Electroweak Data and the Higgs Boson

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- Electroweak corrections: definition and strategies
- Experimental inputs: what's new
- Effective Couplings as a test of the Standard Model
- The electroweak global fit
- m_H limits
- Future prospects in precision EW measurements
- Conclusions

[Many thanks to the LEPEWWG and especially S. Villa!]

Electroweak radiative corrections

- Precision measurements ⇒ knowledge of Standard Model parameters through radiative corrections :

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

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

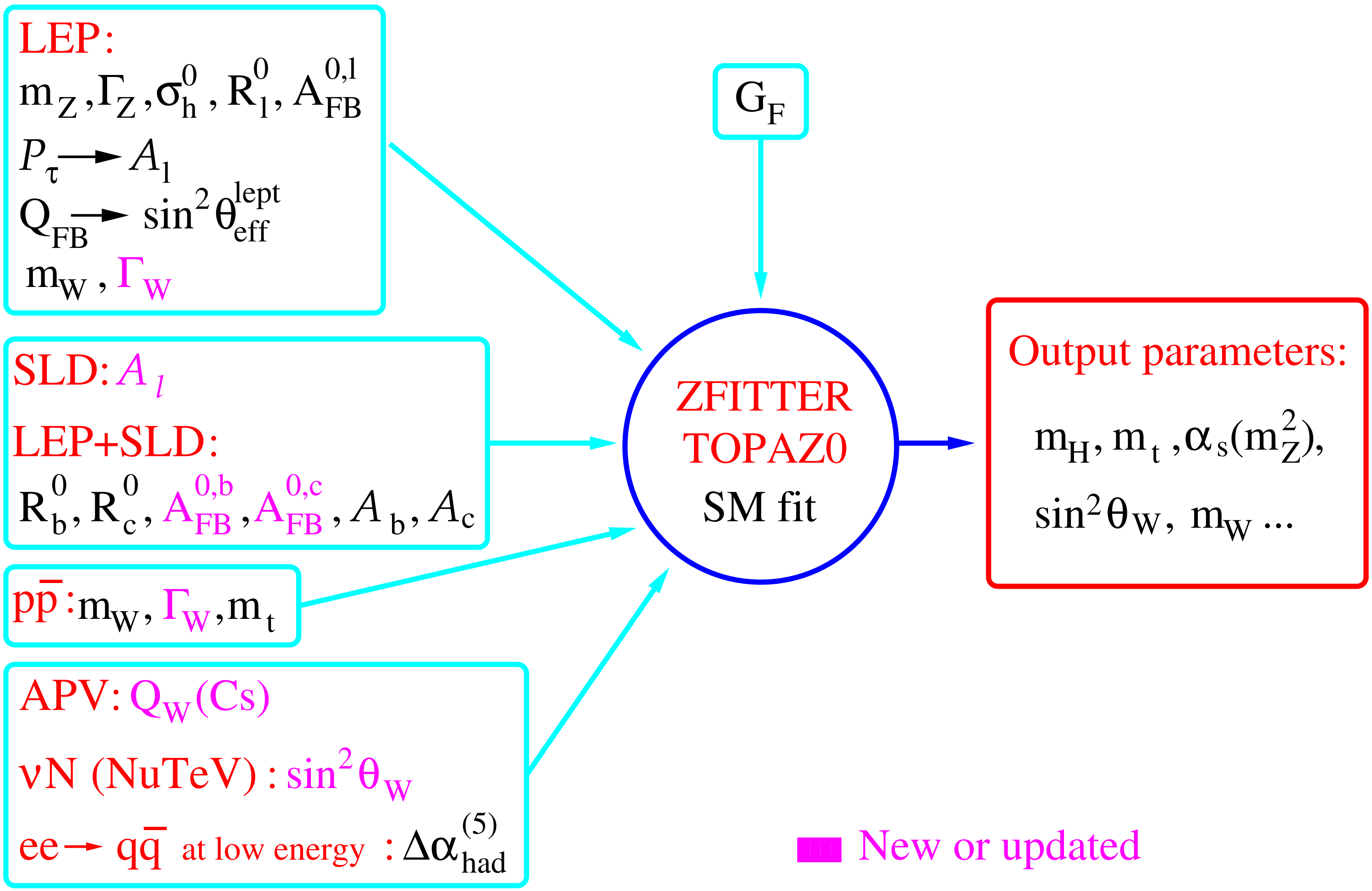
$$m_W^2 = \frac{\pi\alpha}{\sqrt{2}\sin^2\theta_W G_F} \quad \Longrightarrow \quad m_W^2 = \frac{\pi\alpha}{\sqrt{2}\sin^2\theta_W G_F}(1 + \Delta r)$$

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

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

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

Strategy of the global fit



Effective couplings

Some definitions:

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

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

with:

$$g_V = \sqrt{\bar{\rho}}\left(I^{(3)} - 2Q\sin^2\theta_{eff}\right)$$

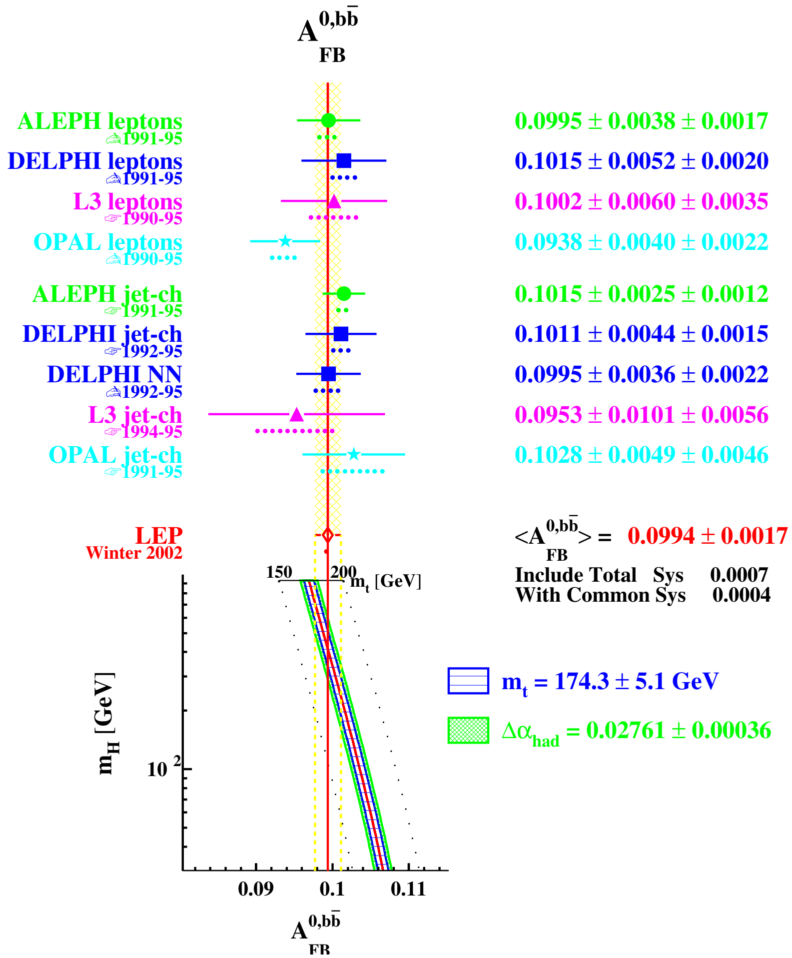
$$g_A = \sqrt{\bar{\rho}}\; I^{(3)}$$

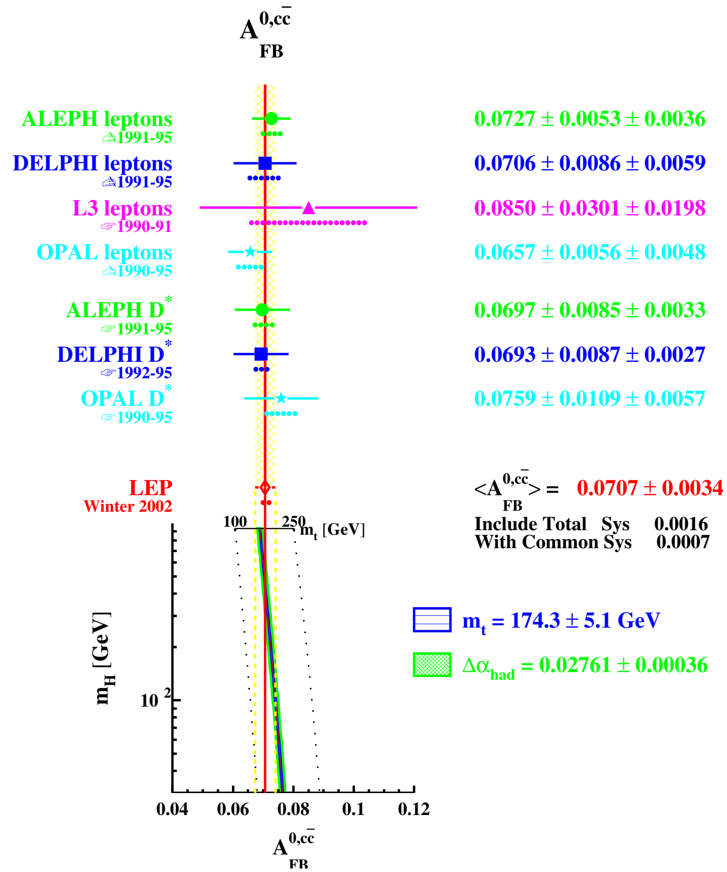
Experimental strategies:

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

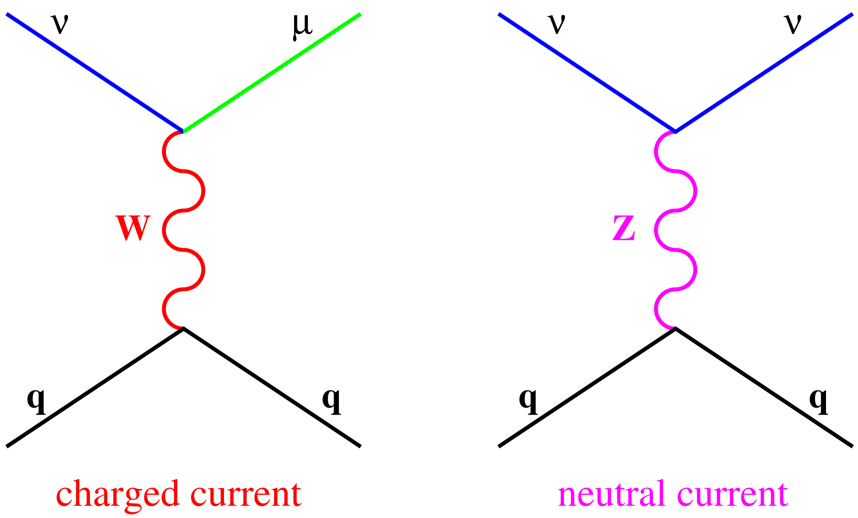
New: $A_{FB}^{0,b}$ e $A_{FB}^{0,c}$ from leptons at Aleph





$A_{FB}^{0,b} \uparrow \frac{1}{4}\sigma$ and $A_{FB}^{0,c} \uparrow \frac{2}{3}\sigma$ since Summer 2001

New: NuTeV final results



ν_μ-nucleon scattering:

CC: coupl. $\propto I^{(3)}_{\text{weak}}$

NC: coupl. $\propto \left(I^{(3)}_{\text{weak}} - Q_{\text{em}} \sin^2\theta_W\right)$

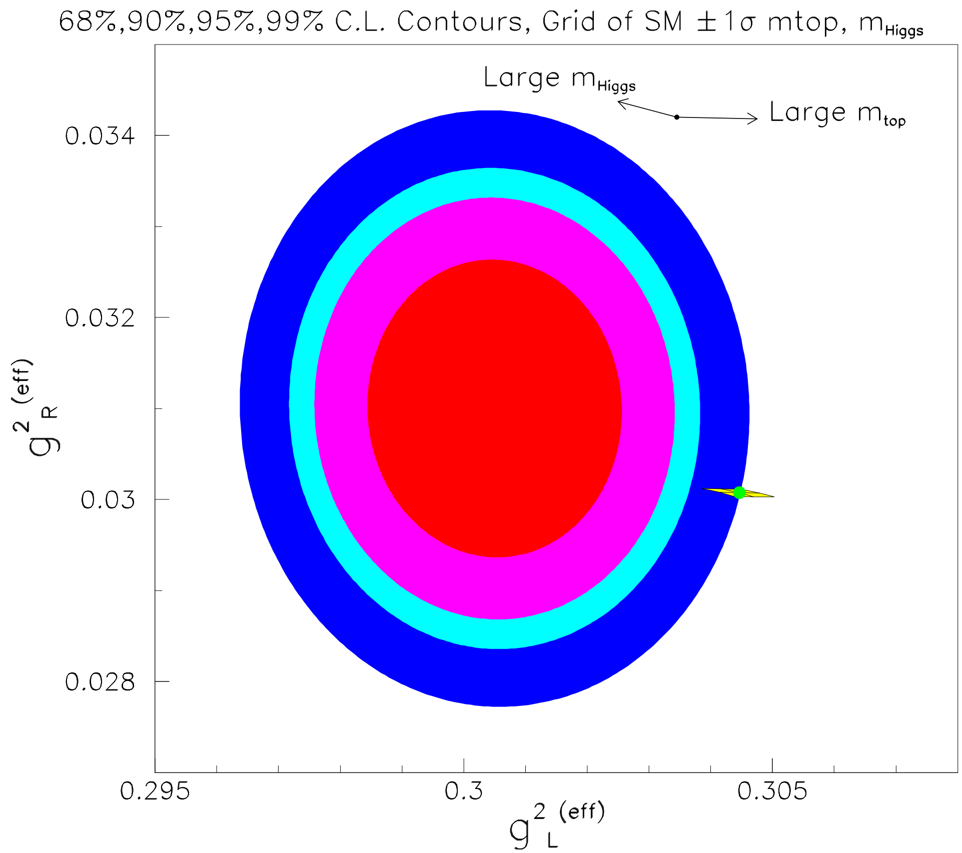
Paschos-Wolfenstein:

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

$\Rightarrow \sin^2\theta_W$ measurement; need ν_μ and $\bar\nu_\mu$ beams

New: NuTeV final results

Fit quark neutral current effective couplings:



Main sources of systematic uncertainties and corrections:

- Beam contamination from ν_e ($+0.0020$ in $\sin^2\theta_W$)
- CC background subtraction from NC signal
- PDF tuning
- Heavy quarks

NuTeV final results: $\sin^2\theta_W$ *and* m_W

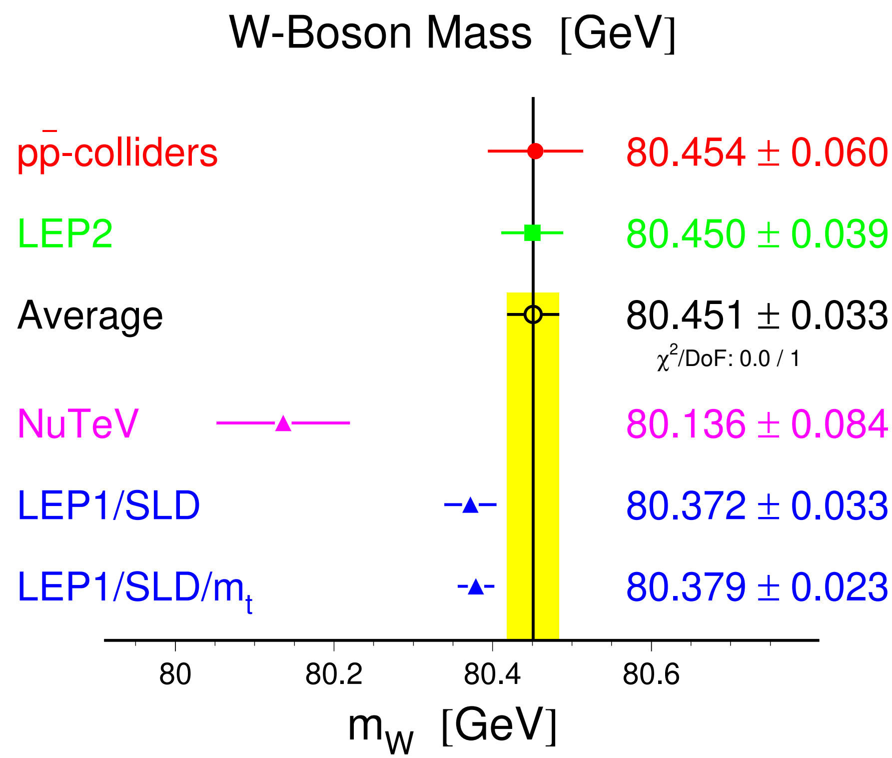
NuTeV:

$$\sin^2\theta_W = 0.2277 \pm 0.0013(\text{stat}) \pm 0.0009(\text{syst}) - 0.00022 \times \left(\frac{m_t^2-(175\ \text{GeV})^2}{(50\ \text{GeV})^2}\right) + 0.00032 \times \ln\left(\frac{m_H}{150\ \text{GeV}}\right)$$

EW fit (without NuTeV):

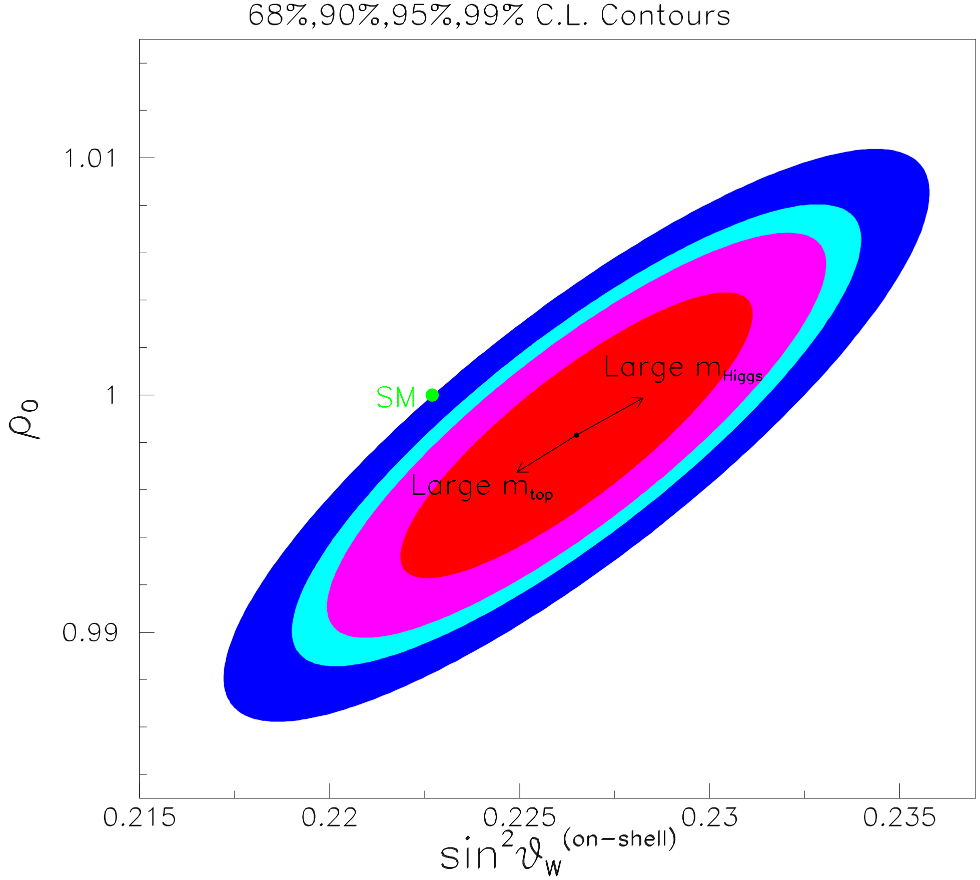
$$\sin^2\theta_W^{\text{fit}} = 0.22255 \pm 0.00036$$

3σ difference



Alternative NuTeV interpretation

Fit both $\sin^2\theta_W$ and ρ_0 simultaneously

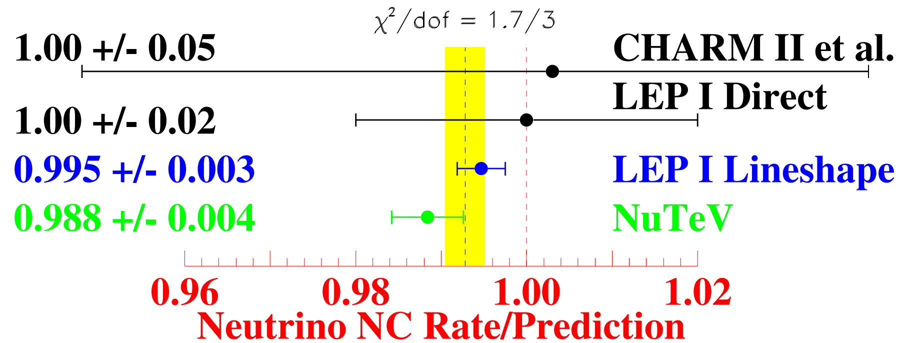


Fix $\sin^2\theta_W$ to "SM" yields

$\rho_0 = 0.9942 \pm 0.0029$

LEP also measured neutrino neutral currents: $Z \to \nu\overline{\nu}$

$$N_\nu = 2.981 \pm 0.0083$$
$$= 3 \times (0.9947 \pm 0.0028)$$



NuTeV "confirms" LEP "low" value of neutrino neutral couplings

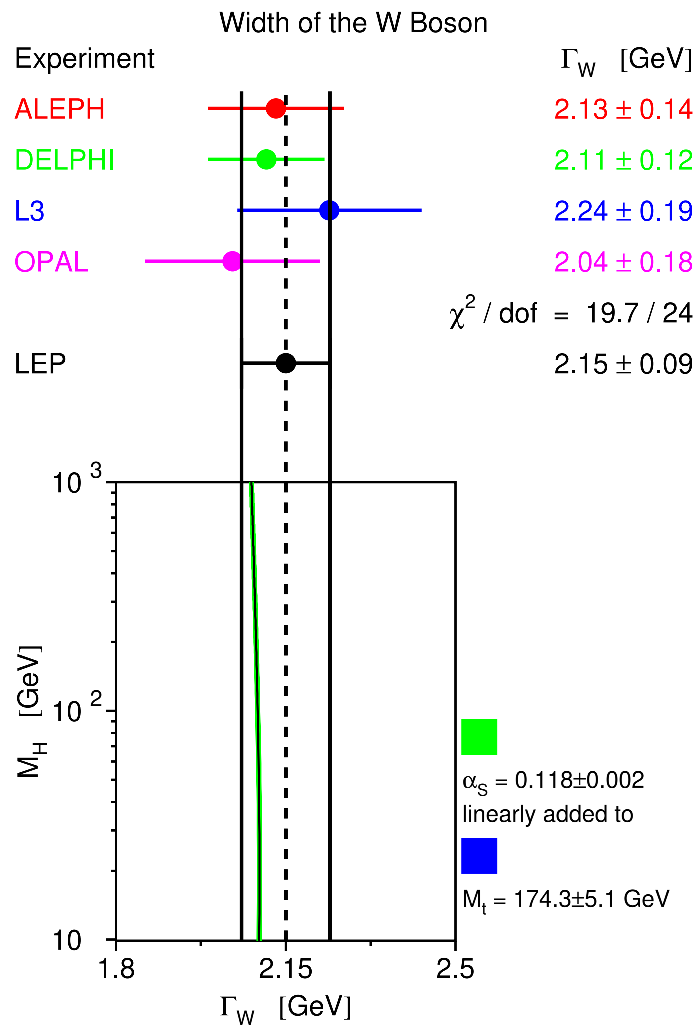
New: inclusion of Γ_W in the fit

Tevatron:

$$\Gamma_W = 2.11 \pm 0.11 \text{ GeV}$$

LEP + Tevatron :

$$\Gamma_W = 2.13 \pm 0.07 \text{ GeV}$$



New: atomic parity violation measurements

Weak charge of the Cesium nucleus:

$$Q_W = -2\,[C_{1u}(2Z+N) + C_{1d}(Z+2N)]$$

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

- Measure the amplitude of the P-violating transition 6S-7S in Cesium, possible due to the S-P mixing induced by neutral currents.
- Transition amplitude + Cesium atomic structure $\Rightarrow Q_W(\mathrm{Cs})$, predicted by the SM.
- Updated estimate, included in the global fit:

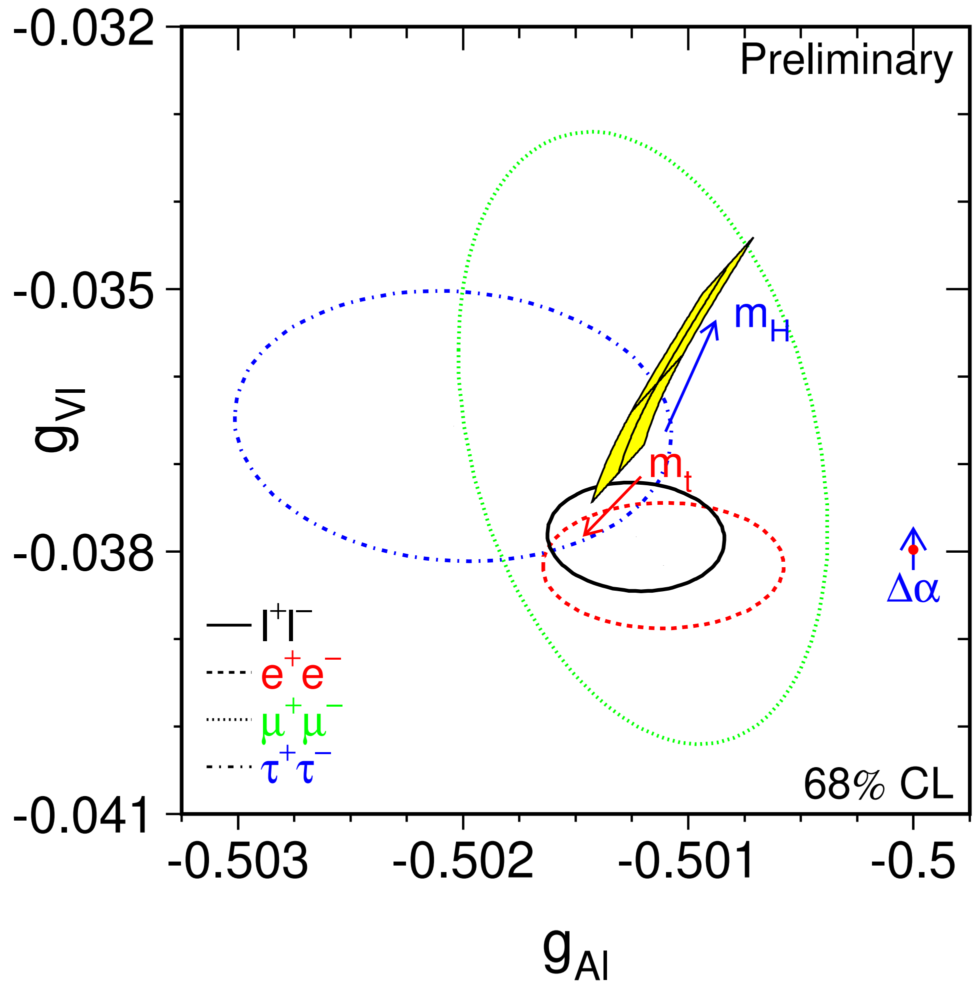
  (V.A. Dzuba, V.V. Flambaum, J.S.M. Ginges, hep-ph/0111019)

$$\boxed{\begin{array}{ll} Q_W(\mathrm{Cs}) & = -72.39 \pm 0.29(\mathrm{exp}) \pm 0.51(\mathrm{th}) \\ (Q_W(\mathrm{Cs})^{SM} & = -72.885) \end{array}}$$

Standard Model tests: $g_{A\ell}, g_{V\ell}$

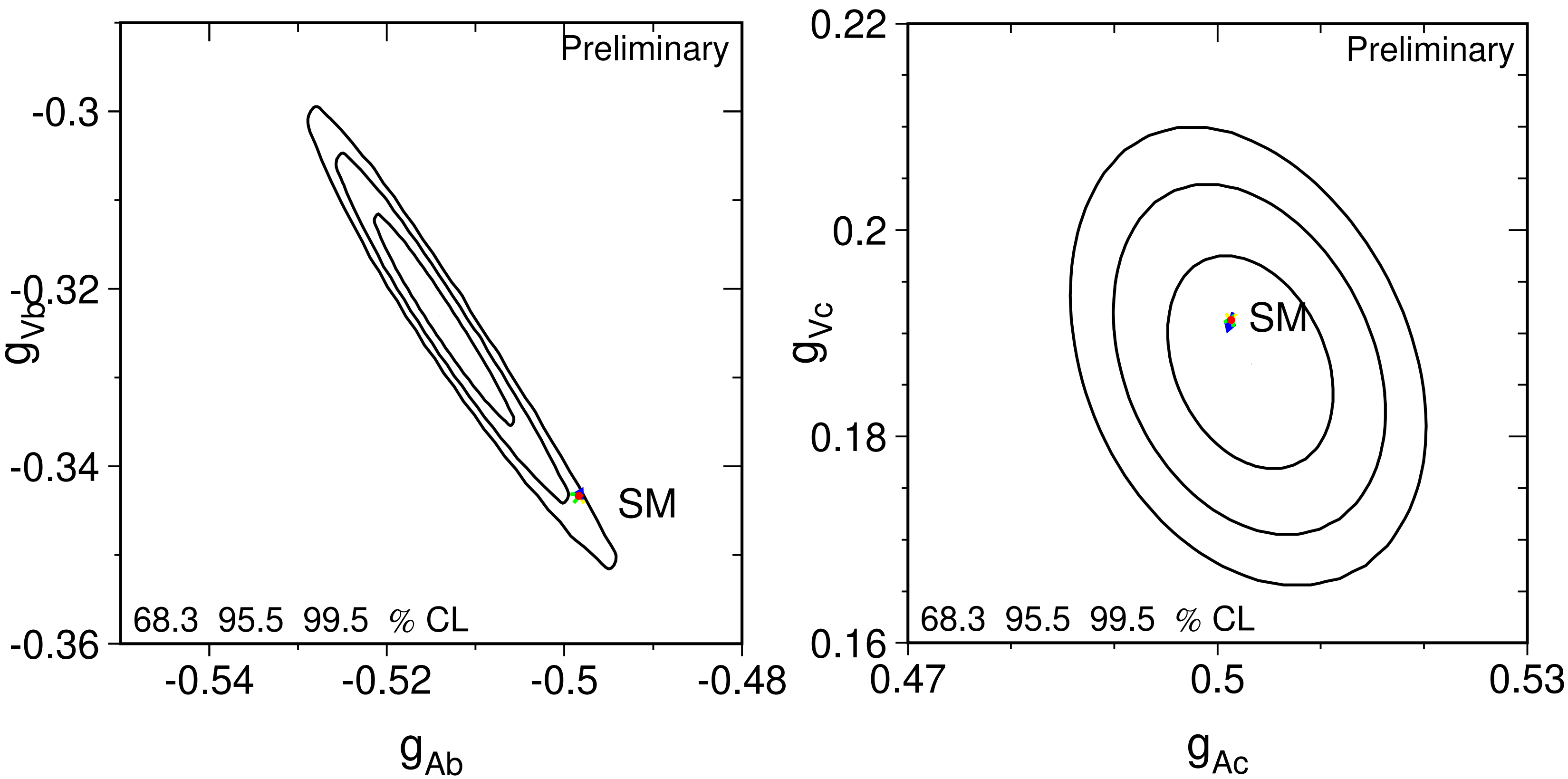
SLD + LEP

- SM band:
  $m_H = [114.1, 1000]$ GeV
  $m_t = 174.3 \pm 5.1$ GeV
- Lepton Universality
- Low m_H favoured



Standard Model tests: $g_{Ab}, g_{Vb}, g_{Ac}, g_{Vc}$

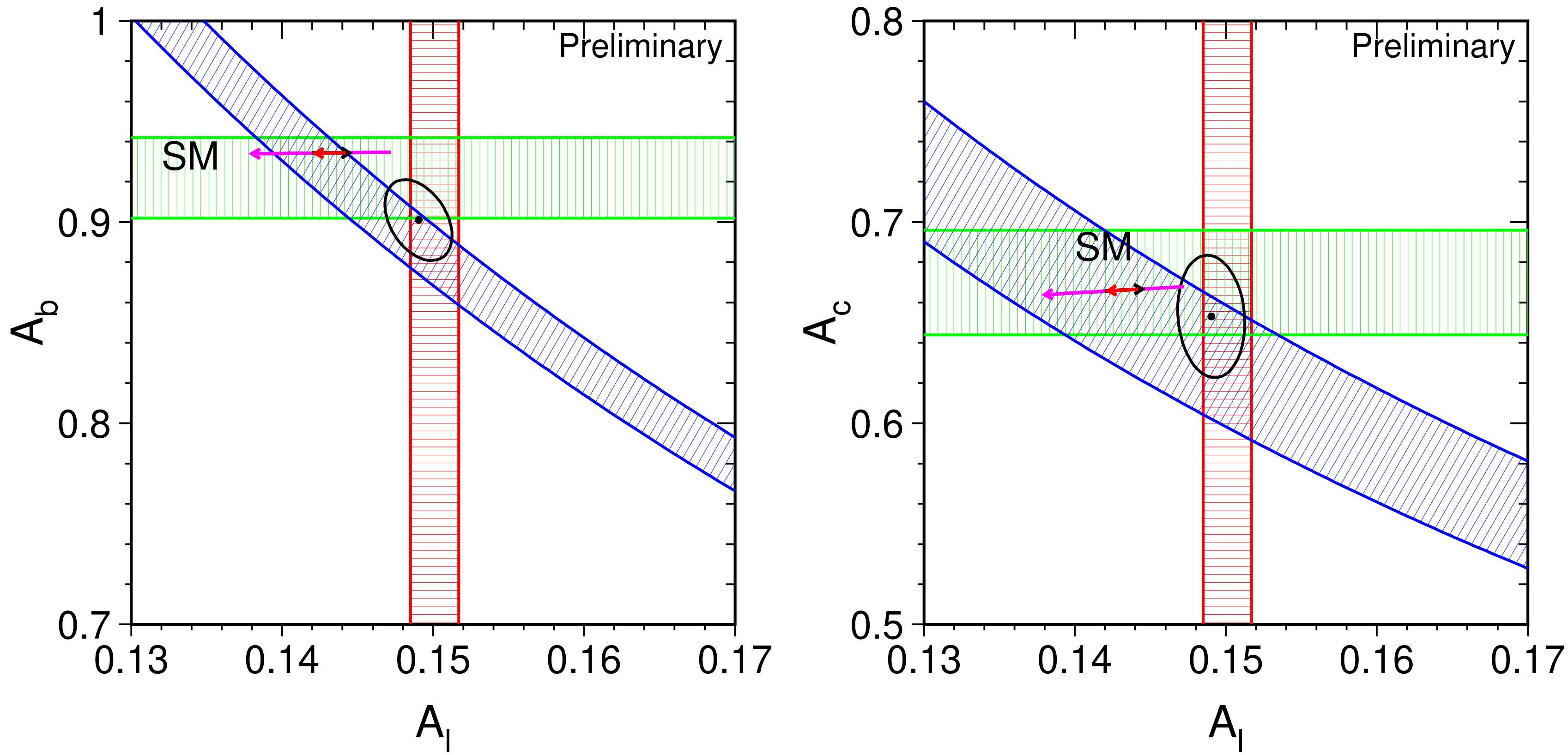
LEP+SLD, assuming lepton universality



Standard Model tests: $\mathcal{A}_{\rm b}$, $\mathcal{A}_{\rm c}$ vs. $\mathcal{A}_\ell$

horizontal band: $\mathcal{A}_{\rm b}$,$\mathcal{A}_{\rm c}$(SLD);   vertical band: $\mathcal{A}_\ell$(LEP+SLD);

diagonal band : $A_{\rm FB}^{0,\rm b}$, $A_{\rm FB}^{0,\rm c}$(LEP); $\longleftarrow$ $m_{\rm H} \in [114, 1000]$



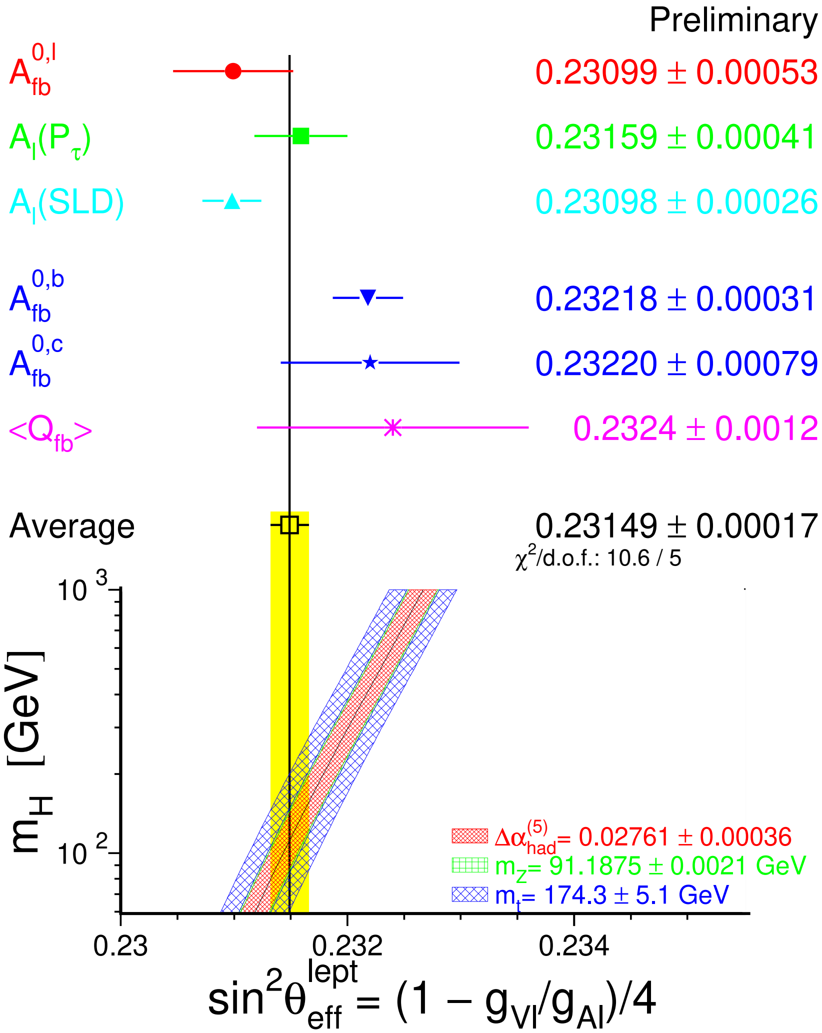
$A_{\rm FB}^{0,\rm b}$ prefers high $m_{\rm H}$; $\mathcal{A}_\ell$ prefers low $m_{\rm H}$

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

Assuming lepton universality :

$$\begin{aligned}
\chi^2/\text{dof(lept.)} &= 1.6/2\ (P = 44.0\%)\\
\chi^2/\text{dof(hadr.)} &= 0.03/2\ (P = 98.5\%)\\
\chi^2/\text{dof(tot.)} &= 10.6/5\ (P = 5.9\%)
\end{aligned}$$

hadrons-leptons $\simeq 3\sigma$



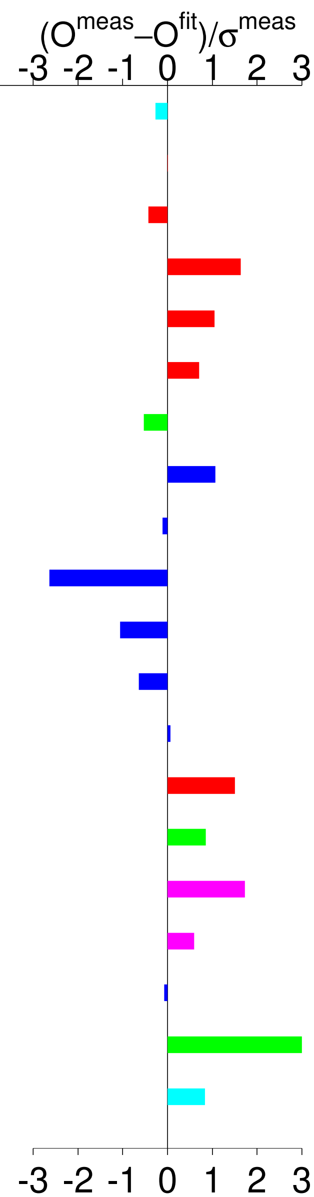
The global electroweak fit

- Based on predictions from ZFITTER and TOPAZ0.
- Fit 21 parameters
- As an output, estimate free parameters: m_{H}, $\alpha_s(m_Z^2)$...
- $\Delta\alpha_{\mathrm{had}}^{(5)}(m_Z^2) = 0.02761 \pm 0.00036$ (BES)
- Fit repeated with and without NuTeV, to evaluate its contribution...

The global electroweak fit

Winter 2002

	Measurement	Pull
$\Delta\alpha^{(5)}_{had}(m_Z)$	0.02761 ± 0.00036	-.27
m_Z [GeV]	91.1875 ± 0.0021	.01
Γ_Z [GeV]	2.4952 ± 0.0023	-.42
σ^0_{had} [nb]	41.540 ± 0.037	1.63
R_l	20.767 ± 0.025	1.05
$A^{0,l}_{fb}$	0.01714 ± 0.00095	.70
$A_l(P_\tau)$	0.1465 ± 0.0033	-.53
R_b	0.21646 ± 0.00065	1.06
R_c	0.1719 ± 0.0031	-.11
$A^{0,b}_{fb}$	0.0994 ± 0.0017	-2.64
$A^{0,c}_{fb}$	0.0707 ± 0.0034	-1.05
A_b	0.922 ± 0.020	-.64
A_c	0.670 ± 0.026	.06
A_l(SLD)	0.1513 ± 0.0021	1.50
$\sin^2\theta^{lept}_{eff}(Q_{fb})$	0.2324 ± 0.0012	.86
m_W [GeV]	80.451 ± 0.033	1.73
Γ_W [GeV]	2.134 ± 0.069	.59
m_t [GeV]	174.3 ± 5.1	-.08
$\sin^2\theta_W(\nu N)$	0.2277 ± 0.0016	3.00
Q_W(Cs)	-72.39 ± 0.59	.84

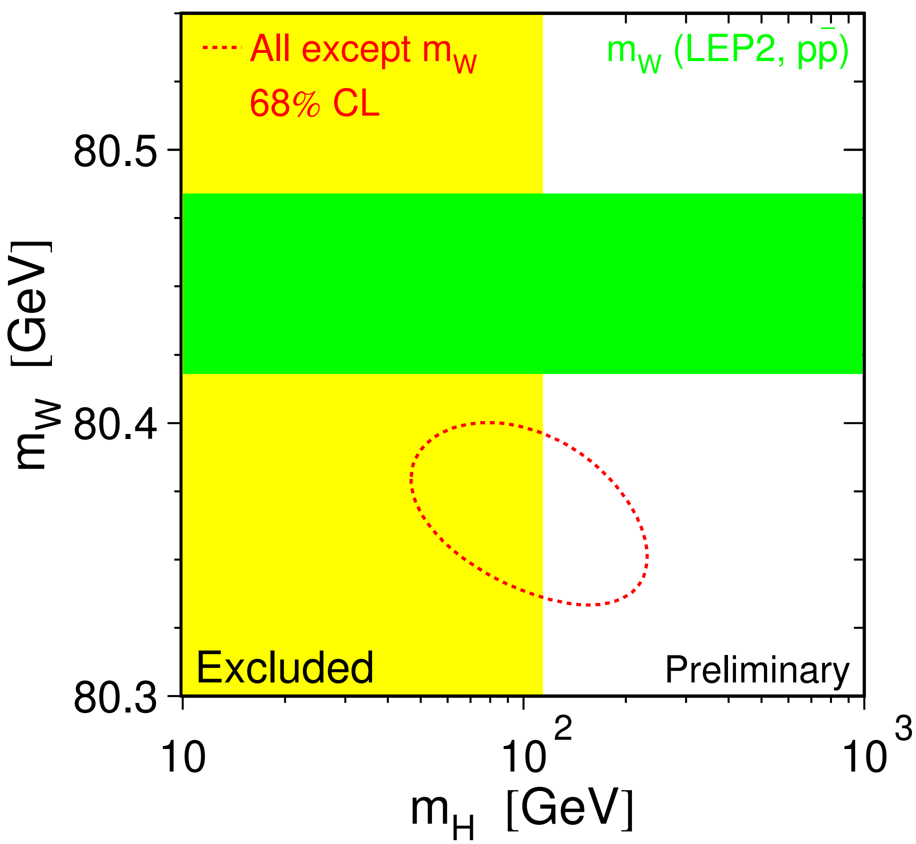


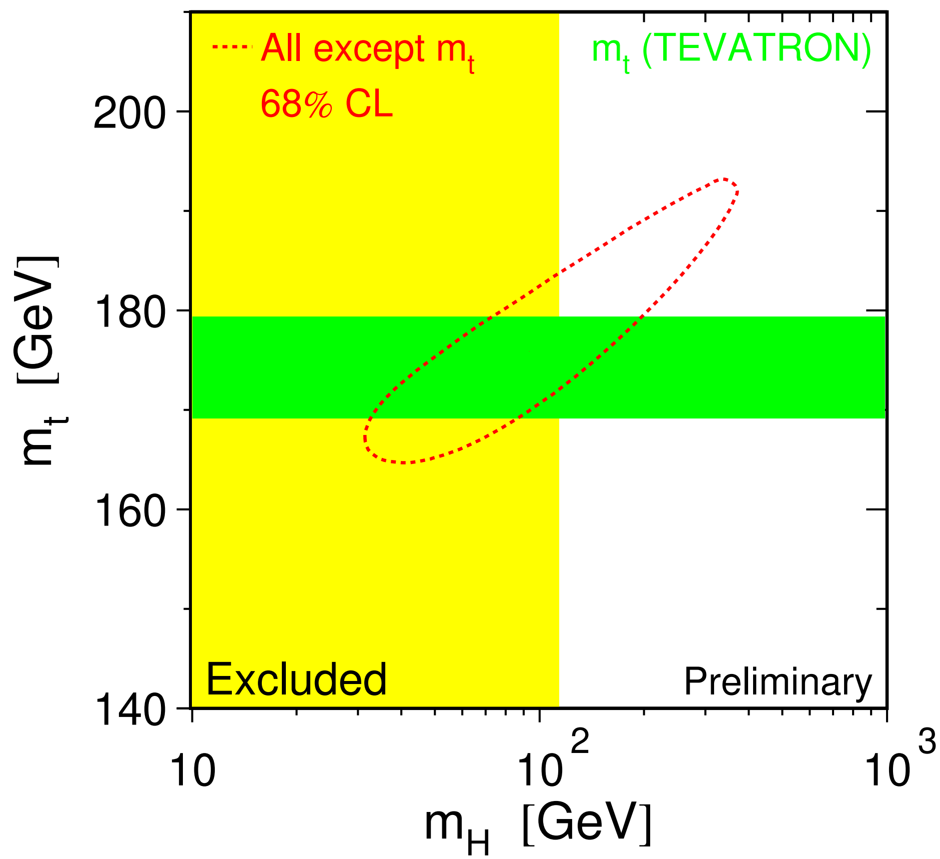
$$\chi^2/\text{d.o.f.} = 28.8/15$$
$$P(\chi^2) = 1.7\%$$

The global fit: results

	LEP1 + LEP2	All but NuTeV	All data
m_t (GeV)	185^{+13}_{-11}	$175.8^{+4.3}_{-4.2}$	$174.7^{+4.5}_{-4.3}$
m_H (GeV)	238^{+373}_{-141}	81^{+49}_{-32}	85^{+54}_{-34}
$\alpha_s(m_Z^2)$	$0.1199^{+0.0032}_{-0.0030}$	0.1182 ± 0.0027	0.1183 ± 0.0027
m_W (GeV)	80.392 ± 0.026	80.403 ± 0.019	80.394 ± 0.018
$\sin^2\theta_{eff}^{lept}$	0.23159 ± 0.00018	$0.23132^{+0.00014}_{-0.00015}$	$0.23137^{+0.00014}_{-0.00015}$
$\sin^2\theta_W$	0.22276 ± 0.00051	0.22255 ± 0.00036	0.22272 ± 0.00036
χ^2/d.o.f.	14.3/9	19.6/14	28.8/15
probab. (%)	11.3	14.3	1.7

The global fit: m_W, m_t, m_H

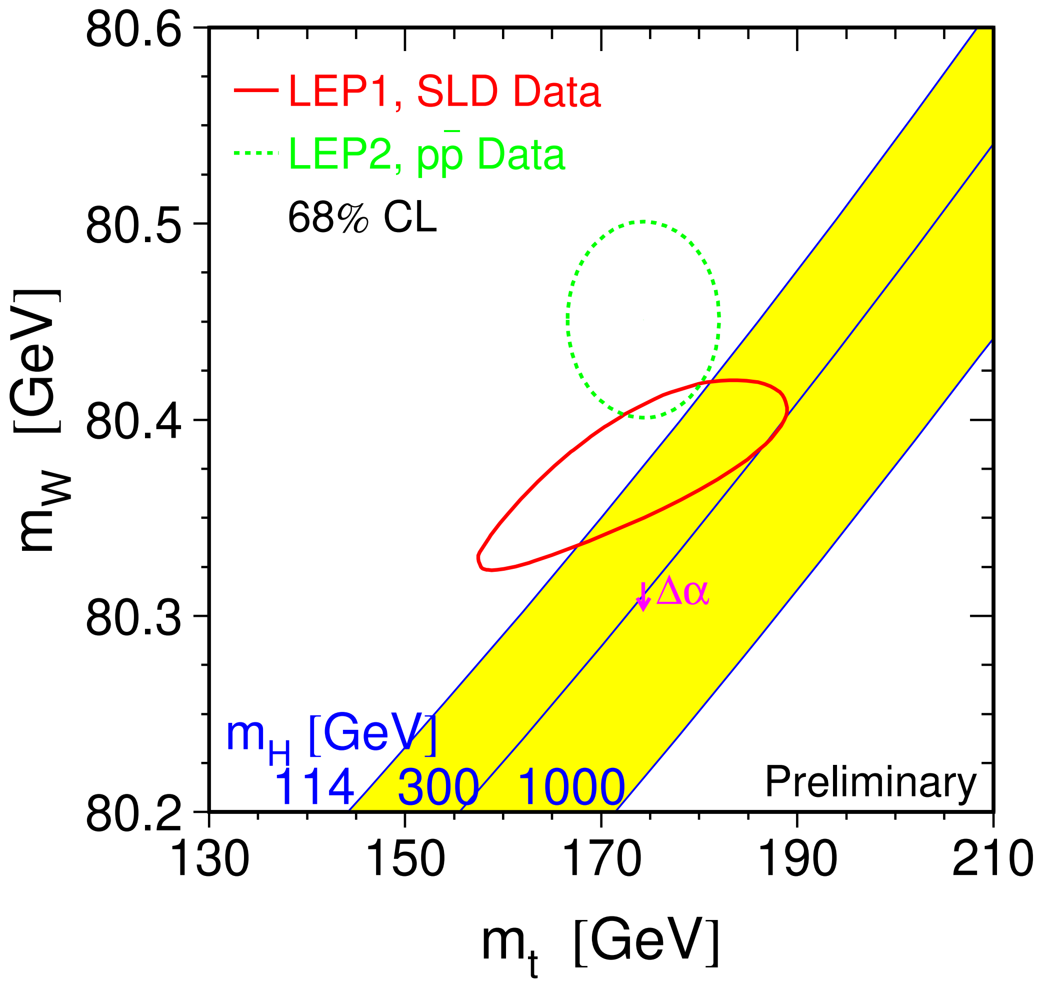




$$m_W = 80.379 \pm 0.023$$

$$m_t = 180.8^{+10.9}_{-8.5}$$

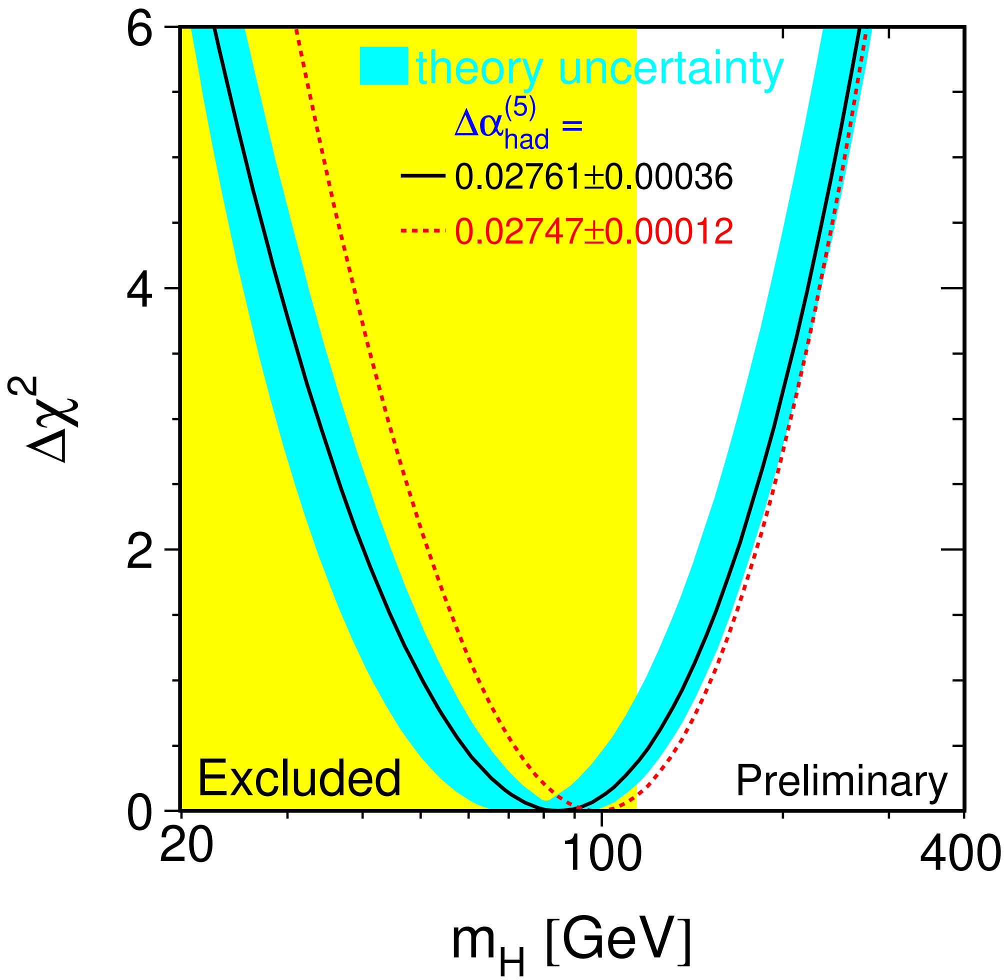
The global fit: m_W, m_t, m_H



Fit leaving m_t and m_W free:

	m_t(GeV)	m_W(GeV)
meas.	174.3 ± 5.1	80.451 ± 0.033
fit	$170.6^{+11.4}_{-9.0}$	80.372 ± 0.033

The global fit: limits on the Higgs mass



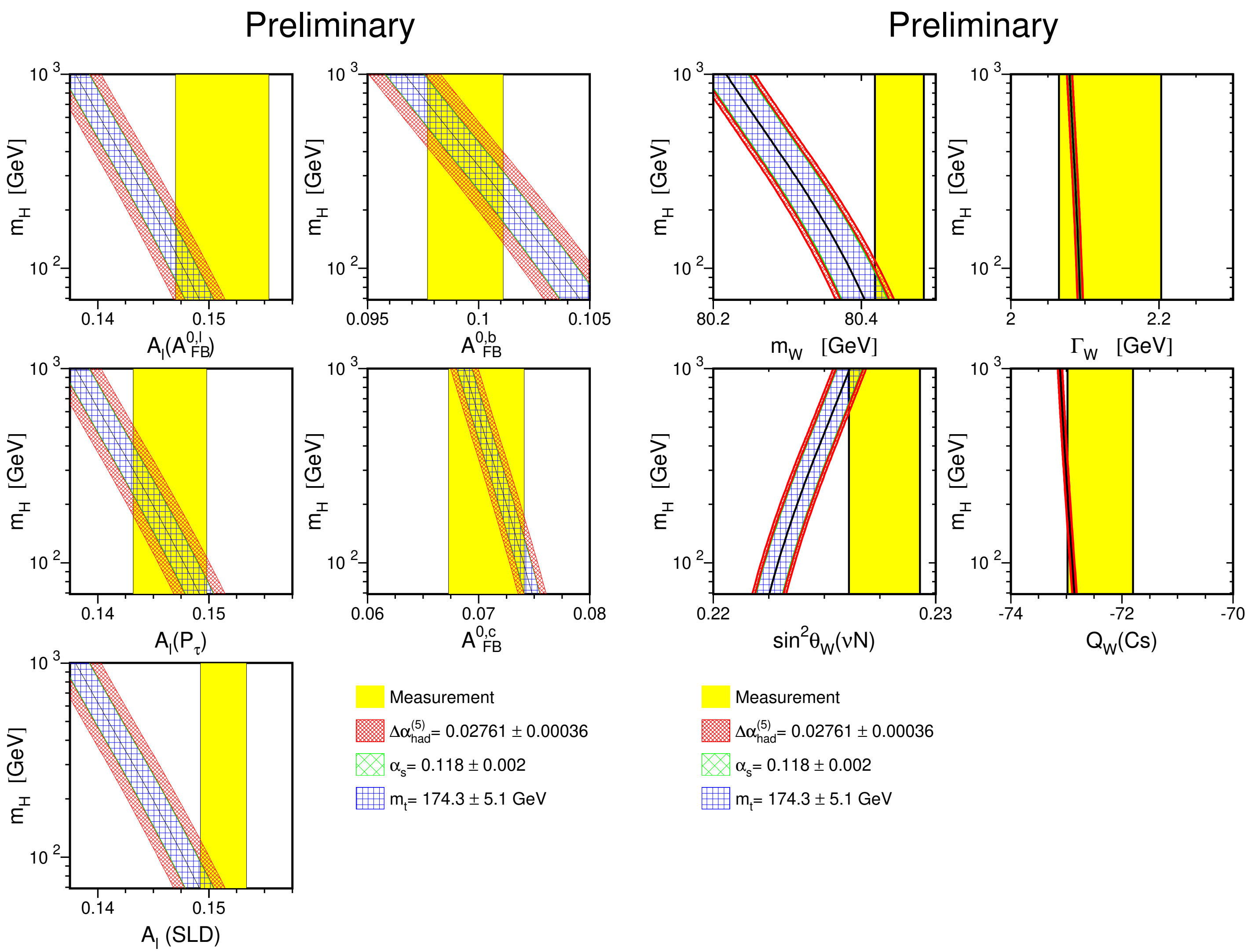
$$m_H = 85^{+54}_{-34}\ \text{GeV}$$
$$m_H < 196\ \text{GeV}, 95\%\text{CL}$$
(theo. unc. incl.)

With further theoretical inputs:

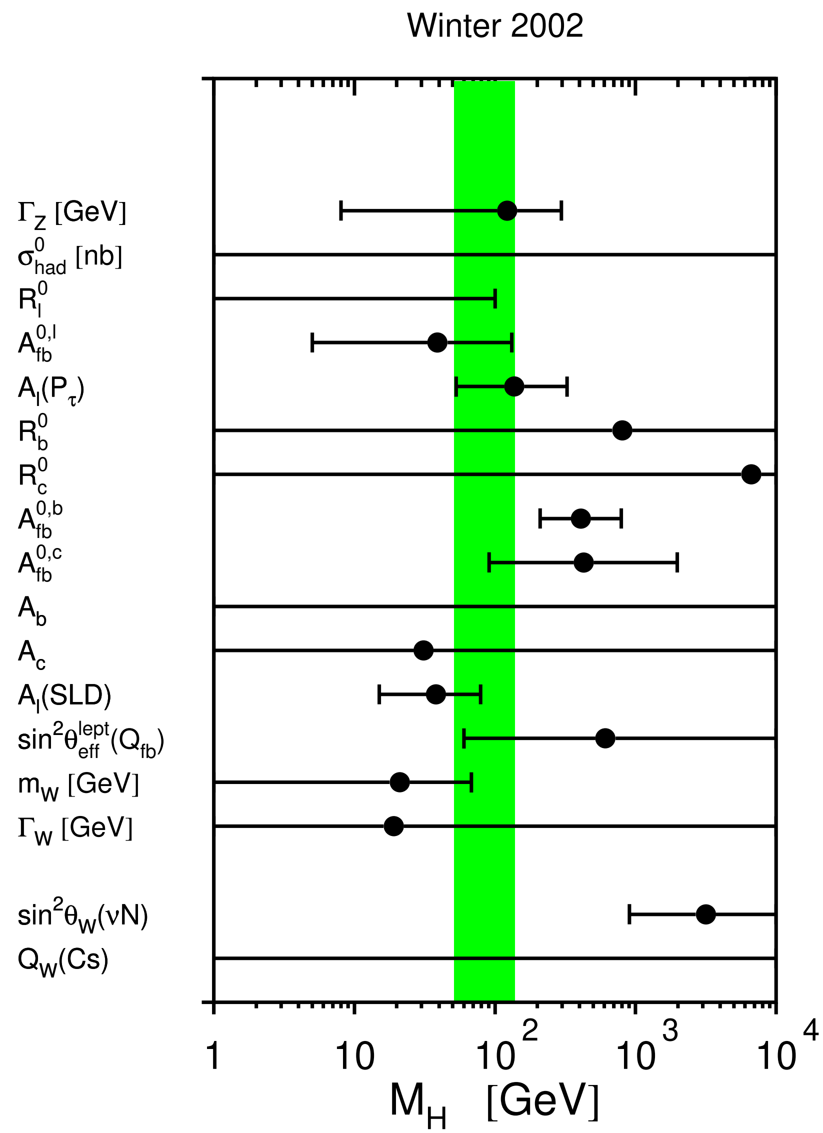
(J.F. de Tracóniz, F.J. Induráin, hep-ph/0107318)

$$\Delta\alpha^{(5)}_{had} = 0.02747 \pm 0.00012$$
$$\Rightarrow m_H < 199\ \text{GeV}, 95\%\text{CL}$$

The global fit: m_H sensitivity



The global fit: m_H sensitivity



Crucial measurements:

- m_W
- $A^{0,b}_{FB}$, $A^{0,c}_{FB}$
- $\sin^2\theta_W$(NuTeV)
- $\mathcal{A}_\ell$(SLD)

Beyond the SM

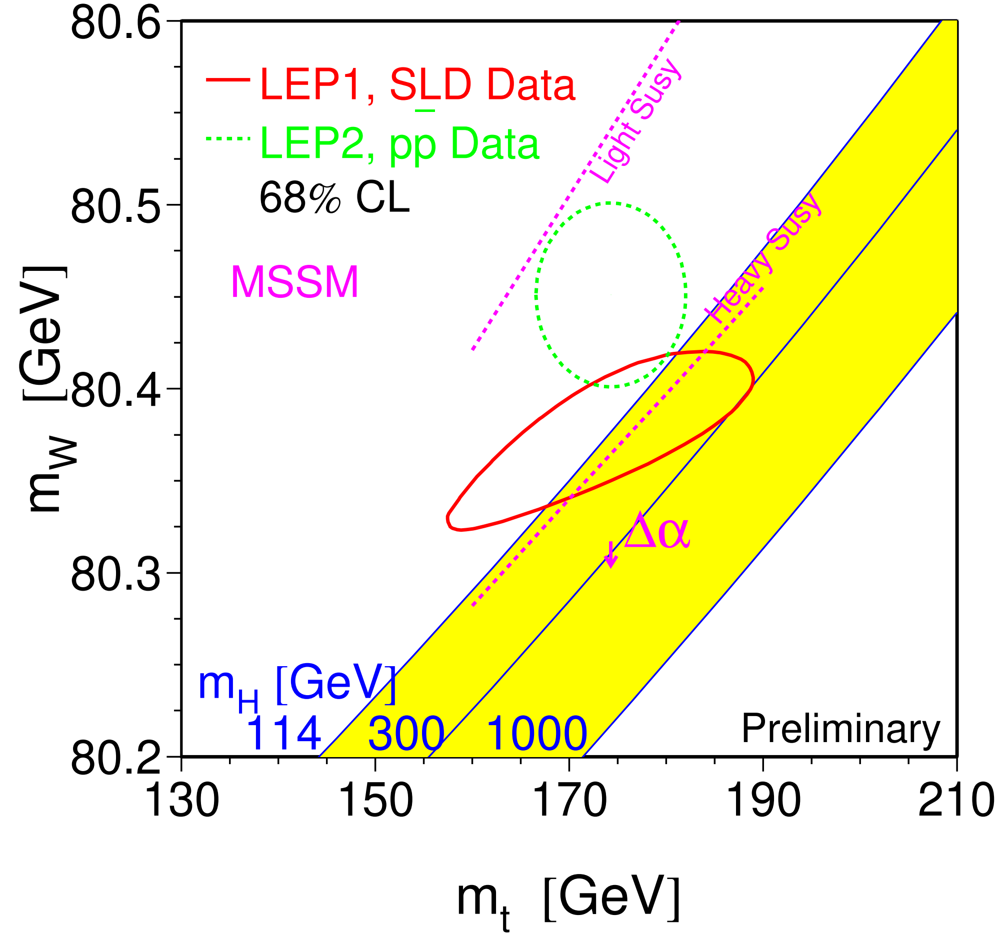
In the SM, the Higgs mass is a free parameter, and m_t and m_W can be related to it.

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 *might* be more compatible with the data...

(MSSM: Heinemeyer, Weiglein, hep-ph/0012364)



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
δm_W [MeV]	33	27	16	12	15	10	7
δm_t [GeV]	5.1	2.7	1.4	1.3	1.0	0.2	0.13
δm_H [MeV]	—	—	$\mathcal{O}(2000)$		100	50	50

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

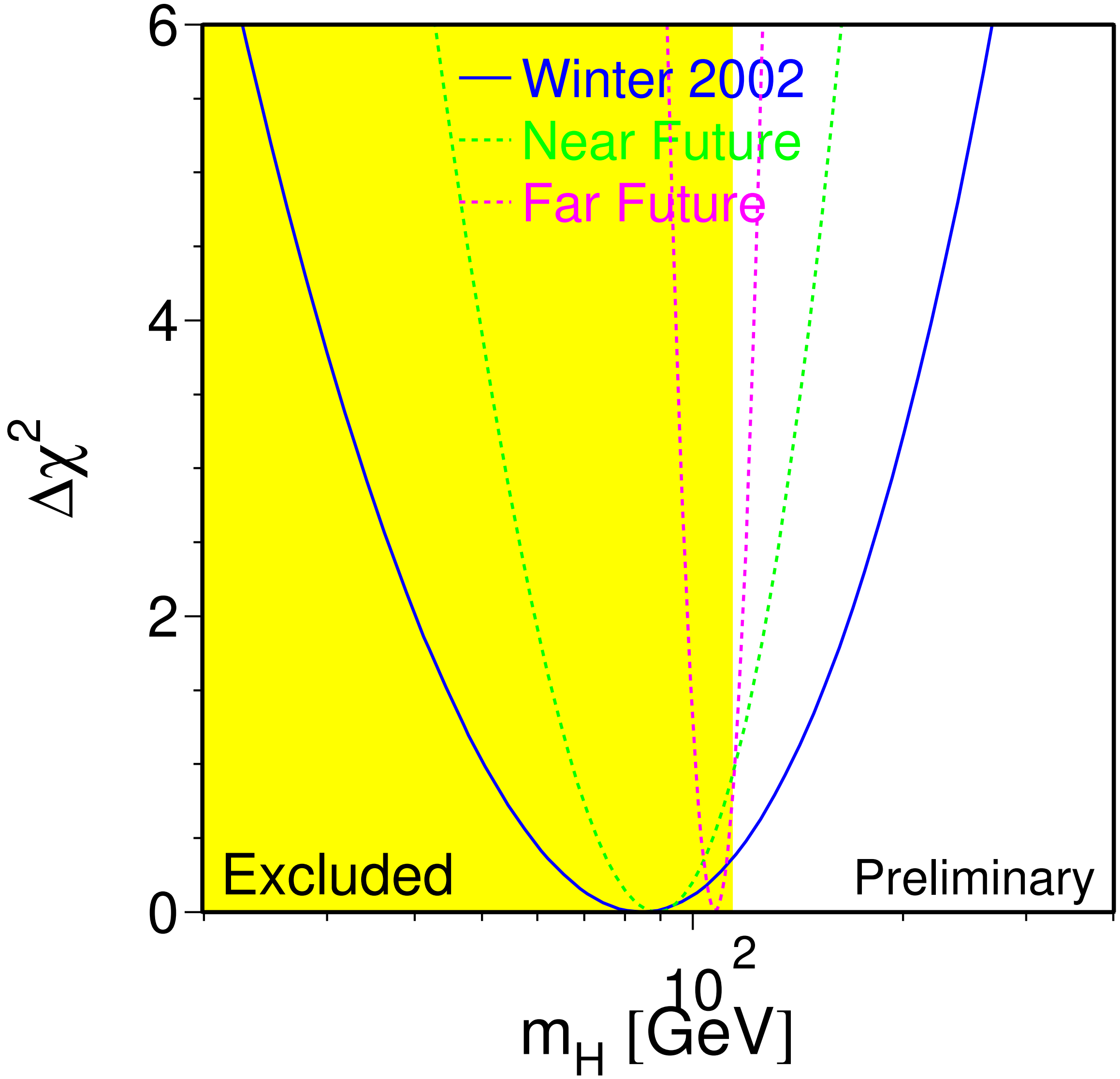
Near future (Run II, LHC):

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

Far future (LC, GigaZ):

- $\delta m_W = 7$ MeV
- $\delta m_t = 130$ 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



Conclusions

- The Standard Model describes with unprecedented precision a huge amount of data
- The largest discrepancies are due to the final NuTeV results and to $A_{FB}^{0,b}$; interpreted as statistical fluctuations ≤ 3 standard deviations.
- Global fit: $m_H < 196$ GeV, 95%C.L..
- 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.
  - New estimates of $\Delta\alpha_{had}^{(5)}$
- Far future:
  - Linear Collider and GigaZ?