LHC Theory

DESY Summer Students Lectures 2011

Gábor Somogyi

LHC Theory 2

Zeuthen, 29 July 2011

Theory at the Large Hadron Collider

- Introduction to collider physics, QCD and basic LHC processes

  Thursday 28 July 2011

- Introduction to EW theory, Higgs physics and BSM physics

  Friday 29 July 2011

Today:

- ***Electroweak theory***
- ***Higgs at the LHC***
- ***Motivations for extensions of SM***
- ***Basics of SUSY and the MSSM***
- ***Alternative models***
- ***Black holes at LHC: will the LHC destroy the Universe?***

Recall the Standard Model

Q What is the world made out of and what holds it together?

- What are the basic building blocks of matter?
- How do they interact?

A Standard Model

- Fermions (constituents of matter, spin ½):

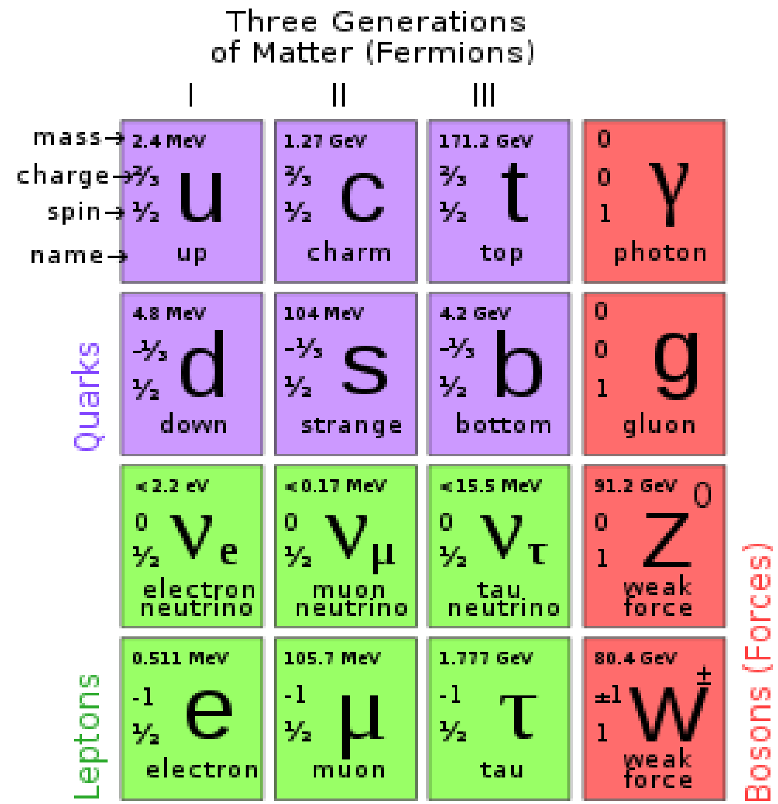
  quarks and leptons

- Bosons (force carriers, spin 1):

  photon, weak bosons, gluon

Q Is that it?

A Not quite...



Recall QFT basics

- The language in which the SM (hence QCD) is phrased is that of Quantum Field Theory (QFT). The basic setup of a QFT is as follows.
  - Prescribe the set of fields (↔ very roughly particles) of the theory.
  - Prescribe the set of symmetries (↔ very roughly interactions) of the theory. This constrains the form of interactions between the fields: some types of interactions may not be allowed by the symmetries.
  - Write the most general Lagrangian/action built out of the given fields that has the prescribed symmetries and is “renormalizable”. This gives the “equations of motion”.
- QCD as an example
  - Fields: for each flavor of quark, introduce a spinor field $(\Psi_f)^a_i$. Here f = u,d,s,c,b,t is the flavor index, and Ψ carries color index “a”, and spinor index “i”.
  - Symmetries: SU(3) “color” gauge symmetry. This is a generalization of the gauge symmetry of electrodynamics. It forces the existence of a gluon field A^α_μ, which carries a color index “α”, and Lorentz index “μ”. It also fixes the precise form of quark-gluon and gluon-gluon interactions.
  - QCD Lagrangian: $\sum_f \bar{\Psi}_f (\mathrm{i}\not{D} - m_f)\Psi_f - \frac{1}{4}\mathrm{tr}\, F^{\mu\nu}F_{\mu\nu}$

Symmetries and the Standard Model

- The Standard Model is based on the dual principles of gauge invariance and renormalizability.
  - Gauge invariance: the physics must be invariant with respect to some specific local gauge transformations. (Generalizations of electromagnetic gauge invariance.) Although perhaps not obvious, this is a very strong restriction on the interactions allowed in the theory. In fact, with renormazibility, it uniquely fixes the interactions!
  - Renormalizability: predictions of the theory must be expressible in terms of finitely many parameters at any energy scale! Notice that renormazibility is only an issue if we assume the theory is valid (in principle) to arbitrarily high energies. (Notice also that renormalization does not have anything directly to do with "infinities" which may be encountered when evaluating higher order corrections in PT.)
- Note that global symmetries of the SM (e.g. baryon and lepton number conservation) are accidental in the sense that they are not specified as defining the model.
  - Baryon and lepton number nonconserving terms are not allowed by renormalizability. Hence B and L are conserved perturbatively.
  - Even so, nonperturbative processes ("EW sphalerons") break both B and L in the SM, although only by a tiny amount. B-L is conserved.

Electroweak theory

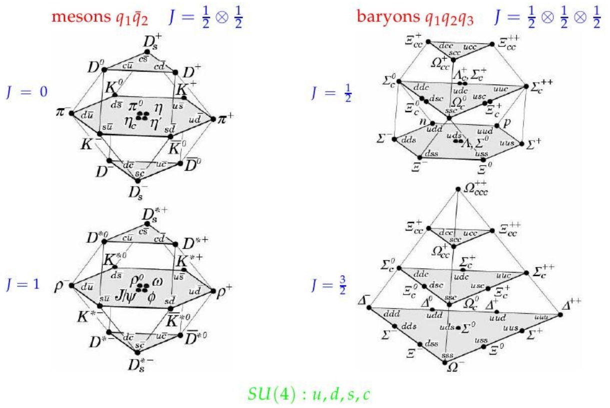
- Fields:
  - Leptons: $\begin{pmatrix} \nu_e \\ e^- \end{pmatrix}_L, \begin{pmatrix} \nu_\mu \\ \mu^- \end{pmatrix}_L, \begin{pmatrix} \nu_\tau \\ \tau^- \end{pmatrix}_L, \; e_R^-, \; \mu_R^-, \; \tau_R^-$
  - Quarks: $\begin{pmatrix} u \\ d \end{pmatrix}_L, \begin{pmatrix} c \\ s \end{pmatrix}_L, \begin{pmatrix} t \\ b \end{pmatrix}_L, \; u_R, \; d_R, \; c_R, \; s_R, \; t_R, \; b_R$
  - Left handed fields carry the “weak isospin” quantum number (with values up or down). Both left handed and right handed fields carry various values of “hypercharge” (Y).
- Symmetries:
  - EW gauge group: $SU(2)_L \otimes U(1)_Y$, i.e. weak isospin times weak hypercharge.
  - The symmetry is spontaneously broken: $SU(2)_L \otimes U(1)_Y \to U(1)_{EM}$, i.e. at low energies, we only observe electromagnetic gauge invariance.
- Lagrangian: $\sum_\psi \bar{\psi} \mathrm{i} \not{D} \psi - \frac{1}{4} \mathrm{tr}\, W^{\mu\nu} W_{\mu\nu} - \frac{1}{4} B^{\mu\nu} B_{\mu\nu} + \mathcal{L}_{\mathrm{Higgs}} + \mathcal{L}_{\mathrm{Yukawa}}$
- Now, what is spontaneous symmetry breaking and where is the Higgs?

Global and local symmetries

> Global symmetries:

- General properties of a system that help classification
- Relates different physical states of the system
- May be broken, i.e. the symmetry is only approximate
- Ex.: SU(4) classification of quark content in hadrons

    Baryon and lepton number conservation



> Local (gauge) symmetries:

- First example in classical electrodynamics. Maxwell's equations are unchanged by

$$V \to V - \frac{\partial f}{\partial t}, \quad \mathbf{A} \to \mathbf{A} + \nabla f$$

- Redundancy in the math. description of the system, physical states are left invariant
- Hence, cannot be *explicitly* broken.
- Ex.: electromagnetic U(1), color SU(3), weak isospin SU(2), hypercharge U(1)

More on symmetries

- To any continuous symmetry one can associate a conservation law and a conserved current (Noether's theorem).
  - Ex.: translational invariance ↔ momentum conservation

    rotational invariance ↔ conservation of angular momentum

    global (EM) gauge invariance ↔ conservation of (electric) charge
- In QFT there are 2 ways in which a symmetry can be realized:
  - Wigner-Weyl $[Q,H] = 0$ and $Q|0\rangle = 0$

    The spectrum falls in multiplets of the symmetry group ($|0\rangle$ is the lowest energy state)
  - Nambu-Goldstone $[Q,H] = 0$ but $Q|0\rangle \neq 0$

    The "equations of motion" are invariant under the symmetry, but the physical vacuum is not. Hence the symmetry is not manifest in the spectrum. It is said to be spontaneously broken.

Spontaneous symmetry breaking

- Spontaneous symmetry breaking: the “equations of motion” of the theory are invariant under the symmetry, but the ground state of the system is not.
- Goldstone's theorem: For each generator, Q, that fails to annihilate the vacuum there exist a massless boson with the same quantum numbers as Q.
- This field has non-trivial transformation properties under the symmetry and a non-vanishing vacuum expectation value (VEV): $\langle 0|\varphi|0\rangle = v \neq 0$.
- Notice:
  - Since spacetime is isotropic, φ must be a scalar (no frame-dependent VEV).
  - Since spacetime is homogenous, the VEV is a constant.
  - φ is not necessarily an elementary field, it may be composite.

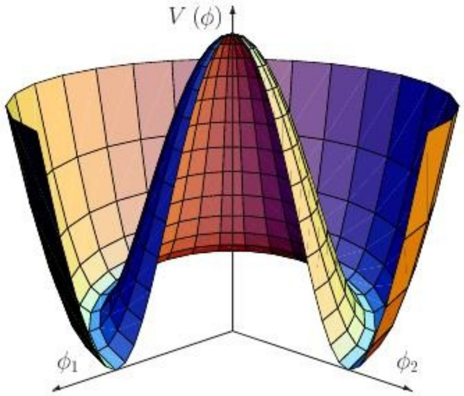
The Higgs mechanism

- A new phenomenon is encountered if gauge symmetry is spontaneously broken.
- The would-be Goldstone bosons are “eaten” by the vector bosons corresponding to the broken gauge symmetry, which become massive.
  - There is no massless scalar (Goldstone boson) in the spectrum.
  - The corresponding degree of freedom is manifested as the degree of freedom associated to the longitudinal polarization of the now massive gauge boson.
- This is known as the Higgs mechanism.
- Observations:
  - Experimentally, weak bosons are massive!
  - Unbroken (nonabelian) gauge invariance implies massless vector bosons (mass terms put in by hand are not gauge invariant). Hence electroweak symmetry must be broken!
  - The only known way to introduce weak boson masses without spoiling gauge invariance and renormalizability of the SM is via spontaneous symmetry breaking!
  - The simplest way to break EW symmetry and give masses to the weak bosons is through the Higgs mechanism.

The Higgs mechanism in the SM

- A new scalar field is added to the SM (a complex weak isodoublet = 4 real fields), with a potential that triggers spontaneous symmetry breaking.

$$V\left(\Phi^\dagger\Phi\right) = -\mu^2\Phi^\dagger\Phi + \lambda\left(\Phi^\dagger\Phi\right)^2, \qquad \mu^2,\lambda > 0$$



- Once a minimum configuration is chosen,

$$|\Phi|^2 = \frac{\mu^2}{2\lambda} \equiv \frac{v^2}{2}$$

this configuration is no longer invariant.

- Expanding around the minimum one finds 3 would-be G. bosons are "eaten up" to give Z and W's masses. The 4th is the Higgs boson.

$$\Phi(x) = \frac{1}{\sqrt{2}}\begin{pmatrix} 0 \\ v + H(x) \end{pmatrix}$$

- The mass terms for weak bosons are generated though the kinetic term of the Higgs field, after spontaneous symmetry breaking occurred!

- Higgs potential after spontaneous symmetry breaking:

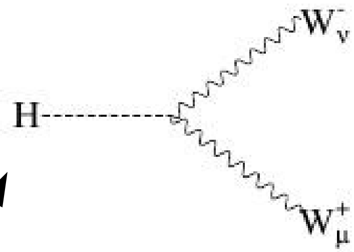
$$V = \frac{1}{2}\left(2\lambda v^2\right)H^2 + \lambda v H^3 + \frac{\lambda}{4}H^4 - \frac{\lambda}{4}v^4 \quad \Rightarrow \quad m_H^2 = 2\lambda v^2$$

Consequences

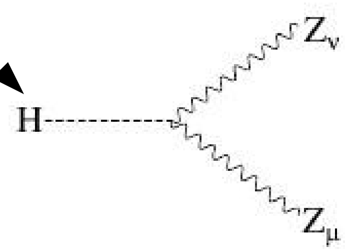
- The weak bosons acquire a mass $m_W^2 = \frac{g^2 v^2}{4}$ $m_Z^2 = \frac{(g^2 + g'^2)\, v^2}{4} = \frac{m_W^2}{\cos^2 \theta_W}$
- The Higgs VEV is constrained by the Fermi constant (low-energy)

$$\frac{G_F}{\sqrt{2}} = \left(\frac{g}{2\sqrt{2}}\right)^2 \frac{1}{m_W^2} \implies v = \sqrt{\frac{1}{\sqrt{2} G_F}} \approx 246.22\,\mathrm{GeV}$$

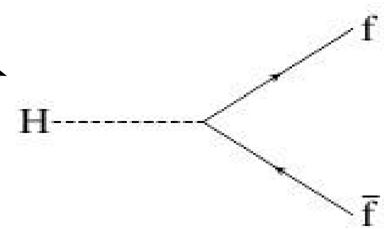
- The photon stays massless
- The only free parameter is the Higgs mass (or, alternatively, the Higgs self-coupling)
- Higgs couplings to gauge bosons and fermions are proportional to masses
- The heavier the Higgs, the stronger its self coupling



$$i g\, m_W\, g_{\mu\nu}$$



$$i g \frac{1}{\cos\theta_W} m_Z\, g_{\mu\nu}$$



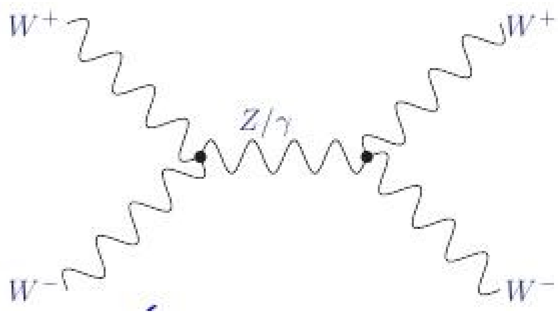
$$-i \frac{m_f}{v}$$

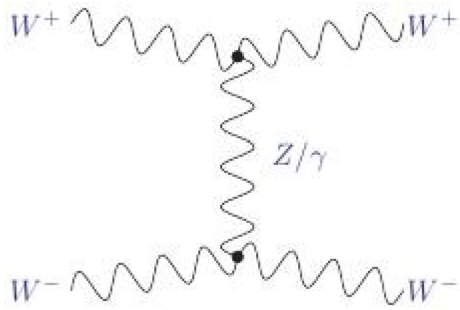
SM without a Higgs?

- The SM describes very well most experimental results. However, when extrapolated to high energies, it turns that the SM without a Higgs is mathematically inconsistent:
  - At the theoretical level the theory is not renormalizable!
  - At the phenomenological level certain scattering amplitudes violate unitarity (meaning that probabilities are not conserved)!
- Consider $W^+(p_+) + W^-(p_-) \to W^+(q_+) + W^-(q_-)$ scattering, as $s \to \infty$
- Dominant contribution at high energy comes from scattering of longitudinal degrees of freedom $\epsilon_L \sim \frac{p}{M_W}$
- General amplitude contributing can be written as

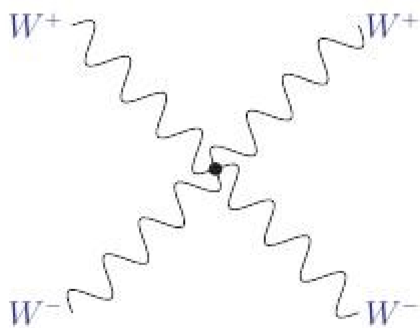
$$\mathcal{A}(s,t) = A\frac{p^4}{M_W^4} + B\frac{p^2}{M_W^2} + C$$

Longitudinal gauge boson scattering





$$\mathcal{A}^{Z/\gamma}(s,t) = g_W^2 \left\{ \frac{p^4}{M_W^4} \left(3 - 6\cos\theta - \cos^2\theta\right) + \frac{p^2}{M_W^2} \left(\frac{9}{2} - \frac{11}{2}\cos\theta - 2\cos^2\theta\right) \right\}$$



$$\mathcal{A}^{\text{quartic}}(s,t) = g_W^2 \left\{ \frac{p^4}{M_W^4} \left(-3 + 6\cos\theta + \cos^2\theta\right) + \frac{p^2}{M_W^2} \left(-4 + 6\cos\theta + 2\cos^2\theta\right) \right.$$

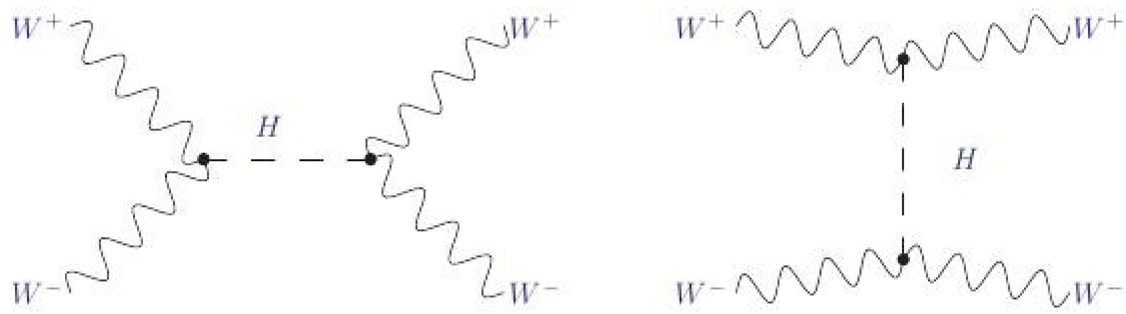
- The resulting amplitude grows indefinitely with p^2. Unitarity is lost!

Longitudinal gauge boson scattering

- According to the optical theorem, expanding the amplitude in partial waves, the coefficients must satisfy $|a_l| < 1$ to avoid unitarity violations.
- From this one gets a hint of the scale where the new physics has to show up to cure the bad energy behavior

$$\frac{g_W^2 \Lambda^2}{16\pi^2 M_W^2} = 1 \qquad \longrightarrow \qquad \Lambda \sim 1.8\text{TeV}$$

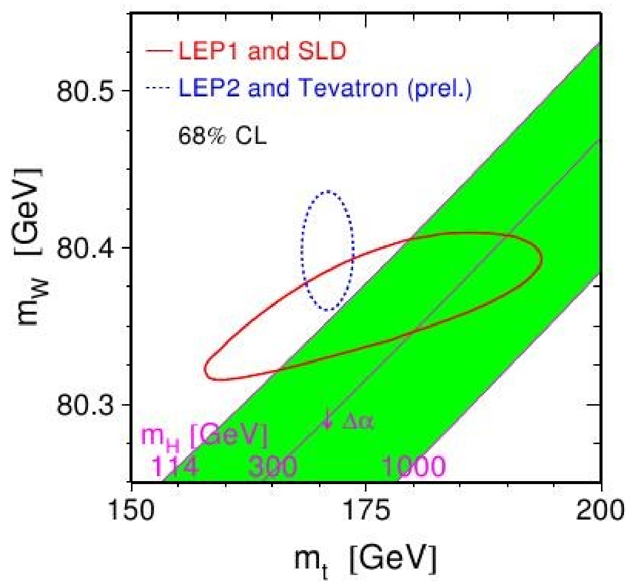
- Adding Higgs exchange one gets rid of the p^2 divergence, restoring unitarity.

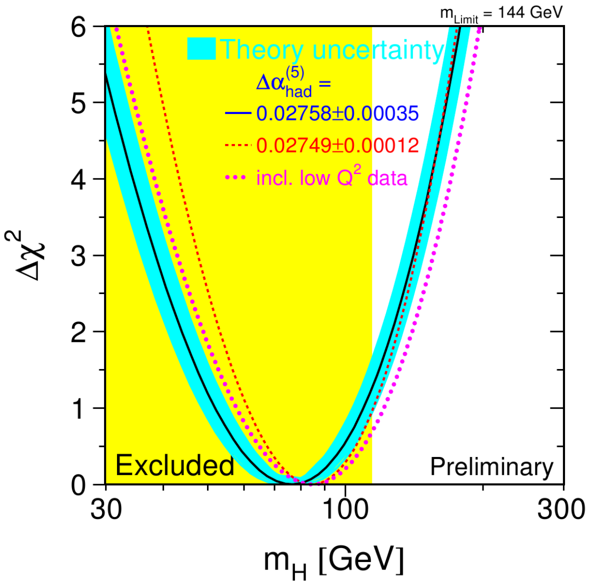


$$\mathcal{A}^H(s,t) = g_W^2 \left\{ \frac{p^2}{M_W^2} \left(-\frac{1}{2} + \frac{1}{2}\cos\theta \right) - \frac{M_H^2}{4M_W^2} \left(\frac{s}{s - M_H^2} + \frac{t}{t - M_H^2} \right) \right\}$$

Issues

> Electroweak precision tests: there are quantities very well measured that do depend on the Higgs mass. There is some tension within the SM.





> Hierarchy problem

- Why is the electroweak scale (~100 GeV) so much smaller that the other relevant scales (unification 10^{16} GeV, Plank 10^{19} GeV)?
- Why is the Higgs mass so low, given that it is unstable under radiative corrections and there is nothing in the SM that prevents it from receiving large corrections?

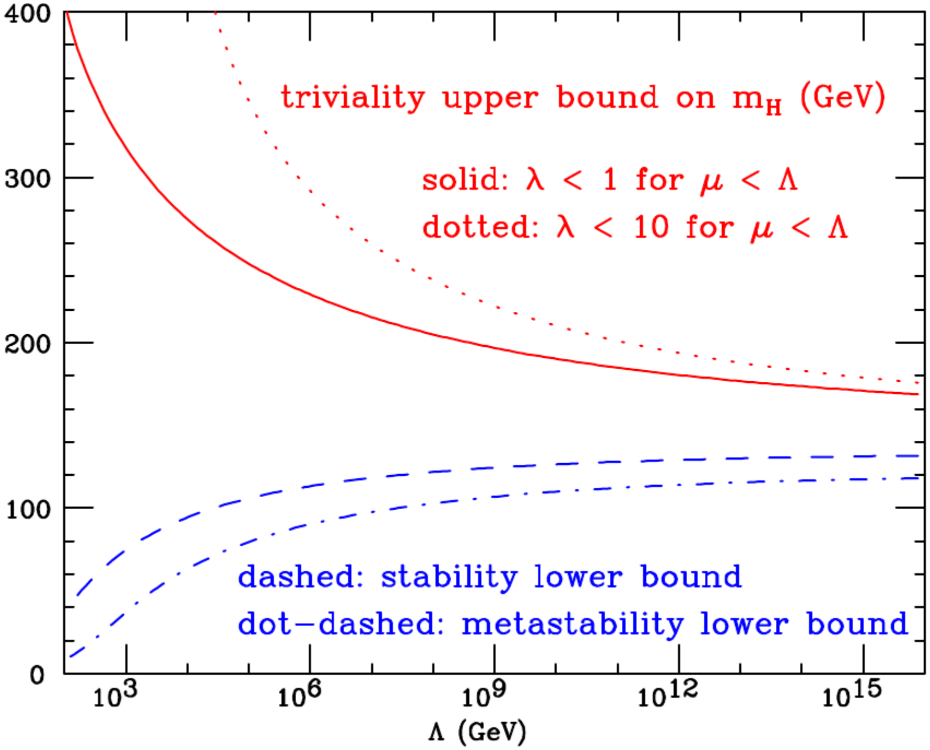
Theoretical bounds on the Higgs boson mass

- The Higgs self-coupling λ is a running parameter

- Upper bound on Higgs mass, otherwise λ leaves the perturbative domain and goes to infinity.

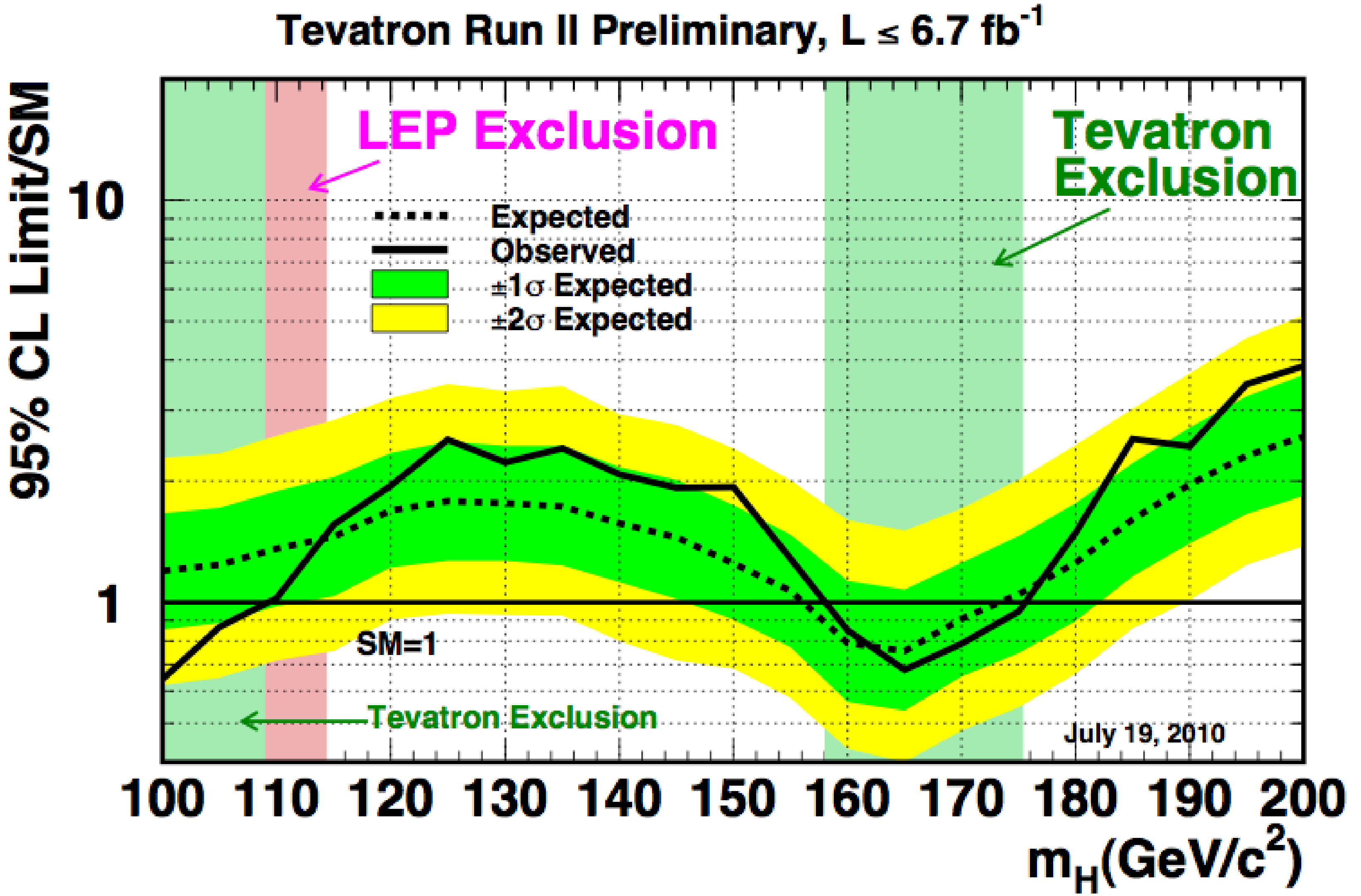
  $\Lambda \to \infty$ only if $\lambda = 0$
  (trivial=no interaction)

- Lower bound: vacuum stability. $\lambda < 0$ for certain value of m_H but Higgs potential bounded from below only if $\lambda > 0$.

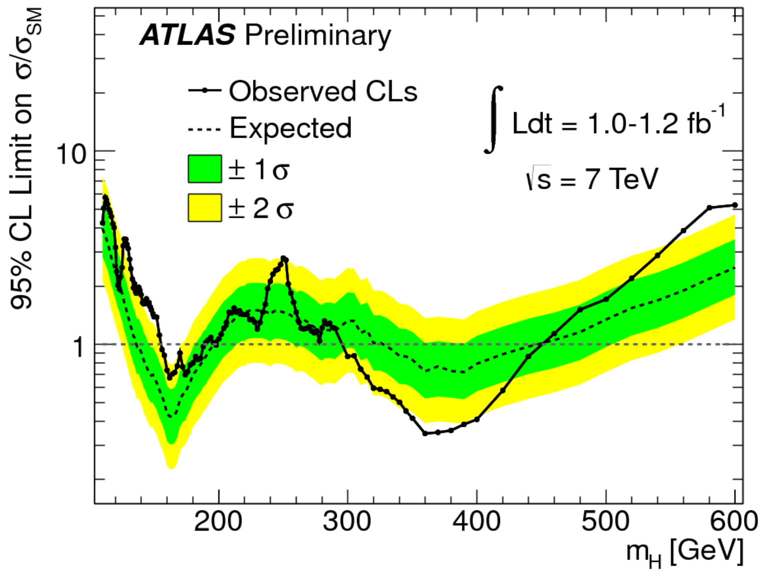


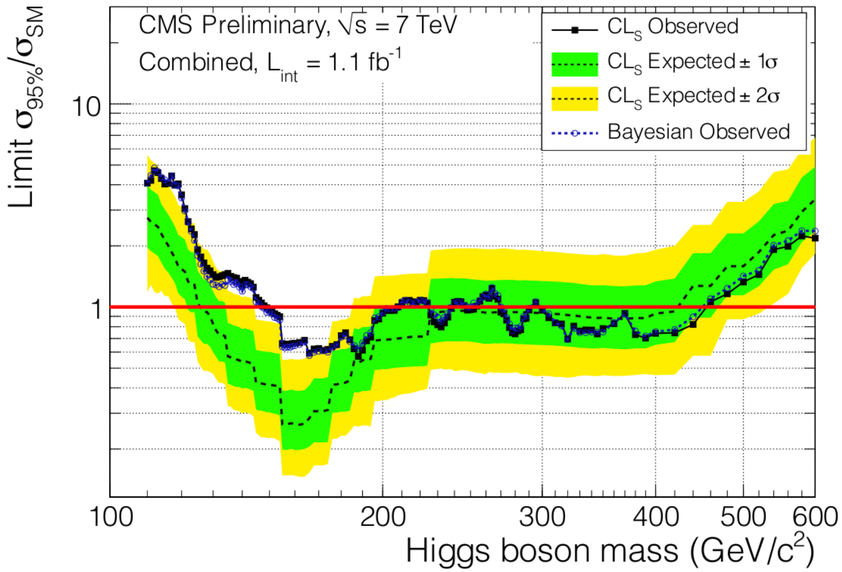
- There's only a small (and basically ruled out!) window of 150 GeV < m_H < 180 GeV that allows the SM with Higgs to be valid up to the Plank scale (10^{19} GeV).

Experimental status after LEP and TeVatron



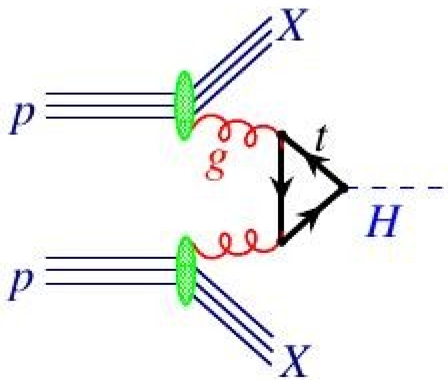
Current experimental status at LHC



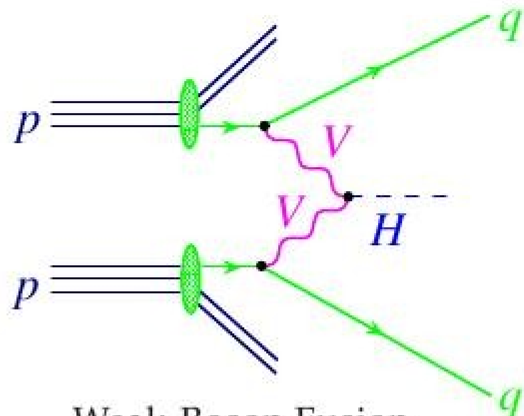


- SM Higgs excluded in mass range 150-200 GeV and 300-450 GeV by both experiments!
- Combining CMS and ATLAS results: probably rules out the high-mass region to about roughly 500 GeV.
- Hints of Higgs around 140 GeV?

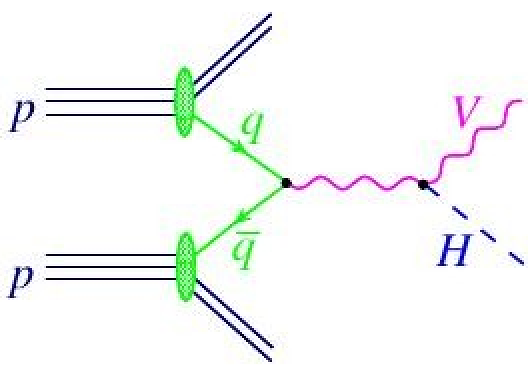
Higgs boson production at the LHC



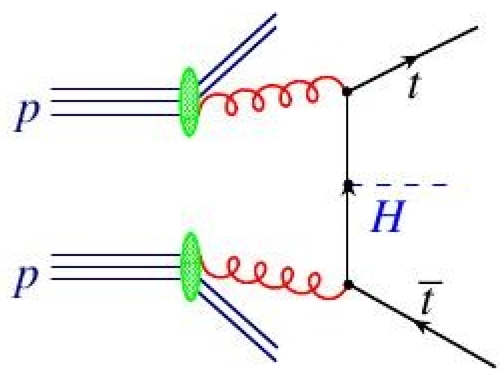
Gluon fusion



Weak-Boson Fusion

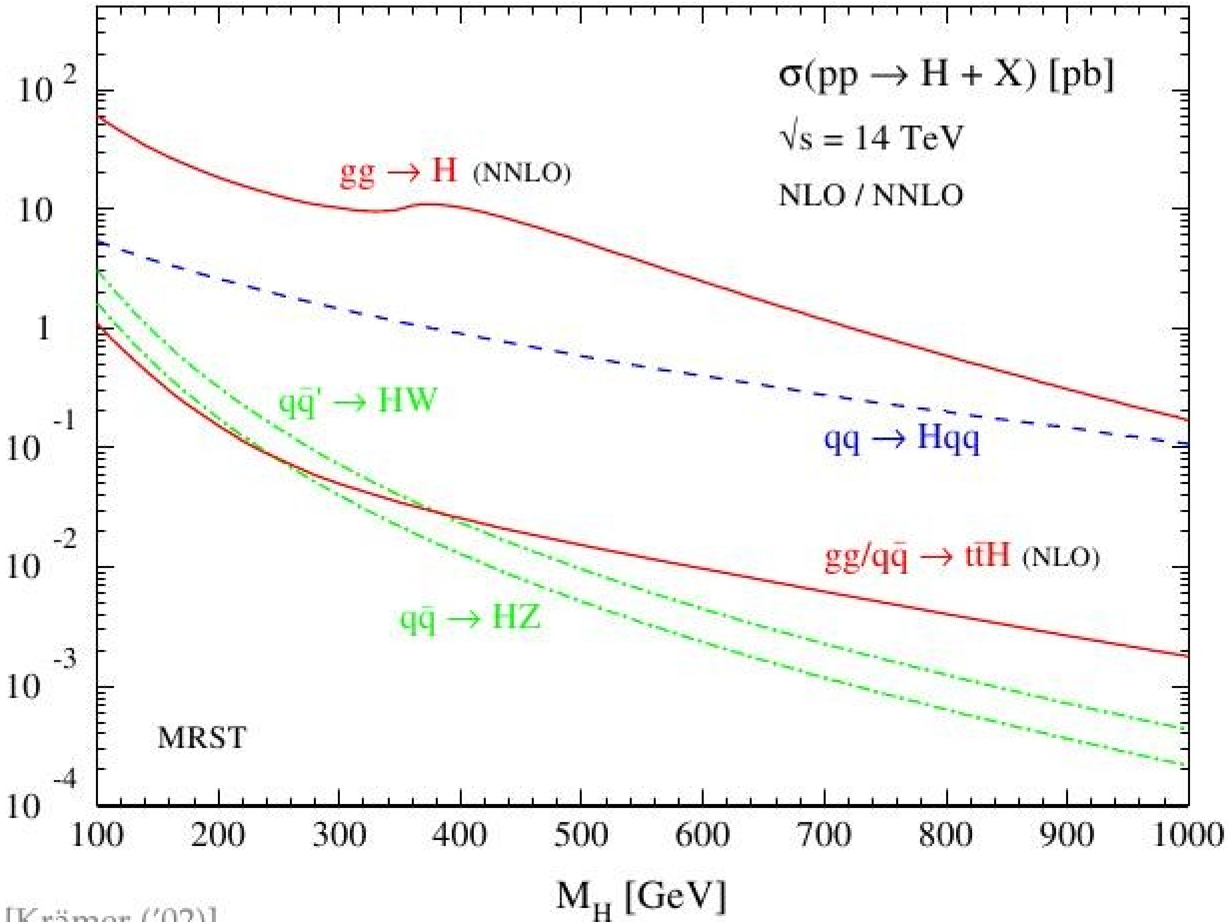


Higgs Strahlung

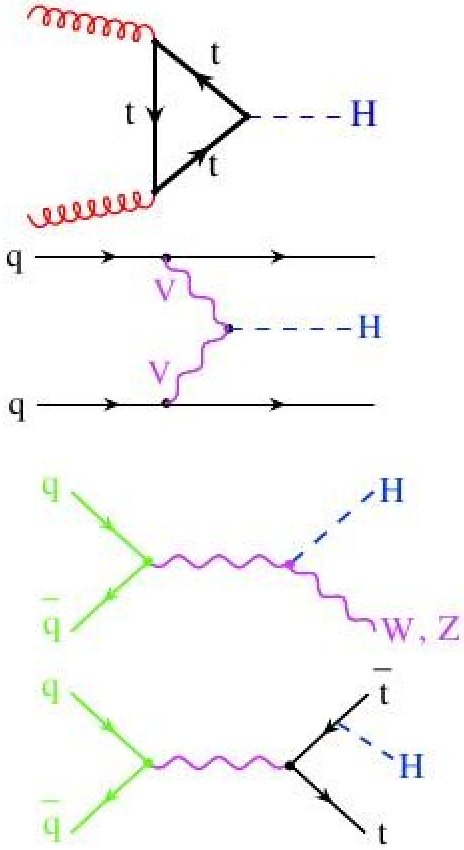


$t\bar{t}H$

Higgs boson production at the LHC

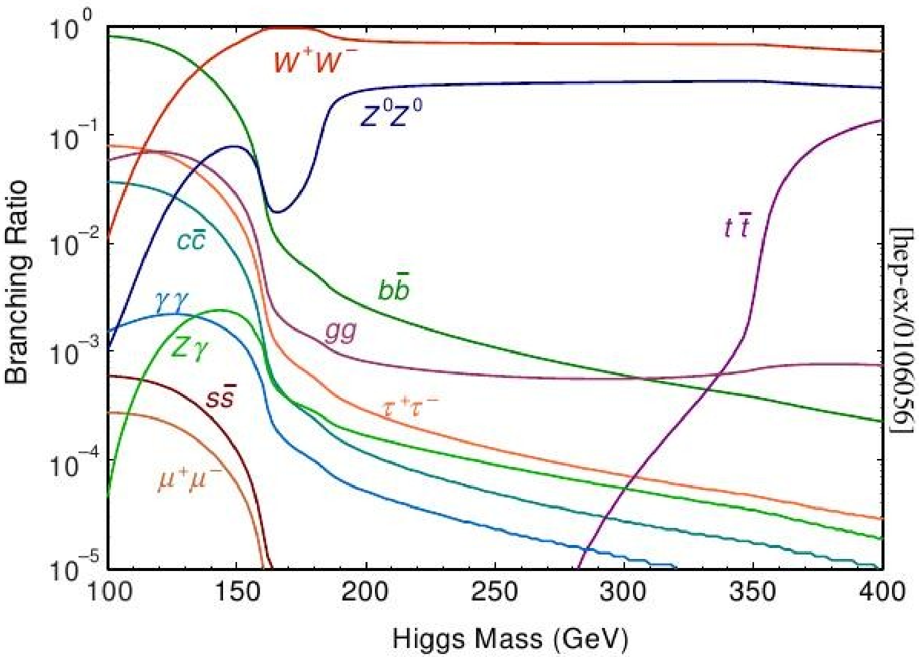


[Krämer ('02)]

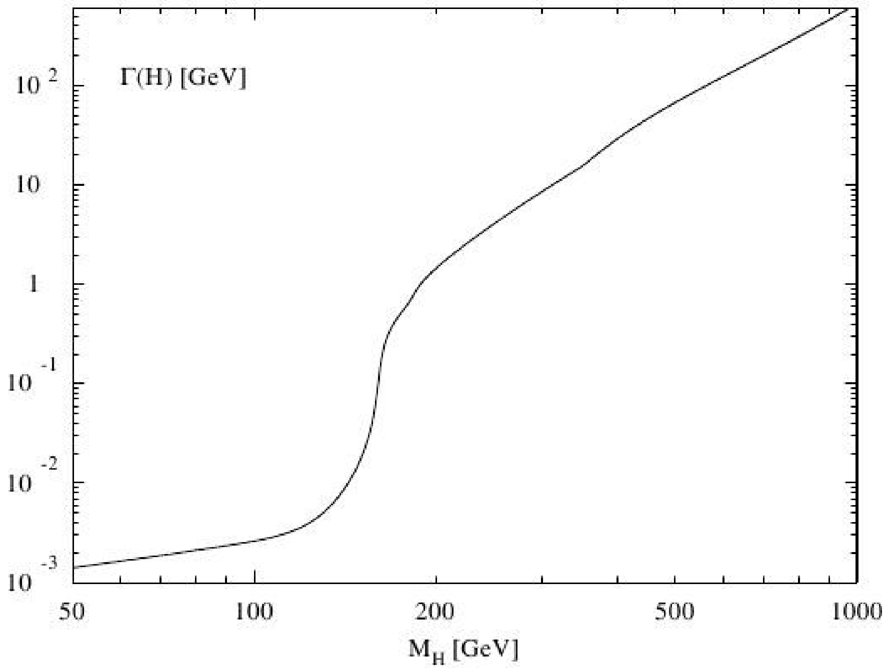


Higgs boson decay

> Decay channels



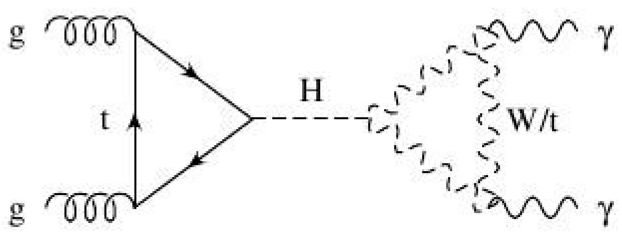
> Total width

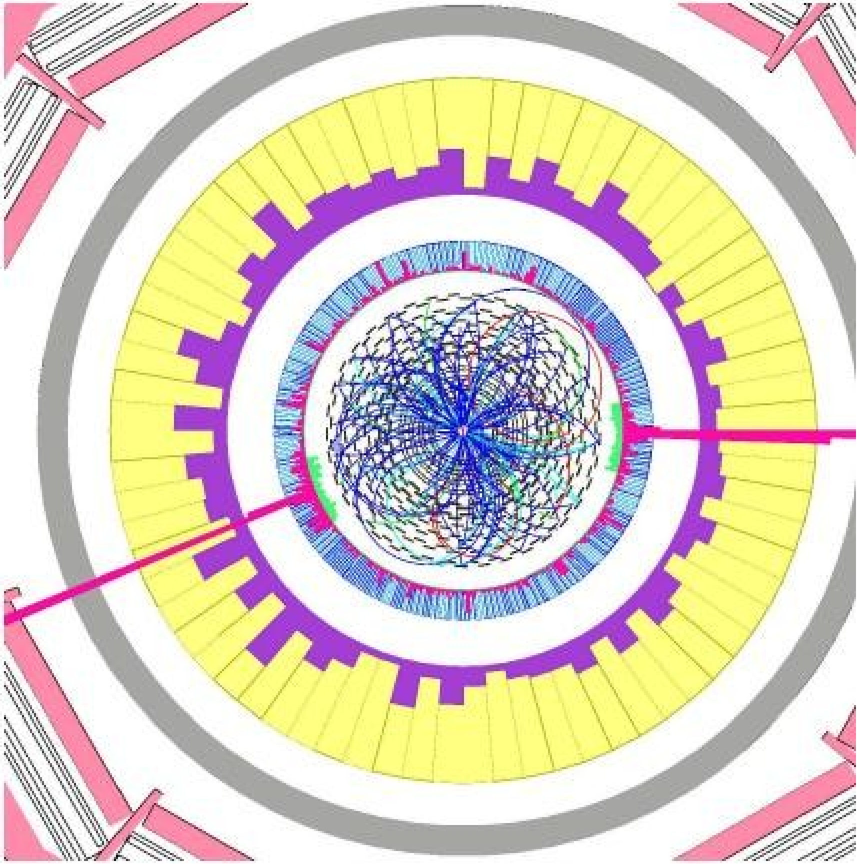


Search channels at the LHC

$$H \to \gamma\gamma$$

$M_H < 150$ GeV



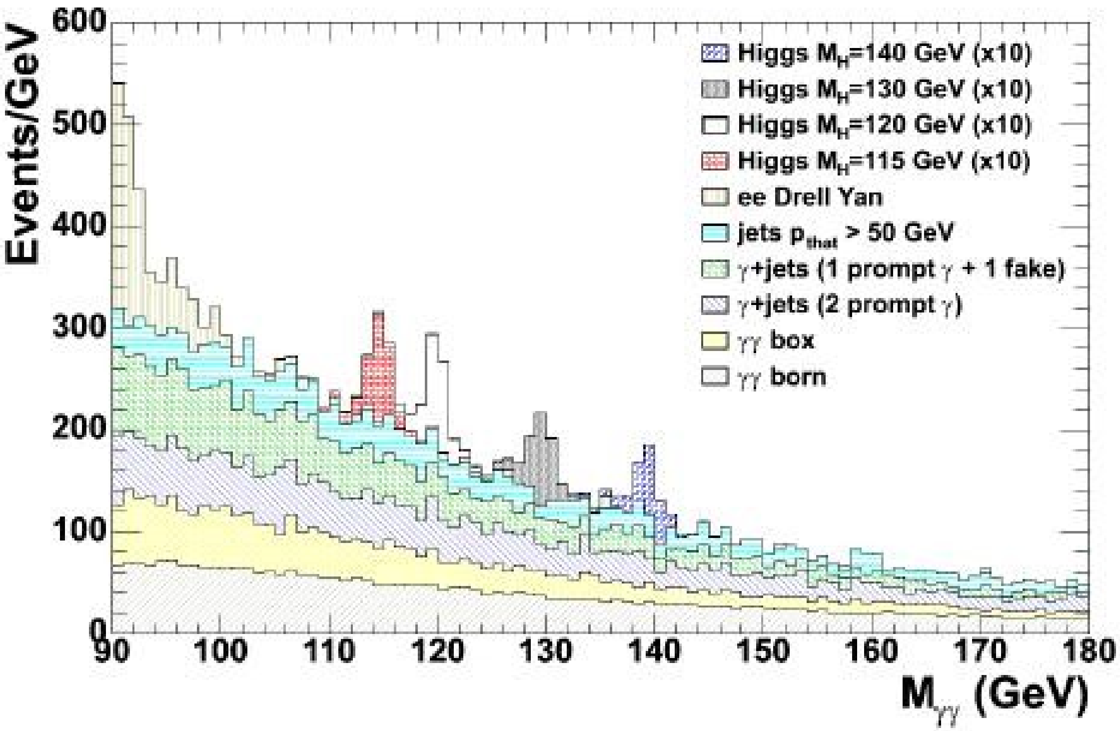


- ✗ $\mathrm{BR}(H \to \gamma\gamma) \approx 10^{-3}$
- ✗ large backgrounds from $q\bar{q} \to \gamma\gamma$ and $gg \to \gamma\gamma$
- ✓ but CMS and ATLAS will have excellent photon-energy resolution (order of 1%)

Look for two isolated photons.

Search channels at the LHC

- Narrow $\gamma\gamma$ resonance, hard to see over the background.
- Reducible background from misidentified jets.
- Discovery with already 30 fb^{-1}

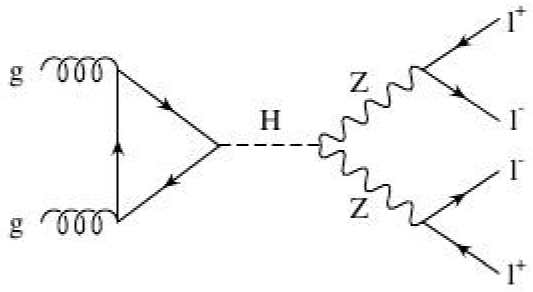


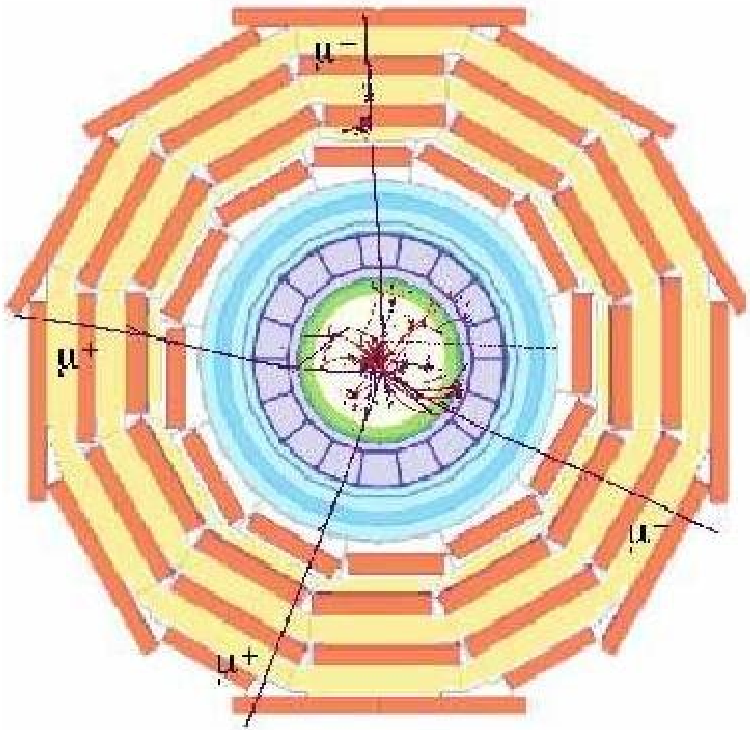
Search channels at the LHC

M_H > 130 GeV
$M_H \neq 2M_W$

$$H \rightarrow ZZ \rightarrow \ell^+\ell^-\ell^+\ell^-$$

The gold-plated mode





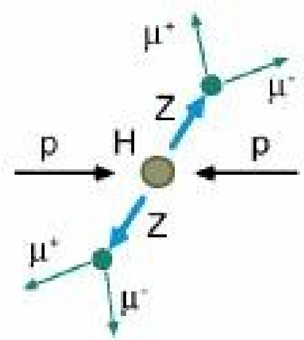
- ✓ This is the most important and clean search mode for $2m_Z < m_H < 600$ GeV.
- ✓ continuum, limited, irreducible background from $q\bar{q} \rightarrow ZZ$
- ✗ small BR$(H \rightarrow \ell^+\ell^-\ell^+\ell^-) \approx 0.15\%$ (even smaller when $m_H < 2m_Z$)

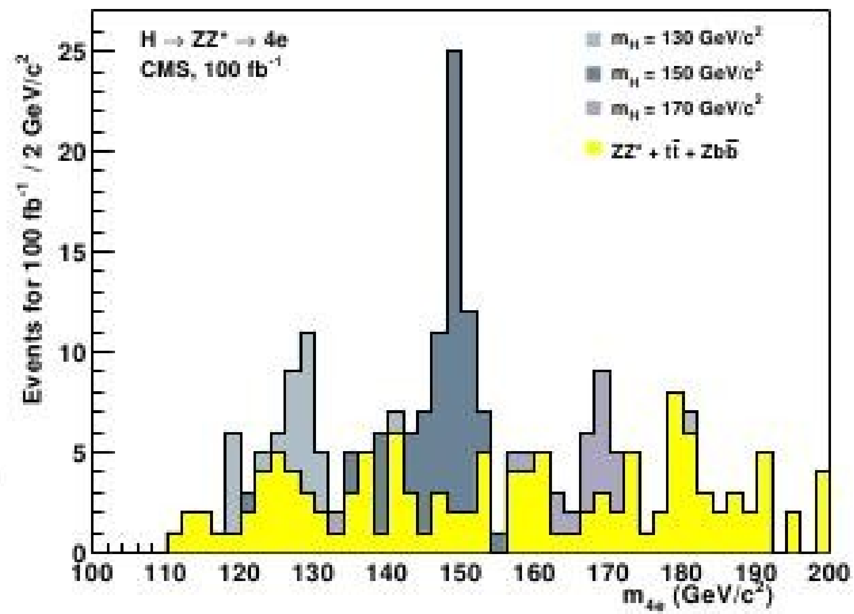
Search channels at the LHC

$$H \to ZZ \to \ell^+\ell^-\ell^+\ell^-$$

M_H > 130 GeV

$M_H \neq 2M_W$





✓ invariant mass of the charged leptons fully reconstructed

For $m_H \approx 0.6$-1 TeV, use the "silver-plated" mode $H \to ZZ \to \nu\bar{\nu}\ell^+\ell^-$

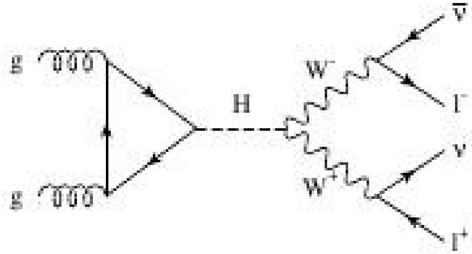
✓ $\mathrm{BR}(H \to \nu\bar{\nu}\ell^+\ell^-) = 6\,\mathrm{BR}(H \to \ell^+\ell^-\ell^+\ell^-)$

✓ the large E_T missing allows a measurement of the transverse mass

Search channels at the LHC

$$H \to WW \to \ell^+ \bar{\nu} \ell^- \nu$$

140 GeV < M_H < 200 GeV

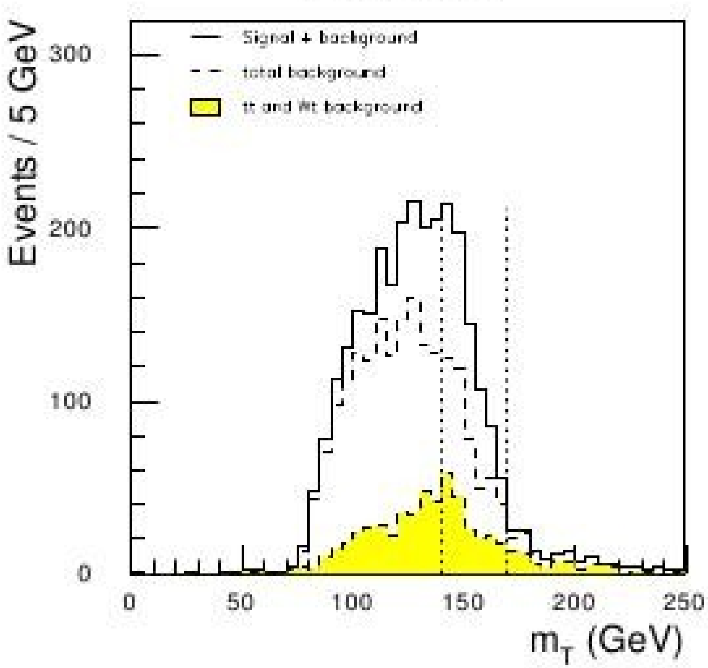


- ✓ No reconstruction of clear mass peak. Measure the transverse mass with a Jacobian peak at m_H

$$m_T = \sqrt{2\, p_T^{\ell\ell}\, \not{E}_T\, (1 - \cos(\Delta\Phi))}$$

- ✓ Exploit $\ell^+\ell^-$ angular correlations
- ✗ Background and signal have similar shape $\Longrightarrow$ must know the background normalization precisely

ATLAS TDR



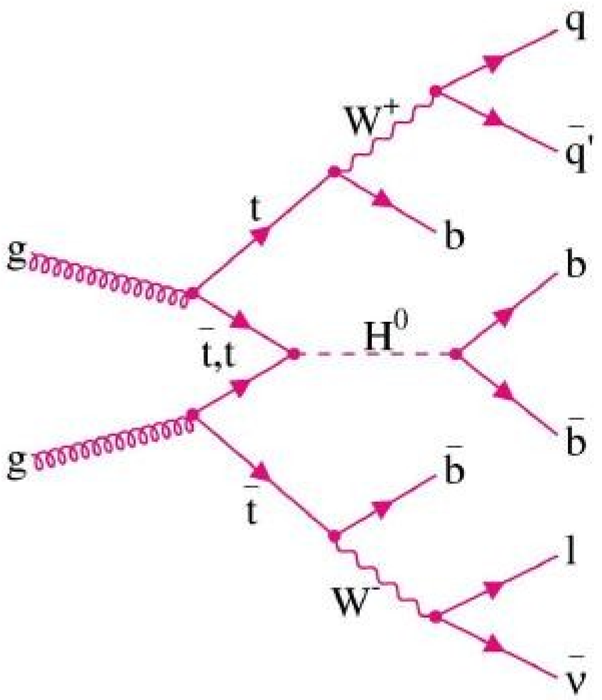
$m_H = 170$ GeV

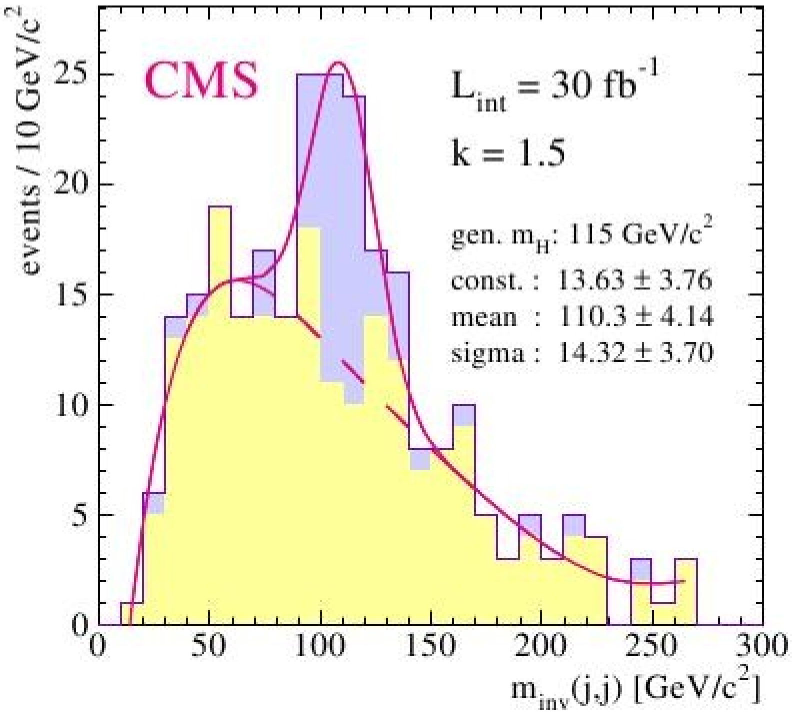
integrated luminosity = 20 fb^{-1}

DESY

Search channels at the LHC

$$t\bar{t}H \longrightarrow t\bar{t}b\bar{b}$$

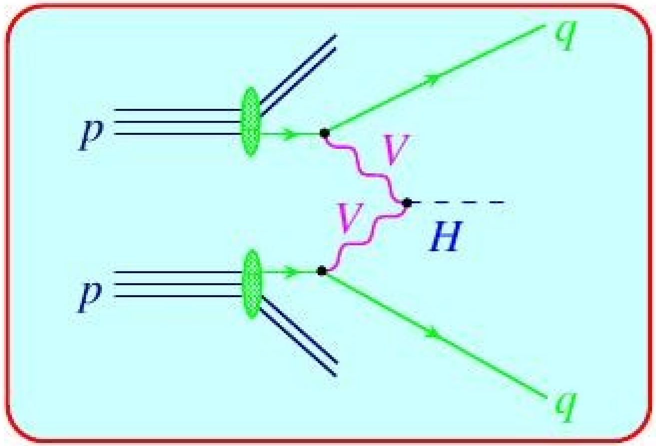


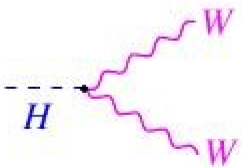


✓ $h_t = t\bar{t}H$ Yukawa coupling $\Longrightarrow$ measure $h_t^2\,\mathrm{BR}(H \to b\bar{b})$

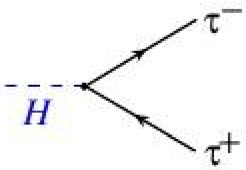
Search channels at the LHC

Weak Boson Fusion

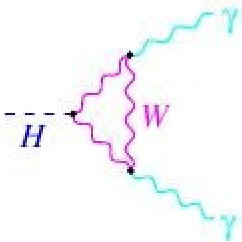




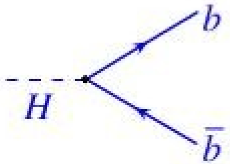
$m_H > 120$ GeV



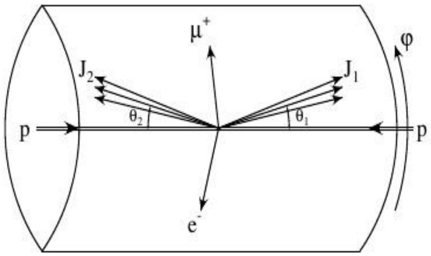
$m_H < 140$ GeV

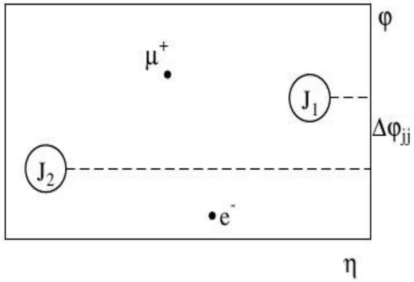


$m_H < 150$ GeV



$m_H < 140$ GeV

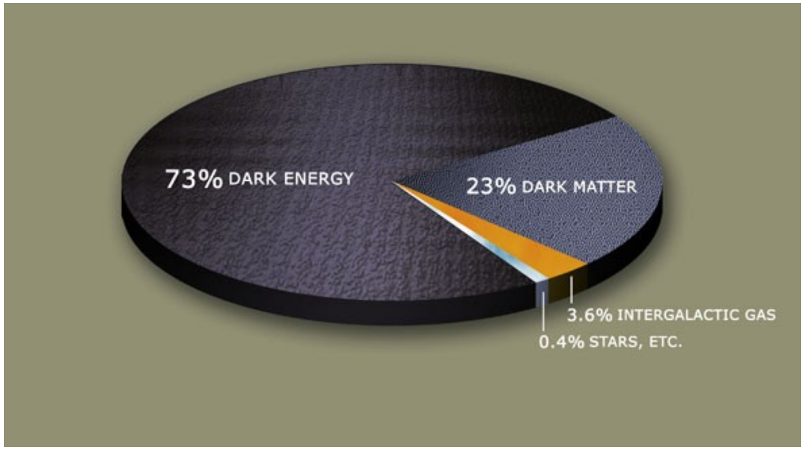




DESY

Recall: open questions

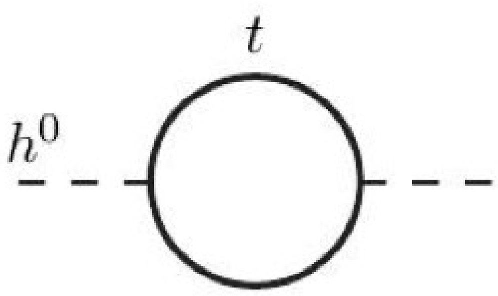
- What is the mechanism of EW symmetry breaking?
  - Does the SM Higgs boson exist?
  - What is the origin of mass?
- Observations not addressed in SM
  - What is dark matter, dark energy?
  - Why is there matter-antimatter asymmetry?
  - Why are neutrinos heavy?
- Conceptual questions
  - Hierarchy problem
  - Why three forces?
  - Why three generations?
  - How to include gravity?



The hierarchy problem

- Hierarchy problem
  - Why is the electroweak scale (~100 GeV) so much smaller that the other relevant scales (unification 10^{16} GeV, Plank 10^{19} GeV)?
  - Why is the Higgs mass so low, given that it is unstable under radiative corrections and there is nothing in the SM that prevents it from receiving large corrections?

- In a QFT, quantities like masses (in our case the Higgs mass) receive radiative corrections.
- If the SM is regarded as an effective field theory, valid up to some high cutoff scale Λ, then the correction "A" from fermion loops is proportional to the square of the cutoff: $A \sim \Lambda^2$.
- E.g. if $\Lambda = \Lambda_{GUT} \sim 10^{16}$ GeV, we need to arrange the cancellation of corrections of order 10^{32} to 28 decimal places ($m_H^2 \sim 10^4$ GeV^2)!
- This is called fine tuning and it looks unnatural.



Fermion loop

$$\mu^2 = +A$$

An example of fine tuning (by M.L.Mangano)

- Try this:
  - Ask ten friend for a real number randomly distributed between -1 and 1
  - Sum them up
  - The results is $< 10^{-32}$! How do you feel ?
- Of course it can happen, but it's more likely that they previously agree on numbers to tell you in order to make a joke on you!
- That's more or less the feeling theorists have concerning the enormous cancellations in radiative corrections to the Higgs boson mass!
- It can't be an accident, there should be some other reasons why the Higgs mass is < 1 TeV.
- Important observation: A parameter is naturally small when sending it to 0 introduces a new symmetry to the system.
- Examples: fermion masses (chiral symmetry)
  gauge bosons masses (gauge symmetry)

Supersymmetry (SUSY)

> SUSY is a symmetry that relates each fundamental particle with a superpartner. The two differ by ½ unit of spin: Bosons ↔ Fermions

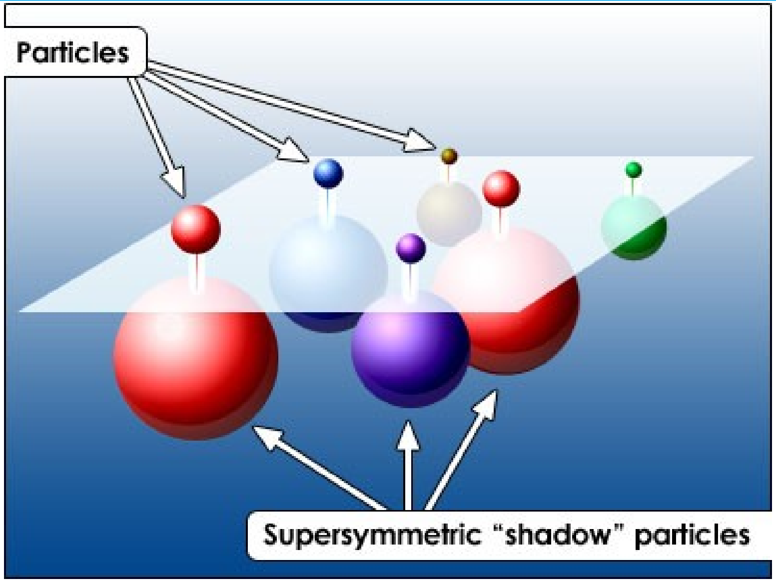
> Coleman-Mandula theorem*:

Symmetries of the S-matrix in interacting QFTs must be a direct product of Poincare symmetry and internal symmetries, i.e. SUSY not allowed!

(*) under certain assumptions!

> Allowing for anti-commuting (spinorial) symmetry generators ("supercharges") it is possible to evade the CM theorem. Extension of Lie algebra to Lie super algebra

> In unbroken SUSY, the particle and its superpartner have the same mass!



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

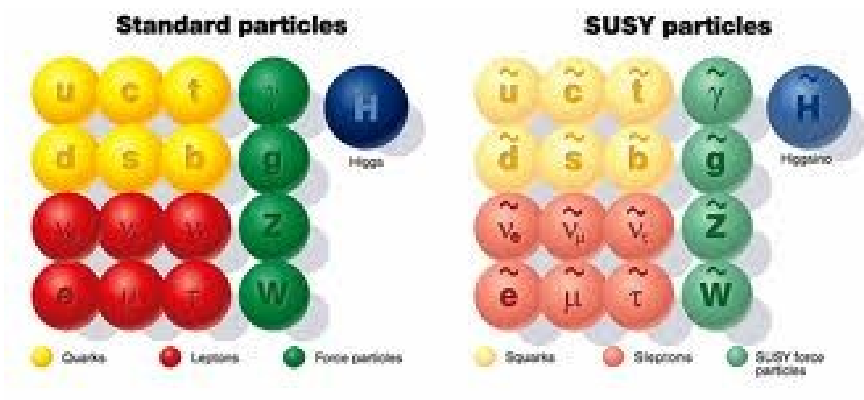
Schematic form:

$$\begin{aligned} &[Q, M_{\mu\nu}] = Q \\ &\{Q, Q^\dagger\} = P^\mu, \\ &\{Q, Q\} = \{Q^\dagger, Q^\dagger\} = 0, \\ &[P^\mu, Q] = [P^\mu, Q^\dagger] = 0, \end{aligned}$$

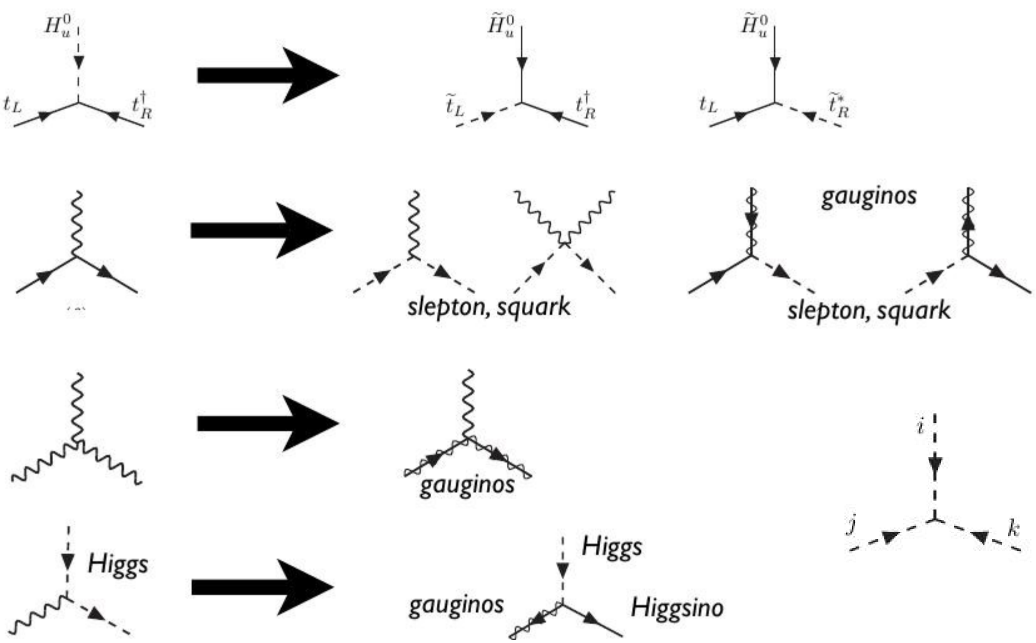
> Experimental evidence shows that SUSY must be broken. Super-partners heavier than SM particle!

DESY

Minimal Supersymmetric Standard Model (MSSM)



- SUSY interactions



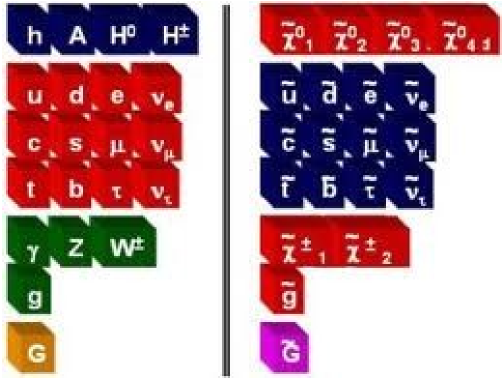
- Minimal extension of SM that realizes SUSY, (more than) doubling the particle content.
- MSSM contains 2 Higgs superfields, 8-3 = 5 physical scalars:
  - 2 neutral CP even (h^0,H^0)
  - 1 neutral CP odd (A^0)
  - A charged pair (H^+,H^-)

MSSM

- In order not to violate baryon and lepton number, leading for example to too fast proton decay, an additional Z_2 symmetry is imposed:

$$\text{R-parity} \Rightarrow R = (-1)^{3(B-L)+2s}$$

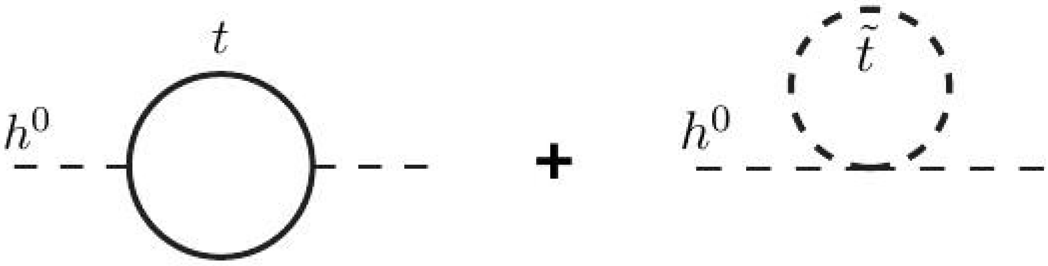
- Important phenomenological consequences:
  - The lightest supersymmetric particle (LSP) is stable and represents a good dark matter candidate.
  - In collider experiments, superpartners are only produced in even numbers.
  - Radiative SUSY corrections to EW observables can only start at one-loop level and result in small corrections.



- EW symmetry breaking is realized in the MSSM only if SUSY is broken!
- Eventually, SUSY must be broken! Quadratic divergences are not re-introduced only if SUSY breaking does not change the Higgs quartic coupling (“soft breaking”).

Solution of the hierarchy problem in the MSSM

- In SUSY, quadratic divergences are cancelled between fermion and sfermion contributions!



Fermion loop | Boson loop

$\mu^2 = +A$ | $\mu^2 = -A + m_{stop}^2\ B$

$\mu^2_{total} \sim m_{stop}^2$

Superpartners expected around v ~ 100 GeV

- Put another way: scalars and fermions are related in SUSY and fermion masses do not receive quadratic corrections.

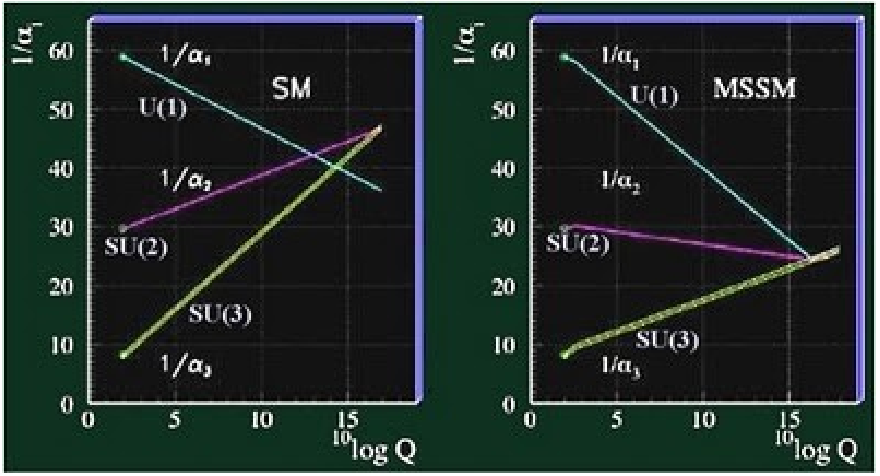
DESY

MSSM

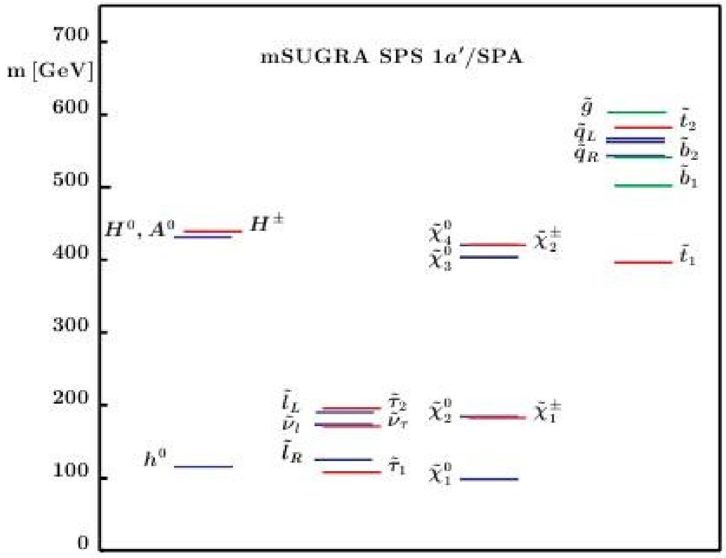
- Unification of running couplings

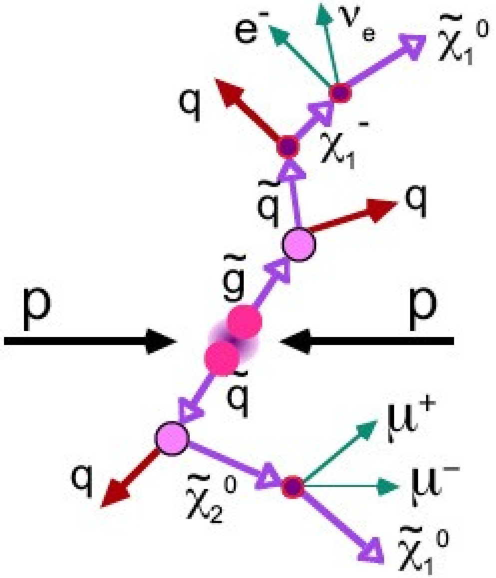
  $SU(3)_C \times SU(2)_L \times U(1)_Y$

  points toward a GUT at 10^{16} GeV!



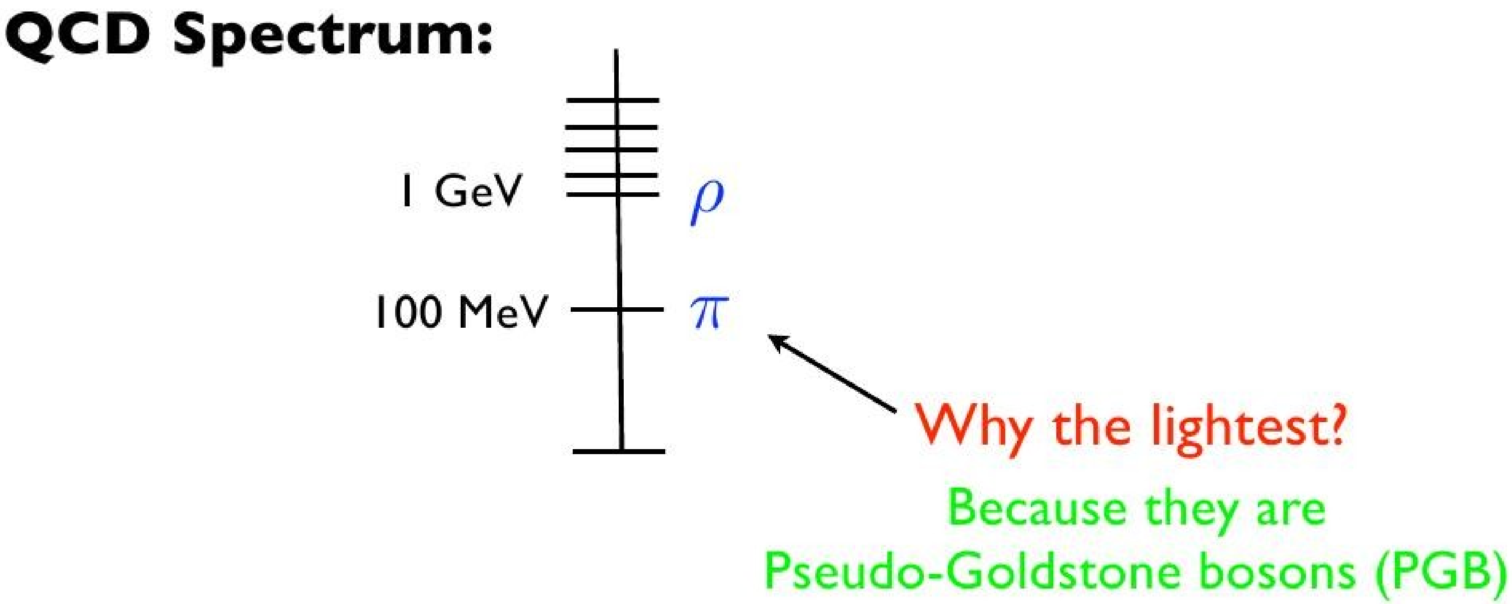
- MSSM phenomenology:
  - Typical signature: multiple jets, high energy leptons and missing energy
  - Example: neutralino production, which is a typical dark matter candidate





Other solutions to the hierarchy problem: technicolor

- Observation: QCD actually breaks EW symmetry, and gives mass to the W and Z, but this mass is too small by orders of magnitude compared to the measured masses (~30-35 MeV only)!
- How?
  - By forming pions! These are the pseudo-Goldstone bosons of the spontaneous breaking of chiral symmetry in QCD.
  - The PGBs, i.e. π^0 and $\pi^\pm$ are “eaten” by the weak bosons, which become massive.



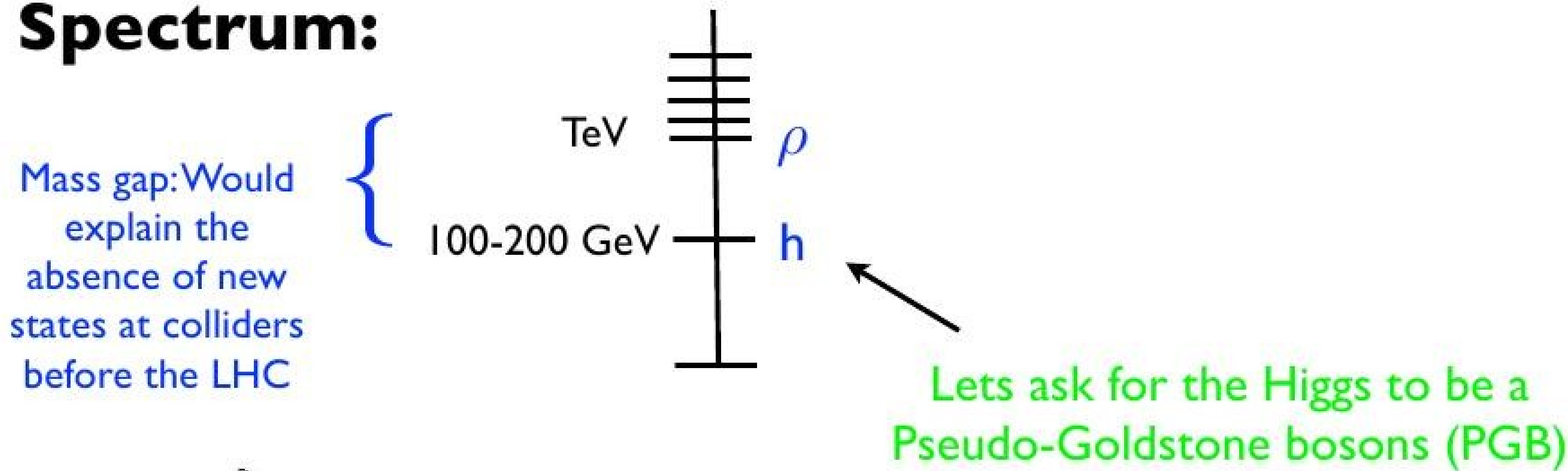
Other solutions to the hierarchy problem: technicolor

- **Technicolor models**: borrow the idea from QCD, but scale it up!
- Introduce a new strongly interacting sector: a new (asymptotically free) gauge interaction coupled to new massless fermions that also interact via the SM weak interactions. Basically another QCD, but at higher scale.
- This TC theory is confining, forms “technipions”, and breaks electroweak symmetry just as QCD.
- The W and Z “eat” the new technipions and acquire masses.
- There are no fundamental scalars! **No Higgs boson**!
- The hierarchy problem is solved since the electroweak scale is generated dynamically. It is the scale at which the TC coupling becomes strong!
  - Just as in QCD there is no tension between Λ_{QCD} (~250 MeV) and M_{pl} (10^{19} GeV).
- TC models are mostly ruled out nowadays, since it is hard to account for e.g. EWPT and quark masses. Usually they lead to FCNCs and CP violation which are too large with respect to experiments.

Other solutions to the hierarchy problem: composite H

- **Composite Higgs models:** there exist strongly interacting sectors with “truly fundamental” fields in some gauge group. The SM particles are mixtures of these fields. The heavier the particle the larger the degree of compositeness. The Higgs is a full composite, so no hierarchy problem. It is naturally light, being a pseudo-goldstone of a dynamically broken global symmetry of this strong sector. It partially unitarizes the WW scattering, but the ultimate scale where the theory is unitarized is the compositeness scale. These models share the virtues of TC and elementary Higgs models, partially avoiding the problems.

Spectrum:

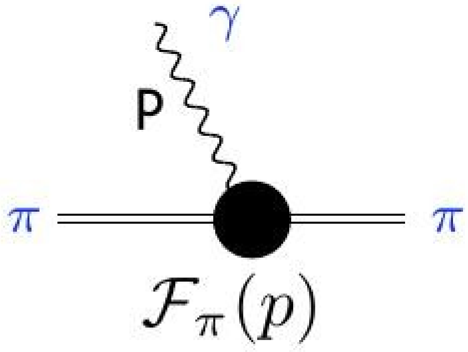


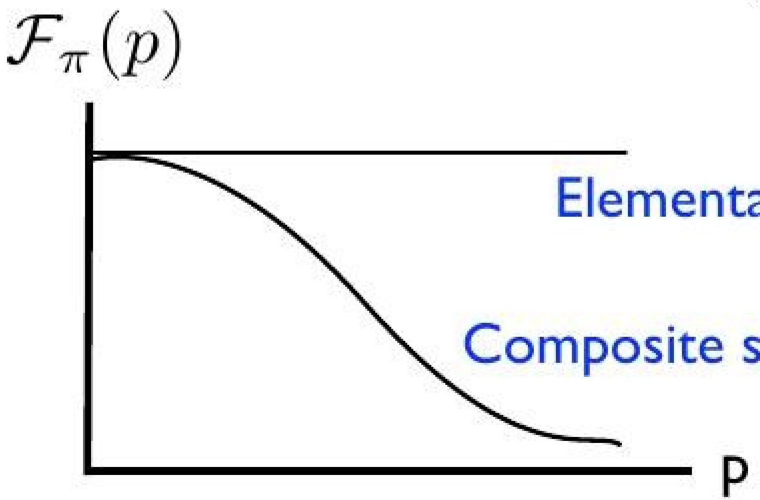
Composite Higgs models

How to unravel the **composite** nature of the Higgs?

Easy in an **ideal** collider:

As we do it with pions in QCD:



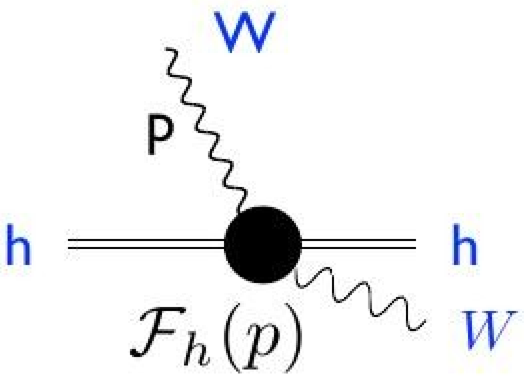


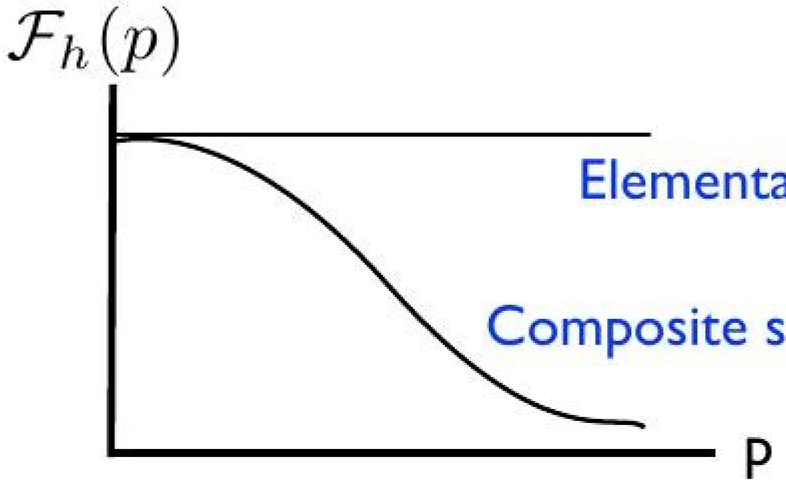
Composite Higgs models

How to unravel the **composite** nature of the Higgs?

Easy in an **ideal** collider:

Similarly for the Higgs:

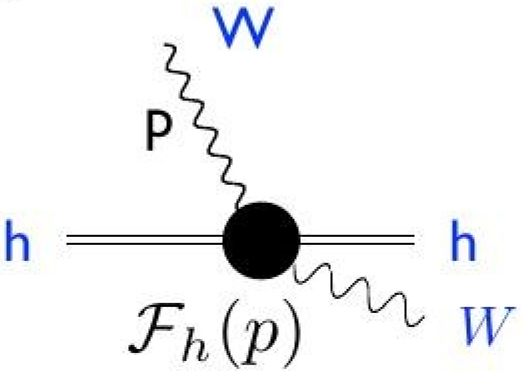


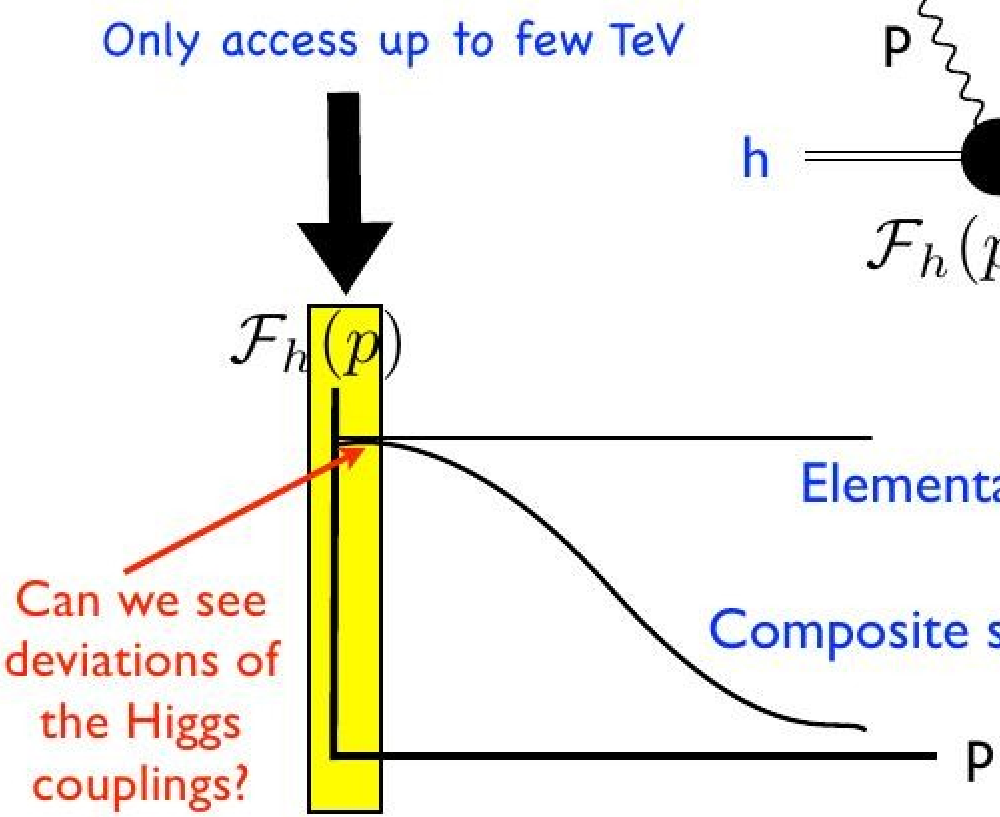


Composite Higgs models

How to unravel the **composite** nature of the Higgs?

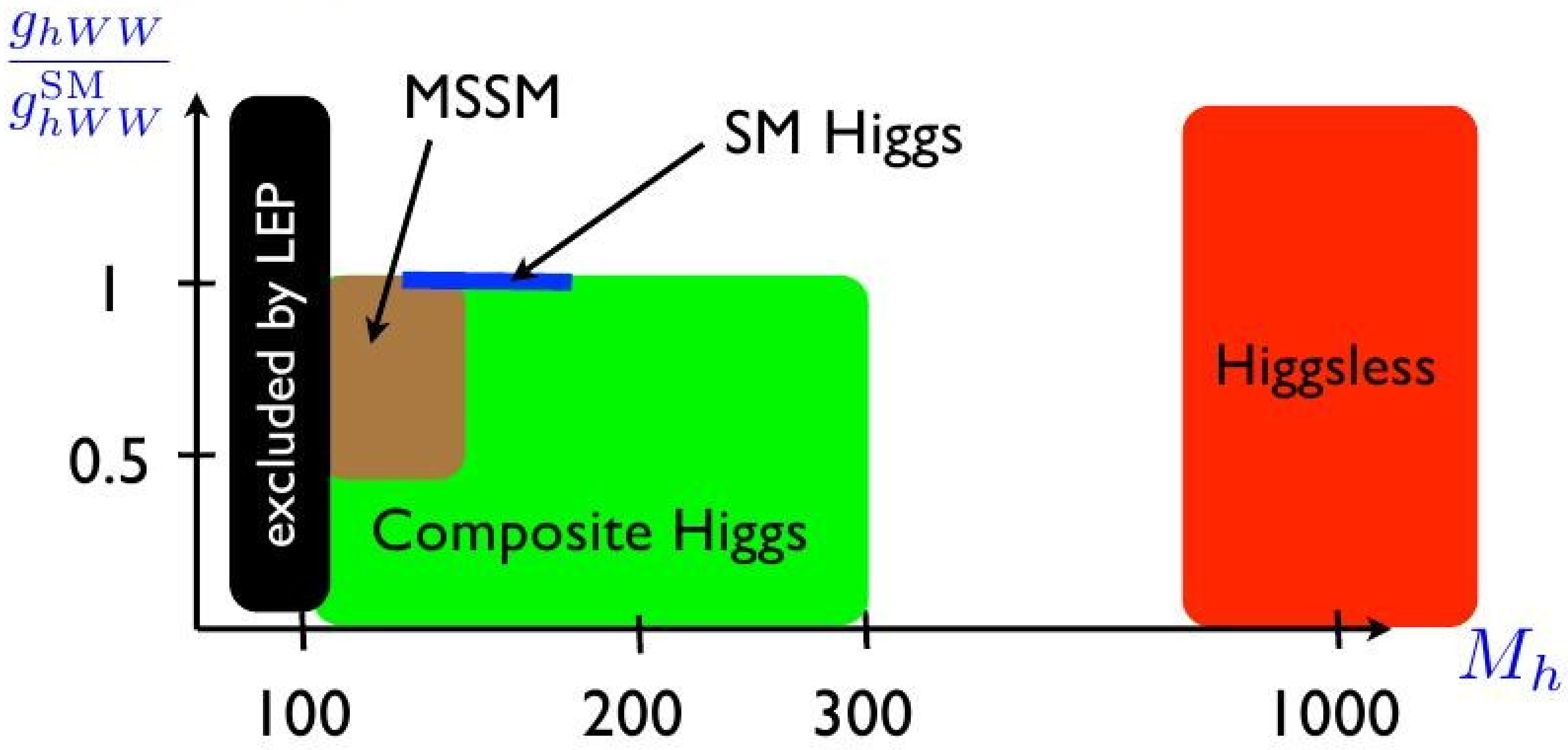
But in a **real** collider (LHC):





Which one is the right theory?

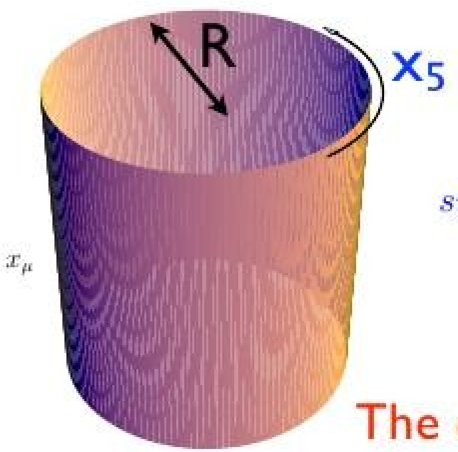
A rough perspective of different theoretical scenarios:



Extra dimensions

- Historically, unification of gravity with electromagnetism in 5D (Kaluza 1919)
- Compactification of 5th dimension (small radius) (Klein 1926)

$R \sim 1/M_P$



In 5 dimensions the gravitational field has more components:

$$h_{MN} = (h_{\mu\nu}, h_{5\mu}, h_{55})$$

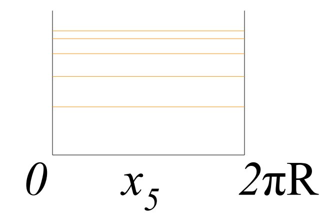
$M = \mu, 5 = 1,2,3,4,5$

symmetric under $M \leftrightarrow N$

4 dimensional gravit. field

4 dimensional EM field

The extra spacial-dimension had to be compactified



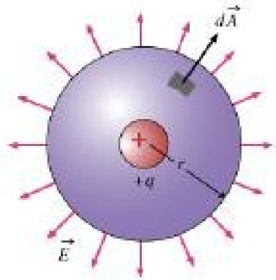
$$p_\mu^2 = p_5^2$$

  - Momentum in 5th dimension is quantized, corresponds to mass in 4D
  - Kaluza-Klein modes are excited states of ordinary particles.
- String theory not consistent in 4D...

Extra dimensions

- Extra dimensions could explain why gravity is weak with respect to other forces.

How? Gauss's law:



$$\oint_S d\Phi \sim Q_{int}$$

4 dim: $V \sim \frac{Q_{int}}{r}$

4+d dim: $V \sim \frac{Q_{int}}{r^{1+d}}$

$S \sim r^{2+d}$

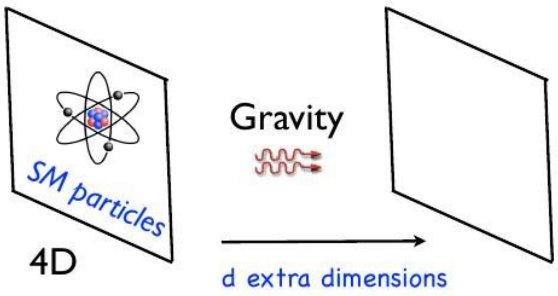
d = number of extra dimensions

At large distances, the strength of a force becomes smaller in higher dimensions

- No hierarchy problem, since the fundamental scale is at M_{Pl} ~ TeV.

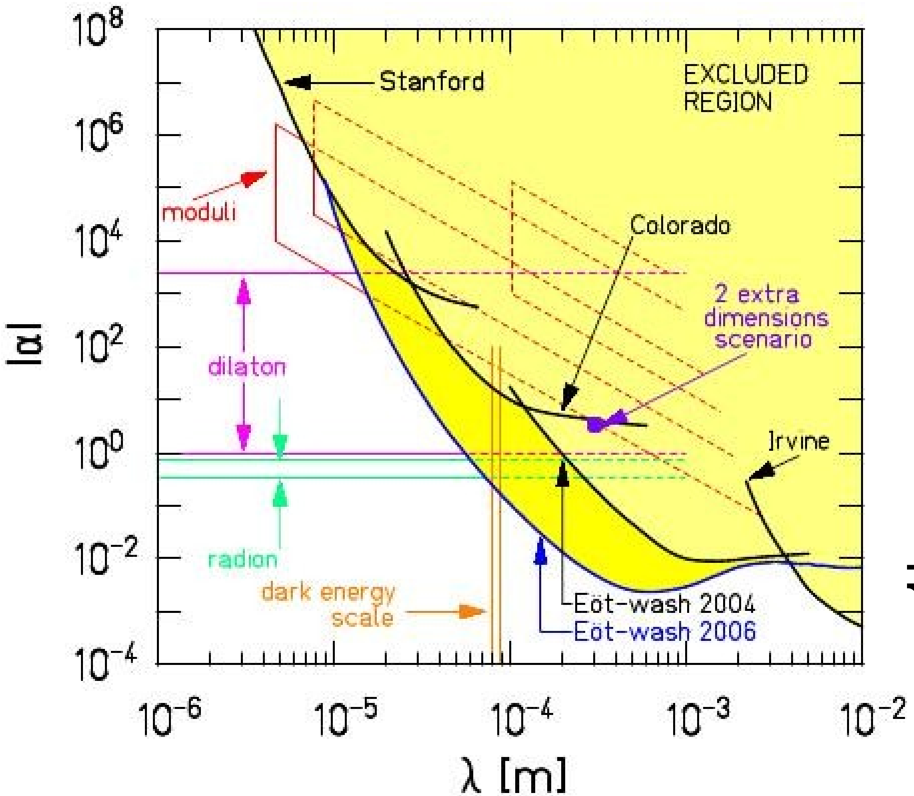
Extra dimensions

- However:
  - All SM fields confined to a 4D brane
  - Only gravity propagates in the extra dim.



- We only see 3 dimensions at large distance, but how large can the compactification radius be?
- We have not measured gravity well at distances lower than 0.1 mm !

$$V = -\frac{Gm_1m_2}{r_{12}}\left[1+\alpha\exp(-r_{12}/\lambda)\right]$$



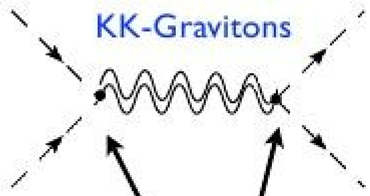
- Extra Dimensions with ≤ 0.04 mm are still possible!

Signatures of extra dimensional models

Model-independent signals from gravity at ~TeV:

Gravity becomes strong at ~ TeV energies:

$$\sum_n$$

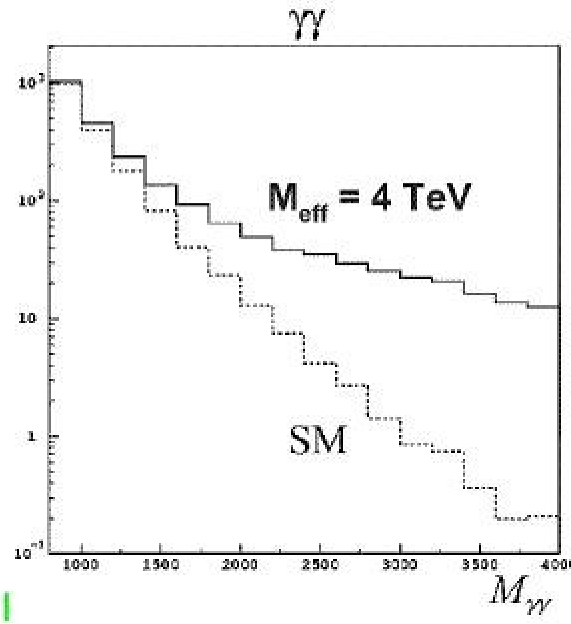


$$\sim \sum_n G_N Q^2 \sim \frac{1}{M^2_{string}} Q^2$$

Sum over all KK-gravitons

$$G_N = \frac{1}{M_P^2}$$

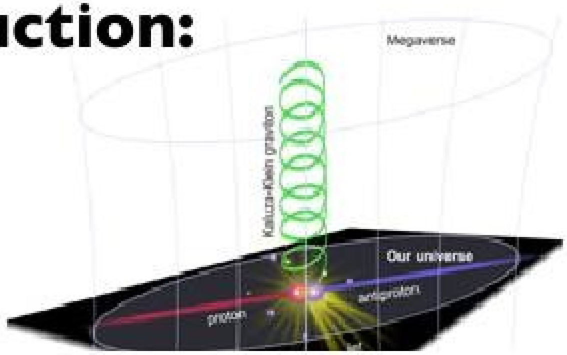
To be seen at LHC as deviations in Drell-Yan cross-sections for SM processes.
Example: deviations in the
γγ invariant mass distribution of pp→γγ:



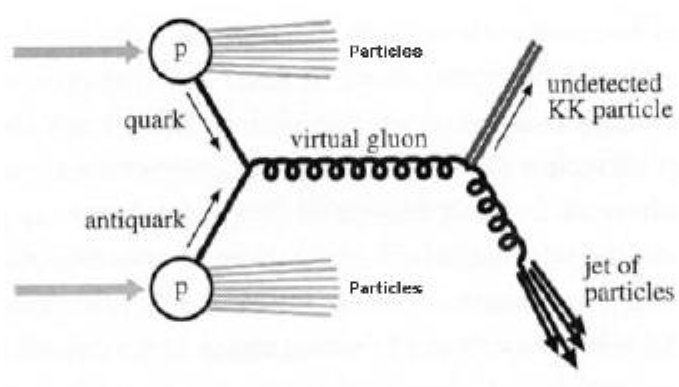
arXiv:hep-ex/0310020v1

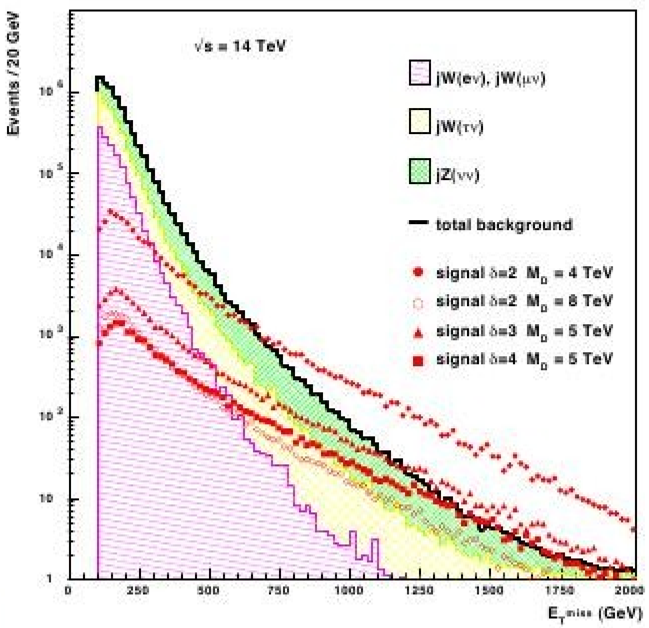
Signatures of extra dimensional models

KK-Graviton production:



Search for:
Mono-jet + Missing energy

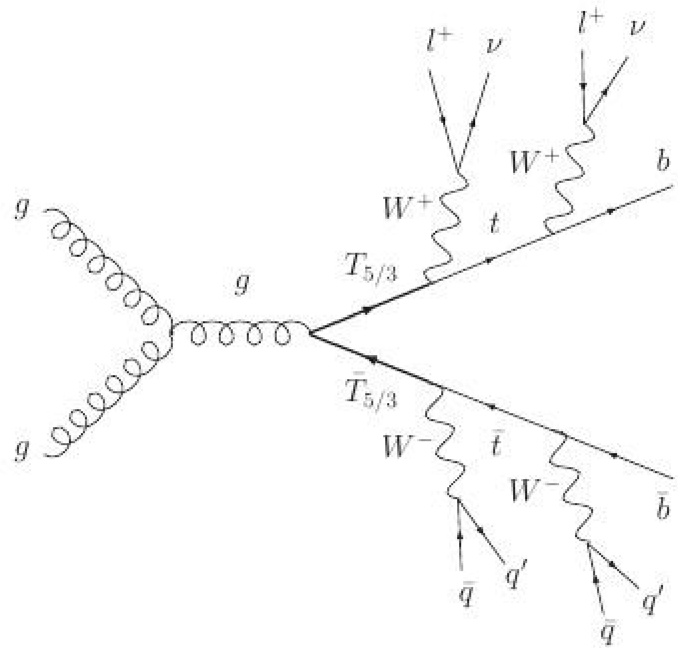




arXiv:hep-ex/0310020v1

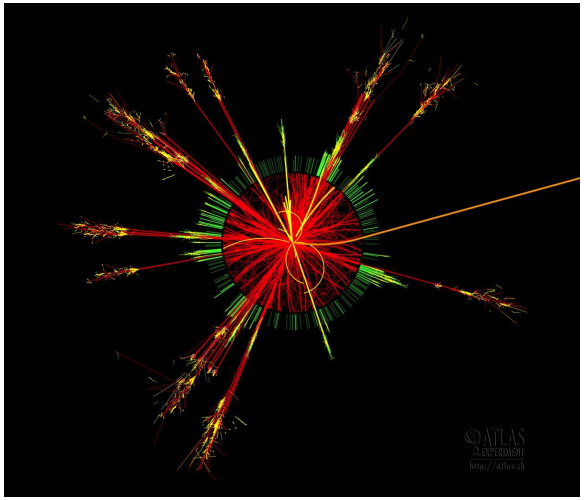
Gauge – Higgs unification in 5 dimensions

- Solution of the hierarchy problem: if the Higgs is the 5th dimensional component of a 5D gauge field, the gauge invariance in 5D protects its mass from receiving large corrections!
- Spectacular signatures:
  - Decays to new gauge bosons W', Z'
  - New states appears, like a new top quark with electric charge 5/3.



Black holes at LHC

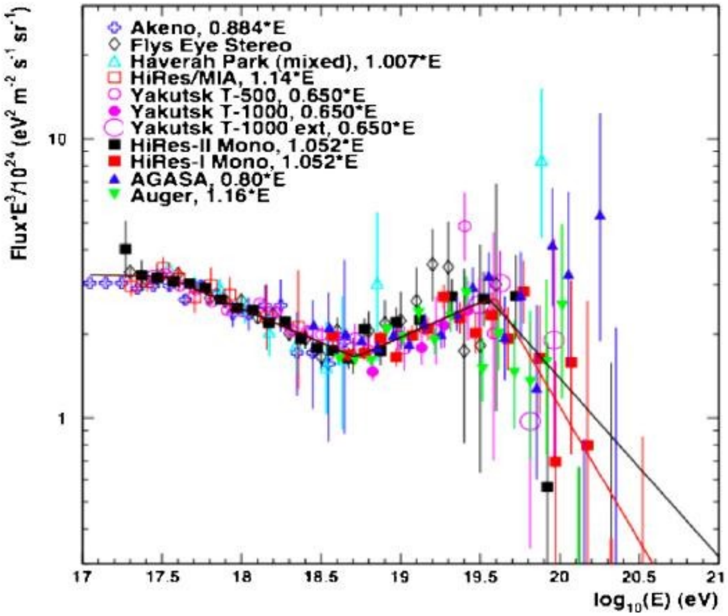
- Microscopic low velocity black holes *may* be produced at the LHC, but only if some large extra dimensional scenario is realized in Nature!
- To the best of our (imperfect) understanding, microscopic black holes evaporate by Hawking radiation and decay very rapidly, in 10^{-27}s, long before being able to accrete.
- Allowing microscopic stable black holes seems to violate basic principles of QM or GR! But even if they are allowed:
  - If charged, cosmic ray black holes would slow down and stop in Earth. None seen.
  - If neutral, they absorb predominantly p and n, becoming charged!

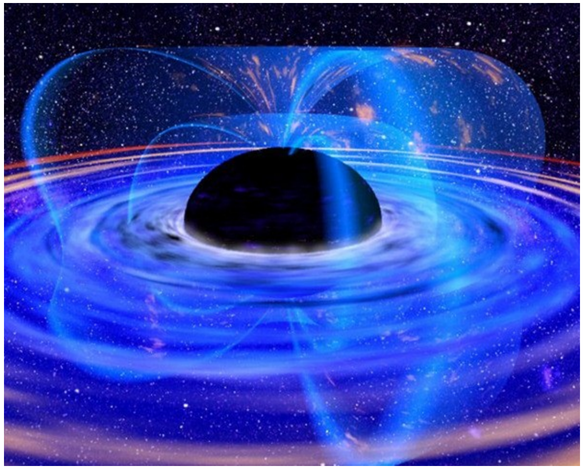


- The experimental signature would be very spectacular: isotropic many body decay.

Will the LHC destroy the Universe?

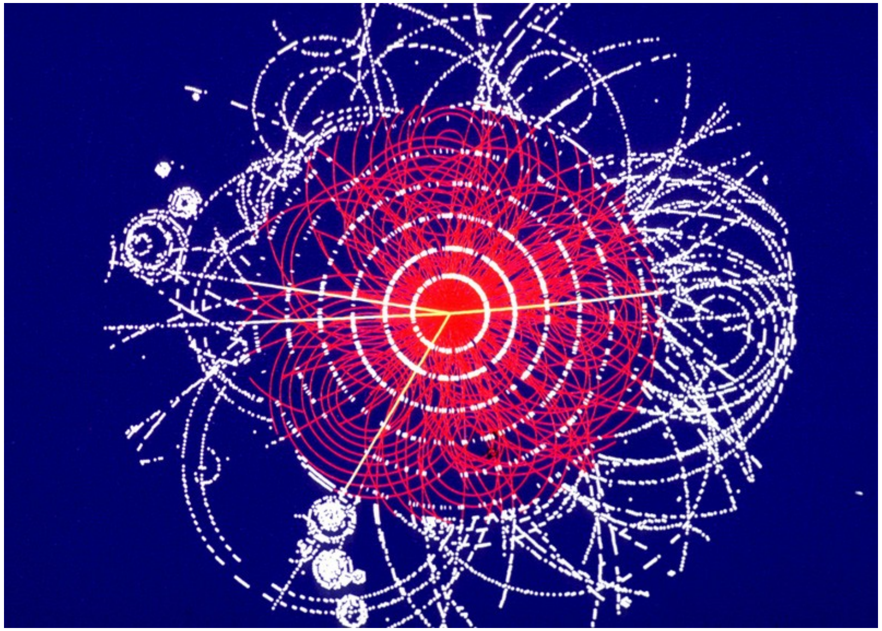
- The Universe replicates the 10^{17} pp collisions to be made at the LHC 10^{13} times per second!
- This has already happened 10^{31} times since the Big Bang, 10^{5} times on the Earth alone. No indication of large-scale catastrophic consequences seen up to now!
- UHE cosmic rays onto white dwarfs or neutron stars could have produced balck holes that could stop inside, but no evidence seen so far!
- If we take seriously the theoretical possibility to produce microscopic black holes, we should also take seriously the theory saying these must decay without leaving black hole remnants behind.





Summary

- *Electroweak theory*
- *Higgs at the LHC*
- *Motivations for extensions of SM*
- *Basics of SUSY and the MSSM*
- *Alternative Models*
- *Black holes at LHC*



Thank you for your attention