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What is the precision electroweak data trying to tell us?

Workshop on indirect searches for
new physics at the time of LHC
Galileo Institute for Theoretical Physics
Firenze, March 2010

More precisely: what is the combination of the PEW data **and** the LEPII limit on m_H trying to tell us?

Canonical: SM fit is great, Higgs boson is light — could be…

But SM fit has a 3.2σ problem, which suggests NP
whether 3.2σ problem is genuine or not:

If due to systematic error (e.g., theoretical), fit predicts m_H much too light $\Rightarrow$ NP with $T > 0$ to raise m_H

Many NP models with custodial SU(2) breaking can then fit PEW data much better than usual SM fit.

Bonus: increased m_H alleviates little hierarchy fine-tuning problem that is generic for light Higgs.

Canonical view might be correct, but the non-canonical interpretation is also worth considering.

Topics

SM fit: implications of A_{LR} - A_{FB}^{b} anomaly

- interpretations of the anomaly
- Higgs mass predictions

New Physics with $SU(2)_{Custodial}$ breaking

- generic
- examples: Z', fourth family

SM Fit

Fits alla EWWG:

- $m_Z, m_t, \Delta\alpha_5, \alpha_S, m_H$ ⇨ $O_{Z\text{-Pole}} + m_W + \ldots$
- Zfitter with 2 loop x_W, m_W
- biggest experimental correlations
- $\Delta\alpha_5$ from BES (Burkhart-Pietryzyk)

  (omit Γ_W – 2.5% error, not part per mil)

Diminished CL(χ^2) = 0.14, primarily from 3.2σ difference between $x_W(A_{LR})$ vs. $x_W(A_{FB}^b)$

Very slight tension with LEPII:

m_H = 89 GeV

CL(m_H > 114 GeV) = 0.23

	Experiment	SM Fit	Pull
A_{LR}	0.1513 (21)	0.1480	**1.6**
A_{FB}^l	0.01714 (95)	0.01644	0.7
$A_{e,\tau}$	0.1465 (32)	0.1480	-0.5
A_{FB}^b	0.0992 (16)	0.1038	**-2.9**
A_{FB}^c	0.0707 (35)	0.0742	-1.0
Q_{FB}	0.23240 (120)	0.23139	1.0
m_W	80.399 (23)	80.378	0.9
Γ_Z	2495.2 (23)	2495.7	-0.2
R_l	20.767 (25)	20.739	1.1
σ_h	41.540 (37)	41.481	-1.6
R_b	0.21629 (66)	0.21582	0.7
R_c	0.1721 (30)	0.1722	-0.04
A_b	0.923 (20)	0.935	-0.6
A_c	0.670 (27)	0.668	0.07
m_t	173.1 (1.3)	173.3	0.1
$\Delta\alpha_5(m_Z^2)$	0.02758 (35)	0.02768	0.3
$\alpha_S(m_Z)$		0.118	
χ^2/dof		17.3/12	
CL(χ^2)		**0.14**	
m_H		**89**	
CL(m_H > 114)		**0.23**	
m_H(95%)		**151**	

$x_W^{\ell,\mathrm{eff}}$: most important observable for m_H fit

A_{LR}	**0.23098 (26)**	$x^\ell[A_L] = 0.23113\ (21)$	**0.23153 (16)**
A_{FB}^{ℓ}	0.23099 (53)	$\chi^2/N = 1.6/2 \quad CL = 0.44$	**3.2σ**
$A_{e,\tau}$	0.23159 (41)		**CL = 0.0014**
A_{FB}^{b}	**0.23221 (29)**	$x^\ell[A_H] = 0.23222\ (27)$	
A_{FB}^{c}	0.23220 (81)	$\chi^2/N = 0.02/2 \quad CL = 0.99$	
Q_{FB}	0.23240 (120)		

Dominated by $x[A_{LR}] \oplus x[A_{FB}^{b}] = 0.23153\ (19)$

3.2σ CL = 0.0016

Combining all six: $\chi^2/N = 11.8/5 \quad CL = 0.037$

A_{FB}^{b}, A_b, $x_W^{\ell,\mathrm{eff}}$ & all that...

$A_{FB}^{b} = 3/4 \cdot A_e A_b$ $\qquad$ $A_f = \dfrac{g_{fL}^2 - g_{fR}^2}{g_{fL}^2 + g_{fR}^2}$

SM: $g_{fL} = t_{3L,f} - q_f x_W^{f,\mathrm{eff}}$ $\qquad$ $g_{fR} = - q_f x_W^{f,\mathrm{eff}}$

$A_b^{(SM)} = 0.935 \pm 0.0005$ ➡ Negligible sensitivity to m_H, m_t

Sensitivity to x_W & m_H resides in A_ℓ (because $A_\ell \propto 1/4 - x_W$)

SM fit *assumes* $\mathbf{A_b^{(SM)}}$: $\quad A_\ell = 4A_{FB}^{b} / 3\mathbf{A_b^{(SM)}}$ ➡ $x_W^{\ell,\mathrm{eff}}$

A_b measured **directly**: A_{FBLR}^{b} ➡ $A_b = 0.923\ (20)$ Agrees with SM

or **indirectly** from A_{FB}^{b} using A_ℓ from A_{LR}, A_{FB}^{ℓ}, $A_{e,\tau}$:

$A_b = 4A_{FB}^{b} / 3 A_\ell = 0.881\ (17)$ $\quad$ 3.2σ from SM; 1.6 σ from A_{FBLR}^{b}

$A_b[\textit{direct}] \oplus A_b[\textit{indirect}] = 0.899\ (13)$ $\quad$ 2.8σ from SM

➡ Evidence for NP in Zbb interaction is equivocal.

Three generic options…

$A_{FB}{}^{b} - A_{LR}$ anomaly could be

- Statistical fluctuation
- New physics
- Underestimated systematic error

Briefly consider each:

Statistical Fluctuation

Significance depends on how question is framed.

- Global CL's fairly reflect likelihood that ***any*** of a set of measurements might fluctuate to become an outlyer:

  E.g., $\chi^2/N = 17.3/12$ → **CL = 0.14**

  Cf., Probability of at least one ≥ 2.86σ outlyer ($A_{FB}{}^{b}$) among 12 independent measurements: **P = 0.05**

- IF we ask for the consistency of the measurements that determine m_H, the answer is

  χ^2, N = 14.2, 7 **CL = 0.05** { Omits σ_H, $R_{b,c}$, $A_{b,c}$

- IF we ask for the consistency of the two highest precision asymmetry measurements that determine m_H, the answer is the nominal CL for 3.2σ, **P = 0.0014**

<u>Most conservative assessment: there is an O(10%) problem.</u>

New Physics in A_b ? — the R_b constraint

1998± : 3σ R_b anomaly understood as systematic error.

Today: $R_b[\mathrm{expt}] / R_b[\mathrm{SM}] = 1.003\ (3)$

$\Rightarrow$ $\delta g_{bL}^2 + \delta g_{bR}^2 \sim 0.0005\ (5)$

A_{FB}^b anomaly: $A_b[A_{FB}^b] / A_b[\mathrm{SM}] = 0.942\ (18)$

$\Rightarrow$ $\delta g_{bL}^2 - \delta g_{bR}^2 \sim -0.009\ (3)$

$\Rightarrow$ $\delta g_{bL}/g_{bL}^{SM} \approx -0.005/-0.42 \approx 0.01$

$\delta g_{bR}/g_{bR}^{SM} \approx 0.03/0.08 \approx \mathbf{0.4}$ **HUGE**

Huge δg_{bR} probably requires tree level NP, hard to find in plausible extensions of the SM but not impossible:

e.g., **b-Q** mixing (Choudury-Tait-Wagner, Morrissey-Wagner)

or **Z-Z'** mixing (He-Valencia, Djouadi-Moreau-Richard)

Systematic uncertainty

$x_W(A_{LR}, A_{FB}^{\ell}, A_{e,\tau})$: $\chi^2/N = 1.6/2$ CL = 0.44

3 very different techniques

Common systematic errors very unlikely

$x_W(A_{FB}^{b}, A_{FB}^{c}, Q_{FB})$: $\chi^2/N = 0.02/2$ CL = 0.99

Challenging and complex measurements and analysis

Many shared systematic issues, e.g.,

- 14 parameter heavy flavor fit
- Disentangling $b \to e^-$, $\overline{c} \to e^-$, $\overline{b} \to \overline{c} \to e^-$
- QCD and hadronization

although quoted error for A_{FB}^{b} is predominantly statistical

14 parameter Heavy Flavor fit

$x_W(A_{FB}^b, A_{FB}^c , Q_{FB})$ are very tightly clustered:

$\chi^2/N = 0.02/2$ CL = 0.99

A_{FB}^b, A_{FB}^c extracted from 14 parameter HF fit,

$\chi^2/N = 53/91$ CL = **0.9995**

suggests possibility of imperfectly understood systematics

EWWG: systematic errors too conservative?

Suppose all HF fit sys errors $\rightarrow$ 0

$\Rightarrow$ $\chi^2/N = 92/91$ CL = **0.45**

But: CL { $x[A_{LR}] \oplus x[A_{FB}^b]$ } = **0.0016** $\longrightarrow$ **0.0007**

CL {$x_W^{\ell,\mathrm{eff}}$} = **0.04** $\longrightarrow$ **0.02**

CL { SM} = **0.14** $\longrightarrow$ **0.03**

Stat. errors only for $A_{FB}^{b,c}$, $A_{b,c}$, $R_{b,c}$

b and c quark identification

$b \to e^-$ and $\bar{c} \to e^-$ are backgrounds for one another:
b <—> $\bar{c}$ mistags are consistent with signs of both the A_{FB}^b and A_{FB}^c anomalies.

Mistags due to primary charm, $Z \to \bar{c}c$, and secondary charm, $\bar{b} \to \bar{c} \to e^-$

Mistags are highly leveraged in A_{FB}^b: 1% mistag for primary charm would shift A_{FB}^b by $+1\sigma$

Cuts specific to the A_{FB}^b measurement (which favor high thrust) might affect the mistag rate relative to the rate in the R_b measurement.

➡ To understand the mistag rate in the A_{FB}^b measurement, it could be interesting to extract R_b with A_{FB}^b analysis cuts and compare with expectation.

QCD and hadronization

- QCD corrections (1 + 2 loop) are large:

$$\Delta_{QCD} \sim 3\,\Delta_{EXPT}$$

Altarelli-Lampe,
Catani-Seymour,
Ravindran-
van Neerven

- Hadronization contributes to systematic uncertainty
  - hadronic thrust axis differs from partonic
  - event selection and analysis cuts favoring high thrust introduce a bias in event topologies which diminishes QCD correction by an amount that cannot be precisely determined. For $B \to \ell + X$,

Most important

$$\text{bias correction} \sim 1/2\,\Delta_{QCD} \sim \Delta_{EXPT} \text{ (from JETSET)}$$

EWWG estimate, based on comparing diff JETSET tunes:

$$\text{QCD/hadronization error} \sim 1/4\,\Delta_{EXPT}$$

but uncertainty of the uncertainty estimate is difficult to quantify

Systematic error: summary

- $x^\ell\,[A_L]$: A_{LR}, A_{FB}^ℓ, $A_{e,\tau}$ $\chi^2/N = 1.6/2$ CL = 0.44
  - relatively simple & clean experimentally
  - no QCD or hadronic Monte Carlo corrections
  - 3 very different techniques: common sys error very unlikely
- $x^\ell\,[A_H]$: A_{FB}^b, A_{FB}^c, Q_{FB} $\chi^2/N = 0.02/2$ CL = 0.99
  - experimentally challenging: flavor tag & charge
  - big QCD corr'ns with detector-dependent bias, estimated with hadronic Monte Carlo + detector simulation.

⇒ Unique, correlated experimental & theoretical systematics which may be difficult to quantify

If A_{FB}^b, A_{FB}^c, Q_{FB} have underestimated sys. error, x_W^ℓ is most reliably obtained from A_{LR}, A_{FB}^ℓ, $A_{e,\tau}$

Consequences of underestimated systematic error

Without excluding the possibility of statistical fluctuation or new physics, we explore the implications of underestimated systematic error as the explanation of the anomaly.

Assume $\mathbf{A_{FB}^b}$, $\mathbf{A_{FB}^c}$, $\mathbf{Q_{FB}}$ have underestimated systematic errors and remove from fit.

➡ SM fit improves

CL: 0.14 ——> 0.77

but tension with LEPII increases:

m_H : 89 ——> 61

CL(m_H > 114): 0.23 ——> 0.03

m_H(95%): < 151 ——> < 105

	Experiment	SM Fit	Pull
A_{LR}	0.1513 (21)	0.1498	0.7
A^l_{FB}	0.01714 (95)	0.01684	0.3
$A_{e,\tau}$	0.1465 (32)	0.1498	-1.0
m_W	80.399 (23)	80.400	-0.001
Γ_Z	2495.2 (23)	2496.4	-0.5
R_l	20.767 (25)	20.743	1.0
σ_h	41.540 (37)	41.480	-1.6
R_b	0.21629 (66)	0.21581	0.7
R_c	0.1721 (30)	0.1724	-0.05
A_b	0.923 (20)	0.935	-0.6
A_c	0.670 (27)	0.669	0.03
m_t	173.1 (1.3)	173.3	0.1
$\Delta\alpha_5(m_Z^2)$	0.02758 (35)	0.02754	0.1
$\alpha_S(m_Z)$		0.118	
χ^2/dof		5.7/9	
CL(χ^2)		**0.77**	
m_H		**61**	
CL($m_H > 114$)		**0.03**	
m_H(95%)		**105**	

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Without excluding the possibility of statistical fluctuation or new physics, we explore the implications of underestimated systematic error as the explanation of the anomaly.

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➡ SM fit improves

CL: 0.14 ——> 0.77

but tension with LEPII increases:

		$\boxed{\delta m_{t\ \mathrm{EXPT}} \times 2}$
m_H :	**89 ——> 61**	**——> 61**
CL(m_H > 114):	**0.23 ——> 0.03**	**——> 0.05**
m_H(95%):	**< 151 ——> < 105**	**——> < 114**

Consequences of underestimated systematic error

Without excluding the possibility of statistical fluctuation or new physics, we explore the implications of underestimated systematic error as the explanation of the anomaly.

Assume $\mathbf{A_{FB}^b}$, $\mathbf{A_{FB}^c}$, $\mathbf{Q_{FB}}$ have underestimated systematic errors and remove from fit.

➡ SM fit improves

CL: 0.14 ——> 0.77

but tension with LEPII increases:

$\Delta\alpha_5$ from Hagiwara et al.:

$\Delta\alpha_5$ **= 0.02760 (15)**

$\mathbf{m_H}$ **:**	**89 ——> 61**	**——> 58**
CL($\mathbf{m_H}$ **> 114):**	**0.23 ——> 0.03**	**——> 0.017**
$\mathbf{m_H}$**(95%):**	**< 151 ——> < 105**	**——> < 97**

Dissecting the Higgs mass prediction

The m_H prediction in the SM fit, with CL(17.3,11) = 0.14,

m_H = 89 GeV, < 151 GeV (95%)

is dominated by three observables, **A_{LR}, A_{FB}^b, m_W** (+ m_t, $\Delta\alpha_5$)

m_H = 89 GeV, < 156 GeV (95%)

with a poor fit, **CL(11.6,2) = 0.003**, casting doubt on reliability of the SM m_H prediction, regardless of the anomaly's origin.

Separately:

A_{LR}: m_H = 37 GeV, < 110 GeV (95%)

m_W: m_H = 61 GeV, < 126 GeV (95%)

A_{FB}^b: m_H = 187 GeV, 187 < m_H < 1+ TeV

A_{LR} – m_W alliance explains why A_{FB}^b has biggest pull in SM fit

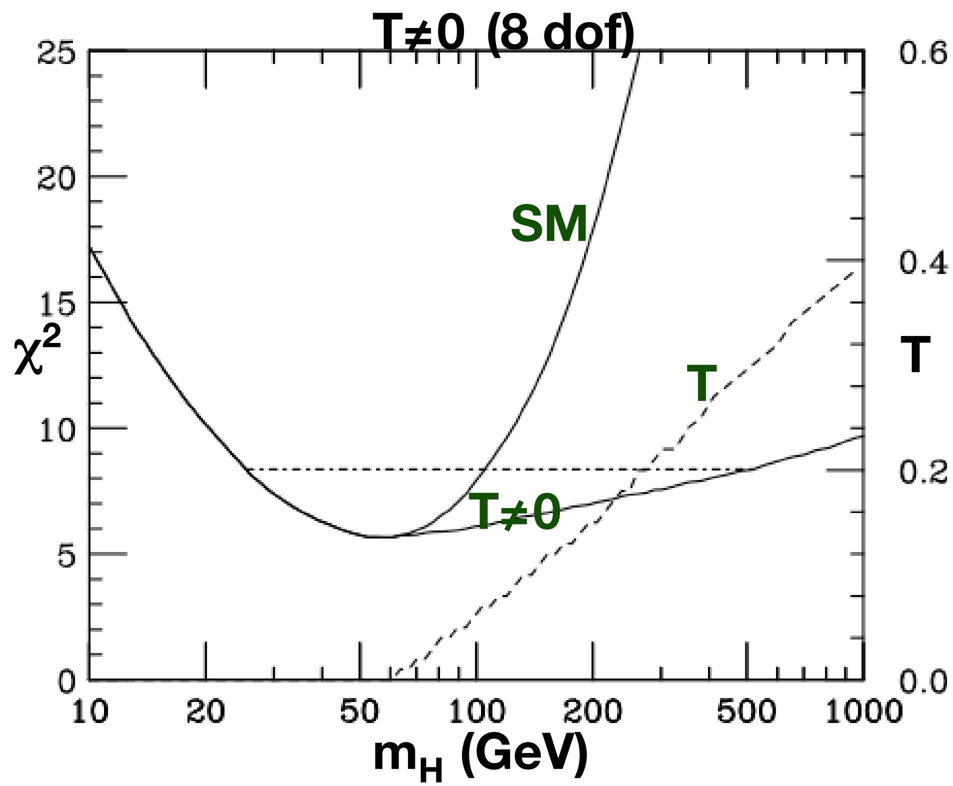
New Physics with Custodial SU(2) breaking

NP with $SU(2)_{Custodial}$ breaking can raise m_H while preserving good χ^2 fit.

Dash-dotted line denotes sym 90% confidence interval:

SM: $m_H < 105$ 95%

$T \neq 0$: $m_H < 520$ 95%

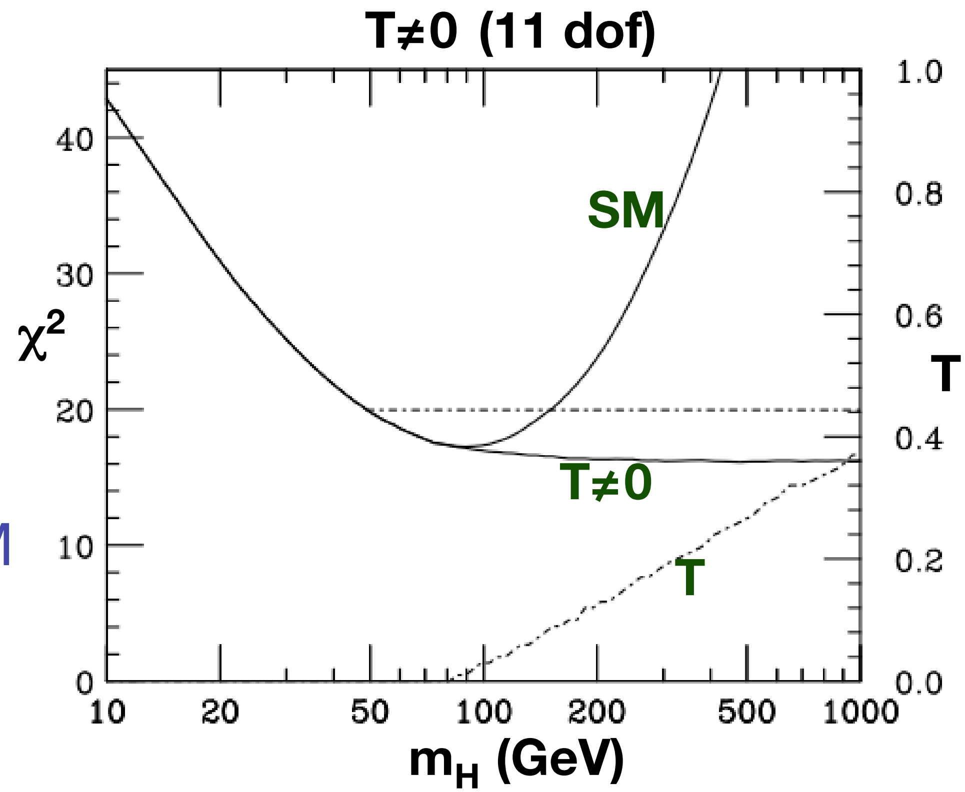


At m_H = 520 GeV, oblique NP fit has CL(8.4,8) = 0.40

But not really so easy: oblique NP typically comes with other corrections ($S \neq 0$ or non-oblique effects) that can degrade the fit.

T≠0 fit to full data set

Fit to full data set, including hadronic asymmetries, has very flat χ^2 for large m_H



Dash-dotted line denotes sym 90% confidence interval for SM

SM: $m_H < 151$ 95%

$T \neq 0$: $m_H < 1+$ TeV

CL of oblique fit at large m_H is ~ CL(16.2,11) = 0.13, similar to SM fit with CL(17.3,12) = 0.14

Example 1: a fourth family

If a 4'th family is discovered the consequences would be at least as profound as those which emerged from the discovery of the 3'rd family, including the possibility of a role in EWSB.

Contrary to popular urban legend, a 4'th family can be consistent with PEW data. (Only please tell me why $m_\nu > m_Z/2$ …)

He *et al.* 2001
Novikov *et al.* 2002
Tait *et al.* 2007

Mass splitting in 4'th family quark and lepton doublets provides $SU(2)_{Custodial}$ breaking, $T > 0$, which raises m_H and can remove tension with LEPII bound for data set without A_{FB}^b, A_{FB}^c, Q_{FB}, as first shown by Novikov *et al.*

Mixing between 3'rd and 4'th families of order $\theta_{Cabibbo}$ is allowed and can further increase m_H prediction.

MC. 2009

Setup

Choose $m_{b'} = m_{t'} - 55\,\mathrm{GeV}$

PEW fits require
$|m_{t'} - m_{b'}| \sim 45\text{–}75$ GeV

$m_{\nu_4} = 100 \qquad m_{l_4} = 145$

Little effect on fit

CDF: $m_T > 311$, $m_B > 338$

Assume predominantly 3-4 mixing, $s_{34} = \sin\theta_{34}$

$$T_4 = \frac{1}{8\pi x_W(1-x_W)}\left\{3\left[F_{t'b'} + s_{34}^2(F_{t'b} + F_{tb'} - F_{tb} - F_{t'b'})\right] + F_{l_4\nu_4}\right\}$$

$$F_{12} = \frac{x_1 + x_2}{2} - \frac{x_1 x_2}{x_1 - x_2}\ln\frac{x_1}{x_2} \qquad x_i = m_i^2/m_Z^2$$

Include other non-decoupling effects: S_4 and Zbb

Results: reduced data set

Example: m_T = 500 GeV

Resolves tension with LEPII

θ_{34} = 0:

m_H = 89

CL(m_H > 114) = 0.28

CL(χ^2) = 0.36

At 95% CL limit for θ_{34},

s_{34} = 0.11

m_H = 280

CL(m_H > 114) = 1.0

CL(χ^2) = 0.13

	Experiment	SM	Pull	SM$_4$	Pull	s_{34}[95%]	Pull
A_{LR}	0.1513 (21)	0.1503	0.5	0.1483	1.4	0.1474	1.8
A^l_{FB}	0.01714 (95)	0.01694	0.2	0.1649	0.7	0.01630	0.9
$A_{e,\tau}$	0.1465 (32)	0.1503	-1.2	0.1483	-0.6	0.1474	-0.3
m_W	80.398 (25)	80.403	0.03	80.423	-1.0	80.425	-1.1
Γ_Z	2495.2 (23)	2496.0	-0.3	2498.5	-1.4	2499.2	-1.7
R_ℓ	20.767 (25)	20.741	1.0	20.729	1.5	20.725	1.7
σ_h	41.540 (37)	41.482	1.6	41.489	1.4	41.491	1.3
R_b	0.21629 (66)	0.21584	0.7	0.21586	0.6	0.2157	1.0
R_c	0.1721 (30)	0.1722	-0.04	0.1722	-0.03	0.1722	-0.05
A_b	0.923 (20)	0.935	-0.6	0.935	-0.6	0.935	-0.6
A_c	0.670 (27)	0.669	0.03	0.668	0.06	0.668	0.08
m_t	172.6 (1.4)	172.3	0.2	172.3	0.2	172.3	0.2
$\Delta\alpha_5(m_Z)$	0.02758 (35)	0.02754	0.1	0.02747	0.3	0.2732	0.7
$\alpha_S(m_Z)$		0.1174		0.1162		0.1168	
$m_{t'}$				500		500	
s_{34}				0.0		0.11	
T_4				0.20		0.35	
S_4				0.15		0.15	
$x_{t'}$				0.0		0.00028	
m_H		50		89		280	
CL(m_H > 114)		0.03		0.28		1.0	
m_H(95%)		105		174		480	
χ^2/dof		5.6/9		9.8/9		13.7/9	
CL(χ^2)		0.78		0.36		0.13	

Table 5: Global fits for the data set without the hadronic asymmetry measurements: the SM, the 4 family SM with $m_{t'}$ = 500 GeV and s_{34} = 0, and again with s_{34} at the 95% confidence level.

Results: full data set

m_T = 500 GeV

Resolves (slight) tension with LEPII

θ_{34} = 0:

m_H = 139

CL(m_H > 114) = 0.67

CL(χ^2) = 0.15

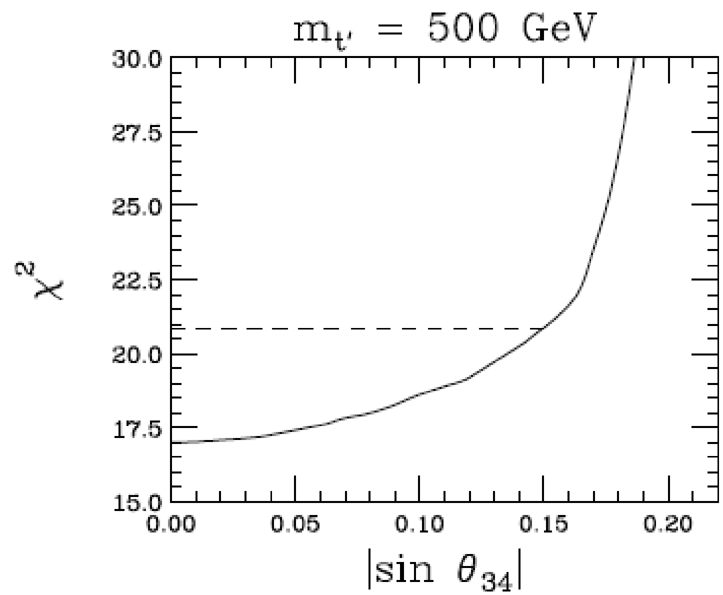
At 95% CL limit for θ_{34},

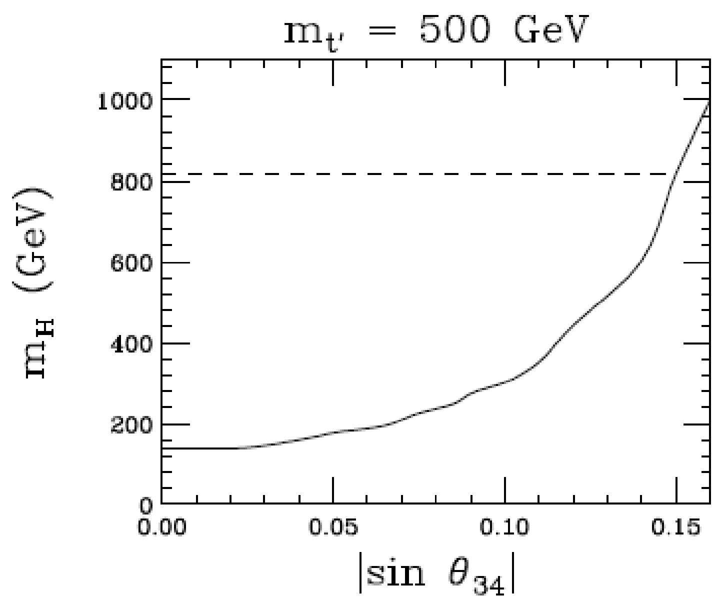
s_{34} = 0.15

m_H = 1000+

CL(m_H > 114) = 1.0

CL(χ^2) = 0.05





Summary: m_T = 300 —> 1000 GeV

$m_{t'}$	T_4	m_H(GeV)	$\lvert s_{34}^{(1)}\rvert$	$\lvert s_{34}^{(2)}\rvert \pm \Delta_{tb'}^{(2)}$	$\lvert c_{34}^{(2)}\rvert$
300	0.46	760	0.32	0.35 ± 0.001	0.94
326	0.47	760	0.28	0.30 ± 0.002	0.95
389	0.48	760	0.21	0.23 ± 0.004	0.97
400	0.47	800	0.20	0.22 ± 0.005	0.98
500	0.48	810	0.15	0.17 ± 0.007	0.99
600	0.48	800	0.12	0.14 ± 0.010	0.99
654	0.48	820	0.11	0.13 ± 0.013	0.99
1000	0.49	820	0.07	0.11 ± 0.10	0.99

All data

$m_{t'}$	T_4	m_H(GeV)	$\lvert s_{34}^{(1)}\rvert$	$\lvert s_{34}^{(2)}\rvert \pm \Delta_{tb'}^{(2)}$	$\lvert c_{34}^{(2)}\rvert$
300	0.35	300	0.25	0.26 ± 0.0008	0.97
326	0.35	280	0.21	0.22 ± 0.0010	0.98
389	0.35	270	0.16	0.17 ± 0.0016	0.99
400	0.35	290	0.15	0.16 ± 0.0016	0.99
500	0.35	270	0.11	0.12 ± 0.0027	0.99
600	0.35	290	0.087	0.095 ± 0.0033	0.995
654	0.35	280	0.078	0.086 ± 0.0035	0.996
1000	0.35	270	0.048	0.059 ± 0.007	0.998

Without A_{FB}^b, A_{FB}^c, Q_{FB}

T_4 and m_H at 95% CL upper limits on θ_{34}

Fits at $\theta_{34} = 0$ for all m_T are similar to fits for m_T = 500 GeV

$s_{34}^{(2)}/ s_{34}^{(1)}$ indicates reliability of perturbation theory, showing breakdown at m_T = 1 TeV, especially for “all data” fit.

$\pm\ \Delta_{tB}^{(2)}$ indicates reliability of two loop results (which are not completely known)

Example 2: anomaly-free Z'

Consider U(1) extensions of the SM which are anomaly-free without extending fermion sector beyond known quarks & leptons

$$\Rightarrow \quad Q_X = \cos\theta_X \frac{Y}{2} + \sin\theta_X \frac{B-L}{2}$$

MC Ellis Gaillard
Appelquist *et al.*

Z - Z' mixing decreases m_Z, equivalent to T > 0

$$\alpha T_X = -\frac{\delta m_Z^2}{m_Z^2} = \frac{r^2 \cos^2\theta_X}{\hat{m}_{Z'}^2} \qquad r = \frac{g_{Z'}}{g_Z}$$

Z - Z' mixing angle: $\theta_M = \dfrac{r\cos\theta_X}{\hat{m}_{Z'}^2}$ $\qquad \hat{m}_{Z'} = \dfrac{m_{Z'}}{m_Z}$

Zff couplings are then modified by Z' admixture,

$$\mathcal{L}_f = g_Z \left(1 + \frac{\alpha T_X}{2}\right) g'_f \overline{f} \not{Z} f \qquad g'_f = g_f + r\theta_M q_X^f$$

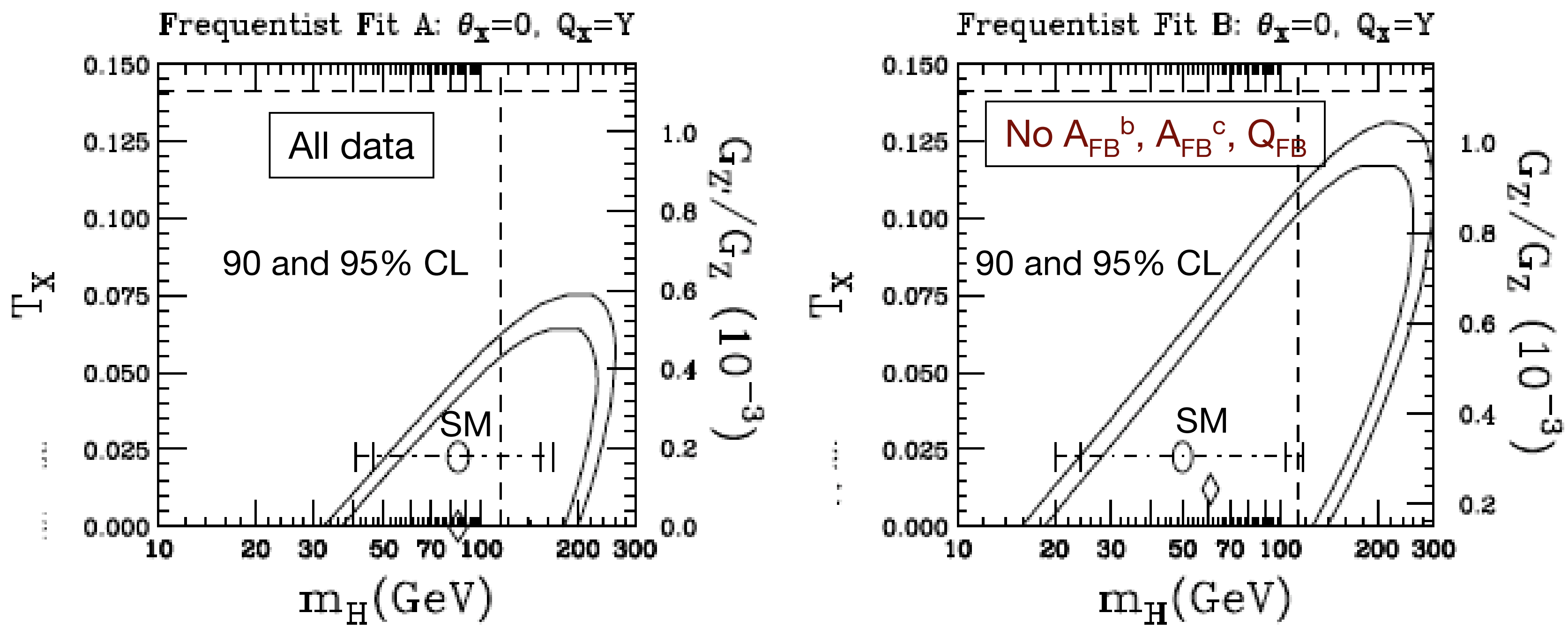
while x_W and m_W are corrected by T_X

Z' fits

Example: $\theta_X = 0$, $Q_X = Y/2$

– occurs in many BSM models, e.g., little Higgs

arXiv:0806.0890
for survey of all θ_X



- Horizontal dashed line: upper limit from LEPII contact interactions

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- Right axis: $G_{Z'}/G_Z = g_{Z'}^2/g_Z^2 \cdot m_Z^2/m_{Z'}^2$

m_H reach to 300 GeV at 95% CL (little change in central value – diamond)

E.g., for $g_{Z'} = g_Z$, $m_{Z'} \approx 2$ - 5 TeV, probably within reach of LHC

What about NuTeV?

SM fits with NuTeV

A) With A_{FB}^{b}, A_{FB}^{c}

$m_H = 94$

$CL(m_H > 114) = 0.33$

$CL(\chi^2) = 0.02$

B) Without A_{FB}^{b}, A_{FB}^{c}

$m_H = 64$

$CL(m_H > 114) = 0.07$

$CL(\chi^2) = 0.12$

⇨ Tension with LEP II moderated but not eliminated

	Experiment	A	Pull	B	Pull
A_{LR}	0.1513 (21)	0.1476	1.8	0.1494	0.9
A_{FB}^{l}	0.01714 (95)	0.01634	0.8	0.1674	0.4
$A_{e,\tau}$	0.1465 (32)	0.1476	-0.3	0.1494	-0.9
A_{FB}^{b}	0.0992 (16)	0.1035	-2.7		
A_{FB}^{c}	0.0707 (35)	0.0739	-0.9		
m_W	80.398 (25)	80.369	1.2	80.391	0.3
Γ_Z	2495.2 (23)	2495.7	0.2	2496.1	-0.4
R_l	20.767 (25)	20.743	1.0	20.743	1.0
σ_h	41.540 (37)	41.477	1.7	41.479	1.7
R_b	0.21629 (66)	0.21586	0.7	0.21584	0.7
R_c	0.1721 (30)	0.1722	-0.04	0.1722	-0.04
A_b	0.923 (20)	0.935	-0.6	0.935	-0.6
A_c	0.670 (27)	0.668	0.07	0.669	0.04
g_L^2	0.30005 (137)	0.30396	-2.9	0.30423	-3.1
g_R^2	0.03076 (11)	0.03009	0.6	0.03004	0.7
$x_W(ee)$	0.23339 (140)	0.23145	1.4	0.23122	1.55
$x_W(Cs)$	0.22939 (190)	0.23145	-1.1	0.23122	-1.0
m_t	172.6 (1.4)	172.3	0.2	172.3	0.2
$\Delta\alpha_5(m_Z)$	0.02758 (35)	0.02768	-0.3	0.02754	0.1
$\alpha_S(m_Z)$		0.1186		0.118	
m_H		94		64	
$\mathrm{CL}(m_H > 114)$		0.33		0.07	
$m_H(95\%)$		172		124	
χ^2/dof		28.4/15		19.0/13	
$\mathrm{CL}(\chi^2)$		0.02		0.12	

Table 1: SM fits with (A) and without (B) A_{FB}^{b} and A_{FB}^{c}.

Z' fits: NuTeV

arXiv:0903.2497

- Status unclear: 3σ —> 2σ from $\bar{s}s$ sea asymmetry measurement?
- Z' models raise m_H central value and 95% limit in fits with NuTeV

For fits without A_{FB}^b, A_{FB}^c, Q_{FB}:

- m_H central value increases by factor ~2
- χ^2 decreases and in some cases CL(χ^2) improves modestly

Model	T_X	χ^2	CL(χ^2)	m_H	CL($m_H > 114$)	$m_H^{95\%}$(Freq.)
SM		19.0	0.12	64	0.07	124
$\theta_X = 0$	0.052	17.9	0.12	120	0.56	215
$\theta_X = \pi/12$	0.052	17.4	0.14	126	0.58	224
$\theta_X = \pi/6$	0.048	16.9	0.15	126	0.59	223
$\theta_X = \pi/4$	0.046	16.5	0.17	126	0.60	230
$\theta_X = \pi/3$	0.037	16.1	0.19	126	0.60	223

Original (NO A_{FB}^b, A_{FB}^c, Q_{FB})

Model	T_X	χ^2	CL(χ^2)	m_H	CL($m_H > 114$)	$m_H^{95\%}$(Freq.)
SM		14.3	0.35	58	0.06	118
$\theta_X = 0$	0.043	13.7	0.32	104	0.42	189
$\theta_X = \pi/12$	0.044	13.3	0.35	109	0.42	197
$\theta_X = \pi/6$	0.043	13.0	0.37	114	0.50	203
$\theta_X = \pi/4$	0.039	12.7	0.39	114	0.50	202
$\theta_X = \pi/3$	0.033	12.4	0.42	109	0.45	201

Revised per $\bar{s}s$ sea asymmetry measurement
(NO A_{FB}^b, A_{FB}^c, Q_{FB})

Conclusion

More than one way to read the PEW oracle bones:

- data may favor a light Higgs boson …
- or maybe it presages NP with custodial SU(2) breaking

PEW data provides important constraints on NP today and will continue to be important to interpret discoveries at LHC

- e.g., discovery of a Z' and measurement of its parameters would imply a prediction for m_H from the PEW fit
- discrepancies between LHC observations and the PEW fit could imply additional, still unobserved NP
- interplay of LHC and PEW data can help us to formulate next steps after LHC has run at initial design parameters

To realize the potential of PEW probes, a next generation Z factory could be an important facility, perhaps at the front end of a future LC.