Electroweak Results from the Colliders: What do we know about the Higgs?

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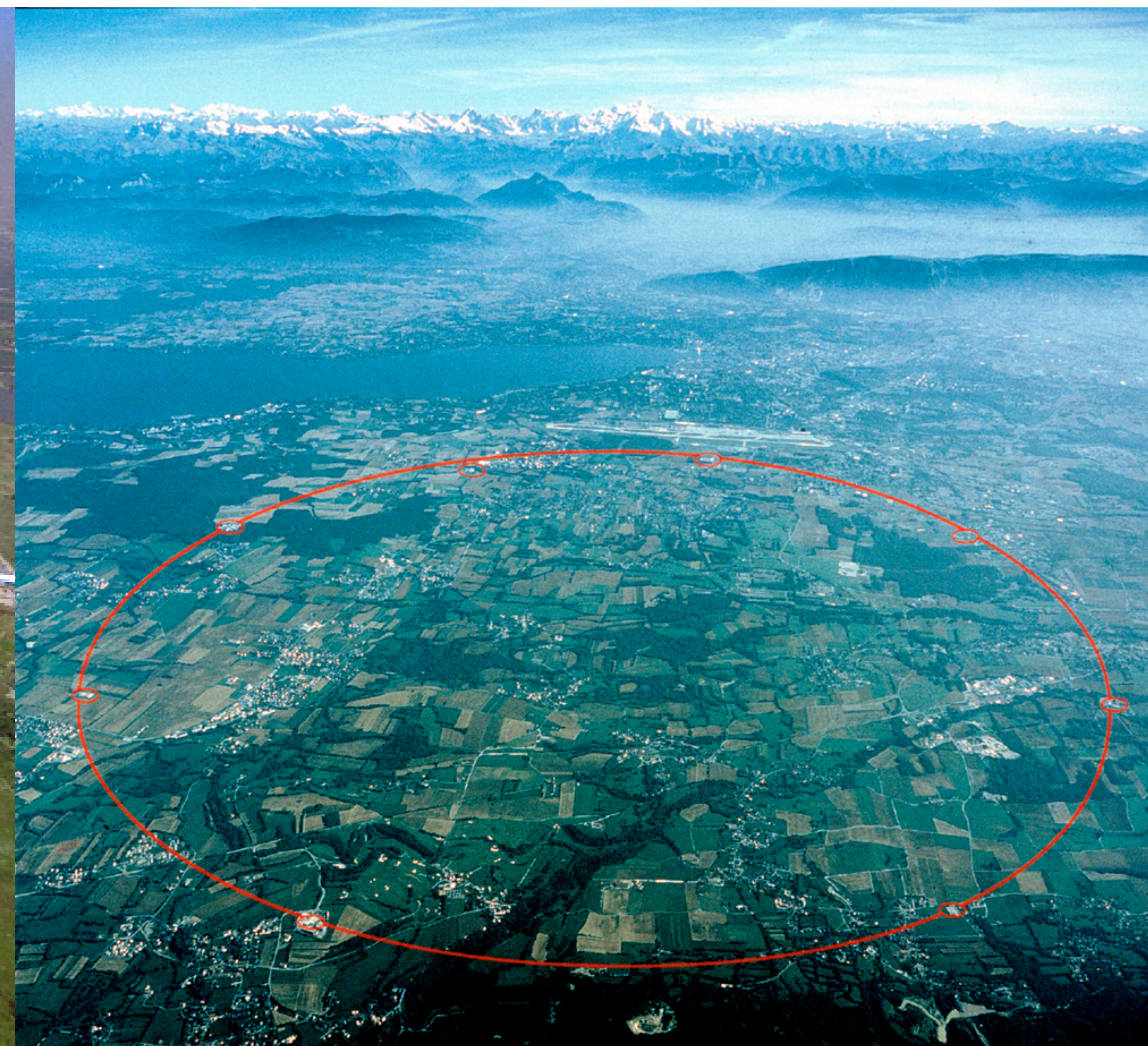
(plus a cast of 1000s!)



Outline

- Electroweak corrections: definitions and strategies
- Experimental inputs
- Effective couplings as a test of the Standard Model
- More experimental inputs
- 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

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

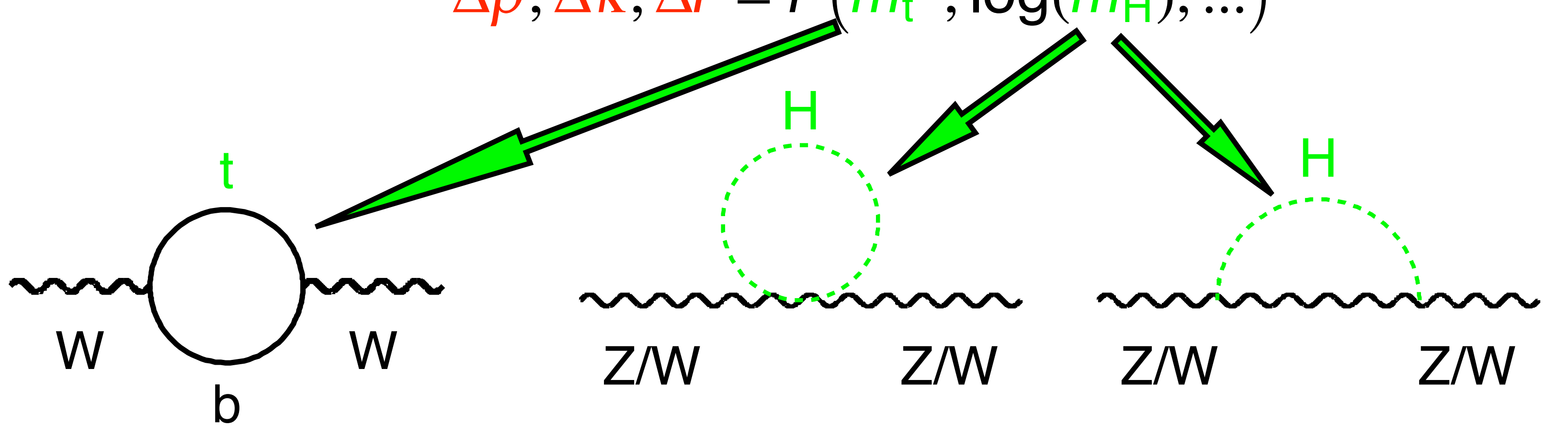
$$\sin^2\theta_W = 1 - \frac{m_W^2}{m_Z^2} \quad \Longrightarrow \quad \sin^2\theta_{\mathrm{eff}} = (1 + \Delta\kappa)\sin^2\theta_W$$

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

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

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

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



Effective Z couplings

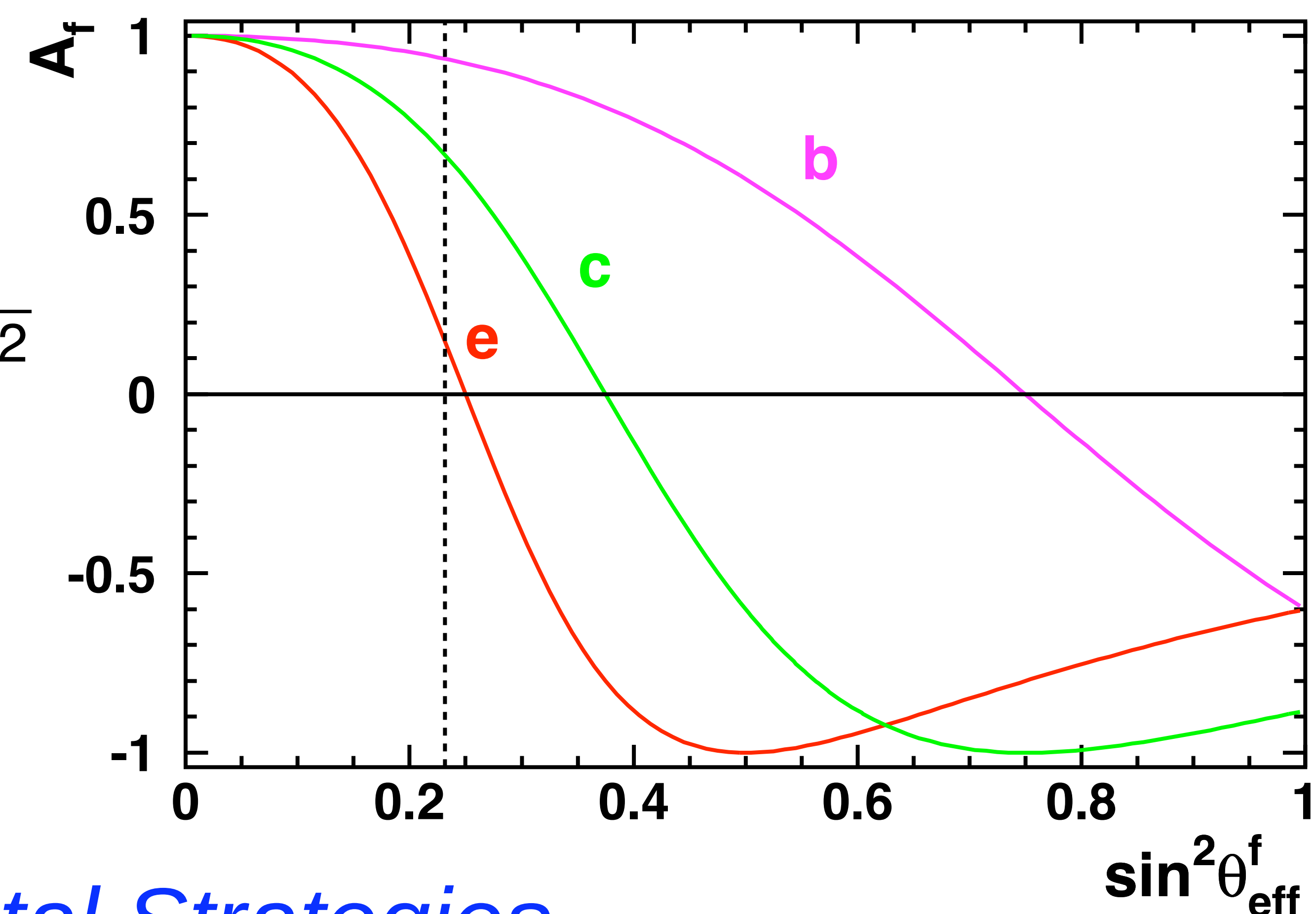
$$g_{Vf} = \sqrt{\bar{\rho}}\left(T_f^{(3)} - 2Q_f \sin^2\theta_{eff}\right)$$

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

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

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

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

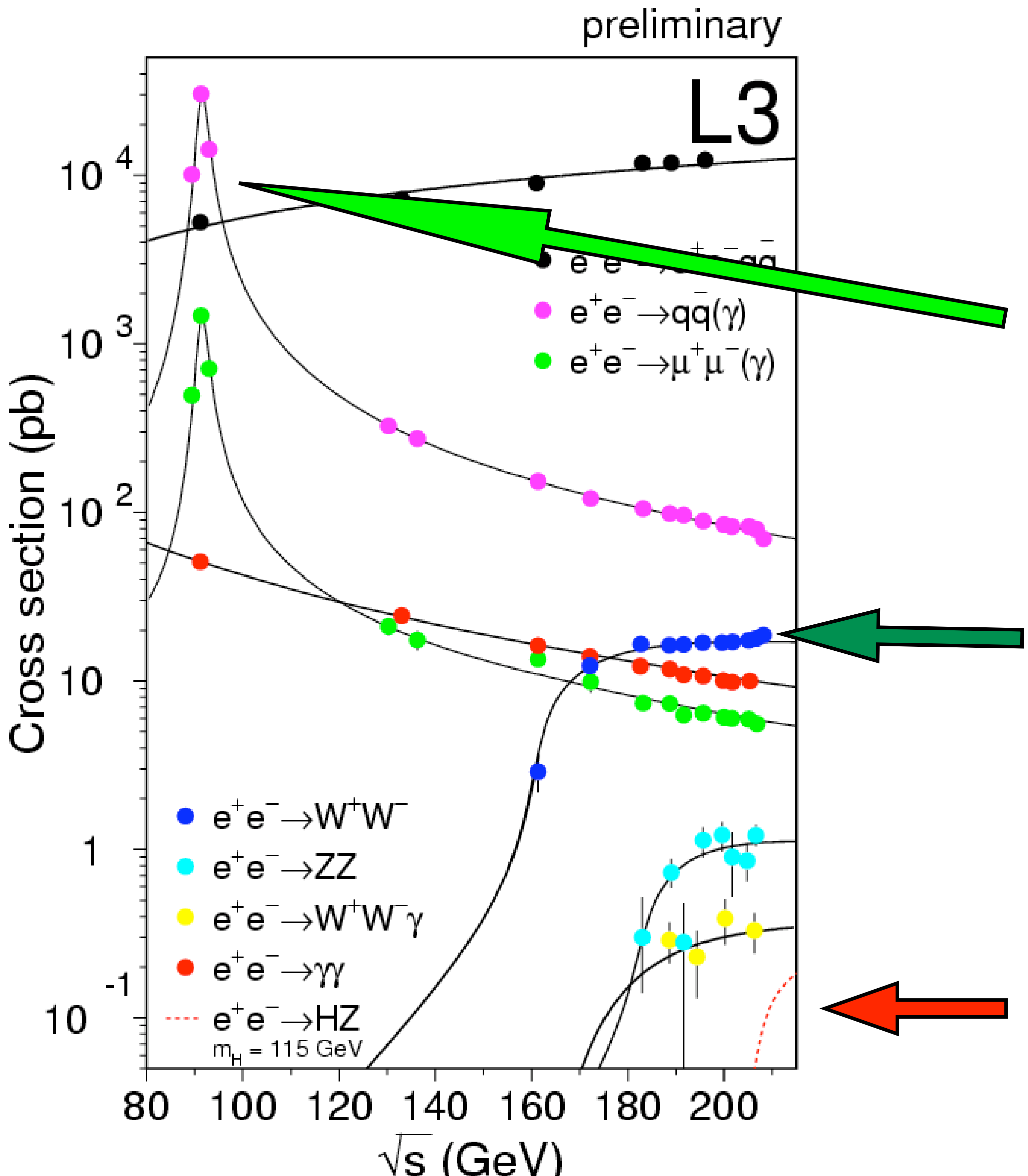


Experimental Strategies

- 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 $\Rightarrow g_V^2 + g_A^2$

The LEP Heritage



In total, for all 4 expts:

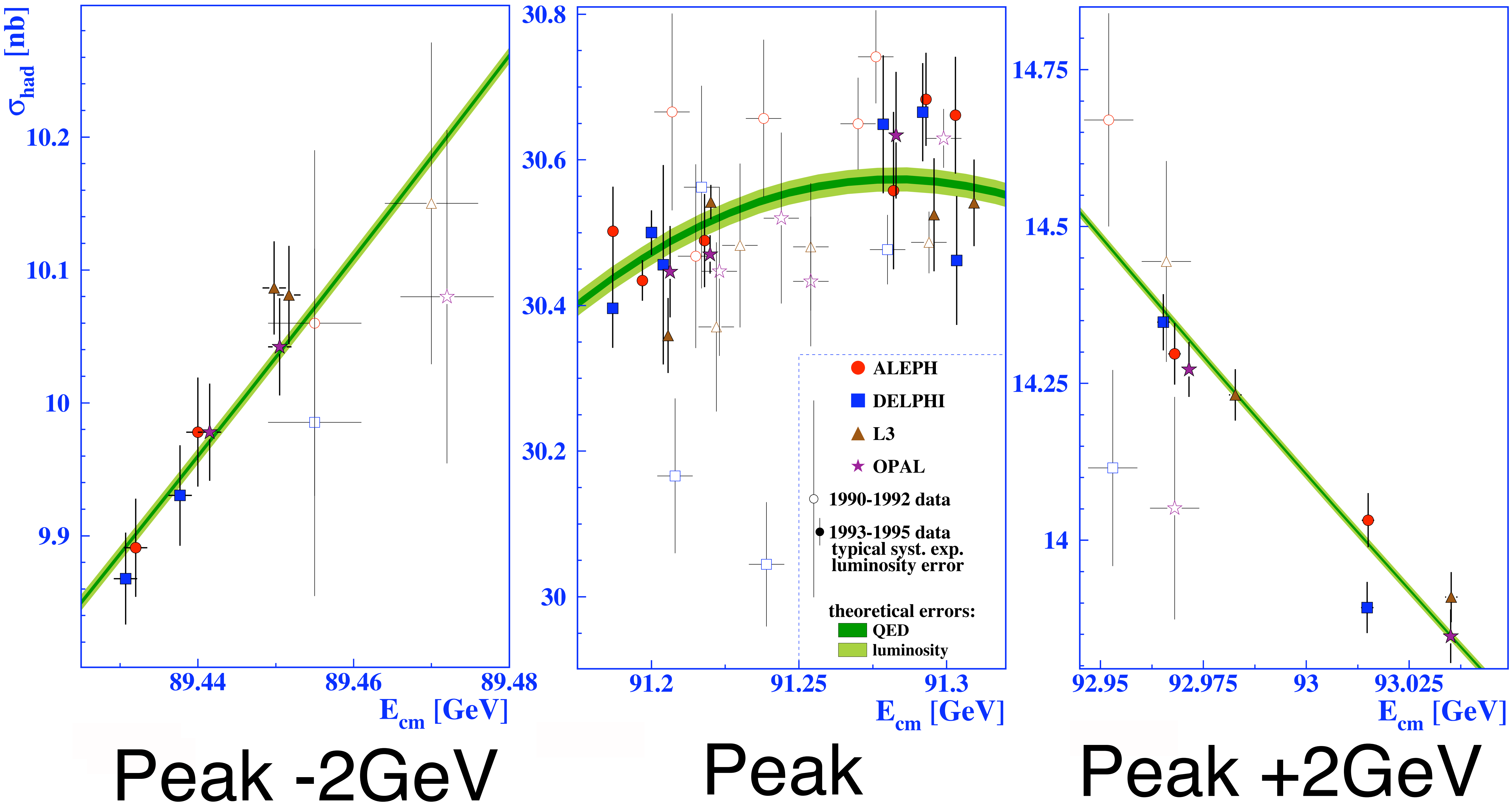
about 16 M Z

about 40000 W

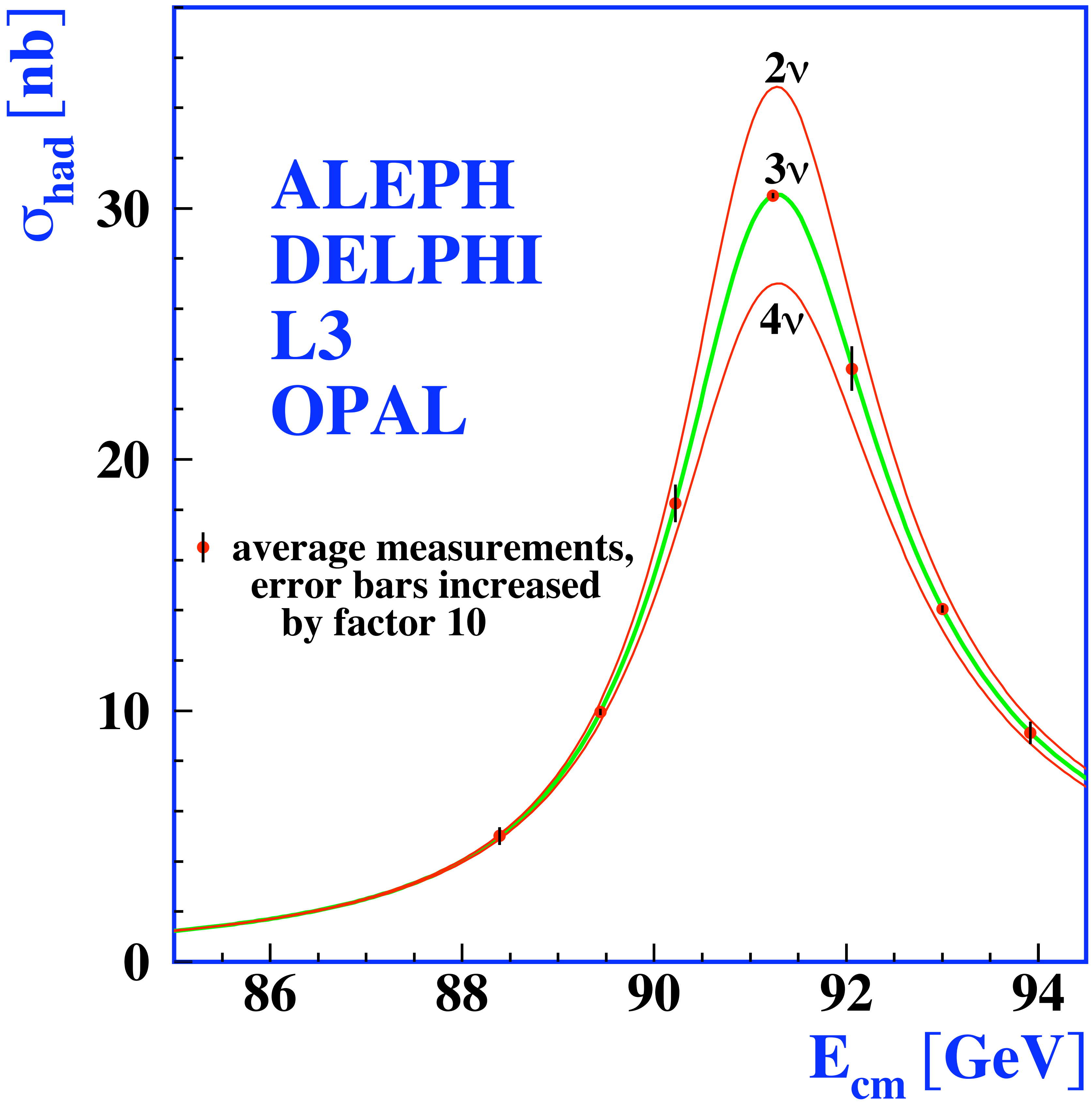
about 0 H

Z Lineshape

Hadronic Cross-section

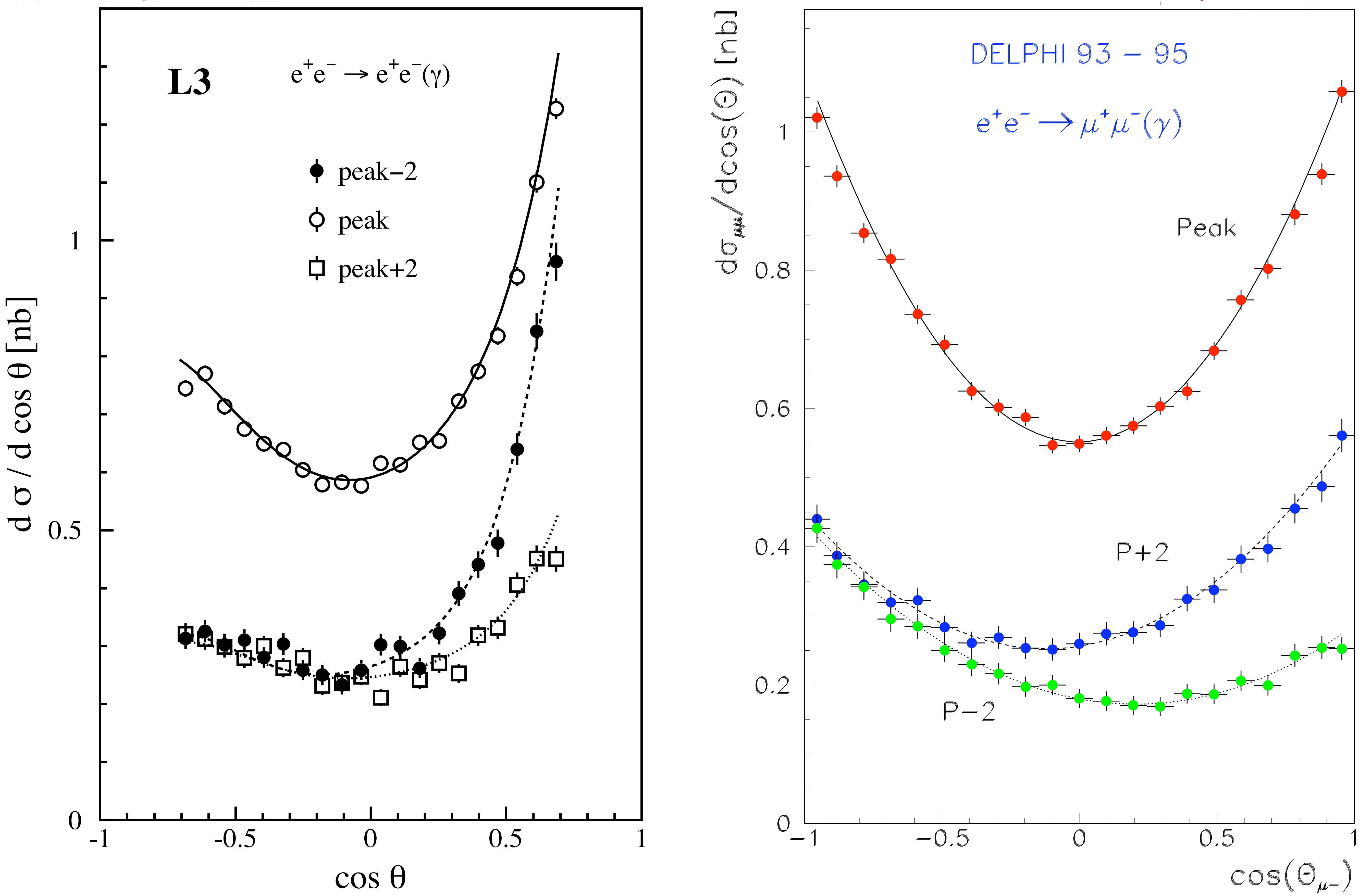


Number of neutrino generations

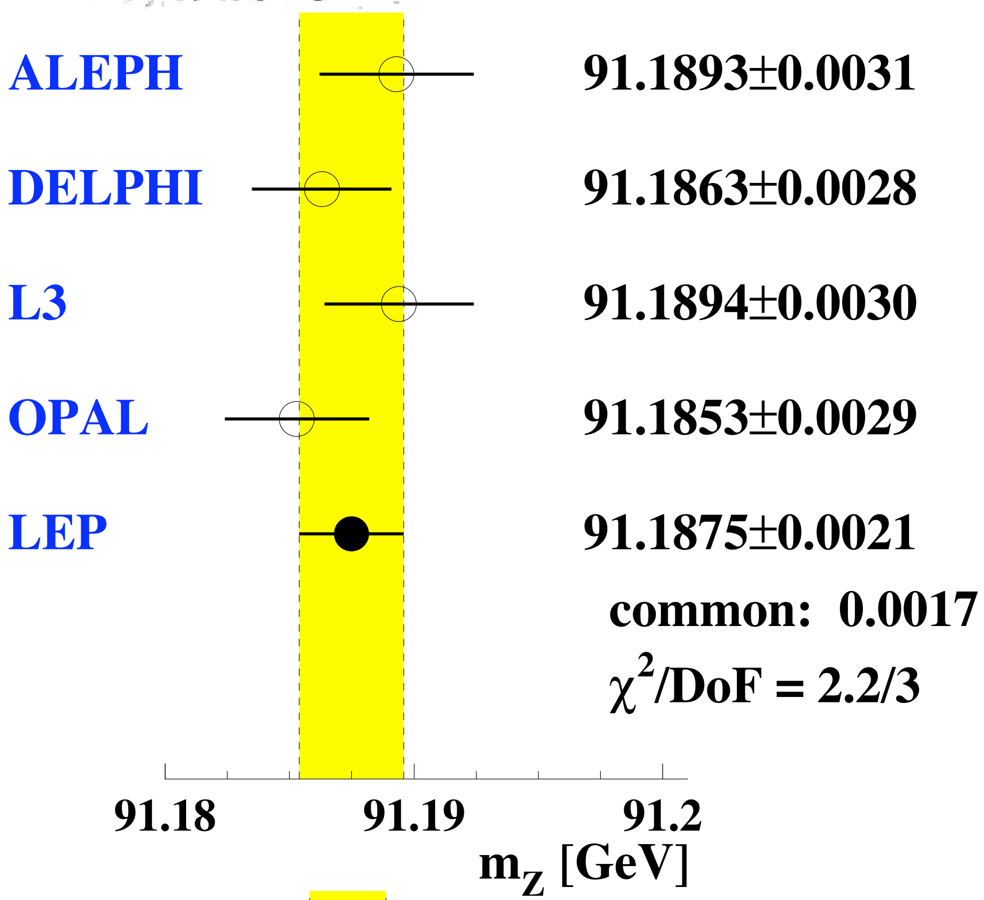


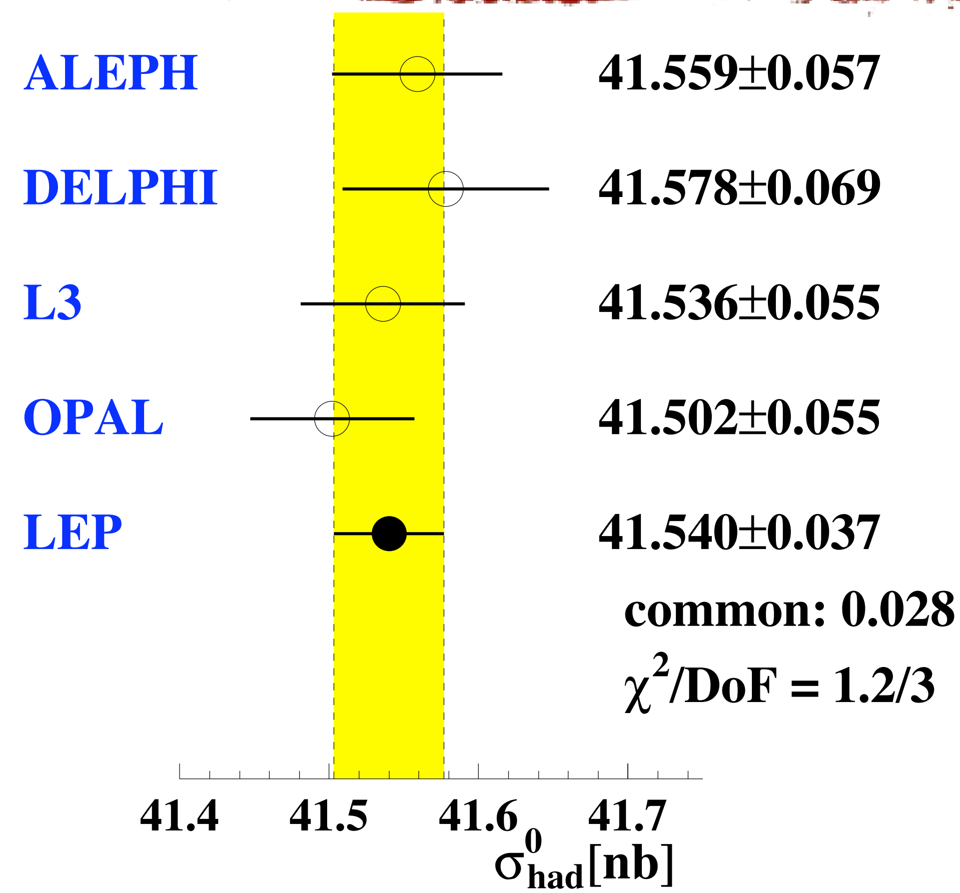
$N_\nu = 2.9841 \pm 0.0083$

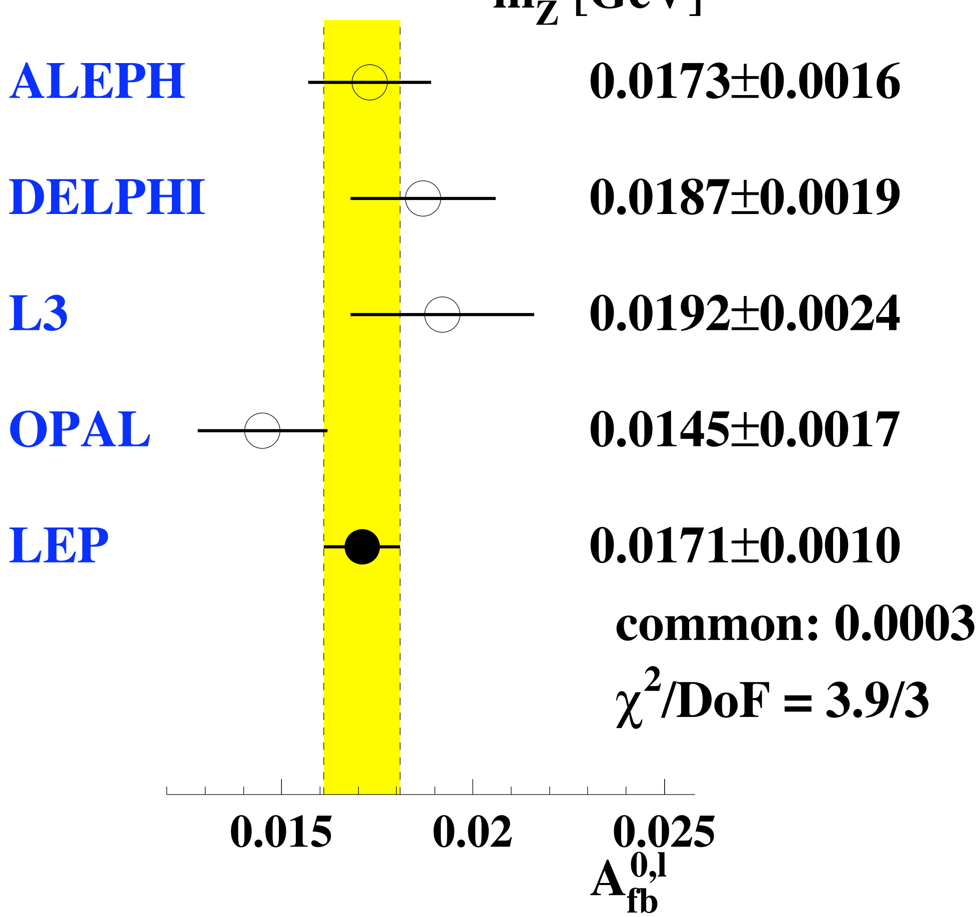
Examples of Lepton Cross-sections and Asymmetries

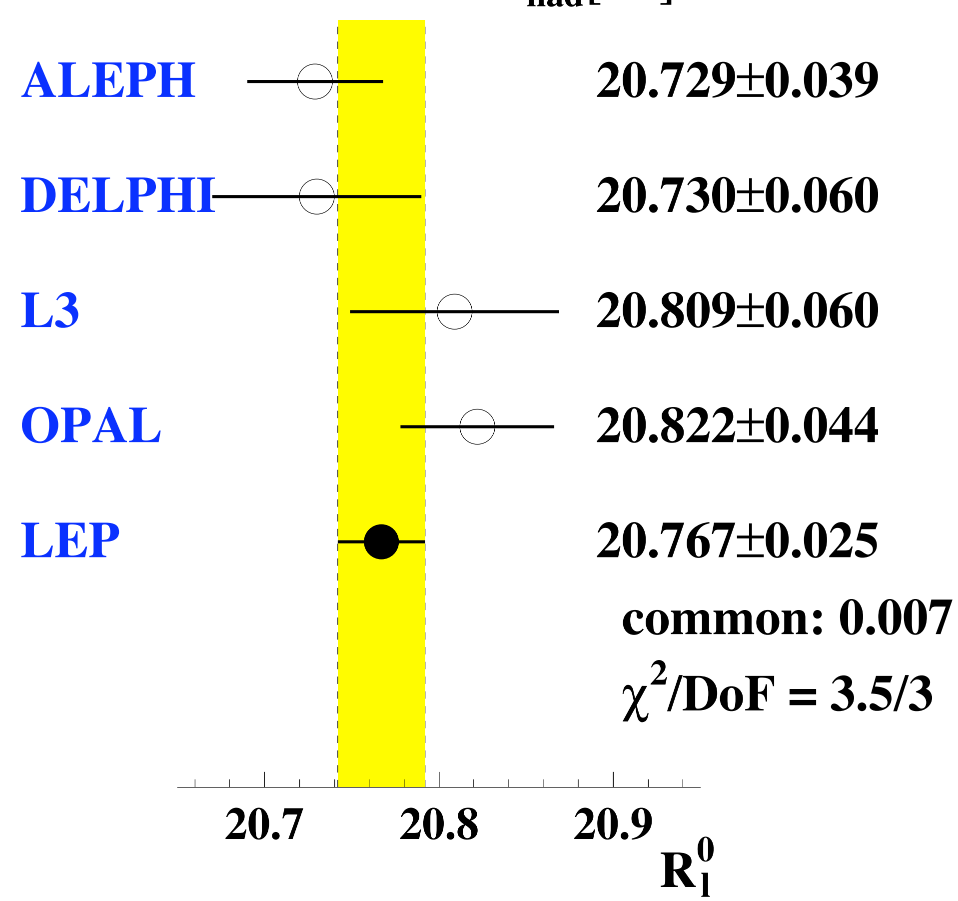


Comparisons of results





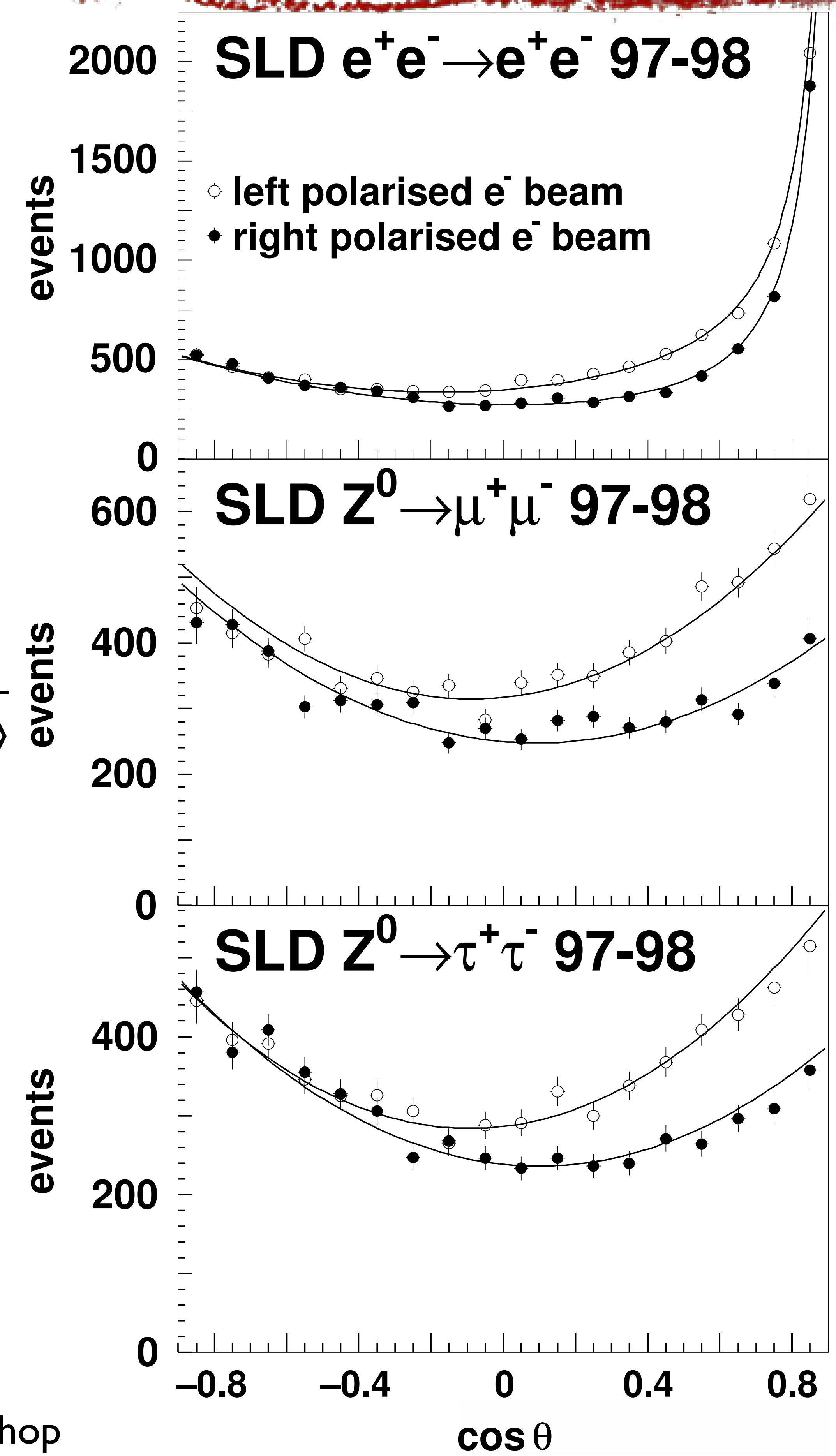




SLD Polarized Asymmetries

- Extraction of $\mathcal{A}_\mu$ and $\mathcal{A}_\tau$ requires

$$A_{\mathrm{LRFB}} = \frac{(\sigma_F - \sigma_B)_L - (\sigma_F - \sigma_B)_R}{(\sigma_F + \sigma_B)_L + (\sigma_F + \sigma_B)_R} \frac{1}{\langle|\mathcal{P}_e|\rangle} = \frac{3}{4}\mathcal{A}_f$$

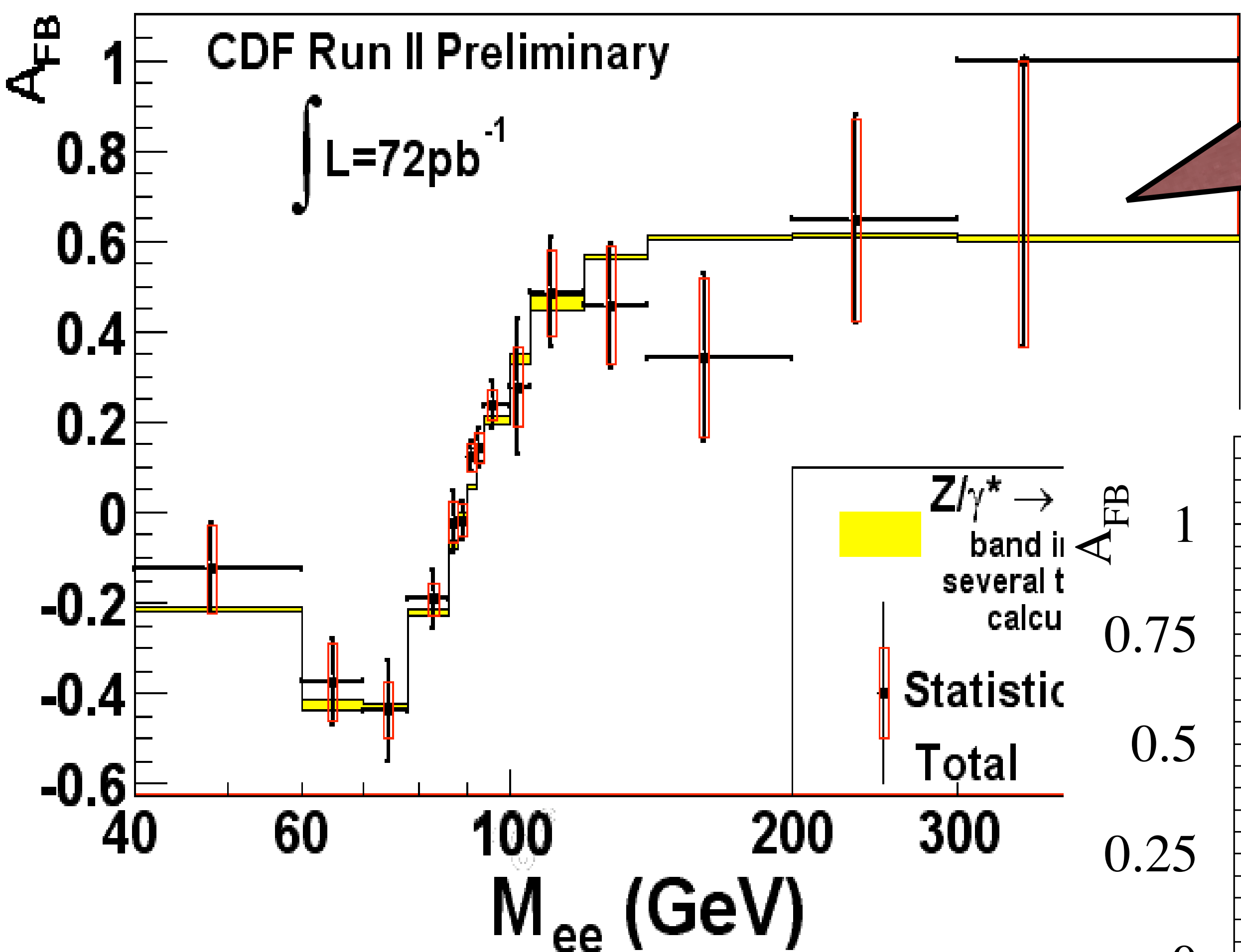


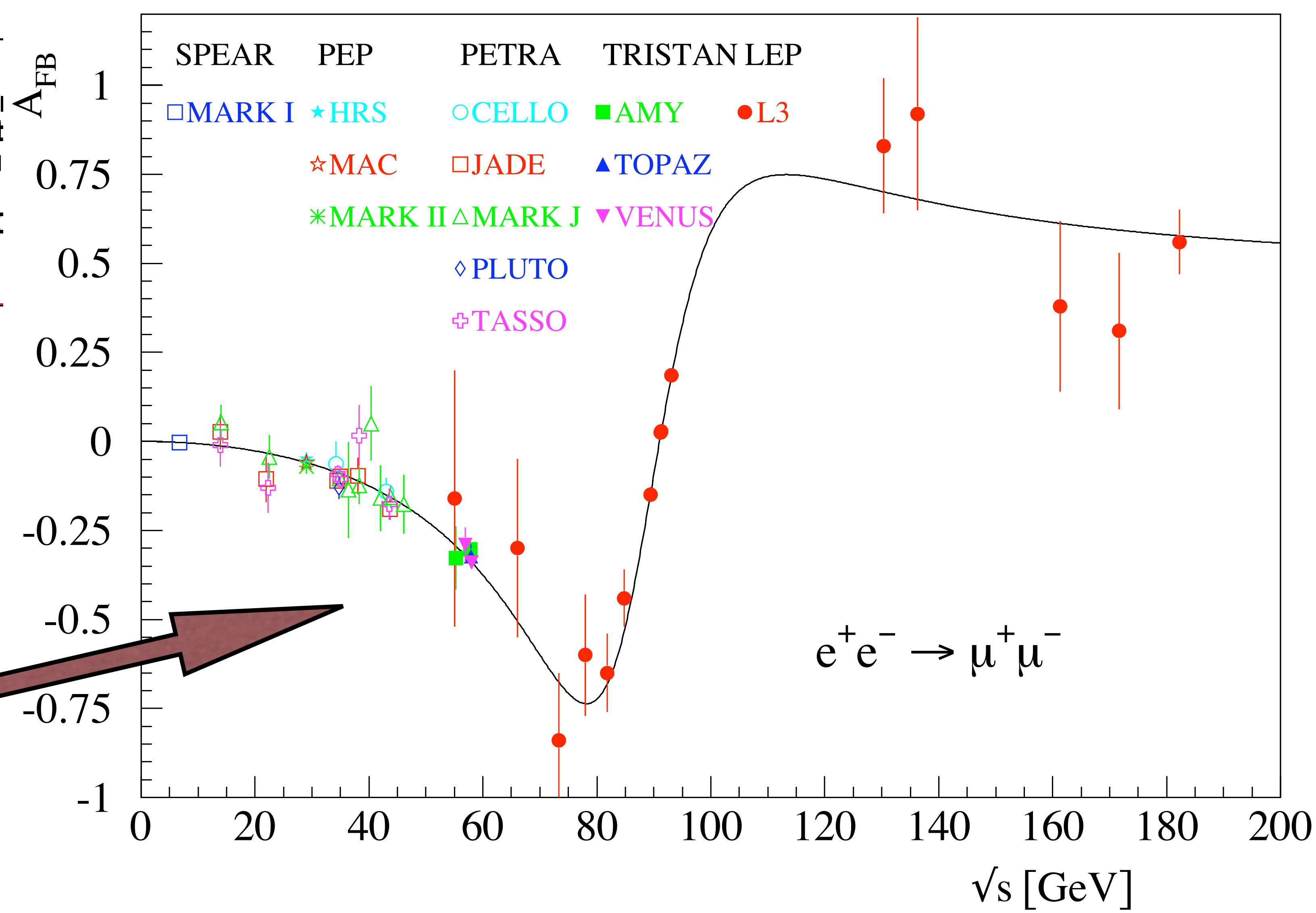
Asymmetries at higher (and lower) energies

CDF has measured forward-backward asymmetry vs $M_{e^+e^-}$

$u\bar{u}(d\bar{d}) \rightarrow Z/\gamma \rightarrow e^+e^-$

Will eventually give $\sin^2\theta_{eff}$





$e^+e^- \rightarrow Z/\gamma \rightarrow \mu^+\mu^-$

Standard Model tests: leptonic couplings

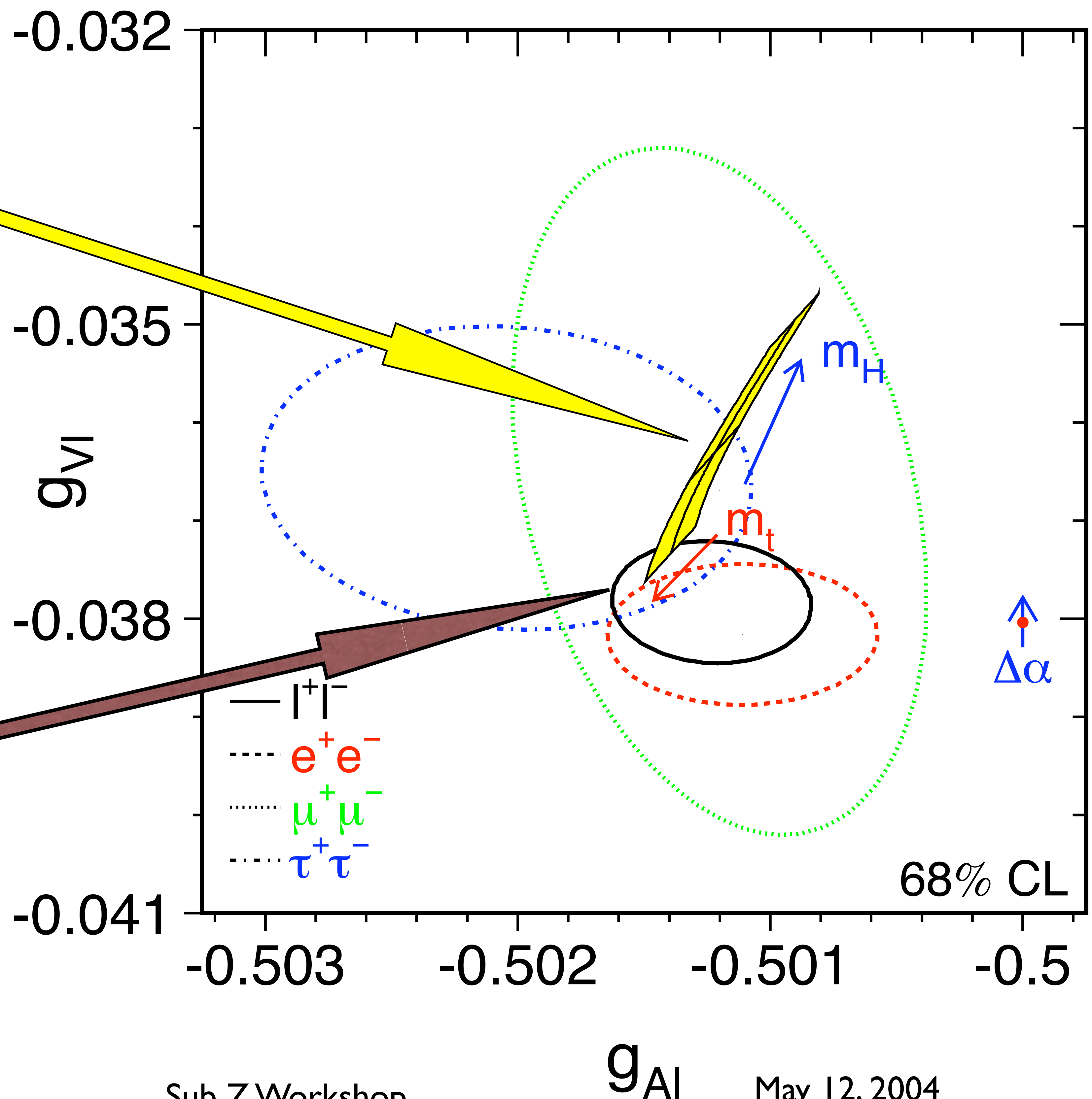
SM :

m_H = [114.1, 1000] GeV

m_t = 178.0 ± 4.3 GeV

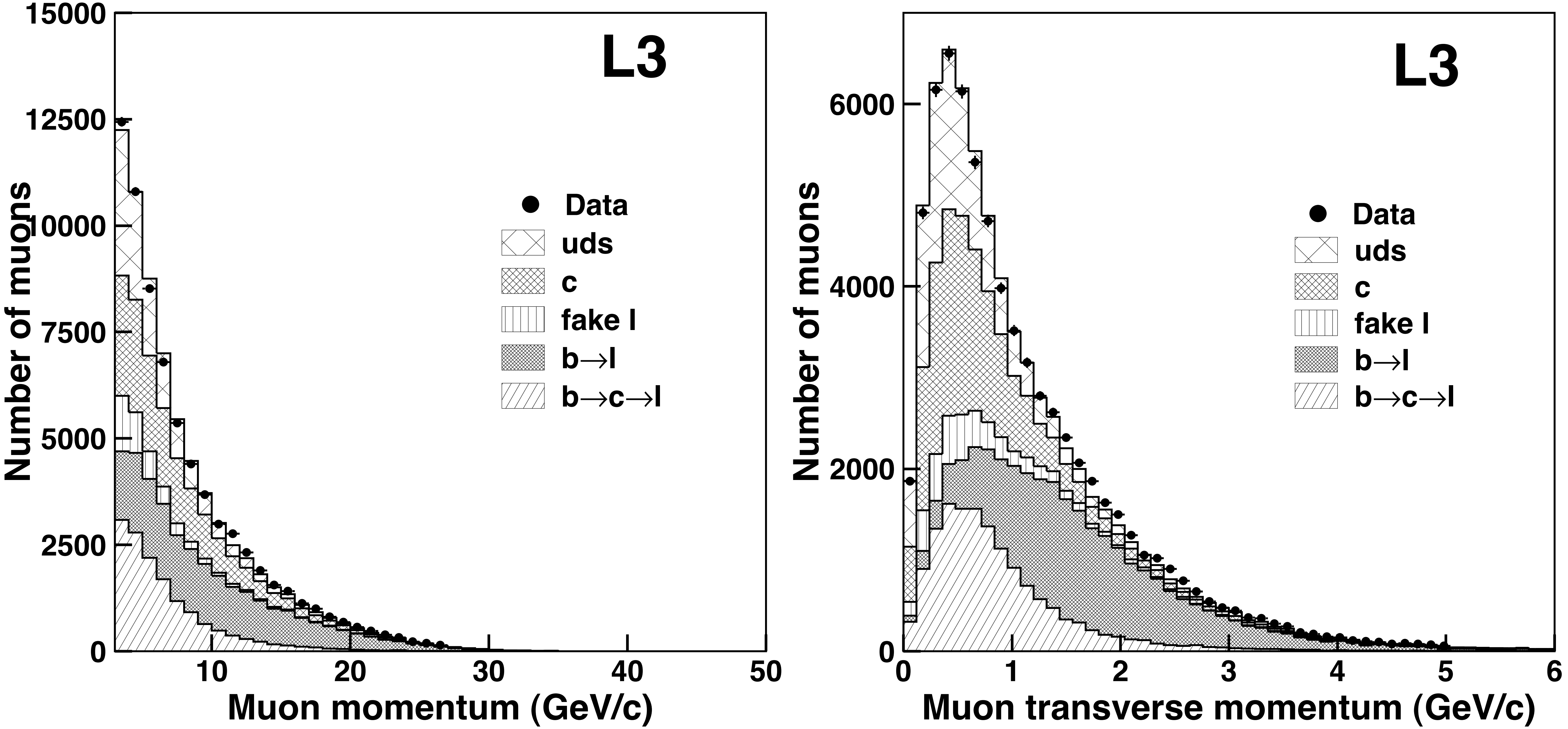
Low m_H favored

lepton universality



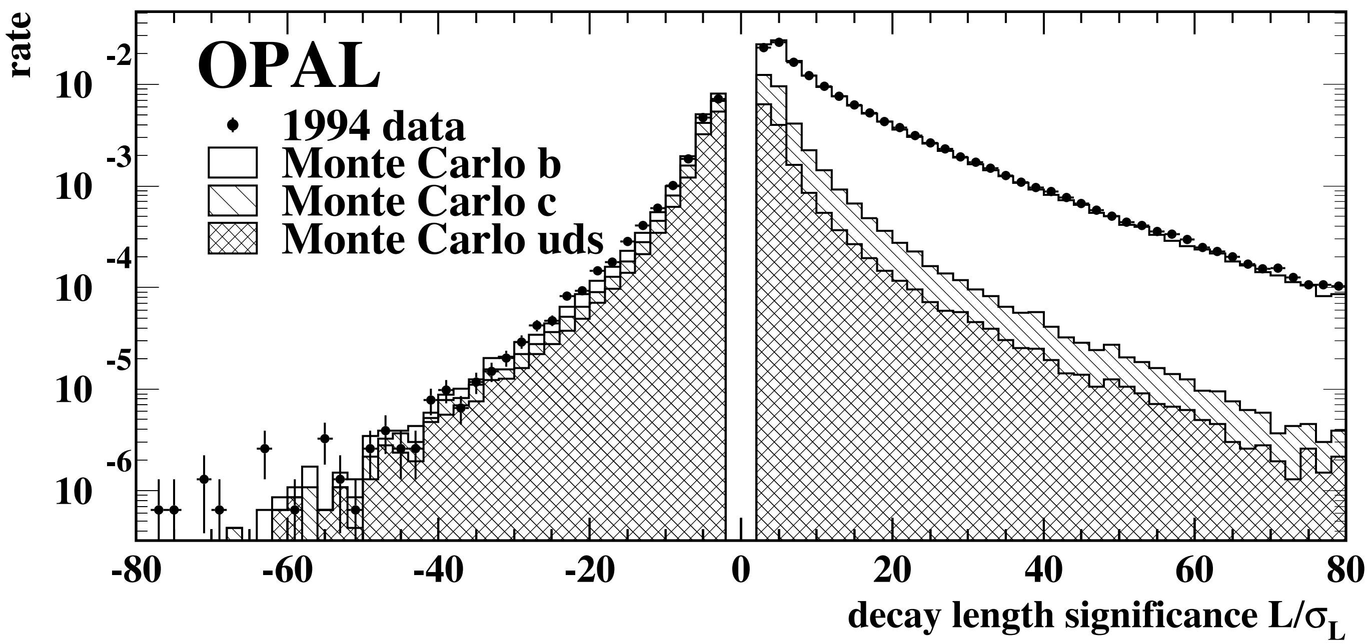
Heavy Flavor Selection Techniques

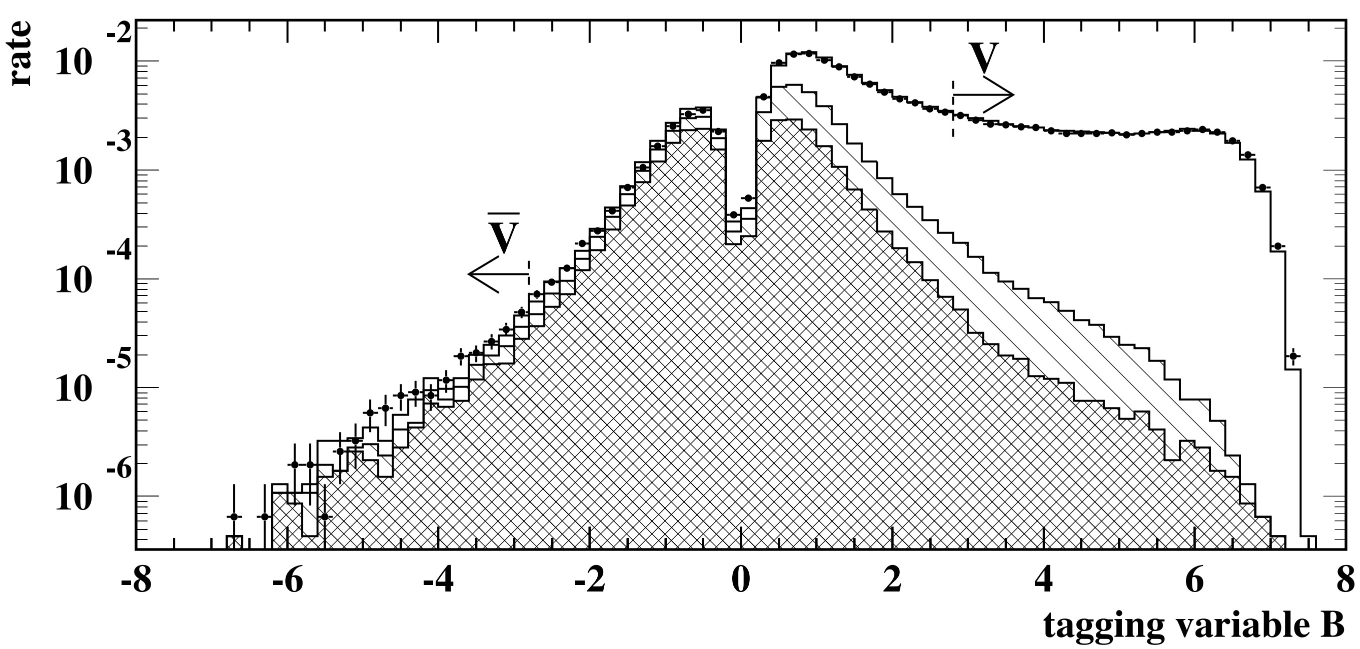
- Lepton tags

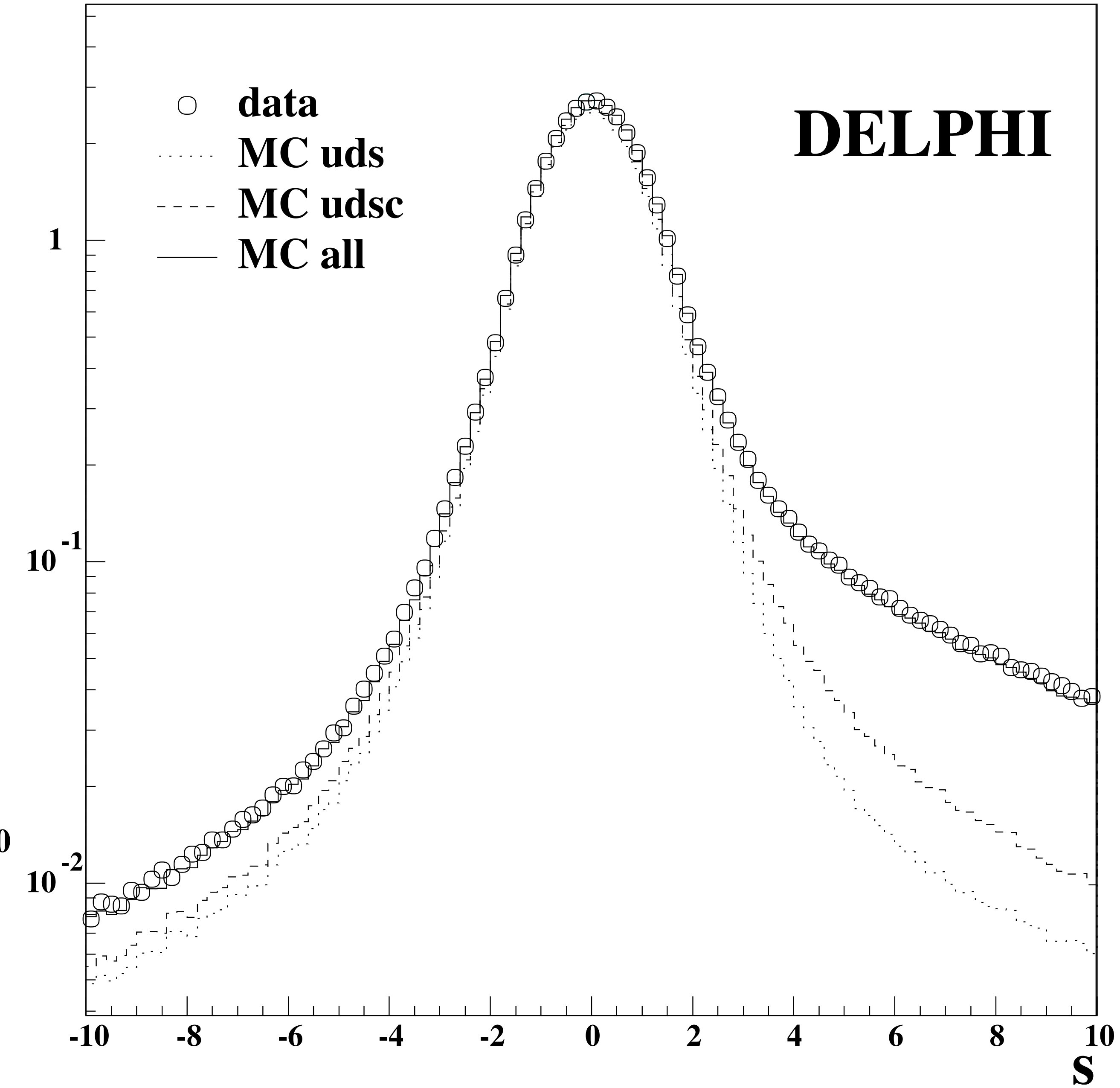


Heavy Flavor Selection Techniques

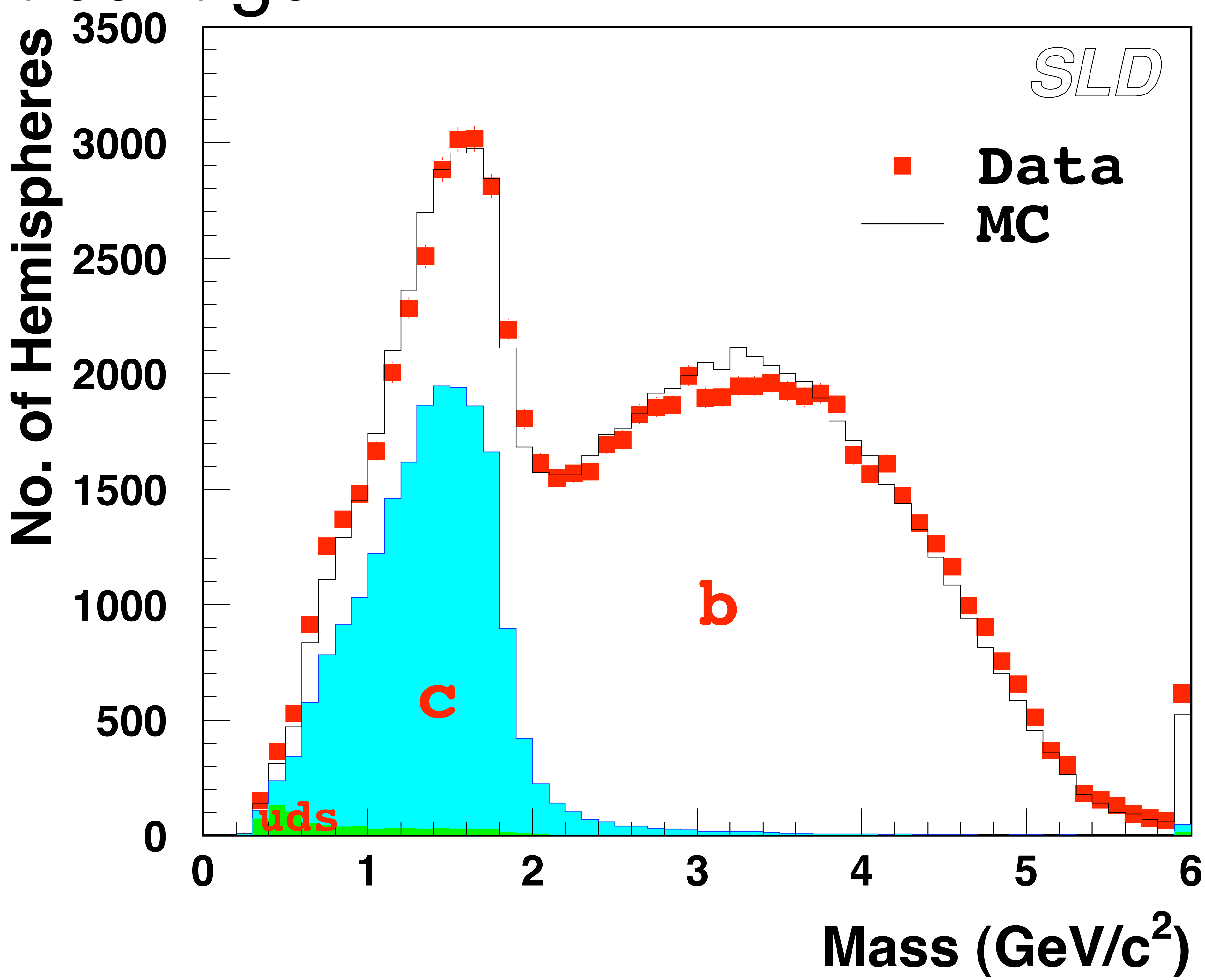
- Lifetime tags





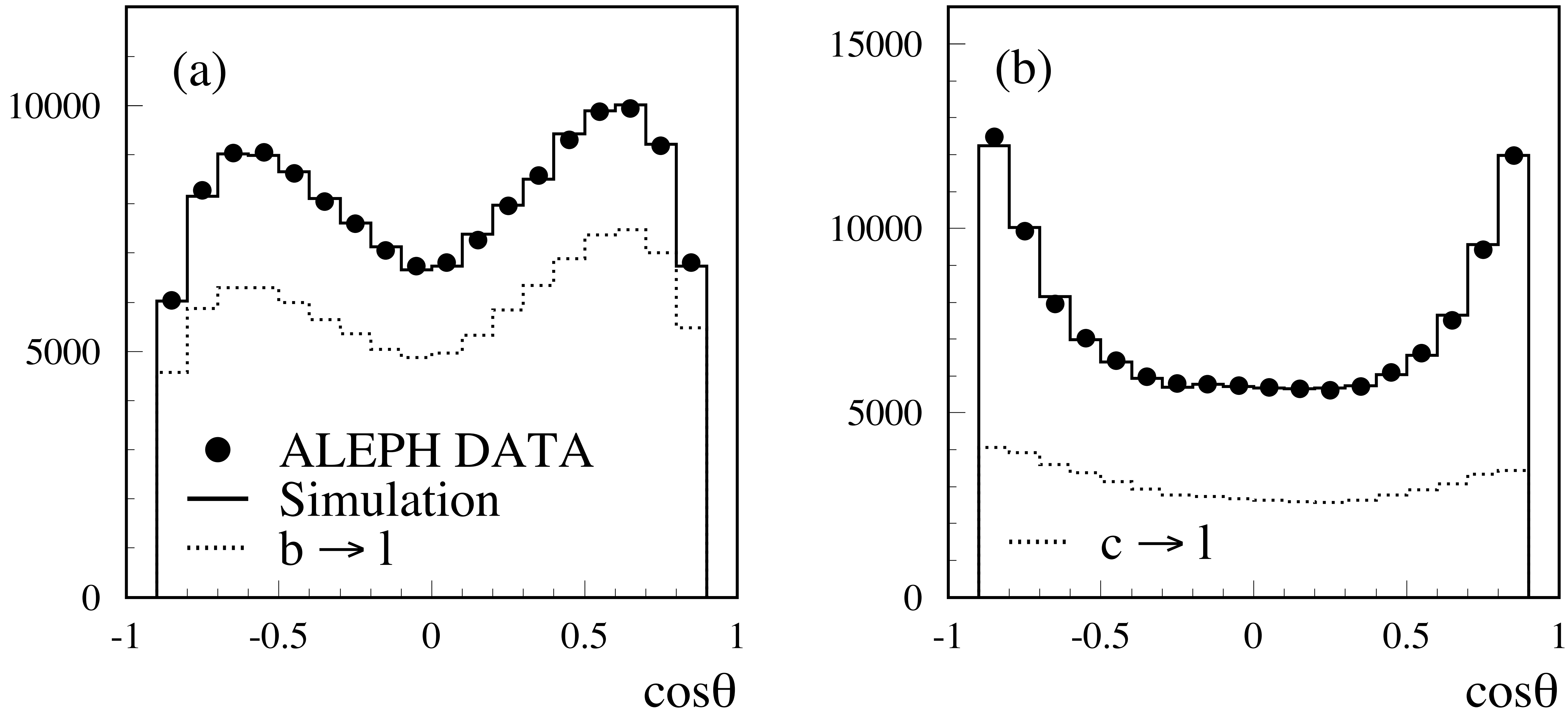


- Mass tags



No. of Hemispheres
3500
3000
2500
2000
1500
1000
500
0
0
1
2
3
4
5
6
Mass (GeV/c^2)
SLD
Data
MC
b
c
uds

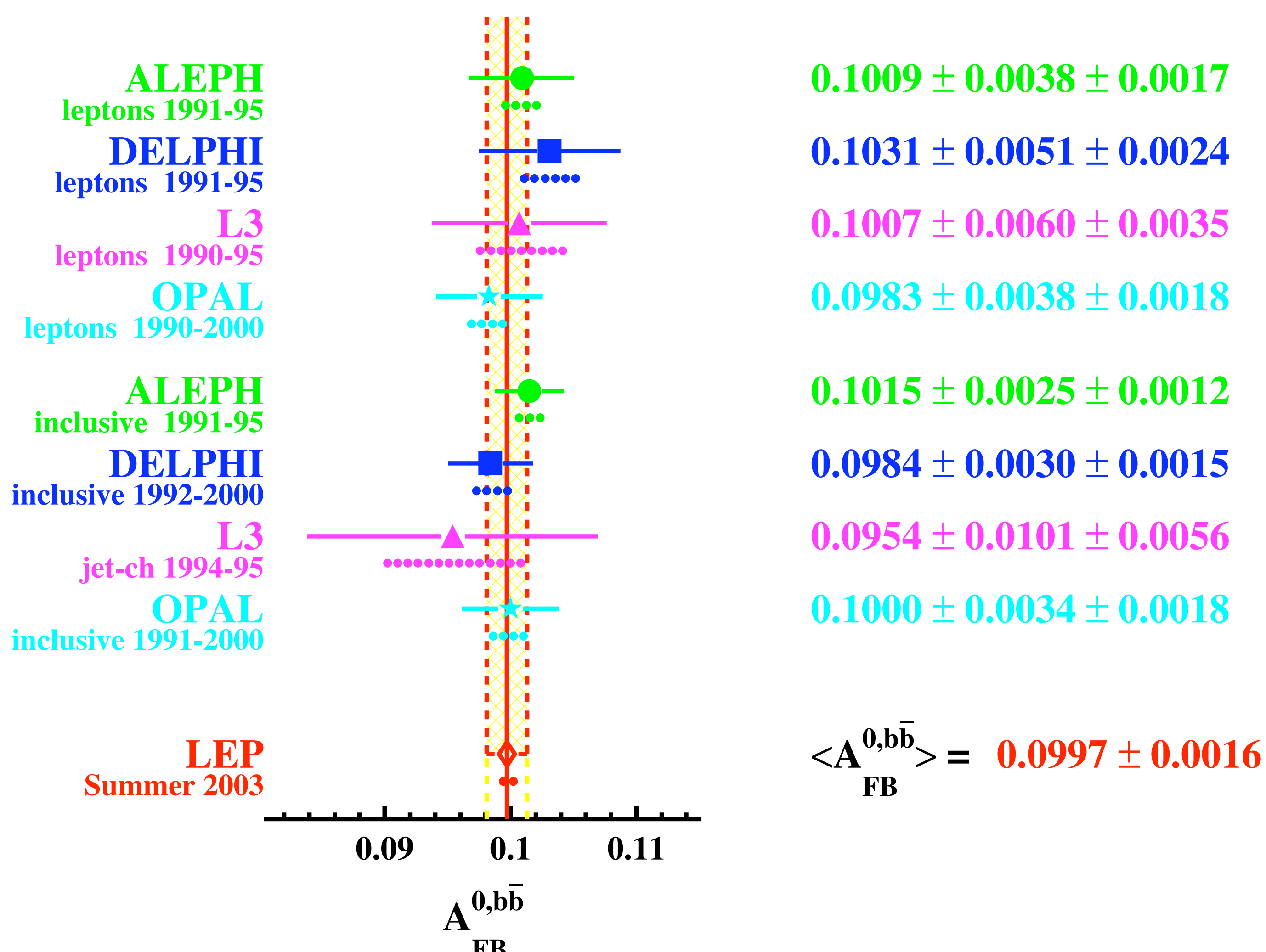
An Example Asymmetry

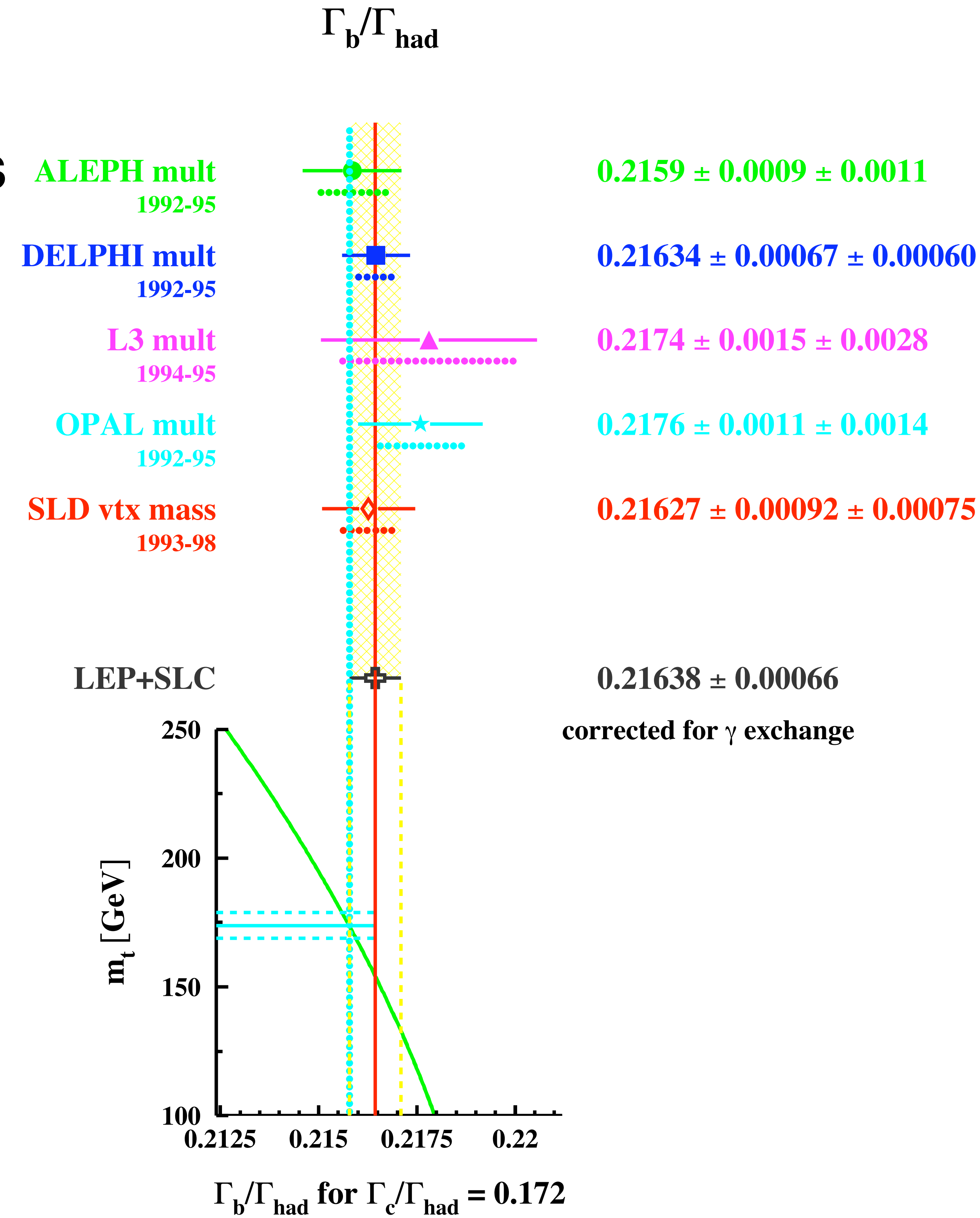


Effective couplings for quarks

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)

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

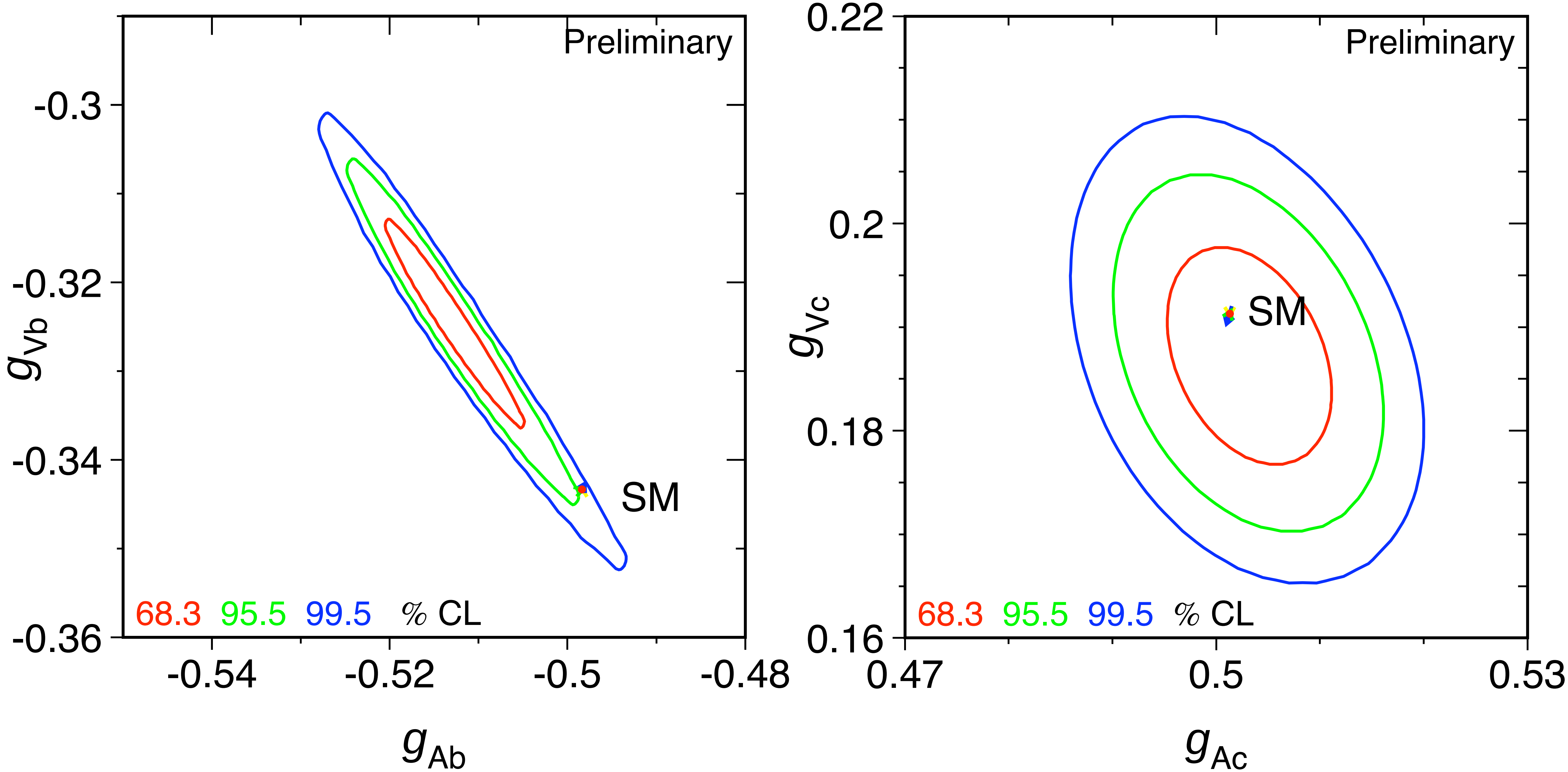




Some results are **still** preliminary

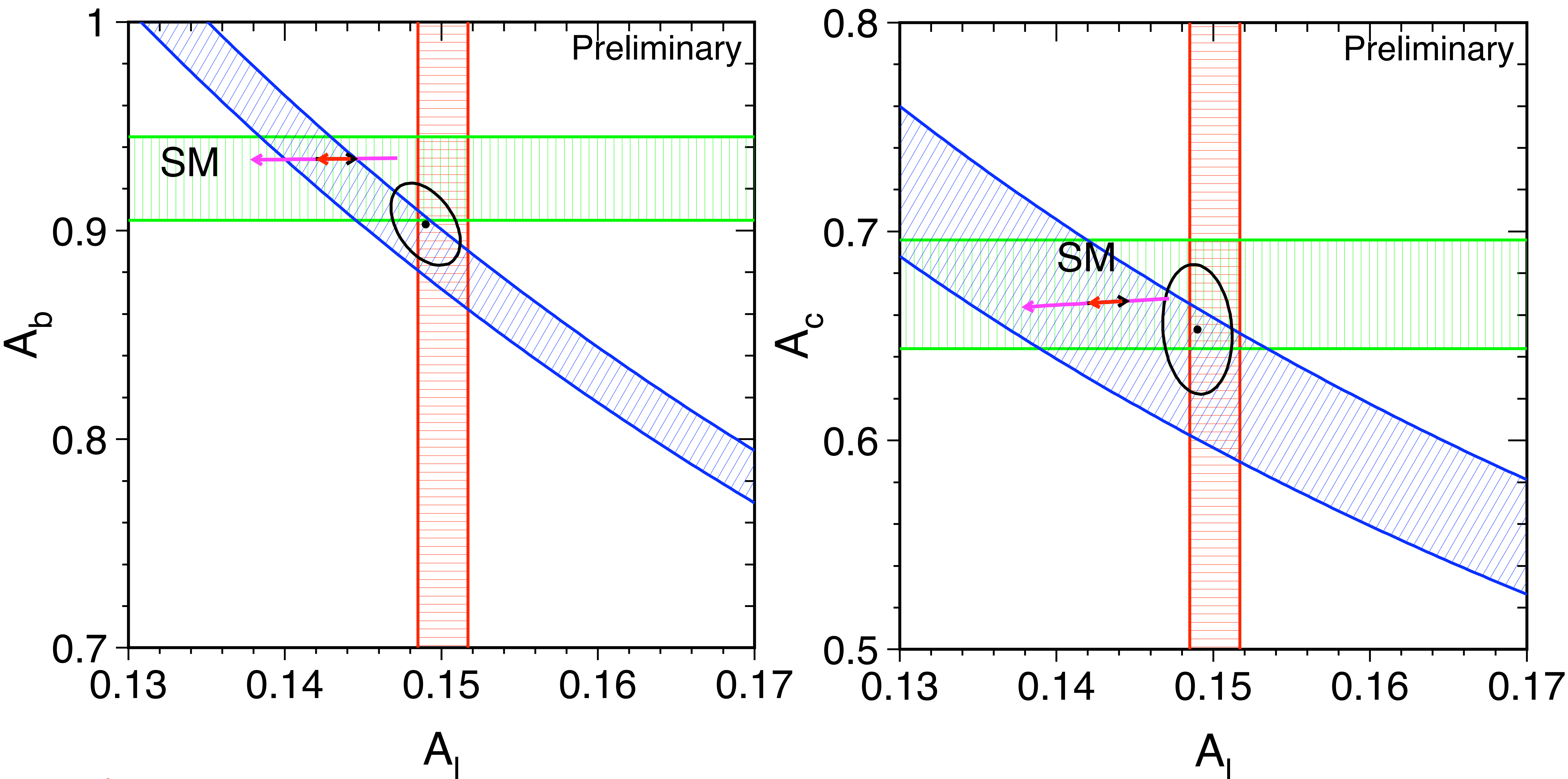
Quark couplings

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



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

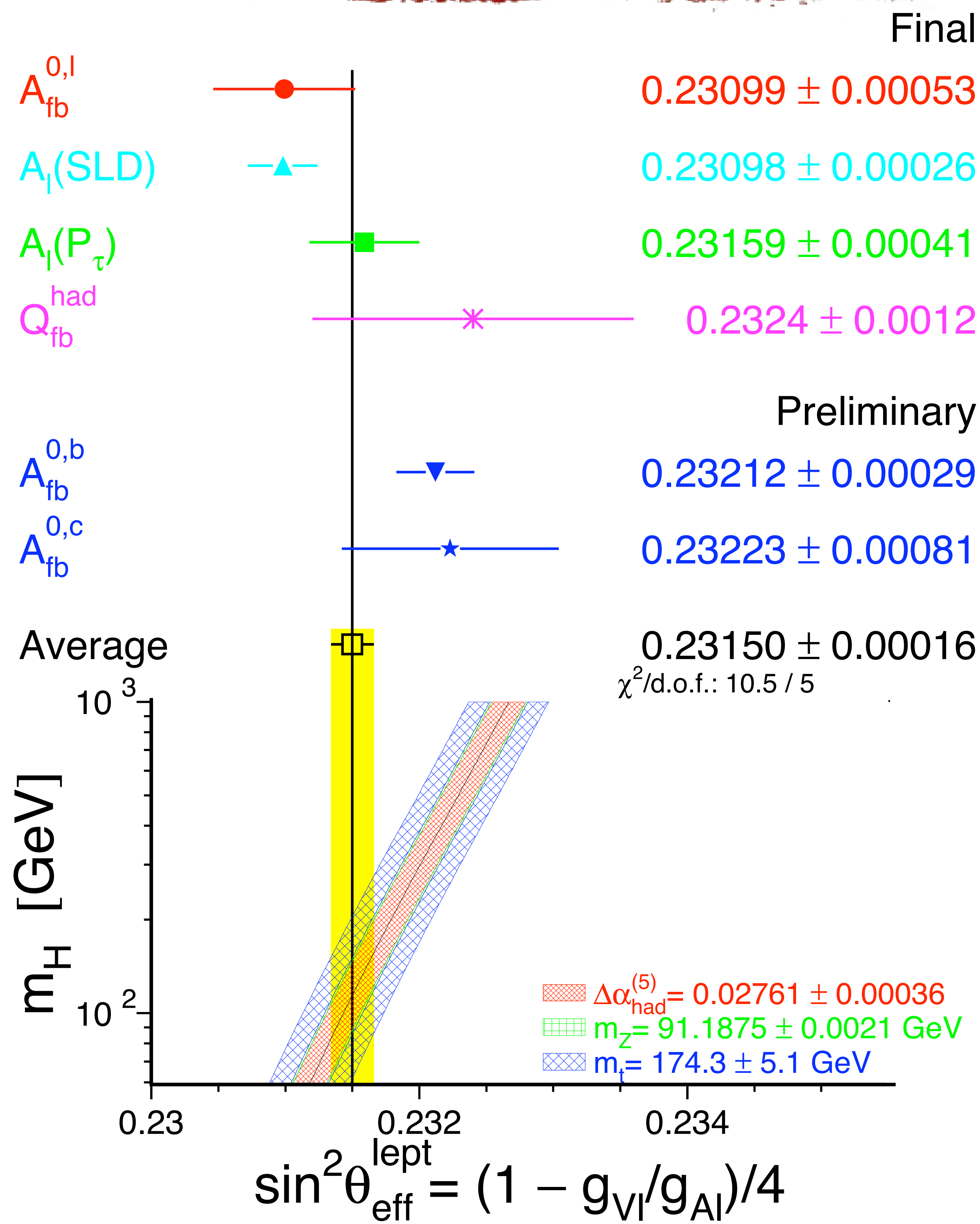
Standard model tests: $\sin^2\theta_{eff}^{lept}$

Assuming lepton universality:

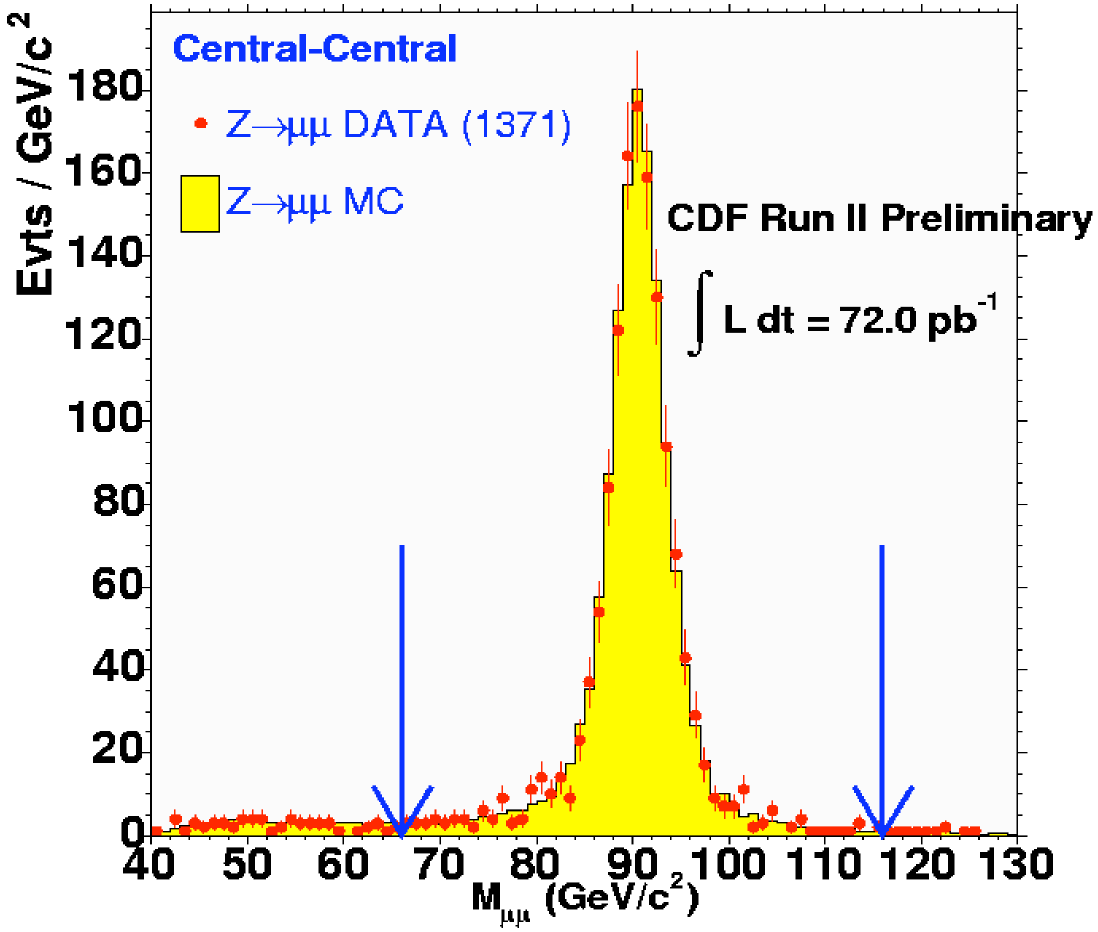
$$\chi^2/\text{dof(lept.)} = 1.6/2 \ (P = 44.0\%)$$
$$\chi^2/\text{dof(hadr.)} = 0.06/2 \ (P = 96.8\%)$$
$$\chi^2/\text{dof(tot.)} = 10.5/5 \ (P = 6.2\%)$$

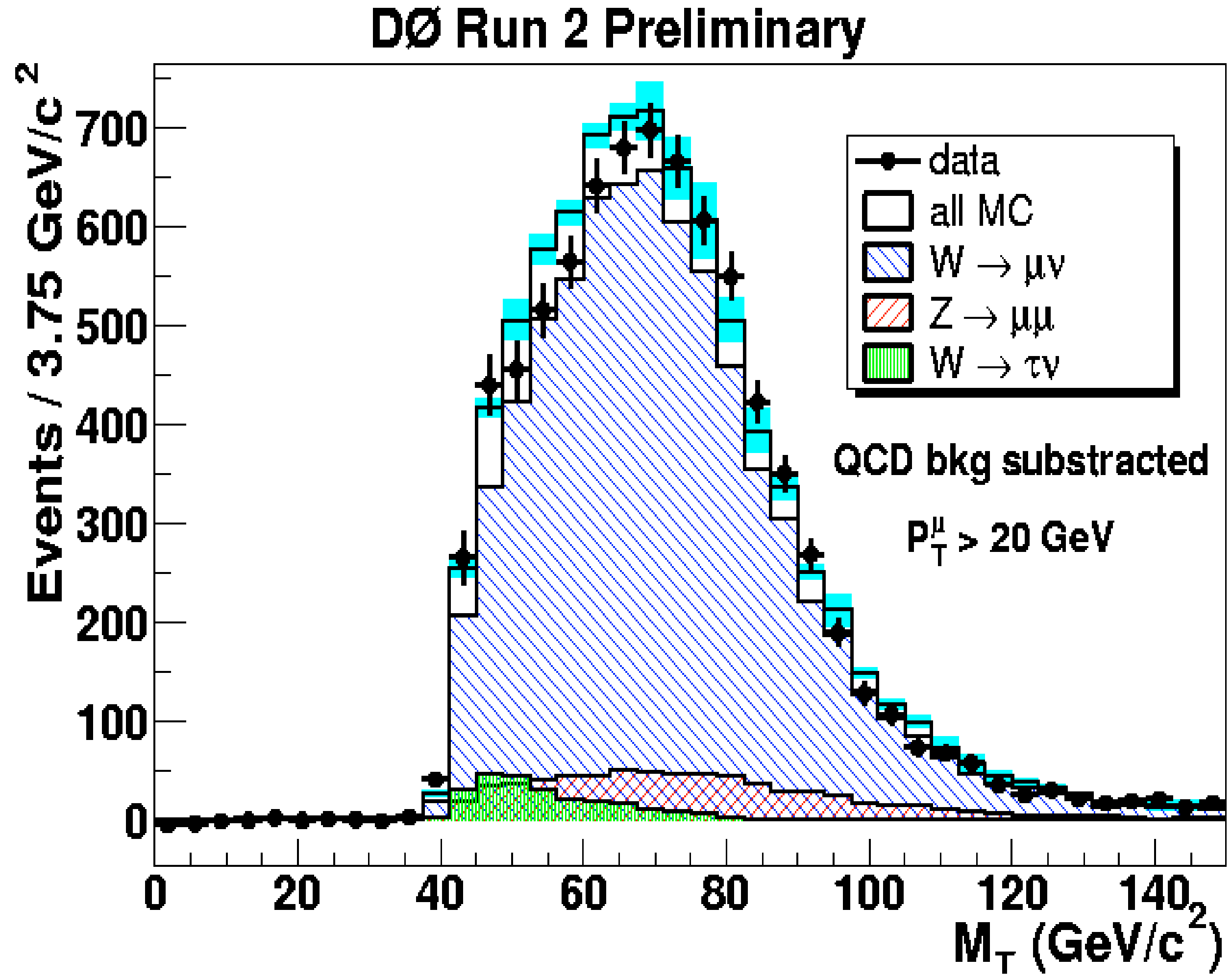
hadrons *vs* leptons 3σ

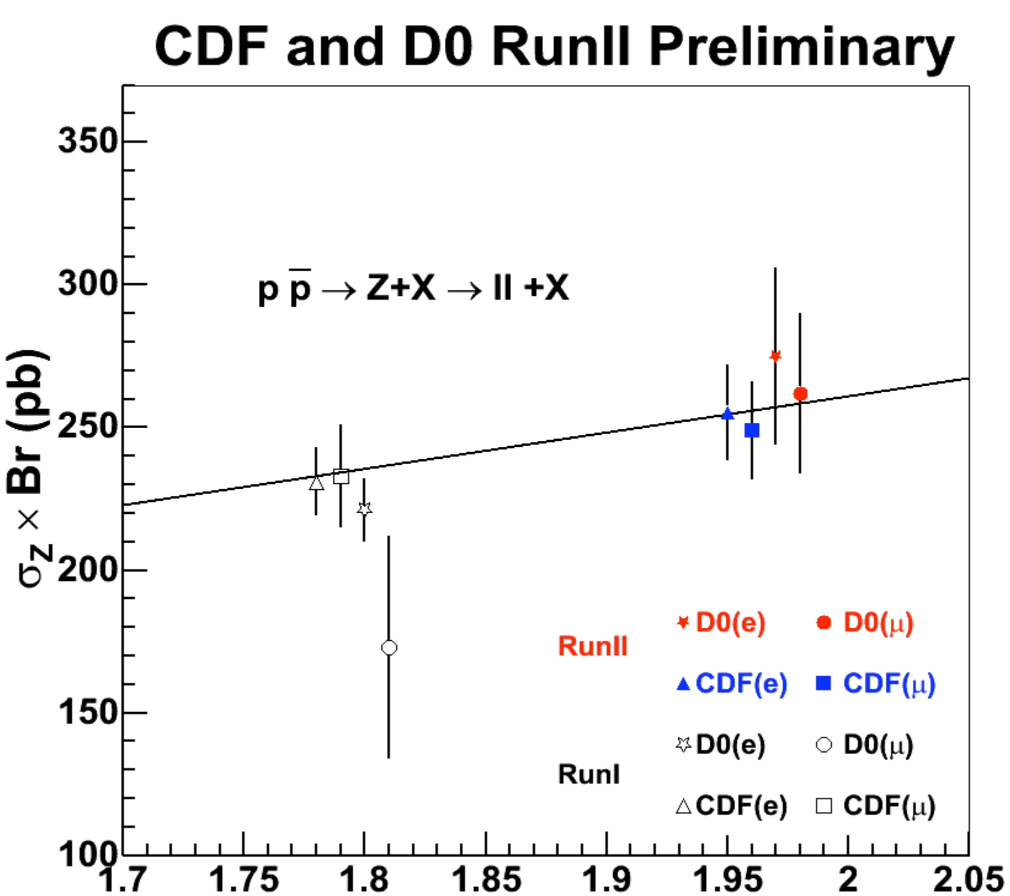
2.9σ between 2 most precise quantities ($\mathcal{A}_\ell$ and $A_{FB}^{0,b}$)

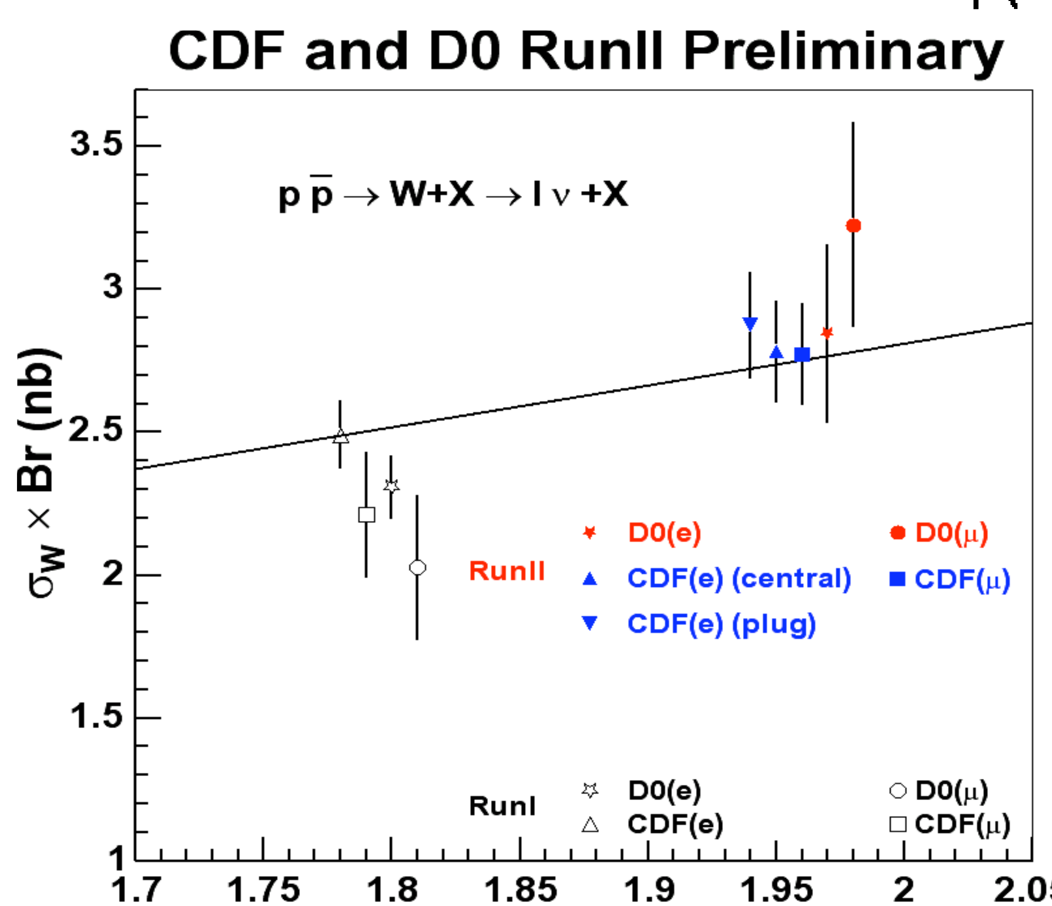


W and Z boson production at CDF/DØ

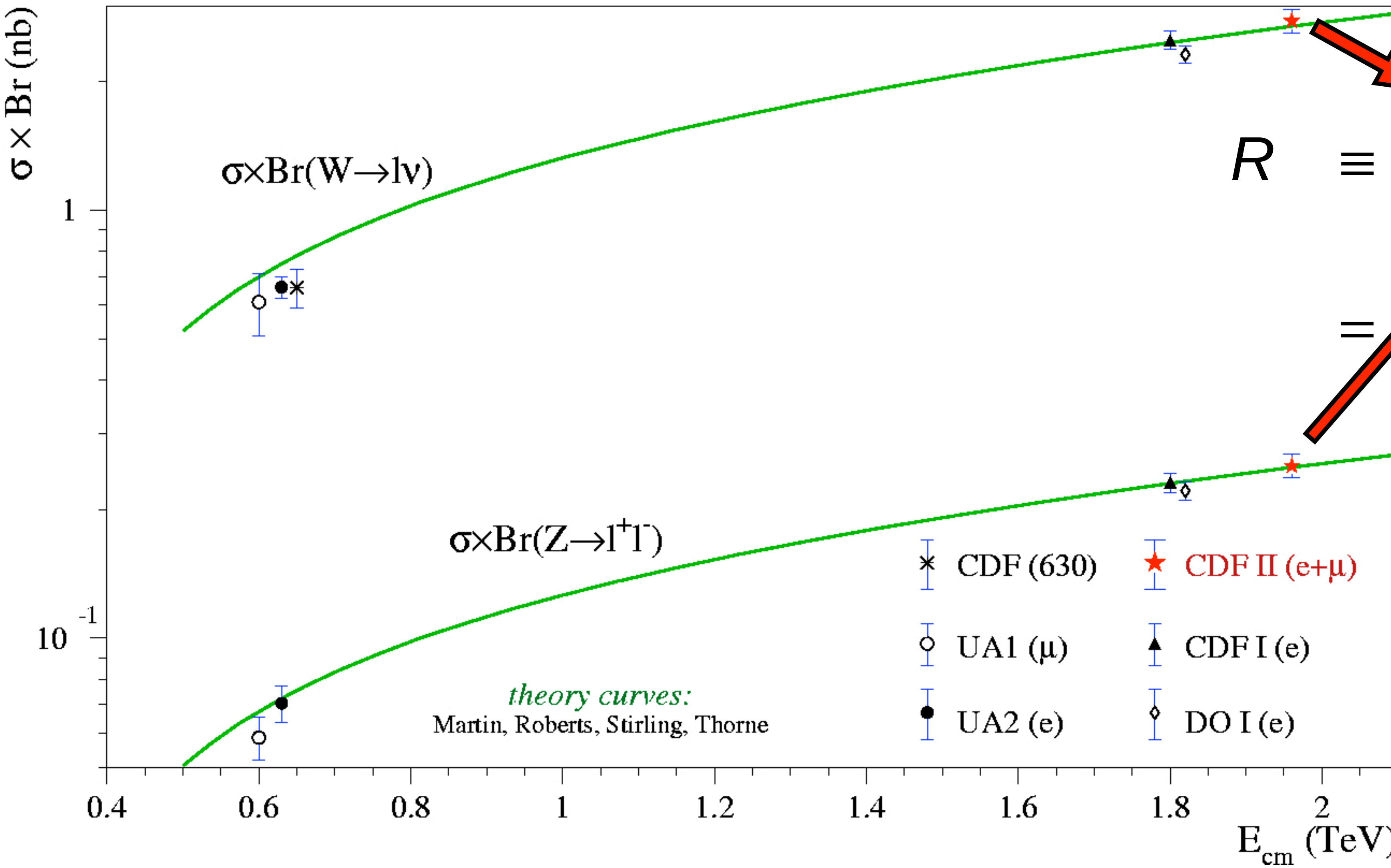








Cross-sections X Branching Ratios



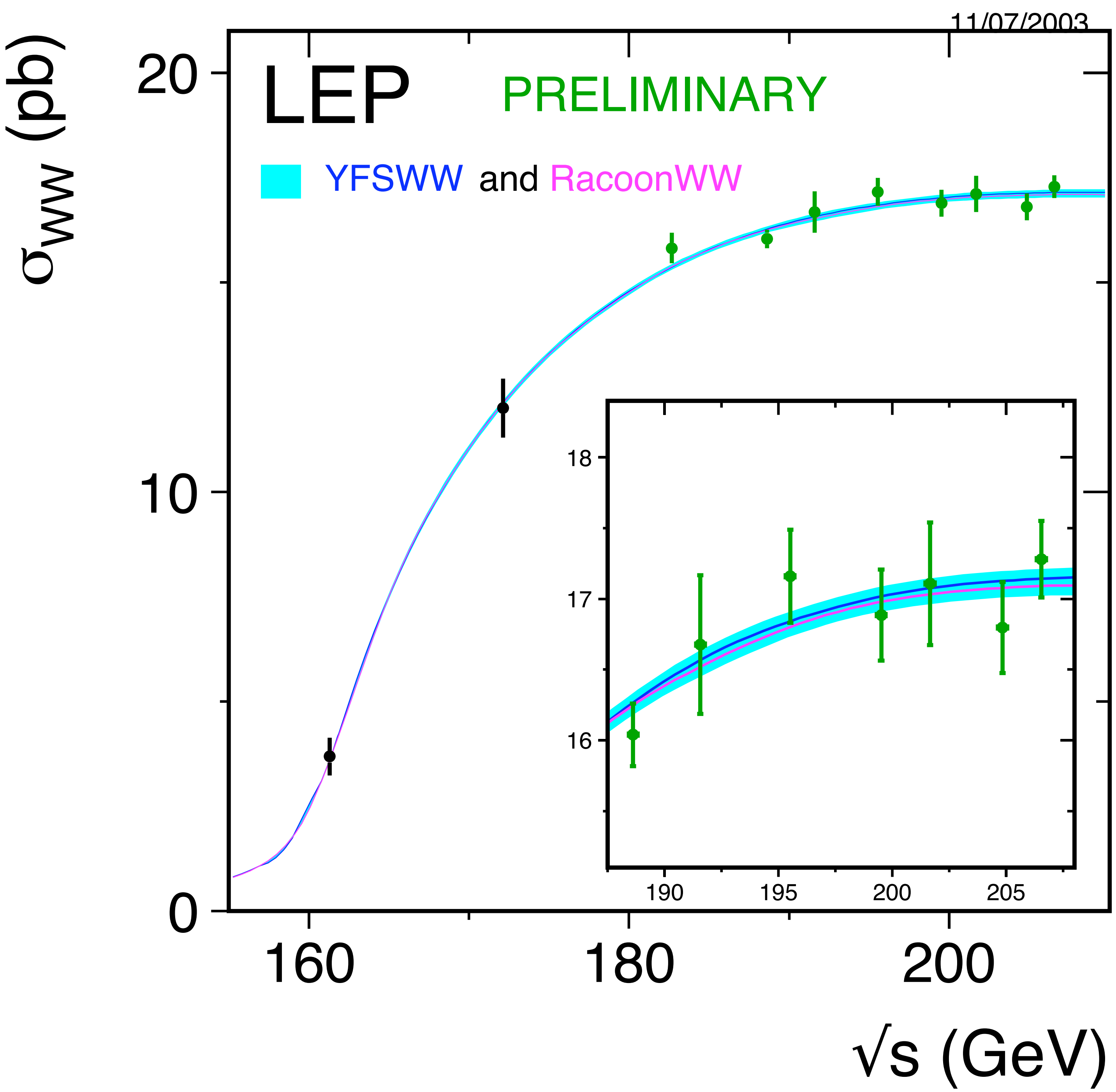
$$R \equiv \frac{\sigma_W \cdot Br(W \to \ell\nu)}{\sigma_Z \cdot Br(Z \to \ell\ell)} = \frac{\sigma_W}{\sigma_Z}\,\frac{\Gamma_Z}{\Gamma(Z \to ee)}\,\frac{\Gamma(W \to e\nu)}{\Gamma_W}$$

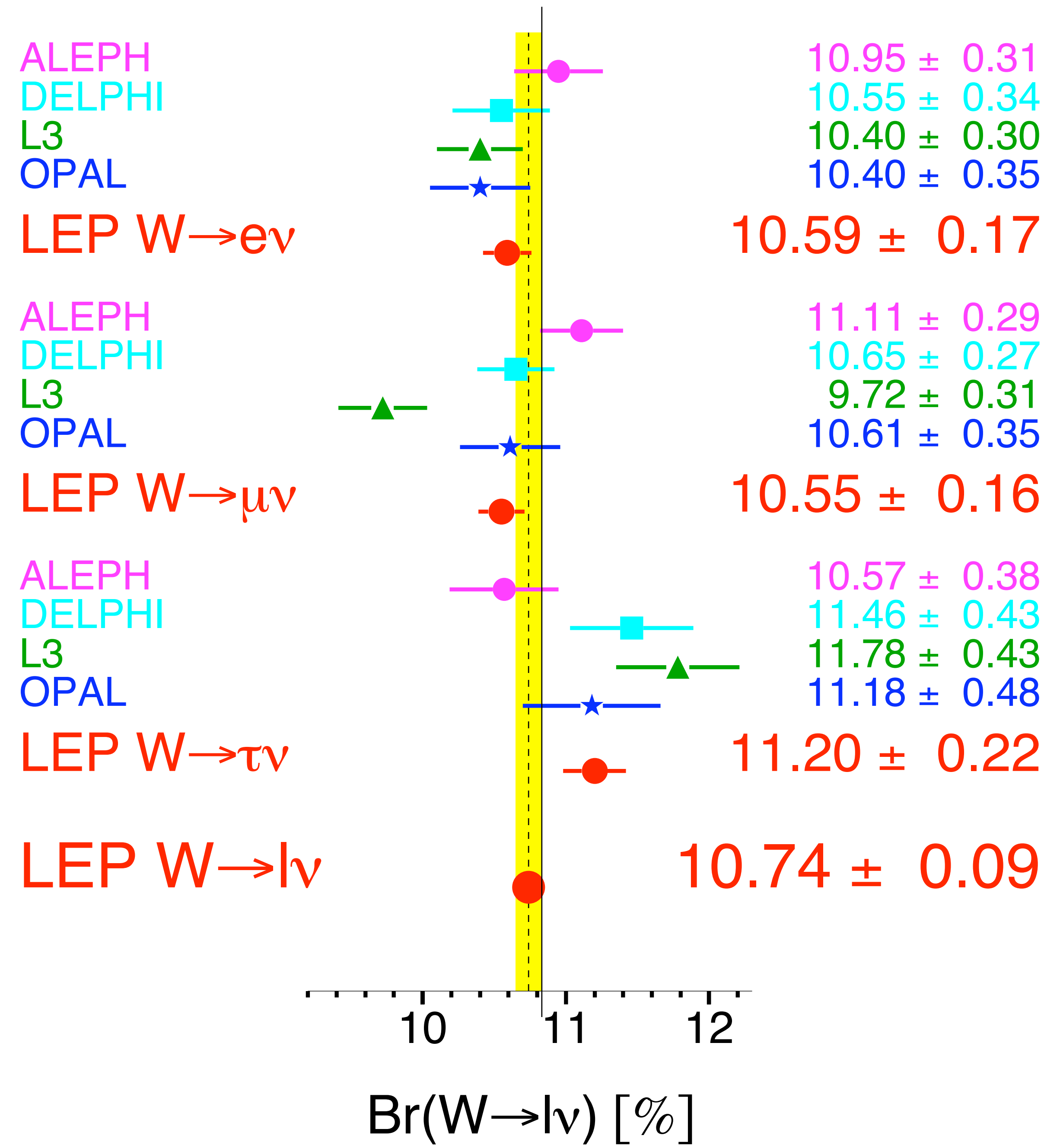
CDF : $Br(W \to \ell\nu) = 0.1055 \pm 0.0038$

DØ : $Br(W \to \ell\nu) = 0.1035 \pm 0.0062$

Run II preliminary

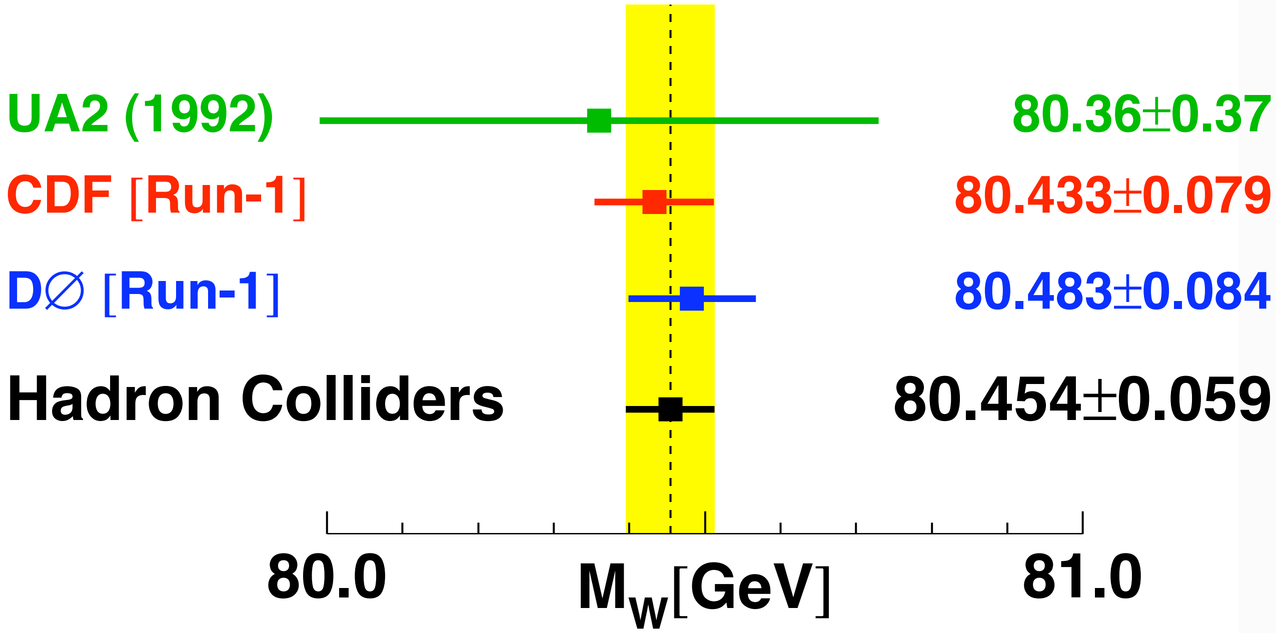
WW Production at LEP

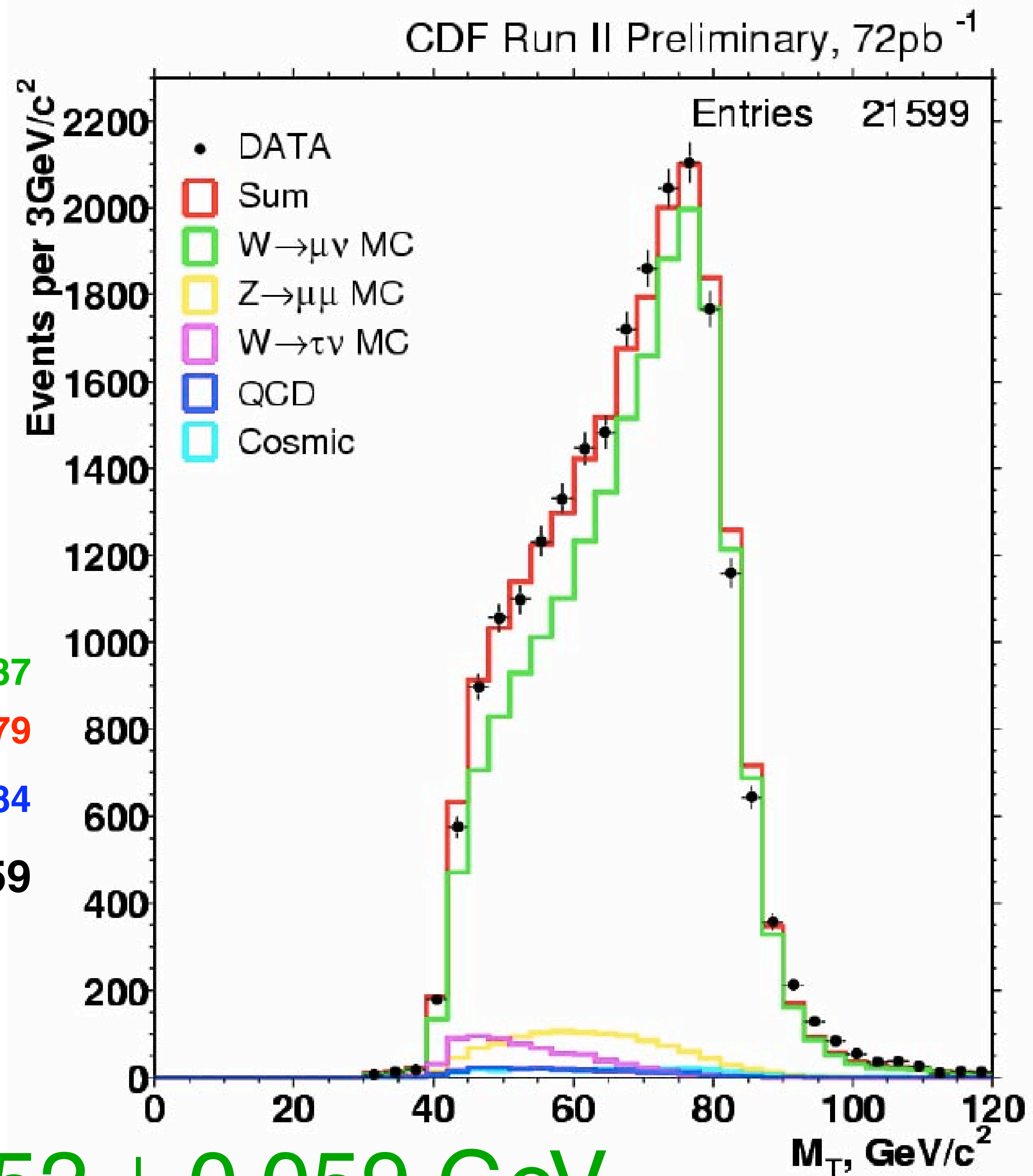




W mass from Tevatron

- Run I results FINAL
- CDF/DØ fit transverse mass
- Systematics will come down with increased statistics:
  - Energy scale controlled by Z events
  - Hadronic recoil also constrained by Z events
- CDF expects X ± 55 (stat) ± 80 (sys) MeV in μ channel for 250 pb^{-1}

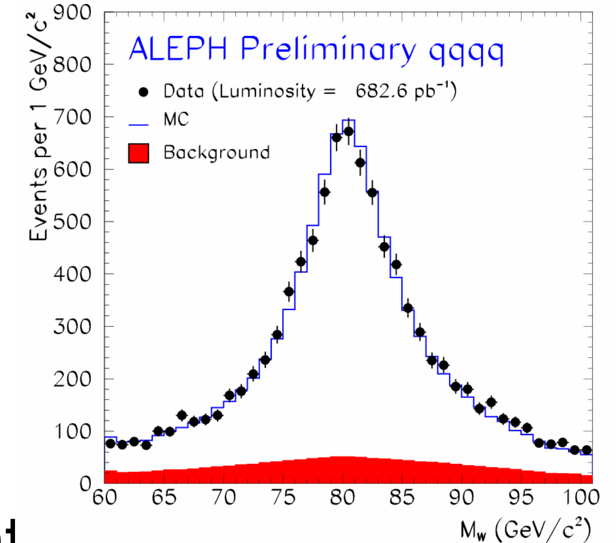


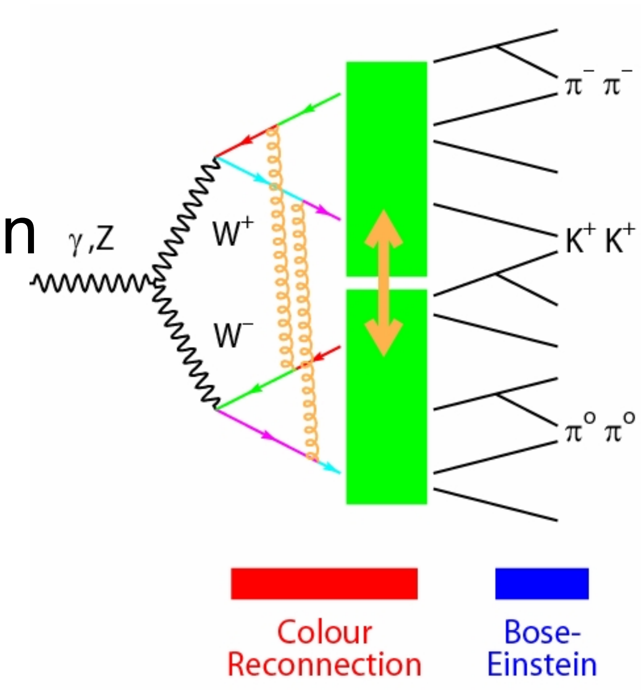


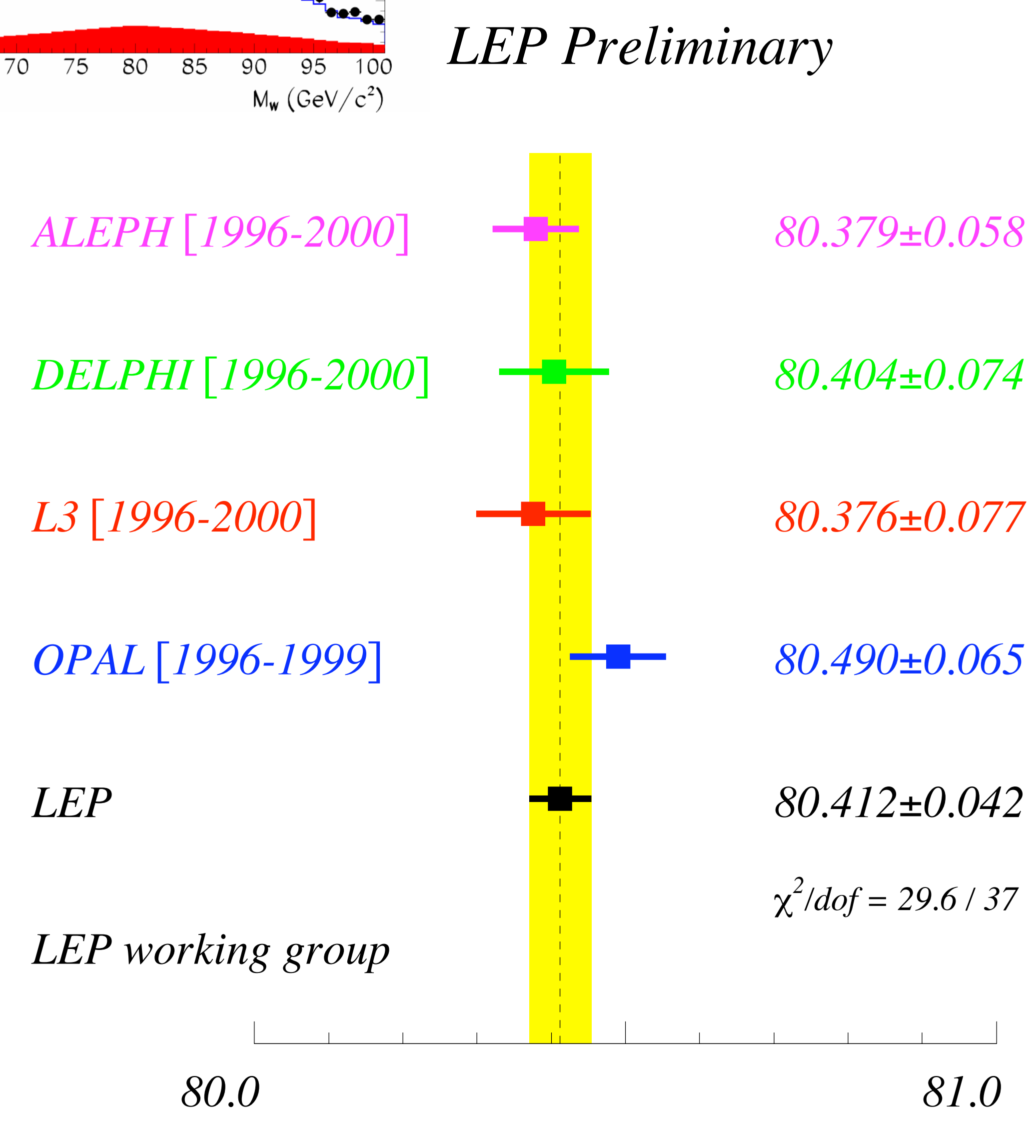
$$m_W = 80.452 \pm 0.059 \text{ GeV}$$ (Joint fit of m_W and Γ_W)

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



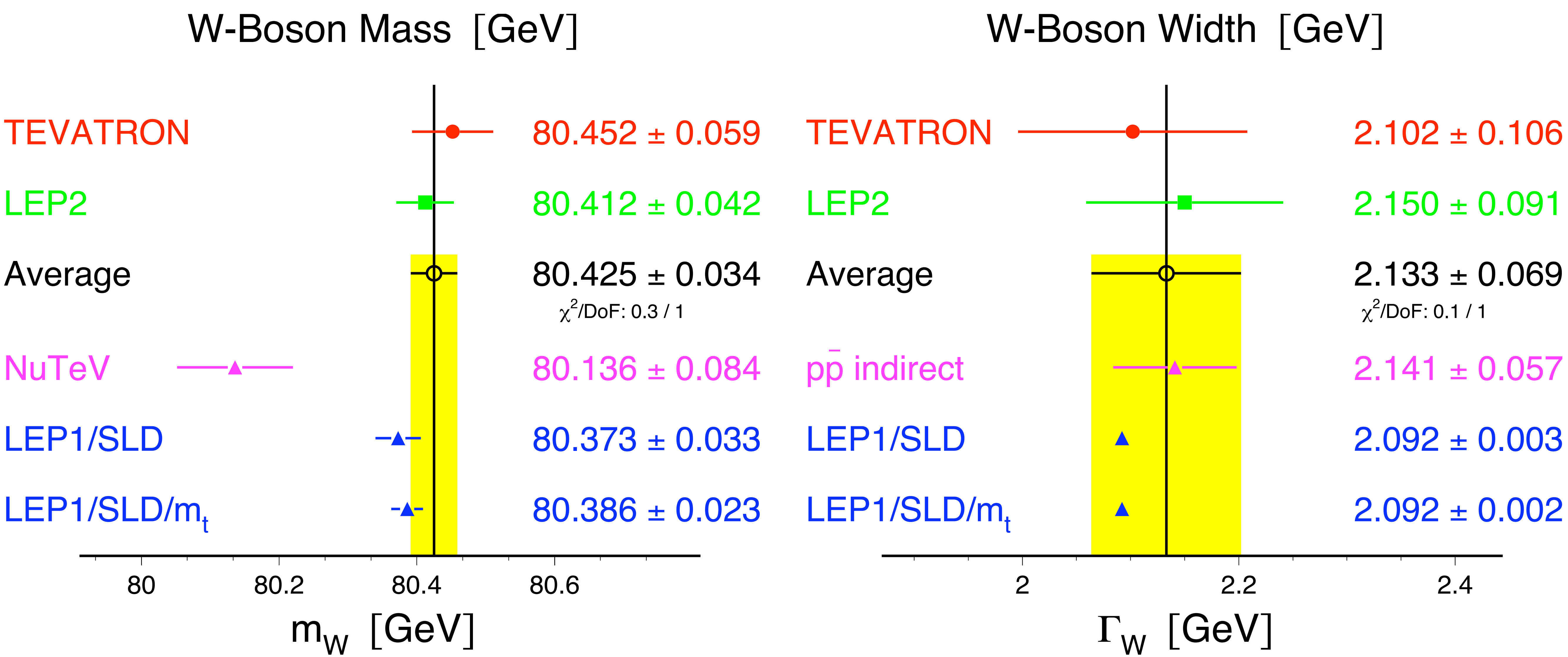




- Experimental cross-check: qqqq and qqlν differ by $\Delta m_W = +22 \pm 43$ MeV

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

World average W mass and width



$$m_W = 80.425 \pm 0.034 \text{ GeV}; \ \Gamma_W = 2.133 \pm 0.069 \text{ GeV}$$

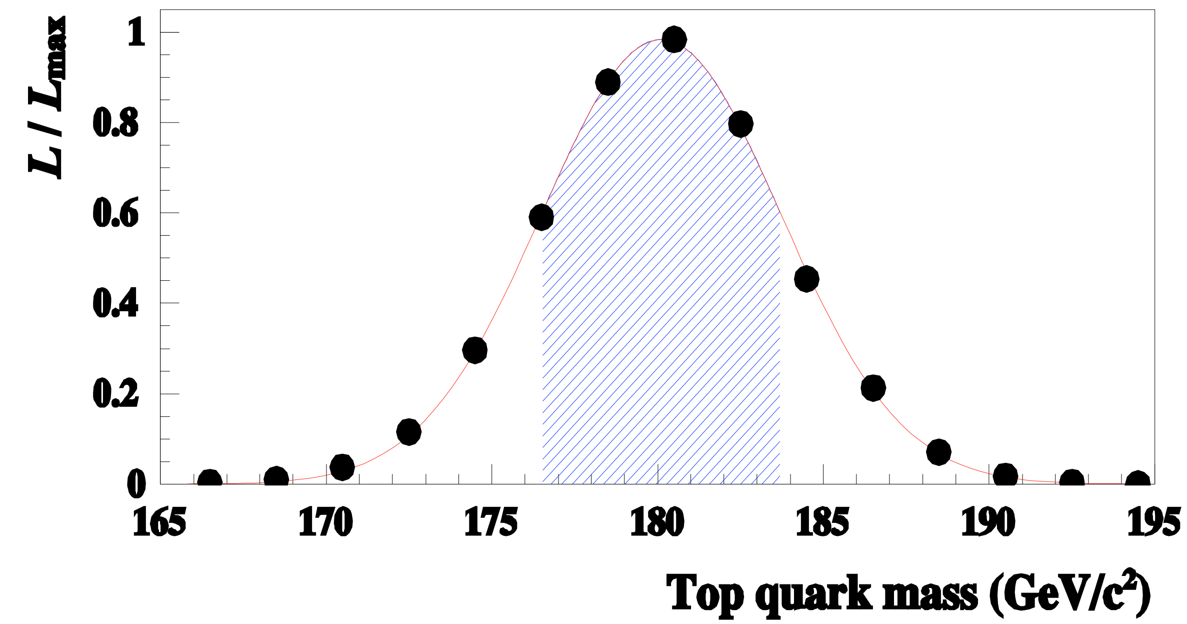
Top quark mass

New DØ Run I lepton+jets top mass

Use individual event probabilities instead of template

Improves statistical error by factor 2.5

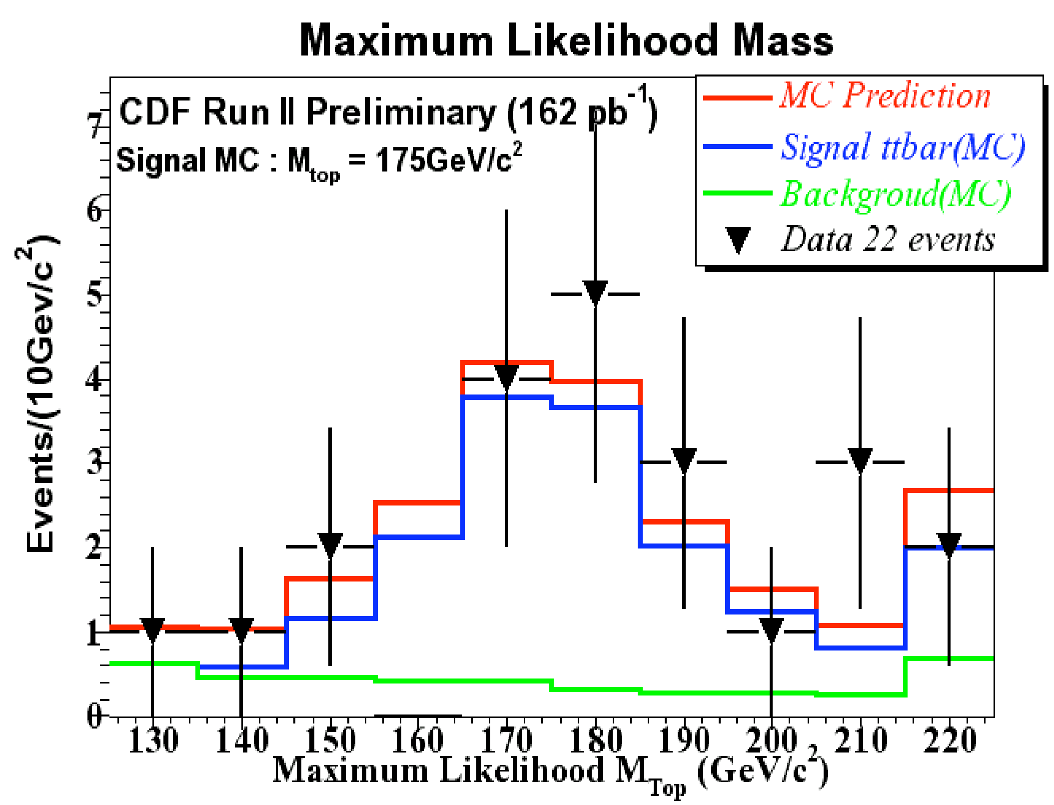
$m_t = 180.1 \pm 3.6 \pm 3.9$ GeV



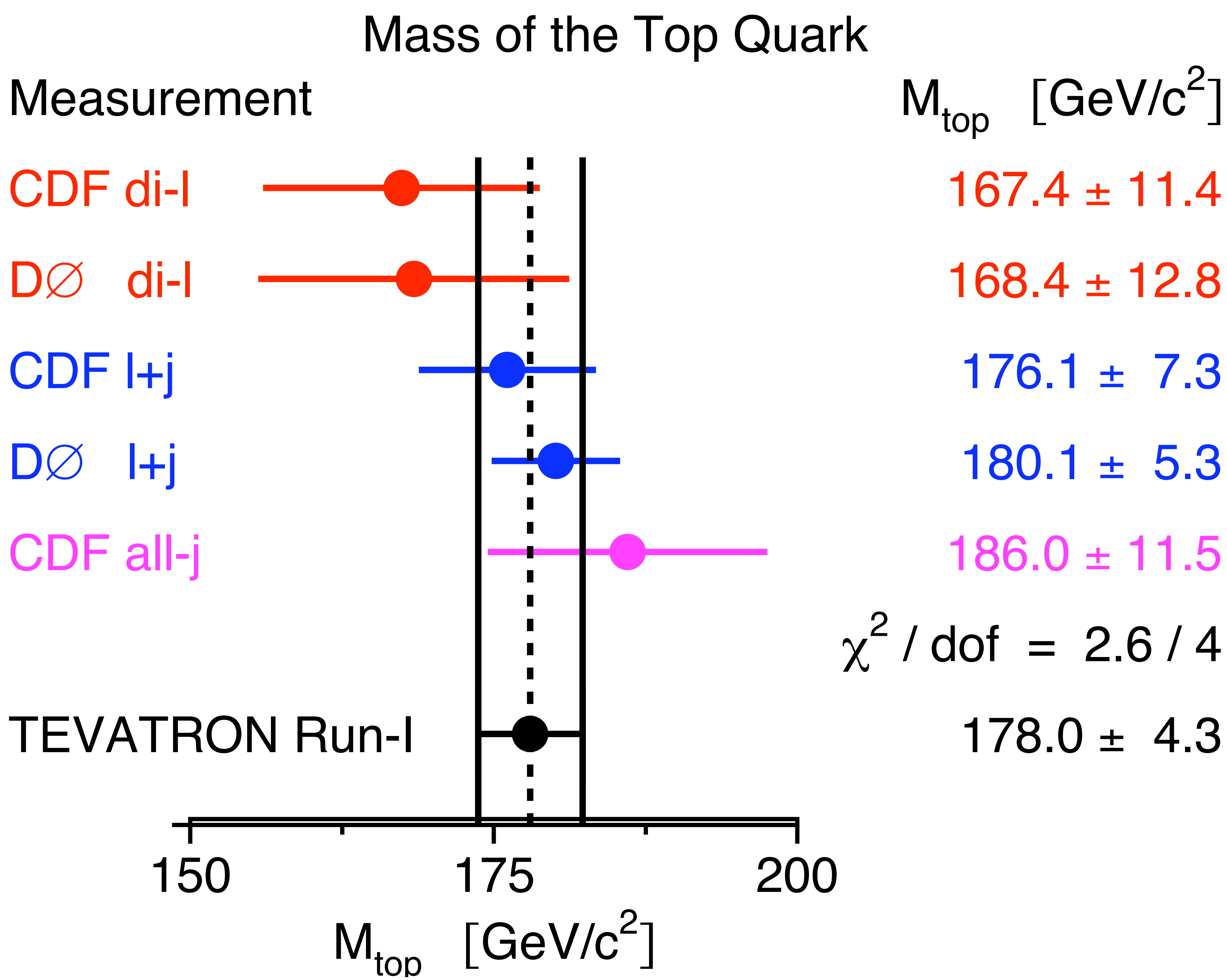
New CDF Run II top mass

$m_t = 177.8^{+4.5}_{-5.0} \pm 6.2$ GeV

Not yet included...

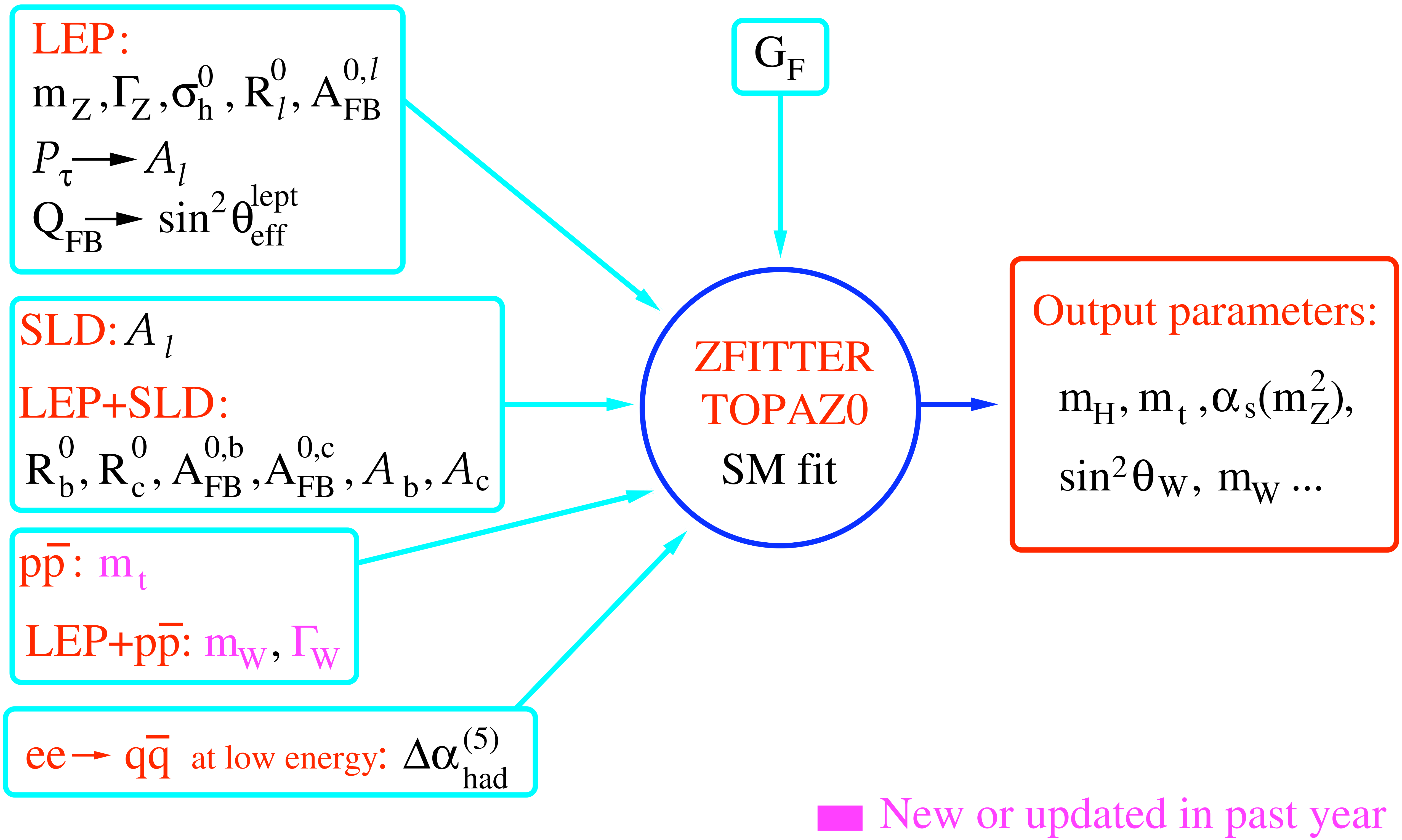


Top quark mass

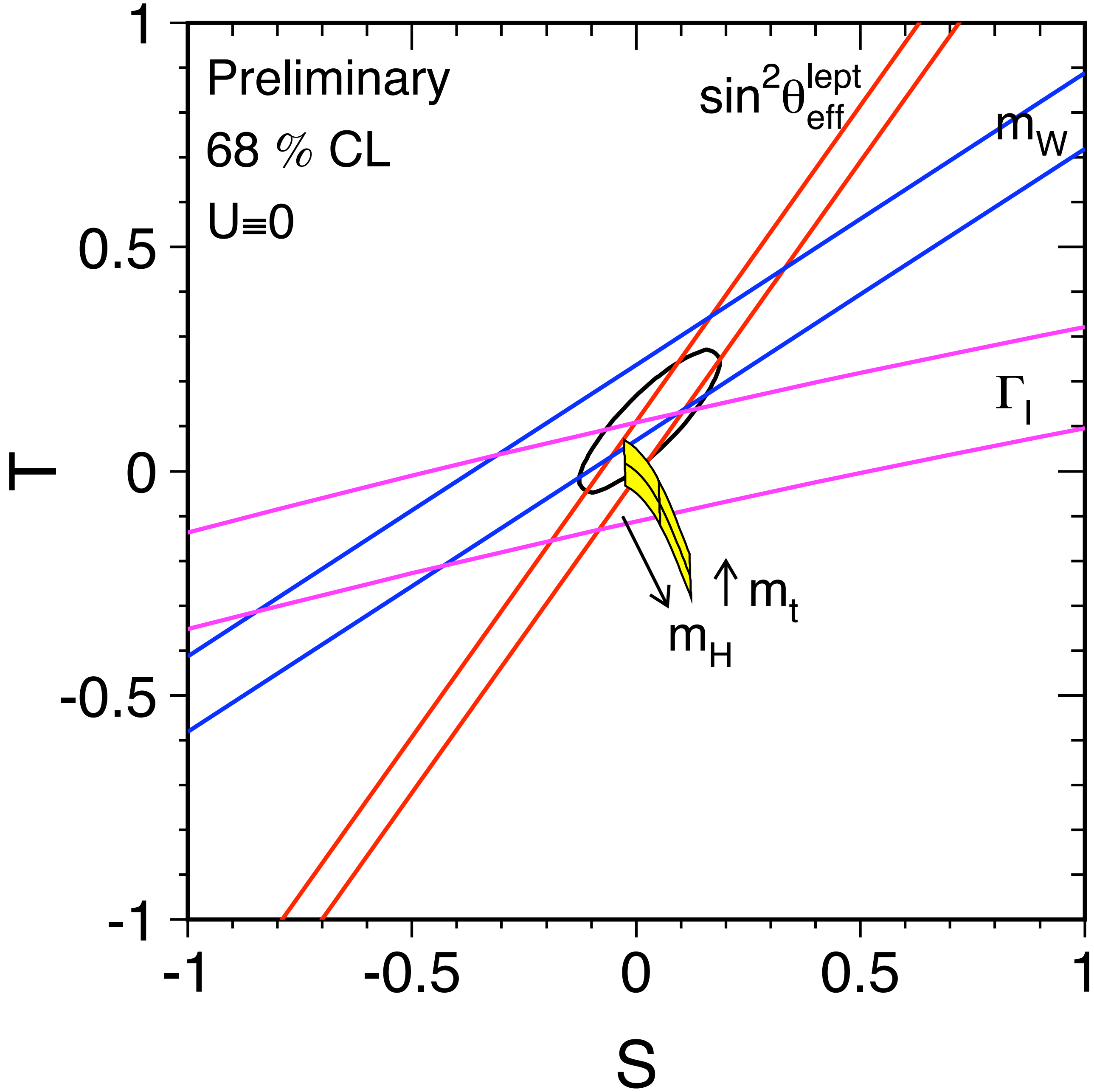


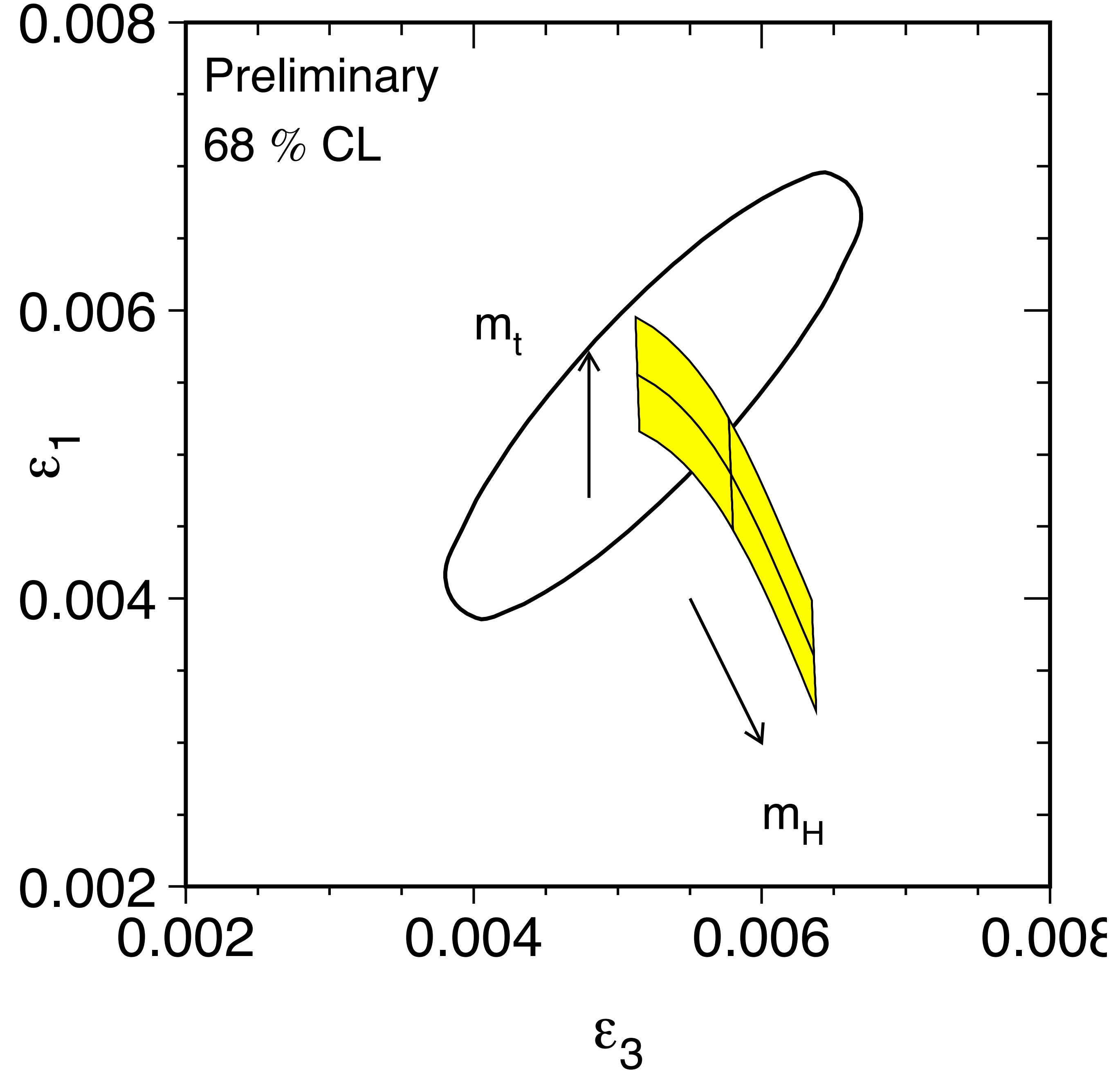
$$m_t = 178.0 \pm 2.7 \pm 3.3 \text{ GeV}$$

Strategy of the global fit



"Model Independent" Fits

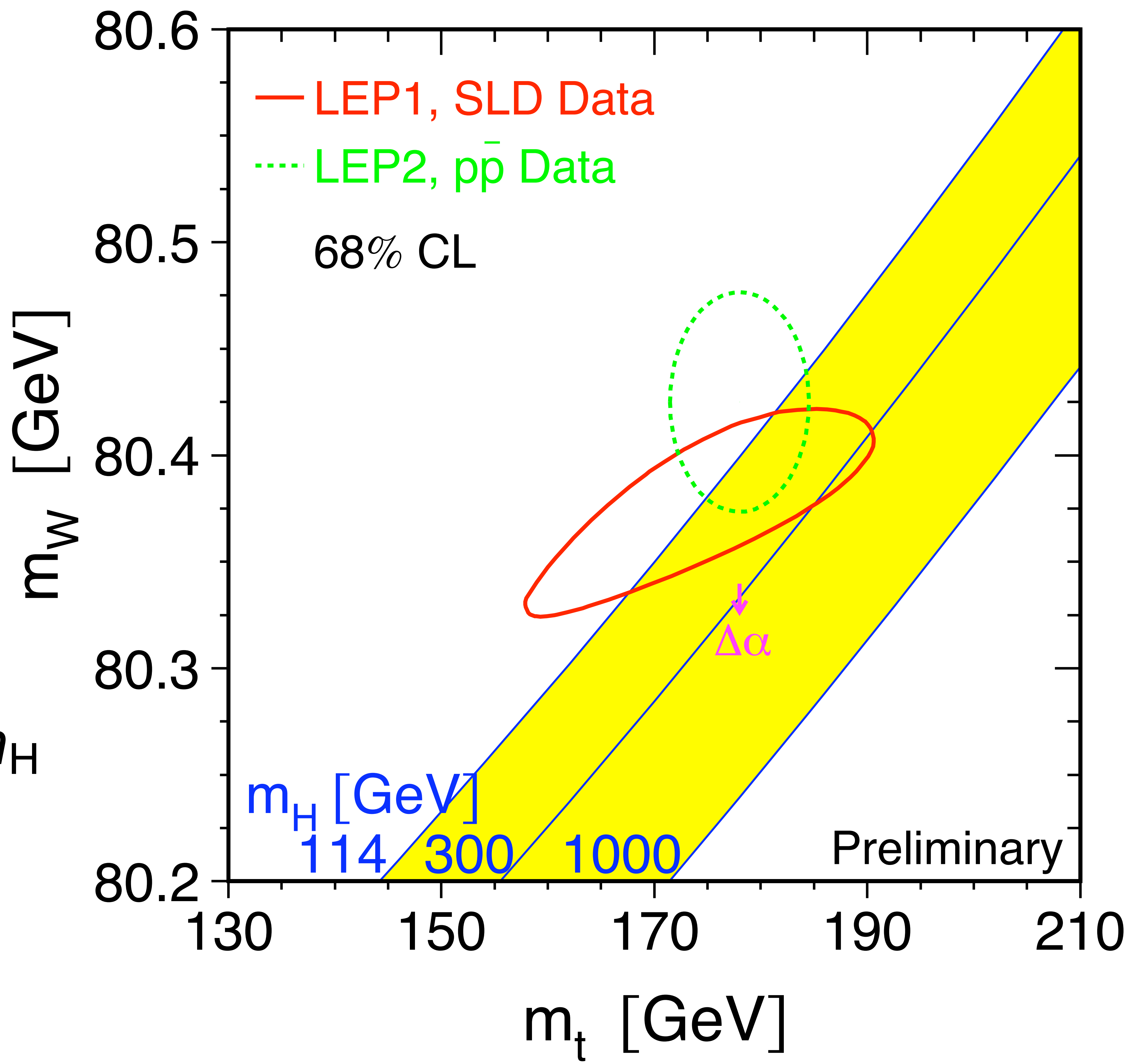




The electroweak fit: cross-checks

- Excellent agreement between direct and indirect

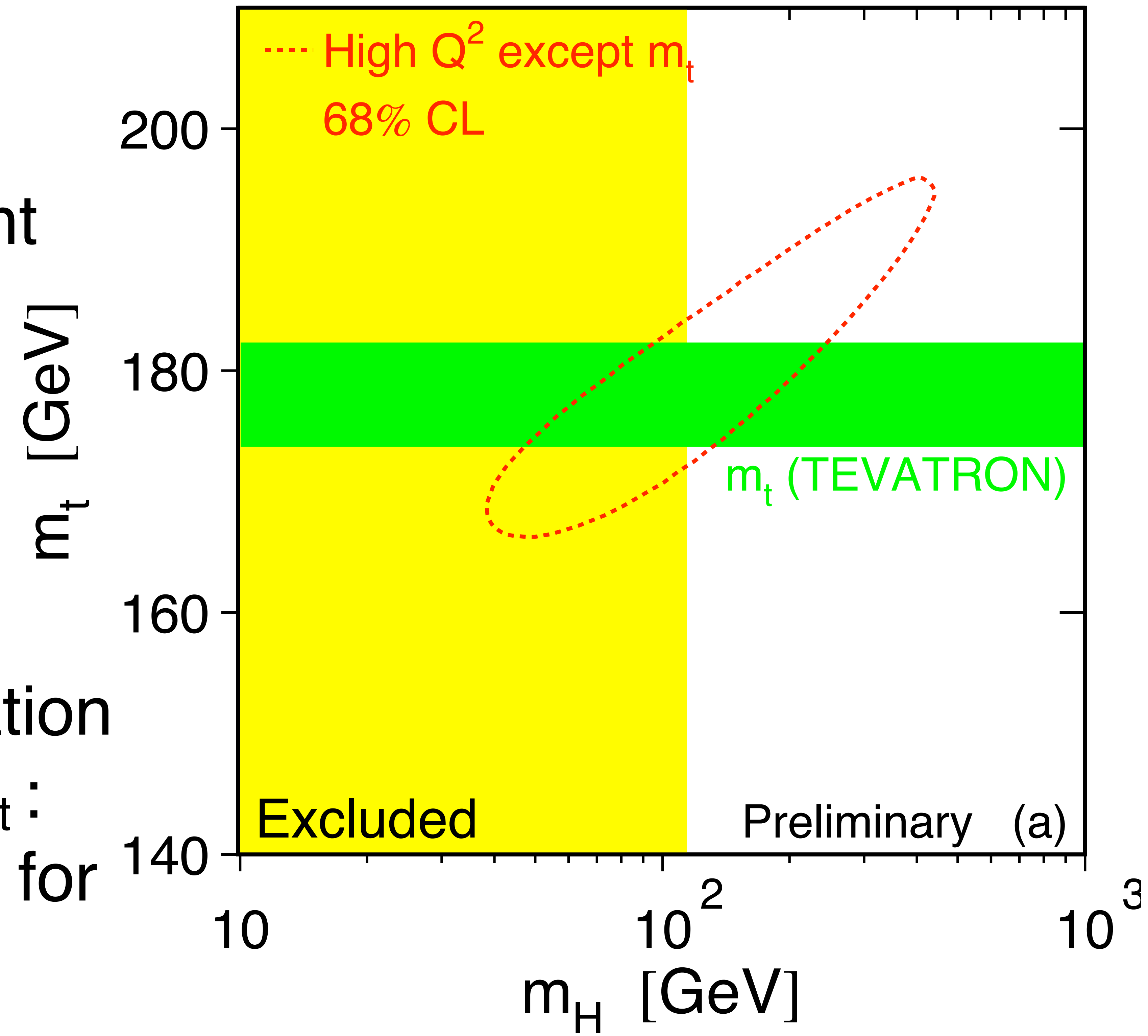
- Both prefer low m_H (though not as much as before...)



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:

$$\begin{aligned}
\Delta\alpha^{(5)}_{\mathrm{had}} &= 0.02768 \pm 0.0035 \\
\alpha_s(m_Z) &= 0.1186 \pm 0.0027 \\
m_Z &= 91.1873 \pm 0.0021\ \mathrm{GeV} \\
m_t &= 178.1 \pm 3.9\ \mathrm{GeV} \\
m_H &= 113^{+62}_{-42}\ \mathrm{GeV} \\
(\log m_H &= 2.05 \pm 0.20)
\end{aligned}$$

- The largest correlations are between

  $\log m_H$ and m_t (0.67) and

  $\log m_H$ and $\Delta\alpha^{(5)}_{\mathrm{had}}$ (–0.48)

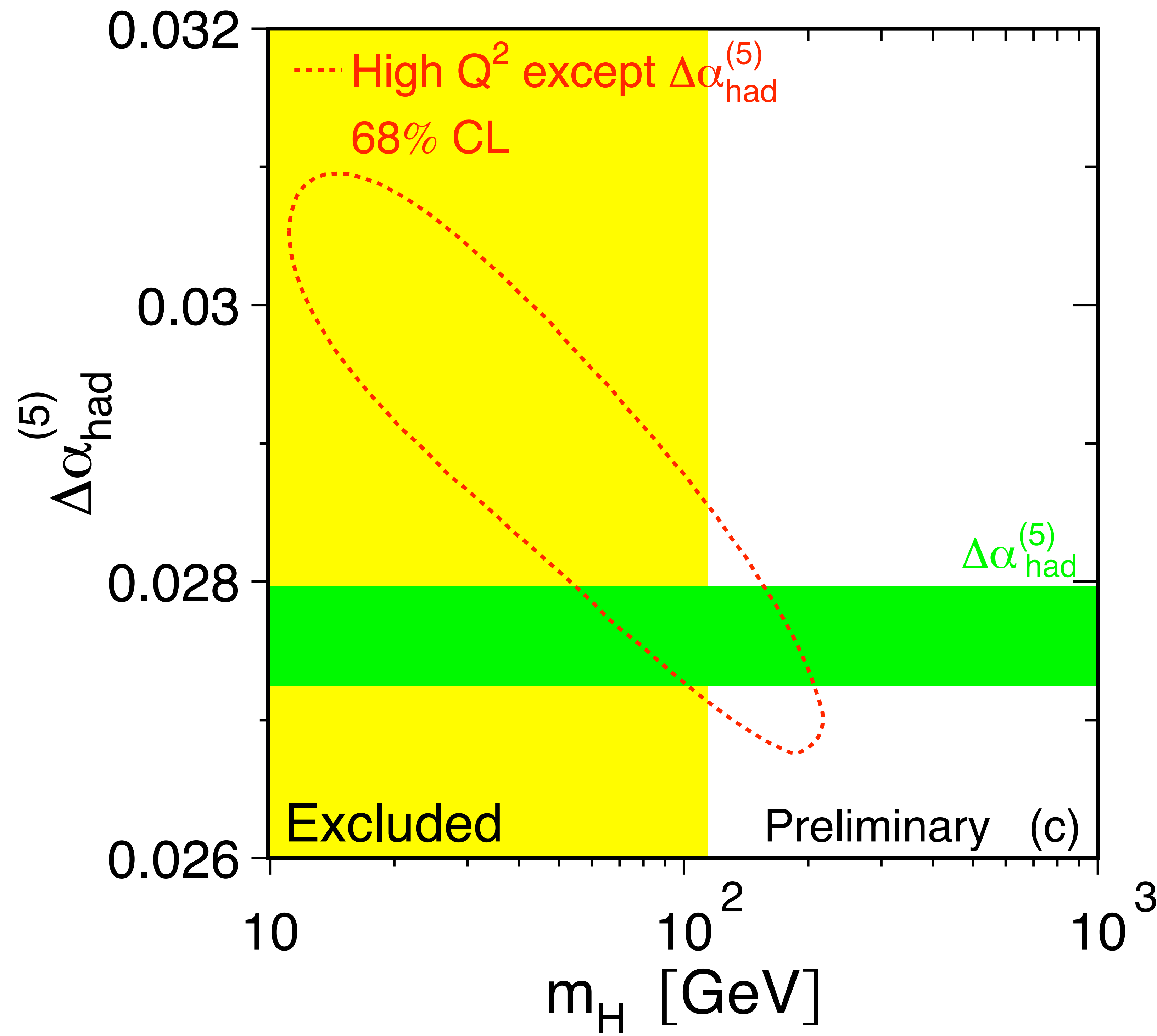
- The fit is good:

  $\chi^2/\mathrm{dof} = 16.3/13 (23\%)$

Hadronic vacuum polarization

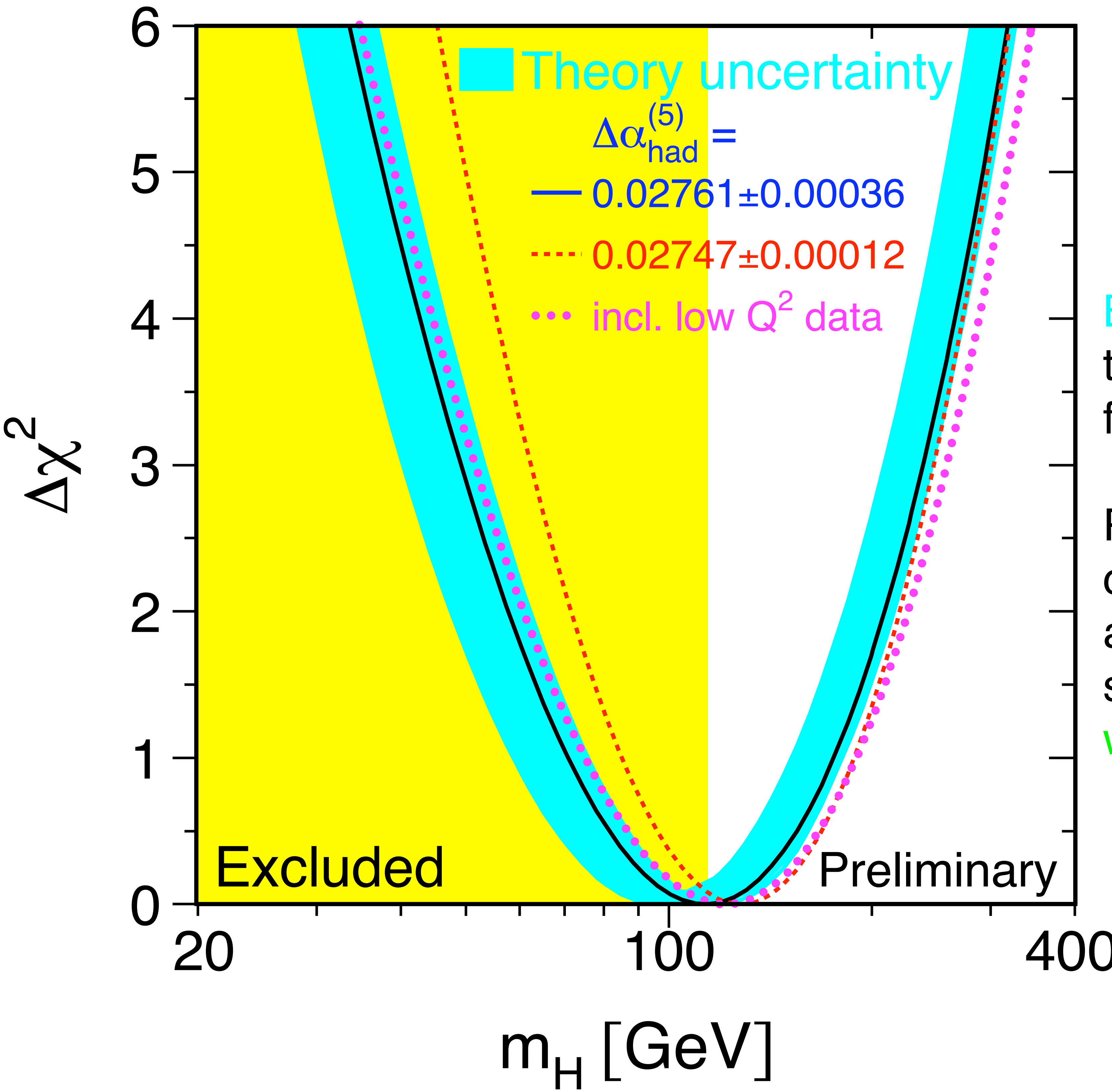
- Experimentally driven value (0.2761±0.00036) used
- Using a more theory driven value (0.2747±0.00012):

$$m_H = 128^{+60}_{-43}\ \text{GeV}$$



More low Q^2 data always appreciated: *eg* CMD-2, KLOE, BaBar, Belle, CLEO-c

The global fit: limits on the Higgs mass



$m_H < 237$ GeV (95% CL)

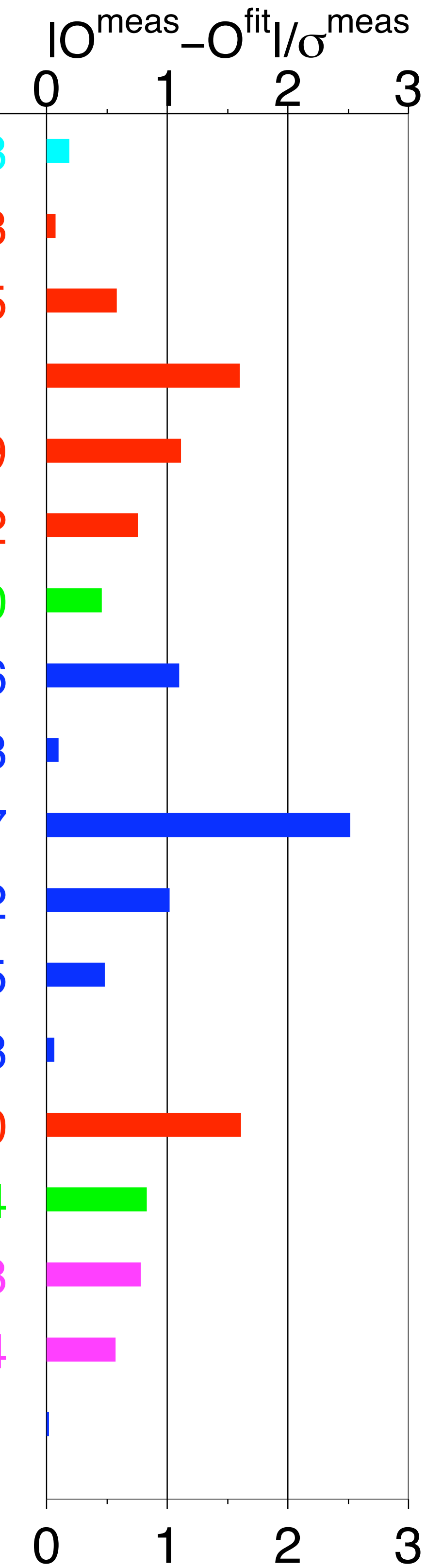
Blue band width is estimate of theoretical uncertainties coming from higher order effects

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

The global electroweak fit

Winter 2004

	Measurement	Fit
$\Delta\alpha_{had}^{(5)}(m_Z)$	0.02761 ± 0.00036	0.02768
m_Z [GeV]	91.1875 ± 0.0021	91.1873
Γ_Z [GeV]	2.4952 ± 0.0023	2.4965
σ_{had}^0 [nb]	41.540 ± 0.037	41.481
R_l	20.767 ± 0.025	20.739
$A_{fb}^{0,l}$	0.01714 ± 0.00095	0.01642
$A_l(P_\tau)$	0.1465 ± 0.0032	0.1480
R_b	0.21638 ± 0.00066	0.21566
R_c	0.1720 ± 0.0030	0.1723
$A_{fb}^{0,b}$	0.0997 ± 0.0016	0.1037
$A_{fb}^{0,c}$	0.0706 ± 0.0035	0.0742
A_b	0.925 ± 0.020	0.935
A_c	0.670 ± 0.026	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]	80.425 ± 0.034	80.398
Γ_W [GeV]	2.133 ± 0.069	2.094
m_t [GeV]	178.0 ± 4.3	178.1



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)

Atomic Parity Violation:

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)).

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

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

$$Q_W(\text{Cs}) = -72.84 \pm 0.29(\text{exp}) \pm 0.036(\text{th})$$

$$Q_W^{\text{fit}}(\text{Cs}) = -72.91 \pm 0.04$$

Very nice!

Møller scattering ($e^- e^-$)

Parity violating *t*-channel process due to γ/Z interference. Experiment E-158 at SLAC using polarized e^- beam.

$$A_{PV} = \frac{\sigma_R - \sigma_L}{\sigma_R + \sigma_L}$$

$$\propto \quad Q_W(e^-) = -4 g_{Ae} g_{Ve}$$

Interpreted as the weak mixing angle at the Z mass:

$$\sin^2 \theta_W^{(\overline{MS})}(Q^2 = m_Z^2) = 0.2306 \pm 0.0021$$

hep-ex/0403010

$$\text{SM} \quad 0.2311 \pm 0.0001$$

Again, very nice agreement

NuTeV results

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

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

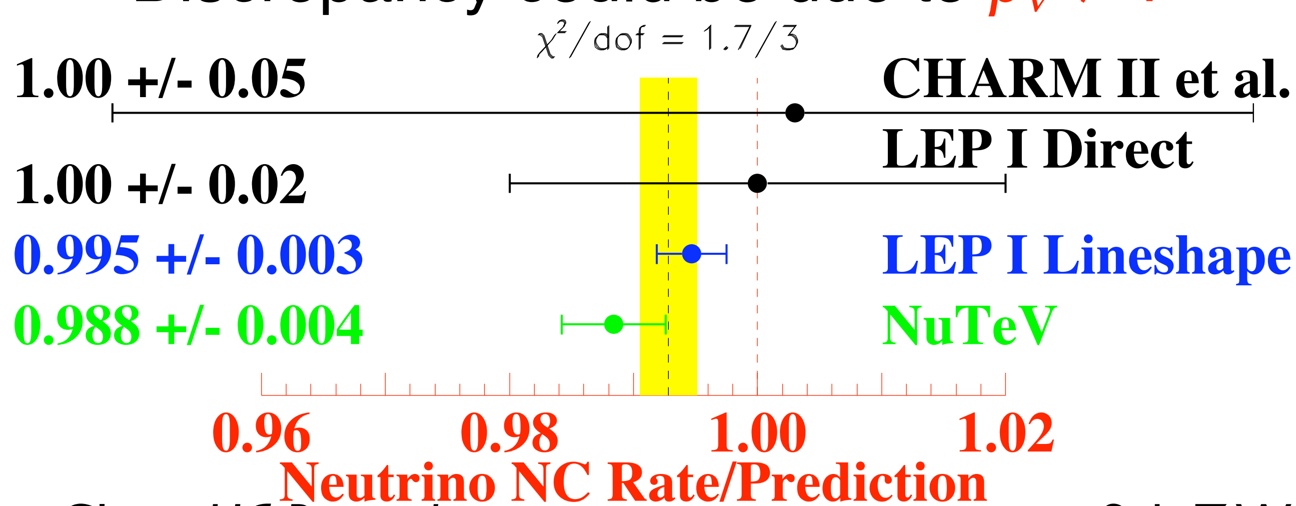
NuTeV actually measures R^{ν} and $R^{\bar{\nu}}$. Discrepancy from R^{ν}.

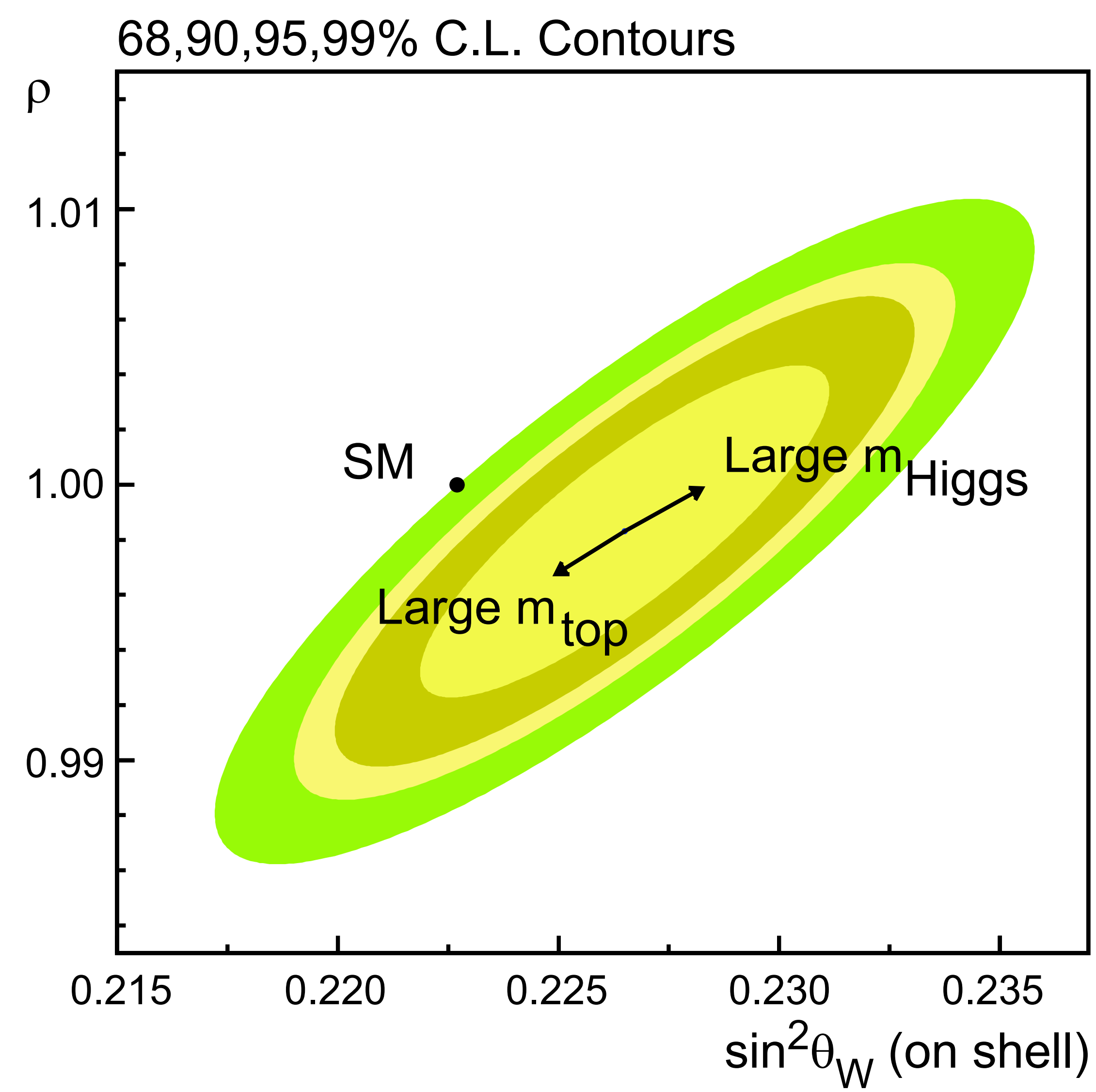
$$\sin^2\theta_W = 0.22773 \pm 0.00135(\text{stat.}) \pm 0.00093(\text{sys.}); \quad \Delta_{SM}\ 3.0$$

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 $\rho_\nu \neq 1$





Beyond the SM – the MSSM

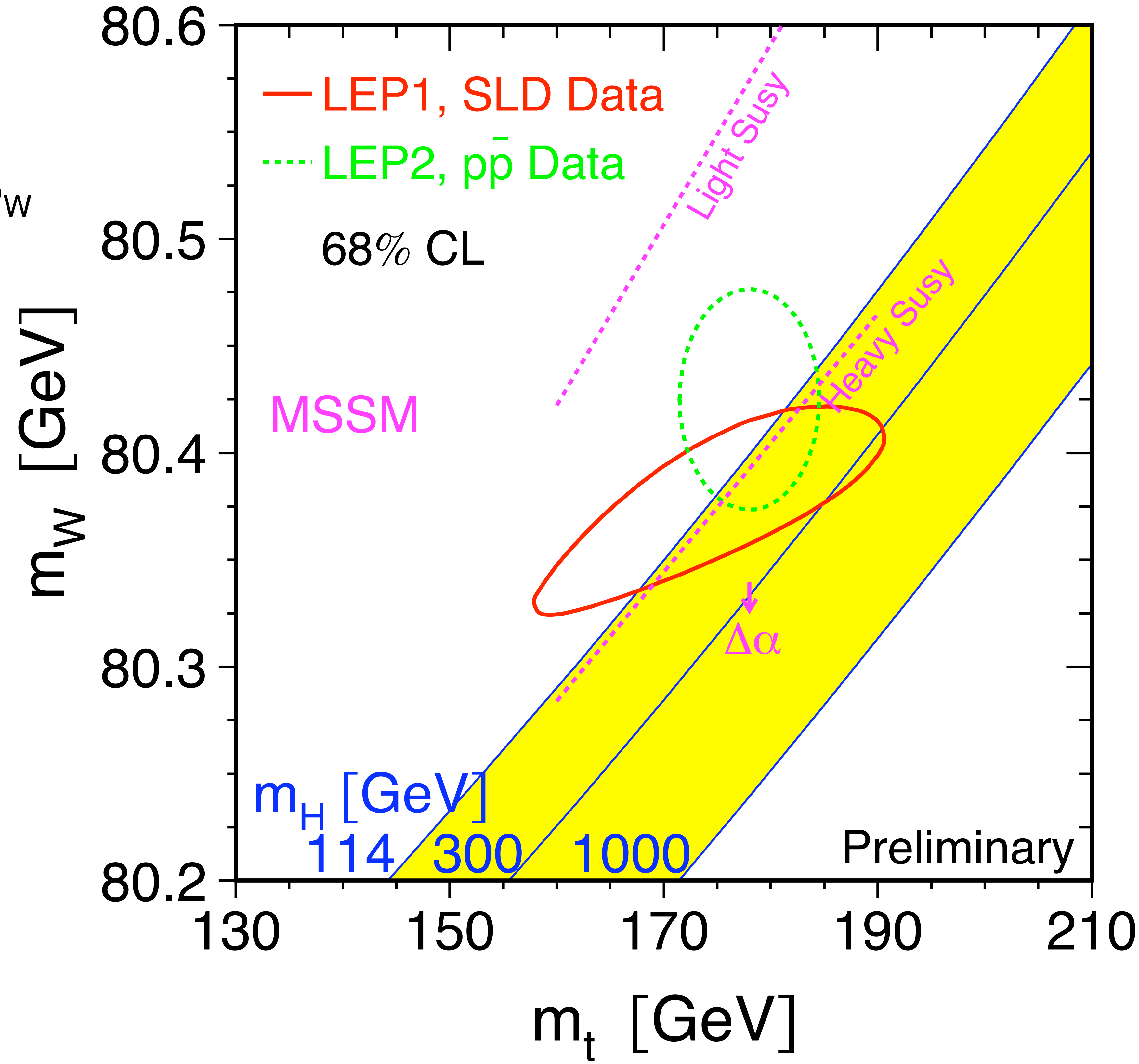
In the SM, the Higgs mass is a free parameter, and m_t and m_W can be related to it.

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

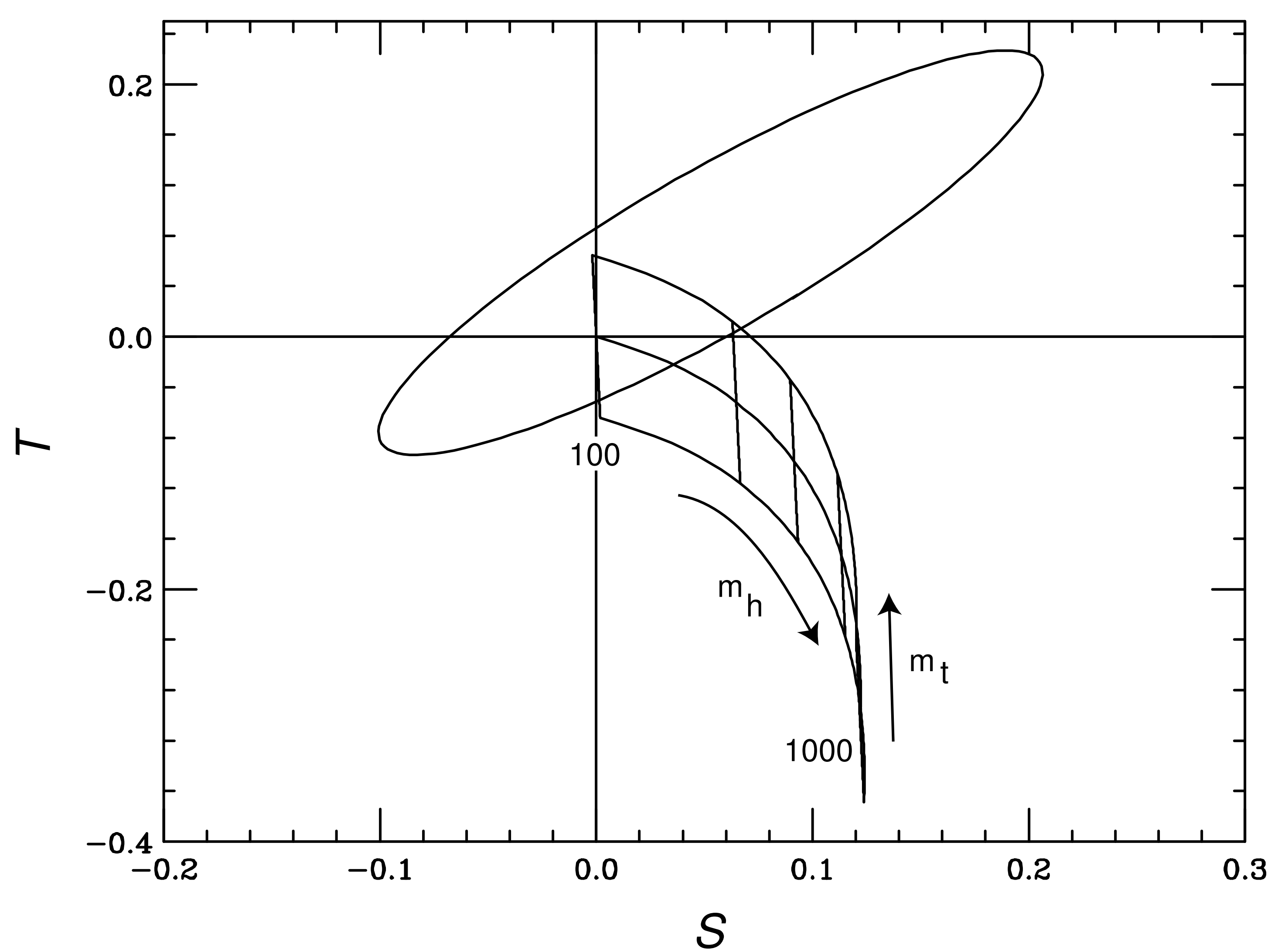
Unfortunately, **they** are free!

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

MSSM: Heinemeyer, Weiglein, hep-ph/0307177



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



Peskin & Wells, PR D64 (2001) 093003

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

- Some Technicolor models contribute negative S (e.g., Luty & Sundrum, hep-ph/9209255)
- An appropriately chosen Z' can move (S,T) in almost any direction, but must be light (< 2 TeV).
- "top-color seesaw" (e.g. 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	LHC	LC	GigaZ
$\delta \sin^2\theta_{eff}^{lept} (\times 10^5)$	17	78	14–20	(6)	1.3
δm_W [MeV]	33	27	15	10	7
δm_t [GeV]	5.1	2.7	1.0	0.2	0.13
δm_H [MeV]	—	—	100	50	50

unbar, et al., Snowmass 2001, hep-ph/0111314

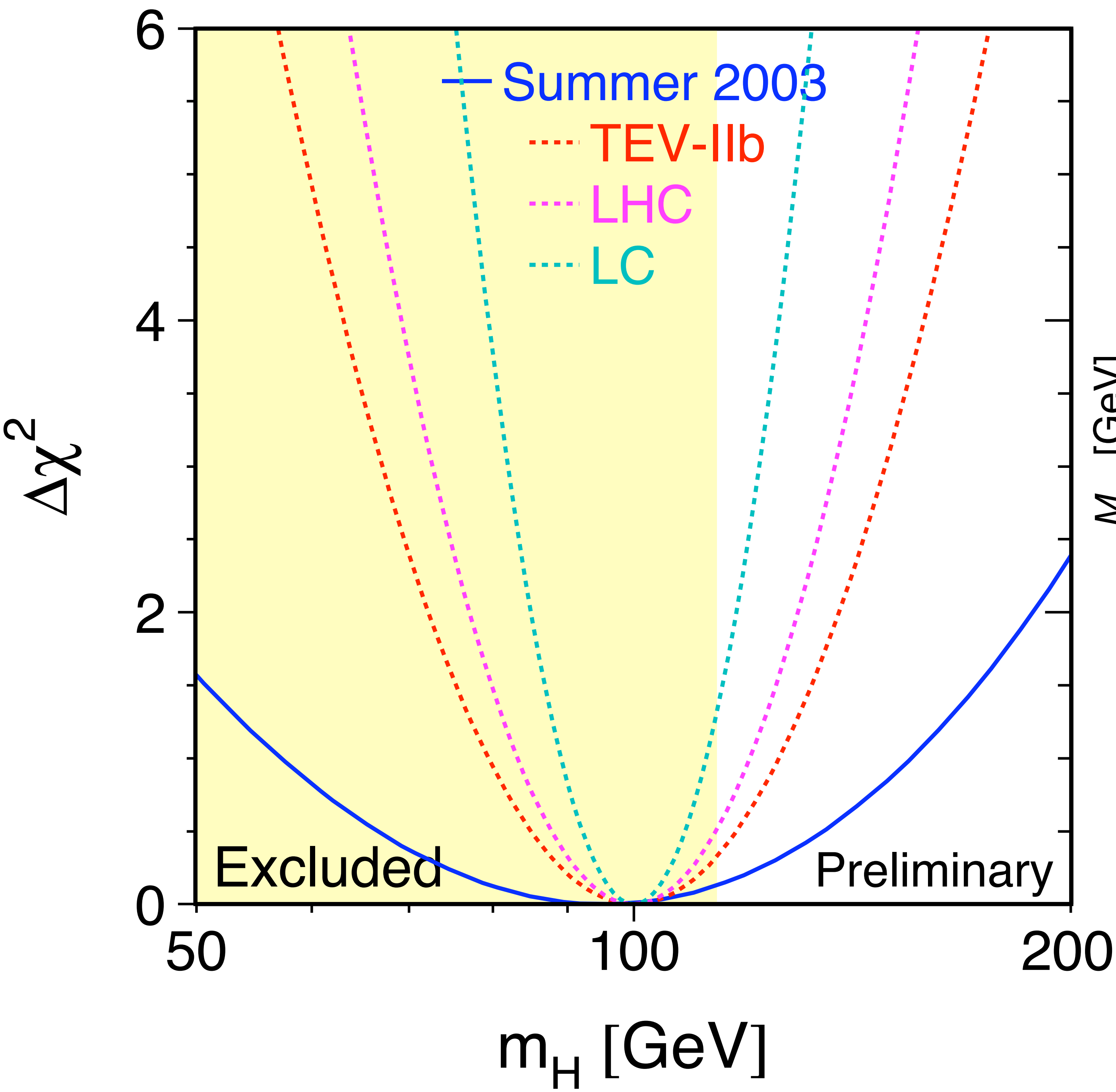
Near future (Run II, LHC):

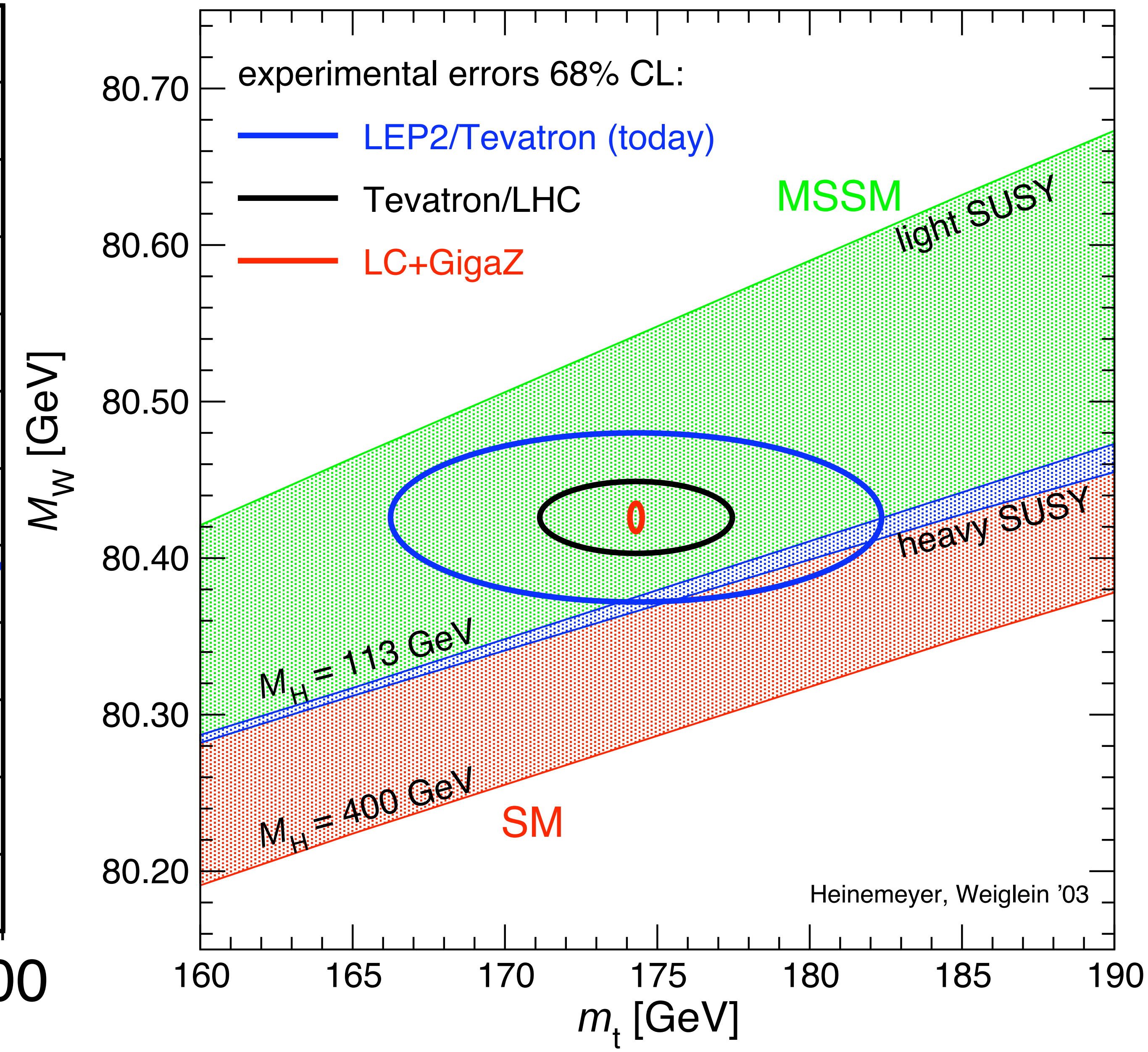
- $\delta m_W = 15$ MeV
- $\delta m_t = 1.5$ GeV
- $\delta\Delta\alpha_{had} = 0.0002$

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





Conclusions

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

$$m_H < 237\ \text{GeV}$$

- 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?