Electroweak Physics at the Tevatron

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For the CDF and DØ Collaborations

Les Rencontres de Physique de la Vallée d'Aoste, La Thuile, Italy

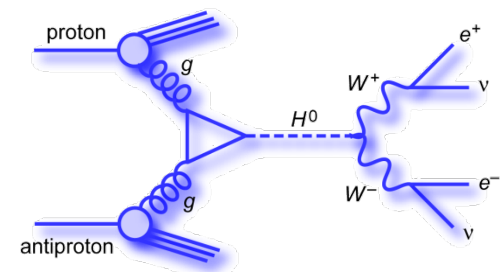
EW Physics at the Tevatron

- Probe of the EW Symmetry Breaking Mechanism

  SM test, SU(2) x U(1) gauge structure

  Indirect new physics searches

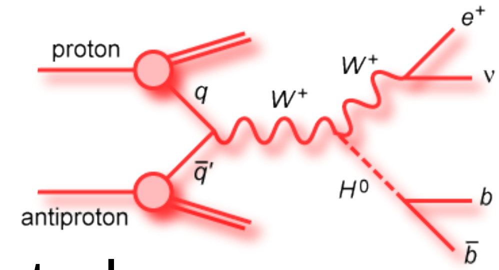
- Cross section measurements, differential distributions, trilinear gauge boson couplings (TGCs)



- Background to Higgs, Top, SUSY

- Higgs Physics

  Proving ground for analysis techniques and statistical treatment used in the Tevatron Higgs searches (MVA)



- Recent EW CDF and DØ results will be presented

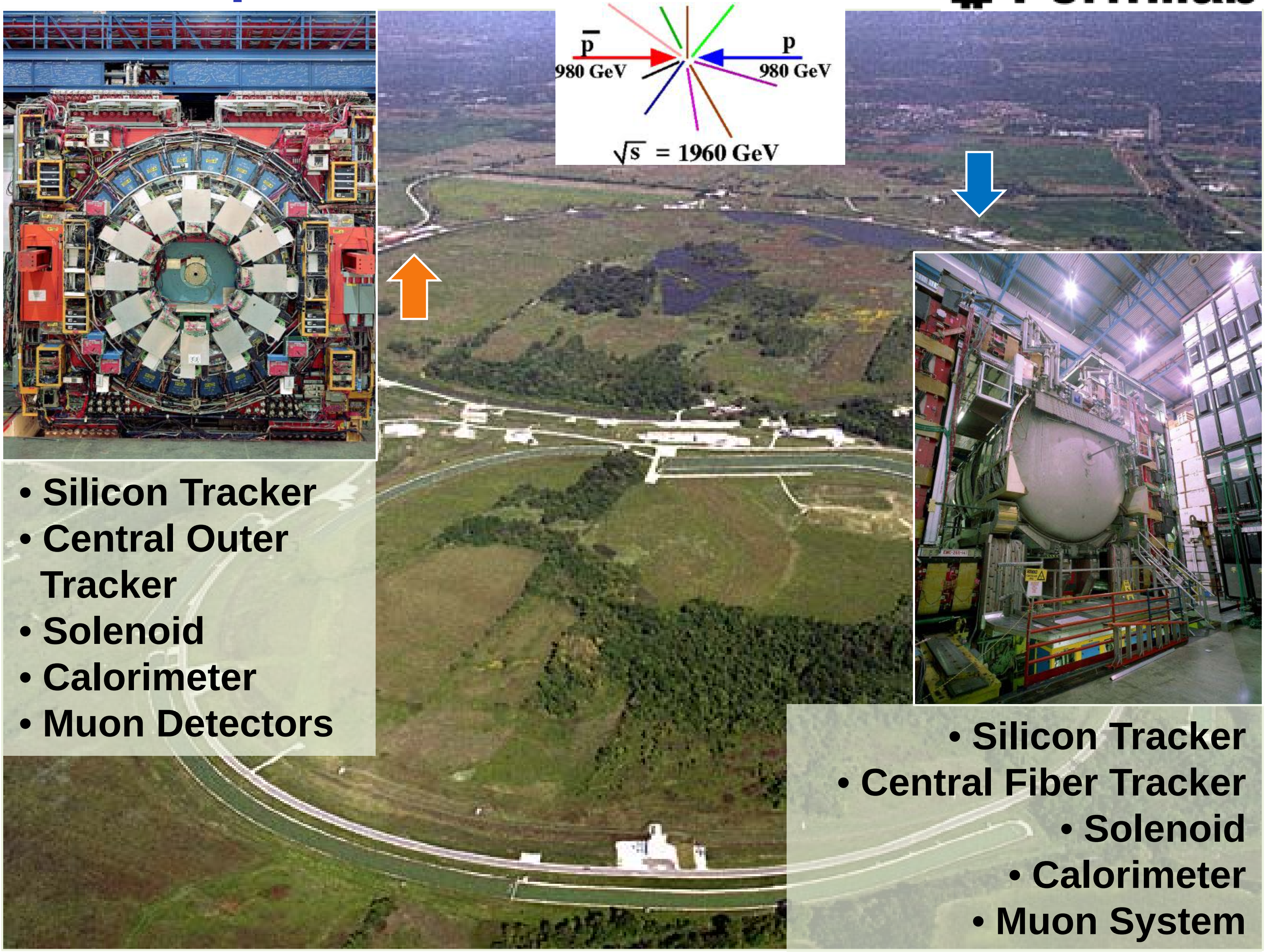
  W/Z measurements and Dibosons

http://www-cdf.fnal.gov/physics/ewk/

http://www-d0.fnal.gov/Run2Physics/WWW/results/ew.htm

Tevatron Experiments

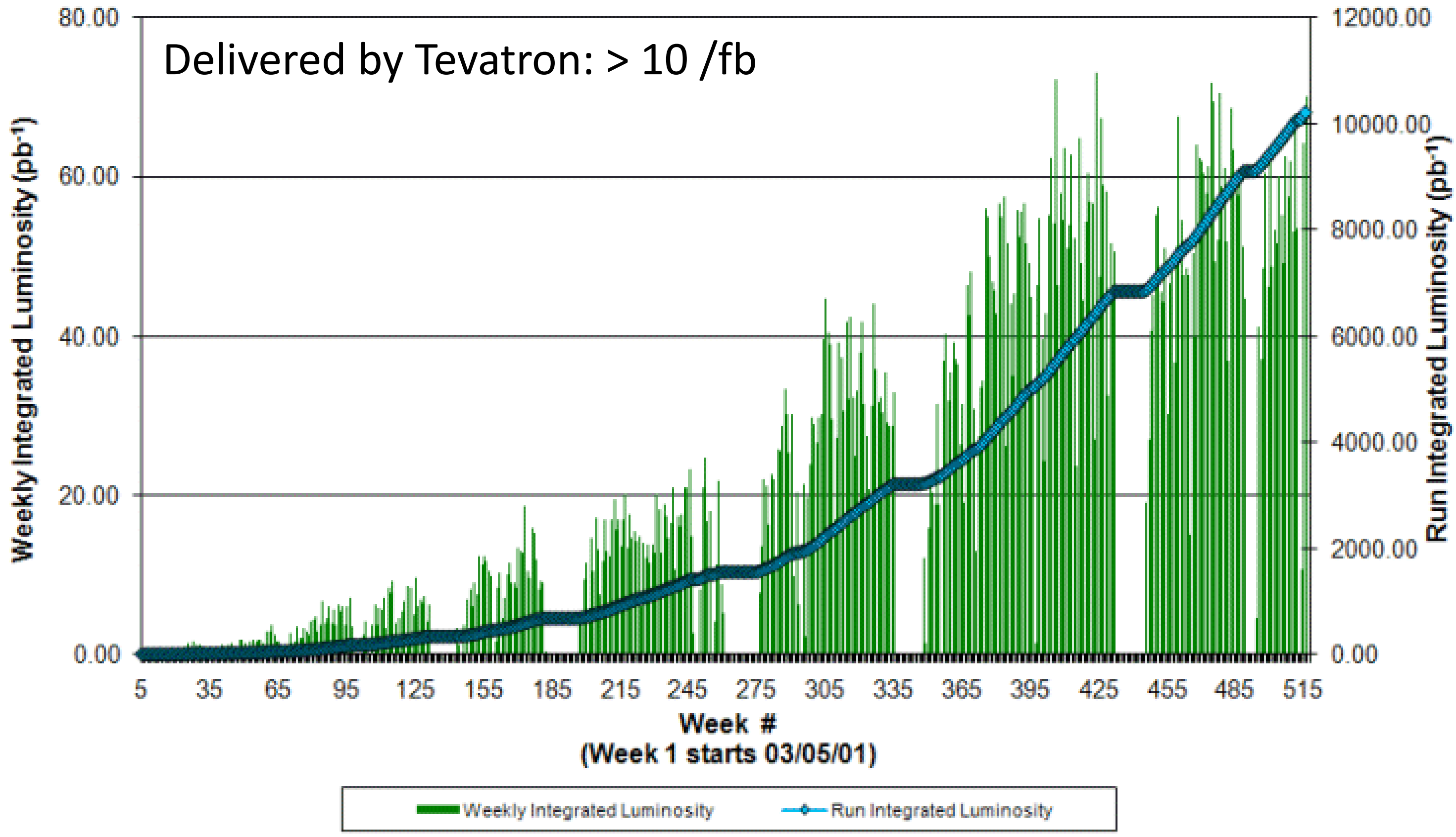
Fermilab



Multipurpose detectors (operate with ~ 90% efficiency)

Integrated RunII Luminosity (recorded) > 9 /fb per experiment

• Expected (recorded): ~10 /fb per experiment before end of Tevatron



Integrated luminosty/week (50 - 60) /pb ⇒ W and Z boson factory

W Mass Measurement

$$m_W = \left(\frac{\pi \cdot \alpha \cdot m_Z^2}{G_F\sqrt{2}}\right)\frac{1}{\sin\theta_W\sqrt{1-\Delta r_W}}$$

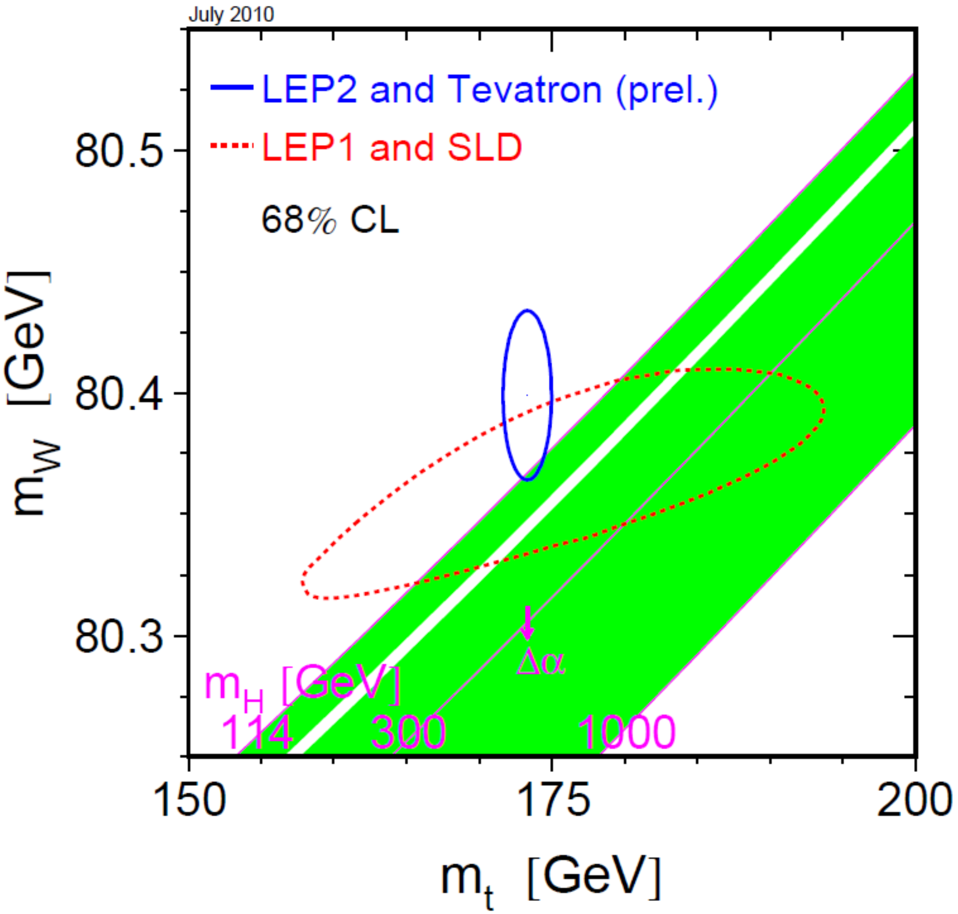
- EW radiative corrections:

$$\Delta r_W = \Delta\alpha + \Delta\rho(m_{top}^2) + \Delta\chi(\ln(m_H))$$

- MSSM $\Rightarrow$ m_W + ~250 MeV

A precise measurement of m_W can be used to make indirect constraints on Higgs mass and possible New Physics

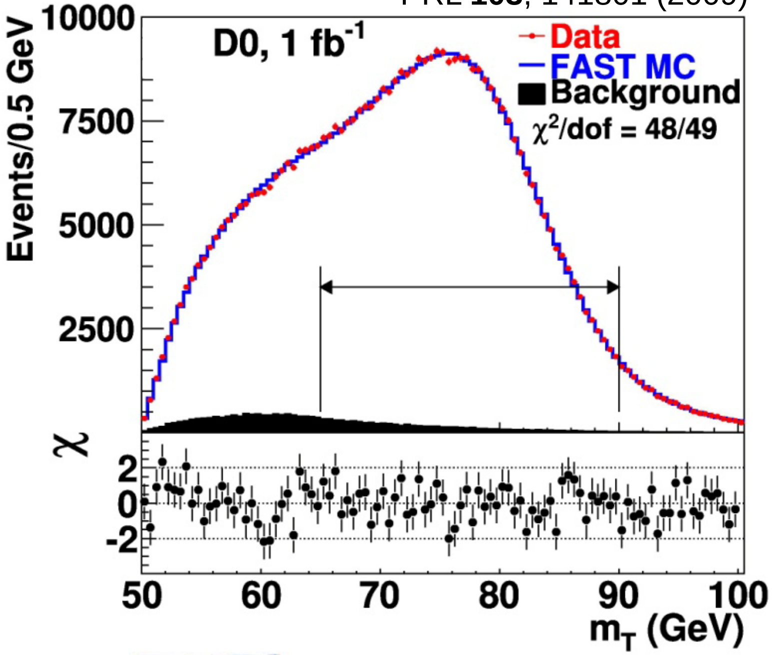
Possible Higgs mass phase space restricted by m_t and m_W
m_t(WA) = 173.3 ± 1.1 GeV

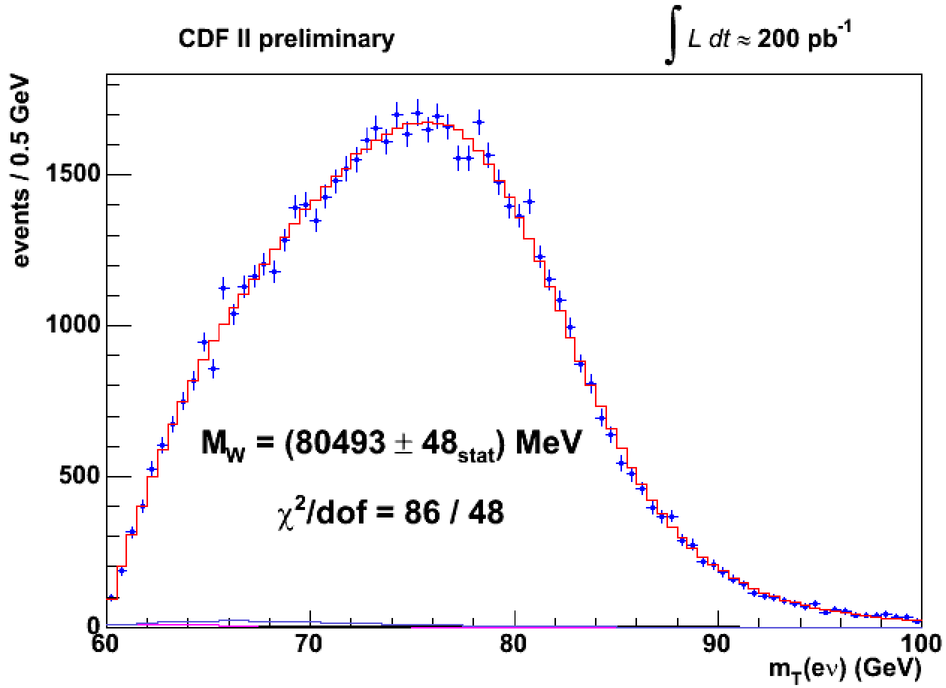


LEP/SLD/CDF/DØ, LEPII direct, combined precision EW measurements: m_H < 186 GeV @ 95% CL

W Mass Measurement

PRL **103**, 141801 (2009)





1.0 /fb (electron)

m_T, lepton p_T, MET combined

m_W (GeV/c^2):
80.401 ± 0.021 (stat) ± 0.038 (syst)

Most precise single W mass measurement

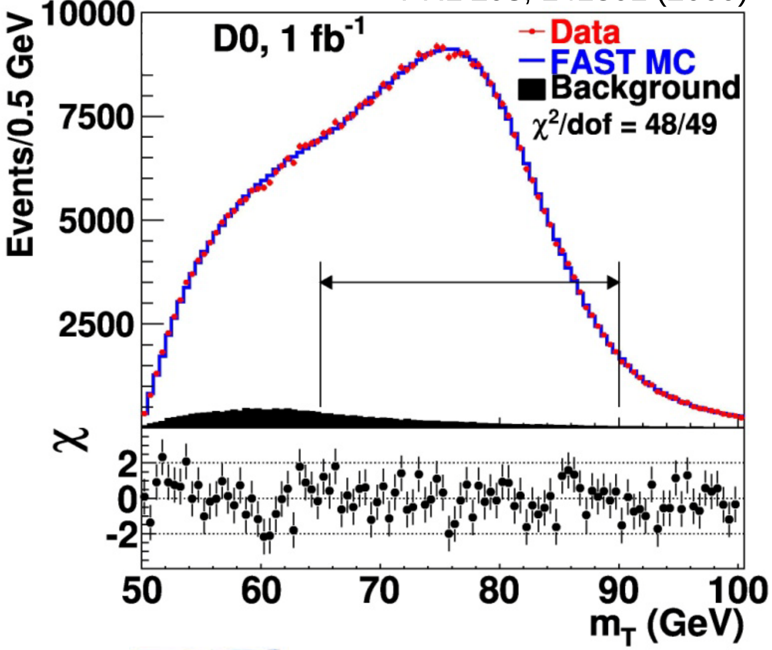
0.2 /fb (electon + muon)

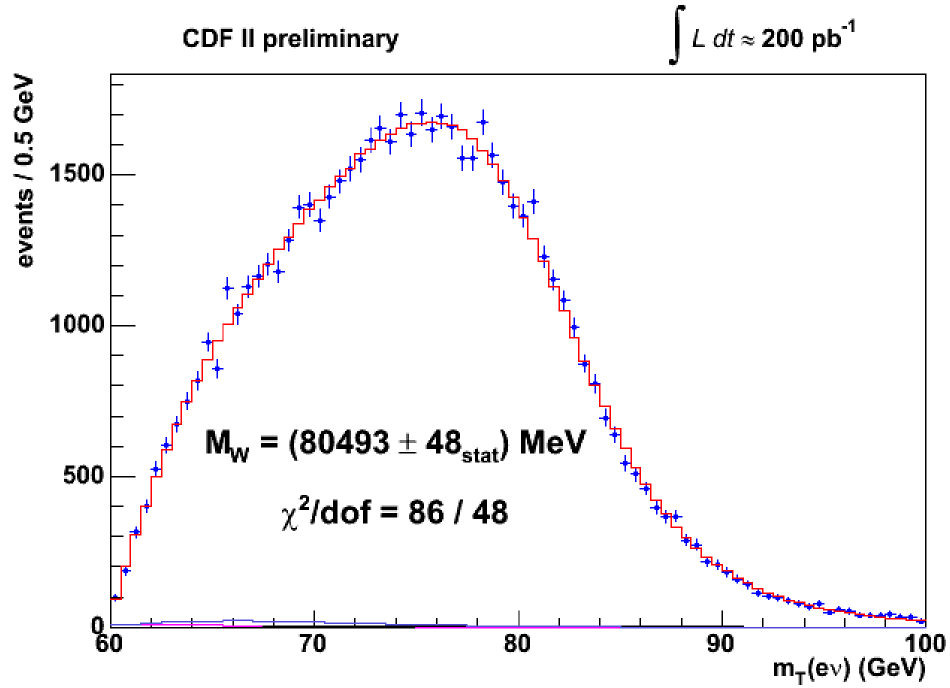
m_T, lepton p_T, MET combined

m_W (GeV/c^2):
80.413 ± 0.034 (stat) ± 0.034 (syst)

W Mass Measurement

PRL **103**, 141801 (2009)





1.0 /fb (electron)

m_T, lepton p_T, MET combined

m_W (GeV/c^2):
80.401 ± 0.021 (stat) ± 0.038 (syst)

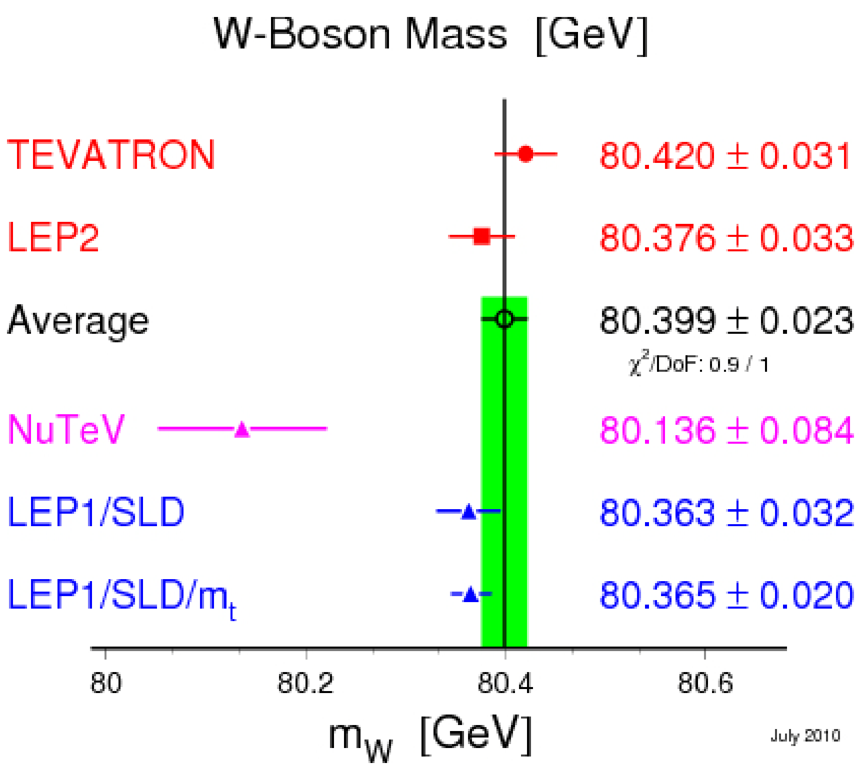
Γ_W from m_T (GeV):
2.028 ± 0.039 (stat) ± 0.061 (syst)
PRL **103**, 231802 (2009)

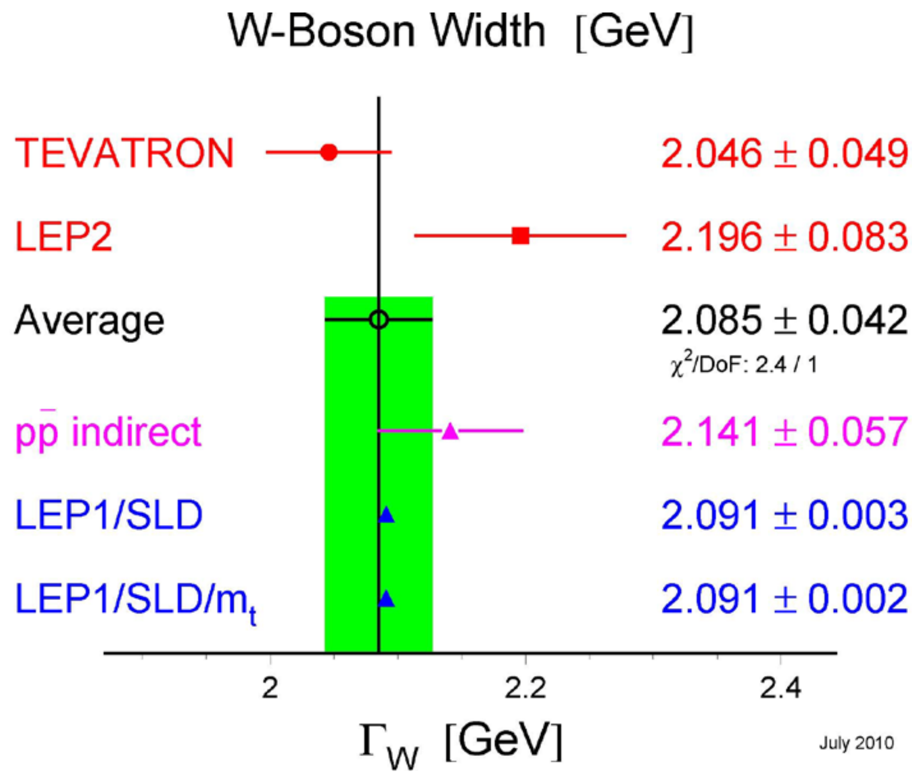
0.2 /fb (electon + muon)

m_T, lepton p_T, MET combined

m_W (GeV/c^2):
80.413 ± 0.034 (stat) ± 0.034 (syst)

Combined Measurements



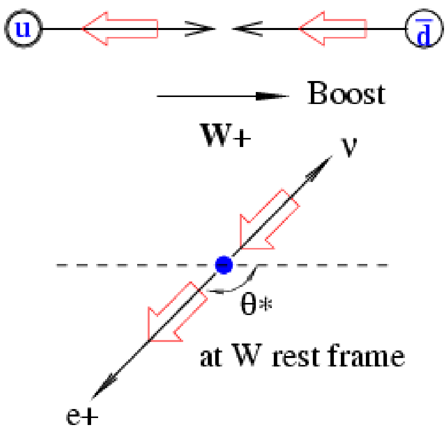


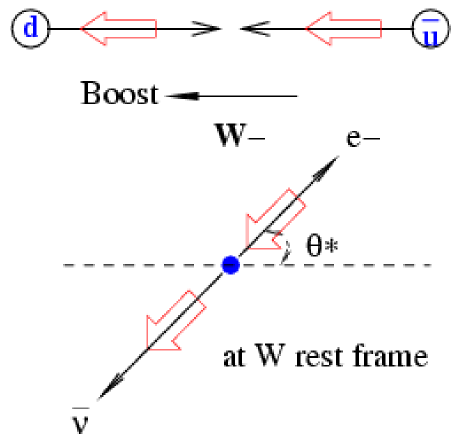
arXiv:0908.1374v1 [hep-ex]

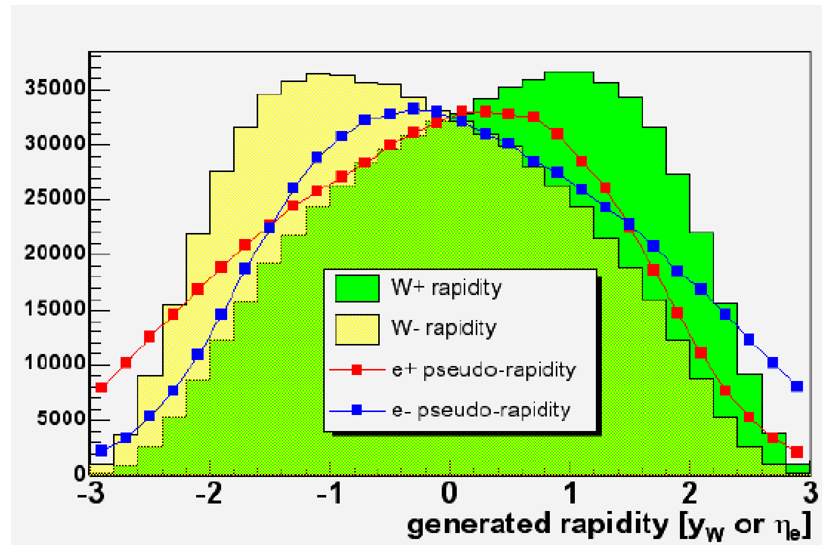
Both CDF and DØ are heading to more precise measurement, ~ 25 MeV/c^2

W Charge Asymmetry

Due to different PDFs of incoming partons in pp-bar collisions

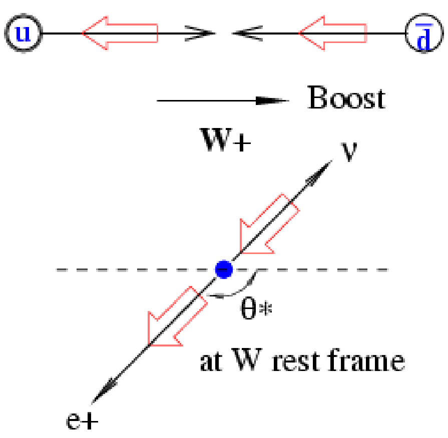


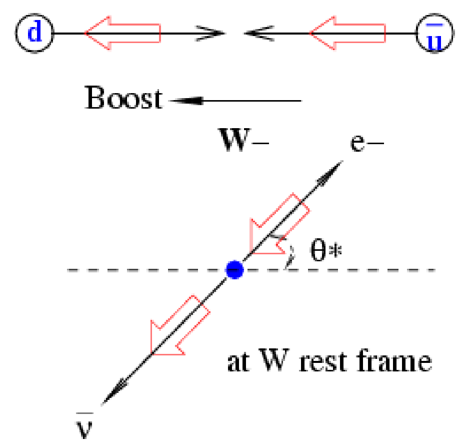


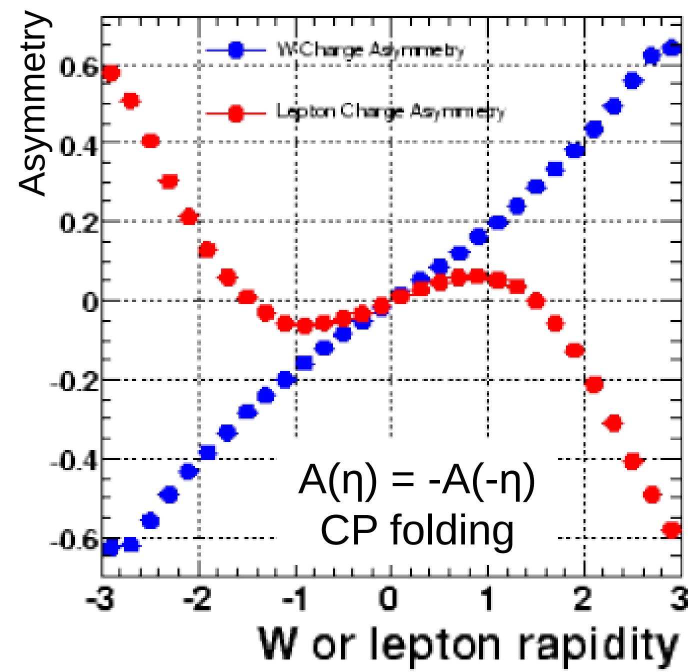


W Charge Asymmetry

Due to different PDFs of incoming partons in pp-bar collisions





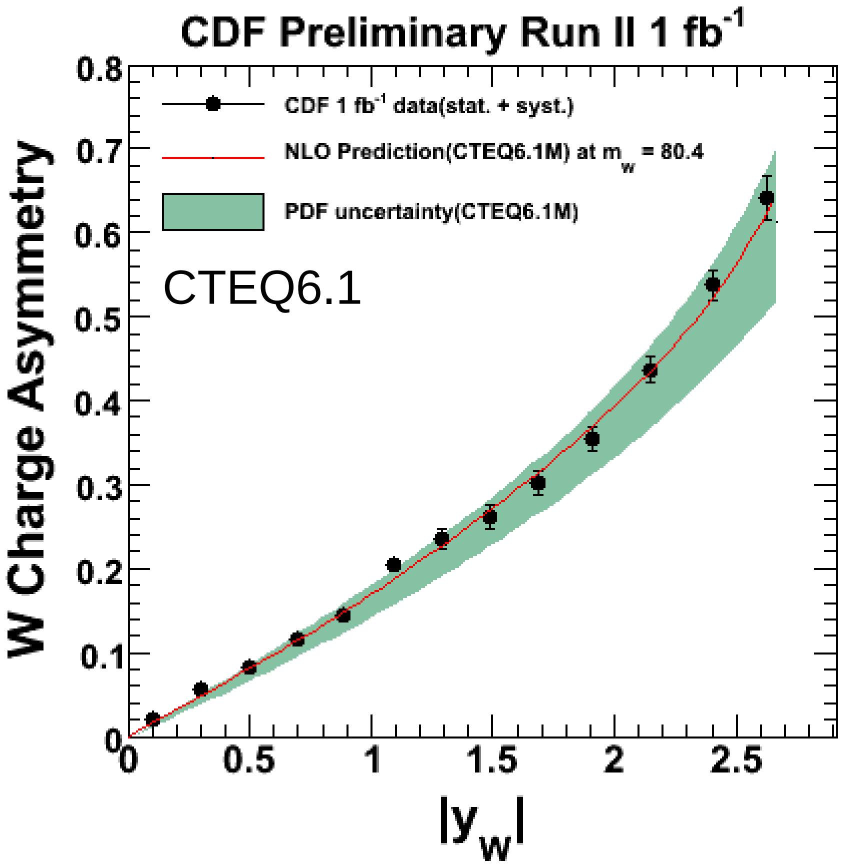


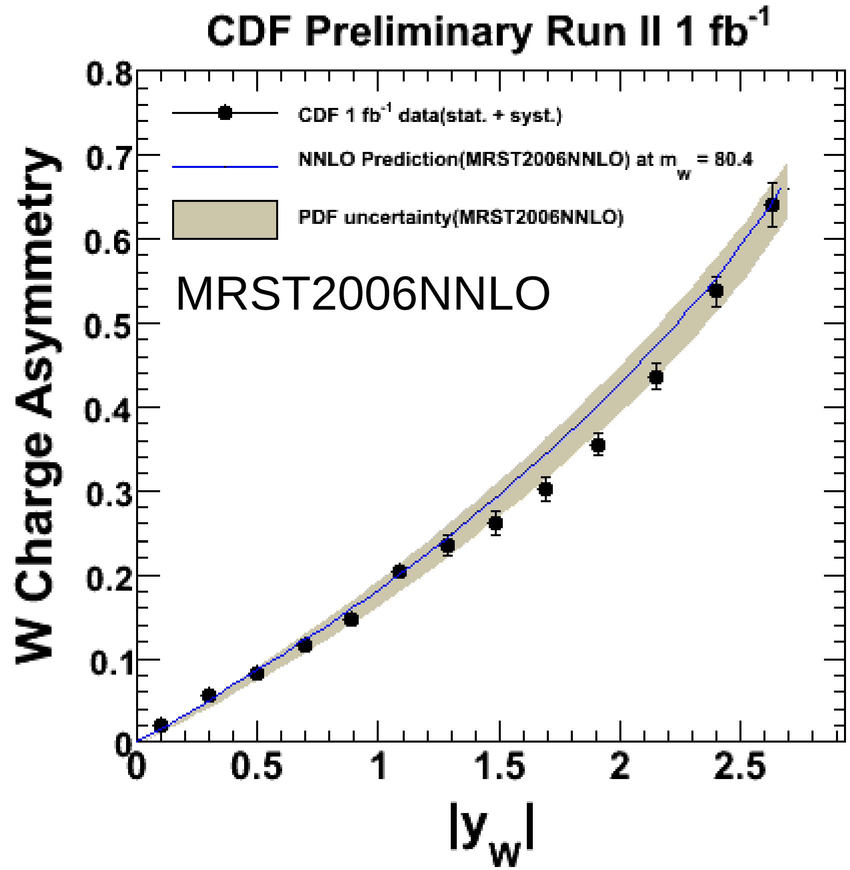
$$A(y_W) = \frac{\frac{d\sigma(W^+)}{dy_W} - \frac{d\sigma(W^-)}{dy_W}}{\frac{d\sigma(W^+)}{dy_W} + \frac{d\sigma(W^-)}{dy_W}} \approx \frac{u(x)}{d(x)}$$

$$A(\eta_l) = \frac{\frac{d\sigma(\eta_l)}{d\eta_l} - \frac{d\sigma(\eta_l)}{d\eta_l}}{\frac{d\sigma(\eta_l)}{d\eta_l} + \frac{d\sigma(\eta_l)}{d\eta_l}} \approx A(y_W) \otimes (V - A)$$

W Charge Asymmetry at CDF

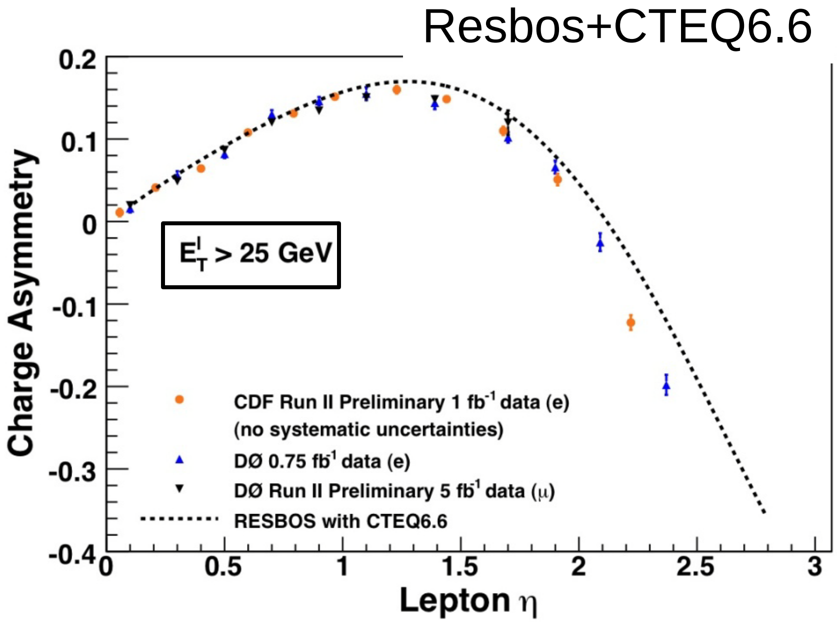
PRL **102**, 181801 (2009)



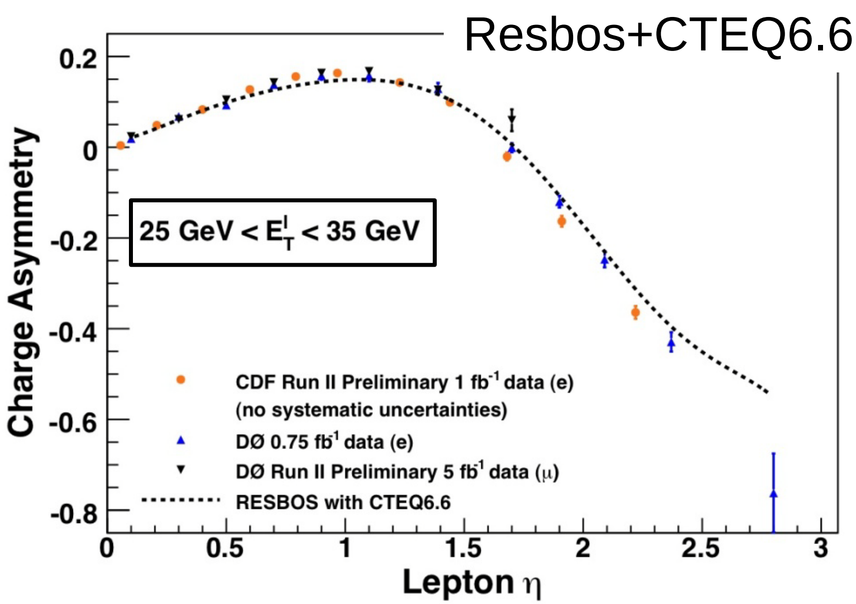


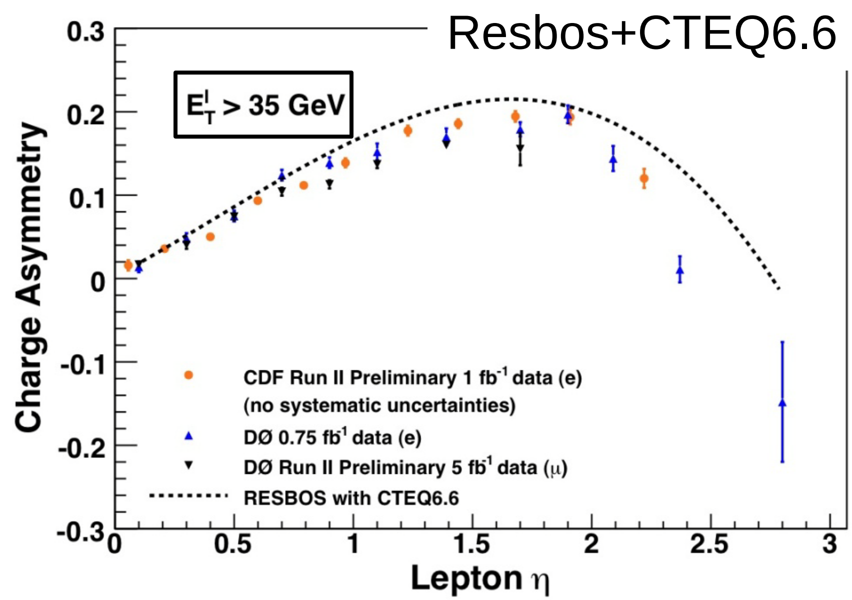
Inclusive W boson charge asymmetry in a good agreement with CTEQ6.1, CTEQ6.6 and MRST2006NNLO

Lepton Charge Asymmetry at CDF and DØ



- CDF data in terms of electron charge asymmetry agree with the DØ data
- Discrepancy in Muon - Electron charge asymmetry (high pT bin)
- New PDFs (CT10, CT10W)

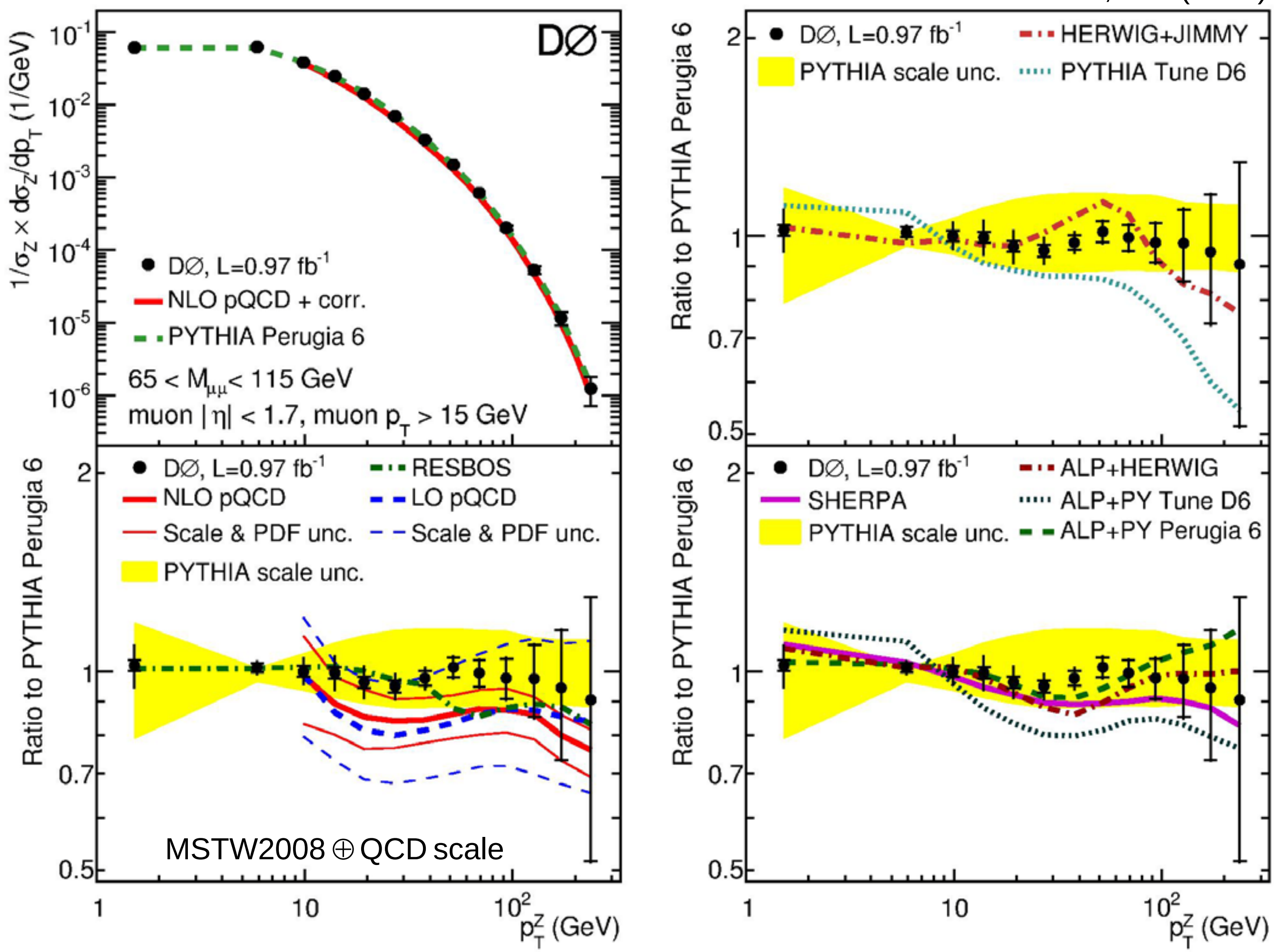




Z/γ* pT Measurement

Test of QCD predictions and current event generators
Unfolded Z/γ* → μμ pT distribution (to the particle level)

PLB **693**, 522 (2010)

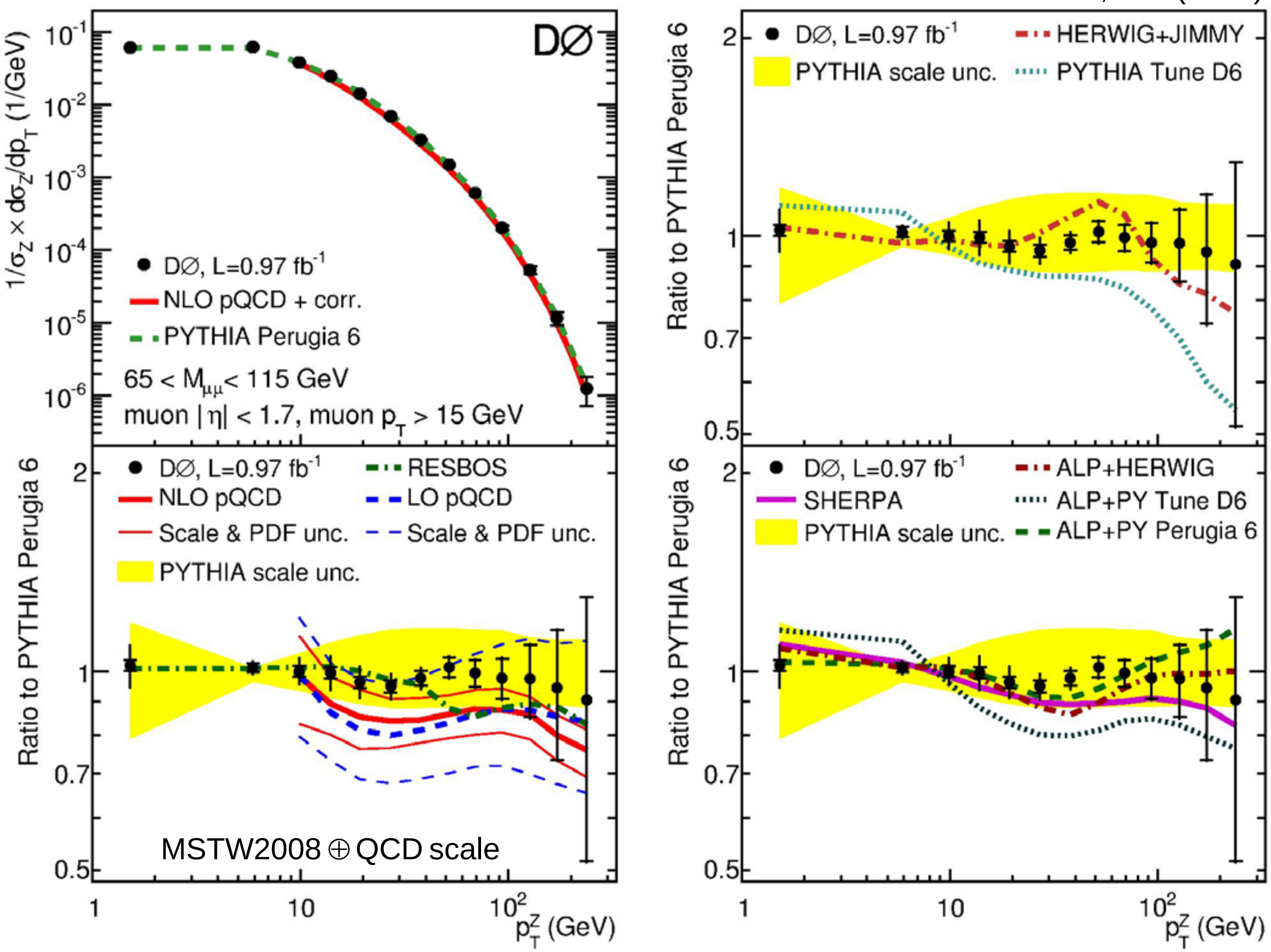


Best description of data with PYTHIA Perugia 6
(tuned to DØ electron channel)

Z/γ* pT Measurement

Resummation describes data well (Z pT < 30 GeV)
NLO pQCD describes data shape the best (Z pT > 30 GeV)

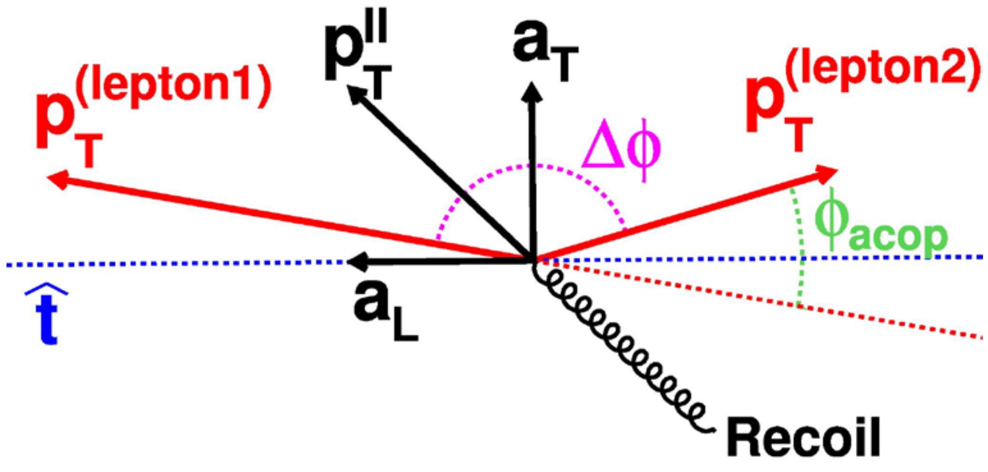
PLB **693**, 522 (2010)



Important input for the tuning of theoretical predictions
Increase sensitivity of searches for rare and new physics

Z/γ^* ϕ^* Measurement

Novel technique, relies on Φ_η^* variable: probes same physics as Z/γ^* pT



a_T: Component of pT(ll) transverse to dilepton thrust axis less sensitive than pT(ll) to detector effects (resolution, efficiency)

Φ_η^*: Highly correlated with (a_T/m_{ll})

θ_η^*: Angle of leptons wrt beam, in the rest frame of dilepton system

Depend on the angular resolution (measured precision of ~1 mrad)

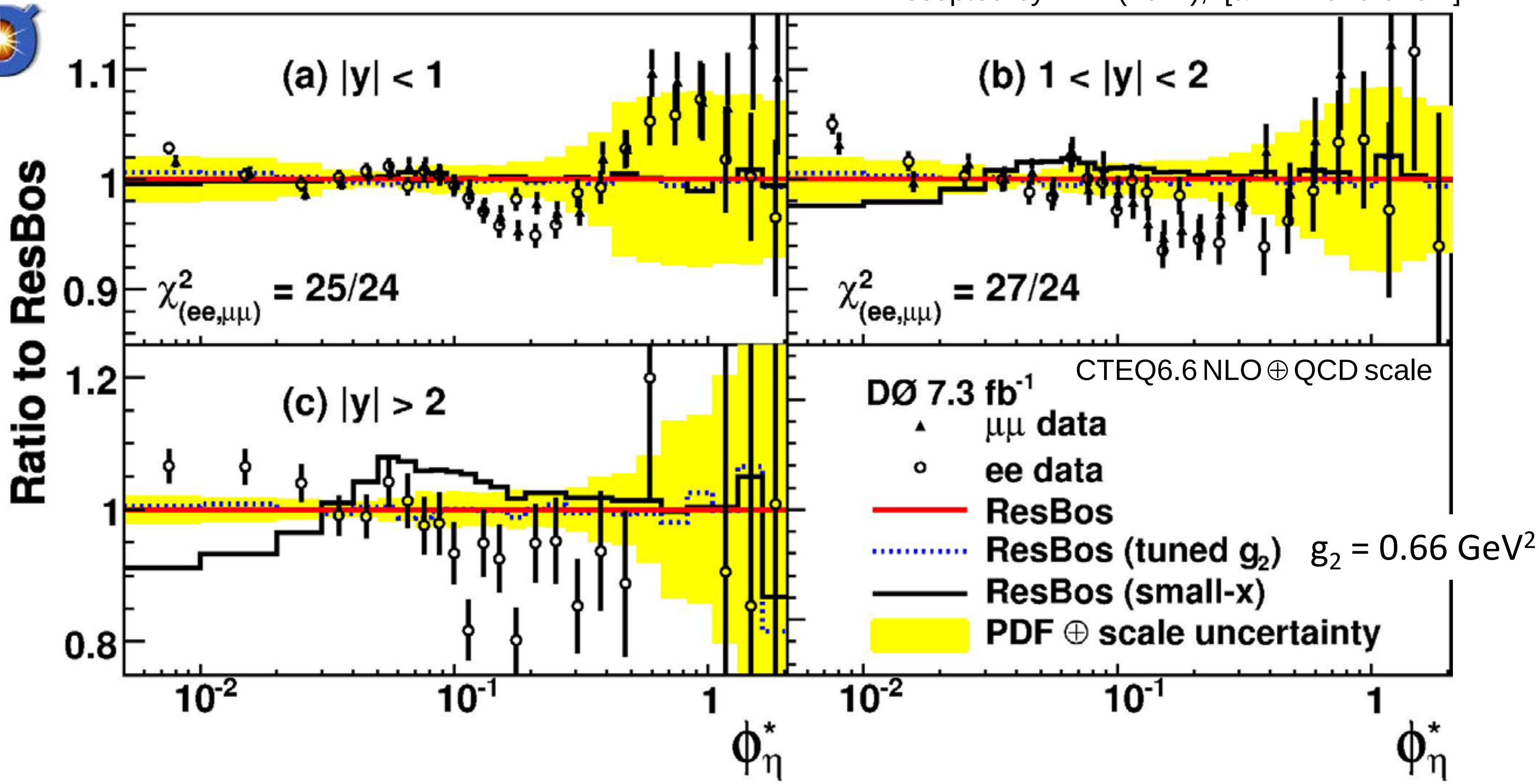
$$\Phi_\eta^* = \tan\left(\frac{\Phi_{acop}}{2}\right)\sin(\theta_\eta^*)$$

Φ_η^* is measured better than any quantity that rely on the pT(ll)

Z/γ* pT Measurement

Unfolded $Z/\gamma^* \rightarrow ee/\mu\mu$ Φ_η^* distributions, normalized as $(1/\sigma)\times(d\sigma/d\Phi_\eta^*)$

Accepted by PRL (2011), [arXiv:1010.0262]

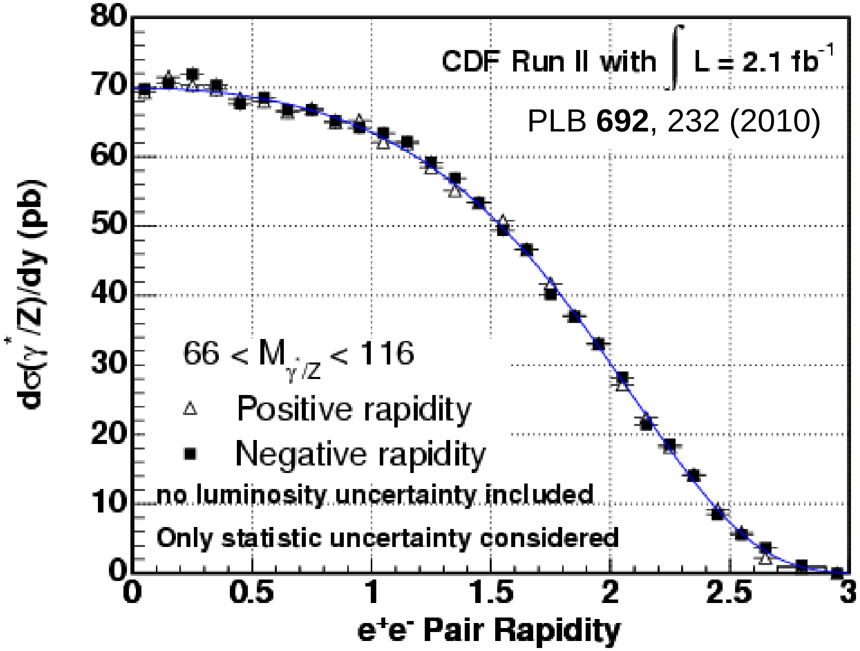


RESBOS does not describe the detailed shape of the data

Small-x broadening prediction is strongly disfavored by data

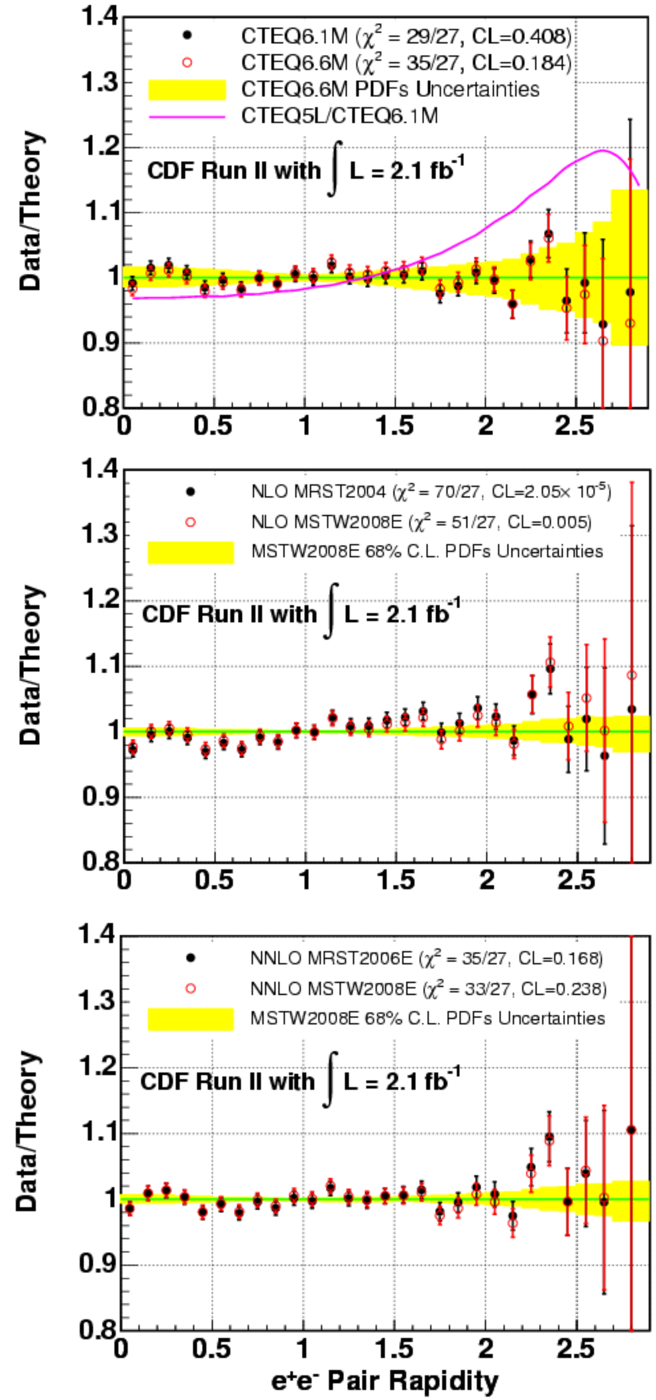
dσ/dy of Drell-Yan e^+e^- pairs

Test of QCD predictions
Unfolded $Z/\gamma^* \to ee$ rapidity distribution



$\sigma \times BR(Z \to ee) = 256.6 \pm 15.5$ (stat + syst)

Model	*Total cross section*
CTEQ5L(LO)	183.3
MRST2001E(NLO)	$241.0^{+2.8}_{-3.4}$
MRST2004(NLO)	241.2
MSTW2008E(NLO)	$242.6^{+4.6}_{-5.5}$
CTEQ6.1M(NLO)	$236.1^{+9.3}_{-9.2}$
CTEQ6.6M(NLO)	$238.7^{+7.1}_{-7.0}$
MRST2006E(NNLO)	$251.6^{+2.8}_{-3.1}$
MSTW2008E(NNLO)	$248.7^{+5.1}_{-4.0}$
Data	$256.6 \pm 0.7 \pm 2.0 \pm 15.4$



Angular Coefficients of Drell-Yan e^+e^- pairs

Angular distribution of the electron in Collins - Soper CM frame:

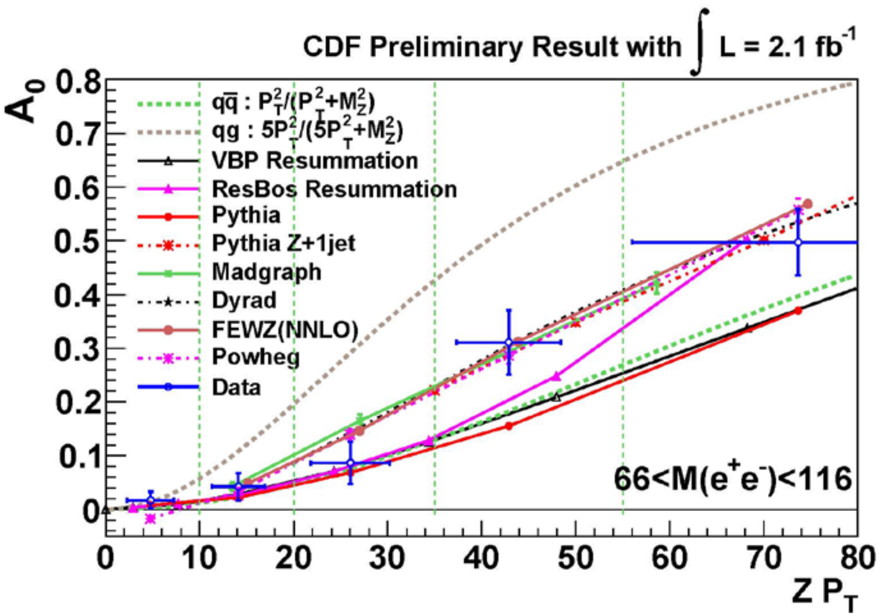
sensitive to $\sin^2\theta_w$

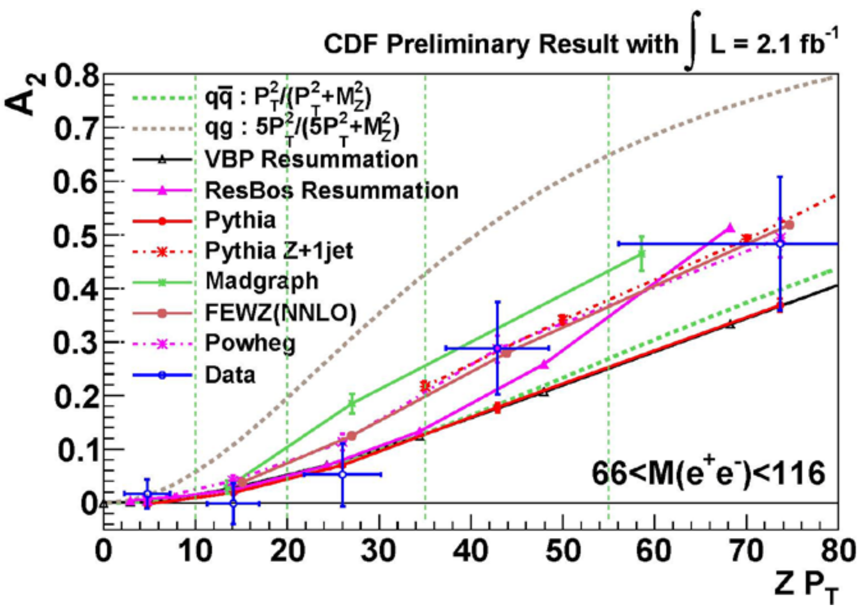
$$\frac{d\sigma}{d\cos\theta} \propto (1+\cos^2\theta) + \frac{1}{2}A_0(1-3\cos^2\theta) + A_4\cos\theta$$

$$\frac{d\sigma}{d\varphi} \propto 1 + \frac{3\pi}{16}A_3\cos\varphi + \frac{A_2}{4}\cos 2\varphi$$

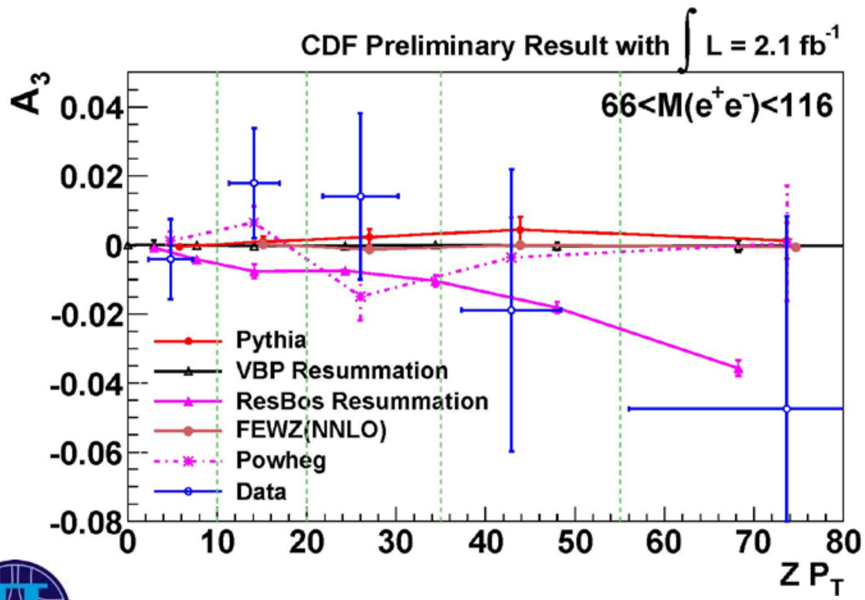
$A_i = f(pT_{ll}, m_{ll}, y_{ll})$, LO pQCD: $A_2 = A_0$

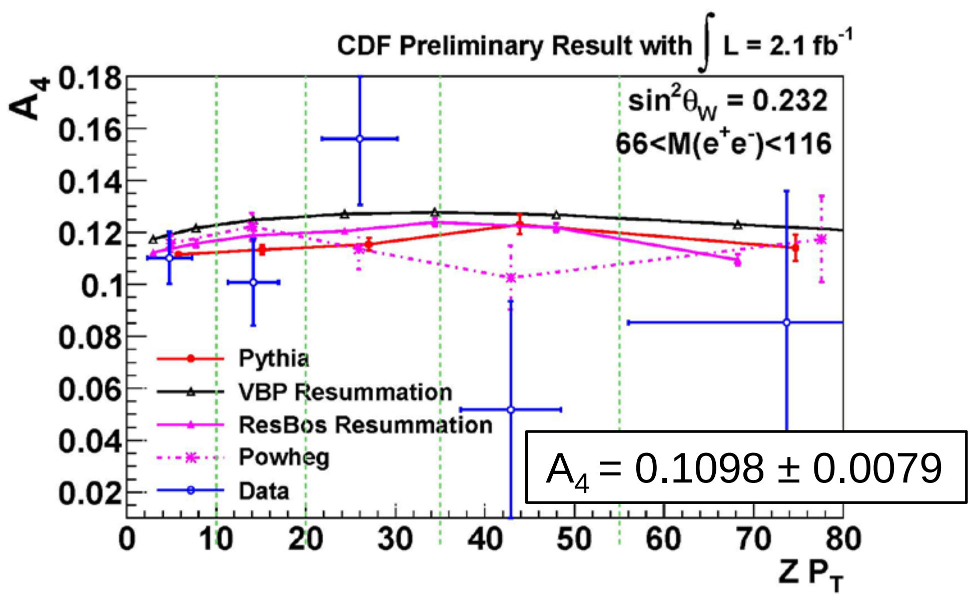
Measurement of coefficients A_i from $Z/\gamma^* \rightarrow ee$ pT distribution

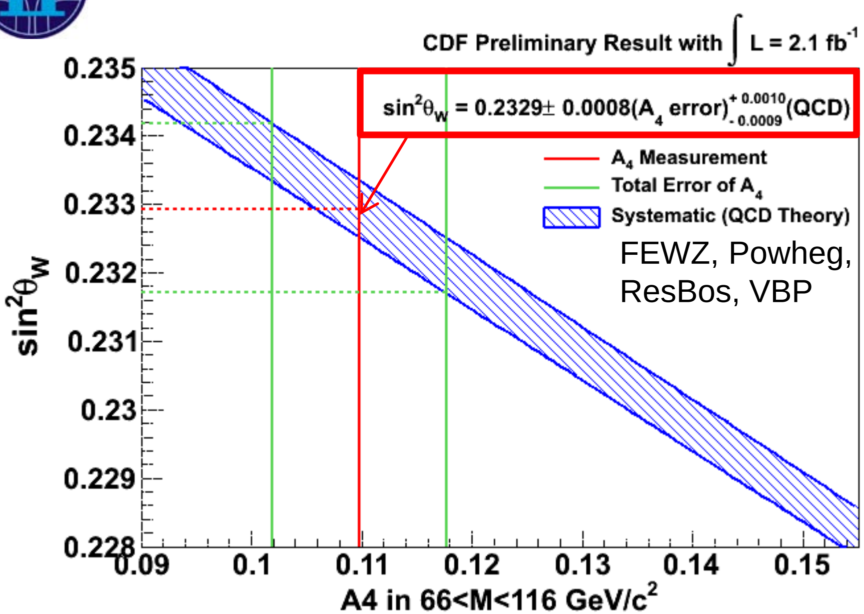


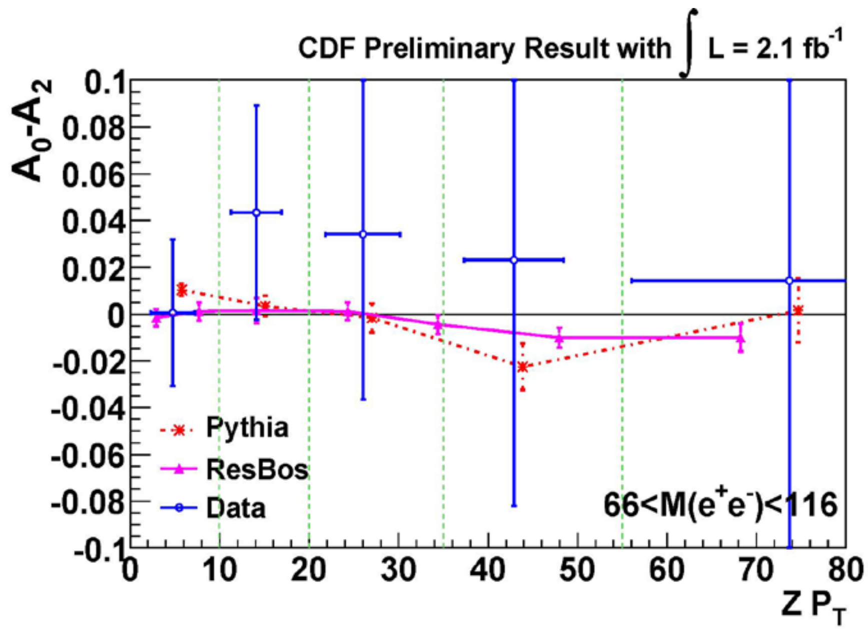


Angular Coefficients of Drell-Yan e^+e^- pairs

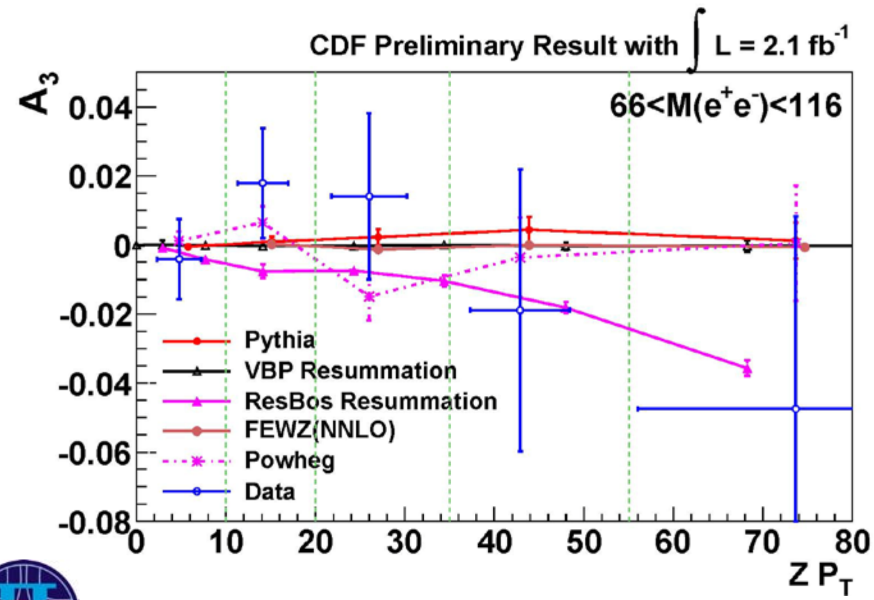


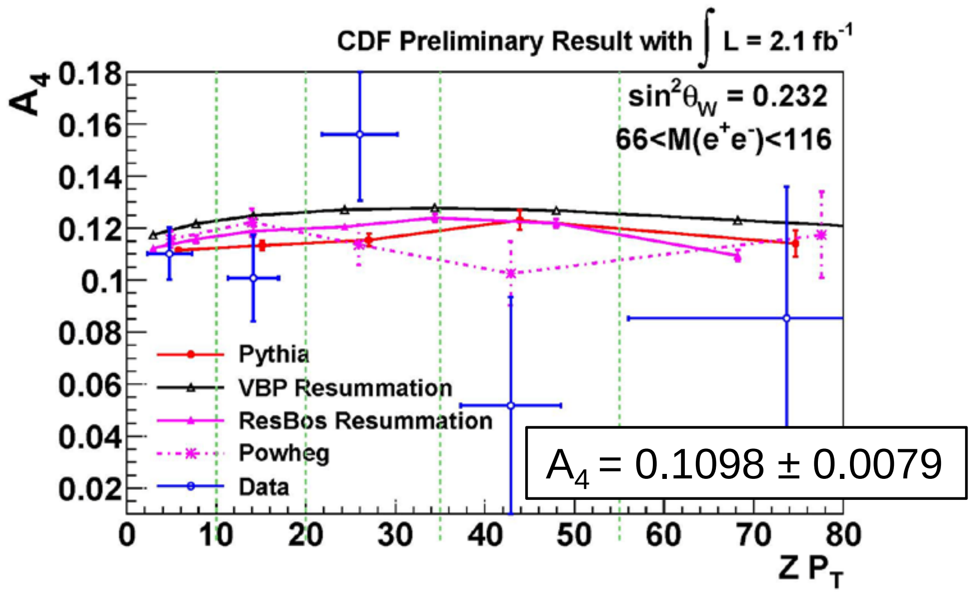




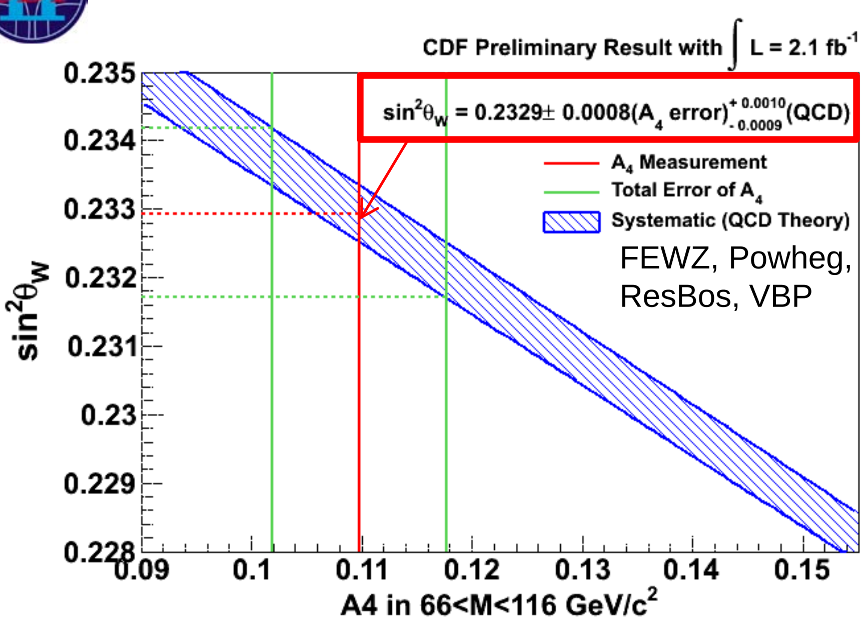


Angular Coefficients of Drell-Yan e^+e^- pairs

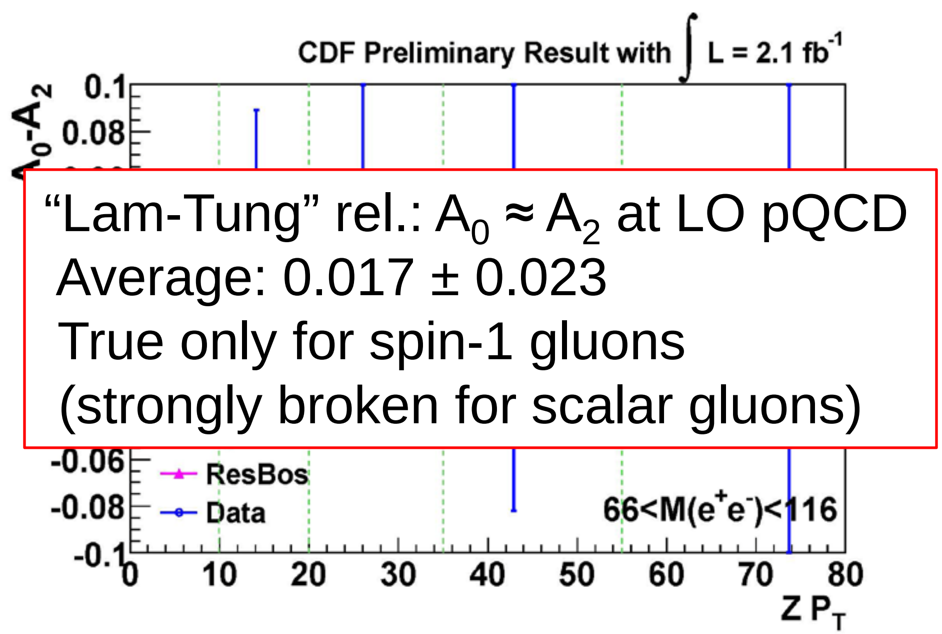




$A_4 = 0.1098 \pm 0.0079$

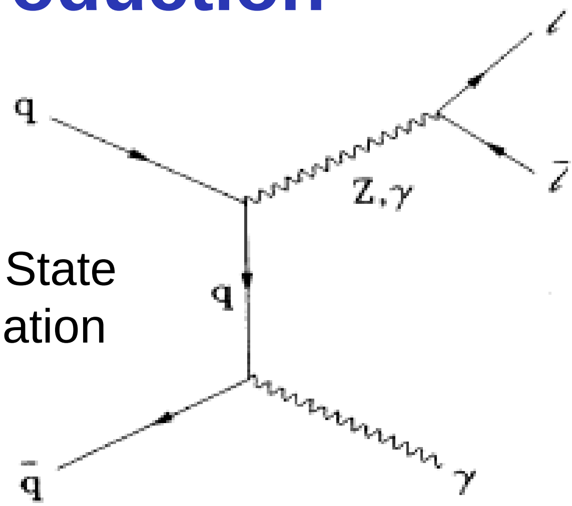


FEWZ, Powheg, ResBos, VBP

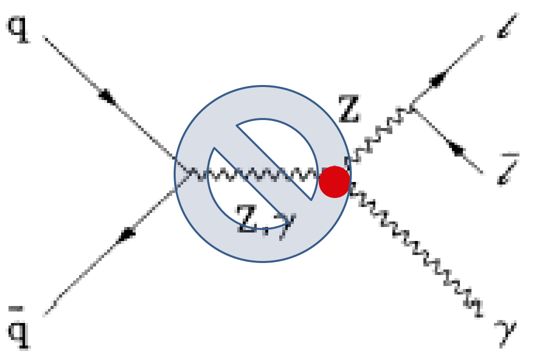


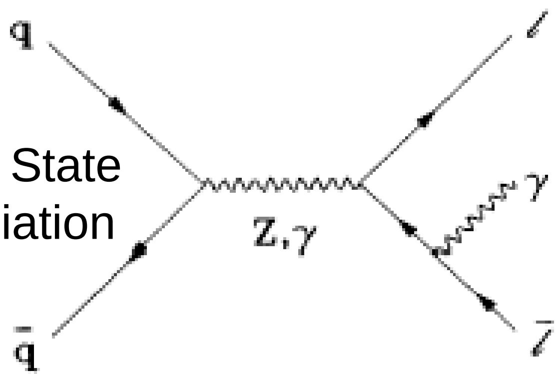
"Lam-Tung" rel.: $A_0 \approx A_2$ at LO pQCD
Average: 0.017 ± 0.023
True only for spin-1 gluons
(strongly broken for scalar gluons)

Zγ Production

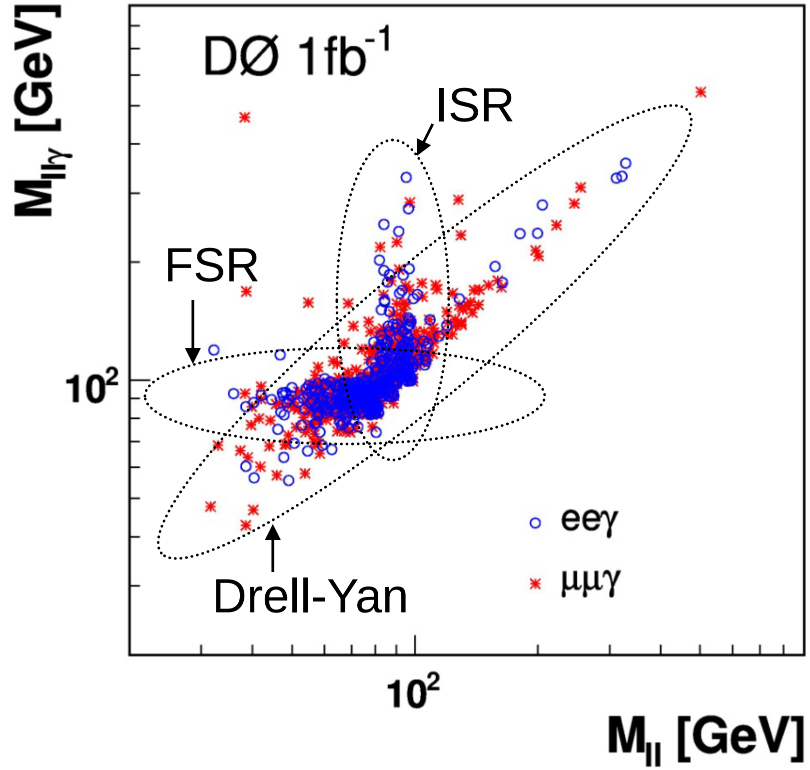


Initial State Radiation





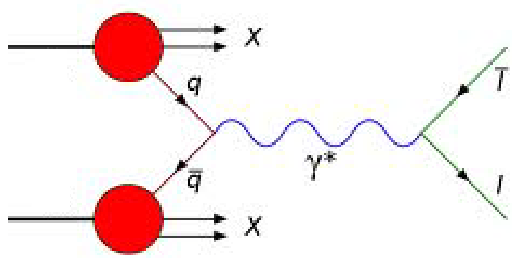
Final State Radiation



ISR: $Z\ (M_{ll} \approx M_Z) + \gamma\ (M_{ll\gamma} > M_Z)$

FSR: $Z\ (M_{ll} \leq M_Z) + \gamma\ (M_{ll\gamma} < M_Z)$

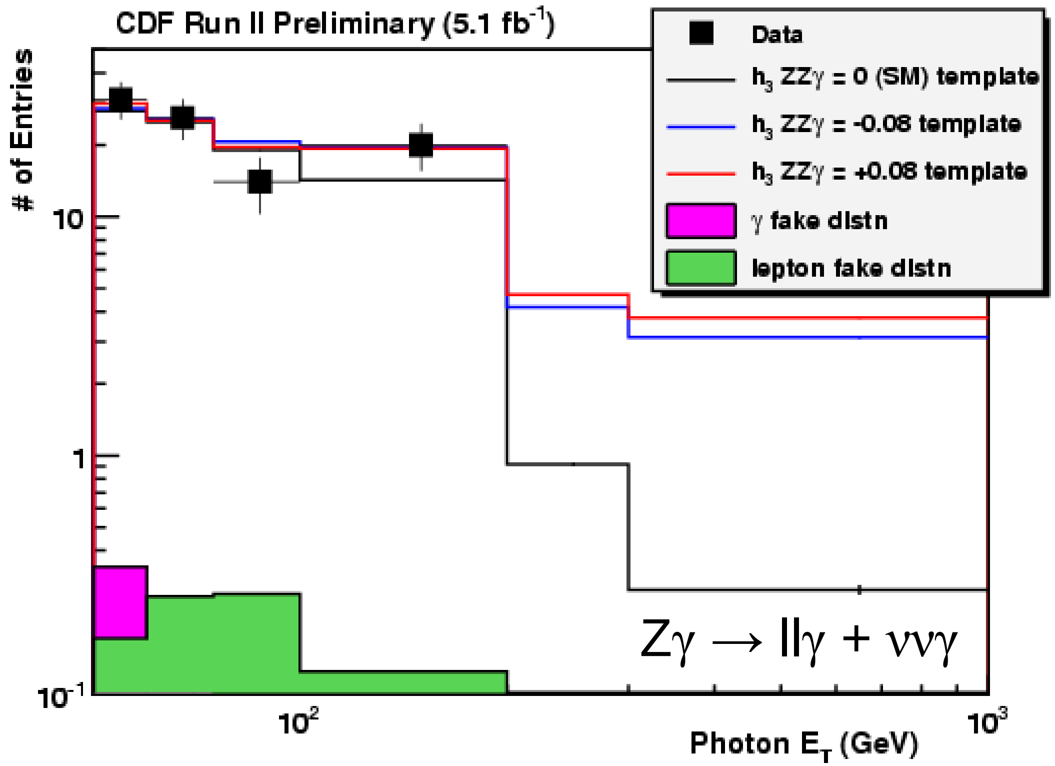
DY: $M_{ll} \approx M_{ll\gamma}$



Drell-Yan

Zγ Production

Candidate Events: 176

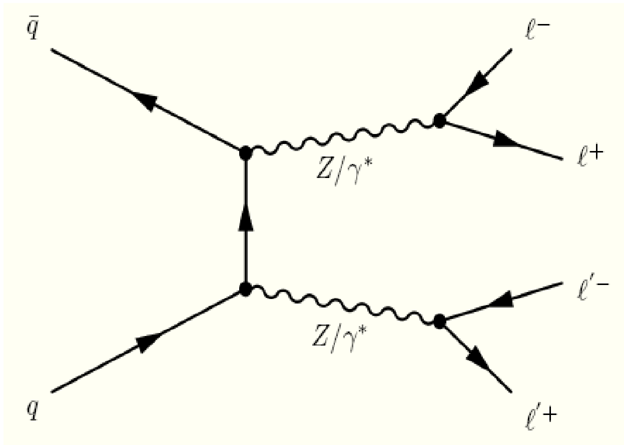


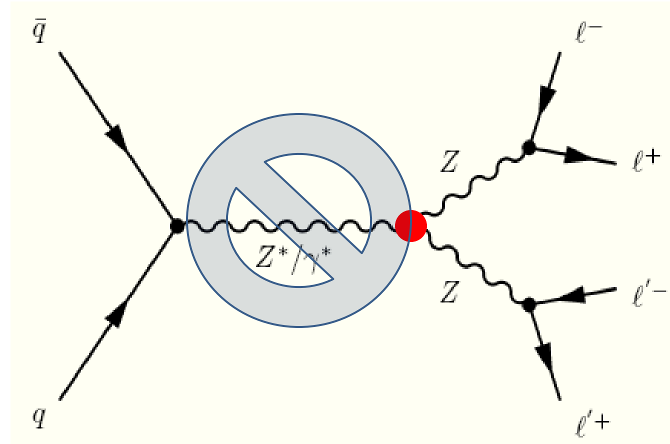
- **Photon E_T spectra for setting the TGC limits**
- **95% CL limits from 1D fit** (Λ = 1.5 TeV)

h_3^Z	[-0.017, 0.016]	**h_4^Z**	[-0.0006, 0.0005]
h_3^γ	[-0.017, 0.016]	**h_4^γ**	[-0.0006, 0.0006]

Tightest limits on γZZ/γγZ couplings to date

ZZ Production

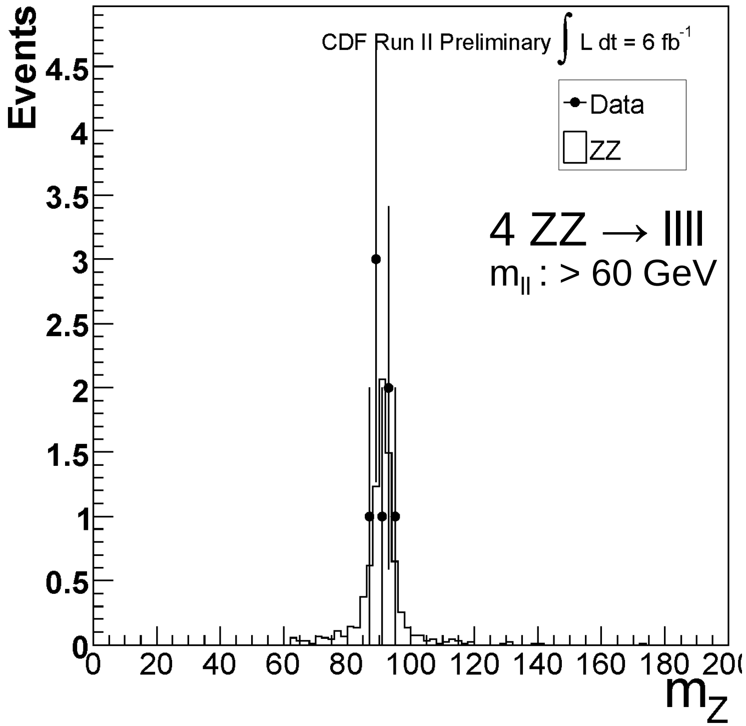




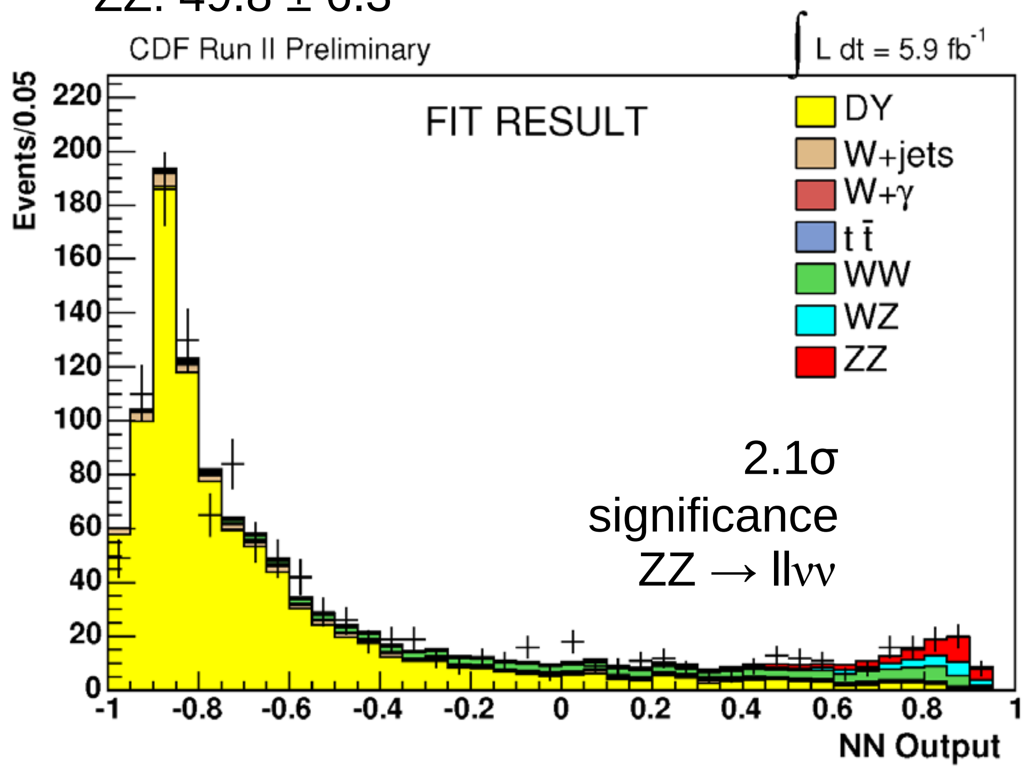
- Most recently observed diboson process at a hadron collider (5.3σ with llll final state using 1.7 /fb @DØ in 2008)
- Theoretical cross section **σ@NLO = 1.4 ± 0.1 pb**
- BR(Z→ll, Z→νν) ≈ 6 × BR(Z→ll, Z→ll) ($\sigma \times BR_{(ZZ\to llll)}$ ≈ 1%)
- Clean signal
- Single lepton cuts optimization / MET reconstruction

ZZ Production

Candidate Events: 6
Background: < 0.01



Candidate Events: 1162
Background: 1113 ± 158
ZZ: 49.8 ± 6.3



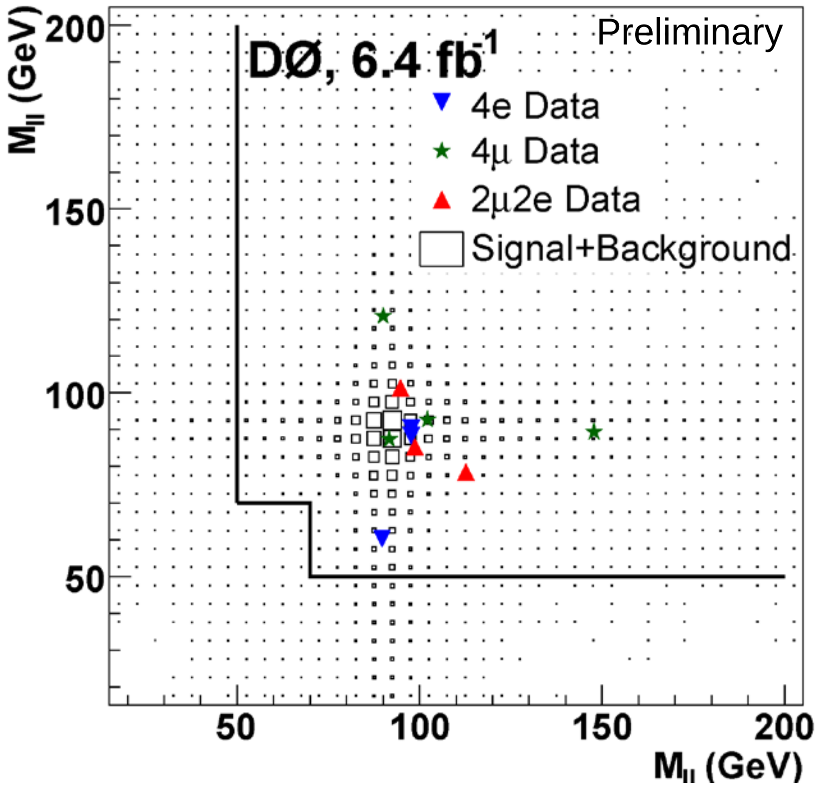
$$\frac{\sigma(p\bar{p} \to ZZ)}{\sigma(p\bar{p} \to Z)} = [2.3^{+1.5}_{-0.9}\,(\text{stat}) \pm 0.3\,(\text{syst})] \times 10^{-4}$$

$$\boldsymbol{\sigma_{(p\bar{p} \to ZZ)} = 1.7^{+1.2}_{-0.7}\,(\text{stat}) \pm 0.2\,(\text{syst})\,\text{pb}}$$

$$\boldsymbol{\sigma_{(p\bar{p} \to ZZ)} = 1.45^{+0.45}_{-0.42}\,(\text{stat})\,^{+0.41}_{-0.30}\,(\text{syst})\,\text{pb}}$$

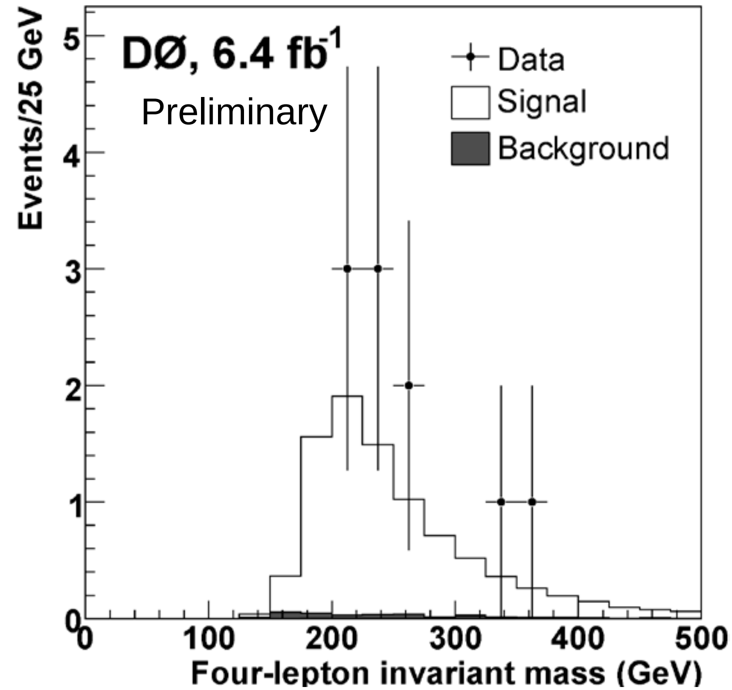
ZZ Production

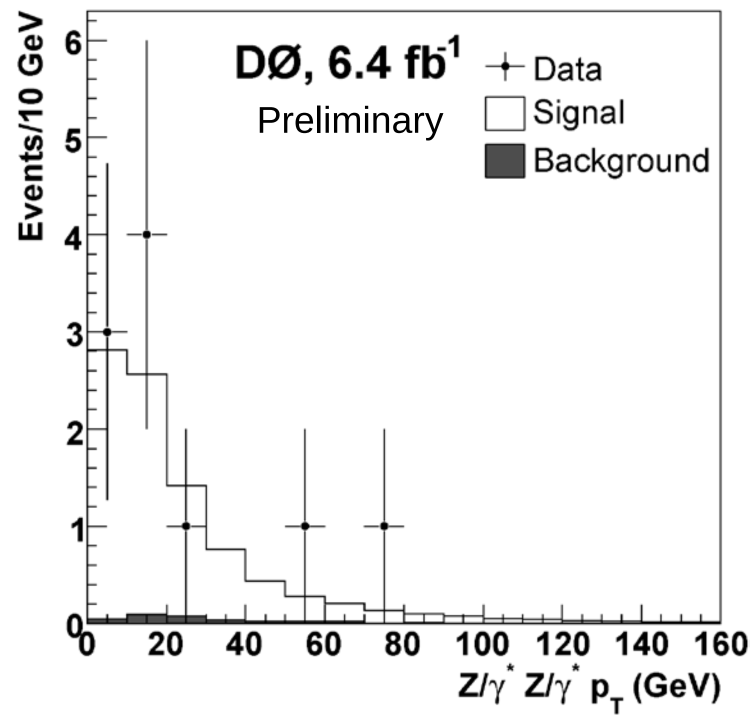
6σ significance, ZZ → llll



Candidate Events: 10
Background: 0.37 ± 0.13
ZZ: 8.73 ± 1.22

$$\sigma_{(p\bar{p}\to ZZ)} = 1.35^{+0.50}_{-0.40}\,(\text{stat}) \pm 0.15\,(\text{syst})\,\text{pb}$$

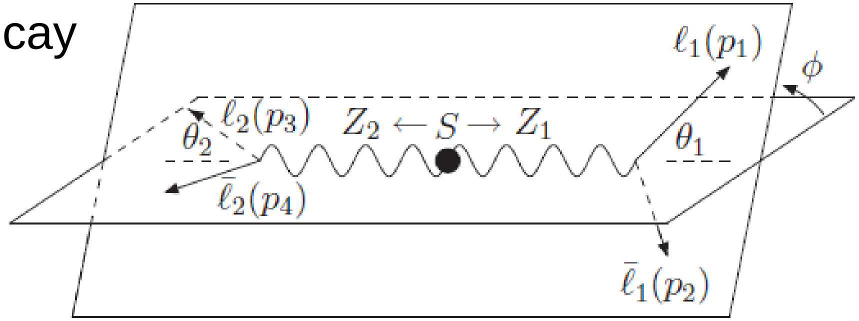


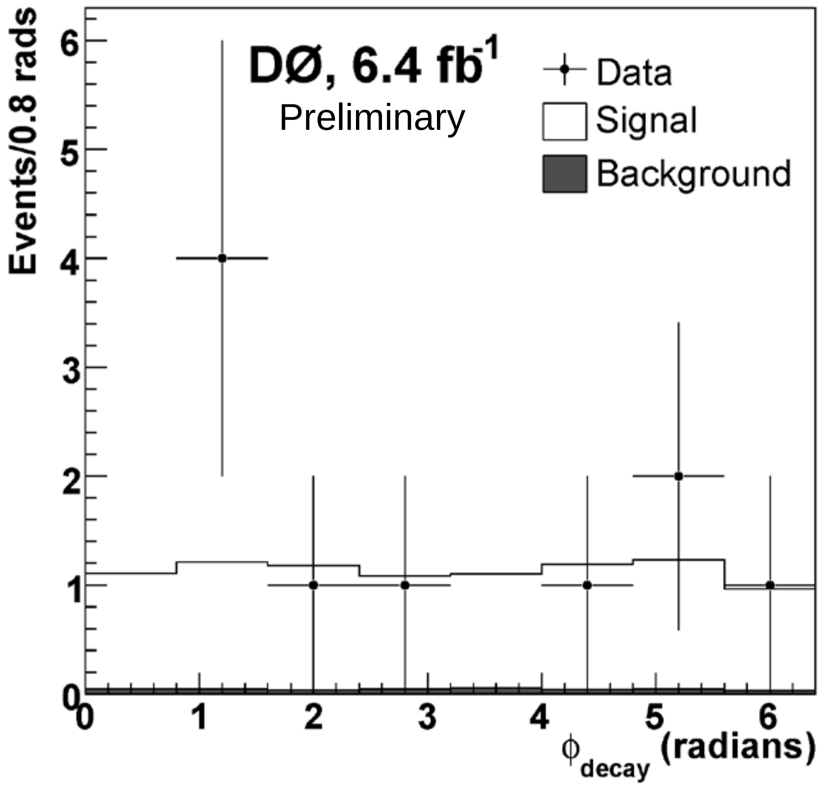


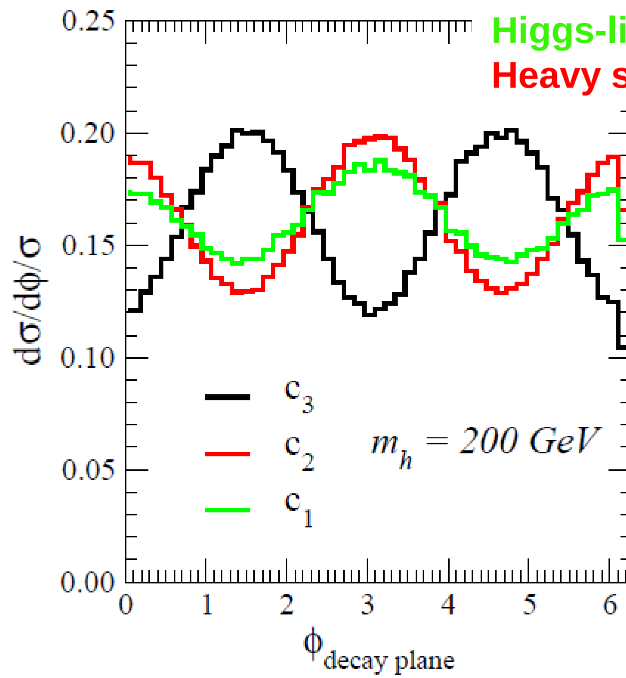
ZZ Production

Q-H. Cao, C.B. Jackson, W-Y. Keung, I. Low, J. Shu, PRD 81, 015010 (2010)

Azimuthal angle between the two Z decay planes ϕ of interest in Higgs searches

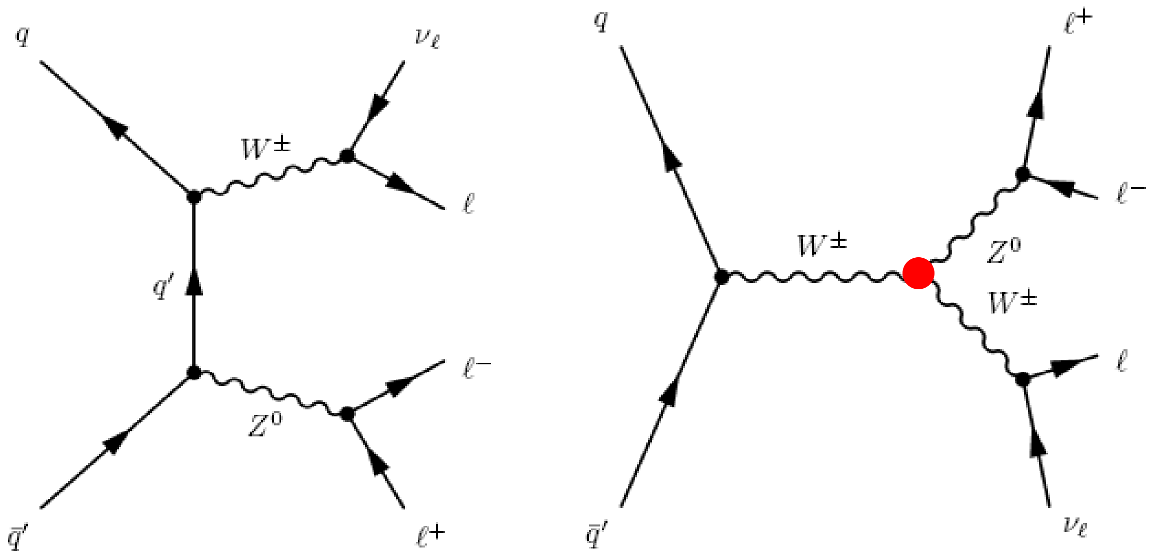






Help to distinguish between different scalar models

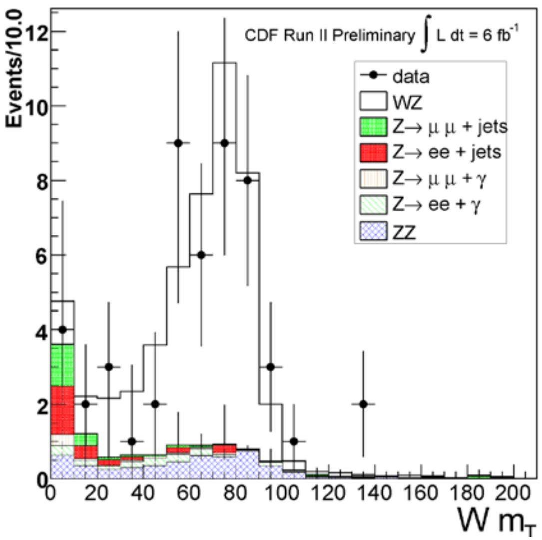
WZ Production

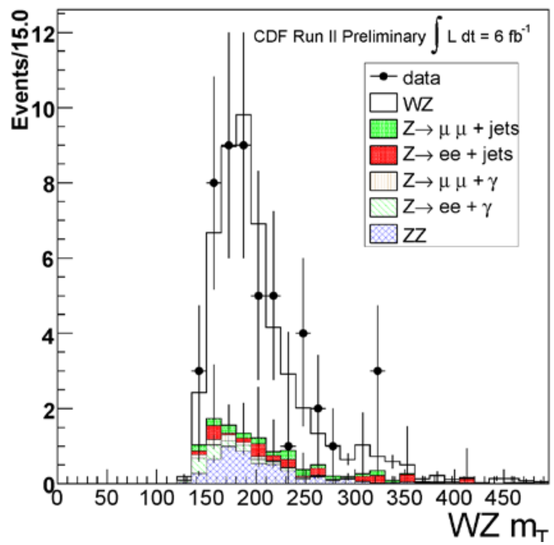


- Not directly accessible at LEP
- ZWW vertex ⇒ κ_Z, λ_Z and g_1^Z couplings, independent of γWW
- Theoretical cross section **σ@NLO = 3.45 ± 0.30 pb**
- BR(W→lν, Z→ll) ≈ 3%
- Very clean signal with small background

WZ Production

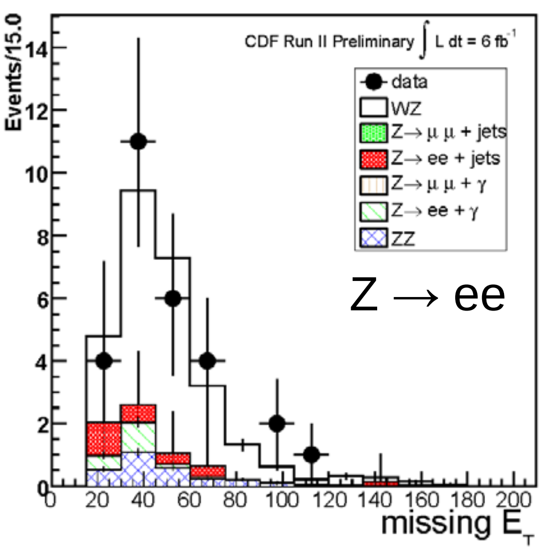
WZ → lνll

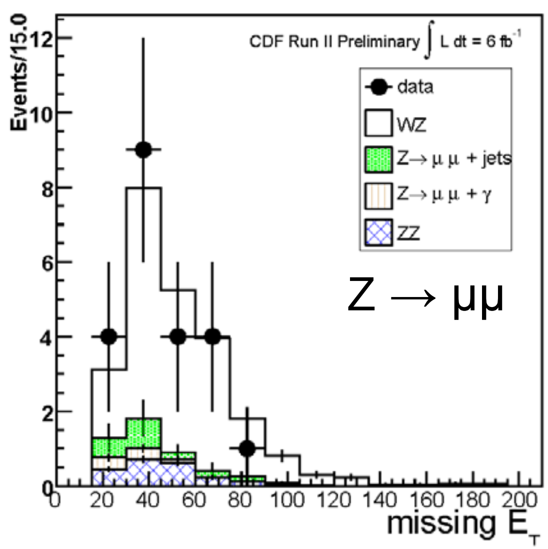




Candidate Events: 50

Background: 11.2 ± 1.63





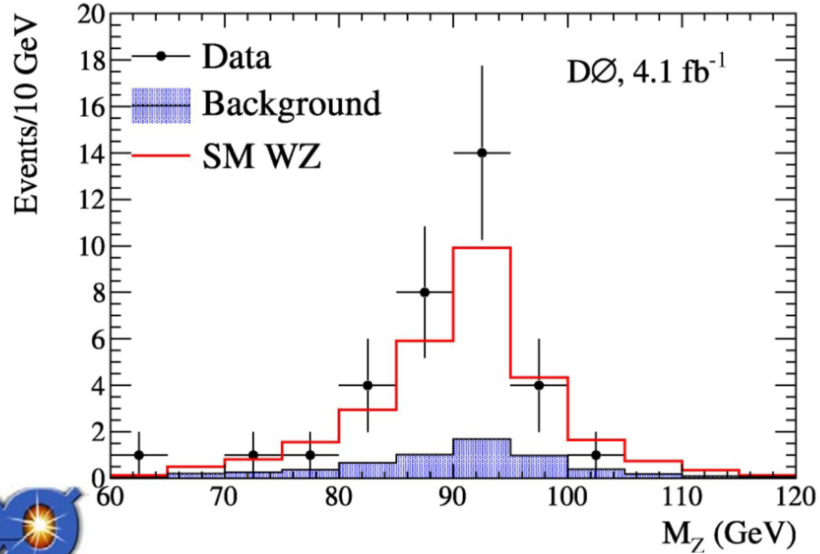
$$\frac{\sigma(p\bar{p} \to WZ)}{\sigma(p\bar{p} \to Z)} = [5.5 \pm 0.9] \times 10^{-4}$$

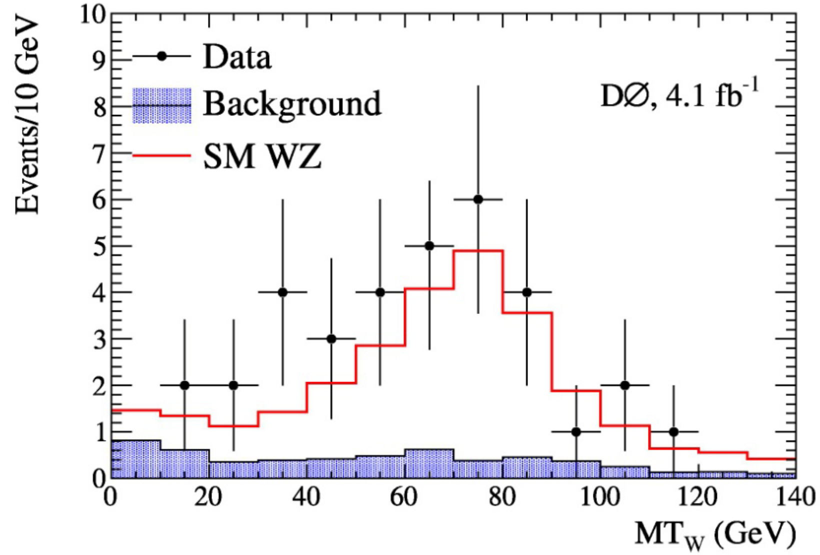
$$\boldsymbol{\sigma_{(p\bar{p} \to WZ)}} =$$

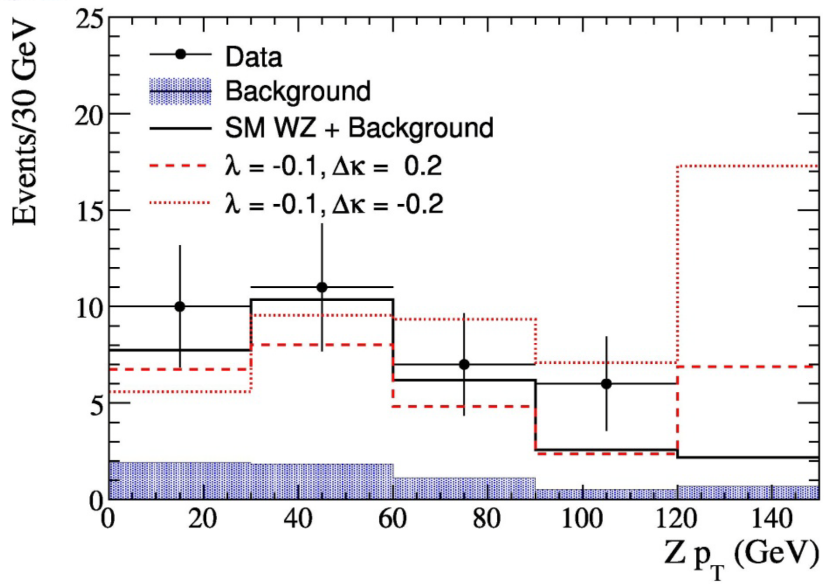
$$\mathbf{4.1 + 0.6\,(stat) \pm 0.4\,(syst)\,pb}$$

WZ Production

PLB **695**, 67 (2011)







Tightest limits on WWZ couplings from direct measurement to date

Candidate Events: 34

Background: 6.0 ± 0.6

WZ: 23.3 ± 1.5

$$\sigma_{(p\bar{p}\to WZ)} = 3.90^{+1.06}_{-0.90}\,(\mathrm{stat}+\mathrm{syst})\,\mathrm{pb}$$

95% CL limits from 1D fit (Λ = 2.0 TeV)

Coupling relation	95% C.L. Limit
$\Delta g_1^Z = \Delta\kappa_Z = 0$	$-0.075 < \lambda_Z < 0.093$
$\lambda_Z = \Delta\kappa_Z = 0$	$-0.053 < \Delta g_1^Z < 0.156$
$\lambda_Z = \Delta g_1^Z = 0$	$-0.376 < \Delta\kappa_Z < 0.686$
$\Delta\kappa_Z = 0$ (HISZ)	$-0.075 < \lambda_Z < 0.093$
$\lambda_Z = 0$ (HISZ)	$-0.027 < \Delta\kappa_Z < 0.080$

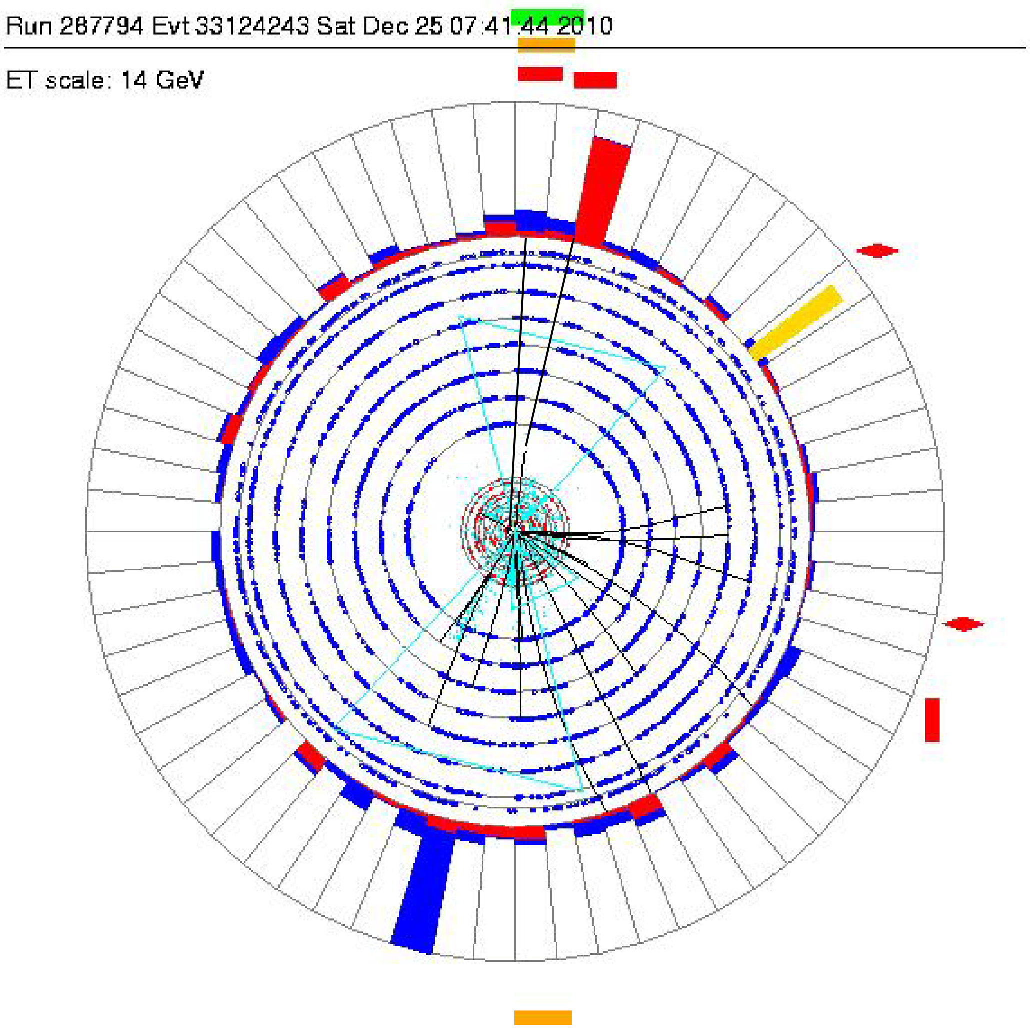
Summary EW Tevatron

- (1 – 7) /fb data analyzed by CDF and DØ
- Agreement with the SM predictions
- Test of different models/predictions
- Importance for Higgs searches
- Most stringent TGC limits set at the Tevatron

- Precise Tevatron Electroweak Measurements ongoing (including dijet final states)

Backup Slides

Event Signature at CDF and DØ



EM cluster (Electron or Photon)
good EM shower shape
small HAD energy
isolated in calorimeter
match to a track if electron

Muons
Isolated in the CAL and tracker
hits in muon system
match to a track

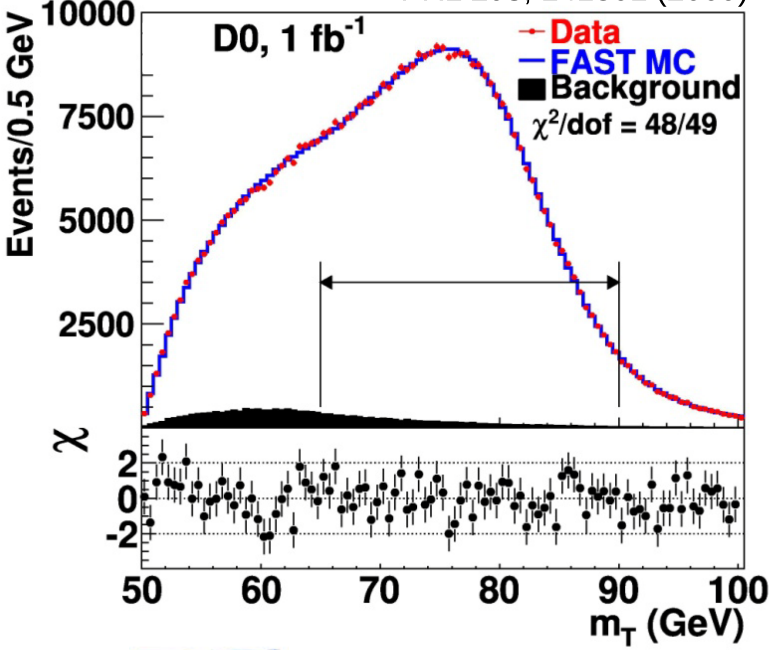
Jets
good HAD shower shape
large HAD energy
minimal EM energy
(match to a tracks)

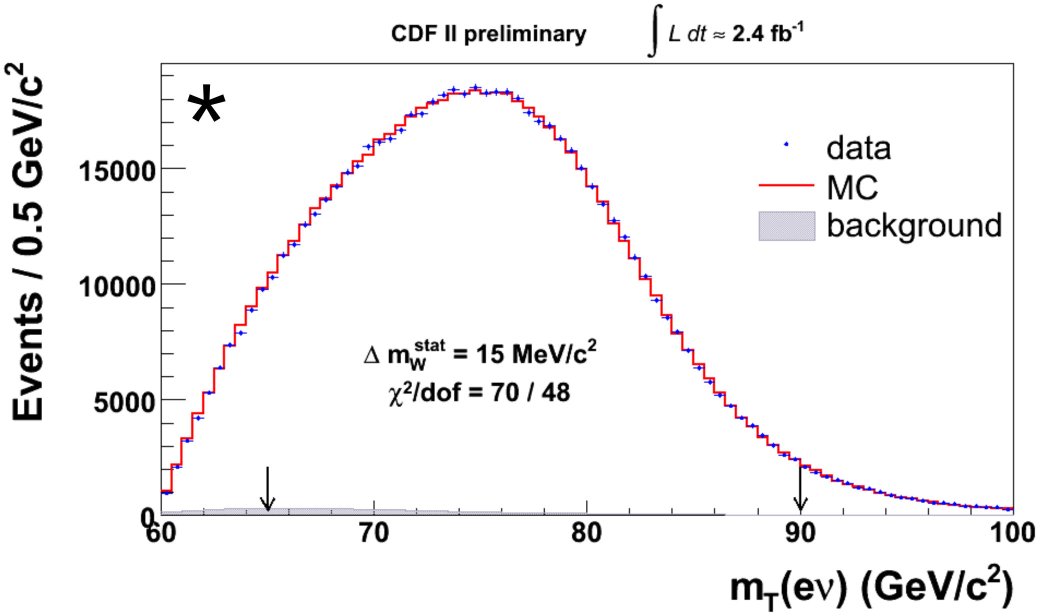
W (leptonic) selection
exactly one charged lepton
energy imbalance in reconstructed event, associated with neutrino (MET)

Z (leptonic) selection
2 oppositely-charged leptons
invariant mass consistent with m_Z

W Mass Measurement

PRL **103**, 141801 (2009)





1.0 /fb (electron)

m_T, electron p_T, MET combined

m_W (GeV/c^2):
80.401 ± 0.021 (stat) ± 0.038 (syst)

Most precise single W mass measurement

0.2 /fb (electon + muon)

m_T, electron p_T, MET combined

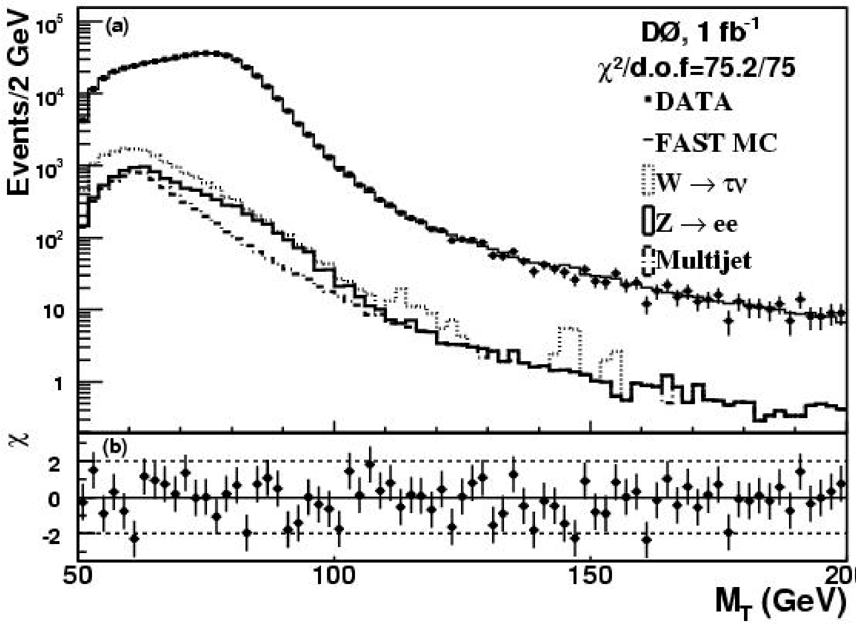
m_W (GeV/c^2):
80.413 ± 0.034 (stat) ± 0.034 (syst)

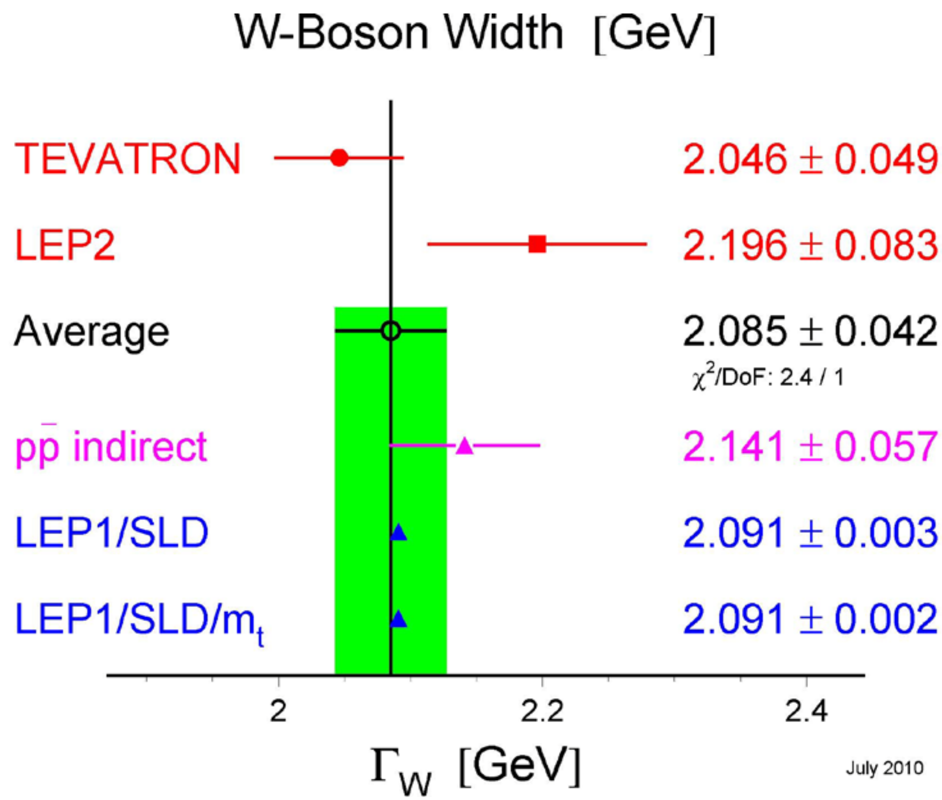
*** 2.4 /fb** (electron) + **2.3 /fb** (muon)

3 × smaller Δm_Z (stat)

W Width Measurement

PRL **103**, 231802 (2009)





Γ_W from m_T (GeV):
2.028 ± 0.039 (stat) ± 0.061 (syst)