# W & Z (+Jets) Cross Sections and Asymmetries

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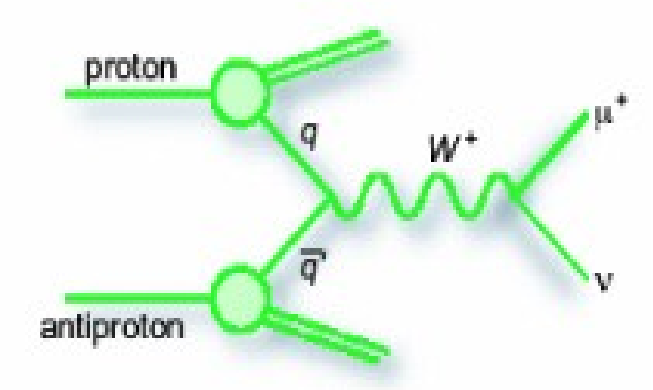
On behalf of the DØ and CDF Collaborations

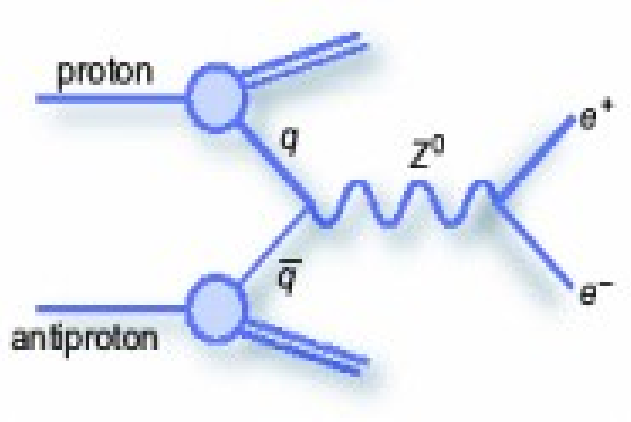
- Inclusive W and Z
- W Charge Asymmetry
- Z Rapidity
- W + Jets
- Z + Jets

XLIrst Rencontres de Moriond:
QCD and High Energy Hadronic Interactions

La Thuile, Val d'Aoste, Italy
18th - 25th March, 2006

# Inclusive W and Z Production




Inclusive W and Z in e and $\mu$ modes:
- large signal samples, low background
- measure cross section to few %:
  - apply cuts, count events
  - efficiencies from data, acceptance from MC.
- systematics limited: need very good understanding of detector, MC

$$\sigma \cdot B = \frac{N_{obs} - N_{bkg}}{A\varepsilon \int L dt}$$

Aims:
- test NNLO theory prediction
- indirect W width
- better understanding of detectors, other physics signals:
  - W and Z background to top, higgs...

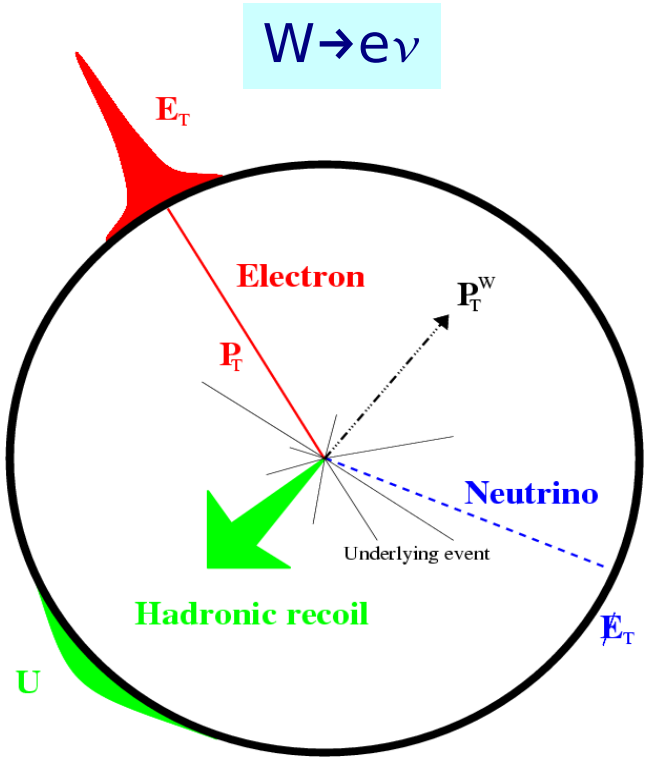
$$R = \frac{\sigma \times Br(W \to l\nu)}{\sigma \times Br(Z \to ll)} = \frac{\sigma_W}{\sigma_Z} \frac{\Gamma(Z)}{\Gamma(Z \to ll)} \frac{\Gamma(W \to l\nu)}{\Gamma(W)}$$

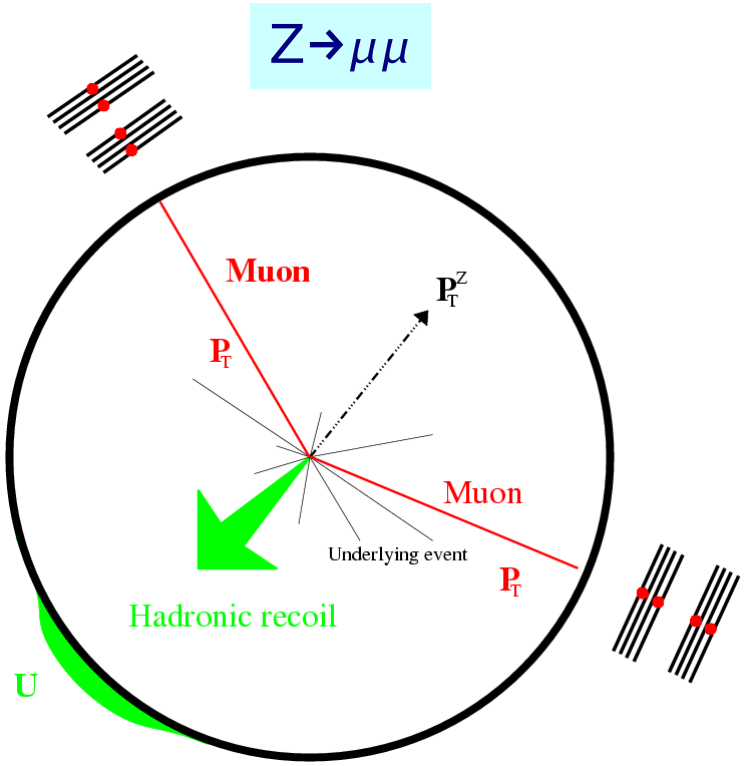
SM

NNLO

LEP

# W and Z Experimental Signatures



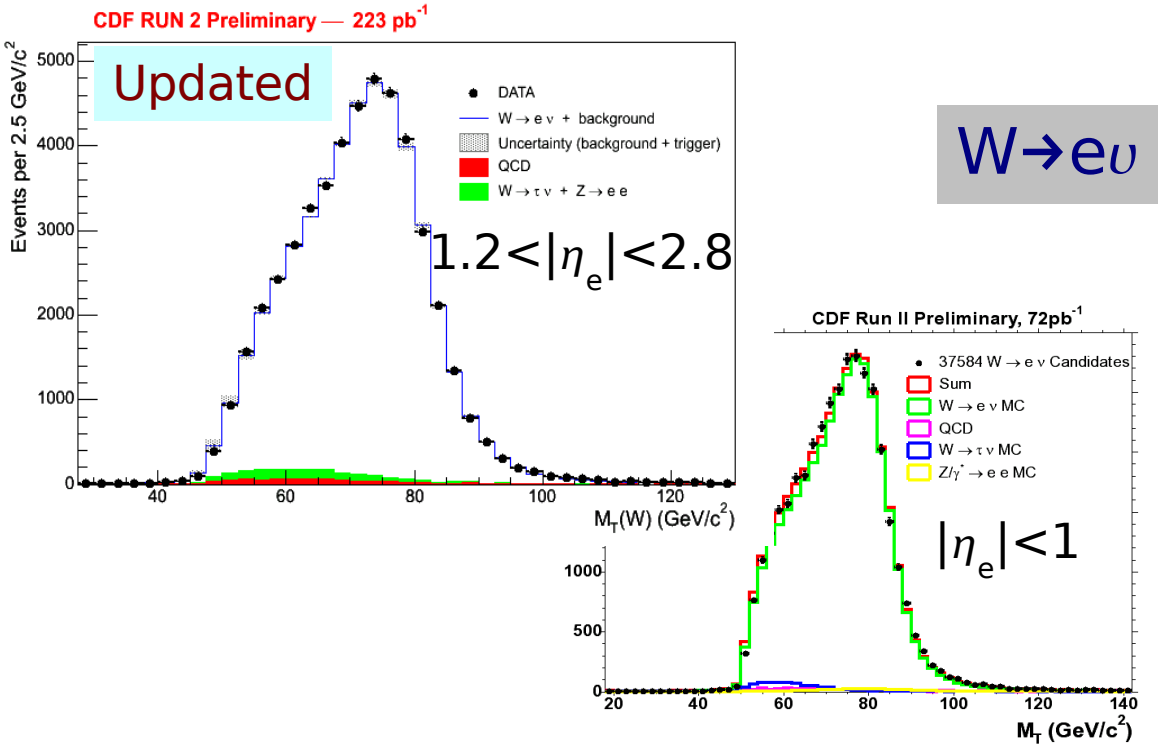

W Event Selection:
- trigger on the lepton
- high pT lepton (20-25 GeV)
- high missing ET (20-25 GeV)

W Backgrounds:
- QCD: semi-leptonic decay ($\mu$, ~1%)
  jets with high EM content (e, ~1%)
- Z→$\mu\mu$/ee (0.3 - 7%)
- W/Z →$\tau$ (~2%)

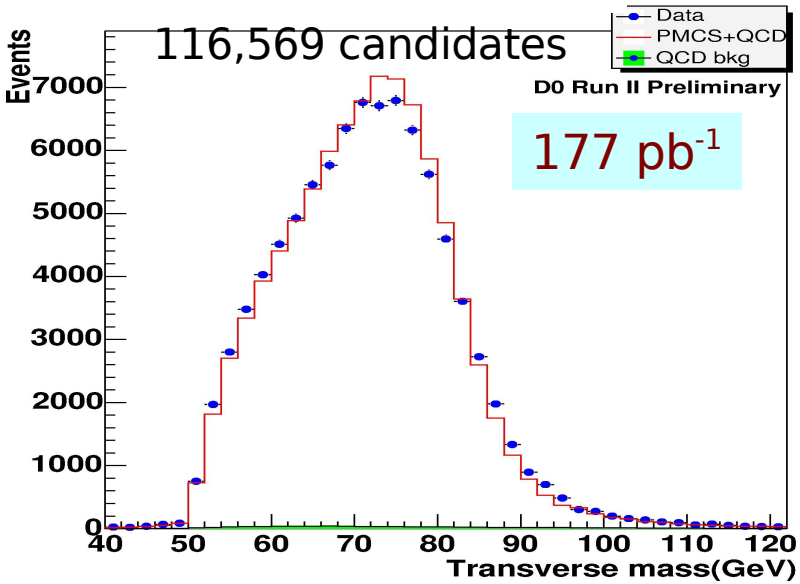
Z Event selection:
- trigger on lepton(s)
- high pT leptons (15-20 GeV)

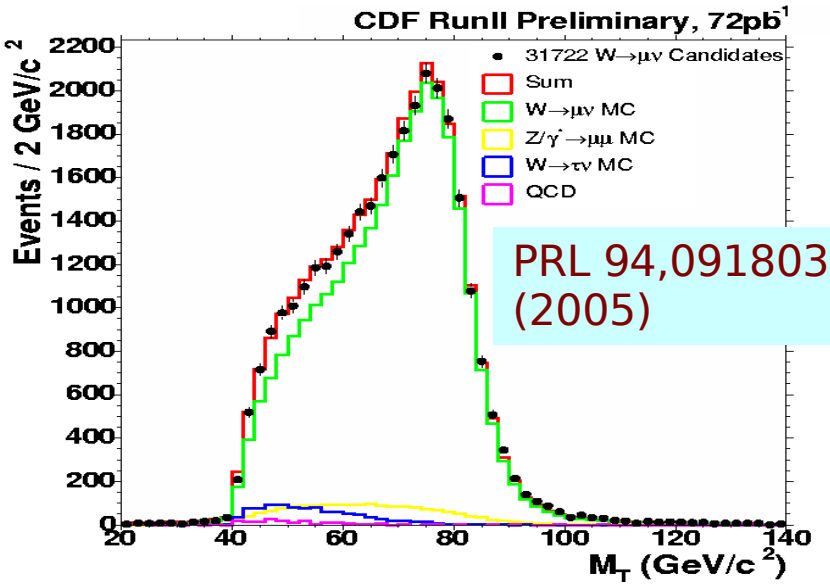
Z Backgrounds:
- QCD: semi-leptonic decay ($\mu$, ~0.5%)
  jets with high EM content (e, ~1%)
- cosmic rays ($\mu$, negligible)
- Z→$\tau\tau$ (<0.5%)

# W Production

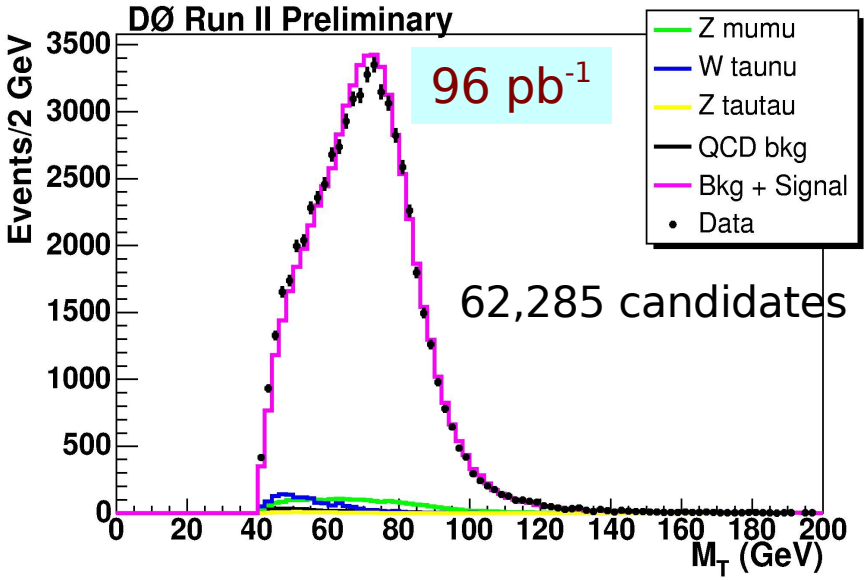



W→eυ

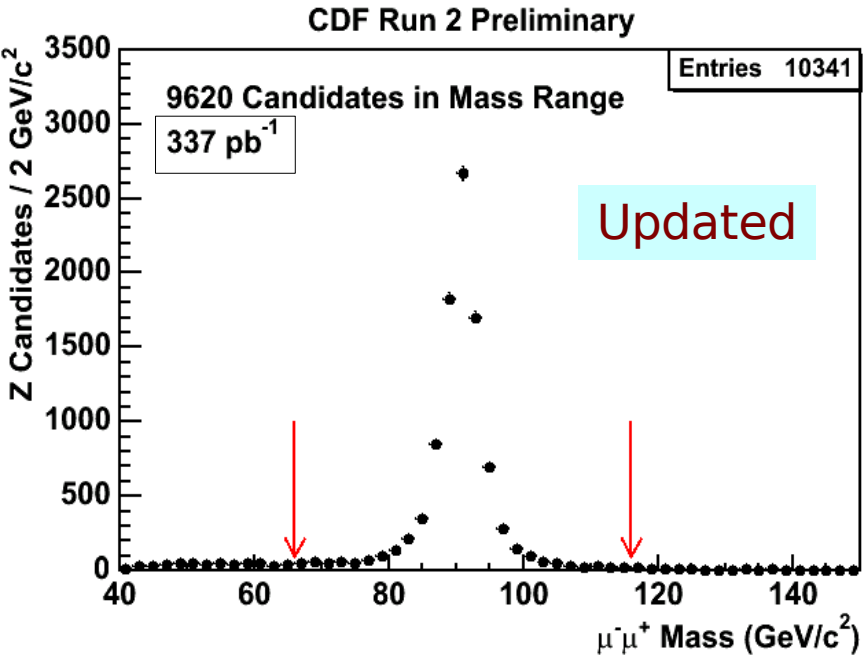


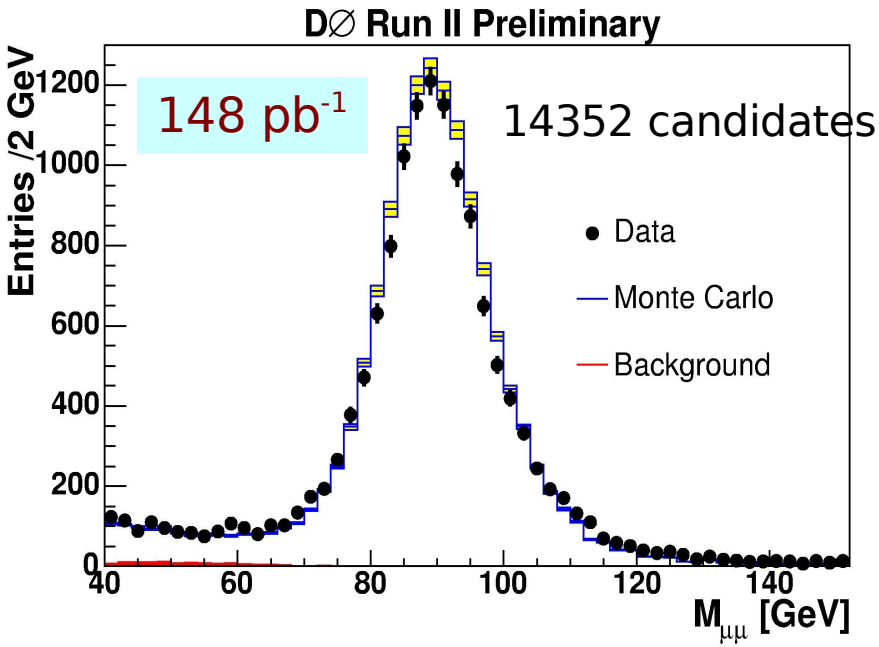

W→μυ

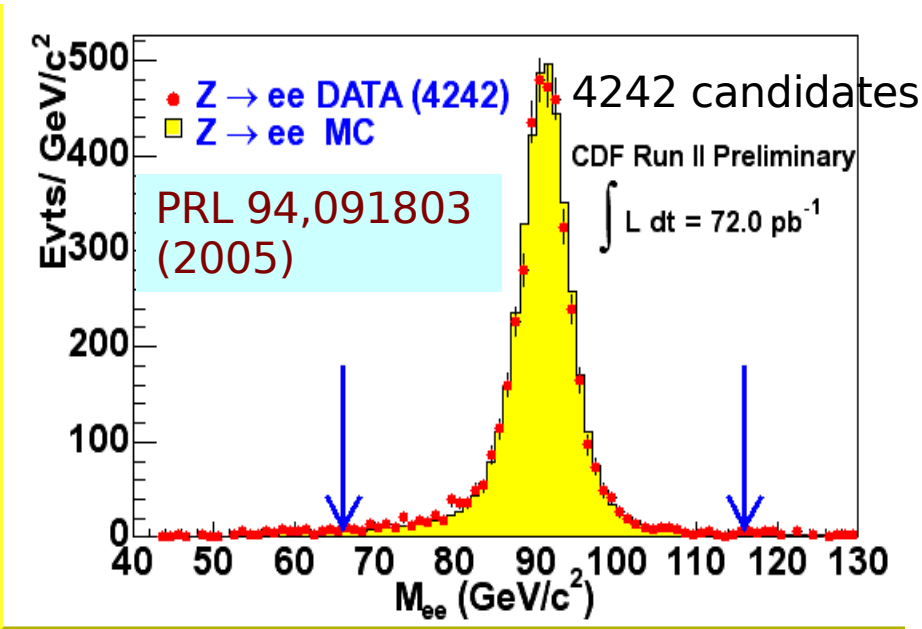


# Z Production

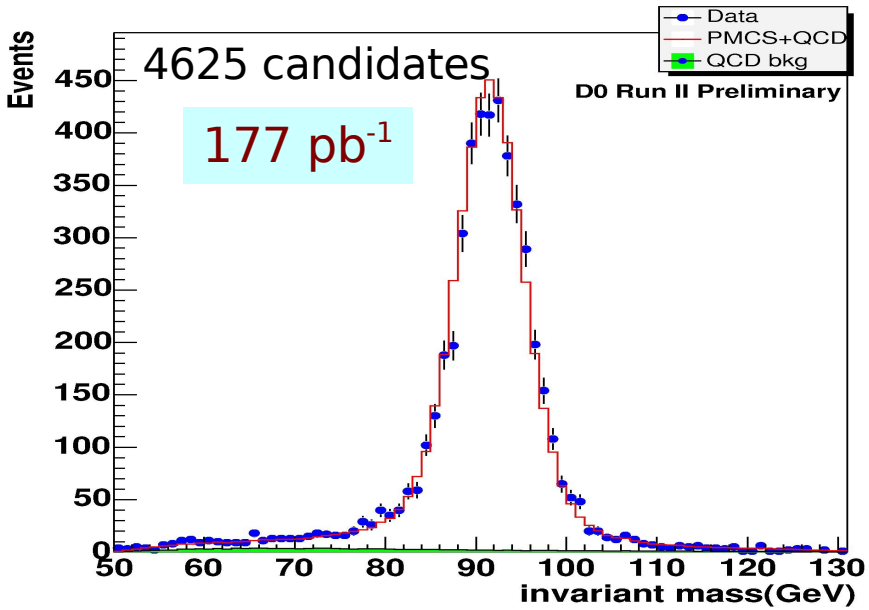



Z→μμ



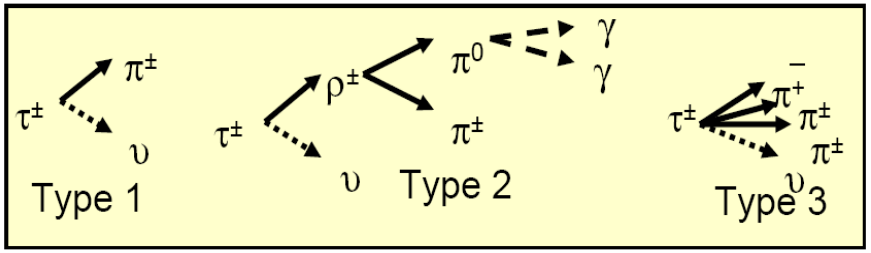




Z→ee

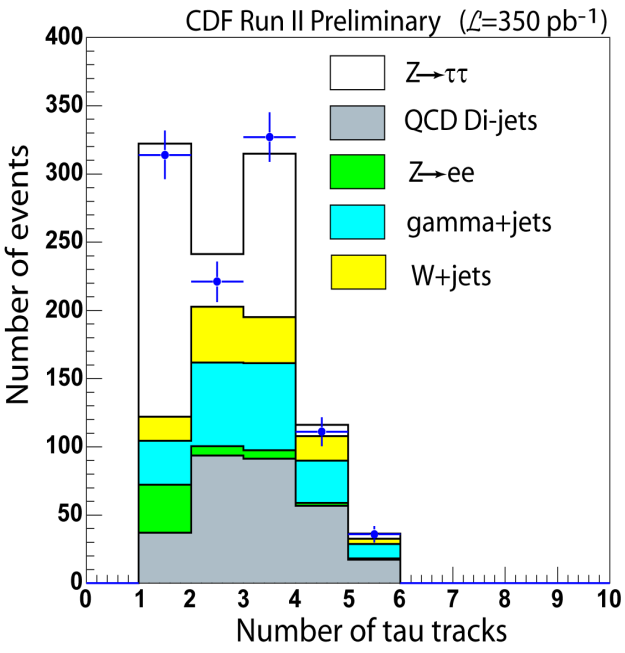


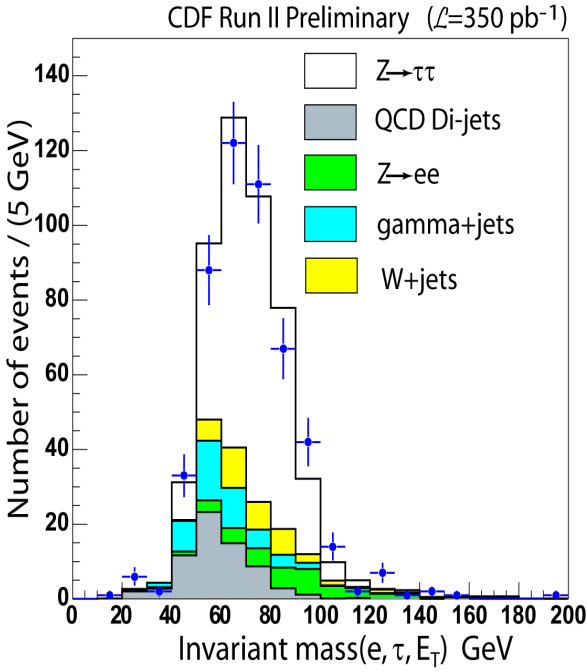
# $Z \rightarrow \tau\tau$

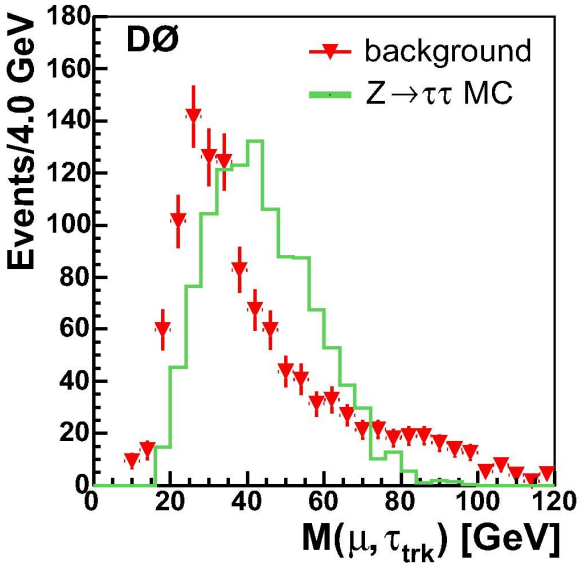
Updated CDF analysis of $Z \rightarrow \tau_e \tau_h$ based on ~350pb$^{-1}$

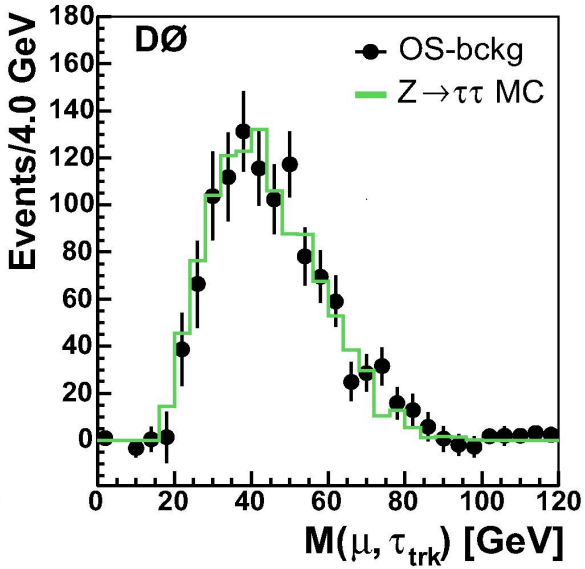



Tau ID based on calorimeter + tracks
Significant QCD background, reduced with event topology cuts.




DØ published analysis of $Z \rightarrow \tau_\mu \tau_h$

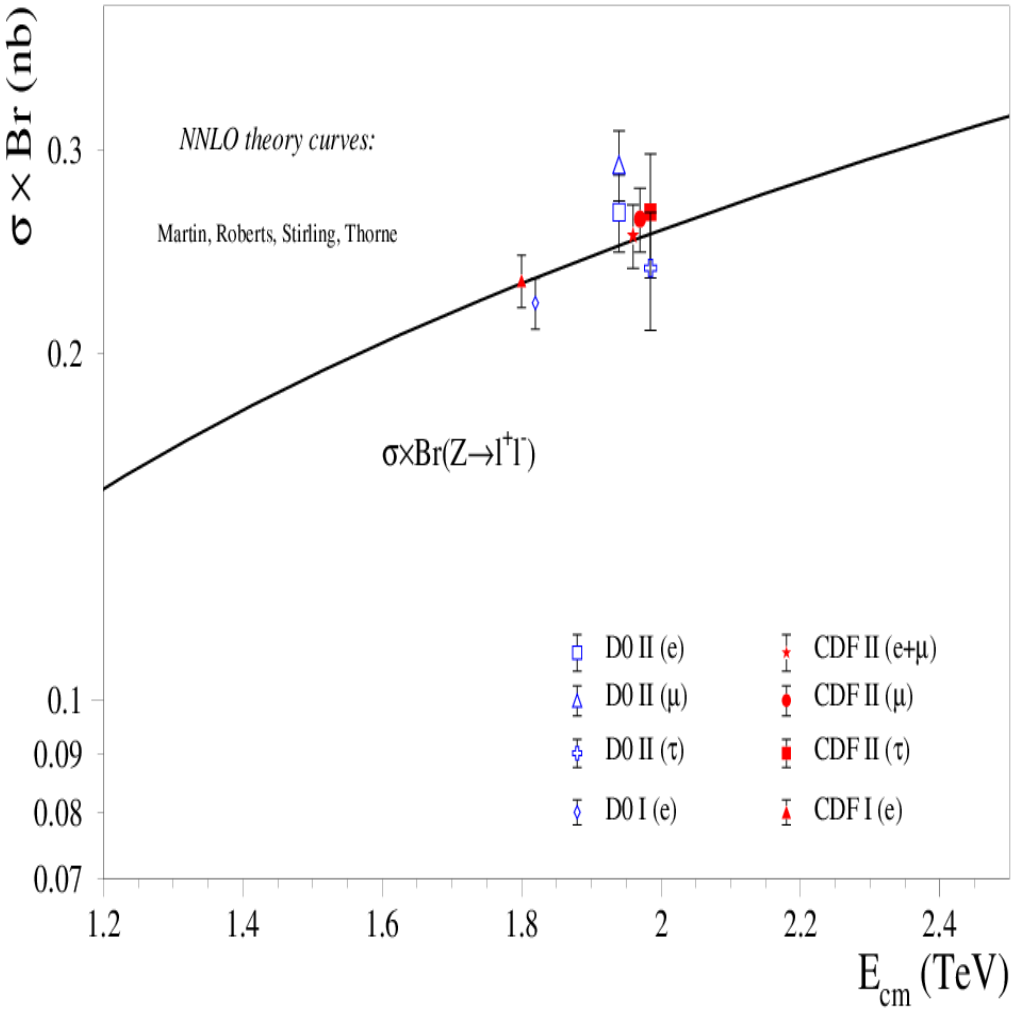
PRD 71, 072004 (2005)

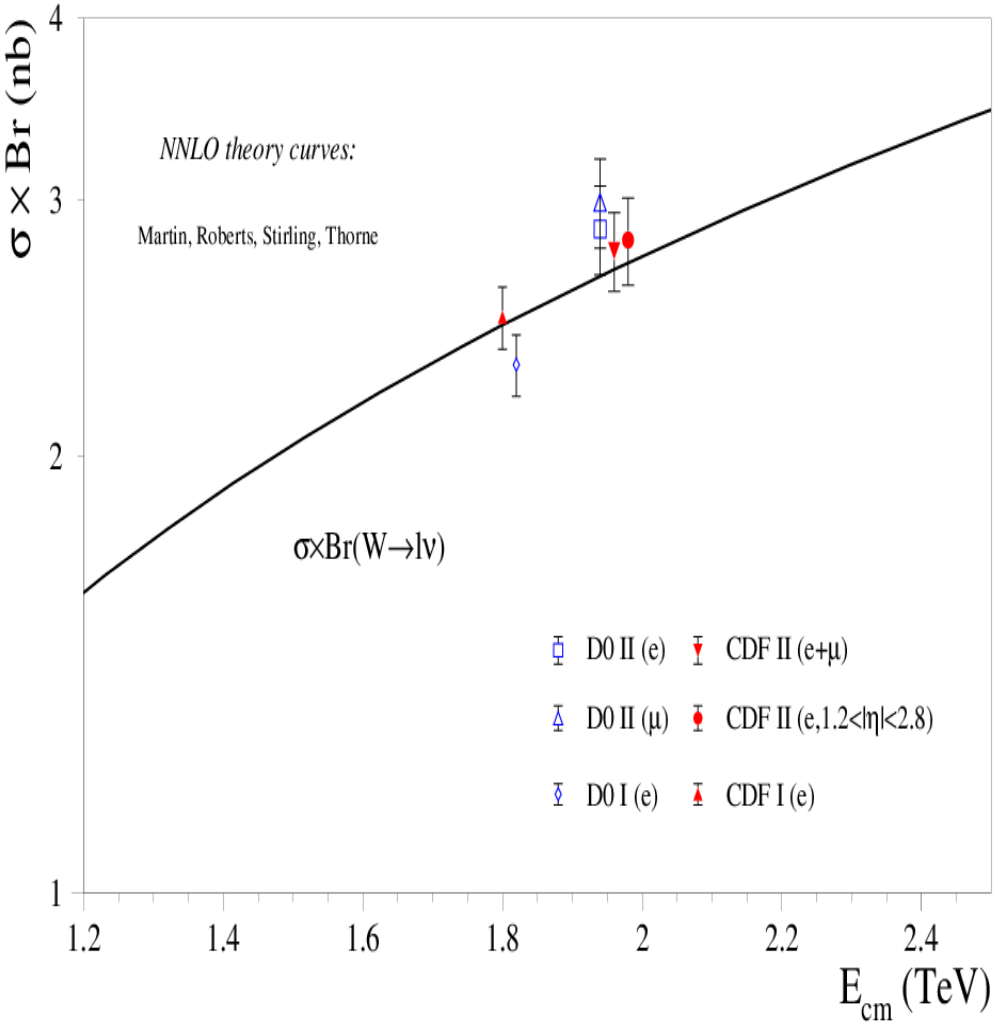
Based on 226 pb$^{-1}$

Uses a NN to identify tau decay types, resulting in smaller systematics

Benchmark tau reconstruction!
Better understanding of, eg:
- searches for SUSY higgs→ττ

# Result Summary Plot




Good agreement with NNLO theory curve (Martin, Roberts, Stirling, Thorne)

Results limited by systematics:

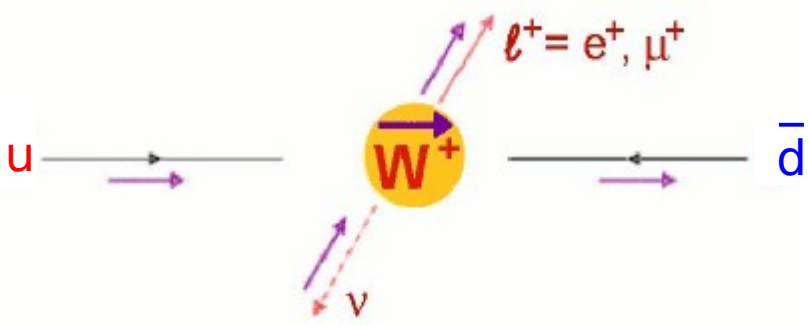
- lepton ID (2-3%, 3-4% for taus),
- PDF uncertainty on acceptance (CTEQ6) ~1-2%
- backgrounds < 1% (~4-5% for $Z \rightarrow \tau\tau$)

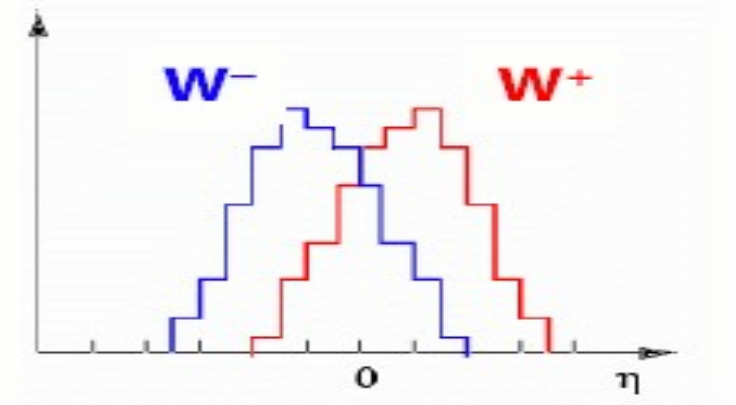
Dominant systematic is the luminosity uncertainty (~6%).

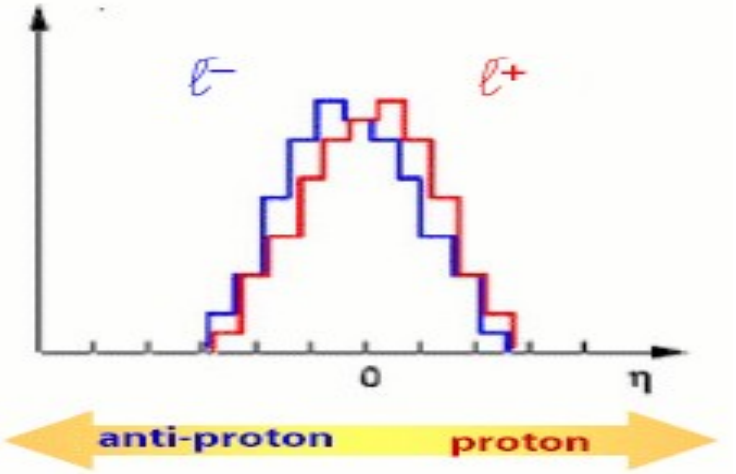
# Result Summary Table

| $\sigma \times BR$ (pb) | DØ | CDF II |
|---|---|---|
| $W \to \mu\nu_\mu$ | $2989 \pm 15_{stat} \pm 81_{sys} \pm 194_{lum}$ (96 pb$^{-1}$) | $2768 \pm 16_{stat} \pm 64_{sys} \pm 166_{lum}$ (72 pb$^{-1}$) |
| $Z \to \mu\mu$ | $291 \pm 3.0_{stat} \pm 6.9_{sys} \pm 18.9_{lum}$ (148 pb$^{-1}$) | $261.2 \pm 2.7_{stat}\ ^{+5.8}_{-6.1}{}_{sys} \pm 15.1_{lum}$ (337 pb$^{-1}$ updated) |
| $W \to e\nu_e$ | $2865 \pm 8.3_{stat} \pm 76_{sys} \pm 186_{lum}$ (177 pb$^{-1}$) | $2780 \pm 14_{stat} \pm 60_{sys} \pm 166_{lum}$ (72 pb$^{-1}$)<br>$2815 \pm 13_{stat}\ ^{+94}_{-89}{}_{sys} \pm 169_{lum}$ (223 pb$^{-1}$) |
| $Z \to ee$ | $264.9 \pm 3.9_{stat} \pm 9.9_{sys} \pm 17.2_{lum}$ (177 pb$^{-1}$) | $255.8 \pm 3.9_{stat} \pm 5.5_{sys} \pm 15_{lum}$ (72 pb$^{-1}$) |
| $R(W/Z) \Rightarrow \Gamma_W^{tot}$ | $10.82 \pm 0.16_{stat} \pm 0.28_{sys} \Rightarrow 2098 \pm 74$ MeV | $10.92 \pm 0.15_{stat} \pm 0.14_{sys} \Rightarrow 2079 \pm 41$ MeV (72 pb$^{-1}$ PRL) |
| SM Theory | $2092.1 \pm 2.5$ MeV | |
| $W \to \tau\nu_\tau$ | — | $2620 \pm 7.0_{stat} \pm 210_{sys} \pm 160_{lum}$ (72 pb$^{-1}$) |
| $Z \to \tau\tau$ | $237 \pm 15_{stat} \pm 18_{sys} \pm 15_{lum}$ (226 pb$^{-1}$ PRD 71, 072004 (2005)) | $265 \pm 20_{stat} \pm 21_{sys} \pm 15_{lum}$ (350 pb$^{-1}$ updated) |

# W Charge Asymmetry




Using the W to probe the proton:

- sensitive to u and d quark PDFs
- presence of W sets $Q^2$ to $\sim M_W$
- probe x ~0.005 - 0.3

$$x_{1(2)} = \frac{M_W}{\sqrt{s}} e^{(\pm) y_W}$$

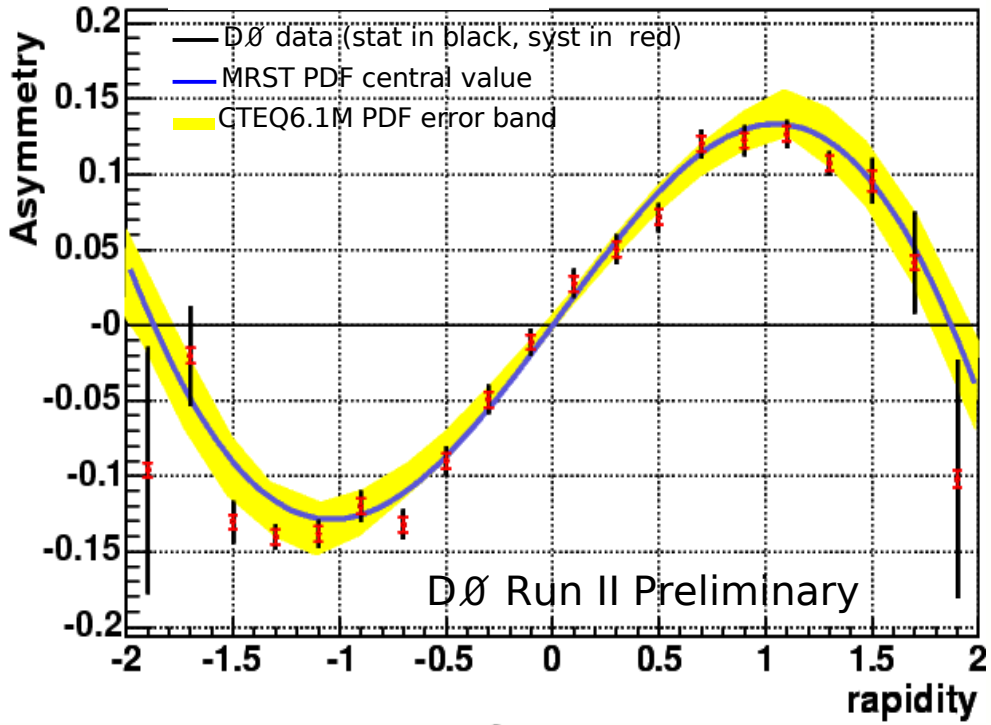
u quarks carry higher momentum fraction
-> W boosted

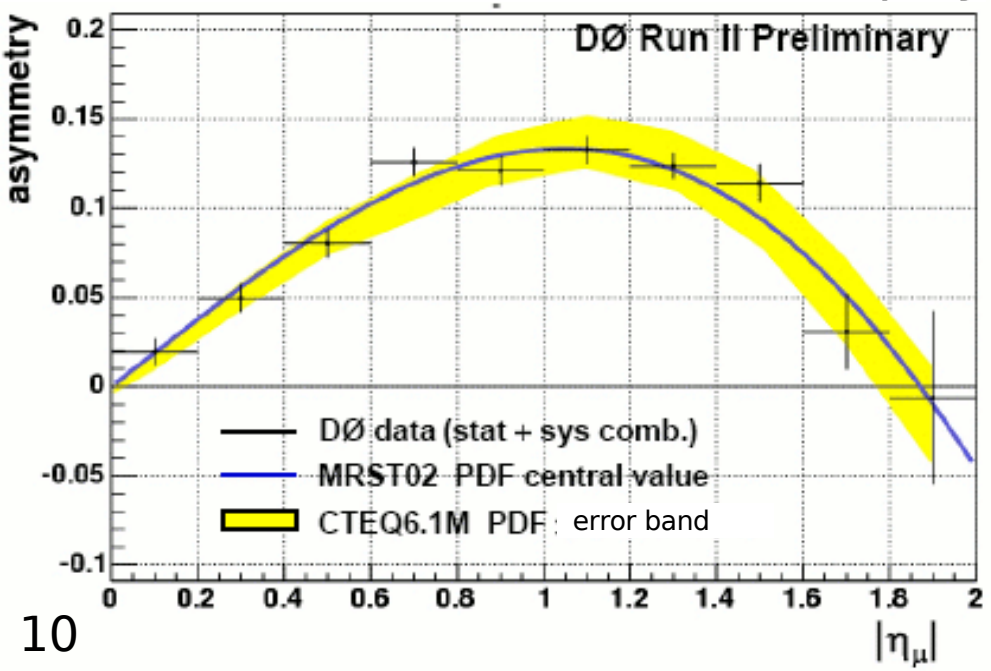
## Measure the lepton charge asymmetry

Convolution of W asymmetry and V-A decay.
Factorises into u and d quark PDFs:

$$A(\eta_\ell) = \frac{d\sigma(\ell^+)/d\eta - d\sigma(\ell^-)/d\eta}{d\sigma(\ell^+)/d\eta + d\sigma(\ell^-)/d\eta} \approx \frac{\mathrm{d}(x)}{\mathrm{u}(x)}$$

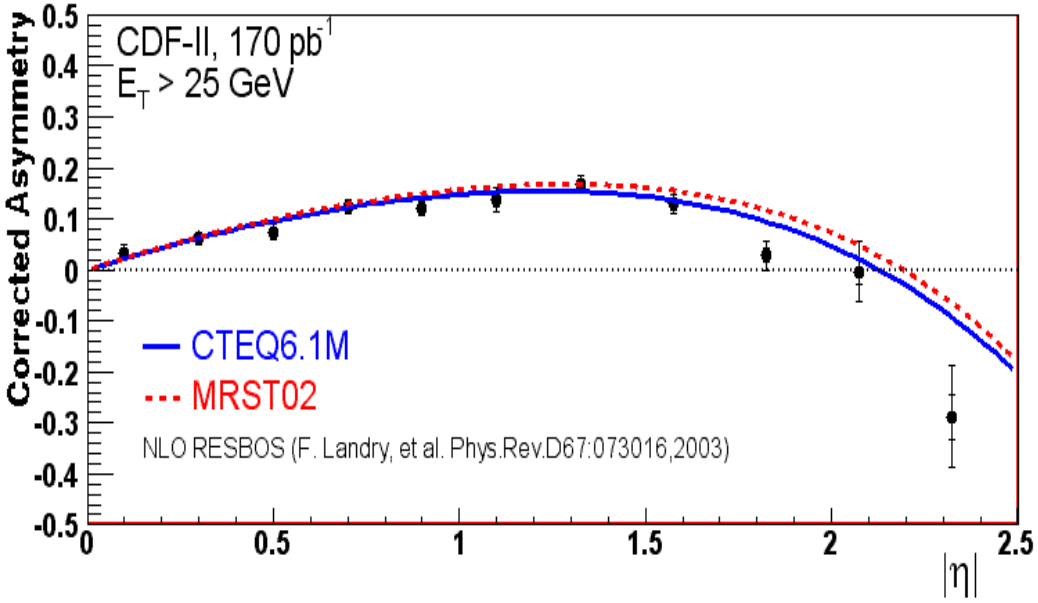
# W Charge Asymmetry




- New DØ result in W→$\mu\upsilon$ channel, based on 230 pb$^{-1}$
- Most sensitive at high rapidity:
  - using full muon system acceptance
- Statistics limited!
- Combine CP states to increase statistics
- Constrain PDF error sets

Published result in electron channel from CDF based on 170 pb$^{-1}$ (PRD 71, 051104, 2005)



# Z Rapidity

Same motivation at W charge asymmetry:

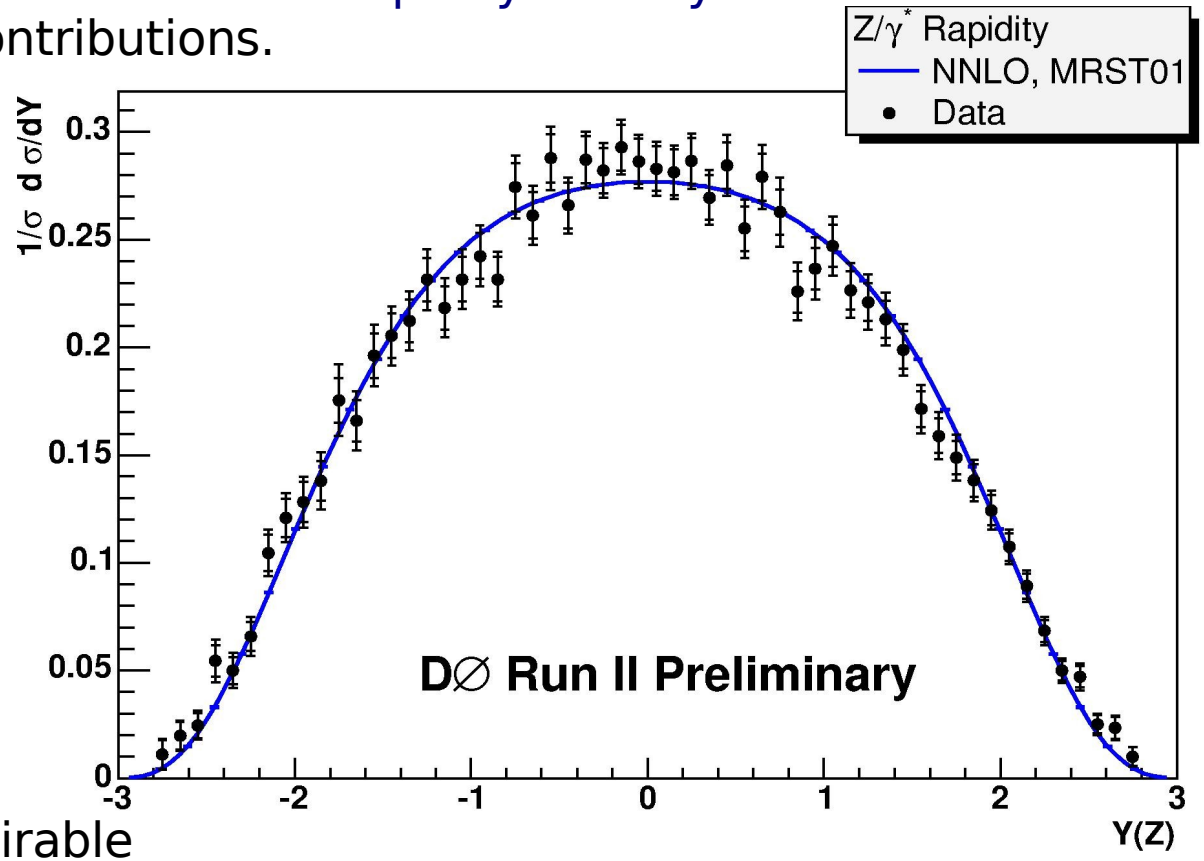
- boost of the Z boson is sensitive to momentum fraction of quarks.
- probing x at high $Q^2$ ($\sim M_Z$)
- test NNLO prediction

In this case, fully reconstruct Z and measure the rapidity directly

- but can't separate u and d contributions.

DØ result in Z→ee channel based on 337 $pb^{-1}$

Measure differential cross section as a function of boson rapidity

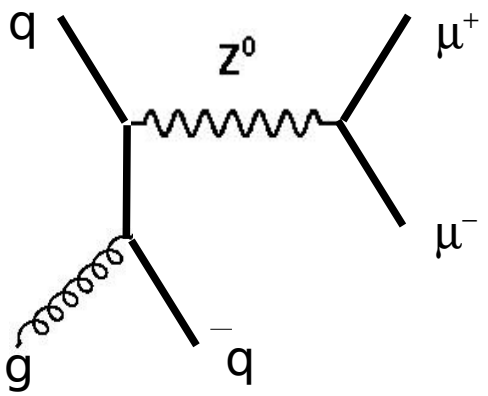



Again, high rapidity coverage desirable

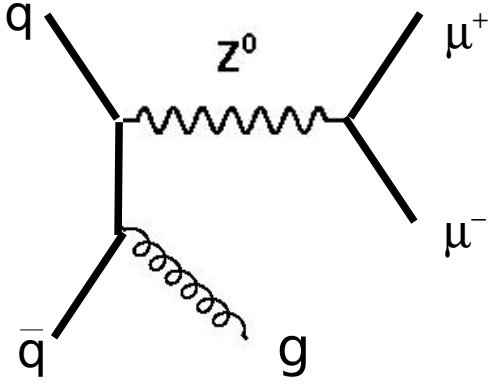
- large systematics at high rapidity: PDF (10 %), lepton ID (20 %)

Good agreement with NNLO calculation, MRST PDF set.

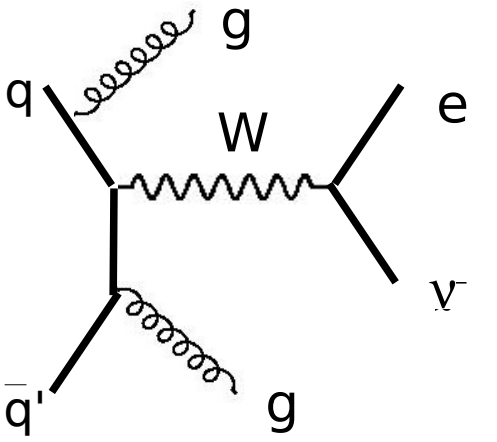
# W/Z + Jets




Use W and Z to probe jet production.
- presence of boson ensures high $Q^2$: pQCD
- Use W / Z to tag event, then study jet properties
  - Z cleaner, lower stats.
  - W has more background, higher stats.




Aim:
- perform a model-independent analysis:
  - restrict phase space of leptons and jets to measured and understood regions
  - cuts on $\eta$, pT.
  - unsmear jet spectra to the hadron level.
- can then perform unbiased checks against theory:
  - ALGPEN, Sherpa, MCFM, MADGRAPH, Pythia...




W/Z + Jets is also an important background:
- studies of the top quark, higgs searches depend on MC description of W/Z + jets.

# W + Jets at CDF

Updated result using 320 pb$^{-1}$

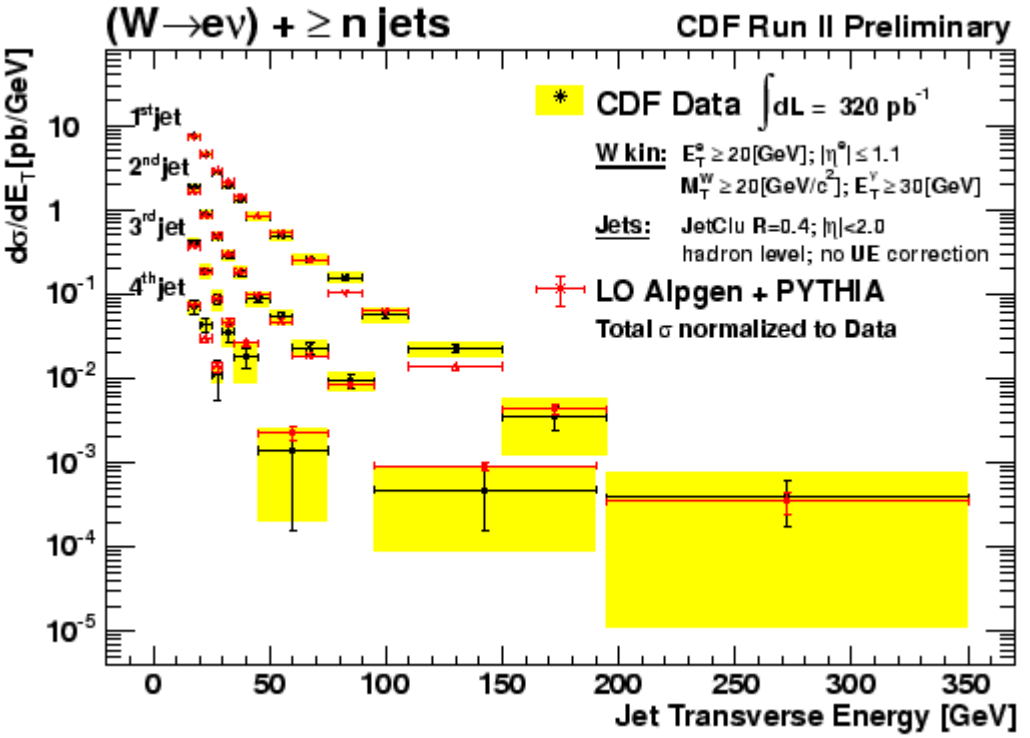
W→eυ selection:

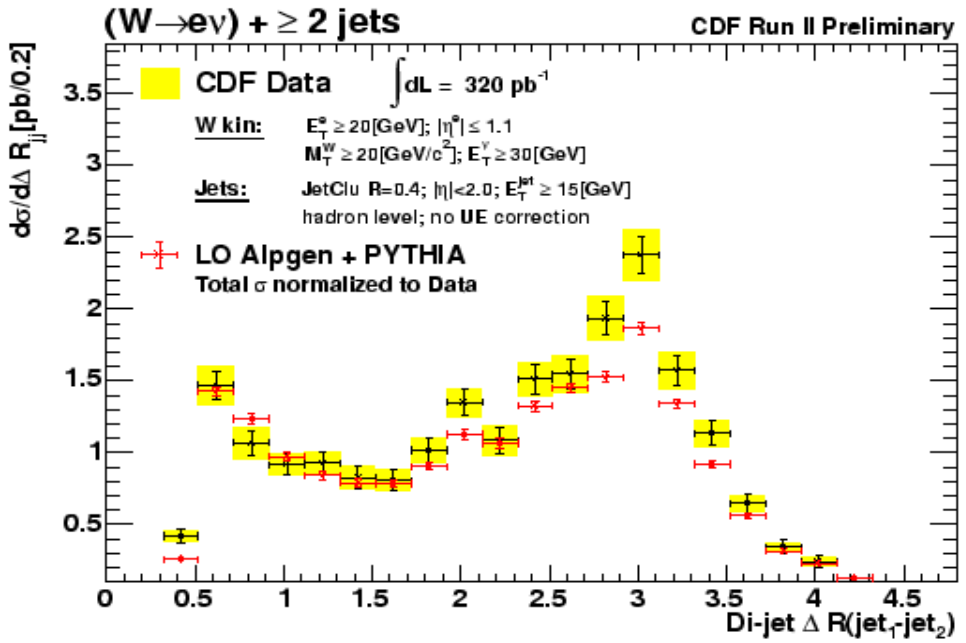
- $pT_e$ > 20, MET > 30, $M_T$>20
- $\eta_e$ <1.1

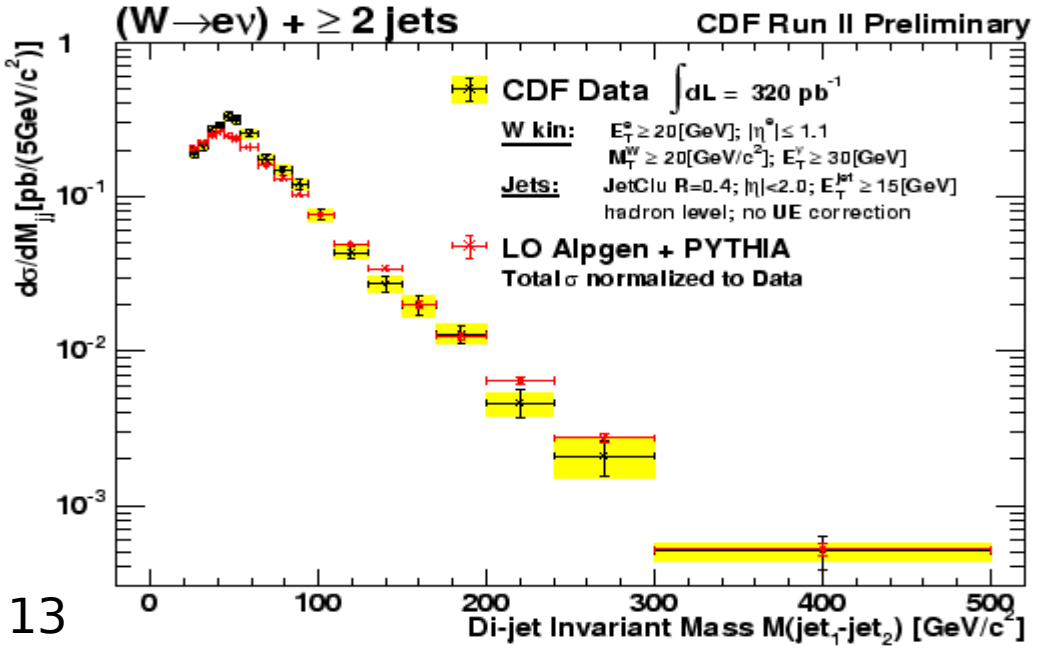
Jet selection:

- JETCLU (R=0.4)
- $E_T$ > 15 GeV, $|\eta|$<2.4

Note: shape comparison only!
LO MC cross sections normalised to data



# Z + Jets at DØ

## Z→ee + Jets, using 343 pb$^{-1}$

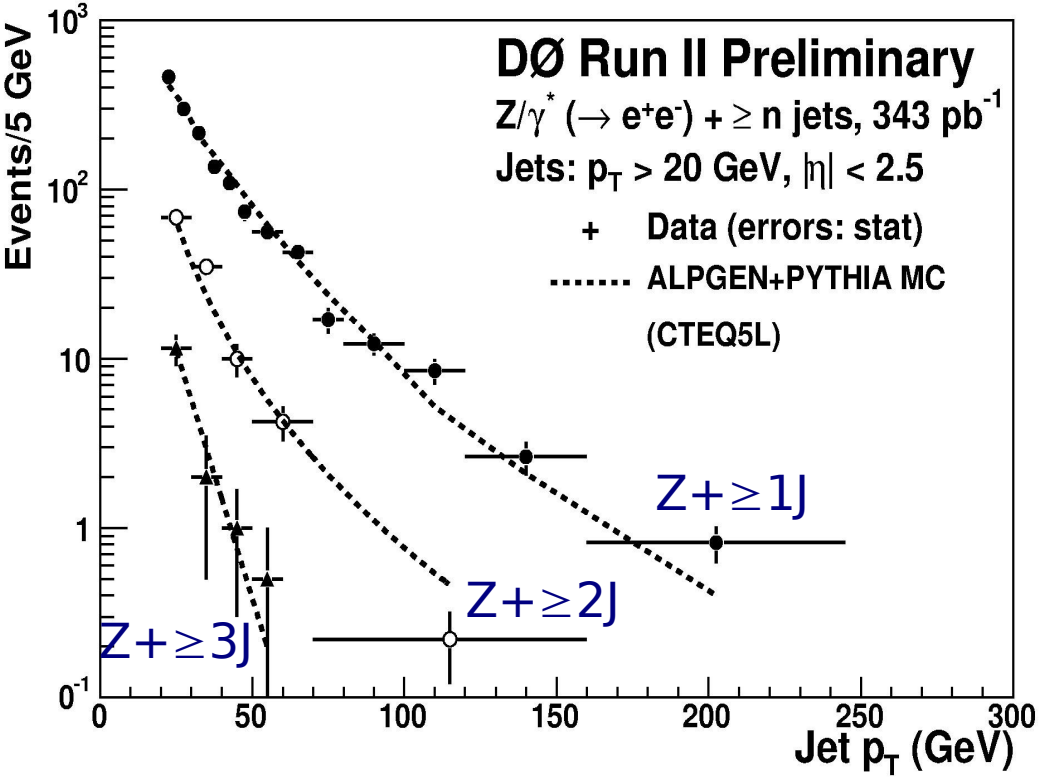
Smaller cross section, much cleaner

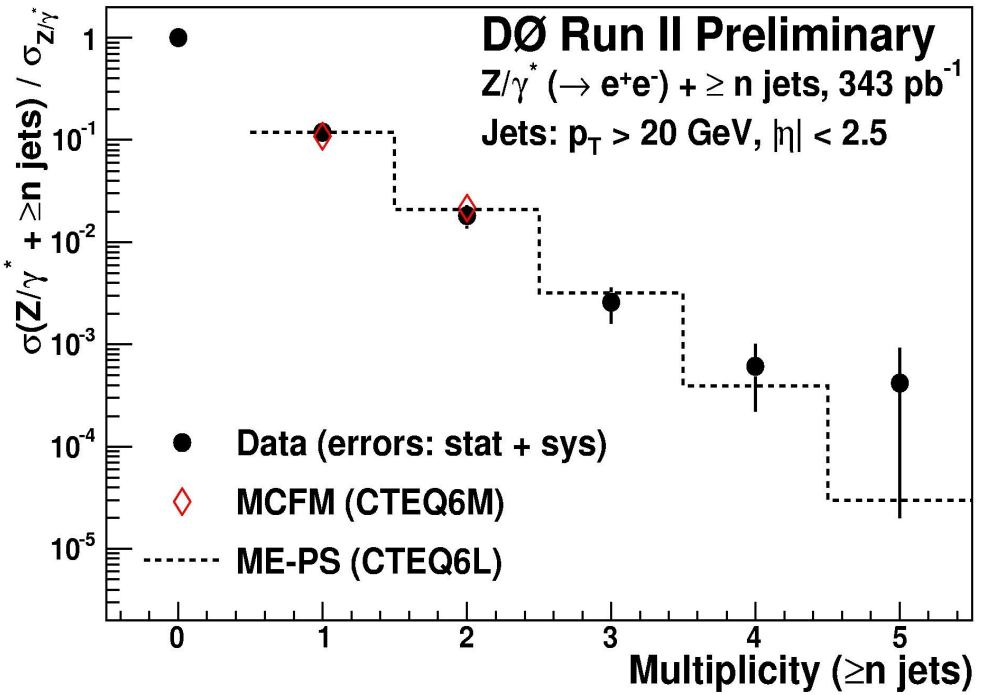
Z selection:

- $pT_e$ > 25 GeV, ($|\eta_e|$<1.1)

Jet selection:

- R=0.5, pT>20 GeV, $|\eta|$<2.5




$$R_n = \frac{\sigma_n}{\sigma_0} = \frac{\sigma[Z/\gamma^*(\rightarrow e^+e^-) + \geq n \text{ jets}]}{\sigma[Z/\gamma^*(\rightarrow e^+e^-)]}$$

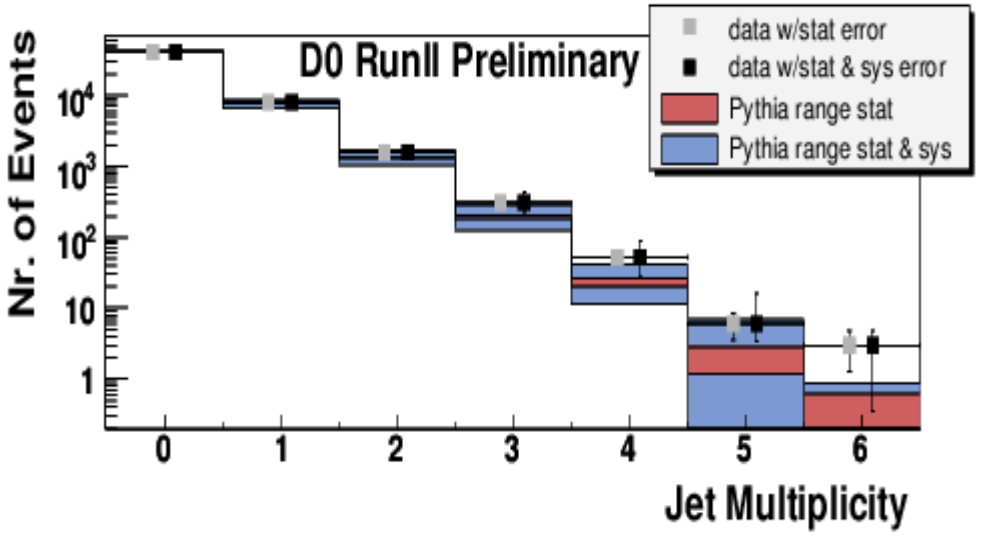
Cross sections well modeled by:

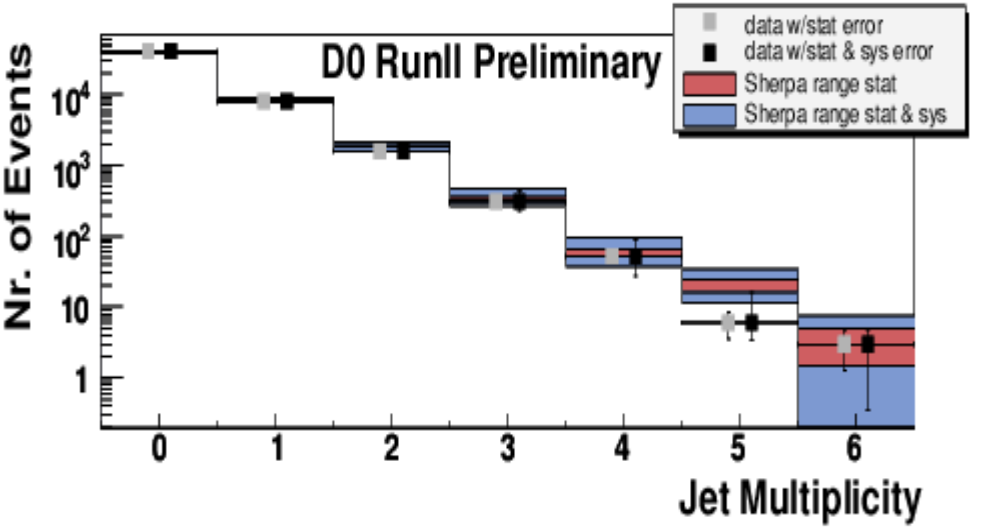
- MCFM: Z+ ≤2p at NLO
- ME + PS: MADGRAPH Z+ ≤3p at tree level
  Pythia used for parton showering

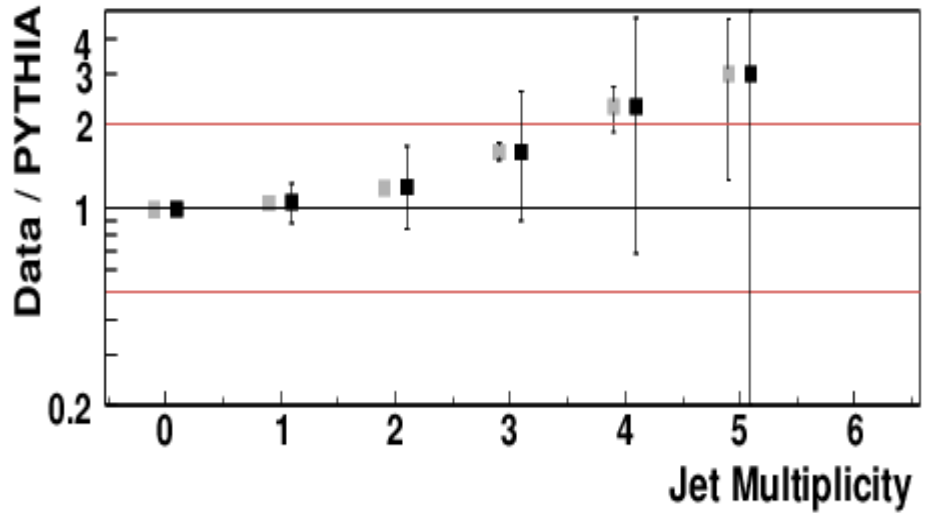
# Z + Jets at DØ: Sherpa

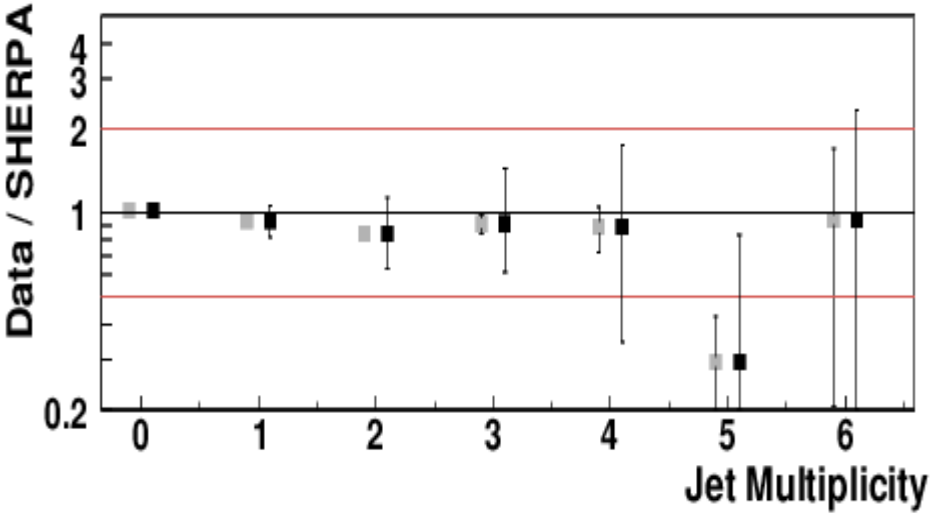
Comparison of DØ data to Sherpa 1.0.6
- matrix element + parton shower, CKKW matching
- also compared to Pythia 6.319

Z→ee events, using 0.95 $fb^{-1}$.
Jet efficiency & resolution from data applied to MC



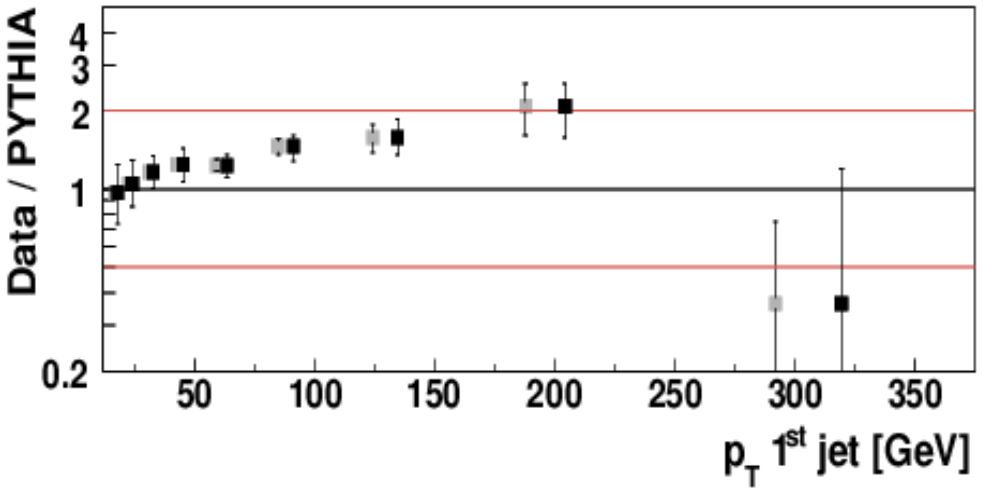



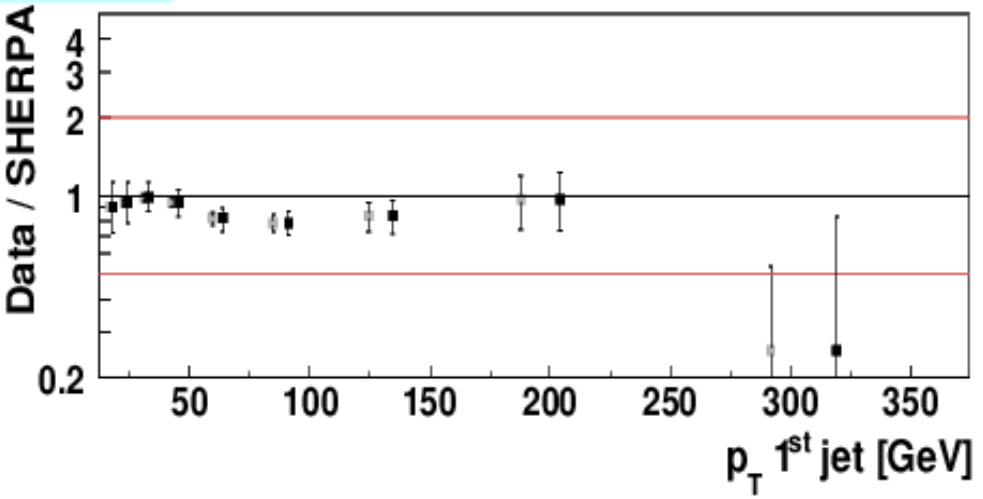



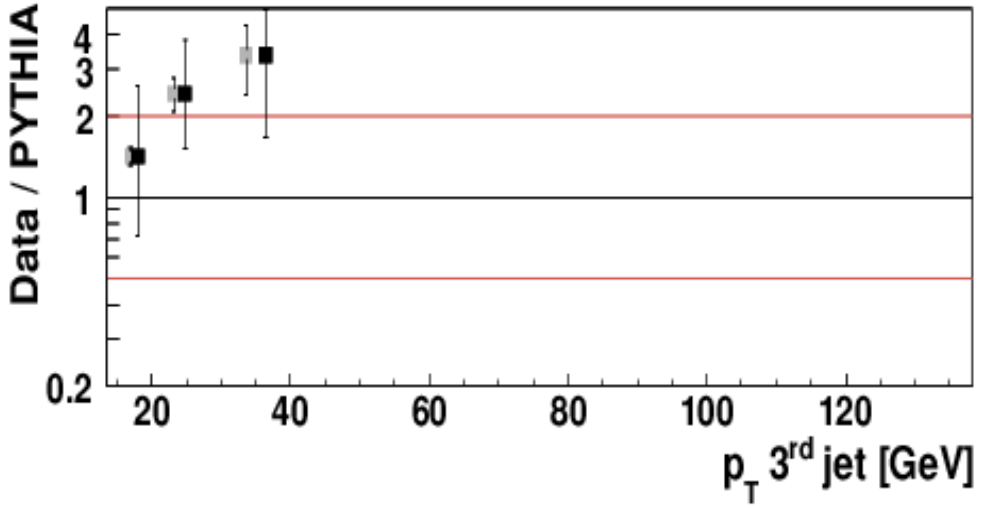
# Z + Jets at DØ: Sherpa

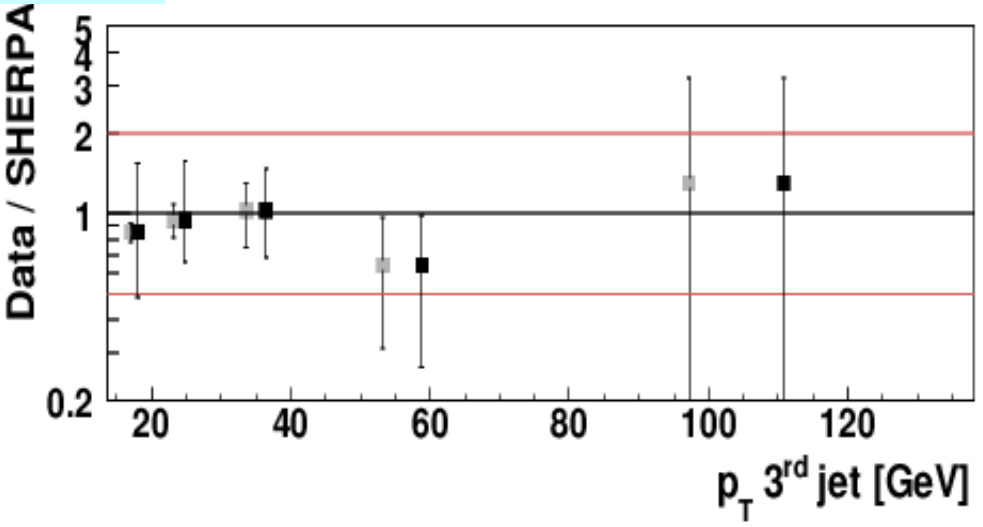
pT of Leading Jet




pT of Third Jet




Sherpa models all studied quantities:

- jet multiplicities
- jet pT (1st , 2nd , 3rd, 4th jets)
- $\Delta\eta$ and $\Delta\phi$( jet, jet)
- Z pT

# Conclusions

Inclusive W and Z in electron and muon channels:

- precision electroweak measurements (~2% level)
- systematics limited – driving our understanding of detector performance
- benchmark high pT lepton analysis.
- test of NNLO theory prediction, world's best measurement of W width.

$Z \rightarrow \tau\tau$:

- challenging analysis, benchmark tau ID
- very interesting for beyond SM physics (SUSY higgs, extra dimensions)

W Charge Asymmetry, Z rapidity:

- build on detailed understanding gained in inclusive measurements
- W asymmetry, Z rapidity provide test of PDF sets, NNLO prediction.

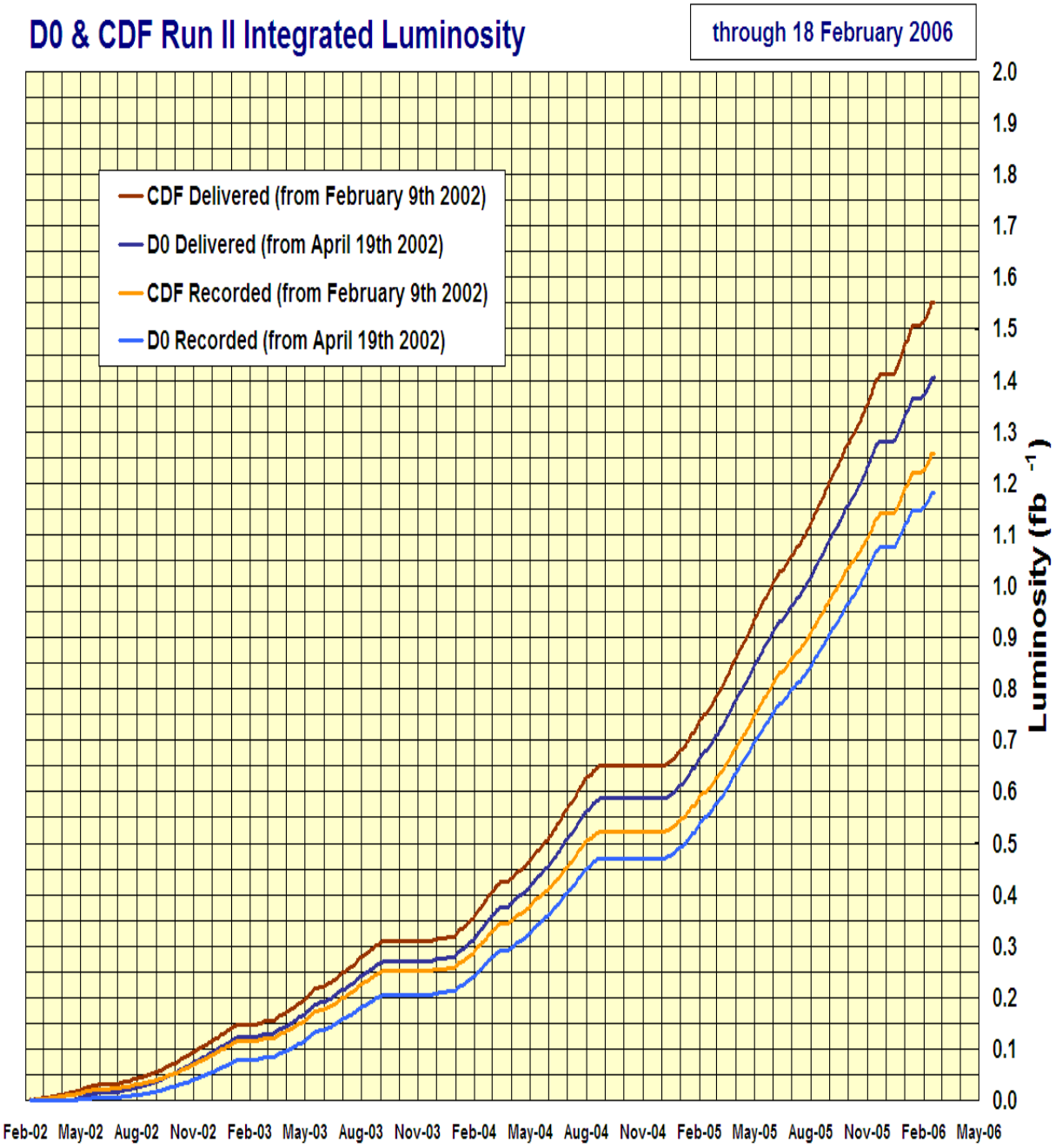
W/Z plus Jets:

- studying pQCD
- important test of different MC: Alpgen, Sherpa, MCFM, MADGRAPH...

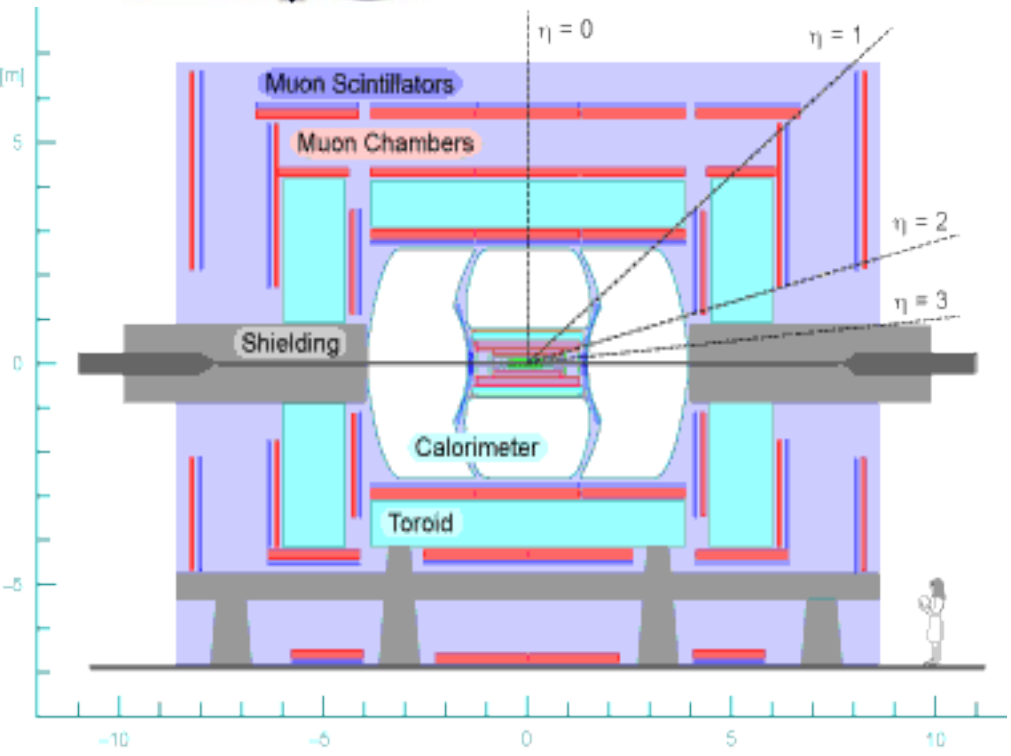
The future:

- more new and updated analyses with 1 $fb^{-1}$!

# Tevatron Performance

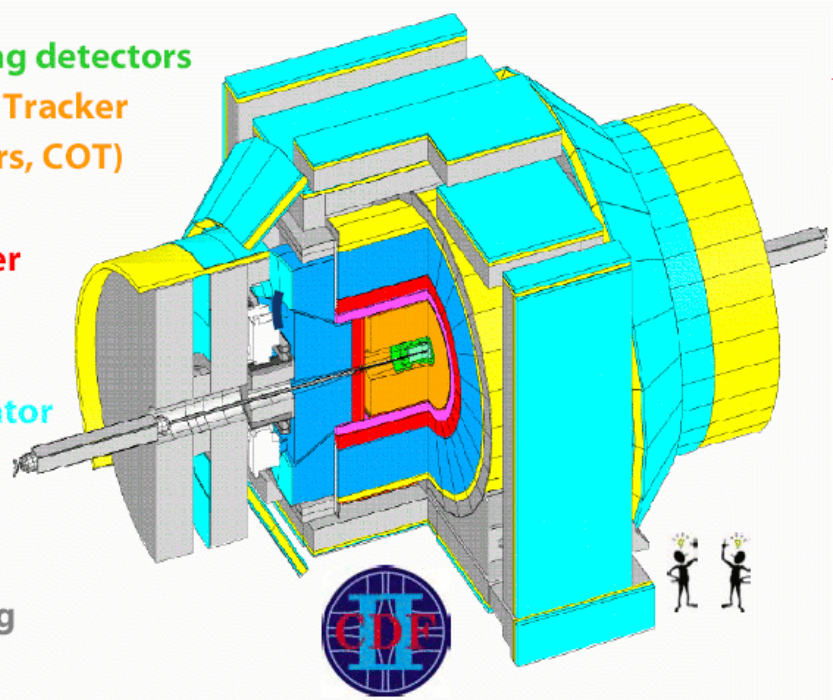



# The Experiments

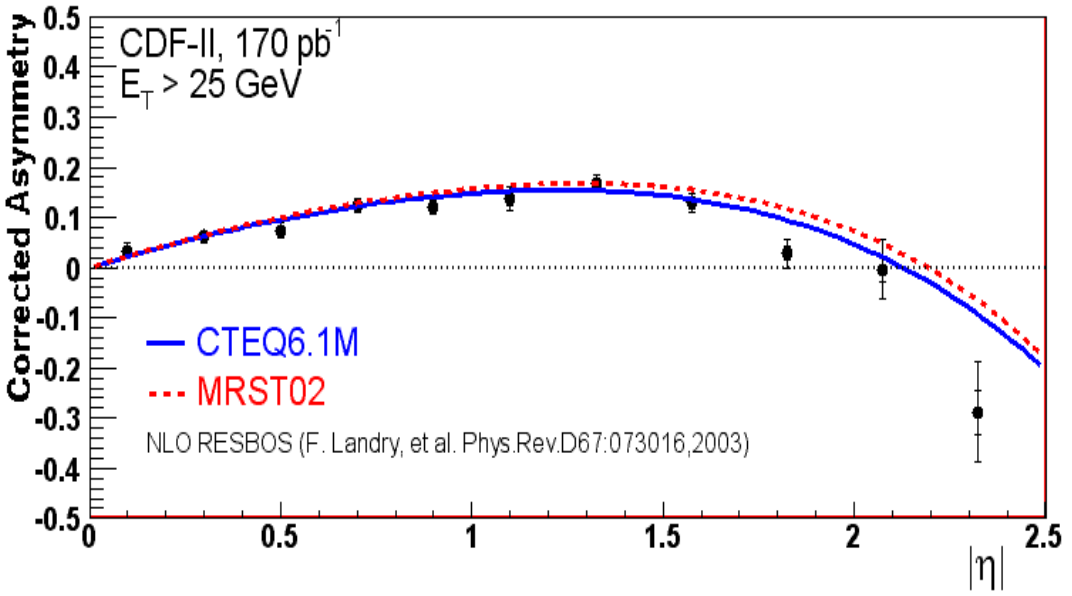


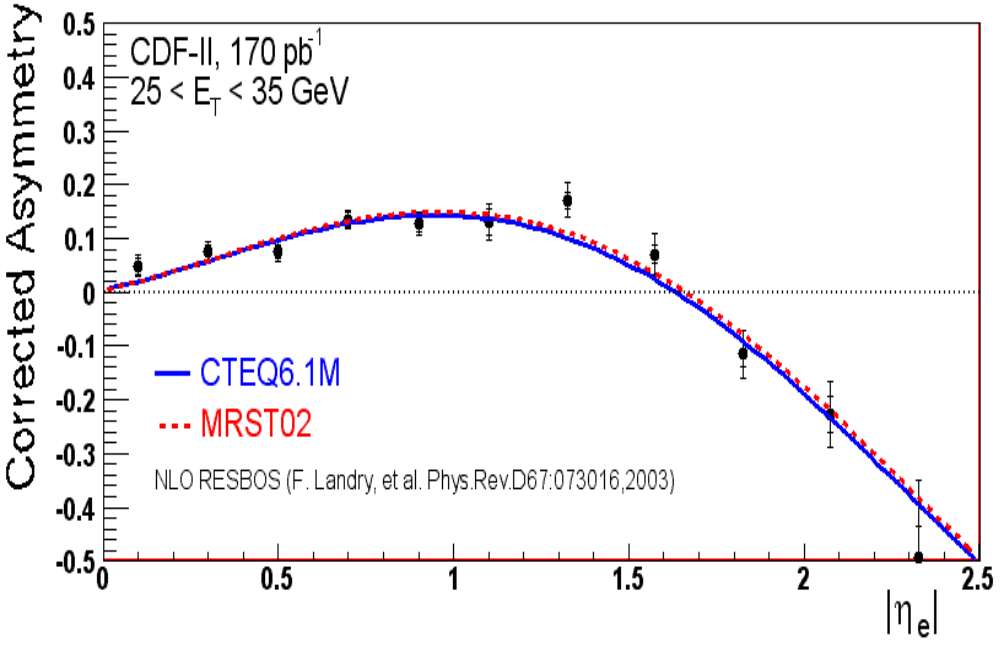

Silicon and fibre trackers in solenoid field
Liquid Argon & Uranium calorimeter
3 layer muon system, with toroid magnet

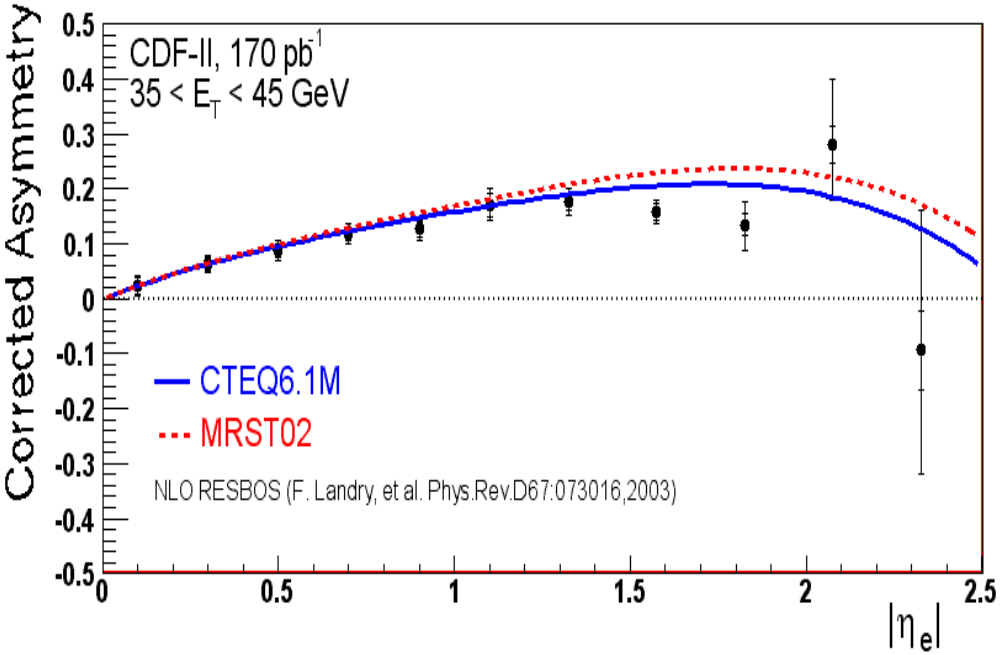
- Silicon tracking detectors
- Central Outer Tracker (drift chambers, COT)
- Solenoid Coil
- EM calorimeter
- Hadronic calorimeter
- Muon scintillator counters
- Muon drift chambers
- Steel shielding



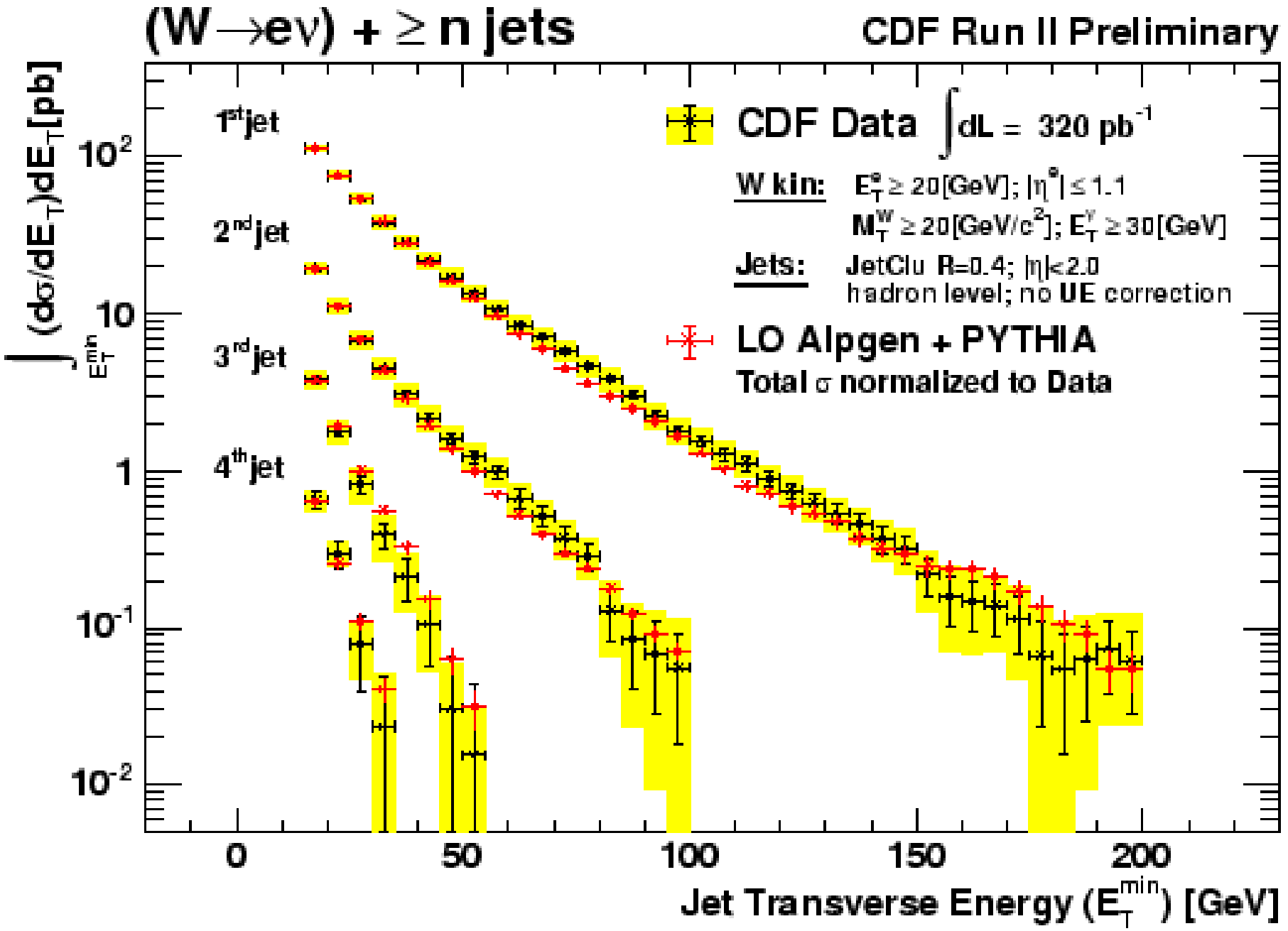
# W Charge Asymmetry



# W + Jets at CDF


(W→eν) + ≥ n jets
CDF Run II Preliminary
CDF Data ∫dL = 320 pb⁻¹
W kin: E_T^e ≥ 20[GeV]; |η^e| ≤ 1.1
M_T^W ≥ 20[GeV/c²]; E_T^ν ≥ 30[GeV]
Jets: JetClu R=0.4; |η|<2.0
hadron level; no UE correction
LO Alpgen + PYTHIA
Total σ normalized to Data
1st jet
2nd jet
3rd jet
4th jet
∫ (dσ/dE_T)dE_T[pb]
E_T^min
Jet Transverse Energy (E_T^min) [GeV]

# SHERPA / CKKW: Which jets ME, which PS?

N-jet events:

Parton Shower jets | Matrix element jets

$$y_{jet} = \frac{(20\ \mathrm{GeV})^2}{\hat{s}}$$

Hard

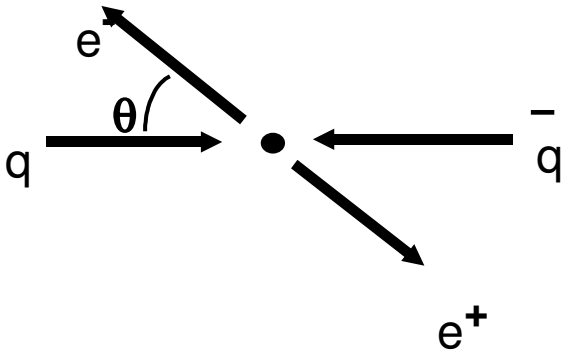
$$y_{ij} = \frac{p_{\perp,i}^2}{\hat{s}}$$

Separated in space

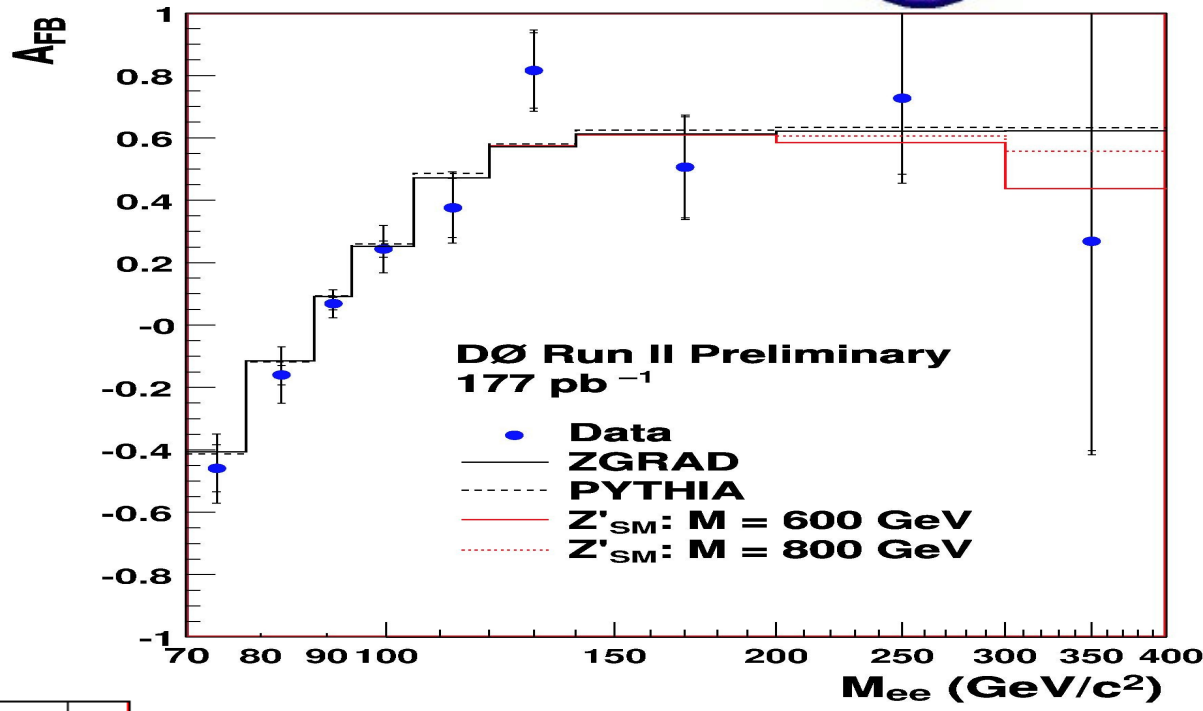
$$y_{ij} = \frac{\min\{p_{\perp,i}^2, p_{\perp,j}^2\}\left[(\eta_i - \eta_j)^2 + (\phi_i - \phi_j)^2\right]}{\hat{s}}$$

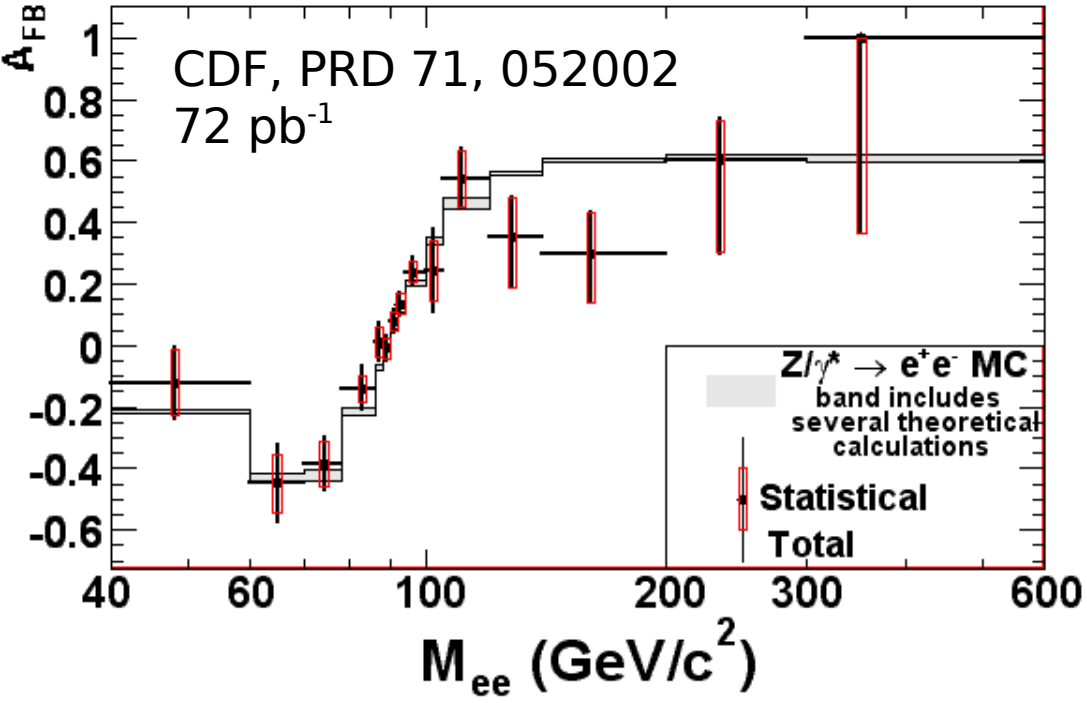
i, j in (1,N): partons

# Z/$\gamma$* F-B Asymmetry




$$A_{FB} = \frac{d\sigma(\cos\theta^* > 0) - d\sigma(\cos\theta^* < 0)}{d\sigma(\cos\theta^* > 0) + d\sigma(\cos\theta^* < 0)}$$




Sensitive to non-SM couplings:
- new neutral gauge boson
- large extra dimensions

CDF and DØ results consistent with SM.