Recent Electroweak Results from Tevatron

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For the CDF and DØ Collaborations

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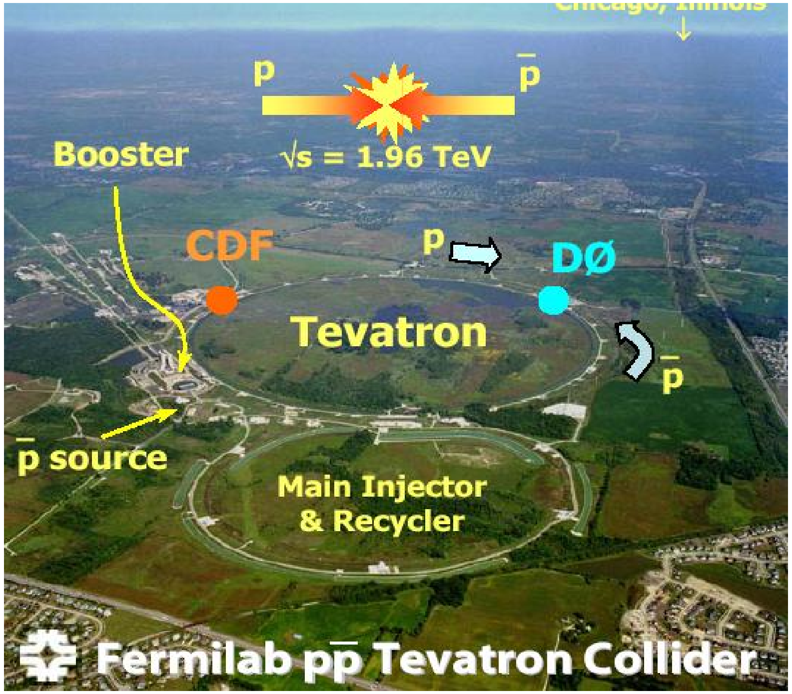
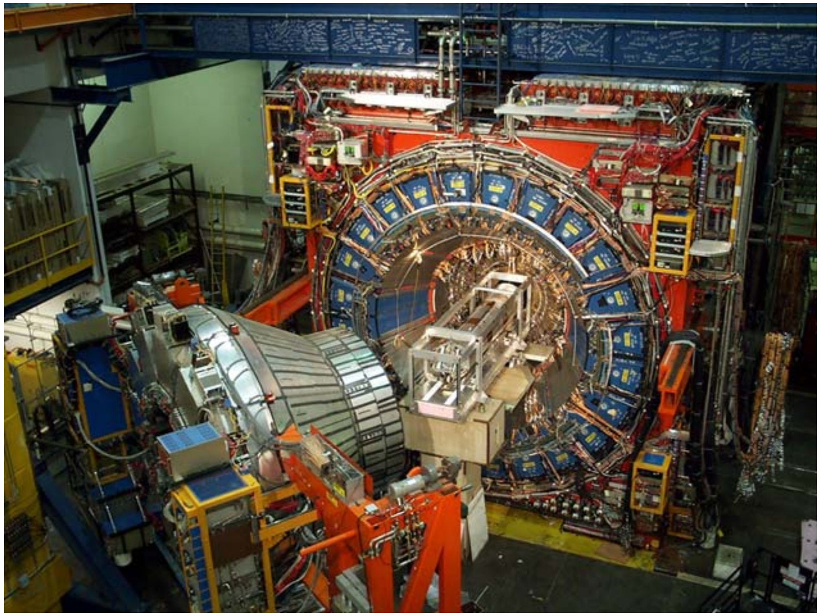
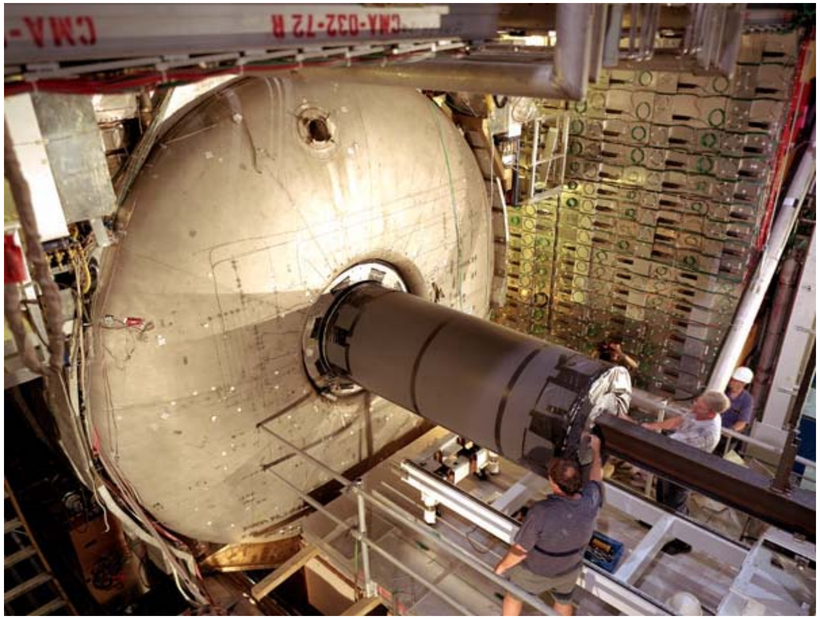
Tevatron, CDF and DØ







- **Vector boson factory:**
  - Rate/week (L ~ 30 pb^{-1})
  - ~700,000 W
  - ~150,000 Z
  - ~400 WW, ~120 WZ, ~50 ZZ, …
- **All physics results:**
  - CDF: http://www-cdf.fnal.gov/physics/physics.html
  - DØ: http://www-d0.fnal.gov/Run2Physics/WWW/results.htm

Electroweak Results 2007

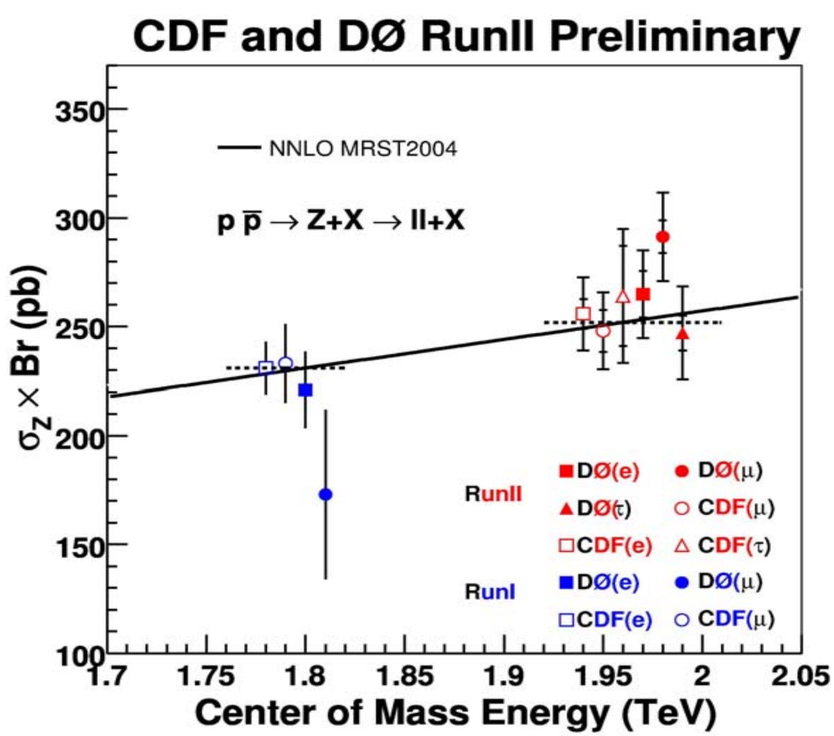
- ***Single W and Z boson production:***
  - Z $\rightarrow \tau\tau$ inclusive cross section (DØ, 1 fb^{-1})
  - Z boson rapidity ($d\sigma/dy$) (CDF 1.1 fb^{-1}, DØ 0.4 fb^{-1})
  - Z boson pT ($d\sigma/dp_T$) (DØ 1 fb^{-1})
  - W charge asymmetry (CDF 1 fb^{-1}, DØ 0.3 fb^{-1})
  - W mass (CDF 0.2 fb^{-1})
  - W width (CDF 0.35 fb^{-1})
- ***Diboson production:***
  - $W\gamma$ (CDF 1 fb^{-1}, DØ 1 fb^{-1})
  - $Z\gamma$ (DØ, 1 fb^{-1})
  - WZ (CDF 1.9 fb^{-1}, DØ 1 fb^{-1})
  - ZZ (CDF 1.5 fb^{-1}, DØ 1 fb^{-1})
  - WW/WZ $\rightarrow l\nu jj$ (CDF 1.2 fb^{-1})

Single W and Z boson production

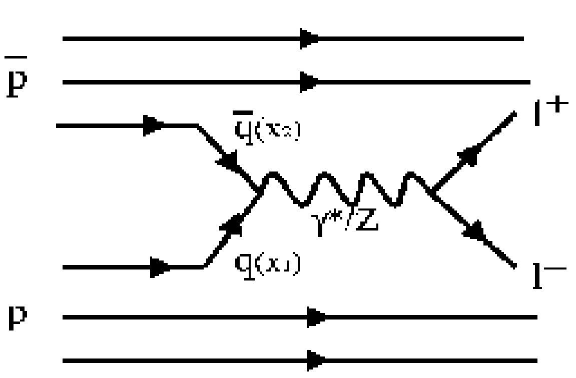
- Properties of the W and Z bosons
- Measure inclusive and differential cross sections
- Tests of SM calculations
- Constrain parton distribution functions (PDFs)

Z→ττ inclusive cross section

- DØ (1 fb^{-1}): Z→τ(→μ)τ(→hadron)
- 1527 candidates with 20% backgrounds
- **σ ($p\bar{p}$→Z)x Br (Z→ττ) = 247 ± 8(stat.) ± 13(syst.) ± 15(lumi.) pb**
- **Consistent with SM prediction $251.9^{+5}_{-11.8}$ pb**
- **Experimentally important for all τ studies such as H→ττ search**

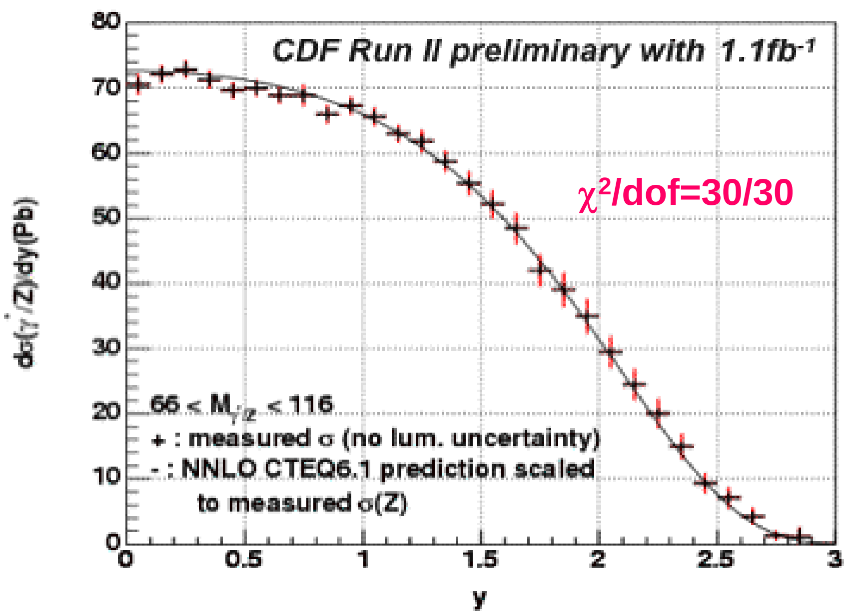


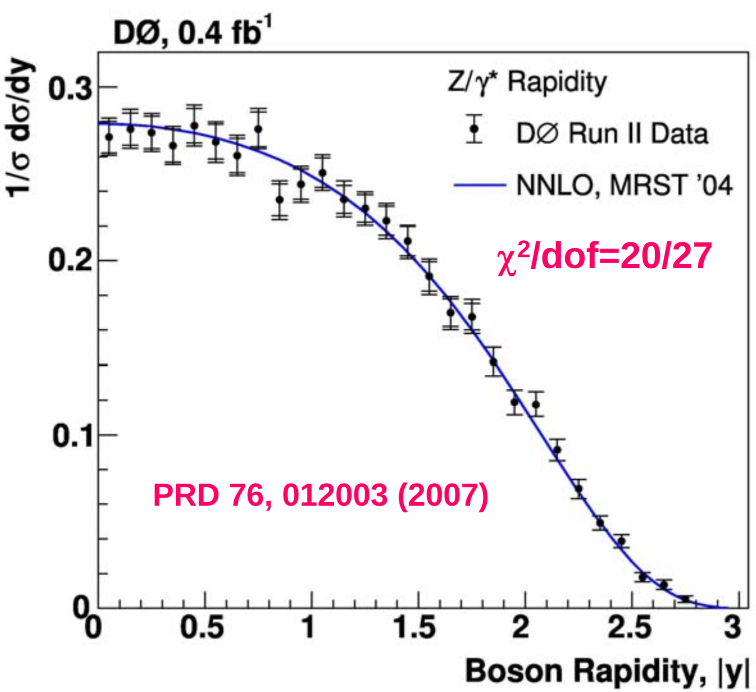
Z boson rapidity (dσ/dy)



- Provides a stringent test of QCD
- Both CDF and DØ results agree well with the NNLO predictions (Anastasiou et.al. PRD 69, 094008 (2004))
- More data needed in order to be sensitive to PDFs

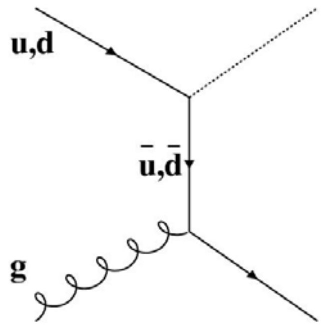
Z boson rapidity and the parton momenta: $x_{1,2} = \frac{M_Z}{\sqrt{s}} e^{\pm y}$



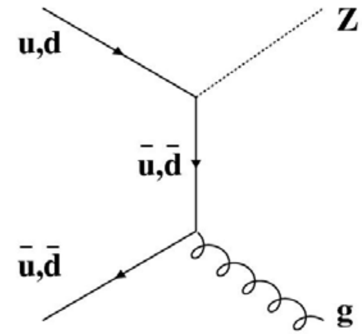


Z boson transverse momentum ($d\sigma/dp_T$)

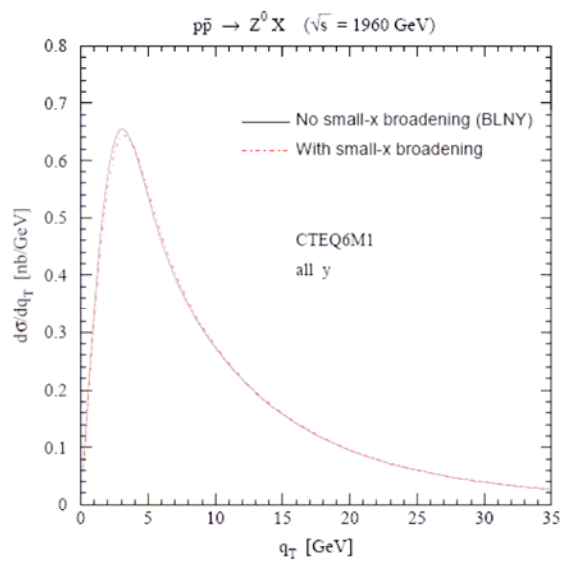
- pT(Z)=0 @ LO
- pT(Z)≠0 @ NLO
- Increased qg and gg contributions can broaden Z boson pT spectrum
- Process involving small-Bjorken-x parton(s), resummation form factor needs to be modified → "small-x broadening effect"
- This effect only shows up for Zs with |y|>2 (0.002<x<0.006)
- Expected to be more pronounced at LHC

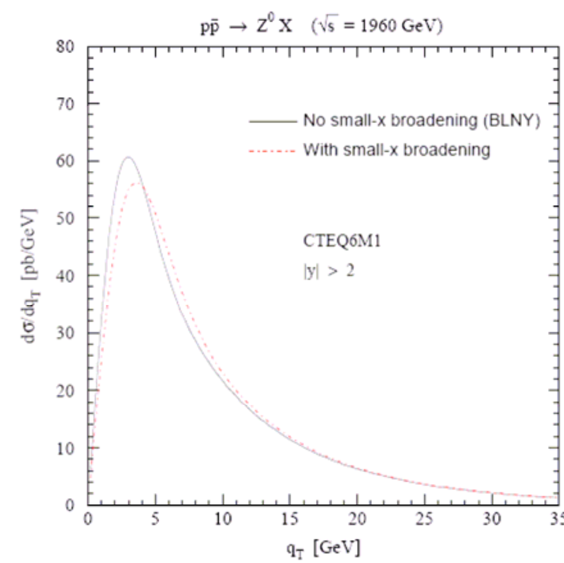


Emission of single high pT parton
Dominated at high pT (pT>50 GeV)
Perturbative QCD calculation



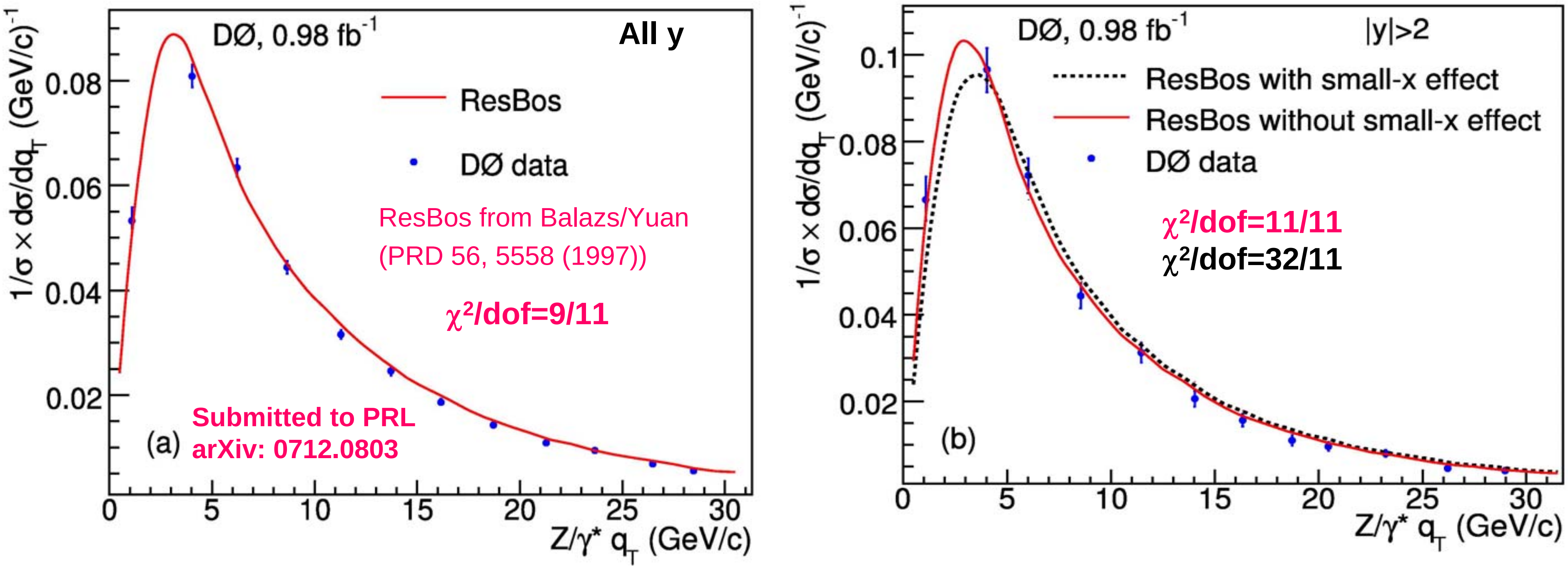
Emission of multiple soft gluons
Dominated at low pT (pT<30 GeV)
Gluon resummation calculation





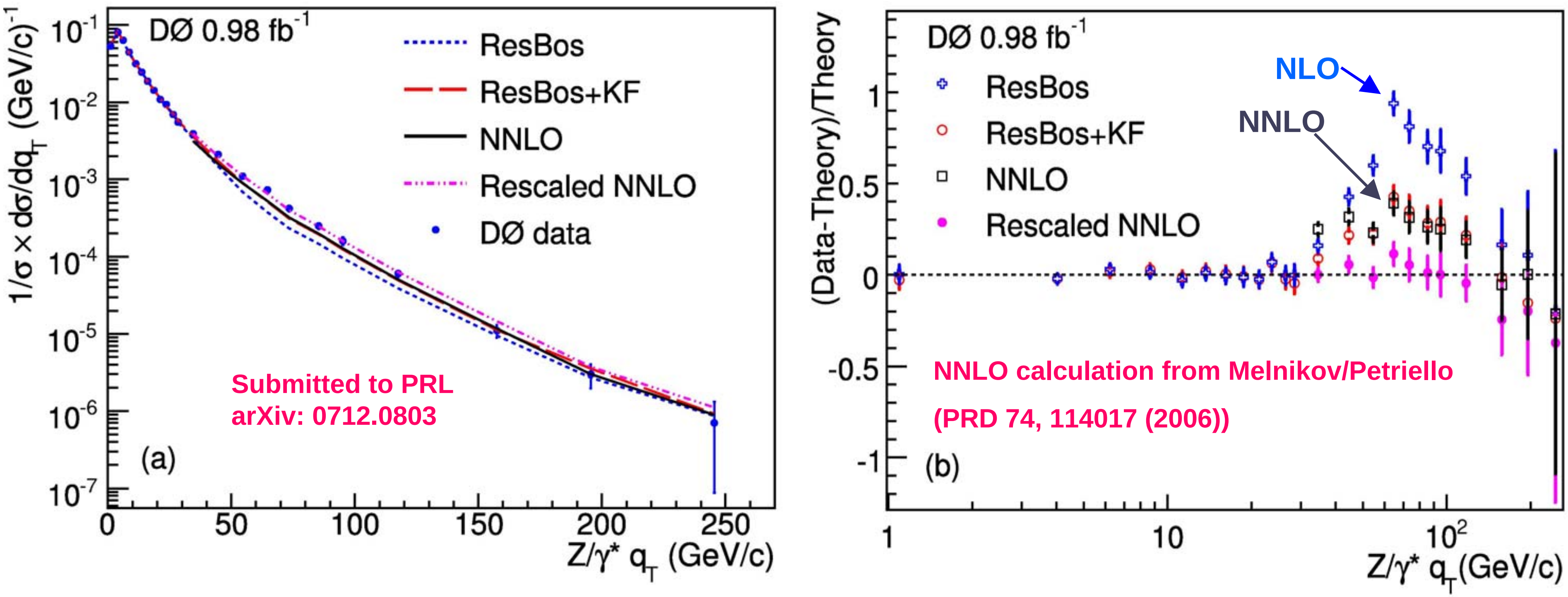
Berge et.al. PRD 72, 033015 (2005)

Z boson pT spectrum for low pT region



- Gluon resummation calculations work well for Zs in all rapidity regions
- First measurement of Z boson pT spectrum for |y|>2 at Tevatron
- First test of “small-x broadening effect” using high rapidity Zs
- Our data prefers the traditional calculation without small-x effect included

Z boson pT spectrum for high pT region



- Normalized differential cross section ($1/\sigma \times d\sigma/dp_T$) for pT<260 GeV
- Highest center-of-mass energy measurement of Z pT over the largest phase space available to date
- Overall uncertainties greatly improved compared with DØ Run I measurement
- Disagreement of the data and NNLO calculations for pT > 30 GeV
- The NNLO calculation agrees in shape with the data

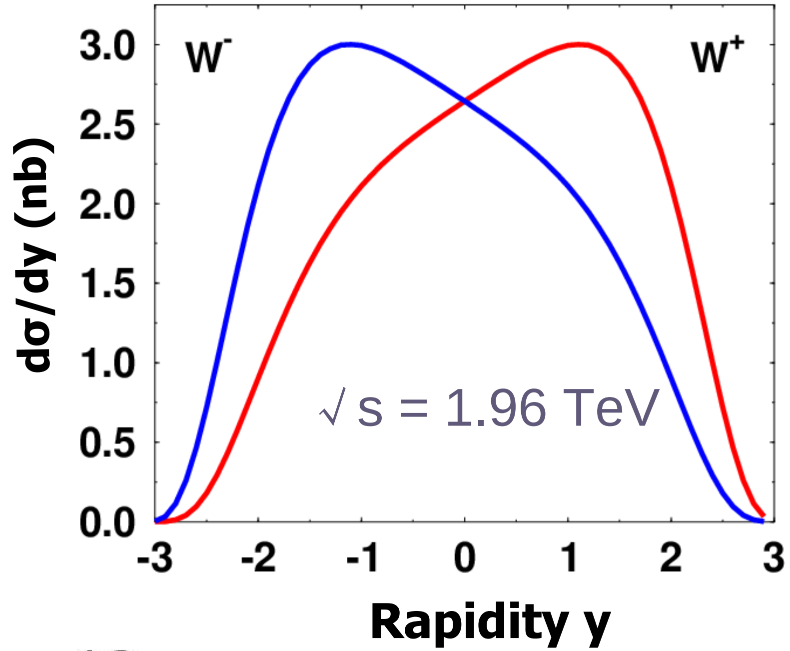
W charge asymmetry

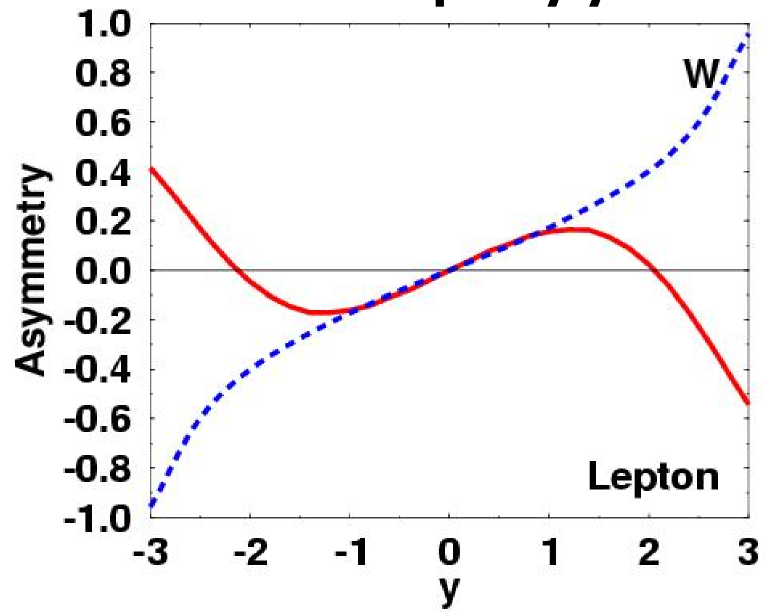
- $u + \bar{d} \rightarrow W^+$ $\bar{u} + d \rightarrow W^-$
- u quarks typically carry more of a proton's momentum than d quarks
- Use W's to probe the proton structure

$$A(y) = \frac{d\sigma(W^+)/dy - d\sigma(W^-)/dy}{d\sigma(W^+)/dy + d\sigma(W^-)/dy}$$

- A(y) sensitive to u(x)/d(x)
- $W \rightarrow l\nu \Rightarrow$ A(y) difficult to measure
- Lepton charge asymmetry: convolution of W asymmetry and V-A interaction from W decay

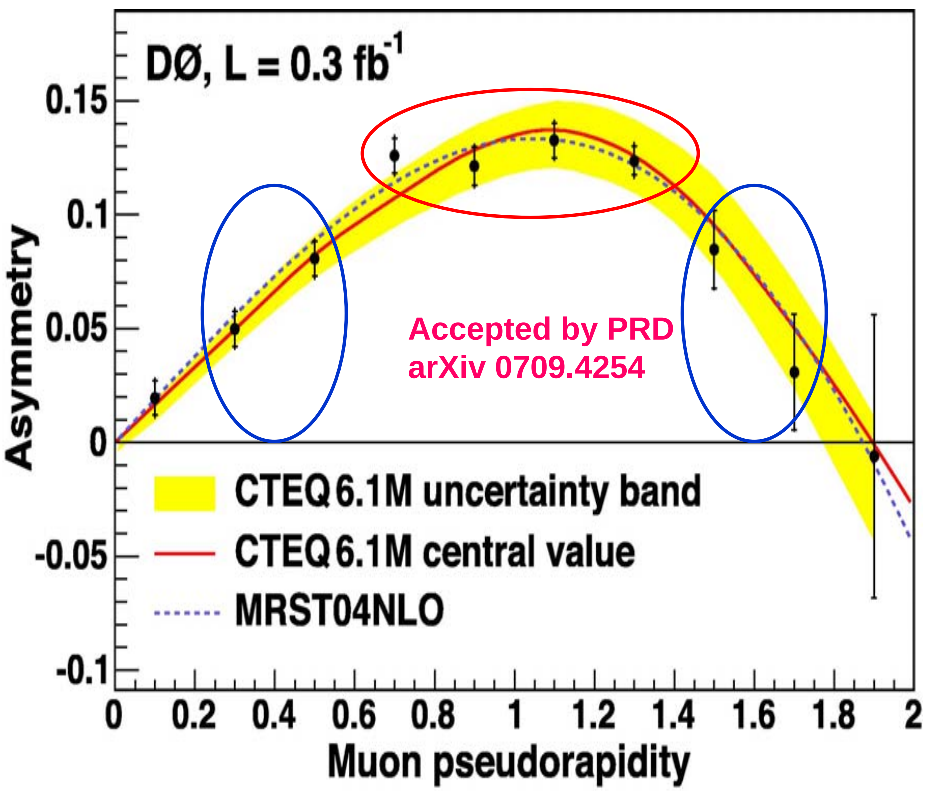
$$A(\eta_l) = \frac{d\sigma(l^+)/d\eta - d\sigma(l^-)/d\eta}{d\sigma(l^+)/d\eta + d\sigma(l^-)/d\eta}$$



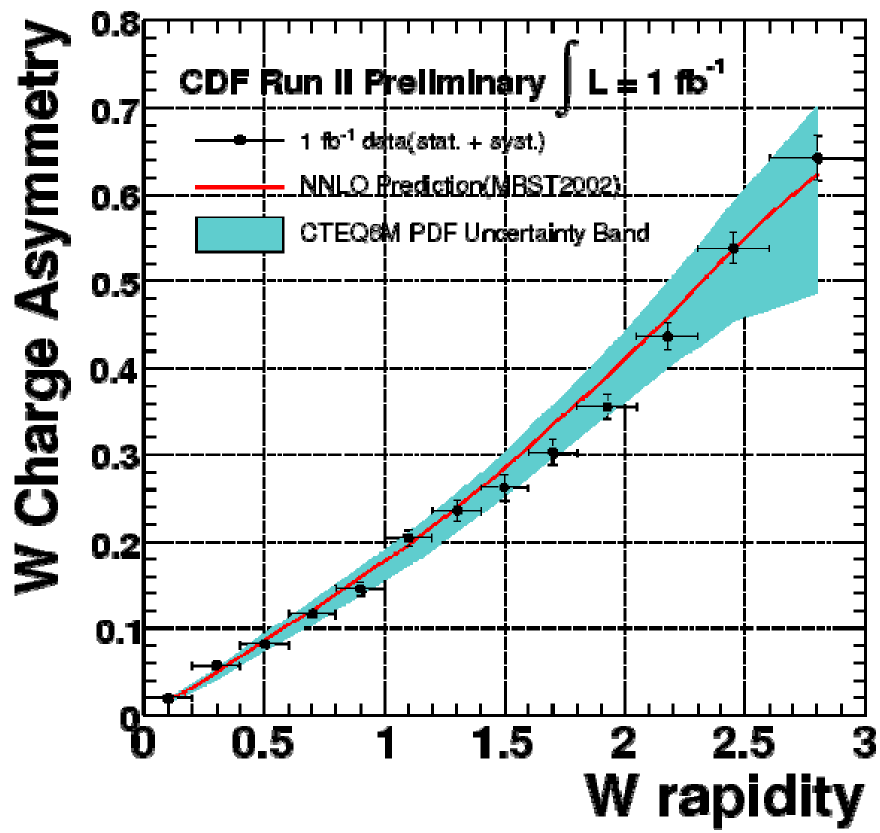


Lepton and W charge asymmetry

- DØ, W → μν: muon charge asymmetry
- Experimental uncertainties are already smaller than or comparable with the CTEQ uncertainties in some regions



- CDF, W → eν: W charge asymmetry
- Reconstruct y_W distribution using W mass constraint
- Weight the two solutions by taking W boson production and decay into account

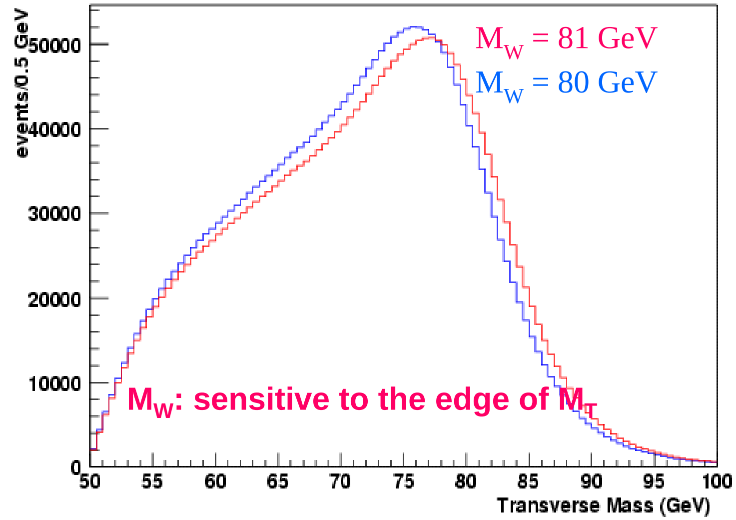


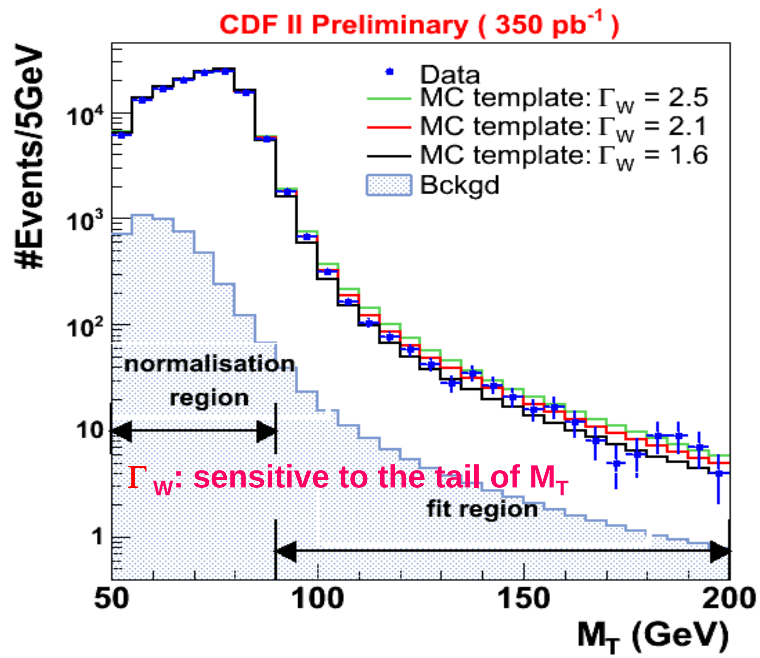
W Mass and Width

- CDF: $W \to e\nu$ and $W \to \mu\nu$ using M_T spectrum

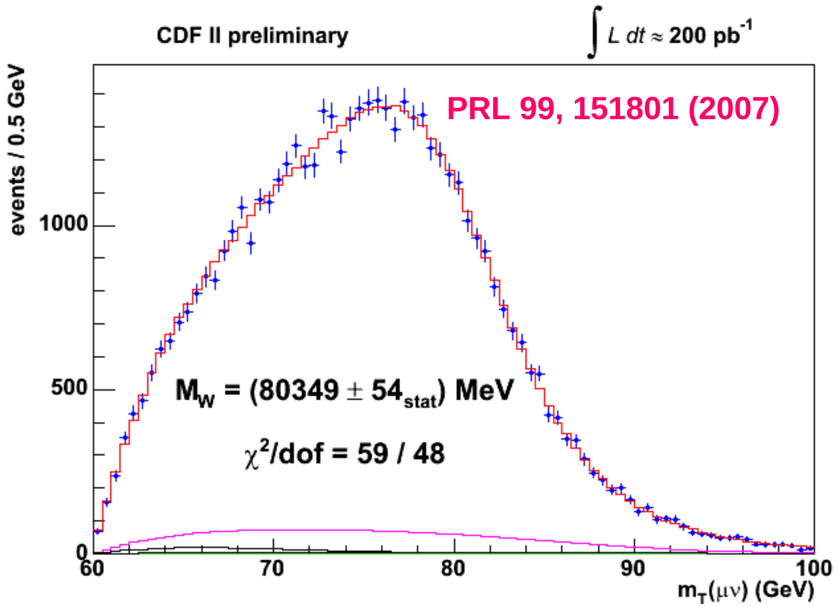
$$M_T = \sqrt{2 p_T^{\,l} p_T^{\,\nu} (1 - \cos\phi_{l\nu})}$$

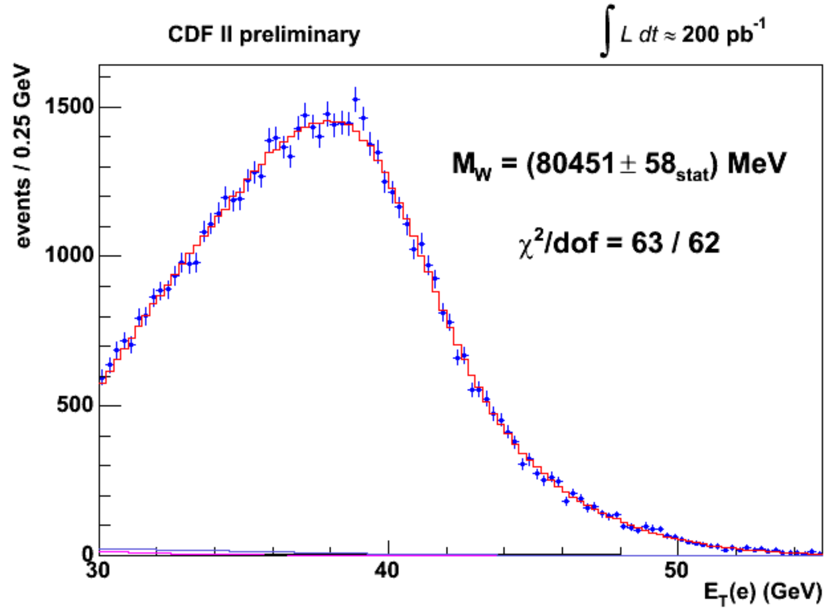
- Simulate $M_T(e\nu/\ \mu\nu)$ distribution with a *fast* parameterized MC
  - MC simulates QCD and QED corrections
  - Utilize real data to calibrate the detector response to lepton and recoil system, parameterize the responses in fast MC
- Fit M_T templates (with W mass and width varying) to the data
- Good understanding of the lepton and recoil system is the key:
  - Muon momentum scale and resolution ($J/\psi, \Upsilon$, $Z \to \mu\mu$ resonances)
  - Electron energy scale and resolution (E/p in $W \to e\nu$ and $Z \to ee$ resonance)
  - Recoil system response ($Z \to ee$ and $Z \to \mu\mu$)

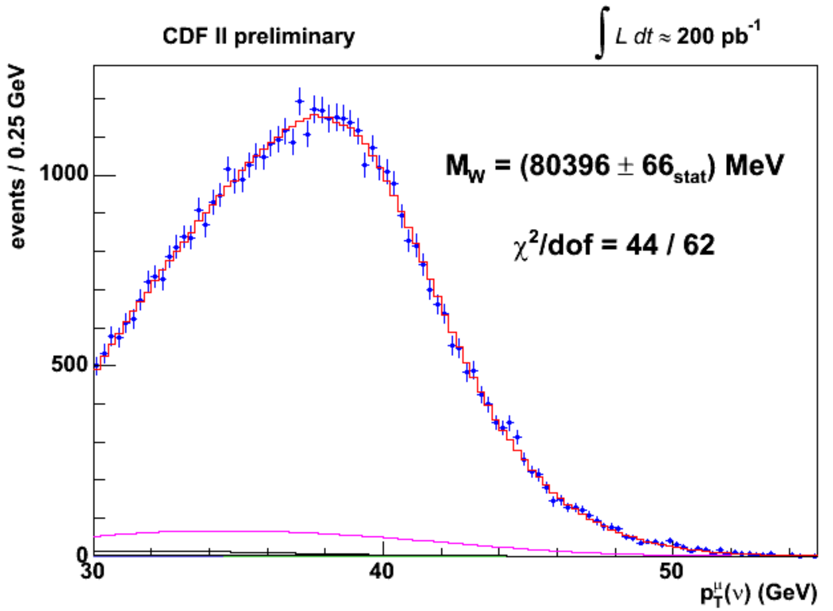




W Mass







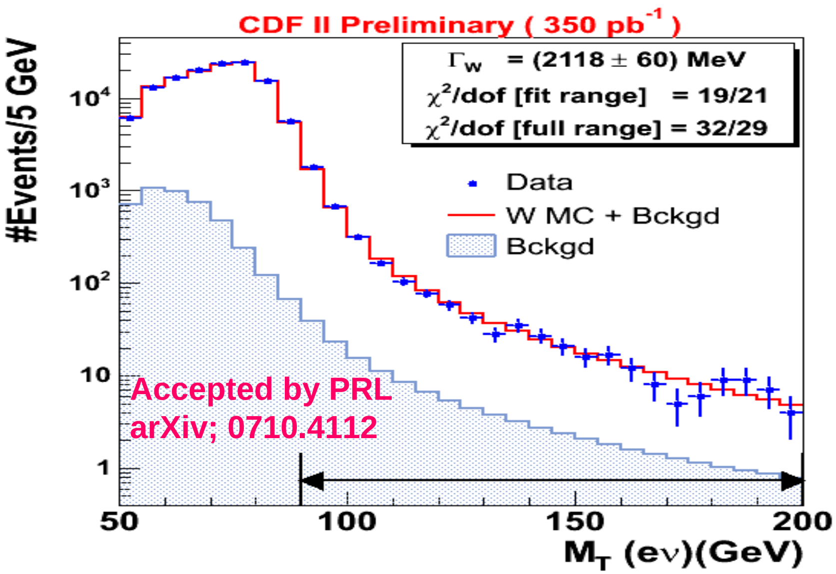
M_W = 80413±48 MeV (0.06%)

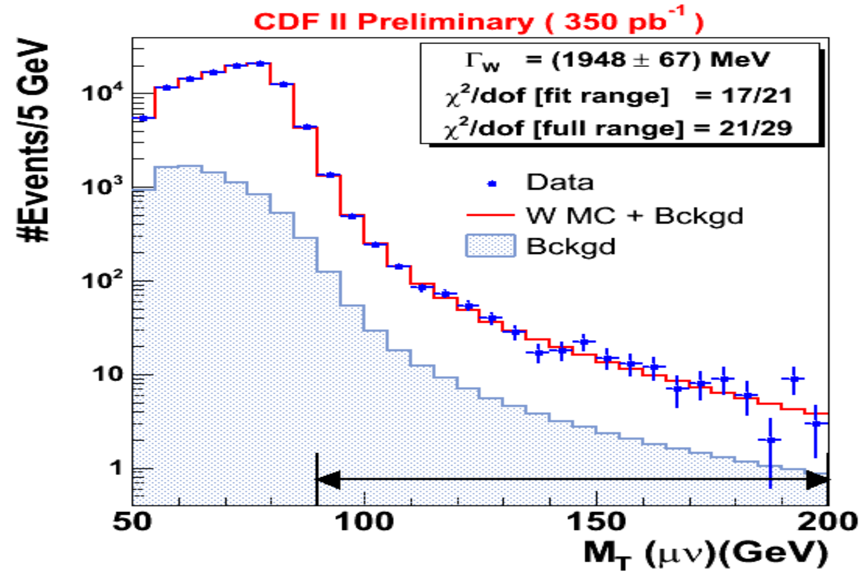
Single most precise measurement to date!

CDF II preliminary $L = 200\ pb^{-1}$

m_T Uncertainty [MeV]	Electrons	Muons	Common
Lepton Scale	30	17	17
Lepton Resolution	9	3	0
Recoil Scale	9	9	9
Recoil Resolution	7	7	7
$u_{\parallel}$ Efficiency	3	1	0
Lepton Removal	8	5	5
Backgrounds	8	9	0
$p_T(W)$	3	3	3
PDF	11	11	11
QED	11	12	11
Total Systematic	39	27	26
Statistical	48	54	0
Total	62	60	26

W Width





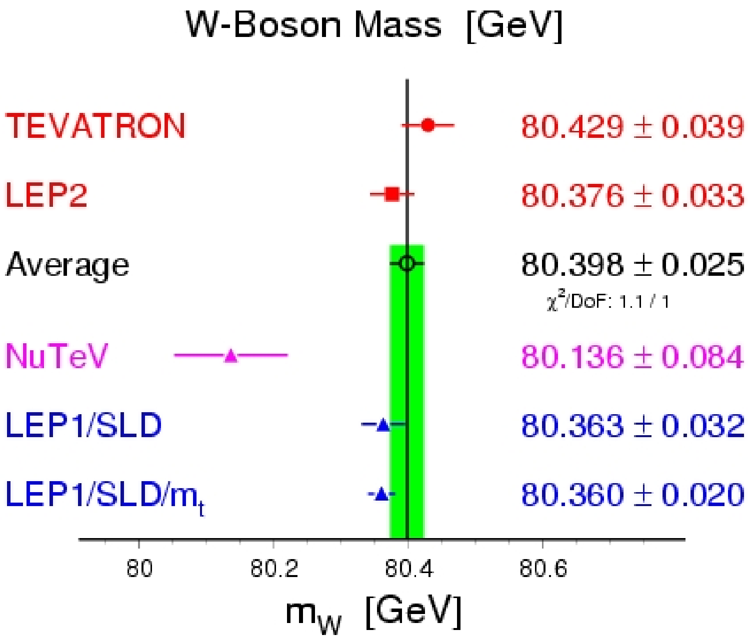
- CDF, 350 pb^{-1}, e + μ channel:

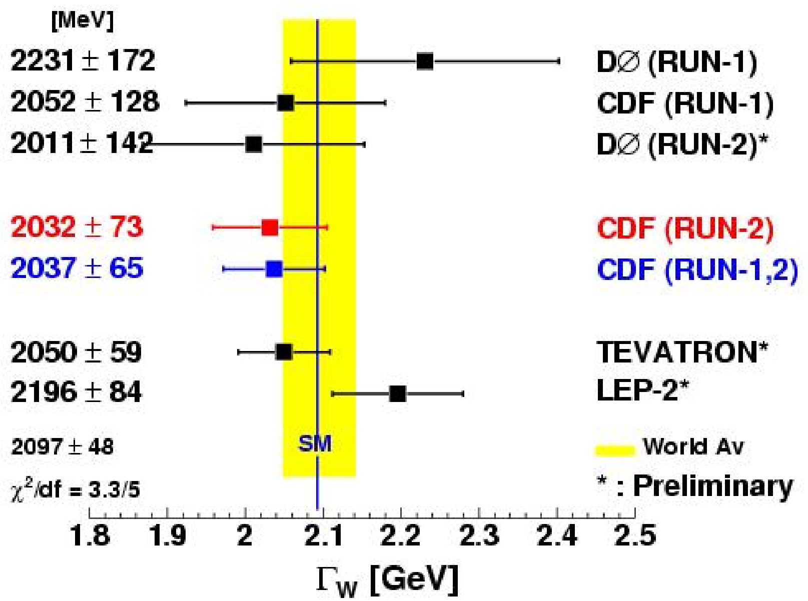
Γ_W = 2032 ± 73 (stat + syst) MeV

Most precise single direct measurement!

	$\Delta\Gamma_W$ [MeV]		
	Electrons	Muons	Common
Lepton Scale	21	17	12
Lepton Resolution	31	26	-
Simulation	13	-	-
Recoil	54	49	-
Lepton ID	10	7	-
Backgrounds	32	33	-
p_T(W)	7	7	7
PDF	20	20	20
QED	10	6	6
W mass	9	9	9
Total systematic	79	71	27
Statistical	60	67	-
Total	99	98	27

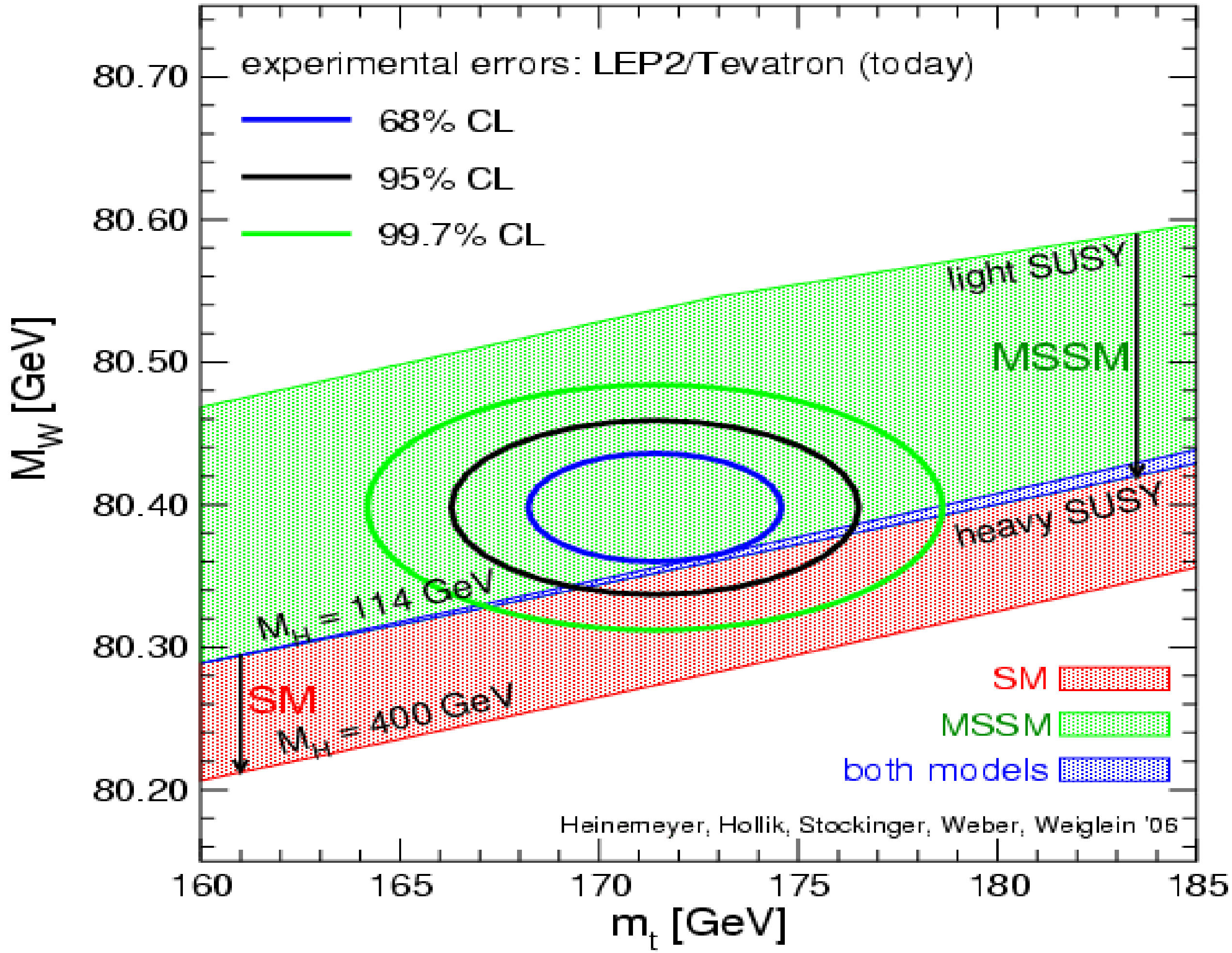
Summary for M_W and Γ_W





- World average uncertainty for M_W reduced by 15%: **29 → 25 MeV**
- World average uncertainty for Γ_W reduced by 22%: **60 → 47 MeV**
- **The Tevatron has now the best measurement of Γ_W**
- **May soon surpass the combined precision of the LEP2 experiments on M_W**
- **By the end of Run II, M_W from Tevatron is expected be known better than 25 MeV**

Effects on SM Higgs mass



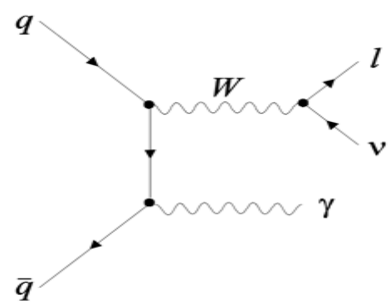
- **Constraint on SM Higgs mass:** $m_H = 76^{+33}_{-24}\,\mathrm{GeV}$ **(< 144 GeV at 95% C.L.)**
- Expect a light SM Higgs

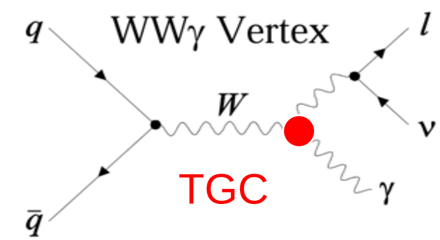
Diboson production

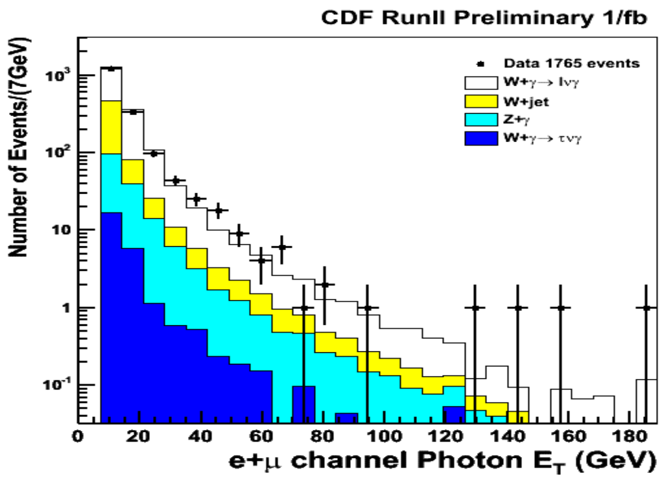
- Measure cross sections
- Probe gauge boson self-interactions
  - consequence of non-Abelian nature of $SU(2)_L \times U(1)_Y$
- Sensitive to new physics in TGC (trilinear gauge couplings)
  - Tevatron complementary to LEP
  - Explores higher center-of-mass energy than LEP
  - Different combinations of couplings
- Backgrounds to Higgs, top, SUSY

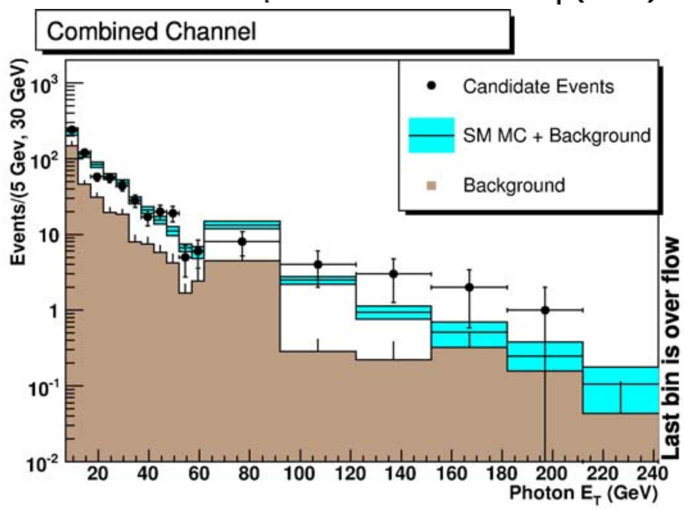
Wγ production

- Sensitive to WWγ coupling
- Variation in Wγ production would be sign of new physics
- Particularly high Pt photons







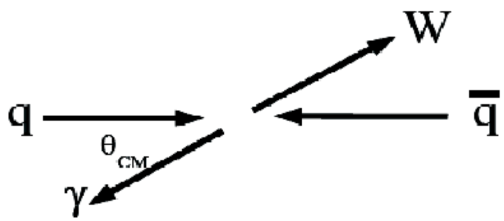


- DØ preliminary $M_T(l\nu\gamma) > 90$ GeV
  μ channel: $\sigma(W \to \mu\nu\gamma) = 3.21 \pm 0.52$ pb
  e channel: $\sigma(W \to e\nu\gamma) = 3.12 \pm 0.42$ pb
  theory: $\sigma(W \to l\nu\gamma) = 3.21 \pm 0.08$ pb

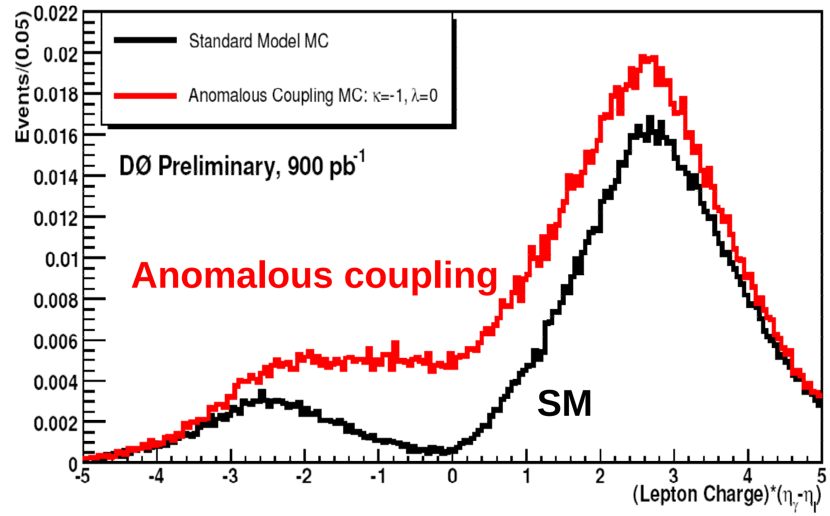
- CDF preliminary $30 < M_T(l\nu) < 120$ GeV:
  e + μ channel: $\sigma(W \to l\nu\gamma) = 18.03 \pm 2.83$ pb
  theory: $\sigma(W \to l\nu\gamma) = 19.3 \pm 1.4$ pb

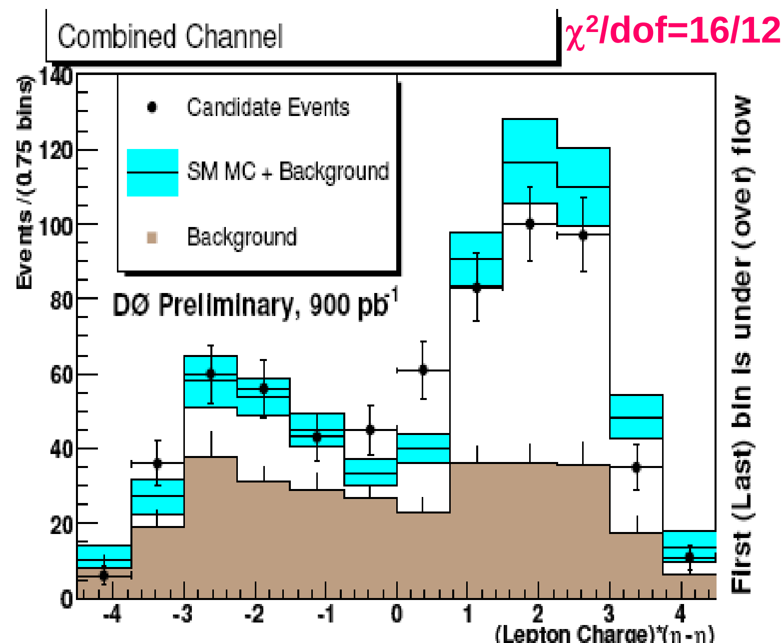
Wγ: Radiation Amplitude Zero

- Radiation amplitude zero: caused by the interference among the tree-level diagrams at $\cos(\theta^*) = \pm 1/3$
- θ^* is the angle between the W and the direction of the incoming quark



- Measure charge-sign photon-lepton rapidity difference $Q \times [\eta(\gamma) - \eta(l)]$, not θ^*
- Test of the SM gauge structure: anomalous WWγ couplings can fill in the dip
- The probability of the dip is found to be in the range of 80% - 90%
- First indication of RAZ in Wγ events at DØ



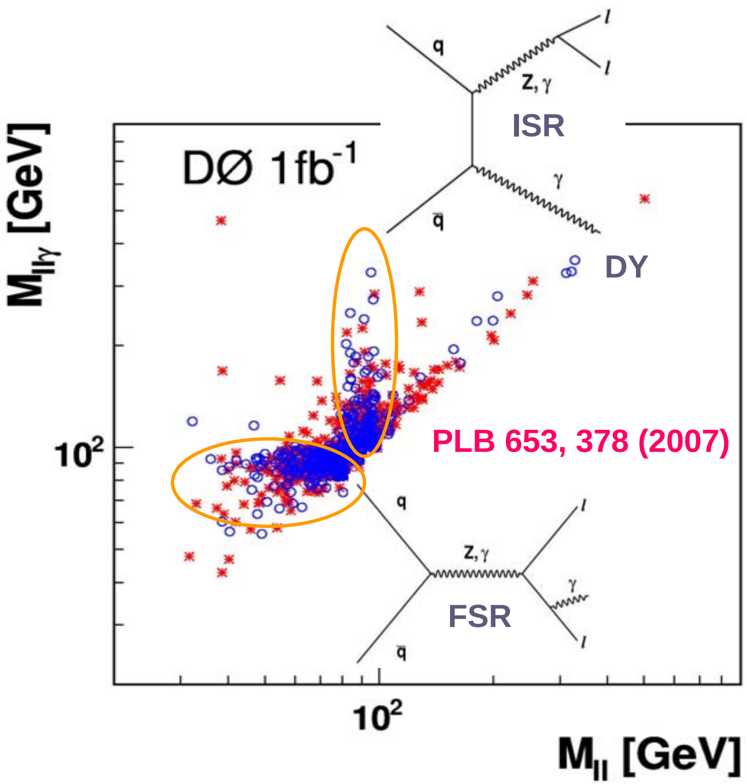


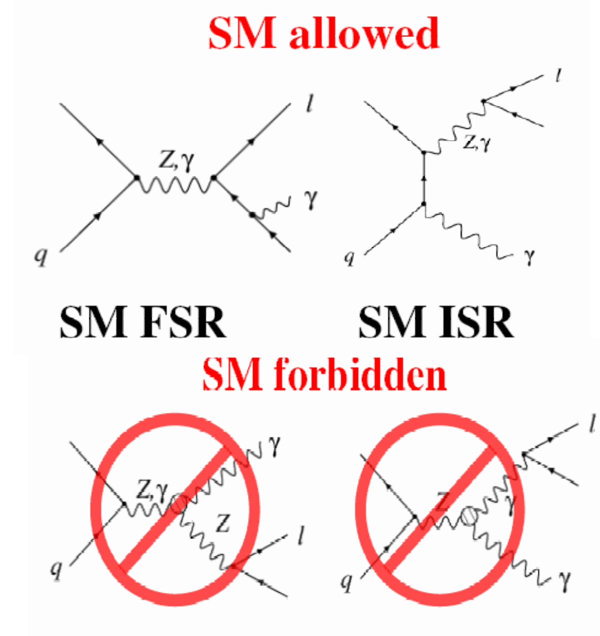
Zγ production

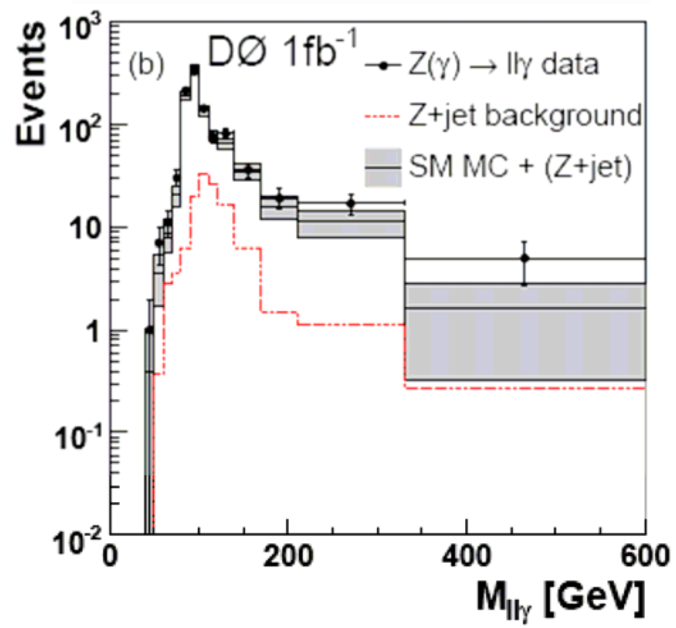
- 968 candidates with 116 ±13 backgrounds
- Cross section for $Z\gamma \rightarrow ll\gamma$ with photon E_T>7GeV, $\Delta R(l\gamma)$>0.9, $M(ll)$ >30 GeV

Measured: $\sigma(Z\gamma \rightarrow l\nu\gamma) = 4.96 \pm 0.42$ pb

Theory: $\sigma(Z\gamma \rightarrow l\nu\gamma) = 4.74 \pm 0.22$ pb

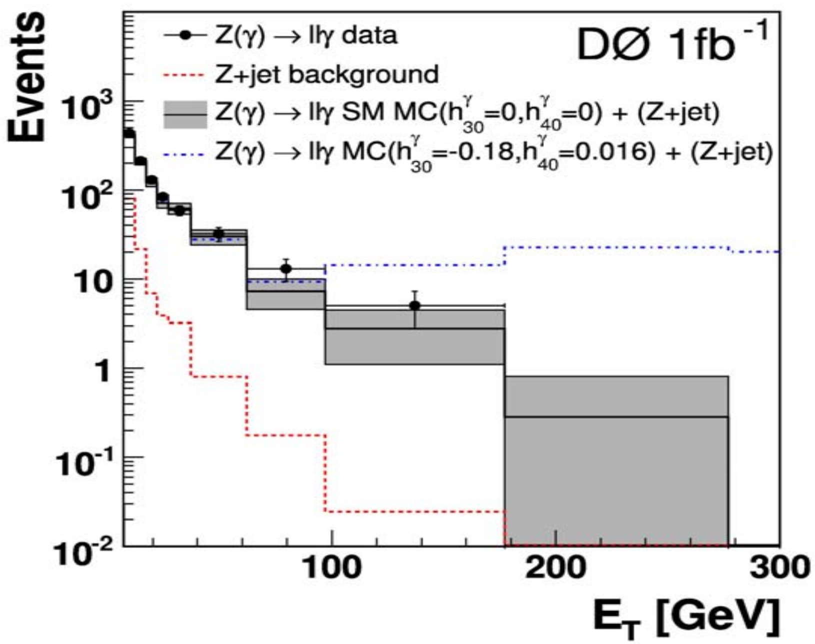




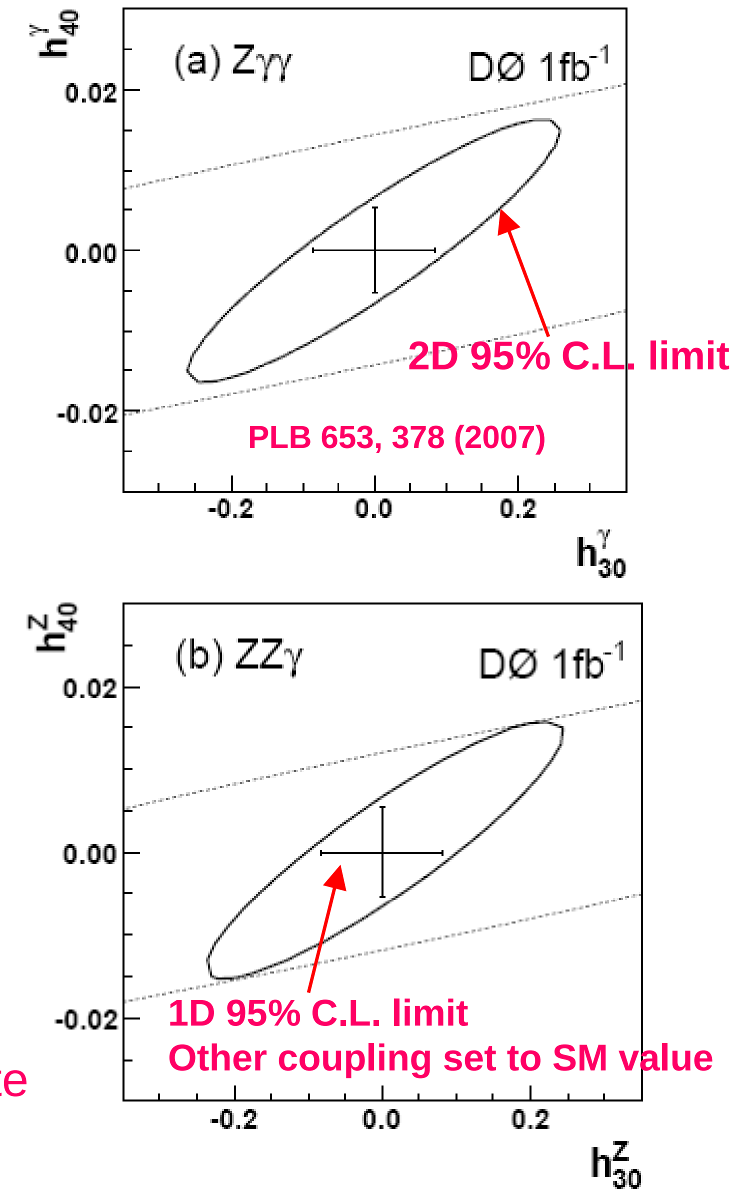


Limits on anomalous ZZγ and Zγγ couplings

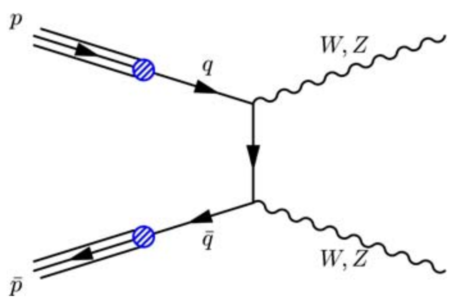
- Various SM extentions predict large values of the trilinear couplings of ZZγ and Zγγ
- Use photon E_T spectrum to set limits on anomalous ZZγ and Zγγ couplings

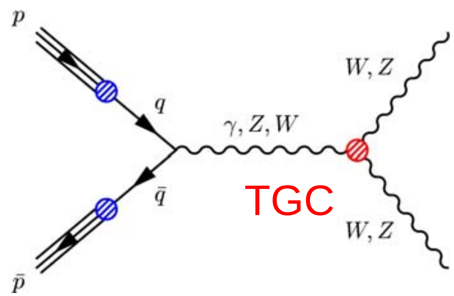


- These new limits represent a significant improvement over previous results
- The limits on $h_{40}(V)$ are the most stringent to date

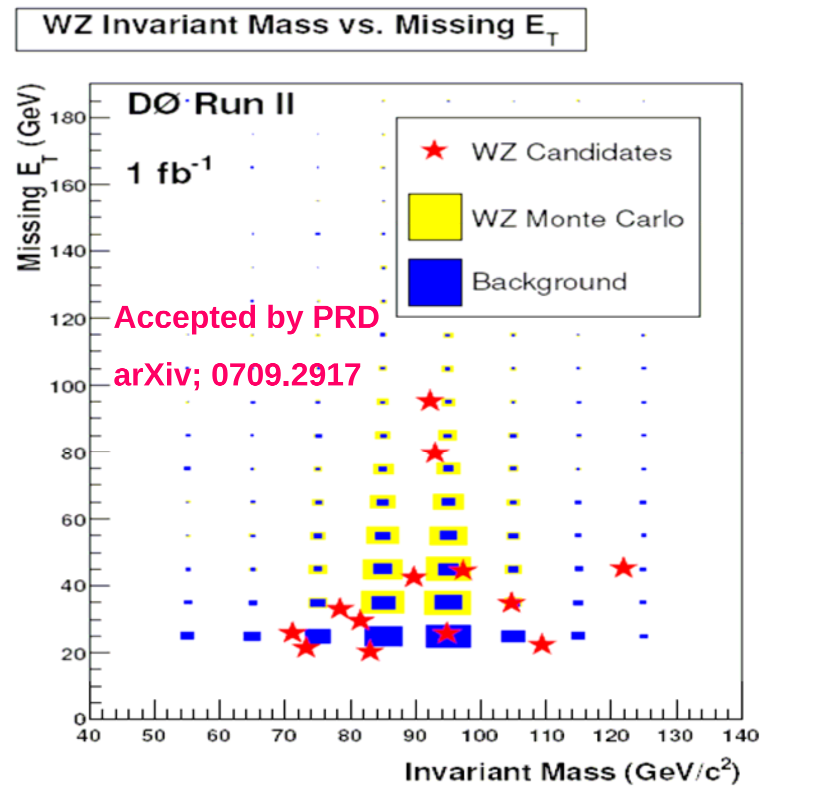


Evidence for WZ





NLO: $\sigma = 3.7 \pm 0.1$ pb

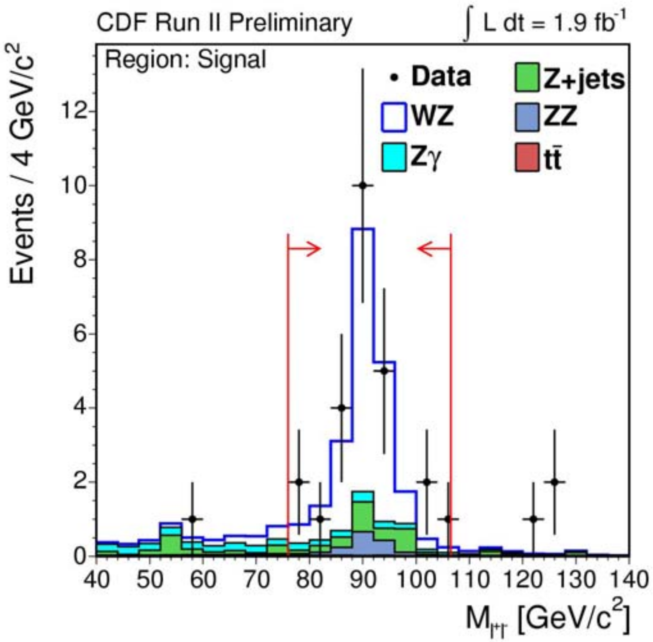


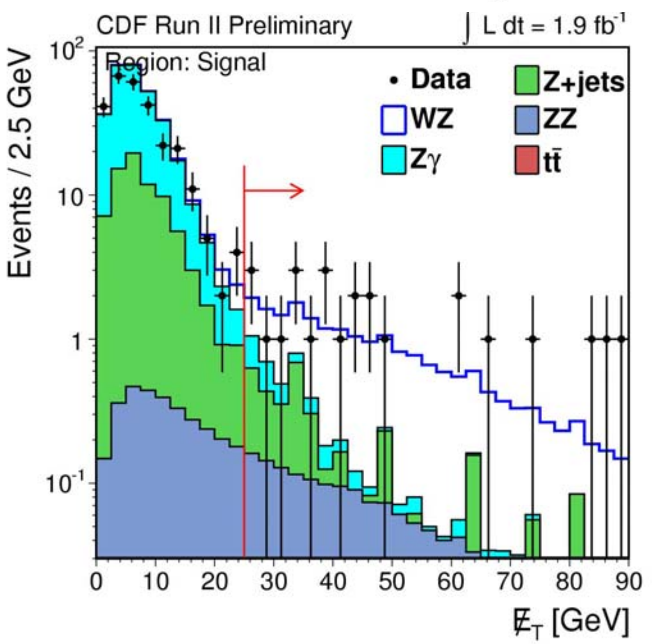
- Unique sensitivity to WWZ coupling
- Final state with 3 e/μ and met
- DØ observed 13 candidates with 4.5 bkgs
- 3 σ significance
- Measured cross section:

$$\sigma(\mathrm{WZ}) = 2.7^{+1.7}_{-1.3}\,\mathrm{pb}$$

Final State	Number of Candidate Events	Expected Signal Events	Estimated Background Events	Overall Efficiency
eee	2	2.3 ± 0.2	1.2 ± 0.1	0.16 ± 0.02
$ee\mu$	1	2.2 ± 0.2	0.46 ± 0.03	0.17 ± 0.02
$\mu\mu e$	8	2.2 ± 0.3	2.0 ± 0.4	0.17 ± 0.03
$\mu\mu\mu$	2	2.5 ± 0.4	0.86 ± 0.06	0.21 ± 0.03
Total	13	9.2 ± 1.0	4.5 ± 0.6	–

Observation of WZ





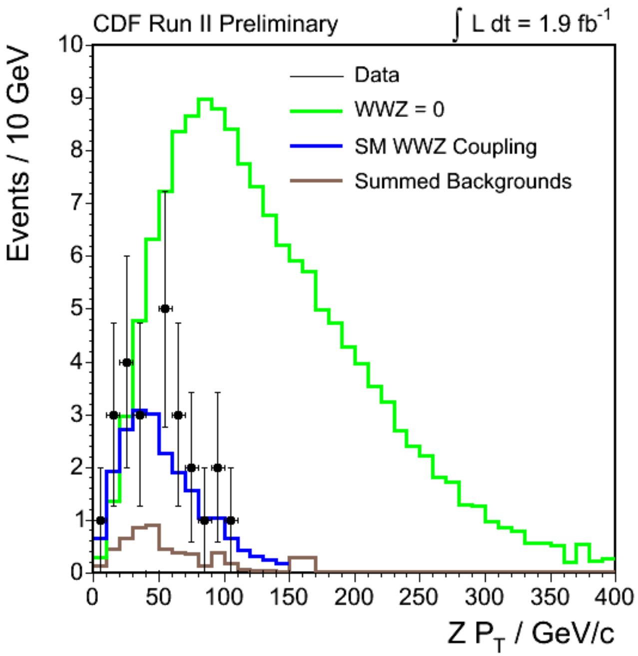
- First observation of WZ process with a 6σ significance using 1.1 fb^{-1} data (PRL 98, 161801 (2007))
- Updated this analysis using 1.9 fb^{-1} data:

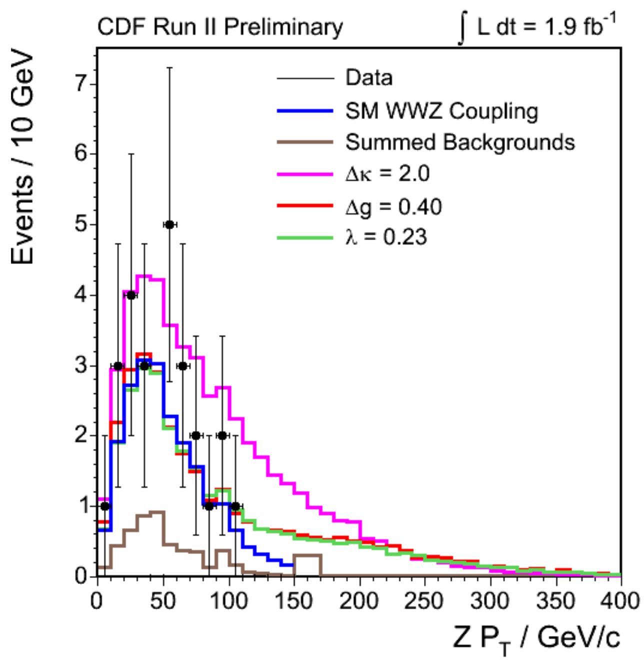
Source	Expected ± Stat ± Syst ± Lumi
Z+jets	2.45 ± 0.48 ± 0.48 ± 0.00
ZZ	1.53 ± 0.01 ± 0.16 ± 0.09
$Z\gamma$	1.03 ± 0.06 ± 0.35 ± 0.06
$t\bar{t}$	0.17 ± 0.01 ± 0.03 ± 0.01
WZ	16.45 ± 0.03 ± 1.74 ± 0.99
Total	21.63 ± 0.48 ± 2.25 ± 1.15
Observed	**25**

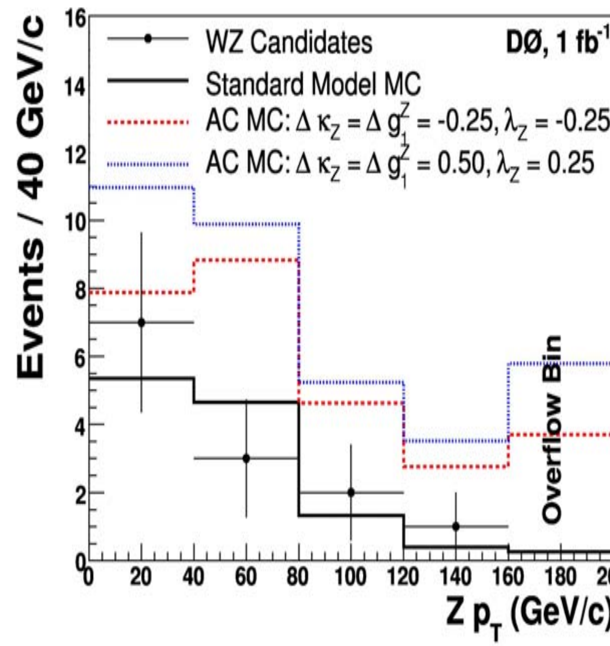
$$\sigma = 4.3^{+1.3}_{-1.0}(\text{stat}) \pm 0.4(\text{syst.}+\text{lumi.})\text{pb}$$

Limits on Anomalous WWZ couplings

- WZ production probes the WWZ coupling directly
- Z boson pT sensitive to TGC





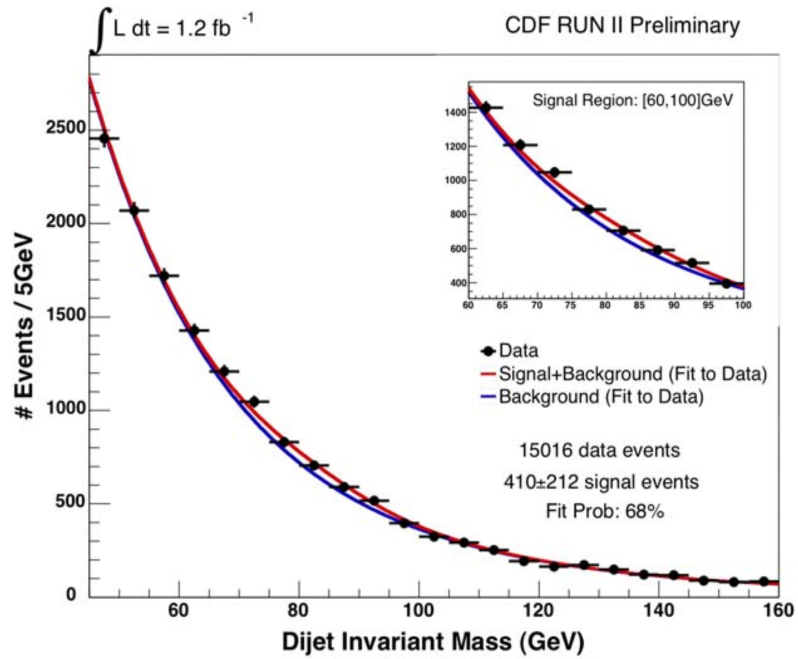


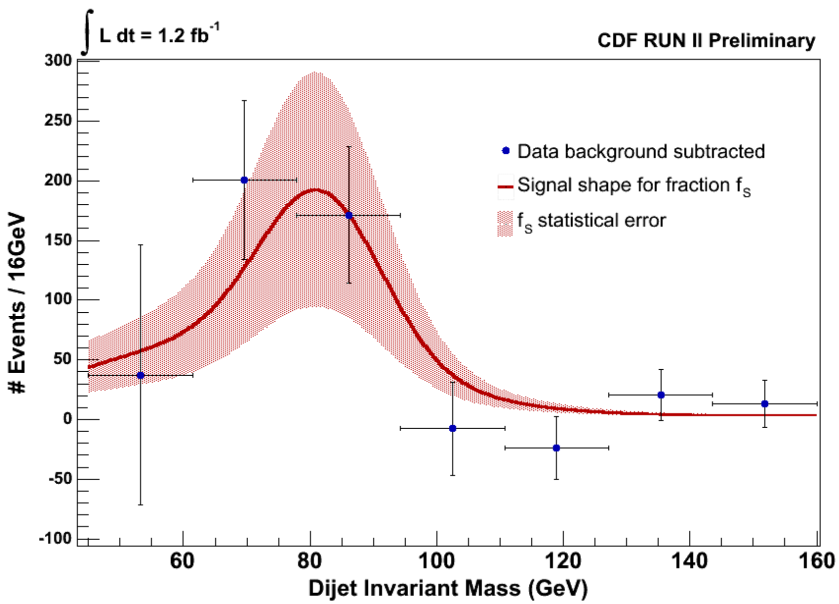
CDF	**Λ=1.5 TeV**	**Λ=2.0 TeV**	**DØ**	**Λ=1.5 TeV**	**Λ=2.0 TeV**
	$-0.14<\lambda_Z<0.16$	$-0.13<\lambda_Z<0.14$		$-0.18<\lambda_Z<0.22$	$-0.17<\lambda_Z<0.21$
	$-0.17<\Delta g_1^Z<0.27$	$-0.15<\Delta g_1^Z<0.24$		$-0.15<\Delta g_1^Z<0.35$	$-0.14<\Delta g_1^Z<0.34$
	$-0.86<\Delta\kappa_Z<1.36$	$-0.82<\Delta\kappa_Z<1.27$		$-0.14<\Delta\kappa_Z=\Delta g_1^Z<0.31$	$-0.12<\Delta\kappa_Z=\Delta g_1^Z<0.29$

best limits to date on WWZ TGC's

Search for WW/WZ→lνjj

- WW/WZ seen only in leptonic channels so far
- Topologically similar to WH
- Bkgs: W/Z+jets, QCD, etc
- S/B < 1% initially
- Use a NN to increase significance by ~30% in the signal region
- Parameterize dijet mass shapes (signal shape fixed with MC, background shape contains free parameters)
- Do an unbinned likelihood fit on data

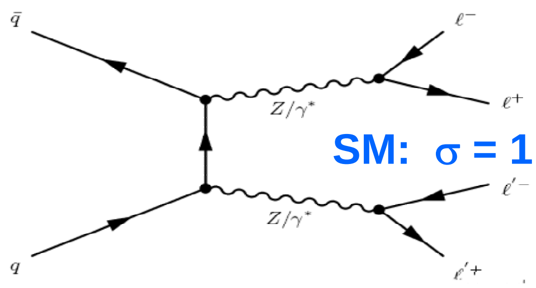




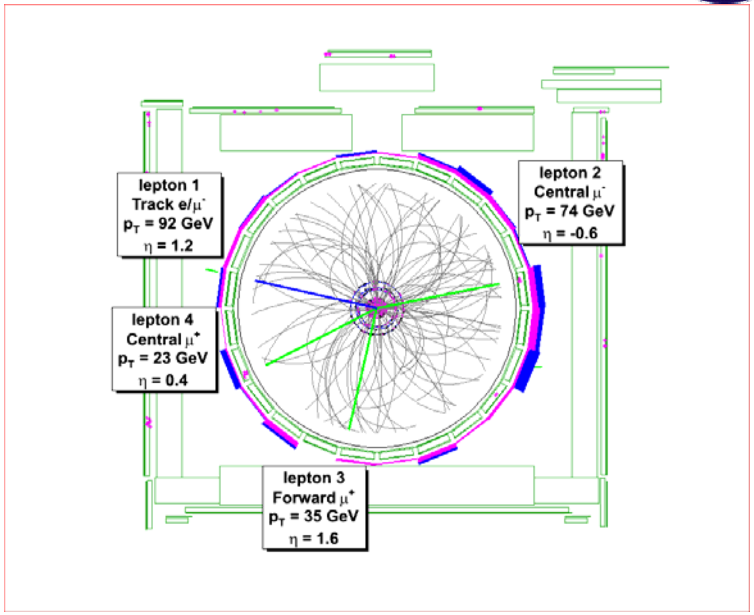
- Statistical significance of 2σ
- Measured cross section:
- $\sigma_{WW/WZ}$x Br(W→lν, W/Z→jj) = 1.47 ± 0.77(stat.) ± 0.38(syst.) pb
- Theory: $\sigma_{WW/WZ}$x Br(W→lν, W/Z→jj) = 2.1 ± 0.2 pb
- 95% CL Upper limit: σ x Br < 2.88 pb

First evidence for ZZ

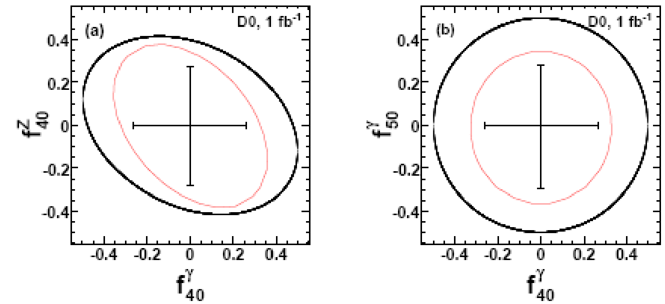
- No self coupling of Z bosons in SM
- Produced in t channel



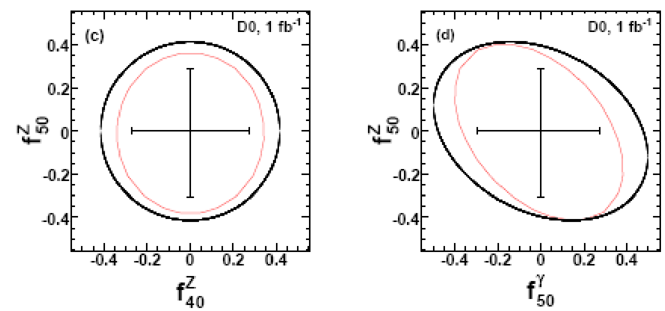
SM: $\sigma = 1.6 \pm 0.1$ pb



- ZZ → 4 charged leptons
- CDF (1.5 fb^{-1}) observed 1 event with 0.03 ± 0.02 backgrounds
  - 2.2 σ significance
- DØ (1 fb^{-1}) observed 1 event with 0.13 ± 0.03 backgrounds
  - $\sigma(ZZ/Z\gamma^*) < 4.4$ pb
  - Set limits on ZZZ and ZZγ^* couplings
  - The first bounds on these anomalous couplings from Tevatron
  - Limits on $f_{40}(Z)$, $f_{50}(Z)$ and $f_{50}(\gamma)$ are more restrictive than LEP results



Submitted to PRL arXiv: 0712.0599



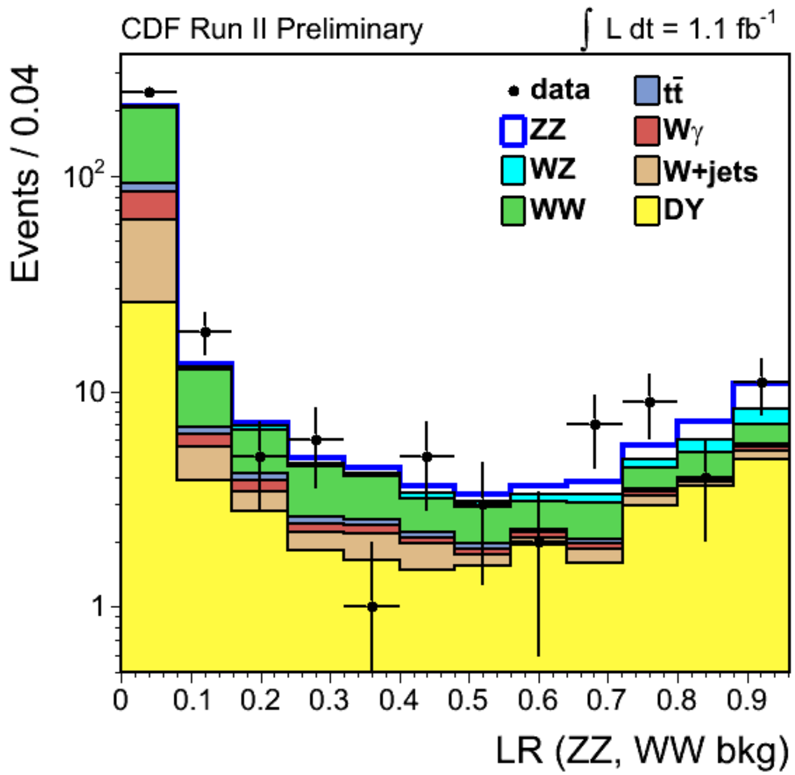
Adding the *ll*+$\nu\nu$ Channel

- CDF also looked at ZZ → 2 charged leptons+2 neutrinos
  - Larger production cross sections
  - Higher WW, DY bkgs
- Signal Extraction:
  - Use matrix element method to define event probability
  - Use event probability to define likelihood ratio (LR):

$$\mathrm{LR} = \frac{P(\mathrm{ZZ})}{P(\mathrm{ZZ}) + P(\mathrm{WW})}$$

  - Fit to extract signal
  - 1.9 σ significance
- Combination with 4 lepton channel
  - Use binned-likelihood
  - 3.0 σ combined significance

$$\sigma(\mathrm{ZZ}) = 0.75^{+0.71}_{-0.54}\,\mathrm{pb}$$



Electroweak Results 2007

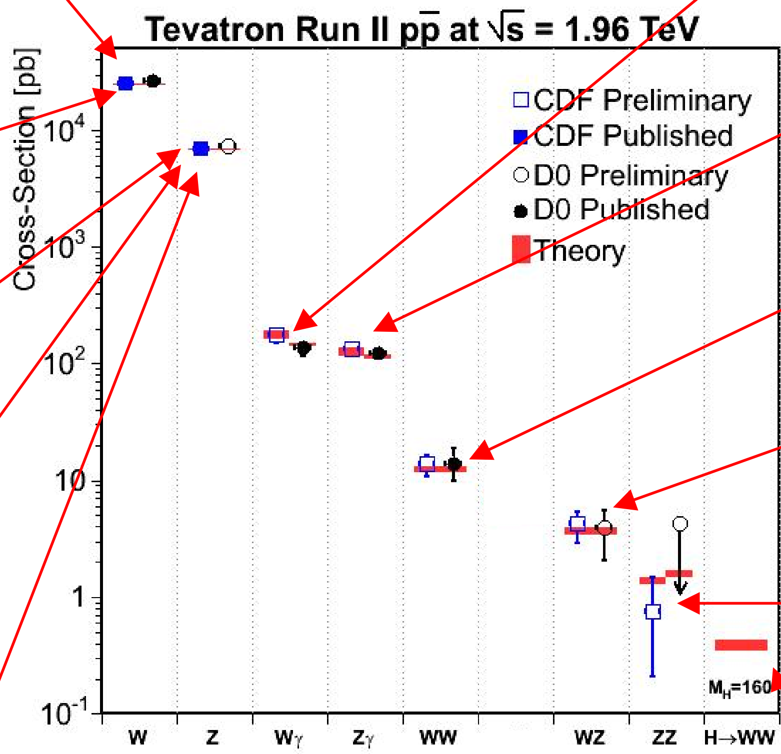
W charge asymmetry
Experimental errors close to or better than CTEQ PDF errors
New method developed

W mass and width
Best single measurement
Mass improved by 15%
Width improved by 22%

Z → ττ cross section
Consistent with SM
Important for H → ττ

Z boson rapidity
Consistent with NNLO
More data needed to be sensitive to PDF

Z boson pT
Gluon resummation calculation works well for all rapidity regions
Data higher than NNLO predictions for high pT region



Wγ
Cross section
Indication of radiation amplitude zero

Zγ
Cross section
Limits on ZZγ and Zγγ couplings

WW/WZ
Indication of WW/WZ → lνjj

WZ
First observation
Limits on WWZ couplings

ZZ
First evidence
Limits on ZZZ and ZZγ* couplings

Constraint on SM Higgs

$$m_H = 76^{+33}_{-24}\,\text{GeV}$$