Precision Electroweak Measurements

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(plus a cast of 1000s!)

- Electroweak corrections
- Experimental inputs
- Effective couplings in the Standard Model
- More experimental inputs
- The Electroweak global fit
- Higgs mass limits
- Conclusions

Electroweak Radiative Corrections

Precision measurements: knowledge of Standard Model parameters through radiative corrections

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

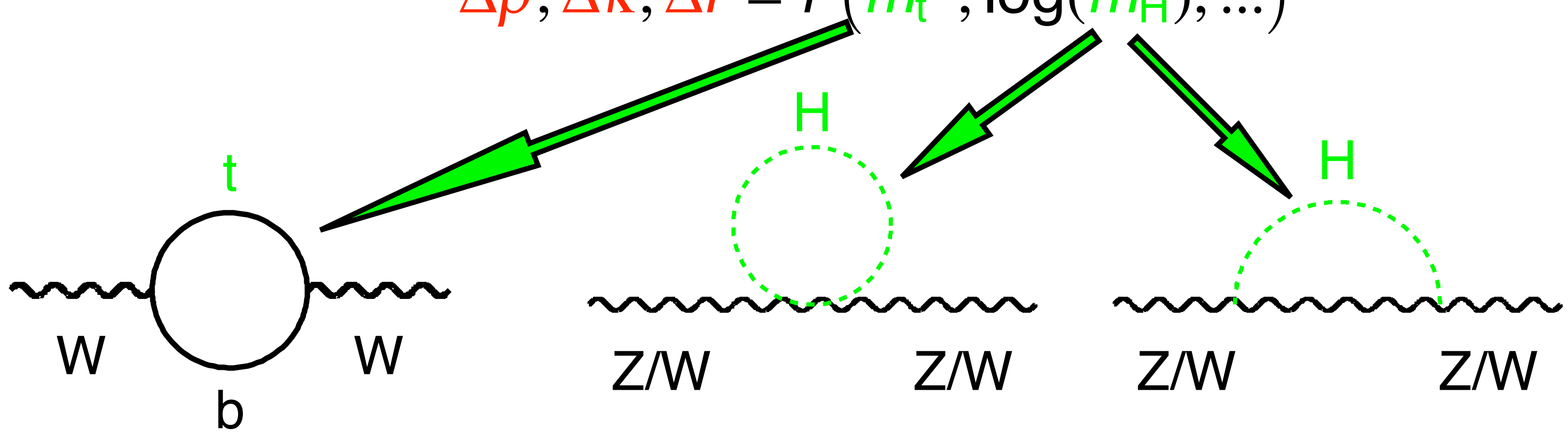
$$\sin^2\theta_W = 1 - \frac{m_W^2}{m_Z^2} \quad \Longrightarrow \quad \sin^2\theta_{\mathrm{eff}} = (1+\Delta\kappa)\sin^2\theta_W$$

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

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

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

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



Effective Z couplings

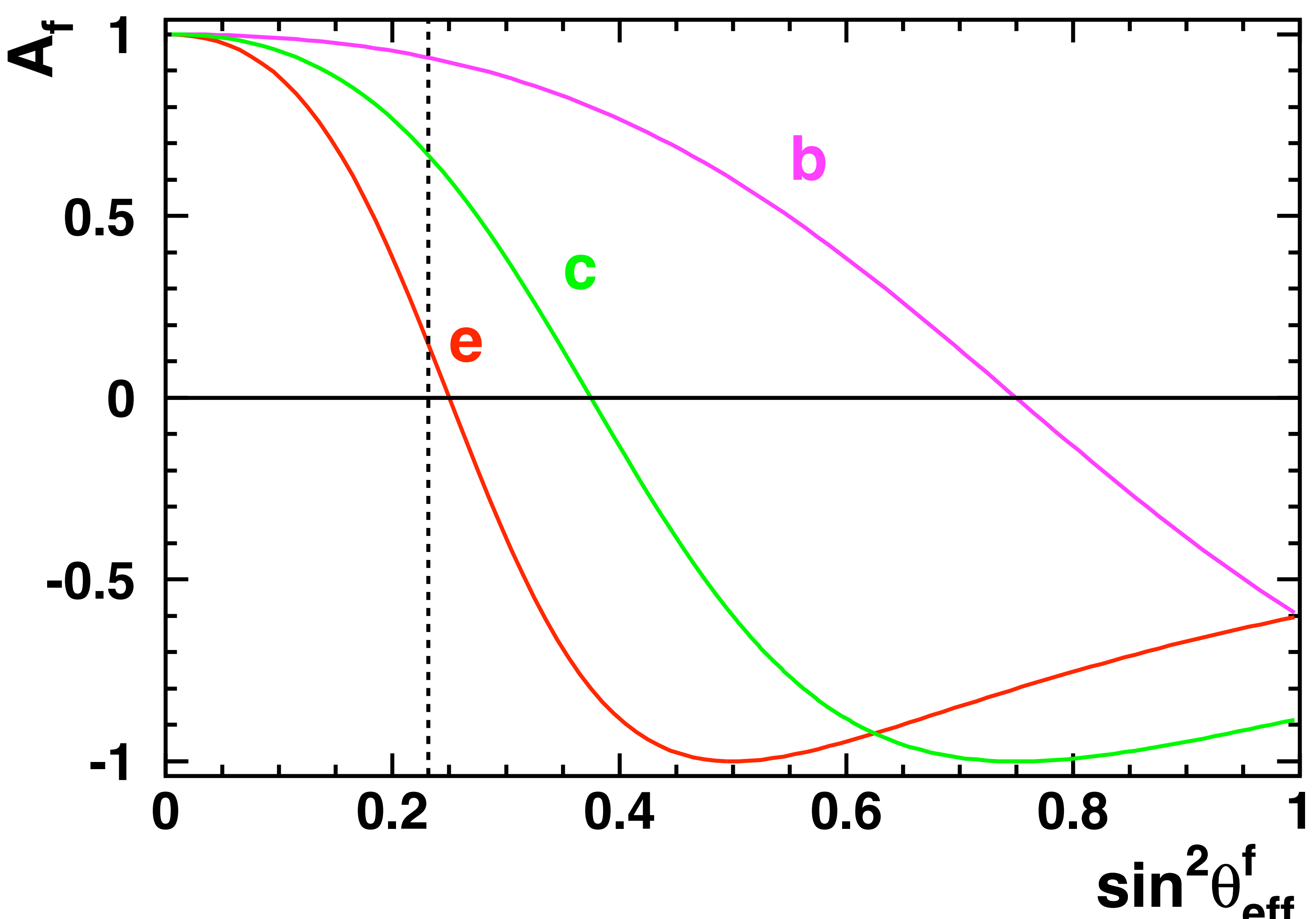
$$g_{Vf} = \sqrt{\bar\rho}\left(T_f^{(3)} - 2Q_f \sin^2\theta_{eff}\right)$$

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

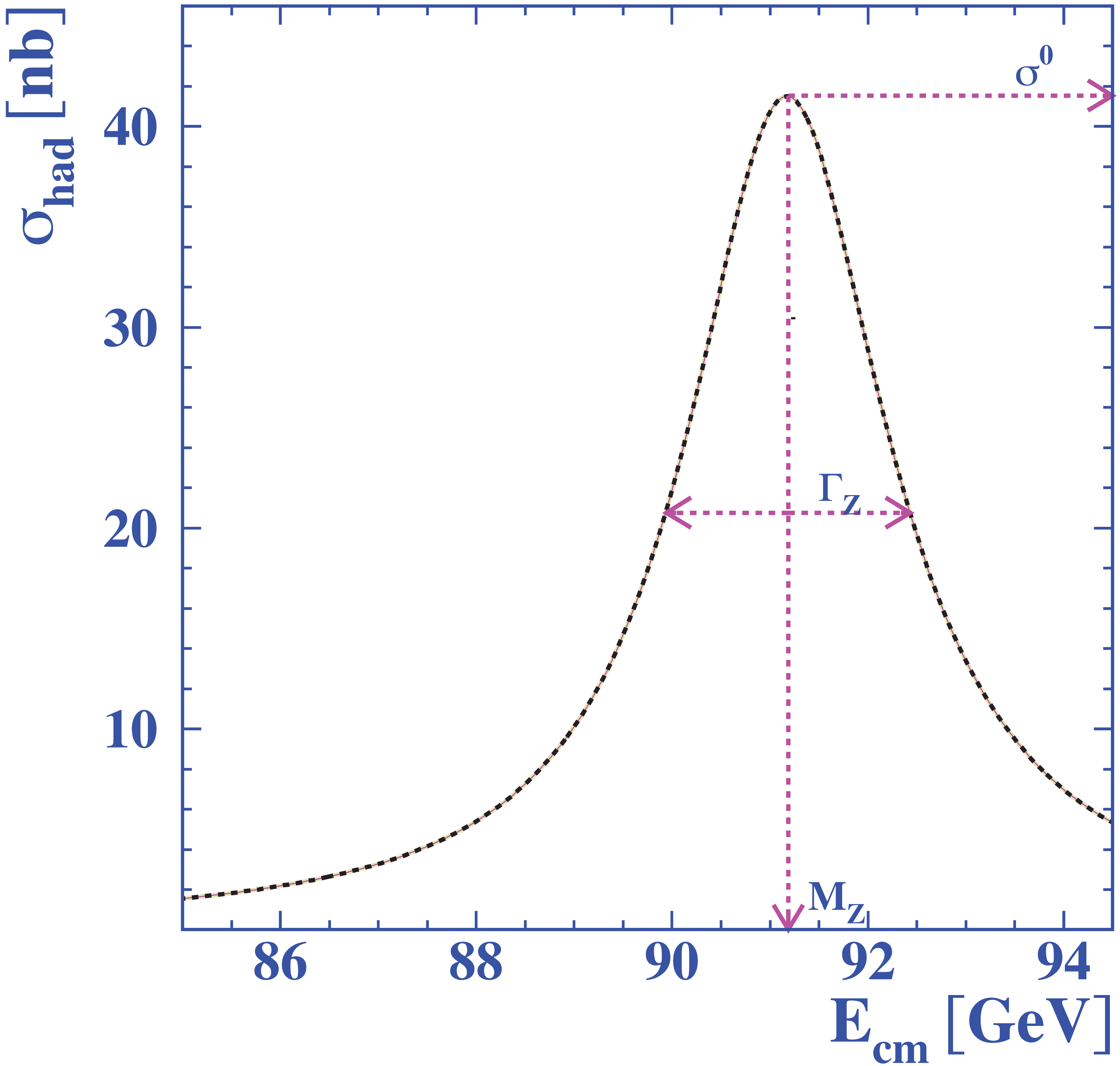
$$\mathcal{A}_f = 2\frac{g_{Vf}\,g_{Af}}{g_{Vf}^2 + g_{Af}^2} = 2\frac{g_{Vf}/g_{Af}}{1+(g_{Vf}/g_{Af})^2}$$

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

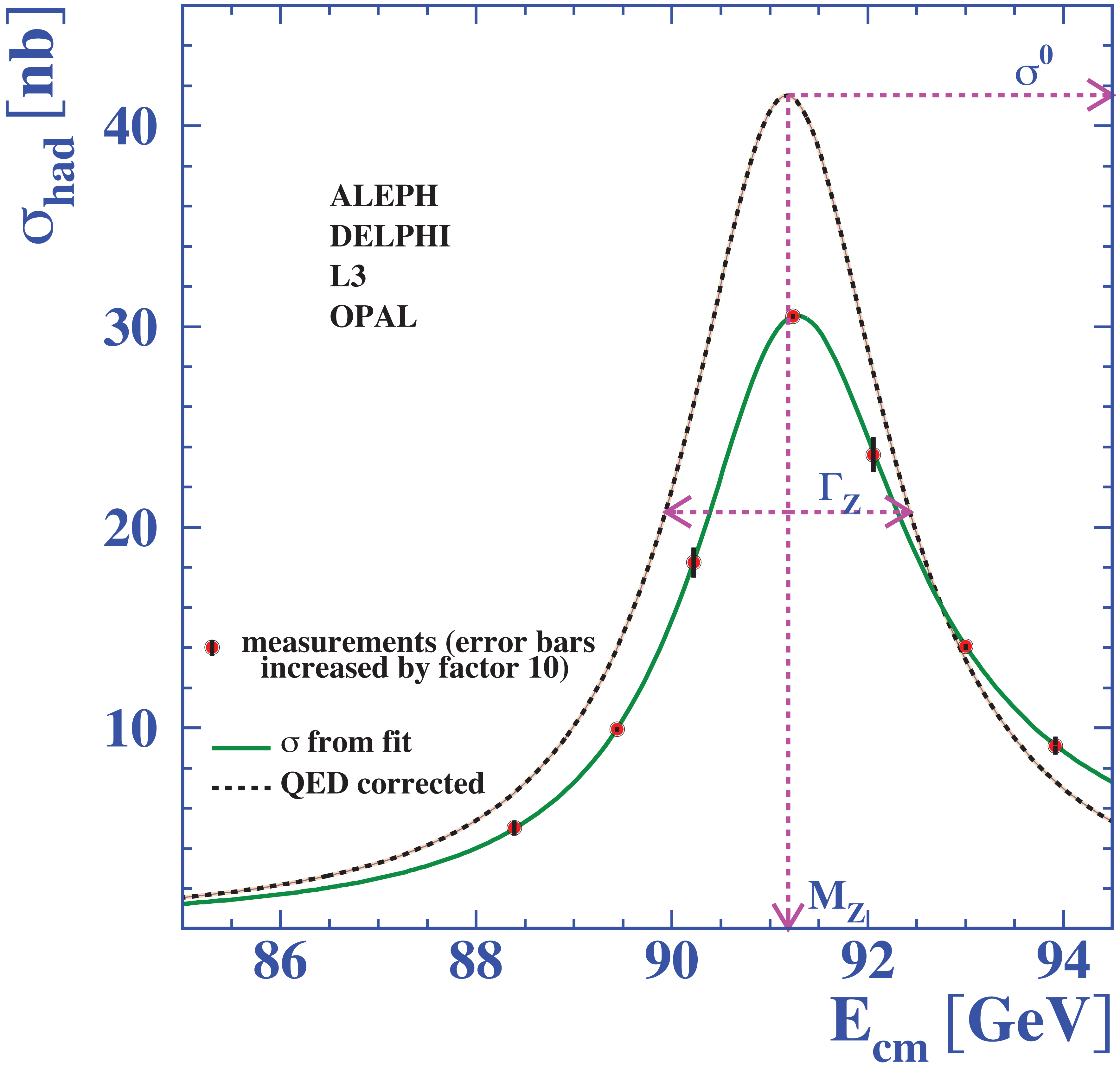
$$\Gamma_{f\bar f} = \frac{G_F m_Z^3}{6\pi\sqrt{2}}(g_{Vf}^2 + g_{Af}^2)$$



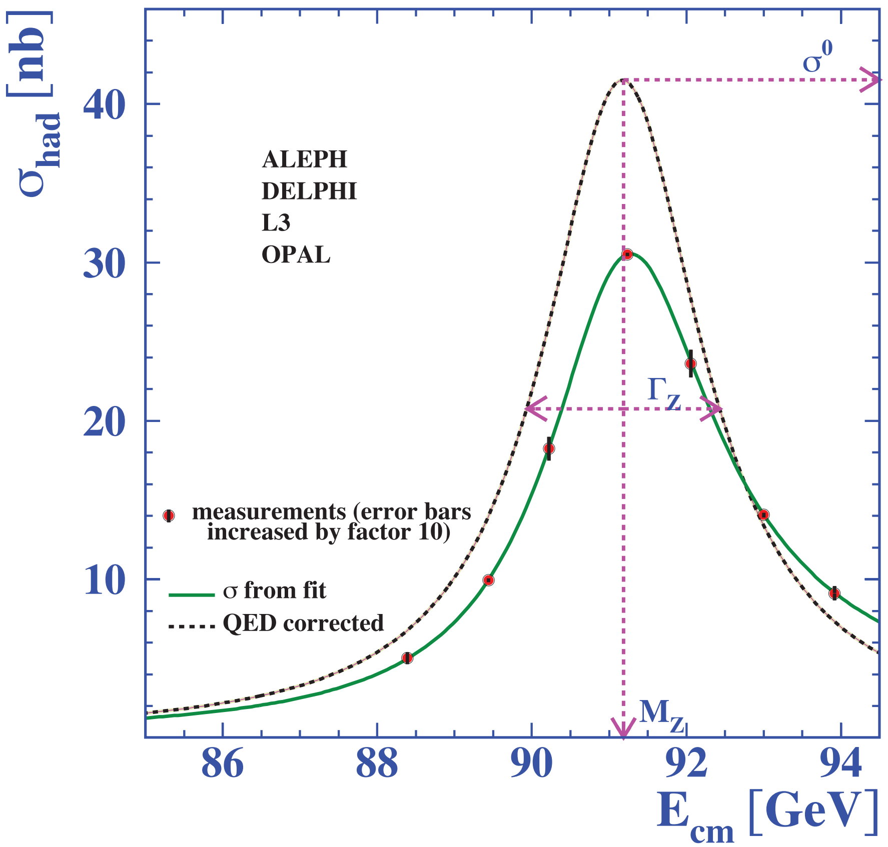
What we would like to have measured



What we really measured



What we really measured



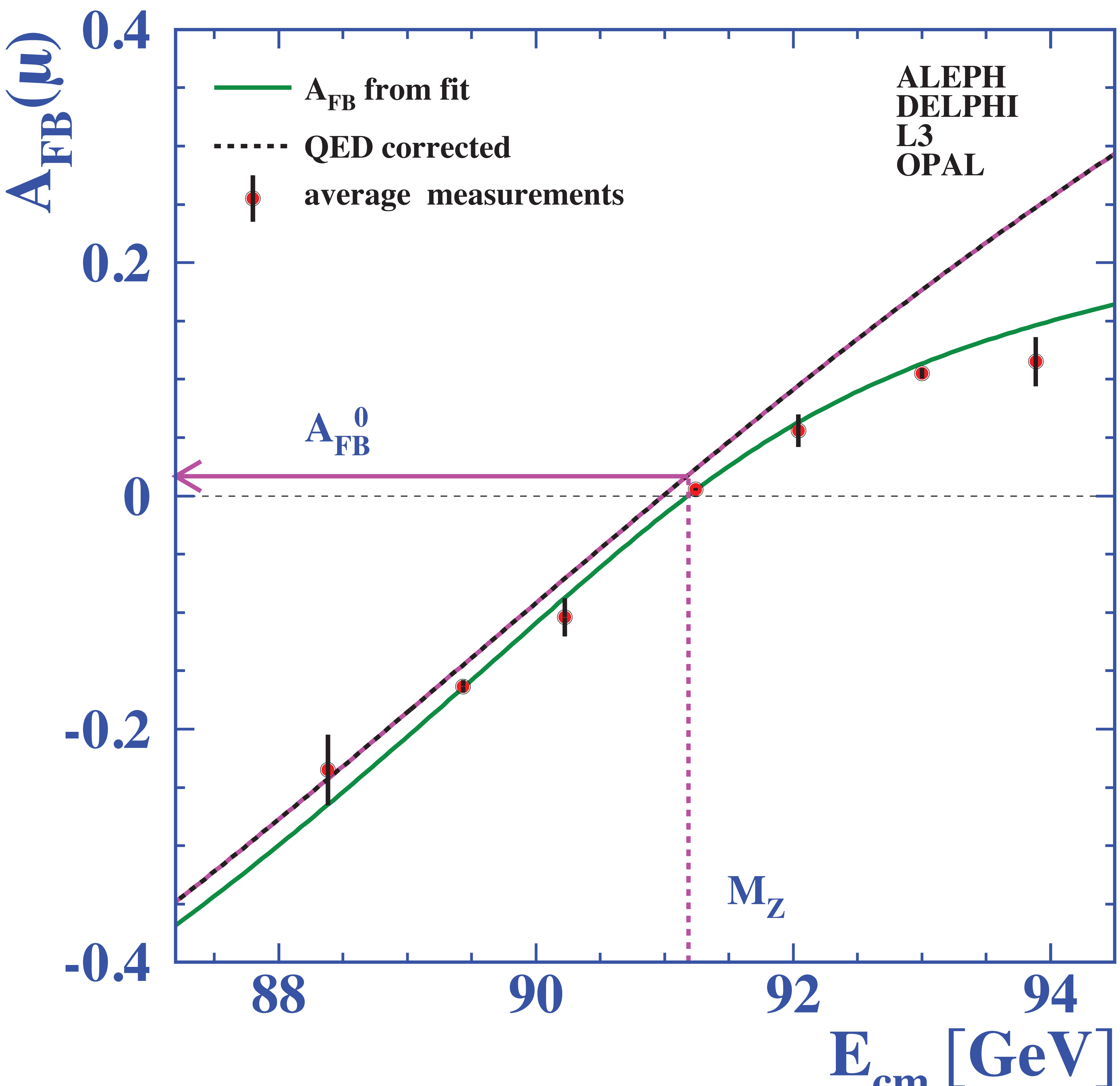
- Handled with a QED radiator function (3rd order):

$$\sigma(s) = \int_{4m_f^2/s}^{1} dz\, H_{QED}^{tot}(z,s)\,\sigma_{ew}(zs)$$

Behrends, van Neerven, Burgers; Montagna, Nicrosini, Piccinni; Jadach, Skryzpek, Pietrzyk,

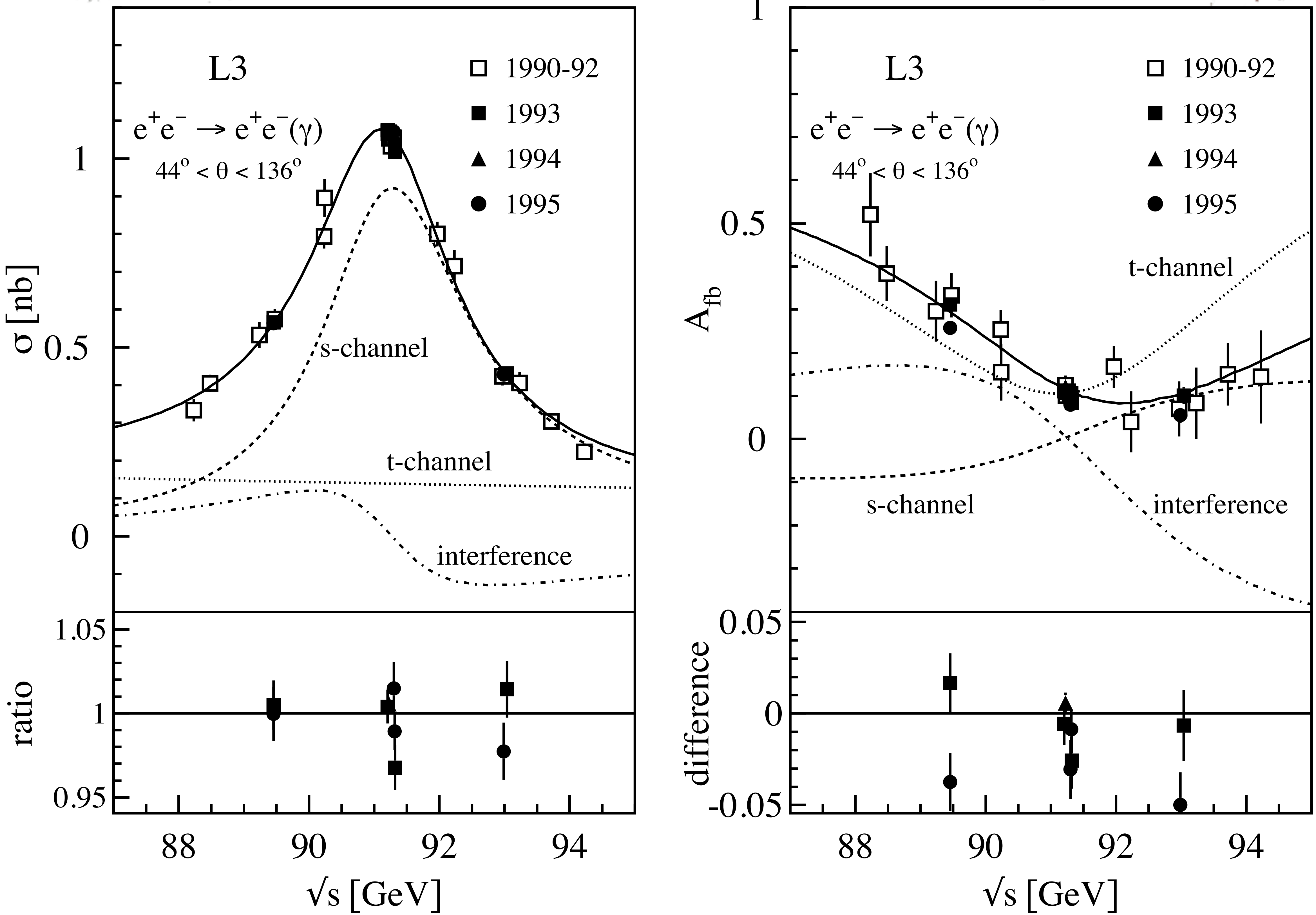
- Estimated error:
  - 0.3 MeV on m_Z
  - 0.2 MeV on Γ_Z
  - 0.02% on σ^0_{had}

Ditto for forward-backward Asymmetries



- Residual uncertainty:
  - 0.0001 on A_{FB}^0

Special care: electron final states

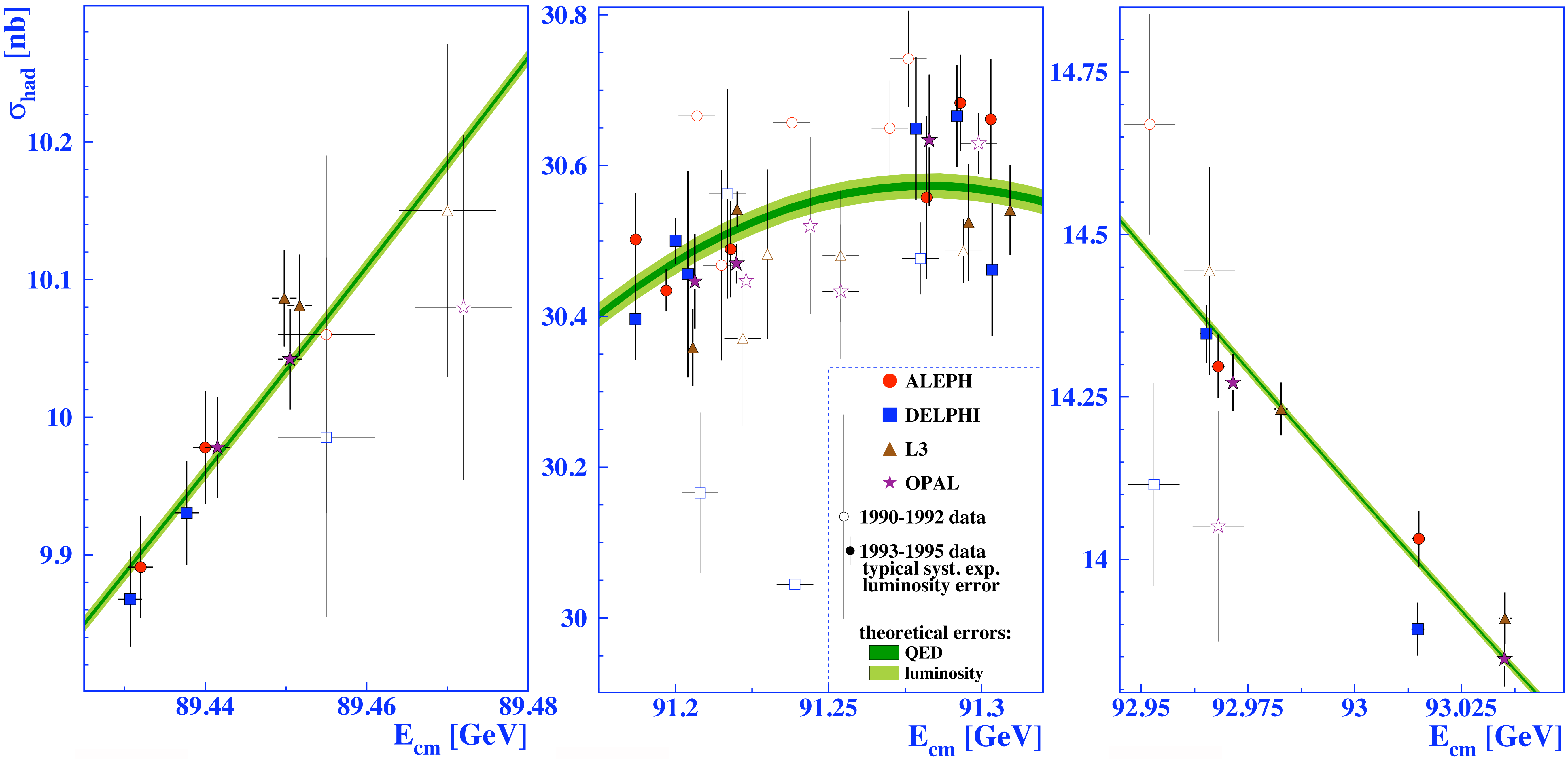


Uncertainty: ~1.1 pb for σ_F; ~0.3 pb for σ_B

Beenakker, Passarino

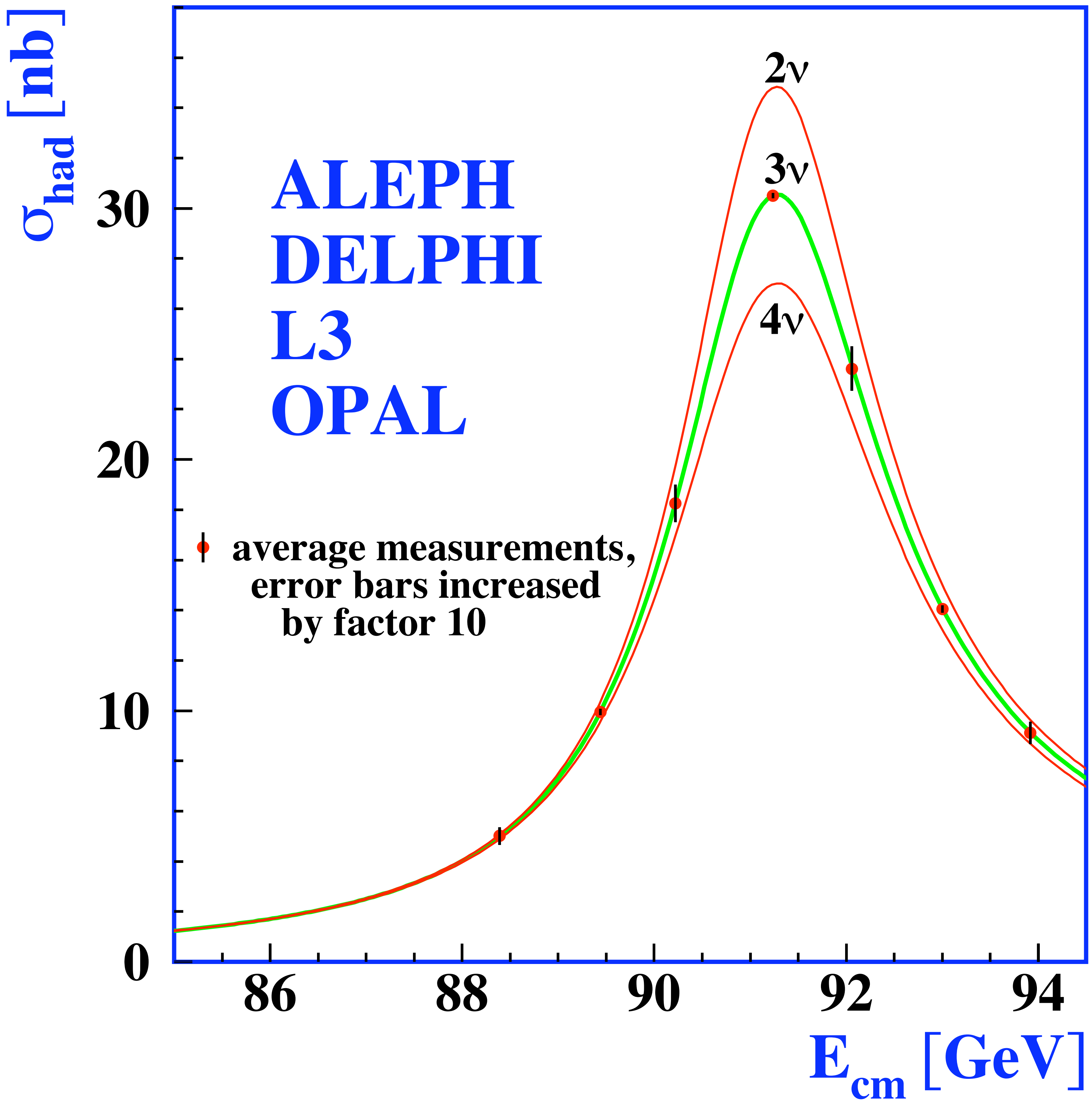
What was actually measured

Hadronic Cross-section



Peak -2GeV　　Peak　　Peak +2GeV

Number of neutrino generations



$N_\nu = 2.9840 \pm 0.0082$

Standard Model tests: leptonic couplings

SM :

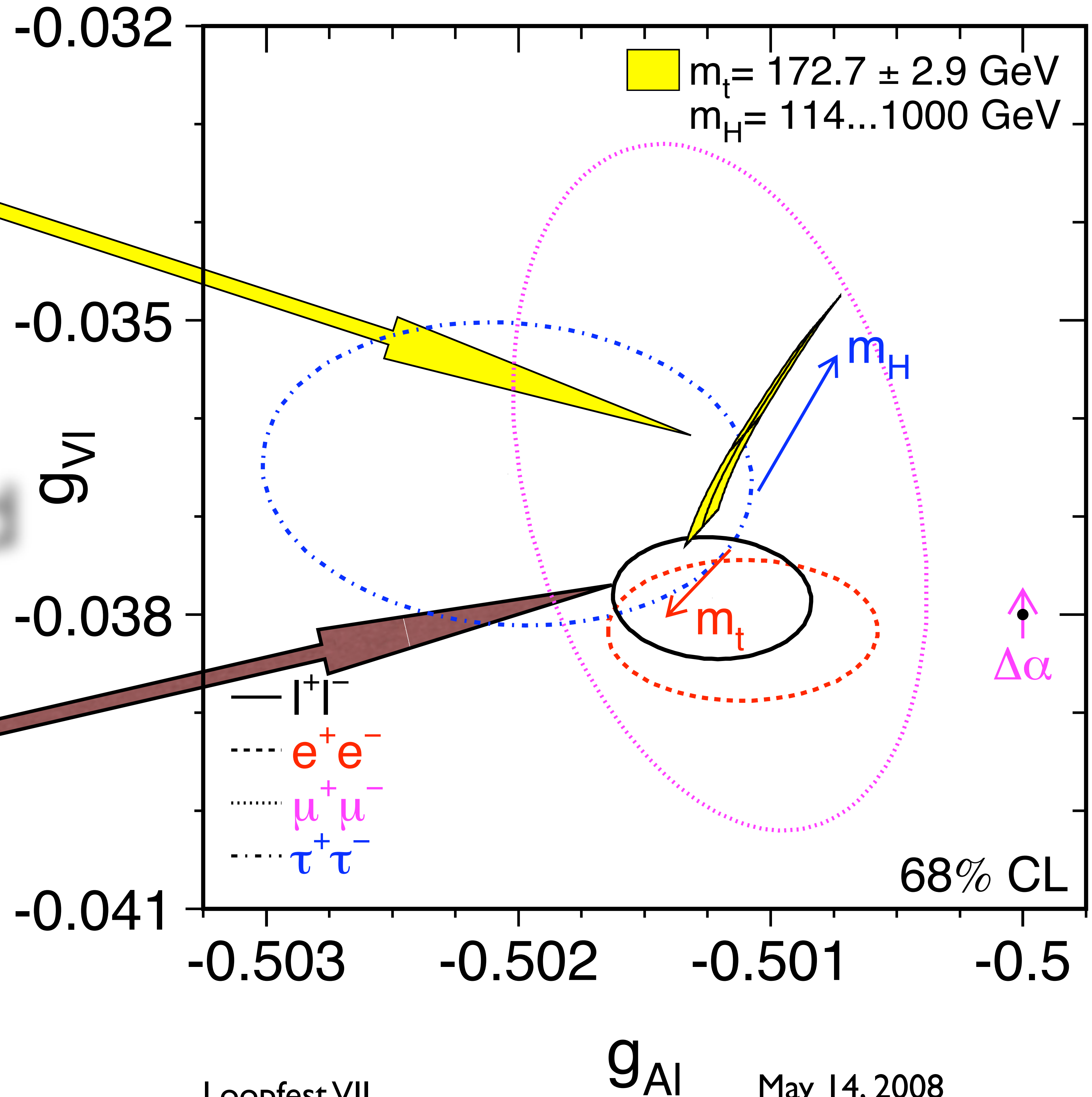
$m_H = [114, 1000]$ GeV

$m_t = 172.7 \pm 2.9$ GeV

Note: old m_t!

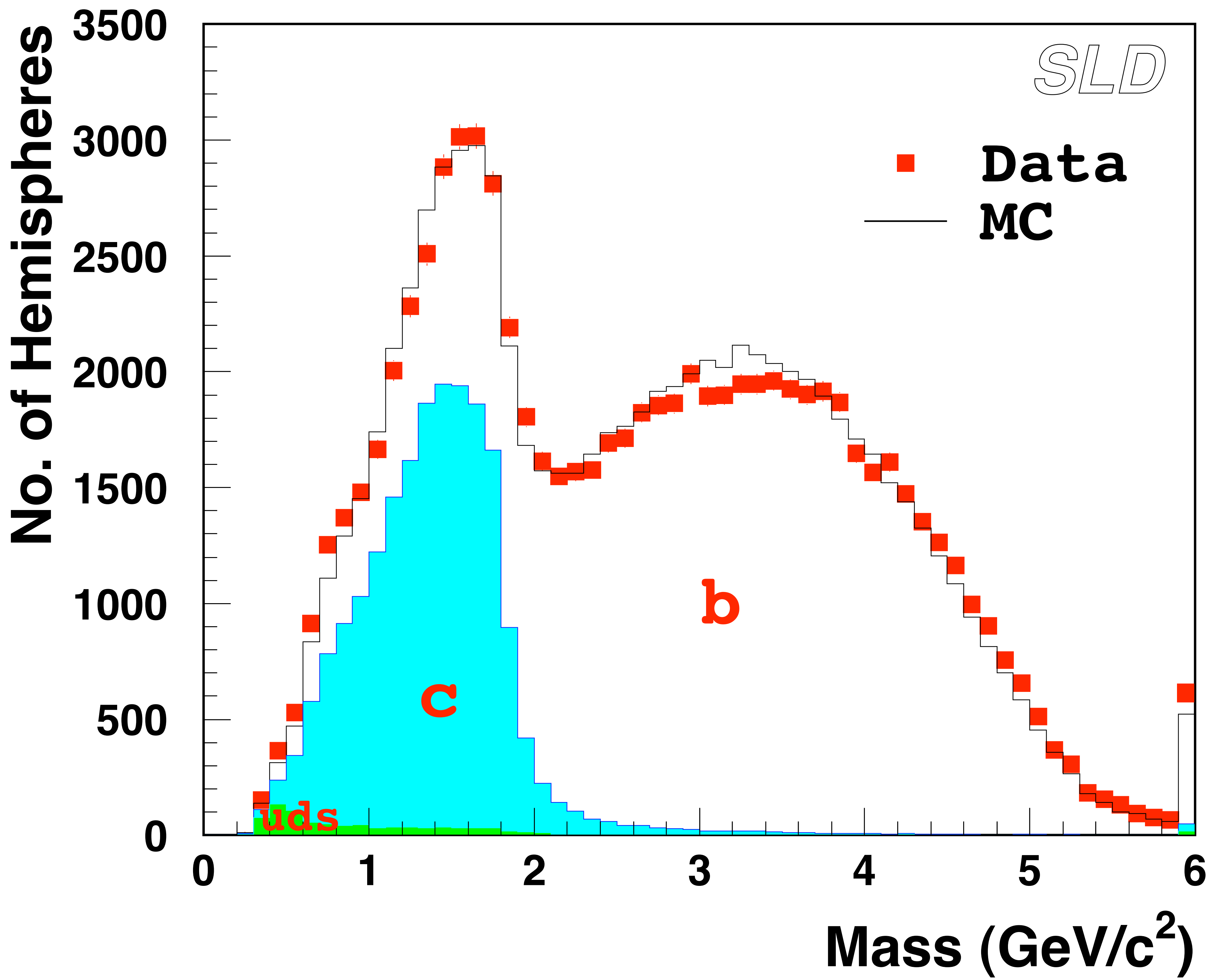
Low m_H favored

lepton universality

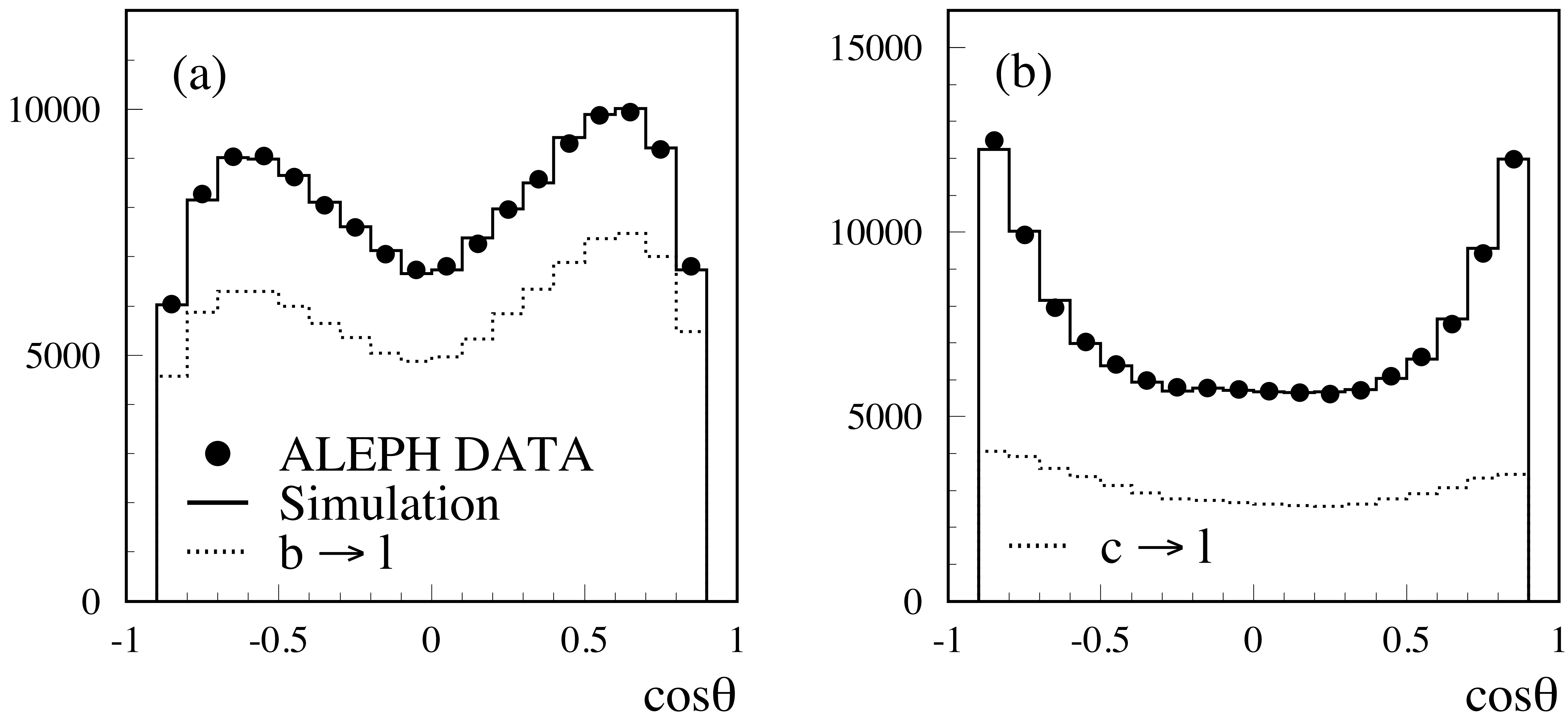


Heavy Flavor Selection Techniques

- Mass tags

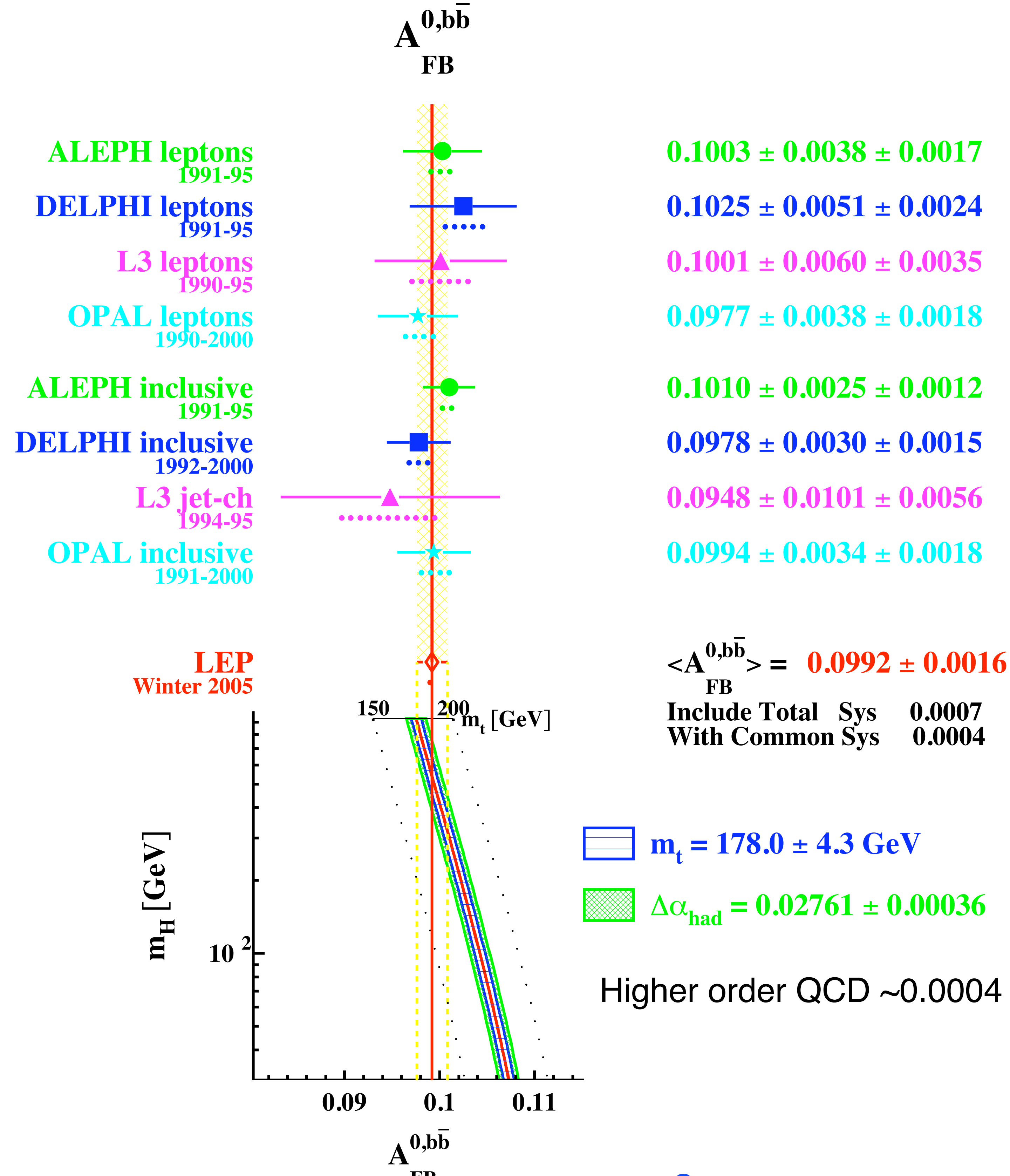


An Example Asymmetry

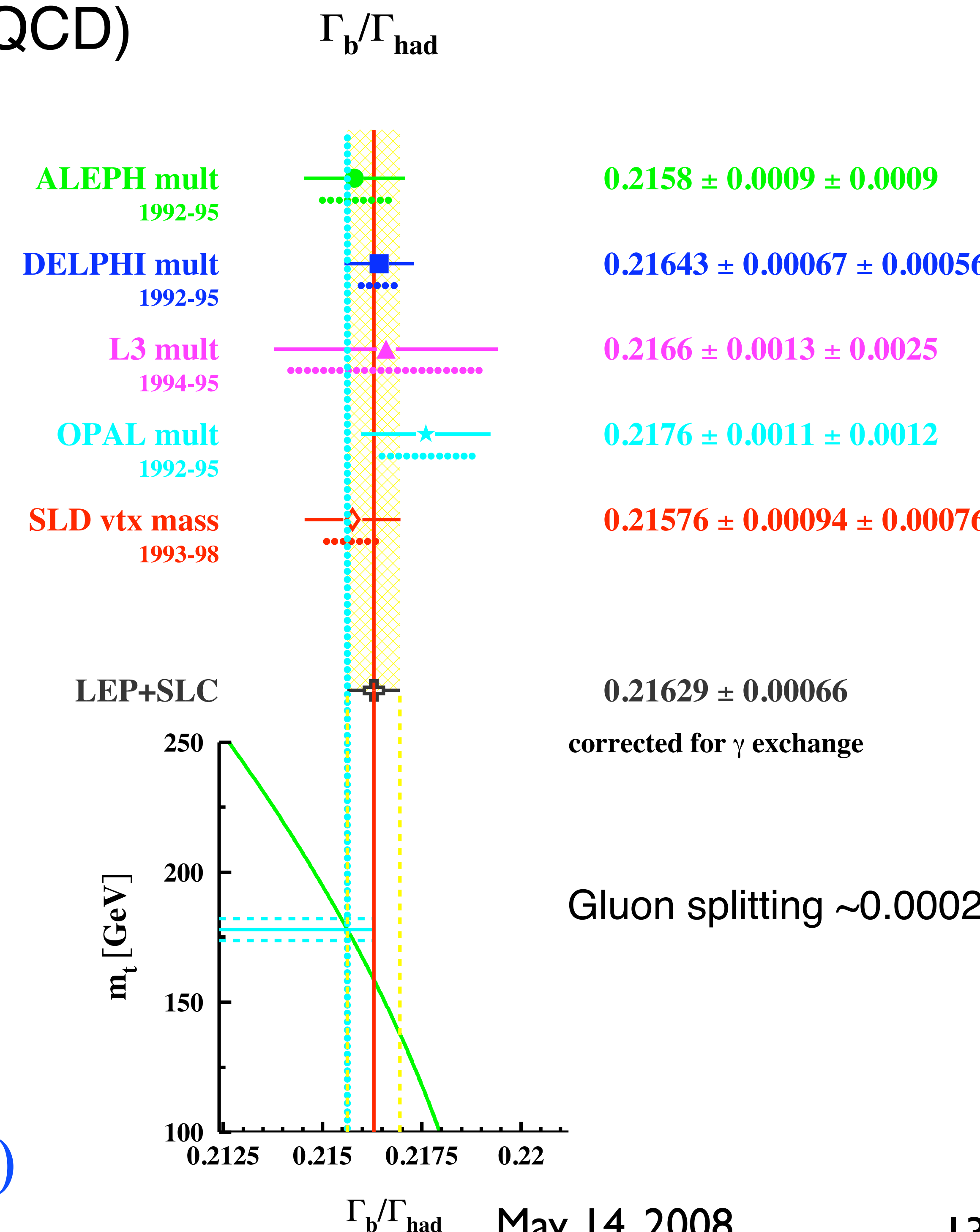


Effective couplings for quarks

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



Higher order QCD ~0.0004

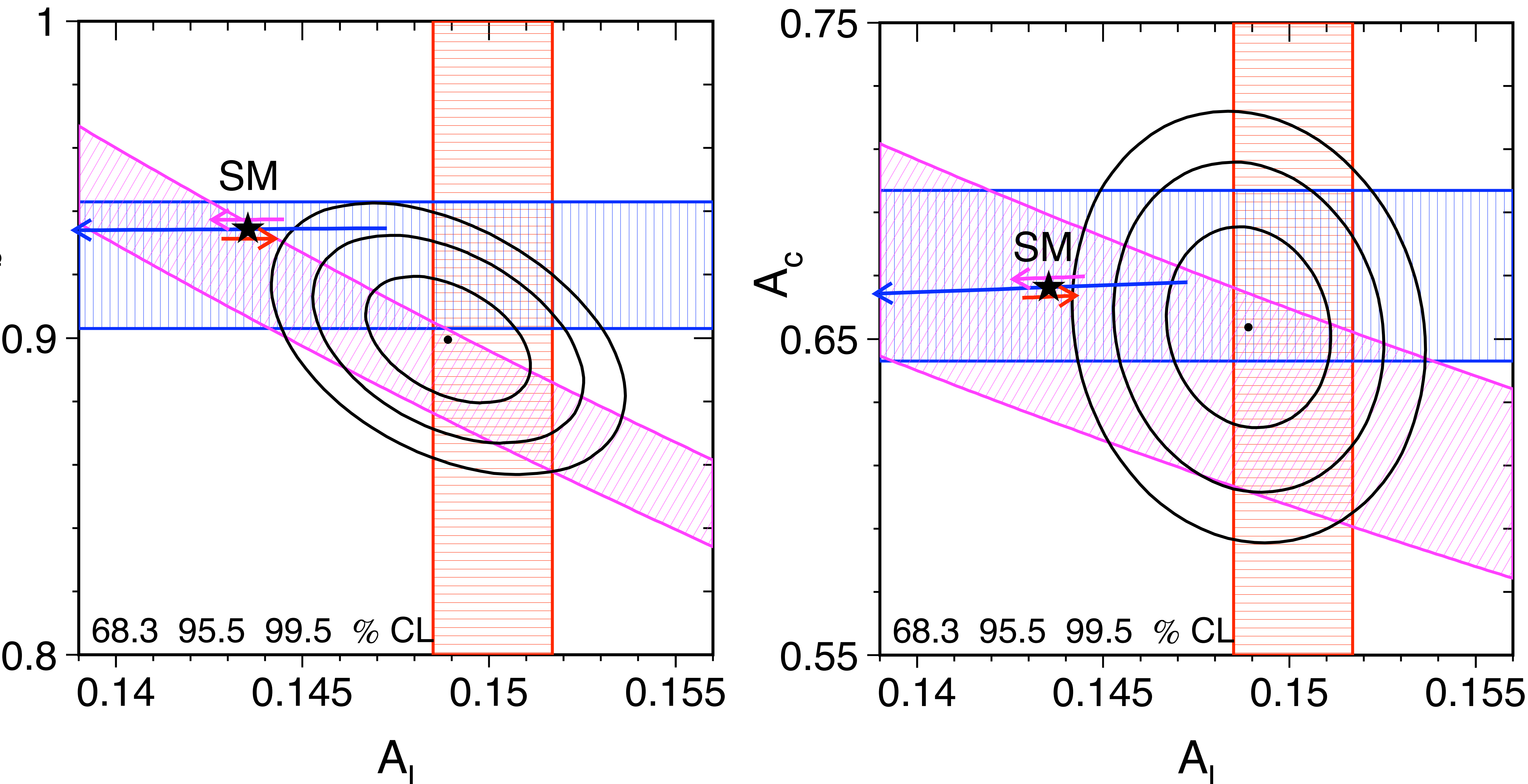


Gluon splitting ~0.00023

$$\chi^2 = 53/(105-14)$$

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); $\longleftarrow m_H \in [114, 1000]$



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

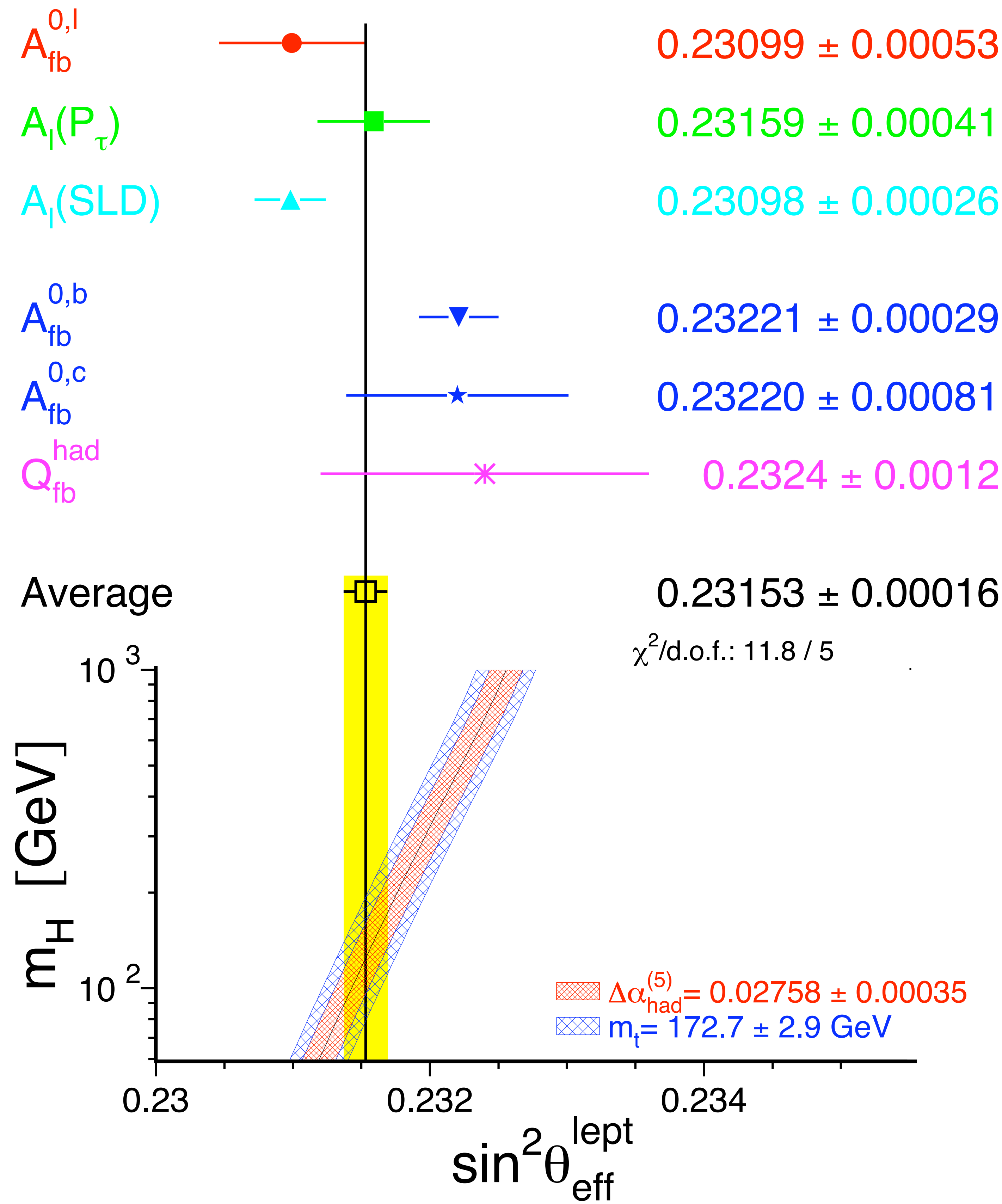
Standard model tests: $\sin^2\theta_{eff}^{lept}$

Assuming lepton universality:

$$\chi^2/\text{dof(lept.)} = 1.6/2\ (P = 44.0\%)$$
$$\chi^2/\text{dof(hadr.)} = 0.02/2\ (P = 98.8\%)$$
$$\chi^2/\text{dof(tot.)} = 11.8/5\ (P = 3.7\%)$$

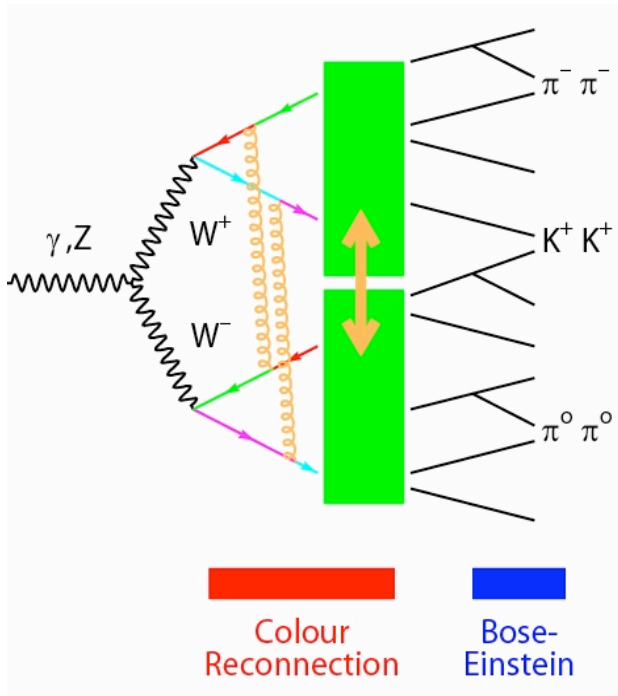
hadrons *vs* leptons 3.2σ

3.2σ between 2 most precise quantities ($\mathcal{A}_\ell$ and $A_{FB}^{0,b}$)



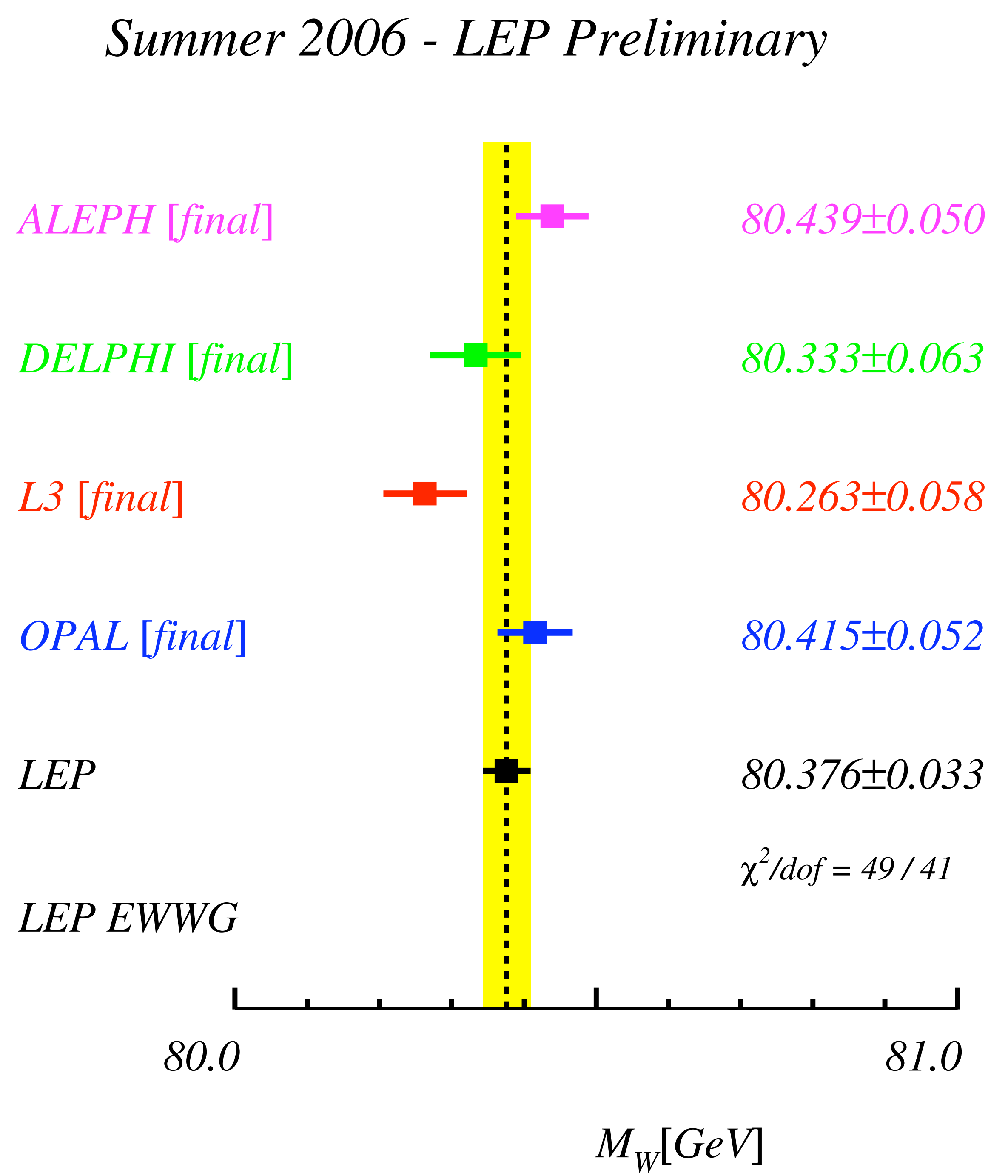
W mass from LEP

- Two types of events used:
  - qqqq
  - qqlν
- Both have similar branching ratios, but currently qqqq contribute only 10% weight:
  - Bose-Einstein
  - Color reconnection dominant error in qqqq final state (35 MeV)



  - Experimental cross-check: qqqq and qqlν differ by $\Delta m_W = -12 \pm 45$ MeV

Results final; only combination is preliminary



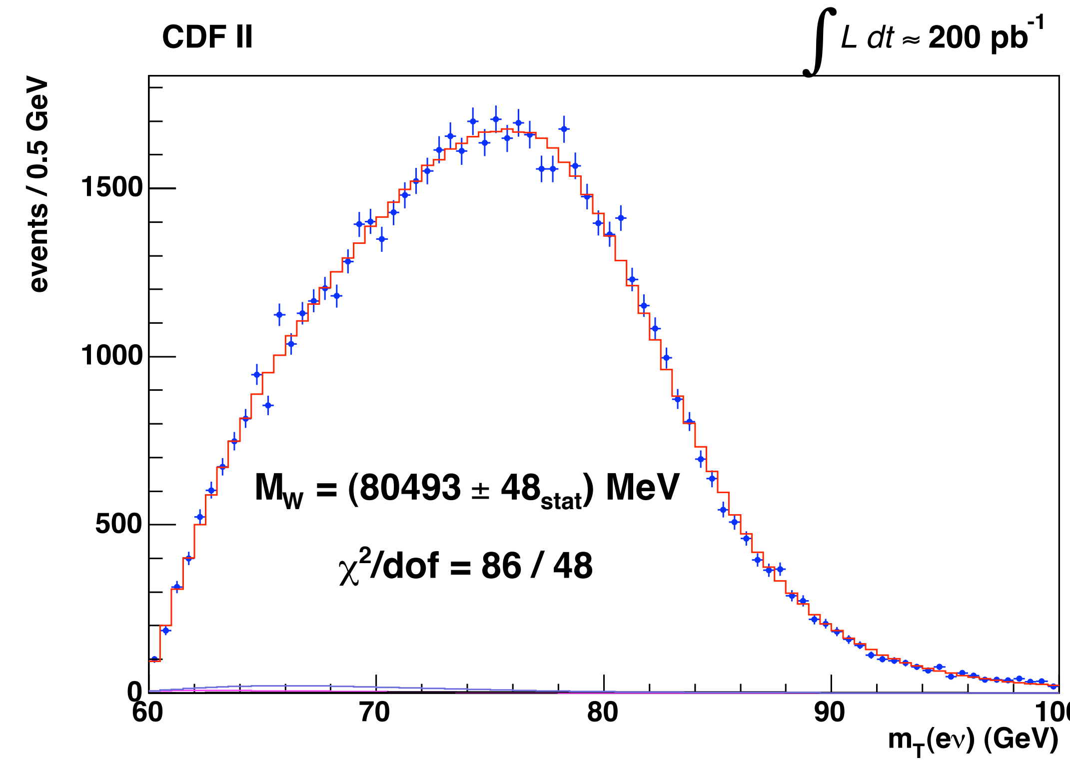
$$m_W = 80.376 \pm 0.025(\text{stat}) \pm 0.022(\text{sys})\ \text{GeV}$$

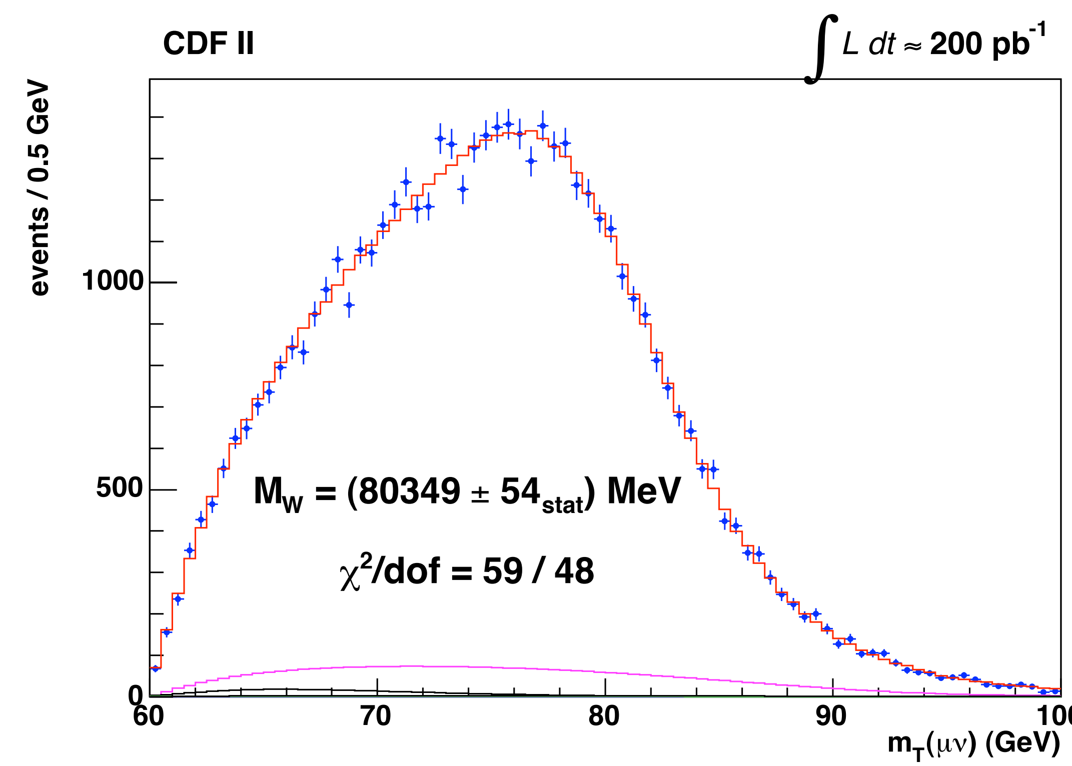
W mass from Tevatron + Combination

- All Run I results FINAL
- CDF/DØ fit transverse mass
- Systematics are coming down with increased statistics:
  - Energy scale controlled by Z events
  - Hadronic recoil also constrained by Z events
- CDF Run II: with only 200 pb-1, already the best single measurement:

$$m_W = 80.413 \pm 0.034(\text{stat}) \pm 0.034(\text{sys})\ \text{GeV}$$

PDFs and QED account for 17 MeV



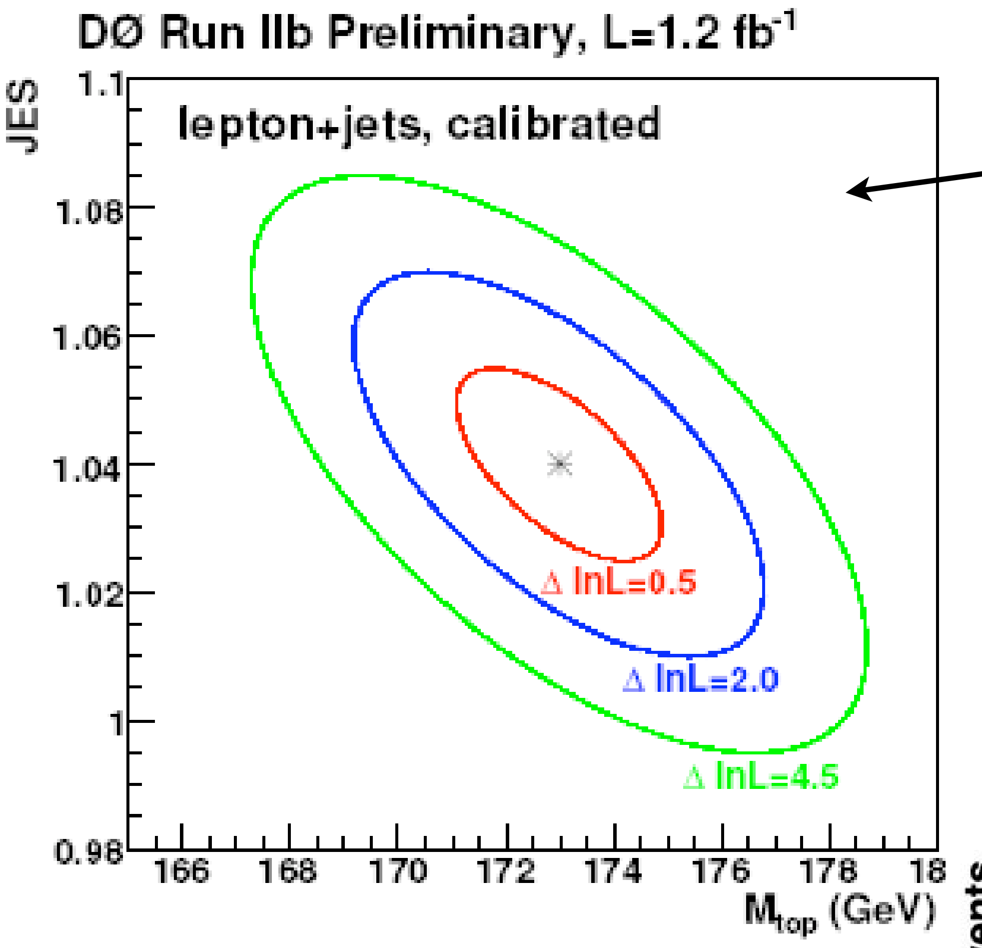


For consistency, the LEP and Tevatron experiments use m_W with a running width: $\frac{d\sigma}{dm} \propto \frac{m^2}{(m^2 - m_W^2)^2 - m^4\Gamma_W^2/m_W^2}$

$$m_W = 80.398 \pm 0.025\ \text{GeV}$$

LEP + Tevatron

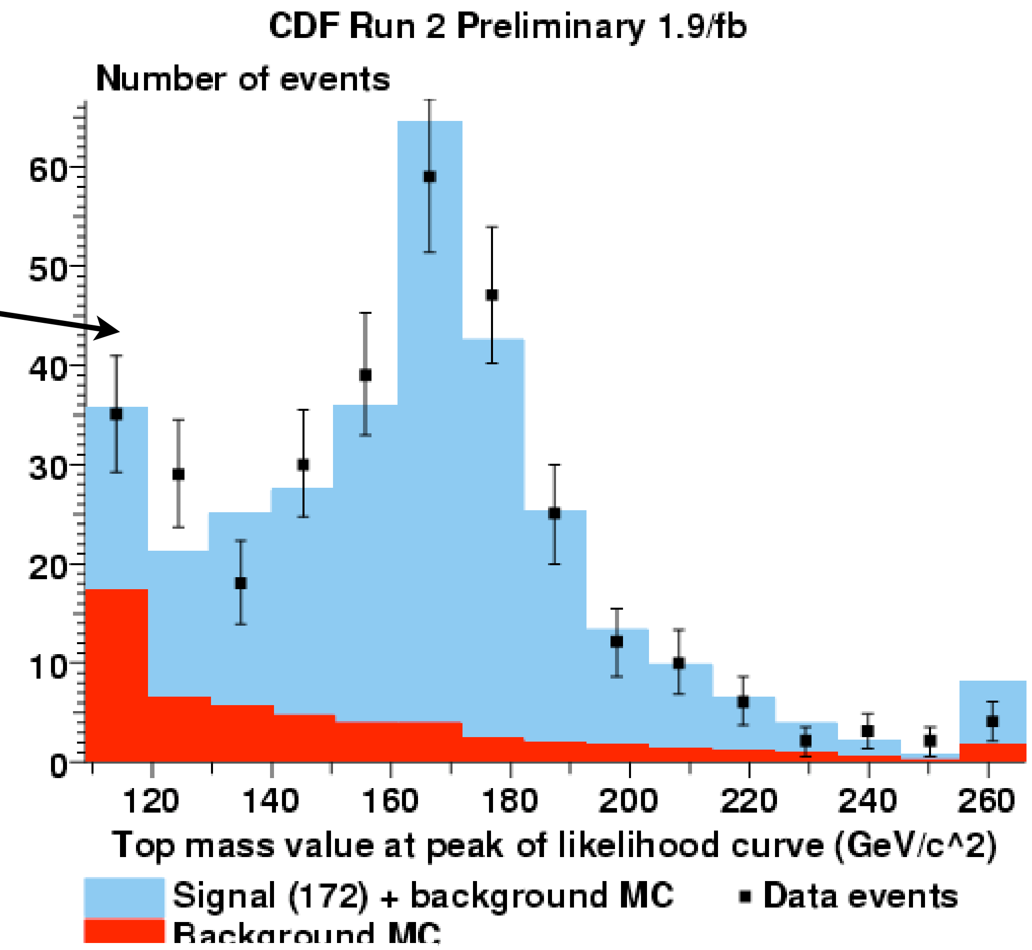
Top quark mass

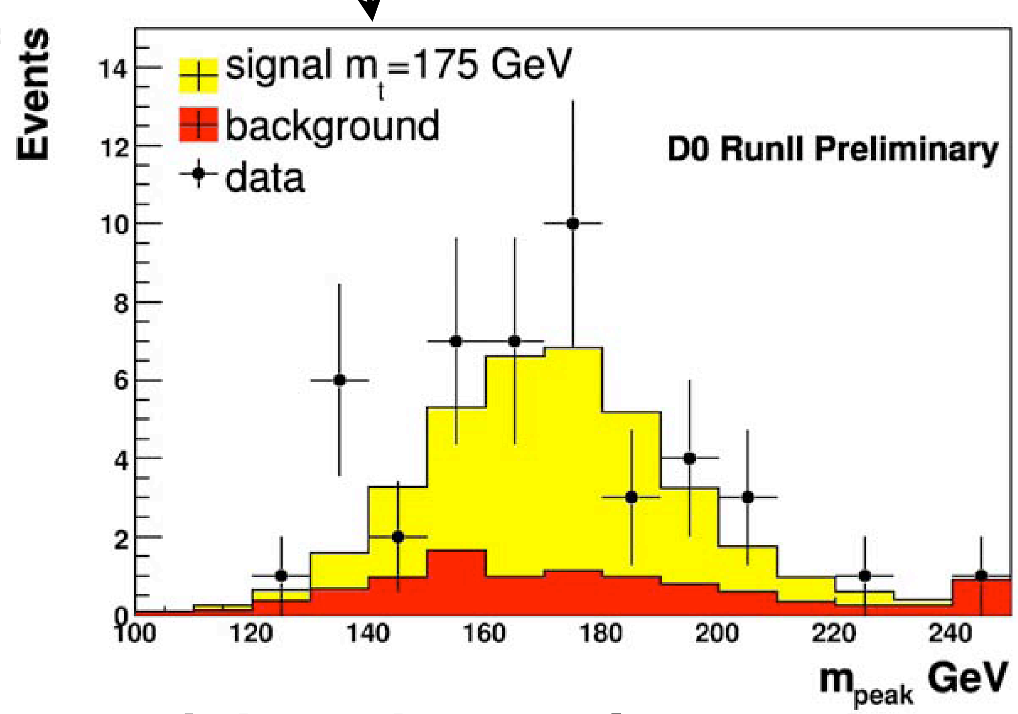


lepton+jet

Examples

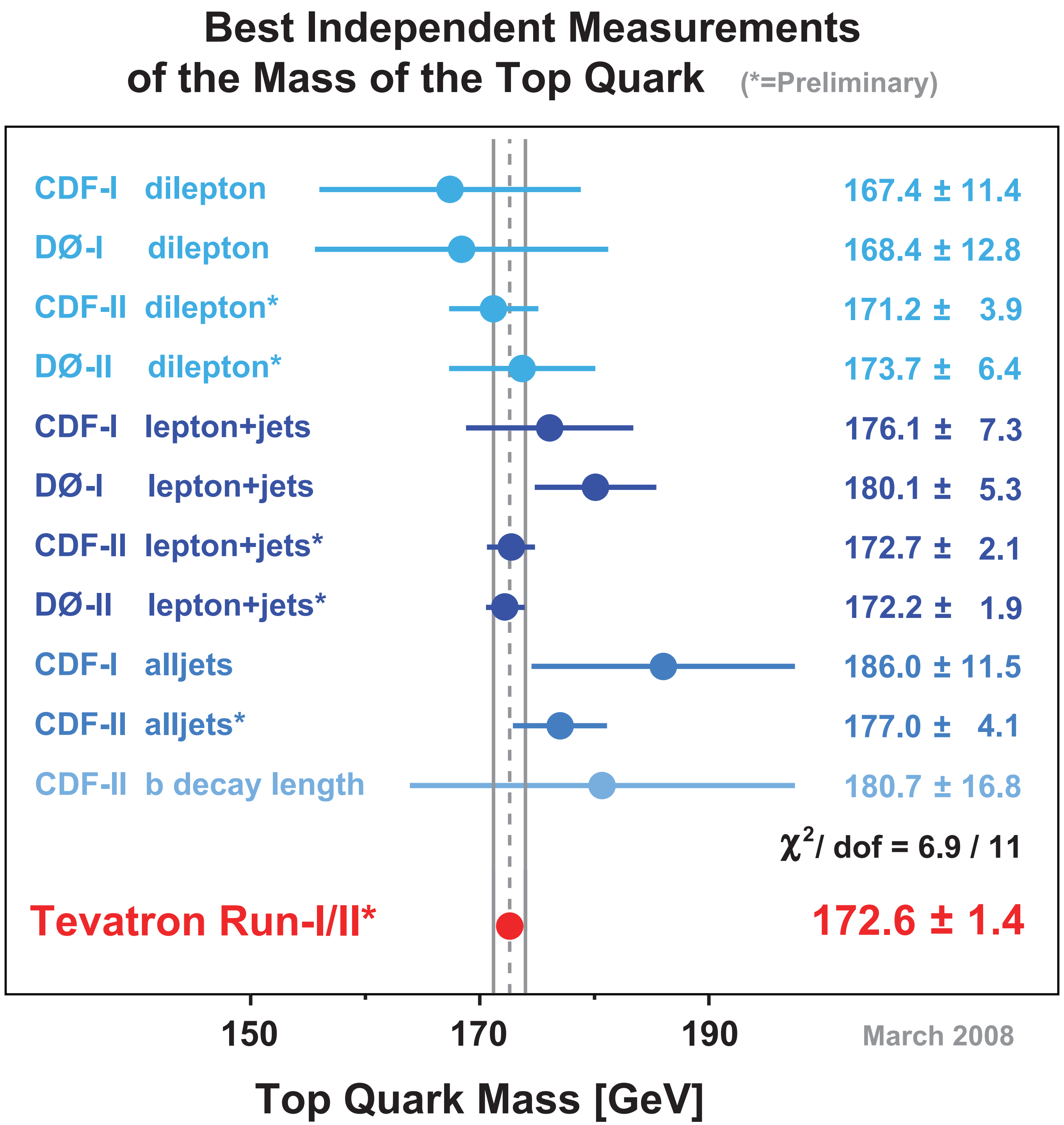
dileptons





Experiments use a combination of matrix element and template methods to fit for the top mass

Top quark mass



- Dominant systematic errors in the combination:
  - JES: 0.9 GeV
  - “Signal” (ISR, FSR, PDF): 0.5 GeV
  - Backgrounds: 0.4 GeV
- CDF/D0 control/measure using data → all should decrease with more luminosity...

$$m_t = 172.6 \pm 0.8 \pm 1.1 \text{ GeV}$$

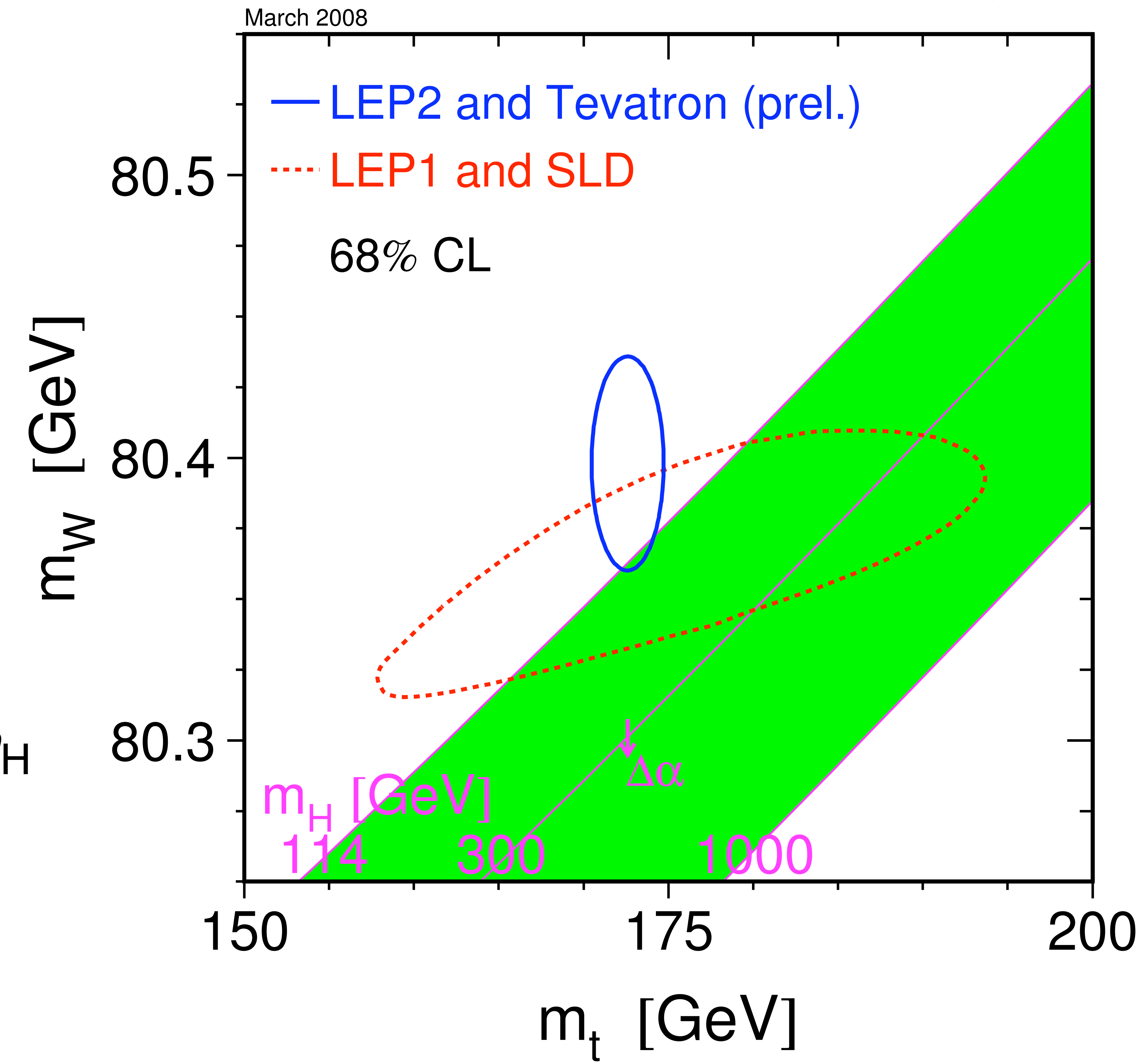
What is m_t?

- The error on m_t is now getting close to the width of the top quark…
- What exactly is m_t?
  - PMAS(6,1) in Pythia!
  - Pole mass?
  - Something else?
- What are effects of Γ_t?
- Need to know that what we measure and what we compare to SM makes sense.

The electroweak fit: cross-checks

- Excellent agreement between direct and indirect

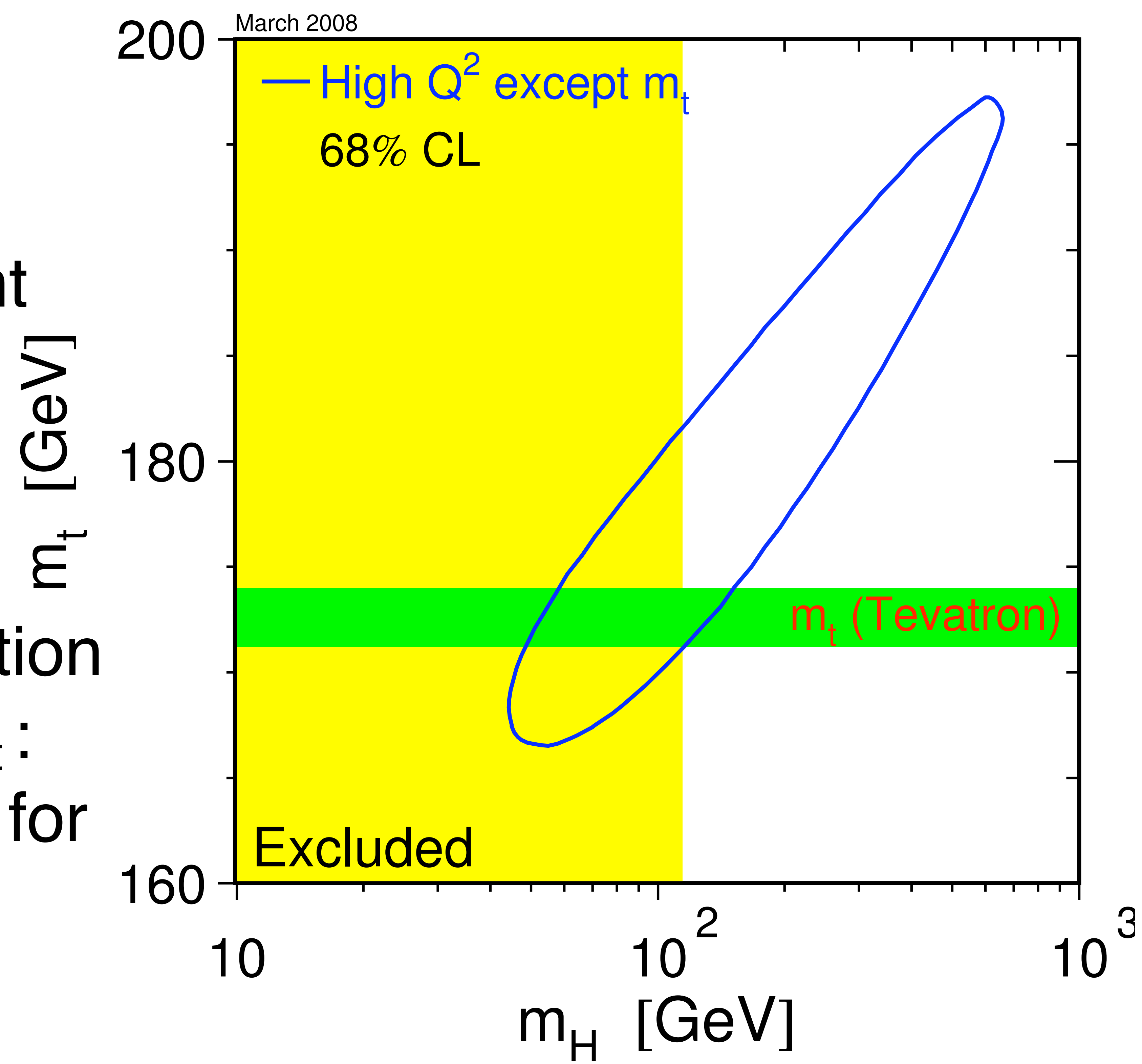
- Both prefer low m_H



The electroweak fit: cross-checks

- Including m_W, still excellent agreement

- Note strong correlation between m_H and m_t: thank you Tevatron for m_t !



The global EW fit

- The 5 primary fit results:

$$\begin{aligned}
\Delta\alpha^{(5)}_{\rm had} &= 0.02767 \pm 0.0034 \\
\alpha_s(m_Z) &= 0.1185 \pm 0.0026 \\
m_Z &= 91.1874 \pm 0.0021 \text{ GeV} \\
m_t &= 172.8 \pm 1.4 \text{ GeV} \\
m_H &= 87^{+36}_{-27} \text{ GeV} \\
(\log m_H &= 1.94 \pm 0.16)
\end{aligned}$$

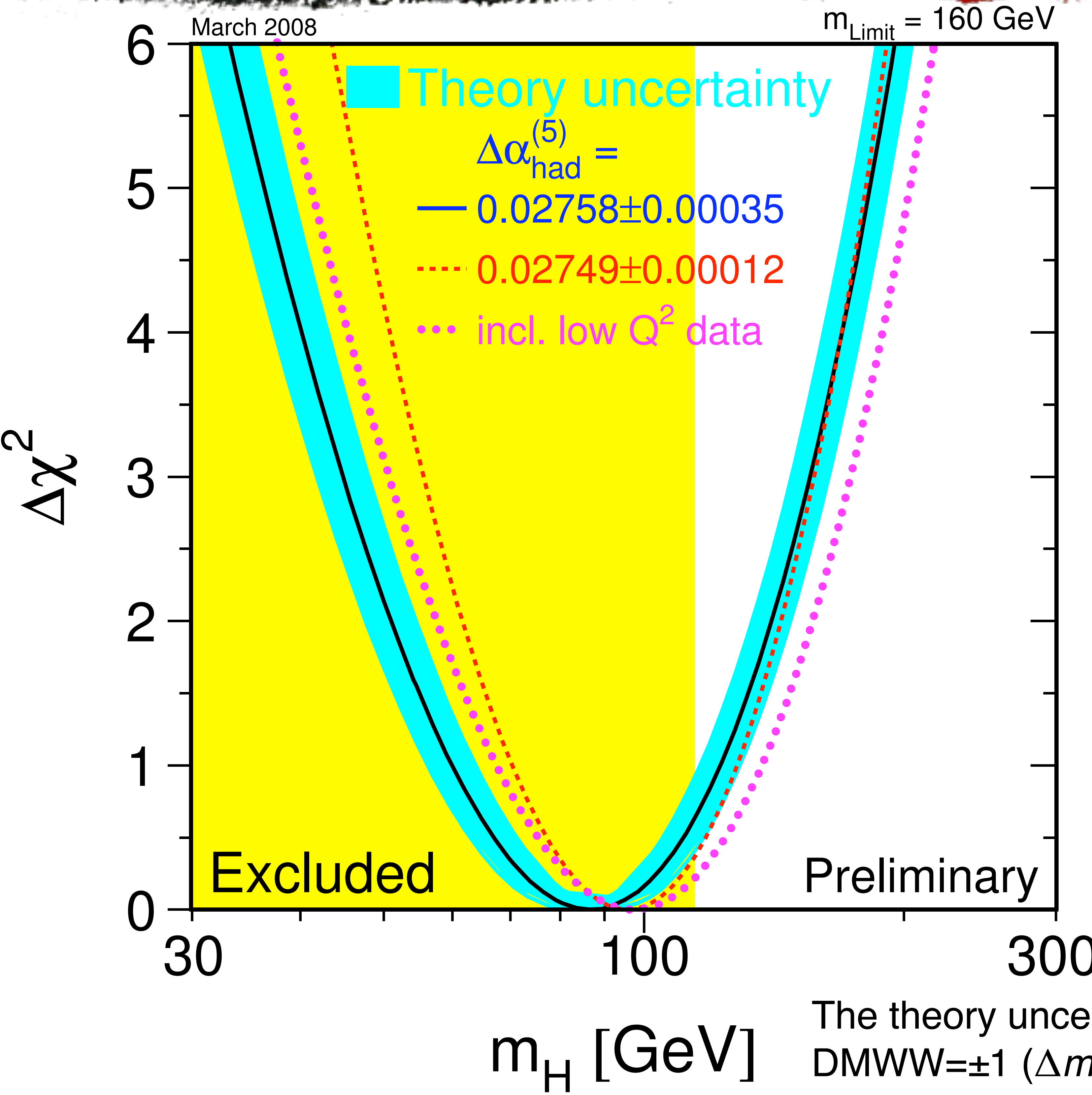
- The largest correlations are between

  $\log m_H$ and m_t (0.32) and
  $\log m_H$ and $\Delta\alpha^{(5)}_{\rm had}$ (–0.56)

- The fit is good:

$$\chi^2/\text{dof} = 17.2/13 \quad (19\%)$$

The global fit: limits on the Higgs mass



$m_H < 160$ GeV (95% CL)

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

Complete two-loop calculations exist for m_W Freitas, Hollik, Walter, Weiglein; Awramik, Czakon, Freitas, Weiglein

Fermionic two-loop for $\sin^2\theta_{eff}^{lept}$ Awramik, Czakon, Freitas, Weiglein

The theory uncertainty is estimated by using Zfitter flags DMWW=±1 (Δm_W=±4 MeV) and DSWW=±1 ($\Delta\sin\theta_{eff}$=±5X10^{-5}).

The dominant error is in DSWW.

The global electroweak fit

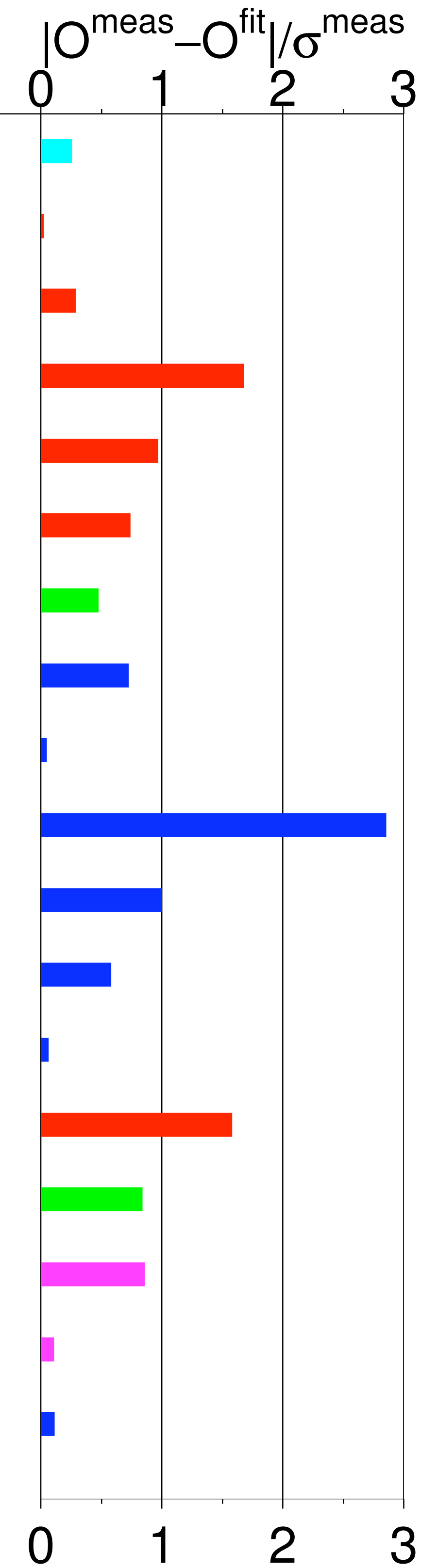
Largest contributions to χ^2 from

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

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

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

	Measurement	Fit
$\Delta\alpha_{had}^{(5)}(m_Z)$	0.02758 ± 0.00035	0.02767
m_Z [GeV]	91.1875 ± 0.0021	91.1874
Γ_Z [GeV]	2.4952 ± 0.0023	2.4959
σ_{had}^0 [nb]	41.540 ± 0.037	41.478
R_l	20.767 ± 0.025	20.743
$A_{fb}^{0,l}$	0.01714 ± 0.00095	0.01643
$A_l(P_\tau)$	0.1465 ± 0.0032	0.1480
R_b	0.21629 ± 0.00066	0.21581
R_c	0.1721 ± 0.0030	0.1722
$A_{fb}^{0,b}$	0.0992 ± 0.0016	0.1038
$A_{fb}^{0,c}$	0.0707 ± 0.0035	0.0742
A_b	0.923 ± 0.020	0.935
A_c	0.670 ± 0.027	0.668
A_l(SLD)	0.1513 ± 0.0021	0.1480
$\sin^2\theta_{eff}^{lept}(Q_{fb})$	0.2324 ± 0.0012	0.2314
m_W [GeV]	80.398 ± 0.025	80.377
Γ_W [GeV]	2.097 ± 0.048	2.092
m_t [GeV]	172.6 ± 1.4	172.8

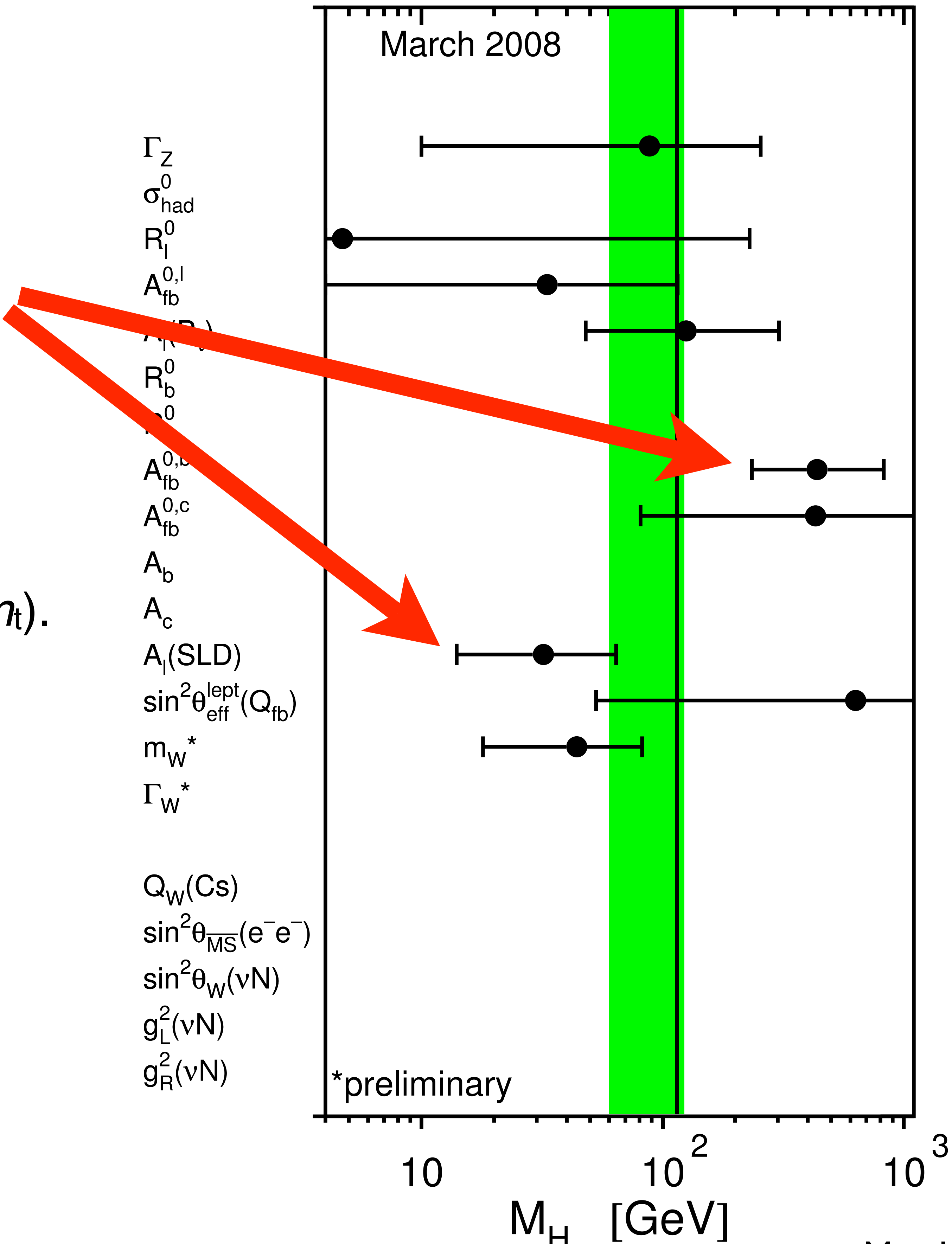


March 2008

Higgs mass and individual measurements

The two “bad” boys:

This plot has correlated constraints ($\Delta\alpha_{had}$, α_s, m_Z, m_t). DON’T try to get m_H from it!



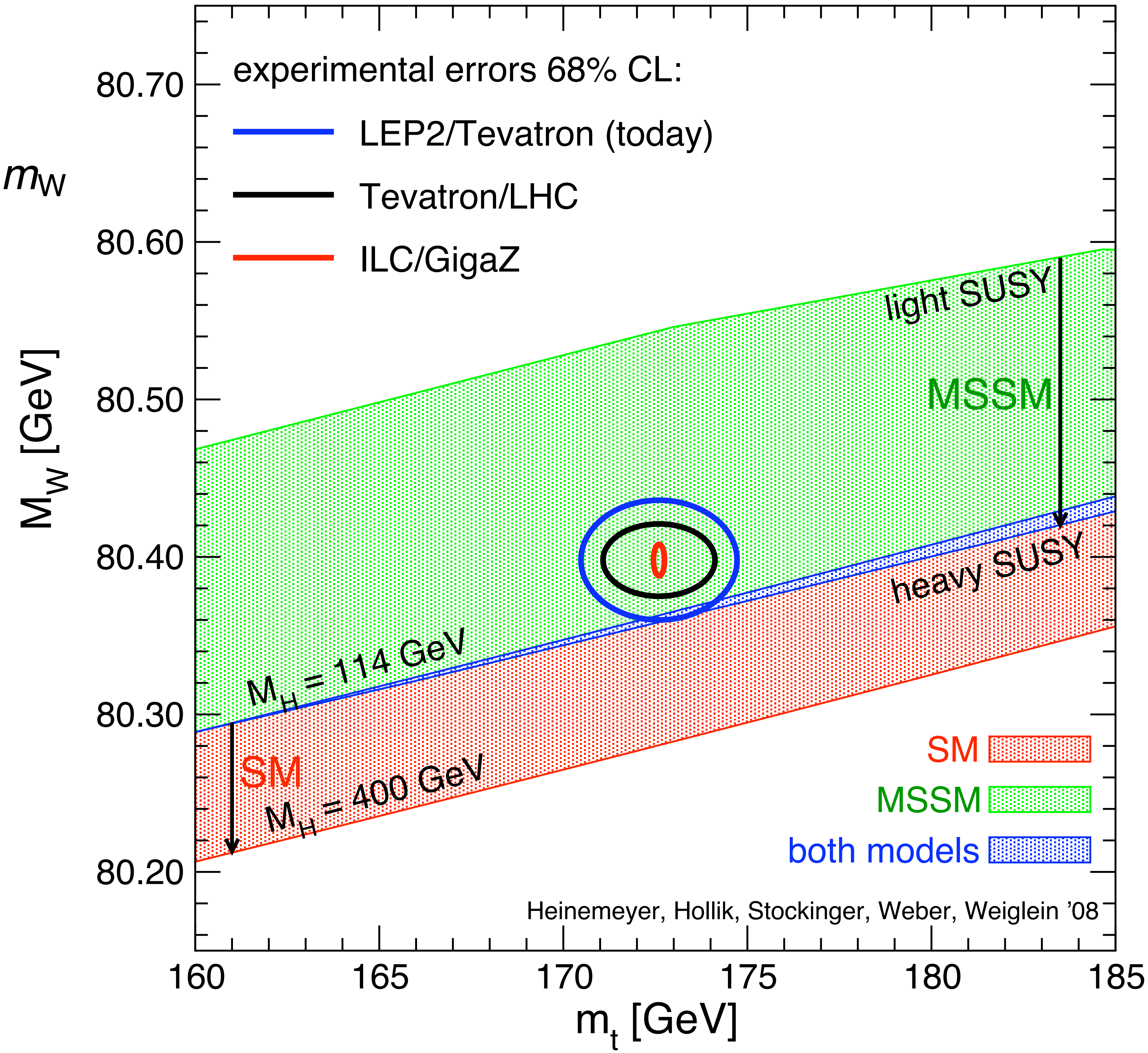
Beyond the SM – the MSSM

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.

Unfortunately, **they** are free!

MSSM seems somewhat more compatible with the data, at least for Heavy SUSY...



Conclusions

- The Standard Model describes with unprecedented precision a huge amount of data
- Theory errors (with the exception of $\sin^2 \theta_{\mathrm{eff}}^{\mathrm{lept}}$) under control.
- The largest discrepancies are due to $\mathcal{A}_\ell$ and to $A_{\mathrm{FB}}^{0,b}$; interpreted as statistical fluctuations they are ≤ 3 σ
- Global fit:

$$m_{\mathrm{H}} < 160 \text{ GeV}$$

- Future inputs:
  - Final results from LEP-II: m_{W}
  - Improved measurements of m_{W}, m_{t} from Tevatron Run II and LHC
- Far far far far future
  - Linear Collider and GigaZ?