Theories of EW symmetry breaking and precision data after LEP2

1) The little hierarchy ‘problem’
2) Relevance of LEP2
3) Universal models: $\widehat{S}, \widehat{T}, W, Y$
4) Extra d, little Higgs, SUSY,. . .

アレサンナロ　スツルミア - 14㈰2㈪05

From works with Barbieri, Marandella, Pomarol, Rattazzi, Schappacher

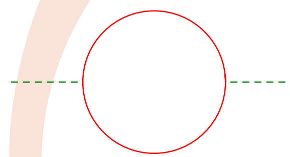
The higgs hierarchy 'problem'...

Recent experimental progress

1) Direct and indirect data showed that the **top is heavy**, $m_t \approx 180\,\text{GeV}$
2) Indirect data suggest the existence of a **light higgs**, $m_h \lesssim 200\,\text{GeV}$

This shifts 'solutions' to the hierarchy problem towards lower energies.
In the SM, cut-offing top loop at $E < \Lambda_{\text{UV}}$

$$\delta m_h^2 \approx \delta m_h^2(\text{top}) =$$



$$\approx \frac{12\lambda_t^2}{(4\pi)^2}\Lambda_{\text{UV}}^2$$

$\delta m_h^2 \lesssim m_h^2$ if $\boxed{\Lambda_{\text{UV}} \lesssim 400\,\text{GeV}}$ no longer few TeV!

But at the same time

3) direct: no new detectable particles, $\tilde{m} \gtrsim 100\,\text{GeV}$.
4) indirect: no new non-renormalizable-operators, $\Lambda \gtrsim 10\,\text{TeV}$.

...and its 'solutions'

A lot of activity before LHC... Two types of solutions:

I New symmetry implies $m_h = 0$; its breaking gives the EW scale

- **Supersymmetry**: $t \to \tilde{t}$ stop stops top.
- Attempts with scale symmetry, 5d gauge invariance, **little Higgs**.

II h becomes an extended object $1/\Lambda \sim$ TeV

- **Technicolor**: $h =$ hadron of a QCD-like group with $\Lambda_{\rm TC} \lesssim$ TeV
- **Large extra dimensions**: $h =$ string with length $\gtrsim 1/$ TeV?
- Warped extra dimension (AdS dual to CFT 'walking technicolor')

Precision data disfavour type II solutions

Extended particles $\leftrightarrow$ form factors

LEP finds that SM fermions, gauge bosons and also the Higgs are point-like.

(Although the Higgs has not been discovered, its properties have been tested because the 3 massive SM vector boson acquired a longitudinal polarization eating 3 components of the Higgs doublet).

Form-factors in QFT are introduced as higher dimensional operators, that encode the low energy effects of new physics too heavy to be directly seen.

Even restricting to SU(2)$_L \otimes$ U(1)$_Y$, B, L, B_i, L_i, CP symmetric operators...

$$\mathscr{L}_{\text{eff}} = \mathscr{L}_{\text{SM}} + \mathcal{O}/\Lambda^2$$

operator $\mathcal{O}$	affects	constraint on Λ
$\frac{1}{2}(\bar{L}\gamma_\mu\tau^a L)^2$	μ-decay	10 TeV
$\frac{1}{2}(\bar{L}\gamma_\mu L)^2$	LEP 2	5 TeV
$\|H^\dagger D_\mu H\|^2$	θ_{W} in M_W/M_Z	5 TeV
$(H^\dagger\tau^a H)W^a_{\mu\nu}B_{\mu\nu}$	θ_{W} in Z couplings	8 TeV
$i(H^\dagger D_\mu\tau^a H)(\bar{L}\gamma_\mu\tau^a L)$	Z couplings	10 TeV
$i(H^\dagger D_\mu H)(\bar{L}\gamma_\mu L)$	Z couplings	8 TeV
$H^\dagger(\bar{D}\lambda_D\lambda_U\lambda_U^\dagger\gamma_{\mu\nu}Q)F^{\mu\nu}$	$b\to s\gamma$	10 TeV
$\frac{1}{2}(\bar{Q}\lambda_U\lambda_U^\dagger\gamma_\mu Q)^2$	B mixing	6 TeV

Cut-off above 10 TeV leaves $\delta m_h^2 \sim 500 m_h^2$: **'little hierarchy problem'**

Heavy universal new physics

Kinds of new physics

- ◦ Generic: p-decay, ν masses. see-saw, GUT
- ◦ B, L conserving: EDM, $\mu \to e\gamma$, ε_K,. . .
- ◦ Minimal Flavour Violation: $b \to s\gamma$, B-mixing,... only SUSY?
- • **'Universal'** (i.e. not coupled to fermions): $\hat{S}, \hat{T}, W, Y$.Little Higgs, extra d
- ◦ Effects only in Higgs: S, T. some technicolor

Heavy universal new physics

'**Universal**': affects only inverse propagators of vectors:

$$p^2 - M^2 + \text{SM loops} + \Pi(p^2)$$

'**Heavy**': expand new physics corrections $\Pi(p^2)$ as

$$\Pi(p^2) = \Pi(0) + p^2\Pi'(0) + \frac{p^4}{2}\Pi''(0) + \cdots$$

3 coefficients for each kinetic term: $\Pi_{W^+W^-}$, $\Pi_{W^3W^3}$, Π_{W^3B}, Π_{BB}.
$3 \cdot 4 = 12$ coefficients. 3 are just redefinitions of the SM parameters g, g', v.
2 combinations vanish because γ must be massless and coupled to $Q = T_3 + Y$.

Adimensional form factors			custodial	$SU(2)_L$
$(g'/g)\hat{S}$	$=$	$\Pi'_{W_3B}(0)$	$+$	$-$
$M_W^2\hat{T}$	$=$	$\Pi_{W_3W_3}(0) - \Pi_{W^+W^-}(0)$	$-$	$-$
$-\hat{U}$	$=$	$\Pi'_{W_3W_3}(0) - \Pi'_{W^+W^-}(0)$	$-$	$-$
$2M_W^{-2}V$	$=$	$\Pi''_{W_3W_3}(0) - \Pi''_{W^+W^-}(0)$	$-$	$-$
$2M_W^{-2}X$	$=$	$\Pi''_{W_3B}(0)$	$+$	$-$
$2M_W^{-2}Y$	$=$	$\Pi''_{BB}(0)$	$+$	$+$
$2M_W^{-2}W$	$=$	$\Pi''_{W_3W_3}(0)$	$+$	$+$
$2M_W^{-2}Z$	$=$	$\Pi''_{GG}(0)$	$+$	$+$

3 are suppressed ($V \ll \hat{U} \ll \hat{T}$ and $X \ll \hat{S}$). 5 remain: $\hat{S}, \hat{T}, W, Y$ and Z

Final result

Adimensional form factor			operator	effect
$(g'/g)\widehat{S}$	$=$	$\Pi'_{W_3B}(0)$	$(H^\dagger\tau^a H)W^a_{\mu\nu}B_{\mu\nu}$	correction to $s_{\rm W}$
$M_W^2\widehat{T}$	$=$	$\Pi_{W_3W_3}(0)-\Pi_{W^+W^-}(0)$	$\lvert H^\dagger D_\mu H\rvert^2$	correction to M_W/M_Z
$2M_W^{-2}Y$	$=$	$\Pi''_{BB}(0)$	$(\partial_\rho B_{\mu\nu})^2/2$	anomalous $g_1(E)$
$2M_W^{-2}W$	$=$	$\Pi''_{W_3W_3}(0)$	$(D_\rho W^a_{\mu\nu})^2/2$	anomalous $g_2(E)$
$2M_W^{-2}Z$	$=$	$\Pi''_{GG}(0)$	$(D_\rho G^A_{\mu\nu})^2/2$	anomalous $g_3(E)$

(We here use canonically normalized vectors)

If the higgs exists, $\widehat{S},\widehat{T},Y,W,Z$ correspond to dimension 6 operators.

Neglected form factors (e.g. U) correspond to dimension 8 operators.

Extended H gives $\widehat{S},\widehat{T}$. Extended vector bosons give W,Y,Z.

- $\widehat{S},\widehat{T}$ probed by comparing $s_{\rm W}(M_W,M_Z)$ with $s_{\rm W}(\alpha,G_{\rm F},M_Z)$ with $s_{\rm W}(g_V^Z,g_A^Z)$
- W,Y probed by comparing (low E with Z-pole) and (Z-pole with LEP2).

$\widehat{S}, \widehat{T}, W, Y$ **from data**

Observables: at and below the Z pole

Corrections to **Z-pole** observables from universal new physics are condensed in

$$\delta\varepsilon_1 = \hat{T} - W - Y\frac{s_W^2}{c_W^2}\,, \qquad \delta\varepsilon_2 = -W\,, \qquad \delta\varepsilon_3 = \hat{S} - W - Y\,.$$

A few observables $(M_Z, M_W, \alpha, G_F, g^Z_{V\ell}, g^Z_{A\ell})$ measured with per-mille accuracy.

Corrections to any **low-energy** observable are easily computed from

$$\begin{aligned}\mathscr{L}_{\rm eff}(E \ll M_Z) \;=\;& \mathscr{L}_{\rm QED,QCD} - 2\sqrt{2}G_F[\bar\nu_L\gamma_\mu\ell_L][\bar d_L\gamma^\mu u_L] + \text{h.c.} + \\ & -4\sqrt{2}G_F(1+\hat{T})\left[\sum_{\psi=Q,L}\bar\psi(T_3 - s_W^2\,k\,Q)\gamma_\mu\psi\right]^2\end{aligned}$$

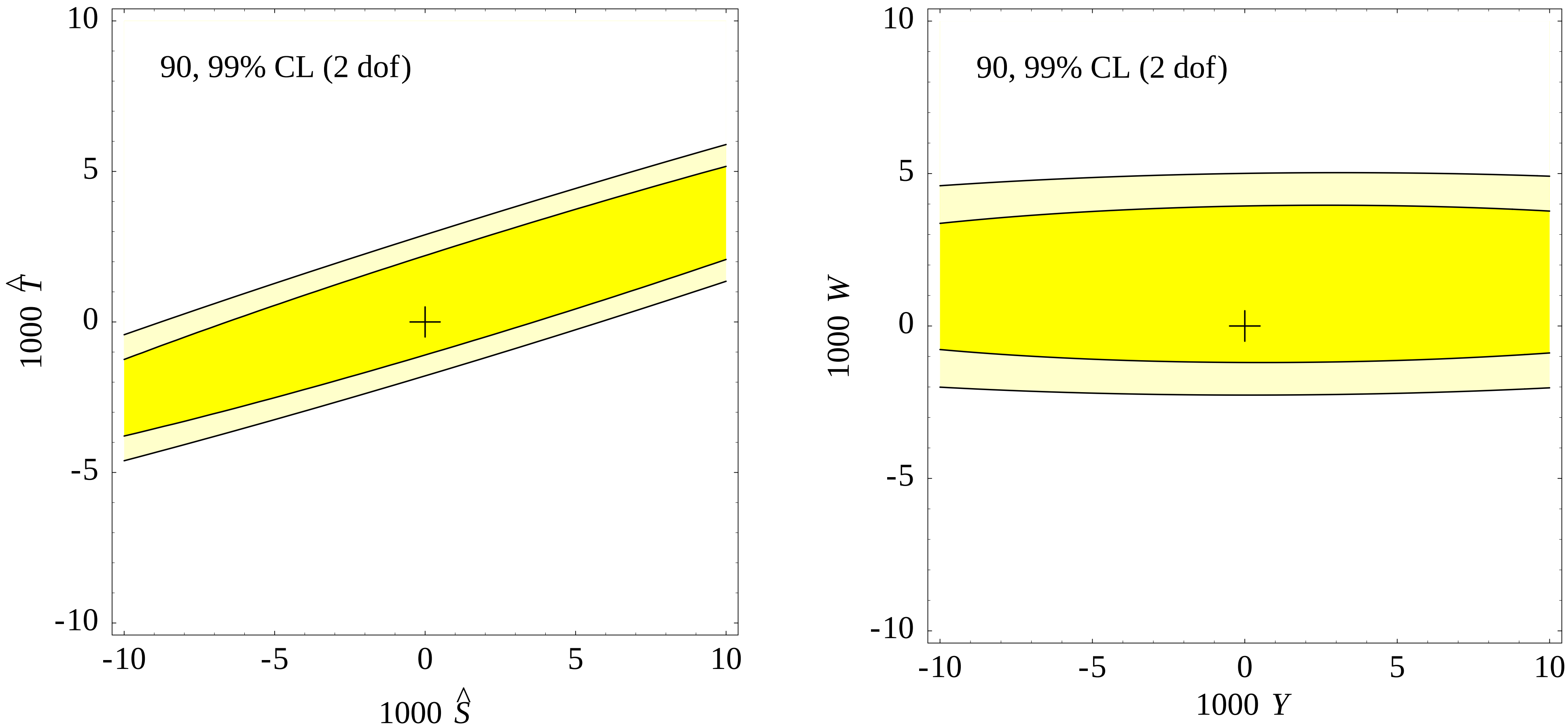
$$k = 1 + \frac{\hat{S} - c_W^2(\hat{T} + W) - s_W^2 Y}{c_W^2 - s_W^2}.$$

Measured with per-cent accuracy: little impact.

Global fit

Large effects still allowed

$$\chi^2(\hat{S},\hat{T}) = \min_{W,Y} \chi^2(\hat{S},\hat{T},W,Y) \qquad \chi^2(W,Y) = \min_{\hat{S},\hat{T}} \chi^2(\hat{S},\hat{T},W,Y)$$

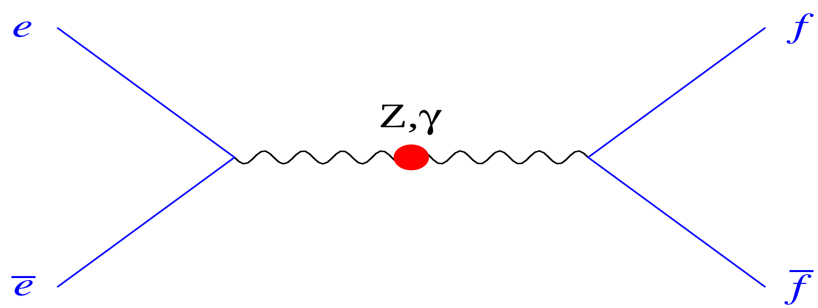


$4-3=1$: $\varepsilon_{1,2,3}$ give bands; adding low-energy transforms into long ellipses.

Observables: above the Z-pole

Corrections to **LEP2** $e\bar{e} \to f\bar{f}$ cross sections: use modified propagators

$$\begin{array}{c|cc} & Z & \gamma \\ \hline Z & \dfrac{1}{p^2-M_Z^2}+\dfrac{\delta\varepsilon_1}{p^2-M_Z^2}-\dfrac{c_{\rm W}^2 W + s_{\rm W}^2 Y}{M_W^2} & = \\ \gamma & -\dfrac{c_{\rm W}^2(\delta\varepsilon_1-\delta\varepsilon_2)-s_{\rm W}^2\delta\varepsilon_3}{s_{\rm W} c_{\rm W}(p^2-M_Z^2)}-\dfrac{s_{\rm W} c_{\rm W}(W-Y)}{M_W^2} & \dfrac{1}{p^2}-\dfrac{s_{\rm W}^2 W + c_{\rm W}^2 Y}{M_W^2} \end{array}$$



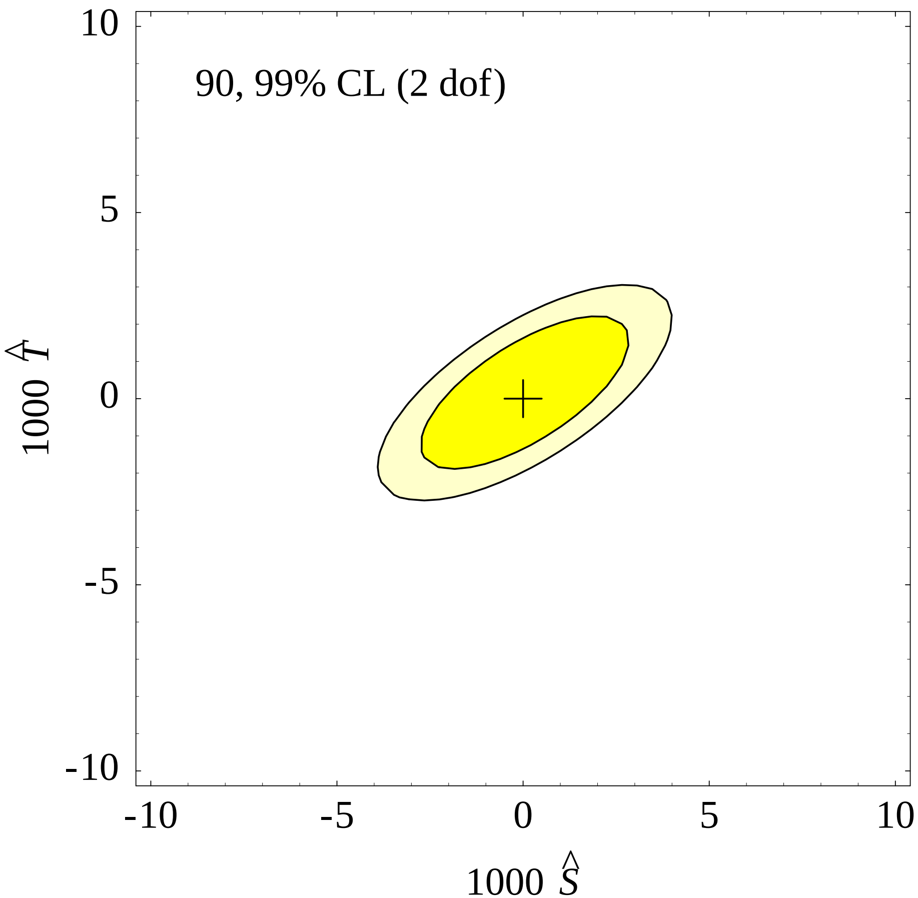
Measured with per-cent accuracy, but effects of W, Y enhanced by $p^2/M_Z^2 \sim 5$

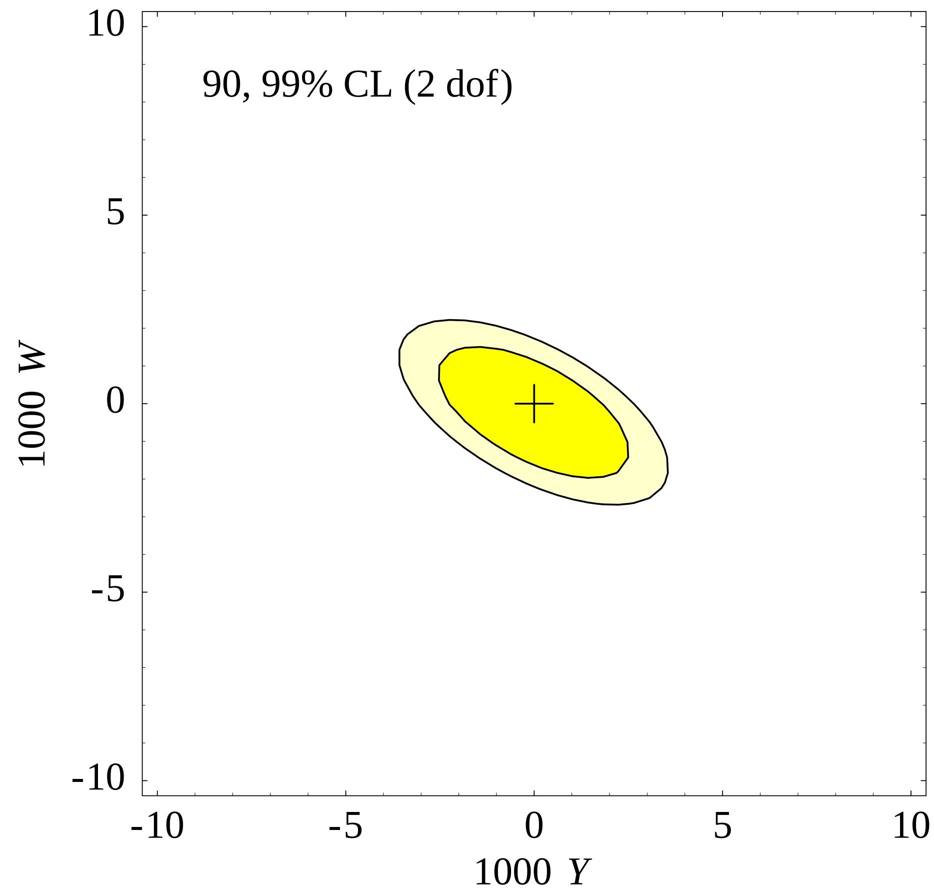
(Measurements of $s_{\rm W}$ below the Z-peak are well emphasized: APV, Møller, NuTeV. LEP2 has comparable accuracy above the Z-peak, and is missed)

Global fit after LEP2

All $\widehat{S}, \widehat{T}, W, Y$ parameters must vanish within few $\cdot 10^{-3}$

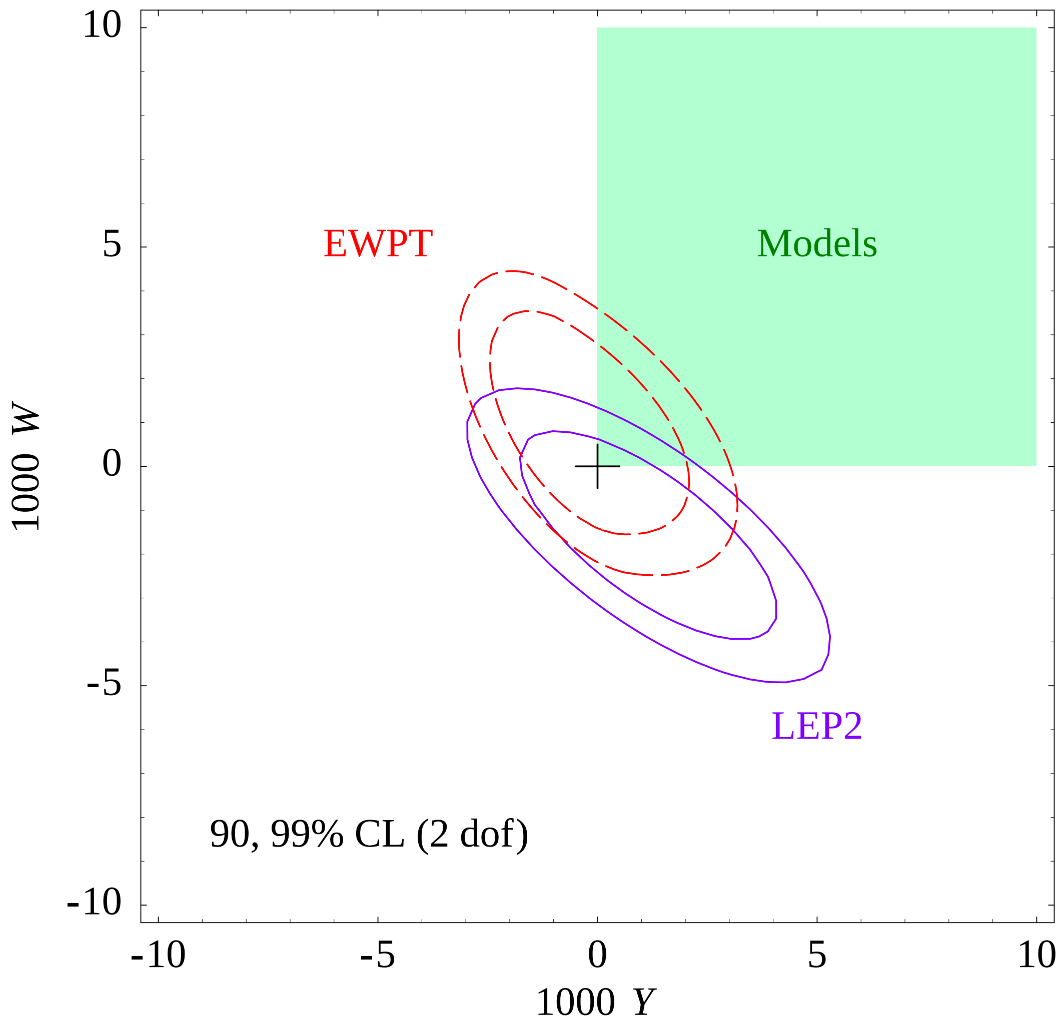
$$\chi^2(\widehat{S}, \widehat{T}) = \min_{W,Y} \chi^2(\widehat{S}, \widehat{T}, W, Y) \qquad \chi^2(W, Y) = \min_{\widehat{S},\widehat{T}} \chi^2(\widehat{S}, \widehat{T}, W, Y)$$





Hard time for Higgsless, little-Higgs etc.

LEP1 vs **LEP2**: $\chi^2(\widehat{S} = 0, \hat{T} = 0, W, Y)$



LEP2 relevant and shifts towards $W < 0$. Models give $W, Y \geq 0$

Precise analysis by LEP2 experimentalists would be welcome

Universal models

Hidden universal models

Popular models (vectors in extra dimensions, little-Higgs,...) have extra heavy vectors coupled to SM fermionic gauge currents J_F.

Integrating out heavy vector mass eigenstates gives additional operators:

$$\mathcal{O} \sim (J_F + J_H)^2 = (\bar\psi\gamma_\mu\psi + iH^\dagger D_\mu H)^2 = \begin{cases} \text{4-fermion operators} \\ \text{corrections to } Z, W, \gamma \text{ couplings} \\ \text{corrections to } Z, W, \gamma \text{ masses} \end{cases}$$

Looks non-universal, so analyses performed by computing all observables. A posteriori can be rewritten as universal: e.g. on shell $J_\mu^B J_\mu^B = (\partial_\alpha B_{\mu\nu})^2/2 \to Y$.

How to skip superfluous steps putting a priori effects in SM vector propagators?

$$\frac{1}{p^2 - m_{\text{SM}}^2} \to \frac{1}{p^2 - m_{\text{SM}}^2} + \frac{1}{p^2 - m_{\text{new}}^2}$$

How to compute $\widehat{S}, \hat{T}, W, Y$

Do not integrate out the heavy vector mass eigenstates.

Integrate out vector bosons not coupled to SM fermions.

⋆ Apparently non-universal operators involving fermions not generated.

⋆ No need of diagonalizing and indentifying heavy mass eigenstates.

It works like a pig $\longrightarrow$ sausage machine:

1) Choose a model; write kinetic matrix Π^{full}_{ij} of neutral $(W_3, B, \ldots)$ and charged $(W^{\pm}, \ldots)$ vectors. $(\ldots$ indicates extra vectors not coupled to SM fermions)

2) $\Pi^{-1} = (\Pi^{\text{full}})^{-1}$ restricted to SM vectors

3) Extract $\widehat{S}, \hat{T}, W, Y$ from Π

4) Compare with $\chi^2(\widehat{S}, \hat{T}, W, Y)$

A simple example: $\mathbf{U(1)}_Y \otimes \mathbf{U(1)}'_Y$

Extra hypercharge vector with mass M not mixed with SM.

1) Kinetic matrix:

$$\Pi^{\rm full} = \begin{array}{c} \\ B_\mu \\ W^3_\mu \\ B'_\mu \end{array} \!\!\begin{array}{c} \begin{array}{ccc} B_\mu & W^3_\mu & B'_\mu \end{array} \\ \begin{pmatrix} p^2 - M_Z^2 s_{\rm W}^2 & M_Z^2 s_{\rm W} c_{\rm W} & 0 \\ M_Z^2 s_{\rm W} c_{\rm W} & p^2 - M_Z^2 c_{\rm W}^2 & 0 \\ 0 & 0 & p^2 - M^2 \end{pmatrix} \end{array}$$

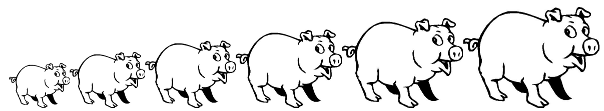
2) Integrate out $B_\mu - B'_\mu$ not coupled to fermions: go to the basis $(B, W^3, B-B')$, invert $\Pi^{\rm full}$ and restrict to B, W^3: the result of course is

$$\Pi^{-1} = \begin{pmatrix} p^2 - M_Z^2 s_{\rm W}^2 & M_Z^2 s_{\rm W} c_{\rm W} \\ M_Z^2 s_{\rm W} c_{\rm W} & p^2 - M_Z^2 c_{\rm W}^2 \end{pmatrix}^{-1} + \begin{pmatrix} 1/(p^2 - M^2) & 0 \\ 0 & 0 \end{pmatrix}$$

3) Extract $\widehat{S} = Y = \widehat{T}/t_{\rm W}^2 = M_W^2/M^2$, $W = 0$. LEP1 not affected: $\delta\varepsilon_{1,2,3} = 0$

Gauge bosons in extra dimension

Kaluza-Klein vectors are like $G \otimes G \otimes G \ldots$ with masses $M = 1/R, 2/R, 3/R \ldots$



Vectors and higgs in 5d; fermions localized on a brane: pig machine produces

$$\frac{1}{\Pi} = \sum_{n=-\infty}^{+\infty} \frac{1}{p^2 - n^2/R^2} = \text{brane to brane propagator}$$

$$\Pi = \frac{p}{\pi R} \tan p\pi R \simeq p^2 + \frac{p^4}{3}\pi^2 R^2 + \cdots$$

KK of SU(2)$_L$ bosons produce W, B_μ KK give Y, gluons KK give Z:

$$W = Y = Z = \frac{\pi^2}{3} M_W^2 R^2.$$

Without LEP2: $1/R > 4.5$ TeV. With LEP2: $1/R > 6.4$ TeV. At 95% CL.

If instead the higgs is localized together with fermions, then one gets also

$$\hat{S} = \frac{\pi^2}{6} M_W^2 R^2 \tan\theta_{\rm W}, \qquad \hat{T} = \frac{\pi^2}{3} M_W^2 R^2 \tan^2\theta_{\rm W}.$$

Without LEP2: $1/R > 3.8$ TeV. With LEP2: $1/R > 6.3$ TeV. At 95% CL.

Little Higgs

Higgs as pseudo-Goldstone

Basic idea:

Higgs is a pseudo-Goldstone boson of a global symmetry broken at a scale f

Happens in QCD, making π lighter than proton.
Solved doublet/triplet problem of SUSY-SU(5).

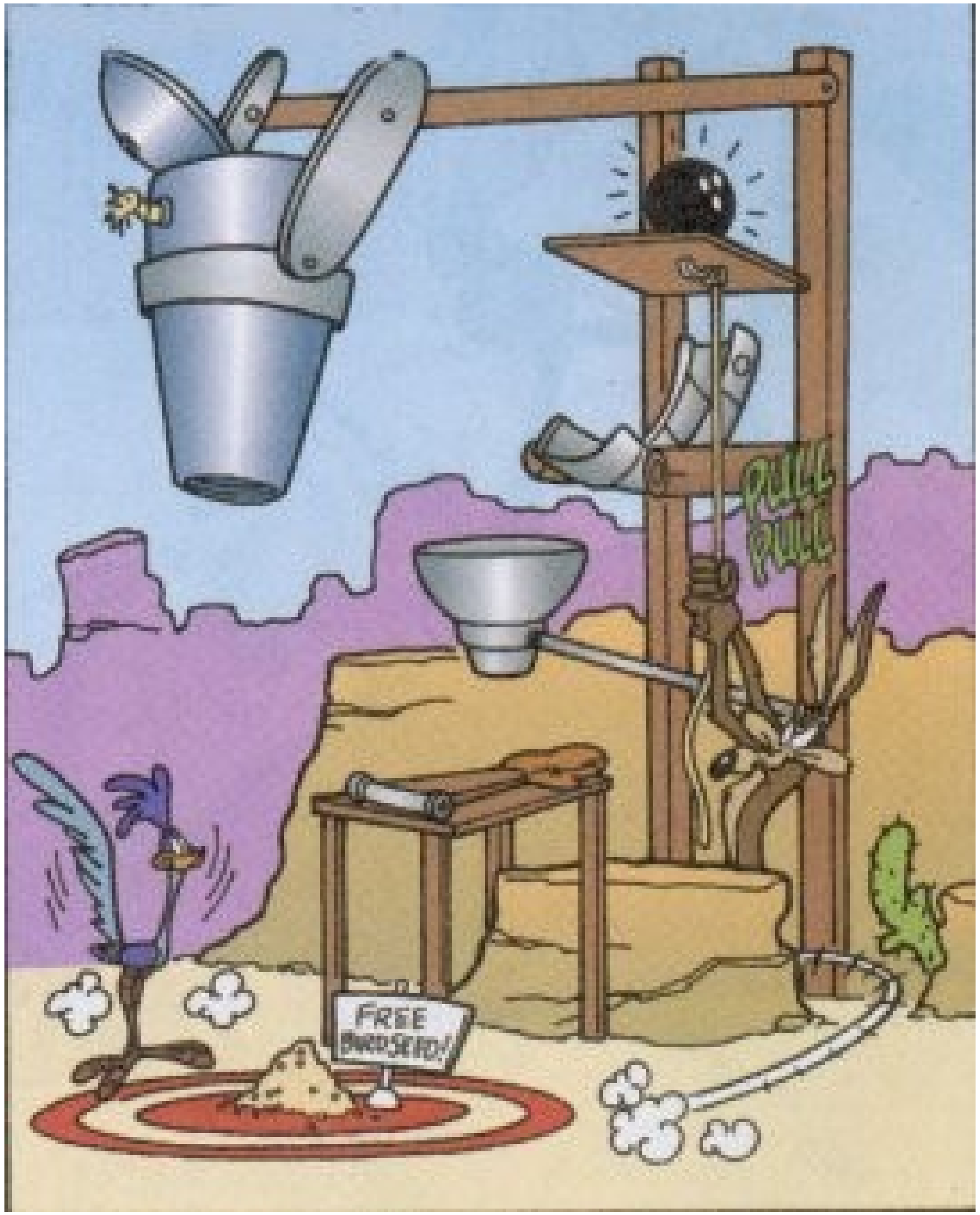
But

The Higgs seems not a Goldstone boson:

– a Goldstone boson π has flat potential: $V \sim 0\pi^2 + 0\pi^4$.
– we want a small Higgs mass, but we need a sizable coupling: $V \sim 0h^2 + \lambda h^4$.

To proceed anyway one needs to build complex machineries: little Higgs models

The little-Higgs mechanism



← A global symmetry contains two copies of the electroweak gauge group, spontaneously broken to the SM at scale f by more than a single Higgs field. As in D/T models the top Yukawa can be obtained by mixing with extra vector tops.

← Basic idea

Little Higgs models

global	gauge	$\widehat{S}$	$\widehat{T}$	W	Y
SU(5)	32211	$\frac{2M_W^2}{g^2 f^2}\left[\cos^2\phi + 5\frac{c_W^2}{s_W^2}\cos^2\phi'\right]$	$\frac{5M_W^2}{g^2 f^2} + \widehat{T}_{\text{triplet}}$	$\frac{4M_W^2}{g^2 f^2}\cos^4\phi$	$\frac{20M_W^2}{g'^2 f^2}\cos^4\phi'$
SU(5)	3221	$\frac{2M_W^2}{g^2 f^2}\cos^2\phi$	$0 + \widehat{T}_{\text{triplet}}$	$\frac{4M_W^2}{g^2 f^2}\cos^4\phi$	0
SO(9)	32221	$\frac{2M_W^2}{g^2 f^2}\left[\cos^2\phi_L + \frac{c_W^2}{s_W^2}\cos^2\phi_R\right]$	$0 + \widehat{T}_{\text{triplet}}$	$\frac{4M_W^2}{g^2 f^2}\cos^4\phi_L$	$\frac{4M_W^2}{g'^2 f^2}\cos^4\phi_R$
SU(6)	32211	$\frac{2M_W^2}{g^2 f^2}\left[\cos^2\phi + 2\frac{c_W^2}{s_W^2}\cos^2\phi'\right]$	$\frac{M_W^2}{2g^2 f^2}(5+\cos 4\beta)$	$\frac{4M_W^2}{g^2 f^2}\cos^4\phi$	$\frac{8M_W^2}{g'^2 f^2}\cos^4\phi'$
SU(6)	3221	$\frac{2M_W^2}{g^2 f^2}\cos^2\phi$	$\frac{M_W^2}{g^2 f^2}\cos^2 2\beta$	$\frac{4M_W^2}{g^2 f^2}\cos^4\phi$	0
$SU(3)^2$	331	$\approx \frac{2M_W^2}{f^2 g^2}$	≈ 0	$\approx \frac{M_W^2}{2f^2 g^2}$	$\approx \frac{g'^2 M_W^2}{2f^2 g^4}$

$\tan\phi = g_2/g_1$, $\tan\phi' = g'_2/g'_1$, $\tan\phi_L = g_L/g_2$, $\tan\phi_R = g_R/g_1$, $\tan\beta = v_2/v_1$

All f normalized such that non-abelian vectors have masses $M^2 = g^2 f^2/4$.

32211 is a shorthand for $SU(3)\otimes SU(2)_1 \otimes SU(2)_2 \otimes U(1)_2 \otimes U(1)_1$, etc

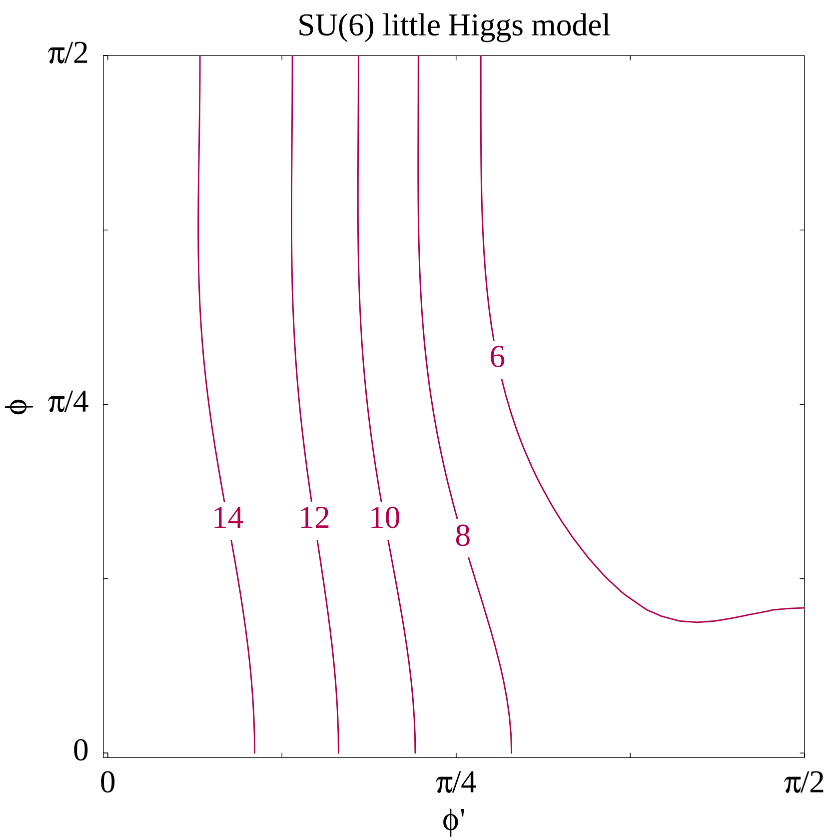
Some models have Higgs triplets with vev v_T: $\widehat{T}_{\text{triplet}} = -g^2 v_T^2/M_W^2$.

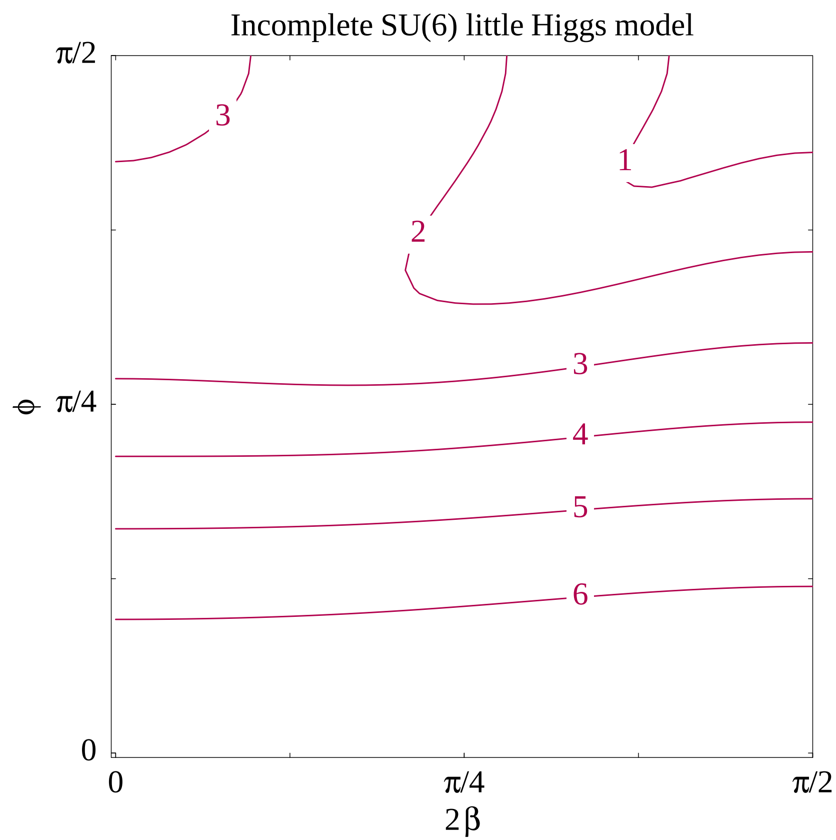
Various disagreements with previous analyses

We will plot 99% C.L. bounds on f i.e. $\chi^2 = \chi^2_{\text{SM}} + 6.6$ (1 d.o.f!)

We assume light higgs. Heavy higgs allowed in models with $\widehat{T} \sim +\text{few}\cdot 10^{-3}$.

Models without Higgs triplets

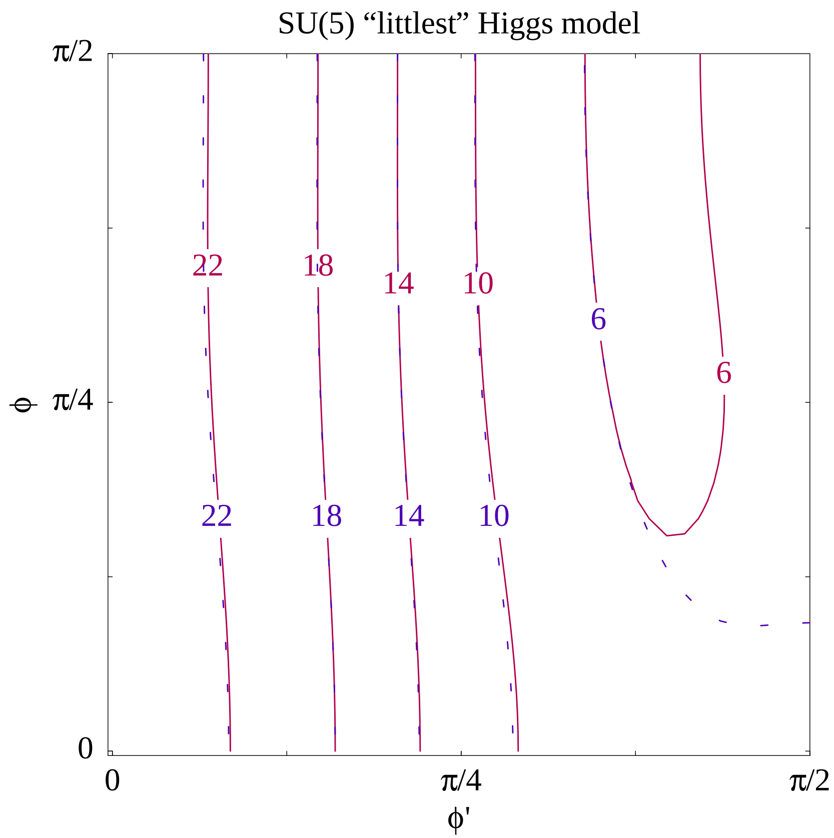


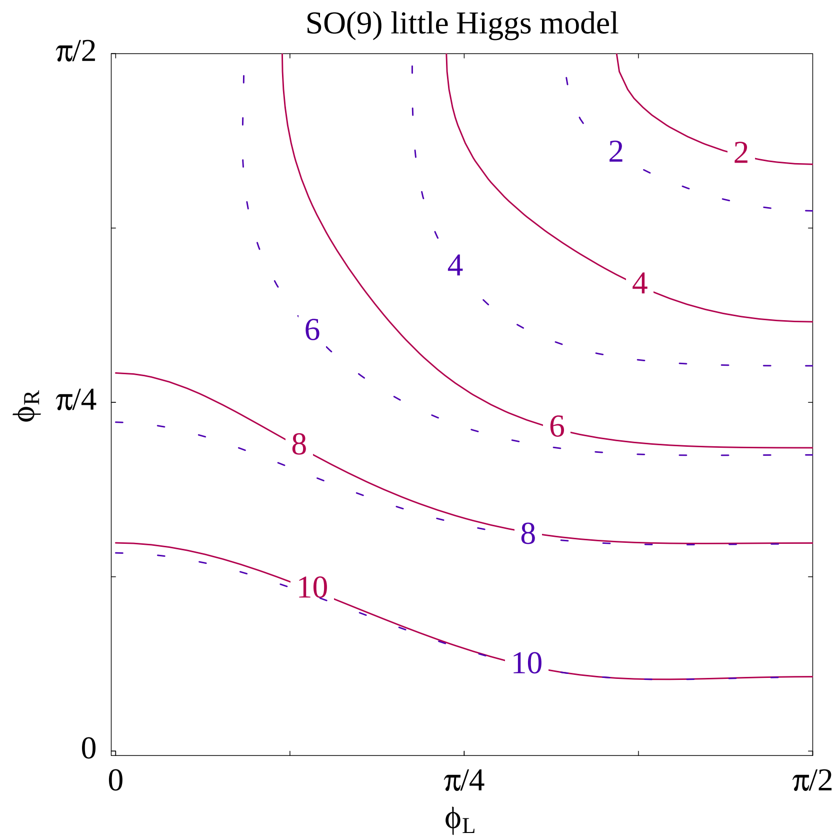


Strongest constraint from extra U(1).

Dropping it the model becomes less constrained but incomplete: $\delta m_h^2 \sim g'^2 \Lambda^2$.

Models with Higgs triplets





Constraint slightly relaxed by an extra $\widehat{T}$ (negative in SU(5), positive in SO(9))

Little Higgs and precision data

All indirect effects condensed in 4 observables: $\hat{S}, \hat{T}, W, Y$.

Not enough to indirectly test models with 4 free parameters.

Nevertheless models predict inequalities, some common to all models:

$$W, Y \geq 0, \qquad S > (W+Y)/2 \qquad \hat{T} \ldots$$

- $\hat{T} = 0$ in models with custodial $SU(2)_R$ or with a single U(1)
- $Y = 0$ in 'incomplete' models with a single U(1)

Above models are fine-tuned: $f >$ few TeV and FT $\sim (f/v)^2 \sim 100 \div 1000$

Sometimes constraint on f stronger than LHC sensitivity.

'Simplest' little Higgs

Basic idea: $\mathrm{SU}(3)\otimes \mathrm{U}(1)_X \xrightarrow{f} \mathrm{SU}(2)_L \otimes \mathrm{U}(1)_Y$ by **two** SU(3) Higgs triplets $H_{1,2}$
(Or a triplet H and an adjoint Σ as in old models for doublet/triplet splitting).

Forbidding $|H_1 H_2|^2$ or $H\Sigma\Sigma^* H$ gives a $\mathrm{SU}(3)\otimes\mathrm{SU}(3)$ global symmetry.
The light Higgs doublet is its pseudo-Goldstone boson.

Non universal corrections to precision observables from an extra Z' boson

$$M^2_{Z'} = \frac{2g^2}{3c^2_{Z'}} f^2 \approx 0.24 f^2 \qquad g_{Z'} = \frac{g}{c_{Z'}} \approx 0.60, \qquad Z' \text{ charge} = T_8 + \sqrt{3} s_{Z'} Y$$

Corrections to most precise precision data described by

$$\hat{S} = 4W = \frac{2M^2_W}{f^2 g^2} = \frac{4Y}{\tan^2\theta_{\rm W}}, \qquad \hat{T} = 0$$

$f > 4.5\,\mathrm{TeV}$ at 99% CL.

Generic Z'

Non universal. Specified by $M_{Z'}$, $g_{Z'}$ and by charges Z'_H, $Z'_{L_{1,2,3}}$, $Z'_{E_{1,2,3}}, \ldots$

A simple approximation holds if e, μ, τ have the same Z' charge:
restrict to charged leptons, better probed than quarks or neutrinos.
Done by integrating out combination not coupled to e_L and e_R:

$$B_\mu \to B_\mu - c_Y Z'_\mu, \qquad W^3_\mu \to W^3_\mu - c_W Z'_\mu$$

$$c_Y = \frac{g_{Z'} Z'_E}{g' Y_E}, \qquad c_W = \frac{2 g_{Z'}}{Y_E g}(Z'_E Y_L - Z'_L Y_E)$$

Get

$$\hat{S} = \frac{M_W^2}{M_{Z'}^2}(c_W - c_Y/t)(c_W - c_Y t - 2 g_{Z'} Z'_H/g), \qquad W = \frac{M_W^2}{M_{Z'}^2} c_W^2,$$

$$\hat{T} = \frac{M_W^2}{M_{Z'}^2}[(c_Y t + 2 g_{Z'} Z'_H/g)^2 - c_W^2], \qquad Y = \frac{M_W^2}{M_{Z'}^2} c_Y^2.$$

Higgsless models

Without the Higgs unitarity lost at $E \gtrsim 4\pi v \sim$ TeV

Some 5d models try to mantain unitarity up to $E \sim (4\pi)^2 v/g \sim 10\,\text{TeV}$.

Proposed models are ‘universal’ and give (with fermions on a brane)

$$\hat{S} \sim \frac{\alpha}{4\pi}\frac{1}{\epsilon_5} \qquad \epsilon_5 \text{ is a 5d loop expansion factor}$$

- If $\epsilon_5 \sim 1$ the model is uncomputable (‘not even wrong’)

- If $\epsilon_5 \ll 1$ the model is excluded, because after LEP2 $|\hat{S}| \ll 0.01$.

Universal extra dimensions

With all SM fields in extra dimensions there are no *computable* tree level effects.

Usual conclusion: $1/R \sim v$ is allowed.
But:

1) More structure (orbifolds...) needed to get chiral 4d fermions from extra dim.s: loop effects are ∞ because they do not respect the tree level setup.

2) More generically, gauge interactions are renormalizable only in 4d ($[g] = 0$): in higher dimension why only would-be renormalizable terms should be present?

Adding higher order operators the reasonable constraint is $1/R > \mathcal{O}(10\,\text{TeV})$.

Additional problems when applied to

Higgsless: why data reproduce SM with light Higgs if there is no Higgs?

Little Higgs with T parity: small $f \sim v$ stabilizes v but new f hierarchy problem.

Supersymmetry

LEP2 indirect data and SUSY

LEP2 saw $N \sim 10^4$ $e\bar{e} \to f\bar{f}$ events at $\sqrt{s} = 200\,\text{GeV}$.

So LEP2 is sensitive to $\mathcal{O} = \dfrac{4\pi}{\Lambda^2}(\bar{e}\gamma_\mu e)(\bar{f}\gamma_\mu f)$ up to $\Lambda \gtrsim \sqrt{\dfrac{sN^{1/2}}{\alpha}} \approx 10\,\text{TeV}$.

Indeed LEP2 collaborations claim $\Lambda \gtrsim 10\,\text{TeV}$.

Sparticles of mass m_{SUSY} generate $\mathcal{O}$ with $4\pi/\Lambda^2 \sim g^4/(4\pi m_{\text{SUSY}})^2$.

So $m_{\text{SUSY}} \gtrsim g^2\Lambda/(4\pi)^{3/2} \approx$ 100 GeV, comparable to direct bounds.

[Years ago attempt with Gambino and Giudice failed because too complex.
Now $\hat{S}, \hat{T}, W, Y$ approximation allowed to understand and proceed correctly].

SUSY is neither universal nor heavy

1) SUSY is not universal: corrections to propagators, vertices and boxes are comparable. Actually only corrections to propagators are cumulative in the number of generations, colors, isospin:

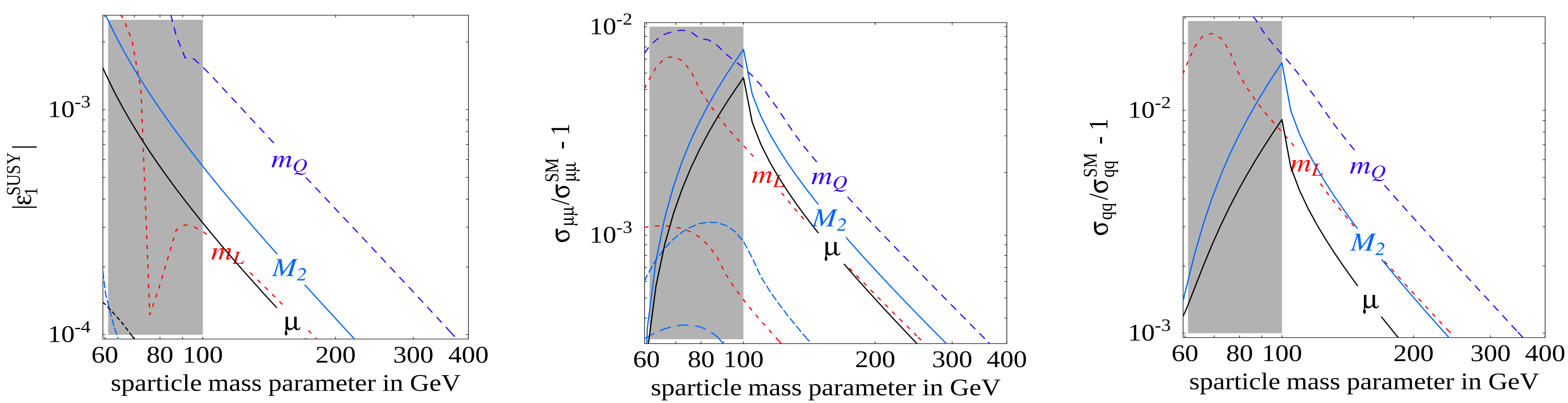
the universal approximation is good within $1/N_{\rm gen} \sim 30\%$.

And SUSY becomes exactly universal if fermionic sparticles are lighter than scalar sparticles ('split' SUSY limit) and in the opposite limit.

2) SUSY is not heavy. Actually $\tilde{m} > 100\,\mathrm{GeV}$ so that at LEP1 the

heavy approximation is good within $(M_Z/2\tilde{m})^2 \lesssim 25\%$.

At LEP2 it misses the resonant enhancement of fermionic sparticles:



Sfermions and Higgs bosons

$$\hat{S} = -\frac{\alpha_2}{24\pi}\left[M_W^2\left(-\frac{1}{6m_L^2}+\frac{3}{2m_Q^2}\right)\cos 2\beta + \frac{1}{2}\frac{m_t^2}{m_Q^2} + \frac{M_W^2}{2m_A^2}\left(1-\frac{M_Z^2}{2M_W^2}\sin^2 2\beta\right)\right]$$

$$\hat{T} = \frac{\alpha_2}{16\pi}M_W^2\cos^2 2\beta\left(\frac{1}{m_L^2}+\frac{2}{m_Q^2}\right) + T_{\text{stop}} + \frac{\alpha_2}{48\pi}\frac{M_W^2}{m_A^2}\left(1-\frac{M_Z^2}{M_W^2}\sin^2 2\beta\right)$$

$$Y = \frac{\alpha_Y}{40\pi}M_W^2\left(\frac{1}{m_E^2}+\frac{1}{2m_L^2}+\frac{1}{3m_D^2}+\frac{4}{3m_U^2}+\frac{1}{6m_Q^2}+\frac{1}{6m_A^2}\right),$$

$$W = \frac{\alpha_2}{80\pi}M_W^2\left(\frac{1}{m_L^2}+\frac{3}{m_Q^2}+\frac{1}{3m_A^2}\right)$$

where $T_{\text{stop}} \approx +\frac{\alpha_2}{16\pi}\frac{(m_t+M_W\cos 2\beta)^2}{m_{Q_3}^2 M_W^2}$ can be better approximated.

Gauginos and higgsinos

$$\begin{aligned}
\hat{S} &\approx \frac{\alpha_2 M_W^2}{12\pi M_2^2}\left[\frac{r(r-5-2r^2)}{(r-1)^4}+\frac{1-2r+9r^2-4r^3+2r^4}{(r-1)^5}\ln r\right]+ \\
&\quad +\frac{\alpha_2 M_W^2}{24\pi M_2\mu}\left[\frac{2-19r+20r^2-15r^3}{(r-1)^4}+\frac{2+3r-3r^2+4r^3}{(r-1)^5}2r\ln r\right]\sin 2\beta, \\
\hat{T} &\approx \frac{\alpha_2 M_W^2}{48\pi M_2^2}\left[\frac{7r-29+16r^2}{(r-1)^3}+\frac{1+6r-6r^2}{(r-1)^4}6\ln r\right]\cos^2 2\beta, \\
Y &= \frac{\alpha_Y}{30\pi}\frac{M_W^2}{\mu^2}, \\
W &= \frac{\alpha_2}{30\pi}\left[\frac{M_W^2}{\mu^2}+\frac{2M_W^2}{M_2^2}\right]
\end{aligned}$$

having neglected $s_{\rm W}^2 \approx 0$ in $\hat{S}, \hat{T}$ and defined $r = \mu^2/M_2^2$.

Unlike W and Y, $\hat{S}$ and $\hat{T}$ are suppressed by $1/\max(\mu, M_2)^2$.

General features

Precision tests compared to $g-2$, $b \to s\gamma$, $B_s \to \mu\bar{\mu}$, m_h, DM

- Insensitive to model details (e.g. NMSSM drastically affects m_h and DM)
- Featureless: no big enhancements nor suppressions (e.g. large $\tan\beta$, coann)
- $W, Y > 0$ can cumulate up to observable level. (LEP2 prefers $W < 0$).
- Depend almost only on few main parameters: $M_2, m_Q, m_L, \mu, \ldots A_t, \tan\beta \ldots$

	CMSSM at M_{GUT}	Gauge mediation at 10^{10} GeV	Anomaly + radion mediation
M_2	$0.82 M_{1/2}$	$0.82 \tilde{M}_{1/2}$	$-0.43 M_{\text{AM}}$
m_Q^2	$m_0^2 + 6.2 M_{1/2}^2$	$6.5 \tilde{m}_0^2 + 5.2 \tilde{M}_{1/2}^2$	$m_0^2 + 16 M_{\text{AM}}^2$
m_L^2	$m_0^2 + 0.52 M_{1/2}^2$	$1.3 \tilde{m}_0^2 + 0.24 \tilde{M}_{1/2}^2$	$m_0^2 - 0.37 M_{\text{AM}}^2$
$\mu^2 + M_Z^2/2$	$0.17 m_0^2 + 2.6 M_{1/2}^2$	$2.9 \tilde{m}_0^2 + 1.7 \tilde{M}_{1/2}^2$	$0.17 m_0^2 + 10 M_{\text{AM}}^2$

- $(m_0, M_{1/2})$-like plots are representative (not only sample slices)

Split SUSY

Universal: simple warming exercise, motivated by anthropic arguments: v small so that we form. Λ small so that we survive. M_2, μ small so that we work.

Only M_2 light.

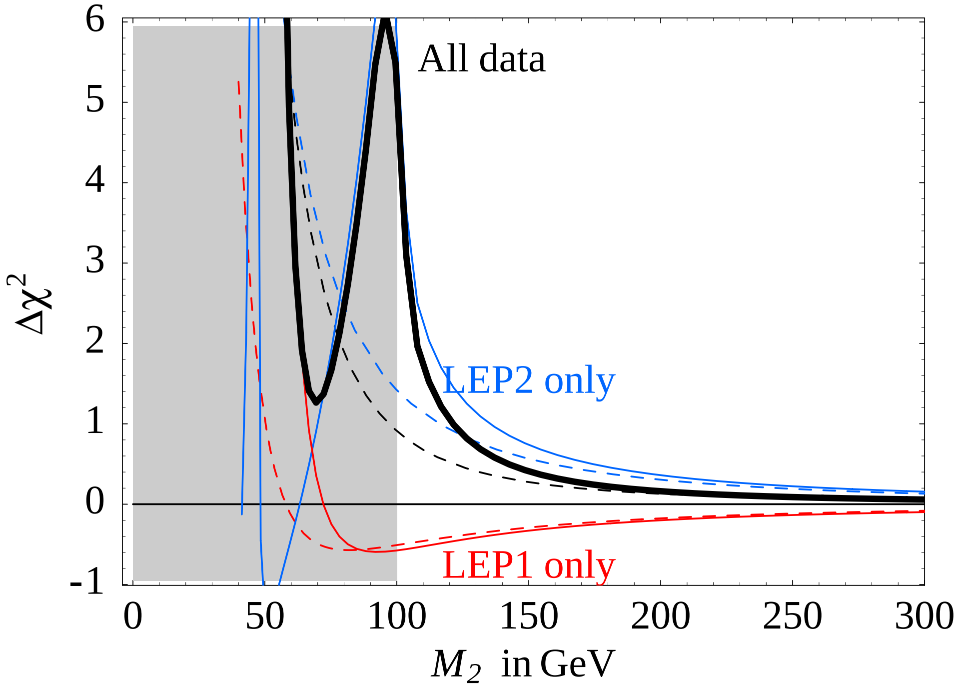
$$\hat{S} = \hat{T} = Y \simeq 0,$$

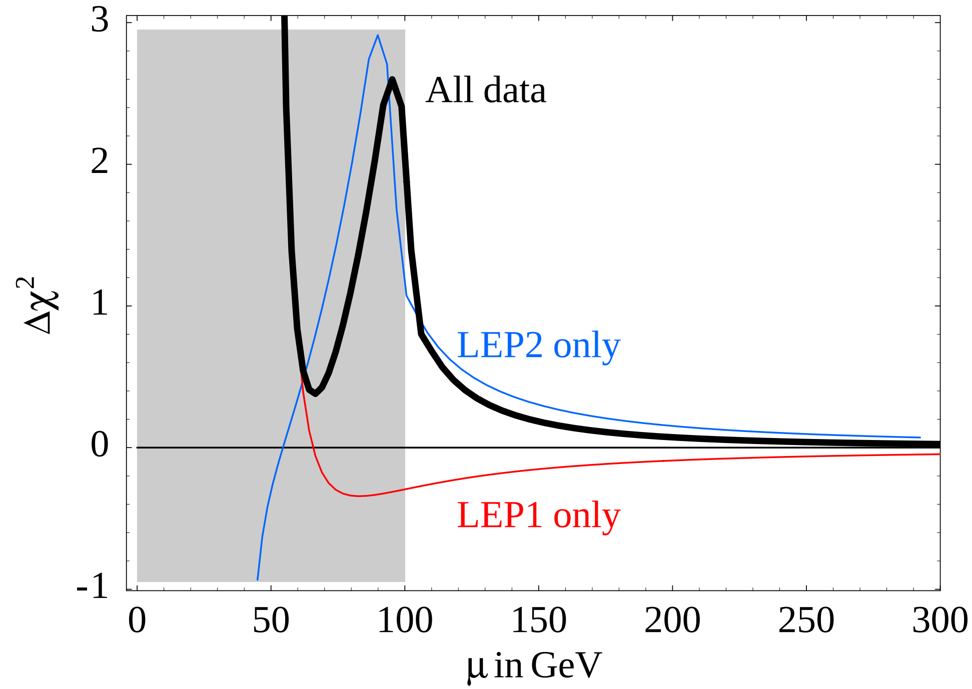
$$W \simeq \frac{\alpha_2}{15\pi} \frac{M_W^2}{M_2^2}$$

Only μ light.

$$\hat{S} = \hat{T} \simeq 0,$$

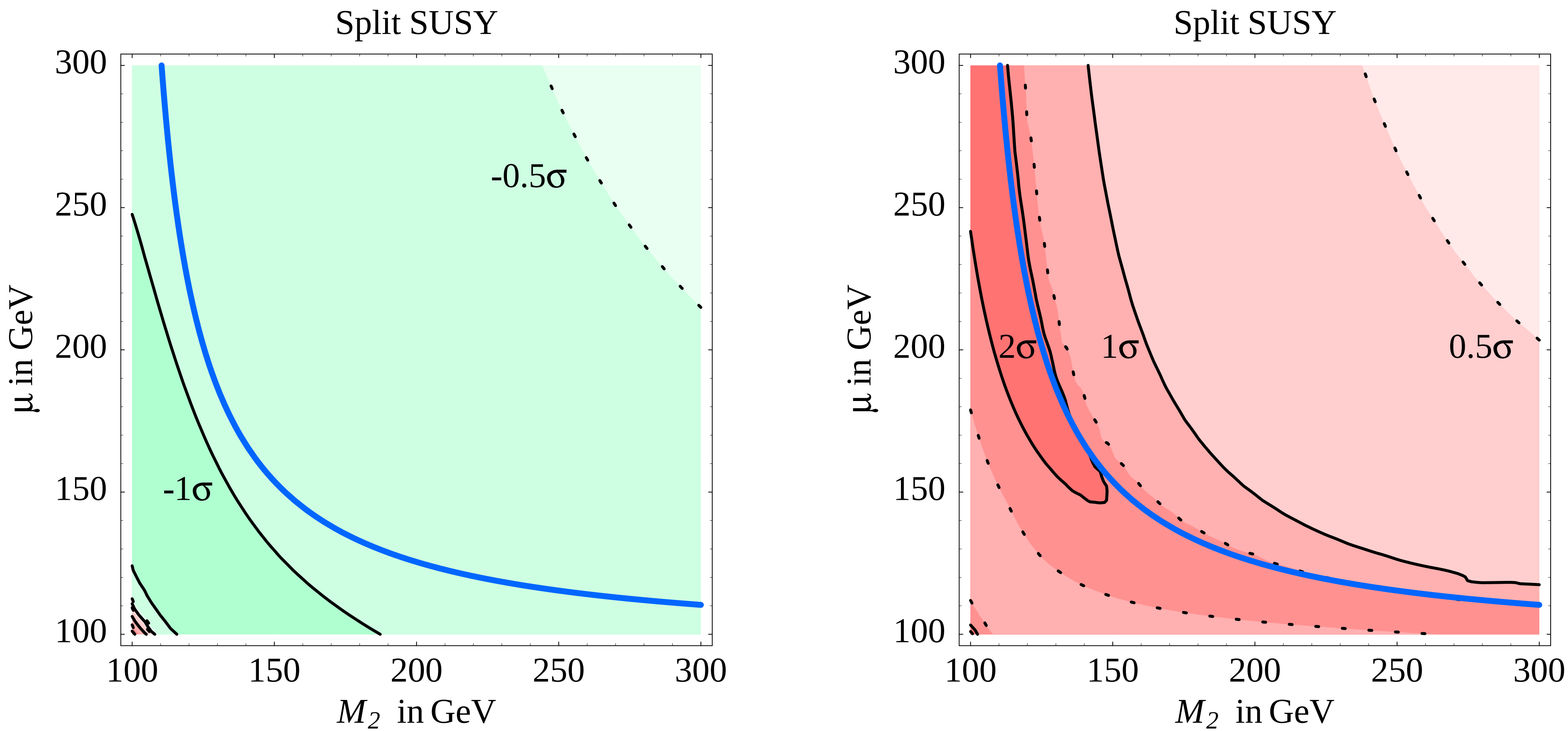
$$W \simeq Y \simeq \frac{\alpha_2}{30\pi} \frac{M_W^2}{\mu^2}.$$





Split SUSY

($\tan\beta = 10$, gaugino unification)

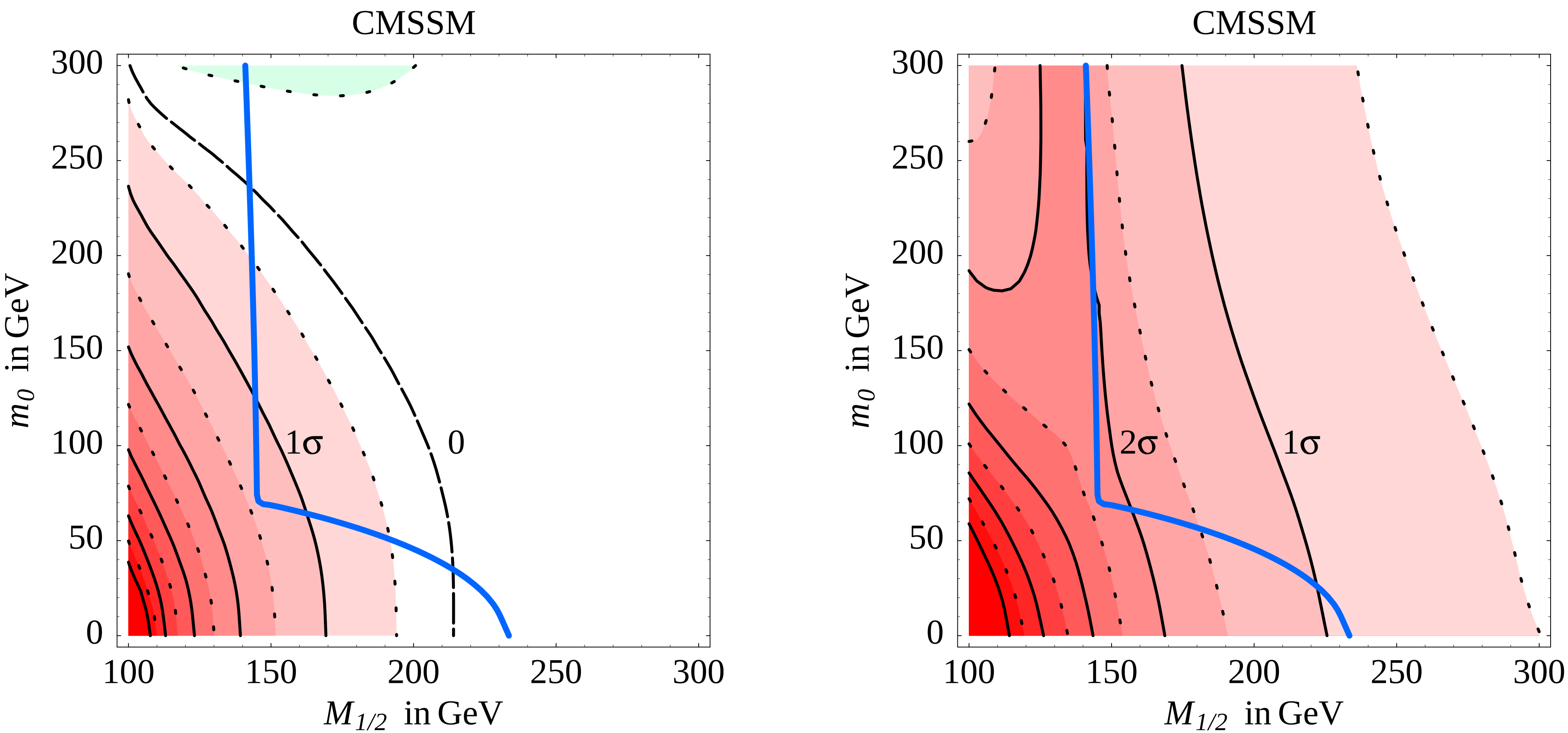


Without LEP2: mildly favoured　　　　With LEP2: mildly disfavoured

The thick blue line is the direct constraint $m_\chi, m_{\tilde{\ell}} > 100\,\text{GeV}$

The CMSSM

$(\tan\beta = 10,\ A_0 = 0,\ \mu > 0)$

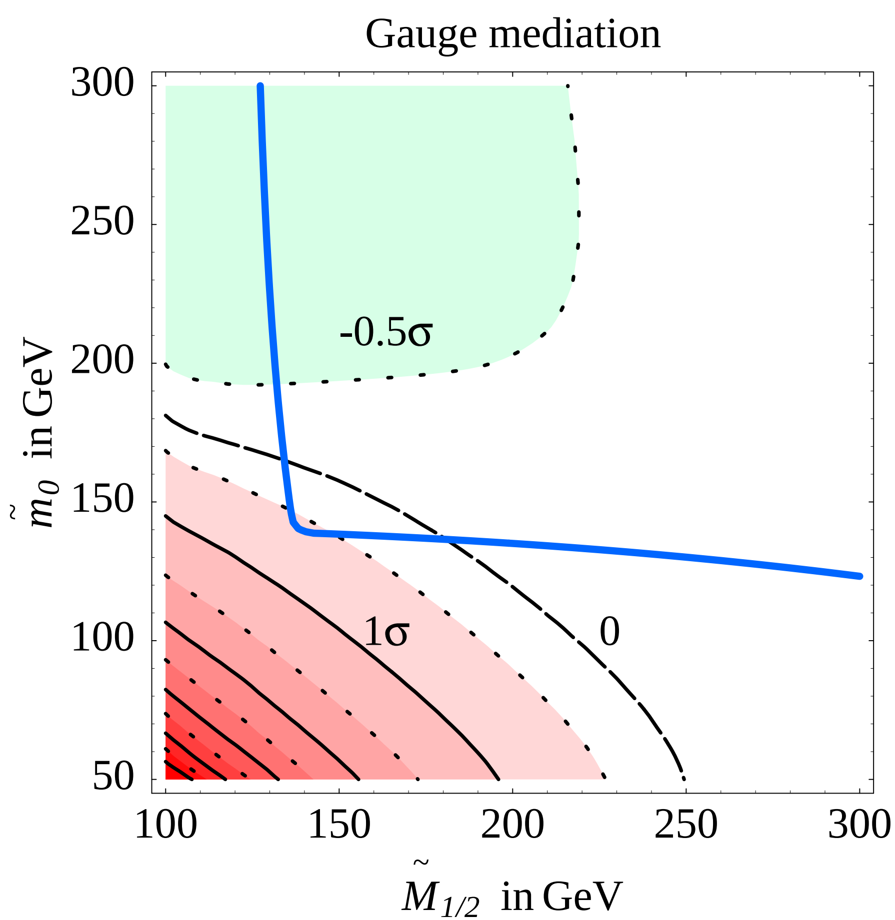


Without LEP2 | With LEP2

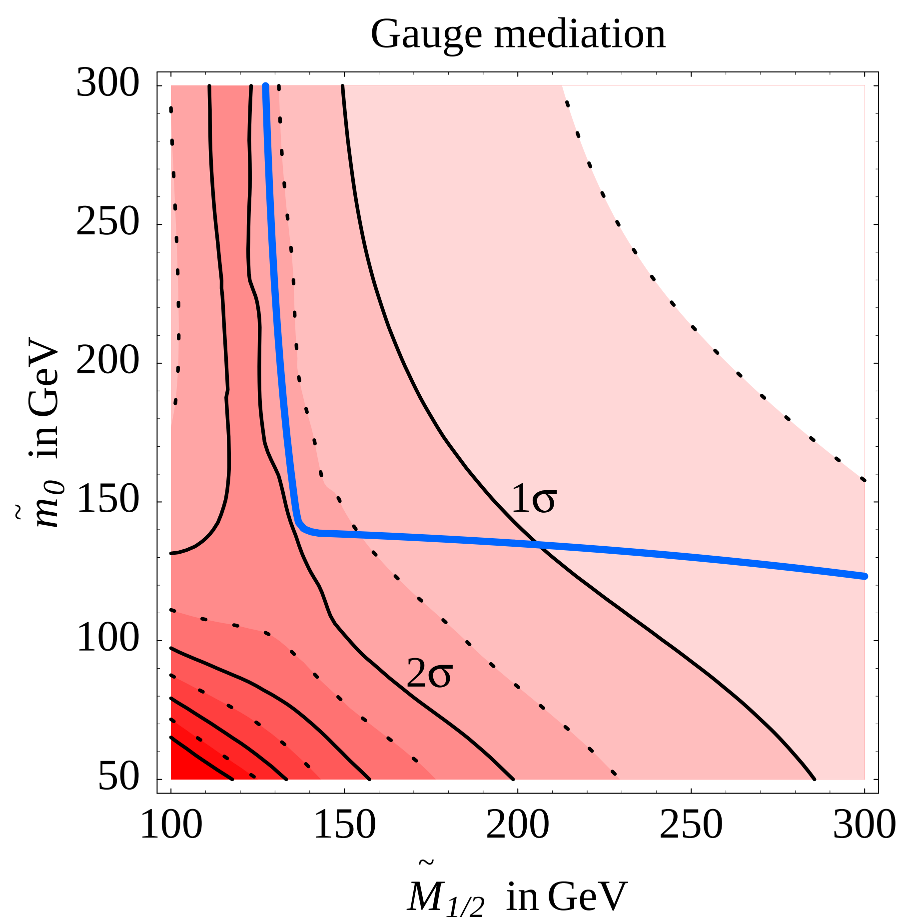
The thick blue line is the direct constraint $m_\chi, m_{\tilde{\ell}} > 100\,\text{GeV}$

Gauge mediation

$(\tan\beta = 10,\ M_{\rm GM} = 10^{10}\,\text{GeV},\ \mu > 0)$



Without LEP2

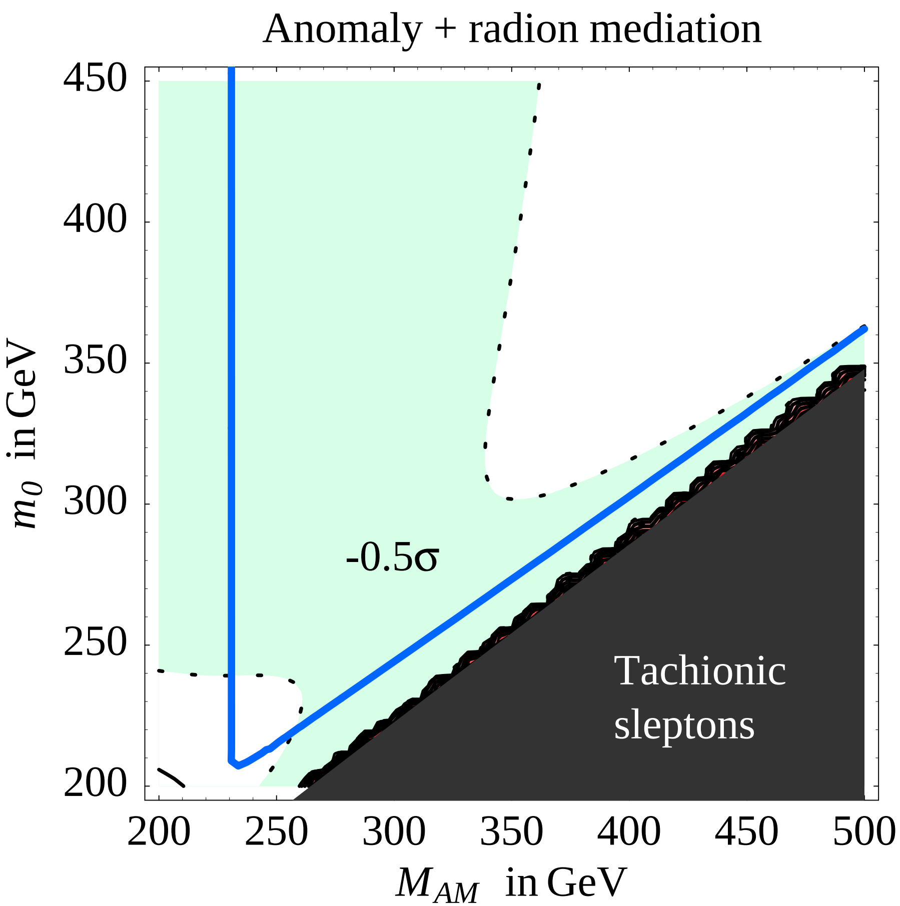


With LEP2

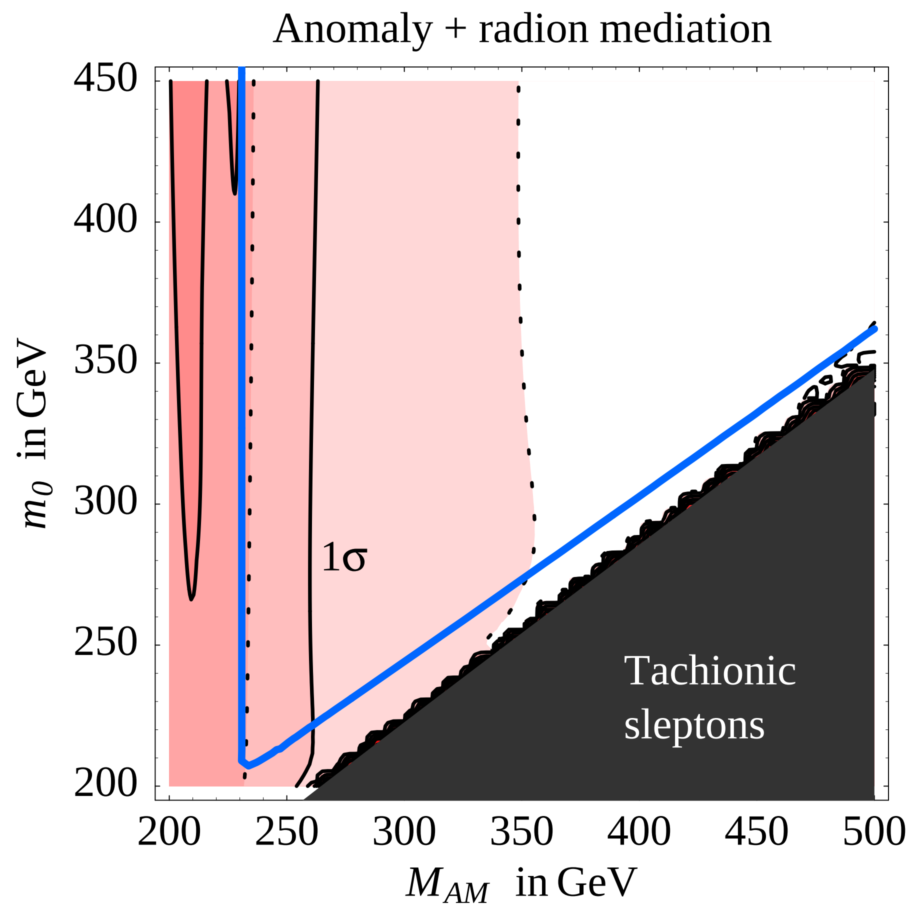
The thick blue line is the direct constraint $m_\chi, m_{\tilde\ell} > 100\,\text{GeV}$

Anomaly + radion mediation

$(\tan\beta = 10,\ \mu > 0)$



Without LEP2

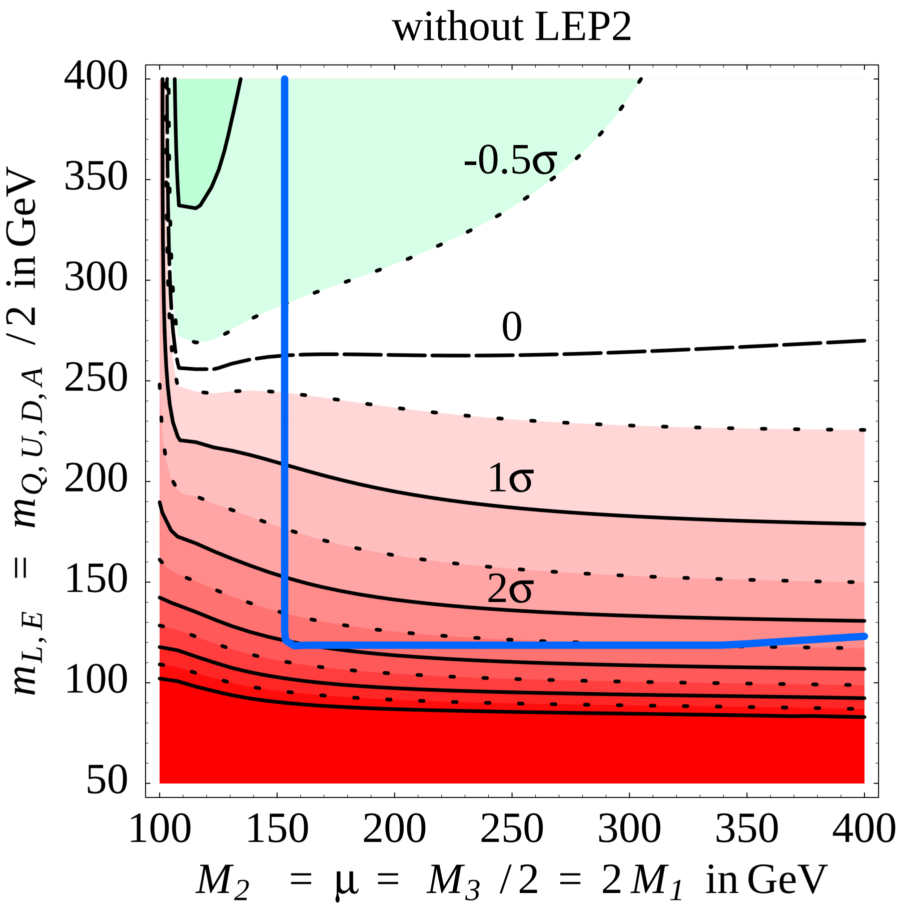


With LEP2

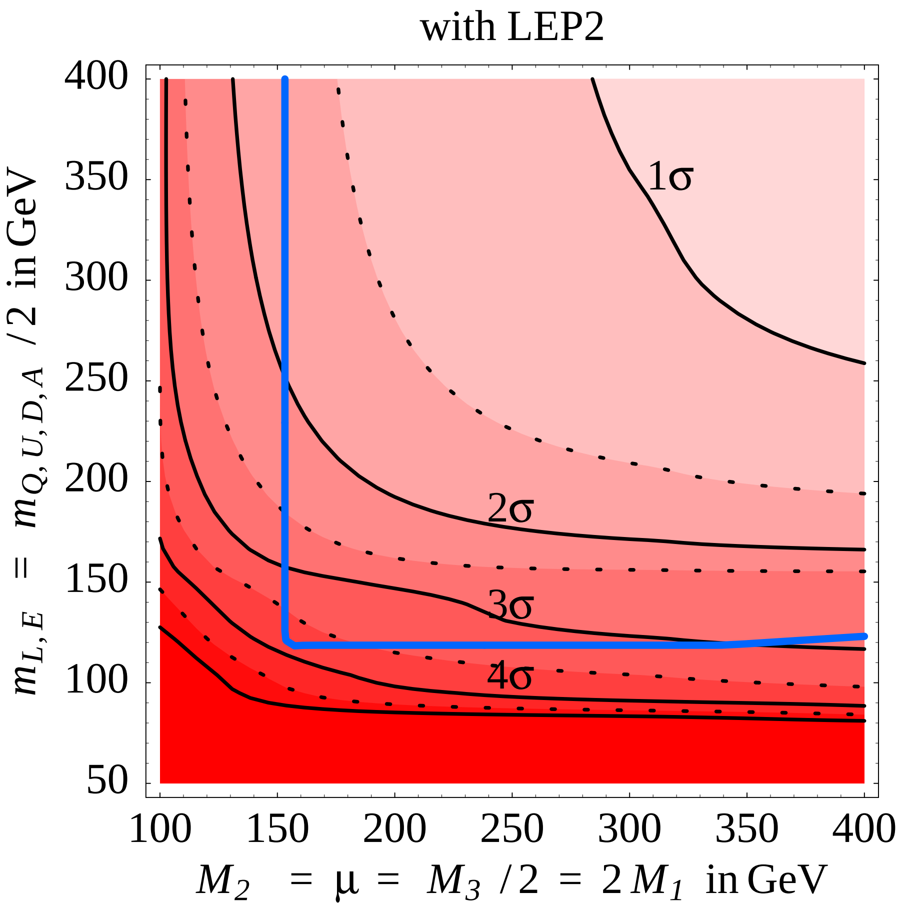
The thick blue line is the direct constraint $m_\chi, m_{\tilde{\ell}} > 100\,\text{GeV}$

A simple model

chosen such that all sparticles can be at the same time
as light as allowed by direct constraints (thick blue line)



Without LEP2



With LEP2

Conclusions

- Precision data: only constraints, but relevant for the hierarchy problem

- LEP2 $e\bar{e} \to f\bar{f}$ data are relevant

- Heavy universal models: $\widehat{S}, \hat{T}, W, Y$ (not S, T, U)
  - Gauge bosons in extra dimensions.
  - Higgsless.
  - Little Higgs: $f >$ few TeV. $\widehat{S} > (W + Y)/2$, $W, Y > 0$.

- Generic Z' approximated with leptonic $\widehat{S}, \hat{T}.W.Y$

- Supersymmetry: LEP2 removes previous hints

あいがとっ。