# W/Z + jet production at Tevatron

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on behalf of the DØ and CDF collaborations

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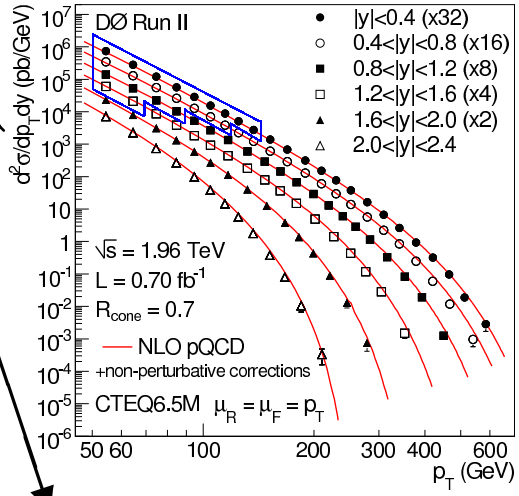
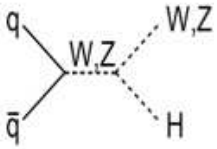
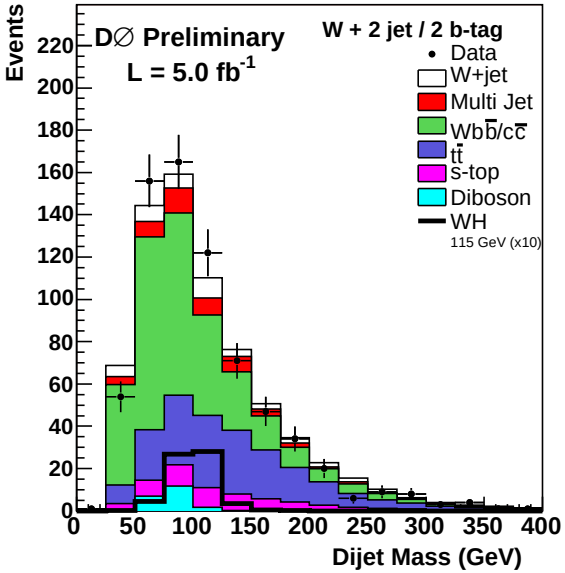
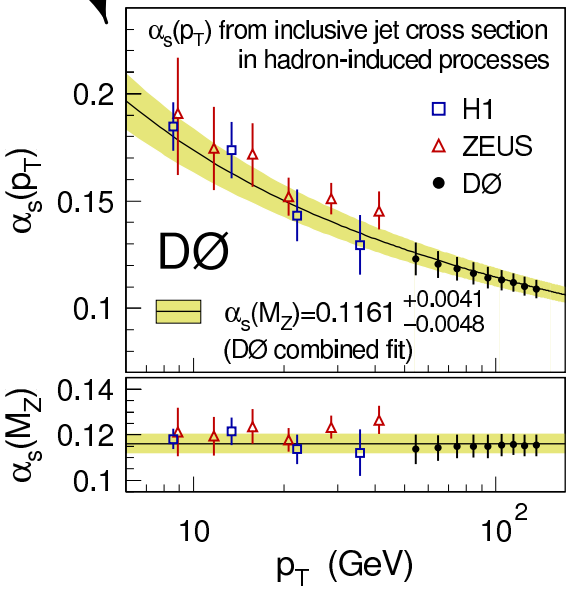
# Outline

- Inclusive jet measurements provide QCD precision tests
  Vector boson + light/heavy flavour jet production
  is interesting for Higgs search, (B)SM processes, etc.
- Contents:
  - Introduction:
    - Tevatron accelerator
    - DØ, CDF experiments
    - vector boson + jet production
    - corrections/unfolding
  - Measurements:
    - Inclusive $Z+$ jet
    - $Z+$ jet $p_T$ balance
    - Inclusive $W+$ jet
    - $W/Z+$ HF jet(s)
  - Conclusions

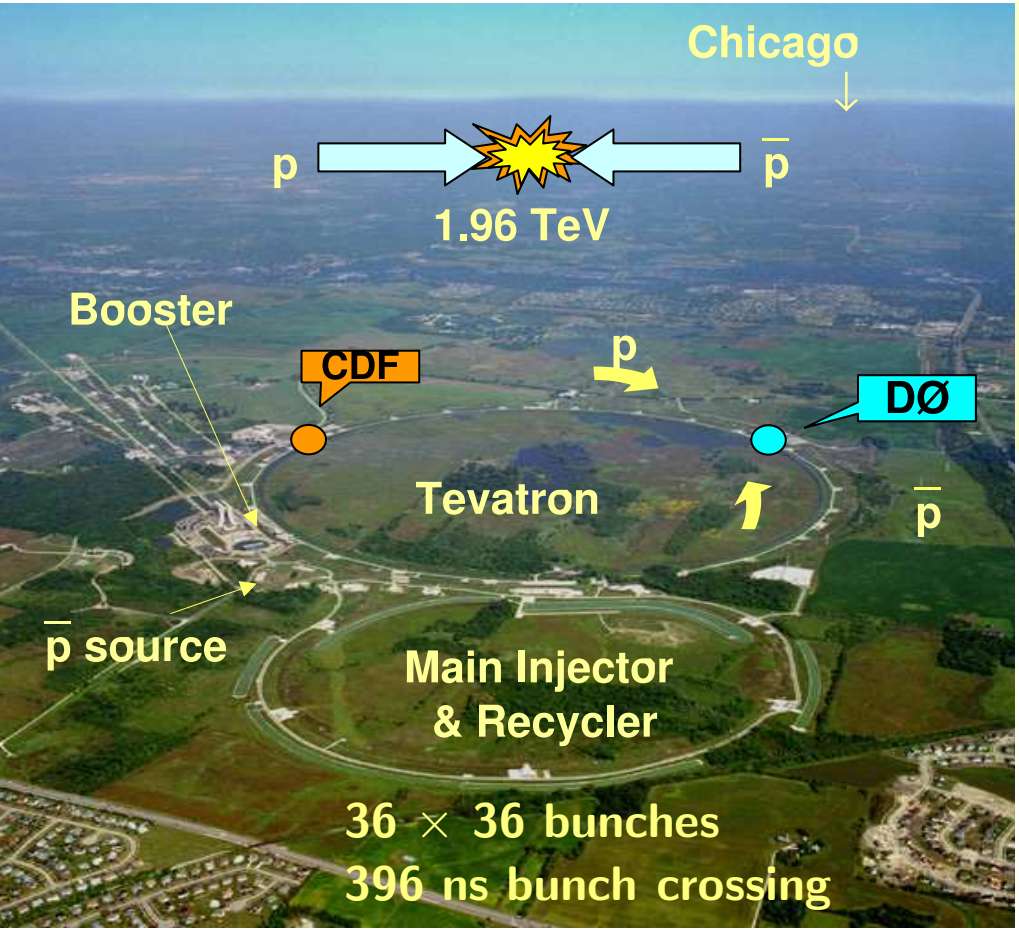


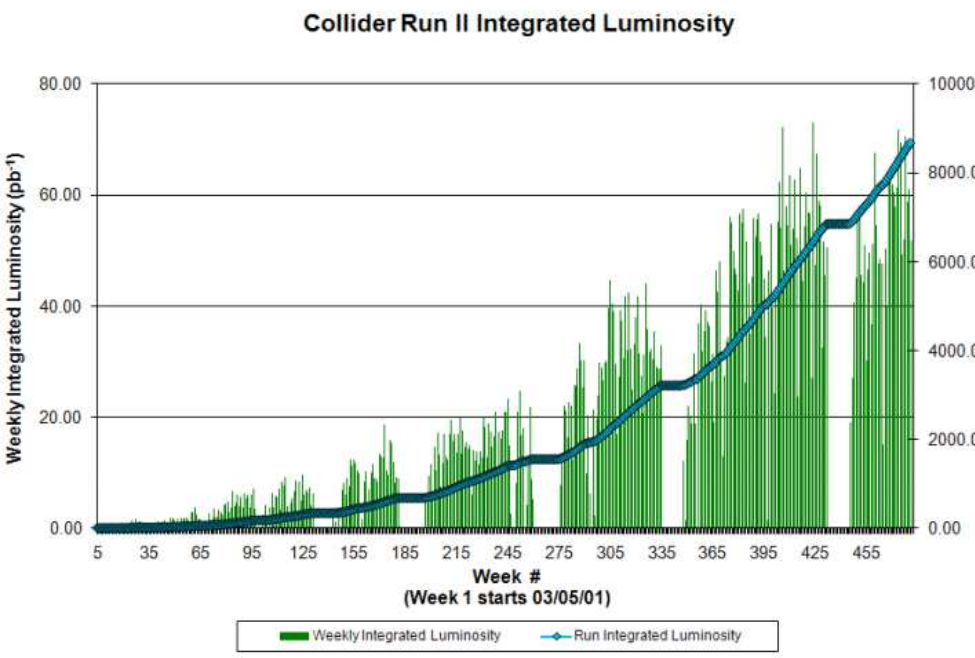



# Fermilab Tevatron Run II



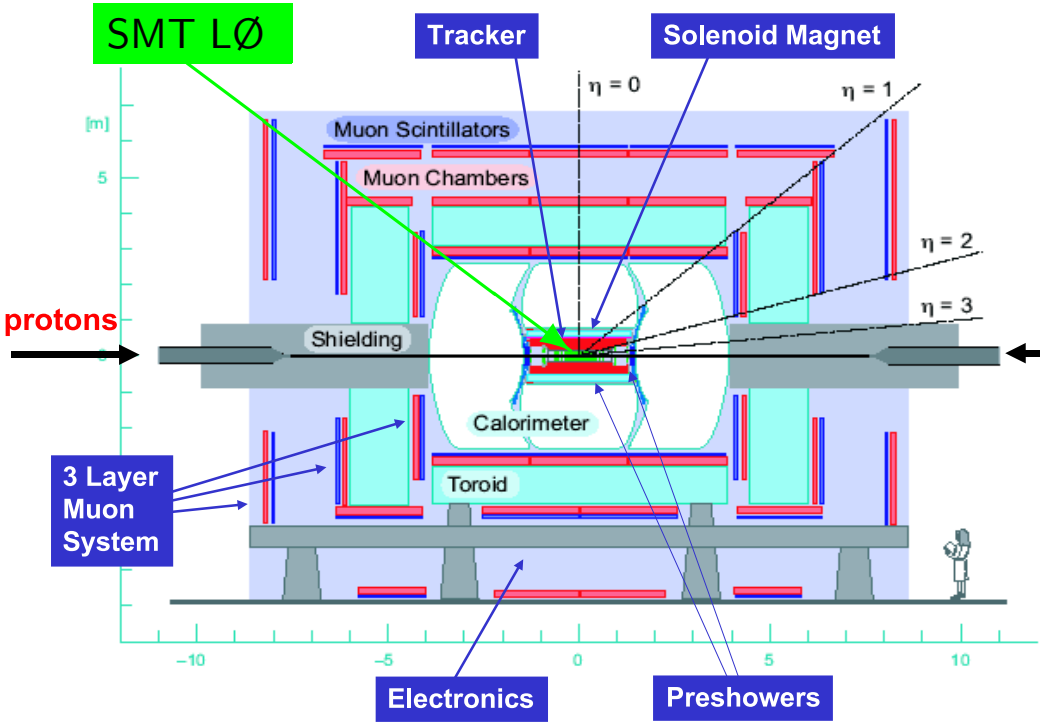

- Run II started in March 2001
- Peak Luminosity: $4 \cdot 10^{32}$ cm$^{-2}$s$^{-1}$
- Delivered: $> 8.8$ fb$^{-1}$
  (Run I: 0.16 fb$^{-1}$ )
- 12 fb$^{-1}$ expected by end of FY 2011



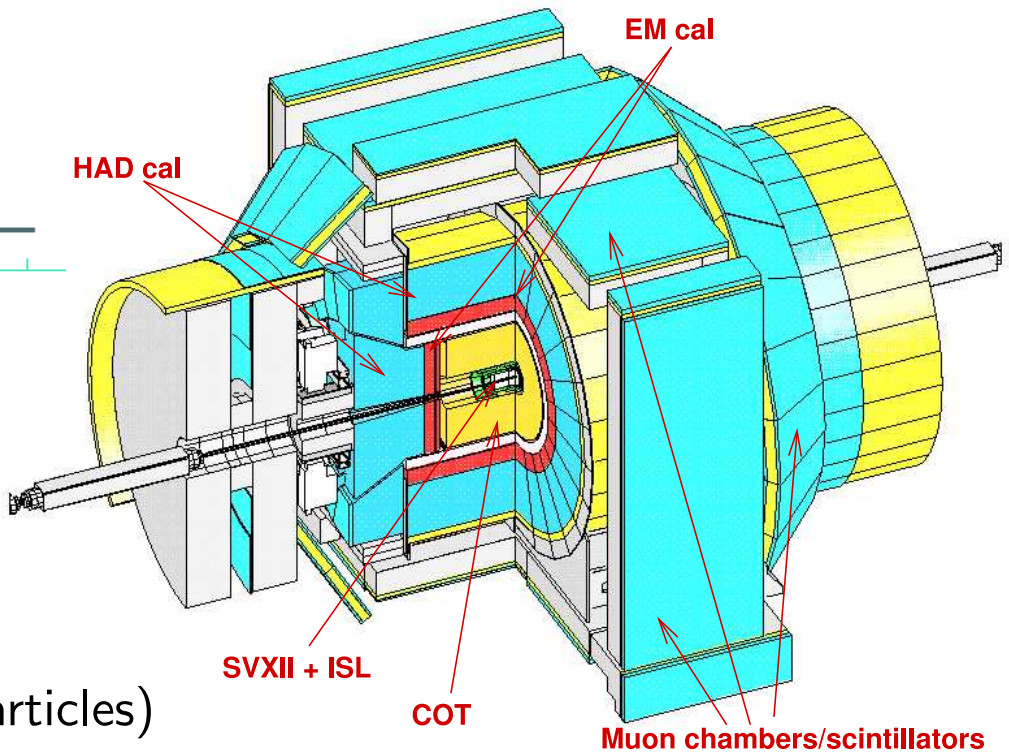

Thanks to all colleagues at the Tevatron for their contributions to this talk

# The DØ and CDF detectors

- Data taking efficiency (DØ & CDF) $\gtrsim 90\%$

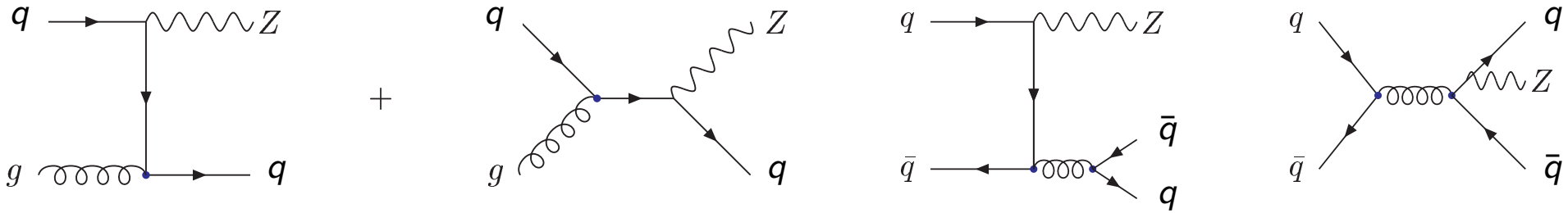



- Multi purpose detectors with broad particle ID capabilities
- Stable detectors and triggers



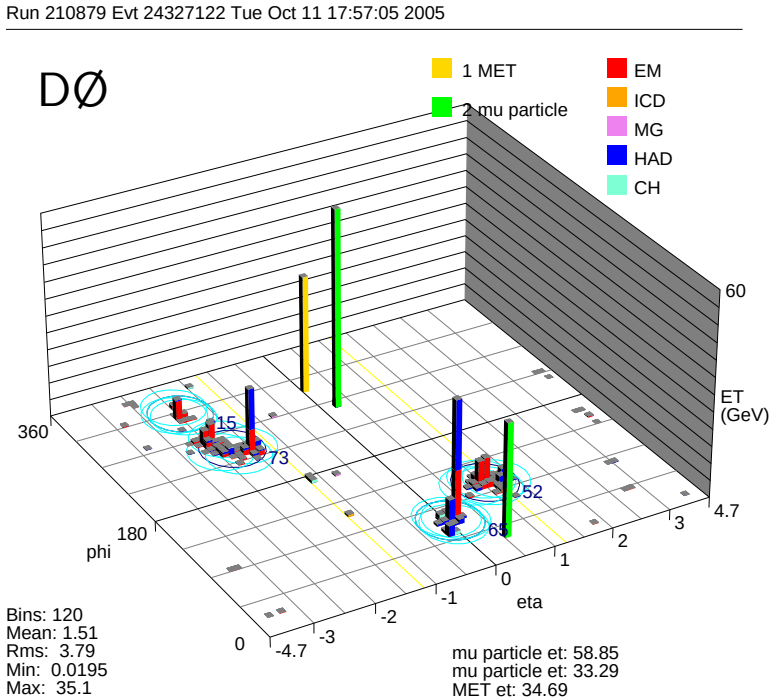

- Calorimeters ($\rightarrow$ jets, $e$, $\gamma$): Fine granularity and good energy resolution
  DØ: $\Delta\eta \times \Delta\phi \sim 0.1 \times 0.1$
  CDF: $\Delta\eta \times \Delta\phi \sim 0.1 \times 0.26$
- Central tracking systems ($\rightarrow$ charged particles)
- Muon spectrometers ($\rightarrow$ muons)

# Aspects of vector boson + jet production



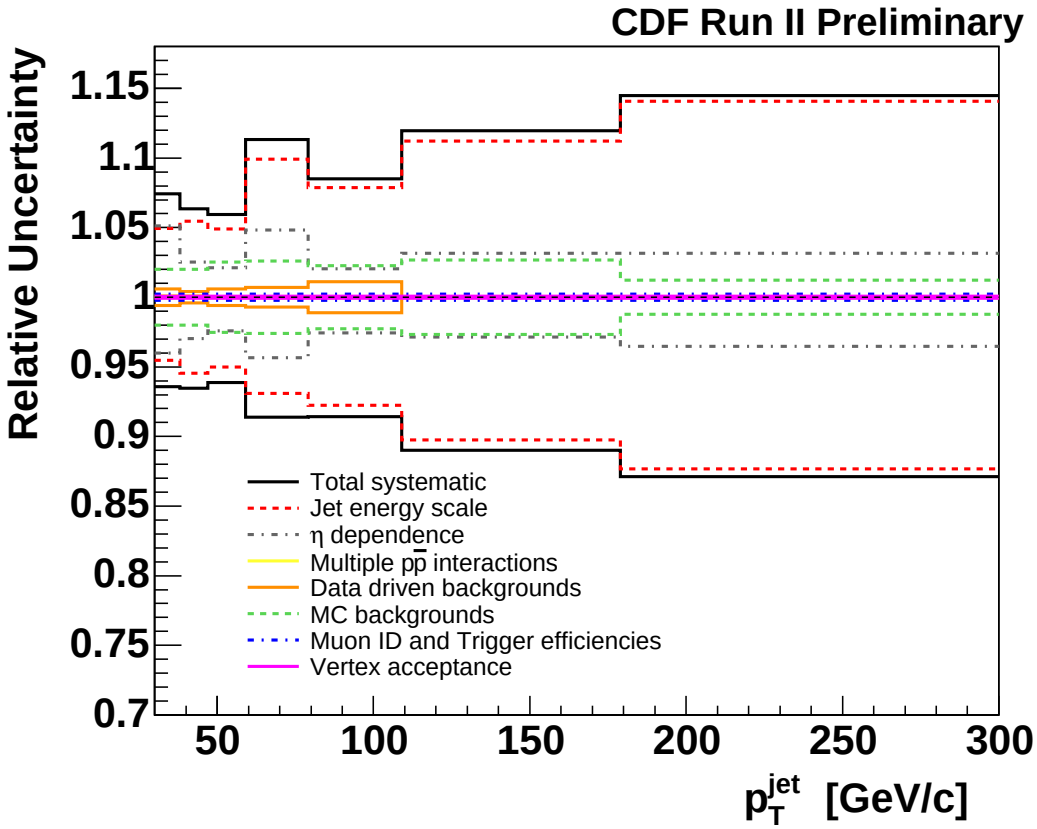

- Precision tests of QCD
  - Complementary kinematic regime to HERA/fixed target
  - Parton distribution functions
  - ISR/FSR gluon radiation
  - $p_T$ spectra
- Standard candles
- Important measurements for MC tuning ((B)SM background)
  - Tevatron dataset is large enough now
  - Unique kinematic overlap with LHC and expected SM Higgs mass range

## $Z(\rightarrow \mu\mu)$ + jets candidate event



# How measurements are done

- Data fully corrected for instrumental effects
  $\Rightarrow$ can be directly used for testing and improving existing event generators and any future calculations/models
- (N)LO pQCD predictions from MCFM are compared taking non-perturbative effects (hadronisation, UE) from simulation into account in the prediction
- Data and theory are compared at the particle level (hadronic final state)




- Relative uncertainties
  (shown here for $Z+$ jets inclusive)
  dominated by Jet energy scale

# Differential $Z/\gamma^* + \text{jets} + X$ cross section $(Z \to ee)$

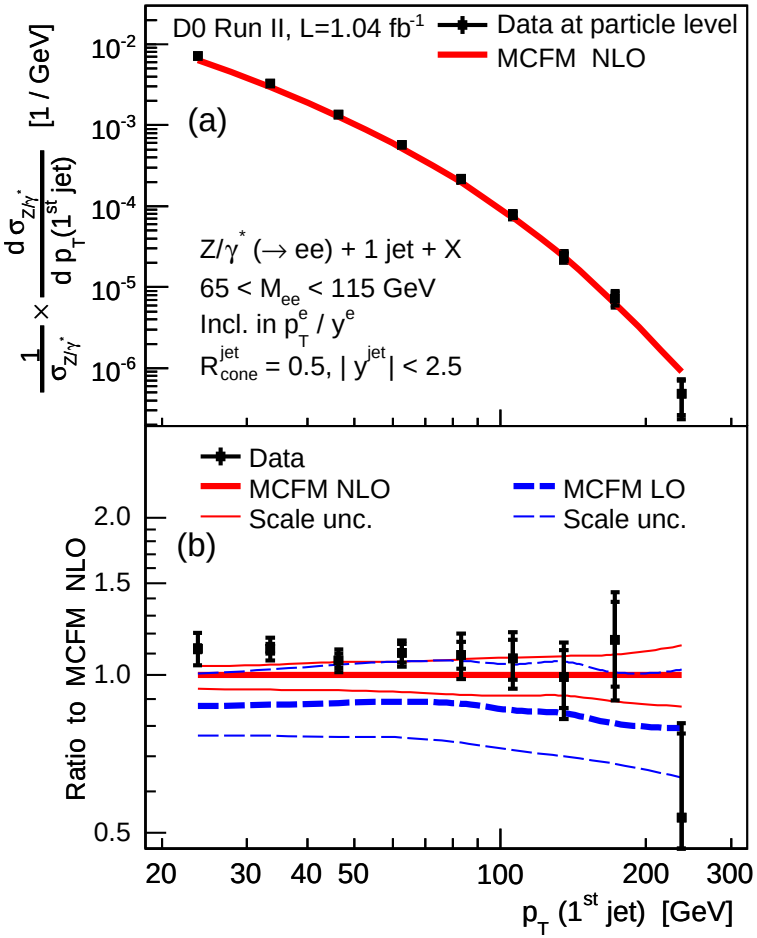
DØ Collab., Phys. Lett. B **678**, 45 (2008)

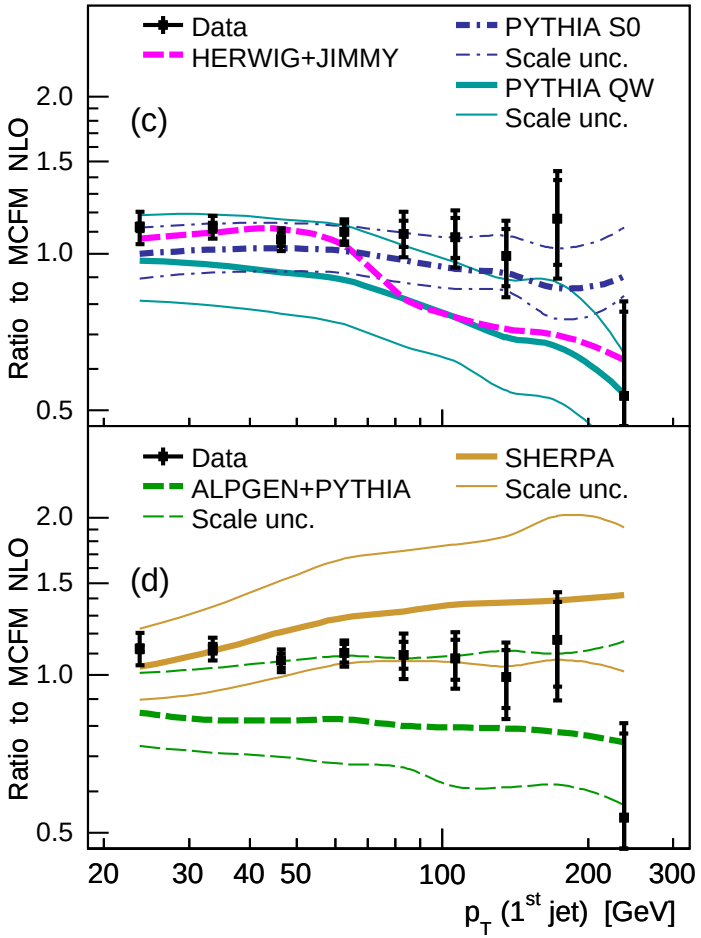
$\mathcal{L} = 1.0\ \text{fb}^{-1}$

$65 < M_{ee} < 115$ GeV, $|\eta_e| < 1.1$, $1.5 < |\eta_e| < 2.5$, $p_T^{\text{jet}}(R=0.5) > 20$ GeV, $|y_{\text{jet}}| < 2.5$

$Z/\gamma^* + 1\text{jet} + X$ bin. Ratios wrt. MCFM NLO + non-pQCD corr.

Normalised to incl. $Z+$ jet production $\Rightarrow$ Uncertainties on $\mathcal{L}$, most of $e$-trigger/ID cancel




Extrapolated to full lepton kinematics

MCFM v5.3
PDF: CTEQ6.1M
$\mu_r^2 = \mu_f^2 = M_Z^2 + p_{T,Z}^2$

PYTHIA 6.416,
HERWIG 6.510 + JIMMY 4.31,
ALPGEN 2.13 + PYTHIA 6.325,
SHERPA 1.1.1 + PYTHIA 6.325,
PDF: CTEQ6.1M

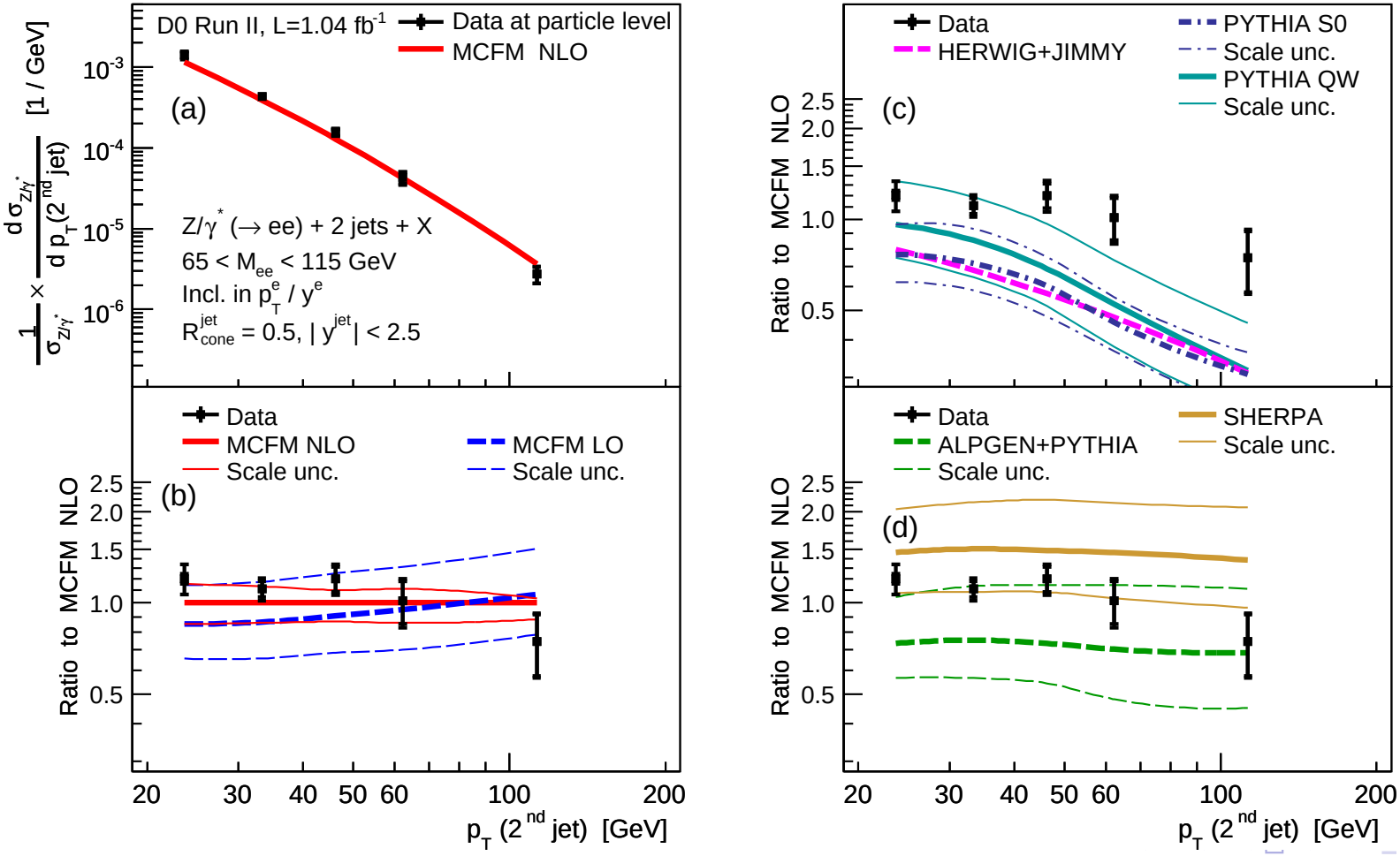
- Large differences between models
- Small experimental errors, dominated by statistics

# Differential $Z/\gamma^* + \text{jets} + X$ cross section ($Z \to ee$)

$Z/\gamma^* + 2\text{jets} + X$ bin. Normalised to incl. $Z+$ jet production.

Uncertainties on integrated luminosity, most of $e$-trigger/ID cancel

Extrapolated to full lepton kinematics: $p_T^e$, $|y_e|$




PYTHIA 6.416,
HERWIG 6.510 + JIMMY 4.31,
ALPGEN 2.13 + PYTHIA 6.325,
SHERPA 1.1.1 + PYTHIA 6.325,
PDF: CTEQ6.1M

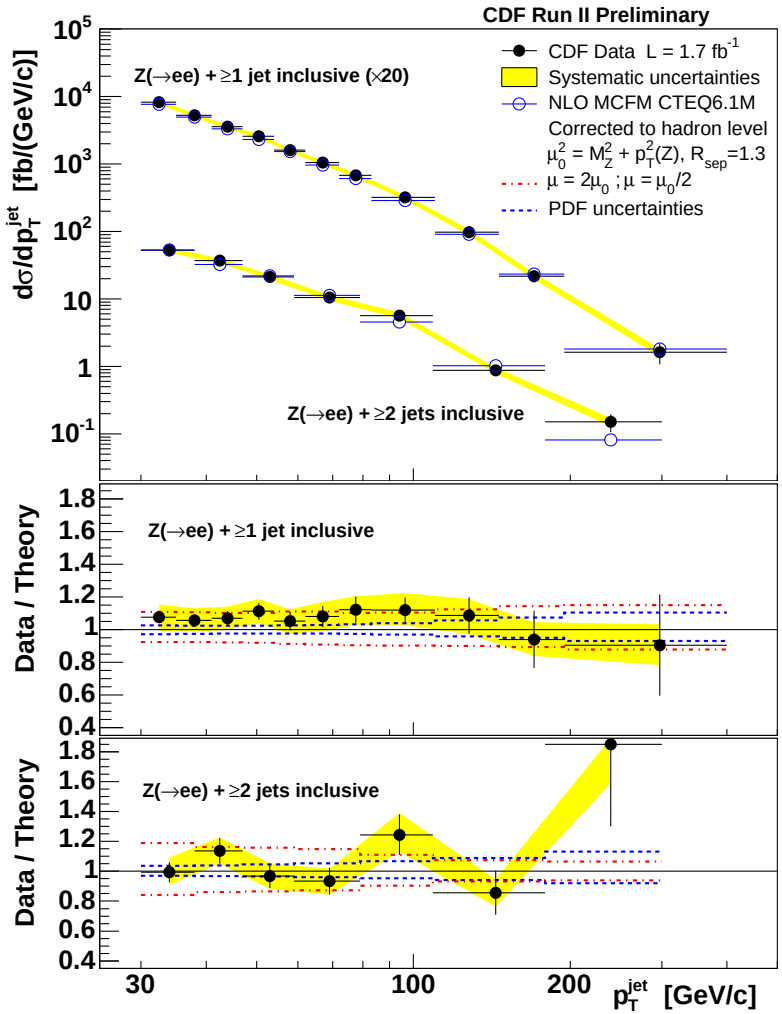
- Large differences between models
- Small experimental errors, dominated by statistics

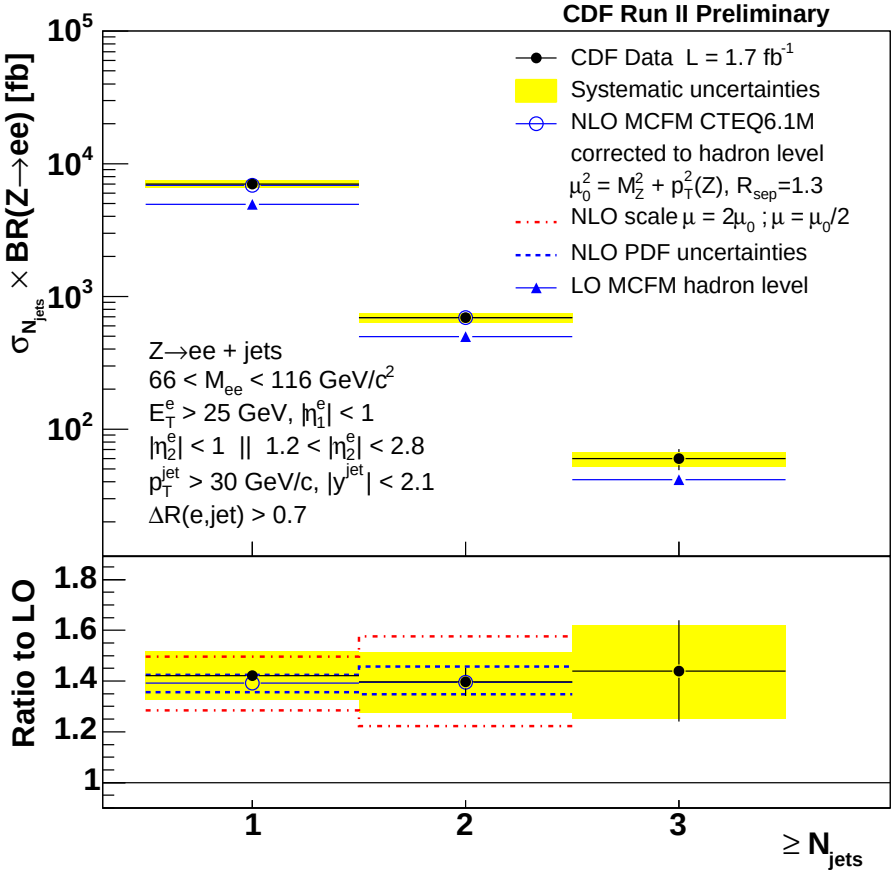
# Inclusive $Z/\gamma^* +$ jets cross section $(Z/\gamma^* \to ee)$

CDF Collab., Phys. Rev. Lett. **100**, 102001 (2008)

$\mathcal{L} = 1.7\ \mathrm{fb}^{-1}$

$66 < M_{ee} < 116$ GeV, $E_T^e > 25$ GeV, $|\eta_e| < 1$, $1.2 < |\eta_e| < 2.8$, $p_T^{\mathrm{jet}}(R=0.7) > 30$ GeV, $|y_{\mathrm{jet}}| < 2.1$



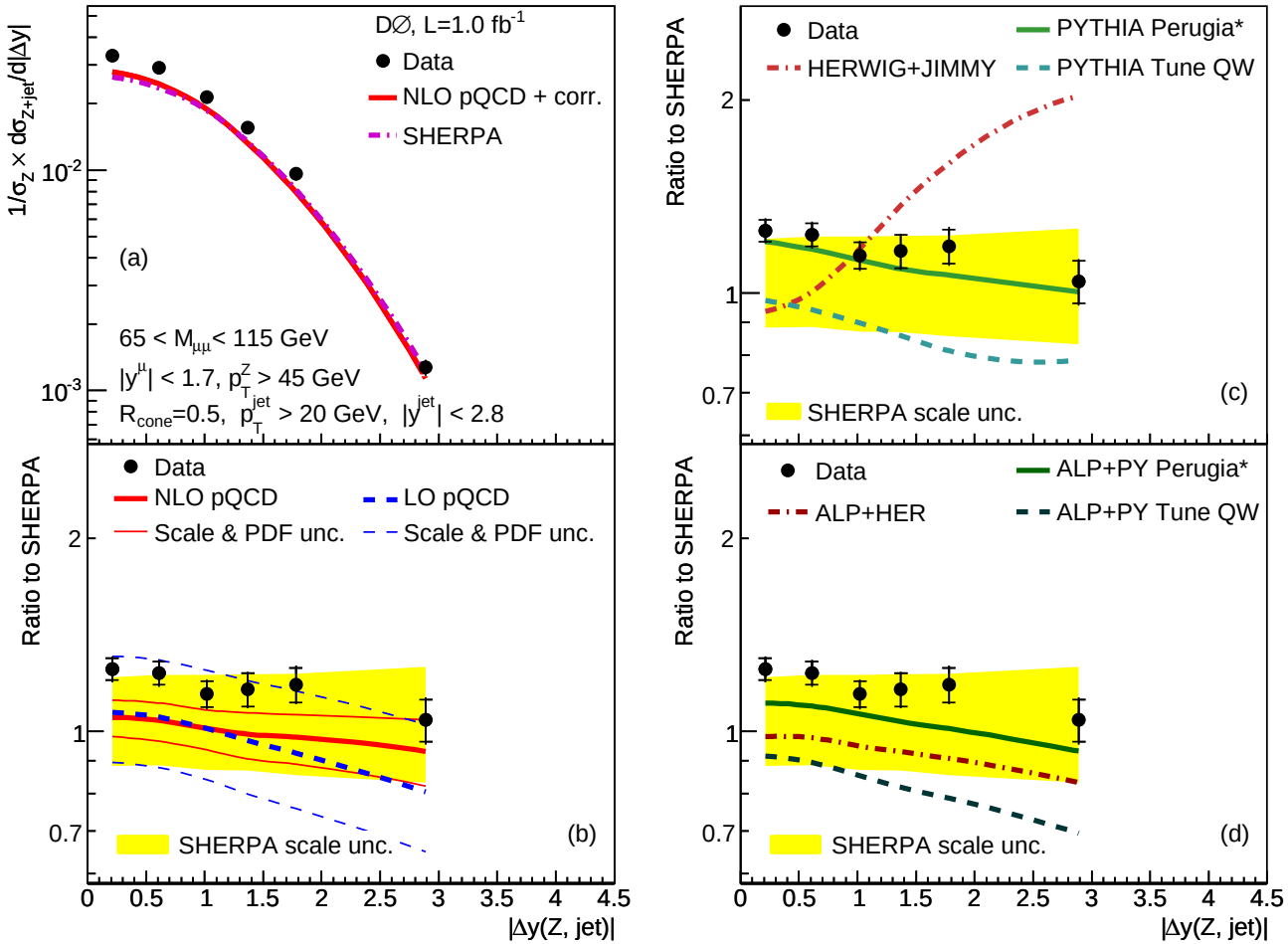

Good agreement between data and NLO pQCD prediction

# Differential $Z/\gamma^* + \text{jet} + X$ angular distributions ($Z \to \mu\mu$)

DØ Collab., Phys. Lett. B **682**, 370 (2010)

$\mathcal{L} = 1.0\ \text{fb}^{-1}$

$65 < M_{\mu\mu} < 115$ GeV, $|y_\mu| < 1.7$, $p_T^Z > 45$ GeV, $p_T^{\text{jet}}(R = 0.5) > 20$ GeV, $|y_{\text{jet}}| < 2.8$




- Rapidity difference between $Z$ and jet

MCFM v5.6
PDF's: MSTW2008
$\mu_r^2 = \mu_f^2 = M_Z^2 + p_{T,Z}^2$

Hadronisation and underlying event correction: PYTHIA 6.421, Tune QW, CTEQ6.1M

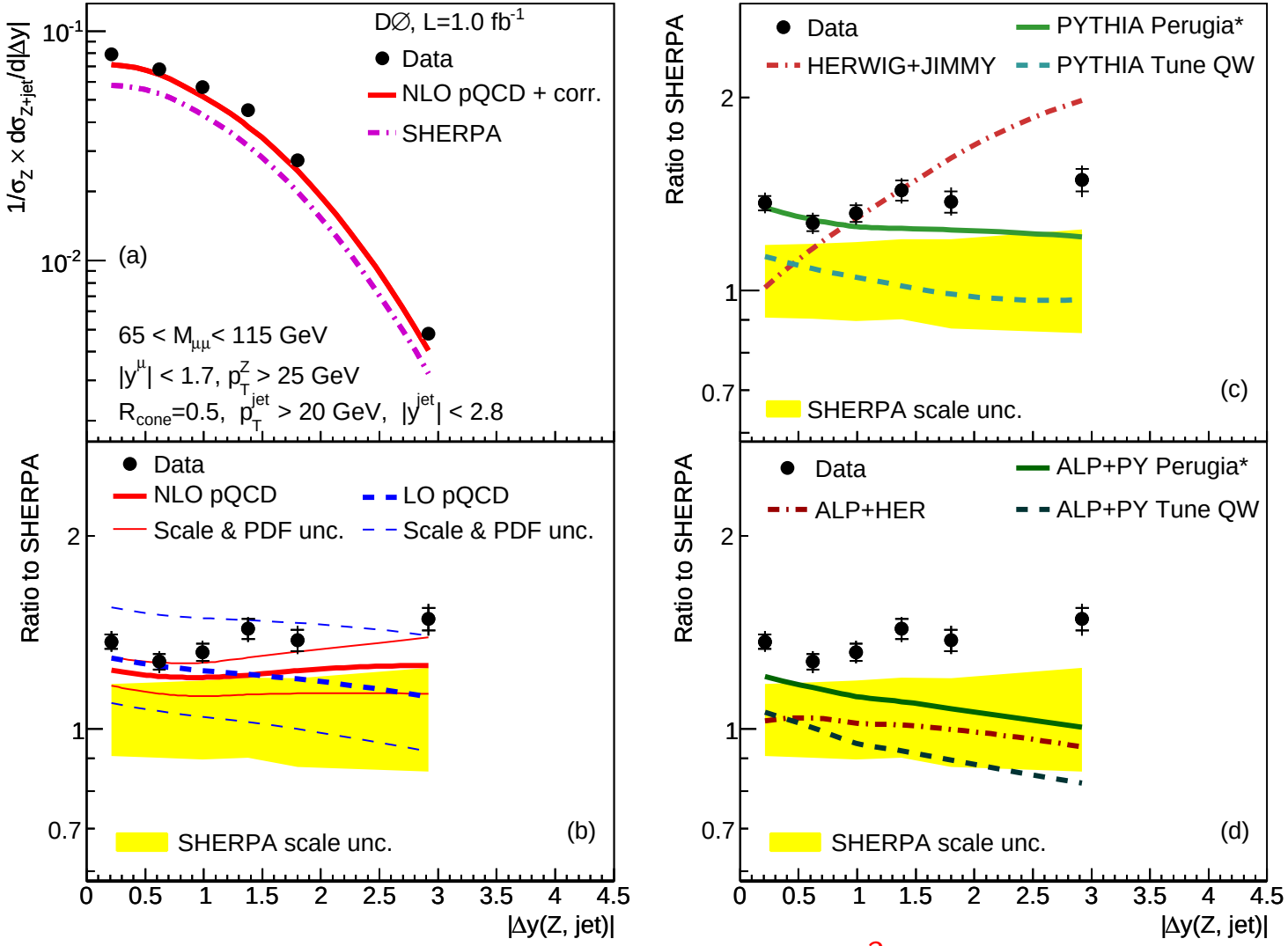
- SHERPA (1.1.3) is able to describe $\Delta y$ for $p_T^Z > 45$ GeV

$\sigma_{Z+\text{jet}}/\sigma_Z = [122 \pm 2(\text{stat.}) \pm 4(\text{syst.})] \cdot 10^{-3}$

pQCD: $[111 \pm 6(\text{scale}) \pm 2(\text{PDF})] \cdot 10^{-3}$ @NLO, $[112 \pm 20(\text{scale}) \pm 1(\text{PDF})] \cdot 10^{-3}$ @LO

# Differential $Z/\gamma^* + \text{jet} + X$ angular distributions ($Z \to \mu\mu$)

$65 < M_{\mu\mu} < 115$ GeV, $|y_\mu| < 1.7$, $p_T^Z > 25$ GeV, $p_T^{\text{jet}} > 20$ GeV, $|y_{\text{jet}}| < 2.8$




PYTHIA 6.421,
HERWIG 6.510 + JIMMY 4.31,
ALPGEN 2.13,
SHERPA 1.1.3,
PDF's: CTEQ6.1M and MRST2007 (LO*) for Perugia*

- ALPGEN + SHERPA: Up to three partons in the matrix element calculations
- Binning chosen such, that detector resolution causes little migrations between bins
- Less agreement between data and prediction in $p_T^Z > 25$ GeV bin

$\sigma_{Z+\text{jet}}/\sigma_Z = [47 \pm 1(\text{stat.}) \pm 2(\text{syst.})] \cdot 10^{-3}$

pQCD: $[40 \pm 3(\text{scale}) \pm 1(\text{PDF})] \cdot 10^{-3}$ @NLO, $[40 \pm 8(\text{scale}) \pm 1(\text{PDF})] \cdot 10^{-3}$ @LO

# SM precision limits from $Z + 1$ jet $p_T$ balance $(Z \to ee, \mu\mu)$

CDF Collaboration, submitted to NIM (2010)

$\mathcal{L} = 4.6\ \mathrm{fb}^{-1}$

$p_T(\ell)$>18 GeV, $p_T(Z)$>25 GeV, $80 < m(\ell\ell) < 100$ GeV,
Leading jet $p_T > 8$ GeV, $\Delta\phi(Z, jet) > 3.0$ rad, $R_{\mathrm{cone}} =$ 0.4(shown here), 0.7, 1.0

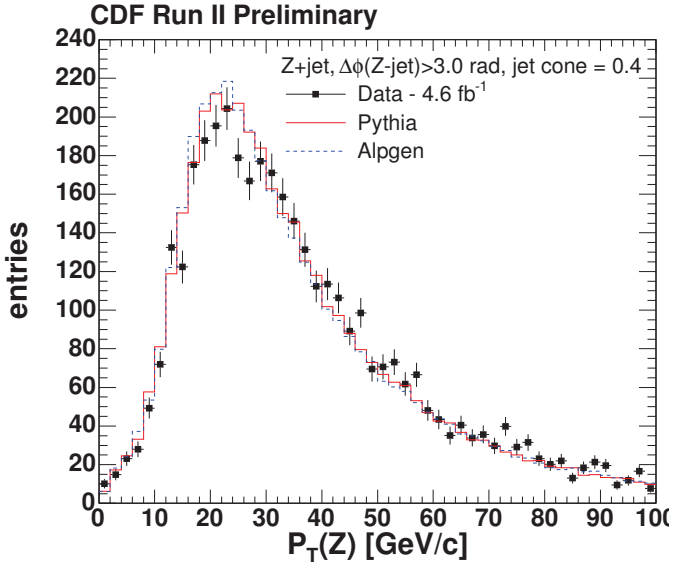
- CDF JES calibrated via tuning calorimeter response to single particles

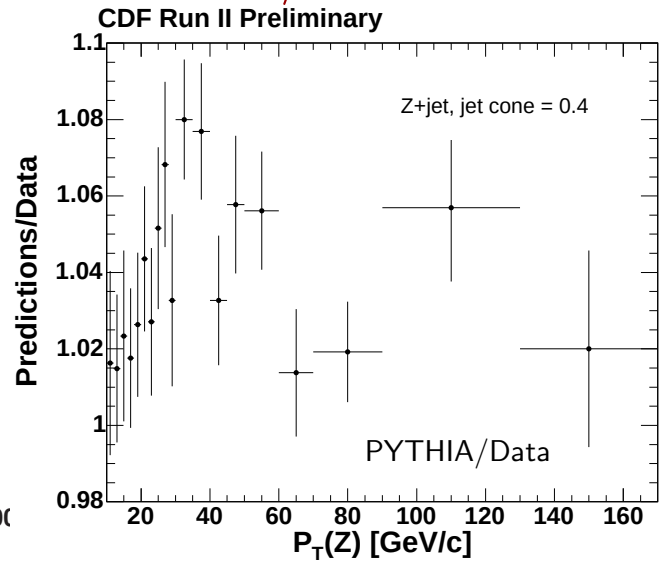
$\Rightarrow$ Test of $p_T(Z)$ balance independent of CDF JES

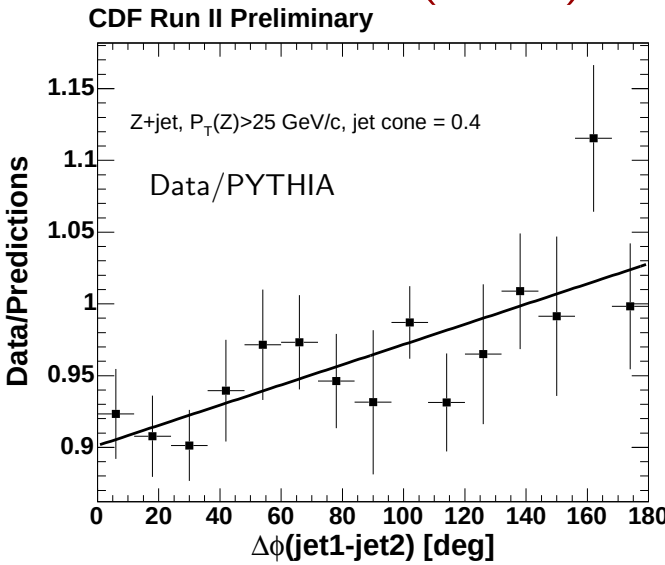
- Track in jet distributions agree with predicted quark/gluon jet fractions
- Observe in data higher rate of sub-leading jets collinear to leading jet

$\Rightarrow$ ATLAS + CMS limitations on $p_T(Z)$ balance JES precision of $\sim 3\%$

Jet / $Z$ transverse momentum balance (ratios)



# SM precision limits from $Z + 1$ jet $p_T$ balance $(Z \to ee, \mu\mu)$

- All sorts of possible sources of uncertainties are considered:
  (Effect (in %) on predicted mean of $p_T(Z)$ balance)

| Source of uncertainty | jet cone = 0.4 | jet cone = 0.7 | jet cone = 1.0 |
|---|---|---|---|
| renormalization and factorization scales | +0.9 -0.0 | +0.9 -0.4 | +0.4 -0.4 |
| FSR parameters in PYTHIA | +0.4 -0.4 | +0.1 -0.1 | +0.1 -0.1 |
| ME's and parton-jet matching | +0.8 -0.0 | +1.1 -0.0 | +0.8 -0.0 |
| single particle response | +2.5 -2.5 | +2.5 -2.5 | +2.5 -2.5 |
| multiple proton interactions | +1.0 -0.0 | +1.2 -0.0 | +1.2 -0.0 |
| large-angle FSR, limitation of PS | +0.0 -2.9 | +0.0 - 0.2 | +1.7 -0.0 |
| Estimate of the total variation | +3.0 -3.8 | +3.1 -2.5 | +3.4 -2.5 |
| The observed discrepancy | +4.7 | +3.2 | +2.0 |

← $\frac{\text{Prediction}}{\text{Data}}$

Only large angle-radiation (FSR) observed as sub-leading jets is able to explain discrepancy

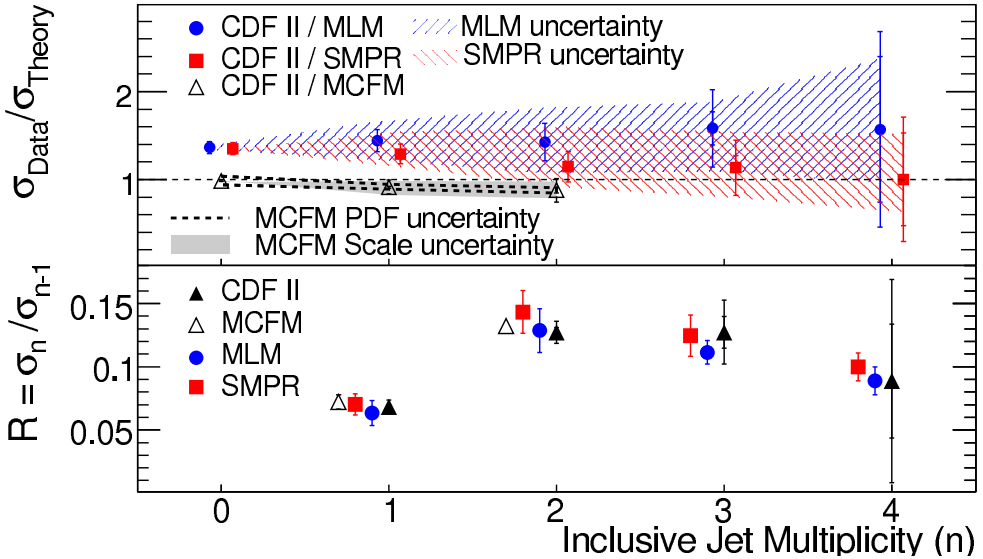
# $\sigma(p\bar{p} \to W + n_{(=1\text{-}4)}$ jets) inclusive cross section ($W \to e\nu$)

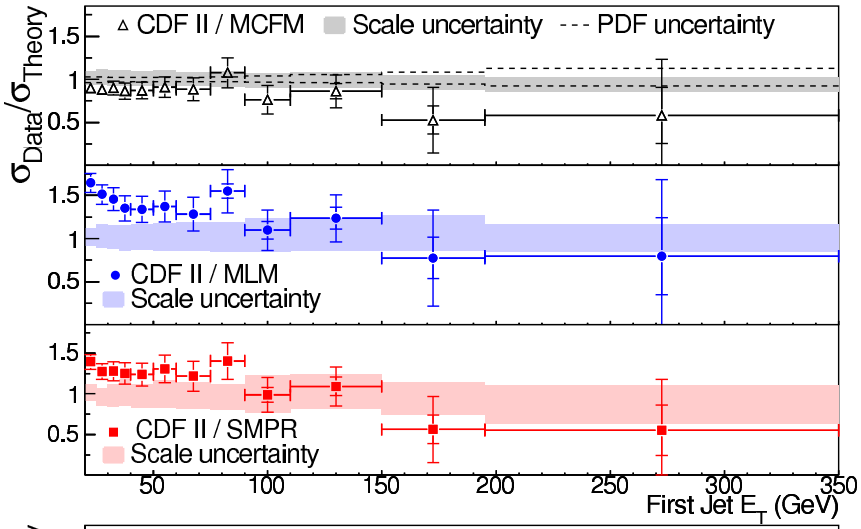
CDF Collab., Phys. Rev. D **77**, 011108(R) (2008)

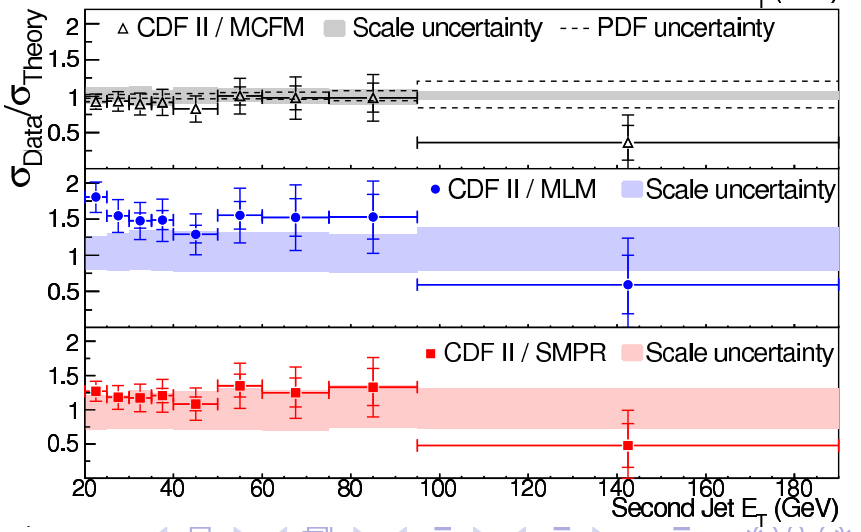
$\mathcal{L} = 320\ \text{pb}^{-1}$

$E_T^{\ell} > 20$ GeV, $|\eta_\ell| < 1.1$, $\not{E}_T > 30$ GeV, $m_T^W > 20$ GeV, $E_T^{\text{jets}}(R=0.4) > 20$ GeV, $|\eta_{\text{jet}}| < 2.0$

- $\times$ 10 more cross section than $Z+$ jets but need to control QCD and Top backgrounds
- Good agreement with pQCD NLO
- At low $p_T$ MC needs better modeling of UE (ALPGEN+PYTHIA)



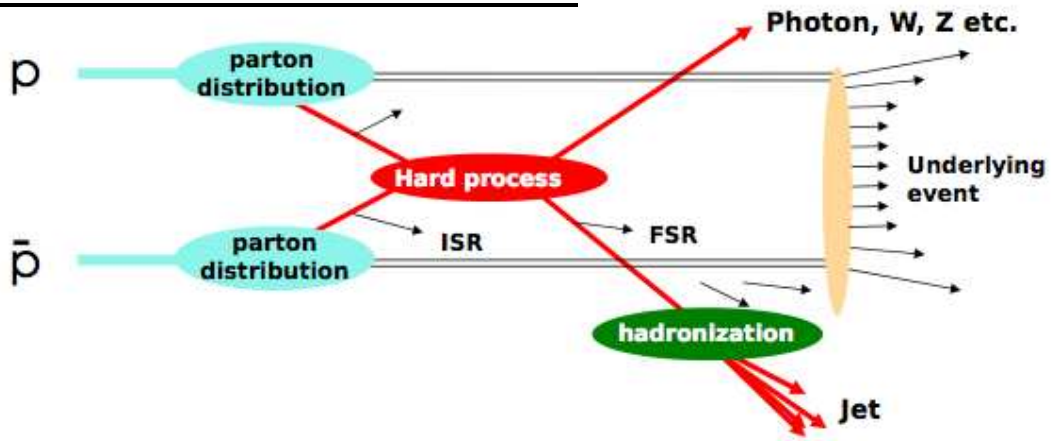



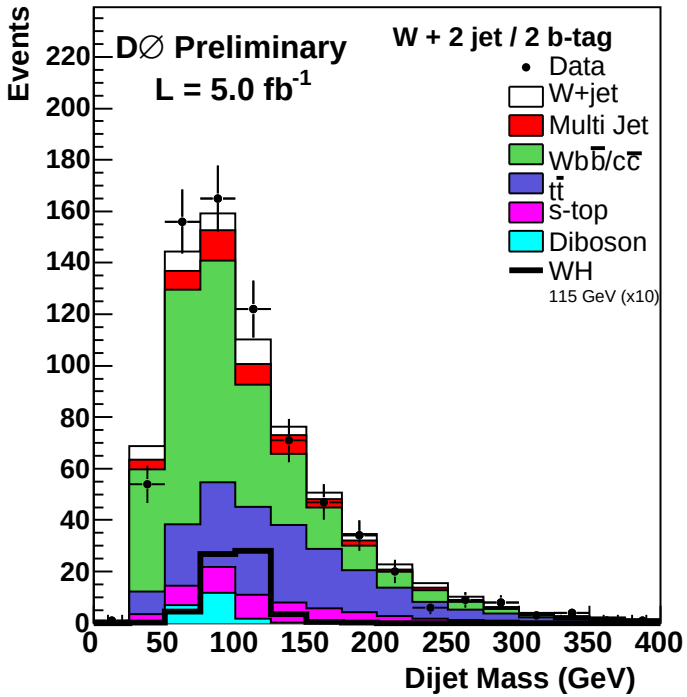



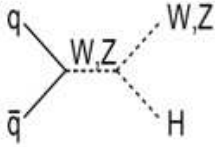
# Vector boson + HF jet production

Important for physics programme at Tevatron and LHC

- Probing theory and models
  - Testing perturbative QCD predictions
  - $W/Z(\gamma^*)$ direct probe of hard scattering dynamics
  - Sensitive to PDF's HF content
- Understanding backgrounds
  - $W/Z$ + HF is background to: $t\bar{t}$, single top, Higgs/SUSY search
  - Challange to accurately simulate data



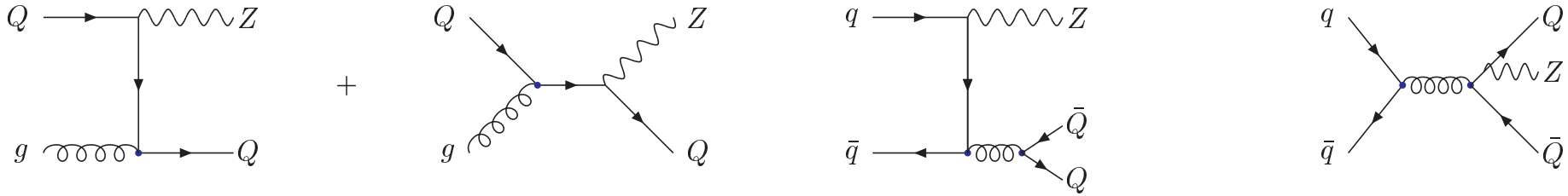



# Incl. $\sigma(p\bar{p} \to Z+b)/\sigma(p\bar{p} \to Z+j)$ ratio $(Z \to e^+e^-, \mu^+\mu^-)$

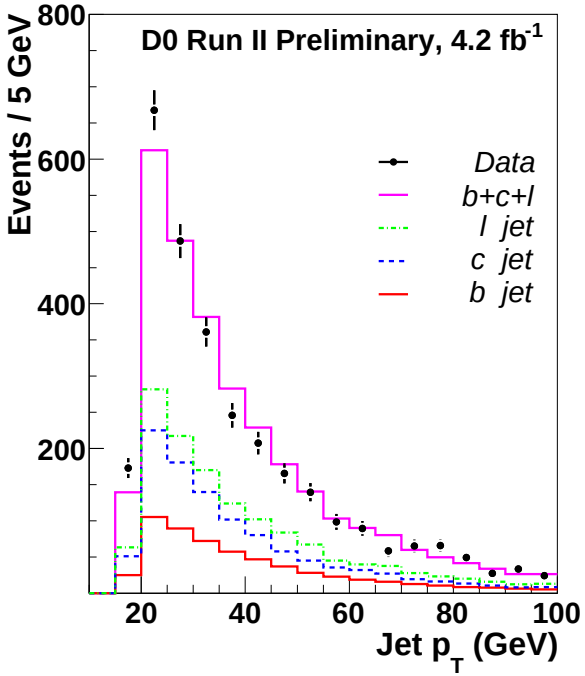
DØ Collab., Preliminary, DØ Note 6053-CONF

$\mathcal{L} = 4.2\ \text{fb}^{-1}$

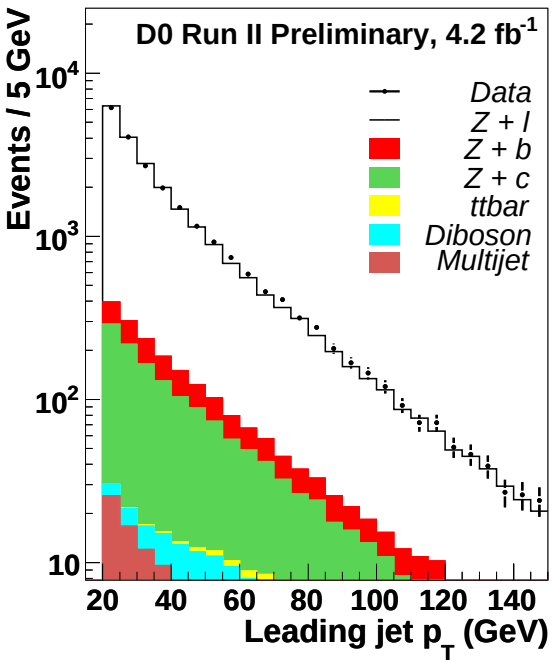



- $p_T(\mu) > 10$ GeV, $|\eta_{\text{det}}| < 2.5$
- $p_T(e) > 15$ GeV, $|\eta_{\text{det}}| < 2.0$
- $p_T(\text{1st jet}) > 20$ GeV, $|\eta_{\text{det}}| < 1.1$
- NN flavour tagging based on lifetimes
- Fit to lifetime variable templates $\Rightarrow$ flavour fractions
- Alpgen 2.11 + Pythia 6.413
- Cross sections taken from NLO

*b*-fraction fit to data




Dimuon channel




$$\sigma(Z+b)/\sigma(Z+j) = 0.0176 \pm 0.0024(\text{stat.}) \pm 0.0023(\text{syst.})$$

Consistent with NLO prediction of $0.0184 \pm 0.0022$

# Incl. $\sigma(p\bar{p} \to Z+b)/\sigma(p\bar{p} \to Z)$ ratio $(Z \to e^+e^-, \mu^+\mu^-)$

CDF Collab., Phys. Rev. D **79**, 052008 (2009)

$\mathcal{L} = 2.0\ \text{fb}^{-1}$

$76 < M_{\ell\ell} < 106$ GeV, $p_T^{\mu_1}, E_T^{e_1} > 18$ GeV, $p_T^{\mu_2}, E_T^{e_2} > 10$ GeV, $E_T^{\text{jet}}(R=0.7) > 20$ GeV, $|\eta_{\text{jet}}| < 1.5$

$\sigma(Z+b)/\sigma(Z) = [3.32 \pm 0.53(\text{stat.}) \pm 0.42(\text{syst.})] \times 10^{-3}$

MCFM NLO: $2.3 \times 10^{-3}$ $(Q^2 = m_Z^2 + p_{T,Z}^2)$

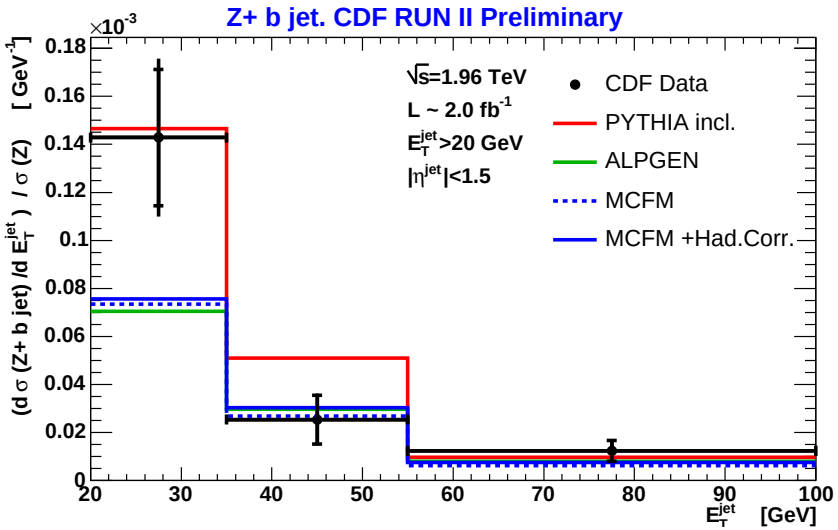
MCFM NLO: $2.8 \times 10^{-3}$ $(Q^2 = p_{T,\text{jet}}^2)$

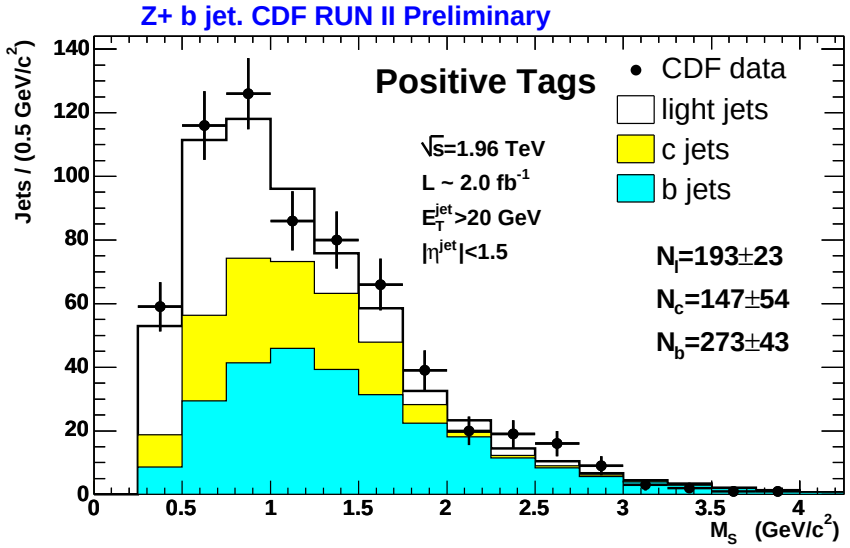
ALPGEN: $2.1 \times 10^{-3}$

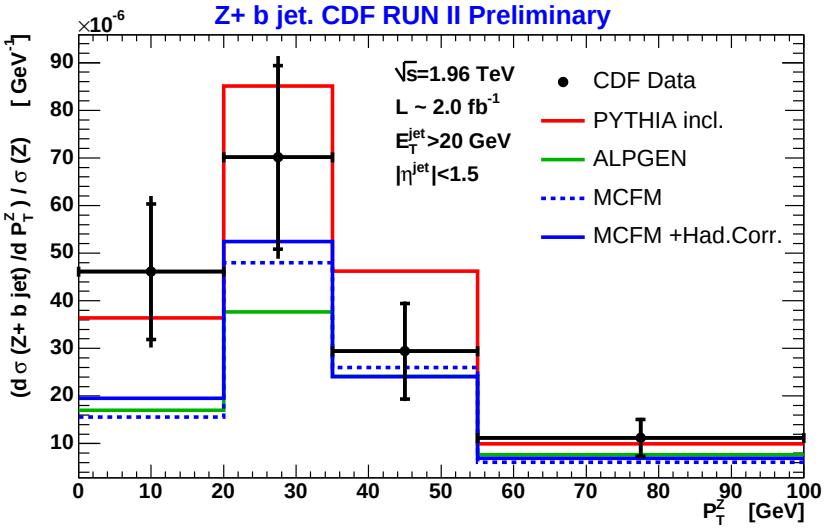
PYTHIA: $3.5 \times 10^{-3}$

- Large uncertainties in data and theory
- No complete NLO prediction for $Z + b\bar{b}$

  $\Rightarrow$ Large scale dependence



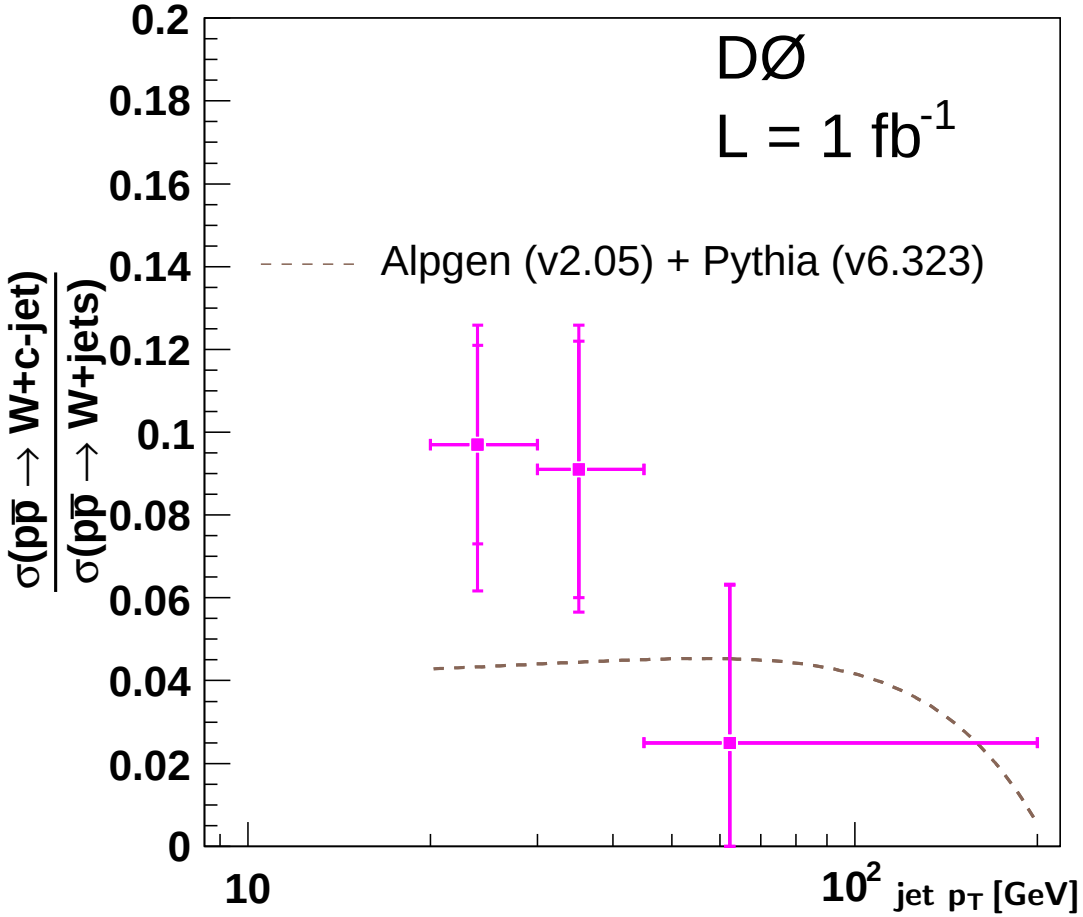



# $\sigma(p\bar{p} \to W + c-\text{jet})/\sigma(p\bar{p} \to W + \text{jets})$ ratio $(W \to \ell\nu)$

DØ Collab., Phys. Lett. B **666**, 23 (2008)

$\mathcal{L} = 1.0\ \text{fb}^{-1}$

$p_T^{\text{jet}}(R{=}0.5) > 20$ GeV, $|\eta_{\text{jet}}| < 2.5$, $p_T^{\ell} > 20$ GeV, $\not{E}_T > 20$ GeV




$W + c$-quark production sensitive to $s$-quark PDF;
Up to $Q^2 = 10^4$ GeV$^2$

$W \leftrightarrow c$ opposite charge sign (OS) $\Rightarrow$ tag oppositely charged $\mu$ in jet from $c$ decay

$$\sigma(W_{(\to \ell\nu)} + c) = \frac{N_{\text{observed}} - N_{\text{bkg}}}{\mathcal{L} \times A \times \epsilon}$$

OS-SS background is small: $\sim 1\%$

Multi-jet backgrounds determined from data

$$\sigma(p\bar{p} \to W + c-\text{jet})/\sigma(p\bar{p} \to W + \text{jets}) = 0.074 \pm 0.019(\text{stat.})^{+0.012}_{-0.014}(\text{syst.})$$

In agreement with theoretical predictions: ALPGEN + PYTHIA $0.044 \pm 0.003$

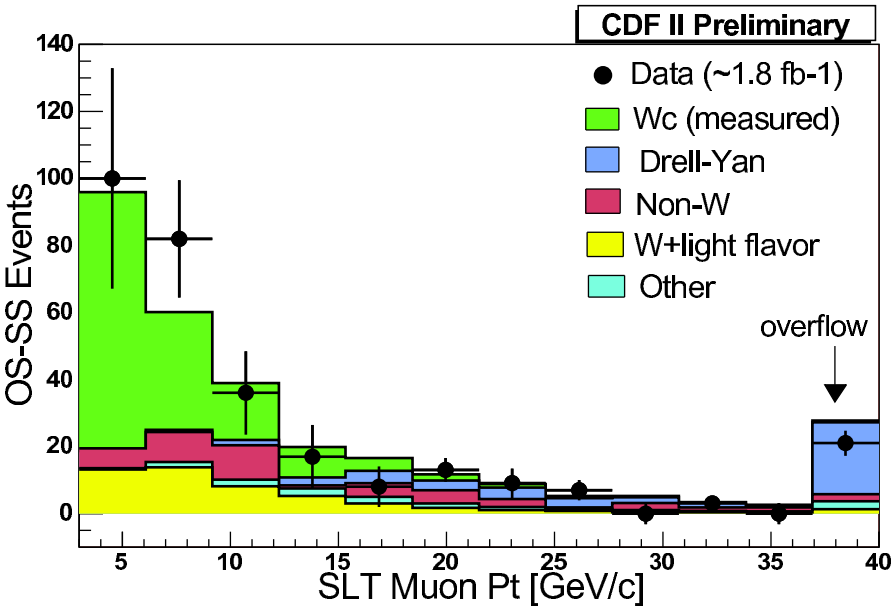
# $\sigma(p\bar{p} \to W + c\text{-jet})$ exclusive cross section $(W \to \ell\nu,\ \ell = e, \mu)$

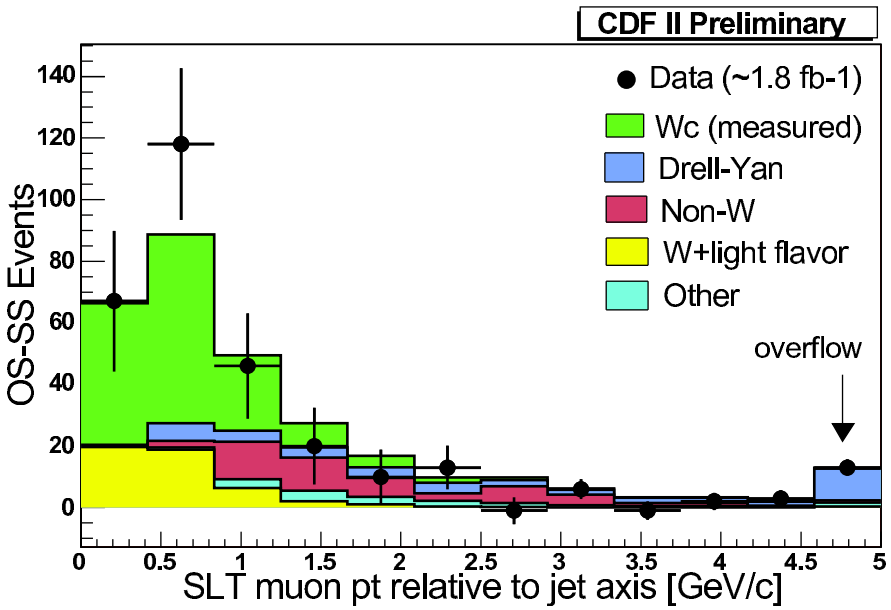
CDF Collab., Phys. Rev. Lett. **100**, 091803 (2008)

$\mathcal{L} = 1.8\ \text{fb}^{-1}$

$p_T^{c\text{-jet}} > 20$ GeV, $|\eta_{c\text{-jet}}| < 1.5$, $(R = 0.4)$, $p_T^{\ell} > 20$ GeV, $|\eta_\ell| < 1.1$, $\not{E}_T > 25$ GeV

Soft $\mu$-in-jet tag. CDF is working on getting results out with soft $e+\mu$-tag (SLT)




$\sigma(W_{(\to\ell\nu)} + c) = 9.8 \pm 2.8(\text{stat.})^{+1.4}_{-1.6}(\text{syst.}) \pm 0.6(\text{lum.})$ pb

NLO prediction: $\sigma(W_{(\to\ell\nu)} + c) = 11.0^{+1.4}_{-3.0}$ pb $(p_T^{c\text{-jet}} > 20$ GeV, $|\eta_{c\text{-jet}}| < 1.5)$

Good agreement between data and theory

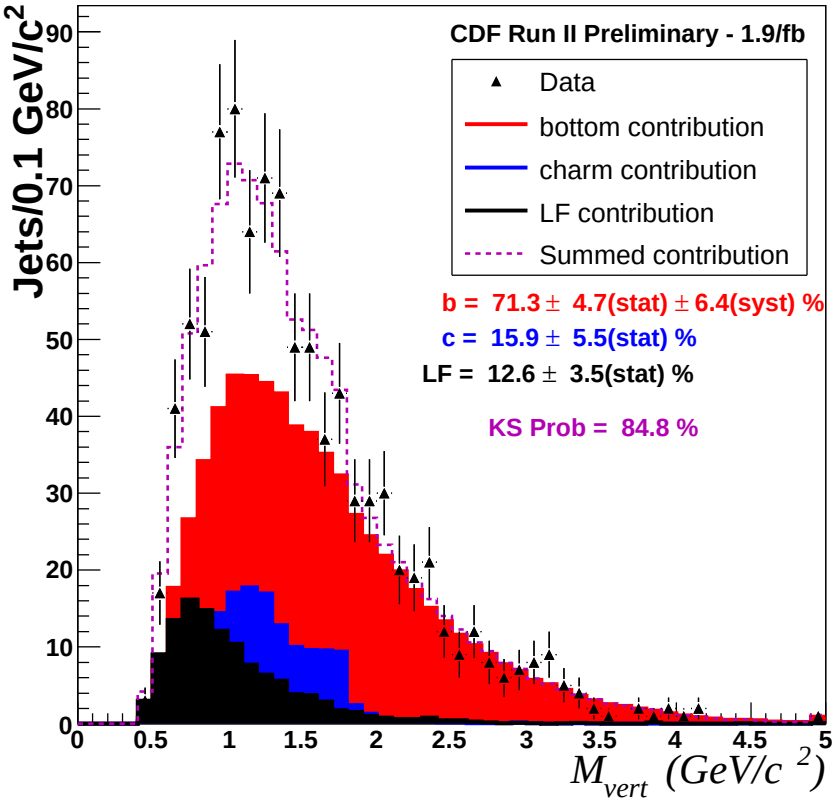
# $\sigma(p\bar{p} \to W + b-\text{jet})$ exclusive cross section $(W \to \ell\nu)$

CDF Collab., Phys. Rev. Lett. **104**, 131801 (2010)

$\mathcal{L} = 1.9\ \text{fb}^{-1}$

$p_T^{b\text{-jet}} > 20$ GeV, $|\eta_{b\text{-jet}}| < 2.0$, $(R_{\text{cone}} = 0.4)$, $p_T^{\ell} > 20$ GeV, $|\eta_\ell| < 1.1$, $p_T^V > 25$ GeV

**Vertex Mass Fit**




- $\sigma(W_{(\to\ell\nu)} + b) = \dfrac{N_{b\text{-tags}} \cdot f_{b\text{-jets}} - N_{\text{bkg}}^{b\text{-jets}}}{\mathcal{L} \times A \times \epsilon}$

Major $b$-jet backgrounds:

$t\bar{t}$ (40% of total background)
single top (30%)
Fake $W$ (15%)
$WZ$ (5%)

Measured cross section larger than ALPGEN and NLO predictions ($\sim 3\sigma$)

$\sigma(W_{(\to\ell\nu)} + b) = 2.74 \pm 0.27(\text{stat.}) \pm 0.42(\text{syst.})$ pb

NLO prediction (J. Campbell *et al.*): $\sigma(W_{(\to\ell\nu)} + b) = 1.2 \pm 0.14$ pb

LO prediction (ALPGEN): $\sigma(W_{(\to\ell\nu)} + b) = 0.78$ pb

# Conclusions

- Many vector boson + light/heavy flavour jet analyses:
  $Z/\gamma^{\text{`}} * (\rightarrow \ell\ell)$+jets (DØ + CDF )
  $Z + 1$ jet $p_T$ balance (CDF)
  $\sigma(Z + b)/\sigma(Z + j)$ ratio ,$Z \rightarrow \ell\ell$ (DØ+ CDF)
  $W + c$ jet (DØ + CDF)
  $W + b$ jet (CDF)
- Perturbative QCD predictions (MCFM) are in good agreement with data in all incl. $V$+jets measurements
  Especially in excl. $W + b$ jet measurement (CDF):
  ALPGEN and NLO predictions $\sim 3\sigma$ below measurement
- Jet/$Z$ $p_T$ imbalance (CDF) shows up limitations for JES precision at LHC experiments ($\sim 3\%$)
- There is no perfect MC event generator:
  This holds for HERWIG+JIMMY, PYTHIA
  as well as for SHERPA, ALPGEN (superior to former PS-MC's)
- Data are corrected for detector effects (hadronic final state)
  $\rightarrow$ can be re-used for MC tuning any time in the future

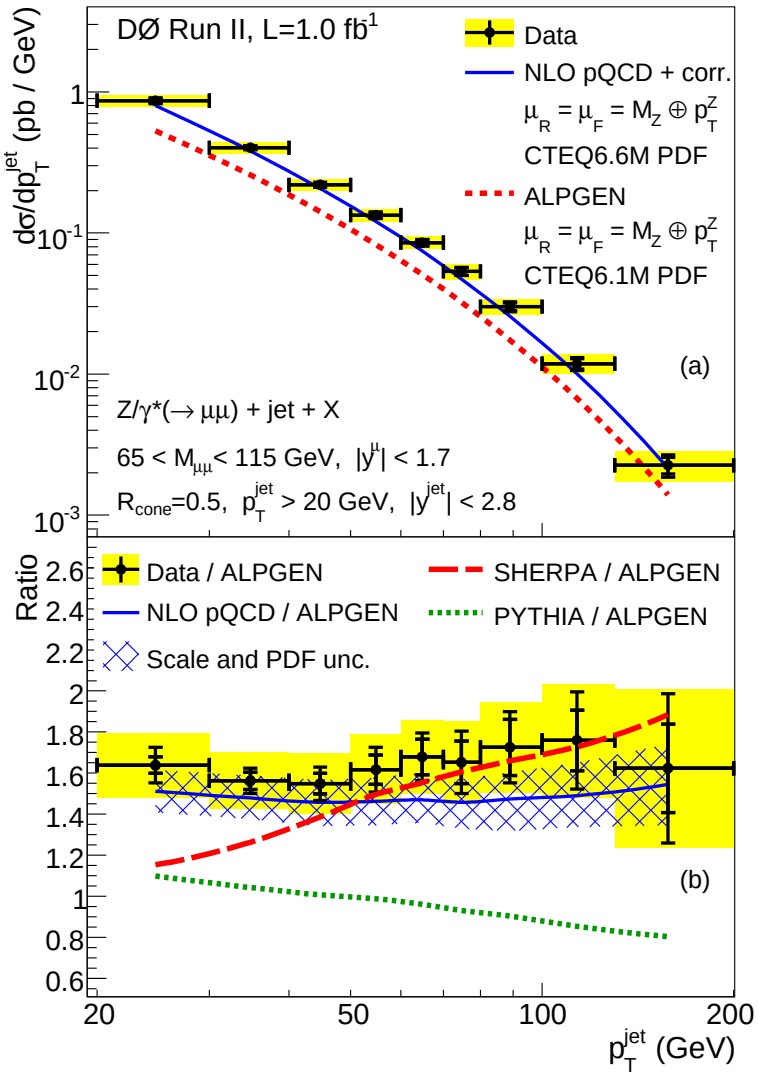
- Backup slides

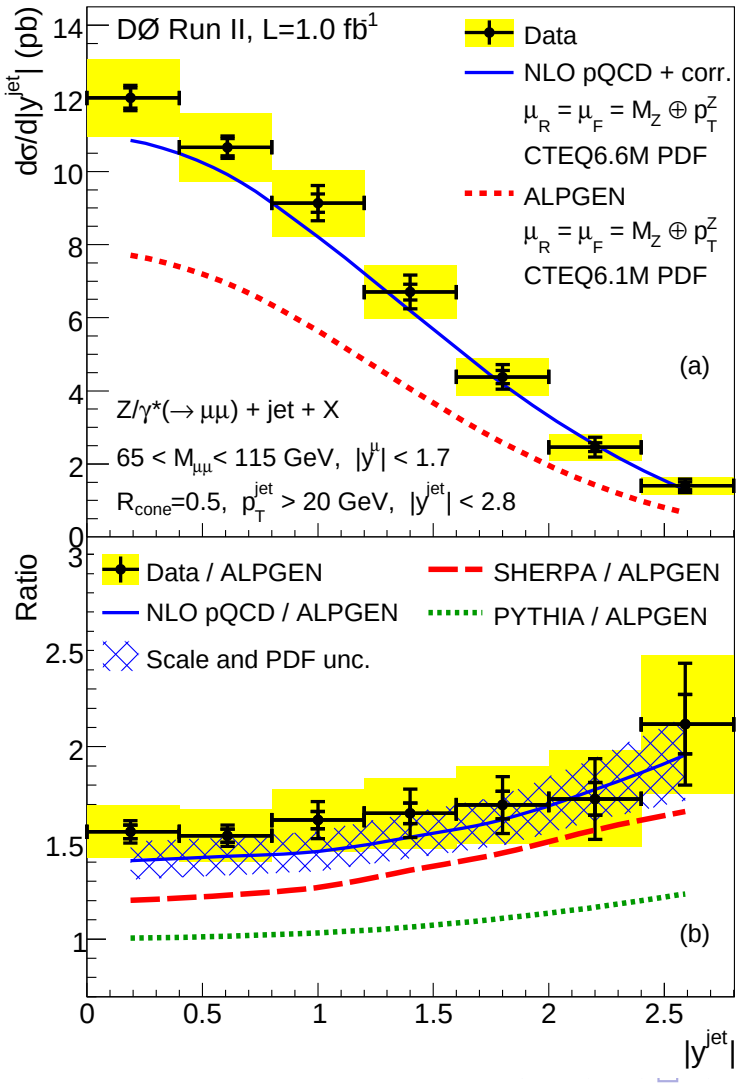
# Differential $Z/\gamma^* + \text{jet} + X$ cross section $(Z \to \mu\mu)$

DØ Collab., Phys. Lett. B **669**, 278 (2008)

$\mathcal{L} = 1.0\ \text{fb}^{-1}$

$65 < M_{\mu\mu} < 115$ GeV, $|y_\mu| < 1.7$, $p_T^{\text{jet}}(R{=}0.5) > 20$ GeV, $|y_{\text{jet}}| < 2.8$




NLO pQCD: MCFM v5.4
PDF: CTEQ6.6M
$\mu_r^2 = \mu_f^2 = M_Z^2 + p_{T,Z}^2$

PYTHIA 6.323,
ALPGEN 2.05,
SHERPA 1.1.1,
PDF: CTEQ6.1M

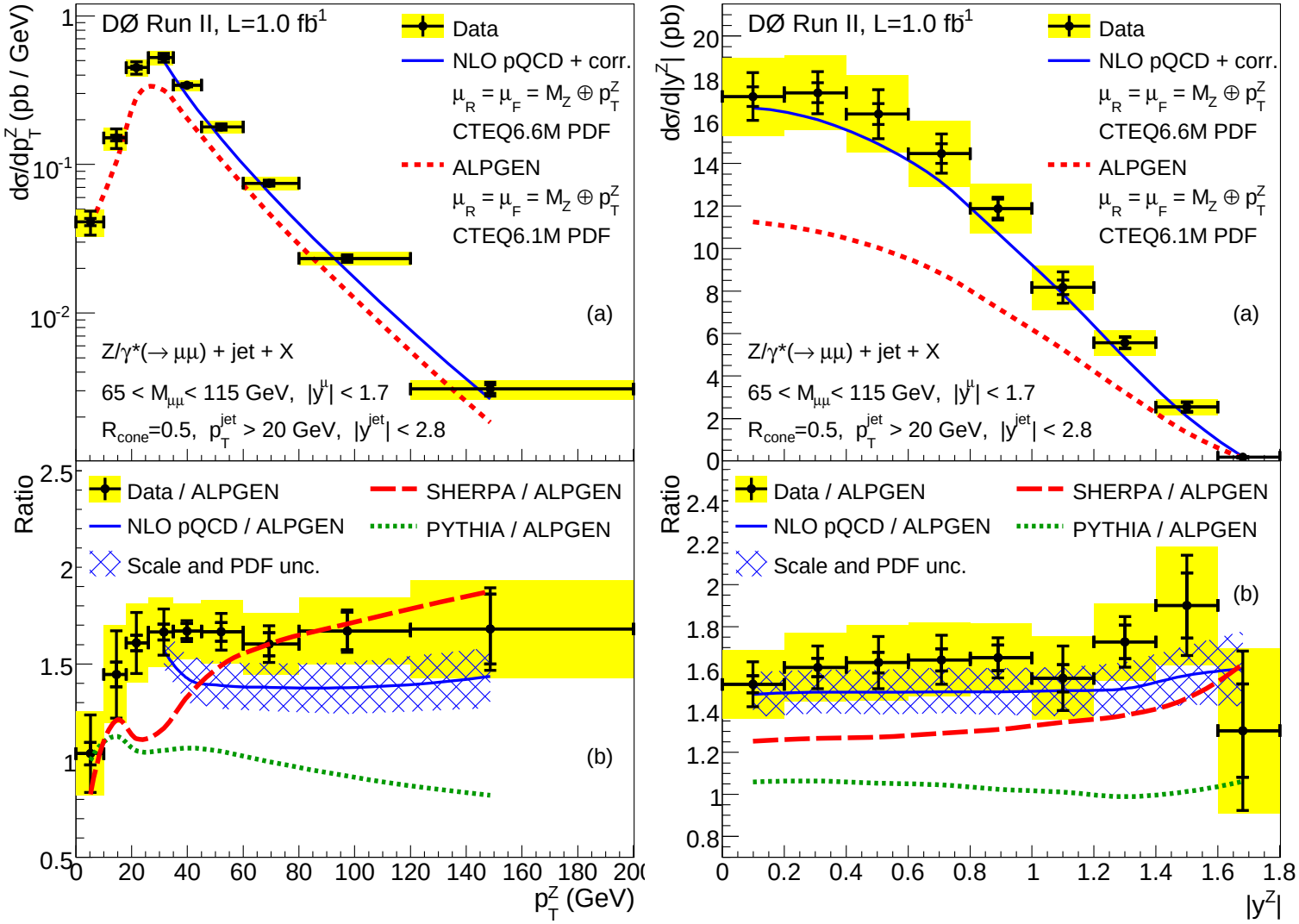
NLO pQCD prediction 5% below measured cross section.

For $p_T(Z) < 30$ GeV prediction sensitive to underlying event

Total cross section prediction of ALPGEN and PYTHIA significantly below data

# Differential $Z/\gamma^* + \text{jet} + X$ cross section $(Z \to \mu\mu)$

$65 < M_{\mu\mu} < 115$ GeV, $|y_\mu| < 1.7$, $p_T^{\text{jet}}(R=0.5) > 20$ GeV, $|y_{\text{jet}}| < 2.8$




NLO pQCD: MCFM v5.4
PDF: CTEQ6.6M
$\mu_r^2 = \mu_f^2 = M_Z^2 + p_{T,Z}^2$

PYTHIA 6.323,
ALPGEN 2.05,
SHERPA 1.1.1,
PDF: CTEQ6.1M

NLO pQCD prediction 5% below measured cross section.

For $p_T(Z) < 30$ GeV prediction sensitive to underlying event

Total cross section prediction of ALPGEN and PYTHIA significantly below data

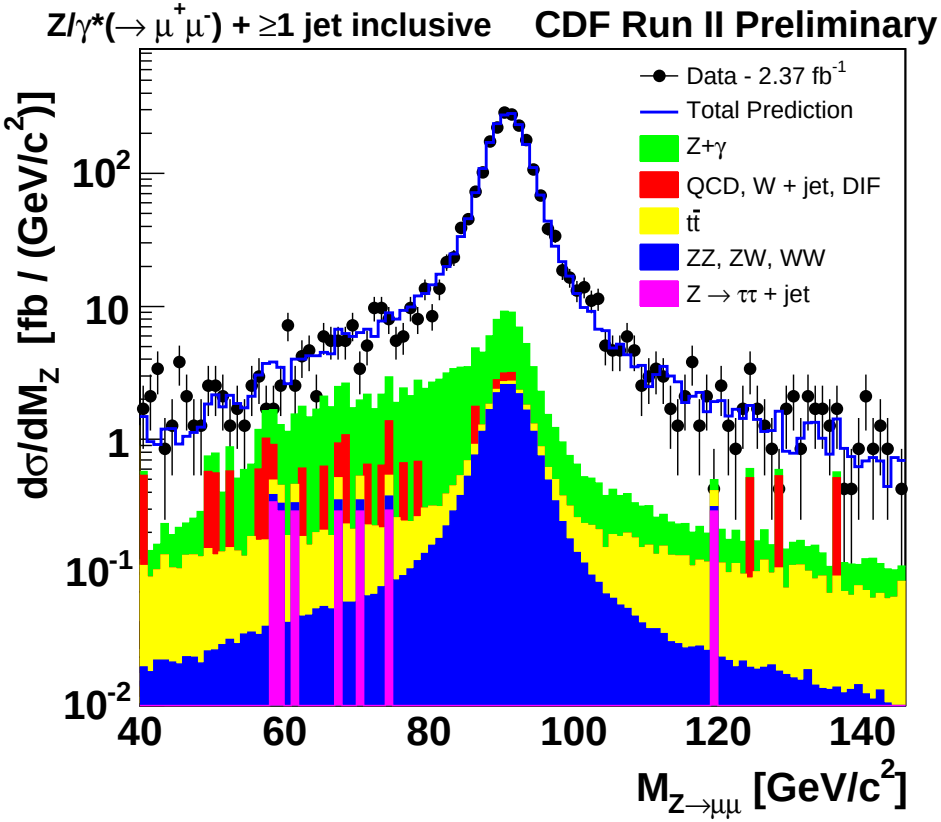
$$\sigma(z/\gamma^*(\to \mu\mu) + \text{jet} + X) = 18.7 \pm 0.2(\text{stat.}) \pm 0.8(\text{syst.}) \pm 0.9(\text{muon}) \pm 1.1(\text{lumi.})\ \text{pb}$$

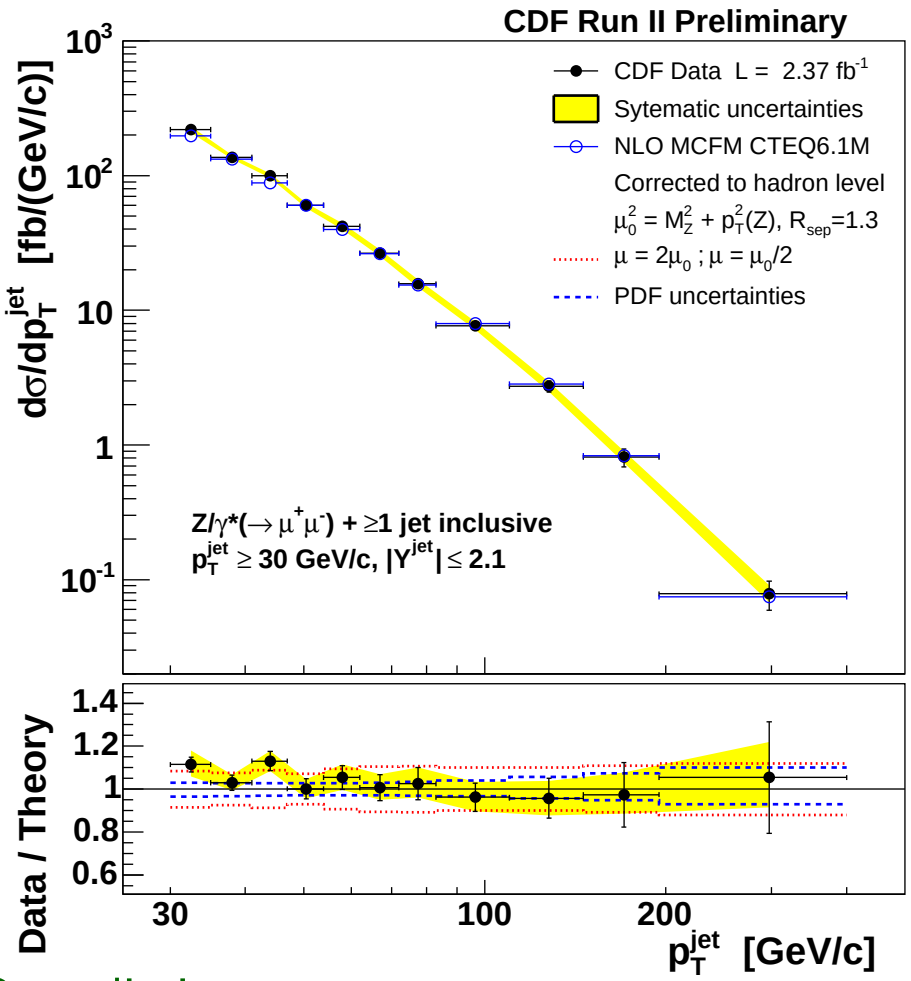
# $\sigma(p\bar{p} \to Z/\gamma^* + 1(2)$ jets) inclusive cross section $(Z/\gamma^* \to \mu\mu)$

CDF Collab., Preliminary (2010)

$\mathcal{L} = 2.4$ fb$^{-1}$

$66 < M_{\mu\mu} < 116$ GeV, $p_T^{\mu} > 25$ GeV, $\eta_\mu < 1.0$, $E_T^{\text{jet}}(R=0.7) > 30$ GeV, $|\eta_{\text{jet}}| < 2.1$



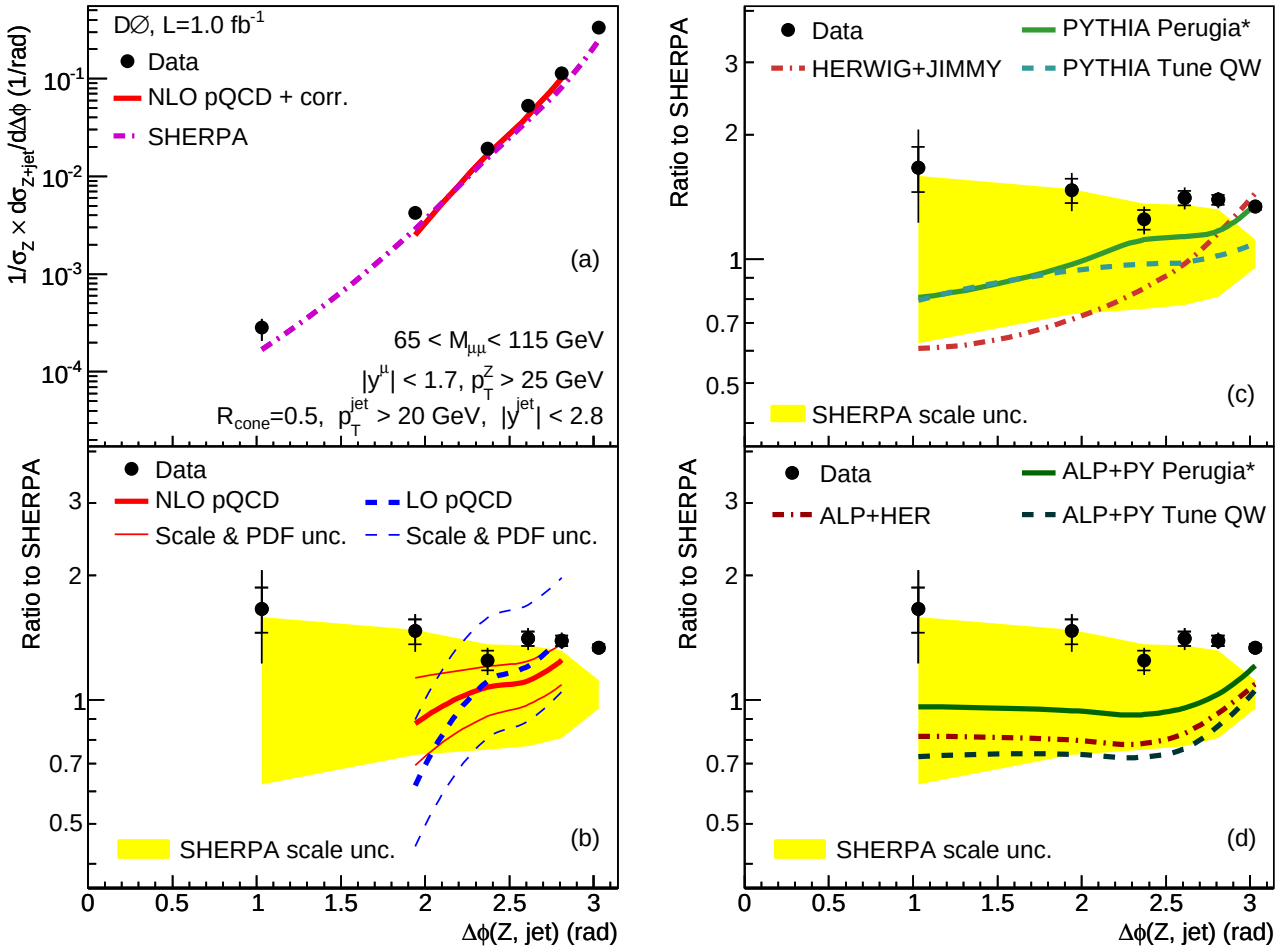

Good agreement between data and NLO pQCD prediction

# Differential $Z/\gamma^* + \text{jet} + X$ angular distributions ($Z \to \mu\mu$)

DØ Collab., Phys. Lett. B **682**, 370 (2010)

$\mathcal{L} = 1.0\ \text{fb}^{-1}$

$65 < M_{\mu\mu} < 115$ GeV, $|y_\mu| < 1.7$, $p_T^Z > 45$ GeV, $p_T^{\text{jet}}(R = 0.5) > 20$ GeV, $|y_{\text{jet}}| < 2.8$




- Azimuthal angle between $Z$ and jet

MCFM v5.6
PDF's: MSTW2008
$\mu_r^2 = \mu_f^2 = M_Z^2 + p_{T,Z}^2$

Hadronisation and underlying event correction: PYTHIA 6.421, Tune QW, CTEQ6.1M

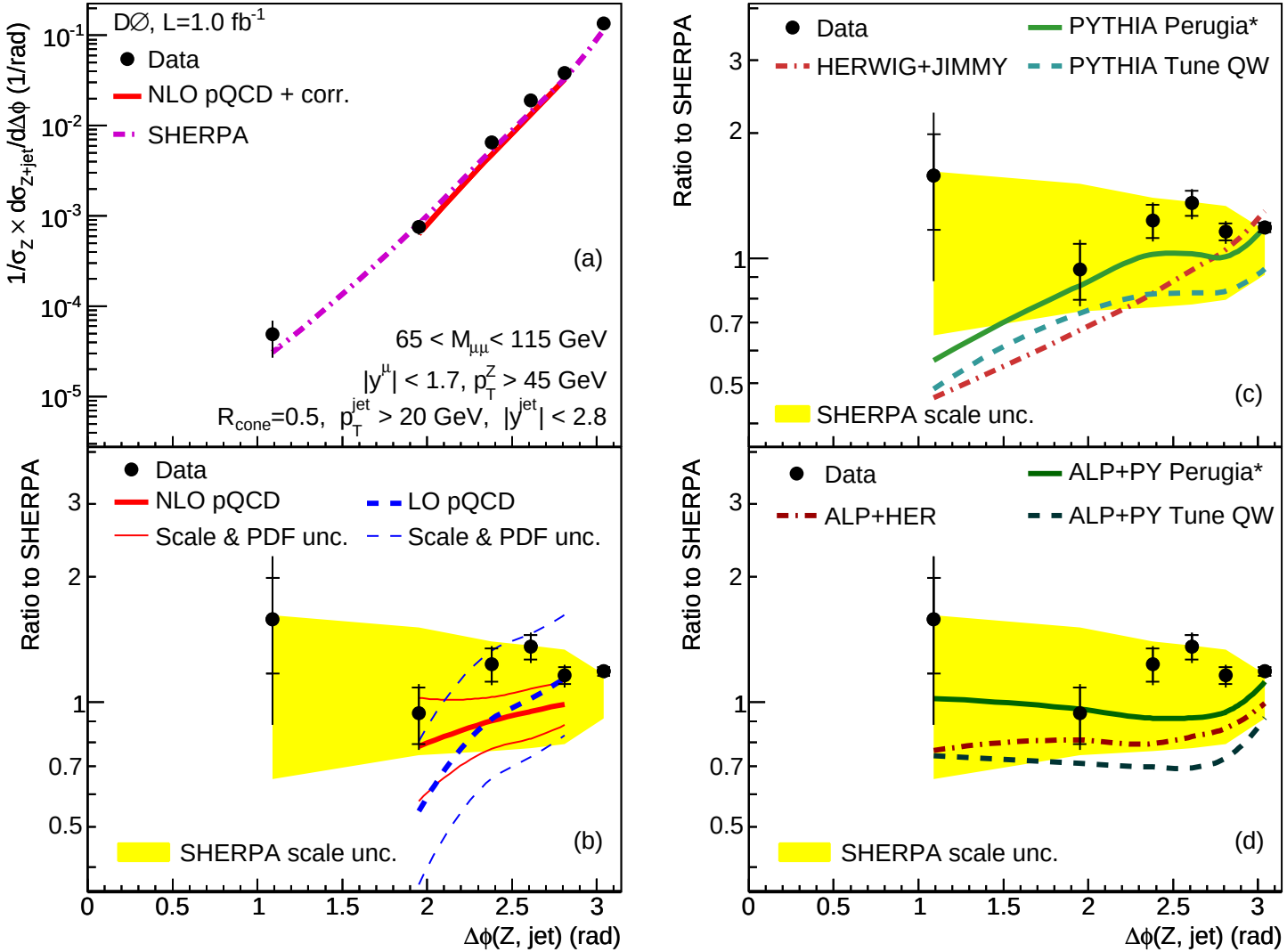
- SHERPA (1.1.3) is able to describe $\Delta\phi$

$\sigma_{Z+\text{jet}}/\sigma_Z = [122 \pm 2(\text{stat.}) \pm 4(\text{syst.})] \cdot 10^{-3}$

pQCD: $[111 \pm 6(\text{scale}) \pm 2(\text{PDF})] \cdot 10^{-3}$ @NLO, $[112 \pm 20(\text{scale}) \pm 1(\text{PDF})] \cdot 10^{-3}$ @LO

# Differential $Z/\gamma^* + \text{jet} + X$ angular distributions ($Z \to \mu\mu$)

$65 < M_{\mu\mu} < 115$ GeV, $|y_\mu| < 1.7$, $p_T^Z > 25$ GeV, $p_T^{\text{jet}} > 20$ GeV, $|y_{\text{jet}}| < 2.8$




PYTHIA 6.421,
HERWIG 6.510 + JIMMY 4.31,
ALPGEN 2.13,
SHERPA 1.1.3,
PDF's: CTEQ6.1M and MRST2007 (LO*) for Perugia*

- ALPGEN + SHERPA: Up to three partons in the matrix element calculations
- Binning chosen such, that detector resolution causes little migrations between bins
- SHERPA (1.1.3) is able to describe $\Delta\phi$

$\sigma_{Z+\text{jet}}/\sigma_Z = [47 \pm 1(\text{stat.}) \pm 2(\text{syst.})] \cdot 10^{-3}$

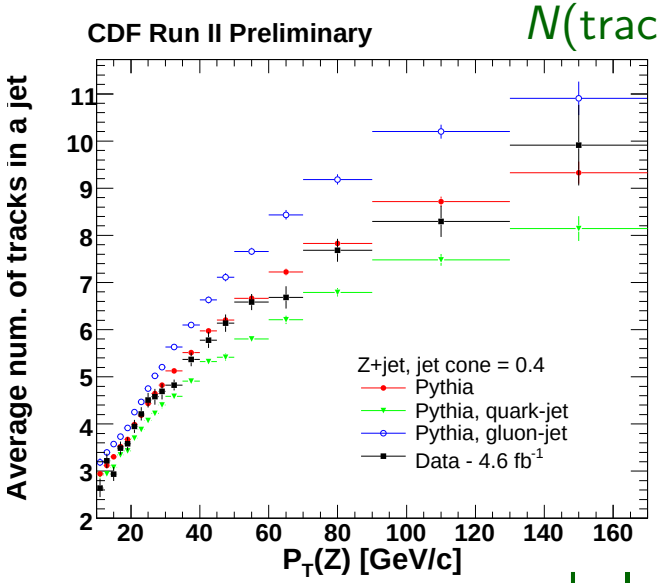
pQCD: $[40 \pm 3(\text{scale}) \pm 1(\text{PDF})] \cdot 10^{-3}$ @NLO, $[40 \pm 8(\text{scale}) \pm 1(\text{PDF})] \cdot 10^{-3}$ @LO

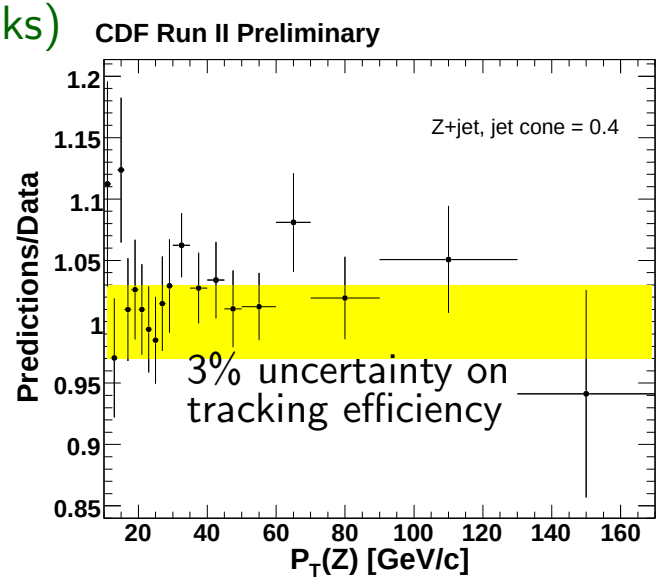
# SM precision limits from $Z + 1$ jet $p_T$ balance $(Z \to ee, \mu\mu)$

CDF Collab., submitted to NIM (2010)

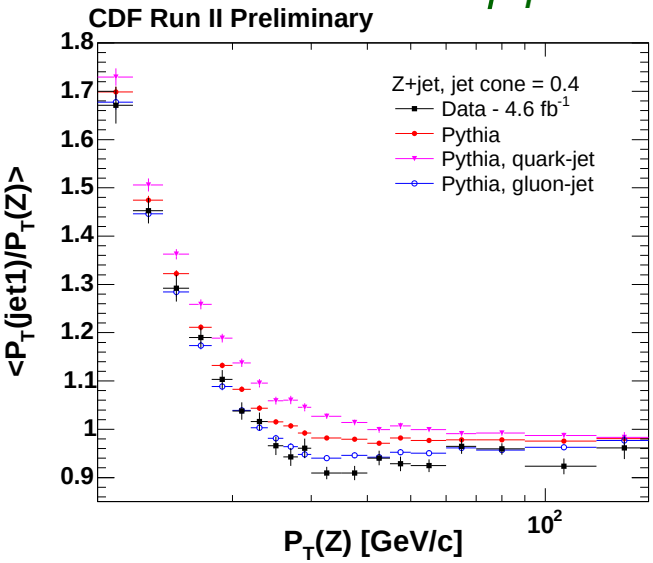
$\mathcal{L} = 4.6\ \mathrm{fb}^{-1}$

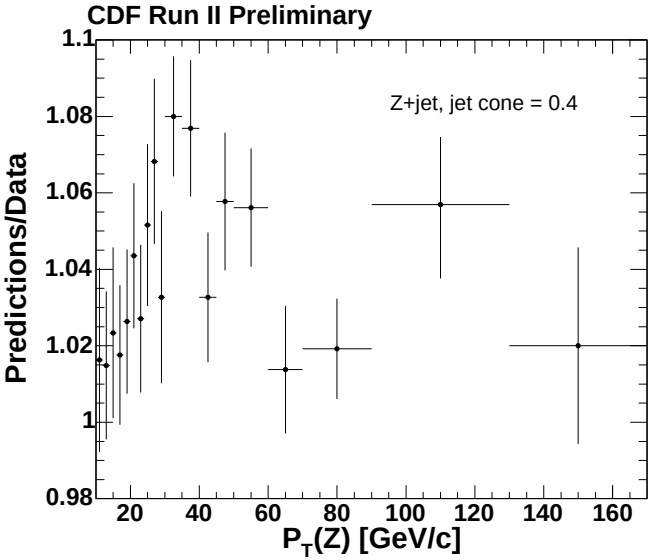
$N$(tracks)




$p_T$ balance




- $p_T(\ell)$>18 GeV, $p_T(Z)$>25 GeV, $80 < m(\ell\ell) < 100$ GeV leading jet $p_T > 8$ GeV, $\Delta\phi(Z, jet) > 3.0$ rad $R_{\mathrm{cone}} = 0.4$(shown here), 0.7, 1.0
- Track in jet distributions show agreement with quark/gluon jet fractions
- Observe in data higher rate of sub-leading jets collinear to leading jet
- Variation of FSR, ISR, $Q^2$-scale multipliers, PDF's within uncertainties is not able to describe observed discrepancy

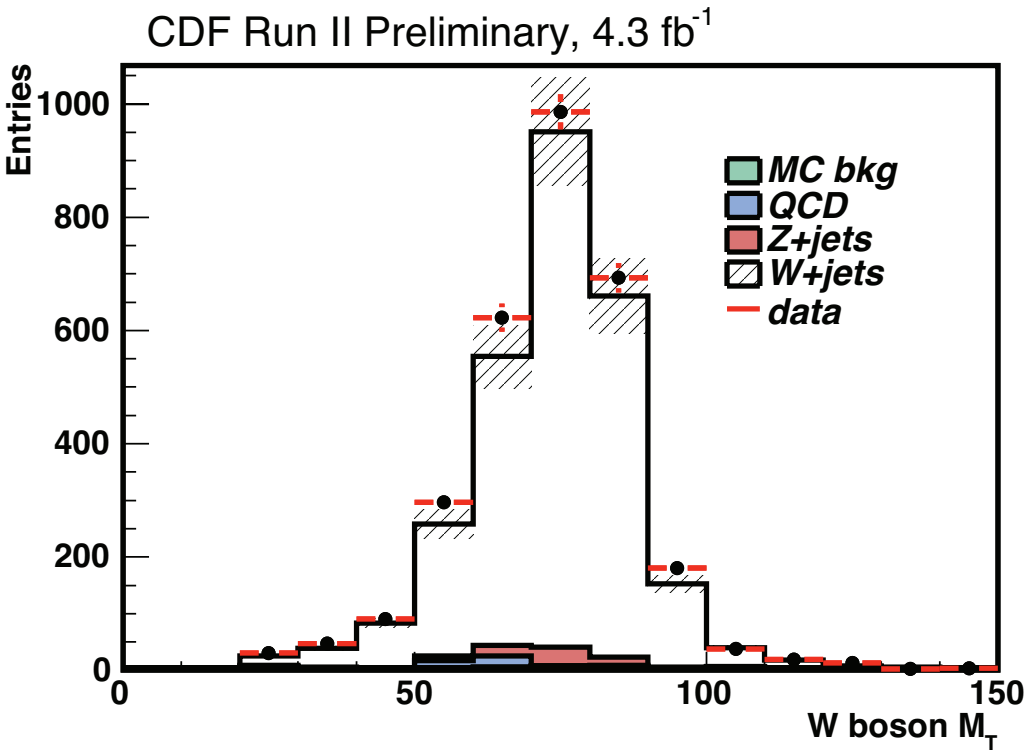
# $\sigma(p\bar{p} \to W + c-\text{jet})$ exclusive cross section $(W \to \ell\nu)$

CDF Collab., Preliminary, CDF Note 10089 (2010)

$\mathcal{L} = 4.3\ \text{fb}^{-1}$

$p_T^{\text{jet}} > 20$ GeV, $|\eta_{\text{jet}}| < 2.0$, $(R=0.4)$, $p_T^{\ell} > 20$ GeV, $\not{E}_T > 30$ GeV

$c$-jet candidate soft electron tag




- $s$-quark gluon fusion:
  $sg \to W^- c$, $\bar{s}g \to W^+ \bar{c}$
  5% of $W + 1$ jet
  Probing $s$-quark PDF

- $\sigma(W_{(\to \ell\nu)} + b) = \dfrac{N_{\text{obs}} - N_{\text{bkg}}}{\mathcal{L} \times A \times \epsilon}$

Backgrounds:

$W$ + jets, $Z$ + jets
Multijets, Drell-Yan
Dibosons, single top (small)

$\sigma(W_{(\to \ell\nu)} + c) = 33.7 \pm 11.4(\text{stat.}) \pm 4.7(\text{syst.})$ pb

NLO prediction: $\sigma(W_{(\to \ell\nu)} + c) = 16.5 \pm 4.7$ pb