Electroweak physics at the Tevatron

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UCL Seminar

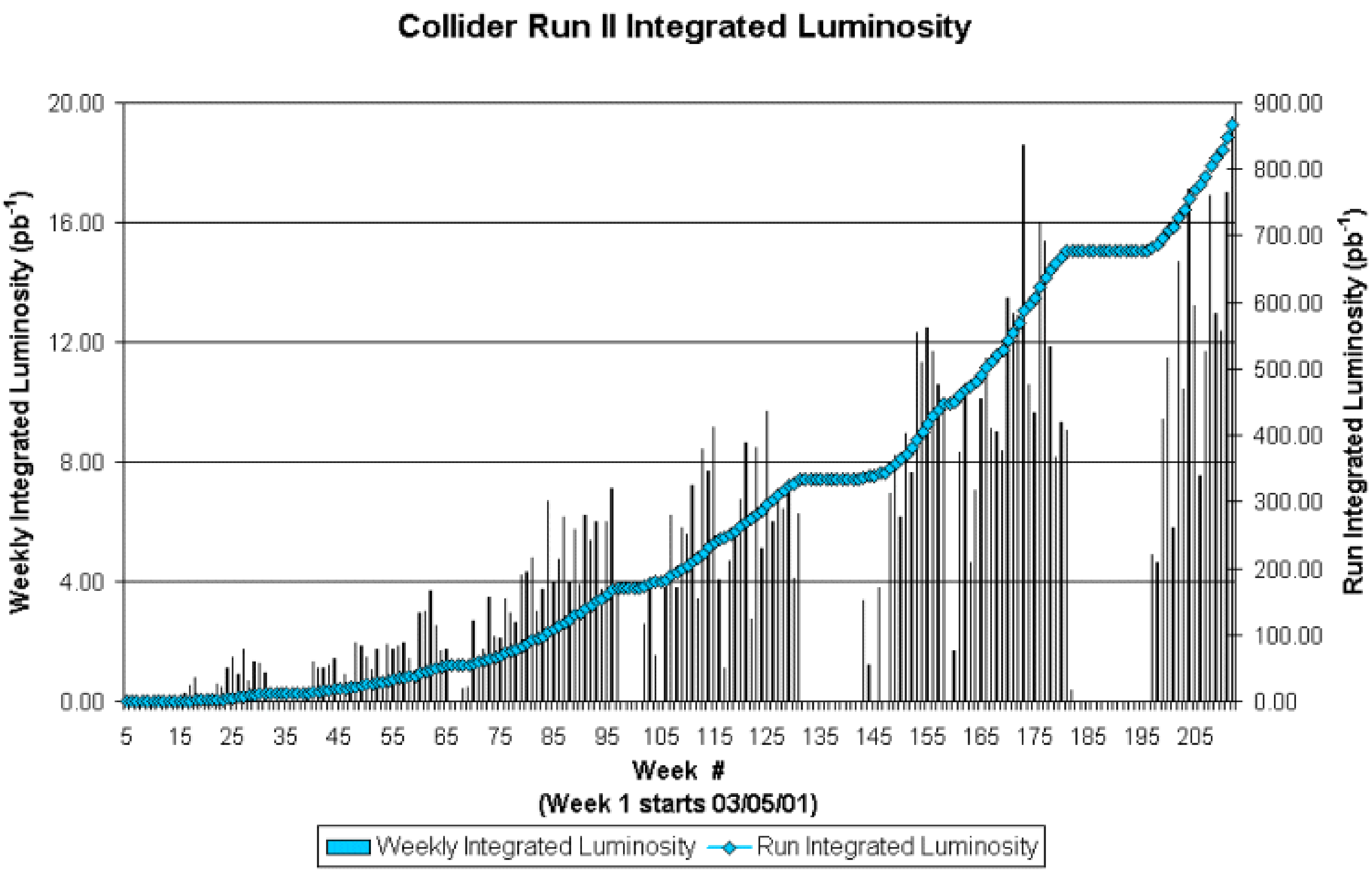
April 2005

OUTLINE

- The Tevatron, CDF and DØ
- Why study Electroweak physics at the Tevatron?
- An example Electroweak analysis: Measurement of the inclusive $p\bar{p} \to Z \to \mu^+\mu^-$ cross section at DØ
- Other Electroweak results from CDF and DØ
- Summary and Future Plans

THE TEVATRON

The highest energy accelerator in the world, collides protons with antiprotons at a centre of mass energy of 1.96 TeV.

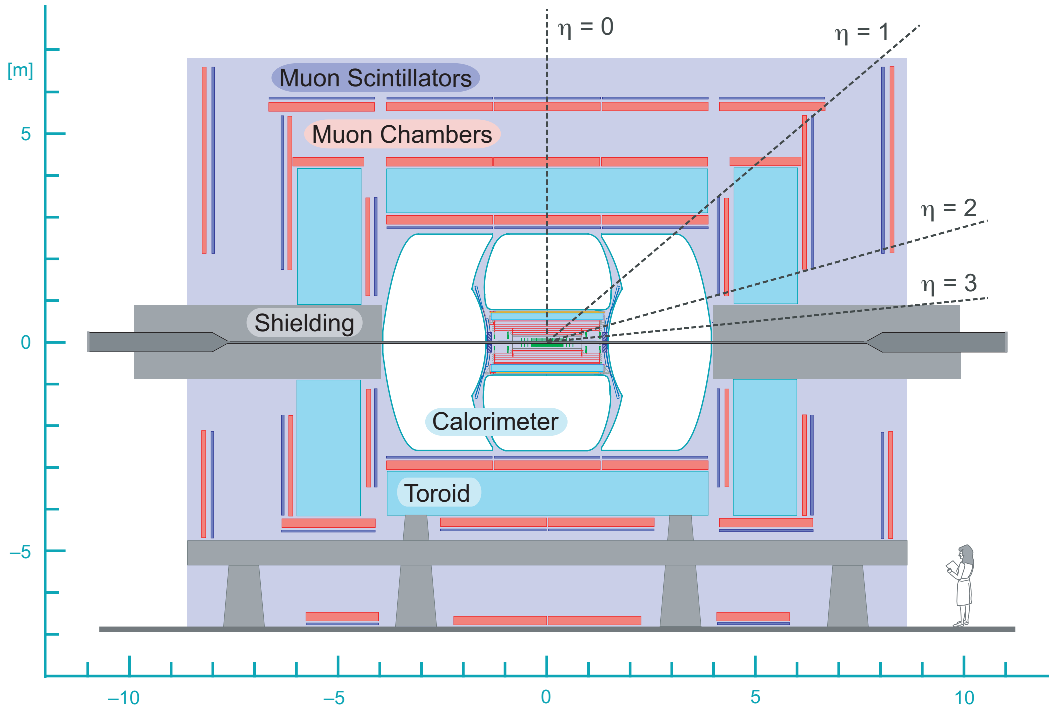


Each experiment has $\sim$0.7 fb^{-1} on tape.

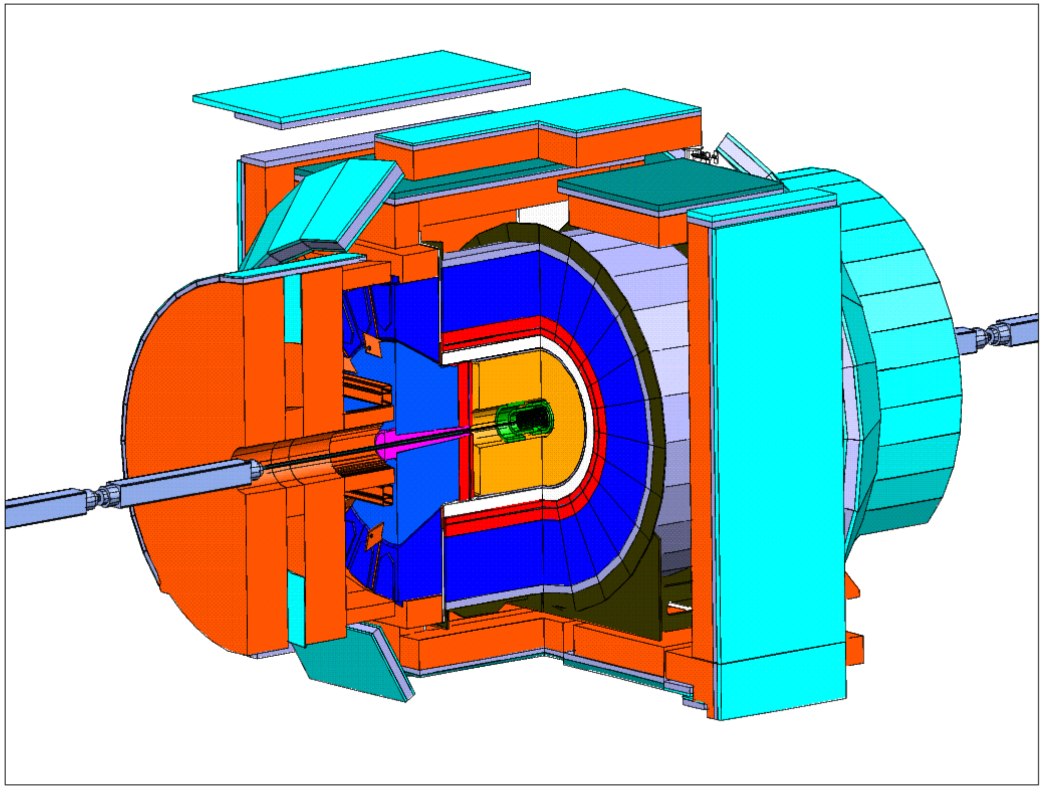
Goal is to reach 4 – 8 fb^{-1} by 2009.

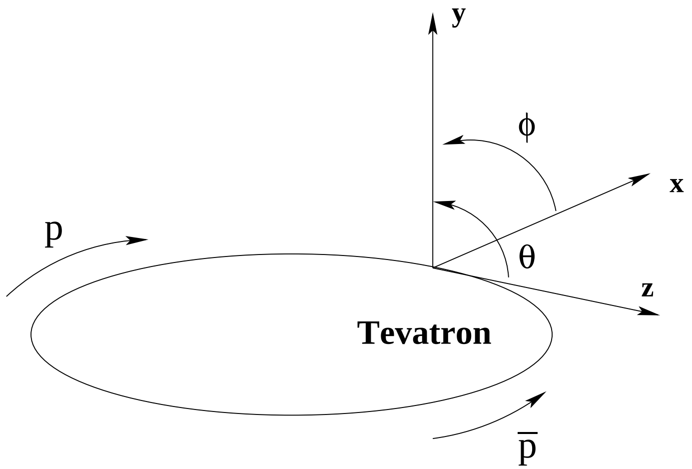
Reported analyses use 70 – 300 pb^{-1}.

DØ



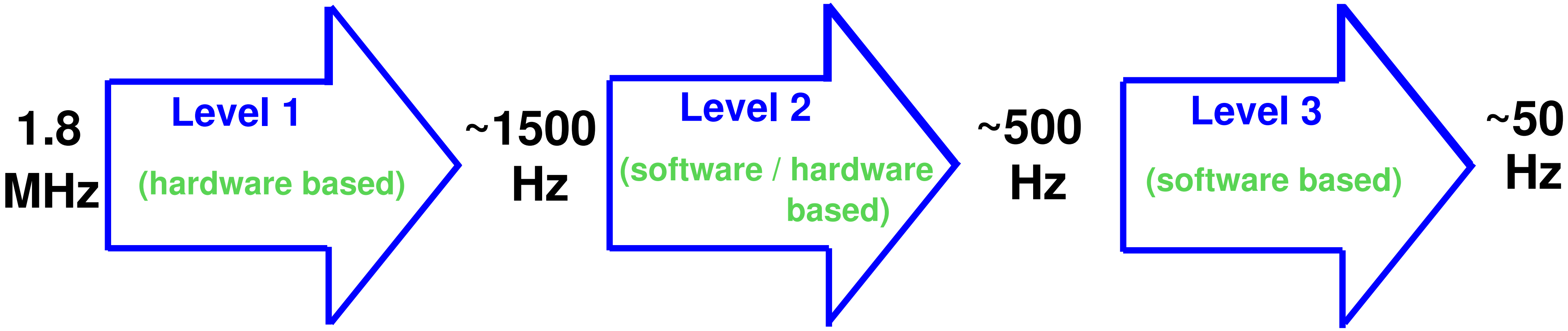
CDF





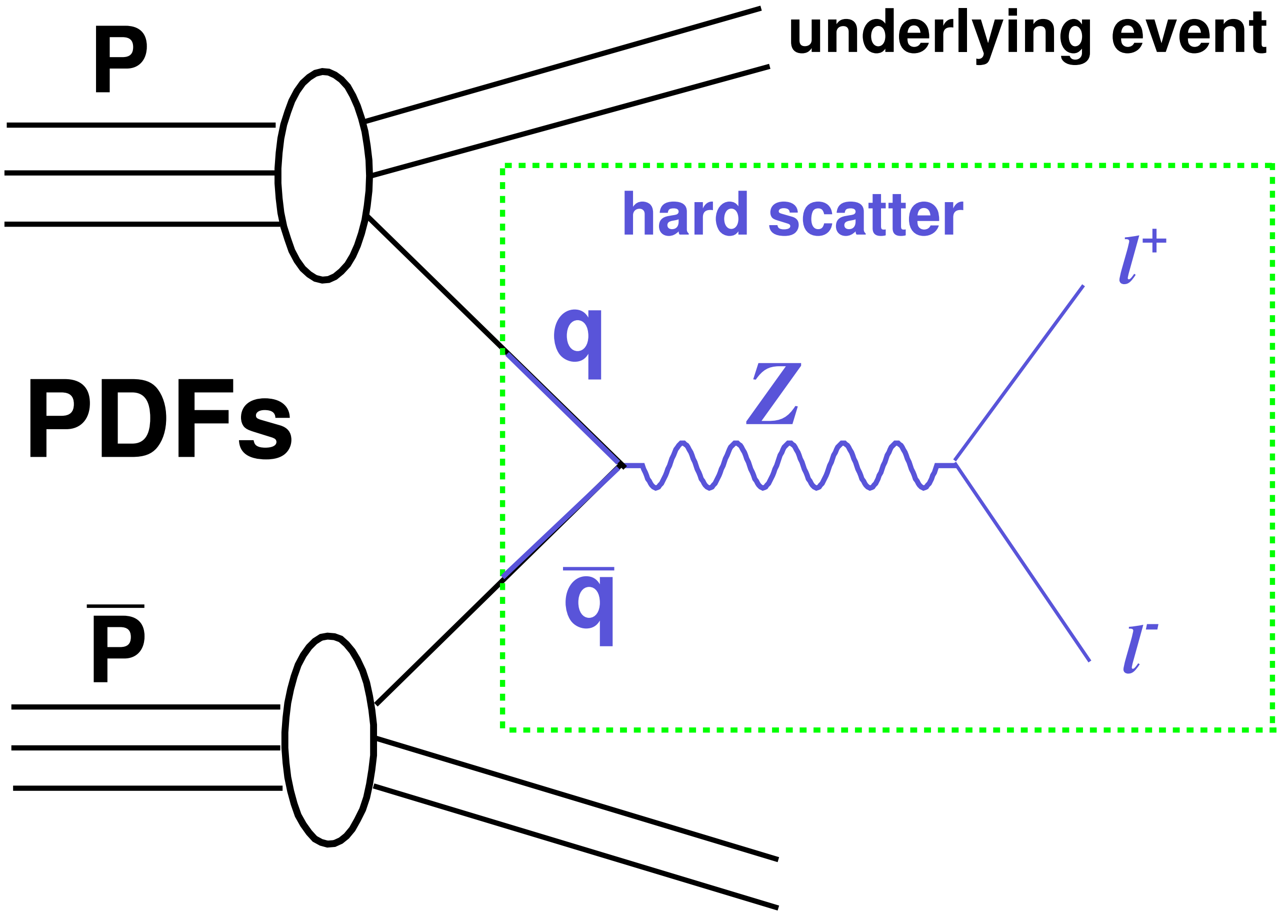
$$\eta = -\ln\left(\tan\frac{\theta}{2}\right)$$

Trigger systems at CDF and DØ



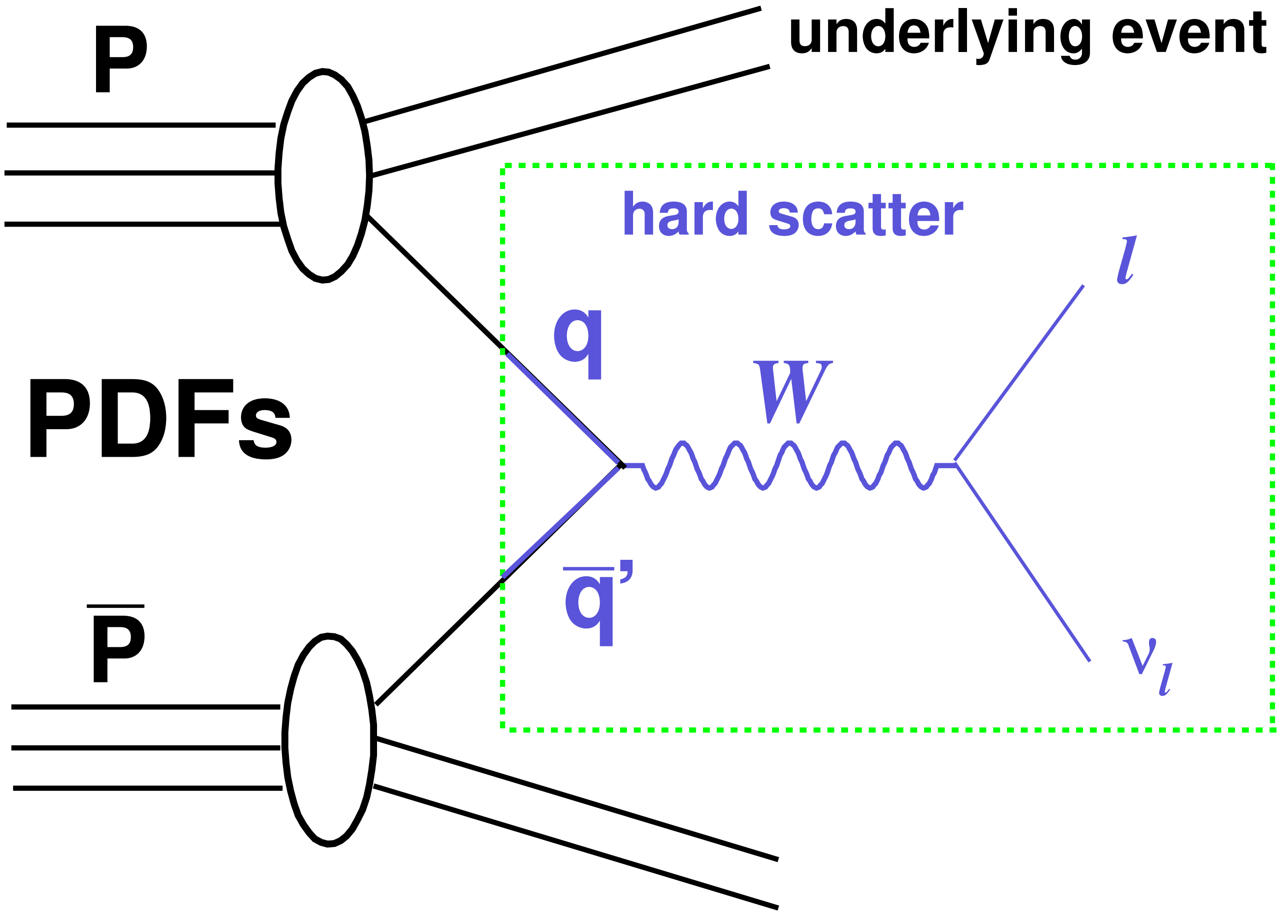
Electroweak physics ...

Z production at the Tevatron



** SIGNATURE: two high p_T charged leptons **

W production at the Tevatron



** SIGNATURE: one high p_T charged lepton, large $\not{E}_T$ **

Electroweak physics at the Tevatron

1. W and Z events as "standard candles": used to measure lepton offline identification and trigger efficiencies and set energy scales.
2. Use measured and predicted W and Z production cross sections to determine luminosity.
3. W/Z kinematics sensitive to QCD aspects of production mechanism:
   - boson p_T $\rightarrow$ testing our understanding of QCD
   - W charge asymmetry, Z rapidity $\rightarrow$ constrain PDFs
4. Electroweak precision measurements:
   - m_W, Γ_W, $\sin^2\theta_W^{eff}$
5. Find di-boson events $\rightarrow$ tri-boson vertex couplings ($WW\gamma/WWZ$)

An example electroweak analysis ...

Measurement of the inclusive $\mathrm{p\bar{p}} \rightarrow Z \rightarrow \mu^+\mu^-$ cross section at DØ

$\mathrm{p\bar{p}} \rightarrow Z \rightarrow \mu^+\mu^-$ events are *indistinguishable* from $\mathrm{p\bar{p}} \rightarrow \gamma^* \rightarrow \mu^+\mu^-$ events, therefore measure $\mathrm{p\bar{p}} \rightarrow Z/\gamma^* \rightarrow \mu^+\mu^-$ cross section with $\mathrm{M}_{\mu\mu} > 40$ GeV before correcting for all γ^* and Z/γ^* interference terms.

$$\sigma(Z/\gamma^*) = \frac{\mathrm{N}_{\mathrm{cand}}(1 - f_{bckg})}{\epsilon_{Z/\gamma^*} \int Ldt}$$

1. $\mathrm{N}_{\mathrm{cand}}$ = Number of Candidate Events: Count events with two high p_T muons that pass certain *selection criteria*.
2. f_{bckg} = Background Fraction: Estimate the remaining background after making all selection criteria.
3. ϵ_{Z/γ^*} = Total Efficiency of Selection Criteria, Triggers and Detector Acceptance.
4. $\int Ldt$ = Integrated Luminosity of Data Sample.

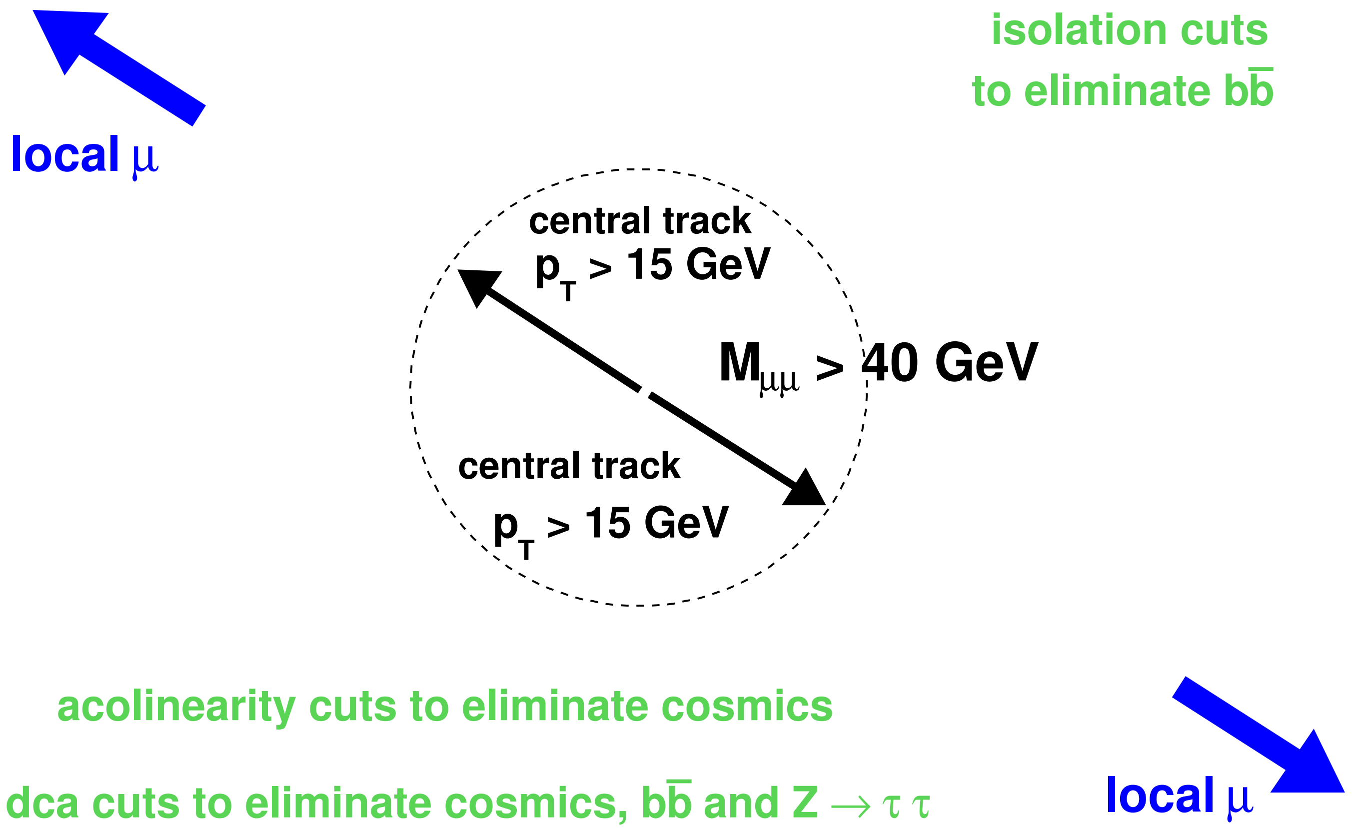
Potential backgrounds

Any event with two high p_T muons is a potential background to $Z/\gamma^* \to \mu^+\mu^-$ events:

- $p\bar{p} \to b\bar{b}$ events where both b quarks decay to muons.
- $Z/\gamma^* \to \tau^+\tau^-$ events where both taus decay to muons.
- A cosmic ray muon passing through the detector mimics two muons (one from its ingoing journey and one from its outgoing journey.)
- W + jets events with a high p_T muon inside a jet.

Selection criteria are optimised to minimise these backgrounds.

OFFLINE EVENT SELECTION

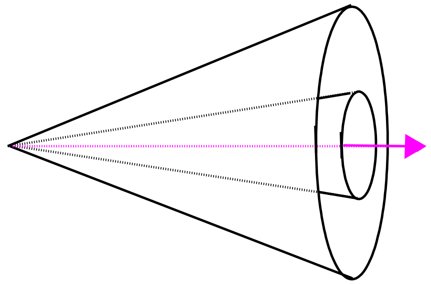


14352 candidate events (with only 1.4% background)

ISOLATION CUTS (remove $b\bar{b}$ background)

2 of the following 4 cuts are required to pass:

- Calorimeter isolation for first μ
- " " for second μ
- Central track isolation for first μ
- " " for second μ

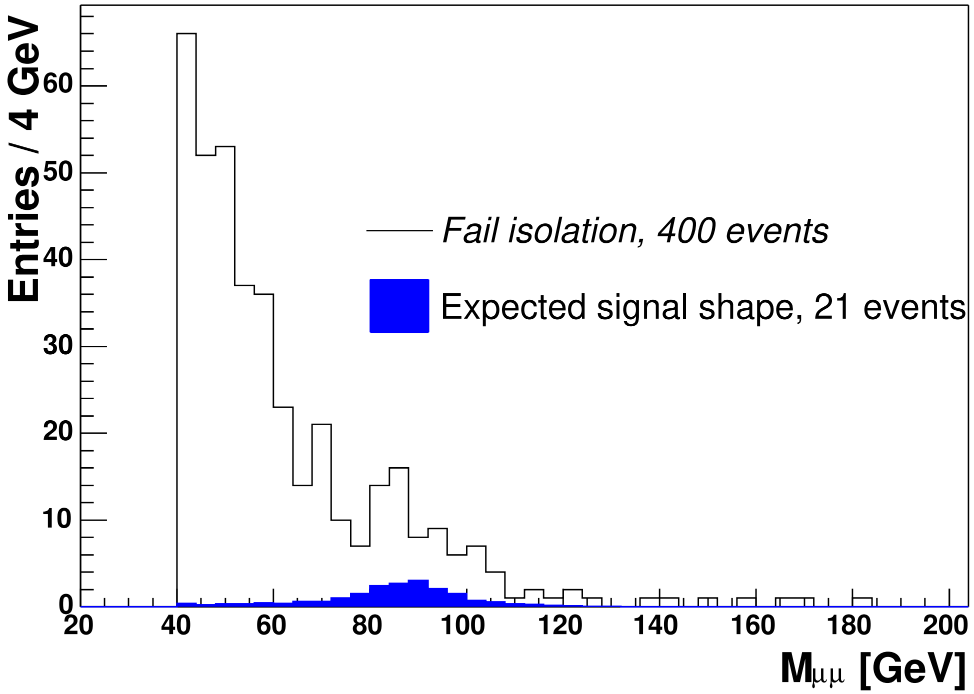


High efficiency:

$\epsilon_{\rm isol} = (99.9 \pm 0.1)\ \%$

Low background:

$f_{\rm bb} = (0.5 \pm 0.3)\ \%$



DETECTOR ACCEPTANCE AND EFFICIENCIES

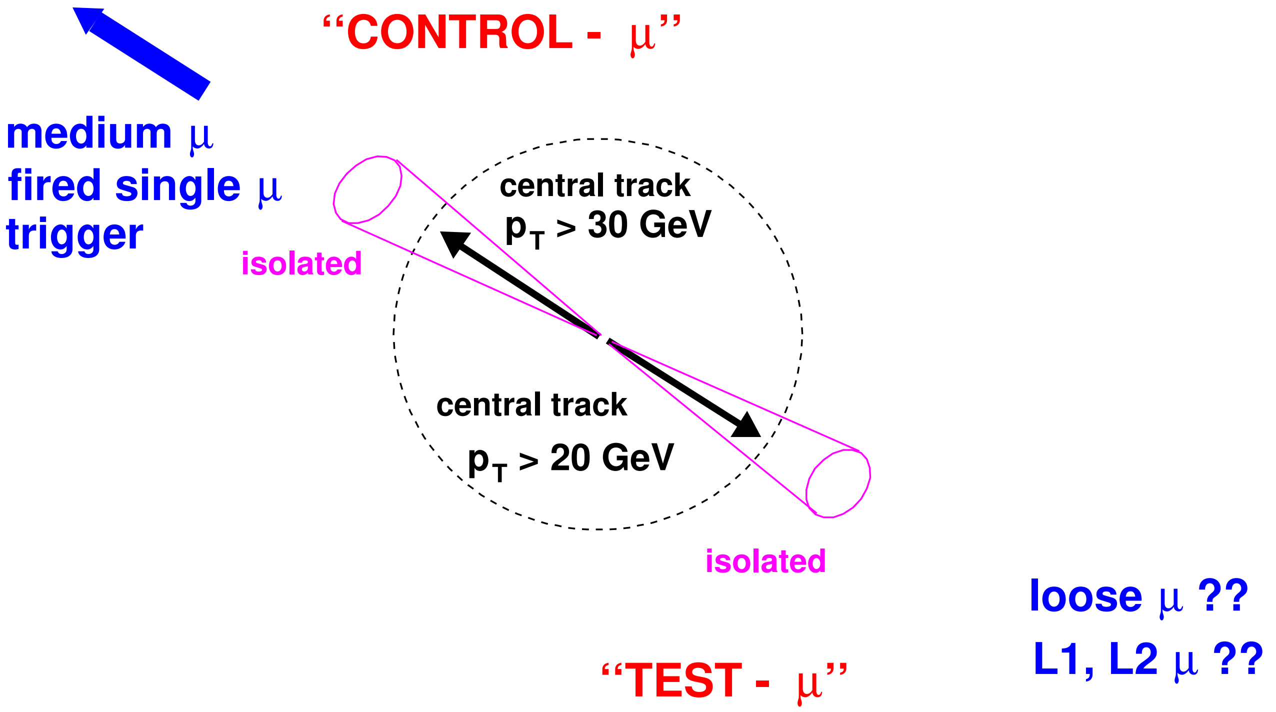
- All offline reconstruction and trigger efficiencies are measured as a function of relevant detector coordinates (e.g: η, ϕ and z of the interaction point).
- Input them into a Parameterised Monte Carlo Simulation (PMCS), using Pythia generator (with CTEQ 6M PDF sets) which then *accepts* a candidate muon according to

$$\varepsilon_{track}(\eta, z) \times \varepsilon_{muon}(\eta, \phi) \times \ldots.$$

- PMCS outputs an acceptance, ϵ_{MC}, which includes kinematic cuts, all inputted efficiencies and the geometrical acceptance of the detector.

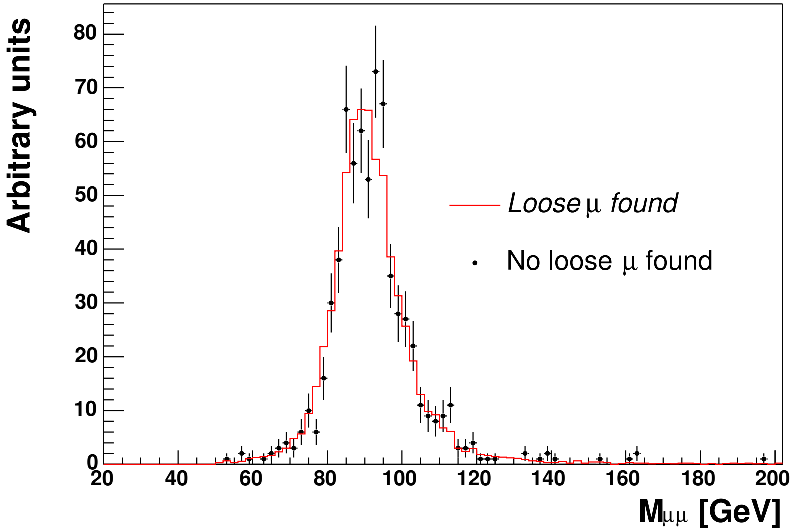
LOCAL MUON ID AND TRIGGER EFFICIENCIES

Select a sample of pure $Z/\gamma^* \to \mu^+\mu^-$ events without the requirement that both muons are reconstructed in the muon chambers.

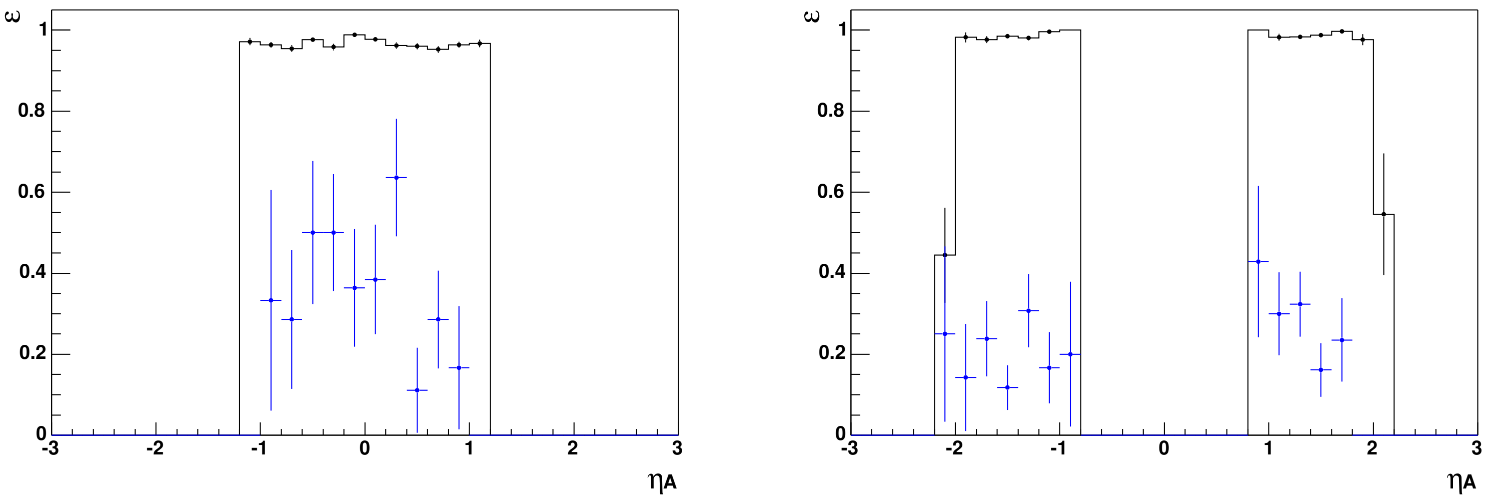


Average efficiency: $\epsilon_{\mathrm{loose}} = (93.9 \pm 0.2)\ \%$

Check purity in *inefficient* sample:



Efficiency as a function of η:



blue: inside muon chamber boundaries

black: outside muon chamber boundaries

INTEGRATED LUMINOSITY

$$\int L dt = \frac{N_{\mathrm{p\bar{p}}}}{\varepsilon_{\mathrm{LM}}\sigma_{\mathrm{p\bar{p}}}}$$

1. $\mathrm{N}_{\mathrm{p\bar{p}}}$ = Number of inelastic $\mathrm{p\bar{p}}$ collisions: measured by Luminosity Monitor which detects the charged remnants of the proton and antiproton after a collision.

2. $\varepsilon_{\mathrm{LM}}$ = Efficiency and acceptance of the Luminosity Monitor.

3. $\sigma_{\mathrm{p\bar{p}}}$ = $\mathrm{p\bar{p}}$ inelastic cross section: measured by the E811 and CDF experiments at $\sqrt{s} = 1.8$ TeV and extrapolated to 1.96 TeV.

$$\int L dt = 148 \text{ pb}^{-1}.$$

MAIN SYSTEMATIC UNCERTAINTIES

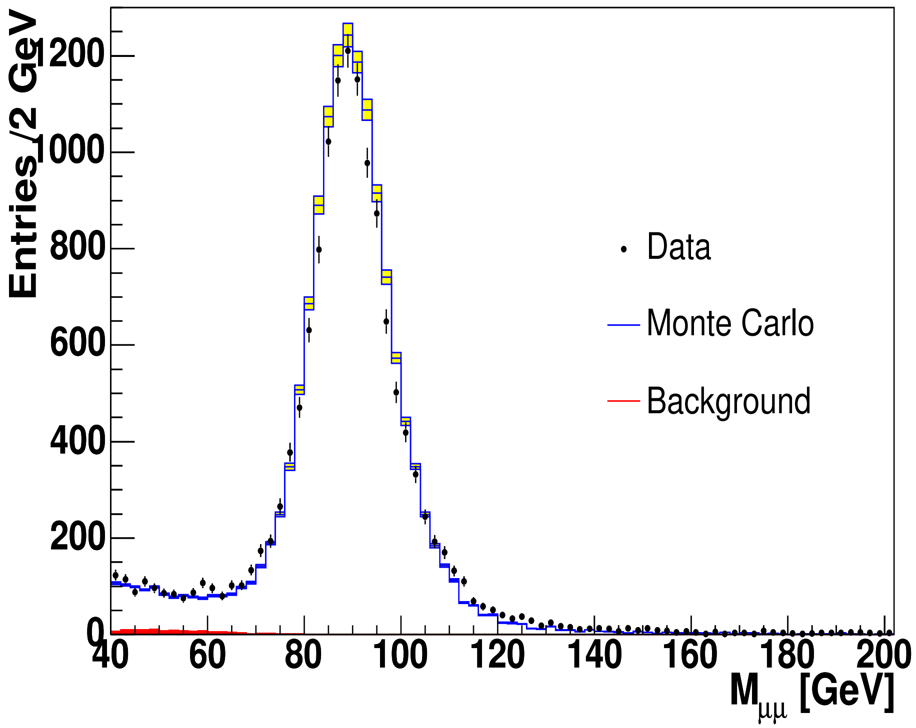
1. luminosity (6.5%): due to the uncertainty on $\sigma_{\mathrm{p\bar{p}}}$ and $\varepsilon_{\mathrm{LM}}$.
2. PDFs (1.7%): evaluated using the 40 CTEQ 6 PDF error sets (20 parameters are varied up and down within their uncertainties).
3. GEANT Monte Carlo (1.1%): The acceptance is re-evaluated using a Monte Carlo simulation that has been passed through a full GEANT simulation of the DØ detector, the difference is a systematic.
4. muon chamber boundary definition (1.0%): The definition of the position of the boundaries is varied by 50%.

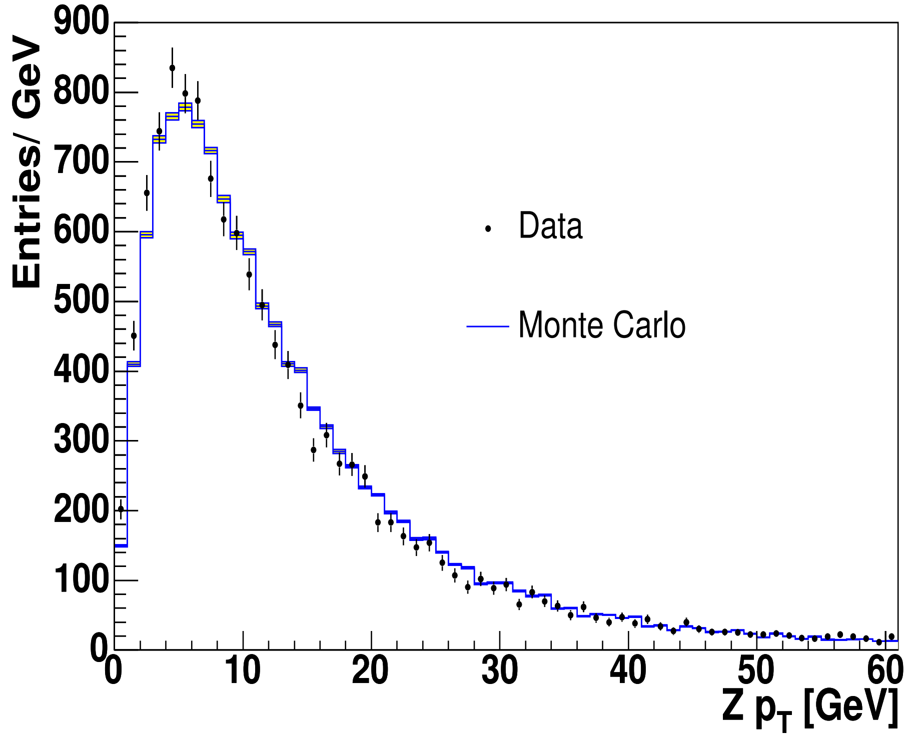
RESULTS (DØ Run II preliminary)

$$\sigma(Z/\gamma^*) = 327.8 \pm 3.4(\text{stat.}) \pm 8.4(\text{syst.}) \pm 21.3(\text{lumi.})\ \text{pb}$$
$$\sigma(Z) = 290.1 \pm 3.0(\text{stat.}) \pm 7.4(\text{syst.}) \pm 18.9(\text{lumi.})\ \text{pb}$$

$$[\text{CDF}: \quad \sigma(Z) = 253.1 \pm 4.2(\text{stat.})\ {}^{+8.3}_{-6.4}(\text{syst.}) \pm 15.2(\text{lumi.})\ \text{pb}]$$

SM NNLO : 252 ± 9 pb[1]





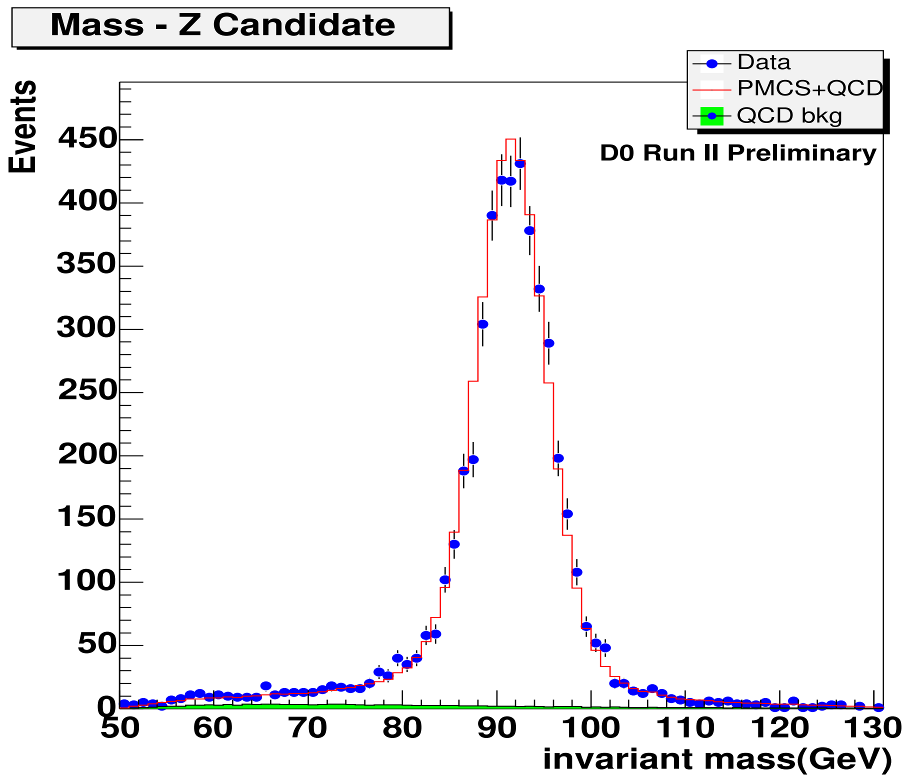
Other electroweak results from the Tevatron ...

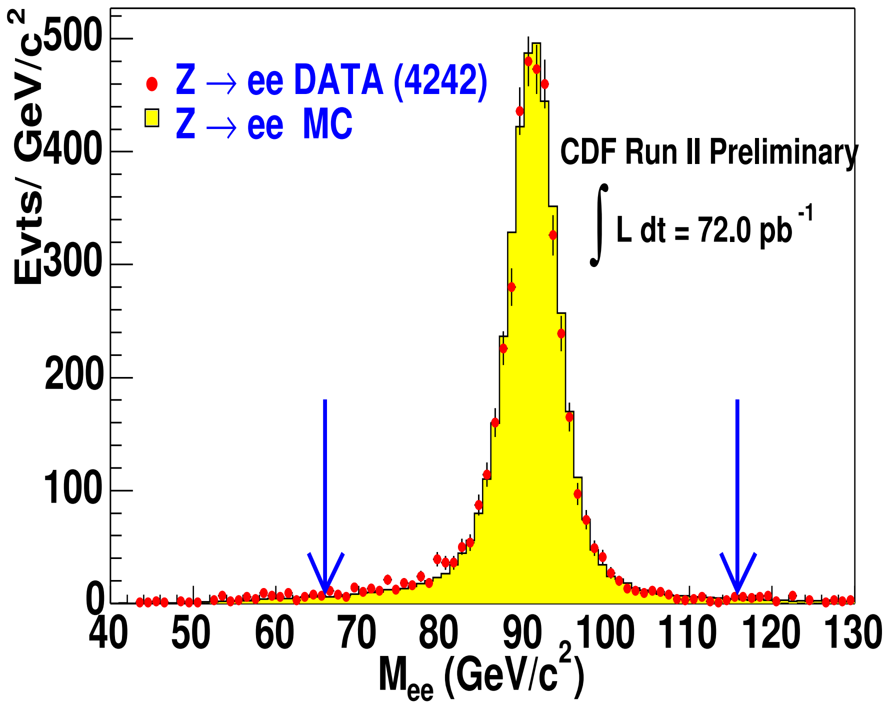
Other electroweak results from the Tevatron

1. Other W and Z cross sections: $Z \to e^+e^-$, $Z \to \tau^+\tau^-$, $W \to \mathrm{e}\nu$, $W \to \mu\nu$ and $W \to \tau\nu$. These give an indirect measurement of the W width.
2. Direct measurement of W width.
3. Z rapidity
4. W charge asymmetry
5. Forward-backward asymmetry in $\mathrm{p\bar{p}} \to Z/\gamma^* \to e^+e^-$ events: $\sin^2\theta_W^{eff}$.
6. Di-boson ($W\gamma/Z\gamma/WW/WZ/ZZ$) production cross sections.

σ for $Z \rightarrow e^+e^-$

SIGNATURE : e^+e^- pair, high p_T





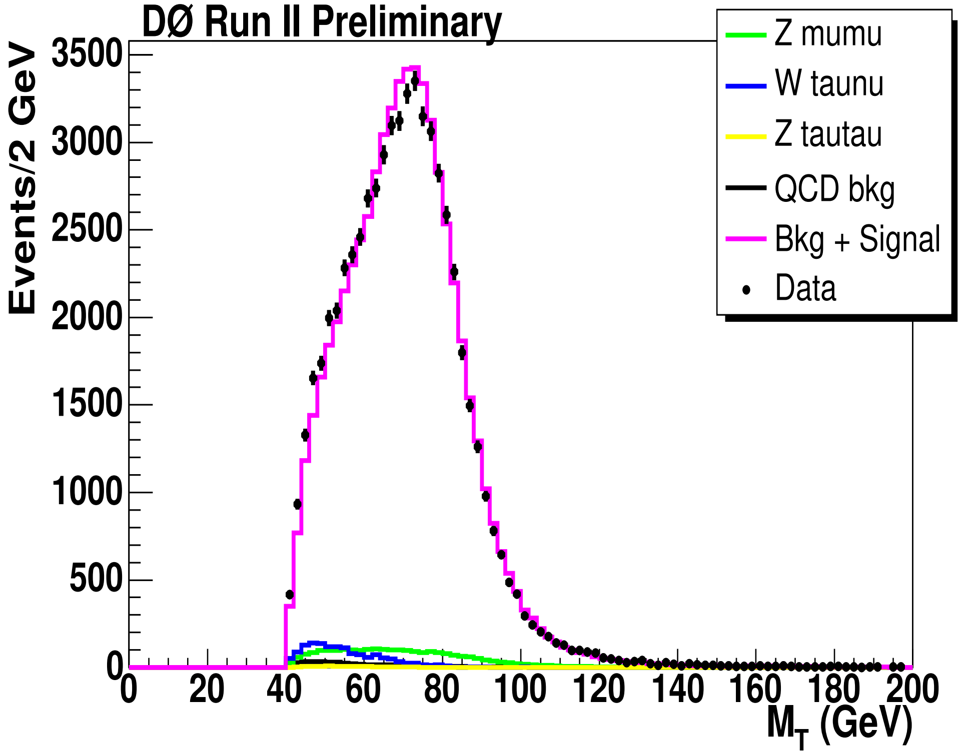
DØ : $\sigma = 264.9 \pm 3.9(\text{stat.}) \pm 9.9(\text{syst.}) \pm 17.2(\text{lumi.})$ pb

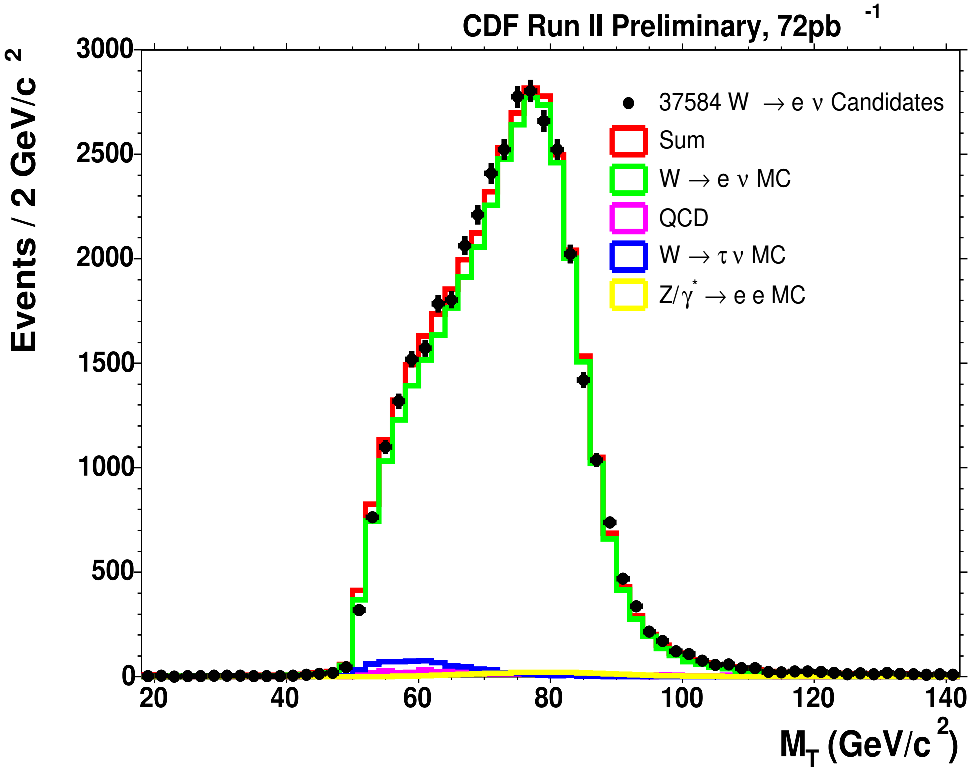
CDF : $\sigma = 255.8 \pm 3.9(\text{stat.}) \pm 5.5(\text{syst.}) \pm 15.4(\text{lumi.})$ pb

SM NNLO : 252 ± 9 pb[1]

σ for $W \to \mu\nu$ and $W \to e\nu$

SIGNATURE : high p_T, isolated lepton, high $\not{E}_T$





DØ : $\sigma(W \to \mu\nu) = 2989 \pm 15(\text{stat.}) \pm 81(\text{syst.}) \pm 194(\text{lumi.})$ pb

CDF : $\sigma(W \to \mu\nu) = 2786 \pm 12(\text{stat.}) {}^{+65}_{-55}(\text{syst.}) \pm 166(\text{lumi.})$ pb

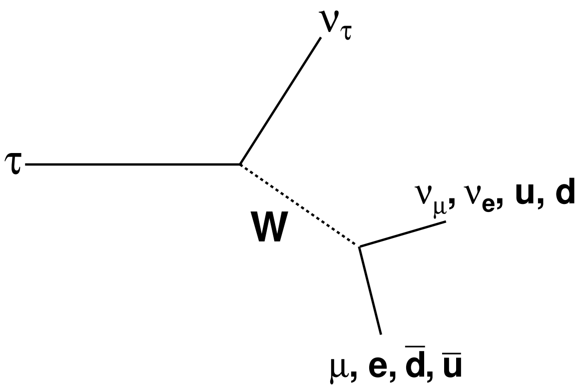
DØ : $\sigma(W \to e\nu) = 2865 \pm 8(\text{stat.}) \pm 74(\text{syst.}) \pm 186(\text{lumi.})$ pb

CDF : $\sigma(W \to e\nu) = 2782 \pm 14(\text{stat.}) {}^{+61}_{-56}(\text{syst.}) \pm 167(\text{lumi.})$ pb

SM NNLO : 2720 ± 100 pb[1]

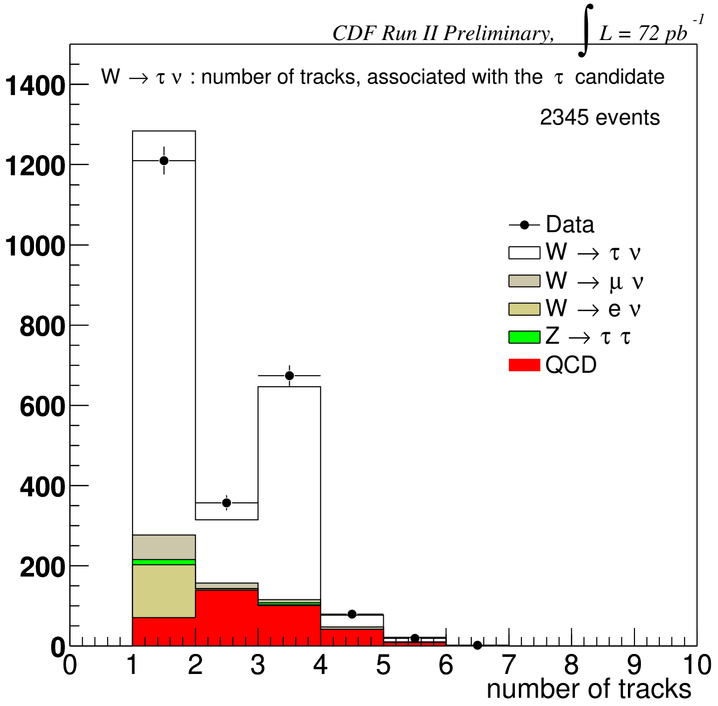
σ for $W \to \tau\nu$ and $Z \to \tau^+\tau^-$

τ will quickly decay. Predominantly to a ν_τ and hadrons.



$Z \to \tau^+\tau^-$ SIGNATURE (one leptonic, one hadronic decay):

isolated lepton, narrow jet with 1 or 3 tracks.



$W \to \tau\nu$ SIGNATURE (hadronic decay):

large $\not{E}_T$, narrow jet with 1 or 3 tracks.

CDF : $\sigma(Z) = 242 \pm 48(\text{stat.}) \pm 26(\text{syst.}) \pm 15(\text{lumi.})$ pb

DØ : $\sigma(Z) = 237 \pm 15(\text{stat.}) \pm 18(\text{syst.}) \pm 15(\text{lumi.})$ pb

CDF : $\sigma(W) = 2620 \pm 70(\text{stat.}) \pm 210(\text{syst.}) \pm 160(\text{lumi.})$ pb

Indirect W width determination

Increased precision of W width measurement places constraints on non SM W decays.

$$R = \frac{\sigma\,(W \to l\,\nu\,)}{\sigma(Z \to l^+ l^-)}$$

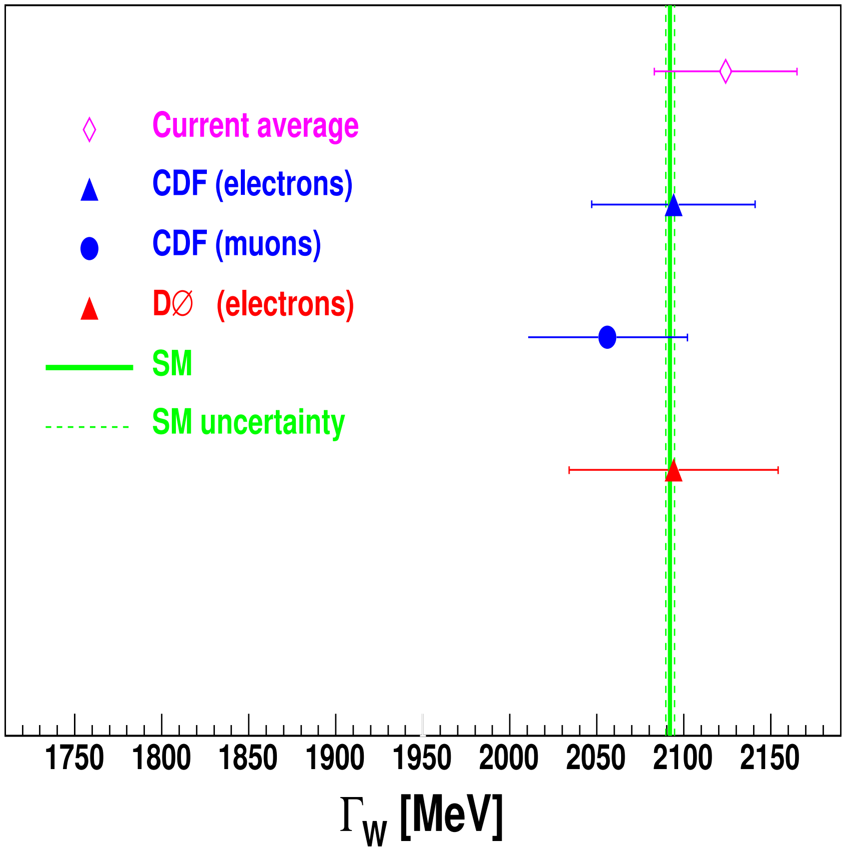
NNLO calculation

LEP

$$R = \frac{\sigma_W}{\sigma_Z}\,\frac{BR(W \to l\nu)}{BR(Z \to l^+ l^-)}$$

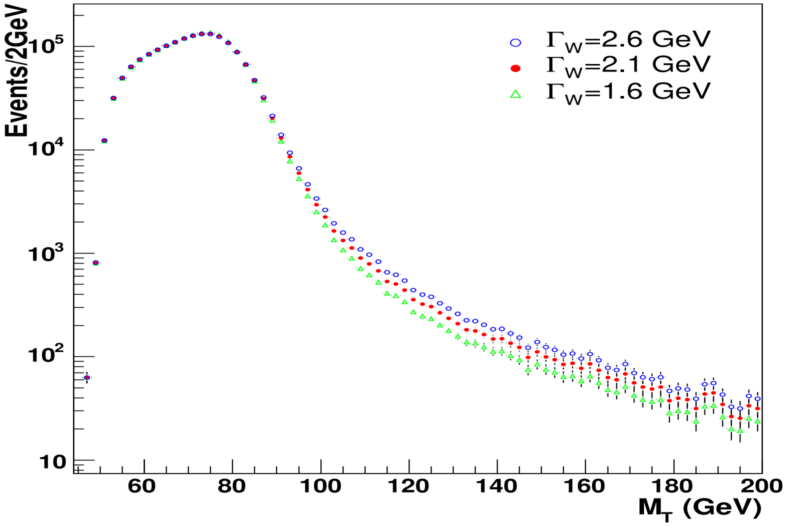
SM

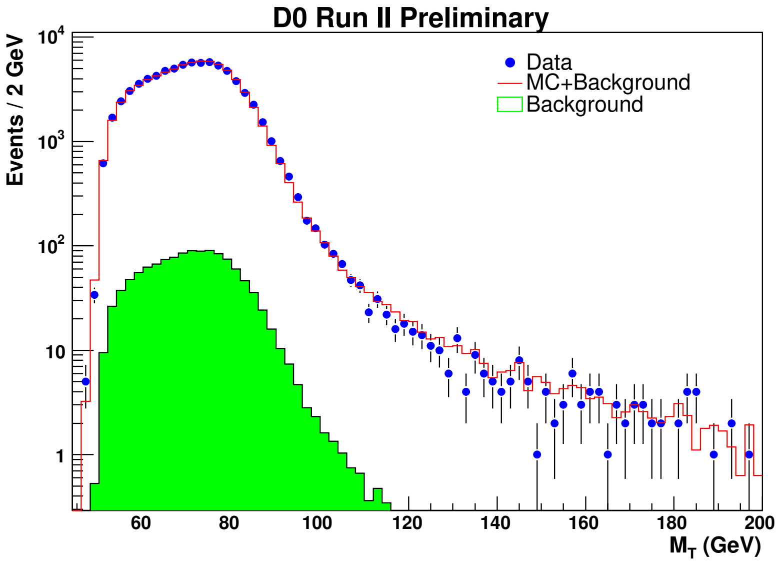
$$BR(W \to l\nu) = \frac{\Gamma(W \to l\nu)}{\Gamma_W}$$

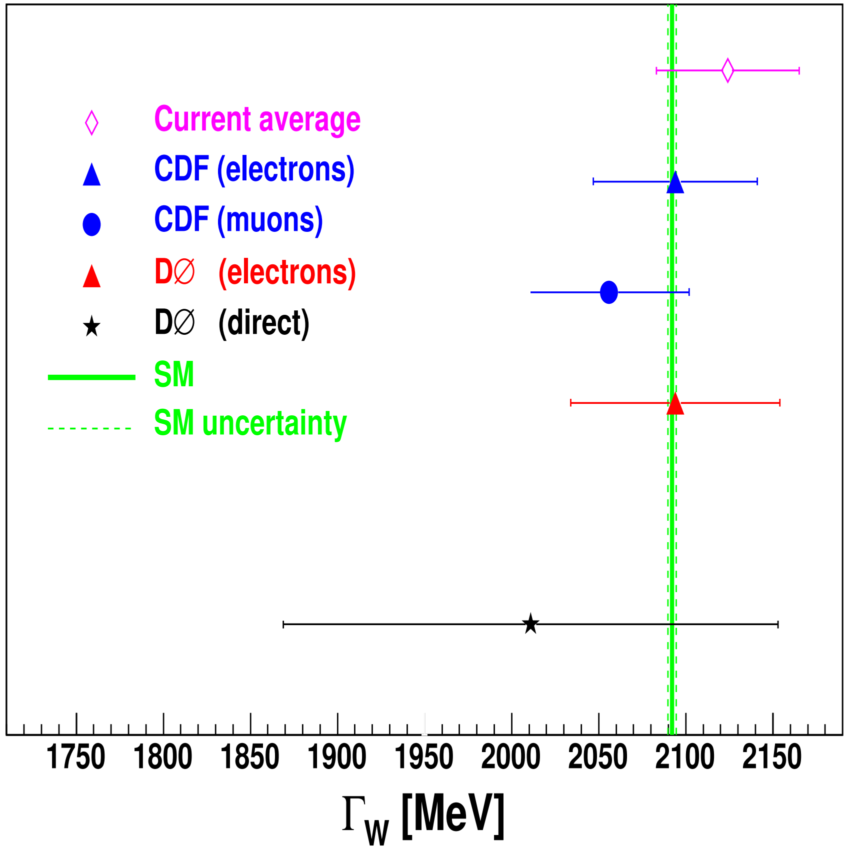


Indirect and direct *W* width determination

The width can also be determined directly from the W transverse mass distribution.

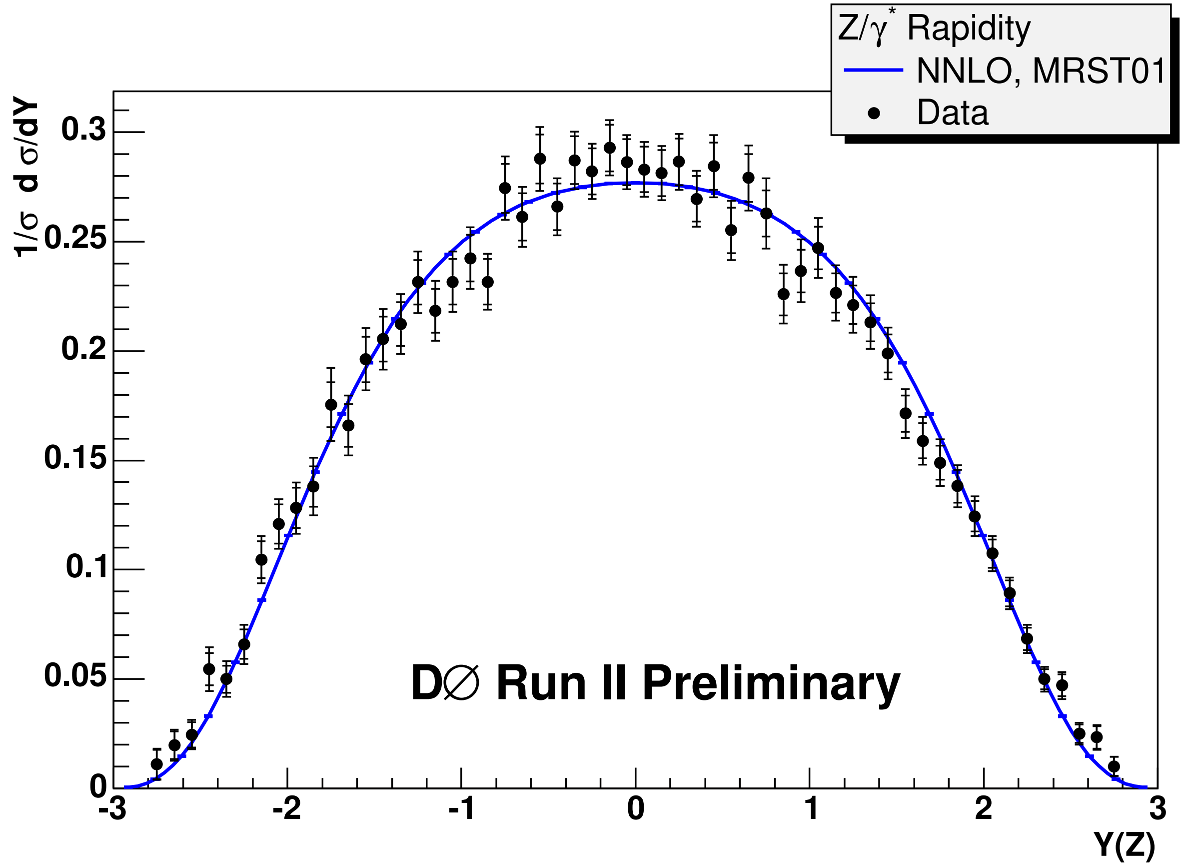






Z rapidity in $Z \to e^+e^-$ events

Since partons carry a varying amount of their parent hadron's momentum, the detectors are not necessarily in the centre of mass frame of each collision $\to$ Z bosons are produced with non zero rapidity.



Constrains PDFs at high Q^2.

Charge asymmetry in $W \rightarrow e\nu$ events

- u quarks carry more momentum than d quarks
- $u\bar{d} \rightarrow W^+$ tends to be boosted in proton direction
- $d\bar{u} \rightarrow W^-$ tends to be boosted in antiproton direction

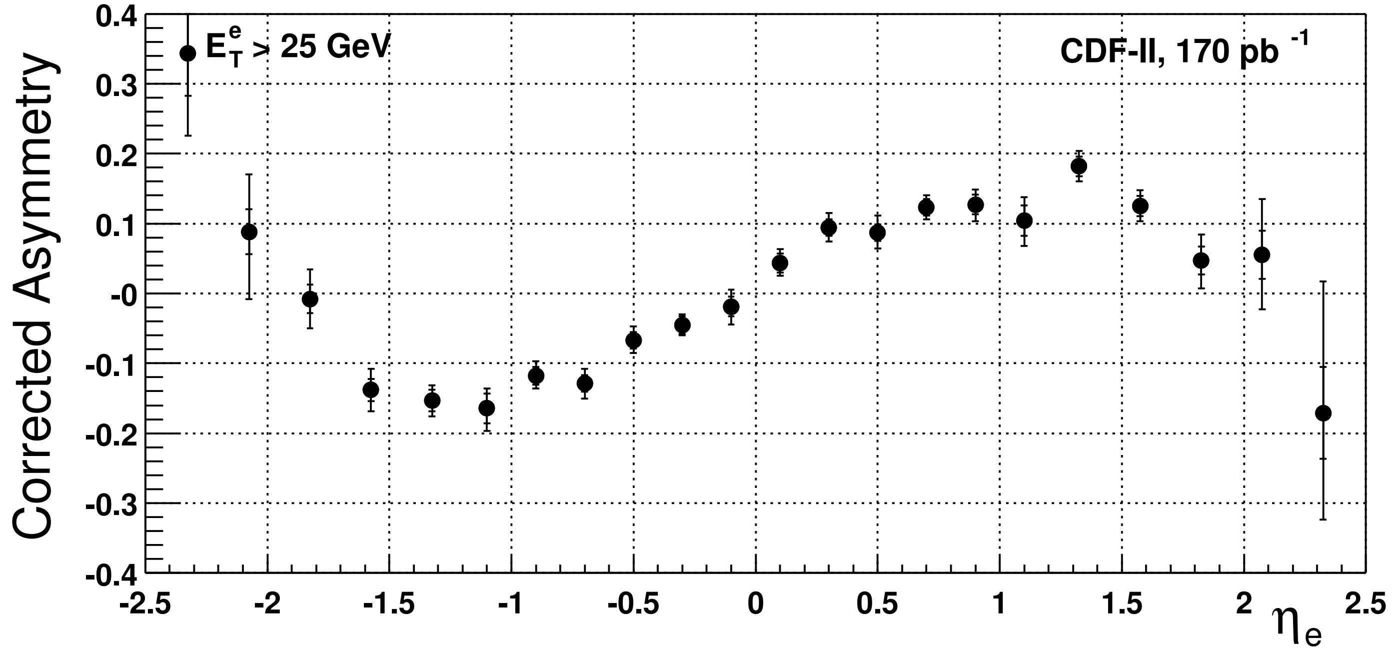
$$A(y) = \frac{d\sigma(W^+)/dy - d\sigma(W^-)/dy}{d\sigma(W^+)/dy + d\sigma(W^-)/dy}$$

HOWEVER... cannot reconstruct W rapidity due to neutrino

Instead measure electron charge asymmetry for $W \rightarrow e\nu$ events.

$$A_l(\eta) = \frac{d\sigma(e^+)/d\eta - d\sigma(e^-)/d\eta}{d\sigma(e^+)/d\eta + d\sigma(e^-)/d\eta}$$

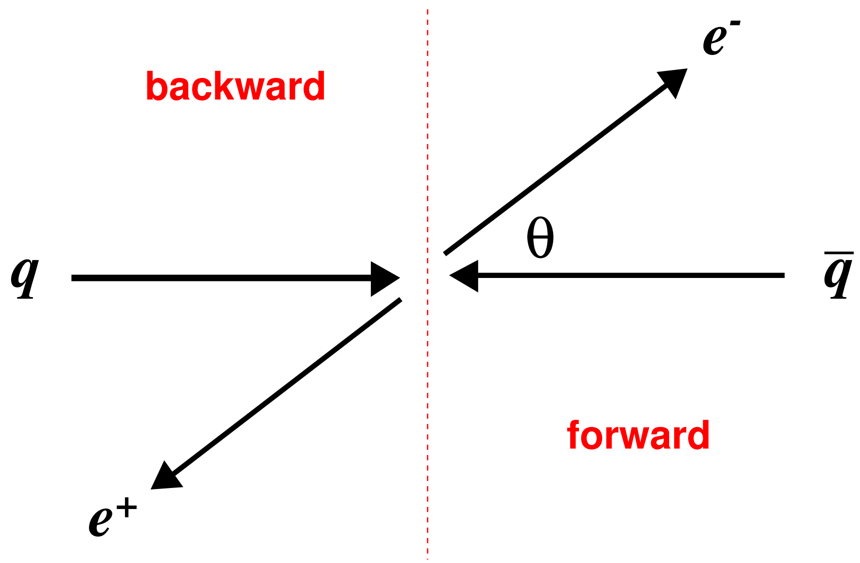
There is also an asymmetry due to the vector-axial coupling of the W to fermions, assuming this is well described $\rightarrow$ constrains the $\frac{d(x)}{u(x)}$ PDF.



Forward-backward asymmetry in $p\bar{p} \rightarrow Z/\gamma^* \rightarrow e^+e^-$ events

γ^* coupling to fermions is pure vector.

Z coupling to fermions has both axial-vector and vector components.



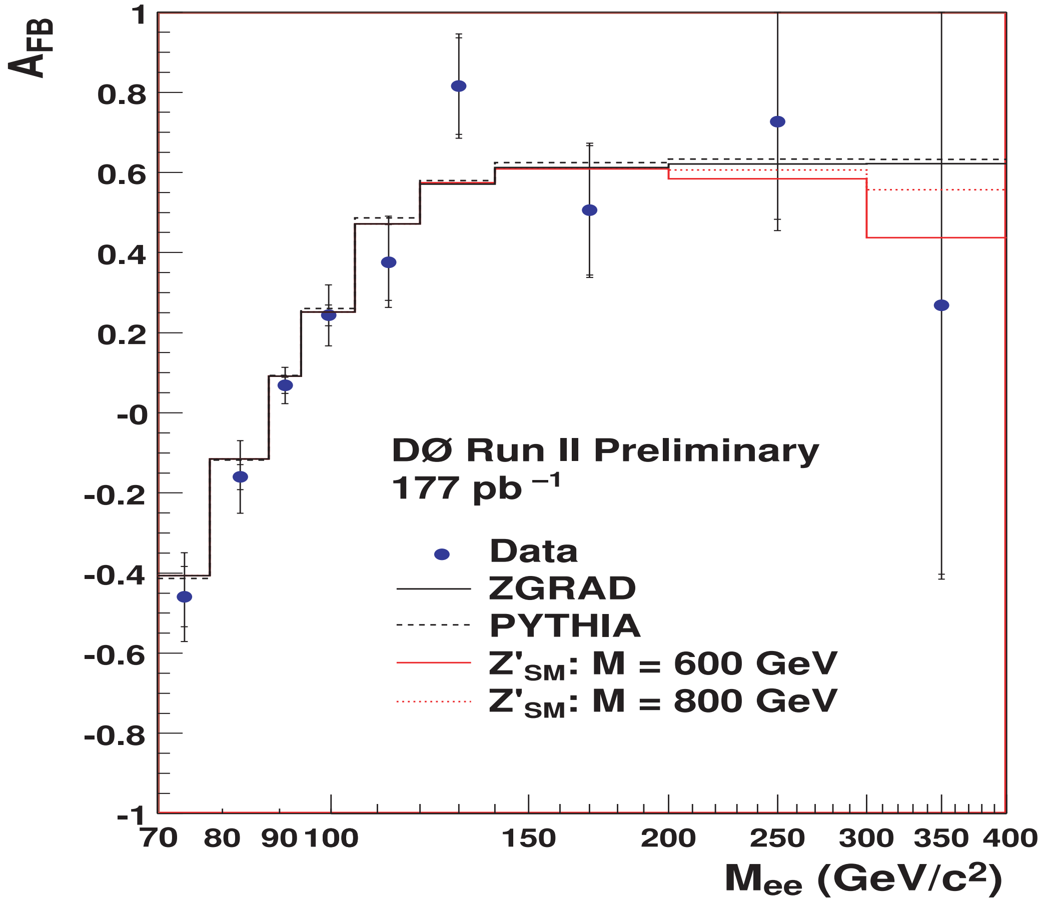
This gives rise to an asymmetry in θ defined as:

$$A_{FB} = \frac{\sigma_F - \sigma_B}{\sigma_F + \sigma_B}$$

where σ_F is the forward cross section and σ_B is the backward cross section.

A_{FB} is dependent on M_{ee}.

A_{FB} in the large M_{ee} region is sensitive to the existence of new neutral gauge bosons or large extra dimensions.

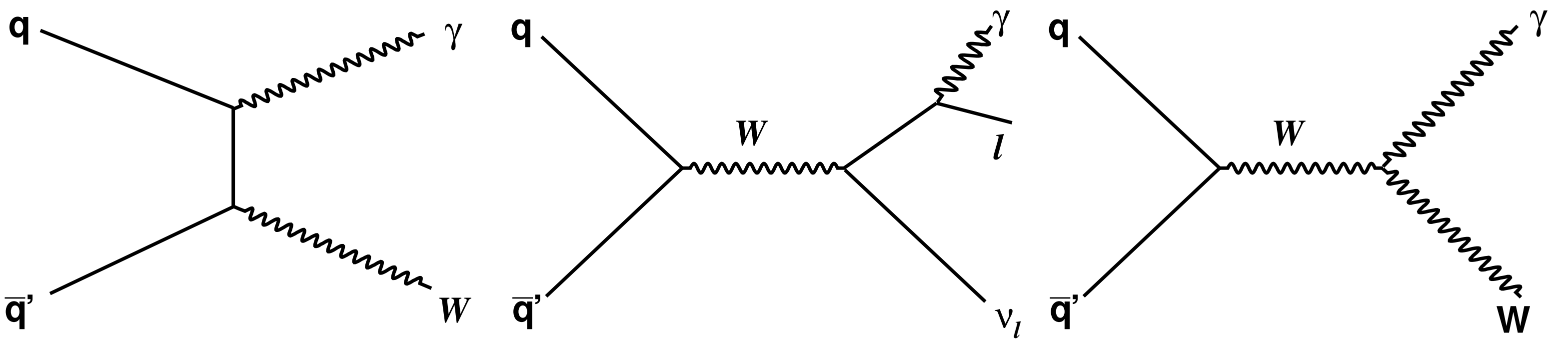


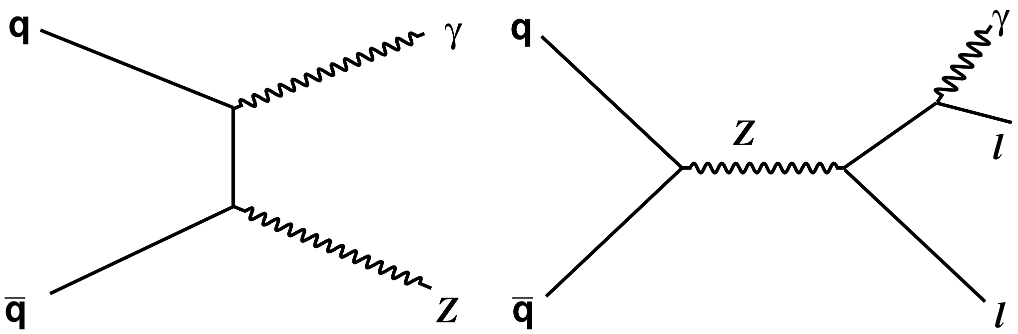
A_{FB} at the Z pole is sensitive to $\sin^2\theta_W^{eff}$.

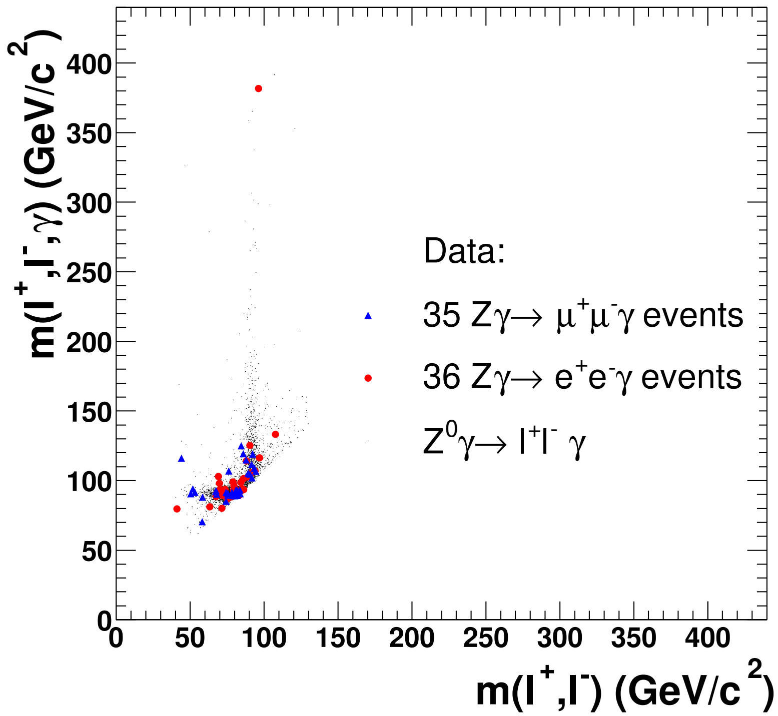
$$\text{CDF}: \sin^2\theta_W^{eff} = 0.2238 \pm 0.0050$$

$$\text{current average} = 0.23150 \pm 0.00016$$

$W\gamma \to \ell\nu\gamma$, $Z\gamma \to \ell^+\ell^-\gamma$ events







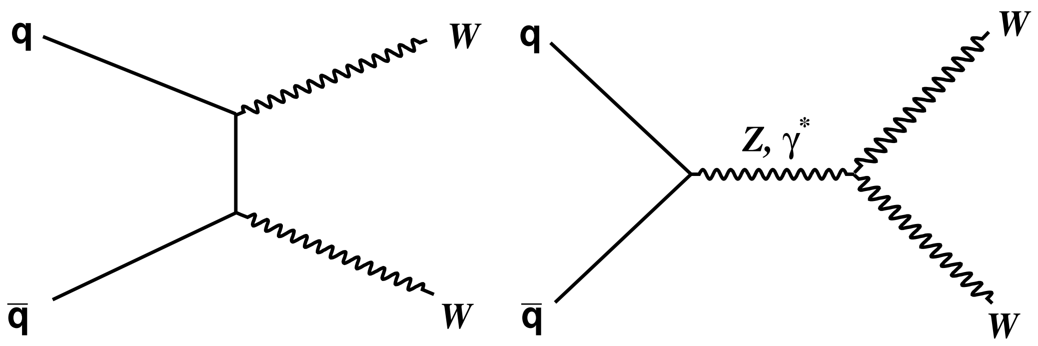
$\mathbf{W}\gamma \to \ell\nu\gamma$, $\mathbf{Z}\gamma \to \ell^+\ell^-\gamma$ events contd...

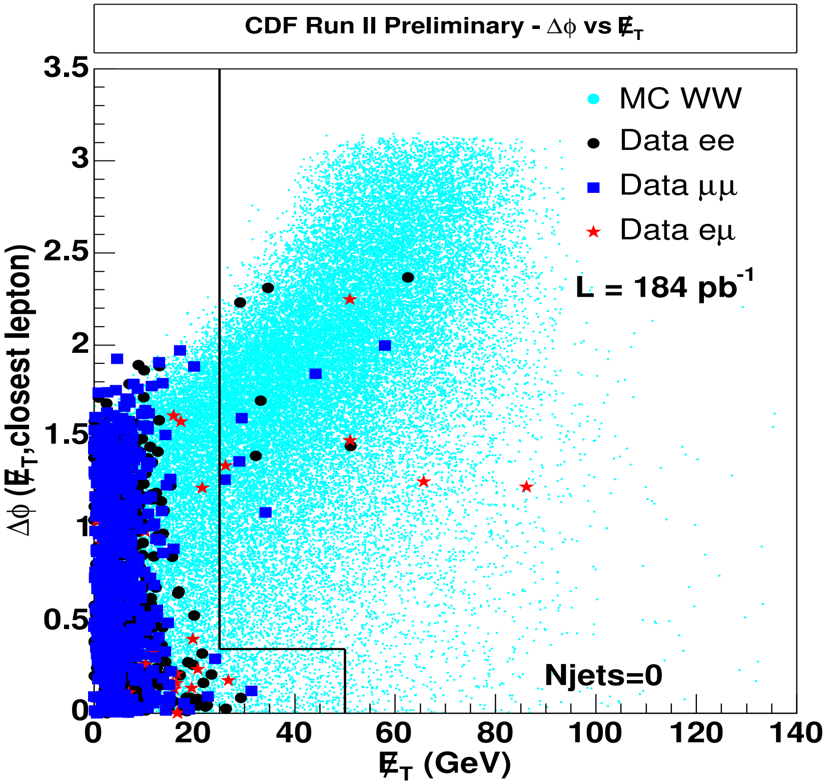
γ required to be well separated from lepton
to suppress contribution from final state bremsstrahlung

DØ : $\Delta R_{\gamma,l} > 0.7$, $E_T(\gamma) > 8$ GeV.
CDF : $\Delta R_{\gamma,l} > 0.7$, $E_T(\gamma) > 7$ GeV.

		(stat.)	(syst.)	(lumi.)	theory (Baur MC)
DØ :	σ (Wγ) = 14.8	$\pm$ 1.6	$\pm$ 1.0	$\pm$ 1.0 pb	(16.0 $\pm$ 0.4 pb)
CDF :	σ (Wγ) = 18.1	$\pm$ 1.6	$\pm$ 2.4	$\pm$ 1.2 pb	(19.3 $\pm$ 1.4 pb)
DØ :	σ (Zγ) = 4.2	$\pm$ 0.4		$\pm$ 0.3 pb	($3.9\ ^{+0.1}_{-0.2}$ pb)
CDF :	σ (Zγ) = 4.6	$\pm$ 0.5	$\pm$ 0.2	$\pm$ 0.3 pb	(4.5 $\pm$ 0.3 pb)

$WW \to \ell^+\ell^-\nu\nu$ events



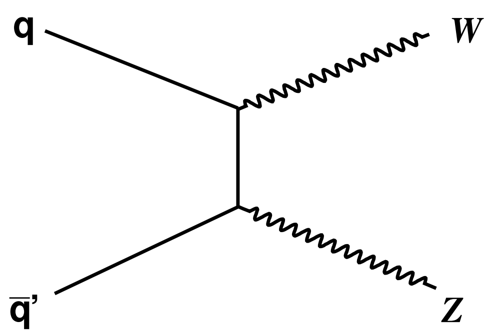


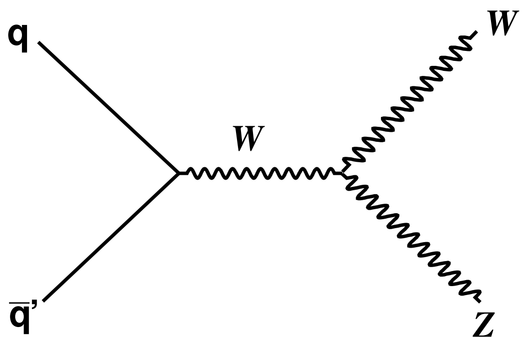
CDF : $\sigma = 14.6\ ^{+5.8}_{-5.1}(\mathrm{stat})\ ^{+1.8}_{-3.0}(\mathrm{syst}) \pm 0.9(\mathrm{lumi})$ pb

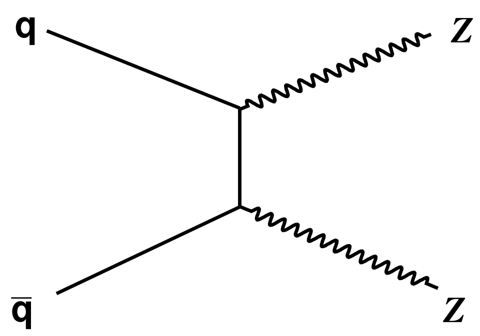
DØ : $\sigma = 13.8\ ^{+4.3}_{-3.8}(\mathrm{stat})\ ^{+1.2}_{-0.9}(\mathrm{syst}) \pm 0.9(\mathrm{lumi})$ pb

Theory (Baur MC) : 12.4 ± 0.8 pb

$\mathbf{WZ \rightarrow \ell\nu\ell^+\ell^-}$ and $\mathbf{ZZ \rightarrow \ell^+\ell^-\ell^+\ell^-}$ events







CDF : σ (WZ + ZZ) $<$ 15.2 pb @ 95% confidence level.

Theory : 5.0 ± 0.4 pb

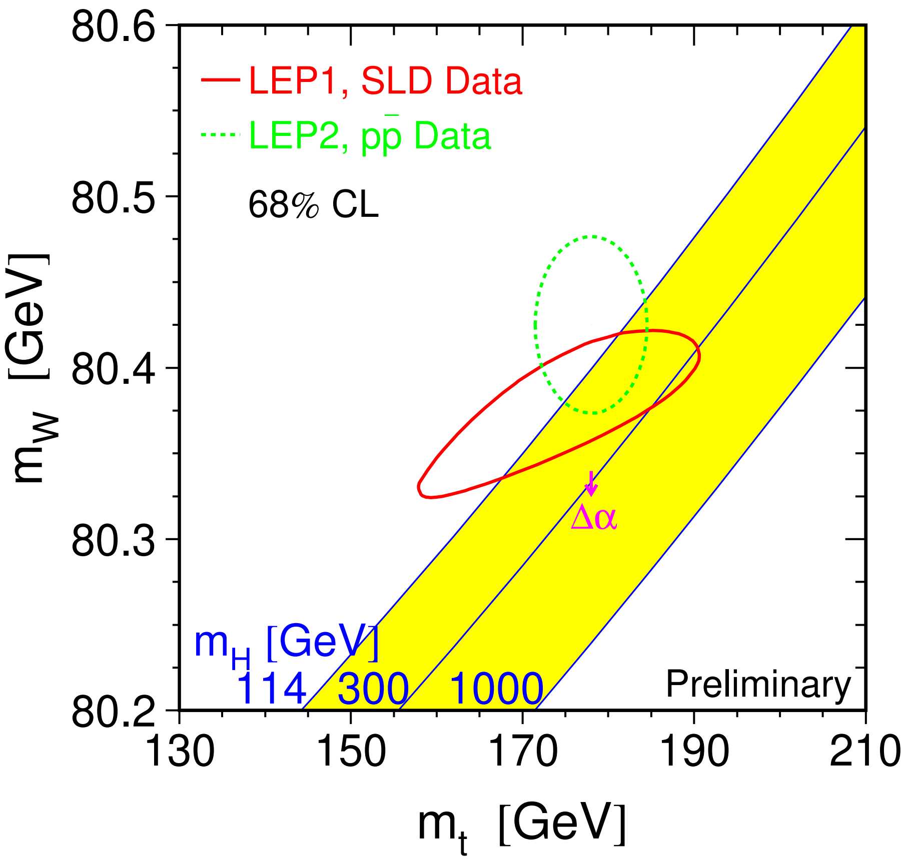
DØ : σ (WZ) $<$ 13.3 pb @ 95% confidence level.

Theory : 3.7 ± 0.1 pb

coming soon ...

W mass

One of the most important measurements to come from the Tevatron will be m_W. Expected precision: 20 – 30 MeV.



Summary and outlook

- Lots of electroweak results starting to appear with Tevatron Run II data.
  - W and Z cross sections $\rightarrow$ indirect W width measurement.
  - Direct measurement of W width.
  - Z rapidity, W charge asymmetry (constrain PDFs).
  - Forward-backward asymmetry in $p\bar{p} \rightarrow Z/\gamma^* \rightarrow e^+e^-$ events: $\sin^2\theta_W^{eff}$.
  - Di-boson ($W\gamma/Z\gamma/WW/WZ/ZZ$) production cross sections.
- No surprises yet but expect higher precisions with the fast increasing data sets: $\sim 10^6$ Ws and $\sim 10^5$ Zs.
- W mass measurement to come soon...