Vector Bosons + jets at the Tevatron

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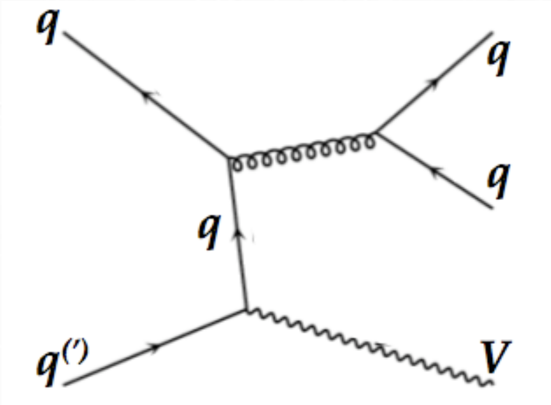
QCD@LHC - Michigan State University

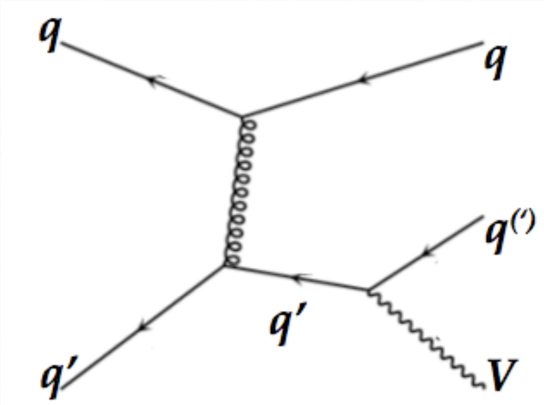
Introduction

- Vector Bosons + jets are good signatures to test pQCD
  - Heavy flavor production is sensitive to b, c quark PDFs
- Vector Bosons + jets events constitute irreducible backgrounds for SM Higgs measurements and New Physics (NP) searches
- N(N)LO predictions not available for many processes of interest, particularly those with large jet multiplicities and heavy flavor components => data measurements crucial.
- MC models are used extensively to simulate signal and backgrounds, particularly for W/Z + multijet topologies.
- Interplay between fragmentation models, tunes, PDFs and scale choices needs to be understood to accurately model W/Z+jets.

Status Tevatron Measurements

- W/Z/γ + light flavor jets
- W/Z/γ + heavy flavor jets





RunII measurements with associated luminosity

Result(1/fb)	DØ	CDF
W+jets	3.8	2.8
Z+jets	1.0	9.4
W+b-jets	0.38	1.9
Z+b-jets	4.2	9.1
W+c-jets	1.0	4.3
γ+jets	1.0	--
γ+b/c jets	8.7	9.1

in black = preliminary
in red = published

In most cases:

- data are corrected to particle level
- particle level measurements are compared to NLO theory
- NLO theory is corrected to particle level using parton shower MC

Comparisons of MC models to the data are also made

NLO pQCD calculations & MC Models

- ➡ Fixed-order pQCD predictions
  - NLO MCFM
  - NLO Blackhat + Sherpa
  - nNLO Loopsim + MCFM (includes double-virtual corrections)
- ➡ Many LO MC programs on the market:
  - MEPS: Alpgen, Sherpa, Ariadne, Madgraph, Helac, Madevent, ...
  - PS: Pythia, Herwig
- ➡ New NLO MC programs
  - POWHEG+Pythia
  - Sherpa MENLOPS
  - High Energy Jets
- ✓ CKKW
  - the separation of ME and PS for different multijet processes is achieved through a k_T-measure
  - undesirable jet configurations are rejected through reweighting of the matrix elements with analytical Sudakov form factors and factors due to different scales in α_s
- ✓ MLM
  - matching parameters chosen, ME and PS jets matched in each n-parton multiplicity, events vetoed which do not have complete set of matched jets
  - further suppression required to prevent double counting of n and n+1 samples (replaces Sudakov reweighting in CKKW)

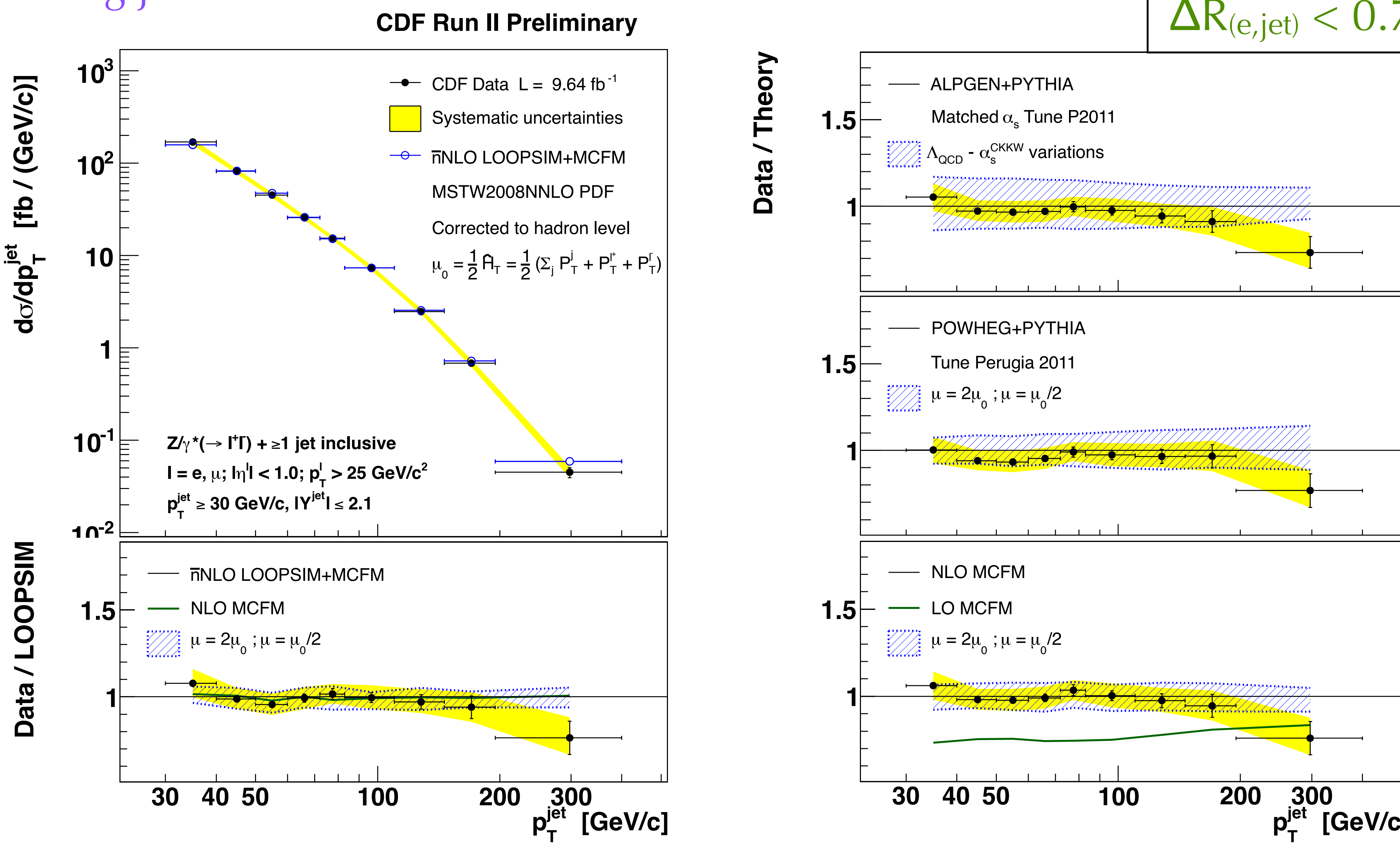
Z+jets

Z provides colorless probe of collision and hard scale; study kinematics of hadronic recoil

$Z/\gamma^* \rightarrow l^+l^-$+jets
Corrected to hadron level with phase space:

- $E_T^{lep} > 25$ GeV
- at least 1 central elec/muon
- $66 < M_{ll} < 116$ GeV/c^2
- $p_T^{jet} > 30$ GeV
- $|y^{jet}| < 2.1$
- R = 0.7 Midpoint cone jets
- $\Delta R_{(e,jet)} < 0.7$

Leading jet observables



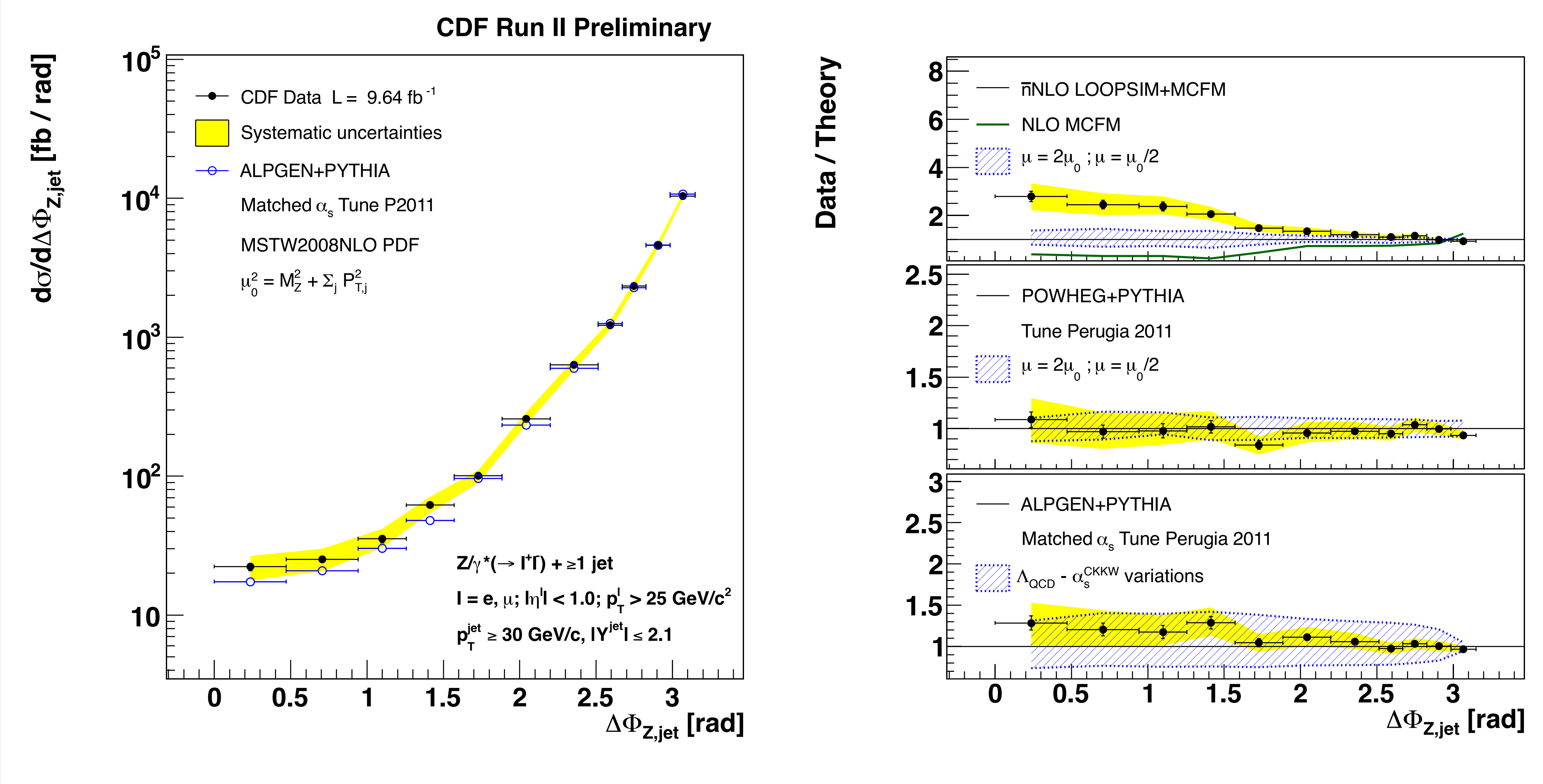
Excellent description of the data

Data uncertainties 5-10%
Scale uncertainties 5-10%

Z+jets - angular variables

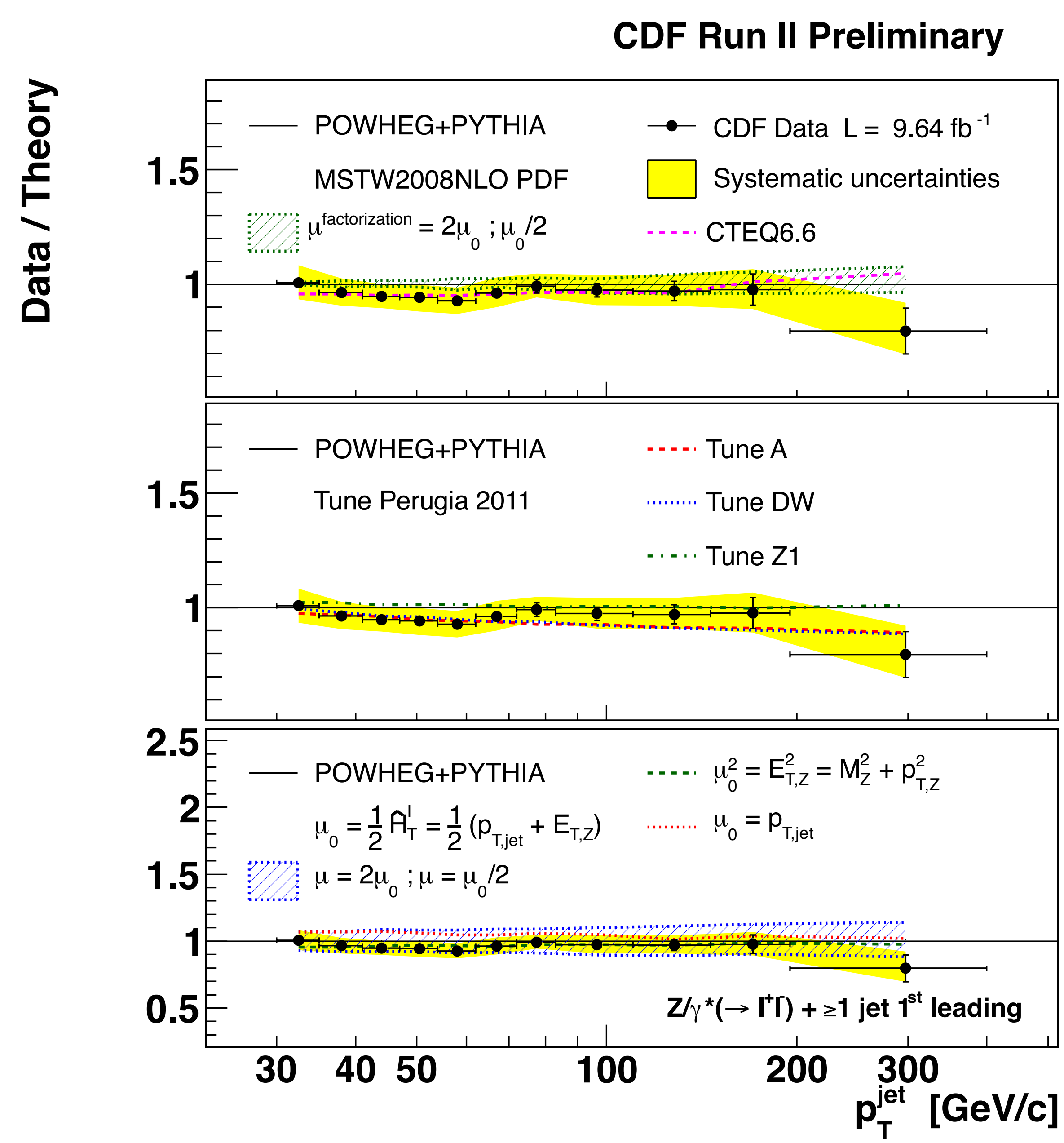
Angular distributions sensitive to additional QCD radiation

Small values of $\Delta\phi$(Z,jet) more sensitive to non-perturbative effects

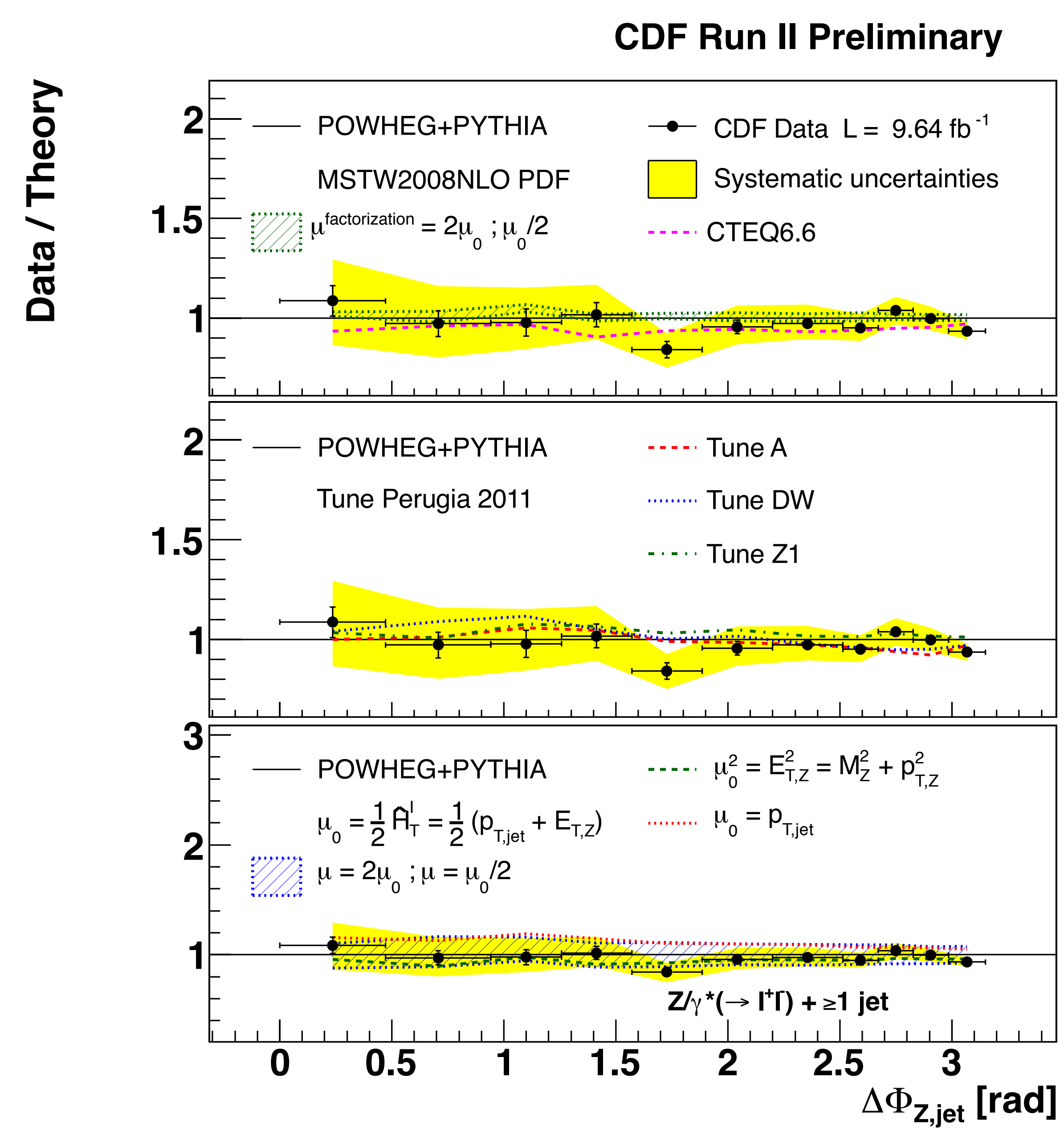


Z+jets

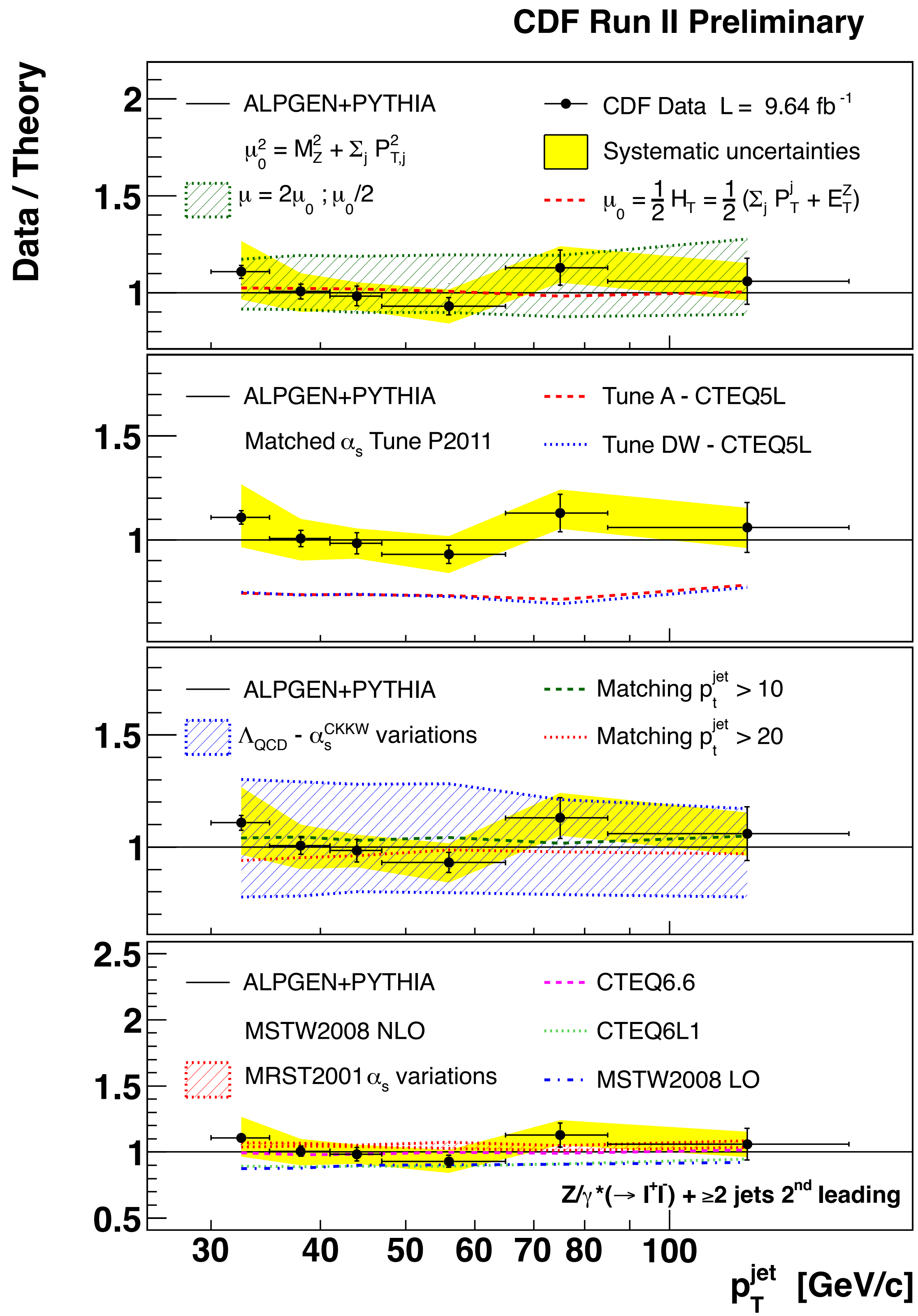
Comparison to POWHEG NLO+PS

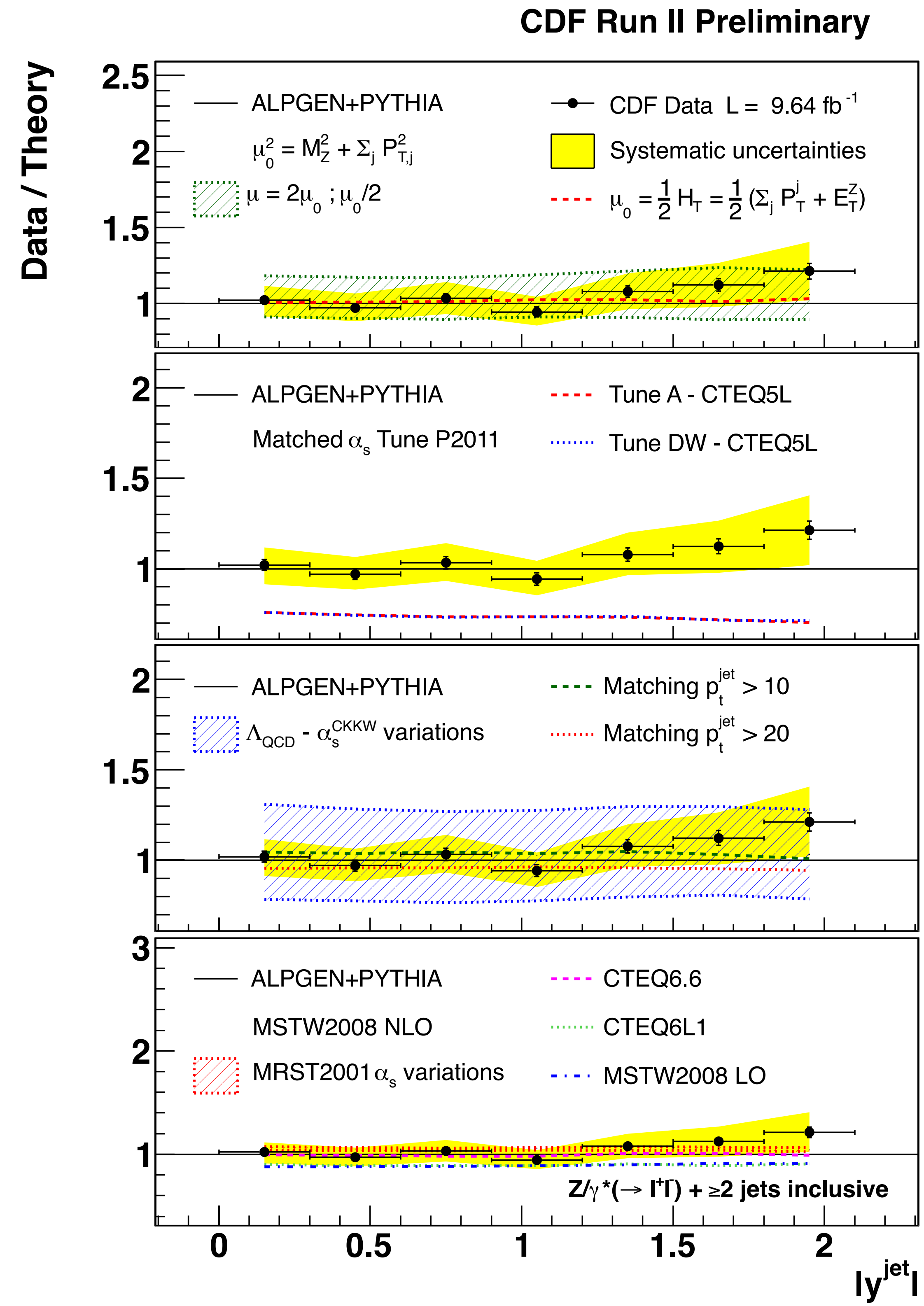


Study dependence on PDF, tune, renormalization, factorization scales



Z+jets: 2 jet observables

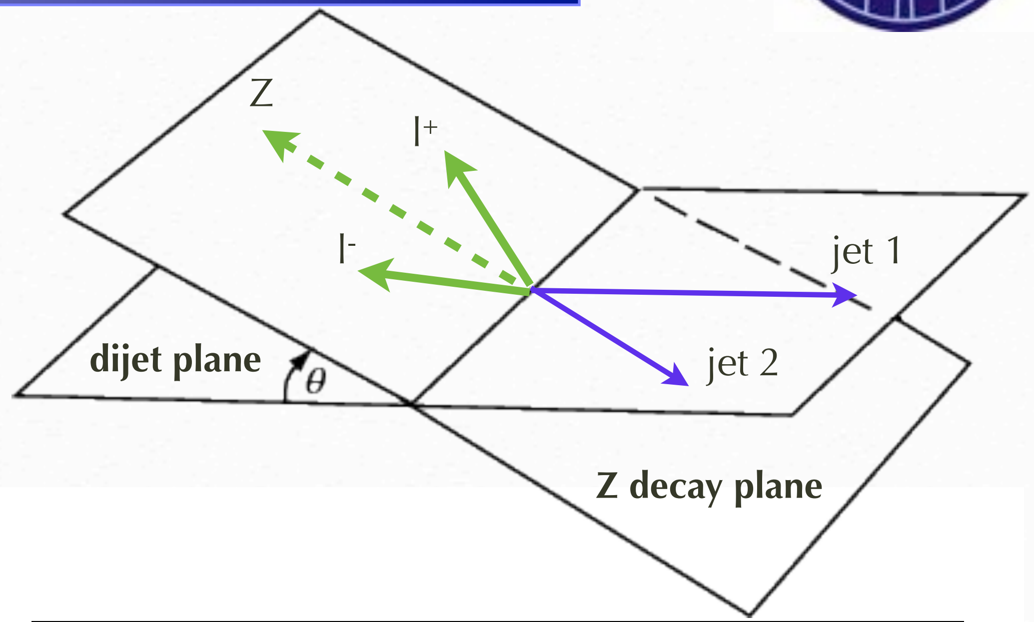


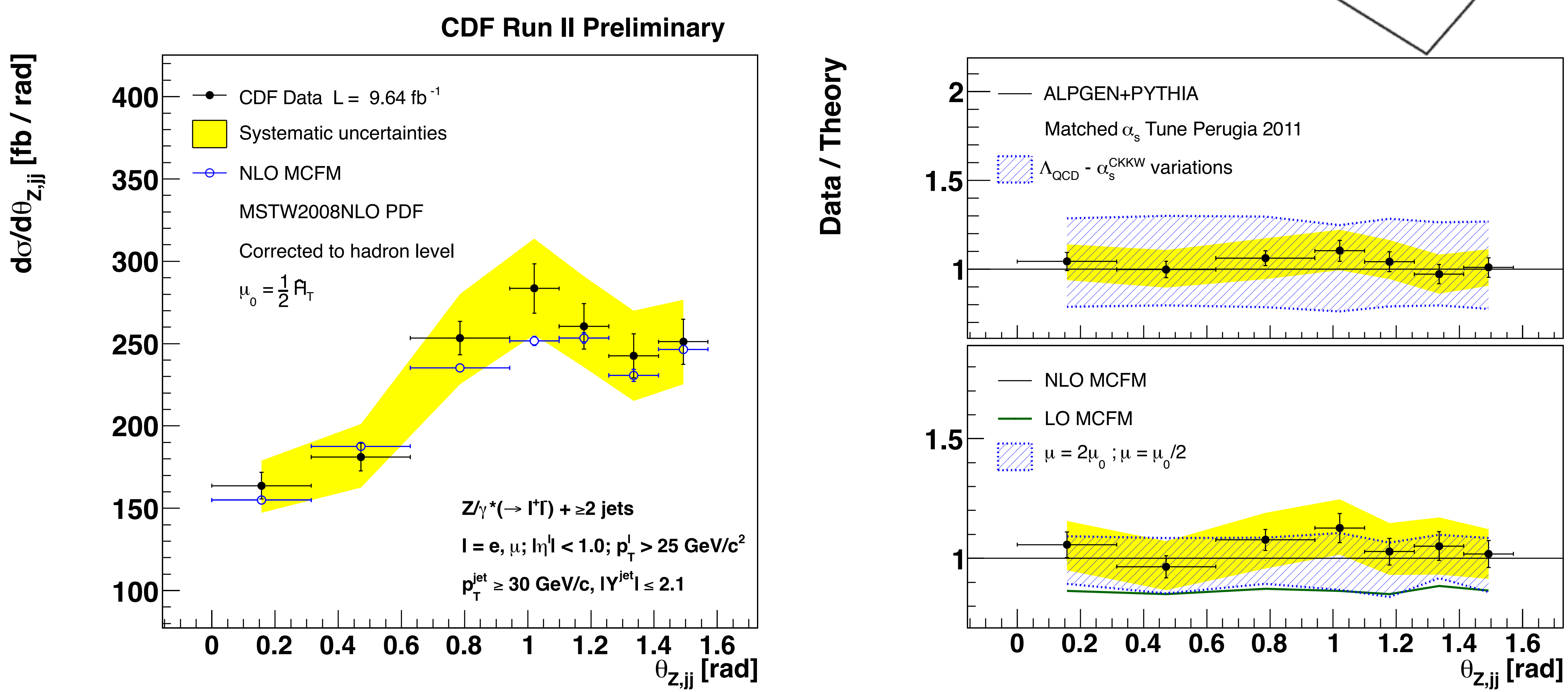


Z+jets - angular variables

New angular variable: $\Theta_{Z,jj}$

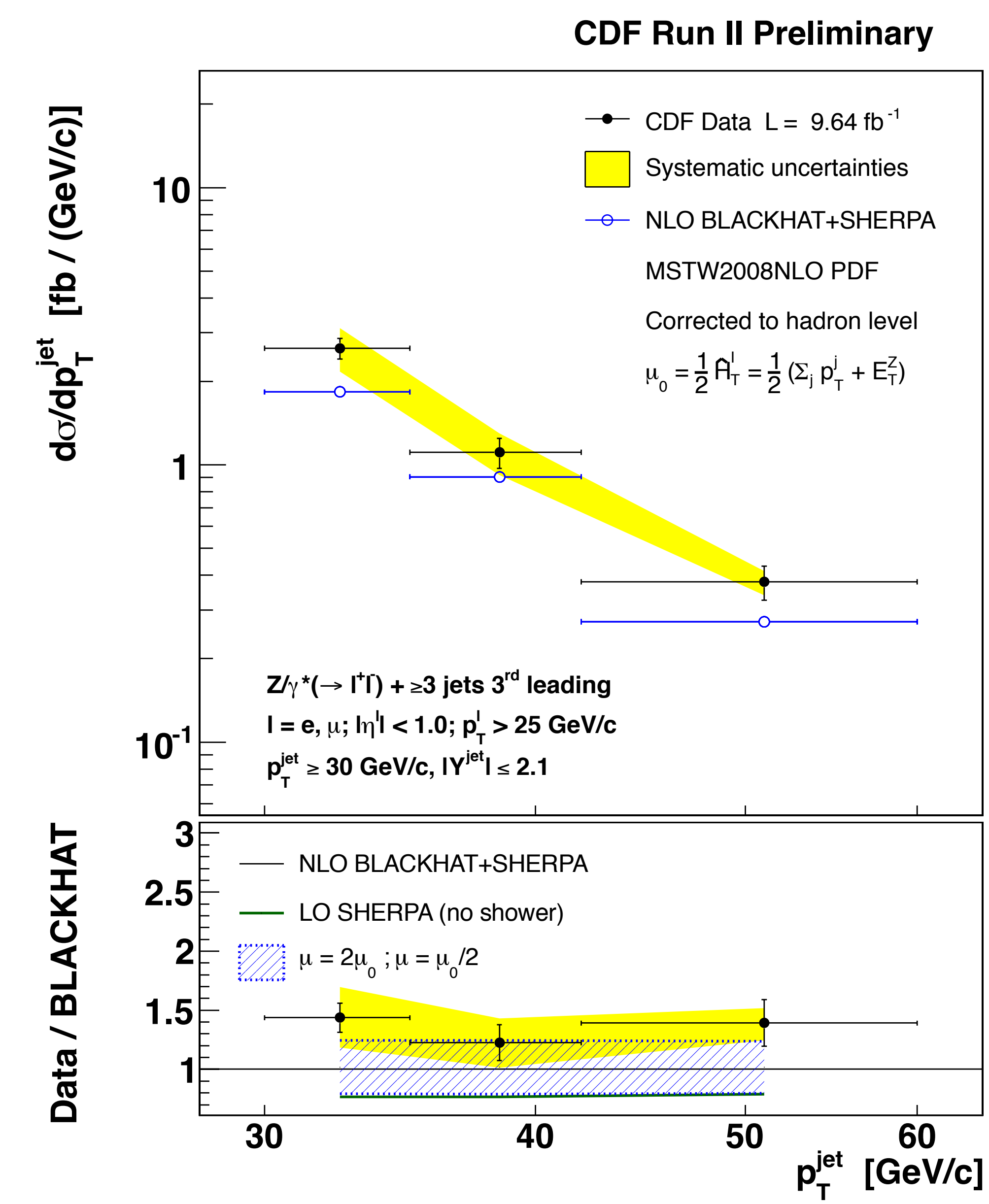
θ = dihedral angle between the $Z/\gamma^{*} \rightarrow l^{+}l^{-}$ decay plane and the di-jet plane

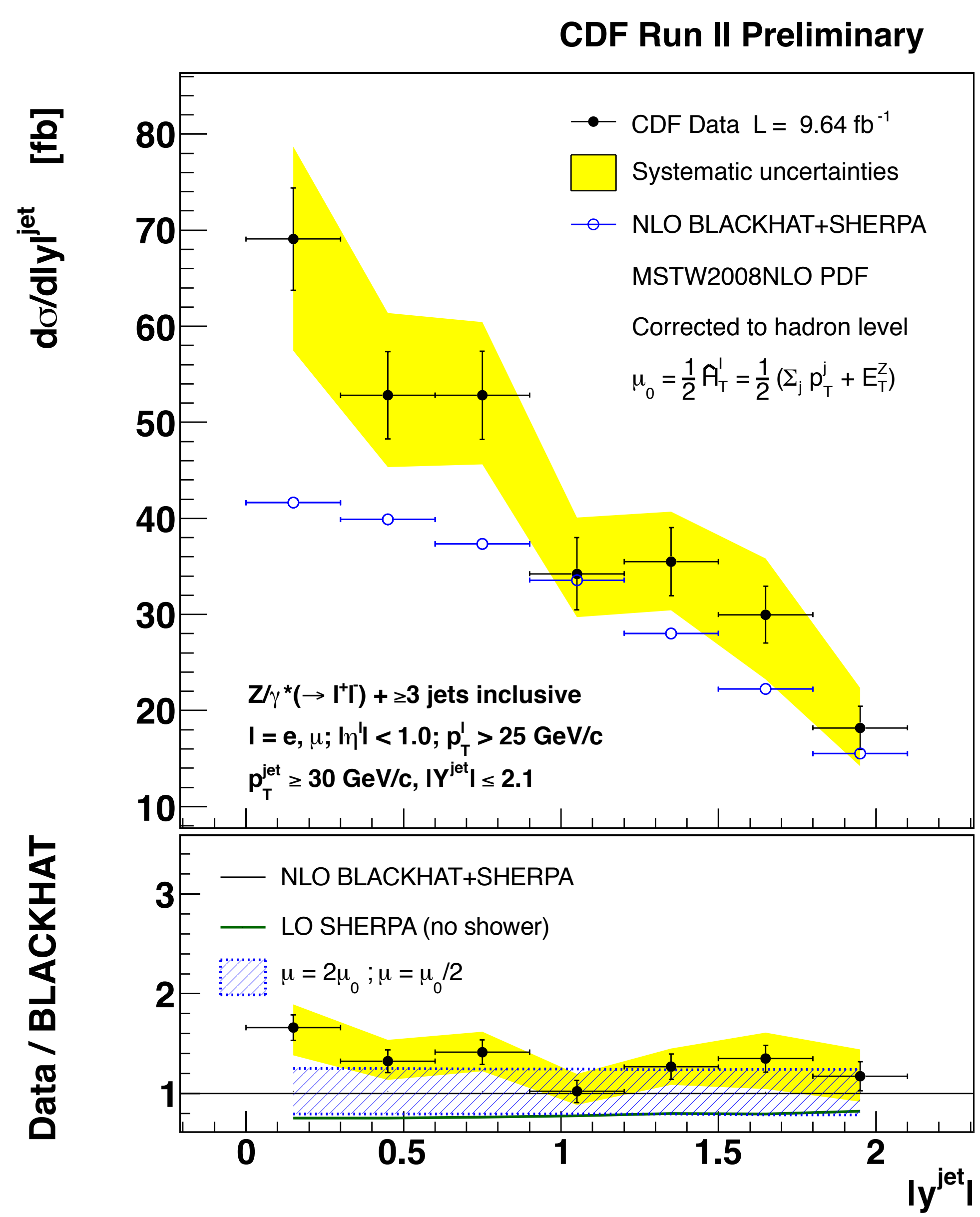




Z+3jets

Direct measurement of jet kinematics with large multiplicities





3rd jet observables

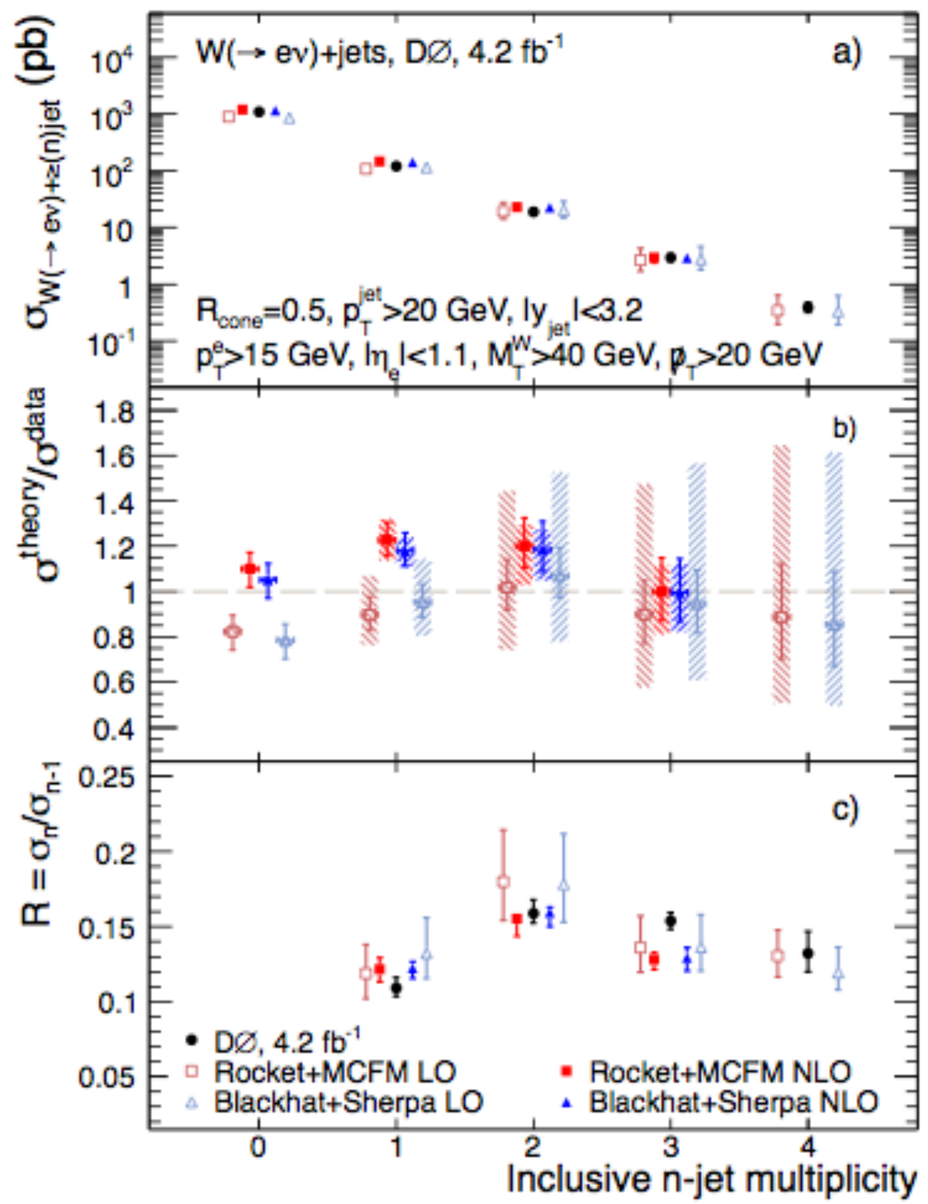
Data uncertainties are generally comparable or smaller than theory

NLO Z+3 jet predictions recently calculated

W+jets

Precise measurements of W+(n)jet (n=1,2,3,4) inclusive cross sections and differentially as function of n^{th} jet p_T

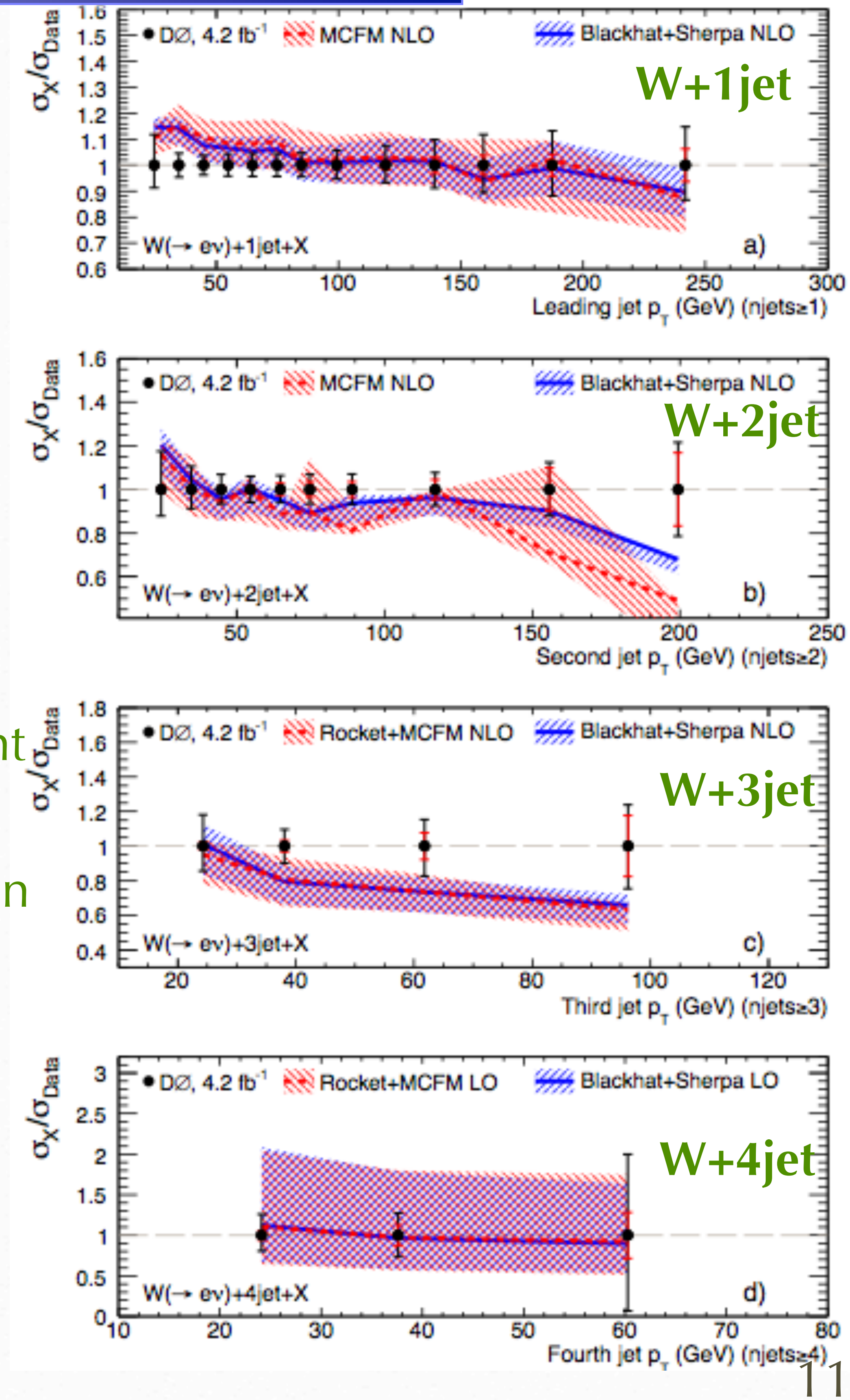
Small data uncertainties allow detailed study of NLO theory



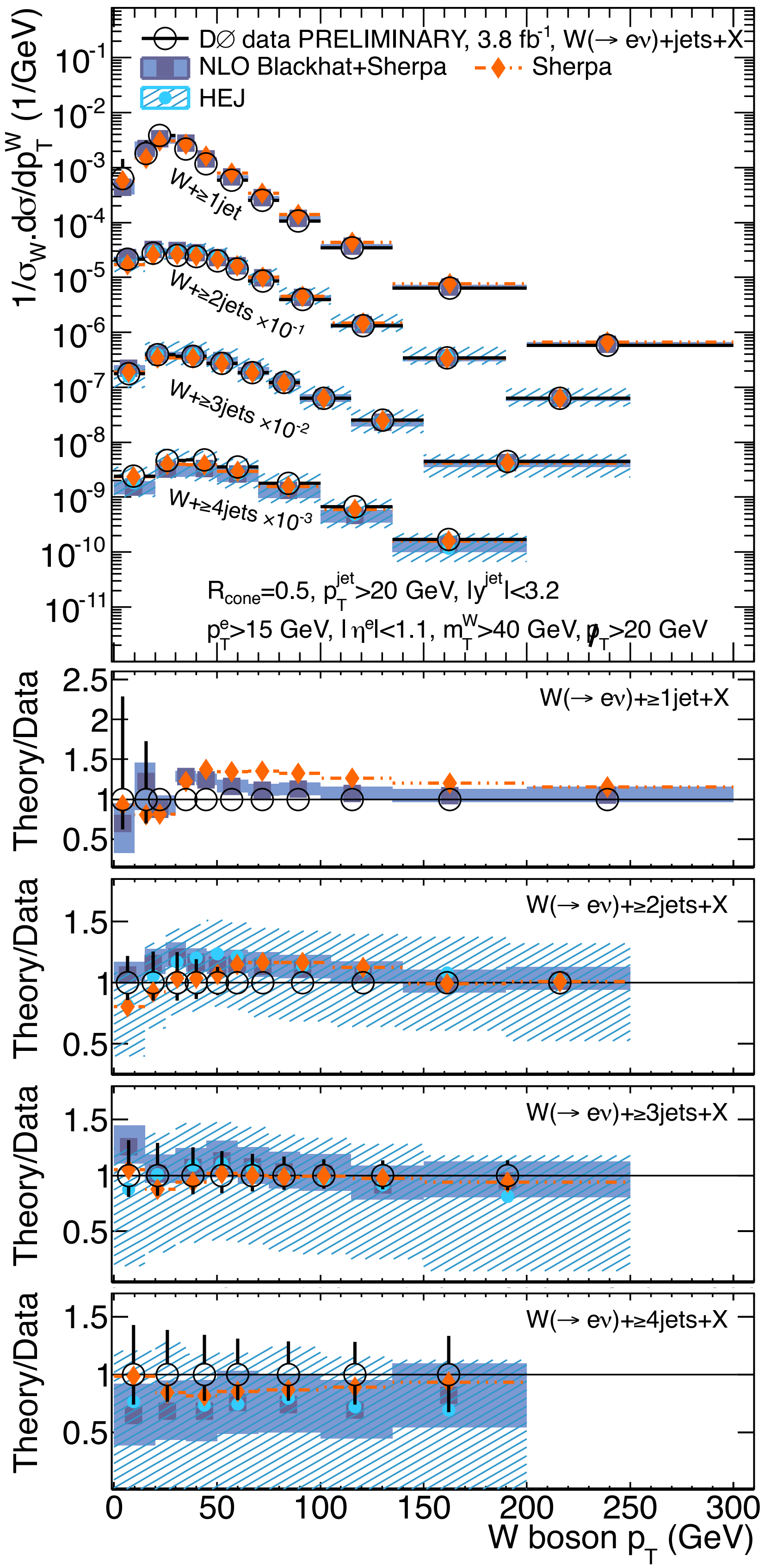
Phase Space:

$p_T^{jet} > 20$ GeV
$|y^{jet}| < 3.2$
R = 0.5 Midpoint cone jets

1 central electron
$p_T^{lep} > 15$ GeV
$\not{p}_T > 20$ GeV
$m_T^W > 40$ GeV



W+jets



New W+(n)jets differential cross-sections for inclusive one to four jet events in many new observables

Measured here as a function of W boson transverse momentum

Comparisons made to various theory predictions:

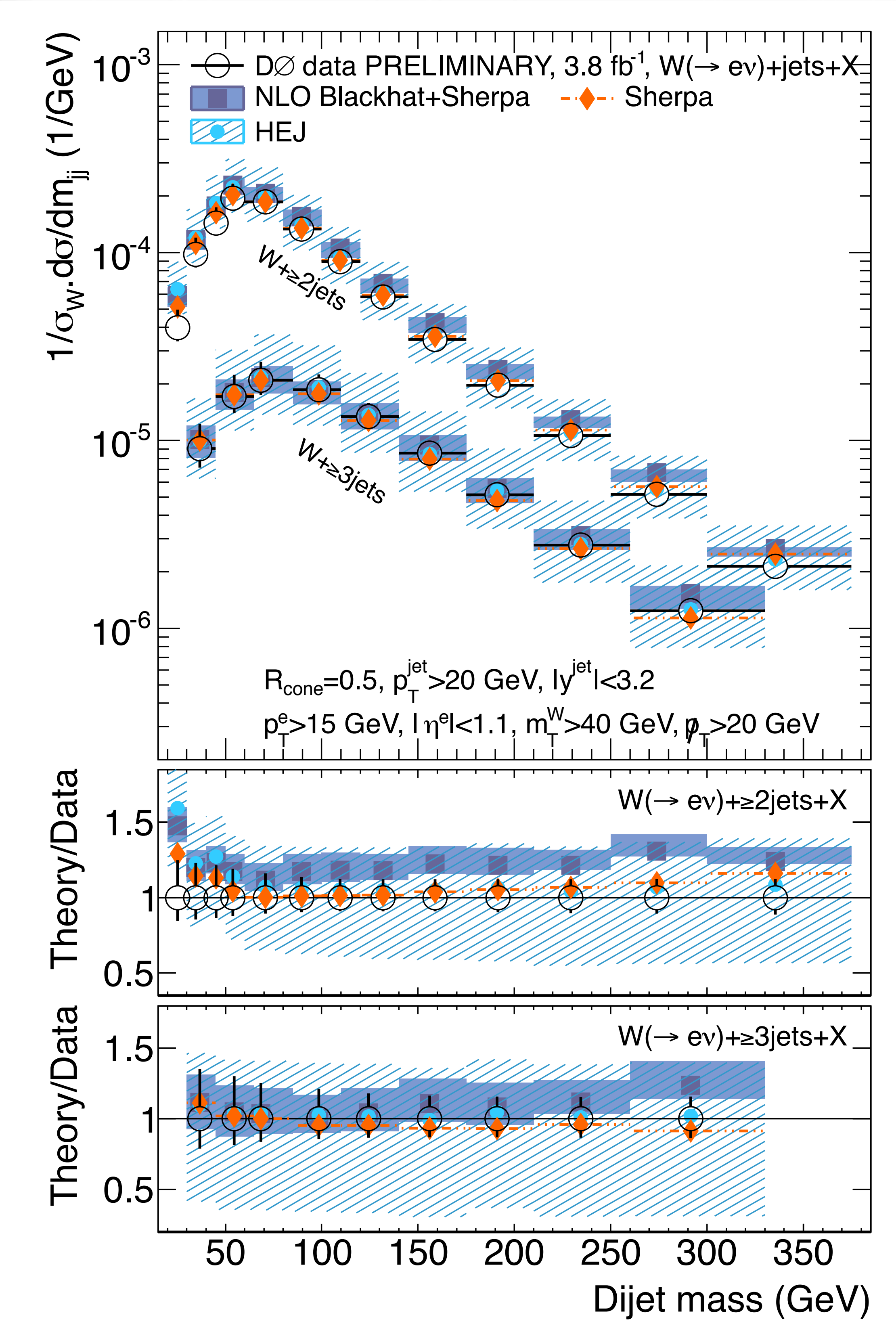
- Sherpa (MEPS event generator)
- NLO Blackhat+Sherpa
- High Energy Jets (HEJ – all-order resummation)

Higher order approaches show good agreement on this fundamental observable

Some breakdown of NLO expected and observed when W $p_T \approx$ jet p_T threshold (20 GeV)

Uncertainties on data smaller or equal in magnitude to uncertainties on theory predictions

W+jets



W+(n)jets differential cross-section measured as a function dijet mass (in inclusive two and three jet multiplicity bins)

Good agreement between data and theory predictions

NLO Blackhat+Sherpa tends to predict slightly higher 2-jet rate than seen in data

W+jets

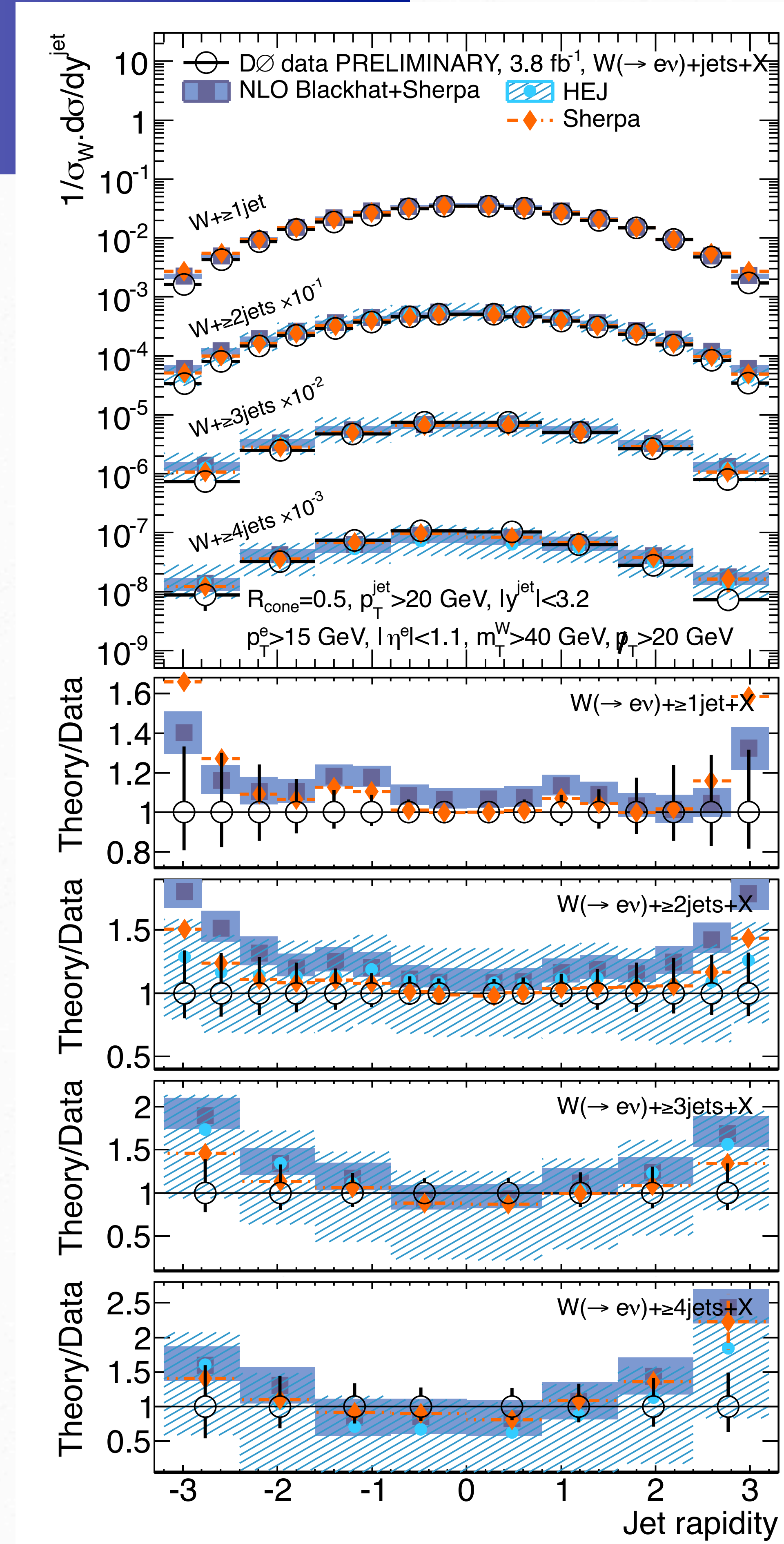
W+(n)jets differential cross-section measured as a function of n^{th} jet rapidity in inclusive n-jet events (for n=1—4)

Good agreement between data and theory at central rapidities, with small uncertainties

Theory predictions tend to overestimate cross-section in forward region: dominated by low p_T jets

Qualitatively similar picture to Z+jets @ CDF (although these measurements extend rapidity region)

Many Tevatron analyses are sensitive to discrepancies in jet rapidity modelling



Tuesday, August 21, 12

W+jets

Probability of third jet emission in inclusive W+dijet events, as a function of dijet rapidity separation(s).

Encouraging agreement between theoretical approaches and data in all jet configurations, even at highest rapidity spans

Notable differences in jet emission into the rapidity gap for p_T and rapidity ordered jets

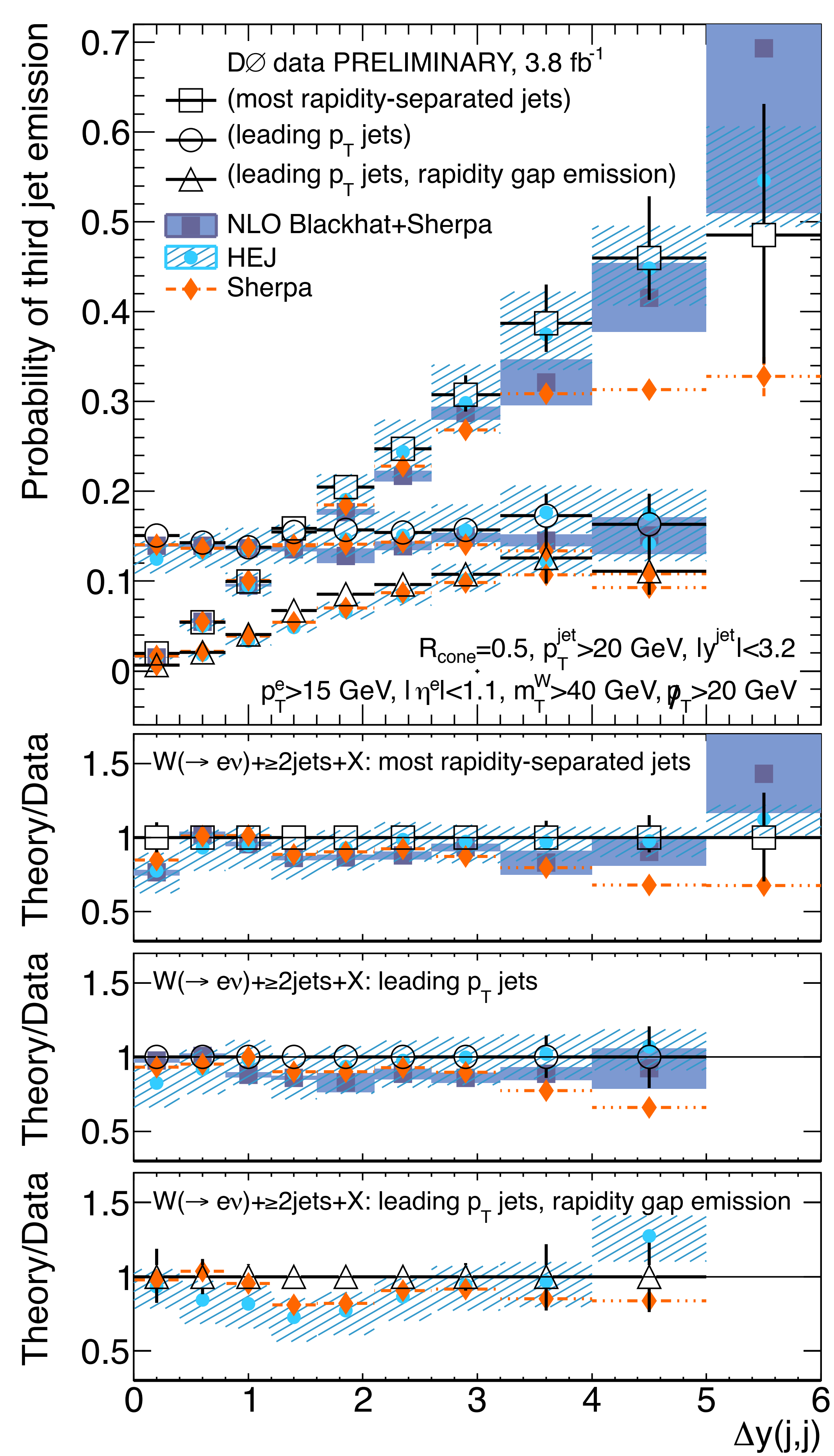
For rapidity-ordered jets:

Blackhat+Sherpa performs well throughout, with increasing uncertainties at large rapidity span

HEJ performs well in the relevant region, with small uncertainties at wide angle

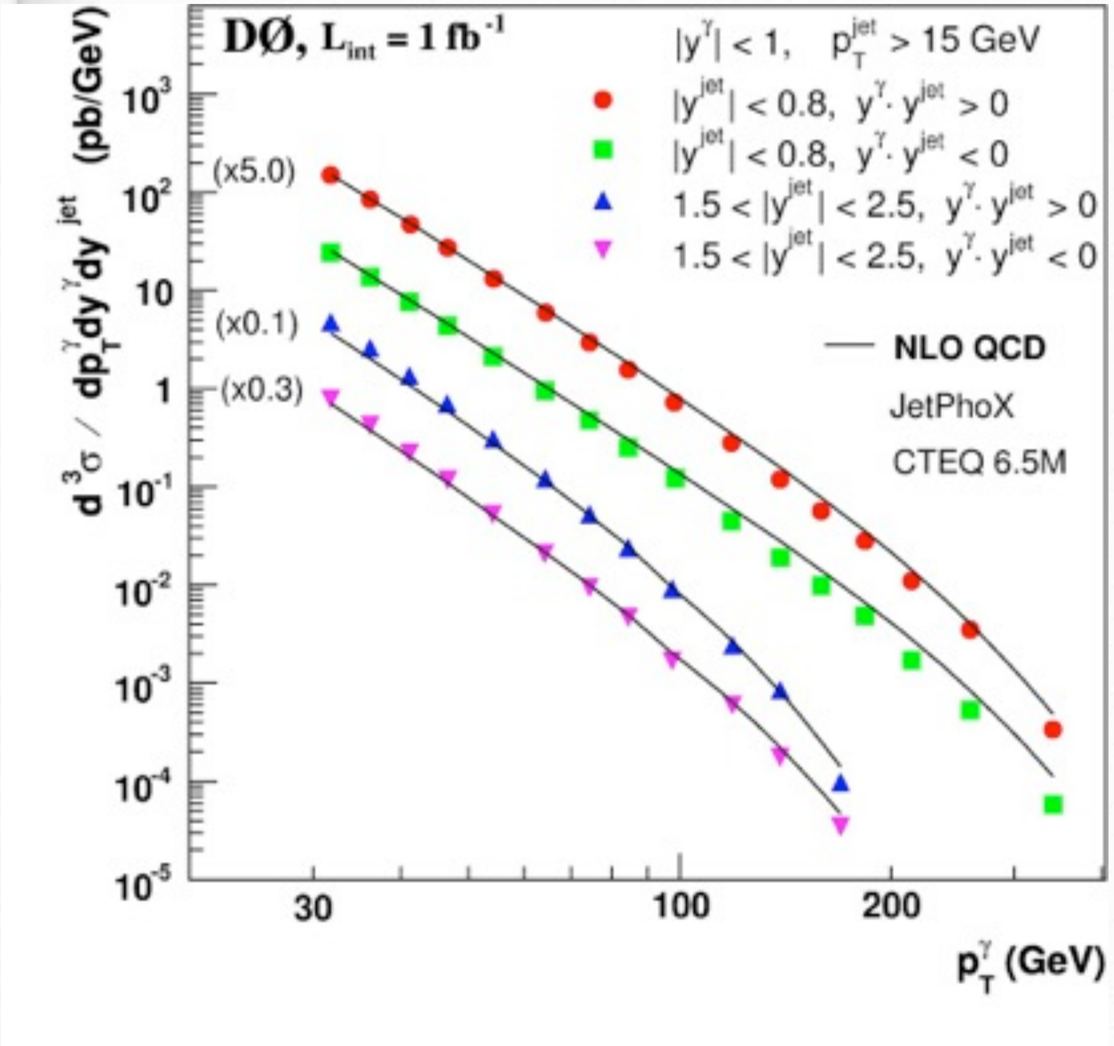
Sherpa behaves like most MEPS (or PS) MCs with insufficient radiation at wide angle

Data can be reinterpreted as a measure of the gap fraction (with a jet veto scale of 20 GeV), relevant for processes like Vector Boson Fusion



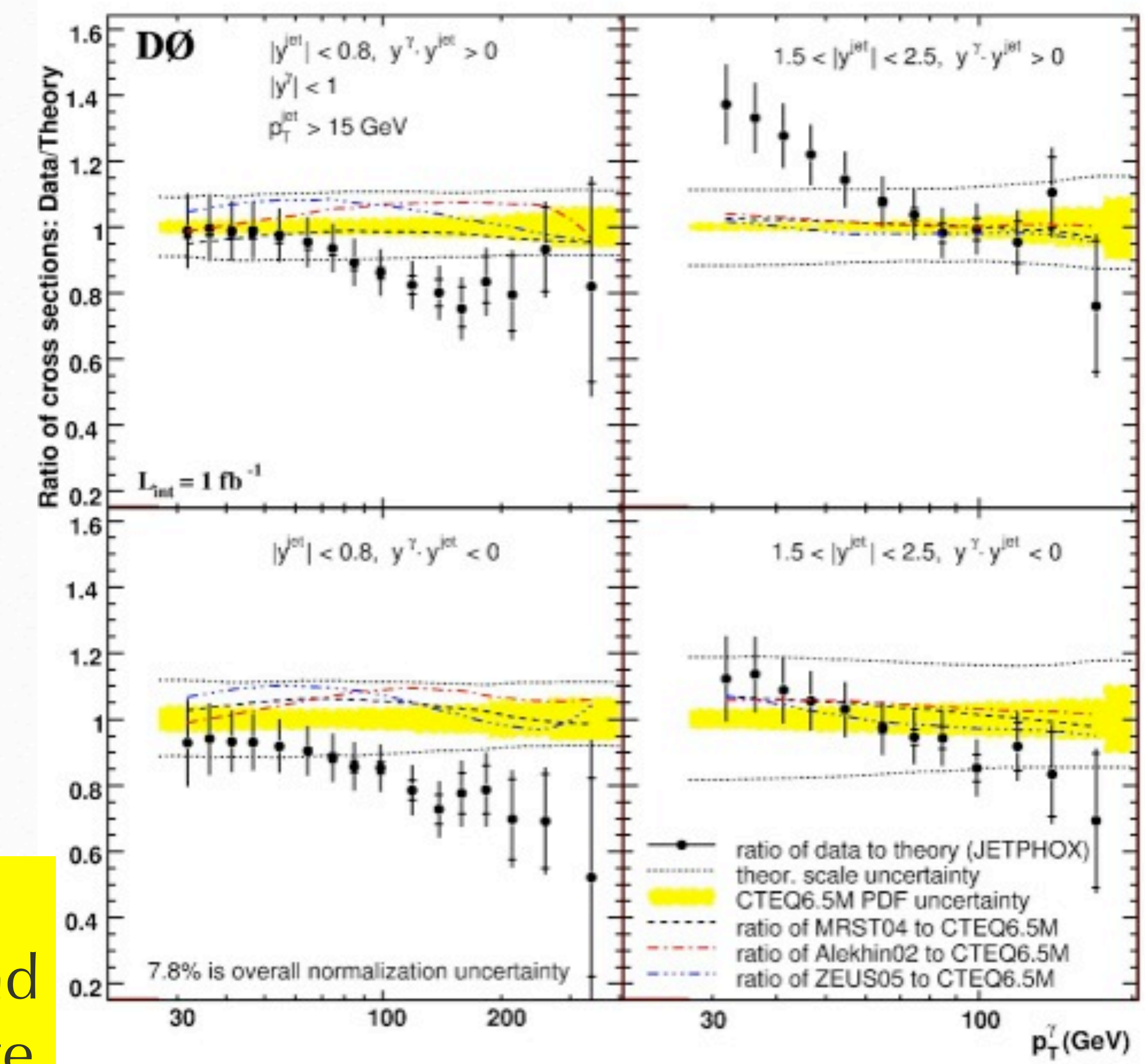
γ+jets

$\mathscr{L}$ = 1.0/fb



Huge statistics compared to W,Z
Triple differential cross sections!

Phys. Lett. B 666, 435 (2008), arXiv.org:0804.1107

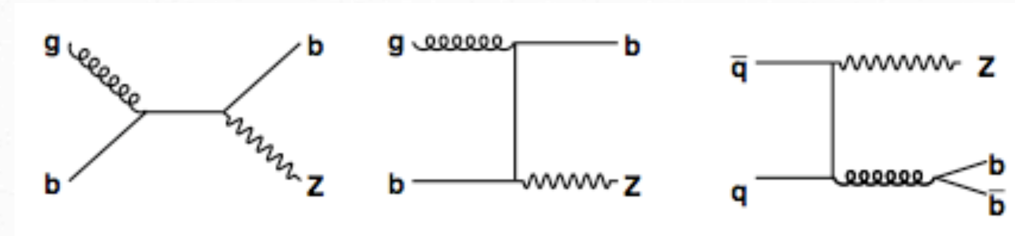


Allows for careful study of dynamics of QCD in different regions of x and Q^2

NLO theory cannot simultaneously describe photon p_T and jet rapidity over entire measured range

Z+b jets

Z → ee/μμ + b + X
jet E_T > 20 GeV, R=0.7
jet |η| < 1.5
secondary vertex tagging

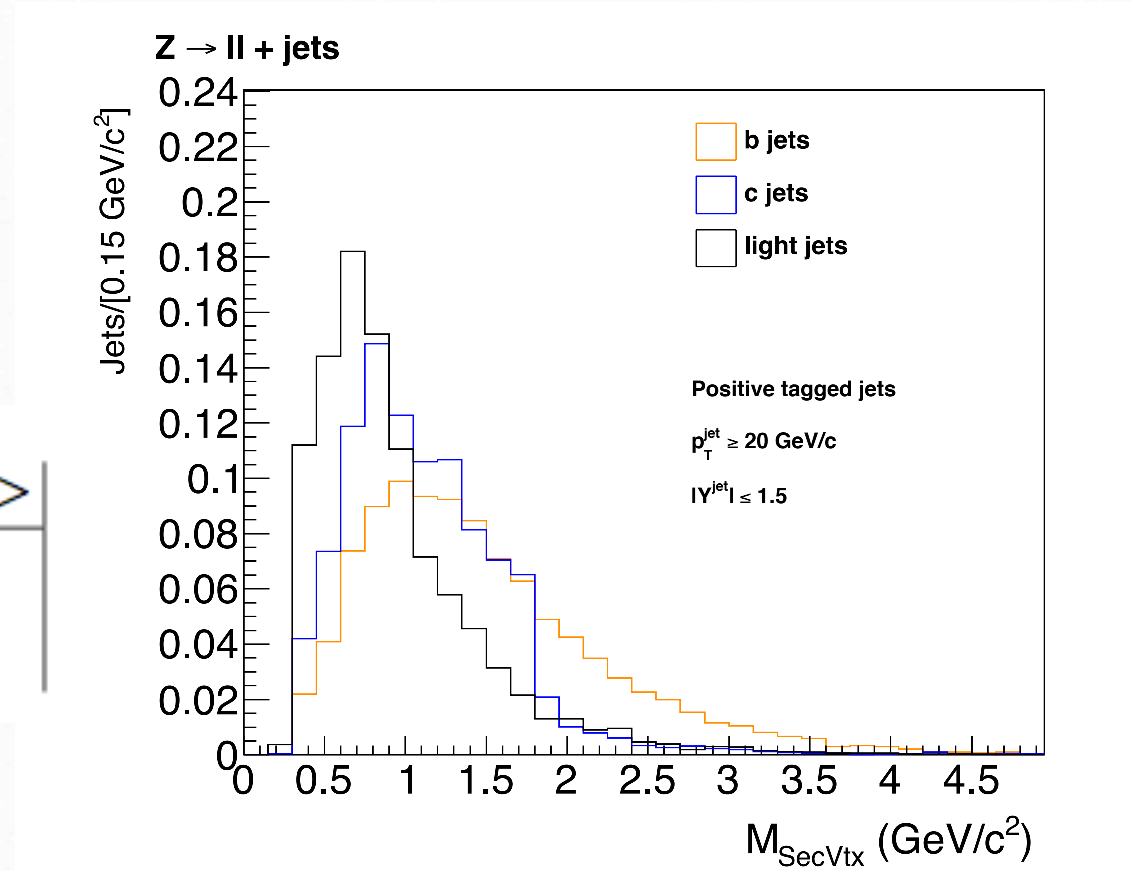


b,c quark fractions determined from likelihood fit to secondary vertex mass

Results:

$$\frac{\sigma_{Z+bjet}}{\sigma_Z} = 0.261 \pm 0.023^{stat} \pm 0.029^{syst}\%$$

$$\frac{\sigma_{Z+bjet}}{\sigma_{Zjet}} = 2.08 \pm 0.18^{stat} \pm 0.27^{syst}\%$$



NLO Predictions (MCFM):

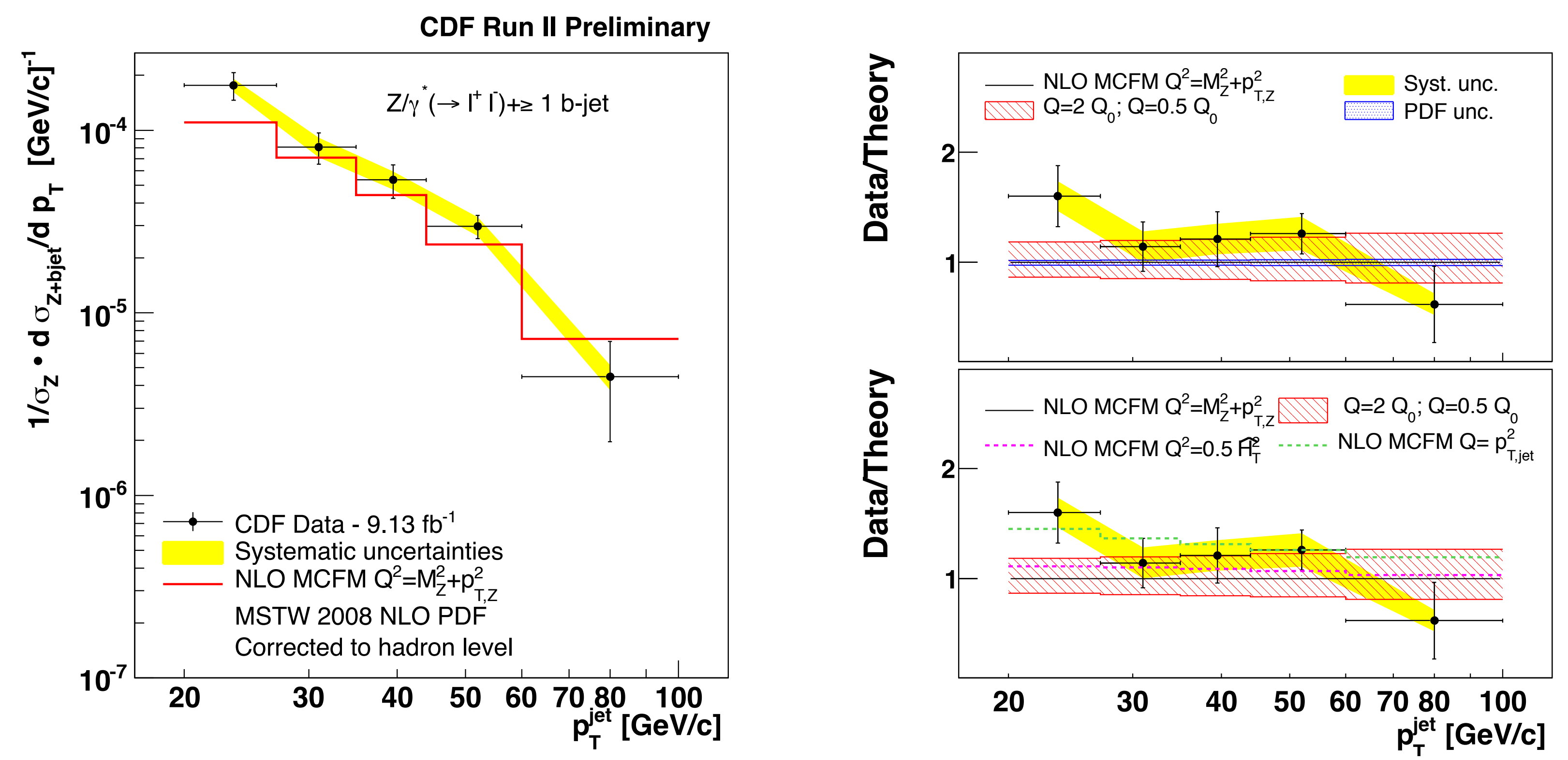
	NLO $Q^2 = m_Z^2 + p_{T,Z}^2$	NLO $Q^2 = < p_{T,jet}^2 >$
$\frac{\sigma(Z+b)}{\sigma(Z)}$	2.3×10^{-3}	2.9×10^{-3}
$\frac{\sigma(Z+b)}{\sigma(Z+jet)}$	1.8×10^{-2}	2.2×10^{-2}

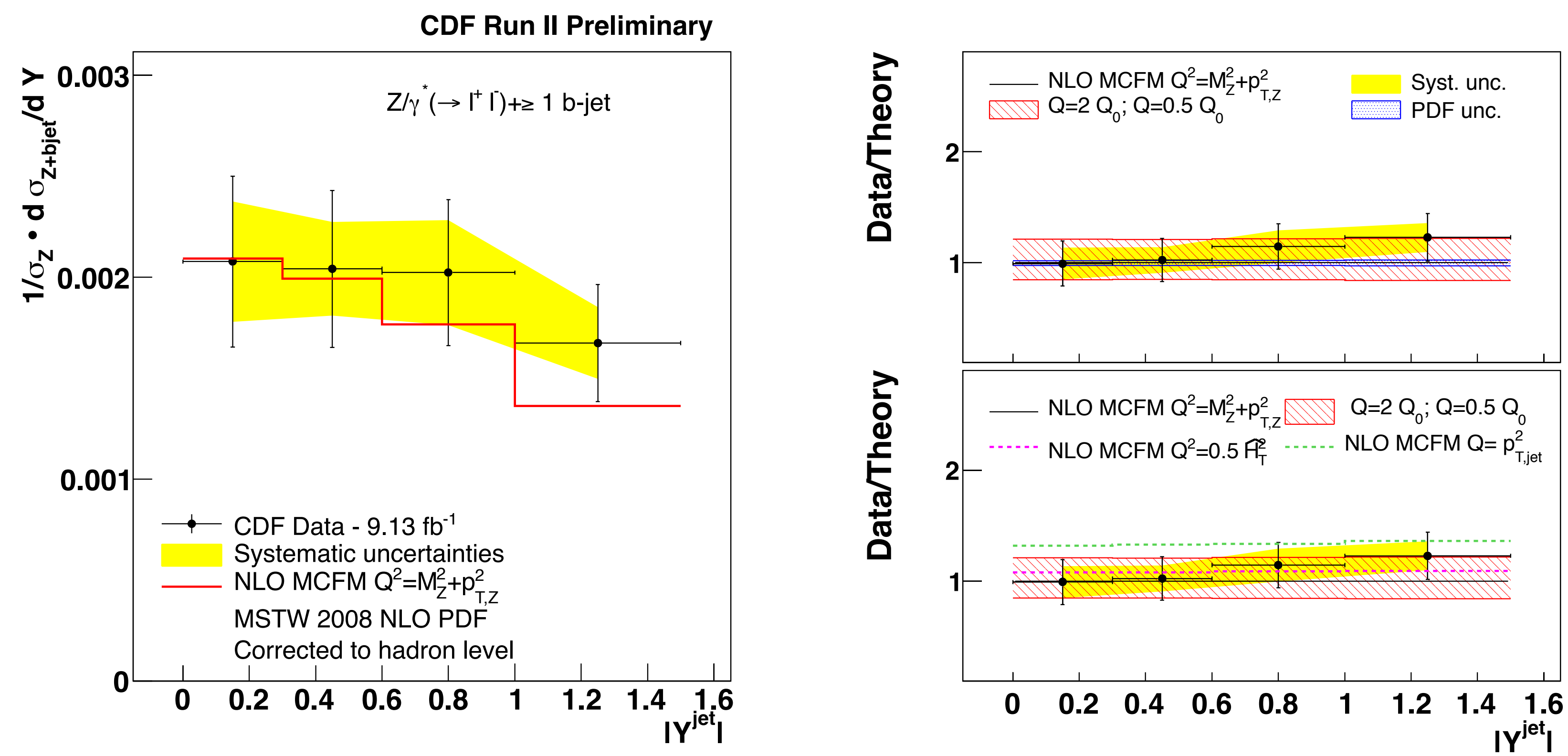
Results are in agreement with NLO theory

Z+b jets

Differential cross sections using full RunII dataset

MCFM can describe the shape of the data, within uncertainties

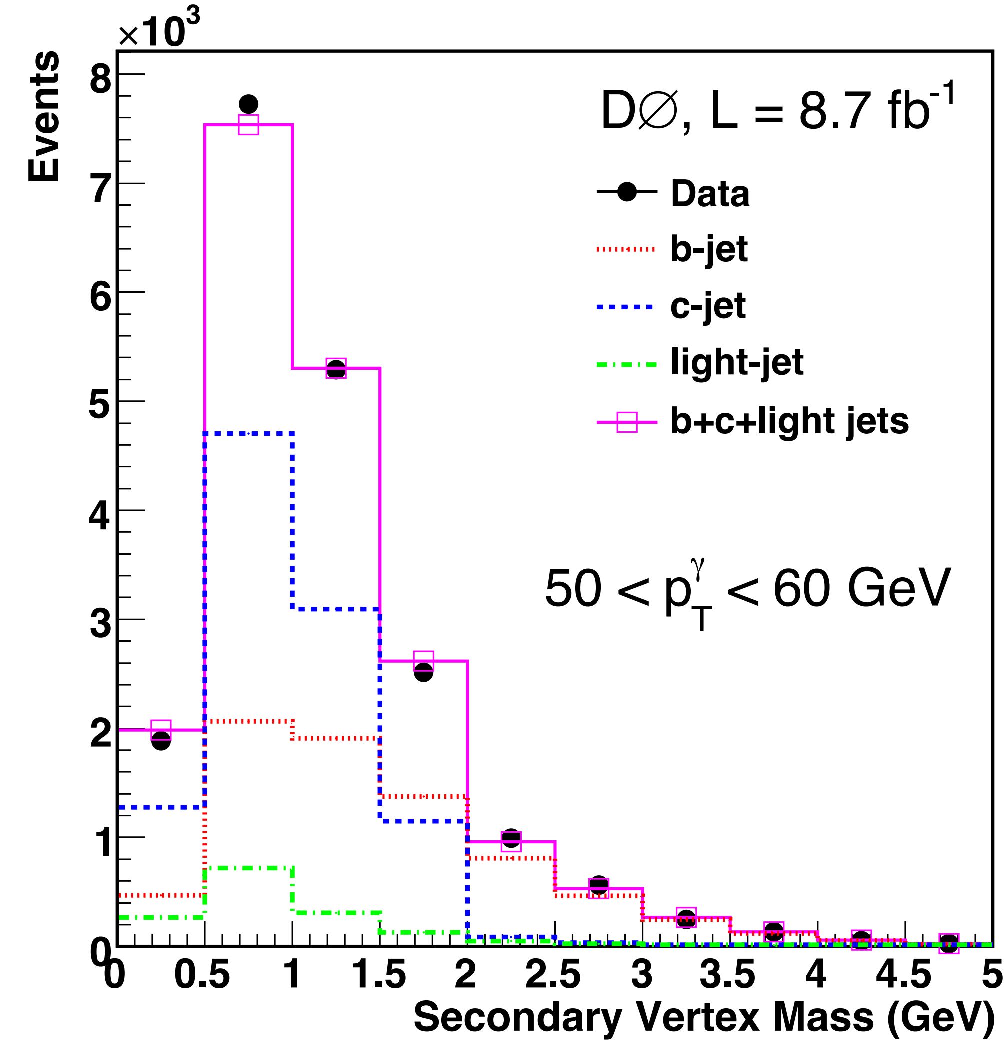




γ+beauty

γ + b + X
jet E_T > 15 GeV, R=0.5
jet |η| < 1.5
secondary vertex tagging

Compton Scattering: gb → γb
$q\bar{q}$ annihilation: $q\bar{q} \to \gamma g \to \gamma b\bar{b}$



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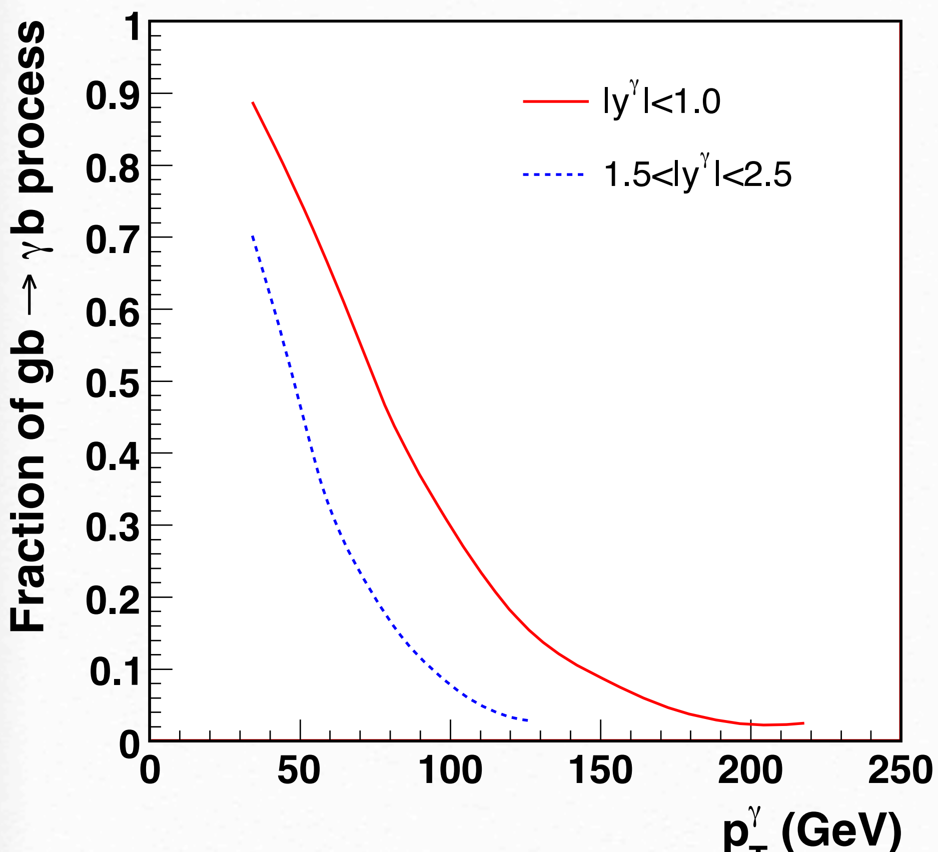


Annihilation process dominates at high-p_T (>70 GeV)
- higher-order corrections would be particularly useful here

γ+beauty

Comparisons made to theory predictions:

NLO QCD (CTEQ6.6) - Stavreva and Owens

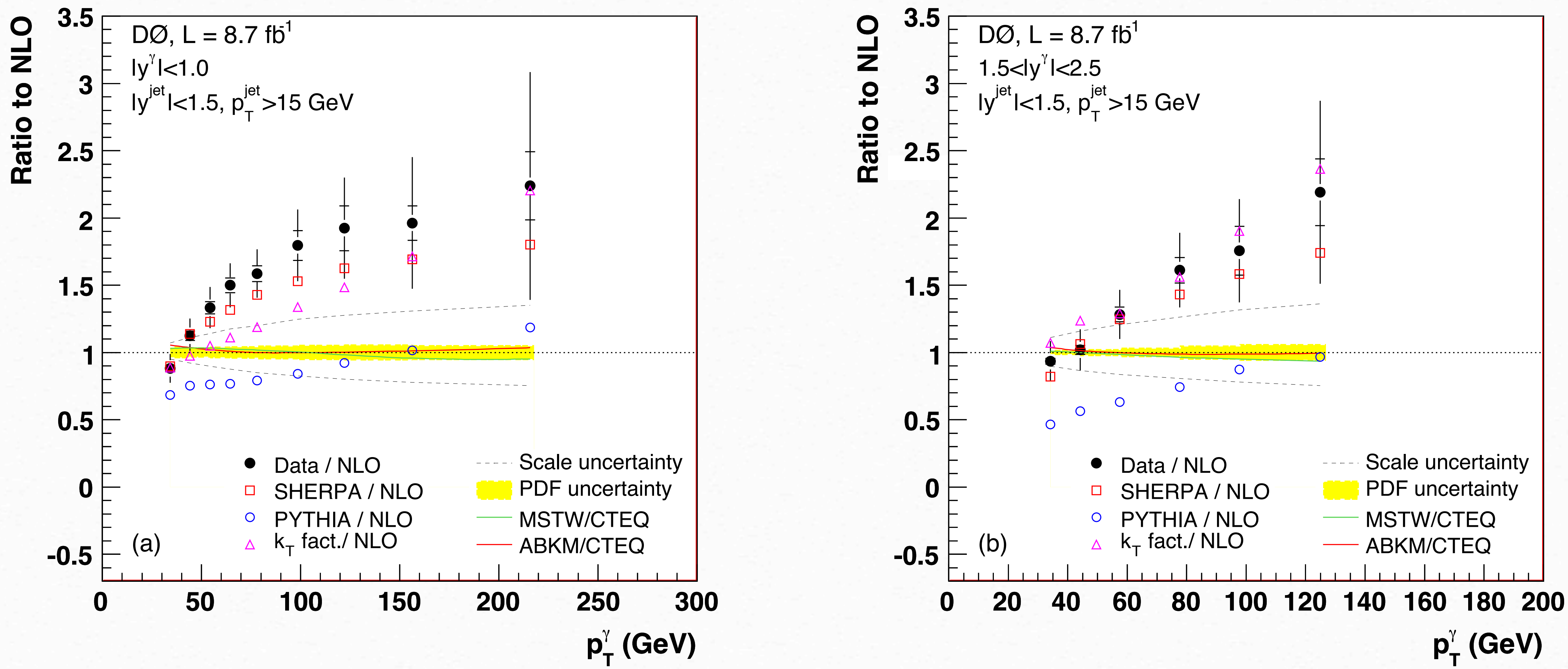
k_T factorization - Lipatov and Zotov with resummed gluon radiation

Sherpa (CTEQ6.6)

Pythia (CTEQ6.1L)

Also updated results from CDF - see talk by K. Vellidis

- All theory exhibit slope in photon pT w.r.t. data
- Data are best described by Sherpa
- k_T factorization approach broadens p_T spectrum
- Higher order pQCD predictions needed, as well as gluon resummation



W+b jets

Backgrounds:
ttbar (40%)
single top (30%)
fake W (15%)
WZ (5%)

Phase space:

- a truth level electron or muon with $p_T > 20$ GeV/c, $|\eta| < 1.1$
- a truth level neutrino with $p_T > 25$ GeV/c
- 1 or 2 total truth level jets with $E_T > 20$ GeV/c^2, $|\eta| < 2.0$

$\mathscr{L} = 1.9$/fb

b-fraction determined from likelihood fit to M_{vert}

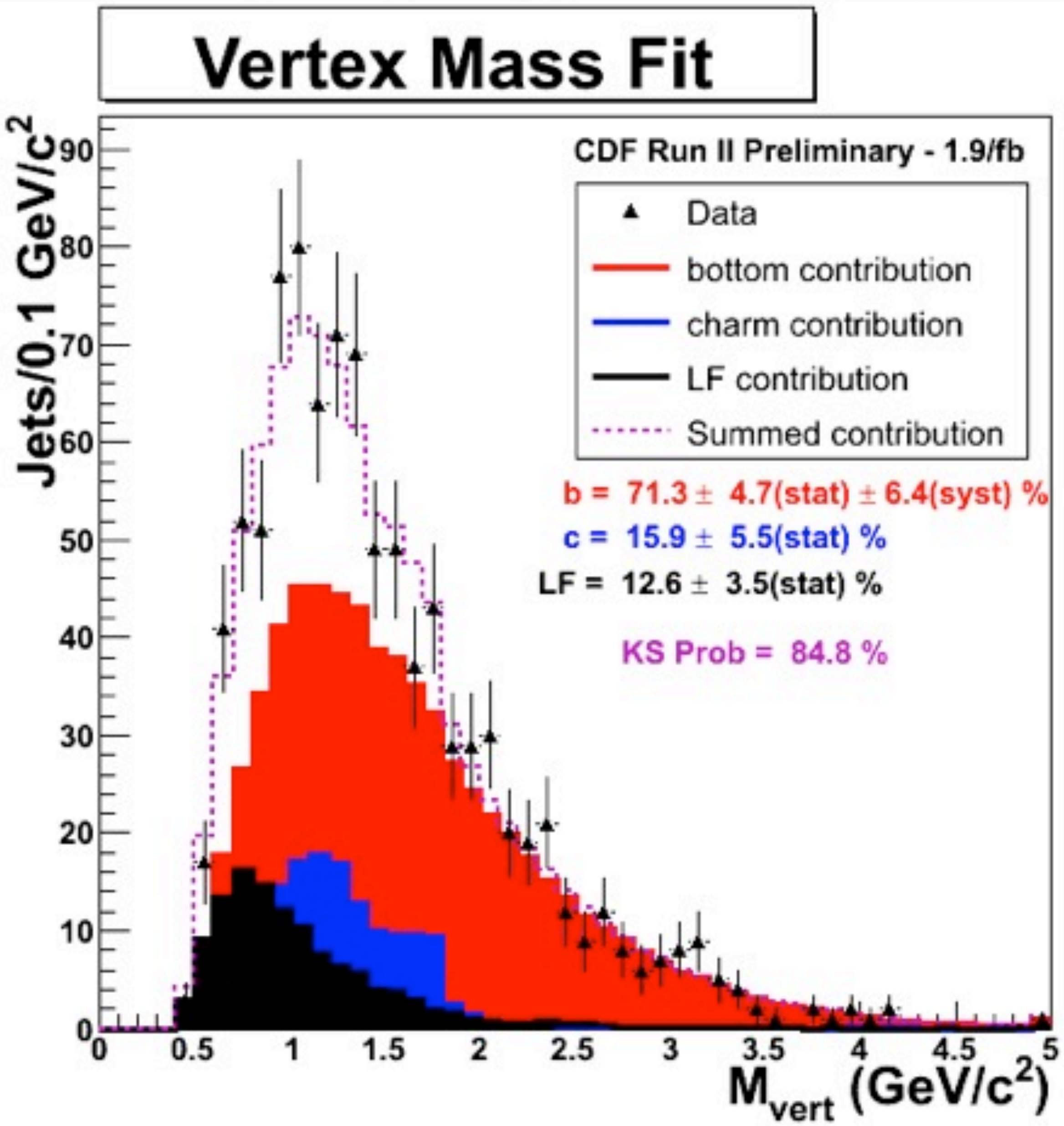
Measure: σ(W+b jets)x BR(W->lnu)

Alpgen prediction: 0.78 pb
Pythia prediction: 1.10 pb
NLO prediction: 1.22 ± 0.14 pb

Result:
2.74 ± 0.27 (stat) ± 0.42 (sys) pb
→ 2.5-3.5x bigger!

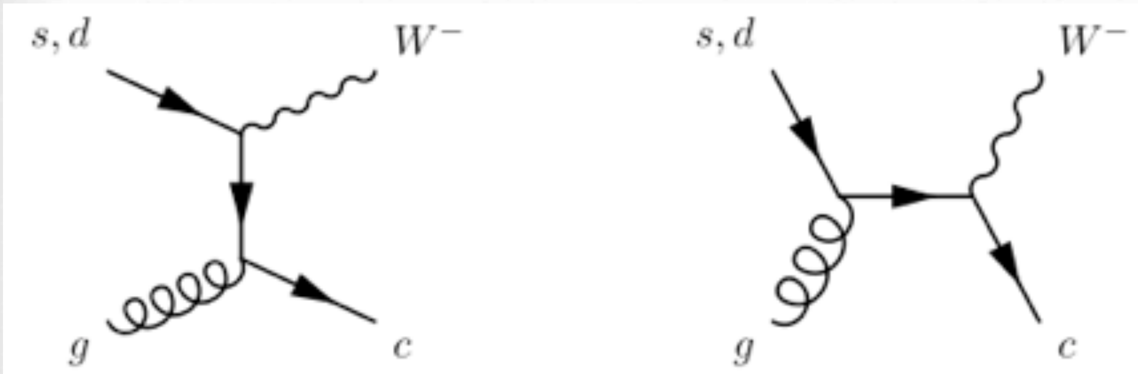
Discrepancy with NLO and LO MC - suggestive of need for improved theory:

- higher order corrections
- b-quark fragmentation model

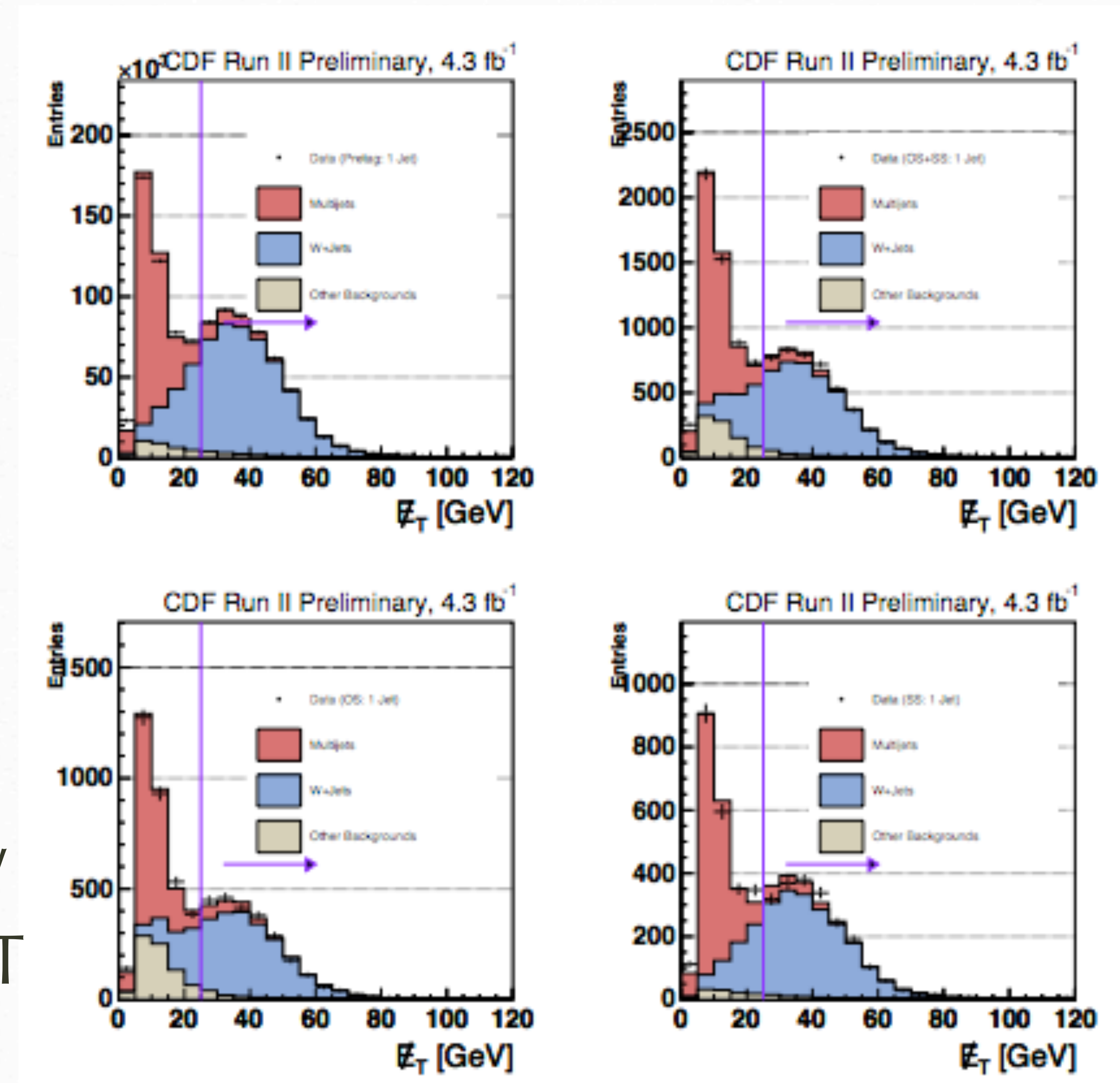


W+charm

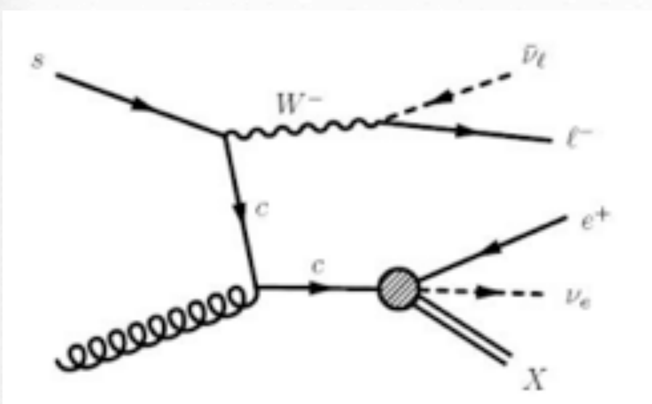
Sensitive to s-quark PDF



$$\sigma_{Wc} \times \mathrm{BR}(W \to \ell\nu) = \frac{N_{\mathrm{tot}}^{OS-SS} - N_{\mathrm{bkg}}^{OS-SS}}{Acc \cdot \int L\, \mathrm{dt}}$$



Soft Lepton Tag (SLT):



Signal is extracted by measuring charge asymmetry between the W lepton and the lepton from the SLT

W+charm

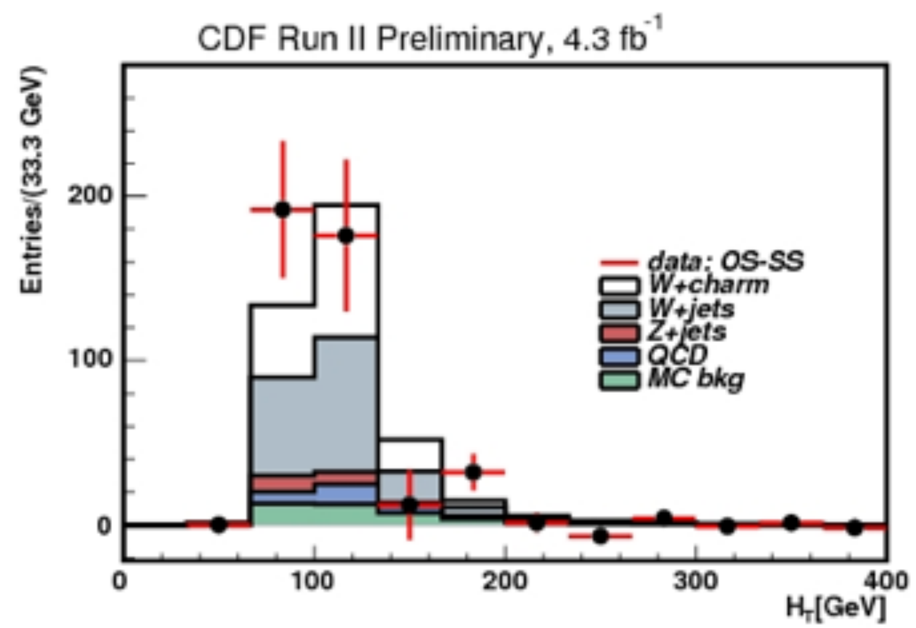
SLT electrons:

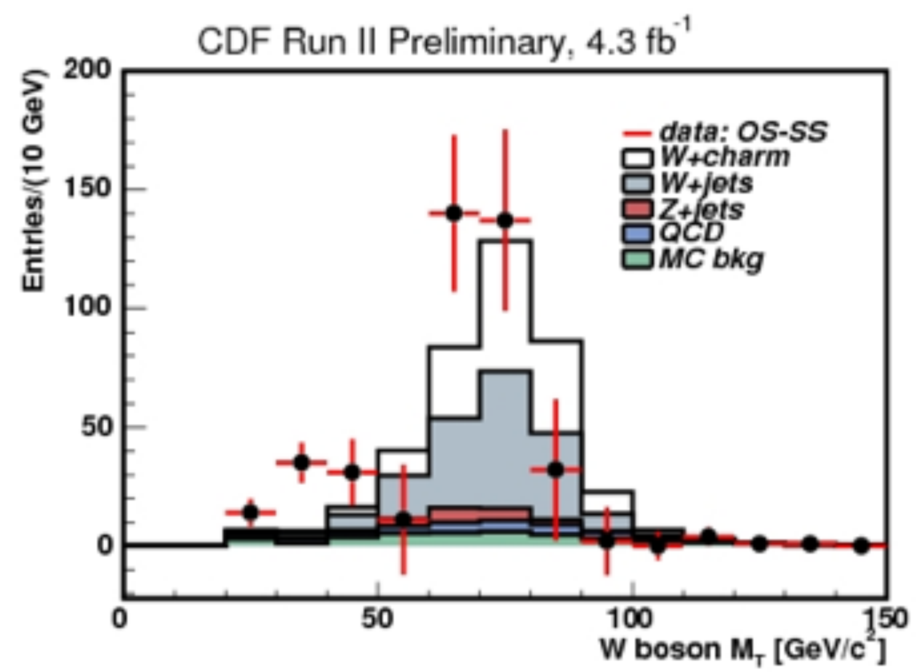
$$\sigma = 13.4 \pm 2.3\,(\text{stat}) \pm 2.4\,(\text{syst}) \pm 1.1\,(\text{lumi})\,\text{pb},$$

SLT muons:

$$\sigma = 14.2 \pm 6.5\,(\text{stat}) \pm 3.4\,(\text{syst}) \pm 1.2\,(\text{lumi})\,\text{pb},$$

NLO Prediction: 11.3 ± 2.2 pb





Source	Relative Uncertainty SLT&mue(%)	Relative Uncertainty SLTe(%)
SLT uncertainties	± 9.2	± 16.6
Factorization/Renormalization scale	± 1.3	± 1.3
Luminosity	± 7.9	± 8.3
QCD estimation	± 6.3	± 9.9
ISR/FSR	± 6.0	± 6.0
Background cross sections	± 5.7	± 4.7
PDFs	± 3.6	± 3.6
W-lepton ID	± 2.2	± 2.2
Jet-energy scale	± 2.0	± 2.0
Total	± 16.7	± 22.9

Summary and Conclusion

CDF and DØ are focused on final measurements with full dataset, allowing detailed exploration of phase space

Precision QCD! - experimental and theoretical uncertainties constantly improving

Crucial for understanding backgrounds to NP searches and SM Higgs precision measurements

Discrepancies with theory suggest HO corrections and/or resummations are needed

RunII measurements with associated luminosity

Result(1/fb)	DØ	CDF
W+jets	3.8	2.8
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W+b-jets	0.38	1.9
Z+b-jets	4.2	9.1
W+c-jets	1.0	4.3
γ+jets	1.0	--
γ+b/c jets	8.7	9.1

Updates coming soon:

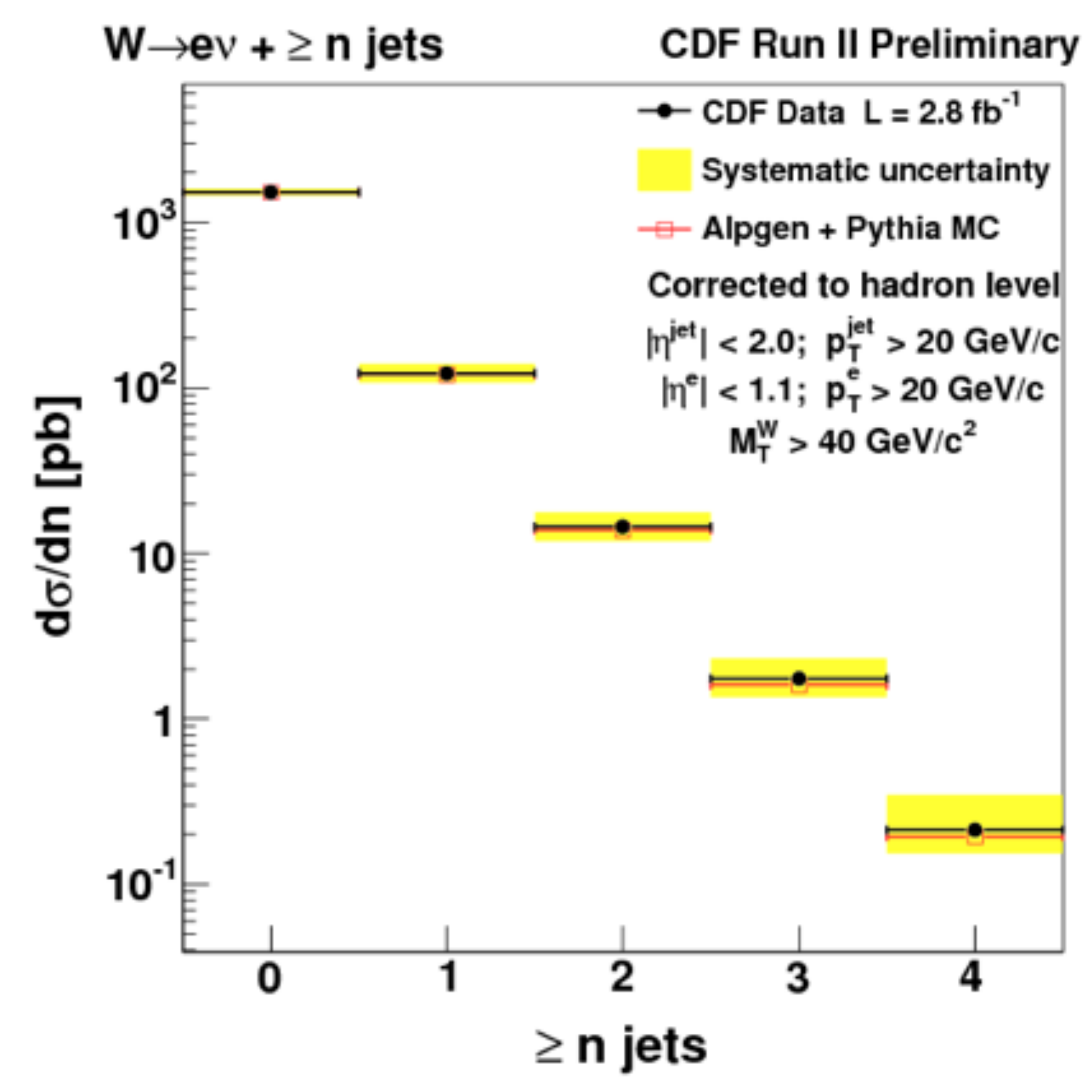
CDF
- **W+b**
- **W+jets**
- **γ+b/c**
- **γ+jets**

DØ
- **Z+b**
- **W+b**
- **W+c**
- **W+jets**
- **γ+c**
- **γ+jets**

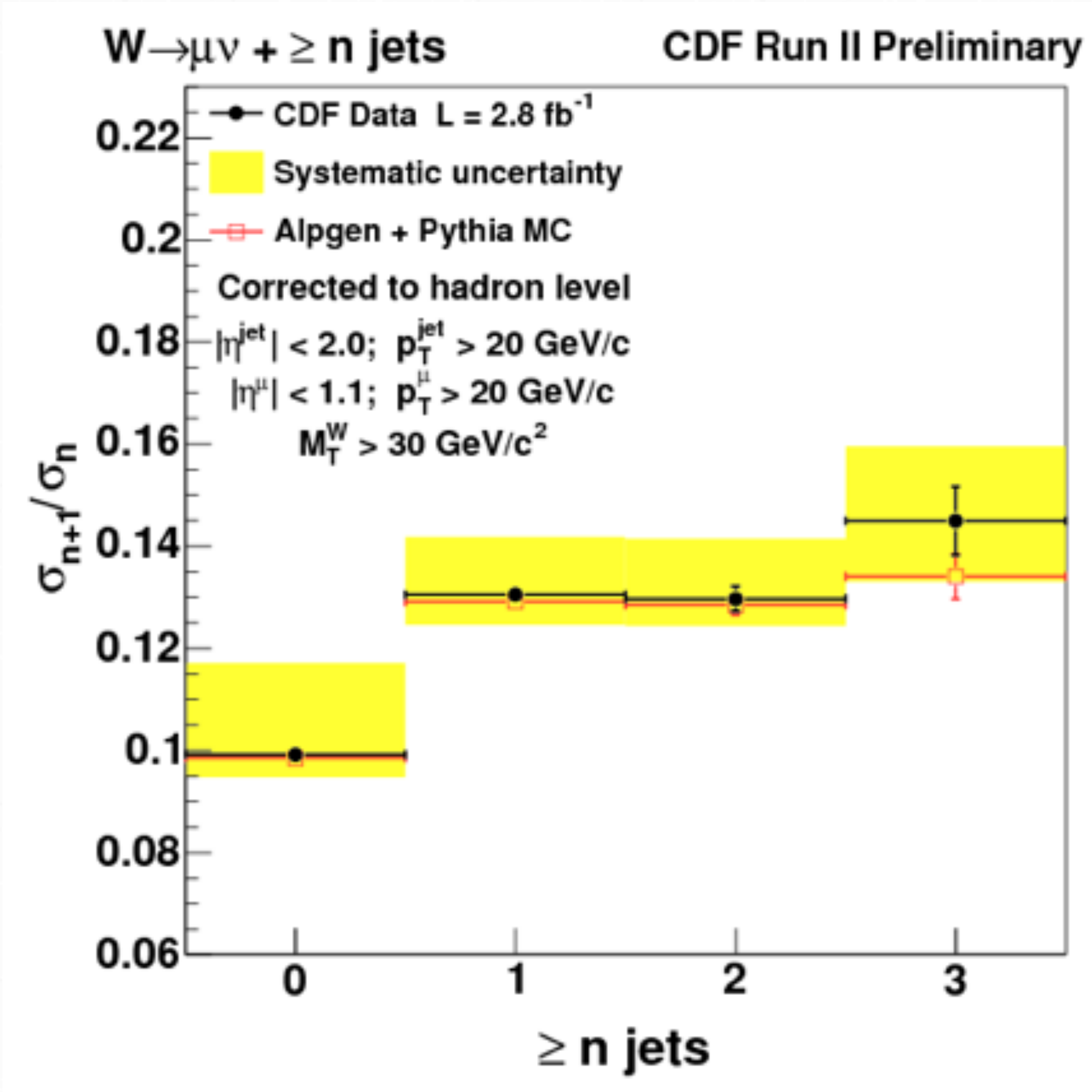
http://www-cdf.fnal.gov/physics/new/qcd/QCD.html **http://www-d0.fnal.gov/Run2Physics/WWW/results/qcd.htm**

Backup

W+jets



W→eν + ≥ n jets
CDF Run II Preliminary
CDF Data L = 2.8 fb^{-1}
Systematic uncertainty
Alpgen + Pythia MC
Corrected to hadron level
$|\eta^{jet}| < 2.0$; $p_T^{jet} > 20$ GeV/c
$|\eta^{e}| < 1.1$; $p_T^{e} > 20$ GeV/c
$M_T^W > 40$ GeV/c^2
dσ/dn [pb]
≥ n jets



W→μν + ≥ n jets
CDF Run II Preliminary
CDF Data L = 2.8 fb^{-1}
Systematic uncertainty
Alpgen + Pythia MC
Corrected to hadron level
$|\eta^{jet}| < 2.0$; $p_T^{jet} > 20$ GeV/c
$|\eta^{\mu}| < 1.1$; $p_T^{\mu} > 20$ GeV/c
$M_T^W > 30$ GeV/c^2
σ_{n+1}/σ_n
≥ n jets

W+c jets

Sensitive to s-quark PDF

$\mathscr{L}$ = 1.8/fb

$$\sigma_{Wc} \times \mathrm{BR}(W \to \ell\nu) = \frac{N_{\rm tot}^{OS-SS} - N_{\rm bkg}^{OS-SS}}{Acc \cdot \int L\, dt}$$

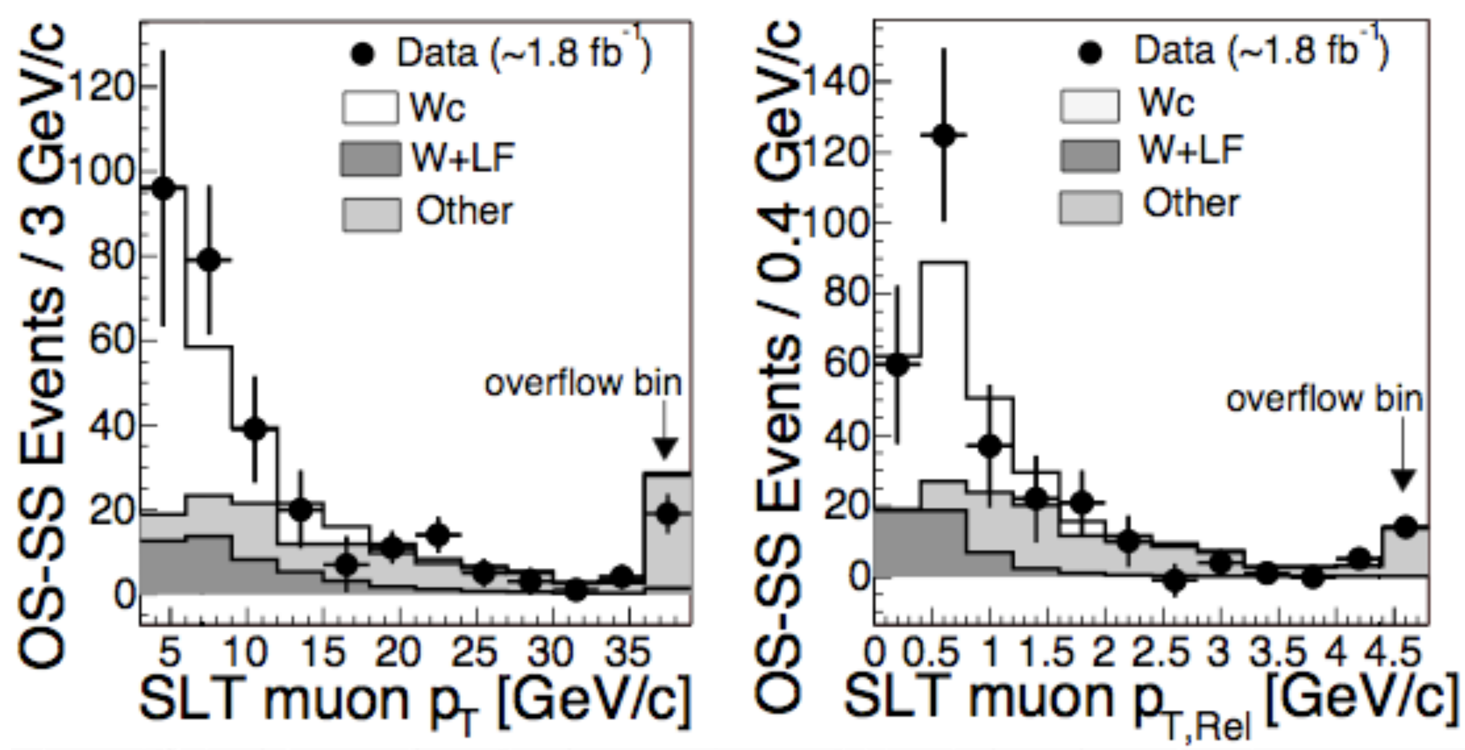
NLO prediction: 11.0 pb

Result:

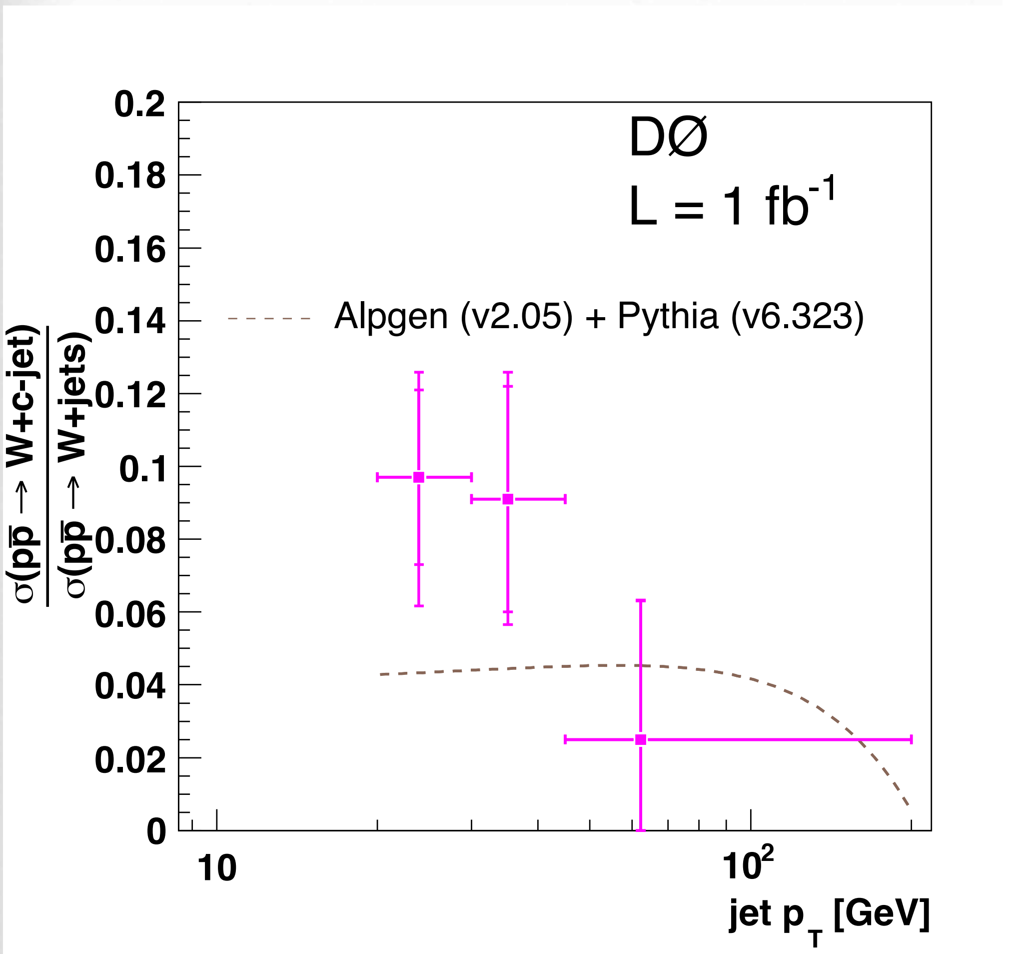
measure σ(W+cjets)xBR(W->lν)

= 9.8 ± 2.8 (stat)$^{+1.4}_{-1.6}$ (sys)

+ 0.6(lumi) pb.



Phys. Rev. Lett. 100, 091803 (2008) , arXiv.org:0711.2901



$\mathscr{L}$ = 1/fb

Alpgen prediction: 0.04 pb

Result: measure σ(W+cjets)/σ(W+jets)

= 0.074 ± 0.019 (stat) ± $^{+0.012}_{-0.014}$ (sys)

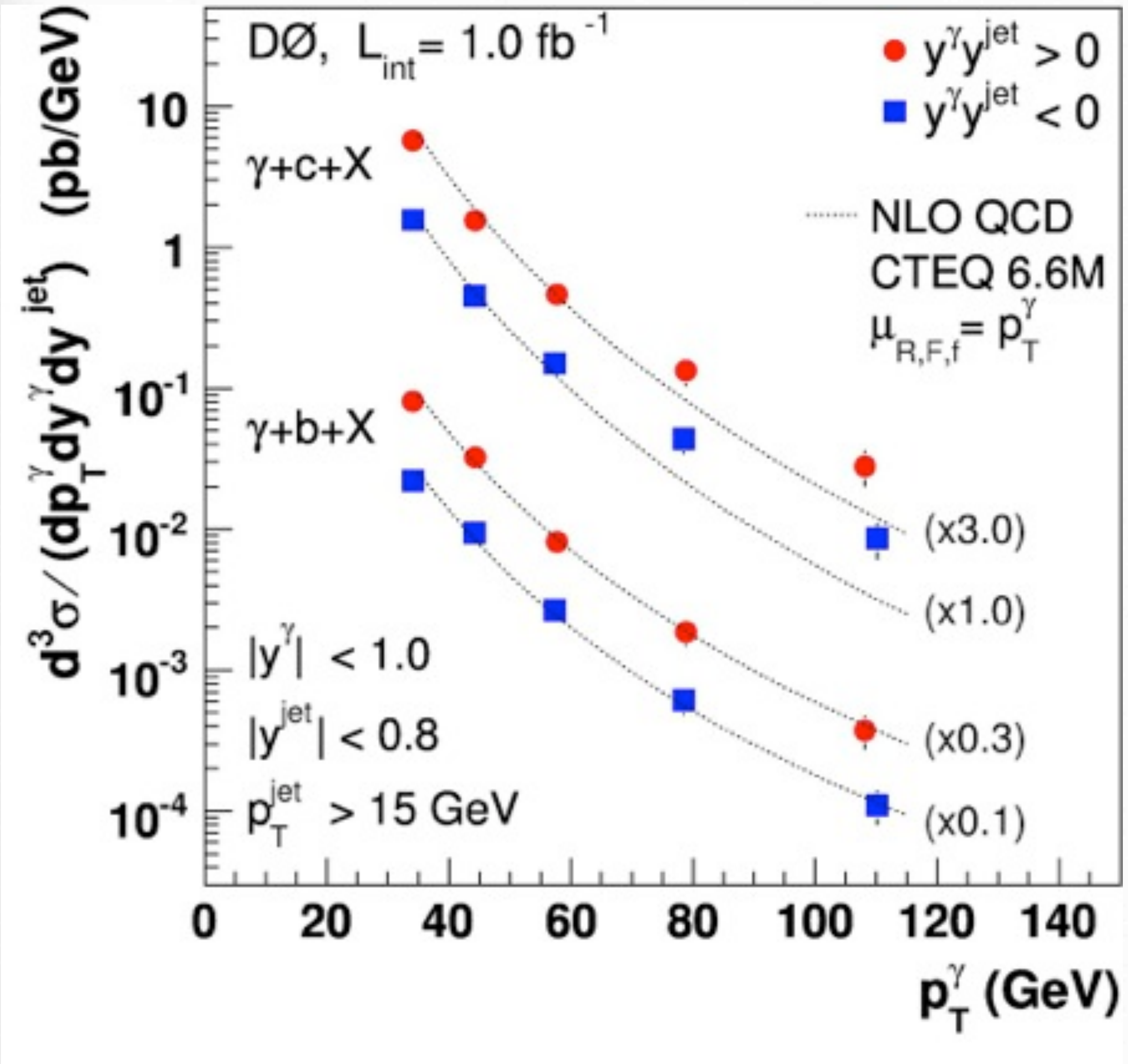
Phys.Lett.B666:23-30 (2008), arXiv.org:0803.2259

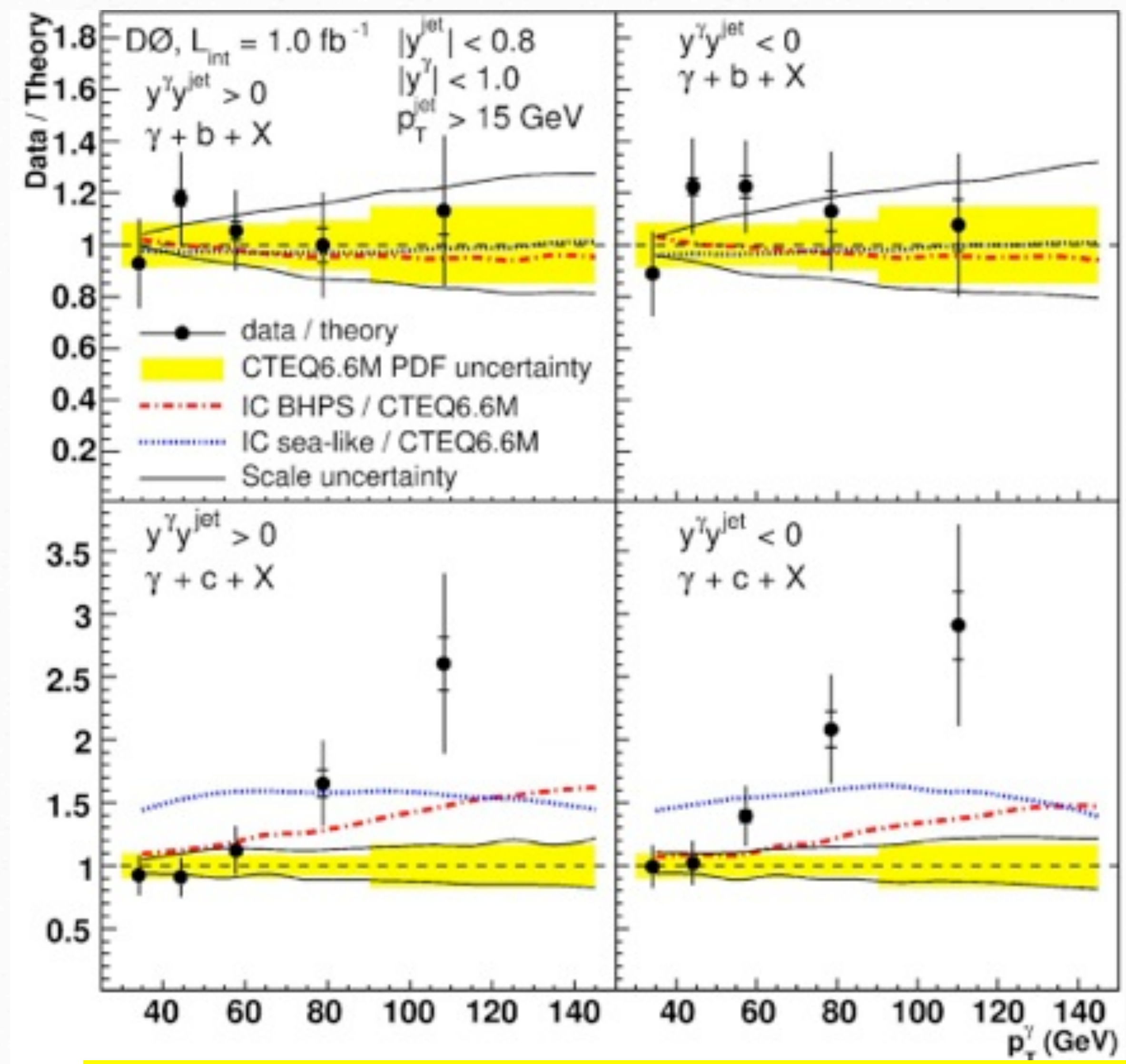
γ+b,c (previous result)

$\mathcal{L} = 1.0/\text{fb}$

Triple differential cross sections!

Phys. Rev. Lett. **102**, 192002 (2009), arXiv.org:0901.0739





Relevant for heavy quark, gluon PDFs for 0.01< x <0.3

Disagreement with theory for photon p_T > 70 GeV where qqbar annihilation dominates

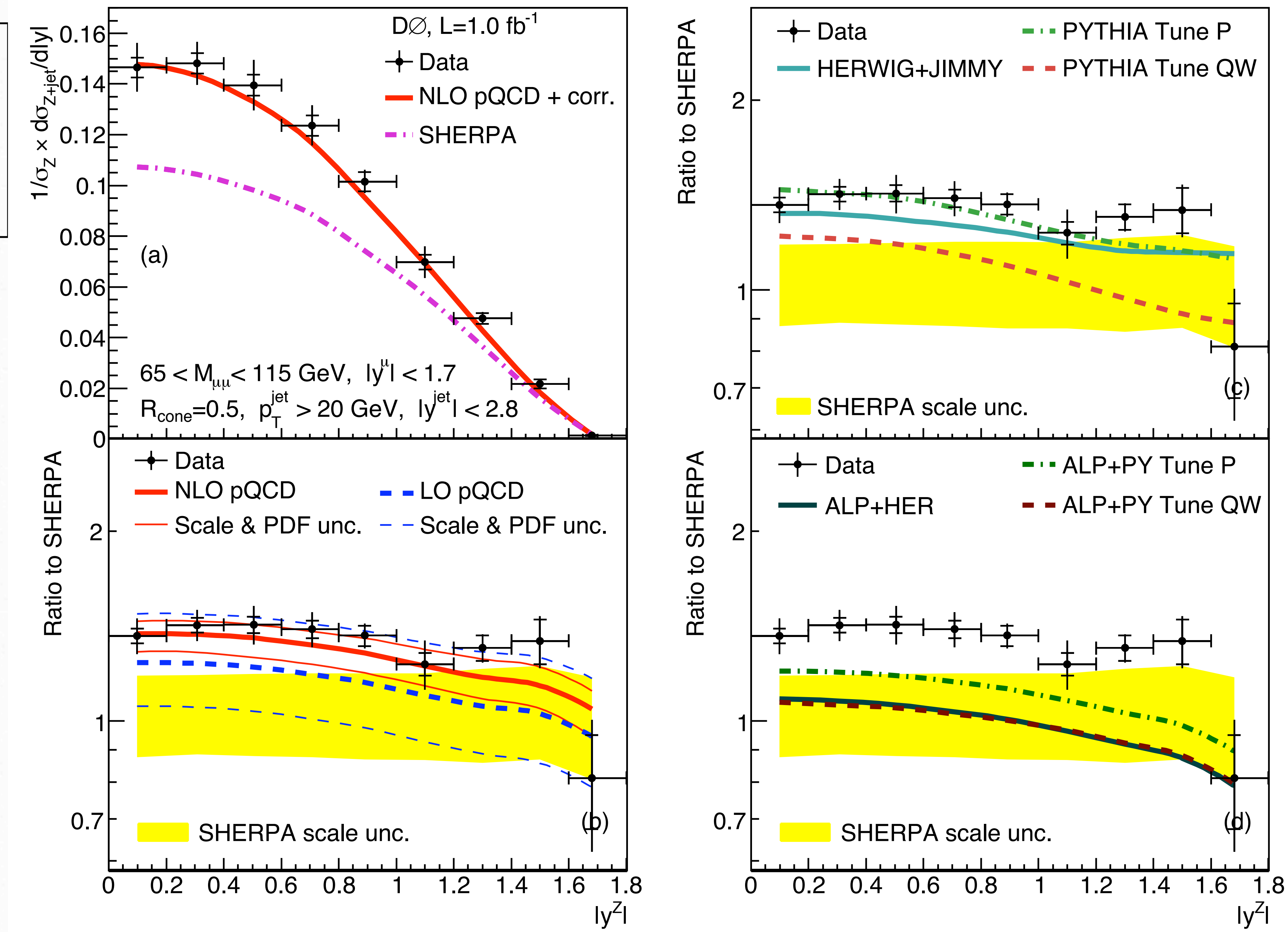
Z+jets

Z->μμ + jet + X

(Z+1jet inclusive)

$\mathscr{L}$ = 1.0/fb

Phase space:
65 GeV< $M_{\mu\mu}$ < 115 GeV,
R_{cone}=0.5, p_T^{jet} > 20 GeV
$|y^{jet}|$ < 2.8, $|y^{\mu}|$ < 1.7



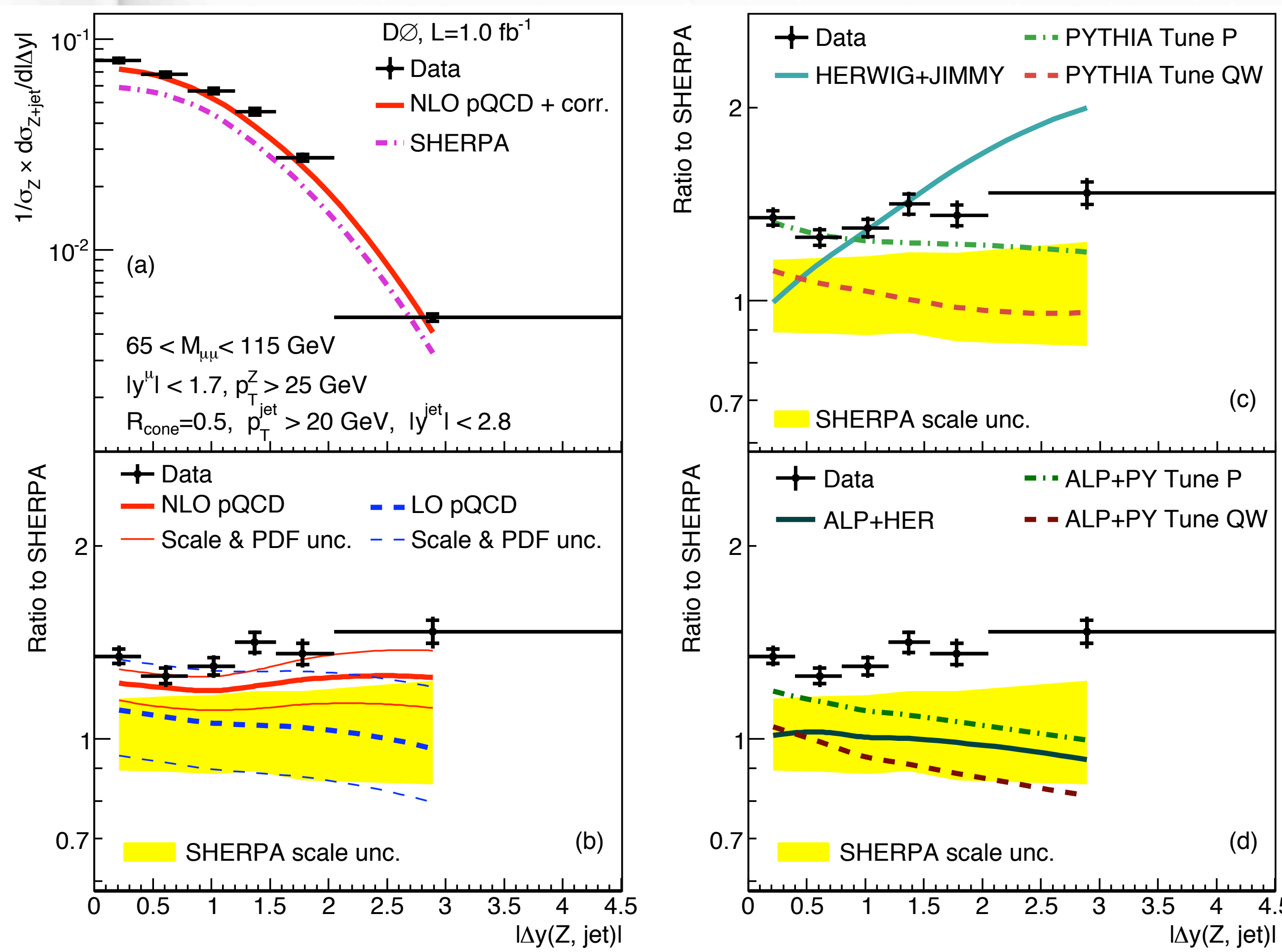
ratios relative to Sherpa v1.1.3

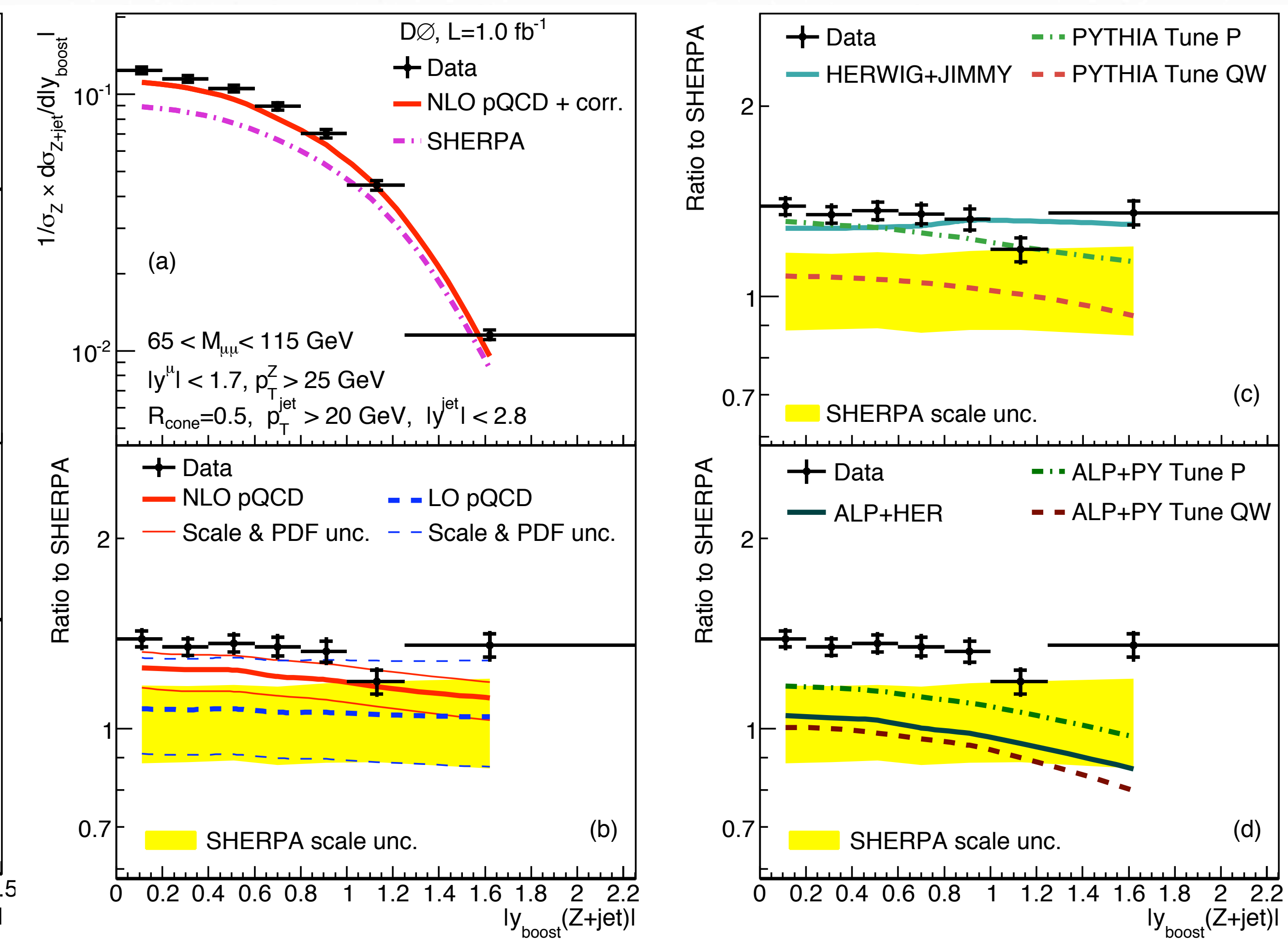
Z+light flavor jets

Z+1jet inclusive angular variables

$\Delta\phi$ (Z,jet)
Δy (Z,jet)
y_{boost}(Z,jet) = ½(y_Z+y_{jet})

Phase space:
65 GeV< $M_{\mu\mu}$ < 115 GeV,
R_{cone}=0.5, p_T^{jet} > 20 GeV
$|y^{jet}|$ < 2.8, $|y^{\mu}|$ < 1.7
p_T^Z > 25 GeV (avoid UE)





Z+light flavor jets

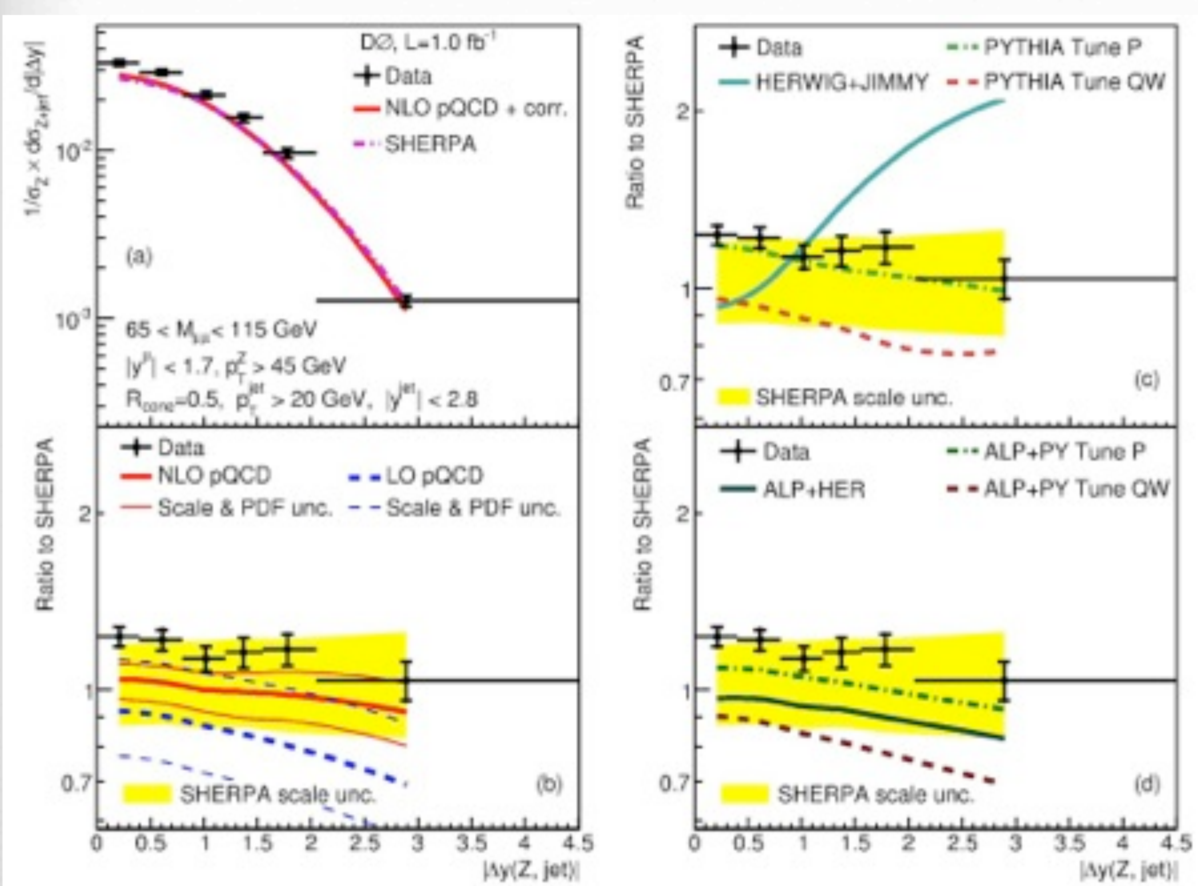
Z+1jet inclusive angular variables

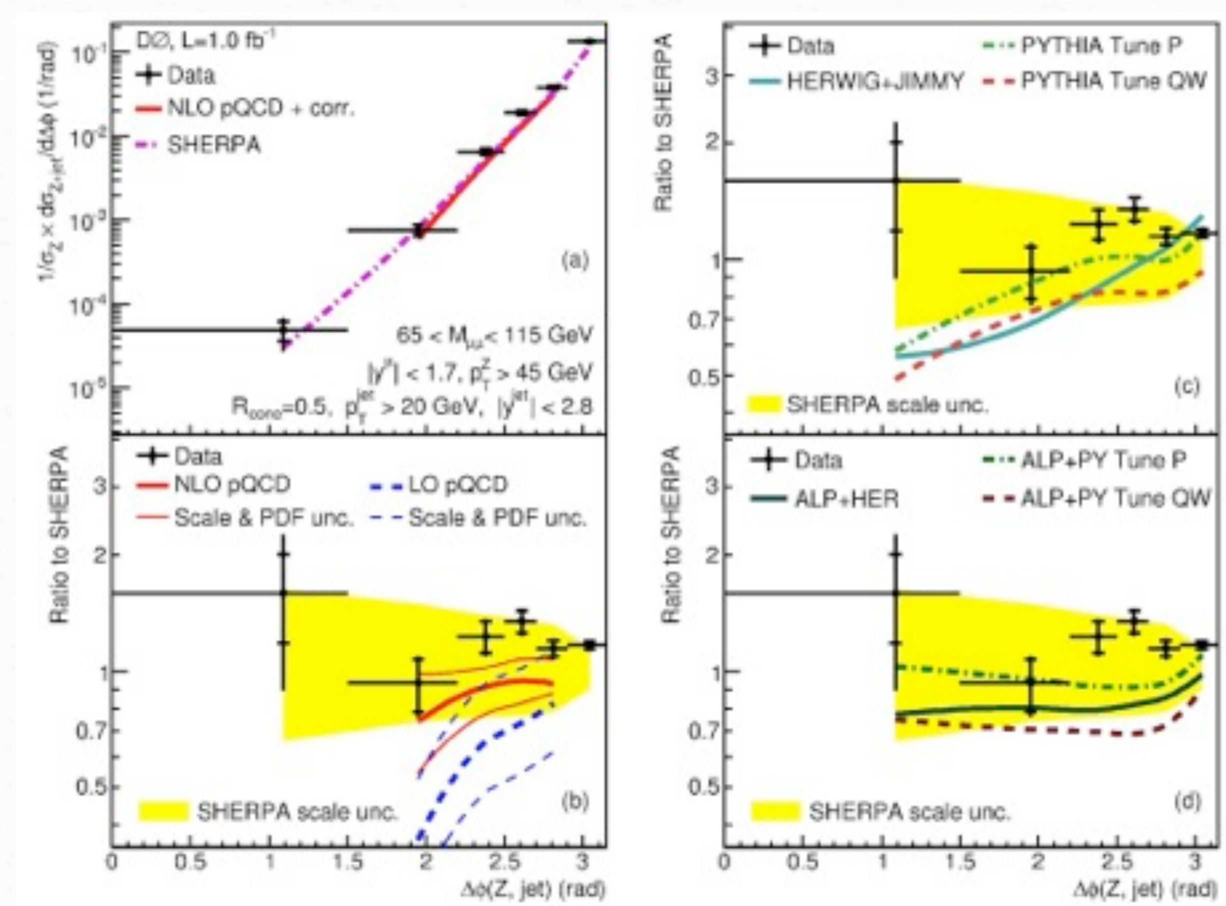
Δφ (Z,jet)

Δy (Z,jet)

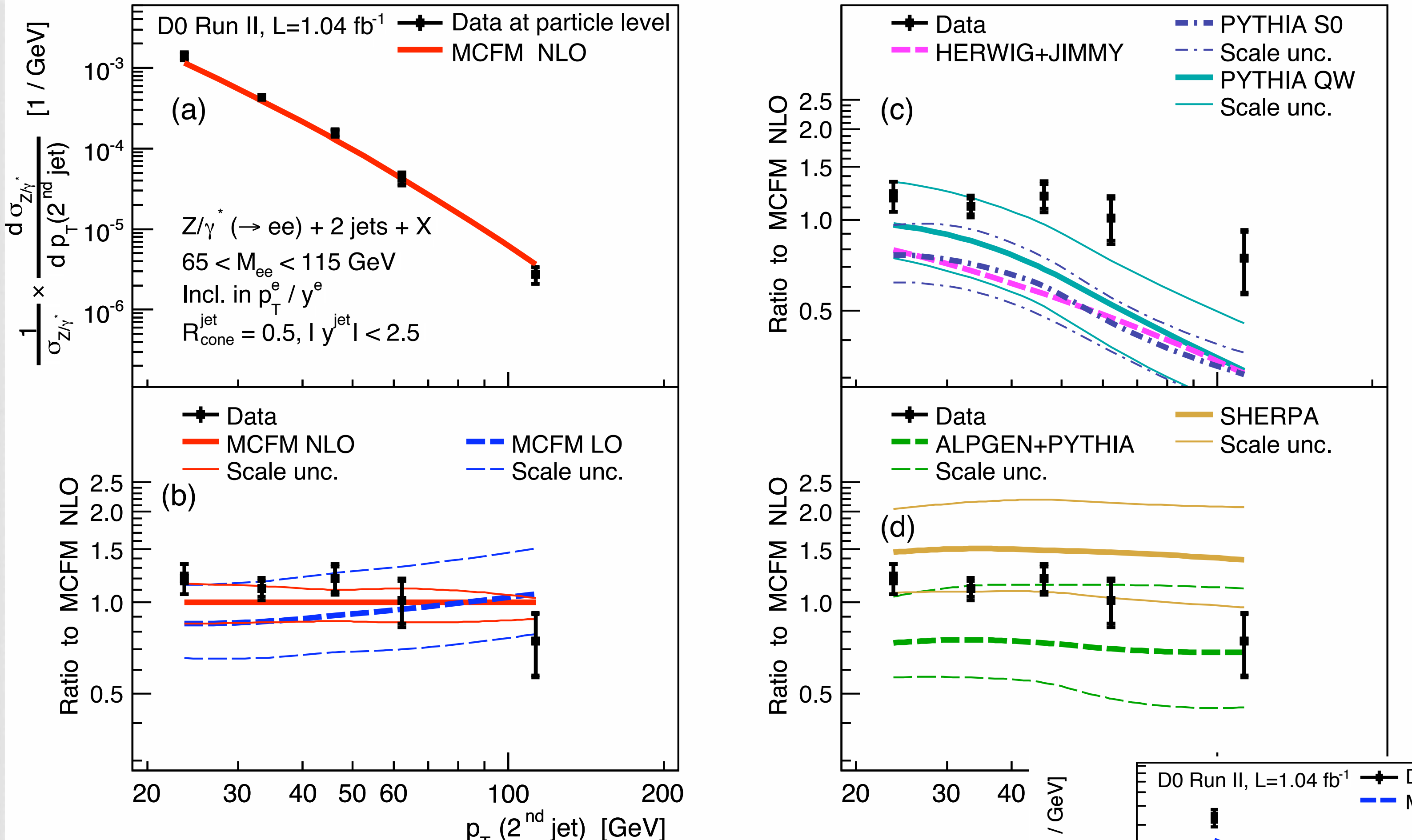
$y_{boost}(Z,jet) = ½(y_Z+y_{jet})$

Phase space:
65 GeV< $M_{\mu\mu}$ < 115 GeV,
R_{cone}=0.5, p_T^{jet} > 20 GeV
$|y^{jet}|$ < 2.8, $|y^{\mu}|$ < 1.7
p_T^Z > 45 GeV (avoid UE)





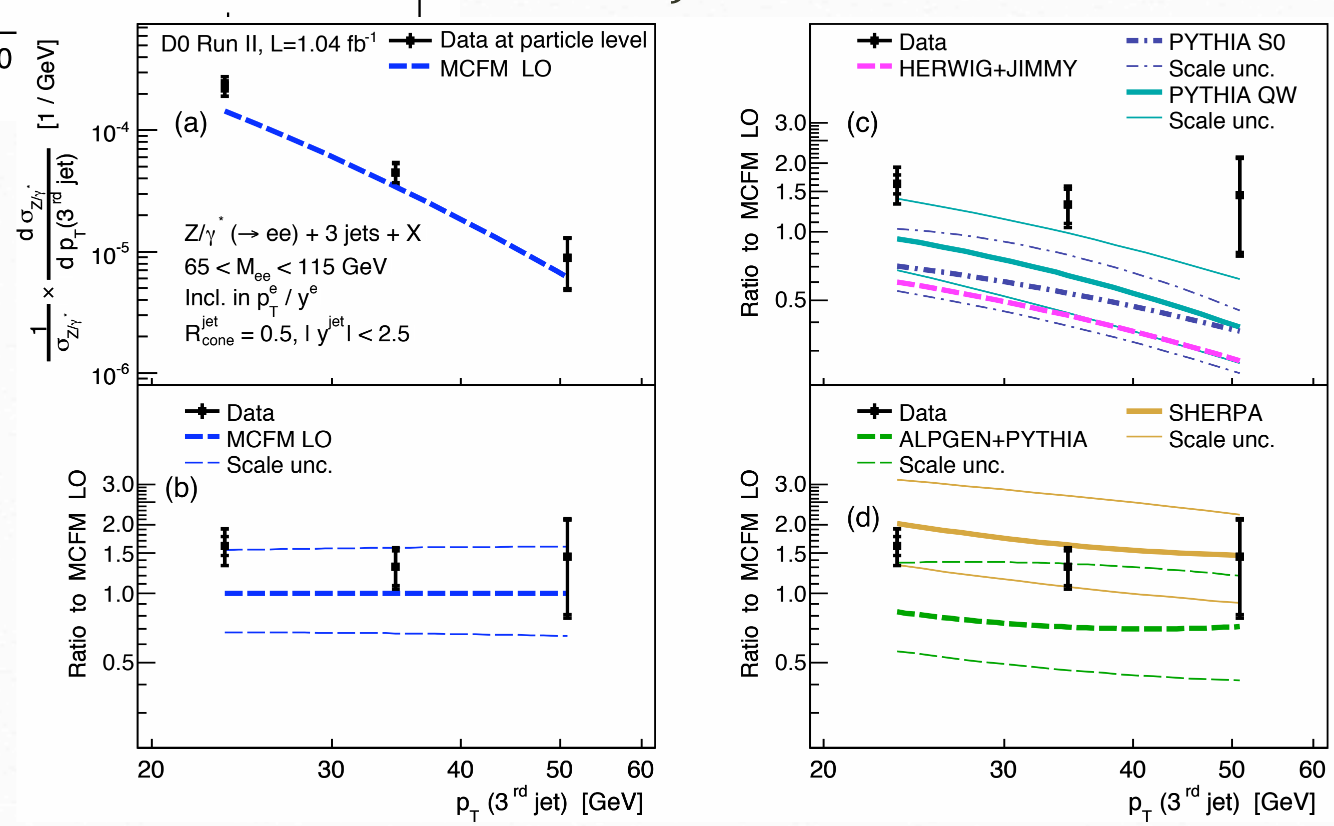
Z+jets   Z->ee + jet + X



2jet exclusive

NLO Z+3 jet predictions recently calculated

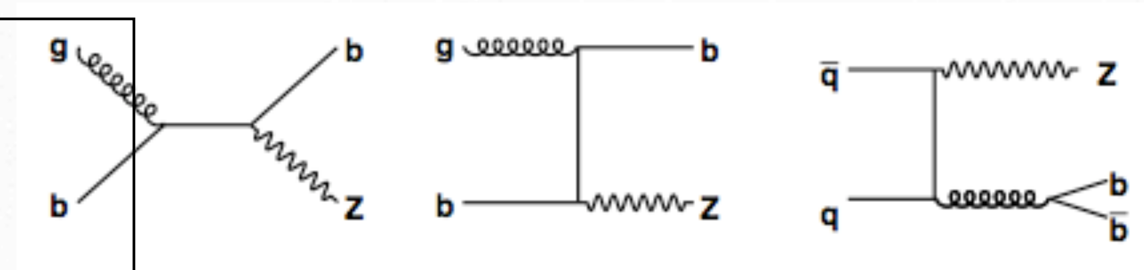
3jet exclusive



MCFM can describe all $p_{T,jet}$ measurements

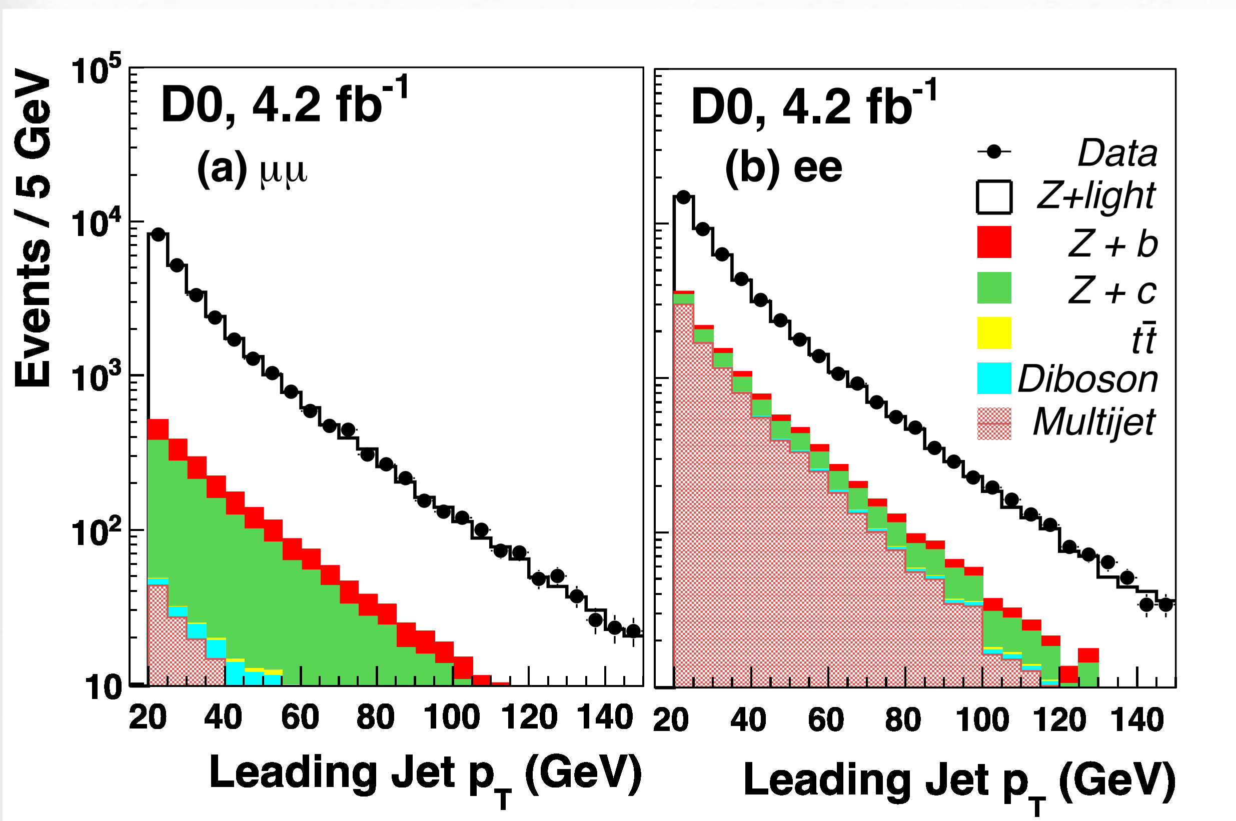
Z+b jets

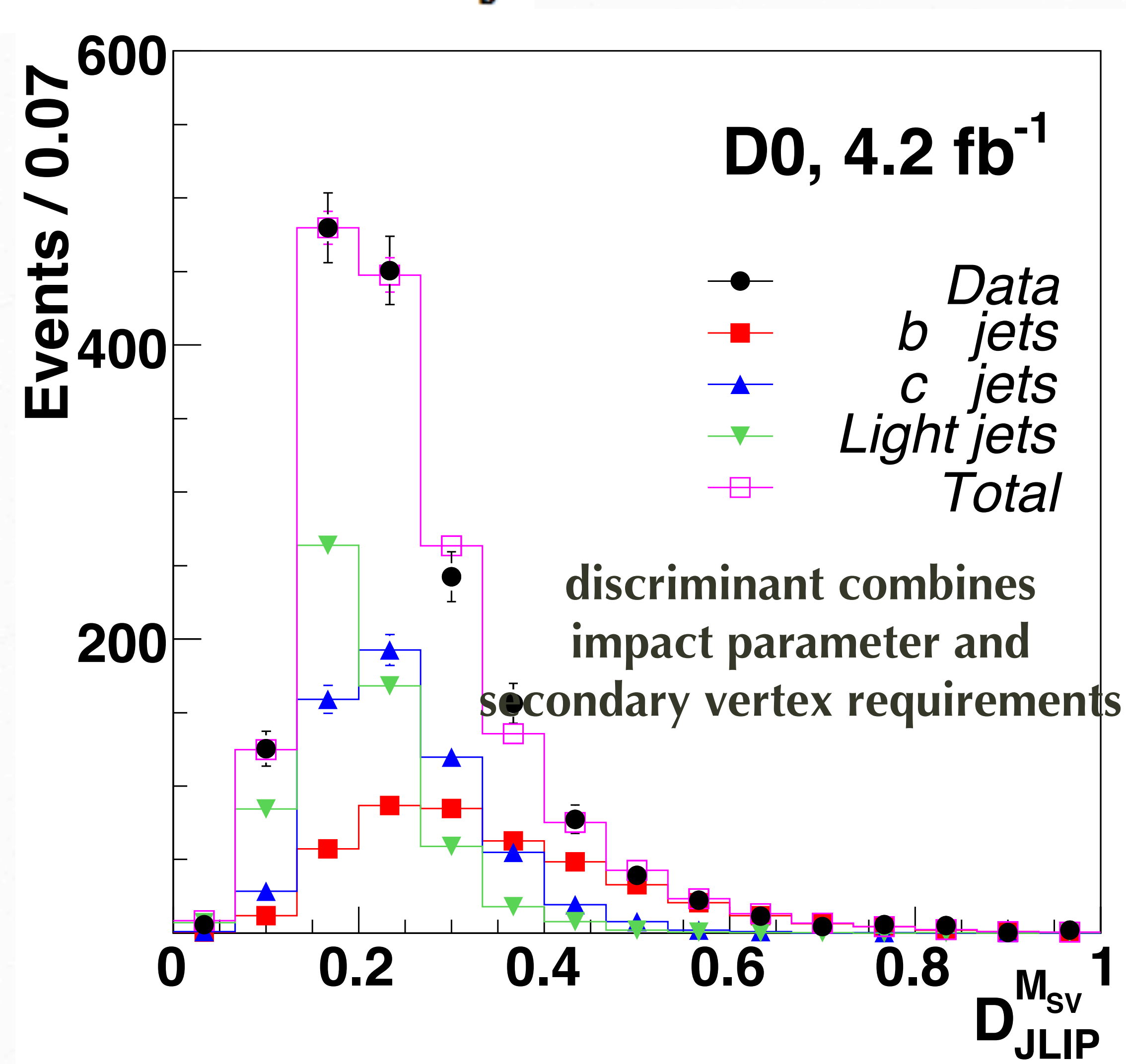
$Z \rightarrow ee/\mu\mu + b + X$
lepton $p_T > 15$ GeV
jet $p_T > 20$ GeV
jet $|\eta| < 2.5$
secondary vertex tagging



R=0.5 cone jets

$\mathcal{L} = 4.2/\text{fb}$





$$\frac{\sigma(Z+b\,\text{jet})}{\sigma(Z+\text{jet})} = 0.0193 \pm 0.0022(\text{stat}) \pm 0.0015(\text{syst})$$

MCFM Prediction: 0.0192 ± 0.0022

Excellent agreement between data and NLO

Z+b jets

$Z \rightarrow ee/\mu\mu + b + X$
jet $E_T > 20$ GeV
jet $|\eta| < 1.5$
secondary vertex tagging

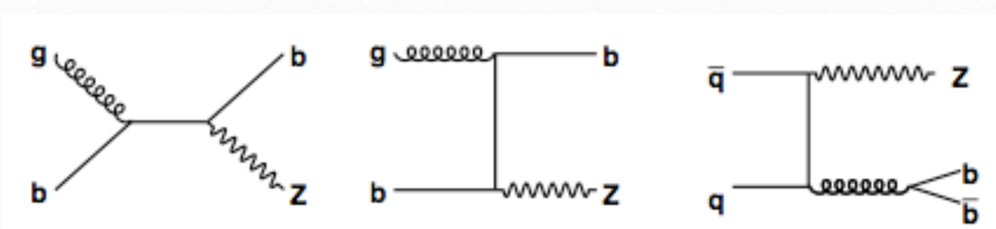
Measure:

$$\frac{\sigma(Z+b\ \text{jets})}{\sigma(Z)}$$

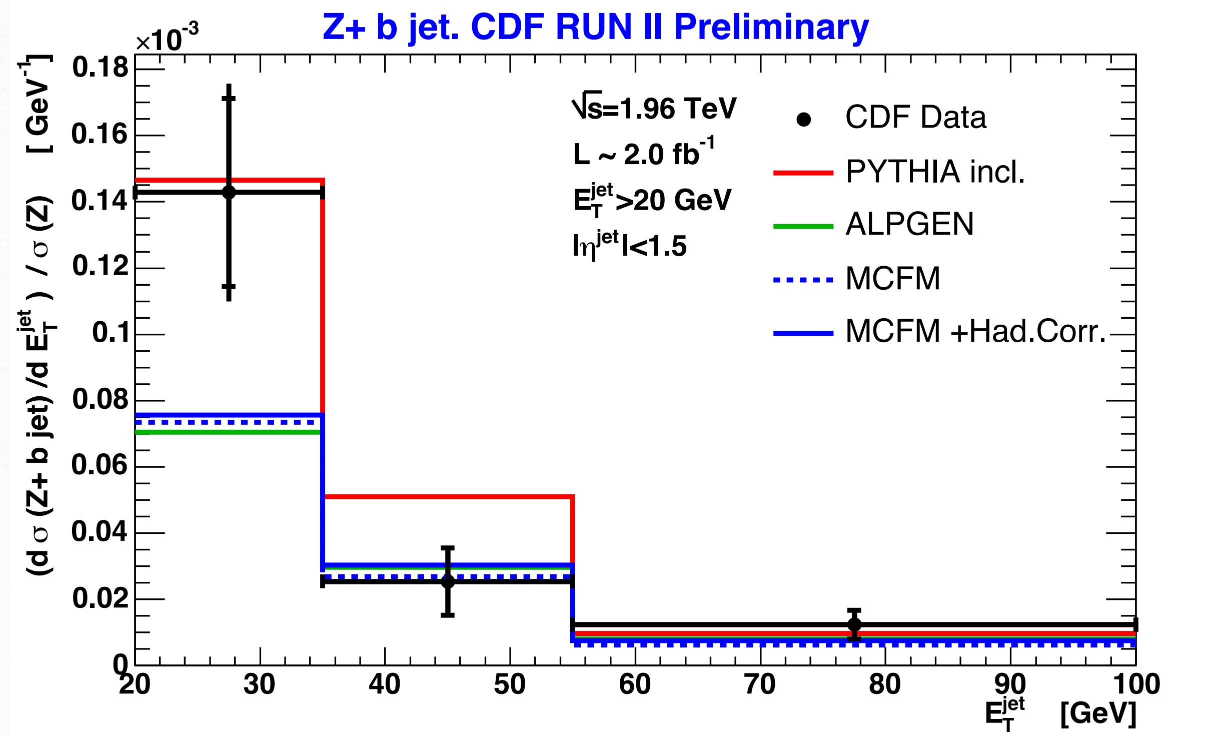
R=0.7 cone jets
data corrected to hadron level
statistics limited

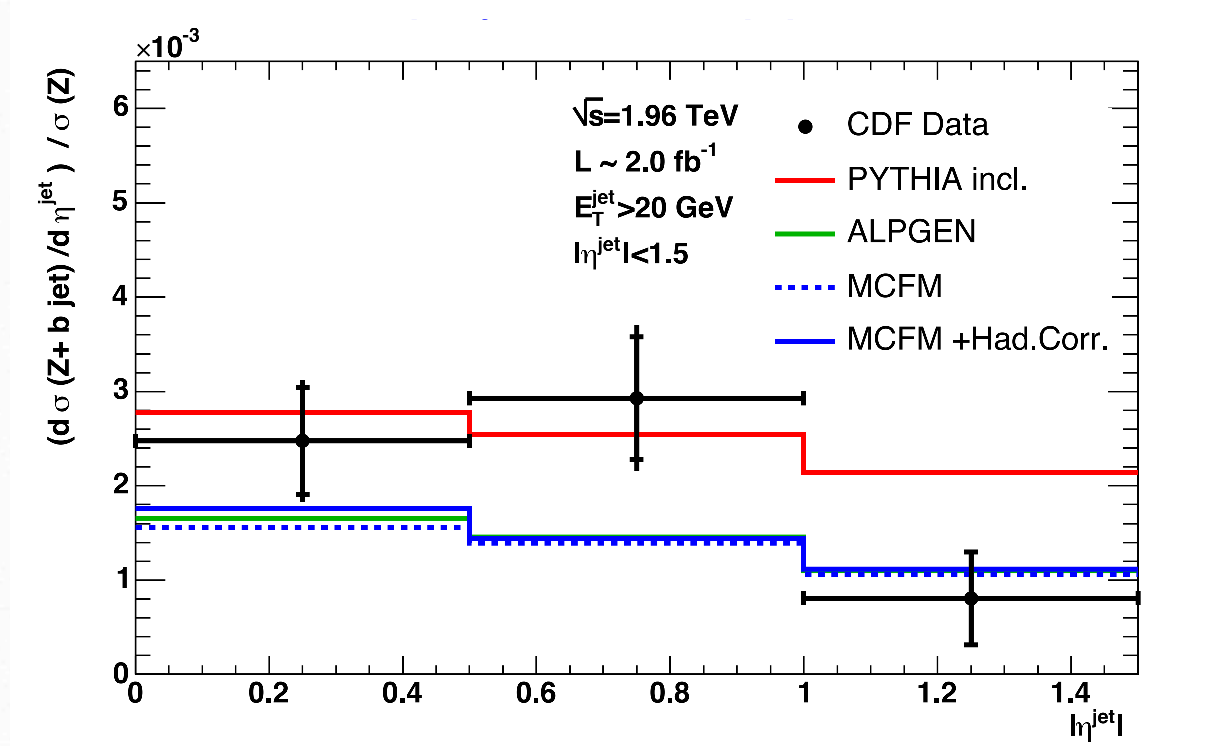
Pythia can describe overall shape, normalization

PYTHIA v6.2
- Tune A, CTEQ5L
ALPGEN v2.13



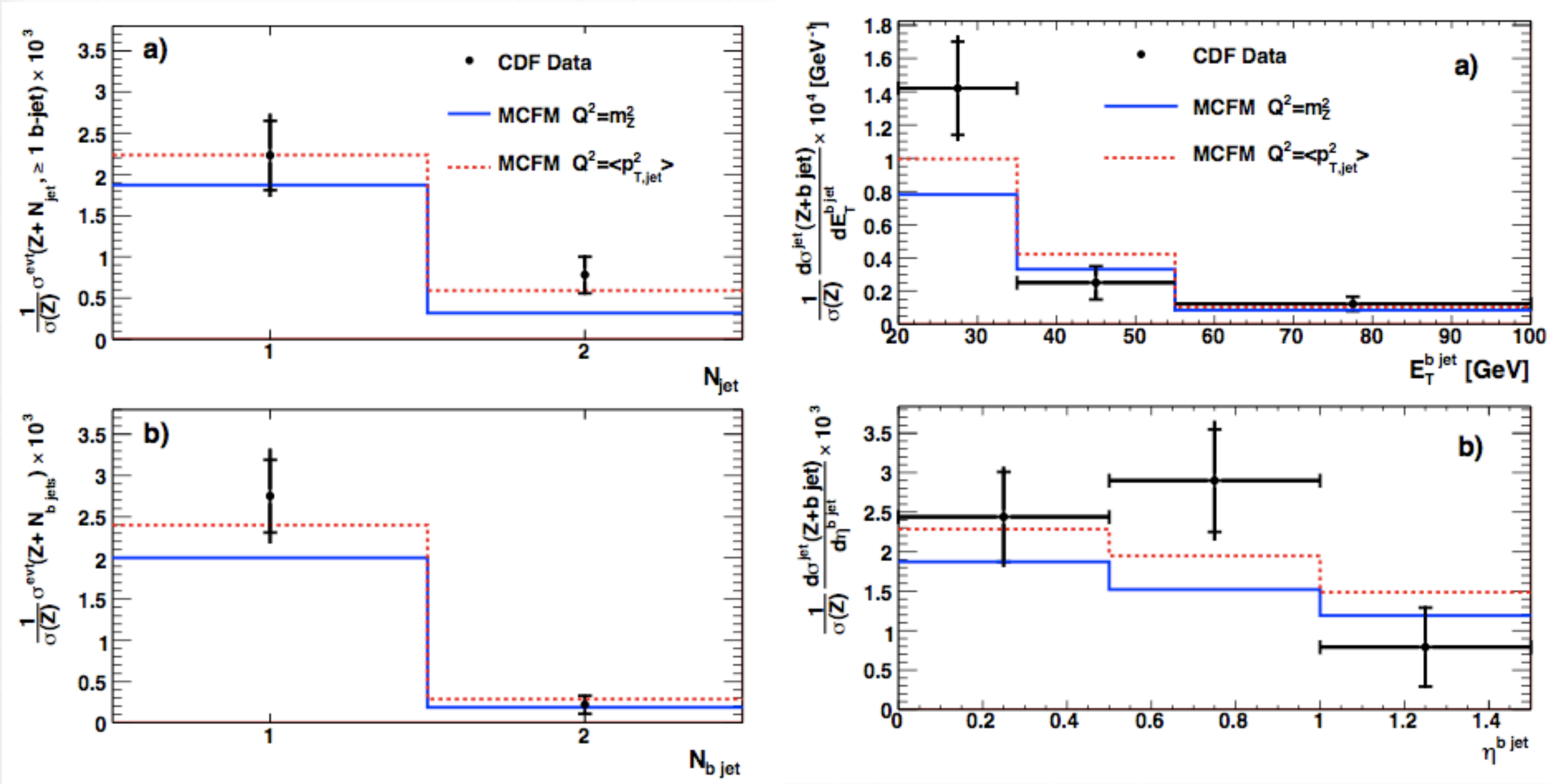
$\mathscr{L} = 2/\text{fb}$





Z+b jets

MCFM Scale variations



Lowering scale choice helps to describe data

Higher order corrections may be important

Z+b/Z+jet ratio consistent with D0