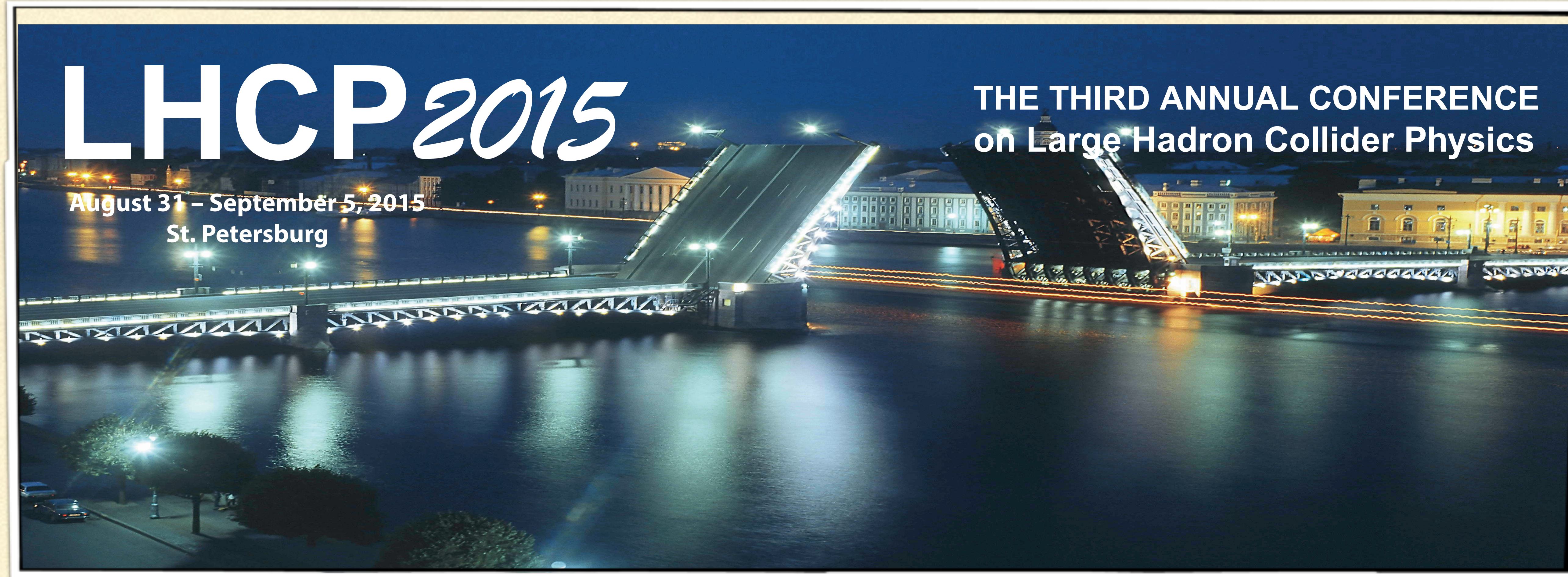


ATLAS JETS RESULTS

Monica Verducci - INFN Rome and CERN

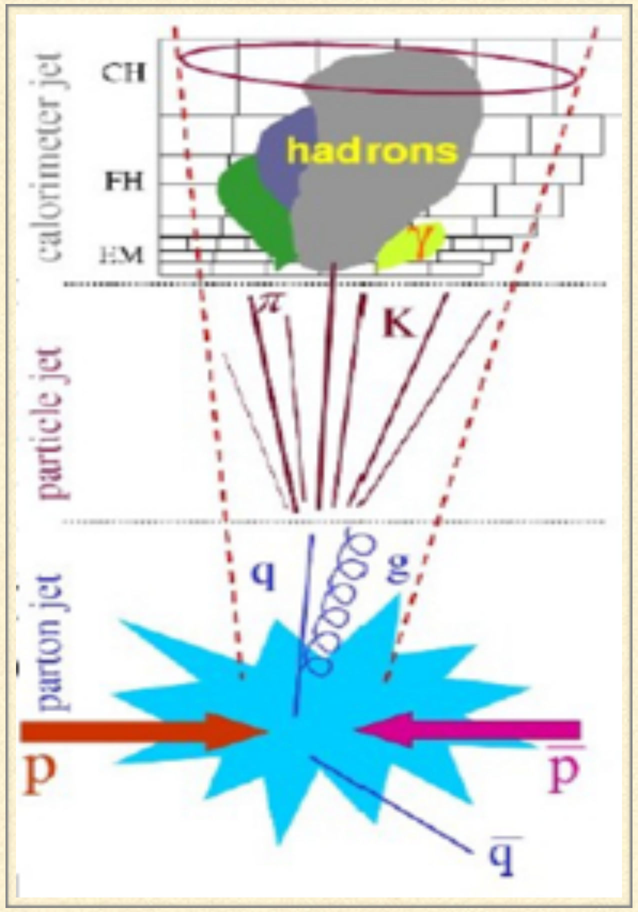
LHCP 2015 St. Petersburg Russia - 2nd September 2015

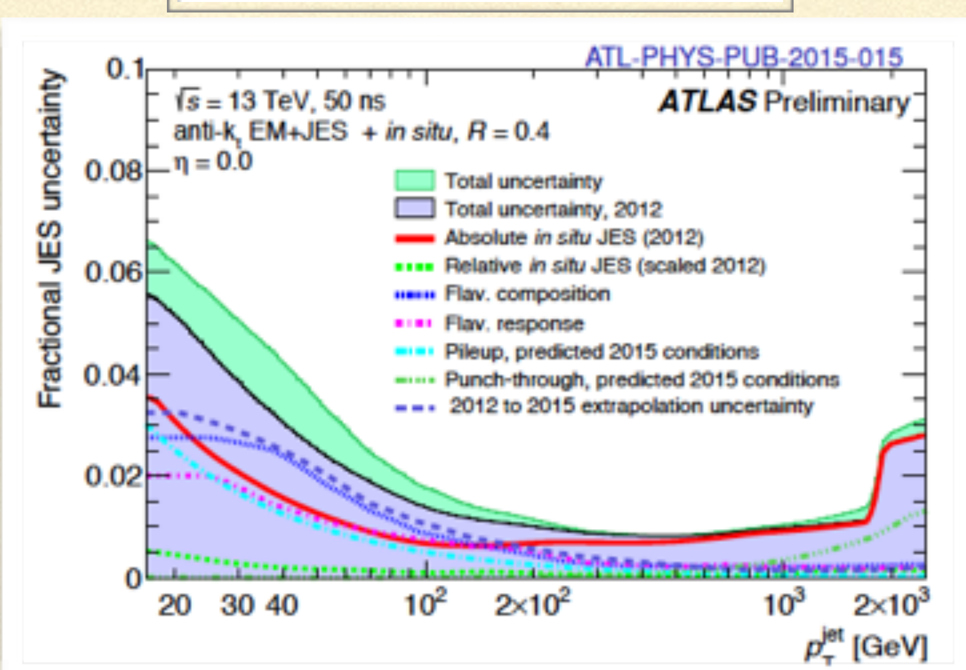
MOTIVATION

Jets measurements provide a test of the quantum chromodynamics (QCD).

- Nearly all LHC physics is connected to the interaction of quarks and gluons
  - **QCD provides the underlying dynamics for basically everything!**
- Our understanding and modelling of QCD interactions have **direct impact on the potential for precision measurements in the Standard Model (SM) physics.**
- We experimentally can improve the descriptions of QCD production mechanisms, **improving the sensitivity to new physics channels.**
  - QCD provides background for nearly all searches!
- We can constrain theory uncertainties by experimental measurements:
  - **new inputs for proton PDF determination and tuning of Monte Carlo generators.**

JETS IN ATLAS





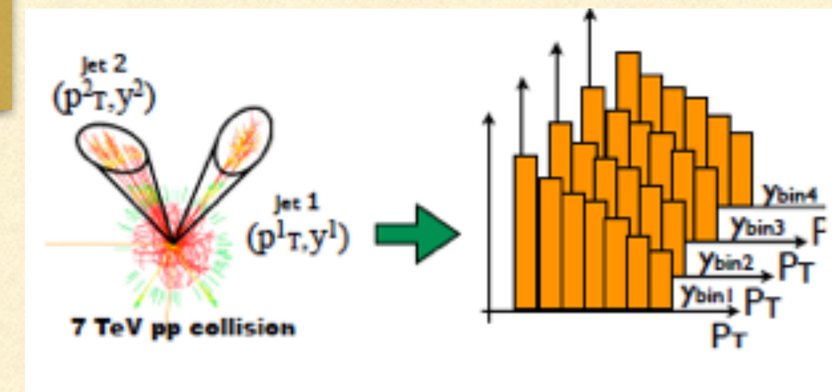
- **Jets are reconstructed by the anti-*kt* algorithm**
  - jets are clustered using two different values of R: 0.4 and 0.6. Topological calorimeter cluster inputs.
- **Detector effects unfolded out of measured jets to produce particle-level jets:**
  - Possible Data-Theory comparison!
- Statistical errors are small → systematic uncertainties from jet algorithm & trigger efficiency, jet energy scale (mostly linearity of calorimeter response), contributions from underlying event and pile-up.
- ATLAS measures jets with: $\sigma_E/E \approx 50(60)\%/\sqrt{E(GeV)} \oplus 1.5(3)\%$

RESULTS ON JETS

- The analyses on jets will impact many QCD measurements
  - Tests of high−order perturbative QCD calculations, MC simulations and measurements of fundamental Standard Model parameter α_s
    - **Inclusive-jet production cross-sections:**
      - 78 pb^{-1} @13 TeV ATLAS-CONF-2015-034 and 4.5 fb^{-1} @ 7 TeV JHEP 02 (2015) 153
    - **Multiple-jet production cross-sections:**
      - Di-jets cross section 4.5 fb^{-1} @ 7 TeV JHEP 05 (2014) 059
      - Three-jets cross section 4.5 fb^{-1} @ 7 TeV Eur. Phys. J. C75 (2015) 228
      - Four-jets cross section 20.3 fb^{-1} @ 8 TeV CERN-PH-EP-2015-181
    - **V+jets → see Nagano's talk**
    - **Jet's Properties**
      - Transverse energy-energy correlation (TEEC) 158 pb^{-1} of data @ 7 TeV CERN-PH-EP-2015-177
      - Jet charge measurement 20.3 fb^{-1} @ 7 TeV ATLAS-CONF-2015-025
  - Constraining Parton Distribution → see Stockton's talk
  - Soft QCD: underlying and minimum bias events → see Martin-Haugh's talk

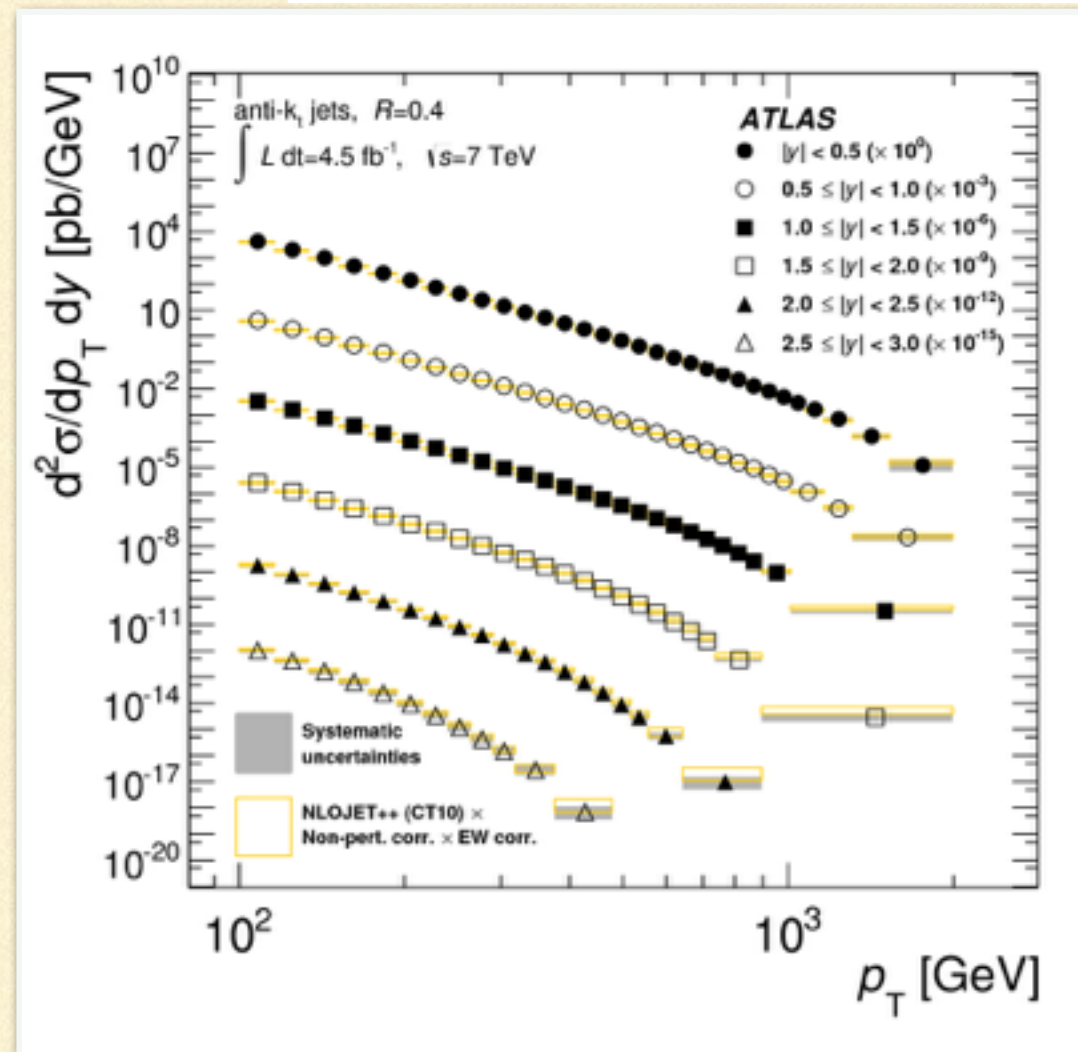
INCLUSIVE JET CROSS SECTION

Motivation: a test of validity of pQCD and probing of the parton distribution functions (PDFs) in the proton.



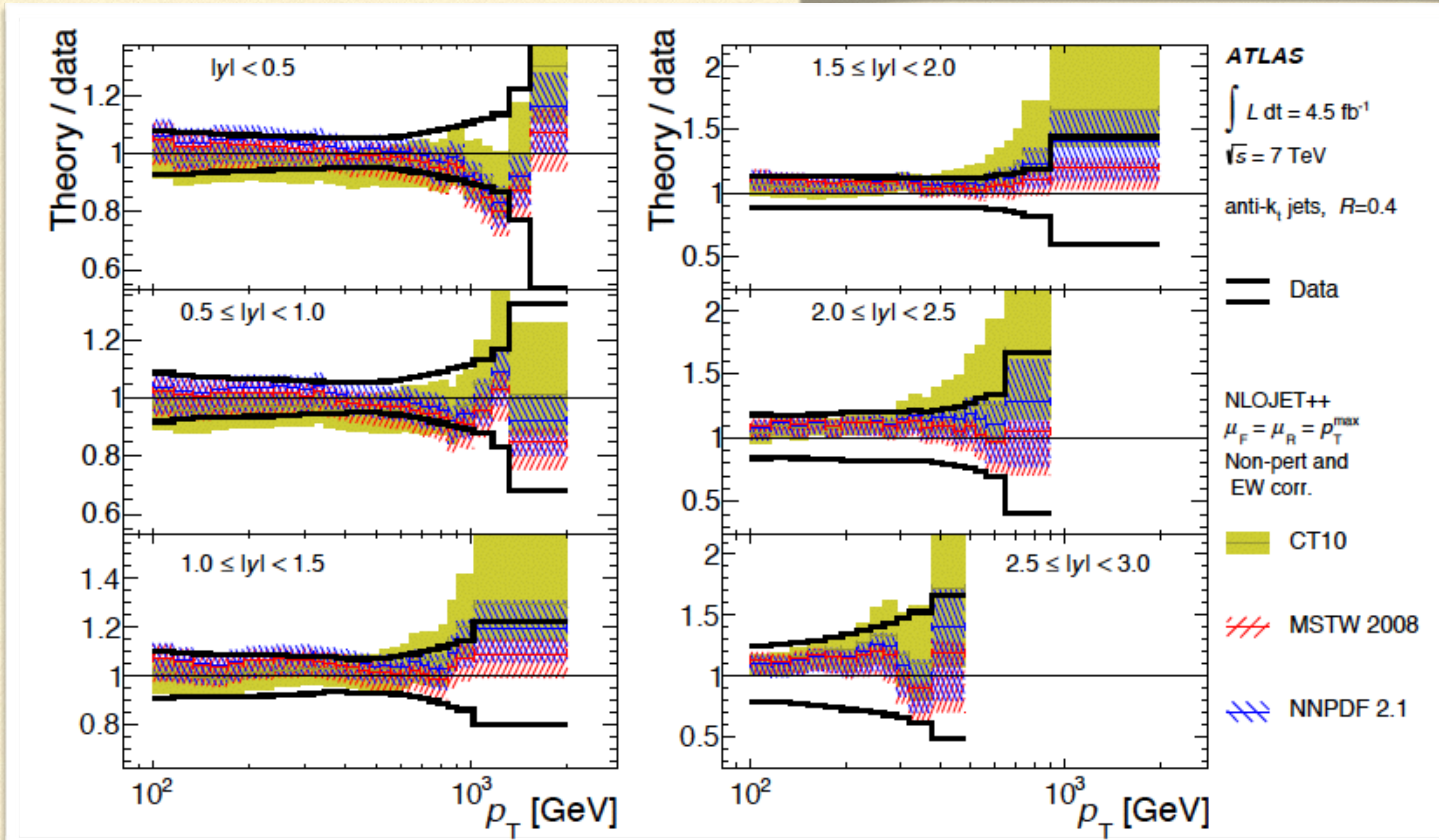
Analysis Strategy

- Jets with p_T>100GeV in rapidity region |y|<3
- Double differential cross section as a function of p_T in regions of |y| of size 0.5
- Jet trigger combination fully efficient over relevant p_T range, full 2011 ATLAS dataset 4.5fb^{-1}
- JES uncertainty 2%(central)-4%(forward) in lower p_T range
- NLOJet++ pQCD predictions corrected for non-perturb. and EW effects



INCLUSIVE JET CROSS SECTION

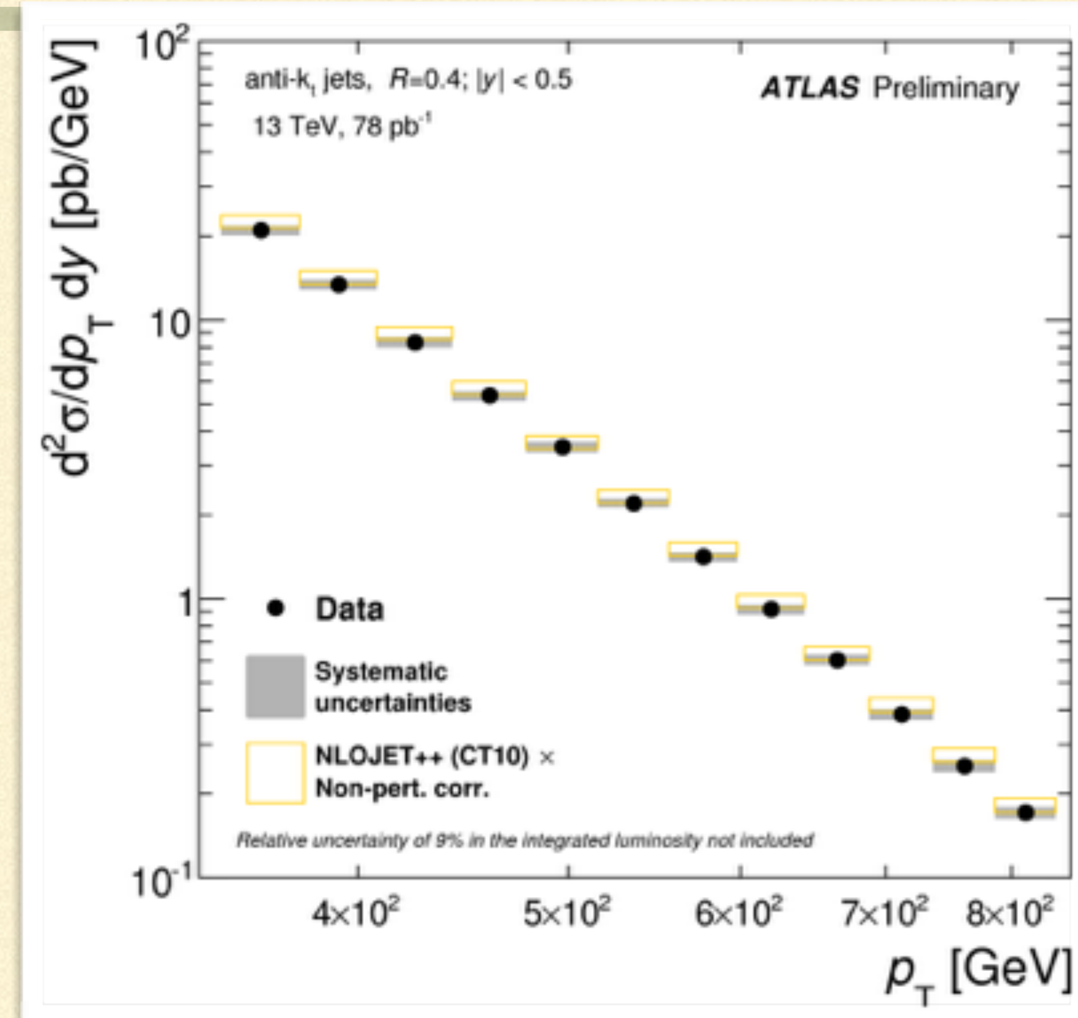
4.5 fb^{-1} @ 7 TeV JHEP 02 (2015) 153



Ratio of NLO pQCD predictions to measured double-diff. inclusive jet X-section vs jet p_T and jet rapidity - different NLO PDF sets used: CT10, MSTW2008 and NNPDF 2.1.

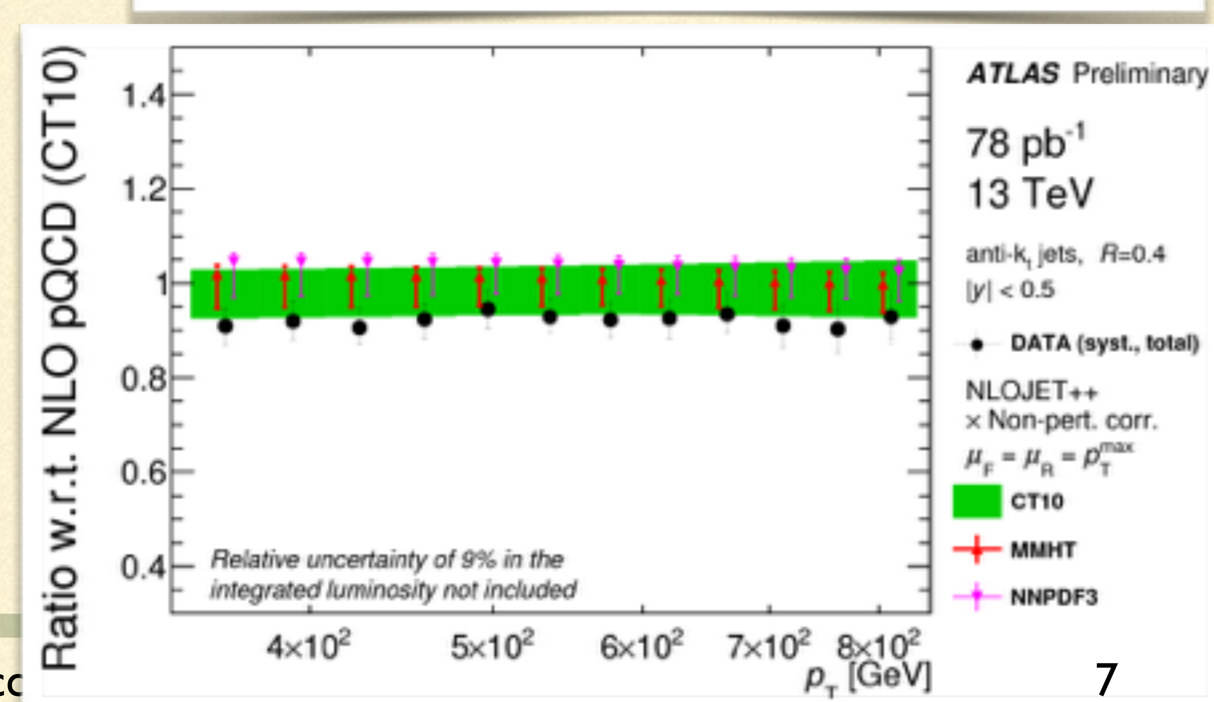
INCLUSIVE JET CROSS SECTION

78 pb^{-1} @ 13TeV ATLAS-CONF-2015-034



Analysis Strategy

- First 78 pb^{-1} of 13 TeV Data
- Cross section as a function of: 346<p_T<838 GeV, in the slice $|y^{jet}|$<0.5
- Total experimental systematics of the order of 5 %, JES uncertainties based on Run1 in-situ calibration.
- NLO is corrected for non-perturbative effects.
- Good agreement between data and NLO predictions.



4.5 fb^{-1} @ 7 TeV JHEP 05 (2014) 059

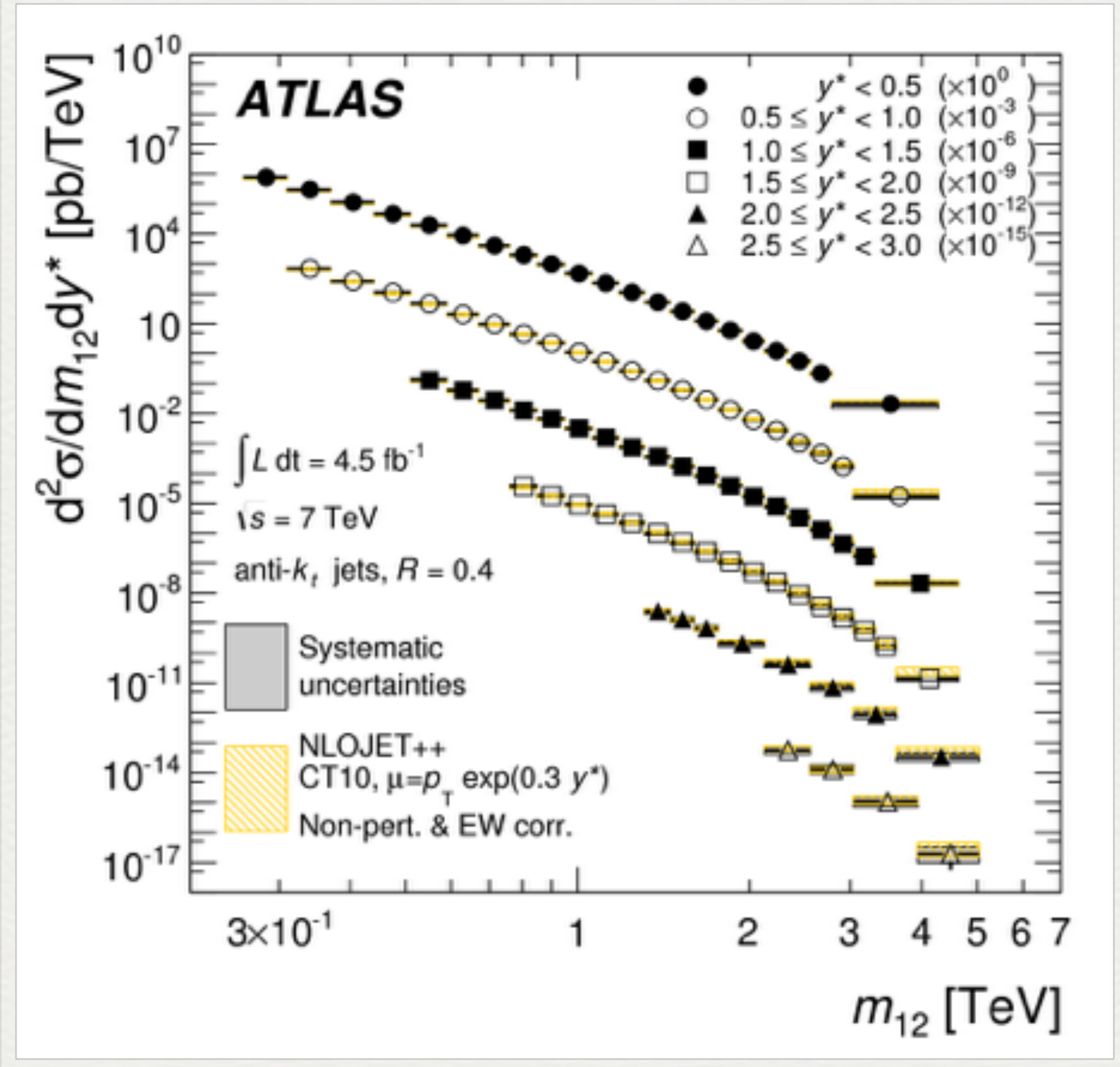
DI-JETS CROSS SECTION

Motivation: useful for understanding QCD and its couplings strength α_S. Cross Section as a function of dijets mass is sensitive to new physics, it can be used to study the partonic structure of the proton, and at high mass range can be used to constrain the gluon PDF.

Analysis Strategy

- 2 leading jets with p_T>100, 50 GeV respectively in the rapidity region |y|<3
- Double differential cross section as a function of $m_{12} = \sqrt{((p_1+p_2)^2)}$ in slices of $|y^*|=|y_1-y_2|/2$
- Combination of fully efficient jet triggers up to 4.5 fb^{-1}
- NLO QCD predictions corrected for non-perturbative and electroweak effects.

Good Agreement between data and theory over 8 orders of magnitude

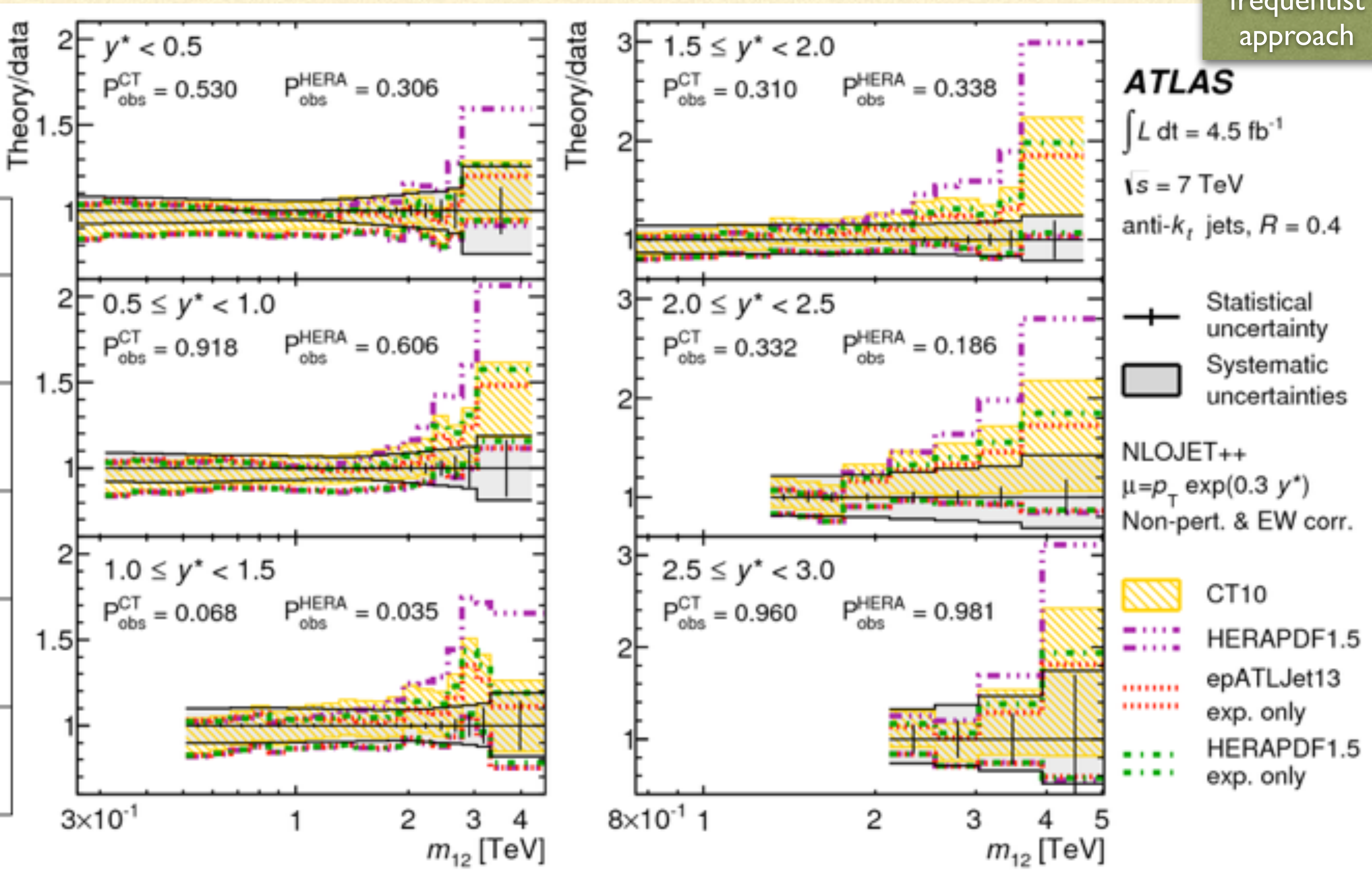


DI-JETS CROSS SECTION

Agreement between Data vs Theory

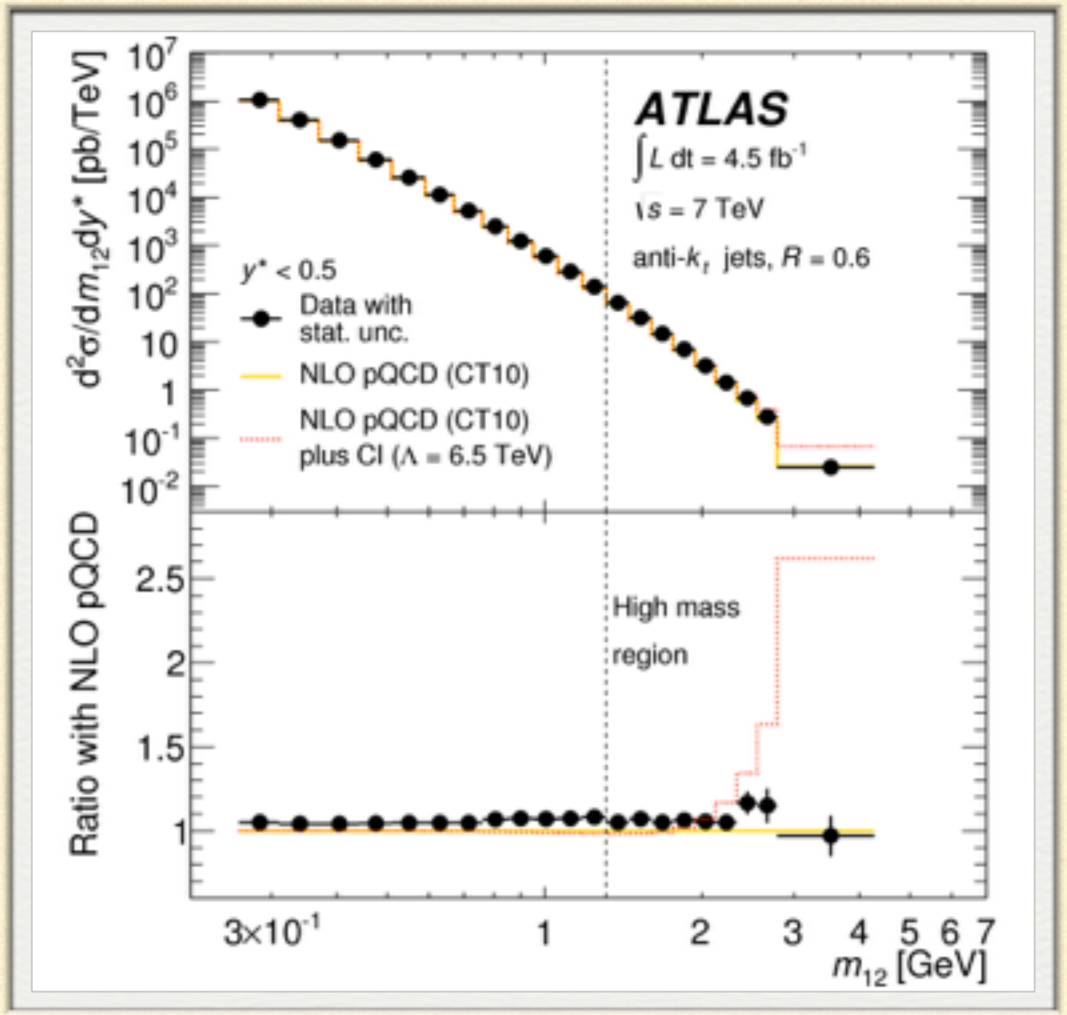
p-value for each PDF, frequentist approach

PDF set	y^* ranges	mass range (full/high)	P_{obs} $R = 0.4$	P_{obs} $R = 0.6$
CT10	$y^* < 0.5$	high	0.742	0.785
	$y^* < 1.5$	high	0.080	0.066
	$y^* < 1.5$	full	0.324	0.168
HERAPDF1.5	$y^* < 0.5$	high	0.688	0.504
	$y^* < 1.5$	high	0.025	0.007
	$y^* < 1.5$	full	0.137	0.025
MSTW 2008	$y^* < 0.5$	high	0.328	0.533
	$y^* < 1.5$	high	0.167	0.183
	$y^* < 1.5$	full	0.470	0.352
NNPDF2.1	$y^* < 0.5$	high	0.405	0.568
	$y^* < 1.5$	high	0.151	0.125
	$y^* < 1.5$	full	0.431	0.242
ABM11	$y^* < 0.5$	high	0.024	$< 10^{-3}$
	$y^* < 1.5$	high	$< 10^{-3}$	$< 10^{-3}$
	$y^* < 1.5$	full	$< 10^{-3}$	$< 10^{-3}$



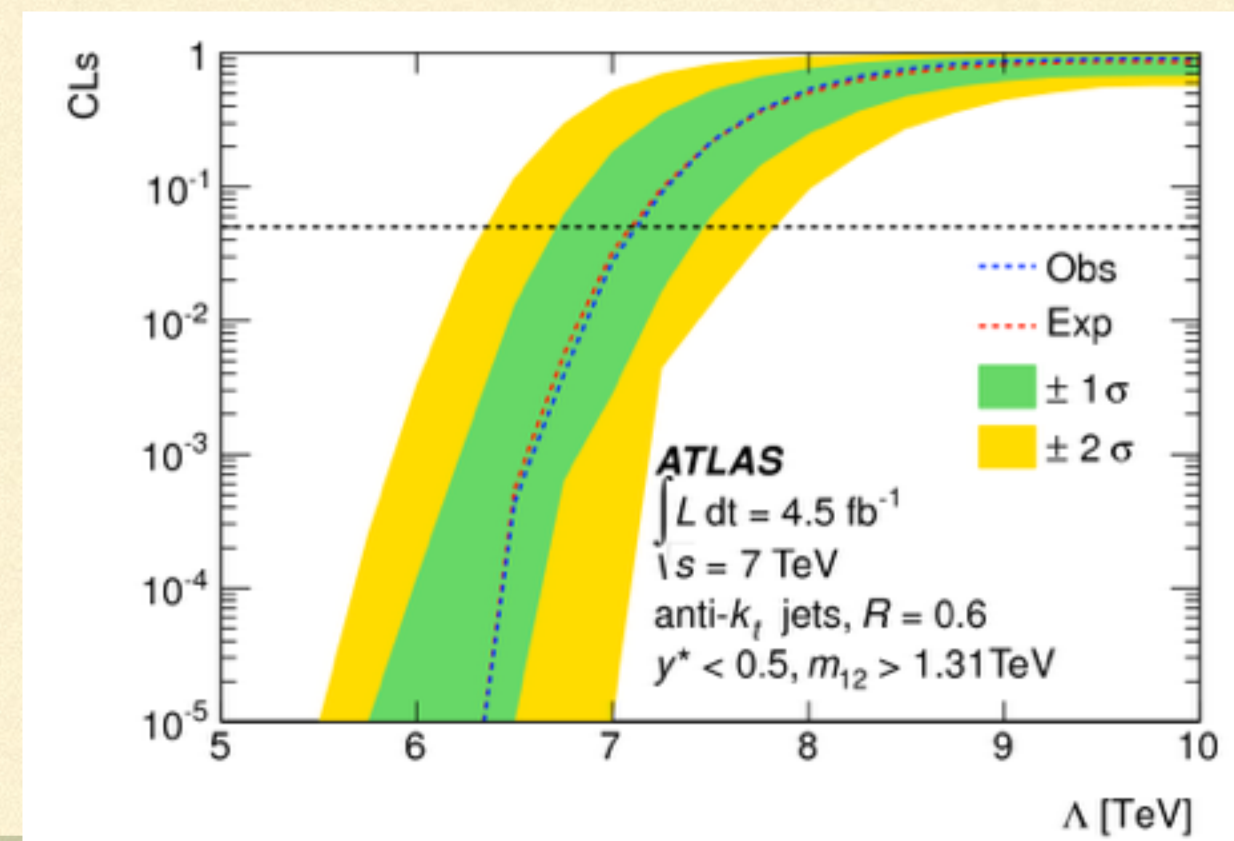
Ratio of NLOJet++ prediction to measurements of dijet double-diff. X-sec vs dijet mass and y* - PDF sets

DI-JETS CROSS SECTION



Limits on contact interactions

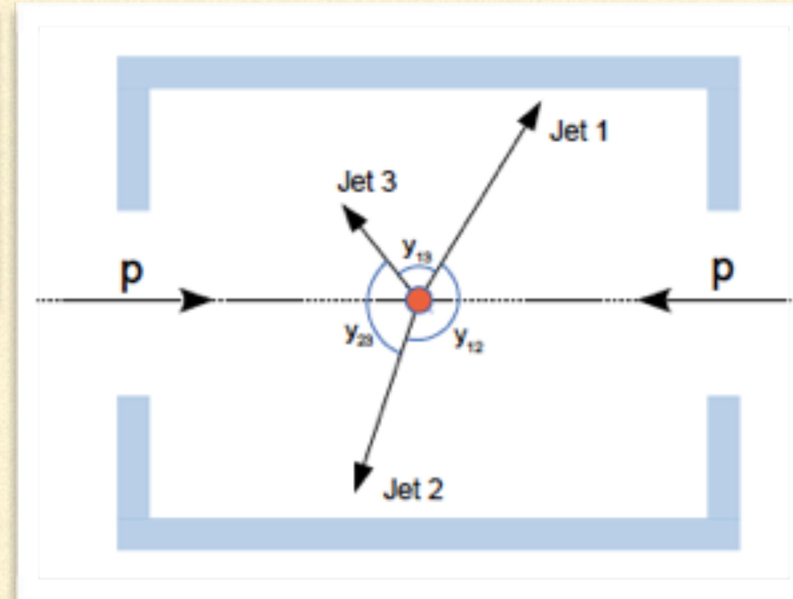
- Using model of QCD + contact interactions calculated using CIJET
- High di-jet mass (m_{12}>1.31 TeV) and low |y*| region, is most sensitive to contact interaction.
- Similar results for R=0.4 and 0.6, some dependence of PDF choice
- The limit setting is done with the unfolded cross-section. Agree with previous analysis: JHEP 01 (2013) 029



Compositeness scale limit @ 95% CL: 6.9 to 7.7 TeV

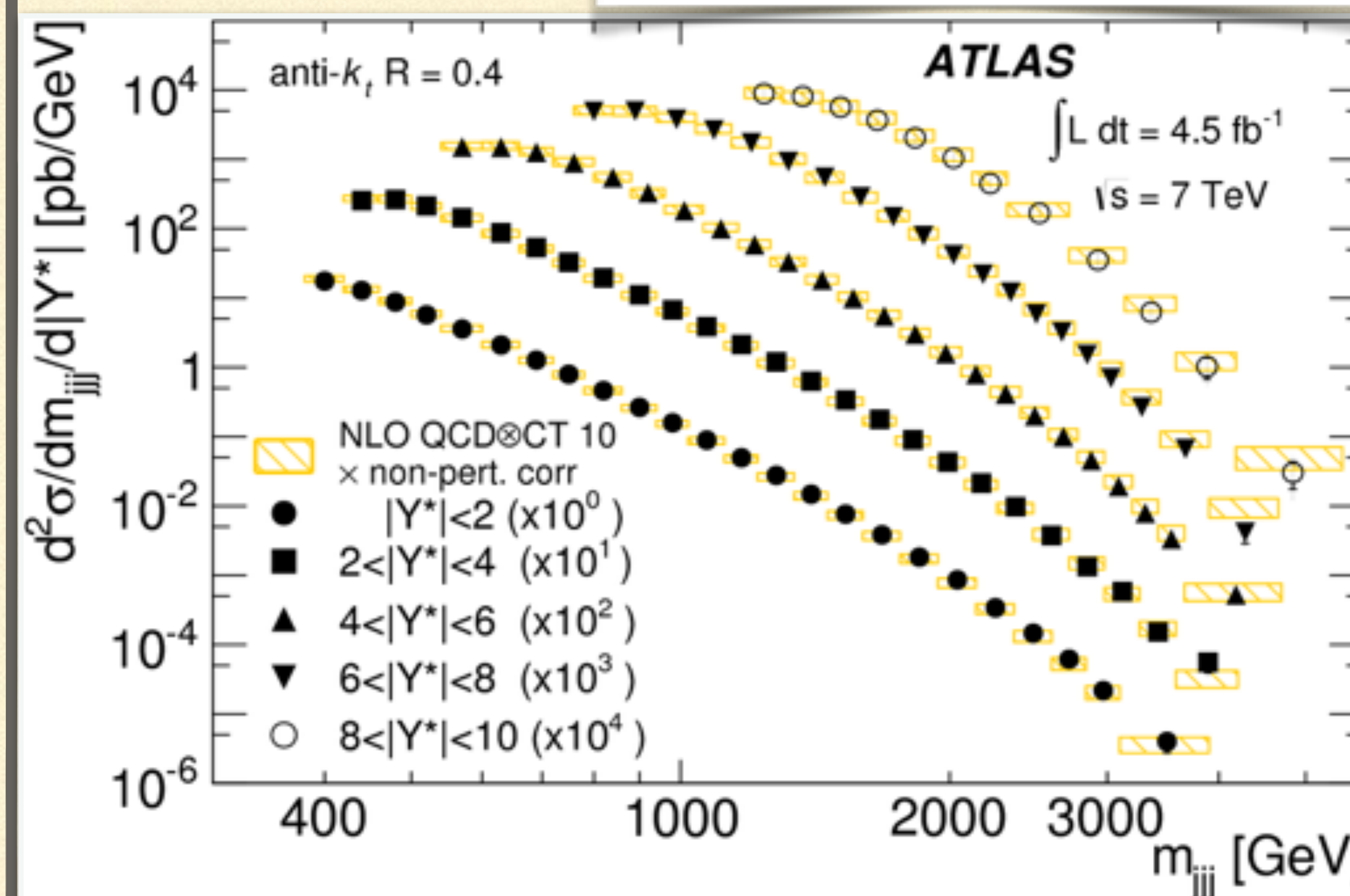
THREE-JETS CROSS SECTION

Motivations: Tests jet calculations at higher multiplicities. Provides complementary to inclusive-jet/dijet information on the PDF and α_S determination.



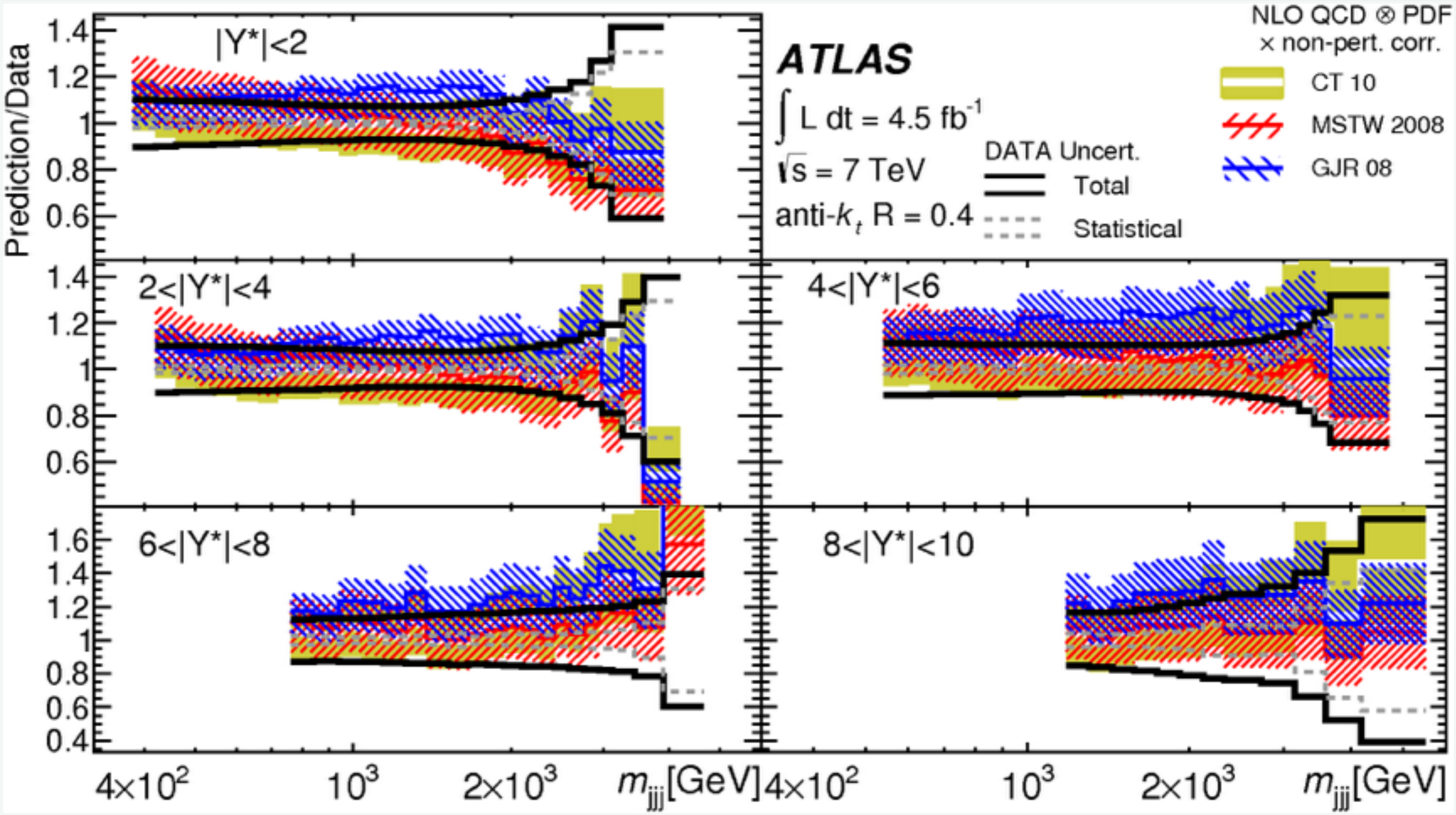
Analysis Strategy

- 3 leading jets with p_T>150, 100, 50 GeV respectively in the rapidity region $|y|<3$.
- Double differential cross section as a function of $m_{jjj} = \sqrt{((p_1+p_2+p_3)^2)}$ in slices of:
  - $|Y^*| = |y_1-y_2|+|y_2-y_3|+|y_1-y_3|$
- Jet trigger combination fully efficient over relevant p_T range, 4.5fb^{-1} dataset.
- JES is the dominant systematics uncertainty (10-20%).
- NLOJet++ pQCD predictions. No EW corrections. Scale: $\mu_R = \mu_F = m_{jjj}$. Uncertainty due to missing high order: scale up/down by 2.



4.5 fb^{-1} @ 7 TeV Eur. Phys. J. C75(2015) 228

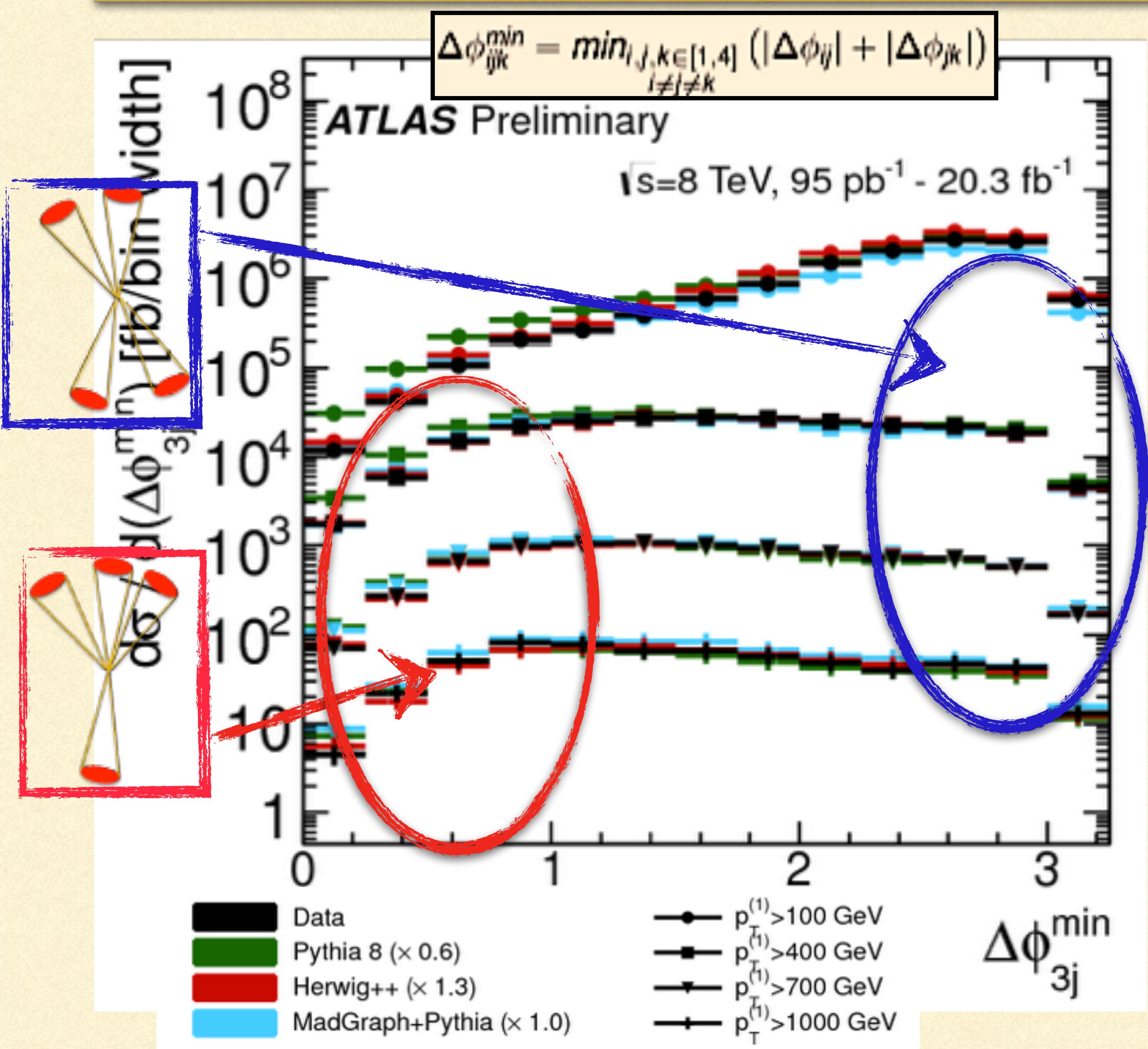
THREE-JETS CROSS SECTION



The ratio of NLO QCD predictions, obtained by using NLOJET++ with different PDF sets (CT 10, MSTW 2008, GJR 08) and corrected for non-perturbative effects, to data as a function of *mjjj* in 5 bins of |*Y*∗|.

FOUR-JETS CROSS SECTION

Motivations: Tests of jet calculations at higher multiplicities: LO (PS and ME+PS) and NLO predictions up to multi-TeV scales. Four-jet mass spectrum probes calculations over six orders of magnitude in the cross-section in the 1–7 TeV range.

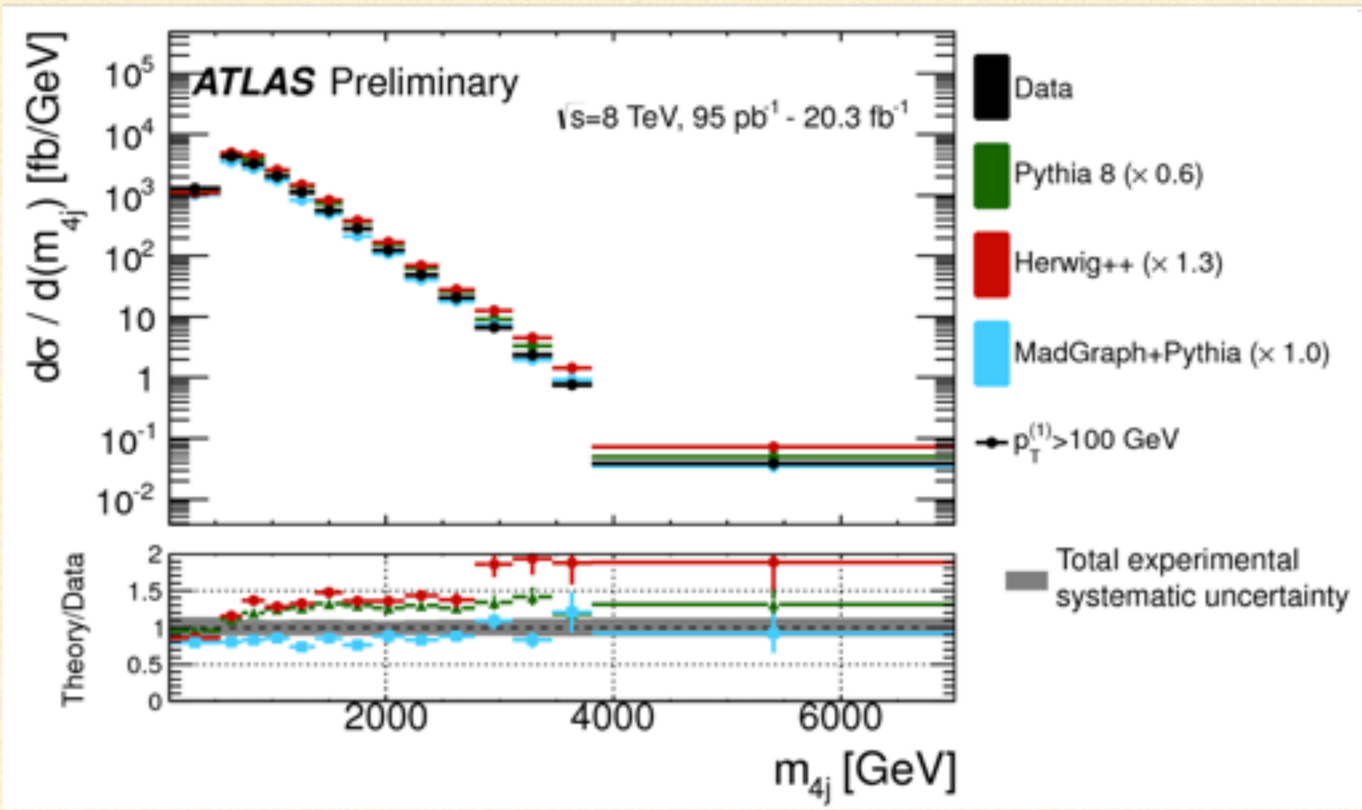


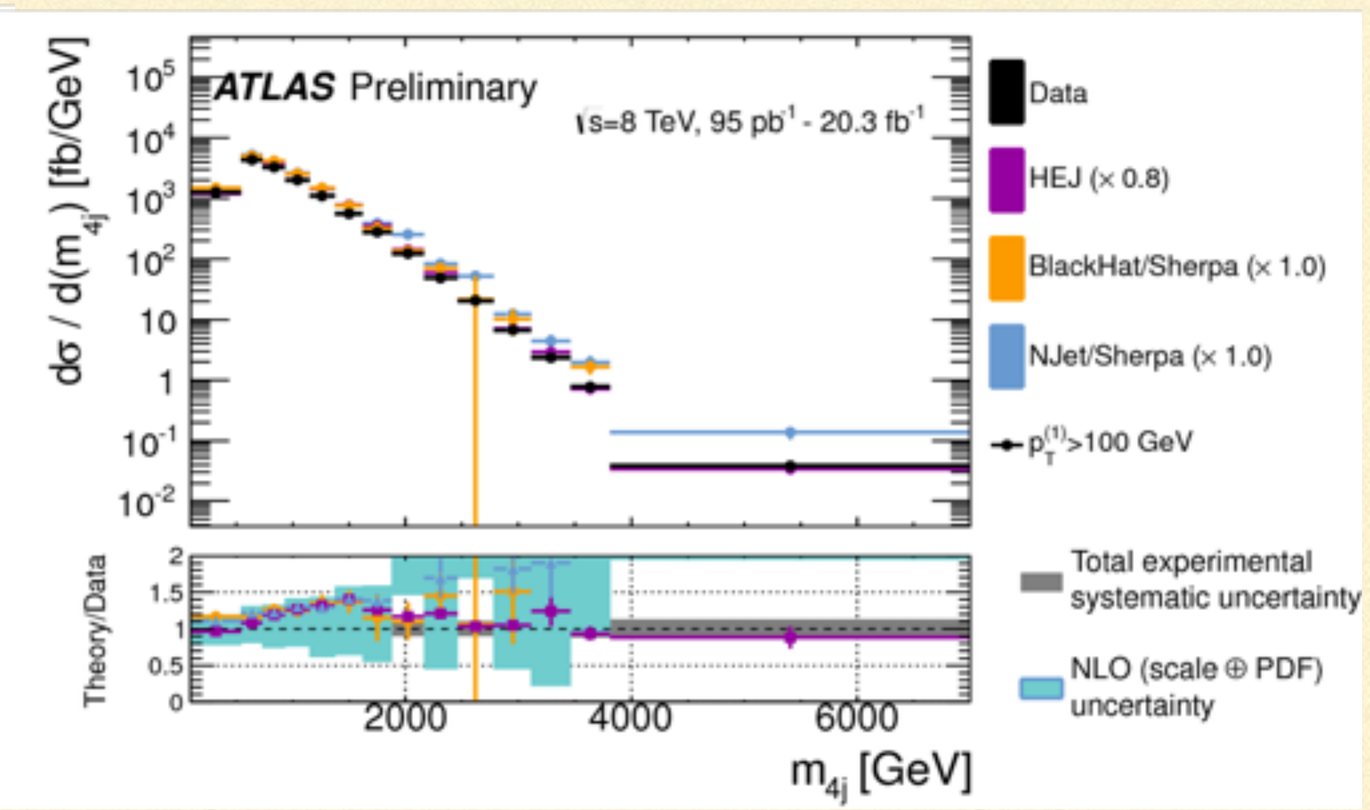
Analysis Strategy

- ATLAS 4−jets cross-sections at 8 TeV, differentially in several variables depending on the jet momenta and angular distributions, in various event topologies.
  - Δφ is very sensitive to soft emissions.
- Unfolded measurements are compared to various MC generators and fixed order predictions
- These measurements test QCD predictions up to scale H_T~7 TeV with
  - p_{T_2} reaching 3 TeV,
  - p_{T_3} ~ 2.5 TeV,
  - p_{T_4} ~2 TeV,
  - p_T ~1.5 TeV
- The total experimental uncertainty is about 8 - 12%

20.3 fb^{-1} @ 8TeV CERN-PH-EP-2015-181

FOUR-JETS CROSS SECTION



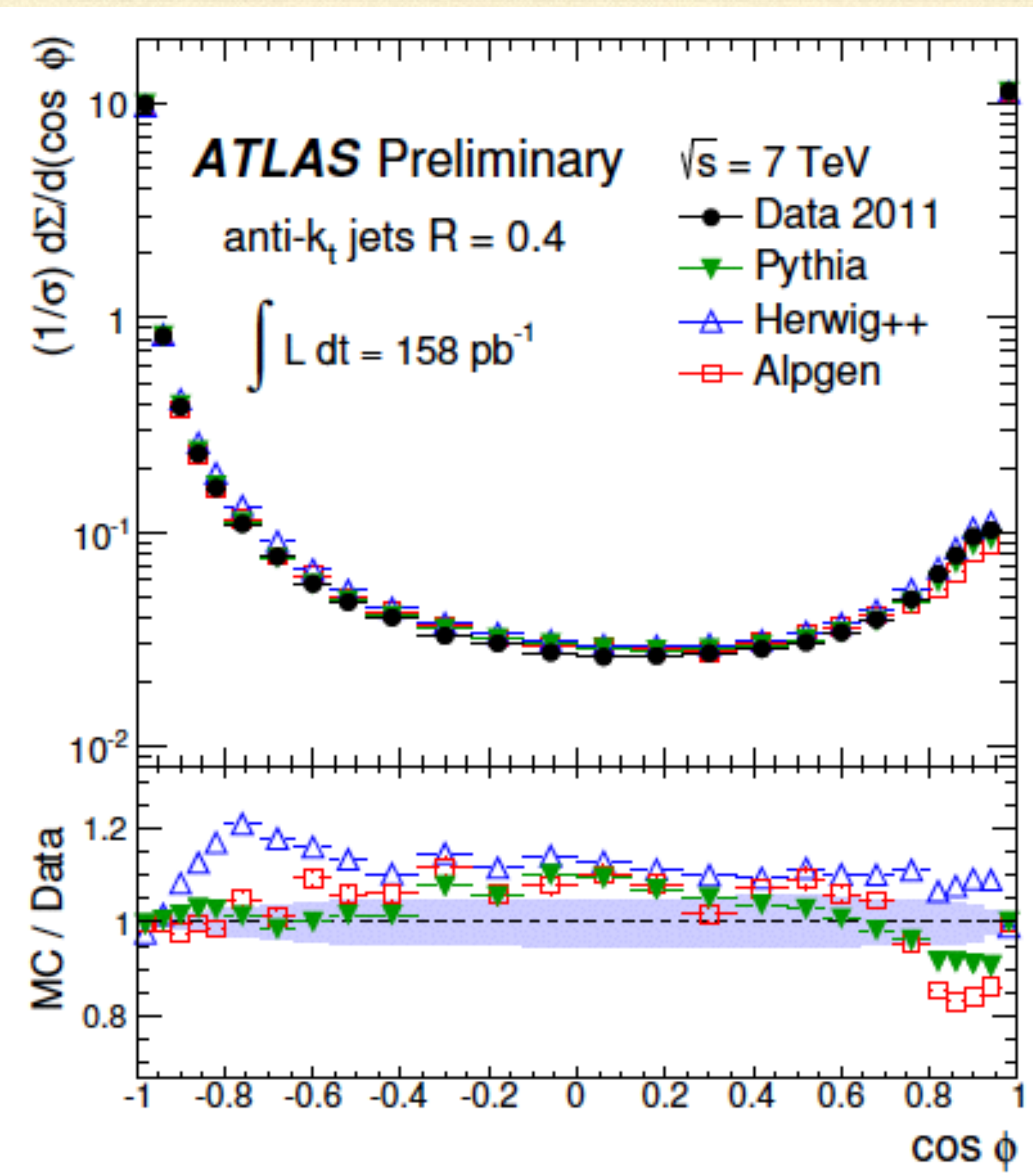


Leading order predictions : Madgraph+Pythia and Pythia 8 provide best description of data
Fixed order calculations : agree with data up to 3 TeV and deviates at higher masses.
The scale uncertainty is large: ~ 30%.
HEJ: good agreement with data in the high mass range (m_{4j} > 2 TeV)

JET–BASED TRANSVERSE ENERGY-ENERGY CORRELATION

158 pb^{-1} @ 7 TeV arXiv:1508.01579

Motivations: the transverse energy correlation (TEEC) and its asymmetry (ATEEC) exhibit a quadratic dependence on the strong coupling constant. This measurement can determine its value.



$$\frac{1}{\sigma}\frac{d\Sigma}{d(\cos\phi)} = \frac{1}{\sigma}\sum_{ij}\int \frac{d\sigma}{dx_{Ti}dx_{Tj}d(\cos\phi)} x_{Ti}x_{Tj}dx_{Ti}dx_{Tj},$$

TEEC

$$x_{Ti} = E_{Ti}/E_T \qquad E_T = \sum_i E_{Ti}.$$

$$\frac{1}{\sigma}\frac{d\Sigma^{asym}}{d(\cos\phi)} \equiv \frac{1}{\sigma}\frac{d\Sigma}{d(\cos\phi)}\bigg|_{\phi} - \frac{1}{\sigma}\frac{d\Sigma}{d(\cos\phi)}\bigg|_{\pi-\phi}$$

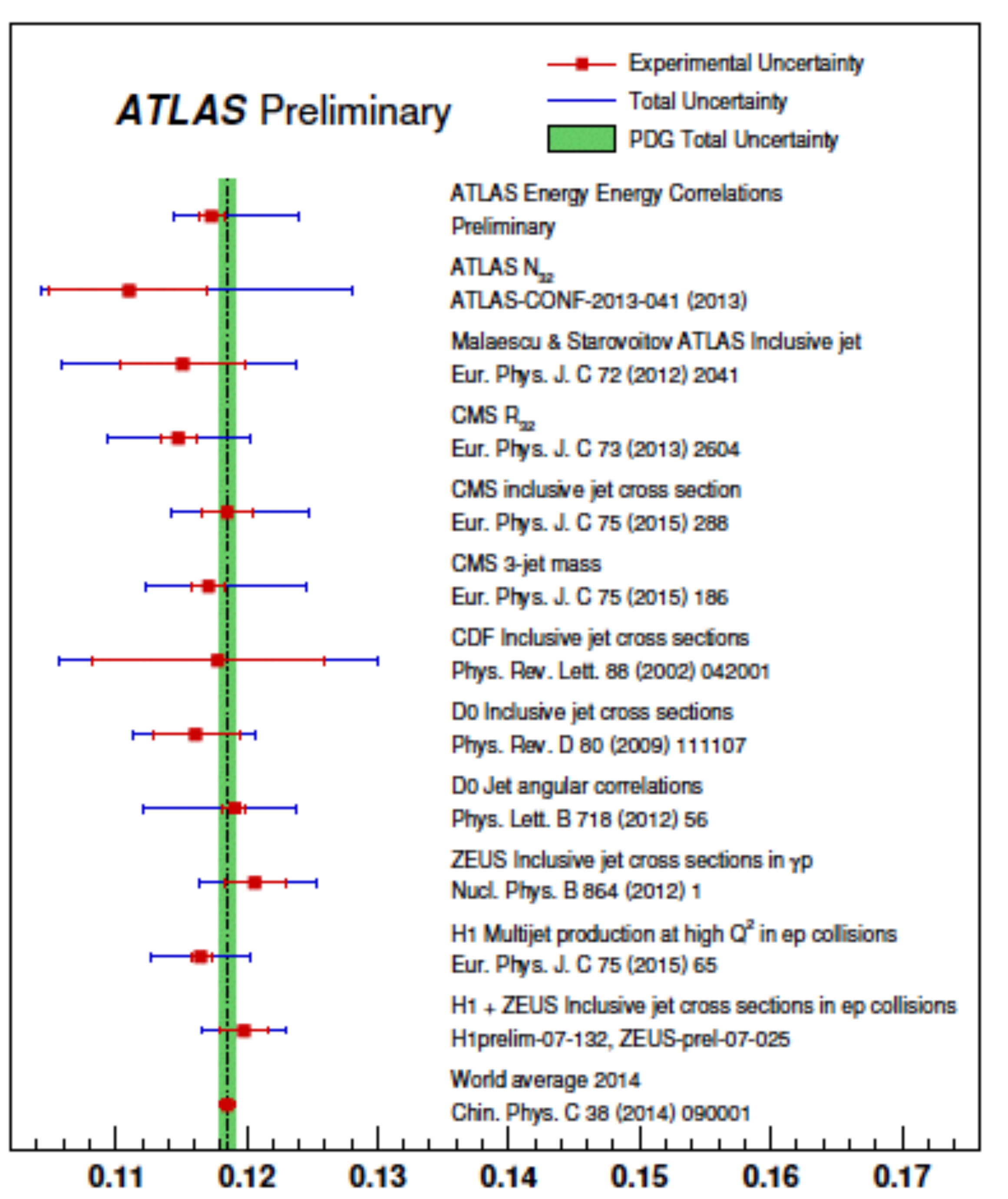
ATEEC

Analysis Strategy

- 158 pb^{-1} of data @ 7 TeV
- ϕ_{ij} azimuthal angle between jets
- $p1_T + p2_T > 500$ GeV; $p(all)_T > 50$ GeV; $|y(jet)| < 2.5$
- total uncertainty is about 5%, dominated by the jet energy scale, pileup and MC parton-shower modelling.
- Pythia/Alpgen predictions agree reasonably well with data, Herwig++ deviates from data by up to 20%.
- NLO theory agrees with data within scale+PDF uncertainties (~15%).

α_S RESULTS

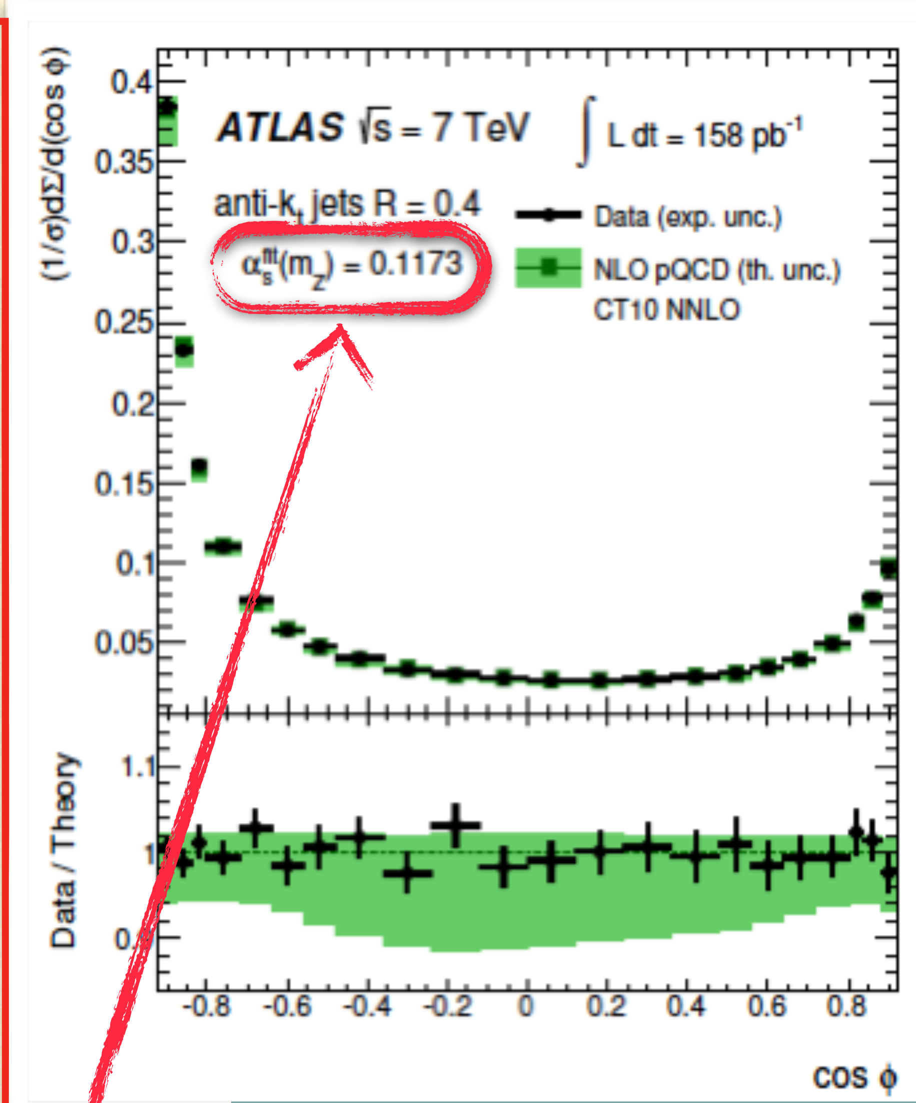
158 pb^{-1} @ 7 TeV arXiv:1508.01579



Excellent compatibility between World Average and ATLAS jet−based measurements, and between hadron and e−p colliders!

NNLO calculations needed for jet processes to improve precision on α_S at hadron colliders

- Theoretical scale uncertainty dominate over exp. uncertainties. The uncertainties on the scales μ_R and μ_F are estimated by varying by a factor of two up and down, with the additional requirement that $0.5 \leq \mu_R/\mu_F \leq 2.0$.



The fitted values of the strong coupling constant are:

$\alpha_S(m_Z)$ = 0.1173 (TEEC)

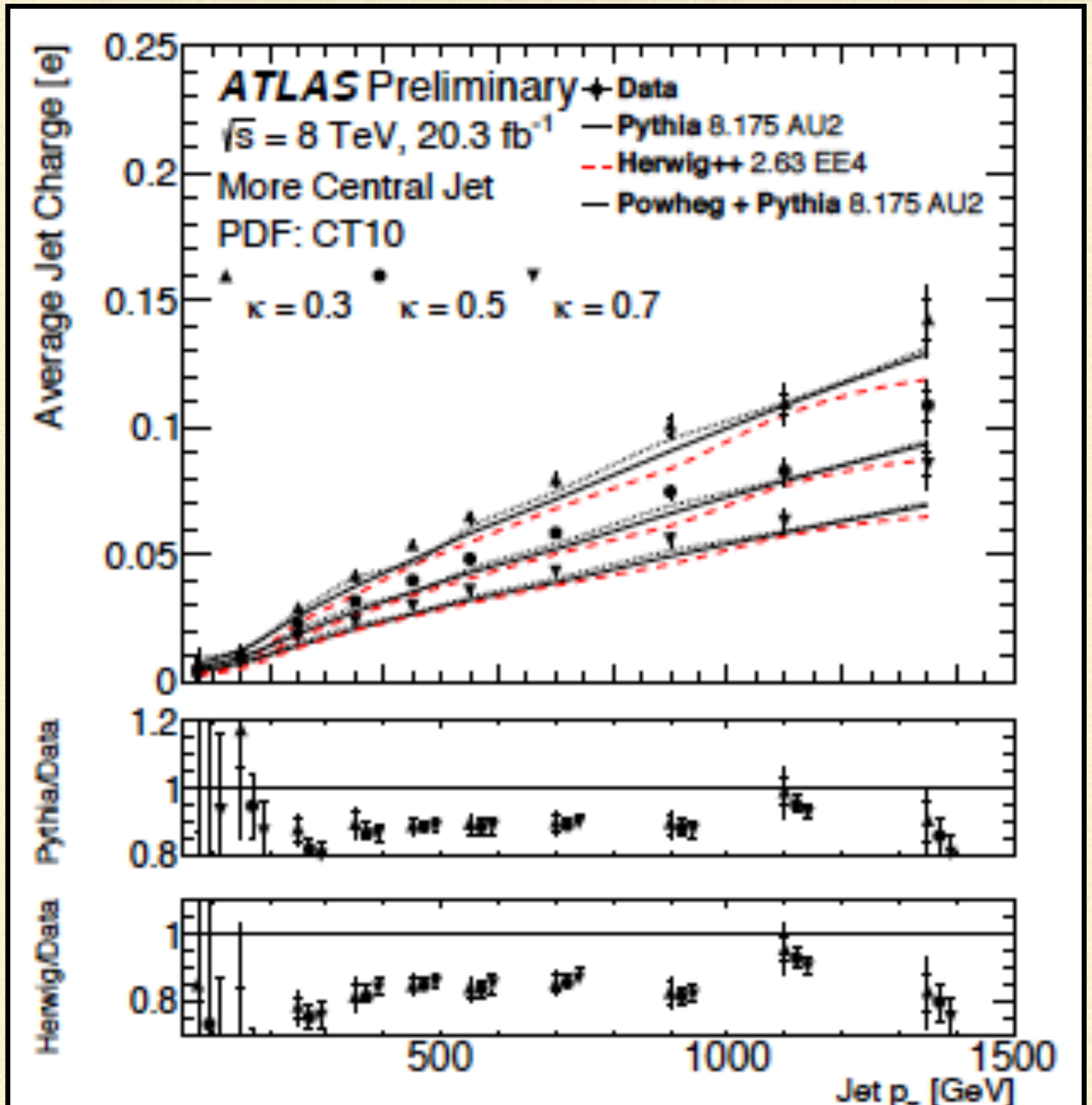
$\alpha_S(m_Z)$ = 0.1195 (ATEEC).

$$\alpha_s = 0.1173 \pm 0.0010(\text{exp})^{+0.0063}_{-0.0020}(\text{scale}) \pm 0.0017(\text{PDF}) \pm 0.0002(\text{NPC})$$

AVERAGE JET CHARGE

ATLAS-CONF-2015-025

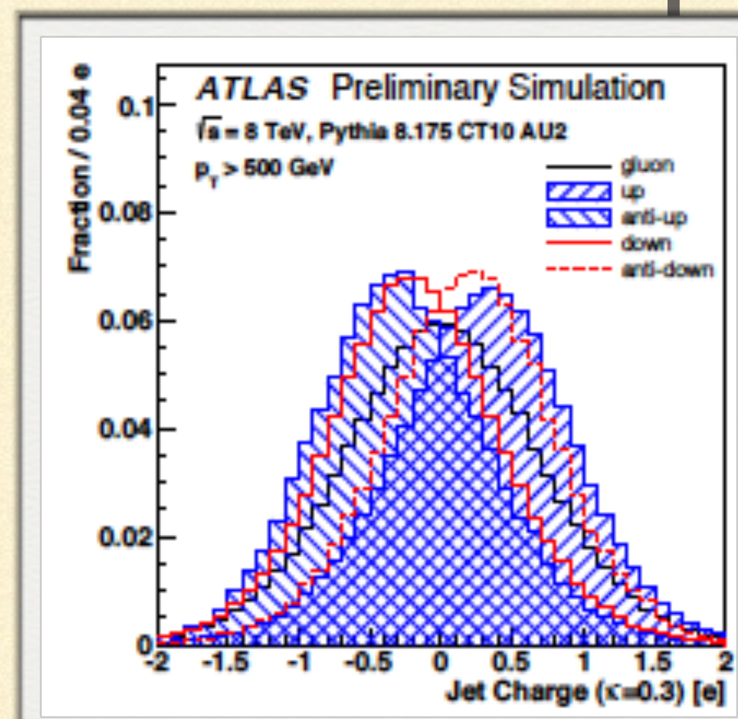
Motivations: the momentum-weighted sum of charged tracks associated to jets is sensitive to the charge of the initiating quark or gluon.



Average jet charge is larger in data of about 10% wrt MCs mostly due to PDF and poor modelling of the fragmentation

Analysis Strategy

- 20.3 fb^{-1} @ 8 TeV
- Dijets events: p_T^{jet} >50 GeV, p_T^1/p_T^2<1.5, $|\eta^{jet}|$<2.1
- Tracks for reco-jet +charged particles for particle-jets
- Track multiplicity and JES are the major systematics.
- Average jet charge increase with the p_T^{jet}

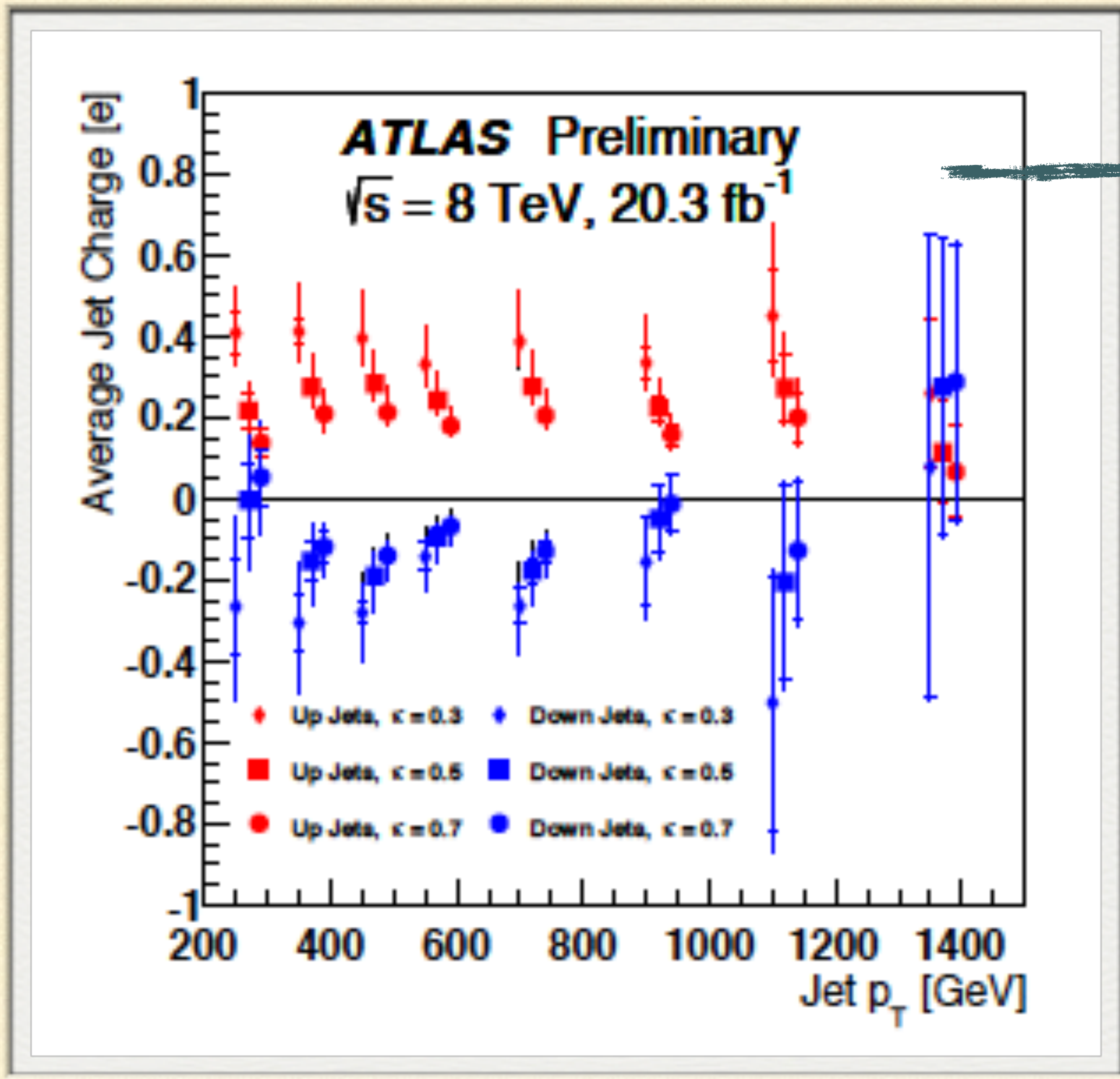


$$Q_J = \frac{1}{(p_T^{jet})^\kappa} \sum_{i \in Tracks} q_i \, (p_T^i)^\kappa, \quad \kappa = 0.3; 0.5; 0.7$$

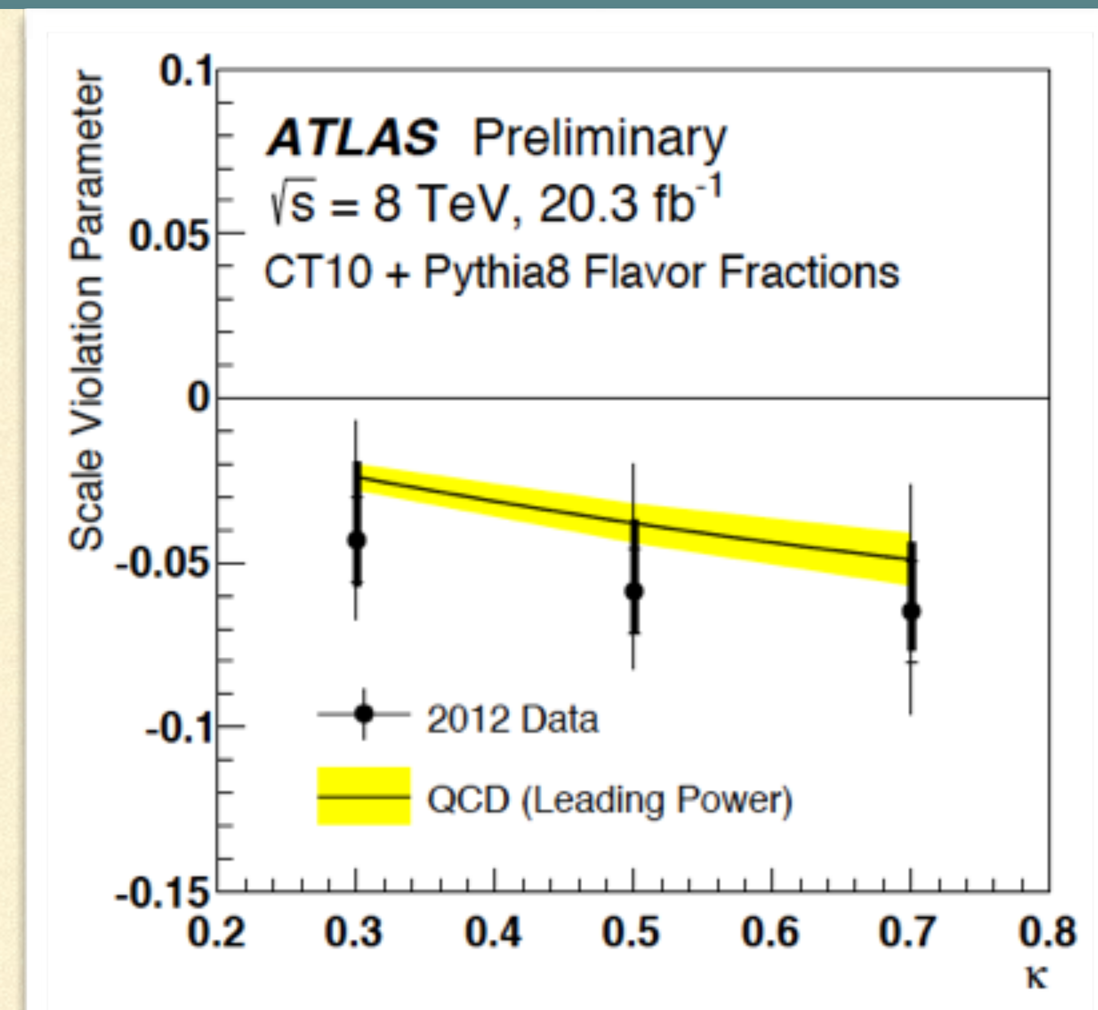
anti-k_t R=0.4 jets

AVERAGE JET CHARGE

ATLAS-CONF-2015-025



Using fractions of up/down quarks information computed in the MC, the charge of up/down quark initiated jets is extracted from data



$$\langle Q_i \rangle \approx \sum_f \alpha_{f,i} \bar{Q}_f \left(1 + c_\kappa \log p_T^i / \bar{p}_T\right)$$

$\alpha_{f,i}$ flavour fraction in the i-th p_T bin;
$\bar{Q}_f$ mean charge at fixed $\bar{p}_T$ = 700GeV

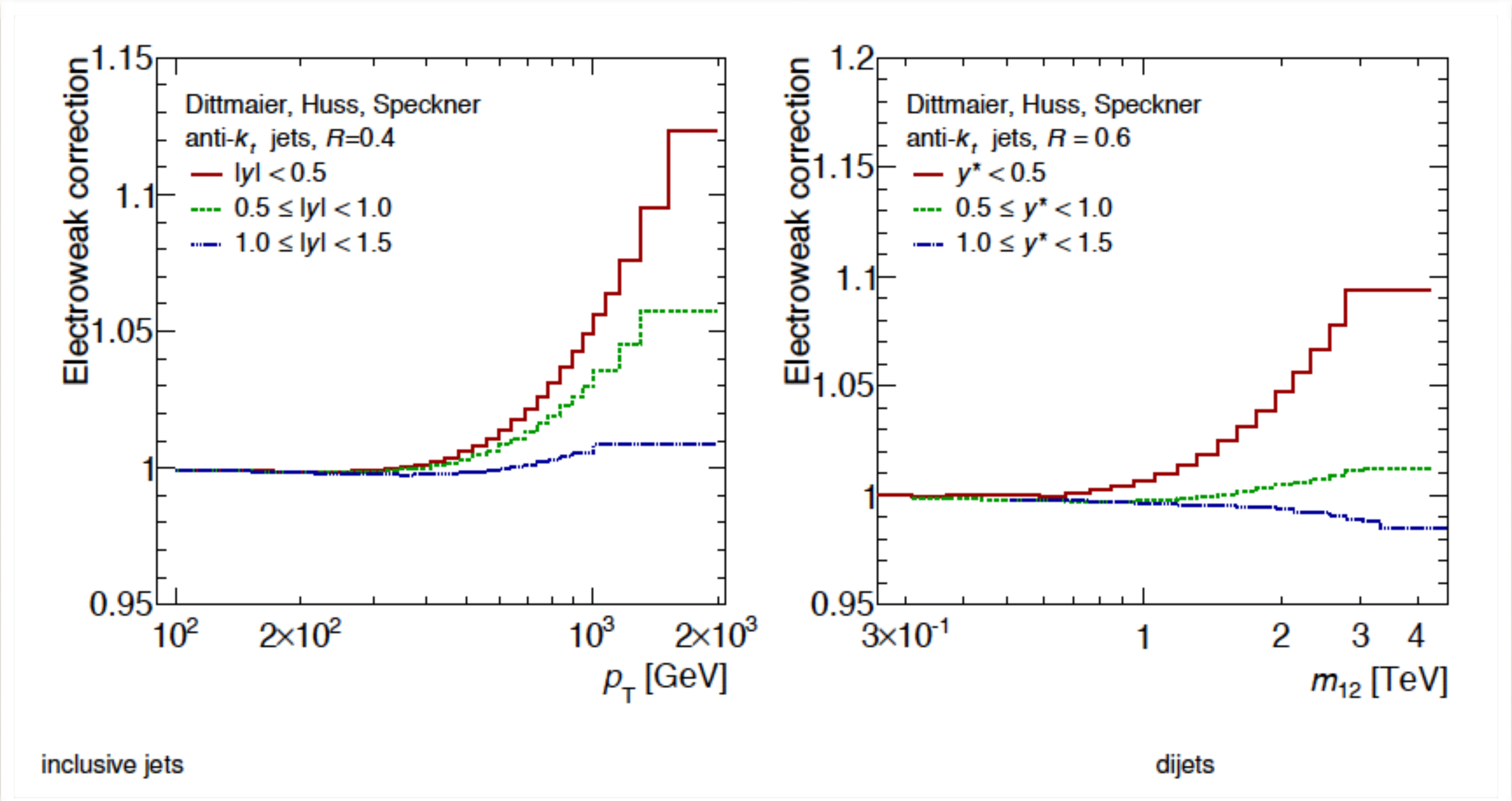
Data supports prediction that:
$c_\kappa<0$ and $\partial c_\kappa/\partial\kappa<0$

CONCLUSIONS

- In ATLAS several measurements have been performed on jet cross sections:
    - the inclusive, dijet, three-jet cross-sections are for 7 TeV only.
    - The inclusive jet cross-section in proton-proton collisions at 13 TeV is also presented!
- In addition, average jet charge (8 TeV) and energy-energy correlation (7 TeV) have been explored.
    - The strong coupling is extracted from the Transverse energy-energy correlation measurements with 0.85% experimental and (+5, -2)% theoretical precision.
- QCD calculations provide good description of the collision data, but NNLO calculations are needed to improve on the interpretation of the jet data.

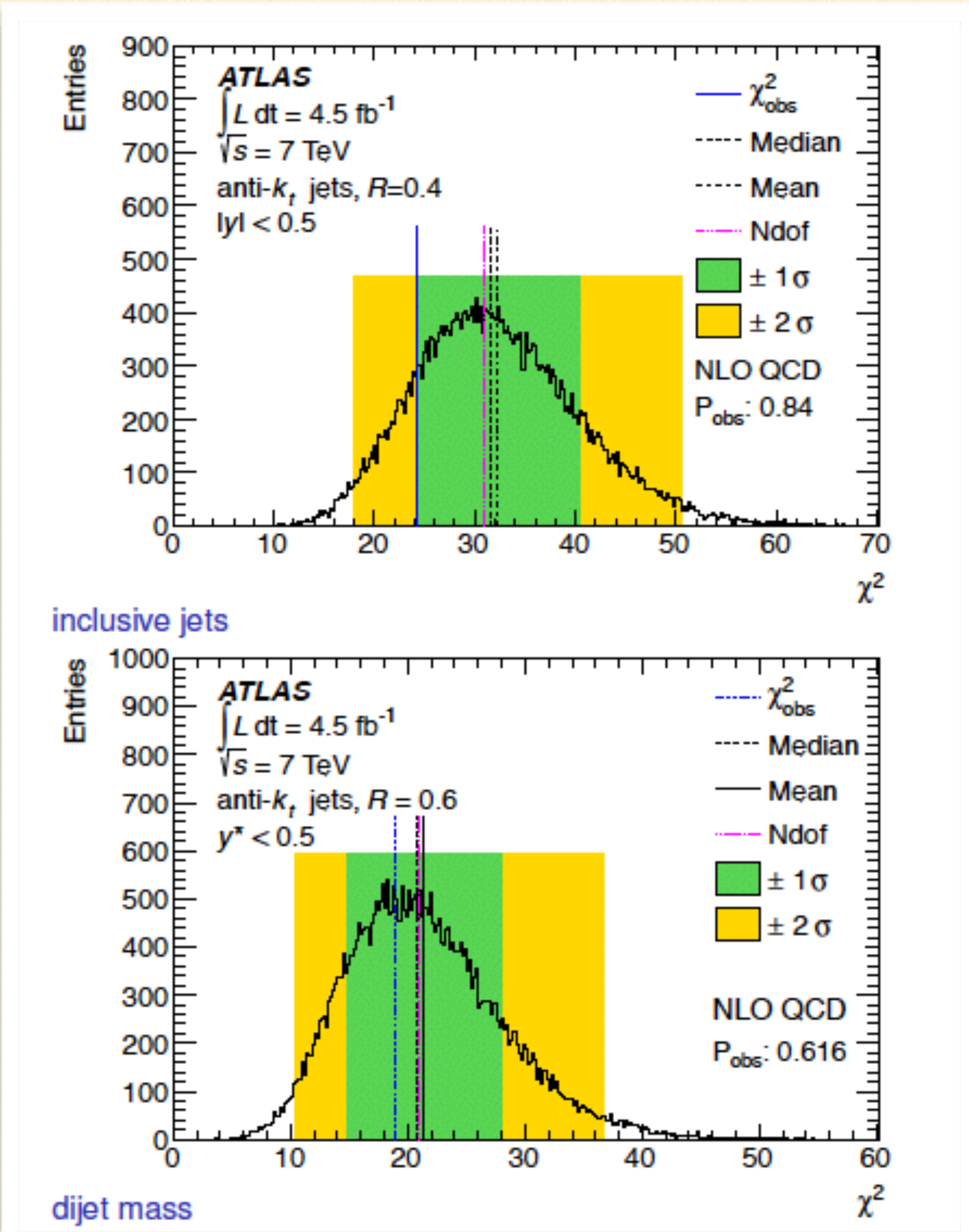
BACKUP

ELECTROWEAK CORRECTIONS



Small impact for p_T(mass) below 600(1000) GeV
Up to 10% effect in the high-p_T(mass) range

COMPARISON WITH THEORY



Pseudo-experiments are generated taken into account full correlation information

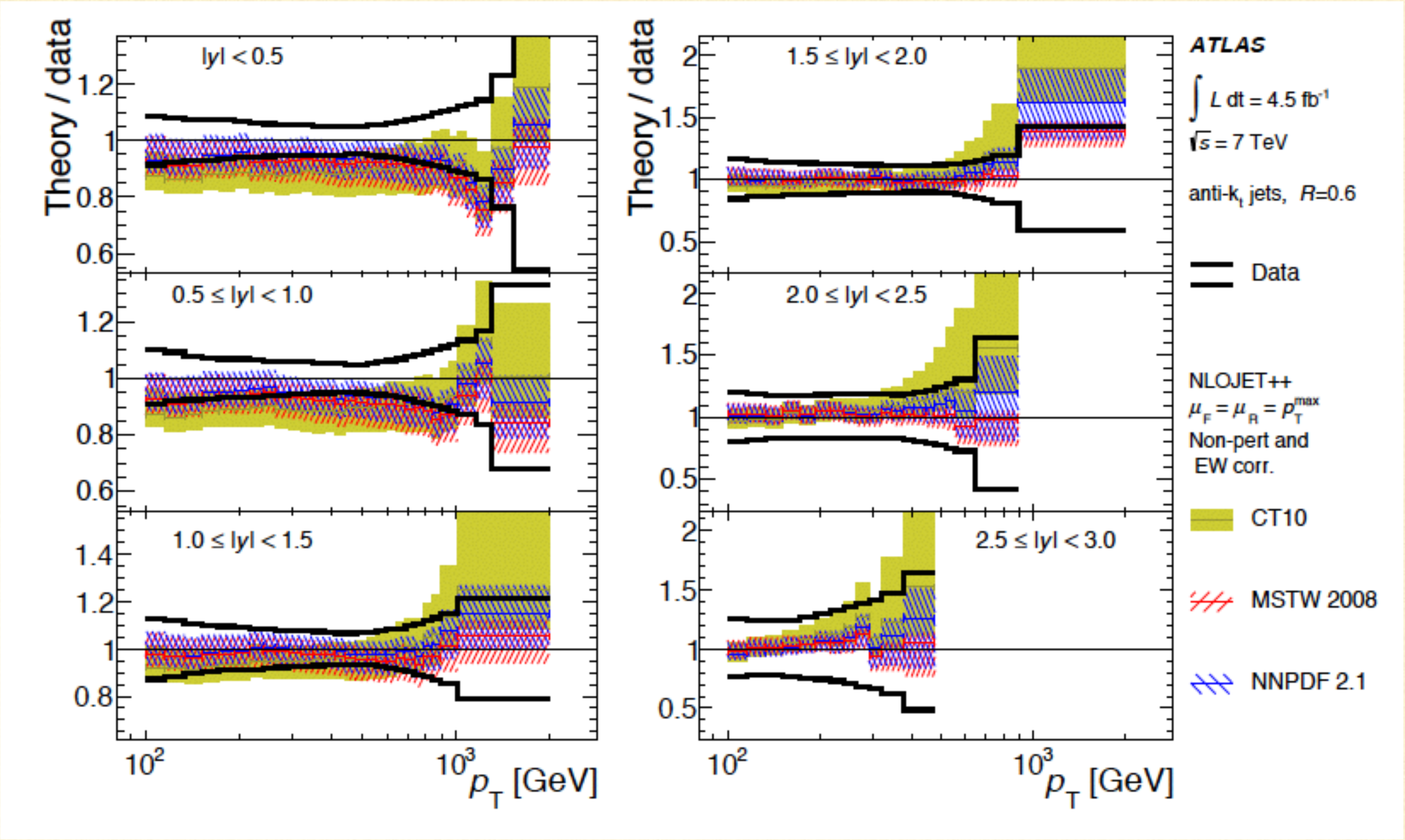
χ^2 is calculated for CT10 PDF

Theory perfectly well describes the measurements

Unfolded cross-sections are used for χ^2-calculations

4.5 fb^{-1} @ 7 TeV JHEP 02 (2015) 153

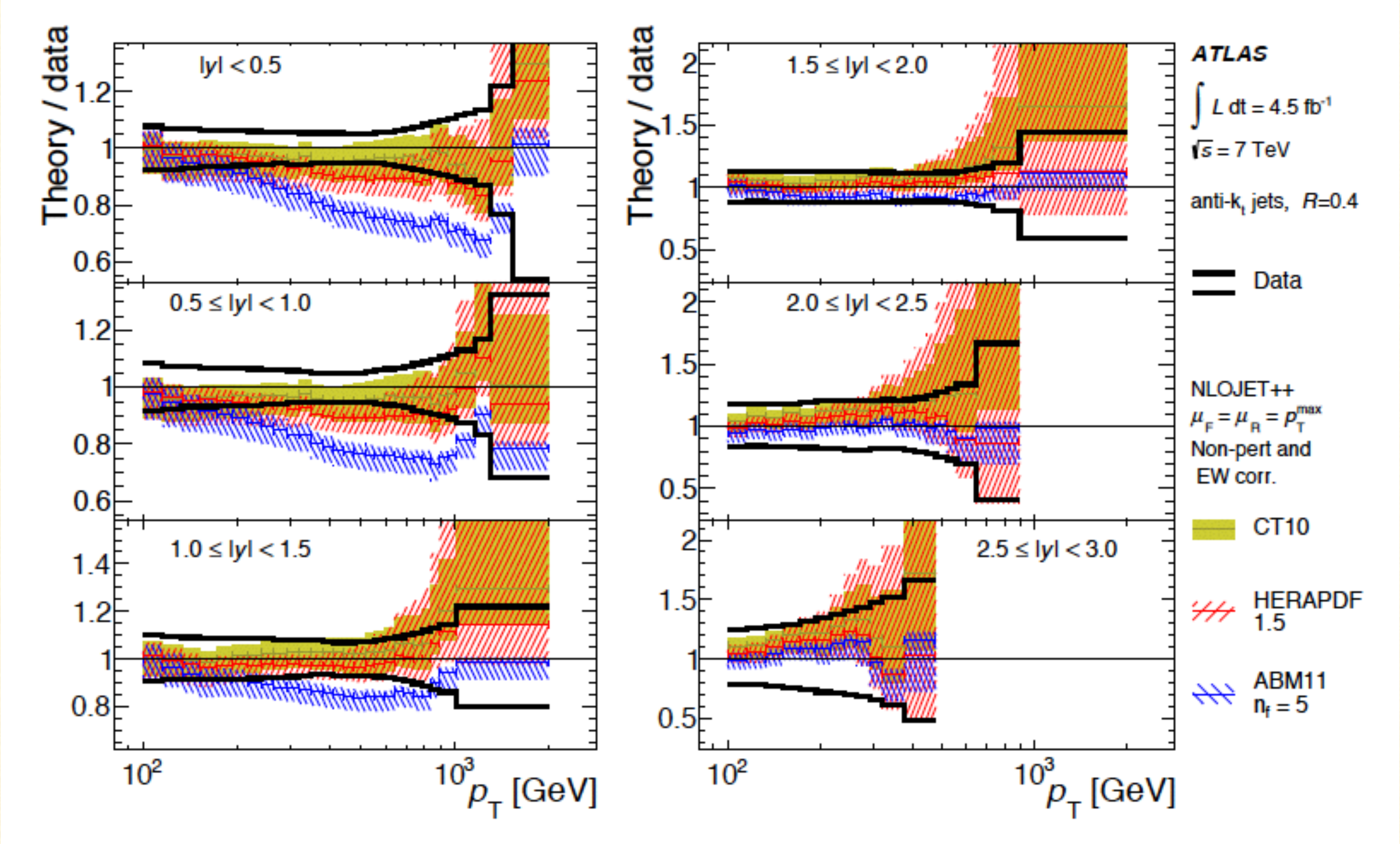
INCLUSIVE JET CROSS SECTION



Ratio of NLO pQCD predictions to measured double-diff. inclusive jet X-section vs jet p_T and jet rapidity - different NLO PDF sets used: CT10, MSTW2008 and NNPDF 2.1.

4.5 fb^{-1} @ 7 TeV JHEP 02 (2015) 153

INCLUSIVE JET CROSS SECTION



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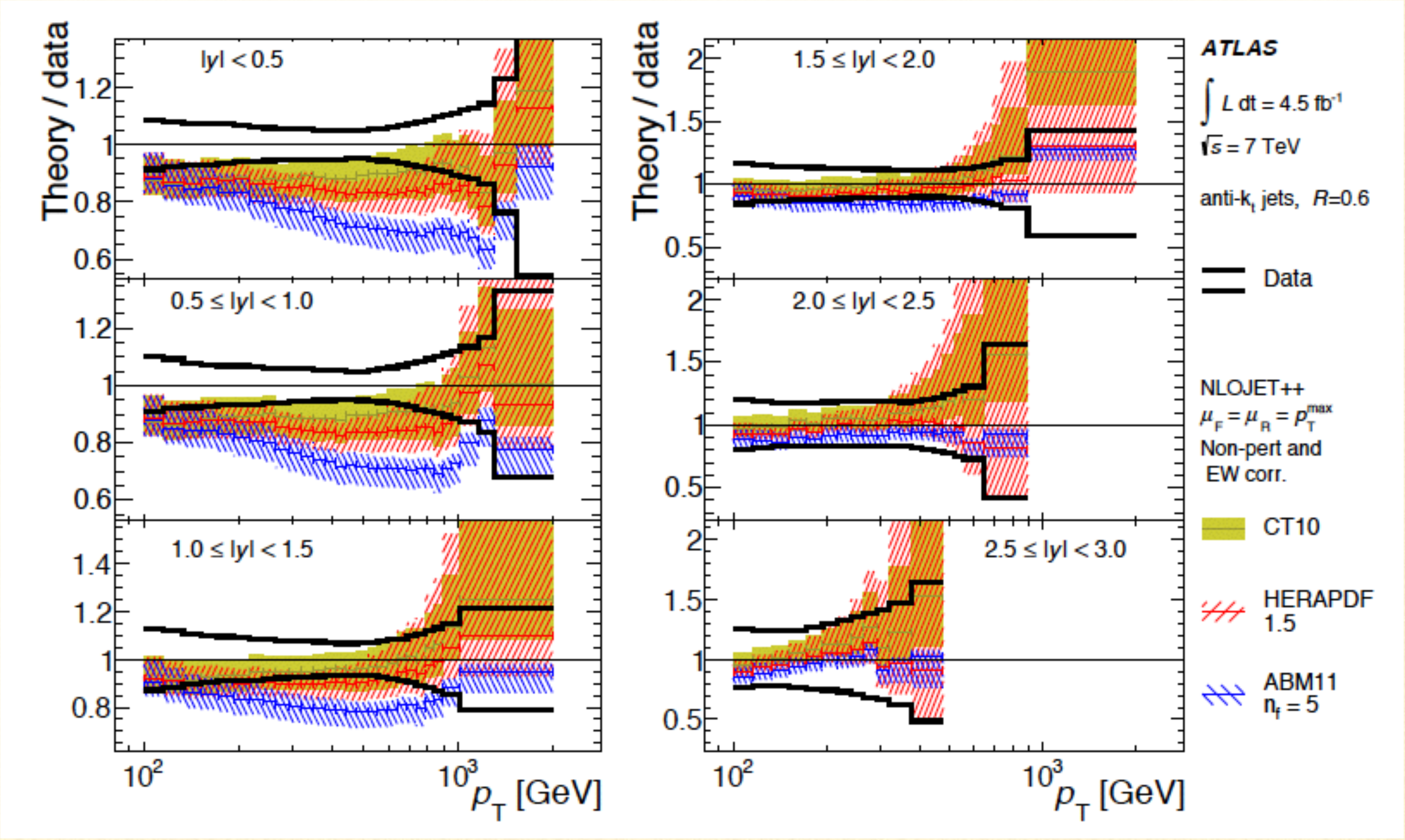
4.5 fb^{-1} @ 7 TeV JHEP 02 (2015) 153

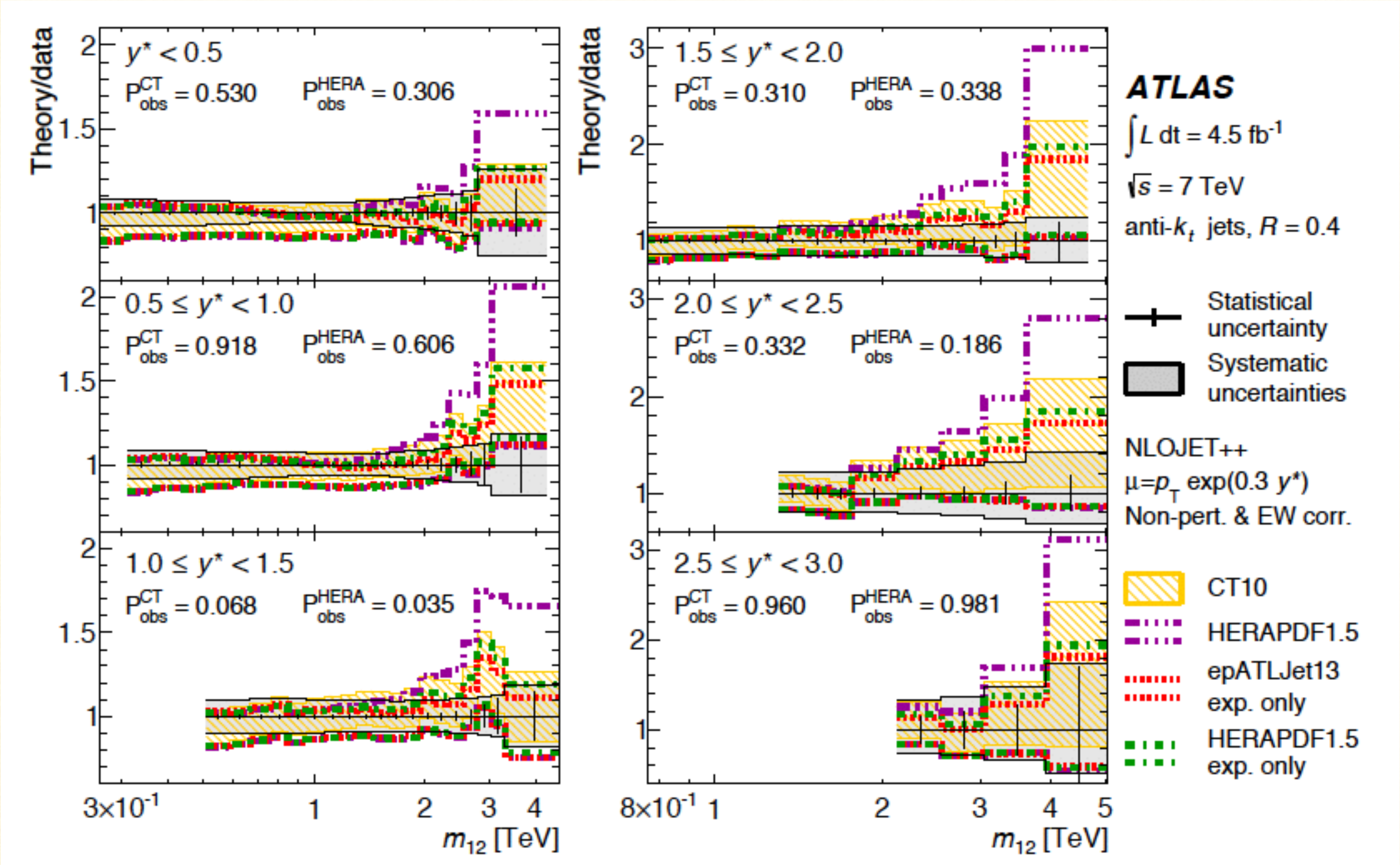
INCLUSIVE JET CROSS SECTION



Ratio of NLO pQCD predictions to measured double-diff. inclusive jet X-section vs jet p_T and jet rapidity - different NLO PDF sets used.

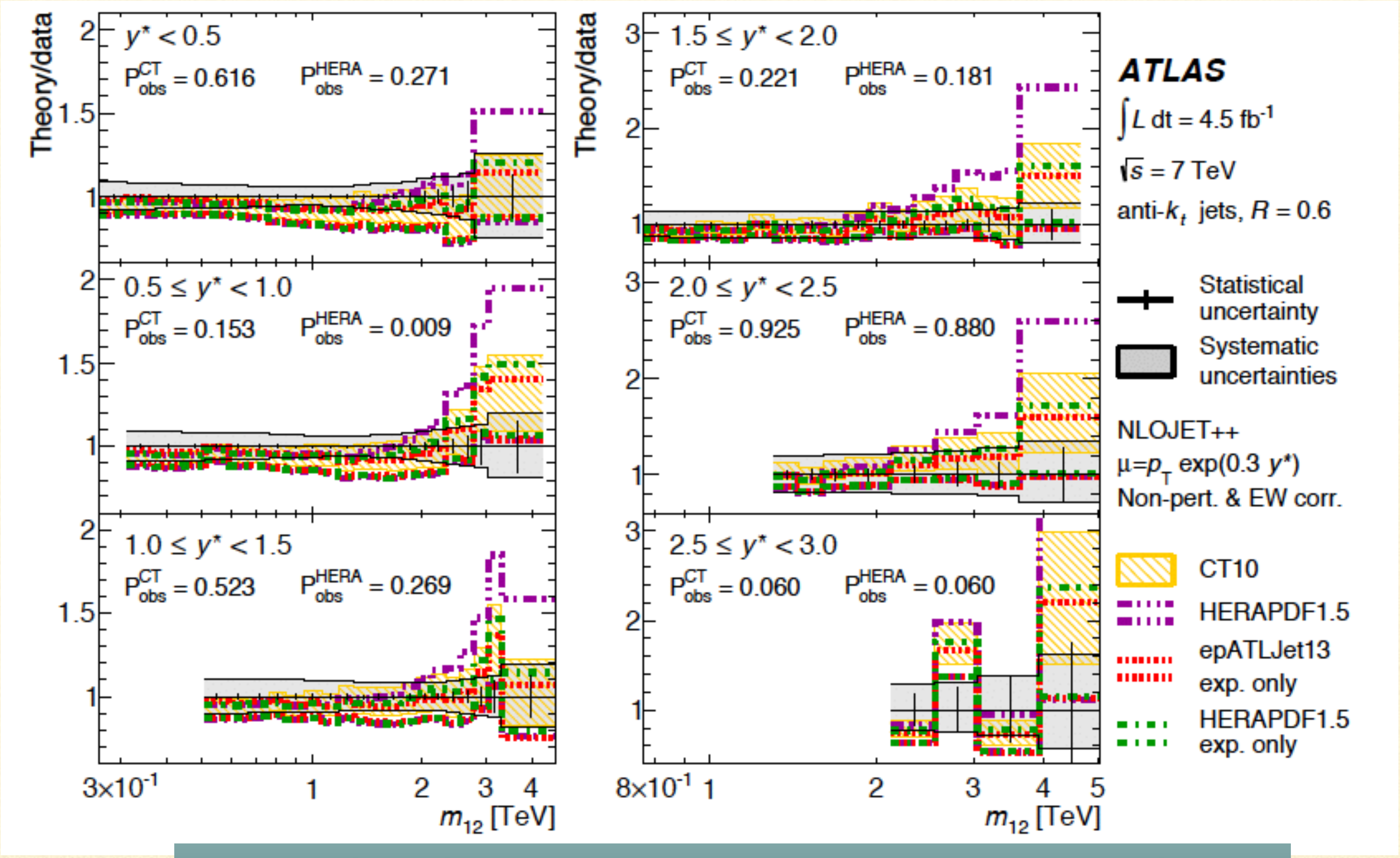
4.5 fb^{-1} @ 7 TeV JHEP 05 (2014) 059

DI-JETS CROSS SECTION



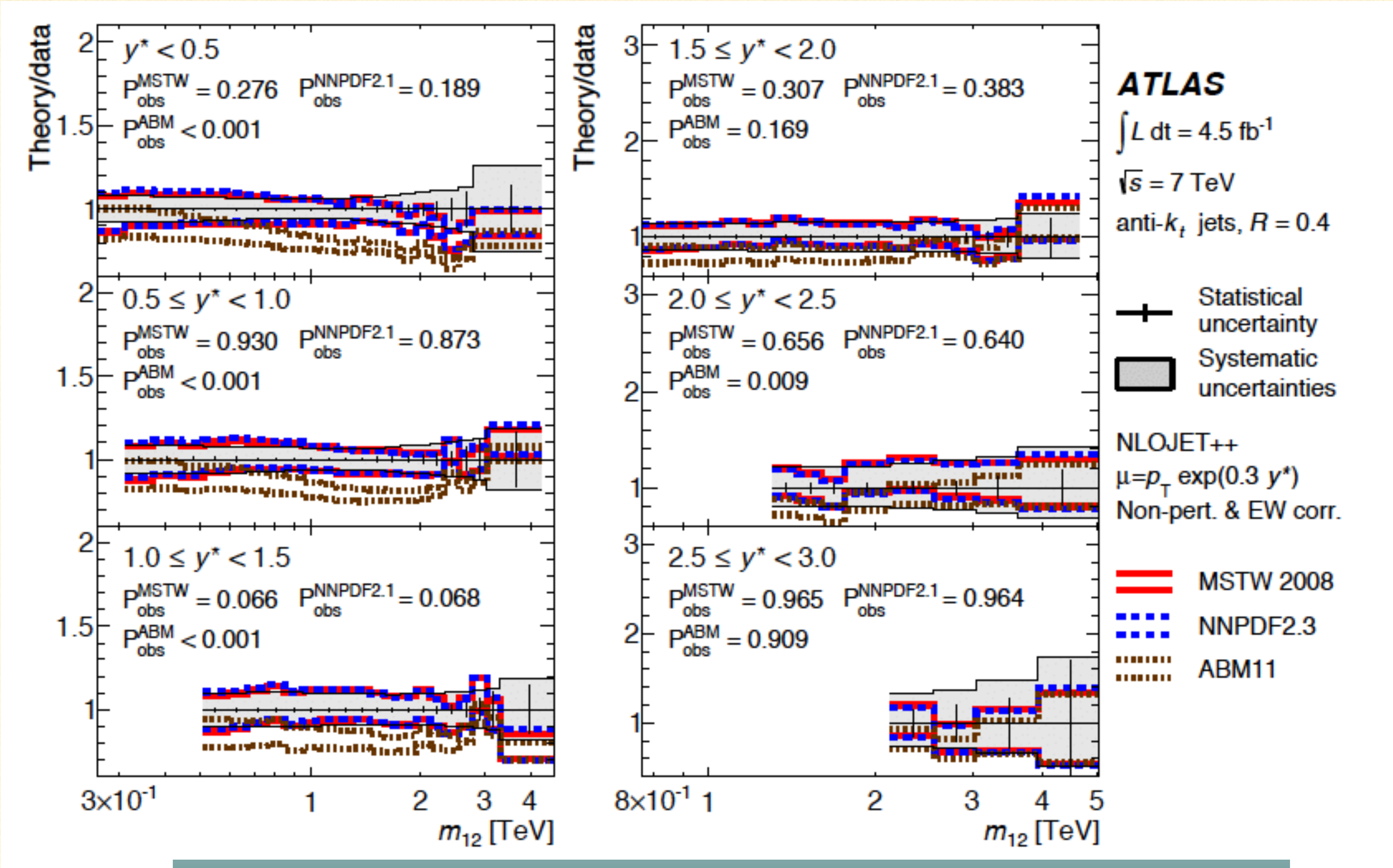
Ratio of NLOJet++ prediction to measurements of dijet double-diff. X-sec vs dijet mass and y* - PDF sets

DI-JETS CROSS SECTION



Ratio of NLOJet++ prediction to measurements of dijet double-diff. X-sec vs dijet mass and y* - PDF sets

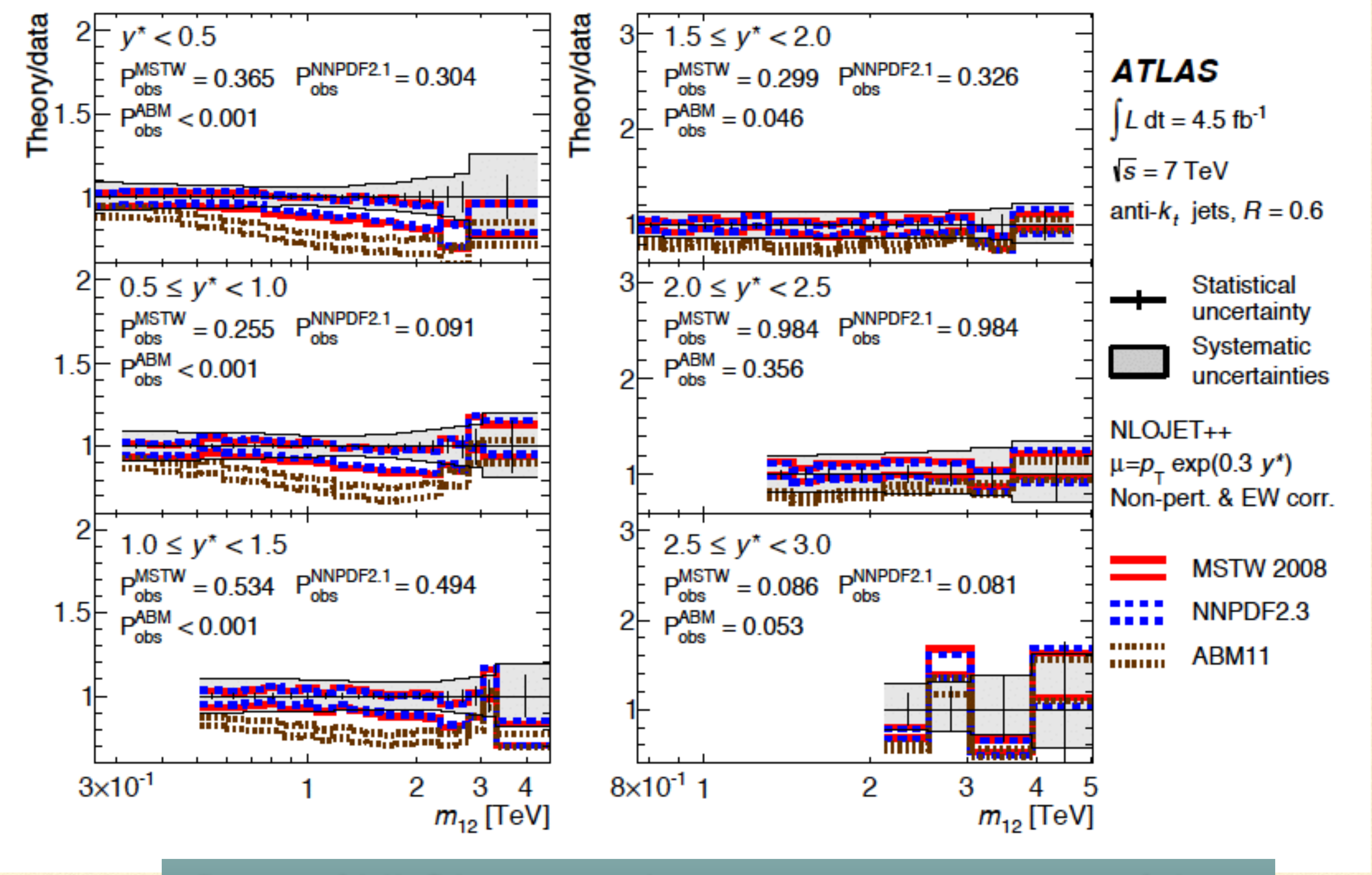
DI-JETS CROSS SECTION



Ratio of NLOJet++ prediction to measurements of dijet double-diff. X-sec vs dijet mass and y* - PDF sets

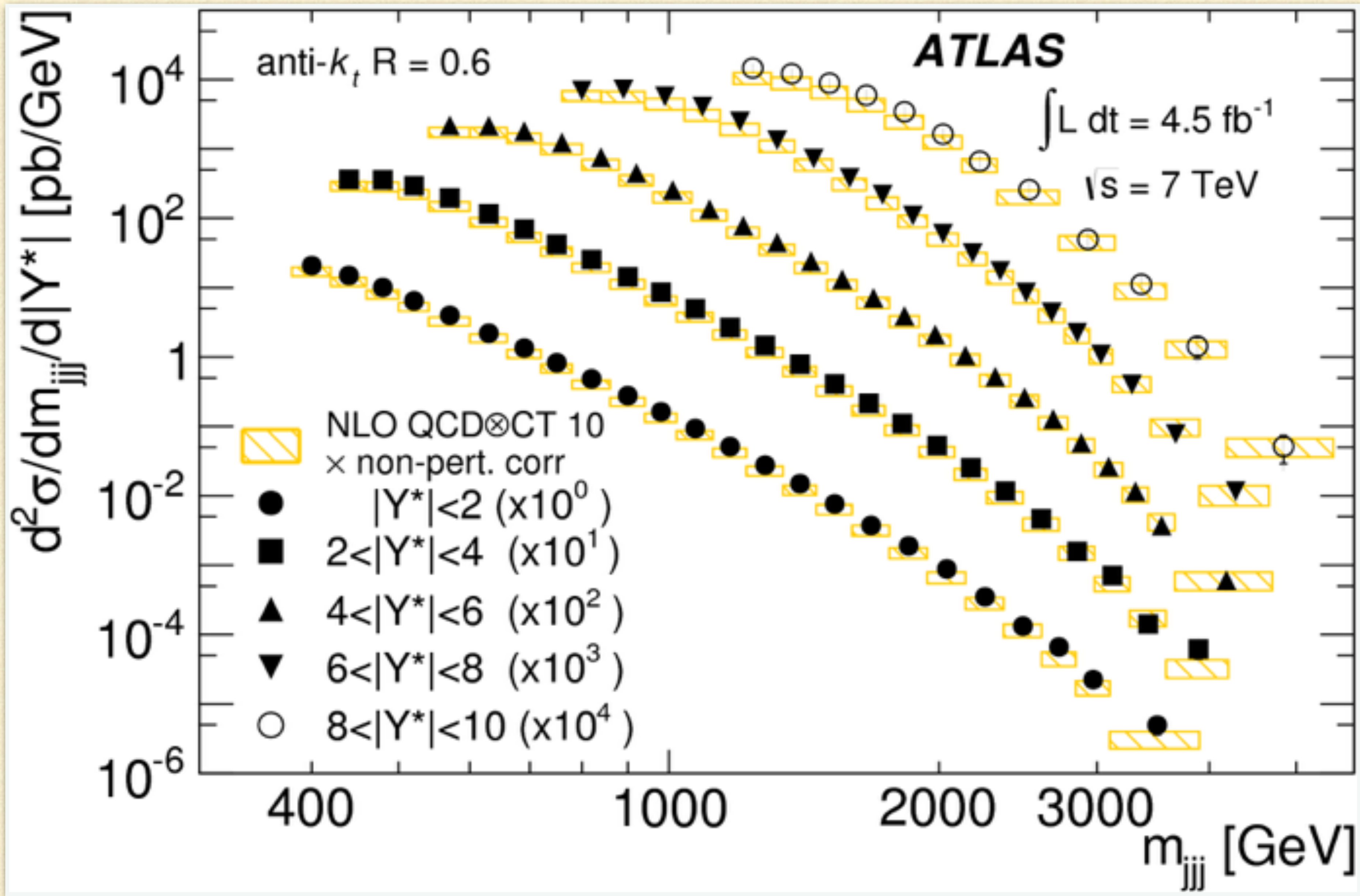
4.5 fb^{-1} @ 7 TeV JHEP 05 (2014) 059

DI-JETS CROSS SECTION



Ratio of NLOJet++ prediction to measurements of dijet double-diff. X-sec vs dijet mass and y* - PDF sets

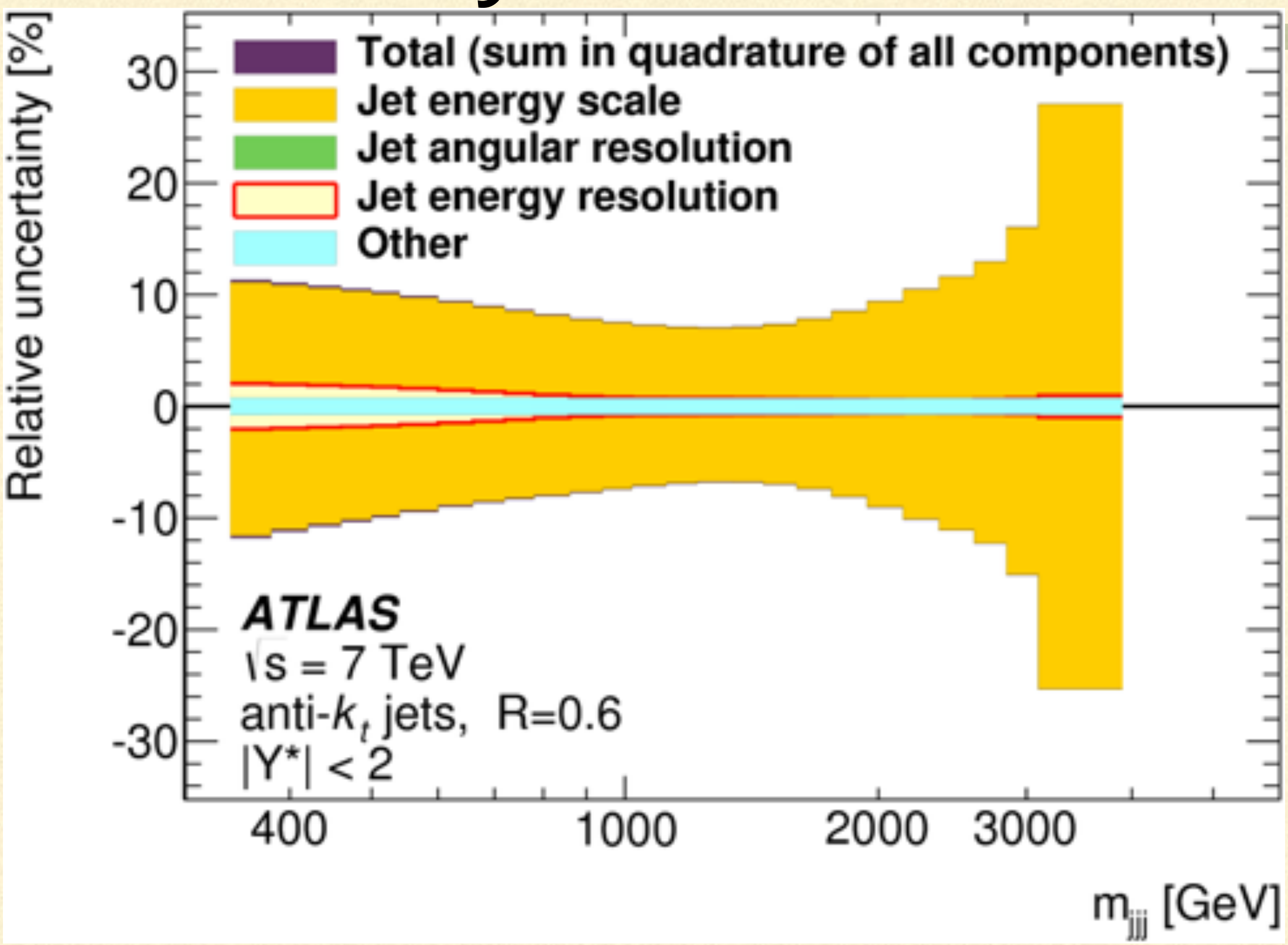
THREE JETS CROSS SECTION

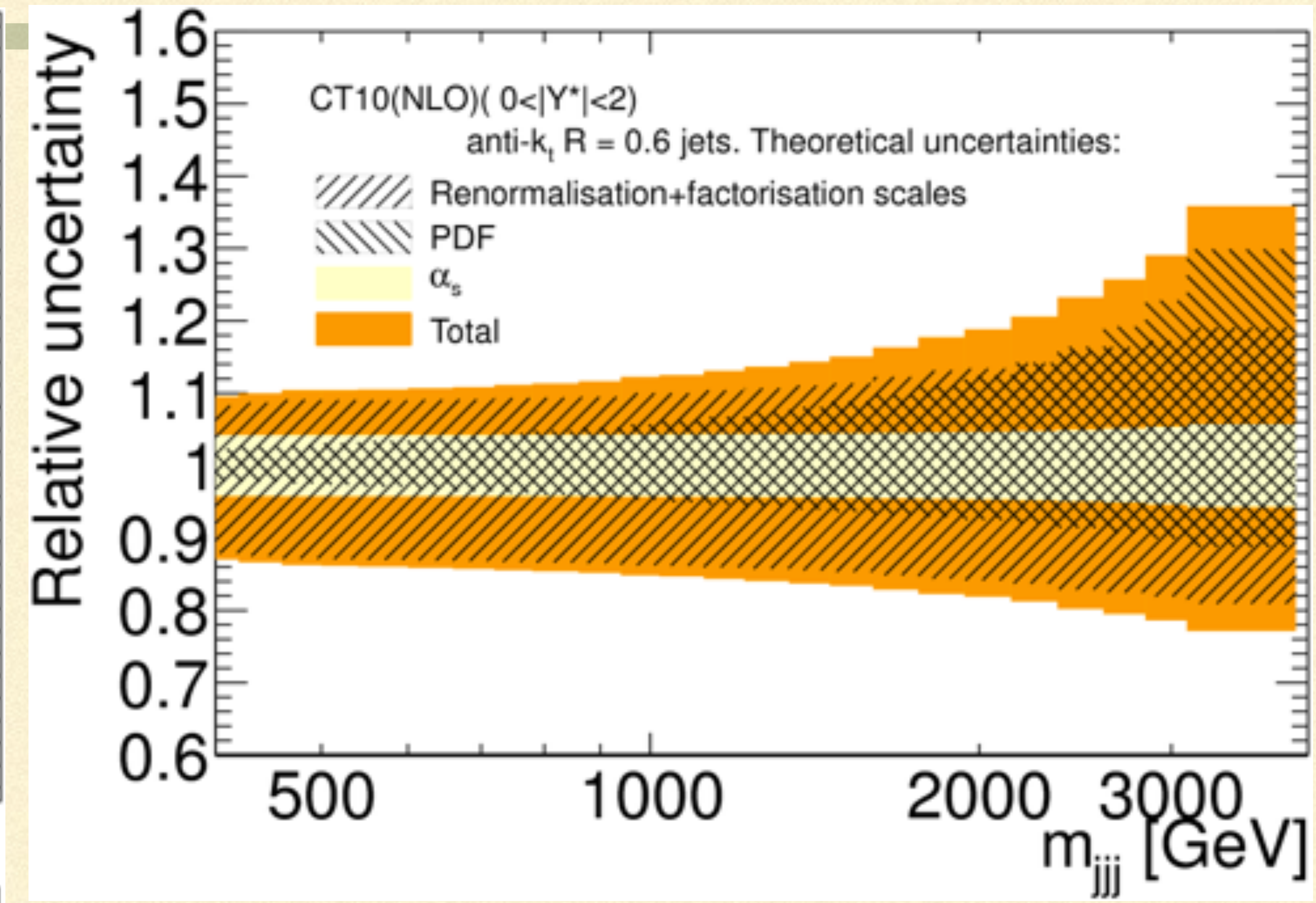


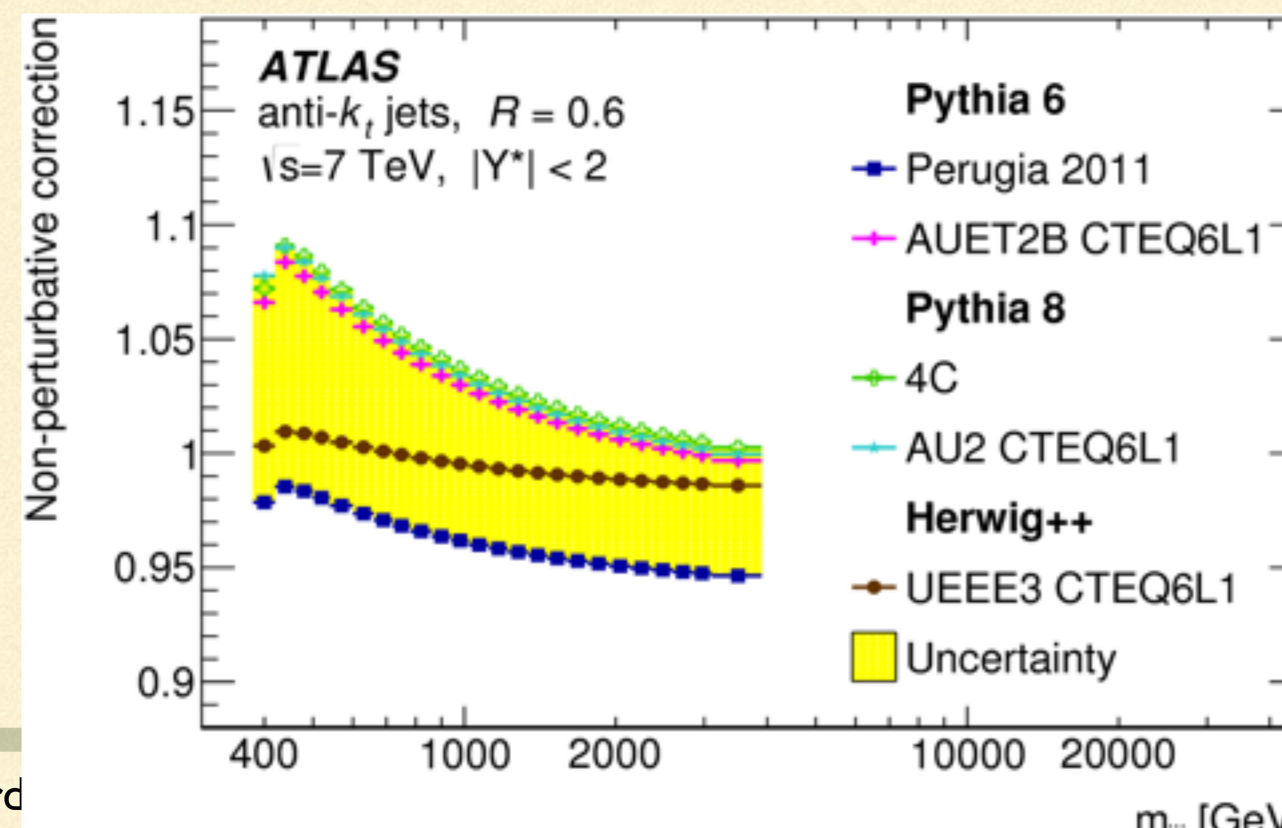
R=0.6

$4.51\ fb^{-1}$ @ 7 TeV   Eur. Phys. J. C (2015) 75

THREE JETS CROSS SECTION



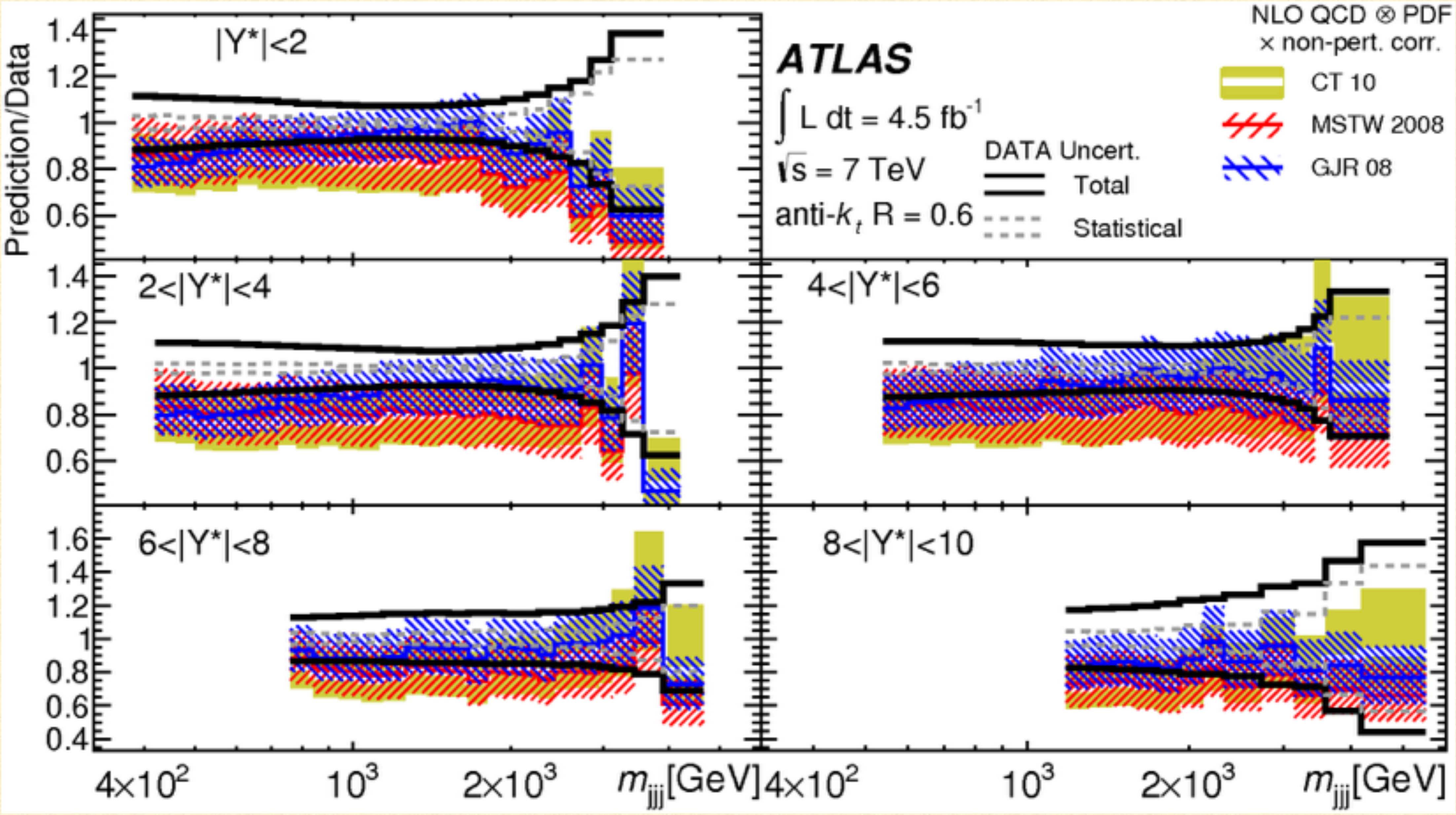




Relative uncertainties on NLO pQCD predictions as a function of mjjj in bins of |Y*| using CT10 PDFs, Total Systematics uncertainties and Relative uncertainties for R=0.6 anti-kt jets.

4.51 fb^{-1} @ 7 TeV Eur. Phys. J. C (2015) 75

THREE JETS CROSS SECTION

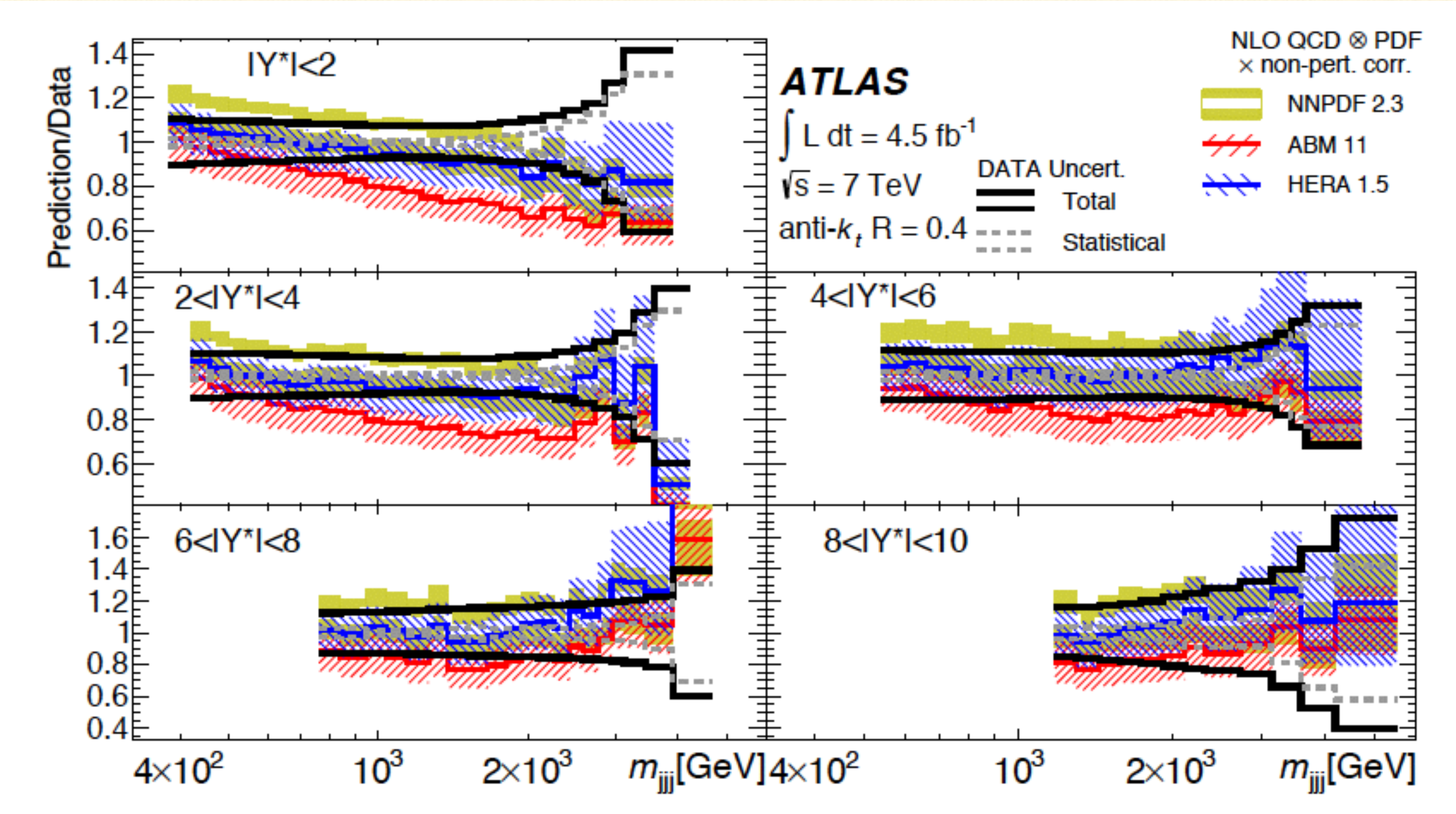


R=0.6

Worst description but consistent with all the PDFs

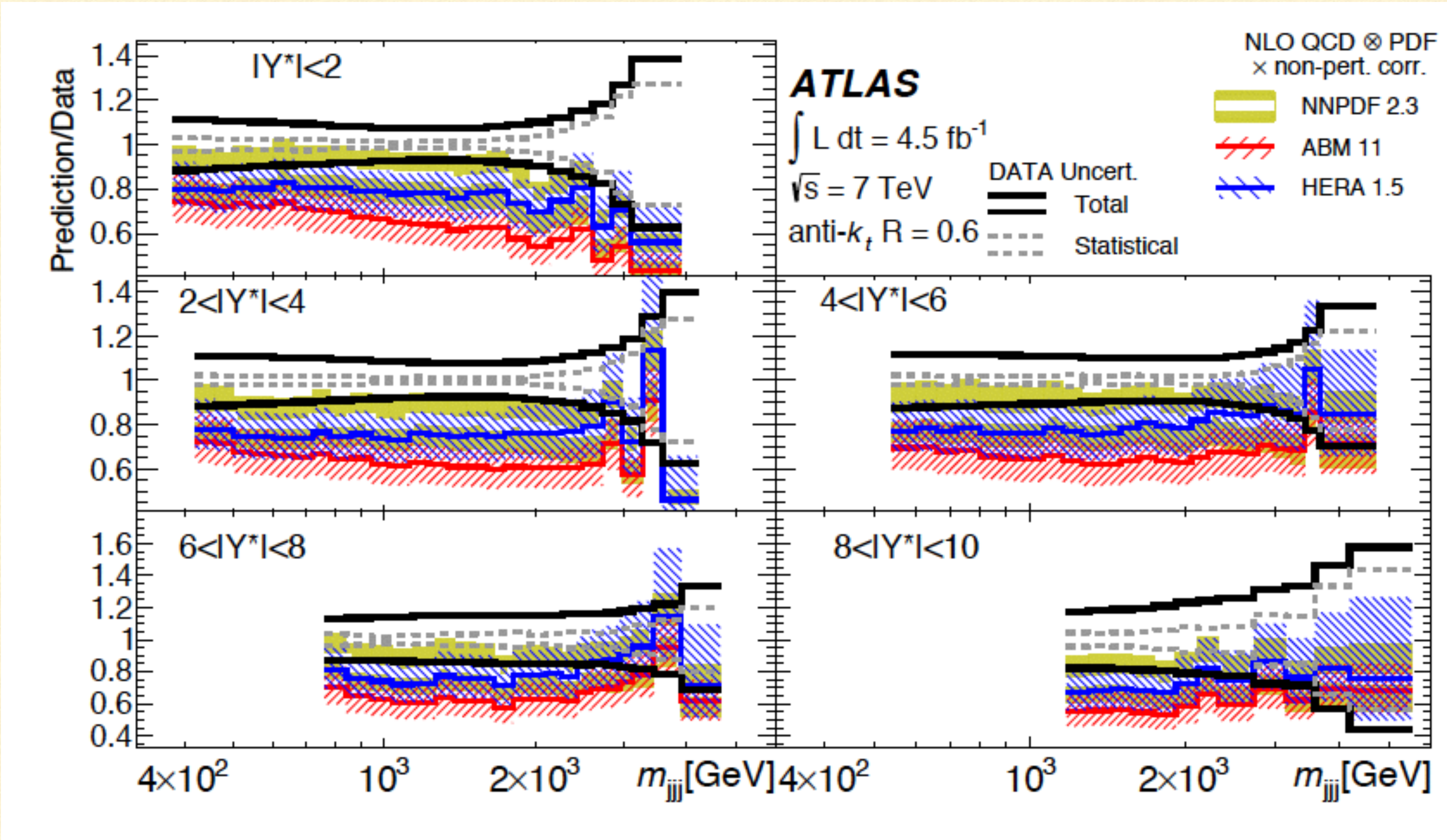
4.51 fb^{-1} @ 7 TeV Eur. Phys. J. C (2015) 75

THREE JETS CROSS SECTION



Different PDF, R=0.4

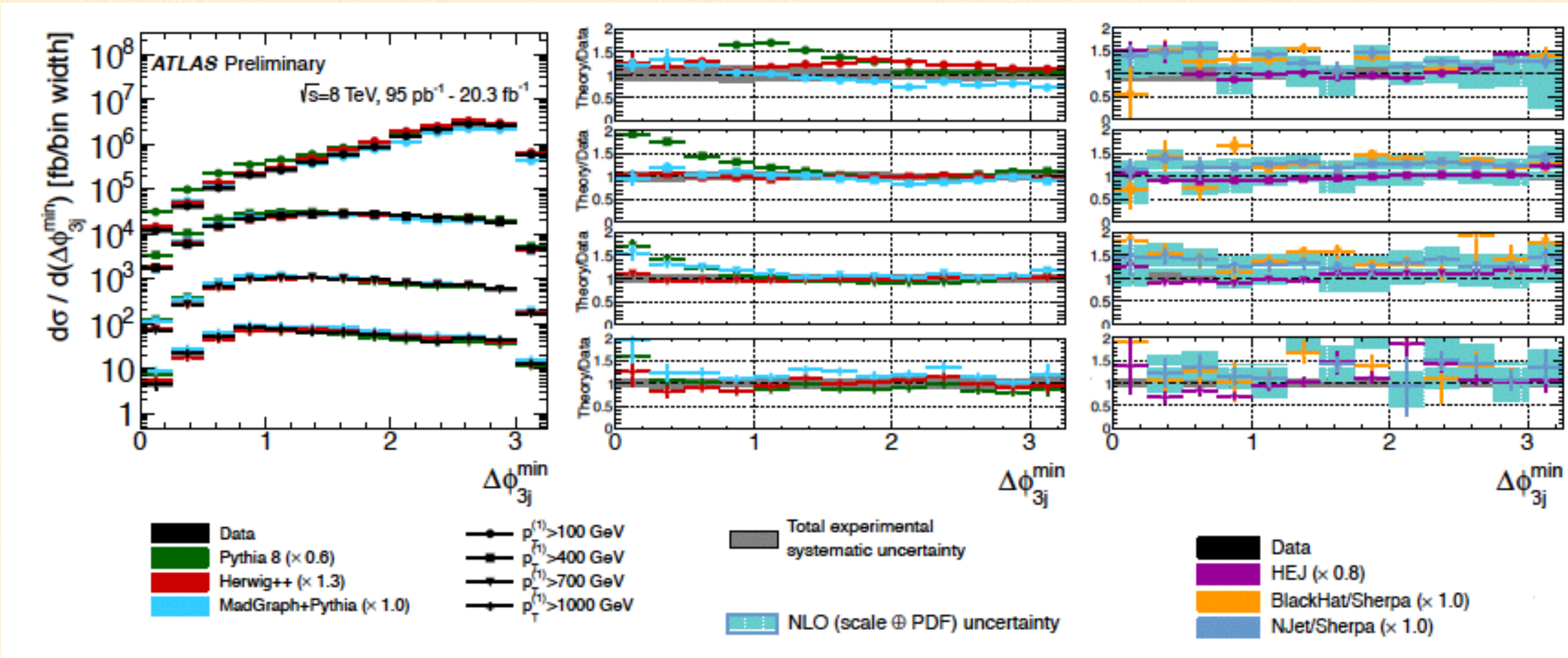
THREE JETS CROSS SECTION



Different PDF, R=0.6

20.3 fb^{-1} @ 8TeV CERN-PH-EP-2015-181

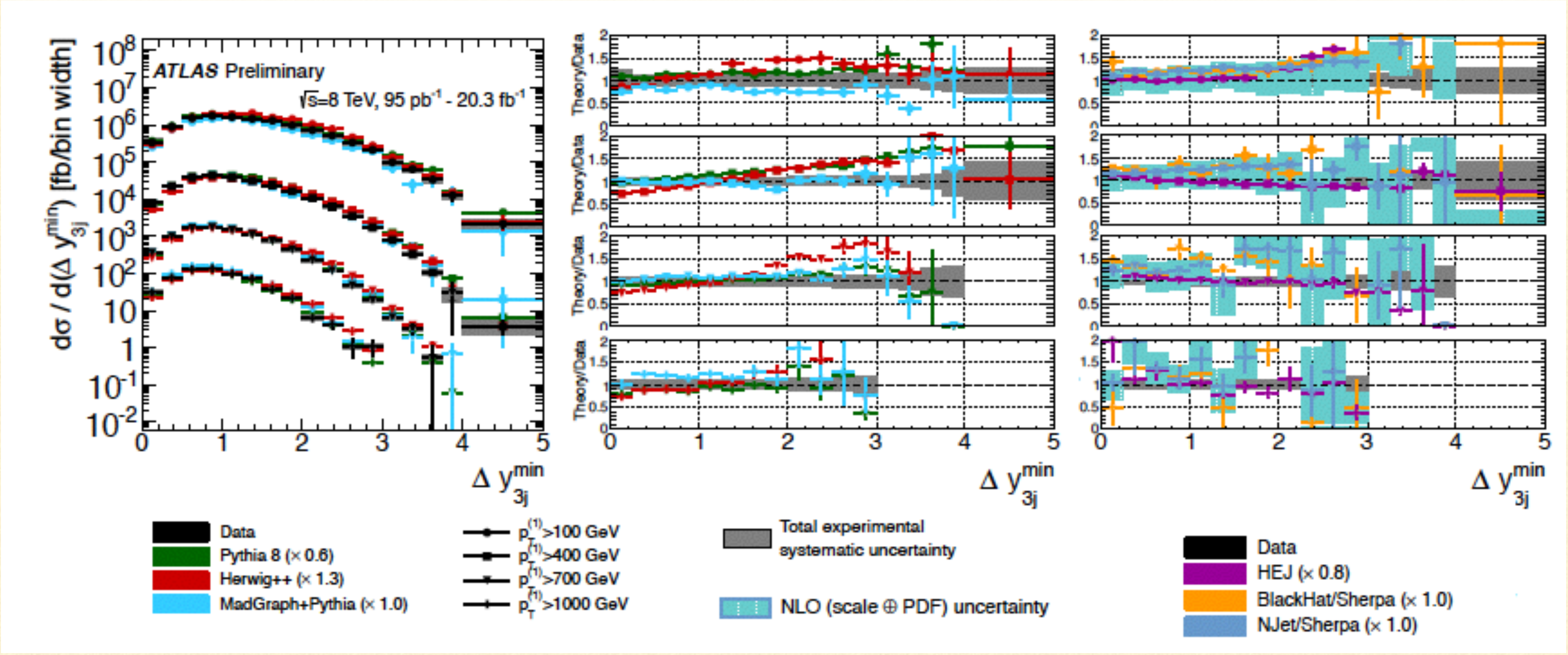
FOUR-JETS CROSS SECTION



LO predictions : Herwig++ provides best description
Fixed order: large scale uncertainty
HEJ : on top of data

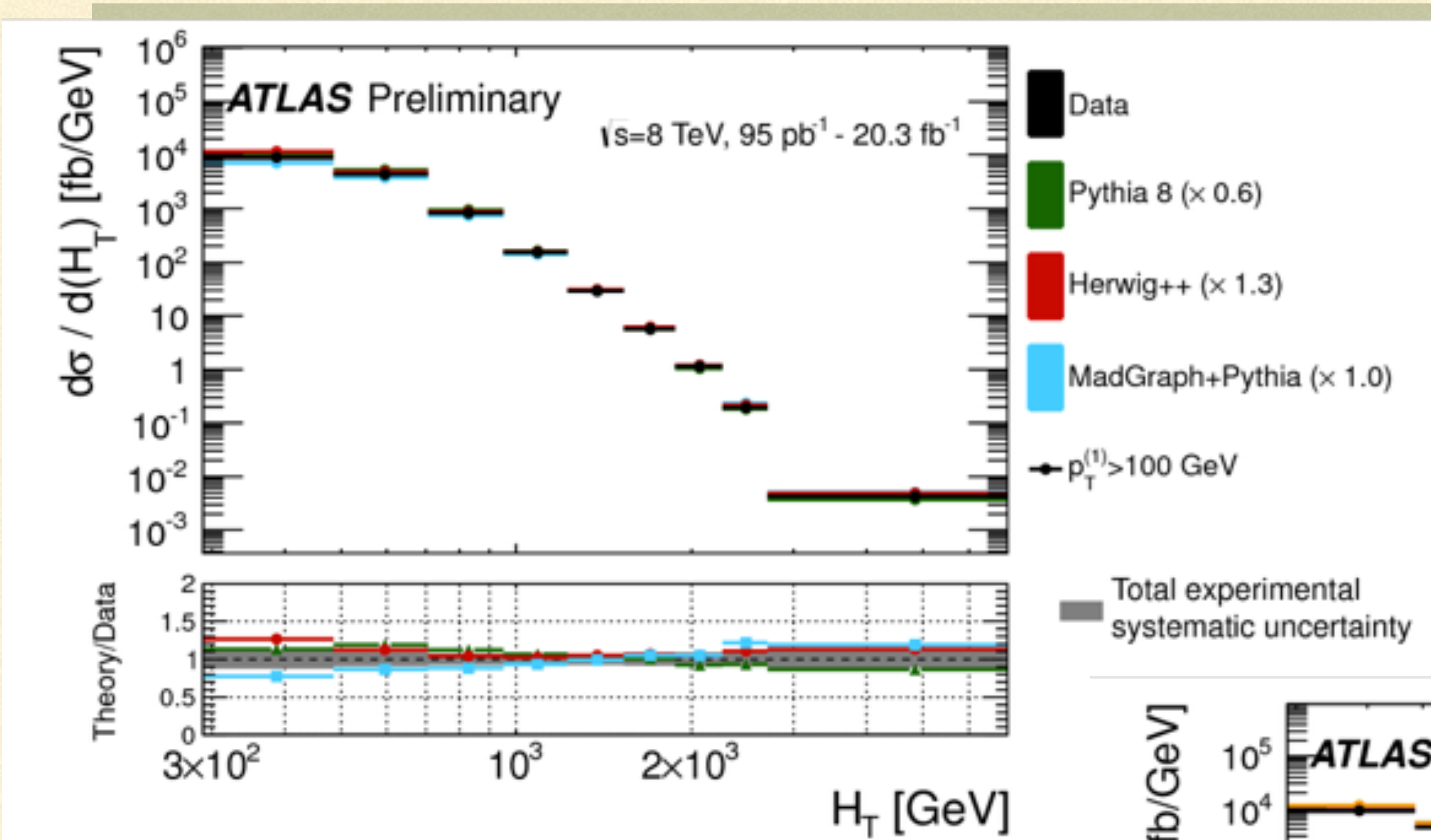
20.3 fb^{-1} @ 8TeV CERN-PH-EP-2015-181

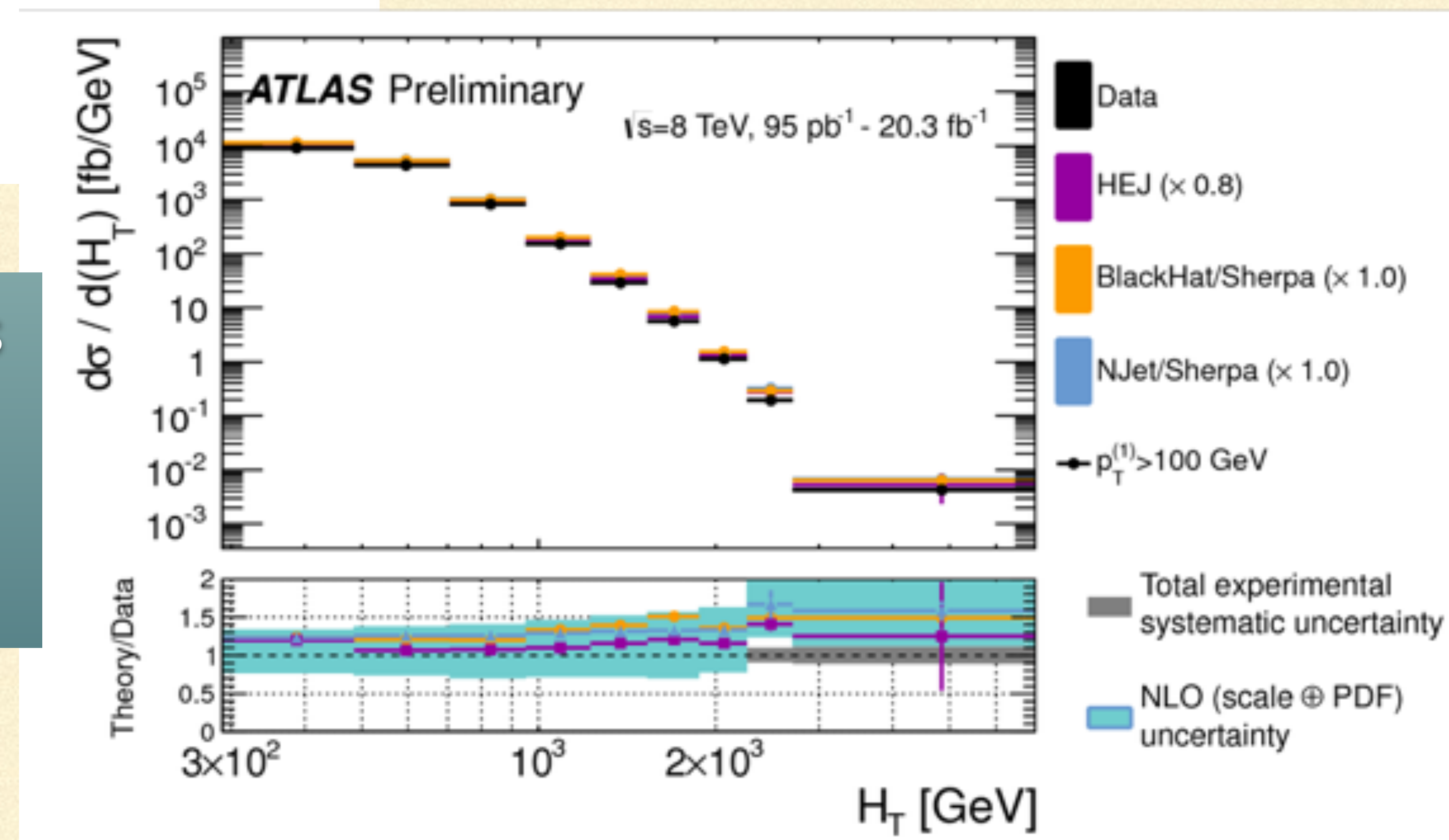
FOUR-JETS CROSS SECTION



LO predictions : Madgraph+Pythia 8 provides best description
Fixed order: large scale uncertainty
HEJ : on top of data in the p^{jet}_T > 400GeV range

FOUR-JETS CROSS SECTION

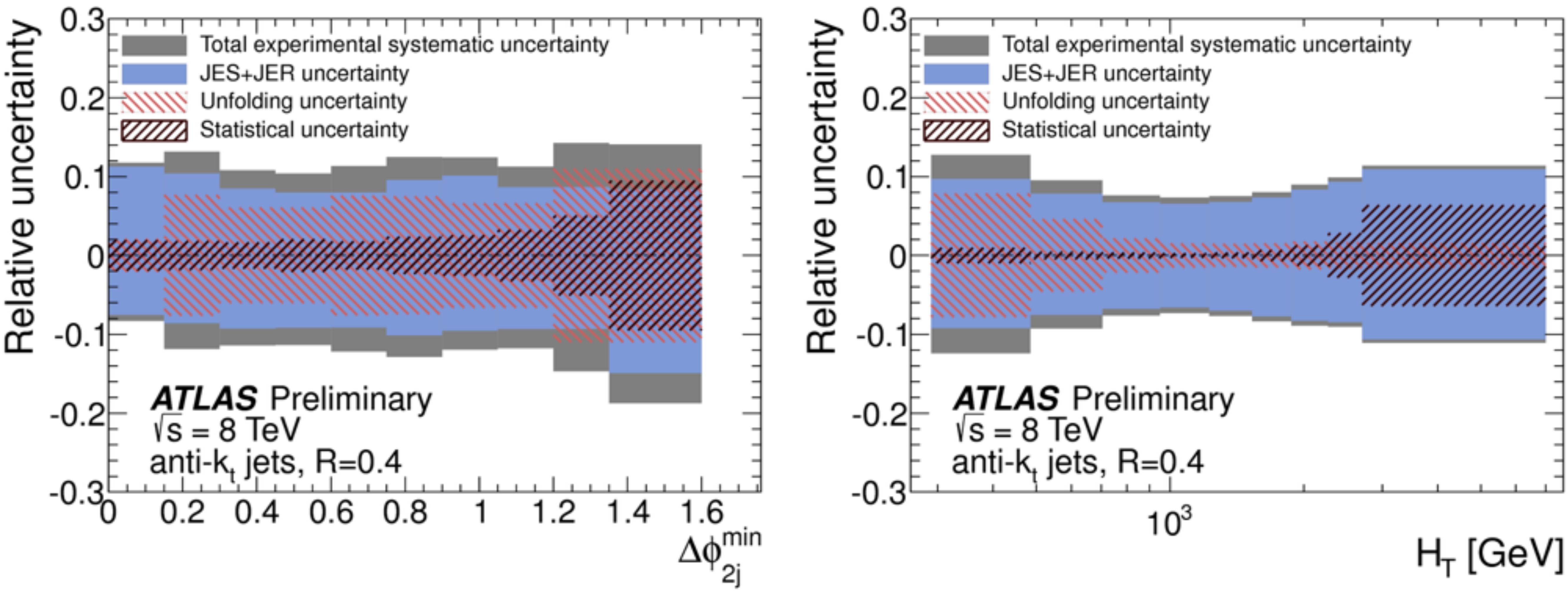




Unfolded four-jet differential cross section as a function of H_T, compared to different theoretical predictions

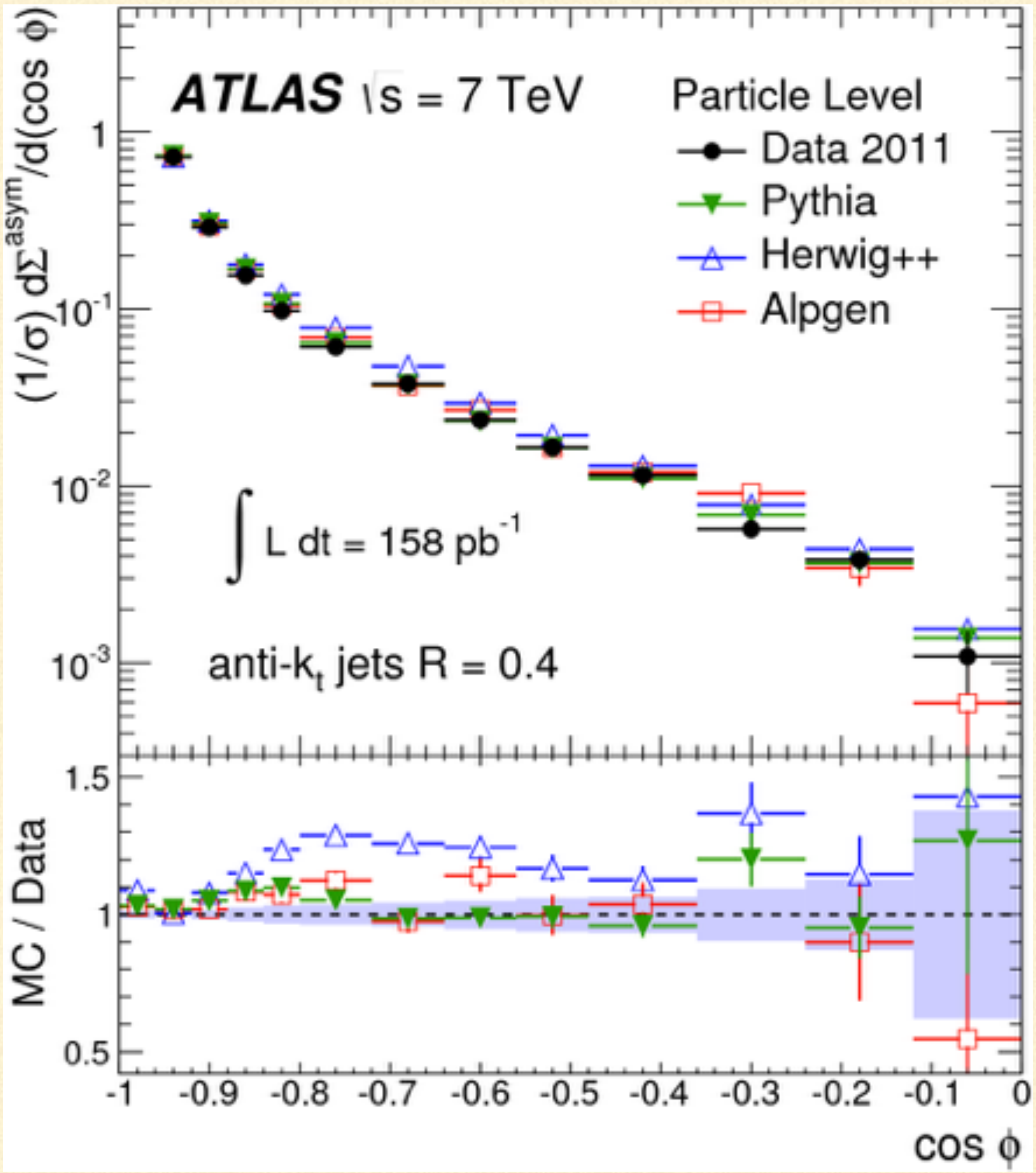
20.3 fb^{-1} @ 8TeV CERN-PH-EP-2015-181

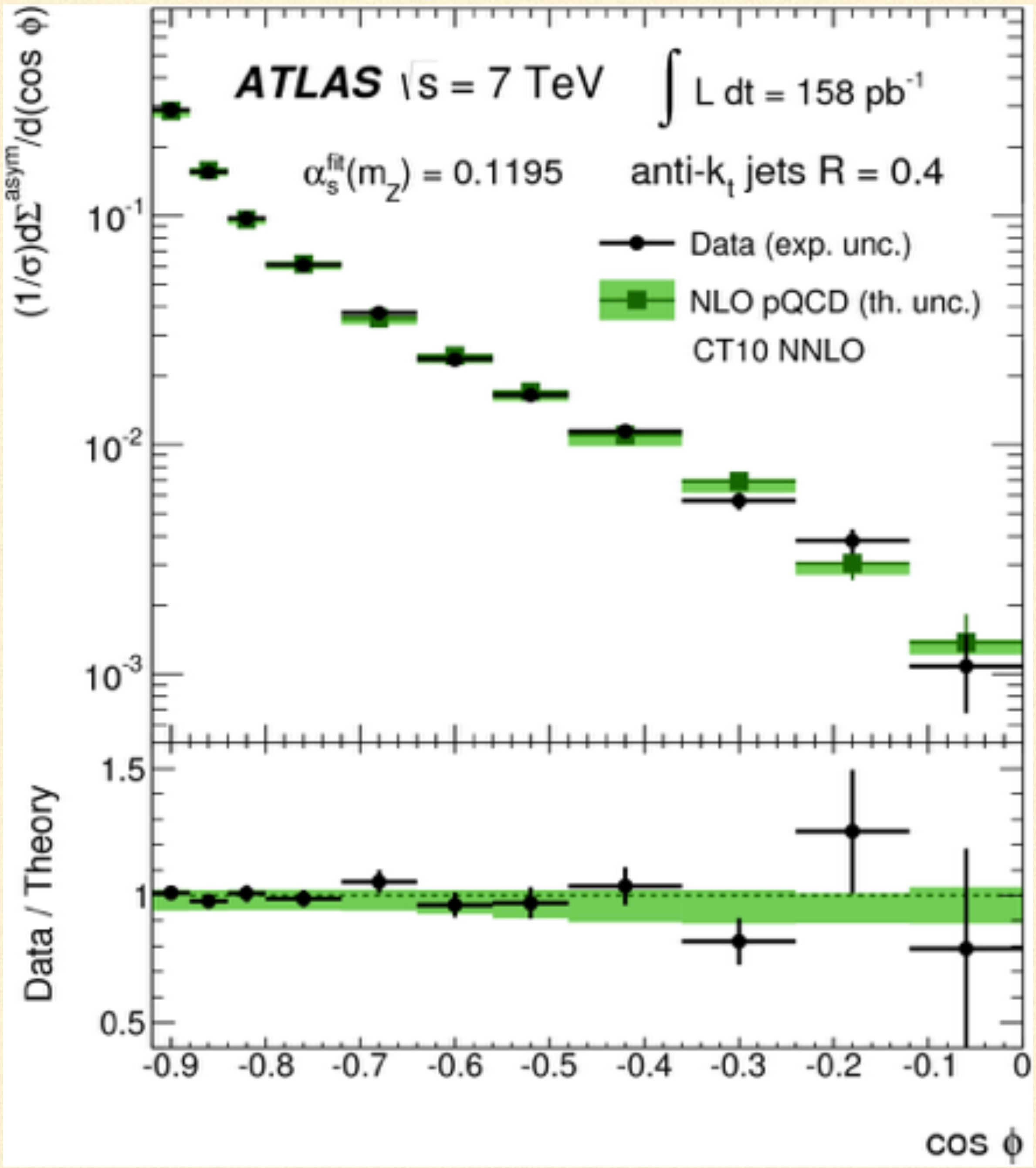
FOUR-JETS CROSS SECTION



JET–BASED TRANSVERSE ENERGY-ENERGY CORRELATION

158 pb^{-1} @ 7 TeV arXiv:1508.01579





Asymmetry of the transverse energy–energy correlation ATEEC

JET-BASED TRANSVERSE ENERGY-ENERGY CORRELATION

158 pb^{-1} @ 7 TeV arXiv:1508.01579