Models as existence proofs, speculations or... peaces of physical reality

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An example of what could happen, based on:

An “ultra-bottom-up” hypothesis

2 concrete realizations (why not a single one?)

The idea

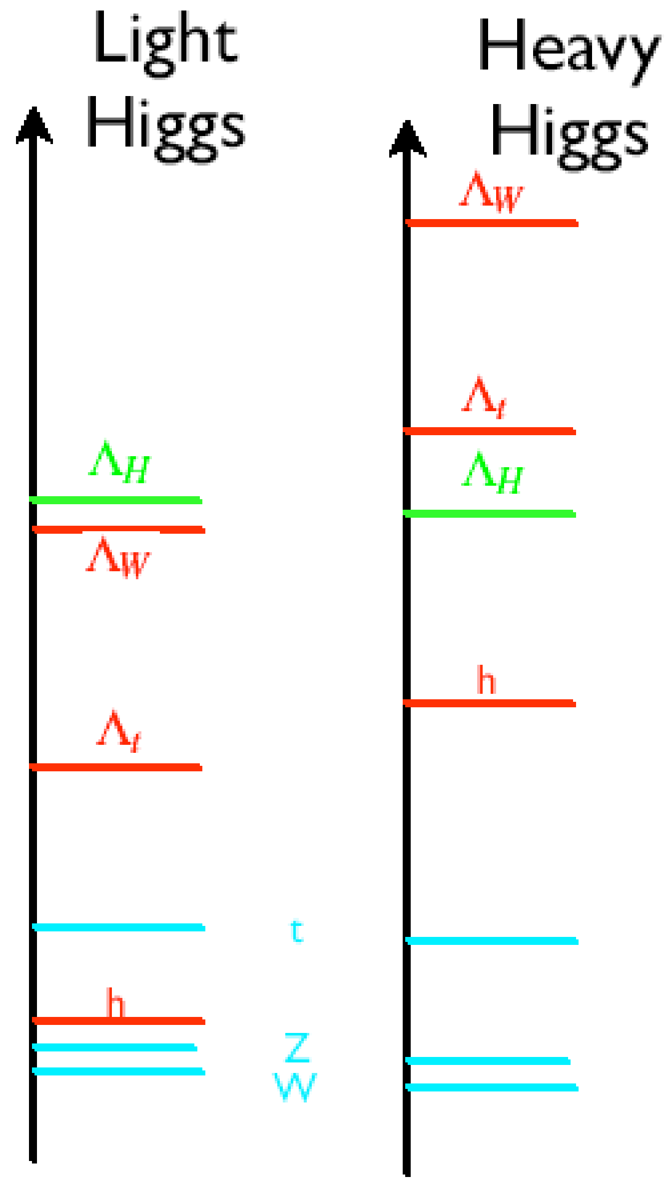
RB, Hall

Seek simple Higgs sector that:

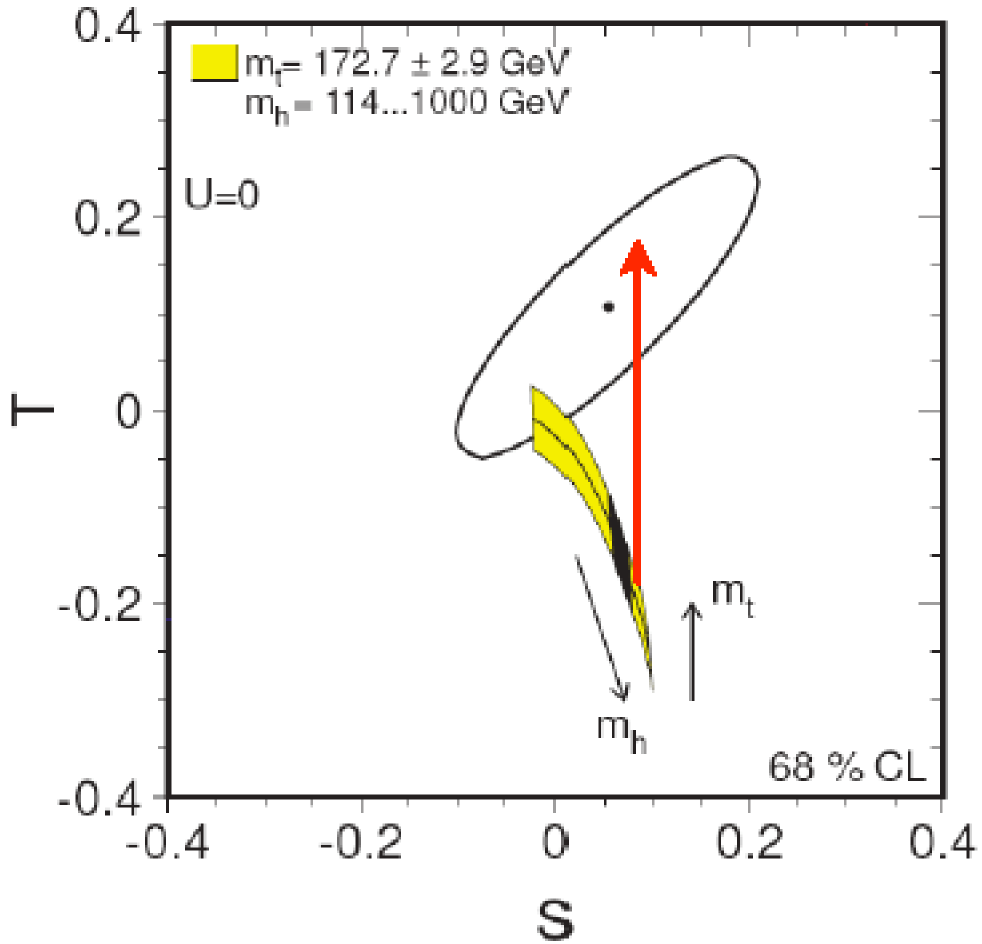
1. Agrees with all data (EWPT)
2. Is fully natural up to 1.5 TeV

   (+ maybe something else)

A modest "ultra-bottom-up" approach, with crucial consequences for LHC



A Heavy SM Higgs and the EWPT



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

A heavy Higgs

$m_h = 400 \div 600\ GeV$

+ a positive ΔT

Origin of ΔT ?? (Peskin, Wells and many others)

prefer models that populate the 1-2σ ellipse in most of parameter space. Are there any?

2 HDM in an alternative phase

RB, Hall, Rychkov

IDM

$$V = -\mu_1^2 H_1^\dagger H_1 + \mu_2^2 H_2^\dagger H_2 + \text{ quartics}$$

For natural flavor conservation impose

$H_2 \to -H_2$

Only H_1 couples to matter

$$H_2 = \begin{pmatrix} H^+ \\ H + iA \end{pmatrix}$$

is "inert"

$v_2 = 0$

This is not the usual phase in the fine-tuned limit of $v_2 \ll v_1$

1. $H_1 = \begin{pmatrix} 0 \\ v + h \end{pmatrix}$ similar to SM Higgs
2. H_2 mass splittings lead to $\Delta T > 0$ *controlled by approximate* $SU(2)_V$
3. $H_2 \to -H_2$ is exact, and not spontaneously broken

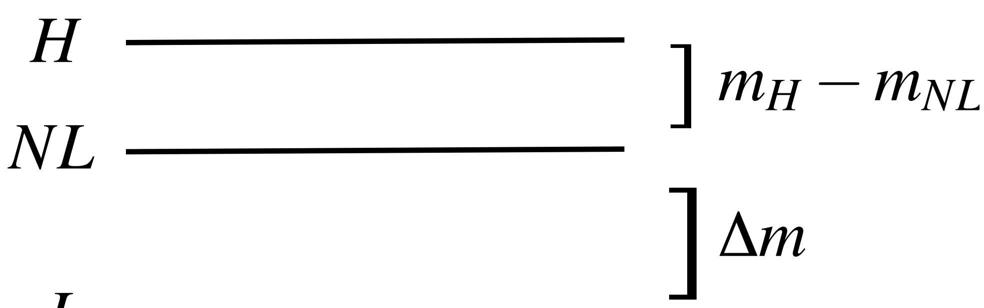
Lightest Inert Particle (LIP) is stable and could be Dark Matter

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

with

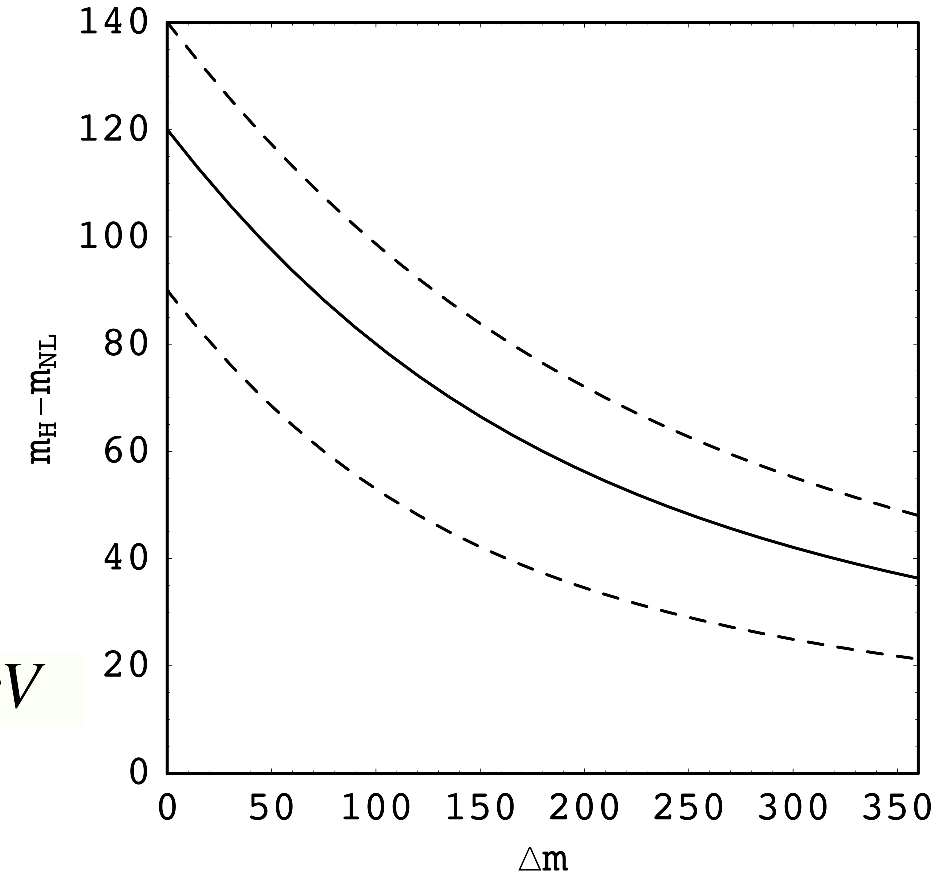
$$m_h = 400 \div 600\ GeV$$

and



and an average mass

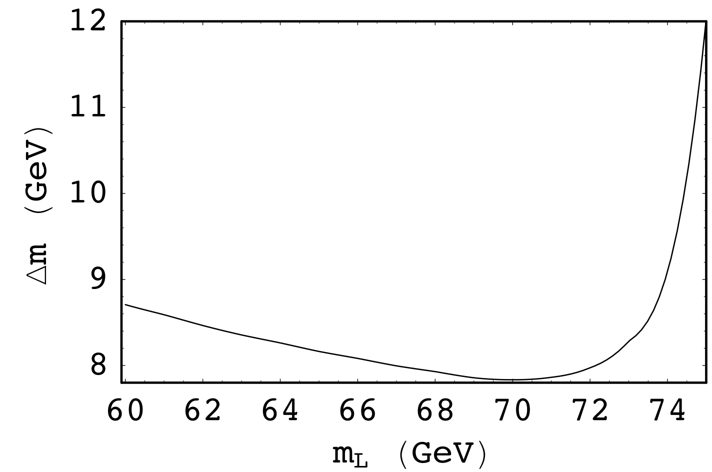
$$m_{av}(m_L, m_{NL}, m_H) \approx 100\ GeV \div 1\ TeV$$



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

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

$\Rightarrow$ What about direct DM detection ?

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

Can one do better than $\Lambda_{nat} \approx 1.5\ TeV$?

("UV completion")

2H doublets ⇔ Supersymmetry
... but without a light Higgs boson!

How??

In the most straightforward way: Add a coupling λ
through $\Delta f = \lambda S H_1 H_2$
with λ only constrained by perturbativity up to 10-12 TeV

⇒ λSUSY ≡ NMSSM with
$\lambda_{low\ energy} \leq 2$
dominating over all other couplings

RB, Hall, Nomura, Rychkov

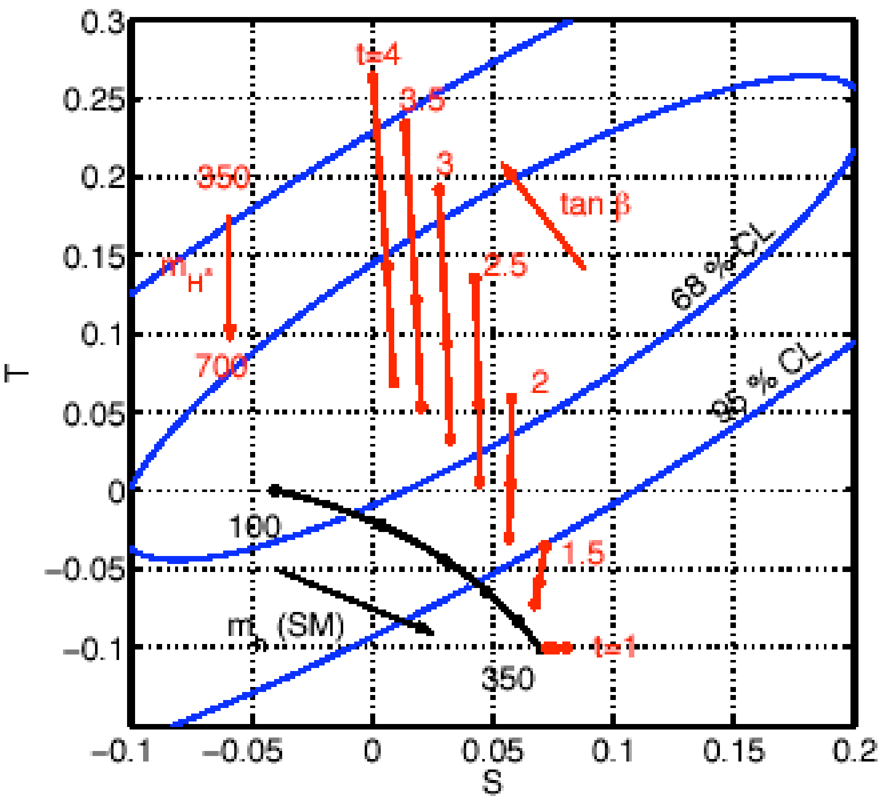
Not consistent with gauge unification?
An open question, depending on the physics above 10-12 TeV

See, e.g., Harnik et al, Gripaios and West

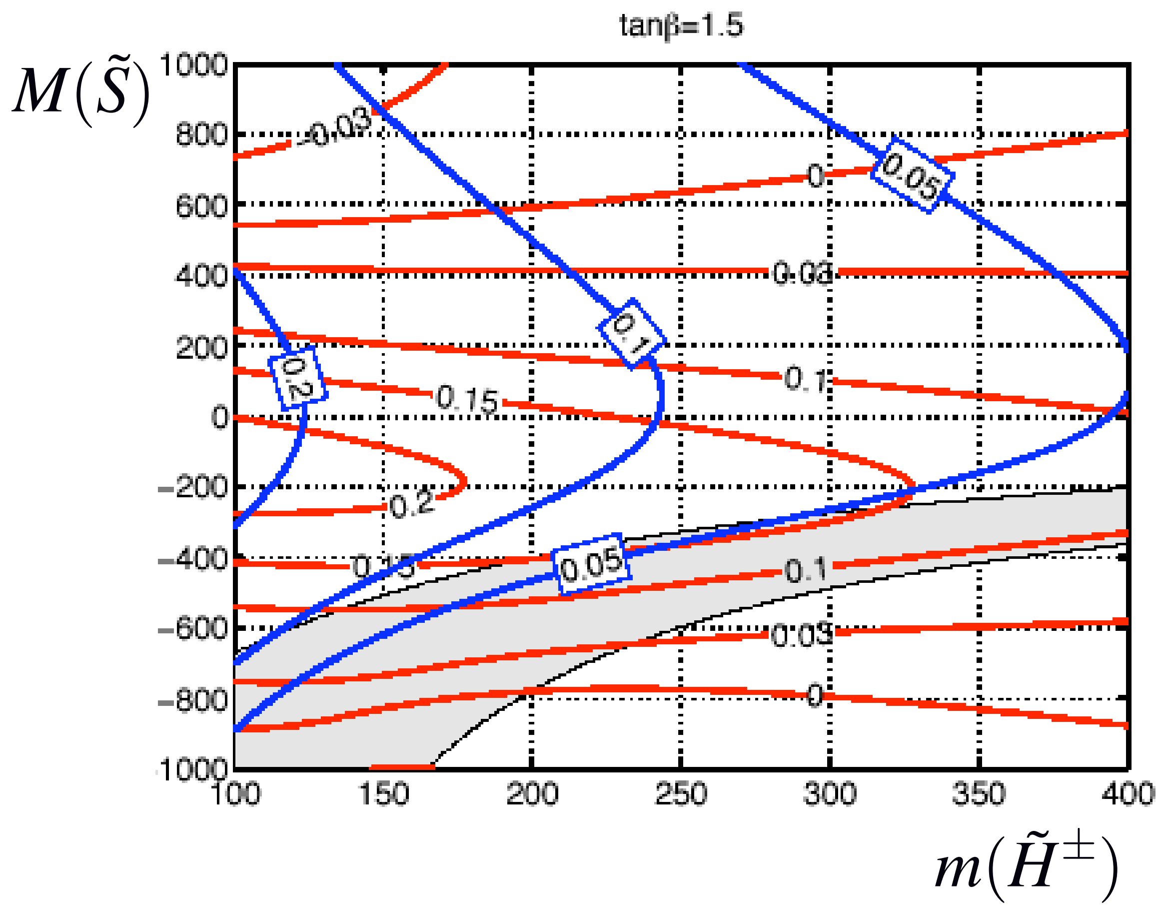
ElectroWeak Precision Tests in λSUSY

$\lambda = 2$

S and T from Higgs's



S and T from Higgsinos



For $\tan\beta \leq 2.5$ and s-particles in their natural range, most of parameter space inside the 1-2σ ellipse

$\tan\beta = 1$ an exact custodial symmetry point

Particle spectrum (naturalness bounds) in λSUSY

$\lambda = 2$

$m_{H^\pm} = 700$ GeV

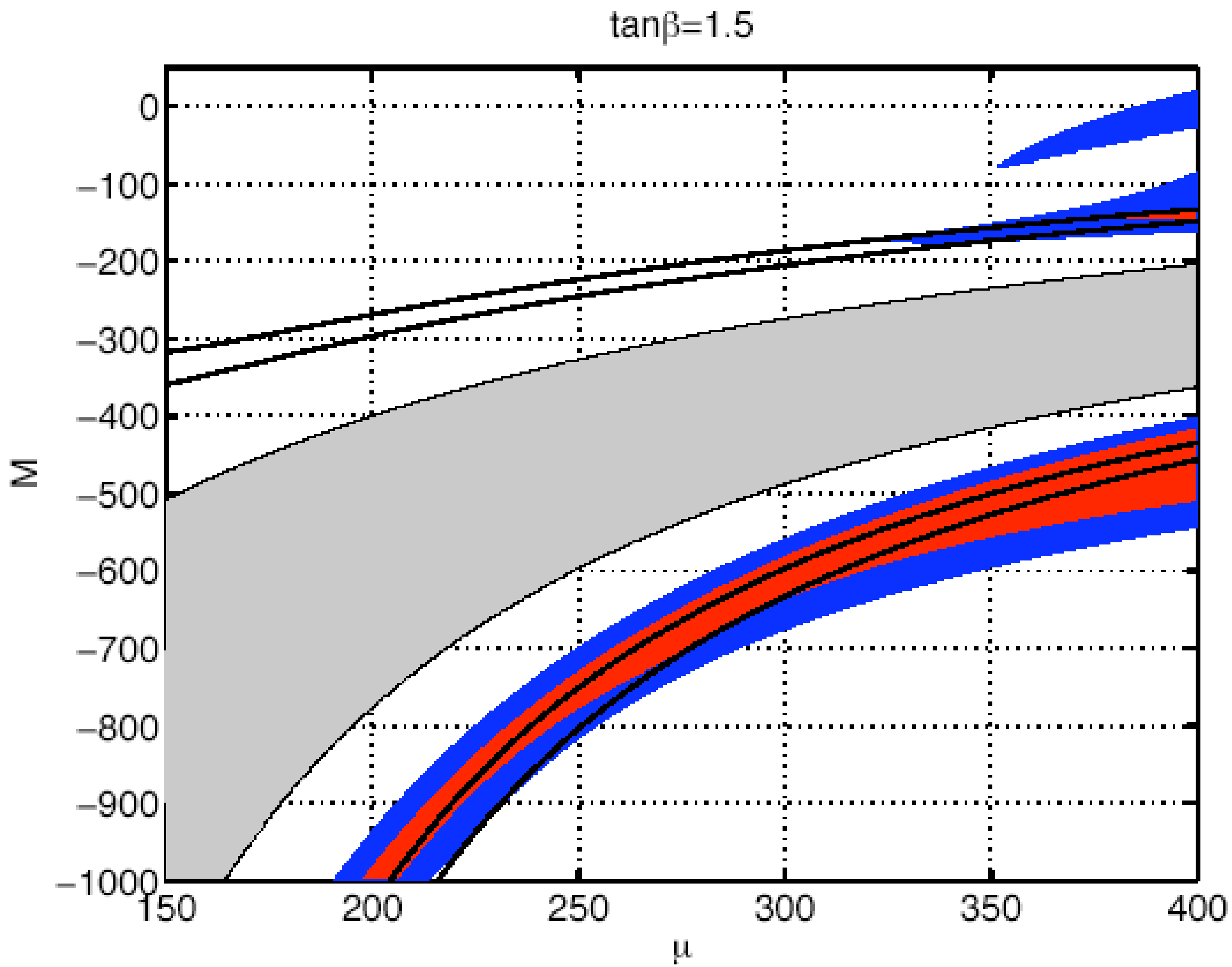
t	m_h	m_H	m_A	$\mu^{\max}$	$m_S^{\max}$	$m_{\tilde{Q},\tilde{t}_R}^{\max}$	$m_{\tilde{g}}^{\max}$
1	350	700	780	490	1000	900	2000
1.5	310	720	780	390	900	800	1750
2	260	740	780	310	750	700	1500
2.5	220	750	780	260	650	600	1250
3	190	760	780	220	550	500	1100

with up to 20% tuning $(m^{max} \propto \sqrt{\Delta/5})$

$\Lambda_{mess} = 100\ TeV$

and no significant bound on other s-fermions and SU(2)xU(1) gauginos

Dark Matter in λSUSY



blue:
$\Omega h^2 = 0.09 \div 0.13$

white:
$\Omega h^2 < 0.09$

red:
$\Omega h^2 > 0.13$

grey:
$m_{LSP} < 45\ GeV$

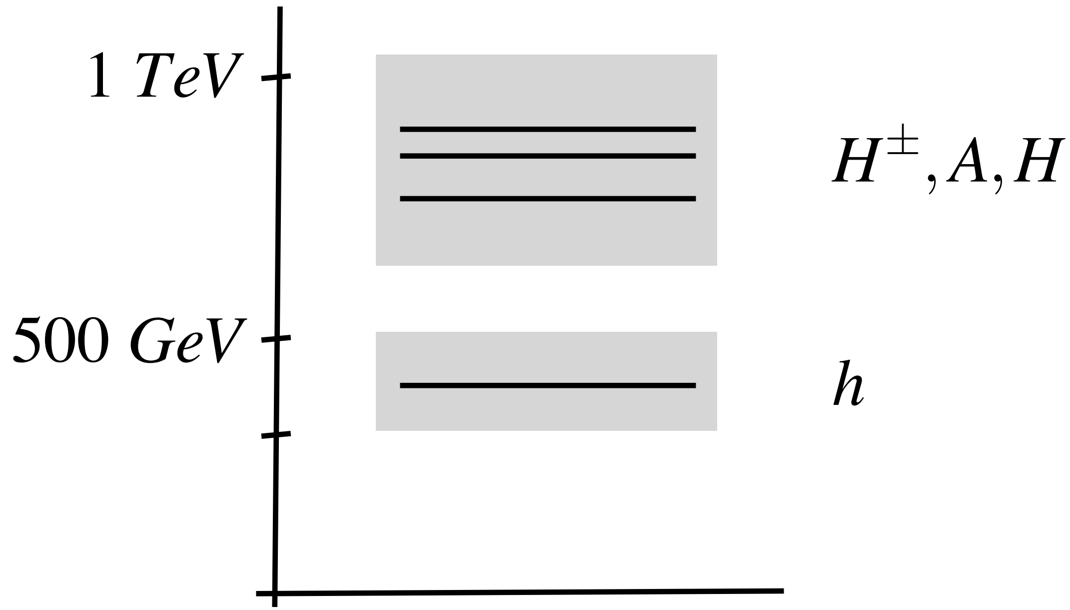
black lines:
$m_{LSP} = m_W, m_Z$

$LSP = \alpha\tilde{S} + \beta\tilde{H}_1 + \gamma\tilde{H}_2$

with no special relation among parameters (MSSM)

Provisional conclusions

Doubling the Higgs multiplet the simplest solution (?) of the l.h.p., realized in several possible ways



+ *possibly something else*

Relevant to supersymmetry itself?

$\Longrightarrow$ *LHC will explore **for the first time** the **relevant** energy range, well above the Fermi scale*

An example: The Inert Doublet Model

RB, Hall, Rychkov

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)

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

$\lambda_L \equiv \lambda_3 + \lambda_4 - |\lambda_5|$

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

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

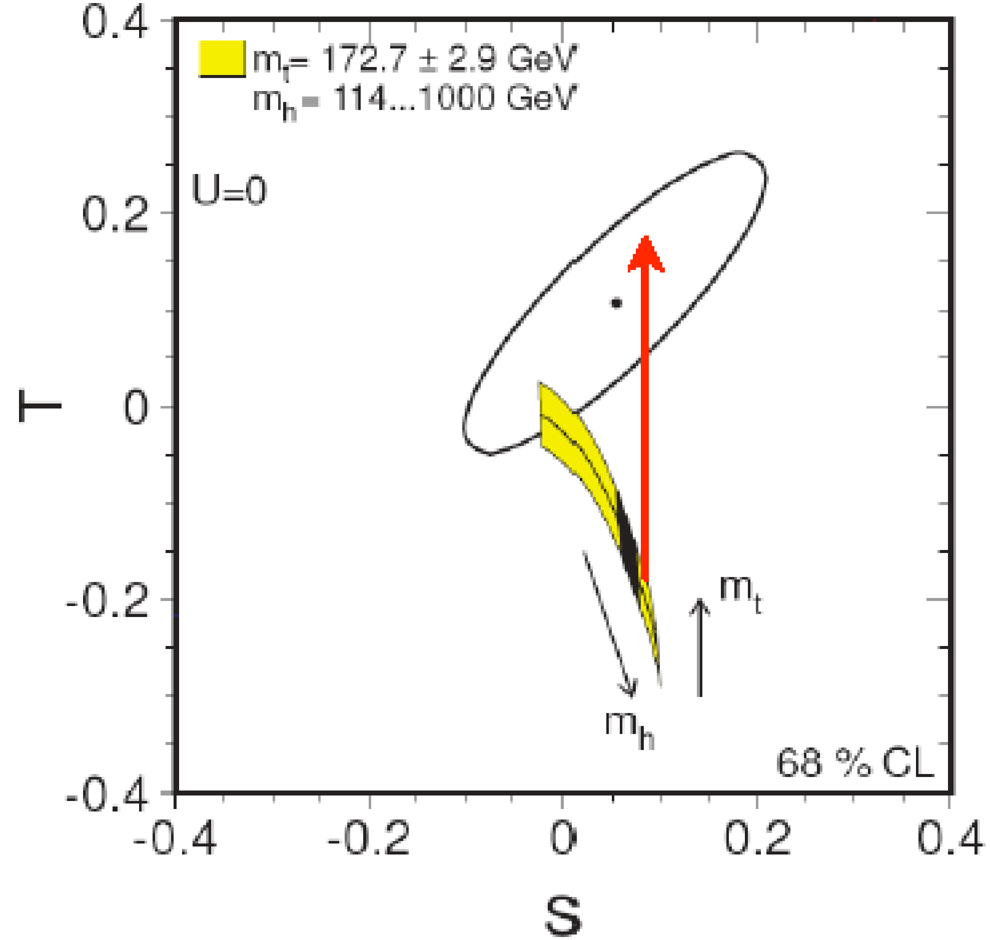
$$16\pi^2 \frac{d\lambda_i}{d \log \Lambda} = \beta_i(\lambda)$$

⇒ A perturbative range of λ's easily characterized with $\Lambda_{nat} = min(\Lambda_i) \approx 1.5\ TeV$

3. EWPT

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

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



ΔS negligible

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

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

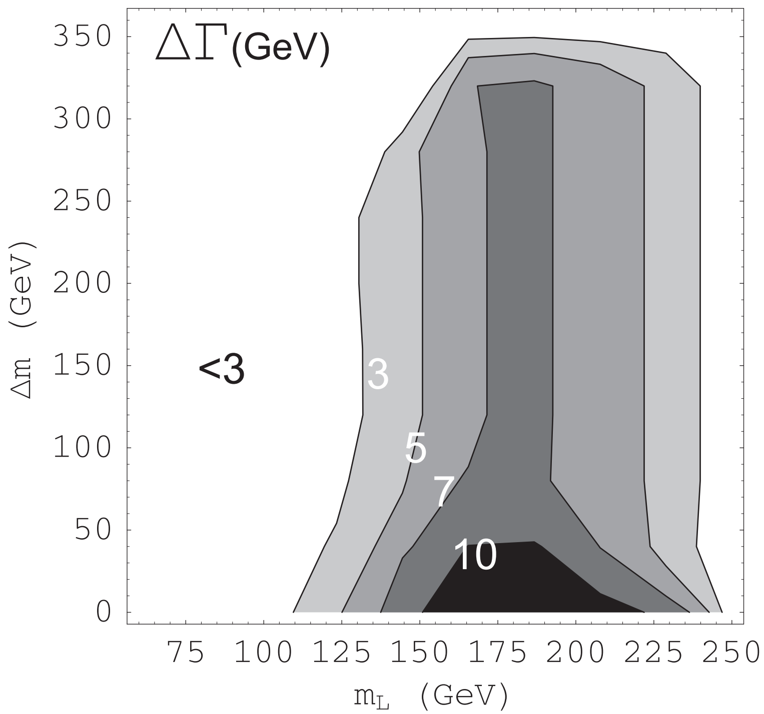
Collider Signals

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