Theories of electroweak symmetry breaking and precision data after LEP2

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The Higgs hierarchy problem

Two main messages from ElectroWeak Precision Tests:

- The Higgs is light ($m_H < 210$ GeV)
- No new physics observed

Some mechanism needed to cut-off the Higgs mass corrections.

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Before the LHC a lot of proposals

1. New symmetries
   - Supersymmetry
   - Little Higgs

Before the LHC a lot of proposals

1. New symmetries
   - Supersymmetry
   - Little Higgs
2. Higgs as a composite object of size $1/\Lambda \sim$ TeV
   - Technicolor
   - Warped extra dimensions (AdS dual of a CFT ”walking technicolor”)

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LEP1: $Z-$ pole measurements

LEP2: above the $Z-$ pole. $e^+e^- \to f\bar{f}$ cross sections up to $\sqrt{s} \simeq 210\,\mathrm{GeV}$

LEP2 data are the only one above the $Z-$ pole: very sensitive to new physics

It is crucial to combine LEP1 and LEP2 data in a consistent way to put contraints on theories beyond the Standard Model

Corrections to precision observables

We want a formalism which allows to analyze corrections to both LEP1 and LEP2 data.

We assume that new physics is:

- universal, i.e. the fermion gauge interactions are

$$\mathscr{L}_{\rm int} = \bar{\Psi}\gamma^{\mu}\left(T^a \bar{W}^a_{\mu} + Y\bar{B}_{\mu}\right)\Psi$$

  $\bar{W}_{\mu}, \bar{B}$ NOT necessarily mass eigenstates

- heavy: there is a gap between the electroweak scale and the new physics scale M:
  M_W^2/M^2 good perturbative expansion parameter

Corrections to precision observables

Under these two assumptions only 4 dimension 6 operators can be generated Grinstein and Wise, 1991

$$\mathcal{O}_{WB} = \frac{1}{gg'}(H^\dagger \tau^a H) W^a_{\mu\nu} B_{\mu\nu} \qquad \to S$$

$$\mathcal{O}_{H} = \left| H^\dagger D_\mu H \right|^2 \qquad \to T$$

$$\mathcal{O}_{BB} = \frac{1}{2g'^2} \left(\partial_\rho B_{\mu\nu}\right)^2 \qquad \to Y$$

$$\mathcal{O}_{WW} = \frac{1}{2g^2} \left(D_\rho W^a_{\mu\nu}\right)^2 \qquad \to W$$

Corrections to precision observables

In terms of the gauge bosons inverse propagators

$$\Pi_{ij}(p^2) = \Pi_{ij}(0) + p^2\Pi'_{ij}(0) + \tfrac{1}{2}p^4\Pi''_{ij}(0)$$
$$i,j = W^\pm, W^3, B$$

Adimensional form factors			operators
$g^{-2}S$	$=$	$\Pi'_{W_3B}(0)$	$\mathcal{O}_{WB} = (H^\dagger\tau^a H)W^a_{\mu\nu}B_{\mu\nu}/gg'$
$g^{-2}M_W^2T$	$=$	$\Pi_{W_3W_3}(0) - \Pi_{W^+W^-}(0)$	$\mathcal{O}_H = \lvert H^\dagger D_\mu H\rvert^2$
$-g^{-2}U$	$=$	$\Pi'_{W_3W_3}(0) - \Pi'_{W^+W^-}(0)$	$-$
$2g^{-2}M_W^{-2}V$	$=$	$\Pi''_{W_3W_3}(0) - \Pi''_{W^+W^-}(0)$	$-$
$2g^{-1}g'^{-1}M_W^{-2}X$	$=$	$\Pi''_{W_3B}(0)$	$-$
$2g'^{-2}M_W^{-2}Y$	$=$	$\Pi''_{BB}(0)$	$\mathcal{O}_{BB} = (\partial_\rho B_{\mu\nu})^2/2g'^2$
$2g^{-2}M_W^{-2}W$	$=$	$\Pi''_{W_3W_3}(0)$	$\mathcal{O}_{WW} = (D_\rho W^a_{\mu\nu})^2/2g^2$

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$g^{-2}M_W^2 T$	$=$	$\Pi_{W_3W_3}(0) - \Pi_{W^+W^-}(0)$	$\mathcal{O}_H$	$=$	$\lvert H^\dagger D_\mu H\rvert^2$
$-g^{-2}U$	$=$	$\Pi'_{W_3W_3}(0) - \Pi'_{W^+W^-}(0)$	$-$		
$2g^{-2}M_W^{-2}V$	$=$	$\Pi''_{W_3W_3}(0) - \Pi''_{W^+W^-}(0)$	$-$		
$2g^{-1}g'^{-1}M_W^{-2}X$	$=$	$\Pi''_{W_3B}(0)$	$-$		
$2g'^{-2}M_W^{-2}Y$	$=$	$\Pi''_{BB}(0)$	$\mathcal{O}_{BB}$	$=$	$(\partial_\rho B_{\mu\nu})^2/2g'^2$
$2g^{-2}M_W^{-2}W$	$=$	$\Pi''_{W_3W_3}(0)$	$\mathcal{O}_{WW}$	$=$	$(D_\rho W^a_{\mu\nu})^2/2g^2$

$\hat{U}, X$ are dimension 8 operators, V is dimension 10

$\hat{S}, \hat{T}, W, Y$ are the only 4 relevant parameters

Corrections to precision observables

- $Z-$ pole observables.
  All effects are encoded in $\varepsilon_{1,2,3}$ Altarelli, Barbieri, 1991

$$\delta\varepsilon_1 \simeq \widehat{T} - W - Y\frac{s_{\rm W}^2}{c_{\rm W}^2}\,, \qquad \delta\varepsilon_2 \simeq -W\,, \qquad \delta\varepsilon_3 \simeq \widehat{S} - W - Y$$

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- $Z-$ pole observables + LEP2 :
  $\hat{S}, \hat{T}, W, Y$ are completely measured
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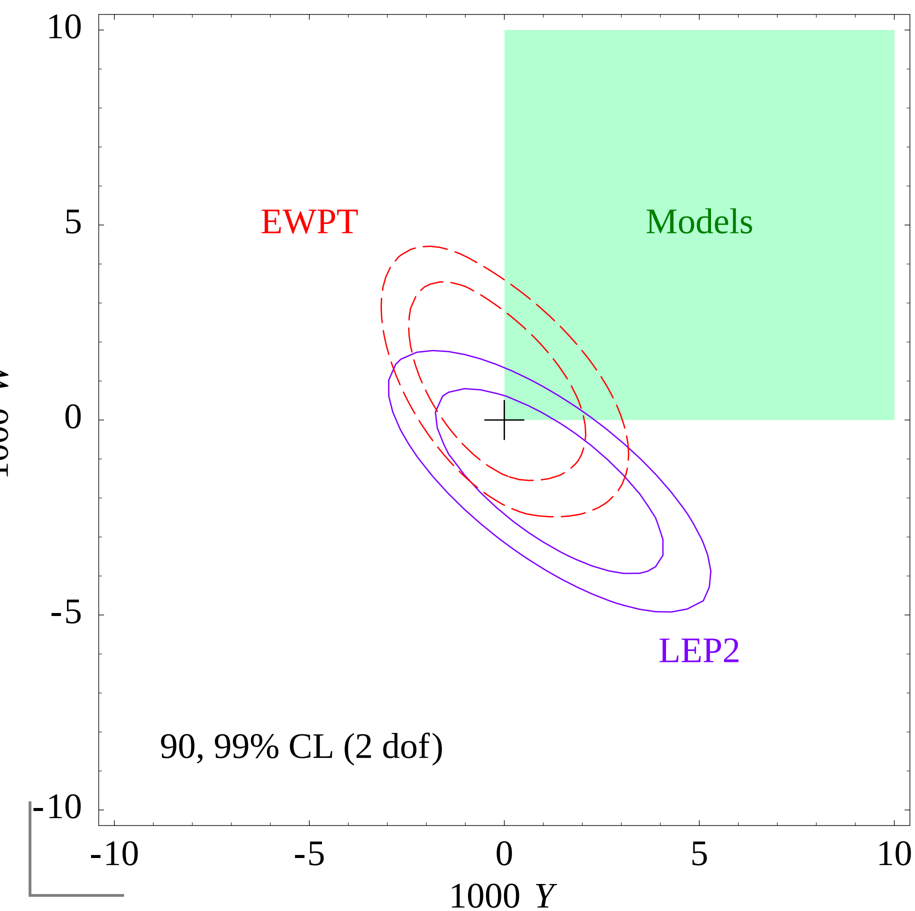
Type of fit	$1000\,\hat{S}$	$1000\,\hat{T}$	$1000\,W$	$1000\,Y$	$\chi^2_{\rm SM} - \chi^2_{\rm min}$
All data	-0.3	-0.6	-0.7	0.4	1.1^2
Excluding NuTeV (our default fit)	0	0.2	-0.2	0	0.5^2
Excluding NuTeV and A^b_{FB}	-0.9	-0.3	-0.4	0.2	1.2^2

LEP1 vs. LEP2

Given a set of data, we build $\chi^2(\hat{S}, \hat{T}, W, Y)$

$$\chi^2(\hat{S}=0, \hat{T}=0, W, Y)$$



LEP2 prefers $W < 0$

At $E \gg M_Z$

$$\frac{\delta\sigma(e\bar{e} \to q\bar{q})}{\sigma(e\bar{e} \to q\bar{q})} \simeq -\frac{2E^2 W}{M_W^2} \frac{c_W^4}{1 - 2s_W^2 + 64 s_W^4/9}$$

LEP2 sees a mild excess of $e^+e^- \to$ hadrons excess

Signifcant impact on new physics models

Little Higgs models

Interpret the Higgs as a pseudo Goldstone boson

- Approximate global symmetry G broken down at $f \sim \mathrm{TeV}$ to a subgroup G'
- Collective symmetry breaking: gauge group $G_1 \otimes G_2$. Both gauge groups needed to make to the Higgs a PGB.
- Quadratic divergences only at 2 loop.

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Some common features

- New heavy vector bosons
- New heavy fermions (top)
- Scalar triplets

Little Higgs models

- Little Higgs model Arkani Hamed et al., 2002
  $G = \mathrm{SU}(5), G' = \mathrm{SO}(5)$
  Gauge group $(\mathrm{SU}(2) \otimes \mathrm{U}(1))^2$
  Fermions charged under $\mathrm{SU}(2)_1 \otimes \mathrm{U}(1)_1$
- $\mathrm{SU}(6)/\mathrm{Sp}(6)$ model Low et al. 2002, Gregoire et al. 2003
  Gauge group $(\mathrm{SU}(2) \otimes \mathrm{U}(1))^2$
  Fermions charged under $\mathrm{SU}(2)_1 \otimes \mathrm{U}(1)_1$
- $\mathrm{SO}(9)/(\mathrm{SO}(5) \otimes \mathrm{SO}(4))$ model S. Chang, 2003
  Gauge group $\mathrm{SU}(2)_L \otimes \mathrm{SU}(2)_R \otimes \mathrm{SU}(2) \otimes \mathrm{U}(1)$
  Fermions charged under $\mathrm{SU}(2) \otimes \mathrm{U}(1)$
- "Simplest little Higgs" M. Schmaltz, 2004
  Gauge group $SU(3)_w \otimes U(1)_X$

Little Higgs models

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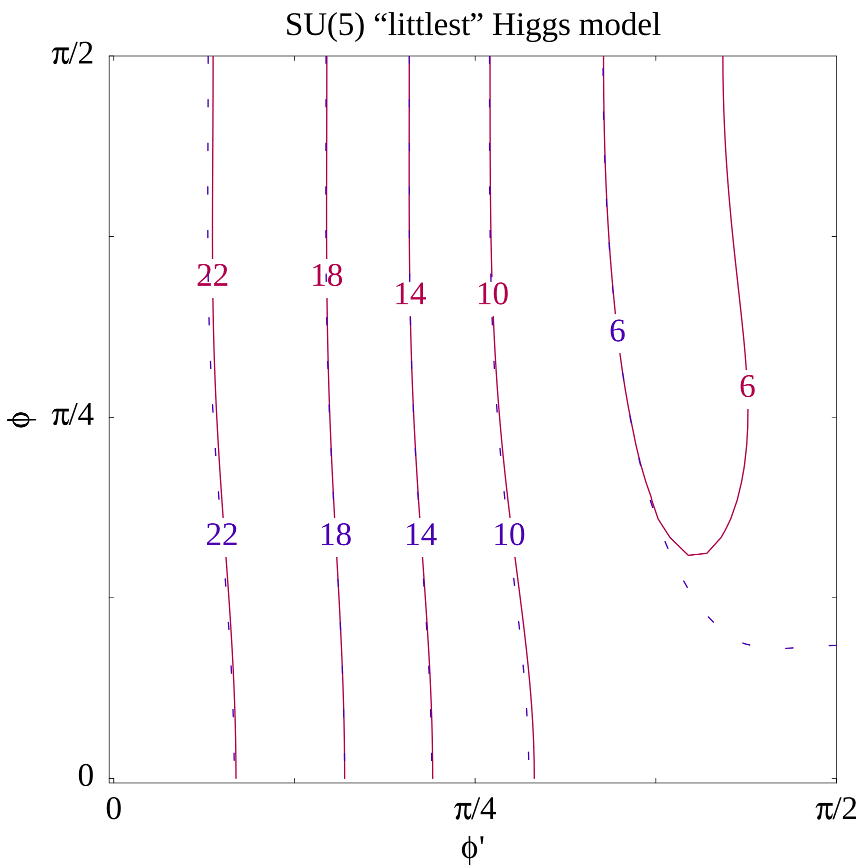
global	gauge	$\hat{S}$	$\hat{T}$	W	Y
$SU(5)$	32211	$\frac{2M_W^2}{g^2f^2}\left[\cos^2\phi + 5\frac{c_W^2}{s_W^2}\cos^2\phi'\right]$	$\frac{5M_W^2}{g^2f^2} + \hat{T}_{\text{triplet}}$	$\frac{4M_W^2}{g^2f^2}\cos^4\phi$	$\frac{20M_W^2}{g'^2f^2}\cos^4\phi'$
$SU(5)$	3221	$\frac{2M_W^2}{g^2f^2}\cos^2\phi$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

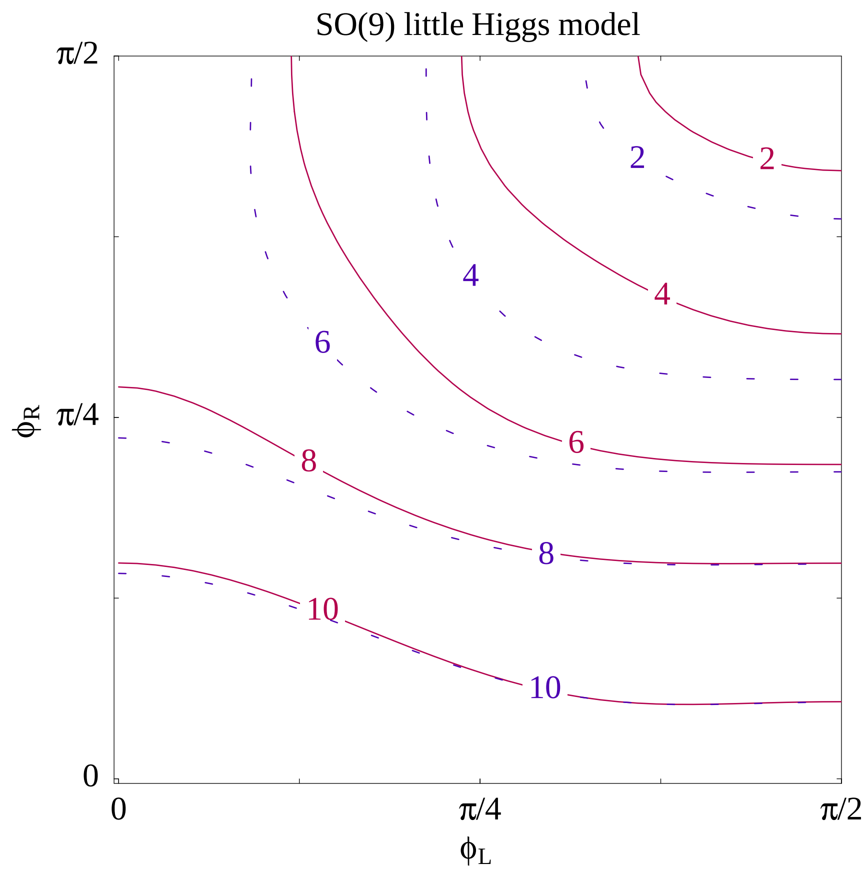
$$\tan\phi = g_2/g_1, \qquad \tan\phi' = g_2'/g_1', \qquad \tan\phi_L = g_L/g_2,, \qquad \tan\phi_R = g_R/g_1,$$

Various disagreements with previous analysis

Little Higgs models

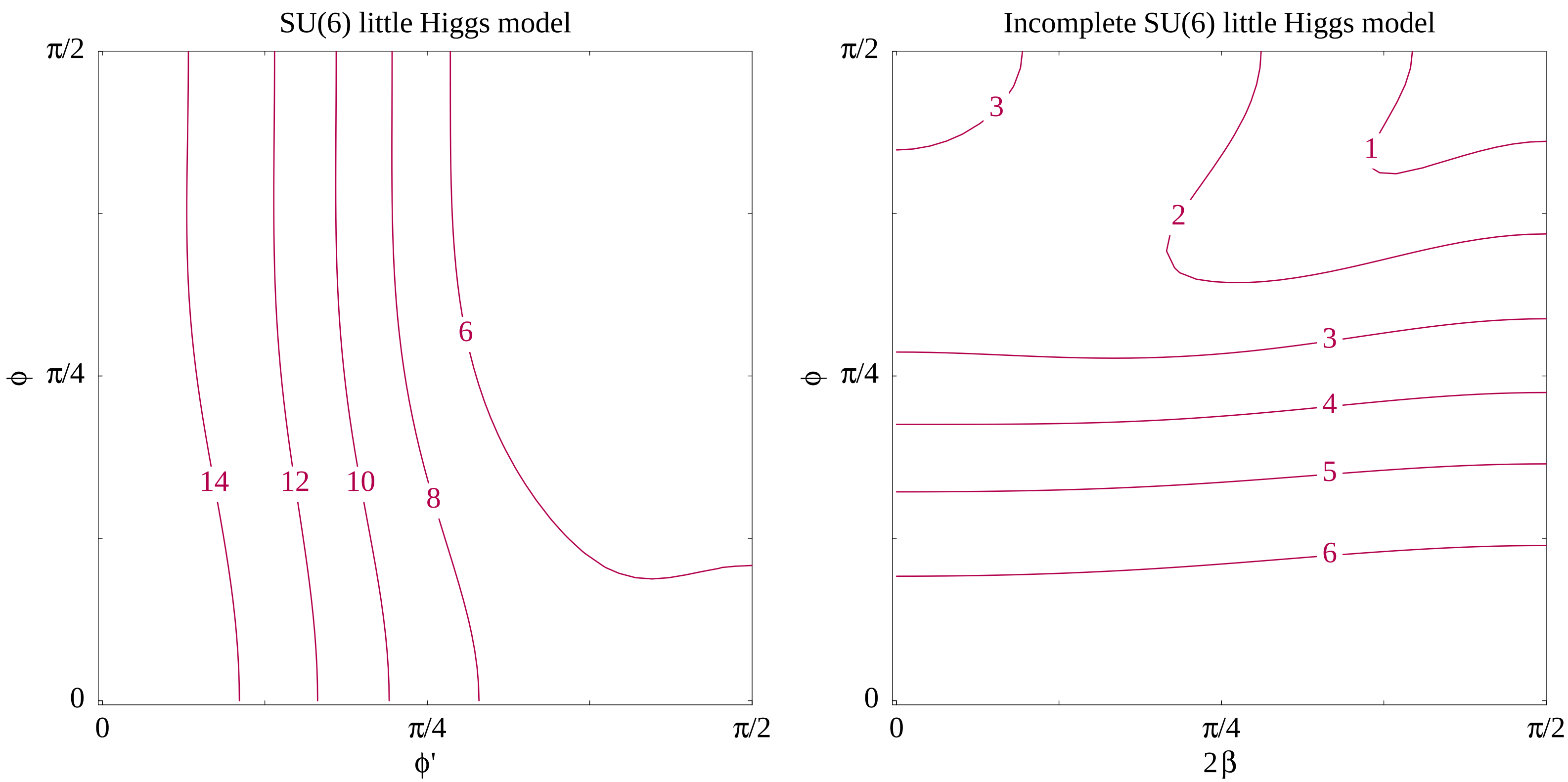
Models with Higgs triplets





Little Higgs models

Models with no Higgs triplets



Simplest Little Higgs: $f > 4.5$ TeV

Little Higgs models

- All the tree level effects condensed in 4 parameters
- No model much better than others: always $f \gtrsim \text{few TeV}$
- Predicted inequalities: $W, Y > 0$, $\hat{S} > (W + Y)/2$

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"Little hierarchy problem ": fine tuning if the same scale Λ

1. Cuts off quadratically divergent corrections to m_h^2
2. Suppresses higher order operators

Little Higgs models realize this problem ($\Lambda \to f$)
but don't solve it

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T-parity: no tree level effects, $f \sim v$.
Origin and stability of the scale $f \ll 10\,\text{TeV}$?

Supersymmetry

General features

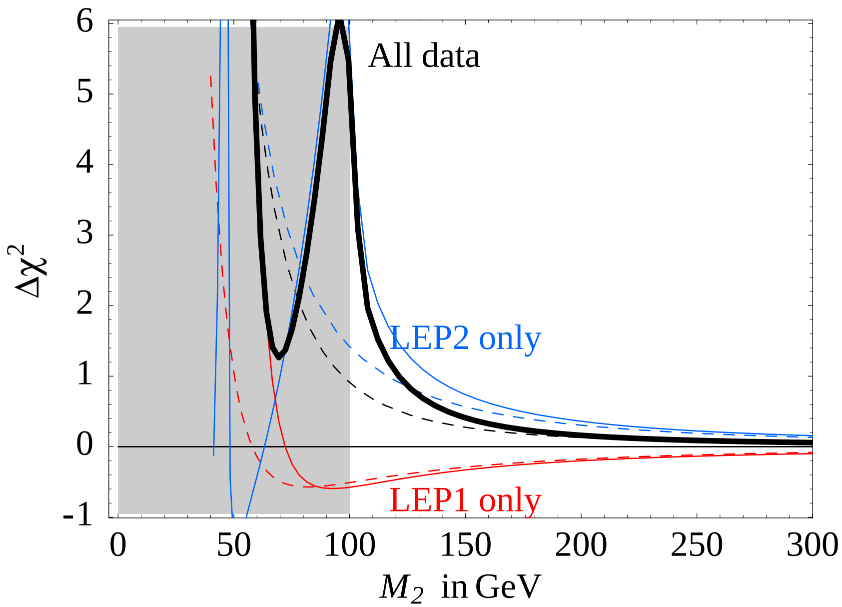
- $\hat{S}, \hat{T}, W, Y$ insufficient:
  SUSY is neither universal nor heavy
- But gaugino/higgsinos and sfermions are separately universal
- Model independence
- No big enhancement or suppressions
- $W, Y > 0$ can be cumulative if all particles are light
- Significant impact of LEP2

Split Supersymmetry

Case $\mu \gg M_2$

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

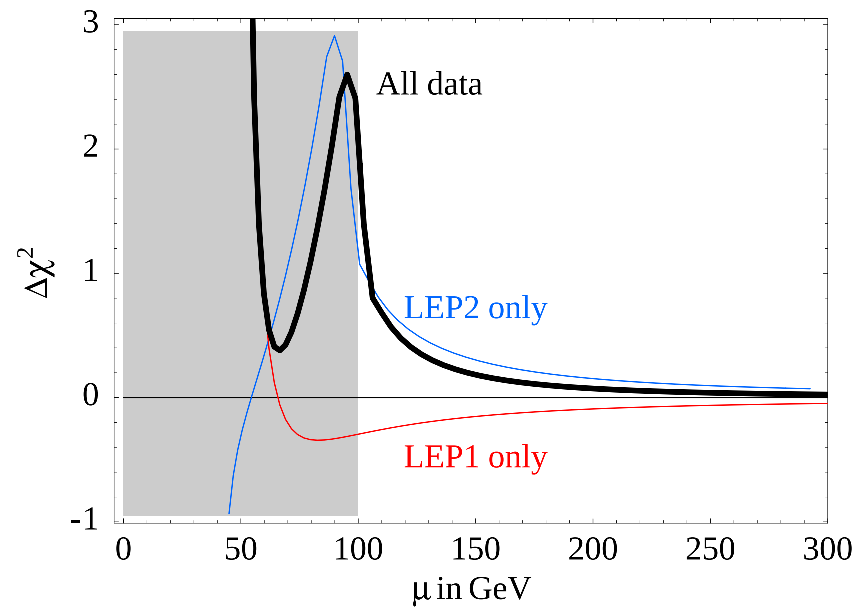
$$W = \frac{\alpha_2}{15\pi}\frac{M_W^2}{M^2}$$



Case $M_2 \gg \mu$

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

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



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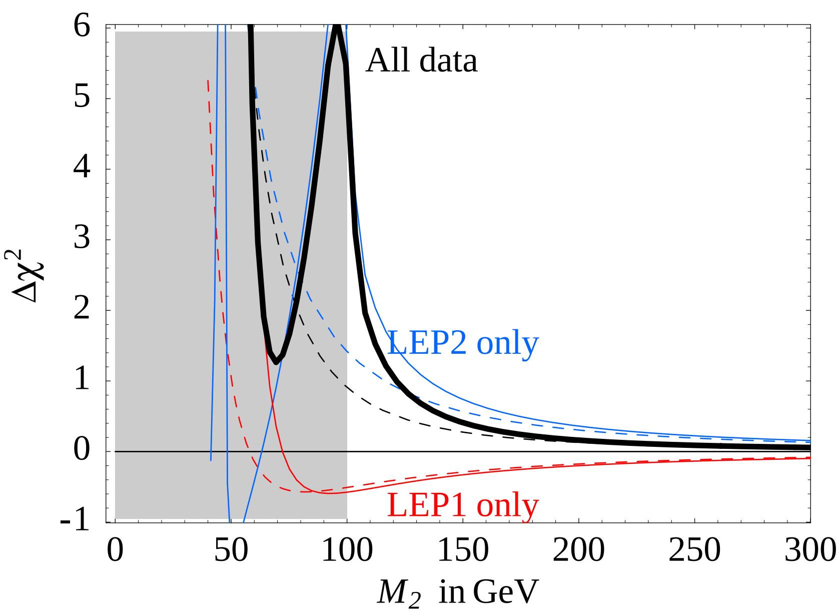
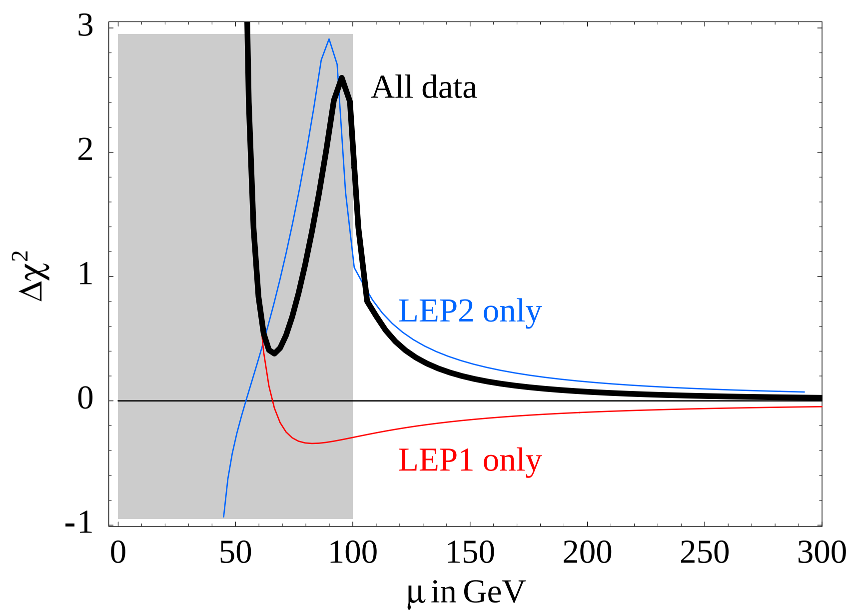
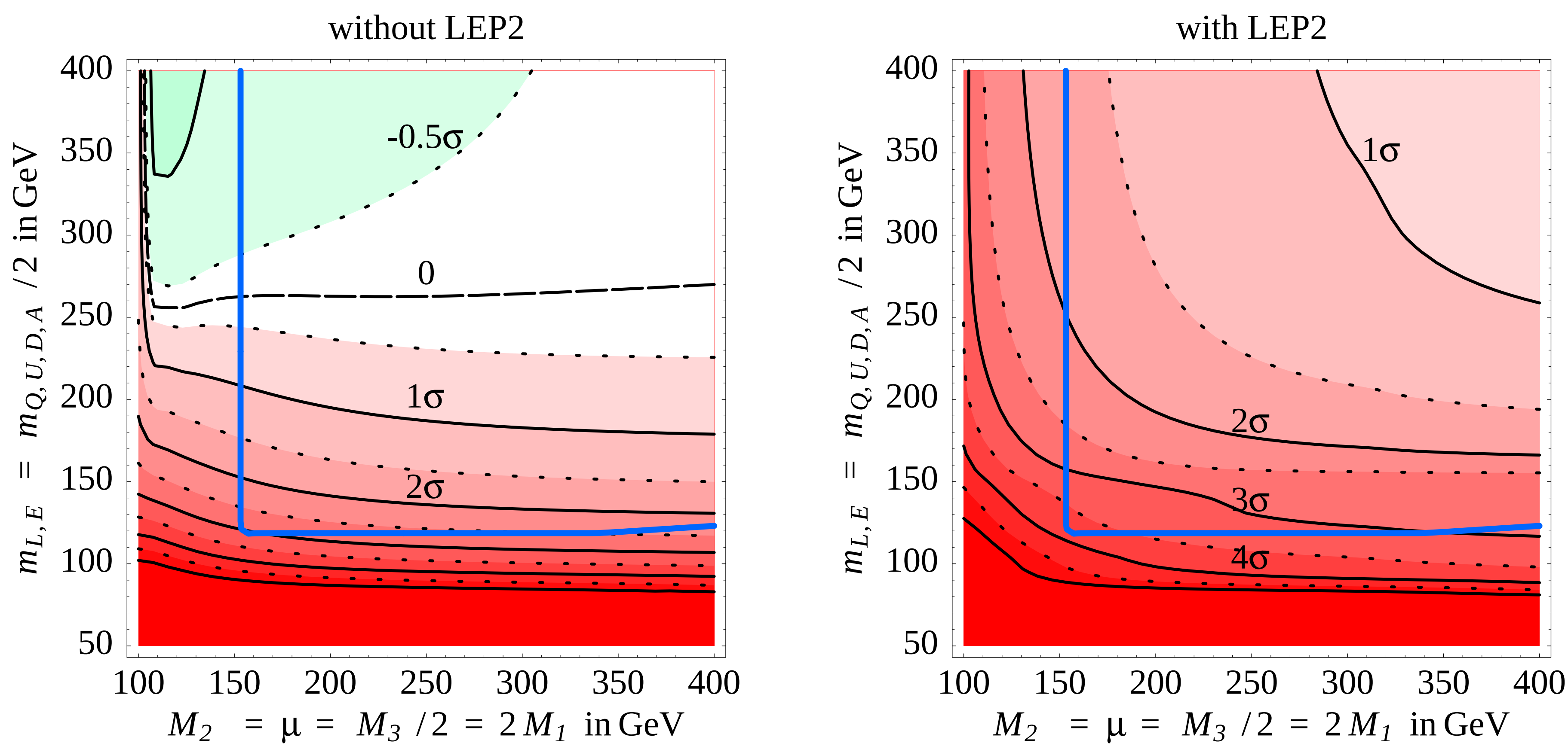




SUPERSPLIT SUPERSYMMETRY FAVORED AT 2.2σ !!

A simple model

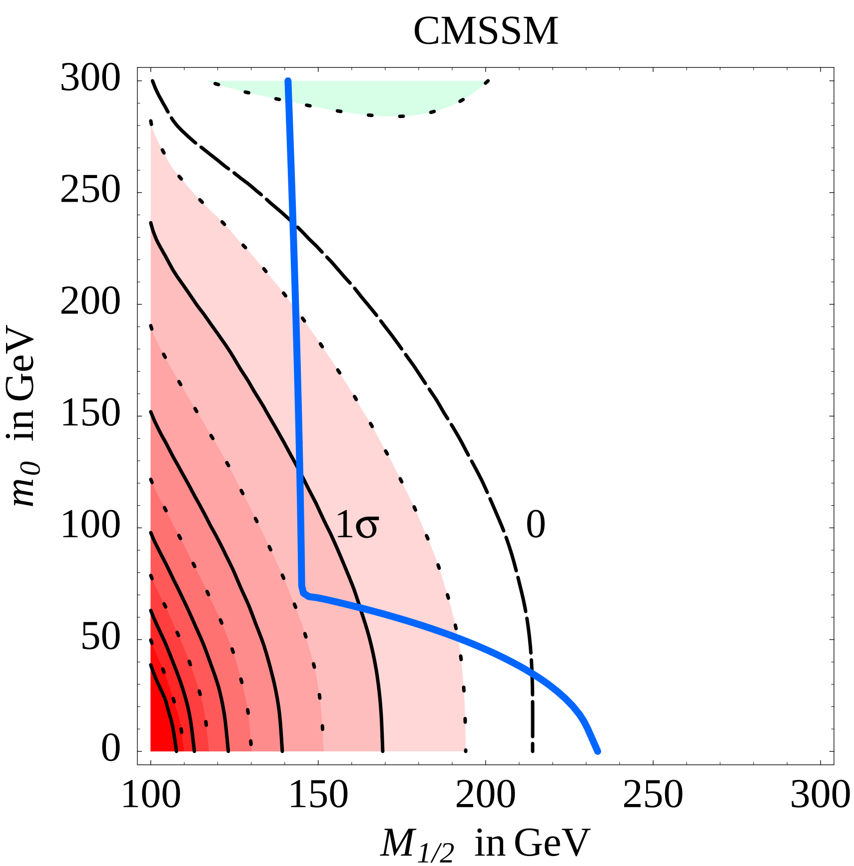
All SUSY particles with the same mass



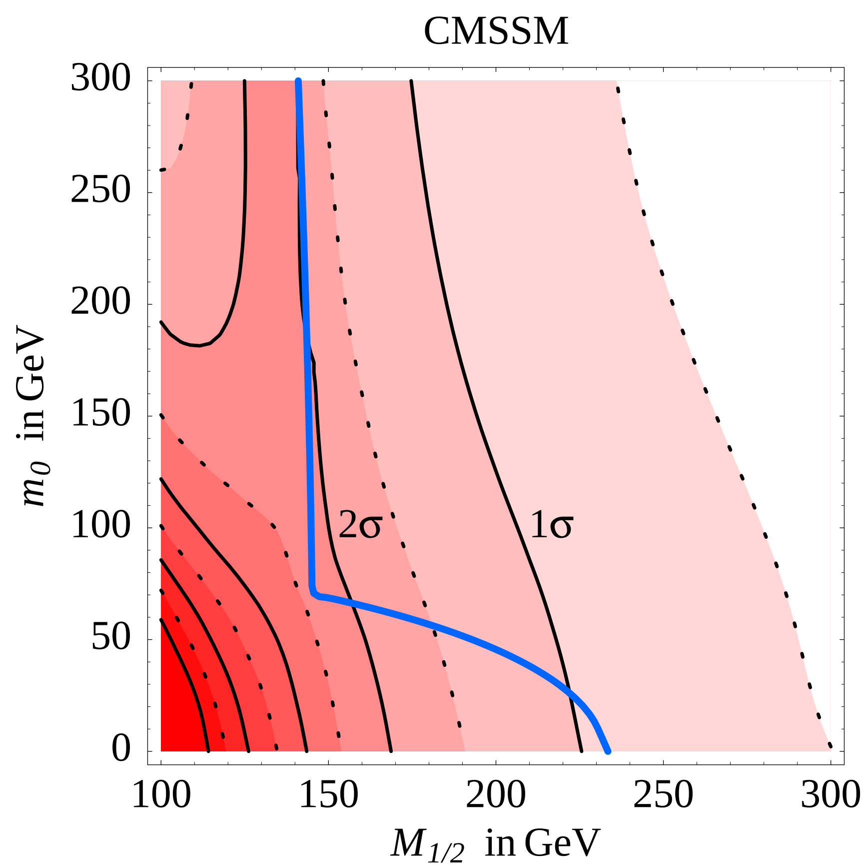
Note the impact of LEP2

The CMSSM

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



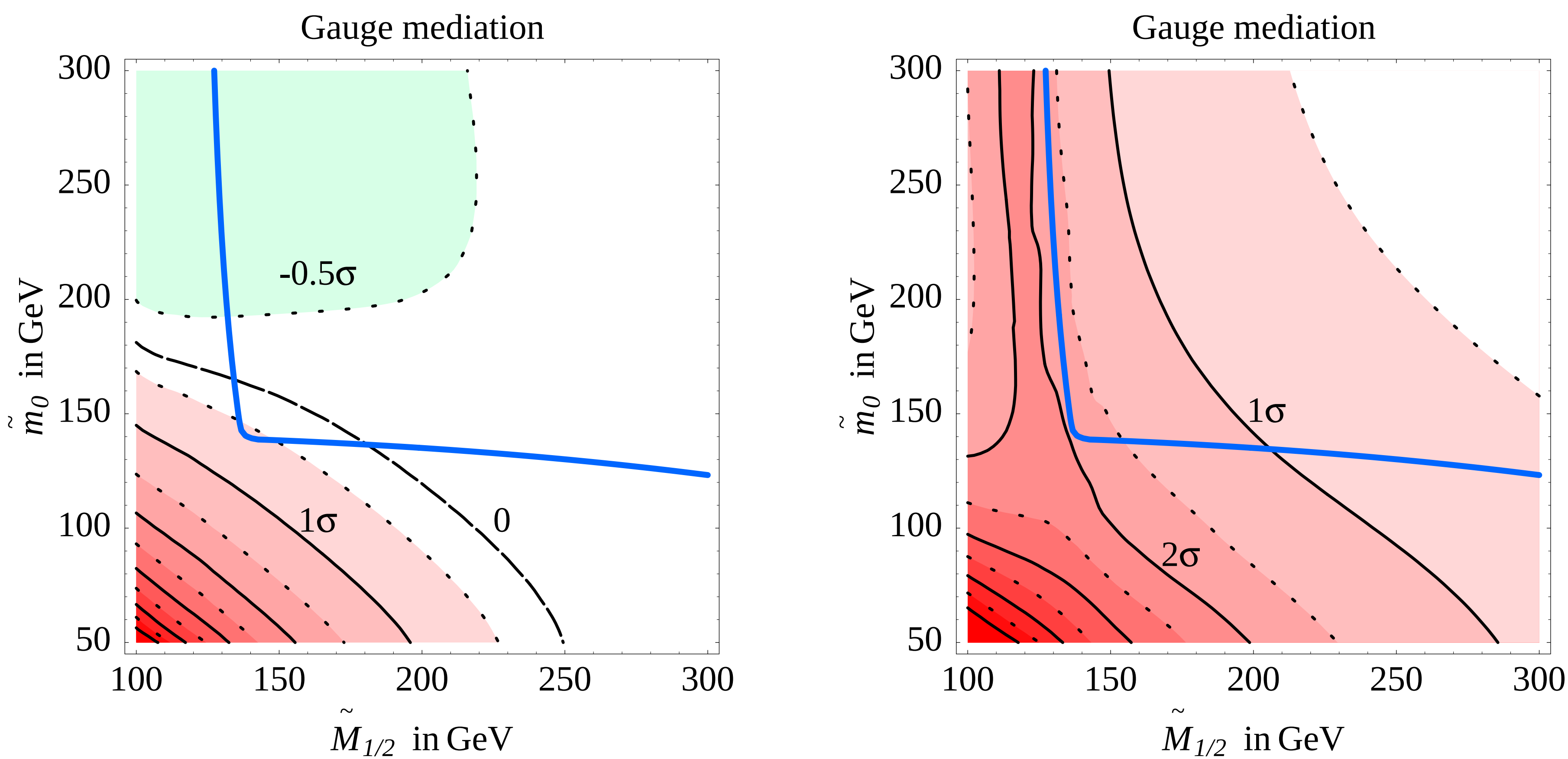
Without LEP2



With LEP2

Gauge mediation

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



Without LEP2 With LEP2

Conclusions

- LEP2 data very important
- Heavy universal models: all the effects are encoded in $\hat{S}, \hat{T}, W, Y$
- Little Higgs: $f >$ few TeV
- Supersymmetry: LEP2 removes previous hints