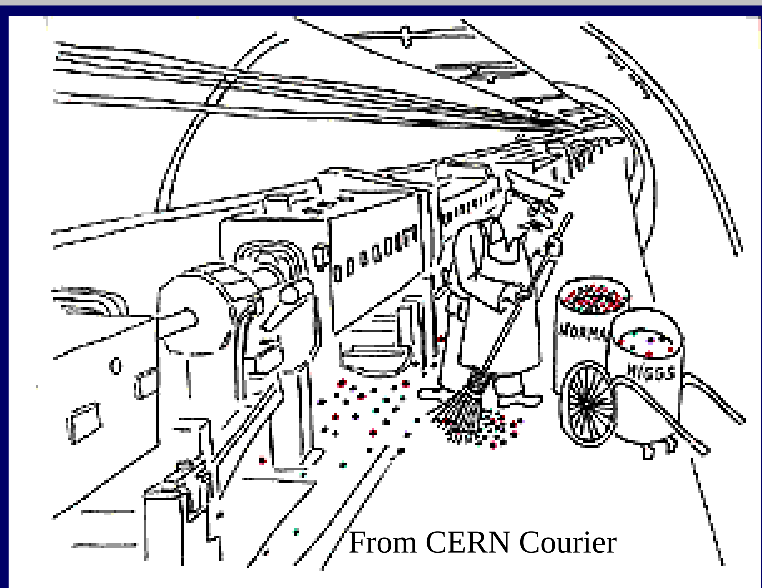
Searching for the Mechanism of Electroweak Symmetry Breaking

Csaba Csáki (Cornell University)



From CERN Courier

University of Virginia
November 17, 2006

Four basic forces:

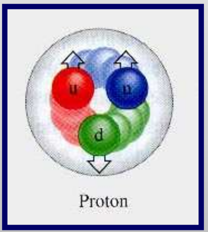
- Electromagnetic force:

  electricity, radiowaves, light

- Weak force:

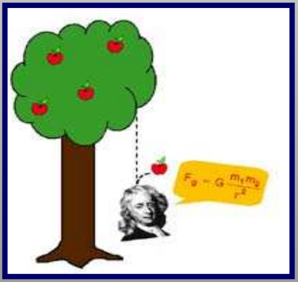
  origin of radioactivity

- Strong force:



  origin of energy from sun, binds nuclei

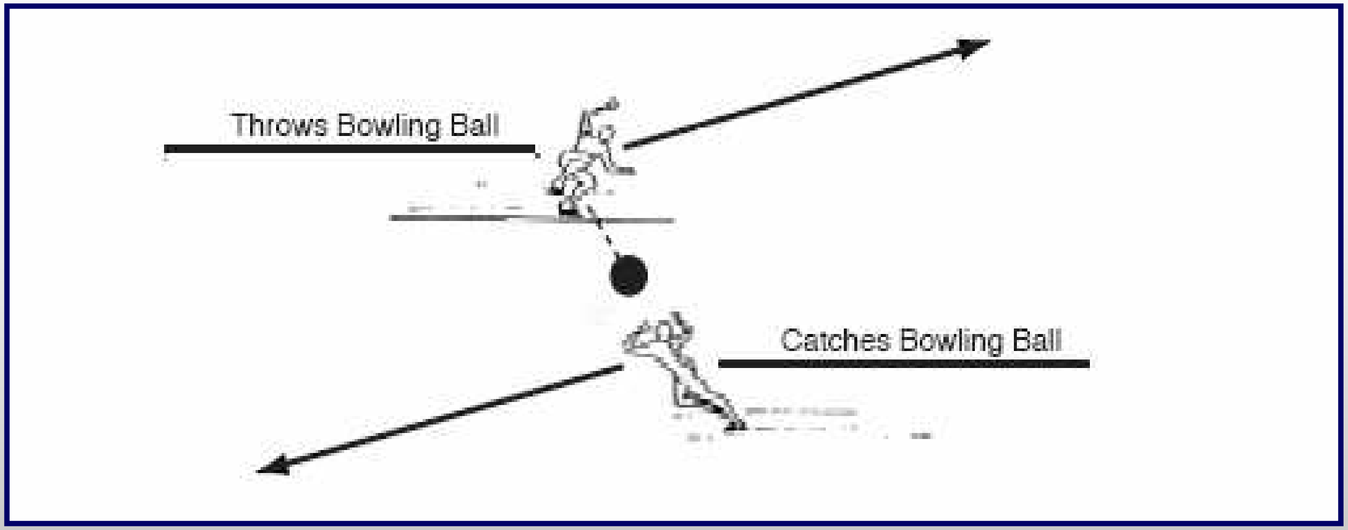
- Gravitational force:



  motion of planets, rockets,...

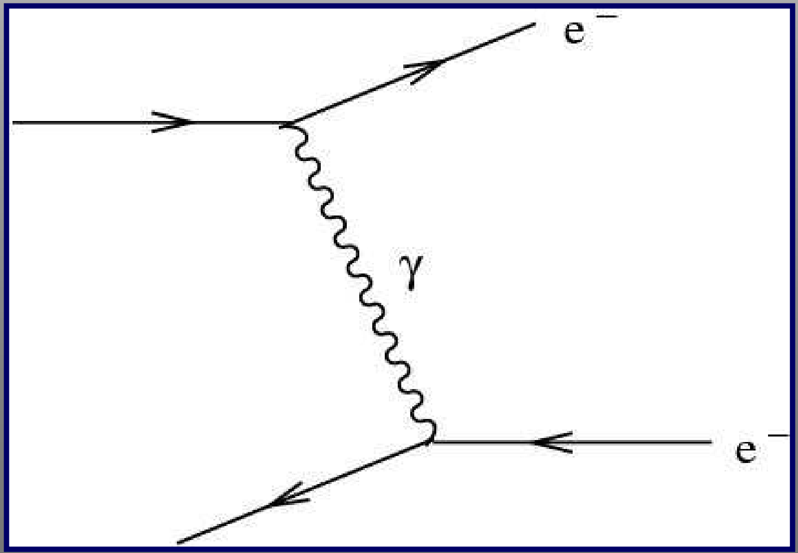
Gravity **very weak** – a small magnet can balance the effect of the ENTIRE Earth, NOT relevant in accelerators

Force between particles: exchange of force carrying particle

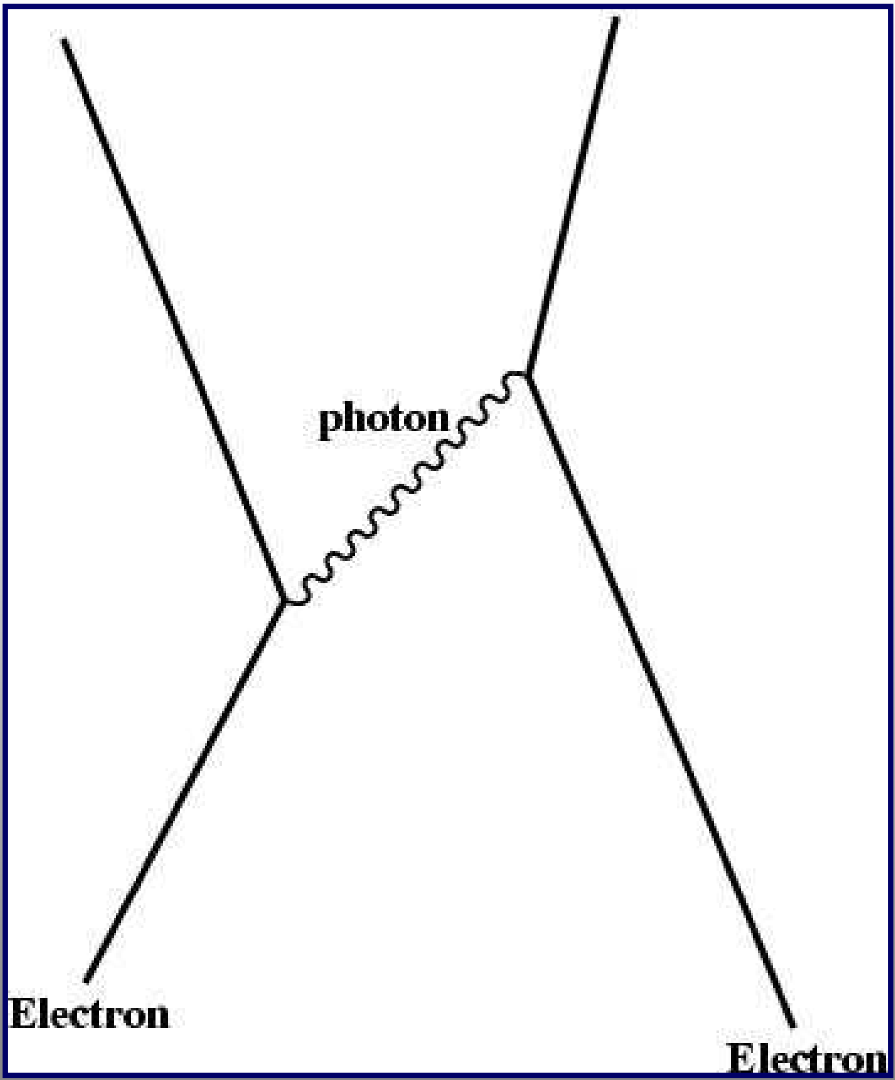


(Courtesy of Ahren Sadoff)

For example: Electromagnetic force



Electromagnetic Interactions



Electric force is described by emission and absorption of photon – the force carrier of electromagnetism

Feynman

QED = quantized version of Maxwell's theory

- Basic principle: gauge invariance: U(1) gauge theory
- Basic object: 4-vector potential

$$A_\mu$$

"Quantum Electrodynamics"

One of Feynman's groundbreaking papers (written at Cornell…)

PHYSICAL REVIEW VOLUME 76, NUMBER 6 SEPTEMBER 15, 1949

Space-Time Approach to Quantum Electrodynamics

R. P. FEYNMAN
Department of Physics, Cornell University, Ithaca, New York
(Received May 9, 1949)

In this paper two things are done. (1) It is shown that a considerable simplification can be attained in writing down matrix elements for complex processes in electrodynamics. Further, a physical point of view is available which permits them to be written down directly for any specific problem. Being simply a restatement of conventional electrodynamics, however, the matrix elements diverge for complex processes. (2) Electrodynamics is modified by altering the interaction of electrons at short distances. All matrix elements are now finite, with the exception of those relating to problems of vacuum polarization. The latter are evaluated in a manner suggested by Pauli and Bethe, which gives finite results for these matrices also. The only effects sensitive to the modification are changes in mass and charge of the electrons. Such changes could not be directly observed. Phenomena directly observable, are insensitive to the details of the modification used (except at extreme energies). For such phenomena, a limit can be taken as the range of the modification goes to zero. The results then agree with those of Schwinger. A complete, unambiguous, and presumably consistent, method is therefore available for the calculation of all processes involving electrons and photons.

The simplification in writing the expressions results from an emphasis on the over-all space-time view resulting from a study of the solution of the equations of electrodynamics. The relation of this to the more conventional Hamiltonian point of view is discussed. It would be very difficult to make the modification which is proposed if one insisted on having the equations in Hamiltonian form.

The methods apply as well to charges obeying the Klein-Gordon equation, and to the various meson theories of nuclear forces. Illustrative examples are given. Although a modification like that used in electrodynamics can make all matrices finite for all of the meson theories, for some of the theories it is no longer true that all directly observable phenomena are insensitive to the details of the modification used.

The actual evaluation of integrals appearing in the matrix elements may be facilitated, in the simpler cases, by methods described in the appendix.

THIS paper should be considered as a direct continuation of a preceding one[1] (I) in which the motion of electrons, neglecting interaction, was analyzed, by dealing directly with the *solution* of the Hamiltonian differential equations. Here the same technique is applied to include interactions and in that way to express in simple terms the solution of problems in quantum electrodynamics.

For most practical calculations in quantum electrodynamics the solution is ordinarily expressed in terms of a matrix element. The matrix is worked out as an expansion in powers of $e^2/\hbar c$, the successive terms corresponding to the inclusion of an increasing number of virtual quanta. It appears that a considerable simplification can be achieved in writing down these matrix elements for complex processes. Furthermore, each term in the expansion can be written down and understood directly from a physical point of view, similar to the space-time view in I. It is the purpose of this paper to describe how this may be done. We shall also discuss methods of handling the divergent integrals which appear in these matrix elements.

The simplification in the formulae results mainly from the fact that previous methods unnecessarily separated into individual terms processes that were closely related physically. For example, in the exchange of a quantum between two electrons there were two terms depending on which electron emitted and which absorbed the quantum. Yet, in the virtual states considered, timing relations are not significant. Olny the order of operators in the matrix must be maintained. We have seen (I), that in addition, processes in which virtual pairs are produced can be combined with others in which only positive energy electrons are involved. Further, the effects of longitudinal and transverse waves can be combined together. The separations previously made were on an unrelativistic basis (reflected in the circumstance that apparently momentum but not energy is conserved in intermediate states). When the terms are combined and simplified, the relativistic invariance of the result is self-evident.

We begin by discussing the solution in space and time of the Schrödinger equation for particles interacting instantaneously. The results are immediately generalizable to delayed interactions of relativistic electrons and we represent in that way the laws of quantum electrodynamics. We can then see how the matrix element for any process can be written down directly. In particular, the self-energy expression is written down.

So far, nothing has been done other than a restatement of conventional electrodynamics in other terms. Therefore, the self-energy diverges. A modification[2] in interaction between charges is next made, and it is shown that the self-energy is made convergent and corresponds to a correction to the electron mass. After the mass correction is made, other real processes are finite and insensitive to the "width" of the cut-off in the interaction.[3]

Unfortunately, the modification proposed is not completely satisfactory theoretically (it leads to some difficulties of conservation of energy). It does, however, seem consistent and satisfactory to define the matrix

[1] R. P. Feynman, Phys. Rev. **76**, 749 (1949), hereafter called I.

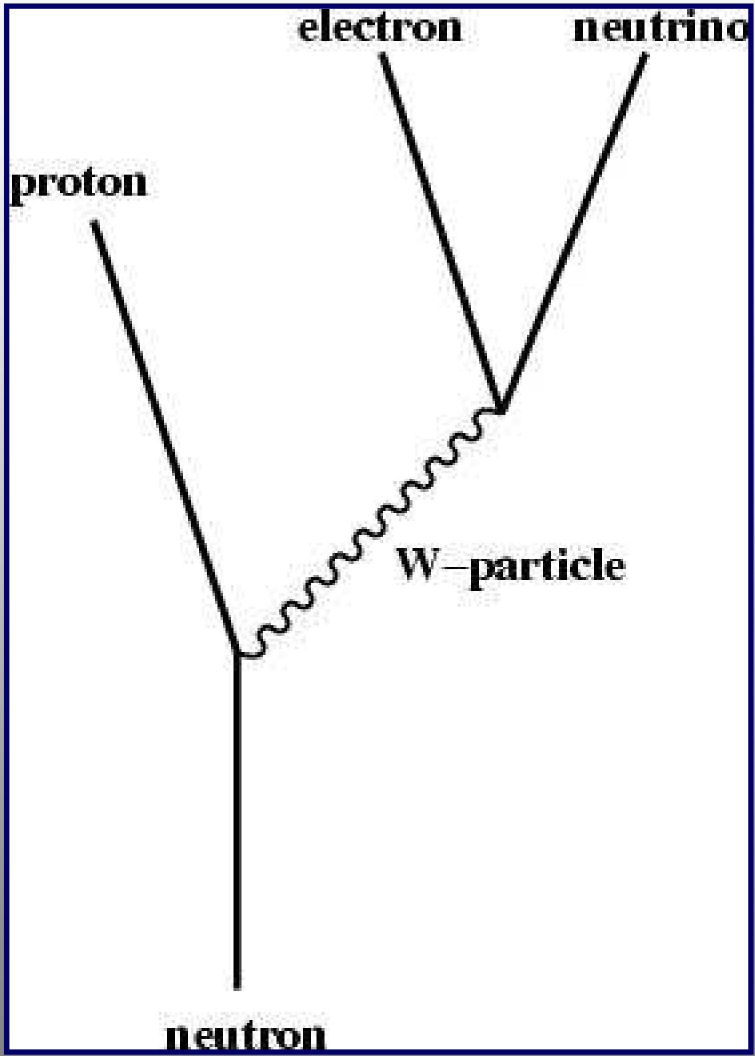
[2] For a discussion of this modification in classical physics see R. P. Feynman, Phys. Rev. **74** 939 (1948), hereafter referred to as A.

[3] A brief summary of the methods and results will be found in R. P. Feynman, Phys. Rev. **74**, 1430 (1948), hereafter referred to as B.

Weak Interactions

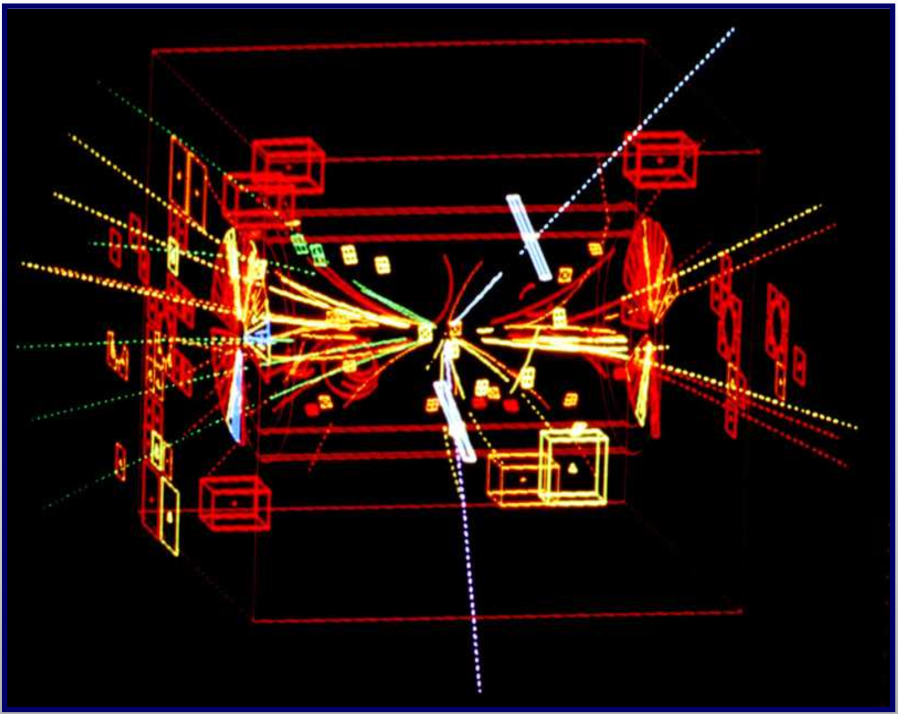
Just like electrodynamics, EXCEPT

- Mediating particle MASSIVE
- Mediating particle CHARGED



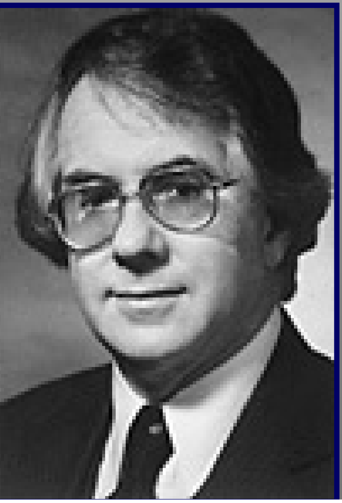
- Instead of photon, mediating particles W and Z bosons
- Otherwise theory just like the previous one

The discovery of the Z-particle at CERN in 1982

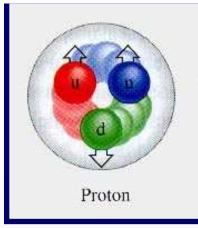


The first event...

Champagne for the Nobel prize
Rubbia and van der Meer 1984



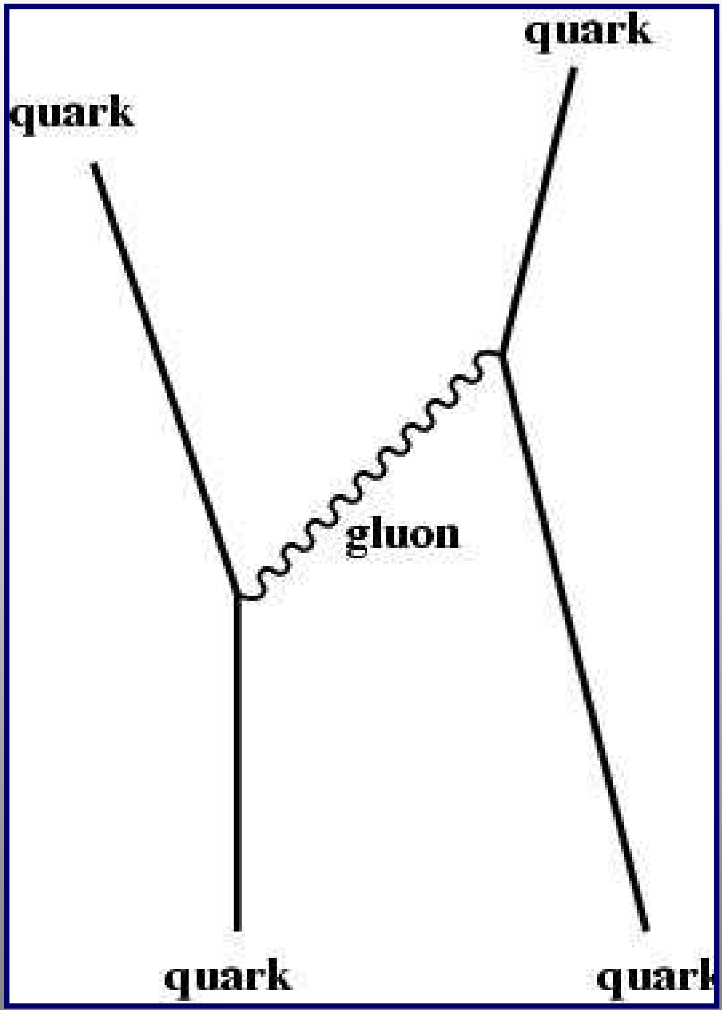
Glashow, Salam, Weinberg:
first worked out **theory**



Strong Interactions

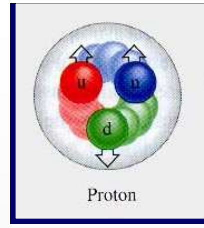
Just like electrodynamics, EXCEPT

- Fundamental particles quarks
- Emission of mediating particle very high probability -- strong interaction...



- Instead of photon, mediating particle gluon ("glues" the quarks into bound state protons, etc)
- Otherwise theory just like the previous one

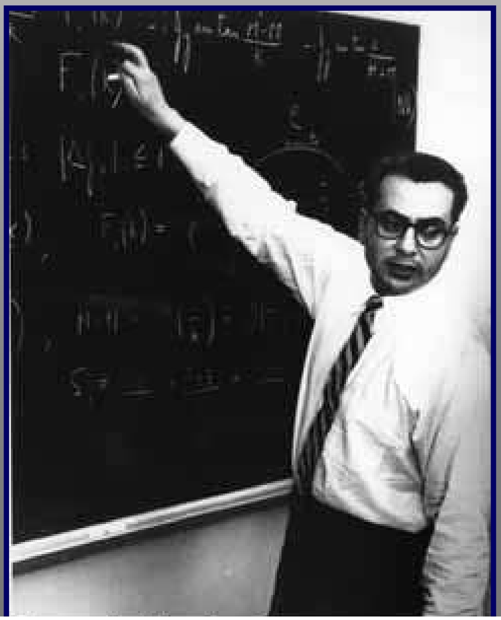
Quarks

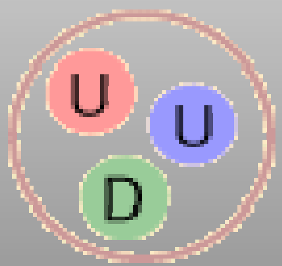


- Basic strongly interacting objects
- Never visible as free particles -- confined
- Form bound states, glued together

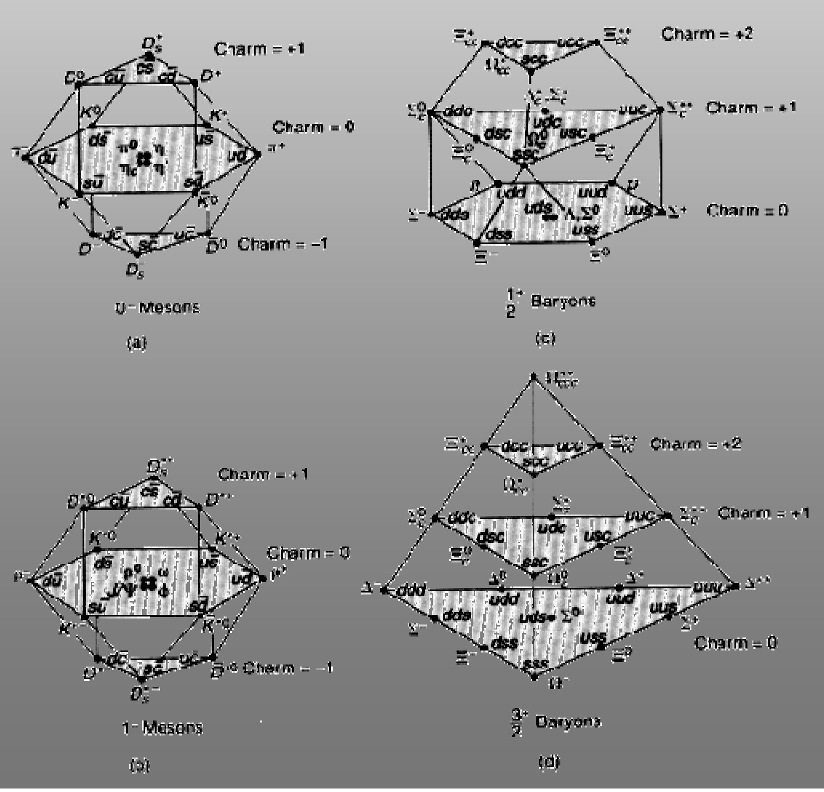
Allows to make sense of the 100's of particles observed...

Gell-Mann

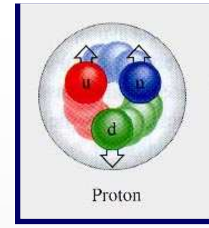




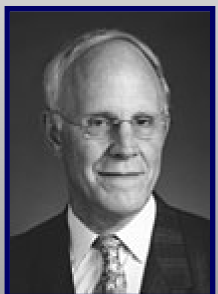
proton

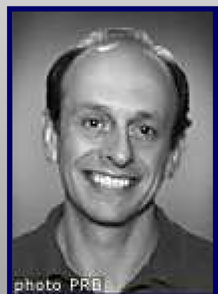


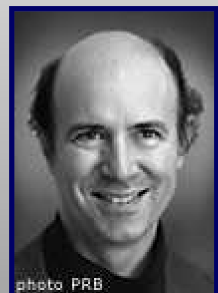
Asymptotic freedom of strong interactions



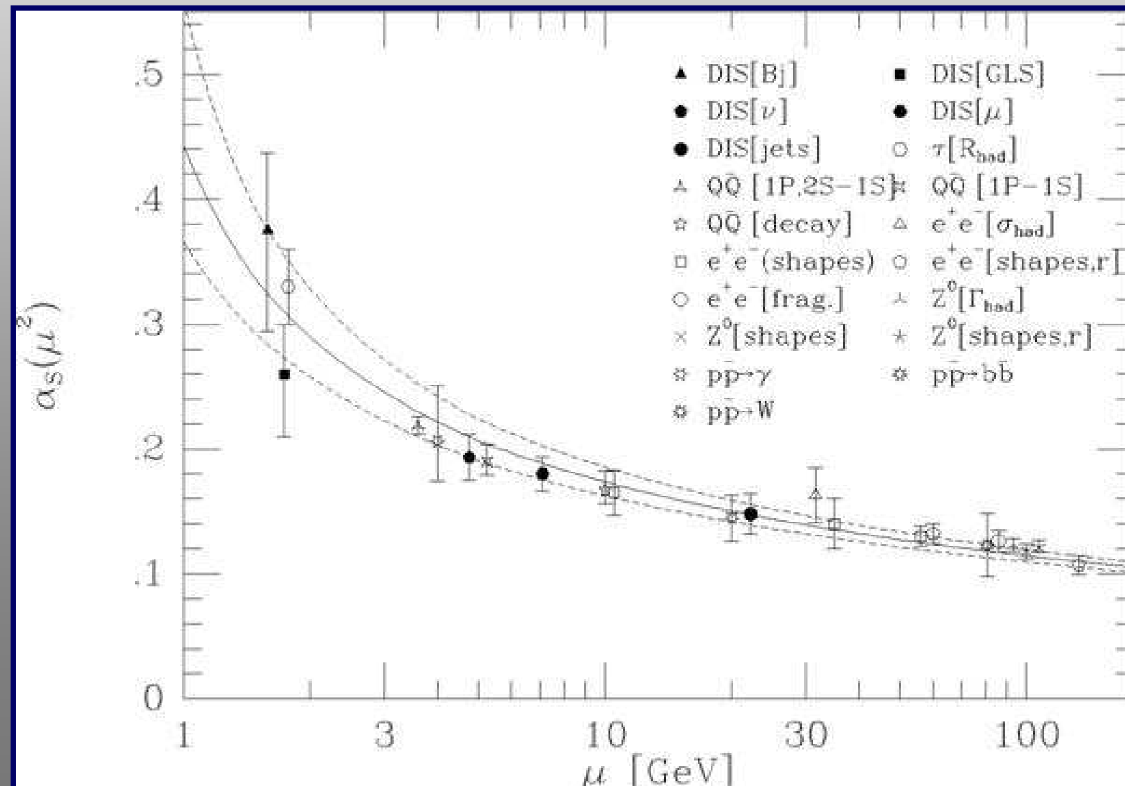
- Very counter intuitive result
- Interaction gets weaker at high energies
- Strong interaction NOT ALWAYS STRONG!
- At low energies interaction so strong, quarks and gluons confined
- At high energies interaction weak, usual Feynman calculus applicable







Gross Politzer Wilczek



Standard Model of

FUNDAMENTAL PARTICLES AND INTERACTIONS

The Standard Model summarizes the current knowledge in Particle Physics. It is the quantum theory that includes the theory of strong interactions (quantum chromodynamics or QCD) and the unified theory of weak and electromagnetic interactions (electroweak). Gravity is included on this chart because it is one of the fundamental interactions even though not part of the "Standard Model."

FERMIONS

matter constituents
spin = 1/2, 3/2, 5/2, ...

Leptons spin = 1/2

Flavor	Mass GeV/c^2	Electric charge
ν_e electron neutrino	$<1\times10^{-8}$	0
e electron	0.000511	–1
ν_μ muon neutrino	<0.0002	0
μ muon	0.106	–1
ν_τ tau neutrino	<0.02	0
τ tau	1.7771	–1

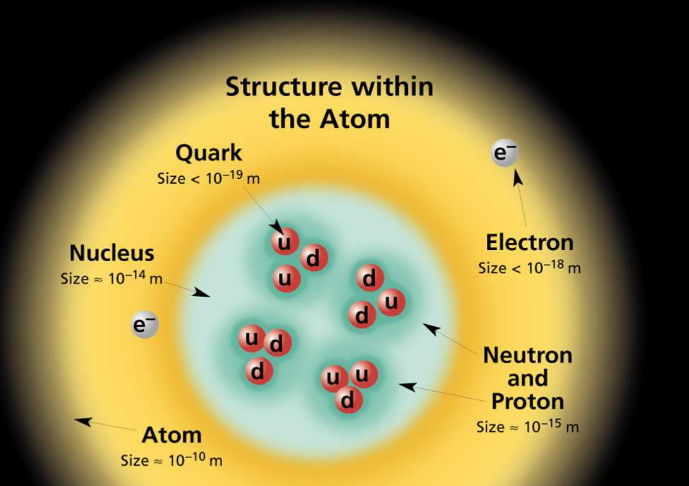
Quarks spin = 1/2

Flavor	Approx. Mass GeV/c^2	Electric charge
u up	0.003	2/3
d down	0.006	–1/3
c charm	1.3	2/3
s strange	0.1	–1/3
t top	175	2/3
b bottom	4.3	–1/3

Spin is the intrinsic angular momentum of particles. Spin is given in units of ħ, which is the quantum unit of angular momentum, where $\hbar = h/2\pi = 6.58\times10^{-25}$ GeV s = 1.05×10^{-34} J s.

Electric charges are given in units of the proton's charge. In SI units the electric charge of the proton is 1.60×10^{-19} coulombs.

The **energy** unit of particle physics is the electronvolt (eV), the energy gained by one electron in crossing a potential difference of one volt. **Masses** are given in GeV/c^2 (remember $E = mc^2$), where 1 GeV = 10^9 eV = 1.60×10^{-10} joule. The mass of the proton is 0.938 GeV/c^2 = 1.67×10^{-27} kg.



If the protons and neutrons in this picture were 10 cm across, then the quarks and electrons would be less than 0.1 mm in size and the entire atom would be about 10 km across.

BOSONS

force carriers
spin = 0, 1, 2, ...

Unified Electroweak spin = 1

Name	Mass GeV/c^2	Electric charge
γ photon	0	0
W^-	80.4	–1
W^+	80.4	+1
Z^0	91.187	0

Strong (color) spin = 1

Name	Mass GeV/c^2	Electric charge
g gluon	0	0

Color Charge

Each quark carries one of three types of "strong charge," also called "color charge." These charges have nothing to do with the colors of visible light. There are eight possible types of color charge for gluons. Just as electrically-charged particles interact by exchanging photons, in strong interactions color-charged particles interact by exchanging gluons. Leptons, photons, and ***W*** and ***Z*** bosons have no strong interactions and hence no color charge.

Quarks Confined in Mesons and Baryons

One cannot isolate quarks and gluons; they are confined in color-neutral particles called **hadrons**. This confinement (binding) results from multiple exchanges of gluons among the color-charged constituents. As color-charged particles (quarks and gluons) move apart, the energy in the color-force field between them increases. This energy eventually is converted into additional quark-antiquark pairs (see figure below). The quarks and antiquarks then combine into hadrons; these are the particles seen to emerge. Two types of hadrons have been observed in nature: **mesons** $q\bar{q}$ and **baryons** qqq.

Residual Strong Interaction

The strong binding of color-neutral protons and neutrons to form nuclei is due to residual strong interactions between their color-charged constituents. It is similar to the residual electrical interaction that binds electrically neutral atoms to form molecules. It can also be viewed as the exchange of mesons between the hadrons.

PROPERTIES OF THE INTERACTIONS

Property \ Interaction	Gravitational	Weak (Electroweak)	Electromagnetic (Electroweak)	Strong: Fundamental	Strong: Residual
Acts on:	Mass – Energy	Flavor	Electric Charge	Color Charge	See Residual Strong Interaction Note
Particles experiencing:	All	Quarks, Leptons	Electrically charged	Quarks, Gluons	Hadrons
Particles mediating:	Graviton (not yet observed)	W^+ W^- Z^0	γ	Gluons	Mesons
Strength relative to electromag for two u quarks at: 10^{-18} m	10^{-41}	0.8	1	25	Not applicable to quarks
Strength relative to electromag for two u quarks at: 3×10^{-17} m	10^{-41}	10^{-4}	1	60	
for two protons in nucleus	10^{-36}	10^{-7}	1	Not applicable to hadrons	20

Baryons qqq and Antibaryons $\bar{q}\bar{q}\bar{q}$

Baryons are fermionic hadrons.
There are about 120 types of baryons.

Symbol	Name	Quark content	Electric charge	Mass GeV/c^2	Spin
p	proton	uud	1	0.938	1/2
$\bar{p}$	anti-proton	$\bar{u}\bar{u}\bar{d}$	–1	0.938	1/2
n	neutron	udd	0	0.940	1/2
Λ	lambda	uds	0	1.116	1/2
Ω^-	omega	sss	–1	1.672	3/2

Mesons $q\bar{q}$

Mesons are bosonic hadrons.
There are about 140 types of mesons.

Symbol	Name	Quark content	Electric charge	Mass GeV/c^2	Spin
π^+	pion	$u\bar{d}$	+1	0.140	0
K^-	kaon	$s\bar{u}$	–1	0.494	0
ρ^+	rho	$u\bar{d}$	+1	0.770	1
B^0	B-zero	$d\bar{b}$	0	5.279	0
η_c	eta-c	$c\bar{c}$	0	2 .980	0

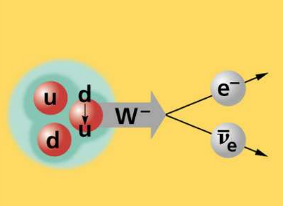
Matter and Antimatter

For every particle type there is a corresponding antiparticle type, denoted by a bar over the particle symbol (unless + or – charge is shown). Particle and antiparticle have identical mass and spin but opposite charges. Some electrically neutral bosons (e.g., Z^0, γ, and $\eta_c = c\bar{c}$, but not $K^0 = d\bar{s}$) are their own antiparticles.

Figures

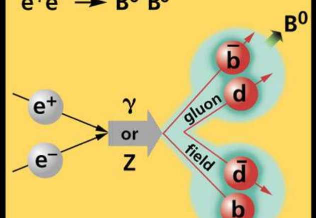
These diagrams are an artist's conception of physical processes. They are ***not*** exact and have ***no*** meaningful scale. Green shaded areas represent the cloud of gluons or the gluon field, and red lines the quark paths.

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



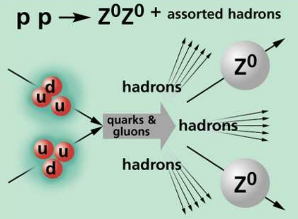
A neutron decays to a proton, an electron, and an antineutrino via a virtual (mediating) W boson. This is neutron β decay.

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



An electron and positron (antielectron) colliding at high energy can annihilate to produce B^0 and $\bar{B}^0$ mesons via a virtual Z boson or a virtual photon.

$p\,p \rightarrow Z^0Z^0$ + assorted hadrons



Two protons colliding at high energy can produce various hadrons plus very high mass particles such as Z bosons. Events such as this one are rare but can yield vital clues to the structure of matter.

The Particle Adventure

Visit the award-winning web feature *The Particle Adventure* at
http://ParticleAdventure.org

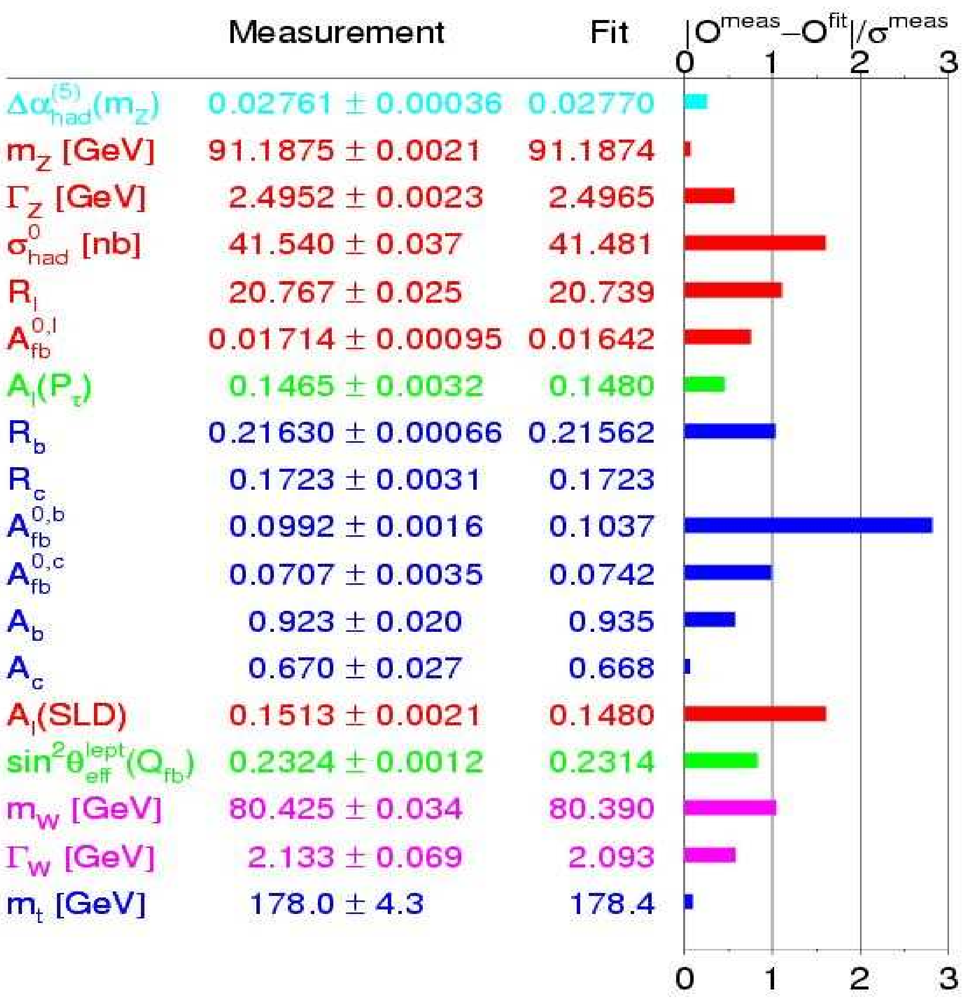
This chart has been made possible by the generous support of:
U.S. Department of Energy
U.S. National Science Foundation
Lawrence Berkeley National Laboratory
Stanford Linear Accelerator Center
American Physical Society, Division of Particles and Fields
BURLE INDUSTRIES, INC.

http://CPEPweb.org

The Standard Model of Particle Physics

	$SU(3)_c$	$SU(2)_L$	$U(1)_Y$	
µ o e ¶ L	1	2	¡ $\frac{1}{2}$	**LEPTONS**
e_R	1	1	¡ 1	
µ u d ¶ L	3	2	$\frac{1}{6}$	**QUARKS**
u_R	3	1	$\frac{2}{3}$	
d_R	3	1	¡ $\frac{1}{3}$	
H	1	2	$\frac{1}{2}$	**HIGGS**

Almost every aspect of SM verified in great detail



(From LEP EWWG)

Experiments:

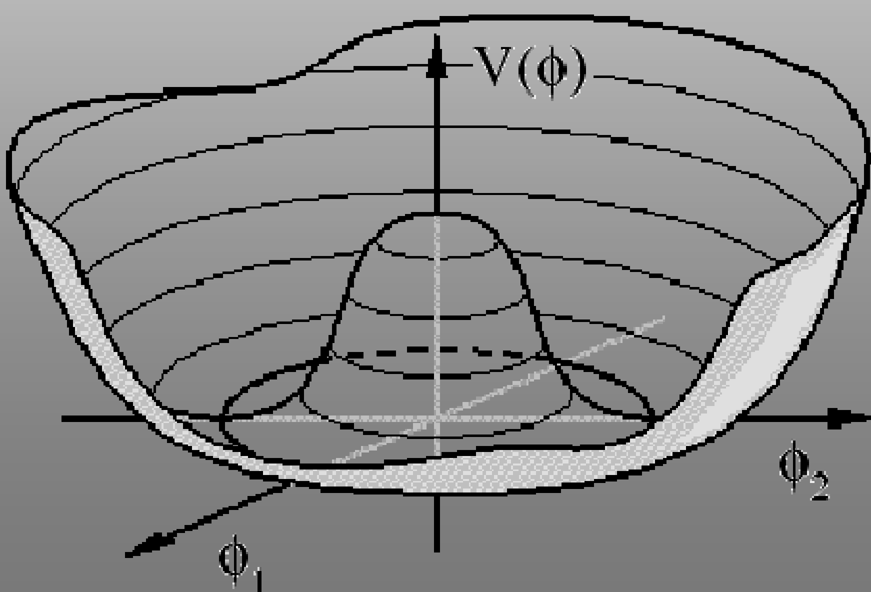
- LEP, LEP2 (CERN)
- SLD (SLAC)
- Tevatron (Fermilab)

However electroweak symmetry broken by Higgs

Gauge invariance forbids gauge boson masses

$A_\mu A^\mu$ is NOT invariant under $A_\mu \to A_\mu + \partial_\mu \eta$

- Similarly, all fermion masses forbidden by gauge invariance
- Need to ASSUME Higgs sector breaks gauge symmetry

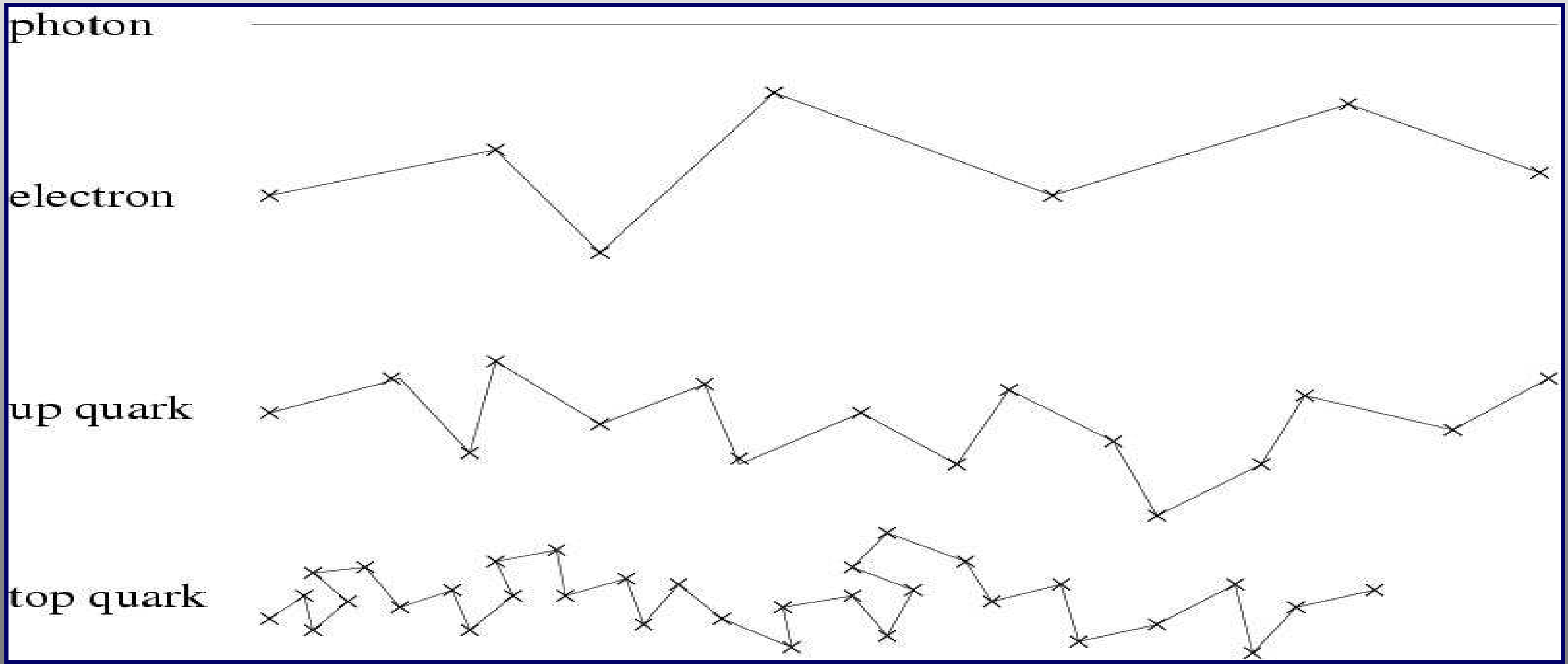


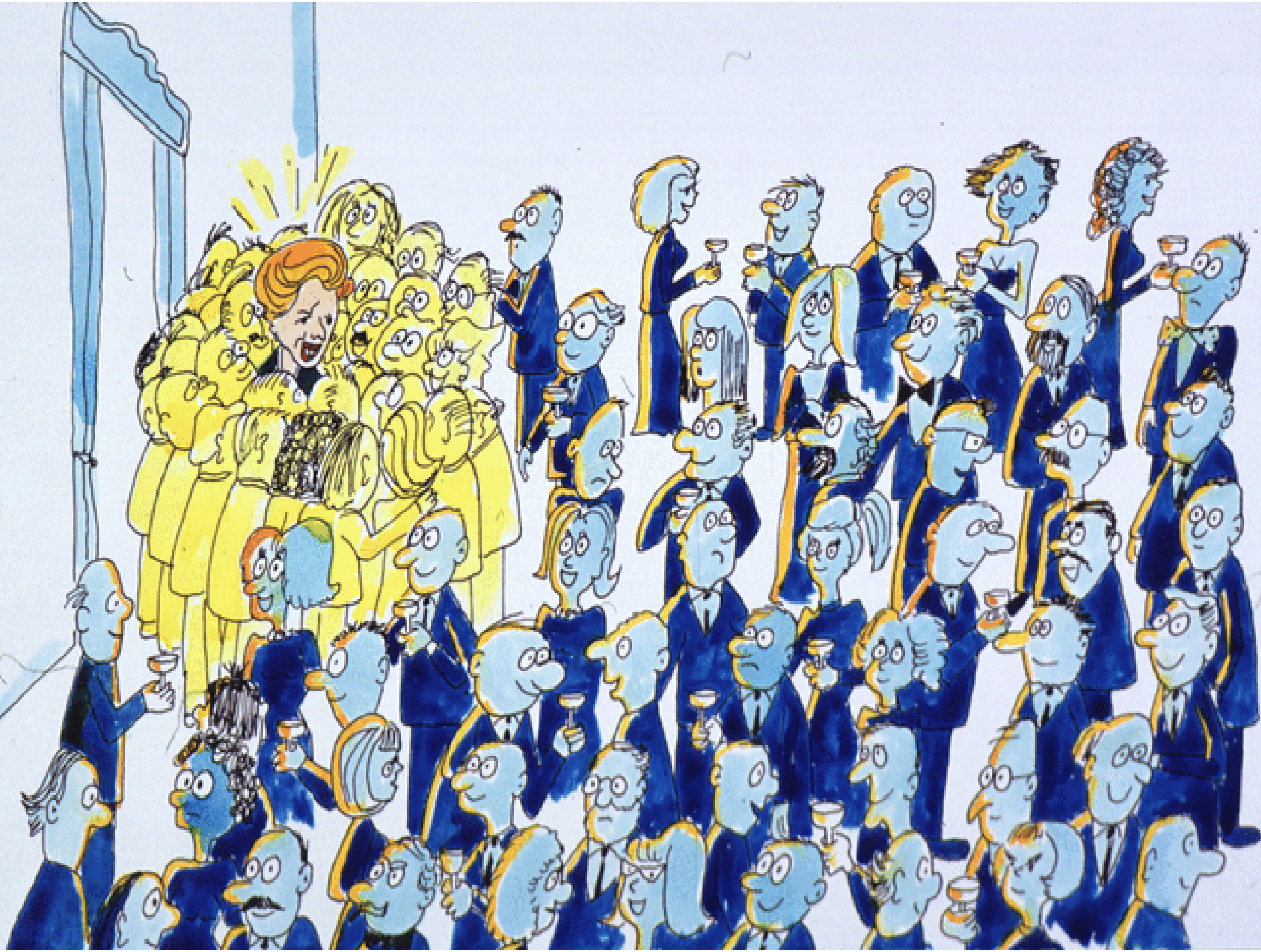
$$V(H) = -\mu^2 H H^\dagger + \lambda (H H^\dagger)^2$$

$$\langle H \rangle = \begin{pmatrix} 0 \\ v \end{pmatrix}$$

- Entire space is filled with Higgs condensate
- Interaction with condensate slows down motion
- Effectively appears as if particles massive

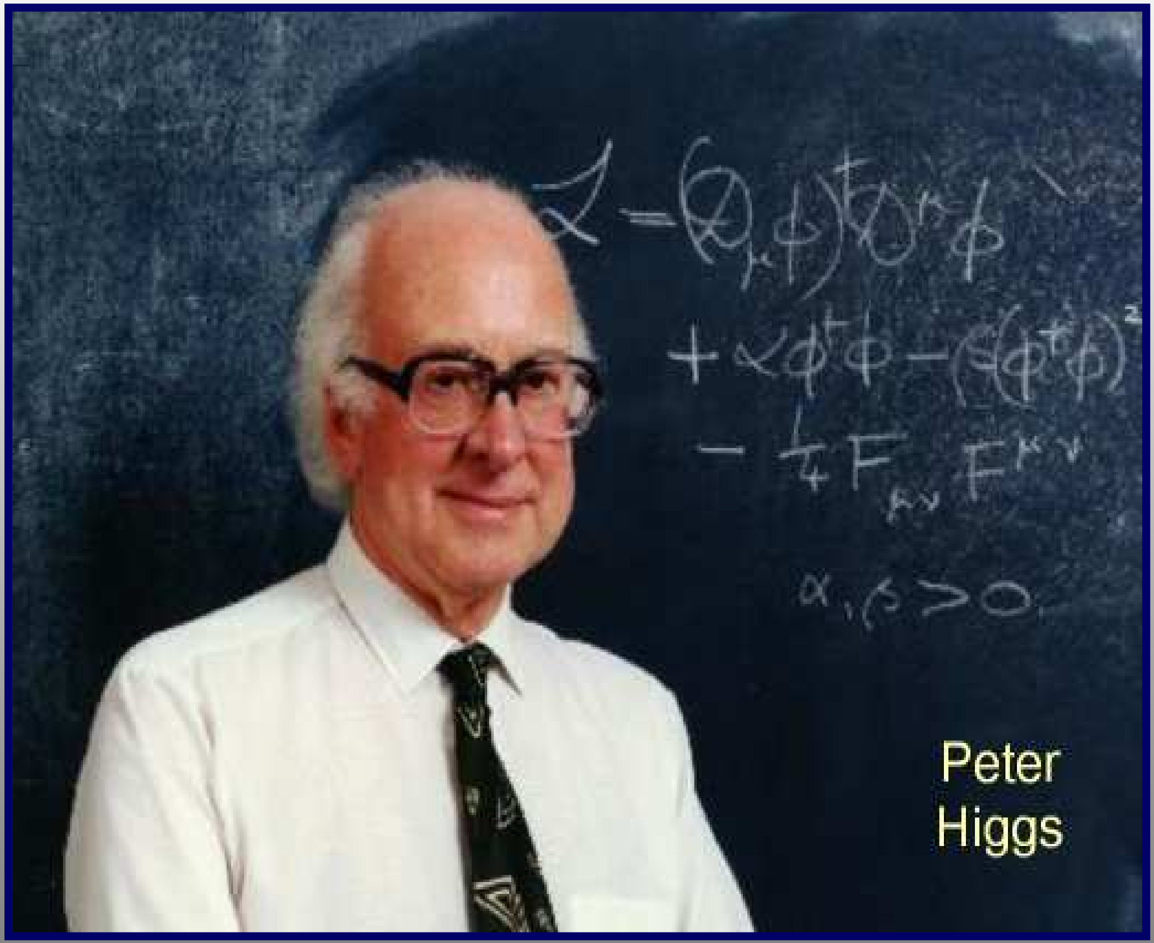
Somewhat like aether theory, but relativistic (need scalar!)





But the only Higgs discovered so far ...

But the only Higgs discovered so far ...



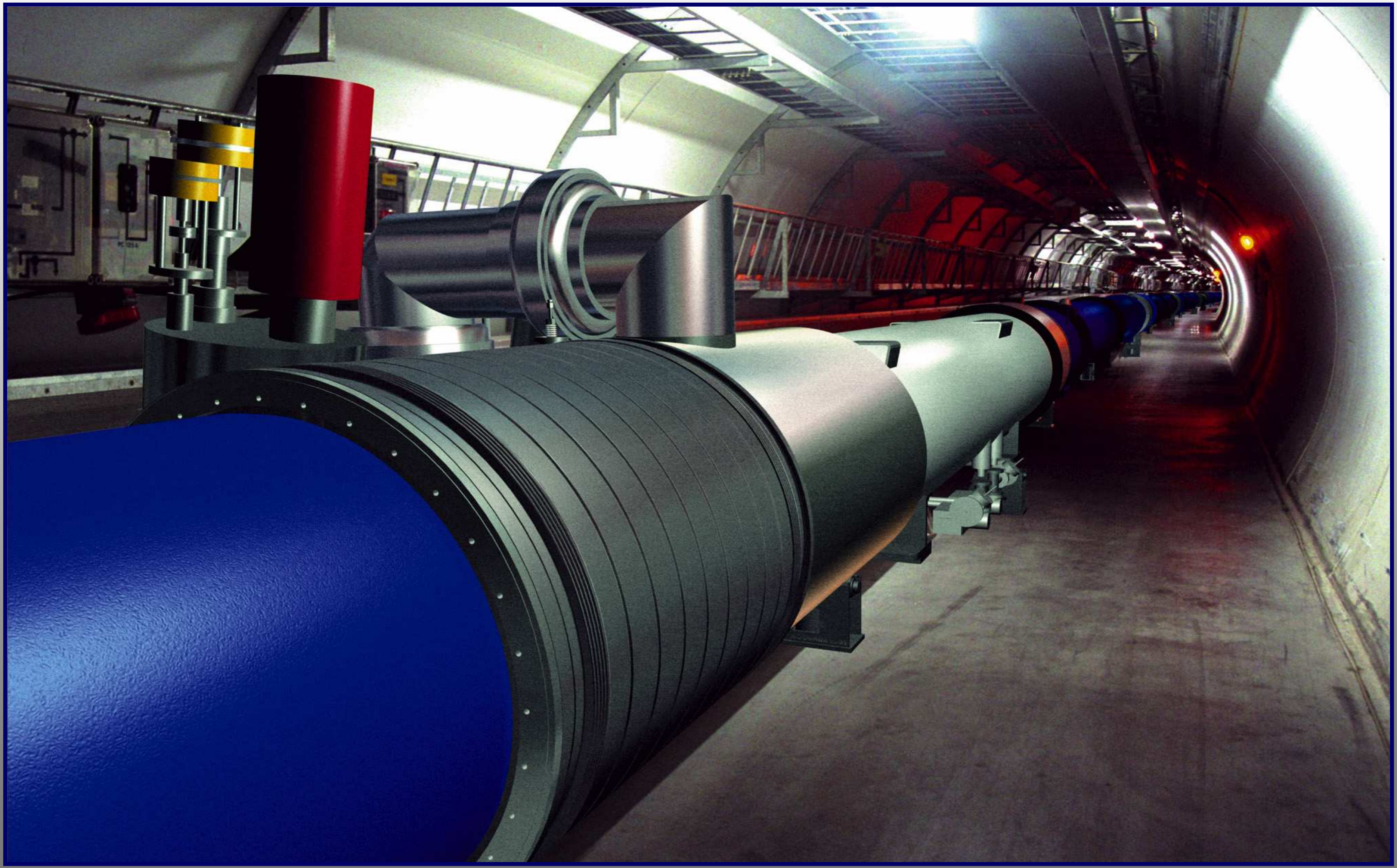
The search for Higgs: LHC at CERN

European Center for Particle Physics, Geneva, Switzerland

17 miles circumference (multi-billion dollars...)

The Large Hadron Collider (LHC)

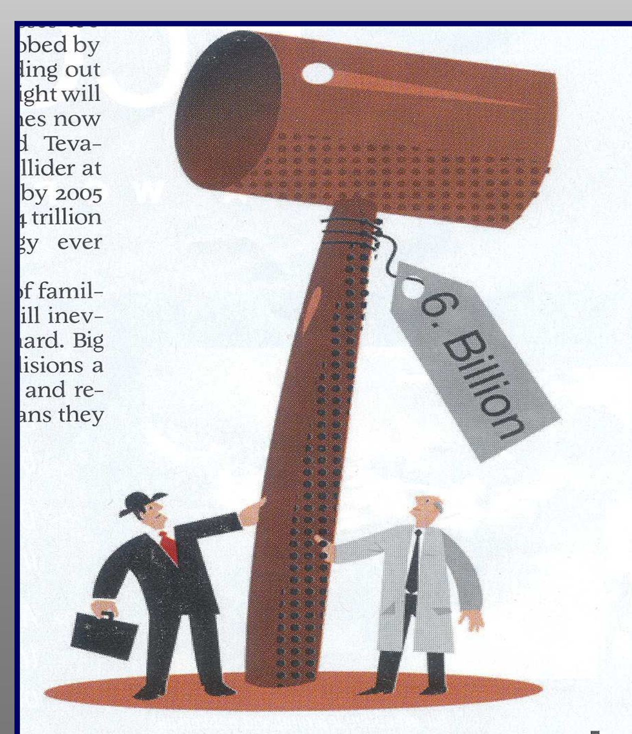
Over 6000 scientists, 500 Universities from 80 countries...



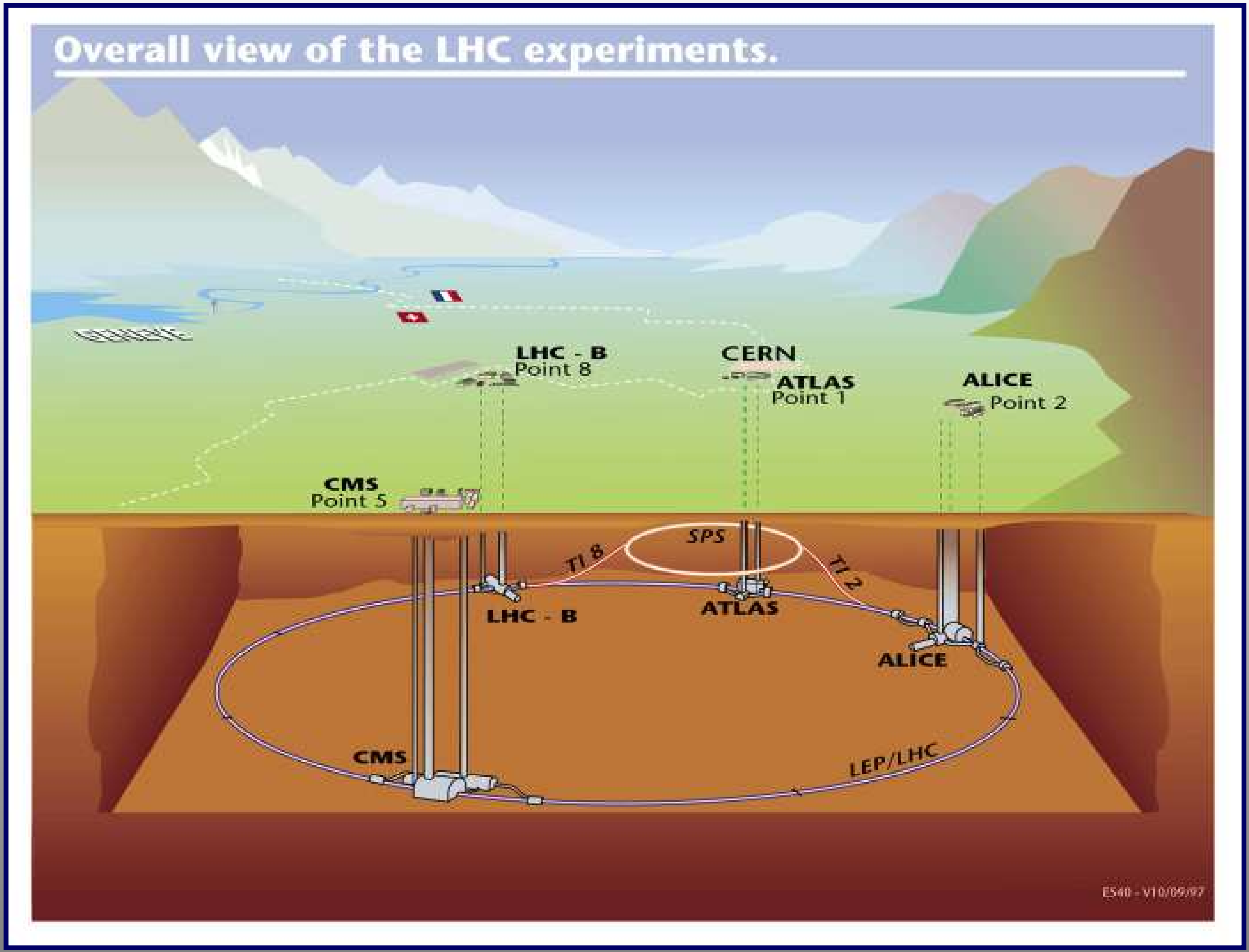
The Economist's cartoon of the LHC...

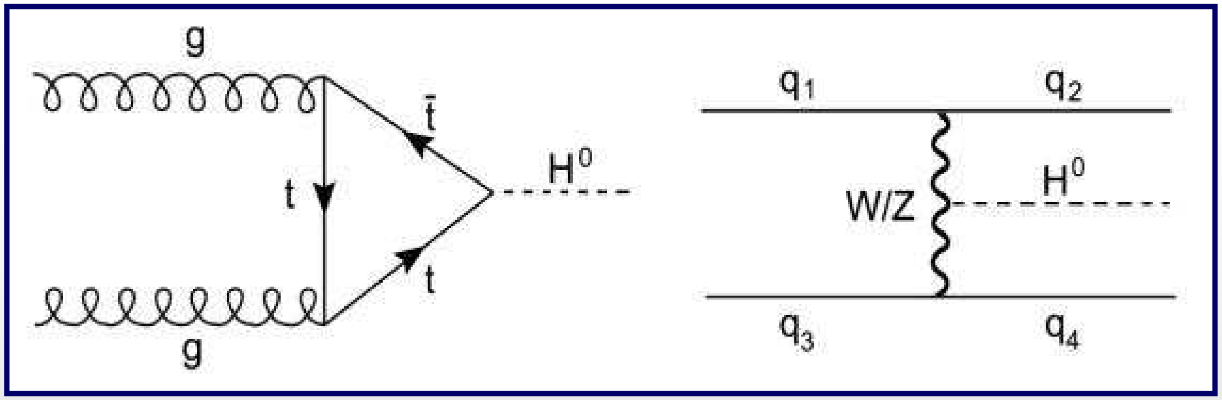
The Economist's cartoon of the LHC...

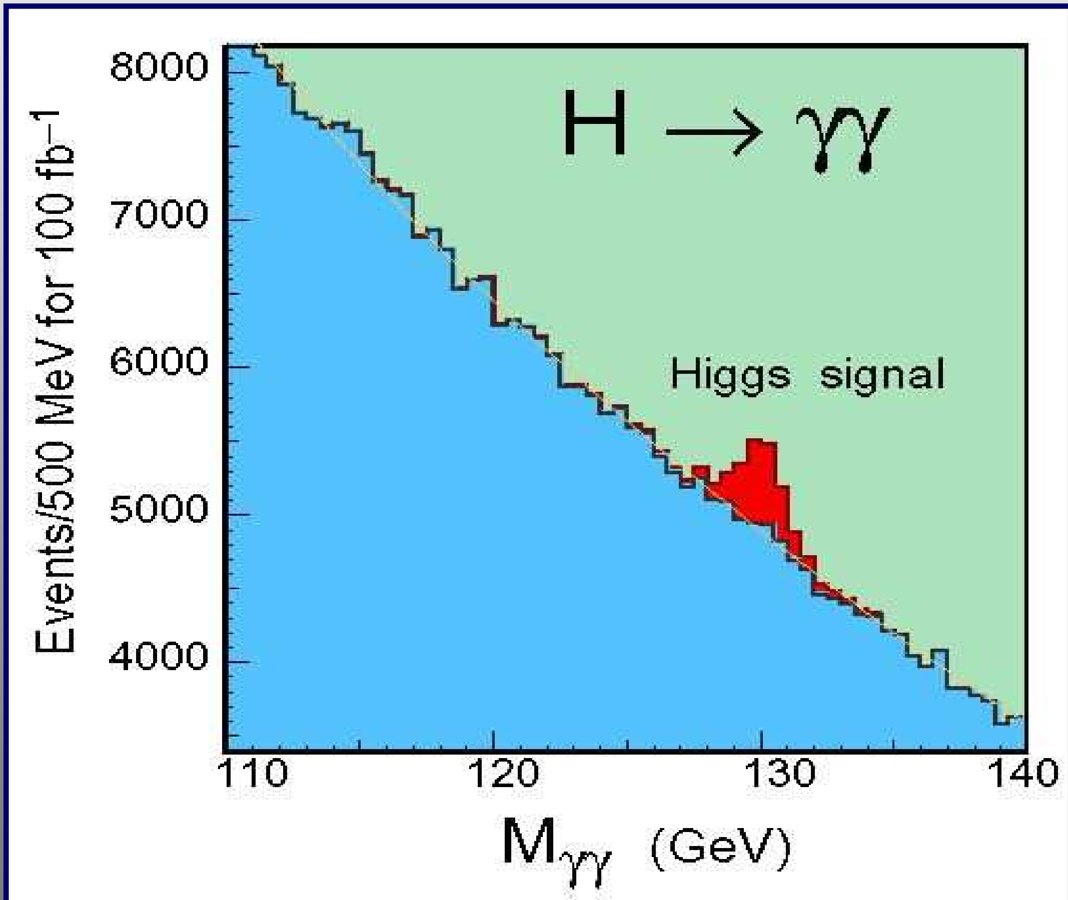
... and its price tag...

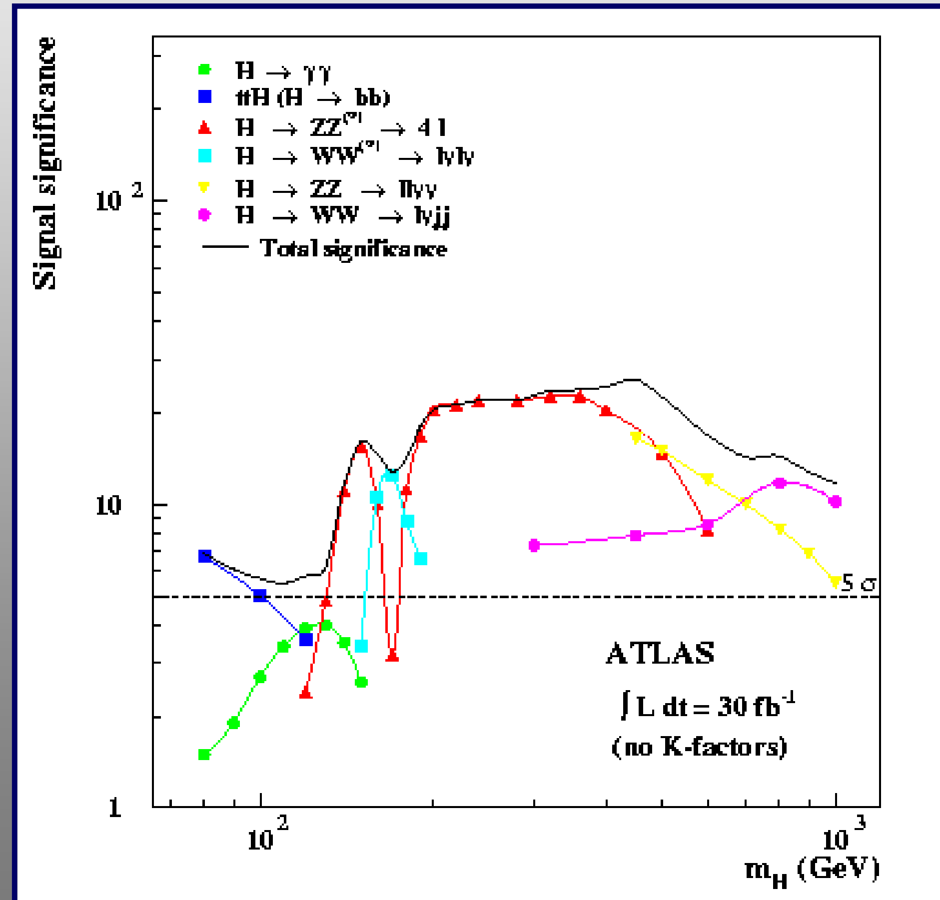


The Higgs search at the LHC




g
g
t
t̄
t
H⁰
q1
q2
W/Z
H⁰
q3
q4

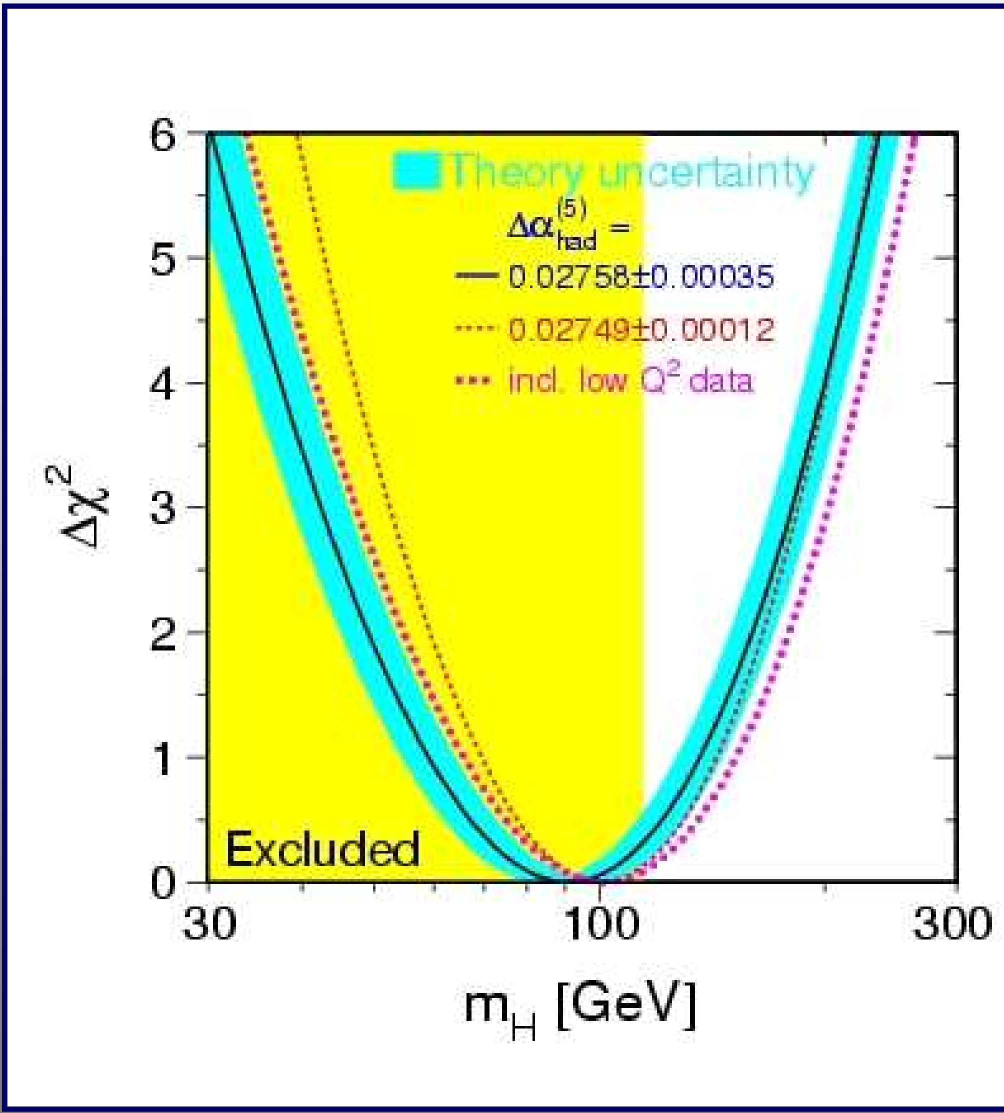

H → γγ
Higgs signal
Events/500 MeV for 100 fb⁻¹
8000
7000
6000
5000
4000
110
120
130
140
Mγγ (GeV)


Signal significance
H → γγ
ttH (H → bb)
H → ZZ(*) → 4 l
H → WW(*) → lνlν
H → ZZ → llνν
H → WW → lνjj
Total significance
10 2
10
1
5 σ
ATLAS
∫L dt = 30 fb-1
(no K-factors)
10 2
10 3
mH (GeV)

Experiments seem to **indirectly** confirming existence of light Higgs: **Electroweak precision observables**

Virtual Higgs loops contribute to observables. LEP precision: ~ **0.1 %** - sensitive to small Higgs loop corrections…

$$\Delta T \propto -\frac{3}{12\pi \cos\theta_W^2} \log m_H$$



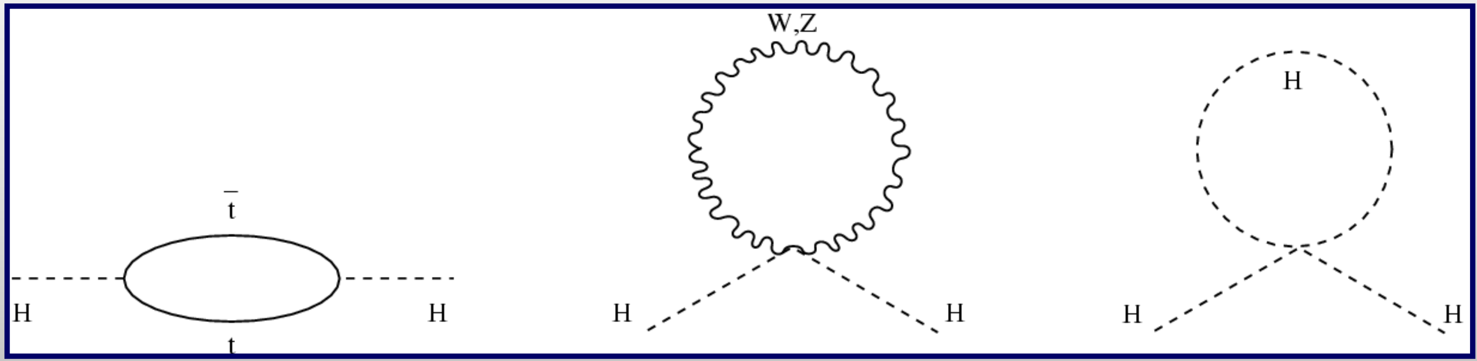
But: **Higgs potential quite ad hoc in SM**

Would expect that some form of dynamics is responsible for electroweak symmetry breaking – whatever it is, if it affects physics at **100 GeV** could not be extremely heavy.

More precise and quantitative formulation of this problem:

Hierarchy problem

All elementary scalars expected to be **ultra heavy**



Mass of Higgs not protected by symmetries (like fermion, Gauge boson.

$$\Delta m_H^2 \propto \frac{g^2}{16\pi^2}\Lambda^2$$

Λ scale of validity (cutoff). Naively expected

$$\Lambda \sim M_{Pl} \sim 10^{19} \text{ GeV}$$

Hierarchy problem specific to elementary scalars

- Fermions protected by chiral symmetry
- Spin 1 gauge bosons protected by gauge symmetry

- In the limit **m→0** a new symmetry appears
- Symmetry forbids mass generation $\mathbf{\Delta m^2 \propto m^2}$
- Small masses could be natural

Need to relate Higgs to fermion or gauge field:

- Fermion: supersymmetry
- Gauge field: gauge-higgs unification (little Higgs)

Resolution: cutoff scale must be low **Λ ~ 1 TeV**

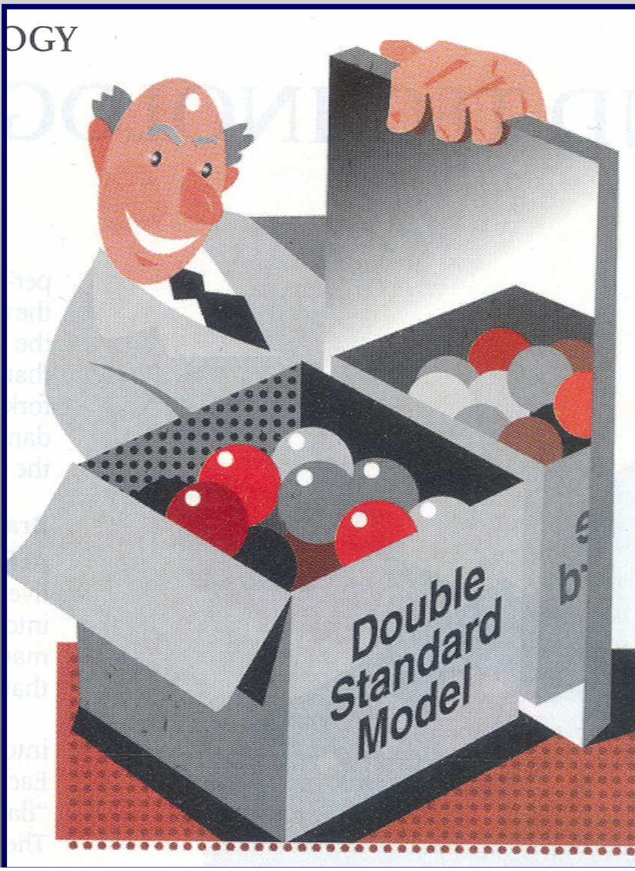
New physics eliminating large corrections to Higgs mass should appear in the range of the LHC!

The most popular such new physics:

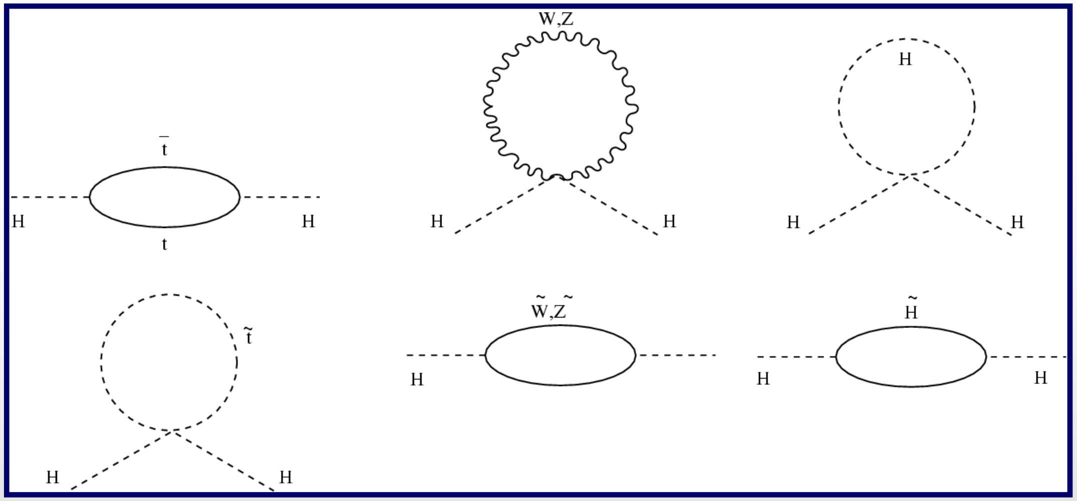
Supersymmetry

Every SM particle ⟷ Superpartner

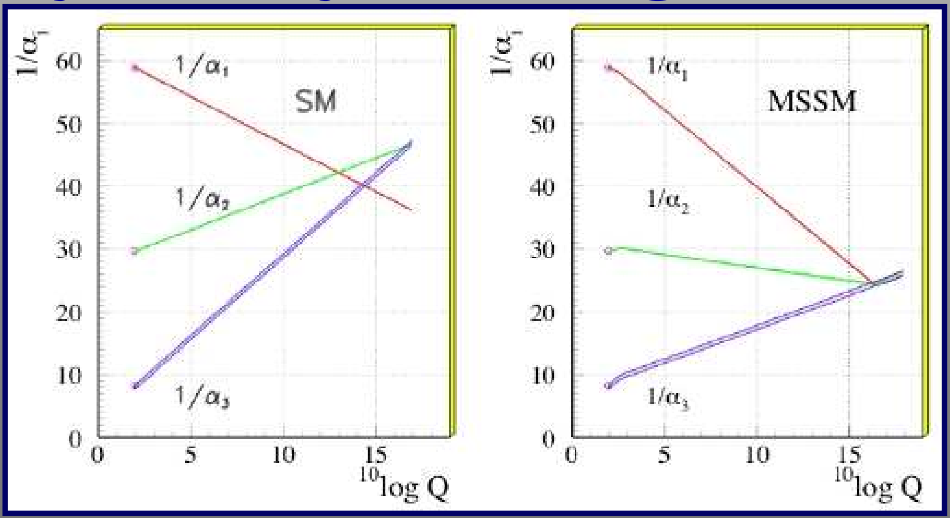
electron	⟷	selectron
quark	⟷	squark
gauge boson	⟷	gaugino
Higgs	⟷	higgsino



Very well motivated:



- Divergences cancelled by superpartners above TeV
- Biggest space-time symmetry possible
- Necessary ingredient for string theory to make sense
- Unification of gauge couplings
- Electroweak symmetry breaking due to top loops



Why are superpartners heavy?

(Isn't it ridiculous that we claim that half the particles have not been seen yet???)

NO!

If SUSY **spontaneously** broken:

- Spin 0 partners of spin ½ fermions (squarks, sleptons)
- Spin ½ partners of gauge bosons (gauginos)

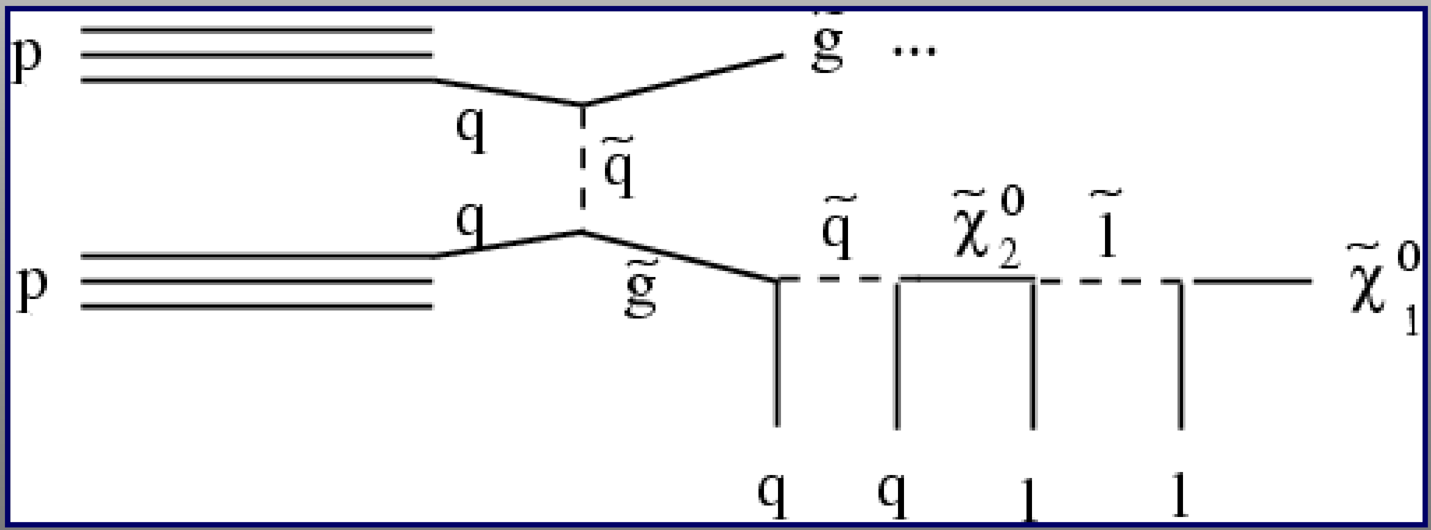
Pick up mass proportional to SUSY breaking

Ordinary particles don't feel SUSY breaking

Consequences:

- Superpartners have to be within reach of LHC
- There has to be a light Higgs
- Lightest superpartner stable

  - Dark matter particle predicted
  - Missing energy signal in colliders



However… this is **exactly** what we have been saying 12 years ago!

> "Moreover, in the most natural scenarios, many sparticles, for example charginos, squarks or gluinos lie within the physics reach of LEP II or the Tevatron"

G. Anderson, D. Castano 1994

$$M_Z^2 = 2\frac{m_{H_1}^2 - m_{H_2}^2 \tan^2\beta}{\tan^2\beta - 1} - \mu^2$$

In usual limit:

$$M_Z^2 \approx \frac{3y_t^2}{2\pi^2} m_{\tilde{t}}^2 \log\frac{\Lambda}{m_{\tilde{t}}}$$

Need to tune parameters to fulfill this relation

Little hierarchy problem

- The solution to the hierarchy problem would require new physics at ~ 1 TeV scale

Dimensions six operators	$m_h = 115\ GeV$ $c_i = -1$	$c_i = +1$	$m_h = 300\ GeV$ $c_i = -1$	$c_i = +1$	$m_h = 800\ GeV$ $c_i = -1$	$c_i = +1$
$(H^\dagger \tau^a H) W^a_{\mu\nu} B_{\mu\nu}$	9.7	10	7.5			
$\lvert H^\dagger D_\mu H \rvert^2$	4.6	5.6	3.4		2.8	
$\frac{1}{2}(\bar{L}\gamma_\mu \tau^a L)^2$	7.9	6.1				
$i(H^\dagger D_\mu \tau^a H)(\bar{L}\gamma_\mu \tau^a L$	8.4	8.8	7.5			
$i(H^\dagger D_\mu \tau^a H)(\bar{Q}\gamma_\mu \tau^a Q)$	6.6	6.8				
$i(H^\dagger D_\mu H)(\bar{L}\gamma_\mu L)$	7.3	9.2				
$i(H^\dagger D_\mu H)(\bar{Q}\gamma_\mu Q)$	5.8	3.4				
$i(H^\dagger D_\mu H)(\bar{E}\gamma_\mu E)$	8.2	7.7				
$i(H^\dagger D_\mu H)(\bar{U}\gamma_\mu U)$	2.4	3.3				
$i(H^\dagger D_\mu H)(\bar{D}\gamma_\mu D)$	2.1	2.5				

From Barbieri & Strumia

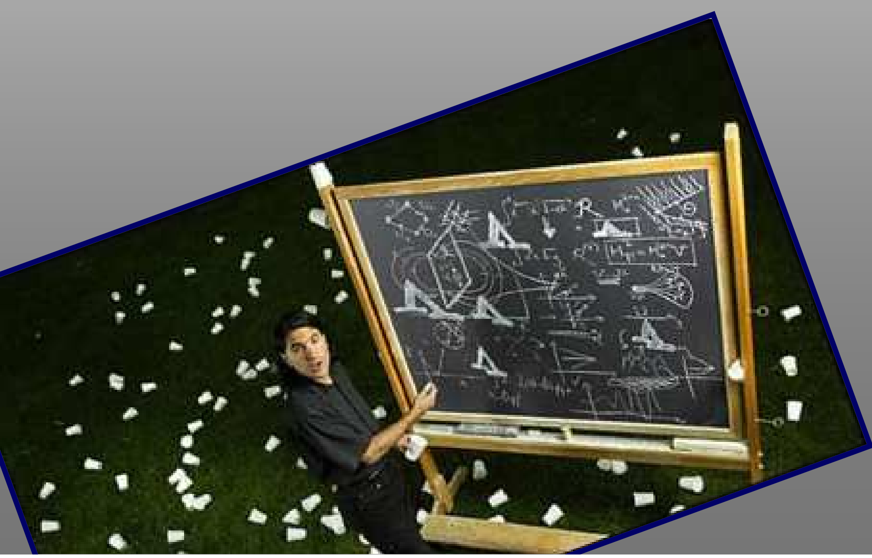
- There **does not** seem to be (generic) new physics at 1 TeV

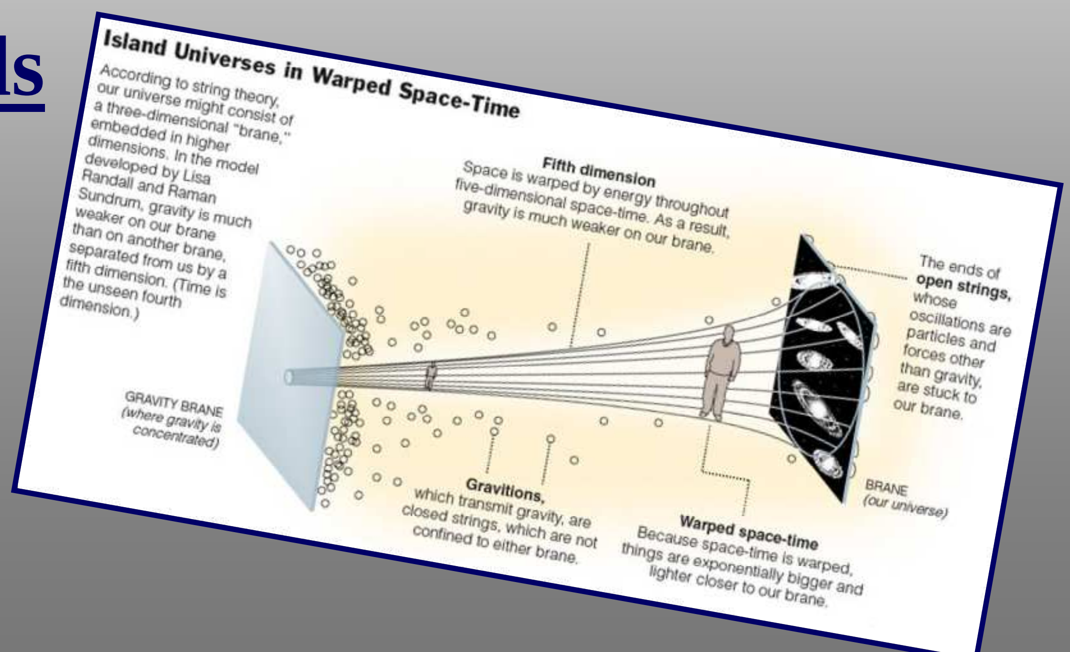
Mesaurements from **LEP1, LEP2, Tevatron** give indirect constraints on new physics

Since supersymmetry in not as good shape as before, search for new models of EWSB/solutions to hierarchy problems

- **Extra dimensional models**
  - **Large Extra Dimensions**
  - **Randall-Sundrum**
  - **Higgsless models**
  - **Gauge-Higgs unification**

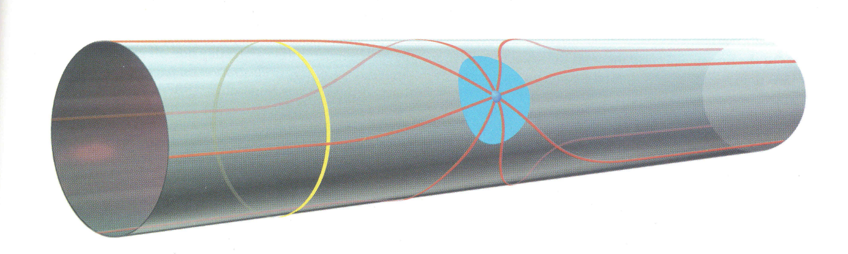
- **Little Higgs models**



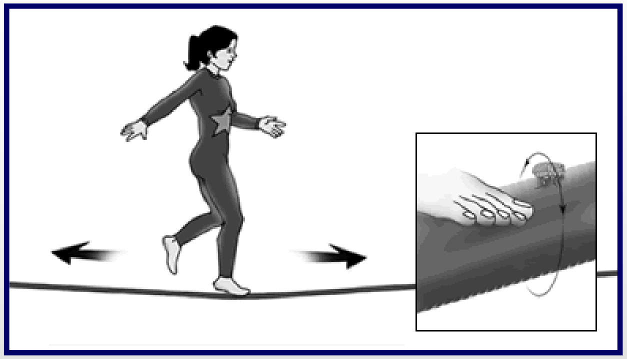


Large extra dimensions

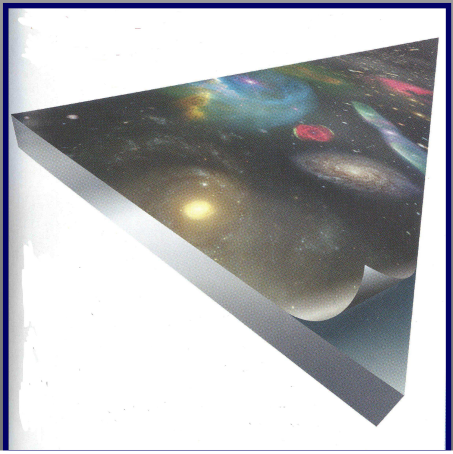
Arkani-Hamed, Dimopoulos, Dvali

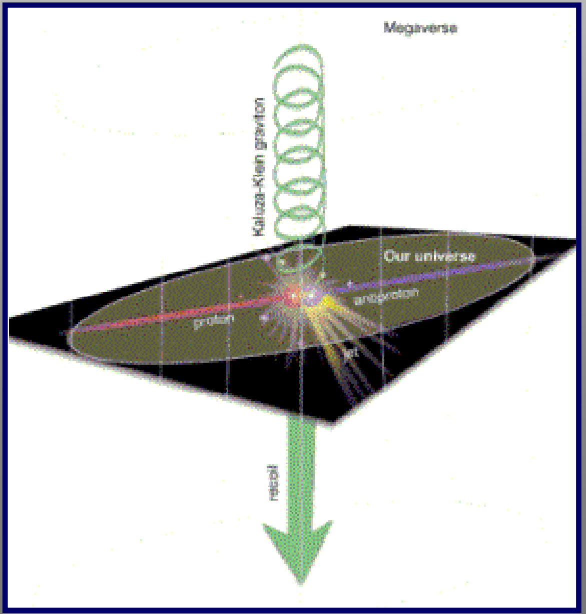


SMALL EXTRA DIMENSION wrapped in a circle (*circumference of tube*) modifies how gravity (*red lines*) spreads in space. At distances smaller than the circle radius (*blue patches*), the lines of force spread apart rapidly through all the dimensions. At much larger distances (*yellow circle*), the lines have filled the extra dimension, and it has no further effect on them.



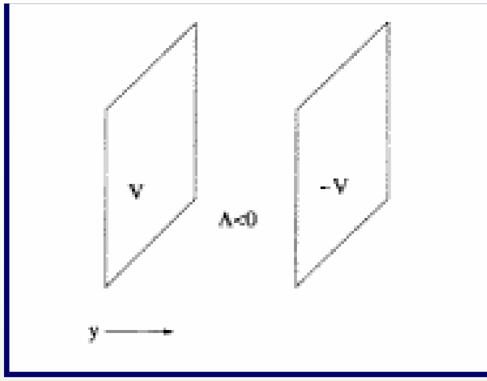
- **TeV** scale is the fundamental scale **$M_* \sim$ TeV**
- Gravity appears weak because it gets diluted by large extra dimensions (while other interactions don’t)
- SM fields localized to “brane”
- Gravity propagates everywhere



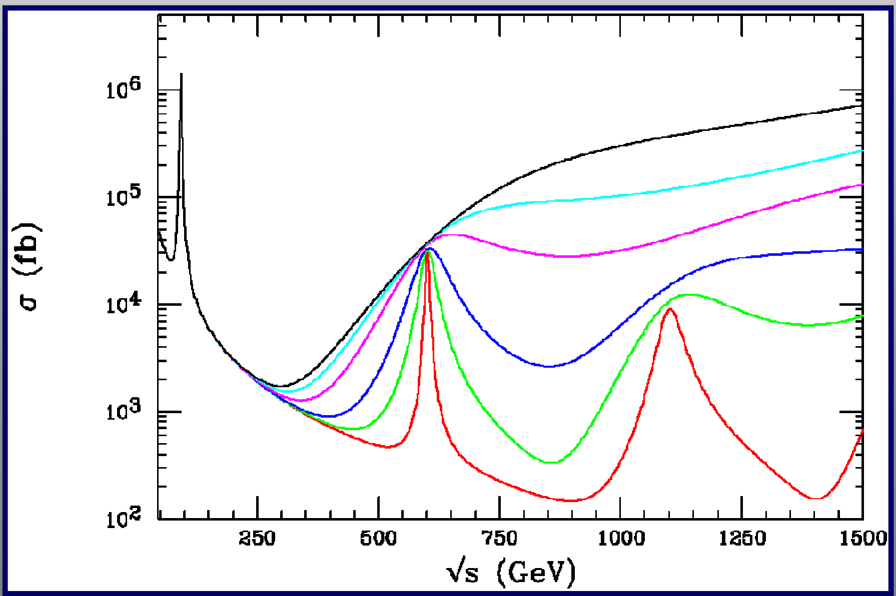


Pictures from Scientific American

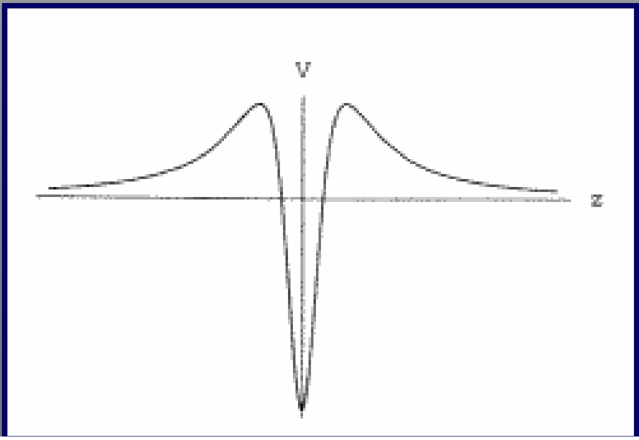
Randall-Sundrum Models



- Gravity weak, because we only feel tail of graviton
- Large curvature along extra dimension
- Graviton likes to live mostly at a point away from us
- Space-time "warped"



From Davoudiasl, Hewett, Rizzo

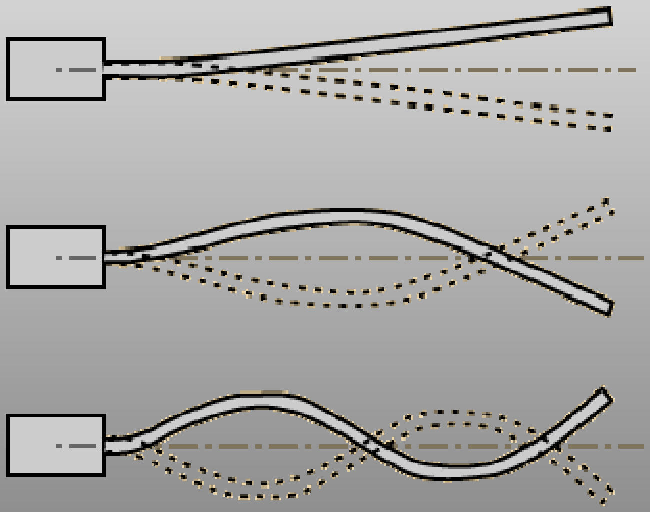


Higgsless models

Grojean, Terning, C.C.+
Murayama, Pilo, Cacciapaglia,…

- If there were extra spatial dimensions:

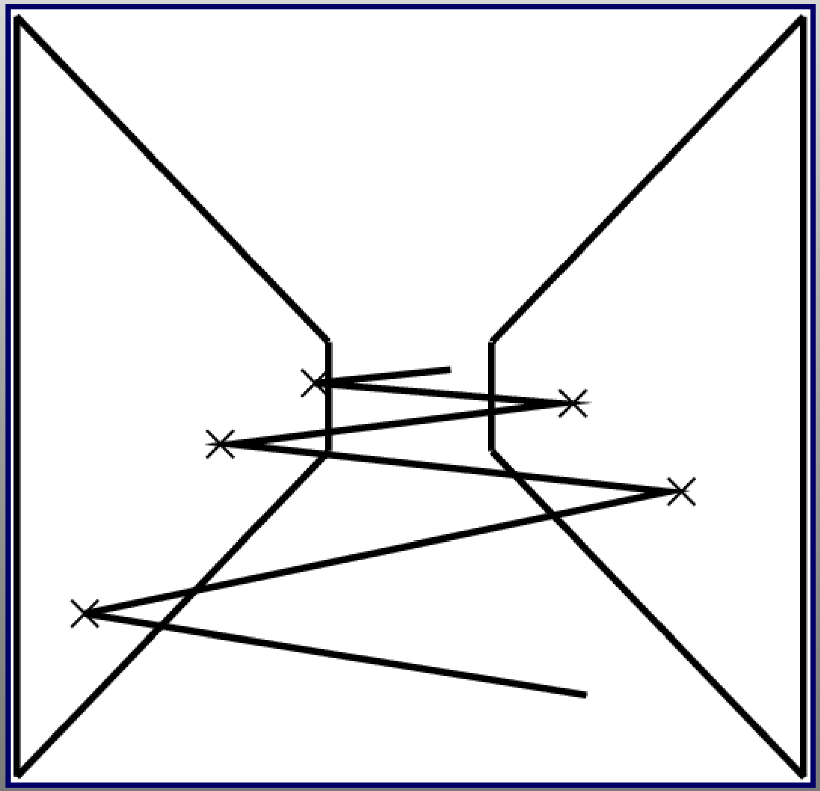
Observed mass spectrum depends on boundary conditions

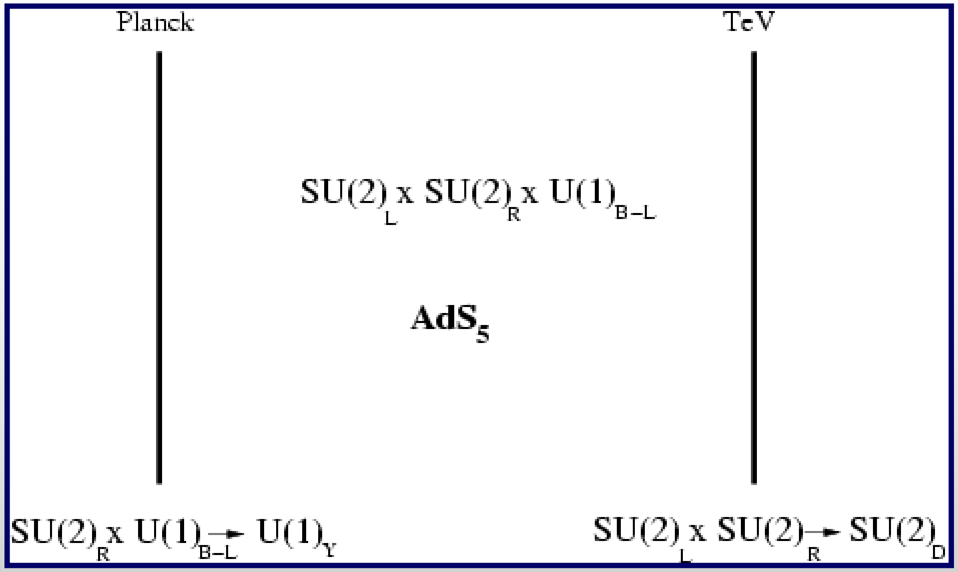


Just like the modes of a vibrating rod

Can obtain massive fields without a Higgs scalar

A particular **higgsless** model based on extra dimensions:

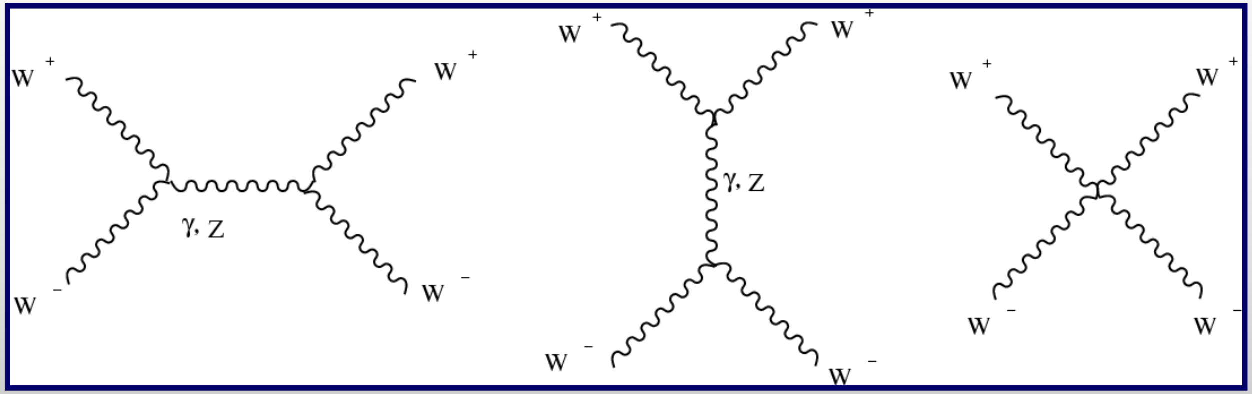




- SU(2)xSU(2)xU(1) gauge symmetry
- Need AdS background to get correct GB mass ratio
- Boundary conditions will follow symmetry breaking structure of Standard Model

But: usual argument for guaranteed discovery of Higgs

Massive gauge bosons without scalar violate unitarity:



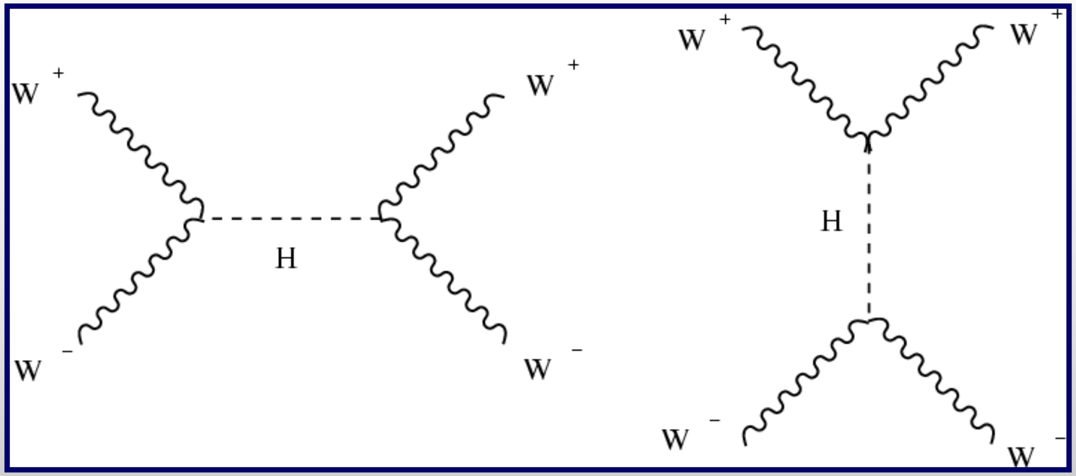
$$A = A^{(4)} \frac{E^4}{M_W^4} + A^{(2)} \frac{E^2}{M_W^2} + \cdots$$

At energy scale $\Lambda = 4\pi M_W / g \approx 1.6\ \mathrm{TeV}$

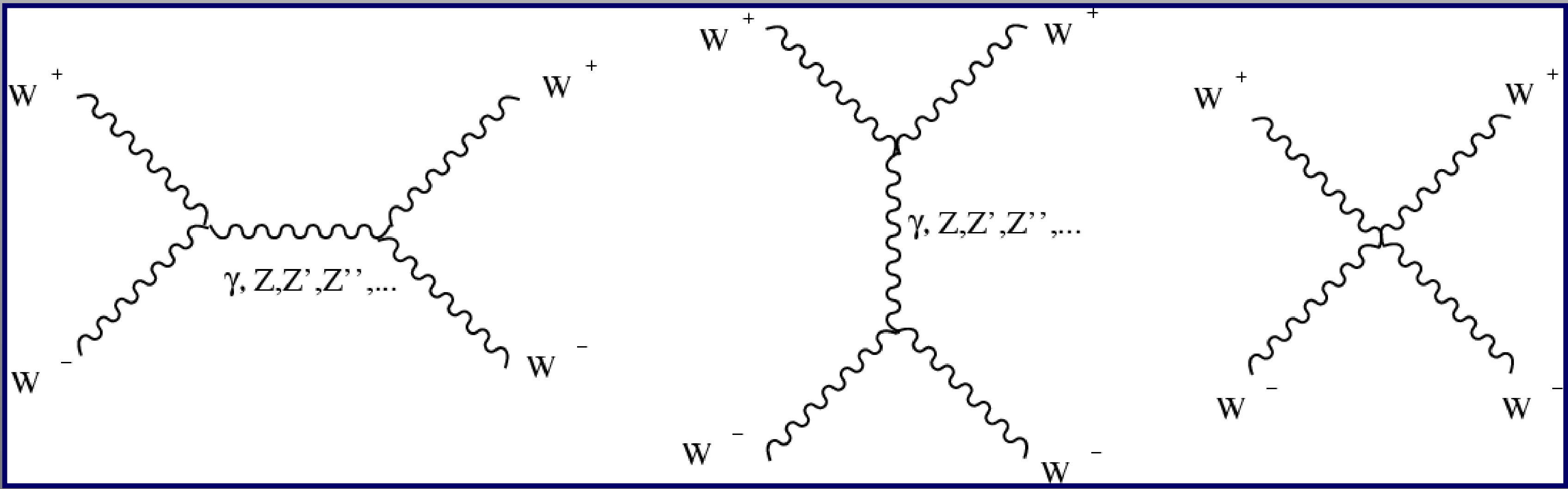
scattering amplitudes **violate unitarity**

Higgs exchange must become important **significantly below** this scale

In SM **Higgs exchange** will cancel growing terms in amplitude



In extra dimensional models, **exchange of KK modes** can play similar role as Higgs:



•**Predicts sum rules** among masses and couplings:

$$g_{WWWW} = g^2_{WW\gamma} + g^2_{WWZ} + \sum_i g^2_{WWZ^i}$$

$$\frac{4}{3} g_{WWWW} M^2_W = g^2_{WWZ} M^2_Z + \sum_i g^2_{WWZ^i} M^2_{Z^i}$$

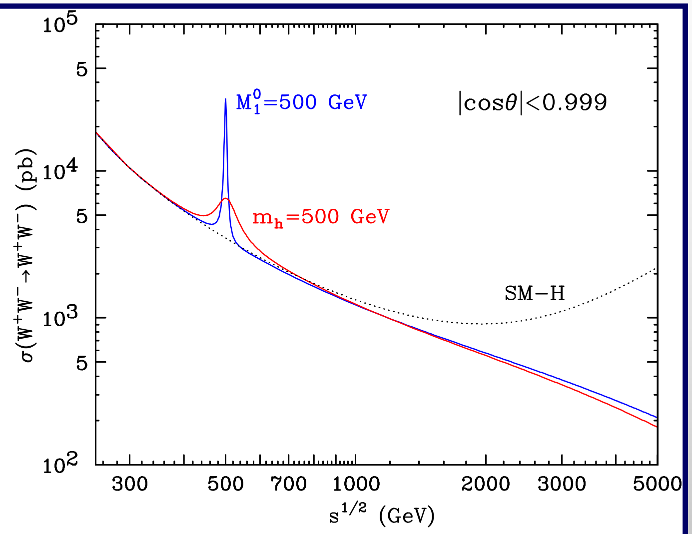
For WW $\longrightarrow$ WW scattering (similar for WZ $\longrightarrow$ WZ)

•Predicts at least W', Z' below 1 TeV, with small but non-negligible coupling to among gauge bosons

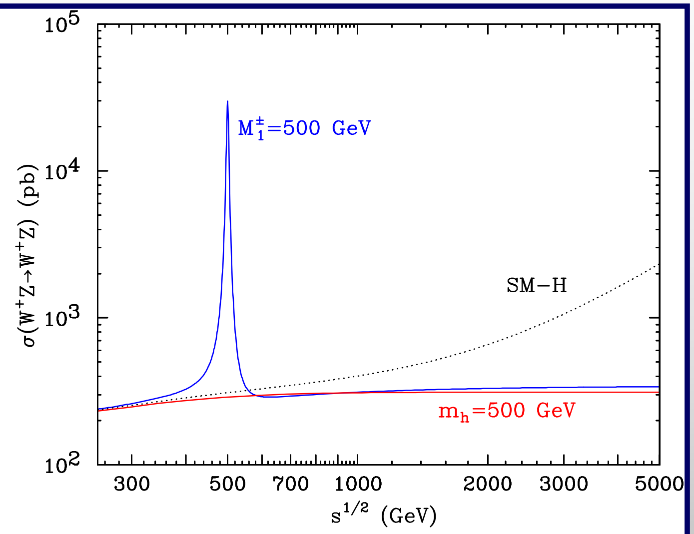
$$g_{WZW^1} \leq 0.04$$

Concrete predictions for the LHC

(Birkedal, Matchev, Perelstein)



WW → WW

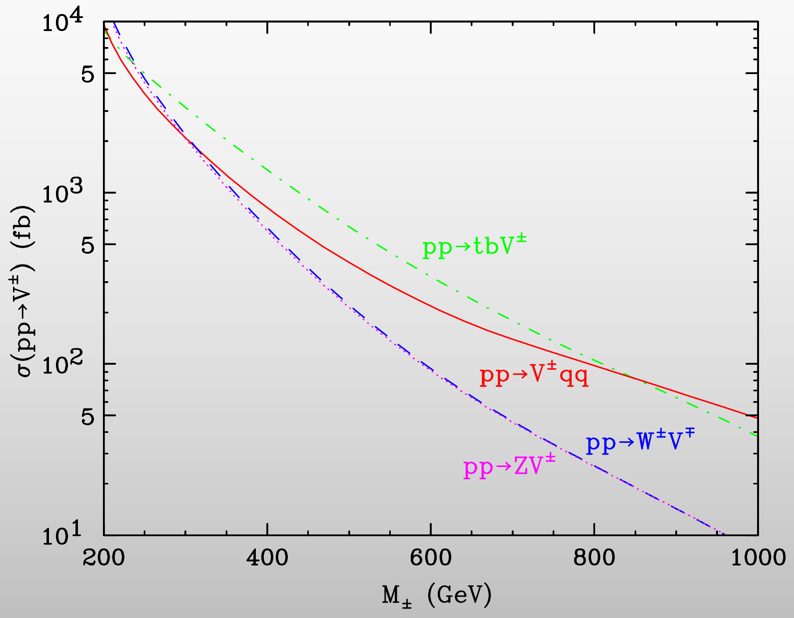


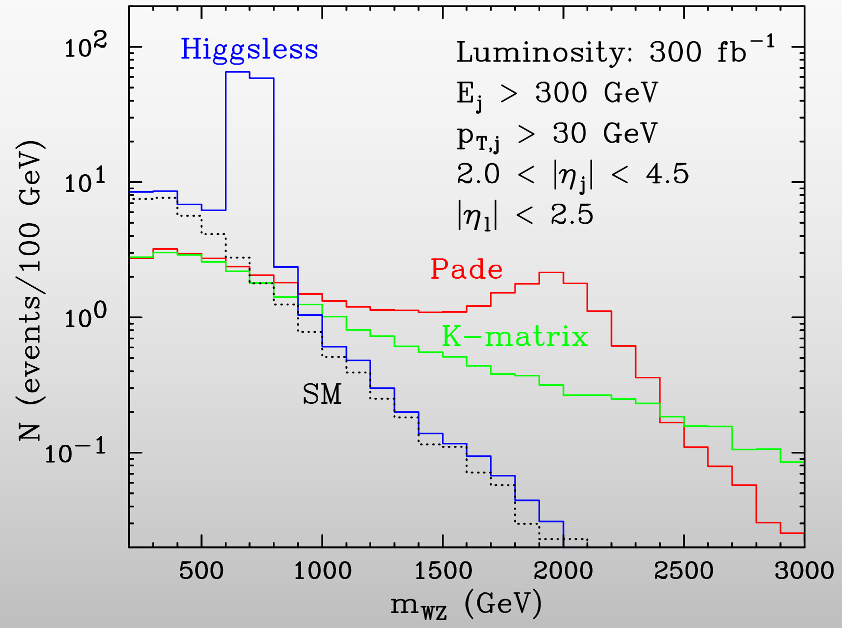
WZ → WZ

- WW scattering not that different from SM
- WZ scattering is **very different** (new peak!)

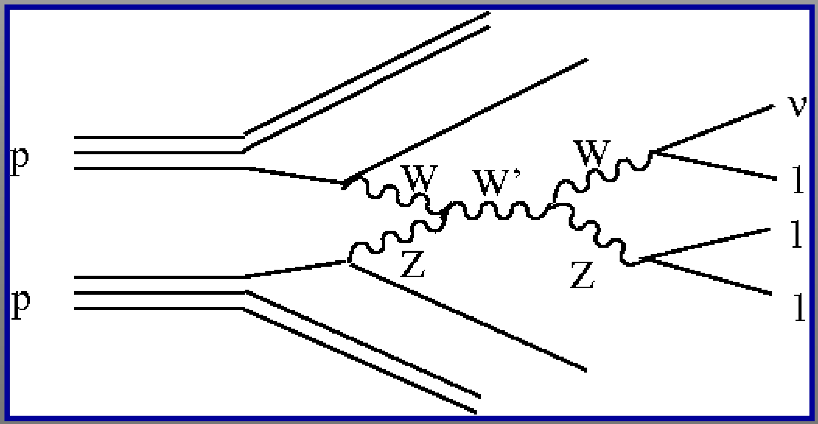
W' production at the LHC

(Birkedal, Matchev, Perelstein)





- 10 fb^{-1} will probe model up to $M_{W'}$<550 GeV
- Need ~ 60 fb^{-1} to probe all the way to 1 TeV



Gauge-Higgs unification

(Manton '79; Hosotani '83; Antoniadis, Benakli, Quiros; C.C., Grojean, Murayama; Scrucca, Serone, Silvestrini,…)

•**Idea**: gauge field in 5D contains additional fields:

$$A_M \rightarrow A_\mu, A_5$$

•Higgs could be $\mathbf{A_5}$

•In SUSY, chiral symmetries of fermion protect Higgs mass, here 5D gauge symmetry

•However, **difficult** to build a **realistic** model w/o tuning

- **Warped space** — Agashe, Contino, Pomarol
- **Flat space** — Cacciapaglia, C.C., Park; Serone, Panico, Wulzer

A simplified and more realistic implementation:

Little Higgs

Arkani-Hamed, Cohen, Katz, Nelson

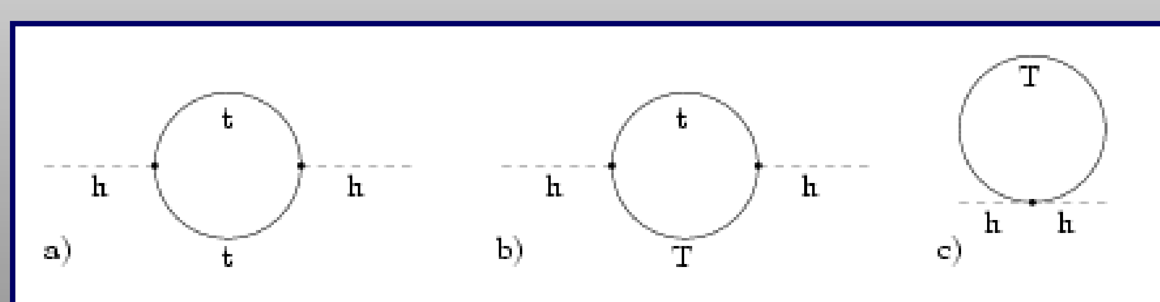
- Another way to protect scalar mass: **Goldstone bosons**

Georgi, Kaplan

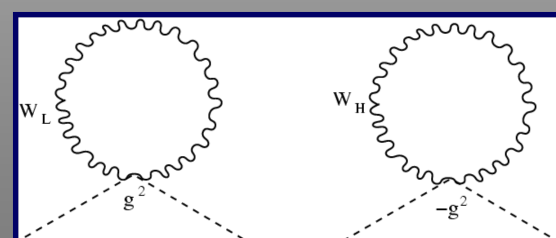
- A **global symmetry** (broken at some scale f) forbids large corrections to scalar mass

- Divergences cancelled by **same spin partners**:

  - Top loops via heavy top partners



  - Gauge loops via heavy gauge boson partners



Predictions of Little Higgs models

- **Same spin** partners around TeV scale
- **Definite relation** among couplings, eg.:

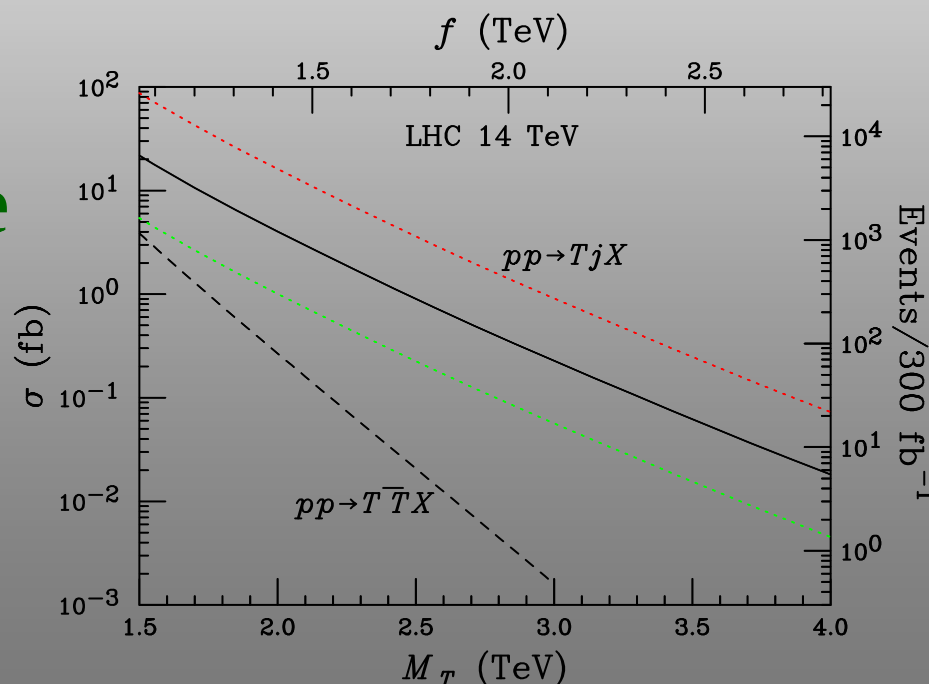
$$\frac{m_T}{f} = \frac{\lambda_t^2 + \lambda_T^2}{\sqrt{2}\lambda_T}$$

m_T heavy top partner mass

f symmetry breaking scale

λ_t top Yukawa coupling

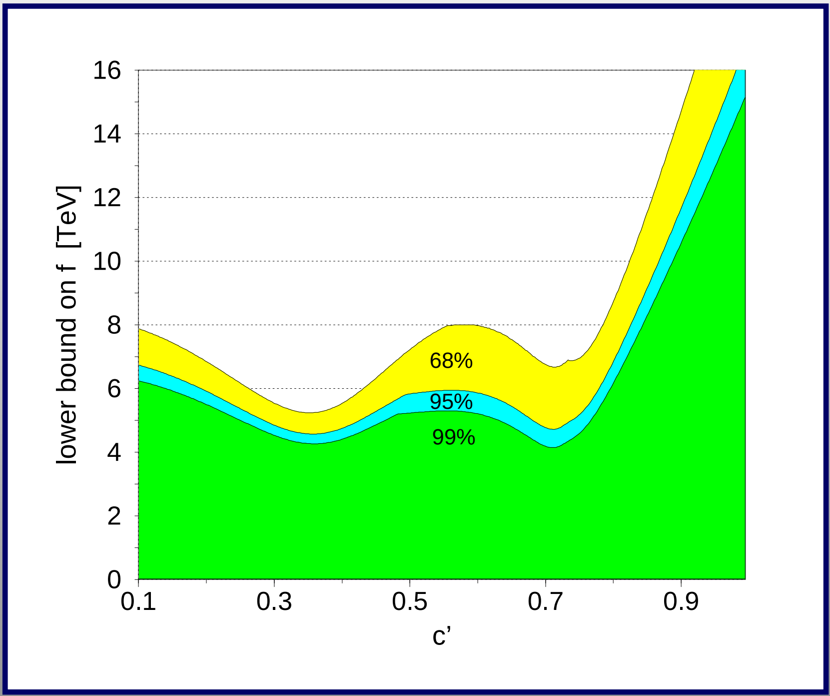
λ_T heavy top Yukawa



(Han, Logan, Wang)

But: simplest versions of Little Higgs give **large corrections** to electroweak precision observables

Just like most others – **little hierarchy**…



C.C., Hubisz, Kribs, Meade, Terning

Ways out:

- **T-parity** – forbids all dangerous couplings Cheng, Low
- **Combine** with supersymmetry

Super-little Higgs

Chankowski, Falkowski, Pokorski;
Schmaltz, Roy;
C.C.,Marandella, Shirman, Strumia

- Solves fine-tuning problem of supersymmetry by also **making it a pseudo-Goldstone** boson

$$m_H^2 \sim \frac{g^2}{16\pi^2} m_{soft}^2 \log \frac{f}{m_{soft}}$$

m_{soft} scale of SUSY breaking **~ few · 100 GeV**

f scale of global symmetry breaking **~ few · TeV**

Both SUSY and (some) little Higgs partners visible at LHC

- If we take little hierarchy seriously:
  - Not SUSY
  - In addition to SUSY more particles should show up

Summary

- LHC will probe mechanism of electroweak SB
- Hierarchy problem implies more than just Higgs should appear
  - **Supersymmetry?**
- Little hierarchy problem: why no indirect evidence yet?
- New directions to address EWSB, little hierarchy
  - **Extra dimensions (large, RS)**
  - **Higgsless**
  - **Gauge-higgs unification**
  - **Little Higgs**
  - **T-parity**
  - **Super-little…**

WILL HAVE SOME IDEA IN ~ 2-4 YEARS!