Electroweak Data Fits
&
the Higgs Boson Mass

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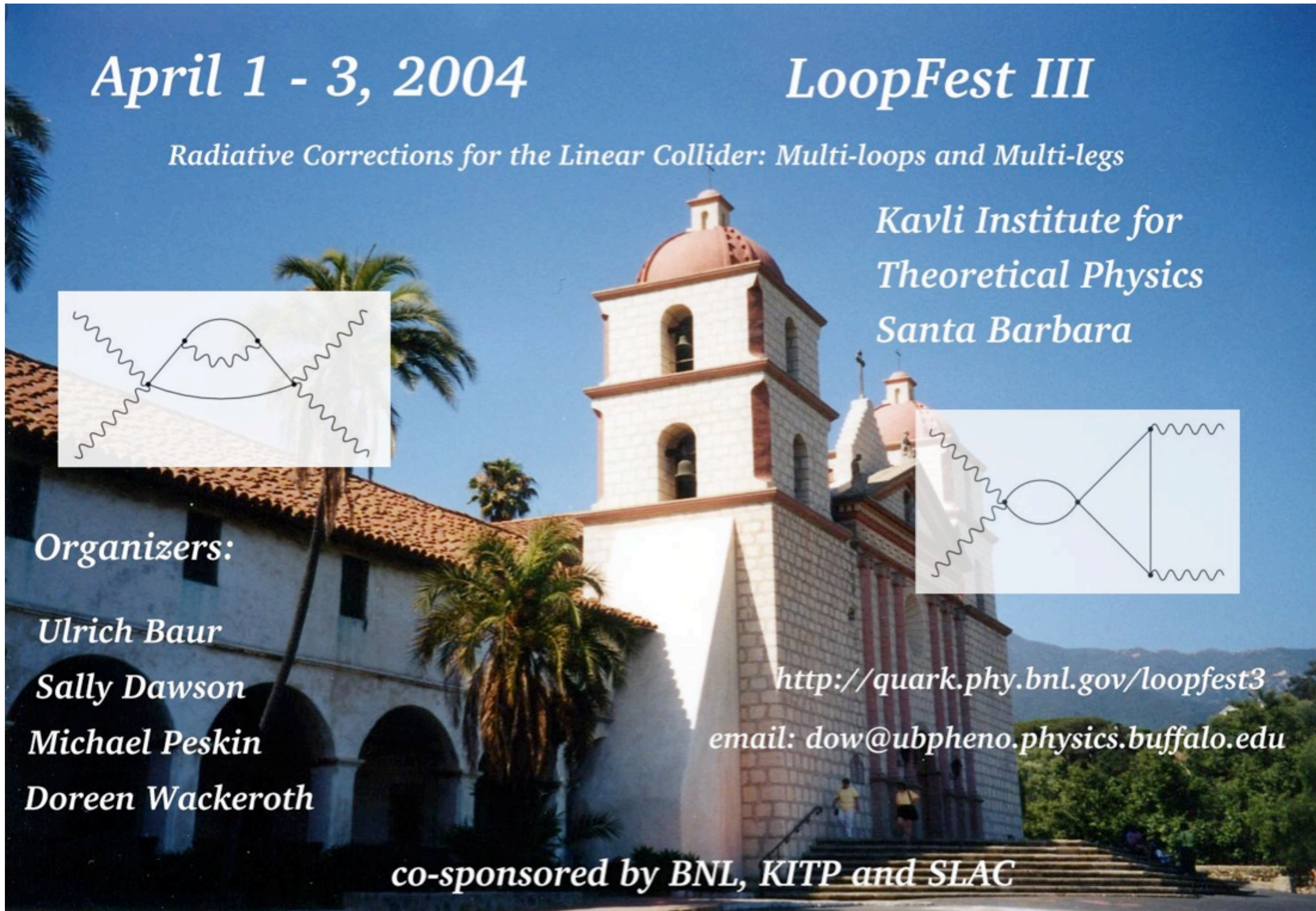


Outline

- Electroweak corrections: definitions and strategies
- Experimental inputs
- Effective couplings as a test of the Standard Model
- The Electroweak global fit
- Higgs mass limits
- Non-SM?
- Future Prospects in precision EW measurements
- Conclusions

Electroweak Radiative Corrections

Precision measurements: knowledge of Standard Model parameters through radiative corrections

$$\rho = \frac{m_W^2}{m_Z^2 \cos^2\theta_W} = 1 \quad \Longrightarrow \quad \bar{\rho} = 1 + \Delta\rho$$

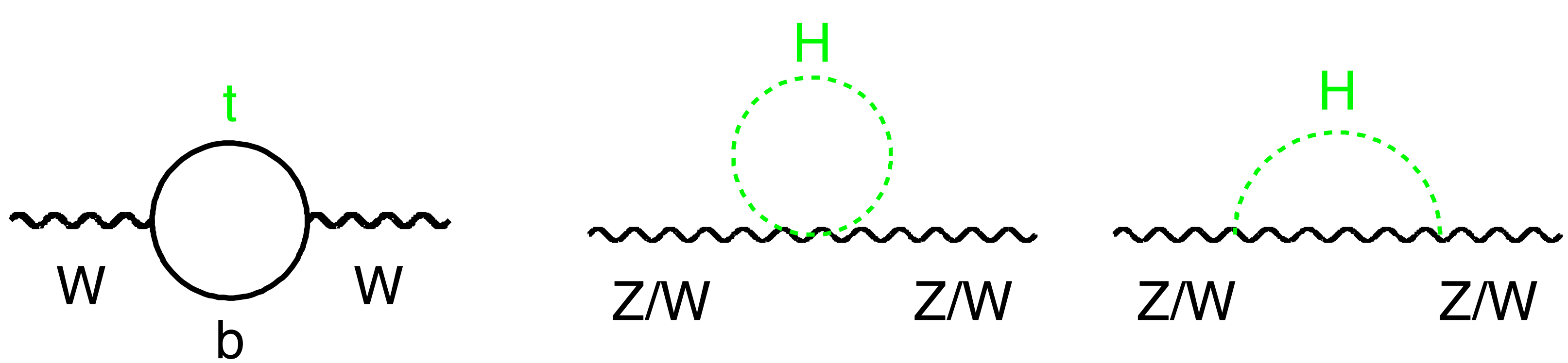
$$\sin^2\theta_W = 1 - \frac{m_W^2}{m_Z^2} \quad \Longrightarrow \quad \sin^2\theta_{\rm eff} = (1 + \Delta\kappa)\sin^2\theta_W$$

$$m_W^2 = \frac{\pi\alpha}{\sqrt{2}\sin^2\theta_W G_F} \quad \Longrightarrow \quad m_W^2 = \frac{\pi\alpha}{\sqrt{2}\sin^2\theta_W G_F}(1 + \Delta r)$$

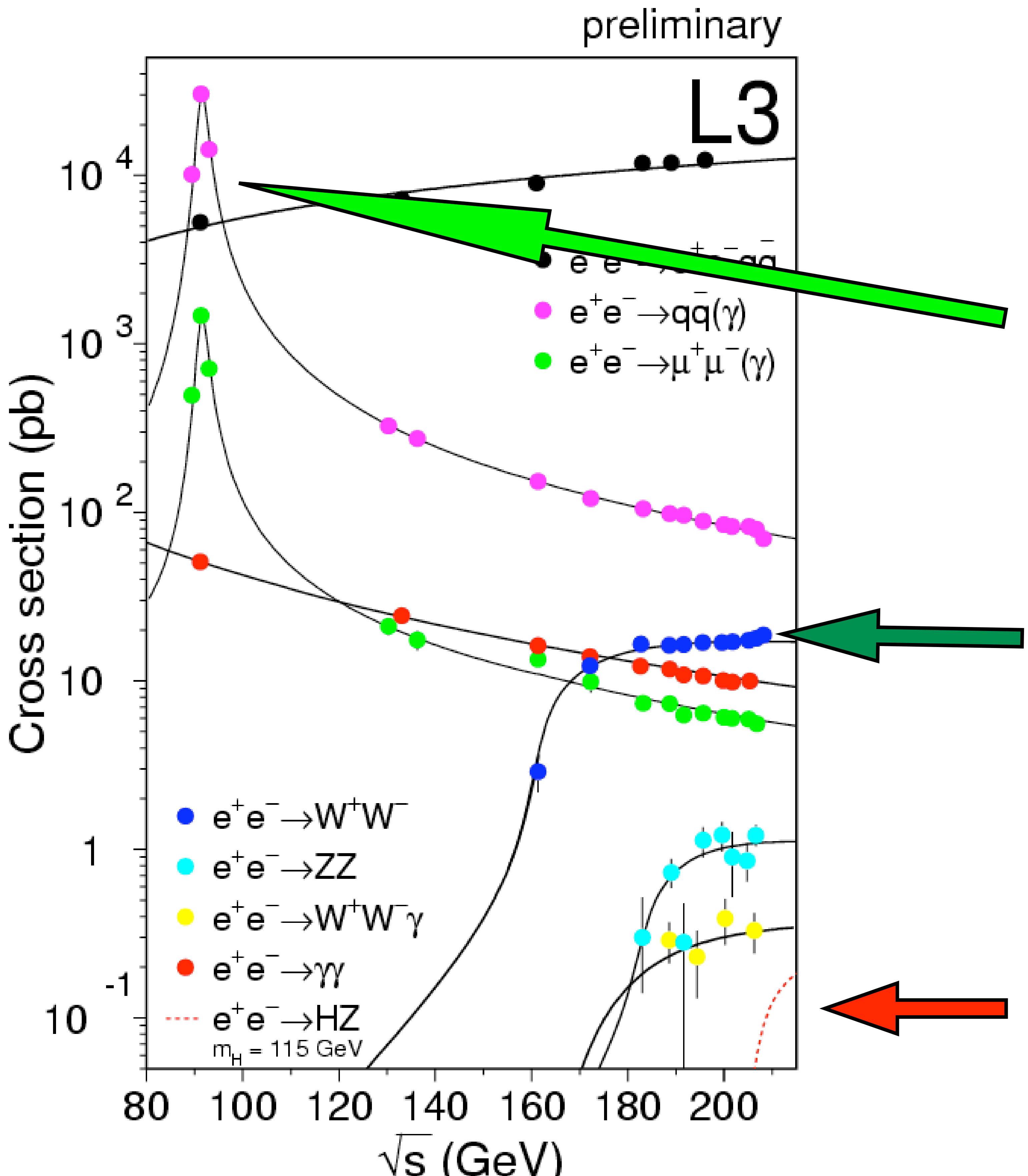
$$\alpha(0) \quad \Longrightarrow \quad \alpha(m_Z^2) = \frac{\alpha(0)}{1 - \Delta\alpha}$$

$$\text{with : } \Delta\alpha = \Delta\alpha_{\rm lept} + \Delta\alpha_{\rm top} + \Delta\alpha_{\rm had}^{(5)}$$

$$\Delta\rho, \Delta\kappa, \Delta r = f\left(m_t{}^2, \log(m_H), \ldots\right)$$



The LEP Heritage



In total, for all 4 expts:

about 16 M Z

about 35000 W

about 0 H

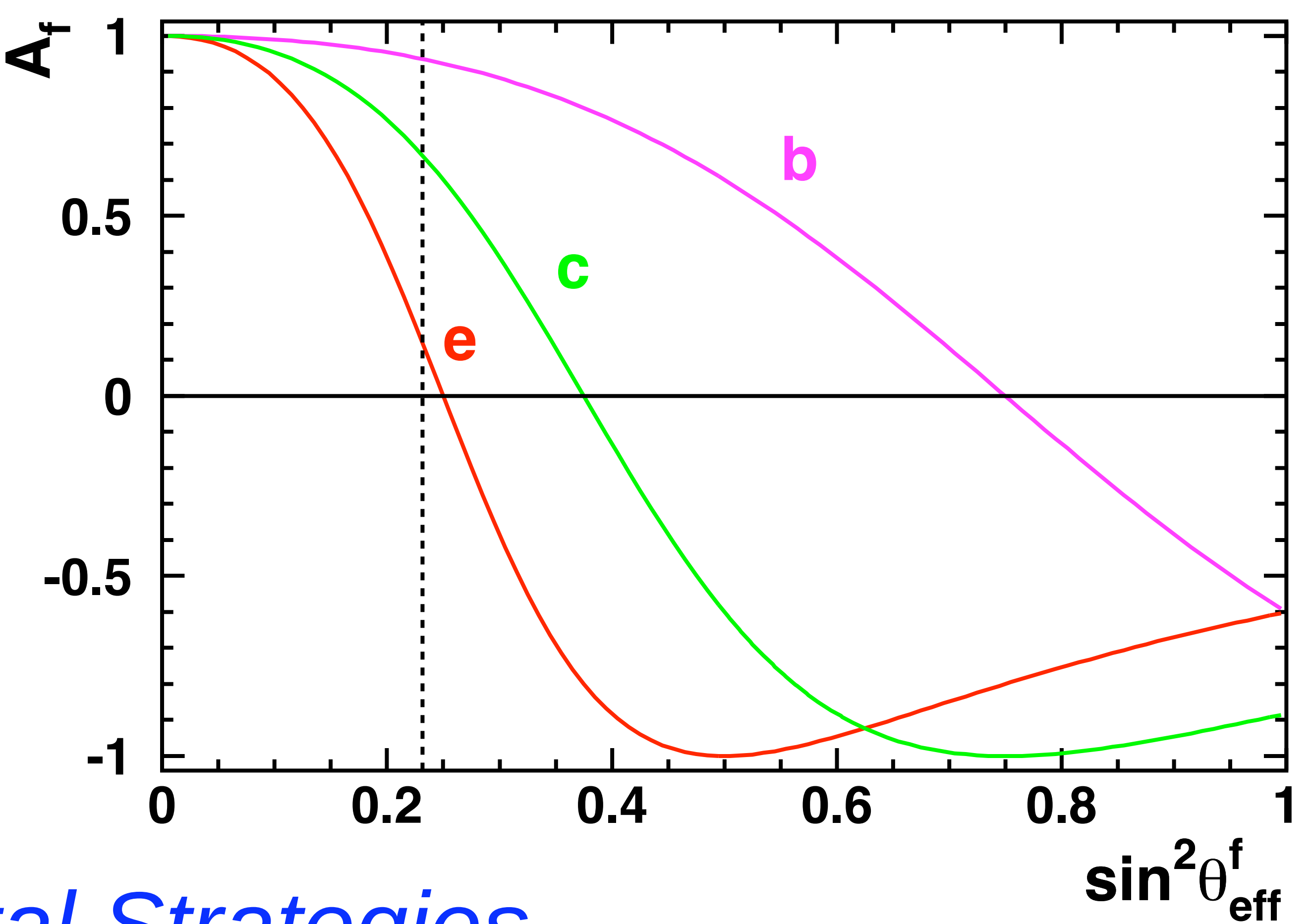
Effective Z couplings

$$g_{Vf} = \sqrt{\bar{\rho}}\left(T_f^{(3)} - 2Q_f \sin^2\theta_{eff}\right)$$

$$g_{Af} = \sqrt{\bar{\rho}}\; T_f^{(3)}$$

$$\mathcal{A}_f = 2\frac{g_{Vf}\, g_{Af}}{g_{Vf}^2 + g_{Af}^2}$$

$$A_{FB}^{0,f} = \frac{3}{4}\mathcal{A}_e \mathcal{A}_f$$



Experimental Strategies

- FB asymmetries $\Rightarrow \mathcal{A}_e \mathcal{A}_f$
- τ polarisation $\Rightarrow \mathcal{A}_e$ and $\mathcal{A}_\tau$ separately
- SLD (polarised beams) $\Rightarrow \mathcal{A}_e$ (and $\mathcal{A}_\mu$, $\mathcal{A}_\tau$)

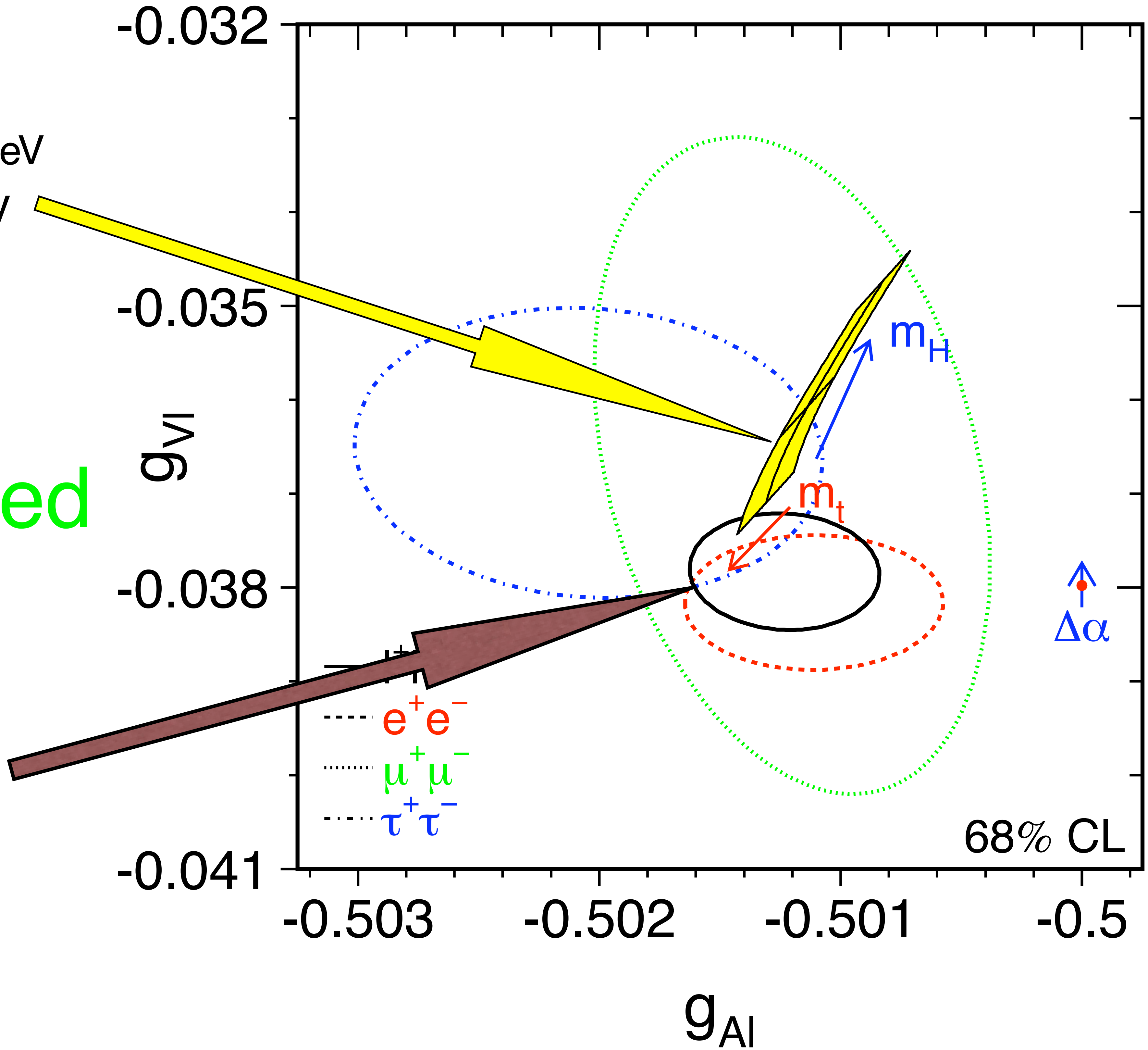
- Asymmetries $\Rightarrow g_V/g_A$
- Z partial decay widths $\Rightarrow g_V^2 + g_A^2$

Standard Model tests: leptonic couplings

SM:

m_H = [114.1, 1000] GeV

m_t = 174.3 ± 5.1 GeV

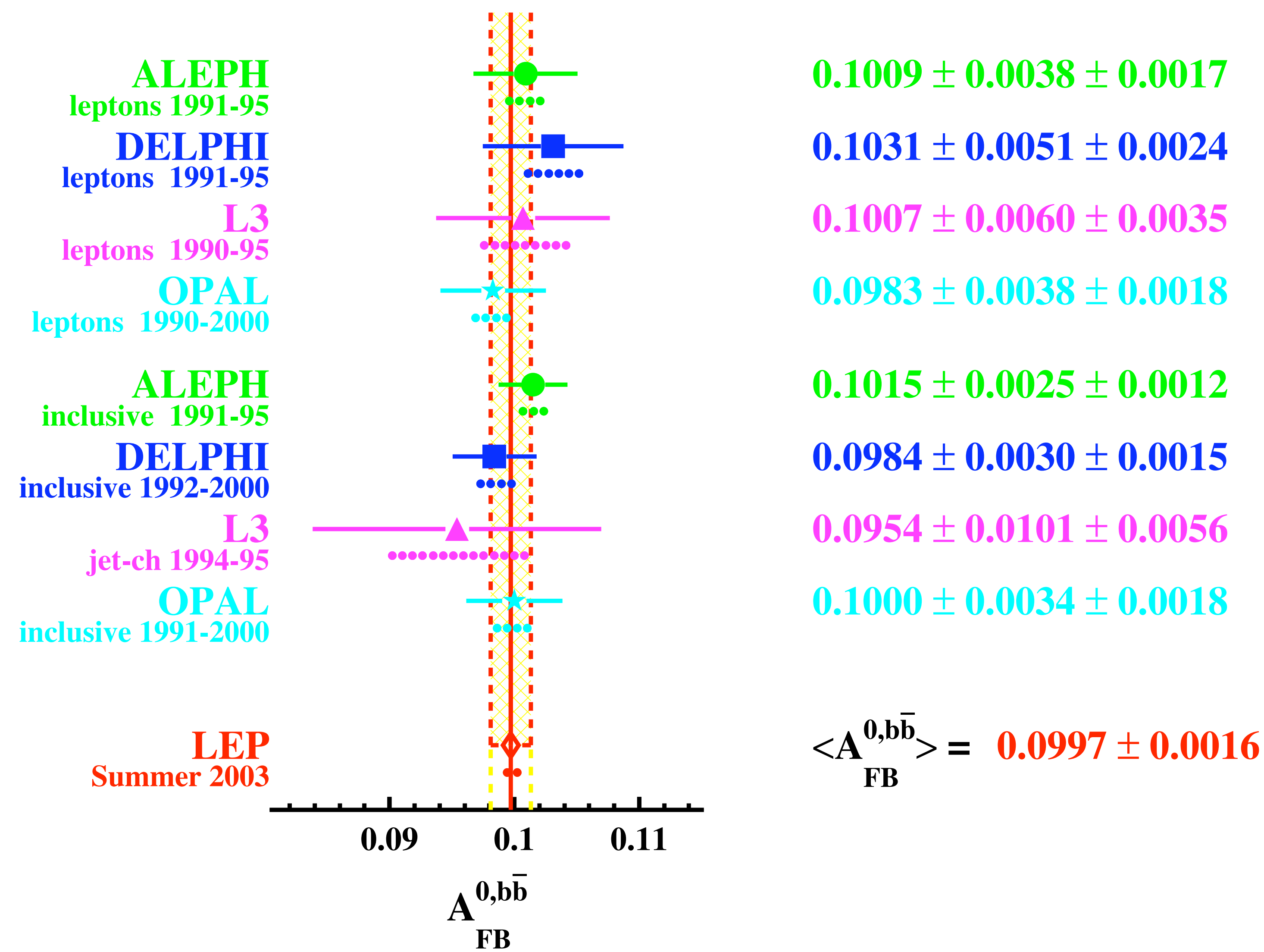


Low m_H favored

lepton universality

Effective couplings for quarks

All heavy flavor results from LEP and SLD are averaged in a combined fit, taking into account interdependencies (like mixing) and correlated errors (like QCD)



$\chi^2 = 57.7/(105 - 14)$

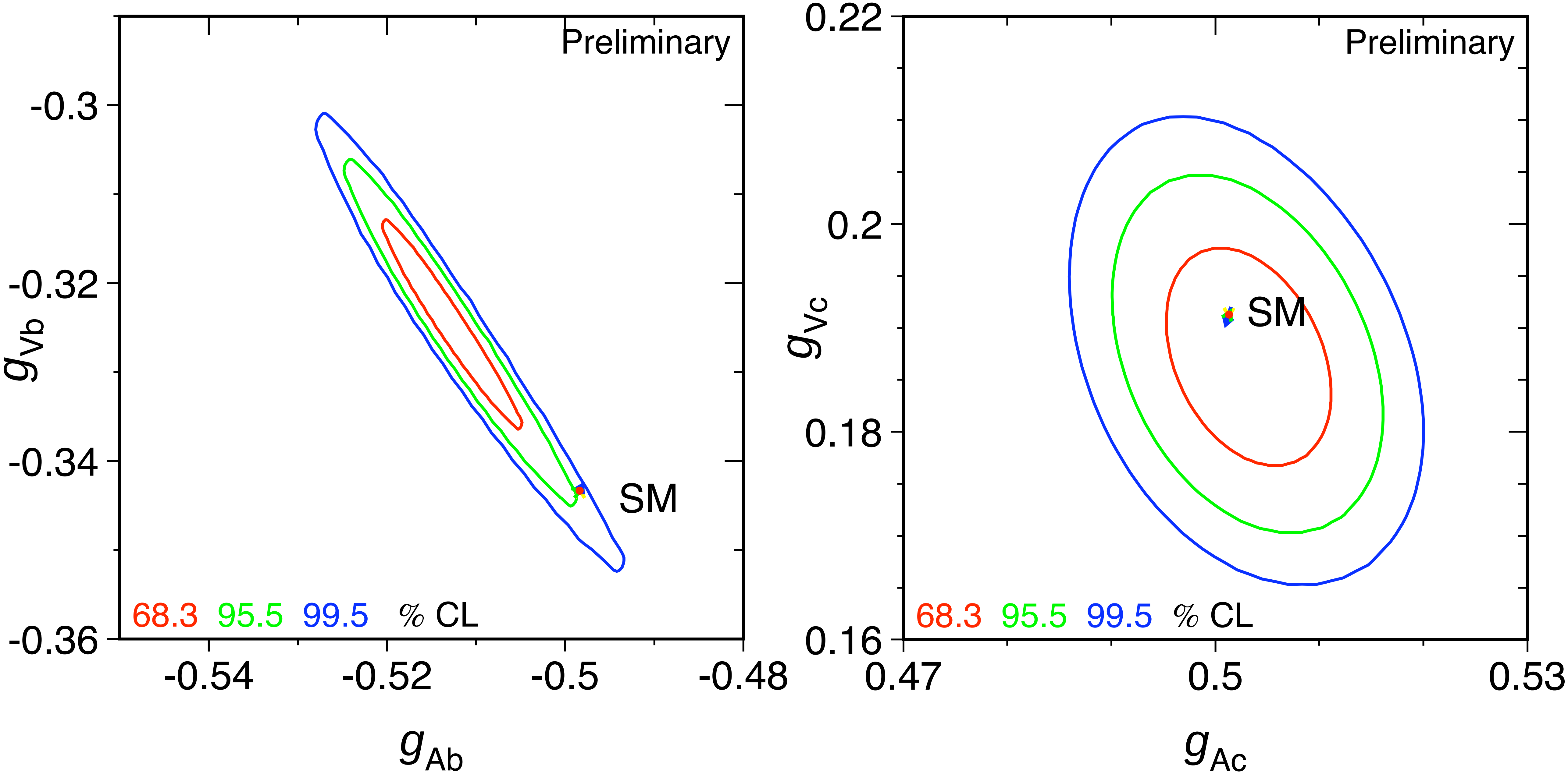
$A_{FB}^{0,b}$ = 0.0997 ± 0.0016(tot sys 0.0007; common sys 0.0004) SM 0.1036

$A_{FB}^{0,c}$ = 0.0706 ± 0.0035(tot sys 0.0017; common sys 0.0009) SM 0.0740

Some results are **still** preliminary

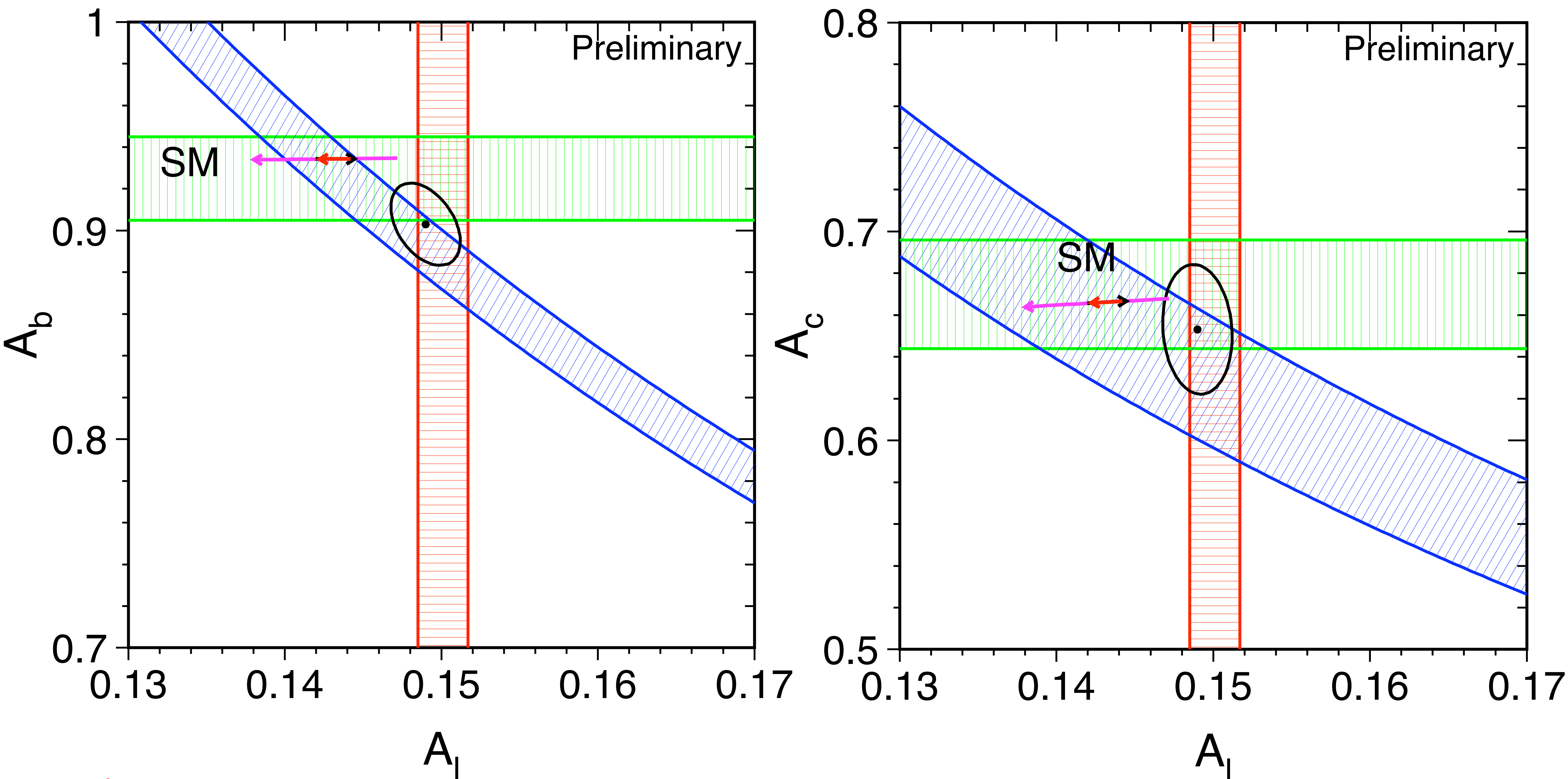
Quark couplings

LEP + SLD, assuming lepton universality



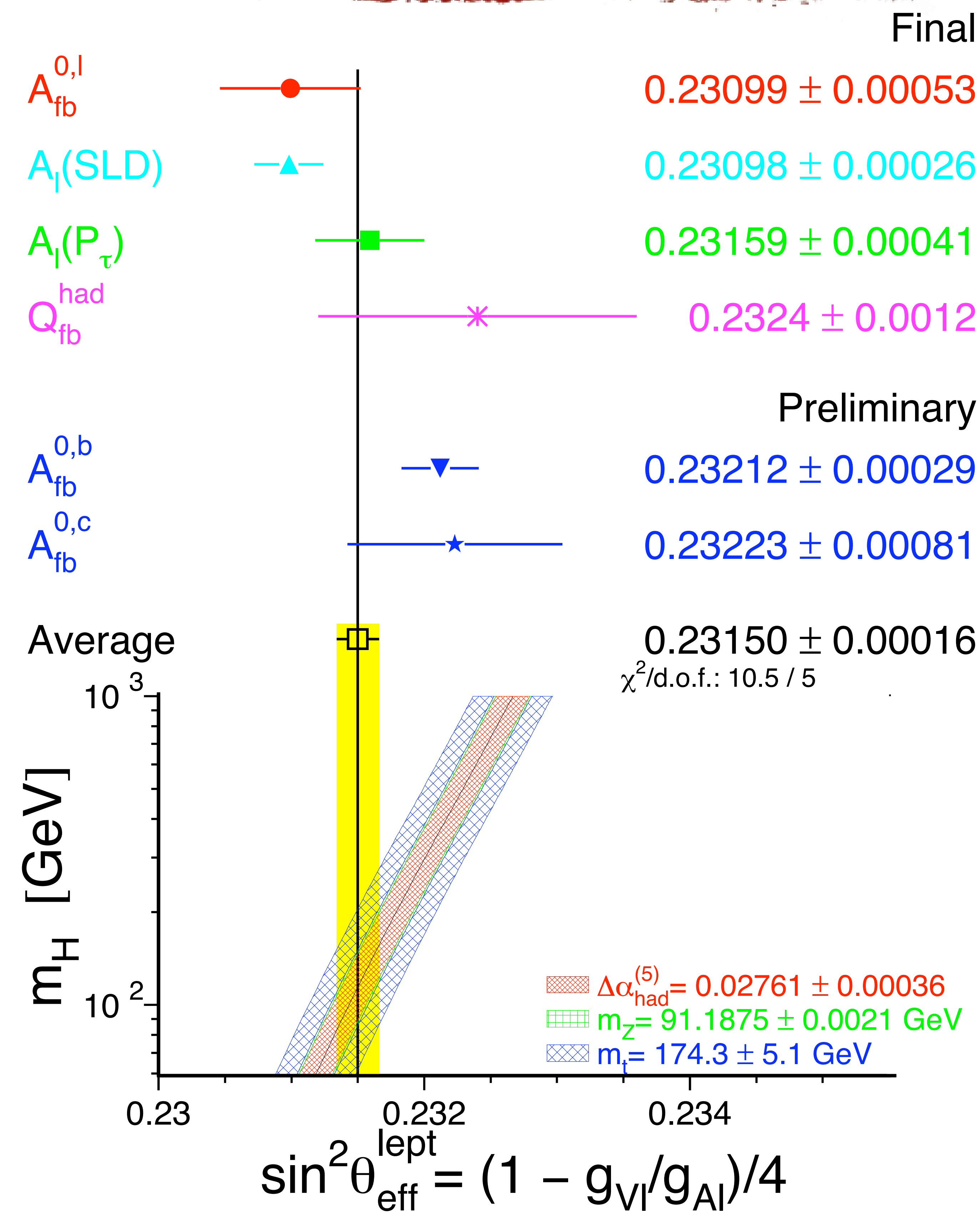
Quarks vs Leptons

horizontal band: $\mathcal{A}_b, \mathcal{A}_c$(SLD); vertical band: $\mathcal{A}_\ell$(LEP+SLD);
diagonal band : $A_{FB}^{0,b}$, $A_{FB}^{0,c}$(LEP); ⟵ $m_H \in [114, 1000]$



$A_{FB}^{0,b}$ prefers high m_H; $\mathcal{A}_\ell$ prefers low m_H

Standard model tests: $\sin^2\theta_{eff}^{lept}$



Assuming lepton universality:

χ^2/dof(lept.) = 1.6/2 (P = 44.0%)

χ^2/dof(hadr.) = 0.06/2 (P = 96.8%)

χ^2/dof(tot.) = 10.5/5 (P = 6.2%)

hadrons *vs* leptons 3σ

2.9σ between 2 most precise quantities

($\mathcal{A}_\ell$ and $A_{FB}^{0,b}$)

Top quark mass

New DØ Run I top mass

Use individual event probabilities instead of template

Improves statistical error by factor 2.5

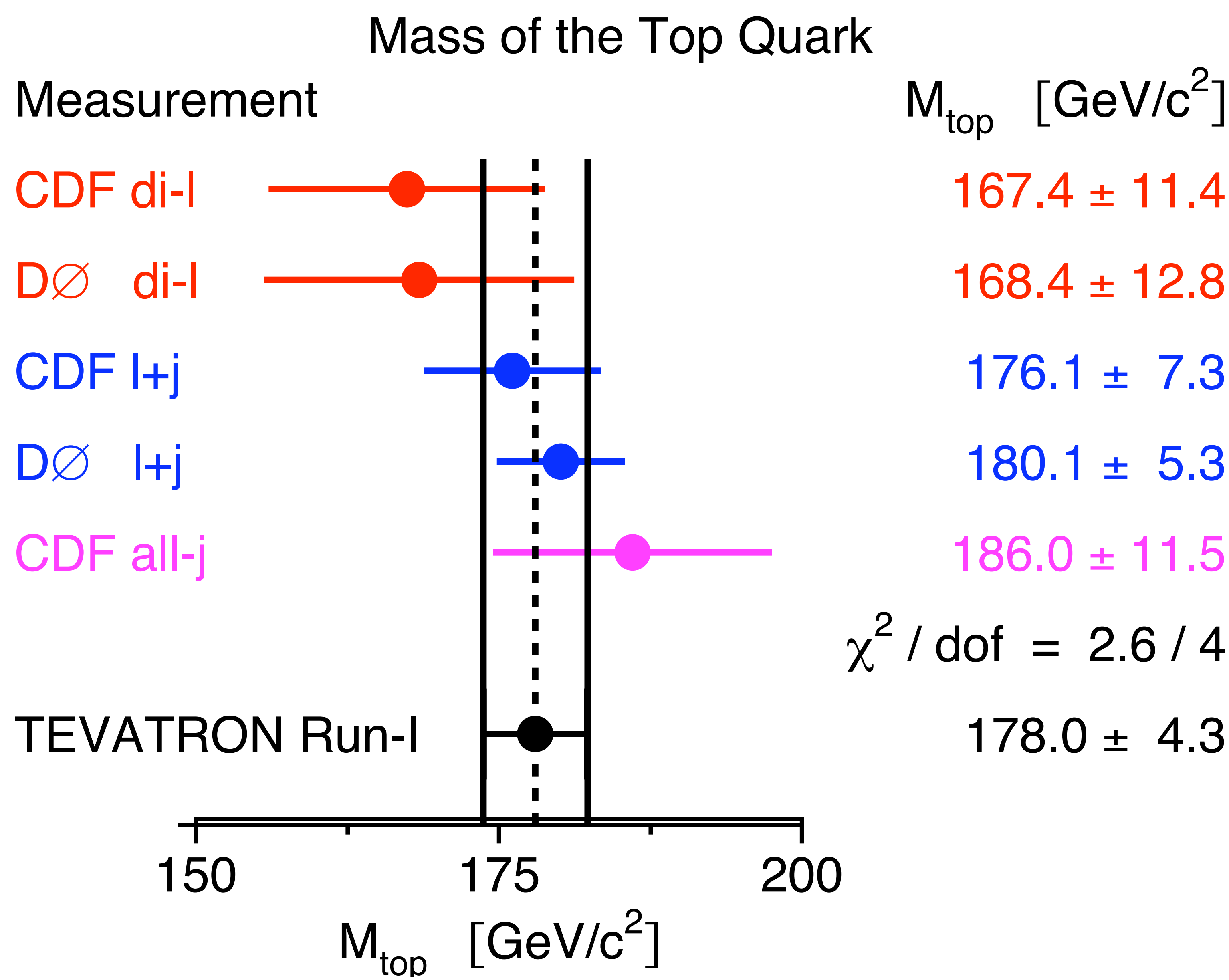
$m_t = 180.1 \pm 3.6 \pm 3.9$ GeV

New CDF Run II top mass

$m_t = 177.5^{+12.7}_{-9.4} \pm 7.1(\ell + \text{jets})$

$m_t = 175.0^{+17.4}_{-16.9} \pm 7.9(\ell\ell)$

Not yet included...



NEW average:

$m_t = 178.0 \pm 4.3$ GeV

W mass from Tevatron

Run I results final

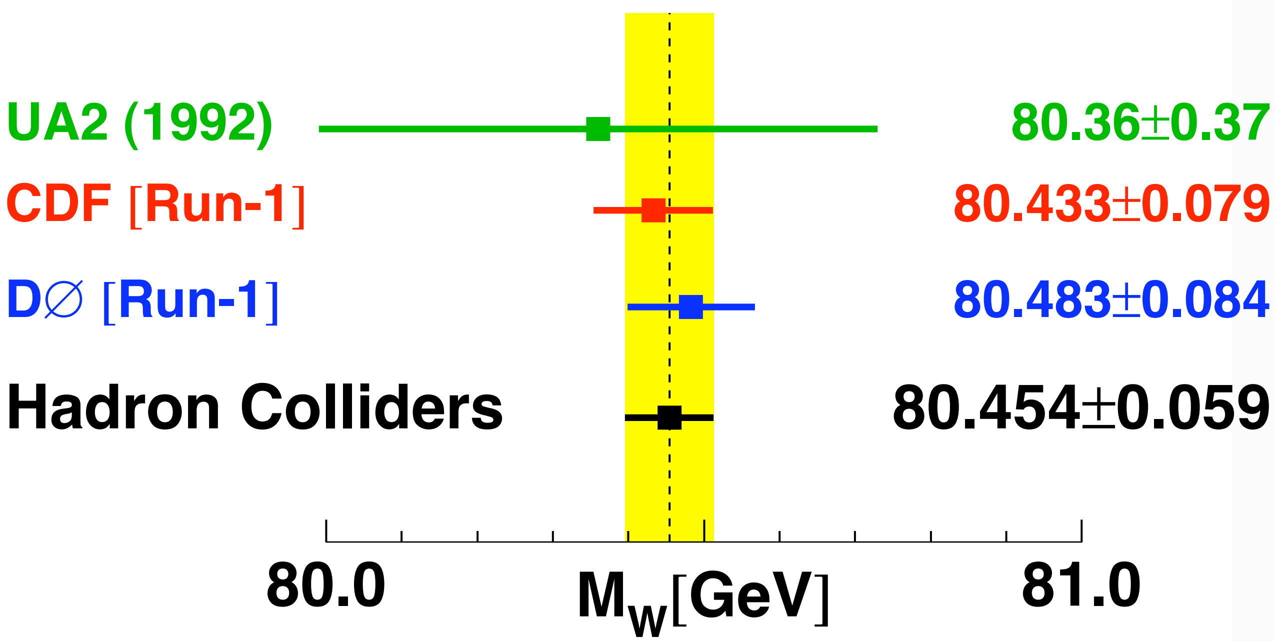
CDF/DØ fit transverse mass (Jacobian)

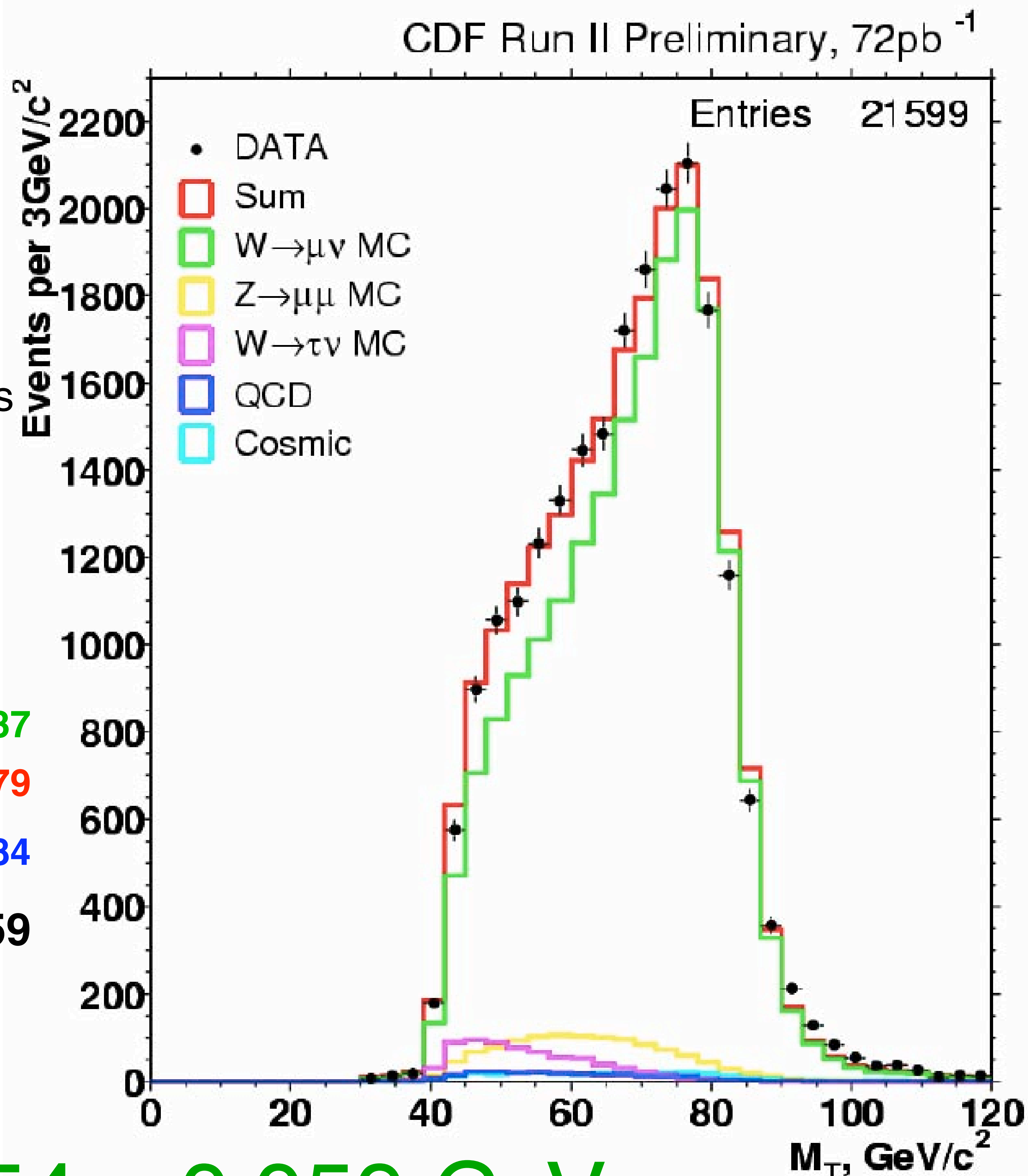
Systematics will come down with increased statistics:

- Energy scale controlled by Z events
- Hadronic recoil also constrained by Z events

CDF expect with 250 pb^{-1} with just μ channel

$$m_W = X \pm 55 \pm 80 \text{ MeV}$$





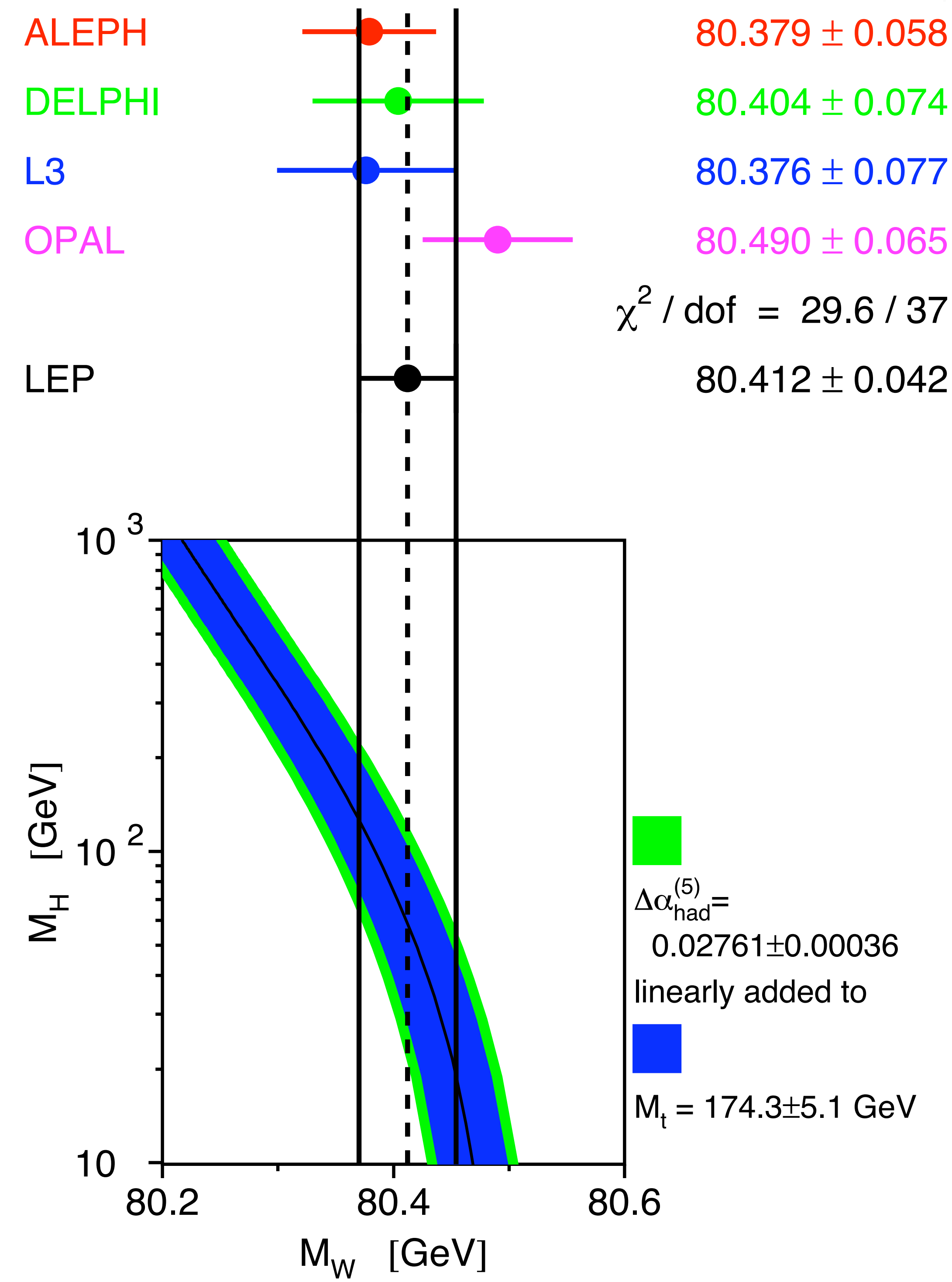
$$m_W = 80.454 \pm 0.059 \text{ GeV}$$

W mass from LEP

All results still preliminary!

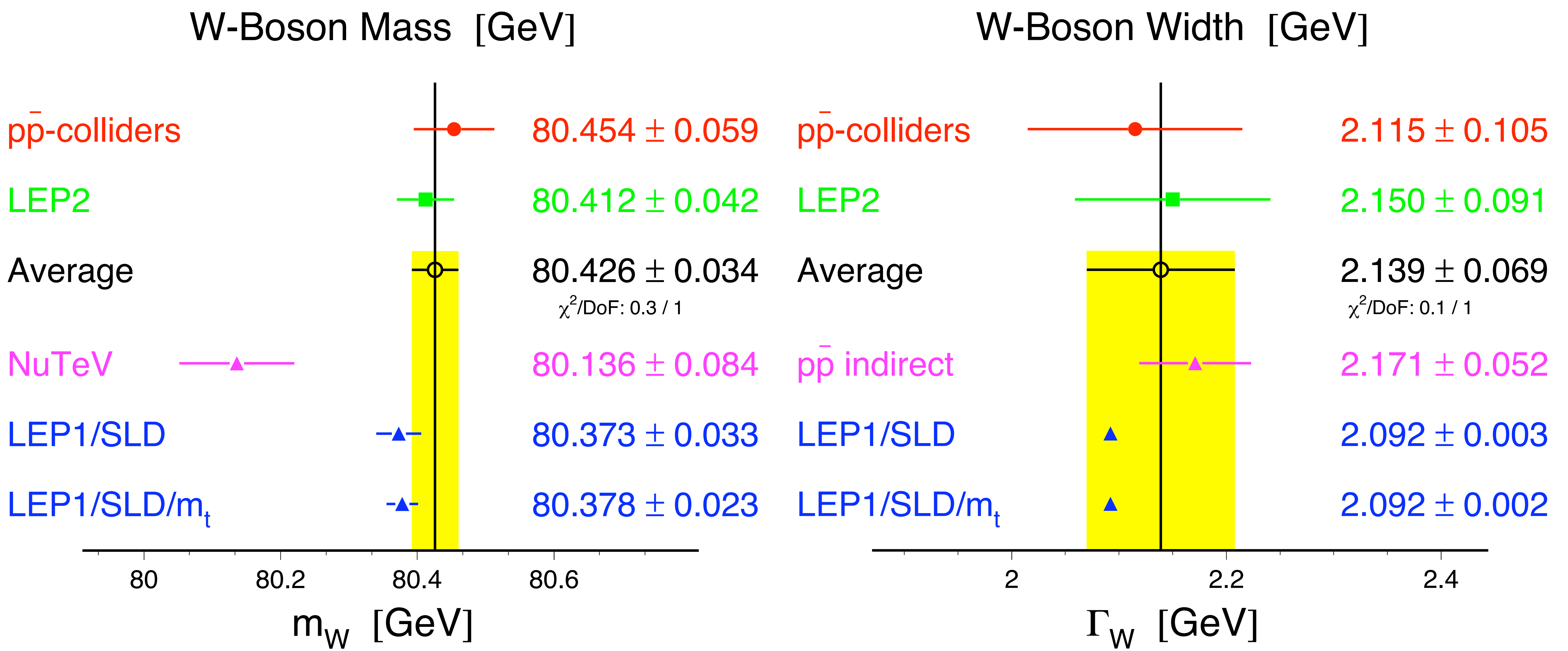
Still possible to improve; currently 4 quark final states have a low weight due to systematic errors from color reconnection and Bose-Einstein correlations. Studies on-going.

Cross-check between qqqq and $qq\ell\nu$: $\Delta m_W = +22 \pm 43$ MeV



$$m_W = 80.412 \pm 0.029(\text{stat}) \pm 0.031(\text{sys})\ \text{GeV}$$

World average W mass and width



$$m_W = 80.426 \pm 0.034 \text{ GeV}; \;\; \Gamma_W = 2.139 \pm 0.069 \text{ GeV}$$

NuTeV results

Paschos-Wolfenstein: CC and NC rates for ν_μ and $\bar{\nu}_\mu$ related to $\sin^2\theta_W$

$$R^- = \frac{\sigma_{NC}^{\nu} - \sigma_{NC}^{\bar{\nu}}}{\sigma_{CC}^{\nu} - \sigma_{CC}^{\bar{\nu}}} = \rho^2 \left(\frac{1}{2} - \sin^2\theta_W \right)$$

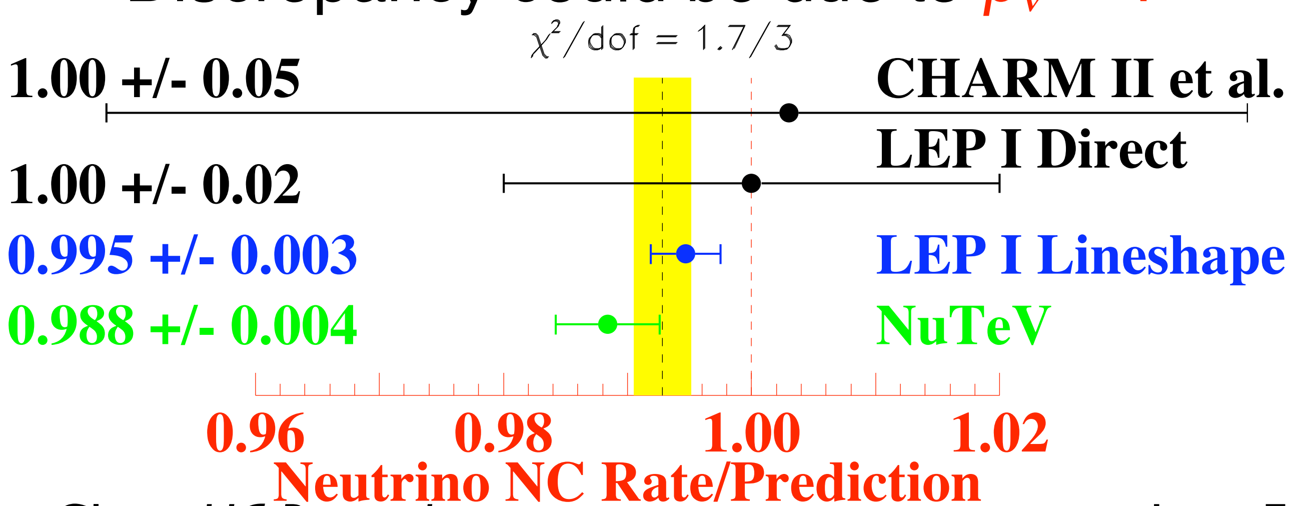
NuTeV actually measures R^ν and $R^{\bar{\nu}}$. Discrepancy from R^ν.

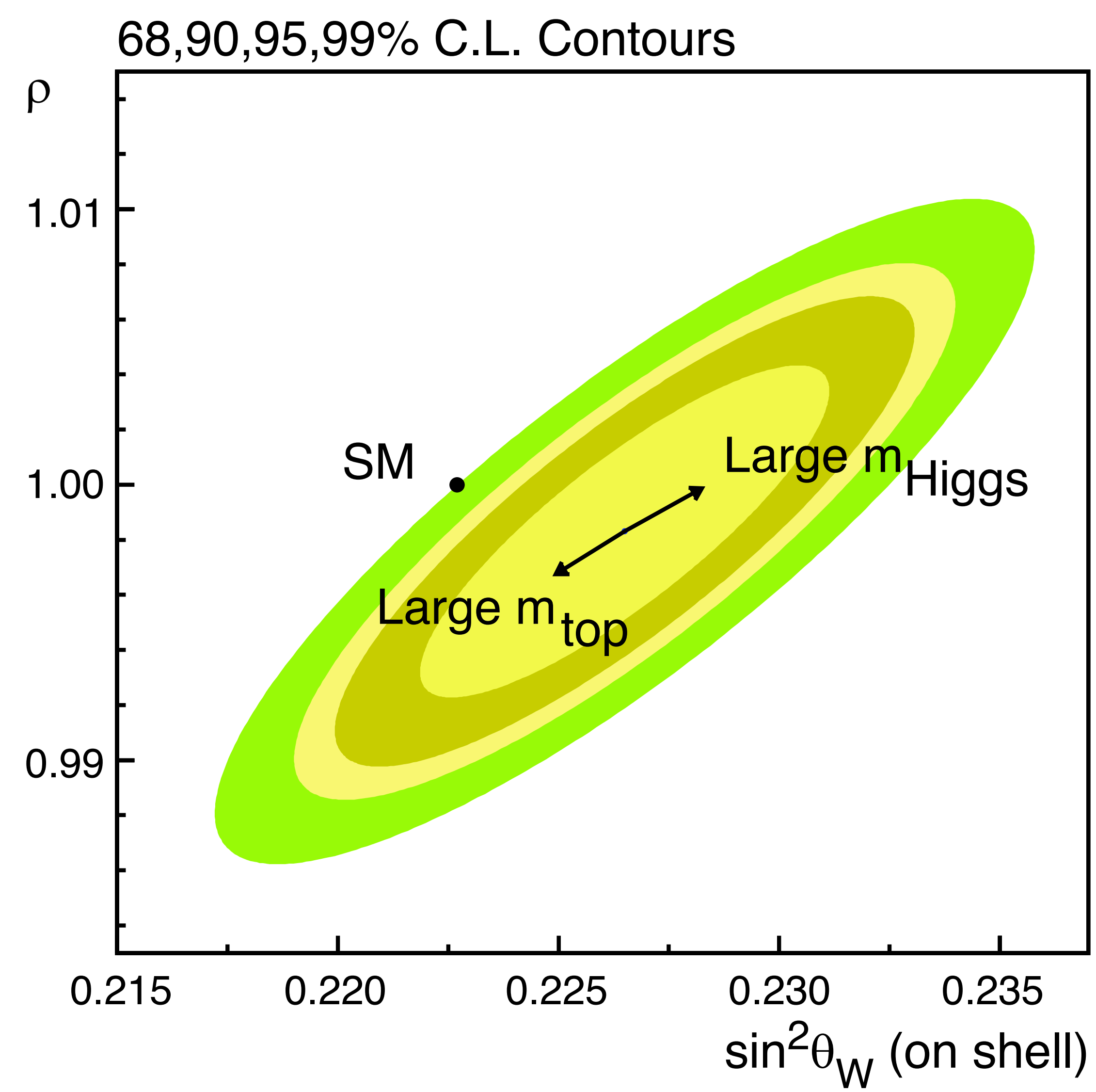
$\sin^2\theta_W = 0.22773 \pm 0.00135(\text{stat.}) \pm 0.00093(\text{sys.})$; Δ_{SM} 3.0

No explanation forth-coming:

- Experimental effects such as ν_e contamination
- PDFs, non-isoscalar contributions
- Strange sea asymmetry (although the debate is ongoing...)
- Higher order EW corrections?

Discrepancy could be due to $\rho_\nu \neq 1$





Atomic parity violation

Weak charge of the Cesium nucleus:

$$Q_W = -2\,[C_{1u}(2Z+N) + C_{1d}(Z+2N)] \text{ with } C_{1q} = 2g_{Ae}g_{Vq},\ e.g.$$

$$C_{1u} = \rho\left[-\tfrac{1}{2} + \tfrac{4}{3}\sin^2\theta_W\right], \quad C_{1d} = \rho\left[\tfrac{1}{2} - \tfrac{2}{3}\sin^2\theta_W\right]$$

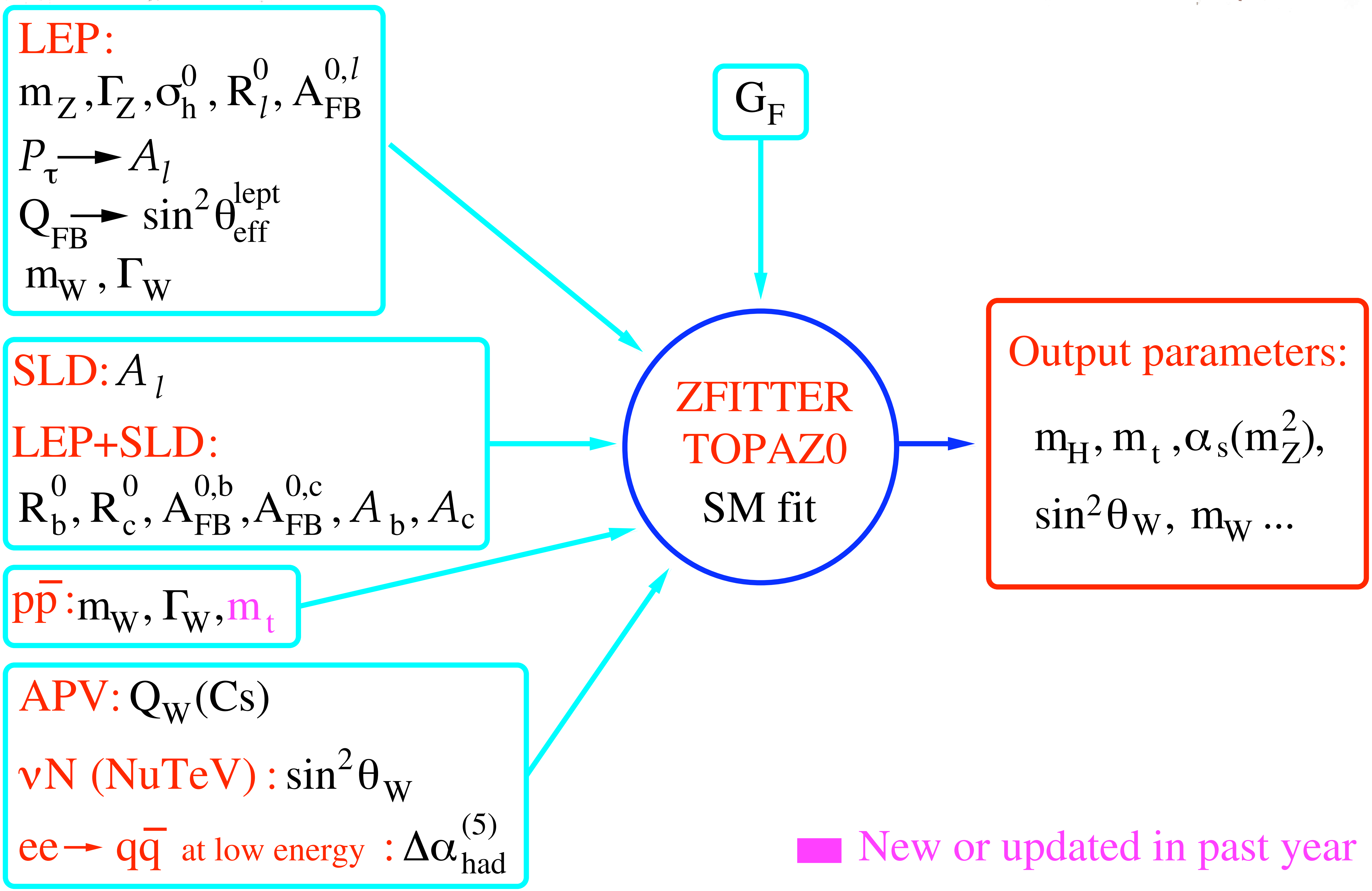
- Measure the amplitude of the parity-violating transition 6S-7S in Ce 133, possible due to the S-P mixing induced by neutral currents. Precise measurement performed by Wood, et al. (Science **275**, 1759 (1997)).
- Transition amplitude + Cesium atomic structure ⇒ Q_W(Cs), predicted by the SM
- At one time, difference between experiment and SM 2σ
- "... an intriguing zigzag road of research ..." found many small corrections that cancel
- Updated estimate, included in global fit

Kuchiev & Flambaum, hep-ph/0305053

$$Q_W(\mathrm{Cs}) = -72.84 \pm 0.29(\mathrm{exp}) \pm 0.36(\mathrm{th})$$

$$Q_W(\mathrm{Cs})^{SM} = -72.90$$

Strategy of the global fit



The global electroweak fit

- Based on predictions from ZFITTER and TOPAZ0
- Fit up to 20 parameters
- Output estimates for: m_t, m_H, $\alpha_s(m_Z^2)$, $\Delta\alpha_{had}^{(5)}$, m_Z
- Fit repeated with and without NuTeV, to evaluate its contribution...

	Z pole	All but NuTeV	All data
m_t (GeV)	$171.5^{+11.9}_{-9.4}$	$175.3^{+4.4}_{-4.3}$	$174.3^{+4.5}_{-4.4}$
m_H (GeV)	89^{+122}_{-45}	91^{+55}_{-36}	96^{+60}_{-38}
$\alpha_s(m_Z^2)$	0.1187 ± 0.0027	0.1185 ± 0.0027	0.1186 ± 0.0027
m_W (GeV)	80.373 ± 0.033	80.394 ± 0.019	80.385 ± 0.019
$\sin^2\theta_{eff}^{lept}$	0.23147 ± 0.00016	0.23138 ± 0.00014	0.23143 ± 0.00014
$\sin^2\theta_W$	0.22313 ± 0.00064	0.22272 ± 0.00036	0.22289 ± 0.00036
χ^2/d.o.f.	14.7/10	16.7/14	25.4/15
probab. (%)	14.3	27.5	4.5

Slightly old numbers

The global electroweak fit

Largest contributions to χ^2 from

$A_{FB}^{0,b}$

$\mathcal{A}_\ell$ (from SLD)

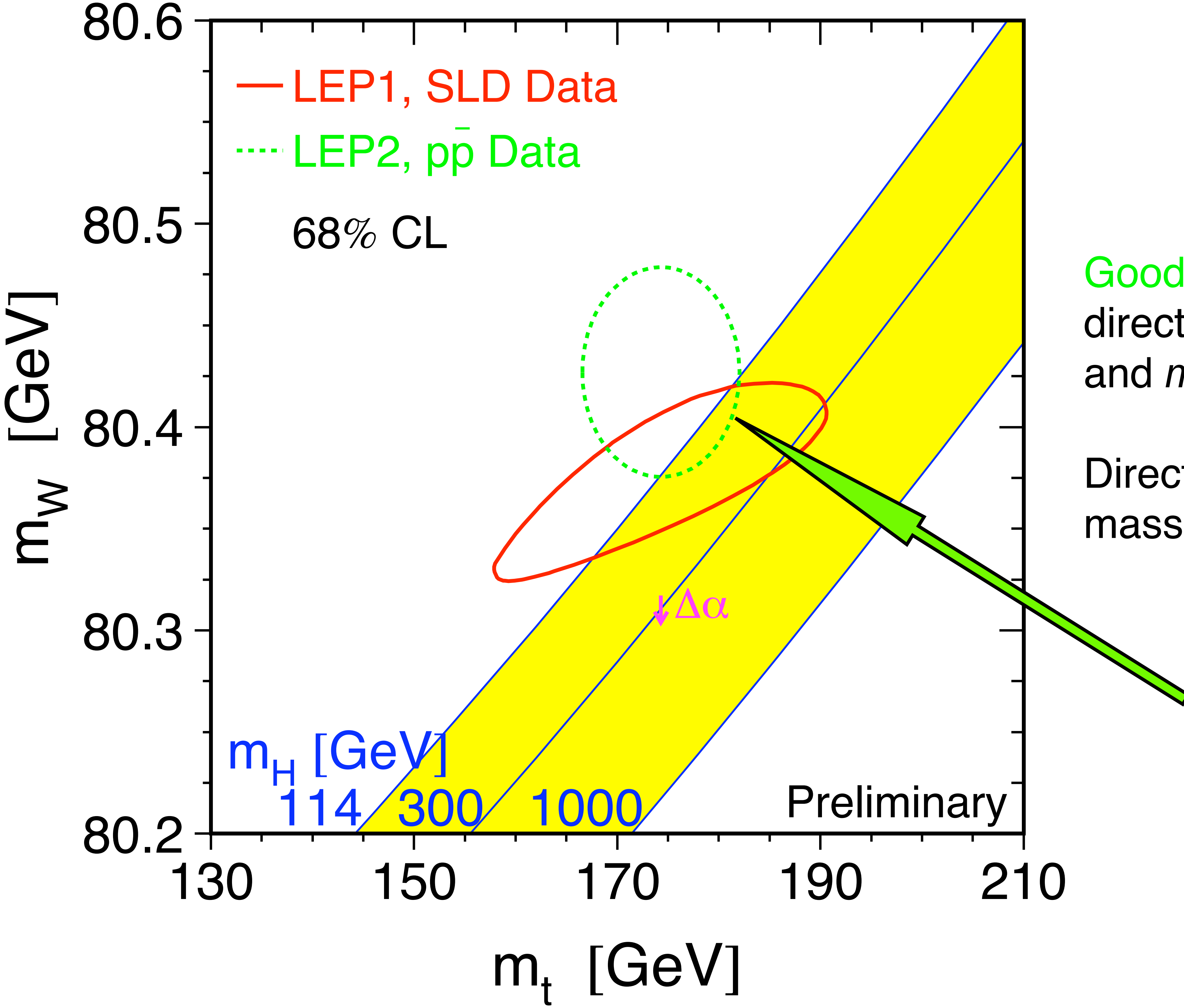
NuTeV

	Measurement	Fit
$\Delta\alpha_{had}^{(5)}(m_Z)$	0.02761 ± 0.00036	0.02767
m_Z [GeV]	91.1875 ± 0.0021	91.1875
Γ_Z [GeV]	2.4952 ± 0.0023	2.4960
σ_{had}^0 [nb]	41.540 ± 0.037	41.478
R_l	20.767 ± 0.025	20.742
$A_{fb}^{0,l}$	0.01714 ± 0.00095	0.01636
$A_l(P_\tau)$	0.1465 ± 0.0032	0.1477
R_b	0.21638 ± 0.00066	0.21579
R_c	0.1720 ± 0.0030	0.1723
$A_{fb}^{0,b}$	0.0997 ± 0.0016	0.1036
$A_{fb}^{0,c}$	0.0706 ± 0.0035	0.0740
A_b	0.925 ± 0.020	0.935
A_c	0.670 ± 0.026	0.668
A_l(SLD)	0.1513 ± 0.0021	0.1477
$\sin^2\theta_{eff}^{lept}(Q_{fb})$	0.2324 ± 0.0012	0.2314
m_W [GeV]	80.426 ± 0.034	80.385
Γ_W [GeV]	2.139 ± 0.069	2.093
m_t [GeV]	174.3 ± 5.1	174.3
$\sin^2\theta_W(\nu N)$	0.2277 ± 0.0016	0.2229
$Q_W(Cs)$	-72.84 ± 0.46	-72.90

Slightly old numbers

$A_{FB}^{0,b}$ and $\mathcal{A}_\ell$ pull in opposite directions (concerning effects on m_H)

The global fit: m_W, m_t, m_H

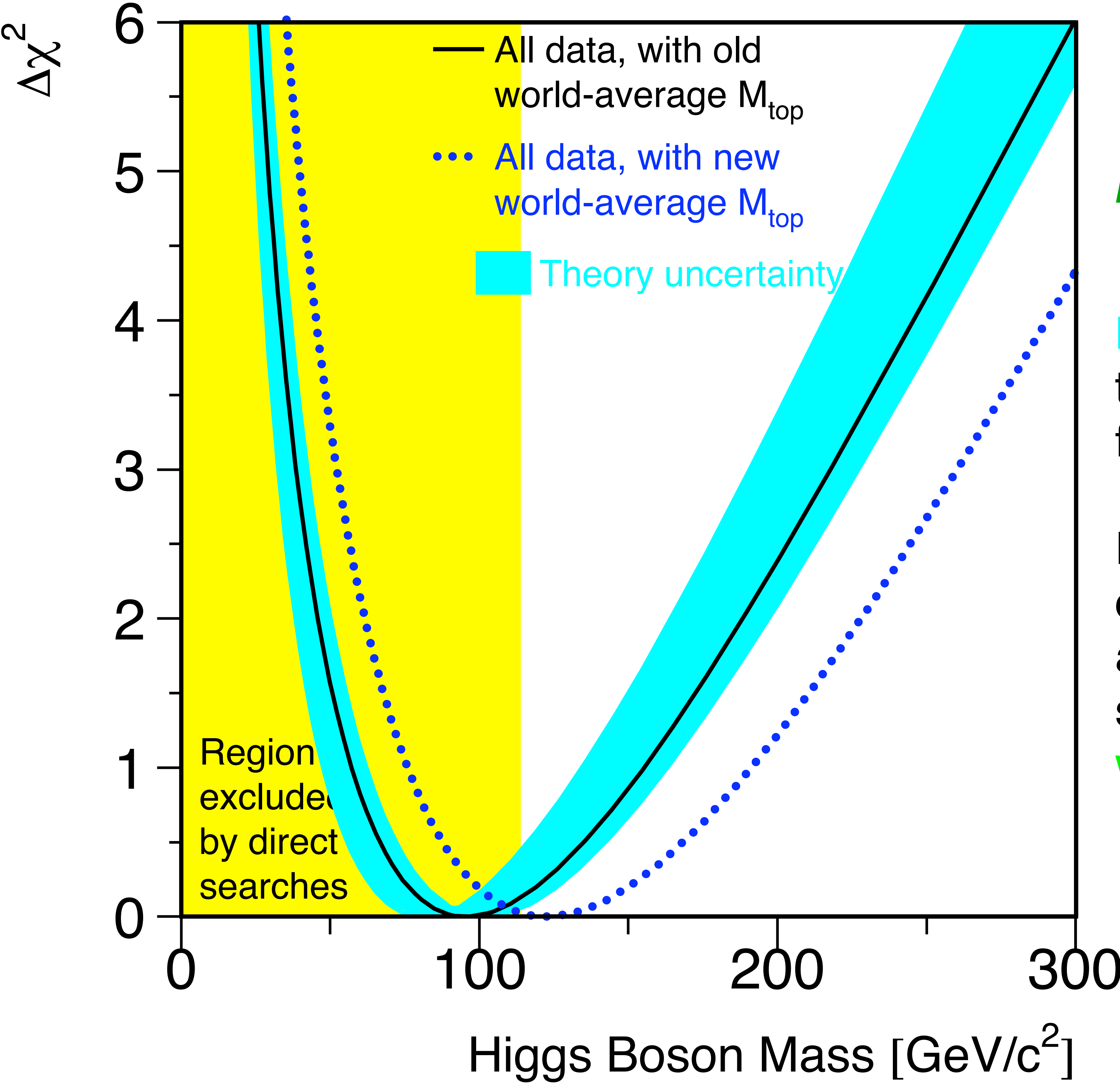


Good consistency between direct and indirect (Z pole) m_W and m_t values.

Direct m_W,m_t prefer low Higgs mass (as does $\mathcal{A}_\ell$)

This should be moved over just a bit

The global fit: limits on the Higgs mass



$m_H < 251$ GeV

Blue band width is estimate of theoretical uncertainties coming from higher order effects

Possibly overestimated as two-loop contributions to m_W (Weiglein, et al.) might be partially canceled by similar contributions to Z partial widths and $\sin^2\theta_{eff}^{lept}$

(Finally an updated plot!)

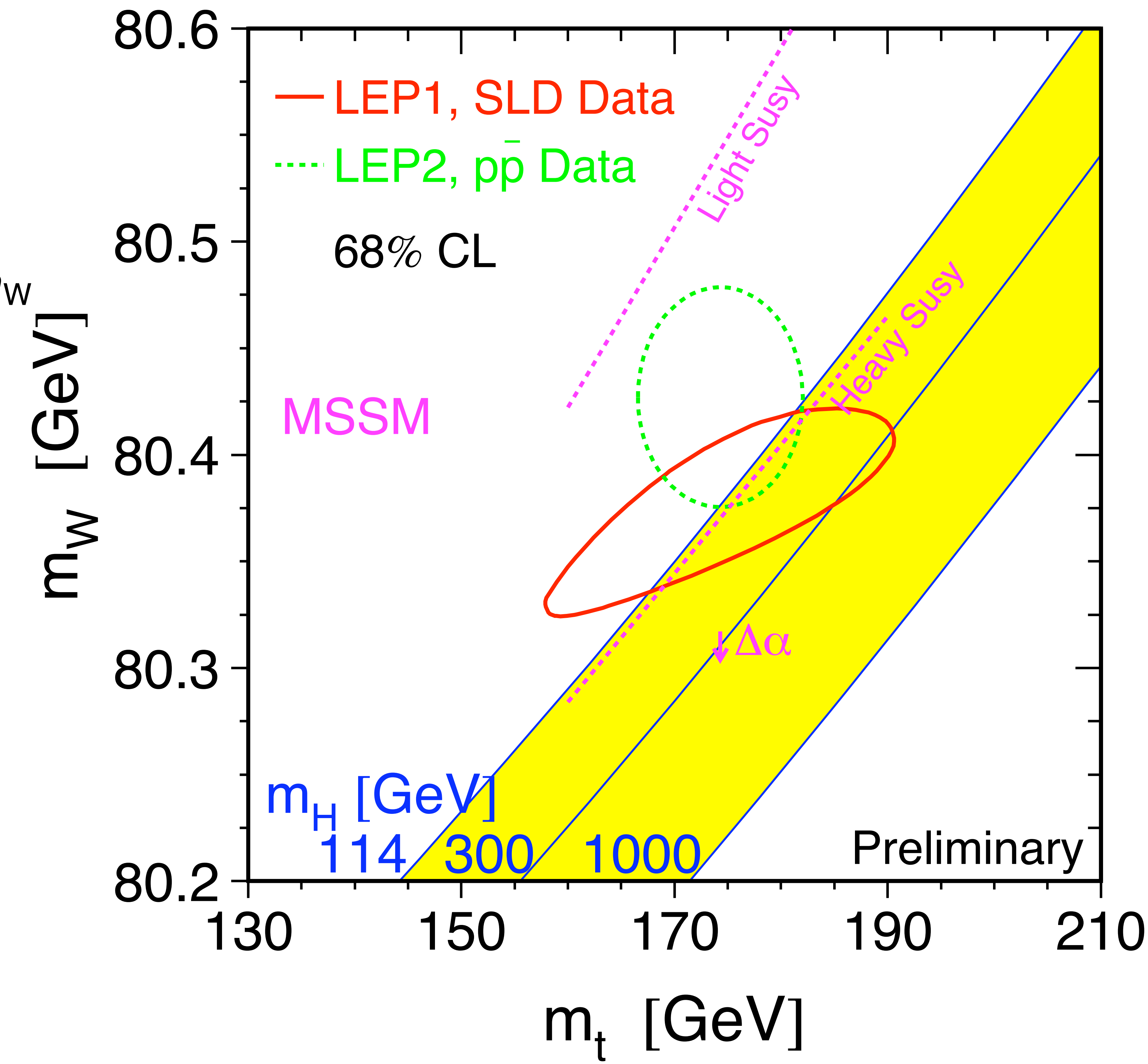
Beyond the SM – the MSSM

In the SM, the Higgs mass is a free parameter, and m_t and m_W can be related to it.

In the MSSM, the Higgs mass is no longer free. m_H, m_t, and m_W depend on the SUSY parameters.

Unfortunatly, **they** are free!

MSSM seems to be a bit more compatible with the data...



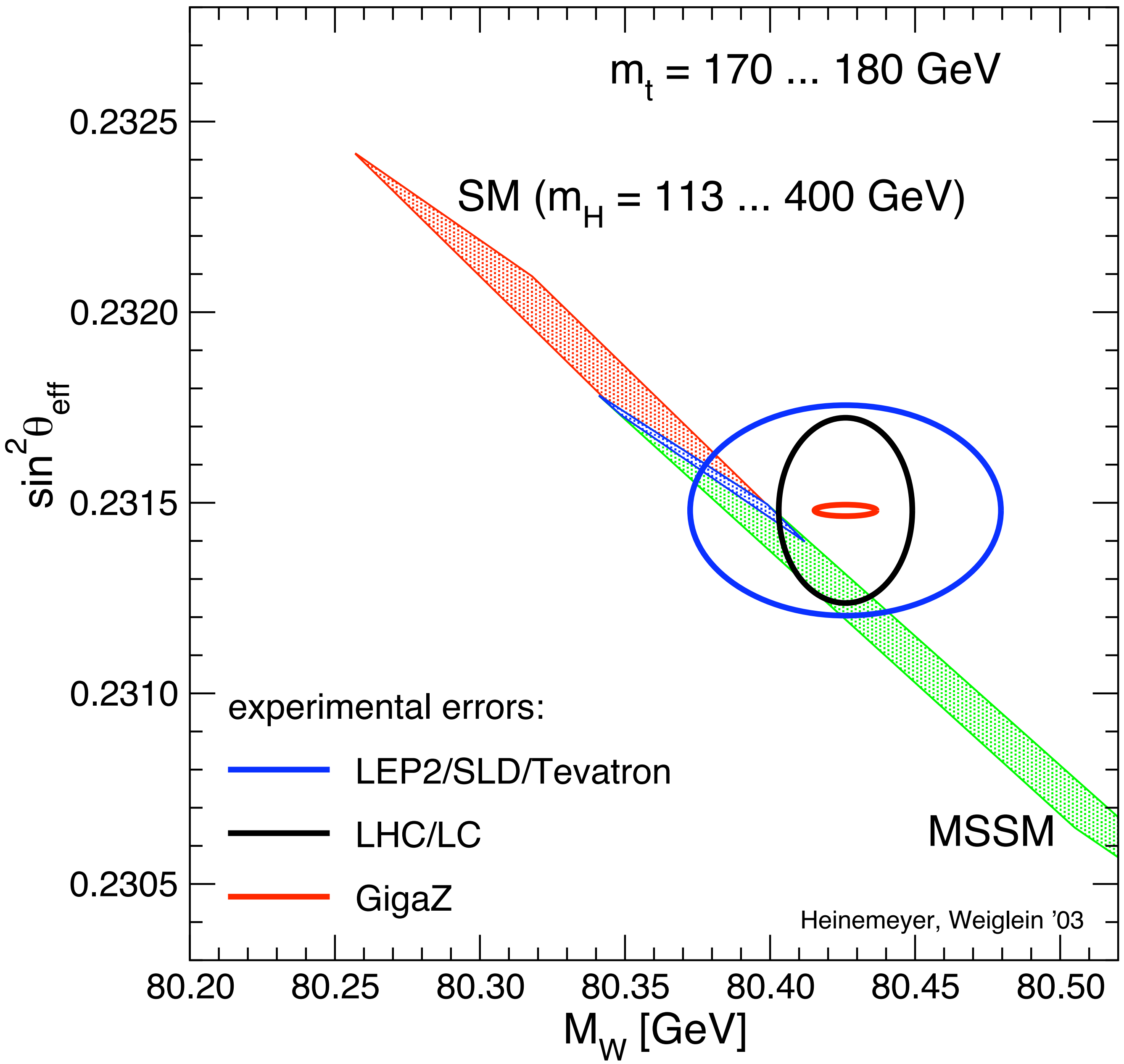
MSSM: Heinemeyer, Weiglein, hep-ph/0307177

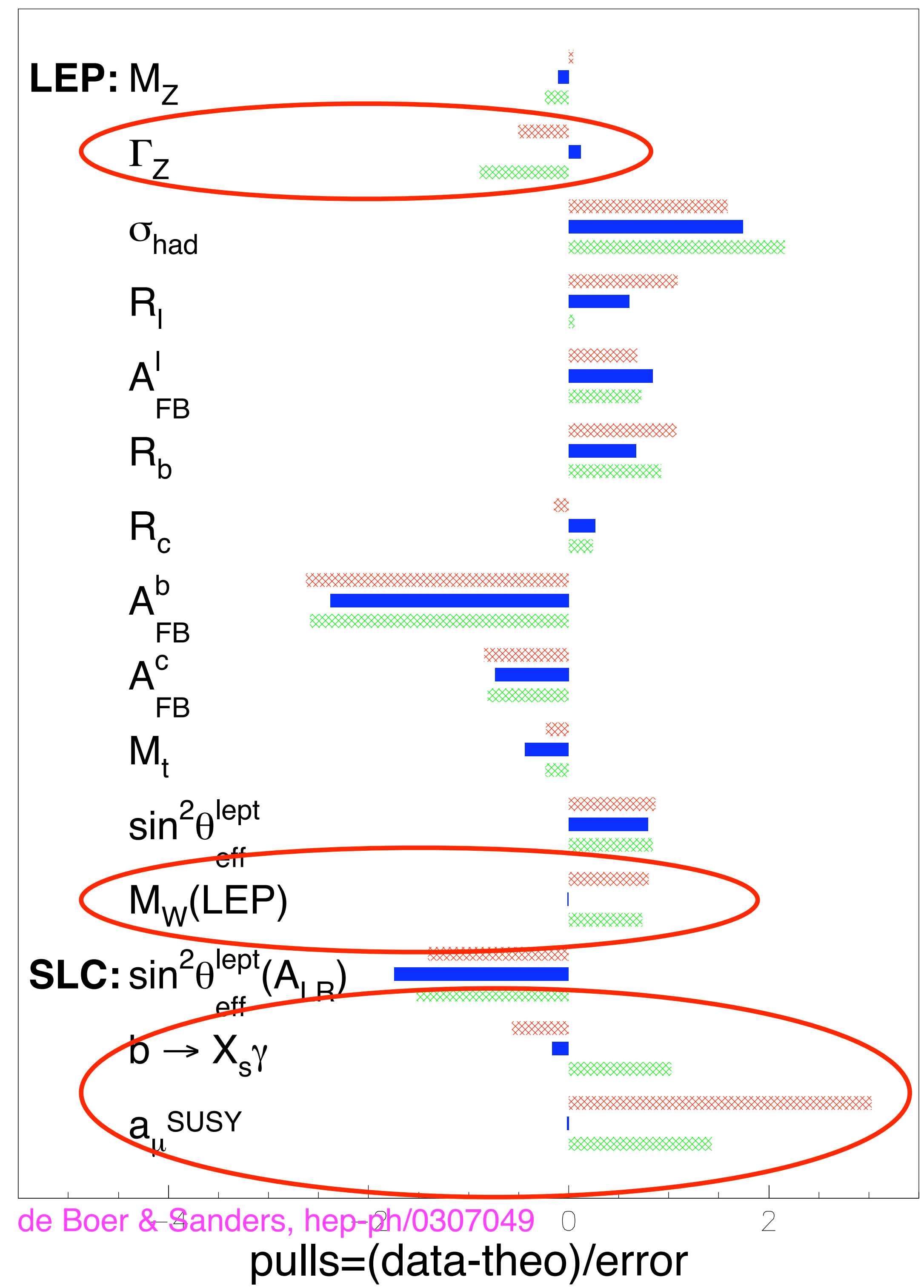
Beyond the SM – the MSSM

SM: χ^2/d.o.f = 27.2/16

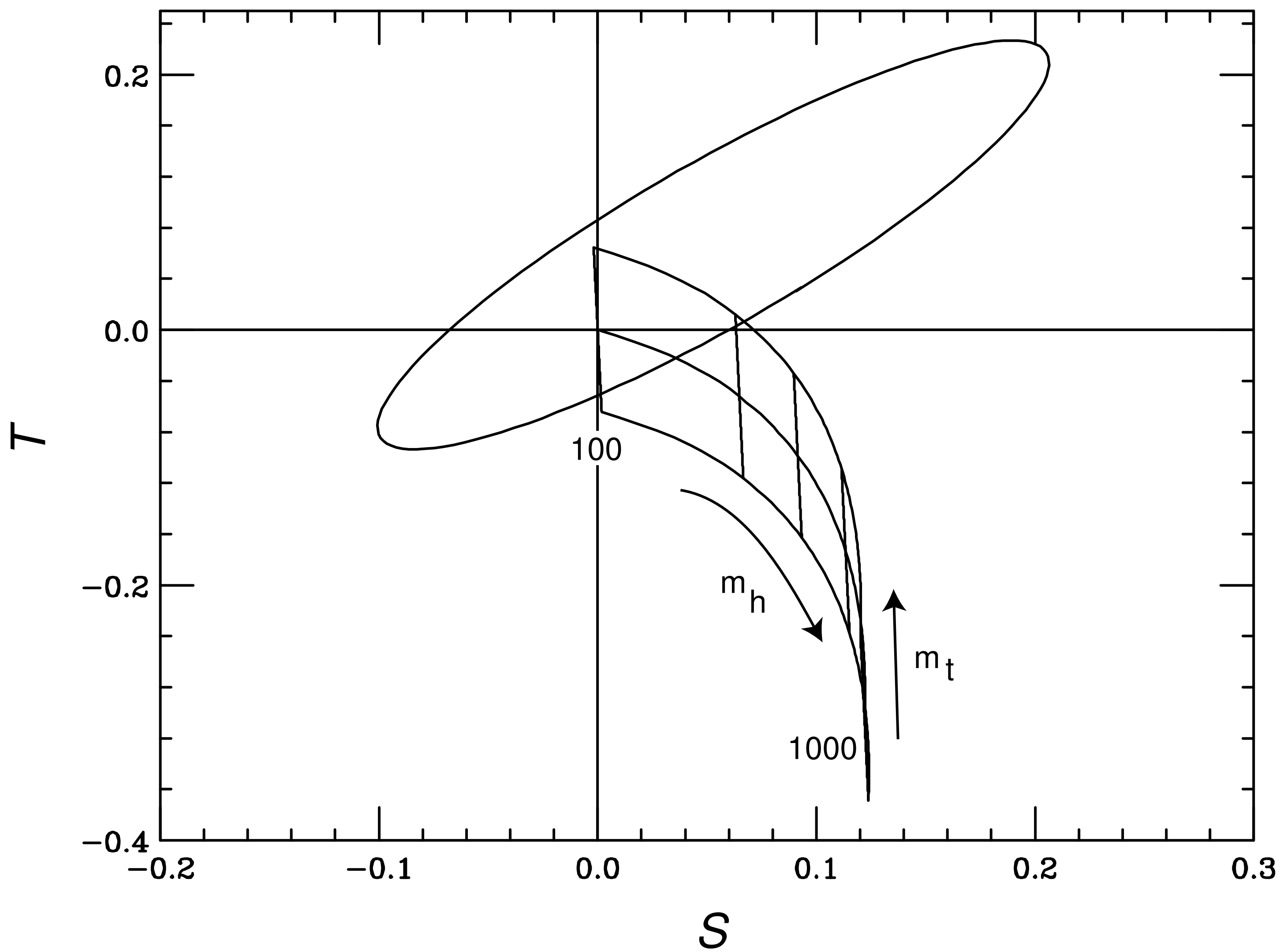
MSSM: χ^2/d.o.f = 16.4/12

CMSSM: χ^2/d.o.f = 23.2/16





Treading on thin ice ... must m_H be small?



Peskin & Wells, PR D64 (2001) 093003

To accomodate a heavy Higgs, need a new theory which contributes either $+\Delta T$ or $-\Delta S$ (or both).

- Some Technicolor models contribute negative S (eg, Luty & Sundrum, hep-ph/9209255)
- An appropriately chosen Z' can move (S,T) in almost any direction, but must be light (< 2 TeV).
- "topcolor seesaw" (eg Dobrescu & Hill, PRL 81, 2634 (1998)) gives $+\Delta T$
- An additional generation of quarks and leptons (He, et al. PL B496, 195 (2000)) can generate $+\Delta T$ (also $+\Delta S$, but that could currently be OK)
- ...

Beyond the Current Experiments

	now	Run IIA	Run IIB	Run IIB*	LHC	LC	GigaZ
$\delta \sin^2\theta_{\rm eff}^{\rm lept} (\times 10^5)$	17	78	29	20	14–20	(6)	1.3
$\delta m_{\rm W}$ [MeV]	33	27	16	12	15	10	7
$\delta m_{\rm t}$ [GeV]	5.1	2.7	1.4	1.3	1.0	0.2	0.13
$\delta m_{\rm H}$ [MeV]	—	—	$\mathcal{O}(2000)$		100	50	50

U.Baur, et al., Snowmass 2001, hep-ph/0111314

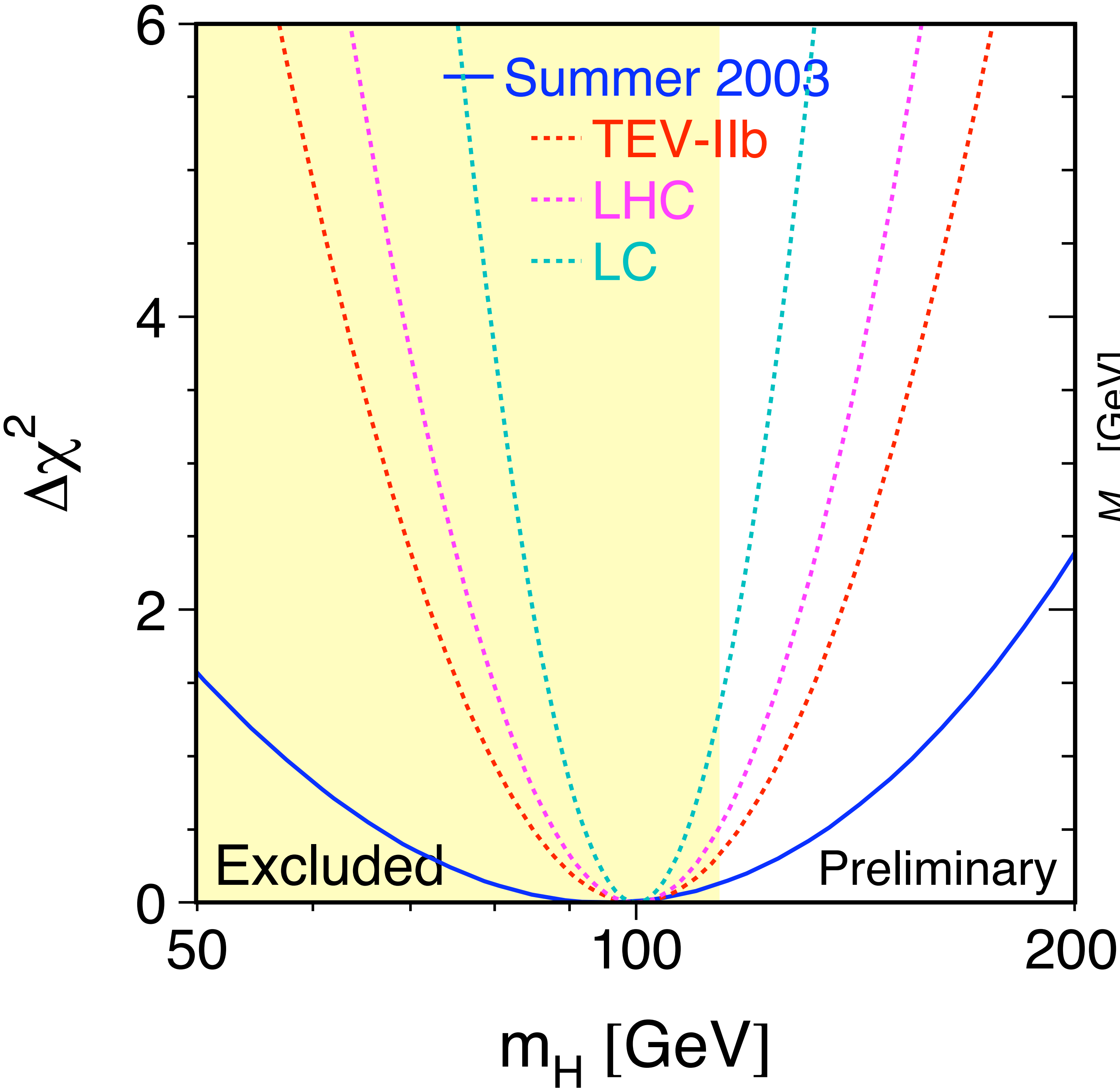
Near future (Run II, LHC):

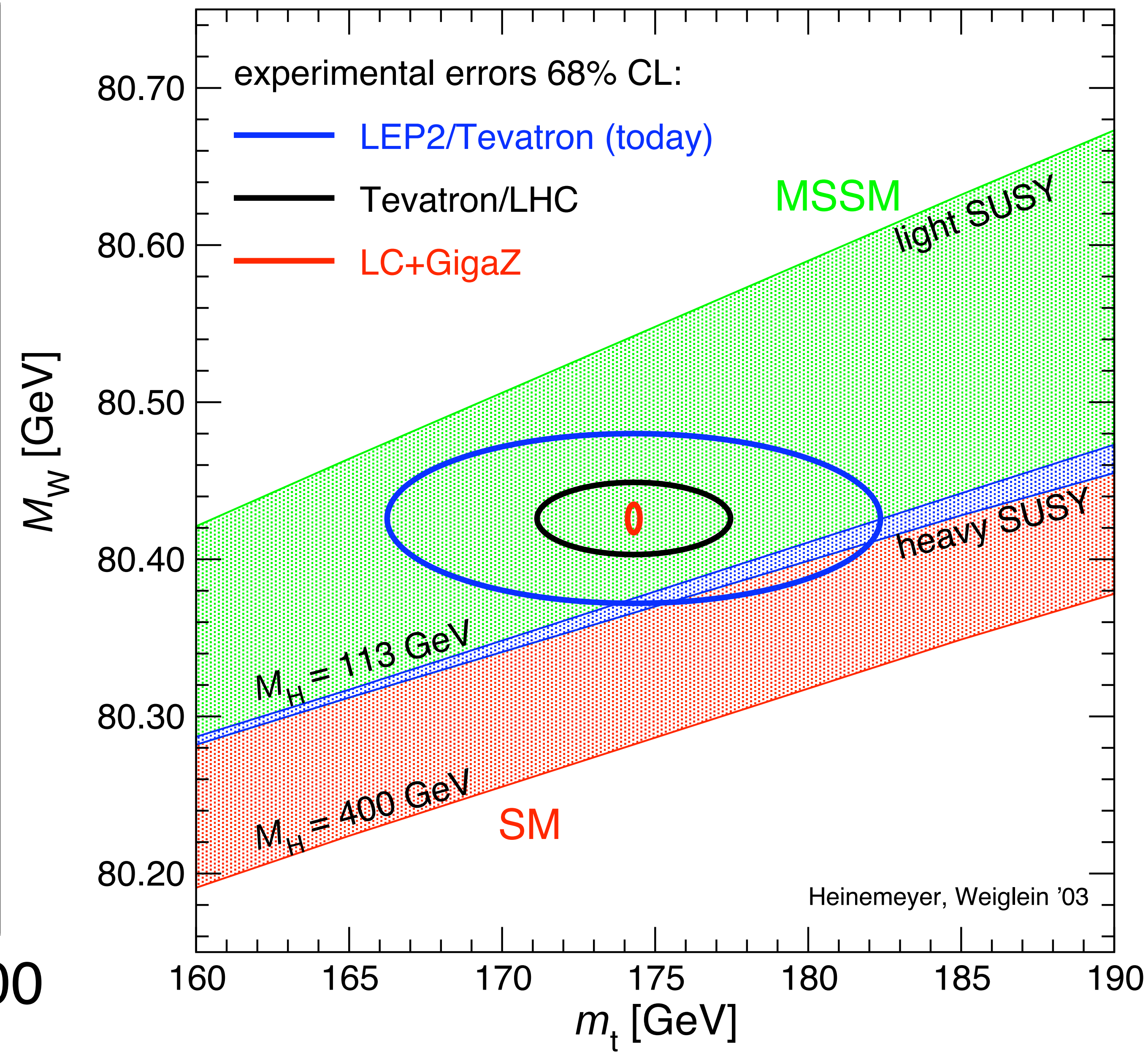
- $\delta m_{\rm W}$ = 15 MeV
- $\delta m_{\rm t}$ = 1.5 GeV
- $\delta \Delta\alpha_{\rm had}$ = 0.0002

Far future (LC, GigaZ):

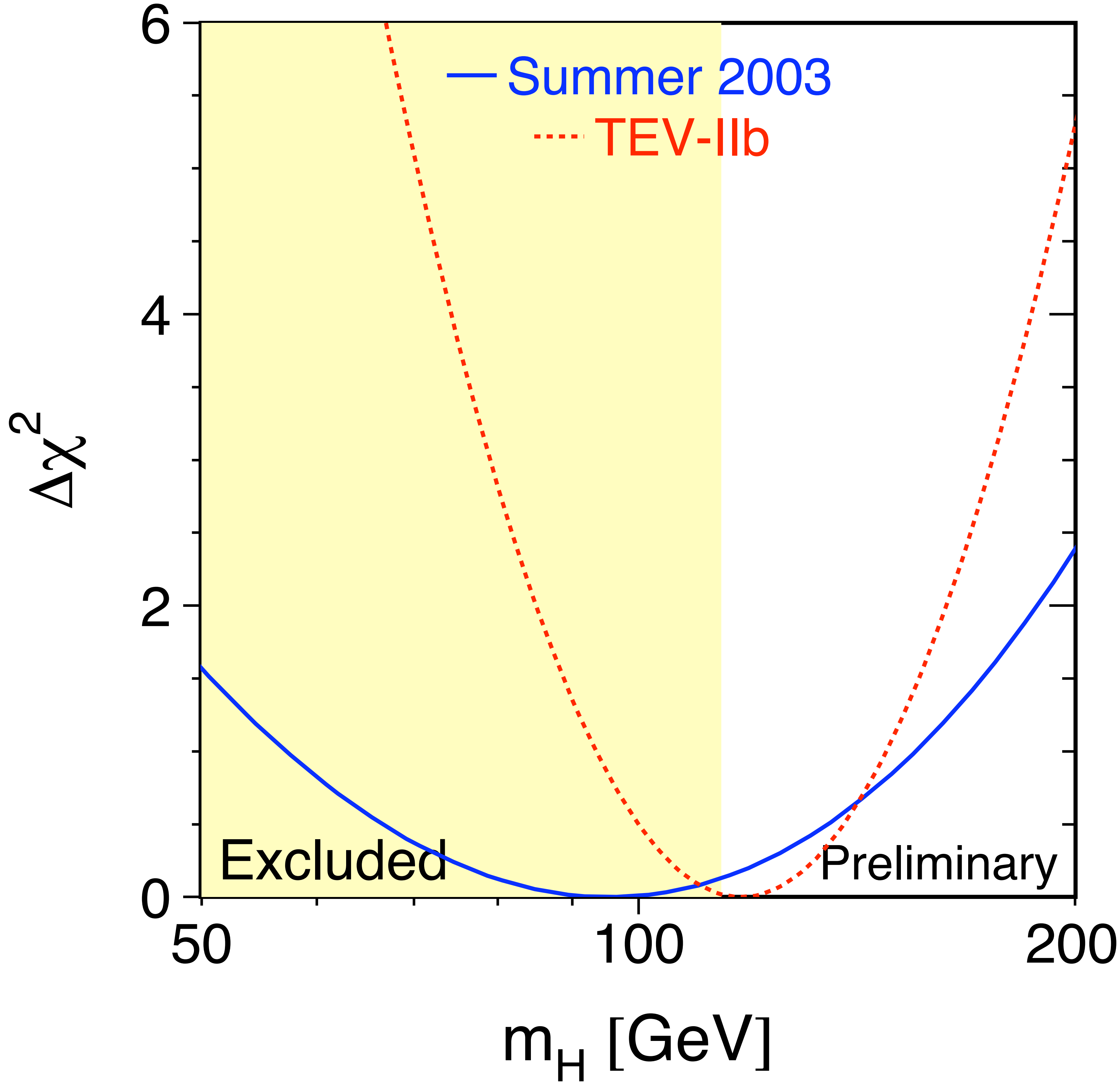
- $\delta m_{\rm W}$ = 7 MeV
- $\delta m_{\rm t}$ = 130 MeV
- $\delta \Delta\alpha_{\rm had}$ = 0.00007
- $\delta \sin^2\theta_{\rm eff}^{\rm lept} = 1.3 \times 10^{-5}$

Beyond the Current Experiments

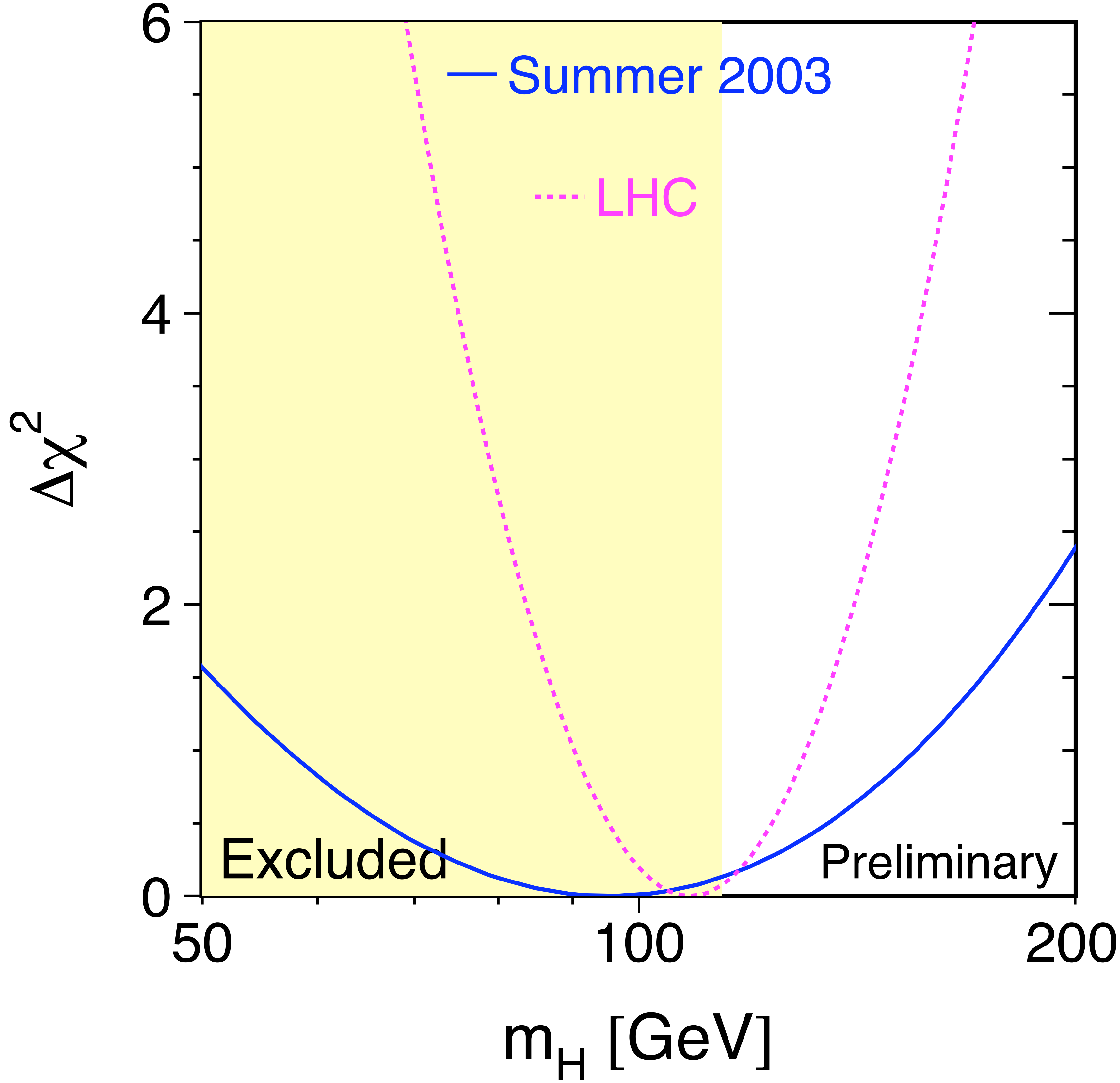




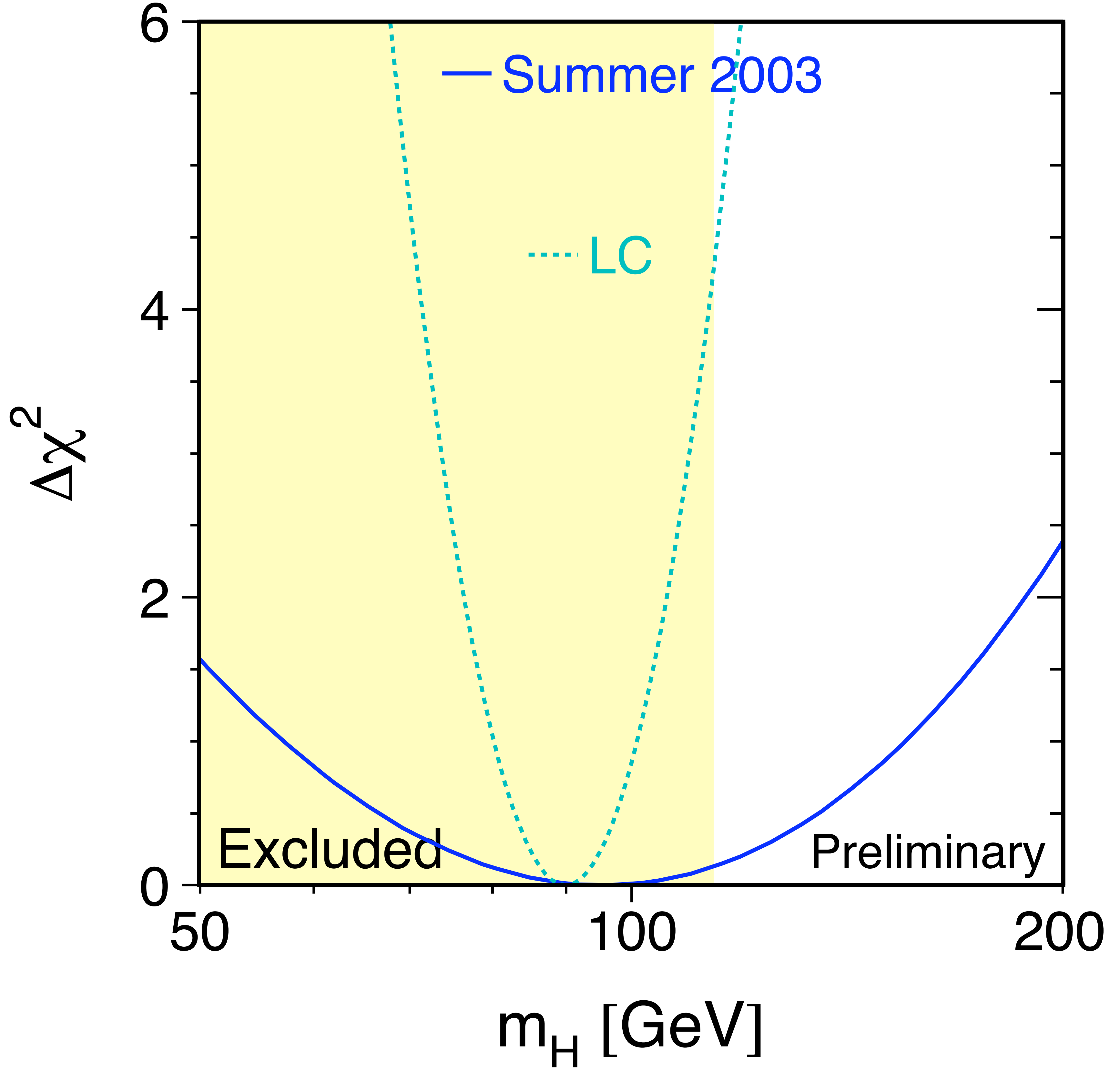
Beyond the Current Experiments



Beyond the Current Experiments



Beyond the Current Experiments



Conclusions

- The Standard Model describes with unprecedented precision a huge amount of data
- The largest discrepancies are due to the NuTeV result and to $A_{FB}^{0,b}$; interpreted as statistical fluctuations they are ≤ 3 σ
- Global fit:
-

$$m_H < 251 \text{ GeV}$$

- Future inputs:
  - Final results from LEP-II: m_W, Γ_W
  - New measurements of m_W, Γ_W, m_t as well as $\sin^2\theta_{eff}^{lept}$ from Tevatron Run II and LHC
- Far future
  - Linear Collider and GigaZ?

What will we find?