Electroweak Precision Measurements in e^+e^- Annihilation into Fermions

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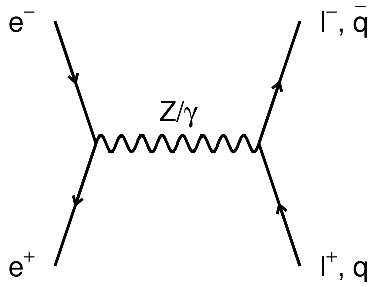
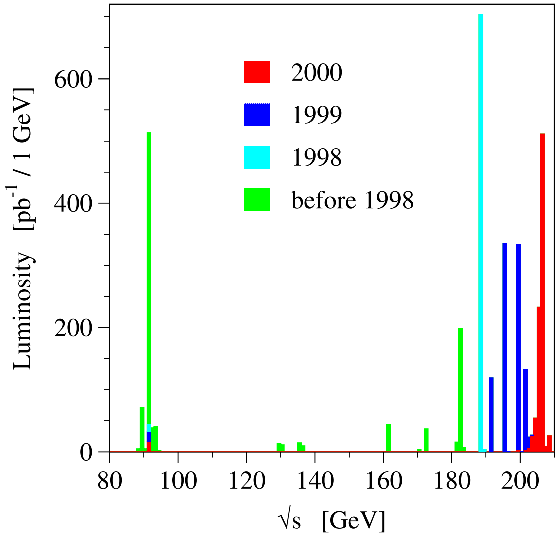
Outline:

- Precision tests of the Standard Model
  - at the Z resonance
  - at LEP2
- Summary

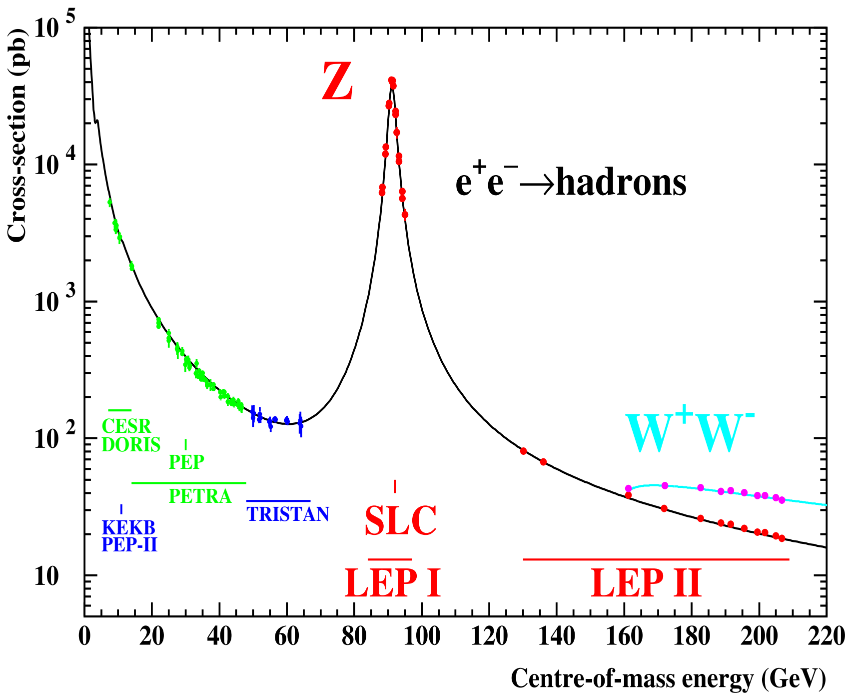
Thanks to the members of the LEP electroweak and LEP-2F working groups and the LEP experiments.



LEP



$\approx 17{\times}10^6$ Z bosons



SLD:

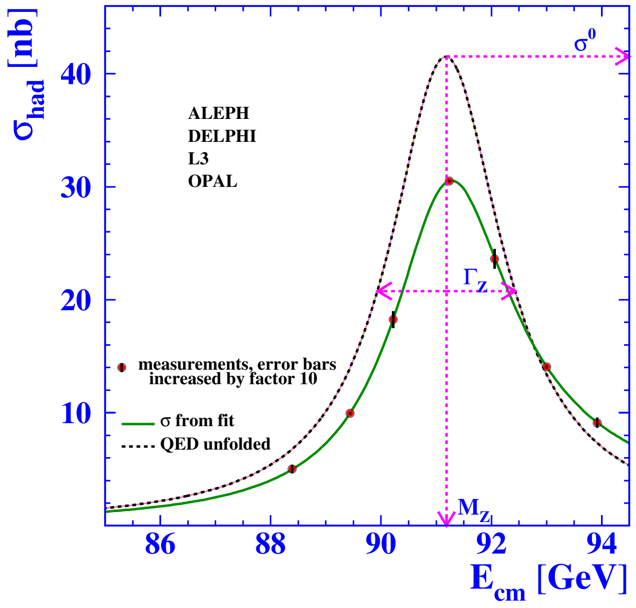
$\approx 5{\times}10^5$ Z bosons;

e^- polarisation

High precision $\Rightarrow$ sensitivity to quantum effects beyond Born approximation

Measurements

- Cross sections
- F-B asymmetries
- τ polarization
- Left-Right asymmetries (SLD)
- m_W(LEP2), $\mathrm{m_W}$, $\mathrm{m_t}$(CDF/DØ)

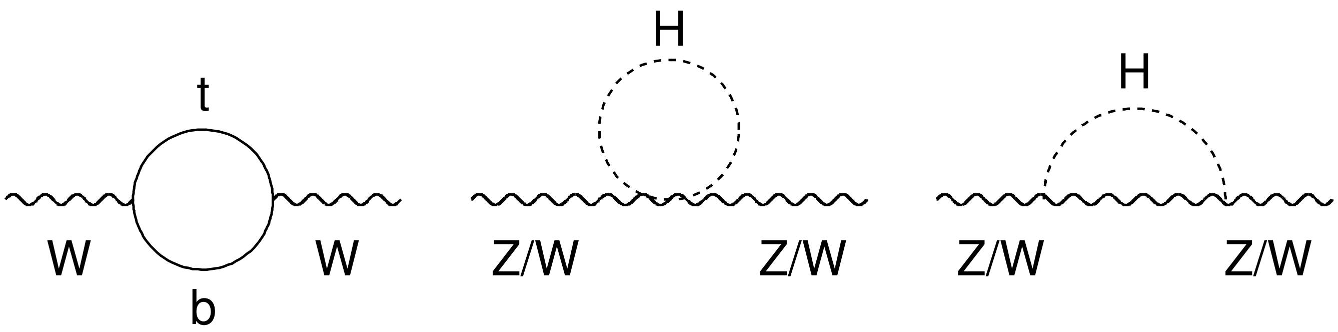


$\Rightarrow$ Pseudo-Observables:

- Widths, Γ_Z
- Z peak cross section
  $\sigma^0_{had} = \frac{12\pi}{m_Z^2} \times \frac{\Gamma_{ee}\Gamma_{had}}{\Gamma_Z^2}$
- Ratios, $R^0_f = \Gamma_{had}/\Gamma_{ff}$ for $f{=}e, \mu, \tau$
  $R^0_q = \Gamma_{qq}/\Gamma_{had}$ for $q{=}b, c, s$
- F-B asymmetry, $A^{0,f}_{FB} = \frac{3}{4} A_e A_f$
- Coupling parameters
  $A_f = \frac{2 g_{Af} g_{Vf}}{g_{Af}^2 + g_{Vf}^2}$
- τ polarisation
  $P_\tau(\cos\theta) = \frac{A_\tau(1+\cos^2\theta) + 2A_e\cos\theta}{1+\cos^2\theta + 2A_e A_\tau \cos\theta}$
- $A_{LR} = A_e, \quad A^{FB}_{LR} = A_f$

(Pseudo)-Observables are functions of SM parameters:

- $\mathrm{m_Z}$ determined by LEP1 data
- $\alpha_s(\mathrm{m_Z})$: Γ_{had}/Γ_{ll}, σ_l^0
- $\Delta\alpha_{had}$, hadronic vacuum polarisation
- $\mathrm{m_t}$, $\mathrm{m_H}$ $\leftrightarrow$ electroweak corrections (up to 2nd order)



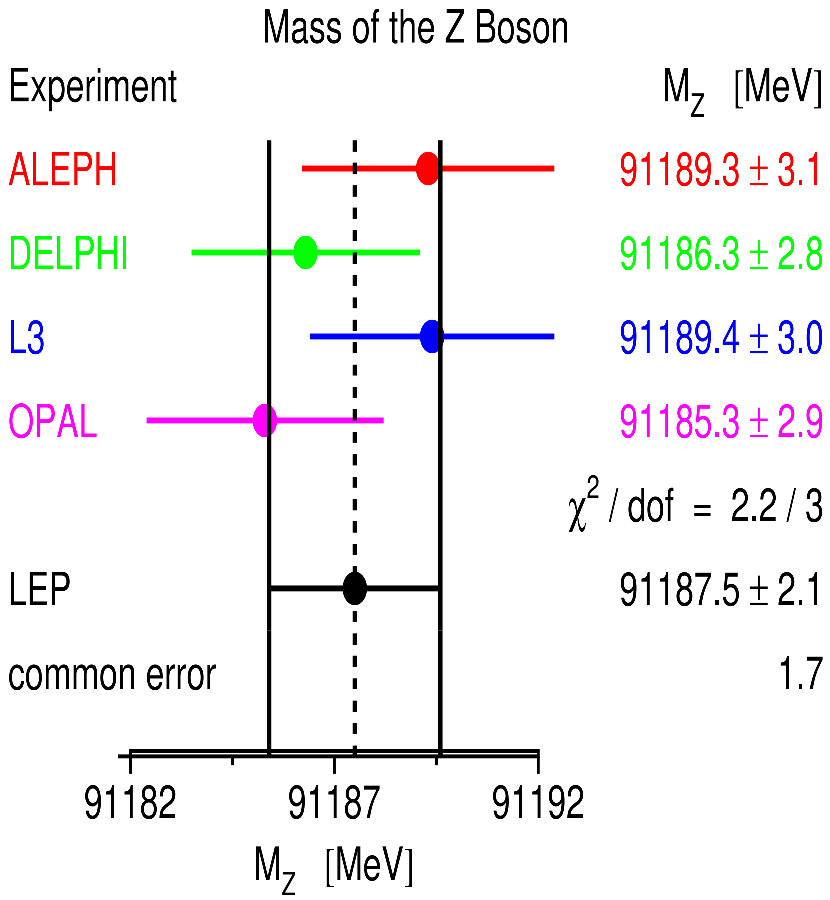
$\delta_t \propto \mathrm{m_t}^2$

$\delta_{\mathrm{H}} \propto \ln \frac{\mathrm{m_H}}{\mathrm{m_W}}$

Analysis programs: ZFITTER, TOPAZ0

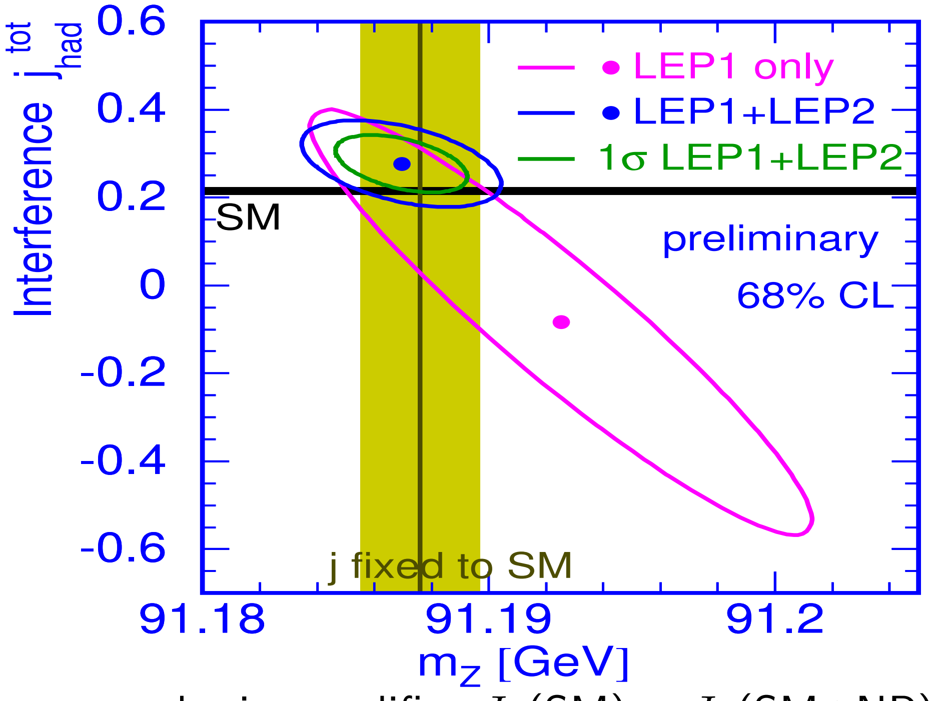
$$m_Z = 91\,187.5 \pm 2.1 \text{ MeV}$$

- Precison of 10^{-5}!
- Dominant error:
  Beam energy measurement, ± 1.7 MeV
  (method of resonant beam depolarisation)
- LC (GigaZ) will not improve this result !!



$$\sigma_f(s) \sim \frac{R_f^\gamma}{s} + \frac{(s-m_Z^2)J_f + sR_f^Z}{(s-m_Z^2)^2 + m_Z^2\Gamma_Z^2}$$

- R_f^Z and J_f contain information about SM ($R_f^Z \sim \Gamma_e\Gamma_f$, $J_f \sim v_e v_f$)
- ee→ hadrons: $J_{had}^{tot} \propto \sum v_e v_q$, not constrained by exclusive A_{FB} measurement
- hadronic γ-Z interference is free parameter; for fits on the Z resonance fixed to SM values



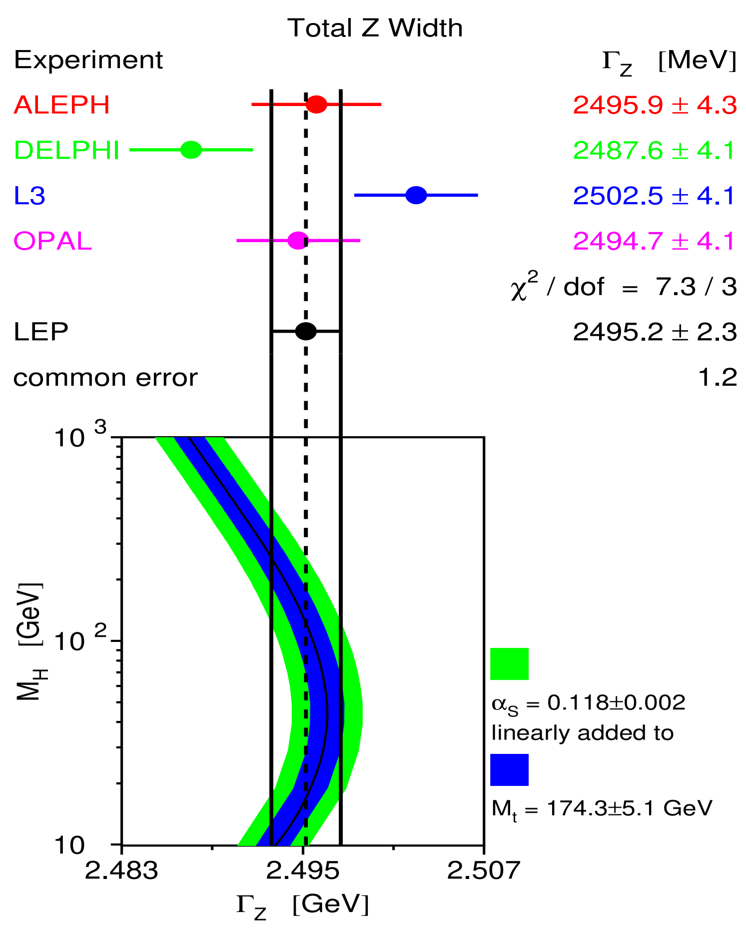
- new physics modifies J_f(SM)→ J_f(SM+NP);

$$J_{had} \sim J_{had}^{SM}\,[1+\Delta(NP)]$$

⇒ measurement of J_f is proof of SM:

$J_{had}^{tot} = 0277 \pm 0.065$ $\quad$ $J_{had}^{SM} = 0215 \pm 0.008$

$$\boxed{\Gamma_Z = \sum \Gamma_{ff}}$$



Number of Light Neutrino Species

$$\boxed{\Gamma_{inv} = N_\nu \Gamma_{\nu\nu}}$$

With

$$R^0_{inv} \equiv \frac{\Gamma_{inv}}{\Gamma_{ll}} = N_\nu \left(\frac{\Gamma_{\nu\nu}}{\Gamma_{ll}}\right)_{\rm SM}$$

we obtain

$$\boxed{N_\nu = 2.9841 \pm 0.0083}$$

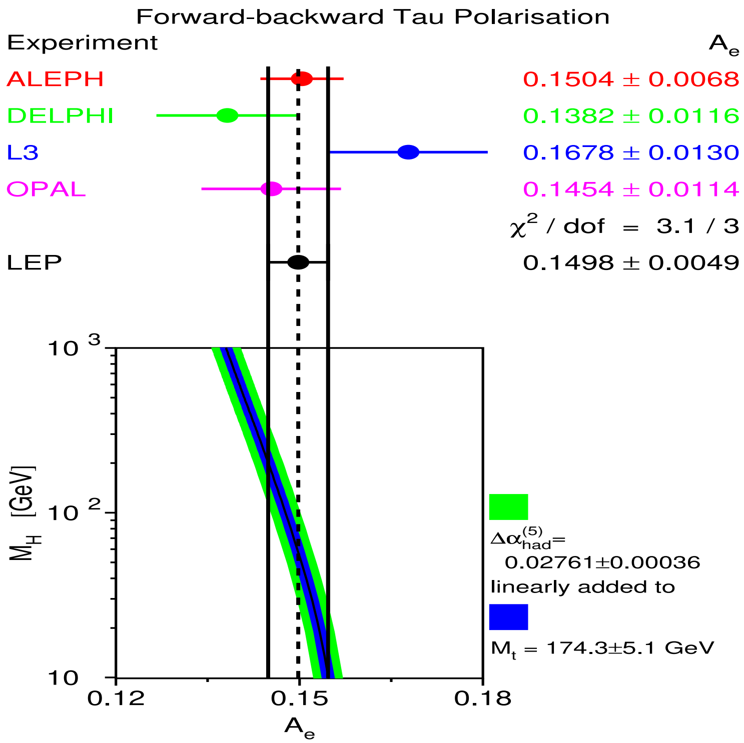
$$A_{FB}^{0,l} = \frac{3}{4} A_e A_f$$

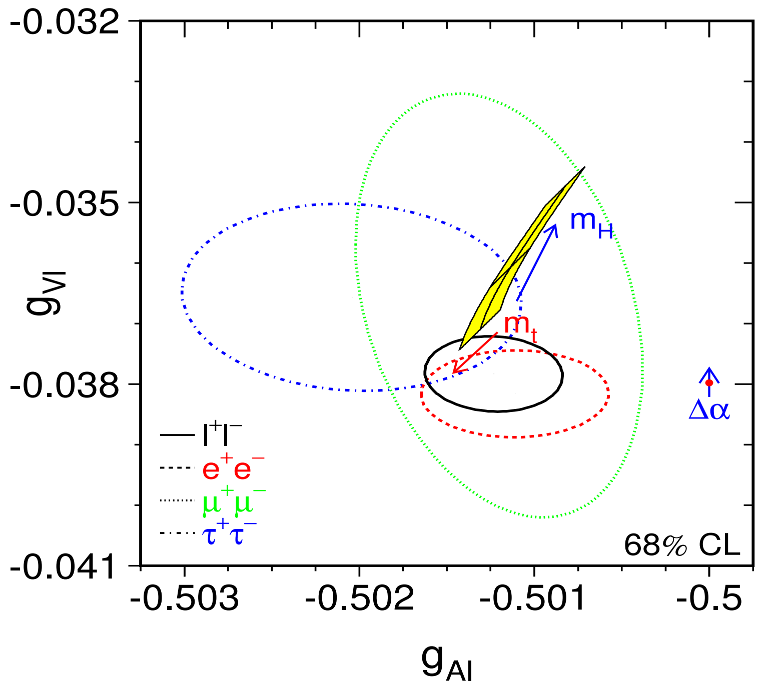
$$P_\tau^0 = -A_\tau$$

$$A_{LR}^0 = A_e, \quad P_{LR}^{0,FB} = A_f$$

$$A_f = 2 \frac{g_{Vf} g_{Af}}{g_{Vf}^2 + g_{Af}^2}$$

$$\Gamma_f \propto \quad g_{Vf}^2 + g_{Af}^2$$

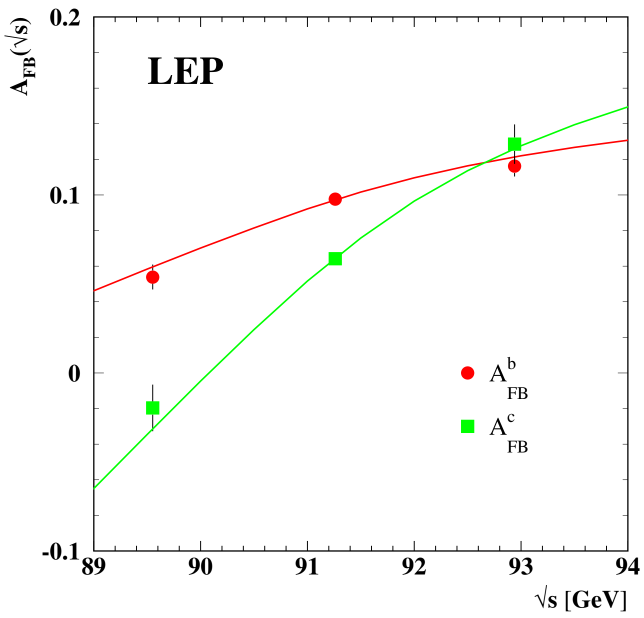


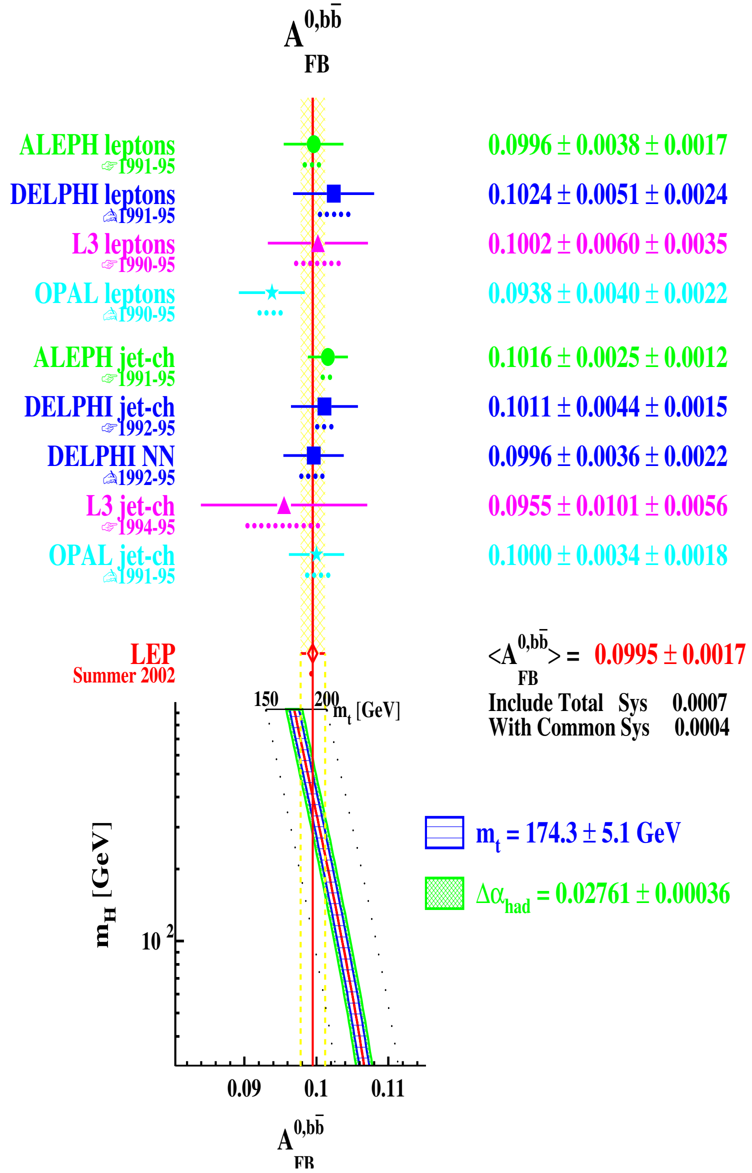


SLD: $A_l = 0.1513 \pm 0.0021$

$$g_{Al} = -0.50123 \pm 0.00026$$

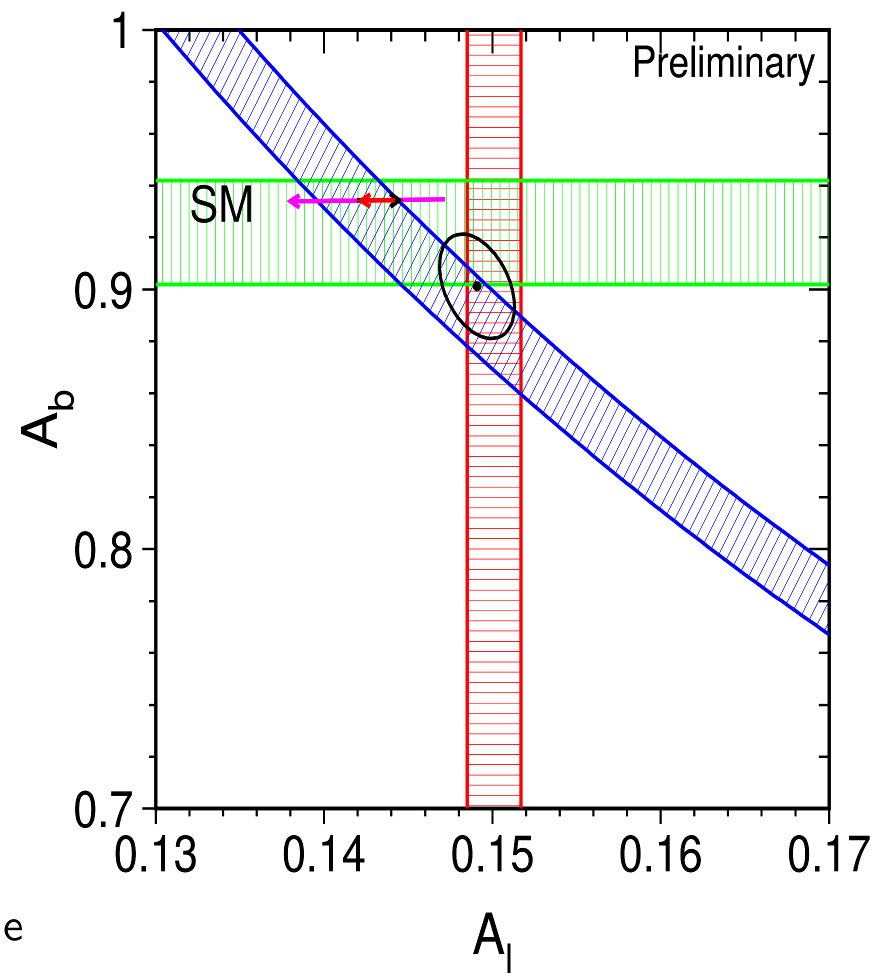
$$g_{Vl} = -0.03783 \pm 0.00041$$





- LEP measurements are consistent
- $A^{0,b\bar{b}}_{FB}$ is the only quantity that prefers high m_H

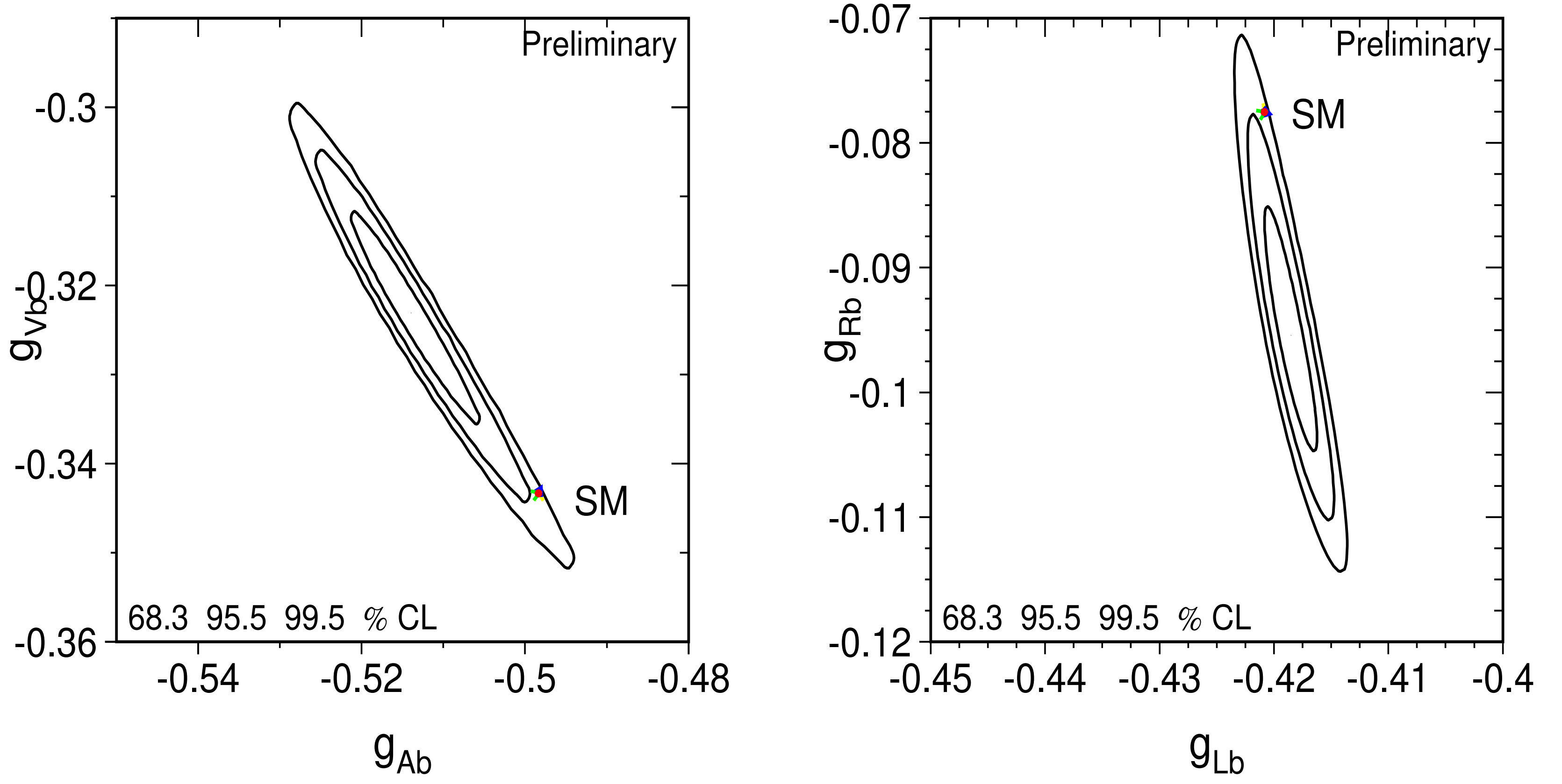
A_l(LEP, A_{FB})	0.1512 $\pm$ 0.0042
A_l(LEP, P_τ)	0.1465 $\pm$ 0.0033
A_l(LEP)	0.1482 $\pm$ 0.0026
A_l(SLD)	0.1513 $\pm$ 0.0021
A_l(LEP+SLD)	0.1501 $\pm$ 0.0016
A_b(LEP)	0.894$\pm$ 0.022
A_b(SLD)	0.922 $\pm$ 0.020
A_b(LEP+SLD)	0.901 $\pm$ 0.013



$$A_{FB}^{0,b} = 3/4 \cdot A_e A_b$$

- LEP and SLD results are compatible
- agreement with SM: A_b(SM) $=$ 0.934
- 'high' A_l(LEP+SLD) converts $A_{FB}^{0,b}$(LEP) to 'low' A_b

From R_b, A_b and $A_{FB}^{0,b\bar{b}}$, assuming lepton universality:

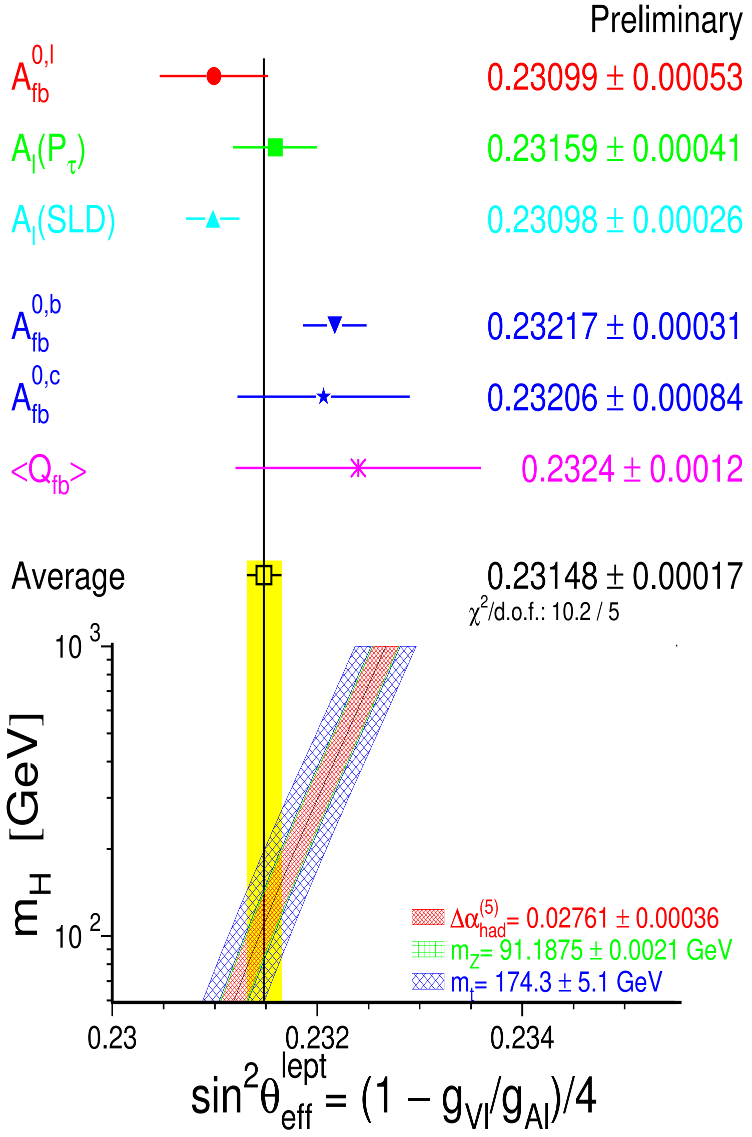


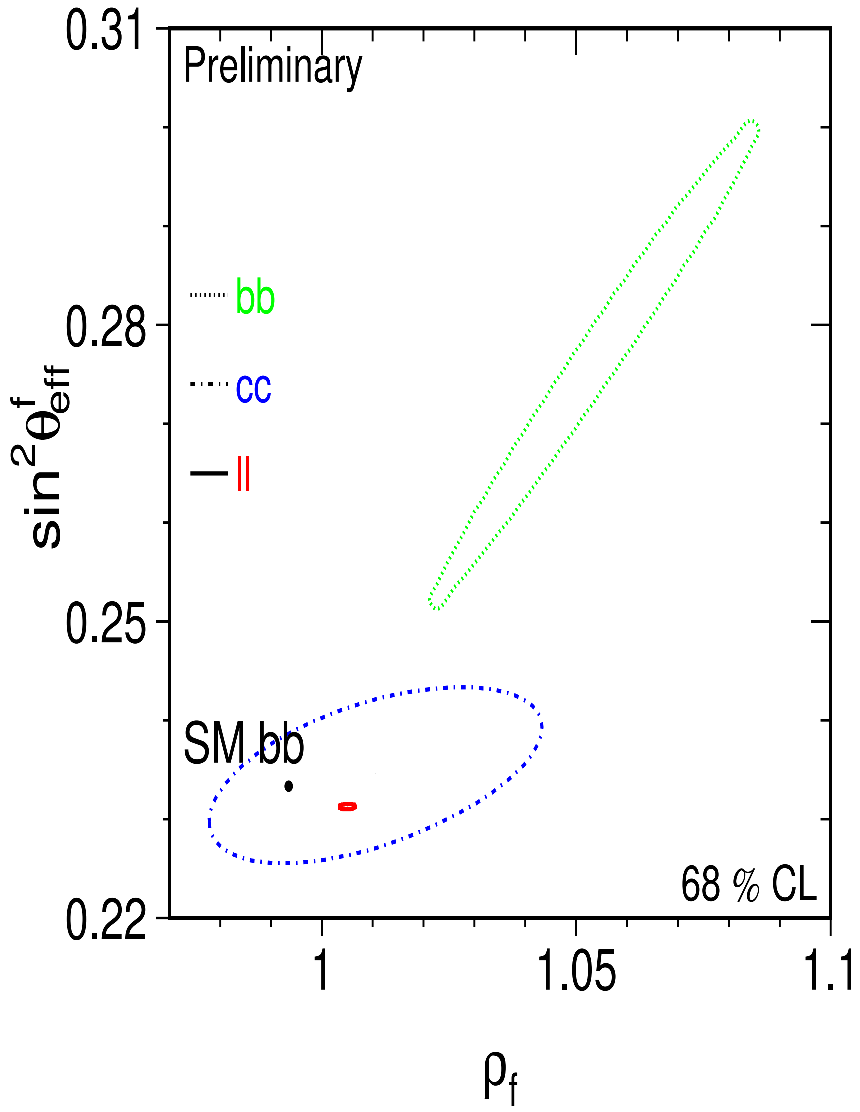
Effective Z$\rightarrow f\bar{f}$ Couplings

$$g_A = \sqrt{\rho_f} I_3^f$$
$$g_V = \sqrt{\rho_f}(I_3^f - 2Q_f \sin^2\theta^f_{eff})$$

$$\sin^2\theta^f_{eff} = (1 - \frac{m_{\mathrm{W}}^2}{m_{\mathrm{Z}}^2}) \cdot \kappa_f$$
$$\kappa_f = \kappa_f(\mathrm{m_t}, \mathrm{m_H}, \alpha_s, ...)$$

- 2.9σ discrepancy between $\sin^2\theta_{eff}$ derived from leptonic and hadronic observbles (A_{LR} and $A^{0,b}_{FB}$)
- cross check for $\sin^2\theta^f_{eff}$: direct measurements of m_t and m_{W}
- Large uncertainty from m_{W}, m_t





$$\boxed{\rho = \frac{m_W{}^2}{m_Z^2 \cos^2\theta_W}}$$

$$\rho_l = 1.0049 \pm 0.0010$$

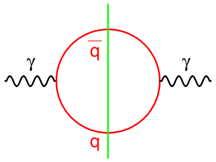
- 5σ above tree level
- Presence of genuine electroweak corrections

Corrections to α due to photon self energy:

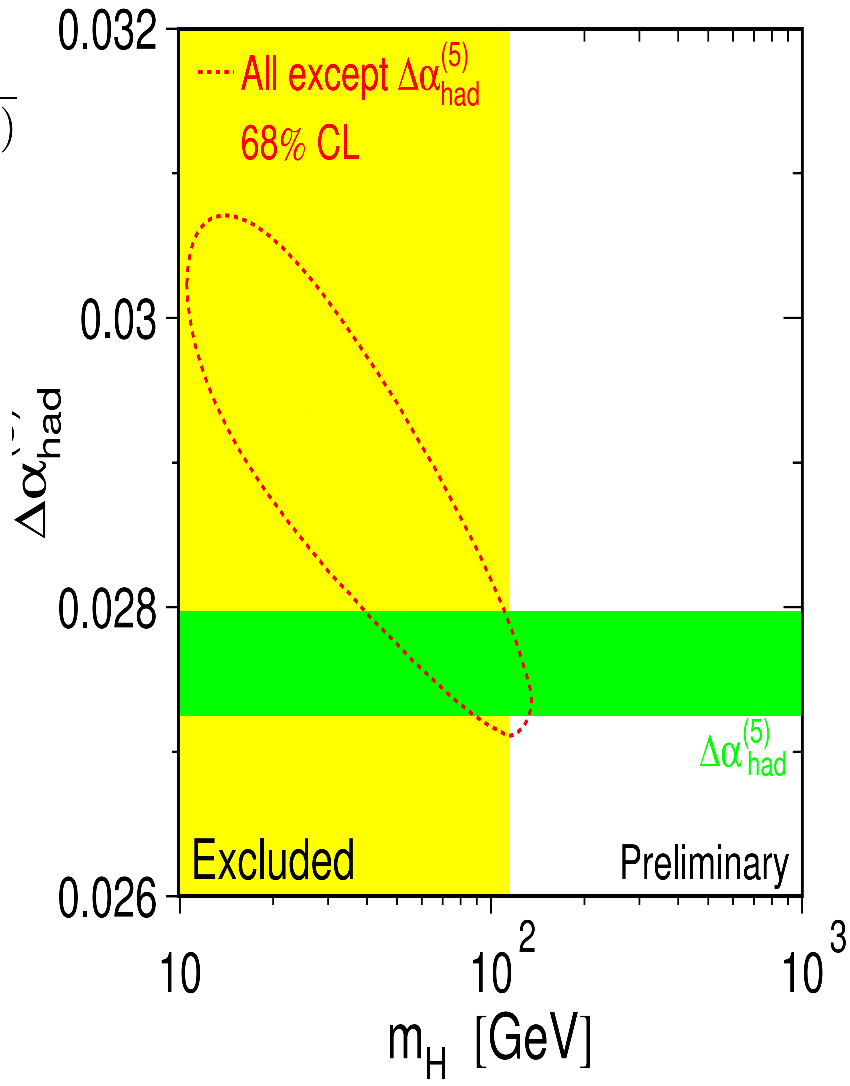
- $\alpha(s) = \dfrac{\alpha(0)}{1 - \Delta\alpha_{lep}(s) - \Delta\alpha^5_{had} - \Delta\alpha^t_{had}(s)}$
- $\Delta\alpha_{lep}(s)$ known to 3-loop level
- $\Delta\alpha^5_{had}$ important; evaluating the dispersion integral

$$\Delta\alpha^5_{had}(s) \propto \int_{4M_\pi^2}^{\infty} \frac{R(s')ds'}{s'(s'-s)}$$

- With low energy data: $\dfrac{\sigma(e^+e^- \to hadrons)}{\sigma(e^+e^- \to \mu^+\mu^-)}$



- Burkhardt, Pietrzyk; PLB513(2001)46: $\Delta\alpha^5_{had}(\mathrm{m_Z}) = 0.02761 \pm 0.00036$

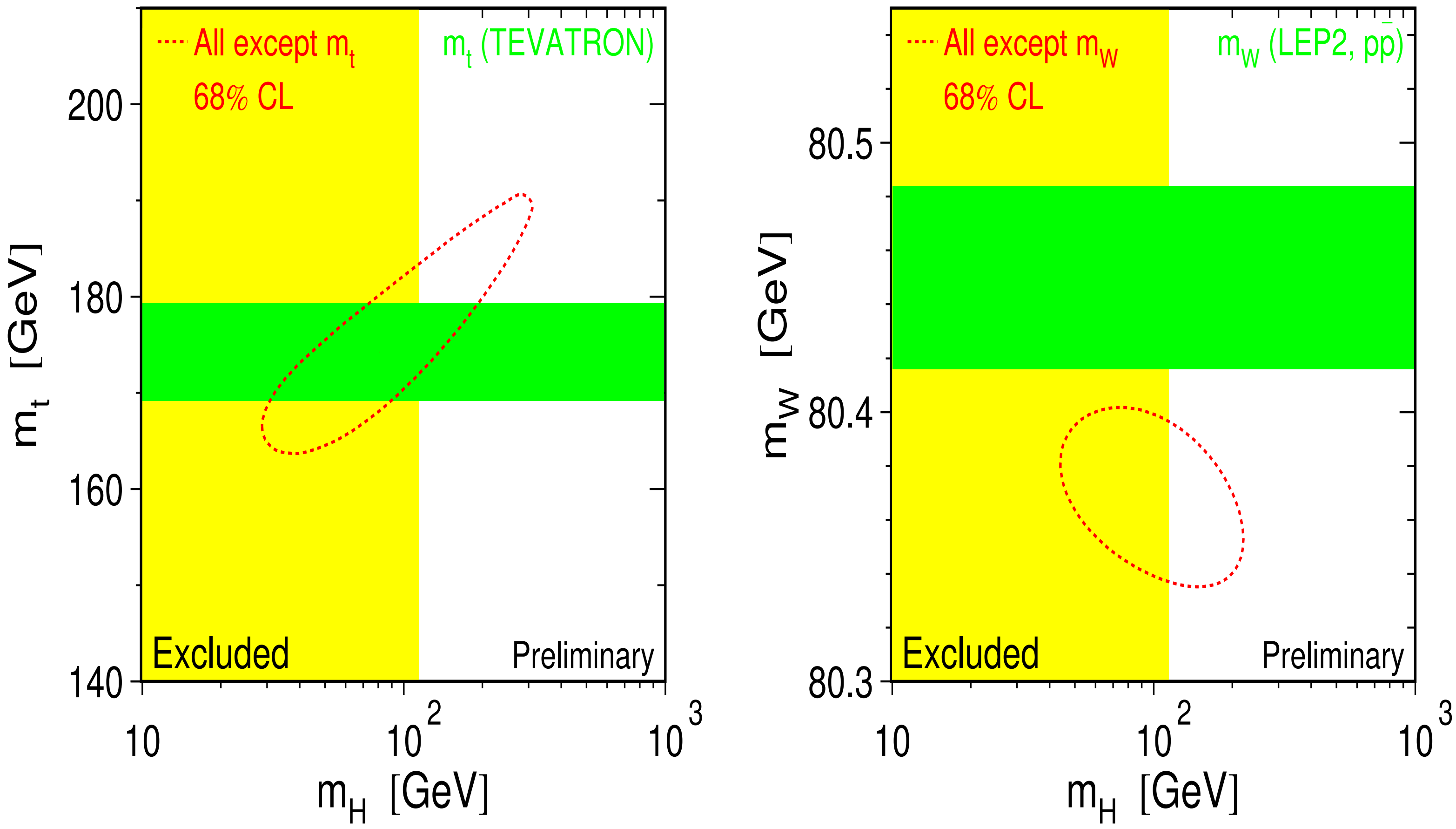


LEP1/SLD: $m_t = 170.7 \pm 10.3$ GeV

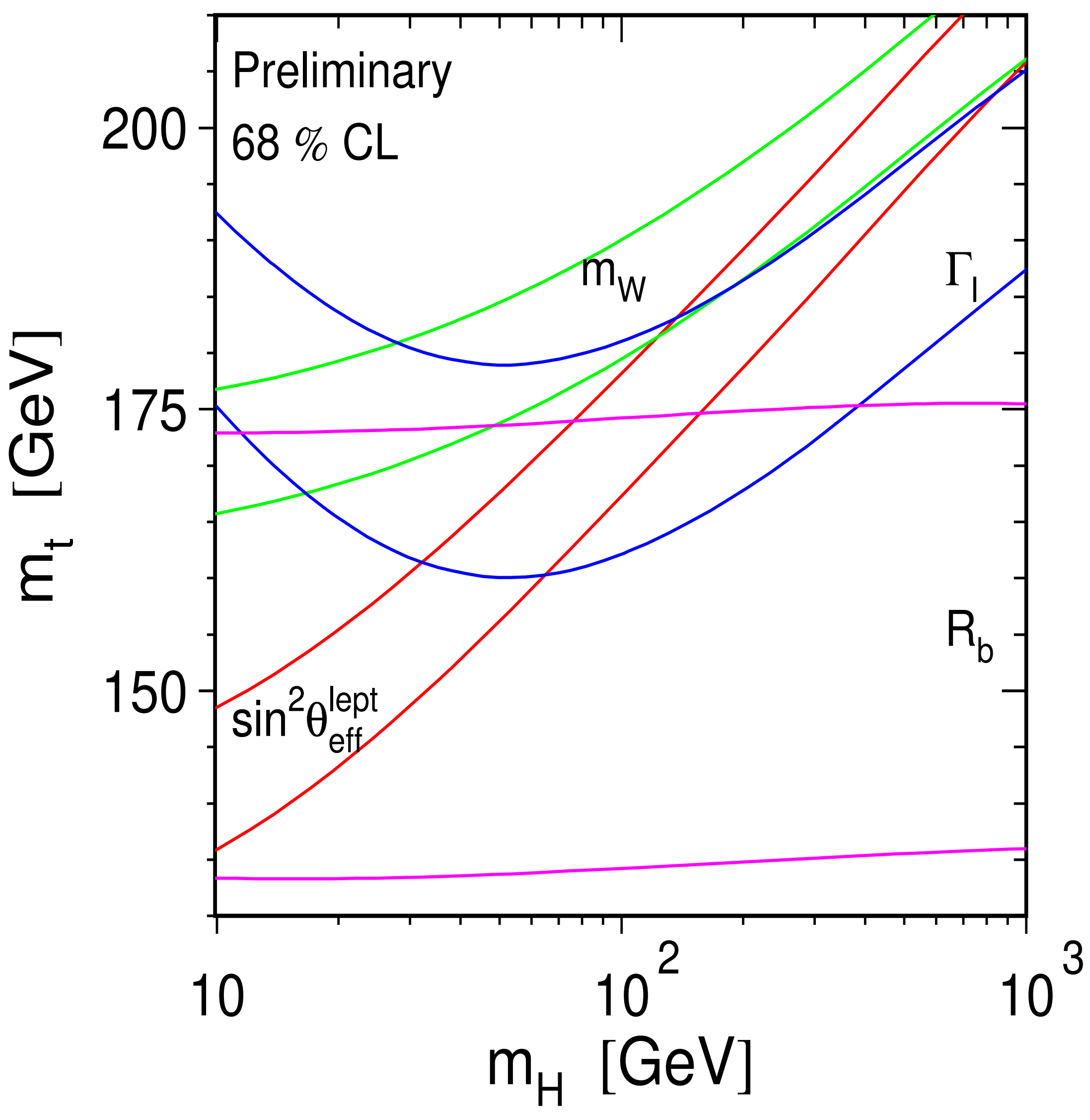
LEP1/SLD/m_W/Γ_W: $m_t = 180.4 \pm 9.7$ GeV

LEP1/SLD: $m_W = 80.373 \pm 0.033$ GeV

LEP1/SLD/m_t: $m_W = 80.380 \pm 0.023$ GeV



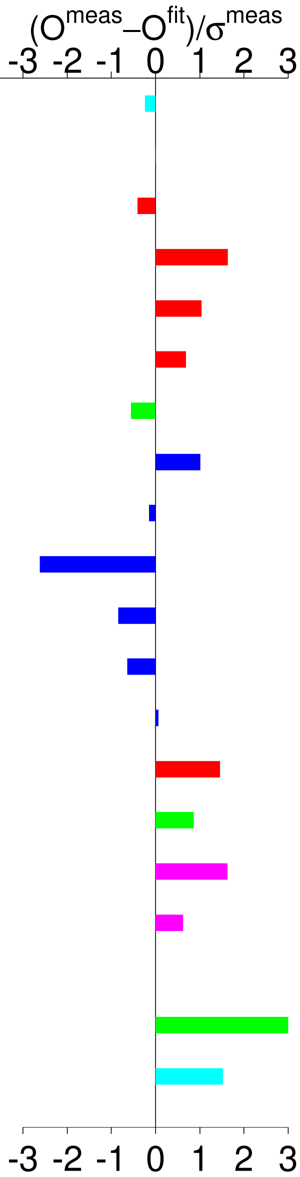
More details about the W mass measurements will follow in Roberto Chierici's talk !



Sensitivity of pseudo-observables to top mass and Higgs mass

Summer 2002

	Measurement	Pull
$\Delta\alpha^{(5)}_{had}(m_Z)$	0.02761 ± 0.00036	-0.24
m_Z [GeV]	91.1875 ± 0.0021	0.00
Γ_Z [GeV]	2.4952 ± 0.0023	-0.41
σ^0_{had} [nb]	41.540 ± 0.037	1.63
R_l	20.767 ± 0.025	1.04
$A^{0,l}_{fb}$	0.01714 ± 0.00095	0.68
$A_l(P_\tau)$	0.1465 ± 0.0032	-0.55
R_b	0.21644 ± 0.00065	1.01
R_c	0.1718 ± 0.0031	-0.15
$A^{0,b}_{fb}$	0.0995 ± 0.0017	-2.62
$A^{0,c}_{fb}$	0.0713 ± 0.0036	-0.84
A_b	0.922 ± 0.020	-0.64
A_c	0.670 ± 0.026	0.06
A_l(SLD)	0.1513 ± 0.0021	1.46
$\sin^2\theta^{lept}_{eff}(Q_{fb})$	0.2324 ± 0.0012	0.87
m_W [GeV]	80.449 ± 0.034	1.62
Γ_W [GeV]	2.136 ± 0.069	0.62
m_t [GeV]	174.3 ± 5.1	0.00
$\sin^2\theta_W(\nu N)$	0.2277 ± 0.0016	3.00
Q_W(Cs)	-72.18 ± 0.46	1.52

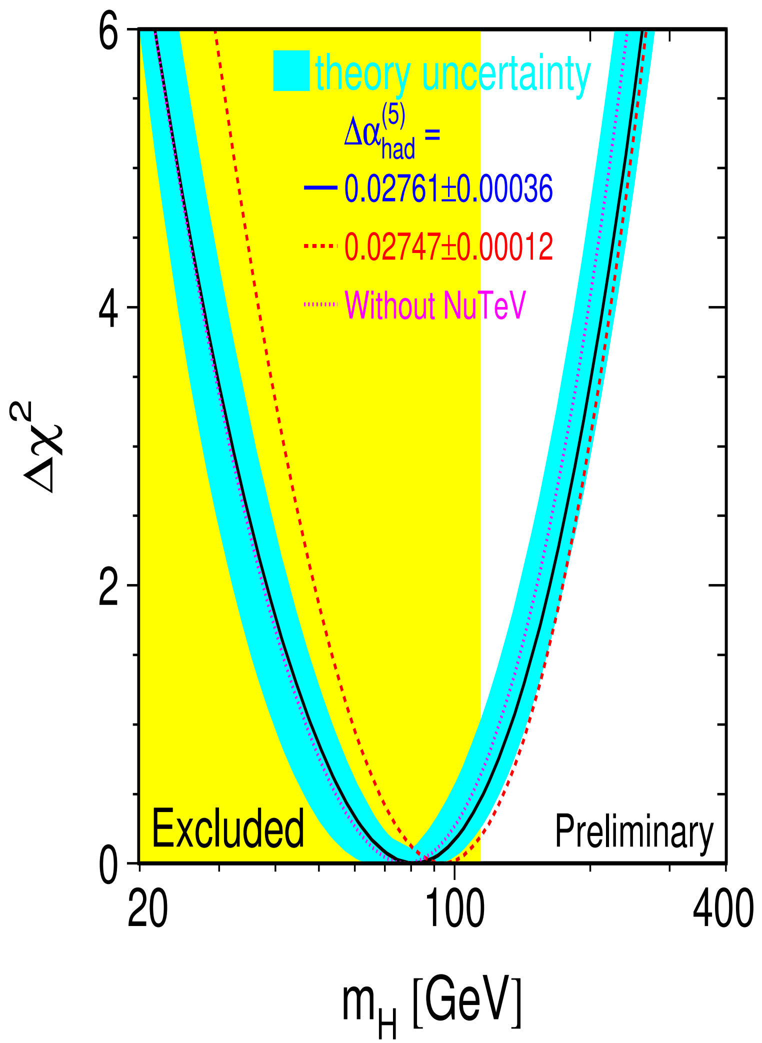


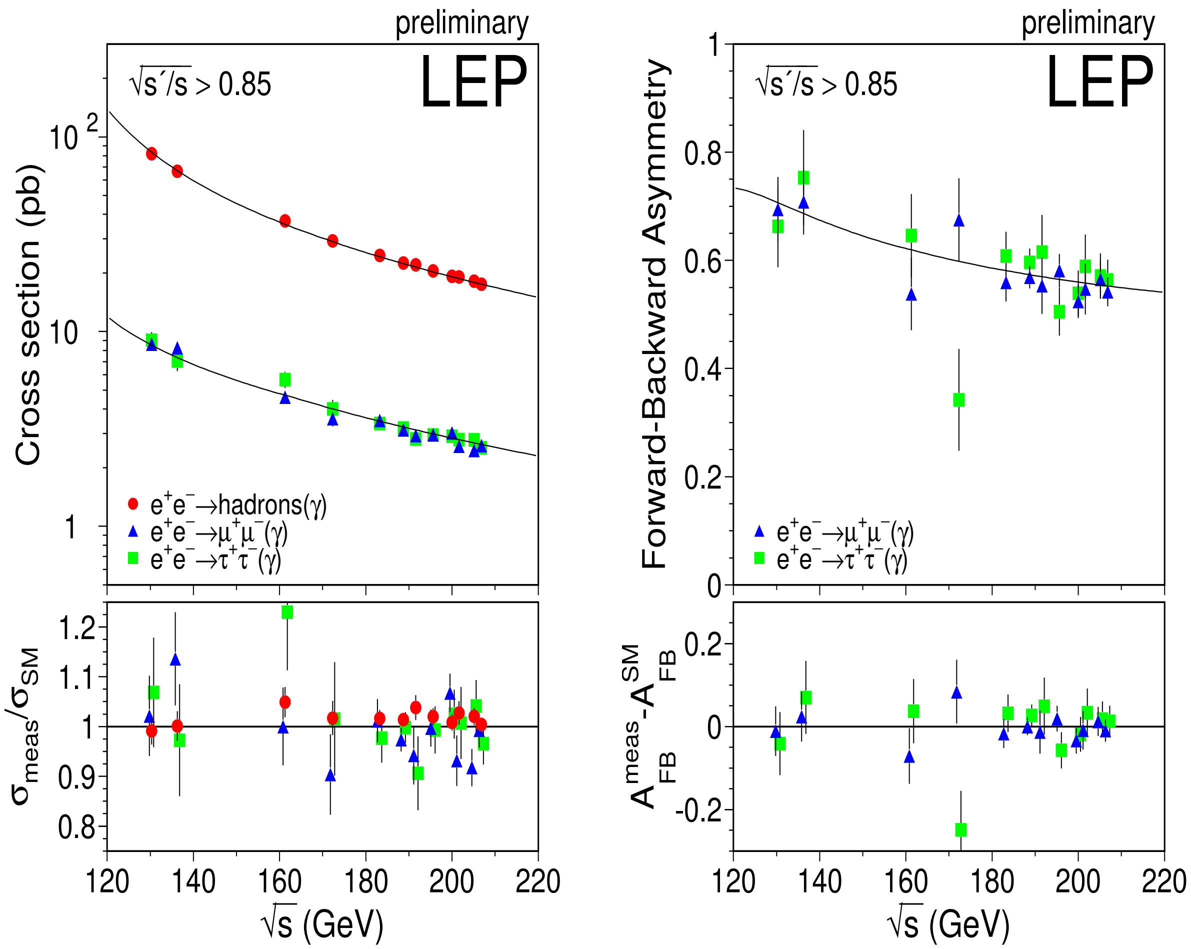
Fit to all data:
$\chi^2/\mathrm{ndof} = 29.7/15$ (1.3%)

Fit without NuTeV:
$\chi^2/\mathrm{ndof} = 20.5/14$ (11.4%)

$m_H = 81\pm^{52}_{33}$ GeV
$m_H < 193$ GeV (95% C.L.)

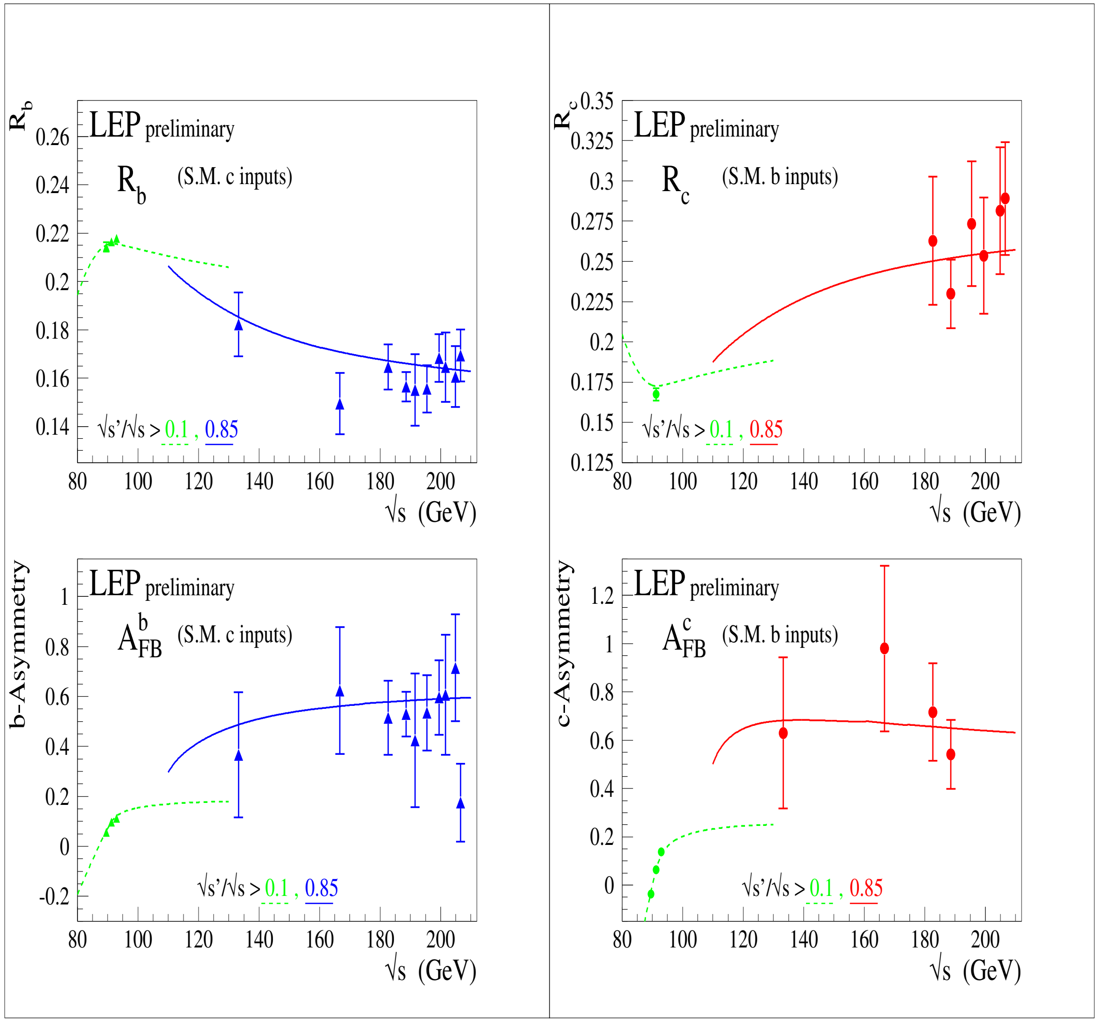
- Δm_t is crucial: strong $m_H - m_t$ correlation ($\approx$70%)
- Result is stable against NuTeV result
- Theory uncertainty!
- For future measurements (GigaZ): Width of 'blueband-parabola' will be shrinked by factor $\approx$5.





- Large QED corrections due to radiative return
- ISR pair production
- ISR-FSR uncertainties

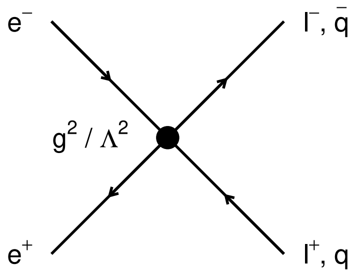
To test the SM at high energies: $\sqrt{s'} > 0.85\sqrt{s}$ $\quad (s' = [1 - E_\gamma/E_{beam}] \cdot s)$



$$R_b = \frac{\sigma_b}{\sigma_{had}}$$

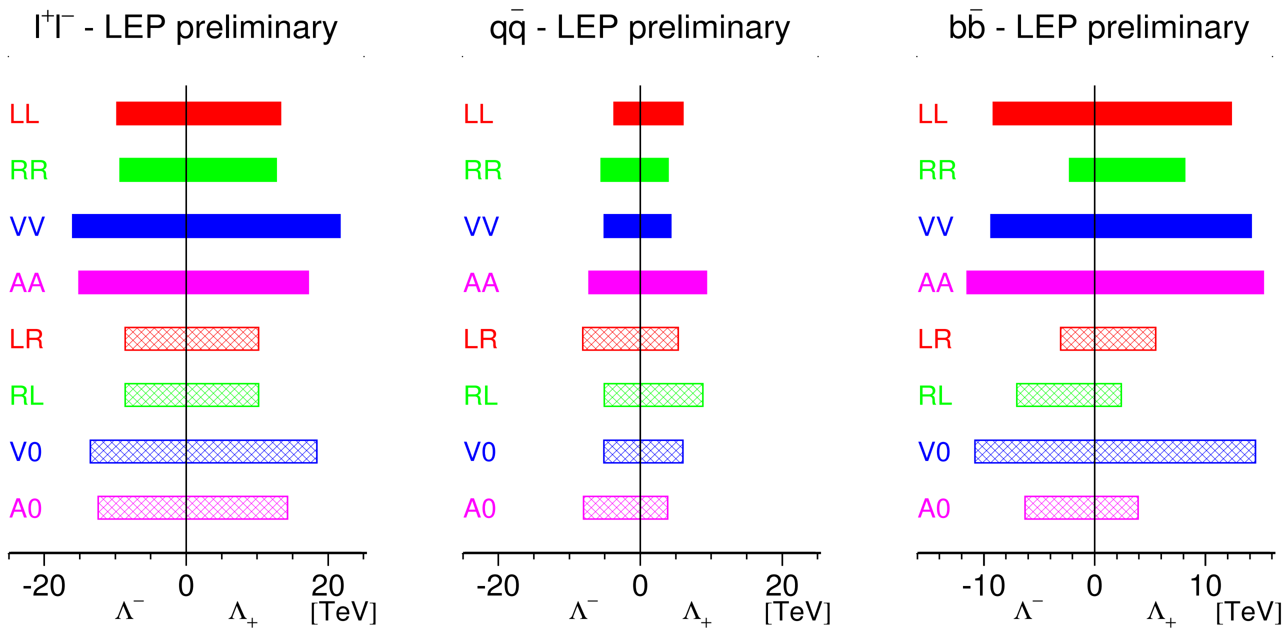
$$R_c = \frac{\sigma_c}{\sigma_{had}}$$

General framework to describe interactions beyond the SM at $\sqrt{s} \ll \Lambda$



$$\mathcal{L}_{CI} = \sum_{L,R} \eta_{i,j} \frac{g^2}{\Lambda^2} \left(\bar{e}_i \gamma^\mu e_i\right) \left(\bar{f}_j \gamma_\mu f_j\right)$$

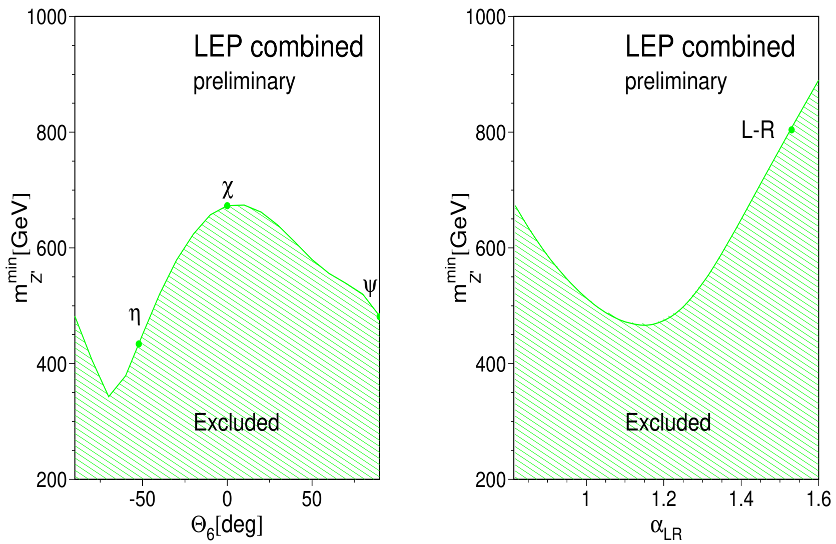
Model	LL	RR	LR	RL	VV	AA	V0	A0
	Parity violating				Parity conserving			
η_{LL}	±1	0	0	0	±1	±1	±1	0
η_{RR}	0	±1	0	0	±1	±1	±1	0
η_{LR}	0	0	±1	0	±1	∓1	0	±1
η_{RL}	0	0	0	±1	±1	∓1	0	±1



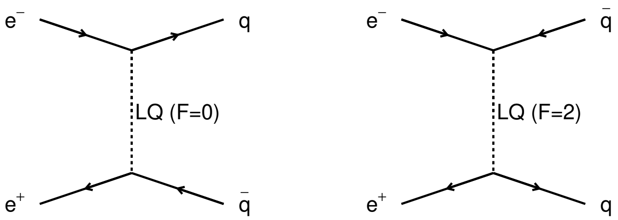
Extra Z Bosons

Z′ model	χ	ψ	η	L-R	SSM
$m_{Z'}$(GeV)	673	481	434	804	1787

ZZ′ mixing is set to 0



Leptoquarks

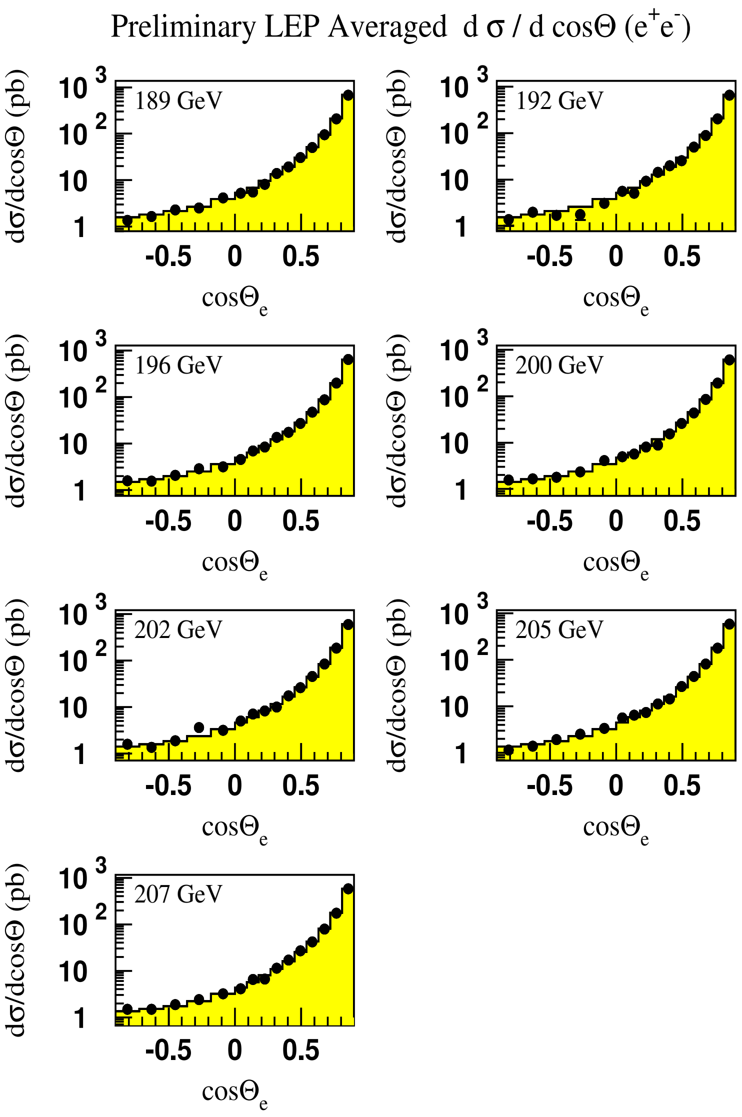


$e^+e^- \longrightarrow q\bar{q}$:

Indirect limits on 1st generation LQ (given in GeV, 95% C.L.)

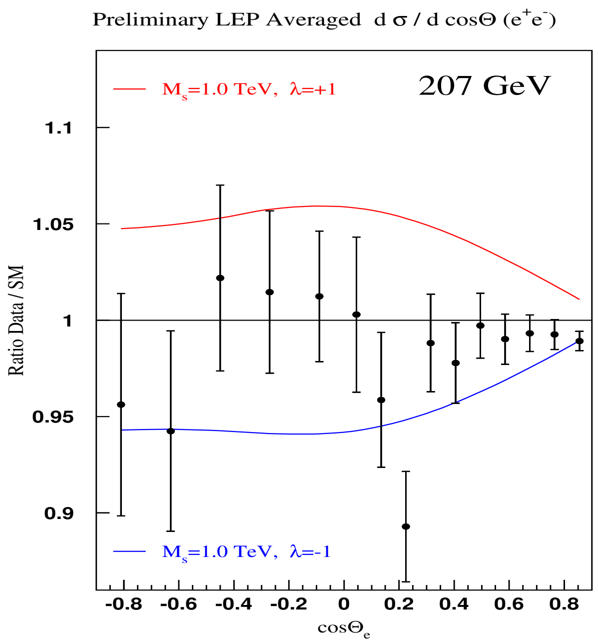
LQ type	m_{LQ}^{min}	LQ type	m_{LQ}^{min}
$S_0(L) \to eu$	655	$V_{1/2}(L) \to ed$	303
$S_0(R) \to eu$	520	$V_{1/2}(R) \to eu,\ ed$	227
$\tilde{S}_0(R) \to ed$	202	$\tilde{V}_{1/2}(L) \to eu$	176
$S_1(L) \to eu,\ ed$	361	$V_0(L) \to e\bar{d}$	917
$S_{1/2}(L) \to e\bar{u}$	178	$V_0(R) \to e\bar{d}$	165
$S_{1/2}(R) \to e\bar{u},\ e\bar{d}$	232	$\tilde{V}_0(R) \to e\bar{u}$	489
$\tilde{S}_{1/2}(L) \to e\bar{d}$	–	$V_1(L) \to e\bar{u},\ e\bar{d}$	659

$$g_{L,R} = \sqrt{4\pi\alpha_{em}}$$



Sensitivity to Low Scale Gravity (LSG)

$$\frac{d\sigma}{d\cos\theta} \propto \left(\frac{d\sigma}{d\cos\theta}\right)_{SM} + \frac{\lambda}{M_S^4} B(\cos\theta) + \frac{\lambda^2}{M_S^8} C(\cos\theta)$$



$\lambda = +1: \quad M_S >$ 1.20 TeV

$\lambda = -1: \quad M_S >$ 1.09 TeV

Last steps to finalize the analysis work are exhausting but still exciting!

- Successfull test of the Standard Model
- High sensitivity to radiative corrections
- Still 3σ effects in $\sin^2\theta_{eff}$

In the future:

- Improved measurements of $\mathrm{m_t},\ \mathrm{m_W},\ \Delta\alpha_{had}$ and $\sin^2\theta_{eff}$
- Precise theoretical calculations needed
- Find the Higgs at Tevatron? LHC ? LC ??

We are looking forward to global precision tests with a Multi-Purpose Linear Collider:

$\Rightarrow$ Direct and indirect studies of the W boson, the Higgs boson, the top quark and hopefully new phenomena