D0 Studies of V+Jets

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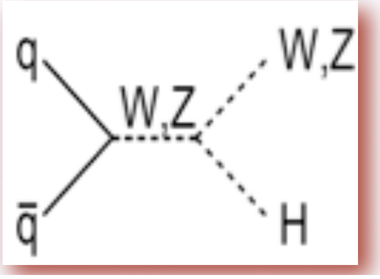
Indiana University

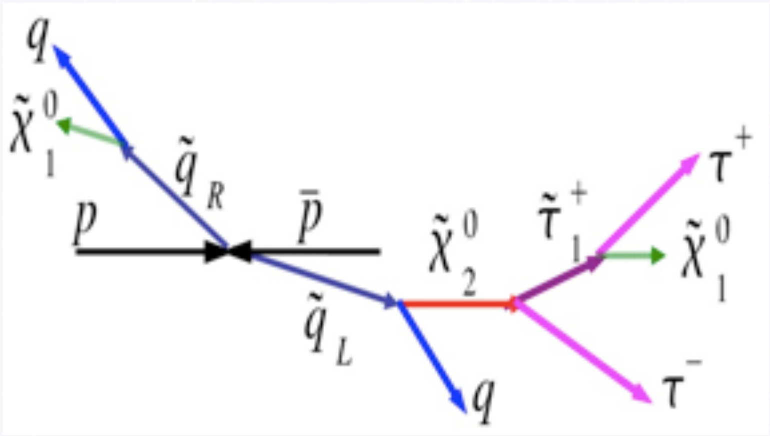
Motivation

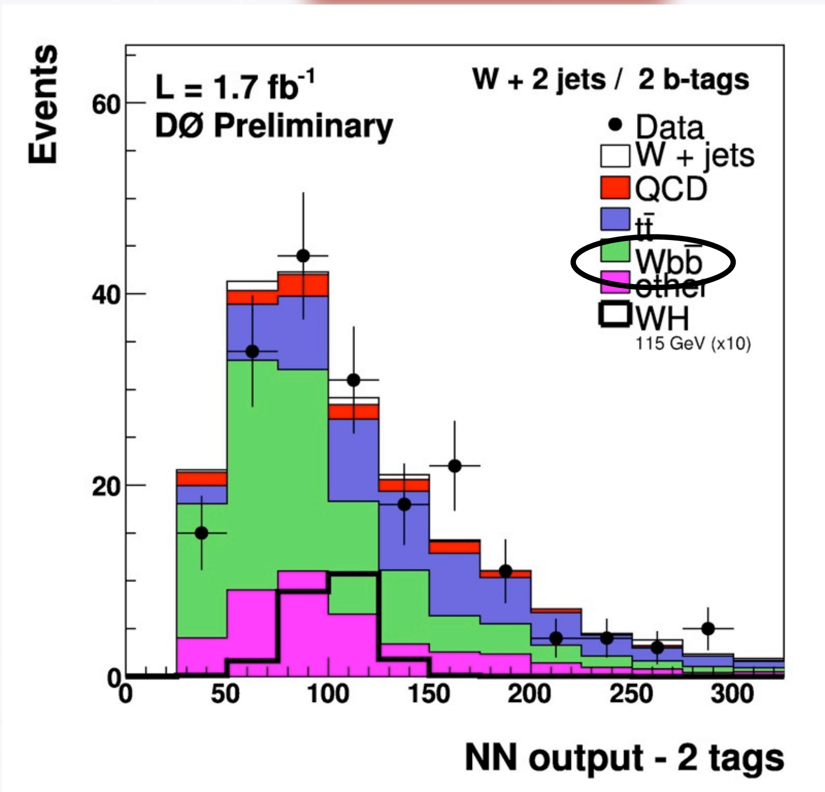
- Vector Bosons + jets are good signatures to test pQCD
  - Heavy flavor production is sensitive to b, c quark PDFs
- Vector Bosons + jets events constitute backgrounds for SM Higgs and New Physics (NP) searches
- N(N)LO predictions not available for many processes of interest, particularly those with 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.

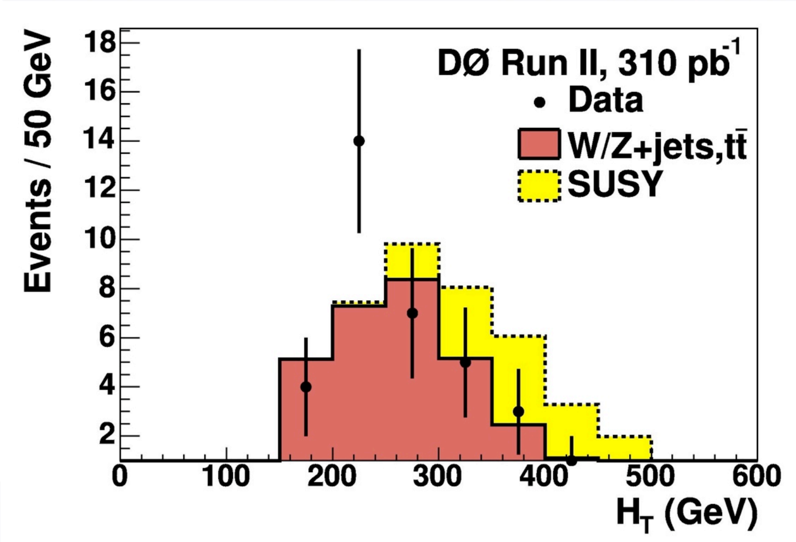
Backgrounds to NP

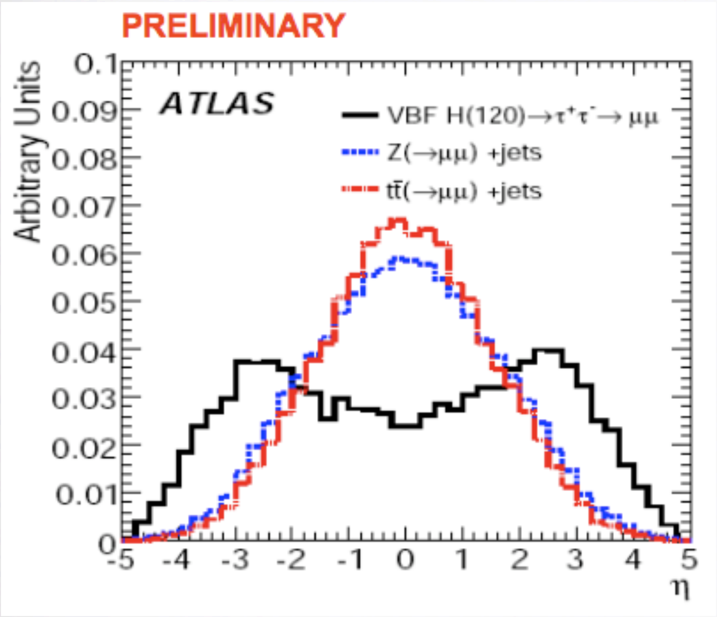
- SM Higgs and New Physics share signatures with irreducible VB + jets backgrounds that are currently being pinned down.
- Interplay between fragmentation models, tunes, PDFs and scale choices needs to be understood to model SM backgrounds

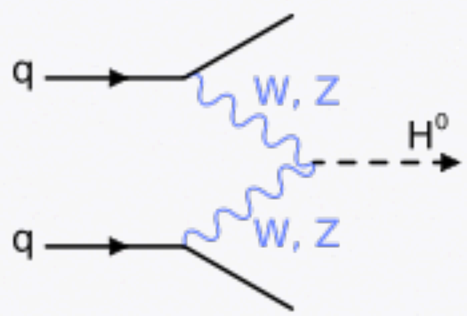


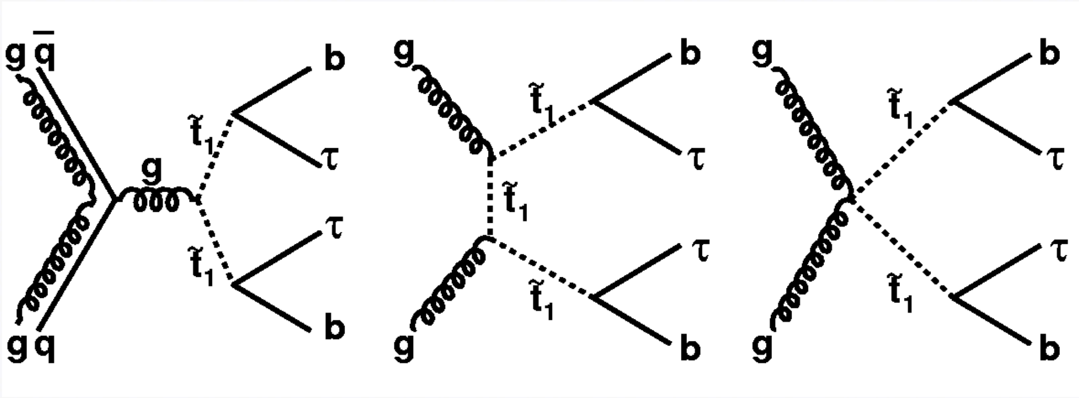






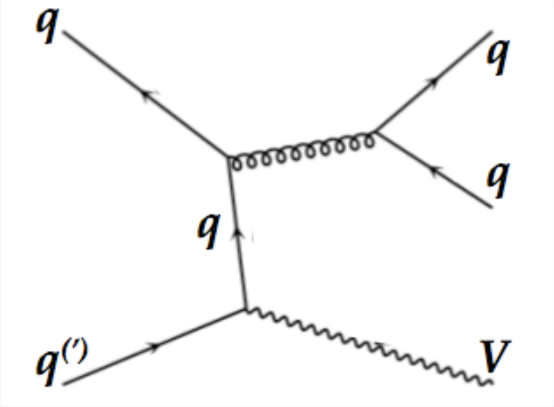


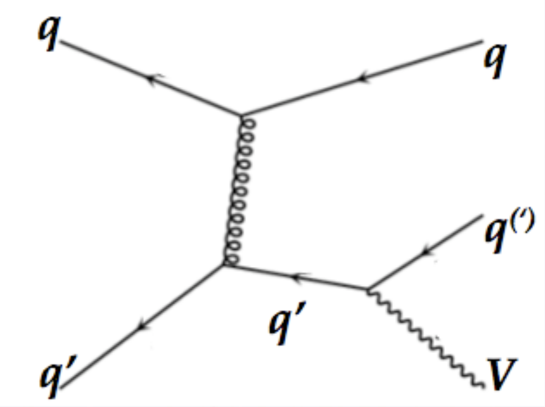




Many Tevatron Measurements

- 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
W+b-jets	--	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

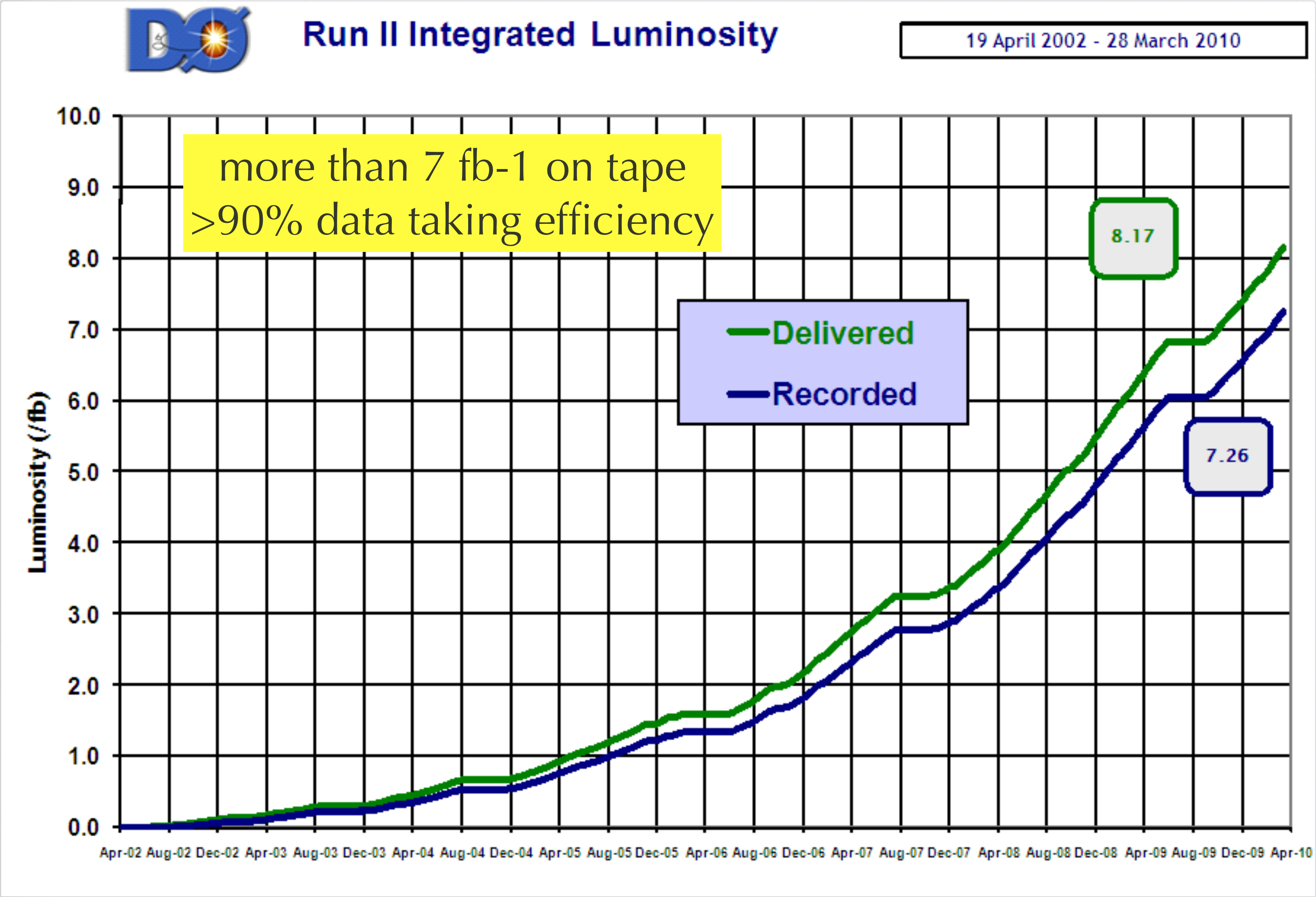
In most cases:

- 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

$$\frac{\text{observable (particle level)}}{\text{observable (parton level)}} * \text{NLO}$$

Detailed comparisons of MC models to the data are also made

D0 RunII data collected

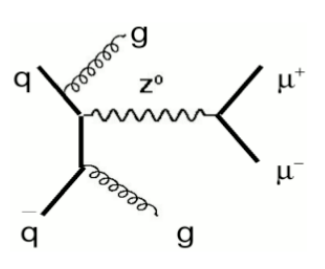


D0 results

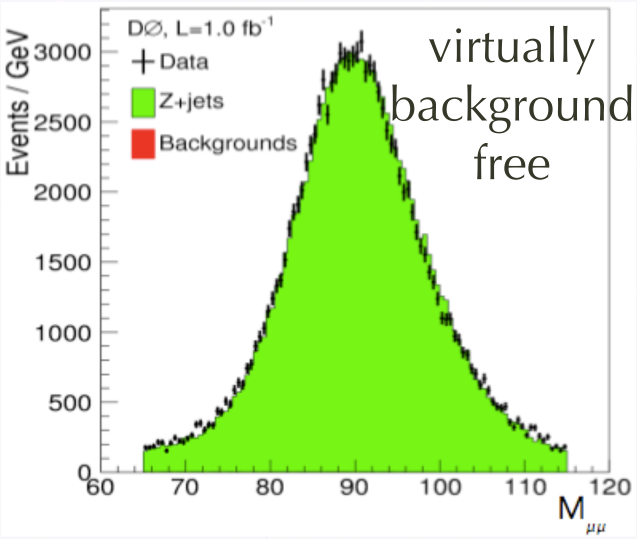
- thorough studies of Z+jets
- Z+b
- W+c
- extensive γ+jets, γ+b/c

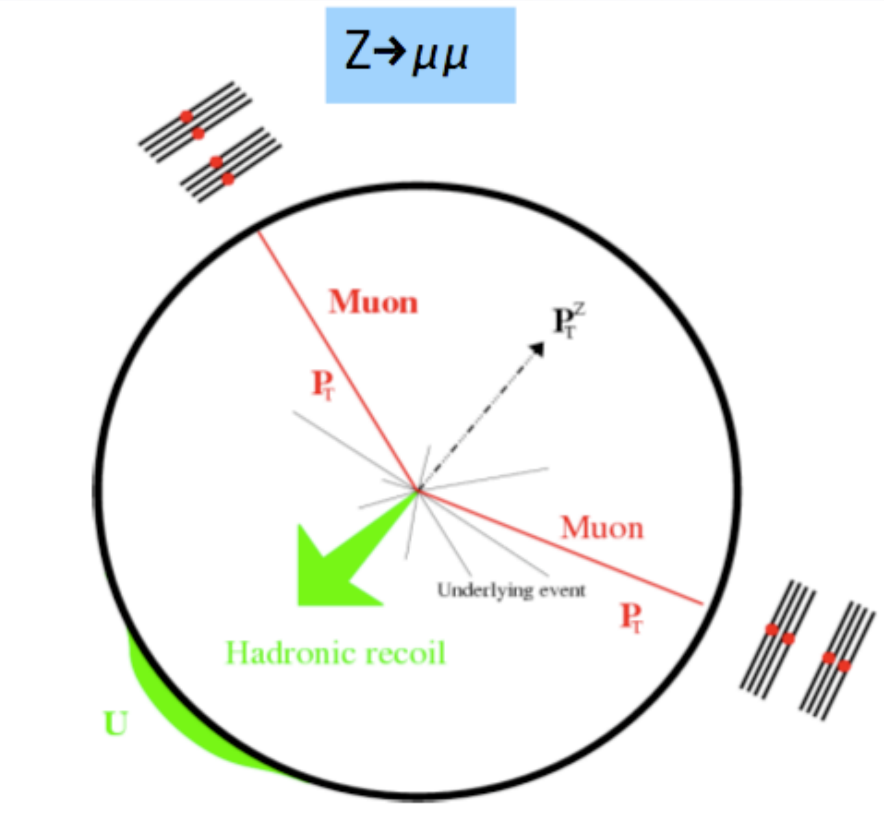
Anticipate updates to Z+b and W+jets very soon.

Z->μμ + jet + X

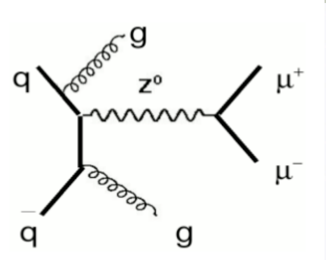


- Z provides colorless probe of collision and hard scale; study kinematics of hadronic recoil
- Z boson decay products (leptons) and jets measured, calibrated
- strict muon isolation cuts provide background free data sample
- corrections applied for acceptance, trigger losses
- data unfolded to particle level
  - accounts for detector resolution and efficiency
- comparisons to predictions
  - NLO pQCD via MCFM
    - Pythia hadronization corrections applied
  - LO ME-PS models - ALPGEN, SHERPA
  - LO PS models - PYTHIA, HERWIG





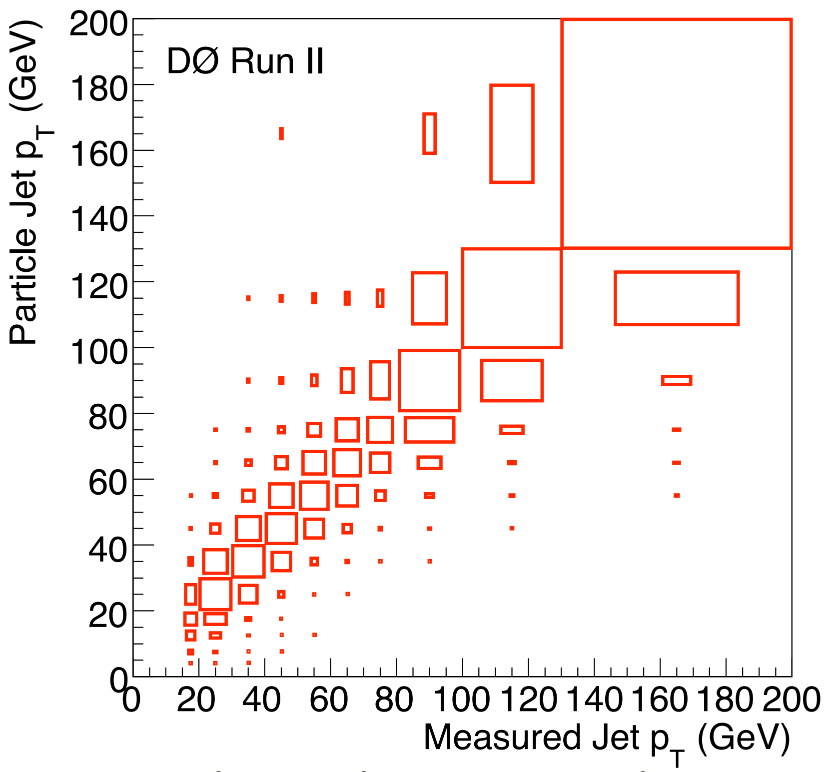
Z->μμ + jet + X - p_T spectra



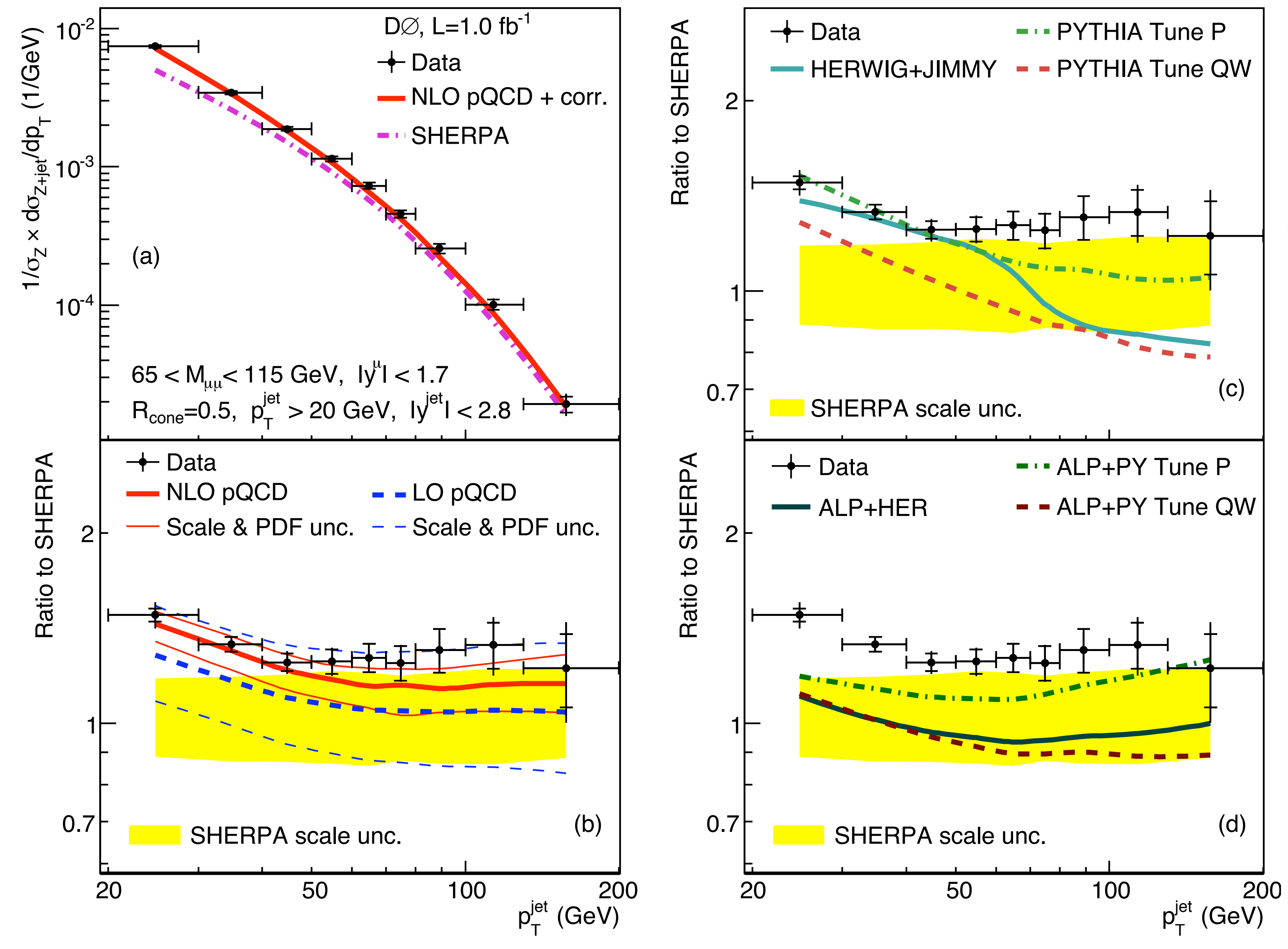
Particle level phase space:
65 GeV< $M_{\mu\mu}$ < 115 GeV,
D0 midpoint R_{cone}=0.5, p_T^{jet} > 20 GeV
$|y^{jet}|$ < 2.8, $|y^{\mu}|$ < 1.7
muons include QED radiation

theory predictions updated since publication

ratios relative to Sherpa 1.1.3



migration matrix
-> used to unfold data
large migrations,
especially at low p_T



MCFM v5.4 PDF: MSTW2008
$\mu_r^2 = \mu_f^2 = p_{T,Z}^2 + M_Z^2$

PYTHIA v6.420
Pythia Tune P
Pythia Tune QW
HERWIG v6.510 + JIMMY v4.31
ALPGEN v2.13+PYTHIA v6.420
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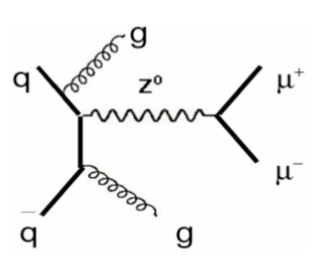
PLB 669, 278 (2008)

Z->μμ + jet + X - p_T spectra



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muons include QED radiation

theory predictions updated since publication

ratios relative to Sherpa 1.1.3

- NLO prediction with Z p_T<30 GeV sensitive to underlying event
- All LO predictions underestimate data normalization
- Pythia can be tuned to reproduce data

MCFM v5.4 PDF: MSTW2008
$\mu_r^2 = \mu_f^2 = p_{T,Z}^2 + M_Z^2$

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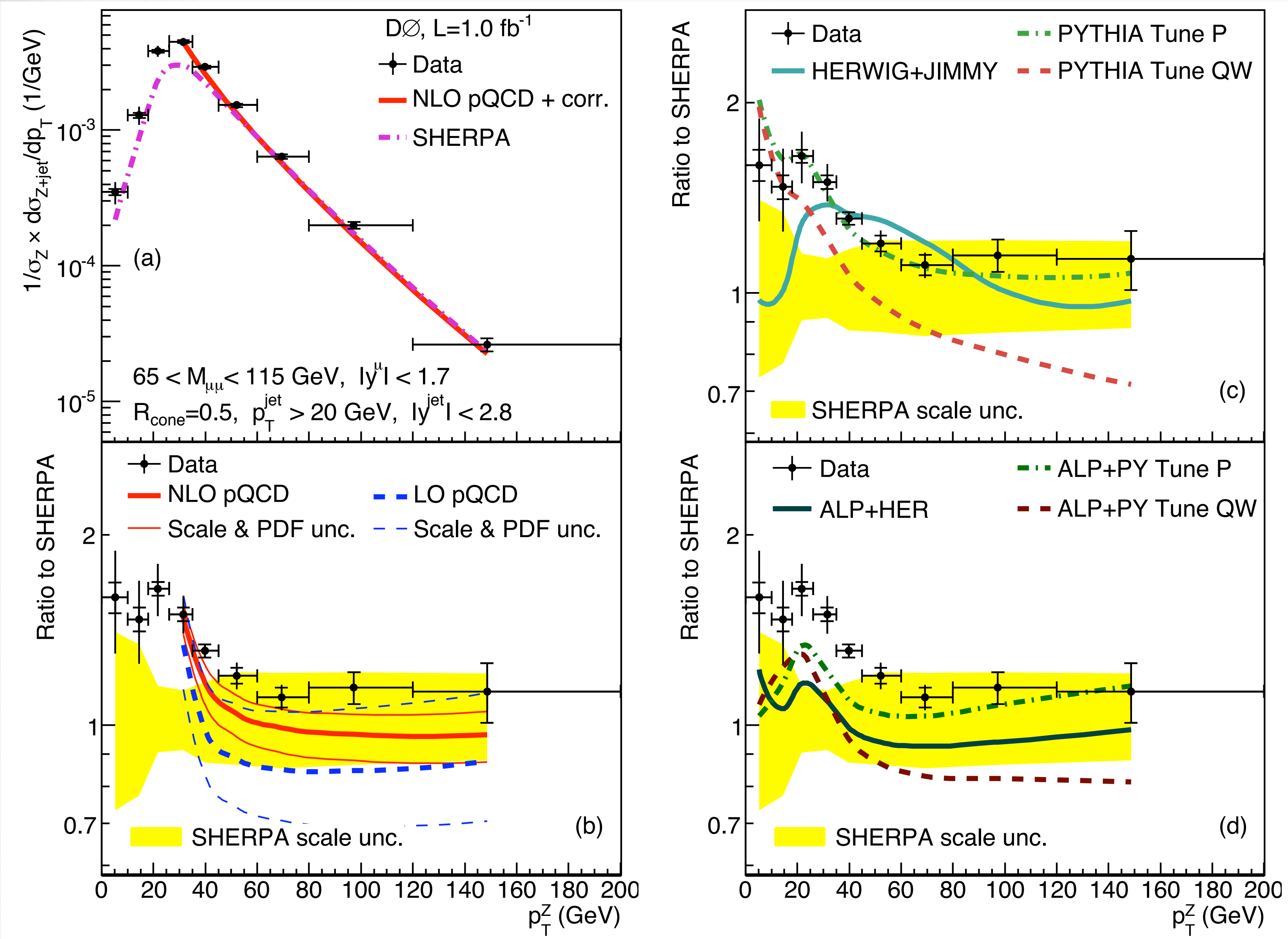
All cross sections normalized to inclusive Z production to reduce systematic errors



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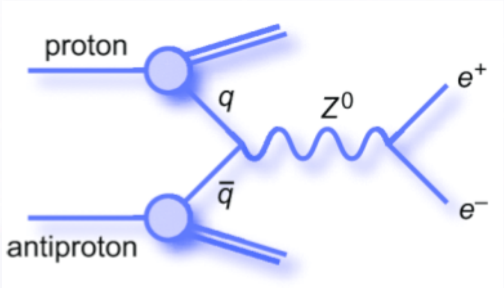
Z->ee + jet + X - p_T spectra

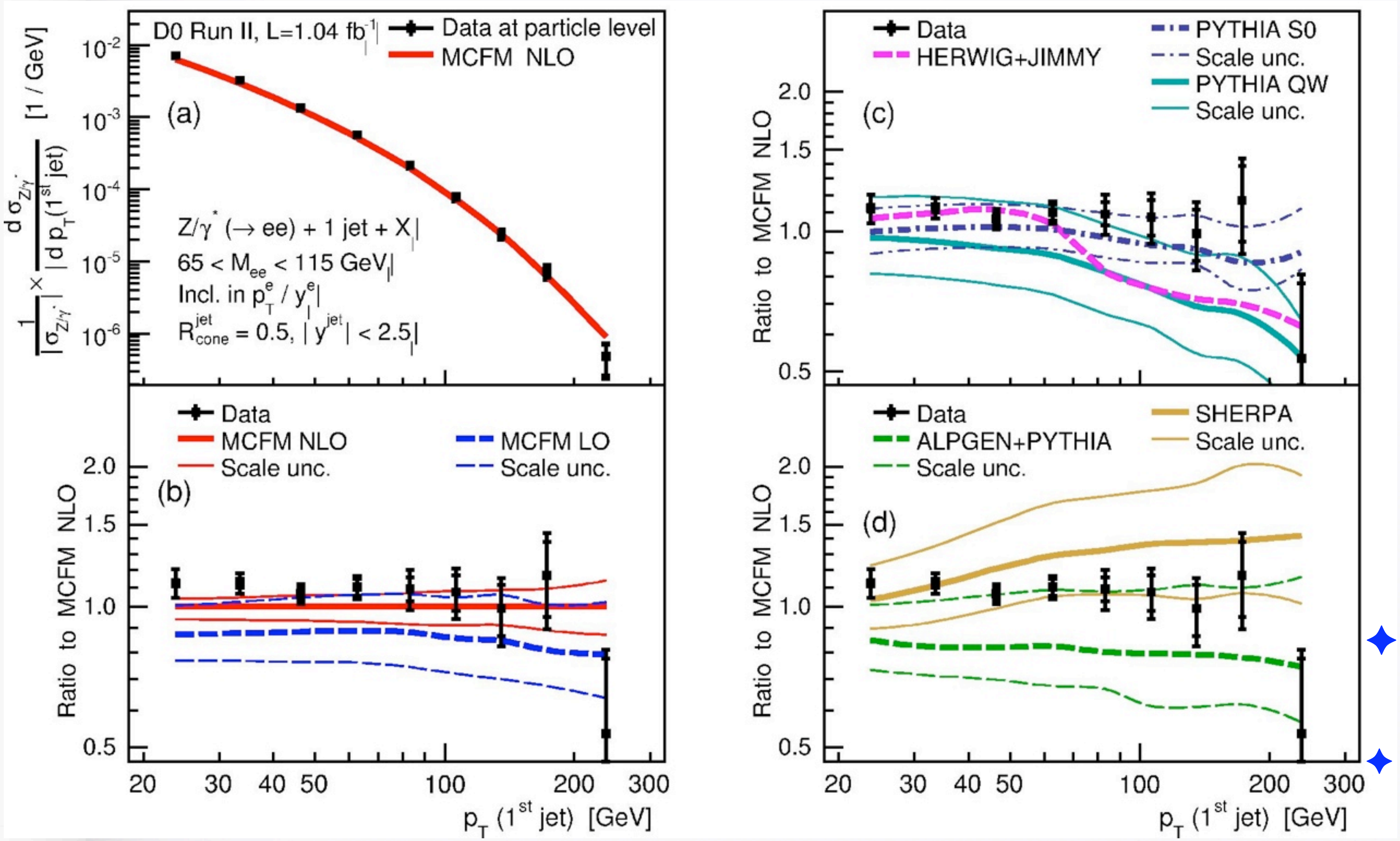


Particle level phase space:
65 GeV< M_{ee} < 115 GeV,
D0 midpoint R_{cone}=0.5, p_T^{jet} > 20 GeV
$|y^{jet}|$ < 2.5, Incl in $p_T^e/|y^e|$

normalized to
inclusive Z production

ratios relative to MCFM NLO

MCFM v5.3 PDF: CTEQ6.6M
$\mu_r^2 = \mu_f^2 = p_{T,Z}^2 + M_Z^2$



PYTHIA v6.416
Pythia Tune SO
Pythia Tune QW
HERWIG v6.510 +JIMMY v4.31

ALPGEN v2.13 +PYTHIA v6.325
SHERPA v1.1.1

- Large differences between models
- Small experimental errors

PLB 678, 45 (2009)

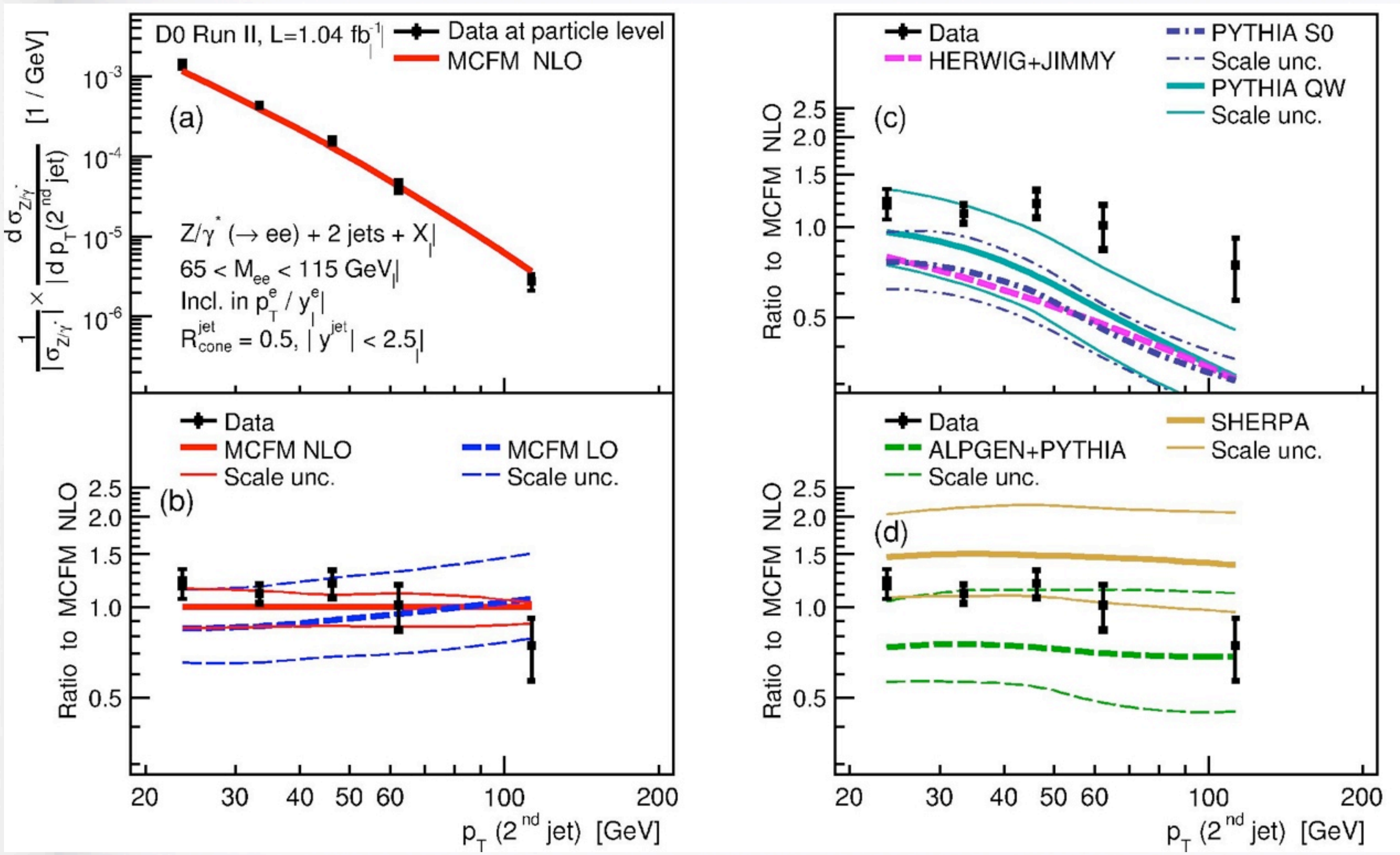
Z->ee + **2jets** + X - p_T spectra

Particle level phase space:
65 GeV< M_{ee} < 115 GeV,
D0 midpoint R_{cone}=0.5, p_T^{jet} > 20 GeV
$|y^{jet}|$ < 2.5, Incl in $p_T^e/|y^e|$

Direct measurement of jet kinematics with large multiplicities

ratios relative to MCFM NLO

MCFM v5.3 PDF: CTEQ6.6M
$\mu_r^2 = \mu_f^2 = p_{T,Z}^2 + M_Z^2$



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

PLB 678, 45 (2009)

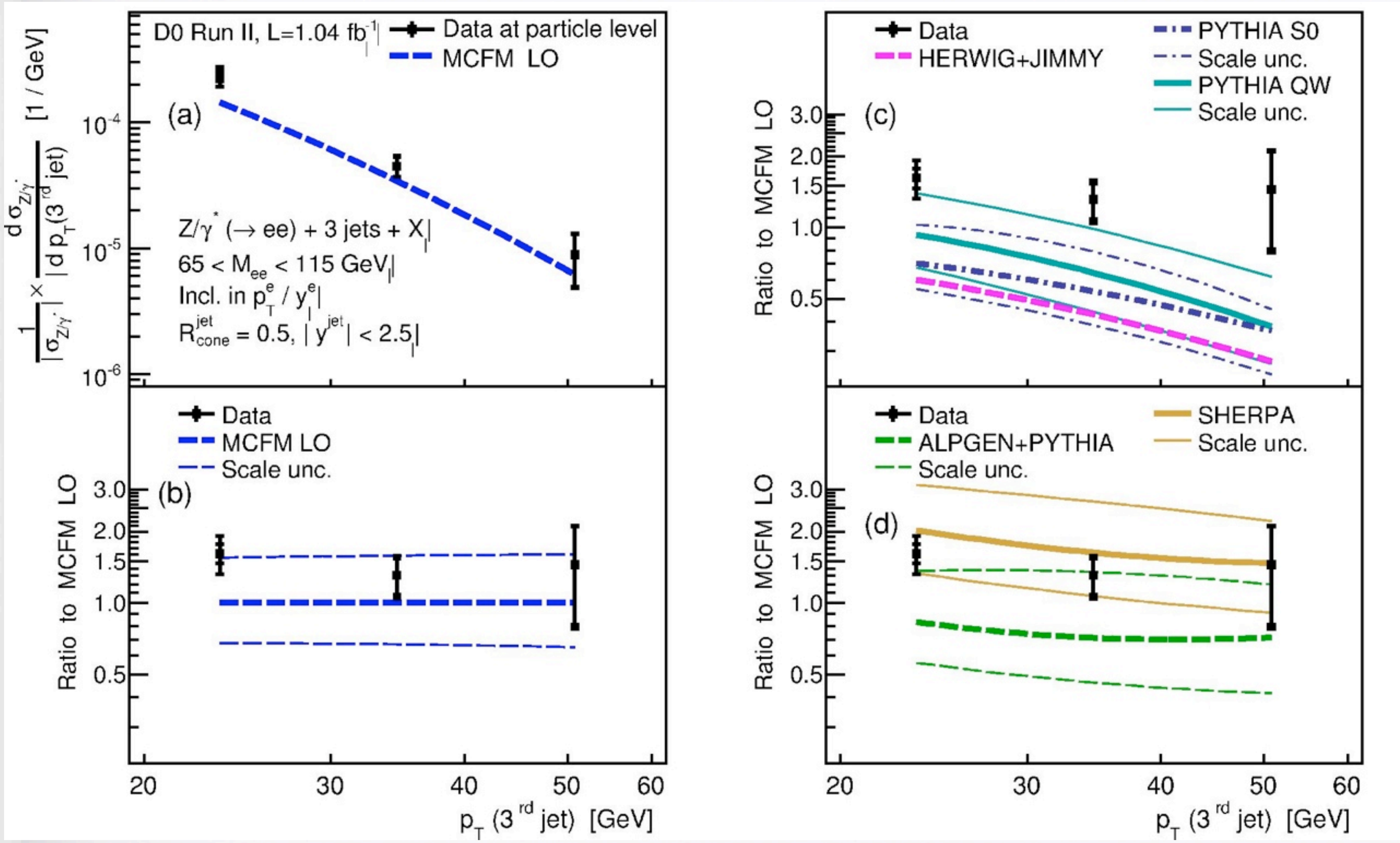
Z->ee + **3jets** + X - p_T spectra

Particle level phase space:
65 GeV< M_{ee} < 115 GeV,
D0 midpoint R_{cone}=0.5, p_T^{jet} > 20 GeV
$|y^{jet}|$ < 2.5, Incl in $p_T^e/|y^e|$

Direct measurement of jet kinematics with large multiplicities

ratios relative to MCFM LO

MCFM v5.3 PDF: CTEQ6.6M
$\mu_r^2 = \mu_f^2 = p_{T,Z}^2 + M_Z^2$



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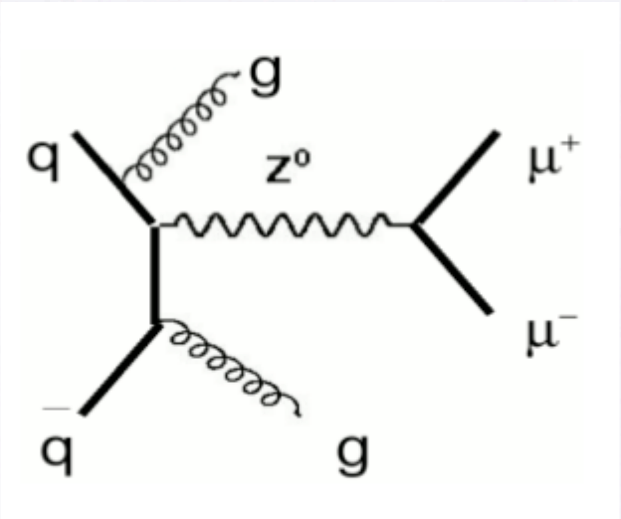
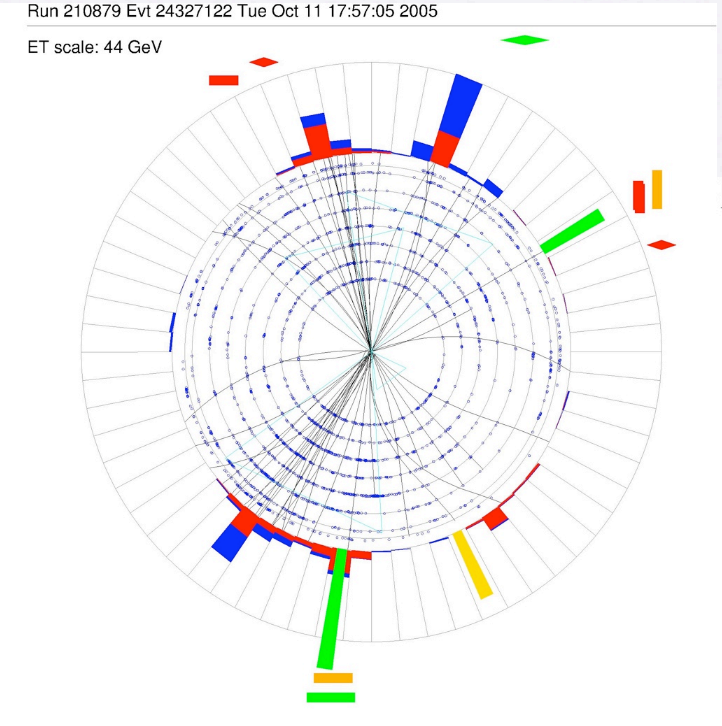
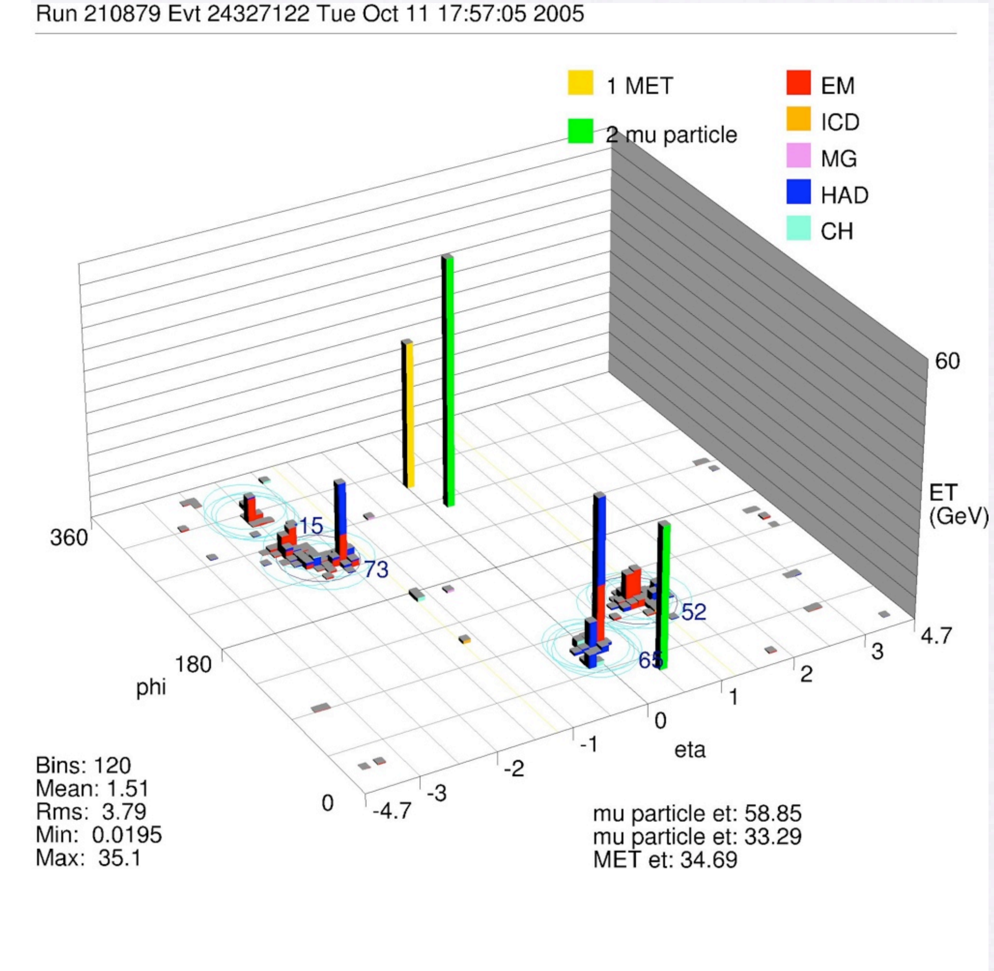
PLB 678, 45 (2009)

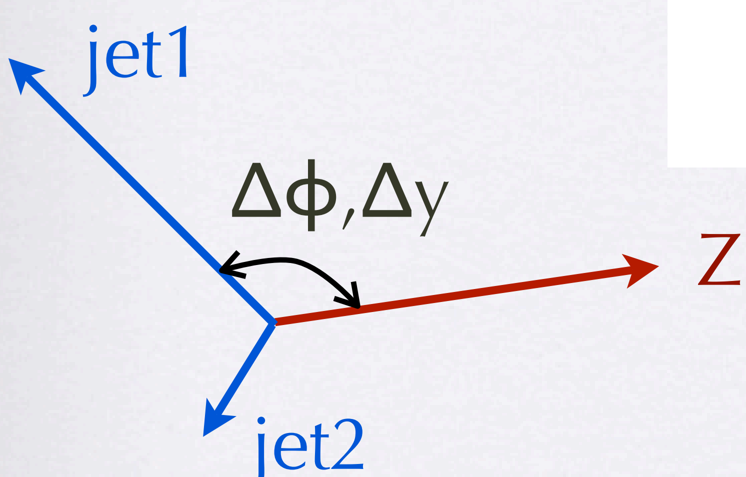
Z+jets - angular observables

- further constrains kinematics
- test of PS model assumptions
- first measurements at hadronic collider of
  - $\Delta\phi$(Z,leading jet)
  - Δy(Z,leading jet)
  - $y_{boost} = 1/2(y_Z+y_{jet})$









rapidity y = 1/2 ln(E+p_z/E-pz)

$\eta = -\ln(\tan\theta/2)$

Z->μμ + jet + X -- jet rapidity

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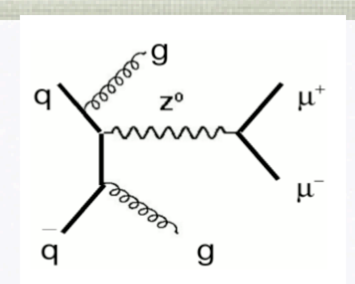
$\eta = -\ln(\tan\theta/2)$



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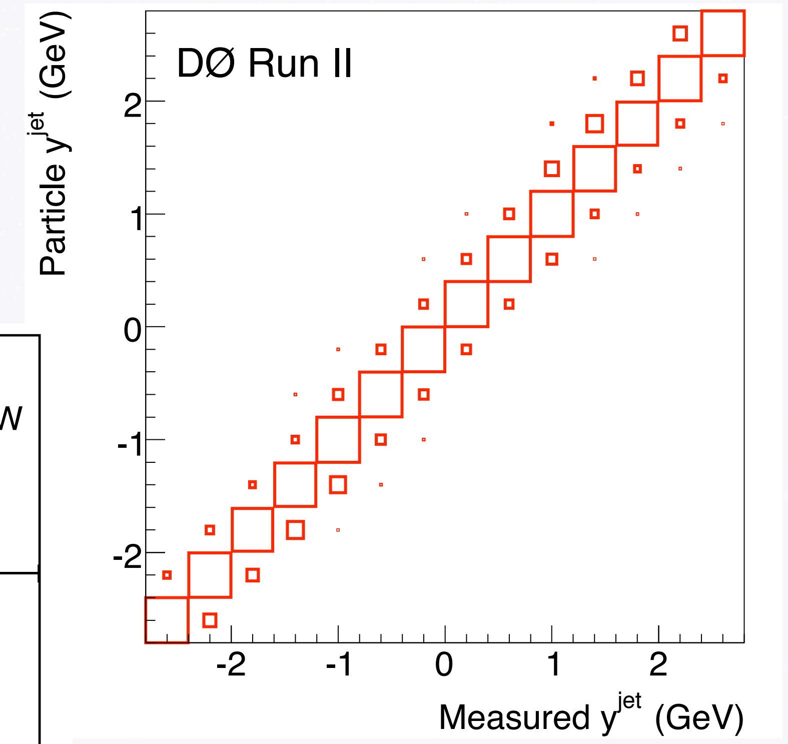
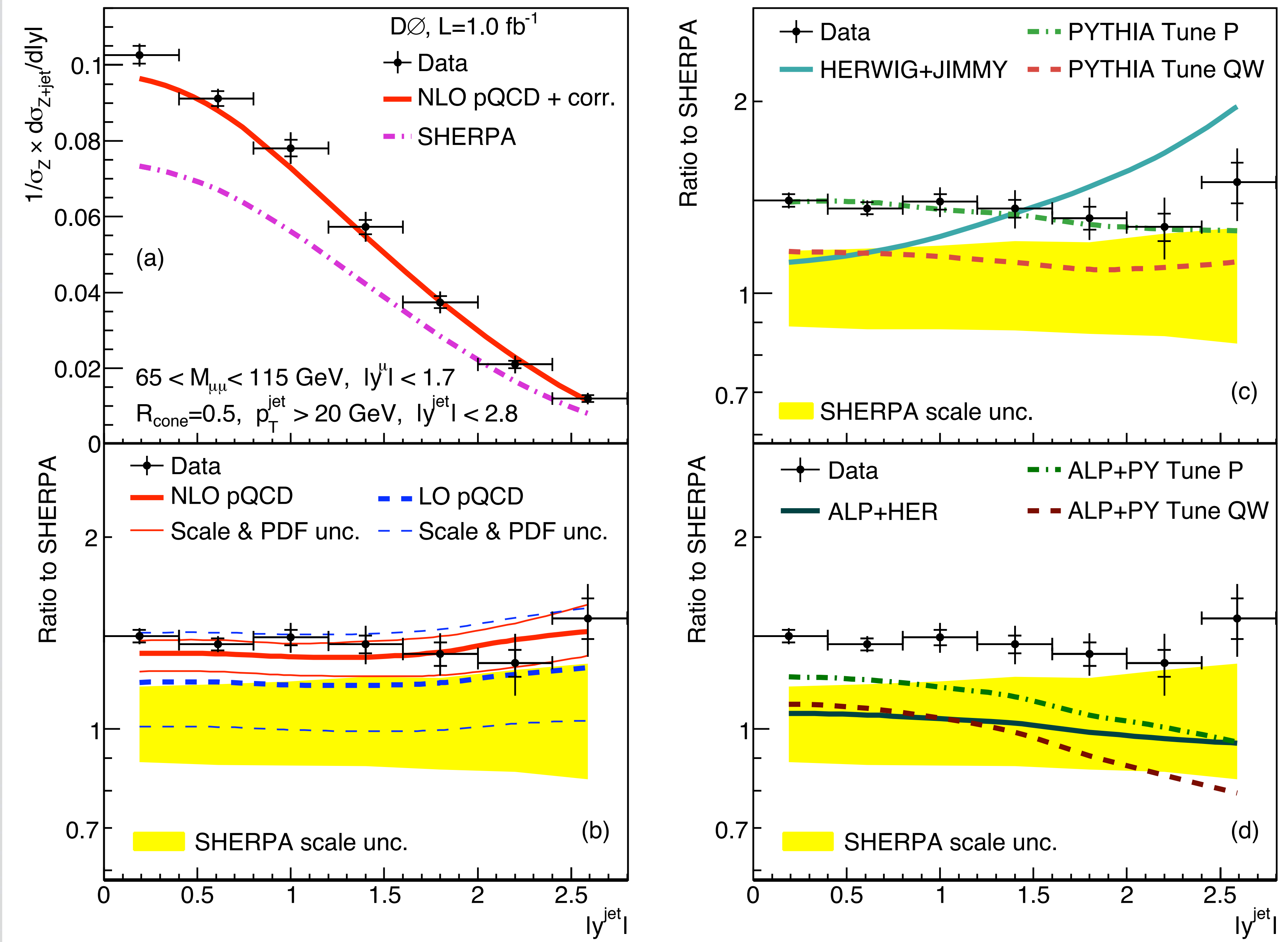
theory predictions updated since publication

ratios relative to Sherpa v1.1.3



migrations much reduced in y^{jet}



- MCFM,Sherpa describe y^{jet} shape well
- Alpgen+Pythia predicts narrower y^{jet} than data
- LO programs underestimate data normalization

PLB 669, 278 (2008)

Z->μμ + jet + X -- Z rapidity

rapidity $y = 1/2 \ln(E+p_z/E-p_z)$
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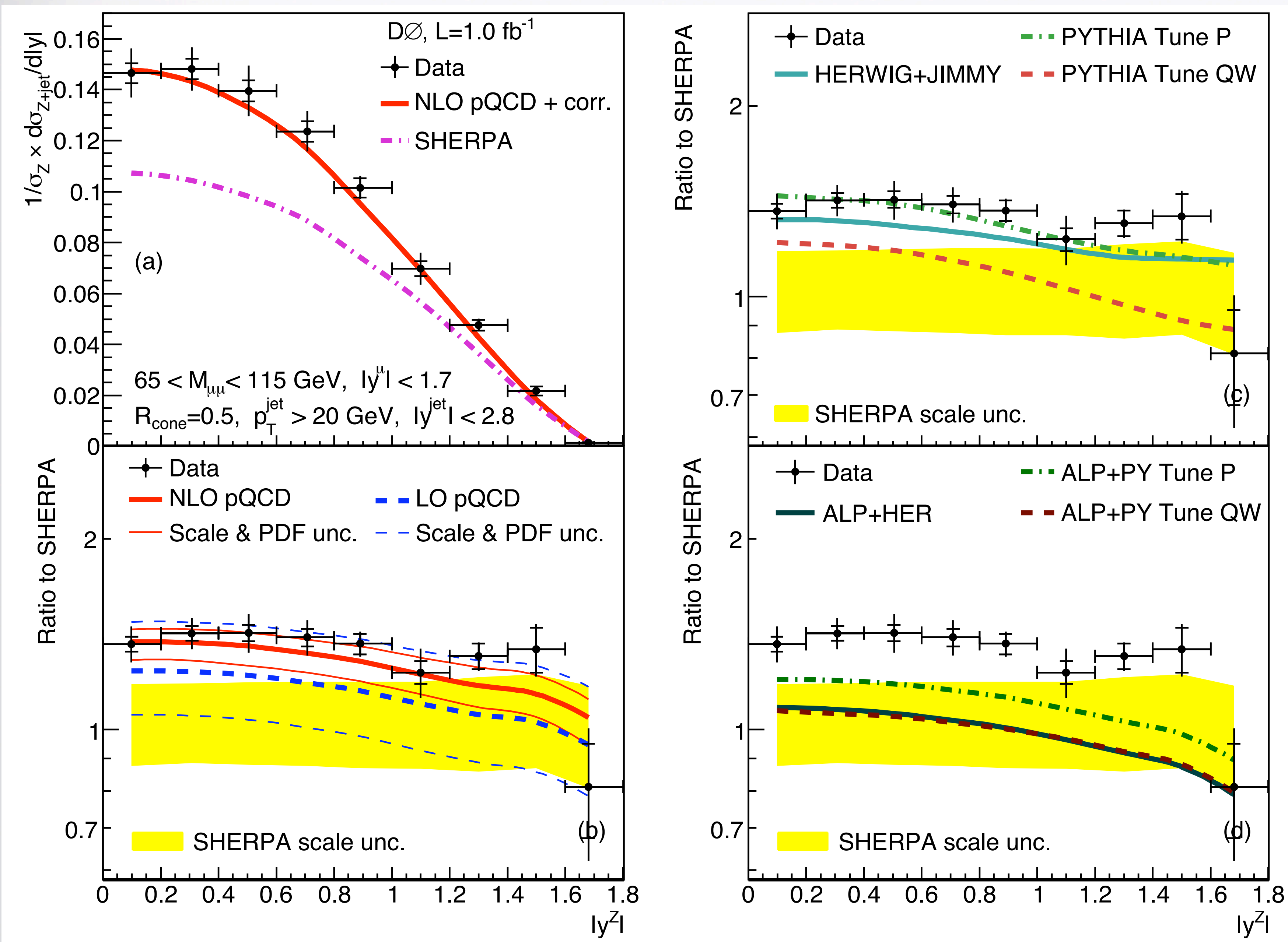

PLB 669, 278 (2008)

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(p_T ordered shower)
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(Q^2 ordered shower)
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ALPGEN v2.13
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ALPGEN v2.13
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CTEQ6.1M PDFs

- ✦ Most predictions describe y_Z shape

Z->μμ + jet + X -- Δφ

First measurement at a hadron collider!

sensitive to additional QCD radiation

Z p_T > 25 GeV

ratios relative to Sherpa v1.1.3

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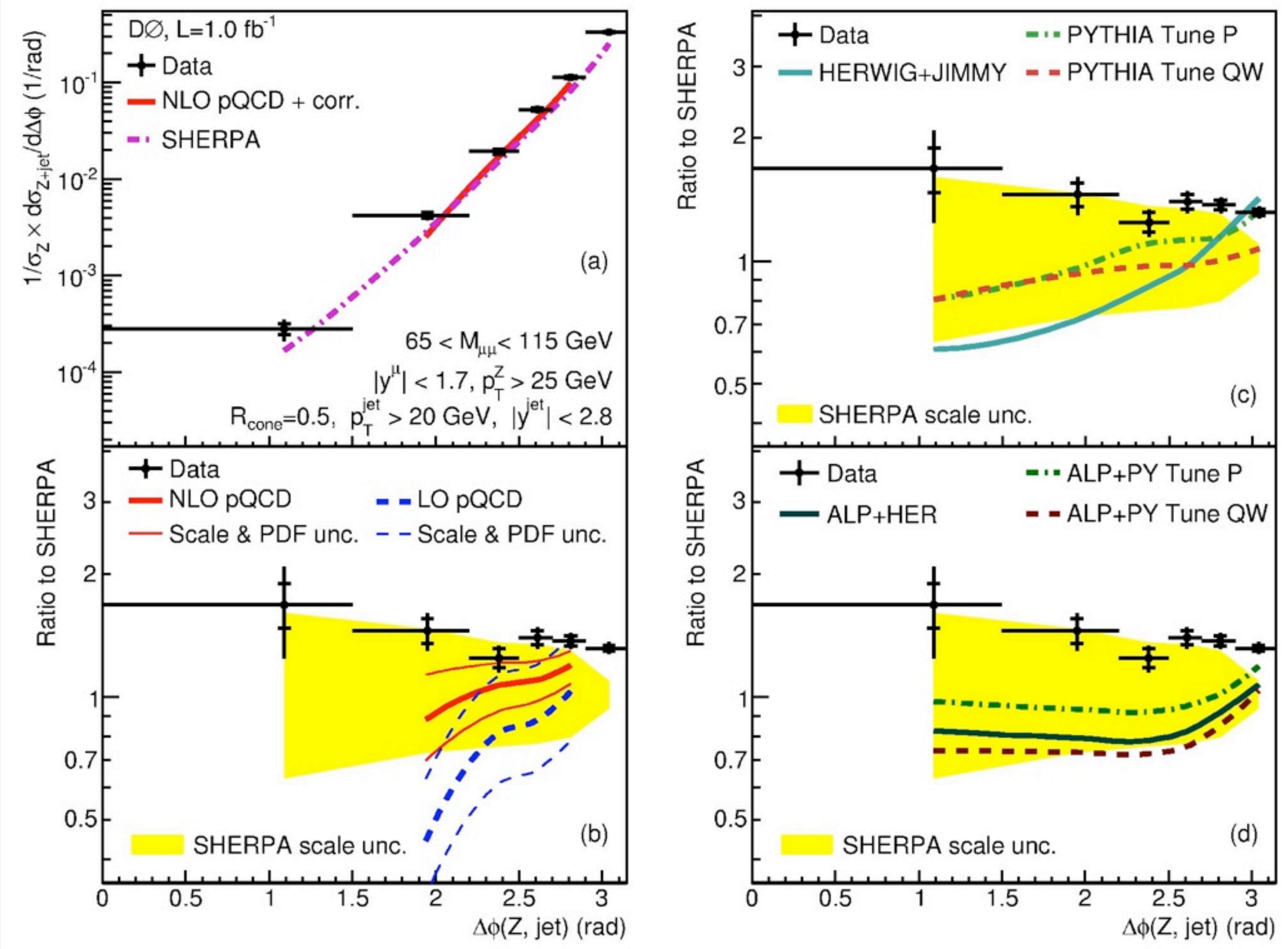
$\mu_r^2 = \mu_f^2 = p_{T,Z}^2 + M_Z^2$



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Small values of Δφ(Z,jet) excluded from MCFM due to importance of non-perturbative effects

Phys. Lett. B **682**, 370 (2010), arXiv.org:0907.4286

Z->μμ + jet + X -- Δφ

First measurement at a hadron collider!

Z p_T > 45 GeV

ratios relative to Sherpa v1.1.3

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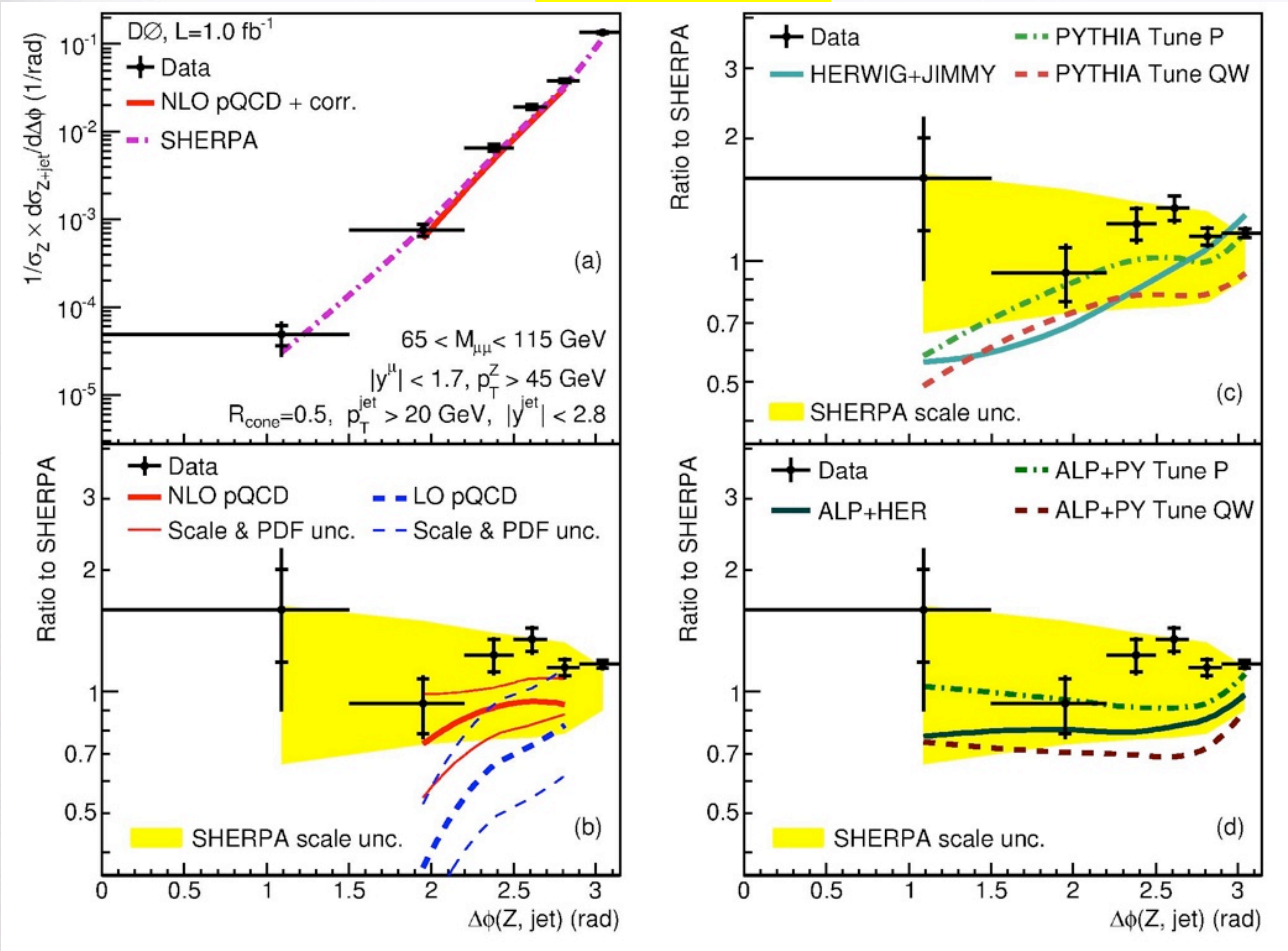

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Sherpa describes Δφ shape

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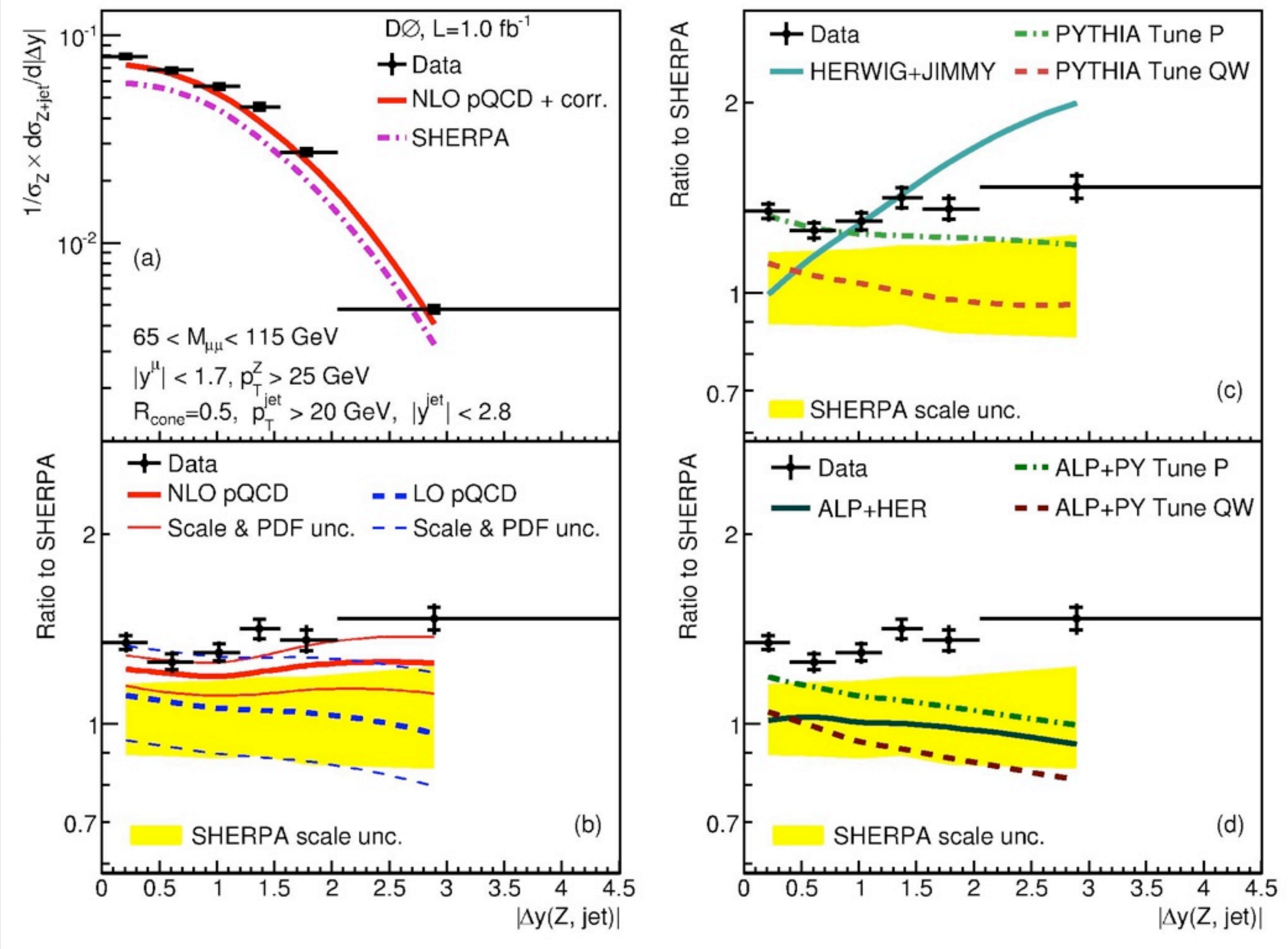

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Sherpa, NLO describe Δφ

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Z->μμ + jet + X -- y_{boost}

$y_{boost} = 1/2(y_Z + y_{jet1})$

First measurement at a hadron collider!

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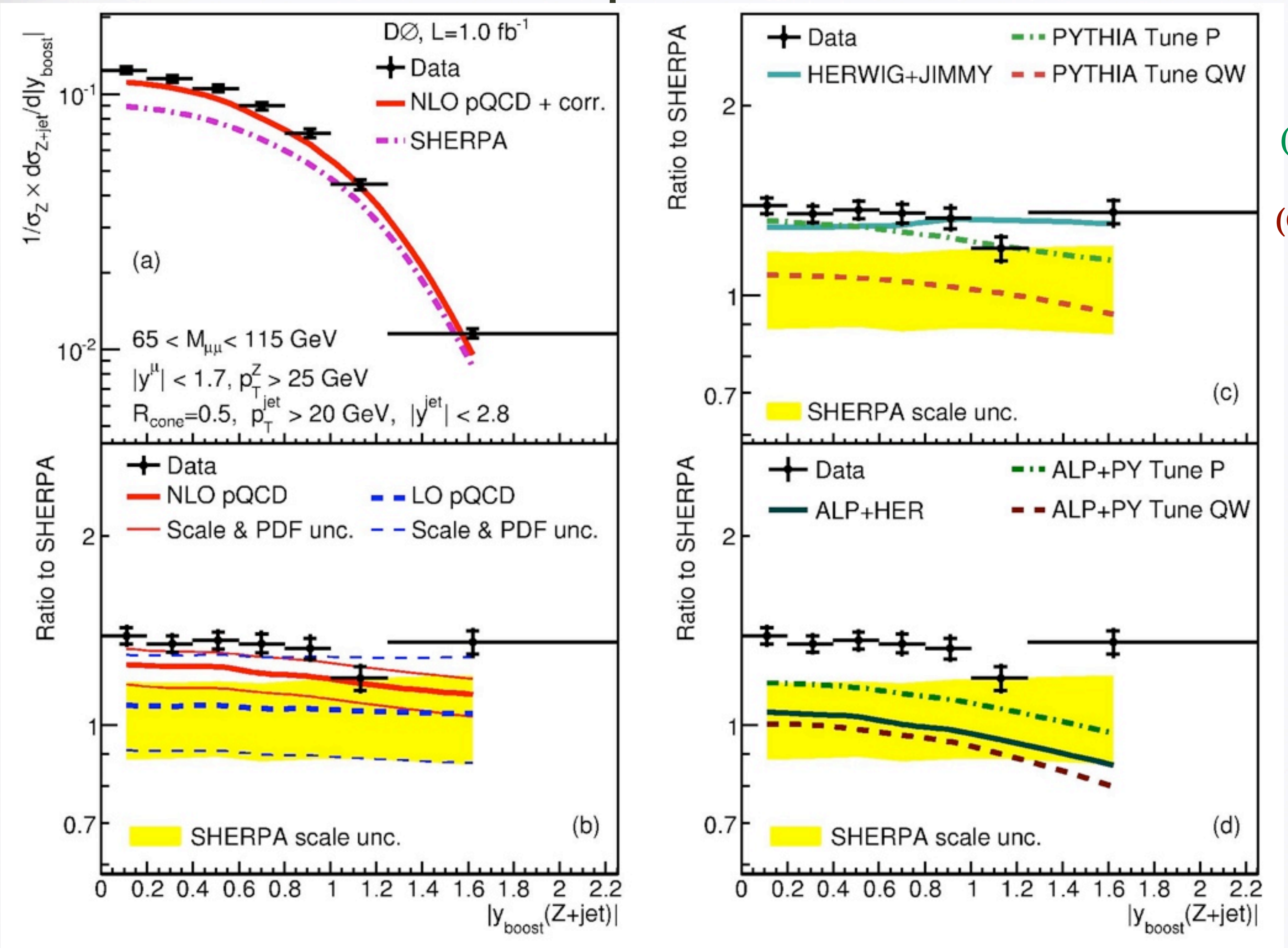

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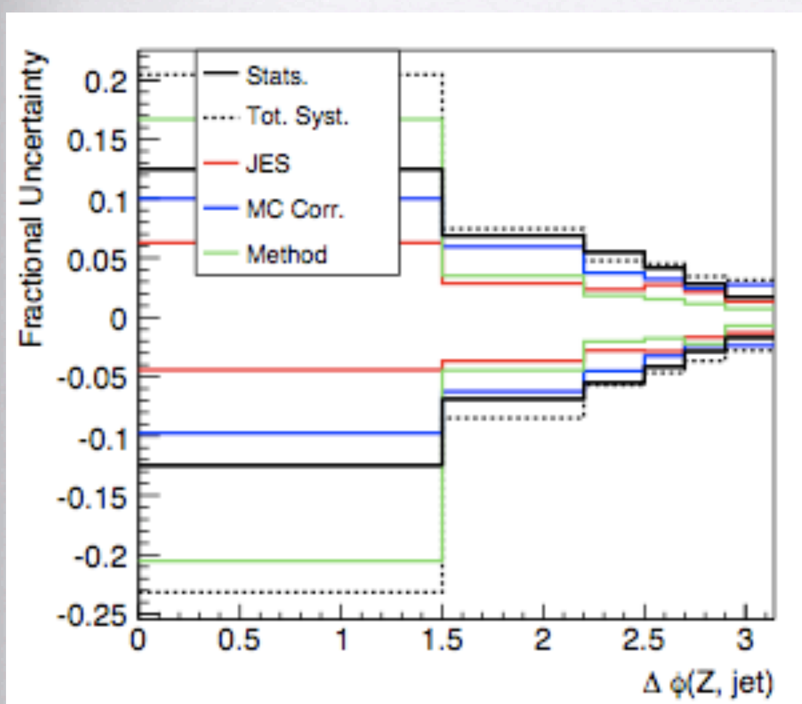
All predictions describe y_{boost}

Phys. Lett. B **682**, 370 (2010), arXiv.org:0907.4286

Uncertainties

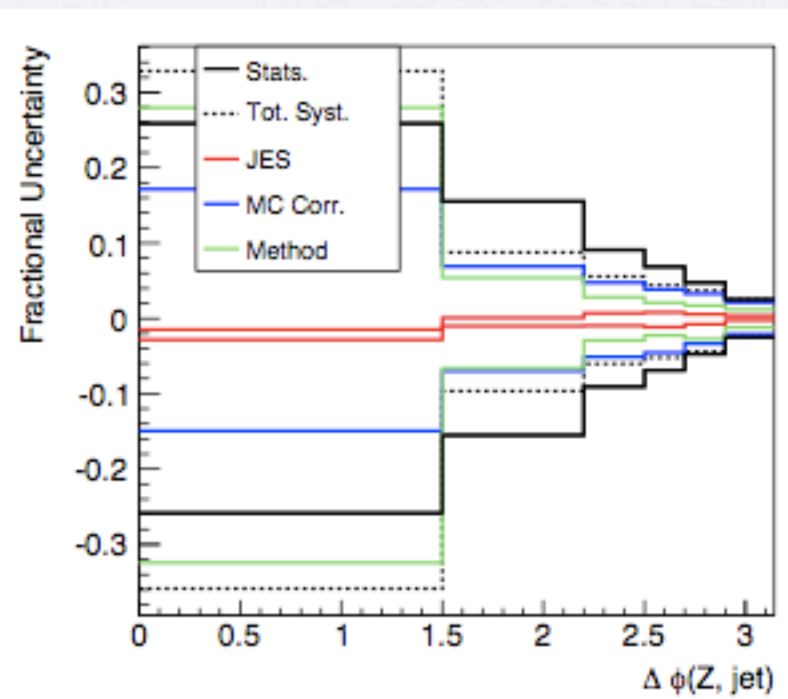
- Jet Energy Scale (JES) - up to 20% (leading jet) at high p_T
- MC Corrections: lepton resolution, jet resolution, efficiency
- Method: unfolding, model/simulation uncertainties

Z p_T > 25 GeV
Statistical, systematic errors are comparable



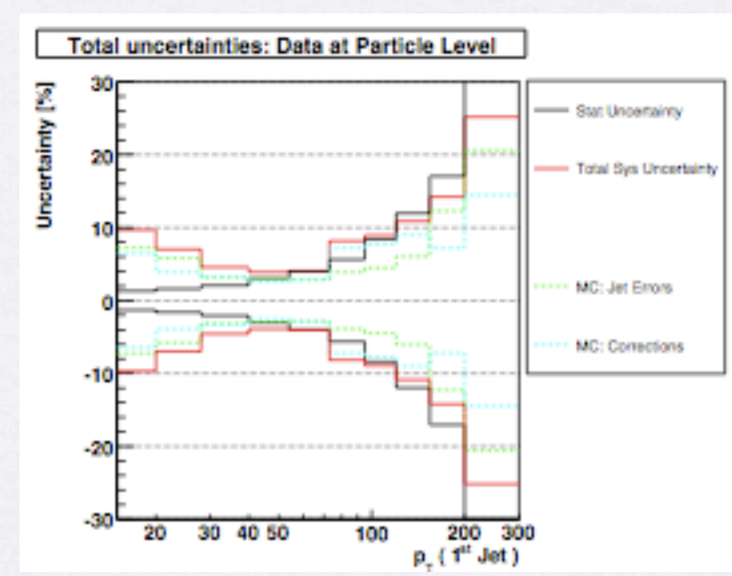
muon channel

Z p_T > 45 GeV
Statistical error dominates in most bins



muon channel

Systematic errors < 10% in bulk of data

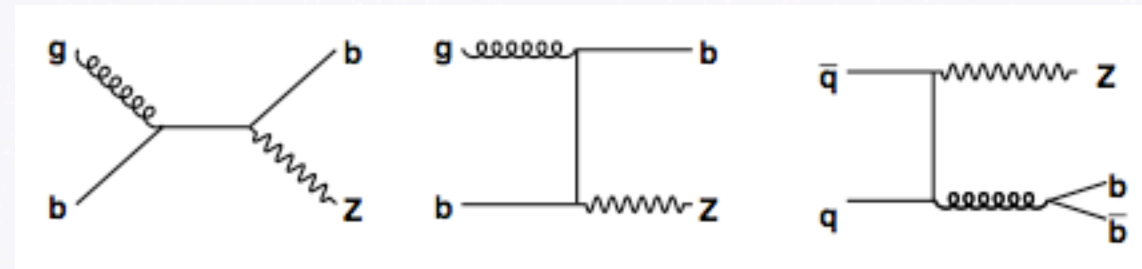


electron channel

Z+b jets

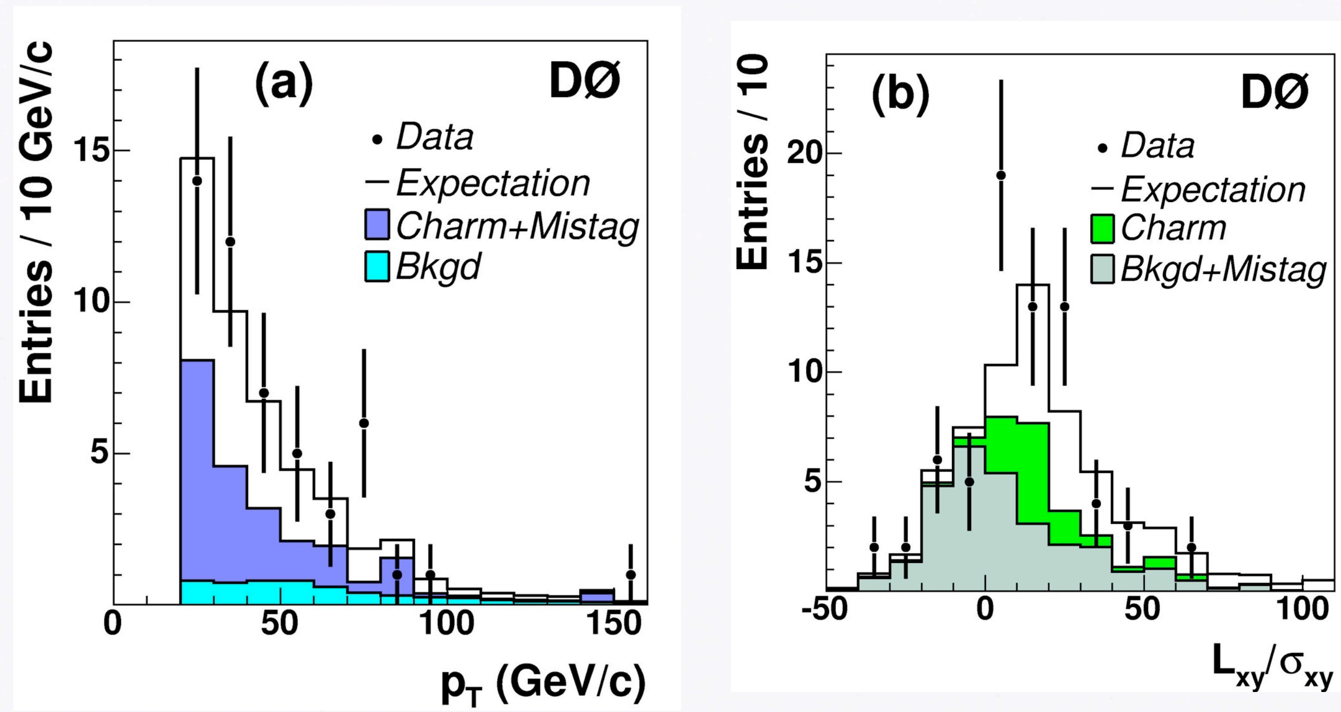
$\mathcal{L}$ = .18/fb

$Z \rightarrow ee/\mu\mu + b + X$
lepton $p_T > 15$ GeV
jet $p_T > 20$ GeV
jet $|\eta| < 2.5$
D0 RunII Midpoint Cone
jets with R=0.5
secondary vertex tagging



Measure:

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



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

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

a new result with 4 fb^{-1} is coming soon

W+c jets

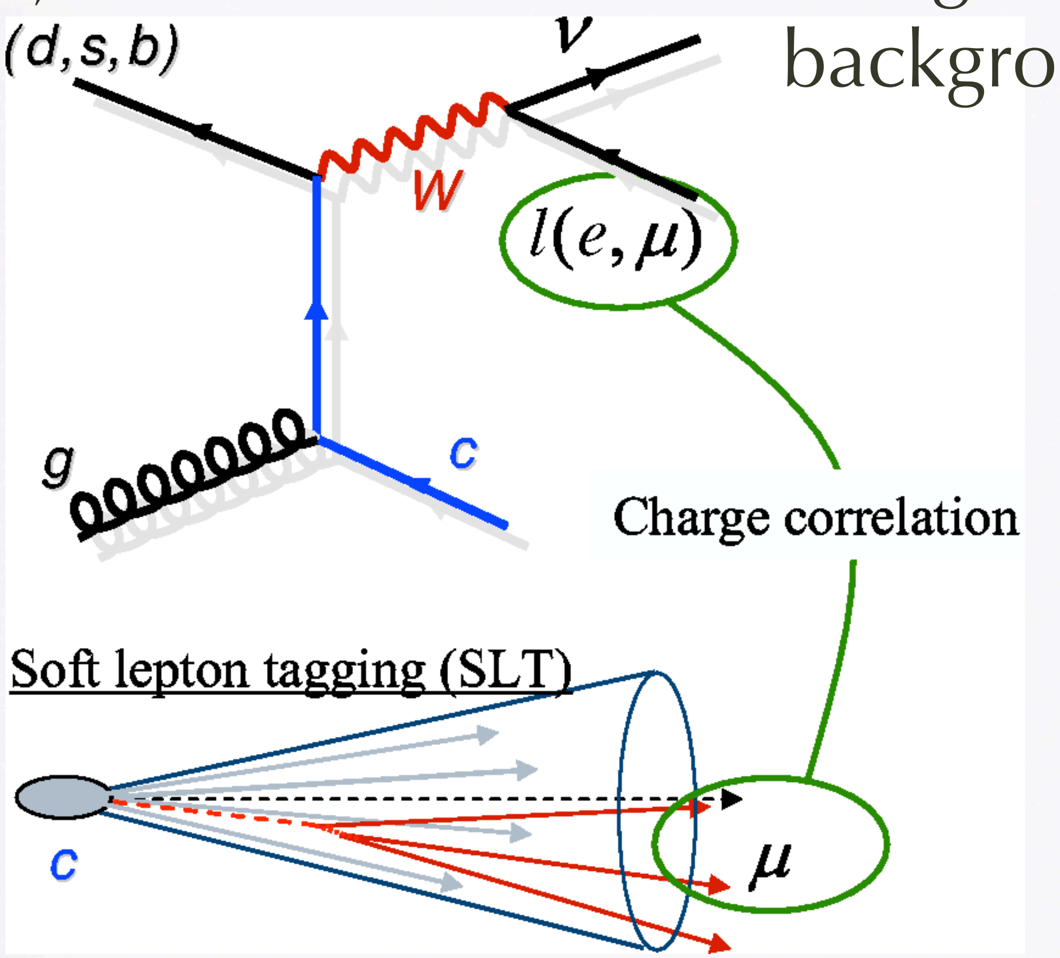
$\mathcal{L}$ = 1/fb

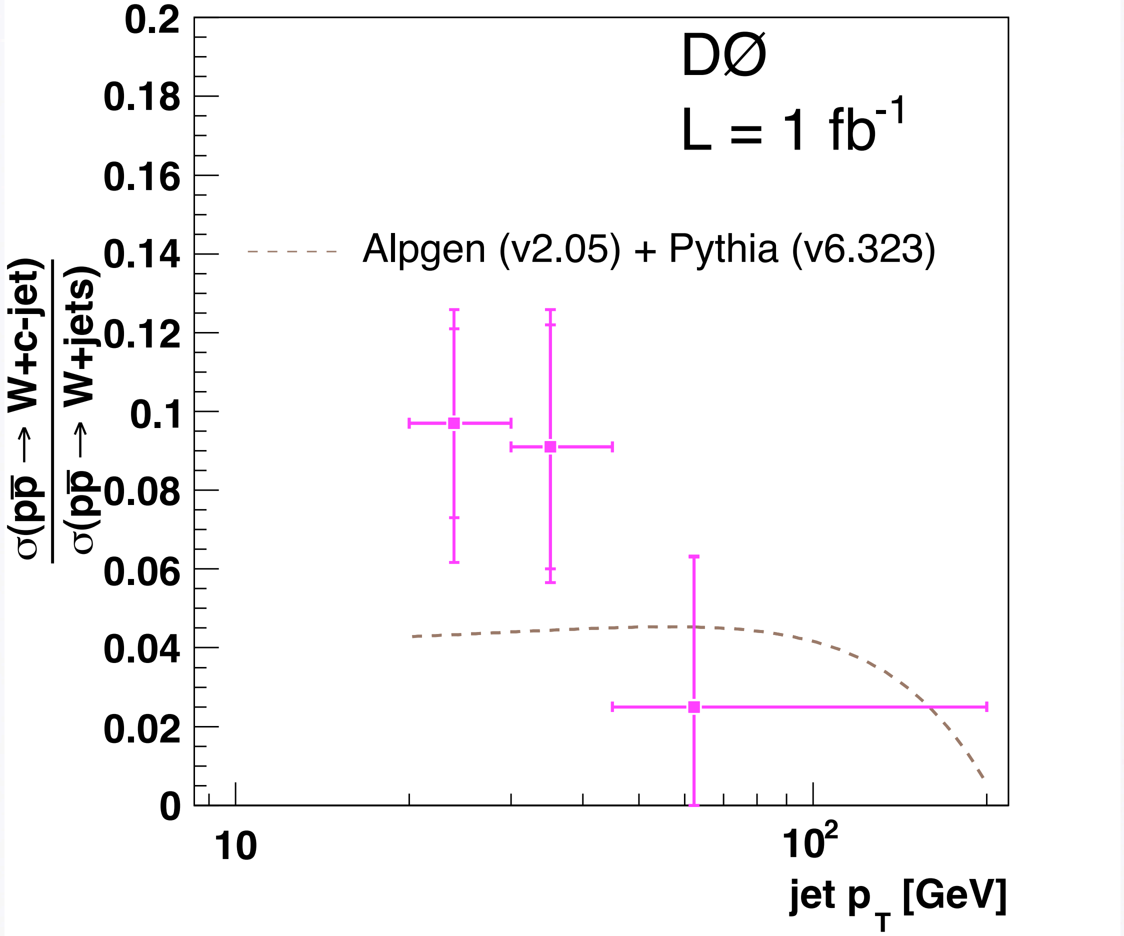
Sensitive to s-quark PDF

90% s, 10% d

signal: OS>>SS
backgrounds: OS~SS

Measurement cuts:
lepton p_T > 20 GeV
missing E_T > 20 GeV
D0 midpoint R_{cone}=0.5,
p_T^{jet} > 20 GeV, $|\eta^{jet}|$ < 2.5



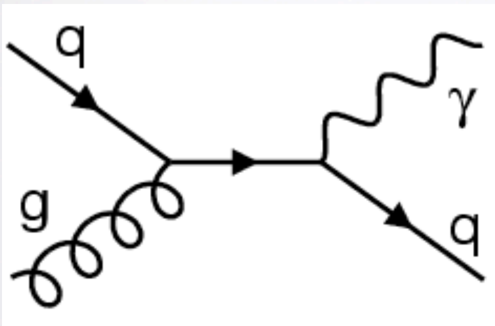


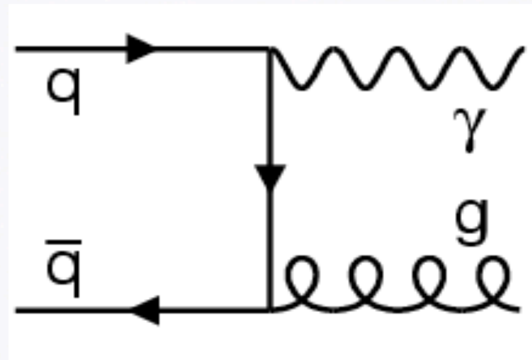
Alpgen prediction: 0.04 pb
Result: measure σ(W+c)/σ(W+jets)
$= 0.074 \pm 0.019\ (\text{stat}) \pm ^{+0.012}_{-0.014}\ (\text{sys})$

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

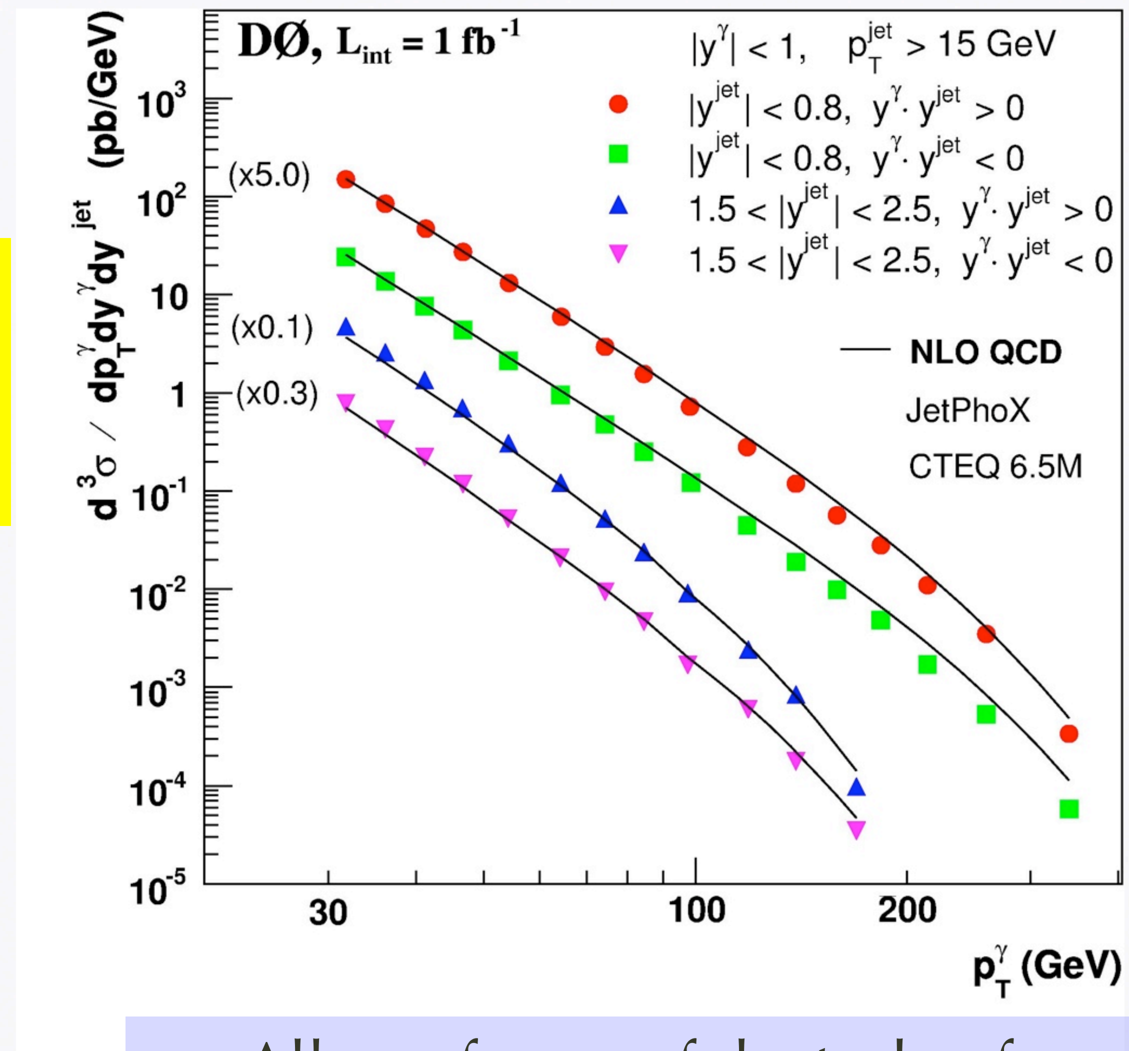
isolated γ+jets

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



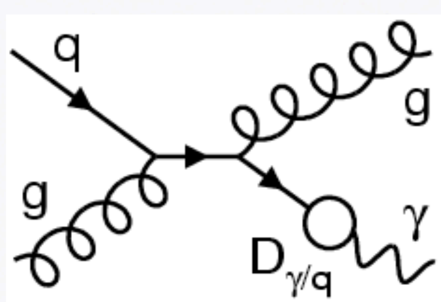


Huge statistics compared to W,Z
Triple differential cross sections!



direct photons emerge from hard subprocess
→ direct probe of hard scattering process
gluon sensitivity at LO

Also fragmentation contributions:



suppress using isolation cuts
observable: isolated photons

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

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

isolated γ+jets

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

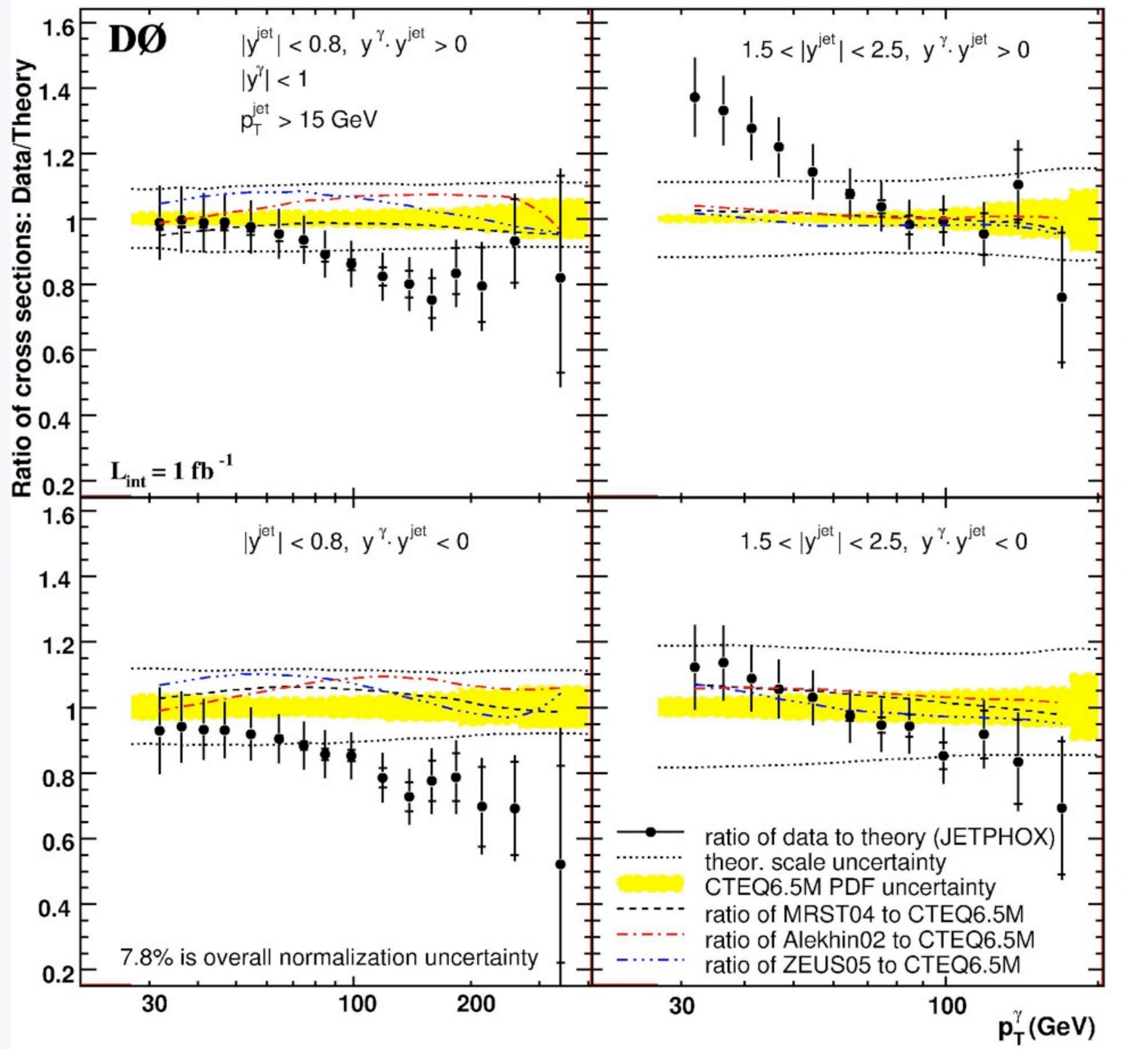
Huge statistics compared to W,Z
Triple differential cross sections!

- measure in 4 regions of y^{γ} / y^{jet}
  - photon: central
  - jet: central / forward
  - same side / opposite side

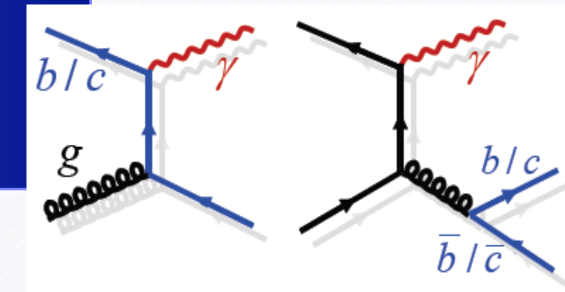
NLO theory cannot simultaneously describe photon p_T and jet rapidity over entire measured range

What's missing?
HO corrections?
Resummation?

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



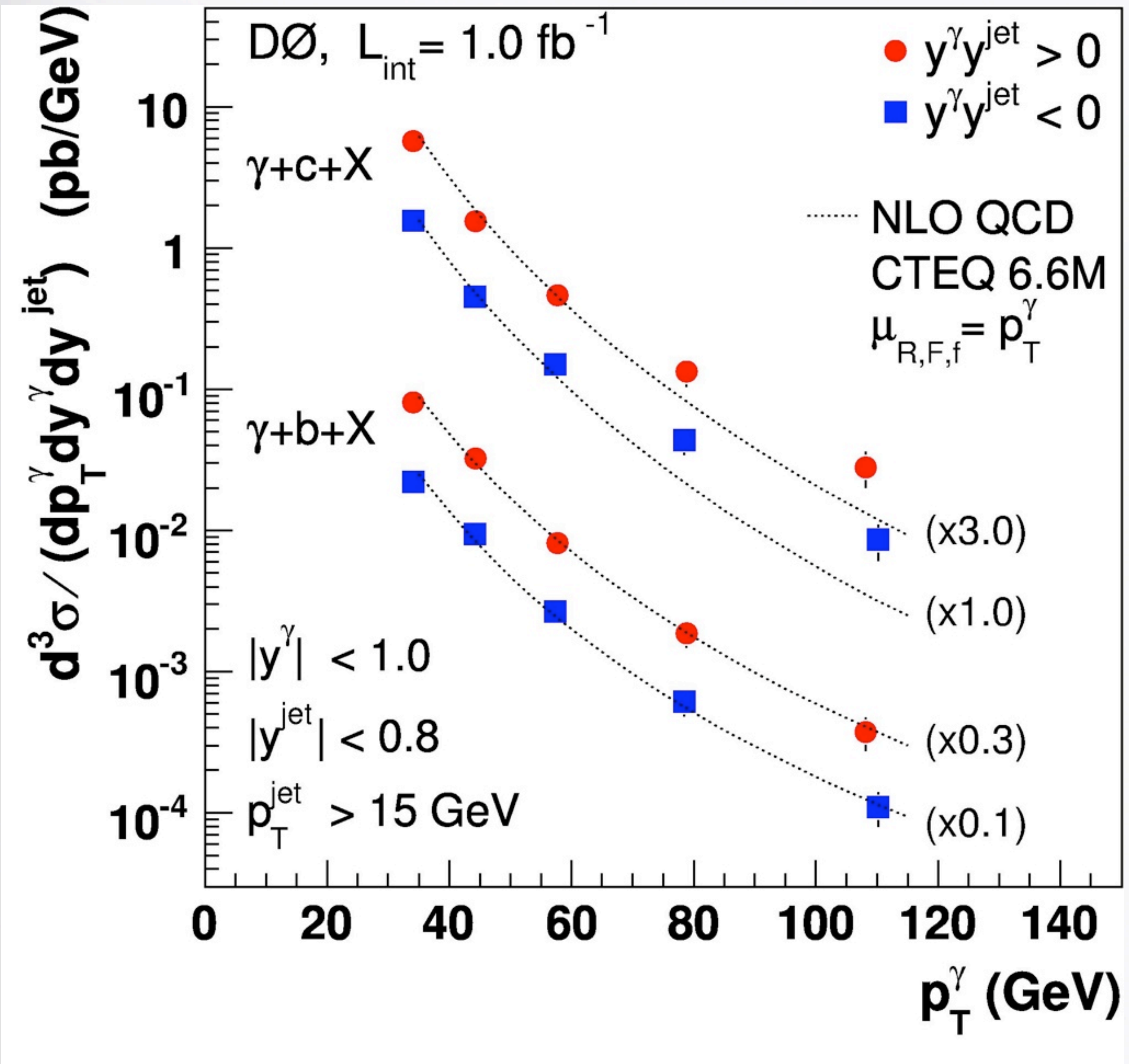
isolated γ+b,c jets

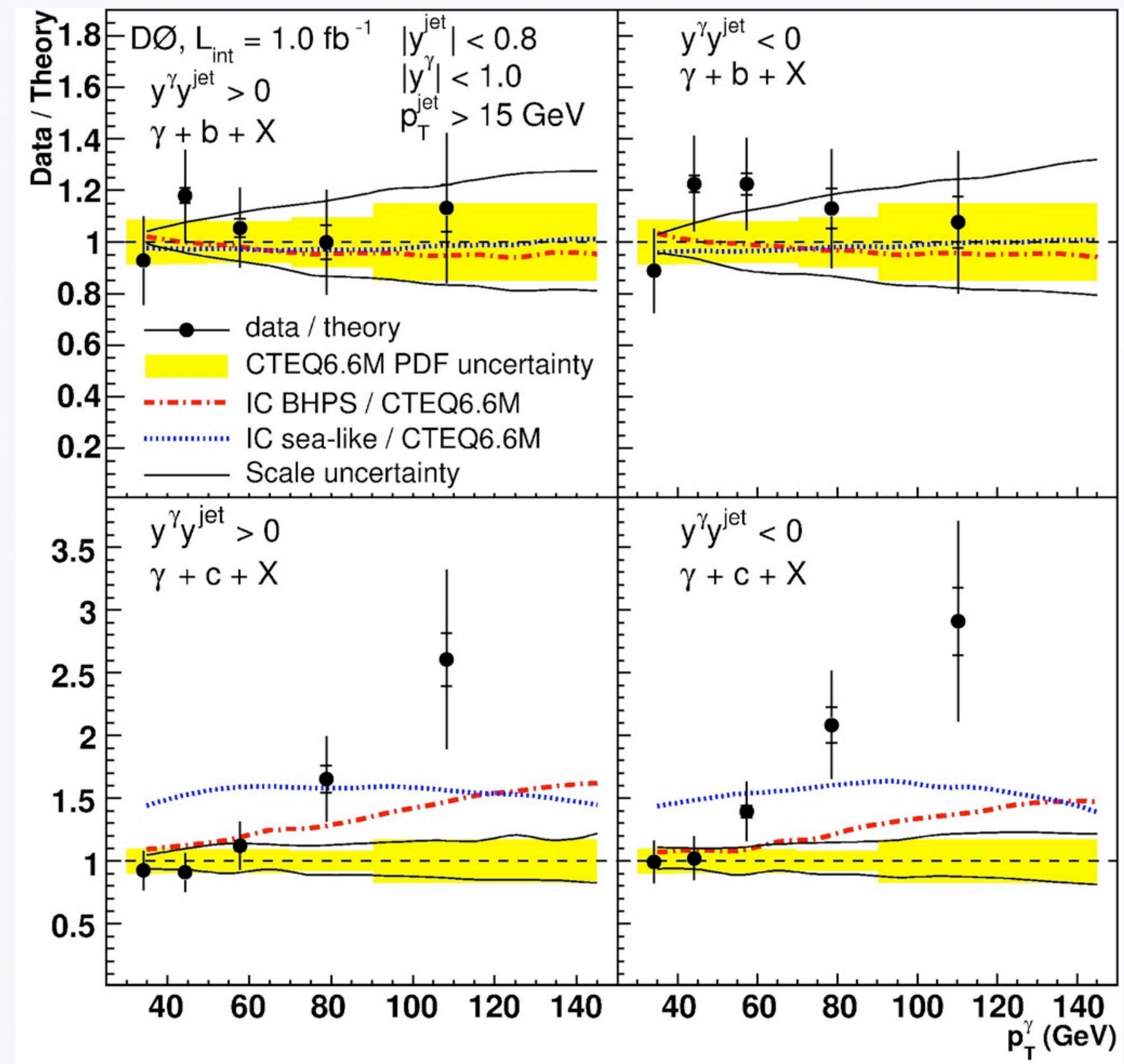


$\mathcal{L} = 1.0/\text{fb}$

Triple differential cross sections

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





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

γ+b: good agreement with NLO

γ+c: Disagreement with theory for photon $p_T > 70$ GeV

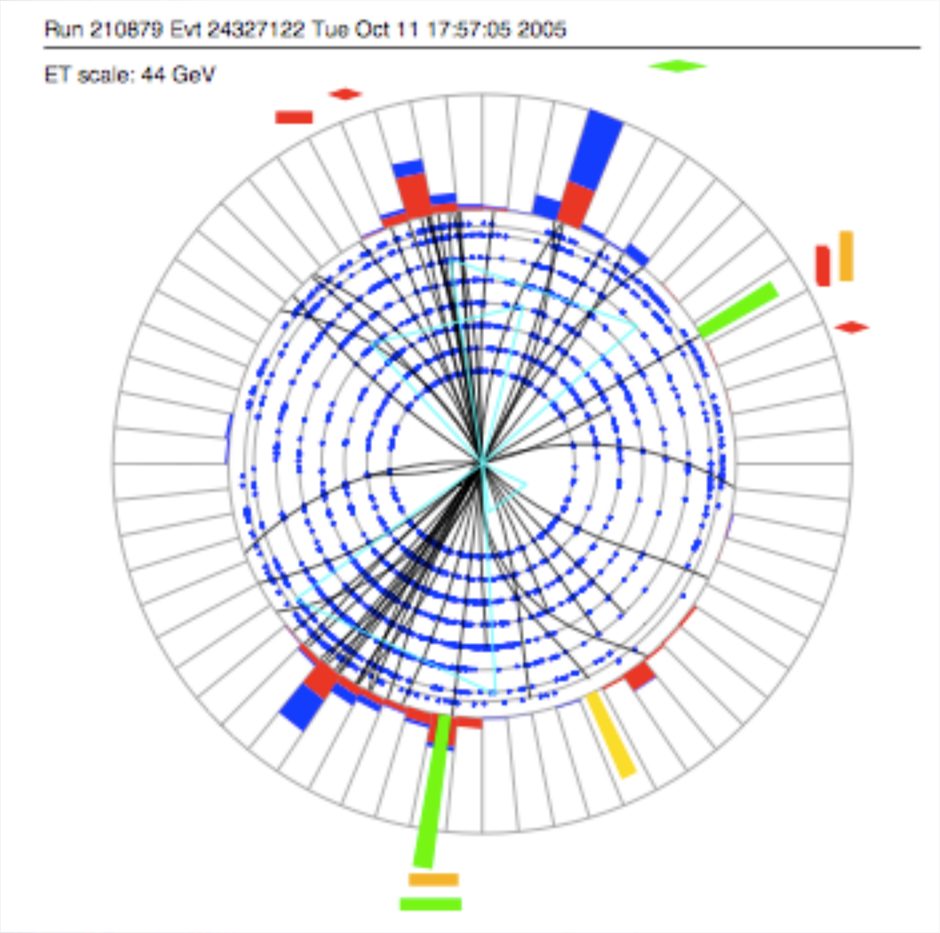
Summary and Conclusion

- 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.
- D0 will continue to explore these processes

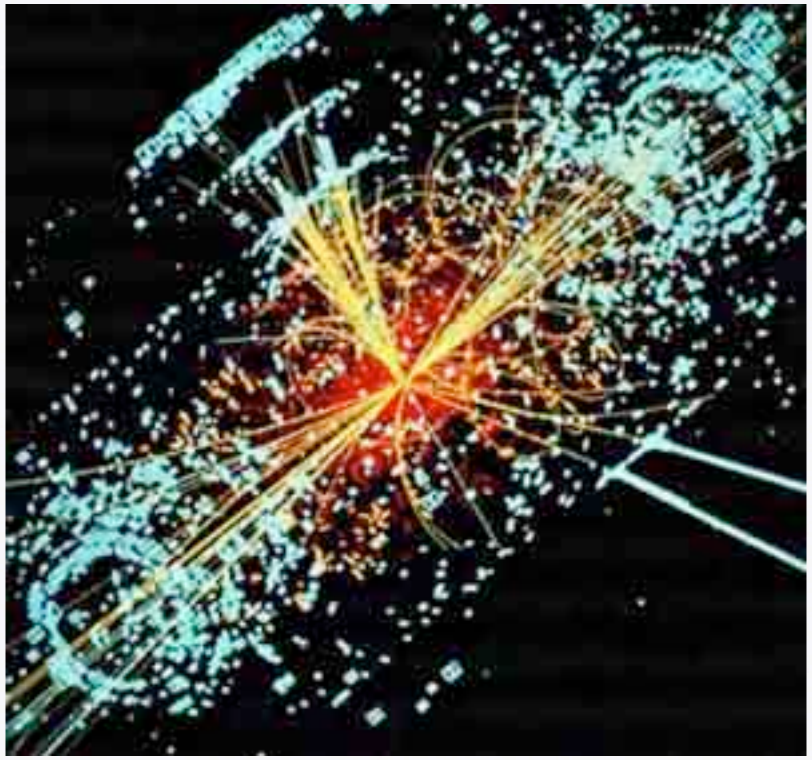
http://www-d0.fnal.gov/Run2Physics/WWW/results/qcd.htm

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

D0 RunII Midpoint Jet Cone Algorithm

"particle" = {experiment: calorimeter towers / MC: stable particles / pQCD: partons}

three parameters: $R_{cone} = 0.5$ or 0.7, $p_{T\,min} = 8$ GeV, overlap fraction $f = 50\%$

- Use all particles as **seeds**
  — make cone of radius $\Delta R = \sqrt{(\Delta y^2 + \Delta\phi^2)} < R_{cone}$ around seed direction
  — proto jet: add particles within cone in the "E-scheme" (adding four-vectors)
  — iterate until stable solution is found with: cone axis = jet-axis
- Use all **midpoints** between pairs of jets as **additional seeds** $\Longrightarrow$ infrared safety!!!
  — (repeat procedure as described above)

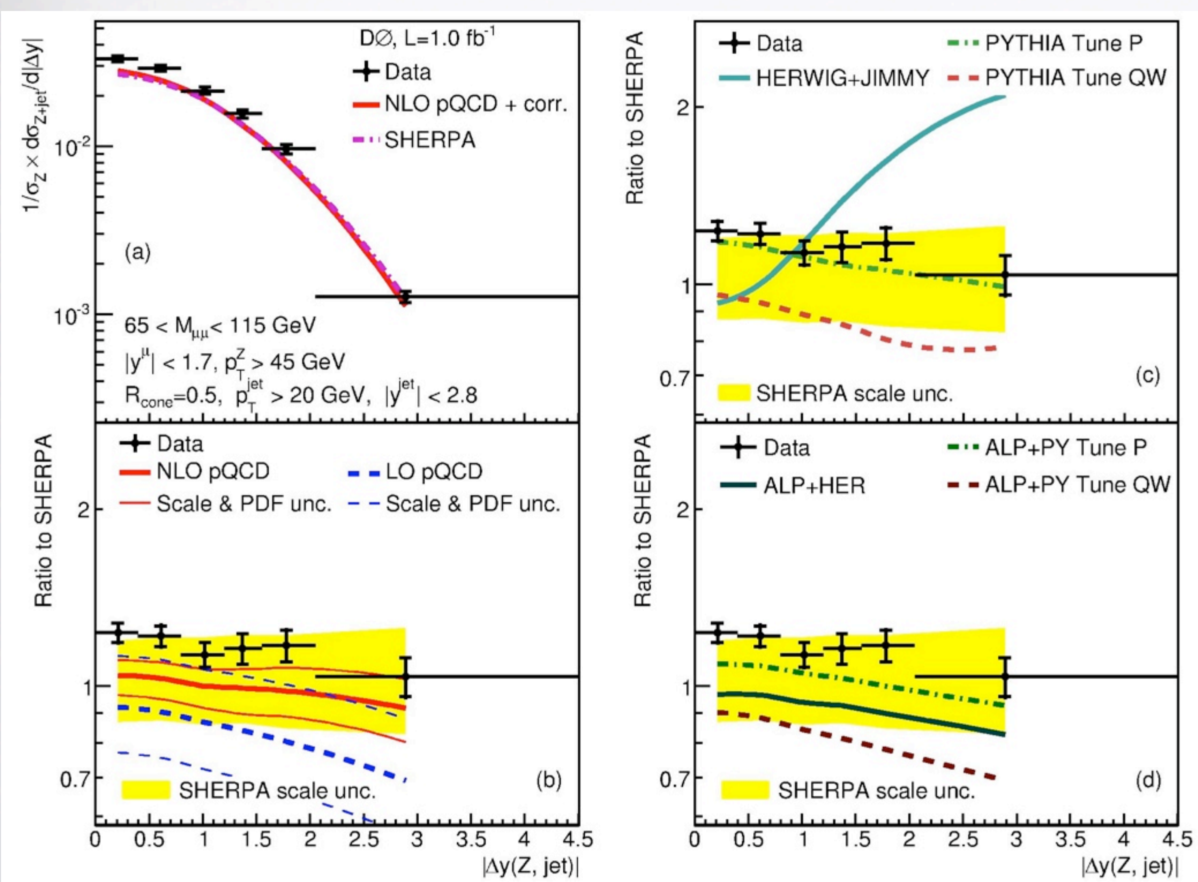
- Take all solutions from the first two steps:
  — remove identical solutions
  — remove proto-jets with $p_{T\,jet} < p_{T\,min}$
- Look for jets with **overlapping cones**:
  — merge jets, if more than a fraction f of $p_{T\,jet}$ is contained in the overlap region
  — otherwise split jets: assign the particles in the overlap region to the nearest jet
  ($\rightarrow$ and recompute jet-axes)

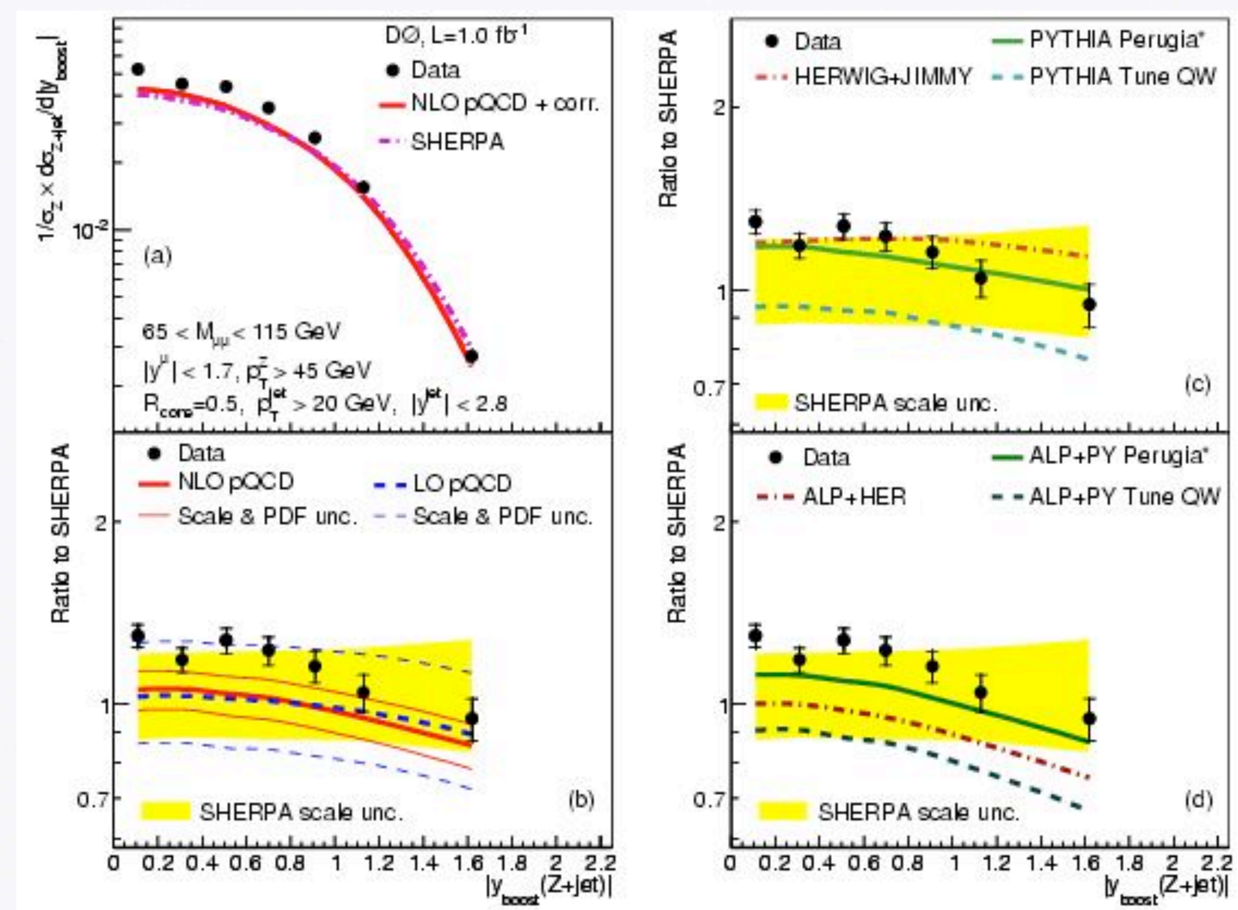
Z->μμ + jet + X - p_T spectra

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 > 45 GeV (avoid UE)





Phys. Lett. B **682**, 370 (2010), arXiv.org:0907.4286

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)