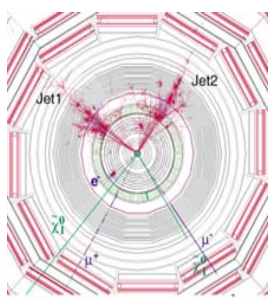


$H \rightarrow \tau\ \ \rightarrow e + \tau_{jet}$("3-prong")

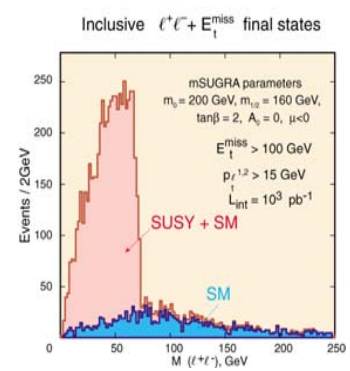


SUSY Higgs bosons. In the MSSM there are 5 Higgs bosons: h^0, H^0, A^0 and $H^\pm$ decaying through a variety of decay modes to γ, $e^\pm$, $\mu^\pm$, $\tau^\pm$ and jets in final states. Above: an example of a SUSY Higgs decay to $\tau\ \tau$ in CMS. On the right is the reconstructed $\tau\tau$ mass spectrum



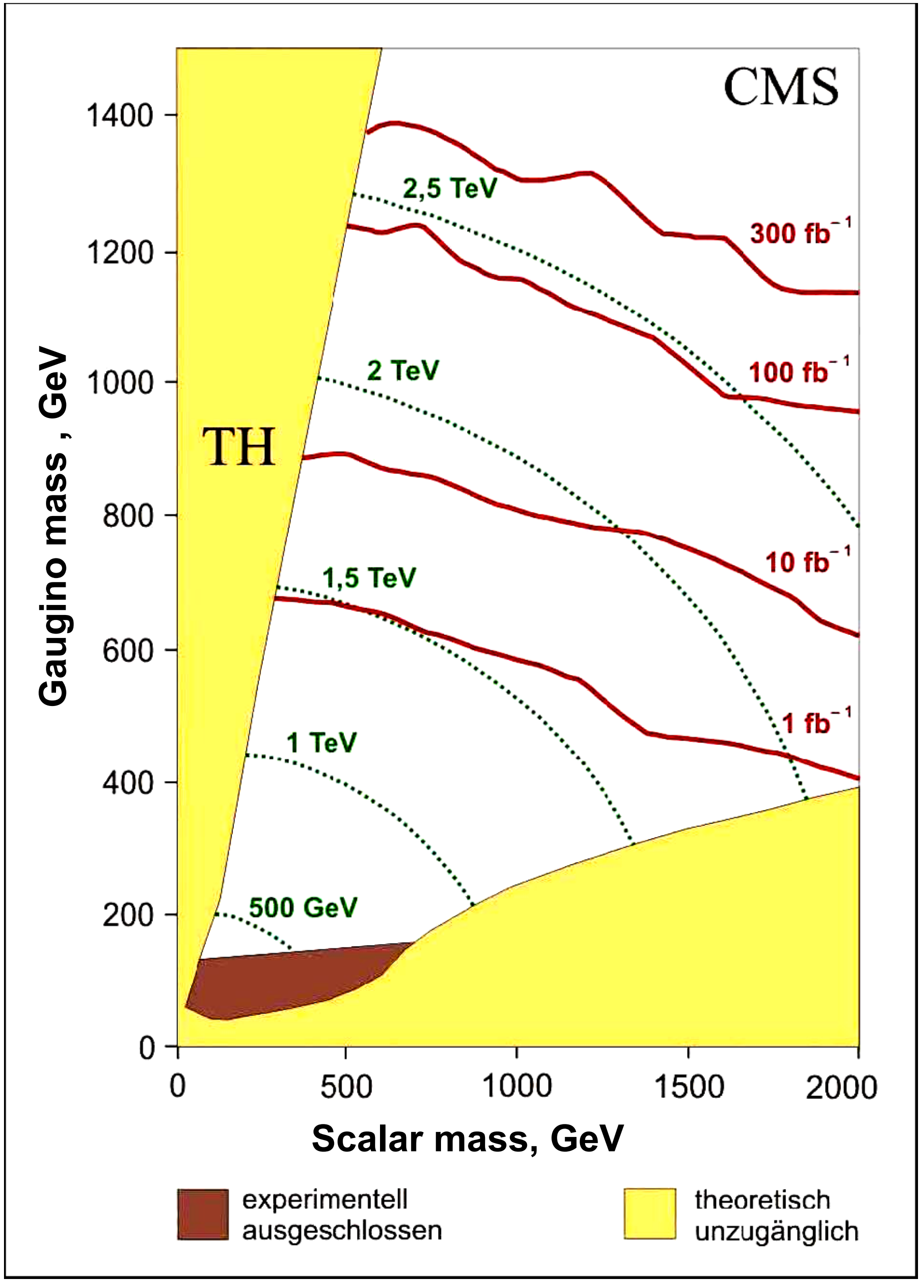


SUSY event with
3 leptons + 2 Jets signature

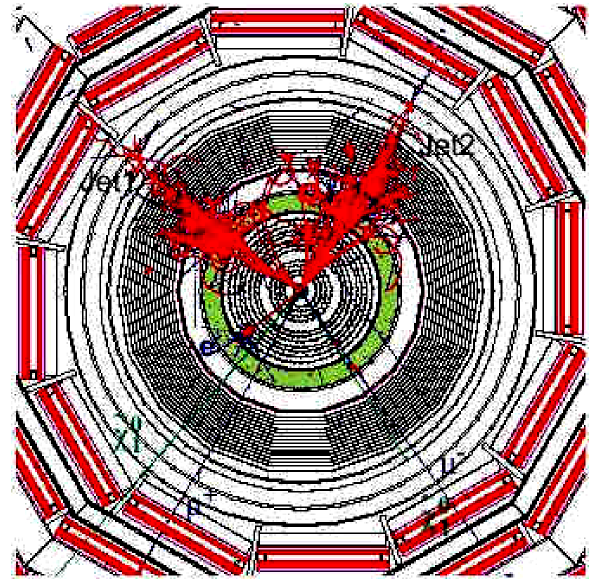


Sparticles. Production of sparticles may reveal itself though some spectacular kinematical spectra, with a pronounced "edge" in the $\,,^+,\ ^-$ mass spectrum reflecting $\chi_2^0 \rightarrow\ ,^+,\ ^-\chi_1^o$ production and decay. An example of such a spectrum in inclusive $,^+,\ ^- + E_t^{miss}$ and of a 3 , $^\pm$ production event are shown below

LHC: minimum Super-Gravity



SUSY @ LHC



SUSY event with 3 leptons + 2 jets

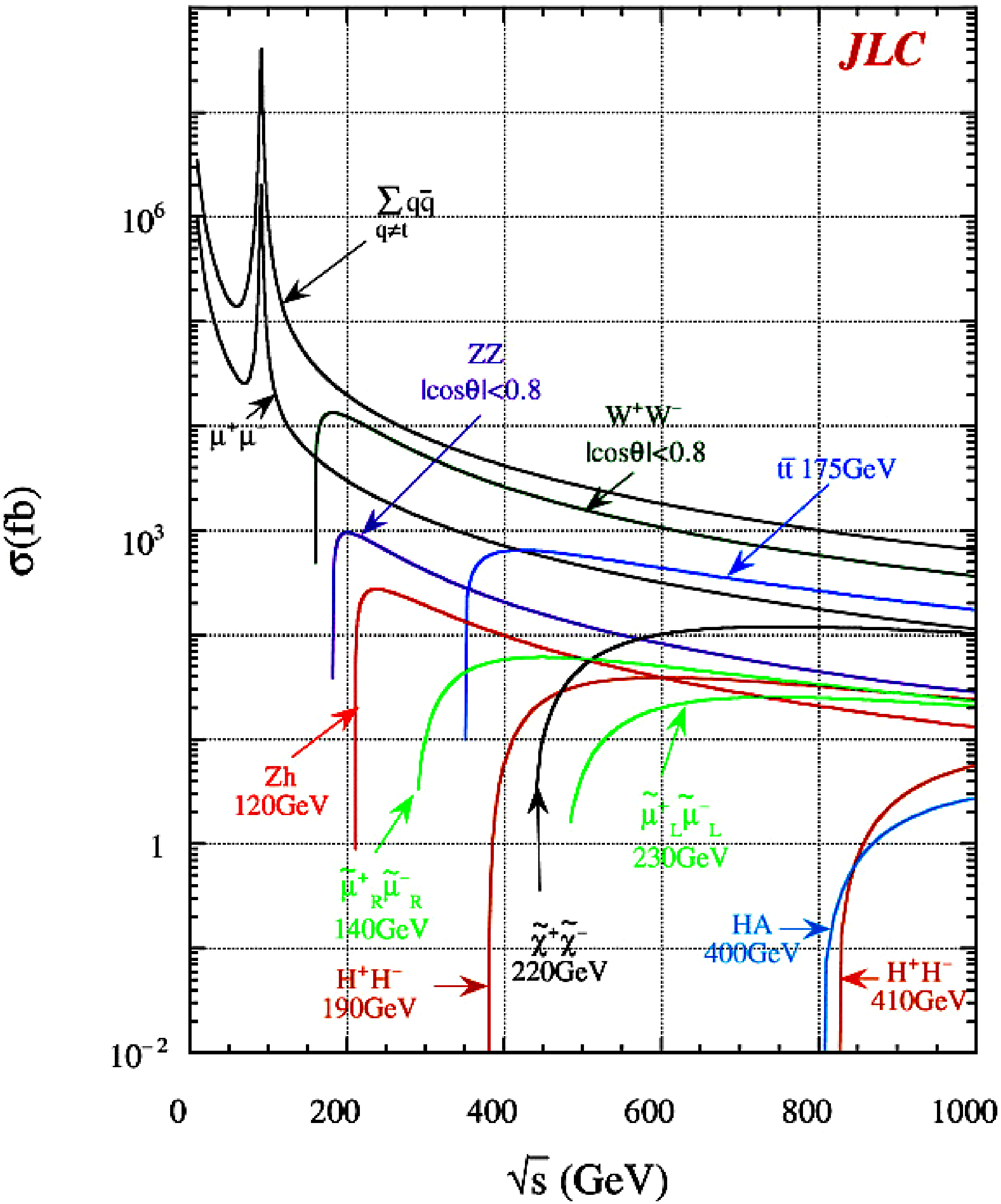
production:
- squarks+gluino strongly prod.

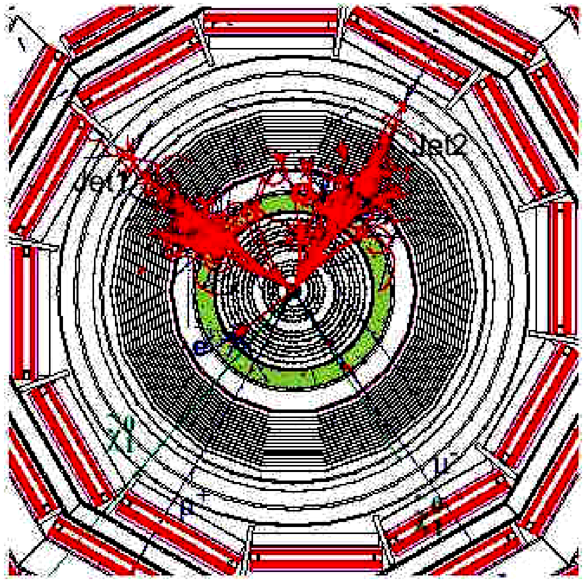
decays:
- missing E_T (LSP)
- jets (squarks/gluino)
- leptons (sleptons)

spin:
- J (neutralino) = 1/2 ?
- J (squark,slepton) = 0 ?

couplings: universal ?

SUSY @ ILC





SUSY event
with 3 leptons + 2 jets

large missing E_T
due to neutralinos

SUSY: rare decays

$\mu^+ \rightarrow e^+ \gamma$

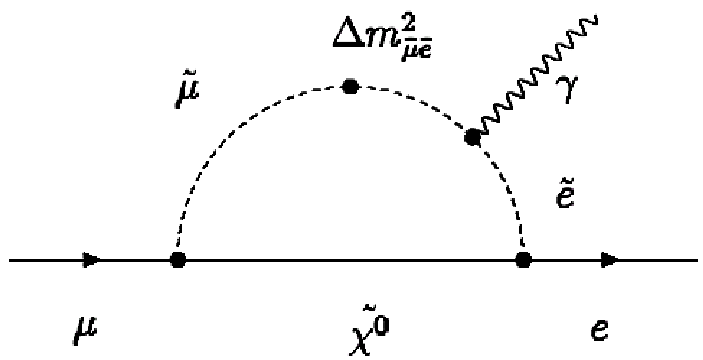
current limit: $< 1.2 \; 10^{-11}$
MEG @ PSI: $< \; 10^{-14}$

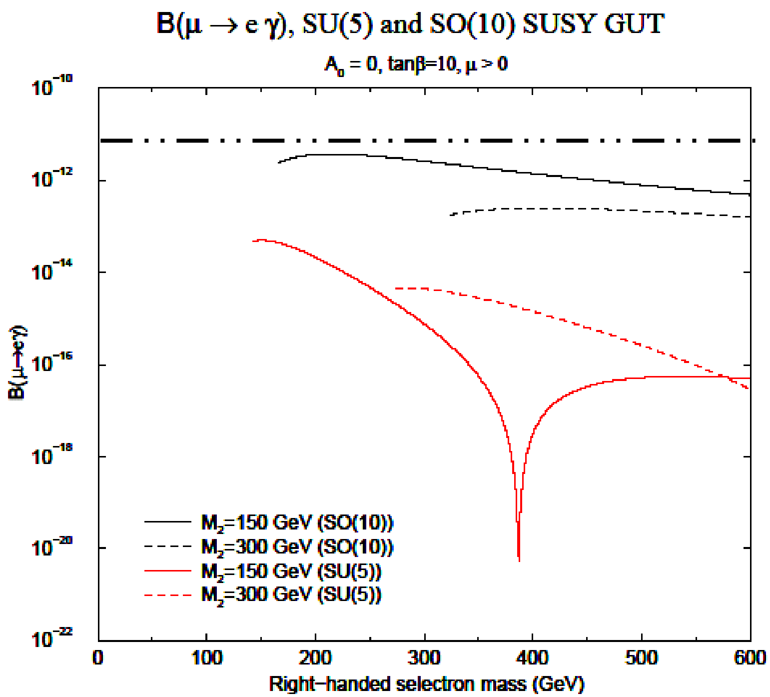
$\mu^+ \rightarrow e^+ e^+ e^-$

current limit: $< \; 10^{-12}$

$\mu^- A \rightarrow e^- A$

current limit: $< 6 \; 10^{-13}$
MECO: $< \; 10^{-16}$
PRISM@JPARC: $< \; 10^{-19}$





Superstrings

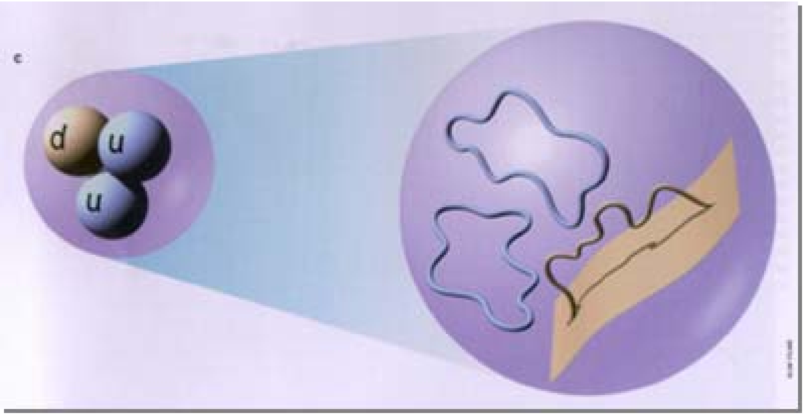
Is the World

2-dimensional ...

3-dimensional ...

10-dimensional ?

Only our 4 dimensions
expanded after the Big Bang.
The other 6 stayed compact.



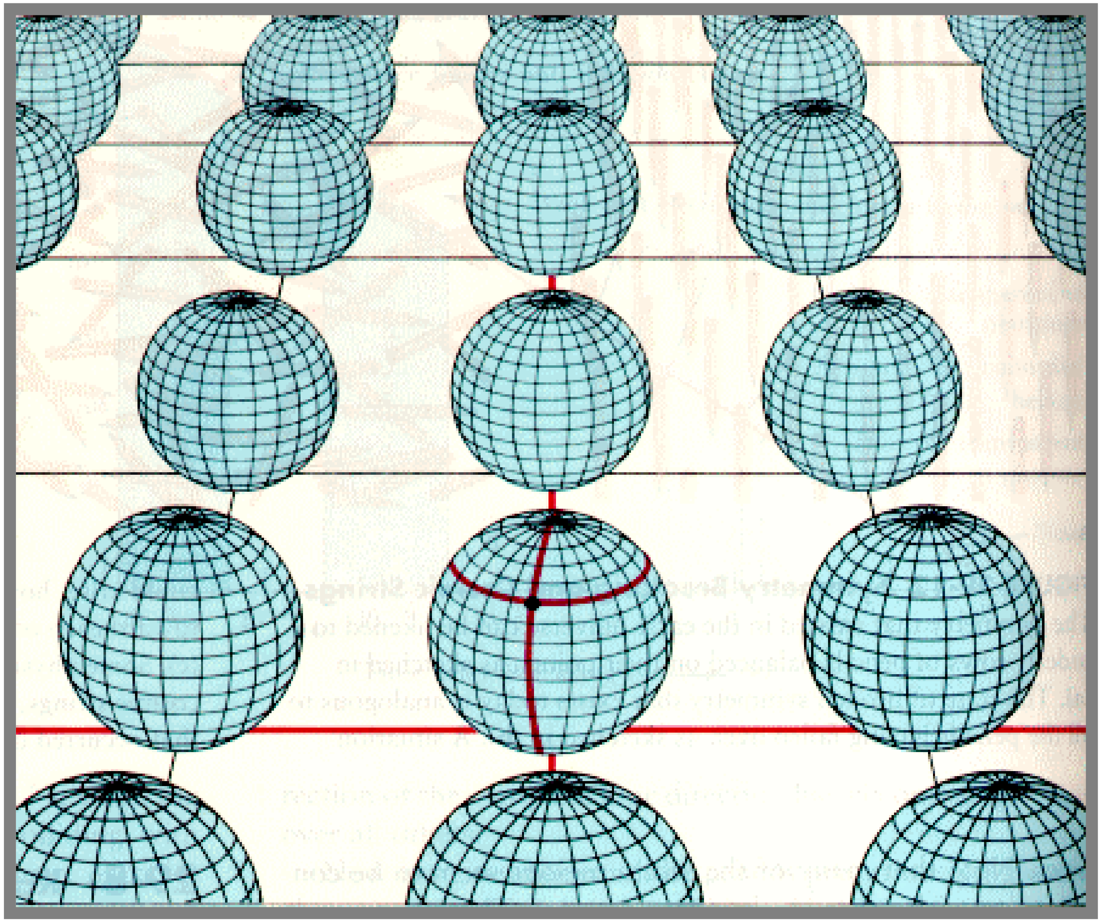
Elementary particles =
string excitations ?

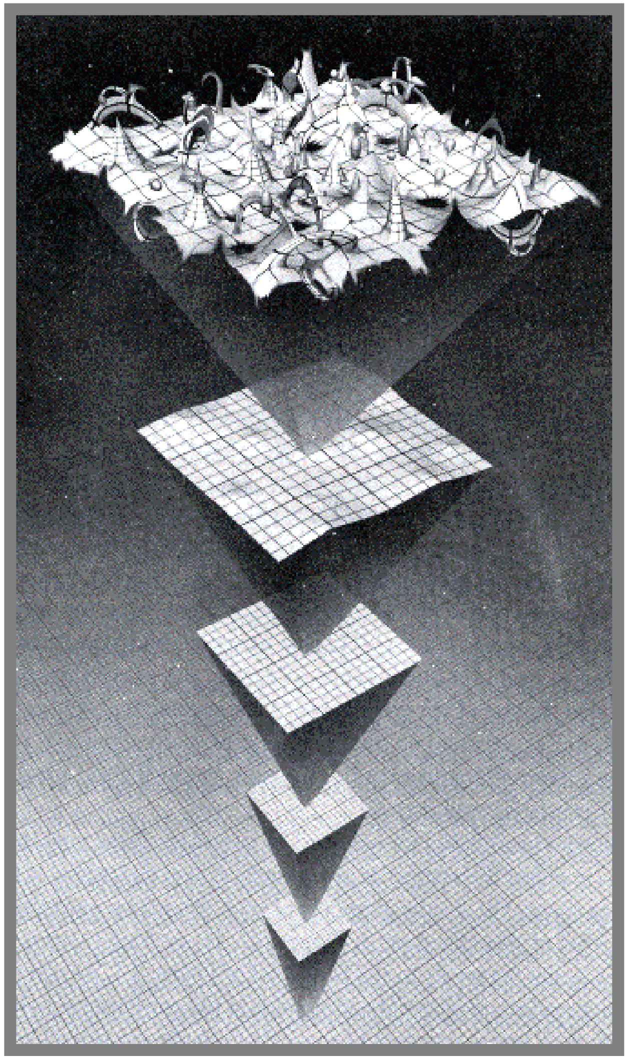
string radius ?

Planck length = $(\hbar G_N/c^3)^{1/2}$
= 10^{-35} m ?

Superstrings

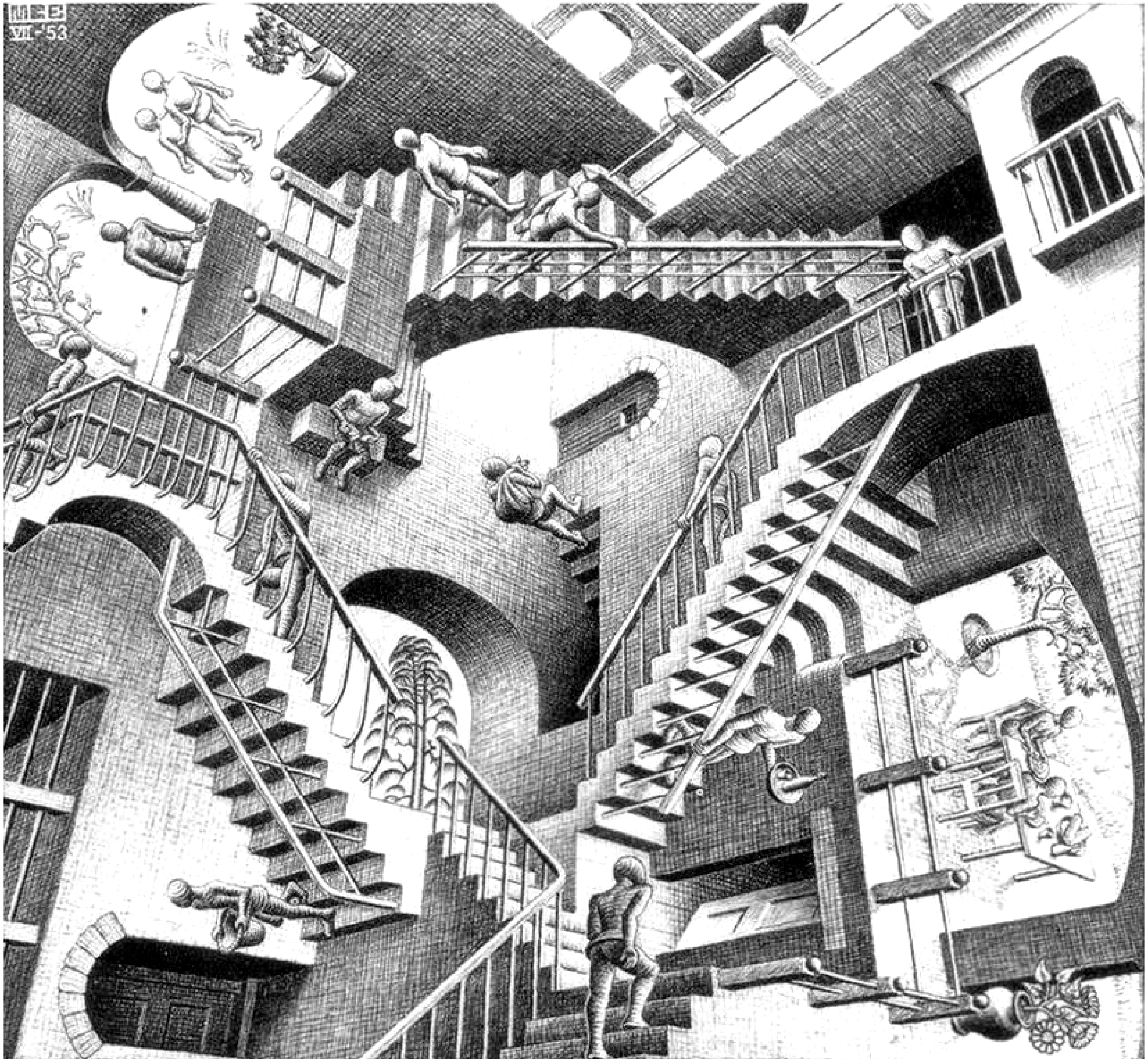
foamy space-time
at Planck length ?





curved extra dimensions
at Planck length = $(\hbar G_N/c^3)^{1/2} = 10^{-35}$ m ?

Extra Dimensions

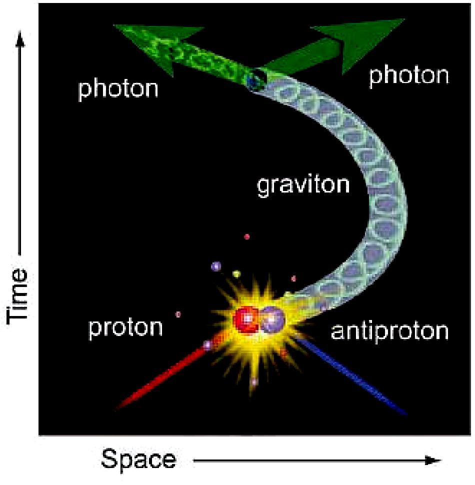


Hierarchy problem:

$M_{elw} / M_{Planck} \sim 10^{-17}$

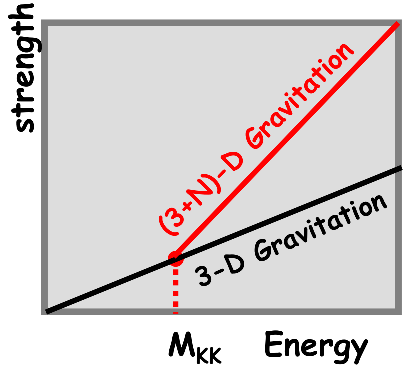
lower gravity scale from $M_{Planck} \sim 10^{19}$ GeV to $M_D \sim 1$ TeV

possible if gravity propagates in 4+n dimensions.



Extra Dimensions

Brane Theories (Arkani-Hamed, Dimopoulos, Dvali, 1998,99)



- elm., strong + weak force act on (3+1) brane
- N extra dimensions compactified with radius R
- only gravitation acts in extra dimensions
  - modification of Newton's law:

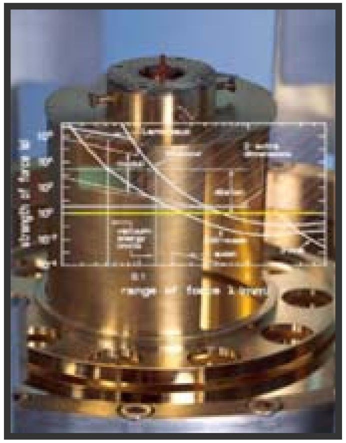
$$F \sim G_N / r^2 \sim 1 / M_{Pl}^2 r^2 \sim 1 / M_{KK}^{2+N} r^{2+N}$$

  - G_N, M_{Pl} ... only effective constants
  - R, M_{KK} ... new, fundamental Planck length, mass

$$M^2_{Pl} \sim G_N^{-1} \sim (10^{19}\,GeV)^2 \sim R^N M_{KK}^{N+2}$$

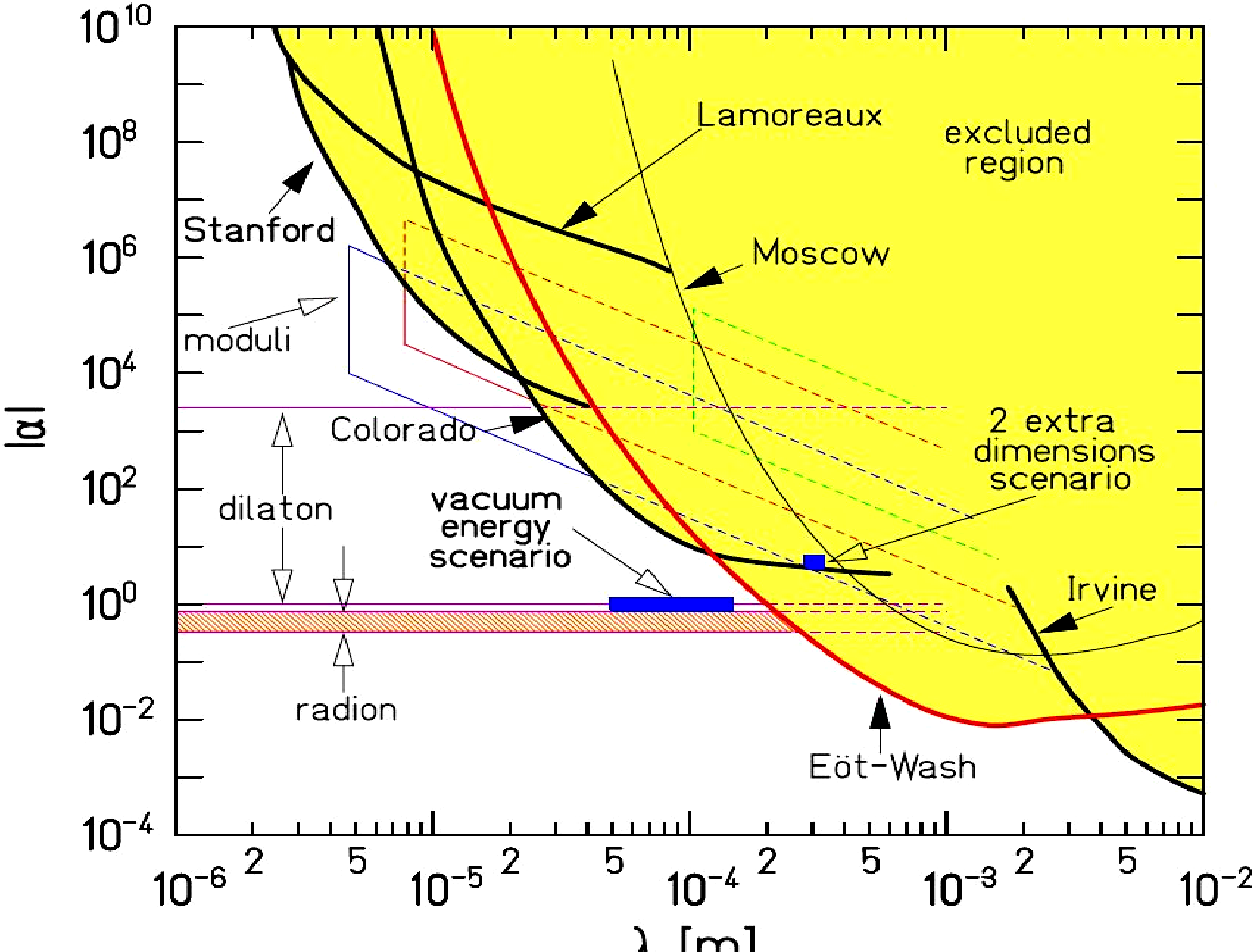
- Grand Unification = gravity becomes strong already at electroweak scale : M_{KK} = 1 TeV :

N=1	R ~ 10^9 km	
N=2	R ~ 1 mm	Eöt-Wash: 1/r ok to 50 µm
...		
N=6,7	R ~ 10 fm	new Planck length



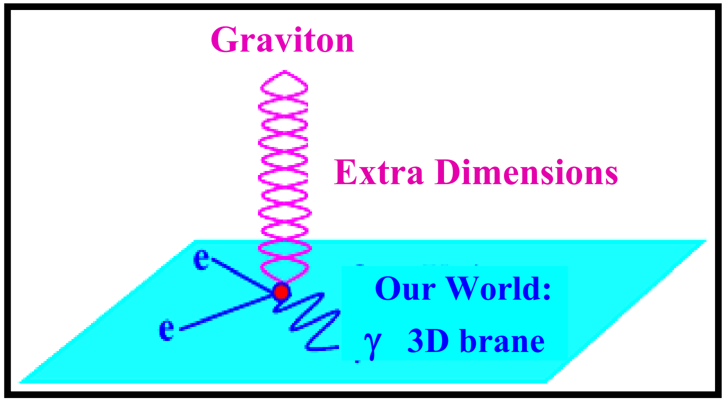
Torsion pendulum
Eöt-Wash Group,
Univ. Washington, Seattle

Extra Dimensions

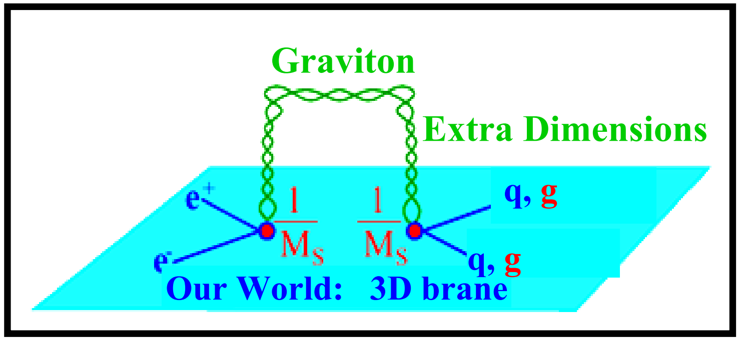


Extra Dimensions

Emission of Kaluza-Klein gravitons in Extra Dimensions

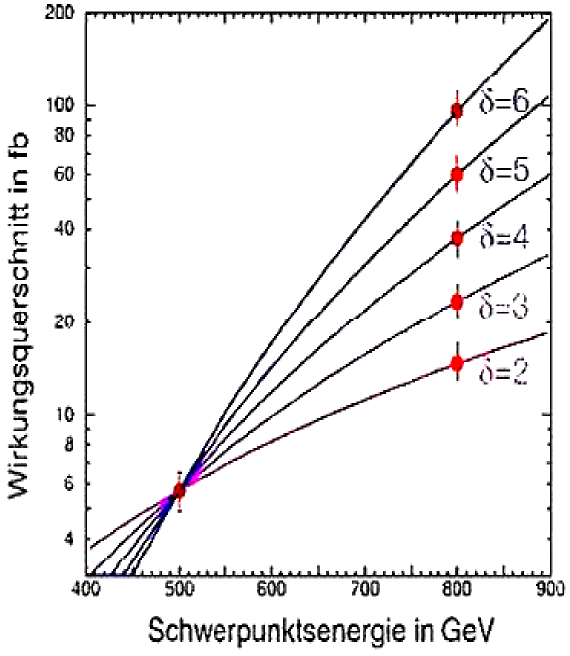


real emission: missing momentum



virtual exchange: larger rates

σ ($e^+e^- \rightarrow G\ X$) for δ extra dim.



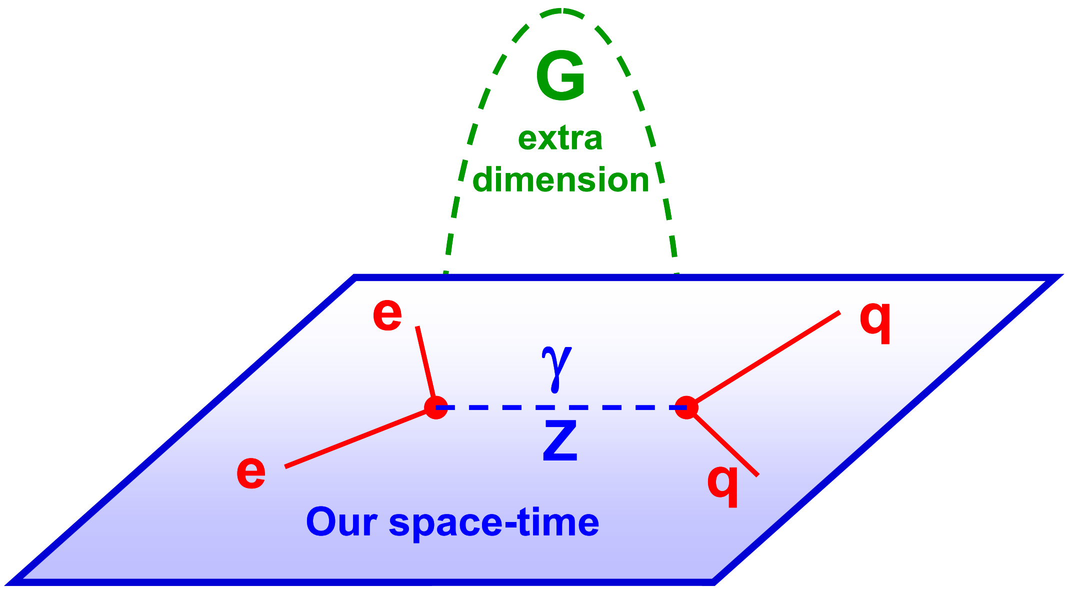
LHC 100 fb^{-1}:

M_{KK} > 9,7,6 TeV for δ = 2,3,4

Graviton: Spin-2 tensor force: angular distribution

Extra Dimensions

Emission of Kaluza-Klein gravitons



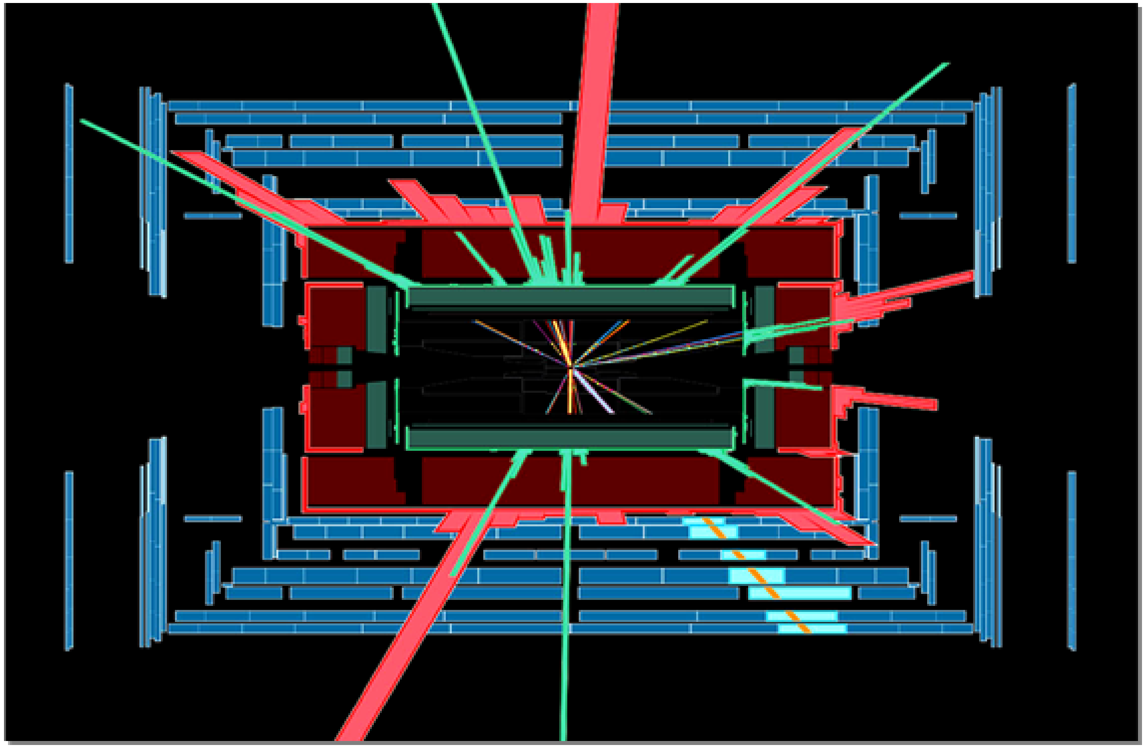
real emission: missing momentum
virtual exchange: larger rates

Graviton: Spin-2 tensor force: angular distribution

Mini Black Holes

- gravitative resonance: decay in SUSY + other particles
- evaporate by Hawking radiation
- quantum theory of black holes in the lab !

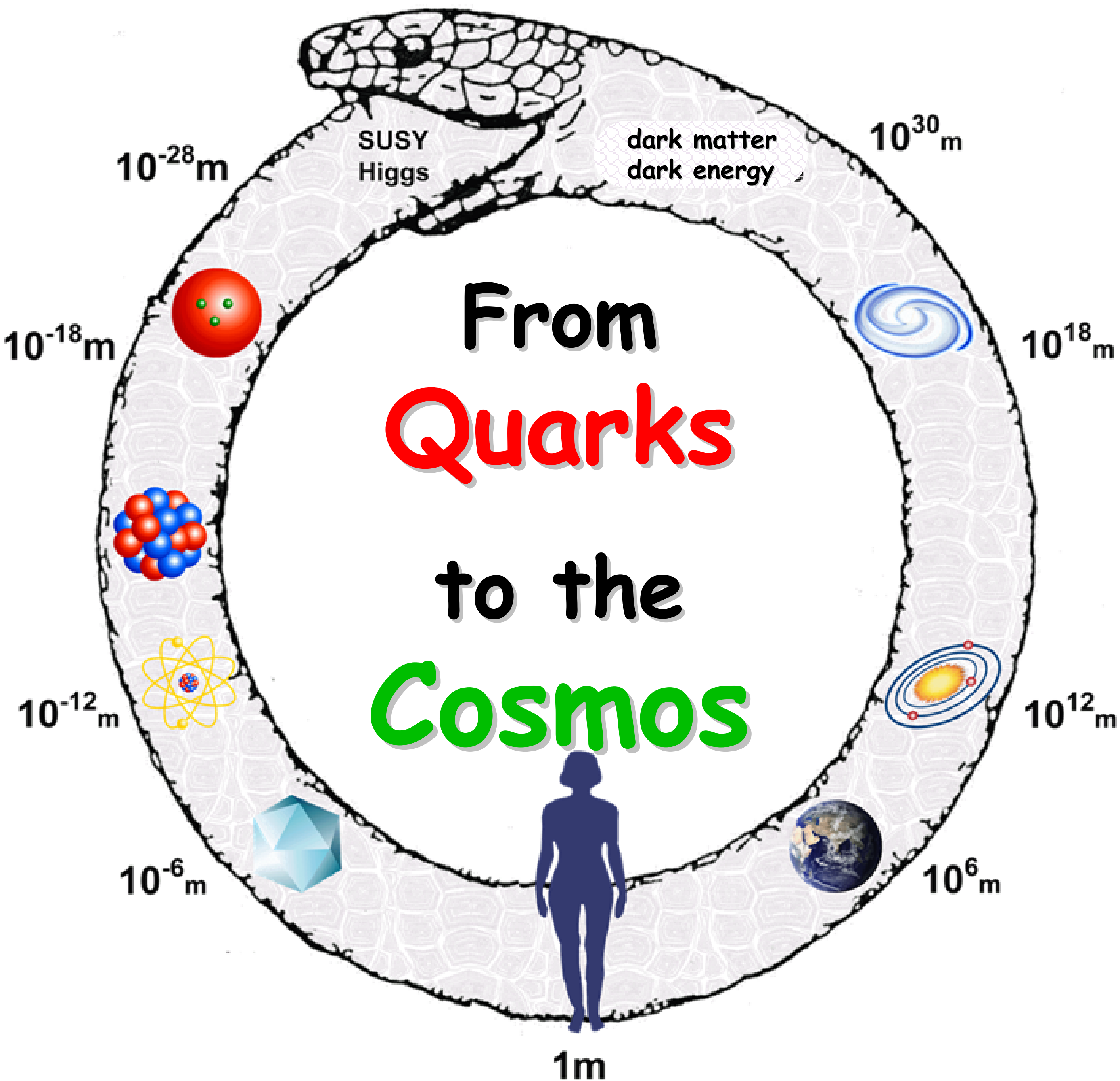
- detect in LHC + cosmic radiation (Auger, ICECUBE)



simulated decay of a Mini Black Hole
in the ATLAS detector at the LHC at CERN

LHC discovery potential

Scenario	LHC Reach
Z',W' $\rightarrow$ ll, lν	~ 5-6 TeV
Leptoquarks	~ 1.5 TeV
Excited quarks	~ 6.5 TeV
Compositeness scale	~ 40 TeV
Extra dimensions gravity scale	~ 9 TeV for 2 extra dimensions
Magnetic monopoles	~ 20 TeV


From
Quarks
to the
Cosmos
SUSY
Higgs
dark matter
dark energy
10^{-28}m
10^{-18}m
10^{-12}m
10^{-6}m
1m
10^{6}m
10^{12}m
10^{18}m
10^{30}m