W Boson Properties

quark - lepton

Seoul, Korea, June 28–30, 2001

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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

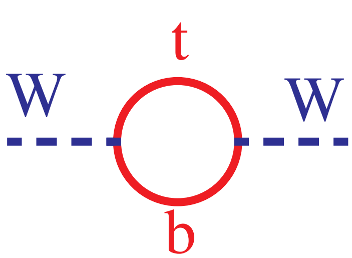
$\langle \phi \rangle_0$ Vacuum EV of the Higgs field

Need three precision measurements

α_{em}:	$\frac{1}{4\pi}\frac{(gg')^2}{g^2 + g'^2}$	(Electron g-2)	0.004 ppm
G_F:	$\frac{1}{\sqrt{8}}\frac{1}{\langle\varphi\rangle_0^2}$	(Muon Lifetime)	9 ppm
m_Z:	$\frac{\langle\varphi\rangle_0}{\sqrt{2}}\sqrt{g^2 + g'^2}$	(LEP I lineshape)	23 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

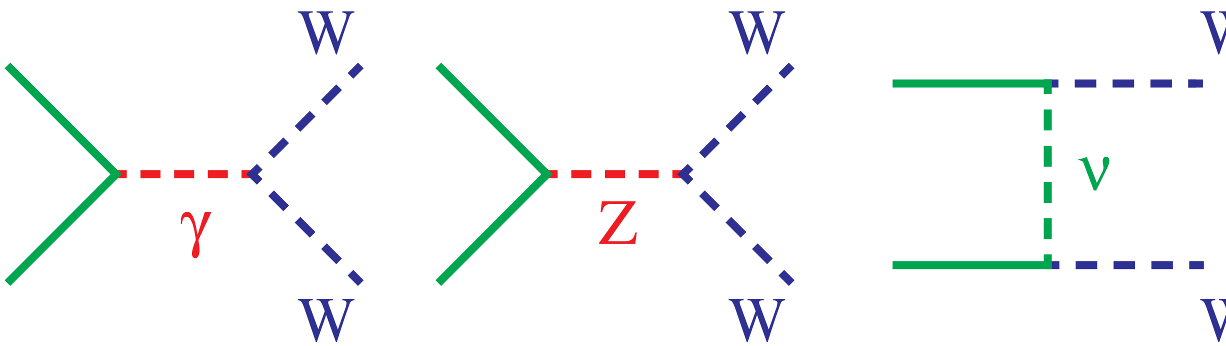
$\bar{p}p$ collisions

Run I 1800 GeV (1992 - 1995)

Run II 1960 GeV (2001 - 200?)

Data Samples

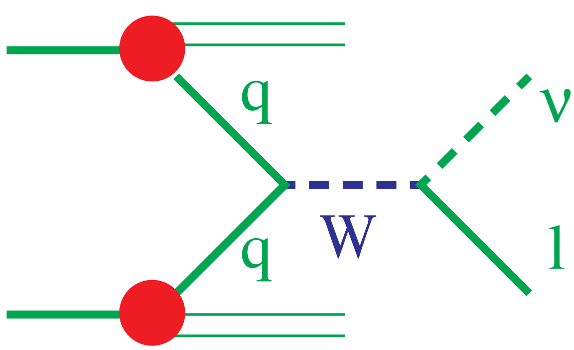
$e^+e^- \to W^+W^-$



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

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

$\bar{p}p \to WX$



Trigger on W → lν only

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

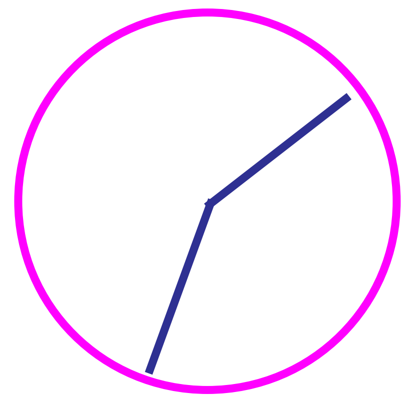
Run I Total: 200k W events (200 pb^{-1})

W Production and Decay

LEP WW Decay Modes

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

SM Rate: 10.6%

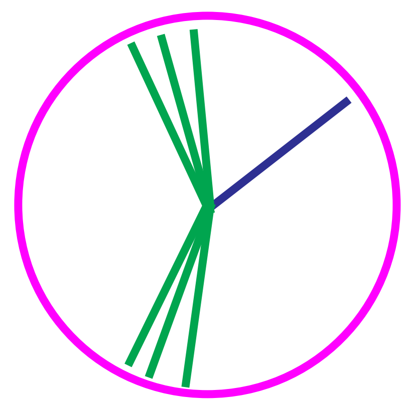


- Two Leptons
- Little Mass Information

ε ~ 60-80% π ~ 90%

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

SM Rate: 43.8%

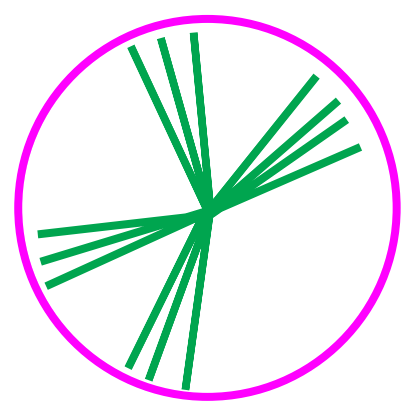


- One Lepton, Two Jets
- Low Backgrounds
- Golden channel for mass

ε ~ 70-85% π ~ 90%

$W^+W^- \rightarrow qqqq$

SM Rate: 45.6%



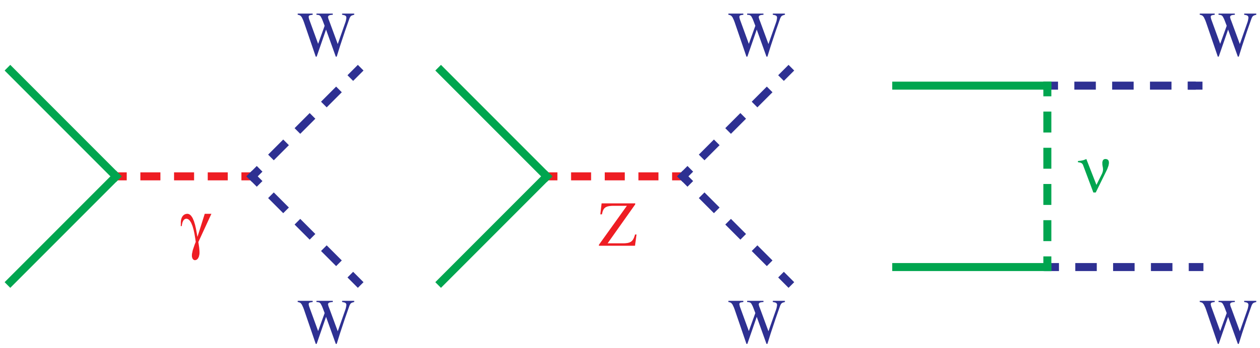
- Four Jets
- Significant Backgrounds
- No Missing Momentum

ε ~ 80-90% π ~ 80%

Worse performance with taus

Four Fermion Amplitudes

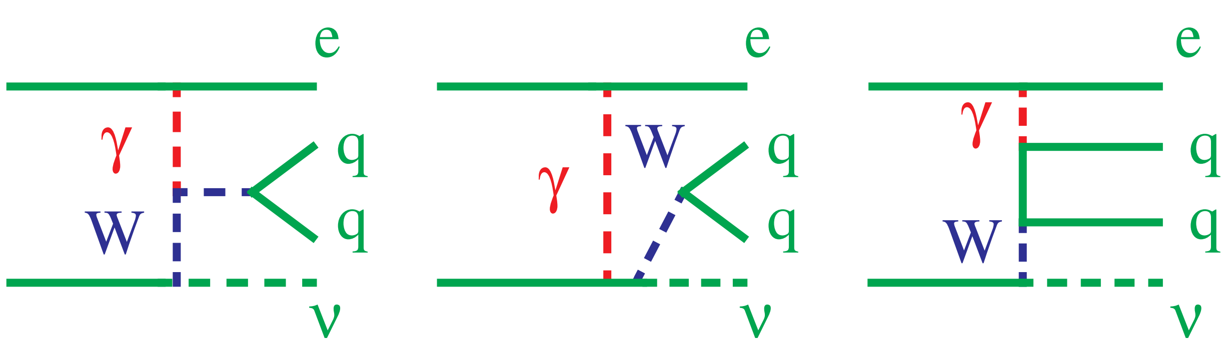
CC03 Amplitudes:



Convenient definition of resonant production

⇛ Other diagrams with identical final states!

$e^+e^- \rightarrow qqe\nu$

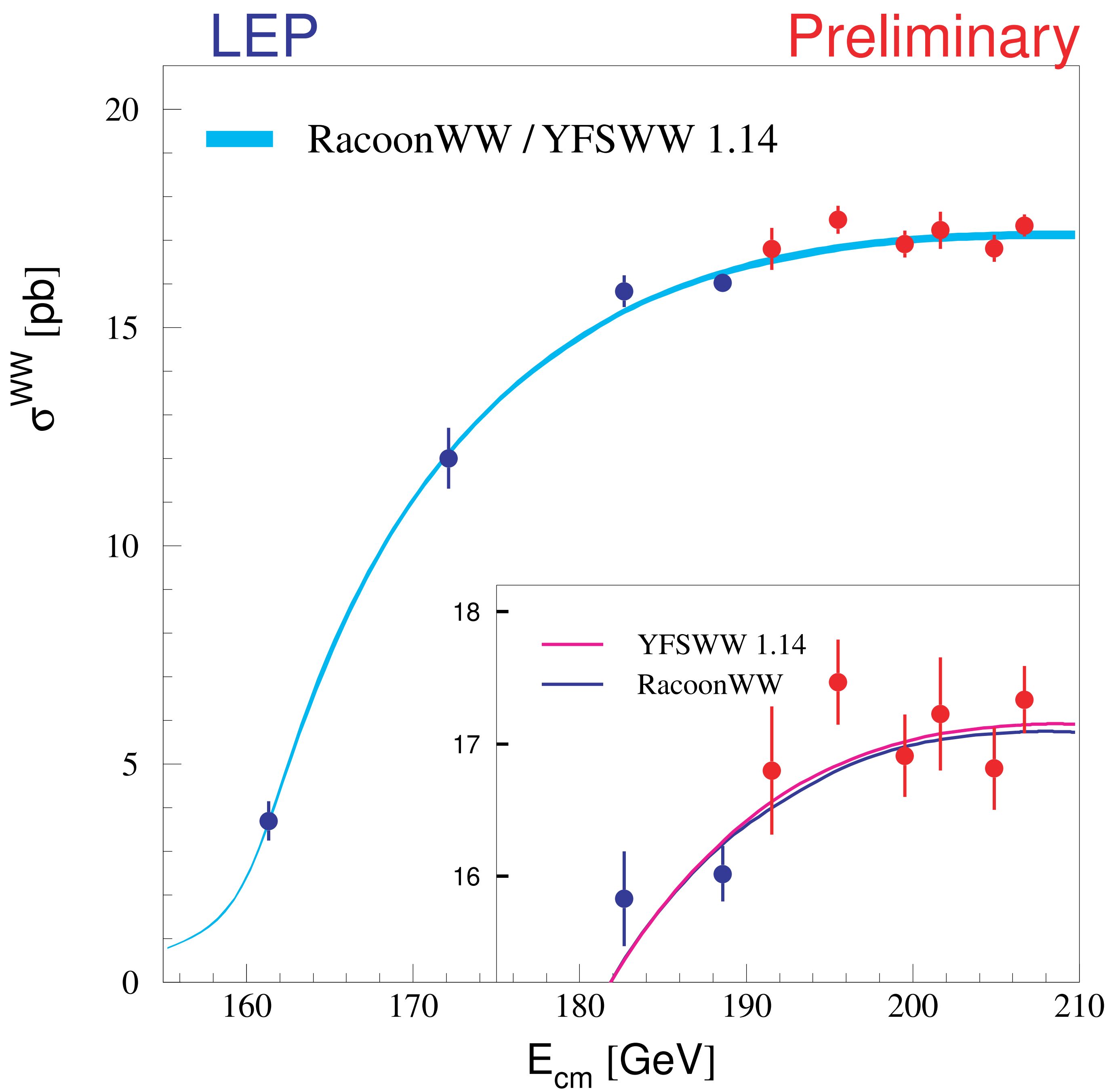


Rely on complete 4f Monte Carlo

⇛ Non-CC03 diagrams ~5%

WW Cross Section

02/03/2001



Complete Order α_{EM} Calculations

RacoonWW: Denner, Dittmaier, Roth, Wackeroth

YFSWW: Jadach, Placzek, Skrzypek, Ward, Was

LEP W Branching Fractions

Leptonic Branching Fractions

Br (W→eν): $10.54 \pm 0.17\,\%$

Br (W→μν): $10.54 \pm 0.16\,\%$

Br (W→τν): $11.09 \pm 0.22\,\%$

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

SM: 10.83%

Assume Lepton Universality

Br (W→qq): $67.92 \pm 0.27\,\%$

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

SM: 67.51%

CKM Interpretation

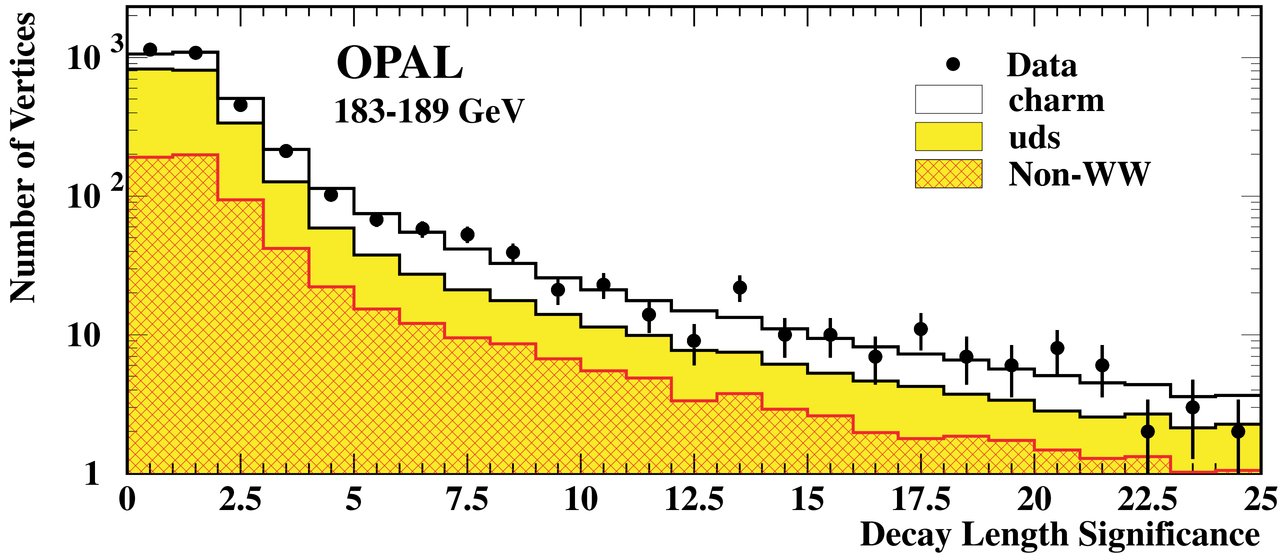
$$\frac{Br(W \to q\bar{q})}{1 - Br(W \to q\bar{q})} \ = \ (1 + \alpha_s(m_W)/\pi) \sum_{(u,\,c),\,(d,\,s,\,b)} \left|V_{ij}\right|^2$$

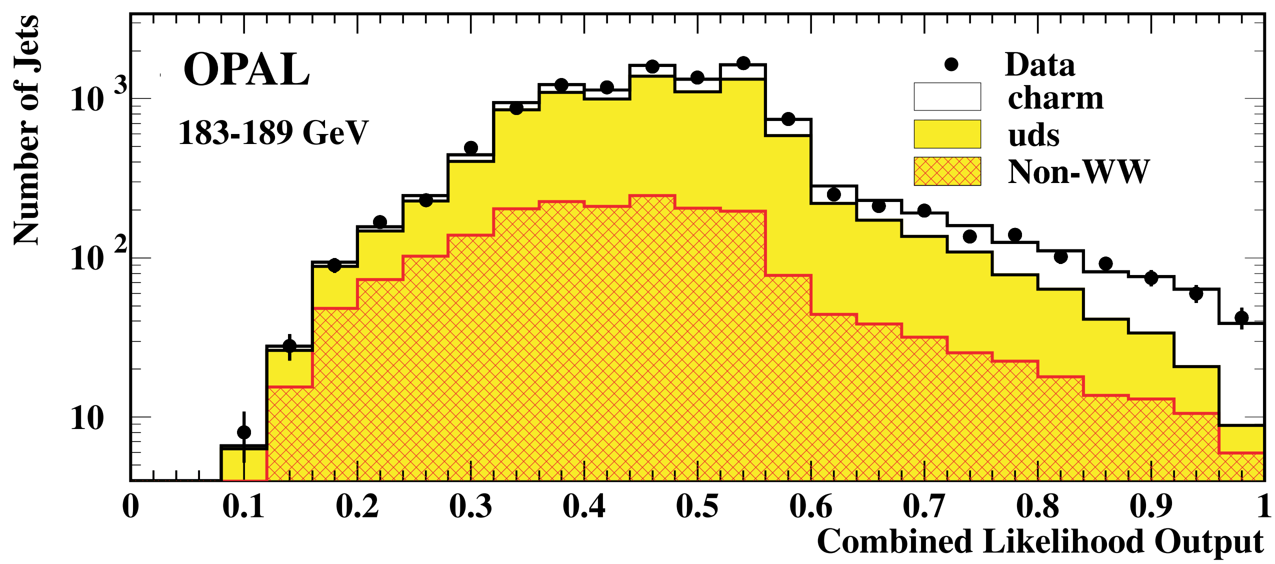
$$\sum_{(u,\,c),\,(d,\,s,\,b)} \left|V_{ij}\right|^2 \ = \ 2.039 \pm 0.025$$

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

[Winter 01 Preliminary LEP Combined]

Charm Production





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

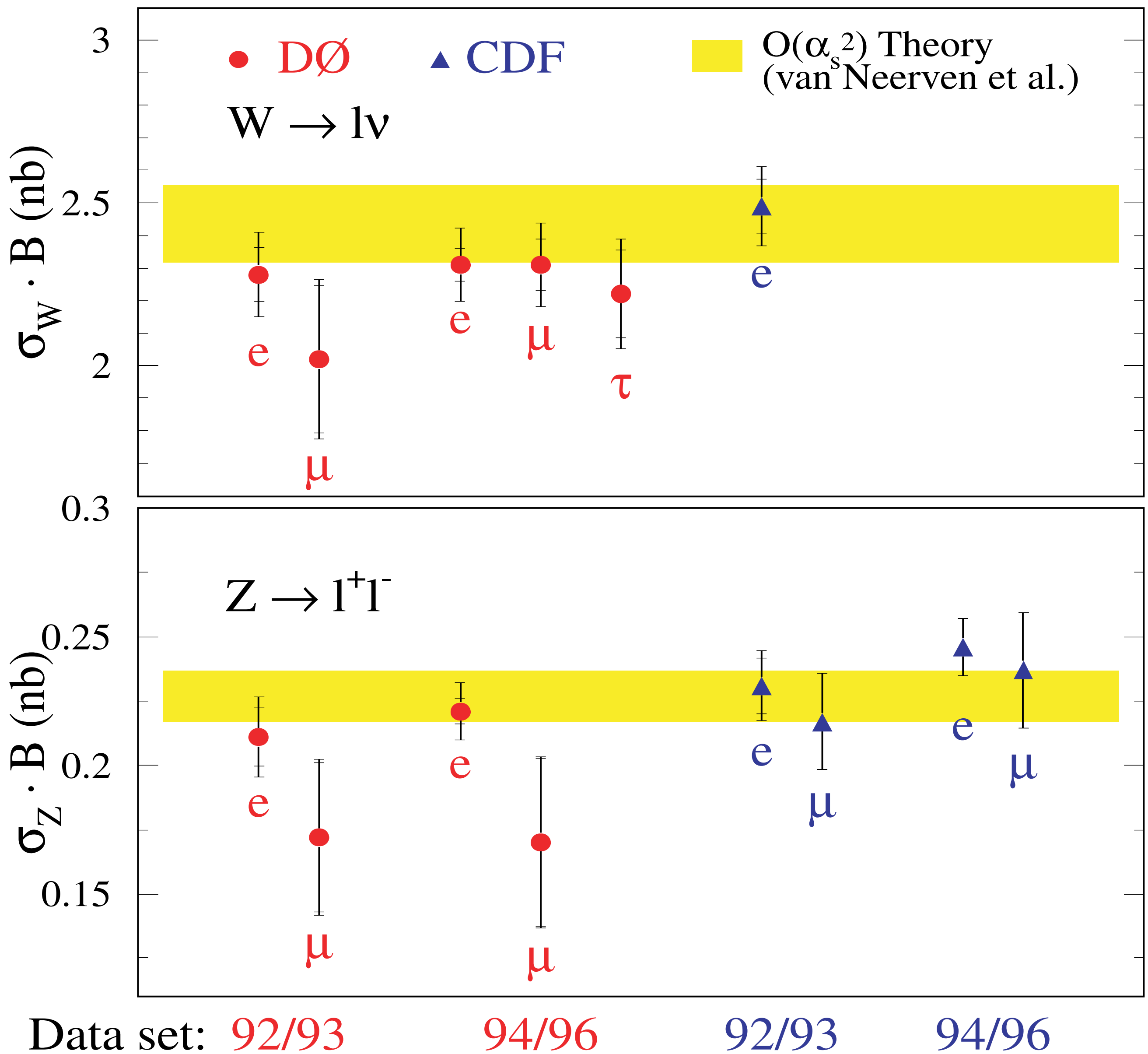
$$\text{Using } \Gamma(W \rightarrow cX) = \frac{CG_F m_W^3}{6\sqrt{2}\pi}(|V_{cd}|^2 + |V_{cs}|^2 + |V_{cb}|^2)$$

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

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

Tevatron W/Z Cross Sections

$\sqrt{s}$ = 1800 GeV



Note different normalization: σ(CDF) = 1.06 σ(D0)

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

Use σBr (W→eν) to measure Run II Lumi?

Tevatron Cross Section Ratio

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

σ_W / σ_Z from QCD

[Hamberg, van Neerven, Matsuura]

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

Extract branching fraction

$$Br(W \to e\nu) = 10.45 \pm 0.20\%$$ (CDF+D0)

Indirect Width

Assume SM partial width

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

[Rosner, Worah, Takeushi]

Extract W width

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

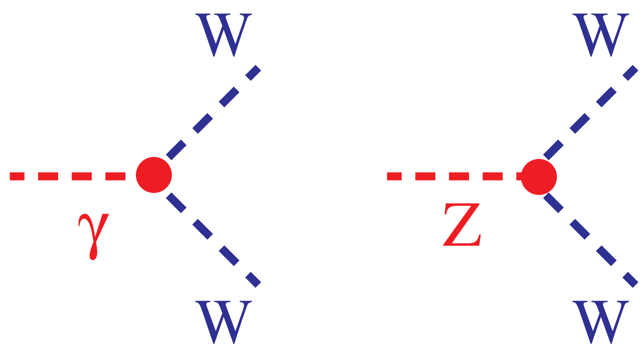
$$\Gamma_W(SM) = 2.093 \pm 0.003 \text{ GeV}$$

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

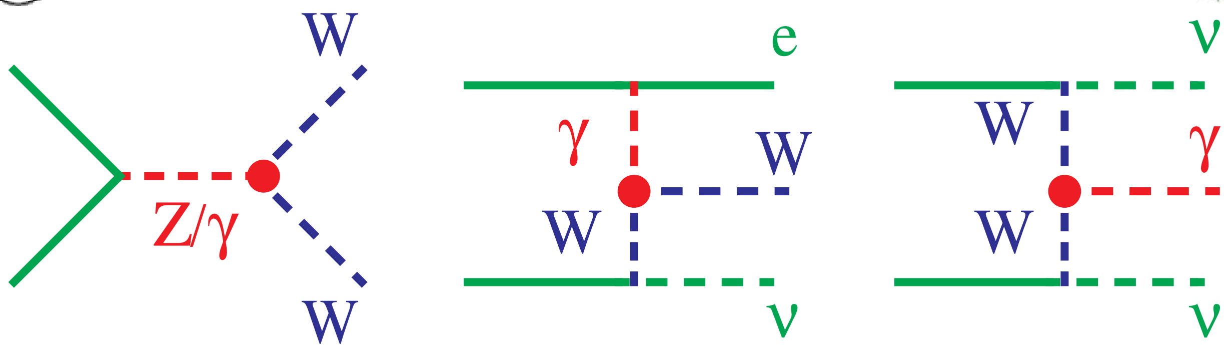
Magnetic Dipole Moment: $\mu_W = e(1 + \kappa_\gamma + \lambda_\gamma)/2m_W$

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

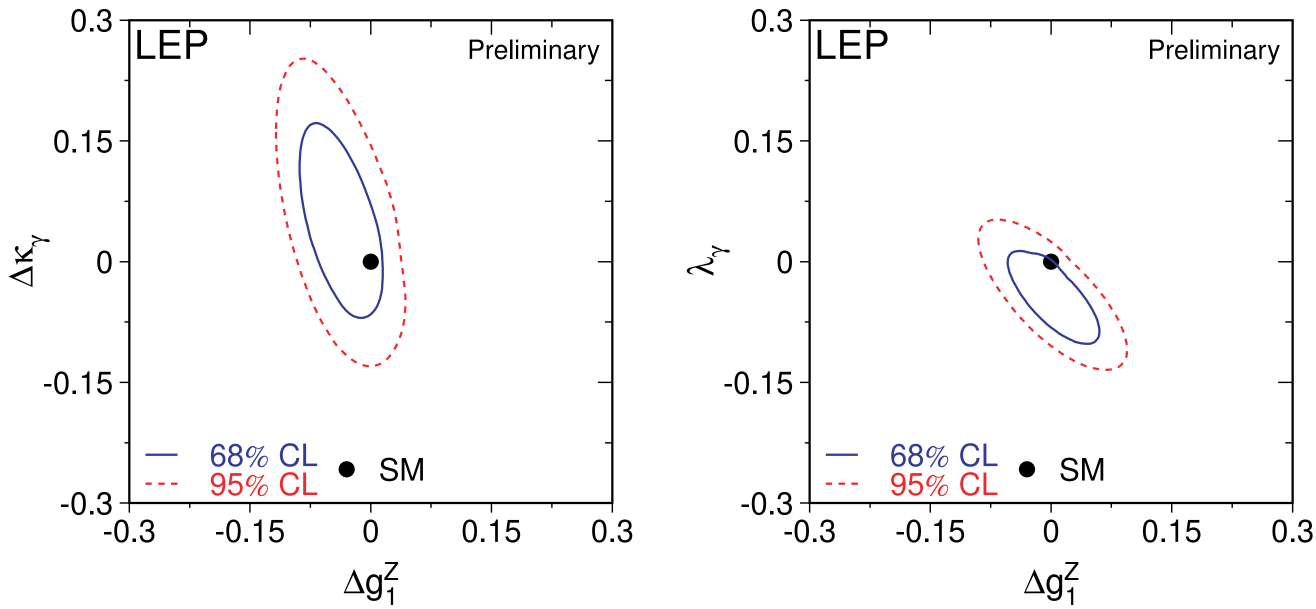
Measure deviations allowed by LEP I

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

LEP TGC Results



Fit Production and Decay Cross Sections



Single Parameter Fits*

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

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

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

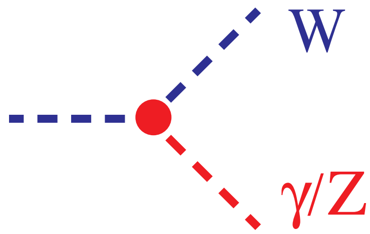
*Summer 2000

Order(α_{EM}) effects

not yet included...

Tevatron TGC Analyses

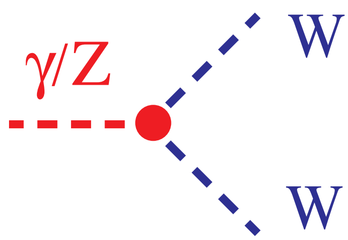
Associated production



⇛ lν+γ, lνll, lνqq, qqll

⇛ WZ final states marginal at Run I

W Pair production



⇛ lνlν, qqlν

D0 combined analysis (lν+γ, lνlν, qqlν)

Measure cross sections and p_T^W

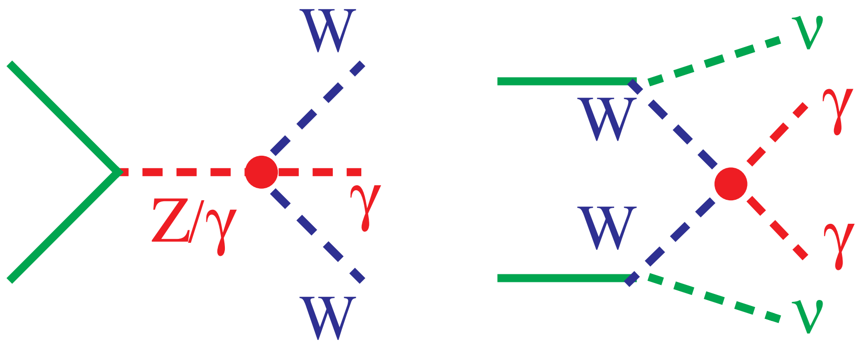
$$-0.25 \le \Delta\kappa \le 0.31 \quad (\lambda = 0)$$

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

⇛ Expect ~2-3X better at Run II

[Competitive with single LEP experiment]

Charged Quartic Gauge Couplings



SM prediction negligible at LEP II

$\Rrightarrow$ Look for anomalous QGCs

Lorentz Structure

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

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

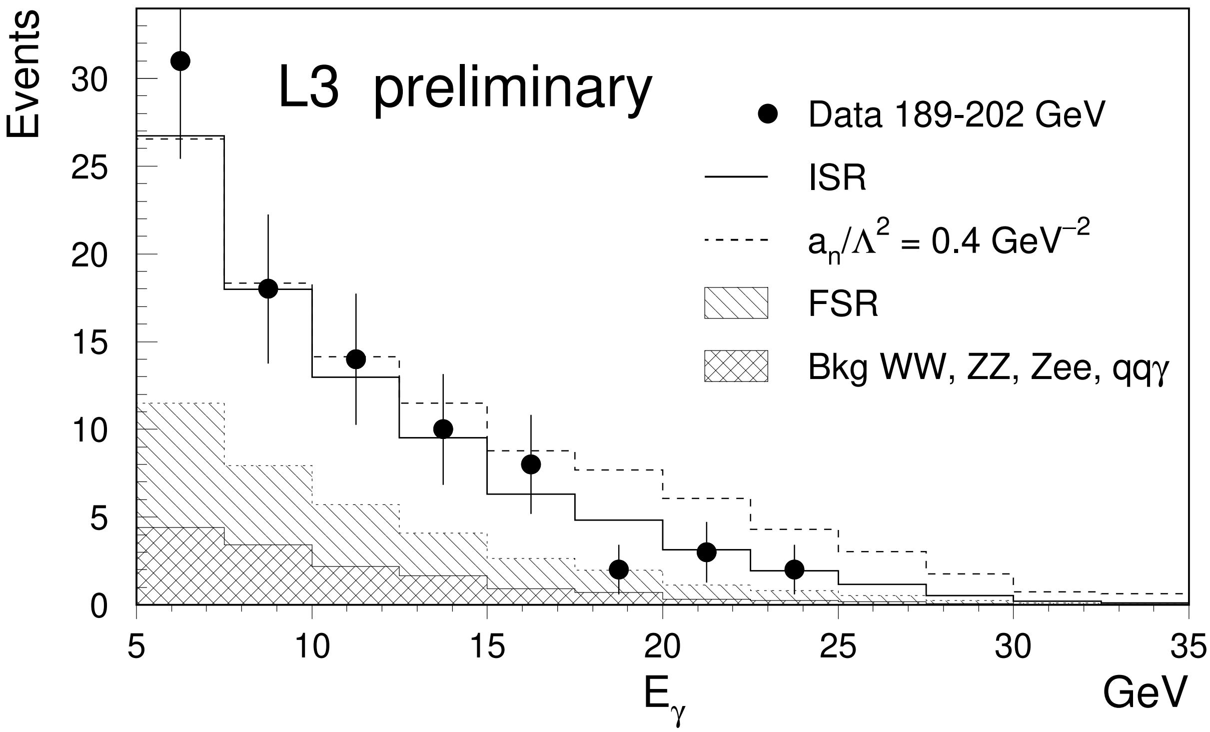
[Belanger and Boudjema, Nucl. Phys. **B288**, 201 (1992)]

$$L_n = -i\frac{e^2}{16}\frac{a_n}{\Lambda^2}\varepsilon_{ijk}W^{(i)}_{\mu\alpha}W^{(j)}_{\nu}W^{(k)\alpha}F^{\mu\nu}$$ CP violating (WWZγ)

[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
ννγγ	189-202 GeV	183-202 GeV	189 GeV
WWγ		183-202 GeV	189 GeV

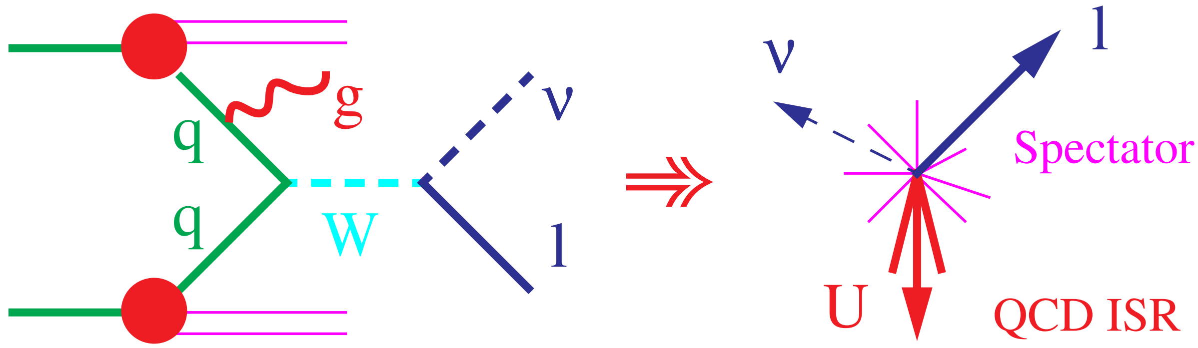
95% CL limits (in GeV^{-2}):

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

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

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: $\overrightarrow{p_T^\nu} = -(\overrightarrow{p_T^l} + \vec{U})$

MC Spectrum $m_T(m_W)$

- Energy scale and resolution $\quad E_T^l$

  $\Delta m_W \sim \pm(80 \oplus 25)$ MeV

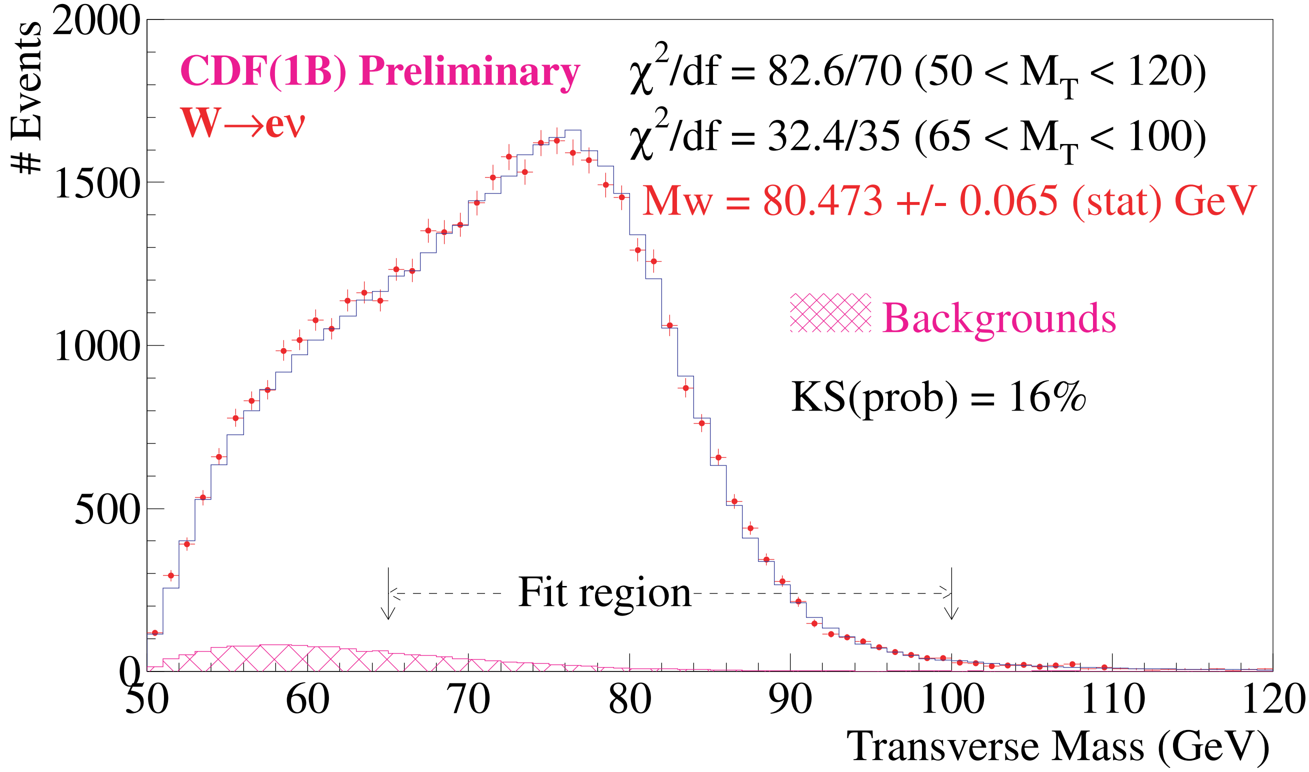
- QCD Recoil model (U) $\quad P_T^W$

  $\Delta m_W \sim \pm 40$ MeV

- PDF model (W Rapidity) $\quad P_Z^W$

  $\Delta m_W \sim \pm 15$ MeV

Run I Mass Results



CDF

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

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

D0

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

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

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

$\Rrightarrow$ Significant room for improvement at Run II

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

D0 Energy Scale

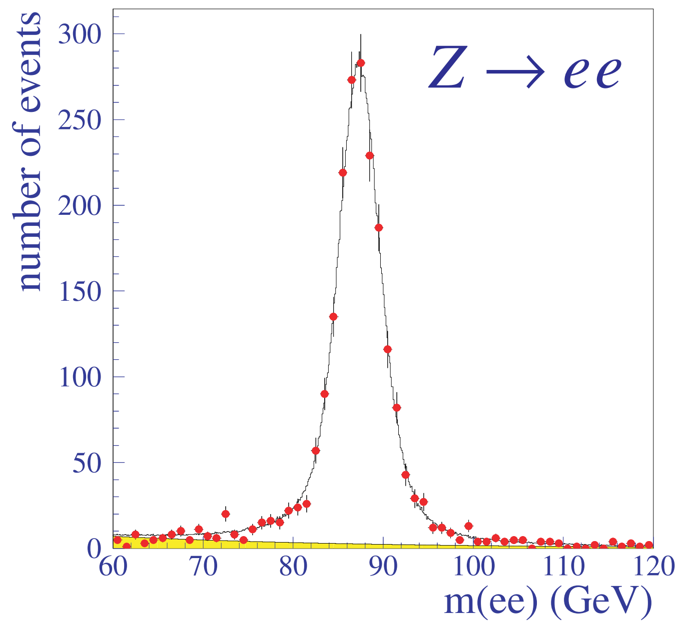
Calibrate using data

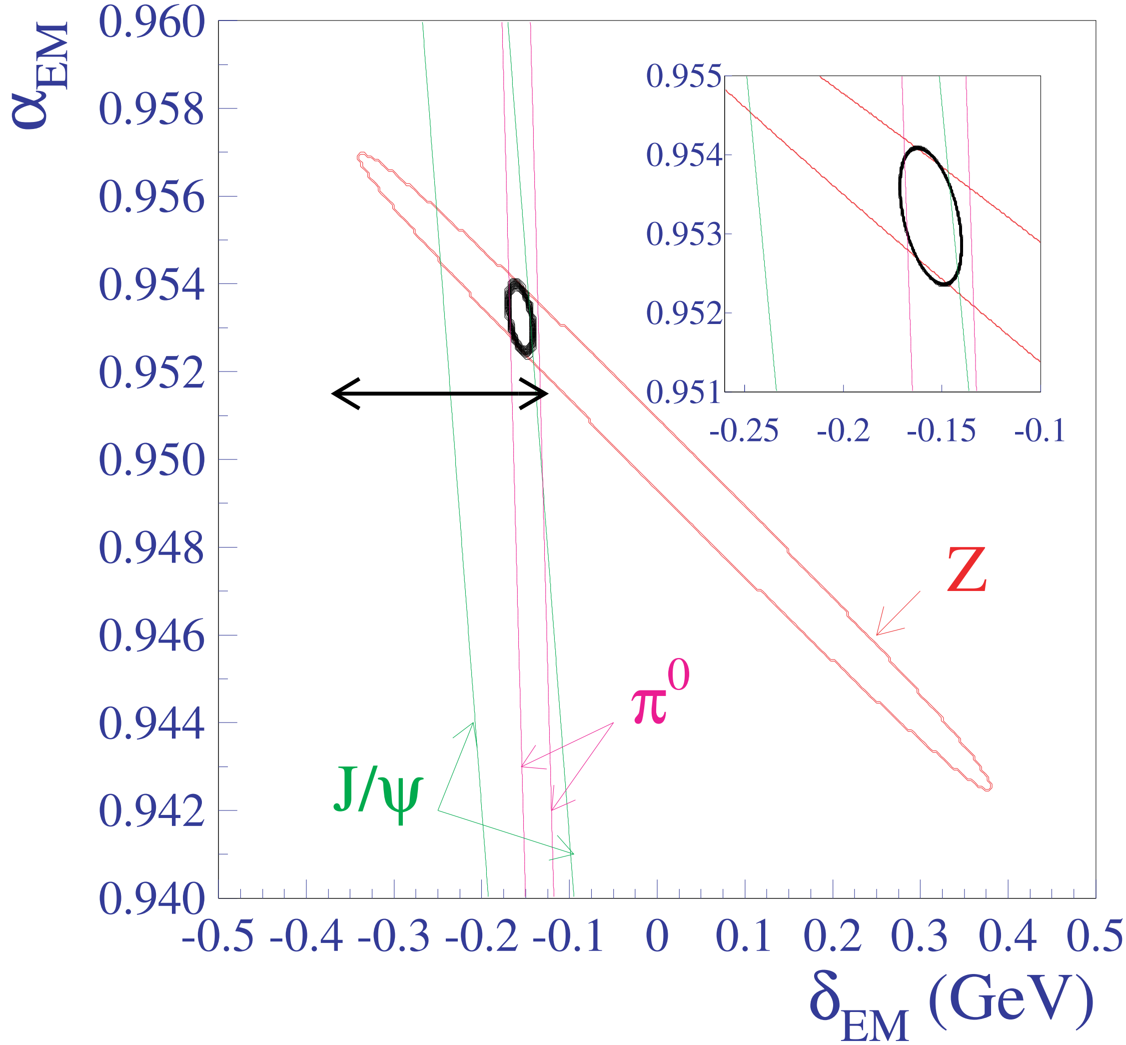
$$E = \alpha E_{meas} + \delta$$

$\pi^0 \rightarrow eeee$

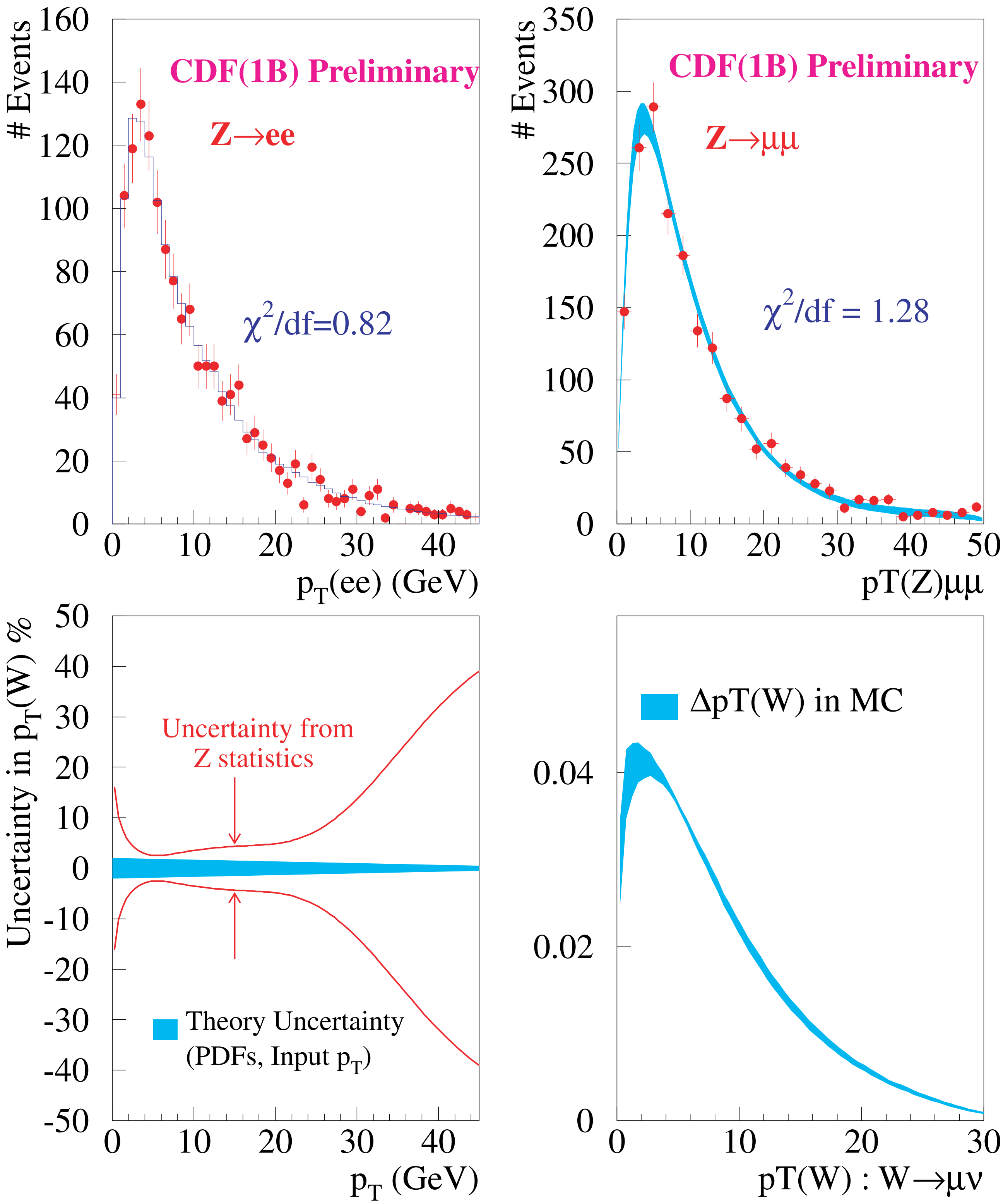
$J/\psi \rightarrow ee$

$Z^0 \rightarrow ee$



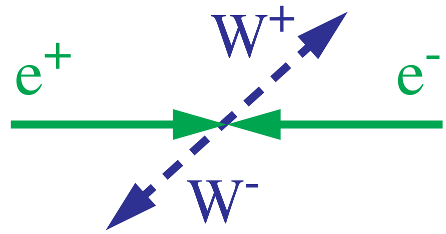


CDF Production Model



LEP Mass Analysis

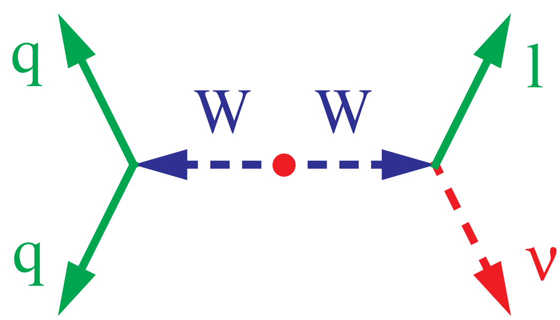
Kinematic fitting



$$E_0 = 2E_{beam}, \overrightarrow{p_0} = 0$$ 4 Constraints

$$m_w^+ = m_w^-$$ 1 Constraint

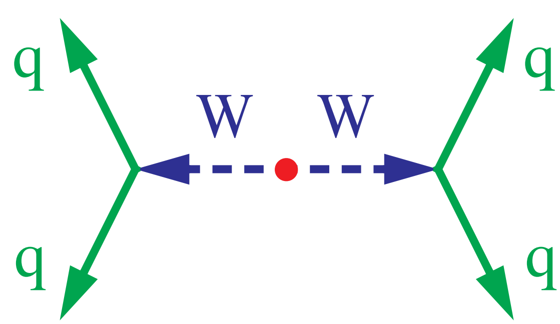
$WW \rightarrow qql\nu$



3 Unknowns

5 - 3 = 2C Fit

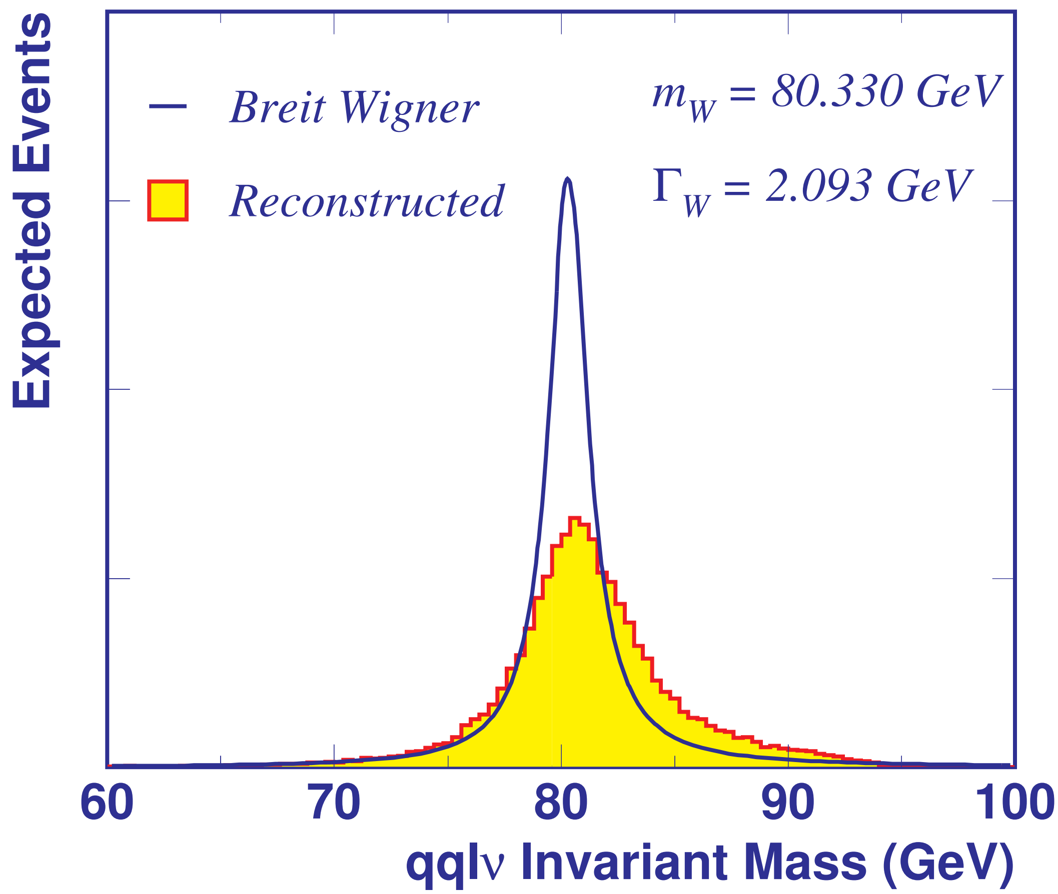
$WW \rightarrow qqqq$



0 Unknowns

5 - 0 = 5C Fit

LEP Mass Spectrum



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

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

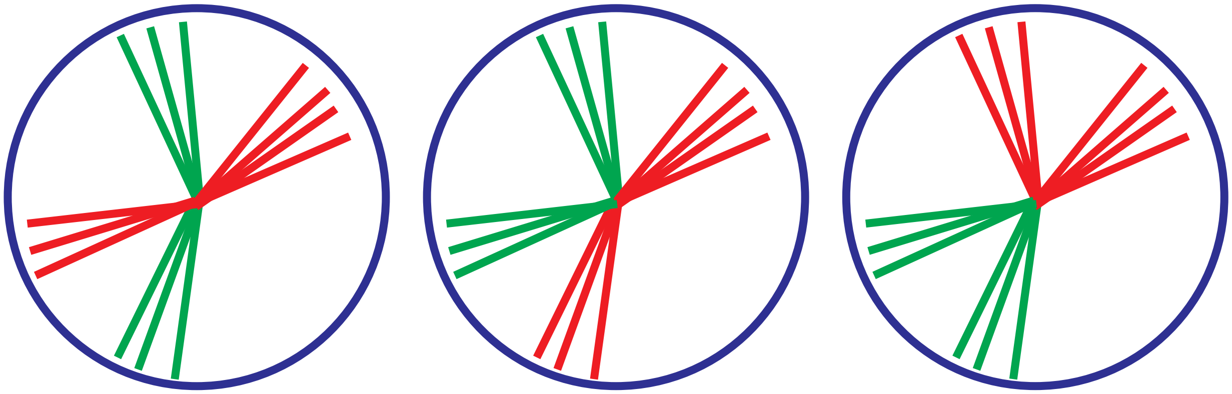
Non-CC03 Diagrams: *qqeν, qqqq*

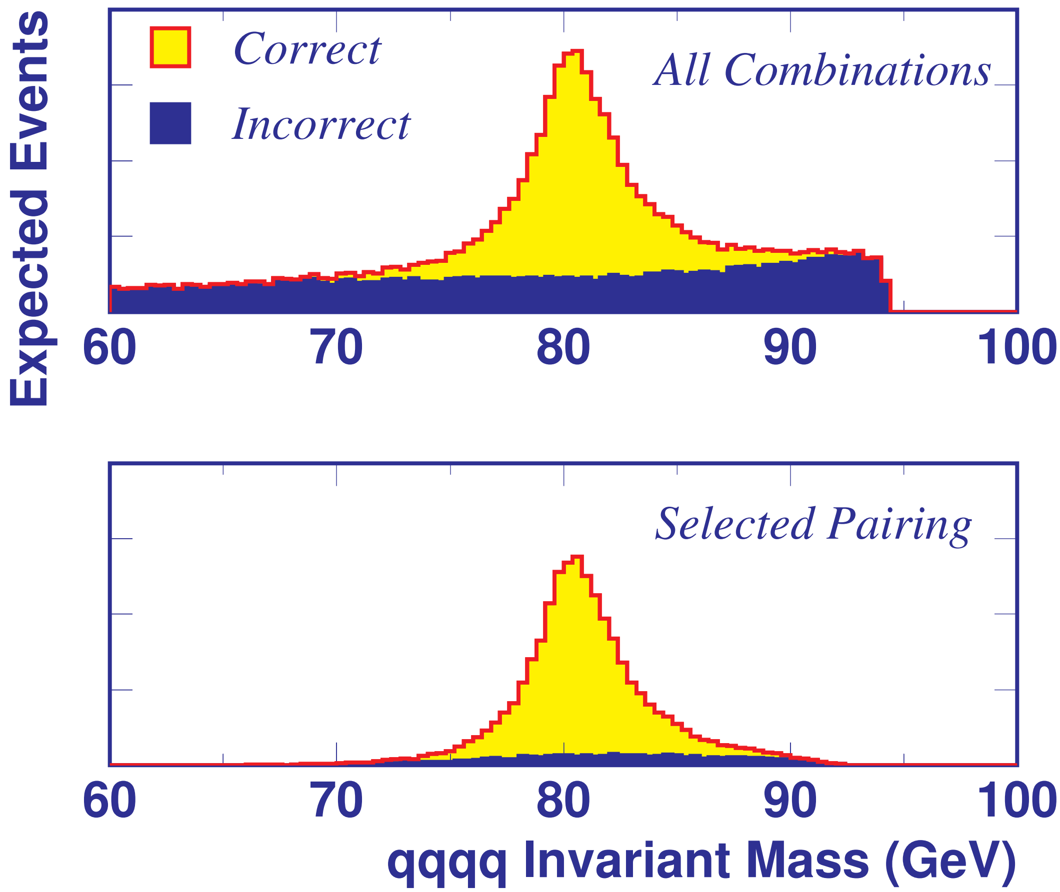
⇛Cannot directly fit Breit-Wigner

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

Delphi: *Likelihood Convolution*

WW → *qqqq* Jet Pairing





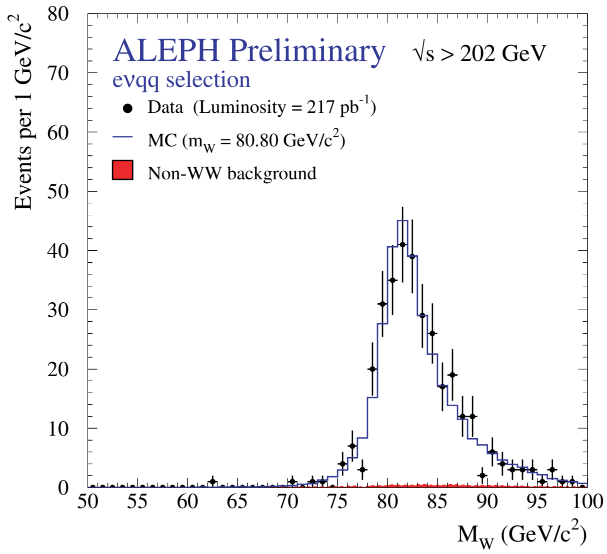
Aleph, Opal: *Jet pairing selection*

L3: *Highest 5C fit probability*

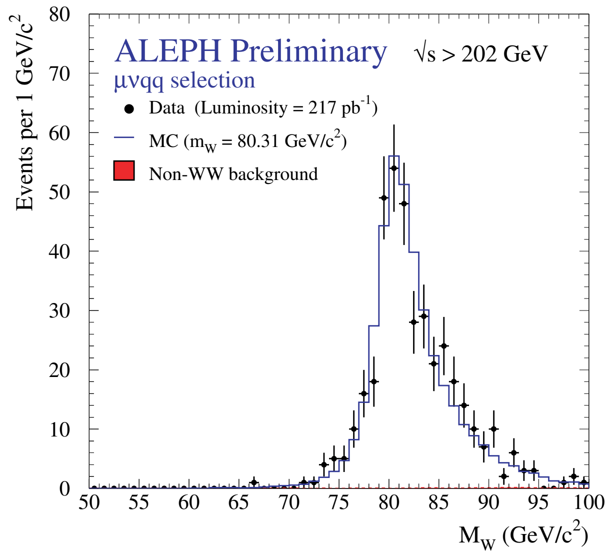
Delphi: *Use all Combinations*

W Mass Spectra

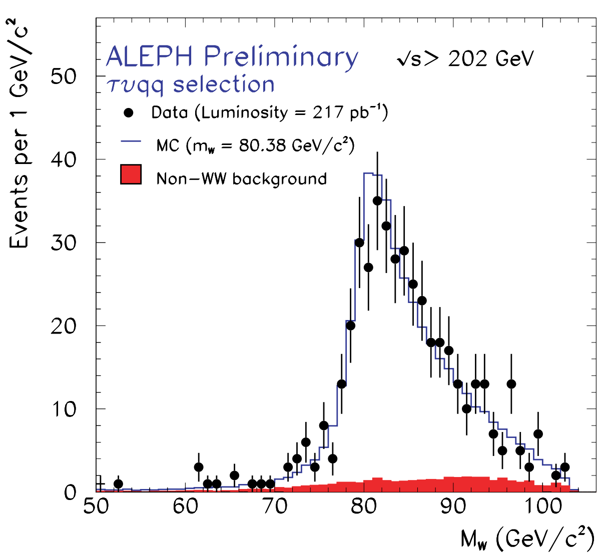
qqeν



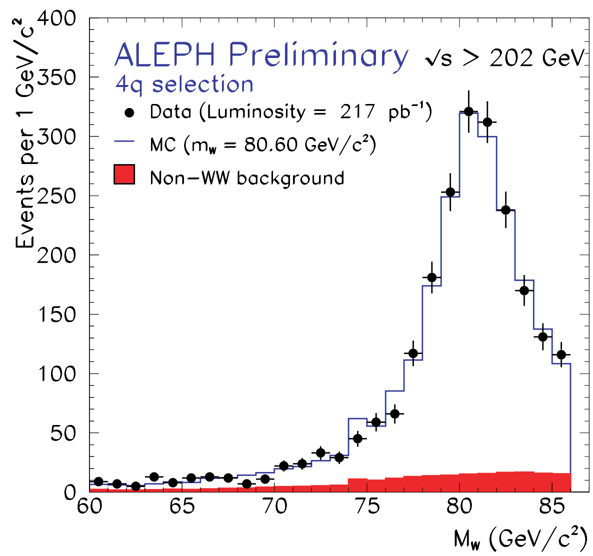
qqμν



qqτν

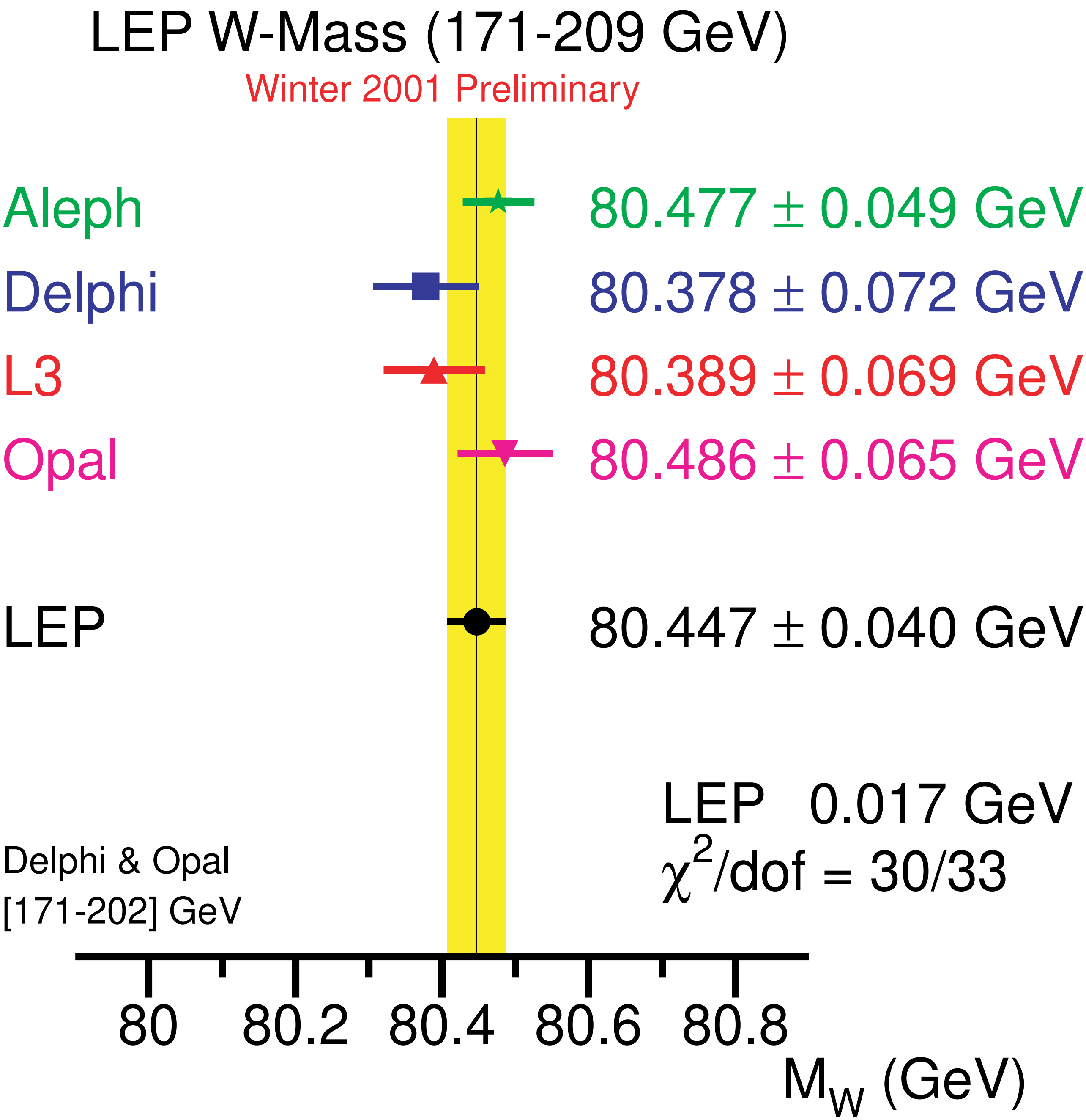


qqqq



⇛ Aleph 2000 data *(preliminary)*

LEP W Mass Results



LEP Combined *(preliminary)*

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

[Including threshold cross section]

LEP Systematic Uncertainties

Direct Reconstruction Results *(preliminary)*

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

$\Rrightarrow$Systematics Limited!

Moriond 2001 Combination

- Preliminary Procedure
- Conservative Correlations

Uncertainty	qqlν [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]

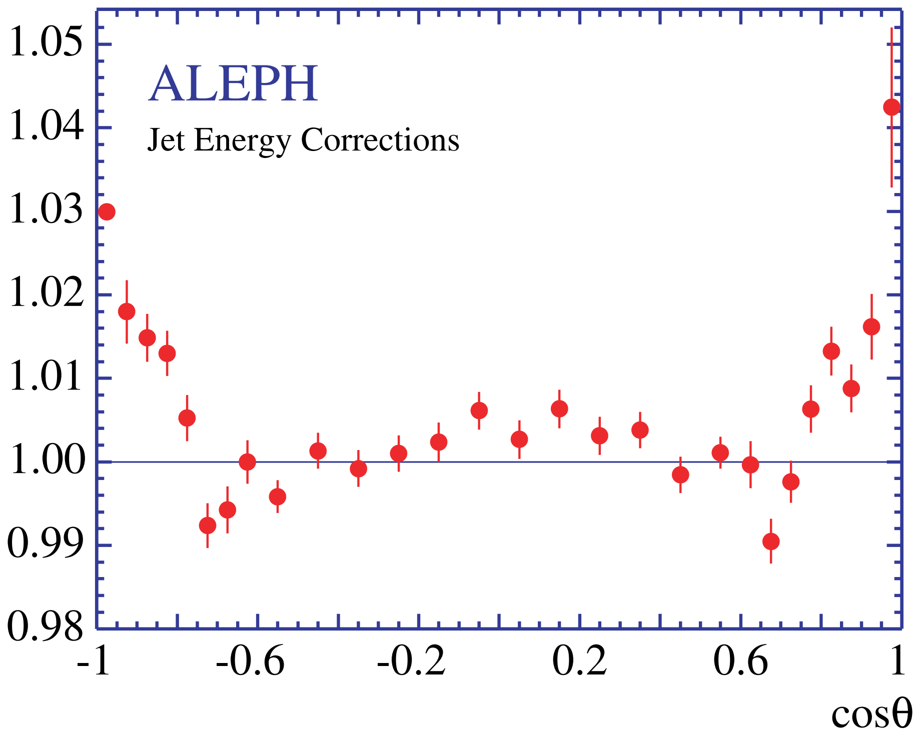
Weight from qqqq only 0.27

δm_W (no syst) = 22 MeV

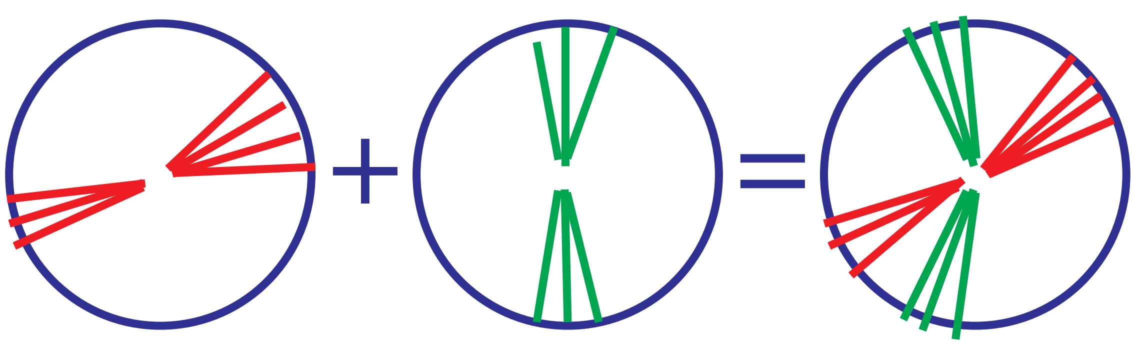
LEP Detector Systematics

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

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

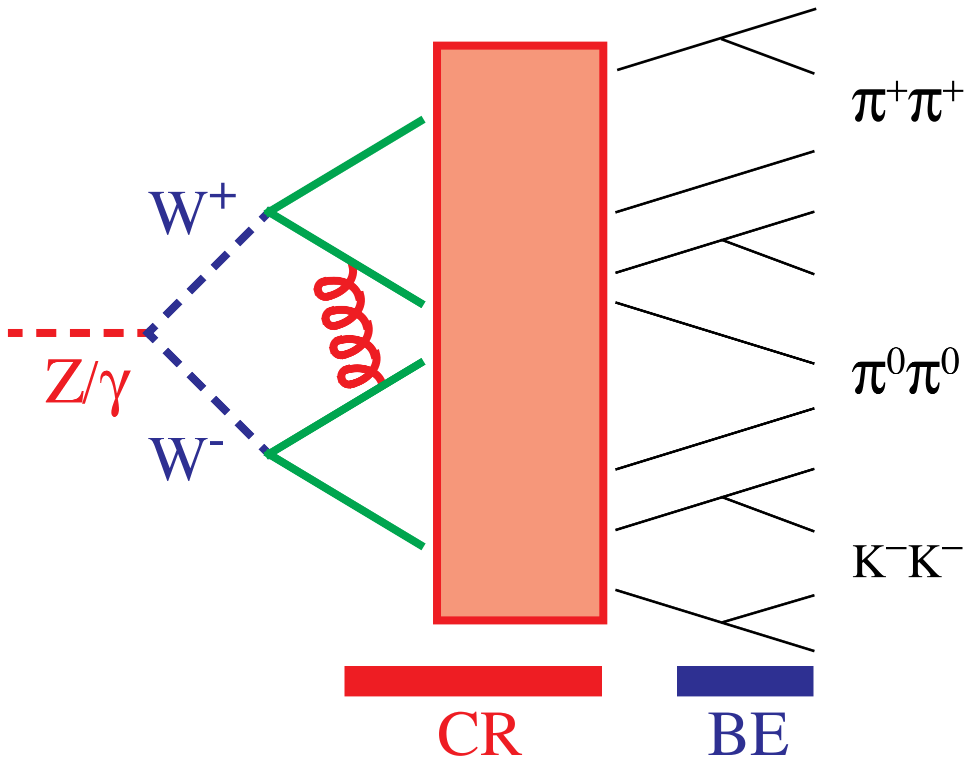


Mixed Lorentz Boosted Z (Delphi)



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

Final State Interactions



Interactions between decay products ➔ shift in M_W

$M_W(qqqq) - M_W(ql\nu) = +18 \pm 46$ MeV

Color Reconnection

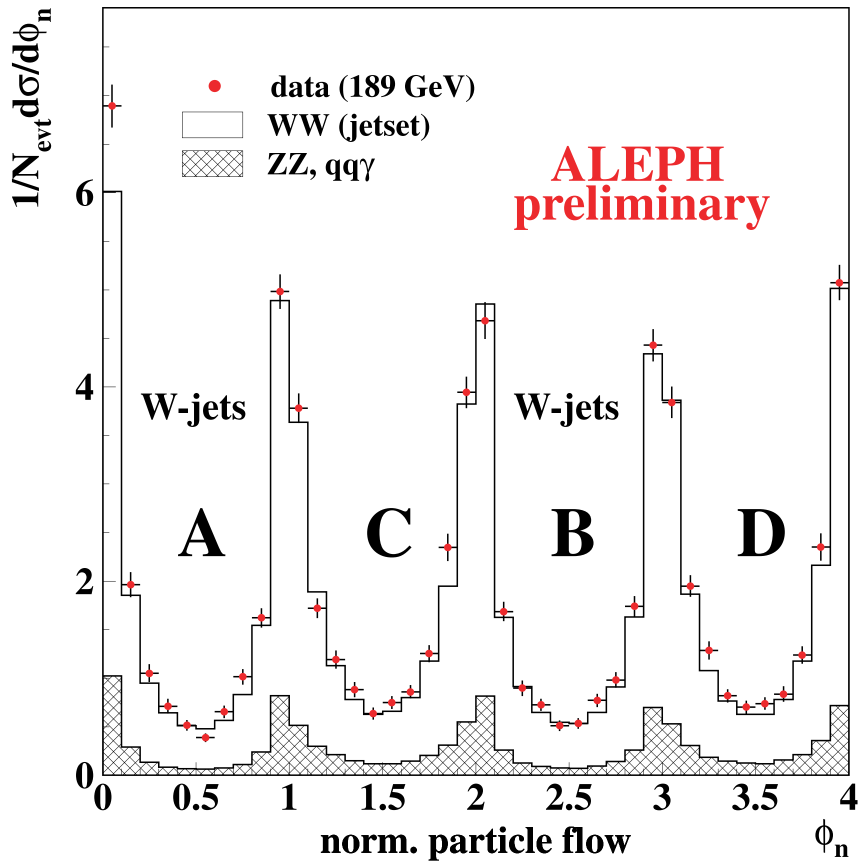
- Strong (QCD) interactions in non-perturbative phase
- Only a few models exist, difficult to calculate

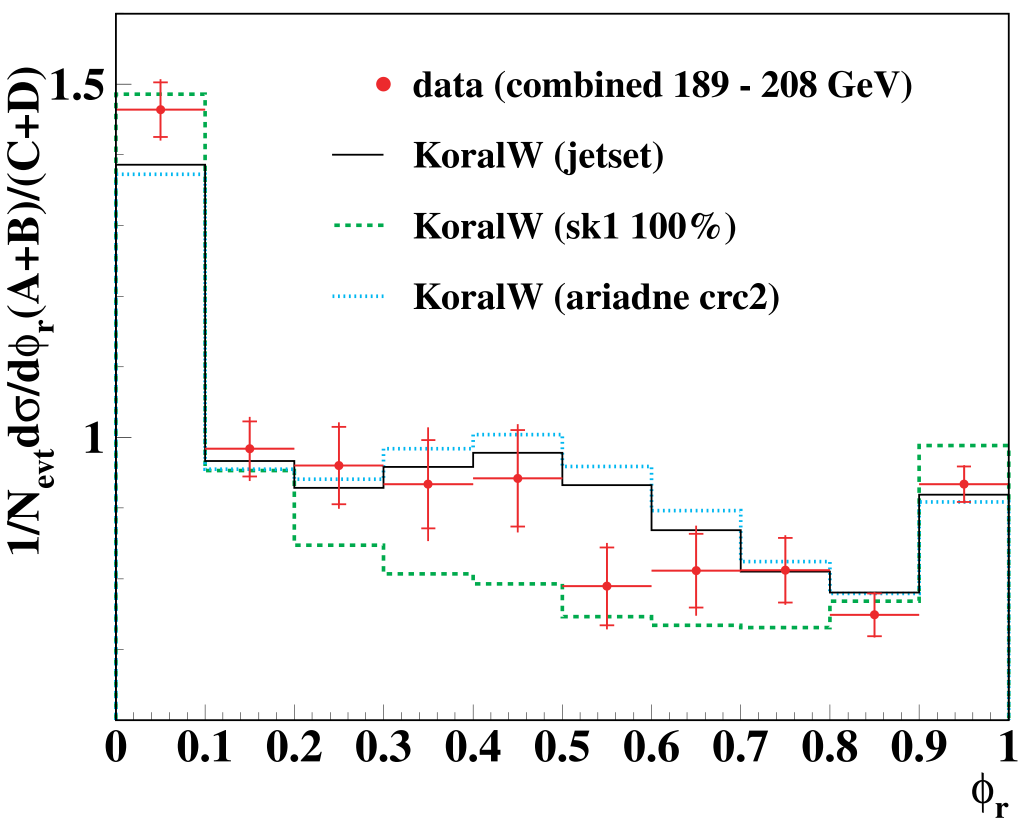
Bose-Einstein Correlations

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

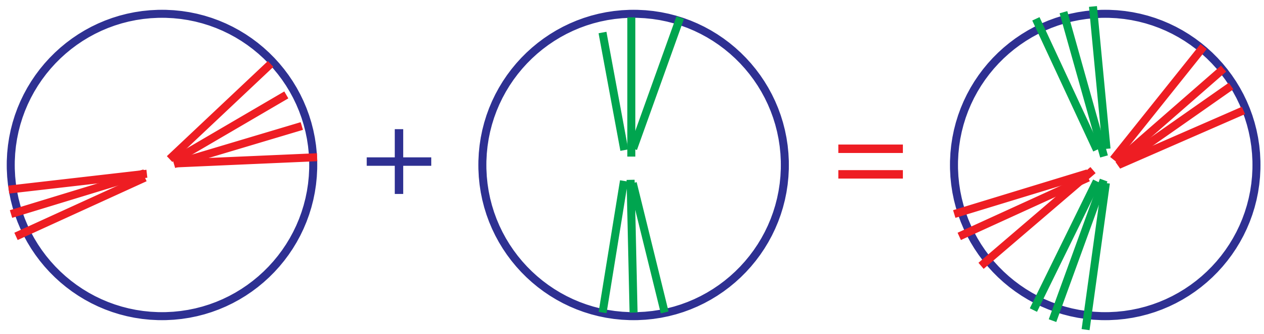
$\Rrightarrow$ Constrain using Data!

Color Reconnection



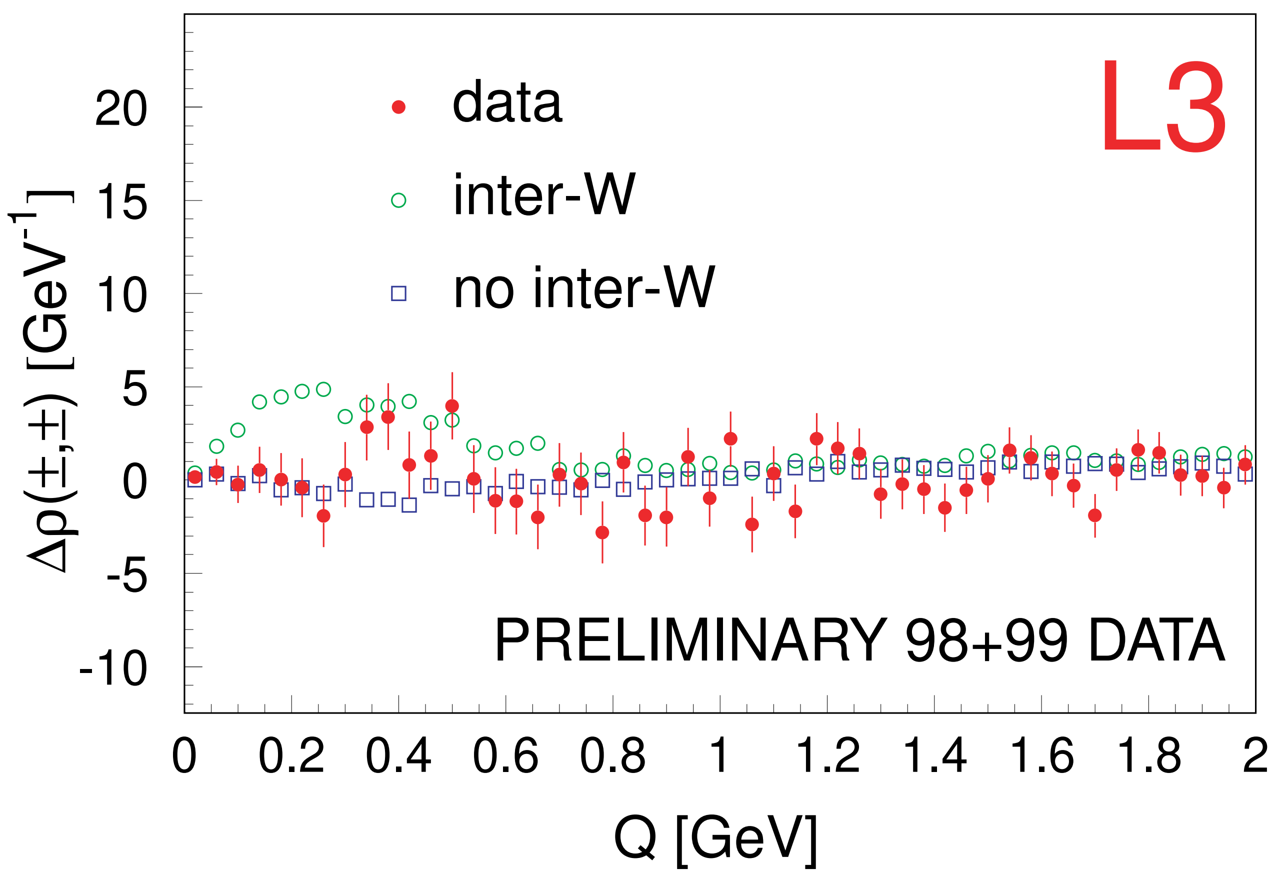


Bose-Einstein Correlations



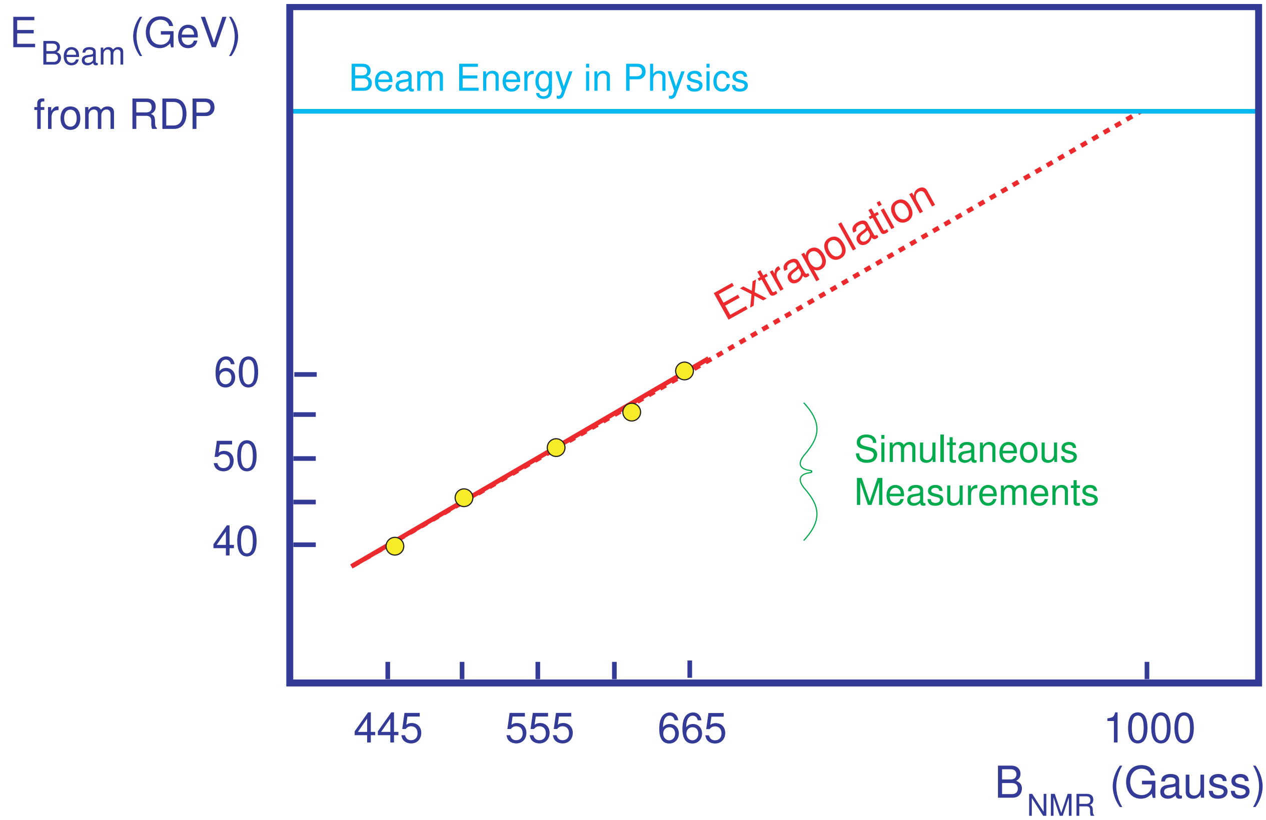
$$\Delta\rho = \rho^{WW} - 2\rho^{W} - 2\rho^{WW}_{mix} \text{ where } \rho = \frac{1}{N}\frac{dn_{pairs}}{dQ}$$

Model Independent!



No evidence for inter-W BE correlations

LEP II Beam Energy



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

  $\Rrightarrow$Limited to $E_{beam} < 60$ GeV

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

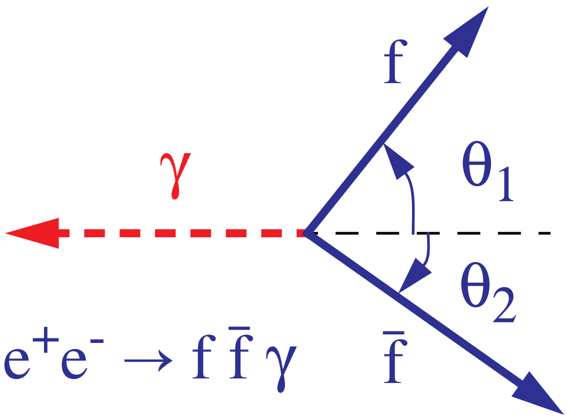
  $\Delta M_W = 17$ MeV

Extrapolation Checks

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

$\Rrightarrow$Work continues...

LEP II Radiative Returns



$e^+e^- \rightarrow f\,\bar{f}\,\gamma$

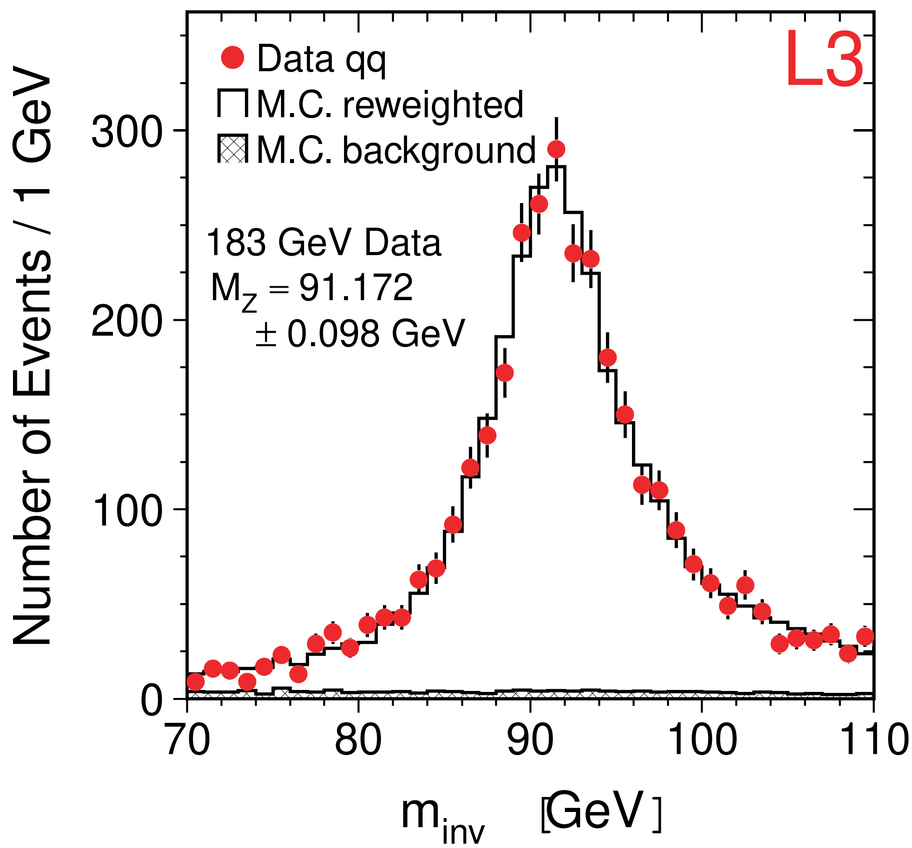
$$\frac{s'}{s} = \frac{\sin\theta_1 + \sin\theta_2 - |\sin(\theta_1+\theta_2)|}{\sin\theta_1 + \sin\theta_2 + |\sin(\theta_1+\theta_2)|}$$

Statistics

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

LEP Combined

Statistics Only



Systematics

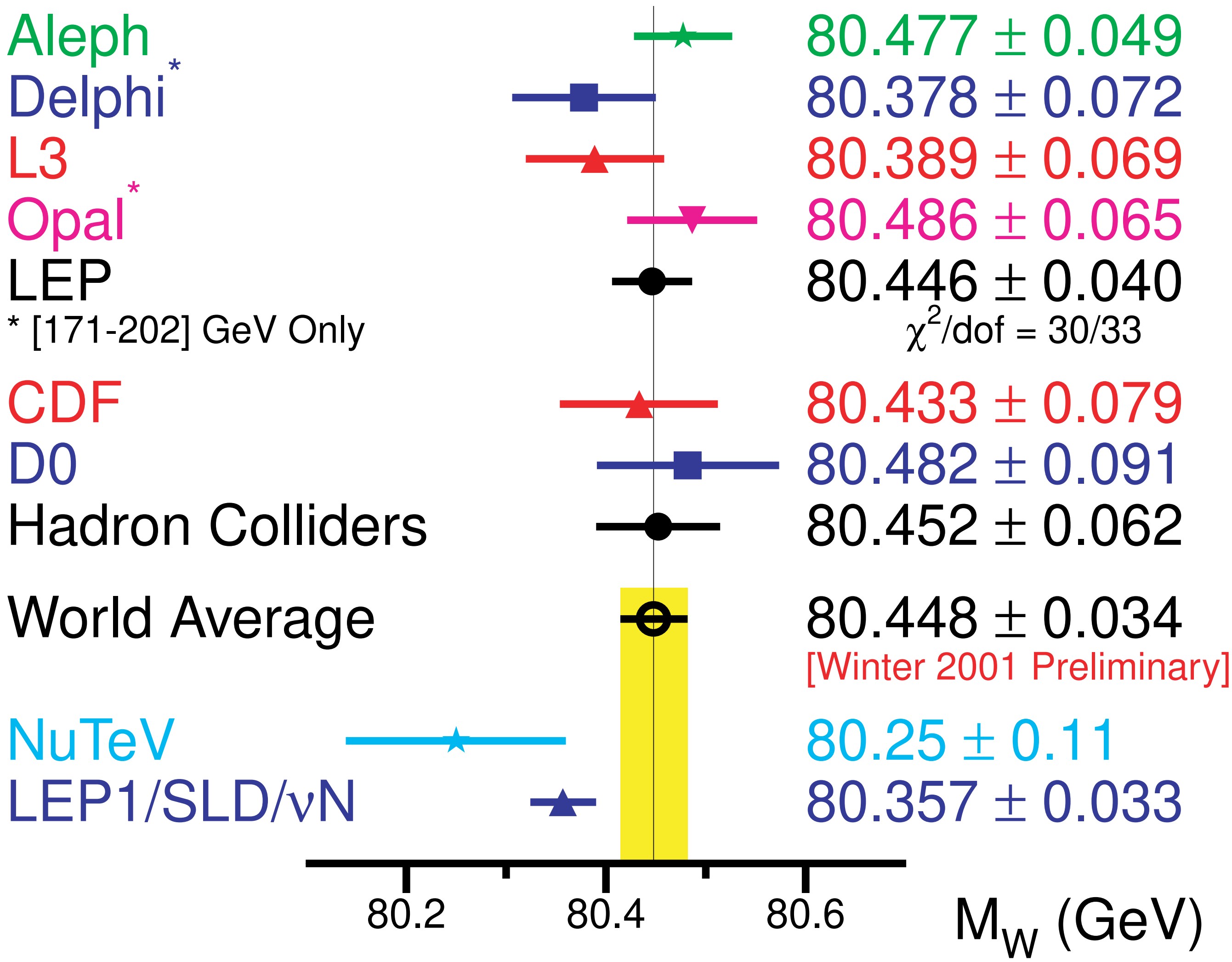
- Theoretical Description
- Hadronization Uncertainties
- Detector Understanding

Preliminary Estimates

$q\bar{q}\gamma$ ΔE_{beam} ~ 70 MeV

$\mu\mu\gamma$ ΔE_{beam} ~ 40 MeV

World W Mass Results

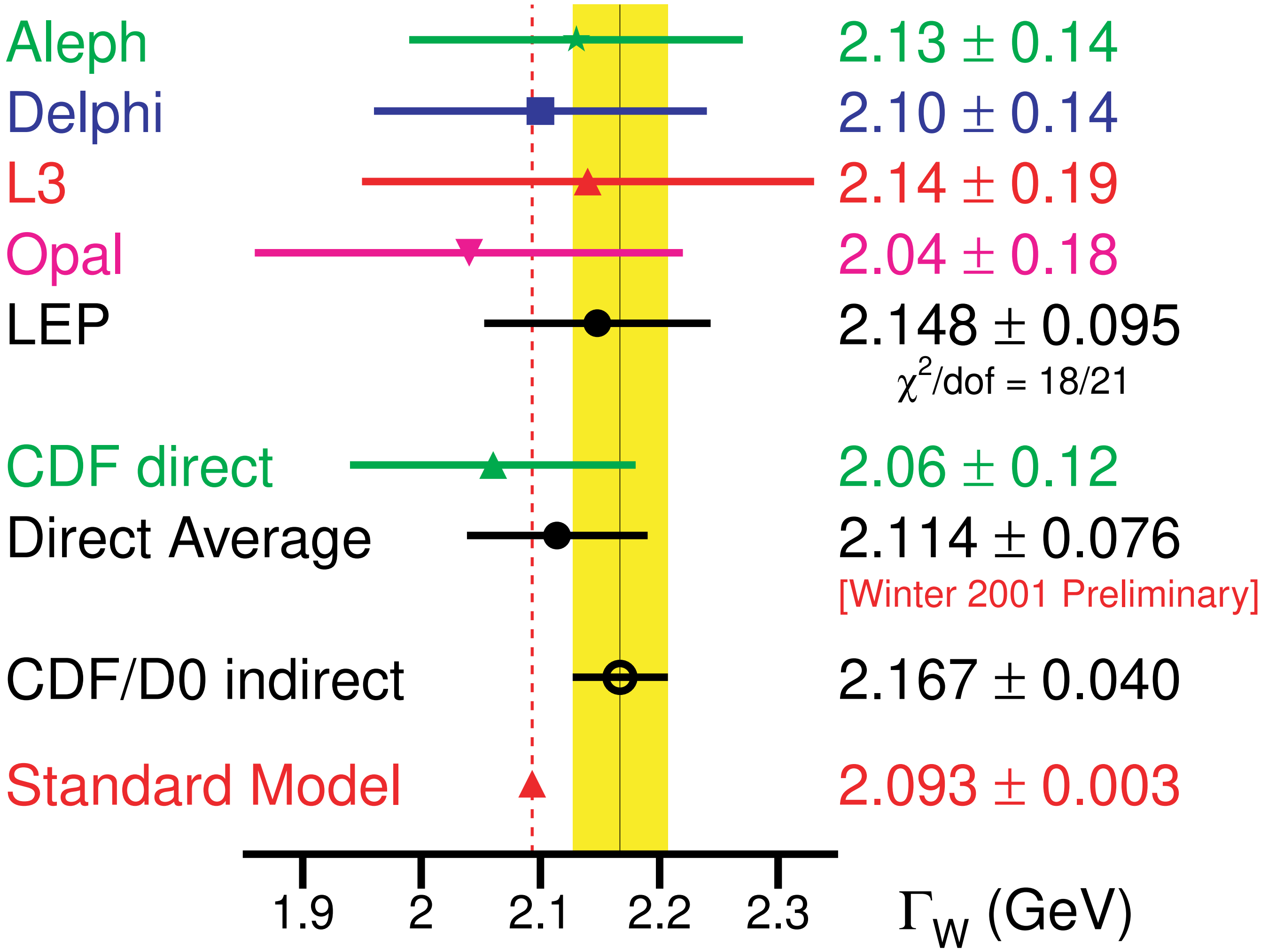


- LEP II Final ΔM_W ~ 20 MeV *(stat)*
  ~ 35 MeV *(total)*?
- Run IIa (2 fb^{-1}) ΔM_W ~ 40 MeV *(each)?*

$\Rightarrow \Delta M_W \sim$ 20 MeV by 2006

- LHC (10 fb^{-1}) ΔM_W ~ 20 MeV *(each)??*

Direct Width



LEP

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

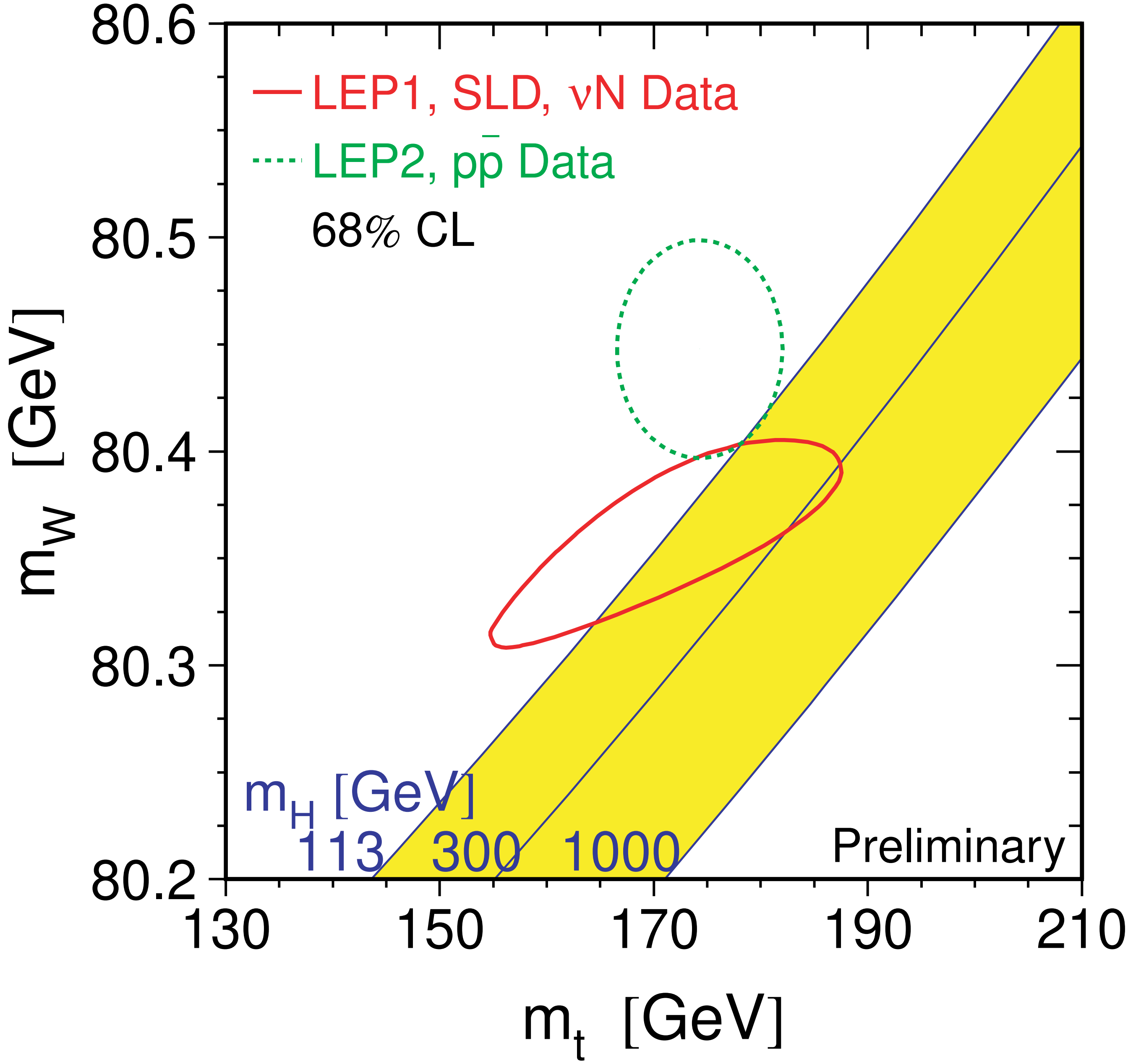
Not all LEPII data analyzed...

Tevatron

D0 direct width coming this summer

Global Results

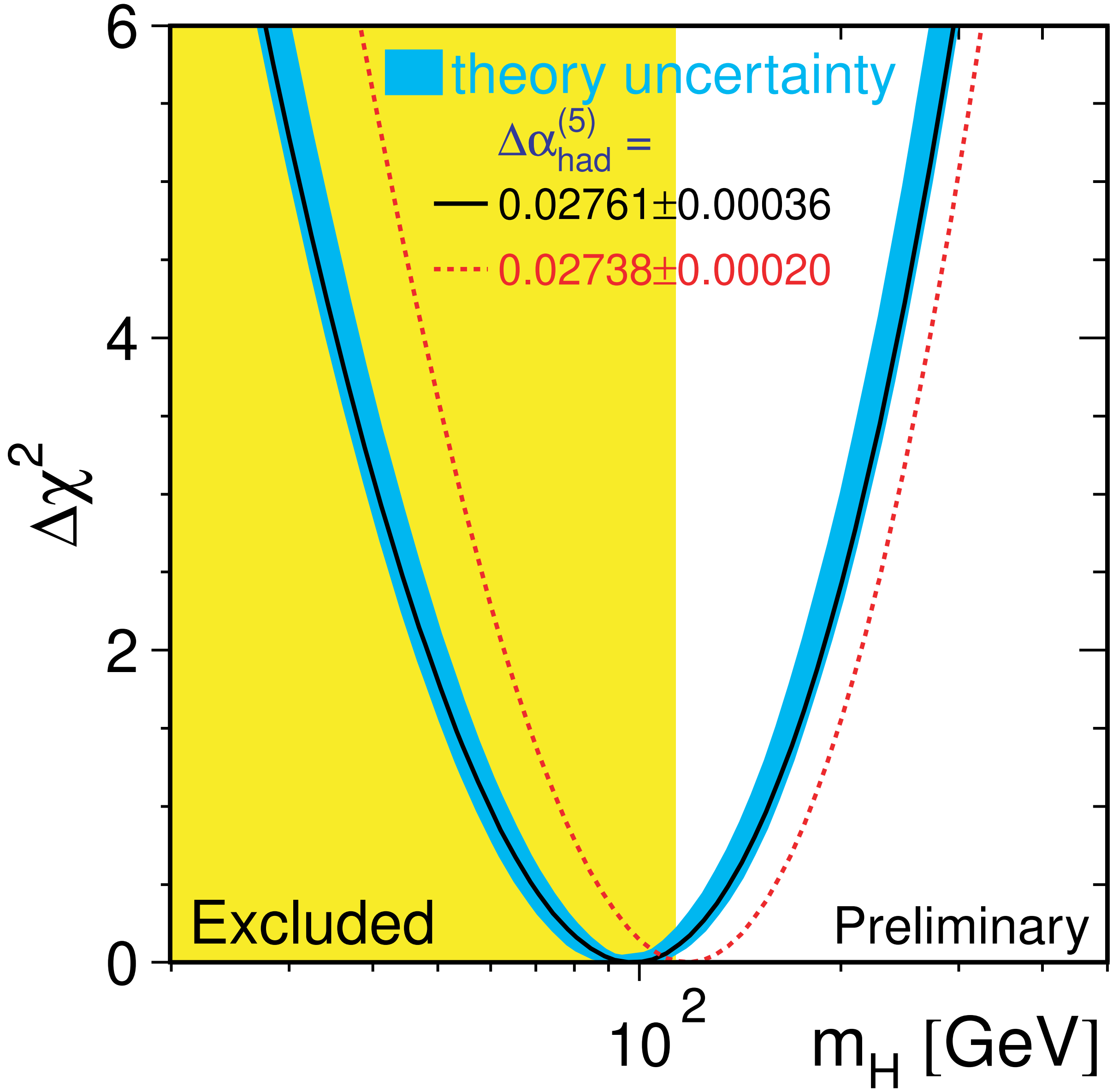
Standard Model Consistency



Direct measurements on the SUSY-side

⇛ Light Higgs preferred!

SM Higgs Boson



Simple Parameterization

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

[Degrassi et al.]

$\Rrightarrow$ Poor man's ZFITTER!

SM Higgs Constraint

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

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

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

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

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

$\Delta m_t = 3$ GeV, $\Delta m_W = 20$ MeV *(expected)*

Using m_W alone

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

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

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

Summary

Final LEP II Performance

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

Physics Highlights

Br (W→qq): $67.92 \pm 0.27\,\%$

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

Triple Gauge Couplings:

3-6% precision achieved

W Boson Mass:

$$\boldsymbol{m_W = 80.446 \pm 0.034\ \mathrm{GeV}}$$

Five Year Plan

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

$$\Delta m_W \sim 20\ \mathrm{MeV} \qquad \Delta m_{top} \sim 3\ \mathrm{GeV}$$

⇛ ***Time for more hadrons!***