# Precision Electroweak Measurements and Constraints on New Physics

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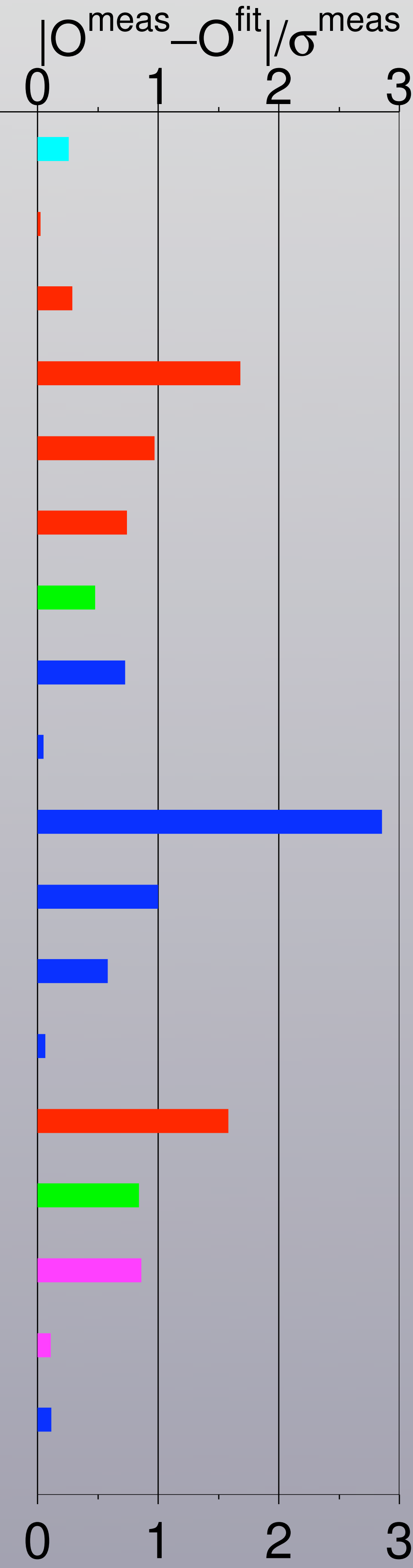
# Outline

- Precision electroweak tests of the Standard Model
- Effective operator approach to BSM physics
- Simple examples
- Little Higgs theories

| | Measurement | Fit |
|---|---|---|
| $\Delta\alpha_{had}^{(5)}(m_Z)$ | 0.02758 ± 0.00035 | 0.02767 |
| $m_Z$ [GeV] | 91.1875 ± 0.0021 | 91.1874 |
| $\Gamma_Z$ [GeV] | 2.4952 ± 0.0023 | 2.4959 |
| $\sigma_{had}^{0}$ [nb] | 41.540 ± 0.037 | 41.478 |
| $R_l$ | 20.767 ± 0.025 | 20.743 |
| $A_{fb}^{0,l}$ | 0.01714 ± 0.00095 | 0.01643 |
| $A_l(P_\tau)$ | 0.1465 ± 0.0032 | 0.1480 |
| $R_b$ | 0.21629 ± 0.00066 | 0.21581 |
| $R_c$ | 0.1721 ± 0.0030 | 0.1722 |
| $A_{fb}^{0,b}$ | 0.0992 ± 0.0016 | 0.1038 |
| $A_{fb}^{0,c}$ | 0.0707 ± 0.0035 | 0.0742 |
| $A_b$ | 0.923 ± 0.020 | 0.935 |
| $A_c$ | 0.670 ± 0.027 | 0.668 |
| $A_l$(SLD) | 0.1513 ± 0.0021 | 0.1480 |
| $\sin^2\theta_{eff}^{lept}(Q_{fb})$ | 0.2324 ± 0.0012 | 0.2314 |
| $m_W$ [GeV] | 80.398 ± 0.025 | 80.377 |
| $\Gamma_W$ [GeV] | 2.097 ± 0.048 | 2.092 |
| $m_t$ [GeV] | 172.6 ± 1.4 | 172.8 |




March 2008

Standard Model agrees with the data better than we hoped it would.

Two discrepancies larger than 2 sigma are F-B asymmetry in b production and NuTeV result for the weak angle.

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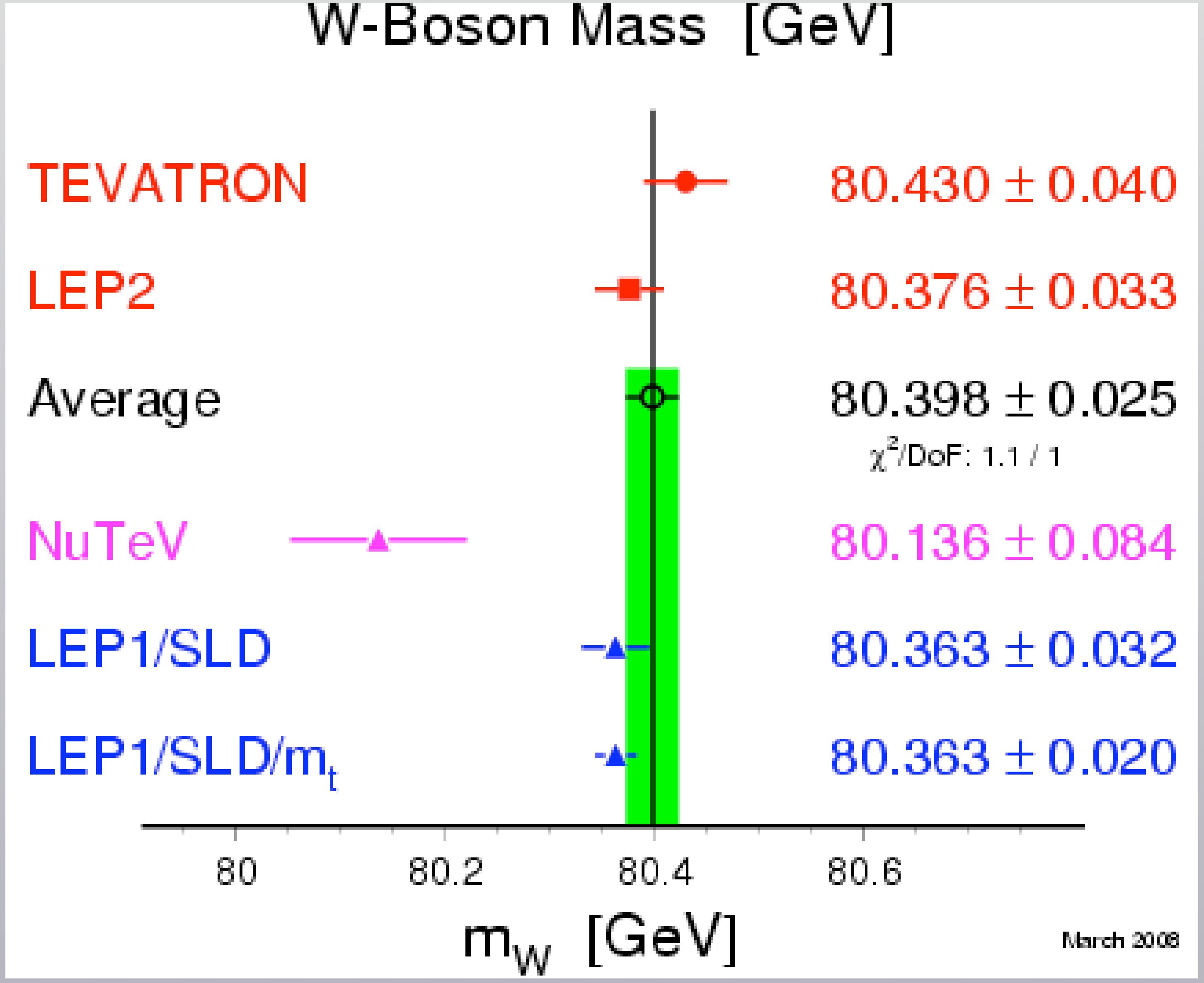


W mass is known with an error of 25 MeV!

The NuTeV result for the weak mixing angle can be translated into a determination of the W mass and the resulting value is lower than other measurements.

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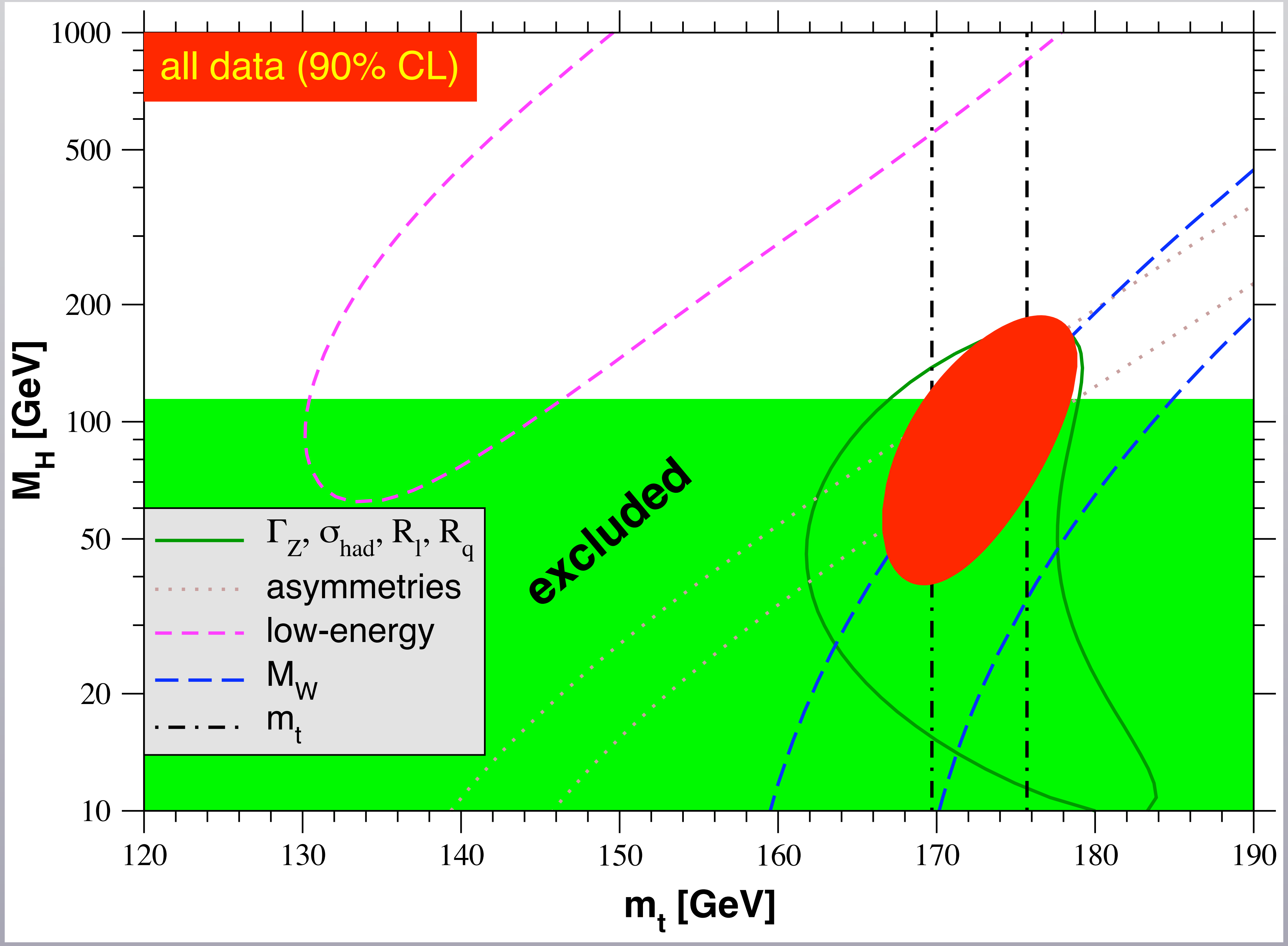
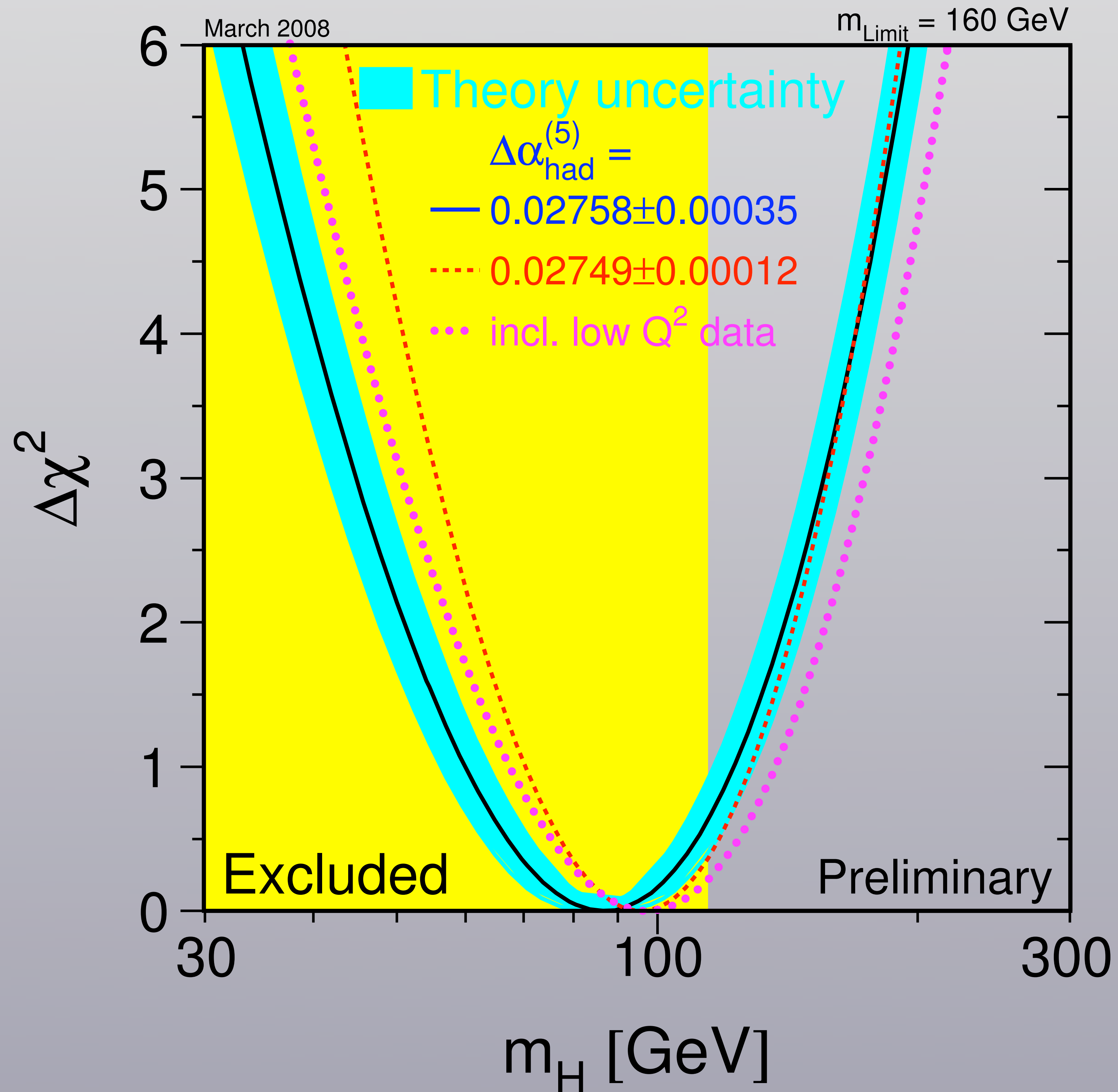
1) Light SM Higgs from Z line shape and cross sections alone

2) The NuTeV result pulls the fit towards larger Higgs mass




Erler, Langacker
PDG '06




Assuming no new physics !

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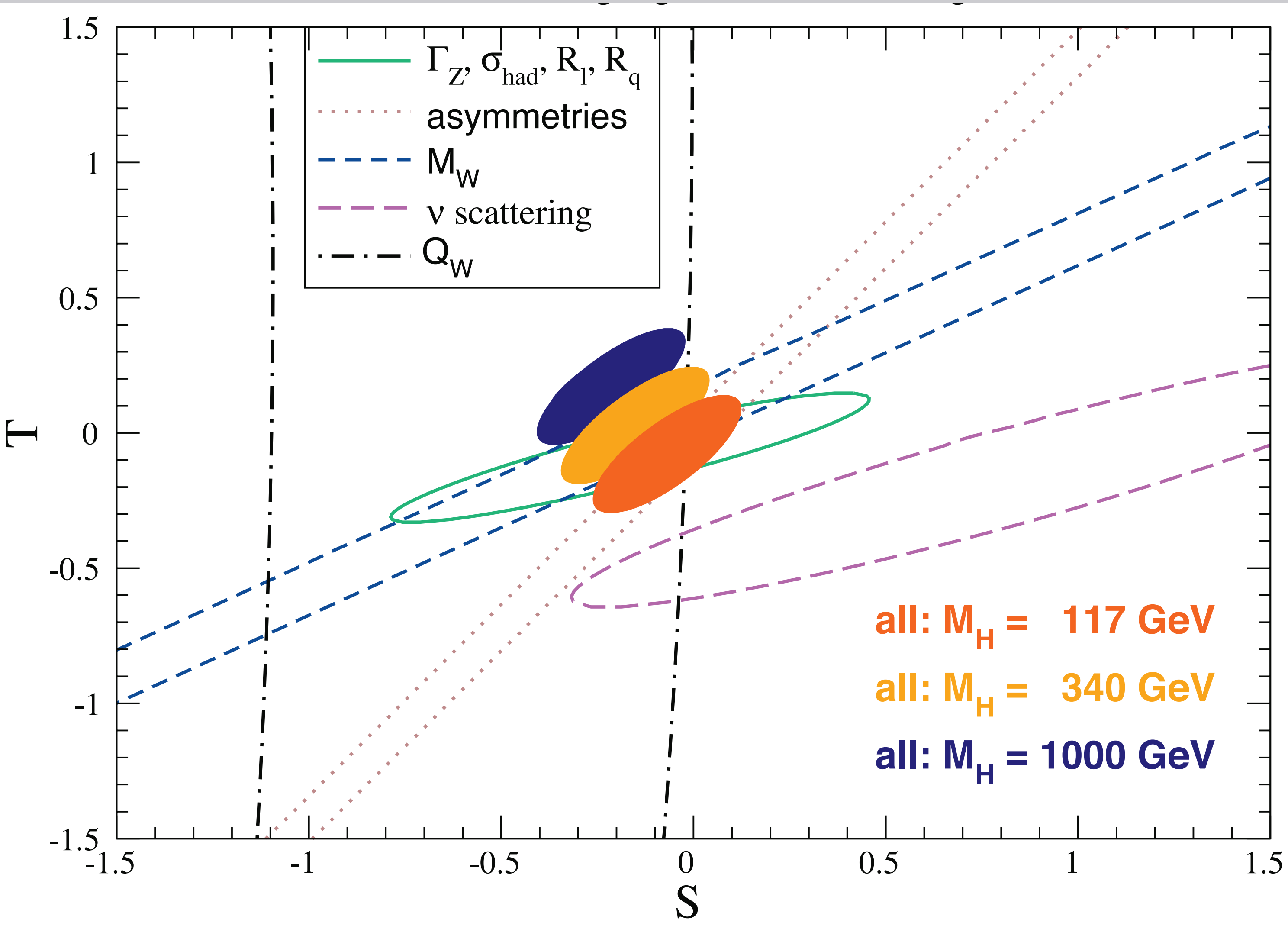
# Heavier Higgs boson can be consistent with the data if there are (positive) contributions to the T parameter




Contributions to T are common in BSM theories

500 GeV Higgs boson OK

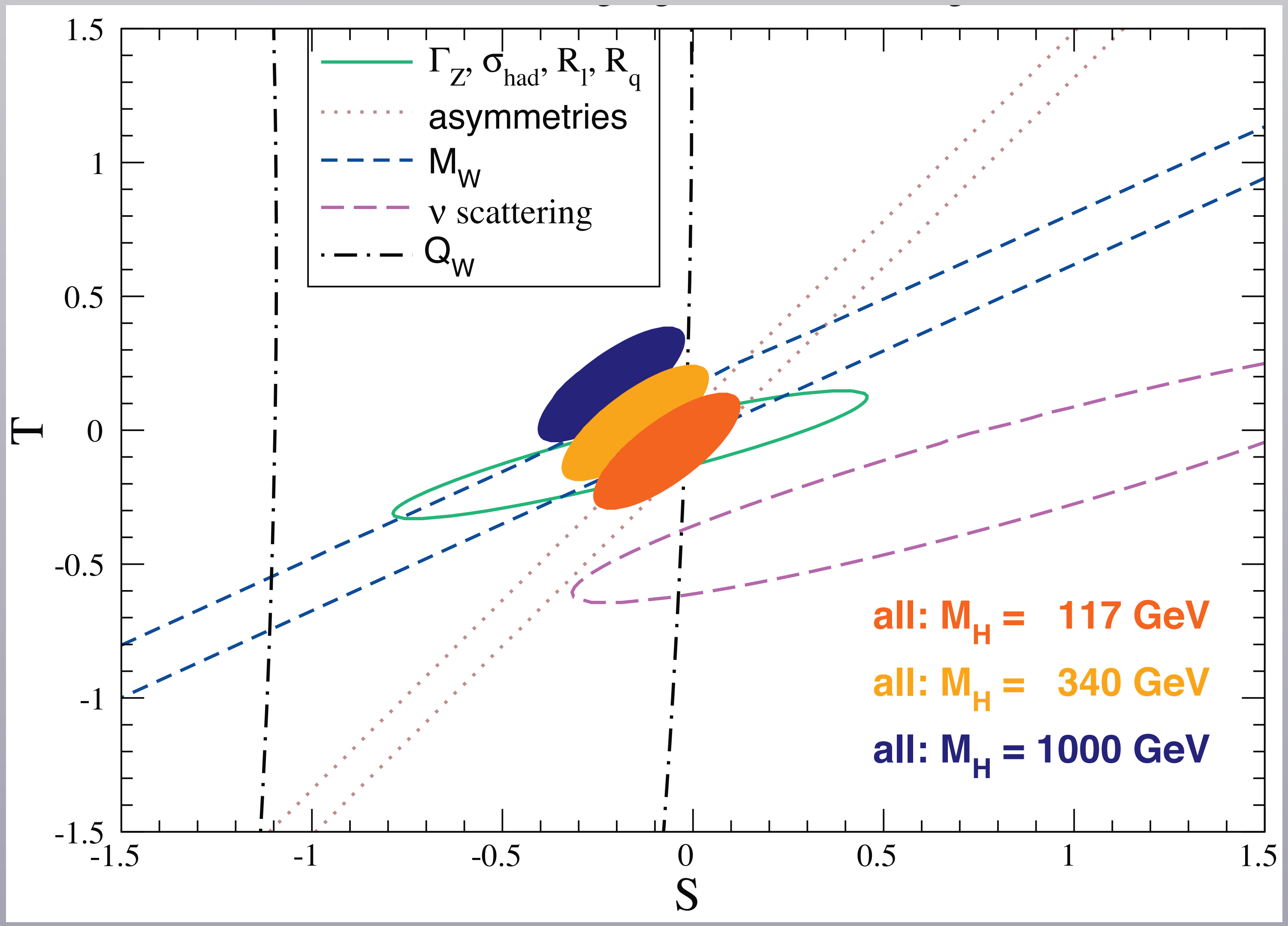
e.g. if there is a triplet with

$$\frac{v'}{v} \approx 0.04$$

Erler, Langacker
PDG

# Effective operator approach

- well known for oblique corrections (S and T parameters)
- correlations between different operators crucial
- no need to compute cross sections, asymmetries, etc.
- all relevant data is distilled into the bounds on S and T



$$\mathcal{L}_{eff} = \mathcal{L}_{SM} + \sum_i a_i O_i$$

- The coefficients $a_i$ encode the dependence on the masses and couplings of the heavy fields.
- The operators $O_i$ contain SM field only and are consistent with SM gauge symmetries and some global symmetries.

Buchmuller & Wyler, Nucl. Phys. B268 (1986) 621:
all operators of dimension 6 that preserve B, L
(80 such operators)

Impose flavor symmetry (U(3))^5

Consider only well-bounded operators

[Reduced flavor symmetry, (U(2)xU(1))^5, later on.]

80 operators

$\downarrow$ CP + flavor symmetry

52

$\downarrow$ some leptons or electroweak gauge fields

34

$\downarrow$ not observable $\left(h^\dagger h F_{\mu\nu} F^{\mu\nu},\ (h^\dagger h)^3, \ldots\right)$

28

$\downarrow$ poorly constrained $O_{fF} \equiv i\,(\bar{f}\gamma^\mu D^\nu f)F_{\mu\nu}$

21 (our basis)

## a) Higgs and gauge fields (2)

$$O_{WB} = (h^\dagger \sigma^a h) W^a_{\mu\nu} B^{\mu\nu} \quad O_h = |h^\dagger D_\mu h|^2$$

$\updownarrow$ $\updownarrow$

$$S = \frac{4scv^2}{\alpha} a_{WB} \qquad T = -\frac{v^2}{2\alpha} a_h$$

## b) 4 fermions (11+10)

$$O_{ff} = (\bar{f}\gamma^\mu f)(\bar{f}\gamma_\mu f)$$

e.g. $O^s_{lq} = (\bar{l}\gamma^\mu l)(\bar{q}\gamma_\mu q) \quad O^t_{lq} = (\bar{l}\gamma^\mu \sigma^a l)(\bar{q}\gamma_\mu \sigma^a q)$

## c) 2 fermions, Higgs, and gauge fields (7+6)

$$O_{hq} = i(h^\dagger D^\mu h)(\bar{f}\gamma_\mu f) + \text{h.c.}$$

e.g. $O^t_{hl} = i(h^\dagger \sigma^a D^\mu h)(\bar{f}\gamma_\mu \sigma^a f) + \text{h.c.}$

## d) gauge fields only (1)

$$O_W = \epsilon^{abc} W^{a\nu}_\mu W^{b\lambda}_\nu W^{c\mu}_\lambda$$

# Experiments

| | Standard Notation | Measurement |
|---|---|---|
| Atomic parity violation | $Q_W(Cs)$ | Weak charge in Cs |
| | $Q_W(Tl)$ | Weak charge in Tl |
| DIS | $g_L^2, g_R^2$ | $\nu_\mu$-nucleon scattering from NuTeV |
| | $R^\nu$ | $\nu_\mu$-nucleon scattering from CDHS and CHARM |
| | $\kappa$ | $\nu_\mu$-nucleon scattering from CCFR |
| | $g_V^{\nu e}, g_A^{\nu e}$ | $\nu$-$e$ scattering from CHARM II |
| Z-pole | $\Gamma_Z$ | Total $Z$ width |
| | $\sigma_h^0$ | $e^+e^-$ hadronic cross section at $Z$ pole |
| | $R_f^0(f = e, \mu, \tau, b, c)$ | Ratios of decay rates |
| | $A_{FB}^{0,f}(f = e, \mu, \tau, b, c)$ | Forward-backward asymmetries |
| | $\sin^2\theta_{eff}^{lept}(Q_{FB})$ | Hadronic charge asymmetry |
| | $A_f(f = e, \mu, \tau, b, c)$ | Polarized asymmetries |
| Fermion pair production at LEP2 | $\sigma_f(f = q, \mu, \tau)$ | Total cross sections for $e^+e^- \to f\bar{f}$ |
| | $A_{FB}^f(f = \mu, \tau)$ | Forward-backward asymmetries for $e^+e^- \to f\bar{f}$ |
| | $d\sigma_e/d\cos\theta$ | Differential cross section for $e^+e^- \to e^+e^-$ |
| $W$ pair | $d\sigma_W/d\cos\theta$ | Differential cross section for $e^+e^- \to W^+W^-$ |
| | $M_W$ | W mass |

For a measured quantity $X$

$$X(a_i) = X(SM) + a_i X_i + a_i^2 \hat{X}_i$$

$$\frac{1}{\Lambda_i^2} \qquad \left(\frac{E/v}{\Lambda_i}\right)^2 \qquad \left(\frac{E/v}{\Lambda_i}\right)^4$$ (neglect!)

$$\chi^2(a_i) \equiv \sum_{observables X_k} \frac{\left(X_k^{th}(a_i) - X_k^{exp}\right)^2}{\sigma_k^2}$$

$$X_k^{th}(a_i) = X_k^{SM} + a_i \hat{X}_{k;i} + \mathcal{O}(a_i^2)$$

$$\chi^2(a_i) = \chi^2_{min} + (a_i - \hat{a}_i)\mathcal{M}_{ij}(a_j - \hat{a}_j)$$

$\hat{a}_i, \ \mathcal{M}_{ij}$ are ***constants*** determined from experiments

# S,T parameters

| | | | | | | | | | | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| $a_{WB}$ | 9.1e4 | | | | | | | | | | | | | | | | | | | | |
| $a_h$ | 2.4e4 | 7.9e3 | | | | | | | | | | | | | | | | | | | |
| $a_{ll}^s$ | −78. | −51. | 5.8e2 | | | | | | | | | | | | | | | | | | |
| $a_{ll}^t$ | −3.9e4 | −1.2e4 | 6.7e2 | 2.2e4 | | | | | | | | | | | | | | | | | |
| $a_{lq}^s$ | −1.4e3 | −1.6e2 | 0. | 1.5e2 | 2.7e3 | | | | | | | | | | | | | | | | |
| $a_{lq}^t$ | −5.5e2 | −1.4e2 | 0. | 5.9e2 | 4.6e2 | 2.9e3 | | | | | | | | | | | | | | | |
| $a_{le}$ | −56. | −9.7 | 2.8e2 | 3.0e2 | 0. | 0. | 1.3e3 | | | | | | | | | | | | | | |
| $a_{qe}$ | 1.3e3 | 72. | 0. | −1.4e2 | −2.7e3 | −7.4e2 | 0. | 2.8e3 | | | | | | | | | | | | | |
| $a_{lu}$ | −4.0e2 | 3.8 | 0. | −1.1e2 | 1.2e3 | −2.5e2 | 0. | −1.2e3 | 7.1e2 | | | | | | | | | | | | |
| $a_{ld}$ | −6.9e2 | −6.9 | 0. | 66. | 1.4e3 | 3.3e2 | 0. | −1.4e3 | 5.8e2 | 7.8e2 | | | | | | | | | | | |
| $a_{ee}$ | −59. | −42. | 5.3e2 | 6.1e2 | 0. | 0. | 2.6e2 | 0. | 0. | 0. | 4.8e2 | | | | | | | | | | |
| $a_{eu}$ | 7.8e2 | 1.1e2 | 0. | −2.1e2 | −1.3e3 | −9.1e2 | 0. | 1.4e3 | −4.8e2 | −7.3e2 | 0. | 8.4e2 | | | | | | | | | |
| $a_{ed}$ | 4.2e2 | −83. | 0. | 1.7e2 | −1.3e3 | 5.5e2 | 0. | 1.3e3 | −7.3e2 | −6.8e2 | 0. | 4.7e2 | 8.8e2 | | | | | | | | |
| $a_{hl}^s$ | −1.7e4 | −4.1e3 | 1.5e2 | 9.7e3 | −5.9e2 | 8.3e2 | 17. | 3.7e2 | −3.9e2 | −1.6e2 | 1.3e2 | 66. | 3.8e2 | 5.5e4 | | | | | | | |
| $a_{hl}^t$ | 5.9e4 | 1.7e4 | −43. | −3.0e4 | −7.1e2 | −6.6e2 | −31. | 6.6e2 | −82. | −3.4e2 | −32. | 4.9e2 | 47. | 1.5e4 | 6.3e4 | | | | | | |
| $a_{hq}^s$ | −1.9e3 | −1.4e3 | 0. | 2.7e3 | −2.6e3 | −72. | 0. | 2.6e3 | −1.2e3 | −1.4e3 | 0. | 1.2e3 | 1.4e3 | −6.6e3 | −8.7e3 | 6.0e3 | | | | | |
| $a_{hq}^t$ | −9.3e3 | −4.5e3 | 0. | 8.7e3 | −49. | 3.5e2 | 0. | 56. | −1.4e2 | −36. | 0. | −64. | 1.8e2 | −2.4e4 | −3.1e4 | 7.7e3 | 2.6e4 | | | | |
| $a_{hu}$ | −6.1e2 | −6.6e2 | 0. | 1.2e3 | −1.2e3 | −4. | 0. | 1.2e3 | −5.1e2 | −6.9e2 | 0. | 5.7e2 | 6.7e2 | −3.7e3 | −4.4e3 | 2.2e3 | 4.1e3 | 1.4e3 | | | |
| $a_{hd}$ | 1.2e3 | 4.3e2 | 0. | −8.1e2 | −1.4e3 | −1.3e2 | 0. | 1.4e3 | −6.9e2 | −7.2e2 | 0. | 6.7e2 | 7.3e2 | 3.3e3 | 3.6e3 | 4.2e2 | −2.9e3 | 1.6e2 | 1.1e3 | | |
| $a_{he}$ | −2.8e4 | −4.6e3 | −1.1e2 | 9.0e3 | 4.6e2 | −1.6e2 | 23. | −4.5e2 | 2.5e2 | 2.4e2 | −96. | −1.7e2 | −3.0e2 | −2.5e4 | −3.2e4 | 4.5e3 | 1.7e4 | 2.3e3 | −2.1e3 | 3.2e4 | |
| $a_W$ | 7.7 | 4.5 | 0. | −4.2 | 0. | 0. | 0. | 0. | 0. | 0. | 0. | 0. | 0. | 6.3 | −1.7 | 0. | 0.8 | 0. | 0. | 1.4 | 2.6 |
| | $a_{WB}$ | $a_h$ | $a_{ll}^s$ | $a_{ll}^t$ | $a_{lq}^s$ | $a_{lq}^t$ | $a_{le}$ | $a_{qe}$ | $a_{lu}$ | $a_{ld}$ | $a_{ee}$ | $a_{eu}$ | $a_{ed}$ | $a_{hl}^s$ | $a_{hl}^t$ | $a_{hq}^s$ | $a_{hq}^t$ | $a_{hu}$ | $a_{hd}$ | $a_{he}$ | $a_W$ |

(Times $10^{12}$ $(\mathrm{GeV})^4$

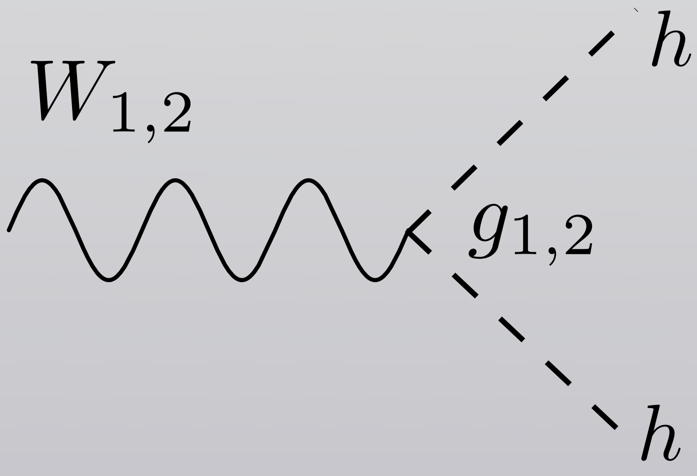
$$\chi^2 = \chi^2_{min} + (a_i - \hat{a}_i)\mathcal{M}_{ij}(a_j - \hat{a}_j)$$

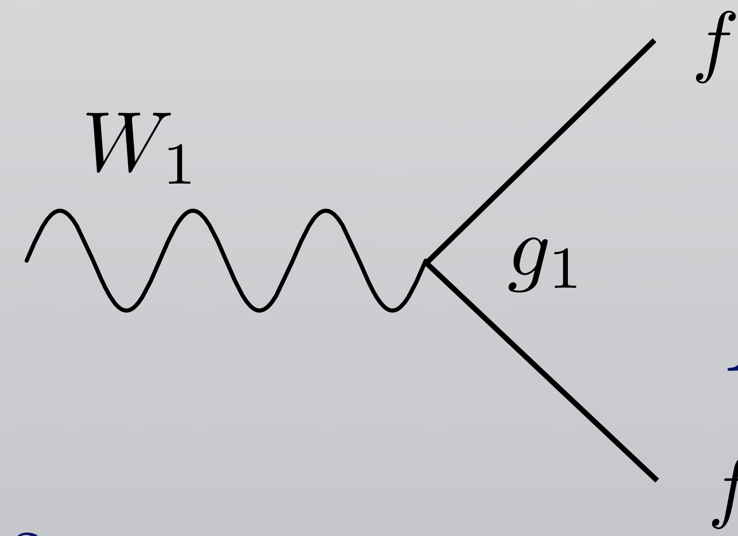
$\mathcal{M}_{ij}$ only depends on the errors (experimental and theoretical), and would change if precision of the data improves

$\hat{a}_i$

depend on the SM predictions, central values of observables, and experimental errors

# W' from SU(2)xSU(2) broken to the diagonal SU(2)_L

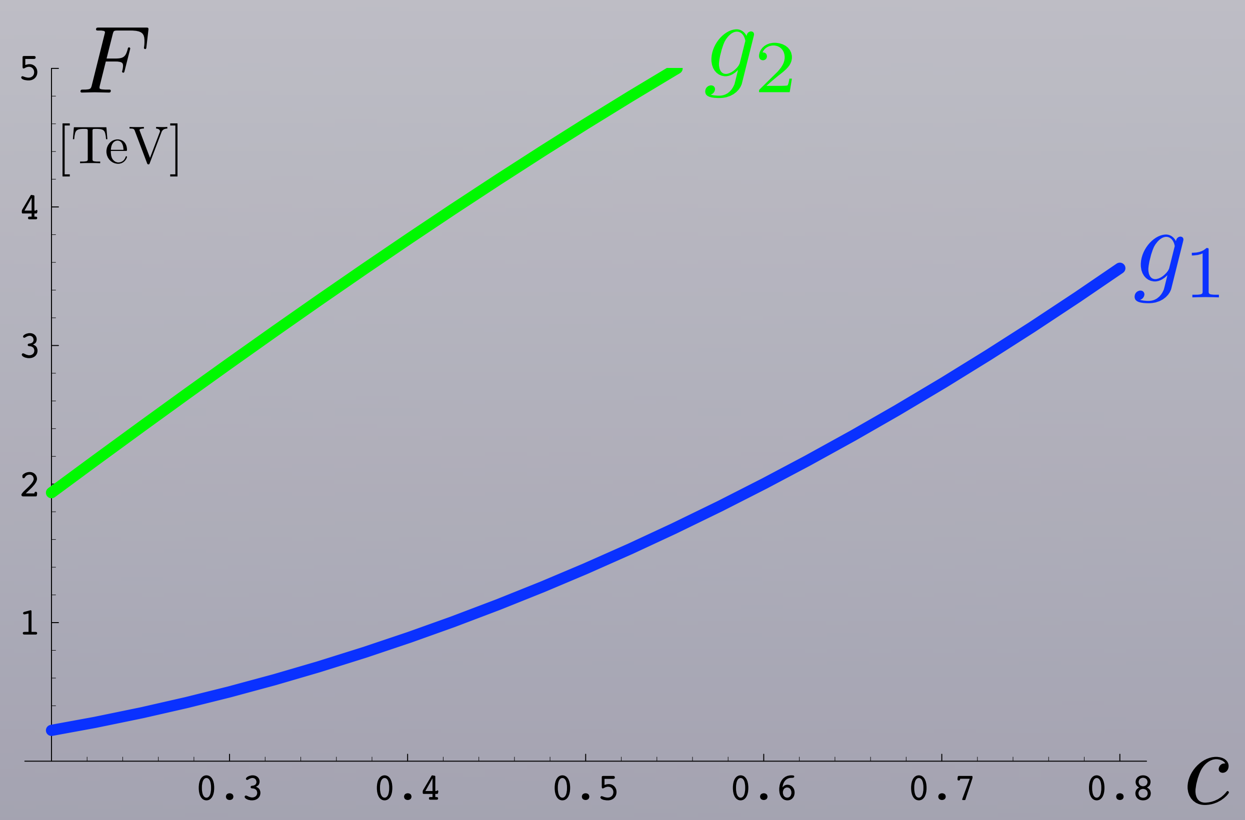



$$g = g_1 s = g_2 c$$

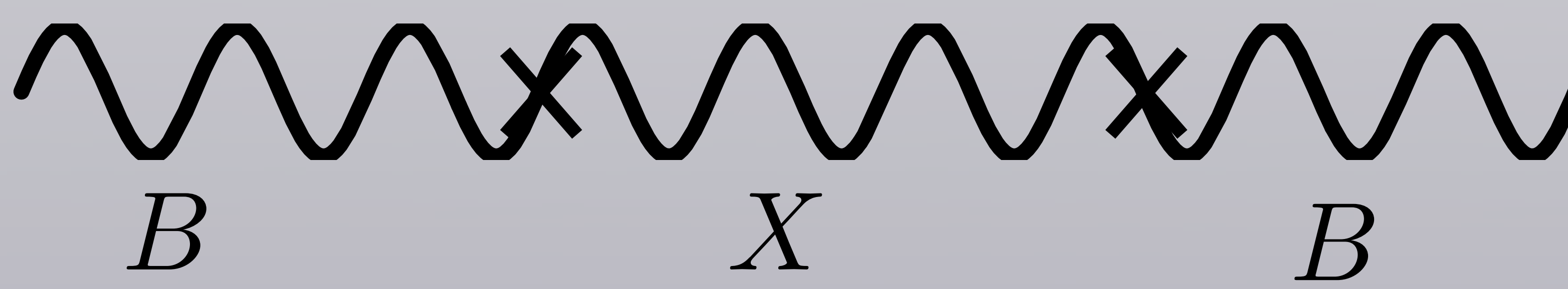
$$M_W^2 \equiv \frac{F^2}{s^2 c^2}$$

$$\mathcal{L}_{eff} = -\frac{g^2 c^4}{F^2} O_{ff}^t - \frac{g^2 c^2 \frac{c^2}{-s^2}}{F^2} O_{hf}^t$$



# Kinetic mixing between hypercharge B and Z'

$$\mathcal{L} = -\frac{1}{4}B_{\mu\nu}B^{\mu\nu} - \frac{1}{4}X_{\mu\nu}X^{\mu\nu} + \frac{\lambda}{2}B_{\mu\nu}X^{\mu\nu}$$

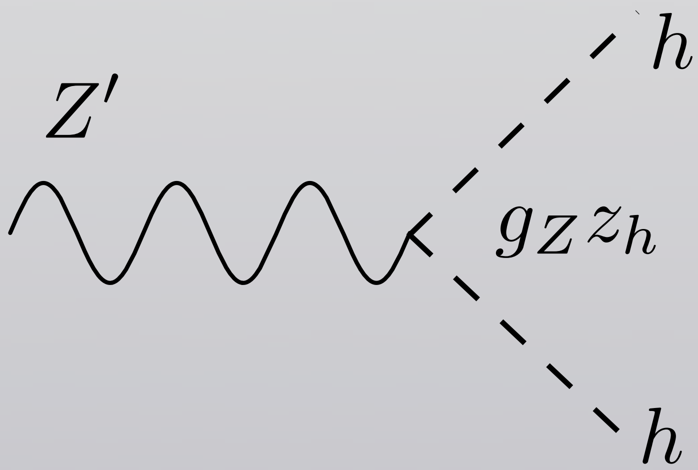


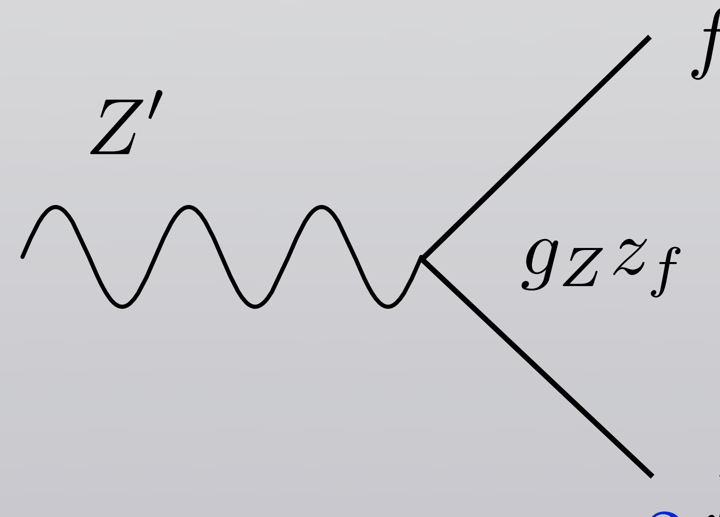

$$\mathcal{L}_{eff} = \frac{\lambda^2}{M_X^2}(\partial^\mu B_{\mu\nu})^2$$

(Related to the Y parameter introduced by Barbieri, Pomarol, Rattazzi, Strumia)

$$-(\frac{0.7}{1\ \mathrm{TeV}})^2 < \frac{\lambda^2}{M_X^2} < (\frac{0.2}{1\ \mathrm{TeV}})^2$$

# Generic Z' boson




$$\mathcal{L}_{eff} = -\frac{g_Z^2 z_H^2}{2M_{Z'}^2} O_h - \sum_{ff'} \frac{g_Z^2 z_f z_{f'}}{4M_{Z'}^2} O_{ff'} - \sum_f \frac{g_Z^2 z_f z_H}{4M_{Z'}^2} O_{hf}$$

Constraints from individual measurements:

$$T \to M_{Z'} > 0.9 \text{ TeV}, \quad \Gamma_Z \to M_{Z'} > 1.2 \text{ TeV}$$

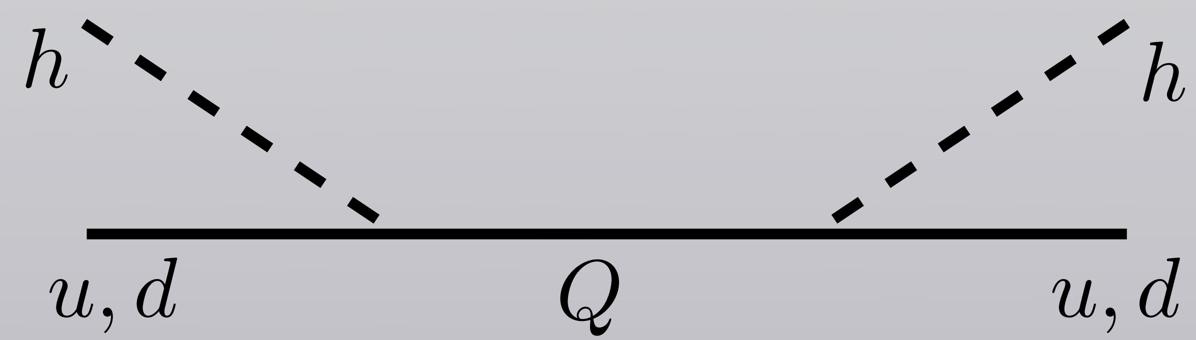
$$A_{LR}^e \to M_{Z'} > 1.0 \text{ TeV}$$

(Assuming $g_z z_h = e,\ g_z z_f = \pm\frac{e}{3}$ )

Global analysis: $M_{Z'} > 2.2\,(2.4)$ TeV

# An extra vector-like doublet of quarks

$$\mathcal{L} = -M\overline{Q}Q - \lambda_d \overline{Q} d h - \lambda_u \overline{Q} u \tilde{h} + \mathrm{h.c.}$$




$$\mathcal{L}_{eff} = \frac{\lambda_d^2}{2M^2} O_{hd} - \frac{\lambda_u^2}{2M^2} O_{hu}$$ **yields 95% CL bounds:**

$$-0.093 < \frac{\lambda_d^2}{2M^2} < 0.036 \quad -0.083 < \frac{\lambda_u^2}{2M^2} < 0.032 \; \left[\frac{1}{\mathrm{TeV}}^{2}\right]$$

(Assuming universal

family couplings)

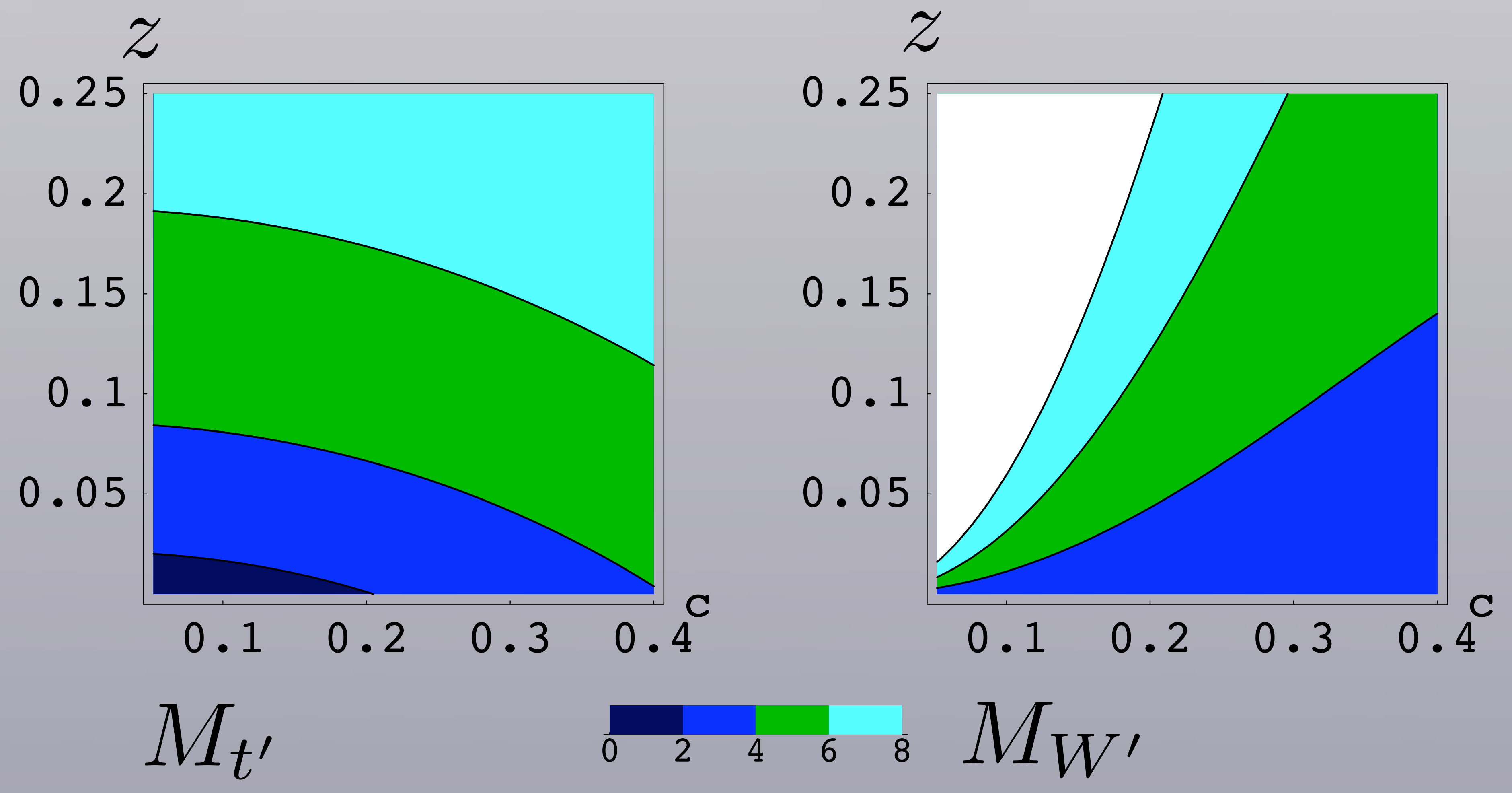
# Littlest Higgs: $(SU(2) \times U(1))^2 \rightarrow SU(2) \times U(1)$

## Contributions from

scalar triplets: $a_h$

Z' bosons: $a_h, a^s_{hf}, a^s_{ff}$

W' bosons: $a^t_{hf}, a^t_{ff}$




$$z = \frac{\lambda^2 F^2}{M_\phi^4}$$

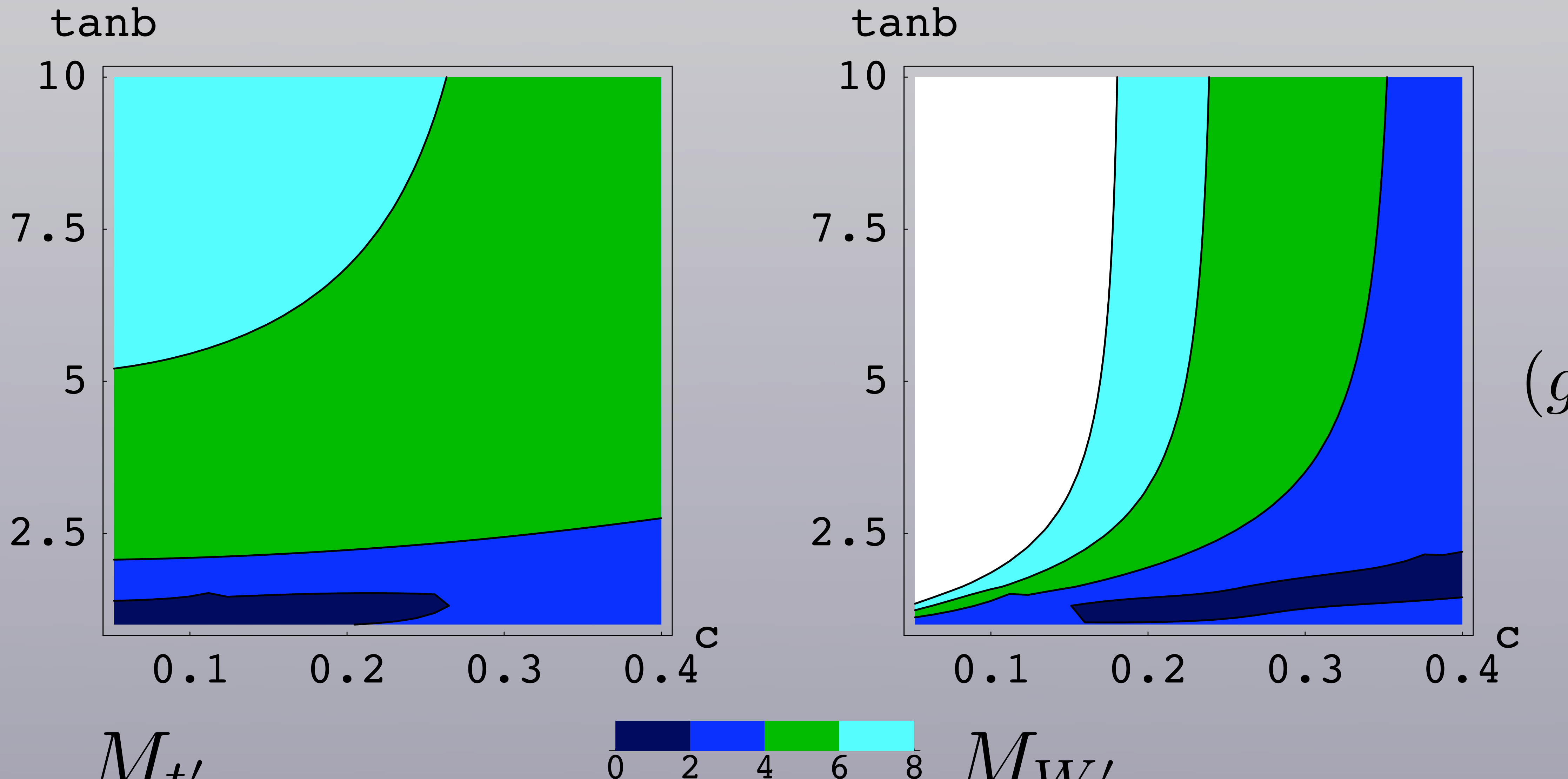
$$(g'_1 = g'_2)$$

# Antisymmetric condensate LH: $(SU(2)\times U(1))^2 \to SU(2)\times U(1)$

## Contributions from

Z' bosons: $a_h, a^s_{hf}, a^s_{ff}$

W' bosons: $a^t_{hf}, a^t_{ff}$




$M_{t'}$ $M_{W'}$

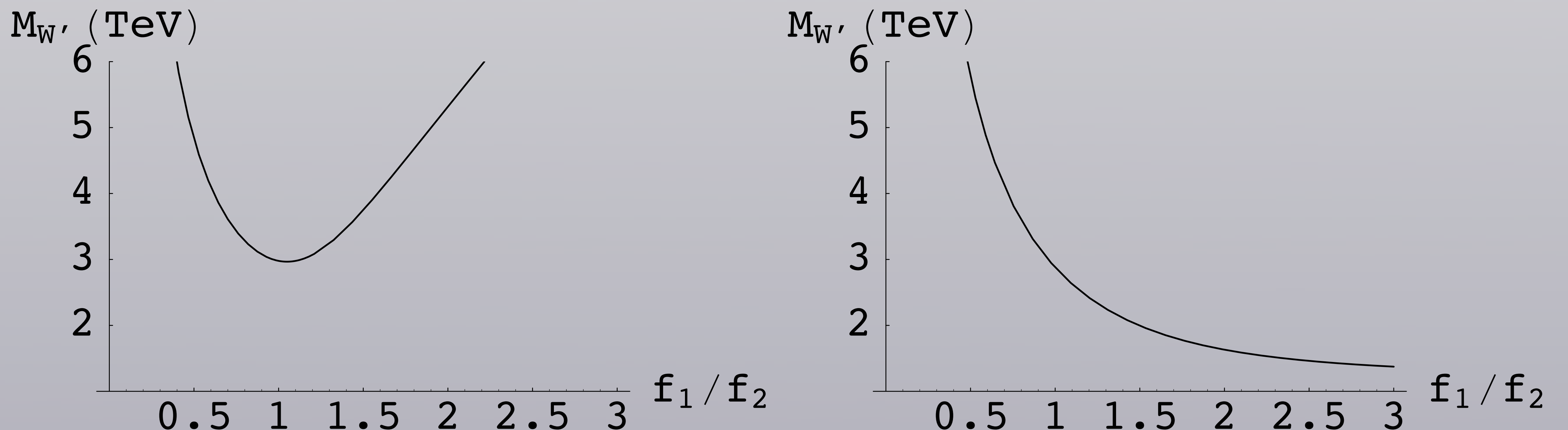
$(g_1' = g_2')$

# Simplest Little Higgs: $SU(3) \times U(1) \to SU(2) \times U(1)$

Contributions from

gauge bosons: $a_h, a^s_{hf}, a^s_{ff}$

and fermions: $a^s_{hf}, a^t_{hf}$

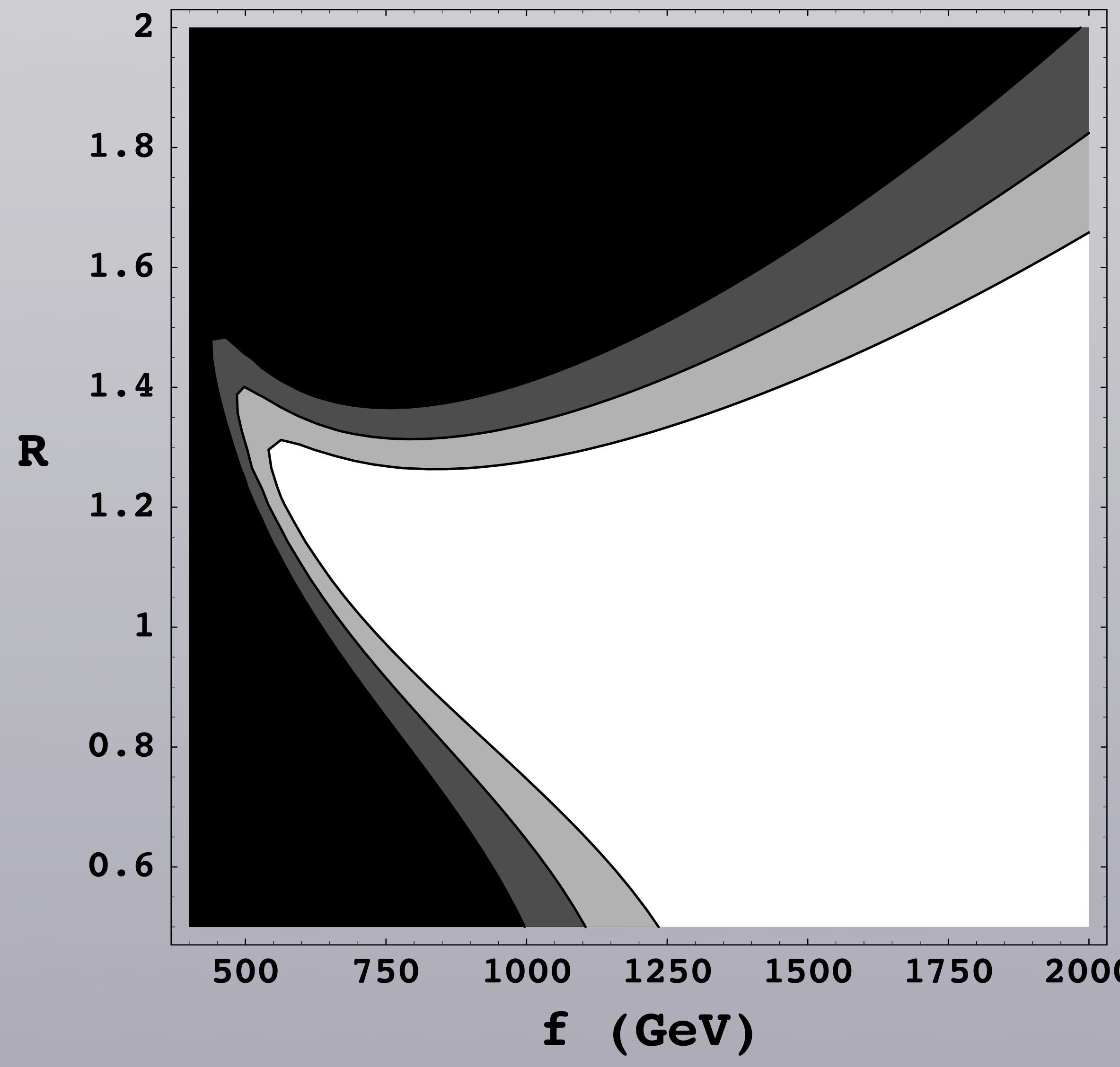



$\lambda_1^d \ll \lambda_2^d$ $\qquad$ $\lambda_2^d \ll \lambda_1^d$

(Two different ways of arranging down quark Yukawa couplings.)

Z. Han
PRD73, 015005

# Little Higgs Models with T parity (H.-C. Cheng+I. Low)




Loop contributions to S and T and to 4-fermi operators

$$R = \frac{\lambda_1}{\lambda_2}$$

(Ratio of Yukawa couplings)

Hubisz, Meade, Noble, Perelstein; JHEP 0601:135

# Summary

- Standard Model works extremely well placing constraints in several TeV range on new states
- No substantial improvement of EW data anytime soon
- Effective Lagrangian approach to “global” analysis is possible, easy, and useful
- Lots of interesting models within the LHC reach

**the end ■**