# Electroweak Data Fits

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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

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

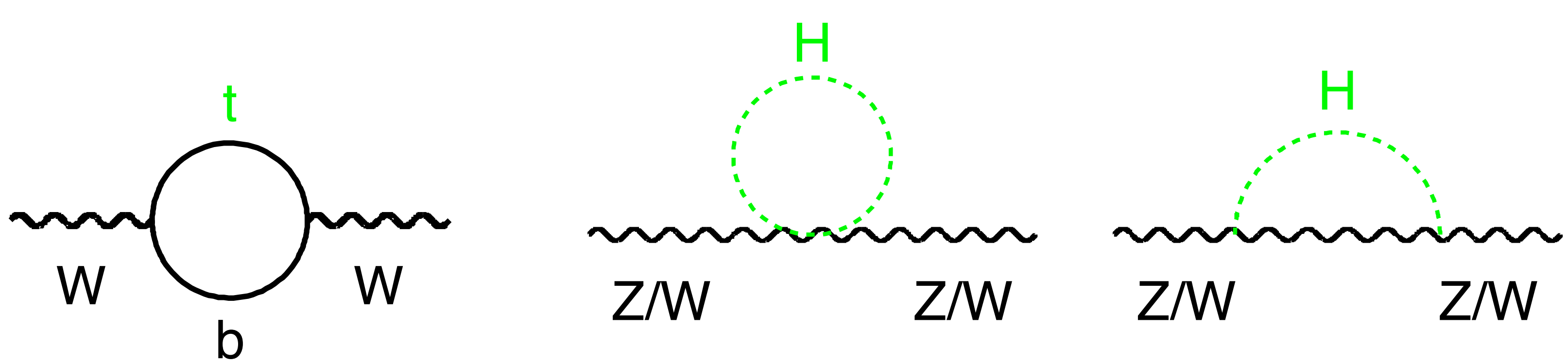
$$\sin^2\theta_W = 1 - \frac{m_W^2}{m_Z^2} \quad \Rightarrow \quad \sin^2\theta_{eff} = (1 + \Delta\kappa)\sin^2\theta_W$$

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

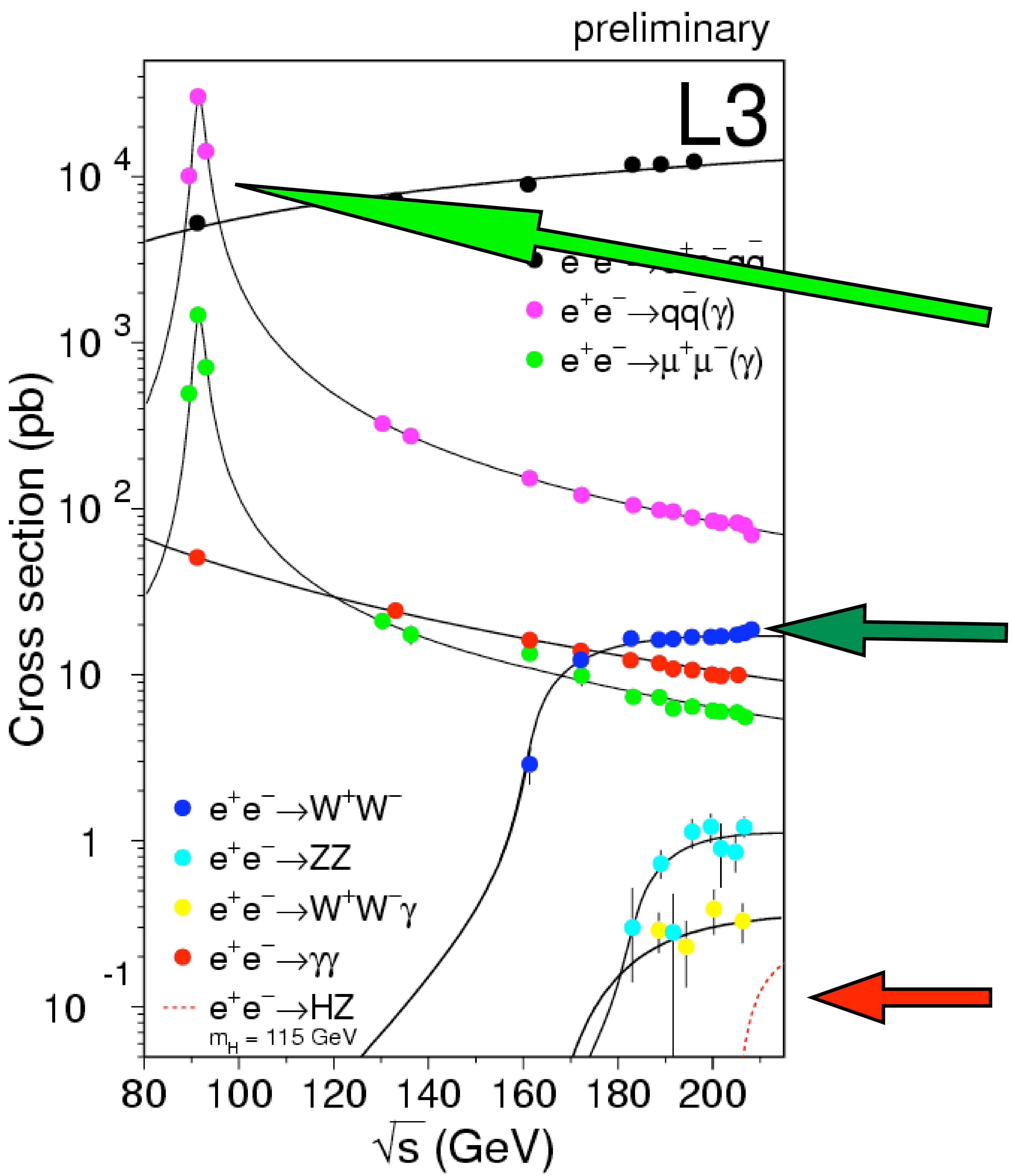
$$\alpha(0) \quad \Rightarrow \quad \alpha(m_Z^2) = \frac{\alpha(0)}{1 - \Delta\alpha}$$

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

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



# The LEP Heritage




In total, for all 4 expts:

about 16 M Z

about 35000 W

about 0 H

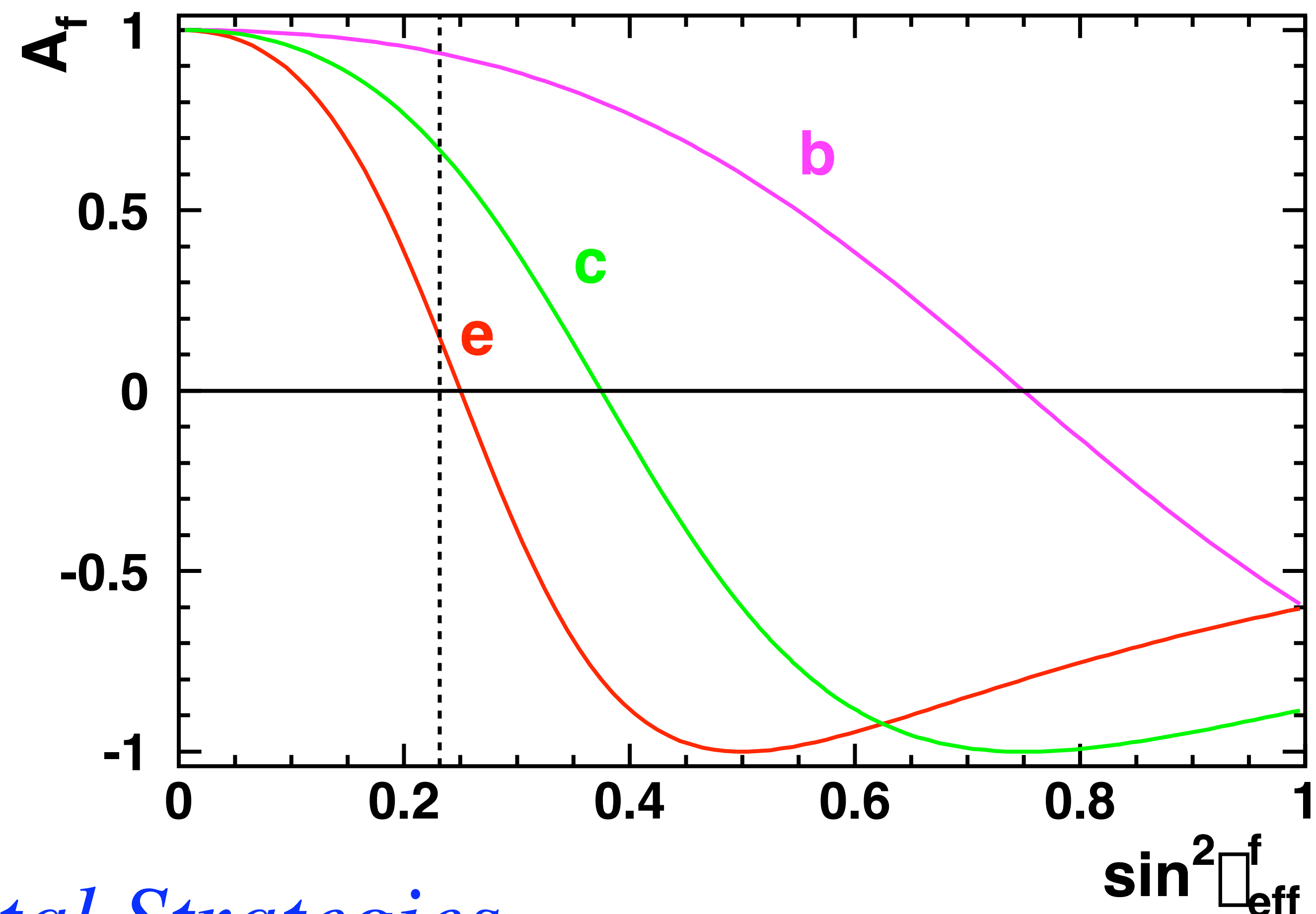
# Effective Z couplings

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

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

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

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




## *Experimental Strategies*

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

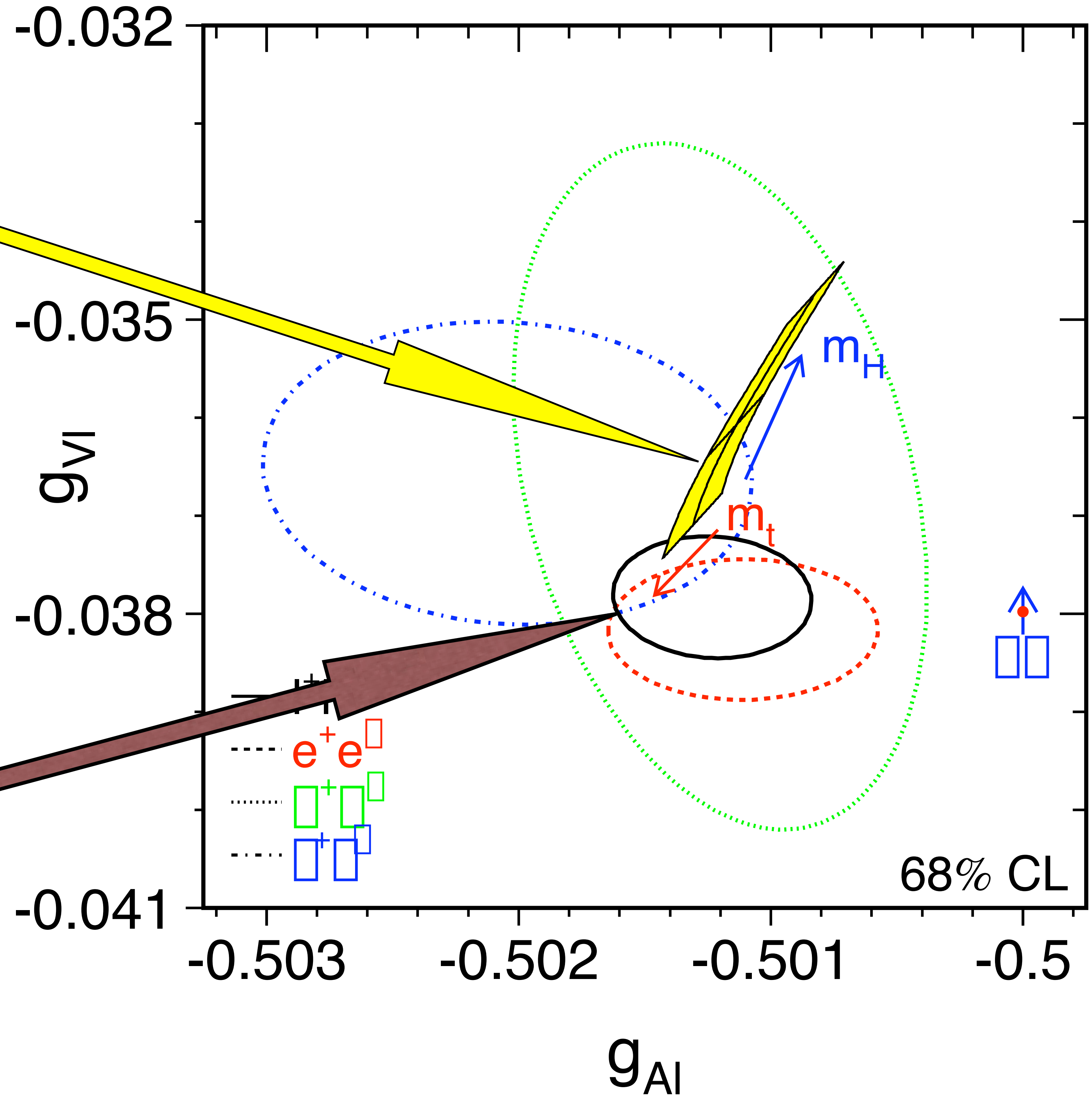
- Asymmetries → $g_V/g_A$
- Z partial decay widths → $g_V^2 + g_A^2$

# Standard Model tests: leptonic couplings

SM:

$m_H$ = [114.1, 1000] GeV

$m_t$ = 174.3 ± 5.1 GeV



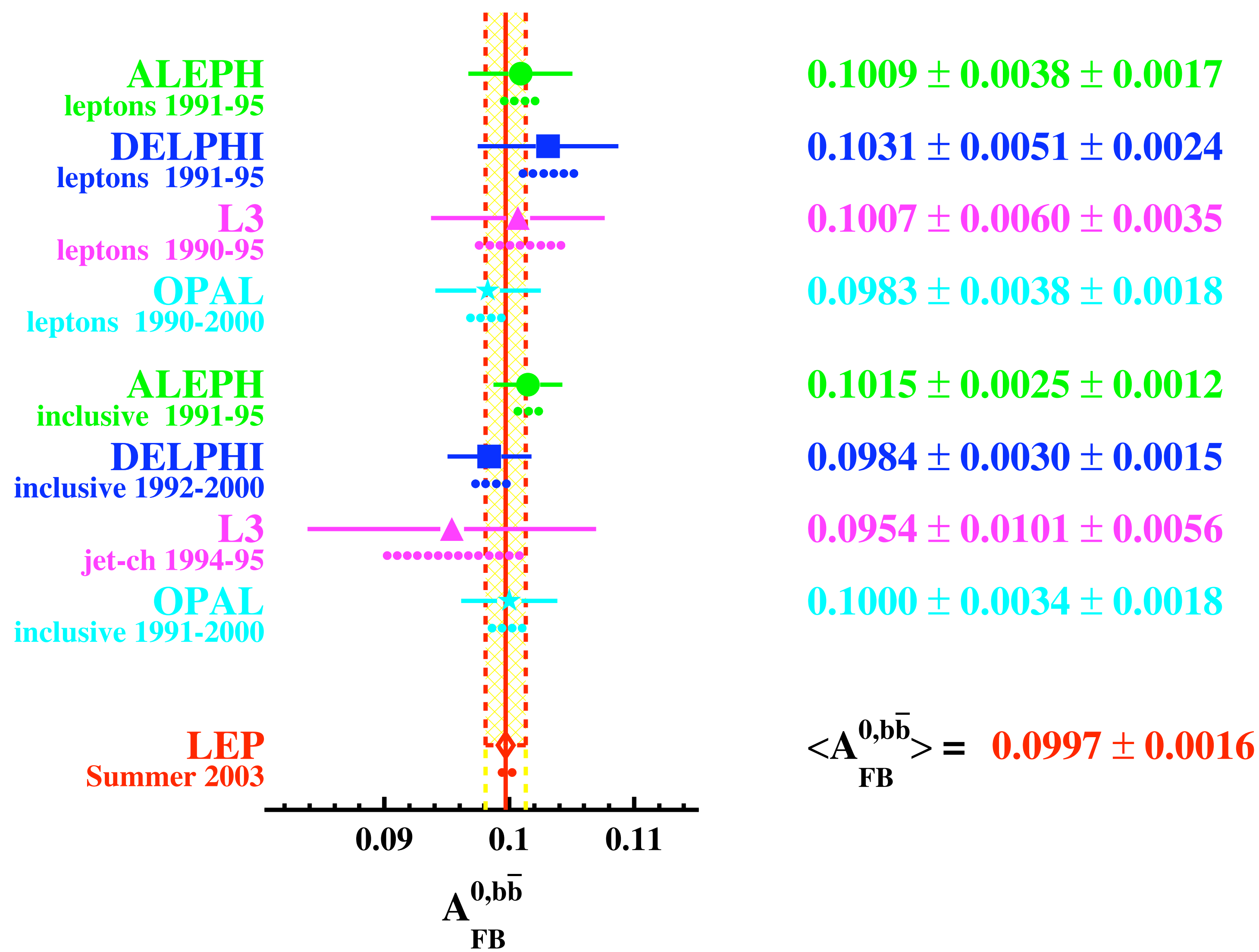

Low $m_H$ favored

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)*

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



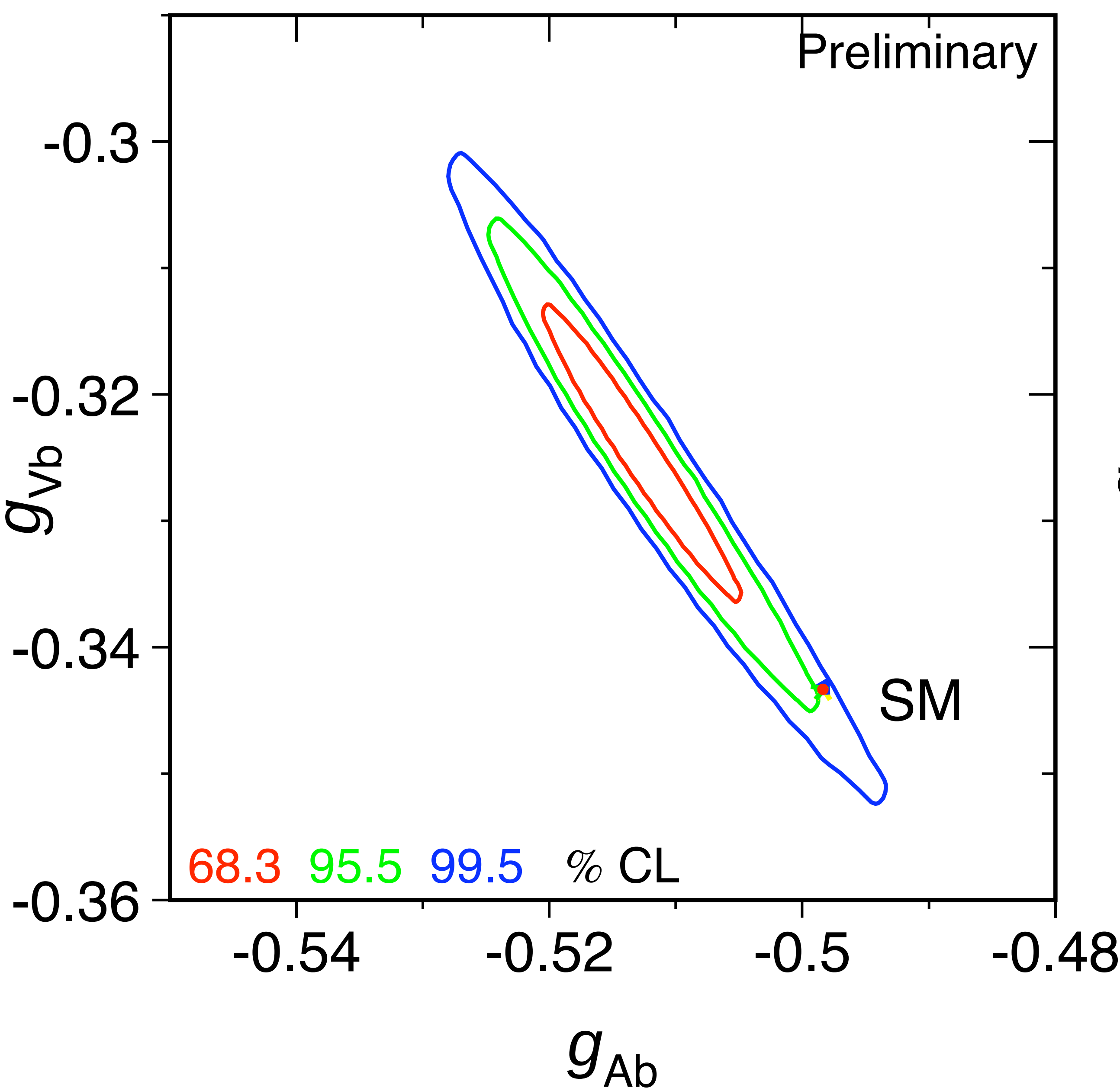

$A_{FB}^{0,b}$ = 0.0997 ± 0.0016(tot sys 0.0007; common sys 0.0004) SM 0.1036

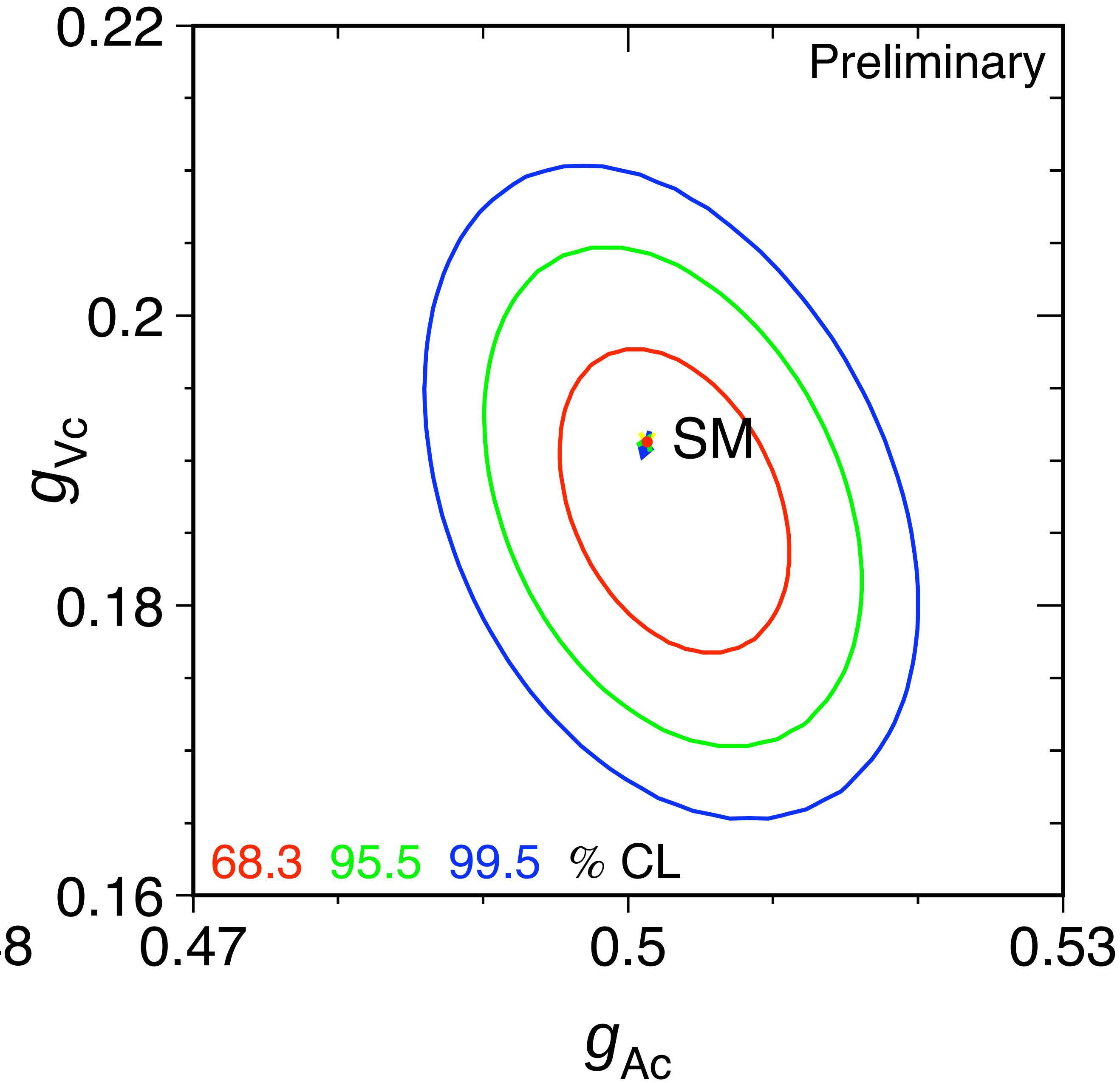
$A_{FB}^{0,c}$ = 0.0706 ± 0.0035(tot sys 0.0017; common sys 0.0009) SM 0.0740

Some results are **still** preliminary

# *Quark couplings*

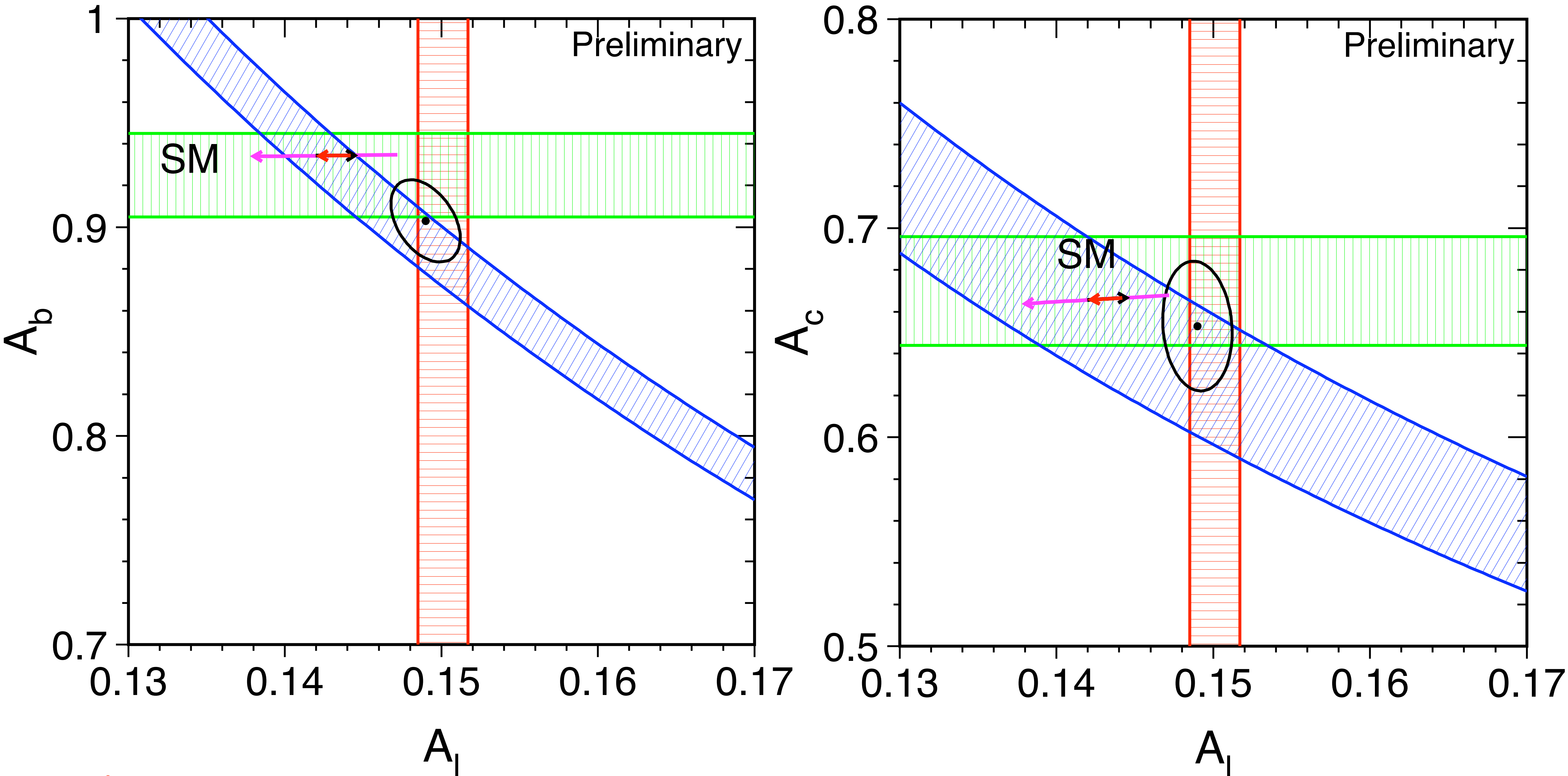
LEP + SLD, assuming lepton universality



# *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);  □□ $m_H$ □ [114, 1000]



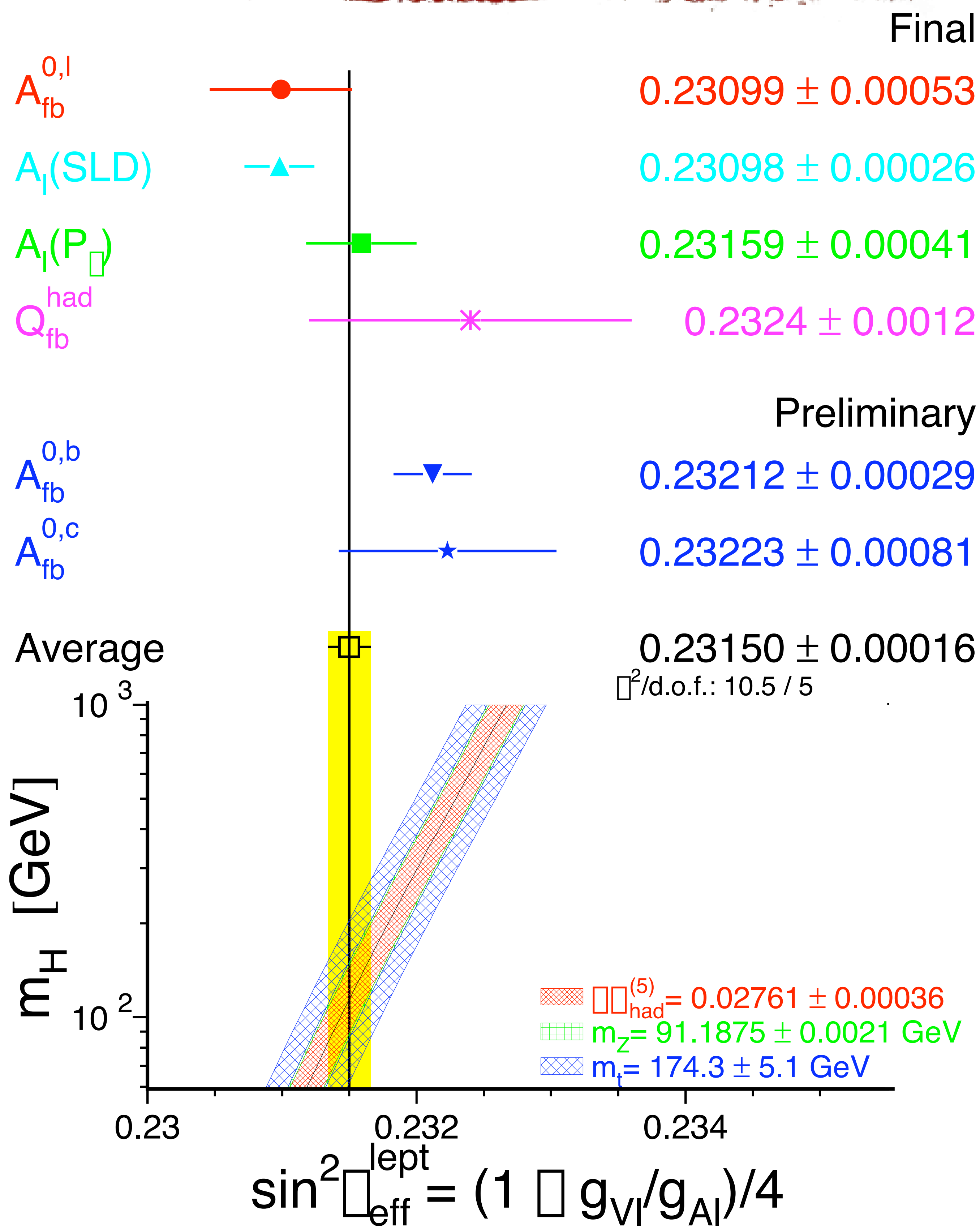

$A_{FB}^{0,b}$ prefers high $m_H$; $\mathcal{A}_\ell$ prefers low $m_H$

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

Assuming lepton universality:

$\chi^2$/dof(lept.) = 1.6/2 ($P$ = 44.0%)
$\chi^2$/dof(hadr.) = 0.06/2 ($P$ = 96.8%)
$\chi^2$/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

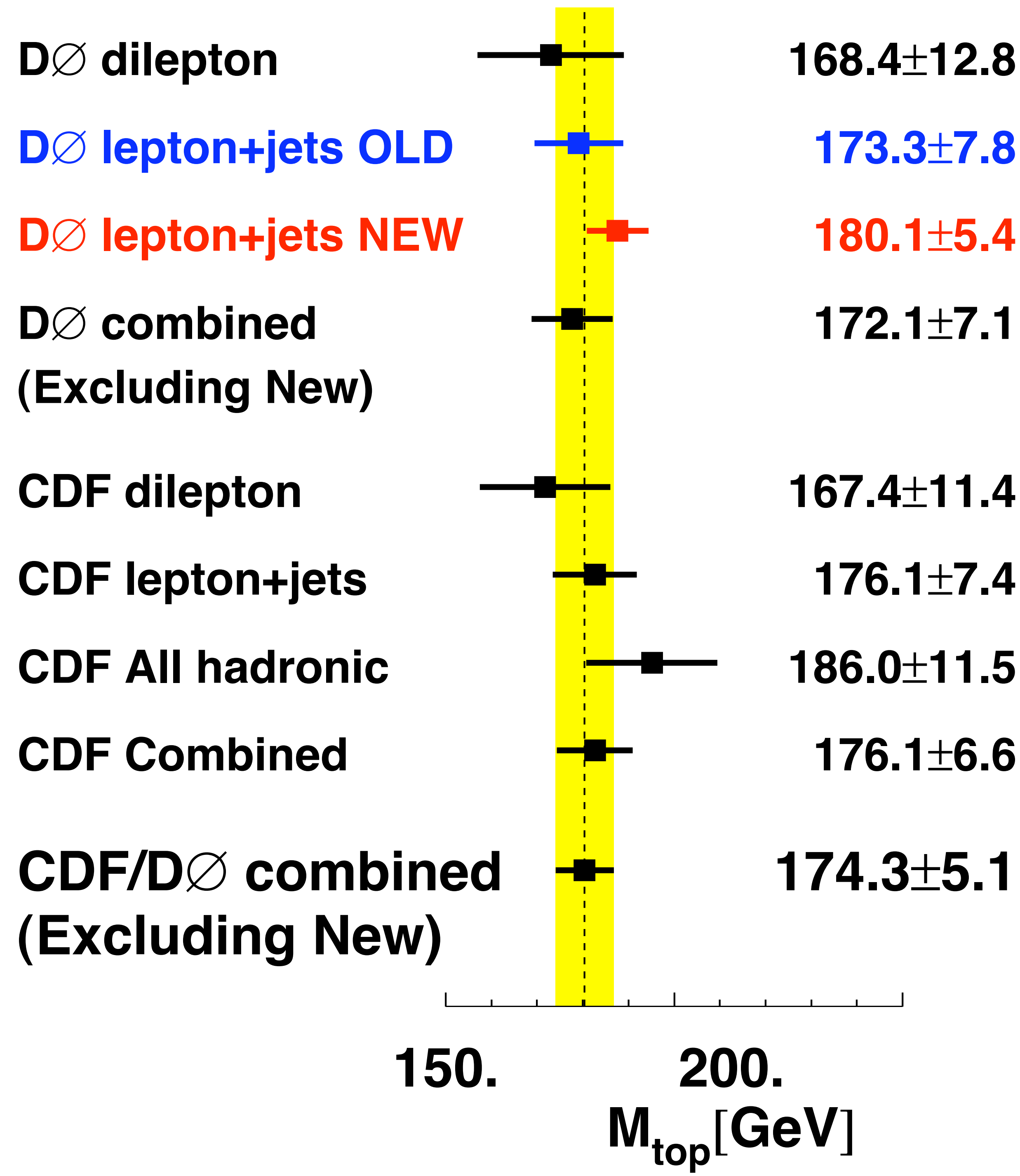
Improves statistical error by factor 2.5

$m_t = 180.1 \pm 3.6 \pm 4.0$ GeV

**New** CDF Run II top mass

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

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




But, still use

$m_t = 174.3 \pm 5.1$ GeV

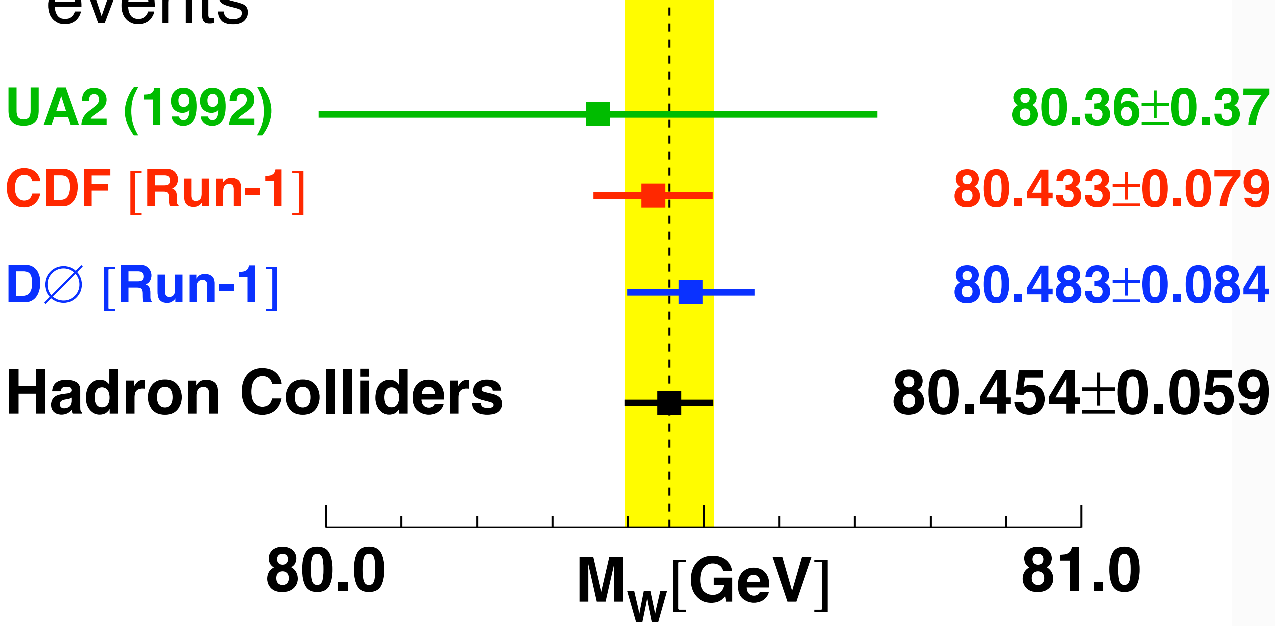
# *W mass from Tevatron*

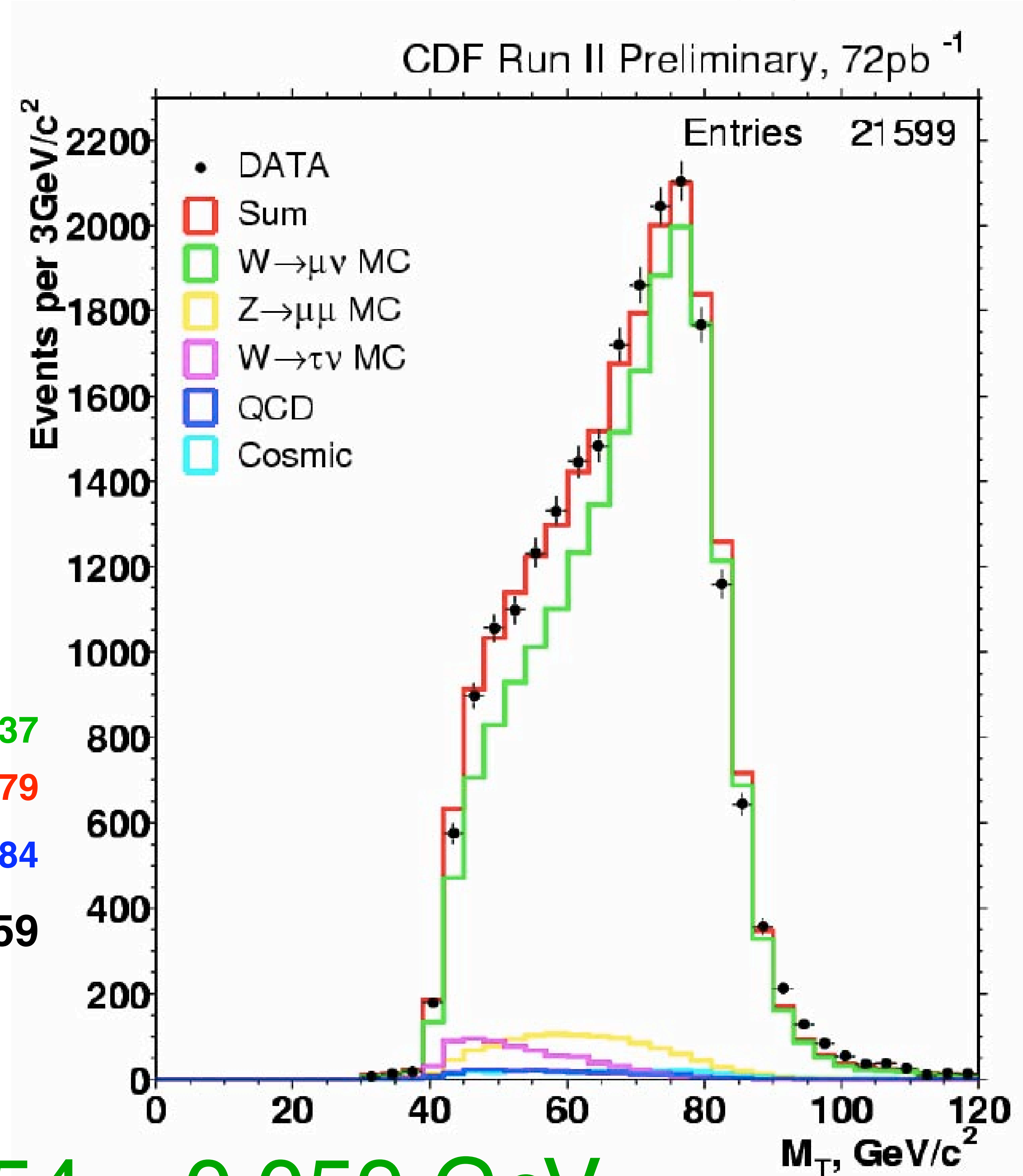
Run I results final

CDF/DO fit transverse mass (Jacobian)

Systematics will come down with increased statistics:

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




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

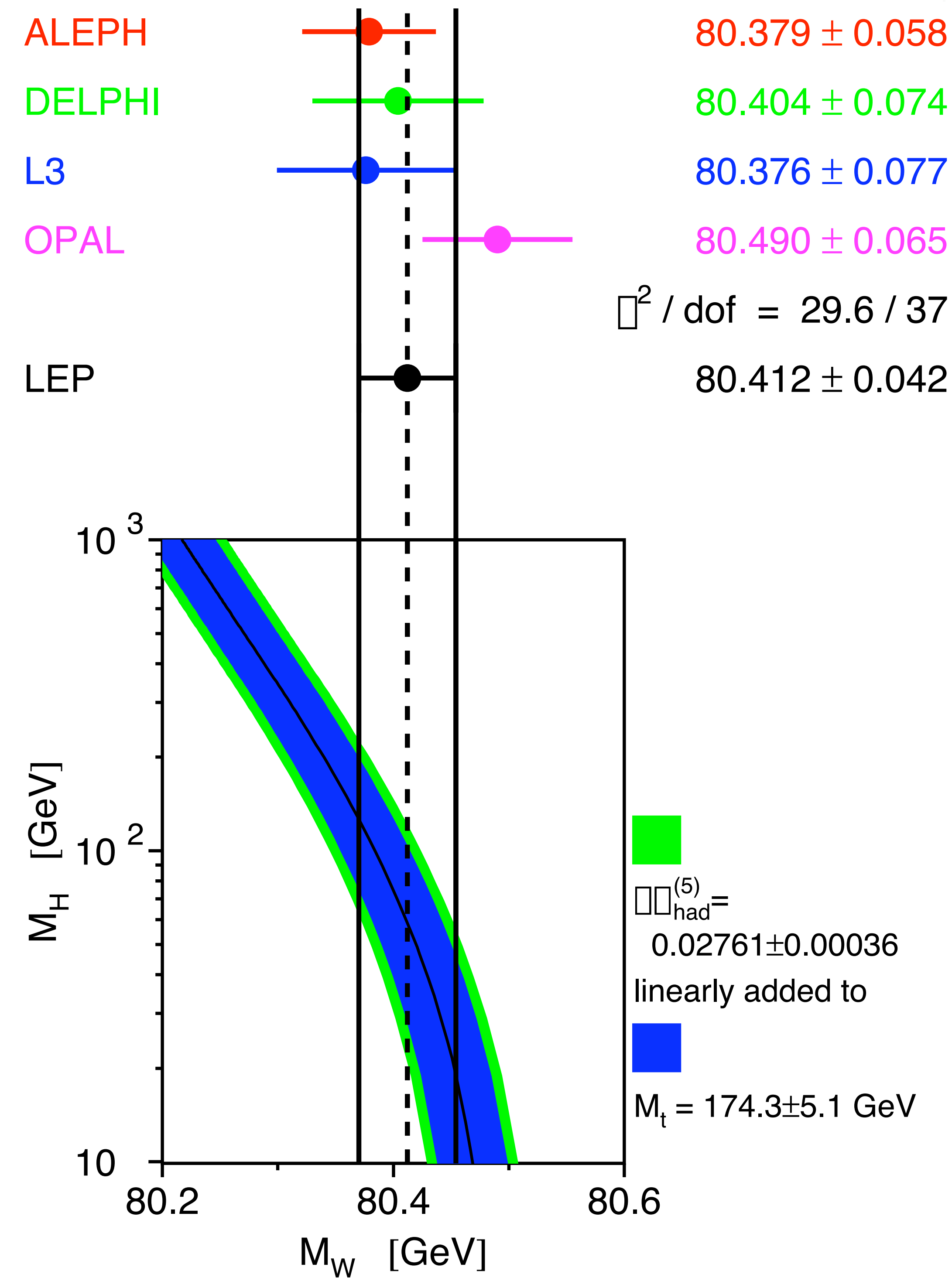
# W mass from LEP

All results still preliminary!

Since last year: new result from Aleph shifts the LEP average by -35 MeV (towards higher Higgs mass

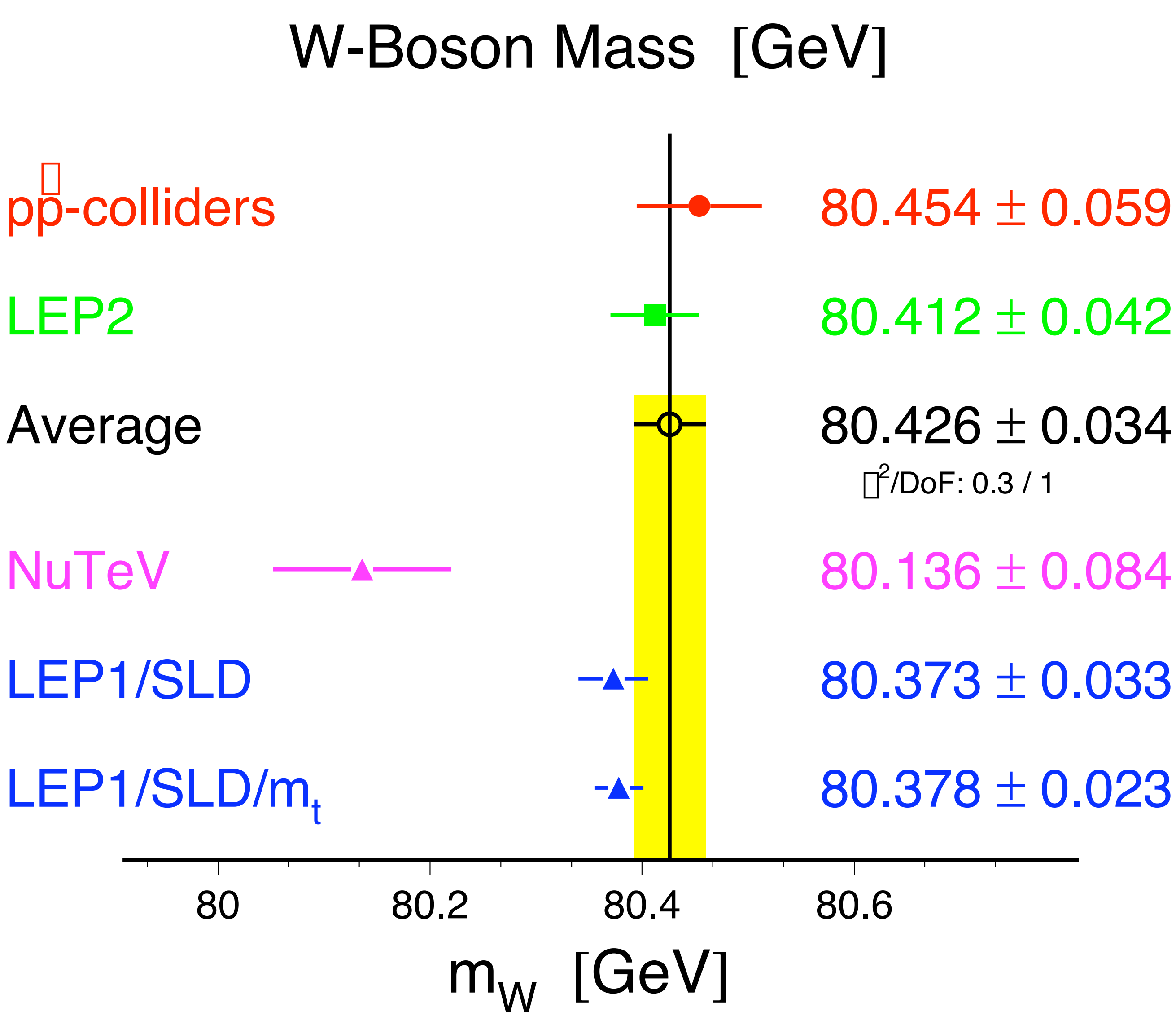
Still possible to improve; currently 4 quark final states have a low weight due to systematic errors from color reconnection and Bose-Einstein correlations. Studies on-going.

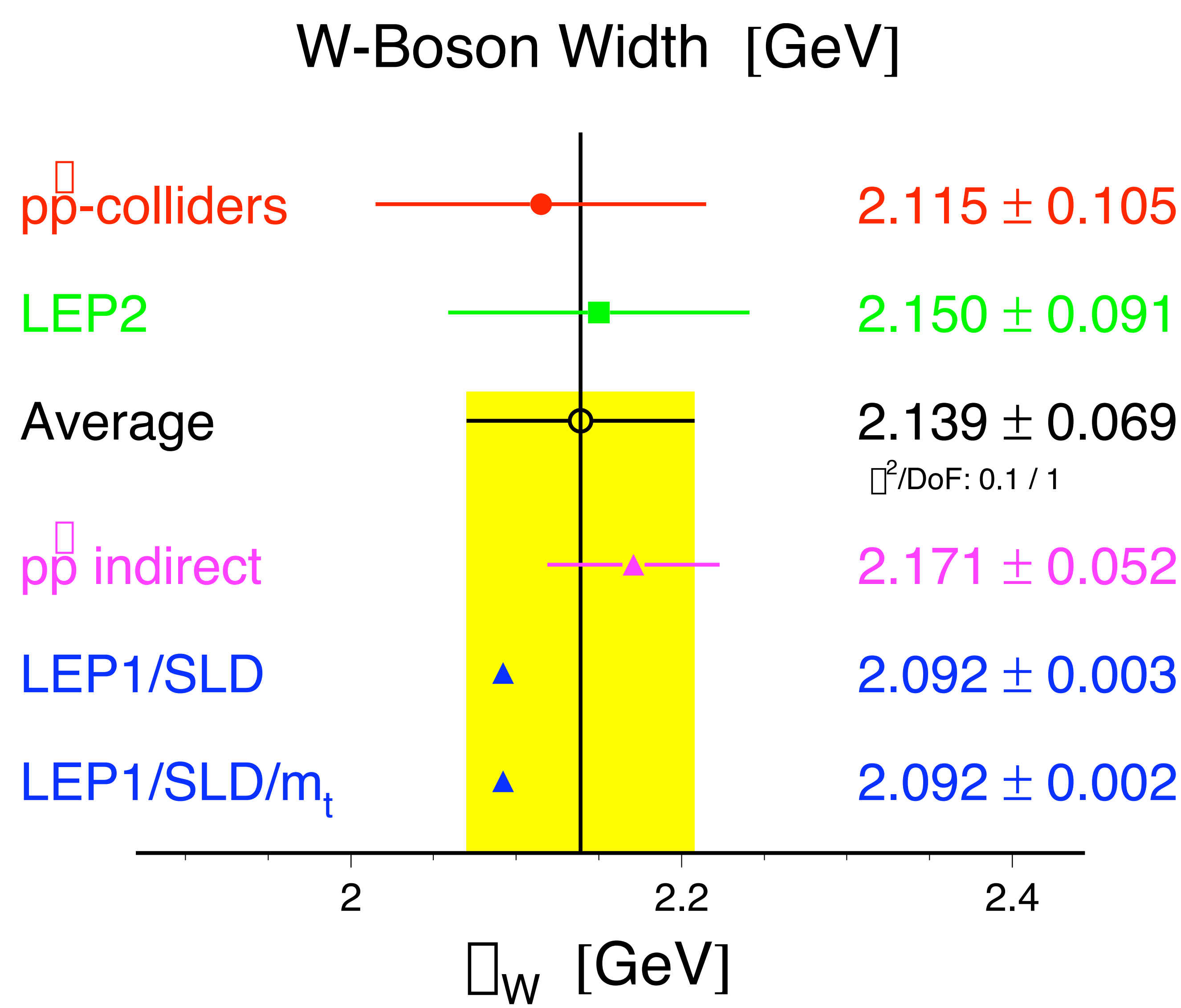
Cross-check between qqqq and $qq\ell\nu$: $\Delta m_W = +22 \pm 43$ MeV




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

# World average W mass and width




$m_W$ = 80.426 ± 0.034 GeV; $\Gamma_W$ = 2.139 ± 0.069 GeV

# NuTeV results

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

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

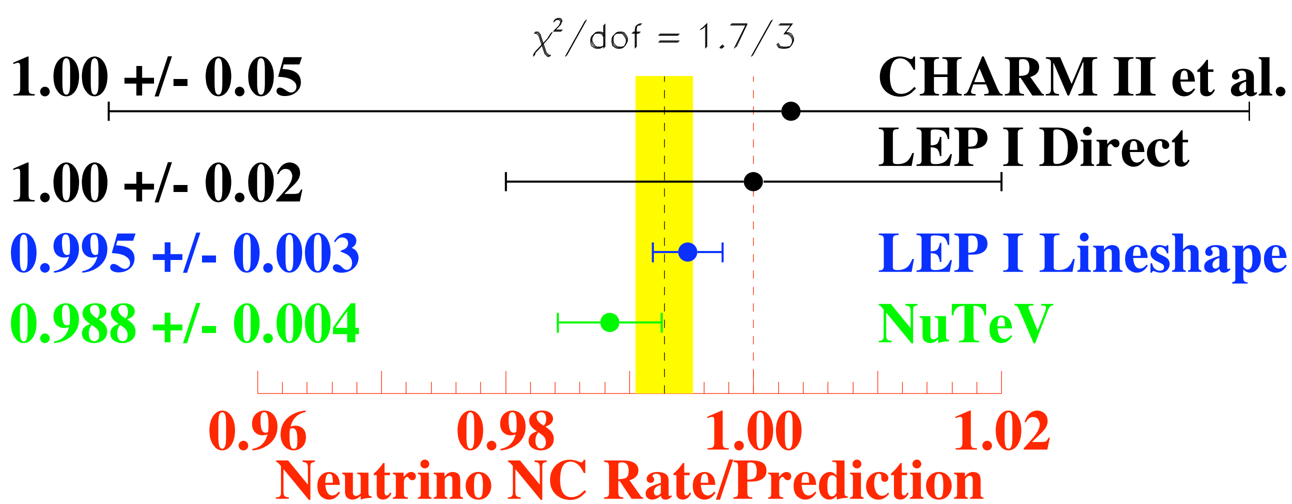
NuTeV actually measures $R^{\nu}$ and $R^{\bar{\nu}}$. Discrepancy from $R^{\nu}$.

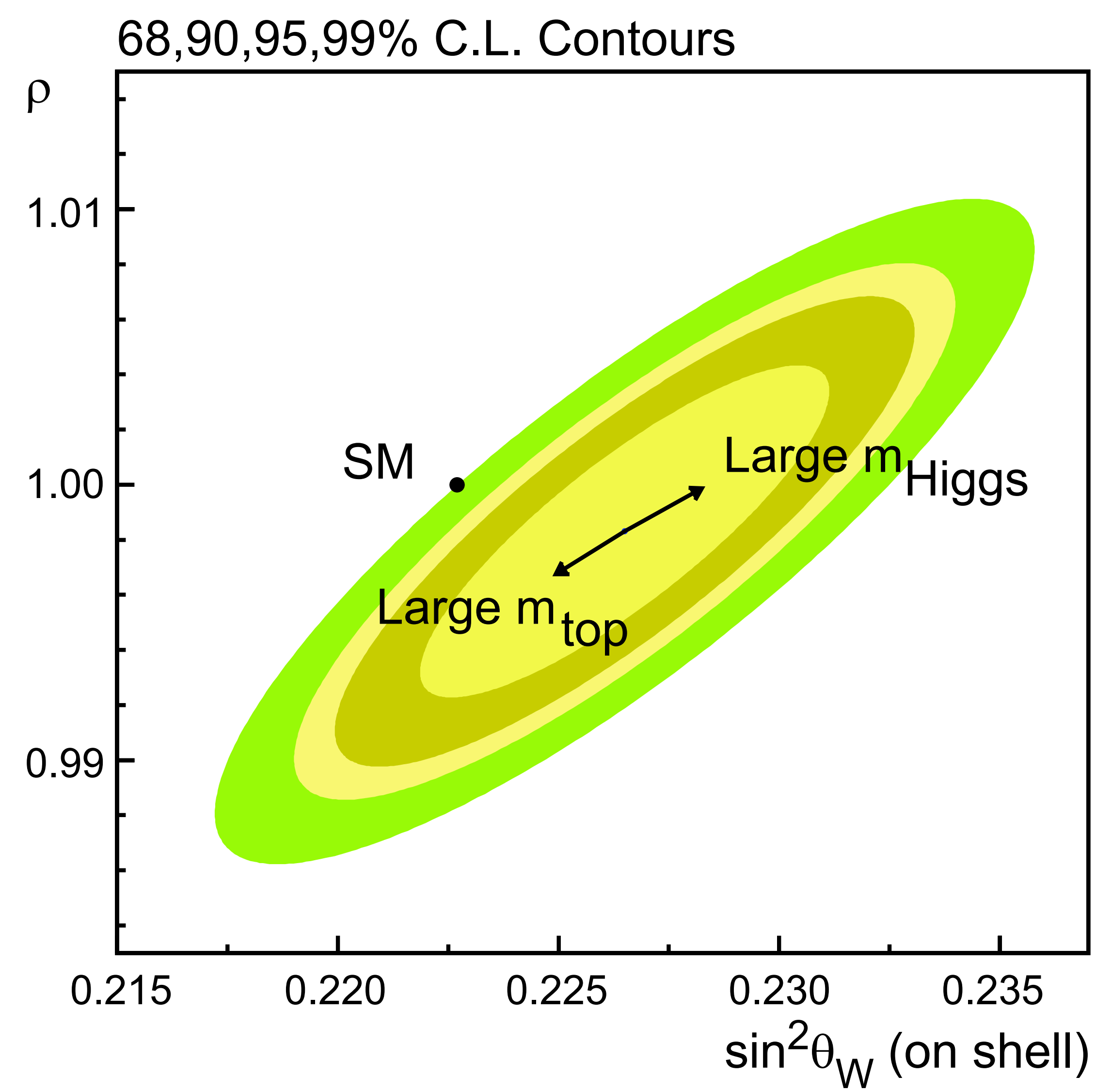
$\sin^2\theta_W = 0.22773 \pm 0.00135(\text{stat.}) \pm 0.00093(\text{sys.});$ $\Delta_{SM}$ 3.0

No explanation forth-coming:

- Experimental effects such as $\nu_e$ contamination
- PDFs, non-isoscalar contributions
- Strange sea asymmetry (although the debate is ongoing...)

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



# Updated: atomic parity violation

Weak charge of the Cesium nucleus:

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

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

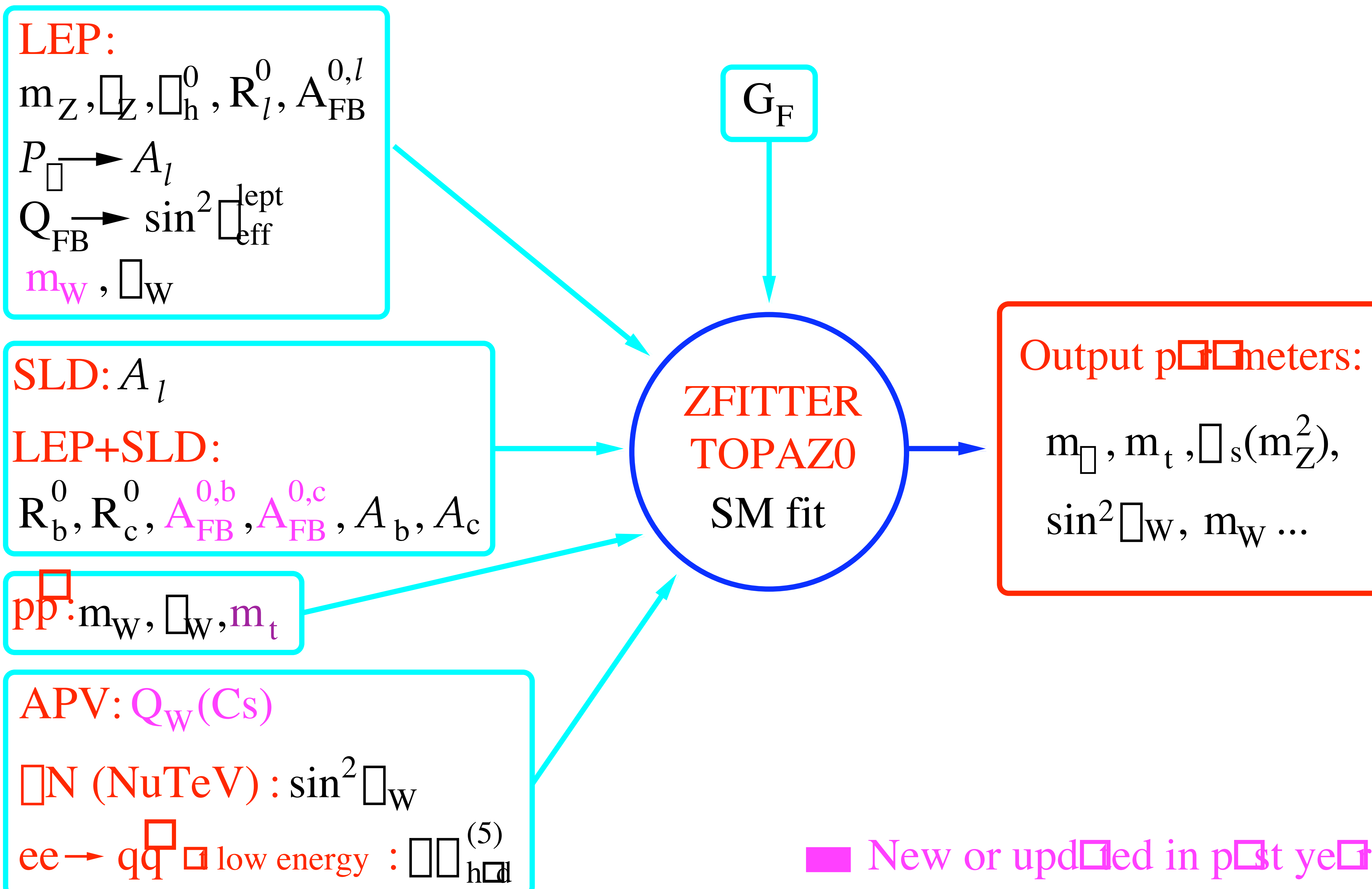
- Measure the amplitude of the parity-violating transition 6S-7S in Ce 133, possible due to the S-P mixing induced by neutral currents. Precise measurement performed by Wood, et al. (Science **275**, 1759 (1997).
- Transition amplitude + Cesium atomic structure ⇒ $Q_W$(Cs), predicted by the SM
- At one 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*

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

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

# 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 |
| $\chi^2$/d.o.f. | 14.7/10 | 16.7/14 | 25.4/15 |
| probab. (%) | 14.3 | 27.5 | 4.5 |

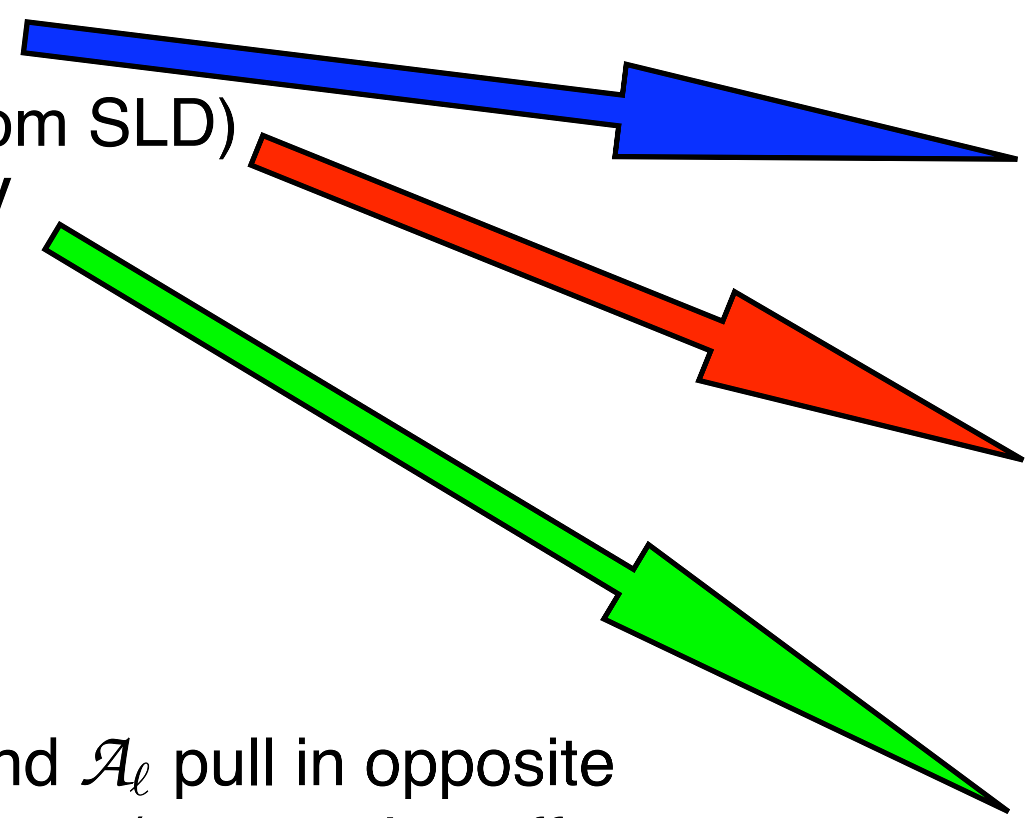
# The global electroweak fit

Largest contributions to $\chi^2$ from

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

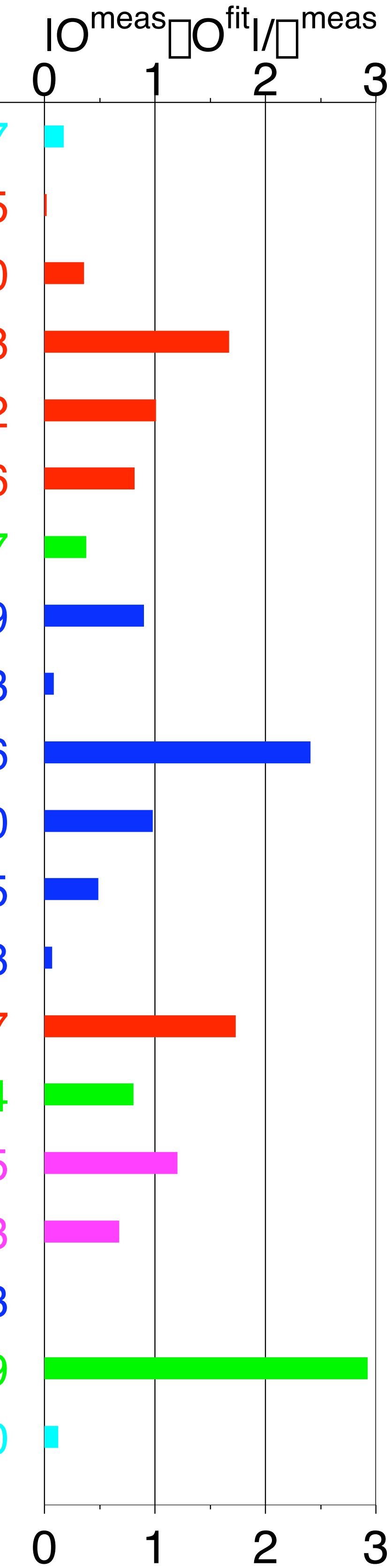
$\mathcal{A}_\ell$ (from SLD)

NuTeV

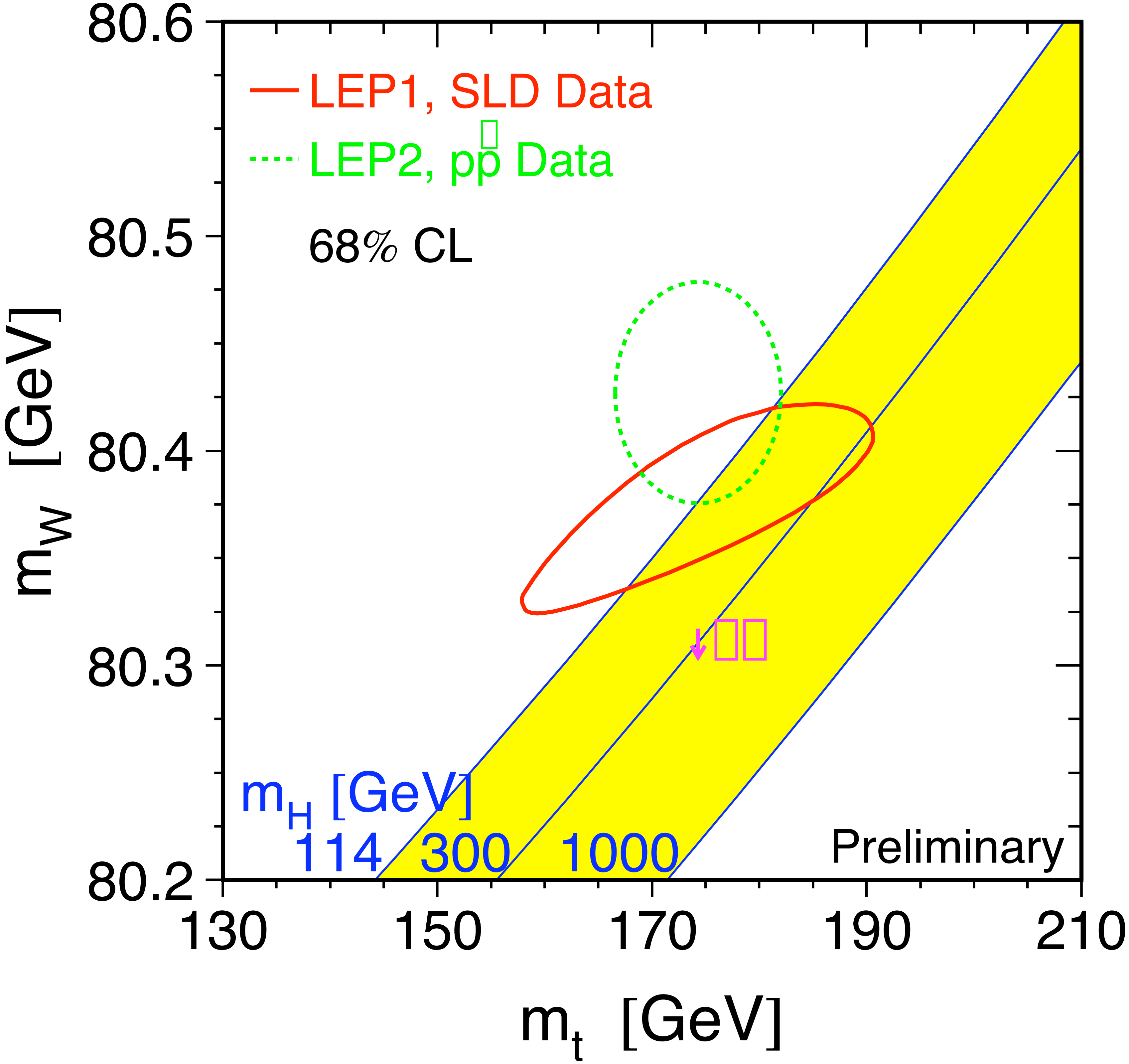


$A_{FB}^{0,b}$ and $\mathcal{A}_\ell$ pull in opposite directions (concerning effects on $m_H$)

| | Measurement | Fit |
|---|---|---|
| $\Delta\alpha_{had}^{(5)}(m_Z)$ | 0.02761 ± 0.00036 | 0.02767 |
| $m_Z$ [GeV] | 91.1875 ± 0.0021 | 91.1875 |
| $\Gamma_Z$ [GeV] | 2.4952 ± 0.0023 | 2.4960 |
| $\sigma_{had}^0$ [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 |
| $\Gamma_W$ [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 |



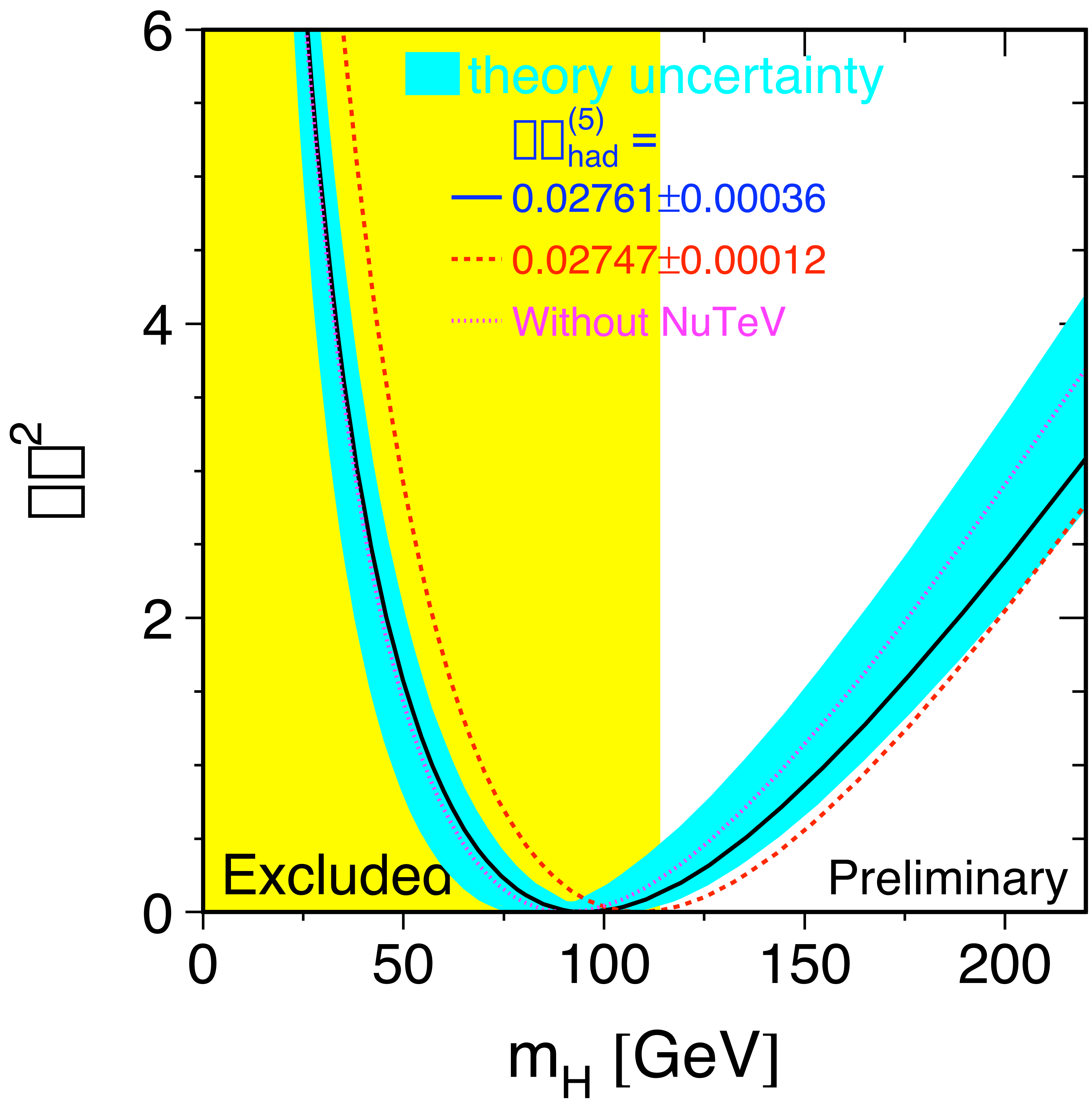
# The global fit: $m_W$, $m_t$, $m_H$




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 $\mathcal{A}_\ell$)

# The global fit: limits on the Higgs mass




## $m_H < 219$ GeV

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

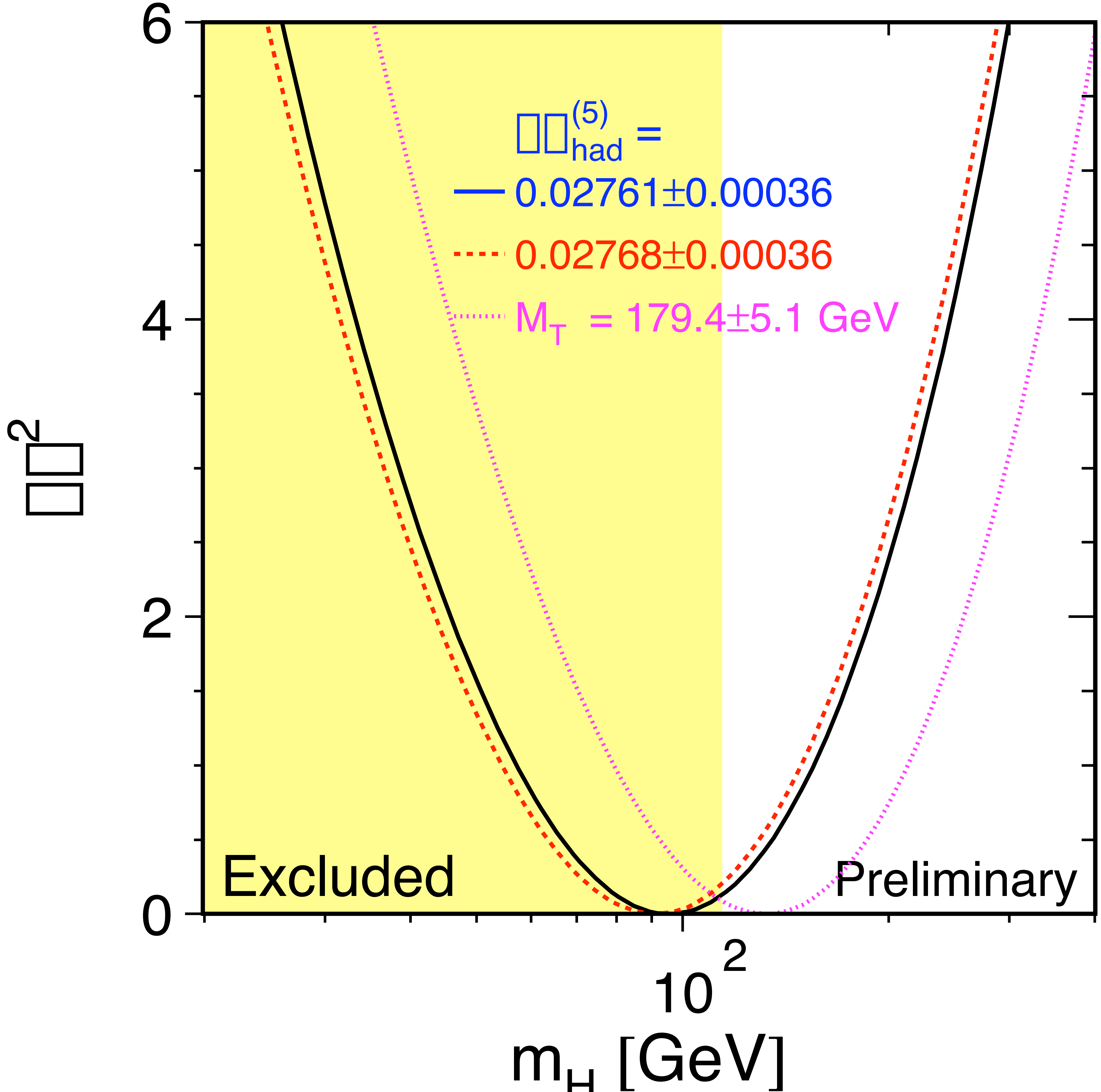
Possibly overestimated as two-loop contributions to $m_W$ (Weiglein, et al.) might be partially canceled by similar contributions to Z partial widths and $\sin^2\theta_{eff}^{lept}$

# *Higgs limits*

But watch $m_t$!!!
1σ increase to 179.4 ± 5.1 GeV gives large shift in $m_H$

(Note: this is not what the new DØ Run I result implies...)

best fit 96 ⇒ 126 GeV
limit 219⇒ 283 GeV



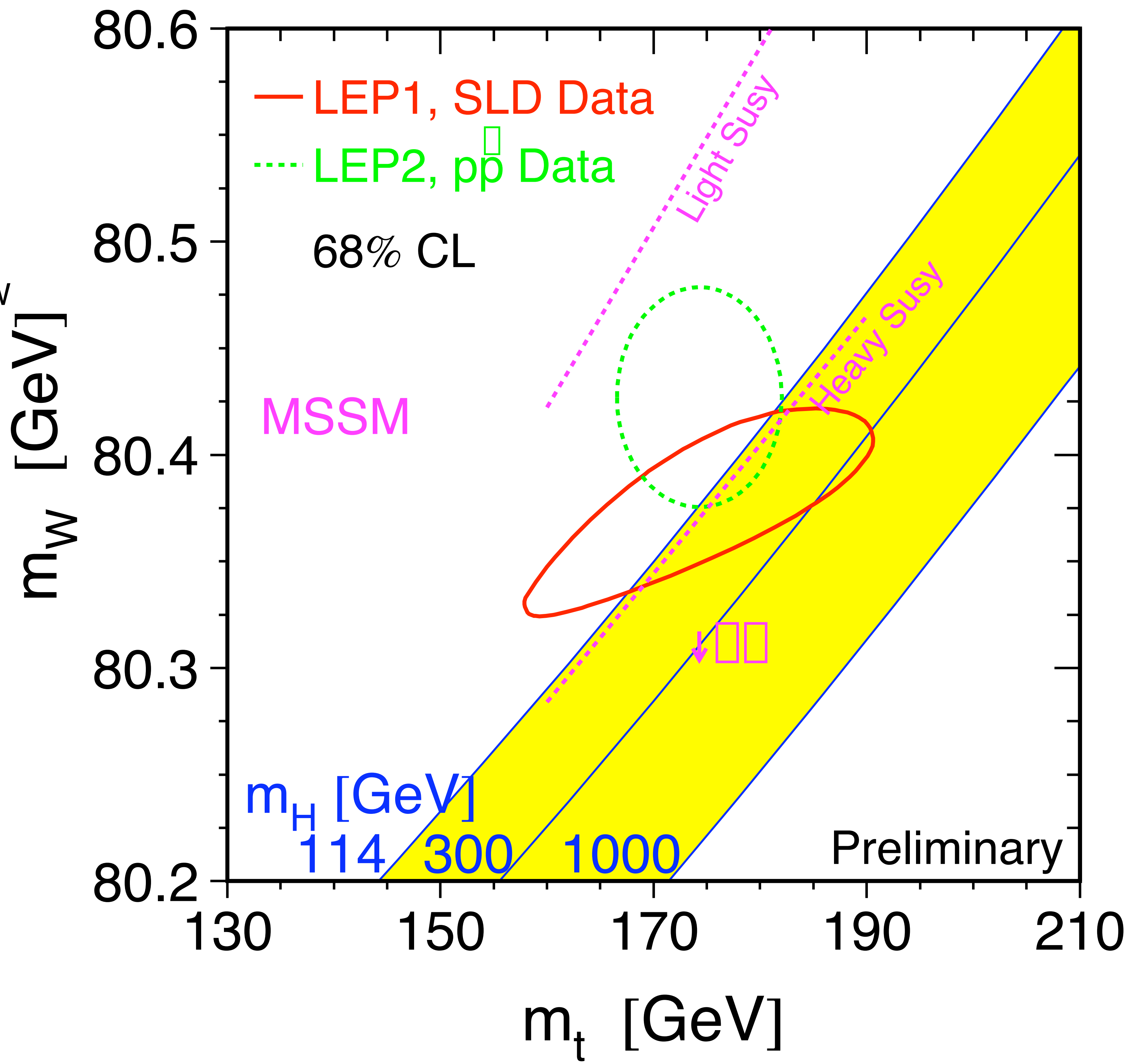
# Beyond the SM – the MSSM

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.

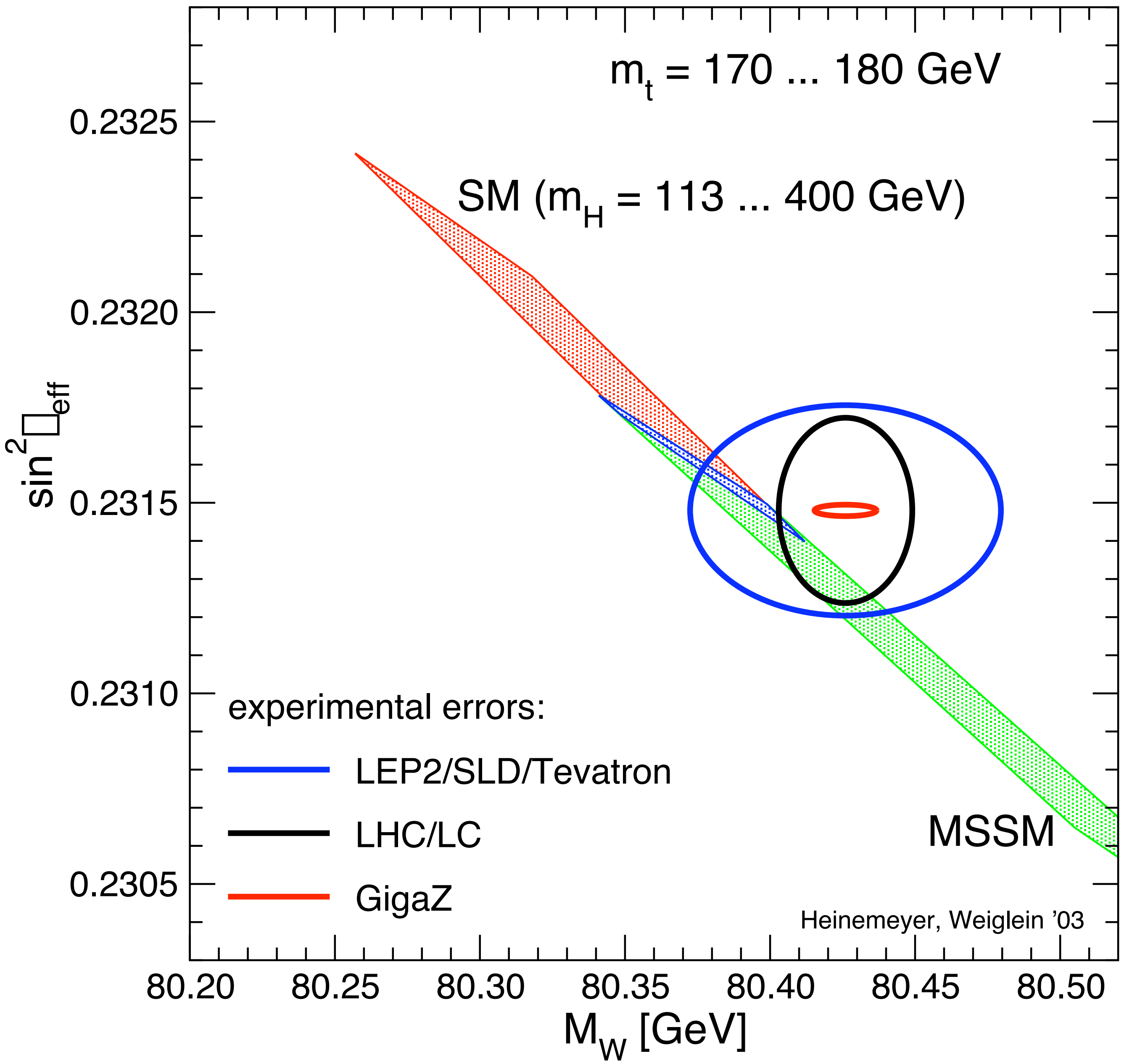
Unfortunatly, **they** are free!

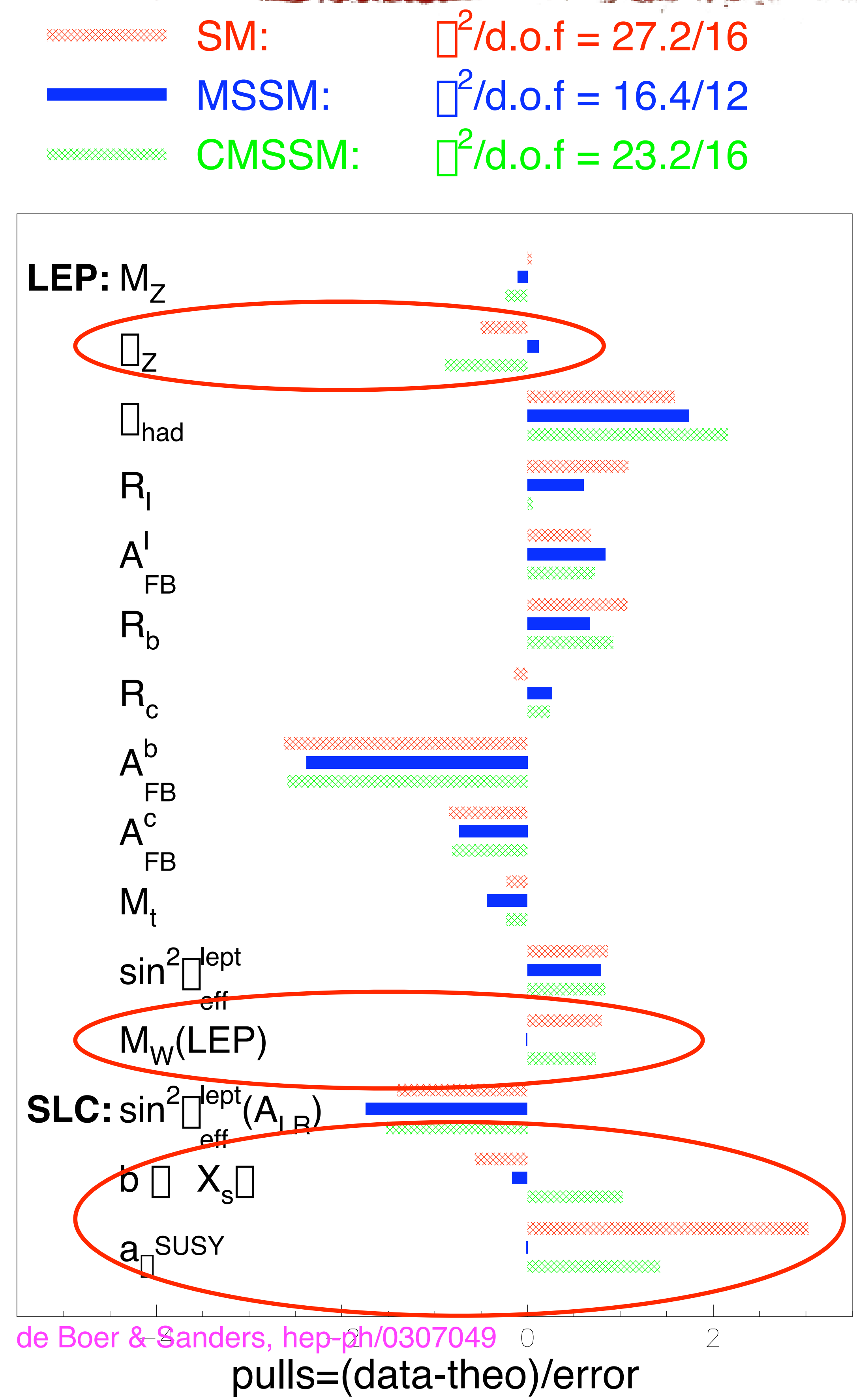
MSSM seems to be a bit more compatible with the data...



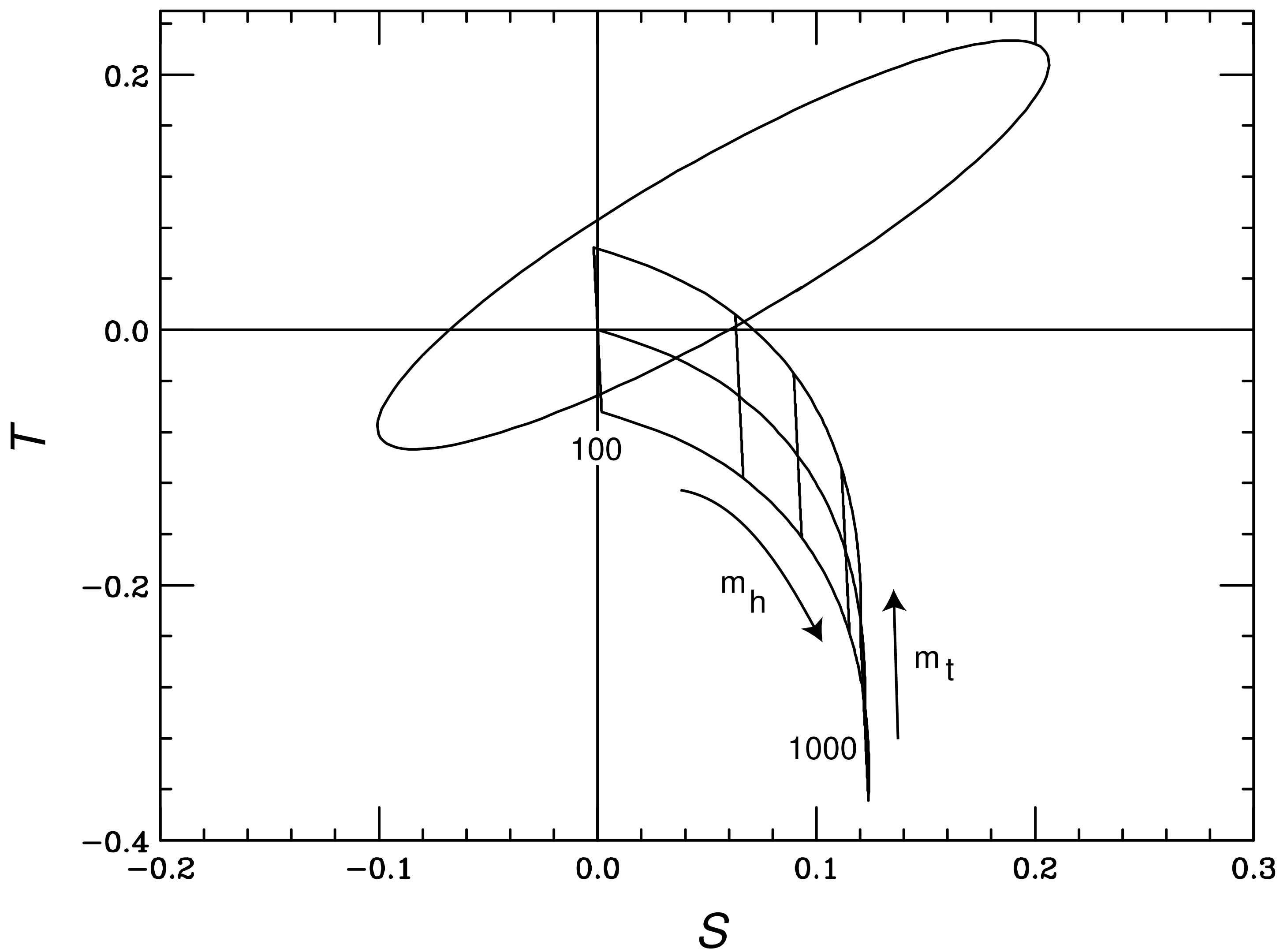

MSSM: Heinemeyer, Weiglein, hep-ph/0307177

# Beyond the SM – the MSSM



# 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 |
|---|---|---|---|---|---|---|---|
| $\Delta\sin^2\theta_{eff}^{lept}$ ($\times 10^5$) | 17 | 78 | 29 | 20 | 14–20 | (6) | 1.3 |
| $\Delta m_W$ [MeV] | 33 | 27 | 16 | 12 | 15 | 10 | 7 |
| $\Delta m_t$ [GeV] | 5.1 | 2.7 | 1.4 | 1.3 | 1.0 | 0.2 | 0.13 |
| $\Delta m_H$ [MeV] | — | — | $\mathcal{O}(2000)$ | | 100 | 50 | 50 |

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

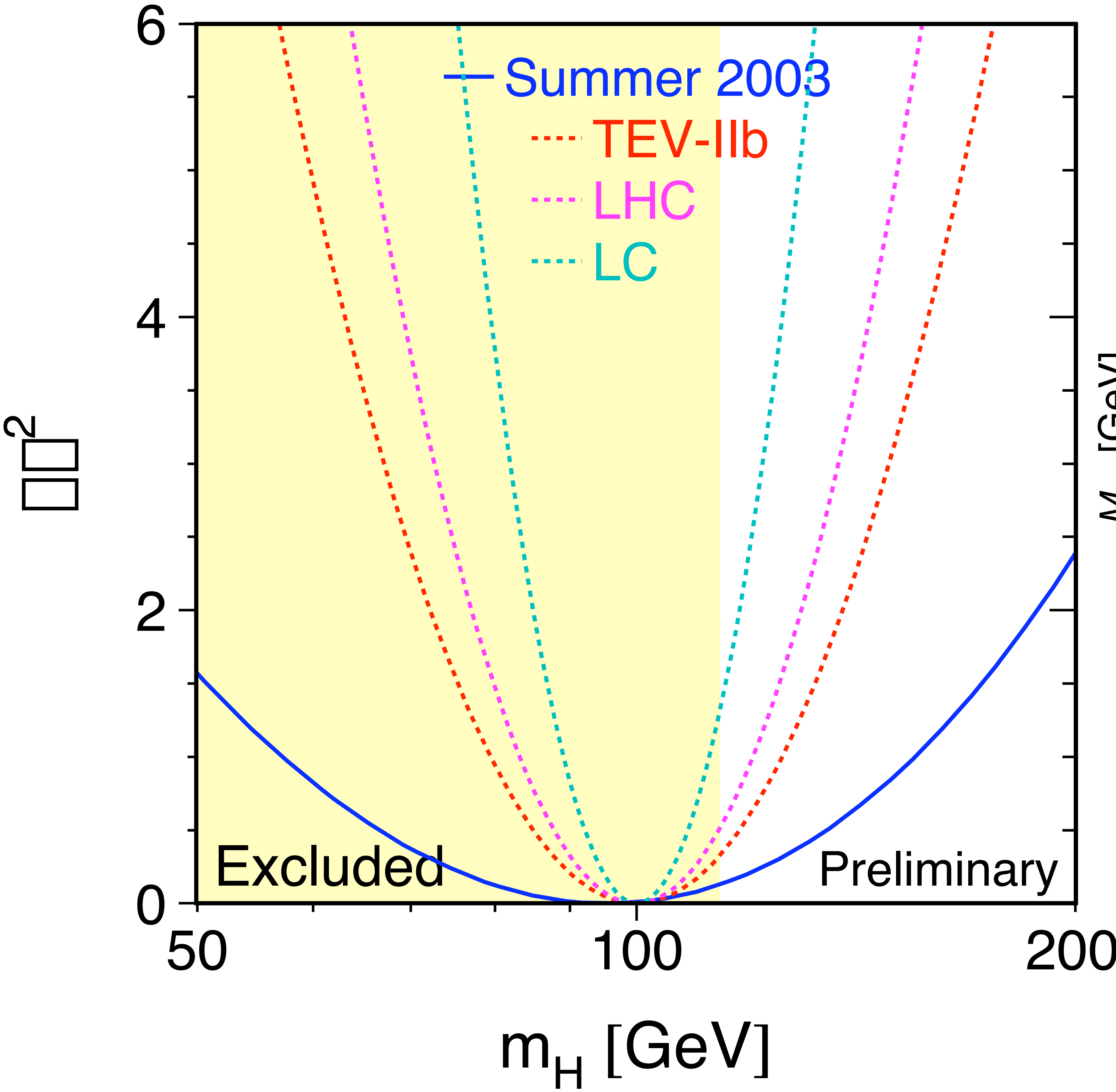
Near future (Run II, LHC):

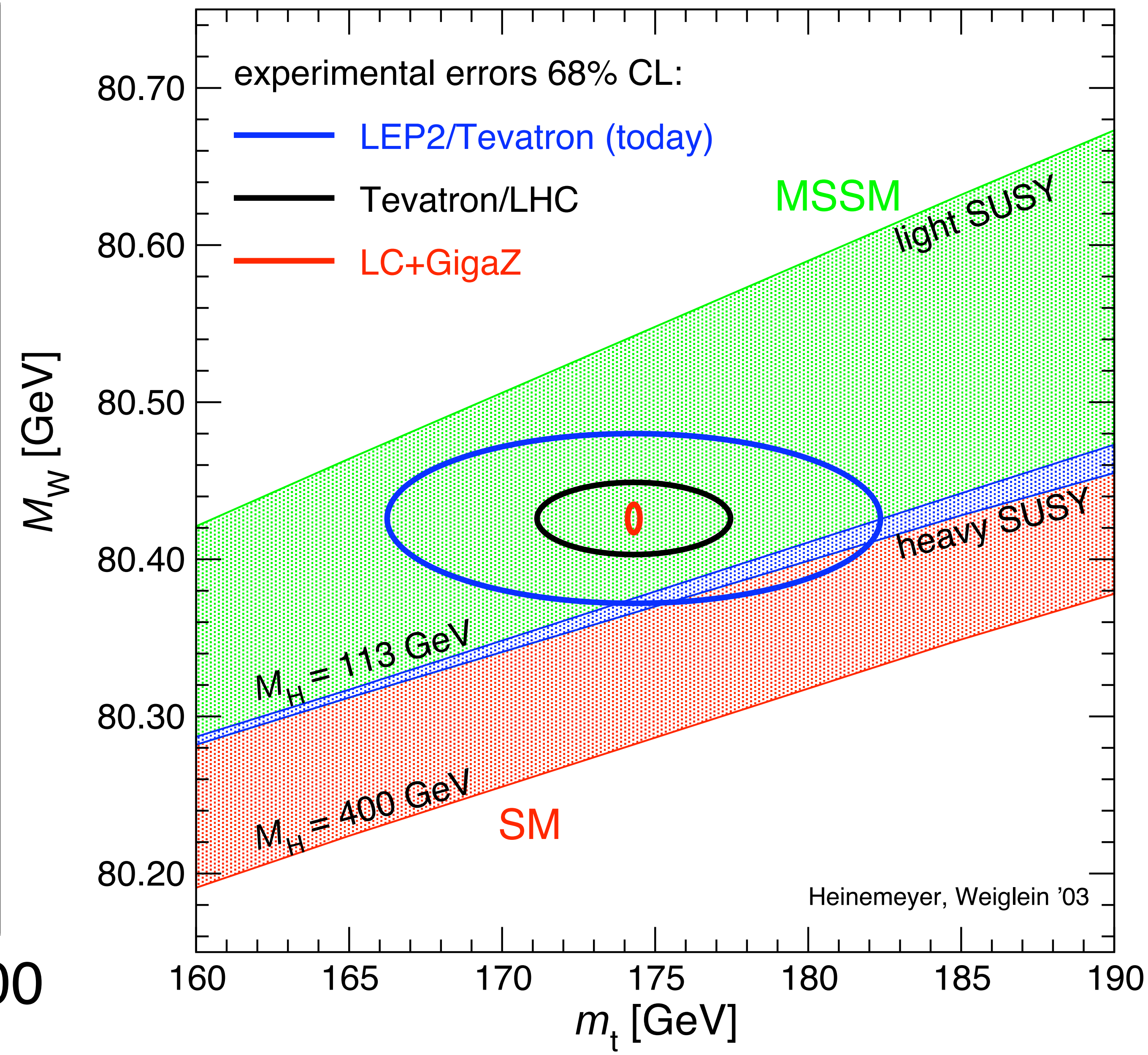
- $\Delta m_W$ = 15 MeV
- $\Delta m_t$ = 1.5 GeV
- $\delta\Delta\alpha_{had}$ = 0.0002

Far future (LC, GigaZ):

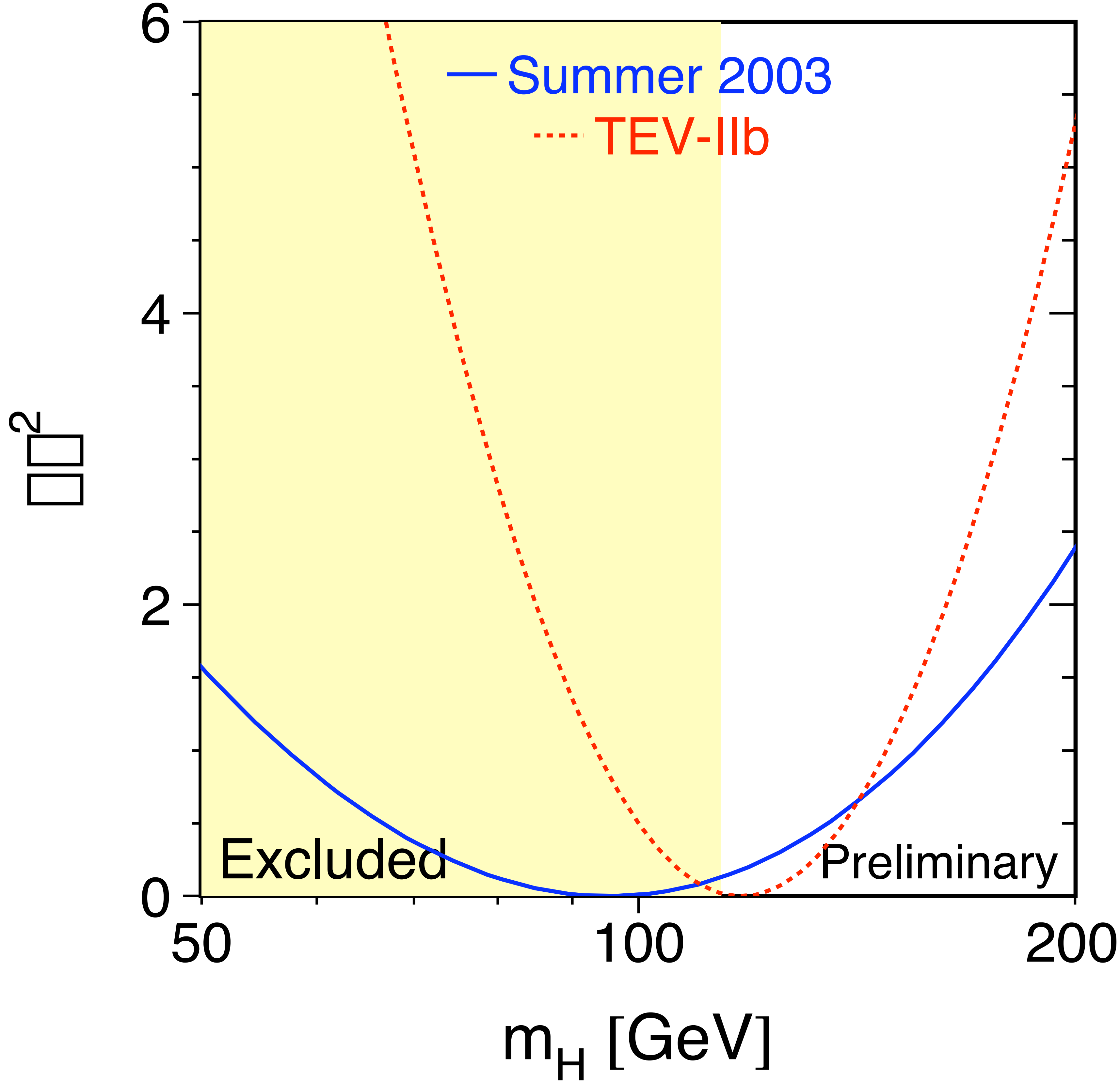
- $\Delta m_W$ = 7 MeV
- $\Delta m_t$ = 130 MeV
- $\delta\Delta\alpha_{had}$ = 0.00007
- $\Delta\sin^2\theta_{eff}^{lept} = 1.3 \times 10^{-5}$

# Beyond the Current Experiments



# Beyond the Current Experiments



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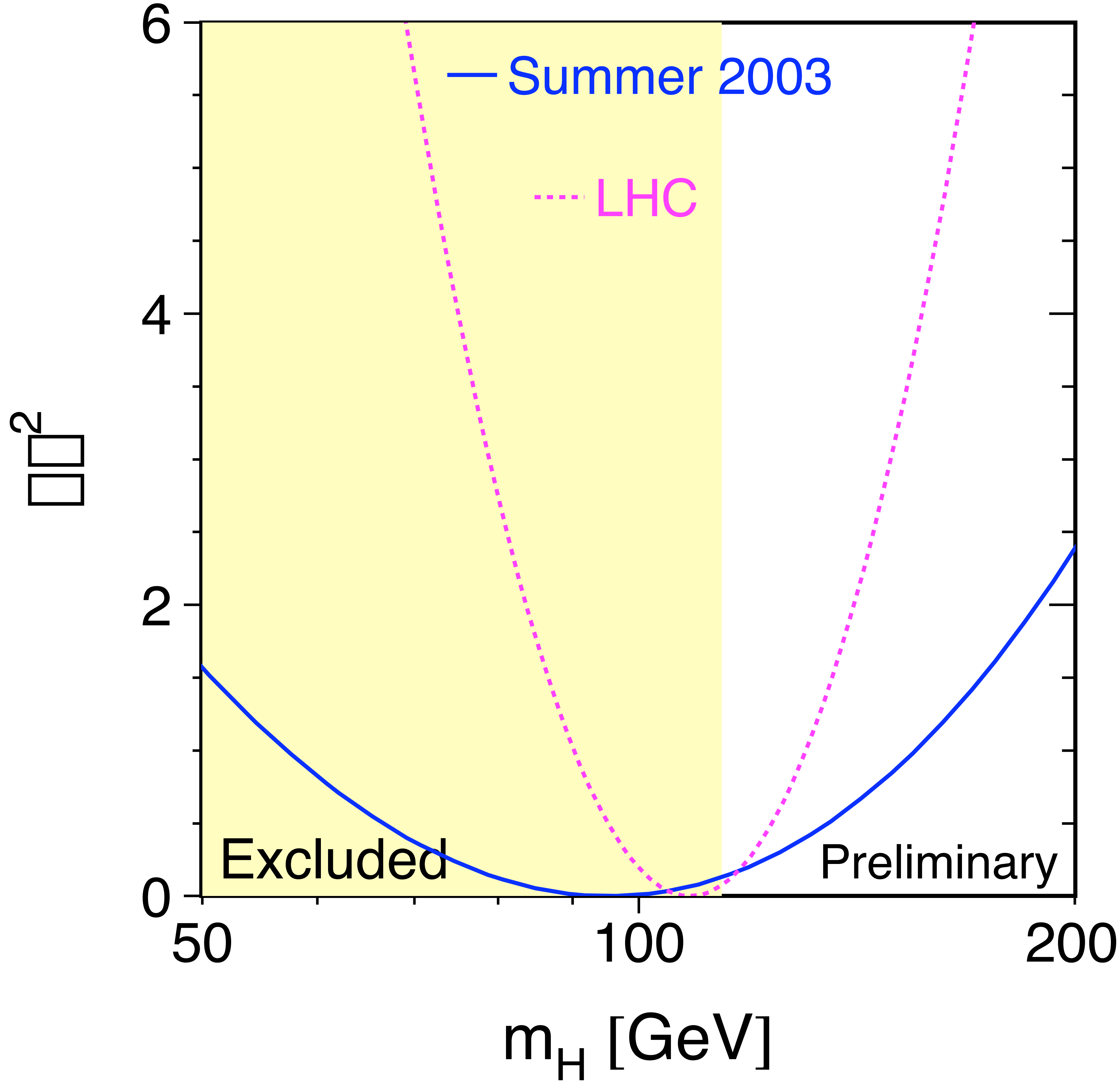
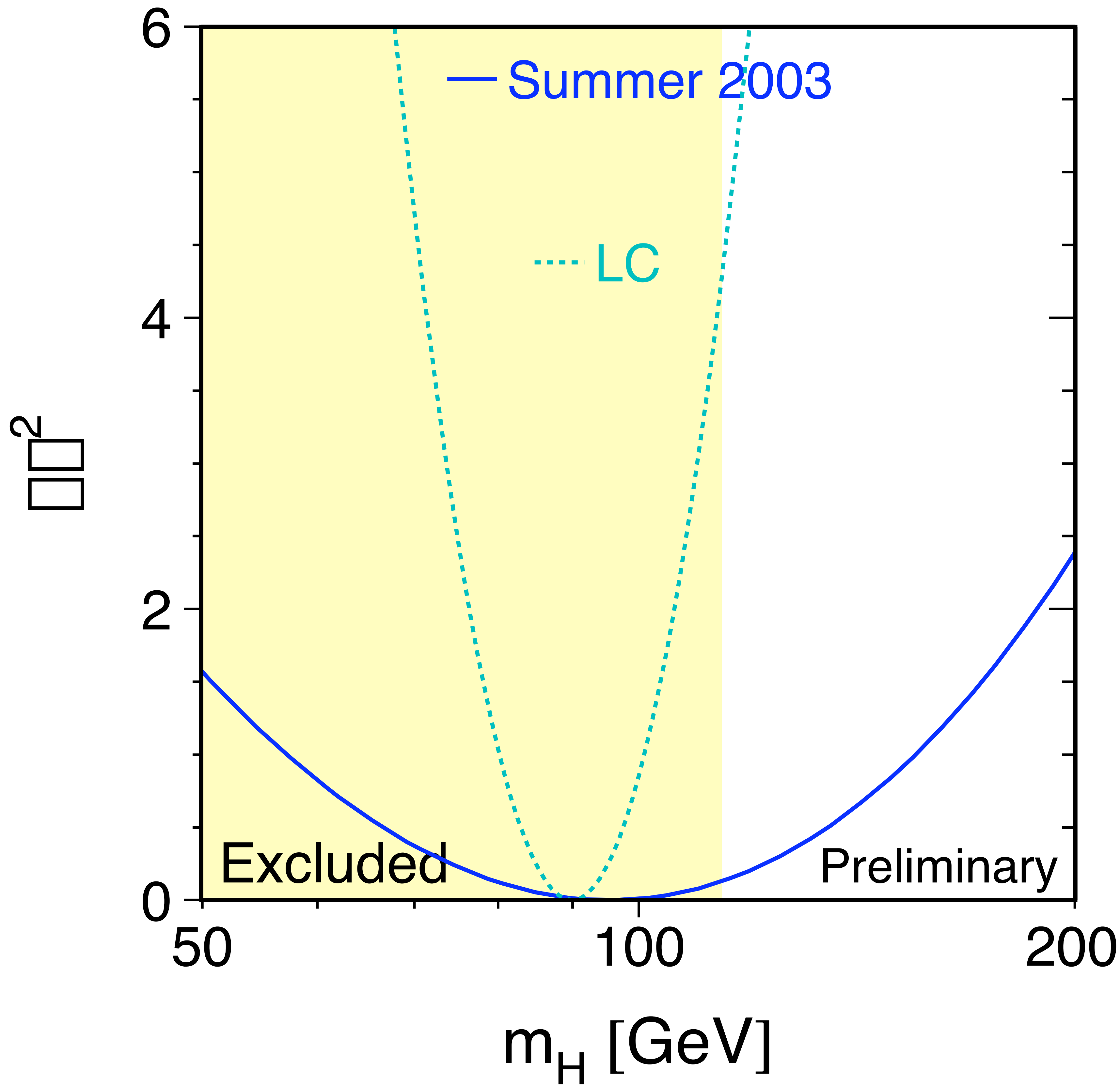


# *Beyond the Current Experiments*



# 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:

  $m_W < 219$ GeV

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

# What will we find?