The H1 Experiment at HERA

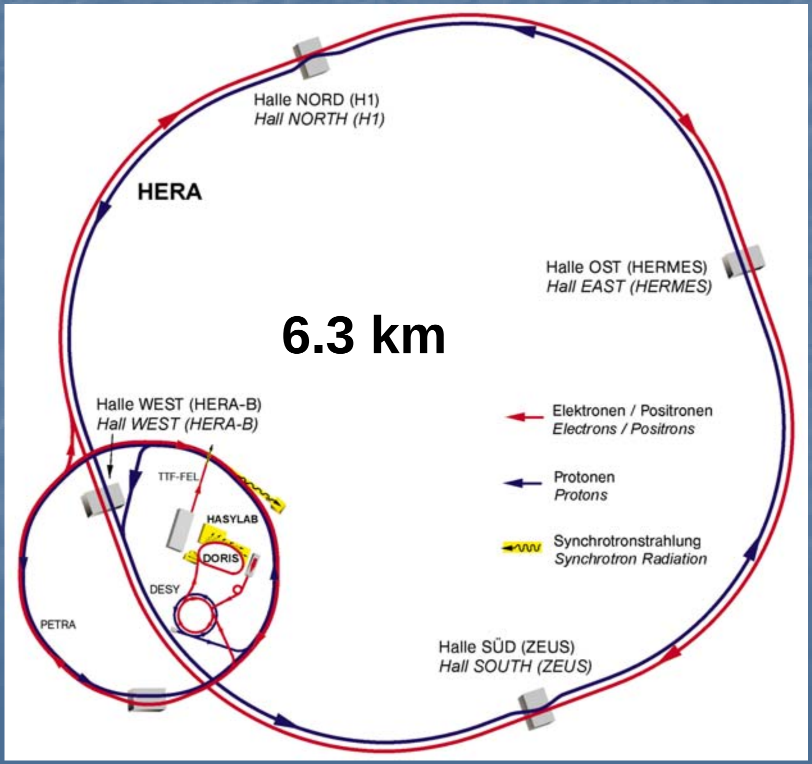
1. The HERA Accelerator
2. Some Examples of H1 ep Physics
3. The H1 Detector

a1

HERA at DESY

2 collider exp's:
H1 / ZEUS : ep physics

2 fixed target exp's:
HERMES : spin physics
HERA-B: CP-violation, B-physics



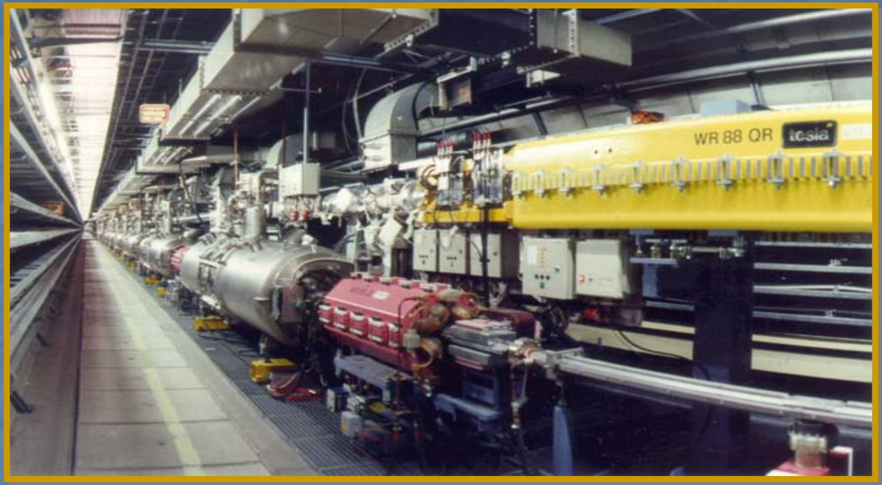
HERA-I 1992 – 2000
HERA-2 2003 – 2007

E_p = 820 / 920 GeV
E_e = 27.5 GeV
→ center of mass energy = 300 / 318 GeV

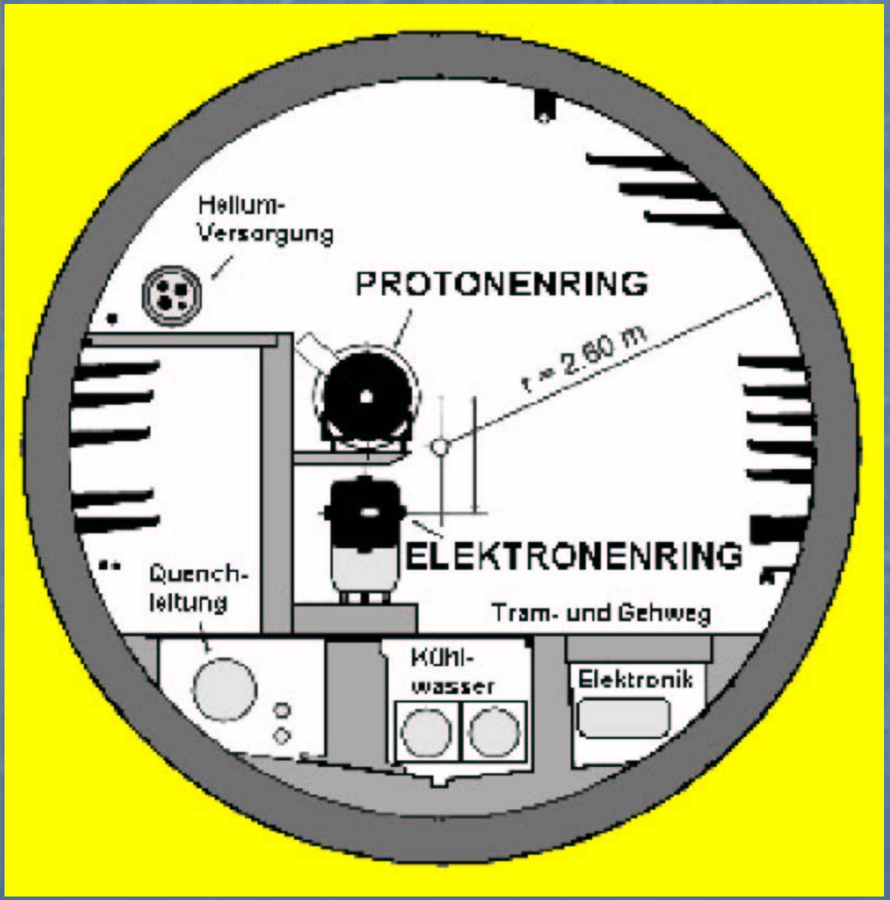
Slide 2

a1 apis, 7/2/2003

HERA Tunnel



15m – 30m under surface



HERA Components

1) Cavities to accelerate: 130 / 2 MV for electrons / protons
2) Magnets to bend and focus the beams

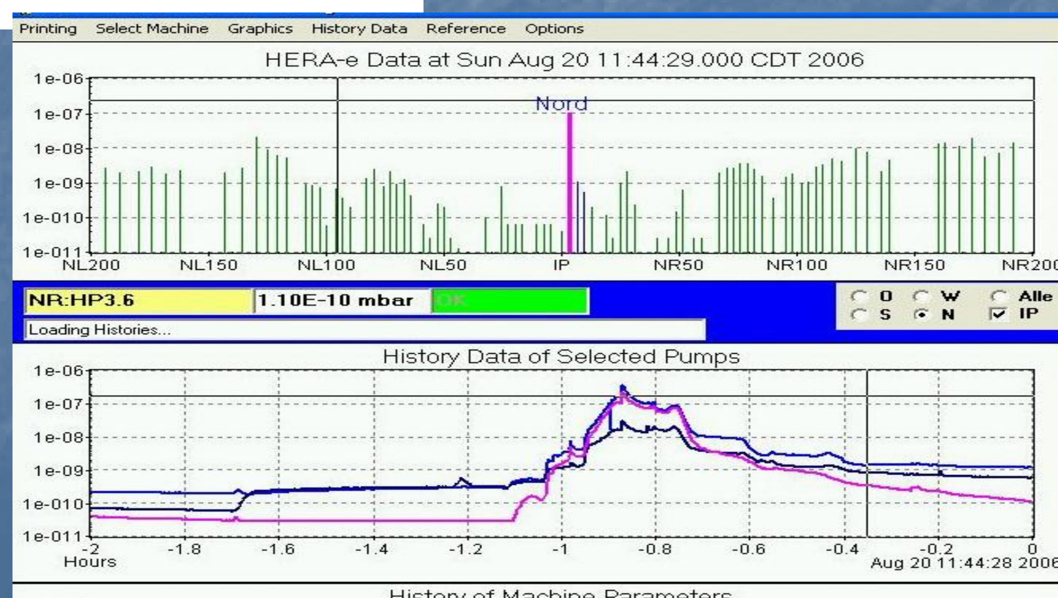
Proton beam needs a high magnetic field (4.68 T)
→ use a superconducting magnet („Kaltbauweise")
→ The magnet yoke is cooled with liquid He to 4 degree

Electron ring need a lower magnetic field (0.16 T)
→ normal conducting magnets are sufficient
→ but compensation of synchrotron radiation loss needed

422	s.c. dipole magnets
224	s.c. main quads,
400	s.c. correction quads
200	s.c. correction dipoles
> 1000	n.c. electron magnets

3) Ulta-high vacuum:
~ 10^{-9} mbar

… much more …



HERA & Collider family

Classification of accelerators ...

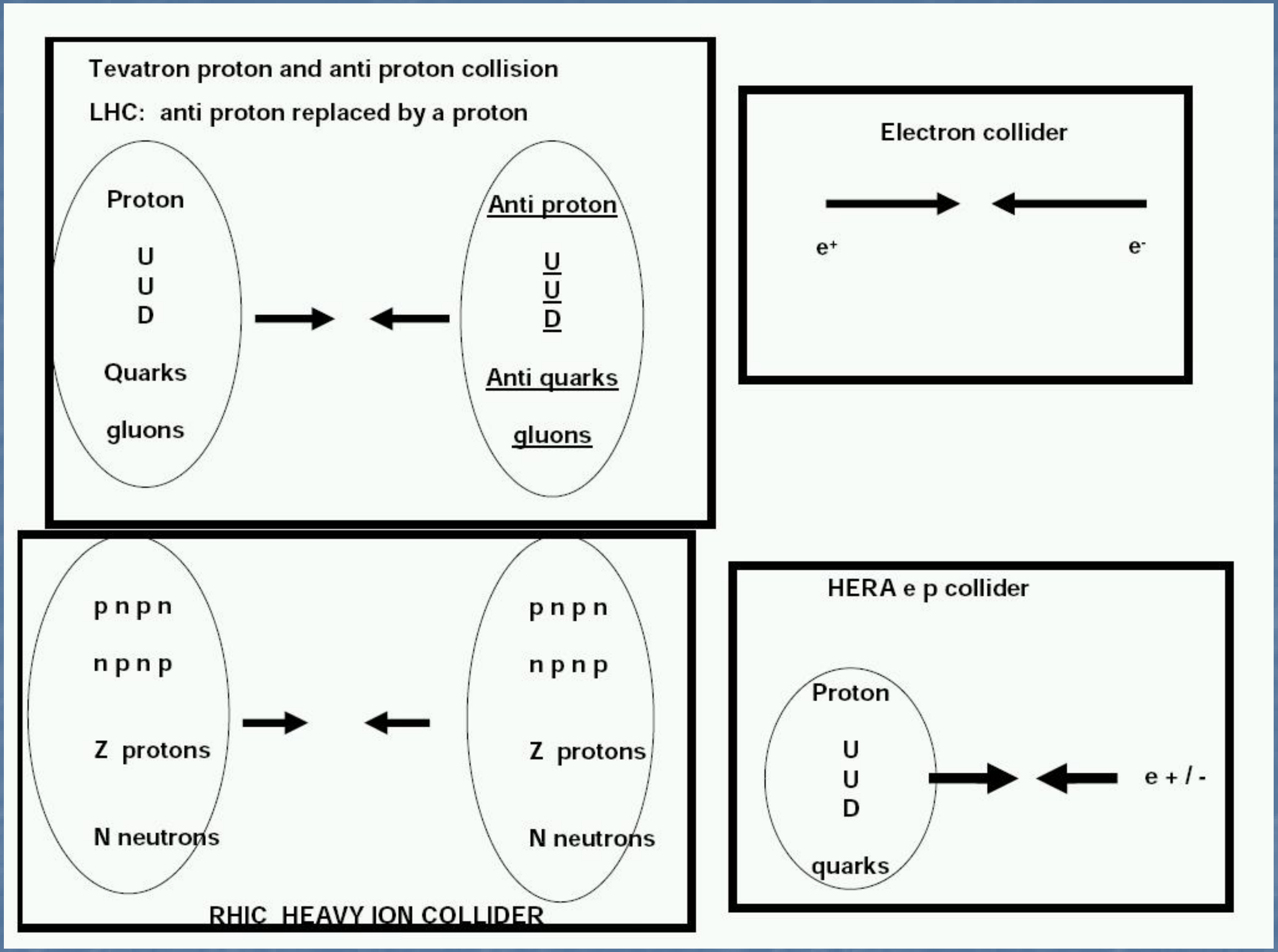
1 - fixed target → low center of mass energy, high luminocity

2 – collider → high center of mass energy, lower luminocity

Pbar-P	P- P	Heavy Ion	e+/- Proton	e^+ - e^-	Linear e^+ e^-
Tevatron FNAL	LHC at CERN	RHIC BNL	HERA DESY	B-factories	NLC TESLA CLIC
1.96 TeV	14 TeV	100 GeV/nucleon	30 GeV e by 920 GeV P	2 x B mass 9.4 GeV	500 GeV cm to 5 TeV cm

Complementary physics programs
HERA is the only ep collider

Why different colliders ?

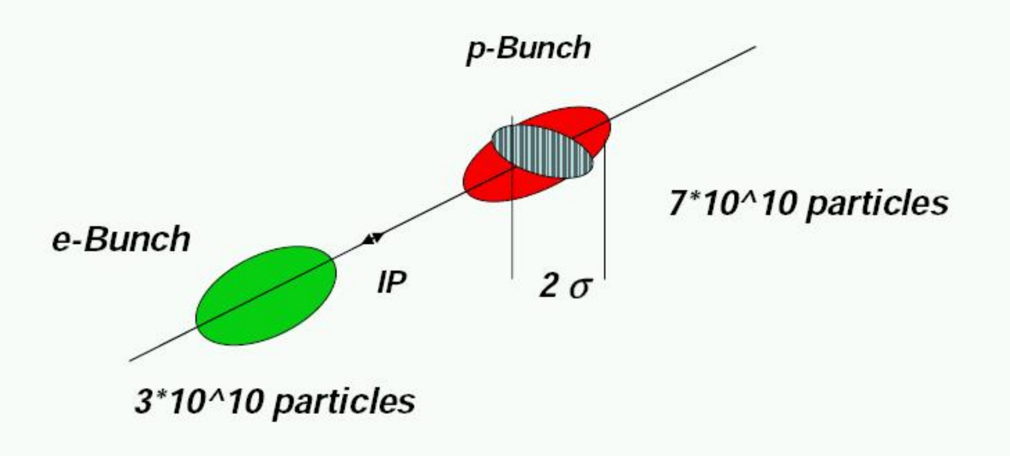


Electrons: “point-like”, lower energy
Protons : sizable objects, higher energy

} access different fields …

Luminocity

Luminocity L determines the event rate N for each cross section σ:



$$N = \sigma \cdot L$$

Luminocity given by accelerator parameters:

$$L = n \cdot f \frac{N_e N_p}{4\pi\sigma_x\sigma_y}$$

Typical values : number of bunches n = 180
bunch crossing time 1/f = 96 nsec
$N_{e/p}$ = 3 / 7 10^{10} ppb
$\sigma_{x/y}$ = 190 / 50 μm

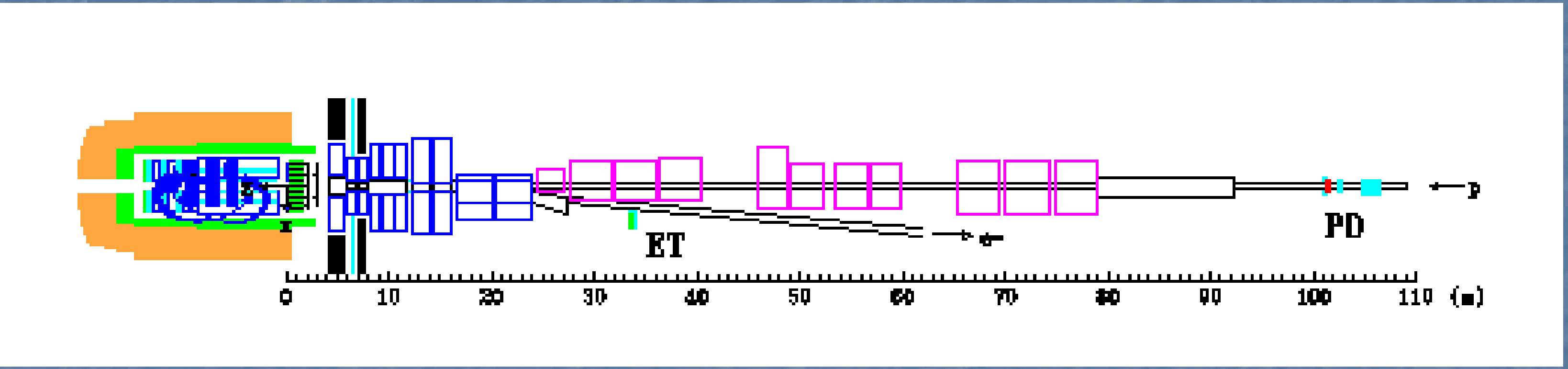
n … number of bunches
f … frequency
$N_{1/2}$ … particles per bunch
$\sigma_{x/y}$ … beam profiles

Luminocity Measurement at H1

Principle: take a known cross section and measure event rate
→ L = N/σ

1) Cross section: Bethe - Heitler process (pure QED !) $ep \to ep\gamma$

2) Event rate: use e-tagger and photon detector close to the beam line



3) Subtract (beam gas) backgrounds

$$L(t) = \left(N_{BH} - N_{Bg}\right) / \sigma_{BH} \cdot t$$

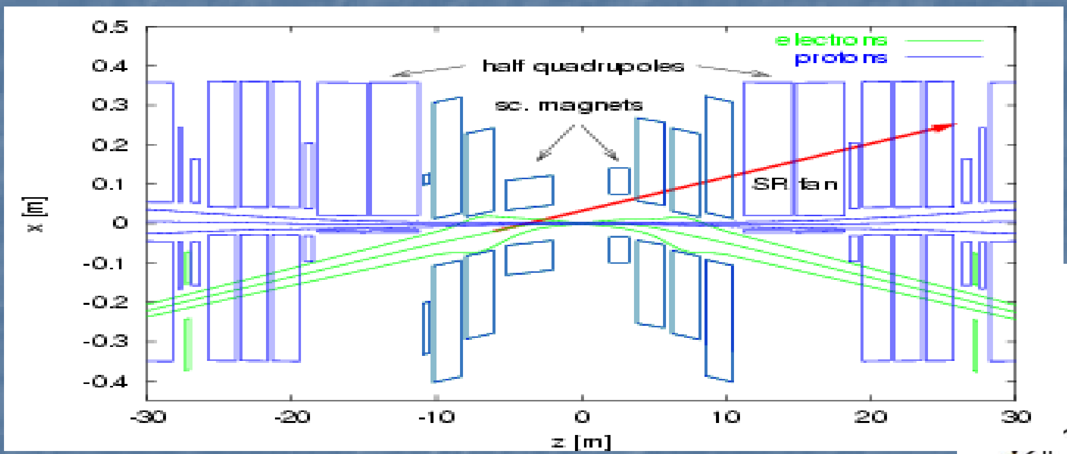
HERA Luminocity Upgrade

Aim: Increase L by factor 4 – 5 to reach at end of HERA integrated 1000 bp^{-1} ???

How:

1) increase the beam currents $I_{e/p}$ = 40/90 mA → 60/140 mA

2) squeeze the beams at the interaction point → magnets in H1/ZEUS

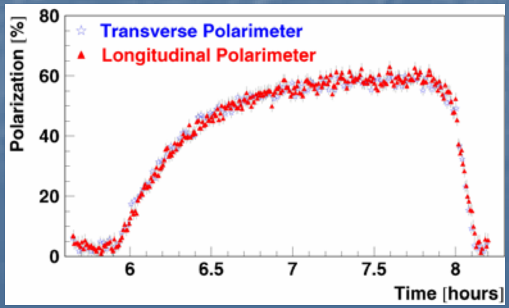


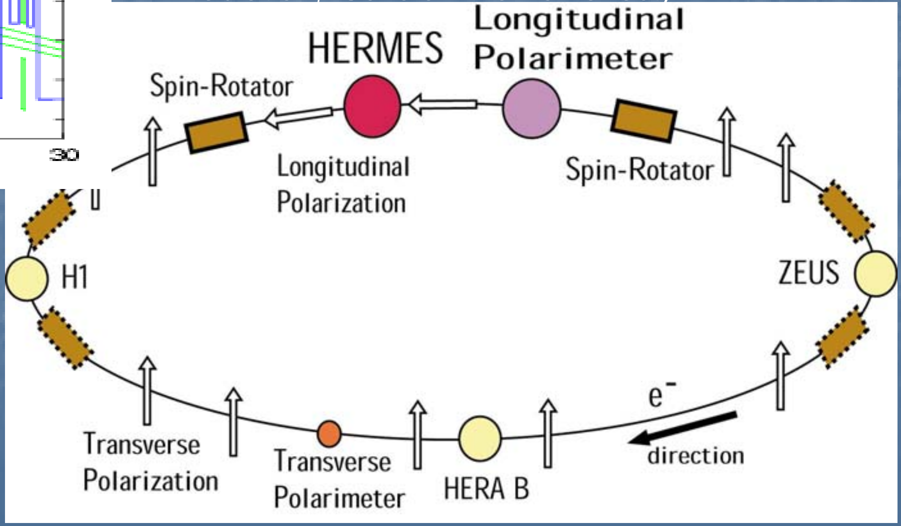
Additional:

longidutinal e polarization

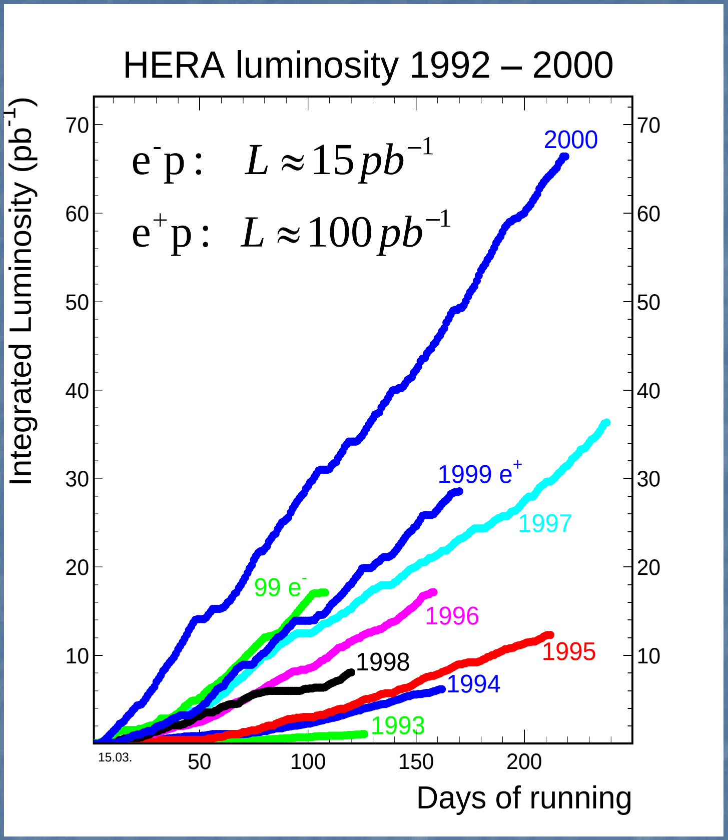
→ Spin rotators

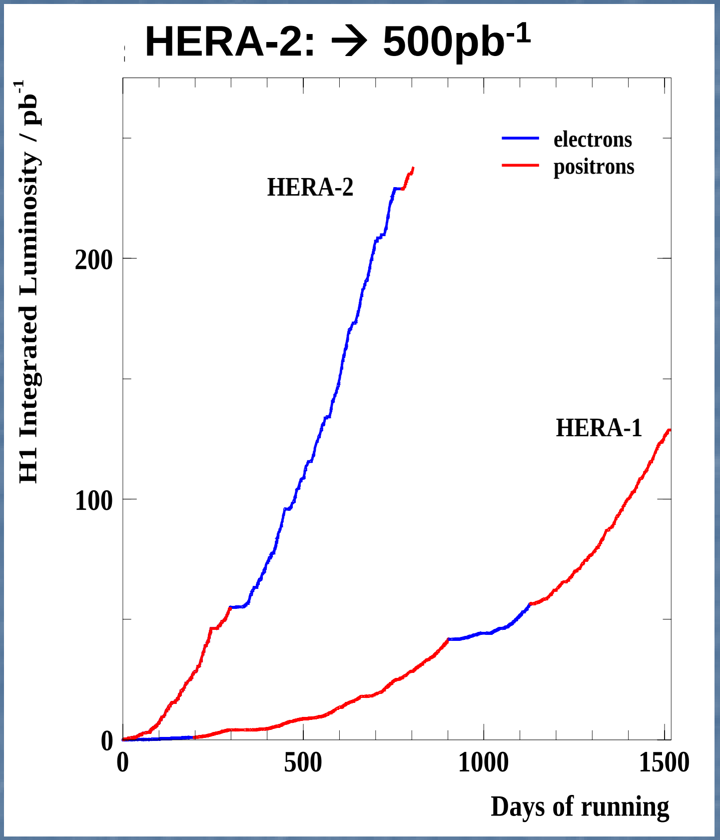
(transverse self-polarization by synchrotron radiation, Sokolov- Ternov effect)





HERA Luminocity





<u>An example - Beauty production</u>

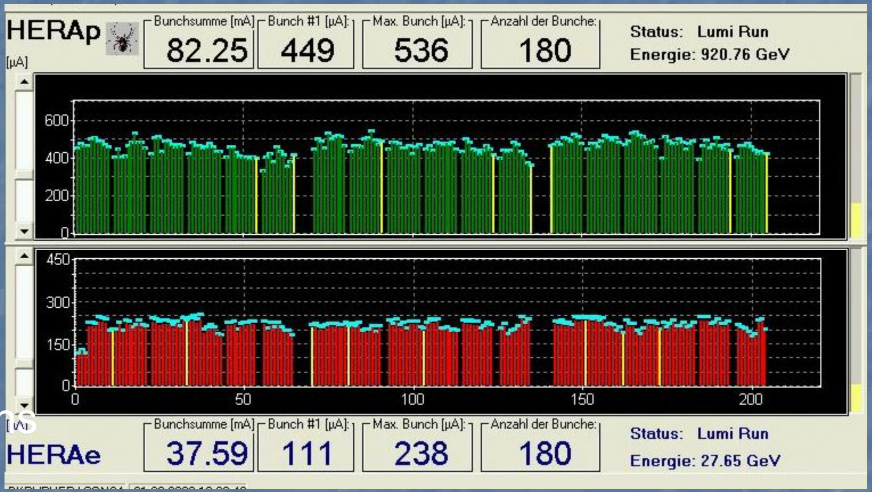
σ^b_{vis}(ep→ eBBX→ eD*μX) ~ 200 pb

For typical sample of 100pb^{-1} N = σ L → 20.000 eD*m events

Branching ratio (D*→ Kππ) ~ 2.5% → few 100 signal events

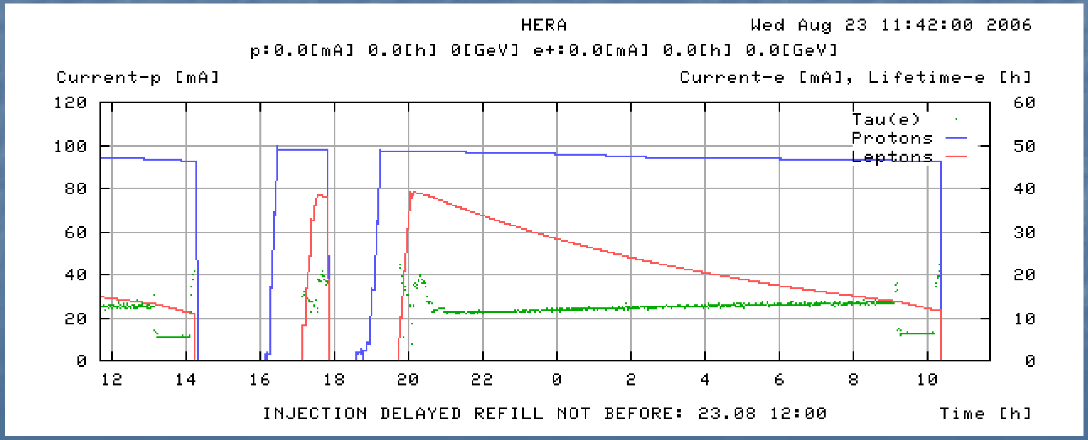
A HERA shift …

1) “massage” magnets: zero rest fields by hysteresis
2) Ramp the protons to 40 GeV
3) Fill the protons in HERA
4) Ramp the protons to 920 GeV
5) Ramp the electrons/positrons to 12 GeV
6) Fill the electrons/positrons in HERA



… nothing happens – no collisions !!!

7) Steer proton and e+/e- bunches to collisions
8) Take data until currents are too low



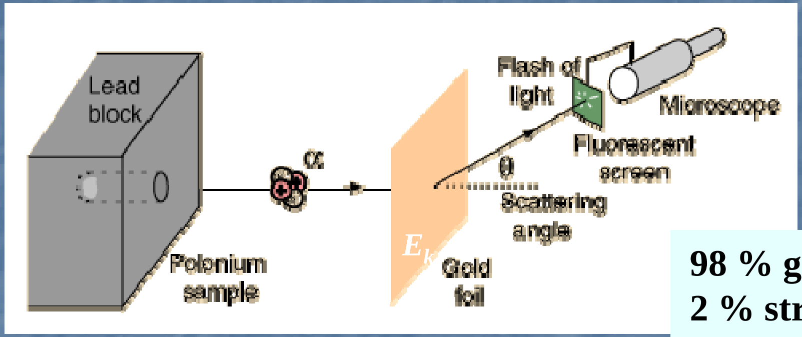
24h history of
a typical HERA fill

Some Milestones to HERA

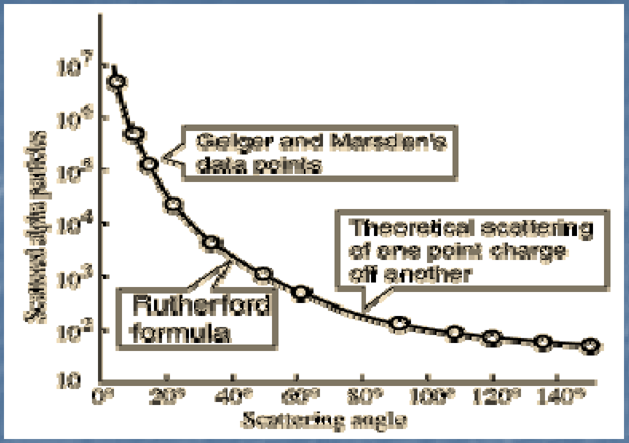
1911 Rutherford: α – particles on Gold
→ atomic structure
1956 Hofstaedter: ep scatterin at 200 MeV
→ proton form factors
1964 Gell-Mann/Zweig: hadron multiplets
→ quarks with Q = +/- 1/3, +/- 2/3
1968 SLAC: ep fixed target scattering at 20 GeV
→ protons made of partons
partons = quarks & gluons
1992 HERA: ep collider experiments H1 and ZEU
→ precise structure of the proton ….

The Rutherford Experiment

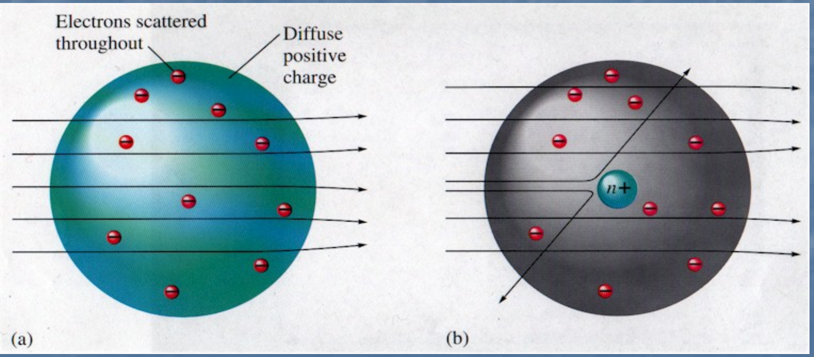
Rutherford 1911



98 % go through
2 % strongly deflected
0.1 % back scattered



$$\frac{d\sigma}{d\Omega} \propto (Z_1 Z_2)^2 \frac{1}{E_k^{\,2}} \frac{1}{\sin^4(\Theta/2)}$$



→ point-like nucleus R~ 10^{-14}m compared to atom size ~ 10^{-10}m
→ positive core with "all" mass, negative cloud (no Plum Pudding structure – Thomson)

Beginning of nuclear / particle physics

Elastic ep Scattering - Theory

From the Rutherford to the Rosenbluth formula …

Electron spin →	$\sigma_{Mott} = \frac{4\alpha^2 E'^2}{Q^2} \cos^2\frac{\Theta}{2} \cdot \frac{E'}{E} \equiv \sigma_{Ruth} \cdot \cos^2\frac{\Theta}{2}$
Proton spin & mass →	$\sigma_{Dirac} = \sigma_{Mott}\left(1 + 2\tau \tan^2\frac{\Theta}{2}\right)$ with $\tau = Q^2 / 4M^2c^2$
Proton form factors → charge distribution ρ(r) magnetic moments μ(r)	$\sigma_{ep} = \sigma_{Mott}\left(A(Q^2) + B(Q^2)\tan^2\frac{\Theta}{2}\right)$ Rosenbluth with: $A(Q^2) = \left(G_E^2 + \tau G_M^2\right) / (1+\tau)$, $B(Q^2) = 2\tau G_M^2$ $Q^2 = 0$: proton charge $G_E(0) = 1$ mag. momentum $G_M(0) = 2.79$ (anomalous!)
Measurements :	
dipole formula →	$G_E(Q^2) = G_M(Q^2)/2.79 \approx \left(\frac{1}{1 + Q^2/M_V^2}\right)^2$ with $M_V^2 \approx 0.8\,\mathrm{GeV}^2$
proton radius via Fourier transformation →	$G_E(Q^2) = \frac{1}{(2\pi)^{3/2}} \int \rho(r) e^{iqr} d^3r$, $G_M(Q^2) = \frac{1}{(2\pi)^{3/2}} \int \mu(r) e^{iqr} d^3r$

Elastic ep Scattering - Experiment

McAllister, Hofstadter : SLAC 1956 188 / 236 MeV electron beam

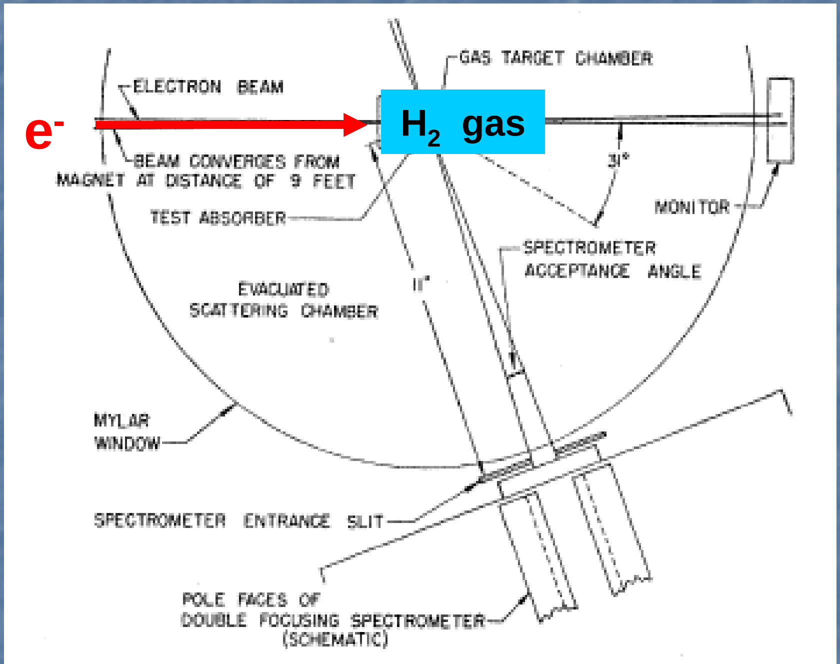
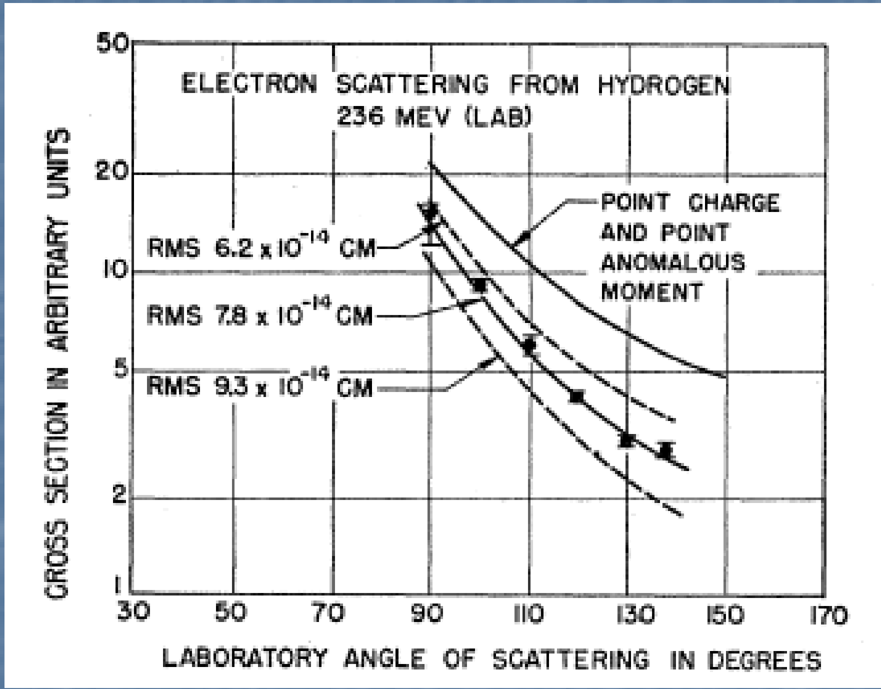


Fig. 2. Arrangement of parts in experiments on electron scattering from a gas target.

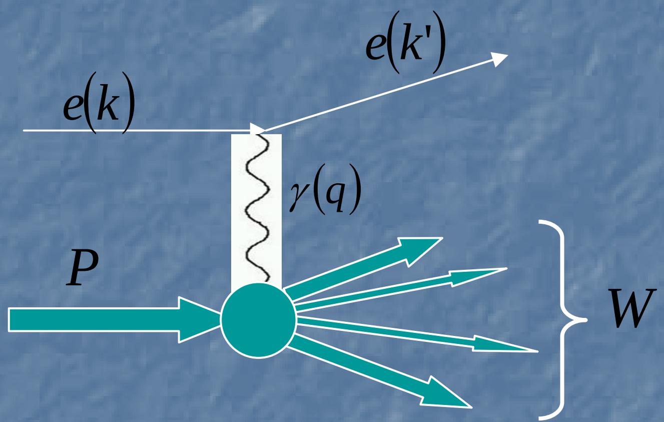


→ **Deviation from point-like object due to proton form-factors**

→ **not sensitive enough for Q^2 – dependence, proton radius ~ 10^{-15} m**

Inelastic ep Scattering - Theorie

- higher energies are more sensitive to smaller objects:
  Heisenberg $\Delta x\, \Delta p \geq \hbar$ → resolution $\lambda \geq \hbar / Q_{max}$
- due to inelasticity complete description needs additional variable: W, ν, ...
- approach 1-photon exchange, higher orders processes suppressed $\alpha_{em} \sim 1/137$



$$q = k - k'$$

$$Q^2 = -q^2 = 4EE'\sin^2(\Theta/2)$$

$$\nu = E - E'$$

$$W = (P+q)^2 = M^2 + 2M\nu - Q^2$$

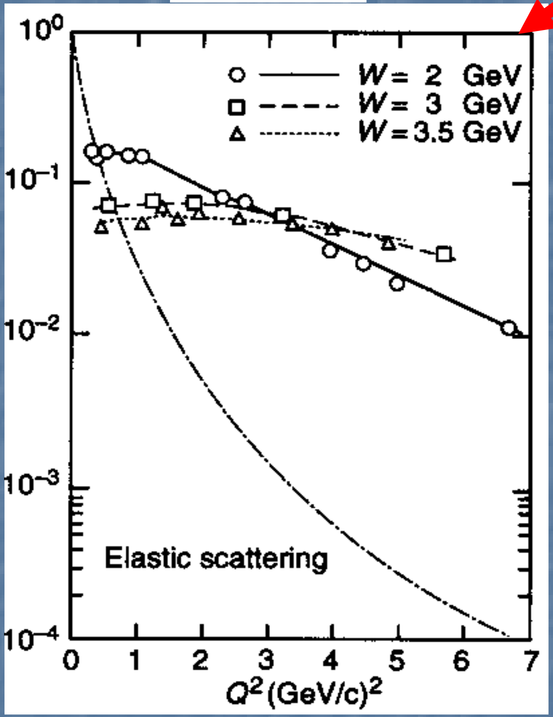
$$\sigma_{ep} = \sigma_{Mott}\left(W_2(\nu, Q^2) + 2W_1(\nu, Q^2)\tan^2(\Theta/2)\right)$$

Form factors (Q^2) → Structure functions (Q^2,ν)

Inelastic ep Scattering - Experiment

SLAC-MIT 1969:
electrons 7 – 18 GeV

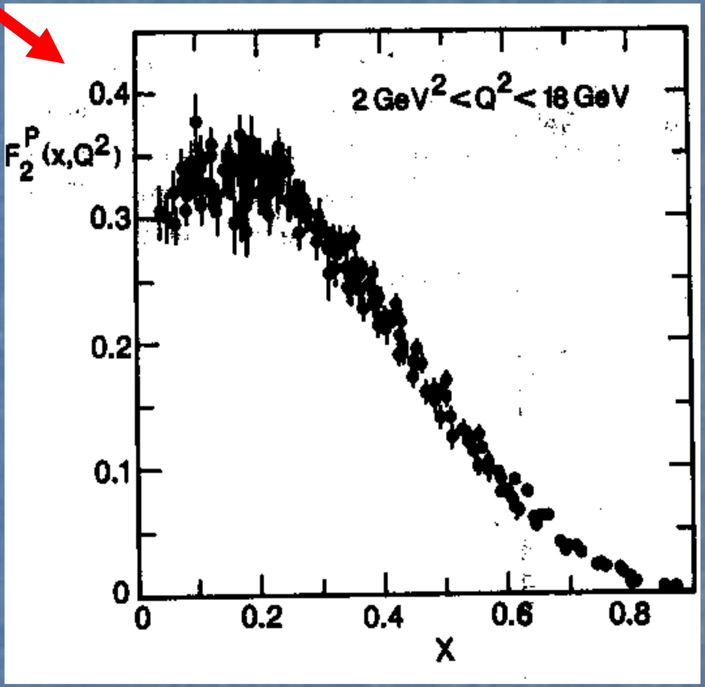
$\sigma_{ep} / \sigma_{Mott}$



Two big surprises:

1) no extrapolation of elastic form factors ~ Q^{-8}
→ like scattering off point-like particles !

2) $\sigma_{ep} / \sigma_{Mott}$ depends weakly on Q^2



Scaling of structure functions
(Bjorken 1967)

$$Q^2, \nu \to \infty \quad \text{define } x = \frac{Q^2}{2M\nu} \; : \quad MW_1(\nu, Q^2) \to F_1(x)$$

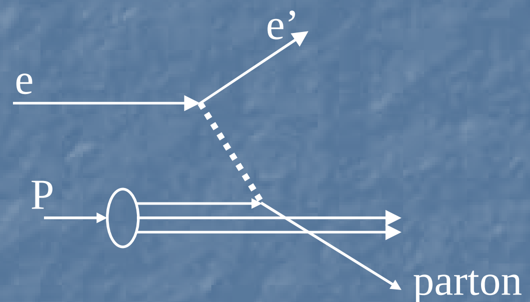
$$\nu W_2(\nu, Q^2) \to F_2(x)$$

Proton Structure : Quark – Parton Model

- Gell-Mann/Zweig 1964: "Eightfold way" - hadrons ordered in SU(3) multiplets
  3 quark flavours q form baryons (qqq) and mesons ($q,\bar{q}$)

- Feynmann 1969-1972 : Parton model - proton made by point-like partons

- Natural ansatz: Partons are Quarks ?
  → inelastic ep scattering = sum of elastic eq scattering
  → parton momentum fraction x with pobability u(x), d(x)



$$F_2 = x\left(\frac{4}{9}u(x) + \frac{1}{9}d(x) + \frac{4}{9}\bar{u}(x) + \frac{1}{9}\bar{d}(x) + \ldots\right)$$

$$2xF_1 = F_2 \qquad \text{for spin 1/2 partons}$$

- Measured : Charged Quarks carry ~ 50% of proton momentum,
  → other half by neutral partons = gluons

Quark-Parton Model : Proton = valence + sea quarks + gluons

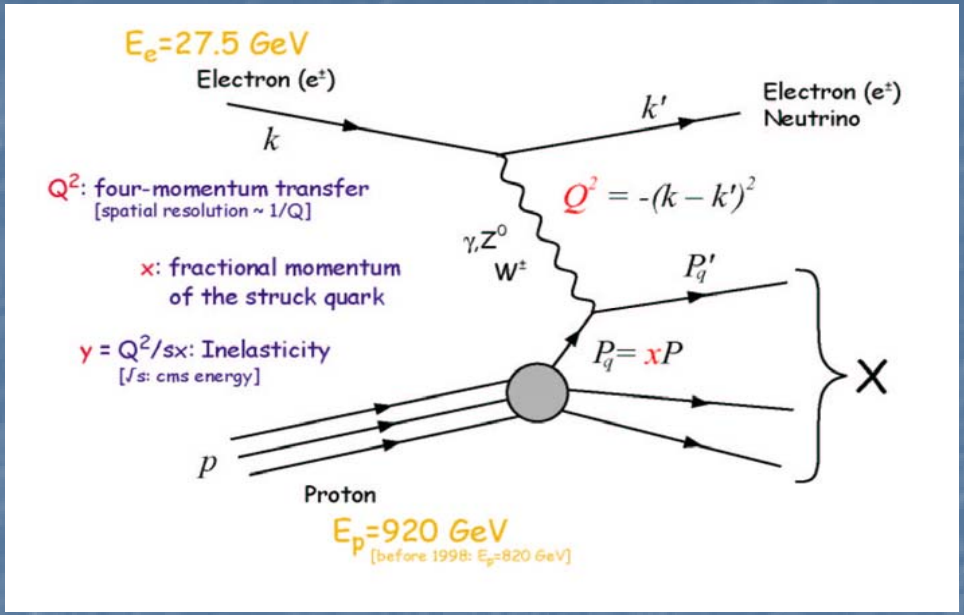
sea quarks quark-antiquark pairs from vacuum …

Physics with H1

1) Kinematics
2) Proton structure
3) Pomeron structure
4) Photon structure

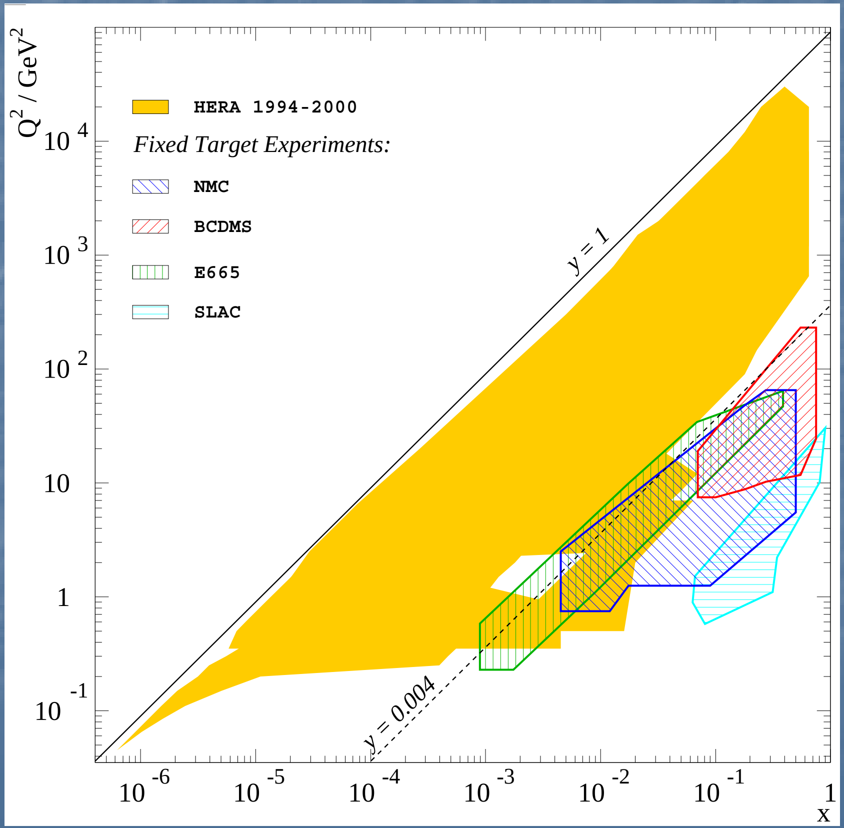
... much more, but not discussed here.

HERA Kinematics



From SLAC to HERA:

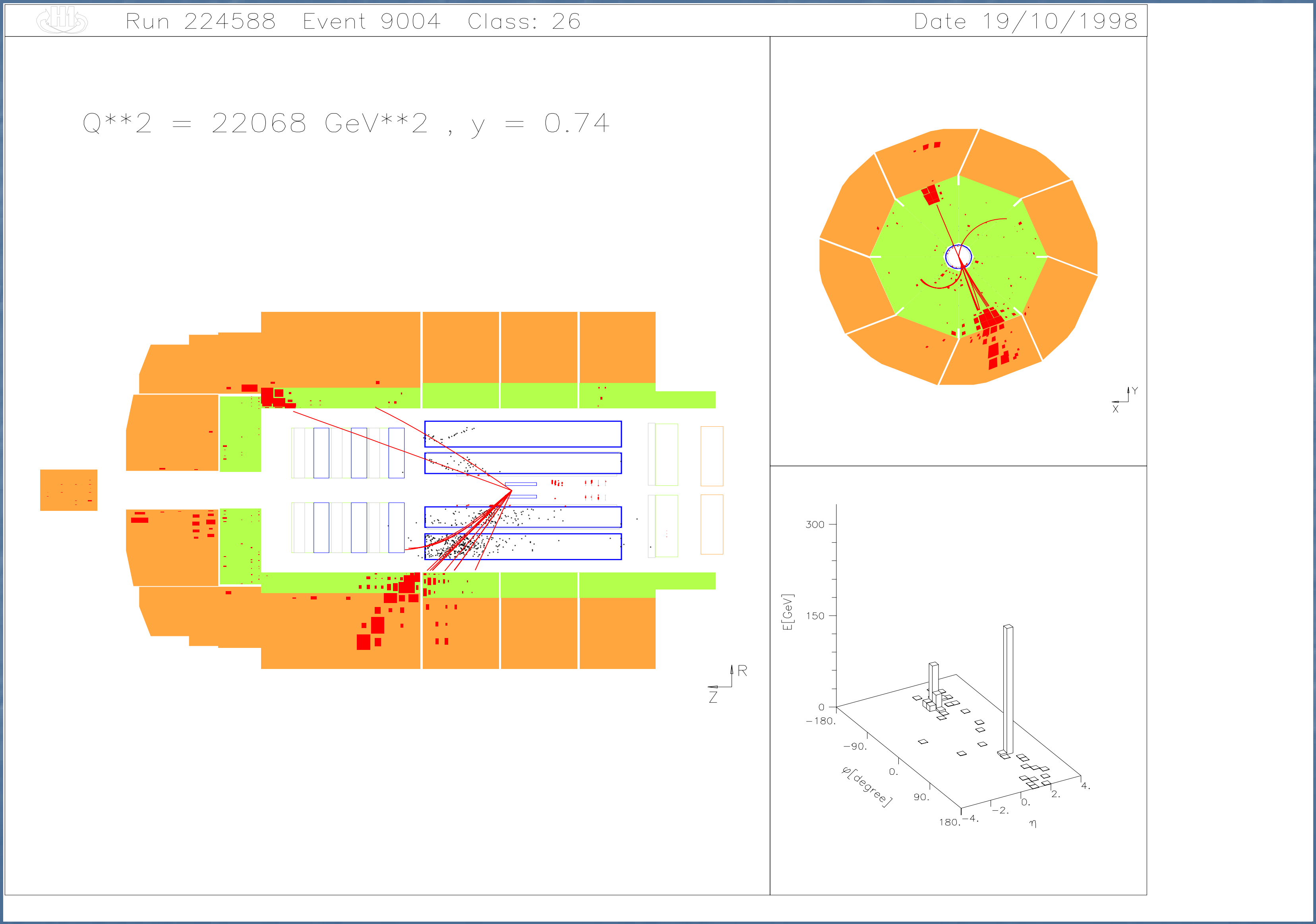
x : 0.1 → 0.0001
Q²: 10 → 10000 GeV²



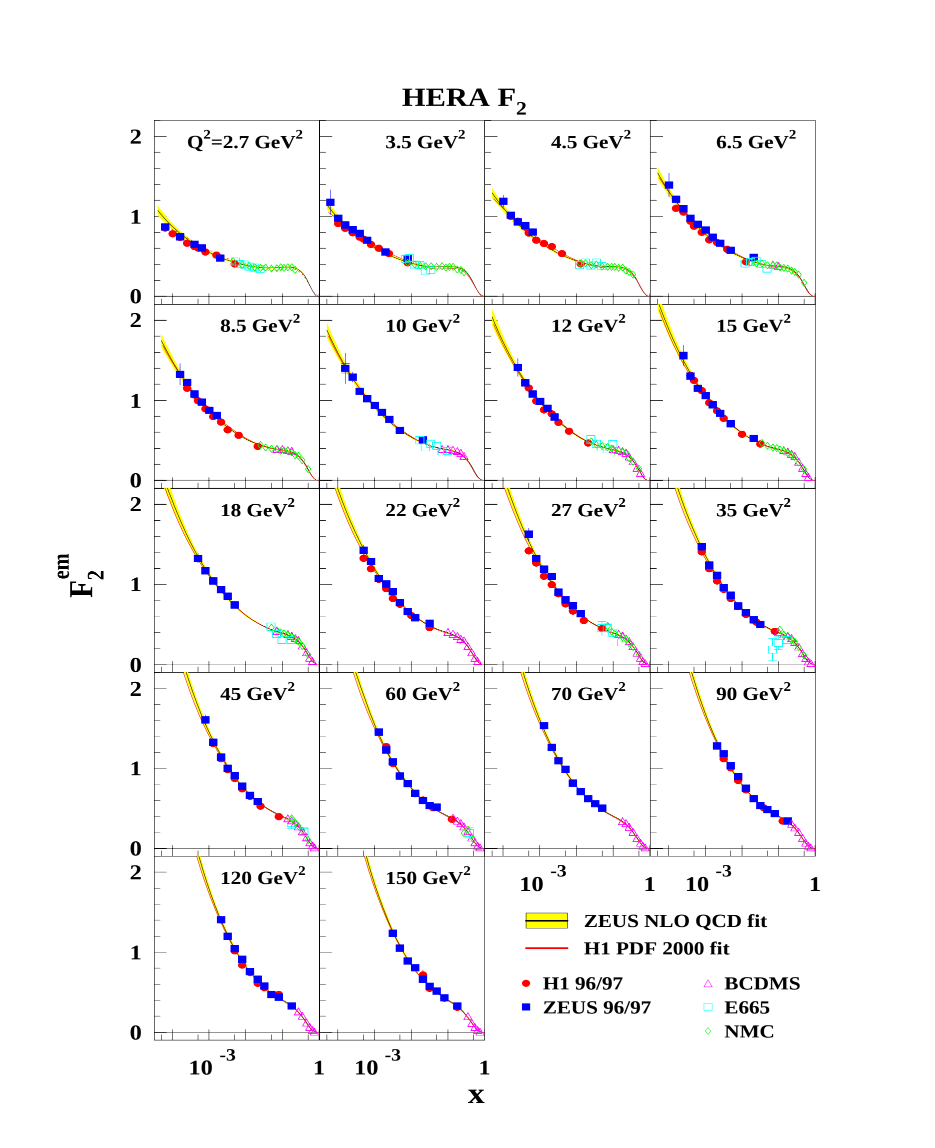
For the inclusive ep scattering
2 variables are sufficient: x and Q^2

→measure: 1) only electron
2) or hadrons
3) or combined (better resolution)

High Q^2 Deep Inelastic Event



Proton Structure : F_2 from H1 / ZEUS



- HERA experiments extend kinematic range in x→ 10^{-4} and Q^2 → 10^4 GeV^2

- F_2 dominates the cross section at small x and not too large y = (E-E') / E

$$\frac{d^2\sigma}{dQ^2 dx} = \frac{2\pi\alpha^2}{Q^4 x}\left[(1-y)F_2 + y^2 x F_1\right]$$

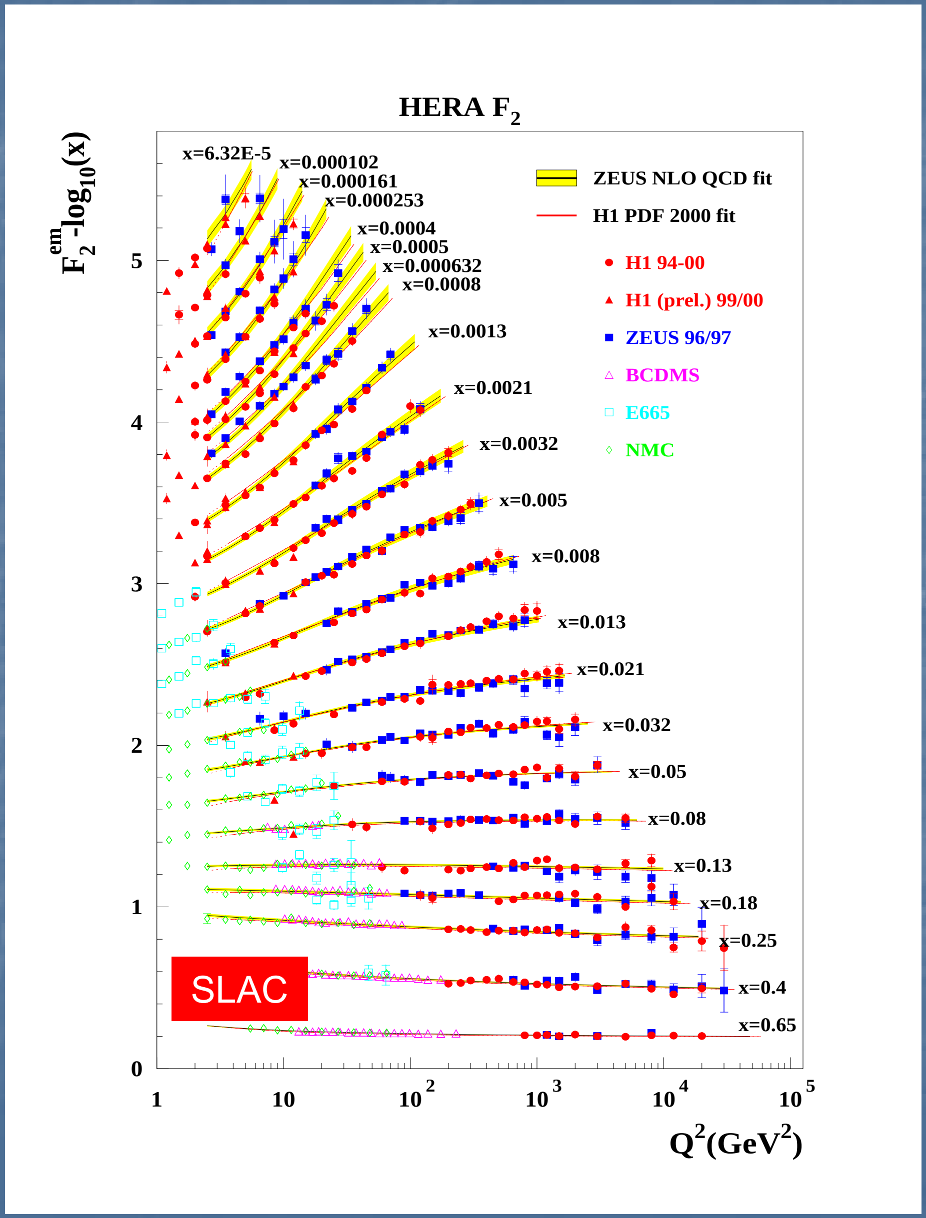
- F_2 increase towards smaller x
  → increasing number of sea quarks

- naïve Quark-Parton model seems to be not the full story:

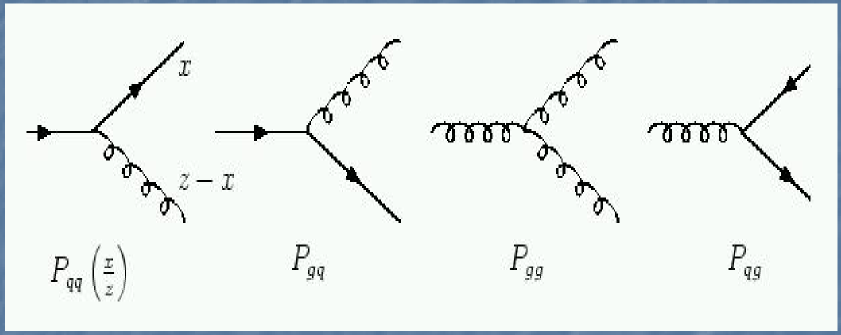
$$F_2(x) \rightarrow F_2(x, Q^2)$$

→ Scaling violations

Proton Structure : QCD



- QCD predicts scaling violations due to the following partonic subprocesses:



splitting functions $P_{qq}(x/z)$ ….

- at higher Q^2 probes smaller distances , the quark might have radiated a gluon not visible at lower Q^2
- evolution of parton densities in Q^2 described by DGLAP equations:

$$\frac{dq\left(x,Q^2\right)}{d\log\left(Q^2\right)} = \alpha_s \int_x^1 \left(q\left(z,Q^2\right) P_{qq}\left(\frac{x}{z}\right) + g\left(z,Q^2\right) P_{qg}\left(\frac{x}{z}\right) \right) \frac{dz}{z}$$

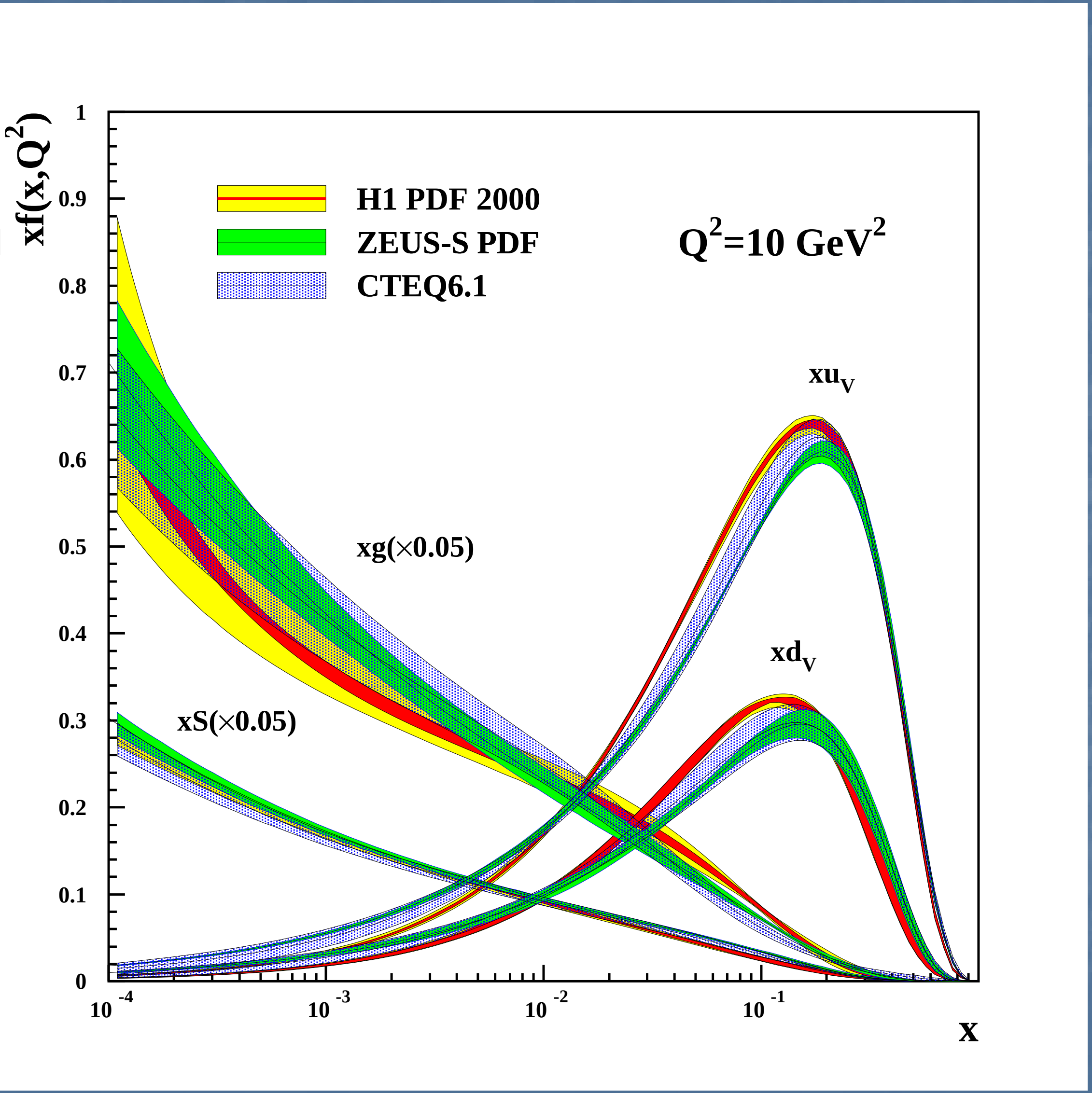
$$\frac{dg\left(x,Q^2\right)}{d\log\left(Q^2\right)} = \alpha_s \int_x^1 \left(q\left(z,Q^2\right) P_{gq}\left(\frac{x}{z}\right) + g\left(z,Q^2\right) P_{gg}\left(\frac{x}{z}\right) \right) \frac{dz}{z}$$

Proton Structure : Parton Density Functions

Procedure:

→ assume $q(x,Q^2)$, $g(x,Q^2)$ at $Q^2_0 \sim 1\ GeV^2$

→ fit ansatz to F_2 by evolving DPFs using DGLAP to higher Q^2 using



Results:

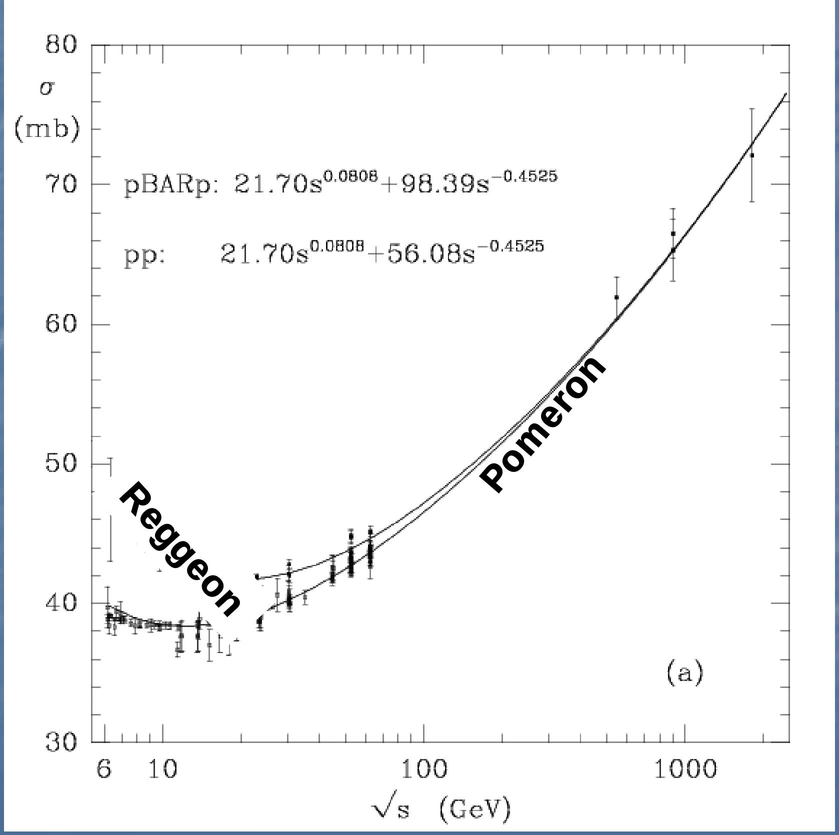
→ **valence quarks dominate above x ~ 0.05**

→ **at lower x mainly gluons and sea quarks**

Pomeron : History

Light scattering: $\sigma_{tot} = 4\pi\lambda \,\mathrm{Im}(A(\Theta = 0))$ ... optical theorem

Hadronic reactions:



Regge model:

→ exchange of Regge trajectories

$$\sigma_{tot} = \frac{1}{s}\mathrm{Im}(A(s, t = 0)) \approx s^{\alpha(t=0)-1}$$

Donnachie,Landshoff:

$$\sigma_{tot} = As^{0.08} + Bs^{-0.45}$$

Leading trajectory, responsible for the cross section increase, is related to the exchange of the Pomeron with ...

$$\alpha_P = 1.08 + 0.25t$$

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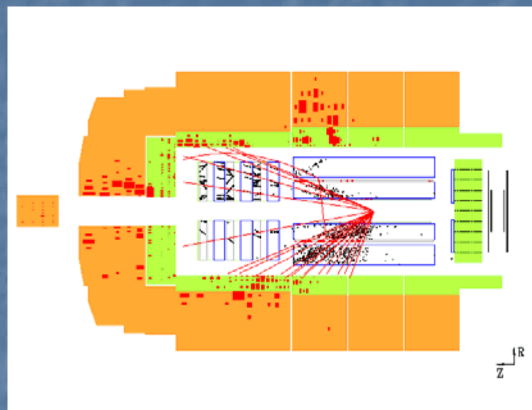
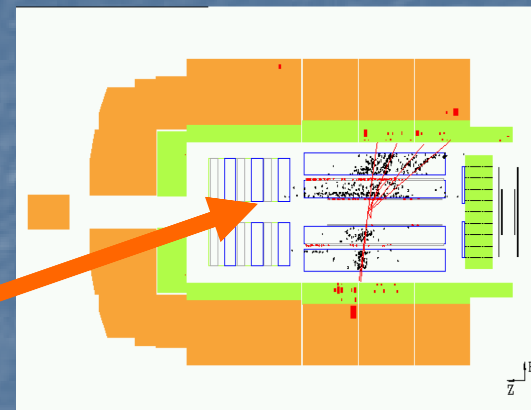
Pomeron : Signatures

non-diffractive event



diffractive event

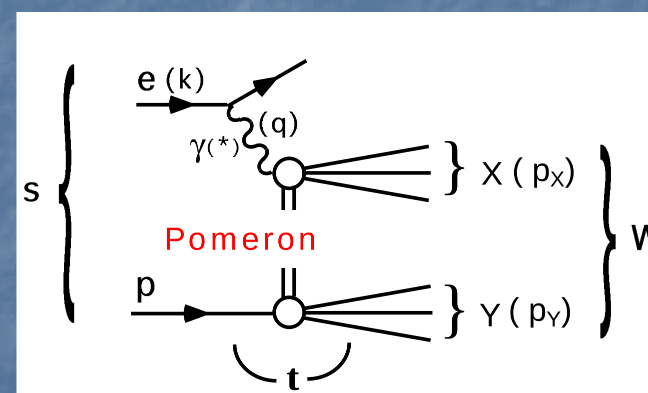


no visible forward activity

Two systems X and Y well separated in phase space with low masses $M_X, M_Y \ll W$

System Y : proton or p-dissociation carries most of the hadronic energy

System X : vector meson, photon or photon-dissociation



Exchange of colourless object - Pomeron with low momentum fraction x_P

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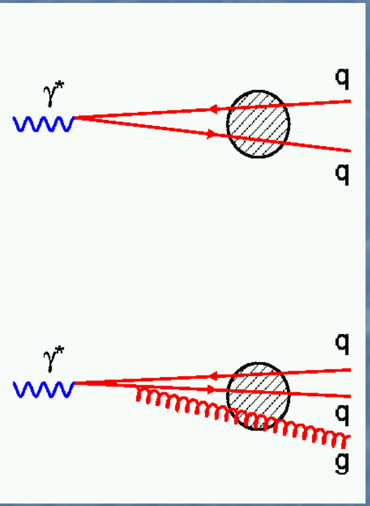
a7 apis, 8/21/2003

a8 apis, 8/21/2003

Diffraction : Models

Notation: hard = perturbative process, parton level

Starting from alternative frames → two classes of models :

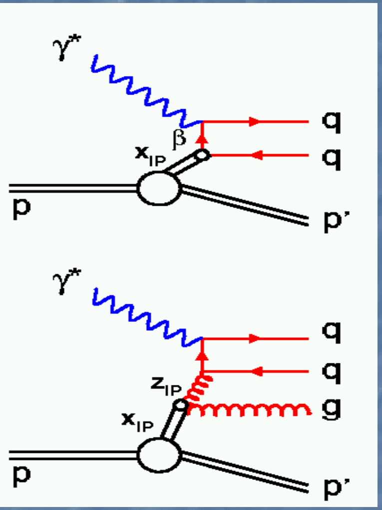


Proton rest frame

formation time
$\tau \sim 1 / M_p x$
long at small x

Breit frame

Standard DIS
scheme



LO: 2 gluons , … gluon ladders ← **Exchange** → object with partonic structure

fluctuates in colour dipoles
$q\bar{q}$, $q\bar{q}$+g, … ← **Virtual photon** → point-like couplings to partons,
standard partonic cross sections

combine soft & hard processes by
different parton transverse momentum ← **Dynamics** → evolve diffractive PDFs in x / Q^2
by DGLAP / BFKL schemes

Colour Dipole Models

Resolved Pomeron Models

Pomeron : Parton Structure

QCD Fit Model:

1) Use QCD hard scattering factorization:

$$\sigma^{\gamma^* p \rightarrow p'X} = \sigma^{\gamma^* i} \otimes f_i^D$$

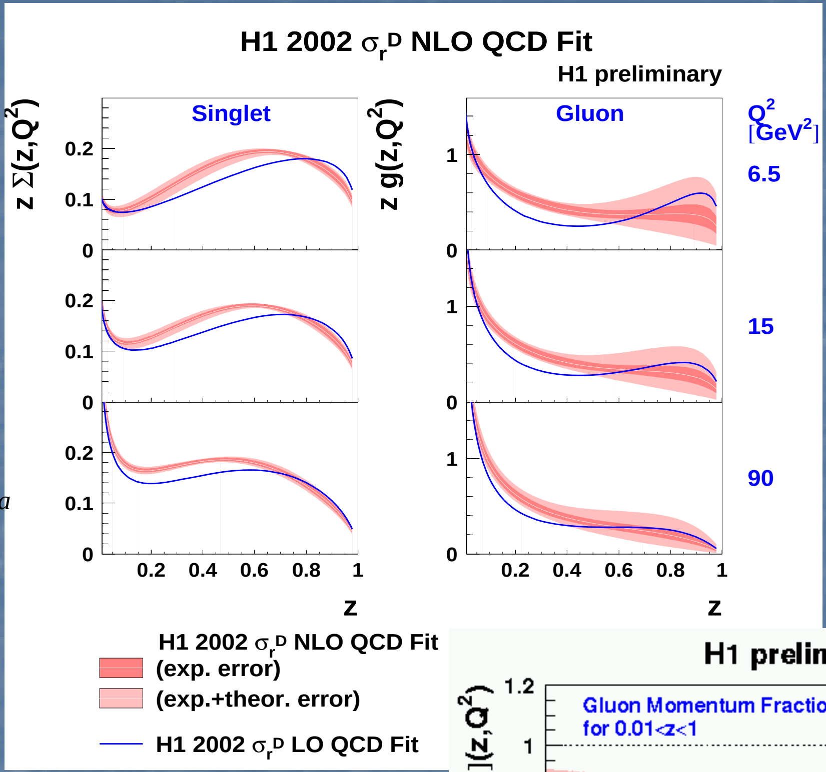
$\sigma^{\gamma^* i}$ = universal partonic cross section same as in inclusive DIS

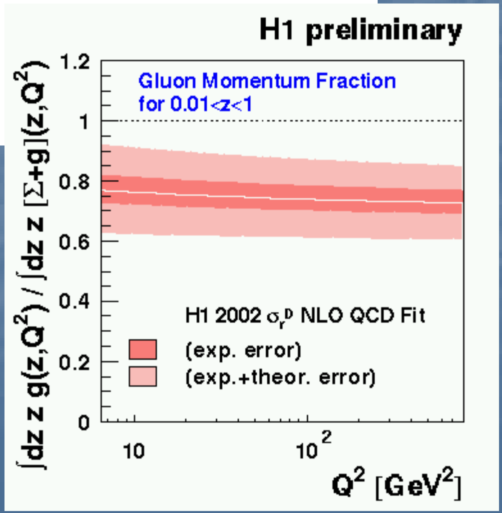
f_i^D = diffractive PDFs, x_P & t = const.

2) Parton ansatz for exchange:

$$Pomeron = \sum q(z) + \bar{q}(z) + g(z)$$

3) Use NLO DGLAP to evolve diffractive PDFs to $Q^2 > Q_0^2 = 3$ GeV^2

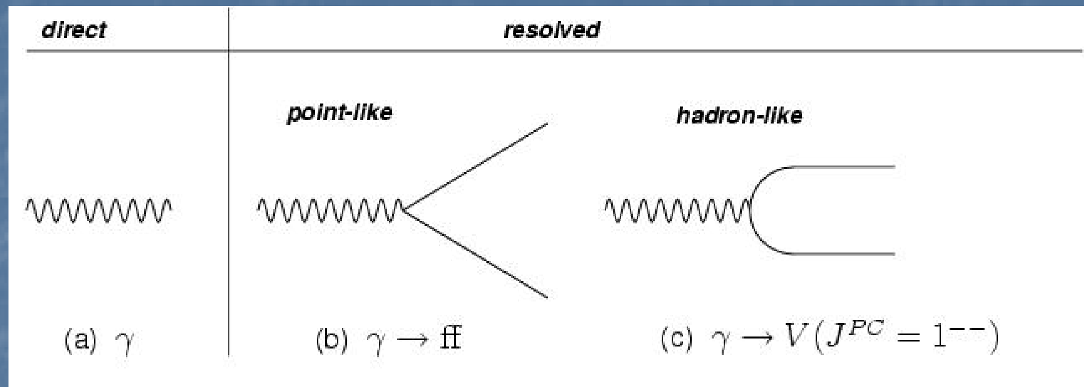




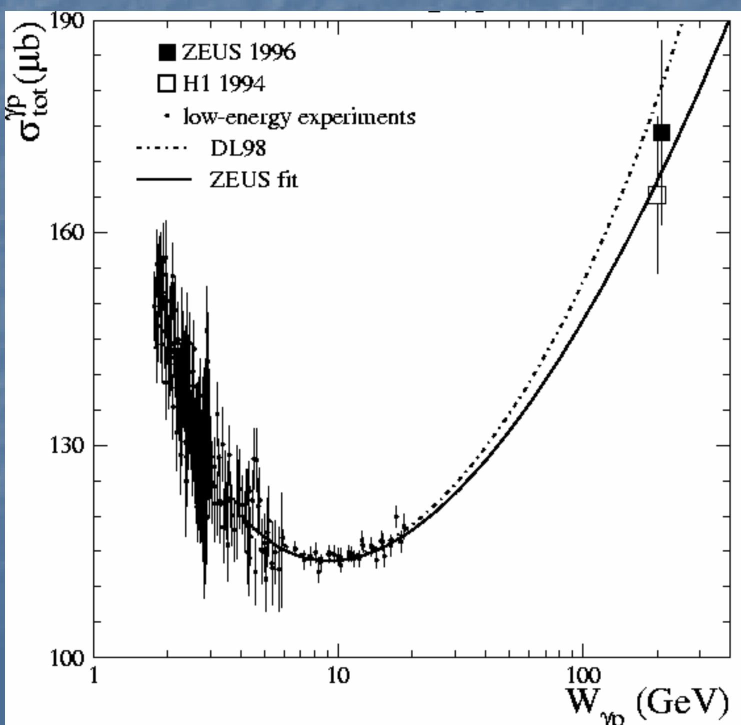
Gluon momentum fraction 75 ±15 % at Q^2 = 10 GeV^2 and remains large up to high Q^2

Photon Structure : Basics

Classic Photon
- pure “electromagnetic”
- no (partonic) structure



Heisenberg
-quantum fluctuations
- partons / hadrons

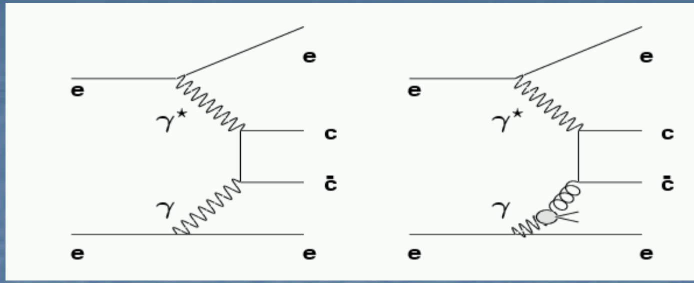


→ Rise described by s $^{\alpha}$ with $\alpha \sim 0.08$
like pp, pp, πp,… hadron reaction

Photon behaves like a hadron
→ what’s the partonic structure ?

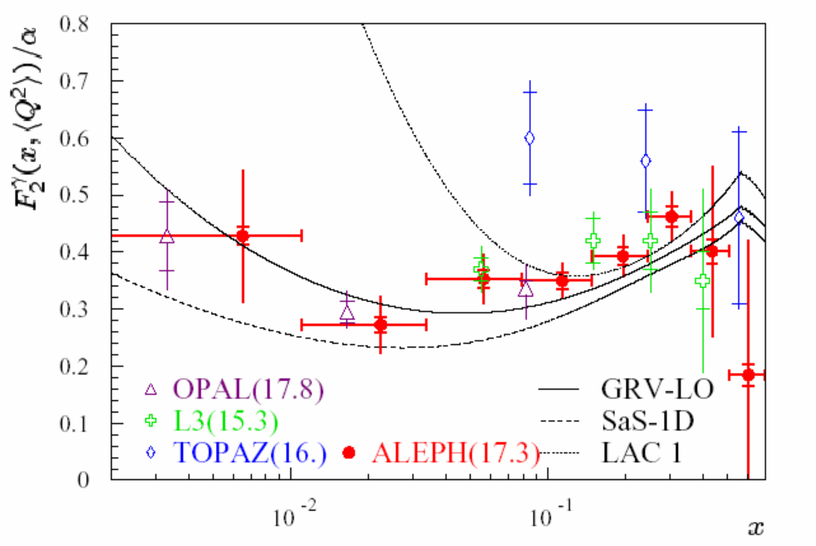
Photon Structure: F_2^γ & LEP

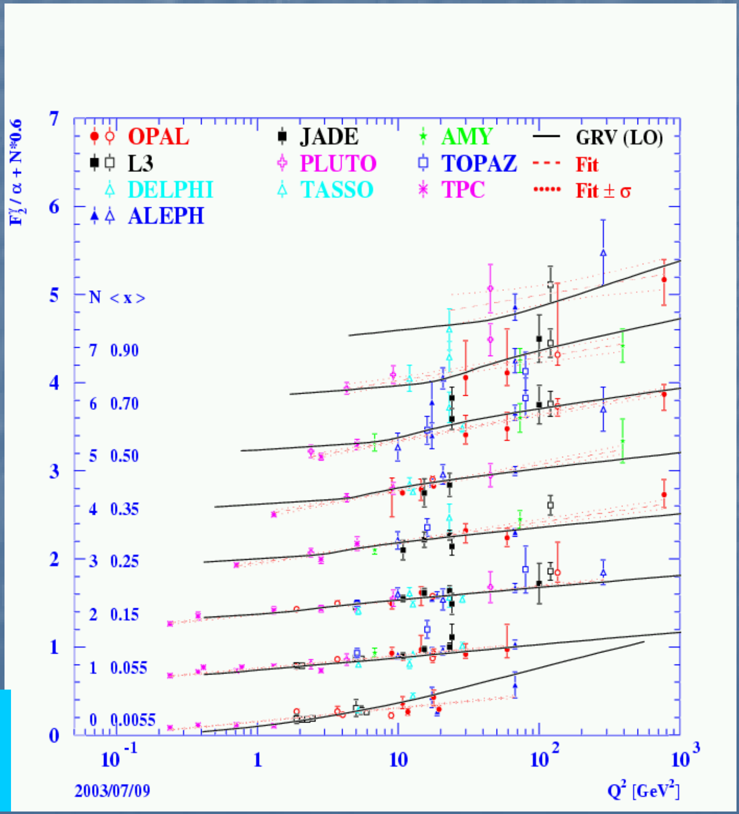
Traditional place is : e^+e^- at LEP
Principle: use highly-virtual photon to probe
a quasi-real photon →



Deep Inelastic photon - photon scattering
→ similar ansatz as for proton structure:

$$\frac{d^2\sigma}{dx\,dQ^2} = \frac{2\pi\alpha^2}{xQ^4}\left[\left(1+(1-y)^2\right)F_2^\gamma\left(x,Q^2\right) - y^2 F_L^\gamma\left(x,Q^2\right)\right]$$





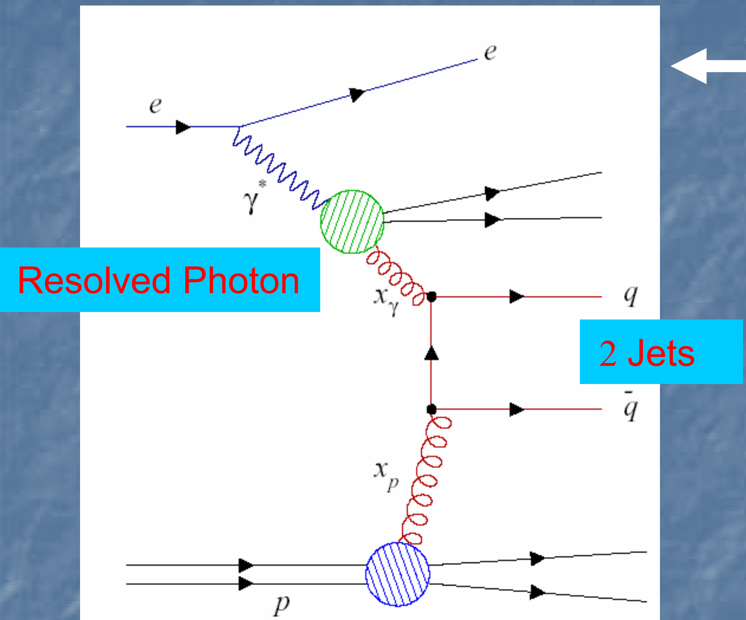
Scaling violations well-described by partonic photon models …GRV

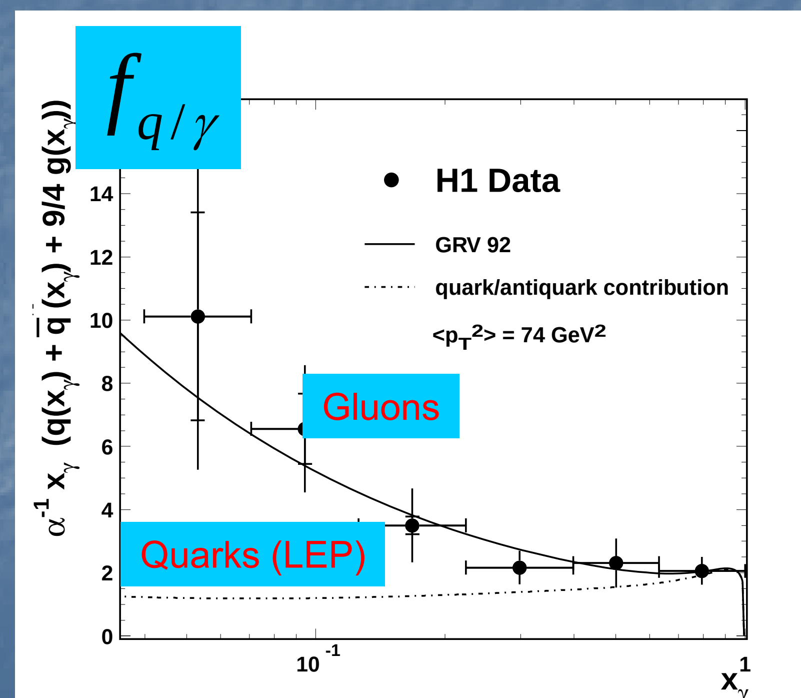
Photon Structure : Parton Density Functions

Use partons of proton to probe the photon

Signature:
2 jets with large transverse energy

$$\sigma_{2\,jet} \propto flux_{\gamma} \cdot f_{q/\gamma} \cdot f_{q/p} \cdot M^2$$





→ **quarks dominate at high x,**
no "valence quark" peak as F_2^p

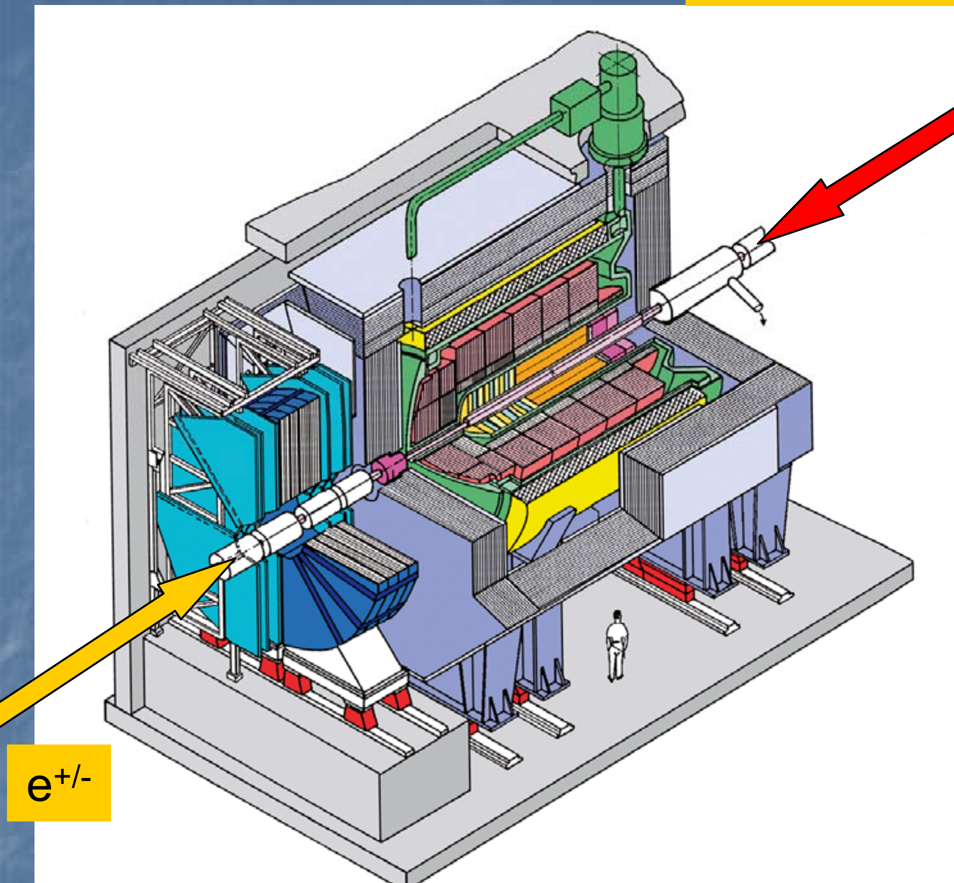
→ **gluons dominate low x**
as expected by QCD

Other Physics Topics …

- Total cross section
- QCD dynamics, running coupling constant α_s
- Electroweak physics
- Heavy flavours : charm, bottom
- Beyond the standard model: SUSY, lepto-quarks, exited Fermions ....

Hope for large luminocity at HERA-2

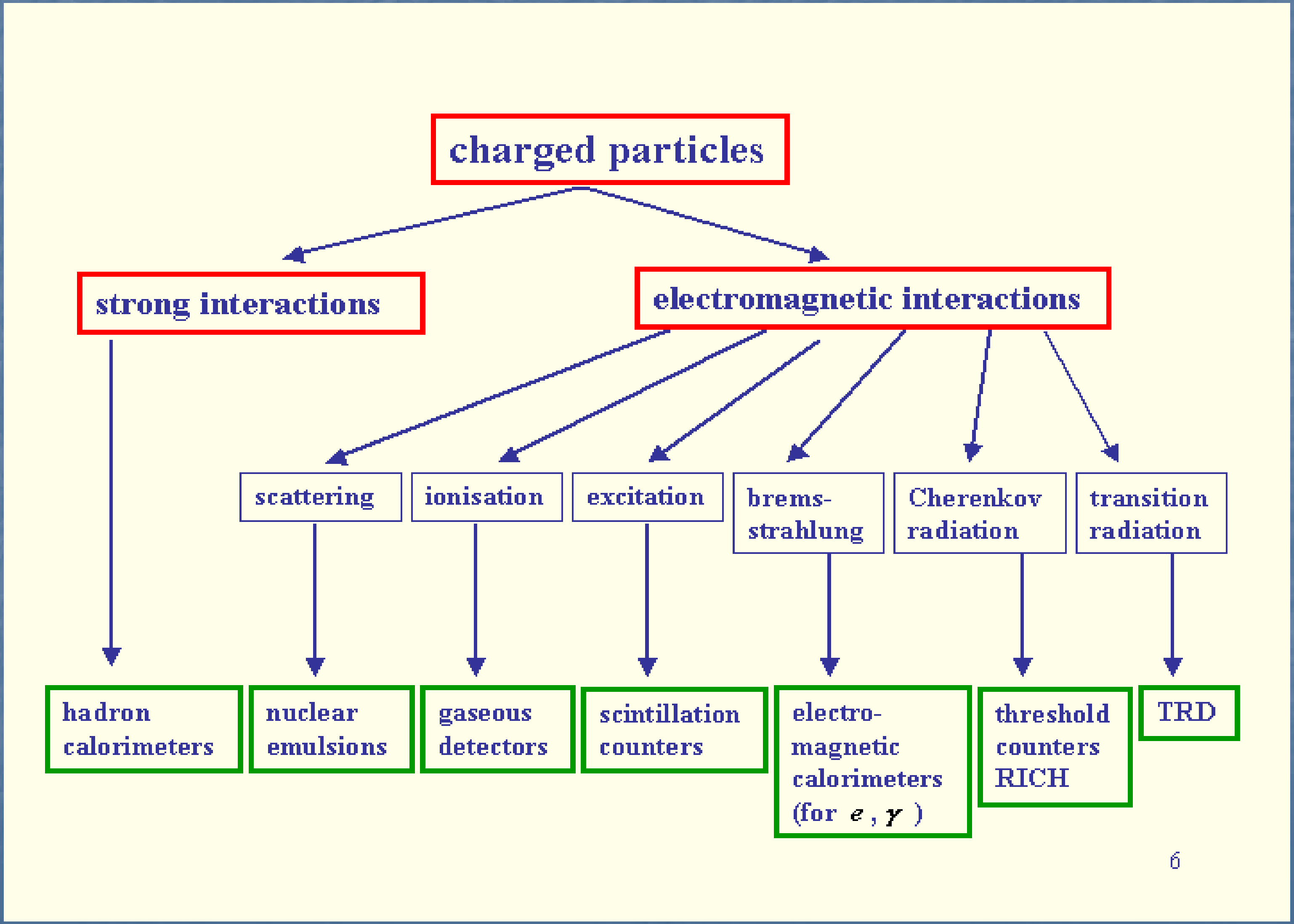
H1 Detector



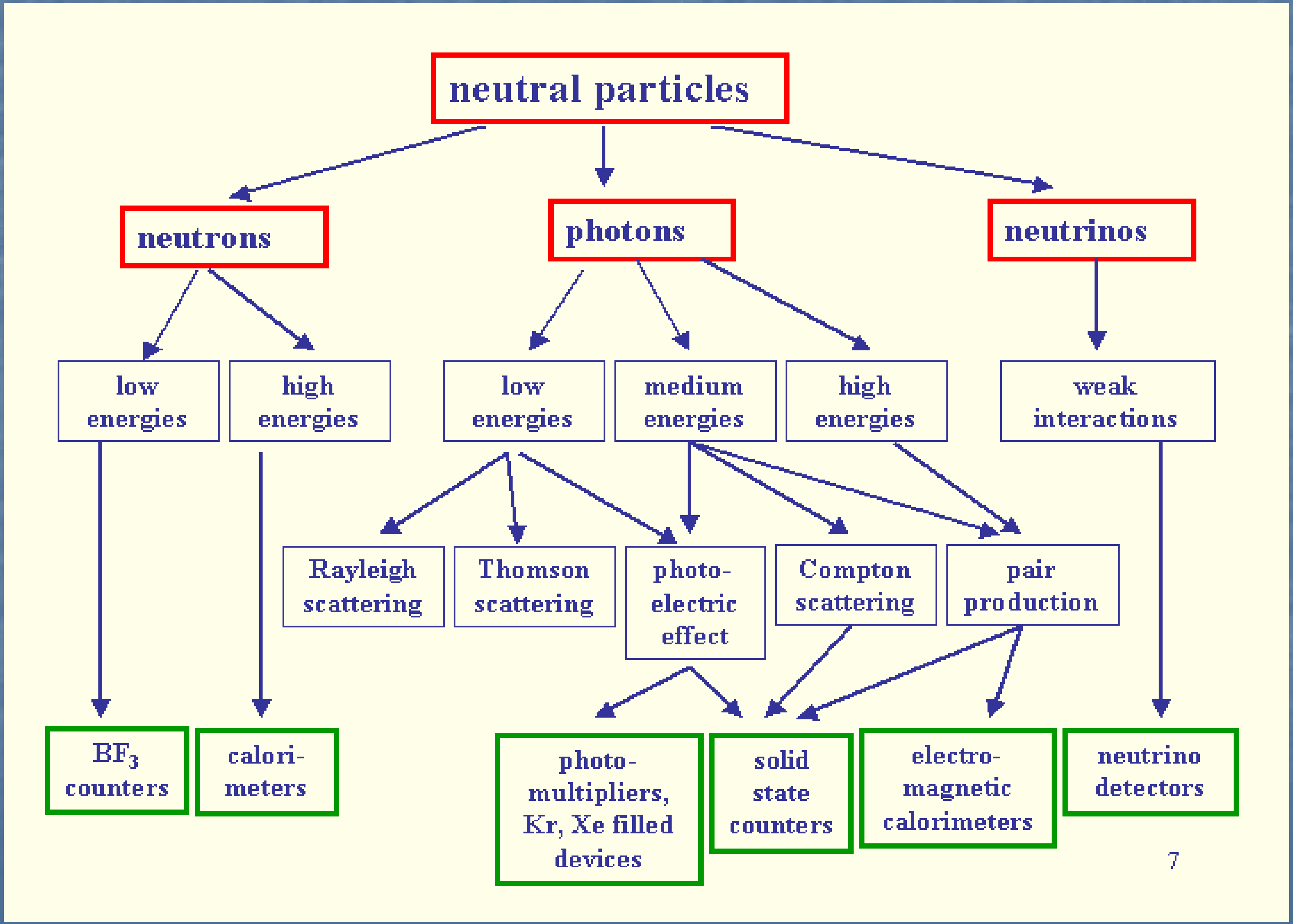
~ 400 physicists
40 institutes
11 countries

~ 2800 t
not visible:
front-end electronics in the trailer

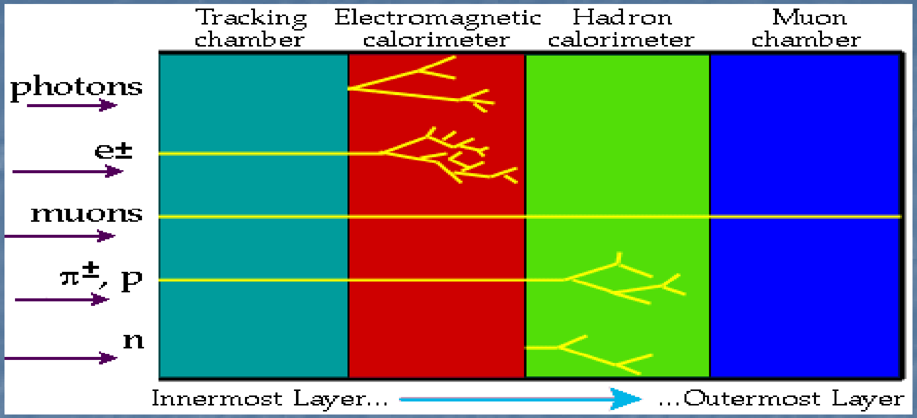
Detector Principles – Charged Particles



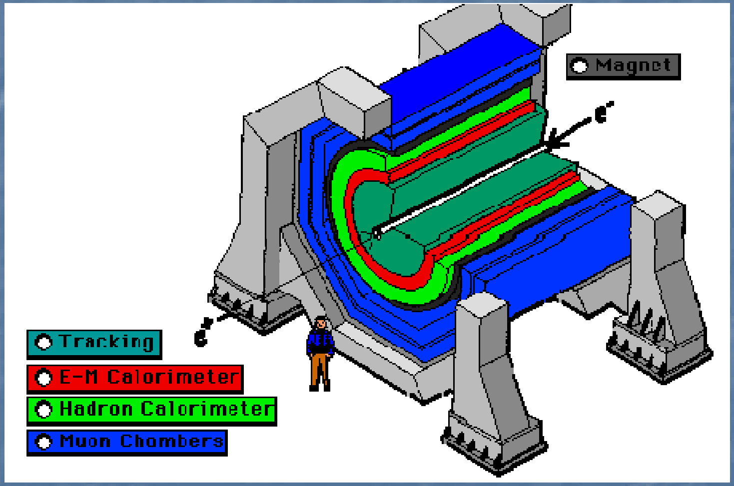
Detector Principles – Neutral Particles

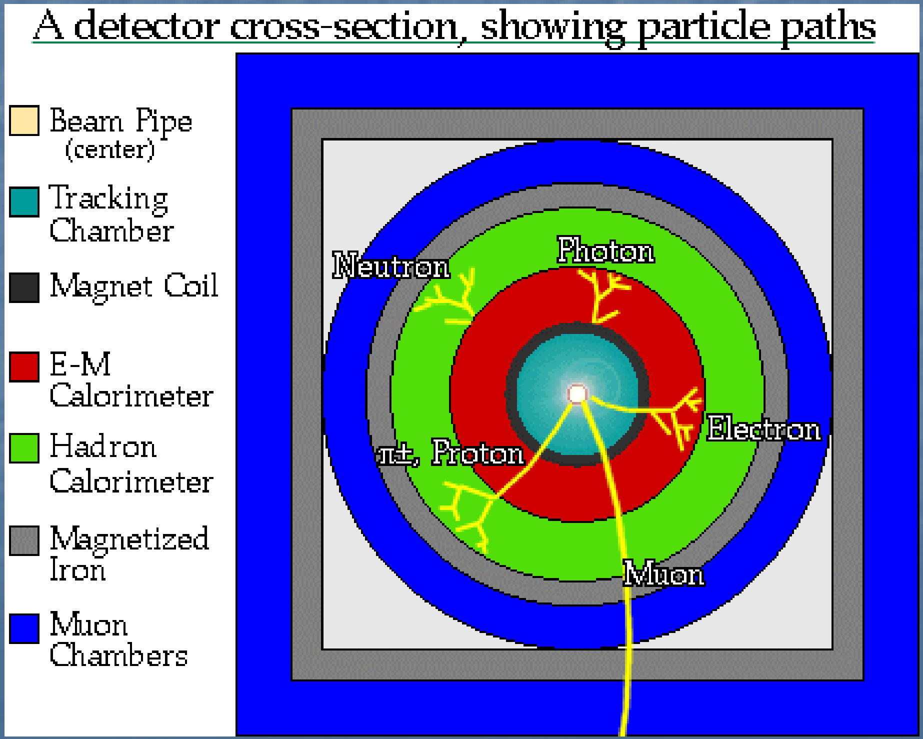


Principle Collider Detector



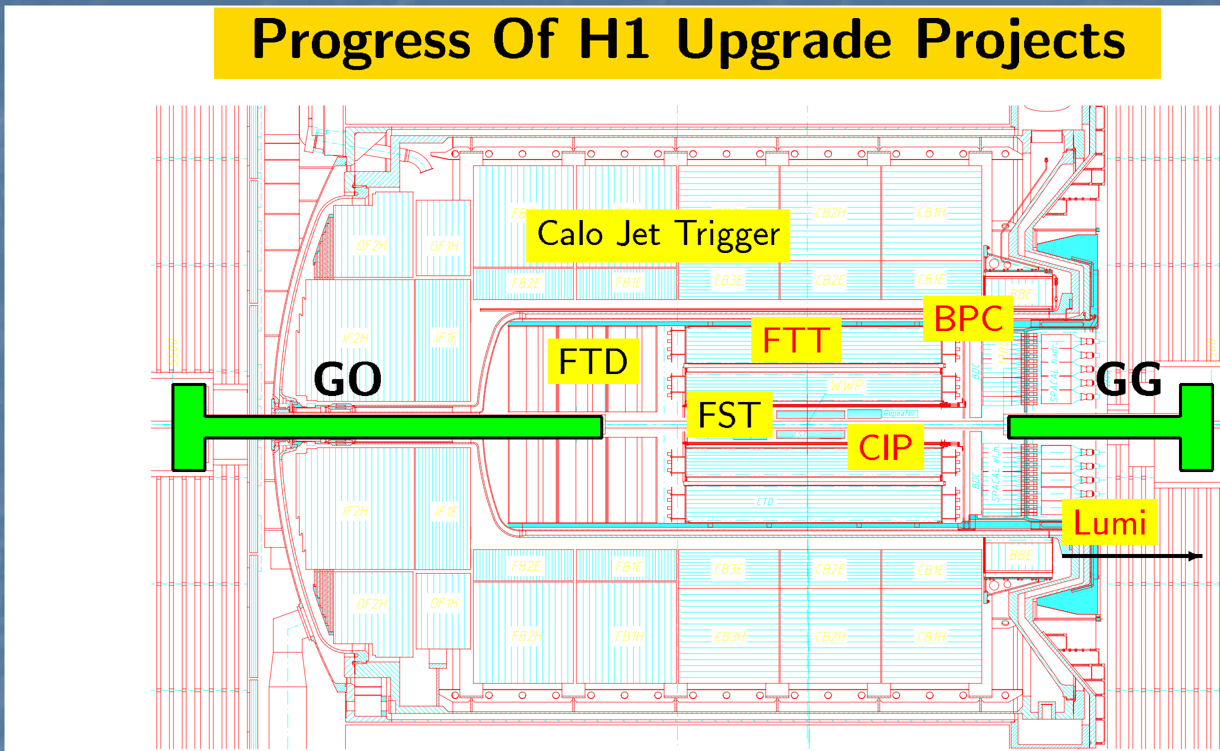
General structure :
order to reach best resolution ….





Add front and rear caps … 4π

H1 Detector – Side View



ons

- beam pipe
- backward Si Tracker
- central Si Tracker
- LAr G0 Support
- Plug
- forward ToF
- FPS/FNC
- Polarimeter

upgrades

- Fast Track Trigger (FTT)
- Lumi Monitors
- Inner Prop. Chamber (CIP)
- Backward Prop. Chamber (BPC)

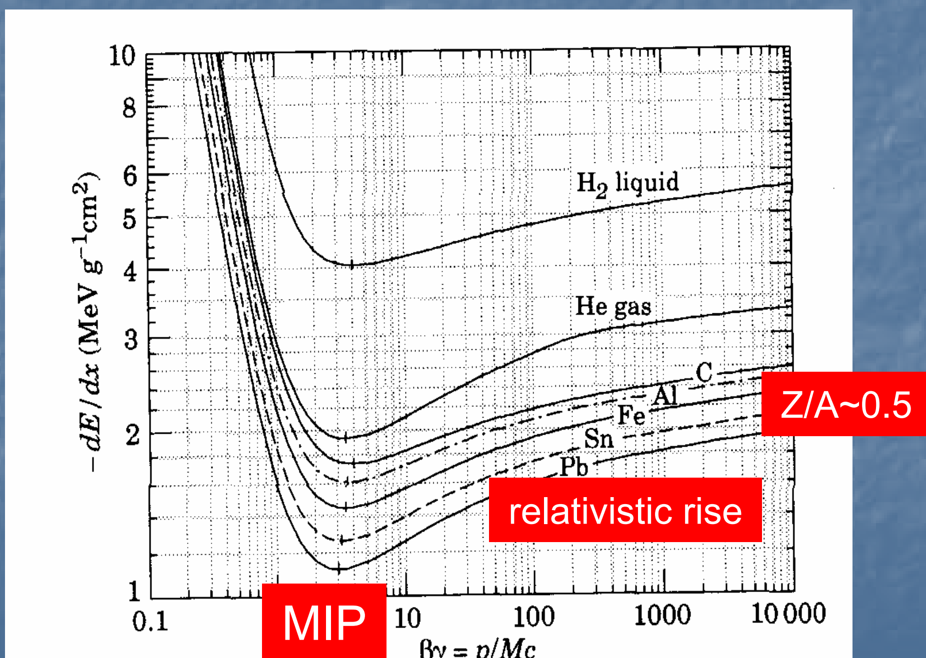
- Forward Tracker (FTD)
- Calo Jet Trigger
- Forward Si Tracker (FST)

Tracking Detectors : Basics

Ionization most relevant process for tracking detectors → Bethe-Bloch formula:

$$\left\langle \frac{dE}{dx} \right\rangle = -4\pi N_A r_e^2 m_e c^2 z^2 \frac{Z}{A}\frac{1}{\beta^2}\left[\frac{1}{2}\ln\frac{2m_e c^2\gamma^2\beta^2}{I^2}T^{max} - \beta^2 - \frac{\delta}{2}\right]$$

Only β dependency, others are constants ..



Gaseous detectors:

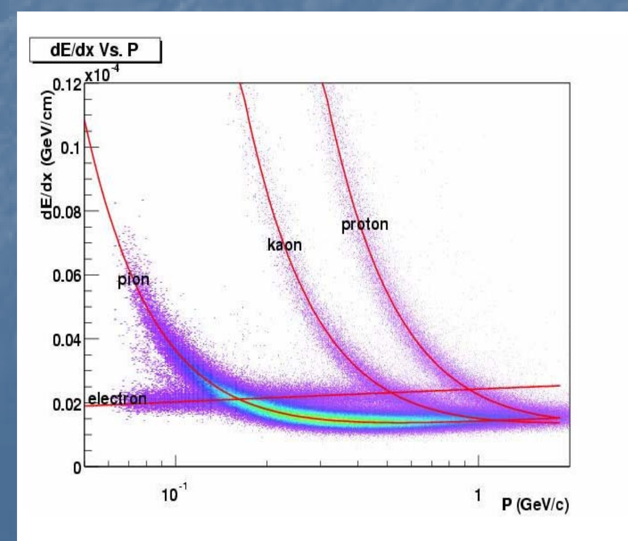
few collisions → charge amplification in strong electric field of anode wires

Silicon detectors:

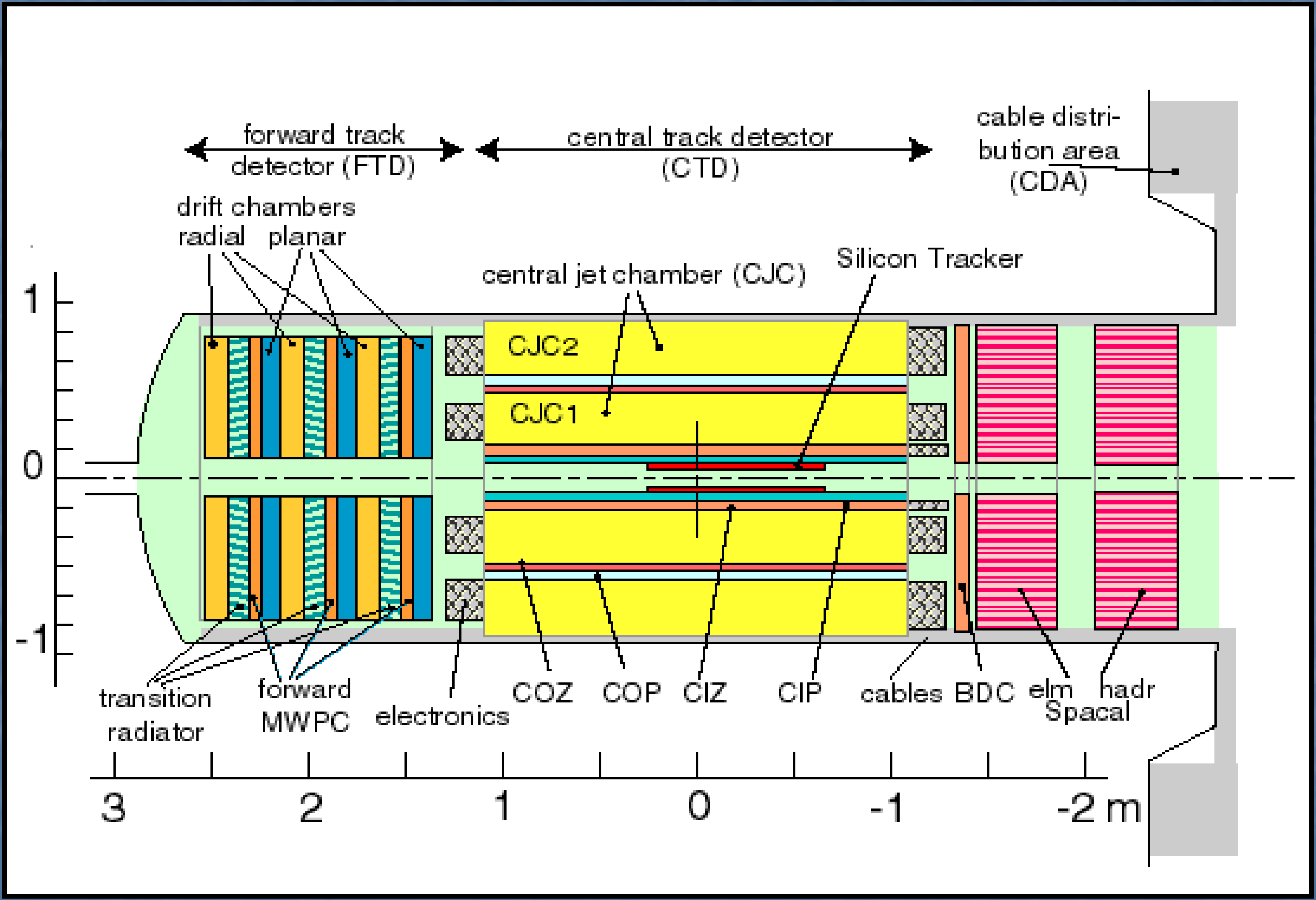
more collisions → charge collection only

Side effect:

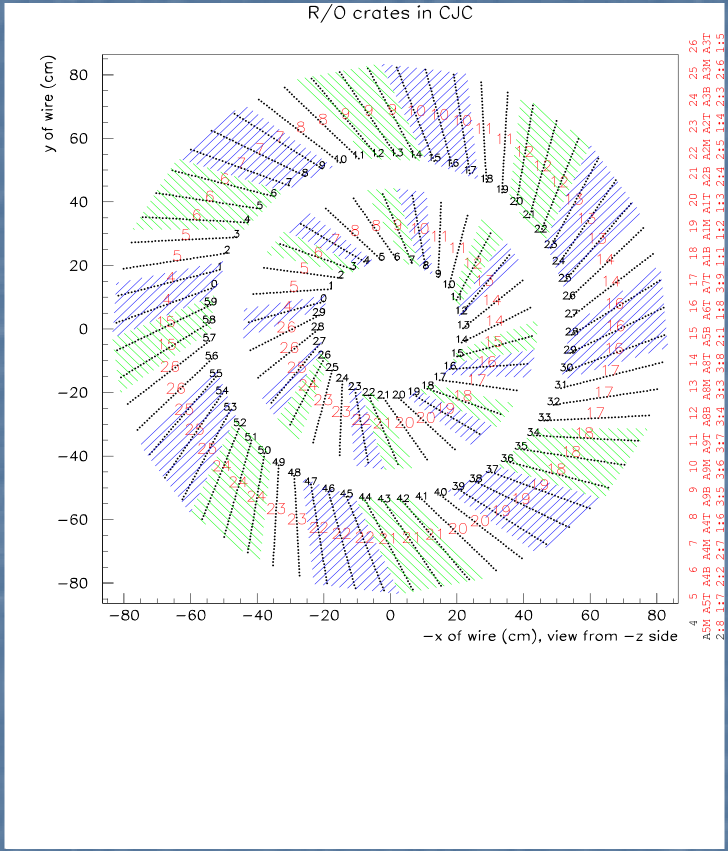
β = β(M) used for particle ID

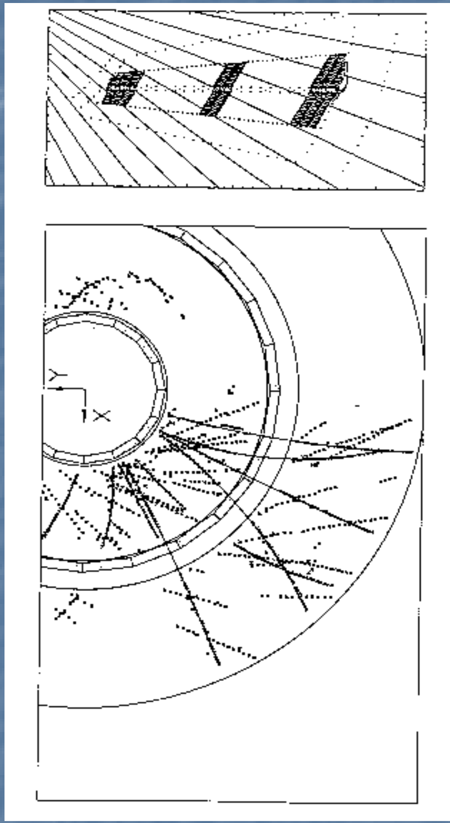


H1 Tracking Detectors



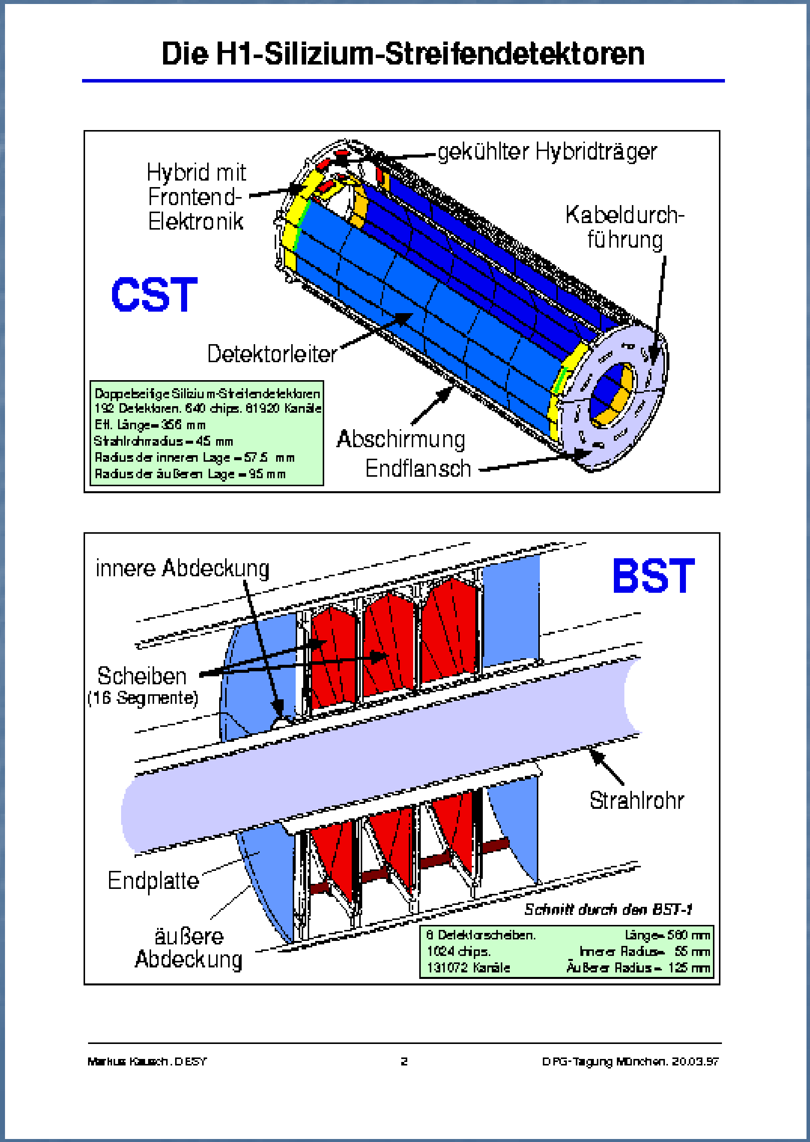
H1 Tracking – Drift Chambers

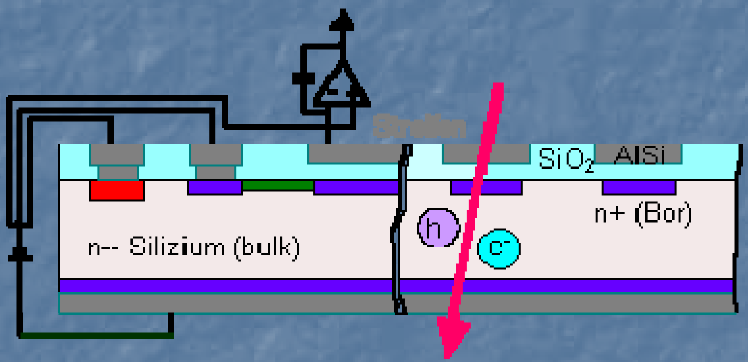




The basic H1 tracking detector,
Resolution~ 0.2 mm

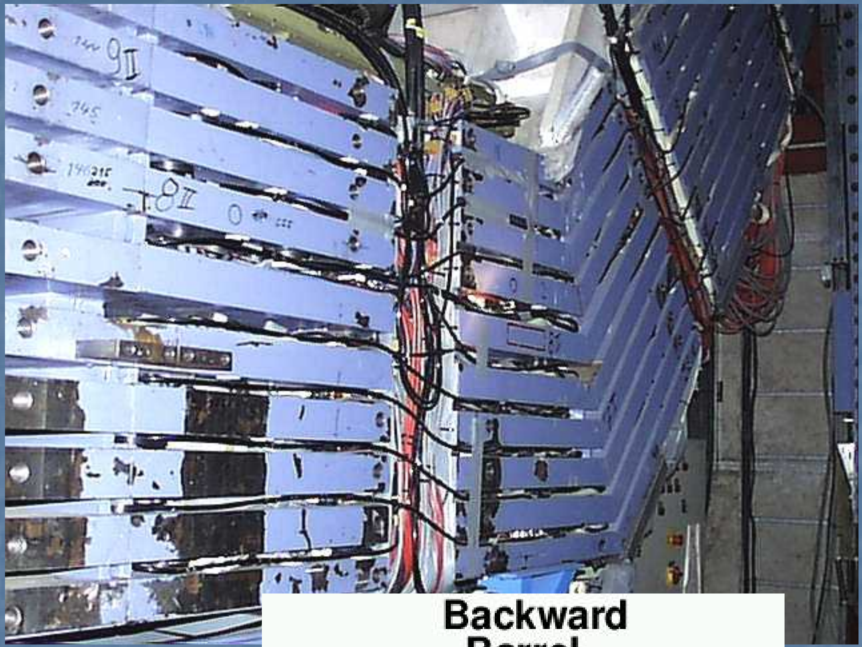
H1 Tracking – Silicon

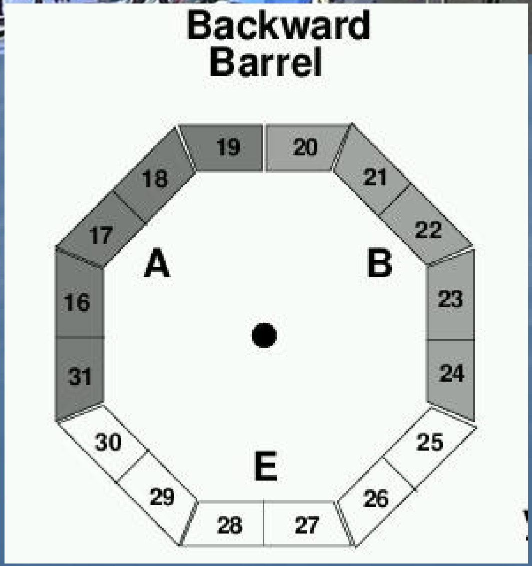




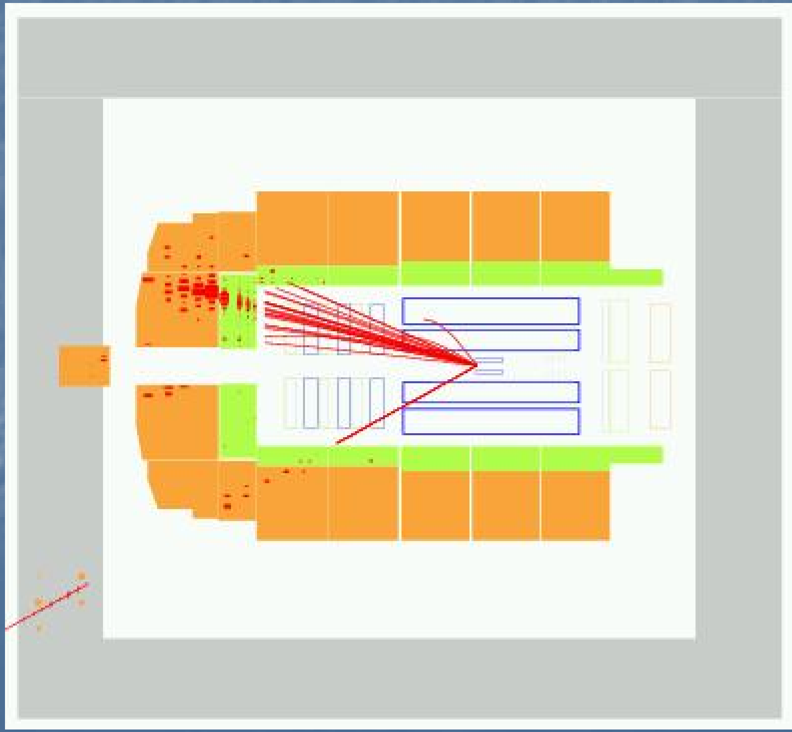
0.3 mm Silicon results
in ~32.000 electron-hole pairs,
Resolution ~ 10 μm

H1 Tracking – Muon Chambers





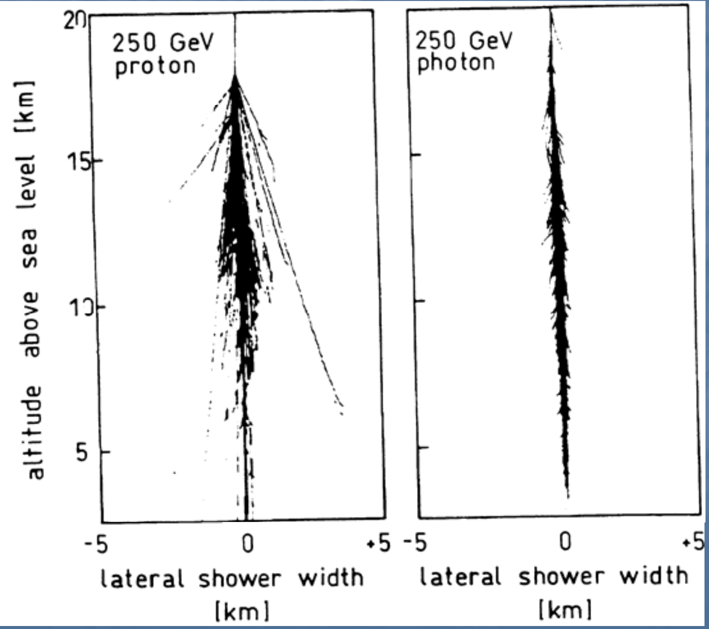
Muon detectors are
instrumented iron layers
In the outermost position



Calorimeter - Basics

Principle: force the particles to shower and "count" number of shower particles (collect all charged particles by fields at electrodes, or convert to light by scintillation on measure light intensity)

2 types of showers: 1) electromagnetic via bremstrahlung & pair production → small lateral size
2) hadonic via strong interaction plus electromagnetic → less contained



Material Properties

	R_L(cm)	E_c (MeV)	λ_a(cm)
Lead	0.56	7.4	17.2
Iron	1.76	20.7	16.8
Tungsten	0.35	8.0	9.6

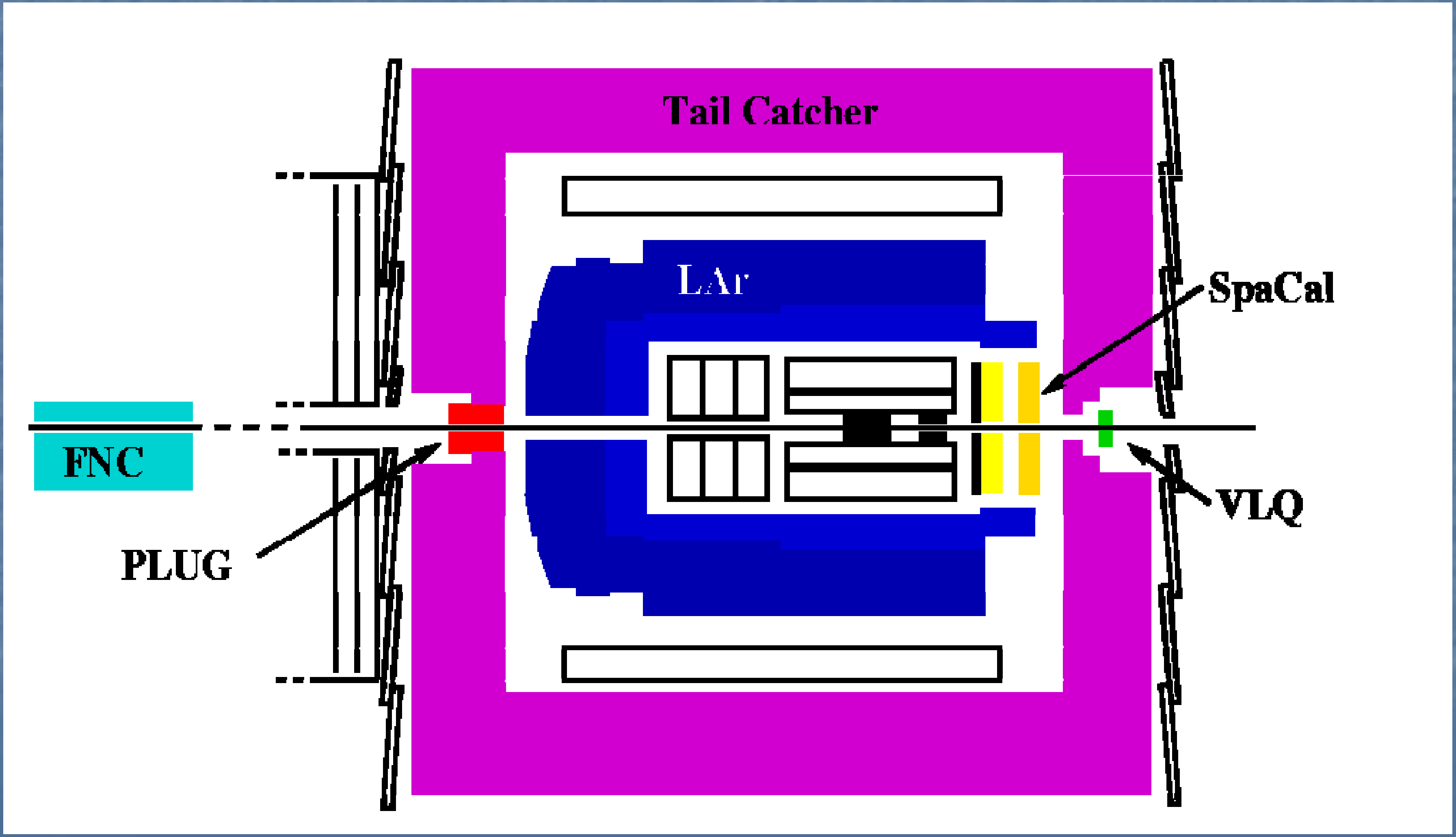
λ_a= nuclear absorption length

Energy resolution:

$$\frac{\sigma_E}{E} = \frac{(7.5-25)\%}{\sqrt{E}} \quad \textbf{EM}$$

$$\frac{\sigma_E}{E} = \frac{(35-80)\%}{\sqrt{E}} \quad \textbf{hadronic}$$

H1 Calorimeters - Overview

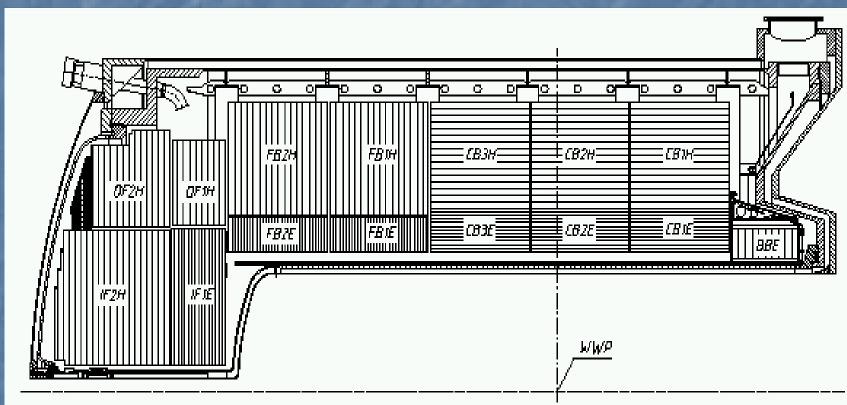


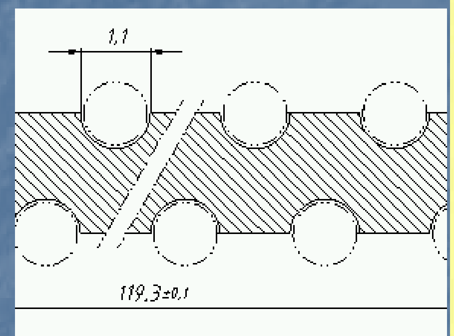
Main Calorimeters – Liquid Argon & Spacal

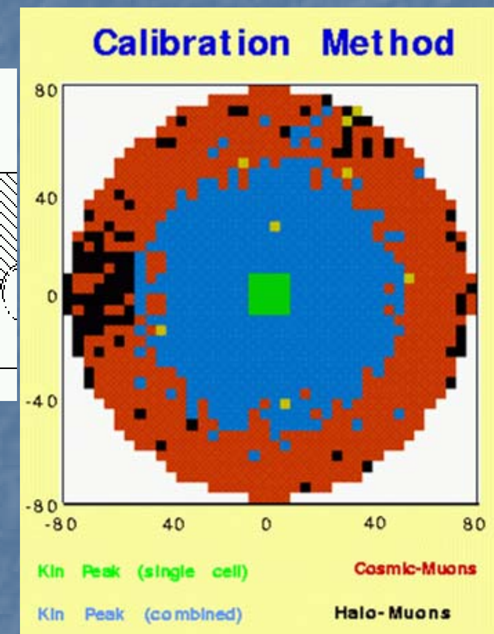
Both are sampling calorimeters (no cristals !) …

Spacal: scilillating fibers embedded in lead matrix
0.5 / 1 mm fibers for EM / hadronic part

LAr: 70m³ Argon interspaced with lead (→ EM)
and steel plates (hadronic)







Energy resolution:
test beam, kinematic peak, cosmic muons, …

$$\text{EM}: \quad \frac{\sigma_E}{E} \sim \frac{10...13\%}{\sqrt{E[GeV]}} + 1\%$$

$$\text{Had}: \quad \frac{\sigma_E}{E} \sim \frac{50\%}{\sqrt{E[GeV]}} + 2\%$$

$$\text{EM}: \quad \frac{\sigma_E}{E} \sim \frac{7\%}{\sqrt{E[GeV]}} + 1$$

$$\text{Had}: \quad \sigma_{\text{E}} \sim 50\%$$

H1 Trigger System

- Despite the vacuum of 10^{-9} bar the p – rest gas interactions dominate by a factor of ~ 1000 over e-p interactions
- → only a Trigger Processor makes e-p physics possible
- H1 trigger has 3 levels:

L1: 2.3 μsec, logical combination of trigger elements of subdetectors stops the pipeline, rate 1 kHz

L2: topological/neuronal decision starts the readout, rate ~ 100...200 Hz

L4: PC farm, event building, data logging, rate ~ 5 Hz

Without Trigger System NO Useful Data !!!

…some spare slides →

The HERA Parameters

HERA parameters	Design Values		Values of 1995	
	e-ring	p-ring	e-ring	p-ring
Circumference (m)	6336			
Energy (GeV)	30	820	27.5	820
Center-of-mass energy (GeV)	314		300	
Injection energy (GeV)	14	40	12	40
Injection time (min)	15	20	45	60
Energy loss per turn (MeV)	127	$1.4 \cdot 10^{-10}$	127	$1.4 \cdot 10^{-10}$
Current (mA)	58	160	30	55
Magnetic field (T)	0.165	4.65	0.165	4.65
Number of bunches	210	210	174+15	174+6
Bunch crossing time (ns)	96			
Horizontal beam size (mm)	0.301	0.276	0.239	0.185
Vertical beam size (mm)	0.067	0.087	0.055	0.058
Longitudinal beam size (mm)	0.8	11	0.8	11
Specific luminosity ($cm^{-2}s^{-1}mA^{-2}$)	$3.6 \cdot 10^{29}$		$5.0 \cdot 10^{29}$	
Instantaneous luminosity ($cm^{-2}s^{-1}$)	$1.6 \cdot 10^{31}$		$4.3 \cdot 10^{30}$	
Integrated luminosity per year (pb^{-1}/a)	35		12.5	

HERA Bunch Structure

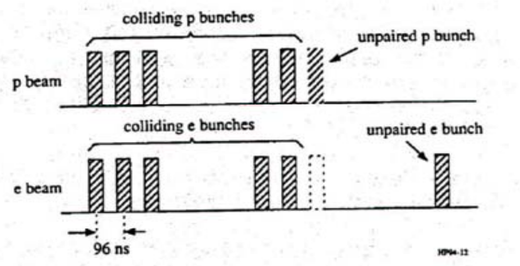


Fig. 13 Sketch of the HERA bunch configuration

→ Unpaired proton bunches, which have no electron partner and vice versa

→ Used for the study of beam induced background and determination of luminosity

Structure of the „proton fill":

- 174 colliding bunches
- 15 positron pilot bunches
- 6 proton pilot bunches

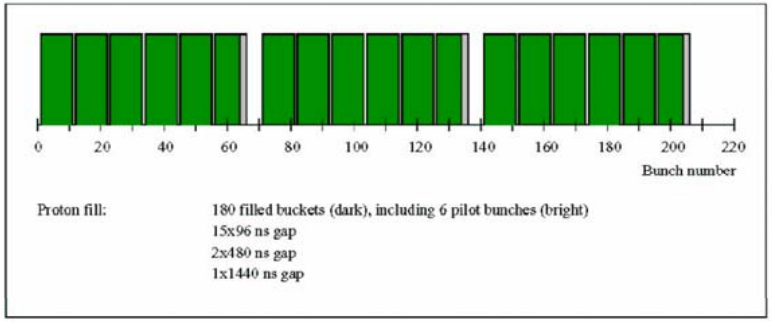


Figure 2: Schematic representation of the bunch structure of a HERA proton–ring fill.

HERA Beam Currents

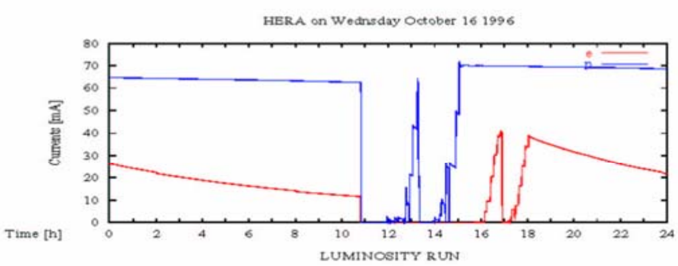
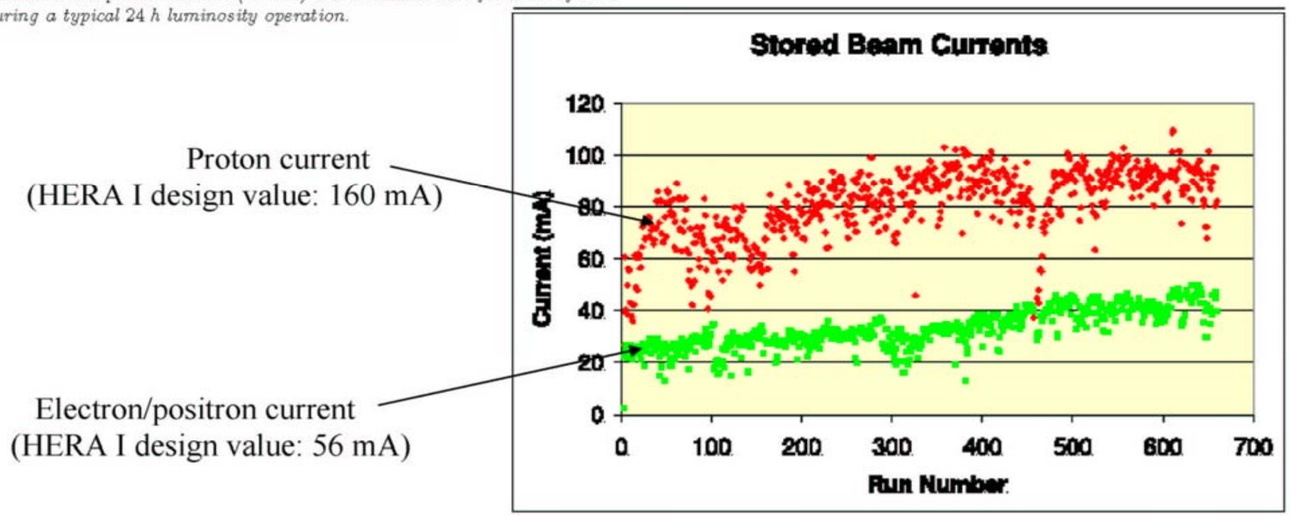
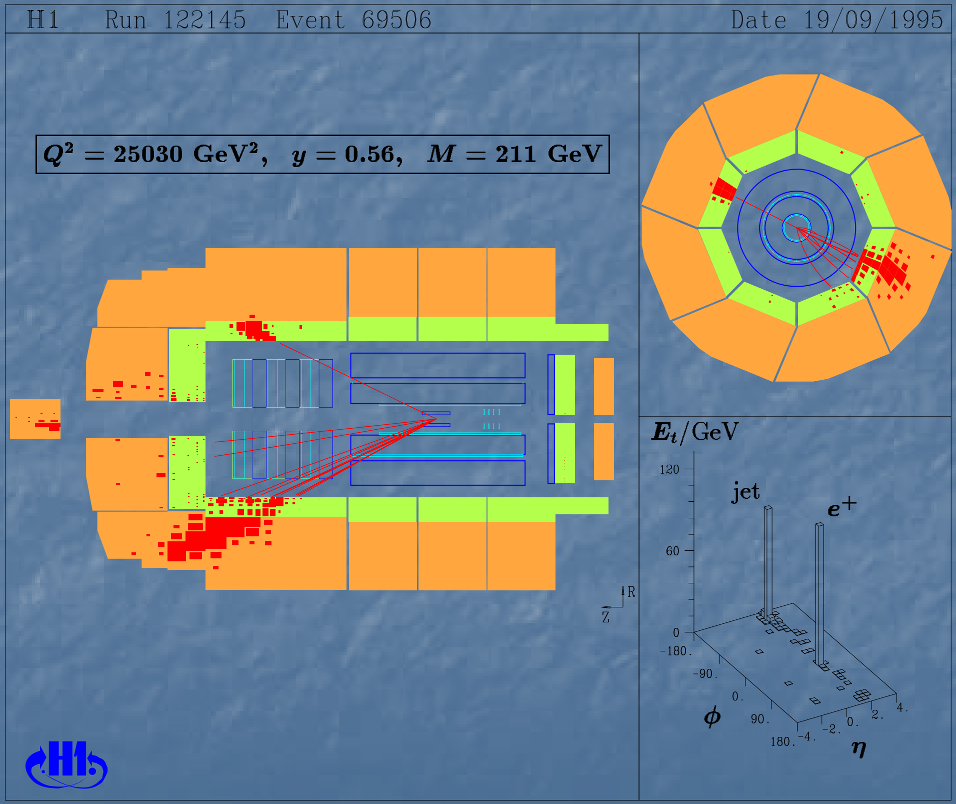


Fig. 9. *Electron and proton current (in mA) within HERA as a function of time (in h) during a typical 24 h luminosity operation.*

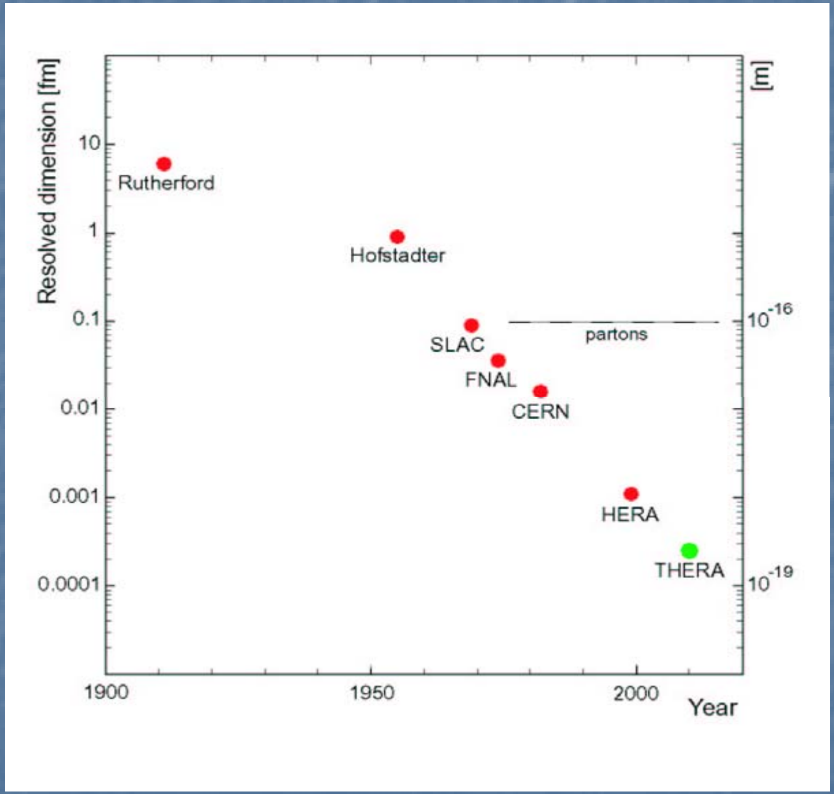


H1- A typical DIS Event

Candidate from NC sample



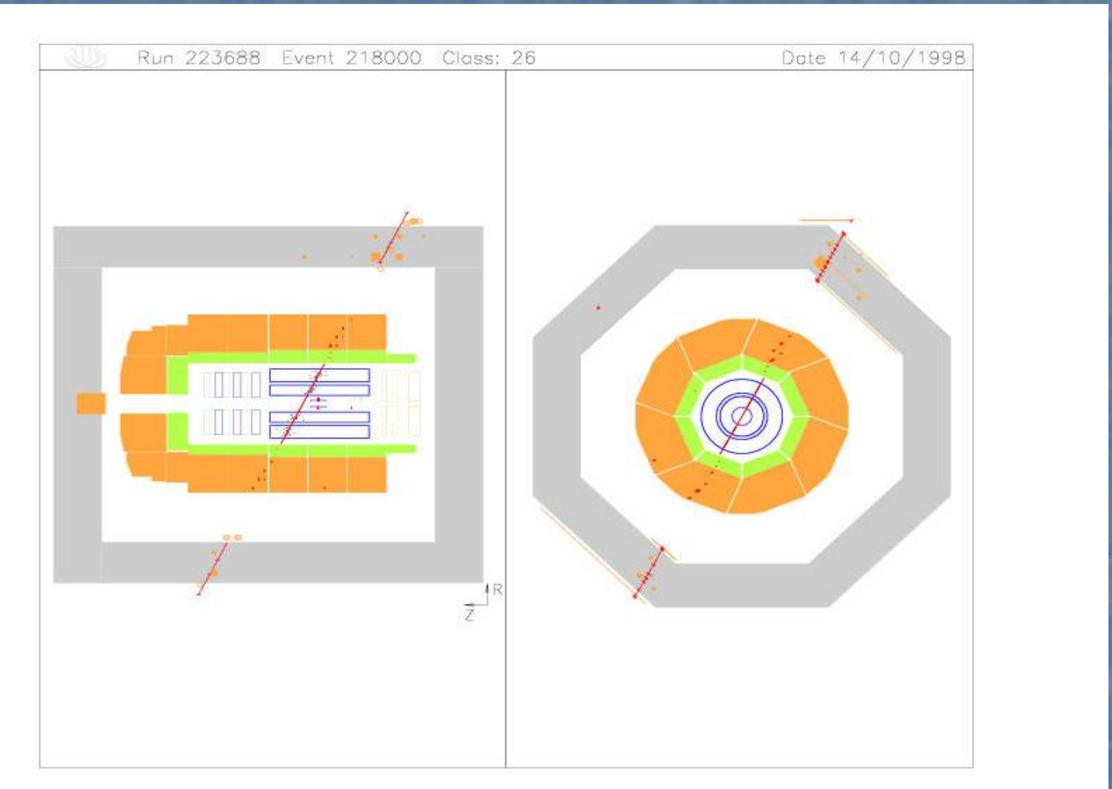
HERA Resolution Power



- Resolution ~ 1/Q
- HERA DIS reaches

$$10^{-18}\,m$$

H1 Cosmic Muons



- No beams needed
- Test subdetectors
- Alignement of components
- Clear input: minimum ionizing particle
- ...