Higgs and Precision Electroweak Measurements

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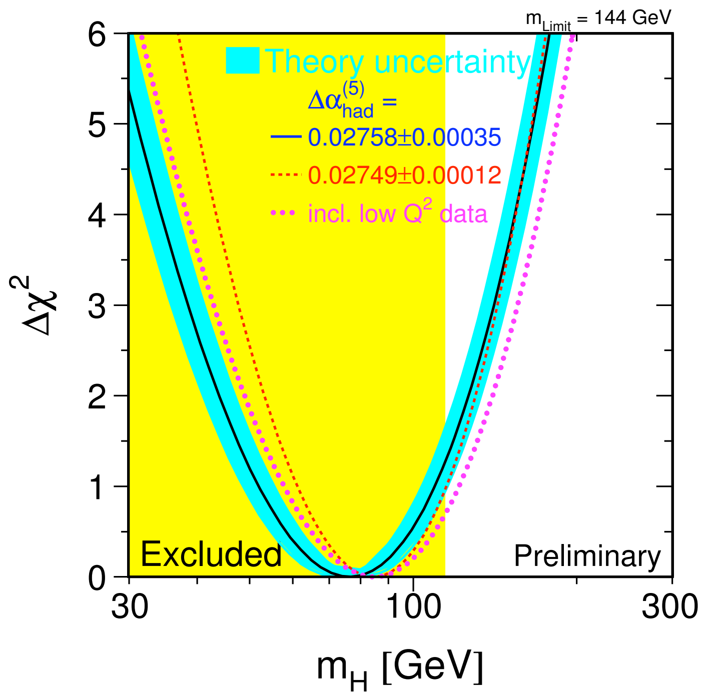
SM with a Light Higgs

[LEP EWWG, summer '07]



input: $m_t = 170.9 \pm 1.8$ GeV

best fit: $m_h = 76^{+36}_{-24}$ GeV

one-sided 95% CL: $m_h < 144$ GeV

SM with a light Higgs works pretty well!

precision measurements + direct search limit: $m_h < 182$ GeV

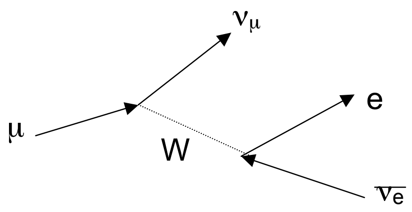
SM with a Light Higgs

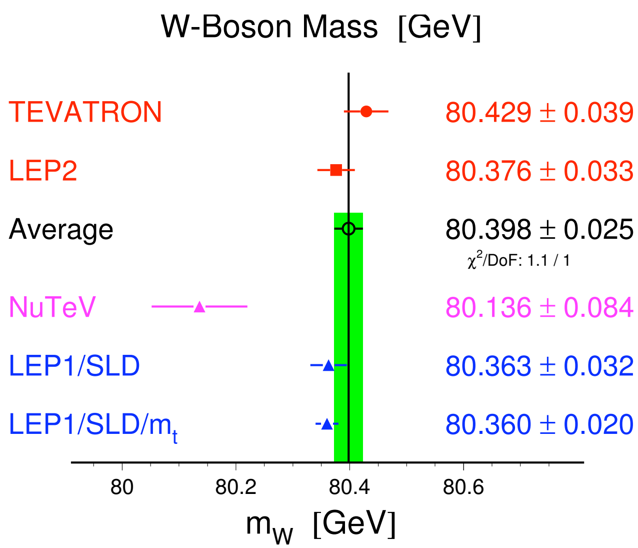
- SM prediction for Mw: input α, M_Z, G_F, M_H → predict M_W

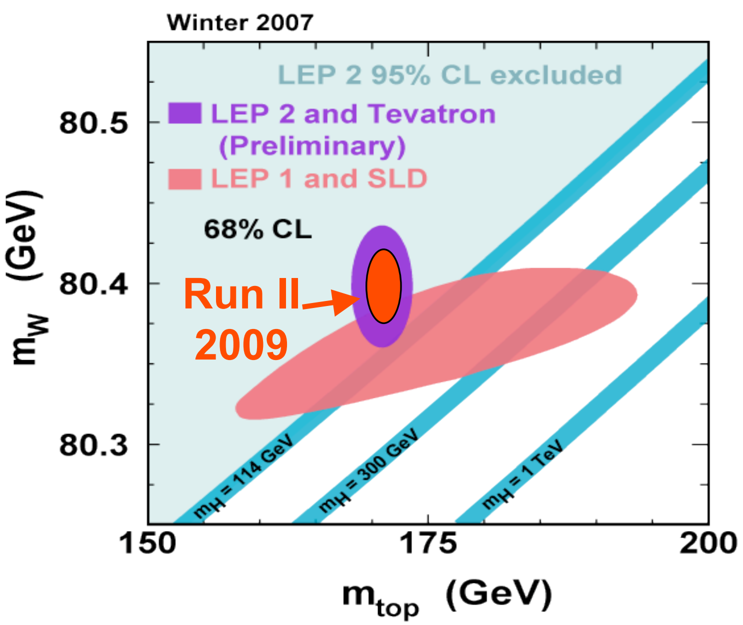
$$M_W^2\left(1-\frac{M_W^2}{M_Z^2}\right)=\frac{\pi\,\alpha}{\sqrt{2}\,G_\mu}(1+\Delta r)$$

$$\Delta r_{1-\mathrm{loop}} = \Delta\alpha - \frac{c_W^2}{s_W^2}\Delta\rho + \Delta r_{\mathrm{rem}}(M_H)$$

	$\Delta\alpha$	$\frac{c_W^2}{s_W^2}\Delta\rho$	$\Delta r_{\mathrm{rem}}(M_H)$
	$\sim \log\frac{M_Z}{m_f}$	$\sim m_t^2$	$\sim \log(M_H/M_W)$
	$\sim 6\%$	$\sim 3.3\%$	$\sim 1\%$



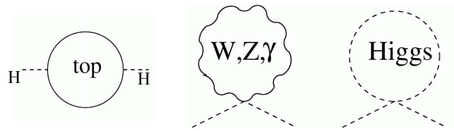




[LEP EWWG, summer '07]

Problems with SM with a Light Higgs

- Gauge hierarchy problem



$$\delta M_H^2 = \frac{G_F}{4\sqrt{2}\pi^2}\Lambda^2\left(6M_W^2 + 3M_Z^2 + M_H^2 - 12M_t^2\right) = -\left(\frac{\Lambda}{0.7\ \mathrm{TeV}}\, 200\ \mathrm{GeV}\right)^2$$

allowing ~10% fine-tuning
→ new physics at ~ 1 TeV

- model independent analysis on dim-6 operators:

$$L = \mathcal{O}_i/\Lambda^2$$

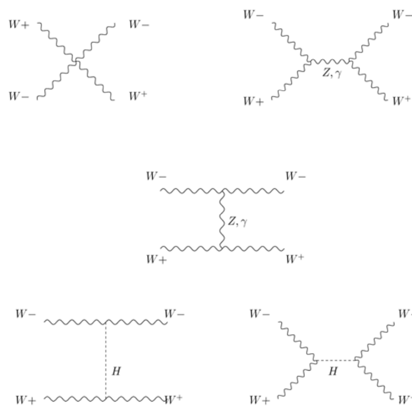
	Operator, $\mathcal{O}_i$	Λ_{min} (TeV)
LEP	$H^\dagger \tau H W^a_{\mu\nu} B^{\mu\nu}$	10
LEP-2	$\bar{e}\gamma_\mu e \bar{l}\gamma^\mu l$	5
Flavor	$H^\dagger \bar{d}_R \sigma_{\mu\nu} q_L F^{\mu\nu}$	9

- tension bt EWPT and scale required for New Physics solution to gauge hierarchy problem

- global fit to some 21 flavor and CP conserving operators show certain directions loosely constrained [Han, Skiba, '04]

Problems with SM with a Light Higgs

- Why do we need a Higgs anyway?
  - Unitarity



$$A \approx g^2 \frac{E^2}{M_W^2}$$

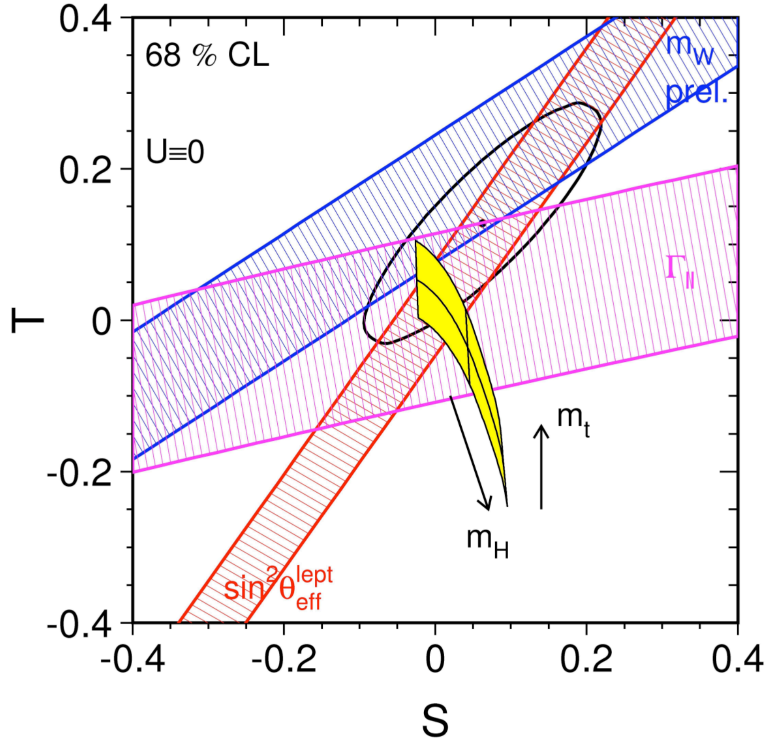
$$A \approx -g^2 \frac{E^2}{M_W^2}$$

Terms which grow with energy cancel for $E >> M_H$

This cancellation requires $M_H < 800$ GeV

  - Give gauge invariant masses to the fermions and W, Z bosons
  - to agree with precision electroweak measurements
- Any new models for EWSB must also do the same

EWPT Constraining New Physics



- new physics contributions

  → oblique corrections: S, T, U

- SM reference point: S=T=U=0

m_t = 170.9 ± 1.8 ; m_H = (114 - 1000) GeV

- low m_H:

  ΔS ~ 0.2 provided ΔS ~ ΔT

- high m_H:

  ΔS ~ 0.1 provided ΔT ~ ΔS + 0.2

Making the Higgs Heavier?

- SM Higgs predicted to be light, yet we have not found it!
- There are several ways to evade the lower bound from LEP data:

$$\Delta T > 0, \quad \Delta S < 0$$ [Peskin, Wells, '01]

- Specific models that have been looked at
  - $\Delta T > 0$
    - ★ 2 Higgs doublet model [Chankowski et al, ...]
    - ★ 4th generation model [Dobrescu & Hill; Kribs, Plehn, Spannowsky, Tait; ...]
  - $\Delta S < 0$
    - ★ extra singlet Majorana fermions [Gates & Turning]
    - ★ extra $SU(2) \times SU(2)$ multiplets [Dugan & Randall]
- models with extended Higgs sector...

Possible New Physics

motivated by gauge hierarchy problem:

- MSSM
- Extra Dimensions
  - gauge-Higgs unification
  - Higgsless
- Little Higgs
- Fat Higgs, Composite Higgs, Twin Higgs...
- Strongly coupled Higgs Sector (Techni-color, top-color, etc...)

motivated by gauge coupling constant unification:

- models with an extended Higgs sector (GUT's, etc...):

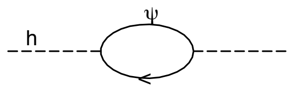
  specifically models with a $SU(2)_L$ triplet Higgs

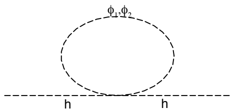
- fourth generation model

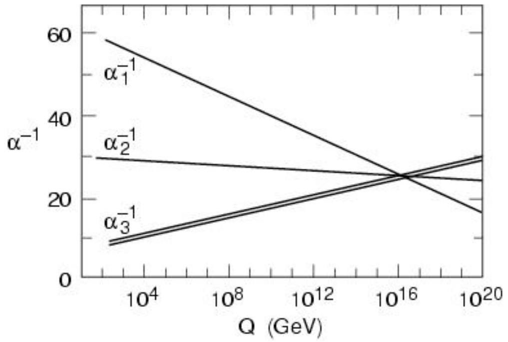
MSSM

Salient features:

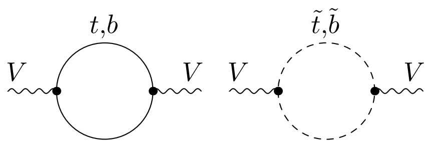
- solution to gauge hierarchy problem







- gauge coupling constant unification
- DM candidate (LSP)
- doubling of particle spectrum
- New Contributions to W and Z self-energies:



Slight disadvantage:

Higgs mass in MSSM:

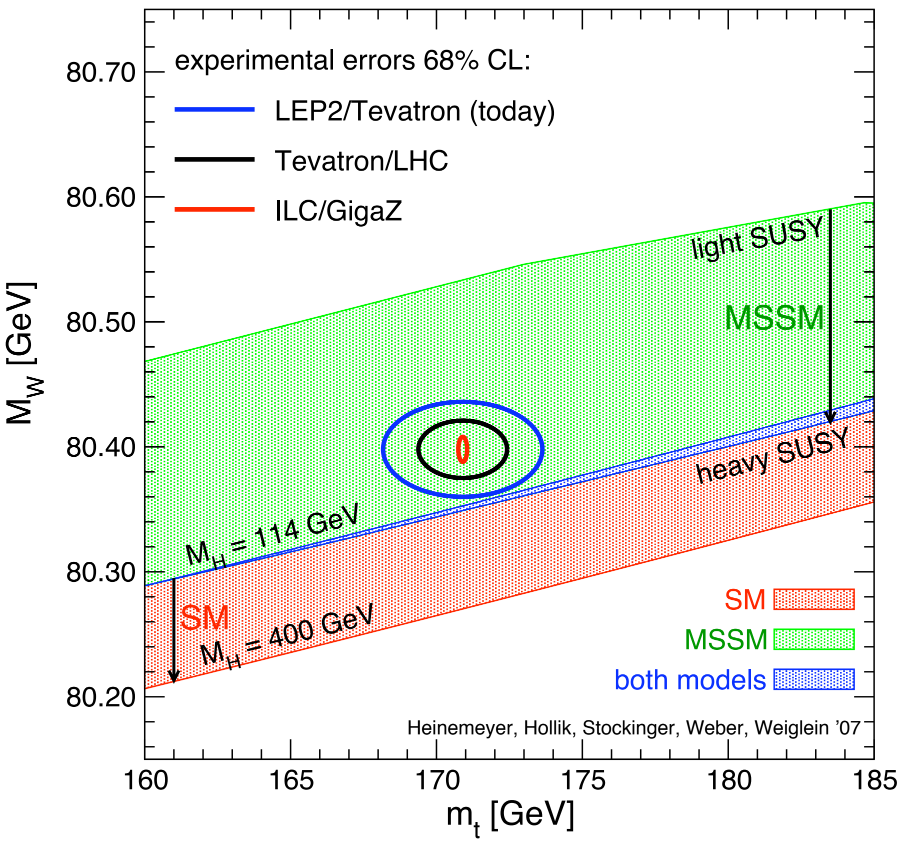
$$M_h^2 < M_Z^2 \cos^2 2\beta + \frac{3G_F}{\sqrt{2}\pi^2} M_T^4 \log\left(\frac{\tilde{M}^2}{M_T^2}\right)$$

LEP limit: $m_H > 114$ GeV, stop needs to be heavy

$\tilde{m}_{t1}\tilde{m}_{t2} > (950\ \ GeV)^2$

"little hierarchy problem" (not a severe problem!)

MSSM



[Heinemeyer, Hollik, Stockinger, Weber, Weiglein, '06]

- favor MSSM over SM!
- MSSM band above SM band:

generic for MSSM even at sub-leading orders:

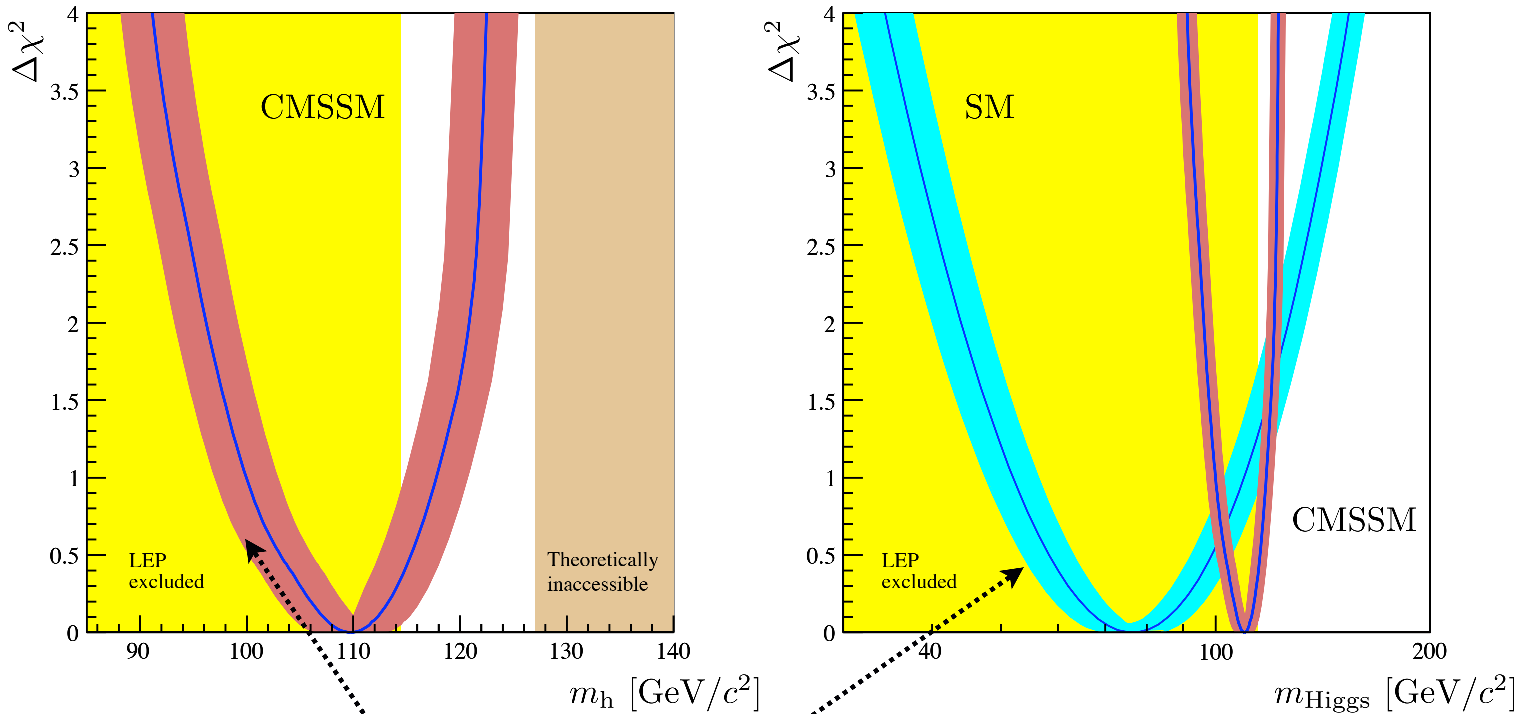
stop and sbottom loops give Mw upward shift

$$
\begin{aligned}
\text{sleptons} &: M_{\tilde F,\tilde F'} = 100\ldots 2000\text{ GeV}\\
\text{light squarks} &: M_{\tilde F,\tilde F'_{\rm up/down}} = 100\ldots 2000\text{ GeV}\\
\tilde t/\tilde b\text{ doublet} &: M_{\tilde F,\tilde F'_{\rm up/down}} = 100\ldots 2000\text{ GeV}\\
&\quad A_{t,b} = -2000\ldots 2000\text{ GeV}\\
\text{gauginos} &: M_{1,2} = 100\ldots 2000\text{ GeV}\\
&\quad m_{\tilde g} = 195\ldots 1500\text{ GeV}\\
&\quad \mu = -2000\ldots 2000\text{ GeV}\\
\text{Higgs} &: M_A = 90 - 1000\text{ GeV}\\
&\quad \tan\beta = 1.1\ldots 60
\end{aligned}
$$

light Higgs mass constrained:

$m_H < 130$ GeV

CMSSM



uncertainty in higher order corrections

[Buchmueller, Cavanaugh, De Roeck, Heinemeyer, Isidori, Paradisi, Ronga, Weber, Weiglein, '07]

- CMSSM: all EWPO included
- minimum @ $m_h^{CMSSM} = 110^{+8}_{-10}$ (exp.) $\pm\, 3$ (theo.) GeV/c^2
- SM: $m_h = 76\ ^{+36}_{-24}$ GeV

Little Higgs Models

- alternative to SUSY as a solution to the gauge hierarchy problem
- minimal realization: littlest Higgs model

  non-linear σ model based on SU(5)/SO(5)

- Higgs as a pseudo-Goldstone boson:

global: $SU(5) \overset{<\Sigma>}{\rightarrow} SO(5)$ $\Sigma = e^{2i\Pi/f}\langle\Sigma\rangle$

gauged: $[SU(2)\times U(1)]_1 \times [SU(2)\times U(1)]_2 \rightarrow [SU(2)\times U(1)]_{SM}$

- **Goldstone bosons:**

$$24 - 10 = 14 = 4 \oplus 10$$

$$= \underbrace{1_0 \oplus 3_0}_{\text{long. comp. of } Z_H,\, W_H,\, A_H} \oplus \underbrace{2_{\pm 1/2}}_{\text{SM doublet } h} \oplus \underbrace{3_{\pm 1}}_{\text{triplet } \phi}$$

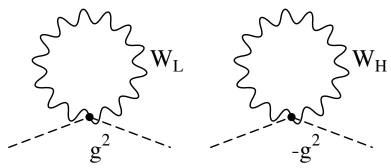
Little Higgs Models

- quadratic contributions to the Higgs mass cancelled at one-loop by new states with same spin-statistics:

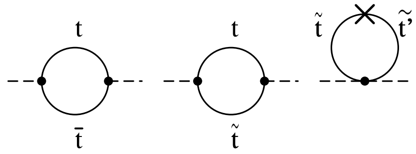
  W, Z, B ↔ W', Z', B'

  t ↔ T

  H ↔ φ



- collective symmetry breaking:

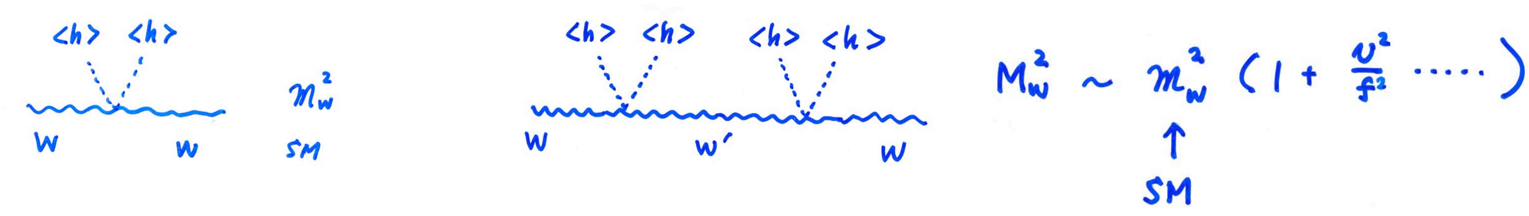


  - opposite signs
  - equality between coupling constants

quadratic contributions to Higgs mass only at two-loop

Little Higgs Models

- naturalness requires f~ (1-2) TeV
- mixing with W' and Z' breaks custodial symmetry at tree level



- tree level constraints: f ~ (3-4) TeV
- one-loop contributions important
  - tree level corrects (higher order terms in ChPT) $\sim \frac{v^2}{f^2}$

    one-loop radiative corrections $\sim \frac{1}{16\pi^2}$

    for f ~ few TeV: $\frac{1}{16\pi^2} \sim \frac{v^2}{f^2} \sim$ a few %

    heavy particles (heavy top, triplet Higgs) contributions important

[M-CC, Dawson, '03]

Little Higgs Models

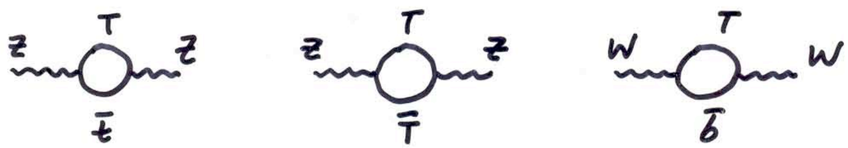
[M.-C.C, Dawson, '03]

contributions from heavy scalar fields:

$$\sim (m_1^2 - m_2^2)\left(1 + \ln \frac{Q^2}{m^2}\right)$$

unless both scalar fields have degenerate masses, the scalar contributions grow with $\Delta m_{21}^2 \sim f^2$

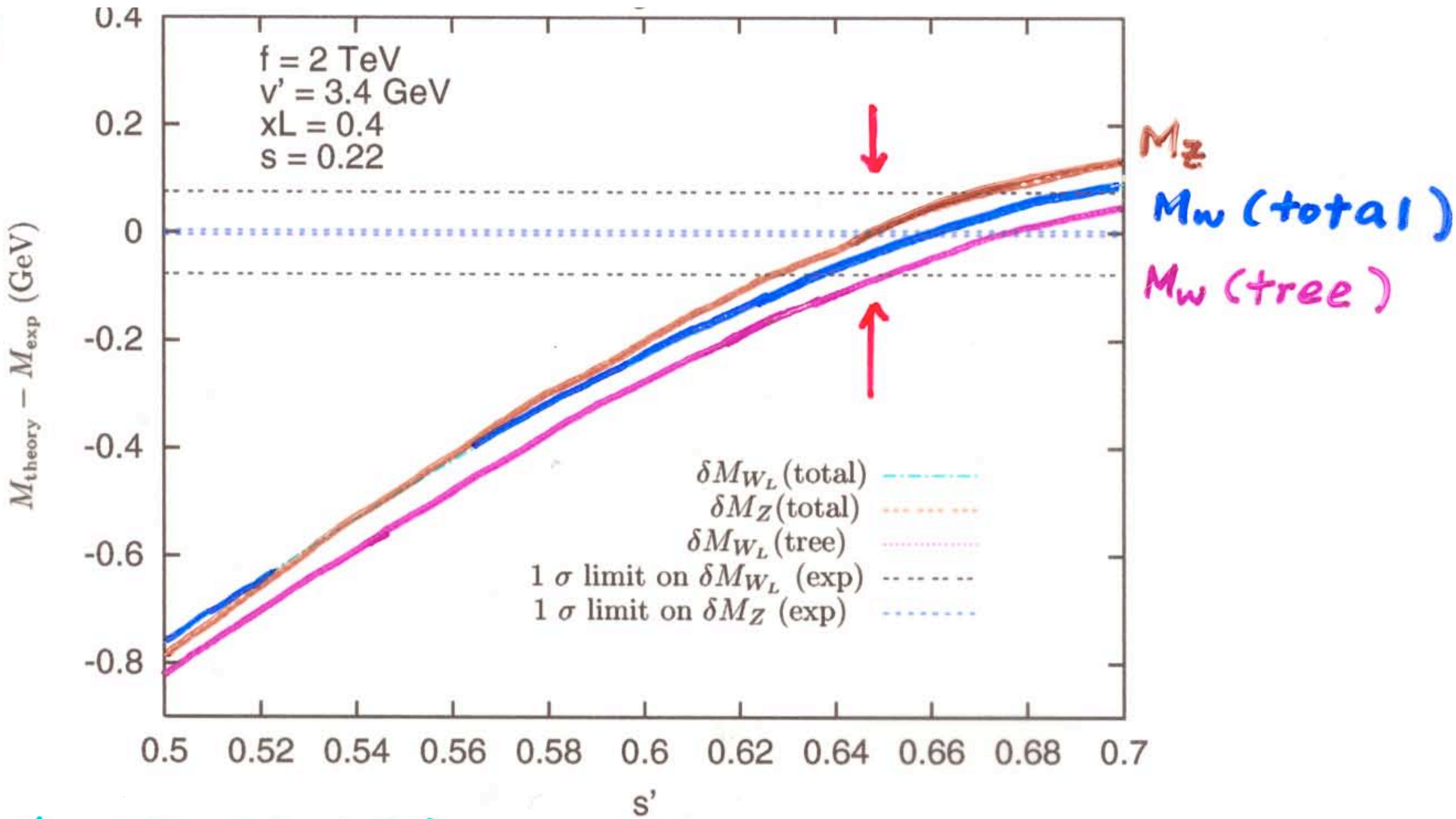
contributions from heavy top: ~ log



- cancellations between tree and one-loop contributions can occur
- low cutoff scale f ~ 2 TeV is allowed by Mw

Little Higgs Models

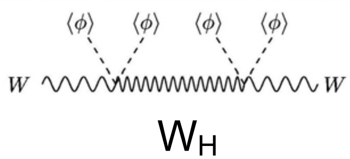
[M-CC, Dawson, '03]

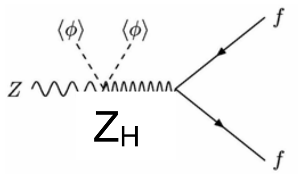


s': $U(1)_1 \times U(1)_2 \to U(1)_Y$

Little Higgs Models

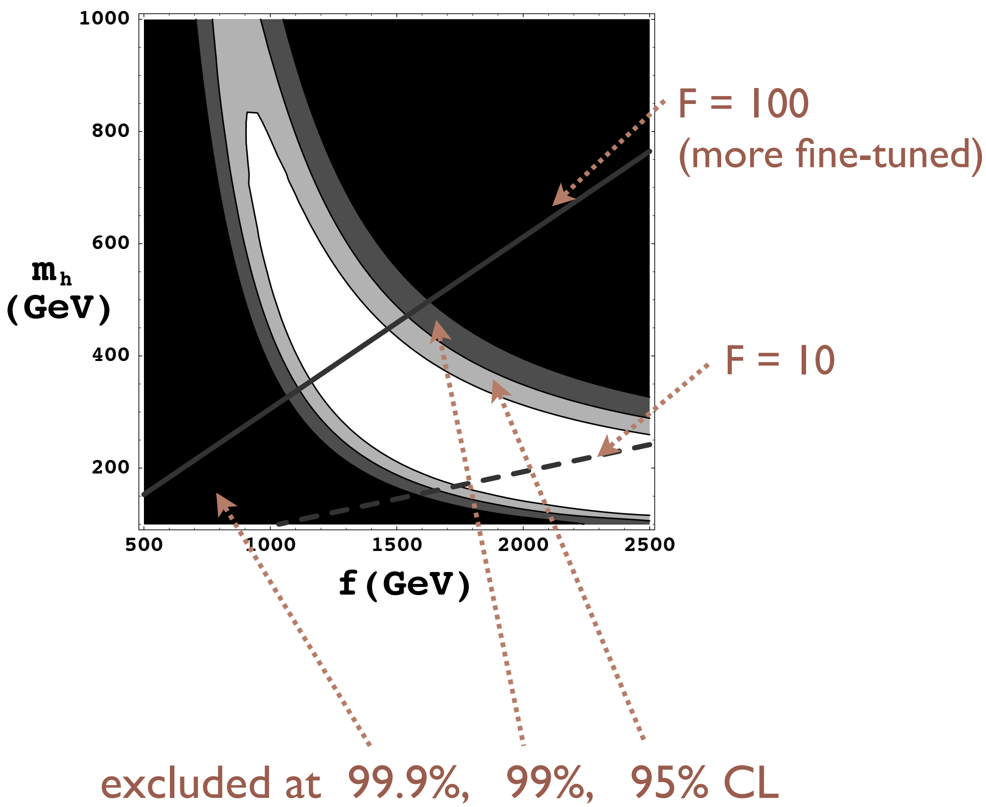
- Mixing of SM gauge bosons with heavy gauge bosons of the littlest Higgs model gives strong constraint on f

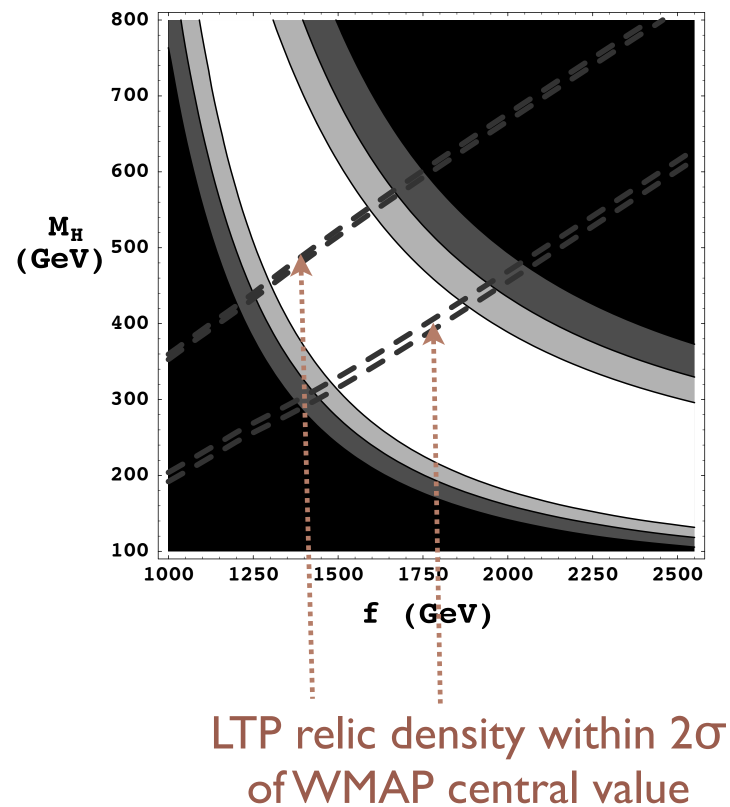




- Imposing T-parity: new particles must be pair produced [Cheng, Low, '04]
- tree level custodial symmetry preserved
  - scale can be as low as f ~ 500 GeV
  - lightest neutral gauge boson A_H can be DM candidate

Little Higgs Models





$$F = \frac{3\lambda_t^2 m_{T+}^2}{4\pi^2 m_h^2} \log \frac{\Lambda^2}{m_{T+}^2}$$

Heavy Higgs allowed in littlest Higgs model with T-parity!

Lightest T-odd Particle can be DM candidate

[Hubisz, Meade, Noble, Perelstein, '05]

Models with a Triplet Higgs

- triplet Higgs present in many models:
  - LR $SU(2)_L$ x $SU(2)_R$ symmetric model, SO(10) GUT...
  - littlest Higgs model
  - SM + triplet Higgs
- what is a triplet Higgs good for?
  - gauge coupling unification without SUSY (no proton decay, though no predictivity either)

$N_{1/2,1}$	$N_{1/2,3}$	$N_{0,2}$	$N_{0,4}$	$N_{1,0}$	$N_{1,2}$	$\alpha_s(m_Z)$	M_U (GeV)
1	0	0	2	0	0	0.106	4×10^{12}
1	0	4	0	0	1	0.112	7.7×10^{12}
1	0	0	0	0	2	0.120	1.6×10^{13}
2	0	0	0	1	0	0.116	1.7×10^{14}
2	0	2	0	0	2	0.116	4.9×10^{12}
2	1	0	0	0	2	0.112	1.7×10^{12}
3	0	0	0	0	1	0.105	1.2×10^{13}

[Gunion, '99]

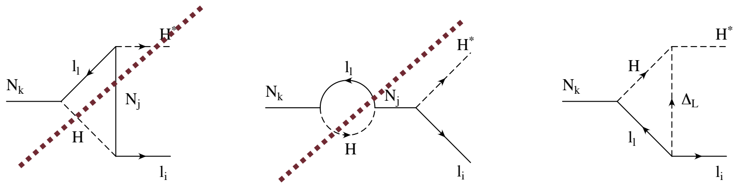
Models with a Triplet Higgs

- what is a triplet Higgs good for:
  - generating neutrino masses

$$f_{ij} L^T_{i,L} \Delta_L L_{j,L} \to f_{ij} (\Delta^0_L \nu_{i,L} \nu_{j,L} + \frac{1}{2} \Delta^+_L [\nu_{i,L} e_{j,L} + e_{i,L} \nu_{j,L}] + \Delta^{++}_{LL} e_{i,L} e_{j,L})$$

  - fij: $\Delta^{++} \to l^+ l^+$ measure neutrino properties at colliders
  - leptogenesis: $\Delta^{++} \to l^+ l^+$

  - leptogenesis: $N_1 \to \ell + H^\dagger$



Minimal LR model with SCPV:
leptogenesis ↔ neutrino oscillation

[M-CC, Mahanthappa '05]

- Higgs spectrum of model with a doublet and a triplet:
  - two neutral Higgses
  - one charged Higgs

$$\begin{pmatrix} H^0 \\ K^0 \end{pmatrix} = \begin{pmatrix} c_\gamma & s_\gamma \\ -s_\gamma & c_\gamma \end{pmatrix} \begin{pmatrix} \phi^0 \\ \eta^0 \end{pmatrix} \qquad H = \begin{pmatrix} \phi^+ \\ \frac{1}{\sqrt{2}}(v + \eta^0 + i\phi^0) \end{pmatrix}$$

$$\begin{pmatrix} G^\pm \\ H^\pm \end{pmatrix} = \begin{pmatrix} c_\delta & s_\delta \\ -s_\delta & c_\delta \end{pmatrix} \begin{pmatrix} \phi^\pm \\ \eta^\pm \end{pmatrix} \qquad \Phi = \begin{pmatrix} \eta^+ \\ v' + \eta^0 \\ \eta^- \end{pmatrix}$$

Models with a Triplet Higgs

- SM: three fundamental parameters in gauge-fermion sector

$$(g,\ g',\ v) \rightarrow (G_\mu,\ M_Z,\ \alpha) \qquad \rho = 1 = \frac{M_W^2}{M_Z^2 c_\theta^2}$$

- in the presence of a (relatively light) $SU(2)_L$ triplet Higgs: [Blank, Hollik '98]

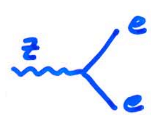
$$(g,\ g',\ v,\ v') \rightarrow (G_\mu,\ M_Z,\ \alpha,\ s_\theta^2) \qquad \rho \neq 1$$

~~relation~~ bt Mw & Mz

valid renormalization scheme requires 4 input parameters

- LEP definition

$$4s_\theta^2 - 1 \equiv \frac{\mathrm{Re}(g_v^2)}{\mathrm{Re}(g_A^e)}$$



: $(g_v + \gamma_5 g_A)$

Models with a Triplet Higgs

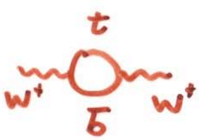
- fixing M_W using μ-decay

$$\sqrt{2}\, G_\mu = \frac{\pi \alpha}{M_W^2 S_\theta^2}\,(1 + \Delta r)$$

$$\Delta r = -\frac{\delta G_\mu}{G_\mu} - \frac{\delta M_W^2}{M_W^2} + \frac{\delta \alpha}{\alpha} - \frac{\delta S_\theta^2}{S_\theta^2}$$

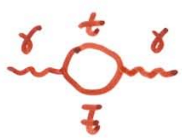
$$= \underbrace{\frac{1}{M_W^2}\left(\Pi^{WW}(0) - \Pi^{WW}(M_W^2)\right)}_{\log.} + \underbrace{\Pi^{\gamma\gamma}(0)'}_{\log.} - \frac{\delta S_\theta^2}{S_\theta^2}$$

top-loop contributions:



$$\frac{1}{M_W^2}\,\Pi^{WW}(0) \to \frac{\sqrt{2}\, G_\mu}{16\pi^2}\,(3 m_t^2)\cdot\left(1 + 2 \ln \frac{Q^2}{m_t^2}\right) + \cdots$$

$$\frac{1}{M_W^2}\,\Pi^{WW}(M_W^2) \to \frac{\sqrt{2}\, G_\mu}{16\pi^2}\,(3 m_t^2)\cdot\left(1 + 2 \ln \frac{Q^2}{m_t^2}\right) + \cdots$$



$$\Pi^{\gamma\gamma}(0)' \to \ln \frac{m_t^2}{Q^2}$$

Models with a Triplet Higgs

$$\rho = 1 = \frac{M_W^2}{M_Z^2 C_\theta^2} \quad , \quad S_\theta^2 = 1 - \frac{M_W^2}{M_Z^2}$$

SM:

$$\frac{\delta S_\theta^2}{S_\theta^2} = \frac{C_\theta^2}{S_\theta^2}\left[\frac{\delta M_Z^2}{M_Z^2} - \frac{\delta M_W^2}{M_W^2}\right] = \frac{C_\theta^2}{S_\theta^2}\left[\frac{\Pi^{ZZ}(M_Z^2)}{M_Z^2} - \frac{\Pi^{WW}(M_W^2)}{M_W^2}\right]$$

$$\frac{\Pi^{ZZ}(M_Z^2)}{M_Z^2} \rightarrow \frac{2\sqrt{2}\,G_\mu}{16\pi^2}\frac{1}{C_\theta^2}(3m_t^2)\ln\frac{Q^2}{m_t^2}$$

$$\Rightarrow \frac{\delta S_\theta^2}{S_\theta^2} \sim m_t^2 \qquad \Rightarrow \Delta r \sim m_t^2$$

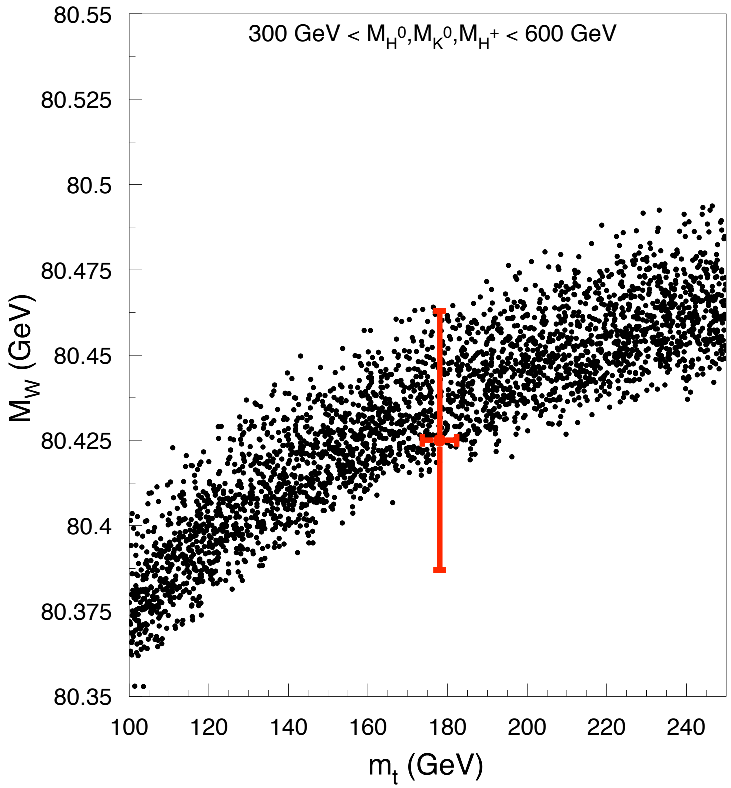
SM + triplet Higgs:

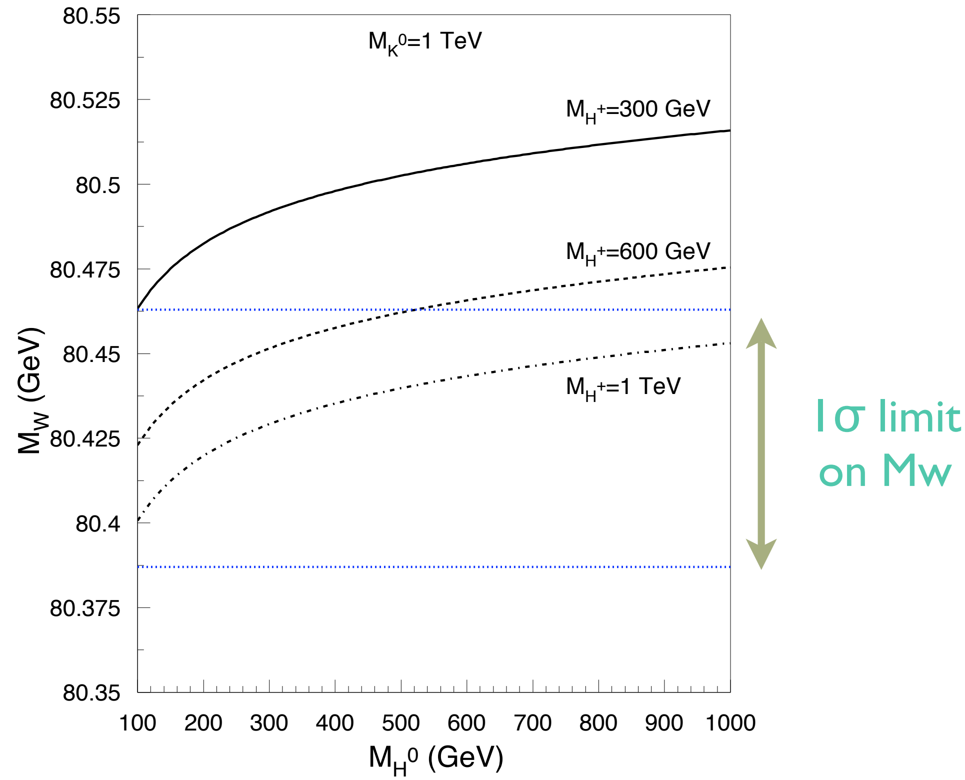
$$\frac{\delta S_\theta^2}{S_\theta^2} = \frac{C_\theta}{S_\theta}\frac{\Sigma^{\gamma Z}(M_Z^2)}{M_Z^2} \sim \ln\frac{m_t^2}{Q^2} \quad !$$

$$\Rightarrow \Delta r \sim \ln m_t^2$$

Models with a Triplet Higgs

- SM + a triplet Higgs

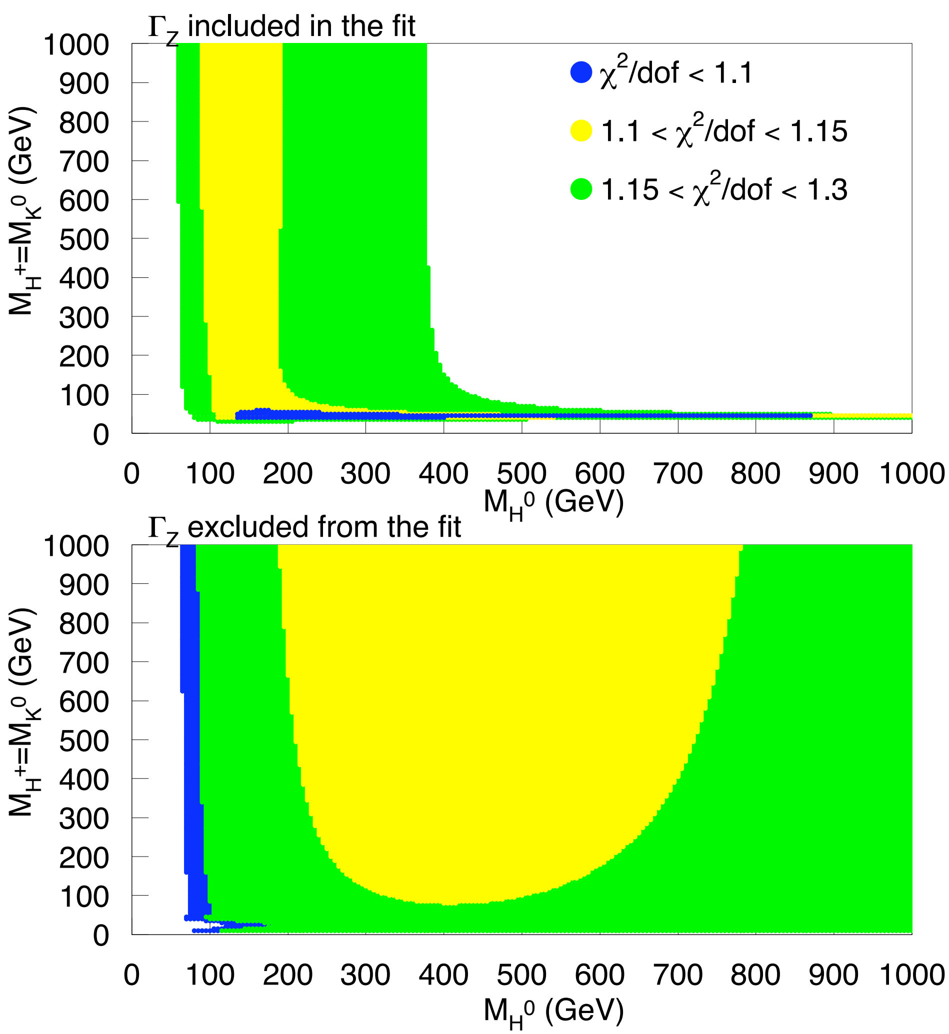




Heavy Higgs allowed by Mw measurement alone

[M-CC, Dawson, Krupovnickas '05]

Models with a Triplet Higgs



observables included in the fit:

Observable	Experimental Value
M_W	80.410 ± 0.032 GeV
Γ_Z	2.4952 ± 0.0023 GeV
R_Z	20.767 ± 0.025
R_b	0.21629 ± 0.00066
R_c	0.1721 ± 0.0030
A_{LR}	0.1465 ± 0.0032
A_b	0.923 ± 0.020
A_c	0.670 ± 0.027
$A_{FB}^{0,l}$	0.01714 ± 0.00095
$A_{FB}^{0,b}$	0.0992 ± 0.0016
$A_{FB}^{0,c}$	0.0707 ± 0.0035

Total Z-width: $\Gamma_Z = \sum \Gamma_f$

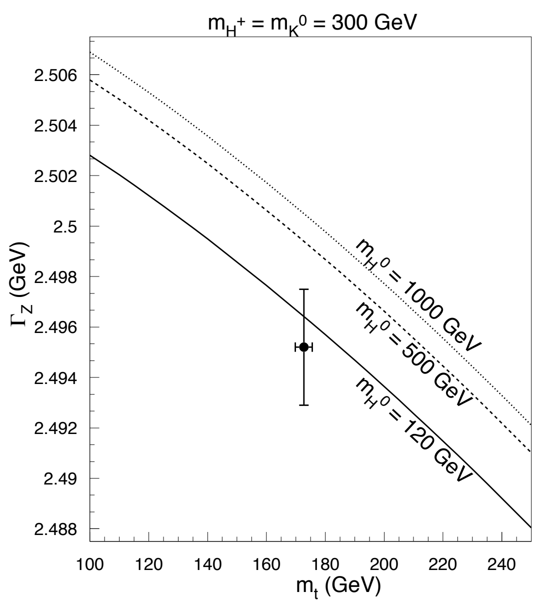
excluded Γ_Z: m_H = (100-1000) GeV
included Γ_Z: m_H = (100-200) GeV

$\Rightarrow$ global fit important!

[M-CC, Dawson, Krupovnickas ‘06]

Models with a Triplet Higgs

- importance of Γ_Z in triplet model:
  - no corrections to asymmetries up to $\mathcal{O}((\frac{1}{16\pi^2})^2)$
  - observables most sensitive to m_t or m_H are M_W and Γ_Z
    - compared to SM case: all observables sensitive to m_t or m_h
  - $\Gamma_Z \sim (m_t)^2$: can still place bound on m_t



[M-CC, Dawson, Krupovnickas '06]

4th Generation Model

- simplest extension of the SM: adding a fourth sequential family

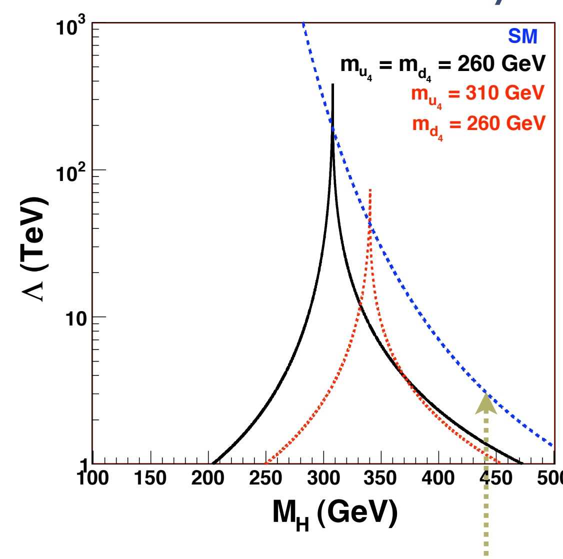
$$(Q_4,\ u_4,\ d_4,\ L_4,\ e_4)$$

- gauge coupling constant unification without SUSY [Hung '98; Frampton, Hung, Sher '99]
- some models of dynamical symmetry breaking would work better with a heavier top quark
- constraints from flavor changing processes
- unitarity of the 4x4 CKM matrix

$$|V_{ud_4}| \lesssim 0.04 \qquad |V_{u_4 d}| \lesssim 0.08 \qquad |V_{tb}| \gtrsim 0.68 \qquad |V_{cd_4}| \lesssim 0.17$$

- non-observation of $\mu \to e\gamma$: mixing bt 1st/2nd & 4th generations < 0.02 for Dirac neutrinos
- limits on t'(→Wb) ~ 265 GeV (with 1fb^{-1})
- limits on b' (→Wj, Wt) ~ 300 GeV

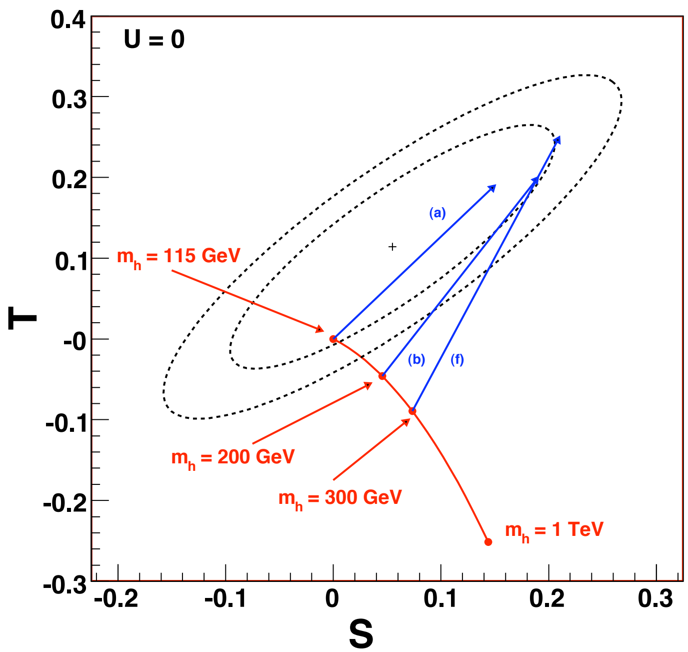
4SM triviality & vacuum stability



SM triviality bound

[Sher '89; Kribs, Plehn, Spannowsky, Tait, '07]

4th Generation Model



parameter set	m_{u_4}	m_{d_4}	m_H	$\Delta S_{\rm tot}$	$\Delta T_{\rm tot}$
(a)	310	260	115	0.15	0.19
(b)	320	260	200	0.19	0.20
(c)	330	260	300	0.21	0.22
(d)	400	350	115	0.15	0.19
(e)	400	340	200	0.19	0.20
(f)	400	325	300	0.21	0.25

[Kribs, Plehn, Spannowsky, Tait, '07]

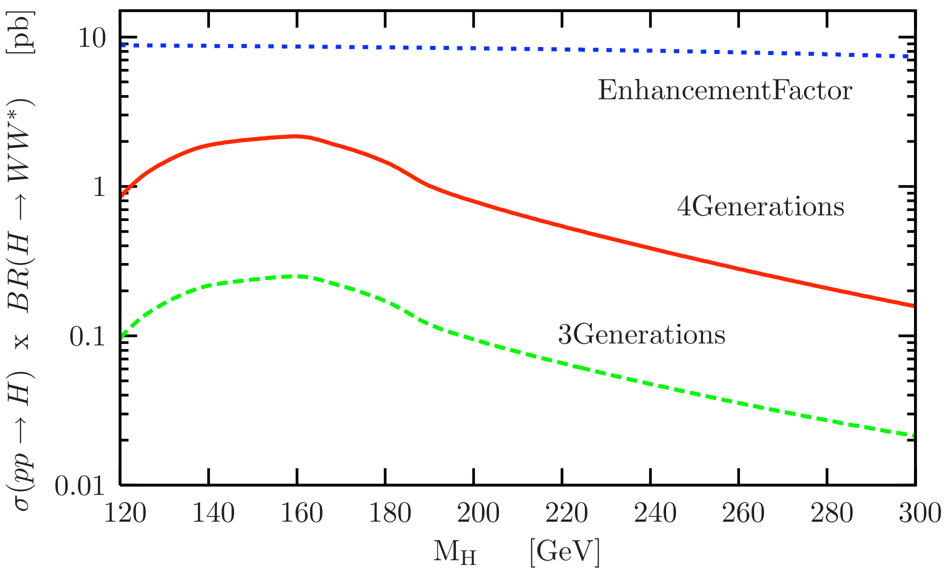
- allowed range for Higgs mass

  m_h = (115-315) GeV @ 68% CL

  m_h = (115-750) GeV @ 95% CL

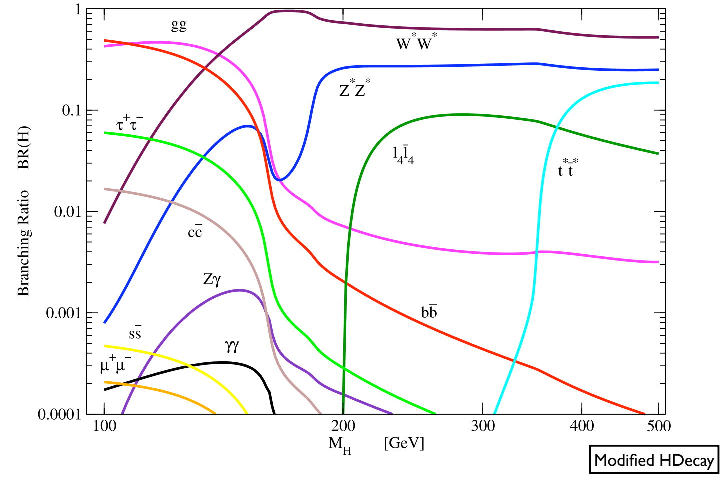
4th Generation Model

new contributions from u_4 and d_4
to H-g-g operator
⇒ enhanced production cross-section

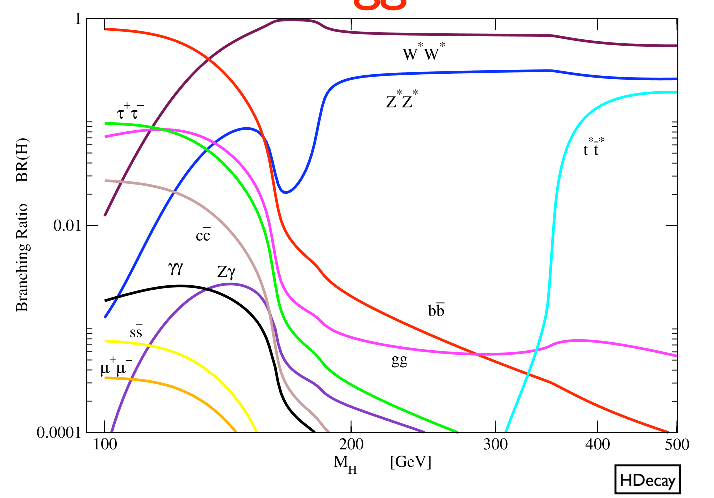


[Kribs, Plehn, Spannowsky, Tait, '07]

Higgs Decays



SM Higgs BRs



Conclusion

- precision measurements slight prefer MSSM over SM
  - best fit value for CMSSM: $m_h = 110$ GeV
  - cf. SM: $m_h = 76$ GeV
- in presence of new custodial violating physics, one has to be careful when extracting EW limits
- global fit important: specific example in SM + (light) triplet

  excluded Γ_Z: $m_H = (100\text{-}1000)$ GeV

  included Γ_Z: $m_H = (100\text{-}200)$ GeV
- heavy Higgs possible: specific example in littlest Higgs with T-parity, 4th generation model, ...