An alternative road to LHC physics: Improved naturalness with a heavy Higgs

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Preliminary considerations

The Inert Doublet Model

Particle Physics in one page

$$\mathcal{L}_{\sim SM} = -\frac{1}{4}F^a_{\mu\nu}F^{a\,\mu\nu} + i\bar{\psi}D\psi$$ *The gauge sector* (1)

$$+\psi_i\lambda_{ij}\psi_j h + h.c.$$ *The flavor sector* (2)

$$+|D_\mu h|^2 - V(h)$$ *The EWSB sector* (3)

$$+N_i M_{ij} N_j$$ *The ν-mass sector (if Majorana)* (4)

(1) : best tested quantitatively

(2) + (4) : main developments of last 5 years, different in nature, both highly significant

(3): the most elusive, so far

What will replace current Page 1?

1. The best theoretical candidate:

Unification + supersymmetry

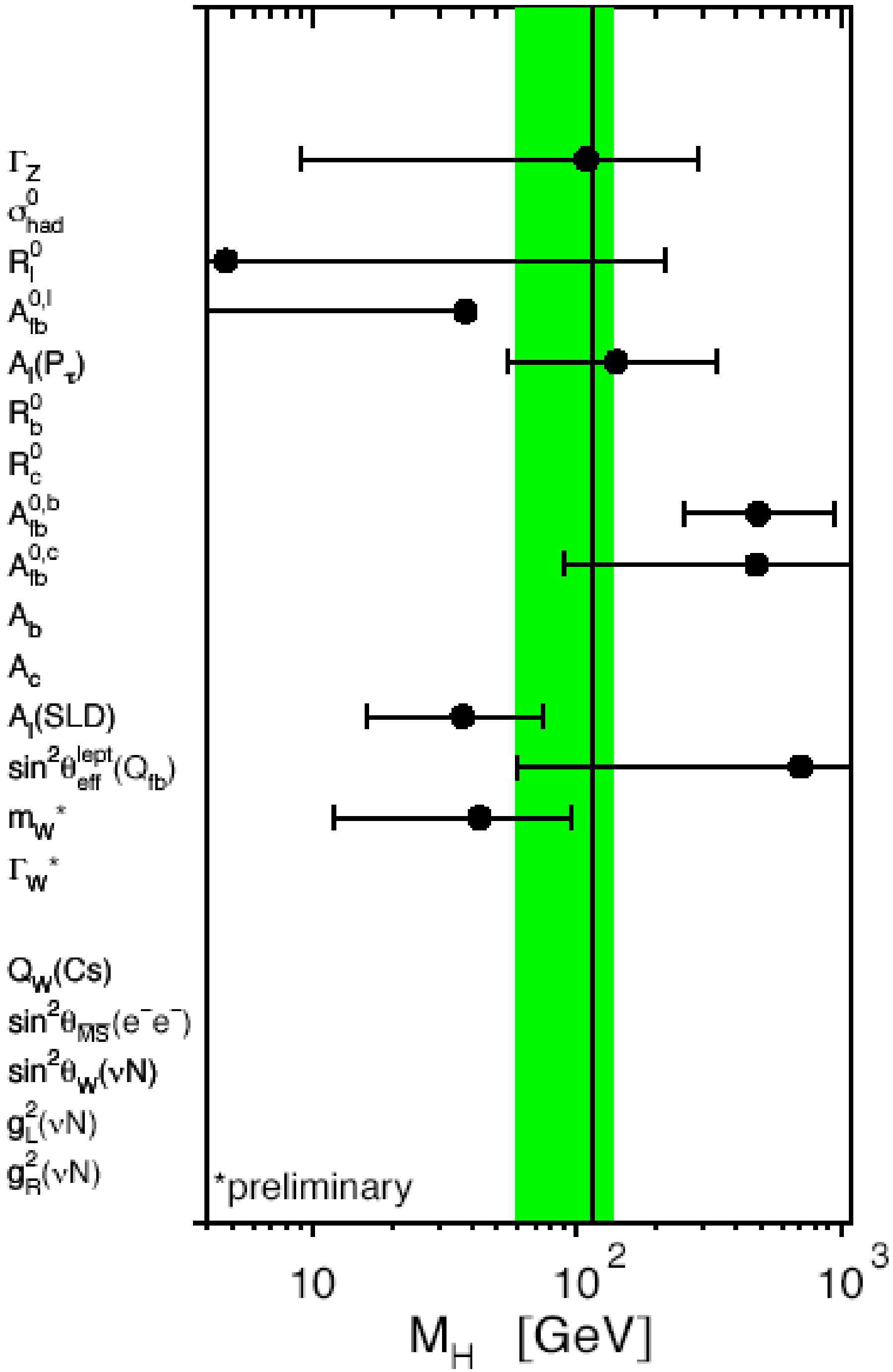
(as developed in the 70's/80's)

Pros	Contras
gauge unification	No susy particles
size of neu-masses	No flavour effects
	No proton decay
	No light Higgs

so far!?

2. Experiments should tell, with LHC playing not the least role

The physics of Electroweak breaking



A⇒ a light Higgs

B from the top loop correction to the Higgs potential

$$m_h^2 = \frac{3\lambda_t^2}{4\pi^2}\Lambda_t^2 \pm m_0^2$$

$$\Lambda_t \approx 400GeV\left(\frac{m_h}{115GeV}\right)D_t^{1/2}$$

What is the related, apparently necessary, new physics?

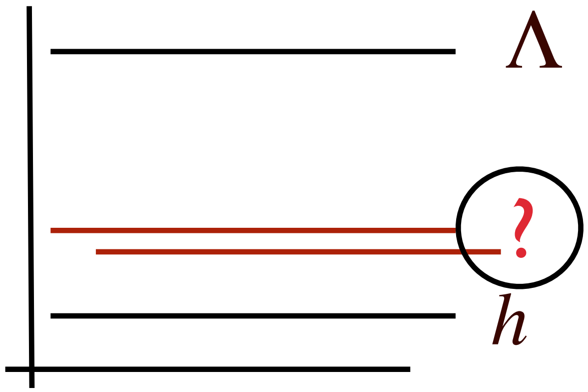
How can Λ_t be so low without disturbing agreement with exps?

the "LEP paradox"

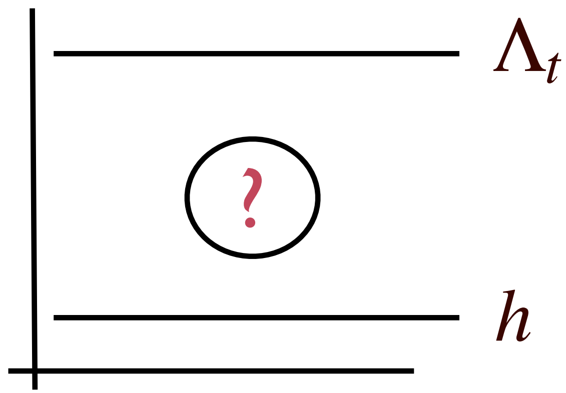
the "little hierarchy problem"

2 (or 3) different ways to go (crucially different for the LHC)

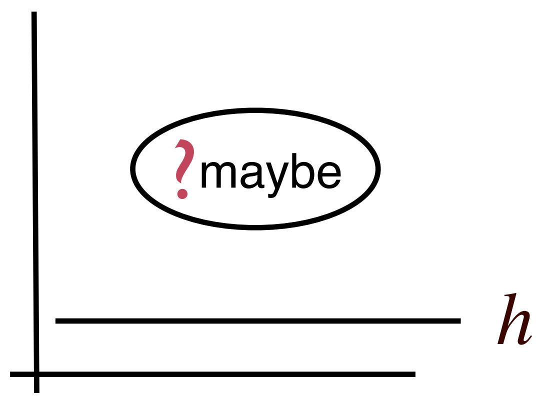
What cancels the top-loop divergence?



Can one raise Λ_t ?



The “landscape”



The Standard Model again

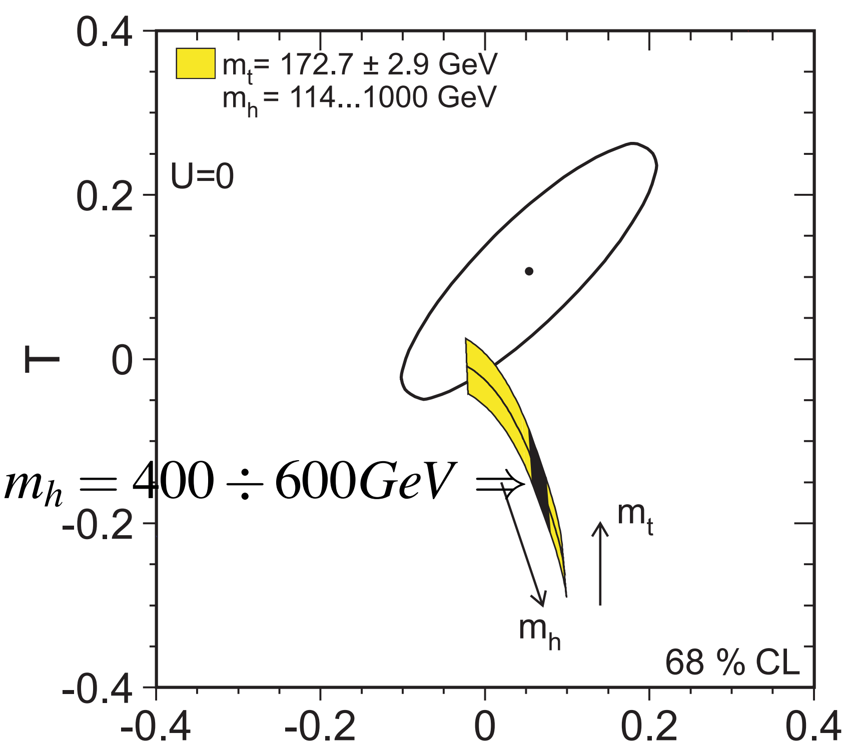
1. Naturalness

$$\delta m_h^2 = \alpha_t \Lambda_t^2 + \alpha_g \Lambda_g^2 + \alpha_h \Lambda_h^2 \quad \Rightarrow \quad \begin{array}{l} \Lambda_t \approx 3.5\, m_h \\ \Lambda_g \approx 9\, m_h > \Lambda_t \\ \Lambda_h \approx 1.3 \text{ TeV} \end{array}$$

2. Perturbativity

m_h,GeV	Λ_P,TeV	Λ_L,TeV
400	2.4	80
500	1.8	16
600	1.6	7.5

3. EWPT



$m_h = 400 \div 600 GeV \Rightarrow$

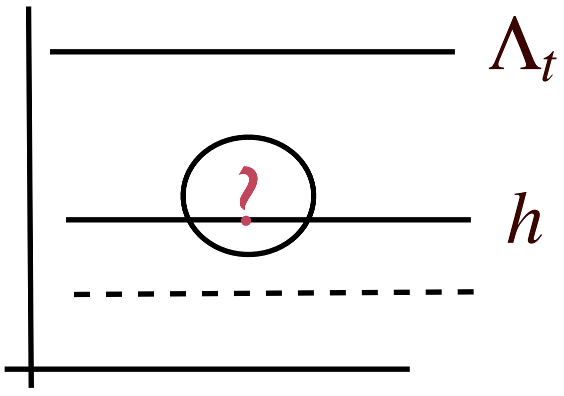
A simple (provisional) conclusion

A Higgs boson in the mass range of 400-600 GeV, if it were consistent with the EWPT, would allow to raise the cutoff to ~1.5 TeV without any cancellation and remaining fully perturbative

Can one raise Λ_t ?

↓

What allows to raise m_h ?



The Inert Doublet Model

Consider the most general 2H doublet model invariant under $H_2 \Rightarrow -H_2$ to get natural flavour conservation

(i.e., only H_1 couples to matter)

$$V = \mu_1^2|H_1|^2 + \mu_2^2|H_2|^2 + \lambda_1|H_1|^4 + \lambda_2|H_2|^4 + \lambda_3|H_1|^2|H_2|^2$$

$$+\lambda_4|H_1^\dagger H_2|^2 + \frac{\lambda_5}{2}[(H_1^\dagger H_2)^2 + \text{h.c.}]$$

$\lambda_4,\ \lambda_5 \Rightarrow$ custodial symmetry

$\lambda_5 \Rightarrow$ PQ symmetry

Take $\mu_1^2 < 0,\ \mu_2^2 > 0$ so that

$$H_1 = \begin{pmatrix} \phi^+ \\ v + (h + i\chi)/\sqrt{2} \end{pmatrix}, \qquad H_2 = \begin{pmatrix} H^+ \\ (S + iA)/\sqrt{2} \end{pmatrix}$$

The Inert Doublet Model (continued)

Parameter space:

$\mu_1^2,\ \lambda_1 \ \Rightarrow v(M_Z),\ m_h$ (in the usual way)

λ_2 (not relevant to the spectrum)

$\mu_2^2,\ \lambda_{3,4,5} \ \Rightarrow m_L, m_{NL}, m_H;\ \lambda_L$

$$m_H^2 = \mu_2^2 + \lambda_3 v^2$$

$$m_S^2 = \mu_2^2 + (\lambda_3 + \lambda_4 + \lambda_5) v^2$$

$$m_A^2 = \mu_2^2 + (\lambda_3 + \lambda_4 - \lambda_5) v^2$$

custodial symm. limit: $m_H = m_S = m_A$

PQ symmetry limit: $m_S = m_A$

absolute minimum:

$$\lambda_{1,2} > 0 \qquad \lambda_3, \lambda_L \equiv \lambda_3 + \lambda_4 - |\lambda_5| > -2(\lambda_1 \lambda_2)^{1/2}$$

Naturalness, perturbativity, EWPT in the IDM

1. Naturalness

$$\delta m_h^2 = \alpha_t \Lambda_t^2 + \alpha_g \Lambda_g^2 + \alpha_{11} \Lambda_{H_1}^2 + \alpha_{12} \Lambda_{H_2}^2$$
$$\delta \mu_2^2 = -\frac{1}{2} \left(\alpha_g \Lambda_g^2 + \alpha_{22} \Lambda_{H_2}^2 + \alpha_{21} \Lambda_{H_1}^2 \right)$$

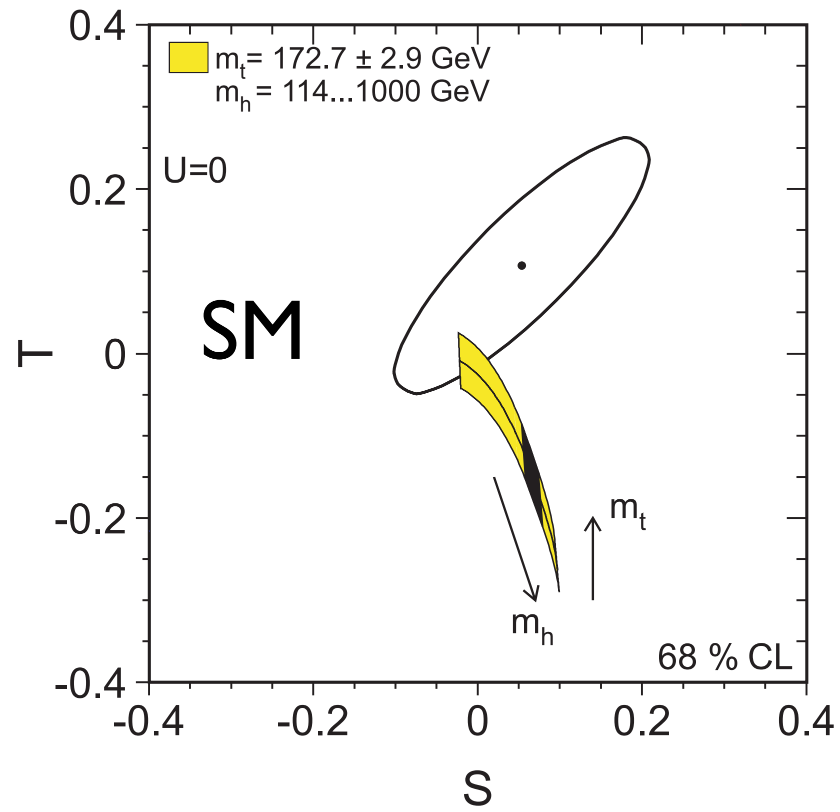
2. Perturbativity

$$16\pi^2 \frac{d\lambda_i}{d \log \Lambda} = \beta_i(\lambda)$$

3. EWPT

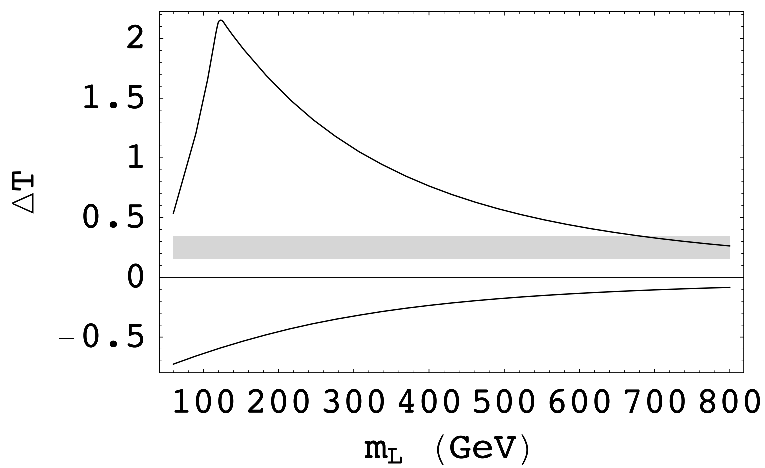
$$T_{IDM} = T_{SM} + \Delta T$$

$$S_{IDM} = S_{SM} + \Delta S$$



ΔS negligible

$$\Delta T \approx \frac{1}{24\pi^2 \alpha v^2}(m_H - m_A)(m_H - m_S)$$



easily constrained by custodial and PQ symmetries

In the Standard Model: $m_h = 91^{+45}_{-32}\ GeV$

In the IDM: $m_h = 400 \div 600\ GeV$

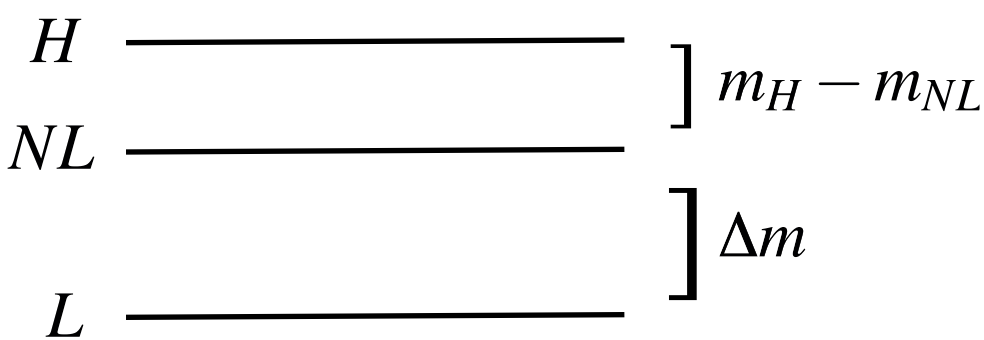
$(m_H - m_S)(m_H - m_A) = M^2,\ M = 120^{+20}_{-30}$ GeV

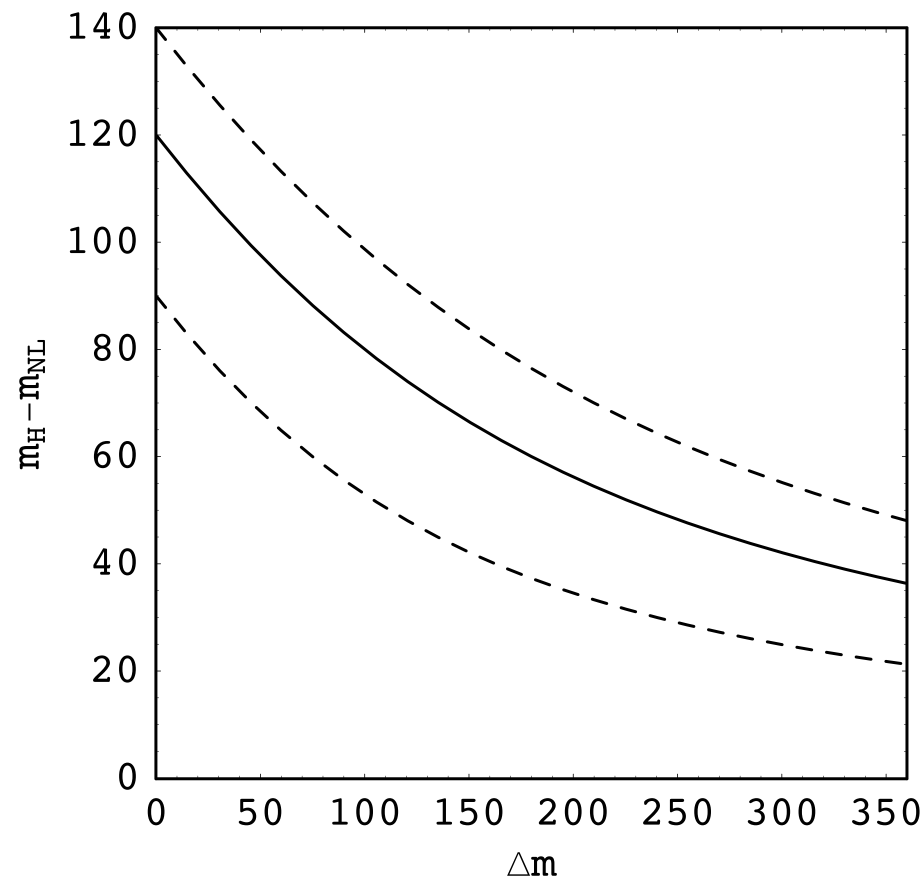
The IDM is natural and perturbative up to ~1.5 TeV (instead of the SM only up to ~ 400 GeV)

with

$$m_h = 400 \div 600\ GeV$$

and

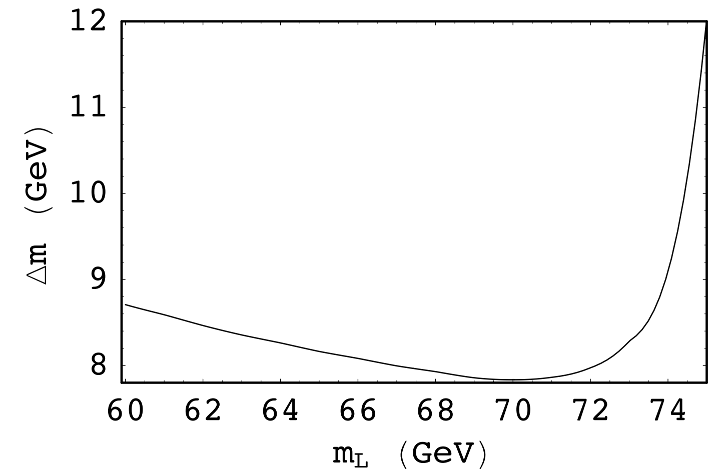




A Dark Matter candidate

Unbroken $H_2 \Rightarrow -H_2$
(for natural flavour conservation) $\Rightarrow$ Inert scalars always in pair
Stable lightest inert scalar

To get the observed Ω_m
need co-annihilation of S, A into light fermions as dominant process $\Rightarrow$



$\Rightarrow$ Shouldn't one have seen S and A at LEP2 via

$$e^+e^- \longrightarrow A + S \longrightarrow (Z^* + S) + S$$

$\Rightarrow$ What about direct DM detection

$$\sigma_h(\mathrm{L}p \to \mathrm{L}p) \approx 2 \times 10^{-9}\ \mathrm{pb} \left(\frac{\lambda_L}{0.5}\right)^2 \left(\frac{70\,\mathrm{GeV}}{m_L}\right)^2 \left(\frac{500\,\mathrm{GeV}}{m_h}\right)^4$$

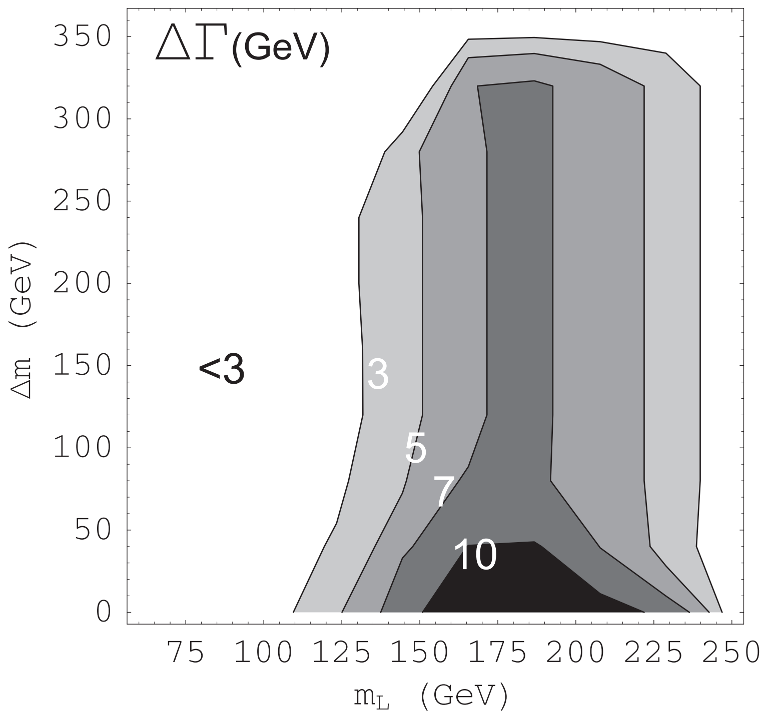
Collider Signals

1. $m_h = 400 \div 600\ GeV$

A standard Higgs boson?

$$h \to SS, AA, H^+H^-$$

$$\Gamma_h = 68\ GeV \quad \text{at} \quad m_h = 500\ GeV$$



2. $pp \to W^* \to HA$ or HS

$$H \to AW \text{ or } SW$$
$$A \to SZ^{(*)}$$

for the DM parameters, looking for 3 charged leptons

$\sigma_{\text{signal}} \approx 3.5$ fb $\qquad \sigma_{\text{bg}} \approx 20$ fb

Conclusions

The SM as an effective low energy theory

⇒ Why the perturbative Higgs among its degrees of freedom?

⇒ Where is the cut-off? $\Lambda_{SM} \approx 400\ GeV\,(\frac{m_h}{115 GeV})$

Qualitatively: supersymmetry, ...

Quantitatively: can we be fooled by the EWPT?

(more modest in scope but physically motivated)

E.g.: The IDM as a simple way to a perturbative and fully natural description of EW physics up to 1.5 TeV

Alternatives? UV completion?

"Beyond the SM" Physics defined

(in absence of a better name)

(NOT a naively reductionistic view,
a definition of hierarchies in physics,
a research program)

Everything that fits in Page 1
by coherent addition or emendation,
meeting the same or better standards of synthesis
and empirical adequacy

The central question:
What will replace current Page 1?