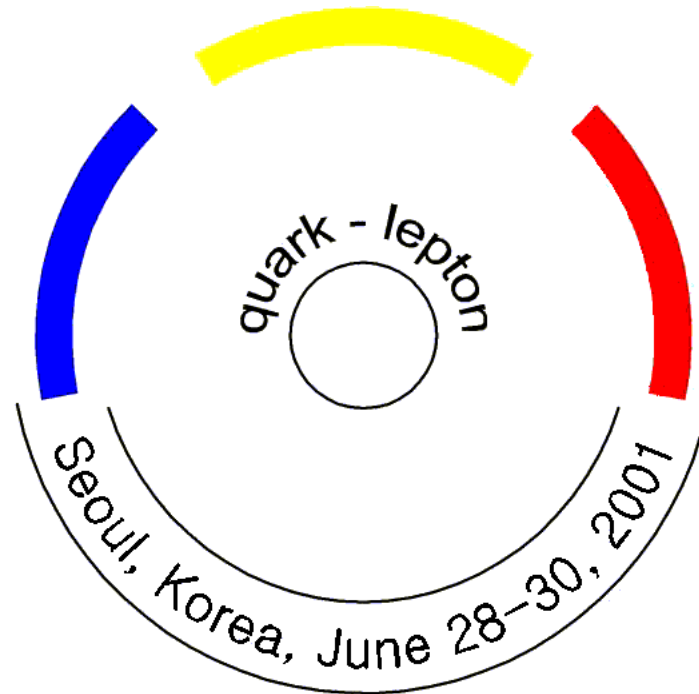




W Boson Properties



Eric Torrence
University of Oregon



formerly
Enrico Fermi Institute
University of Chicago



Overview



- Introduction
- W Boson Production
- Decay Branching Fractions
- Electroweak Couplings
- W Mass and Width
- Conclusions

⇒ All numbers from Moriond 2001

<http://www.cern.ch/torrence/talks/PIC01>



Introduction



Precision EW Tests



Tree Level Parameters

g SU(2)_L weak isospin coupling

g' U(1) weak hypercharge coupling

$\langle \phi \rangle_0$ Vacuum EV of the Higgs field

Need three precision measurements

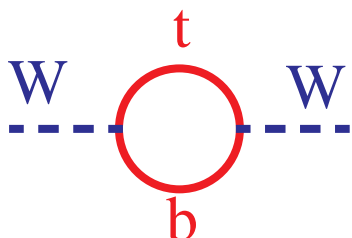
$$\alpha_{em}: \frac{1}{4\pi} \frac{(gg')^2}{g^2 + g'^2} \quad (\text{Electron } g-2) \quad 0.004 \text{ ppm}$$

$$G_F: \frac{1}{\sqrt{8}} \frac{1}{\langle \phi \rangle_0^2} \quad (\text{Muon Lifetime}) \quad 9 \text{ ppm}$$

$$m_Z: \frac{\langle \phi \rangle_0}{\sqrt{2}} \sqrt{g^2 + g'^2} \quad (\text{LEP I lineshape}) \quad 23 \text{ ppm}$$

Measure m_W , $\sin^2 \Theta_w$ to test theory!

Radiative corrections



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

$$\Delta r = f(m_t^2, \ln(m_H))$$



The LEP Collider at CERN



L3



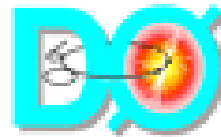
e^+e^- collisions

LEP I ~ 91 GeV (1990 - 1995)

LEP II 161 - 209 GeV (1996 - 2000)



The Tevatron at FNAL



$\bar{p}p$ collisions

Run I 1800 GeV (1992 - 1995)

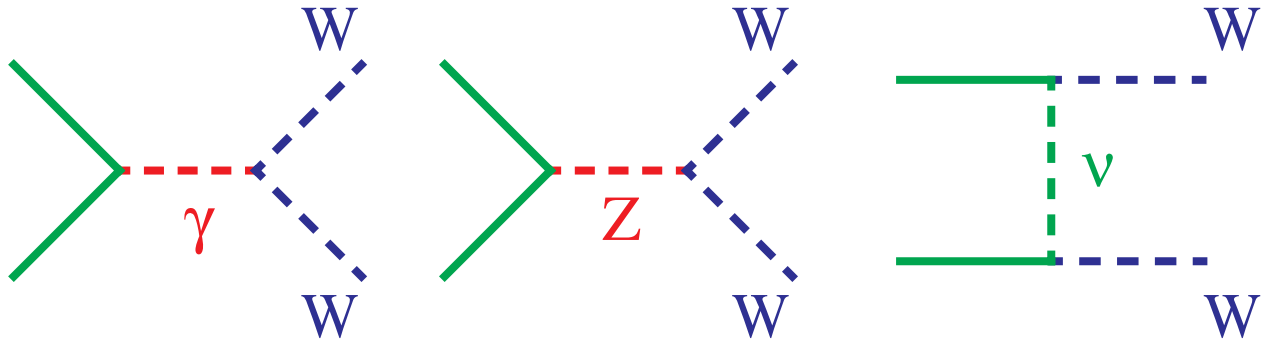
Run II 1960 GeV (2001 - 200?)



Data Samples



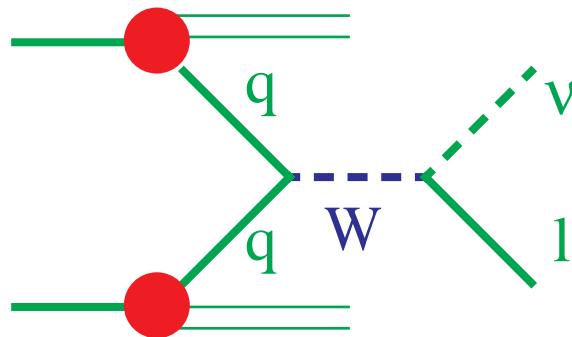
$$e^+e^- \rightarrow W^+W^-$$



$$\sigma_{WW}(200 GeV) \sim 17 \text{ pb}$$

LEP II Total: **35k W pairs** (2700 pb^{-1})

$$\bar{p}p \rightarrow WX$$



Trigger on $W \rightarrow l\nu$ only

$$\sigma_{WX} \cdot B(W \rightarrow l\nu) \sim 2.4 \text{ nb}$$

Run I Total: **200k W events** (200 pb^{-1})



W Production and Decay



LEP WW Decay Modes

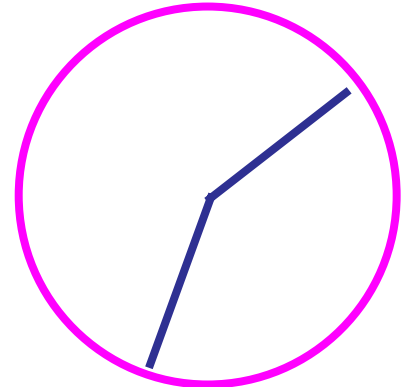


$$W^+W^- \rightarrow l\nu l\nu$$

SM Rate: 10.6%

- Two Leptons
- Little Mass Information

$\epsilon \sim 60\text{-}80\%$ $\pi \sim 90\%$

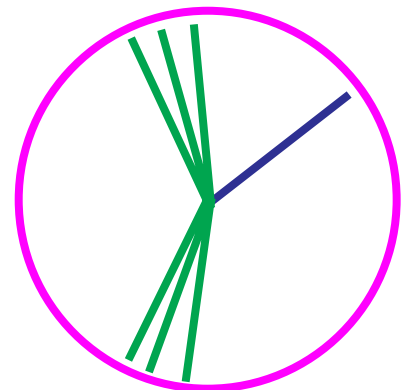


$$W^+W^- \rightarrow qq l\nu$$

SM Rate: 43.8%

- One Lepton, Two Jets
- Low Backgrounds
- Golden channel for mass

$\epsilon \sim 70\text{-}85\%$ $\pi \sim 90\%$

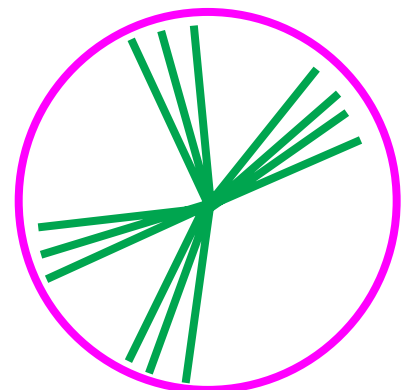


$$W^+W^- \rightarrow qqqq$$

SM Rate: 45.6%

- Four Jets
- Significant Backgrounds
- No Missing Momentum

$\epsilon \sim 80\text{-}90\%$ $\pi \sim 80\%$



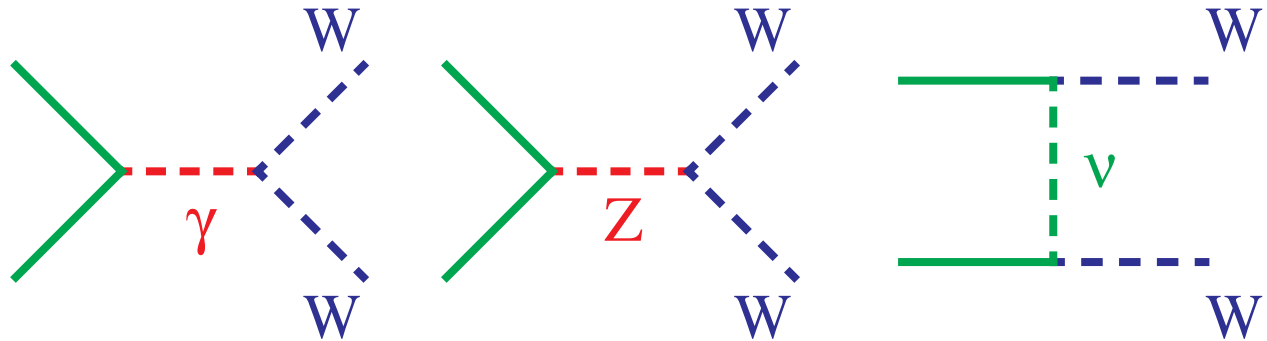
Worse performance with taus



Four Fermion Amplitudes



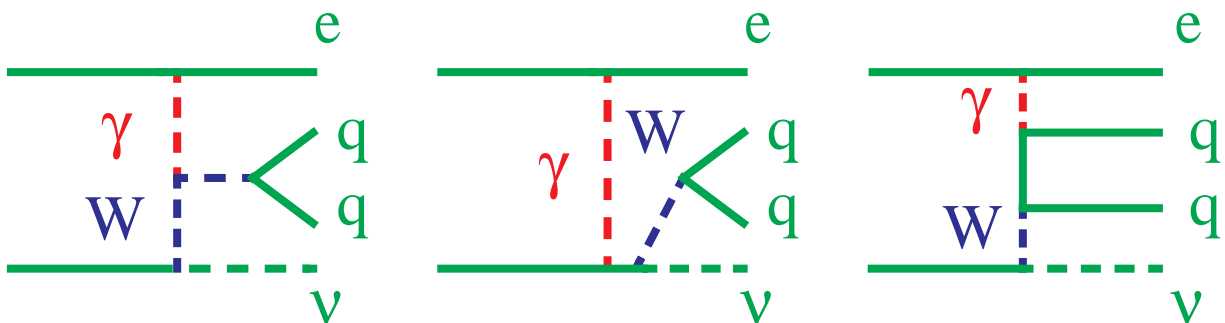
CC03 Amplitudes:



Convenient definition of **resonant production**

⇒ **Other diagrams with identical final states!**

$$e^+e^- \rightarrow qqev$$



Rely on complete 4f Monte Carlo

⇒ **Non-CC03 diagrams ~5%**



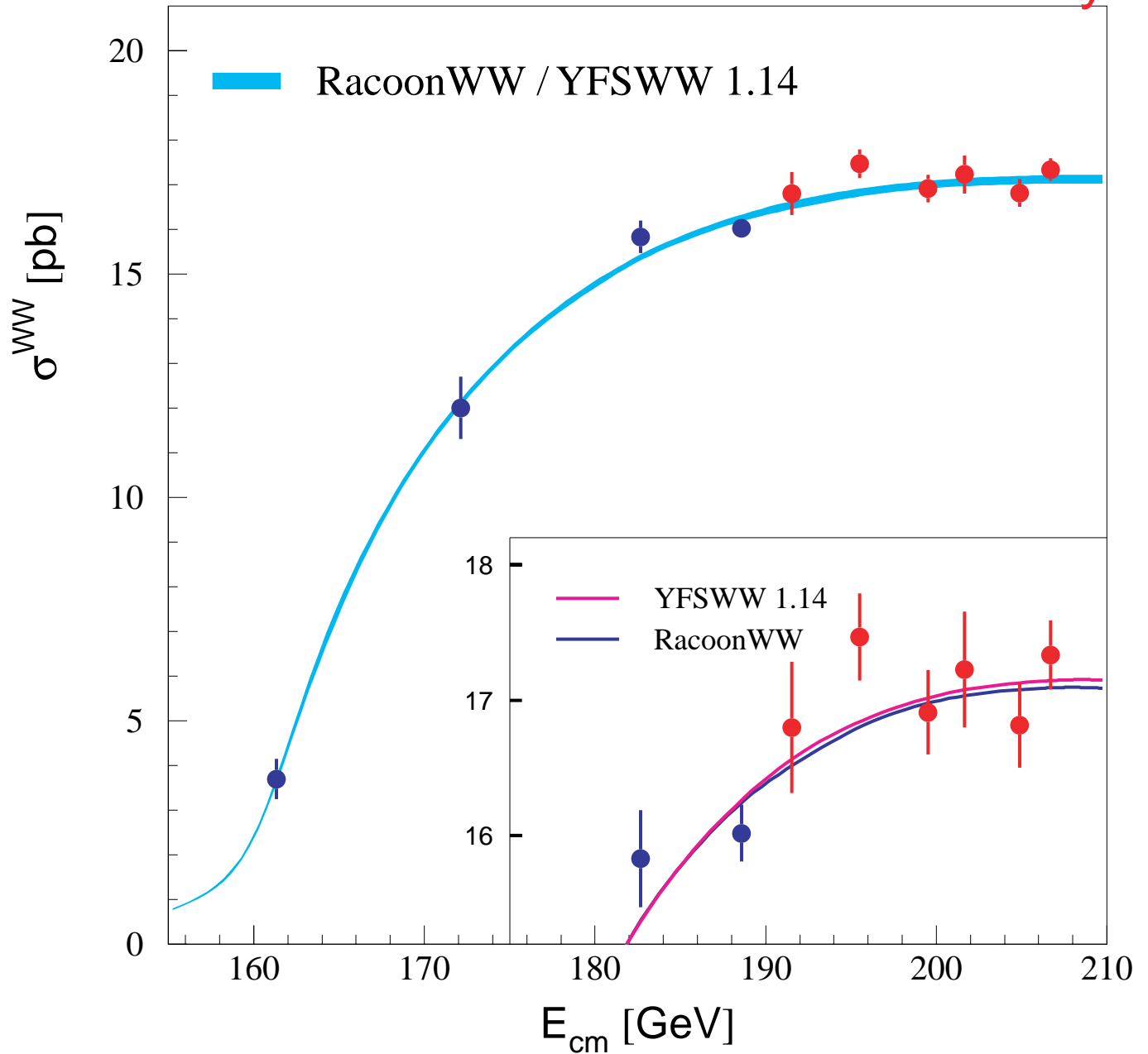
WW Cross Section



02/03/2001

LEP

Preliminary



Complete Order α_{EM} Calculations

RacoonWW: Denner, Dittmaier, Roth, Wackerath

YFSWW: Jadach, Placzek, Skrzypek, Ward, Was



LEP W Branching Fractions



Leptonic Branching Fractions

$$\text{Br}(W \rightarrow e\nu): \quad 10.54 \pm 0.17\%$$

$$\text{Br}(W \rightarrow \mu\nu): \quad 10.54 \pm 0.16\%$$

$$\text{Br}(W \rightarrow \tau\nu): \quad 11.09 \pm 0.22\%$$

$$\chi^2/dof = 14.9/9$$

$$\text{SM: } 10.83\%$$

Assume Lepton Universality

$$\text{Br}(W \rightarrow qq): \quad 67.92 \pm 0.27\%$$

$$\chi^2/dof = 18.8/11$$

$$\text{SM: } 67.51\%$$

CKM Interpretation

$$\frac{\text{Br}(W \rightarrow q\bar{q})}{1 - \text{Br}(W \rightarrow q\bar{q})} = (1 + \alpha_s(m_W)/\pi) \sum_{(u, c), (d, s, b)} |V_{ij}|^2$$

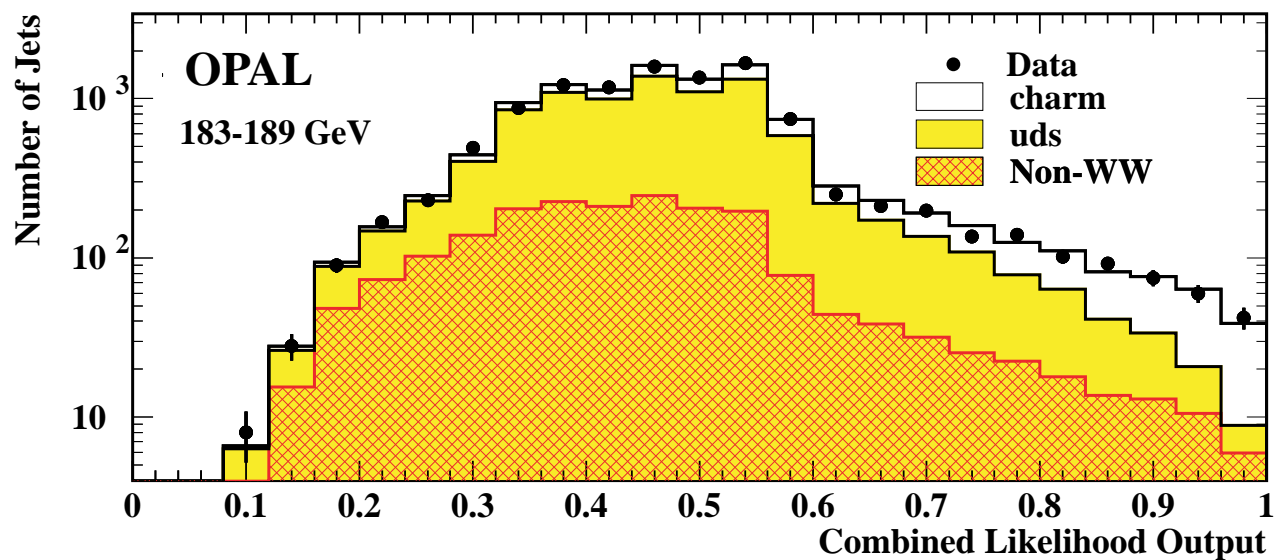
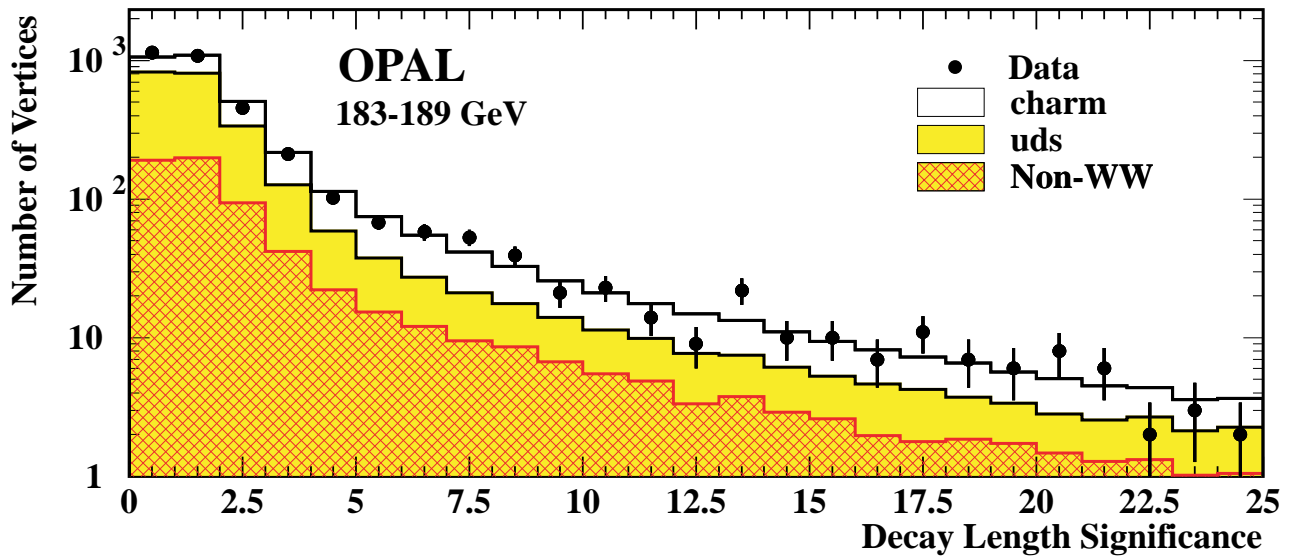
$$\sum_{(u, c), (d, s, b)} |V_{ij}|^2 = 2.039 \pm 0.025$$

$$|V_{cs}| = 0.996 \pm 0.013$$

[Winter 01 Preliminary LEP Combined]



Charm Production



$$R_c^W = 0.481 \pm 0.042(stat) \pm 0.032(syst)$$

$$\text{Using } \Gamma(W \rightarrow cX) = \frac{CG_F m_W^3}{6\sqrt{2}\pi} (|V_{cd}|^2 + |V_{cs}|^2 + |V_{cb}|^2)$$

$$|V_{cs}| = 0.969 \pm 0.058$$

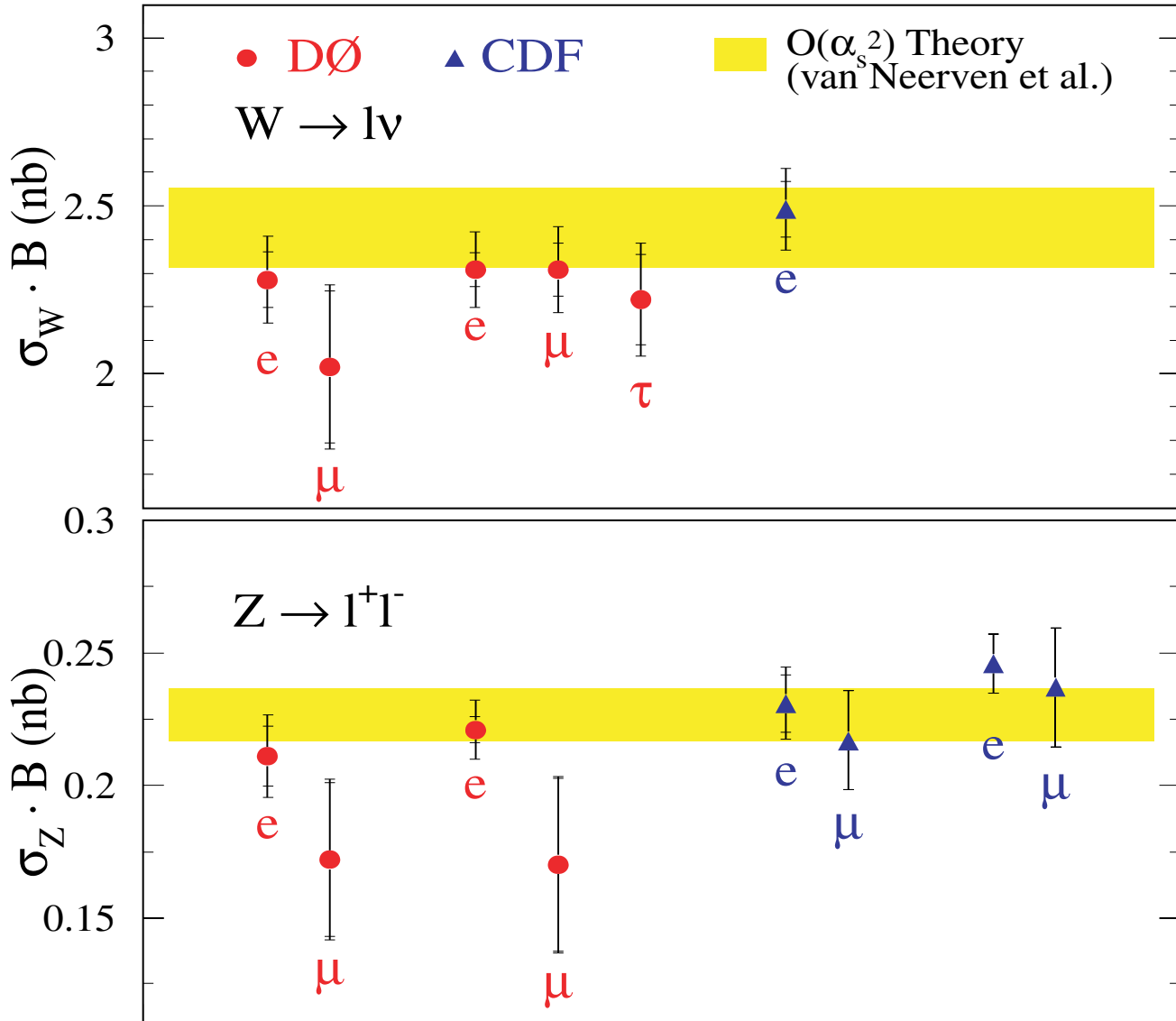
[Opal Collaboration, Phys. Lett. **B490** (2000) 71]



Tevatron W/Z Cross Sections



$$\sqrt{s} = 1800 \text{ GeV}$$



Data set: 92/93 94/96 92/93 94/96

Note different normalization: $\sigma(\text{CDF}) = 1.06 \sigma(\text{D0})$

- Experimental Uncertainty ~ 2%
- Luminosity Uncertainty ~ 4%
- Theory Uncertainty ~ 3% (Dominated by PDFs)

Use $\sigma\text{Br}(W \rightarrow e\nu)$ to measure Run II Lumi?



Tevatron Cross Section Ratio



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

σ_W/σ_Z from QCD

[Hamberg, van Neerven, Matsuura]

$Br(Z \rightarrow ee)$ from LEP I

Extract branching fraction

$$Br(W \rightarrow e\nu) = 10.45 \pm 0.20\% \quad (\text{CDF+D0})$$

Indirect Width

Assume SM partial width

$$\Gamma(W \rightarrow e\nu) = 226.5 \pm 0.3 \text{ MeV}$$

[Rosner, Worah, Takeushi]

Extract W width

$$\Gamma_W(\text{CDF} + \text{D0}) = 2.167 \pm 0.040 \text{ GeV}$$

$$\Gamma_W(\text{SM}) = 2.093 \pm 0.003 \text{ GeV}$$

[PDG 2000]



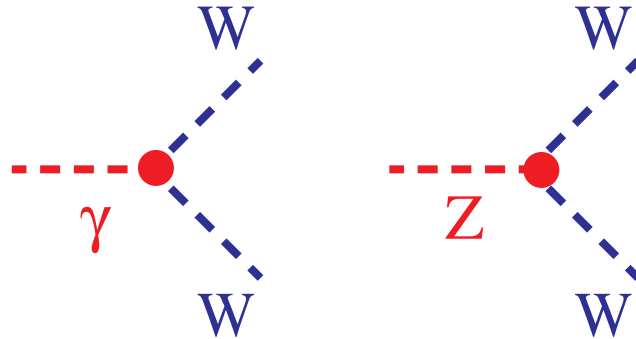
Gauge Boson Couplings



Charged Triple Gauge Couplings



Non-Abelian Gauge Theory



Lorentz invariance

Need 2×7 parameters...

Gauge invariance, C, P, CP conservation

$$\{ \kappa_\gamma, \kappa_Z, \lambda_\gamma, \lambda_Z, g_1^Z \}$$

In SM, $\kappa_\gamma = \kappa_Z = g_1^Z = 1, \lambda_\gamma = \lambda_Z = 0$

Magnetic Dipole Moment: $\mu_W = e(1 + \kappa_\gamma + \lambda_\gamma)/2m_W$

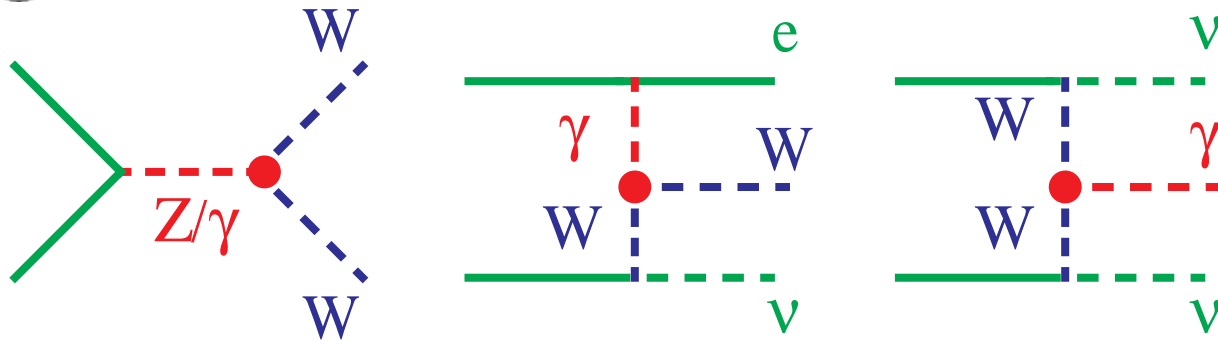
Electric Quadrupole Moment: $Q_W = -e(\kappa_\gamma - \lambda_\gamma)/m_W^2$

Measure deviations allowed by LEP I

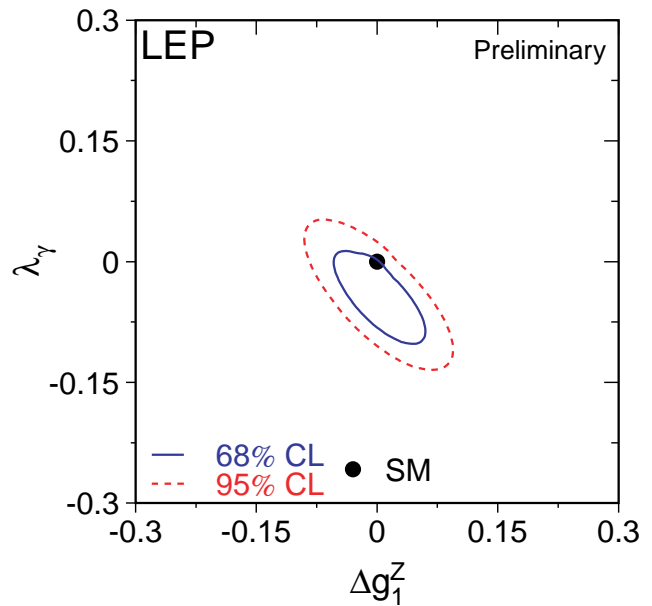
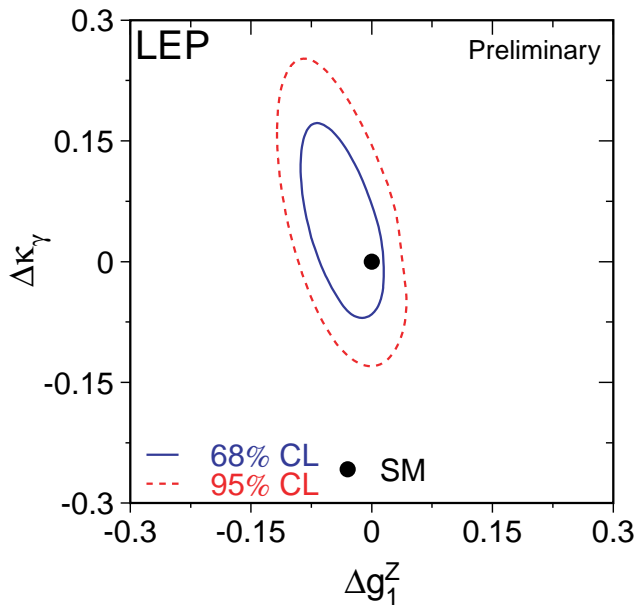
$$\Delta\kappa_\gamma = \kappa_\gamma - 1, \Delta g_1^Z = g_1^Z - 1, \lambda$$



LEP TGC Results



Fit Production and Decay Cross Sections



Single Parameter Fits*

$$\Delta k_\gamma = -0.002 \pm 0.066$$

$$\Delta g_1^Z = -0.025 \pm 0.026$$

$$\lambda = -0.036 \pm 0.028$$

*Summer 2000

Order(α_{EM}) effects

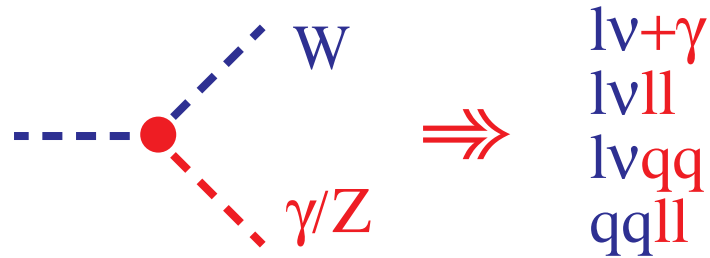
not yet included...



Tevatron TGC Analyses

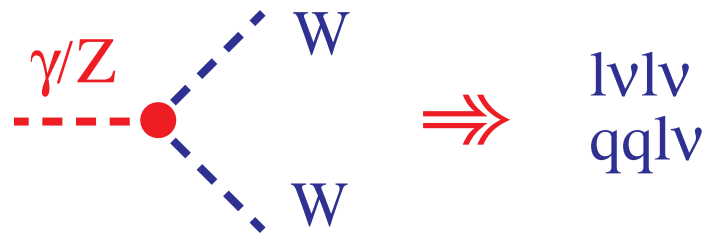


Associated production



\Rightarrow WZ final states marginal at Run I

W Pair production



D0 combined analysis ($lv+\gamma$, $lvlv$, $qqlv$)

Measure cross sections and p_T^W

$$-0.25 \leq \Delta\kappa \leq 0.31 \quad (\lambda = 0)$$

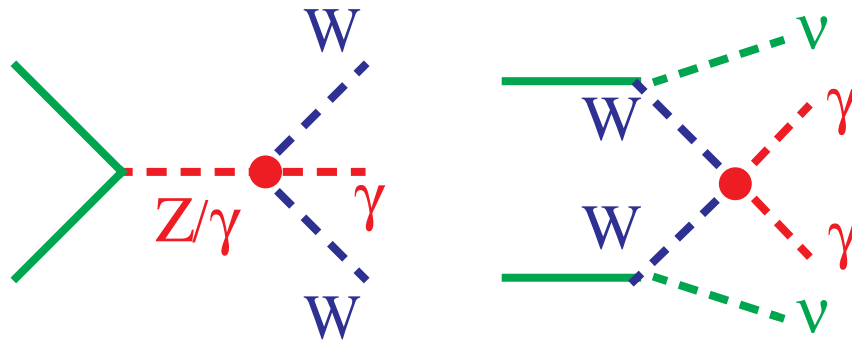
$$-0.18 \leq \lambda \leq 0.18 \quad (\Delta\kappa = 0) \text{ [95\% CL]}$$

\Rightarrow Expect $\sim 2\text{-}3\text{X}$ better at Run II

[Competitive with single LEP experiment]



Charged Quartic Gauge Couplings



SM prediction negligible at LEP II

⇒ Look for anomalous QGCs

Lorentz Structure

$$L_0 = -\frac{e^2 a_0}{16 \Lambda^2} F^{\mu\nu} F_{\mu\nu} \vec{W}^\alpha \cdot \vec{W}_\alpha \quad \text{CP conserving (WW}\gamma\gamma)$$

$$L_c = -\frac{e^2 a_c}{16 \Lambda^2} F^{\mu\alpha} F_{\mu\beta} \vec{W}^\beta \cdot \vec{W}_\alpha \quad \text{CP conserving (WW}\gamma\gamma)$$

[Belanger and Boudjema, Nucl. Phys. **B288**, 201 (1992)]

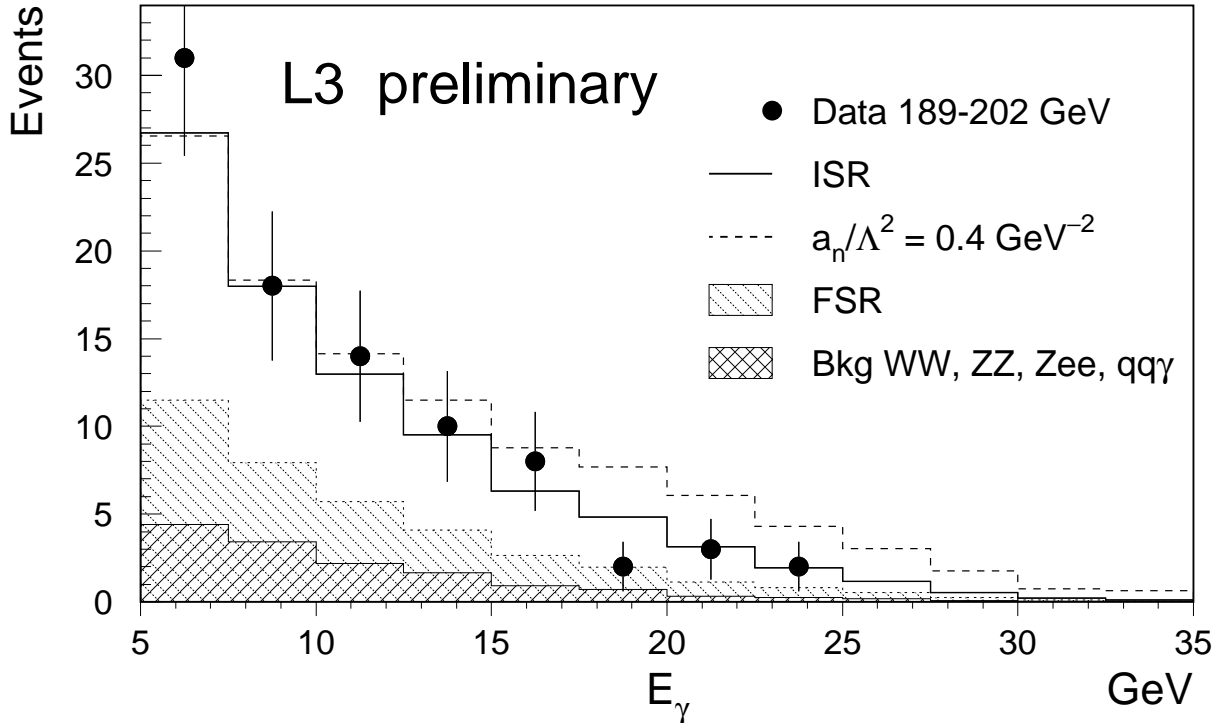
$$L_n = -i \frac{e^2 a_n}{16 \Lambda^2} \epsilon_{ijk} W_{\mu\alpha}^{(i)} W_\nu^{(j)} W^{(k)\alpha} F^{\mu\nu} \quad \text{CP violating (WWZ}\gamma)$$

[Stirling and Werthenback, EPJ **C14**, 103 (2000)]

Measure cross sections, E_γ , or m_{recoil}



LEP QGC Results



Unofficial LEP combination (M. Musy Moriond '01)

	Aleph	L3	Opal
$\nu\nu\gamma\gamma$	189-202 GeV	183-202 GeV	189 GeV
$WW\gamma$		183-202 GeV	189 GeV

95% CL limits (in GeV^{-2}):

$$-0.022 < a_0/\Lambda^2 < 0.021 \quad -0.043 < a_c/\Lambda^2 < 0.058$$

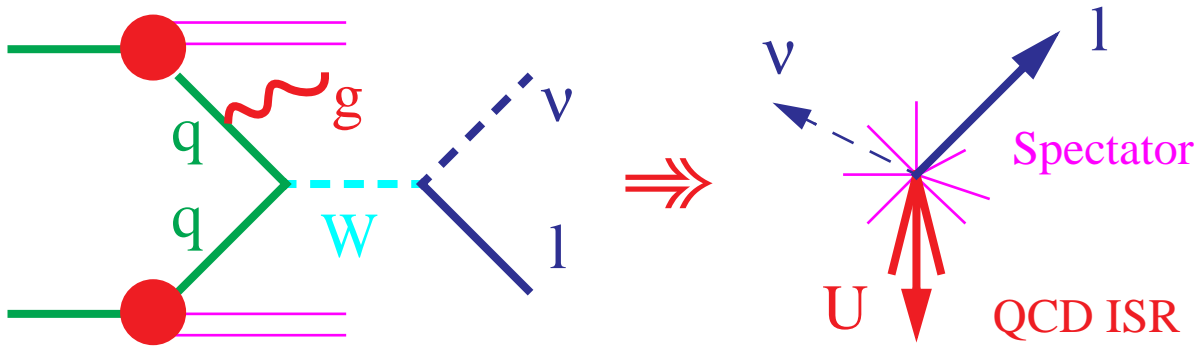
$$-0.22 < a_n/\Lambda^2 < 0.20$$



W Boson Mass



Tevatron Mass Analysis



Transverse Mass

$$m_T = \sqrt{2E_T^l E_T^{\nu} (1 - \cos \phi_{l\nu})}$$

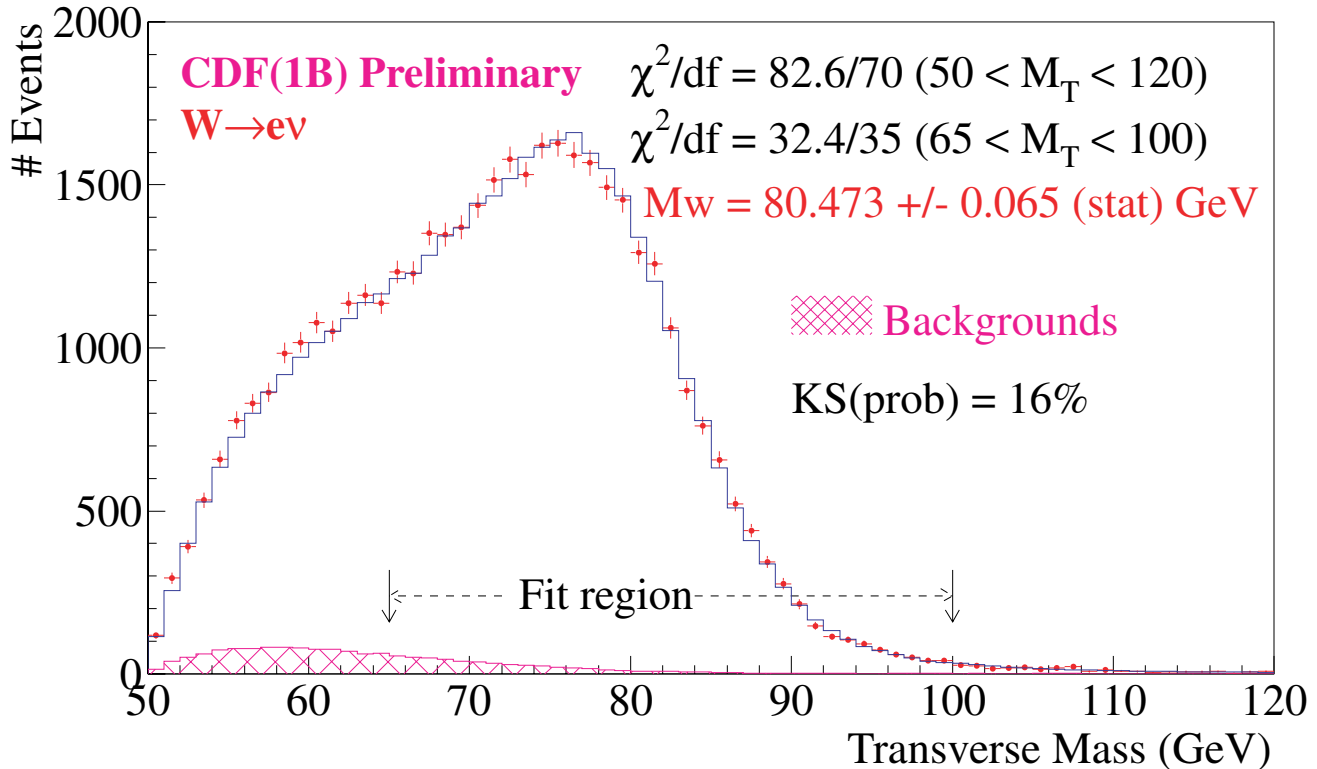
Missing Transverse Momentum: $\vec{p}_T^{\nu} = -(\vec{p}_T^l + \vec{U})$

MC Spectrum $m_T(m_W)$

- Energy scale and resolution E_T^l
 $\Delta m_W \sim \pm(80 \oplus 25) \text{ MeV}$
- QCD Recoil model (U) P_T^W
 $\Delta m_W \sim \pm 40 \text{ MeV}$
- PDF model (W Rapidity) P_Z^W
 $\Delta m_W \sim \pm 15 \text{ MeV}$



Run I Mass Results



CDF

- Use $W \rightarrow e\nu_e$ and $W \rightarrow \mu\nu_\mu$
- Central only $|\eta_l| < 1$

$$m_W(\text{CDF}) = 80.433 \pm 0.079 \text{ GeV}$$

D0

- Use $W \rightarrow e\nu_e$ only, also fit p_T^e & p_T^ν
- Include forward electrons $1.5 < |\eta_l| < 2.5$

$$m_W(\text{D0}) = 80.482 \pm 0.091 \text{ GeV}^*$$



Run I Systematics



“Typical” Uncertainties per Channel

Uncertainty	[MeV]
Statistical	60-100 [†]
scale	80 [†]
resolution	25 [†]
backgrounds	15
recoil	40 ^{†*}
PDF	15 ^{†***}
HOC	15 ^{**}
Systematic	95

[D.Glenzinski, Moriond 2001]

- † largely statistical (constrain with data)
- * correlated between channels
- ** correlated between experiments

⇒ Significant room for improvement at Run II

$$\Delta m_W(2fb^{-1}) < 40 \text{ MeV/exp} ???$$



D0 Energy Scale



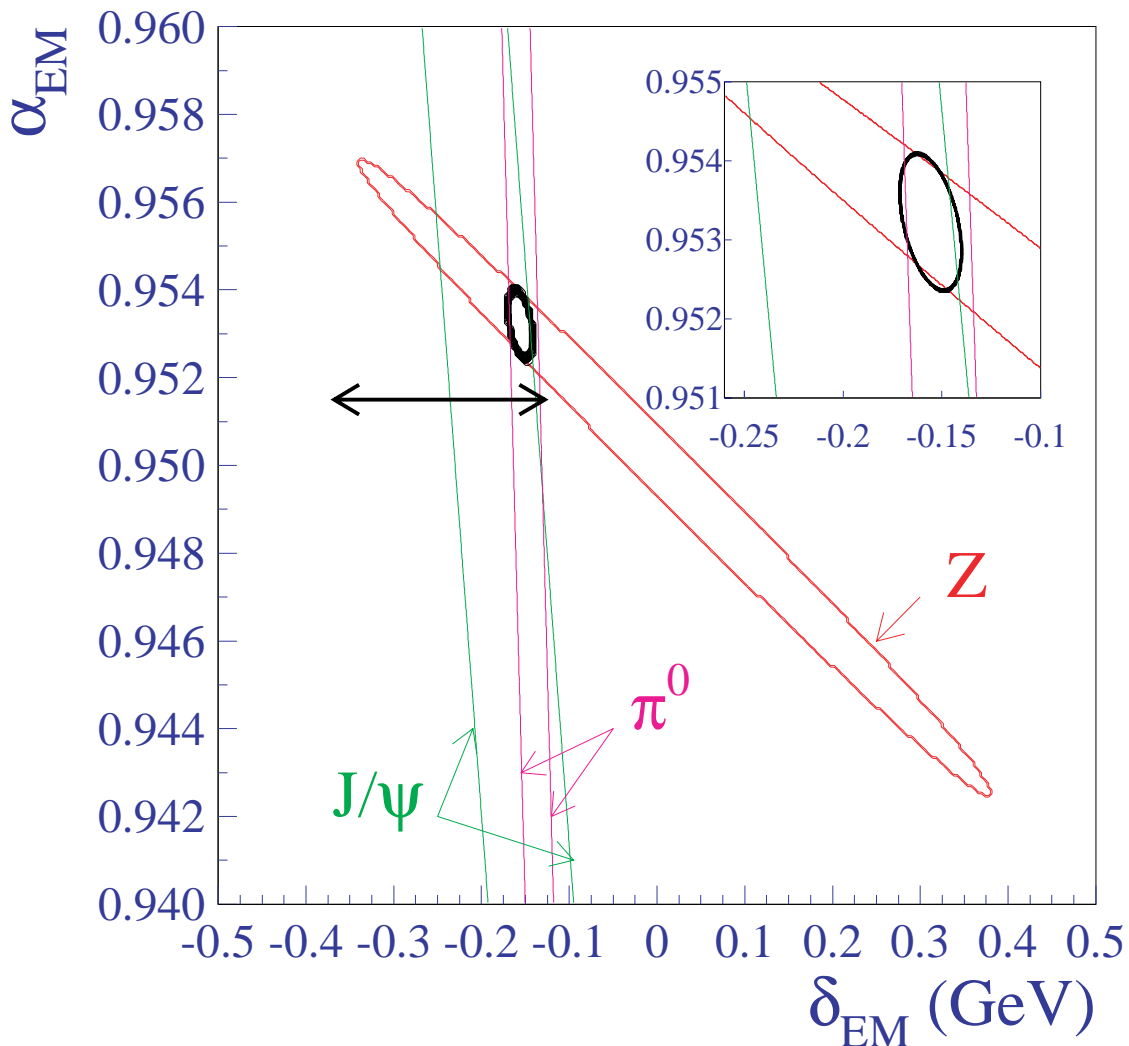
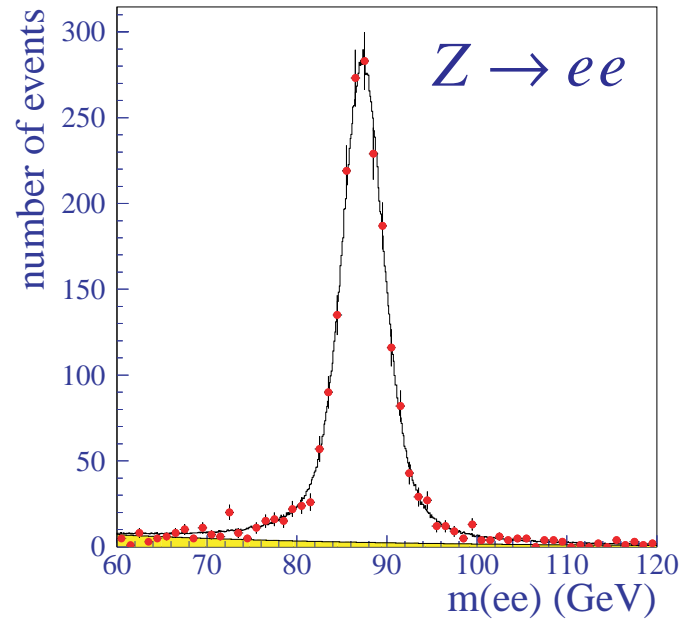
Calibrate using data

$$E = \alpha E_{meas} + \delta$$

$$\pi^0 \rightarrow eeee$$

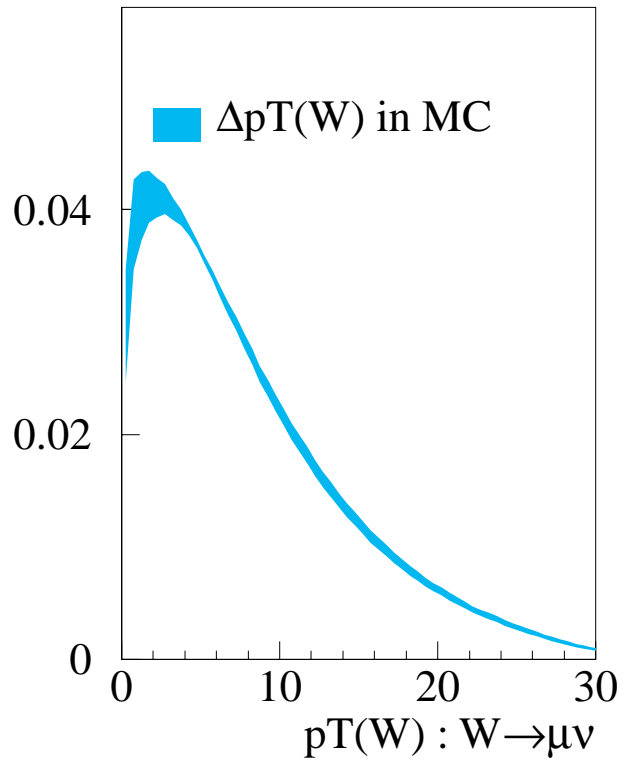
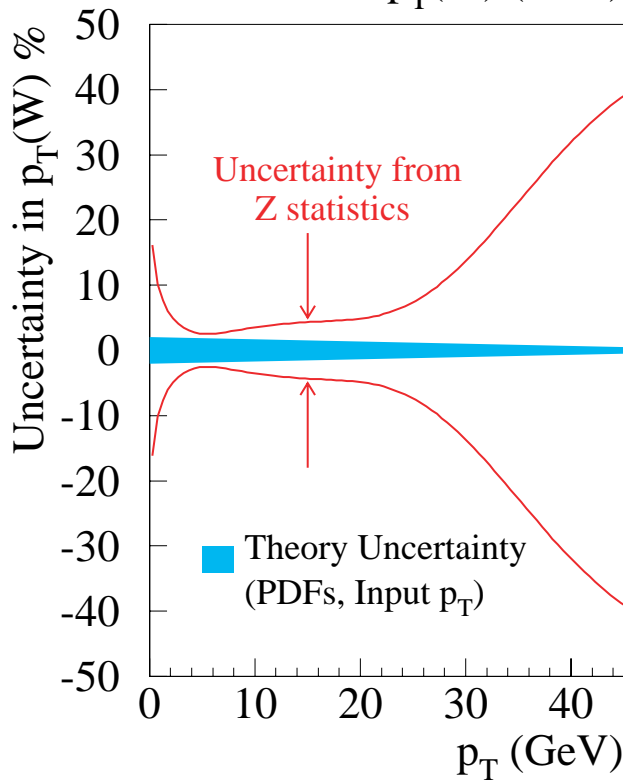
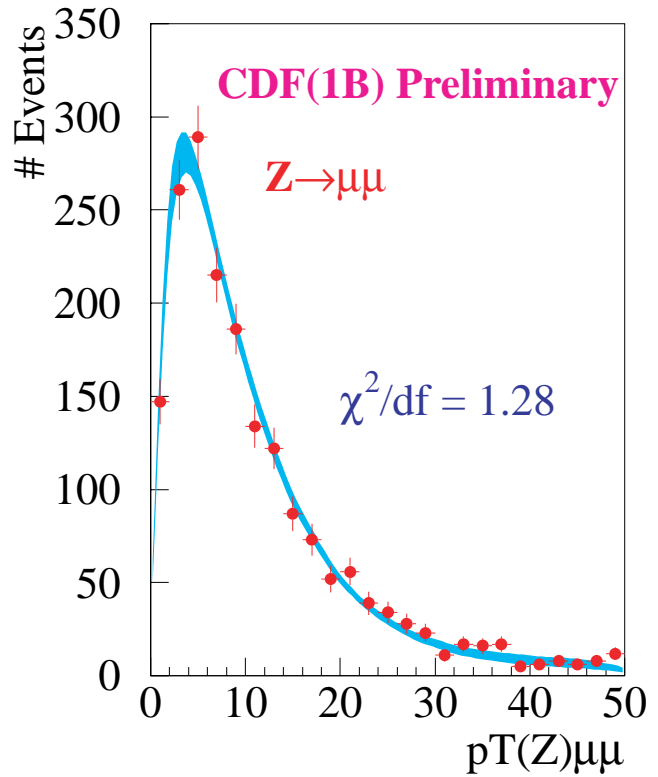
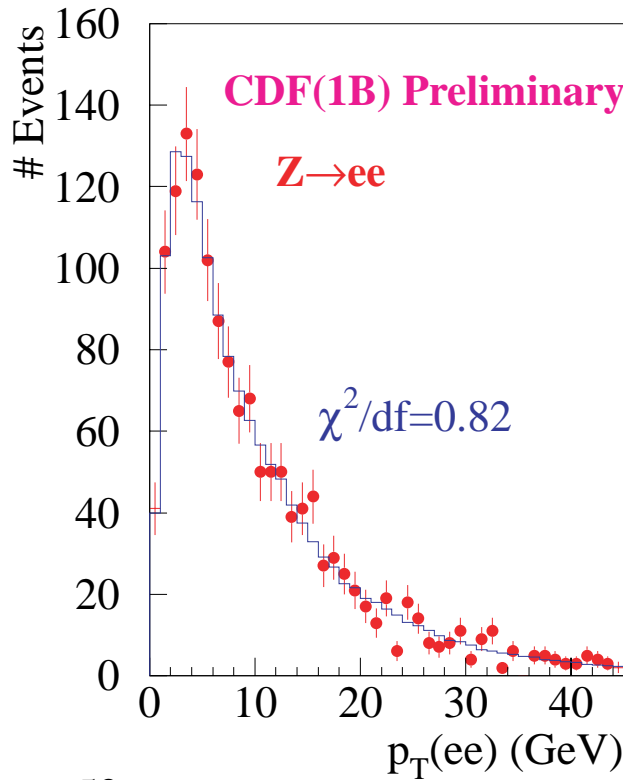
$$J/\psi \rightarrow ee$$

$$Z^0 \rightarrow ee$$





CDF Production Model

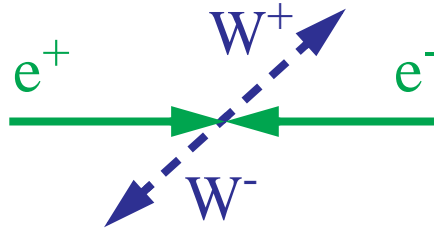




LEP Mass Analysis



Kinematic fitting



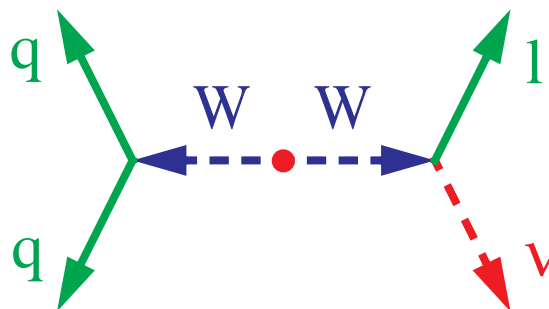
$$E_0 = 2E_{beam}, \vec{p}_0 = 0$$

4 Constraints

$$m_w^+ = m_w^-$$

1 Constraint

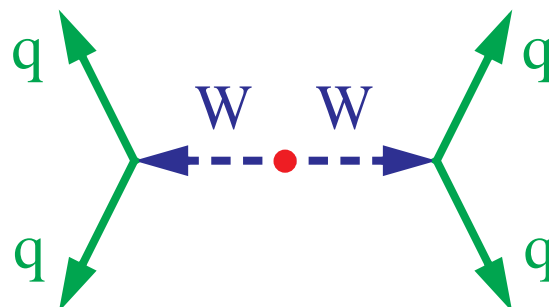
$WW \rightarrow qq\bar{l}\nu$



3 Unknowns

$$5 - 3 = 2C \text{ Fit}$$

$WW \rightarrow qq\bar{q}q$

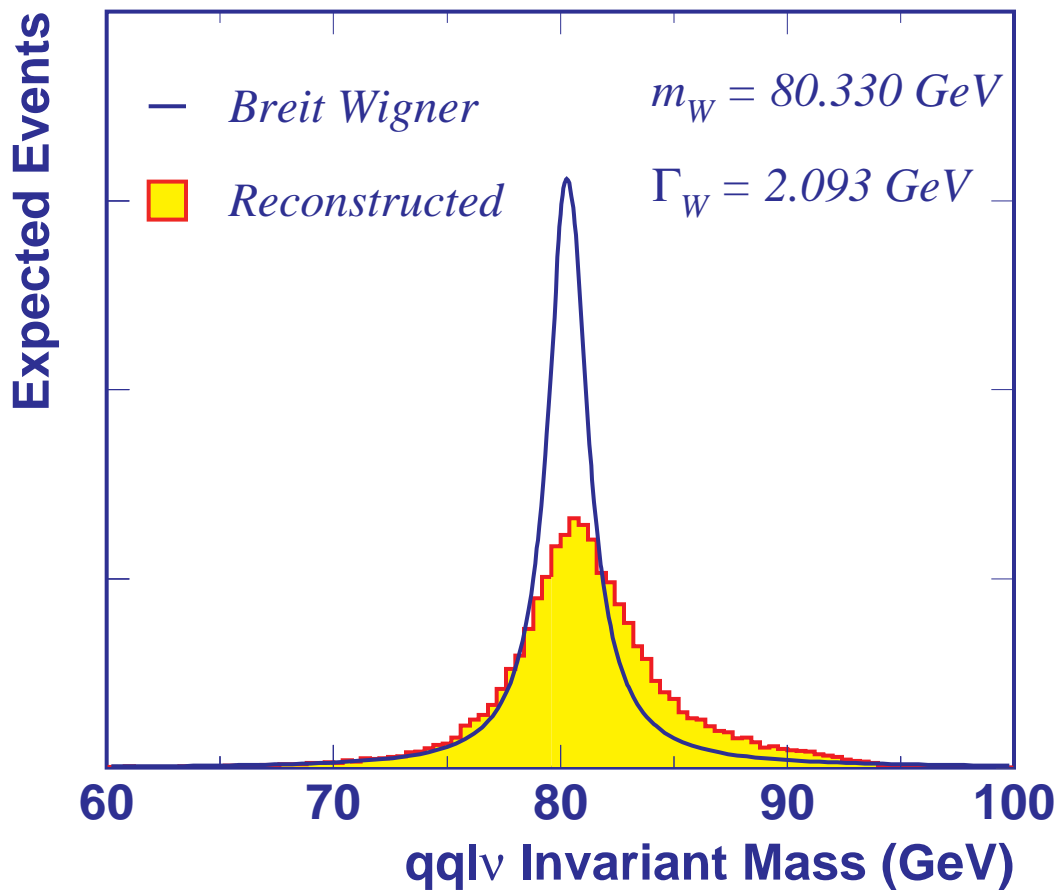


0 Unknowns

$$5 - 0 = 5C \text{ Fit}$$



LEP Mass Spectrum



Initial State Radiation: $E_0 \leq 2E_{beam}$

Detector Resolution: $m_w(rec) \neq m_w(true)$

Non-CC03 Diagrams: $qqev, qqqq$

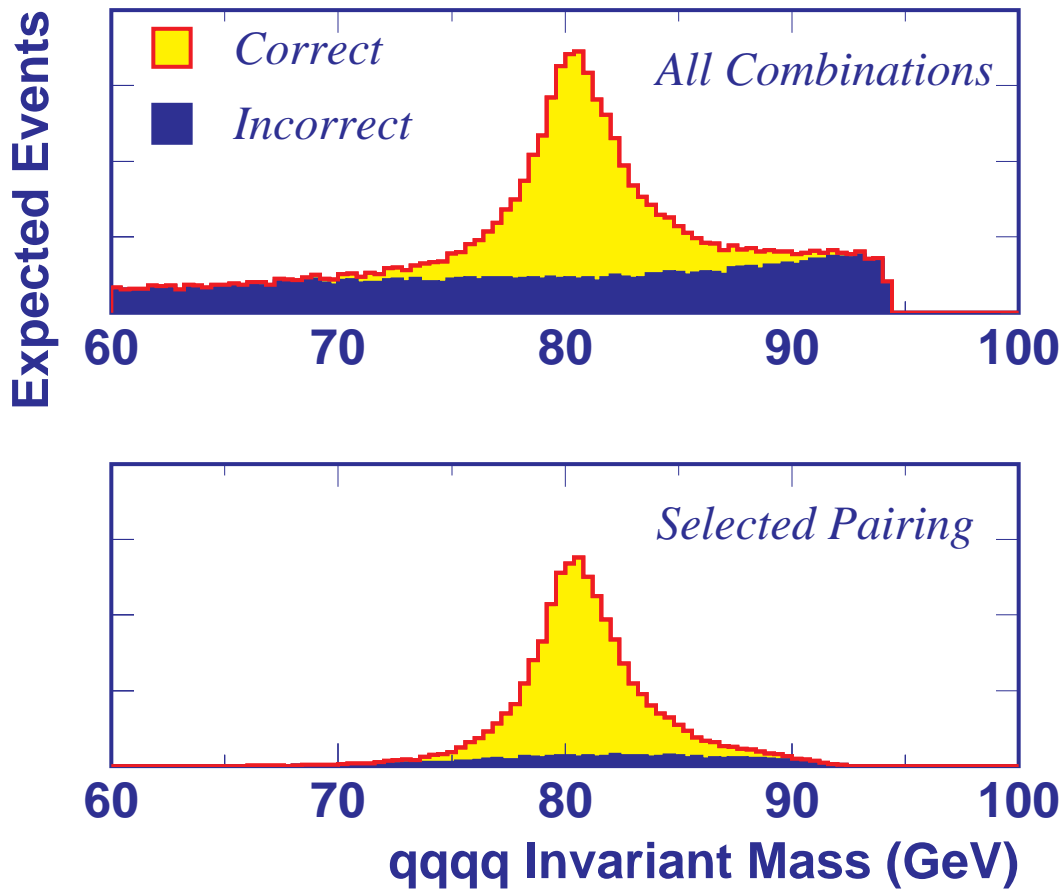
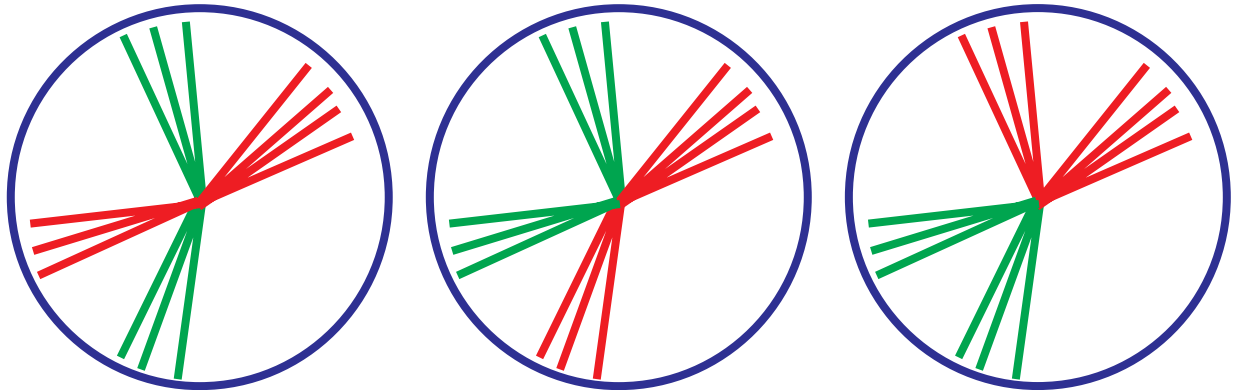
⇒ Cannot directly fit Breit-Wigner

Aleph, L3, Opal: *Reweight MC to Data*

Delphi: *Likelihood Convolution*



$WW \rightarrow qqqq$ Jet Pairing



Aleph, Opal:

Jet pairing selection

L3:

Highest 5C fit probability

Delphi:

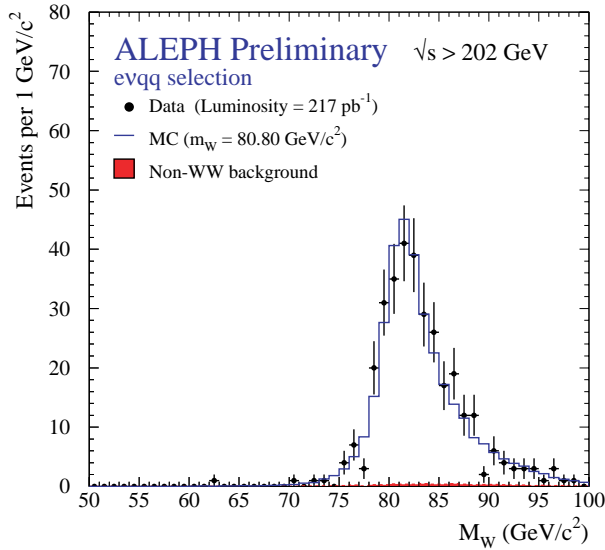
Use all Combinations



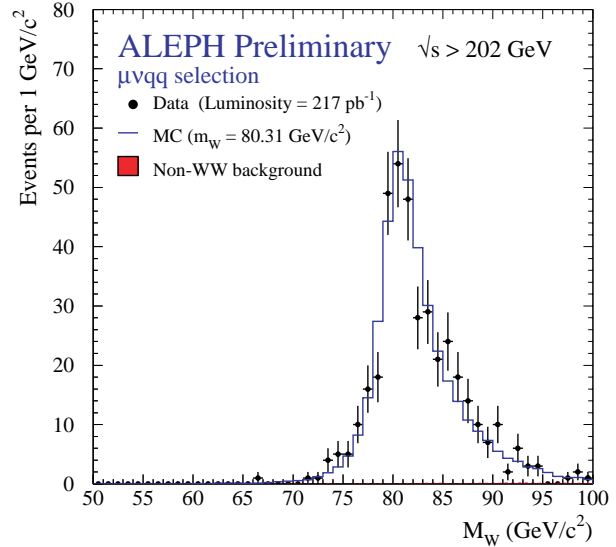
W Mass Spectra



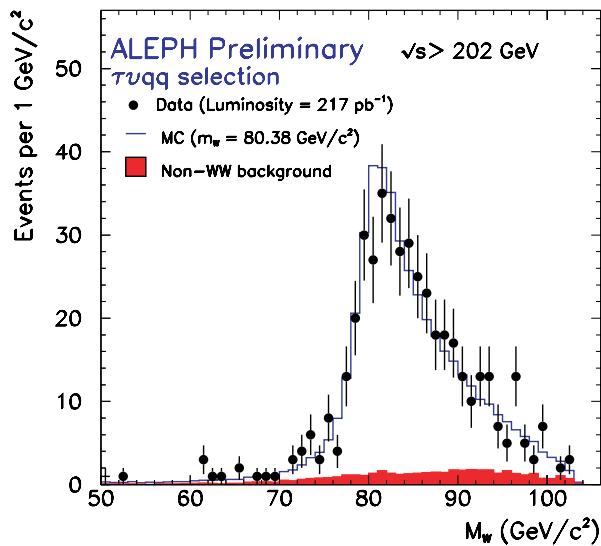
qqev



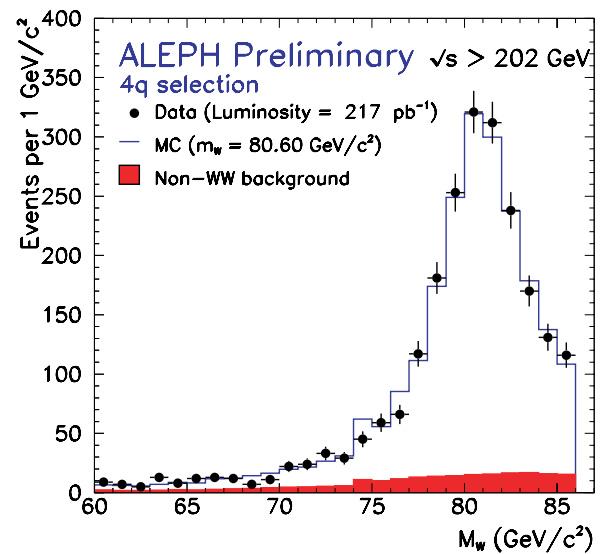
qq $\mu\nu$



qq $\tau\nu$



qqqq



⇒ Aleph 2000 data (*preliminary*)

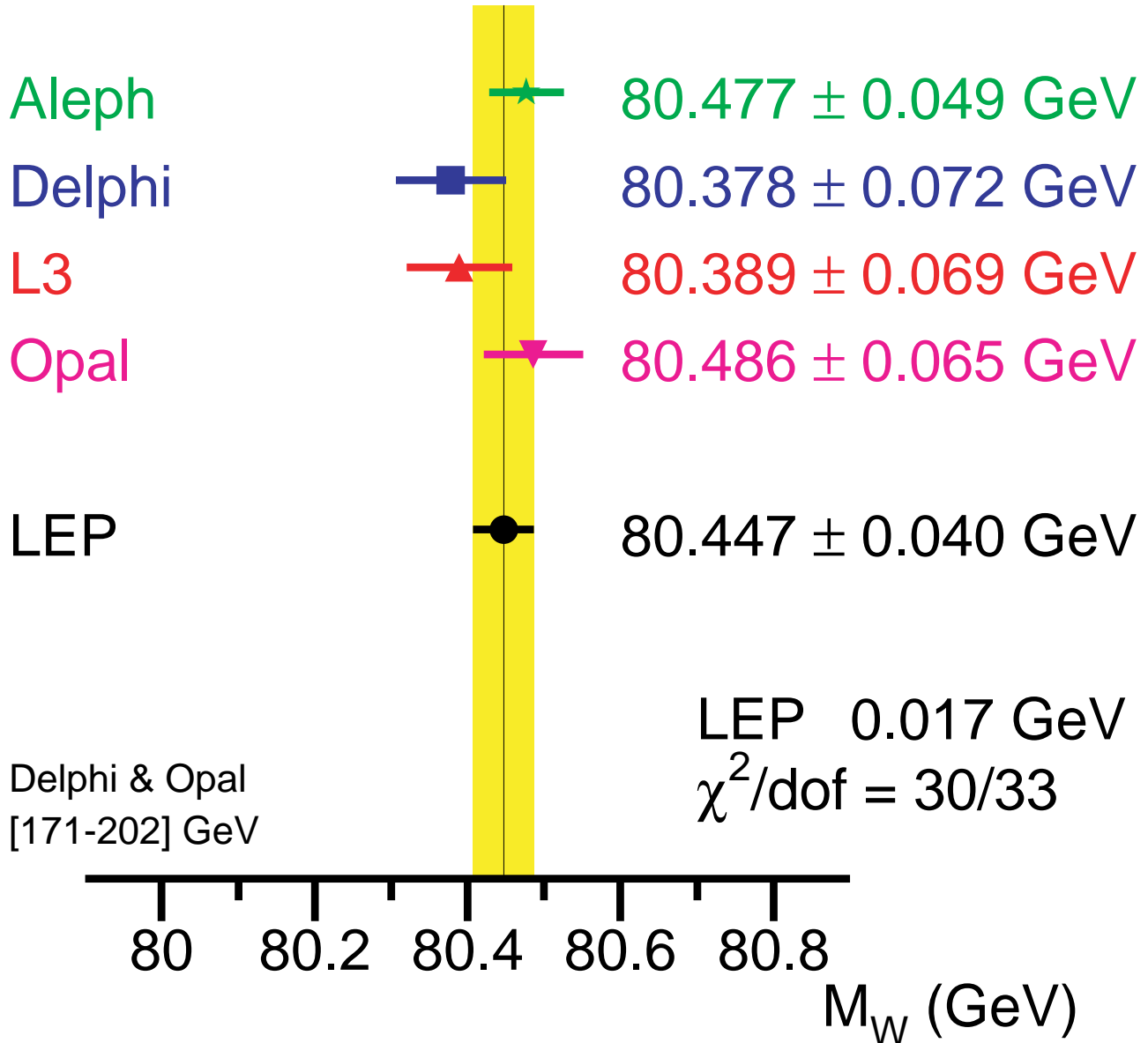


LEP W Mass Results



LEP W-Mass (171-209 GeV)

Winter 2001 Preliminary



LEP Combined (*preliminary*)

$$m_W(\text{LEP}) = 80.446 \pm 0.040 \text{ GeV}$$

[Including threshold cross section]



LEP Systematic Uncertainties



Direct Reconstruction Results (*preliminary*)

$$m_W = 80.447 \pm 0.026(\text{stat}) \pm 0.030(\text{syst})$$

⇒ Systematics Limited!

Moriond 2001 Combination

- Preliminary Procedure
- Conservative Correlations

Uncertainty	qqlv [MeV]	qqqq [MeV]
Detector	11	8
ISR/FSR	8	8
Hadronization	19	17
LEP Beam Energy	17	17
Bose - Einstein Corr.		25
Color Reconnection		40

[Component of total error indicated]

Weight from qqqq only 0.27

$$\delta m_W (\text{no syst}) = 22 \text{ MeV}$$

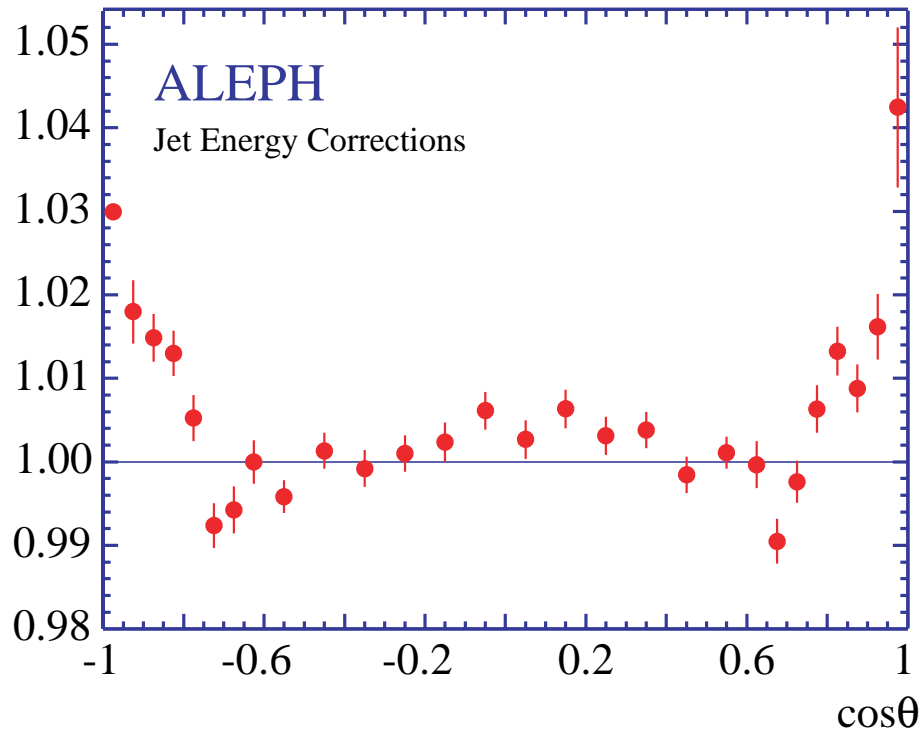


LEP Detector Systematics

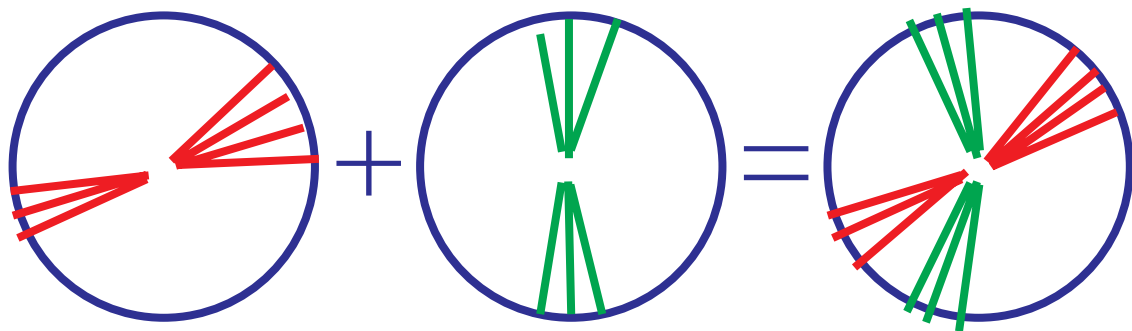


Calibration Data: $Z^0 \rightarrow l^+ l^-$, $Z^0 \rightarrow q \bar{q}$

- Jet/Lepton Energy/Angle Scale/Resolution
- Detector Alignment/Biases



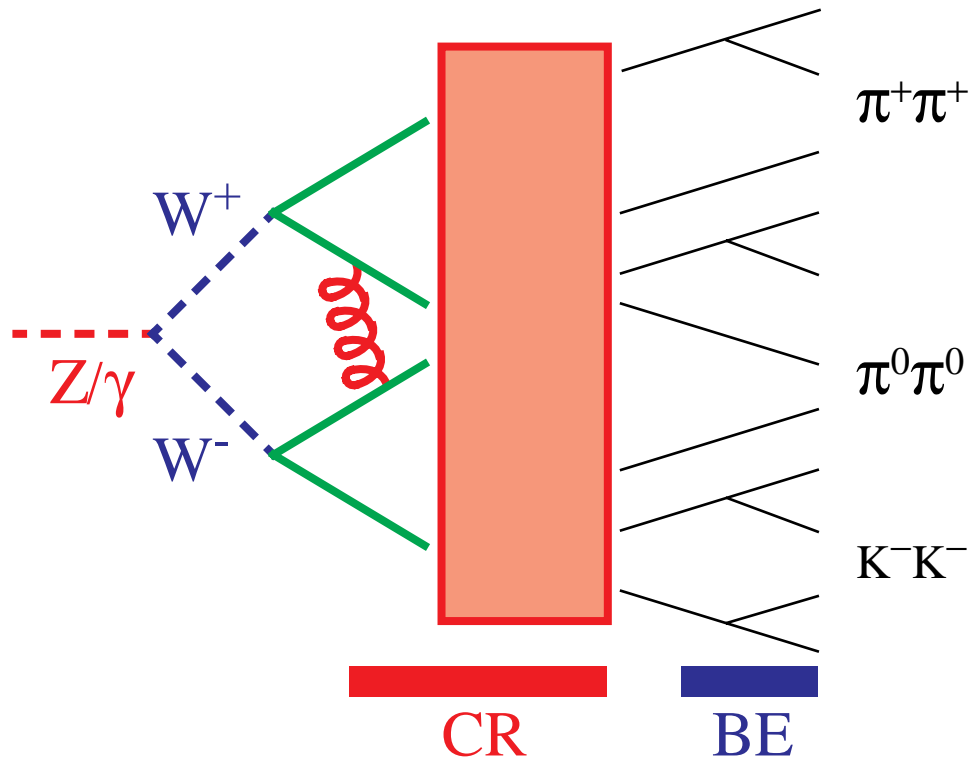
Mixed Lorentz Boosted Z (Delphi)



- Boost to match WW Monte Carlo
- Useful for Fragmentation as well



Final State Interactions



Interactions between decay products → shift in M_W

$$M_W(qqqq) - M_W(qql\nu) = +18 \pm 46 \text{ MeV}$$

Color Reconnection

- Strong (QCD) interactions in non-perturbative phase
- Only a few models exist, difficult to calculate

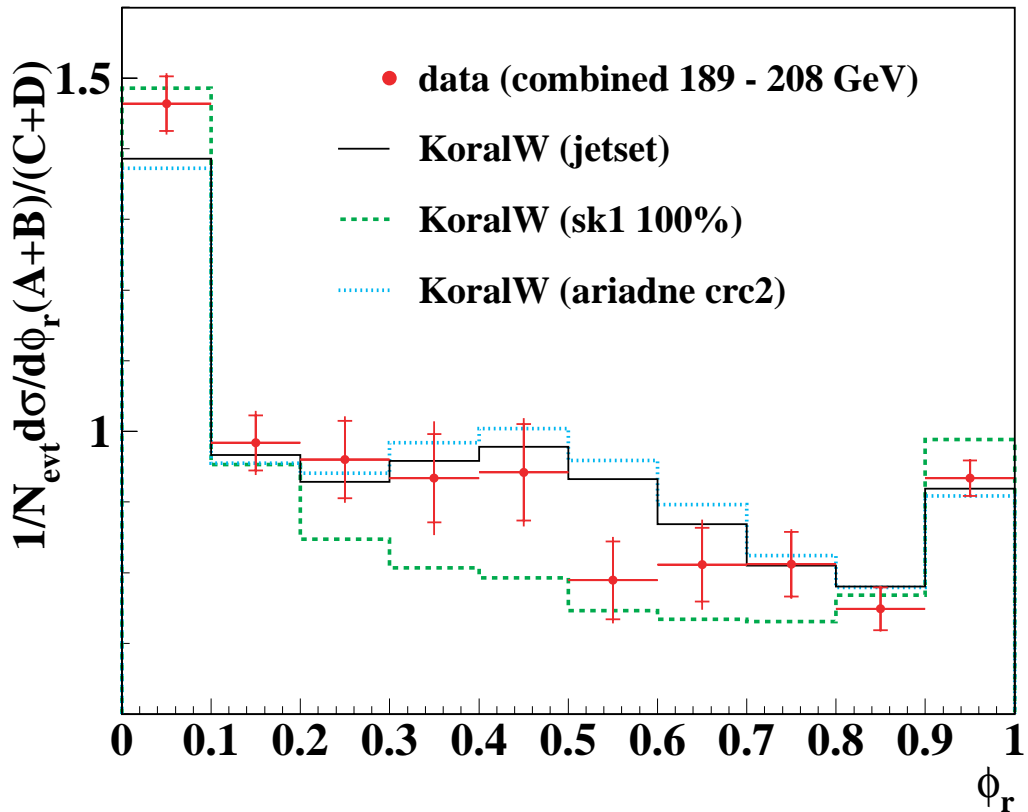
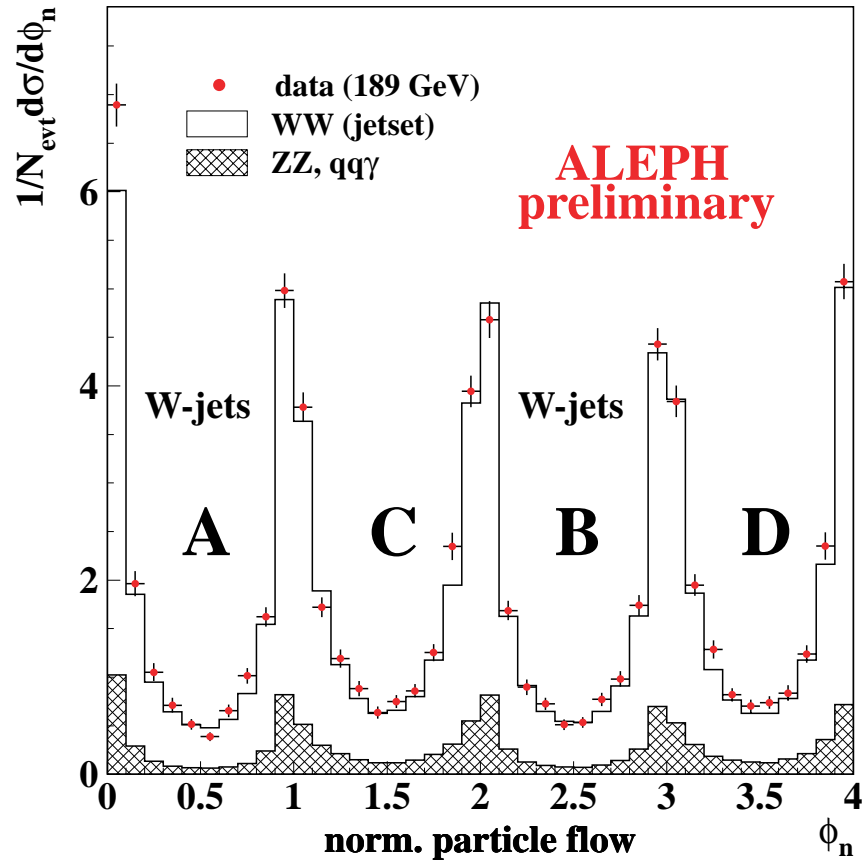
Bose-Einstein Correlations

- Well established in single W or Z decays
- Difficult to model properly in WW system

⇒ Constrain using Data!

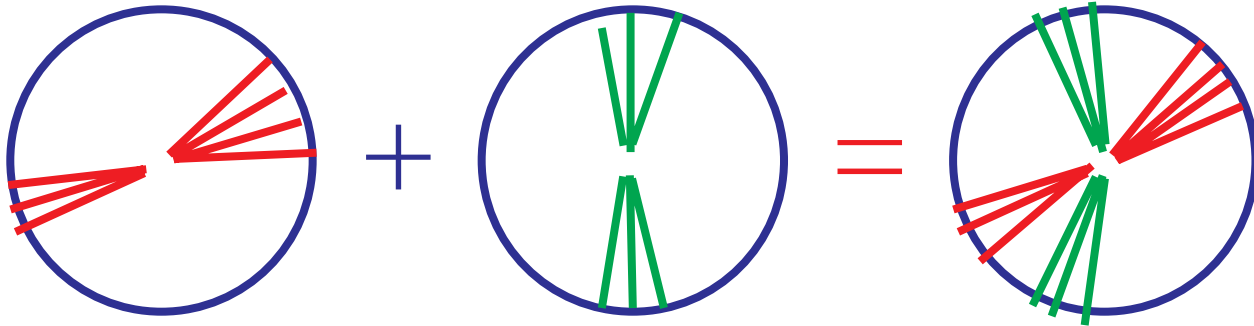


Color Reconnection



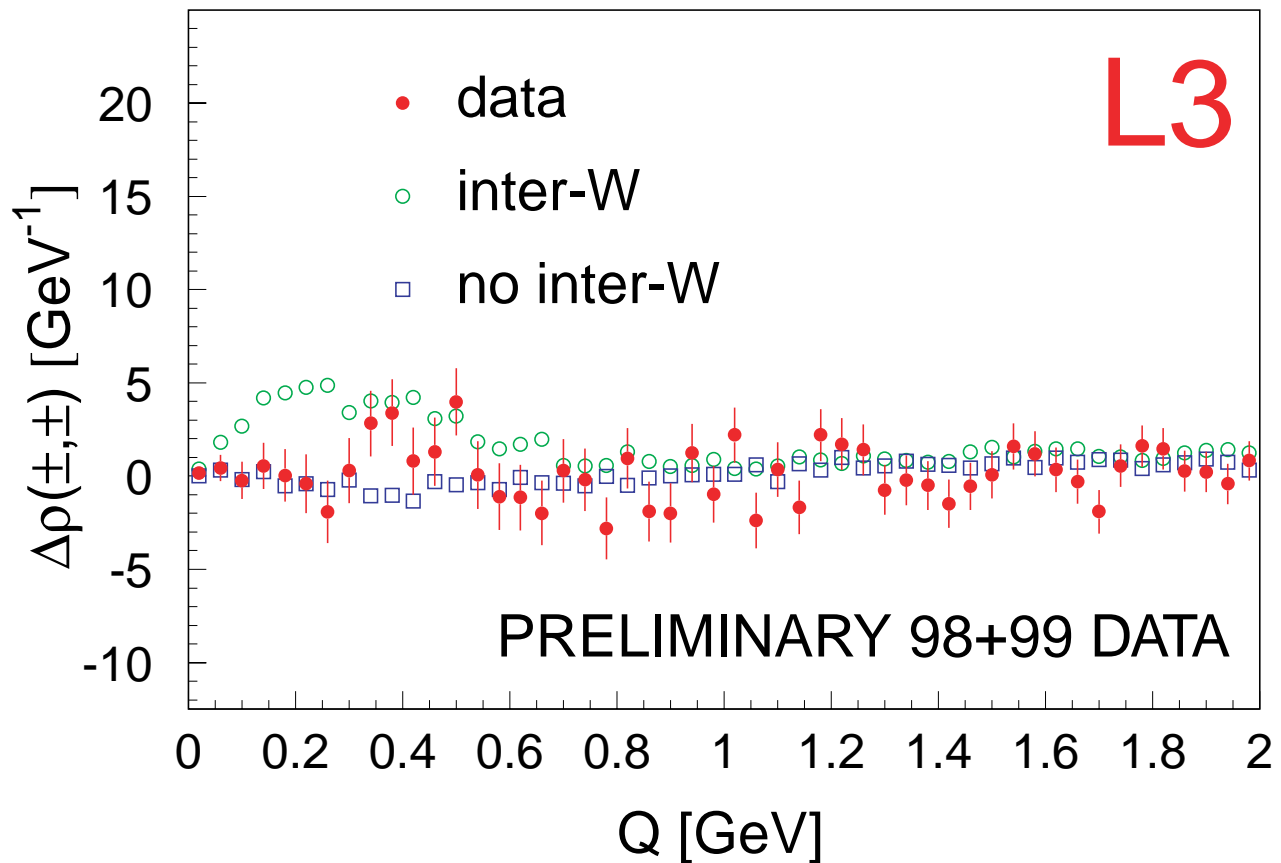


Bose-Einstein Correlations



$$\Delta\rho = \rho^{WW} - 2\rho^W - 2\rho_{mix}^{WW} \text{ where } \rho = \frac{1}{N} \frac{dn_{pairs}}{dQ}$$

Model Independent!



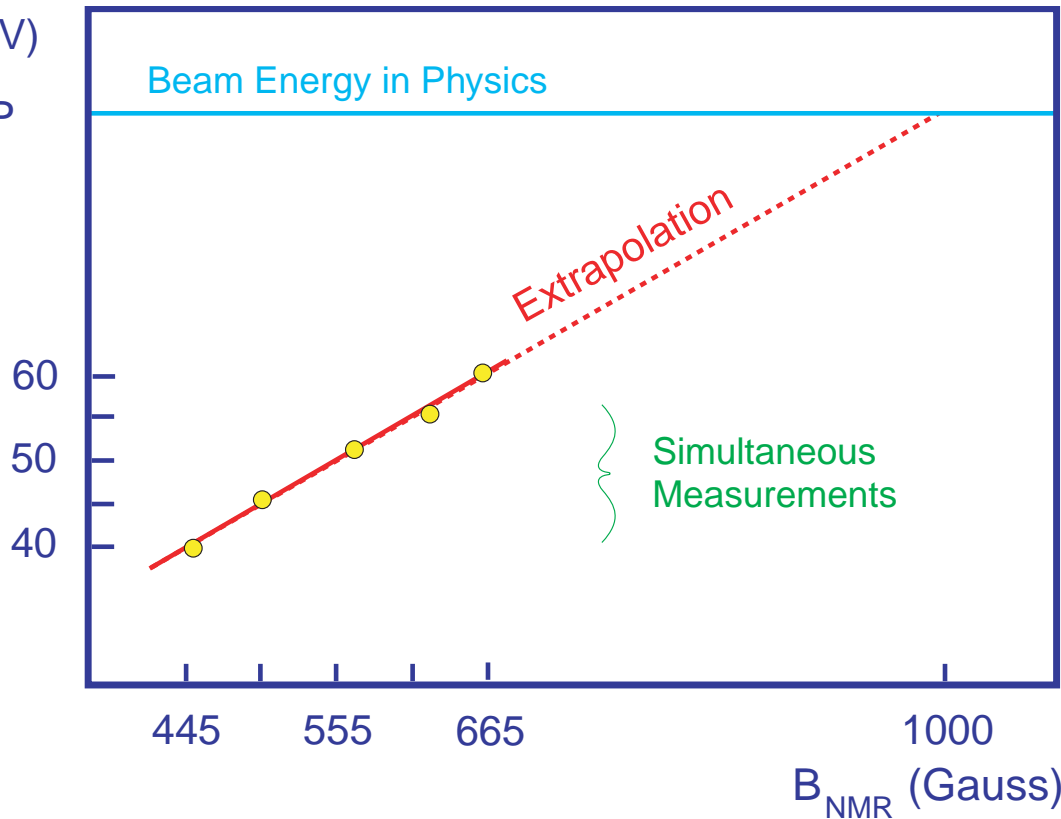
No evidence for inter-W BE correlations



LEP II Beam Energy



E_{Beam} (GeV)
from RDP



- Resonant Depolarization $\Delta E_{\text{beam}} < 1 \text{ MeV}$

\Rightarrow Limited to $E_{\text{beam}} < 60 \text{ GeV}$

- NMR Extrapolation $\Delta E_{\text{beam}} = 20 \text{ MeV}$

$$\Delta M_W = 17 \text{ MeV}$$

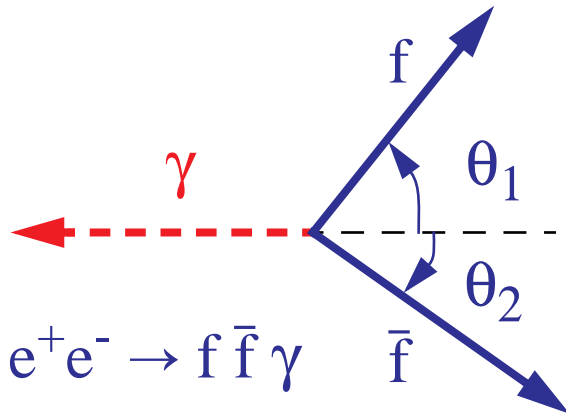
Extrapolation Checks

- Inline Spectrometer $\Delta E_{\text{beam}} = 20 \text{ MeV?}$
- Synchrotron Q_s vs. V_{RF} $\Delta E_{\text{beam}} = 20 \text{ MeV?}$

\Rightarrow Work continues...



LEP II Radiative Returns

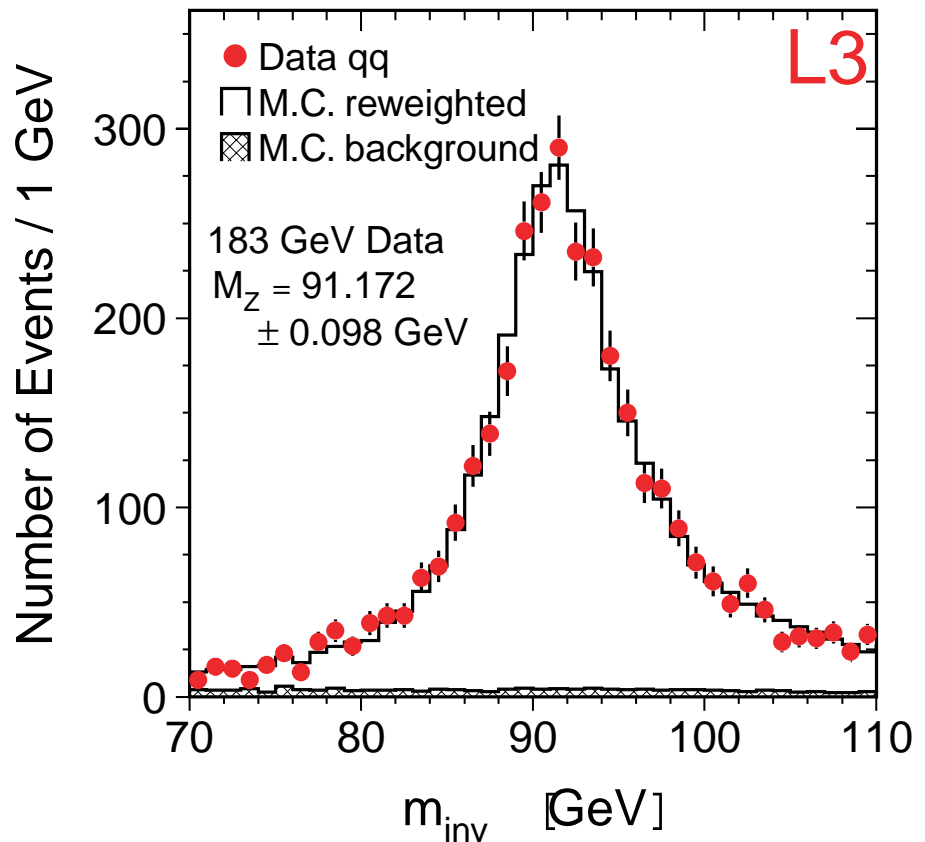


$$\frac{s'}{s} = \frac{\sin\theta_1 + \sin\theta_2 - |\sin(\theta_1 + \theta_2)|}{\sin\theta_1 + \sin\theta_2 + |\sin(\theta_1 + \theta_2)|}$$

Statistics

Channel	ΔE_{beam}
$q\bar{q}\gamma$	$\sim 20 \text{ MeV}$
$\mu\mu\gamma$	$\sim 50 \text{ MeV}$

LEP Combined
Statistics Only



Systematics

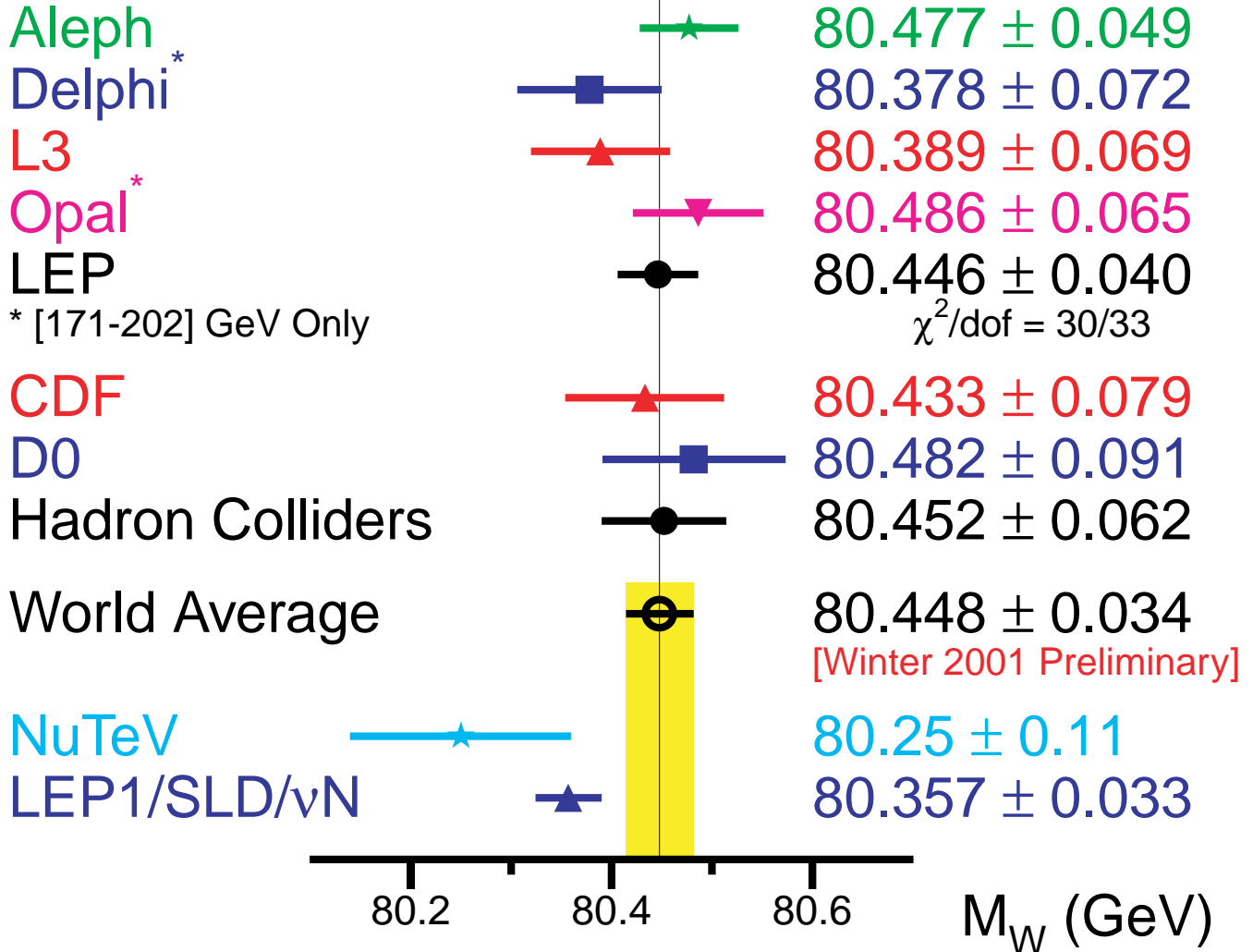
- Theoretical Description
- Hadronization Uncertainties
- Detector Understanding

Preliminary Estimates

$q\bar{q}\gamma$	$\Delta E_{\text{beam}} \sim 70 \text{ MeV}$
$\mu\mu\gamma$	$\Delta E_{\text{beam}} \sim 40 \text{ MeV}$



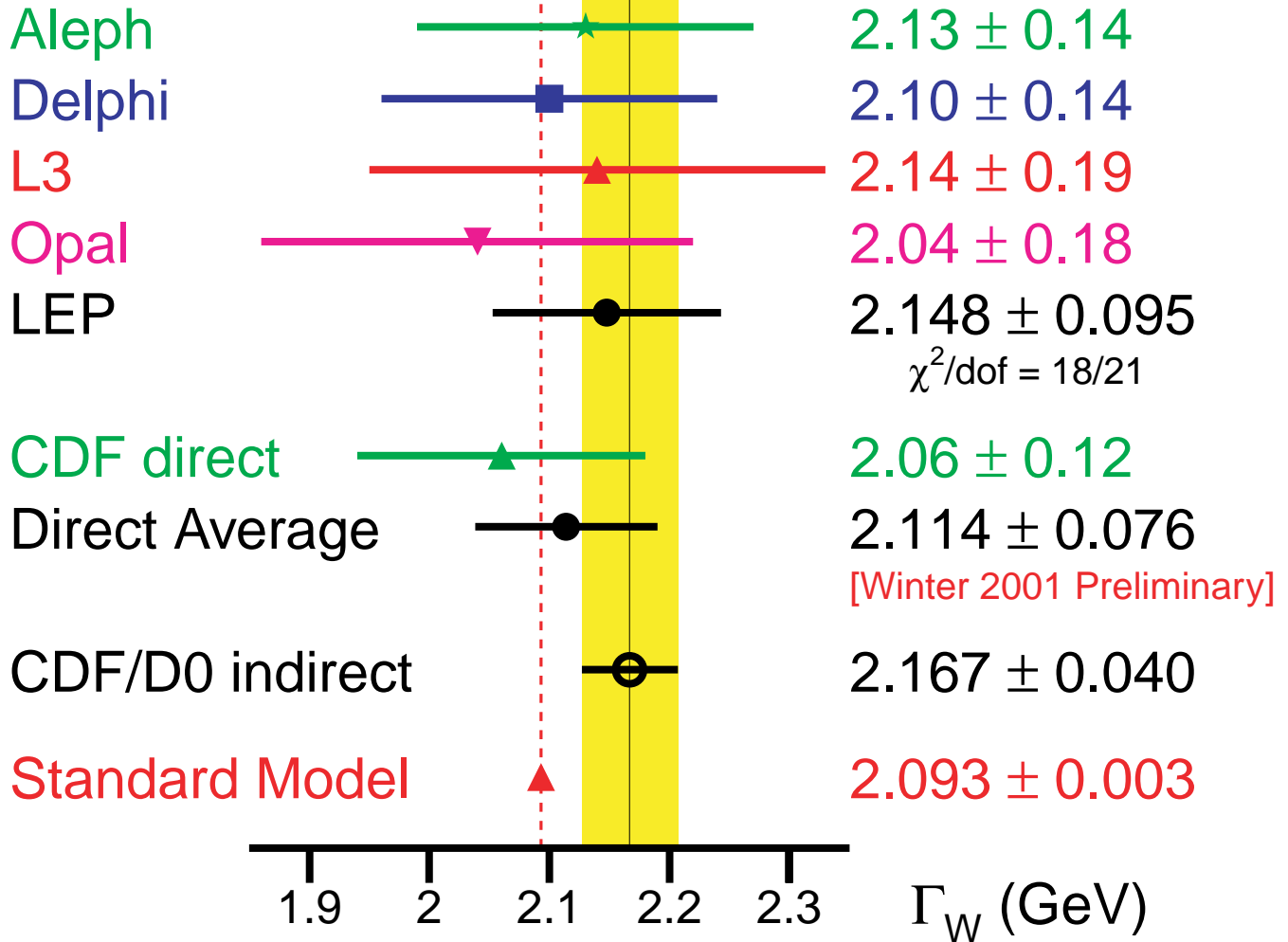
World W Mass Results



- LEP II Final $\Delta M_W \sim 20 \text{ MeV (stat)}$
 $\sim 35 \text{ MeV (total)?}$
- Run IIa (2 fb^{-1}) $\Delta M_W \sim 40 \text{ MeV (each)?}$
 $\Rightarrow \Delta M_W \sim 20 \text{ MeV by 2006}$
- LHC (10 fb^{-1}) $\Delta M_W \sim 20 \text{ MeV (each)??}$



Direct Width



LEP

$\Gamma_W(qqqq) - \Gamma_W(qql\nu)$ useful for **CR**?

Not all LEP II data analyzed...

Tevatron

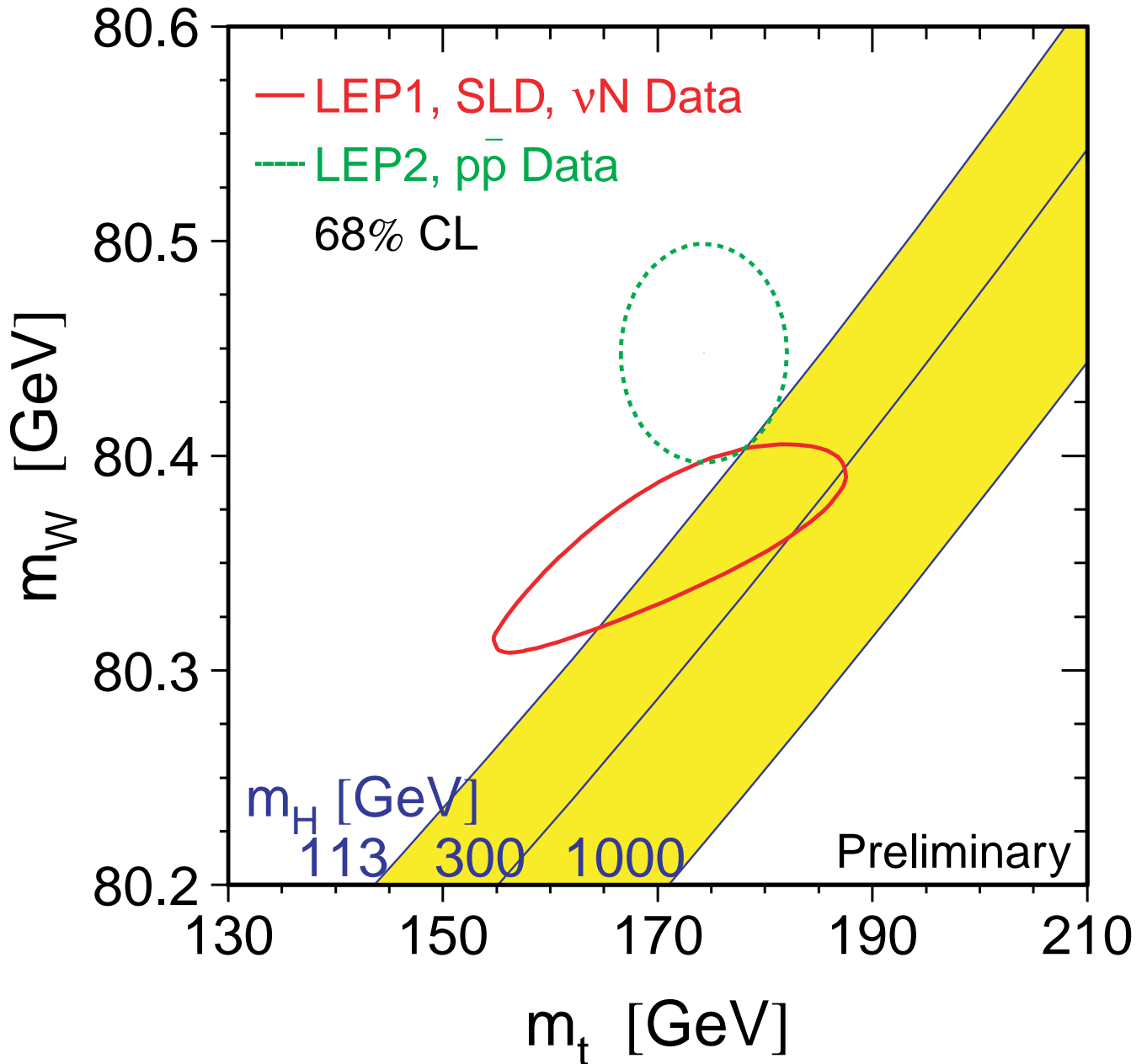
D0 direct width coming **this summer**



Global Results



Standard Model Consistency

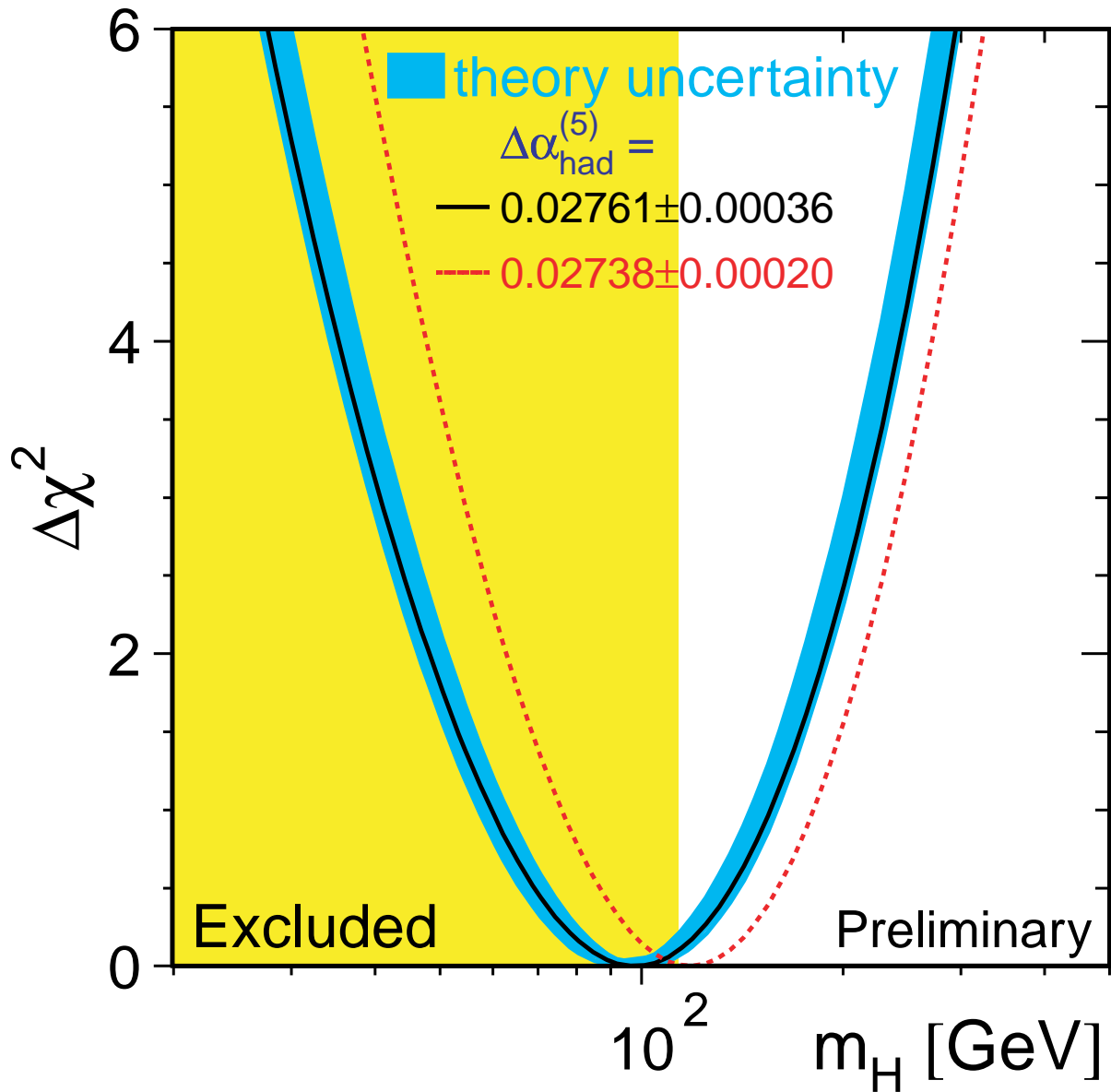


Direct measurements on the SUSY-side

⇒ Light Higgs preferred!



SM Higgs Boson



Simple Parameterization

$$\sin^2 \theta_W^{\text{eff}}, m_W = f(m_{\text{top}}^2, \ln(m_H), \alpha_{\text{QED}})$$

[Degrassi et al.]

⇒ Poor man's ZFITTER!



SM Higgs Constraint



Using $m_W = f(m_{top}^2, \ln(m_H), \alpha_{QED})$

$$\Delta \ln(m_H) = \pm 0.60 \pm 0.55(m_t) \pm 0.11(\Delta\alpha_h) = \pm 0.82(\text{total})$$

Using $\sin^2 \theta_W^{eff} = f(m_{top}^2, \ln(m_H), \alpha_{QED})$

$$\Delta \ln(m_H) = \pm 0.32 \pm 0.31(m_t) \pm 0.24(\Delta\alpha_h) = \pm 0.51(\text{total})$$

After Run IIa (2 fb^{-1})

$$\Delta m_t = 3 \text{ GeV}, \Delta m_W = 20 \text{ MeV (expected)}$$

Using m_W alone

$$\Delta \ln(m_H) = \pm 0.34 \pm 0.32(m_t) \pm 0.11(\Delta\alpha_h) = \pm 0.49(\text{total})$$

Using $\sin^2 \theta_W^{eff}$ alone

$$\Delta \ln(m_H) = \pm 0.32 \pm 0.18(m_t) \pm 0.24(\Delta\alpha_h) = \pm 0.44(\text{total})$$



Summary



Final LEP II Performance

- $L_{\text{int}} \sim 650 \text{ pb}^{-1}$ per experiment
- $E_{\text{CM}} \leq 209 \text{ GeV}$

Physics Highlights

$$\text{Br}(W \rightarrow qq): \quad 67.92 \pm 0.27\%$$

$$|V_{cs}| = 0.996 \pm 0.013$$

Triple Gauge Couplings:

3-6% precision achieved

W Boson Mass:

$$m_W = 80.446 \pm 0.034 \text{ GeV}$$

Five Year Plan

Run IIa: Lots of EW physics in 2 fb^{-1}

$$\Delta m_W \sim 20 \text{ MeV} \quad \Delta m_{\text{top}} \sim 3 \text{ GeV}$$

⇒ Time for more hadrons!