Physics at the LHC

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Programme

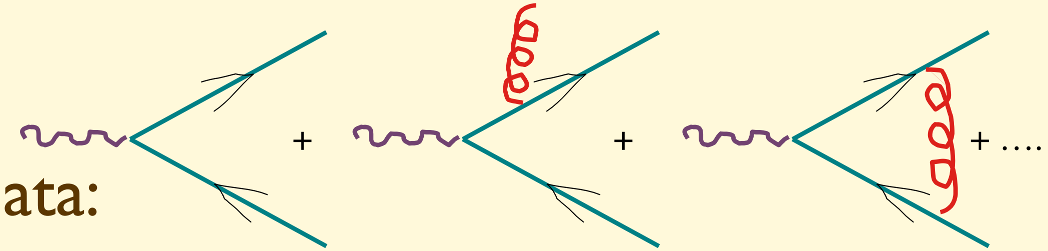
1. General introduction to the LHC physics goals
2. Theoretical description of proton-proton collisions
3. Standard Model studies at the LHC
4. Searches for the Higgs and for phenomena beyond the Standard Model
5. Prospects for early results from the LHC

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 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)

The future of HEP should be driven by the key questions left unanswered by the above picture:

Formal questions:

- Why gauge theory?
- Are particles really pointlike? Strings?? Membranes?

Phenomenological questions:

- Why 3 families of quarks and leptons? => flavour issues
- Why some particles have mass? => EW SB
- Why m(neutrino) ~ 10^{-7} m(e)? => again flavour
- Why is there a matter-antimatter asymmetry in the Universe? => sources of CP violation
- Origin of DM? Dark energy? => ?? possibly EW SB
- Why $F_{gravity} \sim 10^{-40}\ F_{electric}$? => again EW SB
- Why D=3+1? => Quantum gravity, strings, extra dim

More pragmatically, the two leading questions whose understanding is possibly within the reach of the forthcoming generation of experiments are:

The origin of EW SB

The origin of Dark Matter

Better understanding of the first issue is crucial to make progress on the other points (e.g. flavour, neutrino masses, CP violation) and to plan the future of HEP.

Dark Matter

- Clear cosmological evidence: CMB fluctuations, structure formation
- Whatever its origin, it must be coded somewhere in the Lagrangian of HEP => **it is "our" problem**
- Main ingredients:
  - stable weakly interacting particle
  - mass vs annihilation rate such as to decouple (freeze-out) at the appropriate time and with the appropriate density
- It so happens that the required numerics works out to match the expected behaviour of particles with mass O(100 GeV) and weak coupling:

$$\sigma \sim \alpha^2_W / M^2_W$$

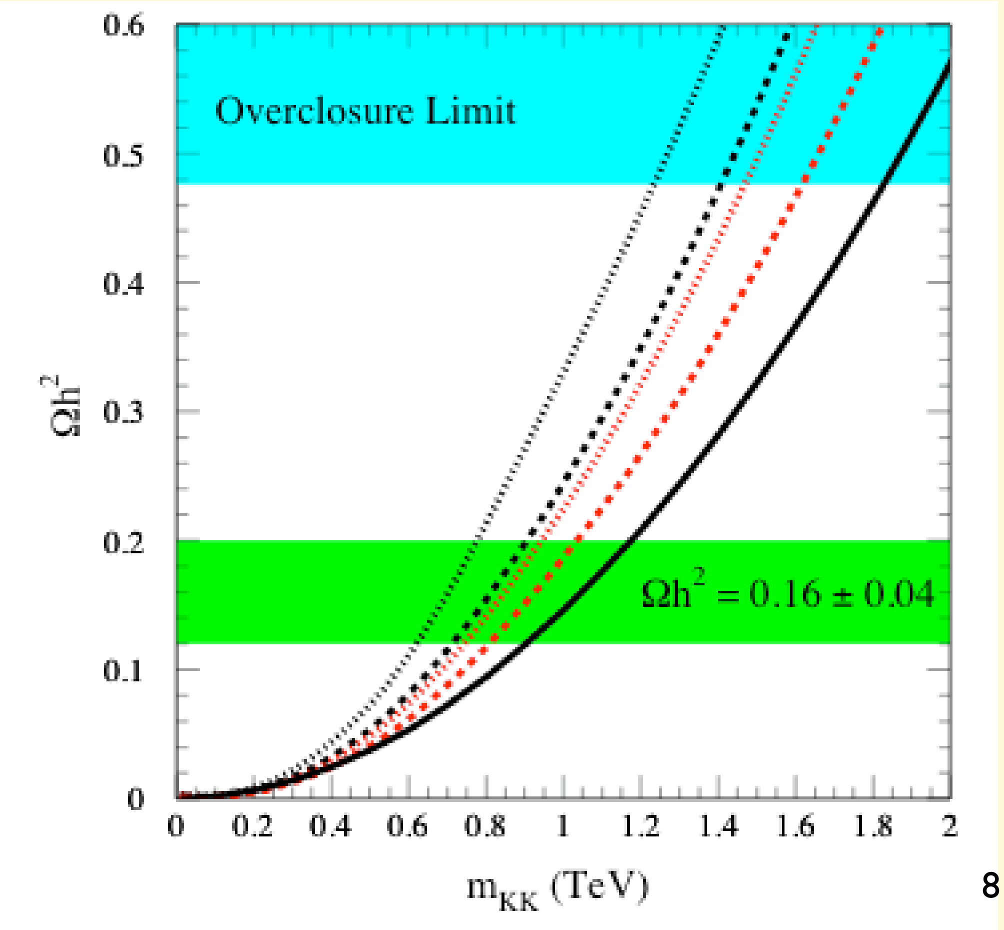
It is unavoidable to speculate that the origin of DM is directly linked to the phenomena responsible for EWSB

It is not surprising that most alternative approaches to the "Higgs" problem (little Higgs, extra-dimensions, etc) provide a possible DM candidate:

Mass scale / coupling strength are inherited by the link to EWSB

Stability is associated to discrete symmetries (like SUSY's R parity)

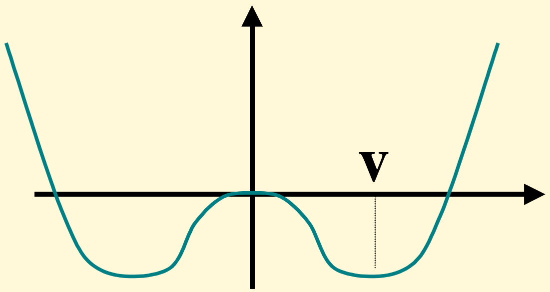
Example from Universal Extra Dimensions (DM=1st photon/ neutrino KK mode)



Géraldine Servant [a,b] and Tim M.P. Tait

hep-ph/0206071

The Higgs mechanism



- Scalar potential: $V(\phi) = -\mu^2|\phi|^2 + \frac{\lambda}{4}|\phi|^4$
- Its minimization: $\delta V(\phi) = 0 \Rightarrow \langle\phi\rangle^2 \equiv v^2 = 2\frac{\mu^2}{\lambda}$
- Coupling of the background (Higgs) field to matter: $y_\psi\, \phi\bar{\psi}\psi$
- Mass of matter field: $m_\psi = y_\psi \langle\phi\rangle \equiv y_\psi v$
- Mass of W gauge bosons: $m(W) = g\,v \Rightarrow v = 175\ \text{GeV}$
- Mass of Higgs field: $m_\phi^2 = \partial^2 V(\phi = v) = 2\mu^2 = \lambda v^2$
- 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:

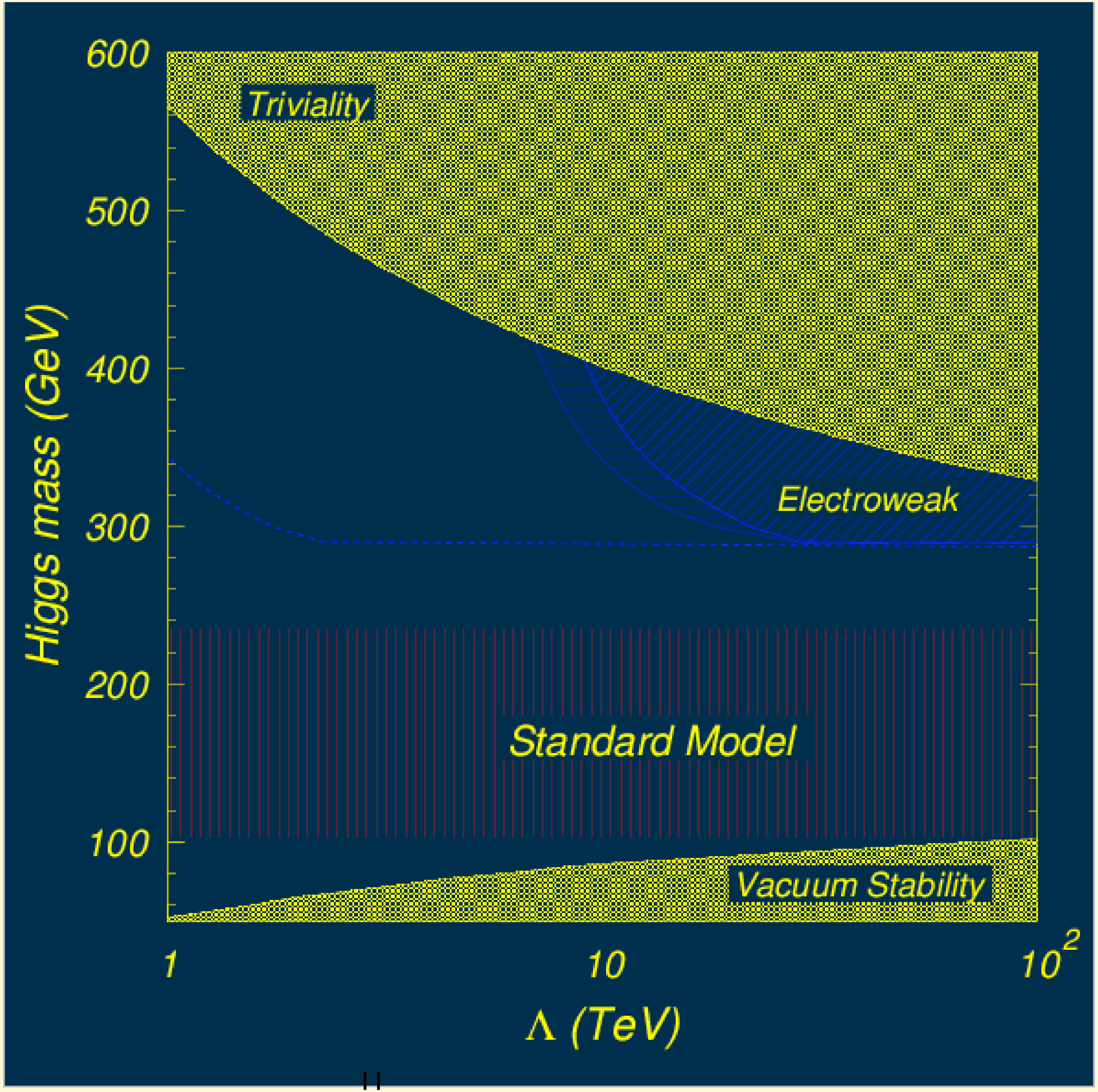
$$\frac{d\lambda}{dt} = \frac{3}{8\pi^2}\,(\lambda^2 - 4y_t^2)$$

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 $\lambda(v)$ too large then $\lambda(Q)$ 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 $\lambda(v)$, and then on m_H. The higher the scale Q, the lower the upper limit on m_H.
- Vacuum stability: if $\lambda(v)$ is too small, the RGE will drive $\lambda(Q)<0$ 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.

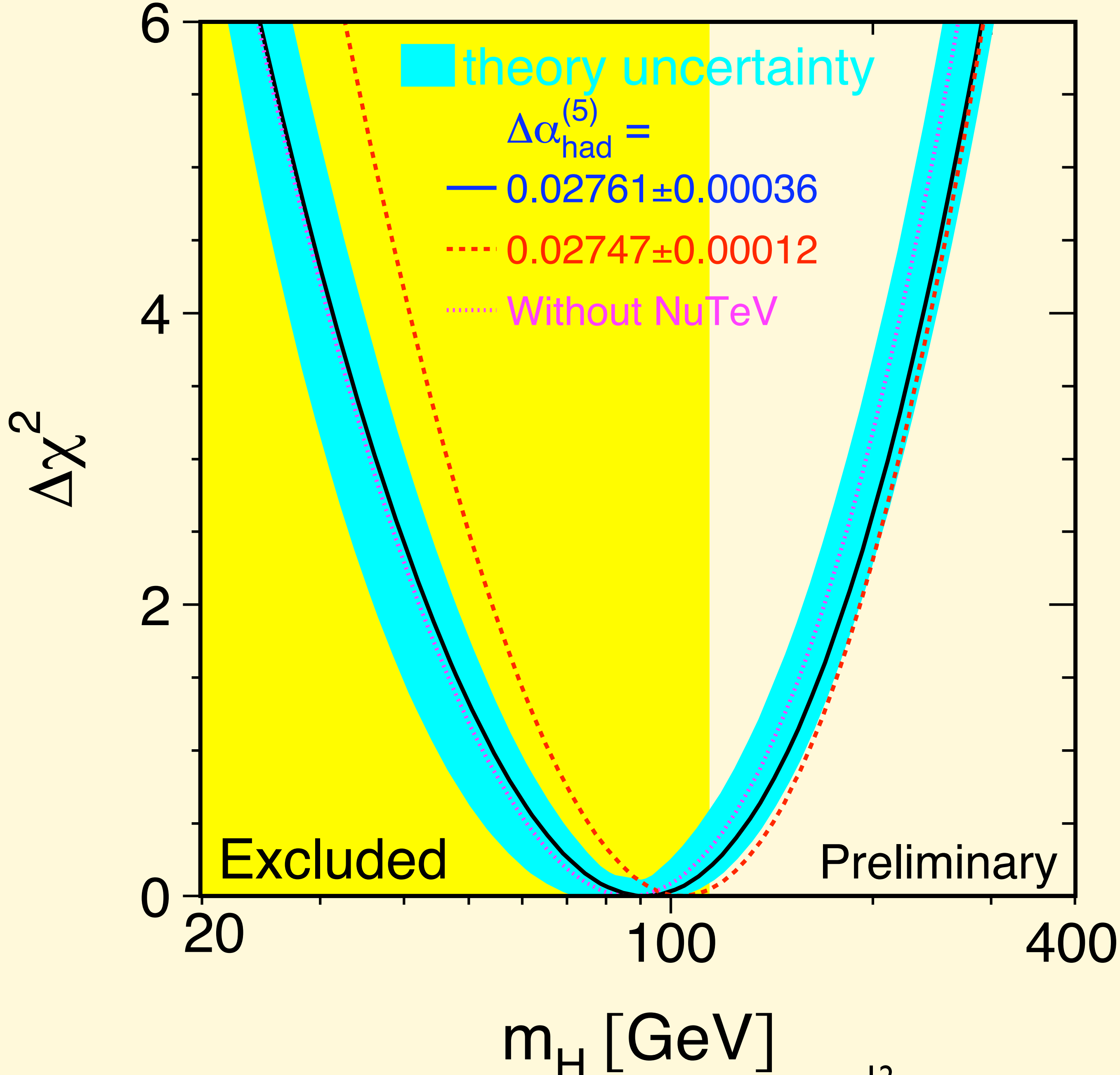
Requiring Q ~10^{16} GeV for both cases gives:

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)

11

Current experimental knowledge on m(H)



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

m(H)=98 $^{+52}_{-39}$ from the EW fits

m(H)<200 GeV at 95%CL From the EW fits

Note

- 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.

This picture, while suggesting a strong confirmation of the SM, presents however an apparent paradox:

On one side m(H)=98+52-36; on the other, SM radiative corrections give

$$\delta m_H^2 = \frac{6G_F}{\sqrt{2}\pi^2}\,(m_t^2 - \frac{1}{2}m_W^2 - \frac{1}{4}m_Z^2 - \frac{1}{4}m_H^2)\Lambda^2 \sim (115\mathrm{GeV})^2 \left(\frac{\Lambda}{400\mathrm{GeV}}\right)^2$$

How can counterterms artificially conspire to ensure a cancellation of their contribution to the Higgs mass?

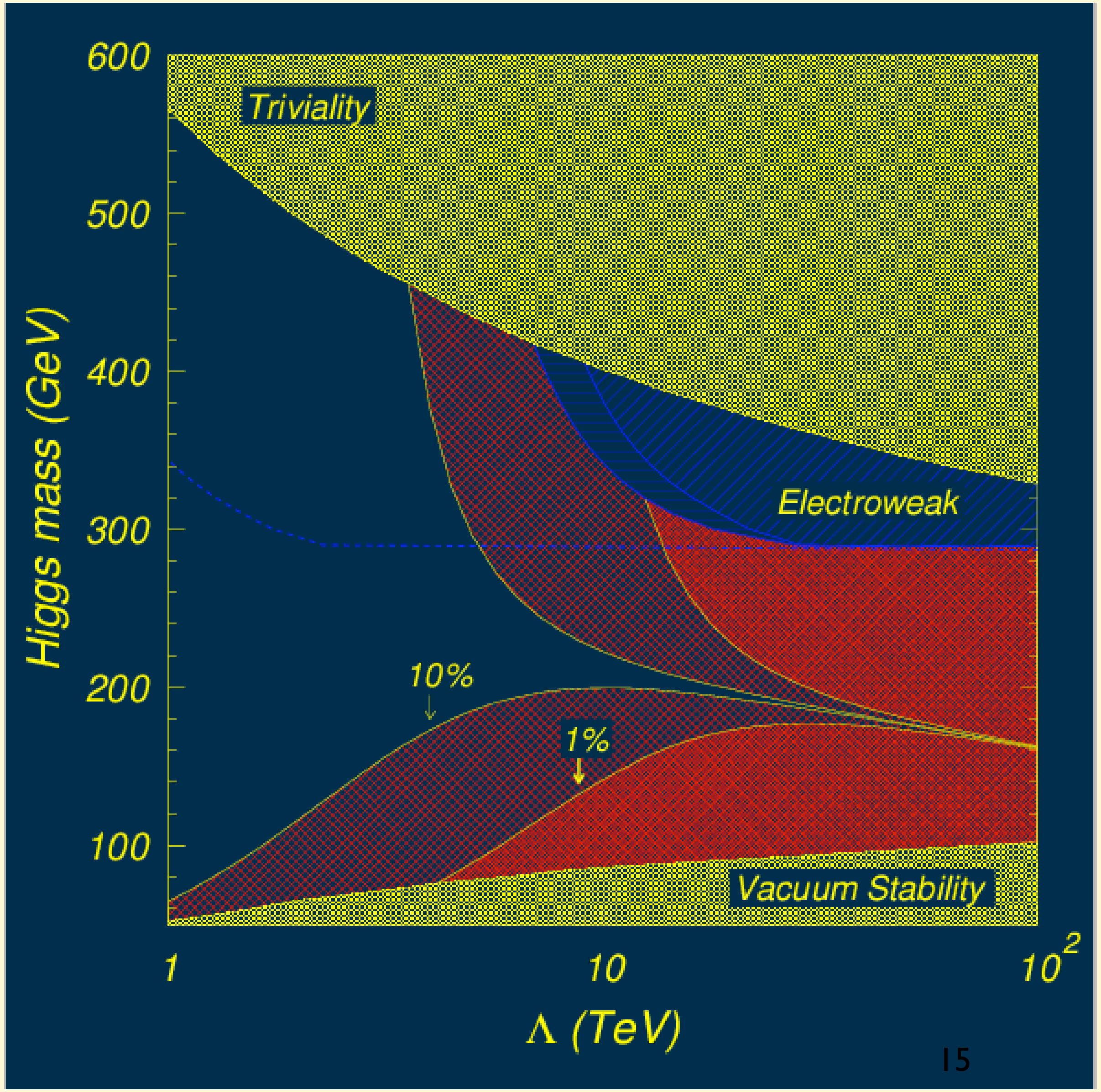
The existence of new phenomena at a scale not much larger than 400 GeV appears necessary to enforce such a cancellation in a natural way!

On the other hand, the accuracy of the EW precision tests at LEP sets the scale for "generic new physics" (parameterized in terms of dim-5 and dim-6 effective operators) at the level of few-to-several TeV.

This puts very strong constraints on the nature of this possible new physics: to leave unaffected the SM EW predictions, and at the same time to play a major role in the Higgs sector.

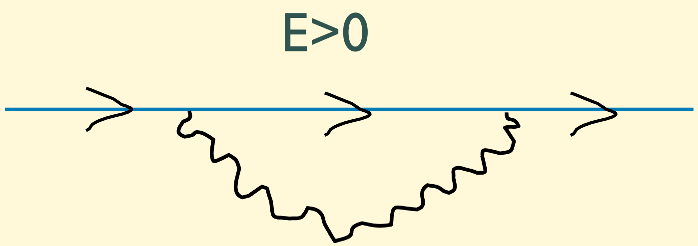
Murayama and Kolda, 2001: allowed regions consistent with fine tuning (to 1 and 10%) of the Higgs mass, assuming a near-to-exact cancellation of the quadratic divergence coefficient in the renormalized Higgs mass:

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



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



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

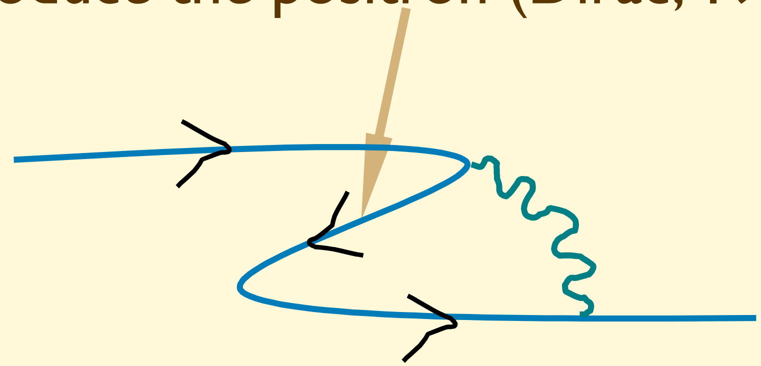
Requiring:

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

$$\Rightarrow$$

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

Introduce the positron (Dirac, 1931)



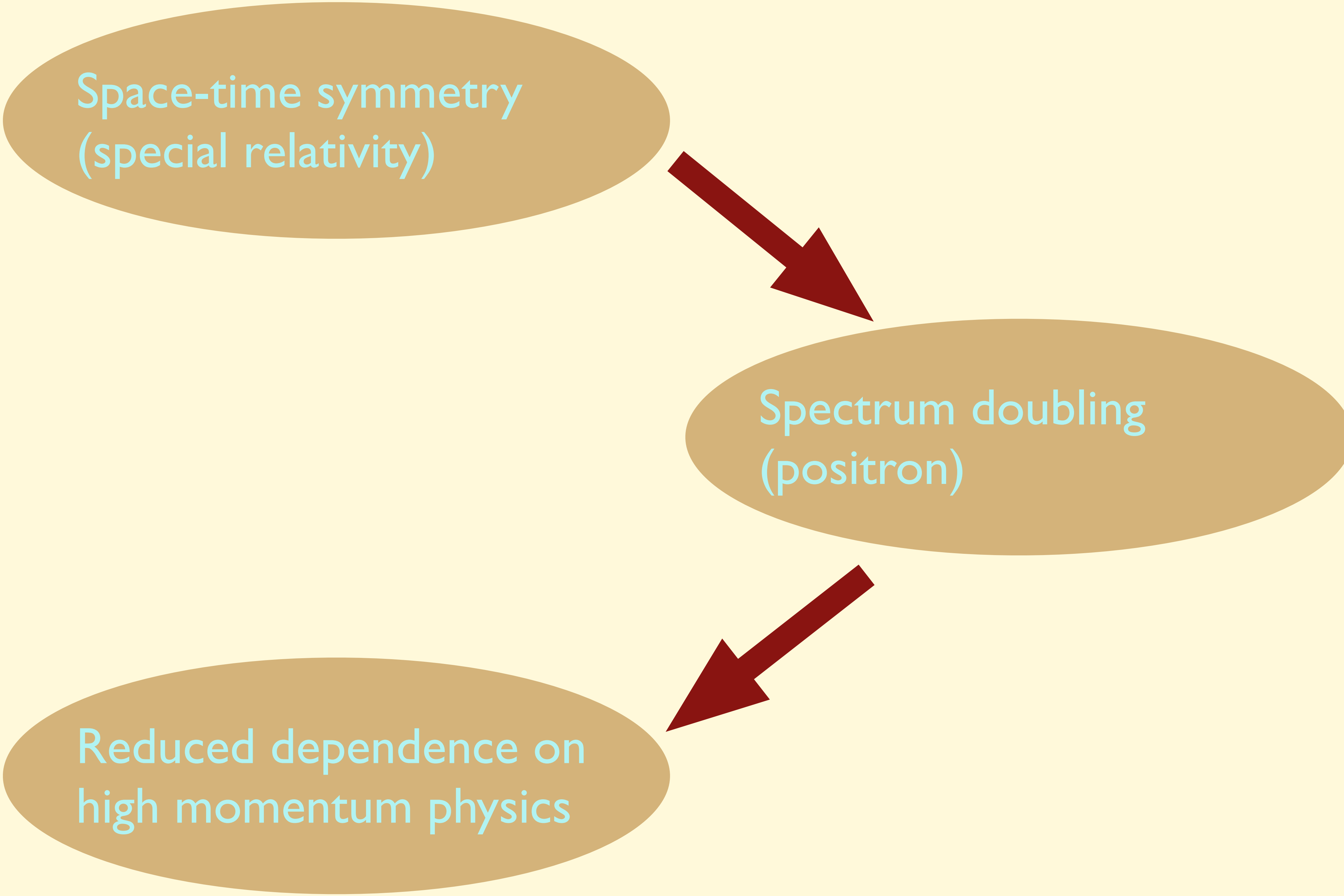
$$\Delta(m)_{E>0 \oplus E<0} \sim e^2 m \log(\Lambda/m)$$

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:

$$x^\mu \to (x^\mu, \theta^\alpha), \text{ with } \{\theta_\alpha, \theta_\beta\} = \varepsilon_{\alpha\beta} = \begin{pmatrix} 0 & 1 \\ -1 & 0 \end{pmatrix}$$

Most general representation of a "scalar" (super)field:

$$\Phi(x,\theta) = \phi(x) + \theta^\alpha \psi_\alpha(x) + F(x)\varepsilon_{\alpha\beta}\theta^\alpha\theta^\beta$$

Invariance under super-translations ($x_\mu \to x_\mu + \varepsilon\sigma_\mu\theta$)

$$[Q_\varepsilon, \phi] = \varepsilon\psi$$

$$[Q_\varepsilon, \psi] = \varepsilon\sigma^\mu \partial_\mu \phi$$

$$[Q_{\bar\varepsilon}, Q_\varepsilon] = \bar\varepsilon\sigma_\mu\varepsilon \; p^\mu$$

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 transformations, therefore to gravity!

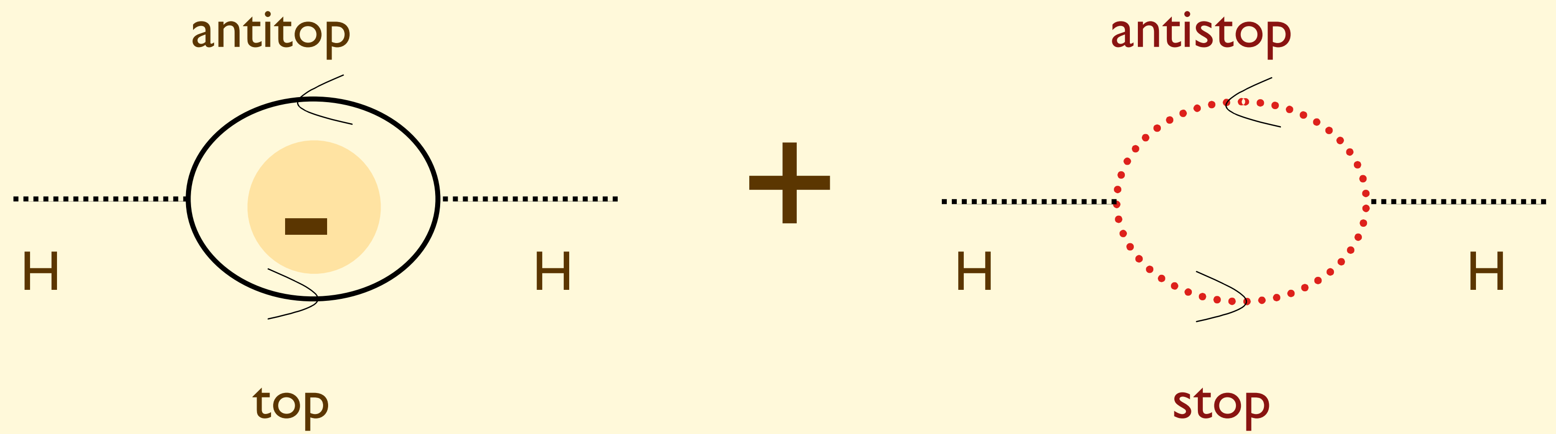
Supersymmetry spectrum

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

$$\Delta m_H^2 \propto \; G_F \, m_t^4 \log(m_t/m_{stop})$$

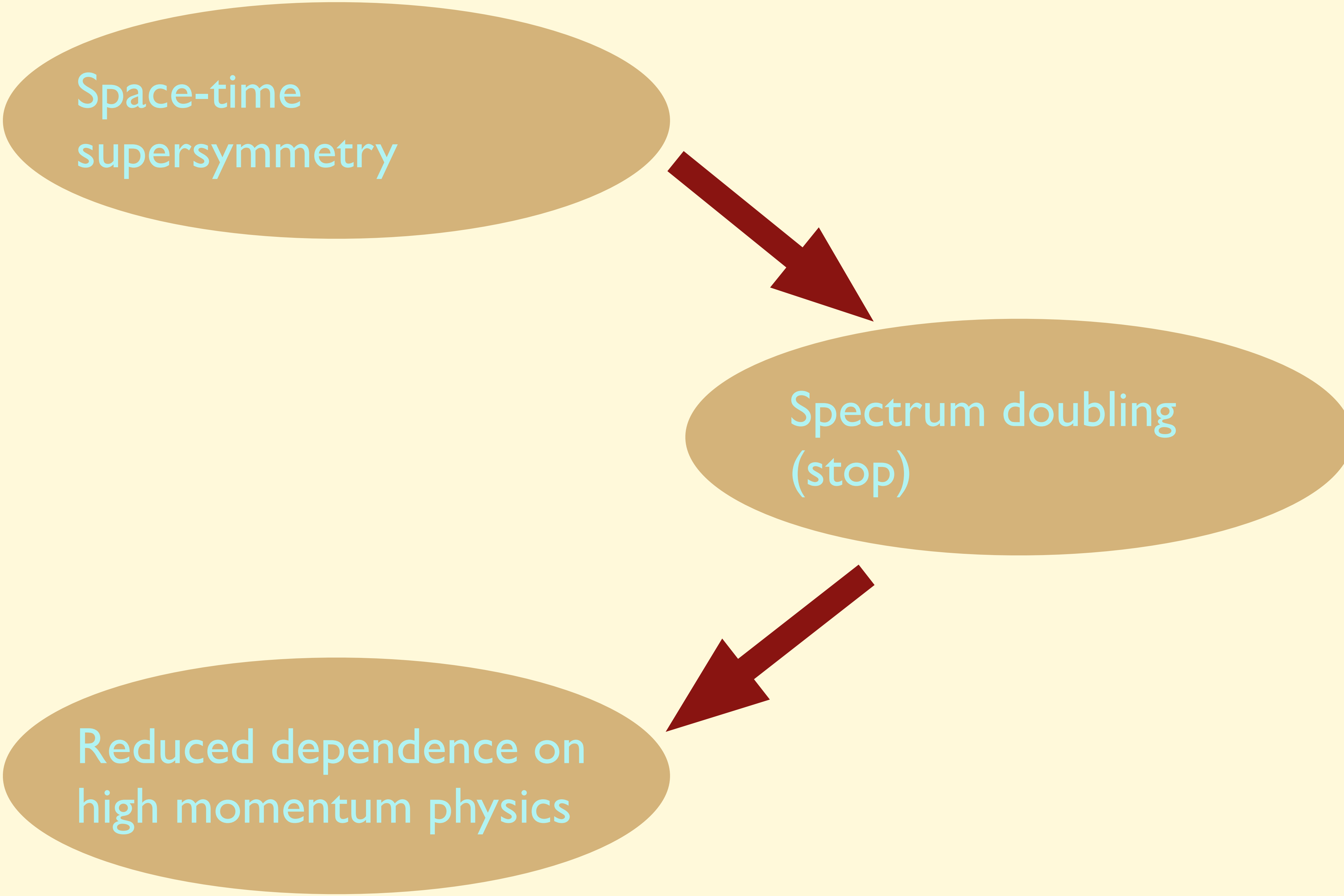
stability of the natural scale of the Higgs mass restored!

(II)

SUSY+ gauge invariance

$\lambda \leftrightarrow g_W$

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


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

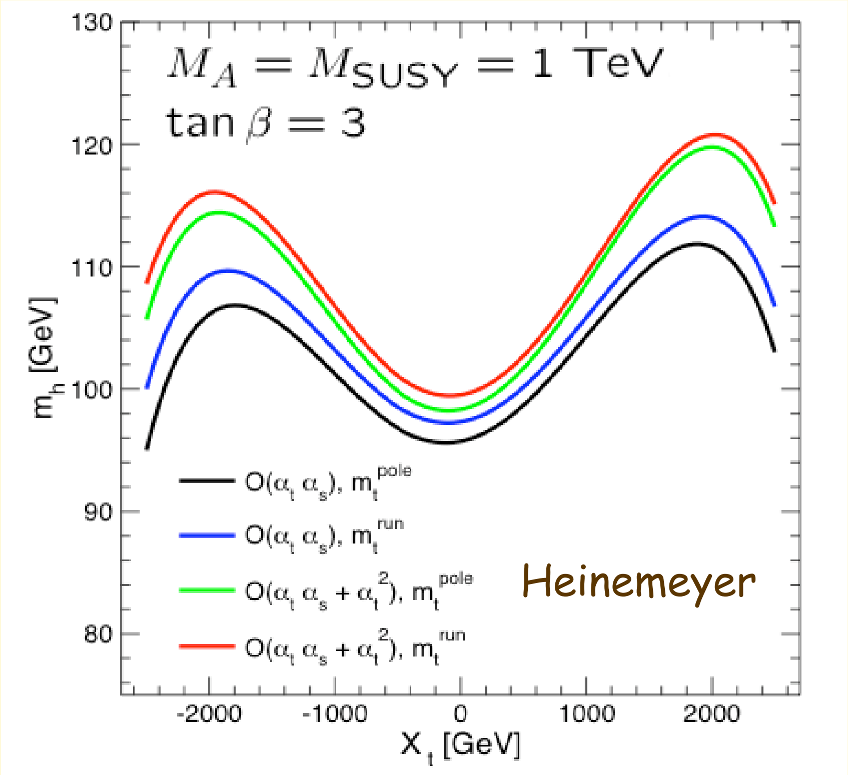
In some more detail:

In Supersymmetry the radiative corrections to the Higgs mass are not quadratic in the cutoff, but logarithmic in the size of SUSY breaking (in this case M_{stop}/M_{top}):

$$m_h^2 < m_Z^2 + \frac{3G_F}{\sqrt{2}\pi^2} m_t^4 \left[\ln\left(\frac{M_S^2}{m_t^2}\right) + x_t^2\left(1 - \frac{x_t^2}{12}\right)\right]$$ with $$M_S^2 \equiv \tfrac{1}{2}(M_{\tilde{t}_1}^2 + M_{\tilde{t}_2}^2) \quad X_t \equiv A_t - \mu \cot\beta \quad x_t \equiv X_t/M_S$$

For $M_{susy} < 2$TeV

$$m_h^{max} \simeq 122 \text{ GeV}, \quad \text{if top-squark mixing is minimal,}$$
$$m_h^{max} \simeq 135 \text{ GeV}, \quad \text{if top-squark mixing is maximal}$$



The current limits on m_H point to M(lightest stop) > 600 GeV. Pushing the SUSY scale towards the TeV, however, forces fine tuning in the EW sector, reducing the appeal of SUSY as a solution to the Higgs mass naturalness:

$$\delta m_Z^2 \sim (90GeV)^2 \left(\frac{M_S}{230GeV}\right)^2 \ln\frac{\Lambda_{UV}}{M_S}$$

In other words, the current lower limit on m_H shows that room is getting very tight now for SUSY, at least in its "minimal" manifestations.

This makes the case for an early observation of SUSY at the LHC quite compelling, and worth investing into!

The search for Supersymmetry is in my view the single most important task facing the LHC experiments in the early days. In several of its manifestations, SUSY provides very clean final states, with large rates and potentially small bg's.

Jets + miss ET
(squarks/gluinos)

Same-sign dileptons + MET
(gluinos)

B_s->mu$^+$mu$^-$

t tbar+ MET
(stop production)

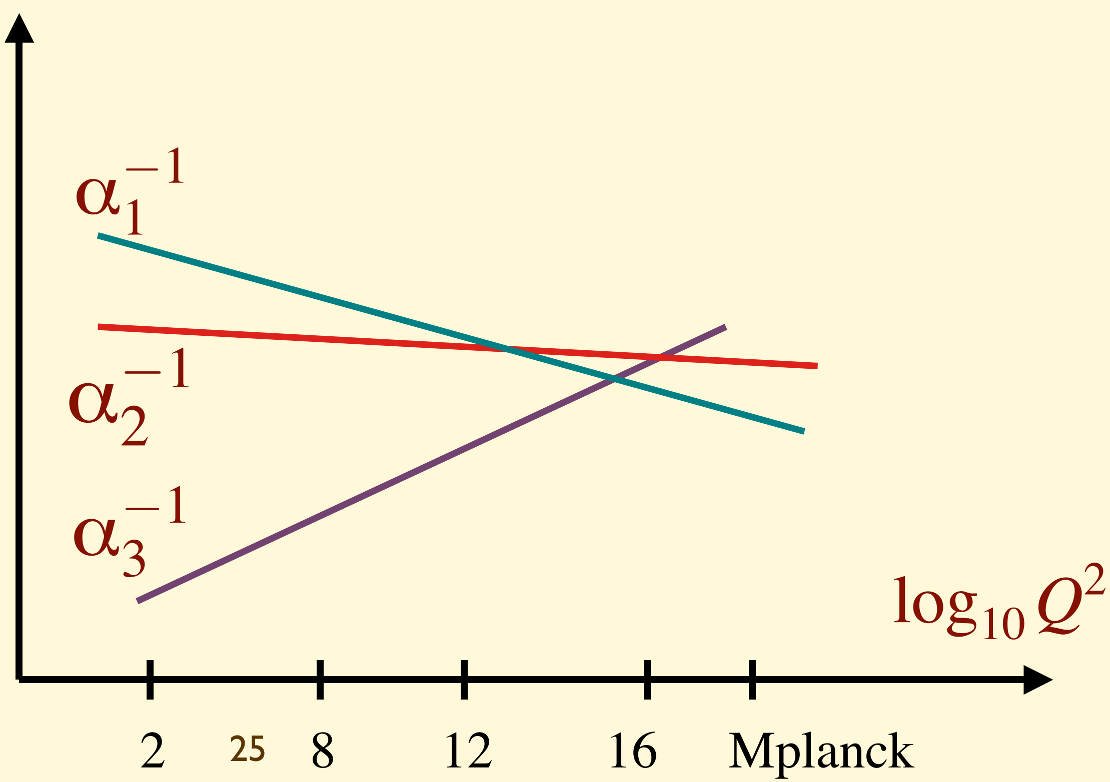
photons+MET
(gauge mediated ~~SUSY~~)

Given the big difficulty and the low rates characteristic of Higgs searches in the critical domain m_H<135 GeV, the detector and physics commissioning should be optimized towards the needs of SUSY searches rather than light-Higgs (for m_H>140 Higgs searches will be almost staightforward and will require proper understanding of only a limited fraction of the detector components -- e.g. muons)

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 $\sqrt{S} = 14\ \mathrm{TeV}$
  - 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: Summer 2007

Production Rates* for benchmark processes at the LHC:

Process	events/s	events/yr
$W \longrightarrow e\nu$	30	3 x 10^8
$Z \longrightarrow e^+e^-$	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

*Assuming L = 10^{33} $cm^{-2}s^{-1}$