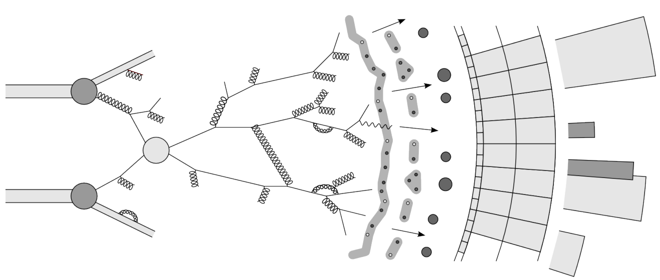
Workshop on Electroweak Corrections for LHC Physics
Sept 23rd – Sept 26th 2012, IPPP Durham

Inclusive Jet and Dijet Production



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on behalf of the ATLAS Collaboration

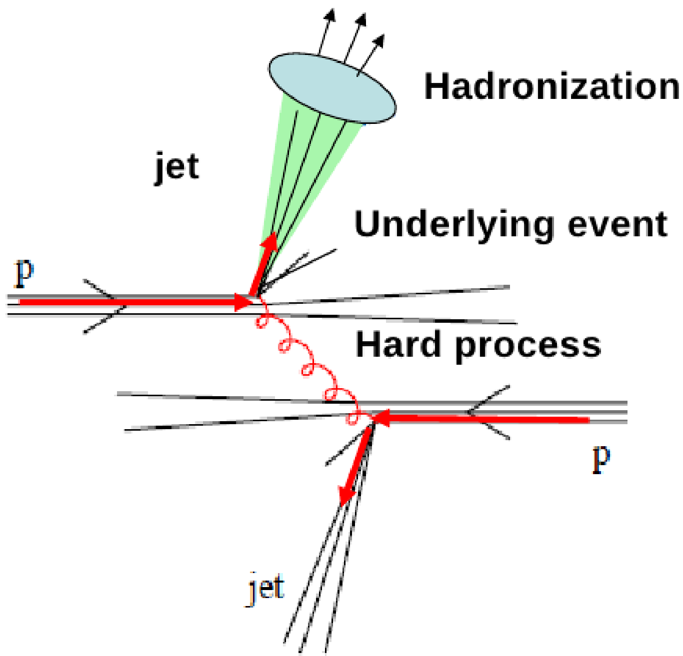
International Research Training Group
Development and Application of Intelligent Detectors

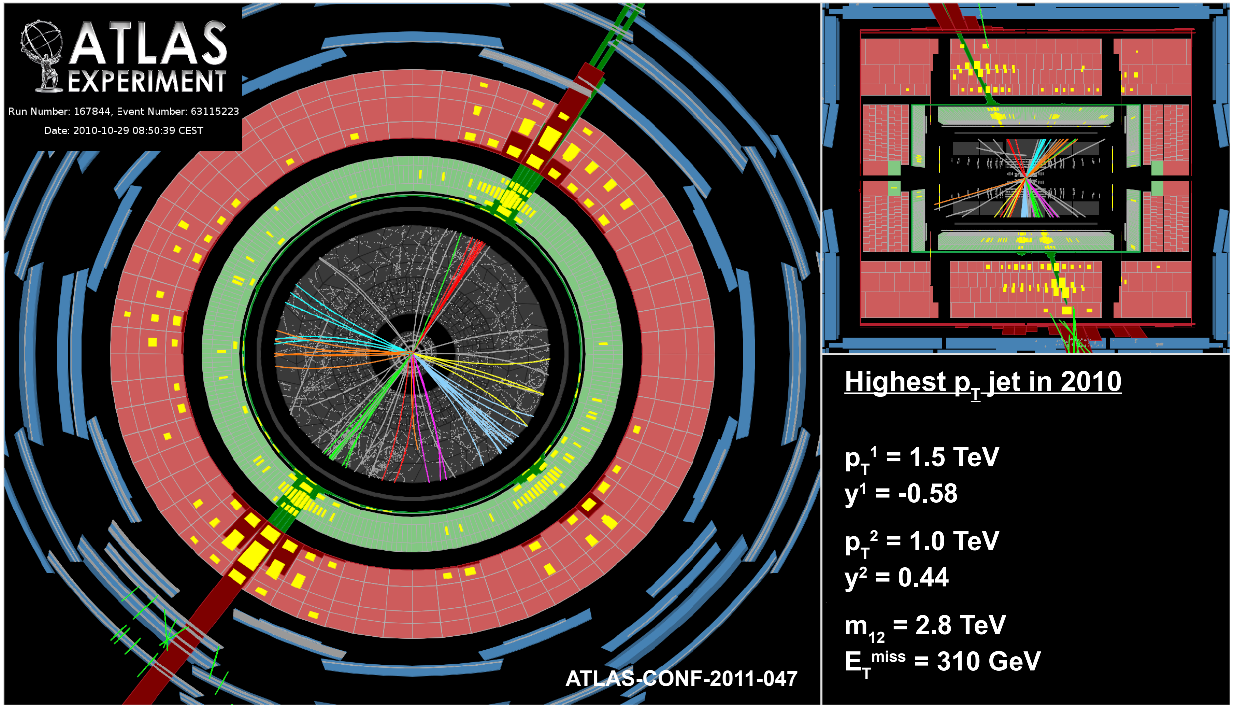
HGSFP

PHYSICS AT THE TERA SCALE
Helmholtz Alliance

FSP 101
ATLAS

Introduction



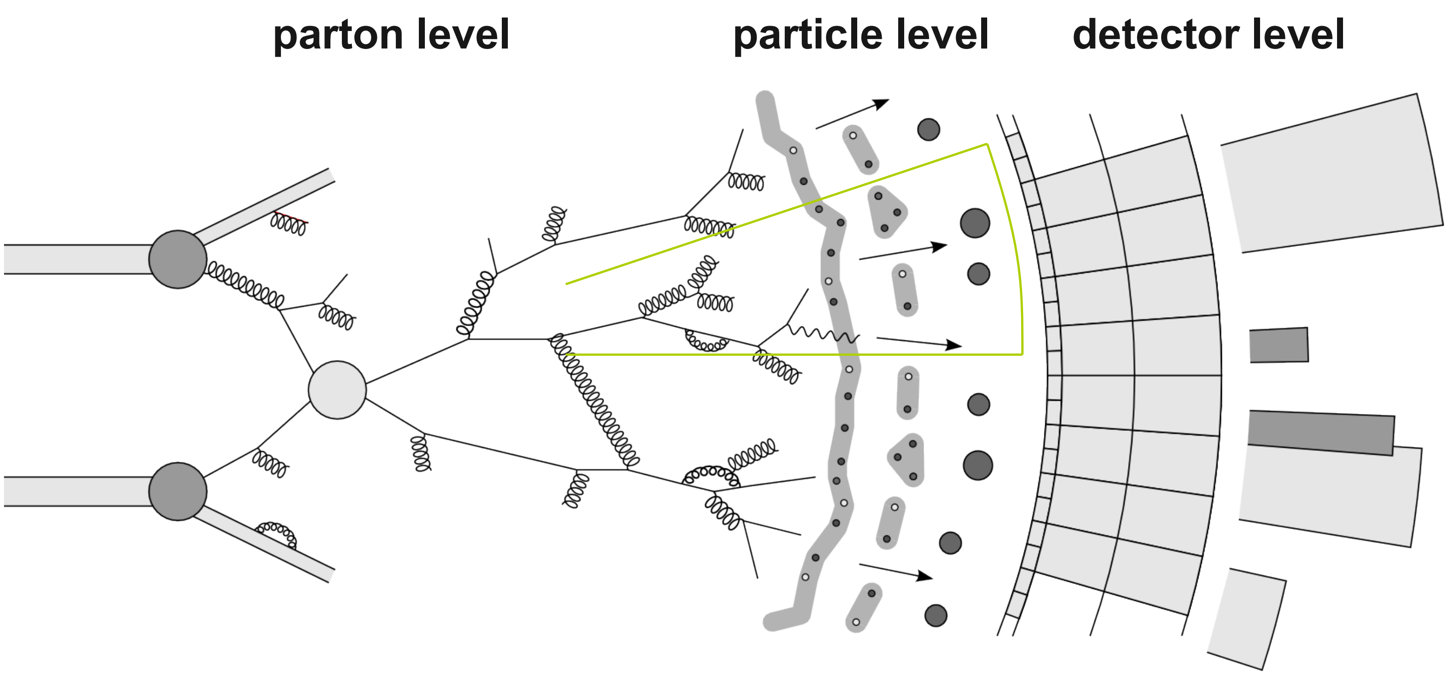


- Jet production is the dominant process at the LHC
- Probe pQCD at high p_T
  - Hard process: scattering of quarks, gluons described by pQCD → proton structure (PDFs)
- Probe non-perturbative effects
  - Underlying event
  - Hadronisation

Outline

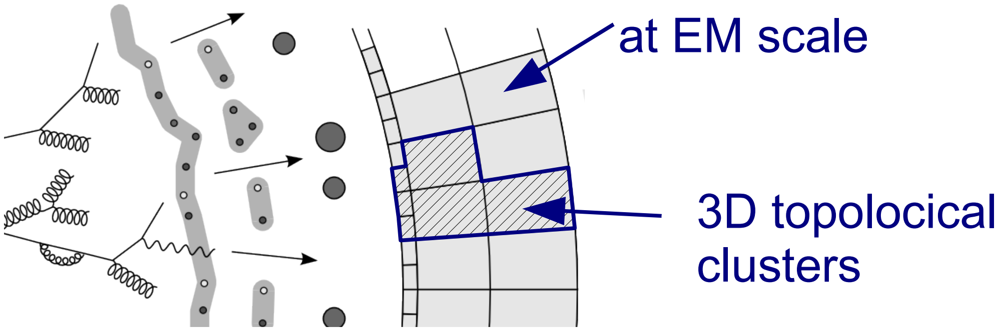
- Introduction to ATLAS jet measurement
- Jet production measurements:
  - Inclusive jet and dijet measurement at 7TeV
  - Ratio measurement between cross sections at 2.76 and 7 TeV
- Studies of effect from electroweak effects on jet measurement
  - Size of additional contributions
  - Effect on jet measurements
- Summary

ATLAS jet measurements: Introduction



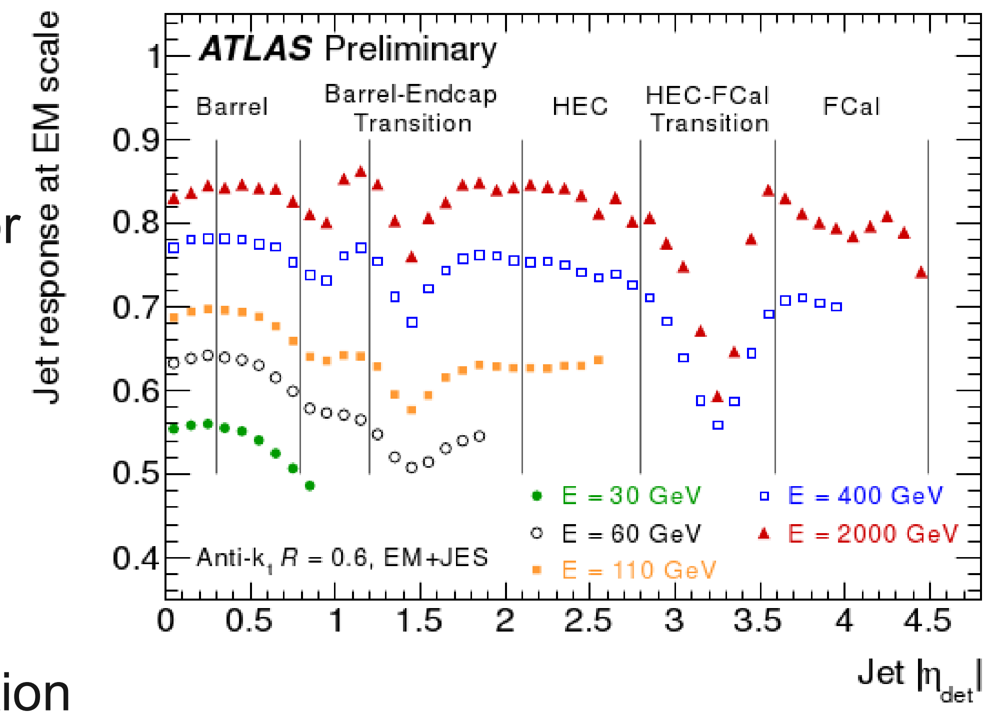
- Jet algorithm: anti-kt with distance parameter R=0.4, R=0.6
  → defined at parton / particle / detector level
- Measurement:
  - Same procedure for all measurements here (next slides)
  - Unfolding of data from detector effects (→particle level)
- Predictions:
  - NLO pQCD with non-perturbative corrections (→particle level)
  - Compare to different generators, tunes and PDFs

Jet Reconstruction and Energy Calibration



- Input: 3D topological clusters measured at EM scale anti k_T algorithm
- (η, p_T) dependent correction factor for each jet:

$$E_{truth} / E_{calo}^{EM}$$



- *EM + JES scheme* simple default Monte Carlo based calibration
  → simple, well understood uncertainty
- Pythia is default Monte Carlo simulation
  - Pythia 6.423, MRST LO* PDF, AMBT1 tune
  → best descriptions of jet properties

Experimental Setup

ATLAS jet data with proton-proton collisions:

- 2010 at 7TeV L = 37.3 ± 1.3 pb^{-1} [p_T > 20 GeV]
- 2011 at 7TeV L = 4.8 ± 0.2 fb^{-1} [extend high p_T]
- 2011 at 2.76TeV L = 202 ± 6 nb^{-1} [ratio measurement]

Event selection:

- ≥1 primary vertex
- Single jet trigger for given p_T / rapidity bin
  (minimum bias at low p_T)
- *EM + JES scheme* calibration
- Jet quality selection criteria
  → remove non-collision jets (cosmics, beam background, noise)

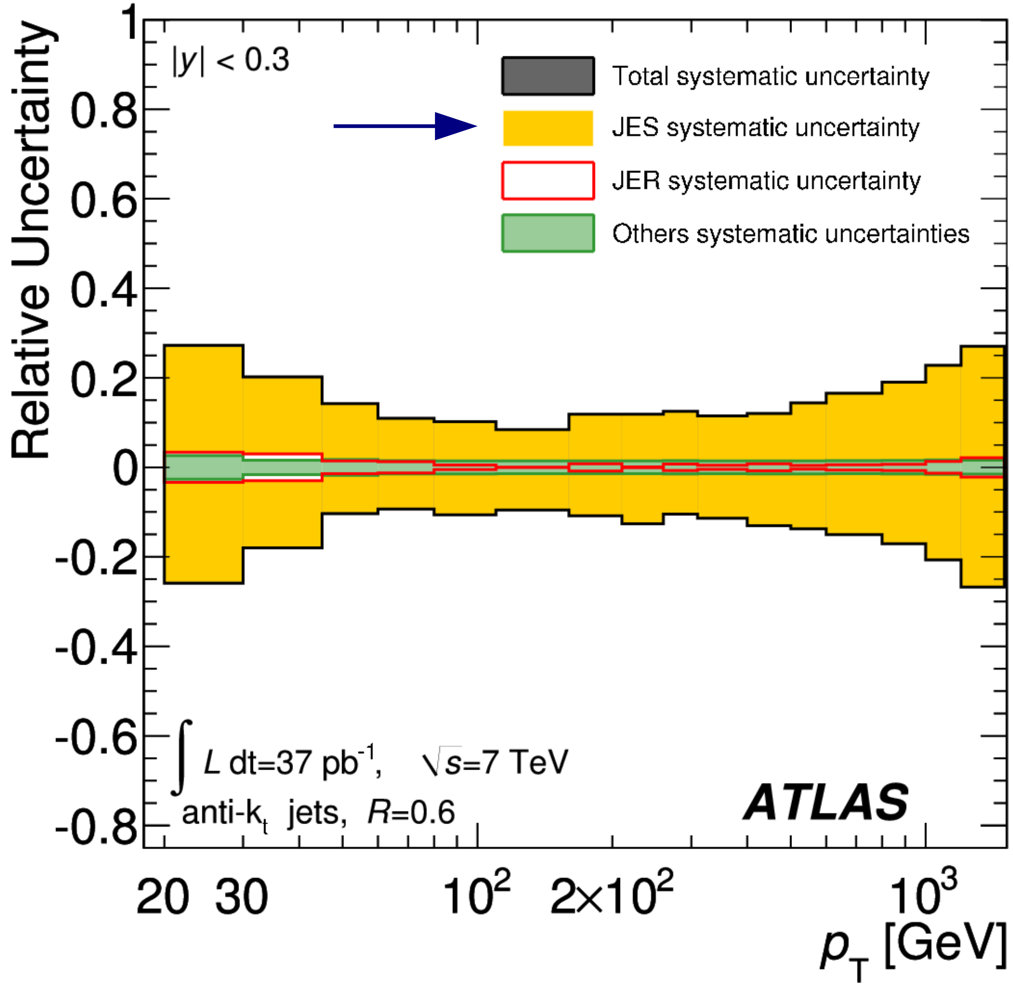
Unfolding

- Iterative, dynamically stabilised (IDS) method
- Using Pythia (as for Jet Calibration)

Experimental uncertainties

Major sources of uncertainty:

- Jet energy scale
- Jet energy resolution
- Trigger efficiency
- Unfolding
- Luminosity [not shown]



Typical systematic uncertainty:

[inclusive jet cross sections at 7TeV]

	25GeV	100GeV	1TeV
|y| ~ 0	30%	10%	30%
|y| ~ 2.5	40%	15%	
|y| ~ 4	>50%		

Evaluation of systematic uncertainties:

- Determined at detector level
- Propagated through unfolding, taking into account all correlations

Theoretical Predictions

- Fixed-order NLO pQCD calculations
  - NLOJET++ 4.1.2
  - CT10 PDF set
  - Scale choice: $\mu_R = \mu_F = p_T^{\max}$

    (different scale for dijets at high y*)
  - Uncertainties:
    PDF, renormalisation and factorisation scale, α_s

- **Non-pertubative corrections**
  - Pythia 6.425 AUET2b
  - CTEQ6L1 PDF

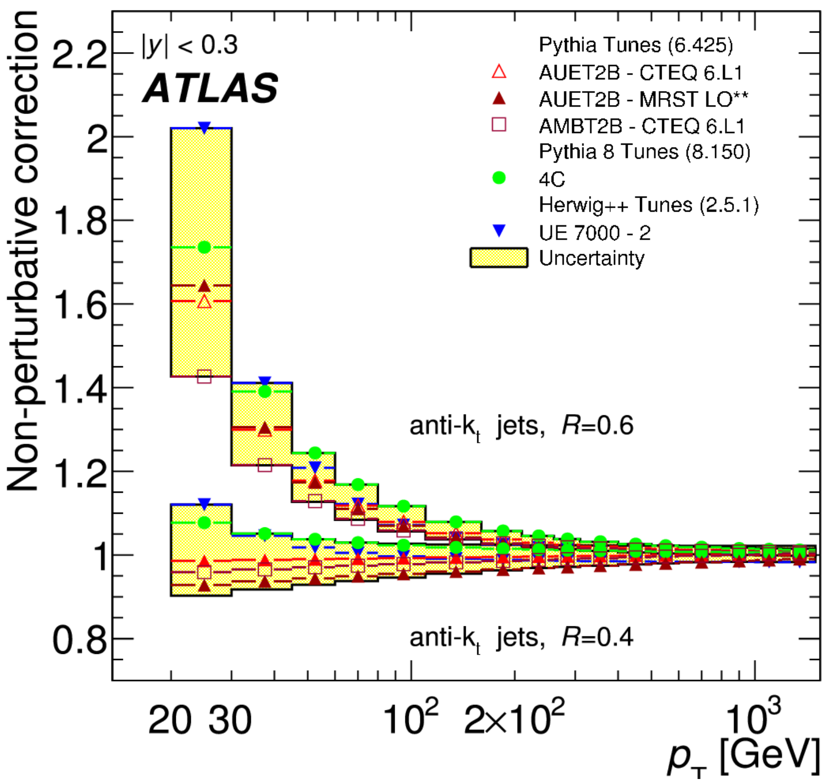
$$C = \frac{\sigma_{Had.\mathrm{ON},UE\ \mathrm{ON}}}{\sigma_{Had.\mathrm{OFF},UE\ \mathrm{OFF}}}$$

  - Uncertainties:
    Envelope of different tunes and parton shower generators

Theoretical uncertainty:

[inclusive jet cross section at 7 TeV]

	25GeV	100GeV	1TeV
|y| ~ 0	<10%	<5%	~20%
|y| ~ 2.5	<10%	~5%	~40%
|y| ~ 4	~10%	>10%	
	scale	**scale, α_S, PDF**	**PDF**



Theoretical Predictions (2)

Baseline for theoretical predictions:

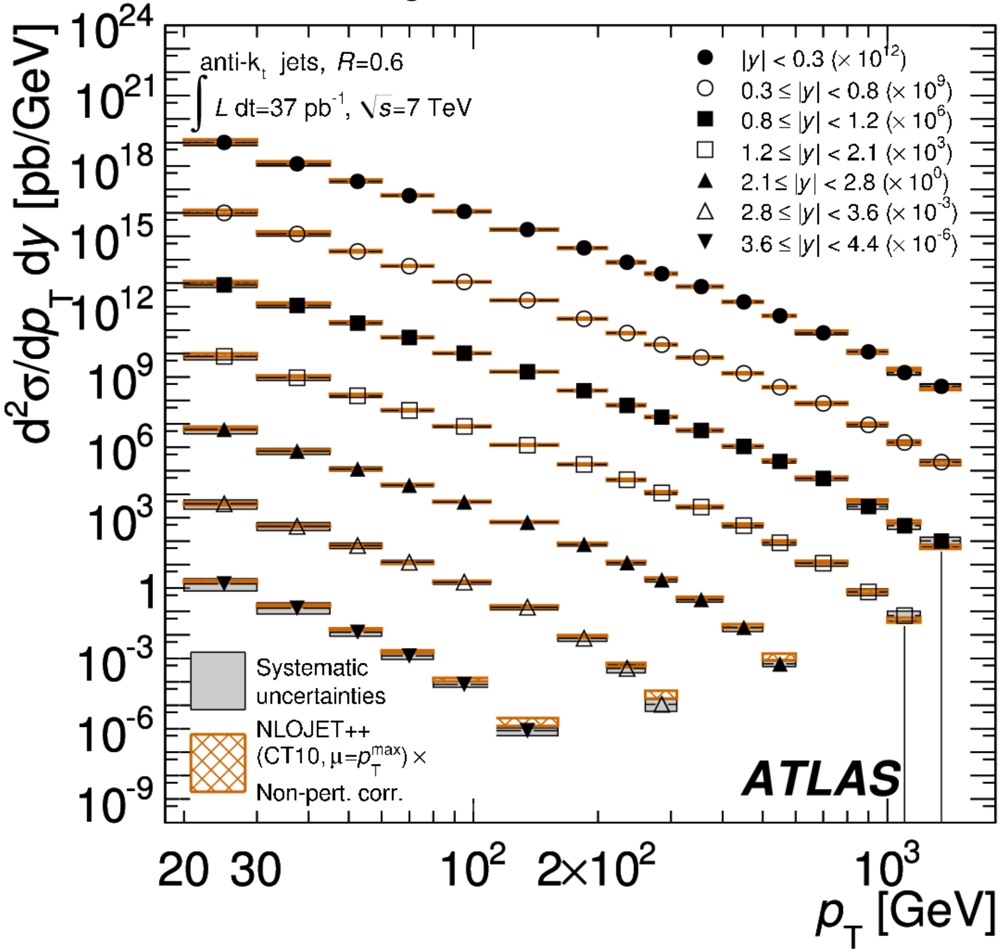
- NLO pQCD predictions with non-perturbative corrections

Strategy to assess theoretical predictions

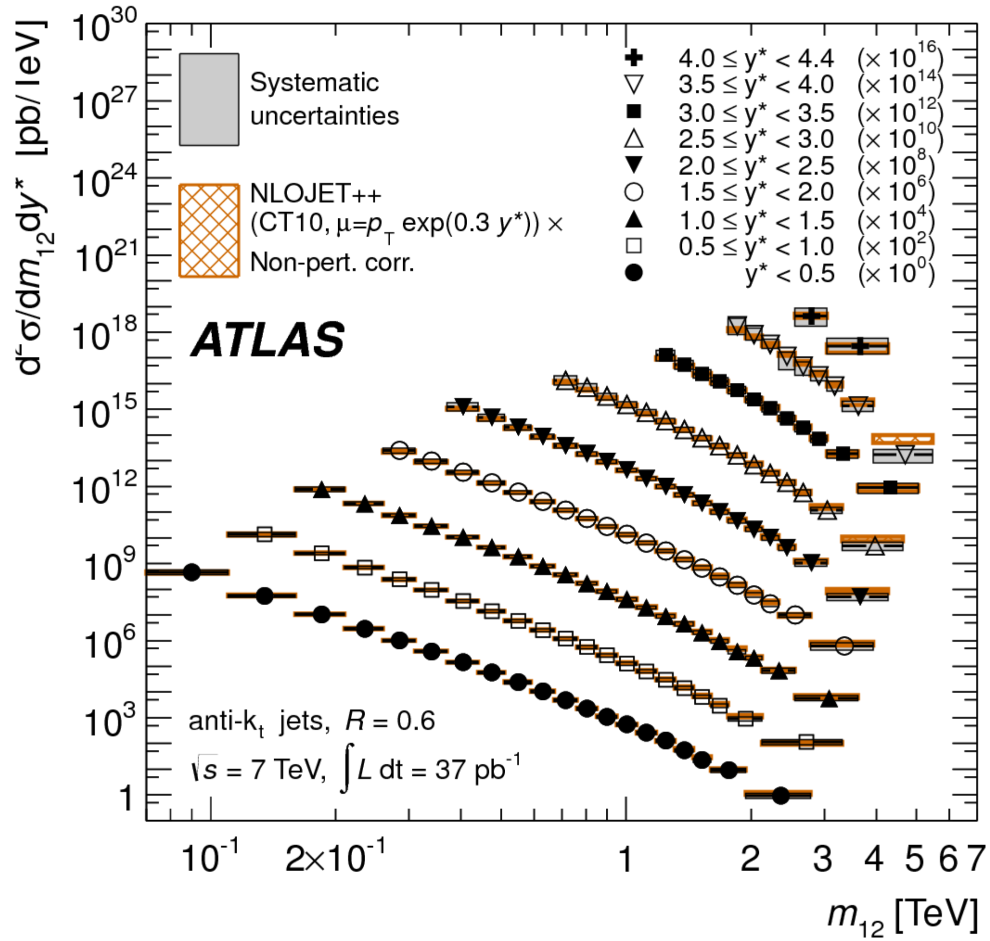
- Different PDF sets
  - Baseline: CT10
  - MSTW 2008, NNPDF 2.1 HERAPDF 1.5
- Modeling of parton showers (and underlying event)
  → POWHEG with different parton shower generators and tunes: Pythia / AUET2B, Pythia / Perugia 2011, Herwig / AUET2
  → Different distance parameters for anti-k_t of R=0.4 and R=0.6
- Modeling of hard scattering
  → NLOJet++ vs. POWHEG

Inclusive Jet and Dijet Cross Section

Inclusive jet cross section



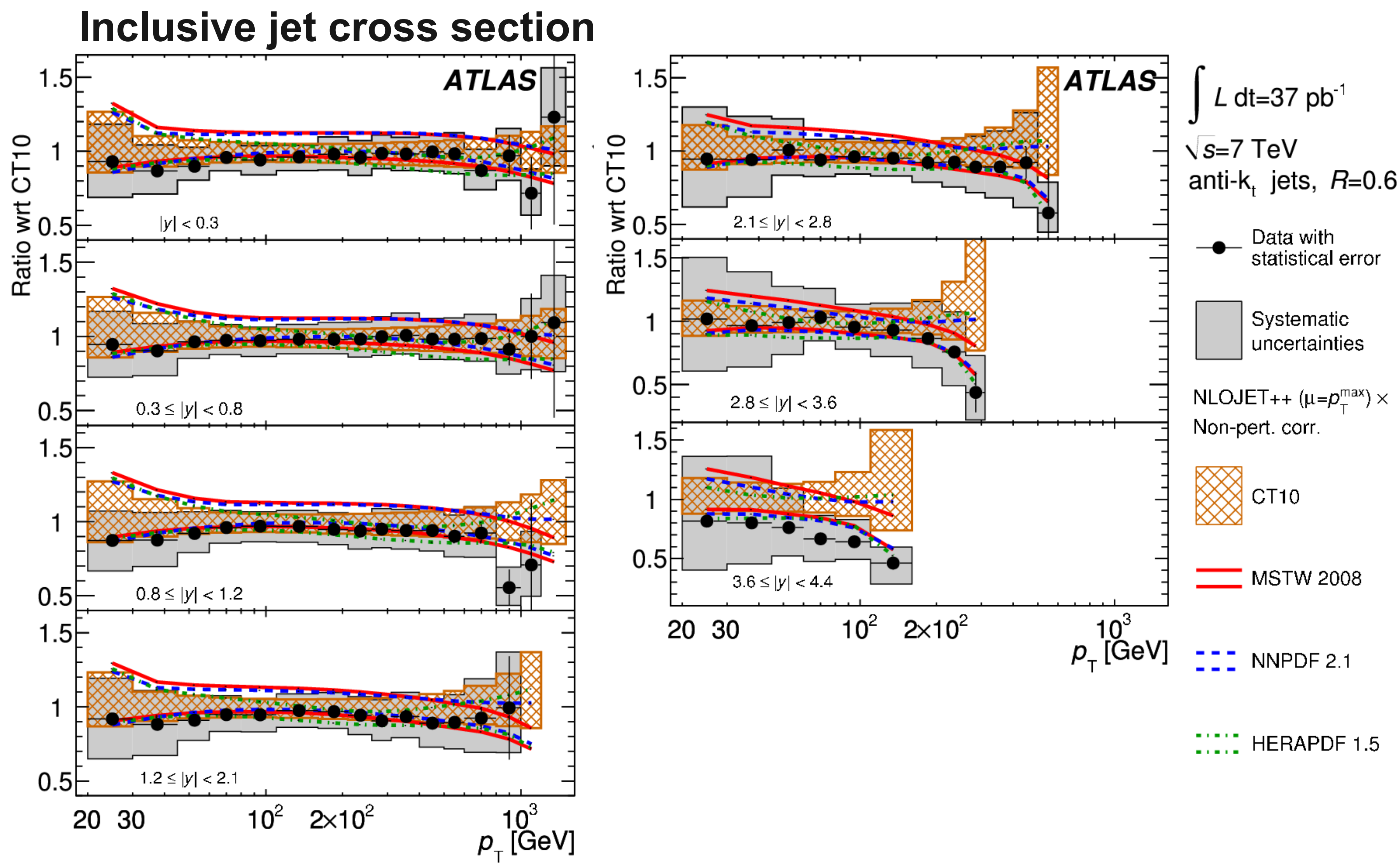
Dijet cross section



- Kinematic range:
  $|y| < 4.4$, $20 < p_T < 1500$ GeV
- Very good agreement over 9 orders of magnitude

- $y^* = |y_1 - y_2| / 2 < 4.4$
  $60\text{GeV} < m_{12} < 4.1\text{TeV}$
- Very good agreement

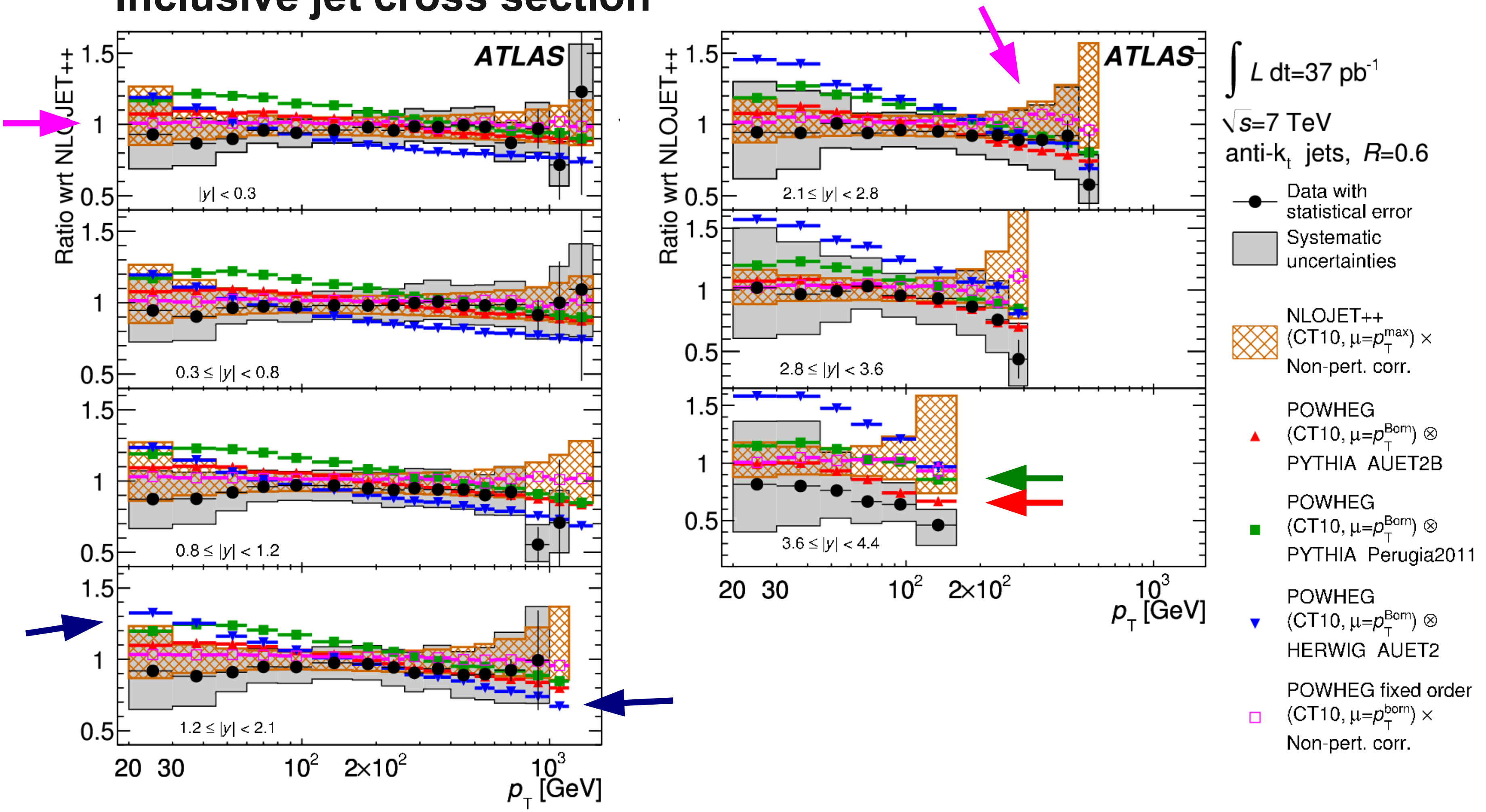
Impact of different PDFs



- Good agreement in general, slight deviations in forward region
- Comparison to MSTW 2008, NNPDF 2.1, HERAPDF 1.5
  → MSTW 2008 follows trend best

Impact of different parton shower models

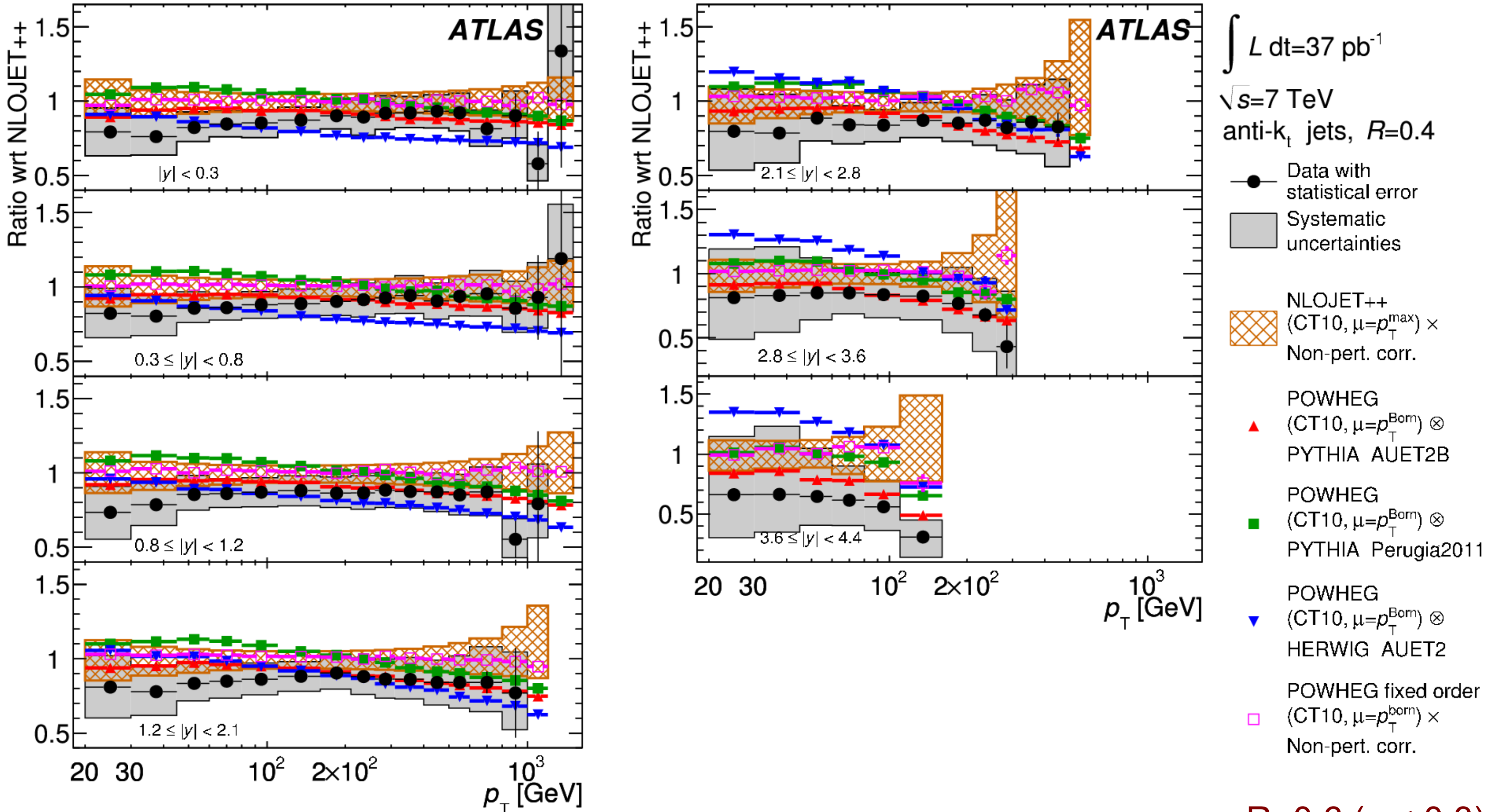
Inclusive jet cross section



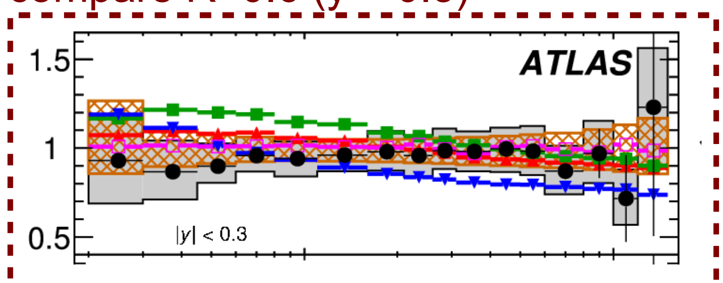
- POWHEG prediction very similar with NLOJET++ at fixed order
- Difference of ~20% between tunes (AUET2B / Perugia)
- Large difference between parton shower generators (Pythia / Herwig)

Impact of different distance parameters

Inclusive jet cross section (R=0.4)

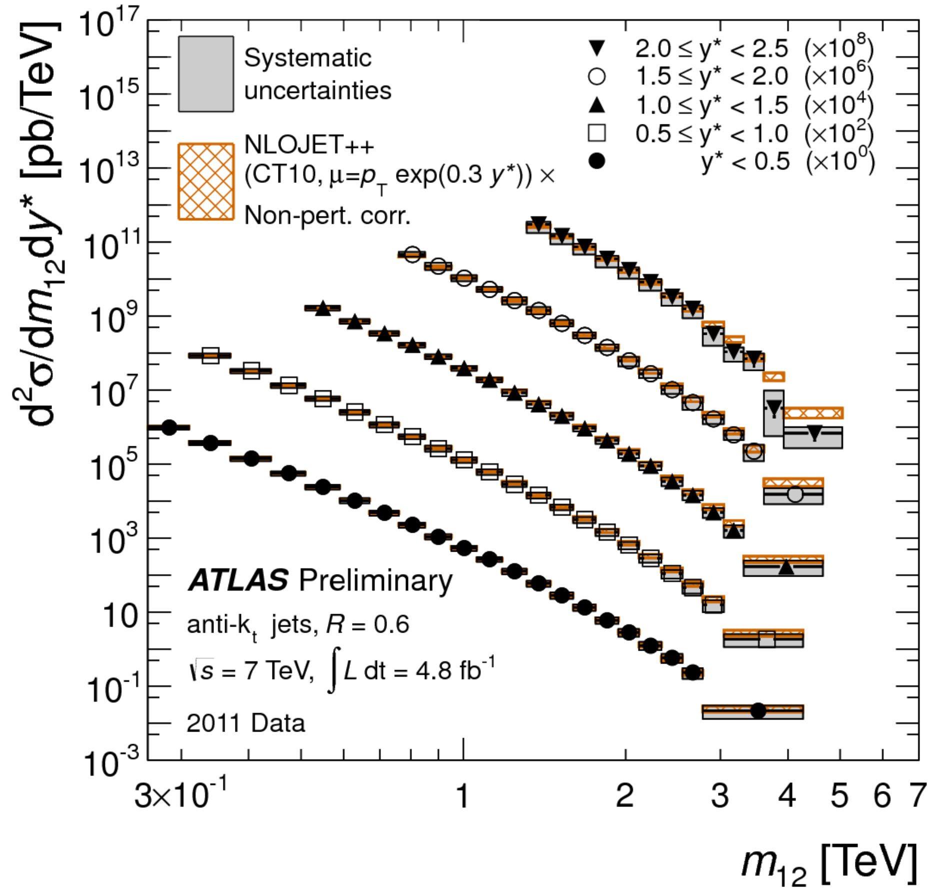


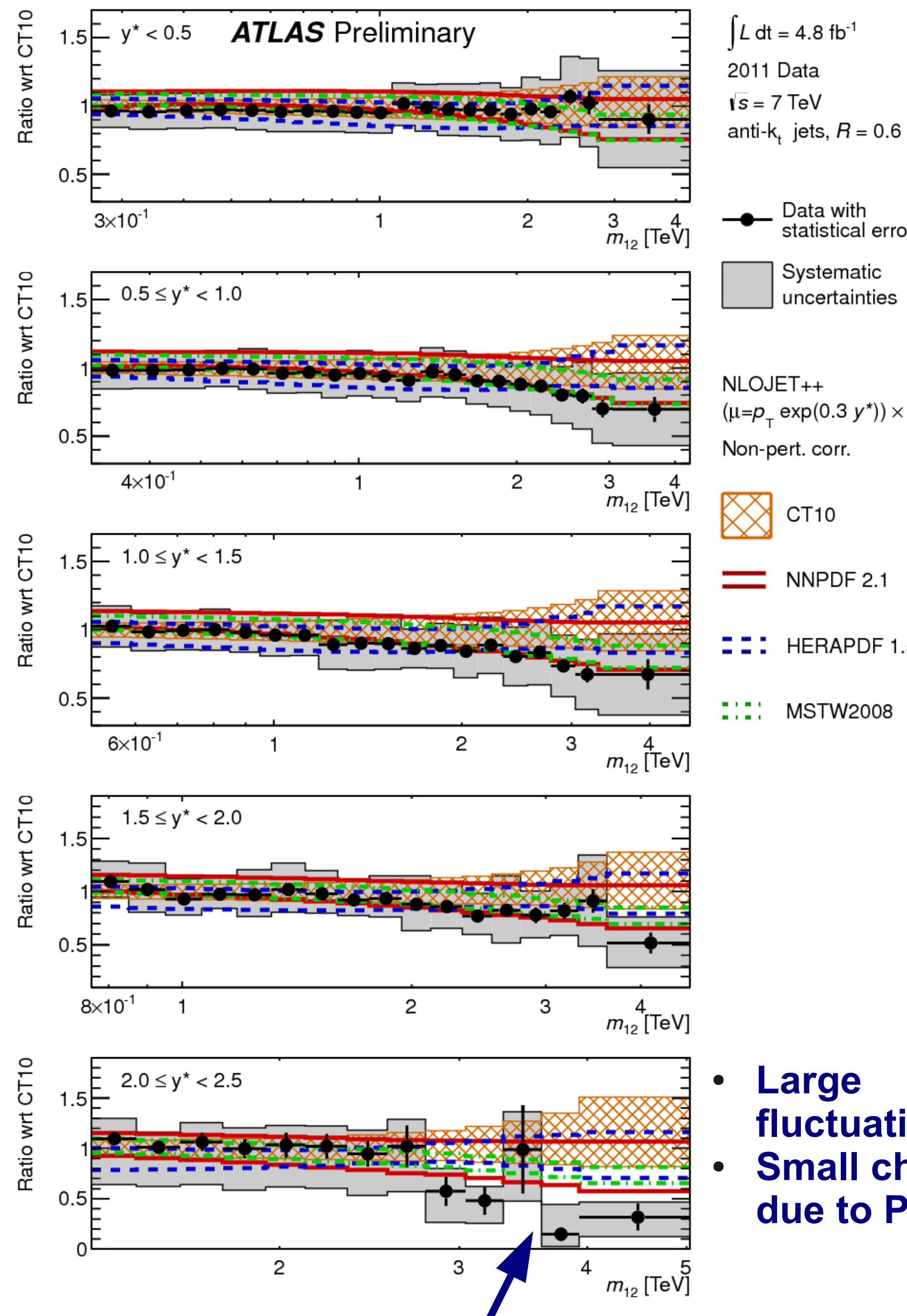
compare R=0.6 (y < 0.3)



- 20% difference between R=0.4 and 0.6 at low p_T with respect to NLO pQCD + npc
- Difference between data and POWHEG is very similar between R=0.4 and 0.6

Dijet Cross Section Measurement at High p_T



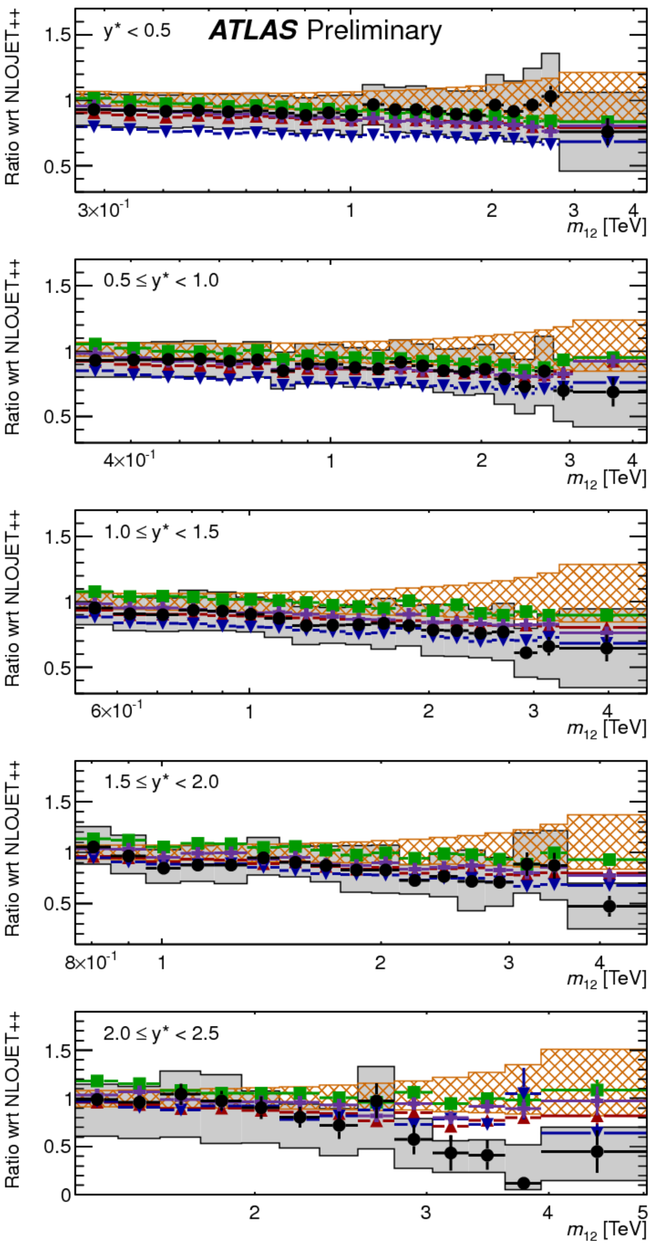


- $L = 4.8\text{fb}^{-1}$ at 7 TeV from 2011 → extend by ~1TeV in m_{12}
- Good agreement in general
- Slight deviations at high m_{12} for large rapidity separation y^*

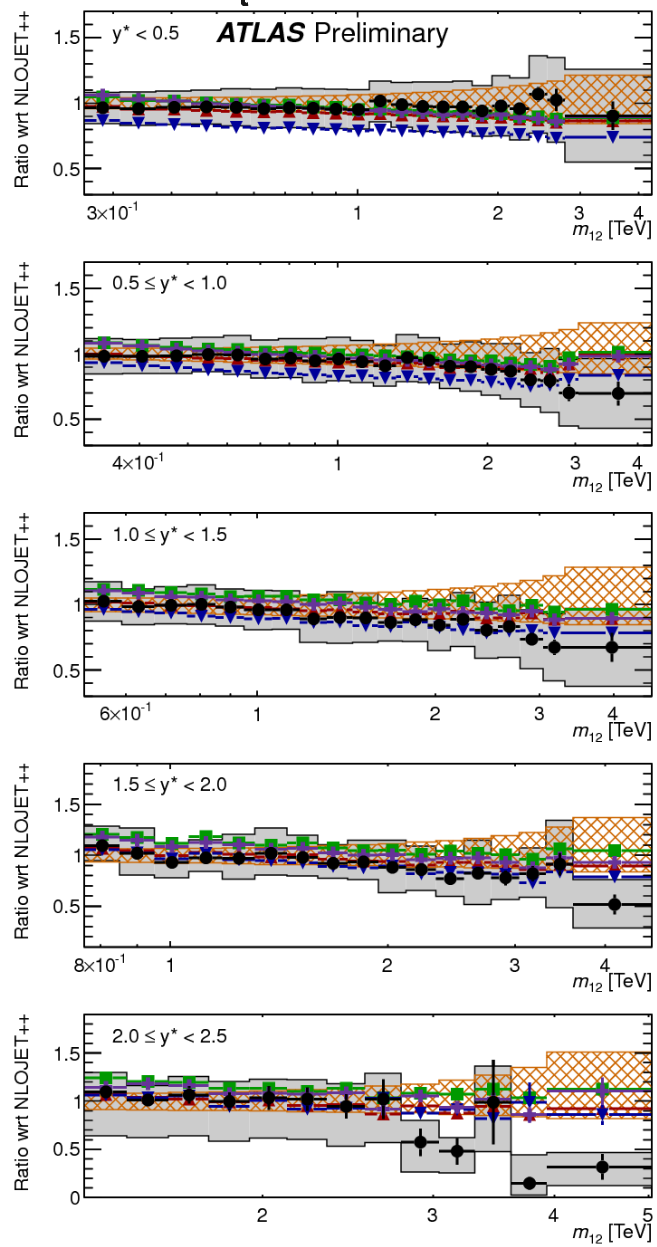
- **Large fluctuations**
- **Small changes due to PDF**

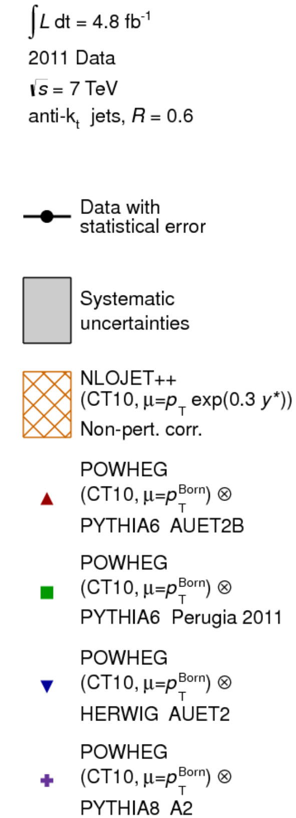
Dijets: Impact of Distance Parameters, Tunes and PS

Anti-k_t with R=0.4



Anti-k_t with R=0.6





- Smaller differences for R=0.4 and R=0.6
- Different shape using NLO pQCD+matched PS
- 20% difference between tunes
- 30% difference between PS Monte Carlo

Jet Cross Section Ratio: 2.76TeV wrt. 7TeV

Jet cross section measured using the same procedure

→ many uncertainties are correlated in the ratio and can be canceled

→ precise test of pQCD

Ratio measurement with two binnings

- p_T binning:

$$R(y, p_T) = \frac{\sigma^{2.76\ \mathrm{TeV}}(y, p_T)}{\sigma^{7\ \mathrm{TeV}}(y, p_T)}$$

$$p_T^{2.76} = 20\ GeV \leftrightarrow p_T^{7.00} = 20\ GeV$$

  - Best cancellation of experimental uncertainties between 2.76 TeV and 7 TeV measurement

- x_T binning:

$$R(y, x_T) = \left(\frac{2.76\ \mathrm{TeV}}{7\ \mathrm{TeV}}\right)^3 \frac{\sigma^{\sqrt{s}=2.76\ \mathrm{TeV}}(y, x_T)}{\sigma^{\sqrt{s}=7\ \mathrm{TeV}}(y, x_T)}$$ with $x_T = 2p_T/\sqrt{s}$

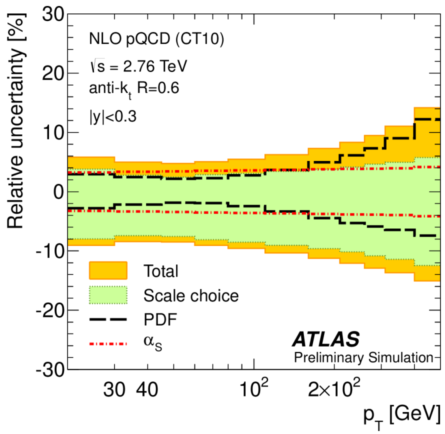
$$p_T^{2.76} = 23.7\ GeV \leftrightarrow p_T^{7.00} = 60\ GeV$$

  - Many uncertainties still cancel
  - More sensitive to deviations from simple parton model due to running of α_s

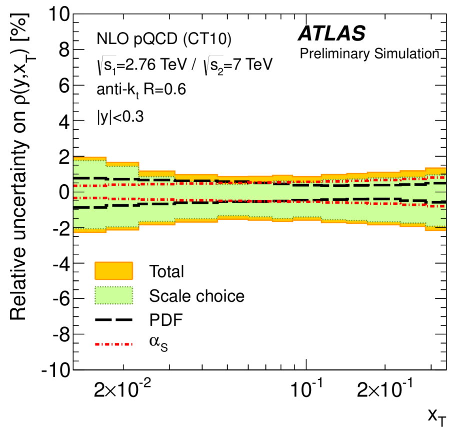
Uncertainties on Cross Section Ratio

- Theory uncertainty

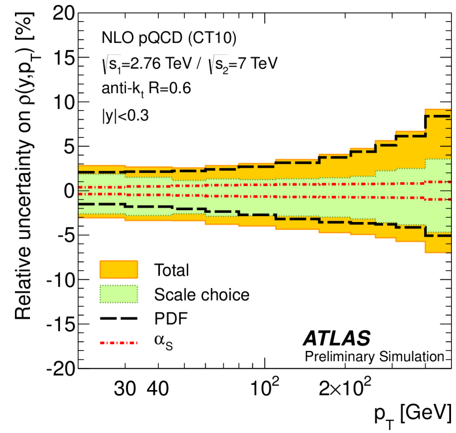
2.76 TeV cross section
$(d\sigma/\sigma)_{pT}^{theo}$ ~ 5 - 15%



ratio: x_T binning
$(d\rho/\rho)_{xT}^{theo}$ ~ 1 - 2%



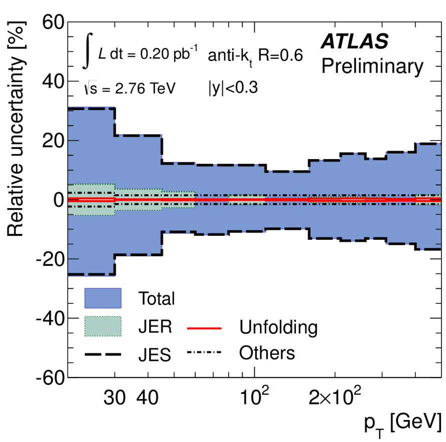
ratio: p_T binning
$(d\rho/\rho)_{pT}^{theo}$ ~ 2 - 8%



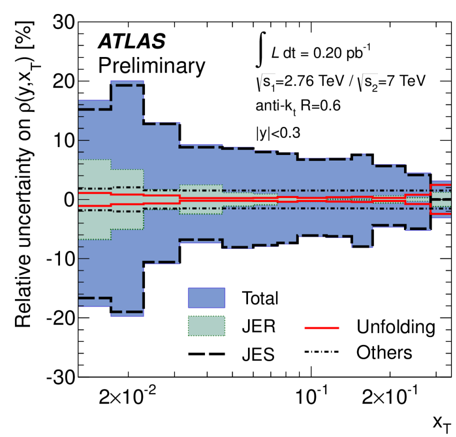
large reduction of theory uncertainty with x_T binning

- Experimental uncertainty

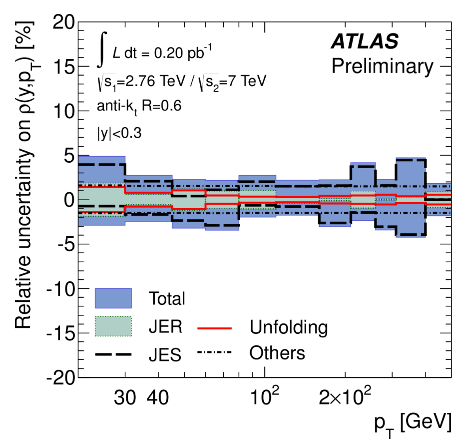
2.76 TeV cross section
$(d\sigma/\sigma)_{pT}^{exp}$ ~ 10 - 30%



ratio: x_T binning
$(d\rho/\rho)_{xT}^{exp}$ ~ 5 - 20%

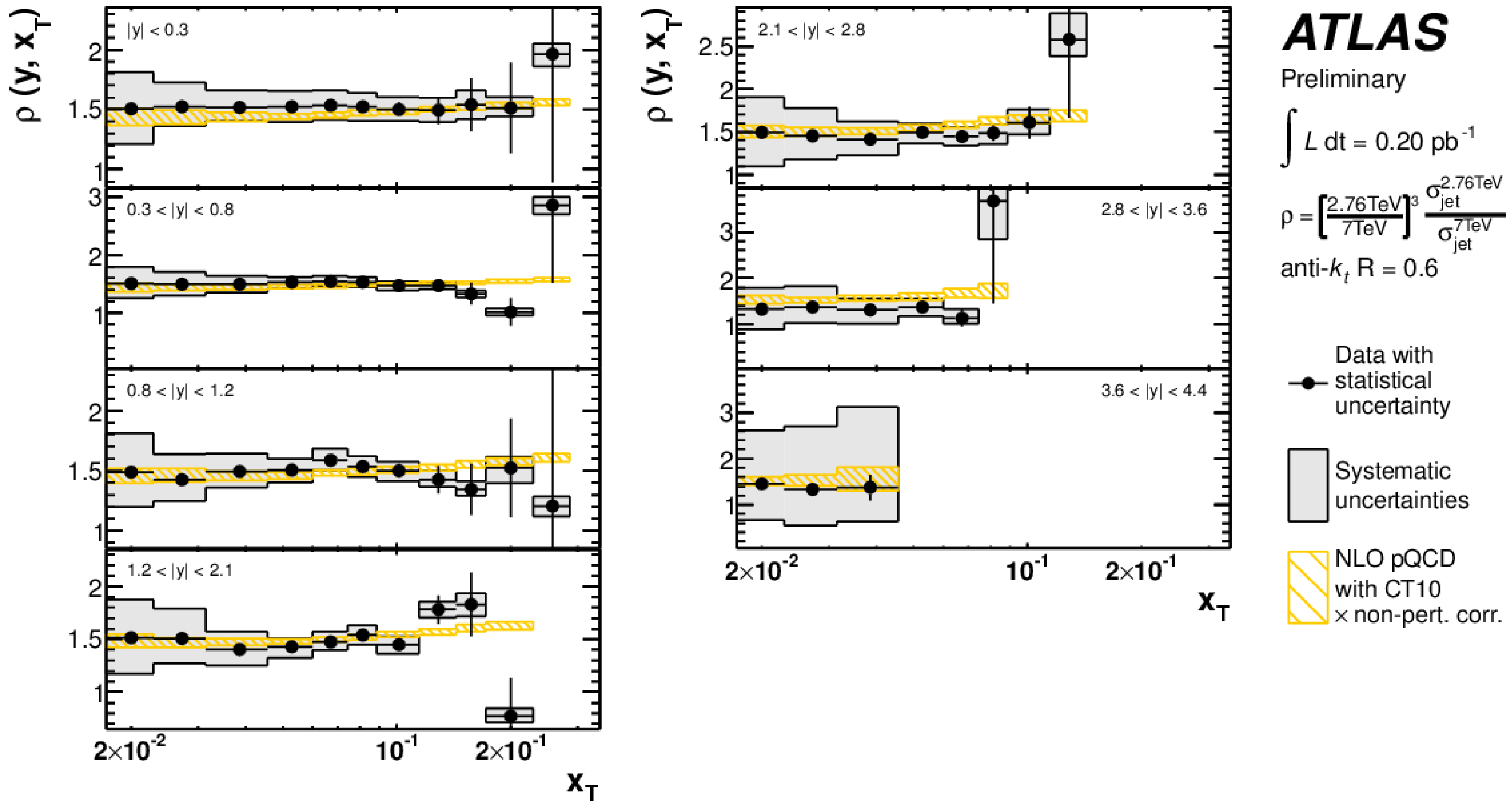


ratio: p_T binning
$(d\rho/\rho)_{pT}^{exp}$ ~ 2 - 5%



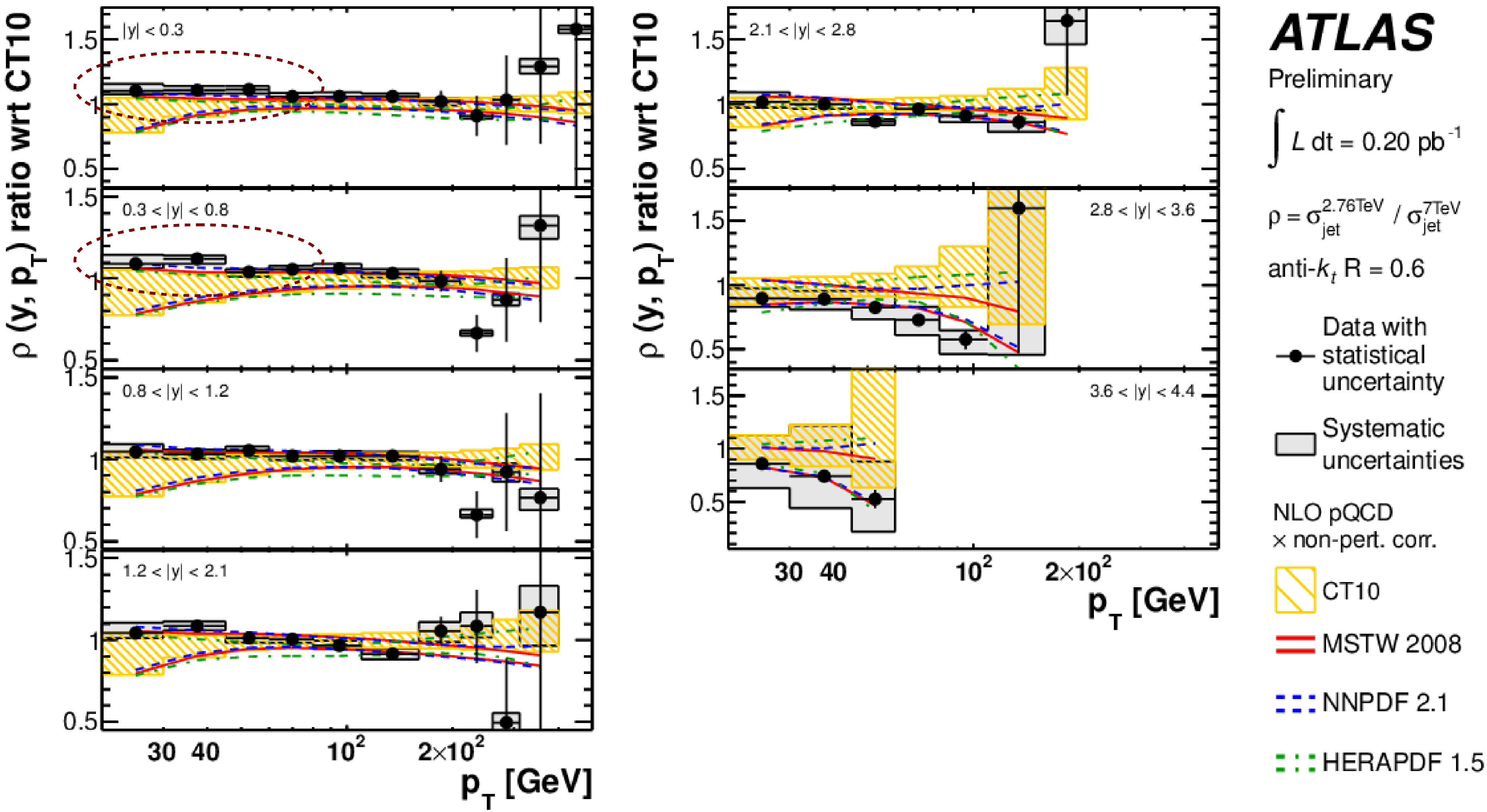
large reduction of experimental uncertainty with p_T binning

Cross Section Ratio (x_T Binning)



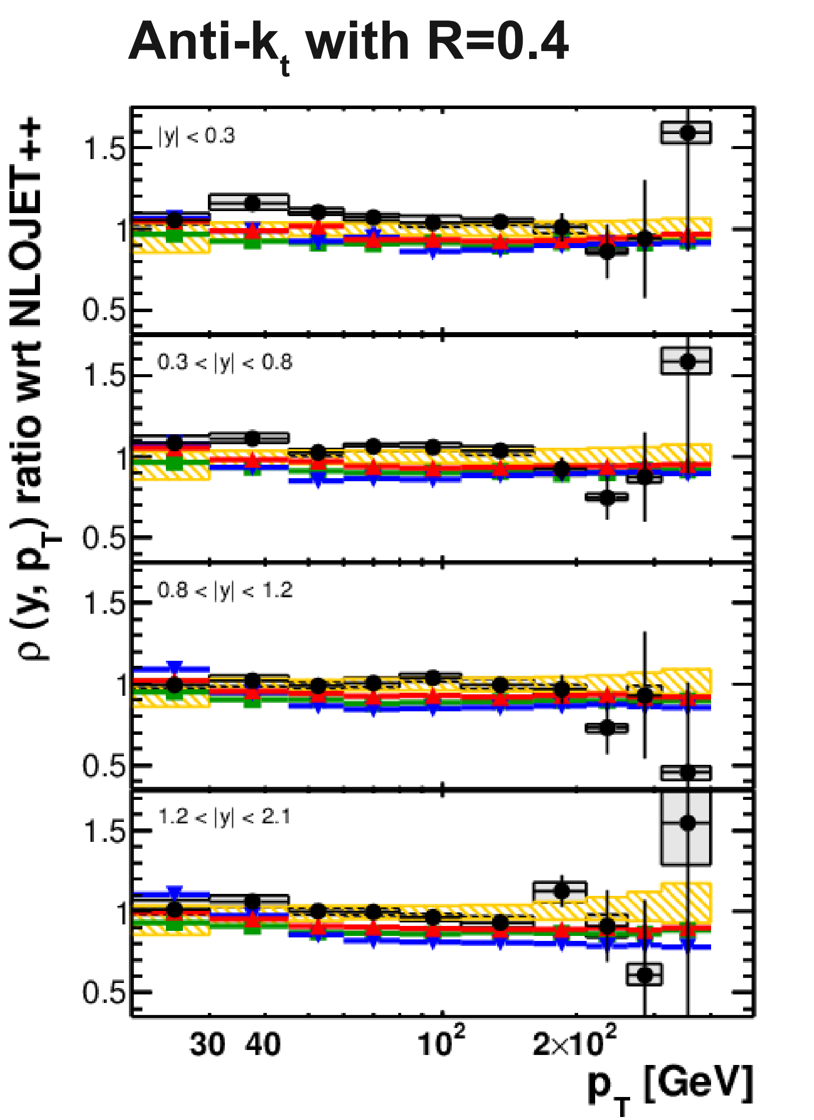
- Very small theoretical uncertainties
- Good agreement with data
- Statistical uncertainty dominates at high x_T

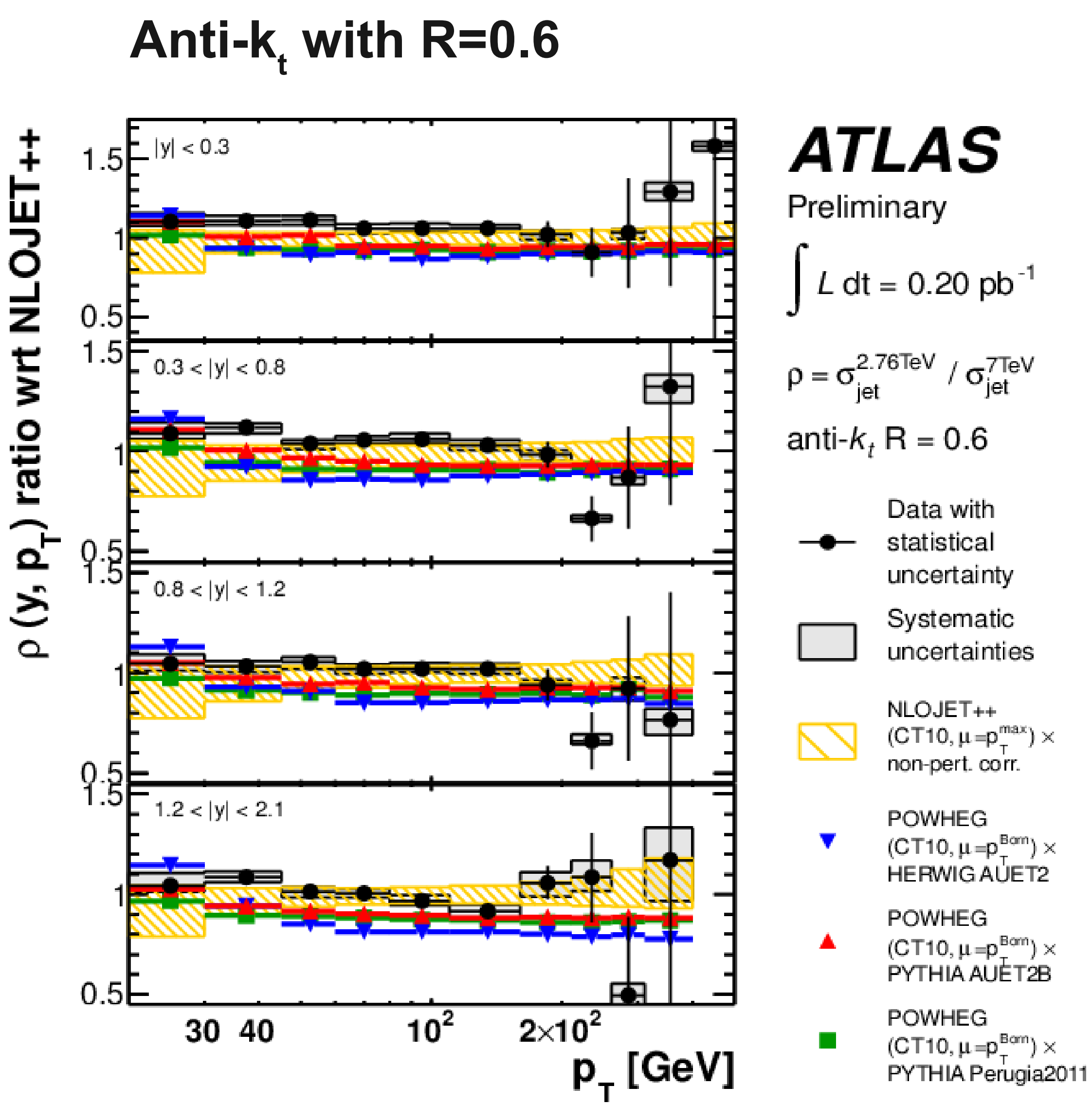
Cross Section Ratio wrt Theory (p_T Binning)



- Very small experimental uncertainties
  → cancellation of jet energy scale uncertainty
- Slightly different trend at low p_T in the central region

Impact of Distance Parameter



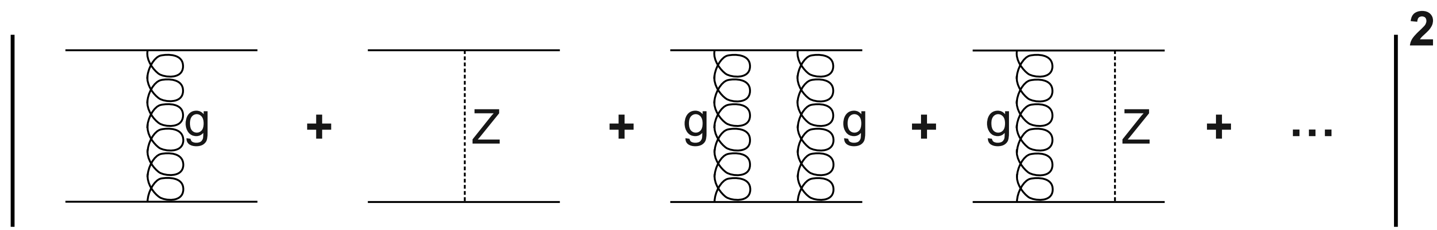


- Very small impact of distance parameter on ratio
  → effects causing the 20% difference for the cross section cancel

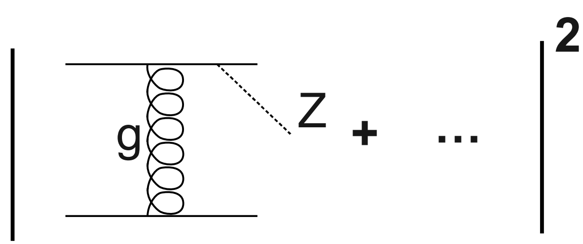
Effect of Electroweak Corrections to Jet Measurements

- Based on studies by M. Campanelli, J. Huston, S. Moretti, D.A. Ross and J. Terron
- Inclusive jet production:
  - Dependence on centre-of-mass energy
  - Decomposition according to initial state partons
  - Dependence on p_T and rapidity
- Dijet production
  - Effects on angular distribution
- Electroweak contributions:

Virtual (loop) corrections



Real corrections (W/Z emission)



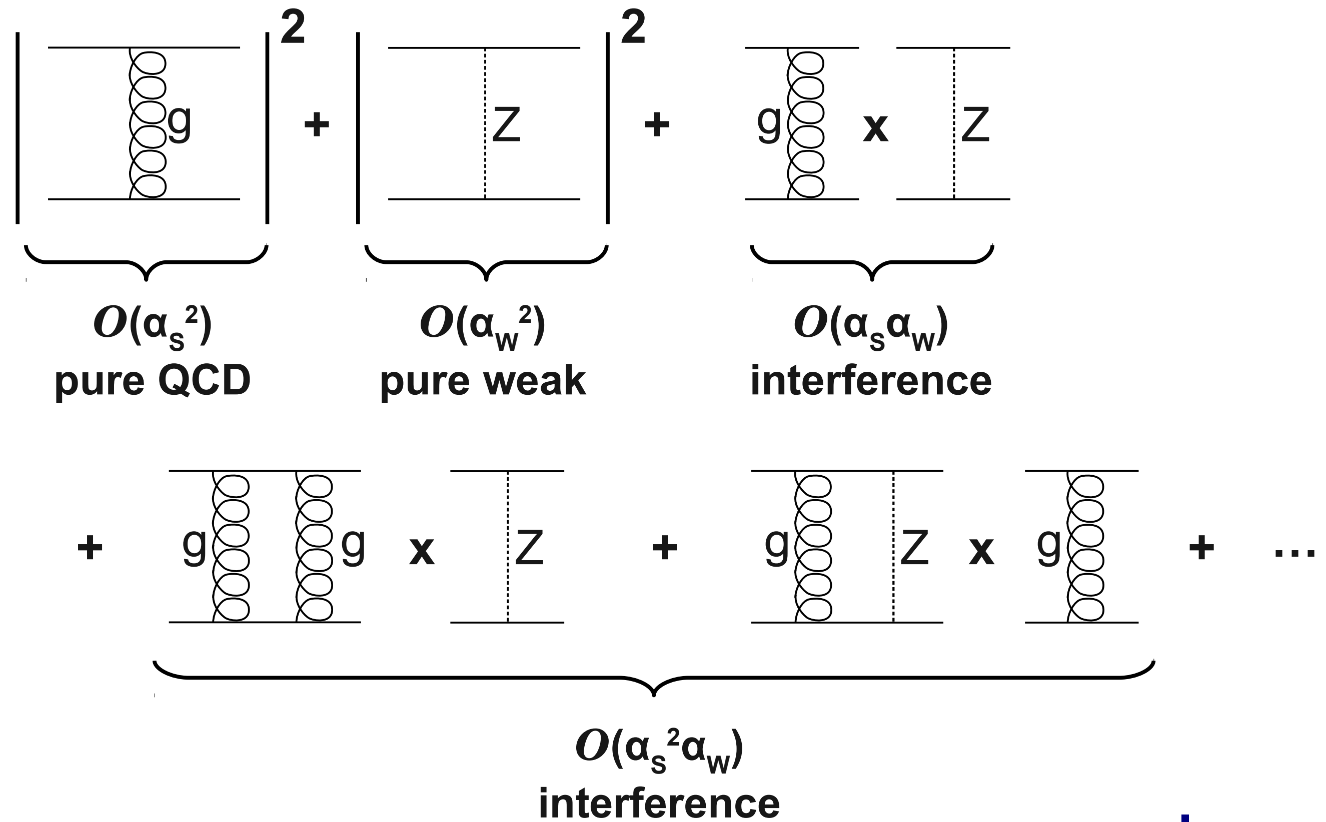
- Corrections may have large impact in jet production at high p_T

  → Especially mixed strong + weak corrections $O(\alpha_S^2 \alpha_W)$

Mixed strong + weak virtual corrections

LO

NLO correction
Mixed strong + weak



large

- Large impact of EW Sudakov factors $\alpha_W \cdot \log^2(\hat{s}/M_V^2)$
- Impact on jet production at 14 TeV:

virtual corrections: - 10% (- 40%) at p_T = 1TeV (4TeV)

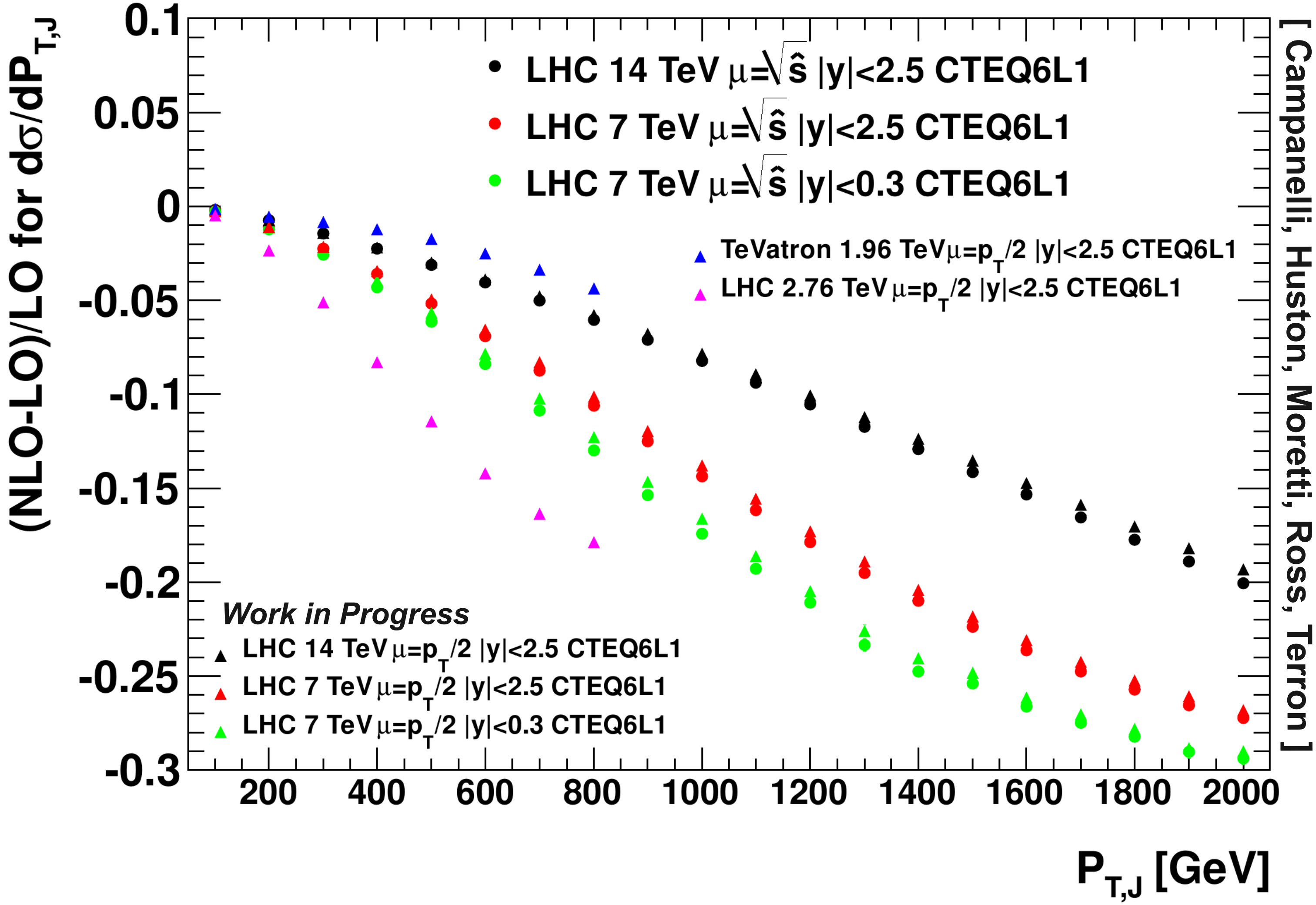
real corrections: +2.5% (+6.5%) at p_T = 1TeV (4TeV)

Moretti, Nolten, Ross
arXiv:hep-ph/0606201v2

U. Baur
arXiv:hep-h/0611241v1

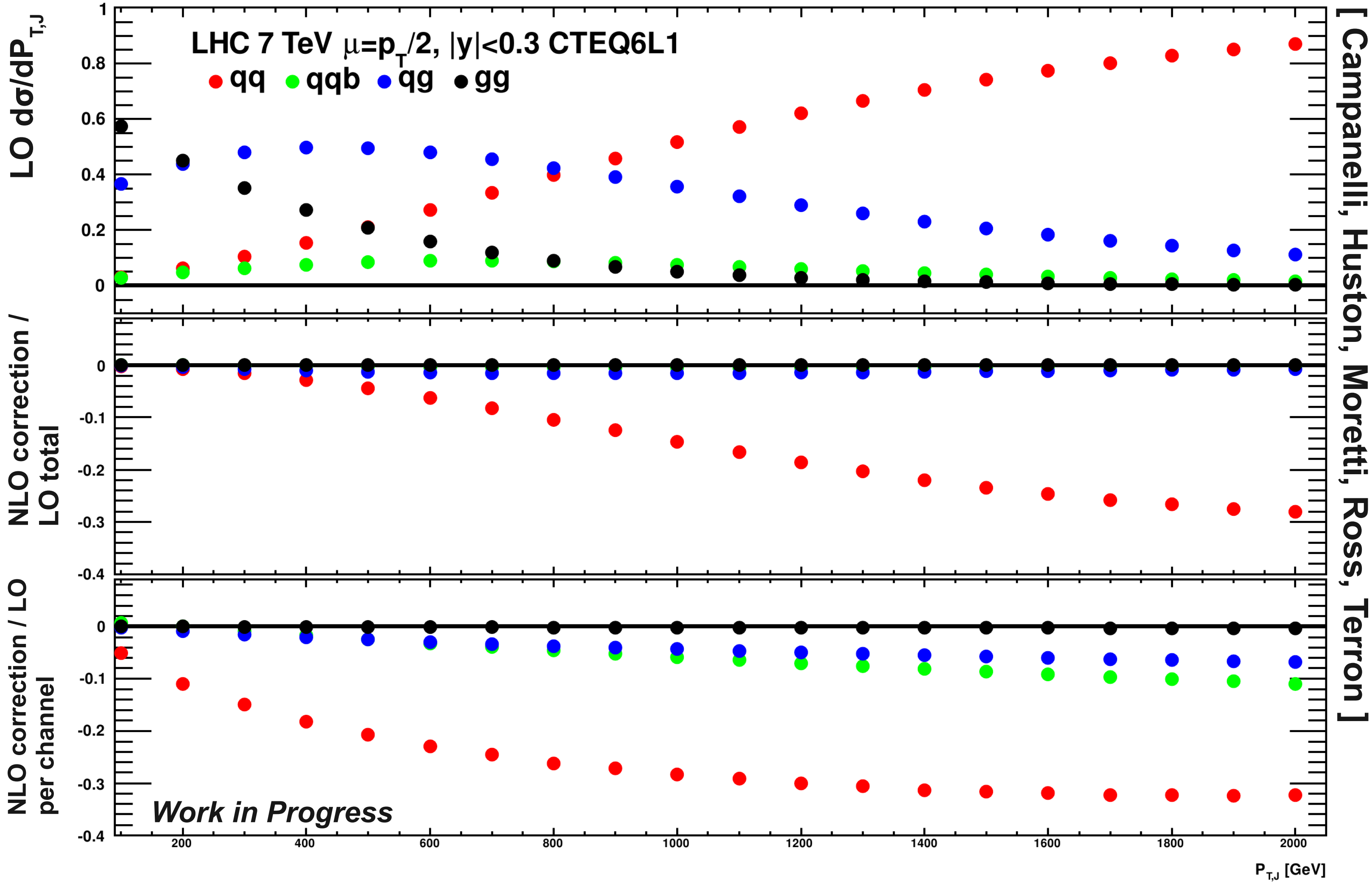
corrections do not cancel

Inclusive jet production: centre-of-mass dependence



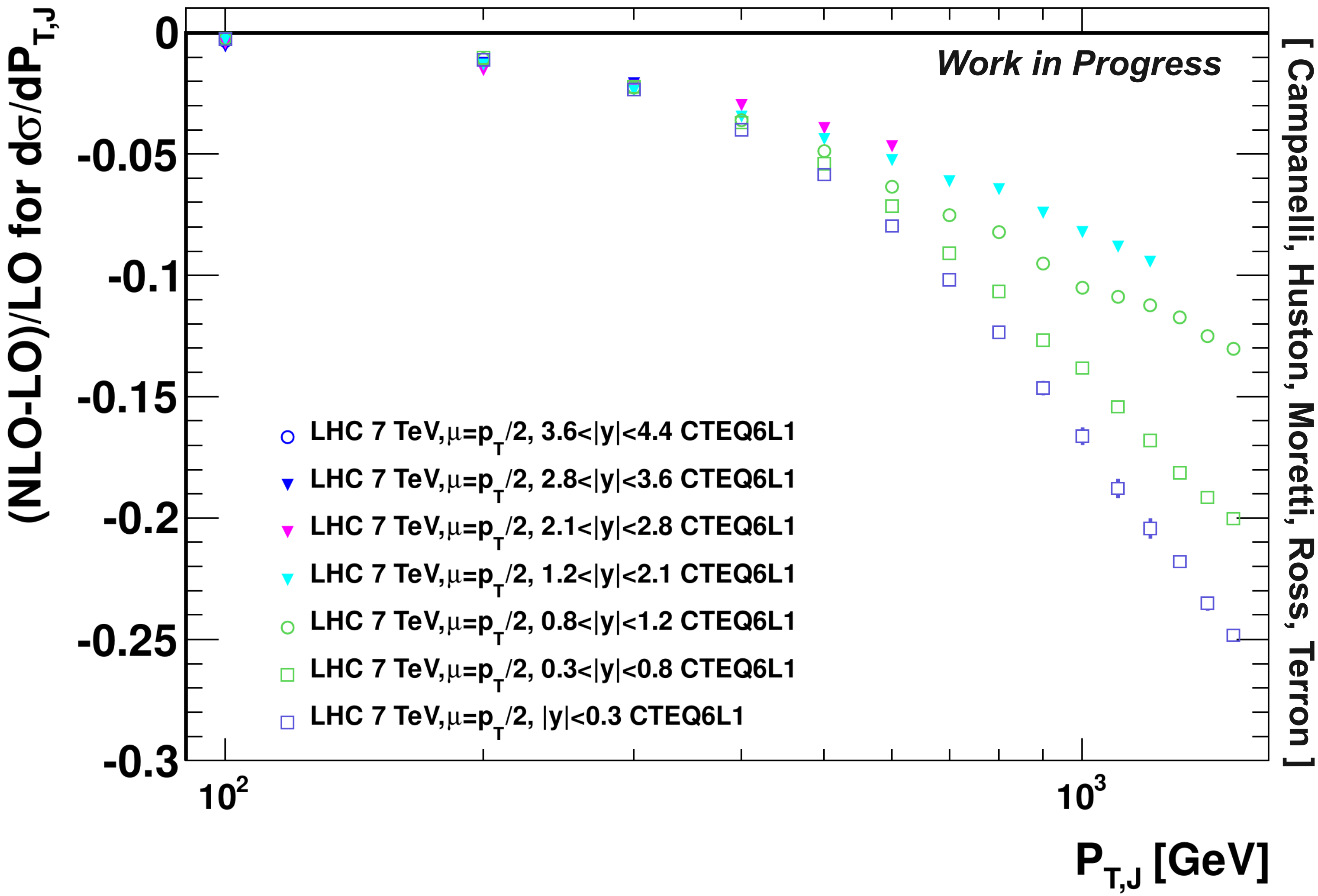
- Larger effects at 2.76 TeV than 7 TeV for fixed p_T in *pp* collisions
- Small effect at Tevatron in $p\bar{p}$ collisions
- Larger effect in the central region

Decomposition According to Initial State Partons



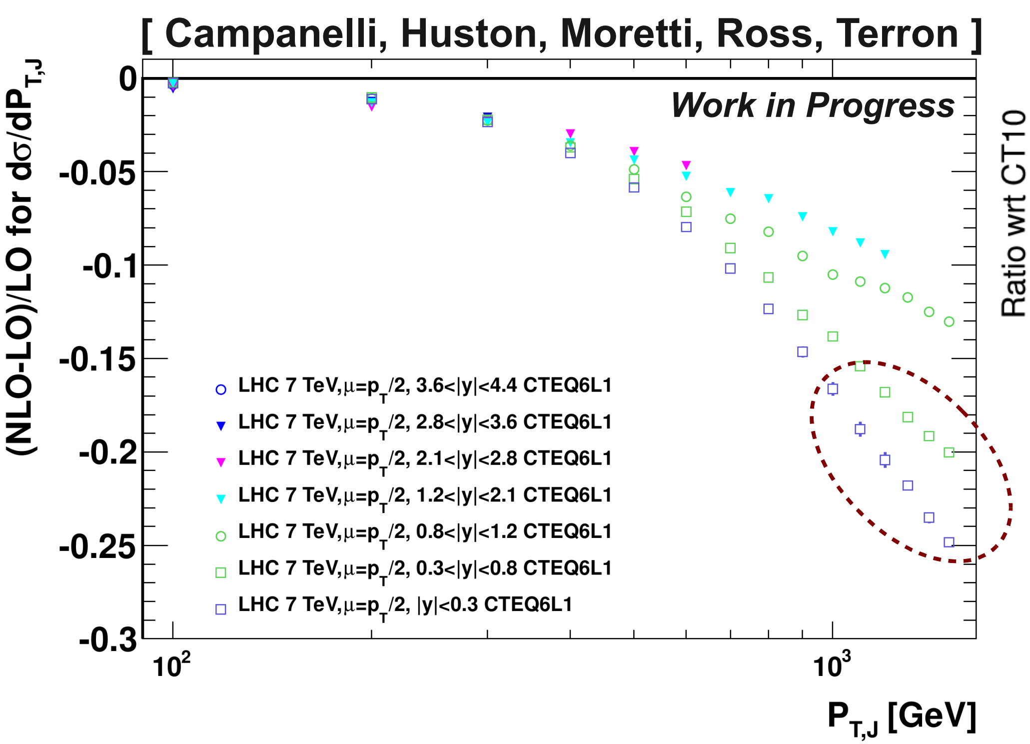
- ***qq* processes drives the effect**
- Varying effect for different centre-of-mass effects due to different fraction of *qq*

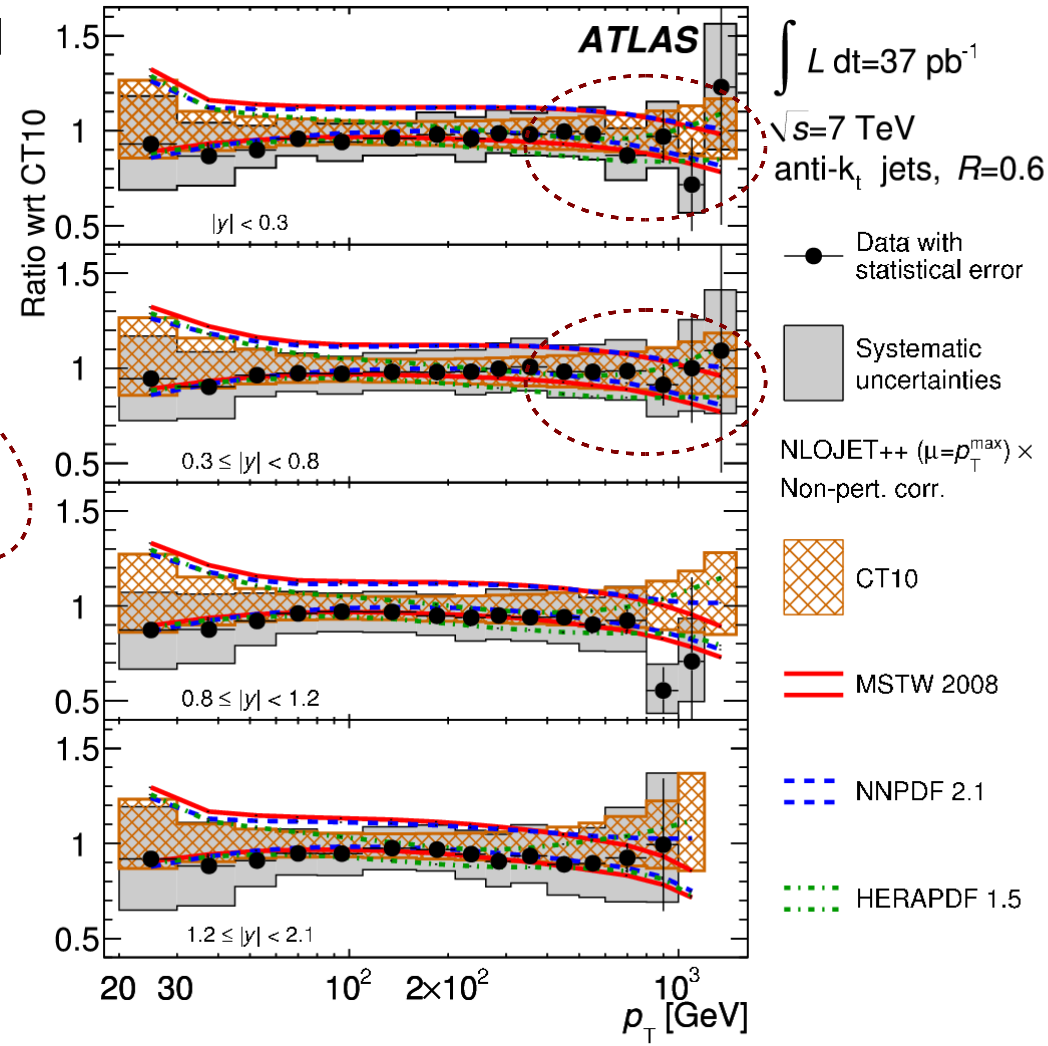
Jet-Rapidity Dependence



- Largest effect in the central region
- **NLO correction decreases in the forward region**
  [although qq fraction increases]

Effect on Inclusive Jet Cross Section Measurement





- Studies suggest deviation between data and theory in high p_T central region
  [net effect may be small]
- Data does not show a strong deviation from NLO predictions
  - Large statistical uncertainty
  - Effect incorporated in PDFs / tunes?

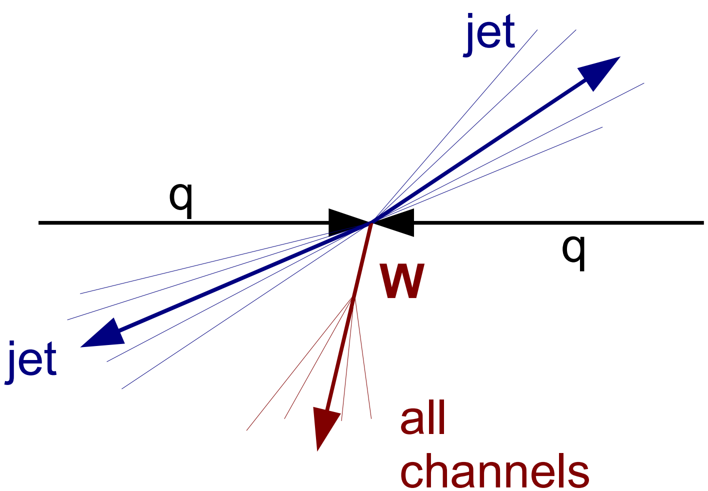
Impact of corrections on dijet angular distributions (1)

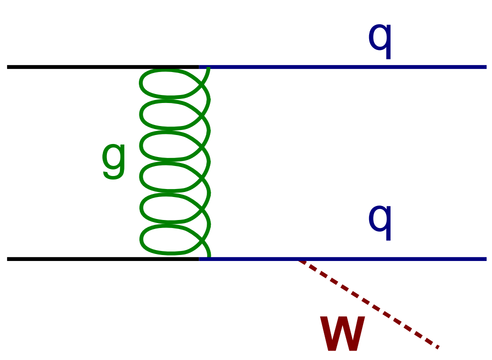
Real weak corrections using MCFM:

- W + 2 jets: $\mathcal{O}(\alpha_s^2\,\alpha_W)$:

gluon and quark exchange

→ qq, qg processes

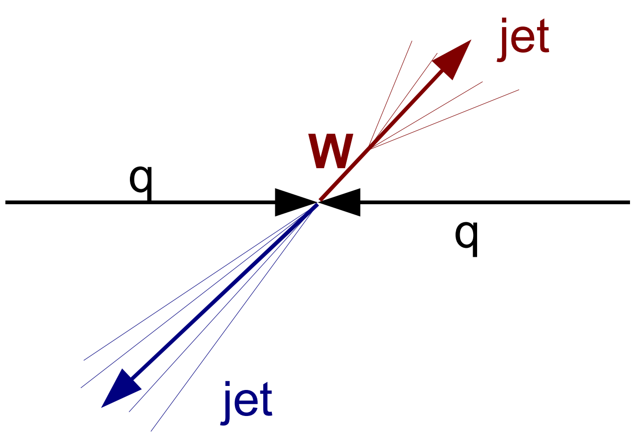


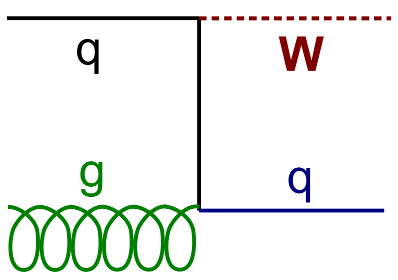


- W + 1 jet: $\mathcal{O}(\alpha_s\,\alpha_W)$:

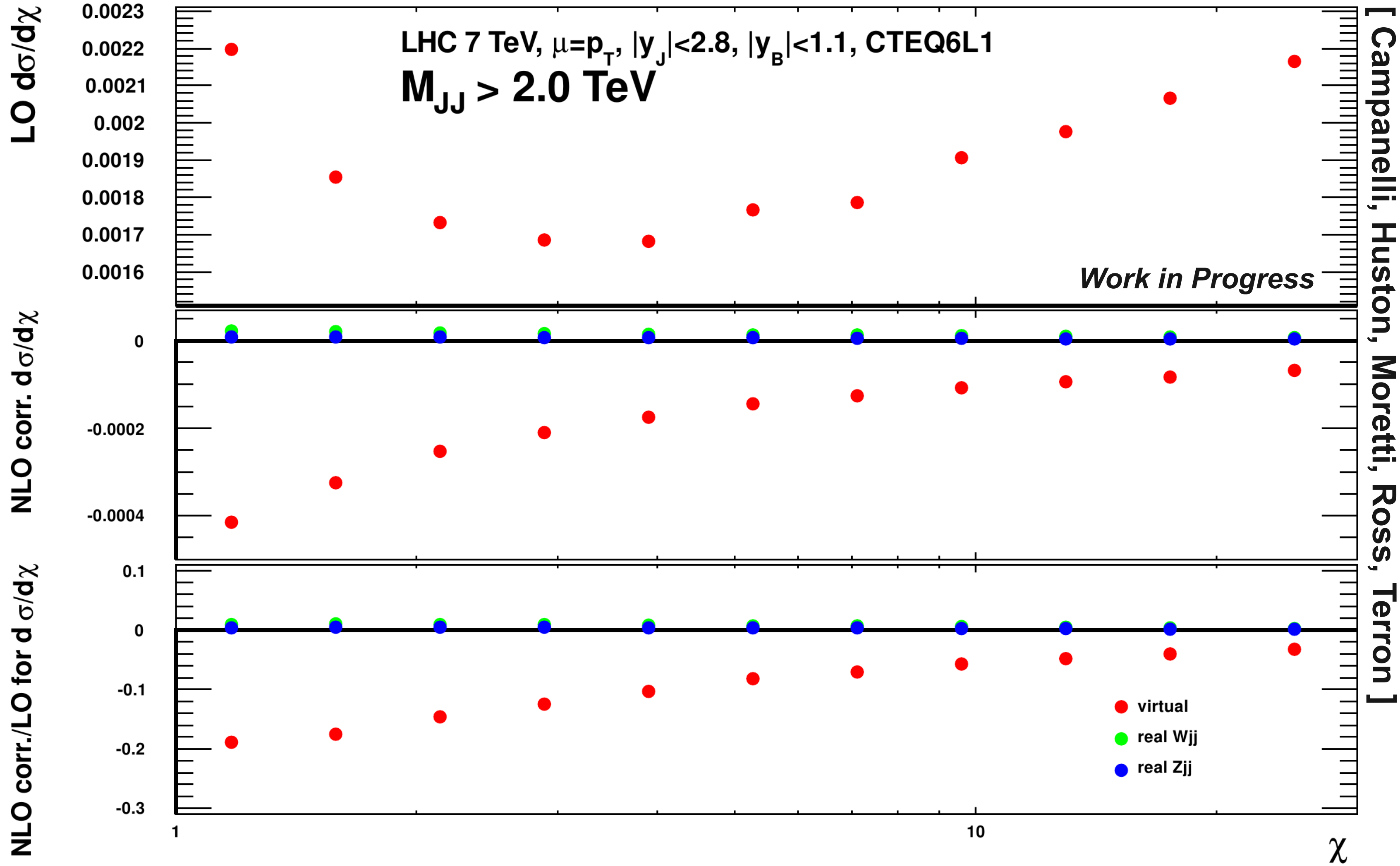
quark exchange

→ qg, $q\bar{q}$ processes





Impact of corrections on dijet angular distributions (2)



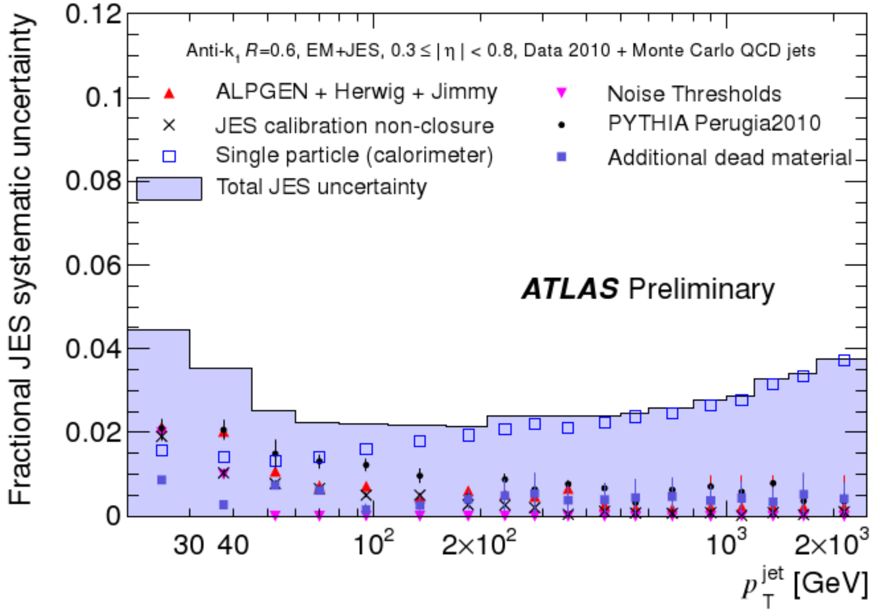
- Real corrections do not cancel the virtual corrections
  $\rightarrow$ Distortion of angular distribuitions at low $\chi = \exp(|y_1 - y_2|)$
  $\rightarrow$ Could mask possible contributions from New Physics

Summary

- Jet measurements can probe several aspects of pQCD
- Presented analyses
  - Jet cross section at 7 TeV
  - Ratio of the measurement of 2.76 TeV and 7 TeV
    → very small uncertainties due to cancelation of systematics
- Assess theoretical predictions by varying
  - Parton shower generator
  - Parton shower tunes
  - PDF sets
- Effect of electroweak corrections
  - Effect is sizable at 2.76 TeV and 7 TeV
    → driven by *qq* fraction
    → corrections become larger at high p_T
    → central region more affected
  - Data does not show large deviations from theoretical predictions w/o electroweak corrections

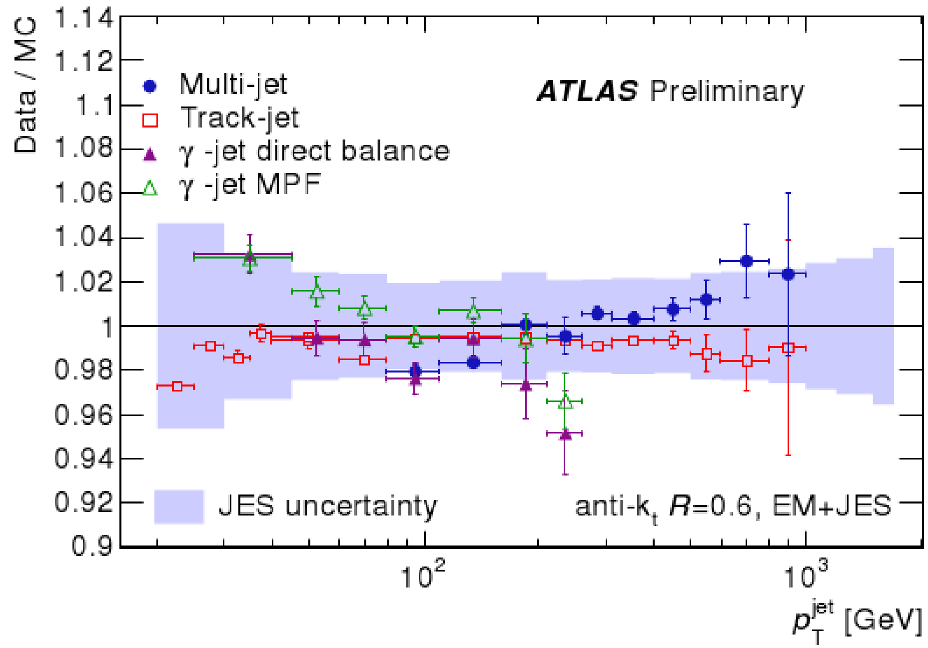
Backup

Jet Energy Scale Uncertainty



- Single hadrons
- Monte Carlo
  (hadronisation, soft physics, generators, noise, dead material)
- Extension to forward region:
  η – intercalibration
- Additional uncertainty from pile-up
  (not shown)

- In-situ tests in agreement with JES uncertainty estimation from MC



Scale Choice for Dijets

- Scale for inclusive jet cross section

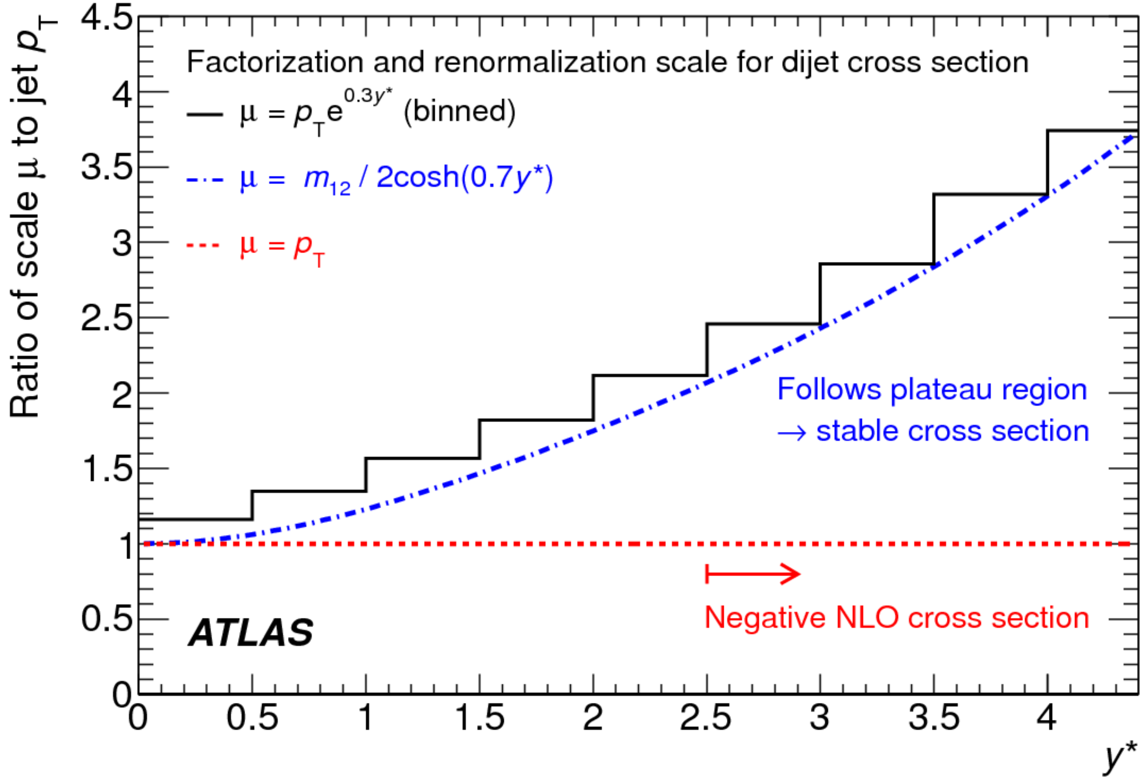
NLOJET++: $\mu = \mu_R = \mu_F = p_T^{\max}$

POWHEG: $\mu = \mu_R = \mu_F = p_T^{\mathrm{Born}}$ (leading order)

- Negative cross section in forward region for dijet predictions with NLOJET++
  → scale as function of y*

$$\mu = \mu_R = \mu_F = p_T e^{0.3y^*}$$

$$\mu = \mu_R = \mu_F = \frac{m_{12}}{2\cosh(0.7y^*)}$$

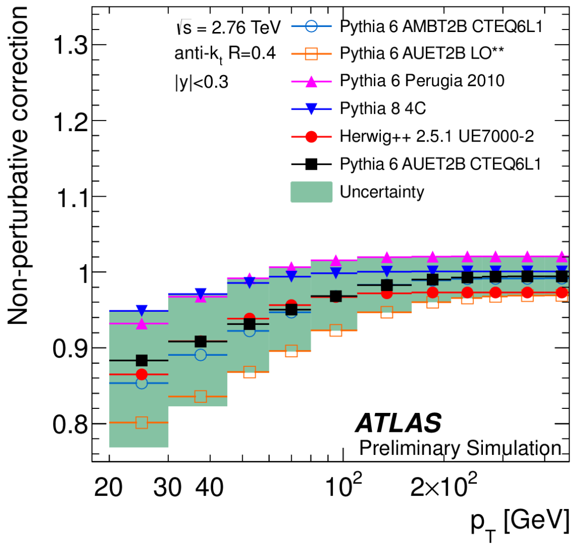


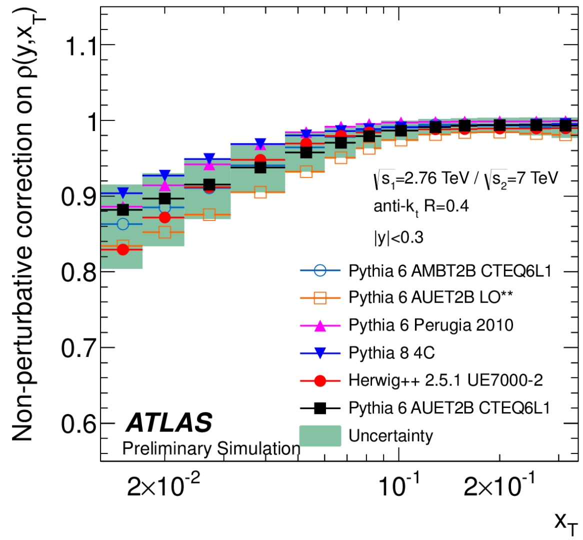
Non-perturbative Corrections for the Ratio

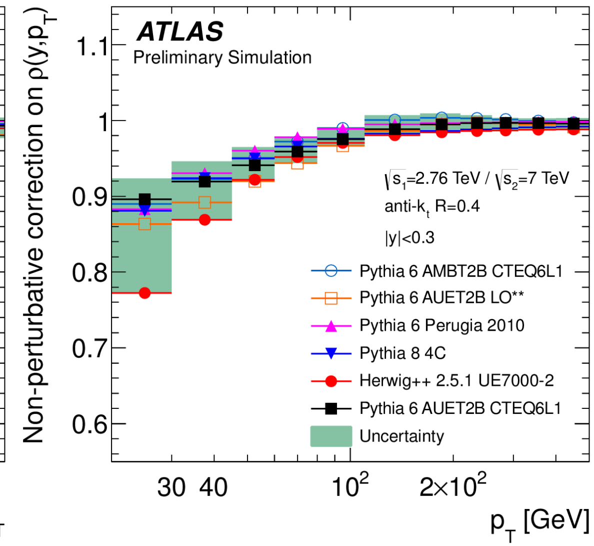
2.76 TeV cross section

ratio: x_T binning

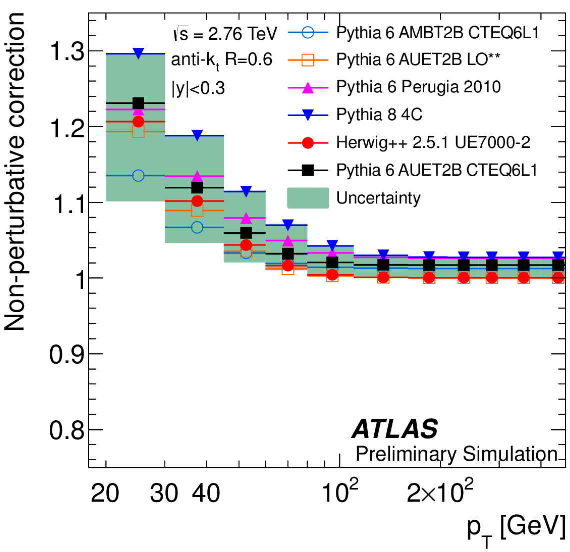
ratio: p_T binning

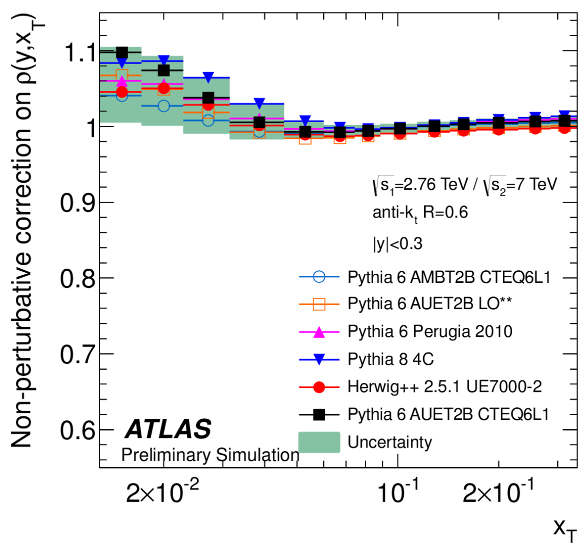


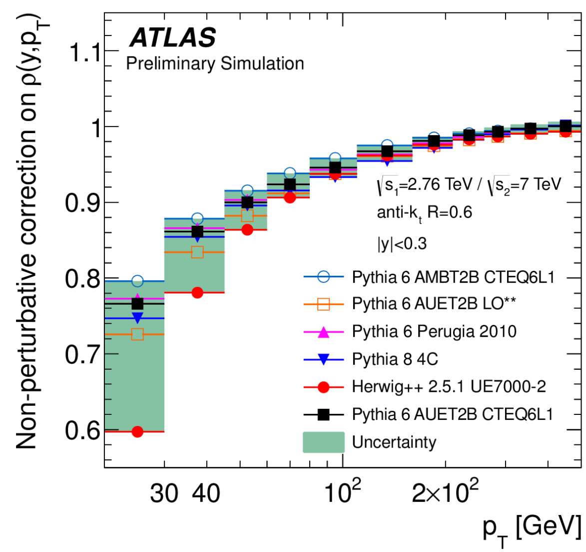




Anti-k_t 0.4

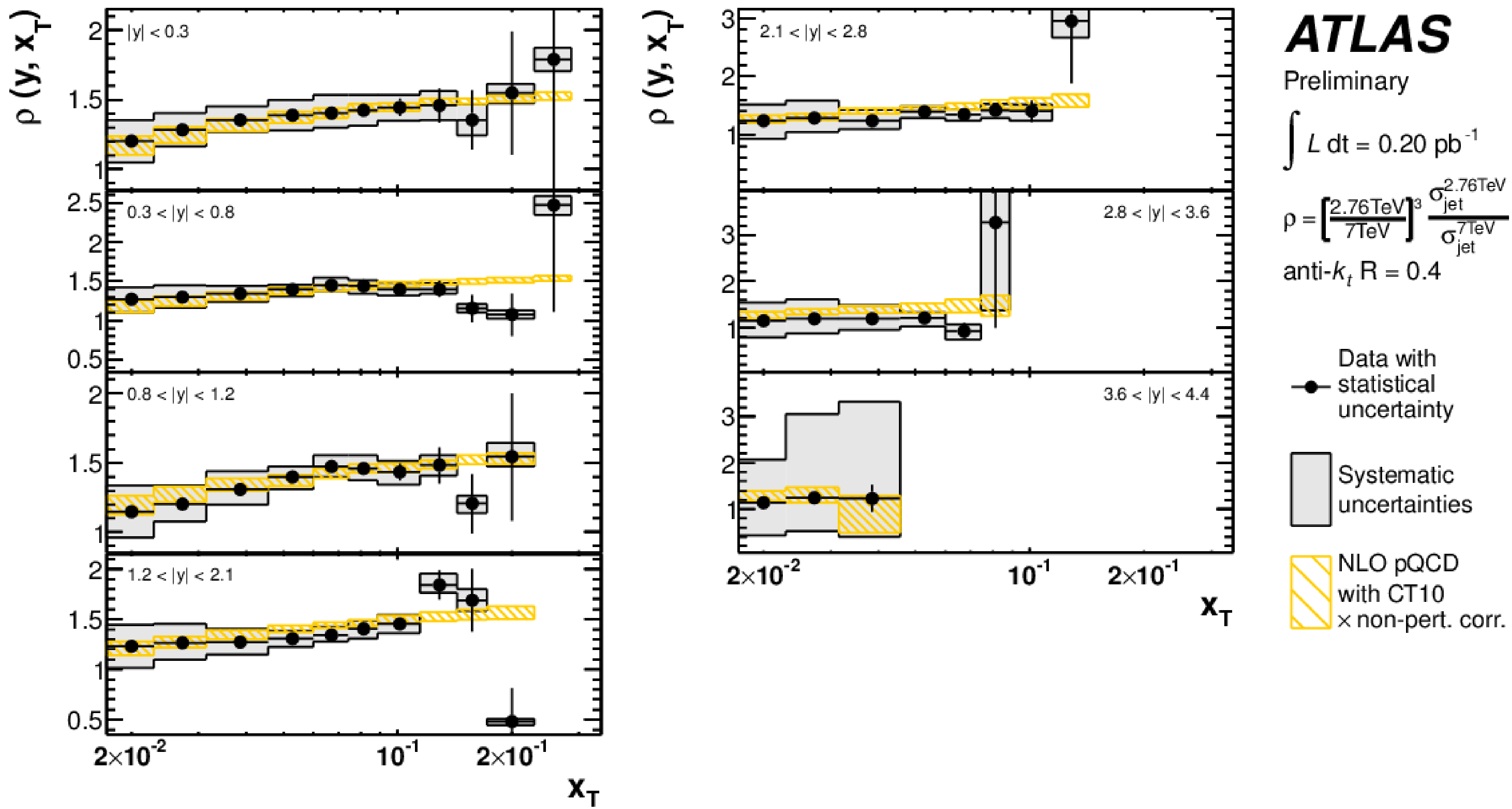




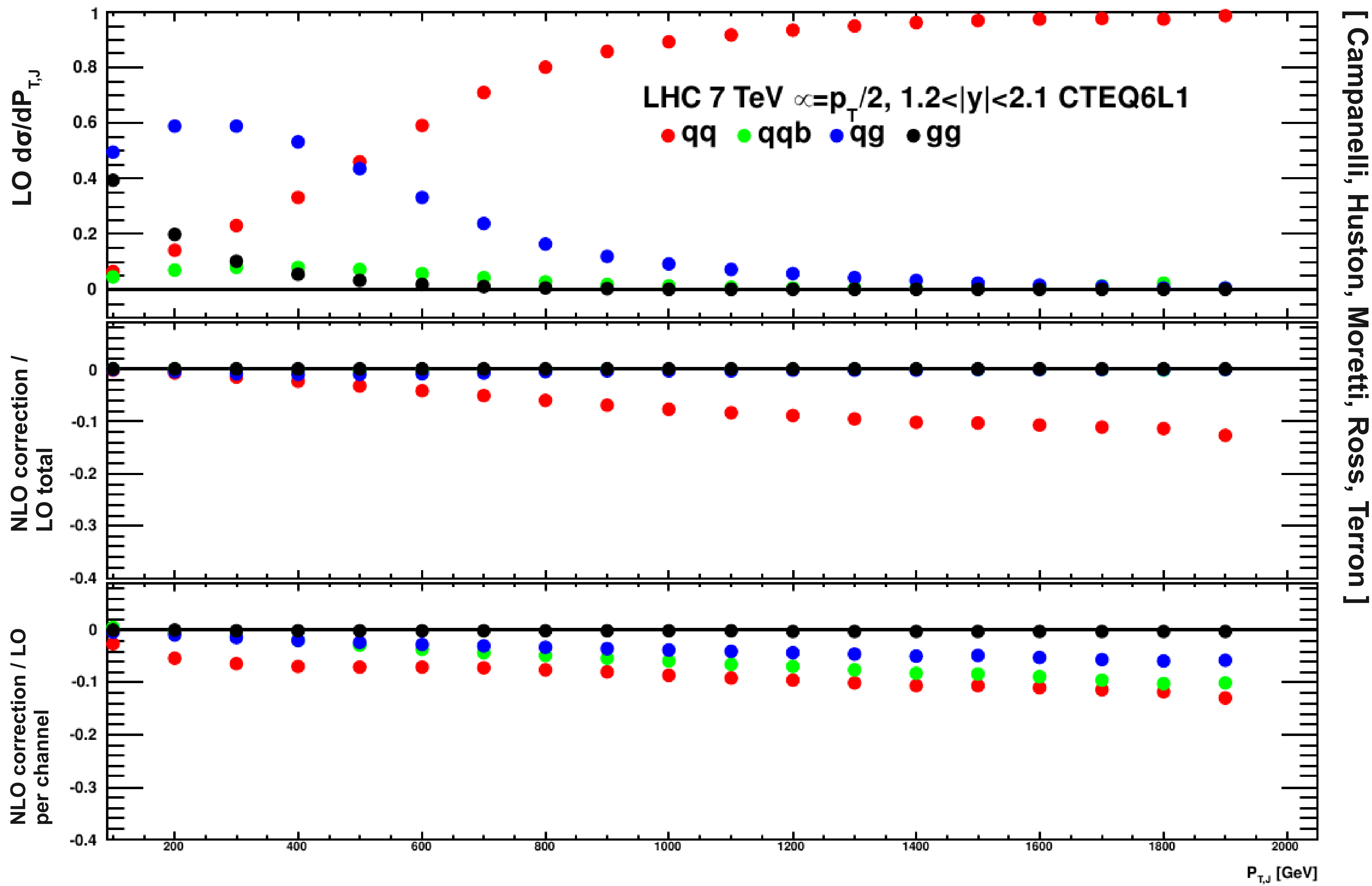


Anti-k_t 0.6

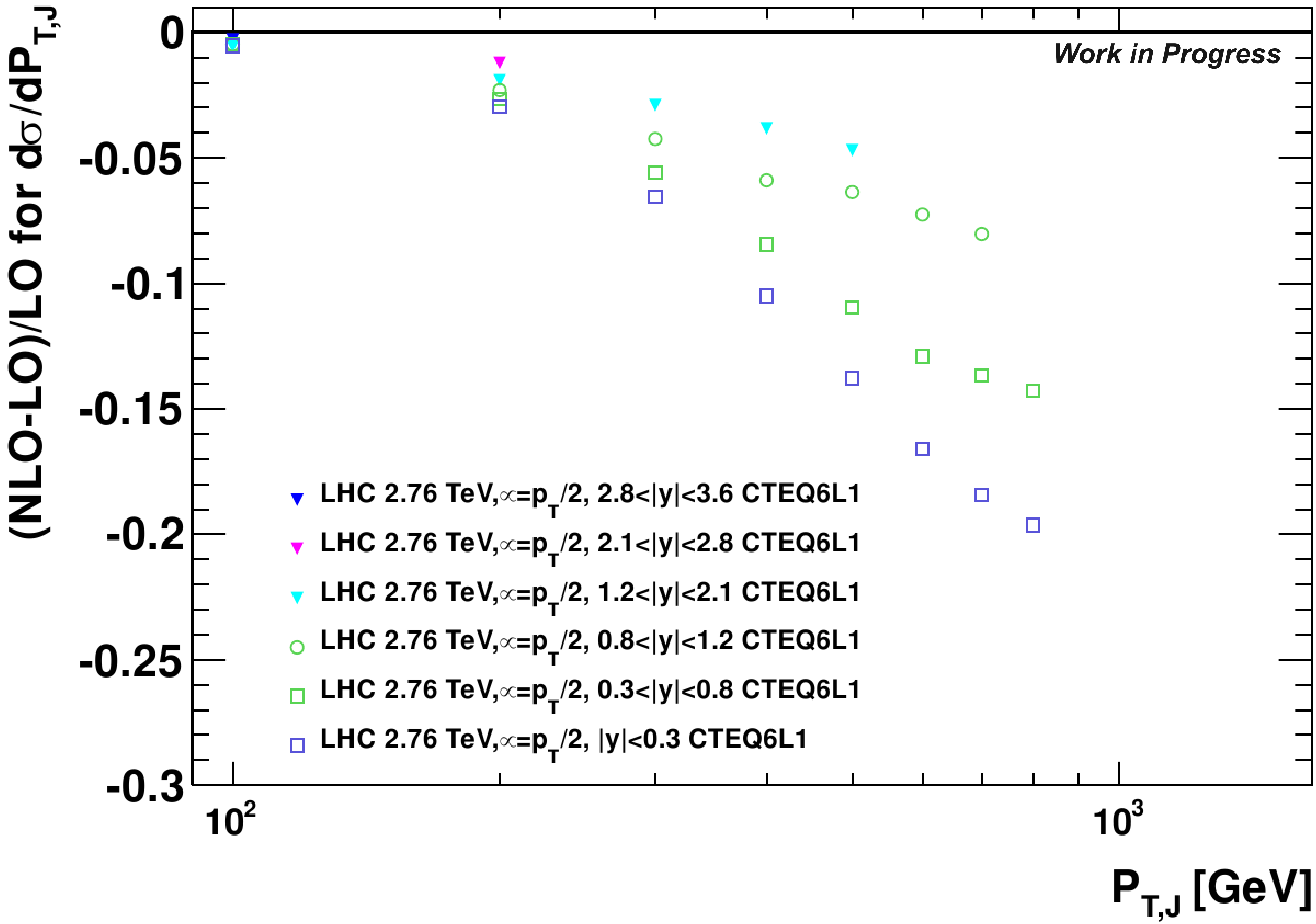
Cross Section Ratio: x_T Binning (R=0.4)



Decomposition in forward region at 7 TeV



Jet-Rapidity Dependence at 2.76 TeV



[Campanelli, Huston, Moretti, Ross, Terron]

Decomposition at 2.76 TeV