# Experimental Tests of the Standard Model

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# *Outline*

- Tests of the electroweak sector of the Standard Model
- Generally not: QCD, heavy flavours, CKM matrix, CP violation
- Emphasis on **new results (changes since last summer)**
  - Z pole heavy flavour forward-backward asymmetries
  - Gauge boson production and properties from LEP2 and Tevatron Run II
  - Top physics from Tevatron Run II
  - Status of muon g-2: interplay of theory and experimental inputs
- Global electroweak fits and the Higgs mass

Many more details can be found in the presentations in the parallel session.

Many thanks to numerous people: LEP, SLD, CDF and D0 electroweak and top working groups, and in particular: P Azzi, E Barberis, E Barberio J Butterworth, D Charlton, R Chierici, B Clare, M Davier, S Eidelman, M Elsing, J Estrada, C Gerber, M Grünewald, A Heinson, A Kotwal, J Kühn, K McFarland, P Murat, P Newman, U Parzefall, B Pietrzyk, G Quast, C Rembser, M Schmitt, A Tapper, R Tenchini, T Teubner, M Verzocchi, T Wengler

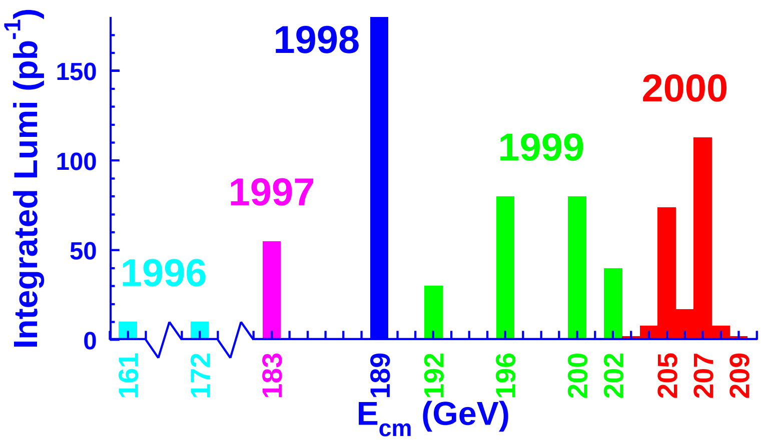
# LEP and SLD: Z pole

# LEP and SLC: $e^+e^-$ collisions

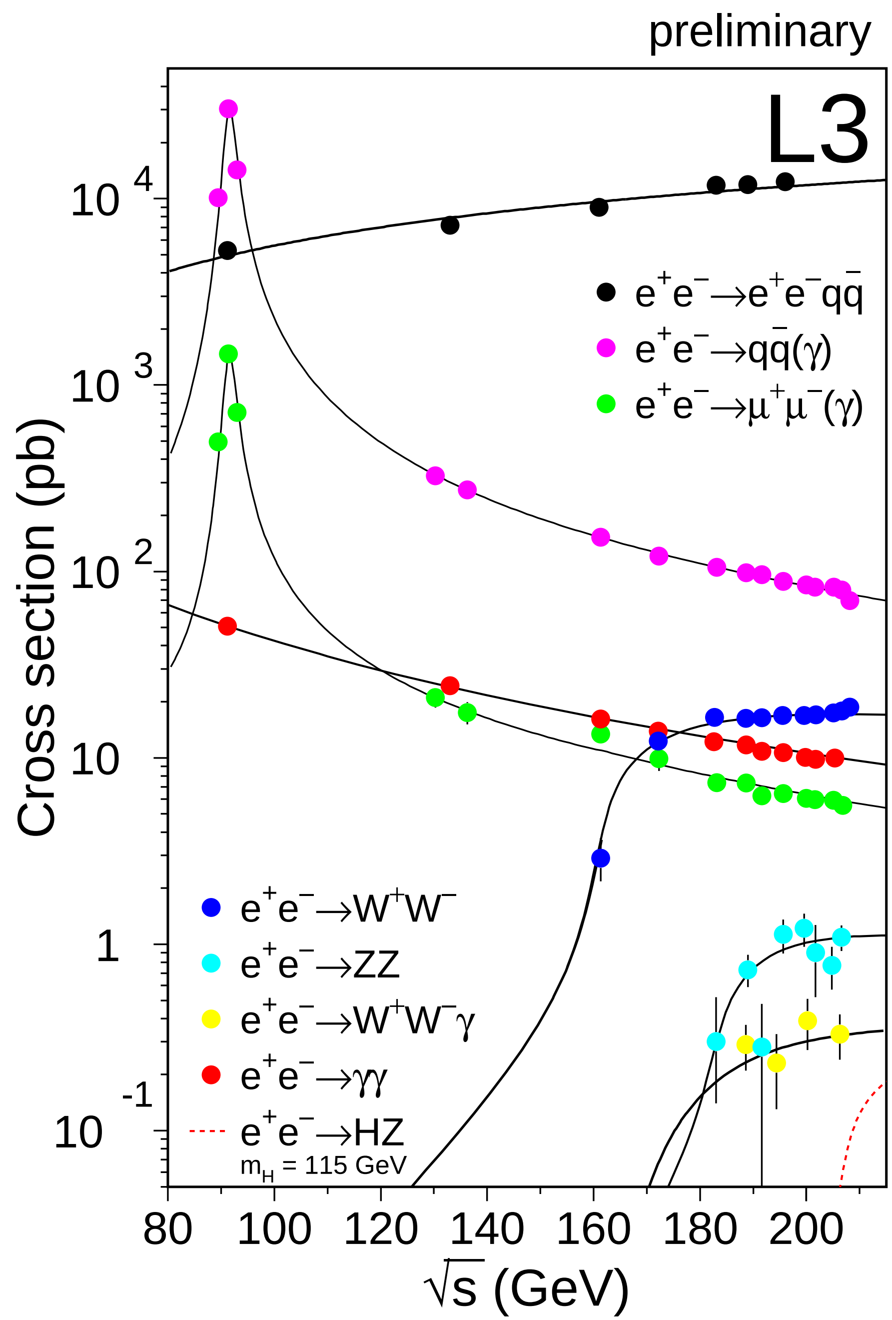
LEP 1989-2000 Total lumi. 1000 $pb^{-1}$
ALEPH, DELPHI, L3, OPAL recorded:

LEP1 4.5M Z per experiment including off-peak data.

LEP2 Above WW threshold.
10k W-pair per experiment




SLD at SLC, 600k Z decays with $e^-$ beam up to 77% polarised



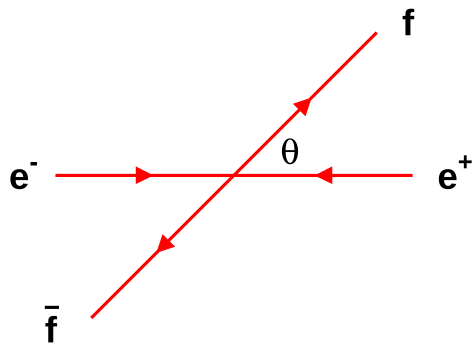
# Z pole

LEP Z lineshape, LEP $A^{\ell}_{FB}$, $\tau$ pol.
SLD $A_{LR}$ and $A^{\ell}_{LRFB}$ asymmetries
} Final for some time. (See global fits)

New: Heavy flavour $A_{FB}$ results
DELPHI (prelim), OPAL (final)

Forward: $\theta < 90^\circ$

$$A_{FB} = \frac{\sigma_F - \sigma_B}{\sigma_F + \sigma_B}$$

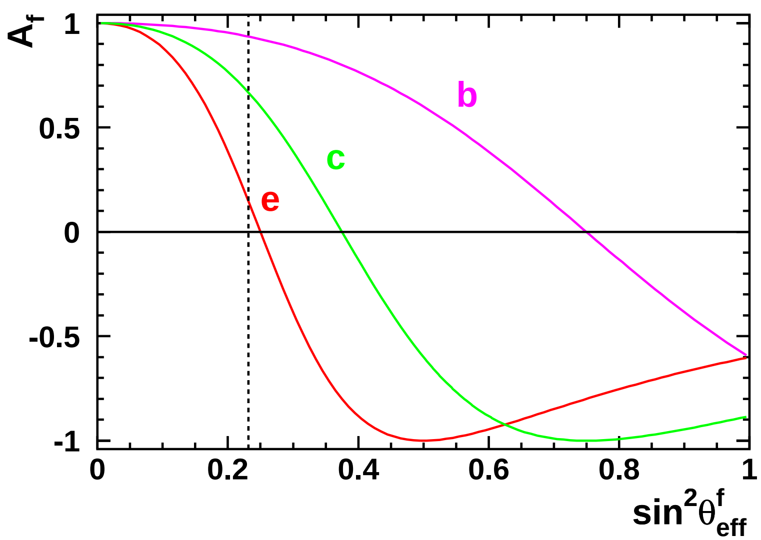



## Z couplings:

$$g_{Vf} = \sqrt{\rho}\left(T^3_f - 2Q_f \sin^2\theta^f_{eff}\right) ; g_{Af} = \sqrt{\rho}\ T^3_f$$

Partial widths $\Rightarrow g^2_{Vf} + g^2_{Af}$; Asymmetries $\Rightarrow g_{Vf}/g_{Af} = 1 - 4|Q_f|\sin^2\theta^f_{eff}$

Define $A_f = 2\dfrac{g_{Vf}\,g_{Af}}{g^2_{Vf} + g^2_{Af}}$ →




Related to Z pole asymmetries by:

$A^{0,f}_{FB} = \frac{3}{4}A_e A_f$ ; $A^0_{LR} = A_e$ ; $A^0_{LRFB} = \frac{3}{4}A_f$

$A^{0,b}_{FB}$ sensitive to $\sin^2\theta^{lept}_{eff}$

# *Heavy flavour forward-backward asymmetries*

Select Z to hadron decays. Quark direction from thrust axis.

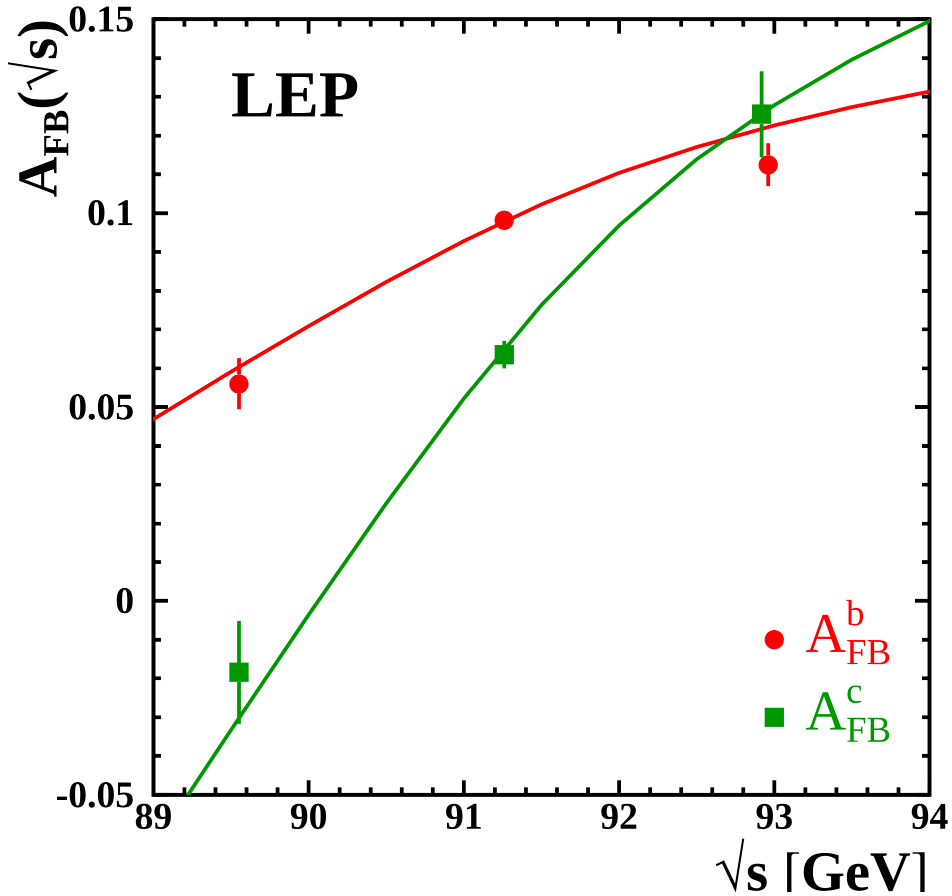
Heavy flavours tagged by leptons (high $p$, $p_T$), B,D lifetime, secondary vertex mass...

Forward vs. backward going quark determined from lepton or inclusive charge tag.

Fit to $\frac{d\sigma}{d\cos\theta} \propto \frac{3}{8}(1+\cos^2\theta) + A_{FB}\cos\theta$ in bins of flavour purity for $A_{FB}^{b\bar{b}}$ (and $A_{FB}^{c\bar{c}}$).

Analyses self-calibrated from data for flavour purity, $B^0$ mixing and charge mistag using double tag methods.

Measurements first combined at Z peak, and $\pm$ 2 GeV away. Then corrected to give pole asymmetries at $\sqrt{s} = M_Z$

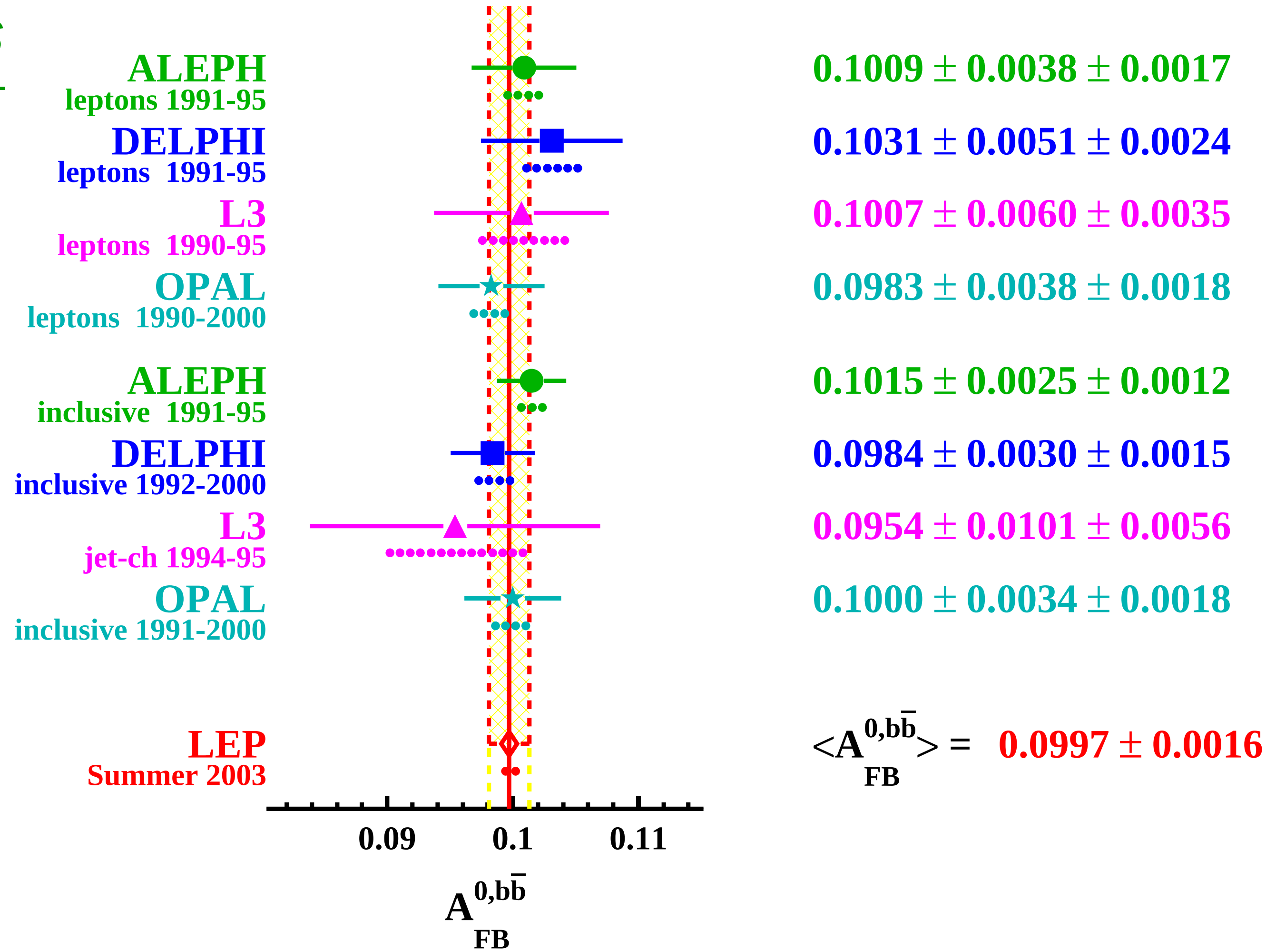


# $A_{FB}^{0,b}$, $A_{FB}^{0,c}$ *results*

$A_{FB}^{0,b}$ with lepton → and inclusive tags

All heavy-flavour quantities from LEP and SLD averaged in a combined fit, accounting for correlated errors and interdependences.

$\chi^2$/dof 52.7/(105-14)




$A_{FB}^{0,b} = 0.0997 \pm 0.0016$, Total sys 0.0007, Common sys 0.0004 ; SM 0.1036

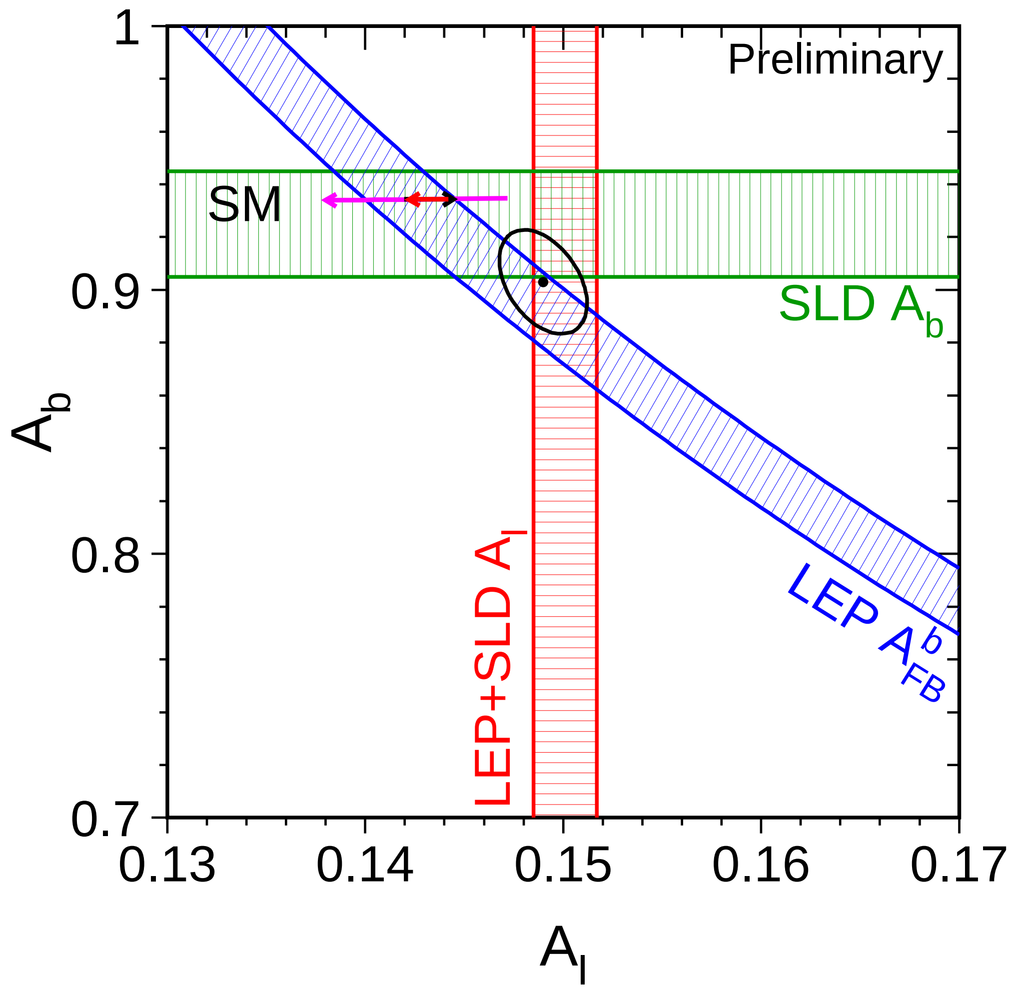
$A_{FB}^{0,c} = 0.0706 \pm 0.0035$, Total sys 0.0017, Common sys 0.0009 ; SM 0.0740

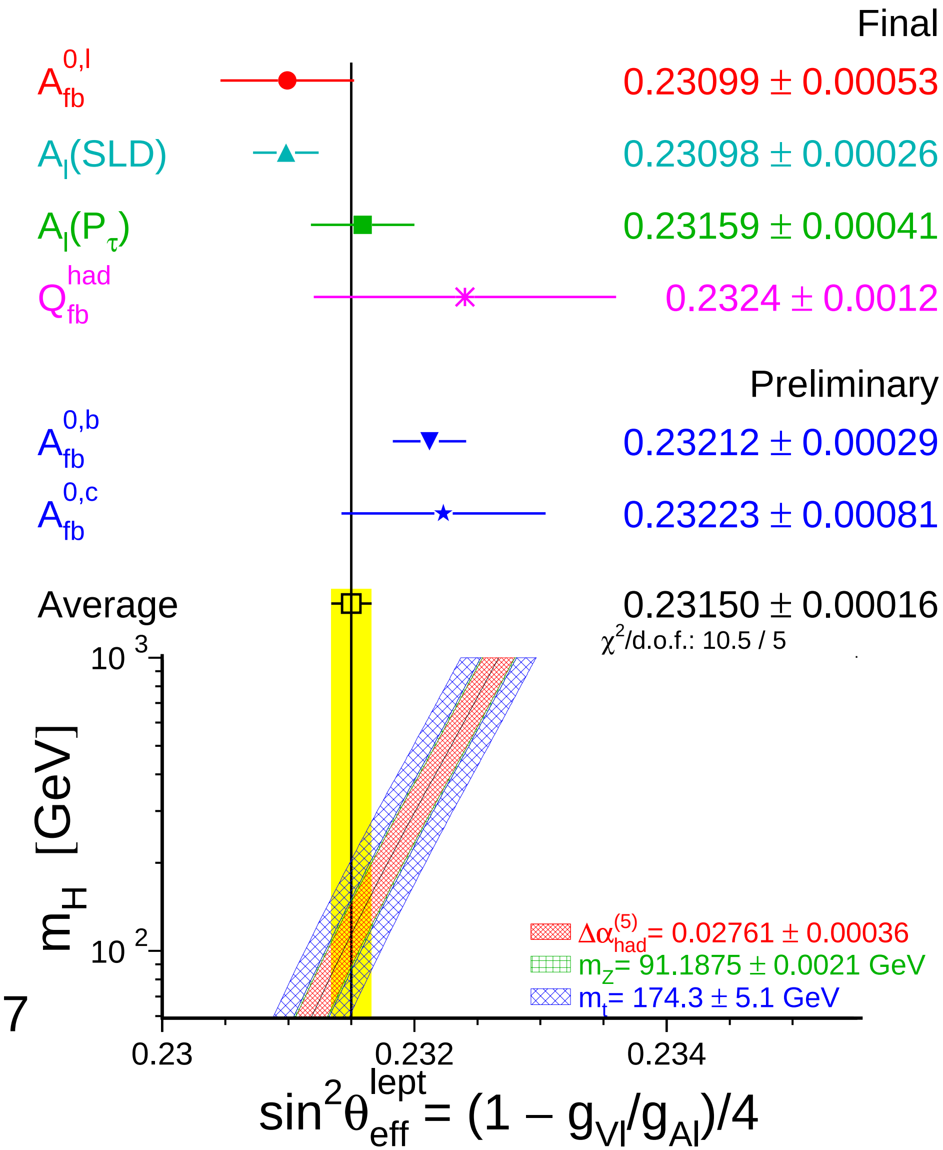
(Summer 2002, $A_{FB}^{0,b} = 0.0995 \pm 0.0017$, $A_{FB}^{0,c} = 0.0713 \pm 0.0036$)

Also waiting for SLD heavy flavour results to be finalised.

# *Comparison of asymmetry measurements &* $\sin^2\theta_{\rm eff}^{\rm lept}$

Recall: $A_{FB}^{0,f} = \frac{3}{4}A_e A_f$



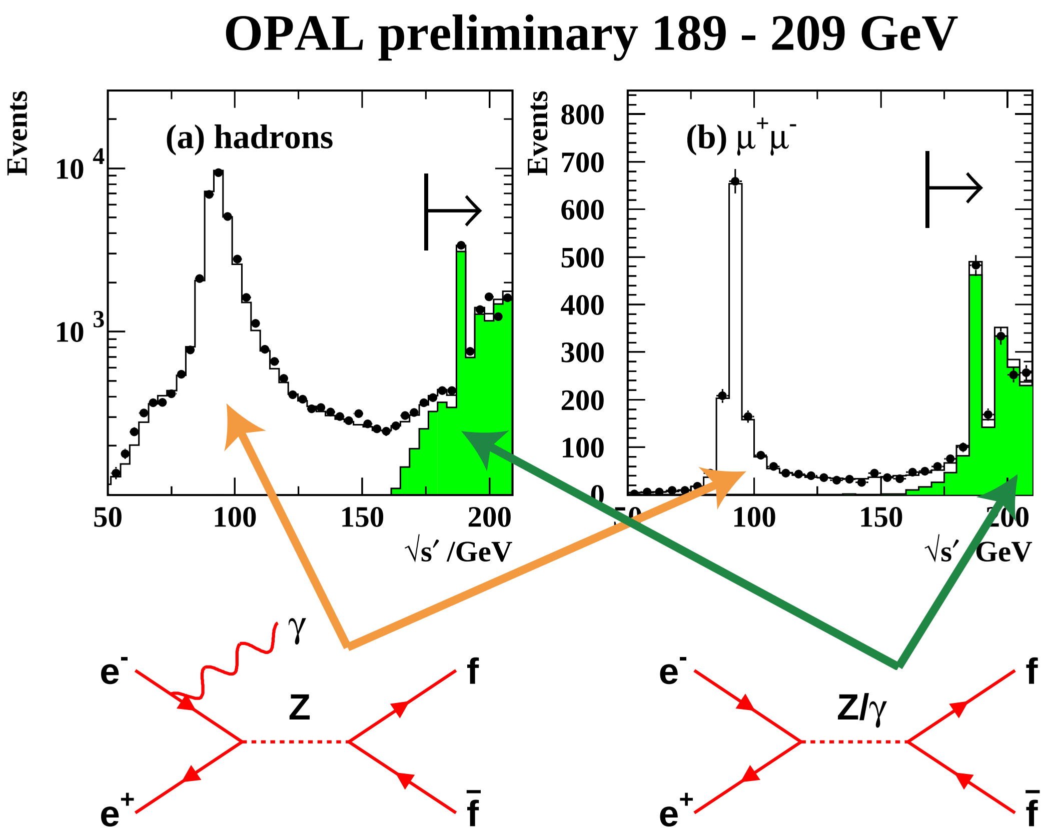




$P(\chi^2) = 6.2\%$ for $\sin^2\theta_{\rm eff}^{\rm lept}$. Two most precise values, $A_{FB}^{0,b}$ and $A_{LR}$, differ by $2.9\sigma$

# LEP2 $f\bar{f}$

# *Fermion pair production at LEP2*

OPAL Update. LEP combination unchanged.




Non-radiative events: $\sqrt{s'/s} > 0.85$ where $\sqrt{s'}$ is $Z/\gamma$ propagator mass

Radiative return peak is at $\sqrt{s'} = M_Z$ if the beam energy calibration is correct.

New: Preliminary $E_{\mathrm{beam}}$ updates from ADLO

Measured average beam energy differs from LEP preliminary value by:

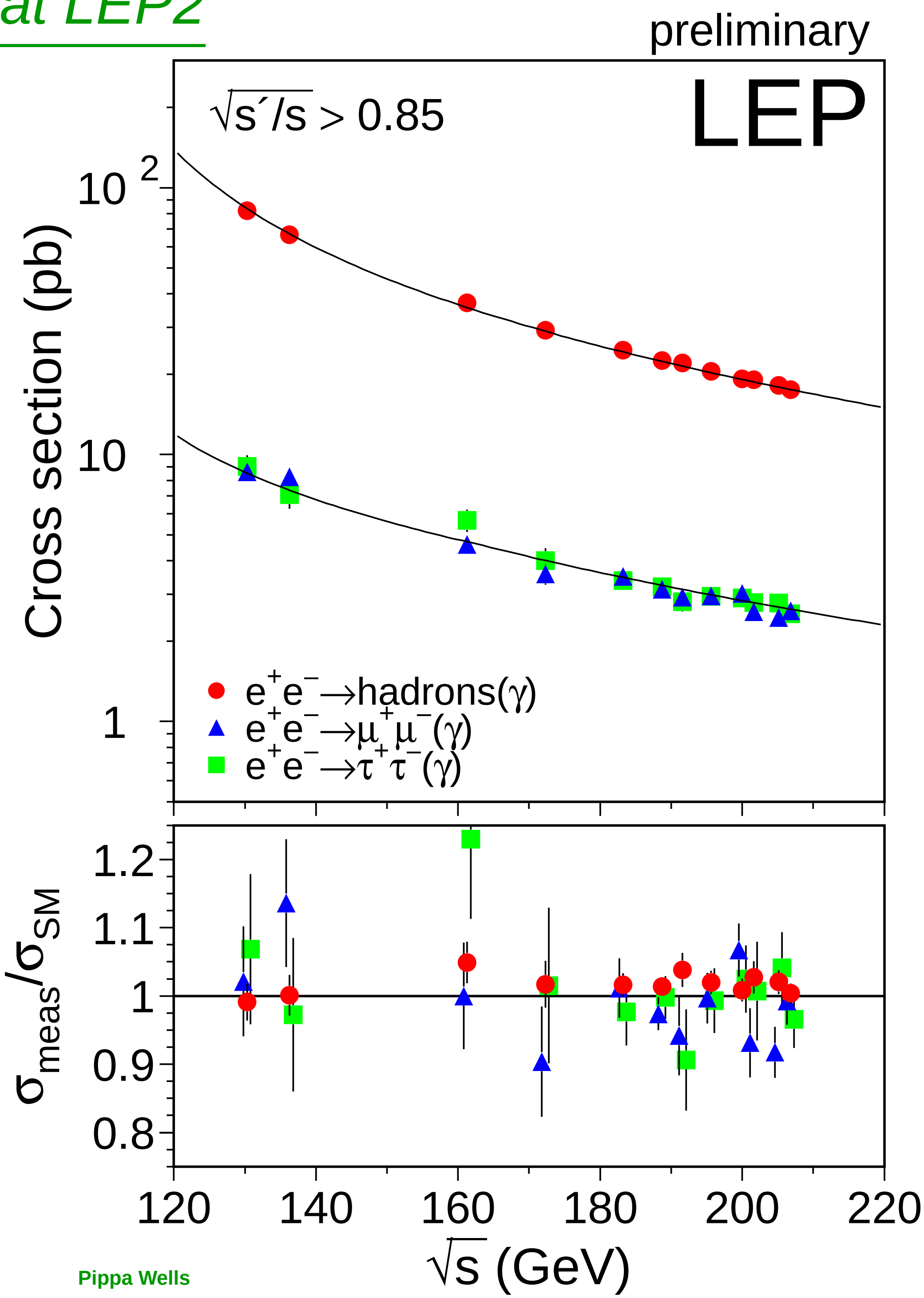
$$\Delta E_{\mathrm{beam}} = -14 \pm 21(\mathrm{stat.}) \pm 20(\mathrm{syst.}) \pm 20(\mathrm{LEP})\ \mathrm{MeV}$$

# *Fermion pair production at LEP2*

LEP combined cross-sections, asymmetries and differential cross-sections available: $q\bar{q}$, $b\bar{b}$, $c\bar{c}$, $e^+e^-$, $\mu^+\mu^-$, $\tau^+\tau^-$.

Good agreement with SM predictions.

Constraints on new physics
(contact interactions, Z'...)
O(1–10) TeV,



# Gauge boson production at Tevatron and LEP

# *Tevatron at Fermilab*

Two experiments CDF and D0 - major Run II upgrades

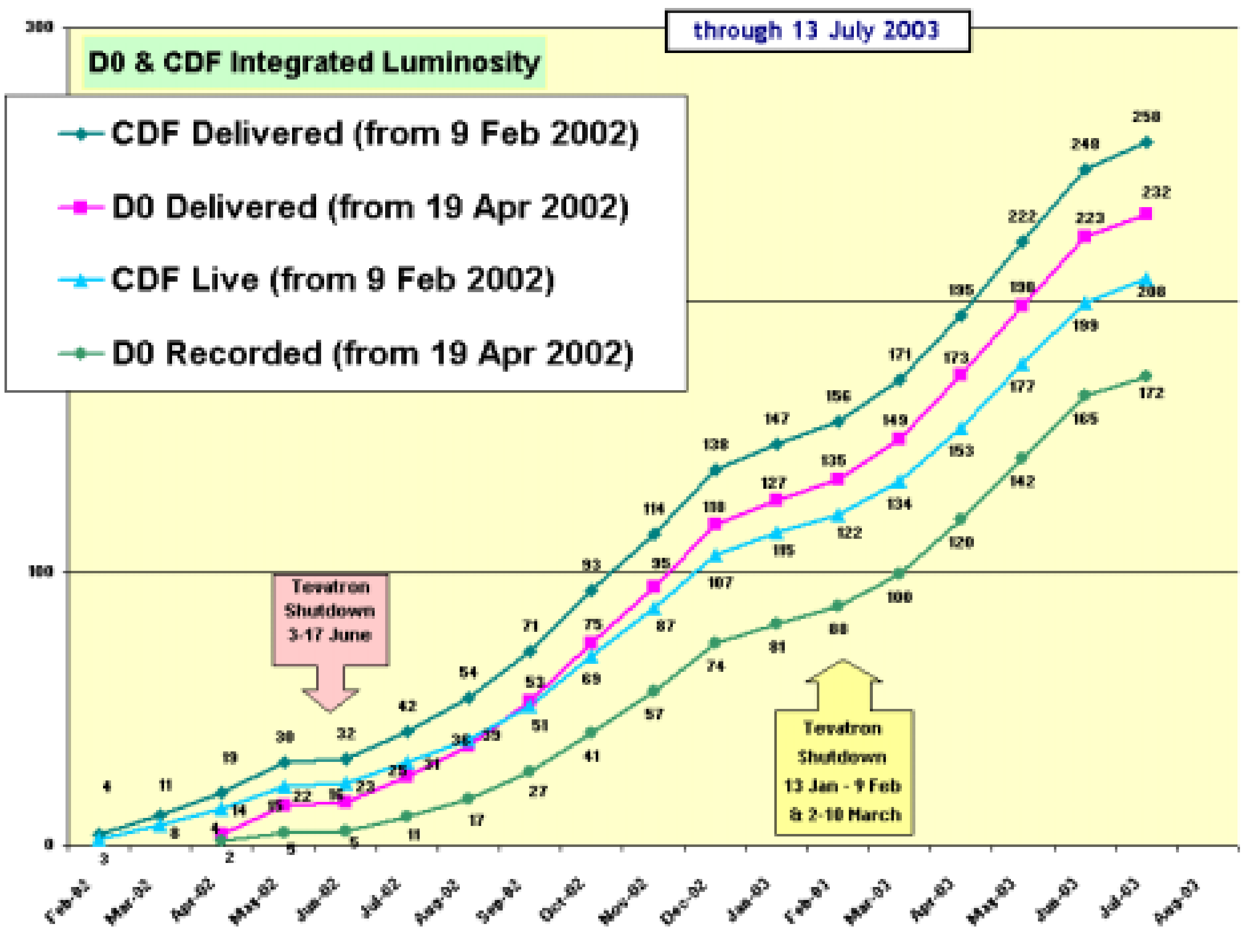
$p\bar{p}$ collisions with $\sqrt{s} = 1.96$ TeV

Run I, 1992-1995 80 $pb^{-1}$ with $\sqrt{s} = 1.8$ TeV

Run IIa in progress. Expect $\sim$300 $pb^{-1}$ FY2003

Run IIb, between 4.5 and 8.5 $fb^{-1}$ by FY2009

`http://www.fnal.gov/pub/now/upgradeplan/`



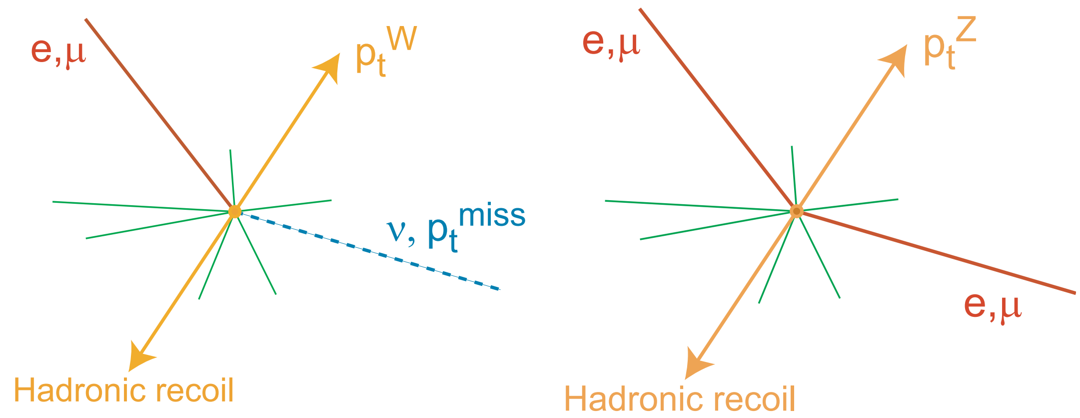

$\leftarrow$ 200 $pb^{-1}$

All Run II results shown here are new since last summer, and use a partial data set (typically 50$pb^{-1}$).

# Tevatron W and Z production

Clean $q\overline{q}' \to W \to \ell\nu$ and $Z \to \ell^+\ell^-$ signatures ($\ell = e, \mu$)

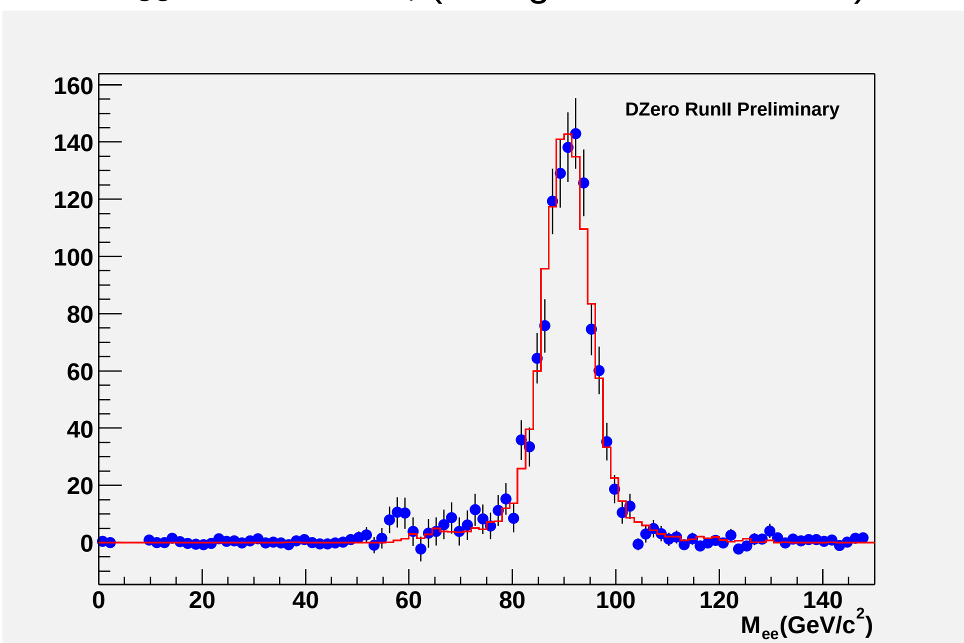
Isolated lepton and $p_T^{miss}$ or two isolated leptons

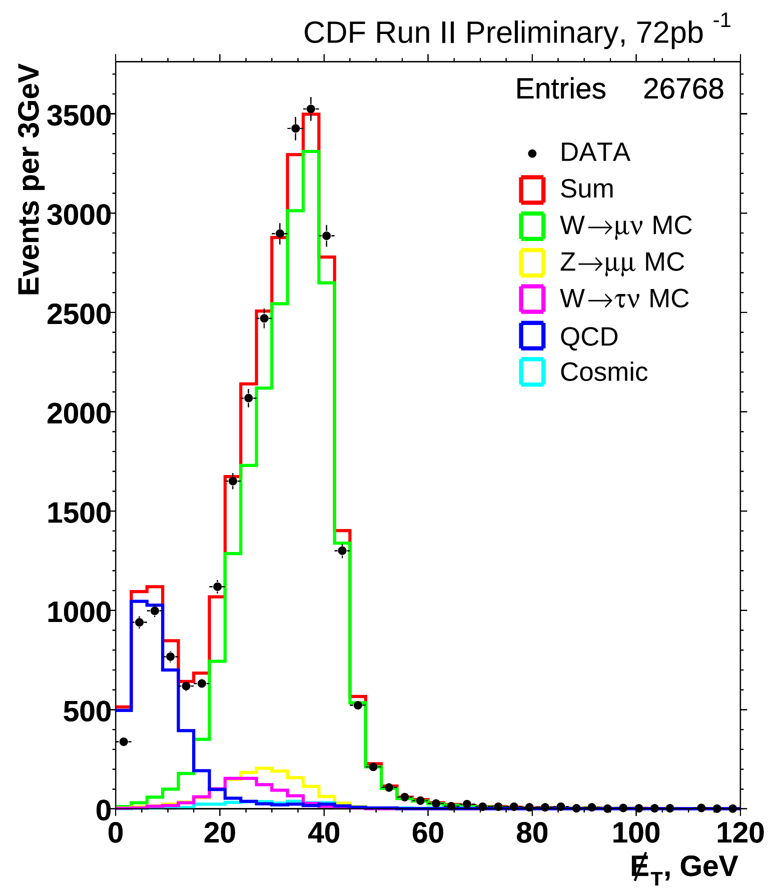



**Distributions from Run II**

D0 preliminary: 41.6 $pb^{-1}$ from run II

$M_{ee}$ for $Z \to ee$, (background subtracted)



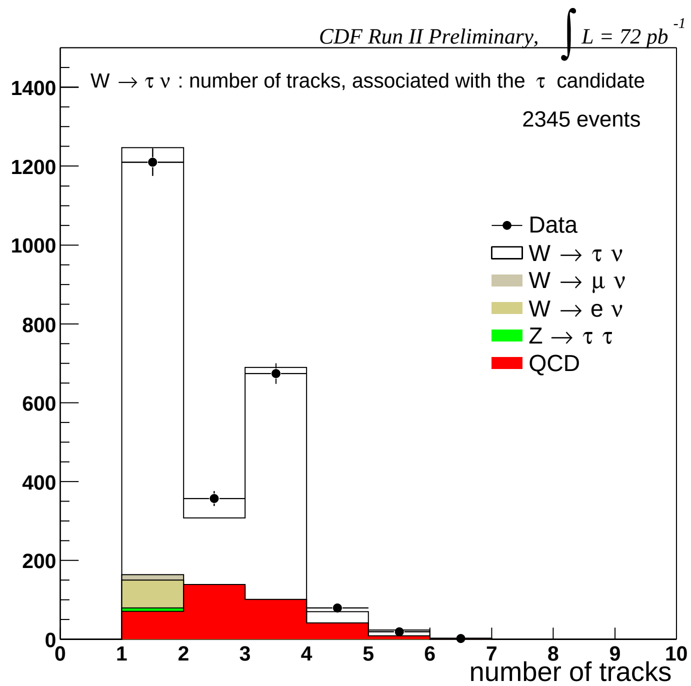



# Tevatron Run II $\sigma_{W,Z} \cdot Br(W, Z \to \text{leptons})$

New Run II

Also measure $\sigma_W \cdot Br(W \to \tau\nu)$

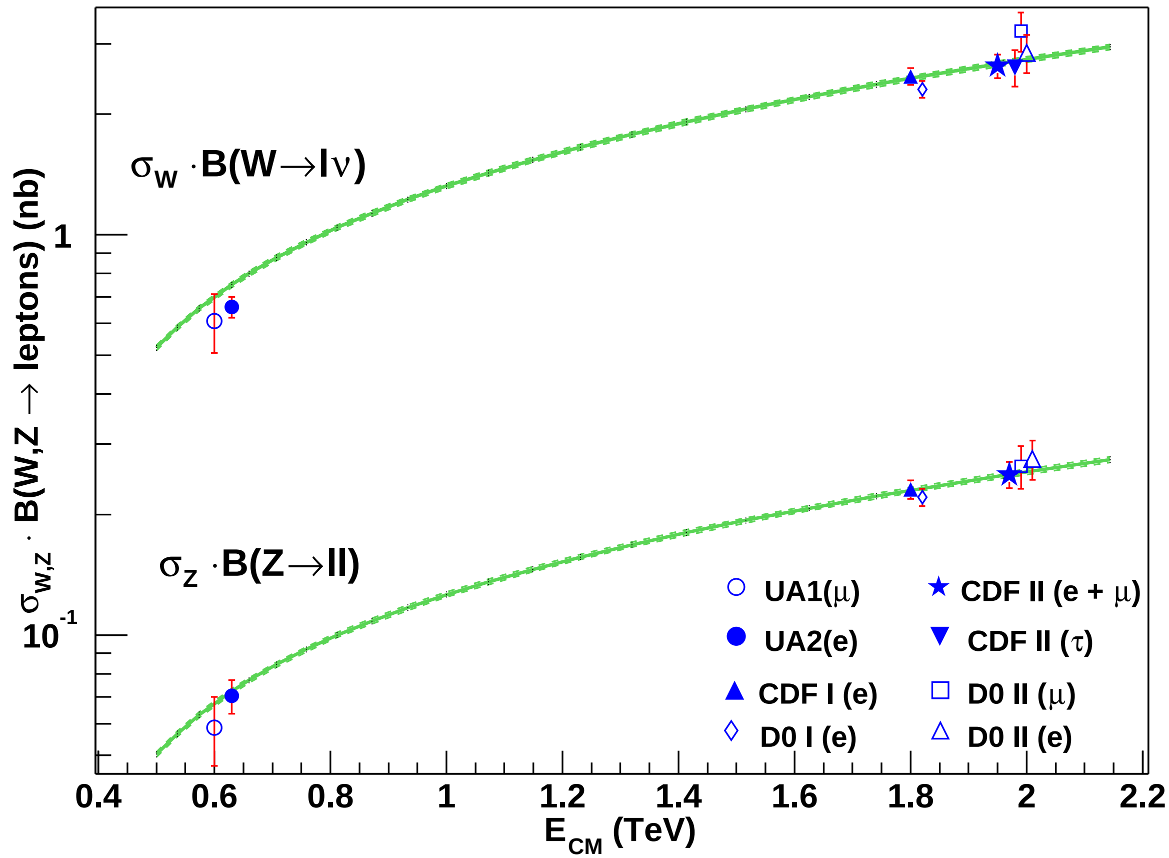
Number of tracks of $\tau$




Lepton universality test in W decays: CDF Run II preliminary:

$$g_\tau/g_e = 0.99 \pm 0.04$$

Cross section × leptonic Br compilation



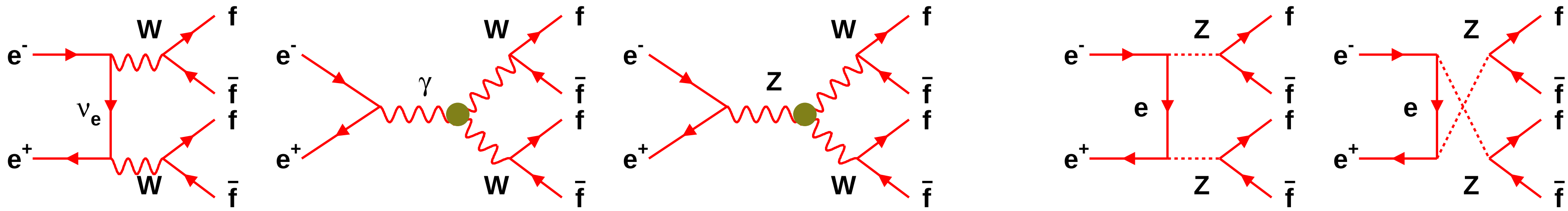

Dominant experimental uncertainties: luminosity, PDFs, hadronic recoil, detector acceptance.

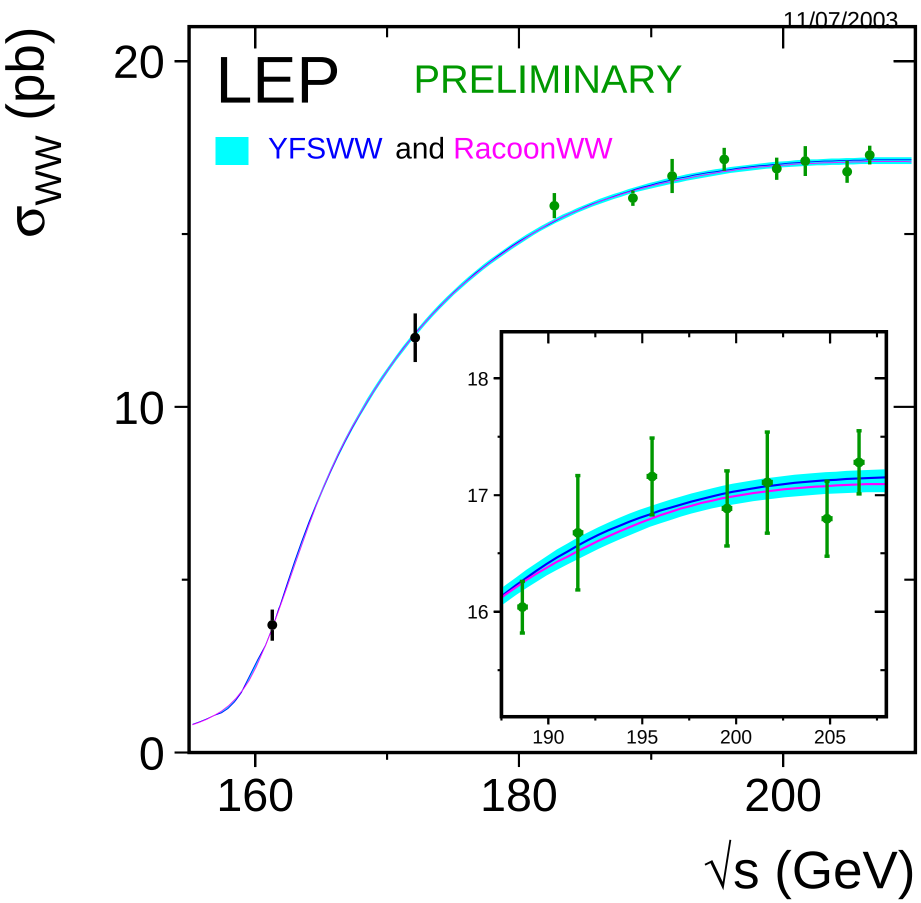
# WW and ZZ production at LEP2

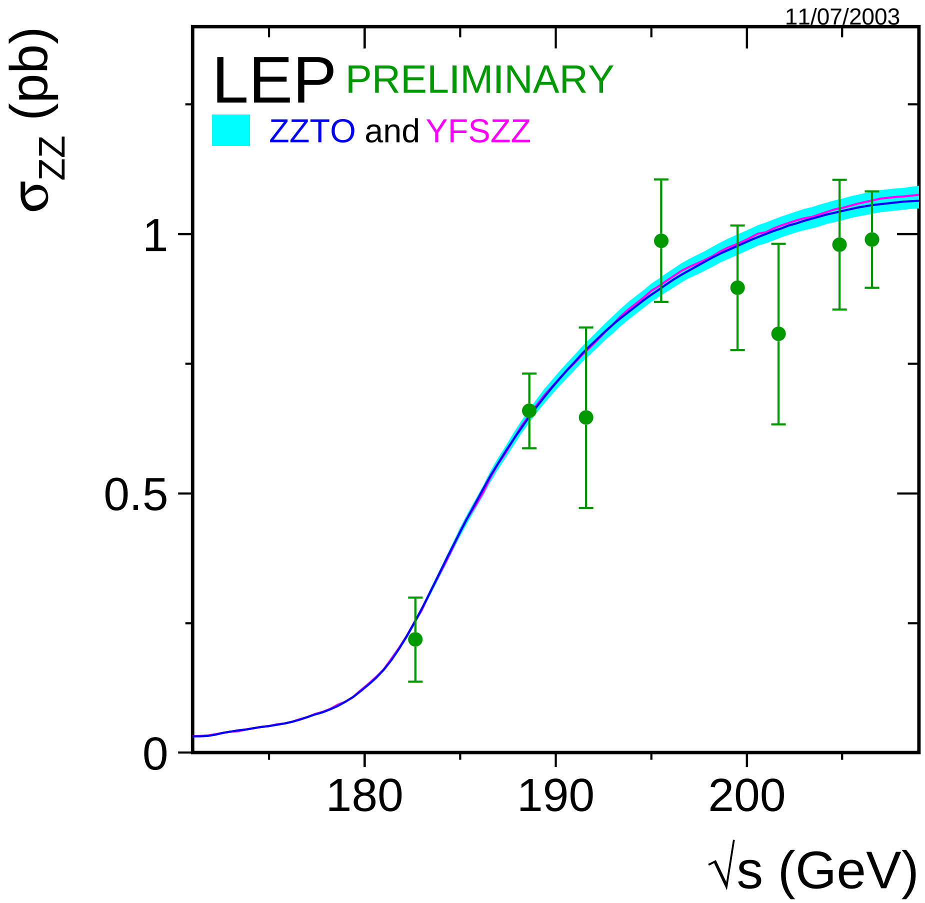
Updates from D(WW) and DLO(ZZ)

3 diagrams "CC03"

2 diagrams "NC02"





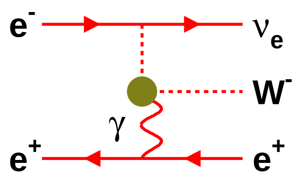




Sensitive to $M_W$ (threshold) and TGCs

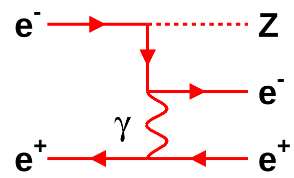
$Z \rightarrow b\bar{b}$ background to SM Higgs search.

# *LEP 2:* $e^+e^- \to e\nu W\,,\ eeZ\,,\ WW\gamma$

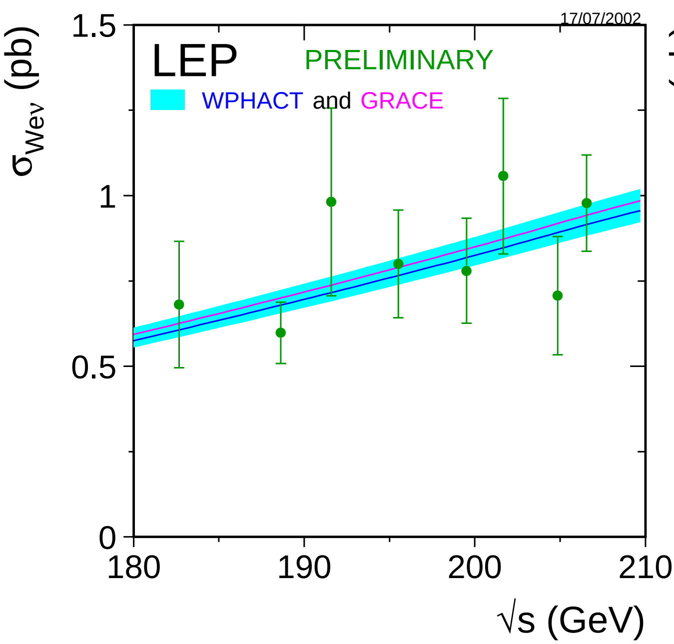
eg.

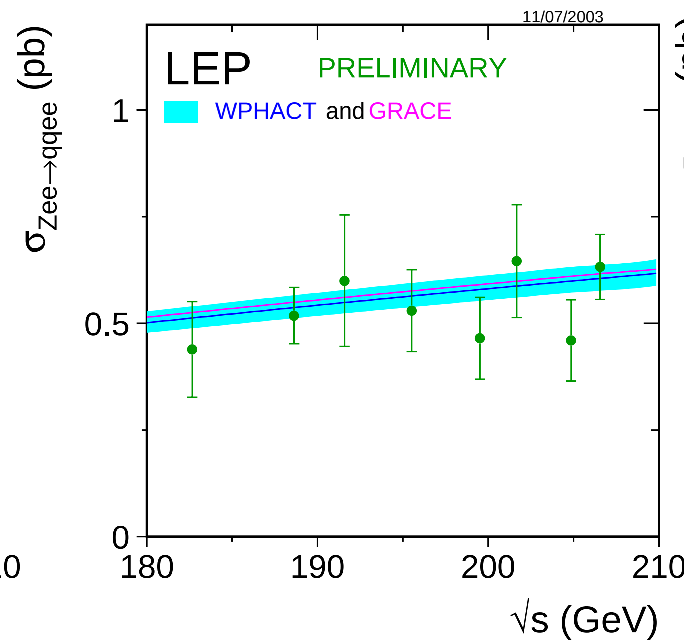


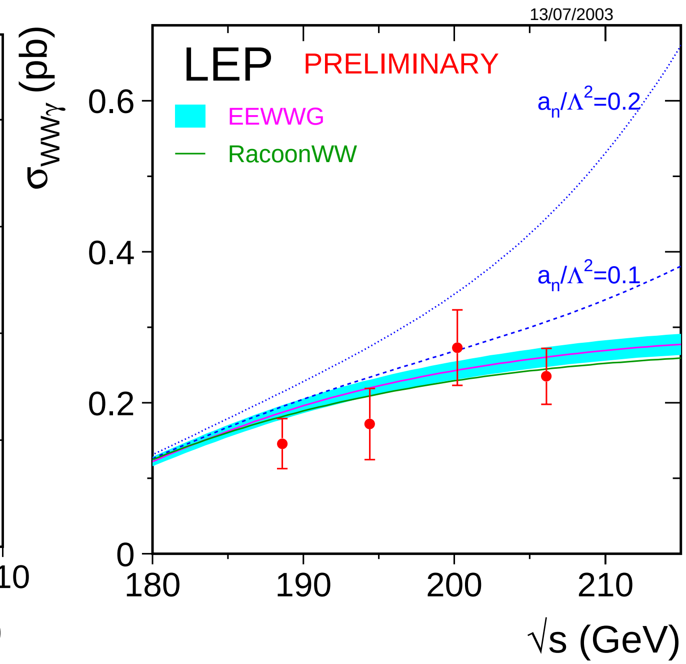

eg.




$WW\gamma$ dominated by ISR and FSR. Sensitive to anomalous QGC.




New: Zee ADL update;
$WW\gamma$ O ⇒ final

Ratio $\sigma$(data)/$\sigma$(MC) for

| | | |
|---|---|---|
| WW | YFSWW | $0.997 \pm 0.010$ |
| ZZ | YFSZZ | $0.945 \pm 0.052$ |
| $We\nu$ | WPHACT | $0.978 \pm 0.080$ |
| Zee | WPHACT | $0.932 \pm 0.068$ |

# W branching ratios from LEP

WW events 46% $q\bar{q}q\bar{q}$, 4 jets

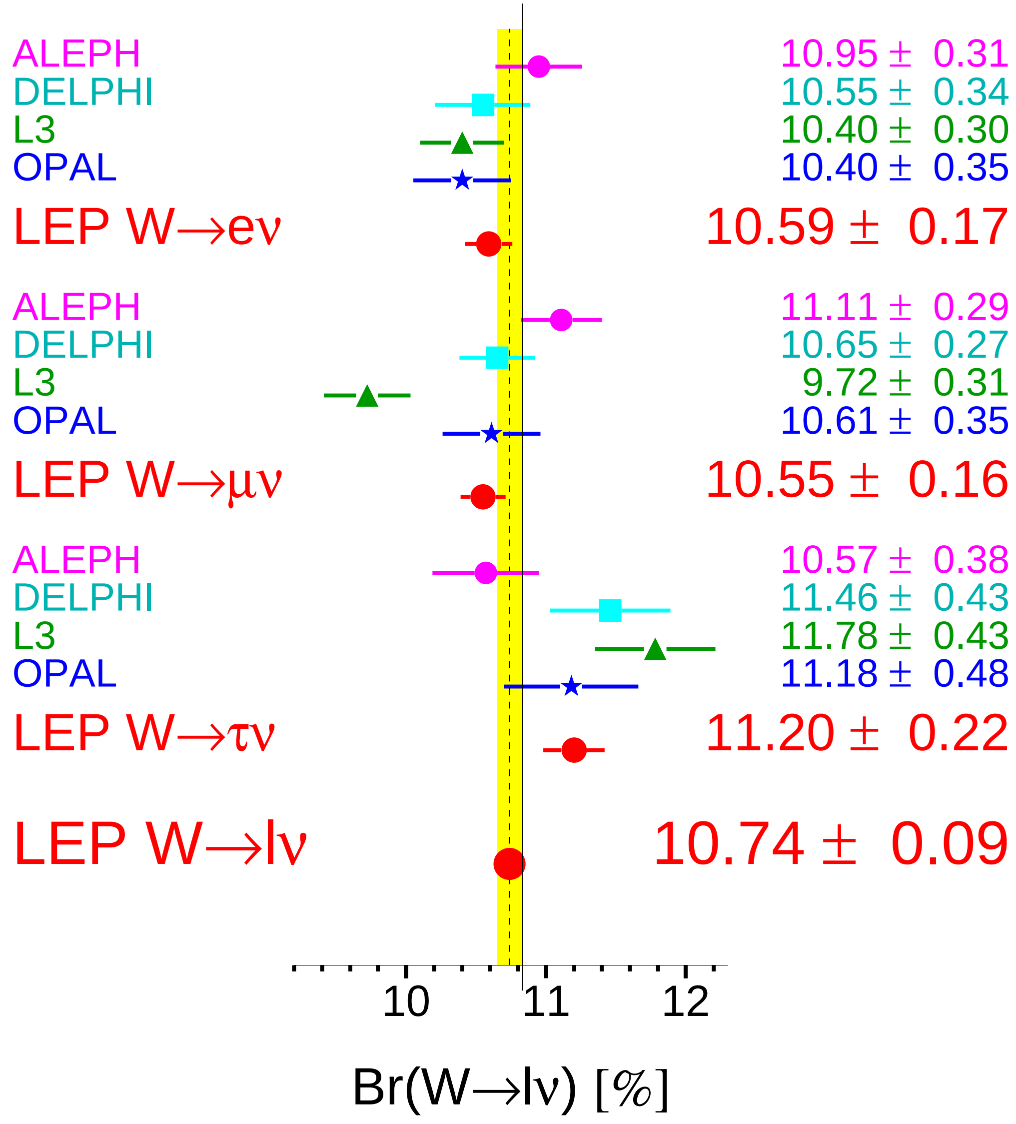
44% $q\bar{q}\ell\nu$, 2 jets, $\ell$, $p^{miss}$

10% $\ell\nu\ell\nu$, 2 $\ell$, $p^{miss}$

New: DELPHI ⇒ final

W leptonic Br's →

Note: Br($W \to \tau\nu$) value high




$$\mathrm{Br}(W \to \ell\nu) = (10.74 \pm 0.09)\%$$
$$\mathrm{Br}(W \to q\bar{q}) = (67.77 \pm 0.28)\%$$
$$|V_{cs}|^2 = 0.989 \pm 0.014$$

# $\mathrm{Br}(W \to \ell\nu)$ *and indirect* $\Gamma_W$ *from Tevatron Run II*

New: Partial cross section ratio from Tevatron Run II

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

Run II: $R = 10.36 \pm 0.31$

LEP $\Rightarrow \mathrm{Br}(Z \to \ell\ell)$,
SM $\Rightarrow \Gamma(W \to e\nu)$,
Theory $\Rightarrow \sigma_W/\sigma_Z$ ( Van Neerven et al.)

} Infer $\mathrm{Br}(W \to \ell\nu)$ or indirect $\Gamma_W$

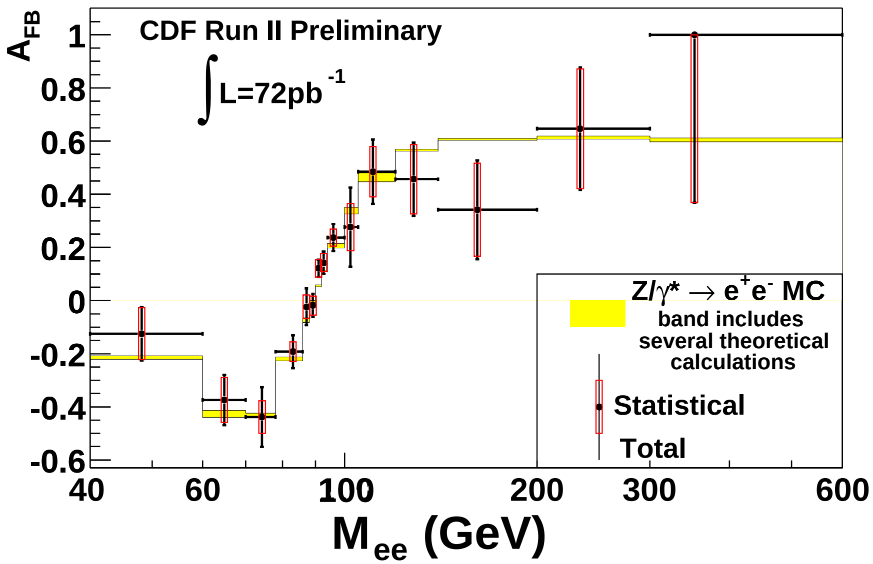
Combining with Run I, correcting for evolution of $\sigma_W/\sigma_Z$ with $\sqrt{s}$.

| | |
|---|---|
| $\mathrm{Br}(W \to \ell\nu)$ | $(10.53 \pm 0.26)\%$ |
| $\Gamma_W$ | $2.150 \pm 0.054$ GeV |

# *Electroweak tests with gauge bosons*

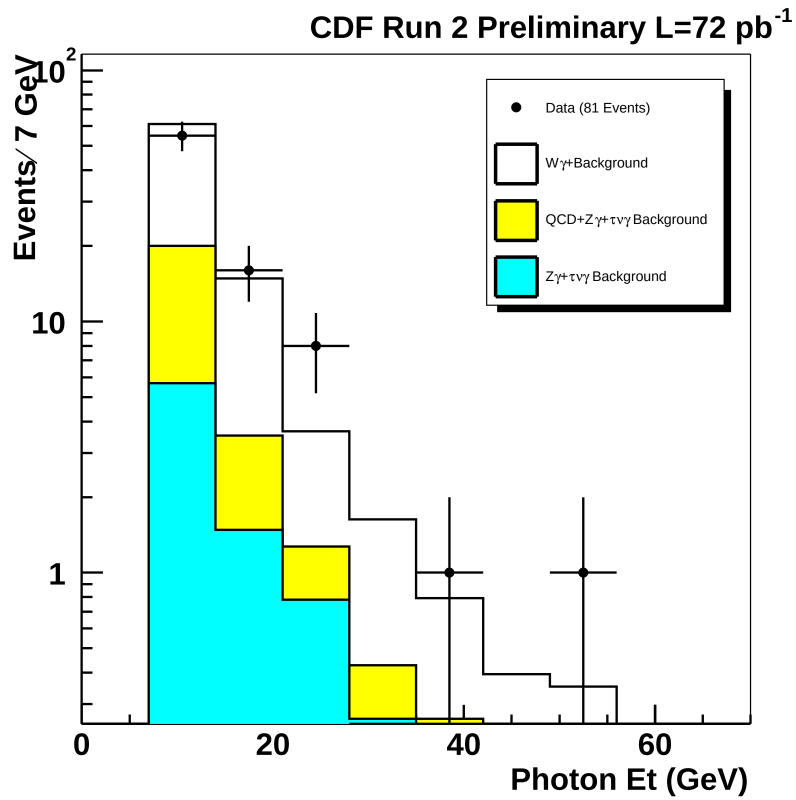
Examples from Run II

Dielectron forward-backward asymmetry vs. $M_{e^+e^-}$ extends far above Z pole




Potential for future precise measurement of $\sin^2 \theta_{eff}^{lept}$.

W$\gamma$ production (e and $\mu$ channels)




81 events, 25.4 expected background.

W$\gamma$, Z$\gamma$, WW and WZ production sensitive to anomalous trilinear gauge couplings.

At present, LEP results generally give stronger constraints.

# Charged triple gauge couplings

14 possible couplings for $WW\gamma$ plus $WWZ$. Reduce to 5 possible anomalous couplings by EM gauge invariance, CP, C & P conservation:

$g_1^z$, $\kappa_\gamma$, $\kappa_z$ (=1 in SM), $\lambda_\gamma$, $\lambda_z$ (=0 in SM)

Impose SU(2)xU(1) relations. Further reduced to 3 anomalous couplings:

$\Delta\kappa_\gamma$, $\Delta g_1^z$, $\lambda_\gamma$ with $\Delta\kappa_z = \Delta g_1^z - \Delta\kappa_\gamma \tan^2\theta_W$ and $\lambda_z = \lambda_\gamma$

These determine the W magnetic dipole and electric quadrupole moment: $(g_1^\gamma \equiv 1)$

$$\mu_W = \frac{e}{2m_W}(g_1^\gamma + \kappa_\gamma + \lambda_\gamma)$$

$$q_W = -\frac{e}{m_W^2}(\kappa_\gamma - \lambda_\gamma)$$

Anomalous TGCs change W helicities and decay angular distributions.

Polarised differential cross section

New: DLO updated Spin Density Matrix elements and W polarisation

Project out SDM elements from lepton decay angles in W restframe ($\ell\nu q\bar{q}$).
CP and CPT tests from off-diagonal SDM elements.

Fraction of longitudinally polarised W's

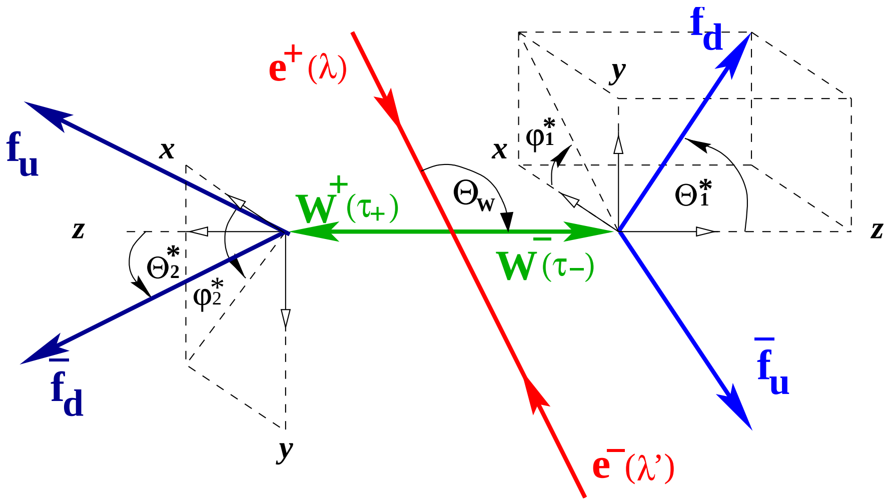
| | $\sigma_L/\sigma_{tot}$ |
|---|---|
| DELPHI | $(24.9 \pm 3.2)$ % |
| L3 | $(21.8 \pm 2.7 \pm 1.6)$ % |
| OPAL | $(23.8 \pm 2.1 \pm 1.4)$ % |
| SM | $23.9 \pm 0.1$ % |

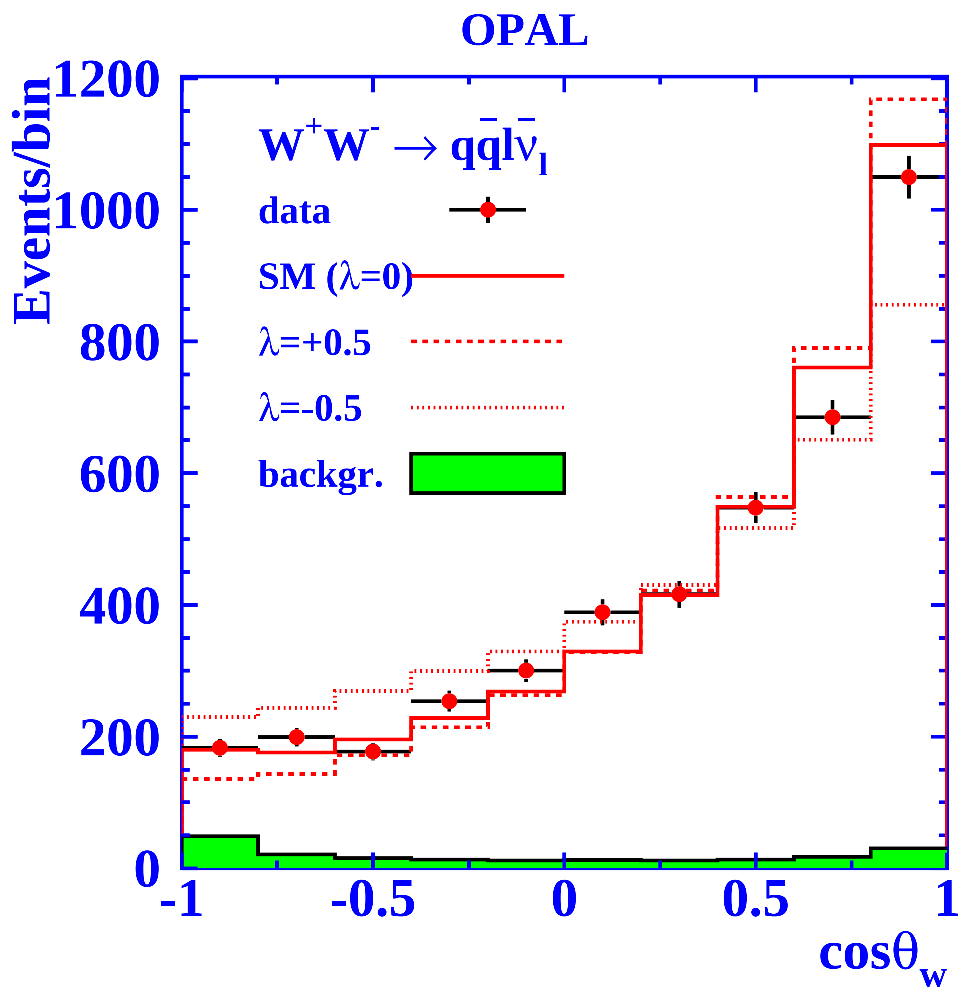
# *Anomalous TGC: angular observables*

Sensitivity to charged TGC from WW, single W and single $\gamma$ production.

Differential cross sections give stronger constraints than total cross sections.

Use "optimal observables" to exploit full information including correlations between angular variables



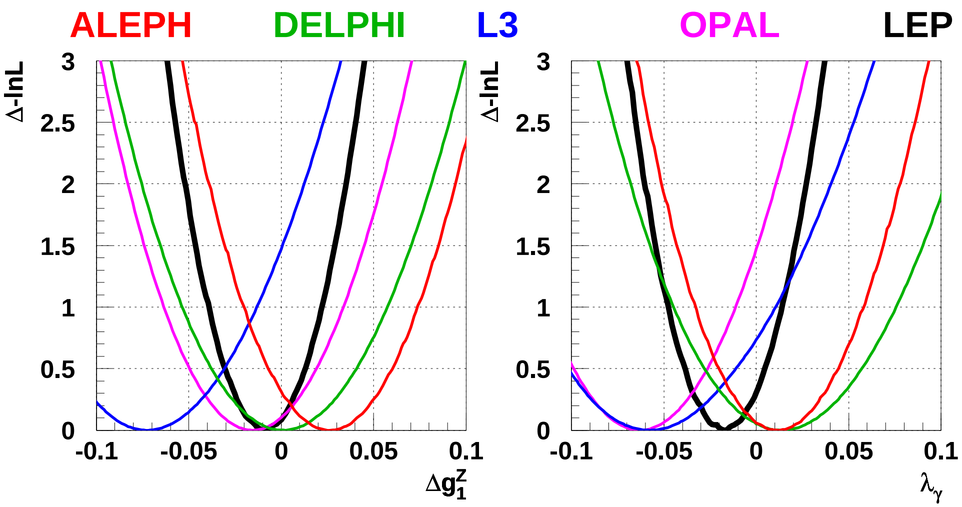



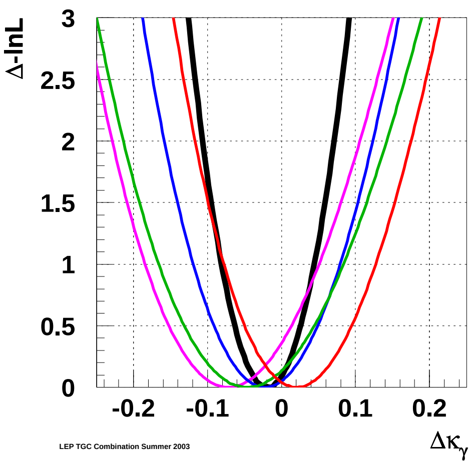

Most sensitive variable is $\cos\theta_W$, W production angle.

# *TGC results*

New: DLO Updated, O → final

1d fits (LEP combined)



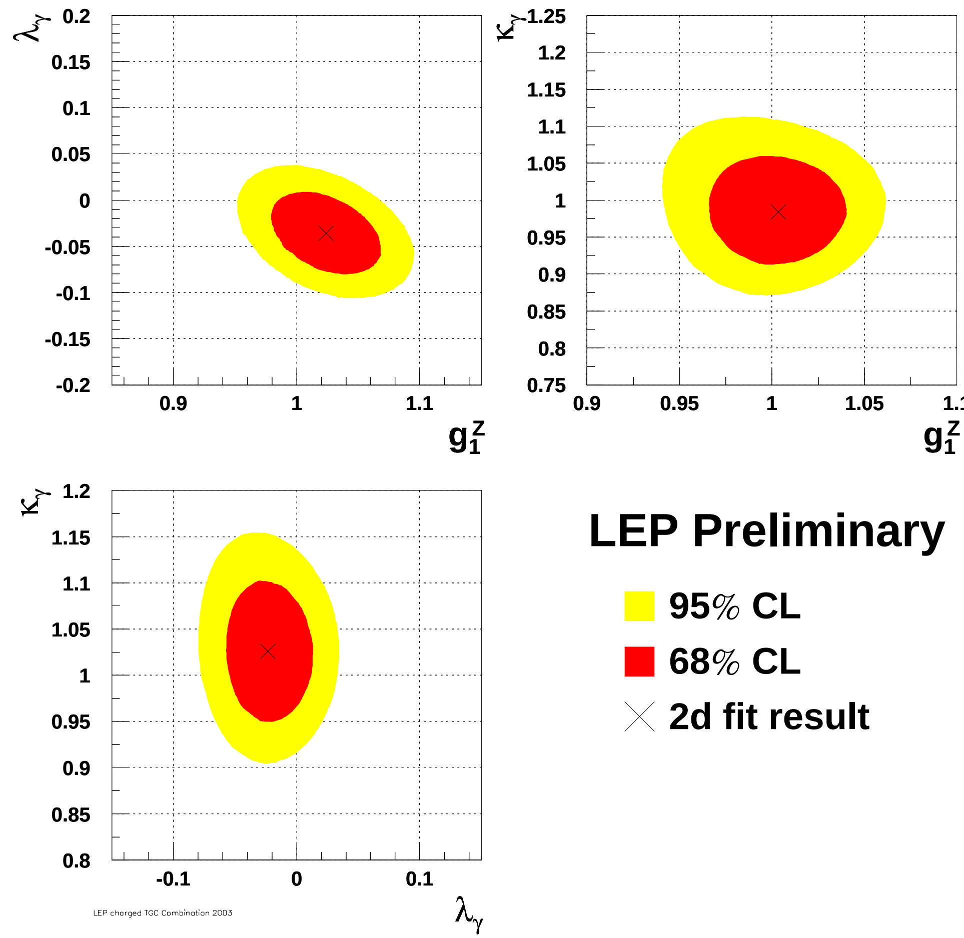

**LEP preliminary**

$$\Delta\kappa_\gamma = -0.016 \;^{+0.042}_{-0.047}$$

$$\lambda_\gamma = -0.016 \;^{+0.021}_{-0.023}$$

$$\Delta g_1^Z = -0.009 \;^{+0.022}_{-0.021}$$

2d & 3d fits also made. 2d fits shown here:




Results combined at the level of likelihoods.

Couplings consistent with SM, with precision of a few %.

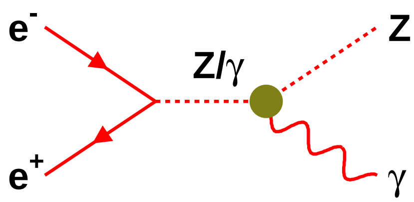
# Neutral TGC

No neutral TGC in SM.

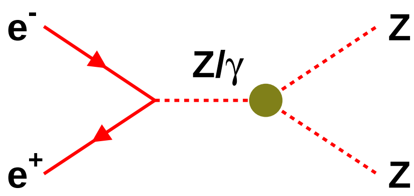
Search for anomalous nTGC from $Z\gamma$ and $ZZ$ cross-sections and differential distributions.

Parametrizations exist of two types of anomalous vertex (final state bosons on shell):

$Z\gamma\gamma$ and $ZZ\gamma$




$ZZ\gamma$ and $ZZZ$




From $e^+e^- \to Z\gamma$, $Z \to q\bar{q}$ or $\nu\bar{\nu}$

Dominant background from ISR.

From $e^+e^- \to ZZ$

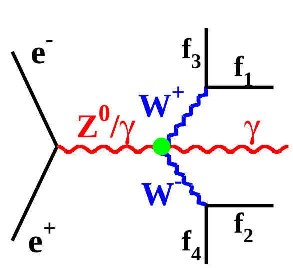
New: LO ZZ results $\Longrightarrow$ final

4 couplings $|h_i^\gamma| \lesssim 0.05$
4 couplings $|h_i^Z| \lesssim 0.15$
(LEP combined, 95% CL, 1d fits)

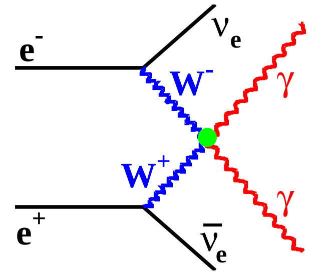
4 couplings $|f_{4,5}^{\gamma,Z}| \lesssim 0.4$
(LEP combined, 95% CL, 1d fits)

# Quartic gauge couplings

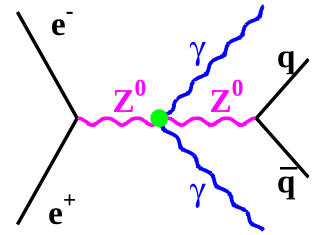
WWWW, WWZZ and WW$\gamma\gamma$ exist in SM, but small.
Look for anomalous QGCs that respect TGCs.




WW$\gamma$




$\nu\nu\gamma\gamma$




Z$\gamma\gamma$, Z $\rightarrow$ q$\bar{\text{q}}$, $\nu\bar{\nu}$

Main background: (double) ISR

Sensitive variables: cross-section, photon energies and angles.

Updates from AO (WW$\gamma$) and A (Z$\gamma\gamma$)

WW$\gamma$ limits on anomalous contributions to the WW$\gamma\gamma$ and WWZ$\gamma$ vertices from ADLO.
LEP combination in progress $\Rightarrow$ quote typical constraints from one experiment.

$\downarrow$

Tighter constraints from Z$\gamma\gamma$. Quote LEP combination (ALO). $\downarrow$

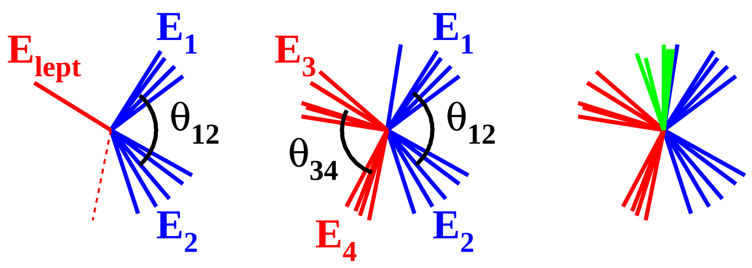
$$-0.02 < a_0^W/\Lambda^2 < 0.02 \text{ GeV}^{-2}$$
$$-0.05 < a_c^W/\Lambda^2 < 0.03 \text{ GeV}^{-2}$$
$$-0.15 < a_n^W/\Lambda^2 < 0.15 \text{ GeV}^{-2}$$

$$-0.0009 < a_0^Z/\Lambda^2 < +0.0026 \text{ GeV}^{-2}$$
$$-0.0033 < a_c^Z/\Lambda^2 < +0.0046 \text{ GeV}^{-2}$$

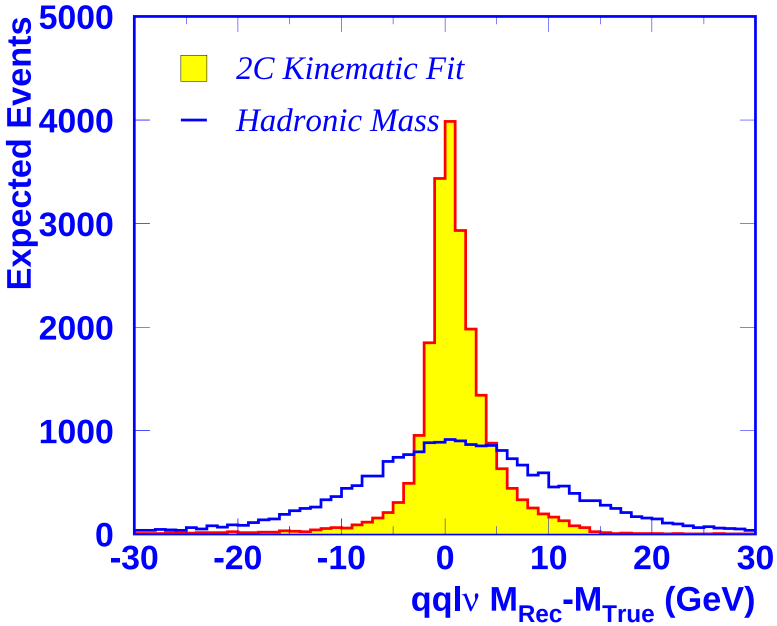
Limits at 95% CL from 1d fits.

# W mass and width

# W mass measurement at LEP




Fit distribution of reconstructed W masses from final state particles - possible with full LEP2 statistics.




$q\bar{q}\ell\nu$: $\nu$ not measured, but no ambiguity assigning particles to W's

$q\bar{q}q\bar{q}$: combinatorial background reduced by jet pairing likelihoods. May allow 5 jets in final state (gluon radiation).

$\ell\nu\ell\nu$: Fit to $E_\ell$ and other kinematic variables (ALEPH, OPAL). Large stat error ($\times$10)

$\Gamma_W$ from SM relation to $M_W$ or fitted.

($M_W$ from threshold cross section - low statistics, only 10pb$^{-1}$)

Kinematic fit: $E$ and $\vec{p}$ conservation, possibly $M_{12} = M_{34}$

$$\delta M_W / M_W \approx \delta E_{beam} / E_{beam}$$

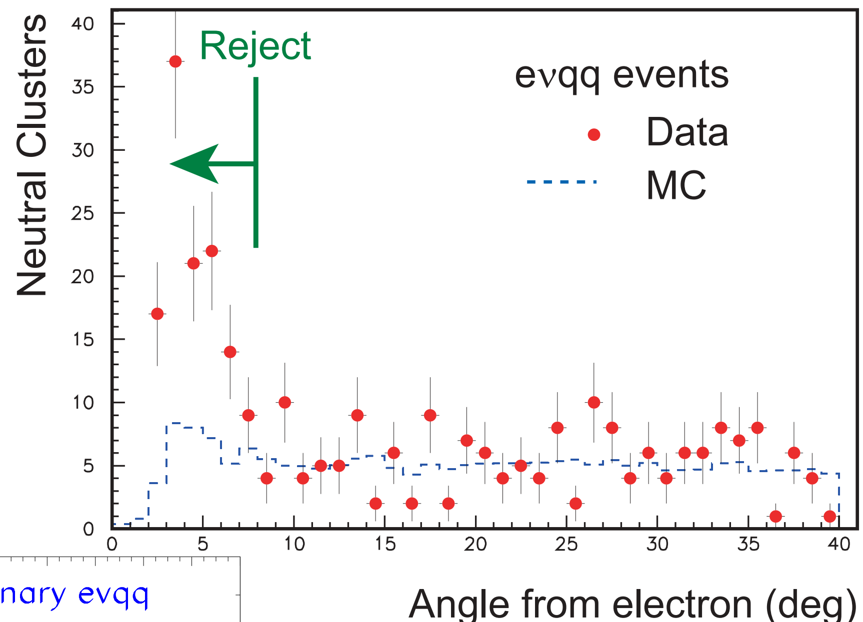
# W mass at LEP

New ALEPH preliminary result. Shift –79 MeV to 80.385 ± 0.059 GeV

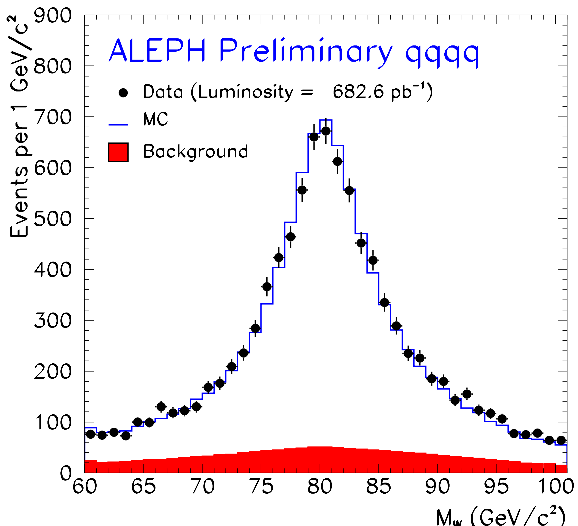
Problem simulating shower satellites in ECAL - low E neutral clusters, especially near electrons. Extra clusters near electron bias jet directions. In general, jet masses biassed.

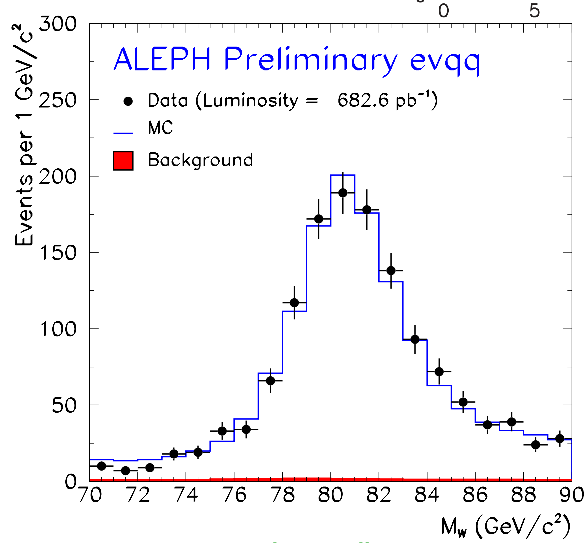
Solutions:

- Improved shower simulation with EGS.
- Reject "single stack" neutral clusters: "cleaning"
- Some discrepancy remains ⇒ reject neutrals within 8 degrees of electron at calorimeter (keep Bremsstrahlung $\gamma$)




No evidence of similar problem in other experiments.



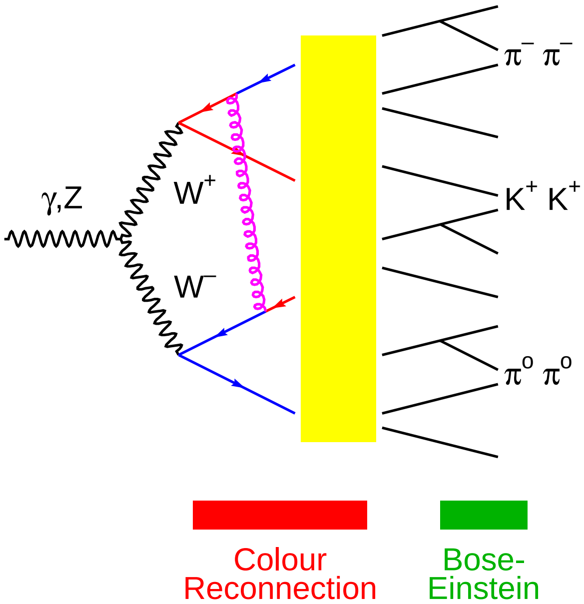

←

Example $M_W$ distributions for $q\bar{q}q\bar{q}$ and $e\nu q\bar{q}$

# *W mass systematics*

Dominant errors (LEP combined)

| | $q\bar{q}\ell\nu$ | $q\bar{q}q\bar{q}$ | Both |
|---|---|---|---|
| ISR/FSR | 8 | 8 | 8 |
| Hadronisation | 19 | 18 | 18 |
| Detector | 14 | 10 | 14 |
| LEP Beam Energy | 17 | 17 | 17 |
| Colour Reconnection | – | 90 | 9 |
| Bose-Einstein | – | 35 | 3 |
| Total Systematic | 31 | 101 | 31 |
| Statistical | 32 | 35 | 29 |




$q\bar{q}q\bar{q}$ result only gets $\lesssim$10 % weight in combination. Why?

WW decay vertices separated by ≈ 0.1 fm. Hadronic distance scale ≈ 1 fm.

Colour reconnection: rearrangement of colour flow

Bose-Einstein correlations between like-sign identical bosons

Even small changes to flow of soft particles between jets from different Ws can change reconstructed W mass by several 10 MeV.

# *Colour reconnection in qqqq final state*

Models: SK-I (free parameter $\kappa$), ARIADNE-II, HERWIG

Particle flow method:

Number of particles between jets from same W and from different W's.

Restricts range of SK-I parameter $\kappa$. Sets present error on $M_W$.

"Cuts and cones": New DELPHI

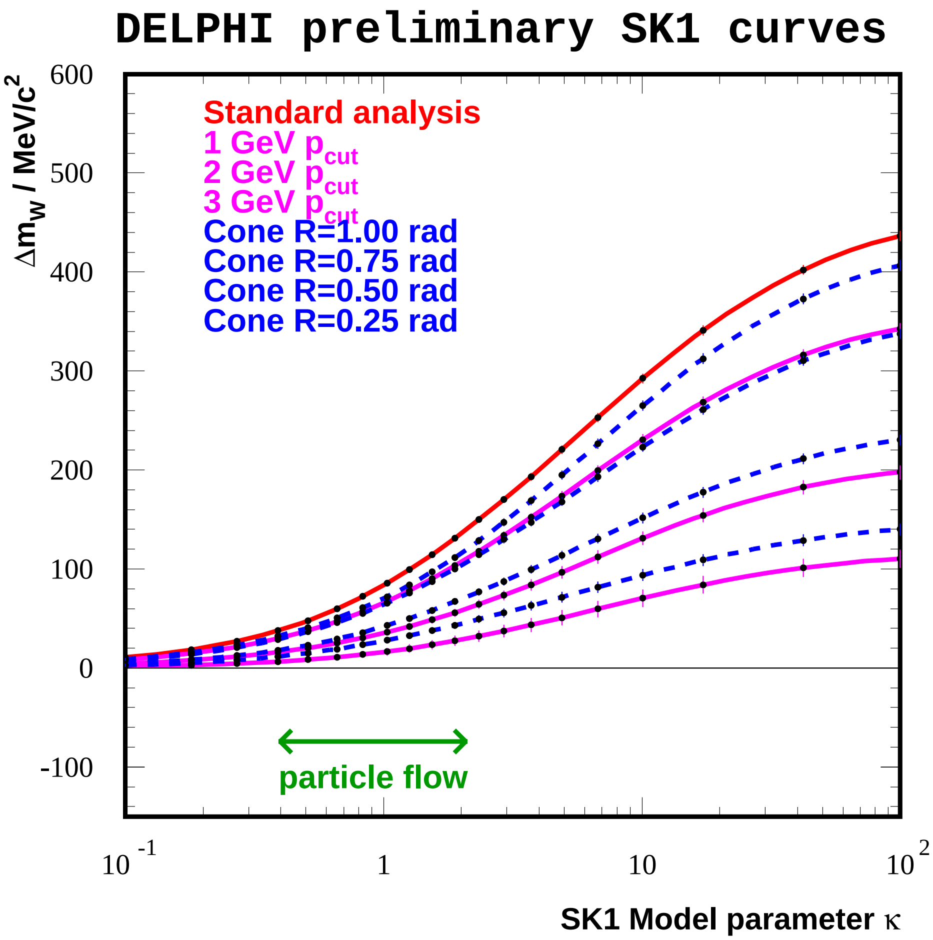
Evaluate W mass when jet properties are determined without low p particles, "cuts", or with cone jet-finder.

Shift in W mass due to CR reduced but statistical error increases.

Data-MC comparison of W mass shift vs. $p$-cut or cone radius further constrains models.

Hope to use this for final LEP W mass.

Studies in gluon jets at LEP1 also disfavour some models.



# Bose-Einstein correlations

New BEC results from ADO

Present error on $M_W$ from full effect of LUBOEI model: $\delta M_W = 35$ MeV

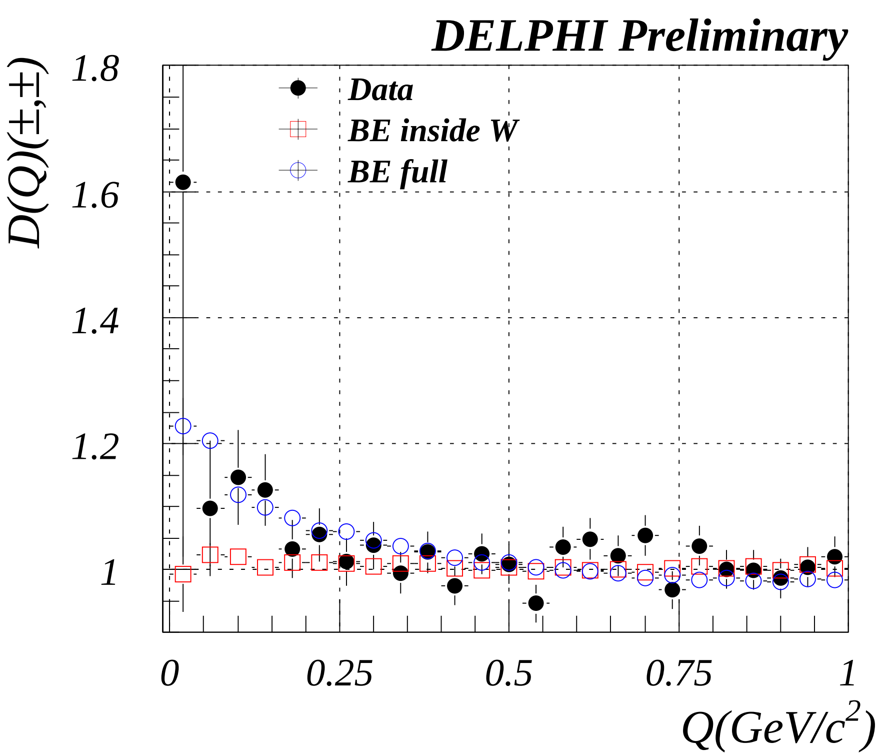
For independent W's, inclusive two-particle density in $q\bar{q}q\bar{q}$ events is ($Q^2 = (p_1 - p_2)^2$)

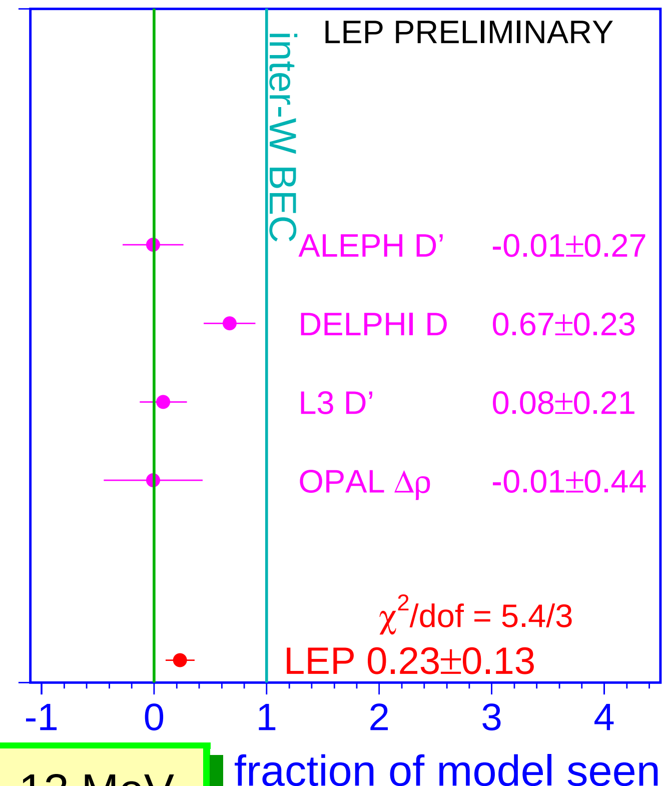
$$\rho^{WW}(Q)_{indep} = 2\rho^{W}(Q) + 2\rho^{WW}_{mix}(Q)$$

$\rho^{W}(Q)$: two-particle density of single W. $\rho^{WW}_{mix}$: from mixing $q\bar{q}$ parts of two $q\bar{q}\ell\nu$ events

Consider difference $\Delta\rho(Q) = \rho^{WW}(Q) - \rho^{WW}(Q)_{indep}$ or ratio $D(Q)$ for like/unlike sign pairs. Compare data and MC with noBEC/BEC in same W/full BEC.

DELPHI: like sign pairs - low $Q$ region




$\delta M_W \Rightarrow 13$ MeV

# W mass from LEP

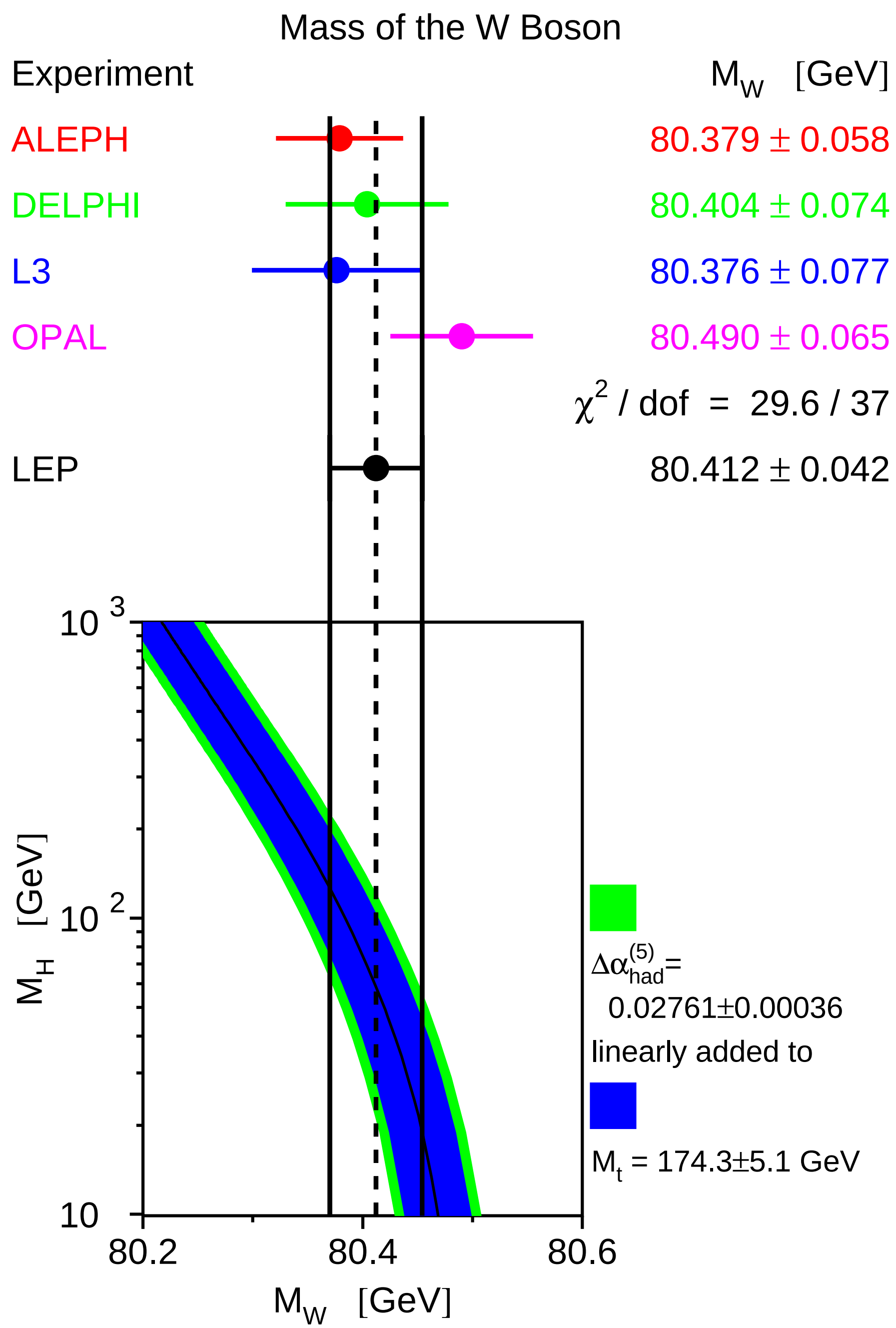
All results preliminary, 1996-2000 data (OPAL 1996-1999 data).

W mass from LEP prefers low $m_H$

New ALEPH result shifts LEP average by $-35$ MeV (towards higher Higgs mass)

Cross check, setting BEC and CR uncertainty to zero:
$q\bar{q}q\bar{q}$ and $q\bar{q}\ell\nu$ difference:

$\Delta M_W = +22 \pm 43$ MeV




$M_W = 80.412 \pm 0.029(\text{stat.}) \pm 0.031(\text{syst.})$ GeV

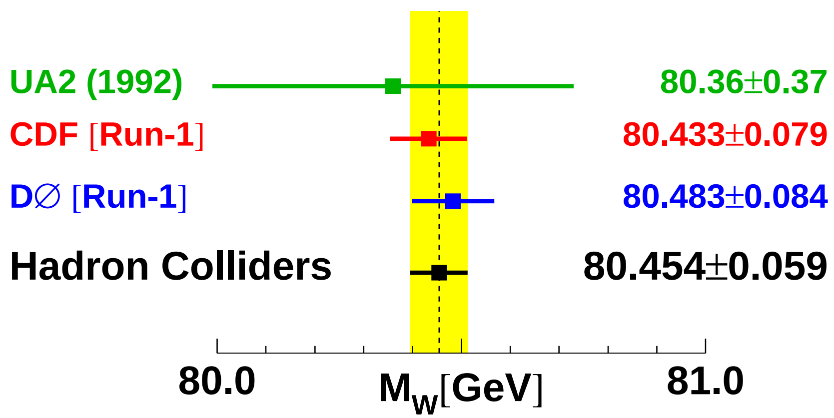
# W mass from Tevatron

Run I results final (CDF e,$\mu$, D0 e). No new result from Run II

Method: fit the W mass from Jacobian edge and width from high mass tail of transverse mass distribution: $M_T^2 = 2p_T^\ell p_T^\nu(1 - cos(\phi^\ell - \phi^\nu))$

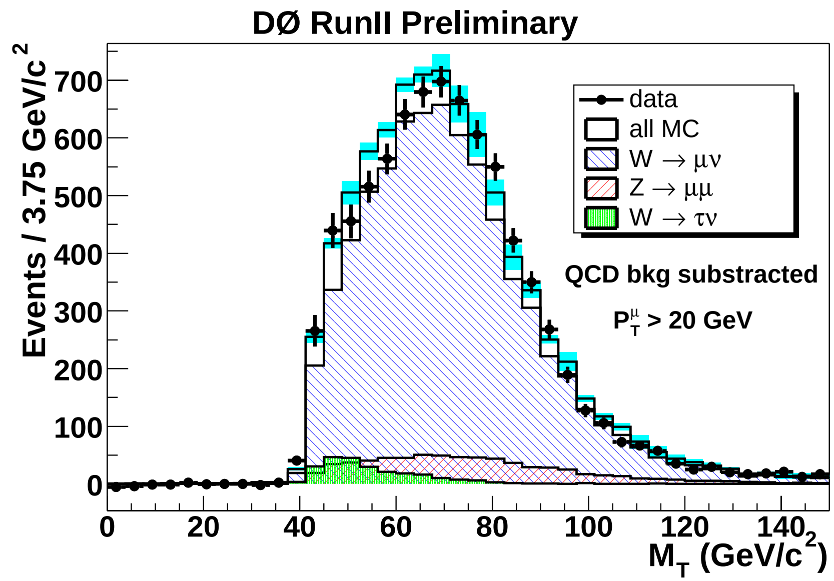
D0 also fit $p_T^\ell$, $p_T^{miss} = p_T^\nu$ and quote combined result

Average from Run I plus UA2




Run I $M_W = 80.454 \pm 0.059$GeV

Example $M_T$ distribution from Run II (D0)

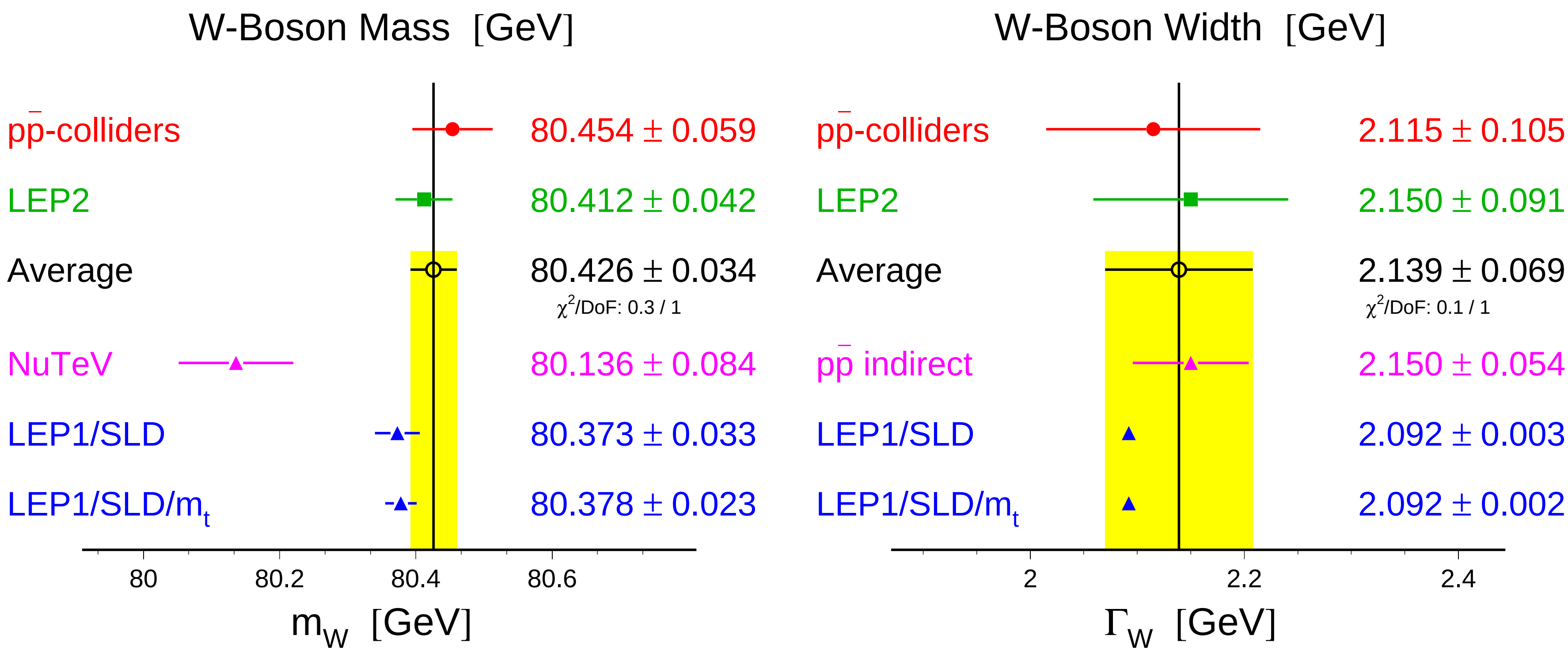



Systematic errors will be reduced with more luminosity

- Energy/momentum scale controlled with Z events (and $J/\psi, \Upsilon, \pi^0$)
- Response to hadronic recoil and $p_T^W$ model also constrained by Z data

# World Average W mass and width

LEP2 updated




$$M_W = 80.426 \pm 0.034 \text{ GeV}, \Gamma_W = 2.139 \pm 0.069 \text{ GeV}$$

Indirect results from global fits will be discussed later.

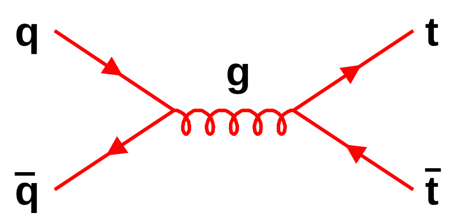
NuTeV measure CC and NC rates for $\nu_\mu$ and $\overline{\nu}_\mu$. Related to $\sin^2\theta_W = 1 - \frac{M_W^2}{M_Z^2}$ (Paschos-Wolfenstein). No new proposals to explain this discrepancy

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

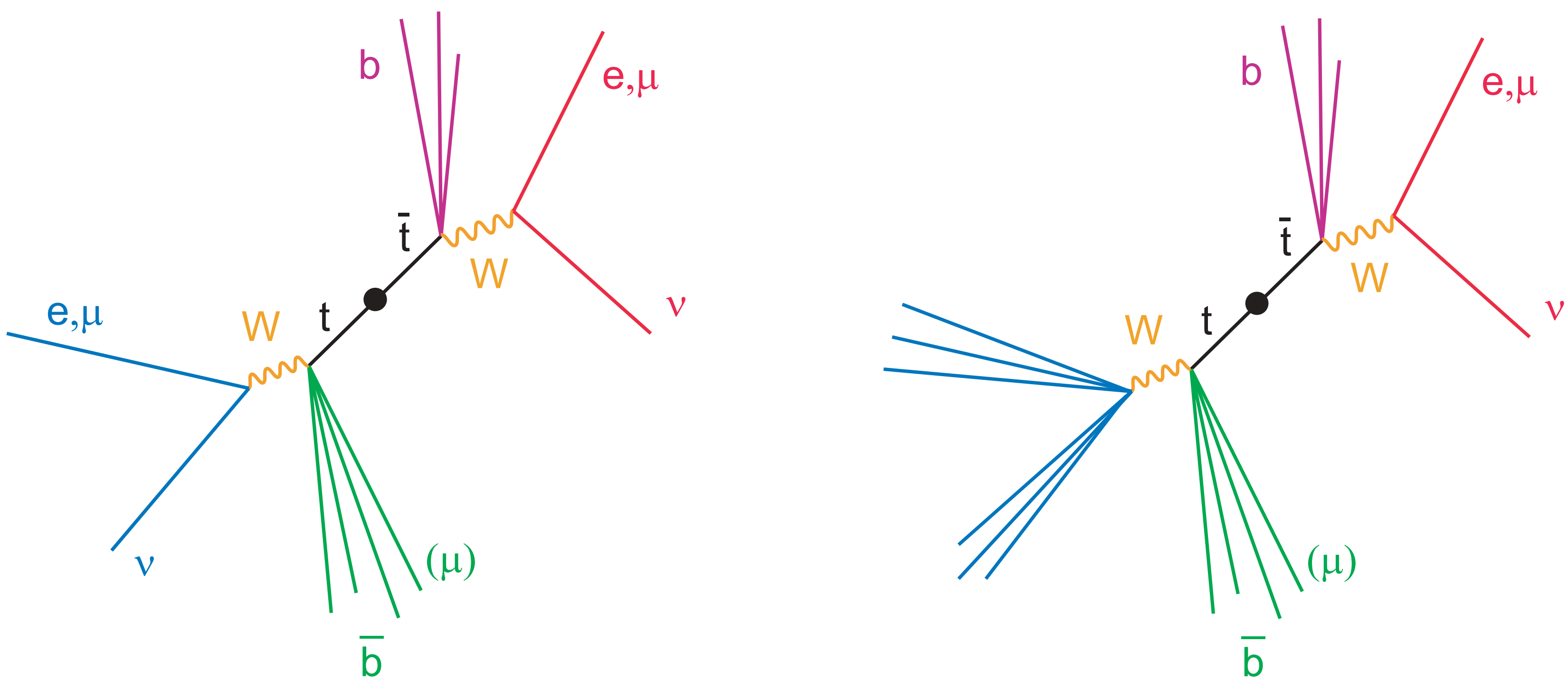
# Top physics

# *Top quark production at Tevatron*

Dominant production mechanism (90%)




Top decays to W boson and b quark. Event topologies depend on W decay.

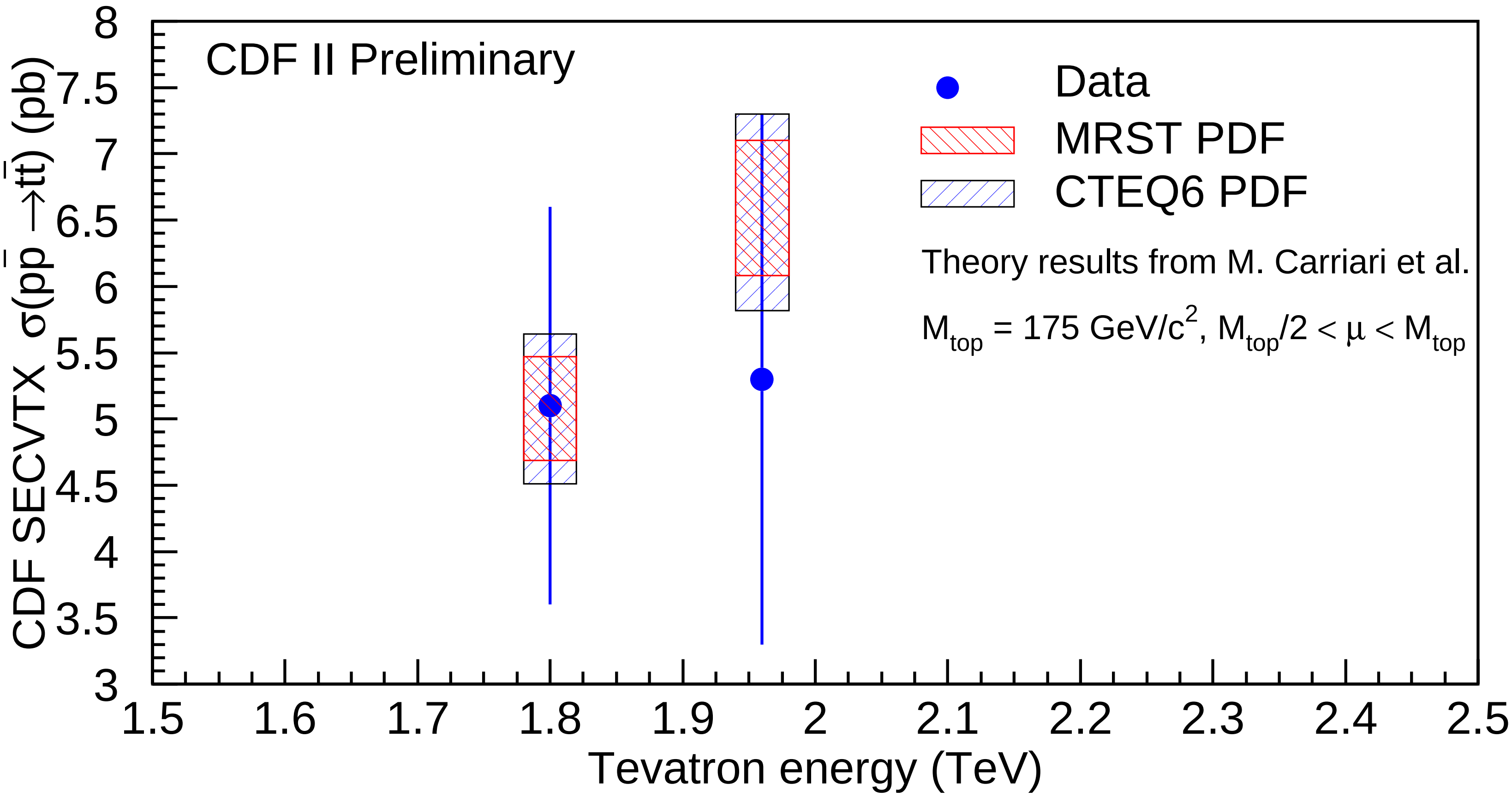



Lepton+jets channel - expect lepton and 4 jets. Soft muon or lifetime tag for b jets improves signal/background.

## *Run II Top cross sections - CDF*

New Run II

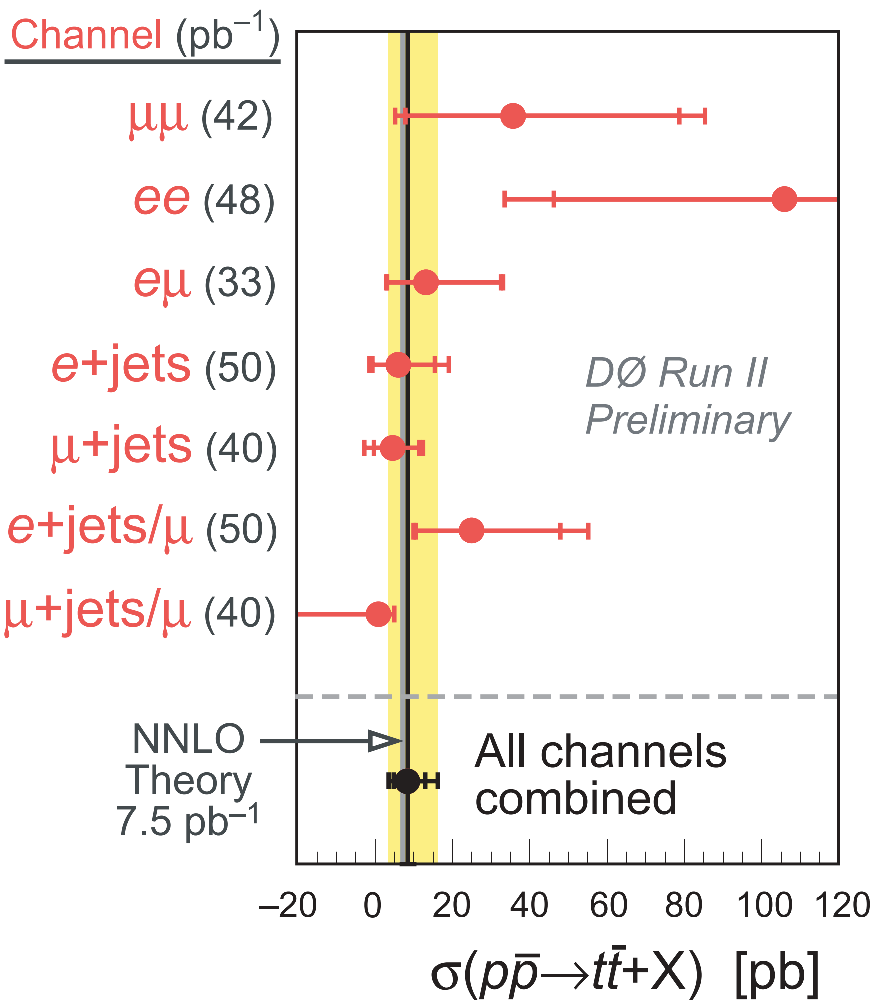
Lepton plus jets with vertex tag at CDF: Run I and Run II results



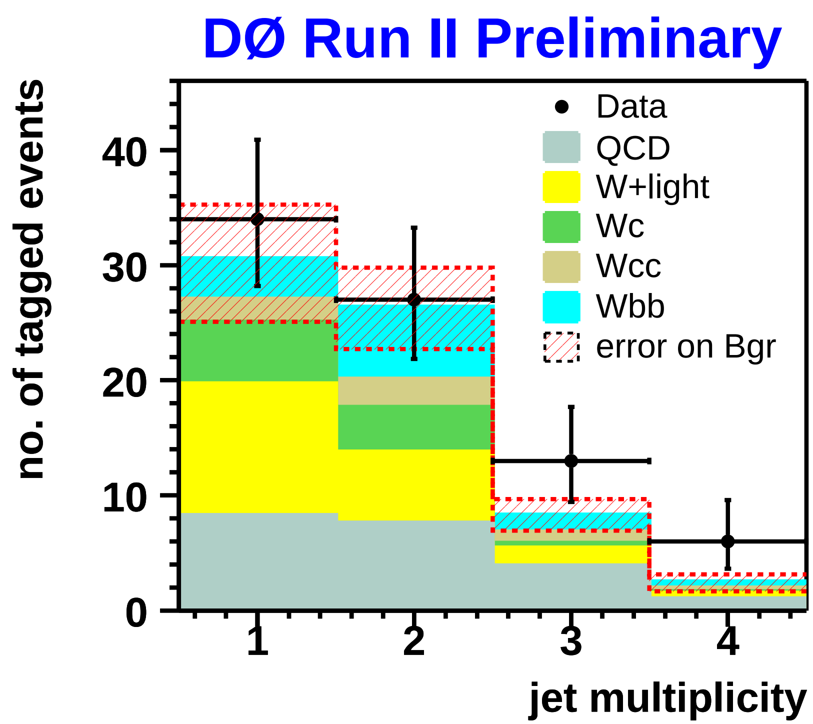

| $\sigma_{t\bar{t}}$ (pb) with stat, syst and lumi errors | |
|---|---|
| CDF dilepton Run II | $13.2 \pm 5.9 \pm 1.5 \pm 0.8$ |
| CDF $\ell$+jets Run II | $5.3 \pm 1.9 \pm 0.8 \pm 0.3$ |

# Run II Top cross sections - D0

New Run II Combined results




Even newer: D0 $\sigma_{t\bar{t}}$ with lifetime b-tag




| $\sigma_{t\bar{t}}$ (pb) with stat, syst and lumi errors | |
|---|---|
| D0 Run II | $8.4\ ^{+4.5}_{-3.7}\ ^{+6.3}_{-3.5} \pm 0.8$ |
| D0 IP b-tag | $7.4\ ^{+4.4}_{-3.6}\ ^{+2.1}_{-1.8} \pm 0.7$ |

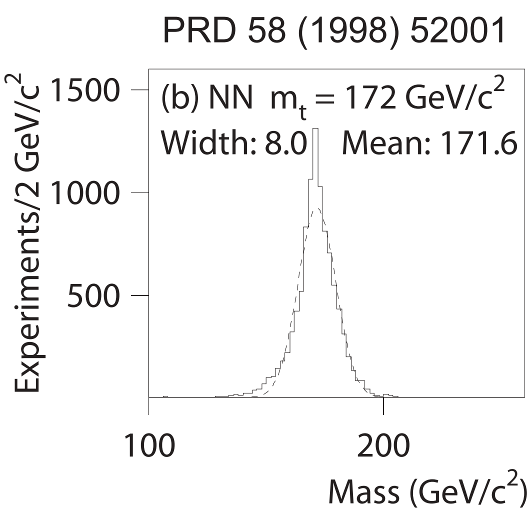
# *Top mass*

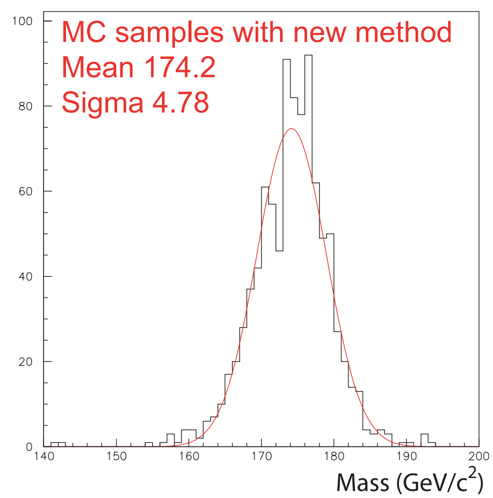
New: D0 Run I top mass (lepton+jets)

77 events (29 signal and 48 background) used in PRD 58 (1998) 052001.

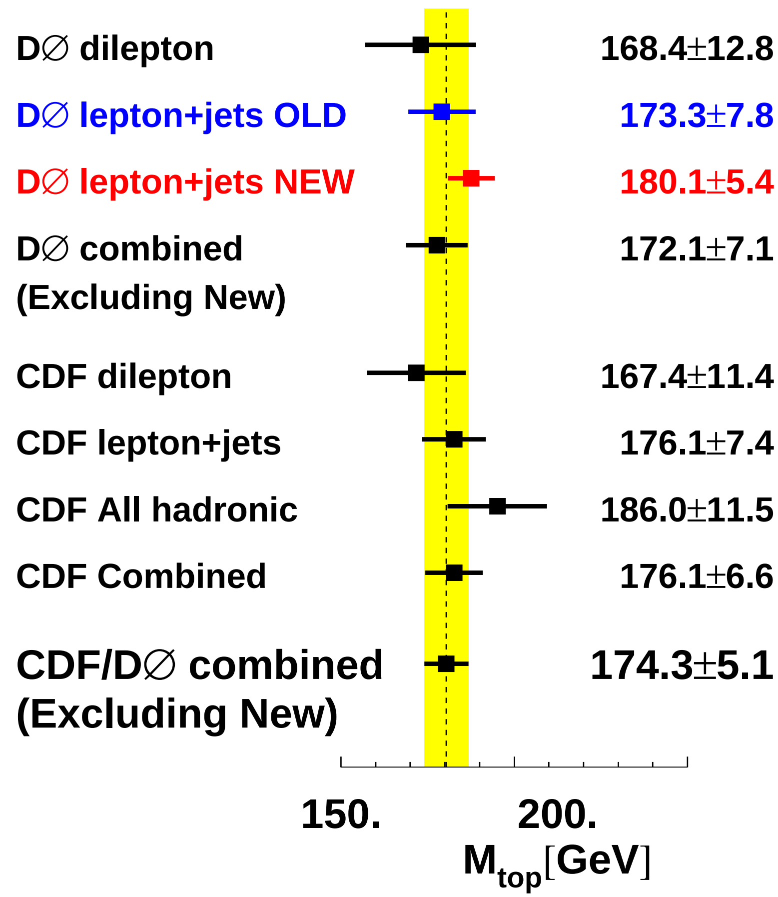
22 events (10 signal, 12 background) reanalysed.

Use individual event probabilities instead of same template for all events.




Comparison with other old results




| | |
|---|---|
| Old Run I average (CDF+D0) | $174.3 \pm 5.1$ GeV |
| New D0 Run I $\ell$+jets only | $180.1 \pm 3.6$(stat.) $\pm 4.0$(syst.) GeV |
| New CDF Run II $\ell$+jets | $171.2 \pm 13.4$(stat.) $\pm 9.9$(syst.) GeV |

# g-2 and $\alpha_{em}(m_Z)$

# Muon (g-2)

Muon (g-2) Collaboration
Brookhaven AGS.
Measure muon spin precession frequency.

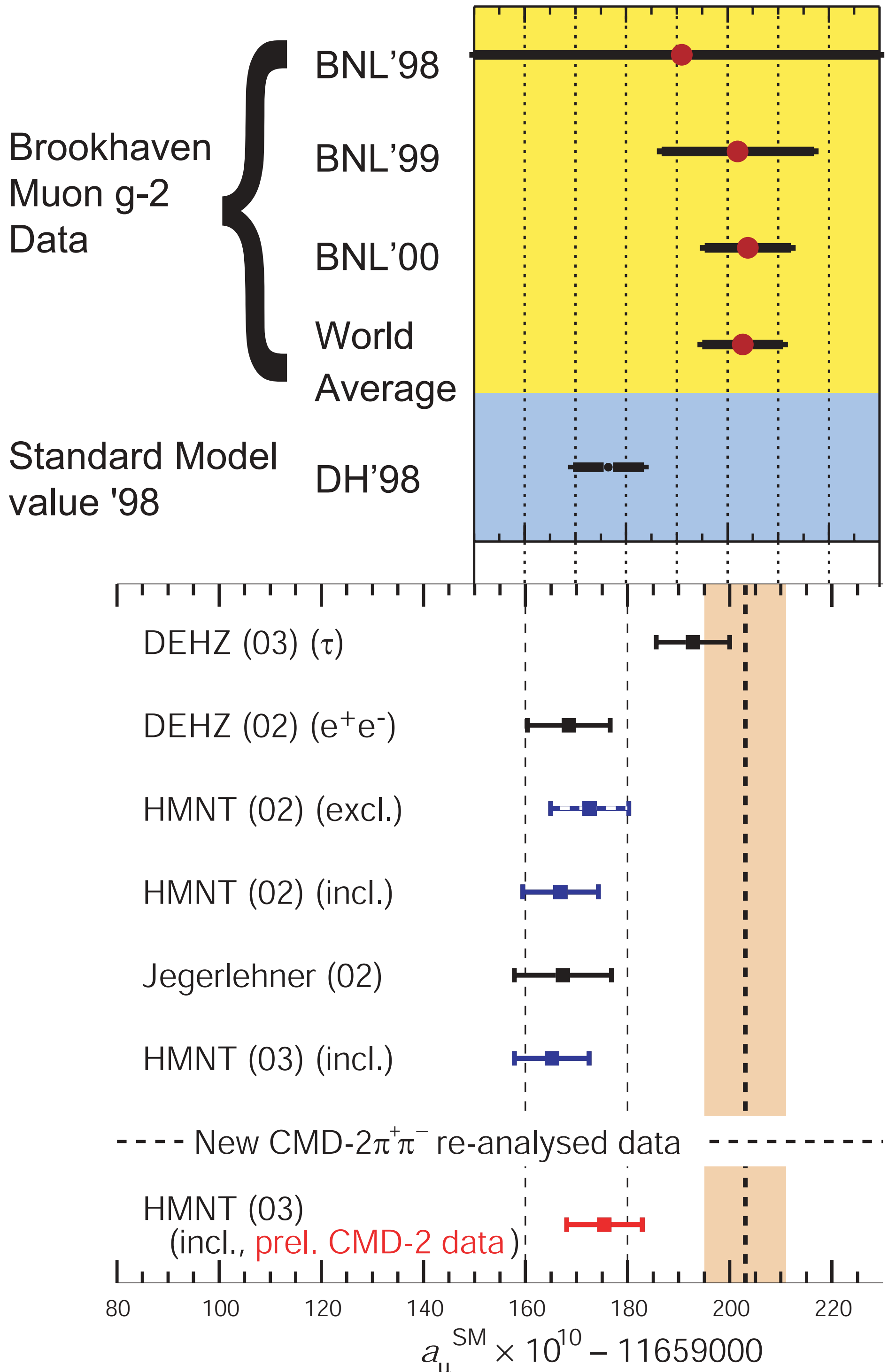
2002:
$\mu^+$ anomalous magnetic moment
$a_\mu = (g-2)/2$ measured to
0.7 ppm using data up to 2000.

$$a_\mu = 11\,659\,203(8) \times 10^{-10}$$

Soon:
Result with 2001 $\mu^-$ data, with similar statistics to 2000 $\mu^+$

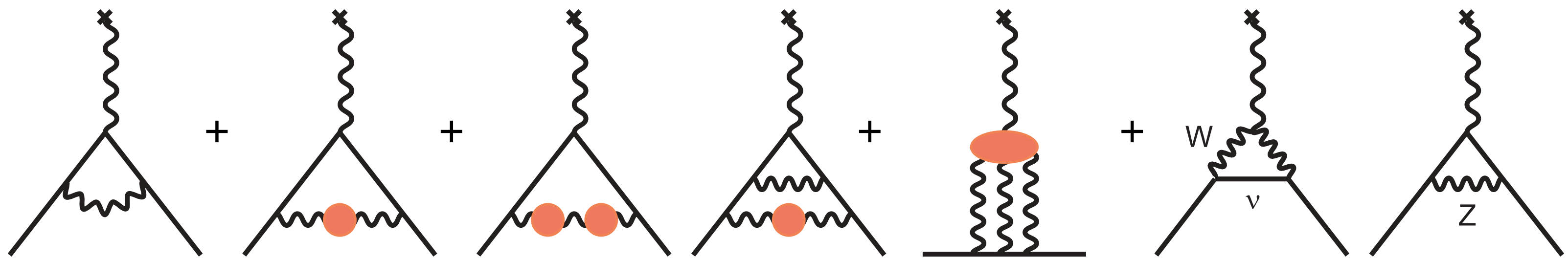
Problem: Value and spread of theoretical predictions

New prelim CMD-2 July 2003!!!



# g-2 prediction

$$a_\mu^{SM} = a_\mu^{QED} + a_\mu^{had,LO} + a_\mu^{had,HO} + a_\mu^{had,LBL} + a_\mu^{weak}$$

= 


= (QED) $(11\,658\,470.35 \pm 0.28)10^{-10}$ (5-loop!)

+ (had,LO) $(684.7$ to $709.0 \pm 6)10^{-10}$ (Big spread, largest error)

+ (had,HO) $(-10.0 \pm 0.6)10^{-10}$

+ (had,LBL) $(8.0 \pm 4.0)10^{-10}$ (sign change since 1998)

+ (weak) $(15.4 \pm 0.2)10^{-10}$ (2-loop)

$a_\mu^{had,LO}$ from data via dispersion integral

$$a_\mu^{had,LO} = \frac{1}{4\pi^3}\int_{4m_\pi^2}^{\infty} \sigma_{had}^0(s)K(s)ds$$

Recent data included CMD-2, SND, BES 2-5 GeV, ALEPH $\tau$.
NEW: CMD-2 prelim update

$\sigma_{had}^0$ bare cross-section for $e^+e^- \rightarrow$ hadrons, i.e. taking out radiative corrections.
QED kernel $K(s) \sim m_\mu^2/3s$, gives strong weight to low energy data.

# *g-2 calculation problems*

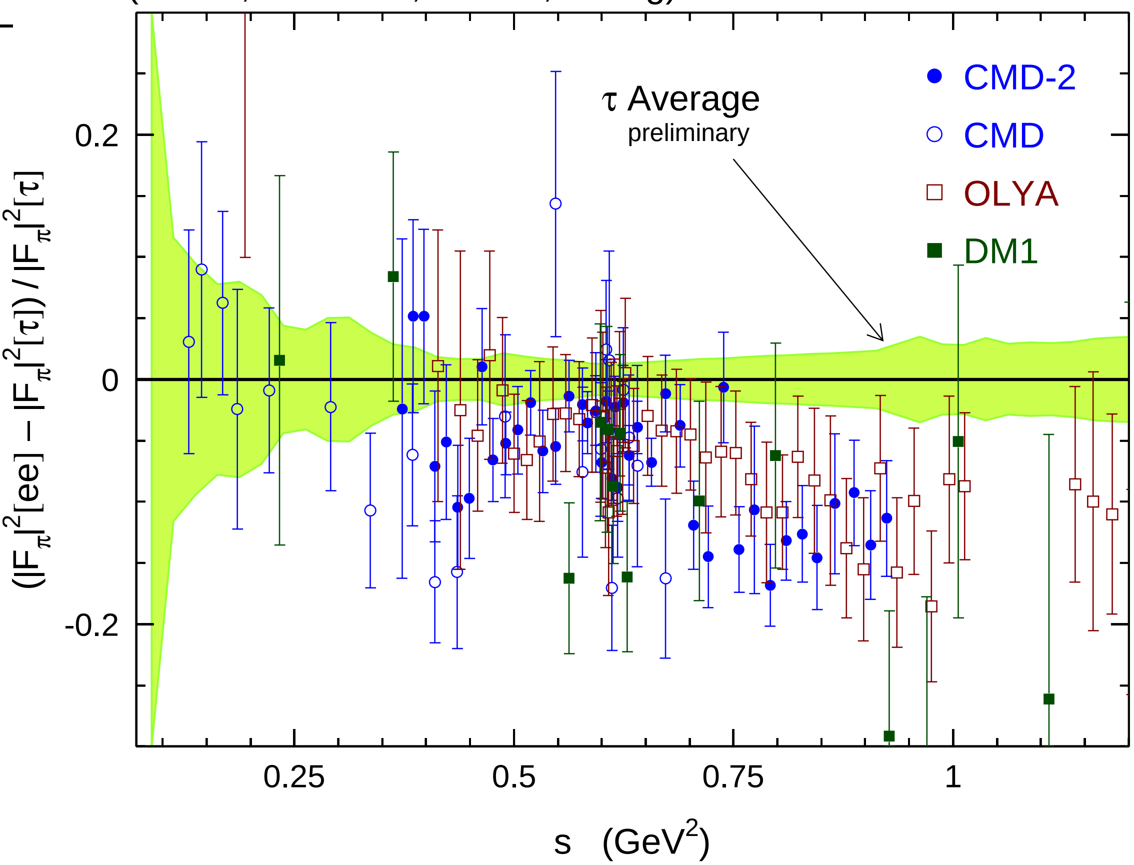
Which radiative corrections are applied to data? (eg. latest CMD-2!). Interpolation choices? Use of pQCD? $\sigma^0_{had}$ from Inclusive vs $\Sigma$ exclusive vs $\tau$ spectral functions?

(Hagiwara, Martin, Nomura, Teubner)

| Range/GeV | $\Delta a_\mu^{had,LO} \cdot 10^{10}$ |
|---|---|
| 0.32 – 1.43 | 605.4 ± 5.2 |
| 1.43 – 2.00 | 32.4 ± 2.5 |
| 2.00 – 11.09 | 42.1 ± 1.1 |

Compare $\pi^+\pi^-$ spectral function from $e^+e^-$ & isospin-breaking corrected $\tau$ data (ALEPH, CLEO,OPAL)

(Davier, Eidelman, Höcker, Zhang)




Crucial to finalise radiative corrections to CMD-2 data.

July 2003: first results from KLOE and Babar radiative return data. KLOE prefers $e^+e^-$ to $\tau$ result

# Calculation of $\alpha(M_Z^2)$

$$\alpha(s) = \frac{\alpha(0)}{1 - \Delta\alpha_\ell(s) - \Delta\alpha_{\mathrm{top}}(s) - \Delta\alpha^{(5)}_{\mathrm{had}}(s)}$$

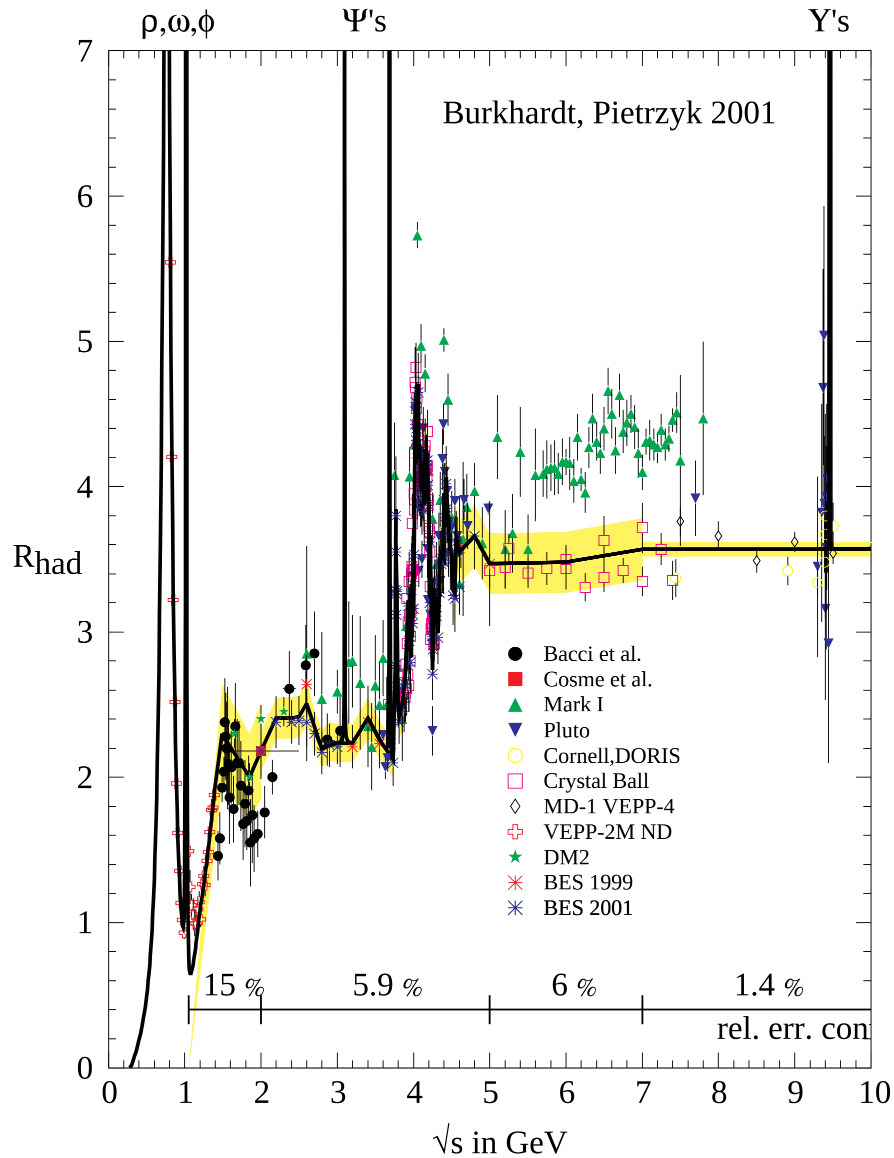
with $\alpha(0) = 1/137.035\,999\,76(50)$

Hadronic part from dispersion integral:

$$\Delta\alpha^{(5)}_{\mathrm{had}} = -\frac{\alpha s}{3\pi} P \int_{4m_\pi^2}^{\infty} \frac{R_{\mathrm{had}}(s')ds'}{s'(s'-s)}$$

$$R_{\mathrm{had}}(s) = \sigma^0_{\mathrm{had}}/(\sigma^0_{\mu\mu} = 4\pi\alpha^2/3s)$$

Biggest recent improvement from BESII. Future: CMD-2, BEPCII, KLOE, BABAR, BELLE (radiative return)

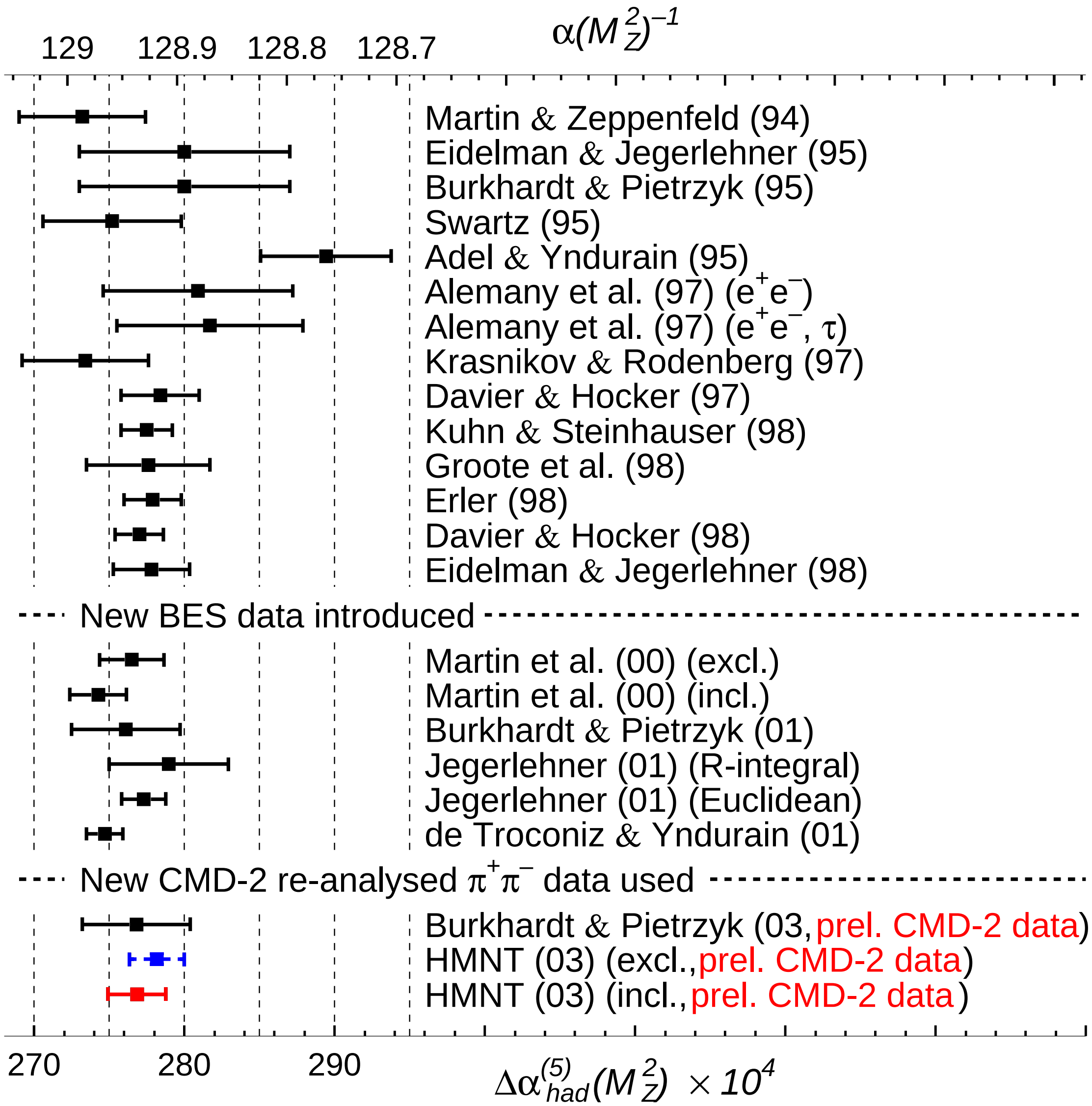



At present LEPEWWG use result based on data: $\Delta\alpha^{(5)}_{\mathrm{had}}(M_Z^2) = 0.02761 \pm 0.00036$
Burkhardt, Pietrzyk 2001

More precise - use pQCD in continuum, eg. $\Delta\alpha^{(5)}_{\mathrm{had}}(M_Z^2) = 0.02747 \pm 0.00012$
Troconiz, Yndurain 2001

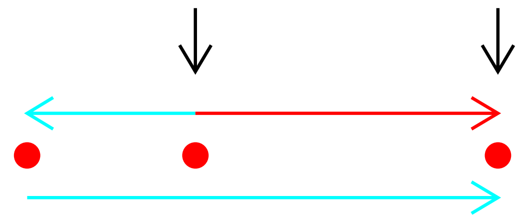
# Impact of new preliminary CMD-2 result on $\alpha(M_Z^2)$

**Brand New**




**Burkhardt, Pietrzyk**

| | 2001 published | 2003 preliminary |
|---|---|---|
| $\Delta\alpha_{had}$ | 0.02761±0.00036 | 0.02768±0.00036 |



| CMD2 | 2001 published | 1999 prelimary | 2003 revised |
|---|---|---|---|
| | -10% | | +18% |

**of total uncertainty on $\Delta\alpha_{had}$**

# Global Electroweak Fits and the Higgs Mass

# Global electroweak fit

Electroweak observables can be calculated from a few parameters, eg.

$$\alpha(M_Z^2)\,,\ \alpha_S(M_Z^2)\,,\ M_Z\,,\ M_W\,,\ m_t\,,\ m_H$$

Calculate radiative corrections (ZFITTER): leading terms in $m_t^2$ and $\log m_H$

$G_F$ known more precisely than $M_W$. Change basis and use this as an input instead. Tree level relation:

$$G_F = \frac{\pi\alpha}{\sqrt{2}M_W^2 \sin^2\theta_W} = 1.16639(1)\cdot 10^{-5}\,\mathrm{GeV}^{-2}$$

Compare input and predicted quantities with measured values. Fits made to several subsets of data, including:

| | All Z pole | All data | All but NuTeV |
|---|---|---|---|
| $m_t$ (GeV) | $171.5^{+11.9}_{-9.4}$ | $174.3^{+4.5}_{-4.4}$ | $175.3^{+4.4}_{-4.3}$ |
| $m_H$ (GeV) | $89^{+122}_{-45}$ | $96^{+60}_{-38}$ | $91^{+55}_{-36}$ |
| $\alpha_S(M_Z^2)$ | $0.1187 \pm 0.0027$ | $0.1186 \pm 0.0027$ | $0.1185 \pm 0.0027$ |
| $\chi^2$/dof (P) | 14.7/10(14.3%) | 25.4/15(4.5%) | 16.7/14(27.5%) |

No external $\alpha_S$ input. Additional theoretical syst. errors not included at this stage

http://lepewwg.web.cern.ch/LEPEWWG/

# *Global electroweak fit*

## Summer 2003

$\alpha$

LEP Z lineshape and lepton $A_{FB}$

LEP tau polarisation

LEP and SLD Z heavy flavour ⋆

SLD $A_{LR}$

LEP hadronic $A_{FB}$ (inclusive)

LEP and Tevatron $M_W$, $\Gamma_W$ ⋆

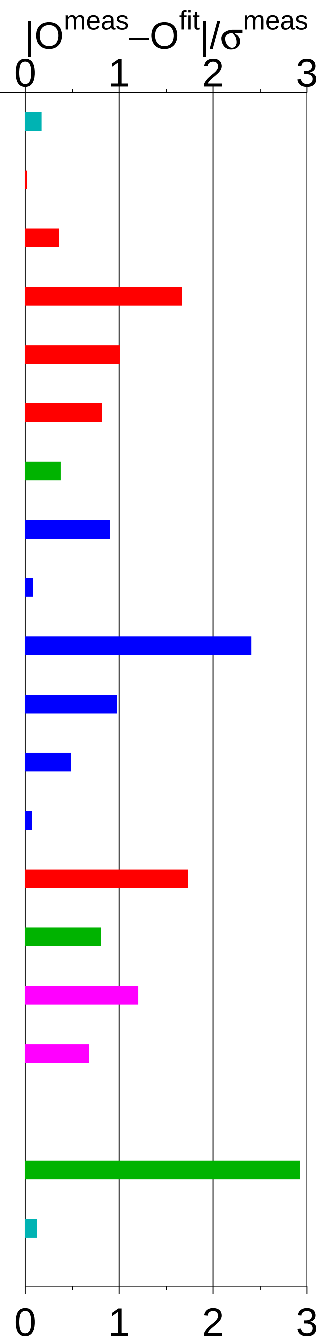
Tevatron top mass

NuTeV $\nu$N scattering

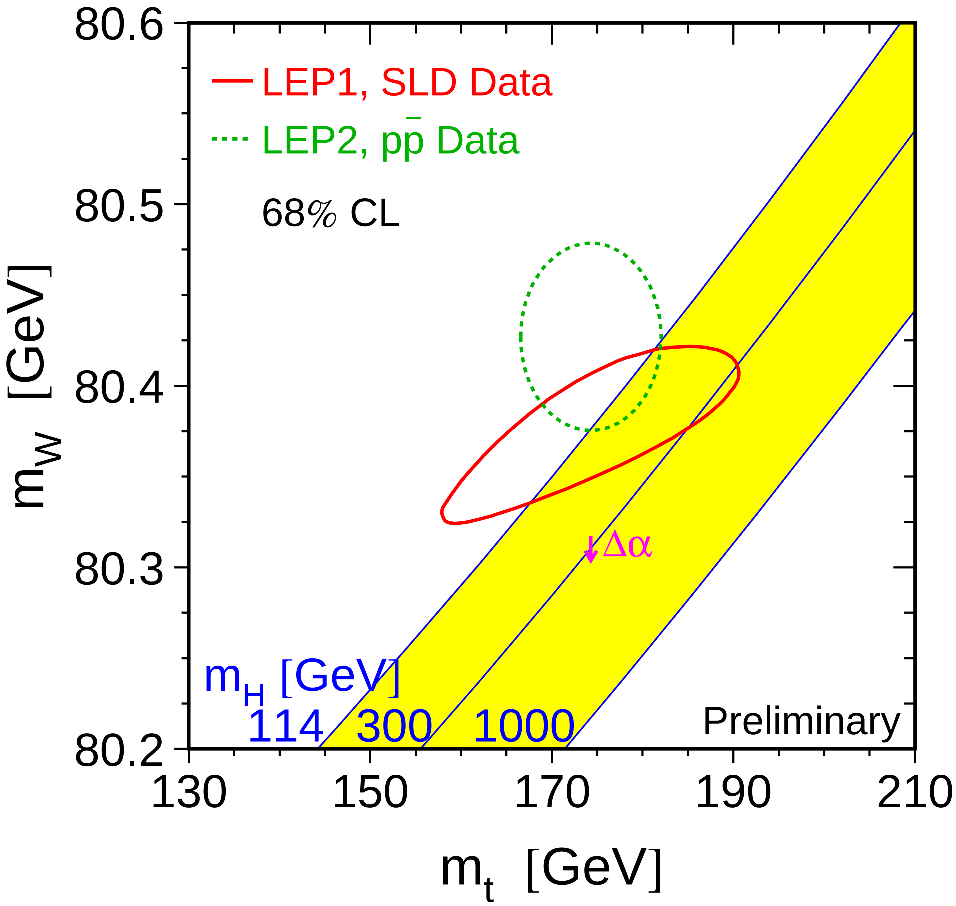
Atomic Parity Violation ⋆

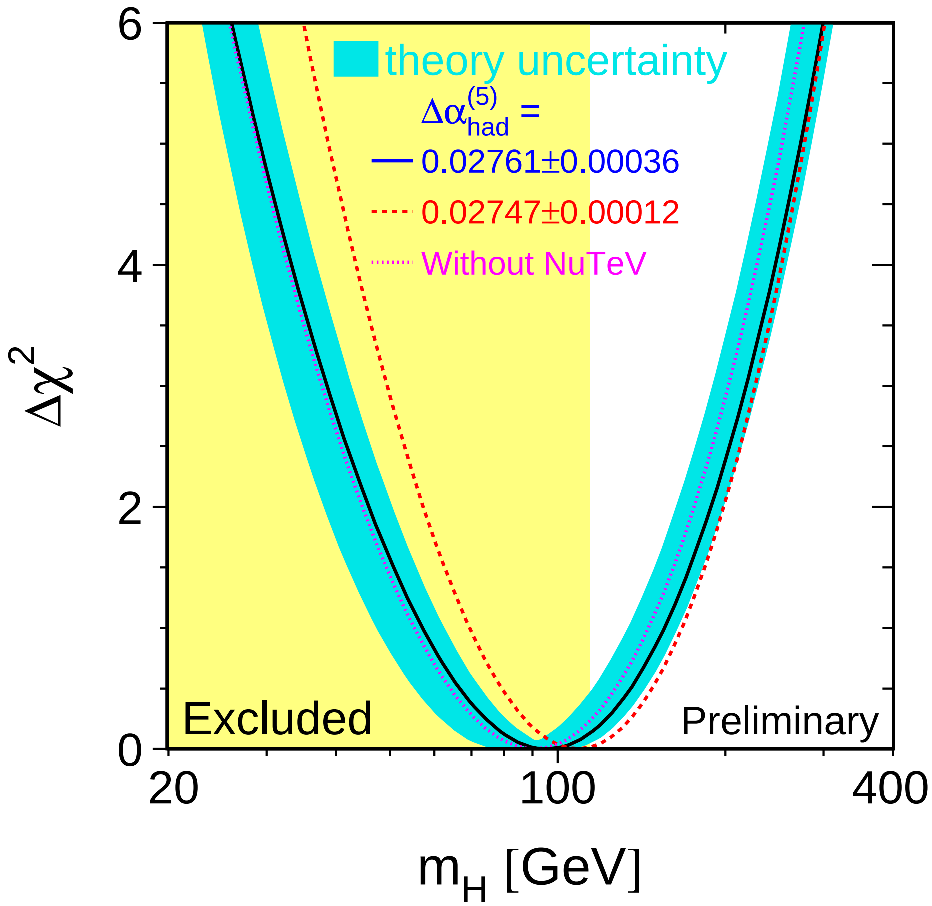
⋆ Updated

| | Measurement | Fit |
|---|---|---|
| $\Delta\alpha^{(5)}_{had}(m_Z)$ | $0.02761 \pm 0.00036$ | 0.02767 |
| $m_Z$ [GeV] | $91.1875 \pm 0.0021$ | 91.1875 |
| $\Gamma_Z$ [GeV] | $2.4952 \pm 0.0023$ | 2.4960 |
| $\sigma^0_{had}$ [nb] | $41.540 \pm 0.037$ | 41.478 |
| $R_l$ | $20.767 \pm 0.025$ | 20.742 |
| $A^{0,l}_{fb}$ | $0.01714 \pm 0.00095$ | 0.01636 |
| $A_l(P_\tau)$ | $0.1465 \pm 0.0032$ | 0.1477 |
| $R_b$ | $0.21638 \pm 0.00066$ | 0.21579 |
| $R_c$ | $0.1720 \pm 0.0030$ | 0.1723 |
| $A^{0,b}_{fb}$ | $0.0997 \pm 0.0016$ | 0.1036 |
| $A^{0,c}_{fb}$ | $0.0706 \pm 0.0035$ | 0.0740 |
| $A_b$ | $0.925 \pm 0.020$ | 0.935 |
| $A_c$ | $0.670 \pm 0.026$ | 0.668 |
| $A_l$(SLD) | $0.1513 \pm 0.0021$ | 0.1477 |
| $\sin^2\theta^{lept}_{eff}(Q_{fb})$ | $0.2324 \pm 0.0012$ | 0.2314 |
| $m_W$ [GeV] | $80.426 \pm 0.034$ | 80.385 |
| $\Gamma_W$ [GeV] | $2.139 \pm 0.069$ | 2.093 |
| $m_t$ [GeV] | $174.3 \pm 5.1$ | 174.3 |
| $\sin^2\theta_W(\nu N)$ | $0.2277 \pm 0.0016$ | 0.2229 |
| $Q_W(Cs)$ | $-72.84 \pm 0.46$ | -72.90 |



# *Global electroweak fit*




Top and W mass consistency between direct measurement and prediction from radiative corrections.

Preference for low Higgs mass.

Without accounting for limit from direct searches, but including spread of theoretical uncertainties

**$M_{Higgs}$ < 219 GeV at 95% CL**

# But what if.......?

Use the new value for $\Delta\alpha^{(5)}_{had}(M_Z^2)$

(Burkhardt+Pietrzyk 2003)?

Small downward shift in $M_{Higgs}$

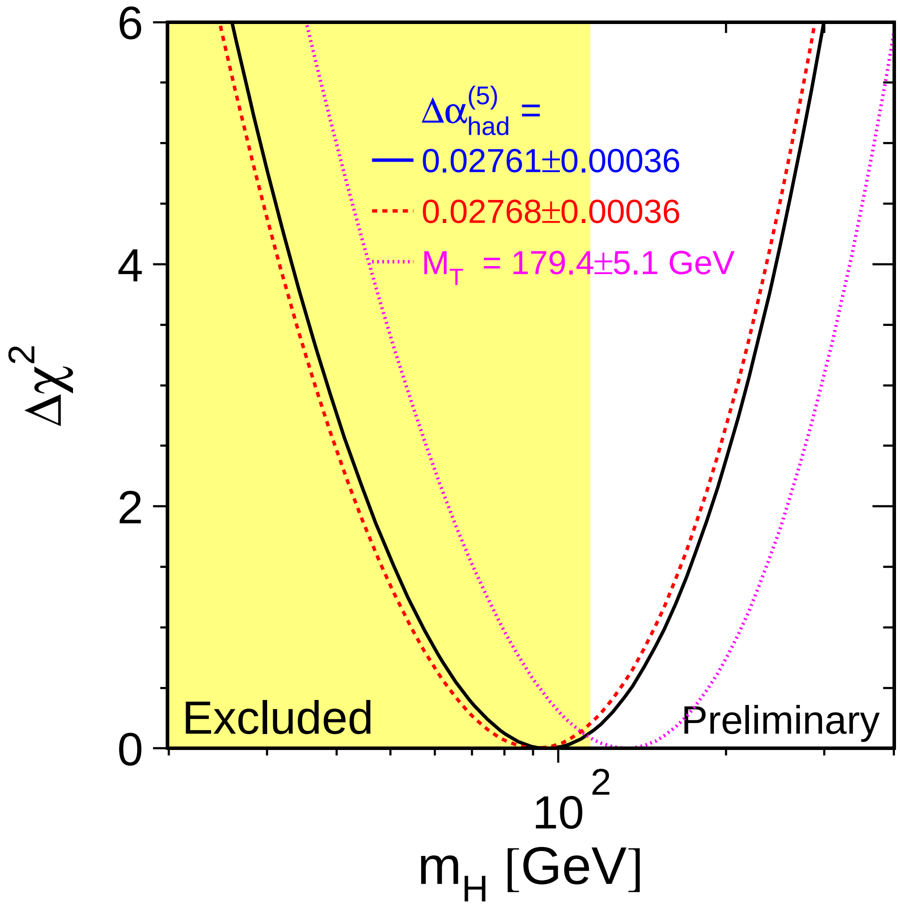
(min. 96→91 GeV, limit 219→210 GeV)

The top mass increases by $1\sigma$ to

$179.4 \pm 5.1$ GeV?

Large upward shift in $M_{Higgs}$

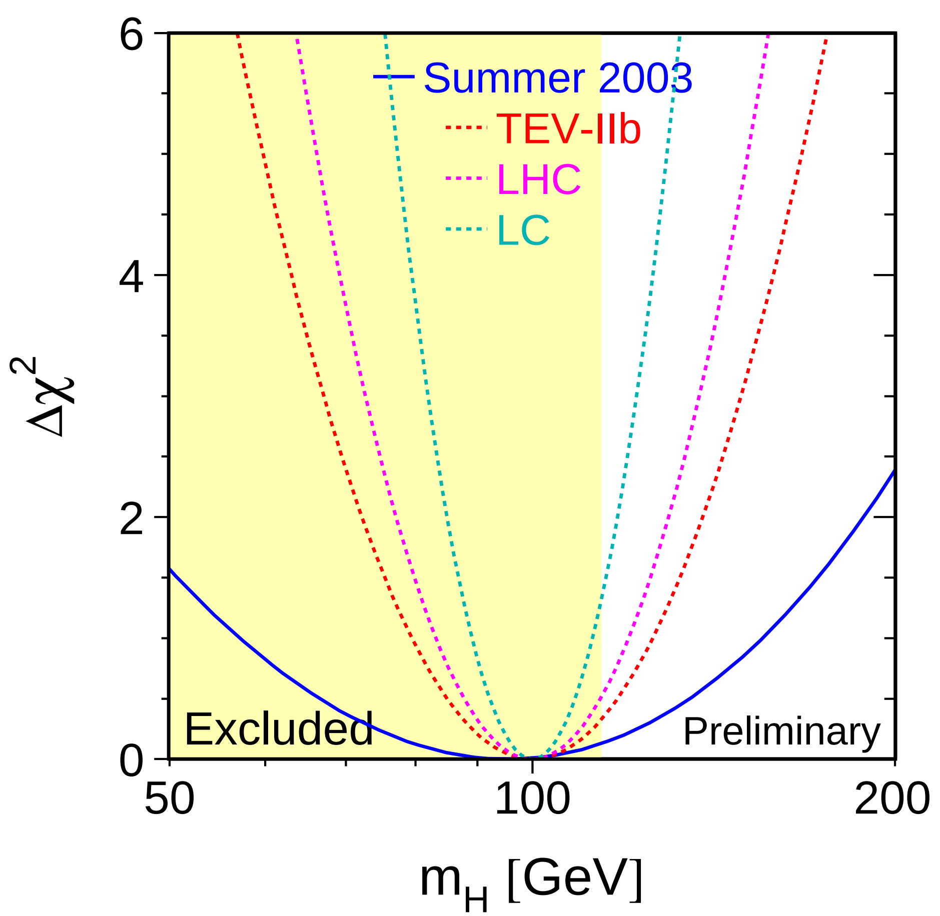
(min. 96→126 GeV, limit 219→283 GeV)

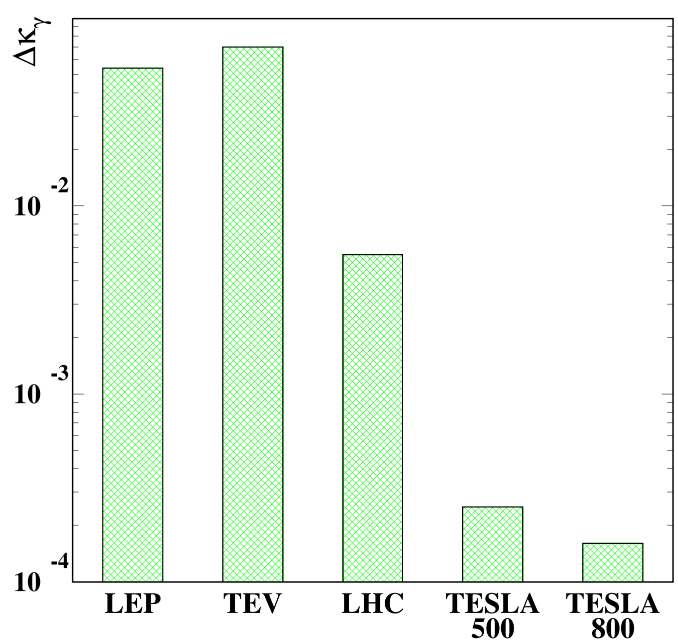


# *Future*

Errors on electroweak parameters in future, taking error on $\Delta\alpha^5_{had}$ to be 0.00012 in each case (theory driven).

| | $M_W$ (MeV) | $m_t$ (GeV) | $\sin^2\theta^{lept}_{eff}$ |
|---|---|---|---|
| Now | 34 | 5.1 | 0.00016 |
| TeV IIB | 17 | 1.3 | 0.00016 |
| LHC | 10 | 1.0 | 0.00016 |
| LC | 7 | 0.2 | 0.000085 |




Also improvements in knowledge of TGCs etc.

# Conclusions

Electroweak Standard Model does a great job of describing a range of parameters with radiative corrections at loop level firmly established.

Any hints of new physics? Largest discrepancies (only $\sim 3\sigma$)

- $A_{FB}^{0,b}$ vs. $A_{LR}$. No experimental progress to be expected in near future.
- NuTeV - little impact on global fit. An unexplained deviation/fluctuation.
- g-2. Importance of settling experimental input from lower energy $e^+e^-$ colliders before chasing the ambulance. Latest CMD-2 update $\Longrightarrow$ discrepancy $\sim 2.5\sigma$.

What to look forward to?

- W and top mass measurements - final LEP2, TeV Run II
- Higgs mass measurement!

Full set of electroweak measurements place strong constraints on any new physics.

Great prospects for further enlightenment in near and not so near future.