Vector Bosons + light and heavy flavor jets at the Tevatron

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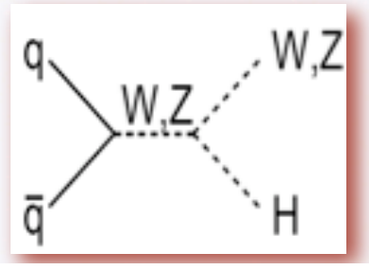
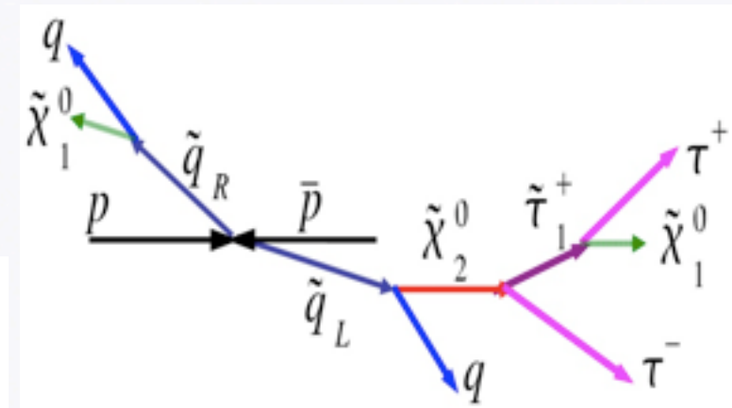
Motivation

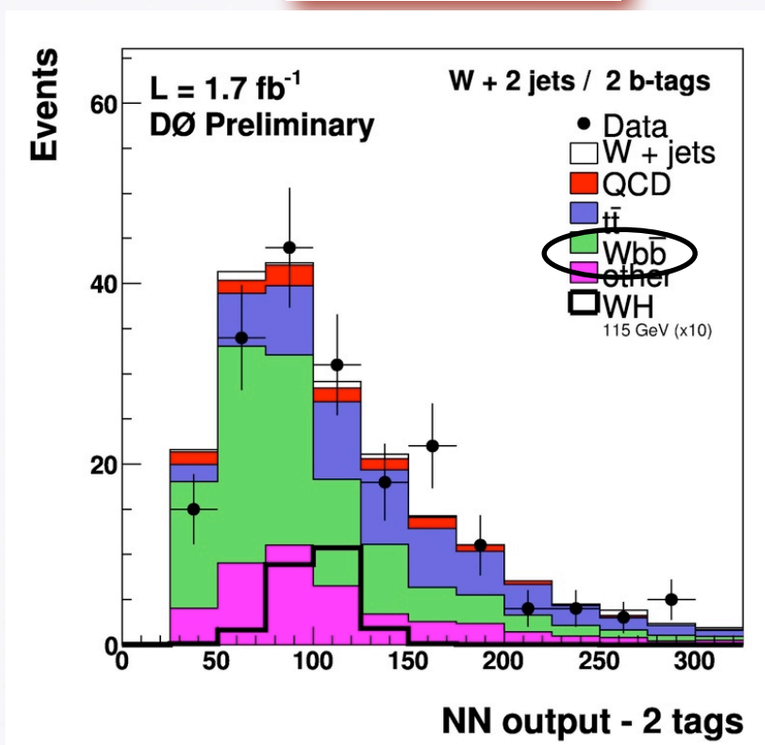
- Vector Bosons + jets are good signatures to test pQCD
  - Heavy flavor production is sensitive to b, c quark PDFs
- Vector Bosons + jets events constitute backgrounds for SM Higgs and New Physics (NP) searches
- N(N)LO predictions not available for many processes of interest, particularly those with large jet multiplicities and heavy flavor components => data measurements crucial.
- MC models are used extensively to simulate signal and backgrounds, particularly for multijet topologies.
- Tevatron dataset is now large enough and systematics are constrained well enough to vet MC models.

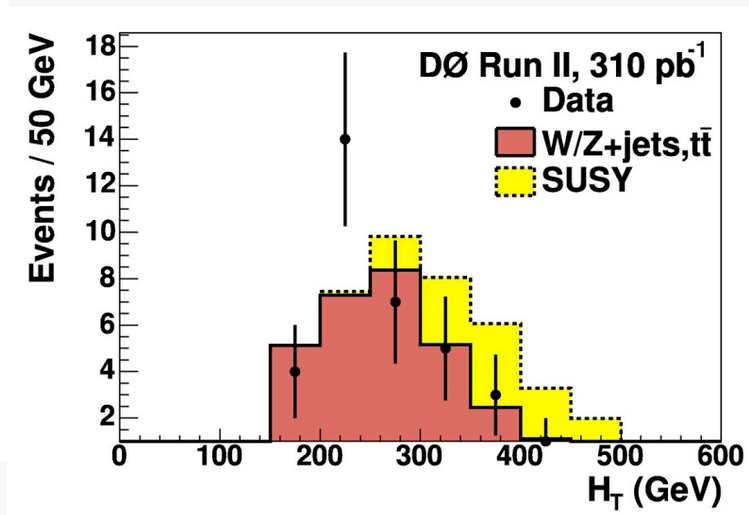
Backgrounds to NP

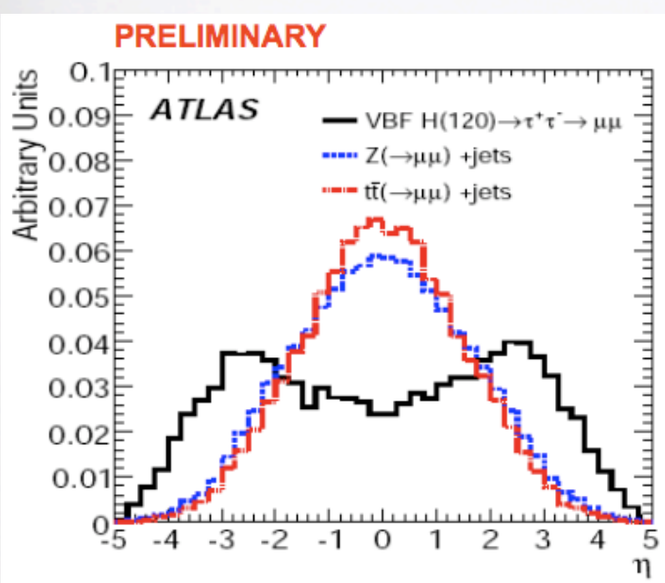
- New Physics share signatures with irreducible VB + jets backgrounds that are currently being pinned down.
- Interplay between fragmentation models, tunes, PDFs and scale choices needs to be understood to model SM backgrounds

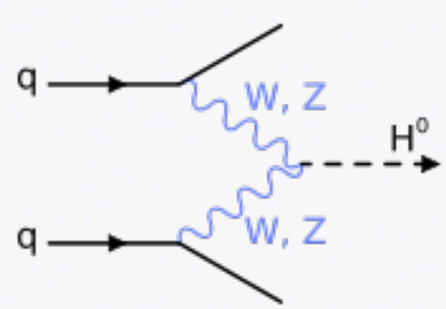


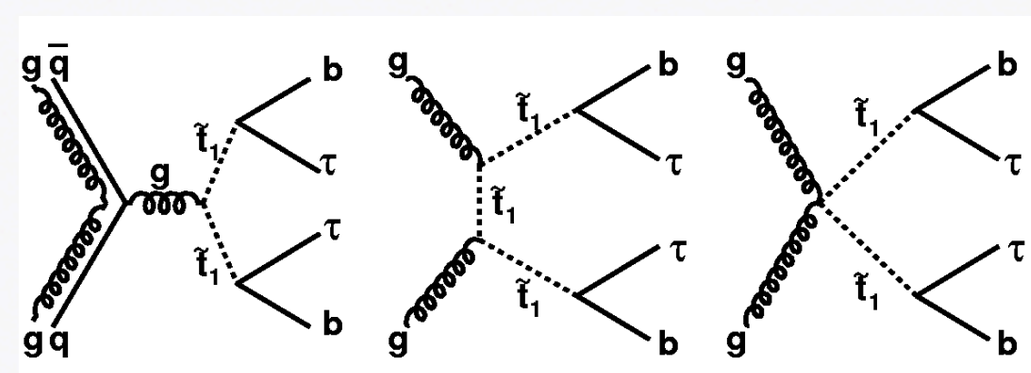






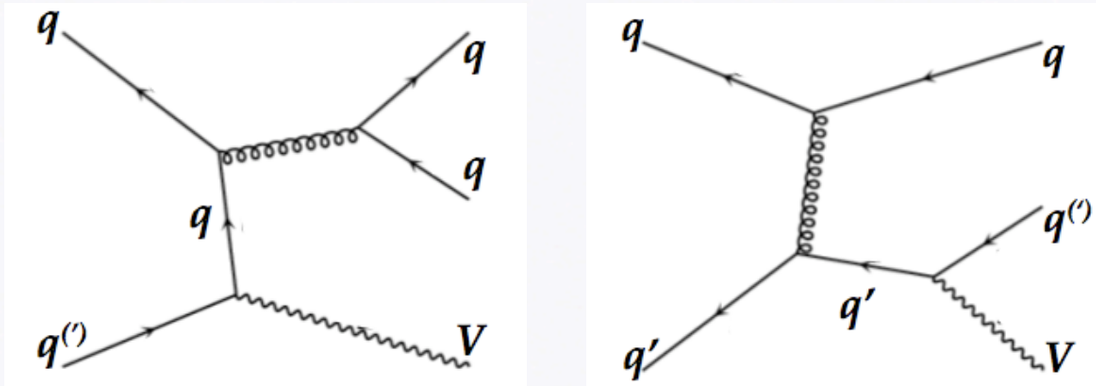






Many Tevatron Measurements

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



V = W,Z,γ

RunII measurements with associated luminosity

Result(1/fb)	DØ	CDF
W+jets	--	0.32
Z+jets	1.0	2.5/1.7
W+b-jets	0.38	1.9
Z+b-jets	0.18	2.0
W+c-jets	1.0	1.8
γ+jets	1.0	--
γ+b/c jets	1.0	0.34

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

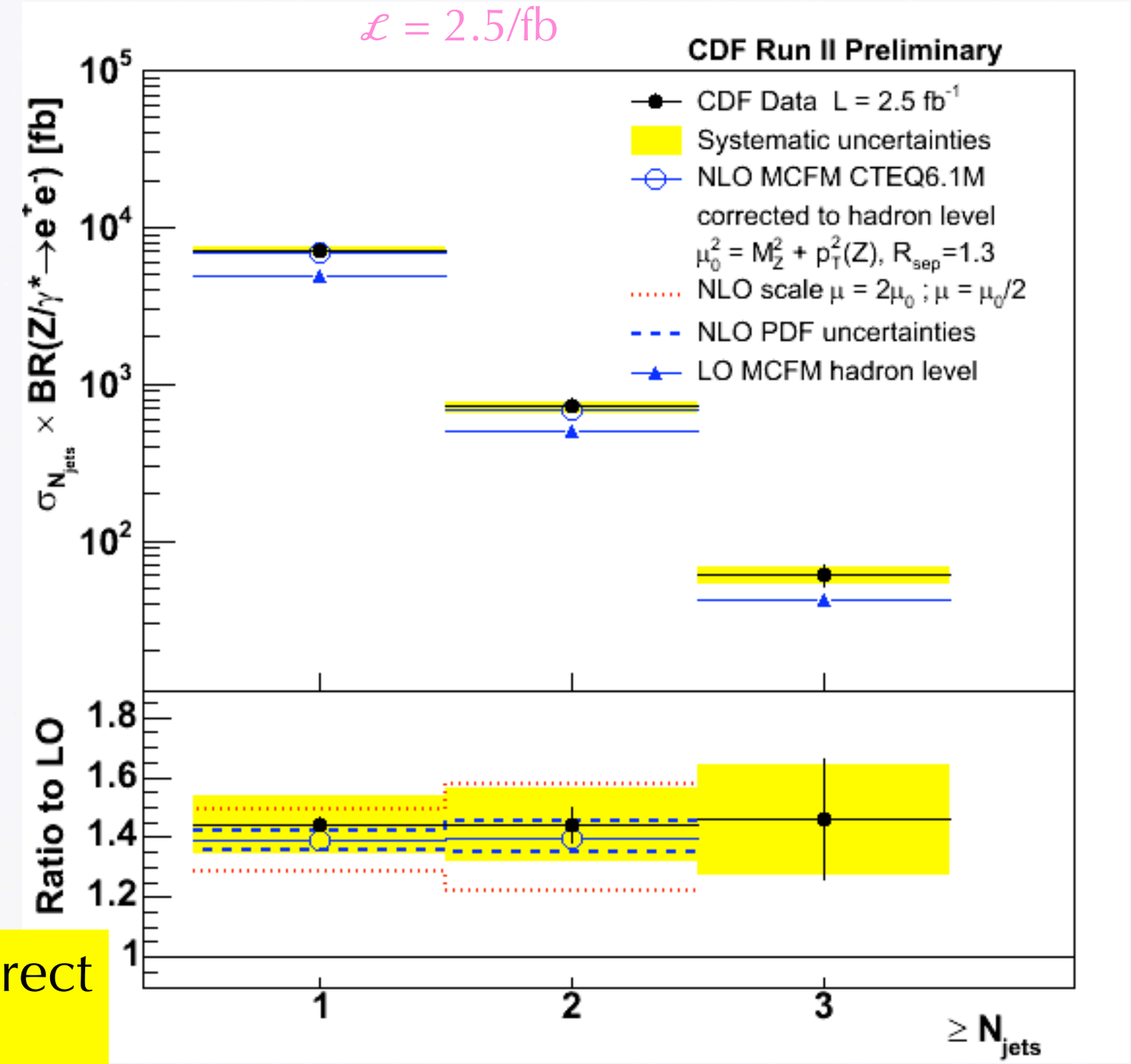
- pQCD predictions calculated with MCFM, JetPhoX,...
- Many LO MC programs on the market:
  - MEPS: Alpgen, Sherpa, Madgraph, Helac, Madevent, ...
  - PS: Pythia, Herwig, Ariadne, ...
- CKKW
  - the separation of ME and PS for different multijet processes is achieved through a k_T-measure
  - undesirable 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

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

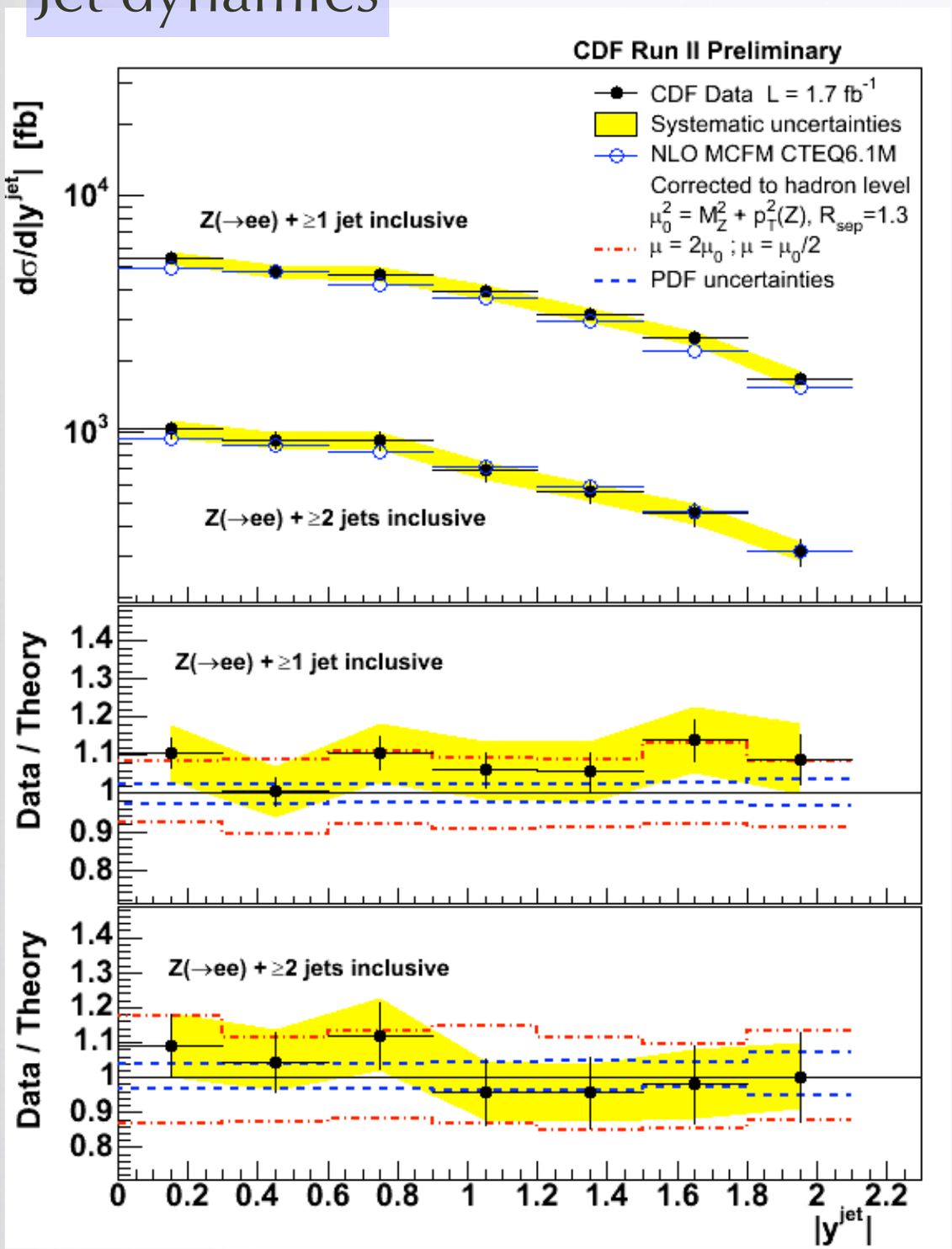
- $E_T^e > 25$ GeV
- at least 1 central electron
- $66 < M_{ee} < 116$ GeV/c^2
- $p_T^{jet} > 30$ GeV
- $|y^{jet}| < 2.1$
- R = 0.7 Midpoint cone jets
- $\Delta R_{(e,jet)} < 0.7$

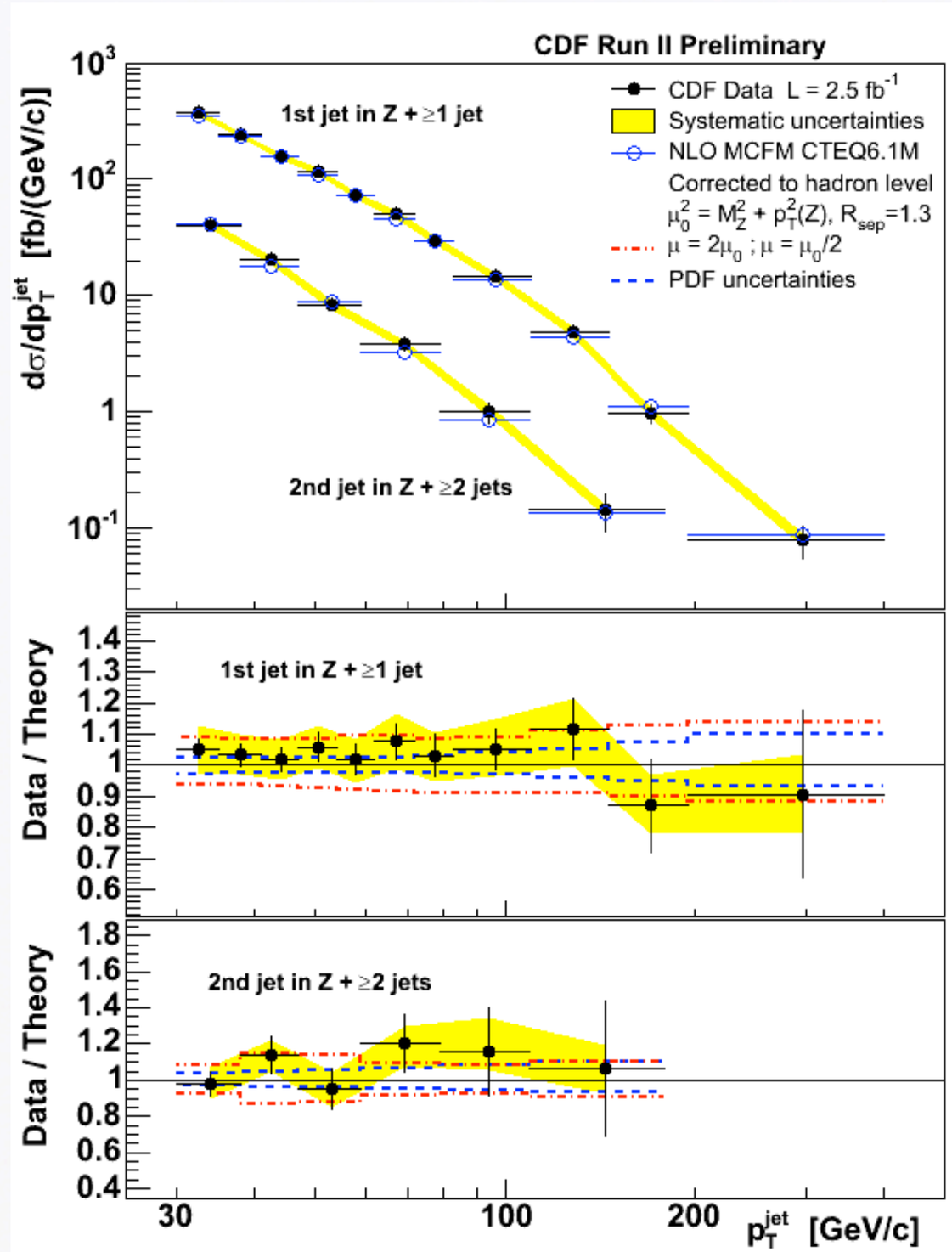


NLO MCFM predicts correct normalization, with LO→NLO K-factor ~1.4

Z+jets

Jet dynamics





Z+jets

Z->μμ + jet + X

$\mathcal{L}$ = 1.0/fb

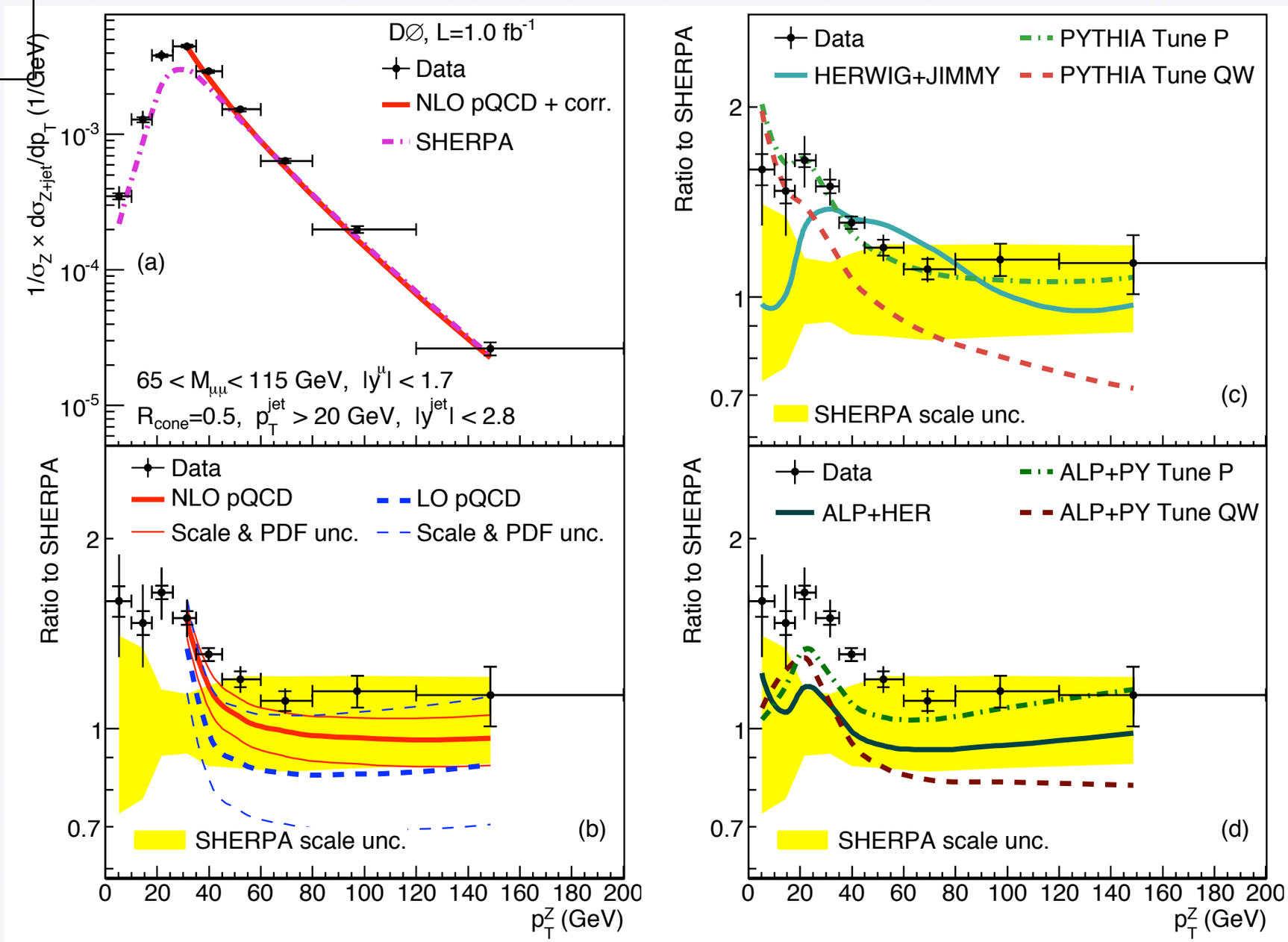
Phase space:
65 GeV< $M_{\mu\mu}$ < 115 GeV,
R_{cone}=0.5, p_T^{jet} > 20 GeV
$|y^{jet}|$ < 2.8, $|y^{\mu}|$ < 1.7

Cross section as a function of p_T^Z

No low p_T NLO
➡ avoid MPI, UE

Data described by NLO theory

Large variations between Pythia tunes



ratios relative to Sherpa v1.1.3

Phys. Lett. B 669, 278 (2008), arXiv.org:0808.1296

Z+jets - angular variables

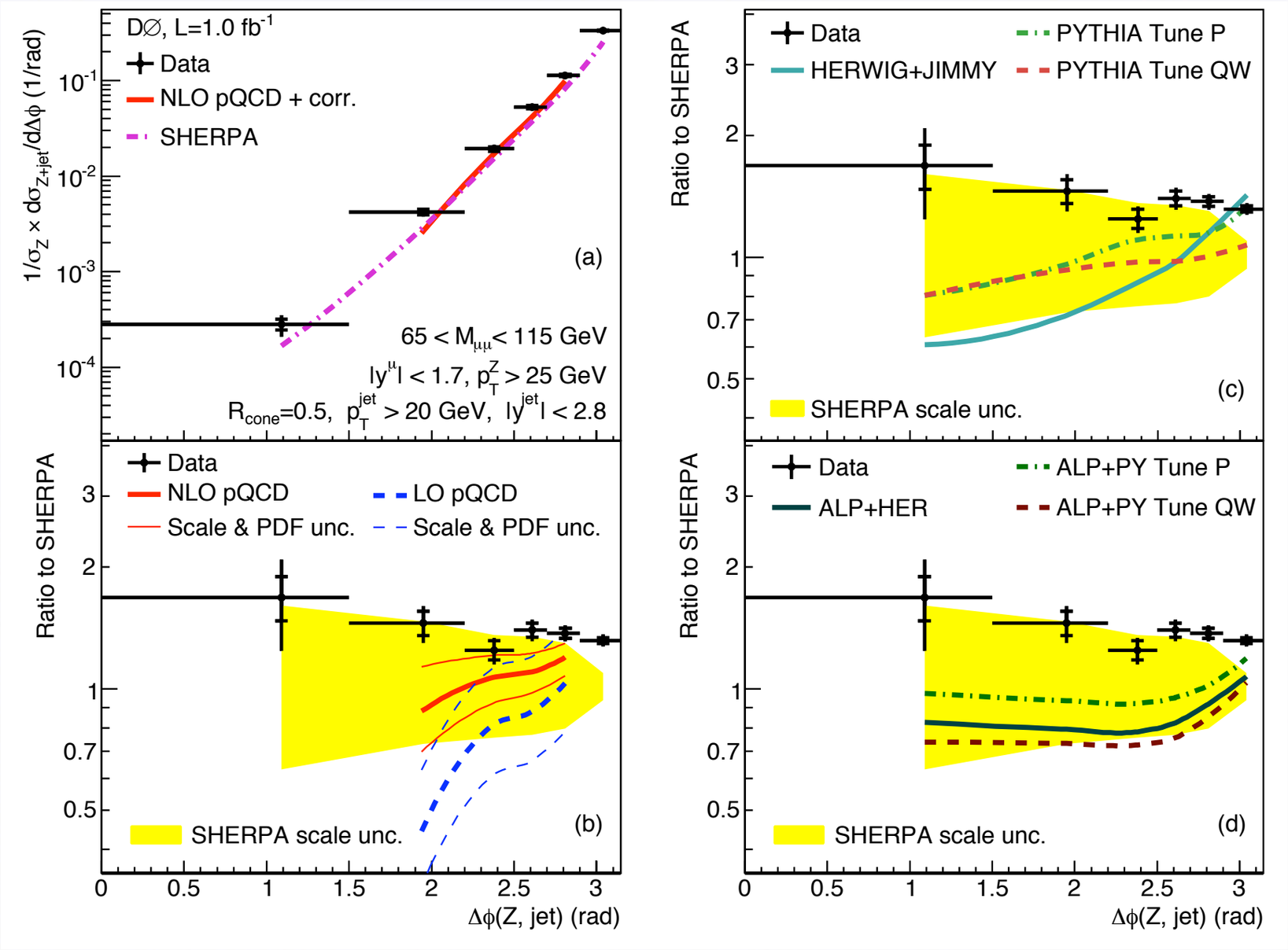
$\Delta\phi$ (Z,jet)
Δy (Z,jet)
$y_{boost}(Z,jet) = \frac{1}{2}(y_Z+y_{jet})$

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 soft effects)

Small values of $\Delta\phi$(Z,jet) excluded from MCFM due to importance of non-perturbative effects

Angular distributions sensitive to additional QCD radiation

Accepted by Phys. Lett. B, arXiv.org:0907.4286



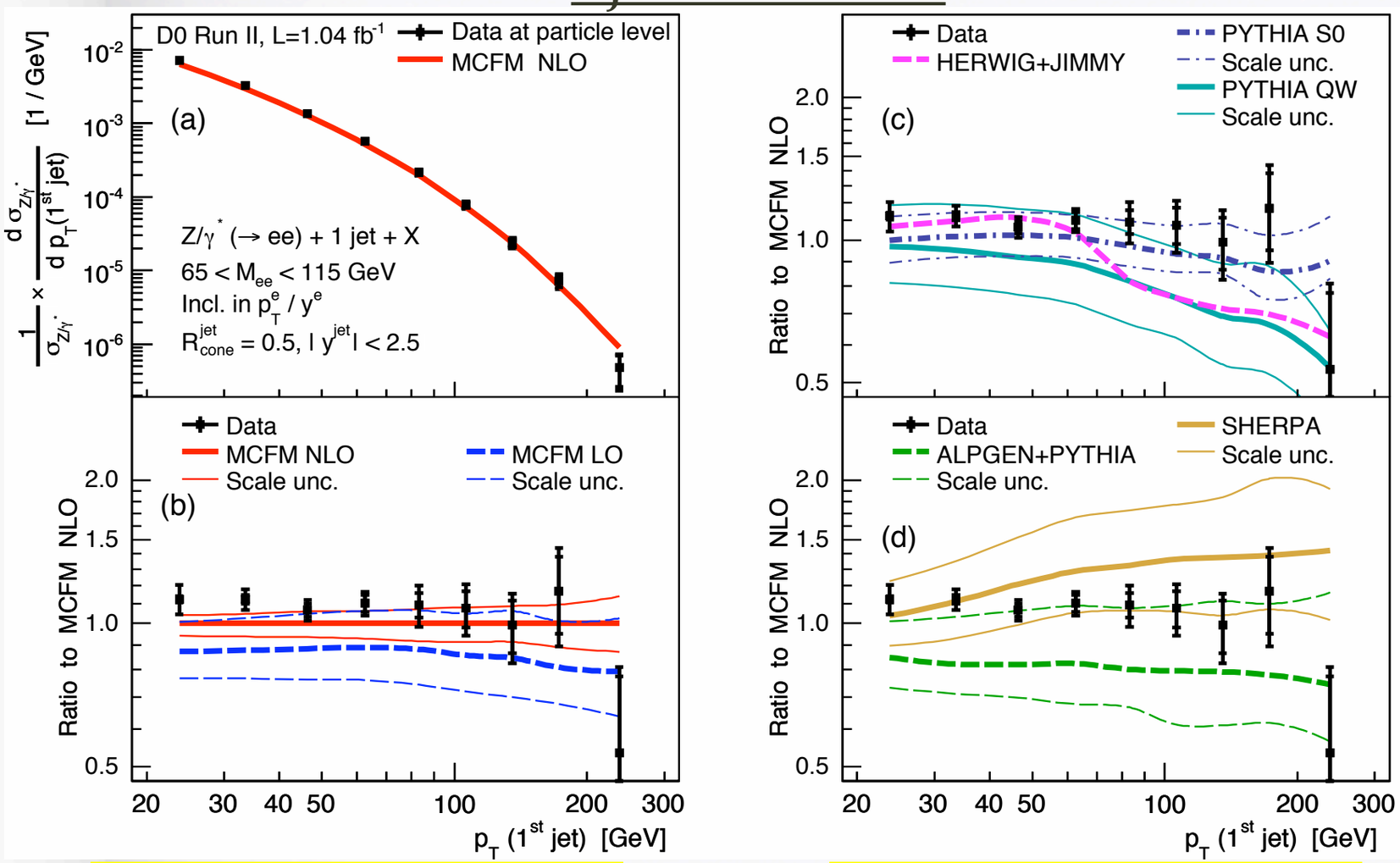
Sherpa describes shape of all distributions

Z+jets - up to 3 jets

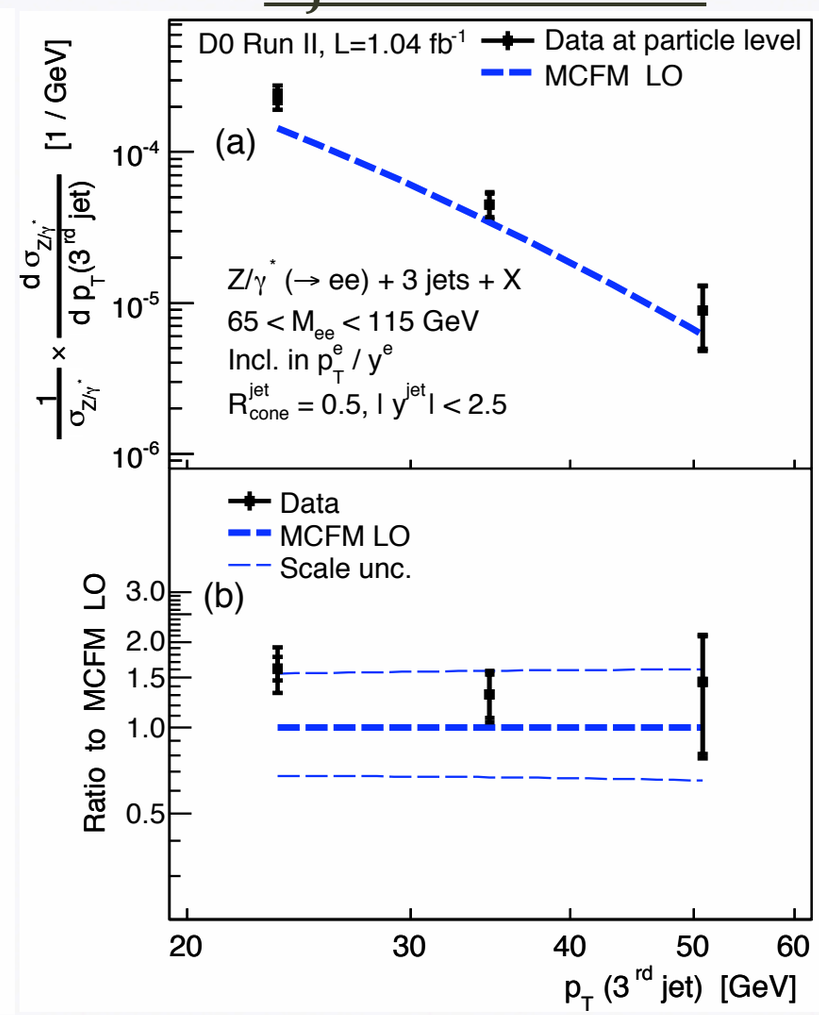
Z->ee + jet + X

Direct measurement of jet kinematics with large multiplicities

1jet exclusive



3jet exclusive



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

Large uncertainties in LO MC models

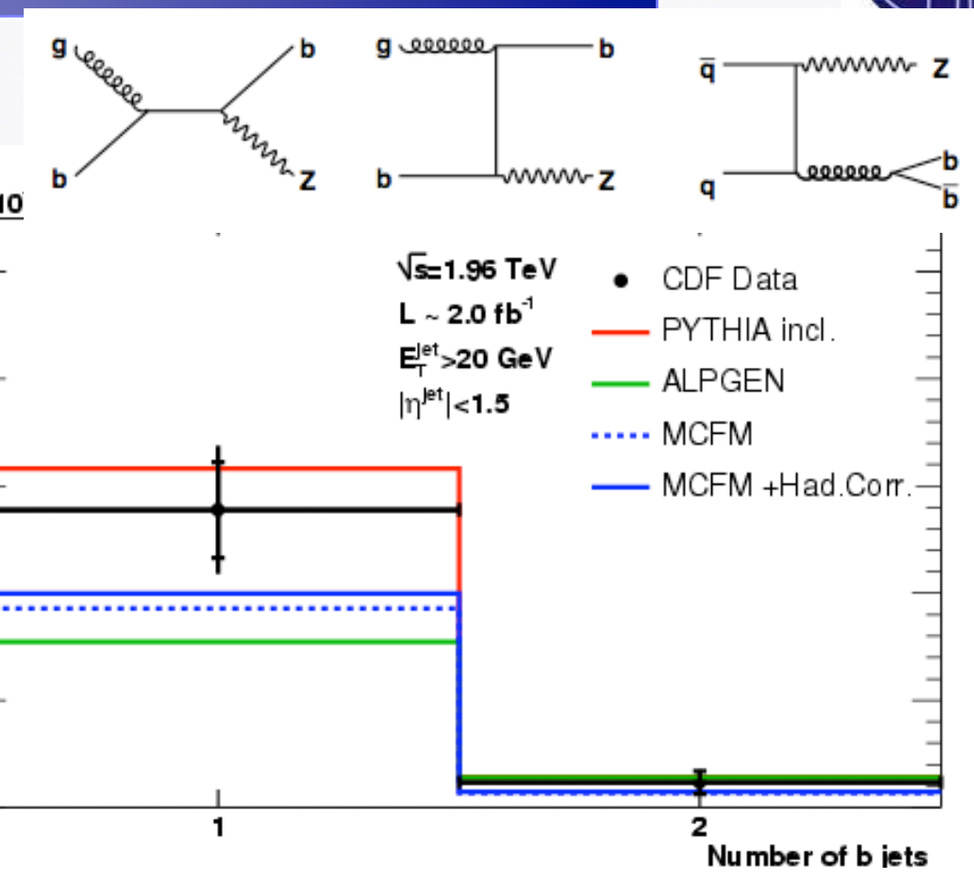
NLO Z+3 jet predictions recently calculated

Phys. Lett. B 678, 45 (2009), arXiv.org:0903.1748

Z+b jets

$Z \rightarrow ee/\mu\mu + b + X$
jet $E_T > 20$ GeV, R=0.7
jet $|\eta| < 1.5$
secondary vertex tagging

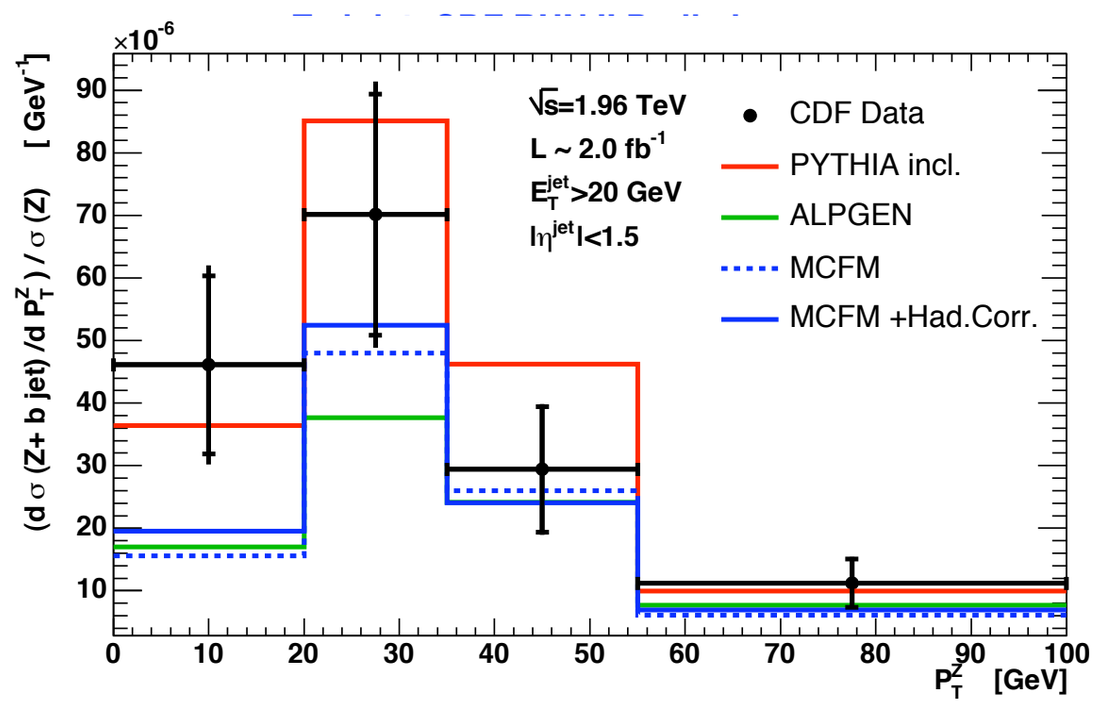
$\mathcal{L} = 2/\text{fb}$



Measure:

$$\frac{\sigma(Z+b\text{ jets})}{\sigma(Z)} = 3.32 \pm 0.53(\text{stat}) \pm 0.42(\text{sys}) \times 10^{-3}$$

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



Pythia can describe overall shape, normalization

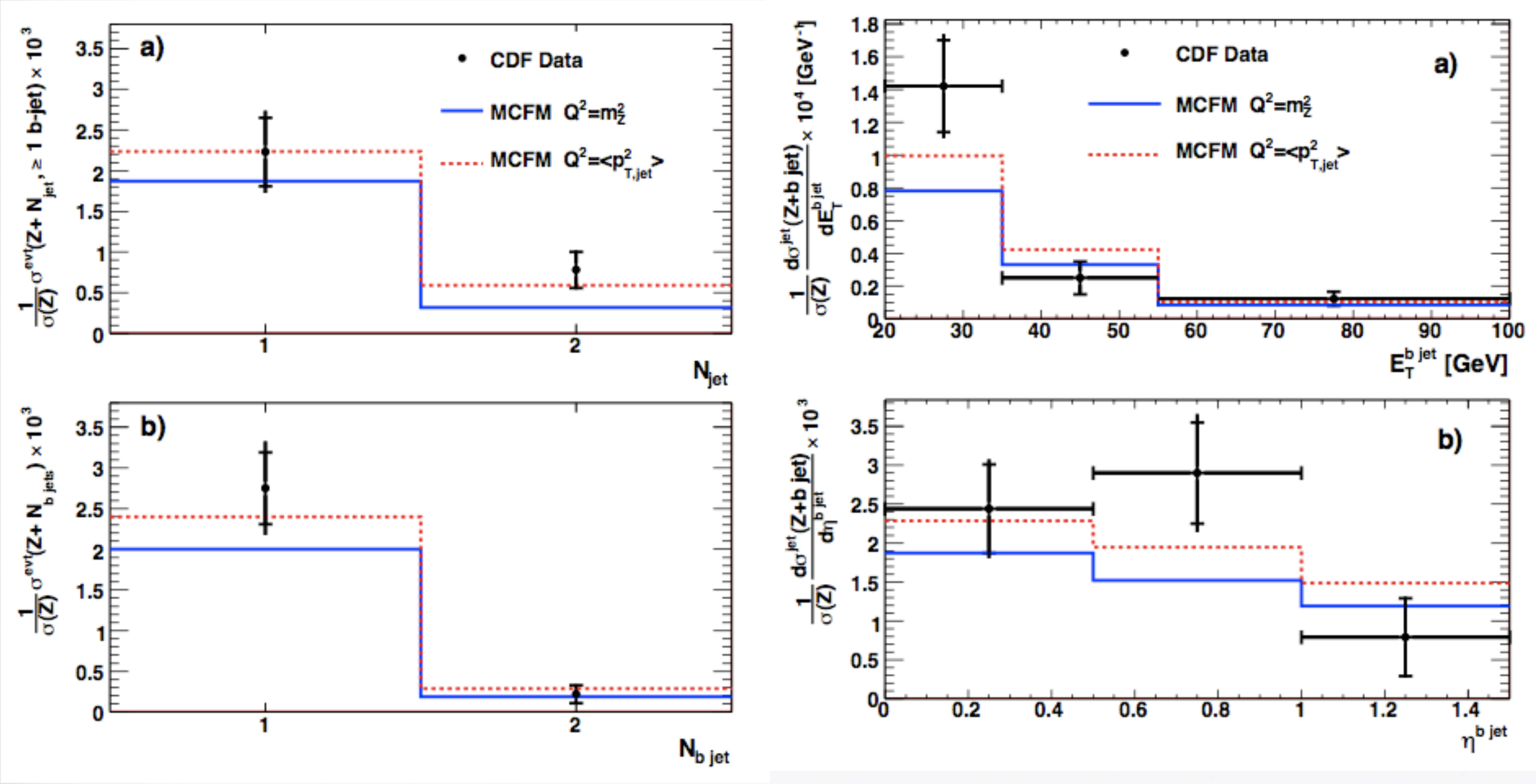
Up to 2σ differences between data & MCFM

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

b-quark fragmentation may need study

Z+b jets

MCFM Scale variations



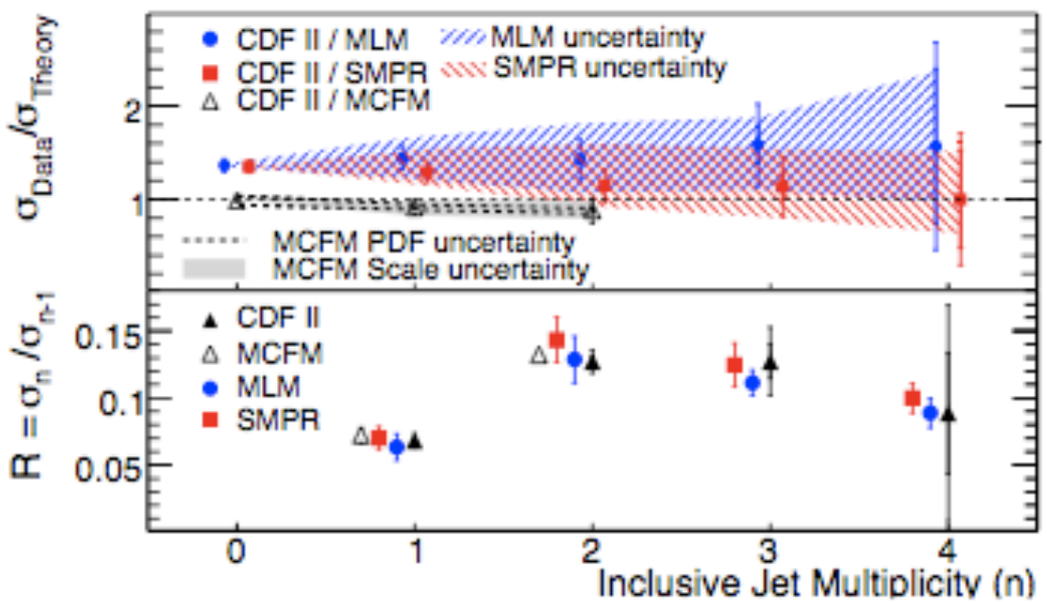
Lowering scale choice helps to describe data

Higher order corrections may be important

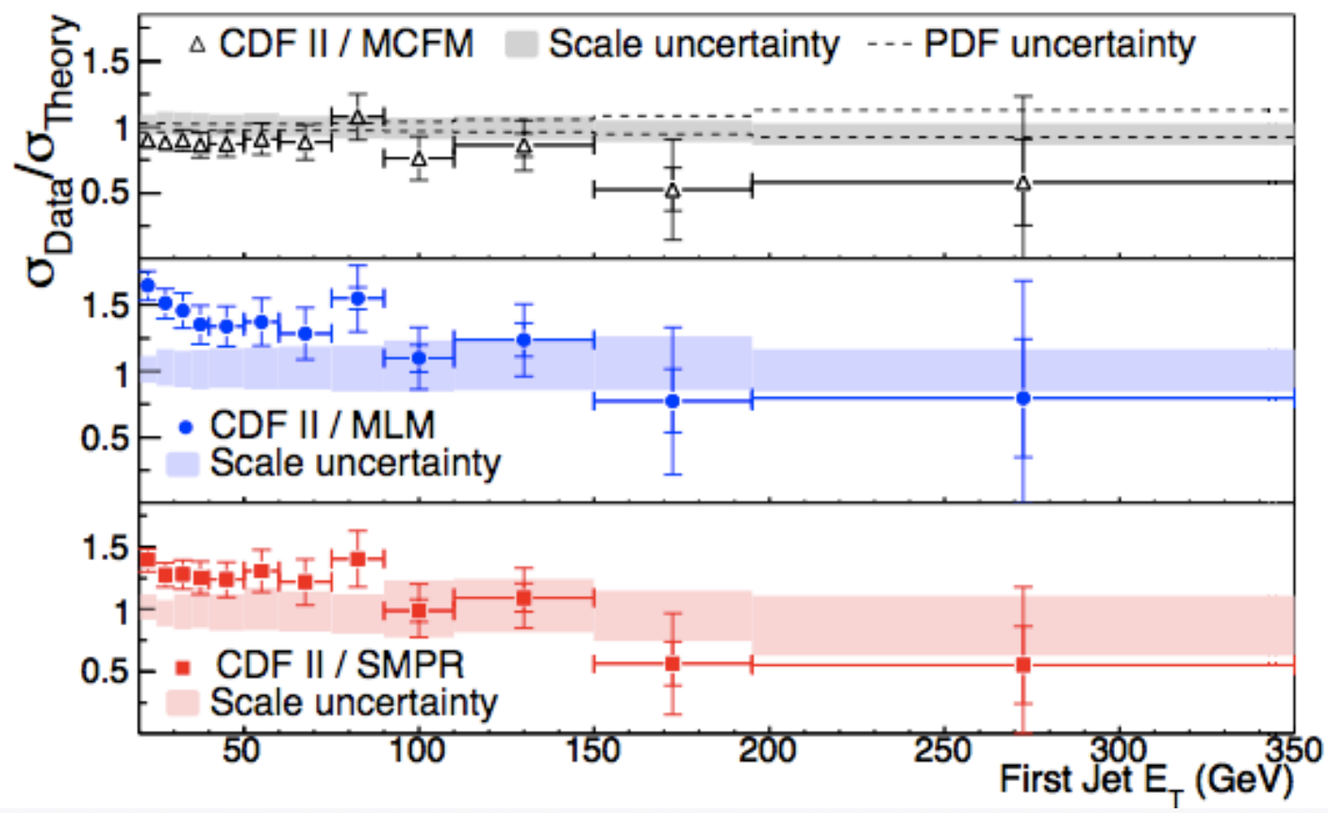
Z+b/Z+jet ratio consistent with D0

W+jets - up to 3 jets

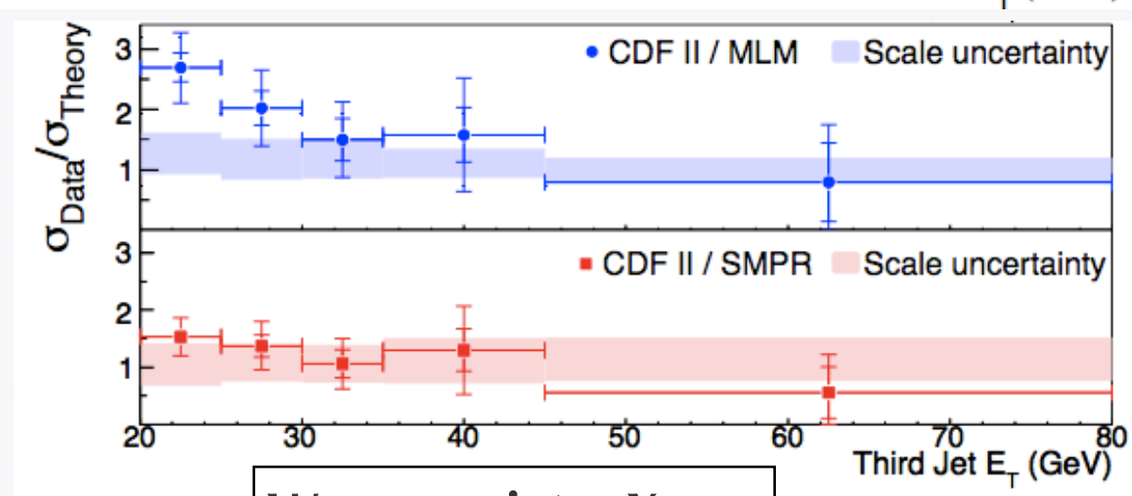
Phys. Rev. D 77, 011108(R) (2008) arXiv.org:0711.4044



$\mathcal{L}$ = .32/fb



- MCFM: NLO, no shower
- MLM: Alpgen+Herwig+MLM matching
- SMPR: Madgraph+Pythia+CKKW matching



NLO does excellent job of modeling jet p_T shape and normalization for <=2 jets

MLM fails, especially at low pT

SMPR does better job at high n-jet

W→ eν + jet + X
electron E_T > 20 GeV
electron $|\eta|$ < 1.1
neutrino E_T > 30 GeV
W M_T > 20 GeV/c^2

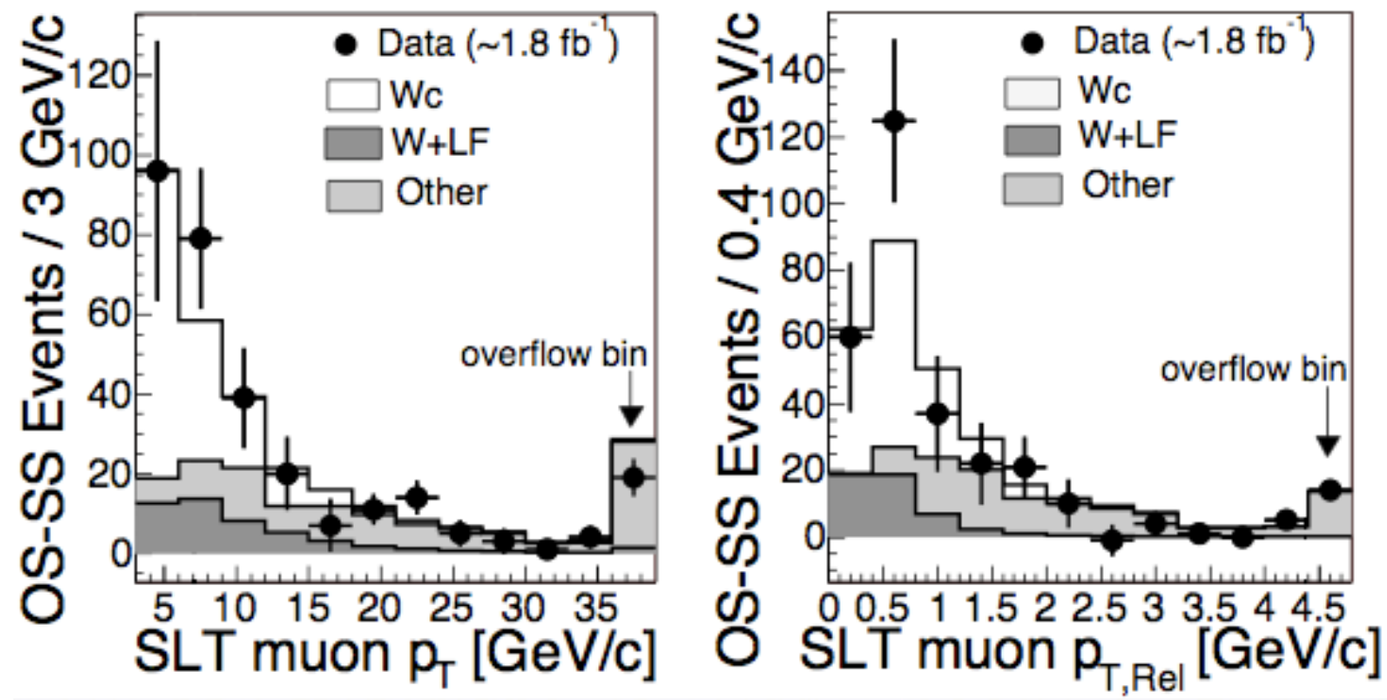
W+c jets

Sensitive to s-quark PDF

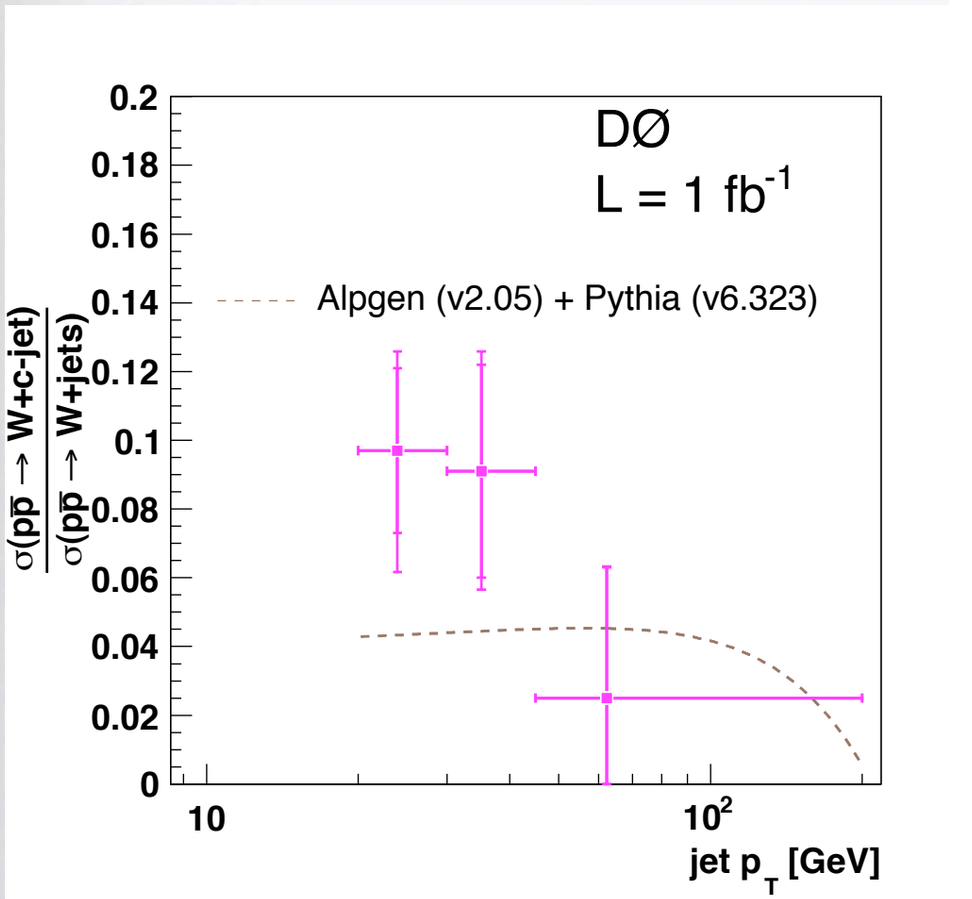
$\mathcal{L}$ = 1.8/fb

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

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



$\mathcal{L}$ = 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

W+b jets

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

$\mathcal{L}$ = 1.9/fb

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, $|\eta| < 2.0$

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

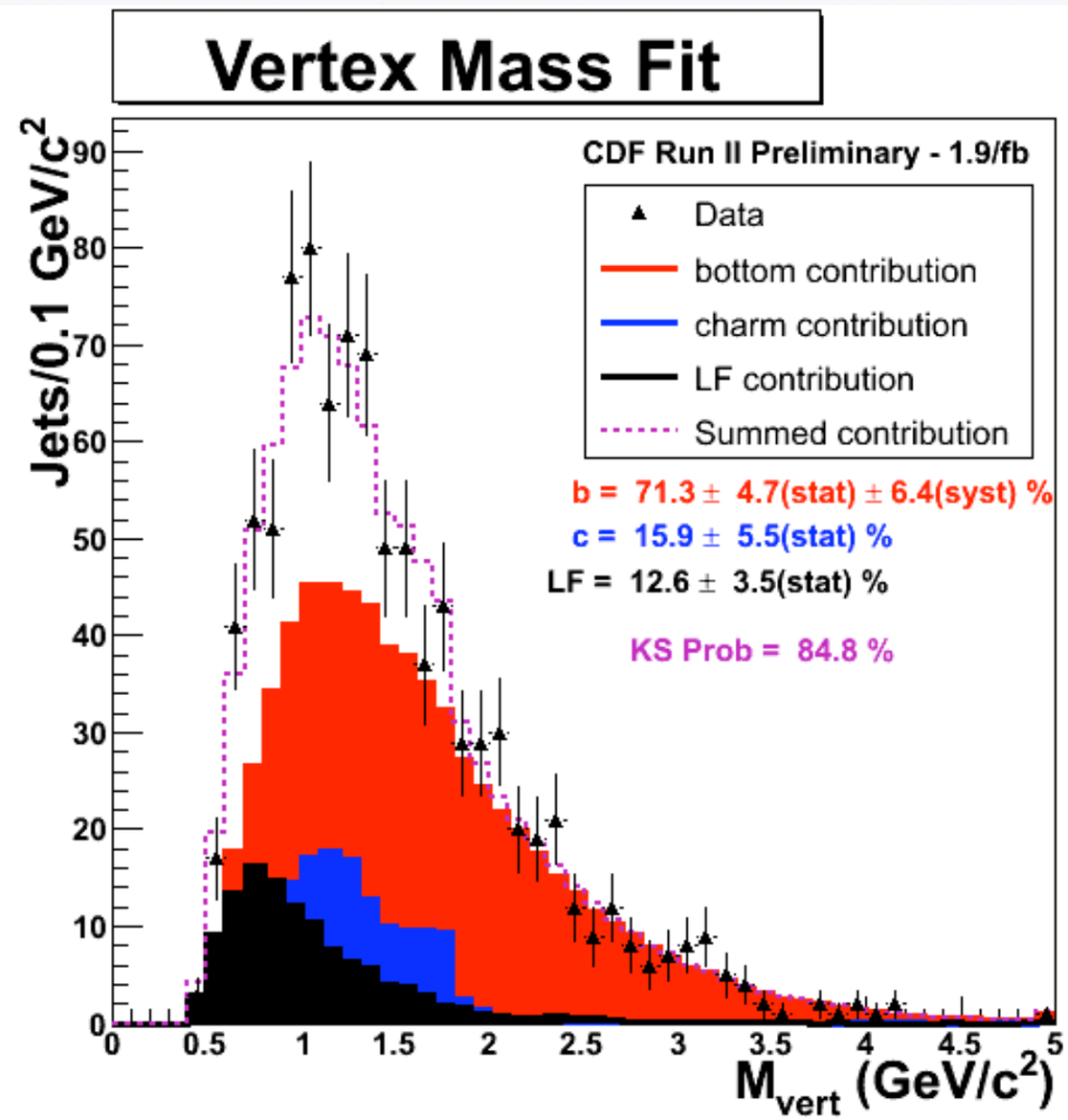
Measure: σ(W+b jets)x BR(W->lnu

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:

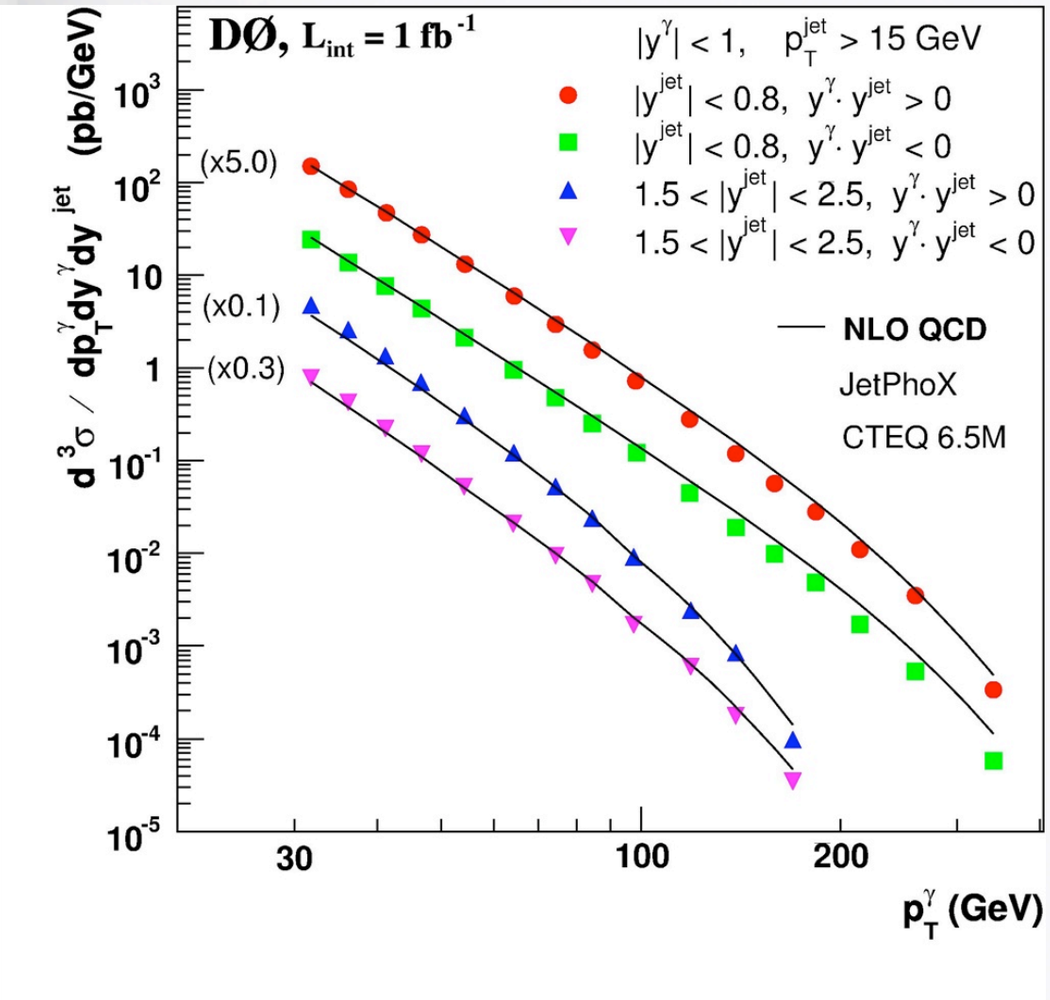
- higher order corrections
- b-quark fragmentation model



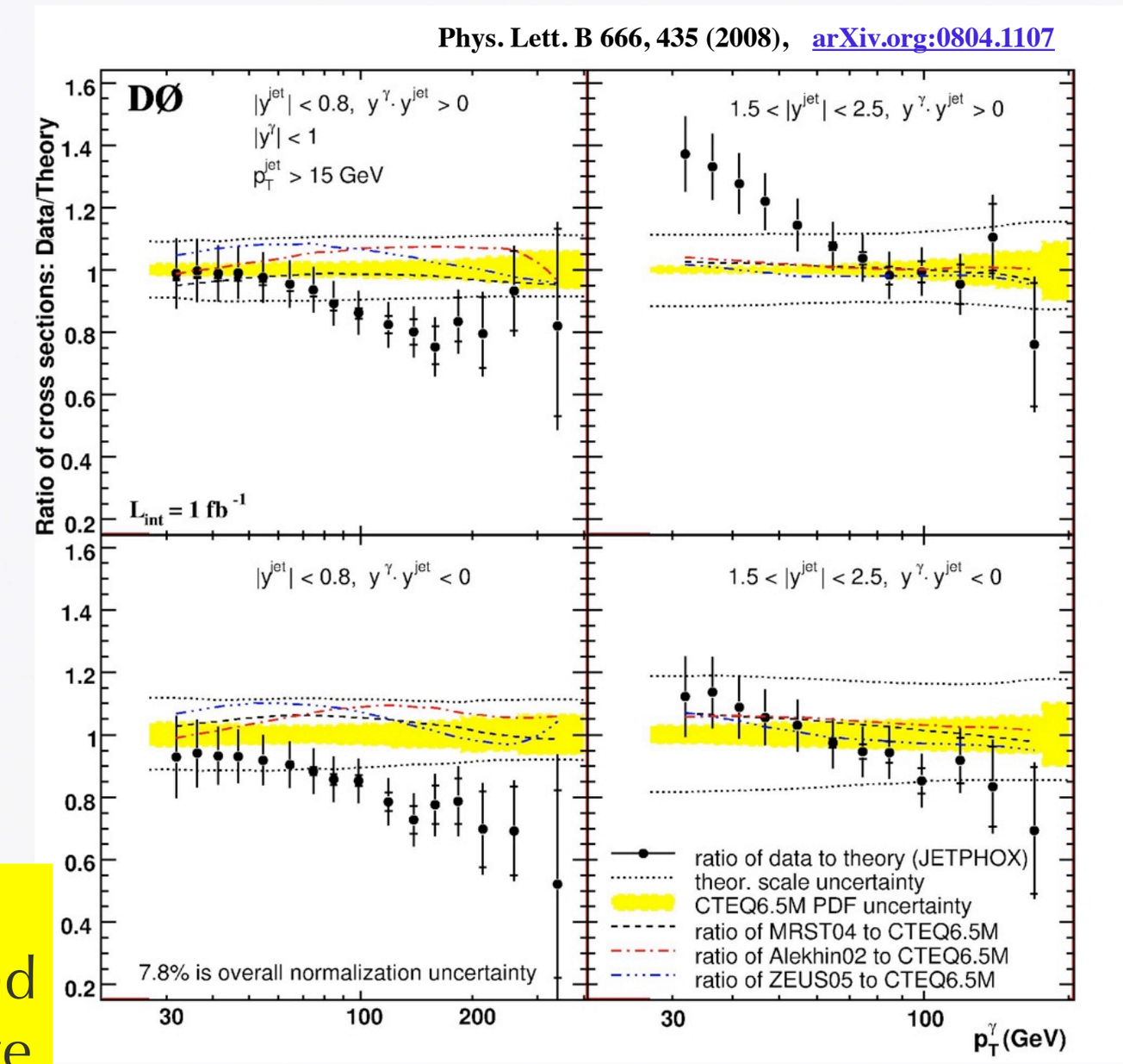
Submitted to PRL

γ+jets

$\mathcal{L}$ = 1.0/fb



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



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

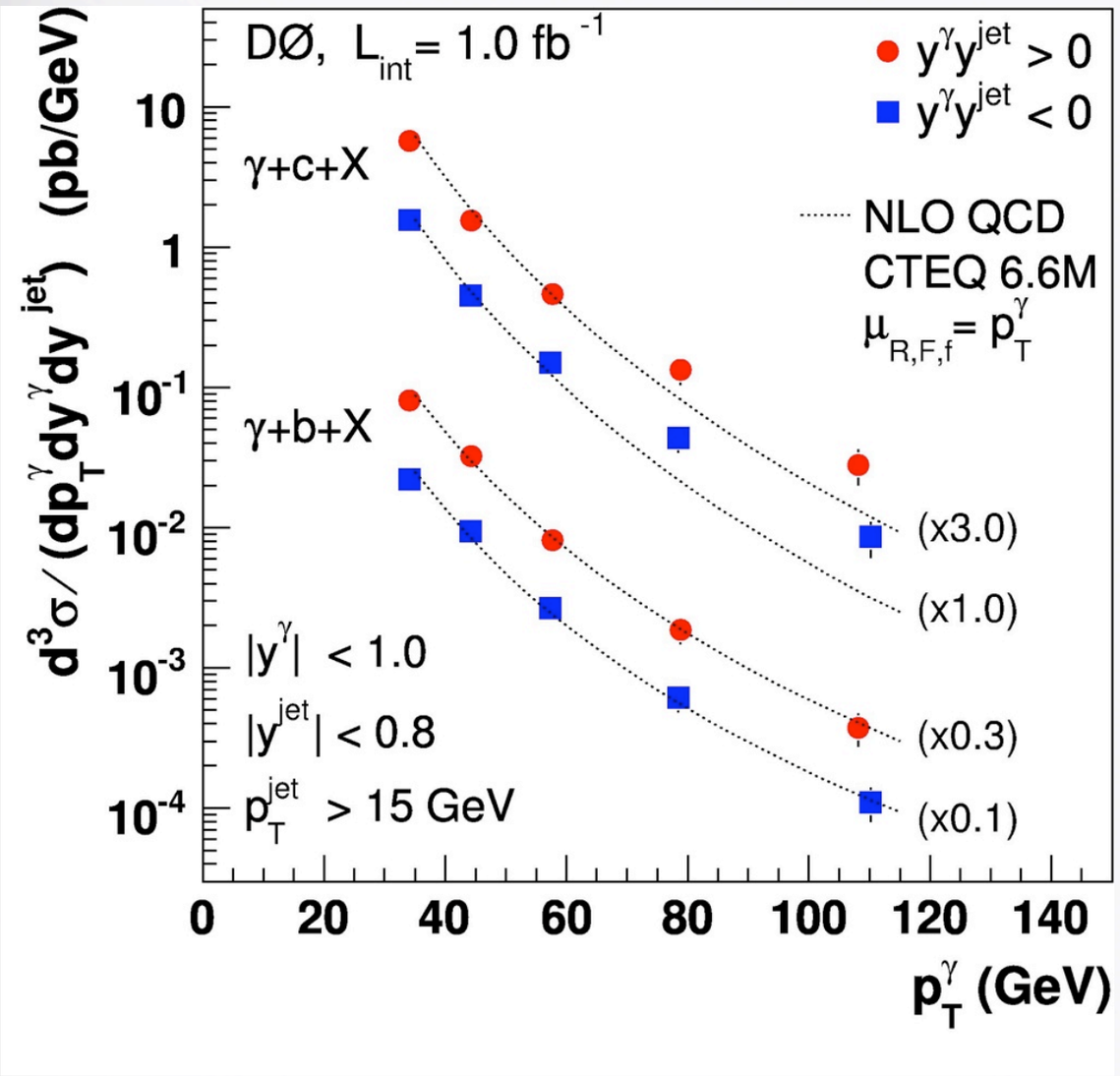
NLO theory cannot simultaneously describe photon p_T and jet rapidity over entire measured range

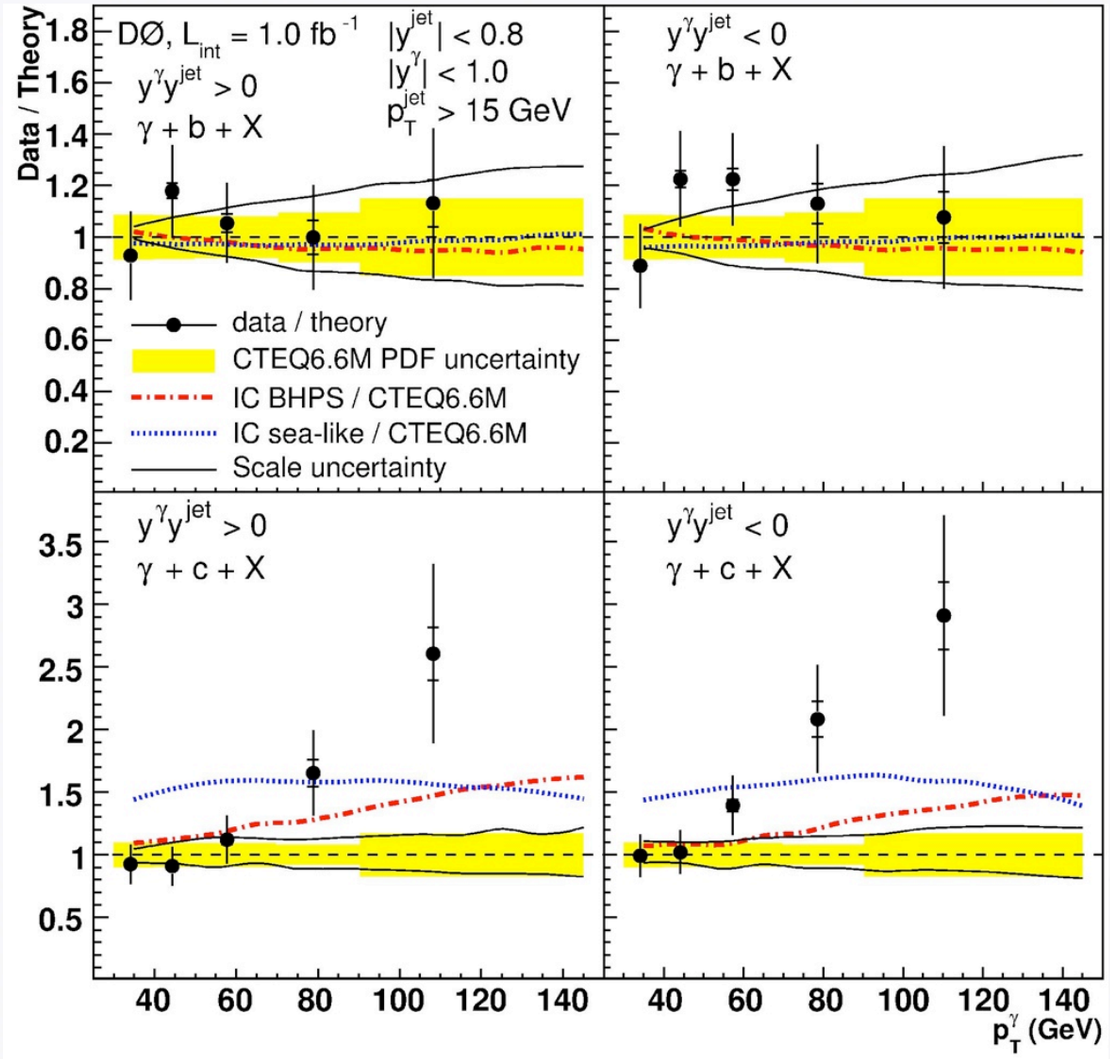
γ+b,c jets

$\mathcal{L}$ = 1.0/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

Summary and Conclusion

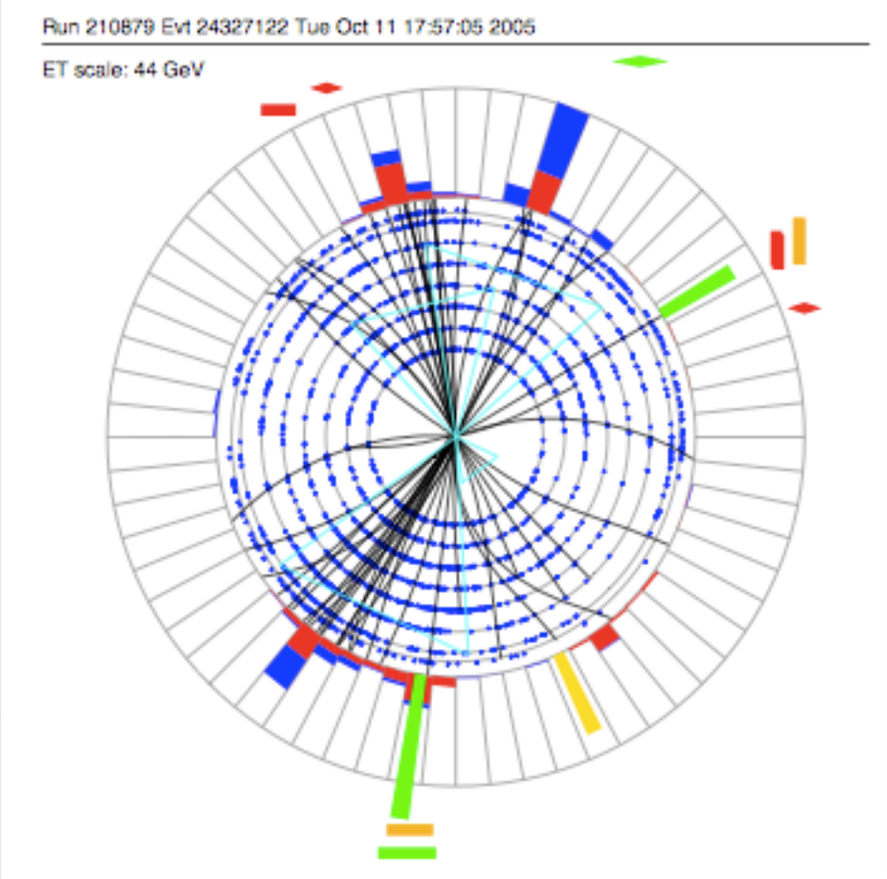
- Many new, interesting results coming from the Tevatron in Vector Boson + jet measurements
  - higher statistics -> measurements become systematics limited
  - we will learn much more, especially in W/Z/γ + heavy flavor by looking at more data
- Crucial for understanding backgrounds to NP and SM Higgs searches
- Discrepancies with theory suggest HO corrections and heavy quark fragmentation may need study; tuning of scale choices, PDFs, etc. ongoing
- The Tevatron will continue to explore these processes

http://www-cdf.fnal.gov/physics/new/qcd/QCD.html

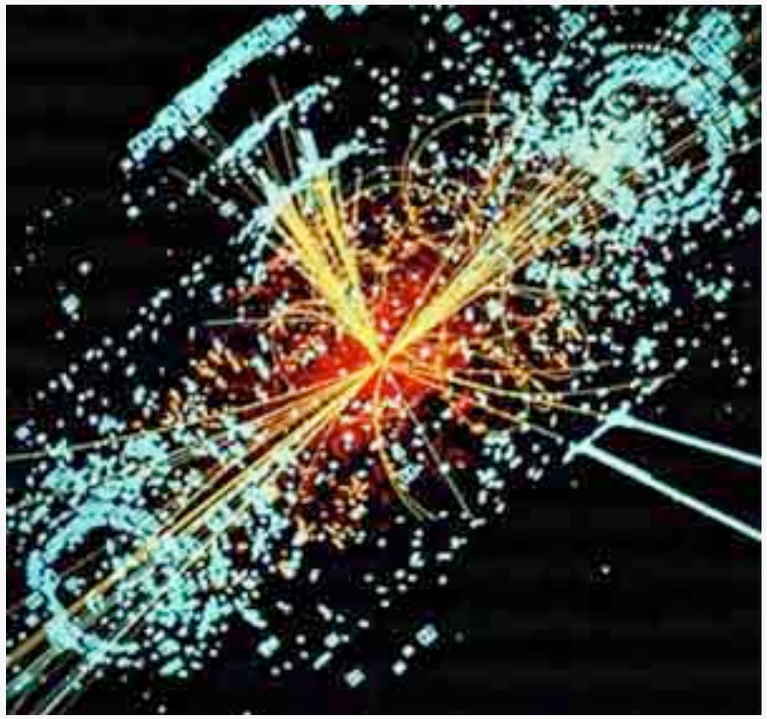
http://www-d0.fnal.gov/Run2Physics/WWW/results/qcd.htm

Final Thought

A concerted effort by experimentalists and theorists is needed to resolve existing puzzles and improve theoretical predictions which are critical for NP searches at both the Tevatron and LHC.
Tuning to Tevatron data is a good opportunity.



TeV-->LHC



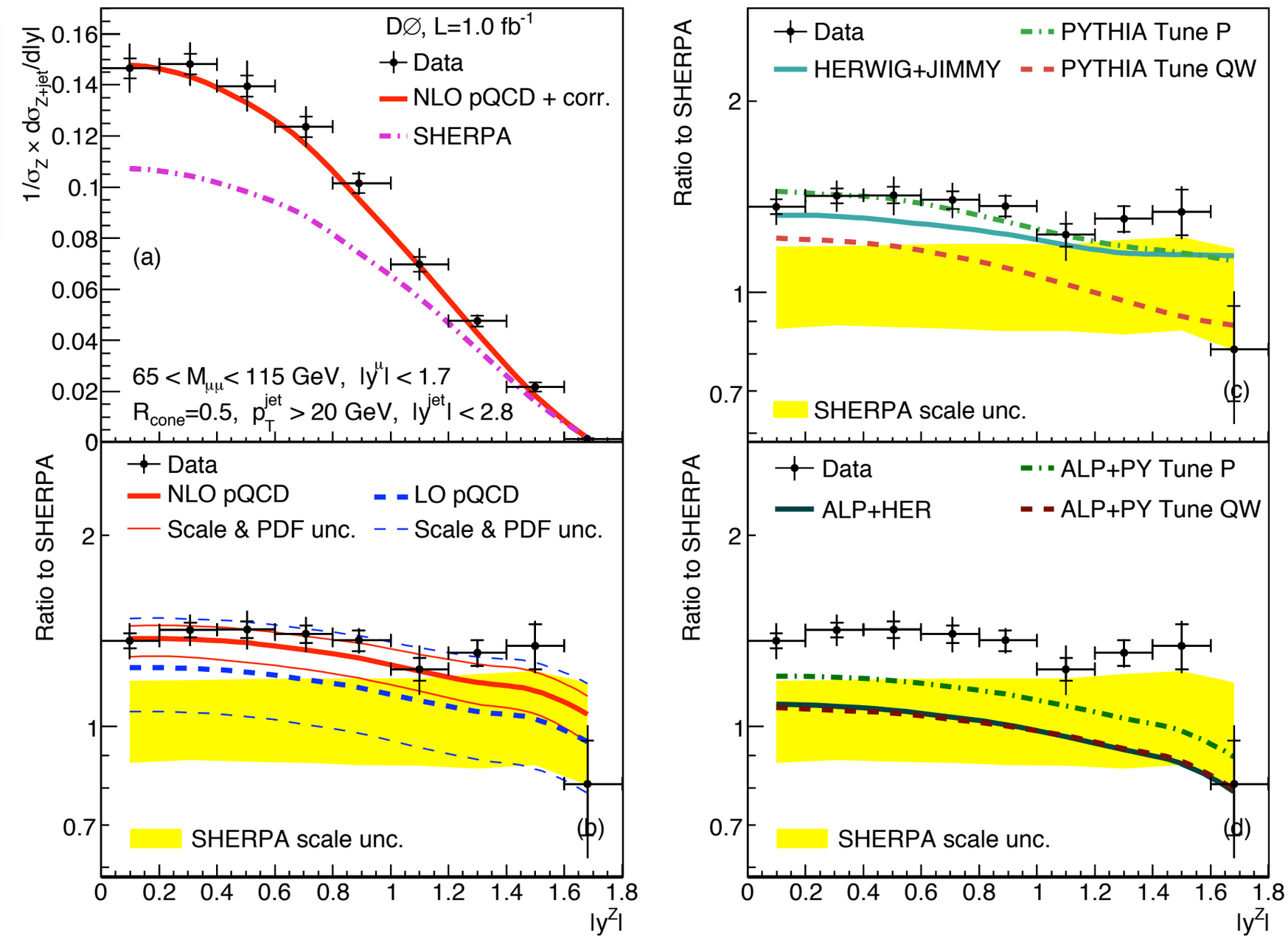
Backup

Z+jets

Z->μμ + jet + X
(Z+1jet inclusive)

$\mathcal{L}$ = 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

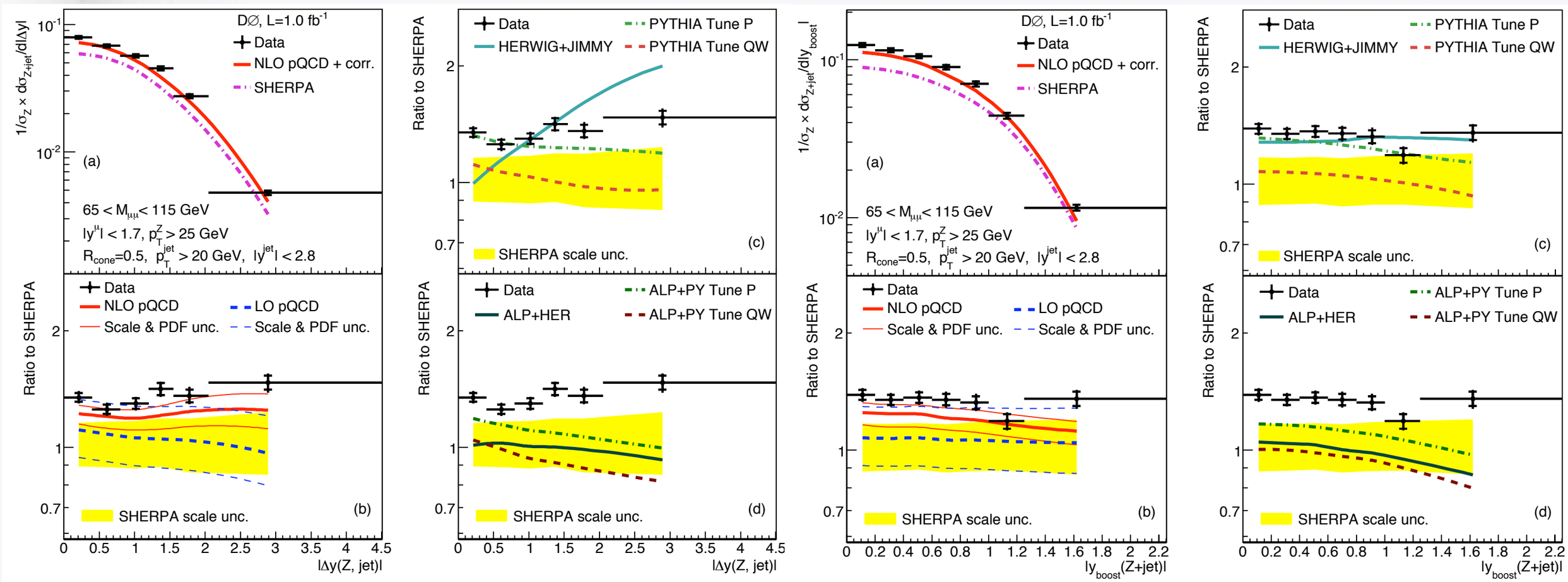
Z+1jet inclusive angular variables

$\Delta\phi$ (Z,jet)

Δy (Z,jet)

$y_{boost}(Z,jet) = \frac{1}{2}(y_Z+y_{jet})$

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)



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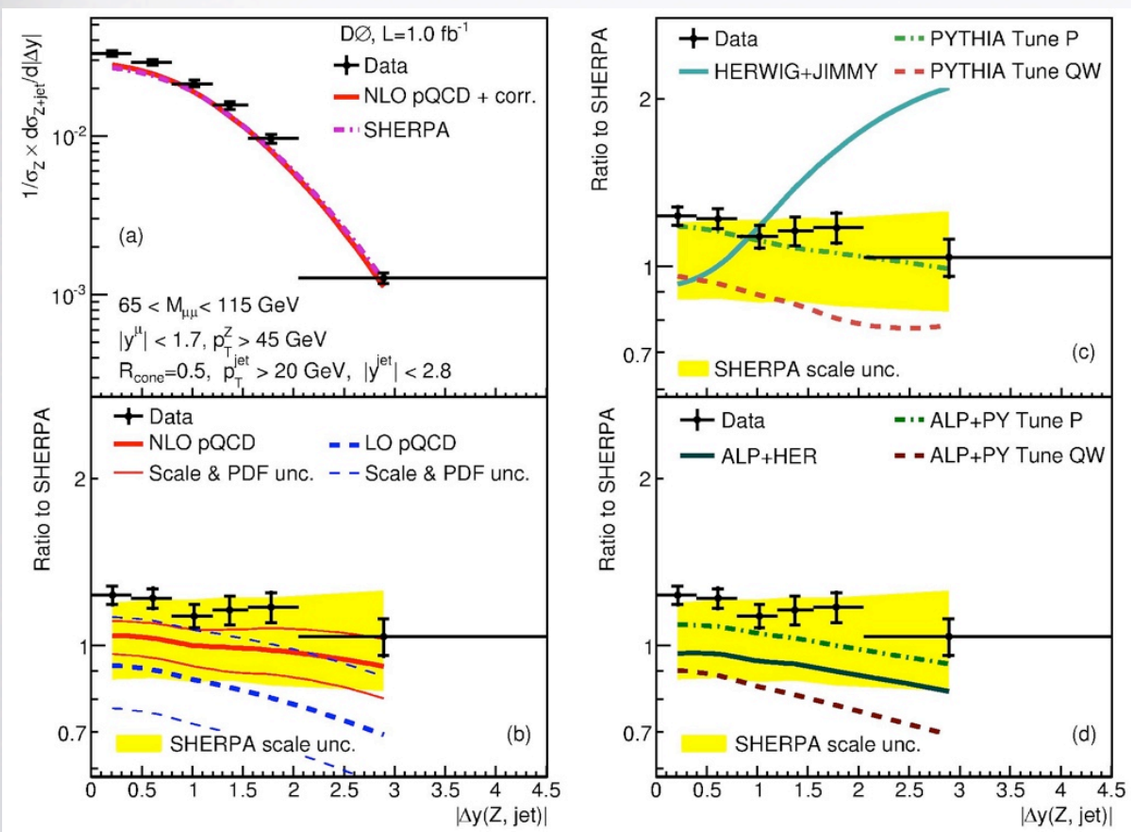
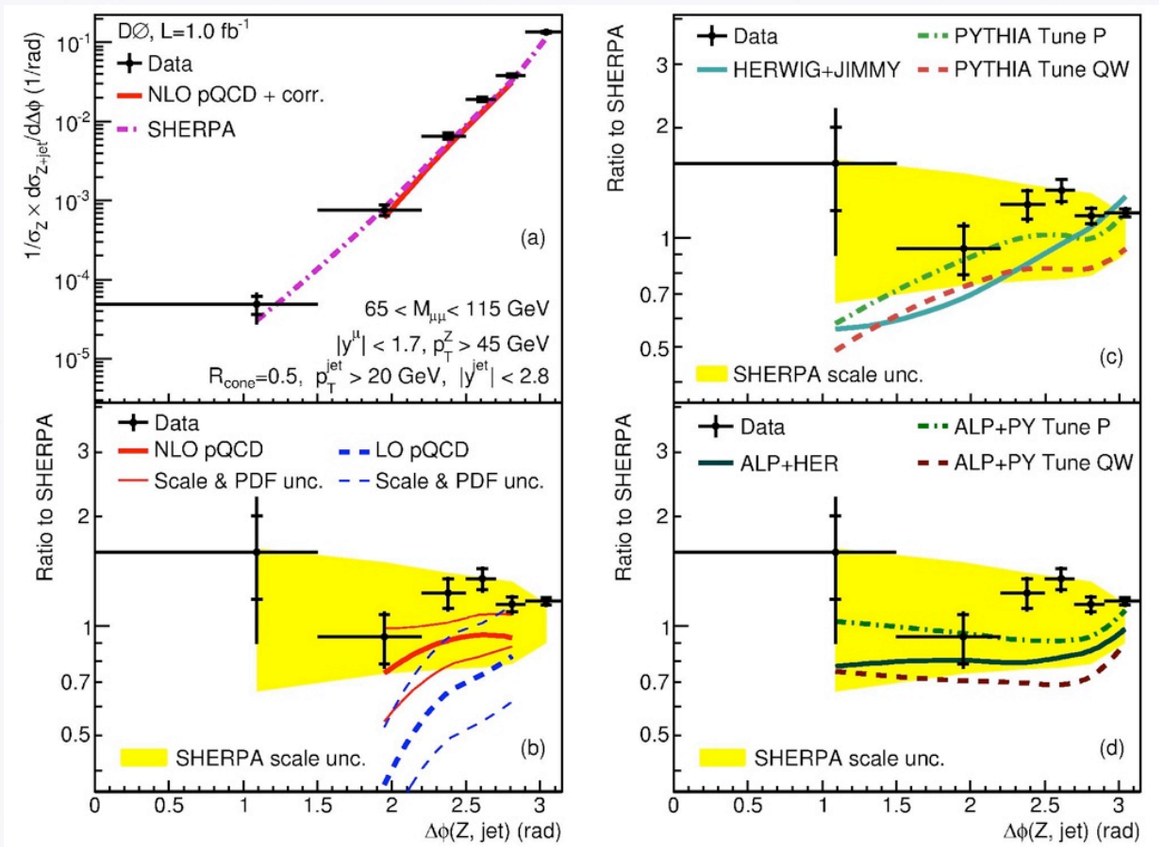
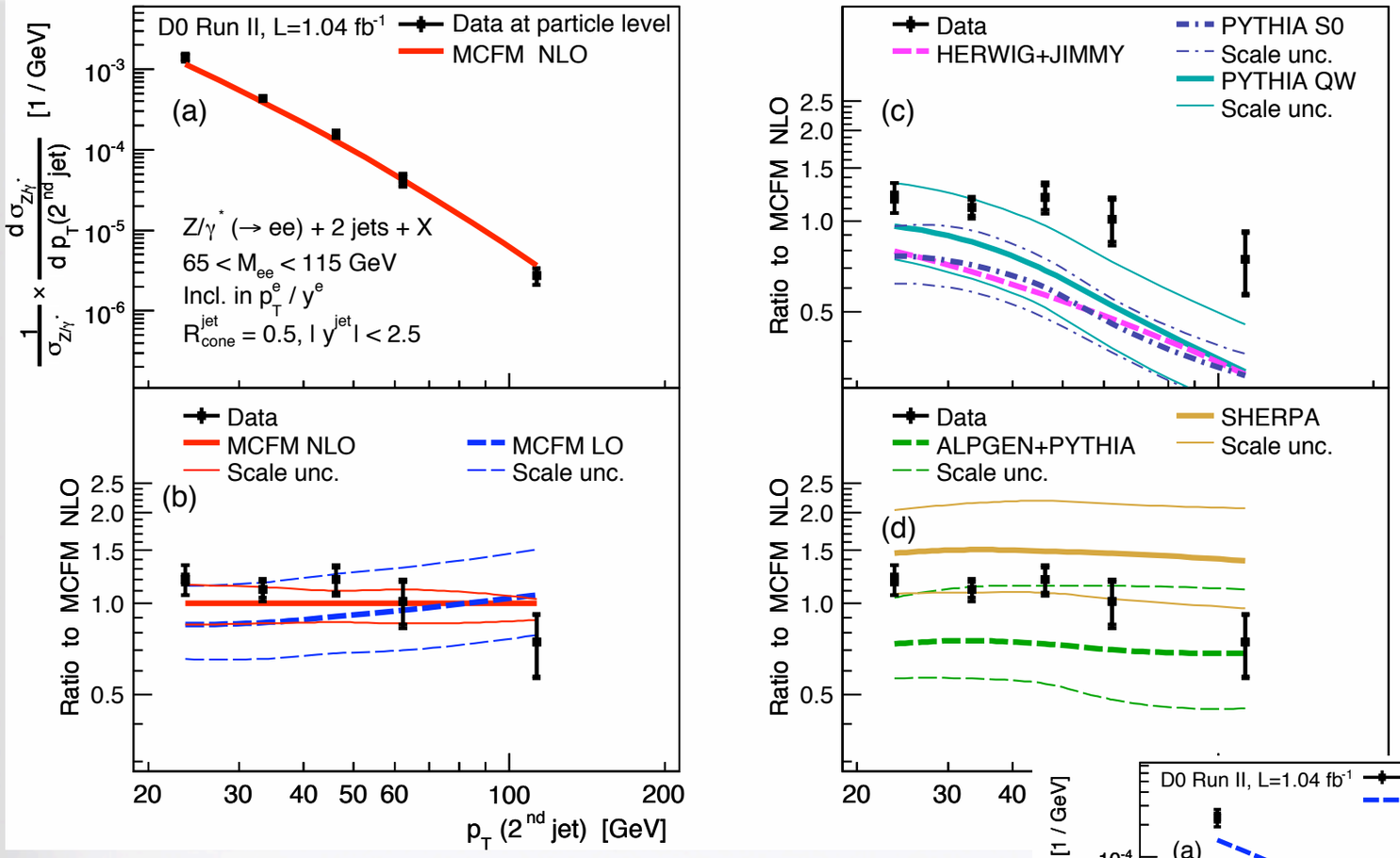
65 GeV< $M_{\mu\mu}$ < 115 GeV,
R_{cone}=0.5, p_T^{jet} > 20 GeV
$|y^{jet}| < 2.8$, $|y^{\mu}| < 1.7$
p_T^Z > 45 GeV (avoid UE)





Z+jets

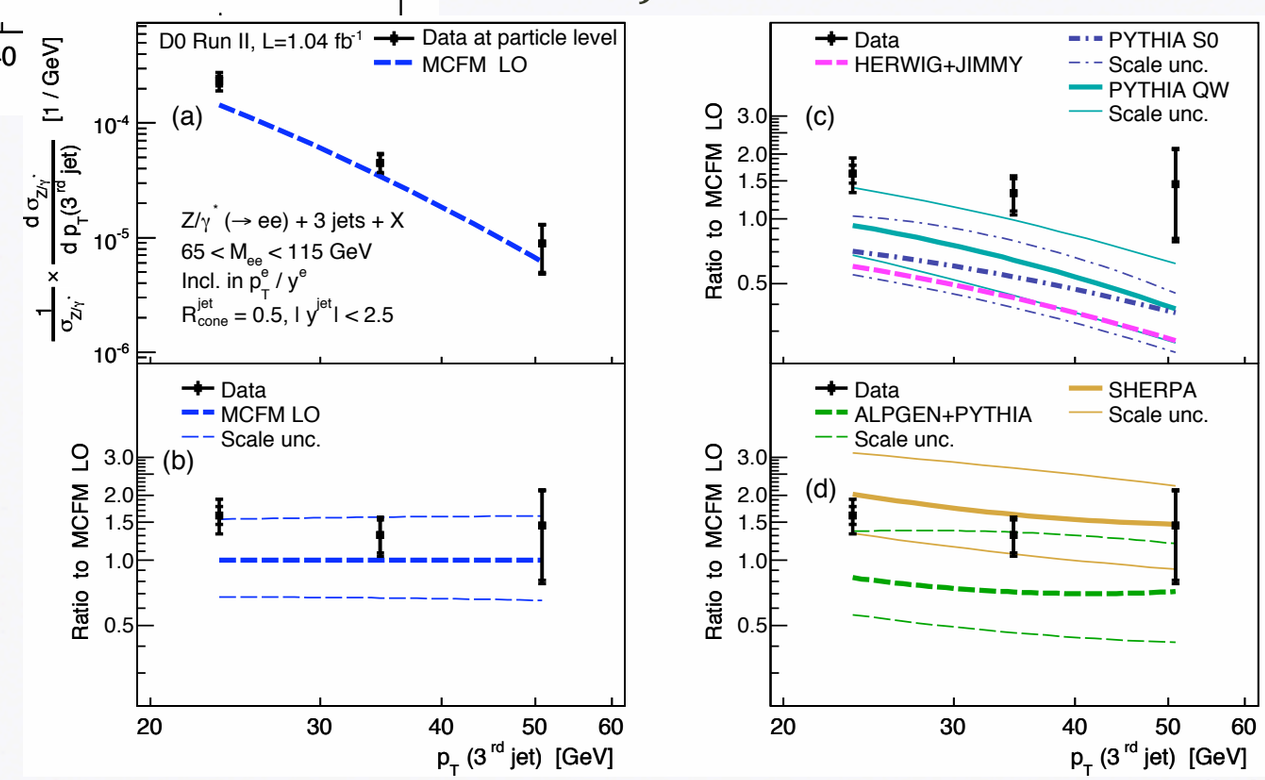
Z->ee + jet + X



2jet exclusive

NLO Z+3 jet predictions recently calculated

3jet exclusive



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

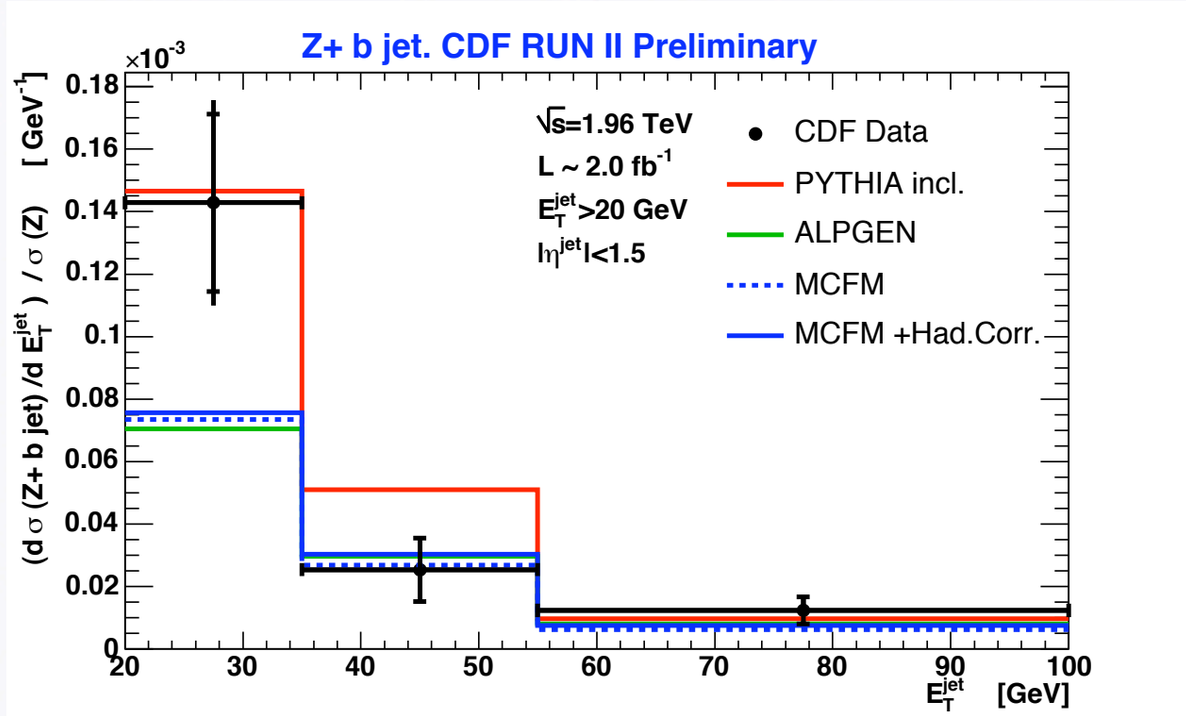
Z+b jets

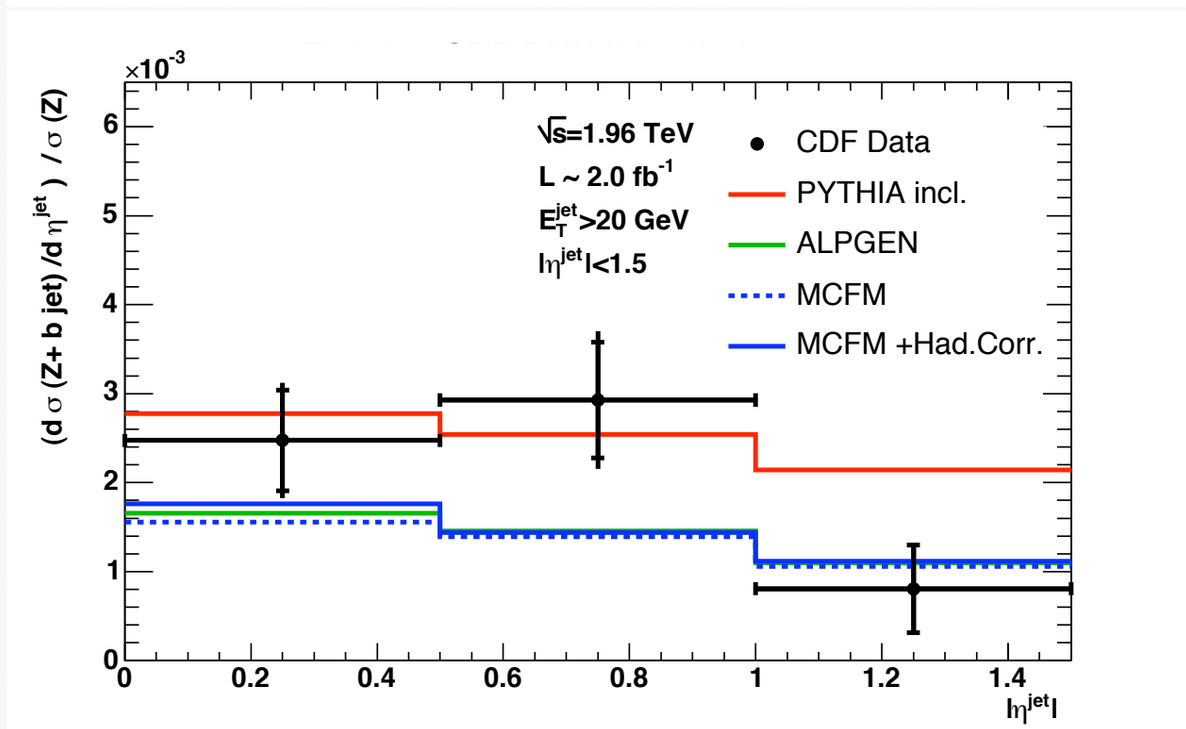
$Z \rightarrow ee/\mu\mu + b + X$
jet $E_T > 20$ GeV
jet $|\eta| < 1.5$
secondary vertex tagging

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

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

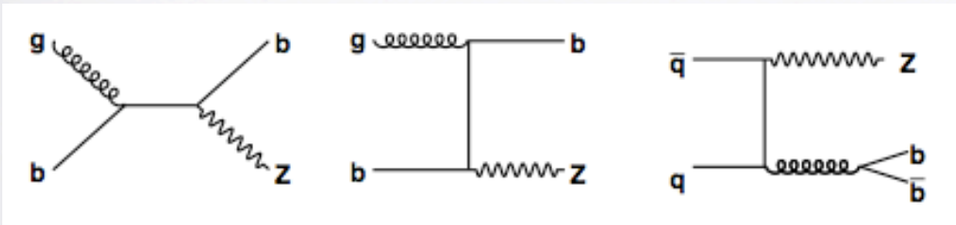
$\mathcal{L} = 2/\text{fb}$





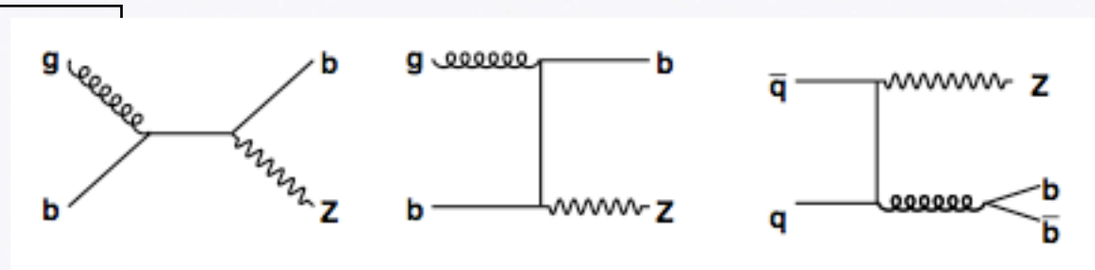
Pythia can describe overall shape, normalization

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



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

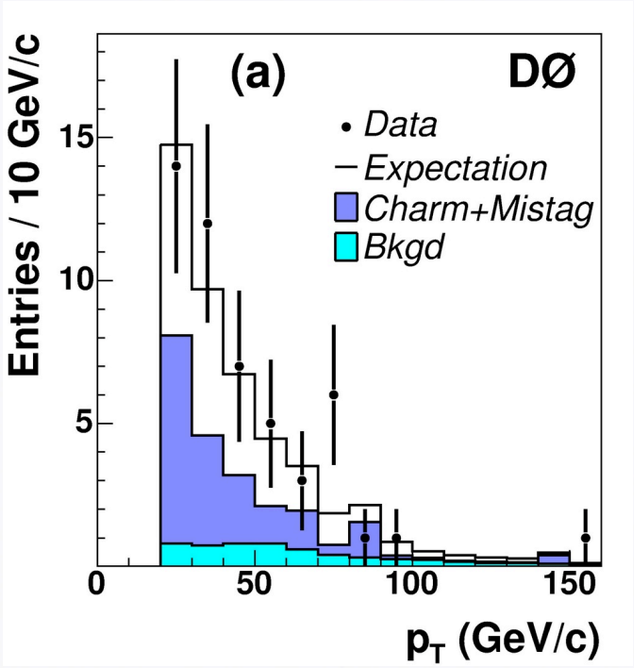


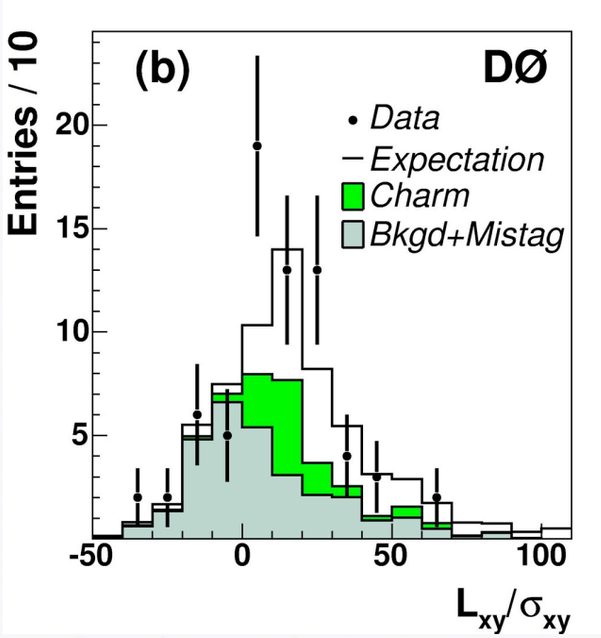
R=0.5 cone jets

$\mathcal{L}$ = .18/fb

Measure:

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





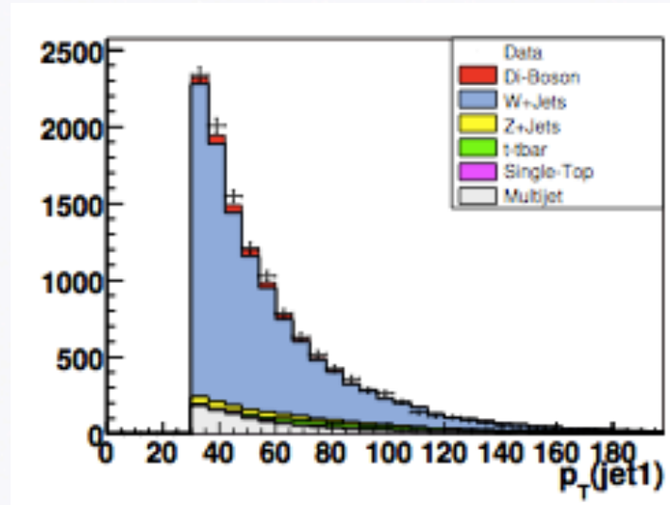
Measurement relied on Pythia MC estimation of c/b tagging efficiency

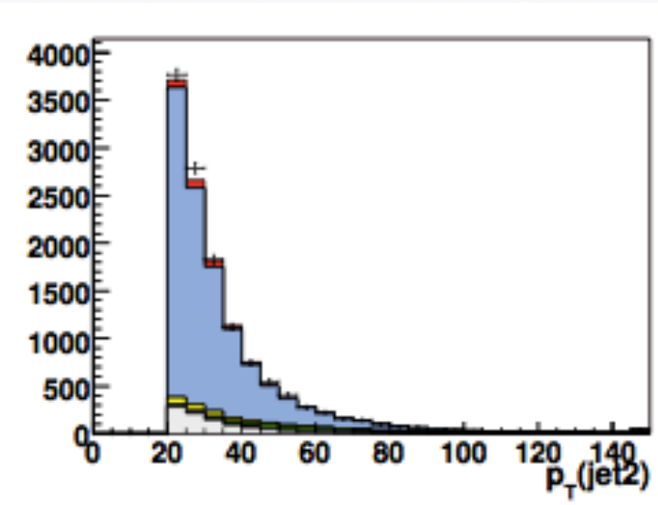
$$\frac{\sigma(p\bar{p} \rightarrow Z + bjet)}{\sigma(p\bar{p} \rightarrow Z + jet)} = 0.023 \pm 0.004$$

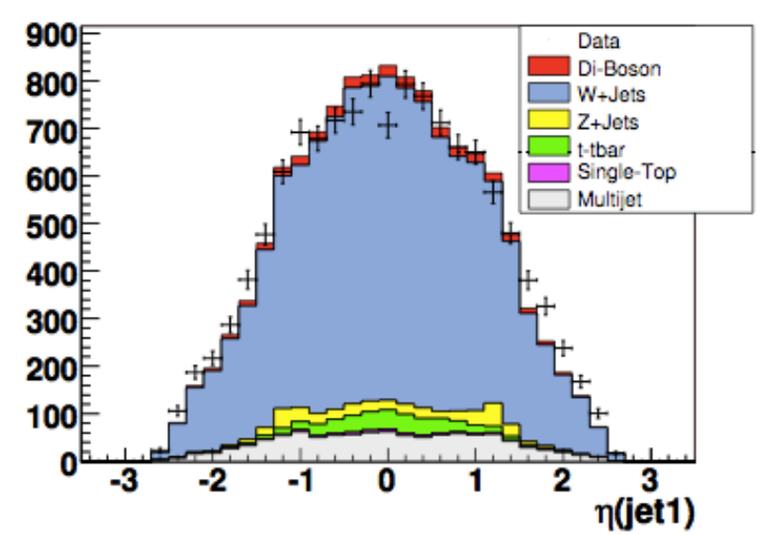
W+light flavor jets

WV->eν+2jets+X
electron p_T > 20 GeV
missing E_T > 20 GeV
jet p_T > 20 GeV
leading jet p_T > 30 GeV
jet |η| < 2.5

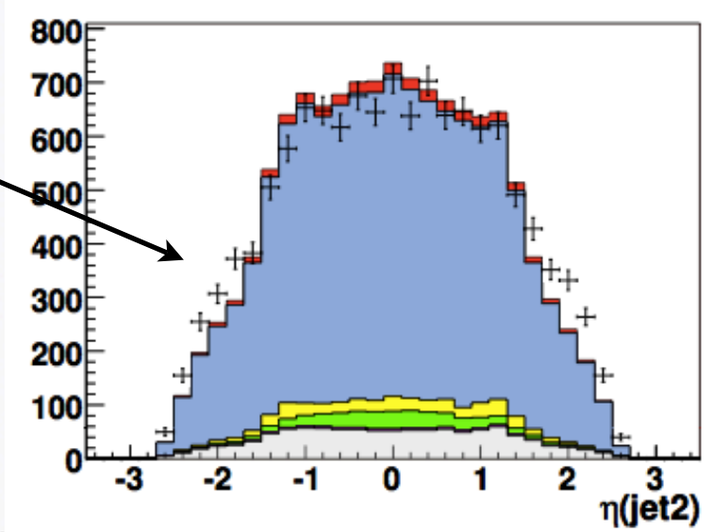
detector level distributions







- p_T spectra well modeled by Alpgen
- Data jet η distribution is broader than Alpgen in particle and reconstructed distributions



DØ work in progress