

Experimental Tests of the Standard Model

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21 July 2003

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

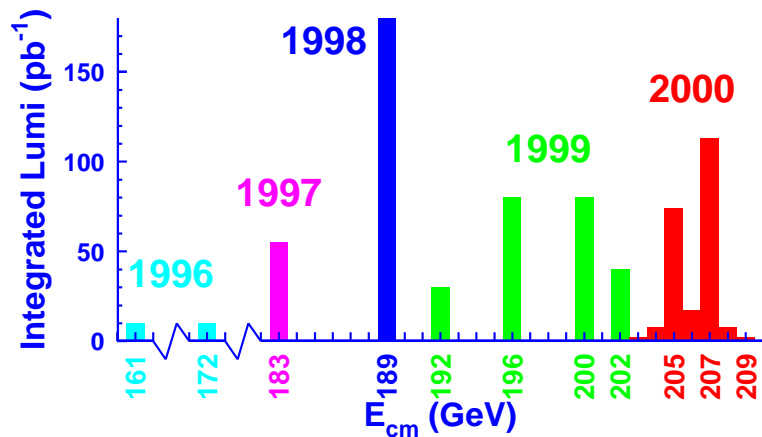
LEP 1989-2000 Total lumi. 1000 pb^{-1}

ALEPH, DELPHI, L3, OPAL recorded:

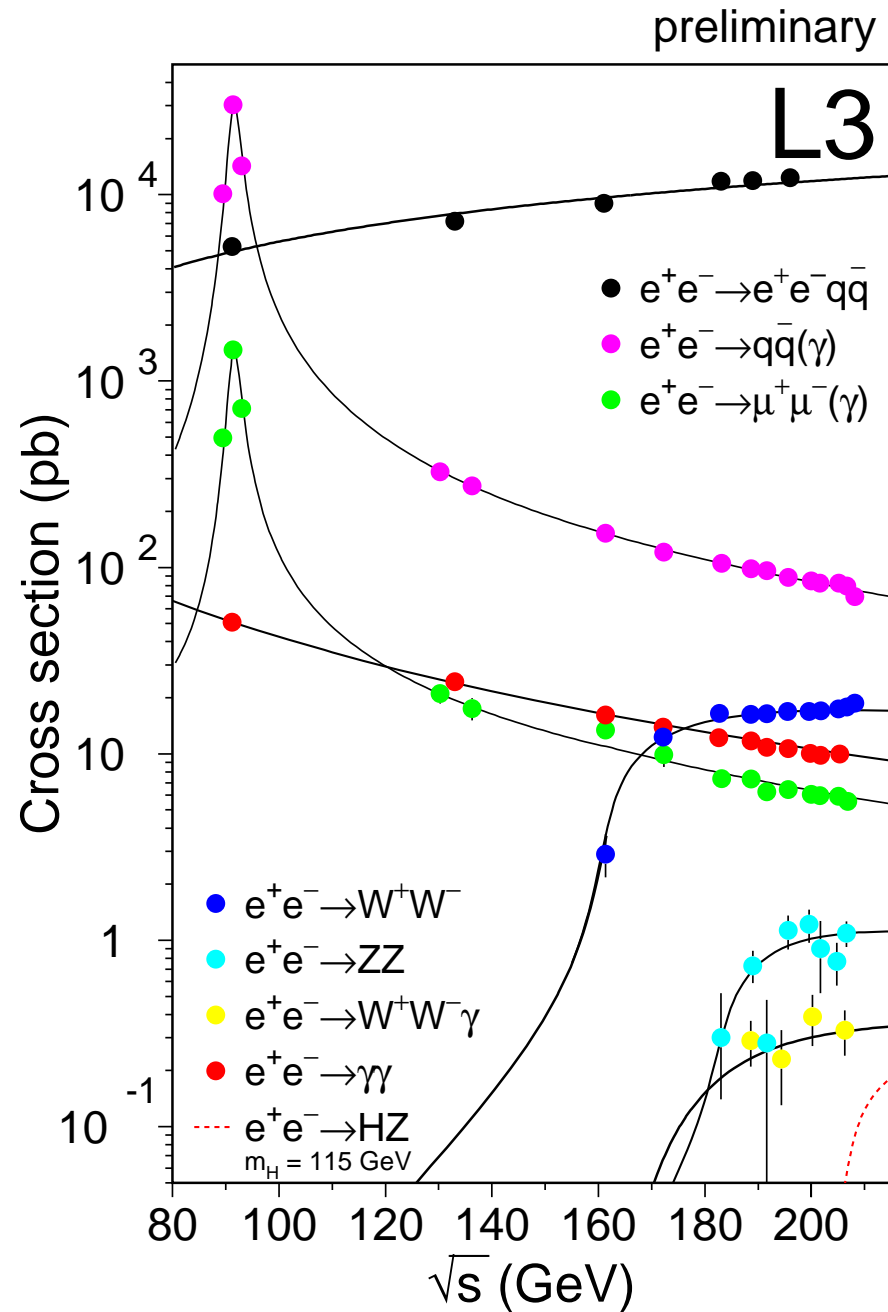
LEP1 4.5M Z per experiment including off-peak data.

LEP2 Above WW threshold.

10k W-pair per experiment



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



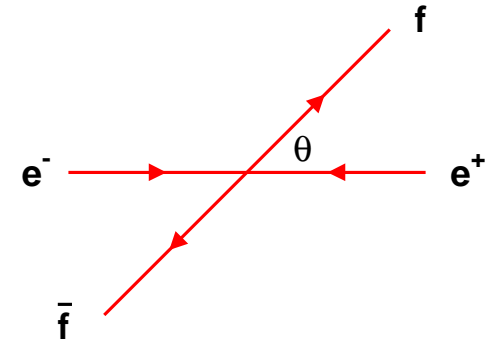
Z pole

LEP Z lineshape, LEP A_{FB}^{ℓ} , τ pol. } Final for some time. (See global fits)
 SLD A_{LR} and A_{LRFB}^{ℓ} asymmetries

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

Forward: $\theta < 90^\circ$

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



Z couplings:

$$g_{Vf} = \sqrt{\rho} \left(T_f^3 - 2Q_f \sin^2 \theta_{\text{eff}}^f \right); \quad g_{Af} = \sqrt{\rho} T_f^3$$

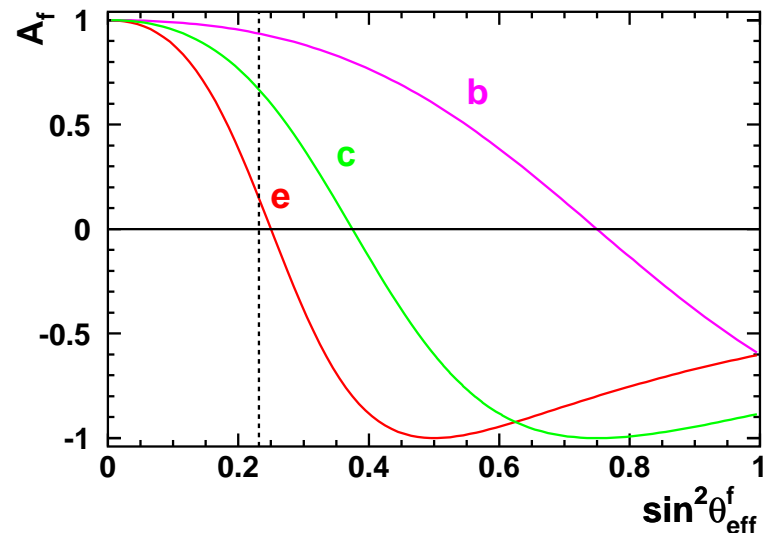
Partial widths $\Rightarrow g_{Vf}^2 + g_{Af}^2$; Asymmetries $\Rightarrow g_{Vf}/g_{Af} = 1 - 4|Q_f| \sin^2 \theta_{\text{eff}}^f$

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

Related to Z pole asymmetries by:

$$A_{\text{FB}}^{0,f} = \frac{3}{4} A_e A_f; \quad A_{\text{LR}}^0 = A_e; \quad A_{\text{LRFB}}^0 = \frac{3}{4} A_f$$

$A_{\text{FB}}^{0,b}$ sensitive to $\sin^2 \theta_{\text{eff}}^{\text{lept}}$



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...

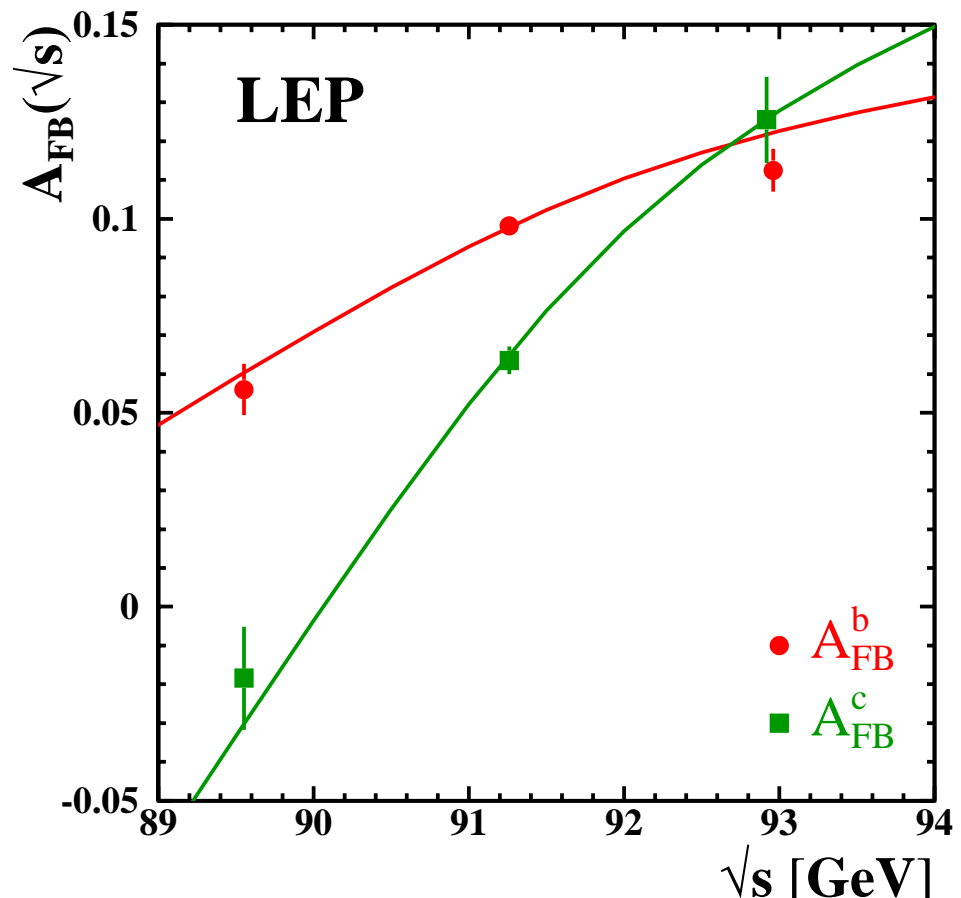
Forward vs. backward going quark determined from lepton or inclusive charge tag.

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 ± 2 GeV away.

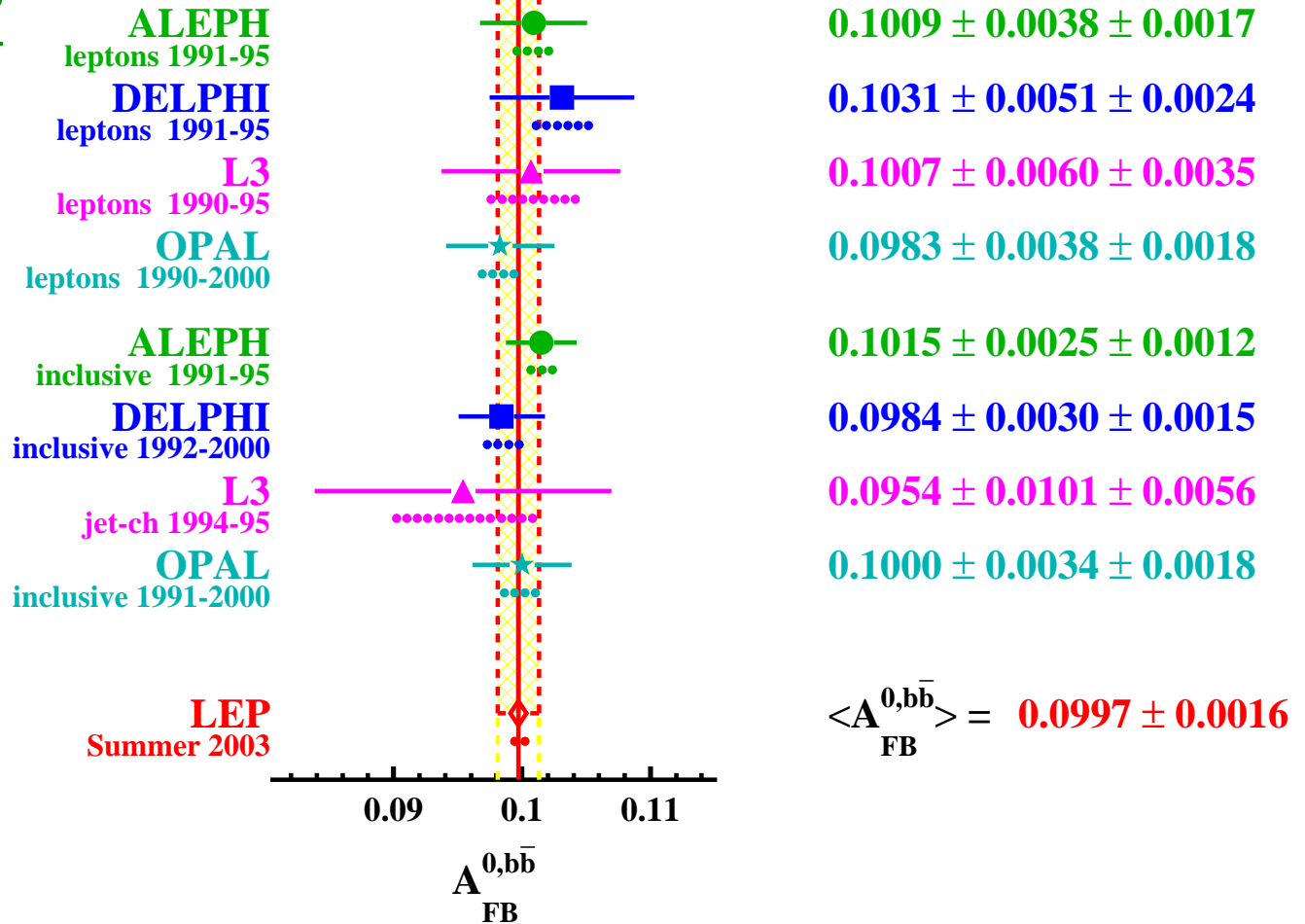
Then corrected to give pole asymmetries at $\sqrt{s} = M_Z$



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

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

All heavy-flavour quantities from LEP and SLD averaged in a combined fit, accounting for correlated errors and interdependences.
 $\chi^2/\text{dof } 52.7/(105-14)$



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

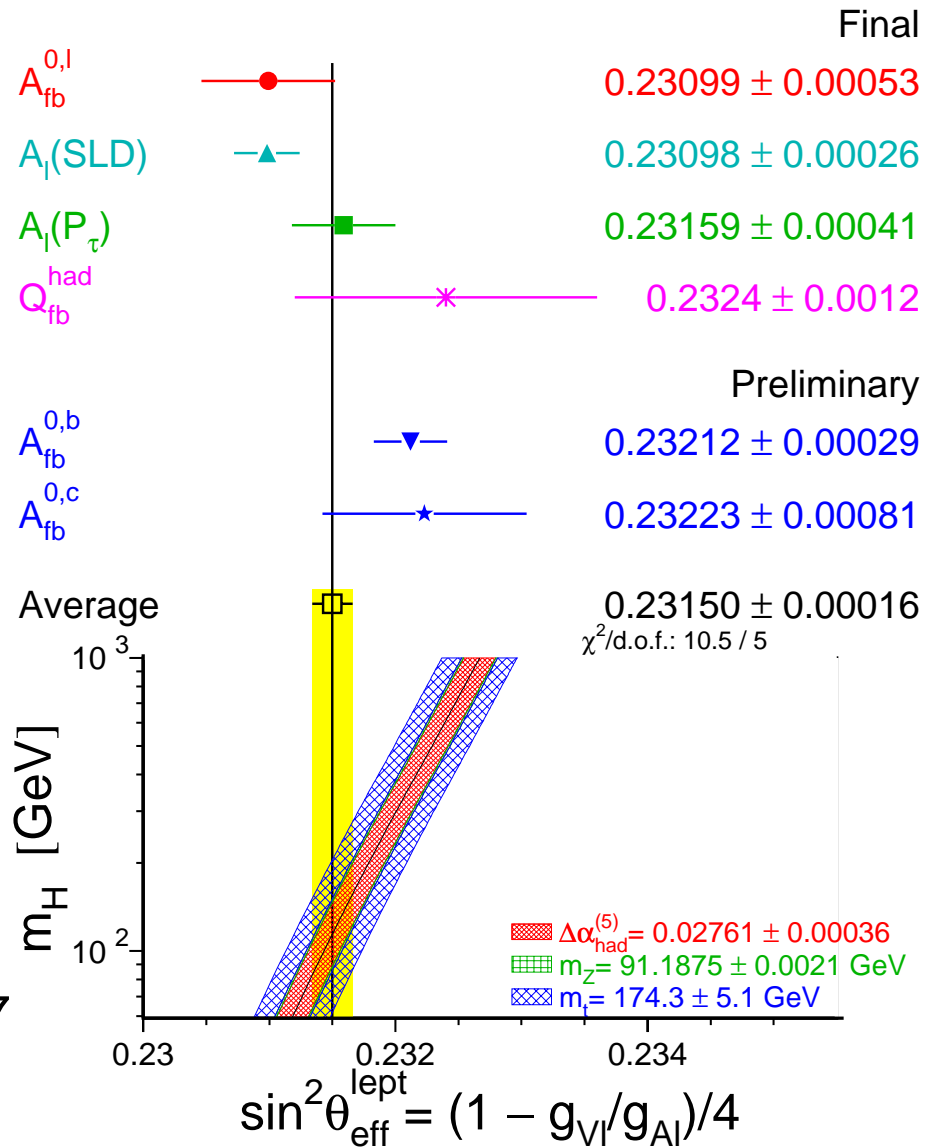
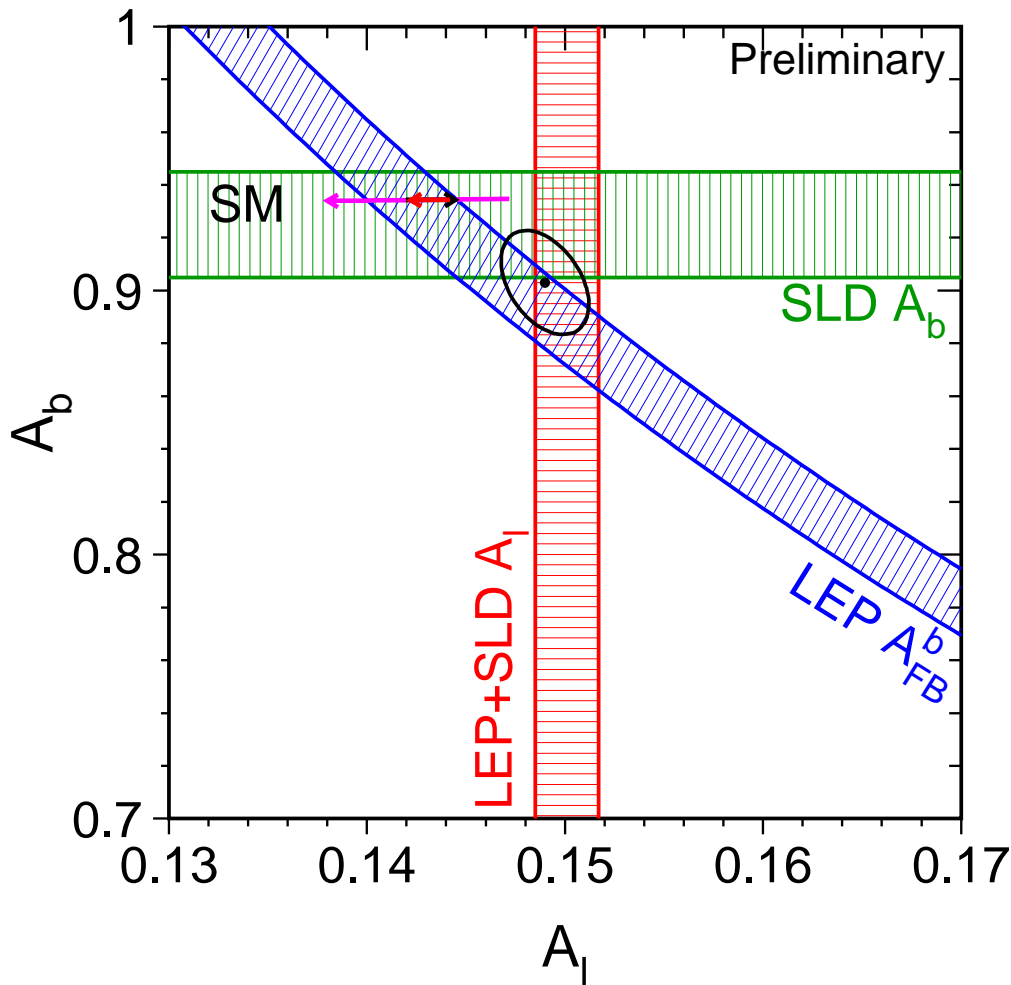
$$A_{FB}^{0,c} = 0.0706 \pm 0.0035, \text{ Total sys } 0.0017, \text{ Common sys } 0.0009; \text{ SM } 0.0740$$

(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 & $\sin^2 \theta_{\text{eff}}^{\text{lept}}$

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

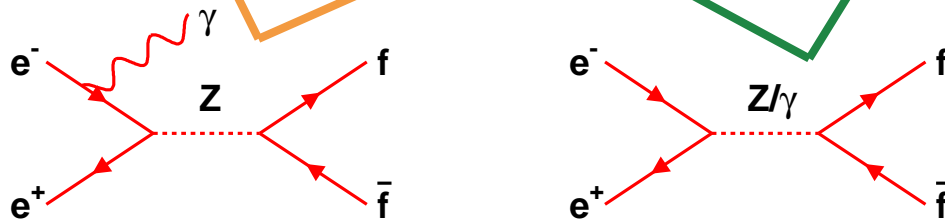
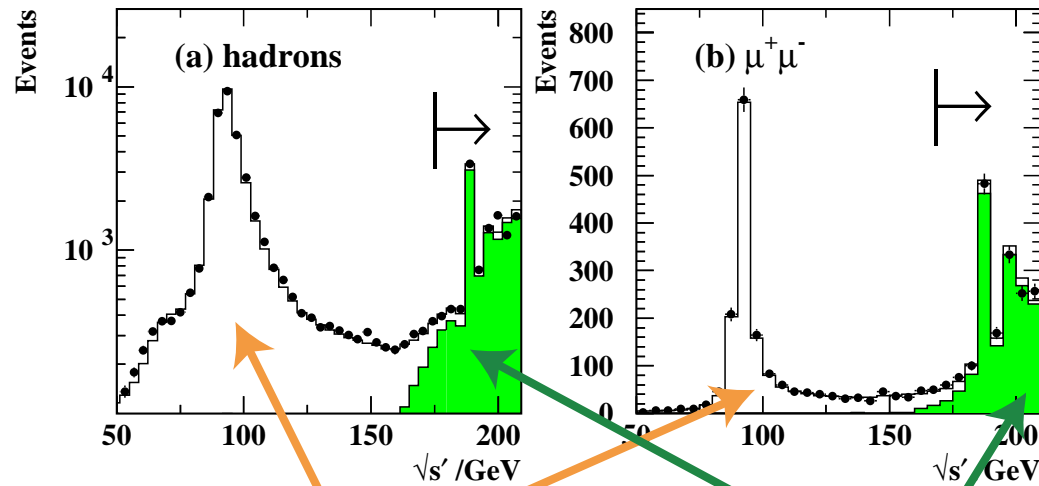


$P(\chi^2) = 6.2\%$ for $\sin^2 \theta_{\text{eff}}^{\text{lept}}$. Two most precise values, $A_{\text{FB}}^{0,b}$ and A_{LR} , differ by 2.9σ

LEP2 $f\bar{f}$

Fermion pair production at LEP2

OPAL preliminary 189 - 209 GeV



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

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

New: Preliminary E_{beam} updates from ADLO

Measured average beam energy differs from LEP preliminary value by:

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

OPAL Update. LEP combination unchanged.

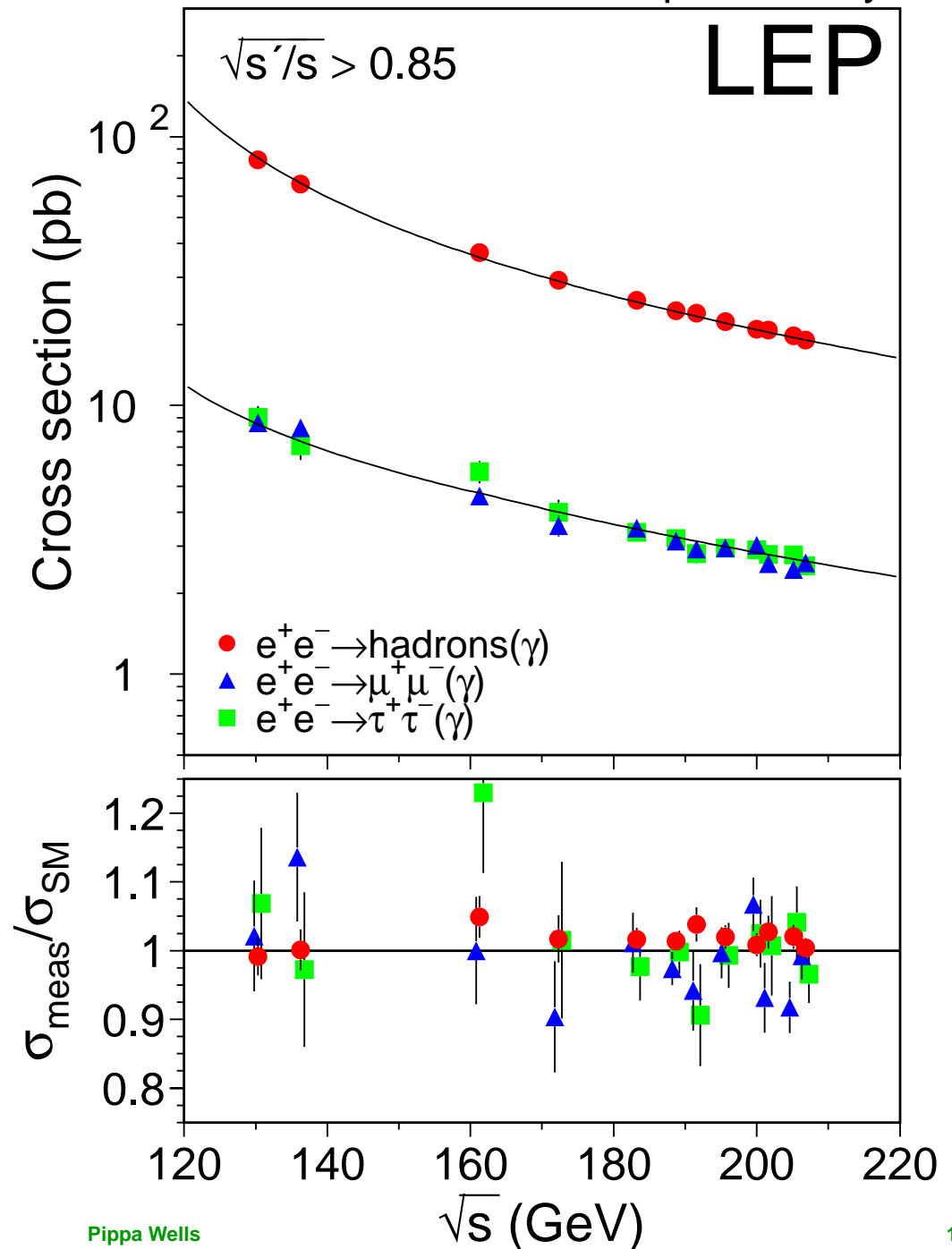
Fermion pair production at LEP2

preliminary

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

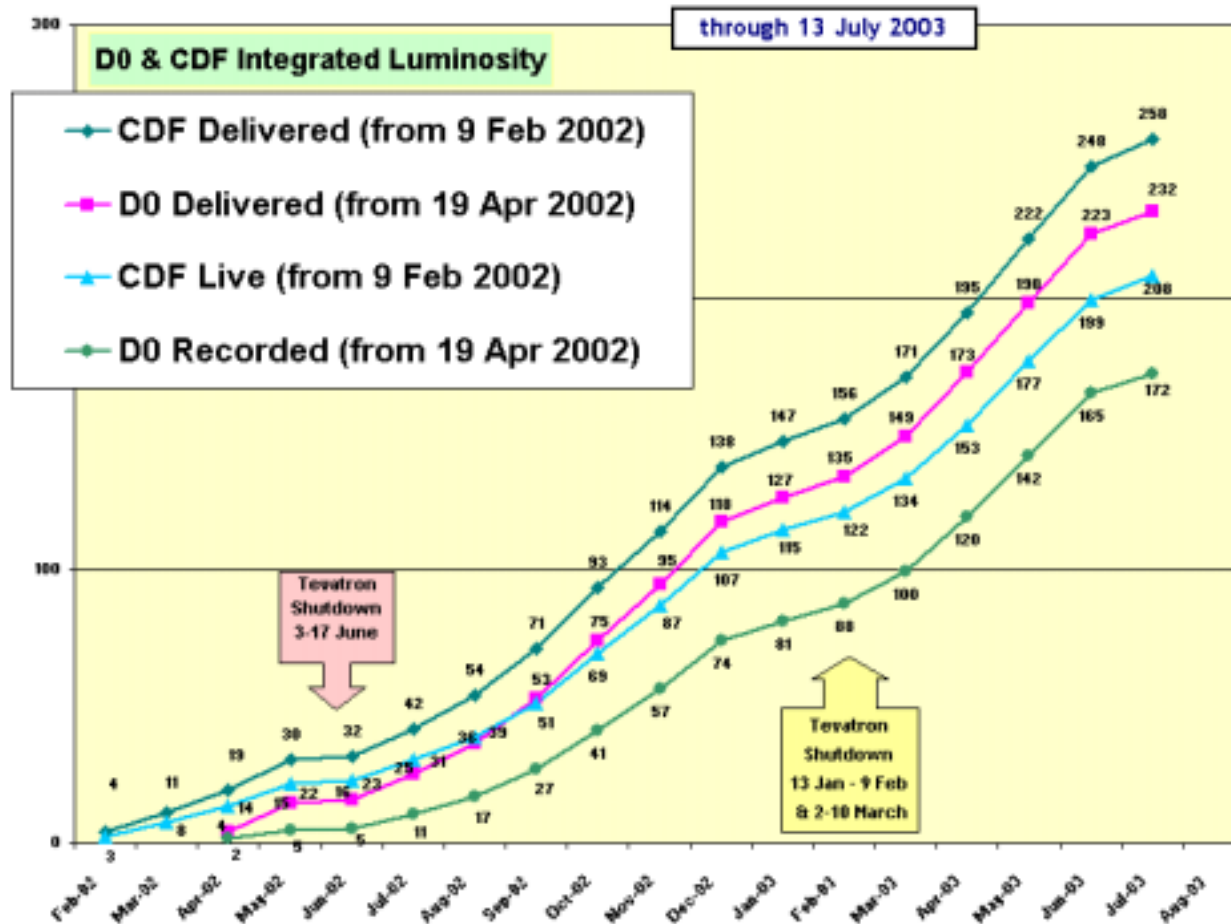
$p\bar{p}$ collisions with $\sqrt{s} = 1.96$ TeV

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

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

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

<http://www.fnal.gov/pub/now/upgradeplan/>

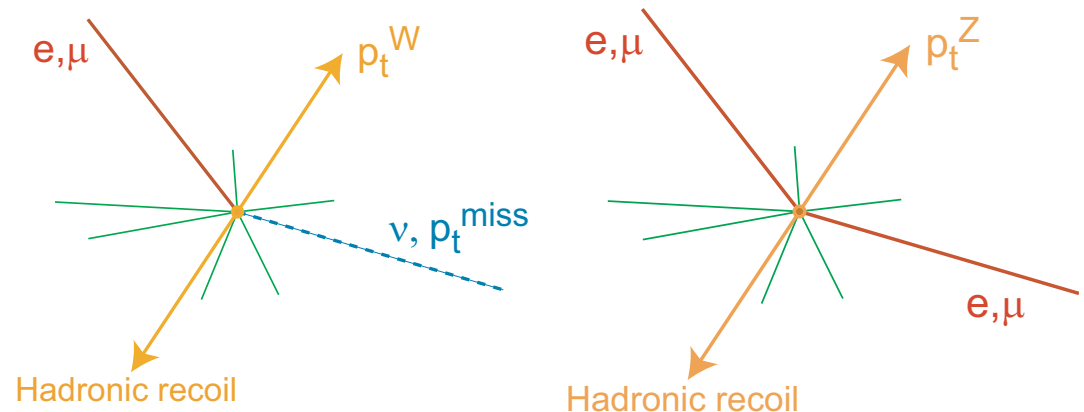


← 200 pb^{-1}

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

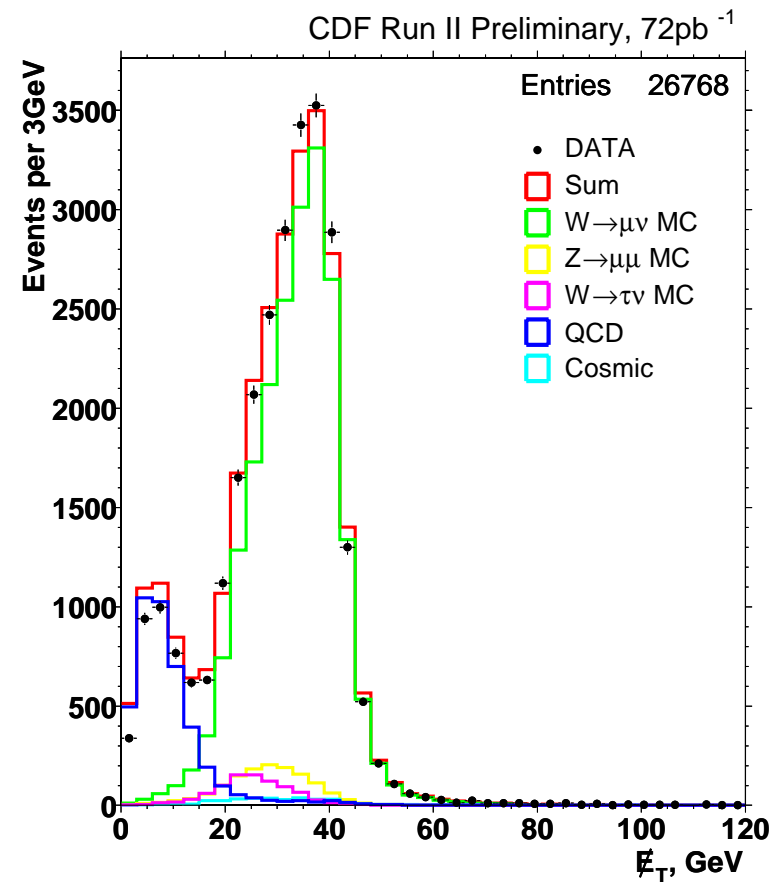
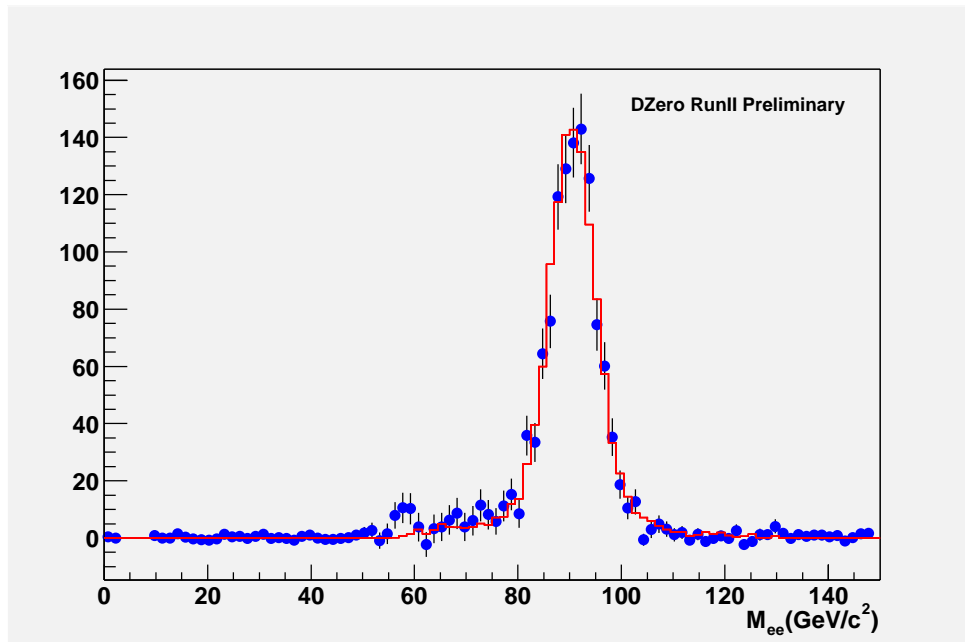
Tevatron W and Z production

Clean $q\bar{q}' \rightarrow W \rightarrow \ell\nu$ and $Z \rightarrow \ell^+\ell^-$ signatures ($\ell = e, \mu$)
 Isolated lepton and p_T^{miss} or two isolated leptons



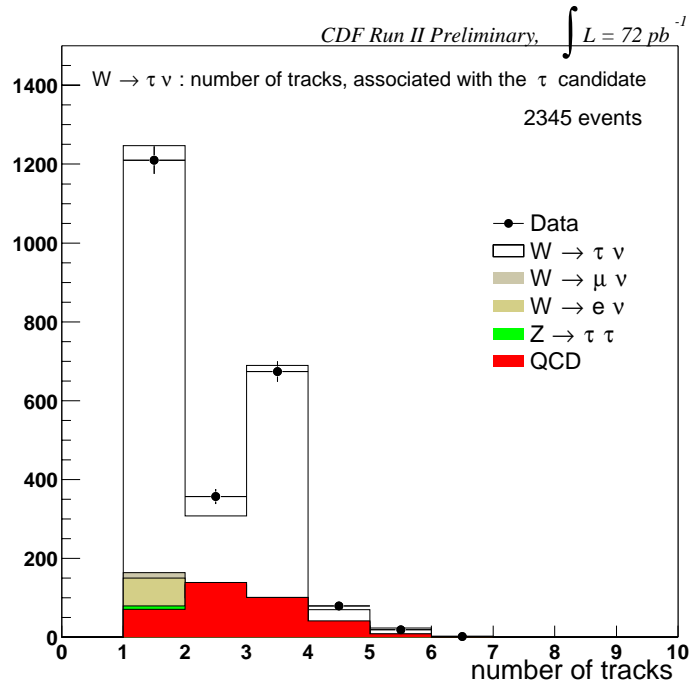
Distributions from Run II

D0 preliminary: 41.6 pb^{-1} from run II
 M_{ee} for $Z \rightarrow ee$, (background subtracted)



Also measure $\sigma_W \cdot \text{Br}(W \rightarrow \tau \nu)$

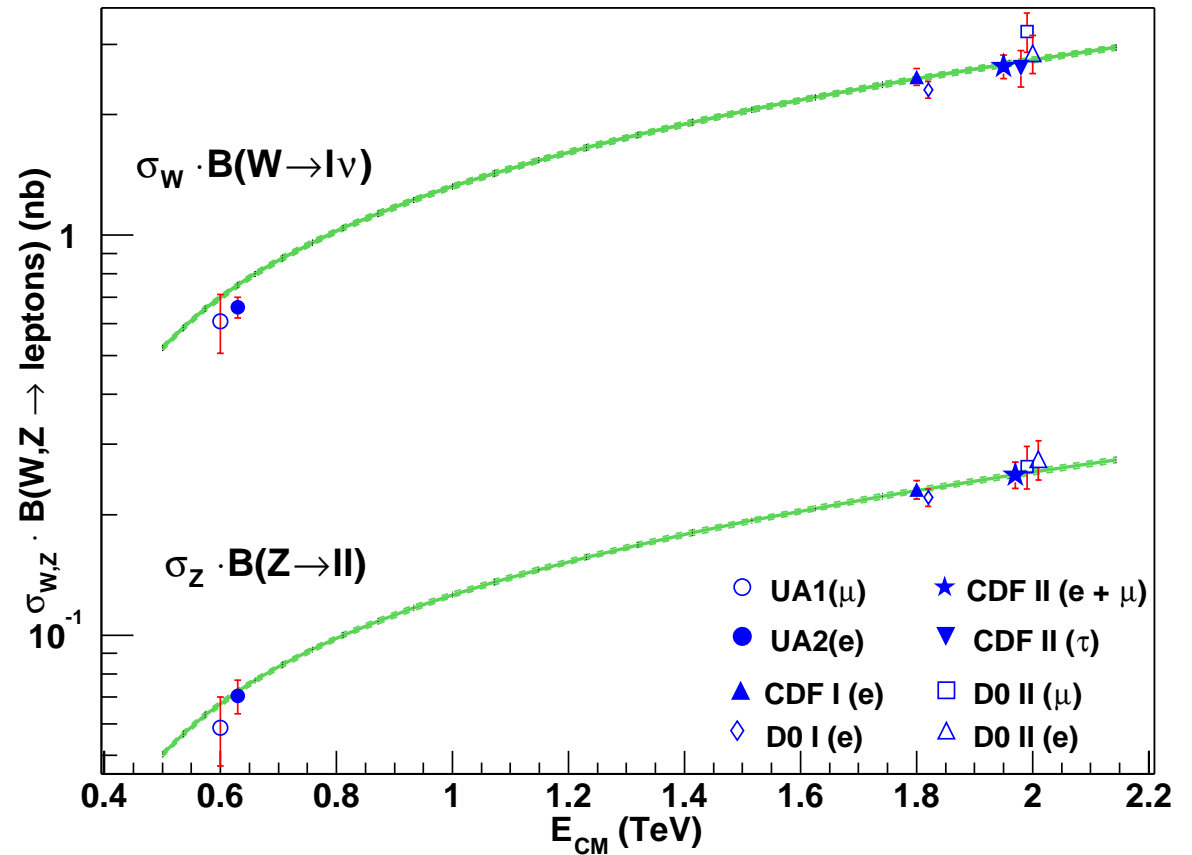
Number of tracks of τ



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

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

Cross section \times leptonic Br compilation

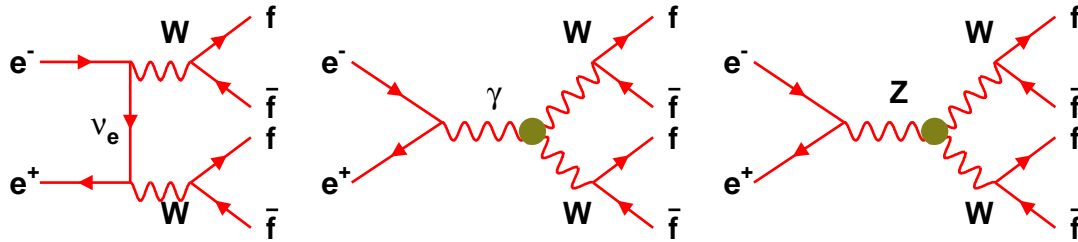


Dominant experimental uncertainties: luminosity, PDFs, hadronic recoil, detector acceptance.

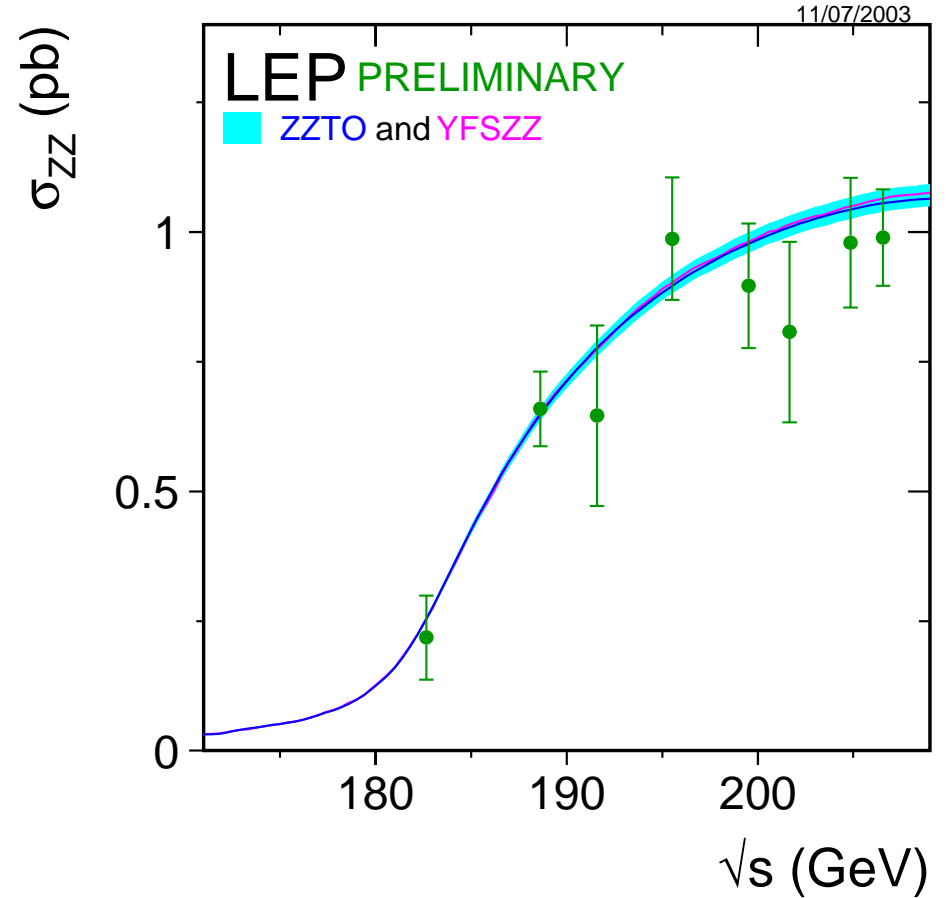
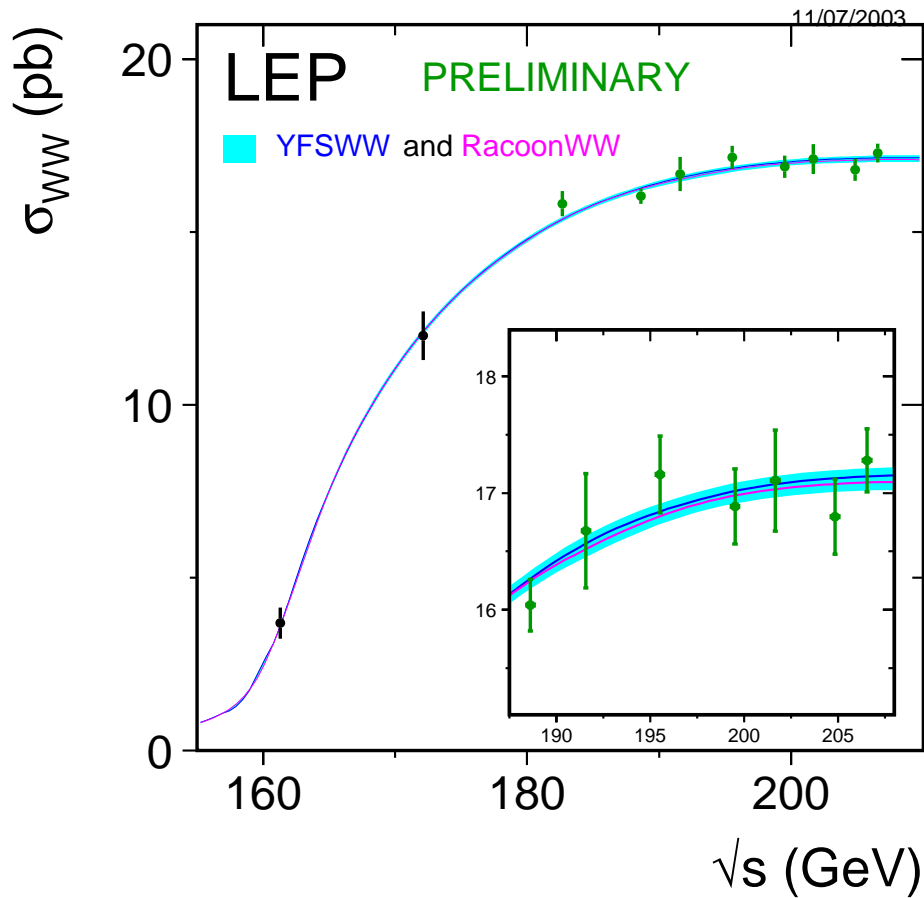
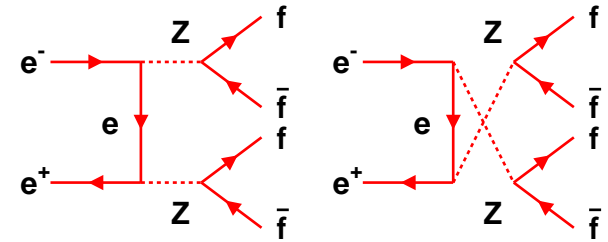
WW and ZZ production at LEP2

Updates from D(WW) and DLO(ZZ)

3 diagrams "CC03"



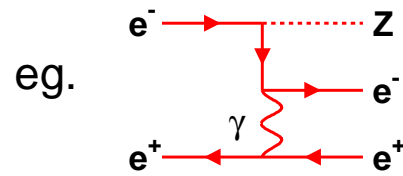
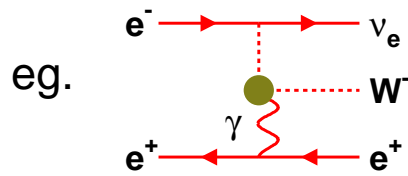
2 diagrams "NC02"



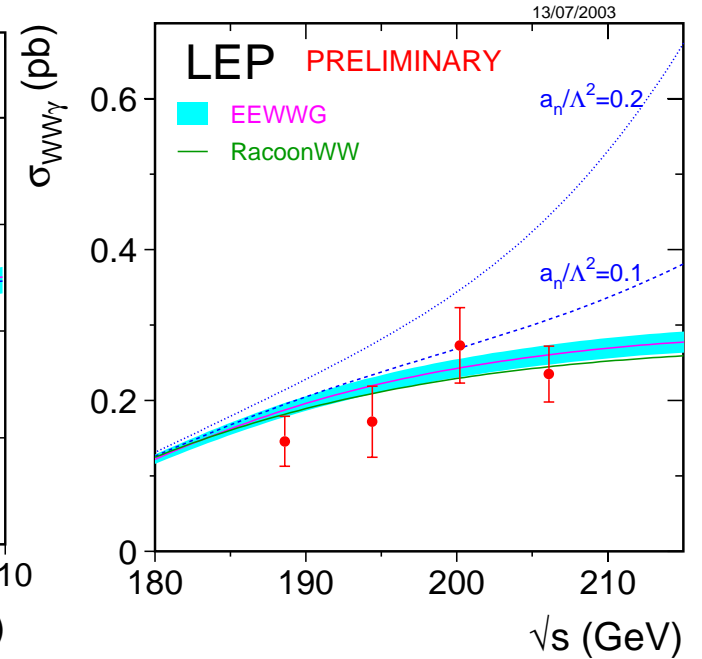
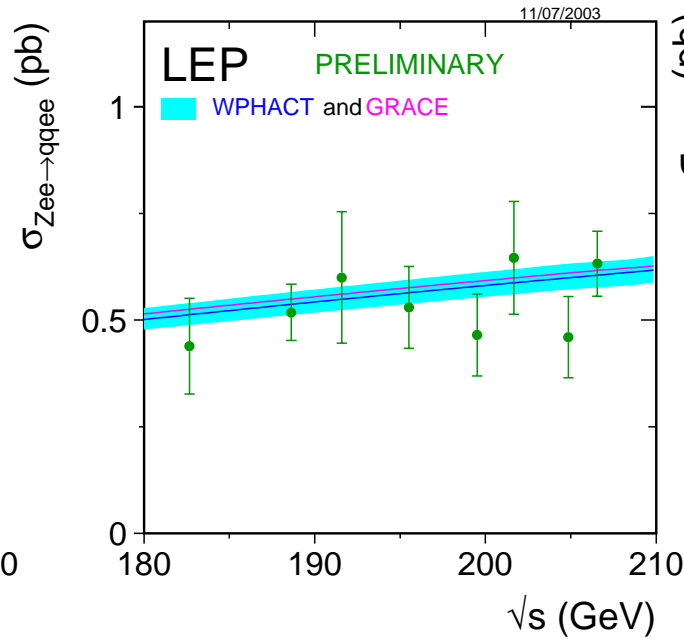
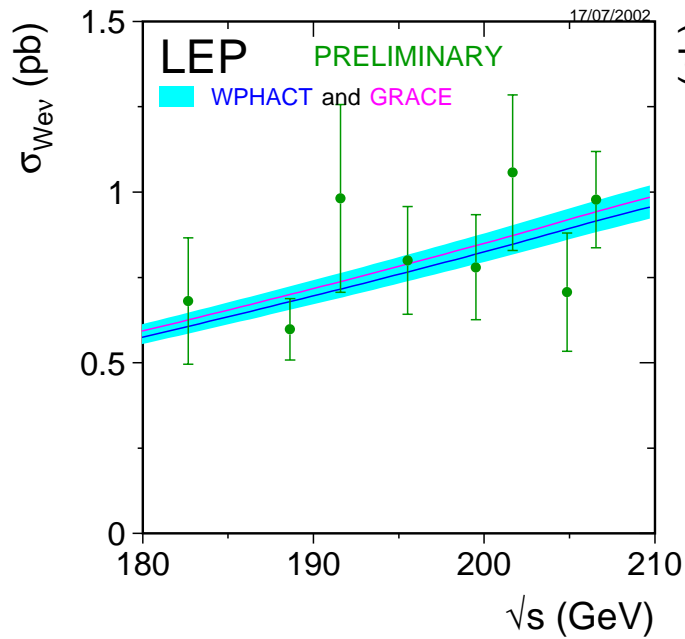
Sensitive to M_W (threshold) and TGCs ●

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

LEP 2: $e^+e^- \rightarrow e\nu W, eeZ, WW\gamma$



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



New: Zee ADL update;
 $WW\gamma$ \Rightarrow final

Ratio $\sigma(\text{data})/\sigma(\text{MC})$ for		
WW	YFSWW	0.997 ± 0.010
ZZ	YFSZZ	0.945 ± 0.052
We ν	WPHACT	0.978 ± 0.080
Zee	WPHACT	0.932 ± 0.068

W branching ratios from LEP

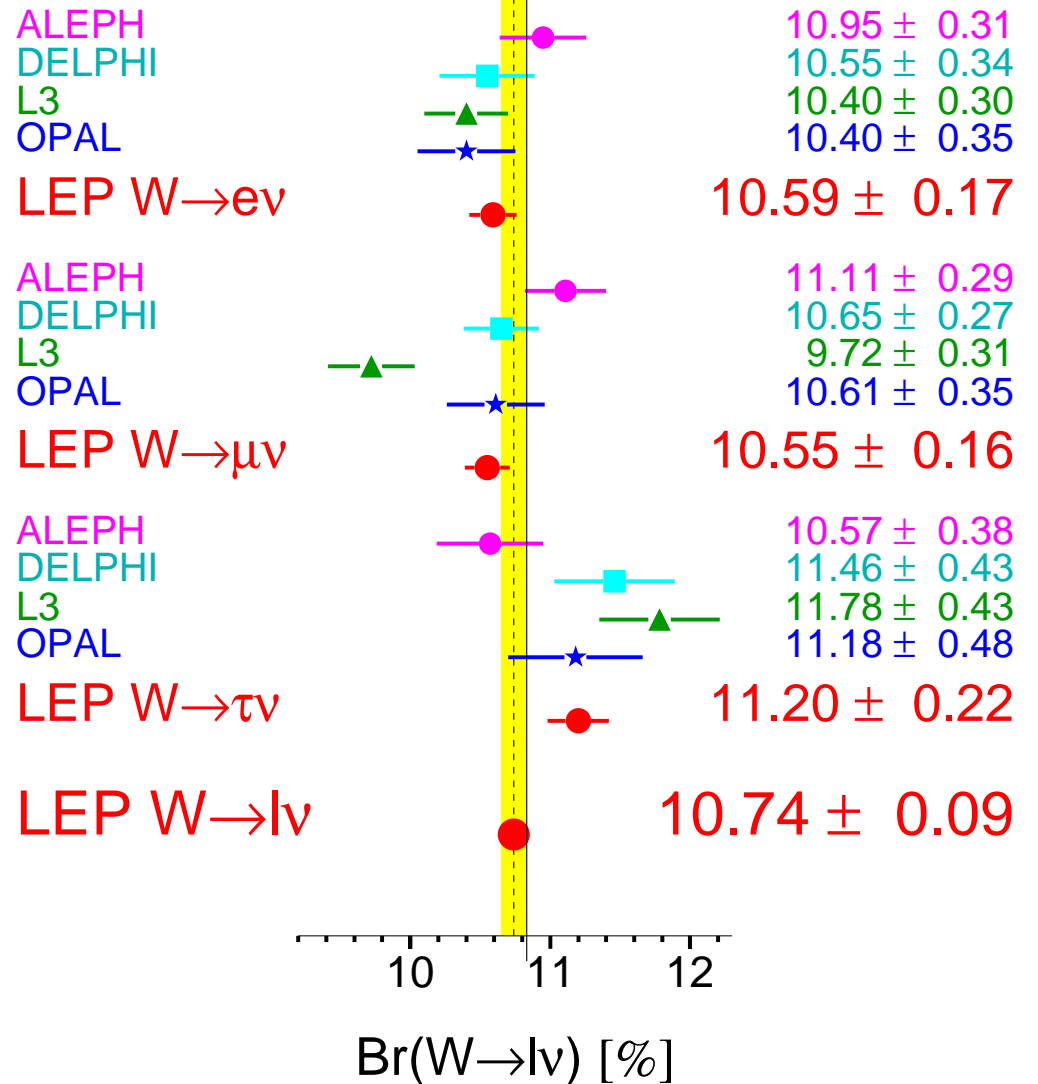
WW events 46% $q\bar{q}q\bar{q}$, 4 jets
 44% $q\bar{q}l\nu$, 2 jets, l, p^{miss}
 10% $l\nu l\nu$, 2 l, p^{miss}

New: DELPHI \Rightarrow final

W leptonic Br's \rightarrow

Note: $\text{Br}(W \rightarrow \tau\nu)$ value high

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



Br(W → ℓν) and indirect Γ_W from Tevatron Run II

New: Partial cross section ratio from Tevatron Run II

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

Run II: $R = 10.36 \pm 0.31$

LEP ⇒ Br(Z → ℓℓ),

SM ⇒ Γ(W → eν),

Theory ⇒ σ_W/σ_Z (Van Neerven et al.)

} Infer Br(W → ℓν) or indirect Γ_W

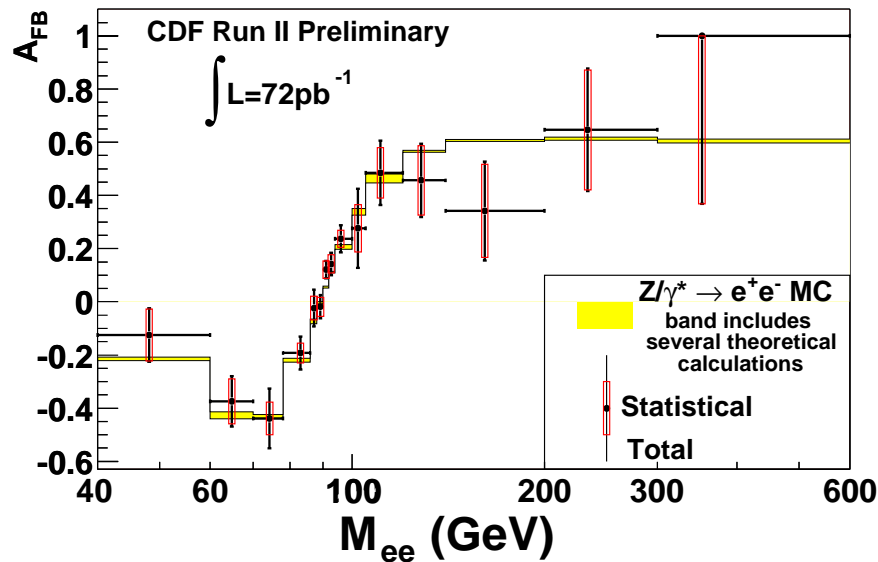
Combining with Run I, correcting for evolution of σ_W/σ_Z with √s.

$$\begin{array}{ll} \text{Br}(W \rightarrow \ell\nu) & (10.53 \pm 0.26)\% \\ \Gamma_W & 2.150 \pm 0.054 \text{ GeV} \end{array}$$

Electroweak tests with gauge bosons

Examples from Run II

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

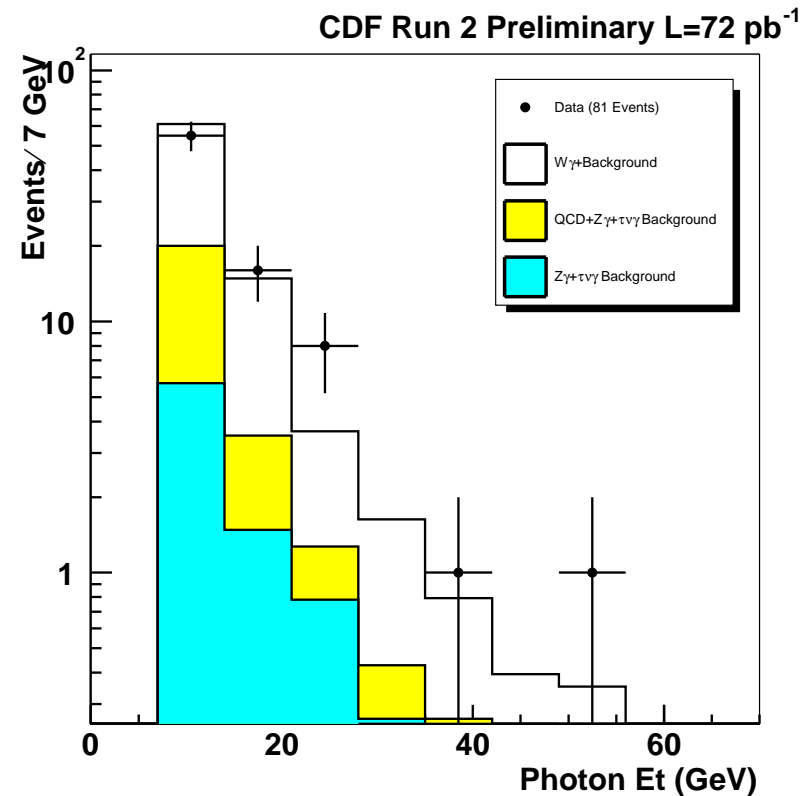


Potential for future precise measurement of $\sin^2 \theta_{eff}^{lept}$.

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

At present, LEP results generally give stronger constraints.

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



81 events, 25.4 expected background.

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 $SU(2)\times U(1)$ 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

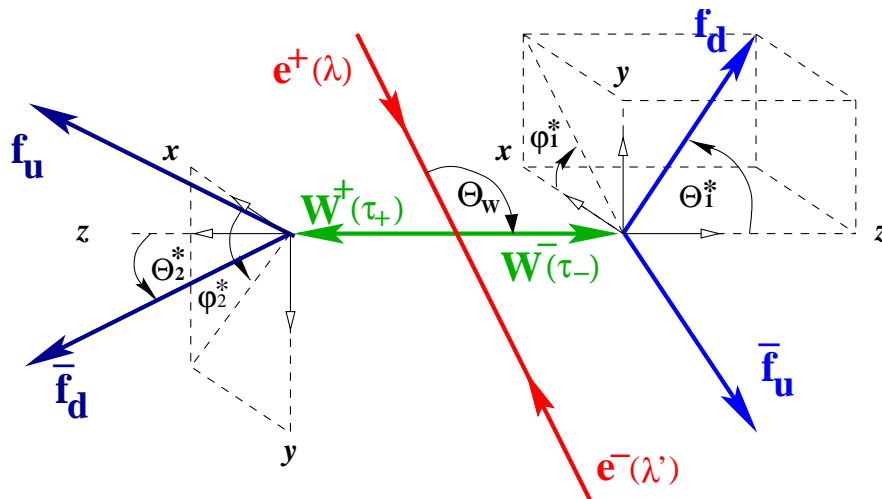
	$\sigma_L/\sigma_{\text{tot}}$
DELPHI	$(24.9 \pm 3.2) \%$
L3	$(21.8 \pm 2.7 \pm 1.6) \%$
OPAL	$(23.8 \pm 2.1 \pm 1.4) \%$
SM	$23.9 \pm 0.1 \%$

Anomalous TGC: angular observables

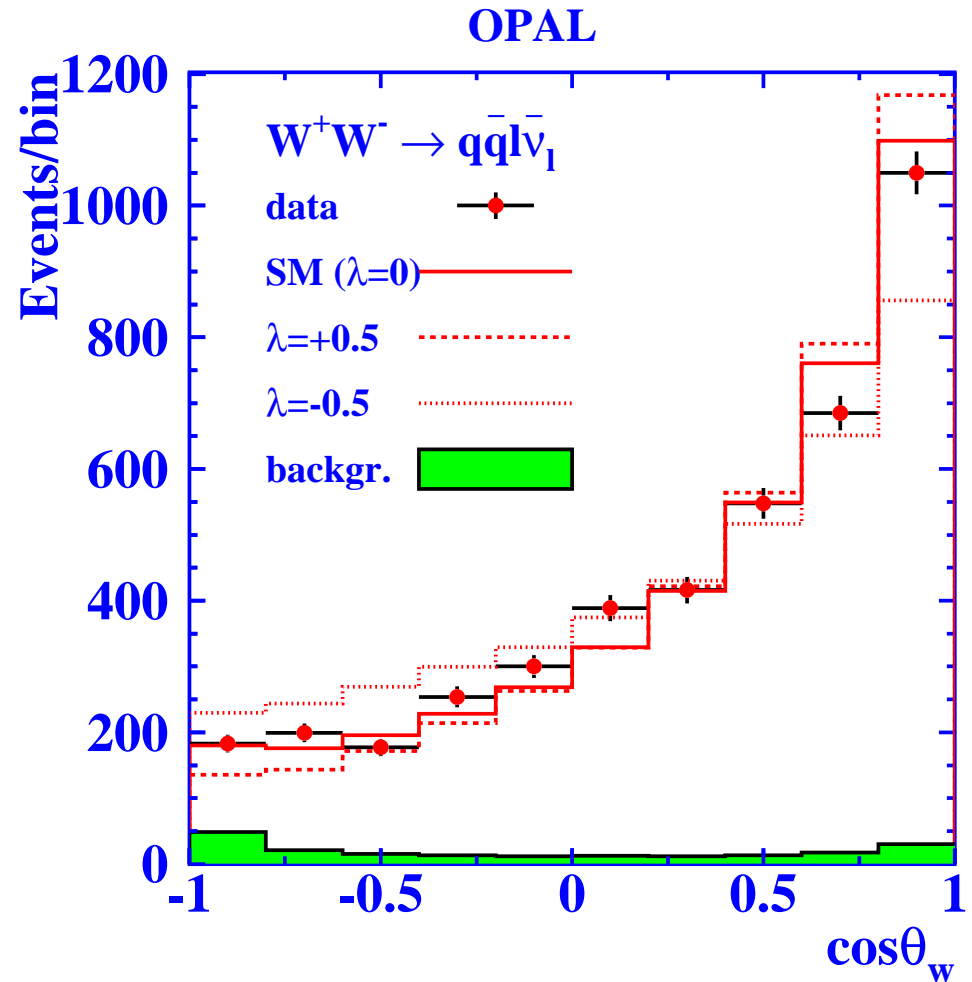
Sensitivity to charged TGC from WW, single W and single γ production.

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.

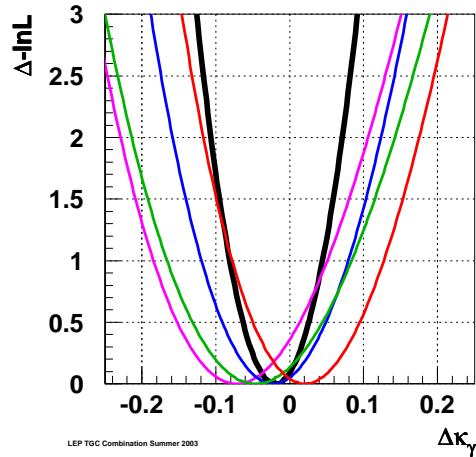
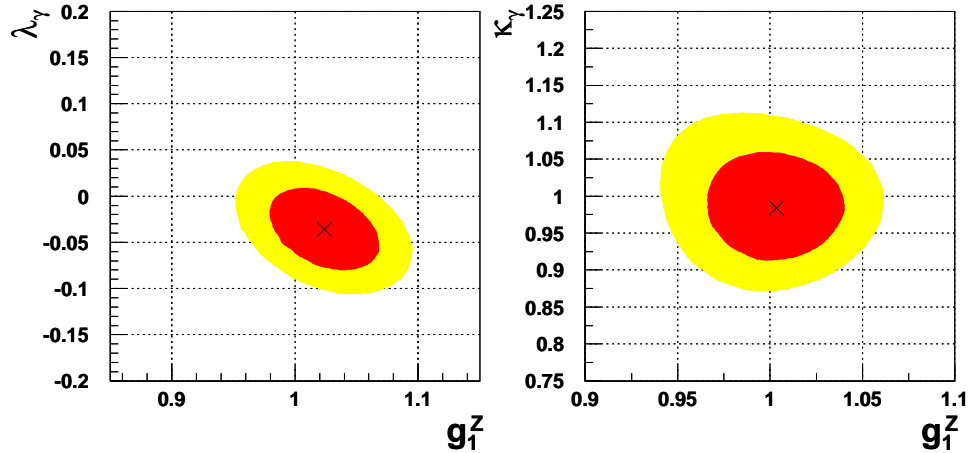
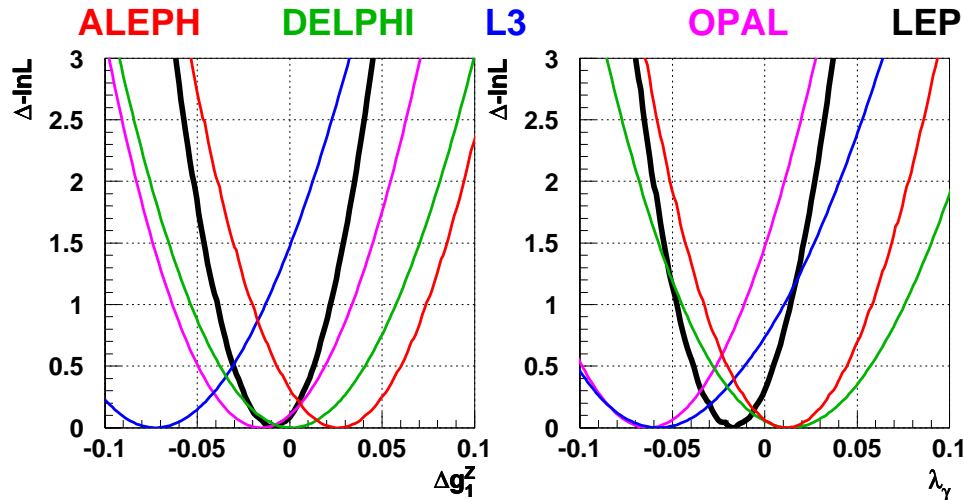


TGC results

New: DLO Updated, O → final

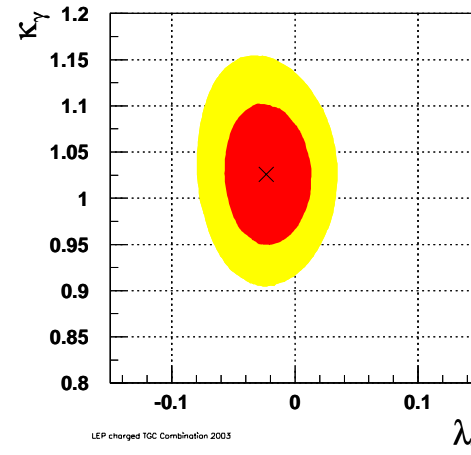
1d fits (LEP combined)

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



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



LEP Preliminary

- 95% CL
- 68% CL
- × 2d fit result

Results combined at the level of likelihoods.

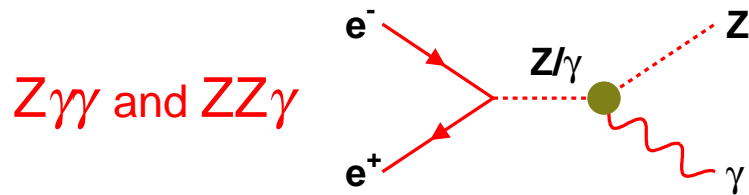
Couplings consistent with SM, with precision of a few %.

Neutral TGC

No neutral TGC in SM.

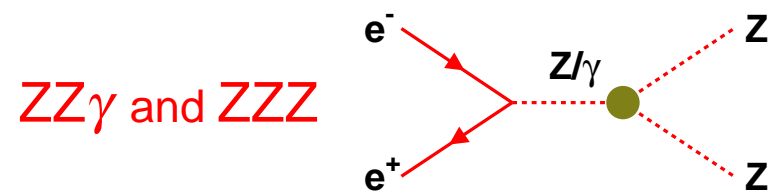
Search for anomalous nTGC from $Z\gamma$ and ZZ cross-sections and differential distributions.

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



From $e^+e^- \rightarrow Z\gamma$, $Z \rightarrow q\bar{q}$ or $\nu\bar{\nu}$
Dominant background from ISR.

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



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

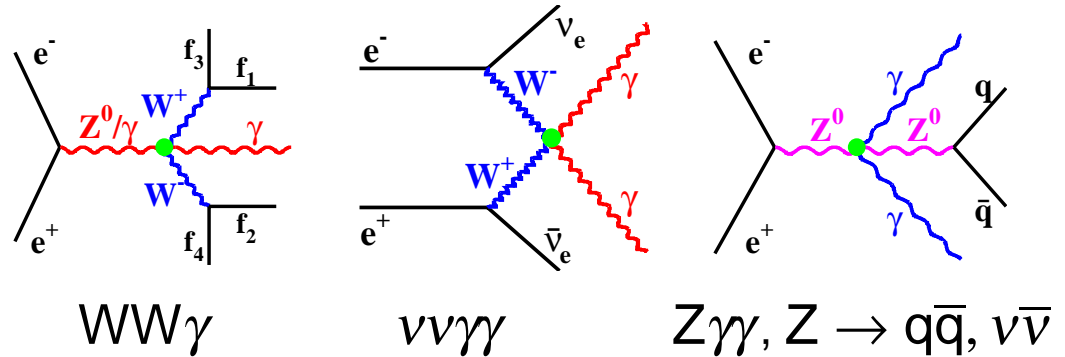
New: LO ZZ results \Rightarrow final

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.



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.



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



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

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

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.

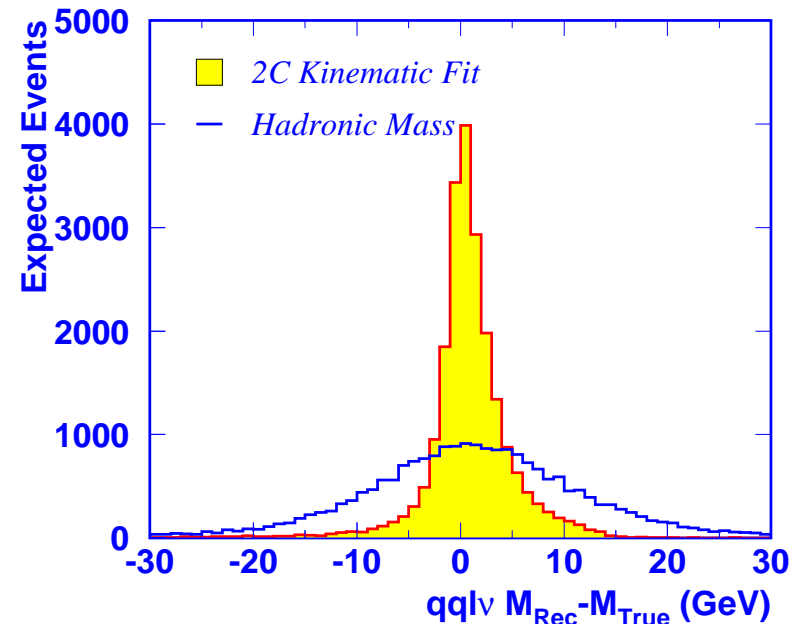
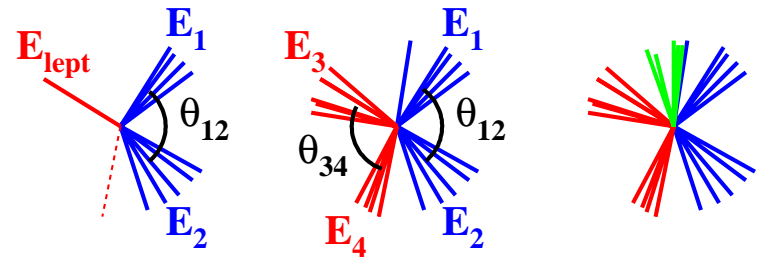
$q\bar{q}l\nu$: ν not measured, but no ambiguity assigning particles to W's

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

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

Γ_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 $M_{12} = M_{34}$

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

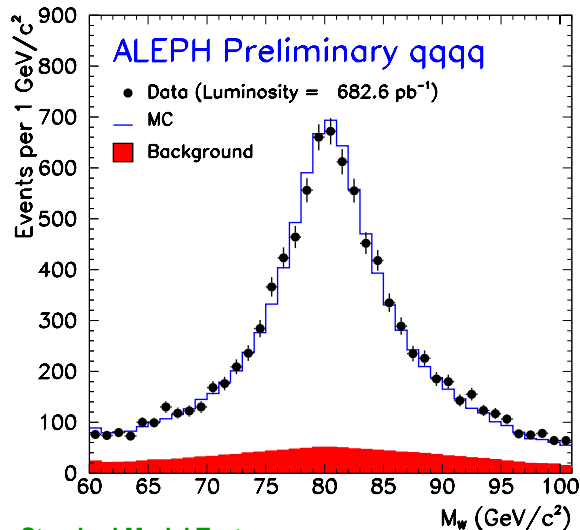
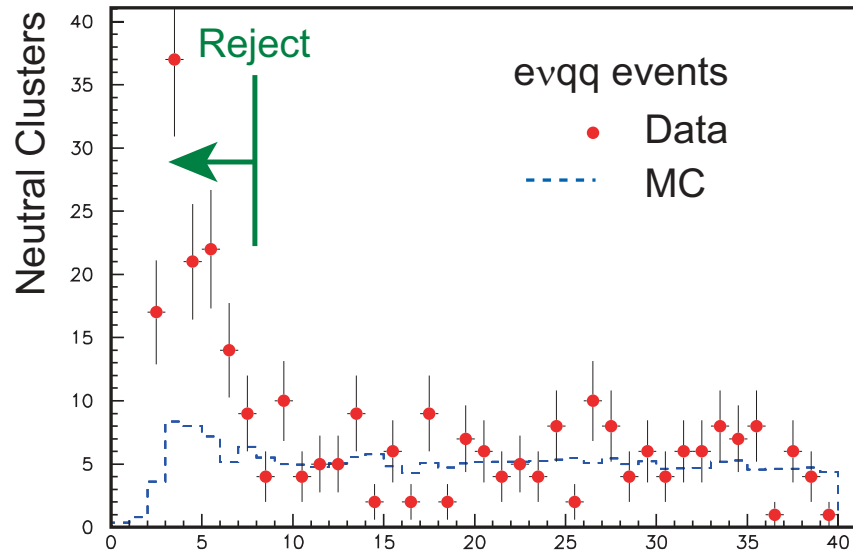
W mass at LEP

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

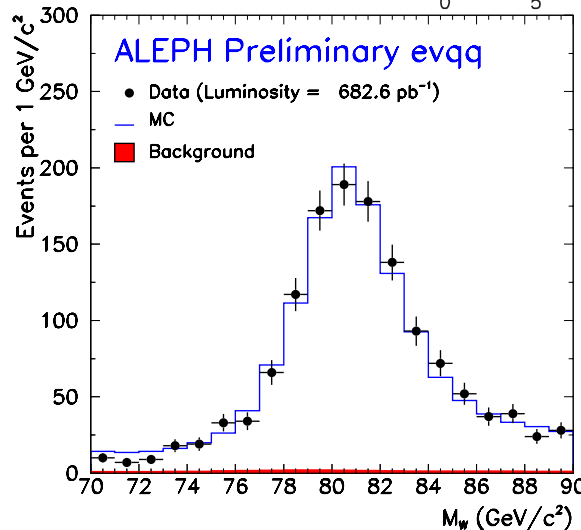
Problem simulating shower satellites in ECAL - low E neutral clusters, especially near electrons. Extra clusters near electron bias jet directions. In general, jet masses biased.

Solutions:

- Improved shower simulation with EGS.
- Reject “single stack” neutral clusters: “cleaning”
- Some discrepancy remains \Rightarrow reject neutrals within 8 degrees of electron at calorimeter (keep Bremsstrahlung γ)



Standard Model Tests



Pippa Wells

Angle from electron (deg)

No evidence of similar problem in other experiments.

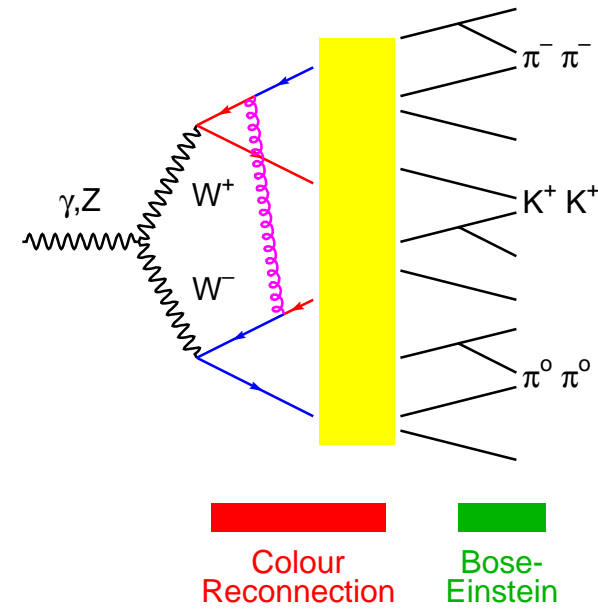


Example M_W distributions for $q\bar{q}q\bar{q}$ and $e\nu q\bar{q}$

W mass systematics

Dominant errors (LEP combined)

	$q\bar{q}l\nu$	$q\bar{q}q\bar{q}$	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 qq̄q̄q̄ final state

Models: SK-I (free parameter κ), 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 κ . 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.

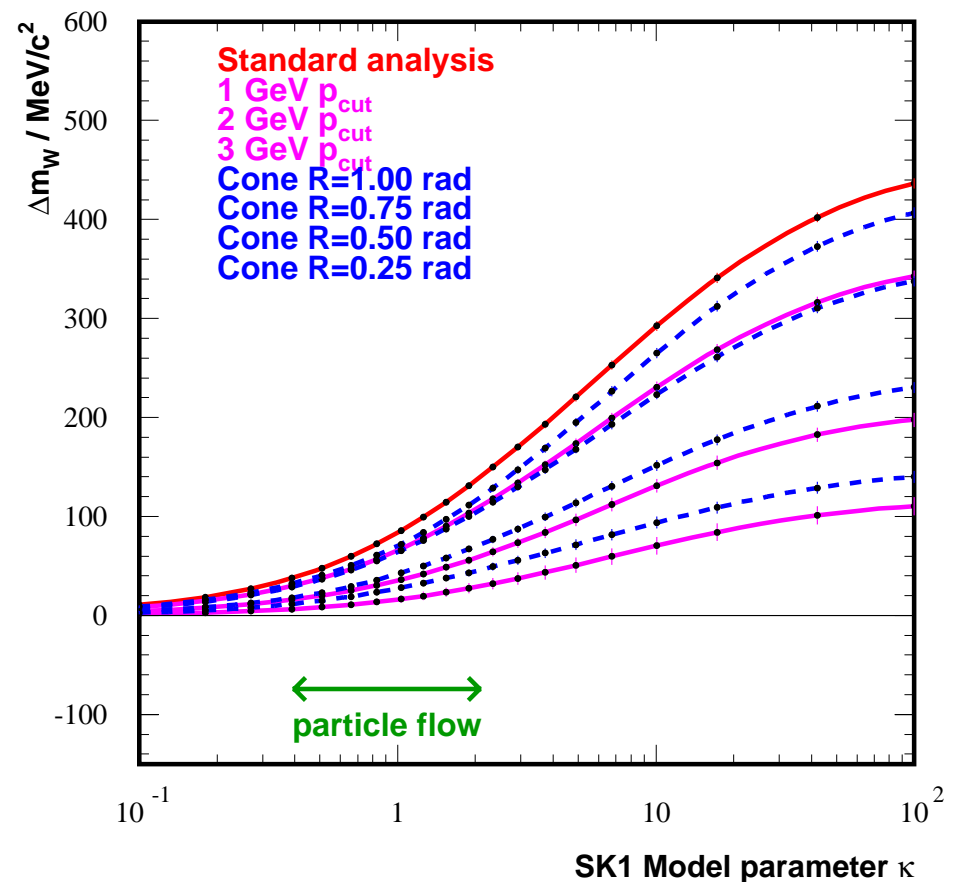
Shift in W mass due to CR reduced but statistical error increases.

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.

DELPHI preliminary SK1 curves



Bose-Einstein correlations

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

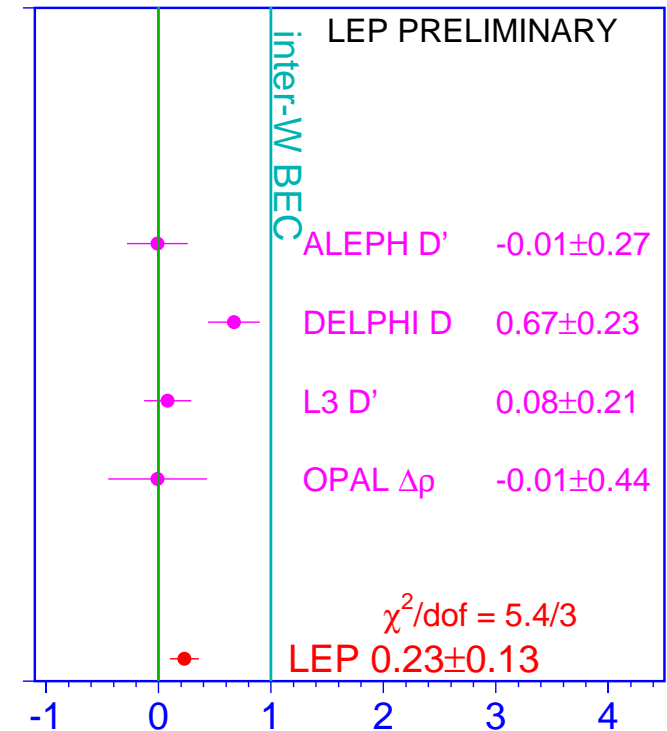
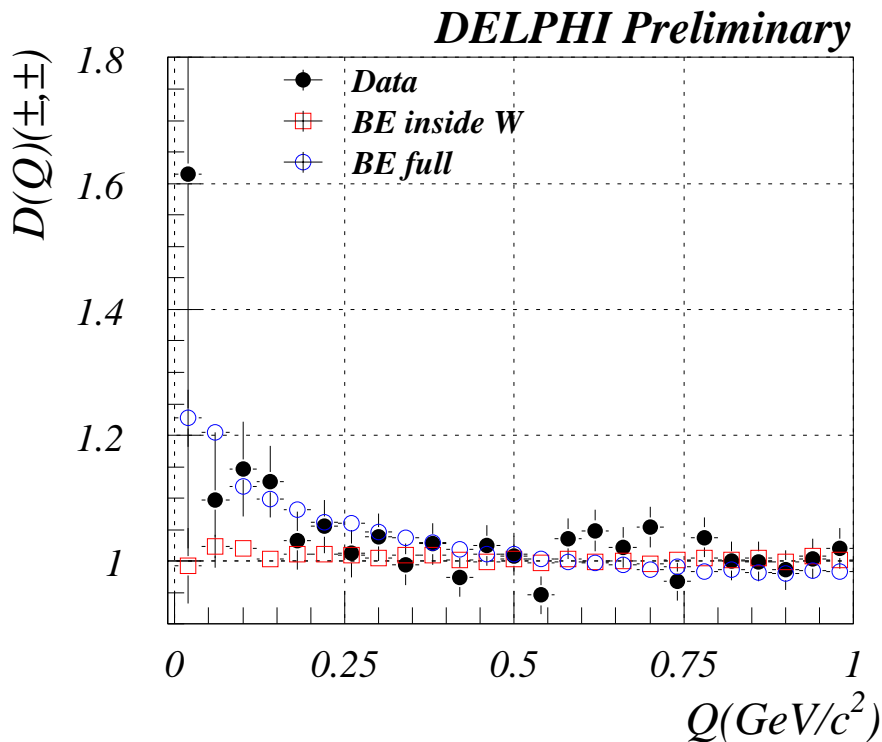
For independent W's, inclusive two-particle density in $q\bar{q}q\bar{q}$ events is ($Q^2 = (p_1 - p_2)^2$)

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

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

Consider difference $\Delta\rho(Q) = \rho^{WW}(Q) - \rho^{WW}(Q)_{\text{indep}}$ 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 fraction of model seen

W mass from LEP

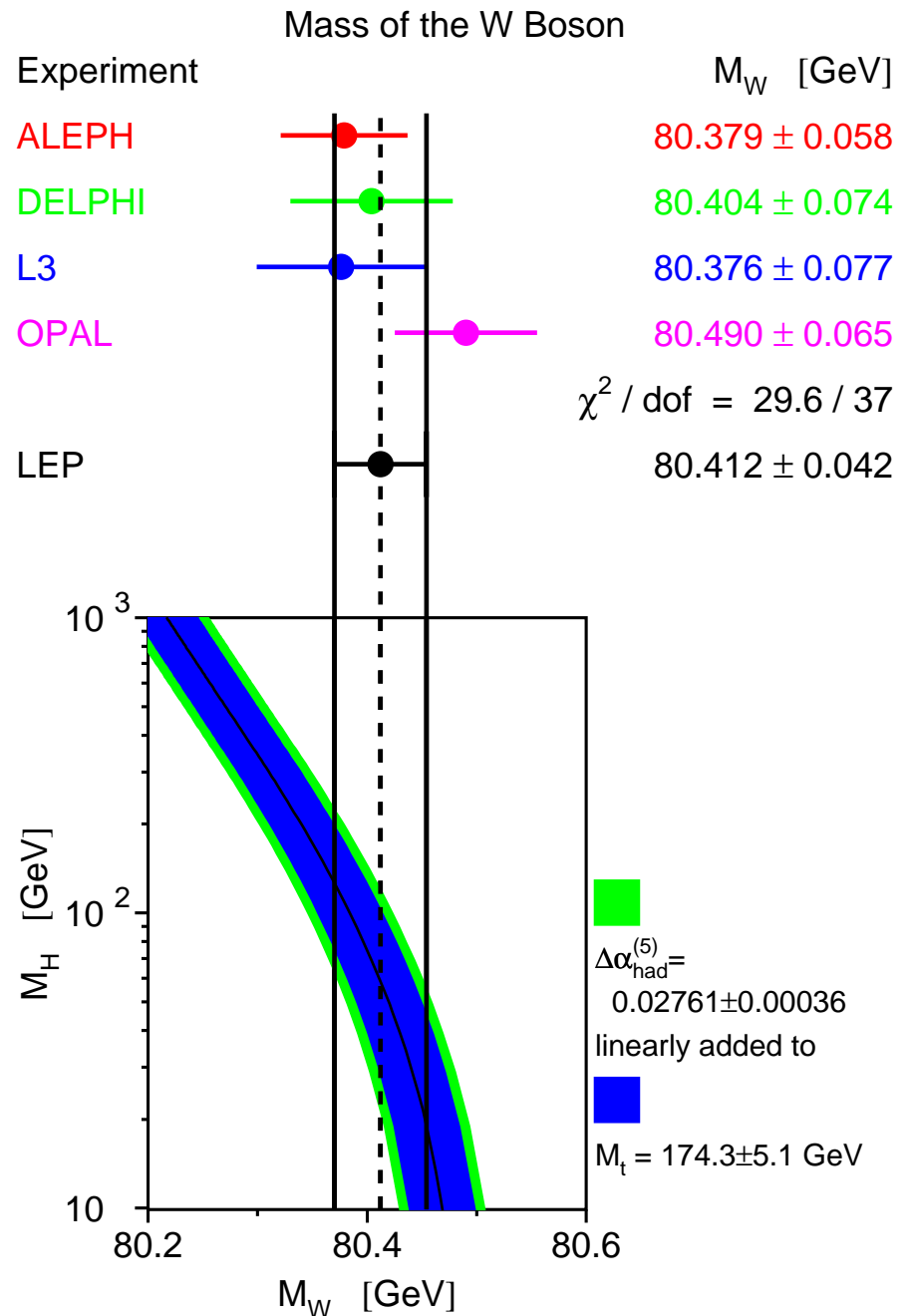
All results preliminary, 1996-2000 data (OPAL 1996-1999 data).

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

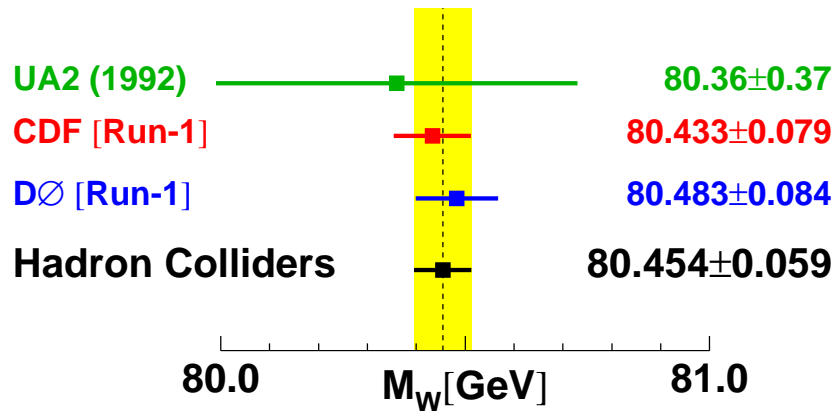
W mass from Tevatron

Run I results final (CDF e, μ , 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: $M_T^2 = 2p_T^\ell p_T^\nu (1 - \cos(\phi^\ell - \phi^\nu))$

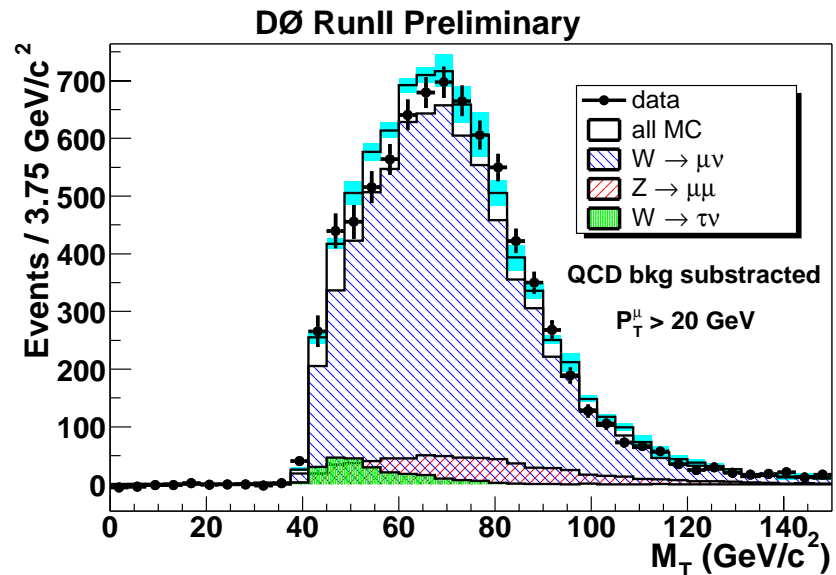
D0 also fit $p_T^\ell, p_T^{\text{miss}} = p_T^\nu$ and quote combined result

Average from Run I plus UA2



Run I $M_W = 80.454 \pm 0.059 \text{ GeV}$

Example M_T distribution from Run II (D0)



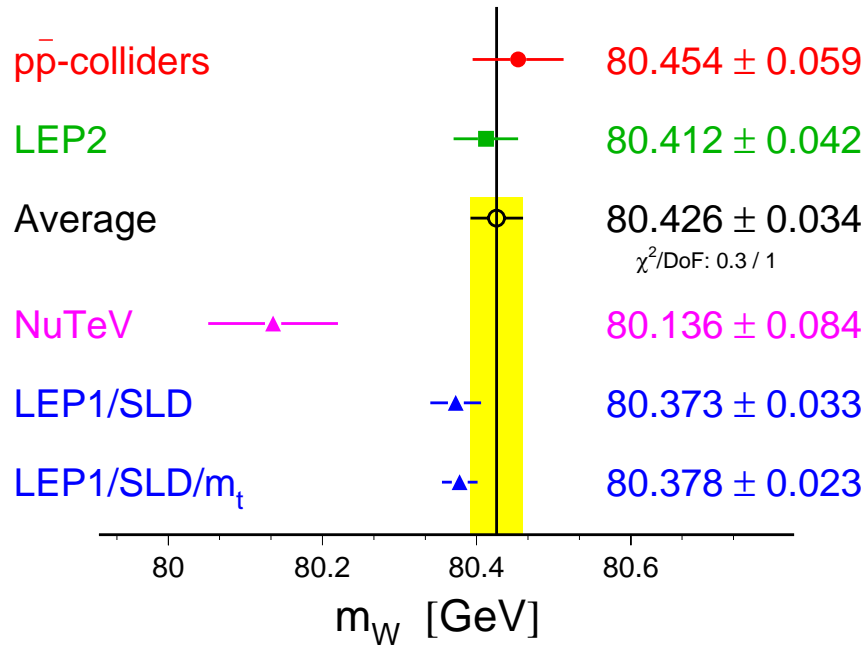
Systematic errors will be reduced with more luminosity

- 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

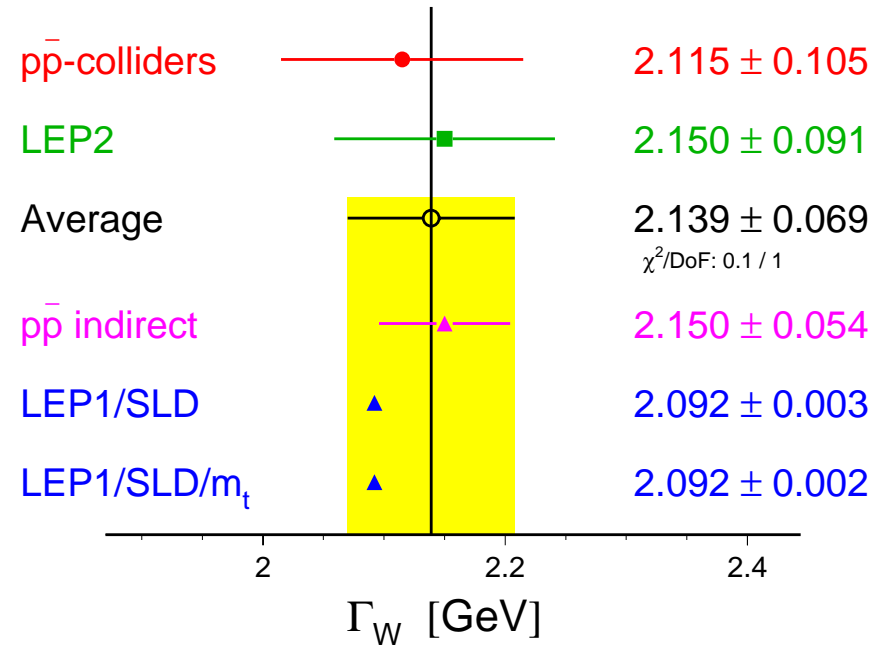
World Average W mass and width

LEP2 updated

W-Boson Mass [GeV]



W-Boson Width [GeV]



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

Indirect results from global fits will be discussed later.

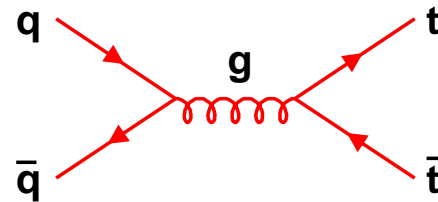
NuTeV measure CC and NC rates for ν_μ and $\bar{\nu}_\mu$. Related to $\sin^2 \theta_W = 1 - \frac{M_W^2}{M_Z^2}$ (Paschos-Wolfenstein). No new proposals to explain this discrepancy

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

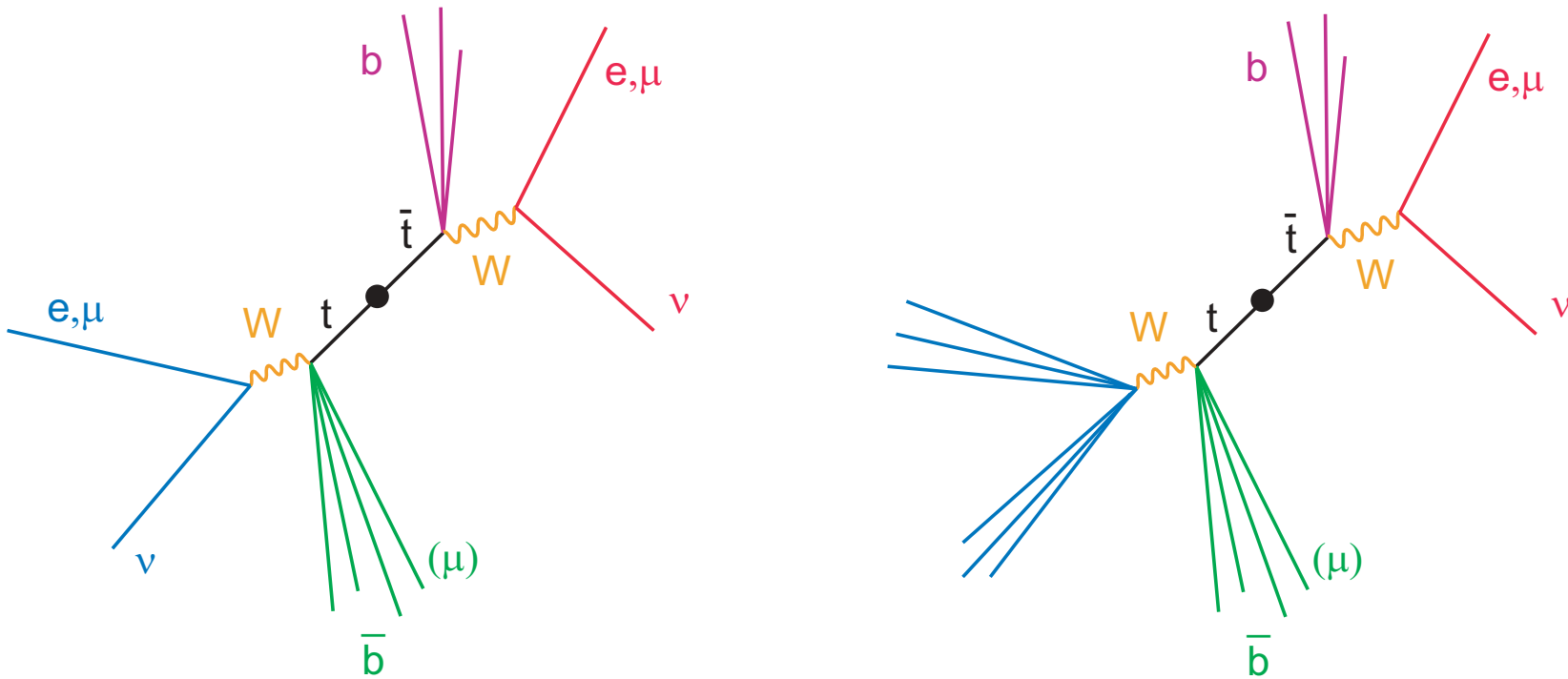
Top physics

Top quark production at Tevatron

Dominant production mechanism (90%)

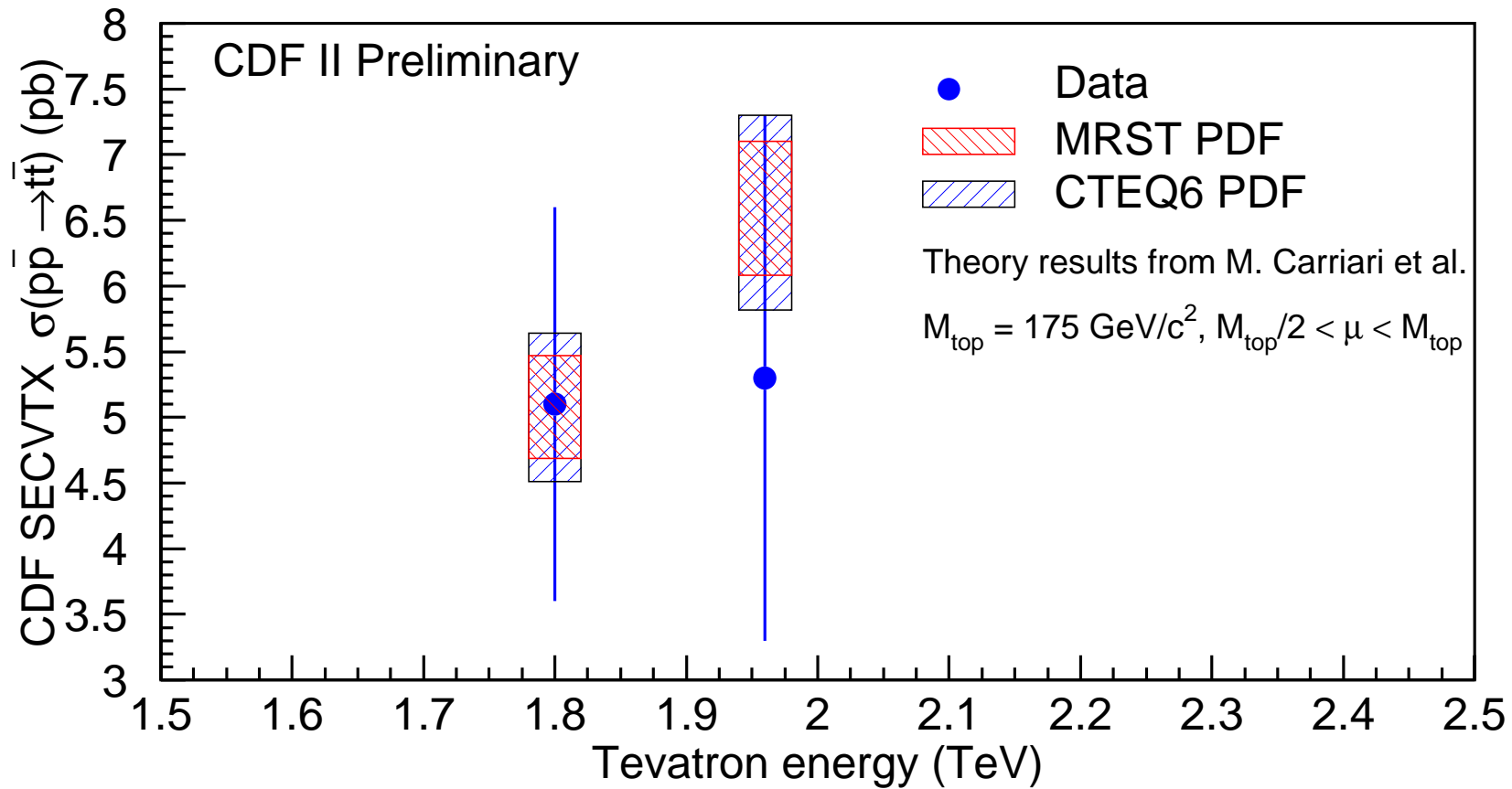


Top decays to W boson and b quark. Event topologies depend on W decay.



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

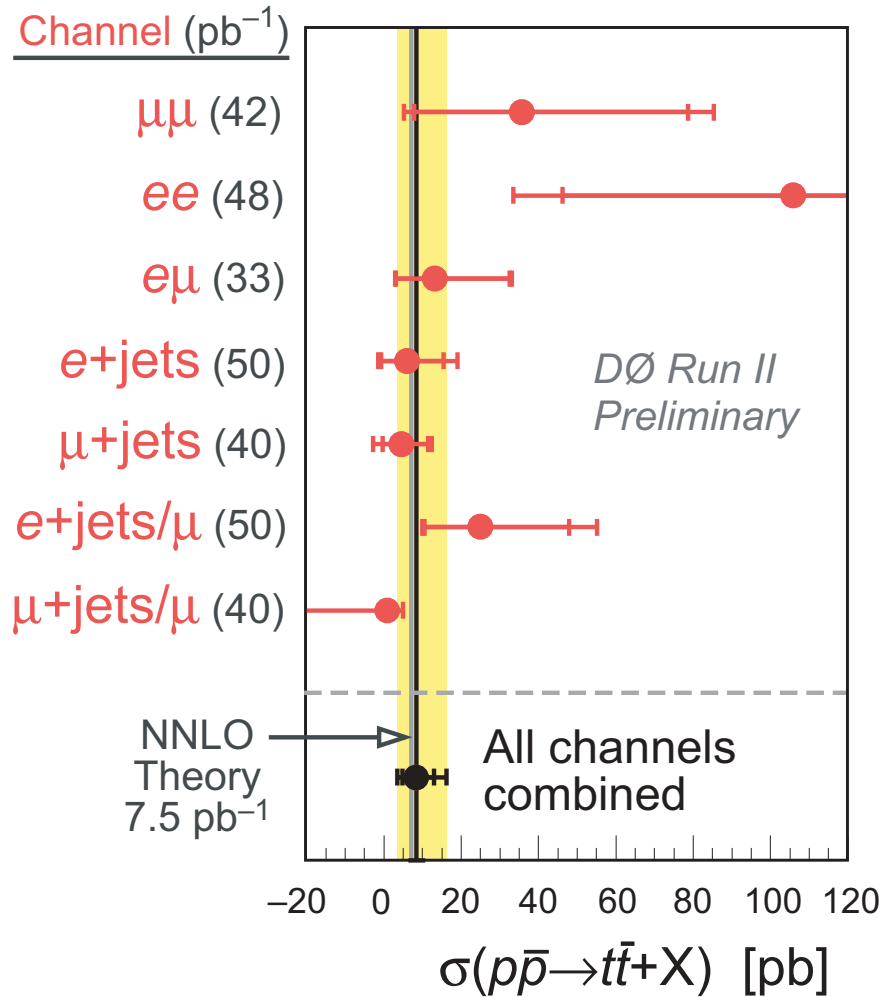
Lepton plus jets with vertex tag at CDF: Run I and Run II results



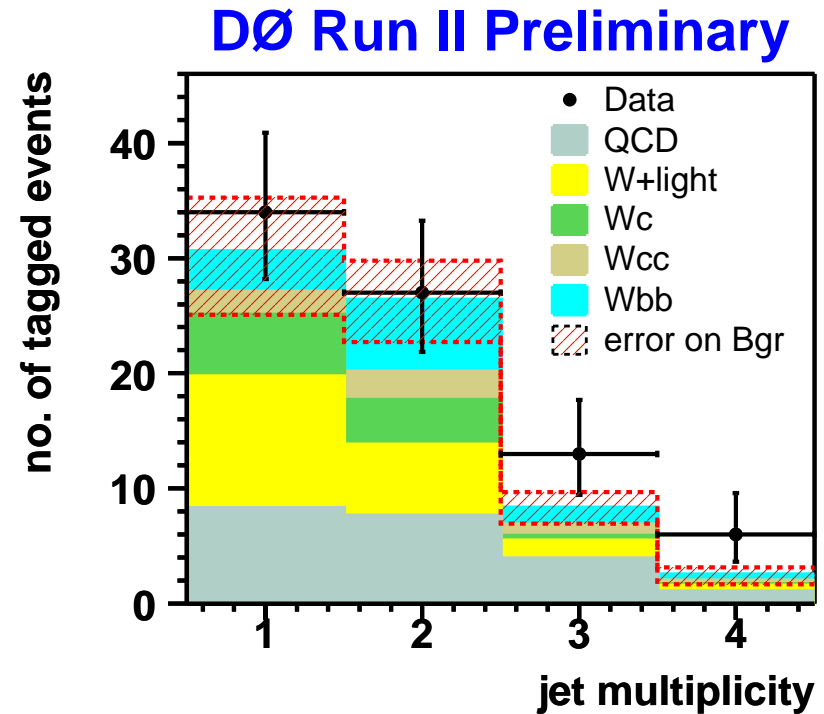
$\sigma_{t\bar{t}}$ (pb) with stat, syst and lumi errors	
CDF dilepton Run II	$13.2 \pm 5.9 \pm 1.5 \pm 0.8$
CDF ℓ +jets Run II	$5.3 \pm 1.9 \pm 0.8 \pm 0.3$

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	+6.3	± 0.8
D0 IP b-tag	7.4	+4.4	+2.1	± 0.7
		-3.7	-3.5	
		-3.6	-1.8	

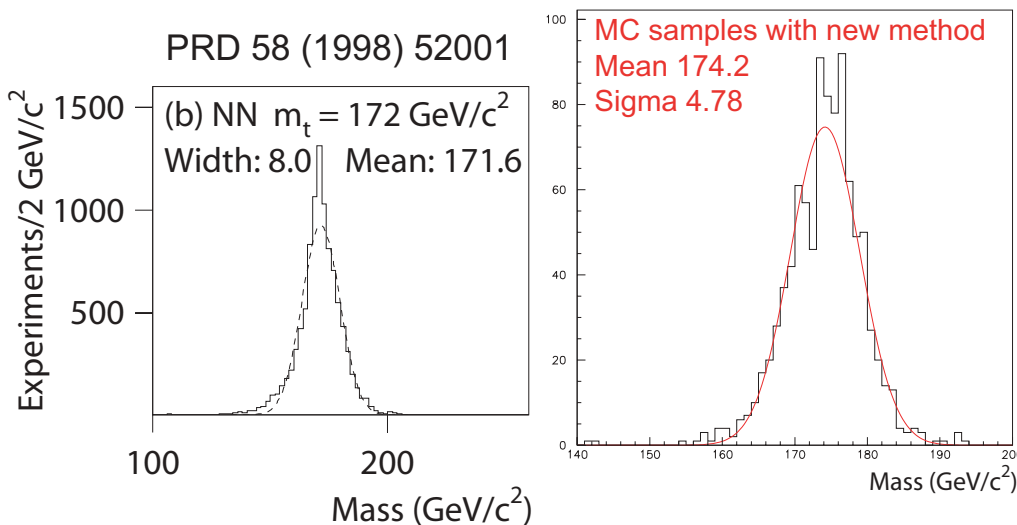
Top mass

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

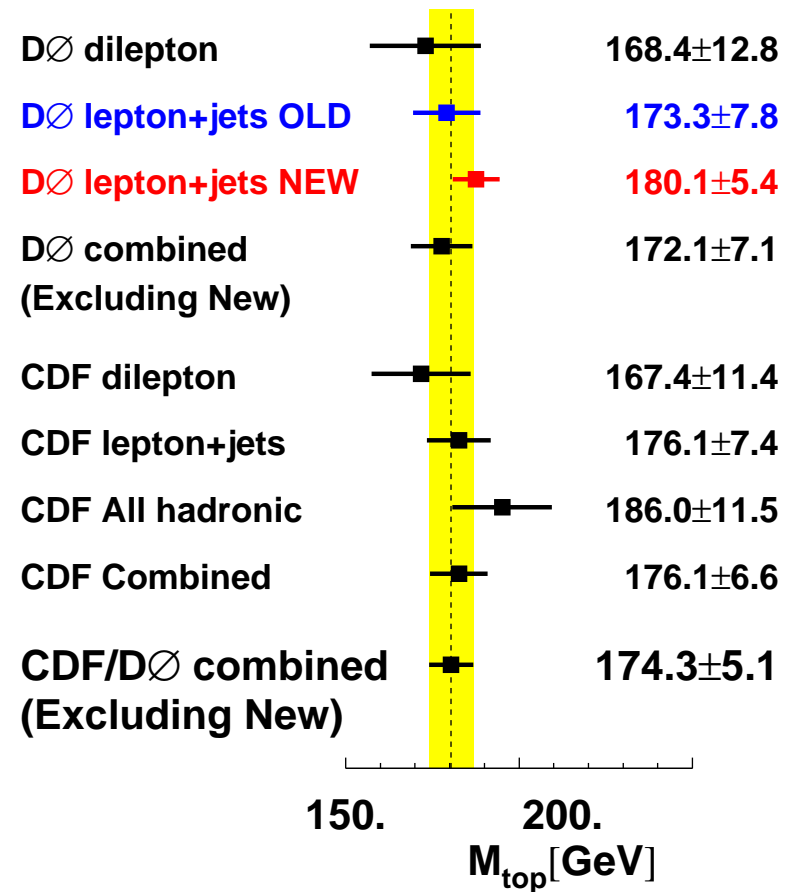
77 events (29 signal and 48 background) used in PRD 58 (1998) 052001.

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 ± 5.1 GeV
New D0 Run I ℓ +jets only	180.1 ± 3.6(stat.) ± 4.0(syst.) GeV
New CDF Run II ℓ +jets	171.2 ± 13.4(stat.) ± 9.9(syst.) GeV

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

Muon (g-2)

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

2002:

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

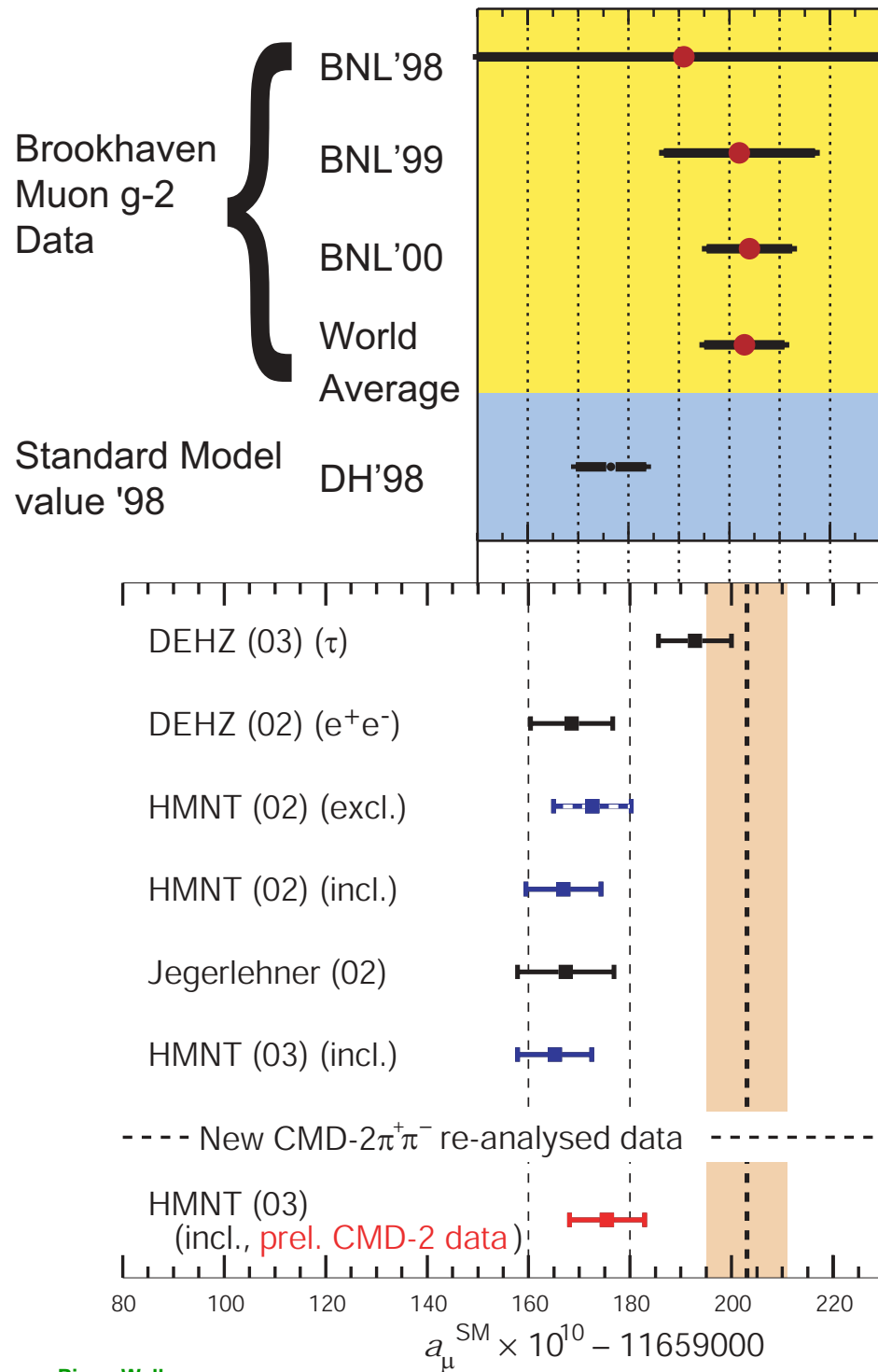
$$a_\mu = 11\,659\,203(8) \times 10^{-10}$$

Soon:

Result with 2001 μ^- data, with
 similar statistics to 2000 μ^+

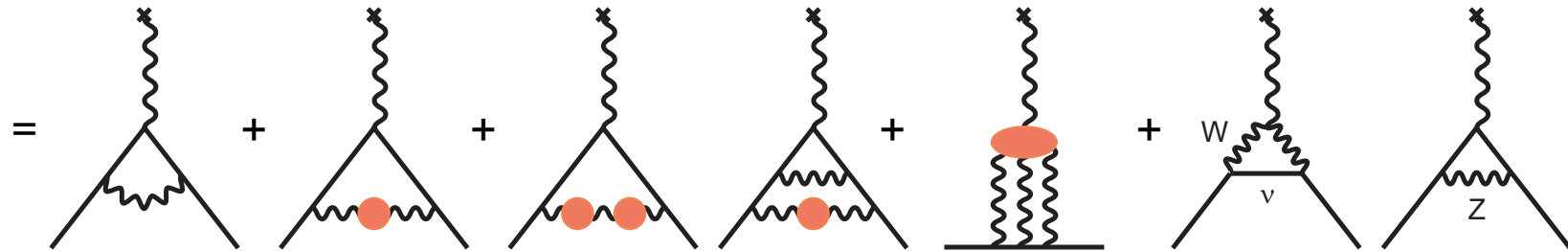
Problem: Value and spread of
 theoretical predictions

$$\text{New prelim CMD-2 July 2003!!!}$$



g-2 prediction

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



$$\begin{aligned}
 &= (\text{QED}) && (11\,658\,470.35 \pm 0.28)10^{-10} \text{ (5-loop!)} \\
 &+ (\text{had,LO}) && (684.7 \text{ to } 709.0 \pm 6)10^{-10} \text{ (Big spread, largest error)} \\
 &+ (\text{had,HO}) && (-10.0 \pm 0.6)10^{-10} \\
 &+ (\text{had,LBL}) && (8.0 \pm 4.0)10^{-10} \text{ (sign change since 1998)} \\
 &+ (\text{weak}) && (15.4 \pm 0.2)10^{-10} \text{ (2-loop)}
 \end{aligned}$$

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

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

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

σ_{had}^0 bare cross-section for $e^+e^- \rightarrow \text{hadrons}$, 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? σ_{had}^0 from **Inclusive vs Σ exclusive vs τ spectral functions?**

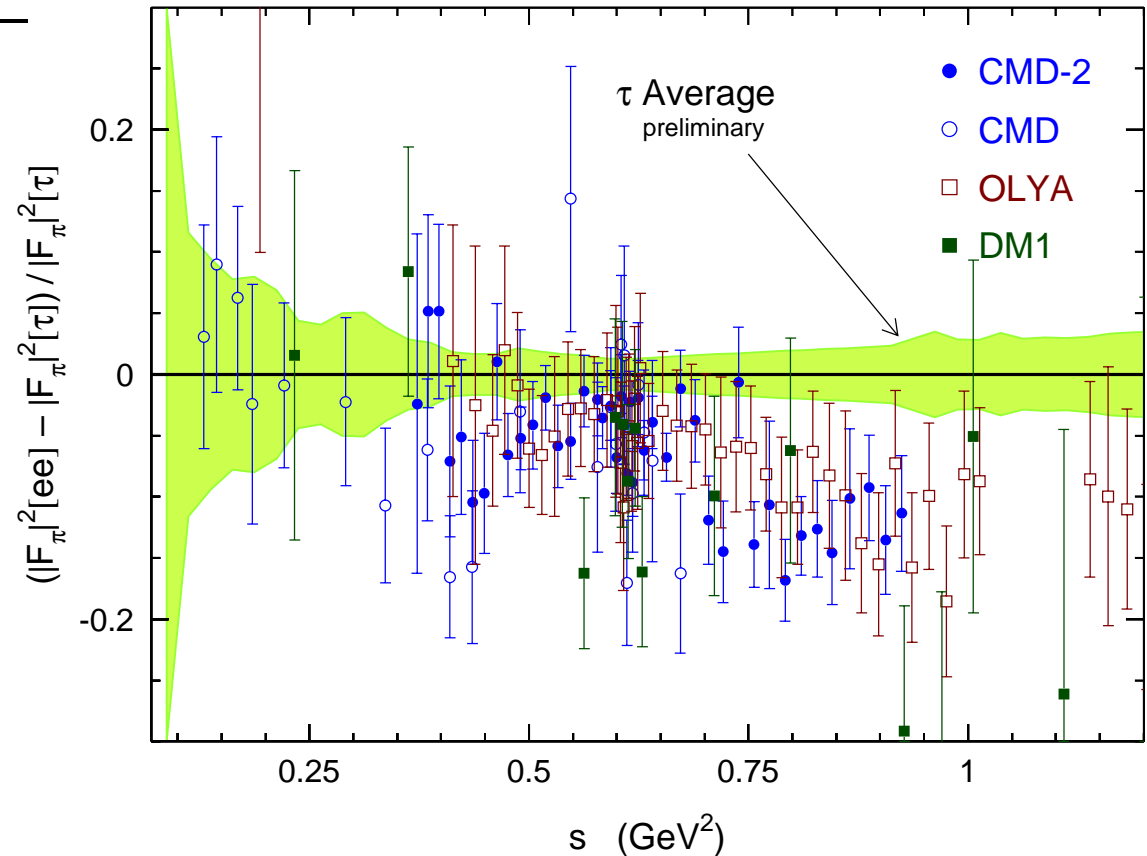
(Hagiwara, Martin, Nomura, Teubner)

Range/GeV	$\Delta a_\mu^{\text{had,LO}} \cdot 10^{10}$
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 τ 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 τ result

Calculation of $\alpha(M_Z^2)$

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

with $\alpha(0) = 1/137.03599976(50)$

Hadronic part from dispersion integral:

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

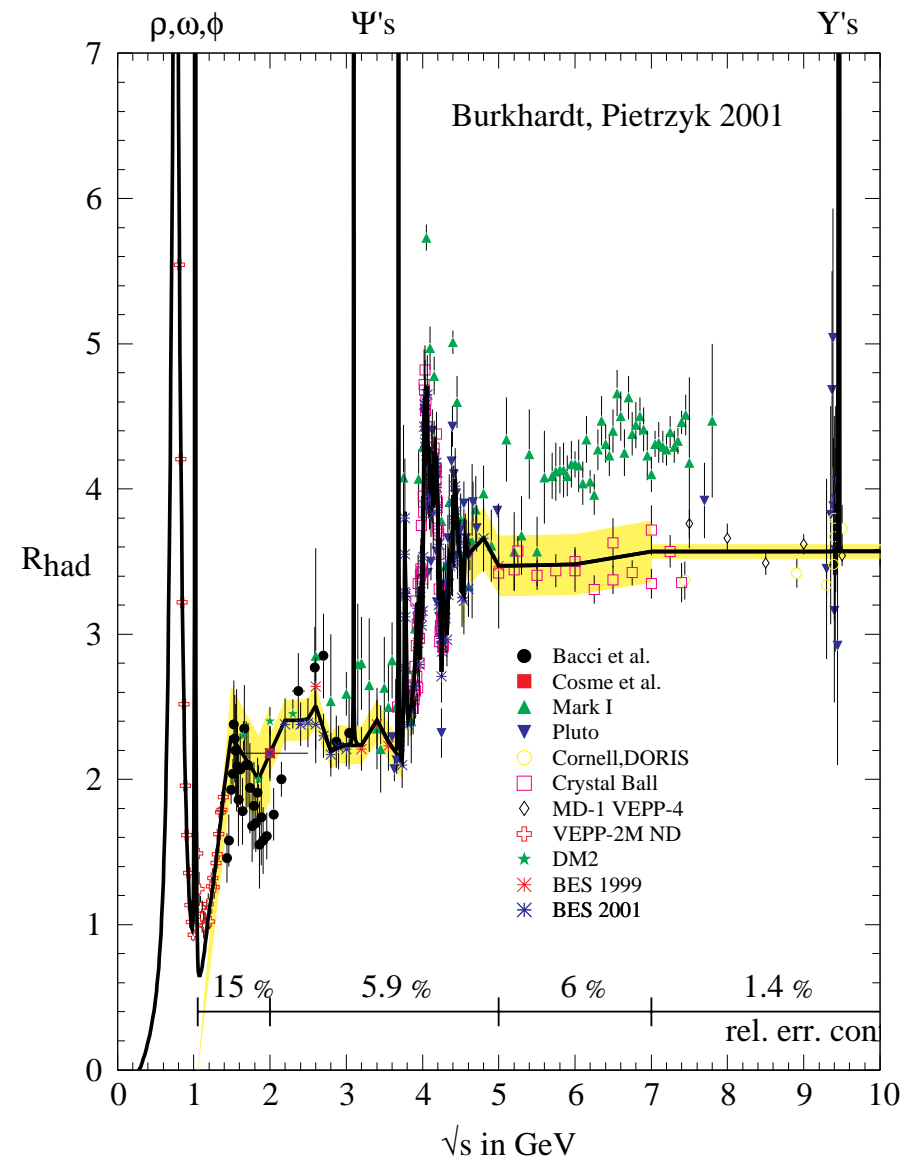
$$R_{\text{had}}(s) = \sigma_{\text{had}}^0 / (\sigma_{\mu\mu}^0 = 4\pi\alpha^2/3s)$$

Biggest recent improvement from BESII.

Future: CMD-2, BEPCII, KLOE, BABAR, BELLE (radiative return)

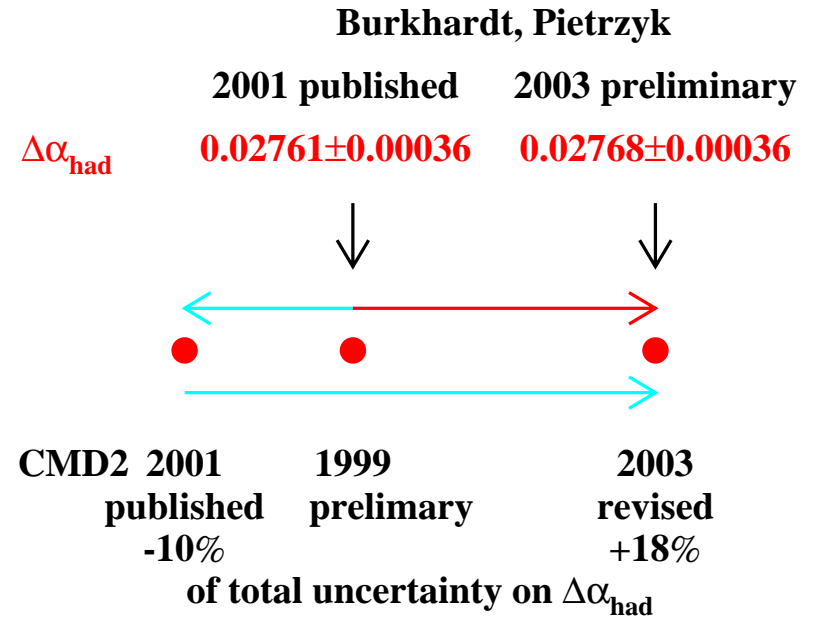
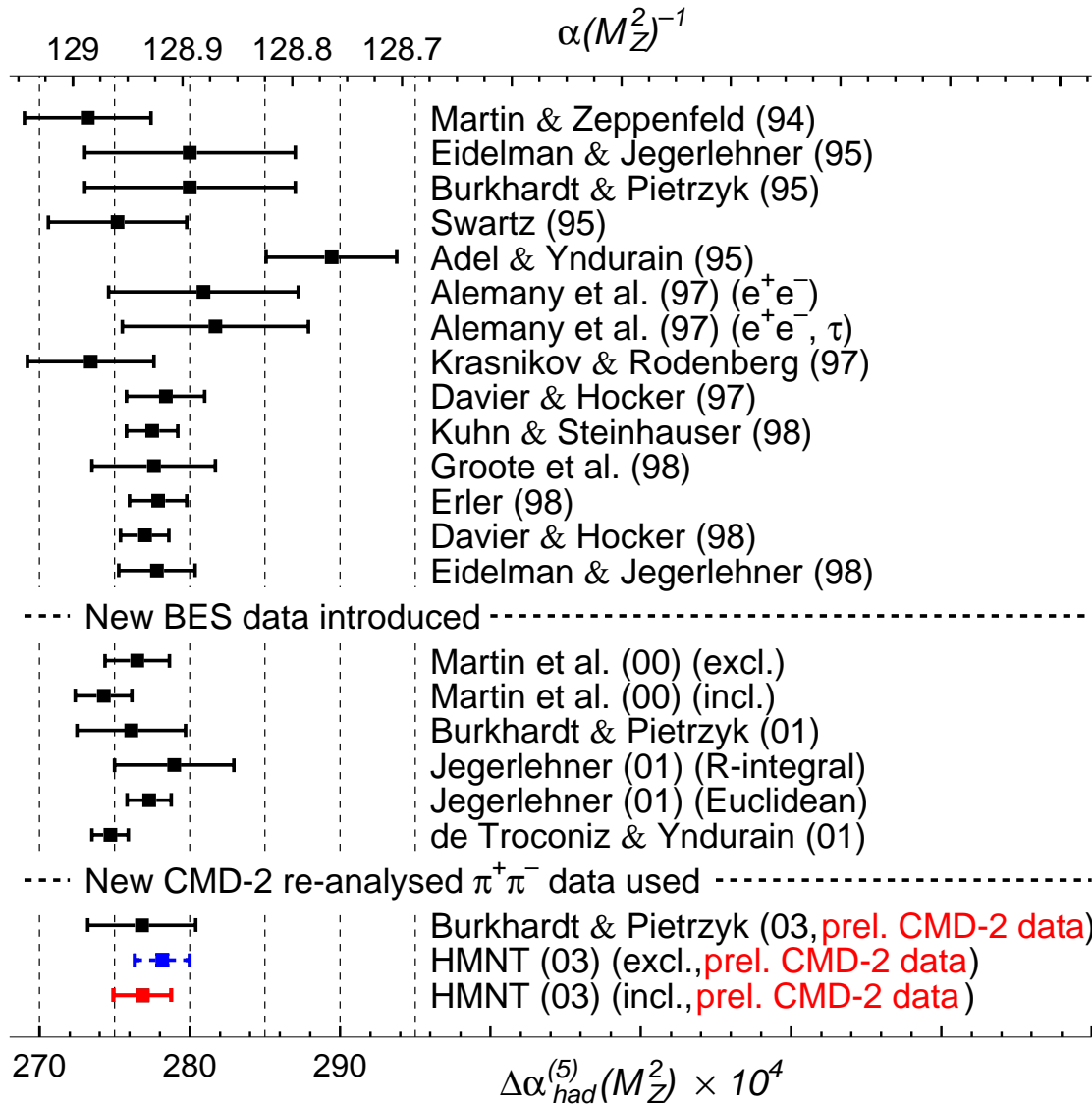
At present LEPEWWG use result based on data: $\Delta\alpha_{\text{had}}^{(5)}(M_Z^2) = 0.02761 \pm 0.00036$
Burkhardt, Pietrzyk 2001

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



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

Brand New



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:

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

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

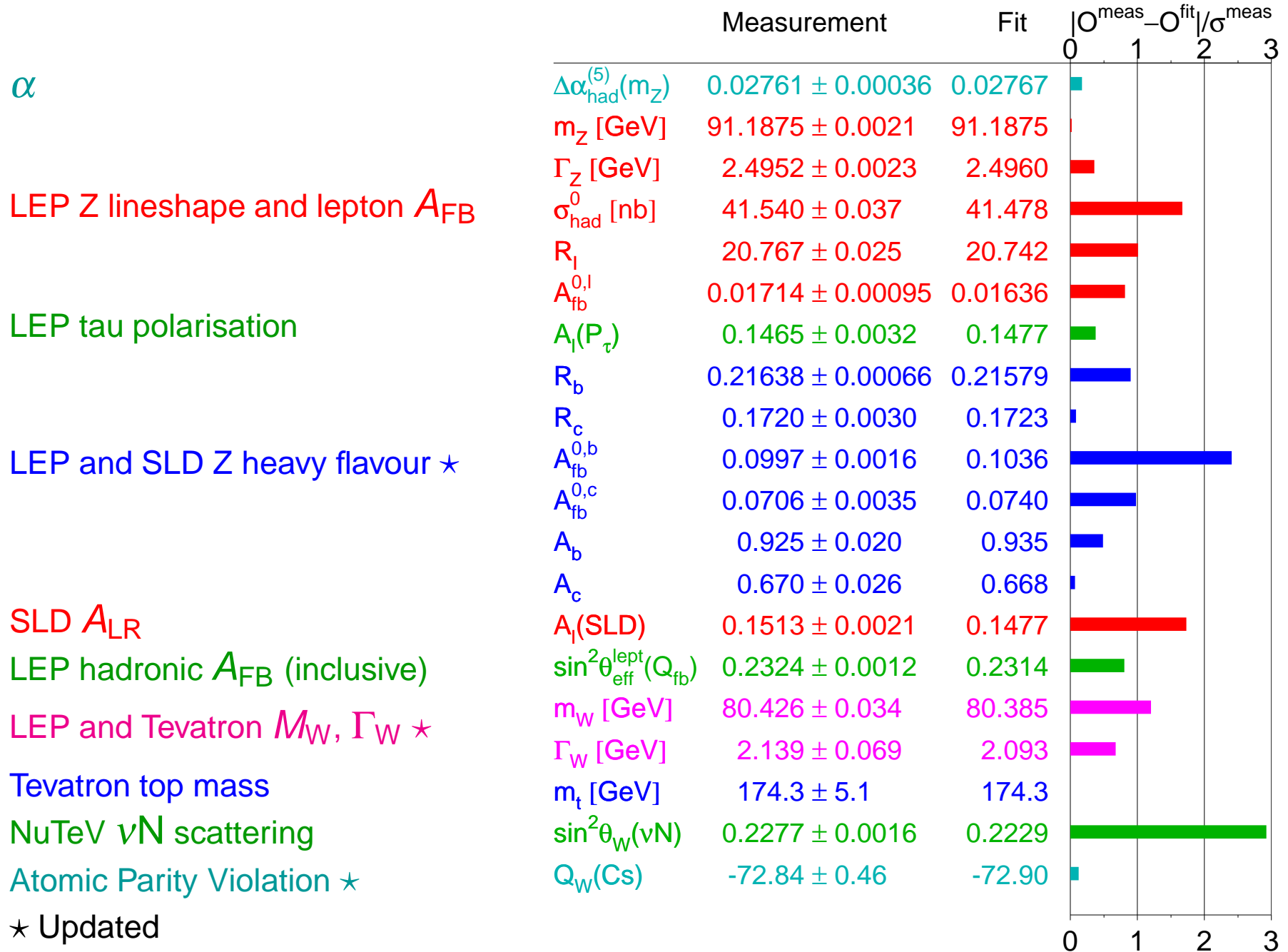
	All Z pole	All data	All but NuTeV
m_t (GeV)	$171.5^{+11.9}_{-9.4}$	$174.3^{+4.5}_{-4.4}$	$175.3^{+4.4}_{-4.3}$
m_H (GeV)	89^{+122}_{-45}	96^{+60}_{-38}	91^{+55}_{-36}
$\alpha_S(M_Z^2)$	0.1187 ± 0.0027	0.1186 ± 0.0027	0.1185 ± 0.0027
χ^2/dof (P)	14.7/10(14.3%)	25.4/15(4.5%)	16.7/14(27.5%)

No external α_S input. Additional theoretical syst. errors not included at this stage

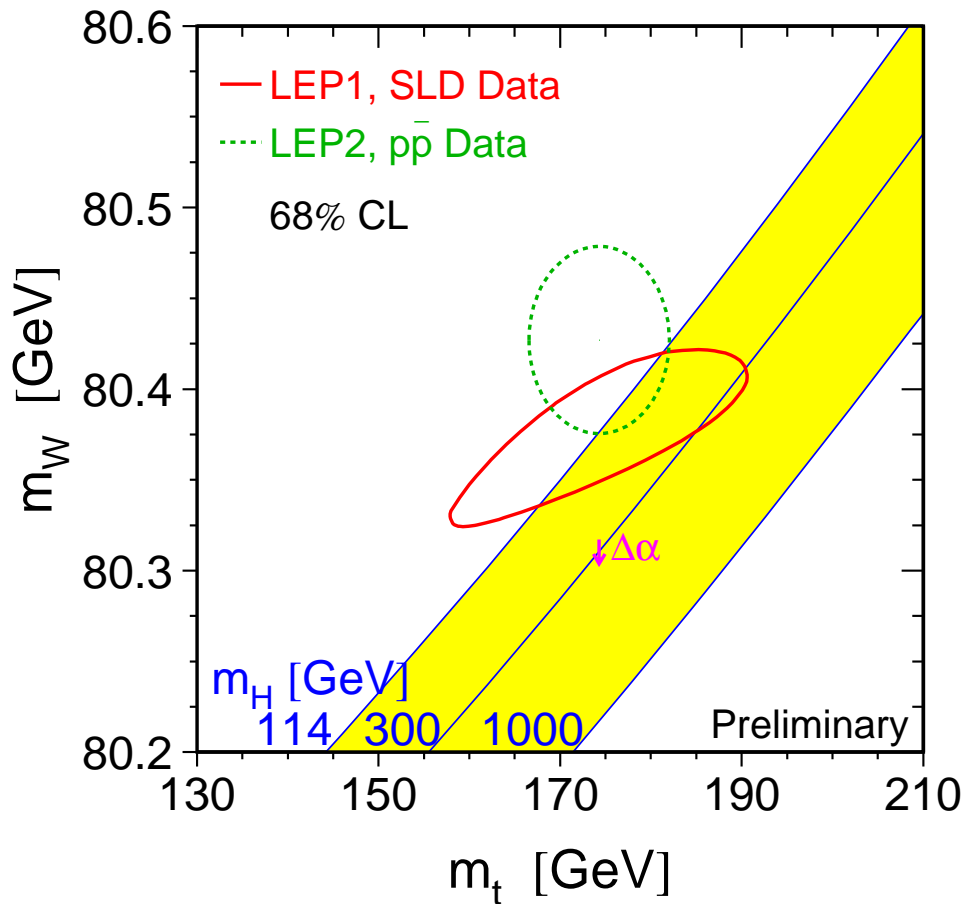
<http://lepewwg.web.cern.ch/LEPEWWG/>

Global electroweak fit

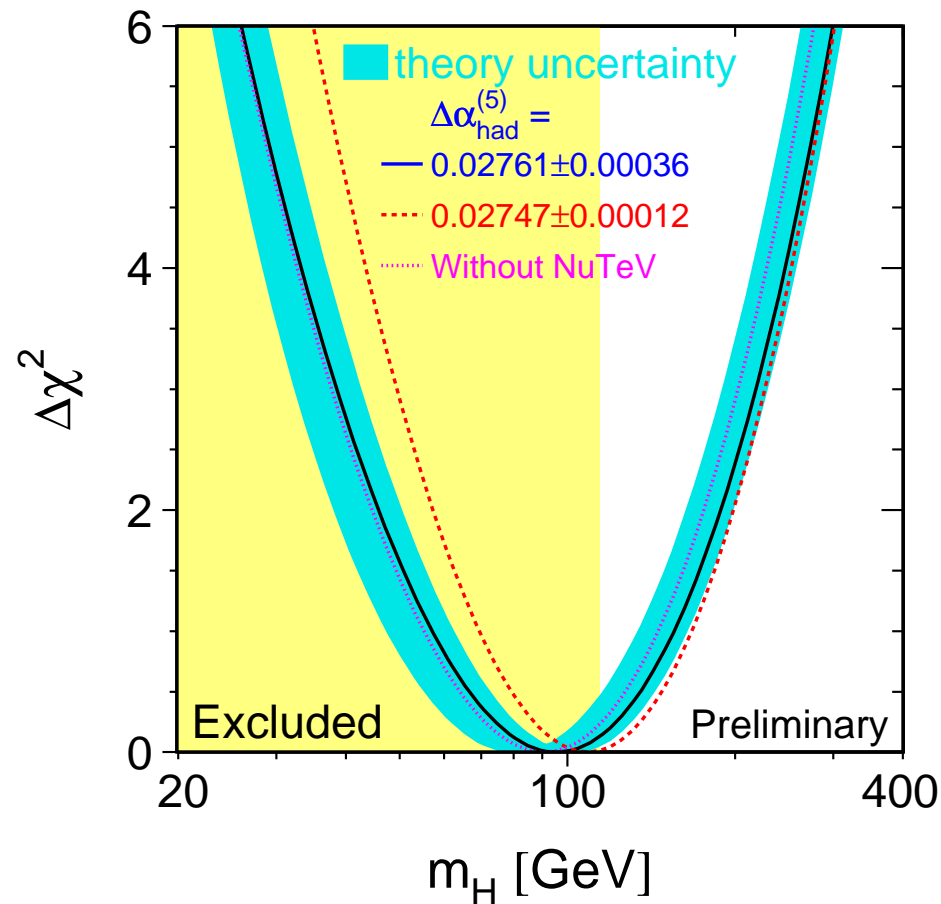
Summer 2003



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

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

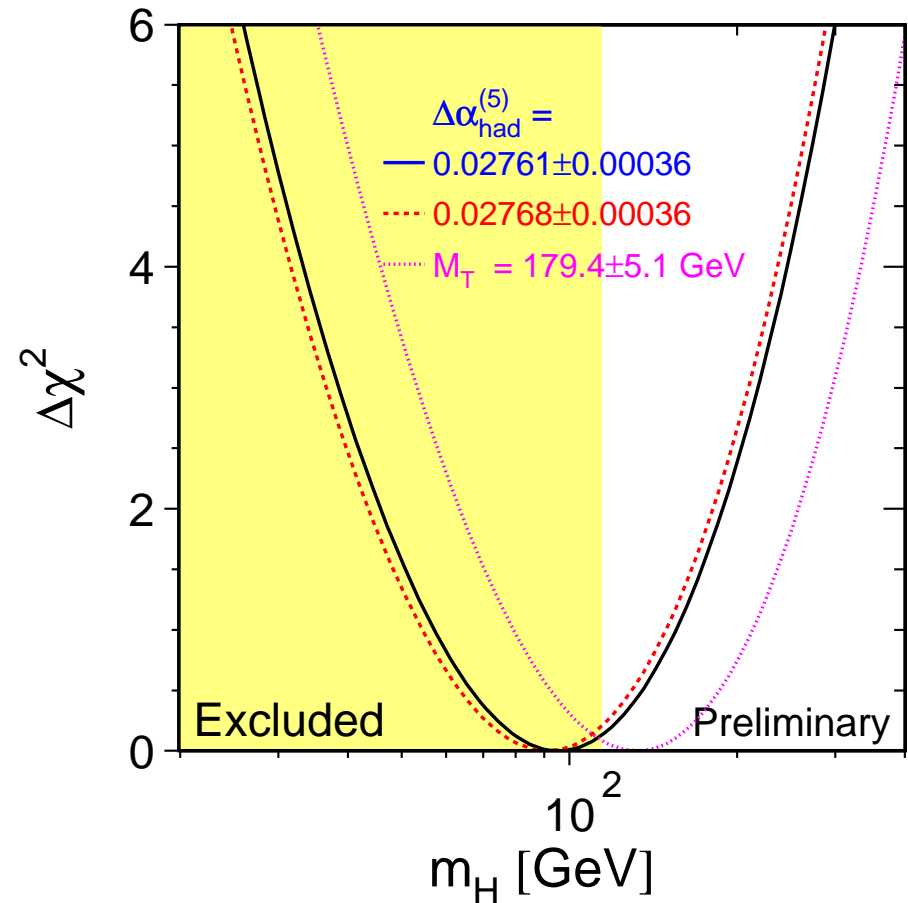
But what if.....?

Use the new value for $\Delta\alpha_{\text{had}}^{(5)}(M_Z^2)$
(Burkhardt+Pietrzyk 2003)?

Small downward shift in M_{Higgs}
(min. 96 \rightarrow 91 GeV, limit 219 \rightarrow 210 GeV)

The top mass increases by 1σ to
 179.4 ± 5.1 GeV?

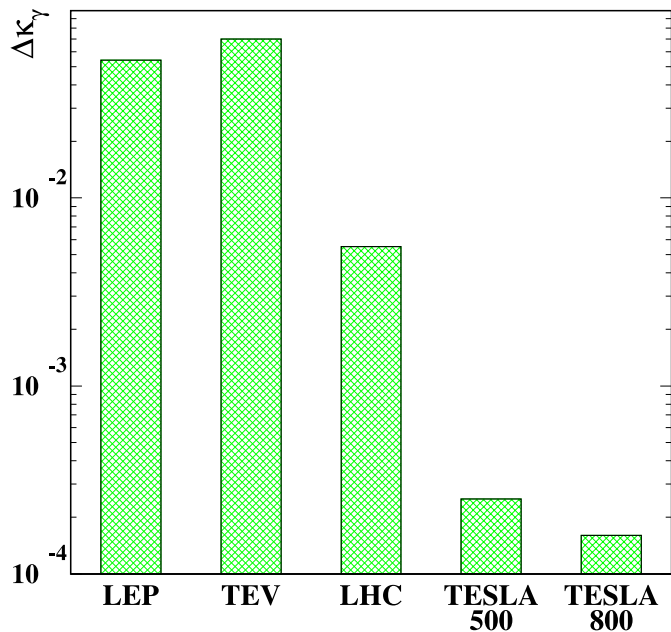
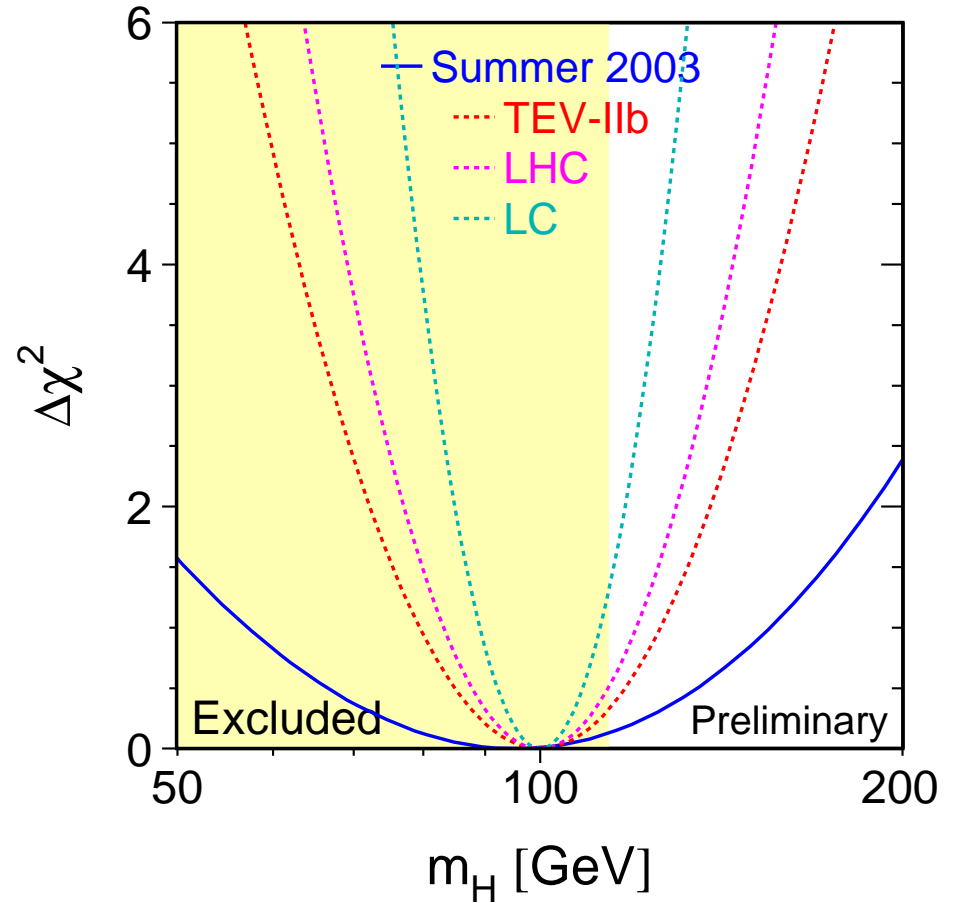
Large upward shift in M_{Higgs}
(min. 96 \rightarrow 126 GeV, limit 219 \rightarrow 283 GeV)



Future

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

	M_W (MeV)	m_t (GeV)	$\sin^2 \theta_{\text{eff}}^{\text{lept}}$
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 $\sim 3\sigma$)

- $A_{\text{FB}}^{0,b}$ 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 \Rightarrow discrepancy $\sim 2.5\sigma$.

What to look forward to?

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

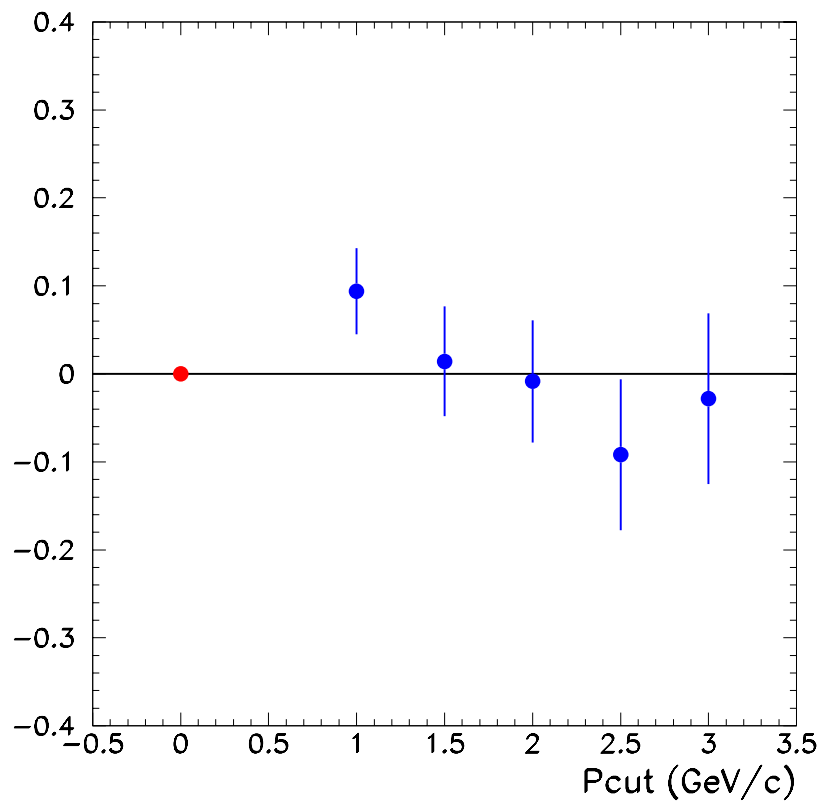
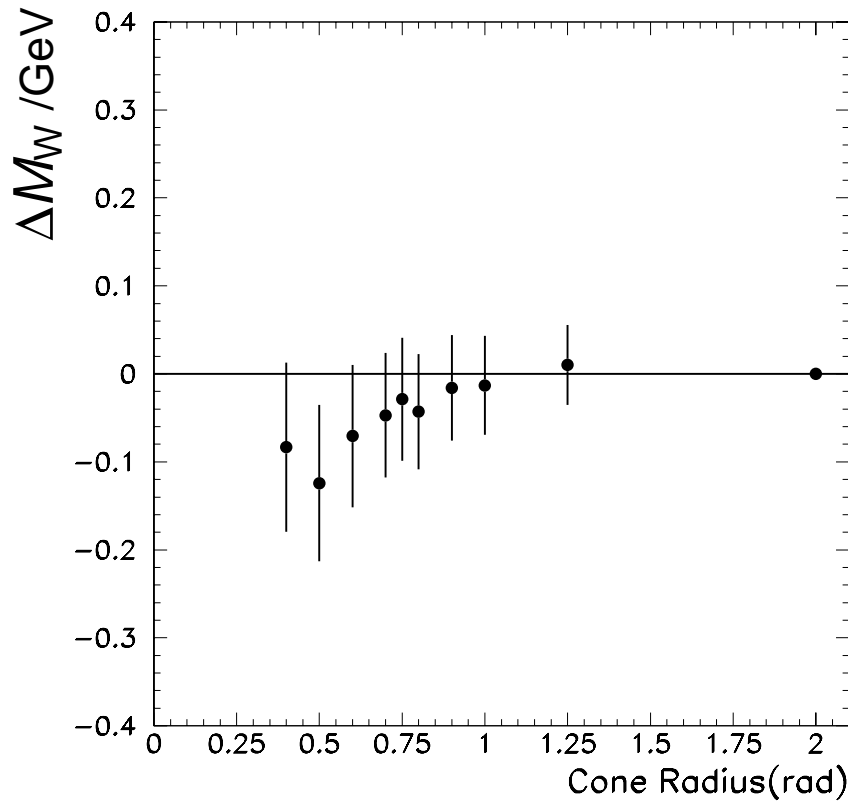
Full set of electroweak measurements place strong constraints on any new physics.

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

Backup slides

Aleph M_W vs. p_{cut} or cone

Mass shifts in GeV/c^2 relative to the standard reconstruction for $e\nu q\bar{q}$ events as a function of cone radius or momentum cut.

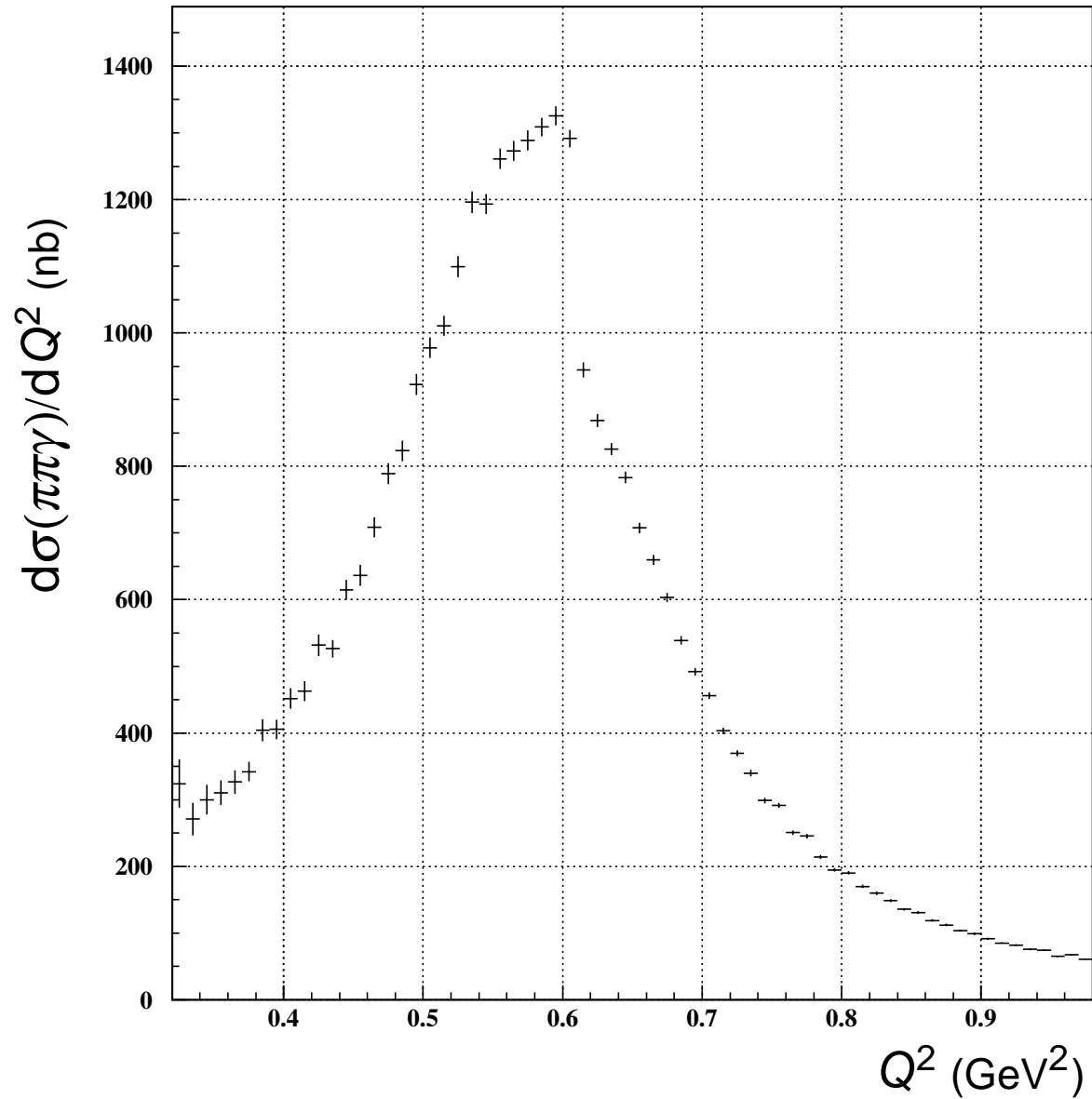


These plots revealed the bias before “cleaning” etc.

Other LEP experiments see stability in these plots.

(NB. Similar plots for the $q\bar{q}q\bar{q}$ channel test the effects of colour reconnection)

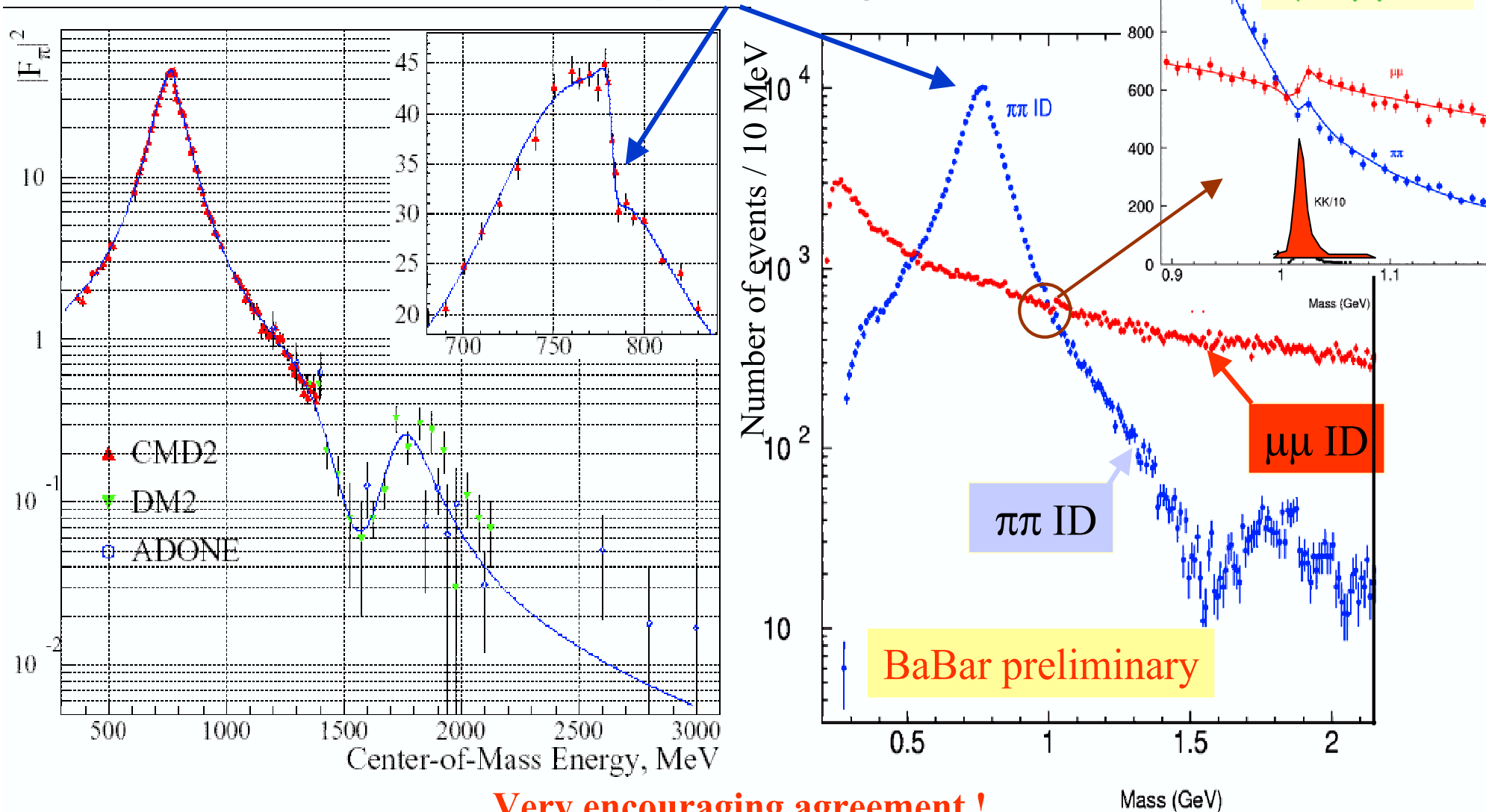
KLOE data quality $\pi^+ \pi^- (\gamma)$





$\pi^+\pi^-\gamma$

Pion Form Factor with ρ - ω interference

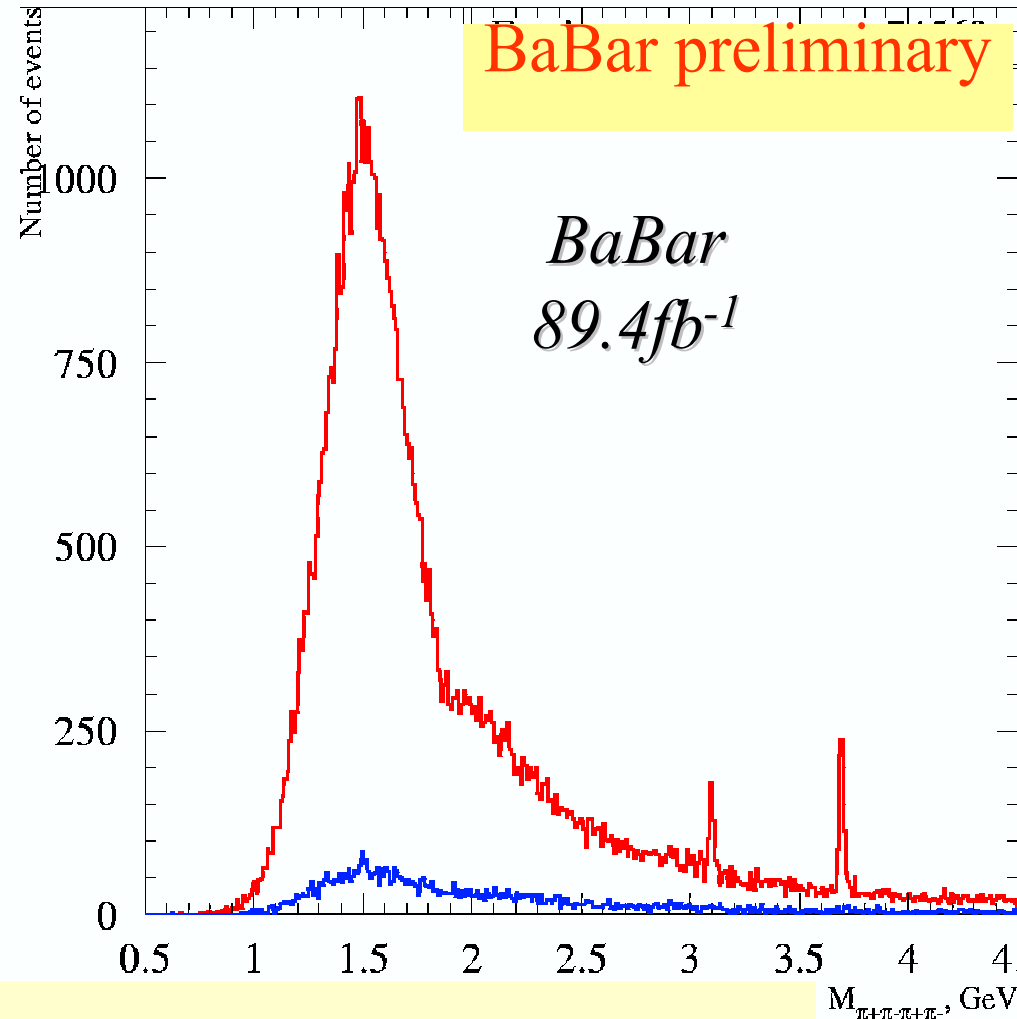
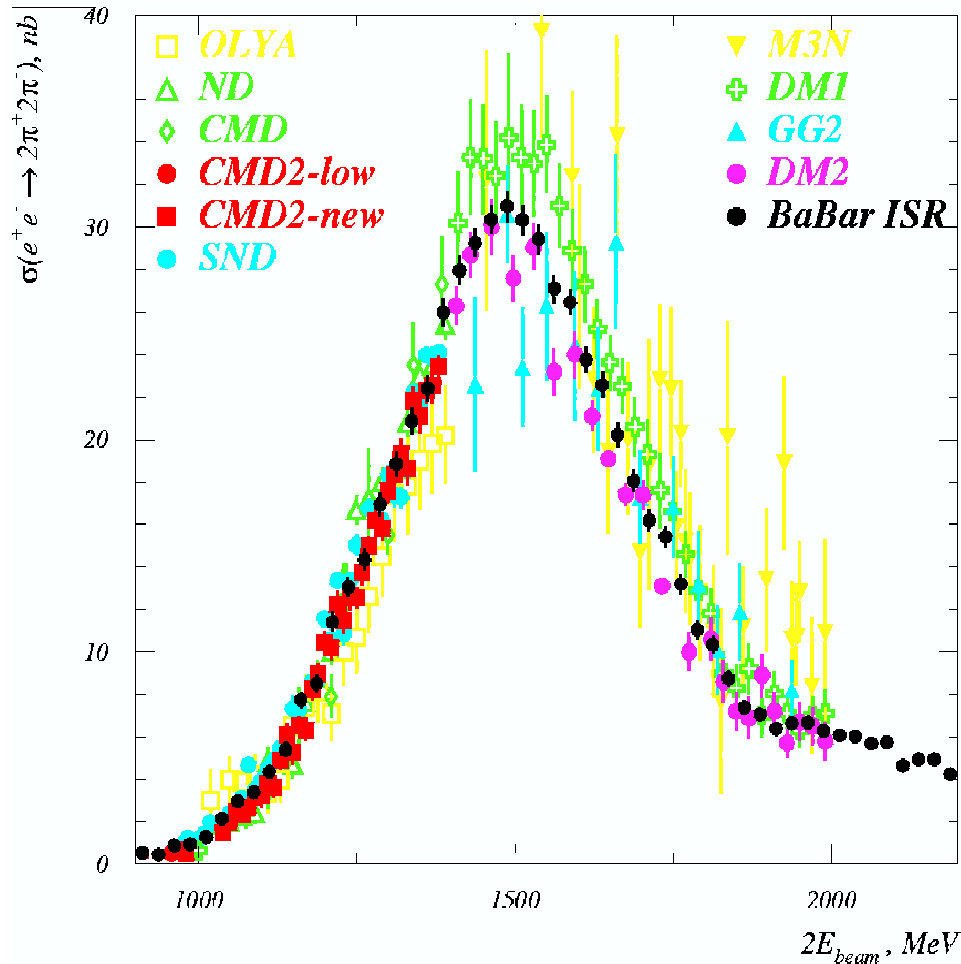


Very encouraging agreement !
hard work! <1% systematic error is needed for g-2



$4\pi^\pm \gamma$

Topology: four charged tracks + hard photon (+ 1C fit in 4π hyp.)



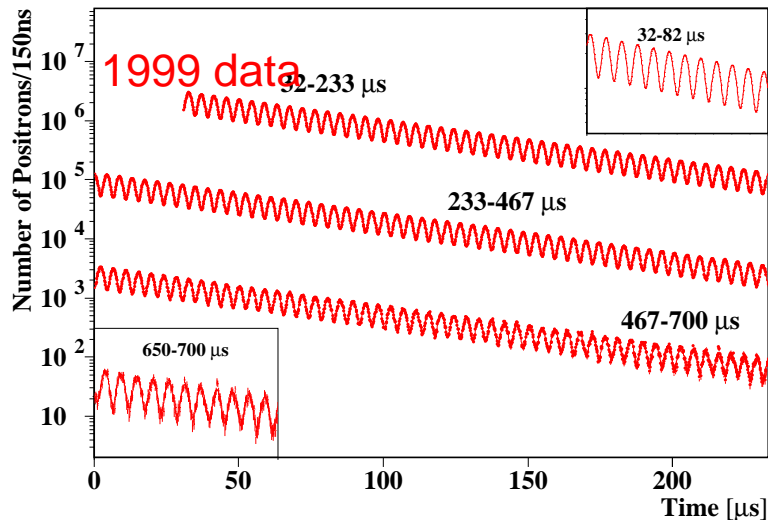
- very clean sample (background~2%)
- whole mass range is covered
- large statistics (~75k events)

Muon (g-2)

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

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

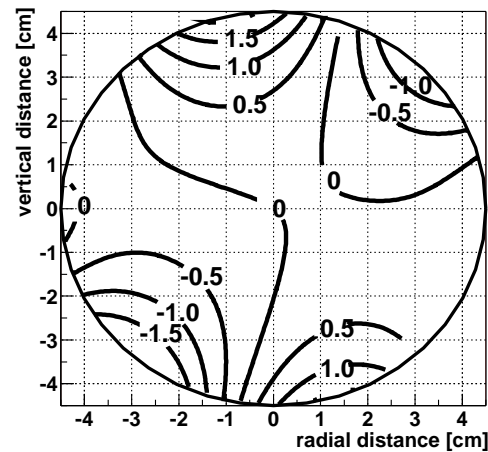
Technique: fit difference frequency ω_a
 between muon spin precession and orbit
 from rate of decay positrons above
 threshold:



At magic $\gamma = 29.3$, ω_a is not affected by
 electrostatic focussing fields.

$$a_\mu = \frac{\omega_a}{\frac{e}{m_\mu c} \langle B \rangle}$$

B field measured by NMR probes on a trolley
 - controlled to ~ 1 ppm

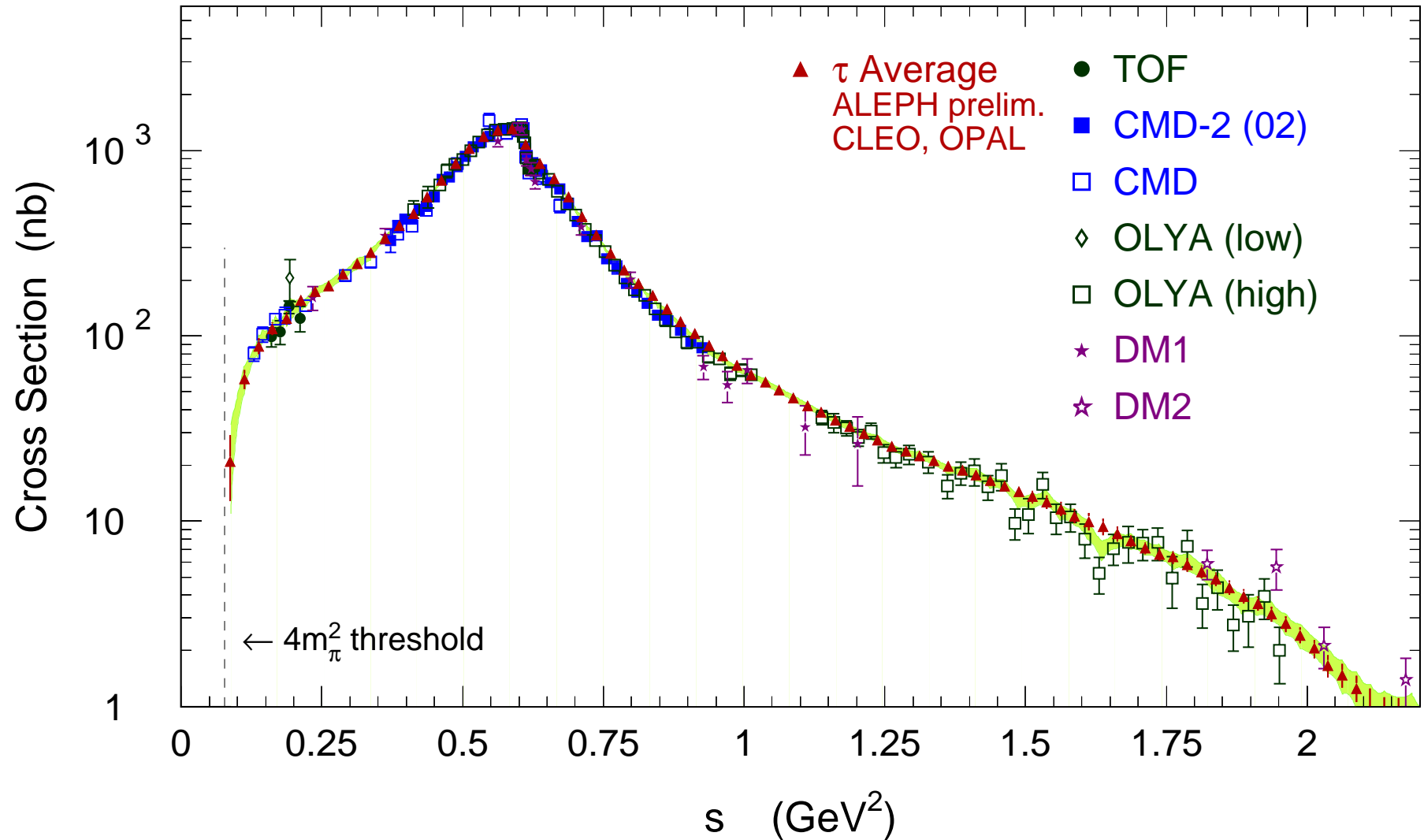


	Multipoles [ppm]	
	normal	skew
Quad	0.24	0.29
Sext	-0.53	-1.06
Octu	-0.10	-0.15
Decu	0.82	0.54

Systematic uncertainties 0.24 ppm

Soon: result with 2001 μ^- data, with sim-
 ilar statistics to 2000 μ^+

Another comparison of e^+e^- and τ spectral function data



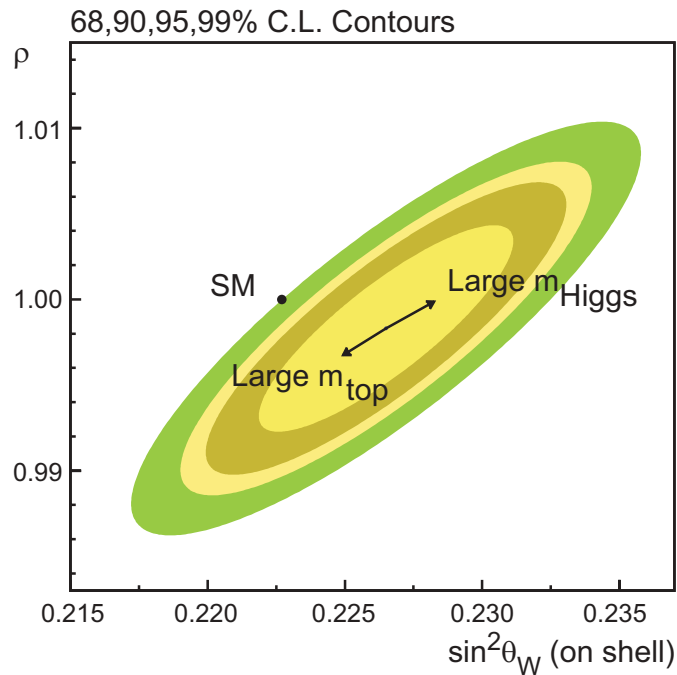
NuTeV result

Paschos-Wolfenstein: CC and NC rates for ν_μ and $\bar{\nu}_\mu$ related to $\sin^2 \theta_W = 1 - \frac{M_W^2}{M_Z^2}$

$$R^- \equiv \frac{\sigma(\nu_\mu N \rightarrow \nu_\mu X) - \sigma(\bar{\nu}_\mu N \rightarrow \bar{\nu}_\mu X)}{\sigma(\nu_\mu N \rightarrow \mu^- X) - \sigma(\bar{\nu}_\mu N \rightarrow \mu^+ X)} = \frac{1}{2} - \sin^2 \theta_W$$

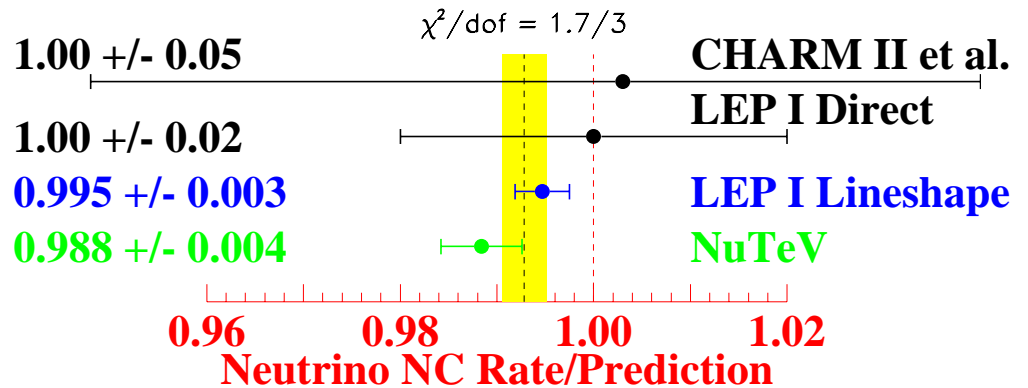
NuTeV actually measure R^ν and $R^{\bar{\nu}}$. Discrepancy from R^ν .

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



No explanation forthcoming from (eg.):

- Experimental effects eg. ν_e CC contamination
- PDFs, non-isoscalar contributions to target
- Strange sea asymmetry, charm mass effects



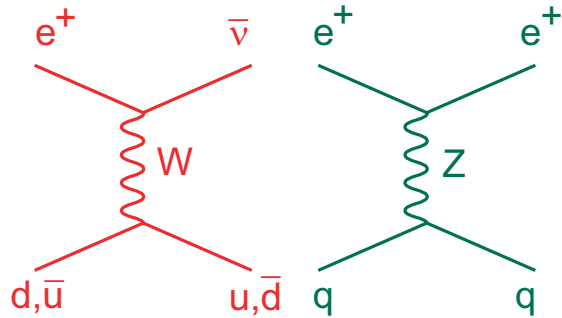
Discrepancy could be due to $\rho_\nu \neq 1$.
(Equivalent to fitting g_L and g_R)

If effect comes from ρ_ν : NuTeV and $\Gamma_{inv}(Z)$ both imply low rate of ν NC.

Results from HERA
 e^-p at $\sqrt{S}=318$ GeV
 e^+p at $\sqrt{S}=300$ and 318 GeV

ZEUS: High- Q^2 CC cross sections

Charged current W exchange:
d-type quark, u-type antiquark.



Signature: large p_T^{miss} .

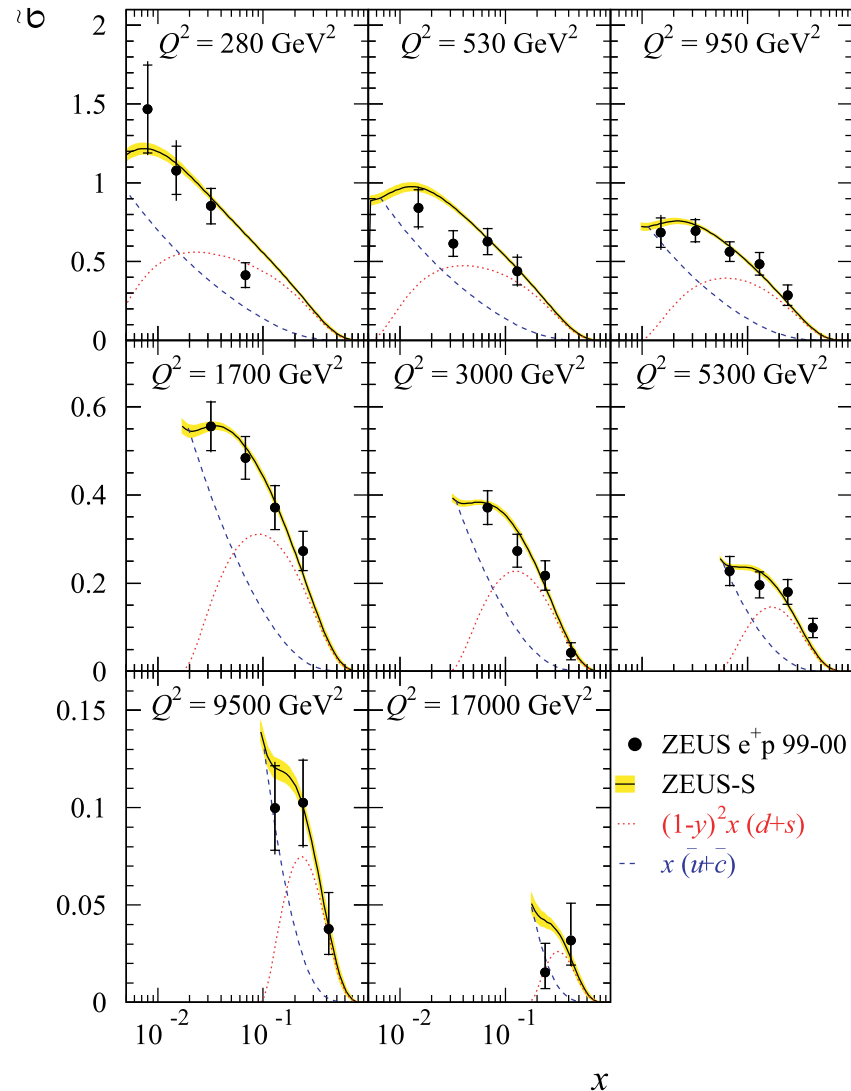
Reduced cross section in LO QCD

$$\tilde{\sigma} = \left[\frac{G_F^2 M_W^2}{2\pi x (M_W^2 + Q^2)} \right]^{-1} \frac{d^2\sigma}{dx dQ^2}$$

$$= x[\bar{u} + \bar{c} + (1 - y^2)(d + s)]$$

where q, \bar{q} are the momentum distributions in the proton.

ZEUS



Fit to $d^2\sigma/dx dQ^2$ gives $M_W = 78.9 \pm 2.0(\text{stat.}) \pm 1.8(\text{syst.})_{-1.8}^{+2.0}(\text{PDF}) \text{ GeV}$

H1: $l p_T^{miss}, ll(l)$

W production: isolated e, μ with p_T^{miss} :
(Dominated by photoproduction)

		Data	SM
e^-p	e	1	1.69 ± 0.22
	μ	0	0.37 ± 0.06
e^+p	e	10	9.9 ± 1.3 (7.2 W)
	μ	8	2.6 ± 0.4 (2.2 W)

With $p_T^X > 25$ GeV (hadronic system) 10 events with 2.92 ± 0.49 expected

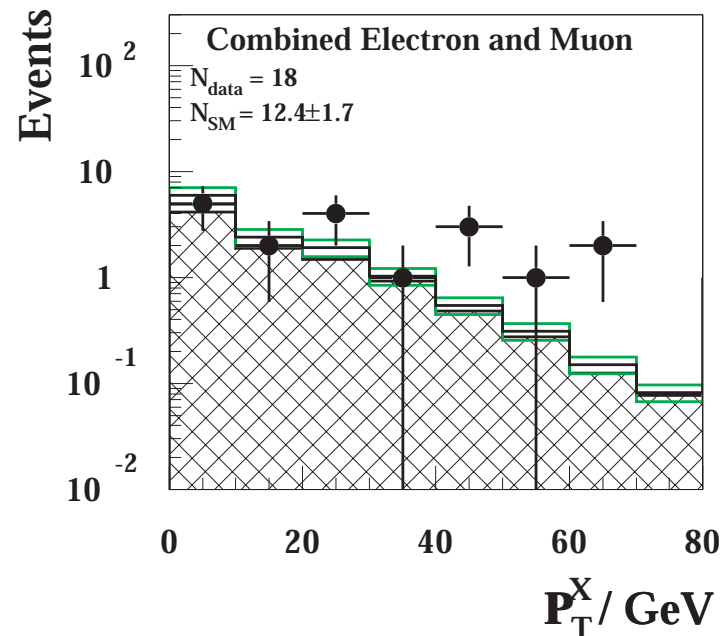
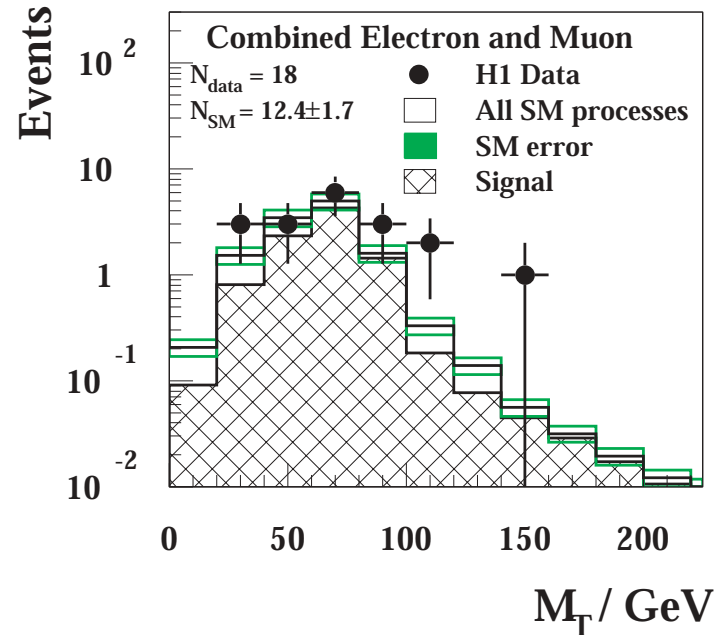
Muon pairs from photoproduction:

Good agreement with SM in rate, even at high mass or p_T^X

Multi-electron events:

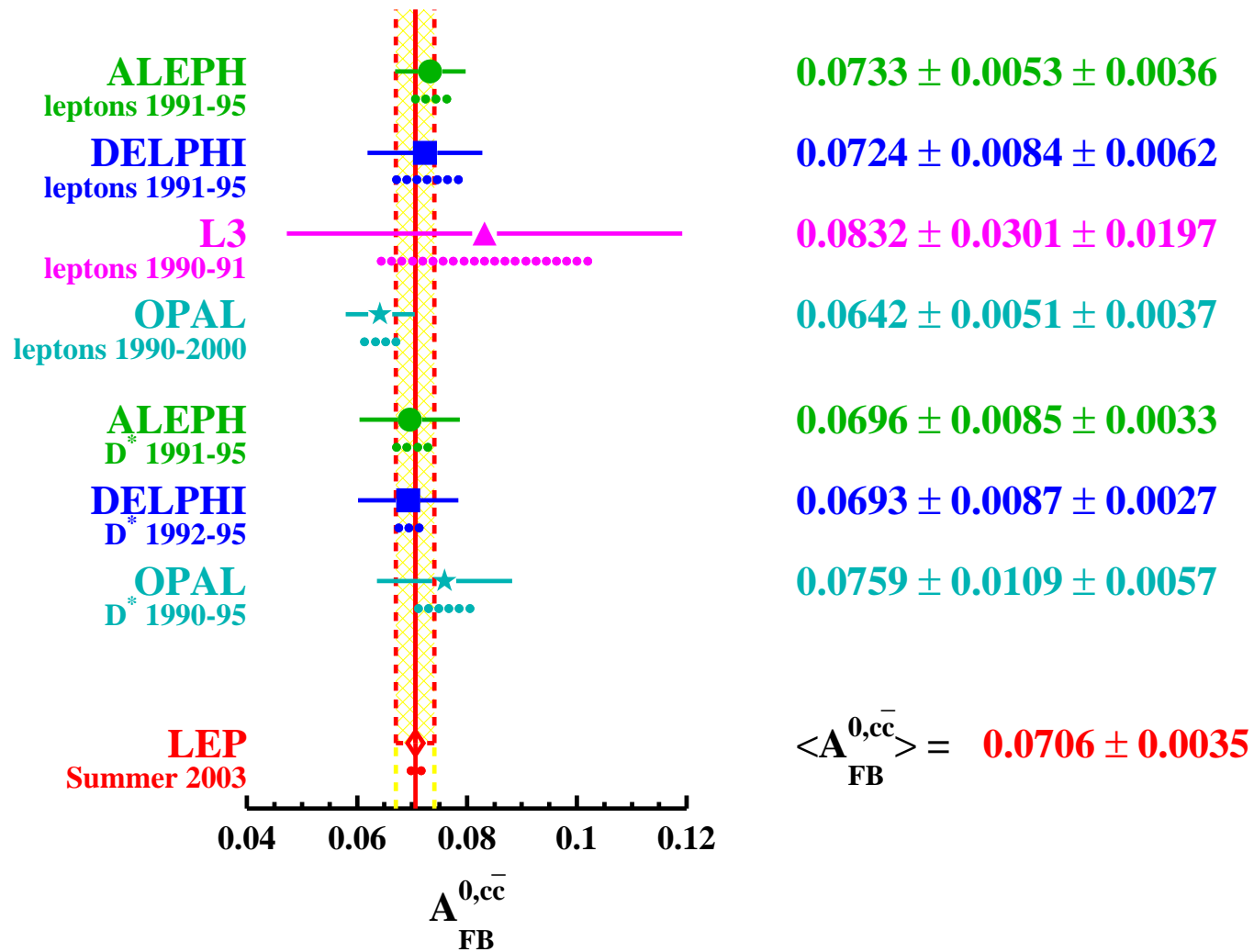
3 ee and 3 eee events with $M_{ee} > 100$ GeV
cf. 0.30 ± 0.04 and 0.23 ± 0.04 expected

H1 e^+p data (1994-2000)



$A_{FB}^{0,c}$ table

Results for $A_{FB}^{0,c}$ with lepton (top) and D meson tag



S-matrix and LEP2 $f\bar{f}$ data

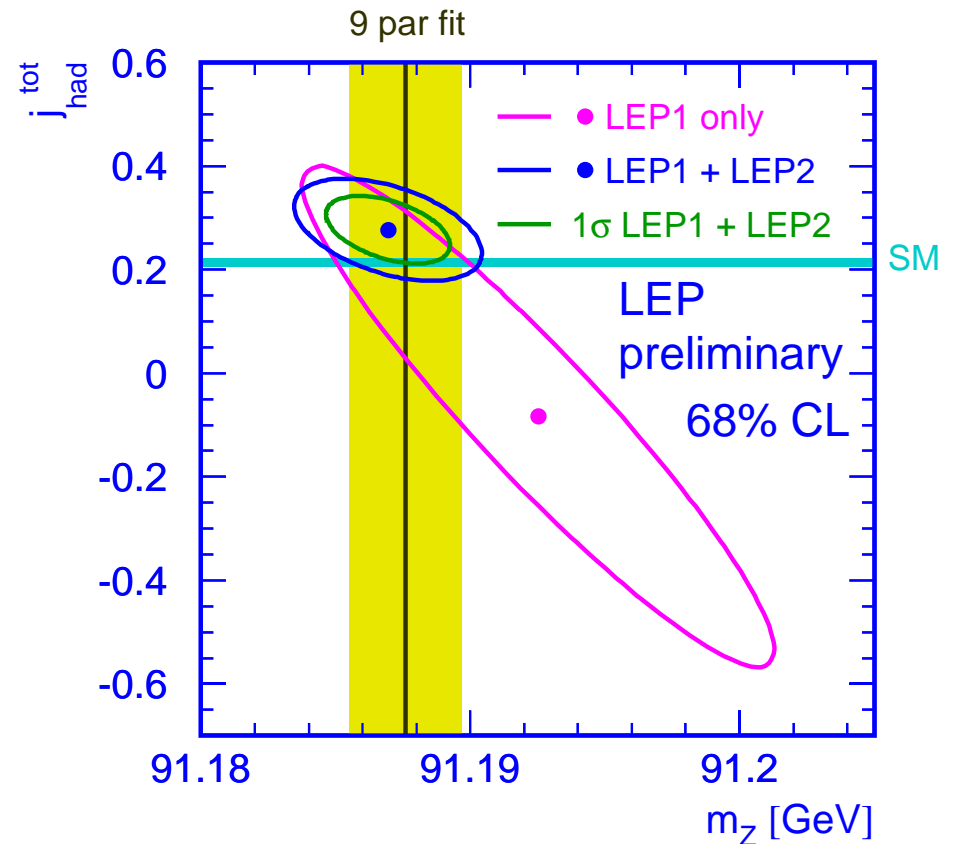
Standard LEP 1 measurement of M_Z
 assumes SM $\gamma - Z$ interference

S-Matrix formalism: fit interference

contribution from data $\propto j_{\text{had}}^{\text{tot}}$

Using LEP1 data only, large correlation
 between $M_Z - j_{\text{had}}^{\text{tot}}$. Precision on M_Z
 recovered with LEP2 data.

Method	M_Z
LEP1 9 param. fit	91.1876 ± 0.0021
LEP1 S-matrix	91.1925 ± 0.0059
LEP1+2 S-matrix	91.1869 ± 0.0023



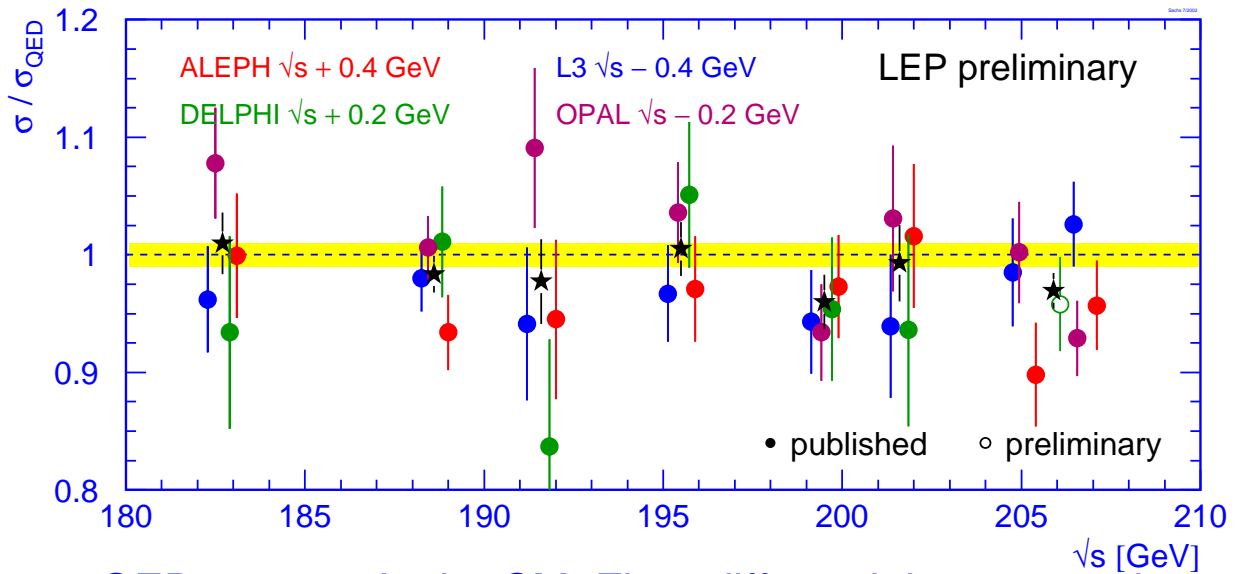
Photon(s) at LEP2

QED test:

$$e^+e^- \rightarrow \gamma(\gamma)$$

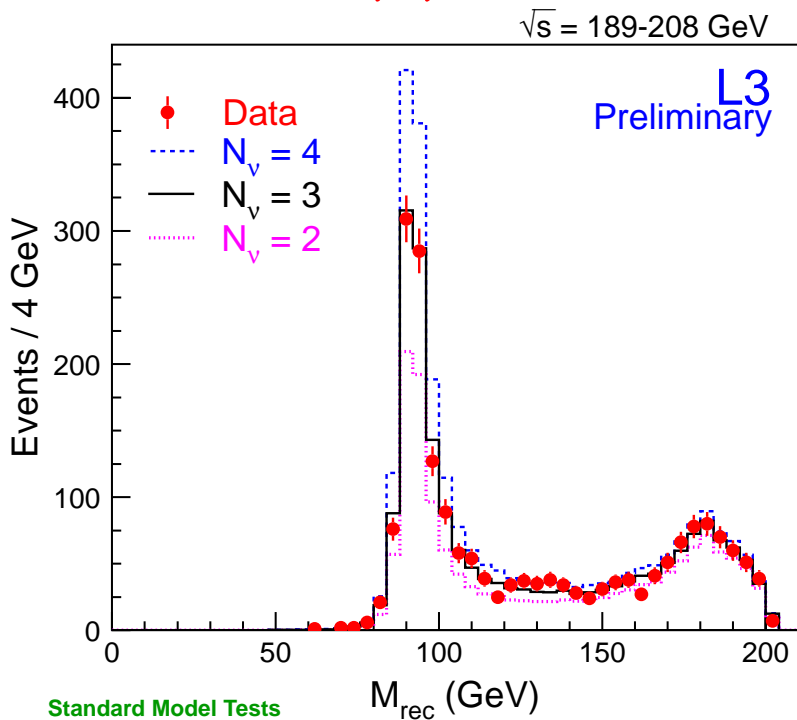
Results final except

DELPHI $\sqrt{s} > 203$ GeV



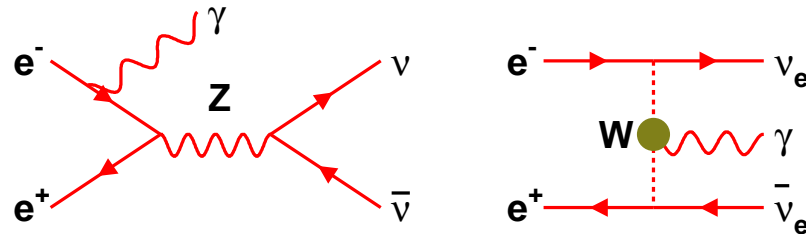
Ratio of $e^+e^- \rightarrow \gamma(\gamma)$ is a pure QED process in the SM. Fit to differential cross-section constrains eg. QED cutoff params $> 350 - 400$ GeV.

$$e^+e^- \rightarrow \gamma(\gamma)X, X \text{ invisible.}$$



Standard Model Tests

Single photon events - examine recoil mass

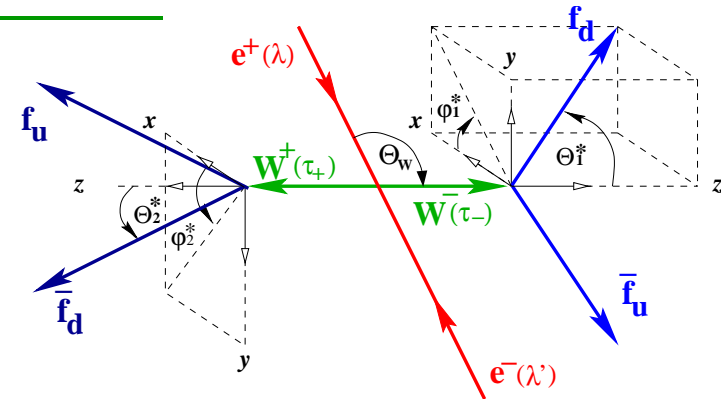


eg. L3 LEP2: $N_v = 2.95 \pm 0.08(\text{stat.}) \pm 0.03(\text{syst.}) \pm 0.02(\text{theo.})$

New particle searches and limits on Quartic Gauge Couplings (see later)

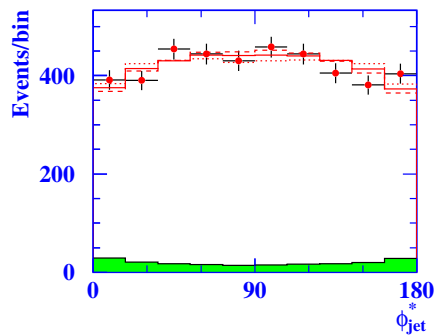
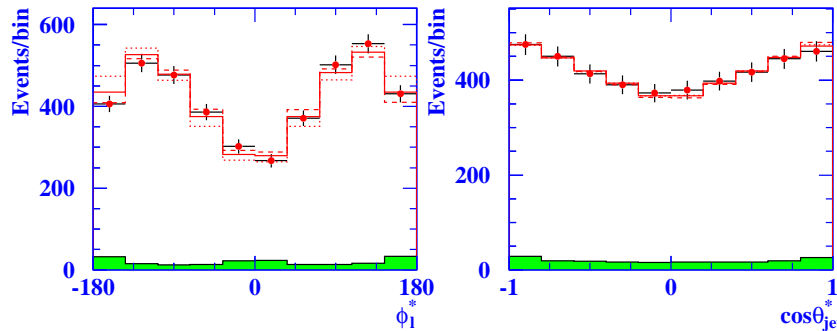
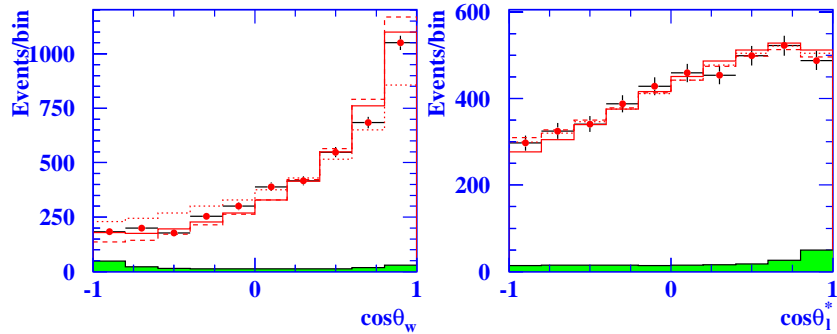
Anomalous TGC: angular observables

Most powerful channel: $q\bar{q}l\nu$

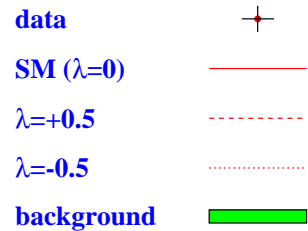


More ambiguity for $q\bar{q}q\bar{q}$

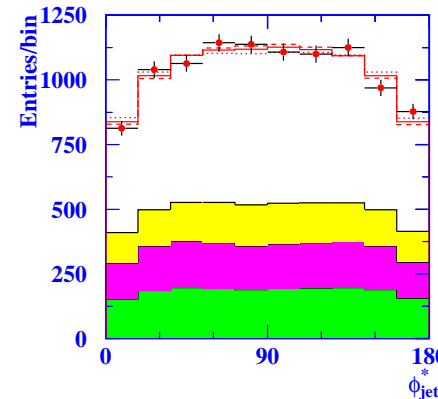
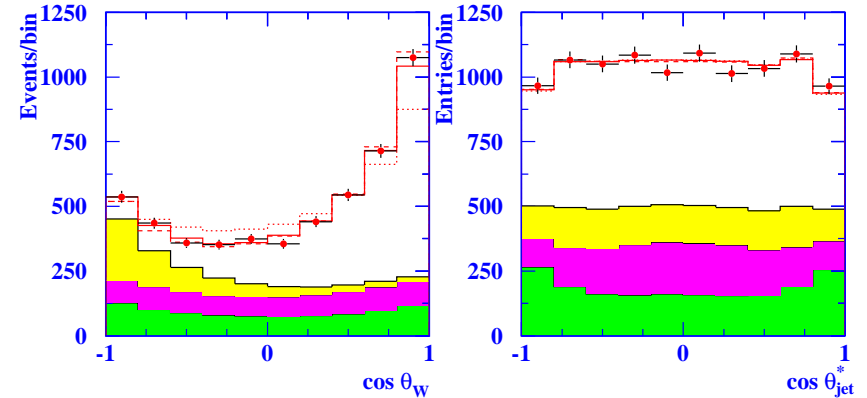
OPAL



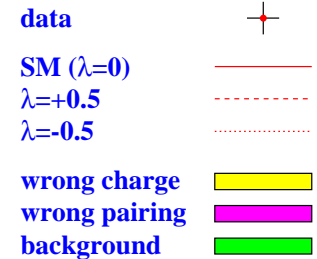
$W^+W^- \rightarrow q\bar{q}l\nu_l$



OPAL



$W^+W^- \rightarrow q\bar{q}q\bar{q}$



Use “optimal observables” to exploit correlations between angular variables

Atomic parity violation

Weak charge of Caesium nucleus, ^{133}Cs , inferred from weak neutral current contribution to parity nonconservation amplitude of forbidden 6S-7S transition.

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

with Z protons, N neutrons, and $C_{1q} = 2g_{Ae}g_{Vq}$ ($q = u, d$)

Precise measurement by Wood et al., *Science* (1997).

Theoretical precision of many-electron correlations correction improved.

2σ discrepancy between theory and experiment developed.

There followed "... an intriguing zigzag road of research...", "... a turbulent period of research during which the experimental data were widely anticipated to be in contradiction with the Standard Model."

Several $\approx 0.5\%$ QED corrections cancel. (Breit, vacuum pol., self-energy and vertex corrections to $Z\alpha^2$, $Z^2\alpha^3$). Latest: Kuchiev and Flambaum [hep-ph/0305053](https://arxiv.org/abs/hep-ph/0305053)

$$Q_W(\text{Cs}) = -72.84 \pm 0.29(\text{exp.}) \pm 0.36(\text{theor.})$$

$$Q_W(\text{Cs}) = -72.90 \text{ SM fit}$$