M. Chanowitz, LBNL
LoopFest III
4/1/04

Update with new top quark mass added on last page

The Direct Limit on the Higgs Mass & the SM Fit

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

LEP II direct limit

$m_H > 114.4$ GeV (95%) $\qquad$ CL(m < 114) << 5%

imposes important constraint on interpretation of EW Data.

To test SM, consider

Fit: $\qquad CL(\chi^2) = 0.02$ $\quad$ { **No** APV $\quad \square_{TH} \sim ?$; **No** $\square_W$ $\quad \square\square_W/\square_W \sim 3/100$ }

AND

$m_H > 114$: $\qquad CL(m_H) = 0.37$ $\quad$ { CL from SM fit that $m_H > 114$ }

Useful to consider **Product:**

$$P_C = CL(\chi^2) \square CL(m_H) = 0.007$$

- interesting to track *relative* values for different fits
- PDF(P_C) = - ln (P_C), $\quad$ < P_C > = 0.25

$$CL(\ P_C < 0.007\ ) = 0.04$$

- EW data $\xrightarrow[\text{Fit}]{\text{SM}}$ $\langle m_H \rangle = 96$ GeV, $m_H < 215$ 95% CL

- Two 3σ anomalies (A_{FB}^b/A_{LR} & νN) Poor SM fit
  - CL(χ^2) = 0.02 { 13 Z-pole observables + m_W, m_t, $x_W^{\nu N}$, $\alpha(m_Z)$, $\alpha_S(m_Z)$
  - anomalies concentrated among m_H-sensitive observables
    CL(χ^2) = 0.004 { 8 Z-pole observables + m_W, m_t, $x_W^{\nu N}$, $\alpha(m_Z)$, $\alpha_S(m_Z)$

→ **How reliable is m_H prediction?**

- To maintain m_H prediction, we must attribute poor CL's to statistical fluctuation **and/or** systematic error.
- Focus of this talk: A_{FB}^b/A_{LR} anomaly

$x_W^{\ell,\mathrm{eff}}$

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

$x^{\ell}[A_L] = 0.23113\ (21)$
$\chi^2/N = 1.7/2$ CL = 0.43

A_{FB}^{b} 0.23212 (29)
A_{FB}^{c} 0.23223 (81)
Q_{FB} 0.23240 (120)

$x^{\ell}[A_H] = 0.23214\ (27)$
$\chi^2/N = 0.06/2$ CL = 0.97

0.23150 (16)
$\chi^2/N = 8.7/1$
CL = 0.003

Dominated by $x[A_{LR}] \oplus x[A_{FB}^{b}] = 0.23149\ (19)$
$\chi^2/N = 8.6/1$ CL = 0.003

Combining all six: $\chi^2/N = 10.5/5$ CL = 0.06

N.B., $0.06 \sim 0.003 \times (6 \times 5 \times 4)/3!$

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

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

2) SM fit of m_H dominated by low probability combination of $x[A_L] \oplus x[A_H]$.

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

Generic explanations of x_W □N & A_L-A_H anomalies:

- ***New physics*** **--- certainly possible**
  - no compelling theoretical explanations, so far…
- ***Statistical fluctuation*** **--- fairly valued**
  - e.g., excluding □N : Pull[A_{FB}^b] = 2.59, CL(2.59□) = 0.0096

    P(≥ 1 2.63□, N = 12) = 1 - (1 - 0.0085)^{12} = **0.10** ~ CL(□^{2}) = **0.17**

    Global CL's correctly reflect probability for outlyers relative to sample size.

    The appropriate statistical ensemble is multiple replays of the 90's @LEP, SLC, TeVatron.
- ***Underestimated systematic uncertainty***

Focus on sys. uncertainty not because it is more likely, but to see if it could improve the SM fit.

LEP II direct lower limit on m_H is central to the analysis.

Systematic error - subtle & important issues

{ Above my pay grade

- ν**N:** theoretical & experimental questions: EWRC, NLO, s-$\bar{s}$ asym., …
- **$x^{\ell}[A_L]$: A_{LR}, A_{FB}^{ℓ}, $A_{e,\tau}$**
  - 3 very different techniques: common sys. error very unlikely.
- **$x^{\ell}[A_H]$: A_{FB}^{b}, A_{FB}^{c}, Q_{FB}**
  - b ⟷ $\bar{c}$ mutual bkgds: consistent w. signs of A_{FB}^{b}, A_{FB}^{c} anomalies
  - 14 parameter Heavy Flavor fit (4 LEP exp'ts + SLC):

$\chi^2/N = 53/(105 - 14)$
CL = 0.9995(!)

{ EWWG: Sys. errors too conservative?

EWWG: reasonable χ^2 if sys errors ⟶ 0 ⟹ $\chi^2/N = 91/91$, CL = 0.48

Fit ⟹ Poorer

CL { $x[A_{LR}] \oplus x[A_{FB}^{b}]$ } = 0.003 ⟶ 0.002

CL { $x_W^{\ell,eff}$ } = 0.06 ⟶ 0.04 — 6 asym's

CL { SM 'All Data' Fit } = 0.02 ⟶ 0.01

CL { SM, no NuTeV } = 0.17 ⟶ 0.10

Systematic error - subtle & important issues {Above my pay grade

- **□N:** theoretical & experimental questions: EWRC, NLO, s-$\bar{s}$ asym., …
- **$x^{\ell}[A_L]$: A_{LR}, A_{FB}^{ℓ}, $A_{e,□}$**

  - 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 much 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}, $A_{e,□}$.

SM Fits

SM EWRC from ZFITTER 6.30 + 2-loop m_W Freitas et al.

→ - (5 - 10) MeV

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

Good agreement with EWWG.

$\Delta\alpha_5$ from BP (BES) -- EWWG default

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, $x_W^{\nu N}$ }
- Correlations alla EWWG

(constrain $\alpha_S = 0.118(3)$ if Γ_Z, R_l, or σ_H not in fit)

Global Fits: CL(χ^2) ⟶ m_H-sensitive only

A) All **A')**
0.02 ⟶ **0.004**

B) $-x_W^{\nu N}$ **B')**
0.17 ⟶ **0.06**

C) $-x[A_H]$ **C')**
0.09 ⟶ **0.02**

D) $-x[A_H]$ $-x_W^{\nu N}$
0.75 ⟶ **0.57** **D')**

- **A', B', C':** problems concentrated in m_H-sensitive sector.

  m_H **in**sensitive: $□_H$, R_b, R_c, A_b, A_c

- **D, D':** bigger* sys. errors for $x[A_H]$, $x_W^{\nu N}$ would improve SM fit.

**Much* bigger

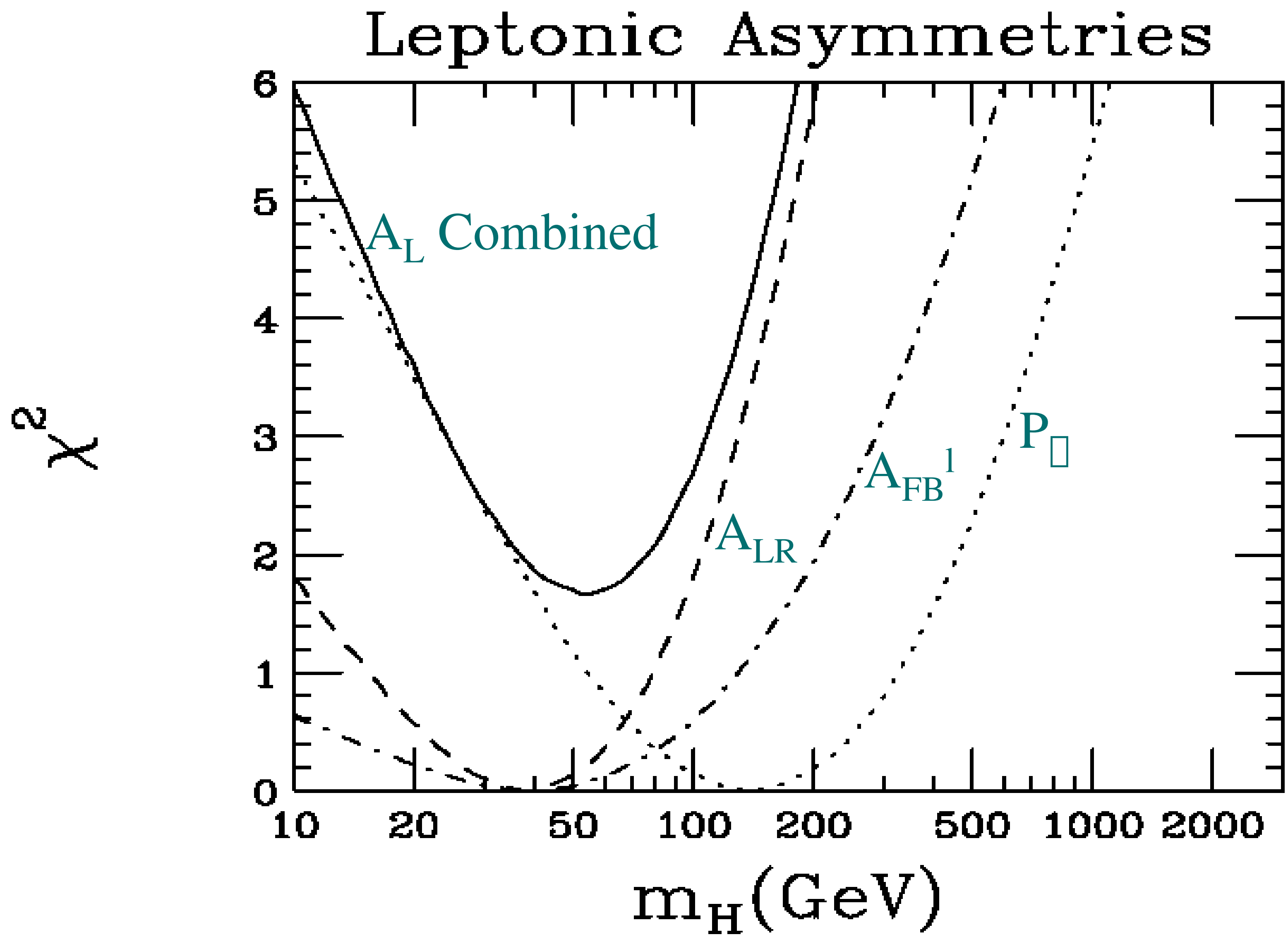
m_H-sensitive observables: m_H predictions

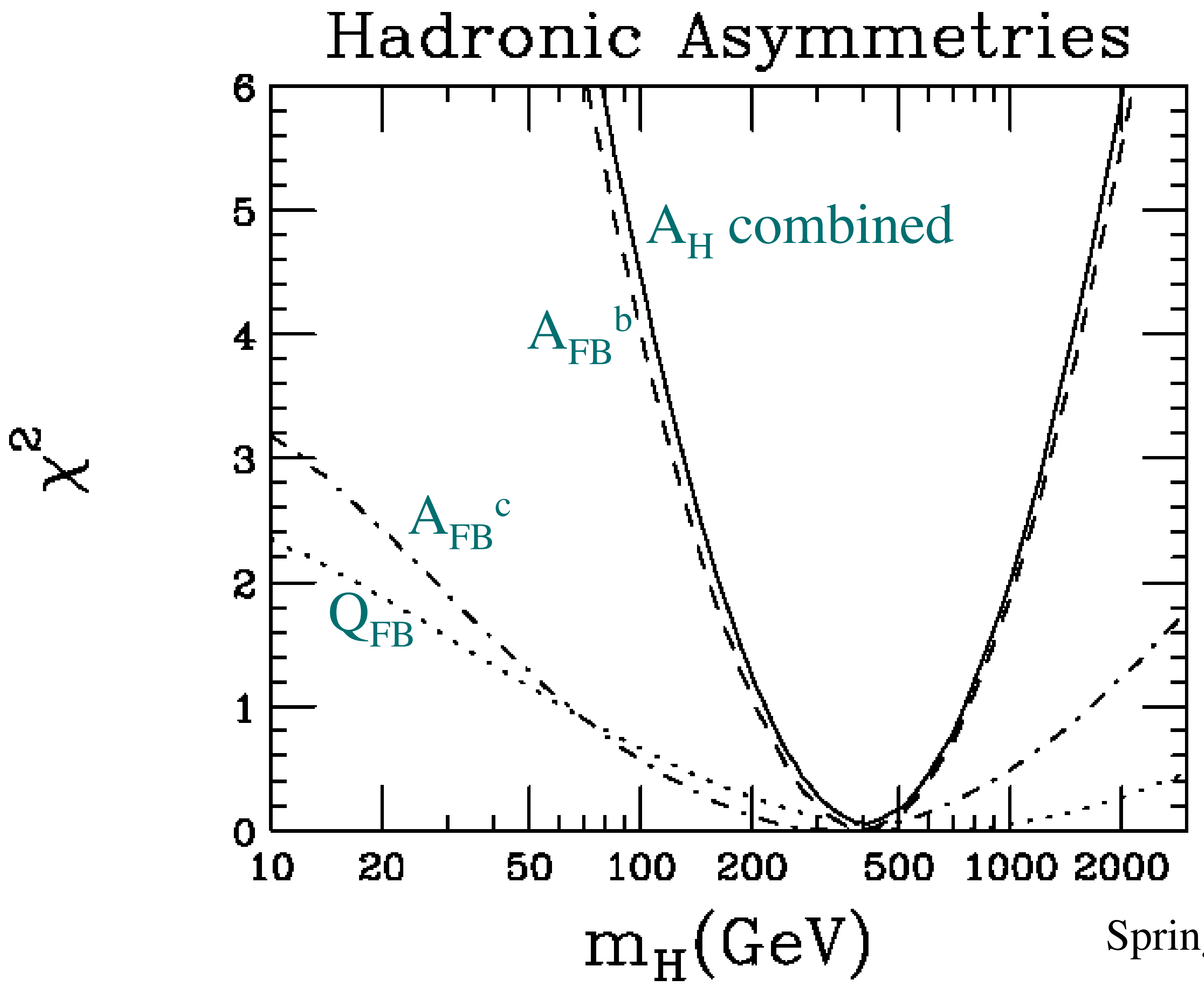
High Precision	m_H	95%	$CL(m_H > 114)$
A_{LR}	39	< 122	0.062
A_{FB}^b	380	$130 < m < 1100$	0.96
m_W	35	< 161	0.12

Aggregates	m_H	95%	$CL(m_H > 114)$
$x[A_L]$	55	< 143	0.10
$x[A_H]$	380	$140 < m < 1100$	0.97
m_W, Γ_Z, R_l	17	< 123	0.057

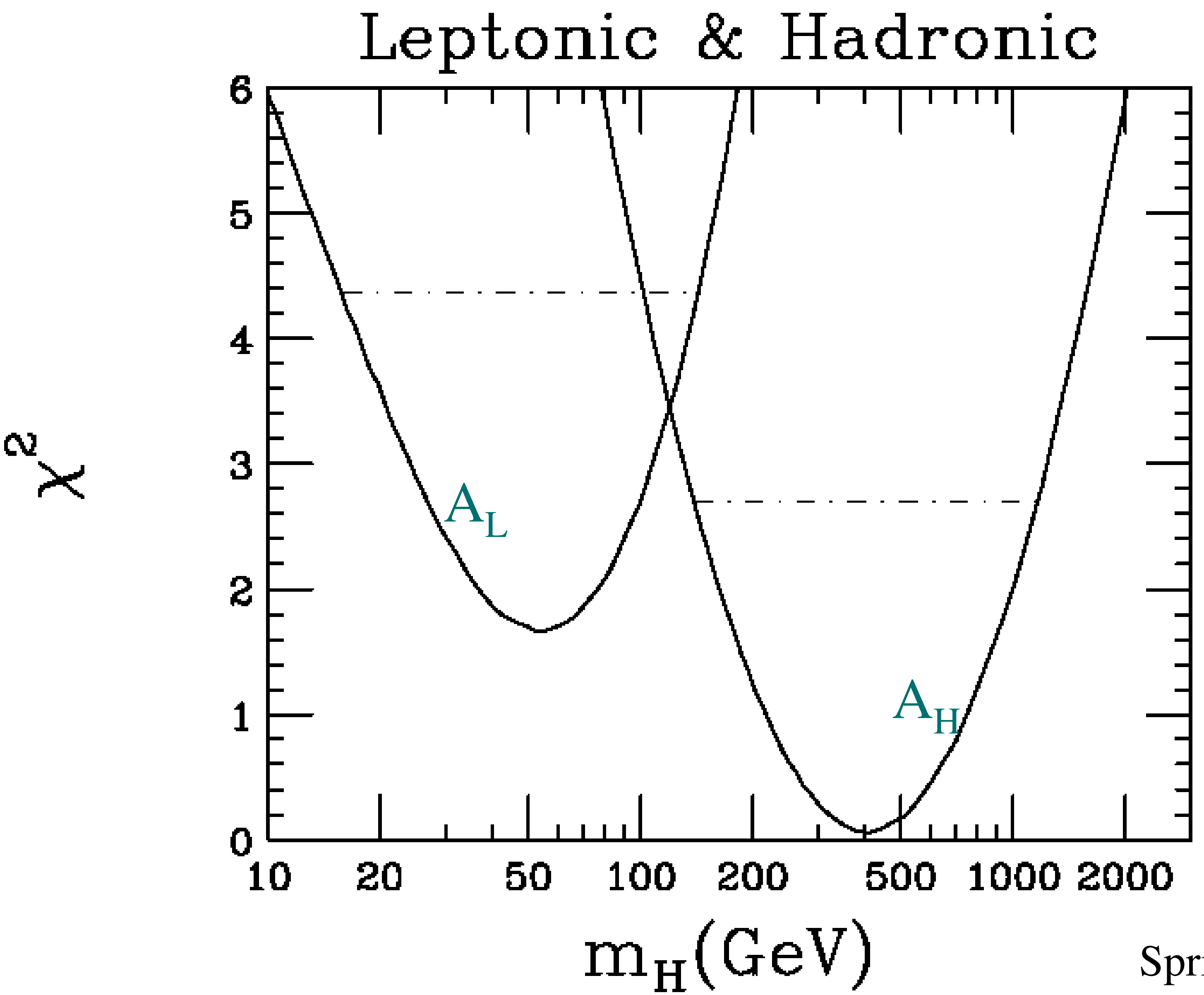
m_W, Γ_Z, R_l → Non-asymmetry observables

Support for m_H >114 only from $x[A_H]$ (+ $x_W^{\nu N}$)

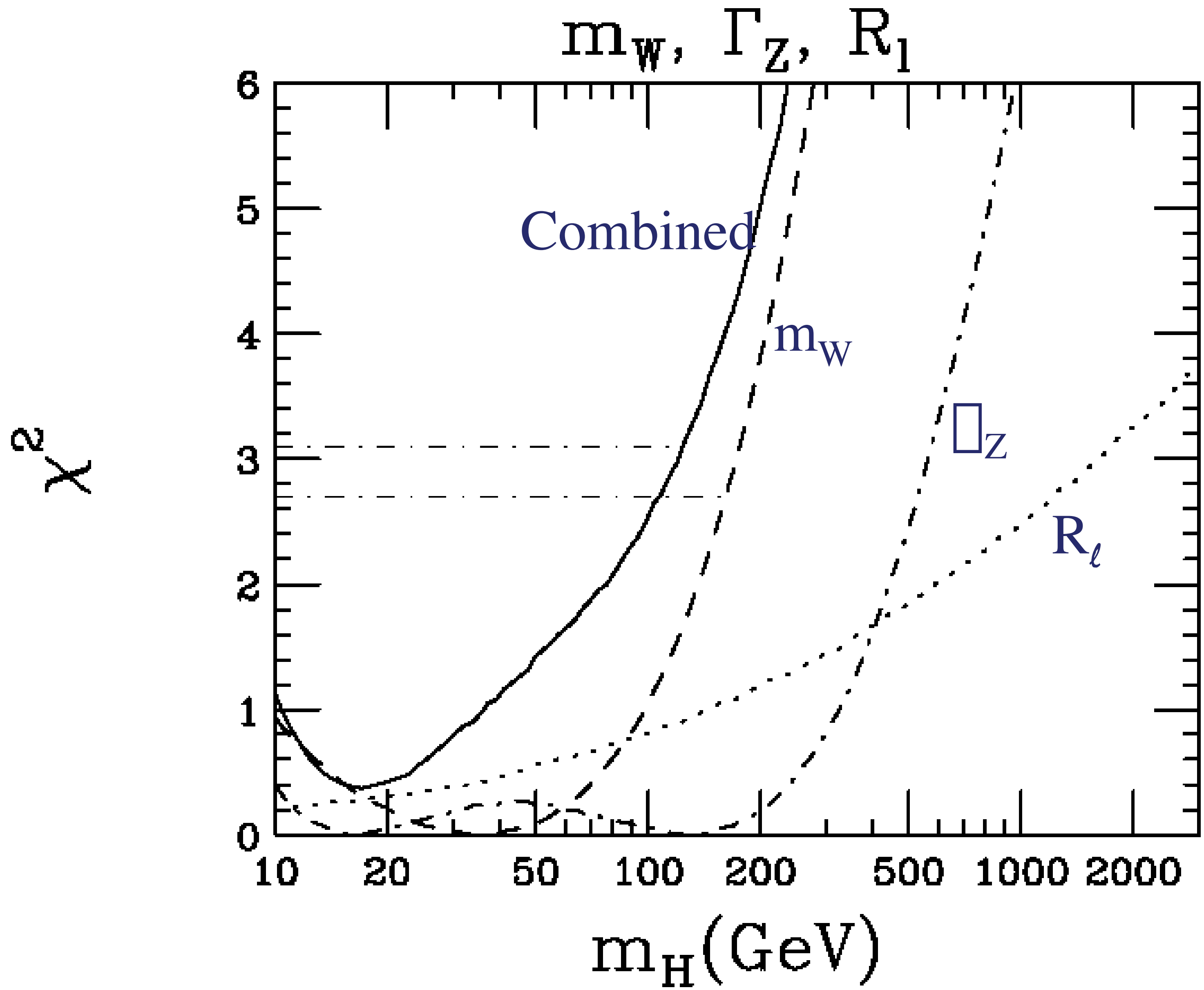

Leptonic Asymmetries
χ²
m_H(GeV)
0
1
2
3
4
5
6
10
20
50
100
200
500
1000
2000
A_L Combined
A_LR
A_FB^l
P


Hadronic Asymmetries
6
5
4
3
2
1
0
10
20
50
100
200
500
1000
2000
χ^2
m_H(GeV)
A_H combined
A_{FB}^b
A_{FB}^c
Q_{FB}

Spring 02


Leptonic & Hadronic
6
5
4
3
2
1
0
10
20
50
100
200
500
1000
2000
χ^2
m_H(GeV)
A_L
A_H

Spring 02



m_W, Γ_Z, R_l
χ^2
Combined
m_W
Γ_Z
R_ℓ
0
1
2
3
4
5
6
10
20
50
100
200
500
1000
2000
m_H(GeV)

Global Fits: $P_C = CL(\chi^2) \times CL(m_H > 114)$

A) **All**

25.7/13

$m_H = 96$

$P_C = 0.019 \times 0.37 = 0.007$

B) **- $x_W^{\nu N}$**

16.5/12

$m_H = 89$

$P_C = 0.17 \times 0.32 = 0.05$

C) **- $x[A_H]$**

16.4/10

$m_H = 45$

$P_C = 0.088 \times 0.069 = 0.006$

D) **- $x_W^{\nu N}$ - $x[A_H]$**

5.9/9

$m_H = 45$

$P_C = 0.75 \times 0.050 = 0.04$

Without $x[A_H]$, SM fit is inconsistent with search limit.

P_C ~ invariant under removal of $x[A_H]$.

CL(□) & CL(m_H > 114) both decrease if heavy flavor sys. errors → 0.

14 parameter HF fit: CL = 0.9995 → 0.44

A: 0.019 | | 0.37 = 0.007 [0.04] → 0.010 | | 0.32 = 0.003 [0.02]

B: 0.17 | | 0.32 = 0.05 [0.20] → 0.096 | | 0.29 = 0.03 [0.13]

C: 0.088 | | 0.069 = 0.006 [0.04] → 0.065 | | 0.052 = 0.003 [0.02]

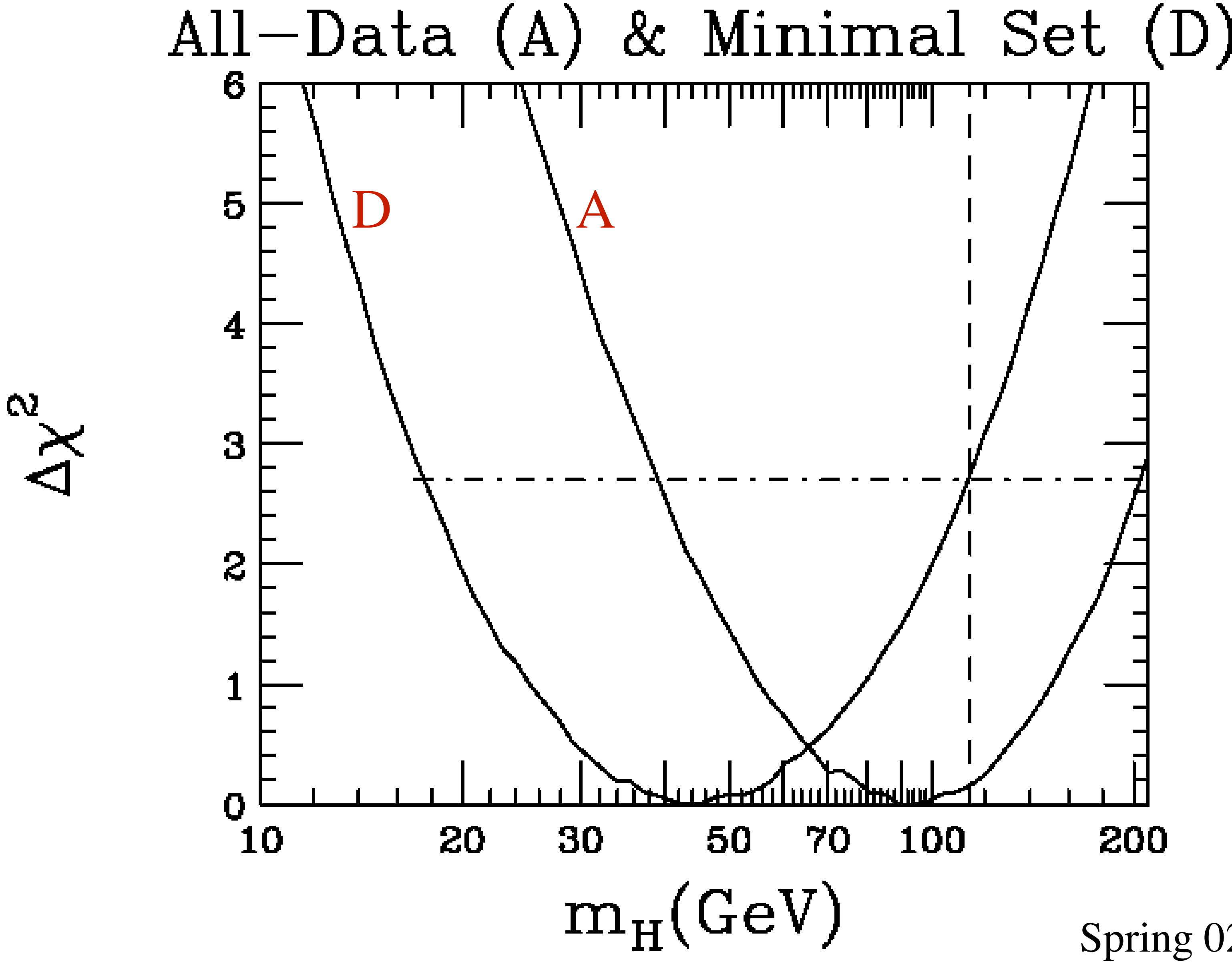
D: 0.75 | | 0.050 = 0.04 [0.17] → 0.42 | | 0.036 = 0.015 [0.08]

[CL(P_C < P)]

(Decrease of CL(m_H > 114) in fits C&D due to secondary effect of m_t on R_b, since m_t increases to fit m_H > 114.)

m_H-sensitive observables only

	CL(□)	$CL(m_H > 114)$	$= P_C$	$CL(P_C < P)$
A	0.004	0.41	= 0.0016	0.01
B	0.058	0.37	= 0.021	0.10
C	0.021	0.068	= 0.0014	0.01
D	0.57	0.052	= 0.030	0.13



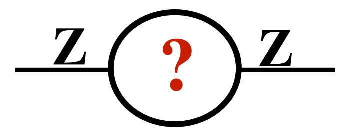
All−Data (A) & Minimal Set (D)
D
A
6
5
4
3
2
1
0
10
20
30
50
70
100
200
$\Delta\chi^2$
m_H(GeV)

Spring 02

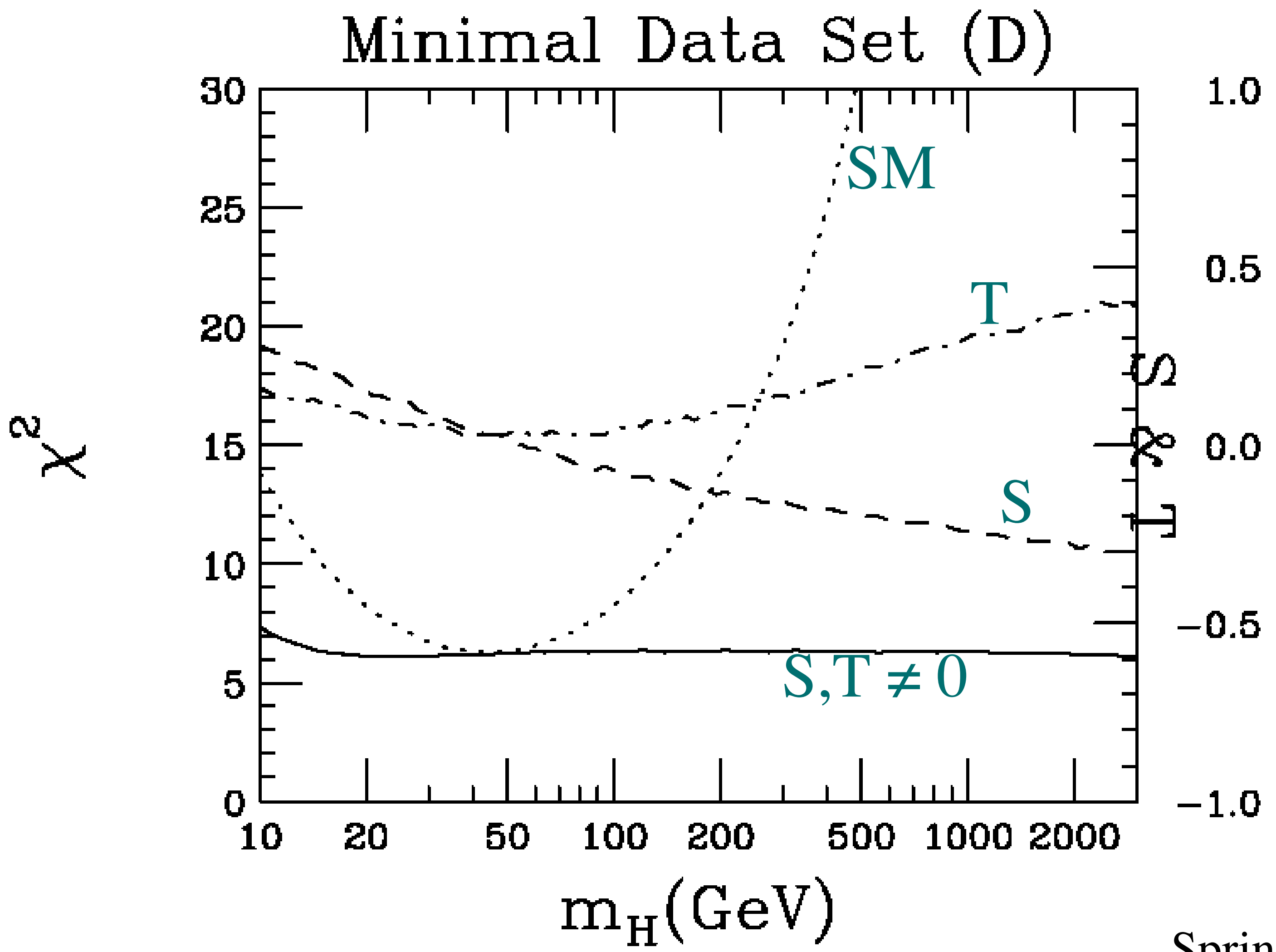
Fit D ⟹ New Physics to increase m_H

- Existing proposals
  - MSSM with 'light' □, $\tilde{\ell}$,… — 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) for fits A, B, C
  - can raise m_H arbitrarily for fit D:

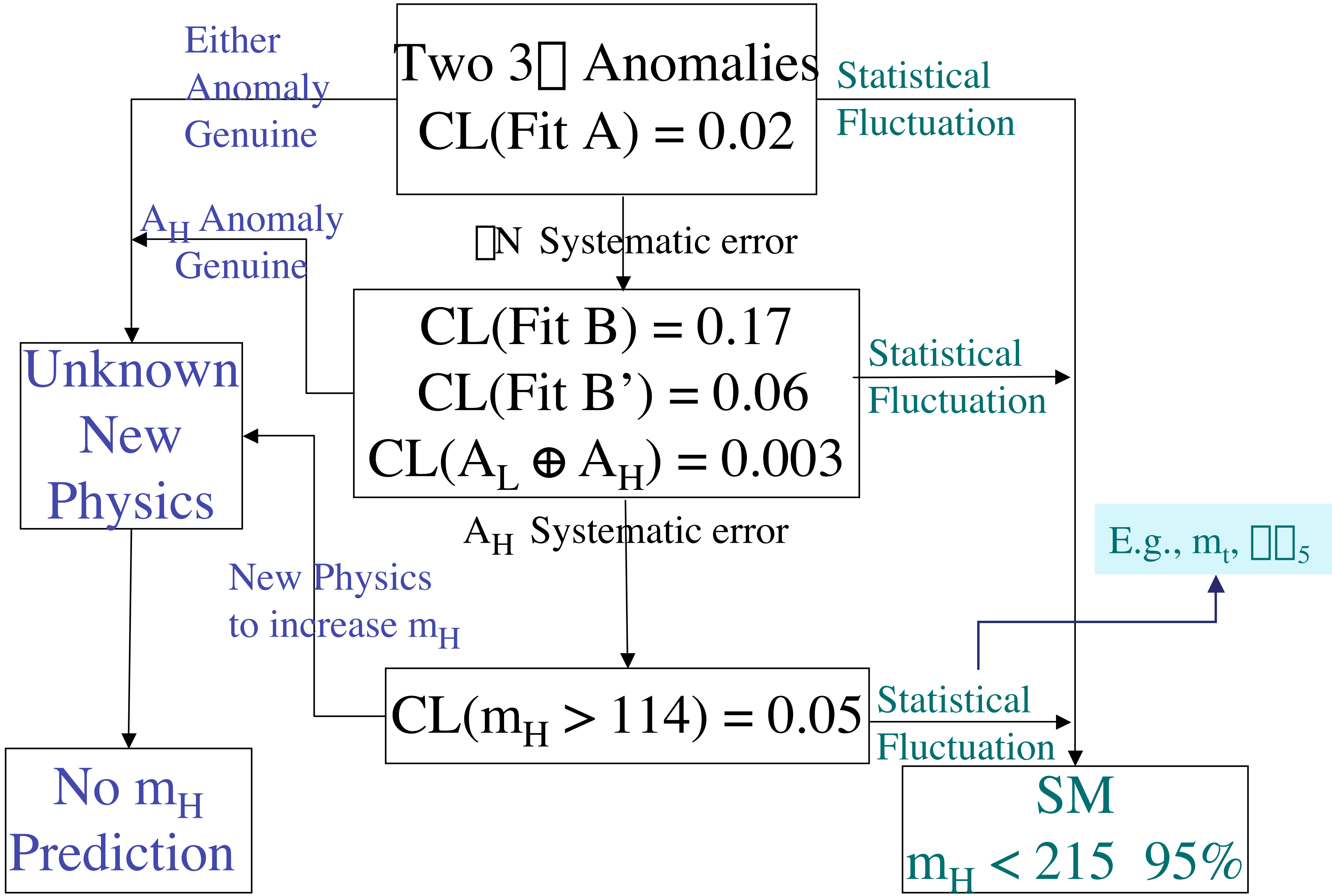


	SM	S,T ≠ 0
χ^2 =	5.9/9	5.7/7
CL =	0.75	0.57
m_H =	45	**All m_H allowed**


Minimal Data Set (D)
30
25
20
15
10
5
0
1.0
0.5
0.0
−0.5
−1.0
10
20
50
100
200
500
1000
2000
m_H(GeV)
χ^2
T & S
SM
T
S
S,T ≠ 0

Spring 02

E-W Schematic Diagram



The $x[A_{FB}^{b}]$ - $x[A_{LR}]$ discrepancy is a stubborn problem that refuses to go away.

LEP II limit on m_H makes problem more persistent:

- New physics indicated 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 statistical fluctuations of both anomalous & non-anomalous measurements --- certainly possible.

What's it all mean?

Beats me --- a great puzzle!

- The answer could begin to emerge at the TeVatron.
  If not, it will emerge at the LHC.
- Final clarity may require revisiting the Z boson with greater precision, e.g., as at Giga-Z, and/or better control of hadronic final state formation.

New top quark mass announced today:

174.3 (5.1) → 178.0 (4.3)

Principal effect is to increase m_H in SM fits.
e.g., in Bob Clare's all-data fit 96 GeV → 117 GeV

Principal effect on analysis presented in this talk is to increase the predicted CL(m_H > 114 GeV) for 'Fit D' (i.e., the fit with $x_W^{\nu N}$ and A_{FB}^b, A_{FB}^c, Q_{FB} excluded)

$$CL(m_H > 114 \text{ GeV})_{\text{Fit D}} = 0.05 \rightarrow 0.11$$

My conclusion:
Diminishes but does not remove the problem.