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LBNL

Precision Electroweak Data and the Direct Limit on the Higgs Mass

Updates previous work, with increasingly precise FNAL measurements of top and W-boson masses.

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.*

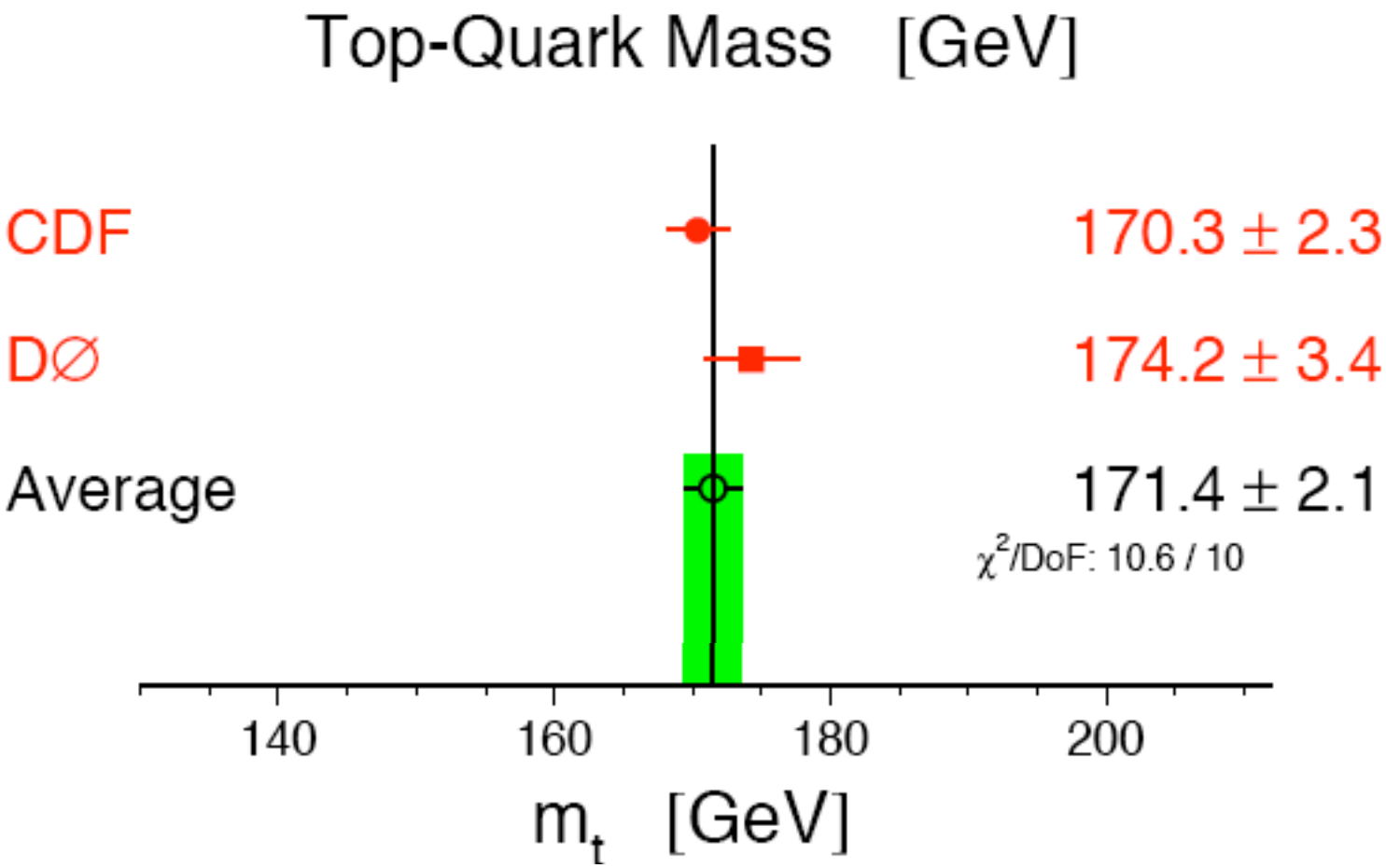
- **If Systematics**: **A_{FB}^b** (+ **A_{FB}^c**, **Q_{FB}**) are most likely culprits.
- **But without A_{FB}^b, m_H from SM fit is far below 114 GeV LEP II direct lower limit** – could be ***statistics or new physics***

Q: How reliable is SM prediction of m_H?

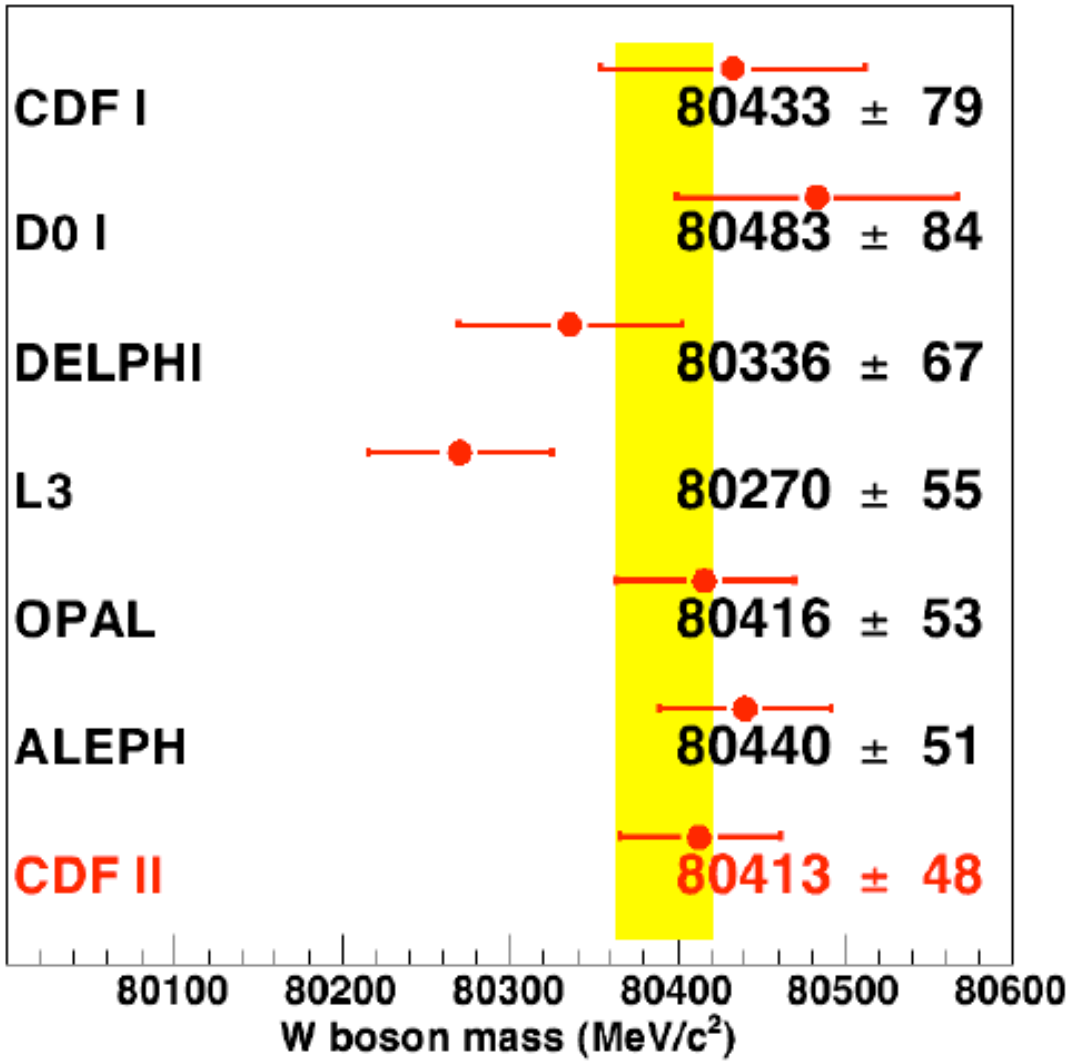
Conflict with LEP II limit sharpened by new FNAL measurements:

Summer 05		Winter 07
$m_t = 178.0 \pm 4.3$	$\longrightarrow$	$m_t = 171.4 \pm 2.1$
$m_W = 80.425 \pm 0.034$	$\longrightarrow$	$m_W = 80.398 \pm 0.25$

New m_{top} measurements



m_W measurements



From Kotwal, FNAL 1/7/07

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 ⟹ $O_{Z\text{-Pole}} + m_W + x_W^{\nu N} + \ldots$

$\Delta\alpha_5$ 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, ≤ 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

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

	χ^2, N	CL
“All” + $x_W{}^{\nu N}$	25.7, 13	0.02
“All”	17.2, 12	0.14

$m_H = 85$
< 150 95%

$x_W{}^{\nu N}$ too imprecise to significantly effect m_H
→ not considered further in this analysis

CL(“All”) = 0.14 roughly reflects probability for outlyers relative to sample size, dominated by 2.82σ pull of $A_{FB}{}^b$:

P(≥ 1 2.82σ, N = 12**)** = $1 - (1 - 0.00480)^{12}$ = **0.06** ~ CL(χ^2) = **0.14**

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

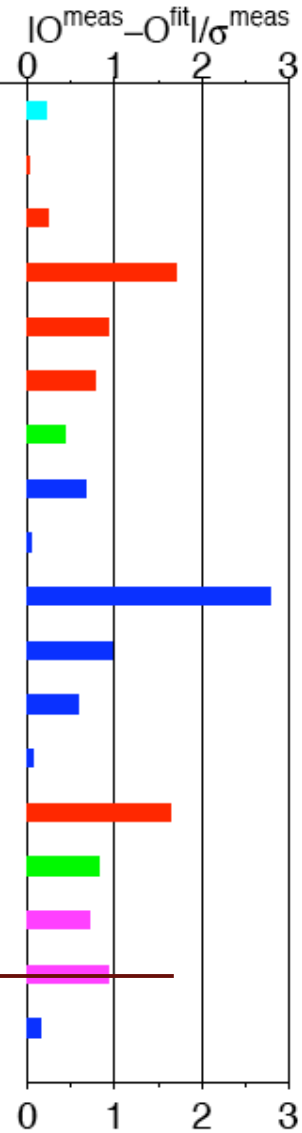
“All” observables

Fall ‘06

(m_W not updated)

Except

	Measurement	Fit
$\Delta\alpha^{(5)}_{had}(m_Z)$	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^0_{had} [nb]	41.540 ± 0.037	41.477
R_l	20.767 ± 0.025	20.744
$A^{0,l}_{fb}$	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
$A^{0,b}_{fb}$	0.0992 ± 0.0016	0.1037
$A^{0,c}_{fb}$	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
$\sin^2\theta^{lept}_{eff}(Q_{fb})$	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



$x_W^{\ell,eff}$: 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)**
$\chi^2/N = 0.02/2$ CL = 0.99

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, $x_W^{\ell,eff}$ & all that…

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

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

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

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

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

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, $A_{e,\tau}$:

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

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

➡ 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) = 0.14**

  Cf, Probability of at least one $\geq 2.82\sigma$ outlyer (A_{FB}^b) among 12 independent measurements: **P = 0.06**

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

  χ^2, N = 14.1, 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>In the 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 expt'l sys. error.

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

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

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

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

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

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

$\Rightarrow$ $\delta g_{bR} \sim 0.009/4g_{bR} \sim$ **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 but not impossible:

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

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

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 **&** have applied lessons from R_b
  - Large δg_{bR} surprising, not impossible

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} $\chi^2/N = 0.02/2$ CL = 0.99
  - $b \longleftrightarrow \bar{c}$ mutual bkgds: consistent w. signs of A_{FB}^{b}, A_{FB}^{c} anomalies
    1% mistag would shift A_{FB}^{b} by + 1σ
  - 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 $\Rightarrow$ $\chi^2/N = 92/91$, CL = 0.45

SM Fit $\Rightarrow$ *Poorer*

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

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

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

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

Systematic error: QCD

- QCD corr'ns (1 & 2 loop) converge slowly & are large

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

Big error ~ 2/3 Δ_{EXPT} found in `99

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

- Event selection & analysis ⇒ bias in event topologies

For $B \to \ell + X$, corr'n ~ 1/2 Δ_{QCD}

Correct with JETSET

Recent IR-safe formulation (Weinzerl) has smaller Δ_{QCD}

➡ might be more reliable, but requires reanalysis of data.

EWWG estimate: error from QCD ~ 1/4 Δ_{EXPT}

but may be difficult to quantify – especially for the bias correction, which is as big as the total error.

Systematic error: summary

- x^ℓ [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^ℓ [A_H]: A_{FB}^b, A_{FB}^c, $Q_{FB\tau}$ $\chi^2/N = 0.02/2$ 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

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")	**0.14**	⟶	**0.80**
CL(m_H sensitive)	**0.05**	⟶	**0.68**
CL(most m_H sensitive)	**0.003**	⟶	**0.69**

$\cancel{A_{FB}^b}$, A_{LR}, m_W

But a new problem emerges: fits prefer m_H << 114 GeV

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, it is interesting to focus on observables in the SM fit that determine m_H.

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

χ^2, N = 14.1, 7 **CL = 0.05**

Cf. "All"
17.1,12
CL = 0.14

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

χ^2, N = 11.7, 2 **CL = 0.003**
m_H = 85 < 155 95%

Compare
m_H = 85
< 148 95%
from "All"

Dominant measurements only consistent at CL = 0.003

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}	32	< 100	0.03
A_{FB}^b	440 & 3000+	160 < m < 3000+	
m_W	42	< 124	0.07

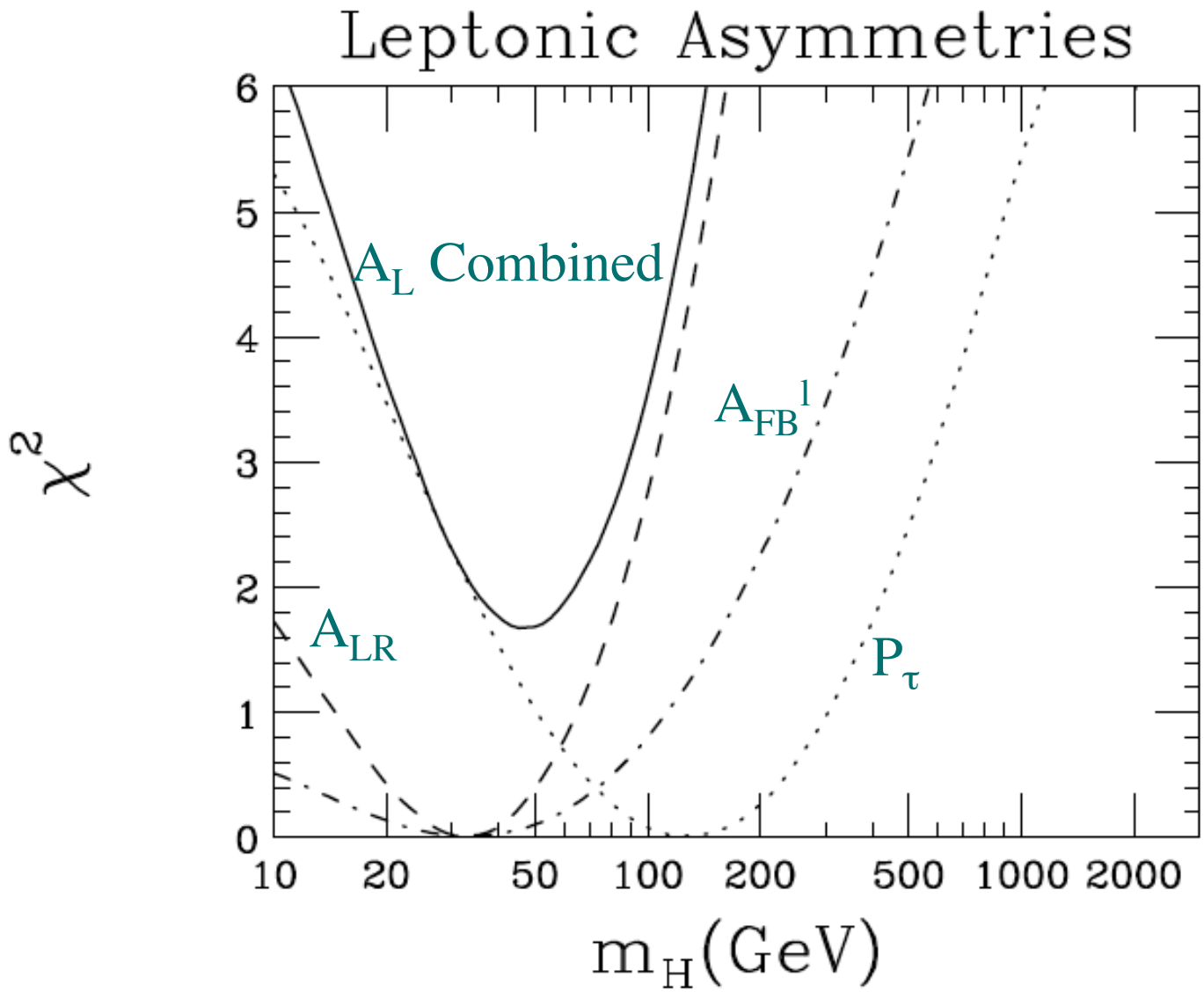
Aggregates	m_H	95%	$CL(m_H > 114)$
$x[A_L]$	45	< 115	0.05
$x[A_H]$	450 & 3000+	170 < m < 3000+	
m_W, Γ_Z, R_l	37	< 123	0.07

m_H sensitive, non-asymmetry observables

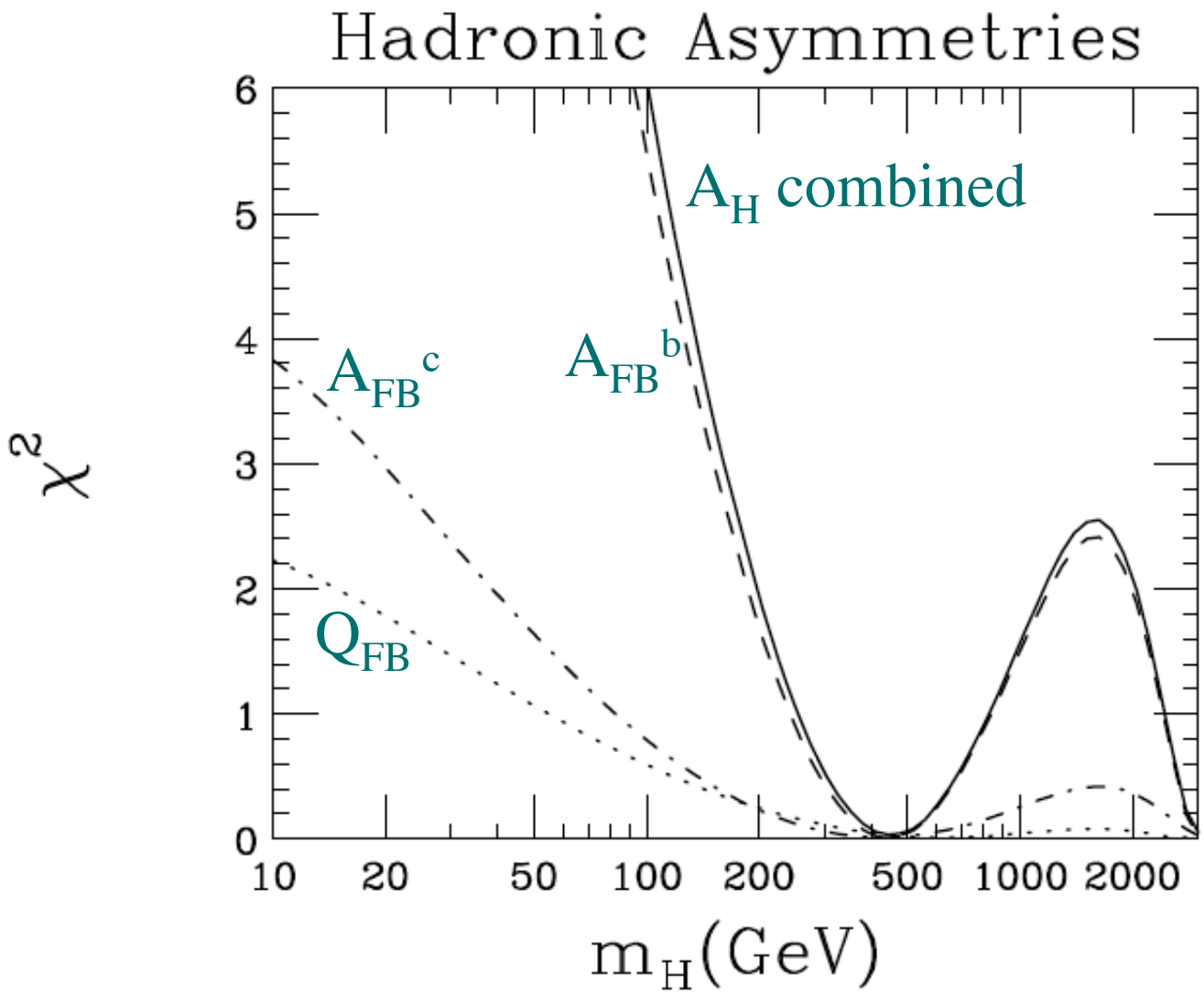
Support for $m_H > 114$ primarily from $x[A_H]$

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

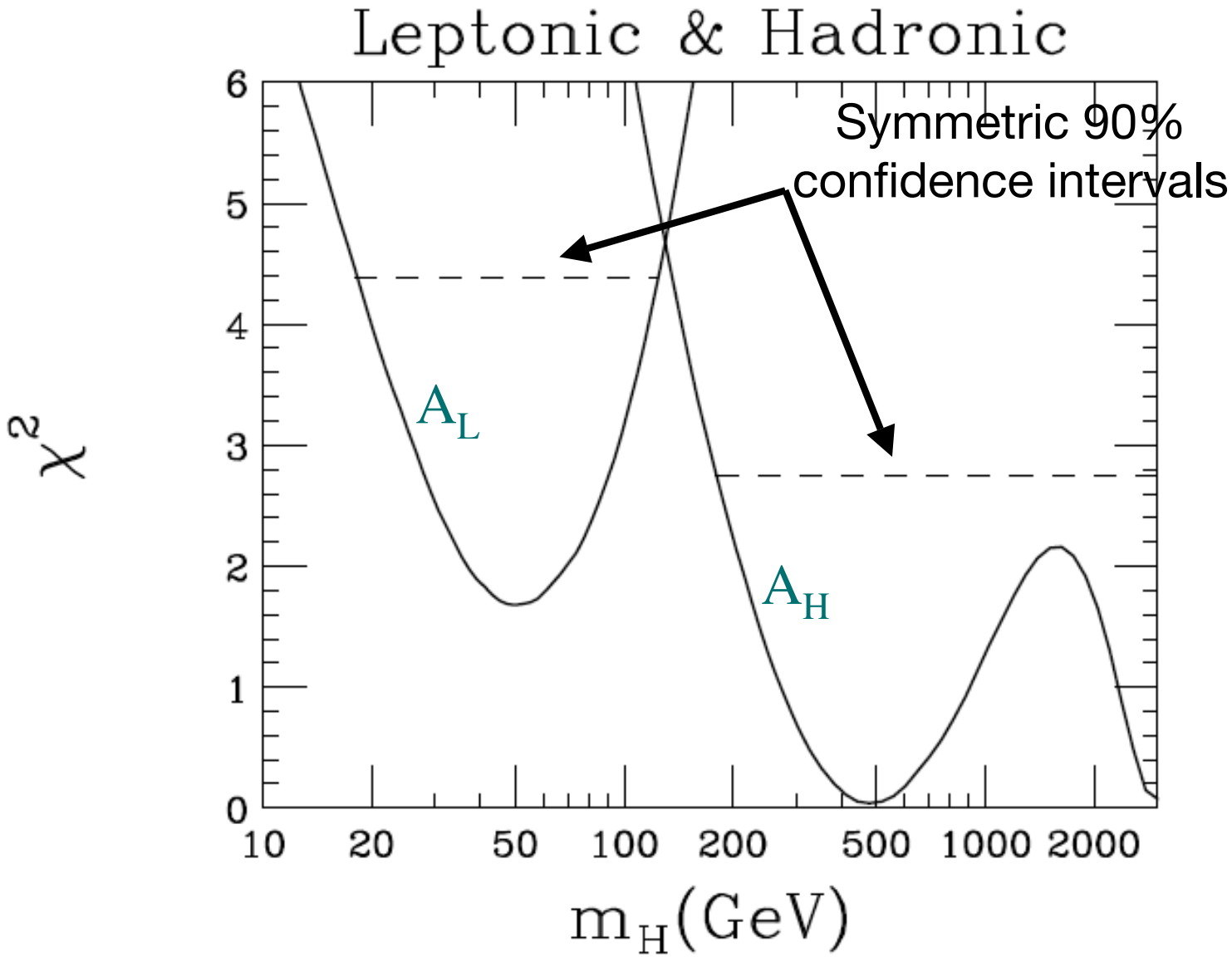
χ^2 Distributions: Leptonic Asymmetries



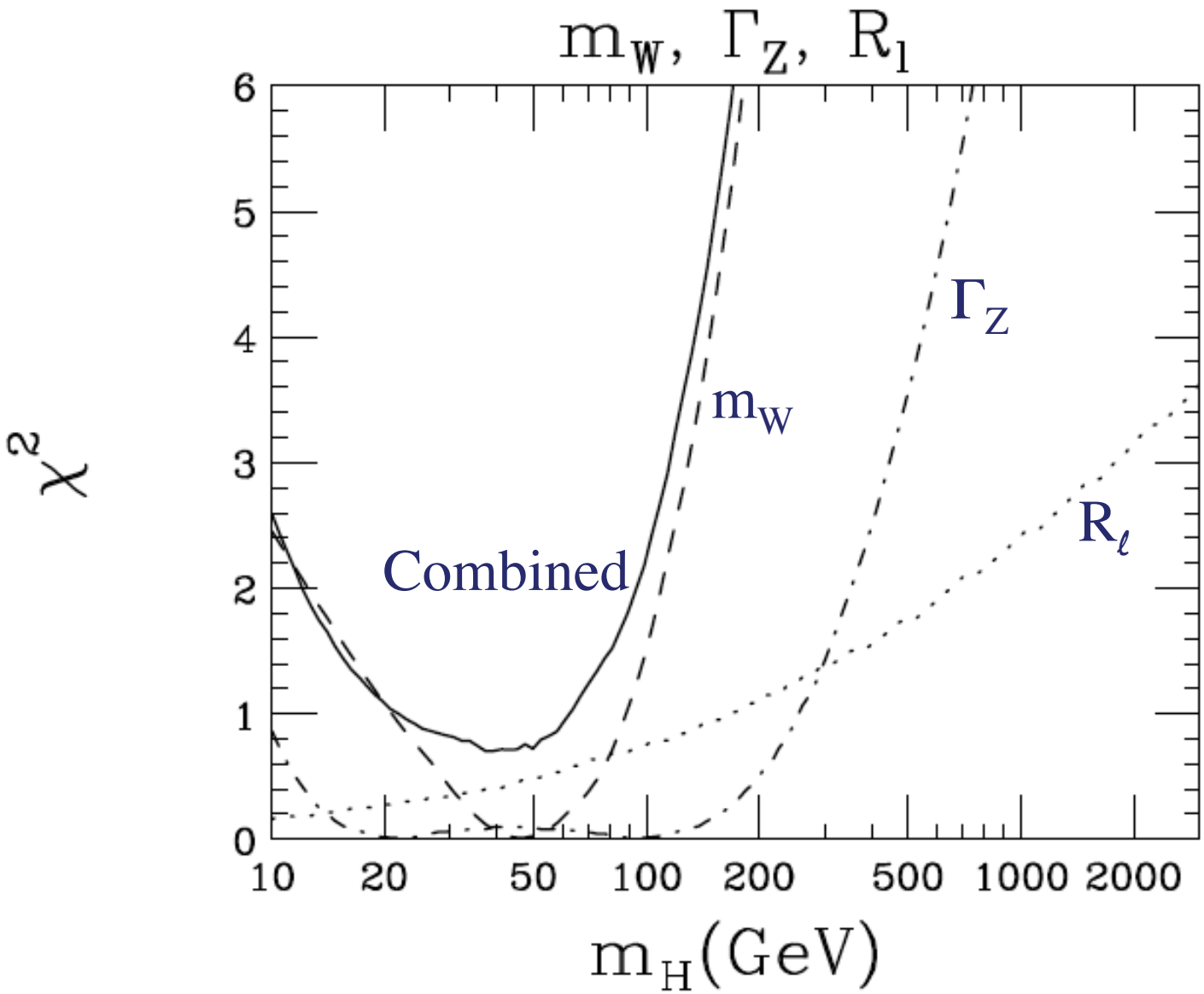
χ^2 Distributions: Hadronic Asymmetries



χ^2 Distributions: Leptonic vs. Hadronic



χ^2 Distributions: m_H-sensitive, nonasymmetry



SM fits & m_H predictions

	CL(χ^2)	m_H	**CL(m_H > 114)**
"All"	**0.14**	85	**0.18**
-x[A_H]	**0.80**	48	**0.021**
m_H sensitive	**0.050**	85	**0.22**
-x[A_H]	**0.68**	43	**0.023**
$A_{LR} \oplus m_W$	**0.69**	41	**0.017**

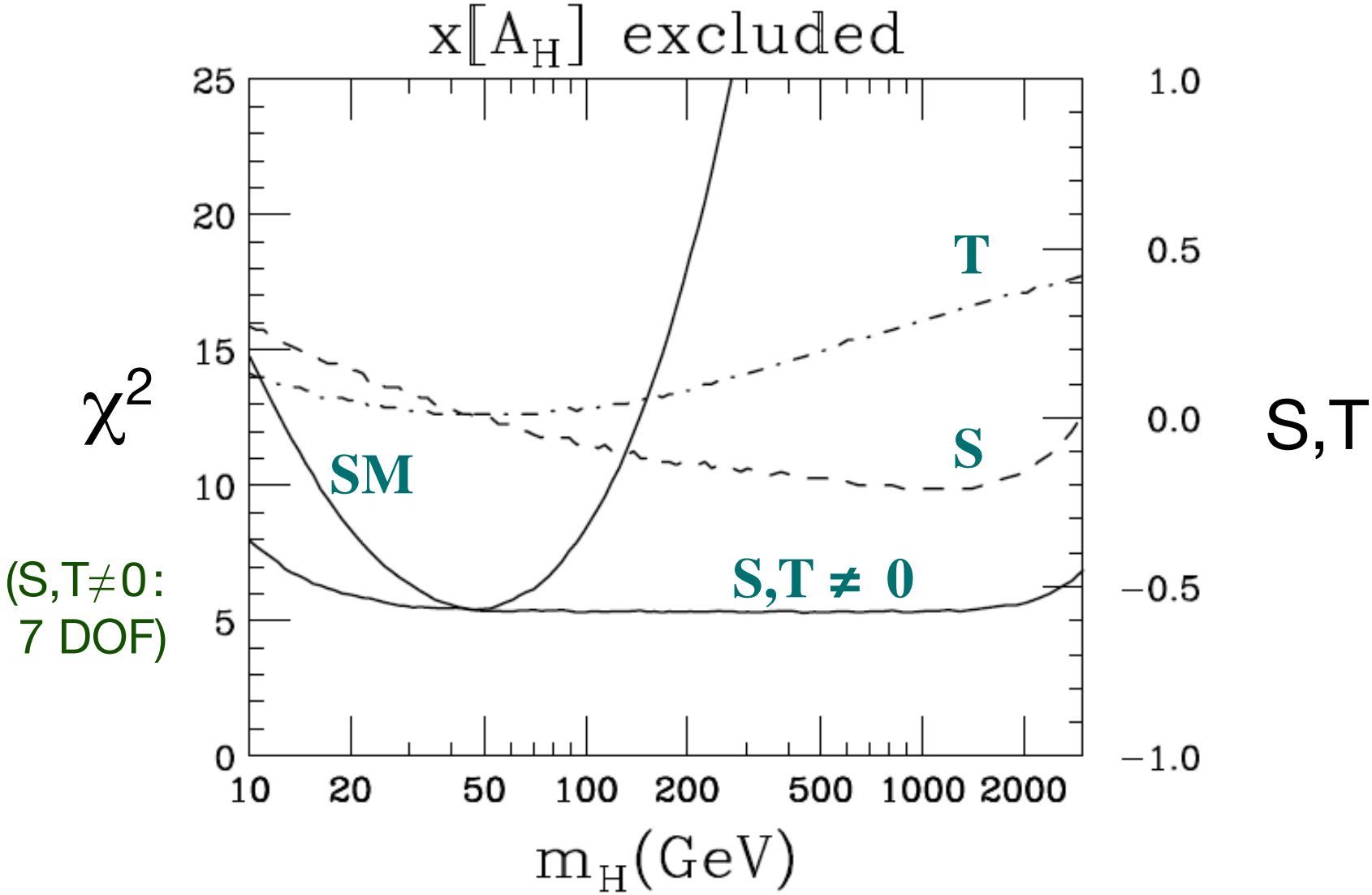
If x[A_H] is removed from fit,
m_H < 114 is strongly favored.

New physics to raise m_H prediction

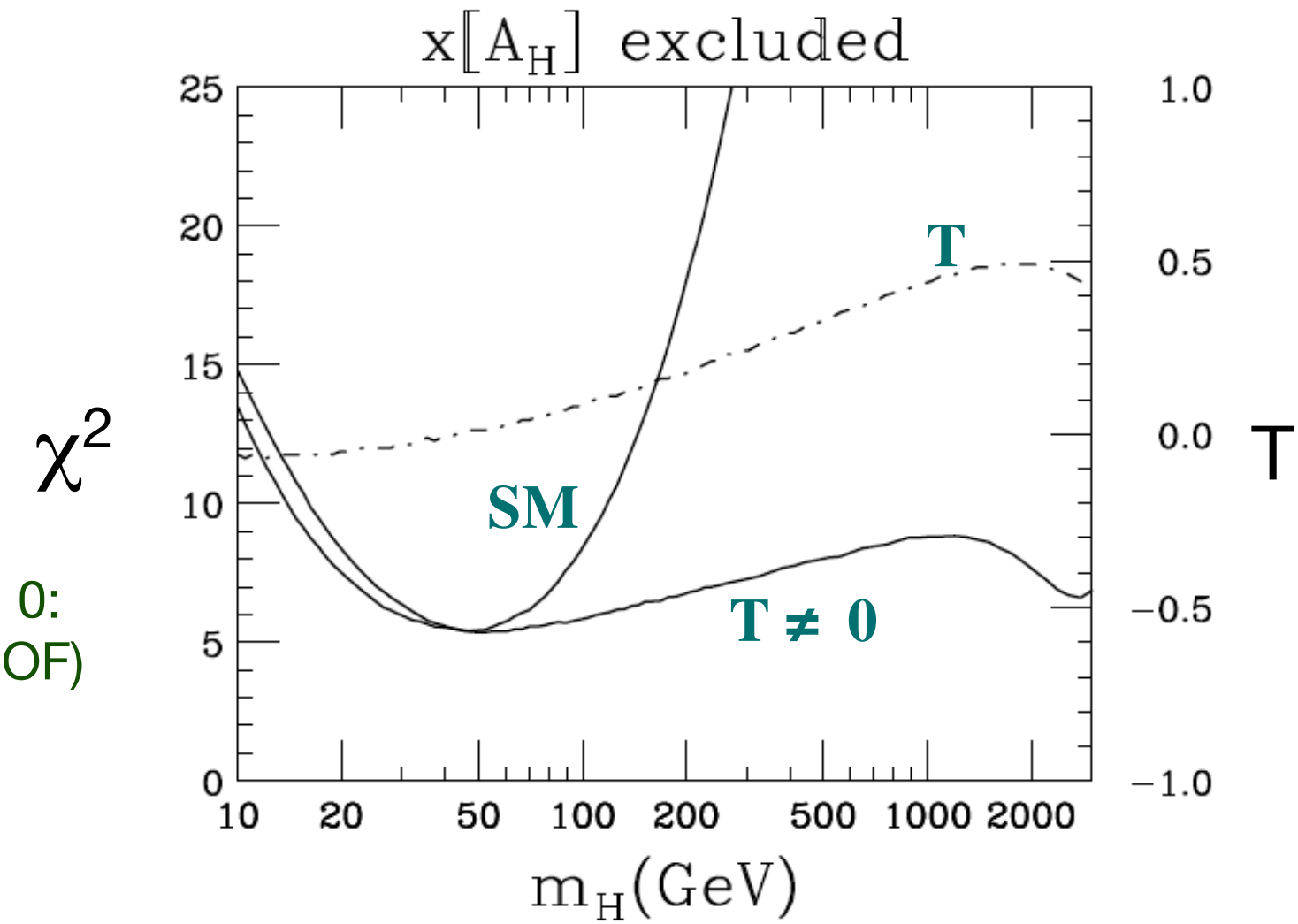
- New physics to raise the predicted value of m_H could reconcile x[~~A_H~~] SM fit with LEPII lower limit on m_H.
- Existing proposals
  - MSSM with 'light' $\tilde{\nu}, \tilde{t}, \ldots$ — Altarelli et al.
  - 4'th family, $m_H \sim$ few 100 GeV — Okun et al.
  - Opaque branes — Carena et al.
- 'Oblique' -- 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	T ≠ 0
χ^2, N = 5.4, 9	5.3, 7	5.4, 8
CL = 0.80	0.63	0.72
m_H = 45	**All m_H allowed**	**m_H < 550, > 1800**

χ^2 Distributions: Oblique New Physics

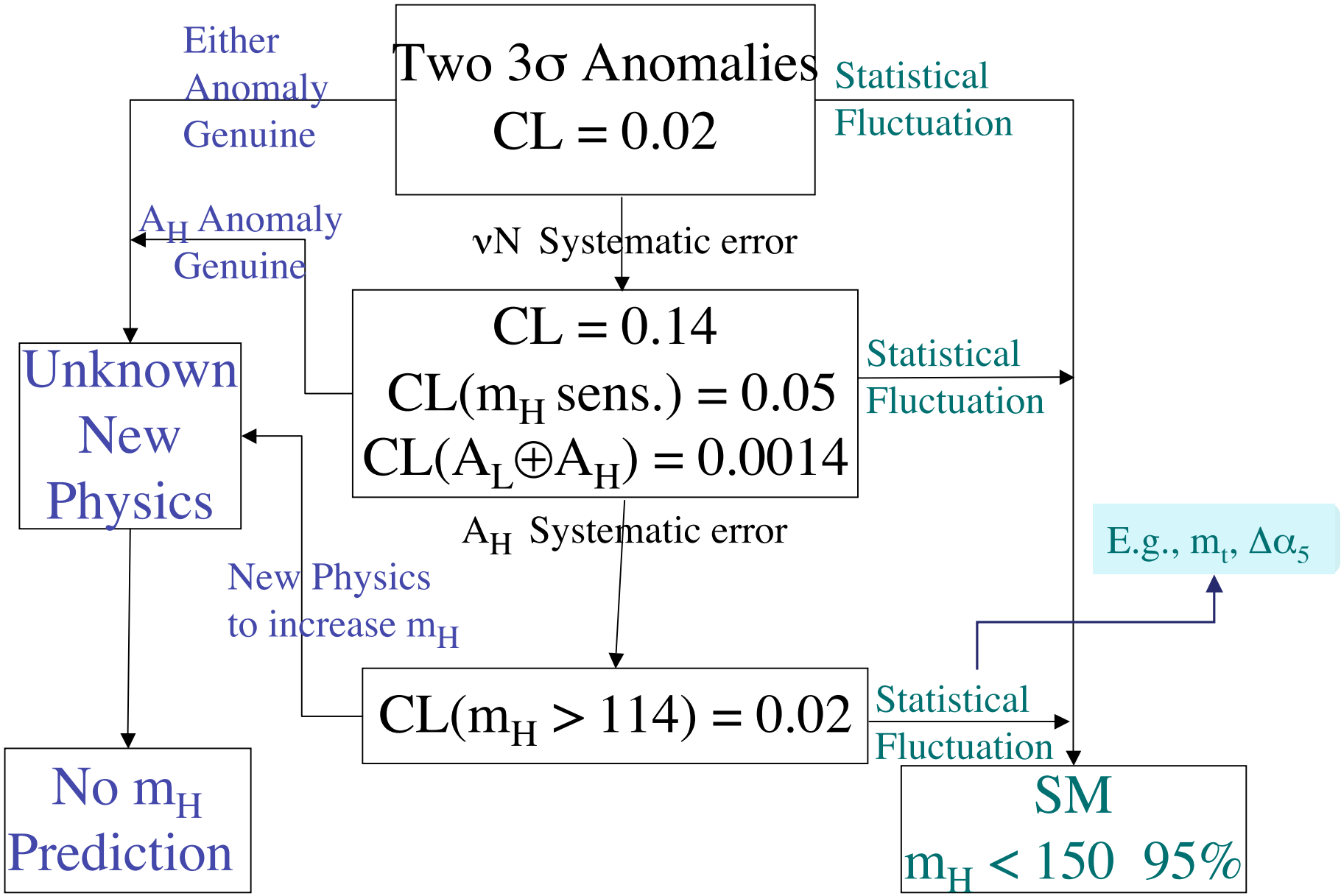


χ^2 Distributions: Oblique New Physics



(T ≠ 0:
8 DOF)

E-W Schematic Diagram



Potential future impact of run 2

Assuming current central values,

	Δm_t	2.1 GeV	1.5	1.2
	Δm_W	25 MeV	20	15
'All'	Fit CL	0.14	0.12	0.10
	m_H	85 GeV	70	64
	$CL(m_H > 114)$	0.18	0.11	0.03
	$m_H(95\%)$	148 GeV	127	108
- x[A_H]	Fit CL	0.80	0.80	0.80
	m_H	48 GeV	48	48
	$CL(m_H > 114)$	0.021	0.010	0.004
	$m_H(95\%)$	97 GeV	90	84

Conclusion

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

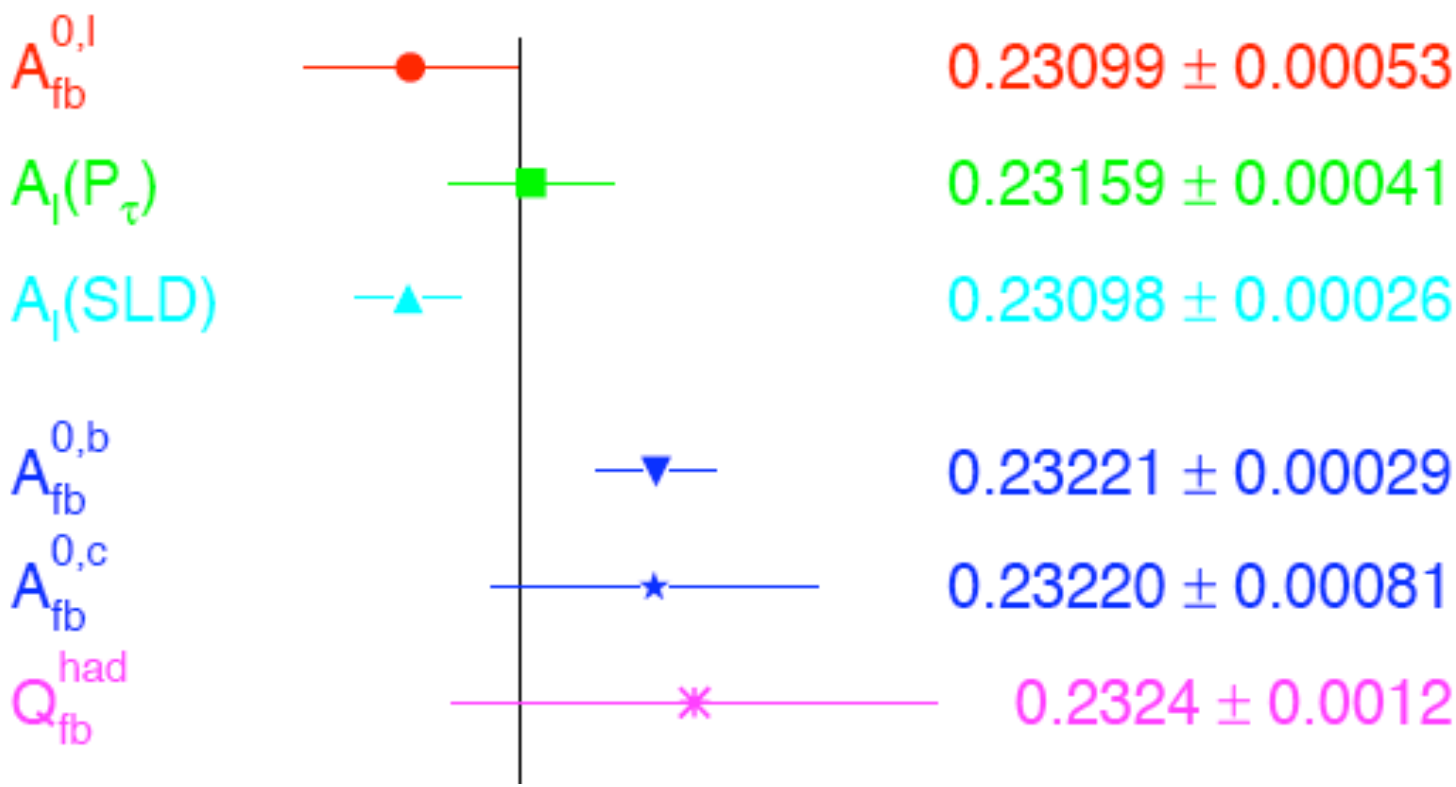
LEP II limit on m_H makes problem more persistent:

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

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

- δA_{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.

PS *Precision EW data will still be relevant after LHC, to guide interpretation of what we see and to triangulate for new physics not yet seen.*

$\sin^2\theta_{eff}^{lept}$: most important observable for m_H fit