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Expectations for the LHC

Physique ATLAS France
Seignosse, 10 September 2007

Plan

1. The SM: how much should we believe it?
2. Supersymmetry: if so, which incarnation?
3. Other motivated new physics and exotics
4. (Temporary) conclusions and outlook

1. The SM: how much should we believe it ?

Only part of SM still under discussion
symmetry-breaking sector
realized by elementary scalar doublet

Spontaneous breaking of the gauge symmetry

$$L_S = (D^\mu \phi)^\dagger (D_\mu \phi) - \left[\mu^2 \left(\phi^\dagger \phi\right) + \lambda \left(\phi^\dagger \phi\right)^2\right]$$

Explicit breaking of the global flavour symmetry

$$L_Y = h^U \overline{q_L} u_R \widetilde{\phi} + h^D \overline{q_L} d_R \phi + h^E \overline{l_L} e_R \phi + h.c.$$

Picture confirmed so far with impressive precision

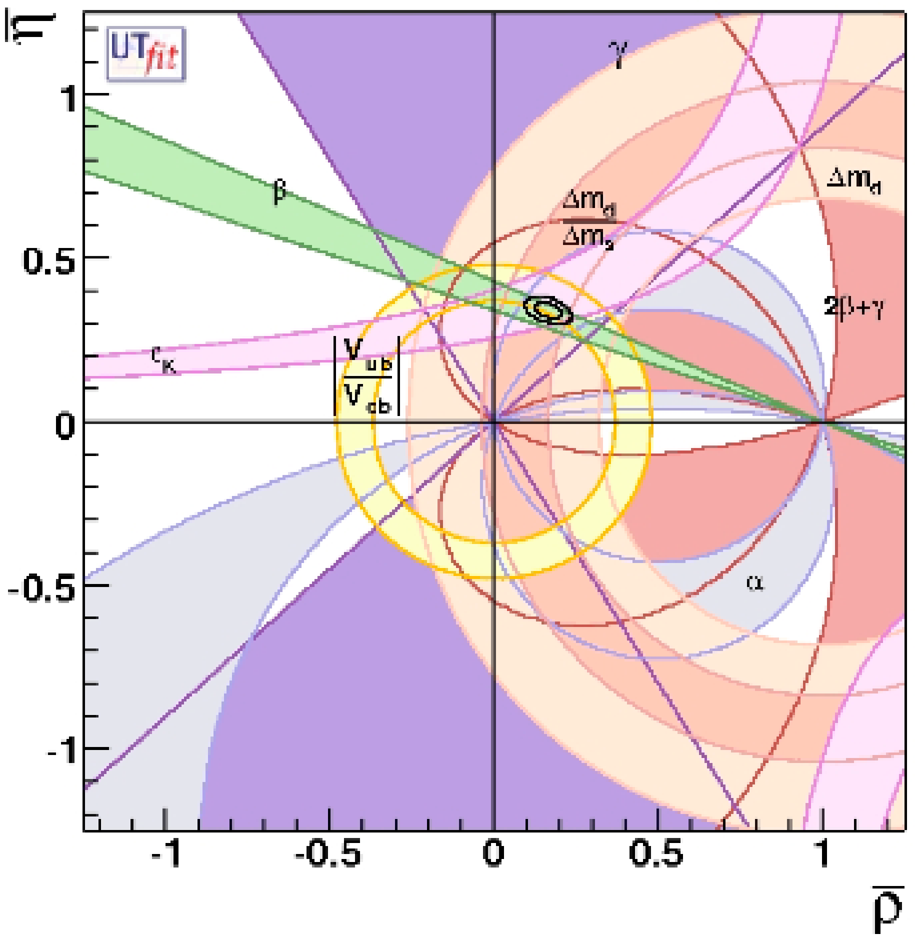
Missing particle (parameter): Higgs boson H (m_H)

LEP direct searches: $m_H > 114.4$ GeV (95% c.l.)

Precision tests of flavour breaking

Impressive recent progress (B-factories, Tevatron):
no significant deviation from SM (GIM, CKM) found

The unitarity triangle



Some recent examples:

$\Delta m_s \quad B \longrightarrow \tau\nu$

$B_s \rightarrow \mu^+\mu^-$ bound

More K and B decays
CP-violation in B system
Tree-level vs. 1-loop UT

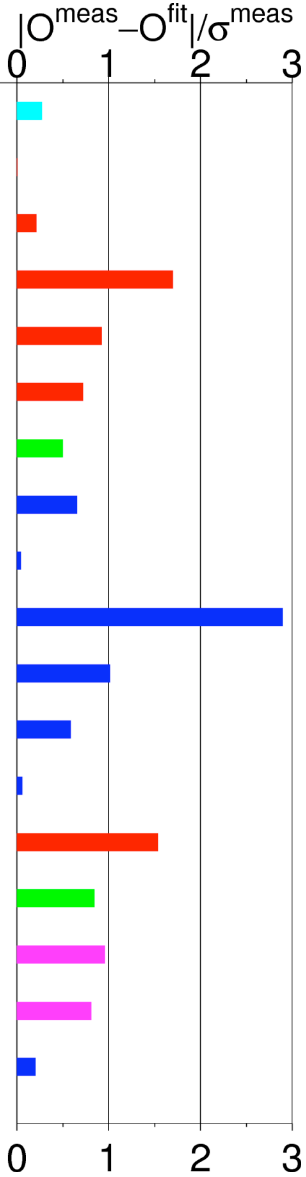
and some older ones:

$B \rightarrow X_s\gamma \quad B \rightarrow X_s l^+ l^- \quad \mu \rightarrow e\gamma$

Message: little room for flavour breaking at TeV scale not in $\mathcal{L}_Y$

Precision tests of EW breaking [Summer 2007]

	Measurement	Fit
$\Delta\alpha_{had}^{(5)}(m_Z)$	0.02758 ± 0.00035	0.02768
m_Z [GeV]	91.1875 ± 0.0021	91.1875
Γ_Z [GeV]	2.4952 ± 0.0023	2.4957
σ_{had}^0 [nb]	41.540 ± 0.037	41.477
R_l	20.767 ± 0.025	20.744
$A_{fb}^{0,l}$	0.01714 ± 0.00095	0.01645
$A_l(P_\tau)$	0.1465 ± 0.0032	0.1481
R_b	0.21629 ± 0.00066	0.21586
R_c	0.1721 ± 0.0030	0.1722
$A_{fb}^{0,b}$	0.0992 ± 0.0016	0.1038
$A_{fb}^{0,c}$	0.0707 ± 0.0035	0.0742
A_b	0.923 ± 0.020	0.935
A_c	0.670 ± 0.027	0.668
A_l(SLD)	0.1513 ± 0.0021	0.1481
$\sin^2\theta_{eff}^{lept}(Q_{fb})$	0.2324 ± 0.0012	0.2314
m_W [GeV]	80.398 ± 0.025	80.374
Γ_W [GeV]	2.140 ± 0.060	2.091
m_t [GeV]	170.9 ± 1.8	171.3



[Grunewald EPS07]

Recent update:
$M_t = 170.9 \pm 1.8$ GeV
(slightly worsens the fit)

- SM still fits well at such high precision!

$\chi^2/\text{dof}=18.2/13(15.1\%)$

- Indication for light Higgs in the SM

$M_H = 76^{+33}_{-24}$ GeV

$M_H < 144$ GeV (95%CL)

Including direct bound:

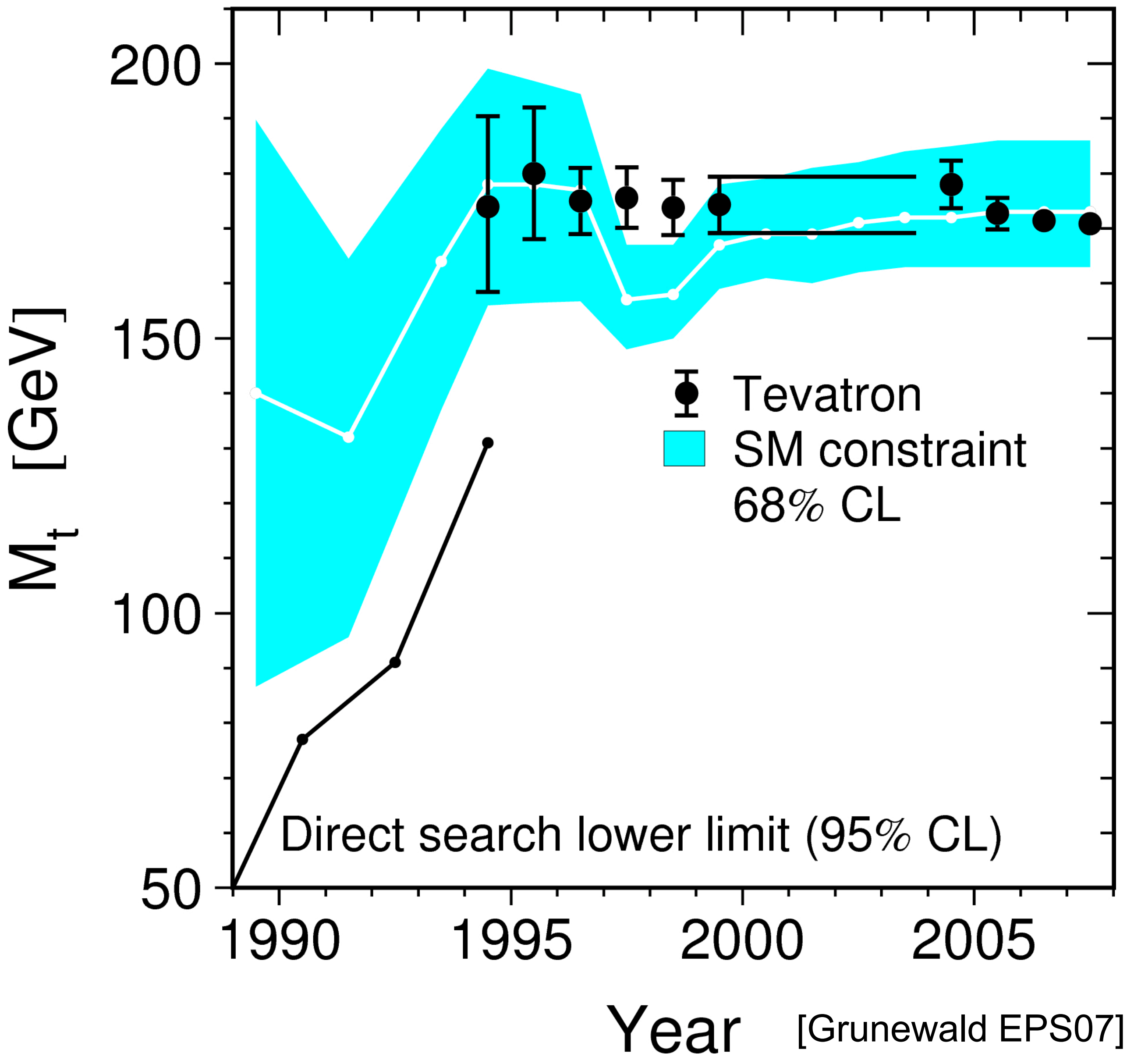
$M_H < 182$ GeV (95%CL)

A successful story: the top quark

Since LEP 1990
or even before
(neutrino DIS):
prediction of the
top quark mass

1995-6: discovery
at the Tevatron
CDF, DØ

But quadratic
sensitivity to M_t
via Veltman's
rho parameter!

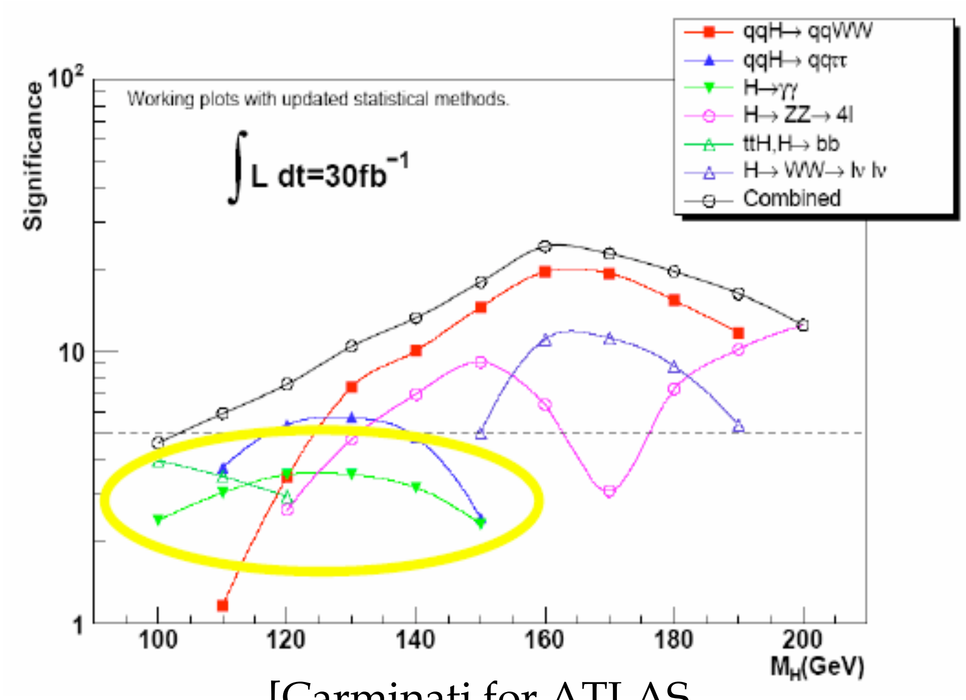


[Grunewald EPS07]

What if there is a SM Higgs with $m_H < 130$ GeV?

The most difficult region for ATLAS and CMS!

Will take time: integrated luminosity, excellent understanding of both detector and background



[Carminati for ATLAS, Physics at LHC 2006]

$$pp \to H + X \quad H \to \gamma\gamma$$

$$pp \to qqH \quad H \to \tau\tau$$

$$pp \to qqH \quad H \to WW$$

$$pp \to t\bar{t}H \quad H \to b\bar{b}$$ (?)

plus other channels good only at higher luminosity

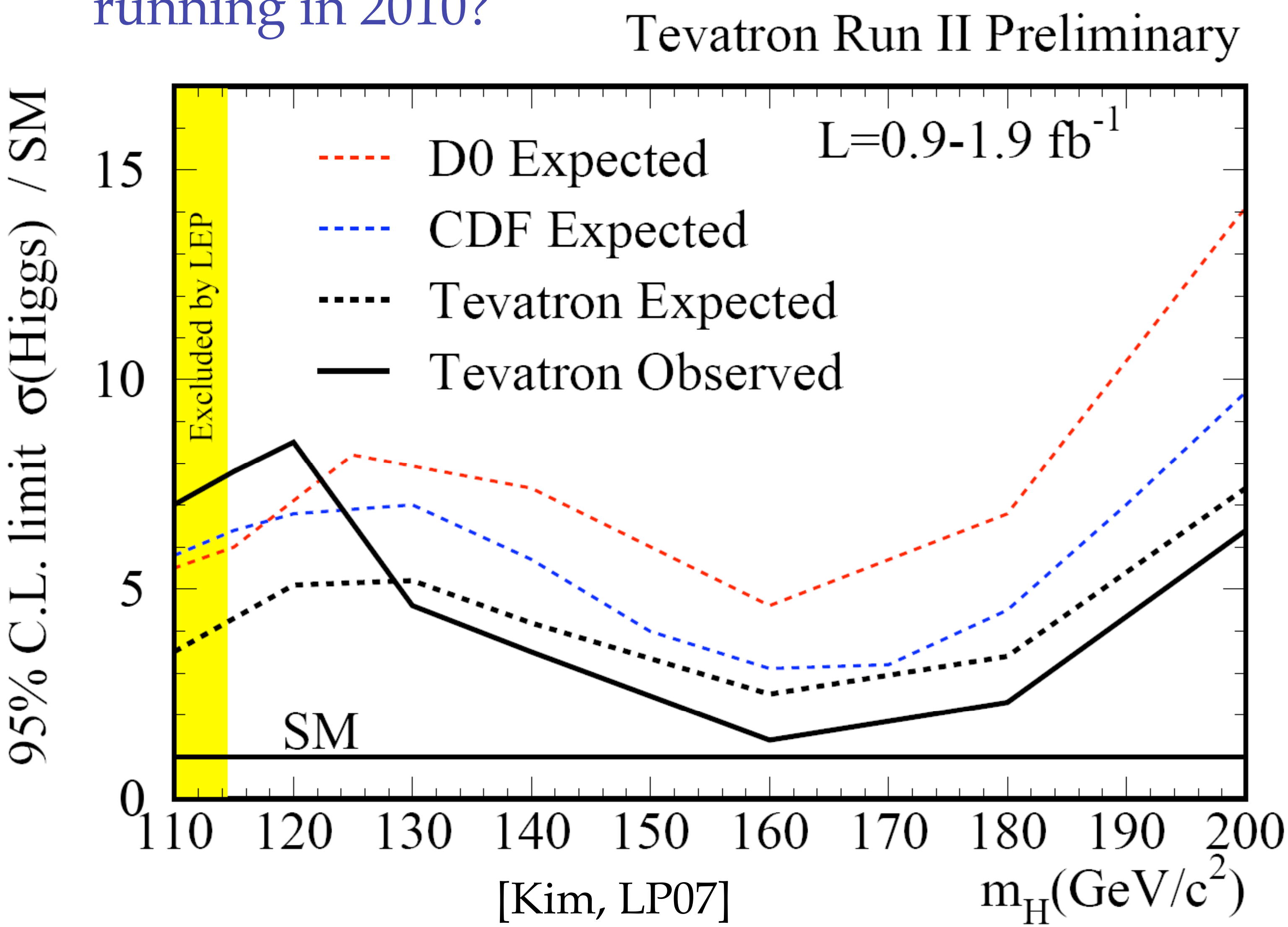
discussed here on Wednesday

Possible LHC/Tevatron Higgs race in 2009-2010?

SM Higgs Searches at Tevatron

New

6-7 fb^{-1} by 2009
running in 2010?



[Kim, LP07]

Can we exclude a heavy SM-like Higgs?

(is working on those analyses a poor investment?)

Within the SM model, the evidence for a light Higgs is not as solid as it may seem (see later)

Beyond the SM, simple (but ad hoc) modifications can reconcile precision tests with a heavier Higgs

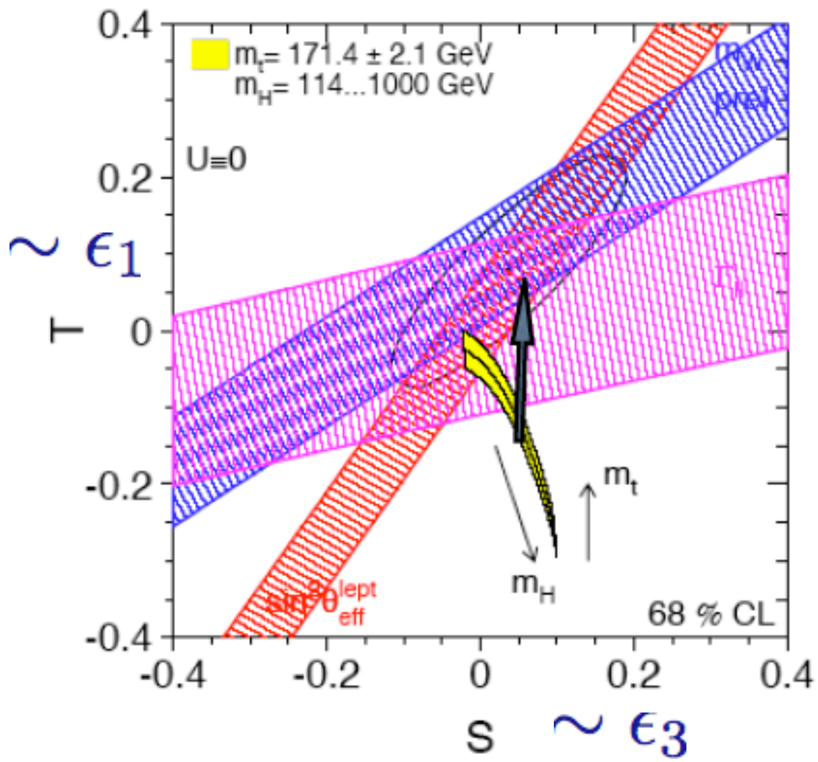
Pushing m_H up requires

$$\Delta T = 0.2 - 0.3 \quad \Delta S = small$$

Various possibilities explored:

[Peskin-Wells, Barbieri et al, …]

- A second "inert" doublet H_2
- SUSY with large NH_1H_2 coupling
- A (tuned) fourth generation
- New EW fermions



Any hints of a SM crisis (at the Fermi scale) ?

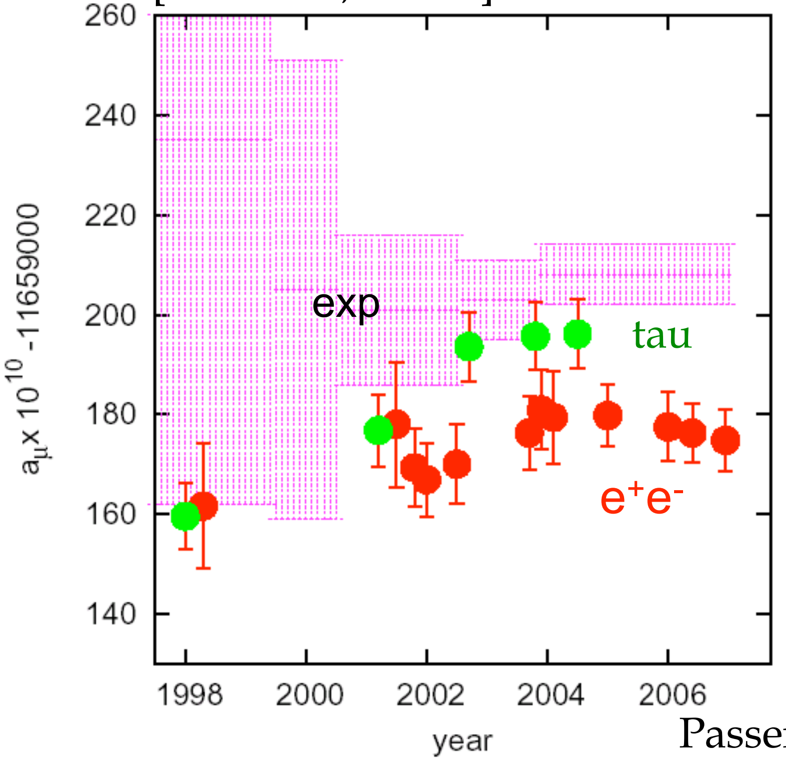
- SM incomplete because of quantum gravity
- String theory the most serious line of attack
- No solid prediction so far at the Fermi scale
- At best some plausible “stringy” scenarios

Will address here the problem more concretely:
combination experiment/theory
(with variable relative weights)

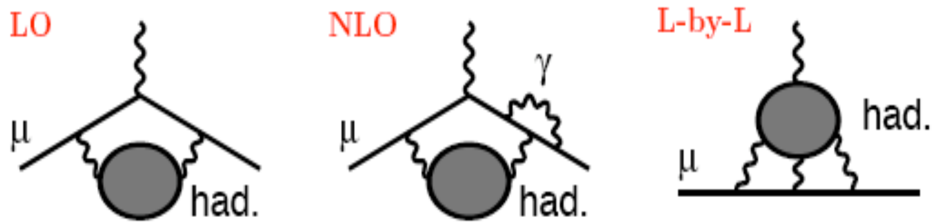
- The muon (g-2) puzzle
- Problems with EW precision tests
- Dark matter
- Naturalness

The muon (g-2) puzzle

[Gambino, EPS07]



dominant TH error: hadronic



Recent progress from data & theory seems to confirm

$\sim 3\sigma$ *discrepancy*

Passera, hep-ph/0702027

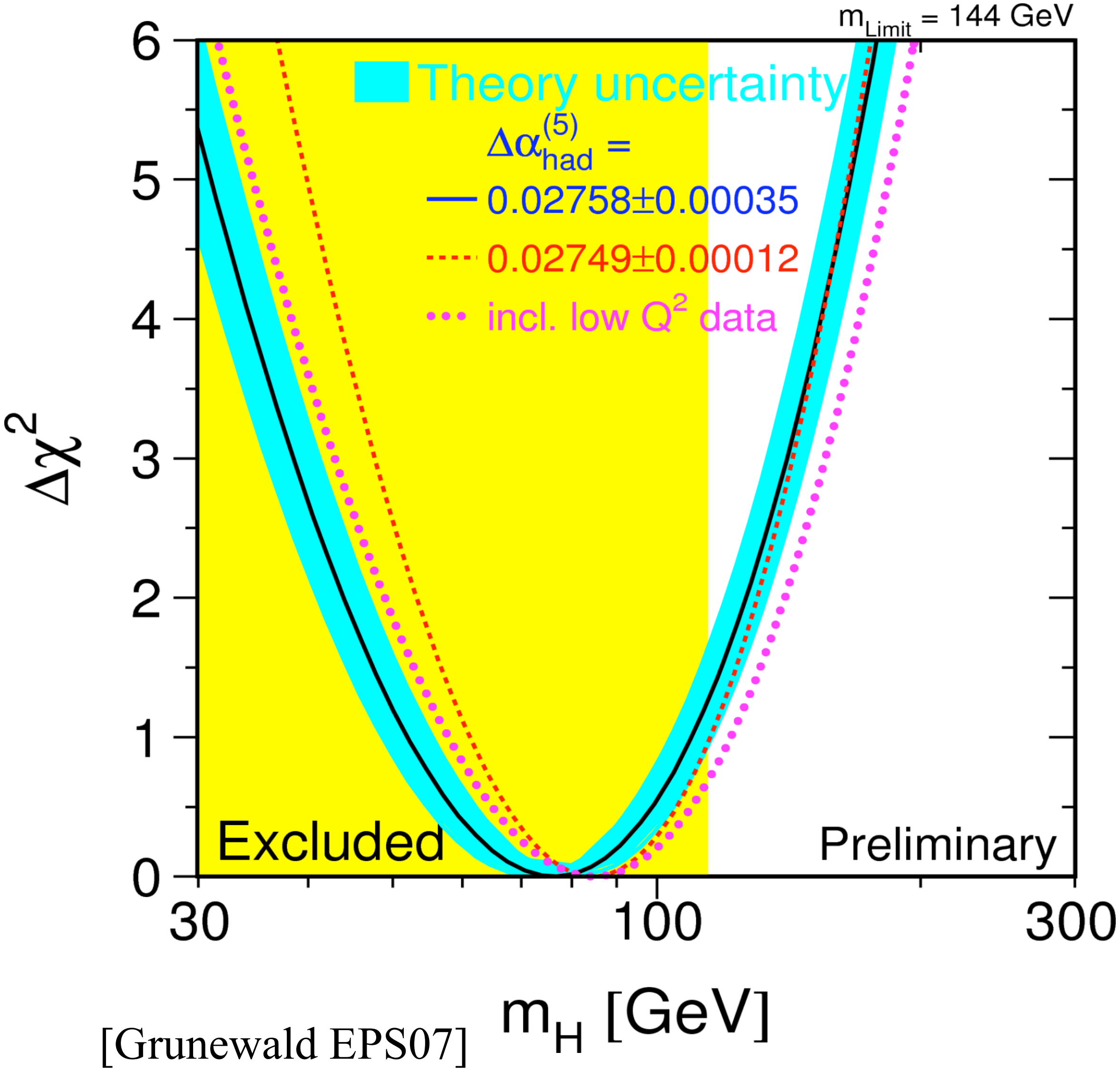
a_μ: Standard Model vs. measurement.

	$a_\mu^{\rm SM} \times 10^{11}$	$\Delta \times 10^{11}$	σ
[68]	116 591 763 (60)	317 (87)	3.7 ⟨3.2⟩
[69]	116 591 748 (61)	332 (88)	3.8 ⟨3.4⟩
[70]	116 591 775 (69)	305 (93)	3.3 ⟨2.8⟩
[71]	116 591 798 (63)	282 (89)	3.2 ⟨2.7⟩
[73]	116 591 961 (70)	119 (95)	1.3 ⟨0.7⟩

LxL: Melnikov Vainshtein

New Physics?
If so, SUSY?
or
Underestimated TH (QCD) systematics?

Direct vs. Indirect Higgs mass bounds



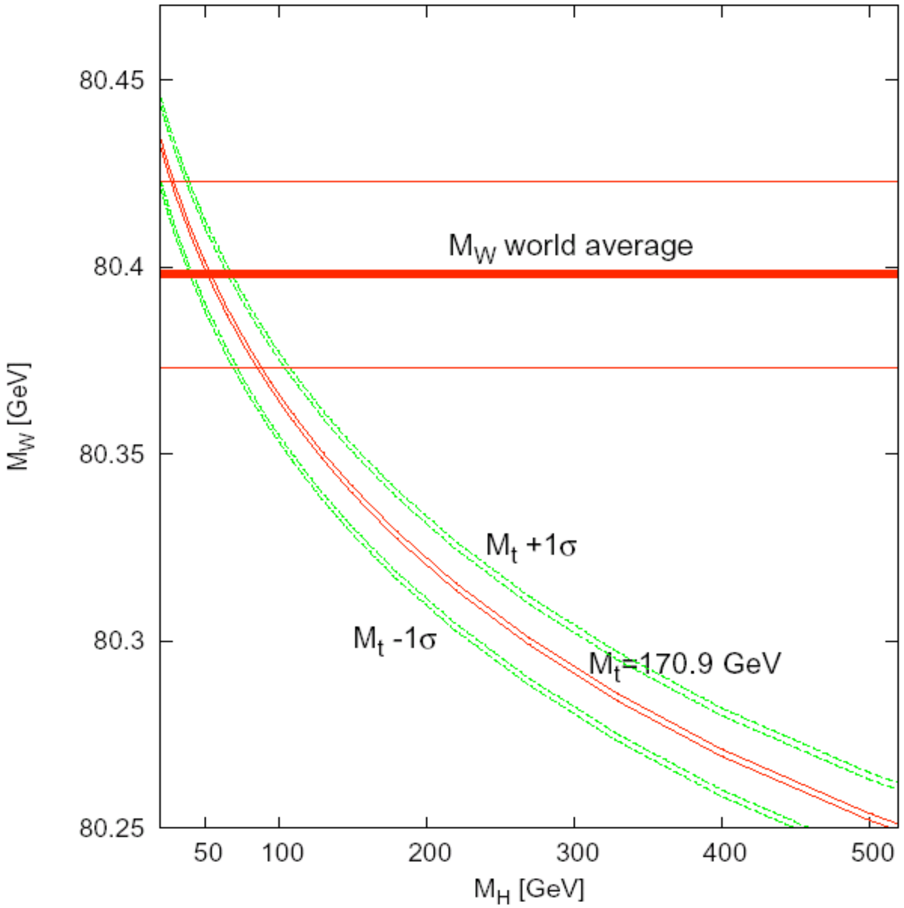
[Grunewald EPS07]

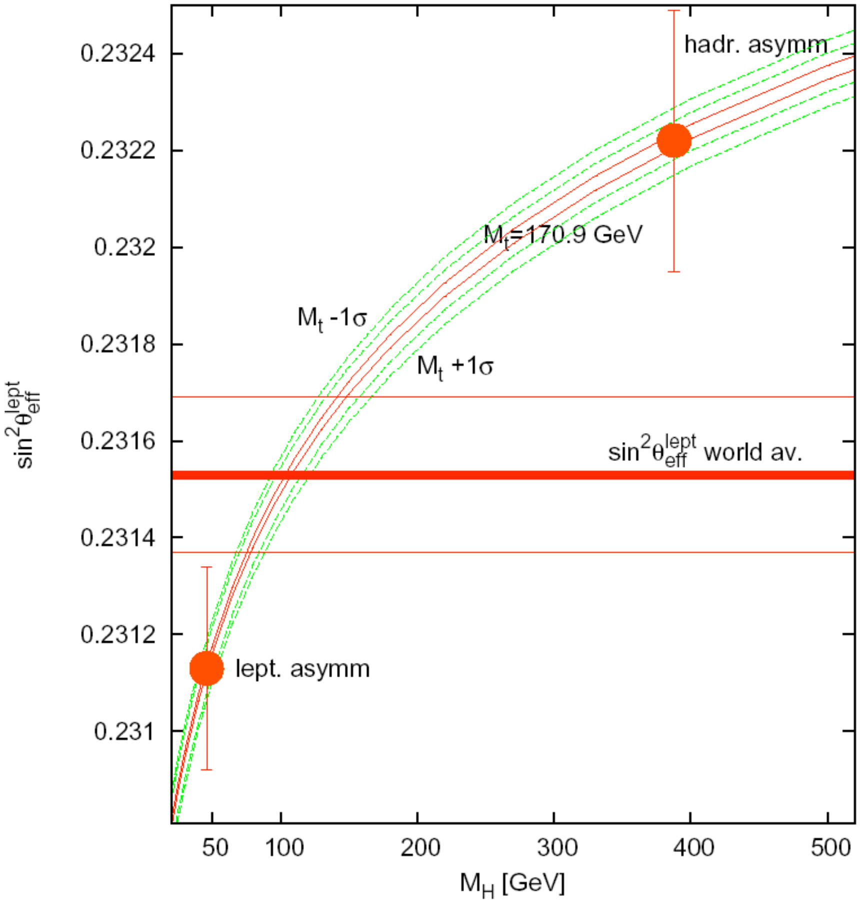
Too small m_H from fit?
Probability of
M_H>114 GeV:
~15%

Nothing dramatic,
but
how does this arise?

What prefers a light Higgs?

[Gambino, EPS07]

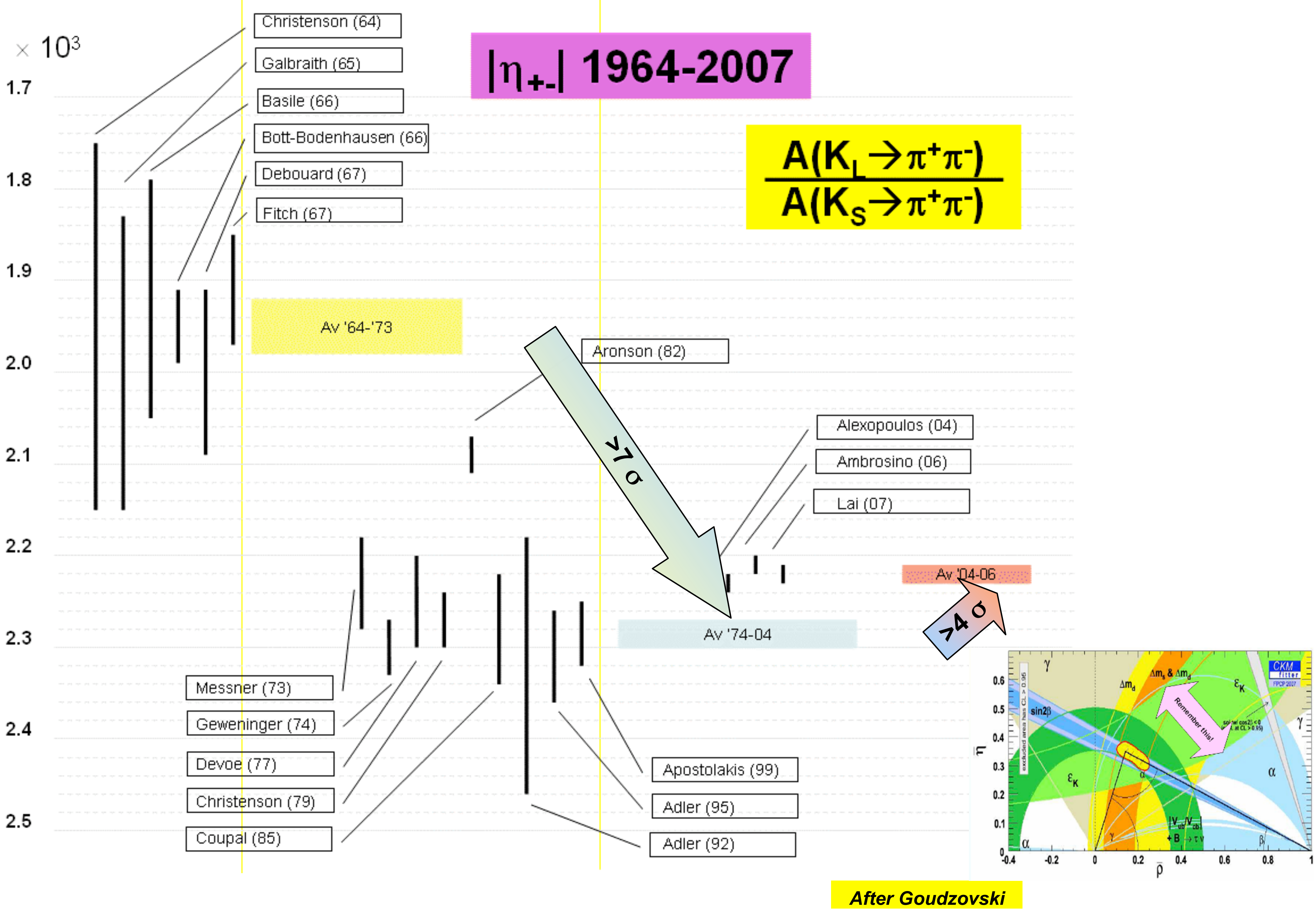




Correlations: $M_{top\downarrow} \rightarrow m_{H\downarrow}$ $M_{W\downarrow} \rightarrow m_{H\uparrow}$ $s2w_{l\downarrow} \rightarrow m_{H\downarrow}$

- M_W points to a light Higgs, with good accuracy
- Some tension in leptonic vs. hadronic asymmetries

Precision measurements are not easy! [Peach, EPS07]



Dark matter

Increasing evidence for dark matter over the years:

- Rotational curves of galaxies
- Cosmic microwave background
- Gravitational lensing

Should account for ~20% of universe energy density

A possible generic dark matter candidate:
WIMP = Weakly Interacting Massive Particle
(not the only acceptable one, see e.g. the axion)

For WIMPs in thermal equilibrium after inflation need

$$\langle \sigma \, v \rangle \sim 1 \, \mathrm{pb}$$

EW-size cross-section for particle with $M=O(10^{1\text{-}3}$ GeV)
Another argument for new physics at the Fermi scale
(once again, quite plausible but not really compelling)

The SM as an effective theory

Λ = effective UV cutoff (not necessarily universal)
= the scale of some (unspecified) new physics

$$L_{eff}^{SM} = \Lambda^4 + \Lambda^2\Phi^2 \qquad (\Lambda^{n>0} \Rightarrow \textit{hierarchy problems!})$$

$$+ (D\Phi)^2 + \overline{\Psi}\, \not{D}\Psi + F\cdot F + F\cdot\widetilde{F} + \overline{\Psi}\Psi\Phi + \Phi^4$$

$$(\textit{controllable}\ \log\Lambda\ \textit{dependence via quantum corrections})$$

$$+\frac{\overline{\Psi}\Psi\Phi^2}{\Lambda} + \frac{\overline{\Psi}\sigma^{\mu\nu}\Psi F_{\mu\nu}}{\Lambda} + \frac{\overline{\Psi}\Psi\overline{\Psi}\Psi}{\Lambda^2} + \frac{\Phi^2 F^{\mu\nu}F_{\mu\nu}}{\Lambda^2} + \ldots$$

$$(\Lambda^{n<0} \Rightarrow \textit{EW tests},\ \ \textit{flavour tests},\ \ \not{B},\ \ \not{L},\ \ \ldots)$$

[triviality and (meta-)stability bounds not very constraining
with present values of the top and Higgs boson masses]

Naturalness ['t Hooft; …]

coefficients small only because of symmetries

electron mass m_e in QED naturally small
chiral symmetry ➔ no linear dependence on cutoff
could have been used in NR theory to predict positron

$$\delta m_e \sim \alpha \Lambda \quad \rightarrow \quad \delta m_e \sim \alpha m_e \log \ldots$$

4-fermion FCNC "box diagram" with 3 light quarks

$$G_F^2 \Lambda^2 \sim G_F^2 m_W^2 \;\; too\ large! \quad \rightarrow \quad G_F^2 m_c^2 \;\; OK$$

Natural solution: GIM mechanism! New physics: charm!

Another example: charged/neutral pion mass difference

Naturalness works, we can take it seriously!

Naturalness problem of the SM

Higgs mass term (weak scale): gauge hierarchy problem

No quantum SM symmetry recovered for $m_H \rightarrow 0$

SM unnatural unless New Physics at the LHC scale

$$\delta m_H^2 \sim -\frac{3\,h_t^2}{8\,\pi^2}\,\Lambda^2 < O(m_H^2) \quad \rightarrow \quad \Lambda < O(600) \times \left(\frac{m_h}{200}\right)\ GeV$$

The lighter the Higgs, the lower the scale of New Physics!

A worse naturalness problem (when gravity is included) is the vacuum energy (10^{-3}eV scale): cosmological constant problem

No natural solution found so far, but not excluded either

Today's puzzle: little hierarchy problem

SM with light Higgs is in precise agreement with data

Naturalness pushes for a low scale of new physics:

$$\Lambda_{NP} < O(500)\ GeV$$

Precision tests push for a high scale of new physics:

$$\mathcal{L}_{eff}^{NP} = \frac{1}{\Lambda_{NP}^2}[c_1(\bar{e}\gamma^\mu e)^2 + c_2 W_{\mu\nu}^I B^{\mu\nu} H^\dagger \sigma^I H + \ldots]$$

$$c_i = O(1) \quad \Rightarrow \quad \Lambda_{NP} > \text{several } TeV$$

Conflict avoided with weakly coupled new physics
affecting low-energy observables only via loops
(and decoupled from flavour-violating operators)

$$c_i \sim \frac{\alpha}{2\pi} \quad and \quad \Lambda_{NP} \sim O(500)\ GeV$$

2. Supersymmetry: if so, which incarnation?

Fundamental motivations for supersymmetry:

- Is most general symmetry of local relativistic Q.F.T.
- Linearly realized, it gives a rationale for elementary scalars, living in N=1 multiplets with chiral fermions
- Local version, supergravity, fits naturally in strings

However, in any realistic model it must be broken [O(10^2 GeV) lower bounds on charged sparticles]

none of above arguments points to LHC scale as preferred scale for superparticle masses

Why at the LHC scale?

SUSY can solve the naturalness problem
thanks to its special renormalization properties

In (many) supersymmetric extensions of the SM:

[qualitative here,
more details below]

$$\delta m_H^2 \sim -\frac{3\, h_t^2}{8\pi^2} m_{\tilde{t}}^2 \log \frac{\Lambda^2}{m_{\tilde{t}}^2}$$

Power-dependence on SUSY-breaking masses
only mild logarithmic dependence on cutoff

Naturalness preserved up to very high scales
if superparticle masses are at the weak scale

The prototype: MSSM [Fayet; Dimopoulos-Georgi; …]

(more on possible variations later)

- Gauge group SU(3) x SU(2) x U(1)

  gauginos $(\widetilde{g},\ \widetilde{W},\widetilde{B})$

- 3 SM generations, 2 Higgs doublets

  squarks $(\widetilde{q})$, sleptons $(\widetilde{l})$, higgsinos $(\widetilde{H}_{1,2})$

- R-parity conserving superpotential

$$W = Q h^U U^c H_2 + Q h^D D^c H_1 + L h^E E^c H_1 + \mu H_1 H_2$$

- Explicit soft supersymmetry breaking

$$-\mathcal{L}_{soft} = \varphi^\dagger m^2 \varphi + \left[(1/2) M_A \lambda_A \lambda_A + m_3^2 H_1 H_2 + \widetilde{q} A^U \widetilde{u}^c H_2 + \widetilde{q} A^D \widetilde{d}^c H_1 + \widetilde{l} A^E \widetilde{e}^c H_1 + h.c. \right]$$

(the source of many troubles: # parameters, flavour)

[see talks on Tuesday for more details and LHC phenomenology]

Two important bonuses

- Effective unification of gauge coupling constants (at a scale $M_U \sim 2\times10^{16}$ GeV not very far from M_P)
- An obvious candidate for dark matter, the LSP typically lightest neutralino (gaugino/higgsino)

Two features so appealing that some proposed to keep them without solving the hierarchy problem, sending all the scalars but SM Higgs to very high mass scales:

SPLIT SUPERSYMMETRY

[ArkaniHamed-Dimopoulos, Giudice-Romanino,…]

A limiting case of the MSSM worth exploring

(for those who feel ready to throw naturalness away)

Advantage: no flavour problems

LHC signature: long-lived gluino

MSSM post-LEP tension

concrete MSSM realization poses some tuning problems, especially when extrapolating the MSSM to high scales

$$m_Z^2 \sim -2m_H^2 = -2\mu^2 + \frac{3\lambda_t^2}{2\pi^2} m_{\tilde{t}}^2 \log\frac{M_P}{m_{\tilde{t}}} + \ldots \sim -2\mu^2 + O(1) m_{\tilde{t}}^2 + \ldots$$

naturalness suggests light SUSY: $m_{\tilde{t}} \sim \mu \sim m_Z$

Things are made worse by the upper bound on the Higgs mass
[Ellis, Ridolfi, FZ; Okada,Yamaguchi,Yanagida; Haber,Hempfling; …]

$$m_h^2 < m_Z^2 + m_t^2 \frac{3\lambda_t^2}{2\pi^2} \log\frac{m_{\tilde{t}}}{m_t} \;\; \& \;\; m_h > 114.4\, GeV \quad \Rightarrow \quad m_{\tilde{t}} > 500\text{-}1000\, GeV$$

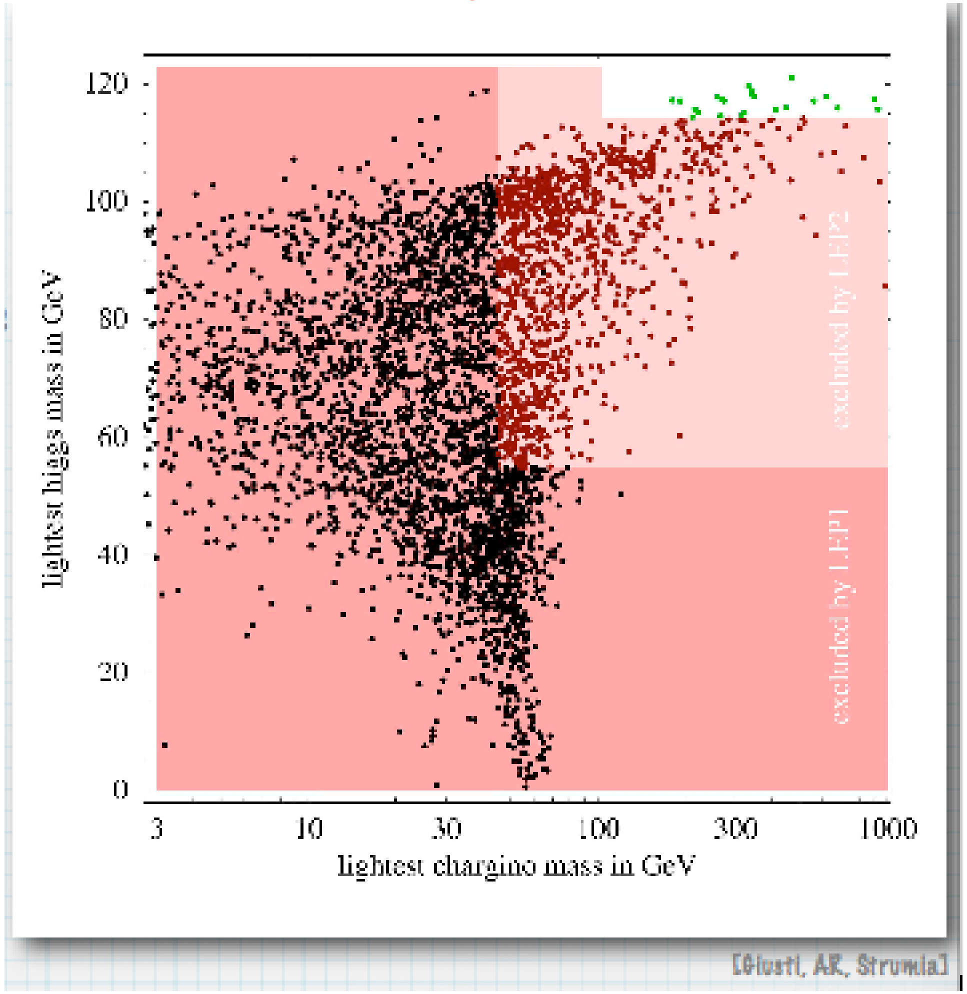
O(few%) fine-tuning required without further theoretical input

There are ways to do better, e.g. adding a singlet (NMSSM), (complicating the analysis of Higgs and neutralino sectors)

An empirical measure of fine-tuning

After LEP-2 ➘

lightest Higgs mass (GeV)



⬅ After LEP-1

lightest chargino mass (GeV)

Beyond the MSSM

Taking the MSSM at face value, its appealing properties

- Solution of "big" hierarchy problem
- Effective unification of gauge couplings
- Natural candidate for dark matter

come with a number of unanswered questions

- Special flavour structure of soft terms
- Relative scale of different soft terms
- Absolute scale of soft terms
- Little hierarchy problem
- Vacuum energy problem

To answer, study spontaneous breaking in the microscopic theory (for the first two issues, enough to know mediation mechanism from the susy-breaking sector to the MSSM)

Models of SUSY breaking

Innumerable models, none of them fully convincing

Irrespectively of models, two broad scenarios
for the effective theory valid at the LHC scale

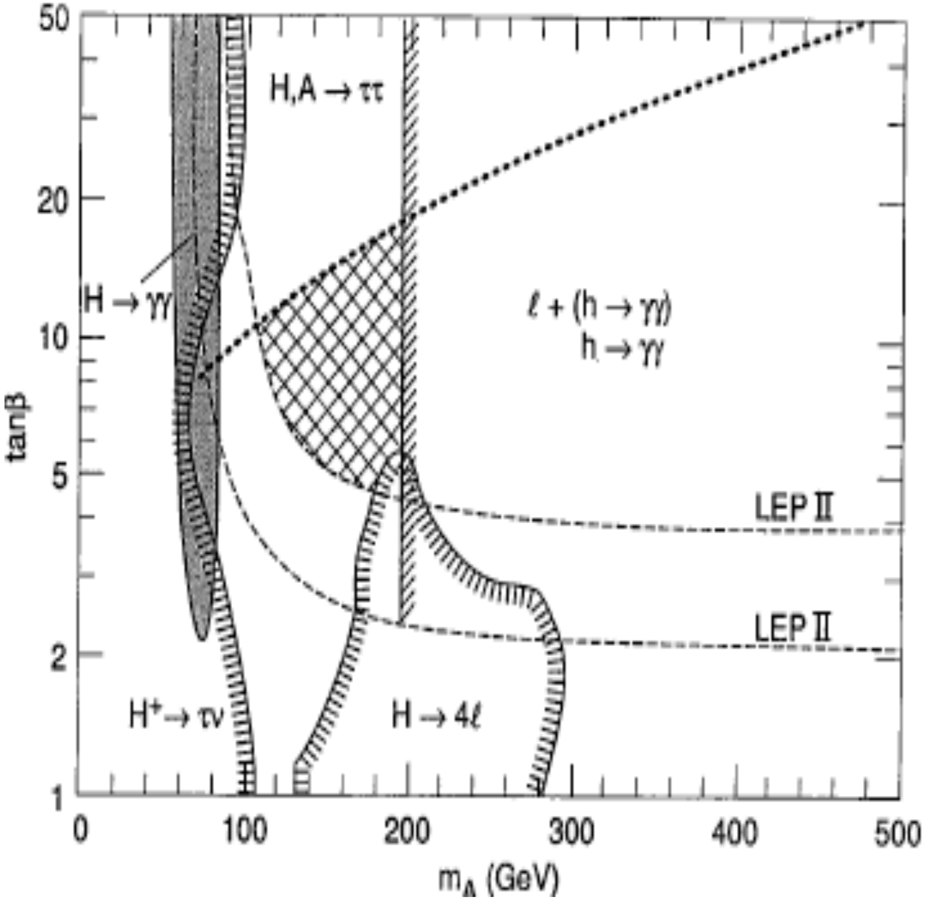
- o Heavy gravitino (weak scale mass)
- • MSSM + soft terms
- • MSSM LSP stable (WIMP dark matter)

- o Light gravitino (mass < keV)
- • MSSM + goldstino multiplet
- • MSSM LSP ➔ particle + (goldstino)

What else is needed for LHC phenomenology?
(too) many mass parameters in terms of a few
benchmark models or even benchmark points
to be taken for what they are worth of

An example: MSSM Higgs bosons at the LHC

An ultra-simplified initial study
(and a personal memory)



[Z.Kunszt & FZ, LHC workshop, Aachen 1990]

Huge amount of work by now, it would take very long to describe it

A very complicated problem:
- Many parameters
- Many new particles around

(even in "constrained" MSSM)

SUSY-Higgs searches intertwined with SUSY-particle searches

"Benchmark scenarios" used so far to optimize detectors and analyses

But data will drive the analyses as long as they come and are progressively understood

3. Other motivated new physics and exotics

What if naturalness fails for the weak scale?
(as it may fail for the vacuum energy scale)
A logical possibility, although not my favourite

Light SM Higgs boson and nothing else at the LHC
(called by some supersplit supersymmetry)

- A triumph for the SM
- A triumph for the Experiments
- A failure for many theorists

Before such possibility, rather consider solutions to the SM naturalness problem, alternative/complementary to SUSY, they all predict testable new physics at the LHC scale
None scores better than SUSY yet, but they are useful alternative benchmarks in a needed broad approach

Higgs as pseudo-Goldstone boson (Little Higgs)

[Georgi-Pais; ArkaniHamed-Cohen-Georgi; …]

- Higgs mass protected by a global shift symmetry (GB)
- Broken explicitly (PGB) for quartic and Yukawa couplings
- Collective symmetry breaking ➔ mass only at two loops
- Problems with precision tests (T-parity+complications)

Minimal natural models?

[Barbieri, Hall, et al …]

Minimalistic approach to little hierarchy problem:
raise the natural cutoff scale of (MS)SM by raising the Higgs mass, with another ingredient to pass EWPT

Extra dimensions

Naturally predicted by string theory, but no prediction about their size (mass scale m_{KK} of first KK excitations)

Relevant at LHC for $m_{KK} \sim$ TeV (or less: ADD models)

Can be combined with susy broken in the compactification

Dynamical problem: understand origin & stability of m_{KK}

Richer possibilities if warped [Randall-Sundrum] ("holography")

Some variants:

- Higgsless models [Csaki, Grojean, Murayama, Pilo, Terning;…]: delay unitarity bound on m_h via KK states; problems with EWPT
- Gauge-Higgs unification [Manton; …]: m_H protected by D>4 gauge symmetry; problems with EWPT, m_h, m_{KK}, flavour

A strongly interacting EW-breaking sector?

Higgs as a bound state of new strong interactions

Traditional implementation (technicolor) strongly disfavoured by precision tests (and our limited understanding of non-perturbative dynamics)

Now being revived with some modern tools:
[Georgi-Kaplan 84; Agashe, Contino, Pomarol, Sundrum, …]
light Higgs as pseudo-Goldstone boson
holographic gauge/gravity correspondence

Warped 5D gravity with SM in bulk (Higgs on brane)
⇔
Technicolor-like theory in 4D

Promising results albeit no fully satisfactory model:
technicolor strikes back?

Hiding the Higgs at the LHC?

One can imagine "nasty" new physics, compatible with existing constraints even if not strongly motivated, that could make life more difficult at the LHC

Simplest example:

[Wise et al, Wilczek et al, Grossman et al, …]

one real singlet scalar (or more) coupled to the SM only via a quartic mixing term in the Higgs potential

dilution of the SM Higgs signals via mixing and/or decays into invisible channels (a hidden sector)

The conterpart of possible "lucky" new physics, e.g. a 4th generation increasing the Higgs signal

"Subtle is the Lord, but not malicious…"

4. (Temporary) conclusions and outlook

- Data alone favour a light SM Higgs and no new physics at LHC scale, but not in a completely clear-cut way

- Naturalness can still be used as strong guiding principle
- It unambiguously predicts new physics at the LHC scale
- Precision tests: new physics must have special properties

- Supersymmetry still the most plausible candidate, but we would have expected it to show up already!
- We may be missing important aspects of susy breaking

- Healthy to have alternatives for new physics at the LHC

conclusions (continued)

Today, no model of new physics fully satisfactory
(naturalness vs. precision tests, and more)

- At the SpS (discovery of the W and Z bosons)
all their relevant properties were known before

- At the Tevatron (discovery of the top quark)
there was some uncertainty only on the mass

- At the LHC, we know that something must be there,
but (theorists) are still unable to tell you exactly what

LHC experimentalists will be soon in a privileged position:
may take the lead in defining the new fundamental theory!