Precision Electroweak Constraints on BSM Physics

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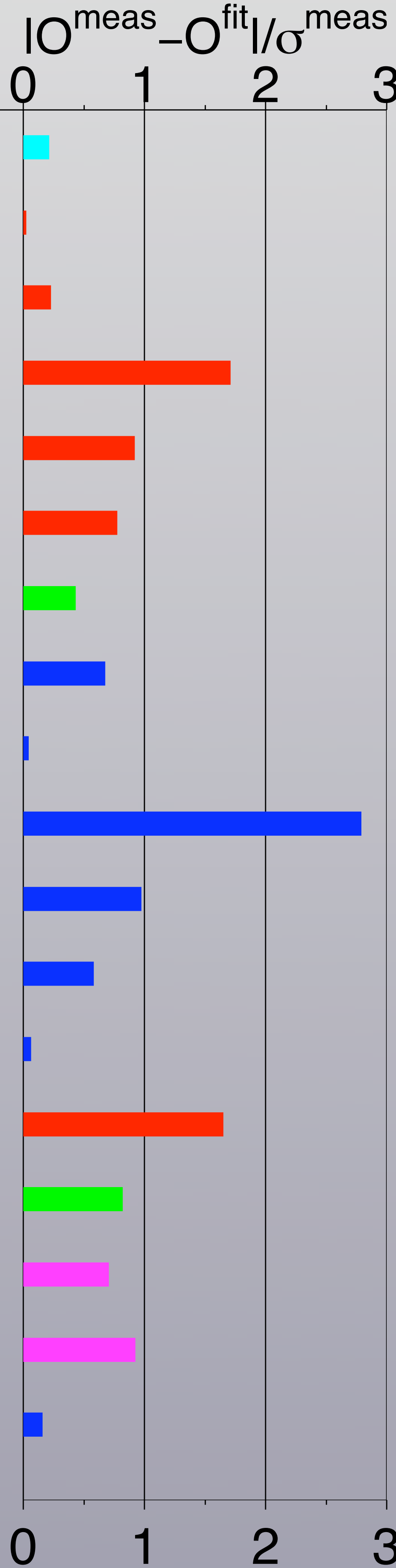
Outline

- 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	0.02766
m_Z [GeV]	91.1875 ± 0.0021	91.1874
Γ_Z [GeV]	2.4952 ± 0.0023	2.4957
σ_{had}^{0} [nb]	41.540 ± 0.037	41.477
R_l	20.767 ± 0.025	20.744
$A_{fb}^{0,l}$	0.01714 ± 0.00095	0.01640
$A_l(P_\tau)$	0.1465 ± 0.0032	0.1479
R_b	0.21629 ± 0.00066	0.21585
R_c	0.1721 ± 0.0030	0.1722
$A_{fb}^{0,b}$	0.0992 ± 0.0016	0.1037
$A_{fb}^{0,c}$	0.0707 ± 0.0035	0.0741
A_b	0.923 ± 0.020	0.935
A_c	0.670 ± 0.027	0.668
A_l(SLD)	0.1513 ± 0.0021	0.1479
$\sin^2\theta_{eff}^{lept}(Q_{fb})$	0.2324 ± 0.0012	0.2314
m_W [GeV]	80.392 ± 0.029	80.371
Γ_W [GeV]	2.147 ± 0.060	2.091
m_t [GeV]	171.4 ± 2.1	171.7



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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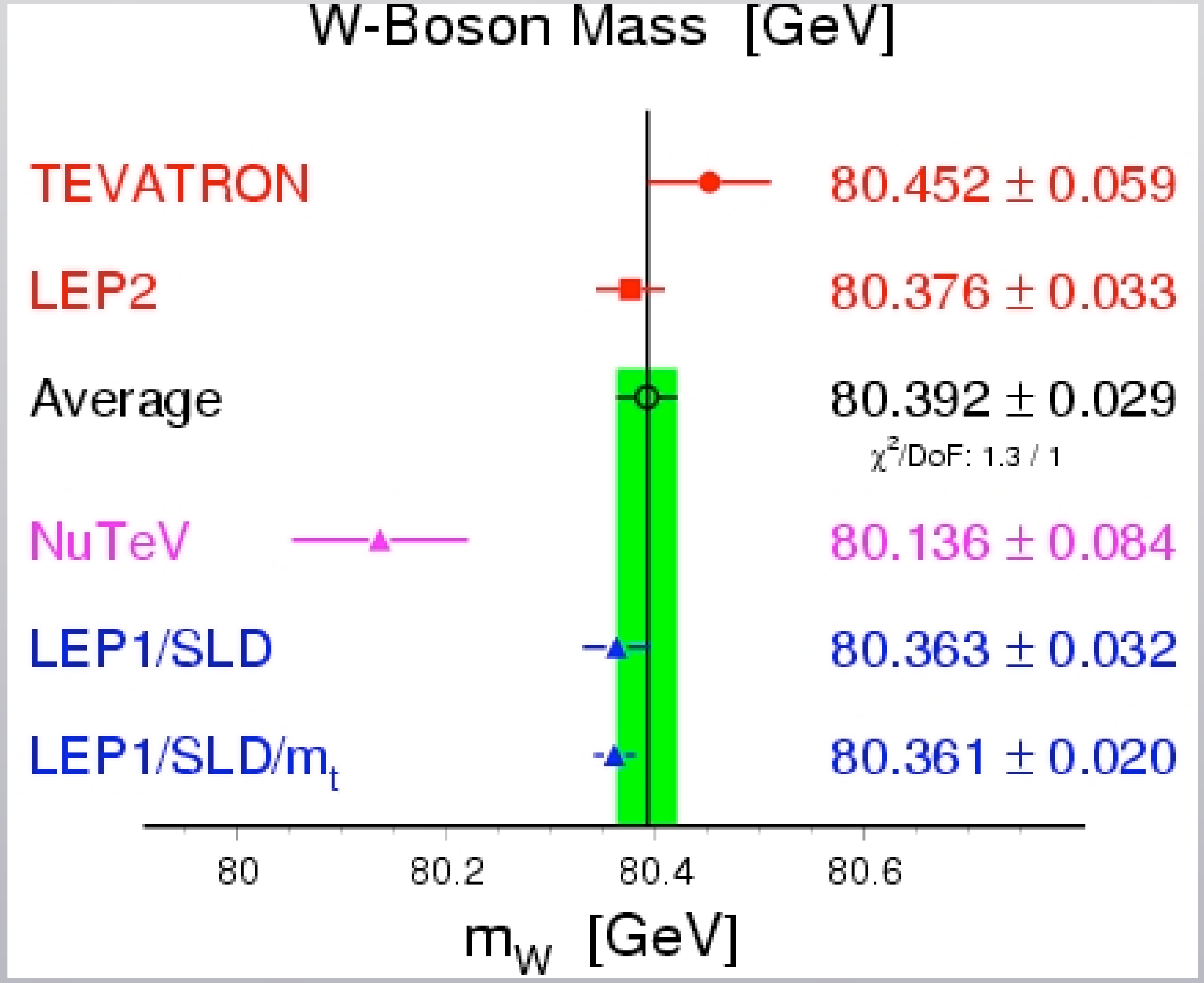

W mass is known with an error of 30 MeV!

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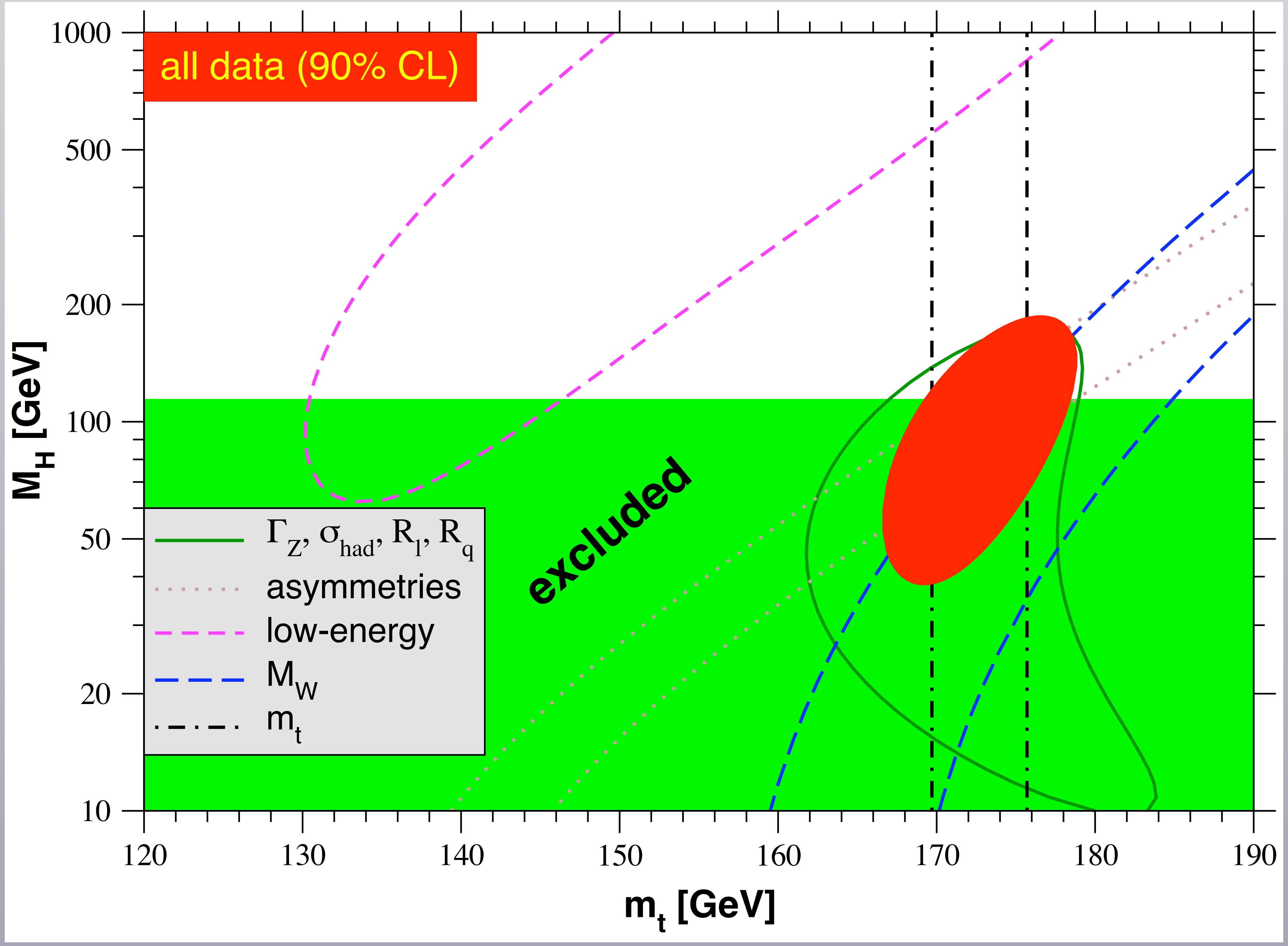
1) Light SM Higgs from Z line shape and cross sections alone

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



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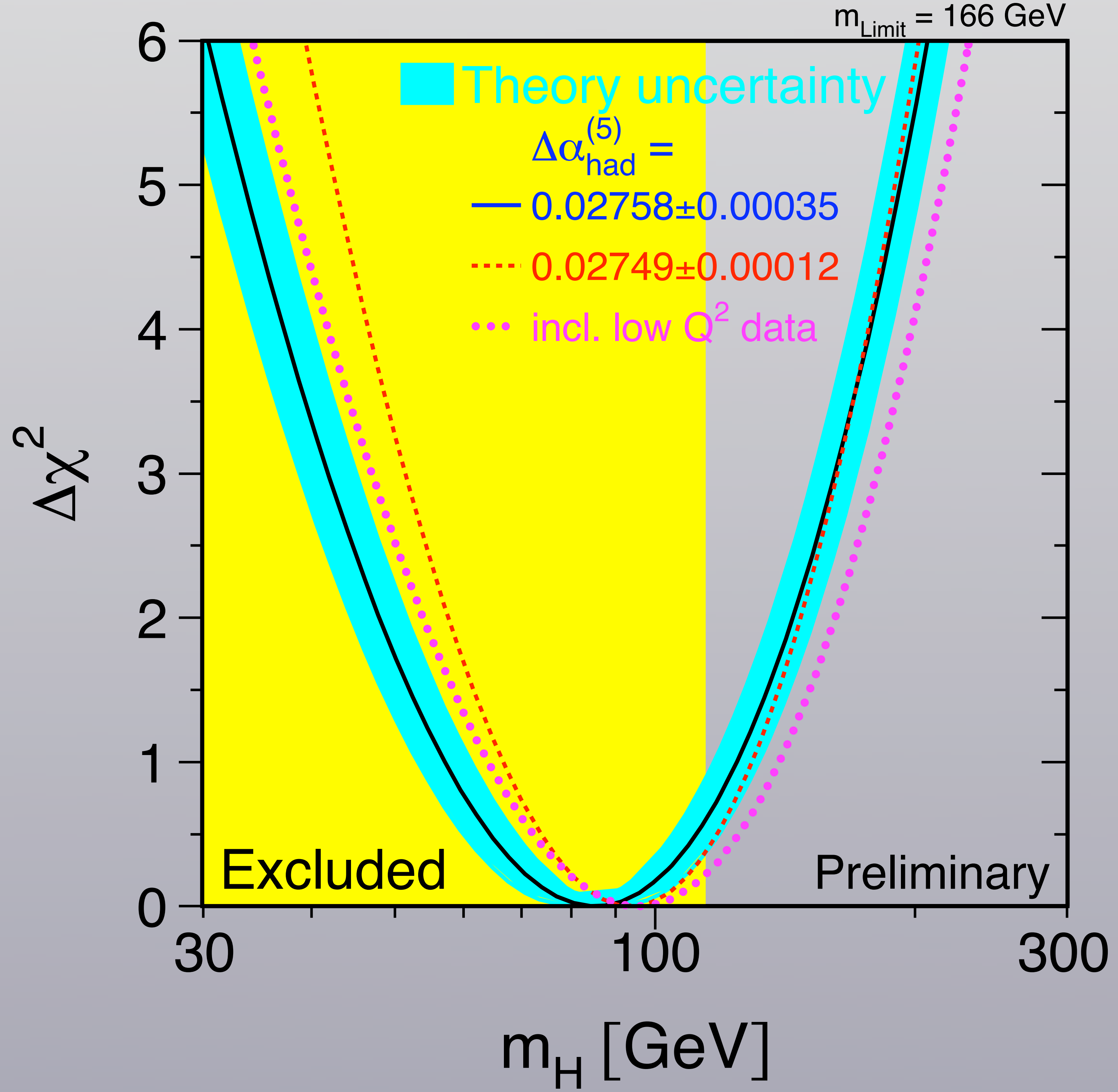

Assuming no new physics !

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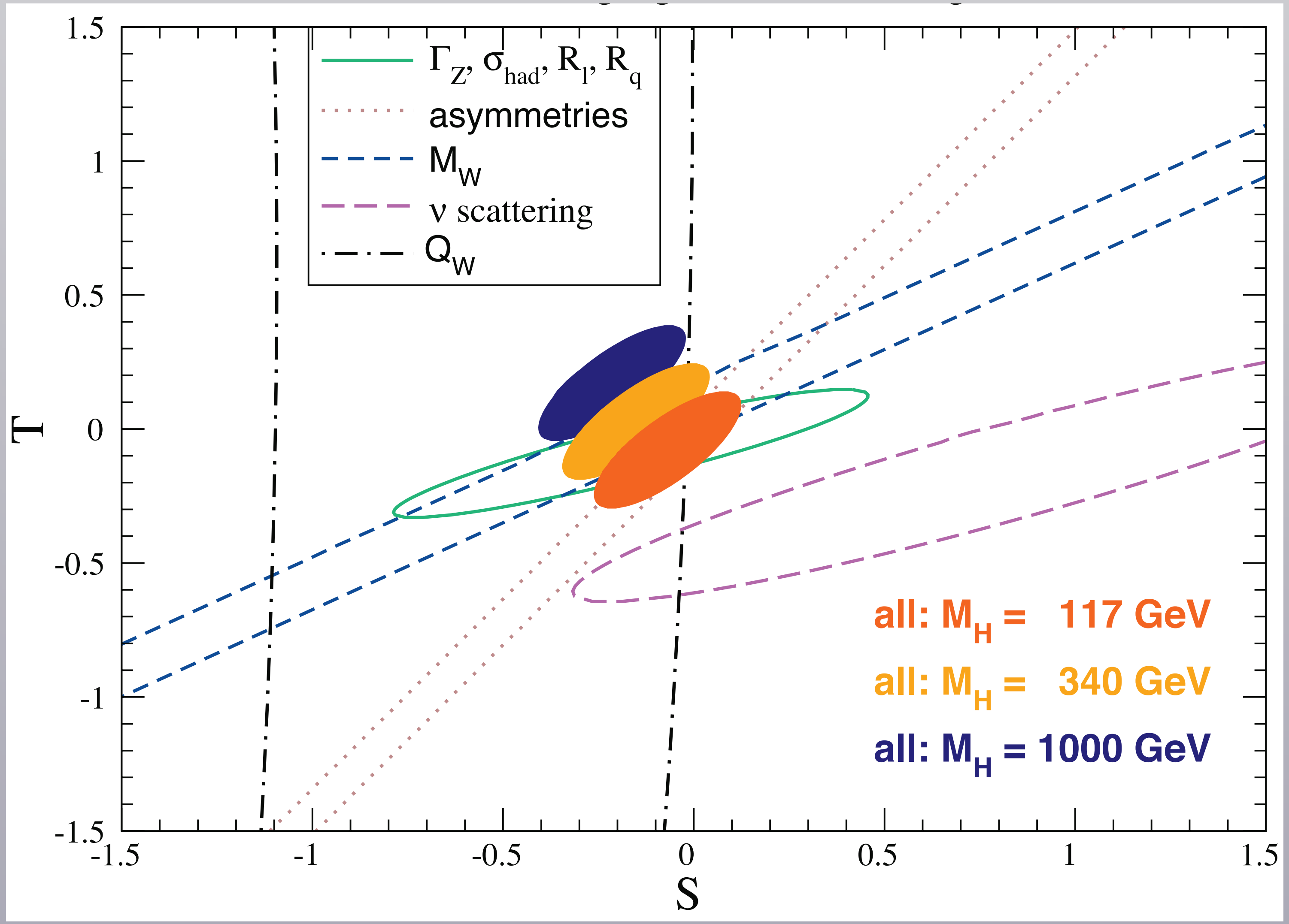
Heavier Higgs boson can be consistent with the data if there are (positive) contributions to the T parameter



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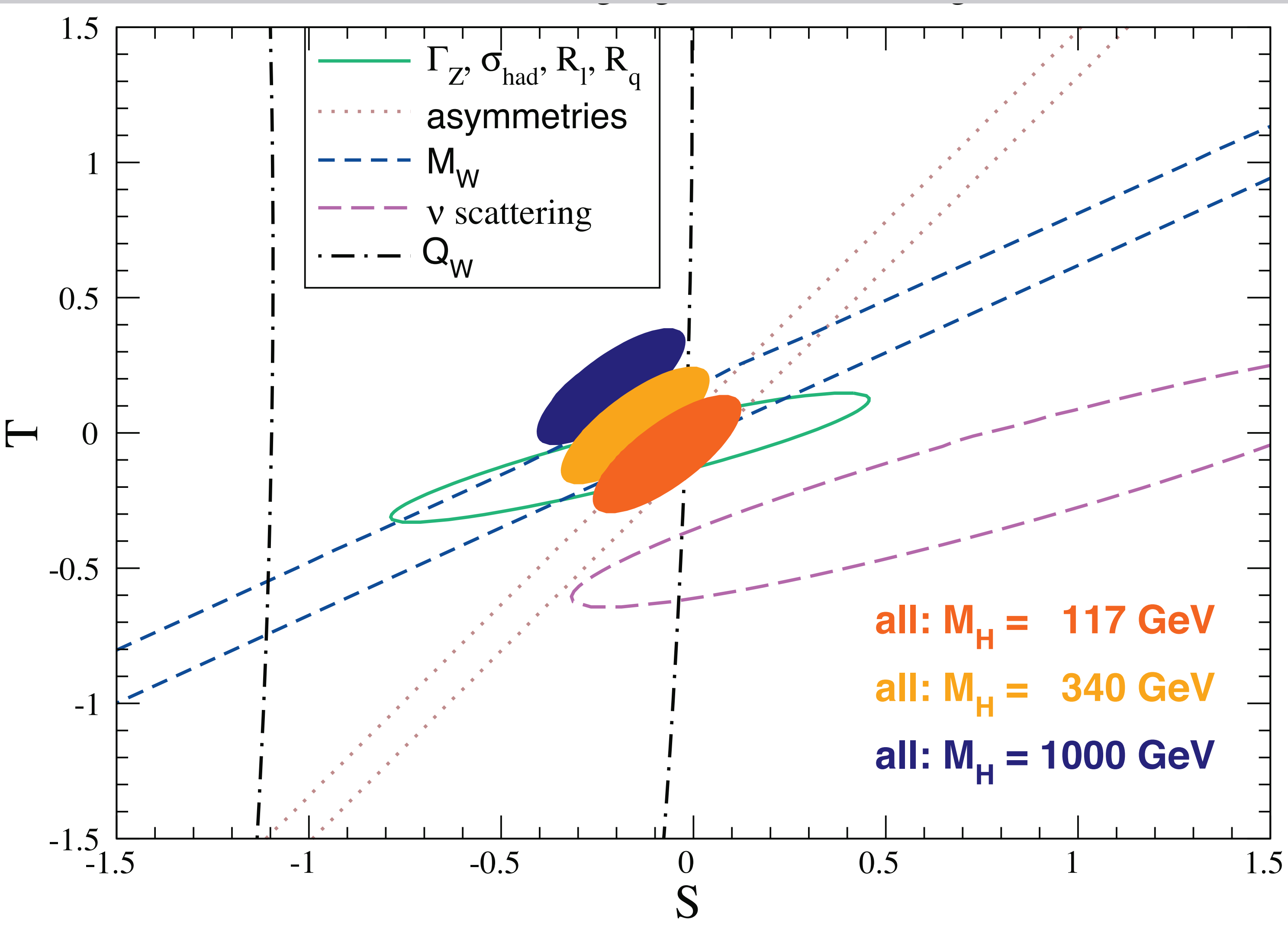

Contributions to T are a dime a dozen

500 GeV Higgs boson OK

e.g. if there is a triplet with

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

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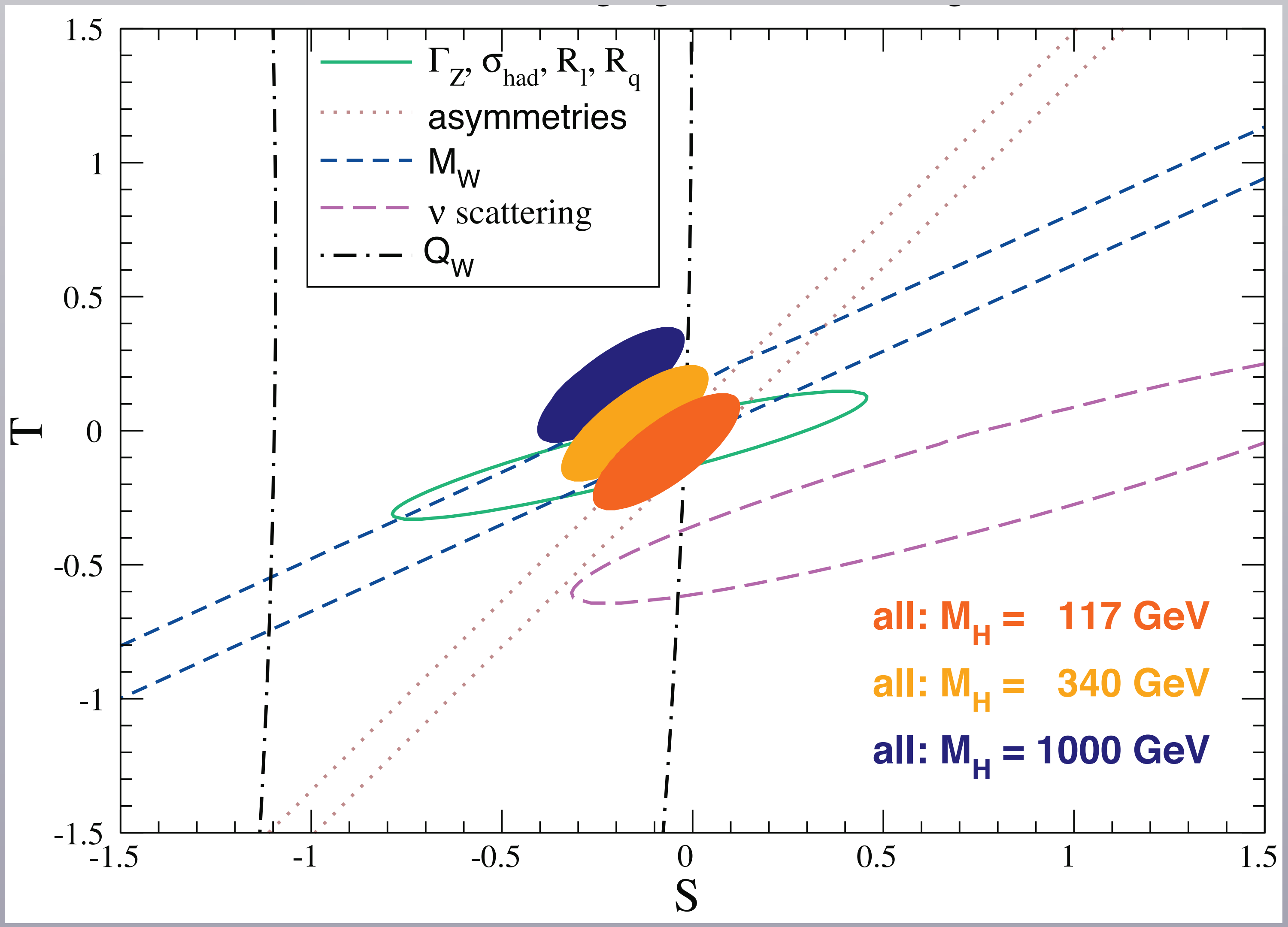
Effective operator approach

- 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.]

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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)

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

$$\updownarrow \qquad\qquad\qquad\qquad \updownarrow$$

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

b) 4 fermions (11+10)

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

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)

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

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

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	ν_μ-nucleon scattering from NuTeV
	R^ν	ν_μ-nucleon scattering from CDHS and CHARM
	κ	ν_μ-nucleon scattering from CCFR
	$g_V^{\nu e}, g_A^{\nu e}$	ν-e scattering from CHARM II
Z-pole	Γ_Z	Total Z width
	σ_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 $e^+e^- \to f\overline{f}$
	$A_{FB}^f(f = \mu, \tau)$	Forward-backward asymmetries for $e^+e^- \to f\overline{f}$
	$d\sigma_e/d\cos\theta$	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!)

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

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

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

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} $(\mathrm{GeV})^4$)

S,T parameters

	a_{WB}	a_h	a^s_{ll}	a^t_{ll}	a^s_{lq}	a^t_{lq}	a_{le}	a_{qe}	a_{lu}	a_{ld}	a_{ee}	a_{eu}	a_{ed}	a^s_{hl}	a^t_{hl}	a^s_{hq}	a^t_{hq}	a_{hu}	a_{hd}	a_{he}	a_W
a_{WB}	$9.1e4$																				
a_h	$2.4e4$	$7.9e3$																			
a^s_{ll}	$-78.$	$-51.$	$5.8e2$																		
a^t_{ll}	$-3.9e4$	$-1.2e4$	$6.7e2$	$2.2e4$																	
a^s_{lq}	$-1.4e3$	$-1.6e2$	$0.$	$1.5e2$	$2.7e3$																
a^t_{lq}	$-5.5e2$	$-1.4e2$	$0.$	$5.9e2$	$4.6e2$	$2.9e3$															
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^s_{hl}	$-1.7e4$	$-4.1e3$	$1.5e2$	$9.7e3$	$-5.9e2$	$8.3e2$	$17.$	$3.7e2$	$-3.9e2$	$-1.6e2$	$1.3e2$	$66.$	$3.8e2$	$5.5e4$							
a^t_{hl}	$5.9e4$	$1.7e4$	$-43.$	$-3.0e4$	$-7.1e2$	$-6.6e2$	$-31.$	$6.6e2$	$-82.$	$-3.4e2$	$-32.$	$4.9e2$	$47.$	$1.5e4$	$6.3e4$						
a^s_{hq}	$-1.9e3$	$-1.4e3$	$0.$	$2.7e3$	$-2.6e3$	$-72.$	$0.$	$2.6e3$	$-1.2e3$	$-1.4e3$	$0.$	$1.2e3$	$1.4e3$	$-6.6e3$	$-8.7e3$	$6.0e3$					
a^t_{hq}	$-9.3e3$	$-4.5e3$	$0.$	$8.7e3$	$-49.$	$3.5e2$	$0.$	$56.$	$-1.4e2$	$-36.$	$0.$	$-64.$	$1.8e2$	$-2.4e4$	$-3.1e4$	$7.7e3$	$2.6e4$				
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}	$1.2e3$	$4.3e2$	$0.$	$-8.1e2$	$-1.4e3$	$-1.3e3$	$0.$	$1.4e3$	$-6.9e2$	$-7.2e2$	$0.$	$6.7e2$	$7.3e2$	$3.3e3$	$3.6e3$	$4.2e2$	$-2.9e3$	$1.6e2$	$1.1e3$		
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

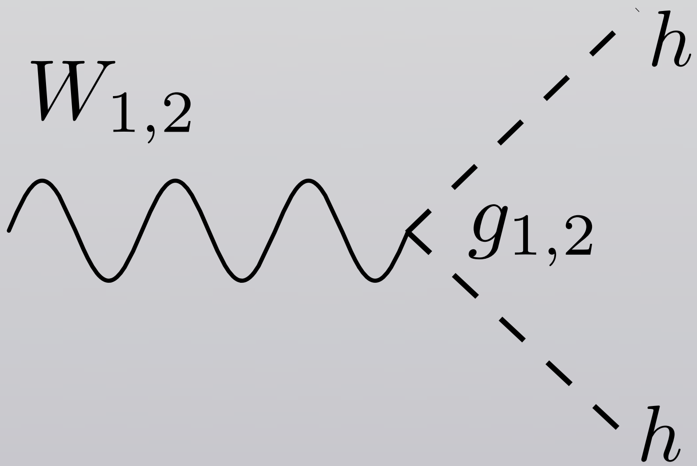
(Times 10^{12} $(\mathrm{GeV})^4$

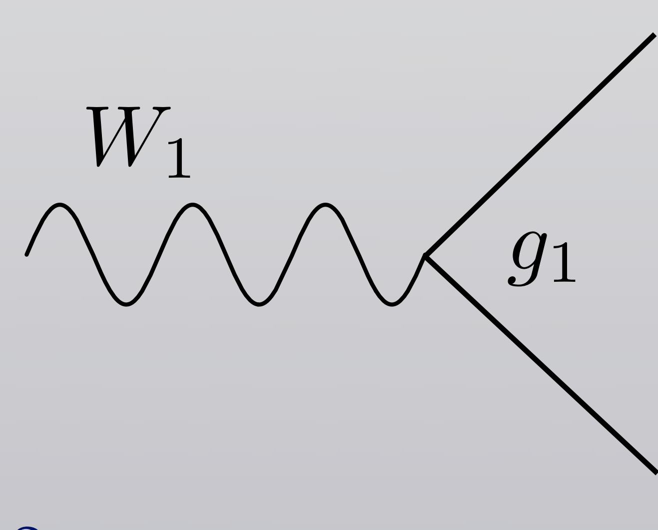
$$\chi^2 = \chi^2_{min} + (a_i - \hat{a}_i)\mathcal{M}_{ij}(a_j - \hat{a}_j)$$

$\mathcal{M}_{ij}$ only depends on the experimental errors, 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

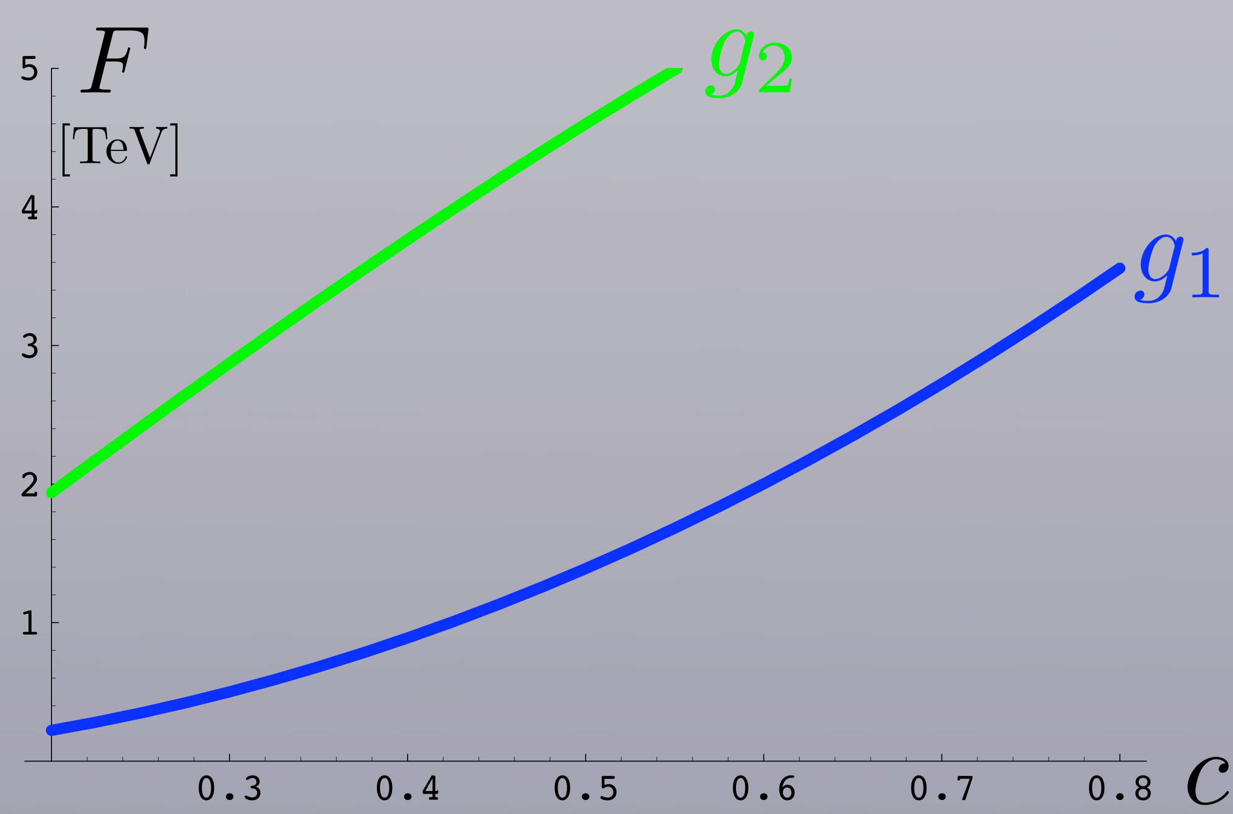




$$g = g_1 s = g_2 c$$

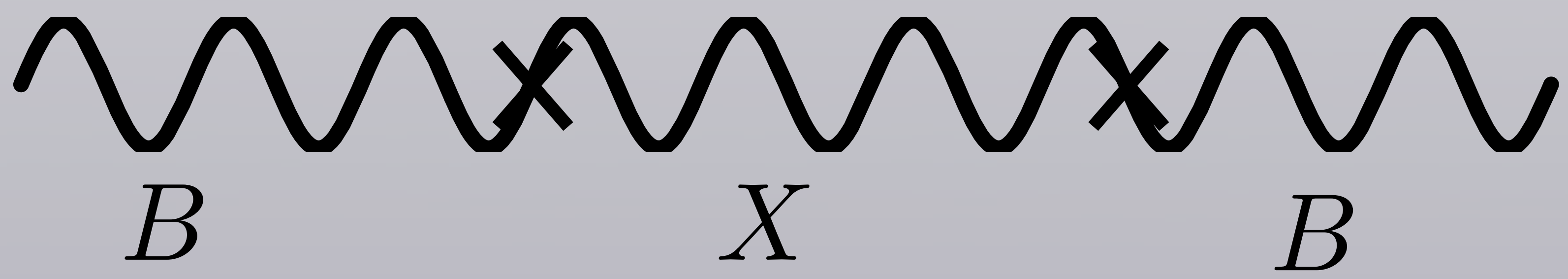
$$M_W^2 \equiv \frac{F^2}{s^2 c^2}$$

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



Kinetic mixing between hypercharge B and Z’

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

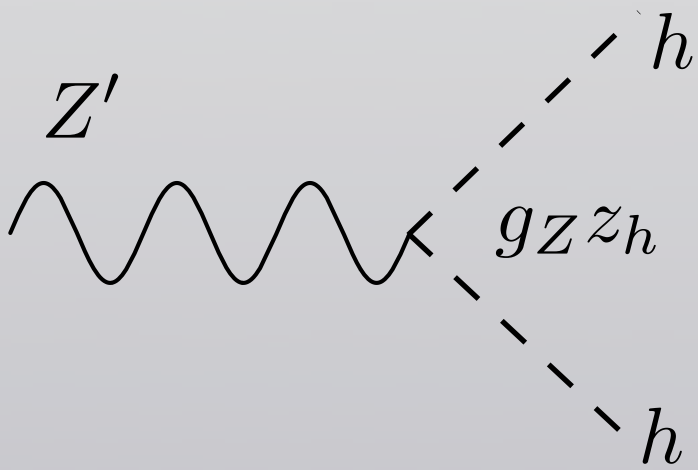


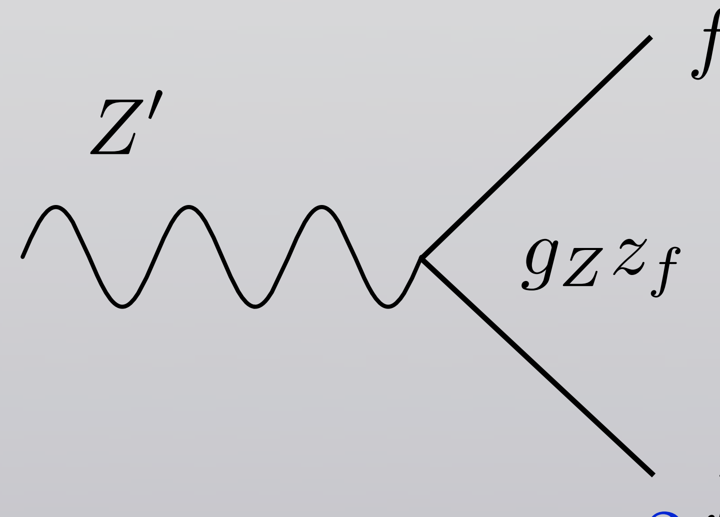
$$\mathcal{L}_{eff} = \frac{\lambda^2}{M_X^2}(\partial^\mu B_{\mu\nu})^2$$

(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:

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

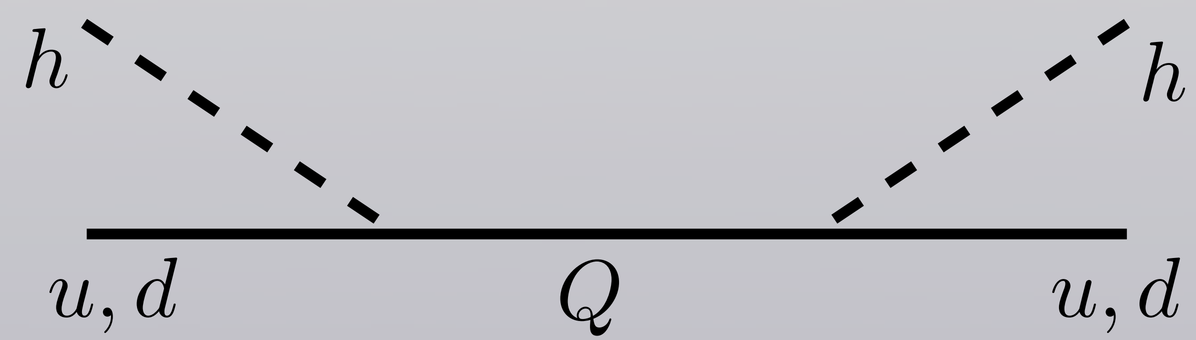
$$A_{LR}^e \to M_{Z'} > 1.0 \text{ TeV}$$

(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

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



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

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

(Assuming universal

family couplings)

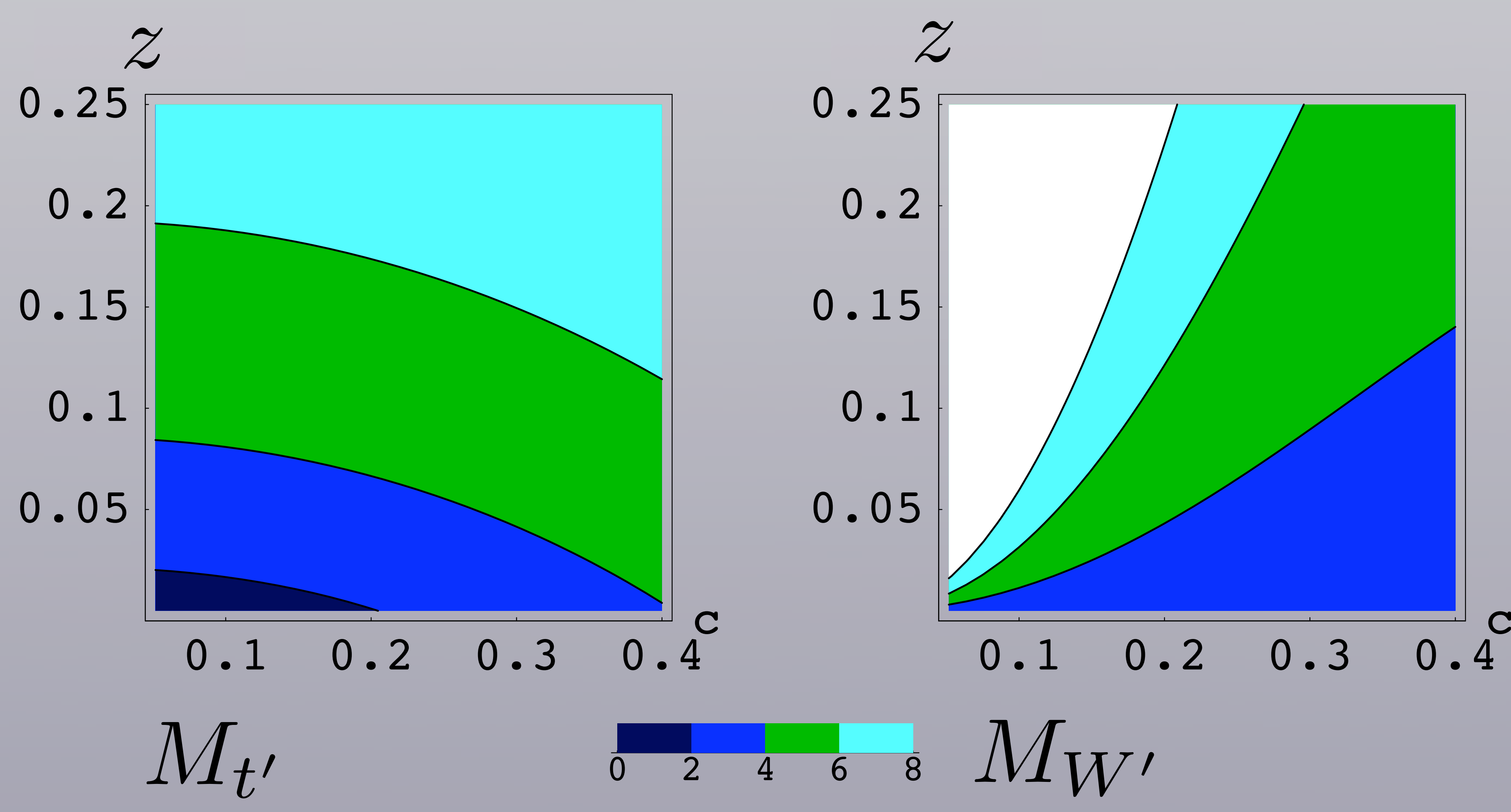
Littlest Higgs: $(SU(2)\times U(1))^2 \rightarrow SU(2)\times U(1)$

Contributions from

scalar triplets: a_h

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

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



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

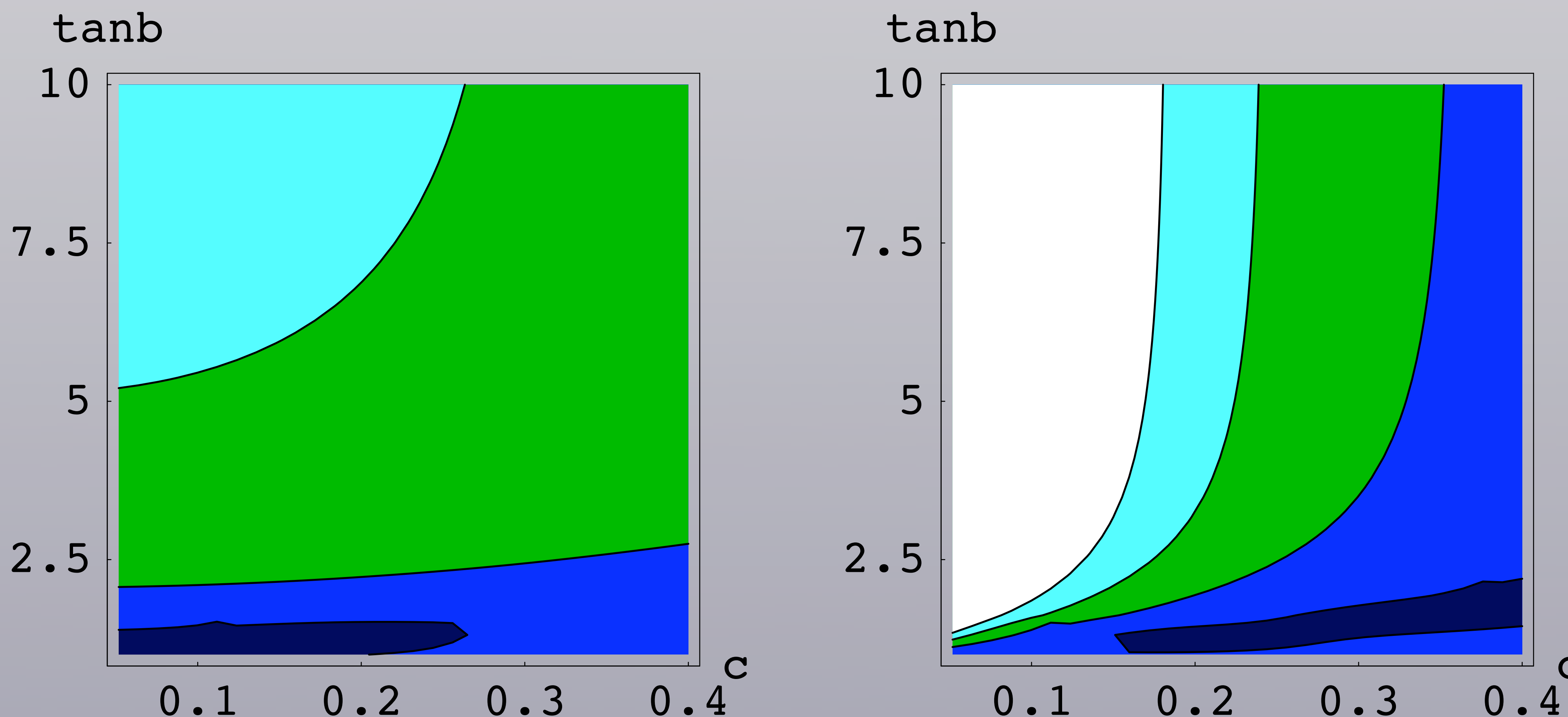
$$(g_1' = g_2')$$

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

Contributions from

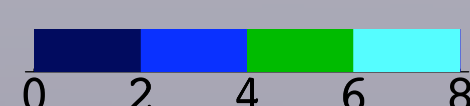
Z' bosons: a_h, a^s_{hf}, a^s_{ff}

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



$(g'_1 = g'_2)$

$M_{t'}$



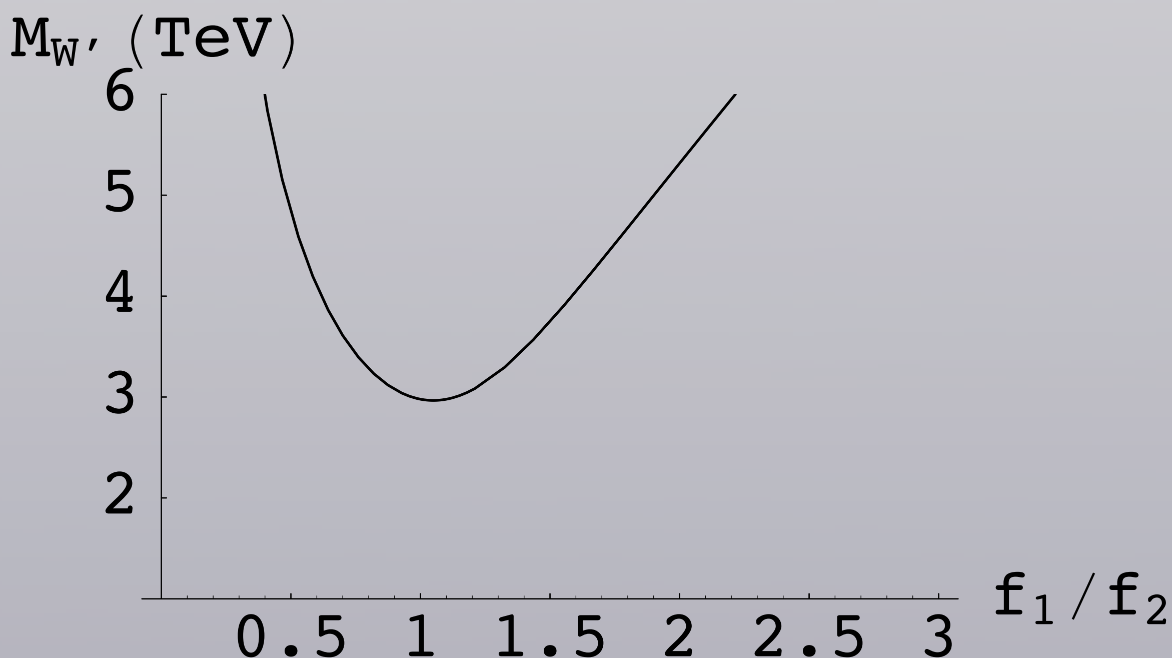
$M_{W'}$

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

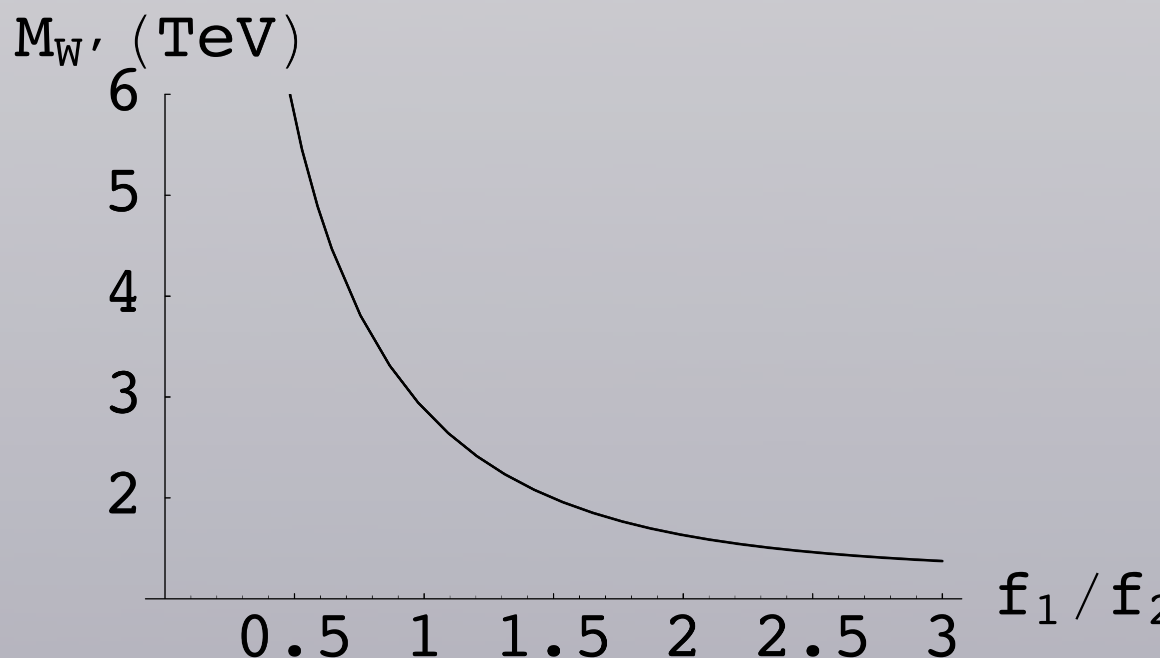
Contributions from

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

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



$\lambda^d_1 \ll \lambda^d_2$

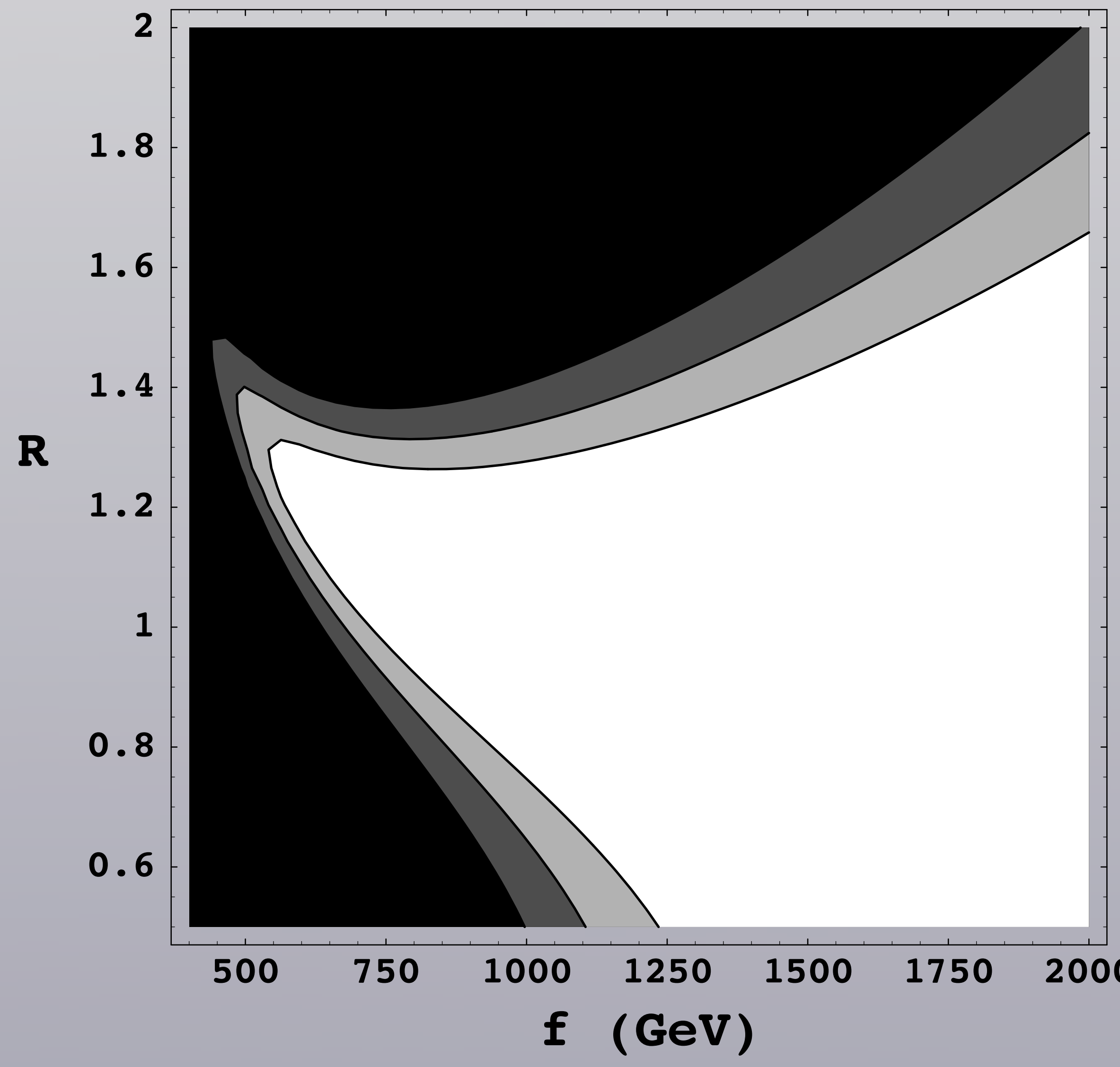


$\lambda^d_2 \ll \lambda^d_1$

(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 ■