M. Chanowitz
LBNL

Precision Electroweak Data and the Direct Limit on the Higgs Mass

Presented at the conference on

Modern Challenges for Lattice Field Theory

KITP - UCSB, April 1, 2005

This talk:
experimental & theoretical update of previous work.

MC PRL 87:231802, 2001
PRD 66:073002, 2002
Zeuthen Workshop, hep-ph 0304199

Executive Summary

February '05: *Final* Z-pole results confirm longstanding discrepancy between the two most precise asymmetry measurements, critical for extraction of m_H from SM fit:

A_{FB}^{b} vs A_{LR}: 3.2 σ CL = 0.0016

Could be *New Physics*, *Statistics*, or *Systematics.*

- **If Systematics**, then $\mathbf{A_{FB}^{b}}$ (+ $\mathbf{A_{FB}^{c}}$, $\mathbf{Q_{FB}}$) are most likely culprits.
- **But** without $\mathbf{A_{FB}^{b}}$, m_H from SM fit is low, appreciably below the 114 GeV LEP II direct lower limit
  - Low fit value for m_H could be ***statistics or new physics***

Conflict with LEP II limit is diminished by D0 m_t measurement but not completely removed. Depending on future evolution of m_t, m_w, $\alpha(m_Z)$, conflict could disappear or get worse.

Technology of SM fits

SM EWRC from ZFITTER 6.30 + 2-loop m_W & (fermionic) x_W

m_Z, m_t, $\Delta\alpha_5$, α_S, m_H $\longrightarrow$ $O_{Z\text{-Pole}} + m_W + x_W^{\nu N} + \ldots$

$\Delta\alpha_5$ from B-P (BES) – EWWG default

Biggest experimental correlations alla EWWG

Do not include Γ_W: $\delta\Gamma_W = 30\ \delta\Gamma_Z$

Good agreement with EWWG, $\approx$ 1-2 parts in 10^5

χ^2 and "Bayesian" likelihood fits:

Vary m_t, $\Delta\alpha_5$, α_S, m_H

Fit m_t, $\Delta\alpha_5$ + all/some of {13 $O_{Z\text{-Pole}}$, m_W, $x_W^{\nu N}$ }

χ^2 agrees with EWWG to within a few tenths

Global Fits

constrained unconstrained

$$\text{“All”} = 13 \times O_{Z\text{-Pole}} + m_W + m_t + \Delta\alpha_5 + (\alpha_S + m_H)$$

	χ^2, N	CL
“All” + $x_W^{\nu N}$	27.0, 13	0.012
“All”	18.0, 12	0.12

$\{ m_H = 132$
$< 260 \;\; 95\%$

$x_W^{\nu N}$ too imprecise to significantly effect m_H

⟹ not considered further in this analysis

CL(“All”) = 0.12 roughly reflects probability for outlyers relative to sample size, dominated by 2.77σ pull of A_{FB}^b :

P(≥ 1 2.77σ, N = 12**)** = 1 - (1 - 0.0056)^{12} = **0.07** ~ CL(χ^2) = **0.12**

Global CL’s are fairly valued: the appropriate statistical ensemble is multiple replays of the 1990’s at LEP, SLC, and FNAL.

I.e., *not* a case of a high bin in a histogram with 1000 bins

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

A_{LR} **0.23098 (26)**
A_{FB}^{ℓ} 0.23099 (53)
$A_{e,\tau}$ 0.23159 (41)

$\}$ $x^{\ell}[A_L]$ = **0.23113 (21)**
$\chi^2/N = 1.6/2$ CL = 0.44

A_{FB}^{b} **0.23221 (29)**
A_{FB}^{c} 0.23220 (81)
Q_{FB} 0.23240 (120)

$\}$ $x^{\ell}[A_H]$ = **0.23222 (27)**
$\chi^2/N = 0.06/2$ CL = 0.97

$\}$ **0.23153 (16)**
3.2σ
CL = 0.0014

Dominated by $x[A_{LR}] \oplus x[A_{FB}^{b}] = 0.23153\ (19)$
3.2σ CL = 0.0016

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

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

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

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 m_H resides in A_ℓ (because A_ℓ $1/4 - x_w$)

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

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}, $A_{e,□}$:

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

A_b[*direct*] ⊕ A_b[*indirect*] $= 0.899\ (13)$ } 2.8□ from SM; CL = 0.006

⟹ Evidence for new physics in A_b is equivocal.

$x[A_L]$ - $x[A_H]$ discrepancy significant for 3 reasons:

1) Failed test for SM $A_q \neq A_q[SM]$

2) SM fit of m_H dominated by low probability combination of $x[A_{LR}] \oplus x[A_{FB}^b]$.

3) Together with $x_W^{\nu N}$, the $x[A_{LR}]$ - $x[A_{FB}^b]$ discrepancy contributes to diminished quality of global SM fit.

Three generic options…

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

- Statistical fluctuation
- New physics
- Underestimated systematic error

Briefly consider each:

Statistical Fluctuation

Significance of anomaly 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., for "All," **CL(χ^2) = 0.12**

Cf, Probability of at least one 2.77σ outlyer (A_{FB}^{b})

among 12 independent measurements: **P = 0.07**

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

In the most conservative assessment there is an O(10%) problem.

New Physics in A_b ? — the R_b constraint

1998± : 3σ R_b anomaly understood as expt'l sys. error.

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

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

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

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

Roughly, from R_b: $\delta g_{bL}^{\,2} + \delta g_{bR}^{\,2} \sim 0$

SM: $g_{bL} \sim -0.42$ $g_{bR} \sim +0.08$

$\Rightarrow\quad \delta g_{bR} \sim 0.009/4g_{bR} \sim$ **0.03** **HUGE**

$\delta g_{bL} \sim -g_{bR}\, \delta g_{bR} / g_{bL} \sim +0.005$

Huge δg_{bR} probably requires new physics at tree level, hard to find in plausible extensions of the SM.

New Physics in A_{FB}^b ?

- Maybe not
  - challenging experimental & theoretical systematics
  - A_b from A_{FBLR}^b agrees with SM
  - Large δg_{bR} hard to explain

- Maybe so
  - persistent statistical significance
  - exp'ters have worked long & hard to understand expt'l systematics <u>**&**</u> have applied lessons from R_b (but problem might be theor. systematics that uniquely afflict A_{FB})

Systematic error

Subtle & Important issues { Above my pay grade

- **$x^{\ell}[A_L]$: A_{LR}, A_{FB}^{ℓ}, $A_{e,\tau}$** $\chi^2/N = 1.6/2$ CL = 0.44
  - 3 very different techniques: common sys. error very unlikely.
- **$x^{\ell}[A_H]$: A_{FB}^{b}, A_{FB}^{c}, Q_{FB}** $\chi^2/N = 0.06/2$ CL = 0.97
  - $b \leftrightarrow \bar{c}$ mutual bkgds: consistent w. signs of A_{FB}^{b}, A_{FB}^{c} anomalies
  - 14 parameter Heavy Flavor fit (4 LEP exp'ts + SLC):

$\chi^2/N = 53/91$

CL = 0.9995(!)

{ EWWG: Sys. errors too conservative?

EWWG: reasonable χ^2 if sys errors $\longrightarrow$ 0 ⇒ $\chi^2/N = 92/91$, CL = 0.45

Fit → *Poorer*

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** 6 asym's

CL { SM "All" } = **0.12** $\longrightarrow$ **0.04**

Systematic error

Subtle & Important issues { Above my pay grade

- $x^{\ell}[A_L]$: A_{LR}, A_{FB}^{ℓ}, $A_{e,\square}$
  - 3 very different techniques: common sys. error very unlikely.
- $x^{\ell}[A_H]$: A_{FB}^{b}, A_{FB}^{c}, Q_{FB}

  Extraction of **quark** asymmetries from **hadron** data requires QCD models of hadronization/charge flow, gluon radiation, …

⇒ Unique, correlated QCD systematics for A_{FB}^{b}, A_{FB}^{c}, Q_{FB} which may be difficult to quantify.

⇒ Systematic errors might be larger than estimates

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

Consequences of underestimated systematic error

Focus on sys. uncertainty not because it is a more likely explanation than statistical fluctutation or new physics, but to see if it could improve the SM fit.

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

➡ Fit CL's improve

CL("All")	**0.12**	⟶	**0.72**	
CL(m_H sensitive)	**0.04**	⟶	**0.47**	
CL(most m_H sensitive)	**0.003**	⟶	**0.84**	~~A_{FB}^b~~, A_{LR}, m_W

But a new problem emerges: fits prefer m_H << 114 GeV
Problem softened by larger m_t, but persists.

N.B., LEP direct limit:

$m_H > 114$ GeV 95% CL

➡ **CL(m_H < 114) << 5%**

IF $m_H = 114$, CL = 5% that H could escape detection.

Fits of m_H sensitive observables

To test reliability of m_H predictiction and probe specifically for new physics in the Higgs sector, it is interesting to focus on the m_H sensitive observables, that determine m_H in the SM fit.

Excluding m_H *in*sensitive (Γ_H, R_b, R_c, A_b, A_c), find that discrepancies are concentrated in m_H sensitive sector:

χ^2, N = 15.1, 7 CL = 0.035

Cf. "All"
18,12
CL = 0.12

and especially in the most m_H sensitive (A_{FB}^b, A_{LR}, m_W):

χ^2, N = 11.8, 2 CL = 0.003
m_H = 139 < 280 95%

Compare
m_H = 132
< 260 95%
from "All"

Poor quality of fits suggests statistics, systematics, or *new physics specifically within the Higgs sector.*

How reliable is m_H prediction from SM fit?

Components of the SM fit

High Precision	m_H	95%	$CL(m_H > 114)$
A_{LR}	55	< 165	0.14
A_{FB}^b	700	$220 < m < 1500+$	
m_W	67	< 210	0.23

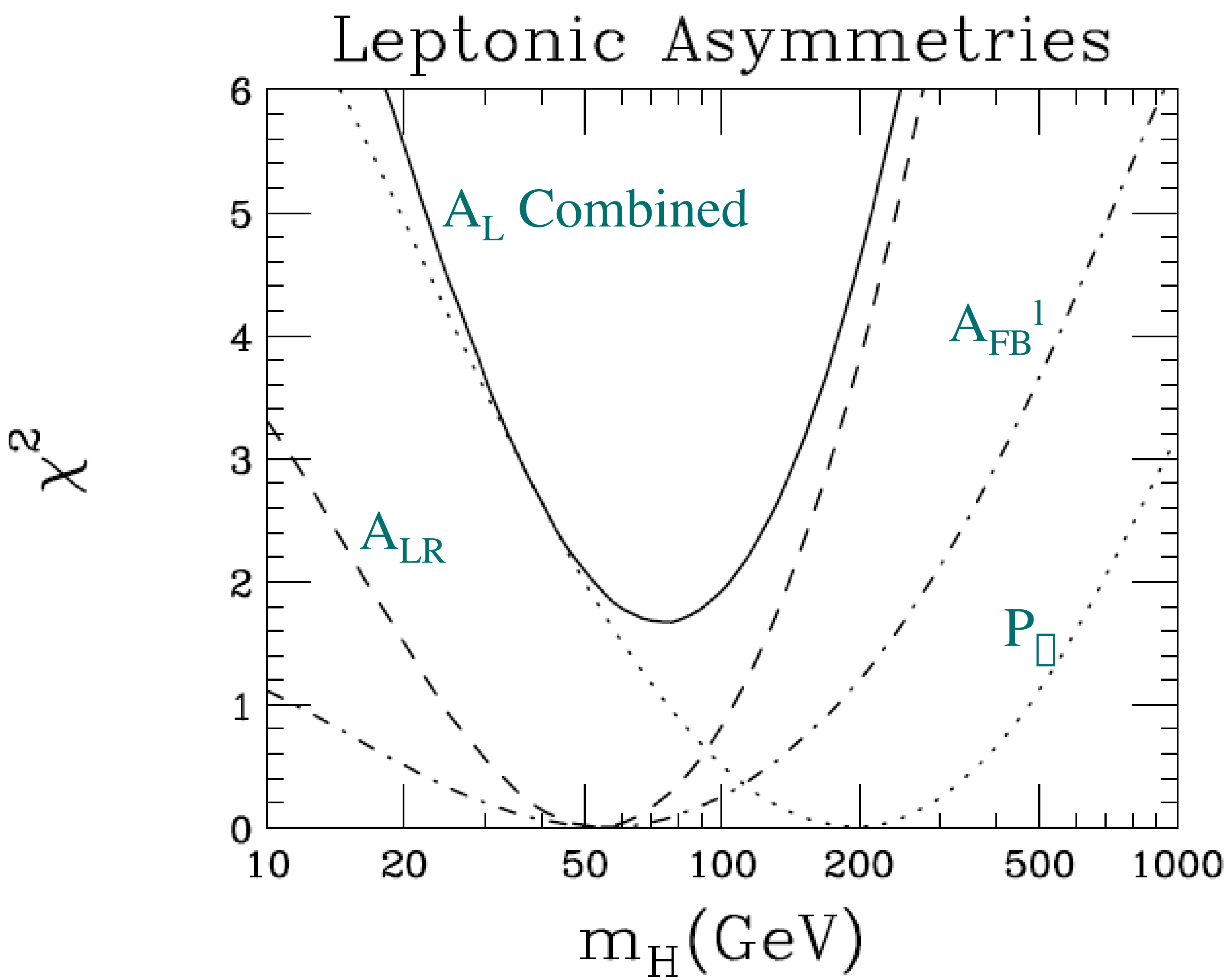
Aggregates	m_H	95%	$CL(m_H > 114)$
$x[A_L]$	77	< 190	0.23
$x[A_H]$	700	$230 < m < 1500+$	
m_W, Γ_Z, R_l	18	< 220	0.18

m_H sensitive, non-asymmetry observables

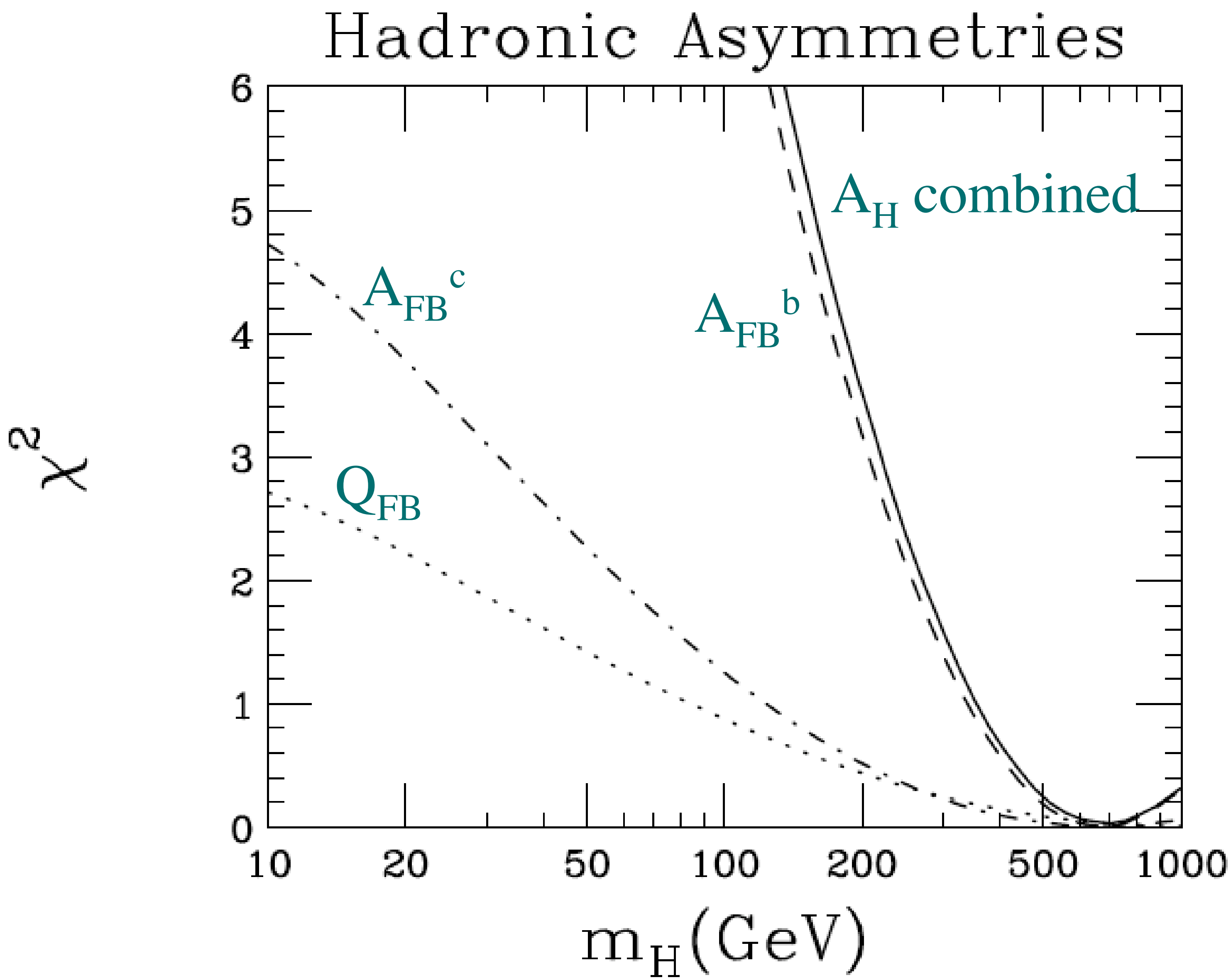
Support for $m_H > 114$ primarily from $x[A_H]$

(N.B., Alliance of $x[A_L]$ & m_W, Γ_Z, R_l explains why A_{FB}^b is the outlyer.)

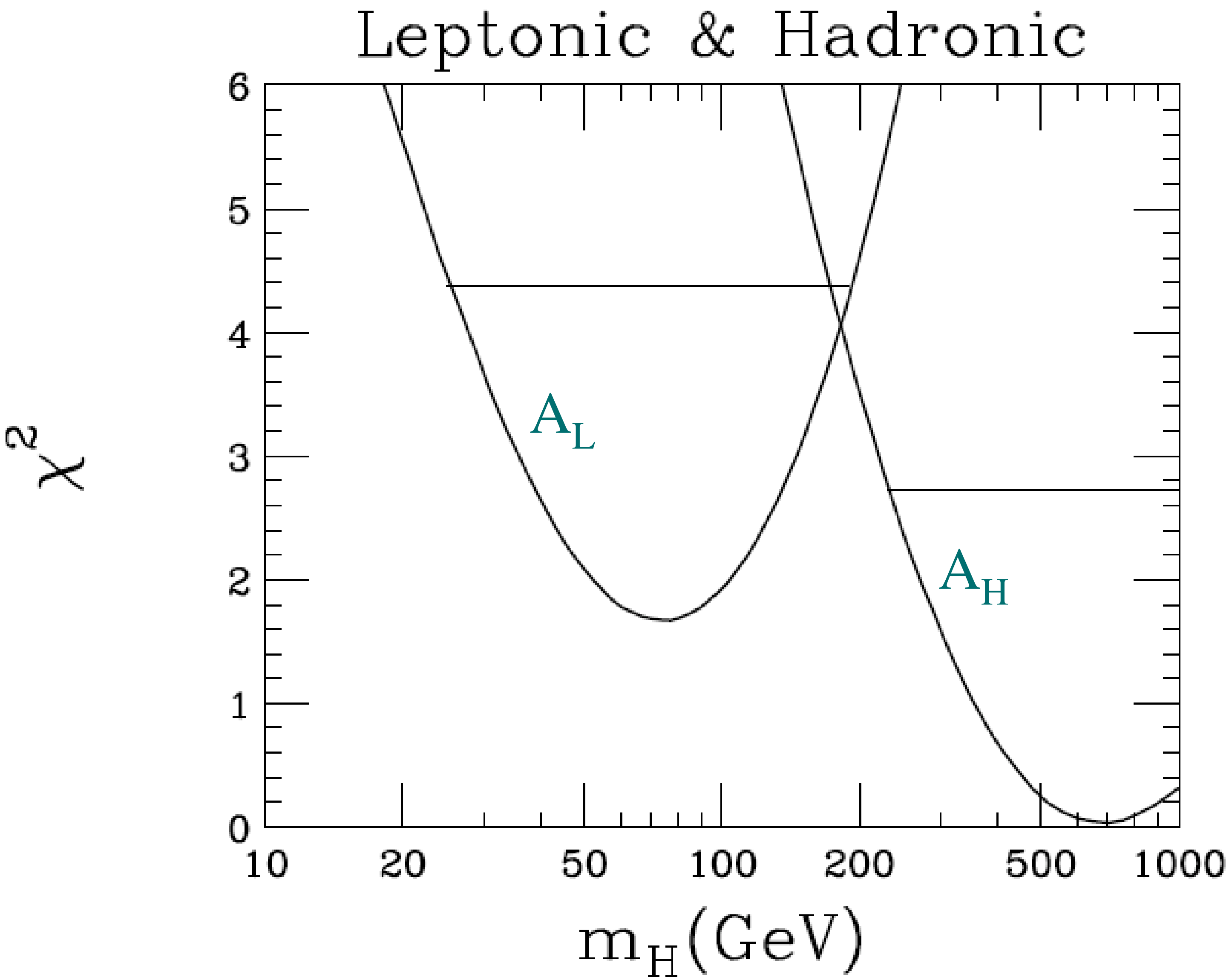
χ^2 Distributions: Leptonic Asymmetries



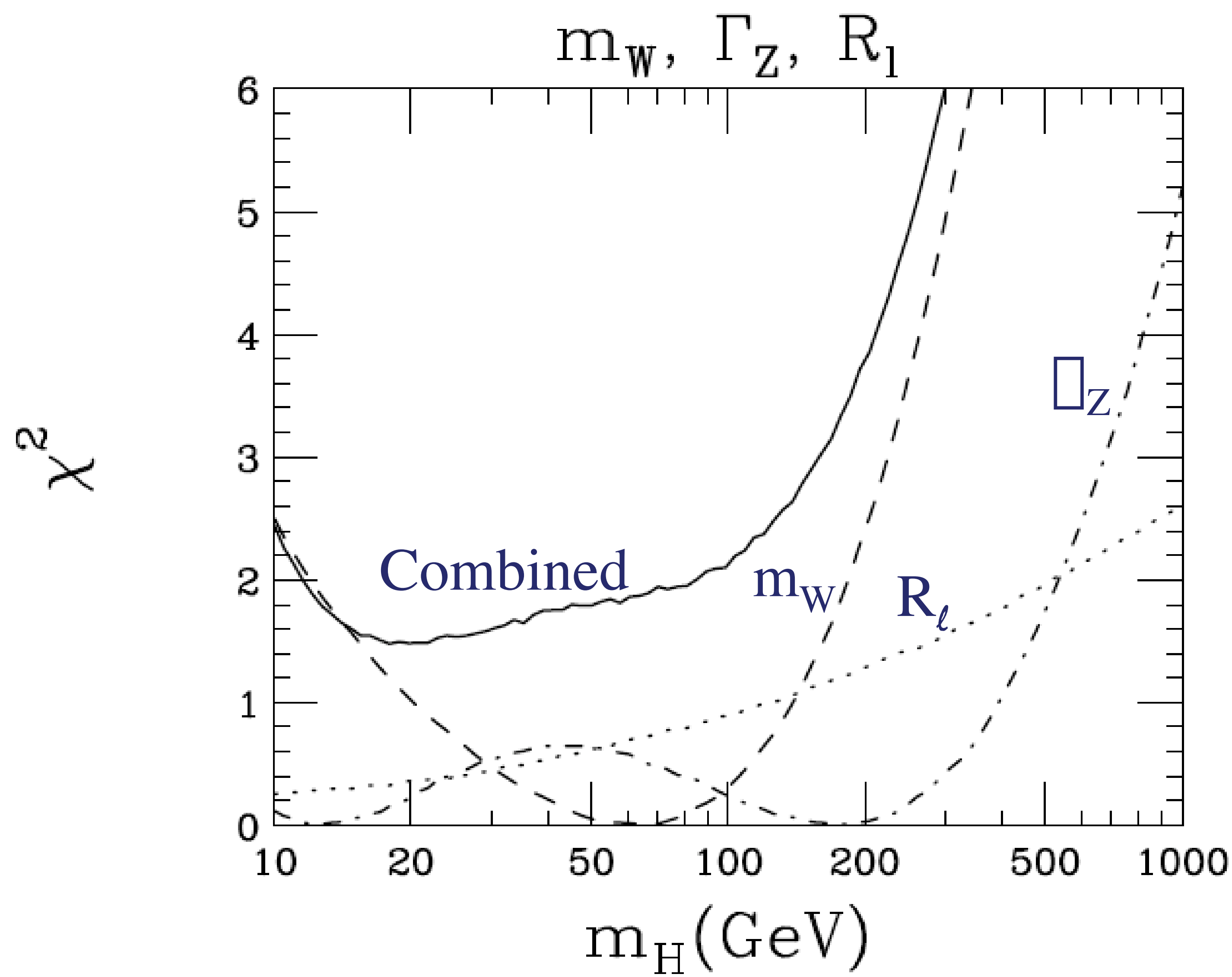
χ^2 Distributions: Hadronic Asymmetries



χ^2 Distributions: Leptonic vs. Hadronic



χ^2 Distributions: m_H sensitive, nonasymmetry



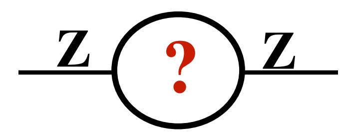
SM fits & m_H predictions

	CL(□^{2})	m_H	**CL(m_H > 114)**
"All"	**0.12**	132	**0.55**
-x[A_H]	**0.72**	70	**0.14**
m_H sensitive	**0.035**	132	**0.62**
-x[A_H]	**0.47**	64	**0.17**
$A_{LR} \oplus m_W$	**0.84**	52	**0.12**

If x[A_H] is removed from fit, m_H < 114 is preferred.

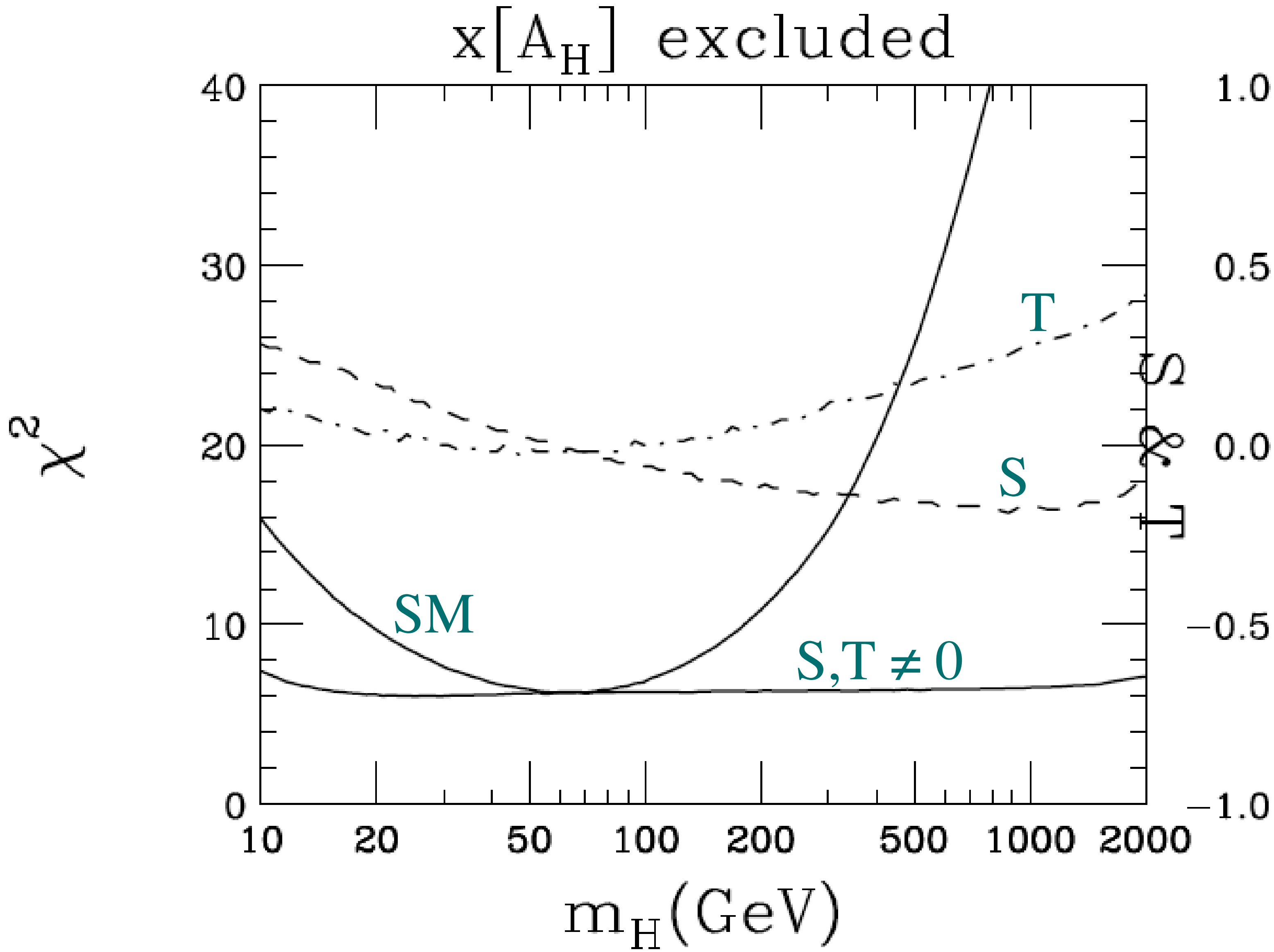
New physics to raise m_H prediction

- New physics to raise the predicted value of m_H could reconcile ~~$x[A_H]$~~ SM fit with LEPII lower limit on m_H.
- Existing proposals
  - MSSM with 'light' $\tilde{\nu}$, $\tilde{l}$,… — Altarelli et al.
  - 4'th family, m_H ~ few 100 GeV — Okun et al.
- 'Oblique' -- dominant new phys. contribution via W, Z, γ vac. pol'ns, parameterized by 'S, T'
  - does not improve CL(χ^2)
  - can raise m_H arbitrarily

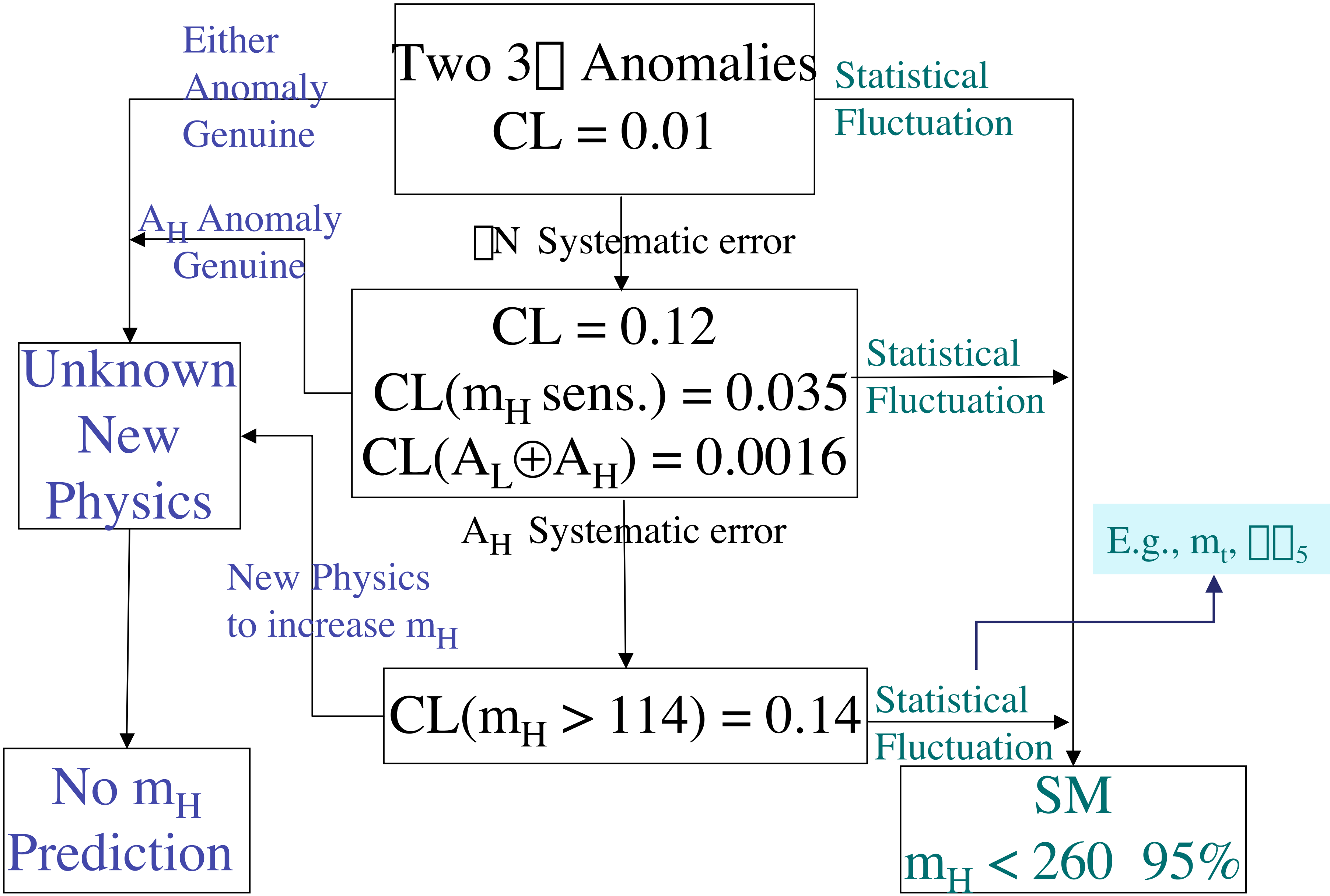


	SM	S,T ≠ 0
χ^2, N =	6.2, 9	6.0, 7
CL =	0.72	0.54
m_H =	70	**All m_H allowed**

χ^2 Distributions: Oblique New Physics



E-W Schematic Diagram



Conclusion

$x[A_{FB}^b]$ - $x[A_{LR}]$: a stubborn problem that won't go away.

LEP II limit on m_H makes problem more persistent:

- New physics preferred if A_{FB}^b attributed to sys. error or not
  → no prediction for m_H until new physics is known.
- SM & usual m_H prediction require O(10%) statistical fluctuations
  → certainly possible.

Also possible one of the O(90%) hints of new physics is genuine:

- □A_{FB}^b requires O(20%) shift in Zb_Rb_R coupling – ***WBSM*** *Way* BSM
- Physics (oblique) to increase m_H is easier to imagine.

The precision EW data leaves ample room for surprises: we are fortunate the LHC can search for the mechanism of EWSB over the entire range of energies allowed by unitarity.