Electroweak Physics at the Tevatron

Thomas Nunnemann

LMU Munich

Physics at LHC
Split – 02.10.08

for the

and

Collaborations

$\sigma(Z)$

$p_T(Z)$

$y(Z)$

W asymmetry

Z: A_{FB}

W mass

ZZ

TGC

Electroweak Physics at the Tevatron

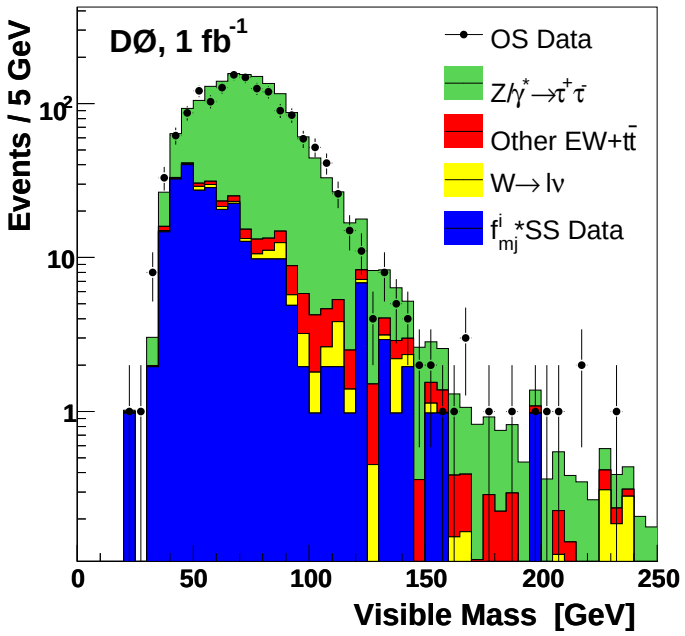
- electroweak interaction
  - g_V and g_A couplings of quarks and leptons
  - triple gauge couplings
  - electroweak production of single top quarks
    $\rightarrow$ J. Wagner-Kuhr (Wed.)
- precision measurement of W mass
  - indirect constraint on Higgs mass due to radiative corrections to M_W
- interplay with *strong interaction*
  - W production asymmetry ($\rightarrow$ PDFs)
  - Z differential cross sections
  - W/Z + jets $\rightarrow$ B. Hirosky, S. Lammers (Wed.)

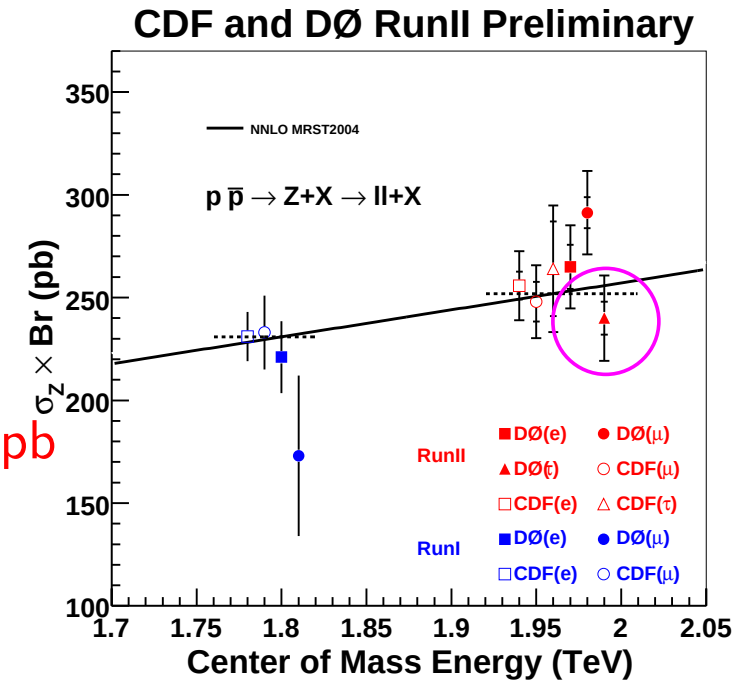
Outline

- single vector boson production
  - inclusive and *differential* production cross sections
  - production asymmetries
- W mass measurement
- di-boson production
  - observation of ZZ production
  - limits on anomalous triple gauge couplings

Inclusive Z prod.

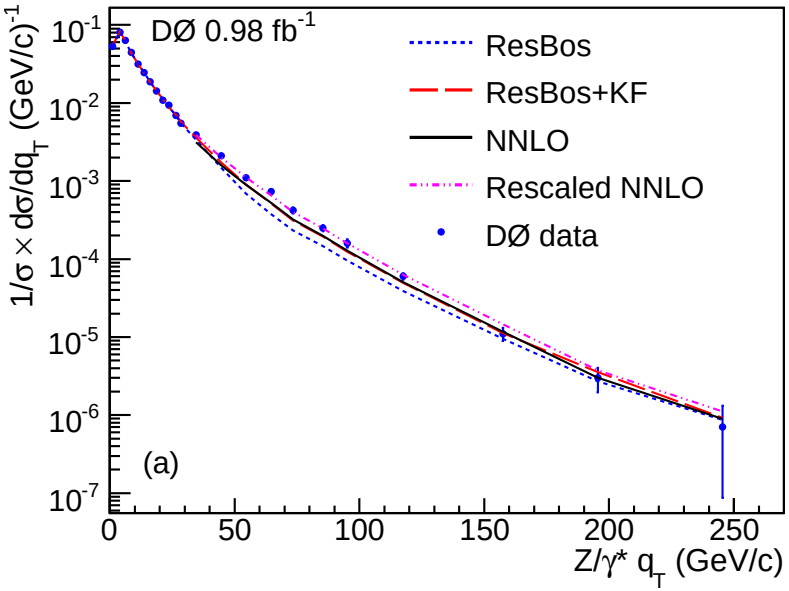
- $Z \to \tau_\mu \tau_{h/e}$
  - new measurement with $1\,\mathrm{fb}^{-1}$, arXiv:0808.1306
  - τ_μ: inclusive muon trigger
  - $\tau_{h/e}$: ID with NNs, 3 classes
    - 1 track, no EM sub-cluster
    - 1 track, ≥ 1 EM sub-cl.
    - ≥ 2 tracks, ≥ 0 EM sub-cl.
  - multi-jet ($b\bar{b}$) bgd. estimated from same-sign τ candidate events
  - visible mass: $m_{\mathrm{vis}} = \sqrt{(P_\mu + P_\tau + \not{P}_{\mathrm{T}})^2}$
  - $\sigma \cdot Br = 240 \pm 8(\mathrm{stat}) \pm 12(\mathrm{sys}) \pm 15(\mathrm{lumi})\,\mathrm{pb}$
    SM: 252 pb
  - reference measurement for $h \to \tau\tau$

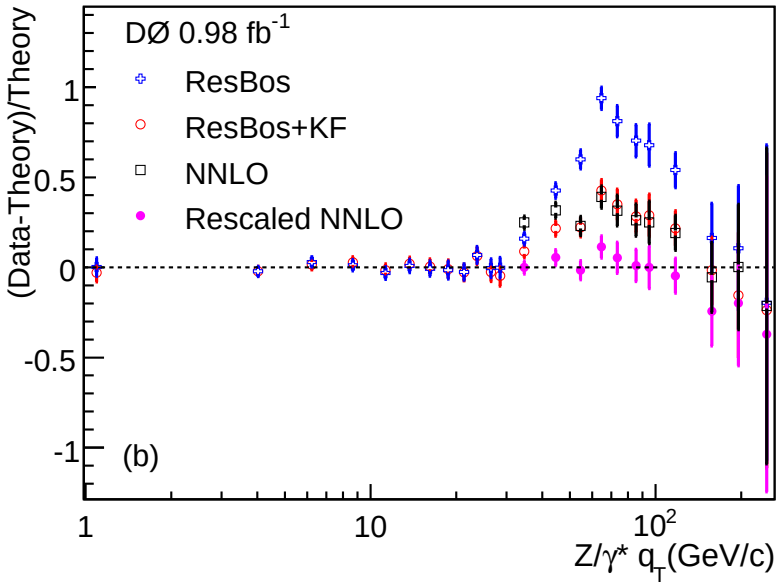




Z p_T

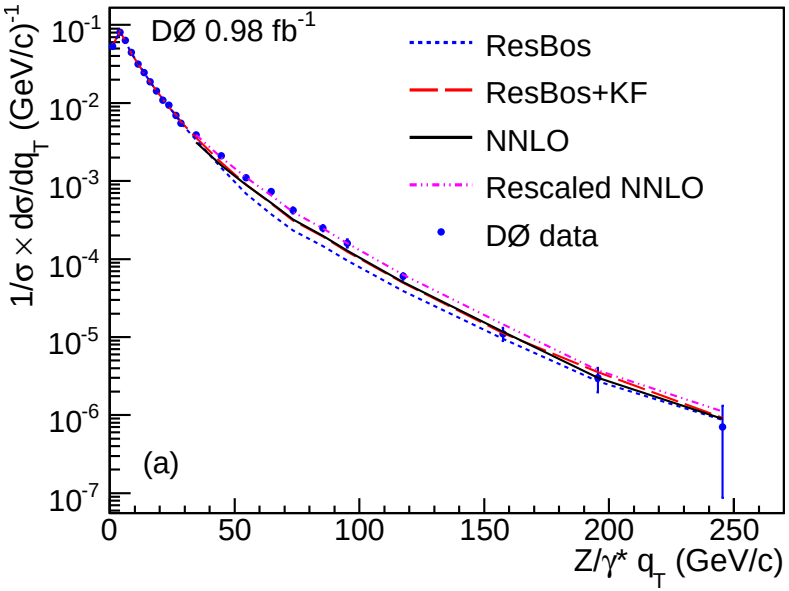
- measurement of $p_T(Z)$ tests QCD corrections
  - small $p_T(Z)$: resummation incl. non-pert. form-factor (BLNY, RESBOS, PRD **67**,073016 (2003))
  - large $p_T(Z)$: NNLO pQCD (Melnikov, Petriello, PRD **74**, 114017 (2006))
- $Z \to e^+e^-$ with $1\,\mathrm{fb}^{-1}$
  - PRL **100** 102002 (2008)
  - $p_T(Z) > 30\,\mathrm{GeV}$: NNLO pQCD describes shape, but underestimates rate by 25%
  - $p_T(Z) < 30\,\mathrm{GeV}$, $|y| > 2$: data disfavors small-x broadening (modification of the BLNY form factor, PRD **72**, 033015 (2005))

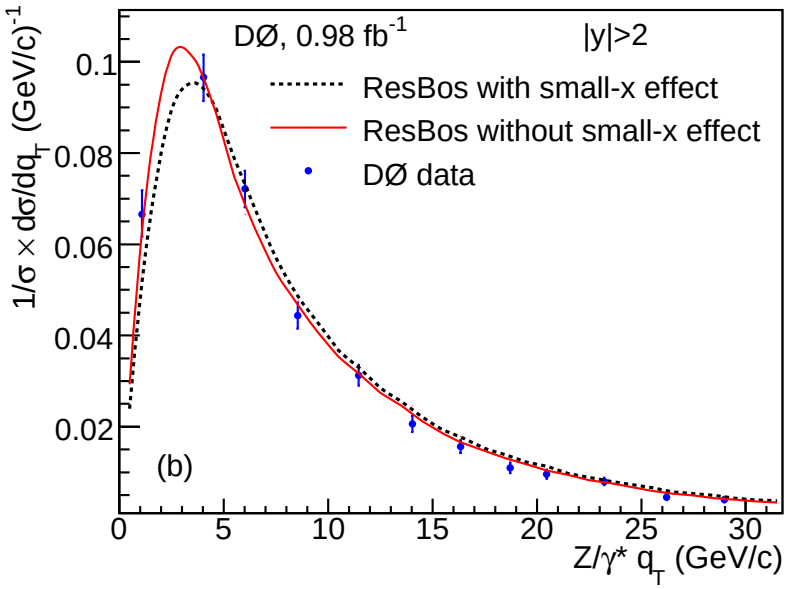




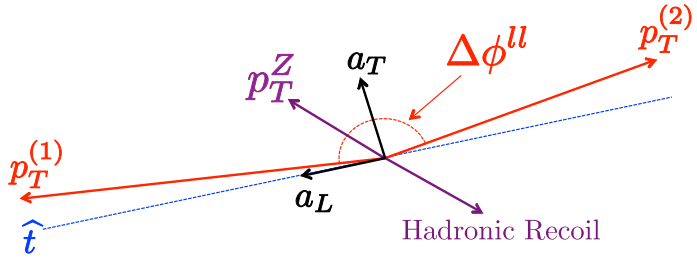
Z p_T

- measurement of $p_T(Z)$ tests QCD corrections
  - small $p_T(Z)$: resummation incl. non-pert. form-factor (BLNY, RESBOS, PRD **67**,073016 (2003))
  - large $p_T(Z)$: NNLO pQCD (Melnikov, Petriello, PRD **74**, 114017 (2006))
- $Z \to e^+e^-$ with $1\,\mathrm{fb}^{-1}$
  - PRL **100** 102002 (2008)
  - $p_T(Z) > 30\,\mathrm{GeV}$: NNLO pQCD describes shape, but underestimates rate by 25%
  - $p_T(Z) < 30\,\mathrm{GeV}$, $|y| > 2$: data disfavors small-x broadening (modification of the BLNY form factor, PRD **72**, 033015 (2005))

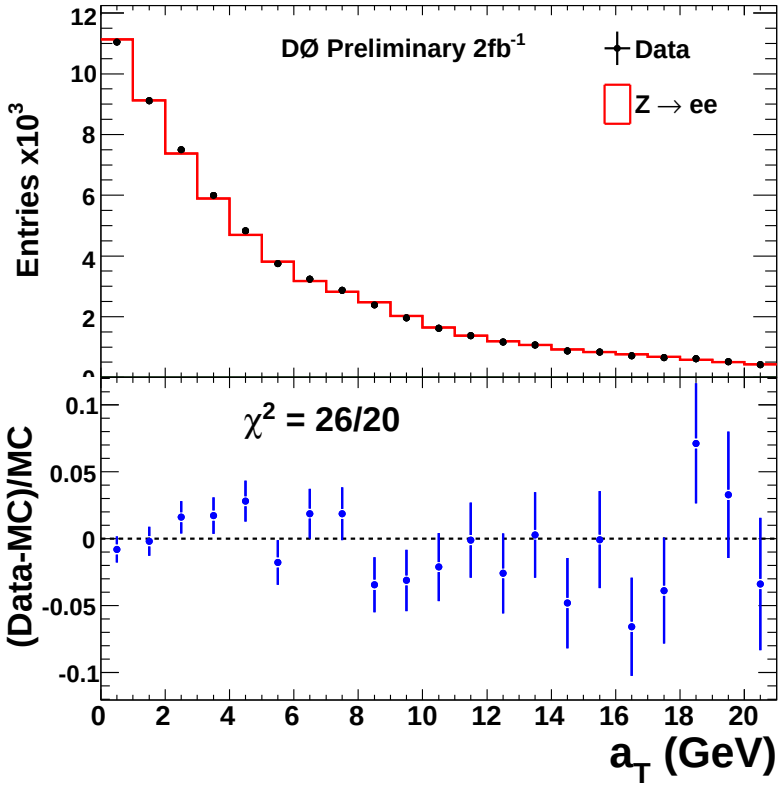




Z p_T form factor

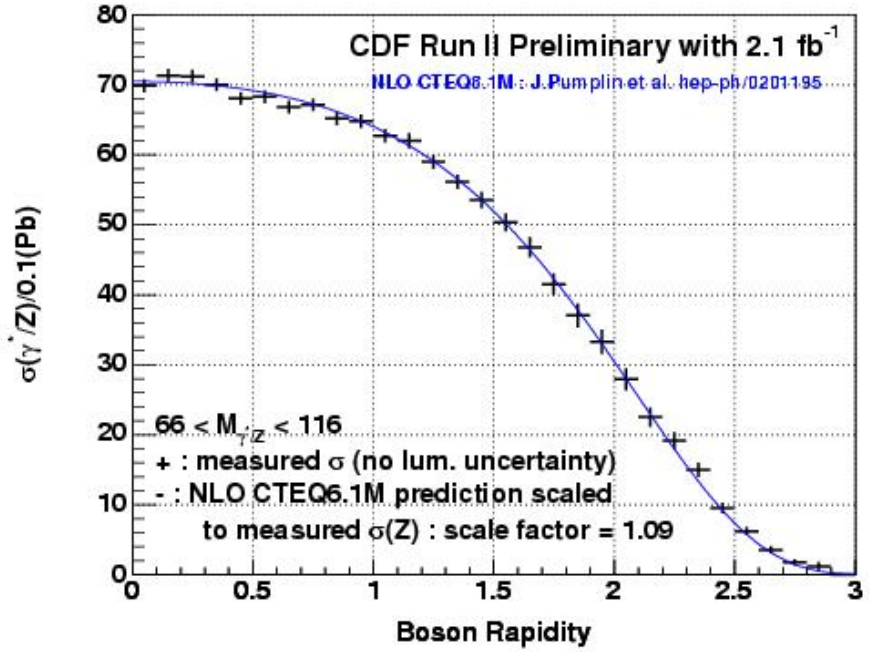


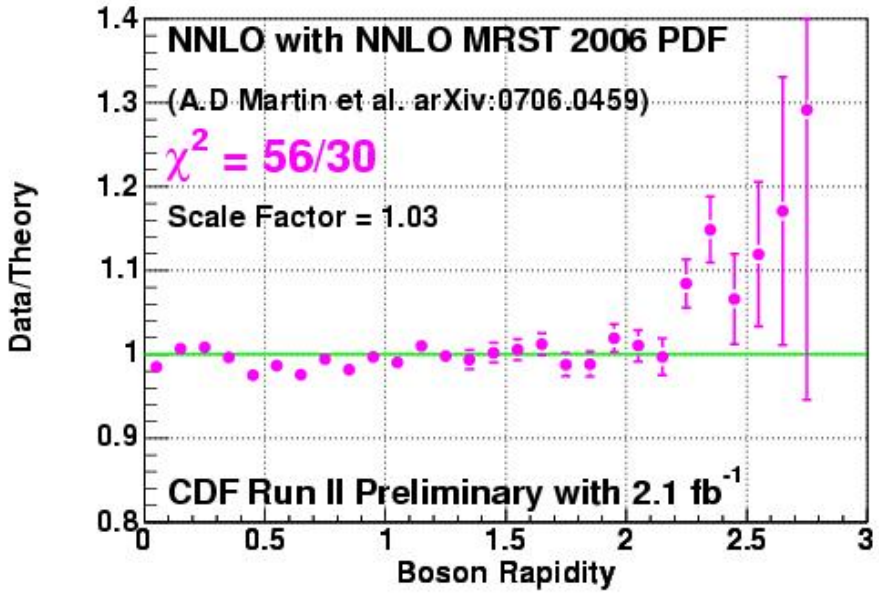
- low $p_T(Z)$: resummation with BLNY form factor
  $S_{NP}(b, Q^2) =$
  $\left[g_1 + g_2 \ln\left(\frac{Q}{2Q_0}\right) + g_1 g_3 \ln(100 x_i x_j)\right] b^2$
- uncertainty on S_{NP}
  $\rightarrow$ uncertainty on M_W
- new method: reduce sensitivity to lepton p_T resolution
  a_T: projection perpendicular to event axis $\hat{t} = p_T^{(1)} - p_T^{(2)}$
- $Z \rightarrow e^+e^-$, $\mu^+\mu^-$ with $2\,\mathrm{fb}^{-1}$:
  $g_2 =$
  $0.63 \pm 0.02(\mathrm{exp}) \pm 0.04(\mathrm{PDF})$
  PDF uncert. from CTEQ6.6
- as precise as world average
  $g_2 = 0.68^{+0.02}_{-0.01}$ (CTEQ3M, no PDF uncert. included)



Z rapidity

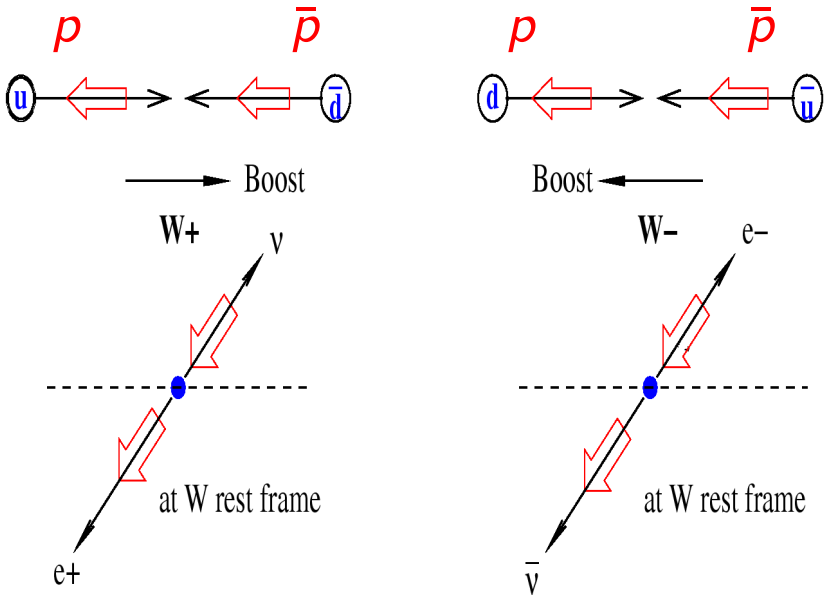
- rapidity y related to parton x (LO): $x_{1,2} = M_Z/\sqrt{s} \cdot e^{\pm y}$
  - large $|y|$: probe PDFs at low x (and high $Q^2 \approx M_Z^2$) and very large x
- $Z \to e^+e^-$ with $2.1\,\mathrm{fb}^{-1}$
  - challenge: electron ID up to $|\eta_e| = 2.8$
  - data consistent with (N)NLO pQCD
  - best agreement found for NLO calculation with CTEQ6.1M

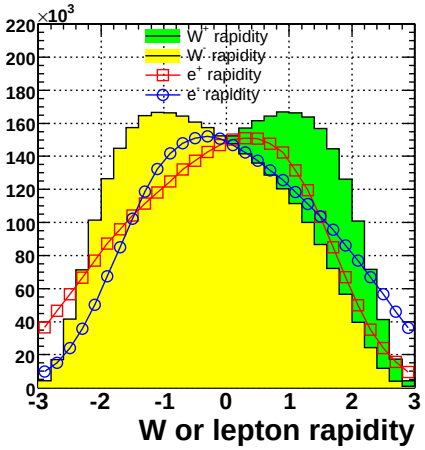


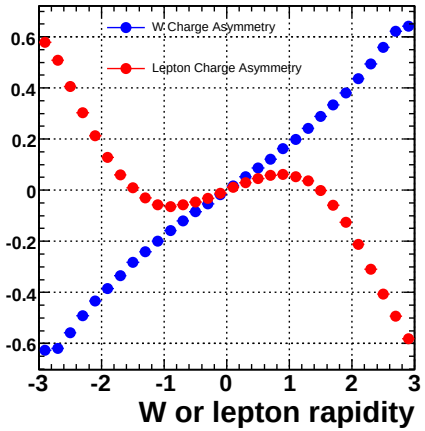


W charge asymmetry

- sensitive to PDFs
- u quarks carry larger average x than d quarks ($\leftarrow F_2^p/F_2^n$)
  - $u\bar{d} \rightarrow W^+$ preferentially boosted along p direction
- W charge asymmetry:
  $A(y) = \frac{d\sigma^+/dy - d\sigma^-/dy}{d\sigma^+/dy + d\sigma^- dy}$
- $A(\eta_l)$ is standard observable
  - convolution of W prod. asymmetry and (V-A) decay
  - assumption: SM $W \rightarrow l\nu$ coupling
  - cancellation of syst. uncert. related to lepton reconstruction

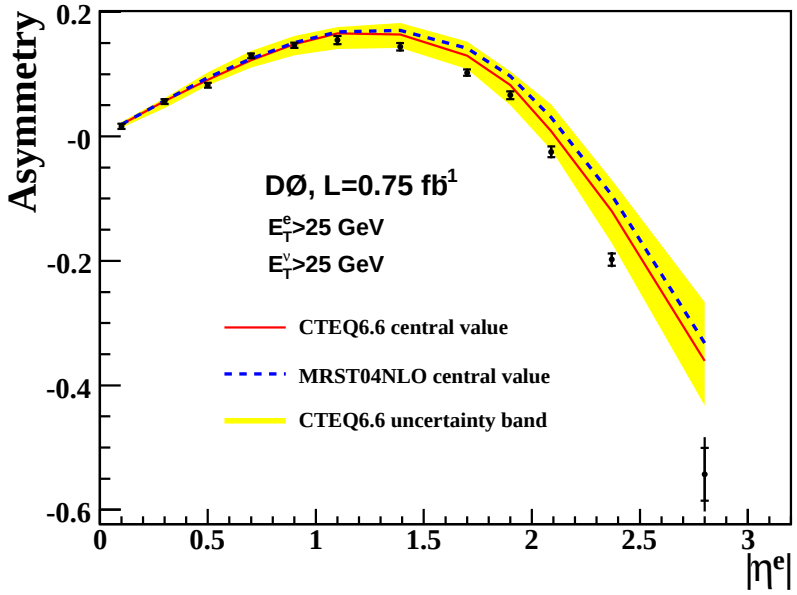


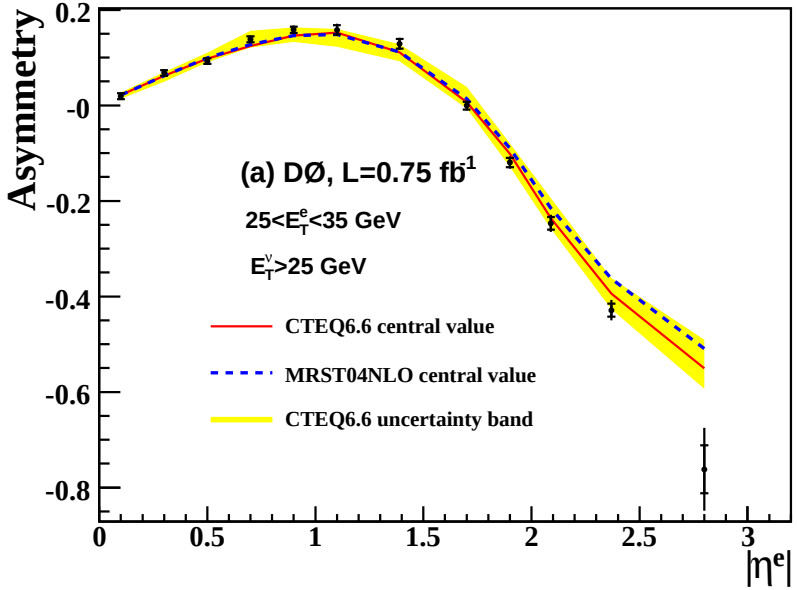




$A(|\eta_e|)$ in W events

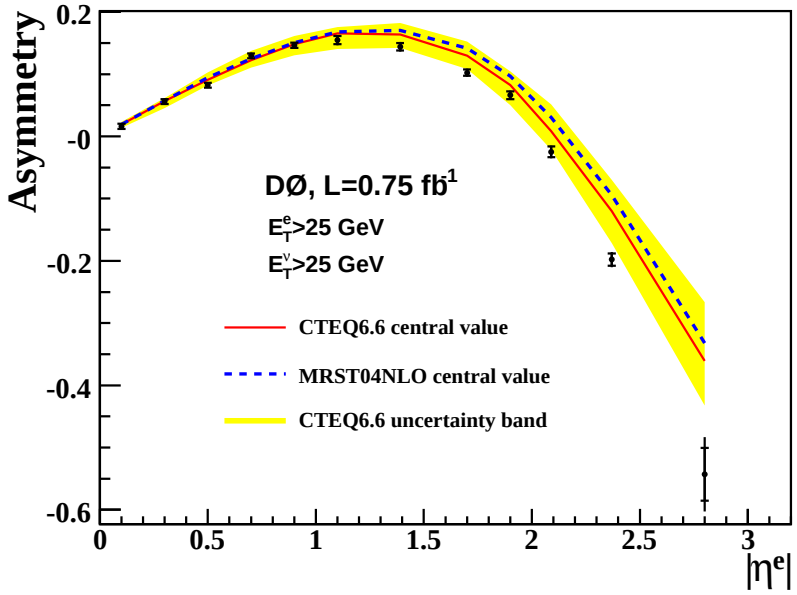
- $W \to e\nu$, $0.75\,\mathrm{fb}^{-1}$
  - arXiv:0807.3367
  - dominant syst. uncert. from multi-jet bgd. and charge mis-ID
  - charge mis-ID rate: 0.2% ($|\eta_e| \approx 0$) to 9% ($|\eta_e| \approx 3$)
  - $A(|\eta_e|)$ in different $E_T(e)$ bins: probe different y_W ($\to x$) for fixed $|\eta_e|$
  - for nearly all $|\eta_e|$ bins: experimental uncertainties much smaller than CTEQ6.6 band
    $\Rightarrow$ expect impact on new PDF fits with improved precision

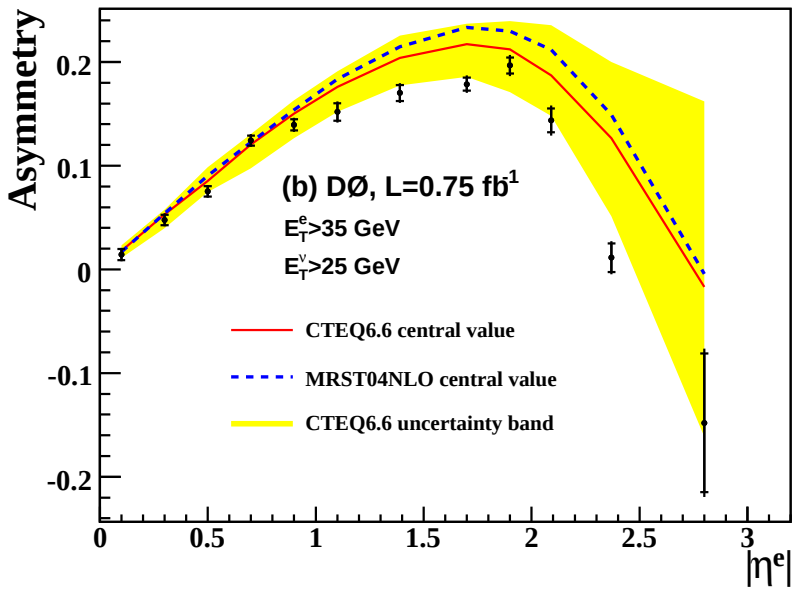




$A(|\eta_e|)$ in W events

- $W \to e\nu$, $0.75\,\mathrm{fb}^{-1}$
  - arXiv:0807.3367
  - dominant syst. uncert. from multi-jet bgd. and charge mis-ID
  - charge mis-ID rate: 0.2% ($|\eta_e| \approx 0$) to 9% ($|\eta_e| \approx 3$)
  - $A(|\eta_e|)$ in different $E_T(e)$ bins: probe different y_W ($\to x$) for fixed $|\eta_e|$
  - for nearly all $|\eta_e|$ bins: experimental uncertainties much smaller than CTEQ6.6 band
    $\Rightarrow$ expect impact on new PDF fits with improved precision





Direct measurement of $A(|y_W|)$

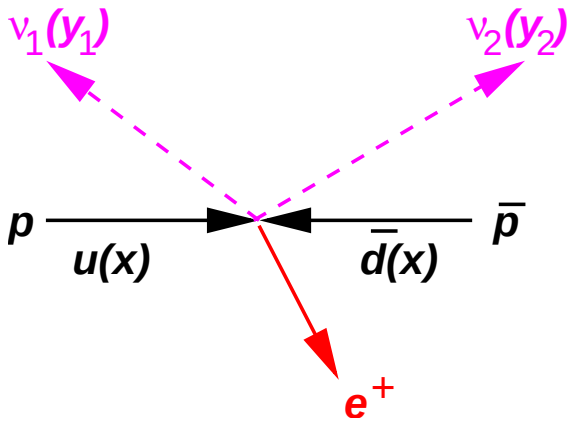
- reconstruct y_W distribution with M_W constraint
  - weight both ν solutions with probability given by production and decay
  - iterate as weight depends on y_W

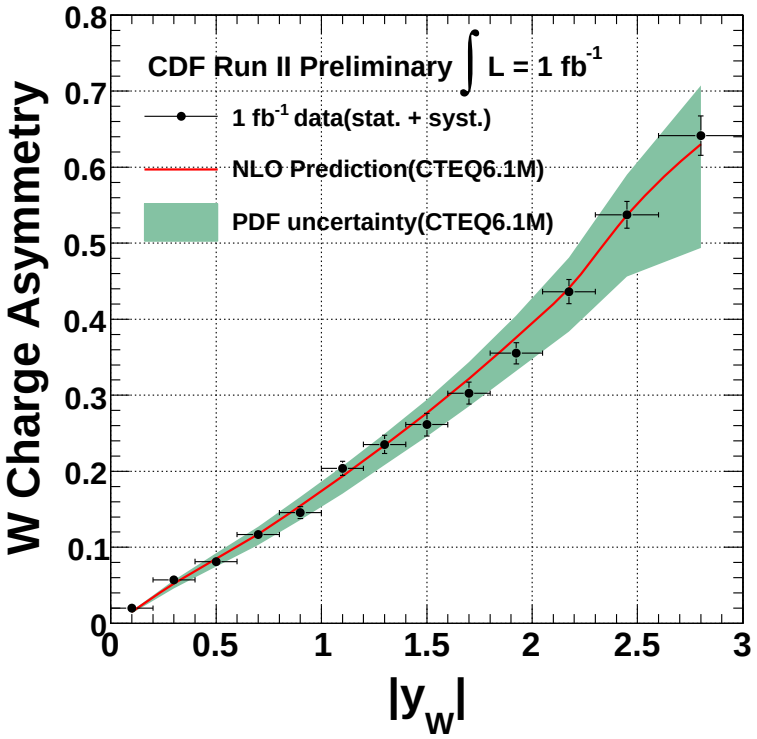
$\Rightarrow$ improved statistical precision w.r.t. $A(\eta_l)$

  - for fixed $y_{W^\pm}$: $\eta_{e^+} \neq \eta_{e^-}$

$\Rightarrow$ different acceptance for W^+/W^-

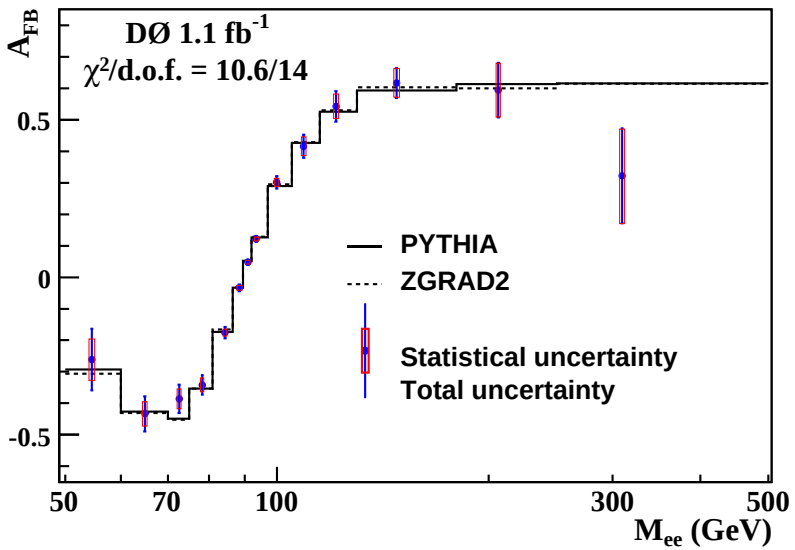
- $W \to e\nu$, $1\,\mathrm{fb}^{-1}$
  - largest syst. uncert.: e-ID efficiency, modeling of hadronic recoil
  - provides new constraints on PDF fits

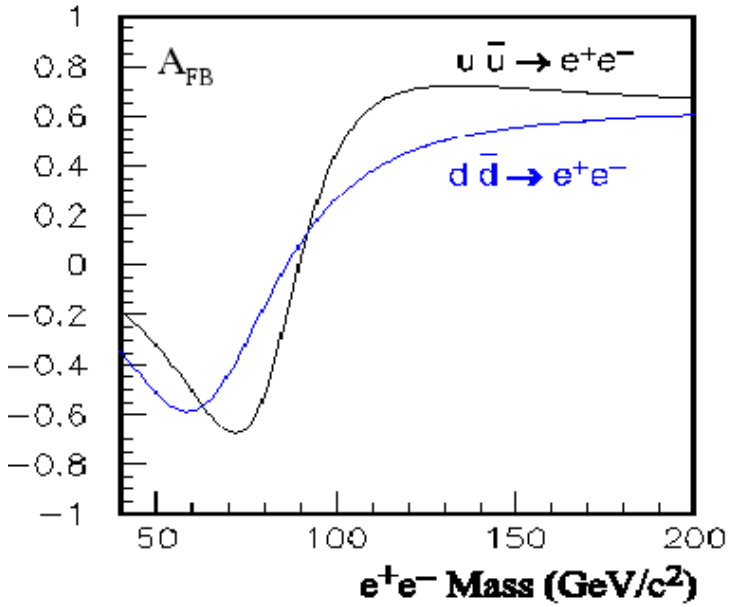




$Z/\gamma^* \to e^+e^-$ forward-backward asym.

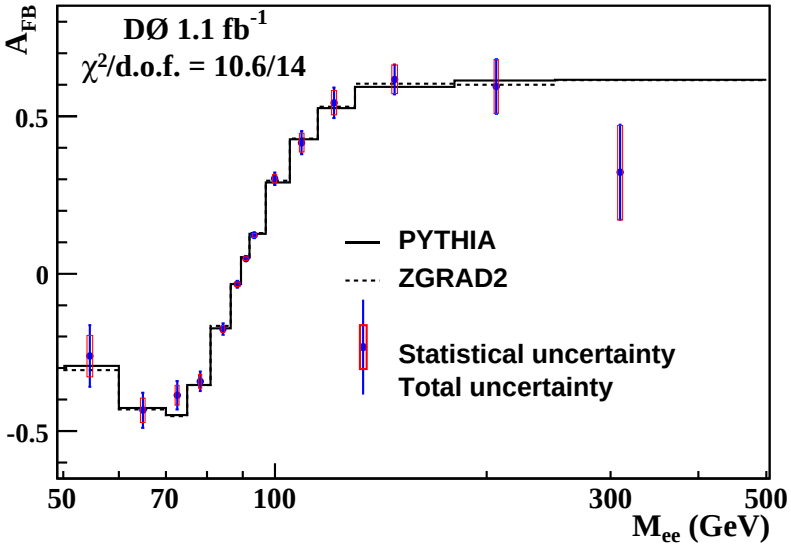
- $A_{FB} = \frac{\sigma(\cos\theta^- > 0) - \sigma(\cos\theta^- < 0)}{\sigma(\cos\theta^- > 0) + \sigma(\cos\theta^- < 0)}$
  $\theta^- = \angle(\ell^-, p)$ in Collins-Soper rest frame
  - interference between γ^* and Z
  - sensitive to $g_{V/A}(q, \ell)$ $(\to \sin^2\theta_W^{\text{eff}})$
  - exchange of Z' bosons would alter A_{FB} around $m_{Z'}$
- previous meas.: CDF, $72\,\text{pb}^{-1}$, PRD **71**, 052002 (2005)
- DØ, $1.1\,\text{fb}^{-1}$, arXiv:0804.3220
  - measurement of unfolded A_{FB}
  - $\sin^2\theta_W^{\text{eff}}$ from uncorrected A_{FB} fitted to PYTHIA templates (full simulation and QCD/EW corrections from ZGRAD)

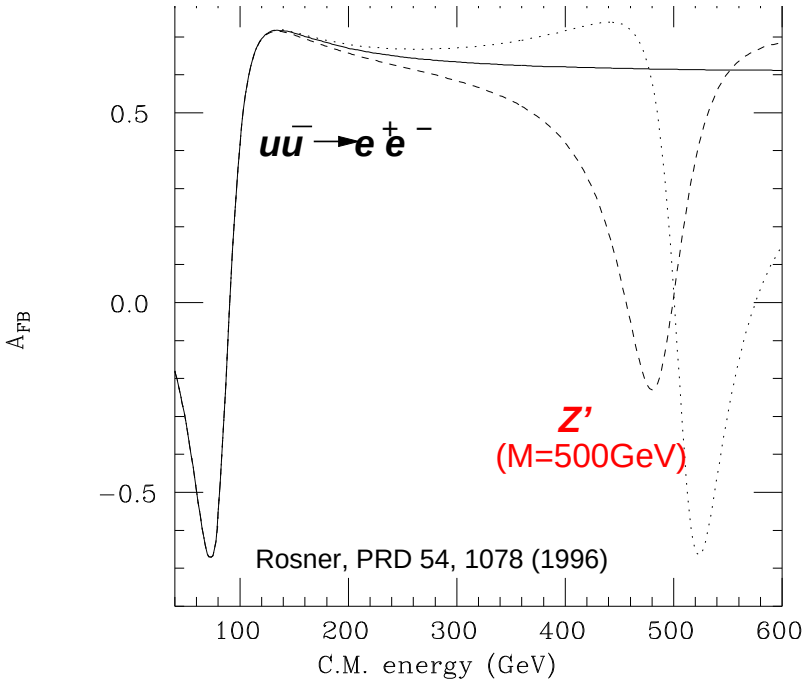




$Z/\gamma^* \to e^+e^-$ forward-backward asym.

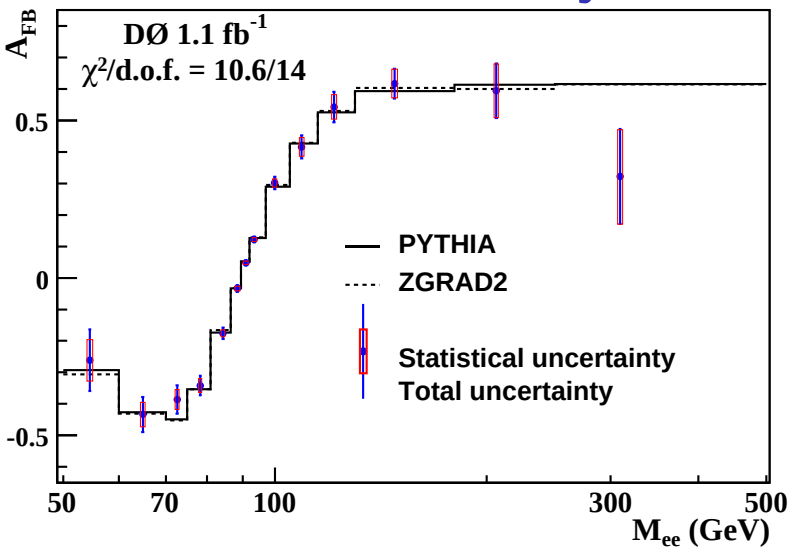
- $A_{FB} = \frac{\sigma(\cos\theta^- > 0) - \sigma(\cos\theta^- < 0)}{\sigma(\cos\theta^- > 0) + \sigma(\cos\theta^- < 0)}$
  $\theta^- = \angle(\ell^-, p)$ in Collins-Soper rest frame
  - interference between γ^* and Z
  - sensitive to $g_{V/A}(q, \ell)$ $(\to \sin^2\theta_W^{\text{eff}})$
  - exchange of Z' bosons would alter A_{FB} around $m_{Z'}$
- previous meas.: CDF, $72\,\text{pb}^{-1}$, PRD **71**, 052002 (2005)
- DØ, $1.1\,\text{fb}^{-1}$, arXiv:0804.3220
  - measurement of unfolded A_{FB}
  - $\sin^2\theta_W^{\text{eff}}$ from uncorrected A_{FB} fitted to PYTHIA templates (full simulation and QCD/EW corrections from ZGRAD)

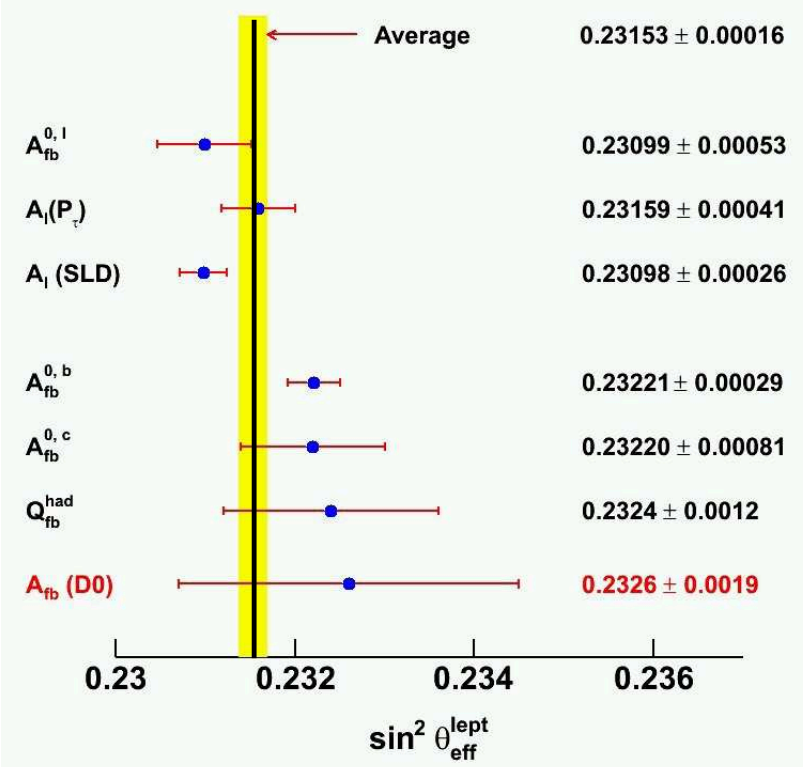




$Z/\gamma^* \to e^+e^-$ forward-backward asym.

- $A_{FB} = \frac{\sigma(\cos\theta^- > 0) - \sigma(\cos\theta^- < 0)}{\sigma(\cos\theta^- > 0) + \sigma(\cos\theta^- < 0)}$
  $\theta^- = \angle(\ell^-, p)$ in Collins-Soper rest frame
  - interference between γ^* and Z
  - sensitive to $g_{V/A}(q, \ell)$ $(\to \sin^2\theta_W^{\text{eff}})$
  - exchange of Z' bosons would alter A_{FB} around $m_{Z'}$
- previous meas.: CDF, $72\,\text{pb}^{-1}$, PRD **71**, 052002 (2005)
- DØ, $1.1\,\text{fb}^{-1}$, arXiv:0804.3220
  - measurement of unfolded A_{FB}
  - $\sin^2\theta_W^{\text{eff}}$ from uncorrected A_{FB} fitted to PYTHIA templates (full simulation and QCD/EW corrections from ZGRAD)





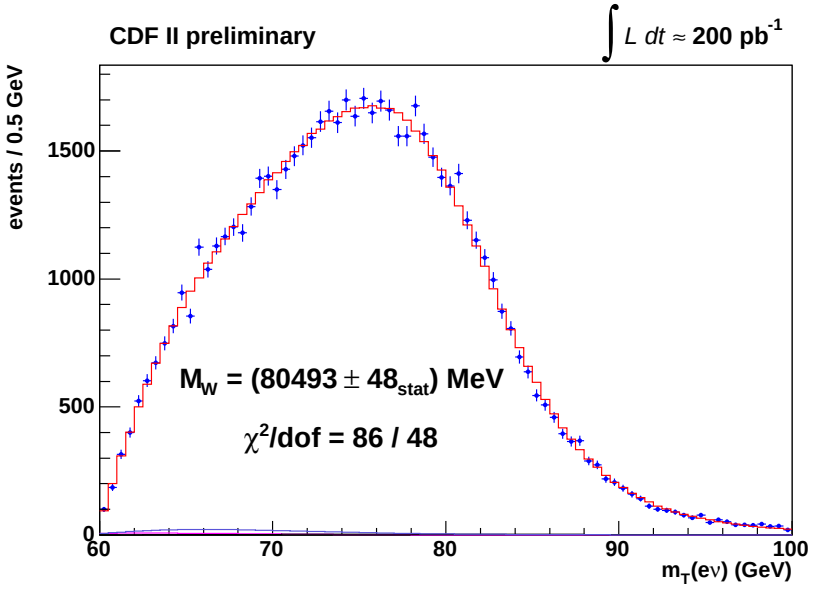
W mass

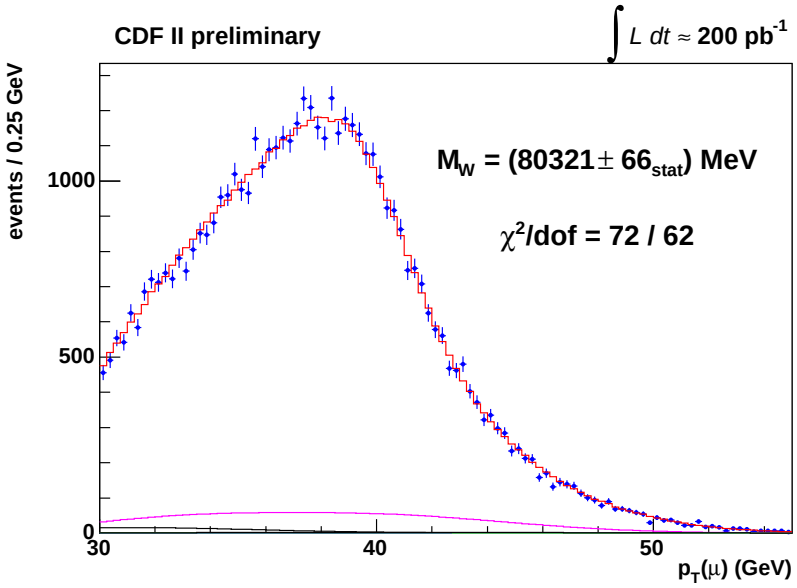
- $W \to e\nu$, $\mu\nu$, $200\,\mathrm{pb}^{-1}$
  - PRL **99**, 151801 (2007), PRD **77**, 112001 (2008)
  - based on m_T, $p_T(\ell)$, $\not{E}_T$

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

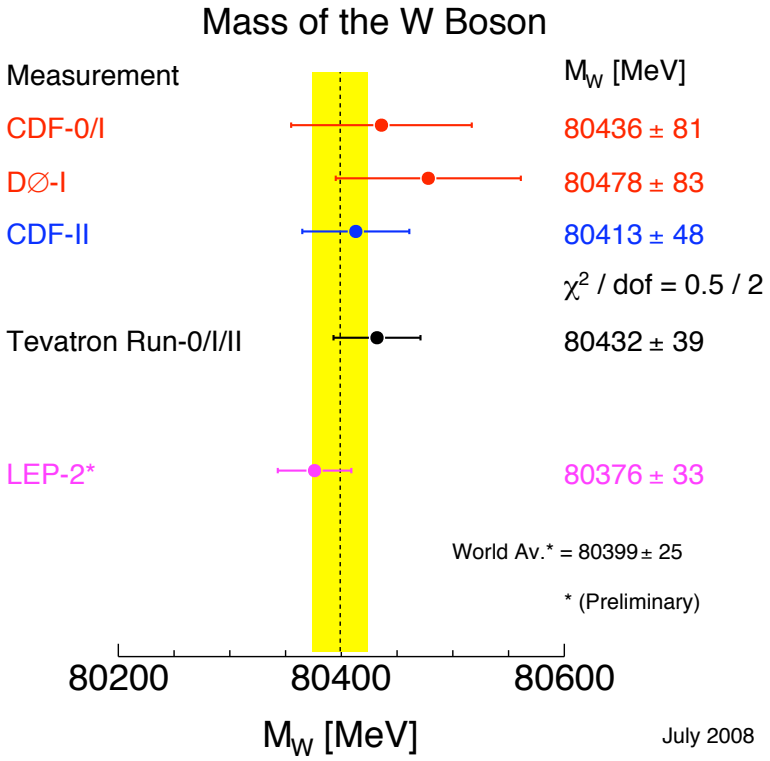
$M_W = 80413 \pm 48\,\mathrm{MeV}$
(stat: $34\,\mathrm{MeV}$, syst: $34\,\mathrm{MeV}$)
$\Rightarrow$ most precise single measurement

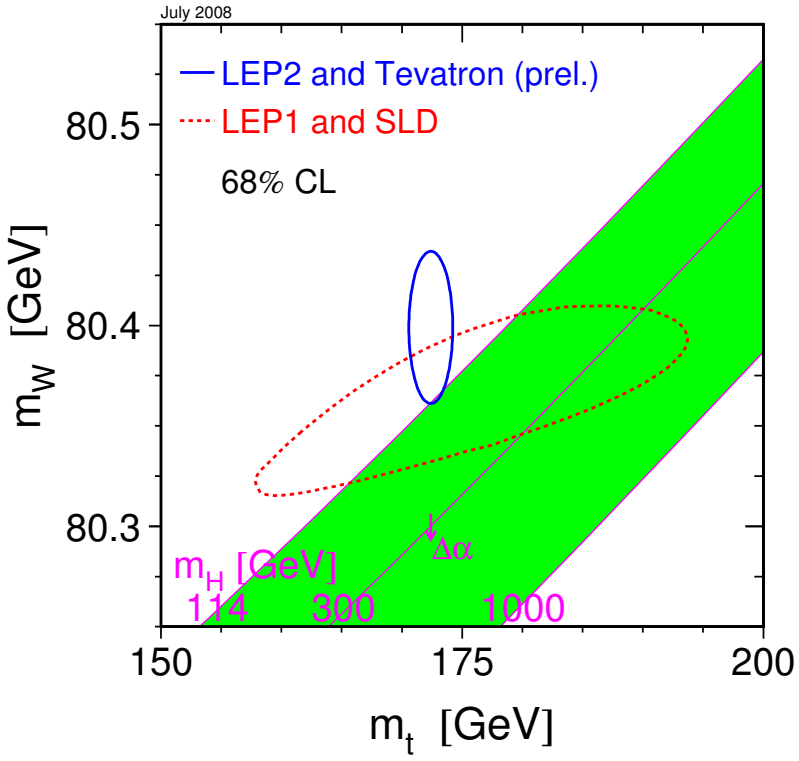




M_W / Γ_W combination

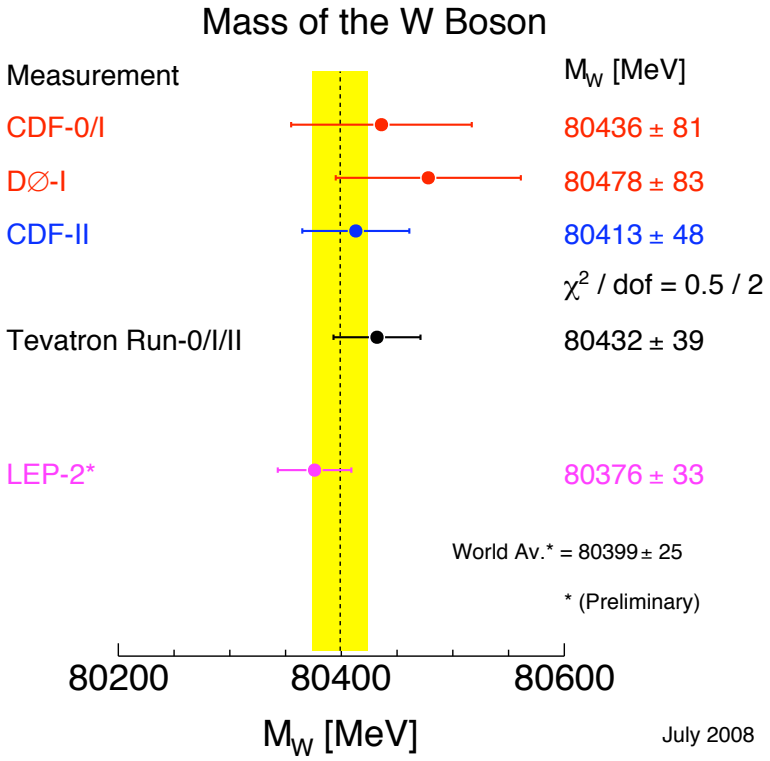
- small changes in Tevatron combination $(+3\,\mathrm{MeV})$
  $\rightarrow$ new world average $(+1\,\mathrm{MeV})$
- for constraints on Higgs mass: $\Delta M_t = 1.2\,\mathrm{GeV}$ corresponds to $\Delta M_W \approx 7\,\mathrm{MeV}$

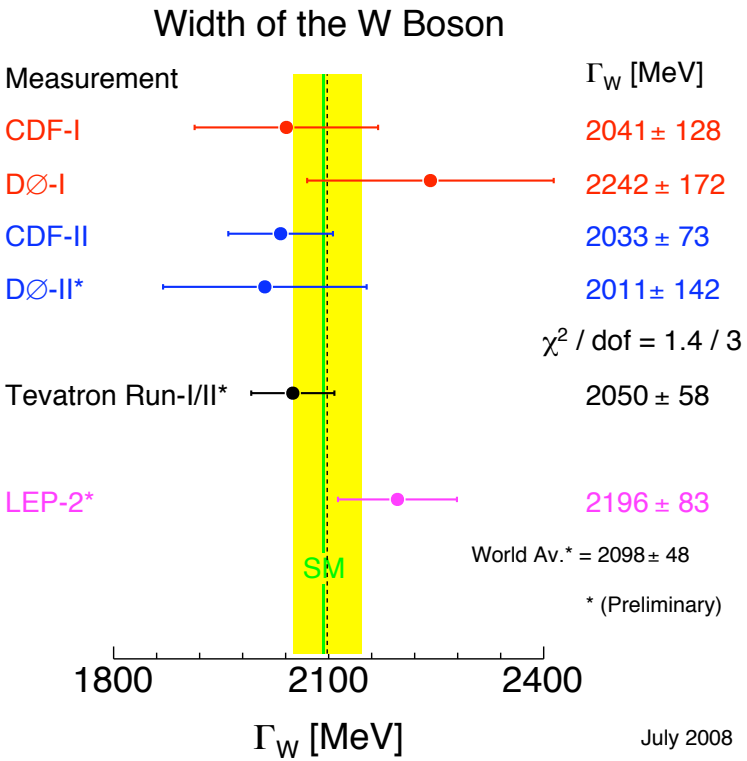




M_W / Γ_W combination

- small changes in Tevatron combination ($+3\,\mathrm{MeV}$)
  $\rightarrow$ new world average ($+1\,\mathrm{MeV}$)
- for constraints on Higgs mass: $\Delta M_t = 1.2\,\mathrm{GeV}$ corresponds to $\Delta M_W \approx 7\,\mathrm{MeV}$

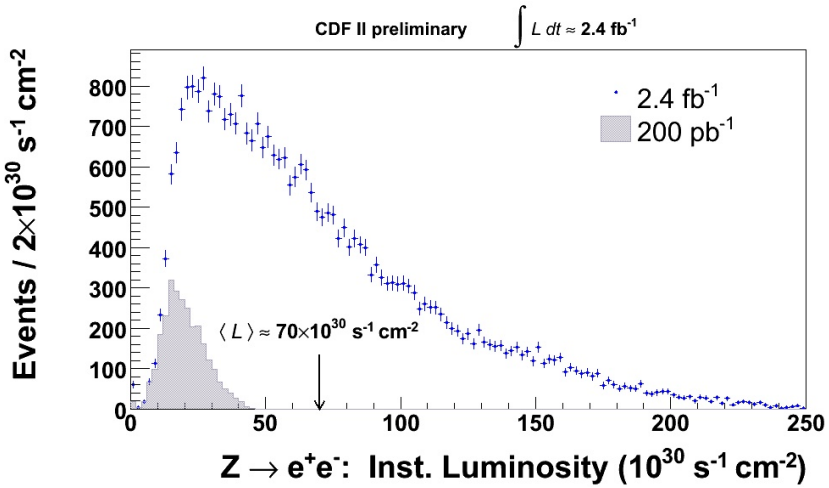


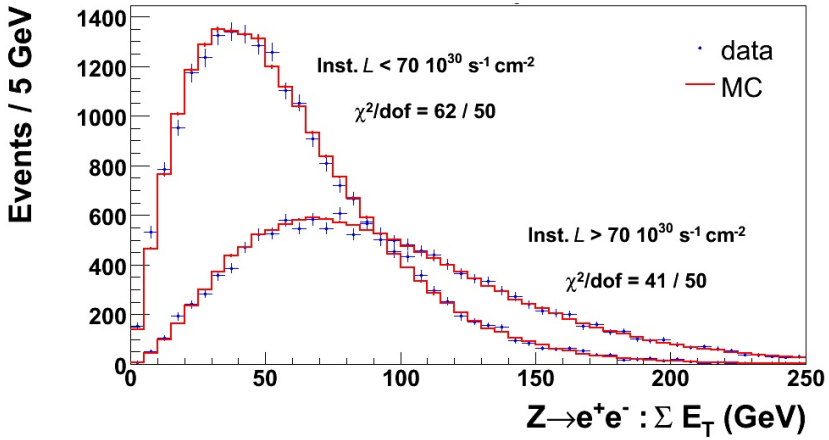


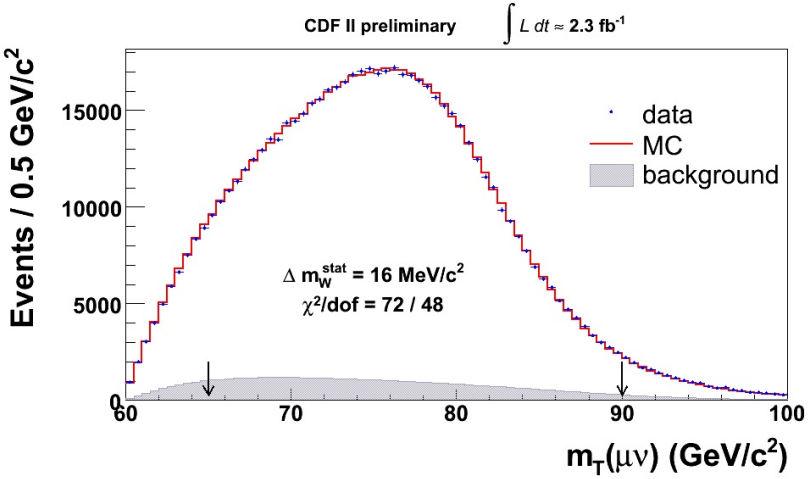
- Γ_W combination
  most precise measurement: CDF, $350\,\mathrm{pb}^{-1}$

W mass update

- preliminary analysis based on $2.3/2.4\,\mathrm{fb}^{-1}$
  - higher instantaneous lumi $\Rightarrow \sum E_T$ in calo increasing due to larger pile-up
  - only statistical uncertainties derived
    $\Delta M_W(stat)$ from m_T:
    e: $48\,\mathrm{MeV} \rightarrow 15\,\mathrm{MeV}$
    μ: $54\,\mathrm{MeV} \rightarrow 16\,\mathrm{MeV}$
    $\Rightarrow$ no degradation with higher lumi
  - expect improvement in lepton scale uncert. with M_Z calib.
    $\Delta M_Z(stat)$:
    e: $67\,\mathrm{MeV} \rightarrow 20\,\mathrm{MeV}$
    μ: $43\,\mathrm{MeV} \rightarrow 12\,\mathrm{MeV}$
    ($200\,\mathrm{pb}^{-1}$: scale is mostly constrained by J/ψ and Υ)

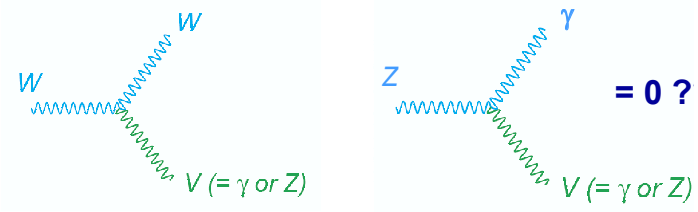


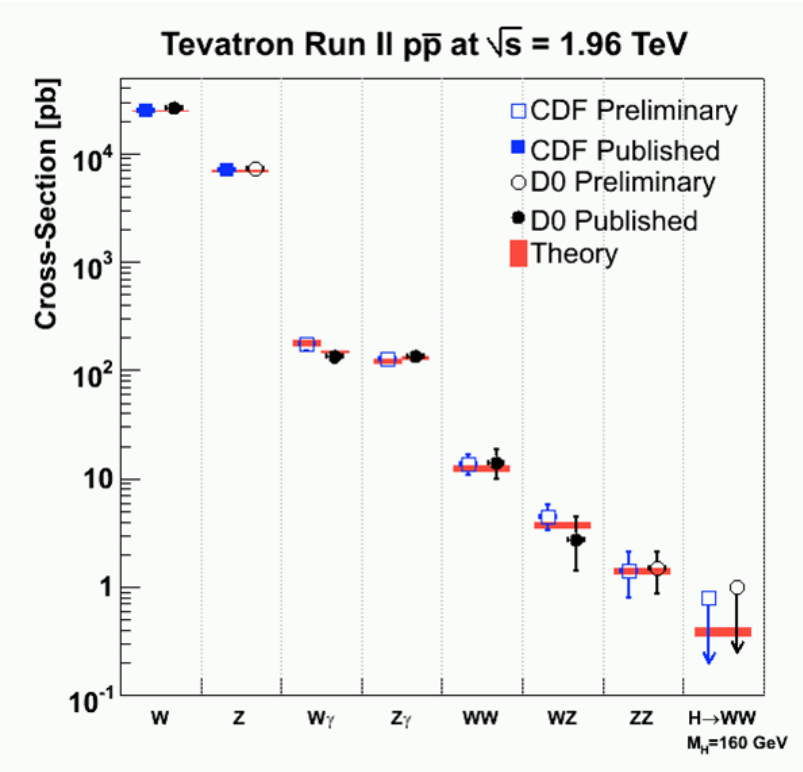




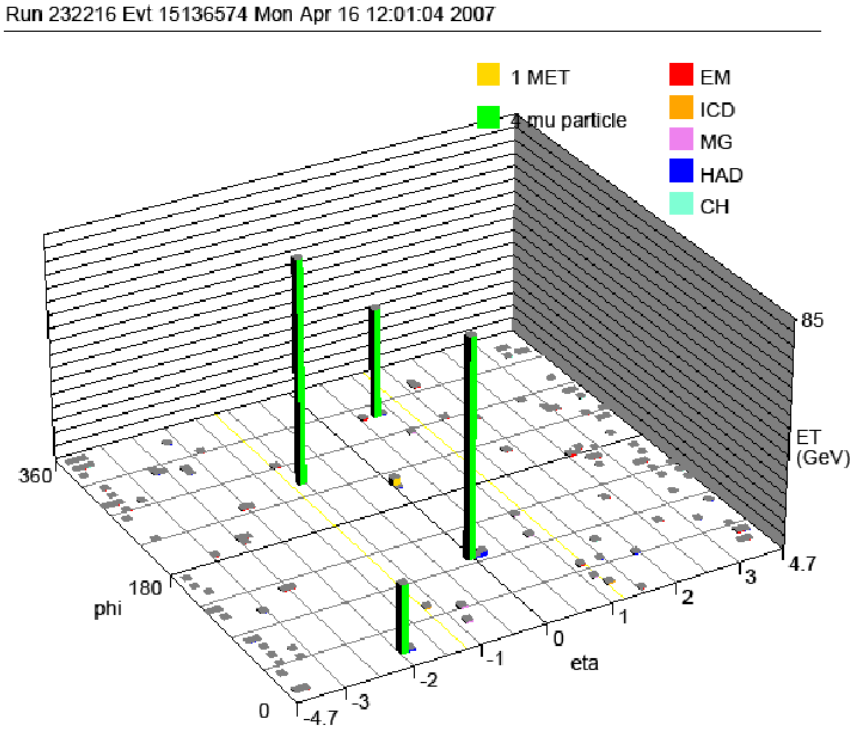
Boson Pair Production

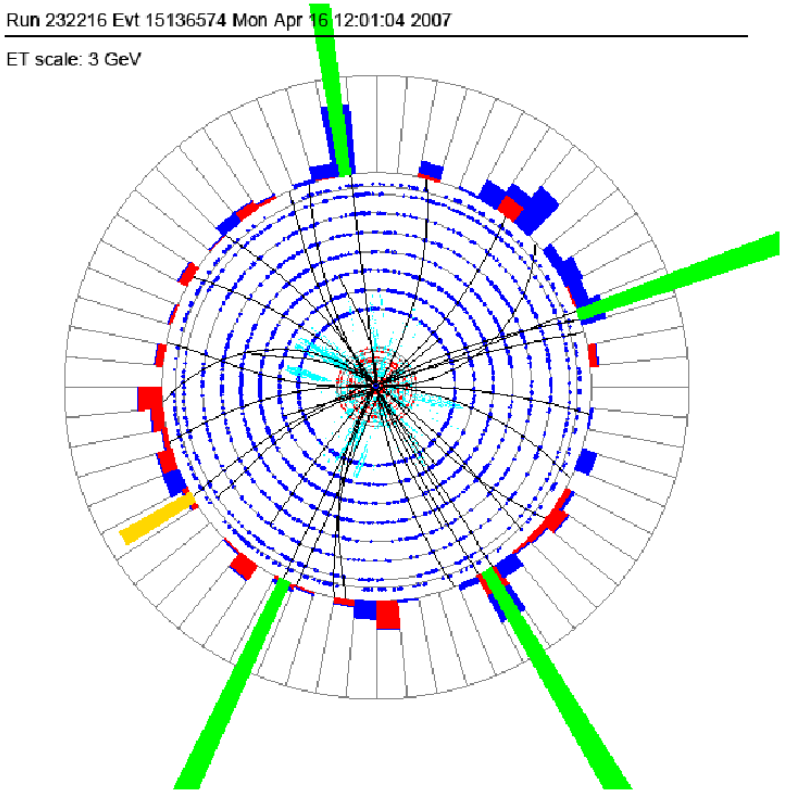
- non-Abelian structure of SM: probe trilinear gauge boson coupling
- sensitive to new physics via anomalous couplings
- Tevatron and LEP complementary
  - at TeV higher $\sqrt{\hat{s}}$ and p_T
  - sensitivity to different combinations of couplings
- background to and reference signal for numerous searches ($H \to WW/ZZ$, SUSY (trilepton))
- small cross sections $\to$ both CDF/DØ have $\sim 4.4\,\mathrm{fb}^{-1}$ recorded





$ZZ \to 4\mu$ candidate





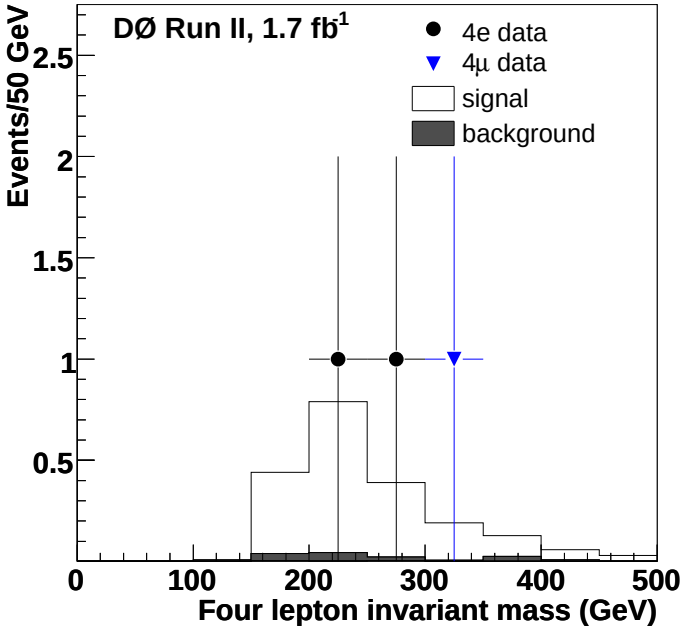
		μ_1^+	μ_2^-	μ_3^-	μ_4^+
4μ candidate	p_T (GeV)	115	77	42	24
	η	0.04	-1.01	0.77	-1.93
	ϕ	1.69	4.26	5.29	0.36
	$M_{\ell\ell}$ (GeV)	$\mu_1^+\,\mu_3^-$ 148^{+32}_{-18}		$\mu_2^-\,\mu_4^+$ 90^{+12}_{-8}	

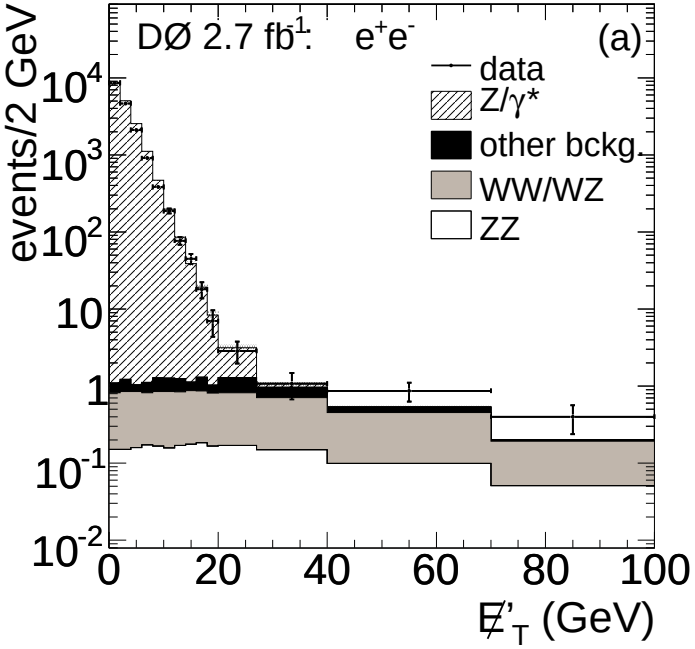
ZZ observation

- previous meas.: CDF $1.9\,\mathrm{fb}^{-1}$, 4.4σ PRL **100** 201801 (2008)
- $ZZ \to \ell\ell\ell'\ell'$, $\ell, \ell' = e, \mu$, $1.7\,\mathrm{fb}^{-1}$
  - arXiv:0808.0703
  - 3 cand. (2 *eeee*, 1 $\mu\mu\mu\mu$) with 0.14 bgd. (mostly Z+jets)
- $ZZ \to \ell\ell\not{E}_{\mathrm{T}}$, $2.7\,\mathrm{fb}^{-1}$
  - arXiv:0808.0269
  - new $\not{E}_{\mathrm{T}}{}'$ estimator $\to$ improved bgd. rejection
  - after $\not{E}_{\mathrm{T}}{}'$ cut: 43 cand. with 26.5 bgd. (incl. 20.3 WW)
  - likelihood to discrim. from WW
- observed significance

$Z \to \ell\ell\ell'\ell'$	$\to \ell\ell\nu\nu$	comb.
5.3σ	2.7σ	5.7σ

$\sigma = 1.60 \pm 0.63(\mathrm{stat})^{+0.16}_{-0.17}(\mathrm{syst})\,\mathrm{pb}$

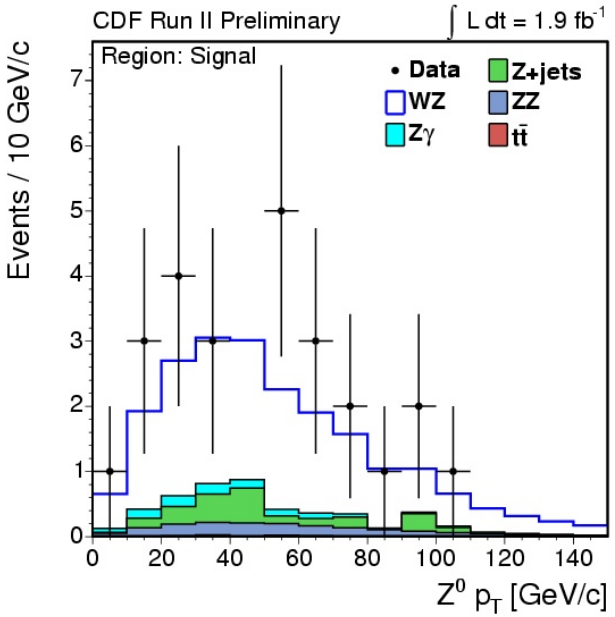


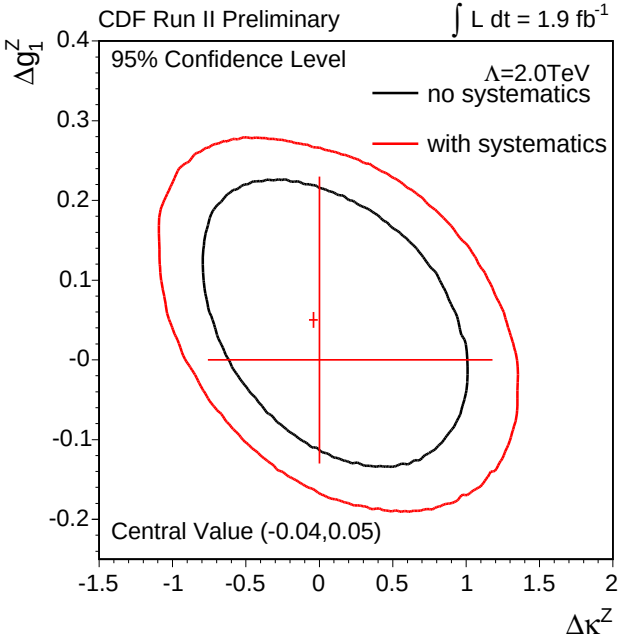


NLO pred.: $1.4 \pm 0.1\,\mathrm{pb}$

Triple gauge couplings

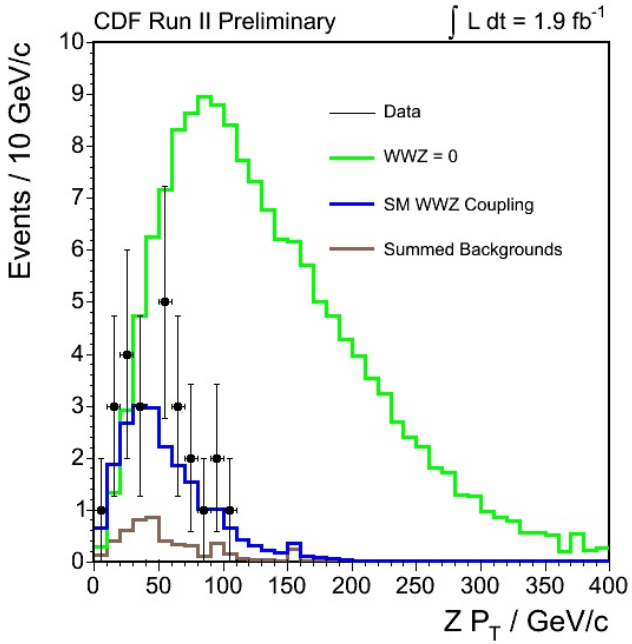
- *WZ* production: study *WWZ* vertex independently of $WW\gamma$
- 3 *CP* conserving coupling parameters (g_1^Z, κ_Z, λ_Z)
  SM: $g_1^Z = 1$, $\kappa_Z = 1$, $\lambda_Z = 0$
- Z p_T distribution sensitive to anomalous couplings
- e.g. $g_1^Z = \kappa_Z = 0$ turns *WWZ* vertex off $\rightarrow$ only *t*-channel *q* exch. contribution

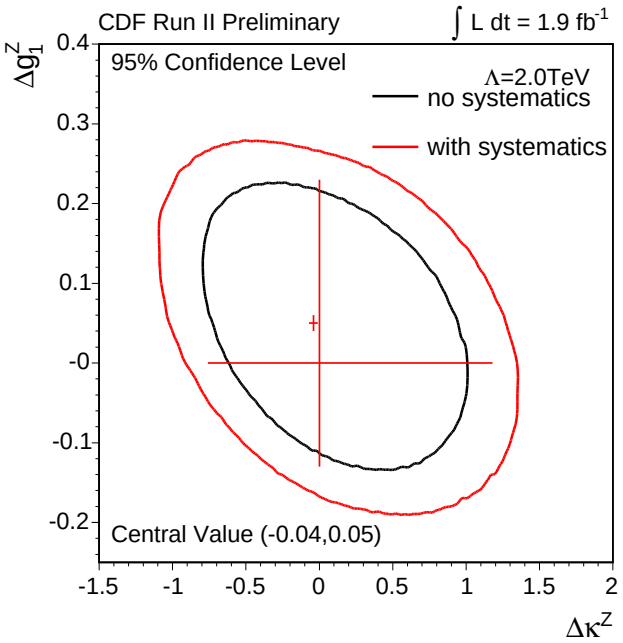




Triple gauge couplings

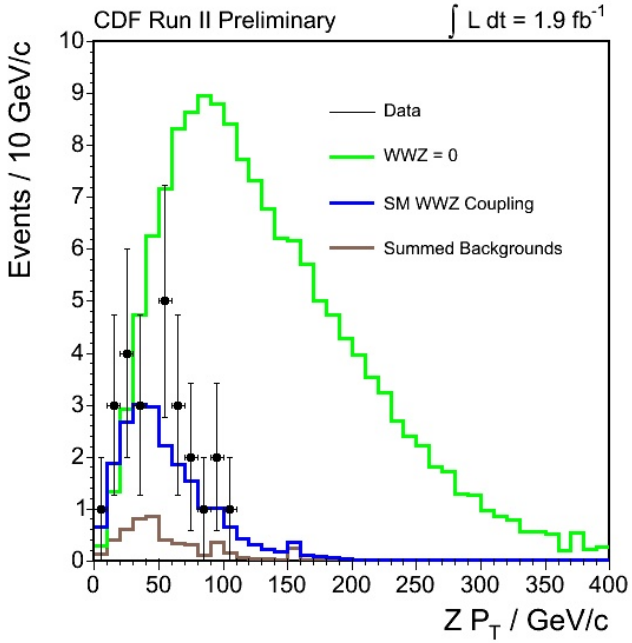
- *WZ* production: study *WWZ* vertex independently of $WW\gamma$
- 3 *CP* conserving coupling parameters (g_1^Z, κ_Z, λ_Z)
  SM: $g_1^Z = 1$, $\kappa_Z = 1$, $\lambda_Z = 0$
- Z p_T distribution sensitive to anomalous couplings
- e.g. $g_1^Z = \kappa_Z = 0$ turns *WWZ* vertex off $\rightarrow$ only *t*-channel *q* exch. contribution

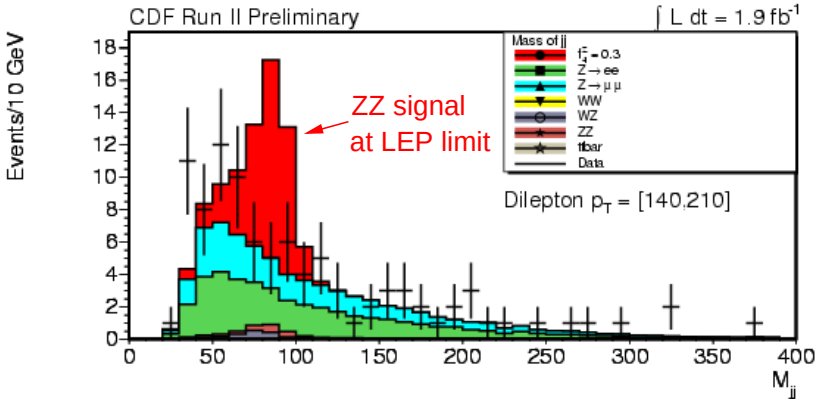




Triple gauge couplings

- *WZ* production: study *WWZ* vertex independently of $WW\gamma$
- 3 *CP* conserving coupling parameters (g_1^Z, κ_Z, λ_Z)
  SM: $g_1^Z = 1$, $\kappa_Z = 1$, $\lambda_Z = 0$
- Z p_T distribution sensitive to anomalous couplings
- e.g. $g_1^Z = \kappa_Z = 0$ turns *WWZ* vertex off $\rightarrow$ only *t*-channel *q* exch. contribution
- also sensitivity beyond LEP for *ZZZ* and $ZZ\gamma$ vertex, e.g. with dijet mass in $Z(\rightarrow \ell\ell)jj$
  LEP: $|f_4^Z| < 0.3$
  $\rightarrow$ CDF: $|f_4^Z| < 0.12$





Conclusions

- High luminosities at Tevatron make numerous precision measurements possible:
  - W mass!
  - di-boson production (ZZ observation!) and triple gauge couplings
  - differential W/Z production cross section
- While doing EWK measurements we learn a lot about QCD:
  - constrain PDF sets and event generators
    $\Rightarrow$ will help analysis at LHC, especially in the first years
- Both CDF and DØ have $\sim 4.4\,\mathrm{fb}^{-1}$ on tape and more data will follow while we are waiting for LHC to take over.