Theoretical physics for the LHC

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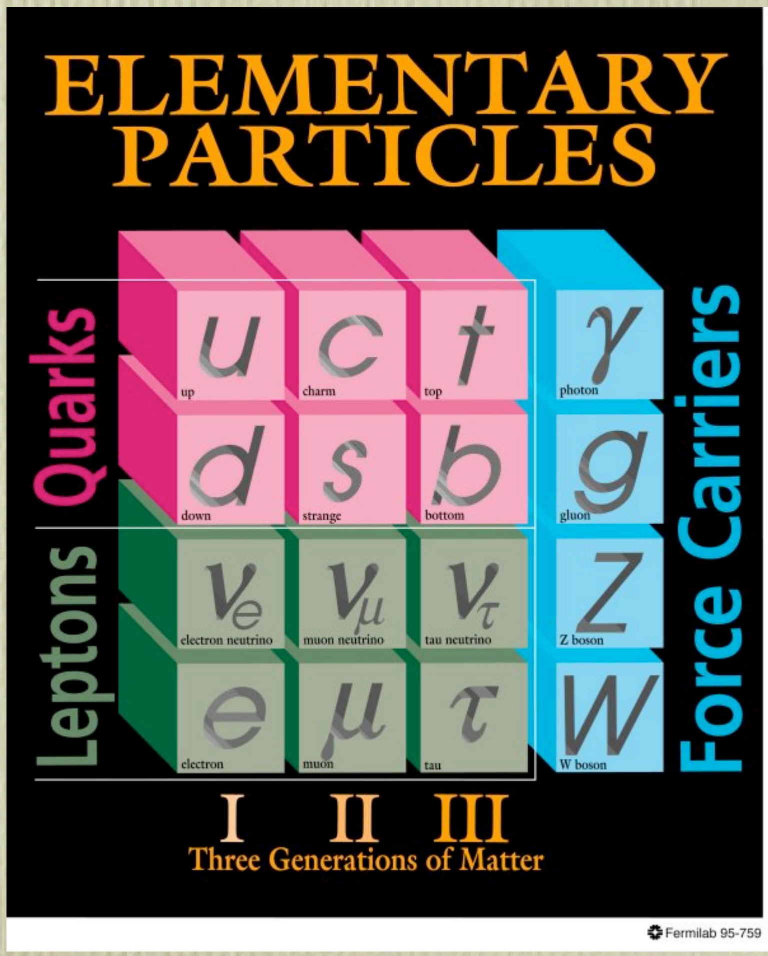
Programme

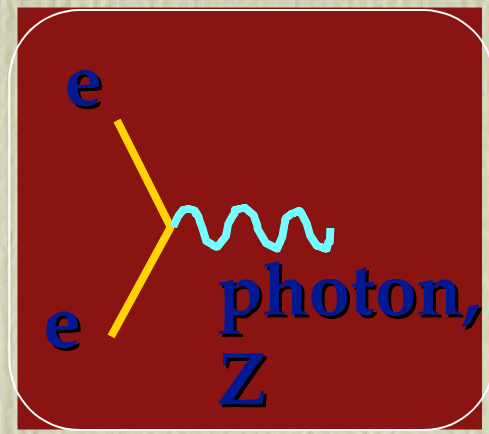
1. General introduction to the LHC physics goals
2. Theoretical description of proton-proton collisions
3. Standard Model studies at the LHC
4. Searches for the Higgs and for phenomena beyond the Standard Model

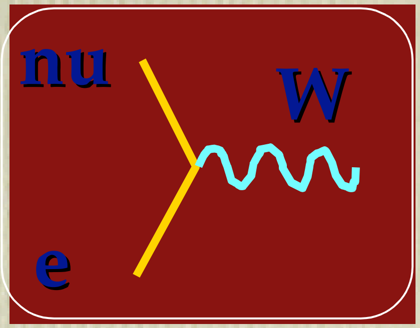
LECTURE I

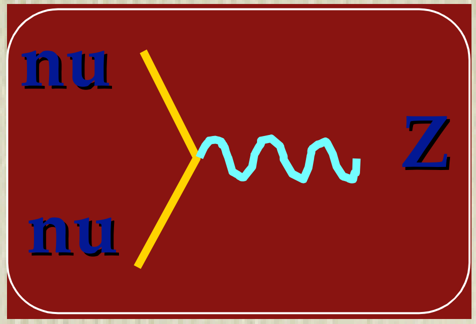
- Elementary Particle Physics: where do we stand?
- Open issues:
  - Particle masses (Higgs phenomenon, Higgs searches)
  - Hierarchy problem (Higgs once more, Supersymmetry, ...)
  - Grand Unification
  - Flavour problem
- What can the LHC do to address these problems?

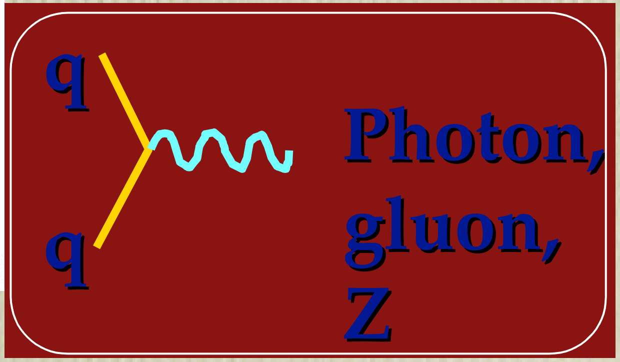
The building blocks of the Standard Model

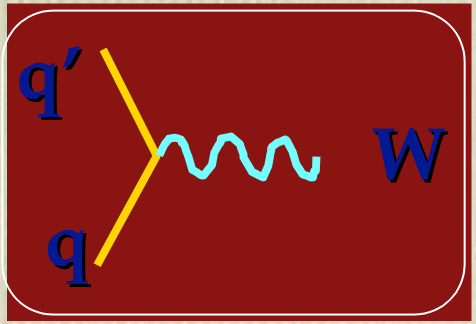






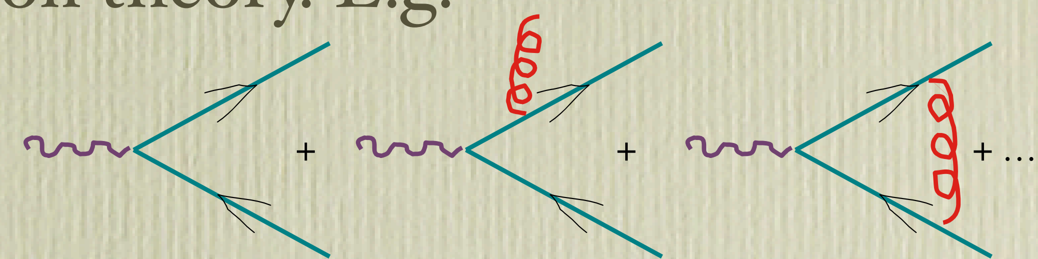






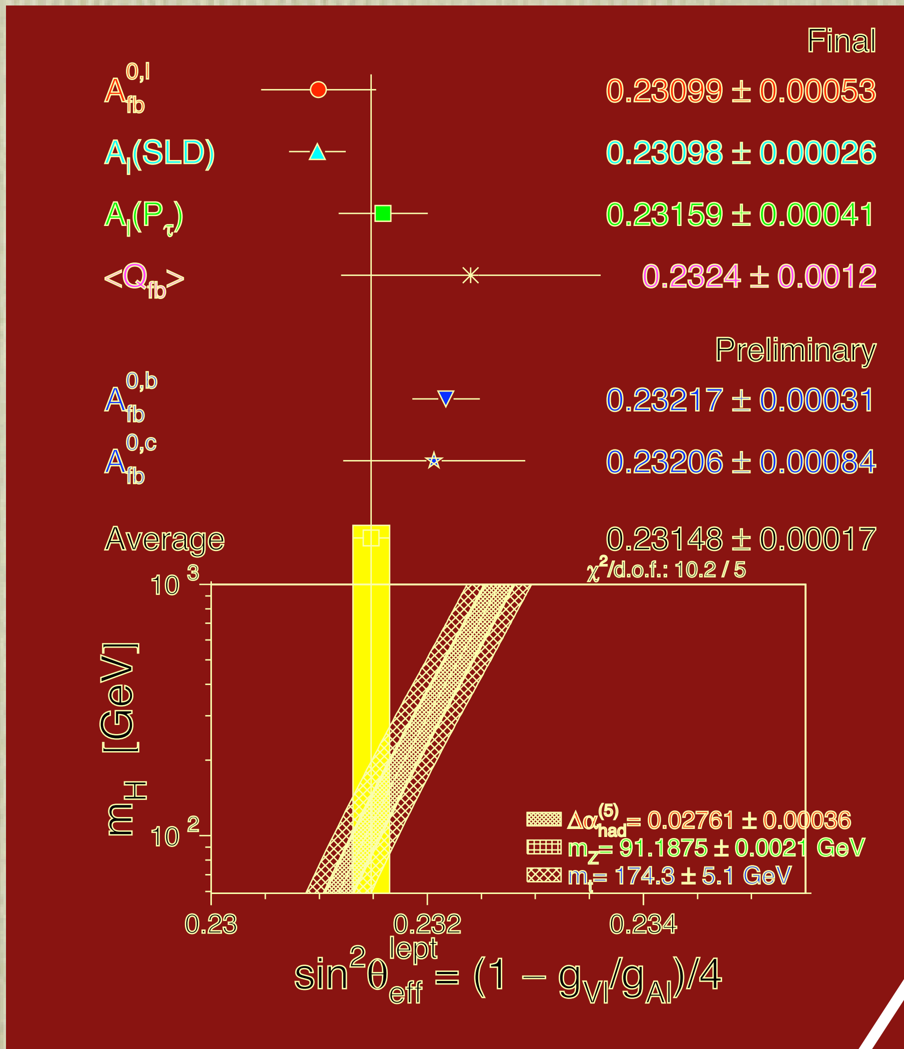
The dynamics of the Standard Model

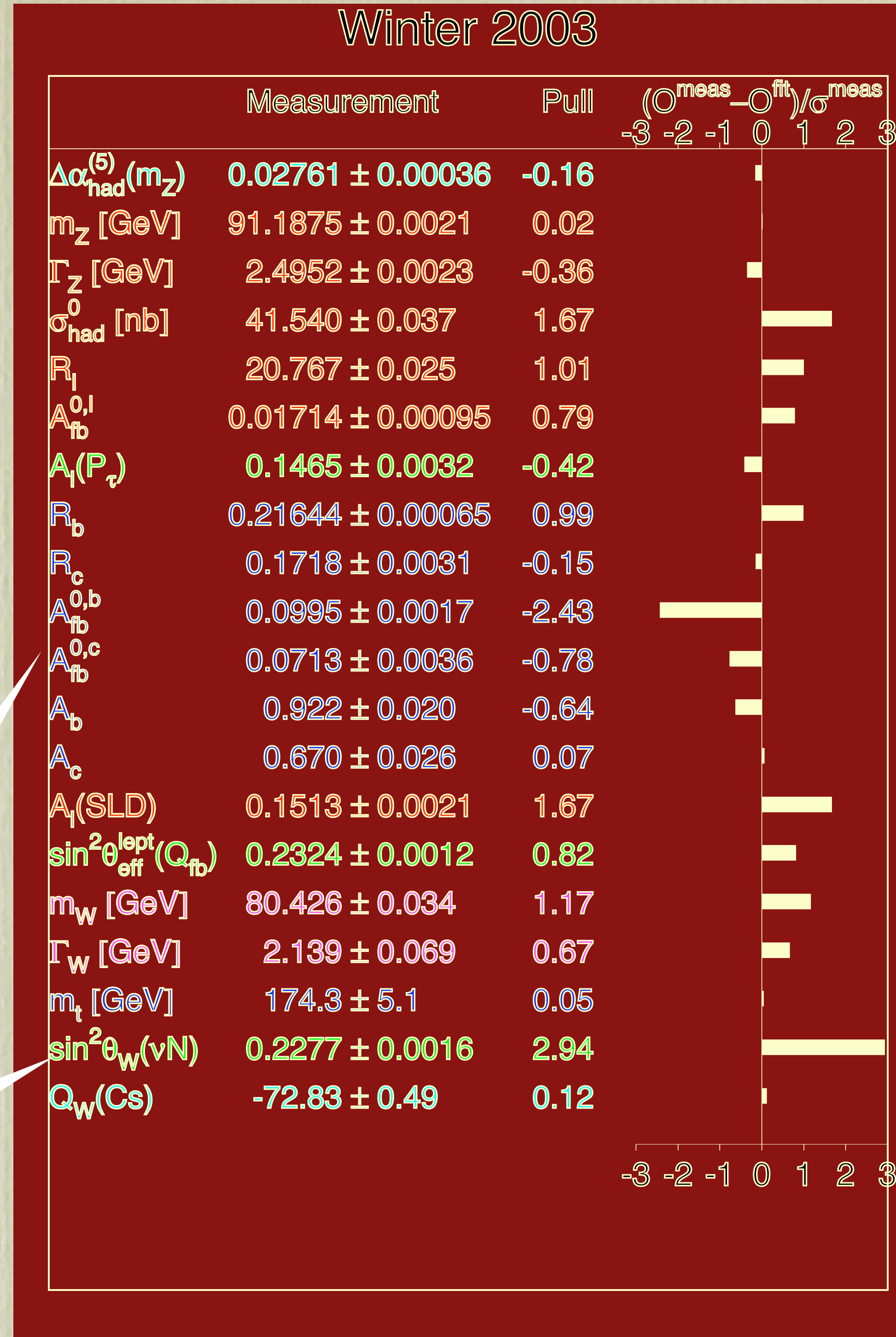
- Renormalizable Quantum Field Theory
- Gauge symmetry principle, with group structure (SU(3)xSU(2)xU(1)) dictated by experimental evidence
- Reliable perturbation theory. E.g.
  - Z->hadrons=



- Well tested against data:
  - U(1) sector to $O(1/10^8)$
  - SU(2) sector to $O(1/10^3)$
  - SU(3) sector to $O(1/10)$

Puzzles in the SM EW fits





$\sin^{2,\mathrm{eff}}_W$ = 0.2311(2) (lepts)
0.2322(3) (hads)

m_W = 80.14(8) NuTeV
80.45(4) direct

So, here we stand

- Most has been learned already, what is left to be understood?
- Today's "how" becomes tomorrow "why":
  - why masses are what they are?
  - why neutrino masses?
  - why symmetry breaking?
  - why Universe dominated by matter? CP violation?
  - why gauge interactions?
  - why $SU(3)xSU(2)xU(1)$?
  - why 3 generations?
  - what about gravity?
  - why 4 dimensions?
- The goal of the next generation of experiments is to start answering these questions.
- The quest will start with the LHC!

Particle masses

$$\{SU(2) : e \rightarrow \nu_e\} \Rightarrow m(e) = m(\nu)$$

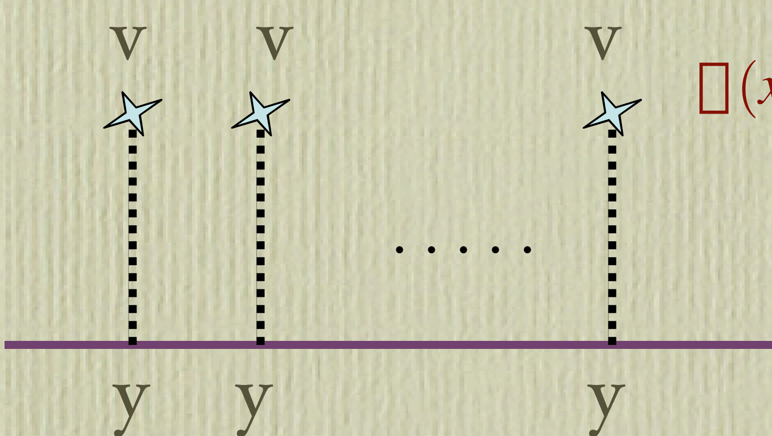
This is experimentally wrong! The arbitrary inclusion of particle masses breaking the gauge symmetry would spoil the key property of the theory which makes it predictable, namely its renormalizability.

The generation of non-gauge-invariant particle masses should be the result of a gauge-invariant dynamics, possibly leading to a non invariant ground state.

This dynamics can be induced by the so-called Higgs mechanism.

A dynamical mass

- Free, massless particle: $$\partial_\mu\partial^\mu \square(x) = \square(x) \Rightarrow \square(x) = \int \frac{e^{ipx}}{p^2}[dp]$$
- Interaction with a background field:



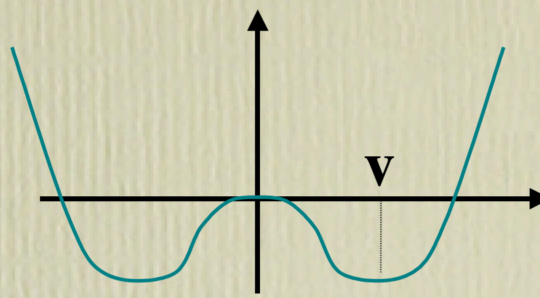
$$\square(x) = \int \frac{e^{ip_1x_1}}{p_1^2}[dp_1][dx_1]\,\square\int \frac{e^{ip_2(x_2-x_1)}}{p_2^2}[dp_2][dx_2]\,\square\cdots =$$

$$\int \square\left(\frac{\square}{p^2}\right)^n e^{ipx}[dp] = \int \frac{[dp]}{p^2-\square}e^{ipx}$$

$$(\partial_\mu\partial^\mu + m^2)\square(x) = \square(x),\ \text{with}\ m^2 = \square = y_\square v$$

- Between interactions with the background field we can still think of the particle as being massless, but for all purposes it does propagate as if it had a mass. The mass terms has two components, one universal (the strength of the background field) and one particle dependent, directly proportional to the coupling to the field itself.

The Higgs mechanism



- Scalar potential: $V(\square) = -\mu^2|\square|^2 + \frac{\square}{4}|\square|^4$
- Its minimization: $\square V(\square) = 0 \Rightarrow \langle\square\rangle^2 \equiv v^2 = 2\,\frac{\mu^2}{\square}$
- Coupling of the background (Higgs) field to matter: $y_\square\;\square\bar{\square}\square$
- Mass of matter field: $m_\square = y_\square\,\langle\square\rangle \equiv y_\square v$
- Mass of W gauge bosons: $m(W) = g\,v \Rightarrow v = 175\ \mathrm{GeV}$
- Mass of Higgs field: $m_\square^2 = \partial^2 V(\square = v) = 2\mu^2 = \square v^2$
- The Higgs field transforms under SU(2) -> its v.e.v. v breaks spontaneously the symmetry
- While the Higgs v.e.v. is known from the relation with the W mass, its self-coupling λ, and therefore its mass, are not !

Theoretical constraints on the Higgs mass

Mostly based on RG evolution of the Higgs self-coupling:

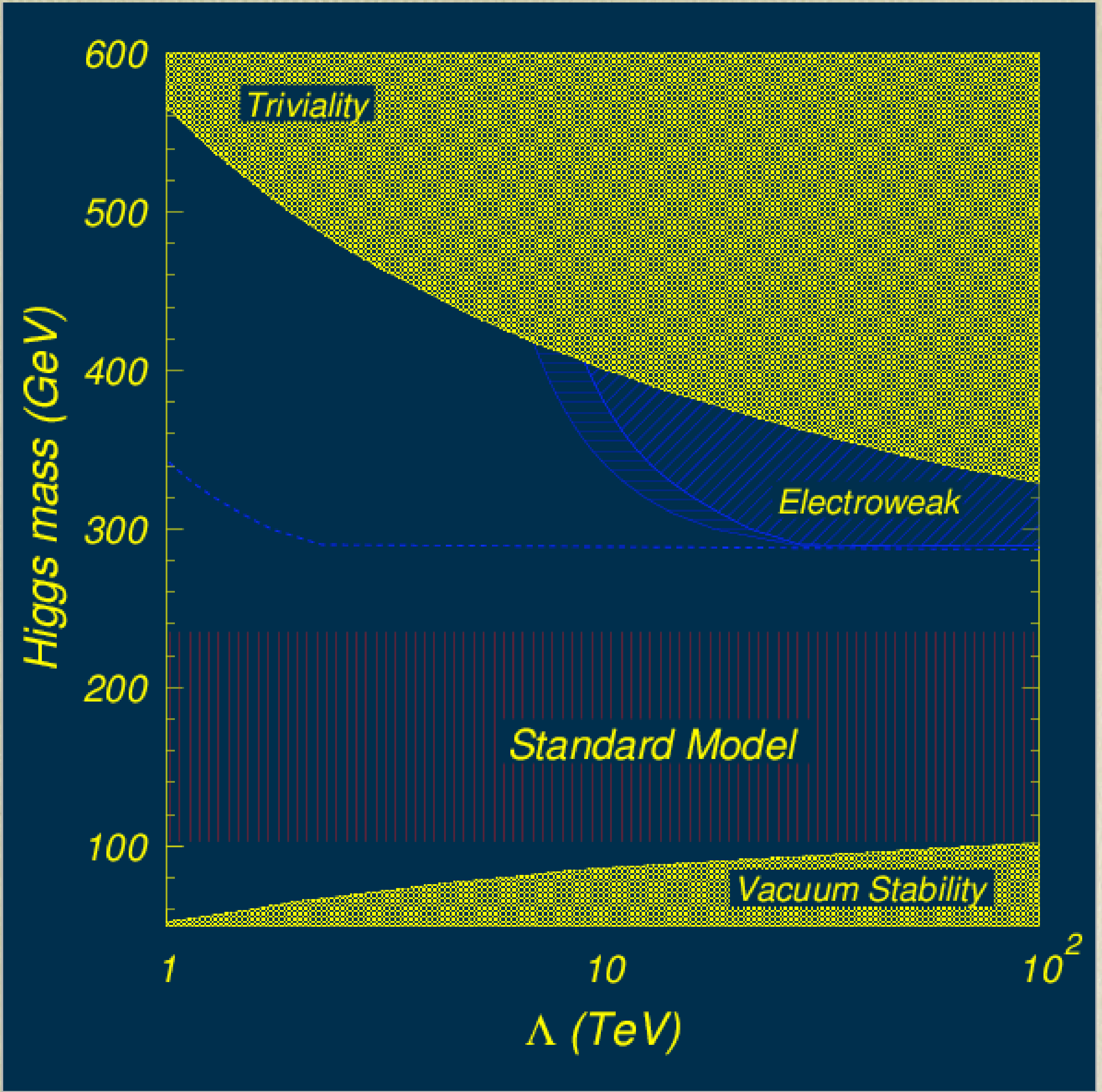
$$\frac{d\lambda}{dt} = \frac{3}{8\pi^2}\left(\lambda^2 - 4y_t^2\right)$$

where t=log(Q/v) and $y_t = m_t/v$. First term from a Higgs loop, second from a loop of top quarks (fermion ⇒ -1 sign)

- Perturbativity of the Higgs interactions (Cabibbo, Maiani, Parisi, Petronzio, 1979)}: if λ(v) too large then λ(Q) will blow up for some value Q. Requiring that Q is below the scale at which some new physics will change the RGE (say the GUT or Plank scale) sets an upper limit on λ(v), and then on m_H. The lower the scale Q, the lower the upper limit on m_H.
- Vacuum stability: if λ(v) is too small, the RGE will drive λ(Q)<0 at some scale Q ⇒ unstable potential. The larger the scale at which this is allowed to happen, the larger the lower limit on m_H.

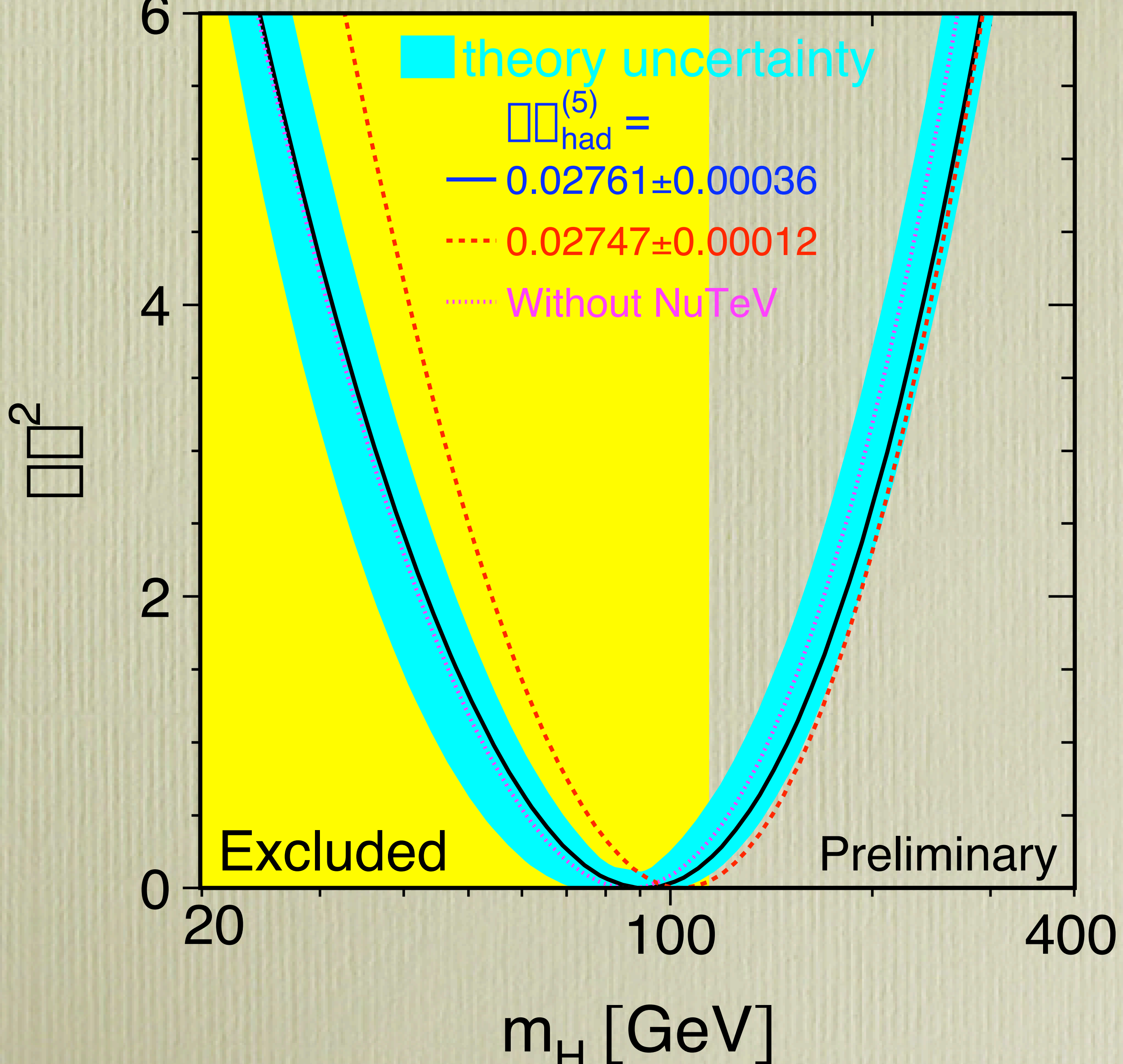
Requiring Q ~10^{16} GeV for both cases gives:

130 GeV < m_H < 200 GeV



600
500
400
300
200
100
Higgs mass (GeV)
Triviality
Electroweak
Standard Model
Vacuum Stability
1
10
10^2
Λ (TeV)

Current experimental knowledge on m(H)



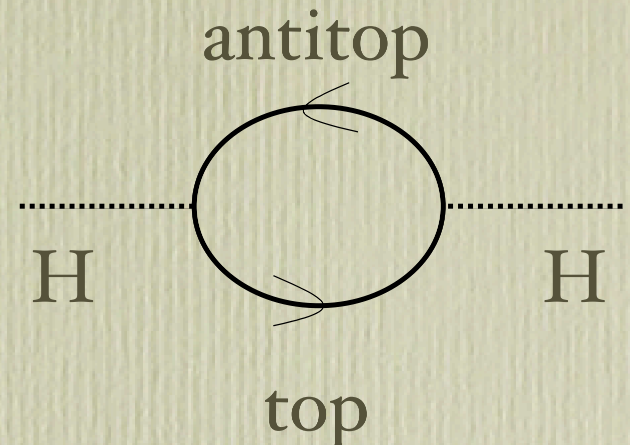
m(H)>114.1 from the non-observation at LEP

m(H)= 91^{+58}_{-37} from the EW fits

m(H)<211 GeV at 95%CL From the EW fits

- The m_H window obtained from theoretical constraints is totally consistent with the current direct and indirect experimental constraints. Notice that in the case of SM EW fits, this consistence is **not** built into the fits, which are not performed under the assumption of perturbative unitarity or vacuum stability.
- Should the Higgs satisfy the above SM constraints, it will be easy prey for the LHC, which has its most interesting reach precisely for the region 130 GeV $< m_H <$ 200 GeV, as will be discussed later.
- From the theoretical viewpoint, however, this would be the least interesting possibility, as no hint for new physics above the Fermi scale would arise from this measurement (Prof. Higgs, Atlas and CMS would go to Stockolm, but the rest of us would be bored to death!).
- From the point of view of a fully rewarding LHC programme (as defined by a theorist!), it is therefore interesting to explore possible way-outs from the above constraints, and study their possible consequences for the LHC.

Higgs self-energy, a problem?



$$\delta m_H^2 = \frac{3}{\sqrt{2}\pi^2} G_F\, m_t^2 \Lambda^2 = (120\ \text{GeV})^2 \left(\frac{\Lambda}{400\ \text{GeV}}\right)^2$$

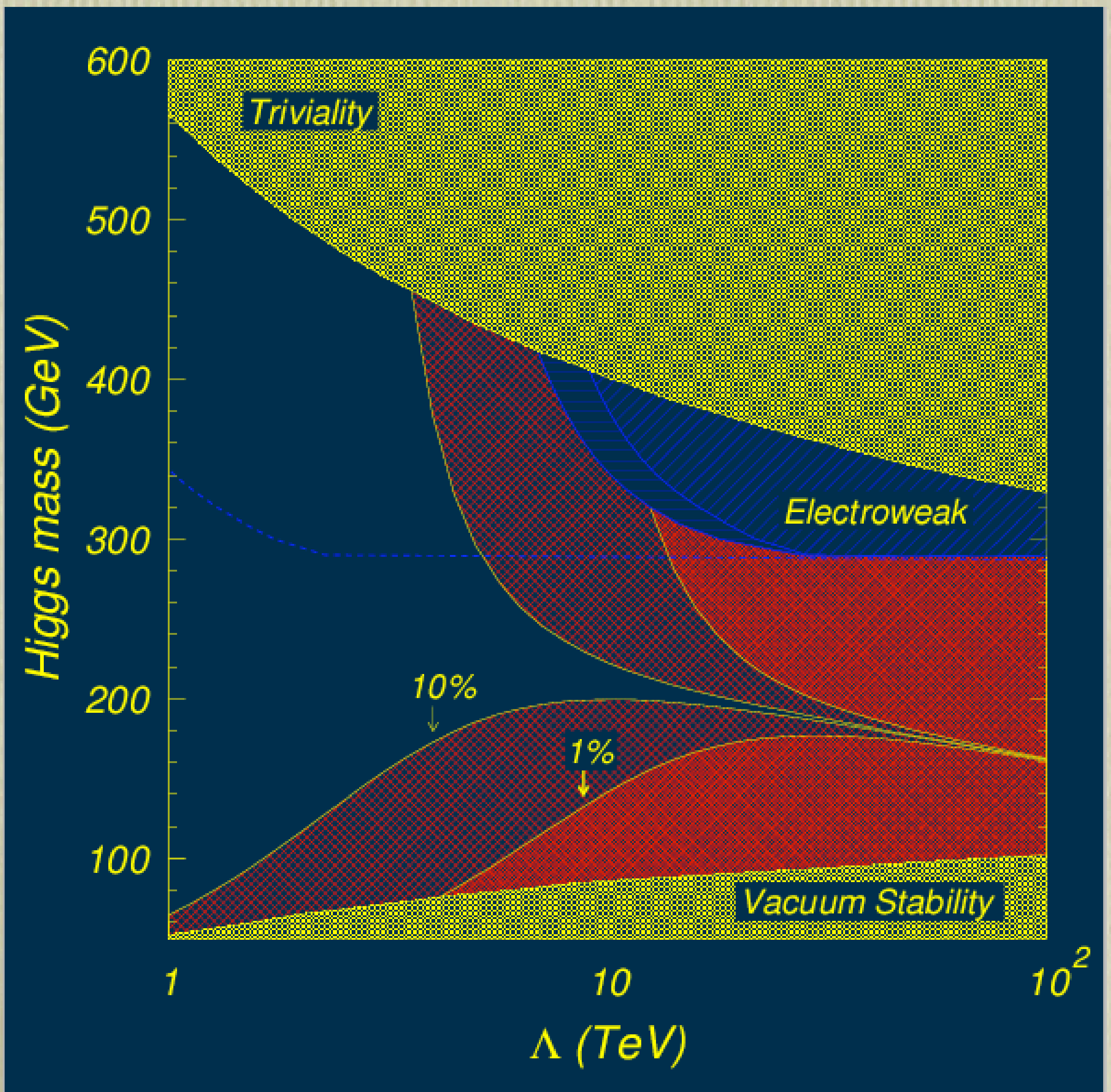
$$m_H^2 = m_0^2 + \delta m_H^2 < (200\ \text{GeV})^2$$

very strong fine tuning on m_0 for large cutoff scale

Hierarchy problem: what prevents the coupling of high mass scales (say the Planck scale) to the EW scale? How can the EW scale be stable?

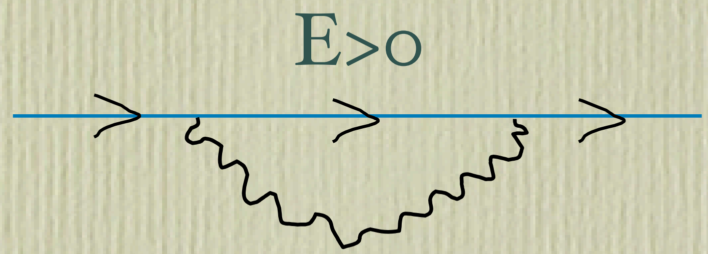
Murayama and Kolda, 2001: allowed regions consistent with fine tuning (to 1 and 10%) of the Higgs mass, assuming a near-to-exact cancellation of the quadratic divergence coefficient in the renormalized Higgs mass:

$$\mu_R^2 = \mu^2 - \frac{3\Lambda^2}{32\pi^2 v^2}(2m_W^2 + m_Z^2 + m_H^2 - 4m_t^2)$$



Unless we are ready to live with extreme, artificial, fine tuning, new degrees of freedom should appear at a scale not larger than few TeV. These degrees of freedom will change the radiative corrections to the Higgs mass, and hopefully remove the fine tuning problem.

Electron self-energy, Lorentz invariance, the positron



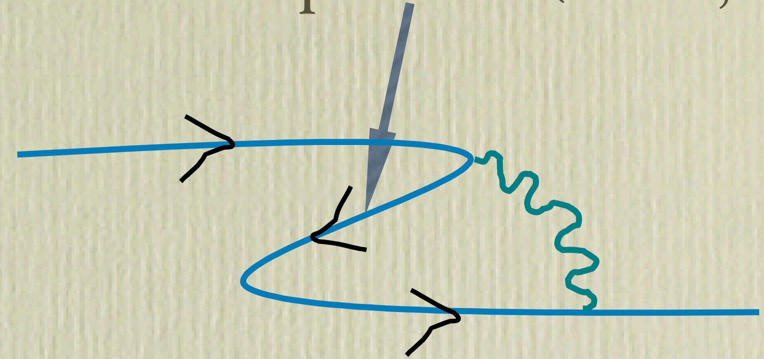
$$\delta(mc^2)_{Coulomb} \sim \frac{e^2}{r}$$

Requiring:

$$\delta m < m = 0.5 \text{ MeV}$$

$$\Lambda \equiv 1/r < 5 \text{ MeV}$$

Introduce the positron (Dirac, 1931)



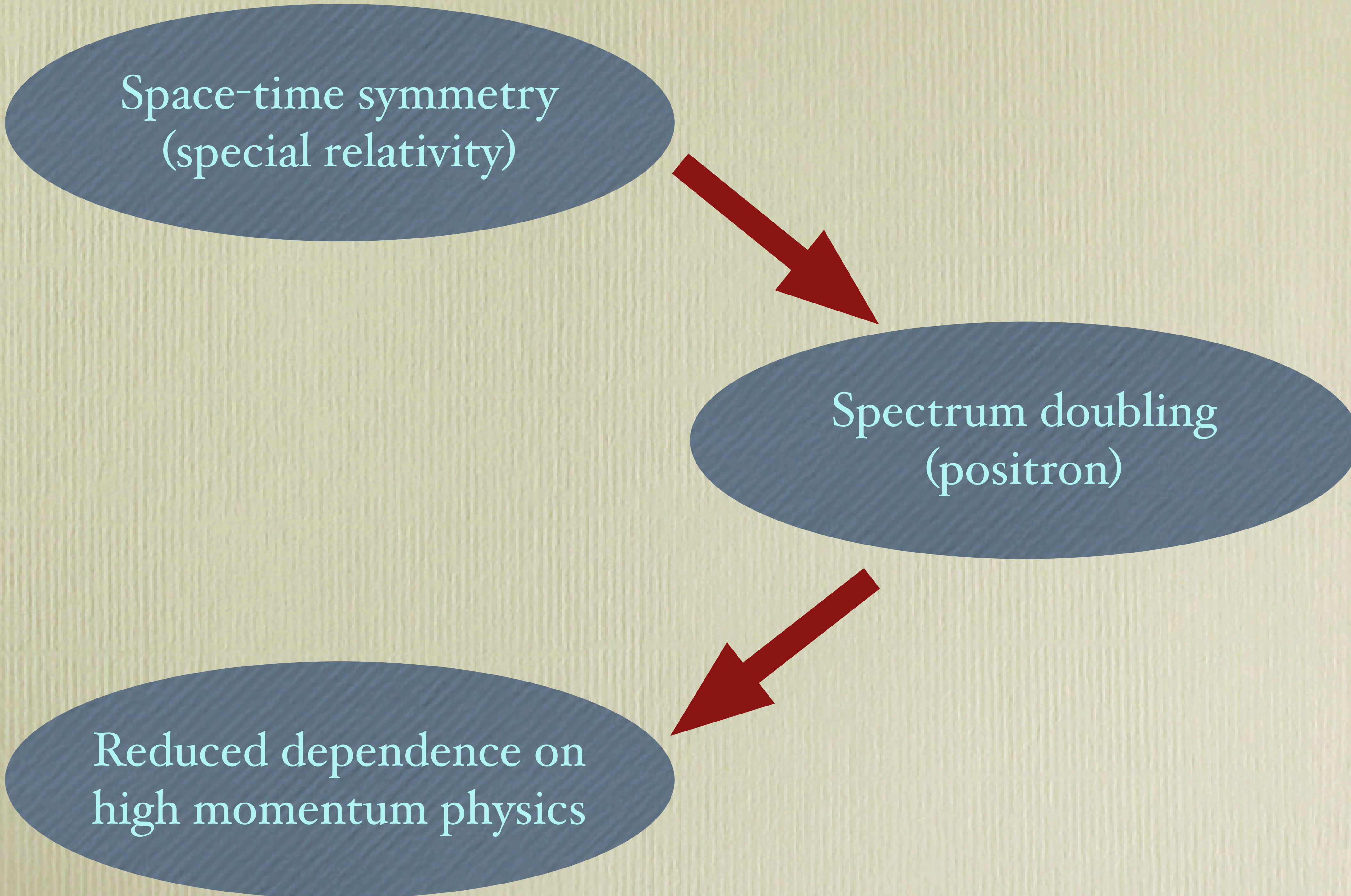
$$\delta(m)_{E>0 \oplus E<0} \sim e^2 m \log(\Lambda/m)$$

which is a correction of only 10% even at scales of the order of the Plank mass:

$$\delta(m)_{E>0 \oplus E<0} \sim 0.1\, m$$

at

$$\Lambda = 10^{19} \text{ GeV}$$


Space-time symmetry
(special relativity)
Spectrum doubling
(positron)
Reduced dependence on
high momentum physics

Supersymmetry

Extend space-time to include anti-commuting coordinates:

$$x^\mu \to (x^\mu, \square^\square), \text{ with } \{\square_\square, \square_\square\} = \square_{\square\square} = \begin{pmatrix} 0 & 1 \\ -1 & 0 \end{pmatrix}$$

Most general representation of a “scalar” (super)field:

$$\square(x, \square) = \square(x) + \square^\square \square_\square(x) + F(x)\square_{\square\square}\square^\square\square^\square$$

Invariance under super-translations $(x_\mu \to x_\mu + \square\square_\mu\square)$

$$[Q_\square, \square] = \square\square$$
$$[Q_\square, \square] = \square\square^\mu \partial_\mu \square$$

$\Longrightarrow$

$$[Q_\square, Q_\square] = \square\square_\mu\square p^\mu$$

The realization of supersymmetry requires the doubling of spectrum: for each bosonic particle there has to be a fermionic partner, and viceversa. Conserved supersymmetry requires these partners to have equal mass

A supersymmetry transformation is related to the square root of a translation: deep relation between supersymmetry and space-time. For example, one expects that gauging supersymmetry would lead to invariance under local coordinate transformation, therefore to gravity!

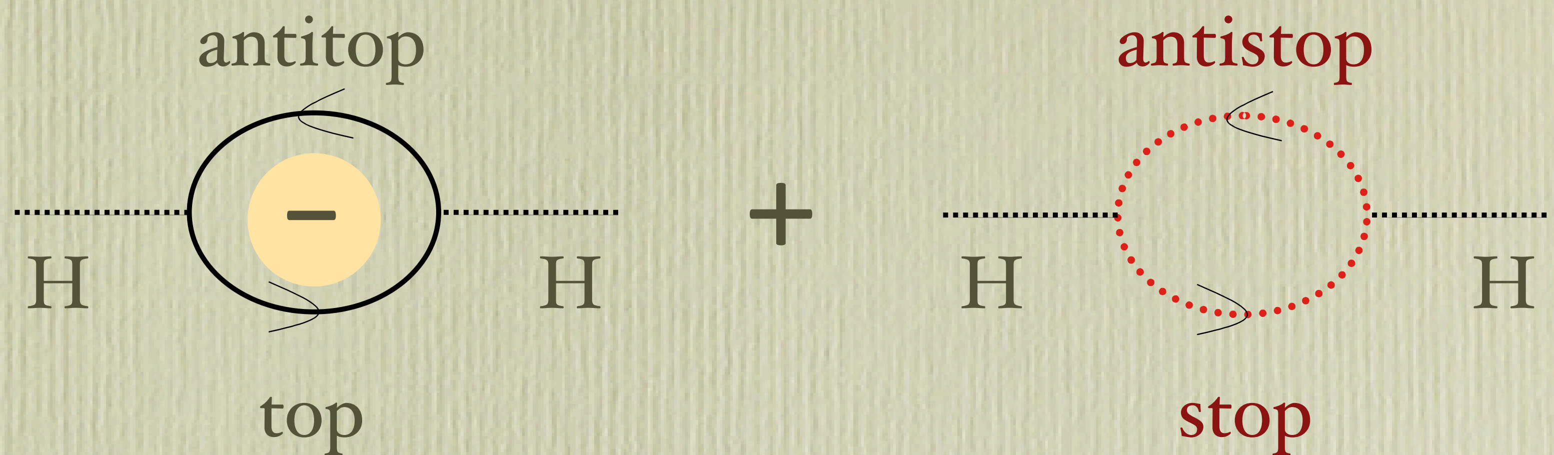
Supersymmetry spectrum

s=0	s=1/2	s=1
$\tilde{e}$, □	e, nu	
$\tilde{q}$	q	
H^0, H±	$\tilde{H}^0$, $\tilde{H}^\pm$	
	$\tilde{w}$, $\tilde{z}$, □	W, Z, gamma
	$\tilde{g}$	gluon

s=3/2	s=2
gravitino, $\tilde{G}$	graviton

In the literature, the fermions obtained by diagonalizing the mass matrix of the partners of charged Higgs and W boson are called charginos (2 states, $\chi^{\pm}_i$), those obtained from the partners of neutral Higgses, Z and photon, are called neutralinos (4 states, χ^{0}_i)

Higgs self-energy, Susy fix



(I)

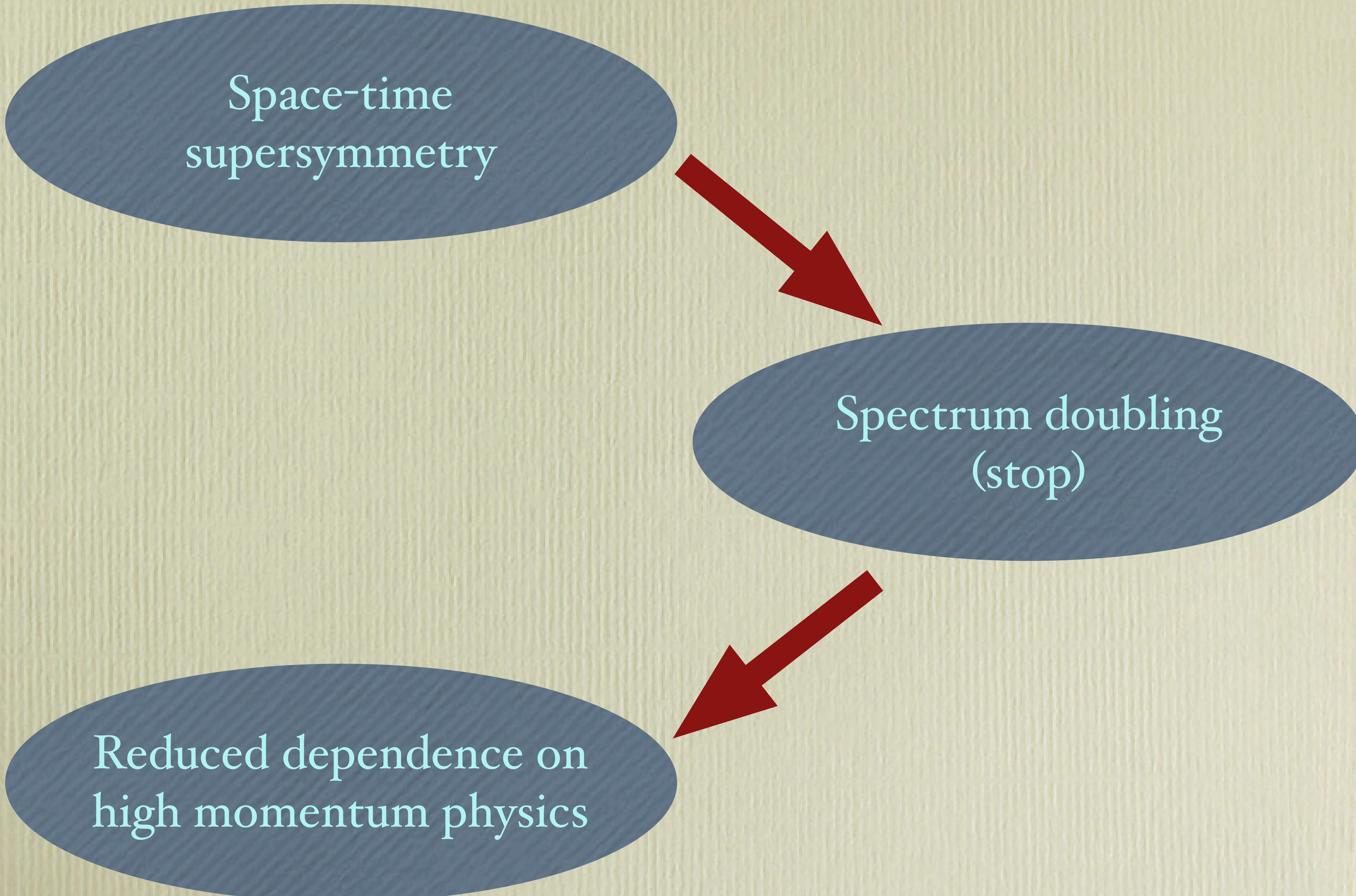
$\Box m_H^2 \qquad G_F\, m_t^4 \log(m_t/m_{stop})$ ➡ stability of the natural scale of the Higgs mass restored!

(II)

SUSY+ gauge invariance ➡

$\lambda \leftrightarrow g_W$ ➡

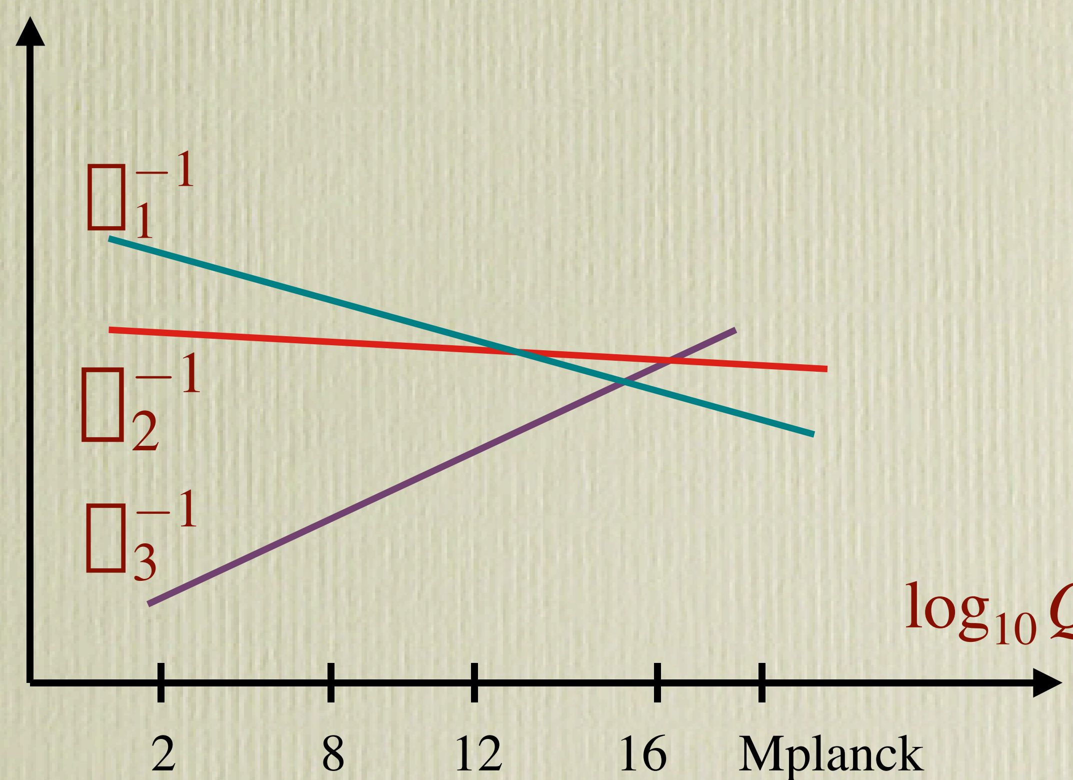
$m_H \leq M_Z +$ radiative corrections ($\log(m_t/m_{stop})$) ≤ 135 GeV


Space-time supersymmetry
Spectrum doubling (stop)
Reduced dependence on high momentum physics

Why SU(3)xSU(2)xU(1)?

- why not?
- Grand Unification: similarly to what happens in the case of SU(2)xU(1) at low energy, a broken symmetry invisible at low energy could get restored at high energy, with SU(3)xSU(2)xU(1) -> SU(5), SO(10), E6, etc
- Crucial prediction of this idea is that the couplings of the 3 low-energy groups run towards the same value at high energy:

$$\frac{d\alpha_G(Q^2)}{d\log Q^2)} = b_G\alpha_G(Q^2)$$



- Within the Standard Model, and fixing the meeting point of the 3 couplings using the accurately known U(1) and SU(2) couplings, we achieve full unification at 10^{15} GeV for $\alpha_s(M_Z) = 0.073 \pm 0.002$
- inconsistent with the measurement of $\alpha_s(M_Z) = 0.119 \pm 0.003$ and with the proton lifetime
- in presence of Supersymmetry, the predicted value of the SU(3) coupling $\alpha_s(M_Z) = 0.13 \pm 0.01$ is instead consistent with the data, and so is the expected proton lifetime, which can be pushed to above 10^{16} GeV
- Predictions of SUSY GUTS: relations among the gaugino masses, radiative EW symmetry breaking, mass relations. Several of them testable, at least in part, at the LHC!

LHC in a nutshell

- proton-proton collisions, at $\sqrt{S} = 14$ TeV
  - cfr. 2 TeV at the current highest energy accelerator, the Tevatron
- luminosity: $10^{33-34} \mathrm{cm}^{-2} \mathrm{s}^{-1}$
  - 10^8 proton-proton collisions per second
- event size: 1MB, event storage rate: 100Hz, data to tape: 10^6GB/yr
- Experiments:
  - ATLAS and CMS (general purpose)
  - LHCb: physics of b-flavoured mesons
  - ALICE: heavy ion (Pb) collisions at 5.5TeV/nucleon
- Expected starting date: 2007

Production Rates for benchmark processes at the LHC:

Process	events/s	events/yr
$W \rightarrow e\prod$	30	3 x 10^8
$Z \rightarrow e^+e^-$	3	3 x 10^7
$t\bar{t}$	0.8	8 x 10^6
$b\bar{b}$	5 x 10^5	5 x 10^{12}
jets, Et>1TeV	1.5 x 10^{-2}	5 x 10^5
$H\ (m_H = 130\ GeV)$	0.02	2 x 10^5
$\tilde{g}\tilde{g}(m_{\tilde{g}} = 1\ TeV)$	10^{-3}	10^4