Jets and Multijets in ATLAS

Gino Marceca

Universidad de Buenos Aires

JVMO Workshop, 19th September 2016

Outline

1. Inclusive-jet cross-section at 13 TeV

2. Four-jet cross-section at 8 TeV

Overview

- Introduction and Motivation
- Event Reconstruction and Selection
- Cross-section definitions
- Theoretical Predictions
- Uncertainties
- Results
- Conclusions

Measurement of the inclusive-jet cross section in $\sqrt{s} = 13$ TeV proton-proton collisions using the ATLAS detector

ATLAS-CONF-2016-092
(21 Aug 2016)

Introduction and Motivation

- Measurement of inclusive-jet cross section at 13 TeV with 2015 data (3.2fb^{-1}).
- Measured cross-section is compared to NLO QCD calculations corrected for non-perturbative and electroweak effects.
- The analysis follows the same techniques as the 7 TeV 2011 paper.
  - Inclusive-jet at 7 TeV publication: JHEP02(2015)153

Event Reconstruction and Selection

Jets:

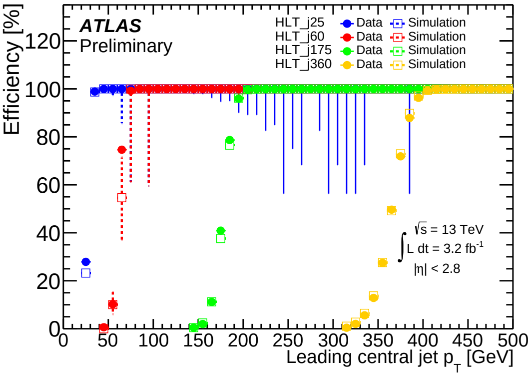
- reconstructed using the anti-k_t algorithm, with radius parameter R=0.4
- calibrated using Monte Carlo simulation and data-driven methods

Phase-space Jets within the rapidity region $|y| < 3.0$ and $p_T > 100$ GeV.

Trigger Data is selected using several jet transverse energy thresholds.

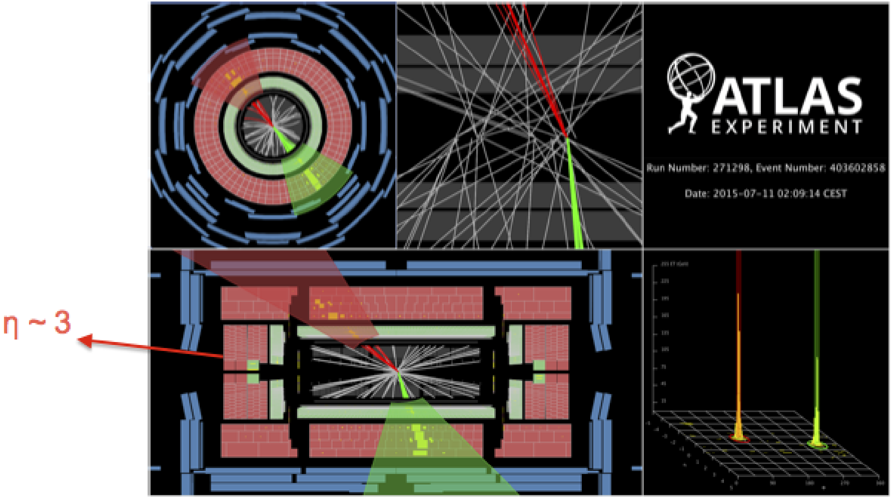
Trigger strategy Exclusive combination of single-jet triggers. arXiv:0901.4118

Jet Trigger Efficiency ATL-DAQ-PUB-2016-001



Dijet event in ATLAS

How is a di-jet event seen in ATLAS?



Cross-section definition

The **inclusive-jet** cross-section is measured as a function of the jet p_{T} and absolute jet rapidity $|y|$.

The full rapidity range is divided in six equidistant jet rapidity bins:

$$|y| < 0.5, \quad 0.5 \leq |y| < 1.0, \quad 1.0 \leq |y| < 1.5,$$
$$1.5 \leq |y| < 2.0, \quad 2.0 \leq |y| < 2.5, \quad 2.5 \leq |y| < 3.0.$$

Theoretical Predictions

- Simulated events using the Pythia 8.186 MC generator with NNPDF 2.3 LO PDFs and A14 tune are used to:
  - Deconvolute detector effects (unfolding).
  - Estimate experimental systematic uncertainties.
- QCD calculations to compare with data: NLOJET++ calculation + Non-perturbative and Electroweak corrections

Scale choice:

- p_T^{max}, leading jet p_T.

PDFs: CT10, CT14, NNPDF 3.0, MMHT14, HERAPDF, ABM12

Uncertainties in the NLO calculation:

- (μ_R, μ_F) scale variations (dominant at low p_T).
- PDFs (dominant at high p_T).
- α_s variation (mostly constant in all p_T and y ranges).

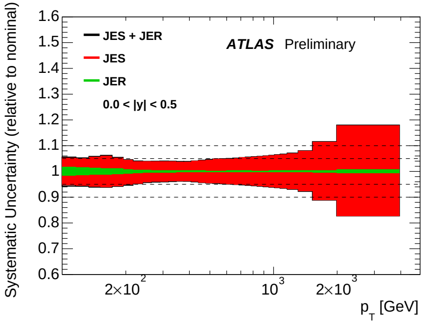
Uncertainties (ATLAS-CONF-2016-092)

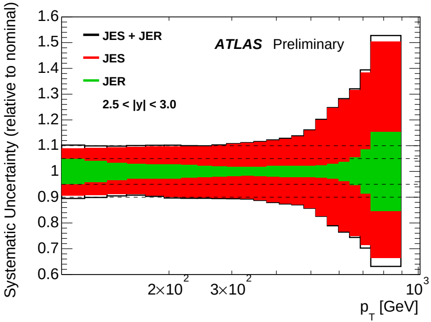
Experimental Uncertainties

- The Jet Energy Scale, Jet Energy Resolution and Luminosity uncertainties were estimated and taken into account using MC and data-driven techniques.
- The JES is the dominating uncertainty.

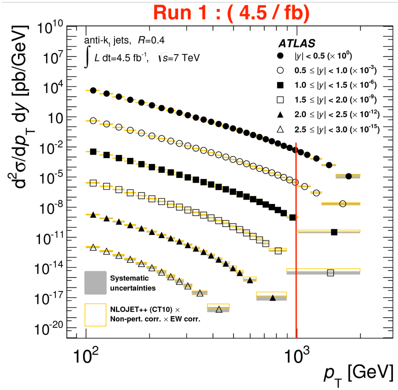
Unfolding uncertainties

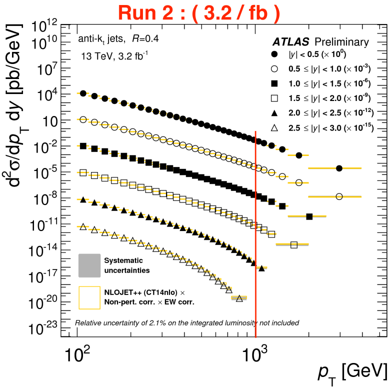
- Takes into account shape differences between data and MC.





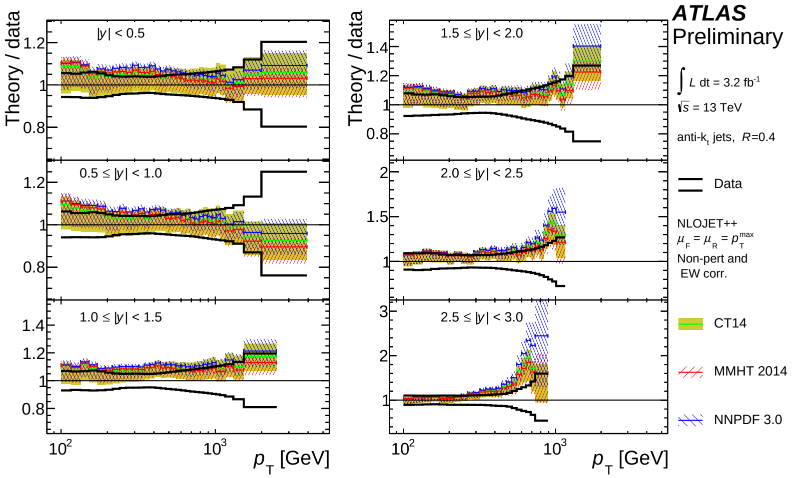
Results: Cross-section comparison (ATLAS-CONF-2016-092)





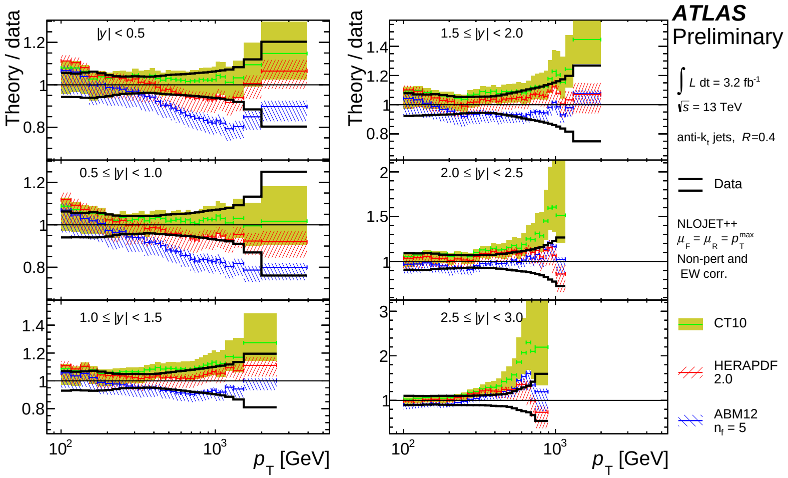
- The inclusive-jet cross-section at 13 TeV covers the jet p_T range from 100 GeV to $\sim$ 3.2 TeV within $|y| < 3.0$.
- Huge improvement in systematics and range compared with 7 TeV measurement.

Results: NLOJet++ vs Unfolded Data (ATLAS-CONF-2016-092)



- NLO pQCD predictions describe the data within uncertainties.
- NNPDF 3.0 overestimates the cross-section for the last two $|y|$ bins.

Results: NLOJet++ vs Unfolded Data (ATLAS-CONF-2016-092)



- NLO pQCD predictions describe the data within uncertainties.
- Disagreement with ABM12, consistent with 7 TeV measurement, observed for the first two $|y|$ bins.

Conclusions

- The measurement of the inclusive jet cross-section in proton–proton collisions at $\sqrt{s} = 13$ TeV was presented.
- The measurement is based on the Data collected with the ATLAS detector during 2015 corresponding to an integrated luminosity of $3.2\,\mathrm{fb}^{-1}$.
- The measurement extends up to 3.2 TeV in jet transverse momentum.
- NLO pQCD calculations, to which corrections for non-perturbative and electroweak effects are applied, are compared to the measurement.
- Predictions describe the data within uncertainties, confirming the validity of perturbative QCD at $\sqrt{s} = 13$ TeV *pp* collisions in the measured kinematic regions.

Measurements of four-jet differential cross sections in $\sqrt{s} = 8$ TeV proton-proton collisions using the ATLAS detector

JHEP12(2015)105
(16 Dec 2015)

Introduction and Motivation

Test of theoretical predictions at LO and NLO: the predictions are expected to display various levels of agreement with data in different kinematic regimes.

Data-MC comparisons were made in order to study how predictions describe:

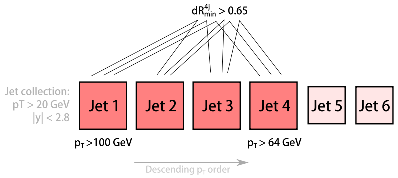
- scale of multi-jet processes,
- angular variables sensitive to forward and nearby jets,
- range of energy scales relevant to QCD calculation,
- regimes sensitive to NLO effects,

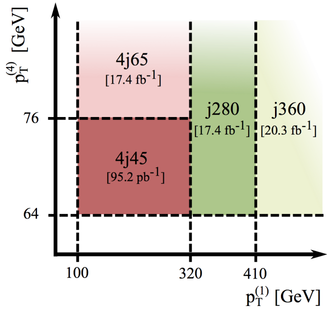
Study of QCD background: several searches have many jets in the final state; it is thus crucial to understand the QCD contribution to this kind of events.

Event Reconstruction and Selection

Jets:

- reconstructed using the anti-k_t algorithm, with radius parameter R=0.4
- calibrated using Monte Carlo simulation and data-driven methods



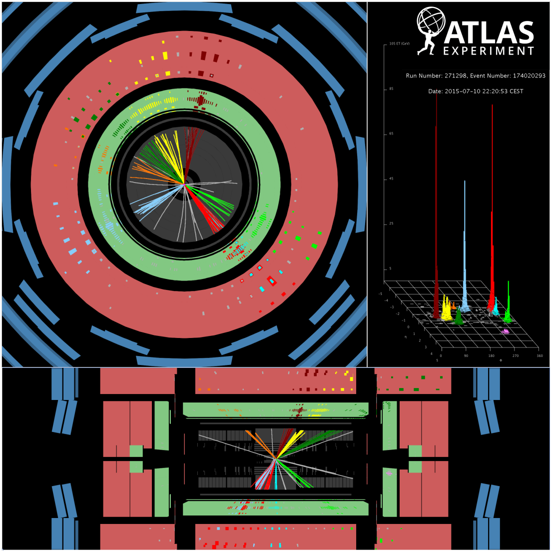


Phase-space At least 4 jets within the rapidity region $|y| < 2.8$, with $p_T^{(1)} > 100$ GeV & $p_T^{(4)} > 64$ GeV, separated by $\Delta R_{ij} > 0.65$.

Trigger Exclusive combination of two single-jet and two 4-jet triggers. The p_T and ΔR_{ij} cuts are implemented to have $> 99\%$ trigger efficiency.

A seven-jet event as seen in ATLAS

How is a multi-jet event seen in ATLAS?



Cross-section definitions

Probed multijet topologies by measuring the distributions of event variables:

Momentum

- $p_T^{(i)}$: p_T of the i-th jet, $i = 1, 2, 3, 4$
- H_T: scalar sum of the p_T of the 4 jets
- $\Sigma p_T^{\text{central}}$: scalar sum of the p_T of the 2 central jets

Mass

- m_{4j}: invariant mass of the 4 jets
- $m_{2j}^{\text{min}}/m_{4j}$: ratio of the minimum invariant mass of 2 jets and m_{4j}

Angular

- $\Delta y_{2j}^{\text{min}}$, $\Delta\phi_{2j}^{\text{min}}$: minimum angular separation between 2 jets
- $\Delta y_{3j}^{\text{min}}$, $\Delta\phi_{3j}^{\text{min}}$: minimum angular separation between 3 jets
- $\Delta y_{2j}^{\text{max}}$: maximum rapidity separation between 2 jets

- Only the 4 leading jets in p_T are used.
- Inclusive cuts were applied to the transverse momentum, rapidity and mass in order to probe different kinematic regimes.
- Distributions were unfolded using the Bayesian Iterative method.

Theoretical Predictions

Monte Carlo simulations are used to:

- estimate experimental systematic uncertainties,
- deconvolute detector effects,
- compare with data.

Name	Hard scattering + PS/UE	LO/NLO	PDF
Pythia 8	Pythia 8 + Pythia 8	LO ($2 \to 2$)	CT10
Herwig++	Herwig++ + Herwig++	LO ($2 \to 2$)	CTEQ6L1
MadGraph	Madgraph + Pythia 6	LO ($2 \to 4$)	CTEQ6L1
HEJ	HEJ†		CT10
BlackHat	BlackHat/Sherpa	NLO ($2 \to 4$)	CT10
NJet	NJet/Sherpa	NLO ($2 \to 4$)	CT10

(†) The HEJ sample is based on an approximation to all orders in α_s.

- Pythia 8 is used for unfolding and to estimate systematic uncertainties.
- Herwig++ and Madgraph were used for cross checks and uncertainties.
- All predictions were compared to data.
- The LO and HEJ simulations were rescaled to facilitate comparison with the data.

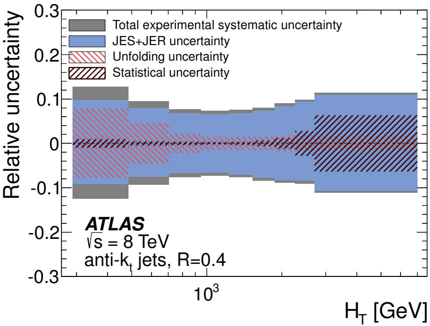
Uncertainties (arXiv:1509.07335)

Experimental Uncertainties

- The Jet Energy Scale, Jet Energy Resolution, Jet Angular Resolution and Luminosity uncertainties were estimated and taken into account.
- The JES is the dominating uncertainty. Typical size is 4-15%.

Unfolding uncertainties Main component comes from the different MC descriptions of the particle- and reco-level association efficiency. Typical size is 2-10%

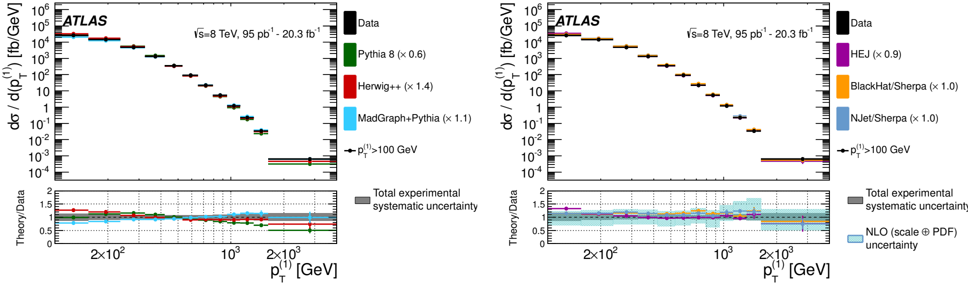
Theoretical uncertainties The scale and PDF uncertainties are obtained for `NJet` and `HEJ`. (Only `NJet`'s are shown.)



Results: Momentum Variables (arXiv:1509.07335)

First leading jet p_T ($p_T^{(1)}$).

Data compared to LO (left) and NLO and HEJ (right) predictions.

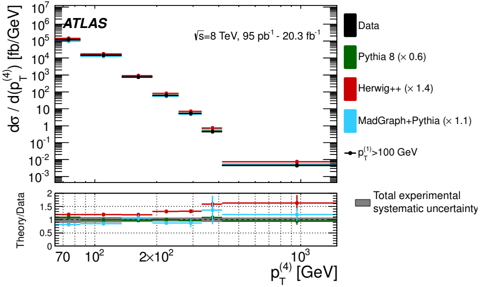


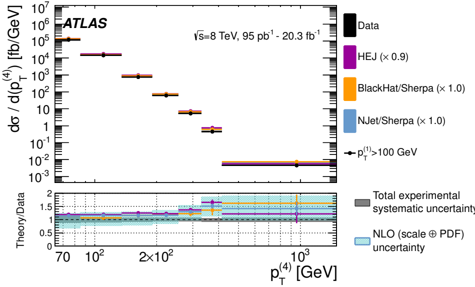
- All LO generators show a slope with respect to data, Madgraph being the only one with a positive slope in $p_T^{(1)}$.
- Madgraph is within experimental uncertainties above $\sim$ 300 GeV.
- HEJ and NJet are very good for the leading jet.

Results: Momentum Variables (arXiv:1509.07335)

Fourth leading jet p_T ($p_T^{(4)}$).

Data compared to LO (left) and NLO and HEJ (right) predictions.

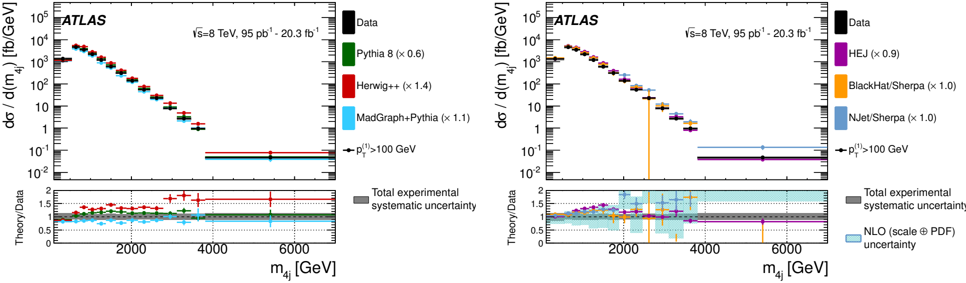




- Pythia gives a good description of the $p_T^{(4)}$ distribution.
- HEJ and Herwig++ overestimate the number of events with high $p_T^{(4)}$.
- NJet / Sherpa shows a similar trend at high $p_T^{(4)}$. Discrepancy mostly covered by uncertainties.

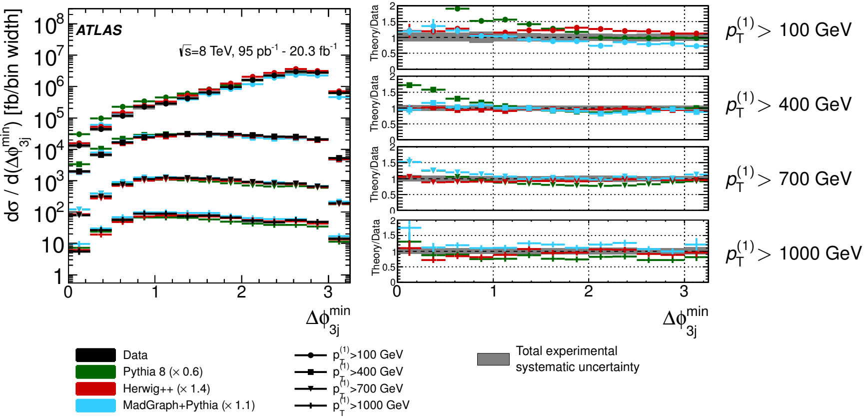
Results: Mass Variables (arXiv:1509.07335)

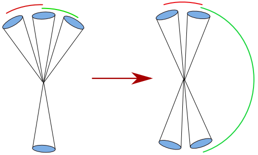
Invariant Mass of the 4 leading jets (m_{4j}).
Data compared to LO (left) and NLO and HEJ (right) predictions.



- Variable sensitive to the separation between jets.
- `Pythia` and `Madgraph` describe the data well, as does `Herwig` above 1 TeV.
- `HEJ` and `NJet` present a bump structure in the 1-2 TeV region; the difference is covered by the NLO uncertainties.

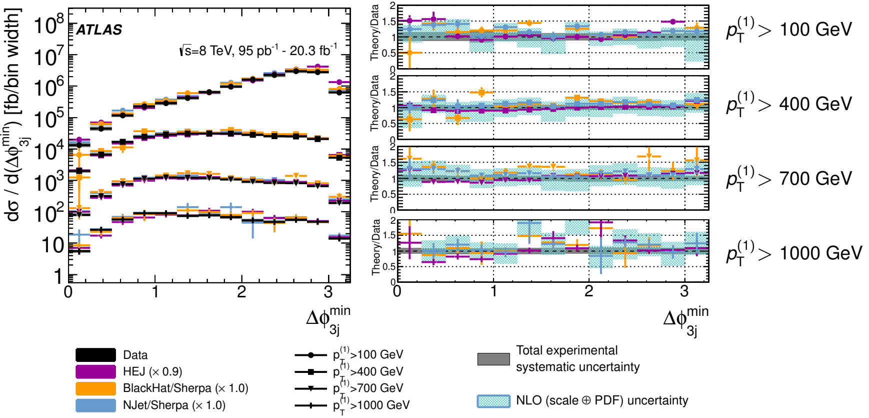
Results: Angular Variables - LO (arXiv:1509.07335)





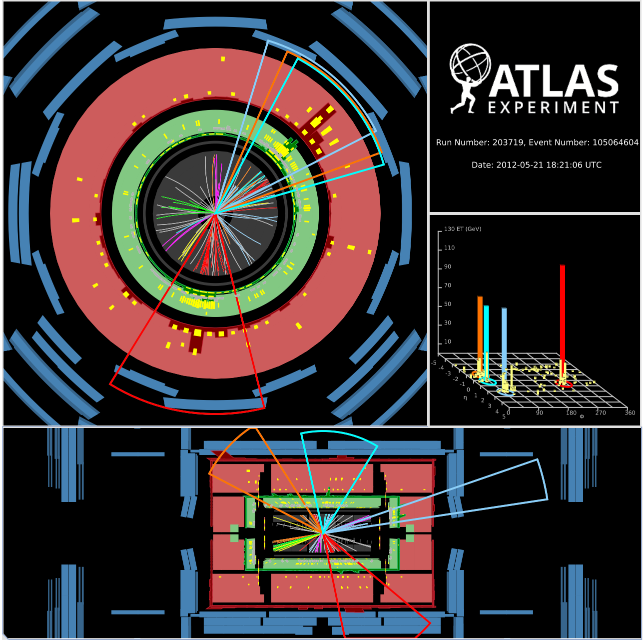
$$\Delta\phi^{min}_{ijk} = min_{\substack{i,j,k\in[1,4] \\ i\neq j\neq k}} \left(|\Delta\phi_{ij}| + |\Delta\phi_{jk}|\right)$$

Results: Angular Variables - NLO and HEJ (arXiv:1509.07335)

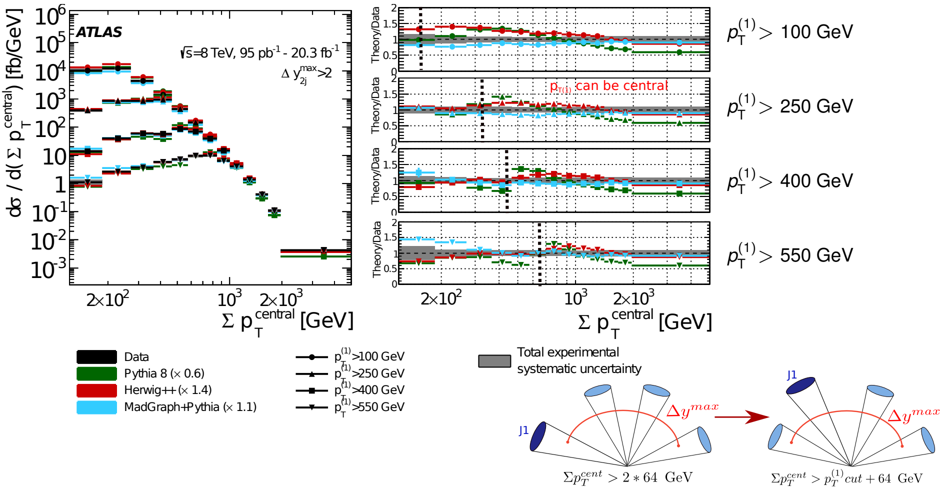


- HEJ provides a good description of all angular variables for $p_T^{(1)} > 400$ GeV, but shows significant discrepancies in all variables for lower $p_T^{(1)}$ values.
- NJet describes the data well within uncertainties.

Event with small value of $\Delta\phi_{ijk}^{min}$



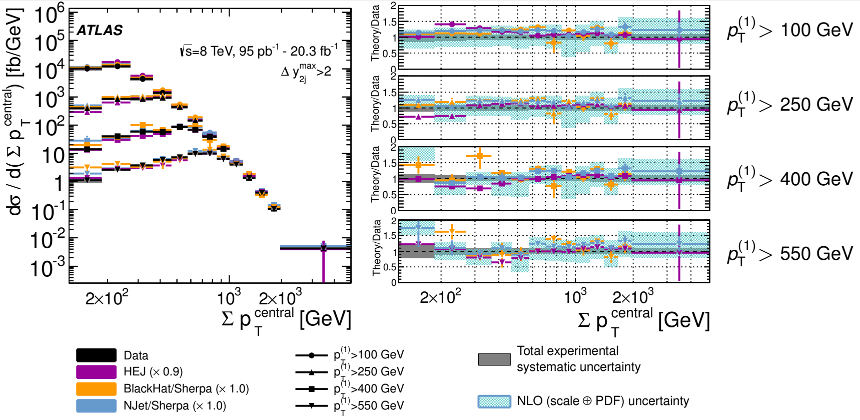
Results: $\Sigma p_{\mathrm{T}}^{\mathrm{central}}$ for $\Delta y_{2j}^{\max} > 2$ - LO (arXiv:1509.07335)



- All 2 $\rightarrow$ 2 predictions have issues describing this transition.
- The discrepancies worsen for larger $\Delta y_{2j}^{\max}$ and $p_{\mathrm{T}}^{(1)}$ cuts.
- `Madgraph` provides the best description, especially at low $p_{\mathrm{T}}^{(1)}$.

Results: $\Sigma p_T^{central}$ for $\Delta y_{2j}^{max} > 2$ - NLO and HEJ

(arXiv:1509.07335)



- Testing the HEJ framework, which is set to describe topologies with 2 jets significantly separated, and 2 additional high-p_T jets.
- HEJ describes better the high $\Sigma p_T^{central}$ region, the lower part shows more shape differences.
- NJet overestimates the values for low $\Sigma p_T^{central}$ but otherwise describes the data well.

Conclusions

- Four-jet differential cross sections were studied for various kinematic and topological variables

Performance of the predictions:

- The NLO predictions `BlackHat/Sherpa` and `NJet/Sherpa` are mostly compatible with data within theoretical uncertainties, which are found to be large ($\mathcal{O}$(30%) at low momenta) and asymmetric.
- `HEJ`, `BlackHat/Sherpa` and `NJet/Sherpa` provide good descriptions of the leading jets but disagree with data for $p_{T}^{(4)}$
- `Madgraph` provides a good description of all variables, although it shows a slope in the jet p_{T}'s.
- Mass & angular variables: `BlackHat/Sherpa`, `NJet/Sherpa`, `HEJ` and `Madgraph+Pythia` do a remarkable job overall

These measurements expose the shortcomings of $2 \rightarrow 2$ plus parton shower predictions in a variety of scenarios and highlight the importance of the more sophisticated calculations.

Thank you!

BACK UP SLIDES

Inclusive-jet cross-section at 13 TeV

Unfolding: Method

- IDS (bayesian iterative) method is used, using 1 iteration.
  http://arxiv.org/abs/0907.3791

- Based on the MC transfer matrix.
  - Matching criteria: Closest reco and truth jets within a $\Delta R = 0.3$ distance.

- Three steps of the unfolding procedure:
  - Multiply the raw spectra by the matching efficiency at reco level.
  - Unfold the spectrum using the TM.
  - Divide the unfolded spectra by the matching efficiency at truth level.

Statistical Uncertainty

- Using the bootstrap method to determine the statistical uncertainty.
- MC contribution evaluated by building replicas of the Transfer Matrix.
- Data contribution evaluated by building detector level data replicas.

Theoretical Predictions

Non-Pertubative correction

Considers effects from underlying-event and hadronisation.

- $C_{NP} = \frac{MC(UE\_ON, HAD\_ON)}{MC(UE\_OFF, HAD\_OFF)}$
- Evaluation done using Pythia and Herwig with various tunes.
  - Central value: Pythia A14 NNPDF LO.
  - Envelope is uncertainty.

- The uncertainties in the non-perturbative corrections are $[-8\%, +2\%]$ at low p_{T} over the whole rapidity range.
- At high p_{T} the uncertainties are $[-2\%, +0.4\%]$ for the two outermost $|y|$ bins and $[-1\%, +0.3\%]$ for the remaining four bins.

Theoretical Predictions

Electroweak corrections

- NLO pQCD predictions are corrected for the effects of γ and $\mathrm{W}^{\pm}/\mathrm{Z}$ interactions at the tree and 1-loop level
- The correction is defined as the ratio

$$\frac{\sigma\left(2\rightarrow 2,\mathrm{LO}^{(\mathrm{QCD})}+\mathrm{NLO}^{(\mathrm{EW})}\right)}{\sigma\left(2\rightarrow 2,\mathrm{LO}^{(\mathrm{QCD})}\right)}$$

- The correction is found to be negligible at low p_{T}, reaching 1.08 (0.95) for central (forward) jets for the highest p_{T} values covered by of the measurement.

Four-jet cross-section at 8 TeV

Cross-section definitions

Momentum

variable	definition	cuts
$p_\mathrm{T}^{(i)}$	transverse momentum	64/100 GeV - 2 TeV
H_T	$\sum_{i=1}^{4} p_\mathrm{T}^{(i)}$	290 GeV - 7 TeV
$\Sigma p_\mathrm{T}^\mathrm{central}$	$\lvert p_T^c\rvert + \lvert p_T^d\rvert$	$\Delta y_\mathrm{2j}^\mathrm{max} > 1, 2, 3, 4,\ p_\mathrm{T}^{(1)} > 100, 250, 400, 550$

Mass

m_4j	$\left(\left(\sum_{i=1}^{4} E_i\right)^2 - \left(\sum_{i=1}^{4} \mathbf{p}_i\right)^2\right)^{1/2}$	100 GeV - 7 TeV
$m_\mathrm{2j}^\mathrm{min} / m_\mathrm{4j}$	$\min_{\substack{i,j\in[1,4]\\ i\neq j}} \left((E_i + E_j)^2 - (\mathbf{p}_i + \mathbf{p}_j)^2\right)^{1/2} / m_\mathrm{4j}$	$m_\mathrm{4j} > 0.5, 1, 1.5, 2$ TeV

Angular

$\Delta\phi_\mathrm{2j}^\mathrm{min}$	$\min_{\substack{i,j\in[1,4]\\ i\neq j}} \left(\lvert\phi_i - \phi_j\rvert\right)$	$p_\mathrm{T}^{(1)} > 100, 400, 700, 1000$ GeV
$\Delta y_\mathrm{2j}^\mathrm{min}$	$\min_{\substack{i,j\in[1,4]\\ i\neq j}} \left(\lvert y_i - y_j\rvert\right)$	$p_\mathrm{T}^{(1)} > 100, 400, 700, 1000$ GeV
$\Delta\phi_\mathrm{3j}^\mathrm{min}$	$\min_{\substack{i,j,k\in[1,4]\\ i\neq j\neq k}} \left(\lvert\phi_i - \phi_j\rvert + \lvert\phi_j - \phi_k\rvert\right)$	$p_\mathrm{T}^{(1)} > 100, 400, 700, 1000$ GeV
$\Delta y_\mathrm{3j}^\mathrm{min}$	$\min_{\substack{i,j,k\in[1,4]\\ i\neq j\neq k}} \left(\lvert y_i - y_j\rvert + \lvert y_j - y_k\rvert\right)$	$p_\mathrm{T}^{(1)} > 100, 400, 700, 1000$ GeV
$\Delta y_\mathrm{2j}^\mathrm{max}$	$\Delta y_{ij}^\mathrm{max} = \max_{i,j\in[1,4]} \left(\lvert y_i - y_j\rvert\right)$	$p_\mathrm{T}^{(1)} > 100, 250, 400, 550$

Unfolding Method

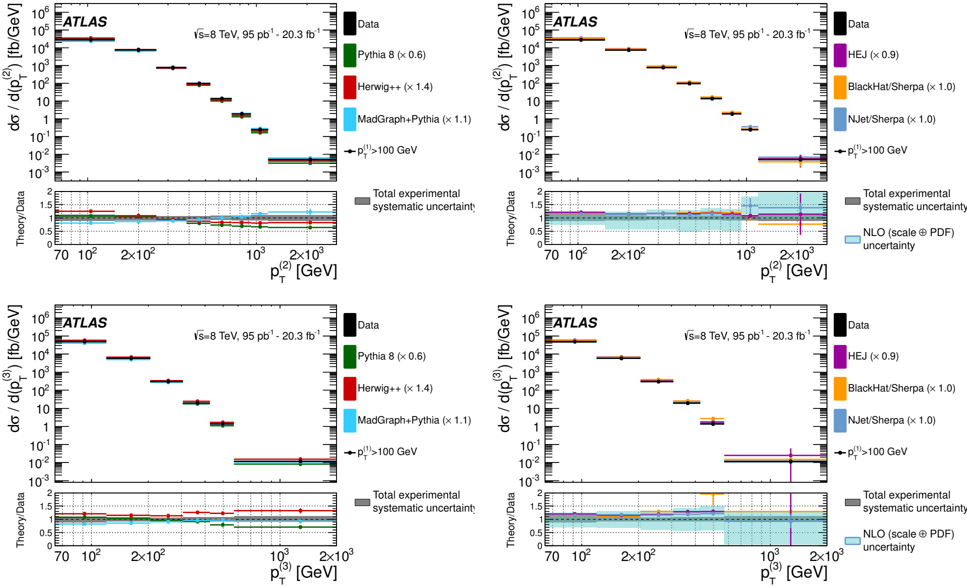
Bayesian Iterative method is used, using 2 iterations. This method corrects for:

- migrations between bins
- background events
- detector inefficiencies

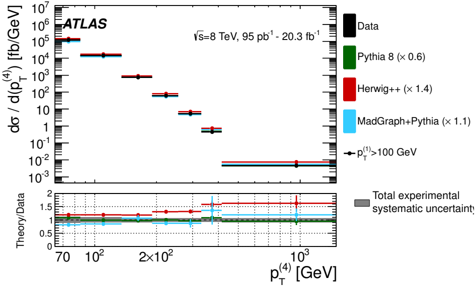
Unfolding matrix built with `Pythia`, with event by event reco-level and particle-level matching. No jet-by-jet spatial matching is applied.

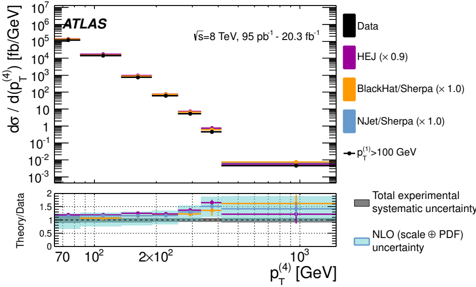
Binning was determined to get a bin by bin purity between 70 and 90%, and a statistical uncertainty in data below 10%

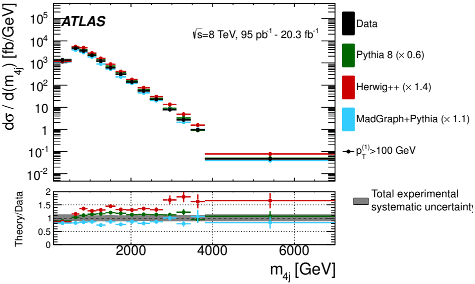
Results: $p_T^{(2)}$ and $p_T^{(3)}$ (arXiv:1509.07335)

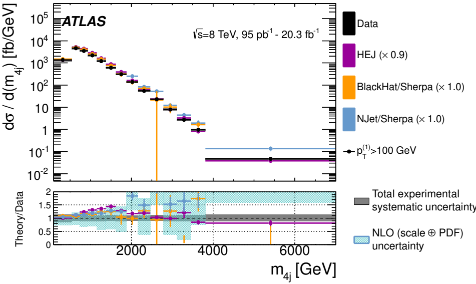


Results: $p_T^{(4)}$ and m_{4j} (arXiv:1509.07335)

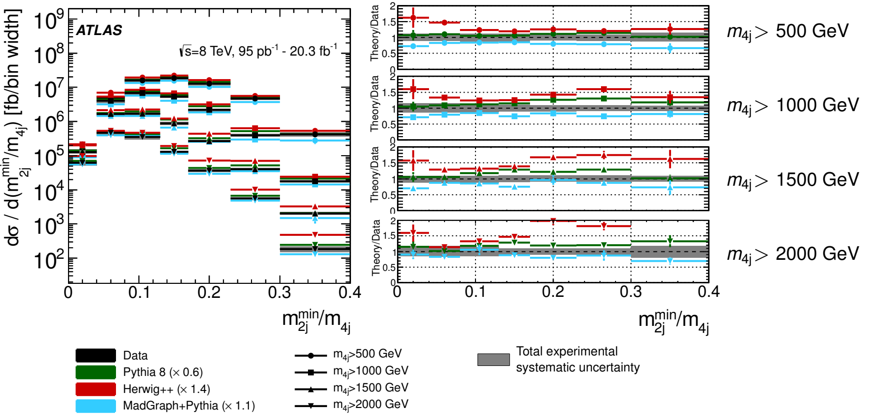






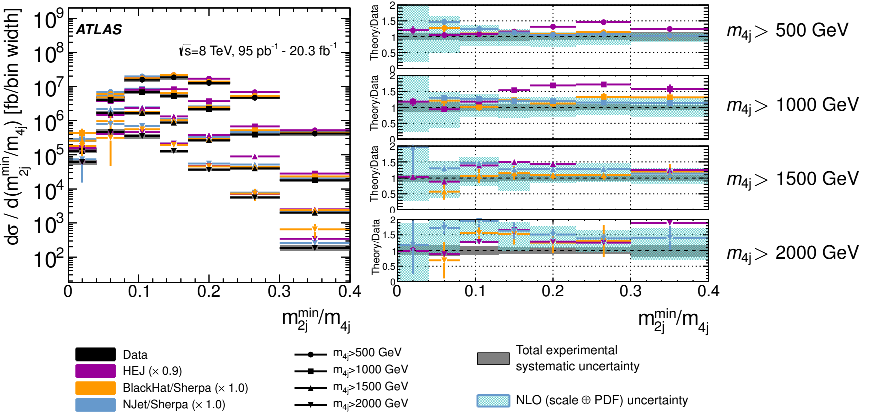


Results: Mass Variables - LO (arXiv:1509.07335)



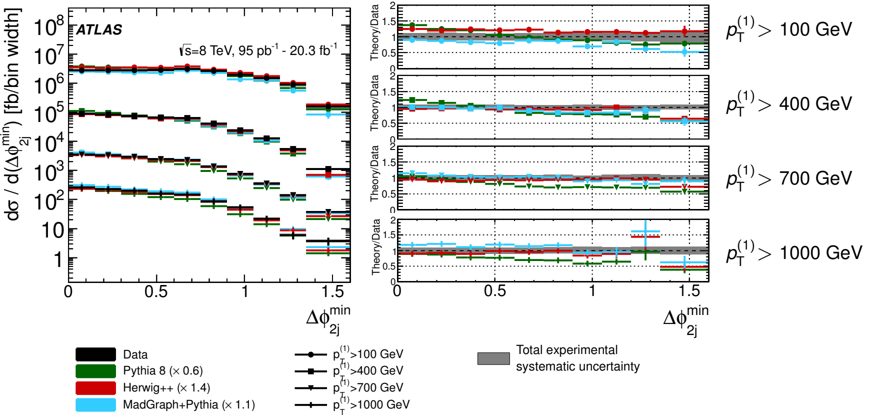
- Mass variables are sensitive to the separation between the jets
- $m_{4j} > 1$ TeV is well described by the LO predictions, particularly `Madgraph`, but normalisation is off by 20-40%.
- `Pythia` and `Herwig` overestimate the events for low m_{2j}^{min}/m_{4j}, worse for higher m_{4j}.
- m_{2j}^{min}/m_{4j} is well described by `Madgraph` for all m_{4j} cuts, providing the best description for mass variables.

Results: Mass Variables - NLO and HEJ (arXiv:1509.07335)

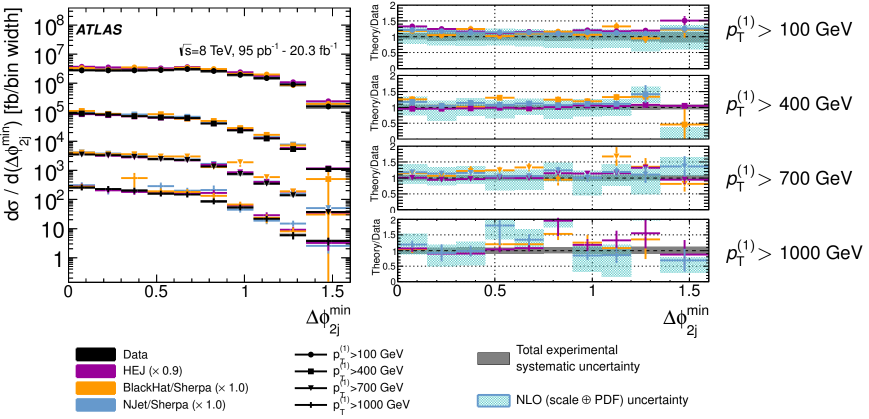


- m_{4j} is well described by HEJ and NJet, though presenting a bump structure.
- m_{2j}^{min}/m_{4j} is well described by HEJ at low m_{4j}, differences are covered by the large theoretical uncertainties.
- NJet overestimates the first bin values, but otherwise agrees with data within uncertainties

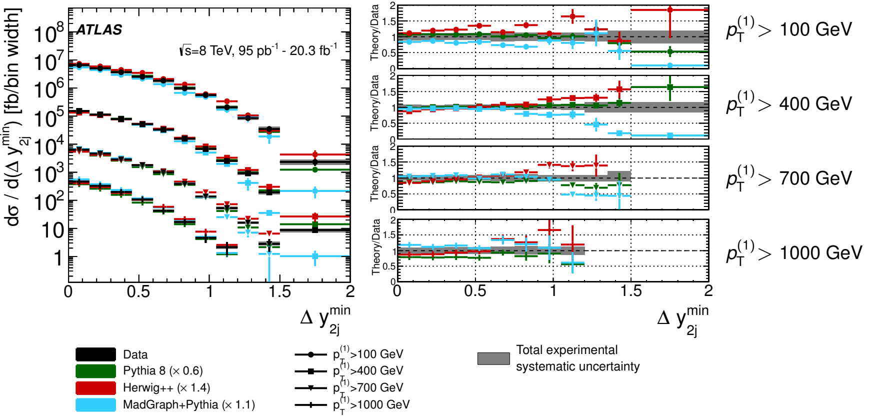
Results: $\Delta\phi_{2j}^{min}$- LO predictions (arXiv:1509.07335)



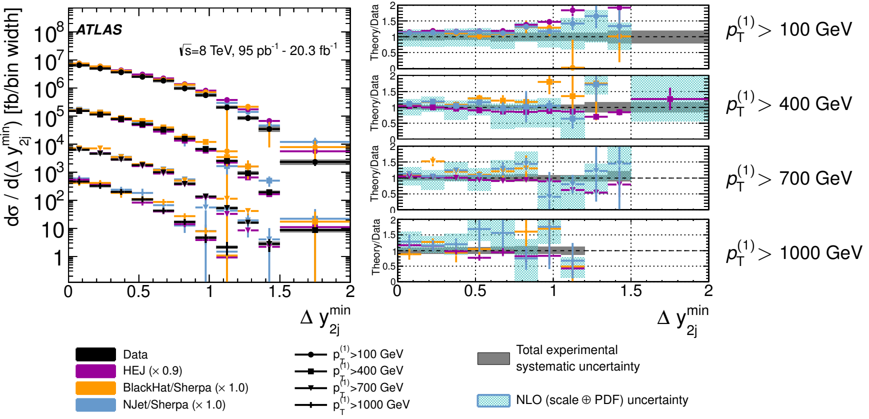
Results: $\Delta\phi_{2j}^{min}$- NLO and HEJ (arXiv:1509.07335)



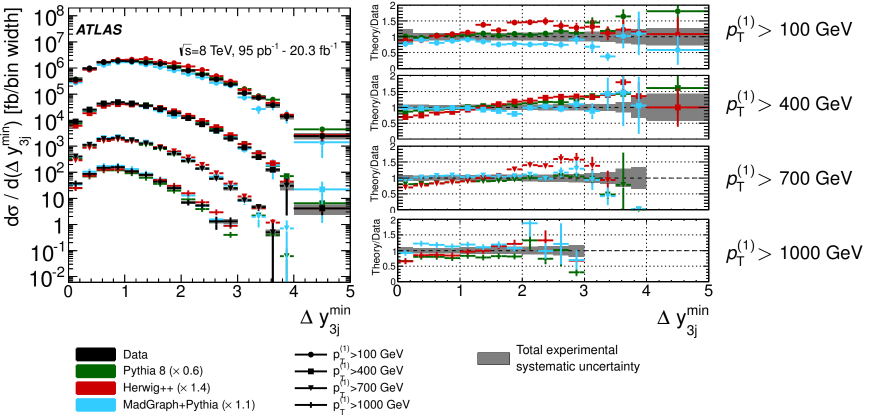
Results: Δy_{2j}^{min}- LO predictions (arXiv:1509.07335)



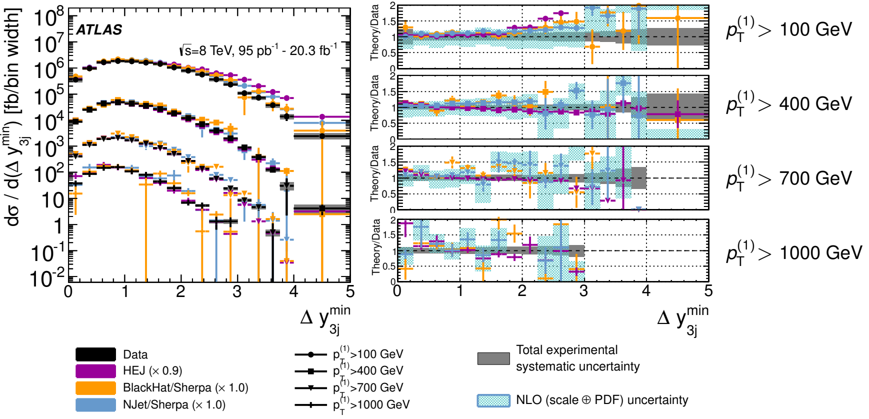
Results: Δy_{2j}^{min}- NLO and HEJ (arXiv:1509.07335)



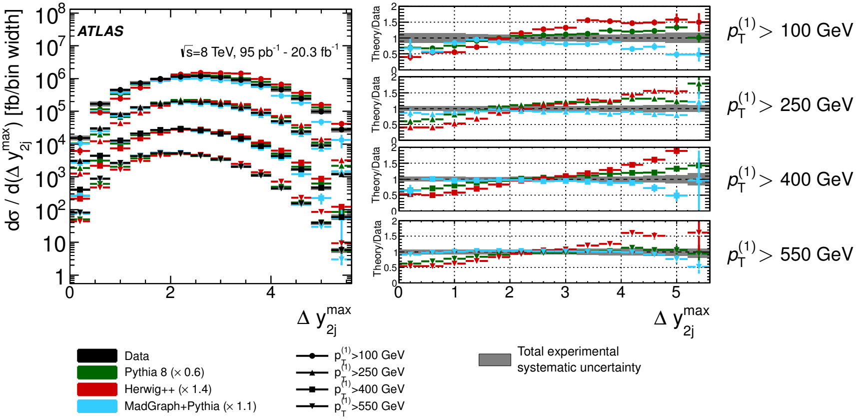
Results: Δy_{3j}^{min}- LO predictions (arXiv:1509.07335)



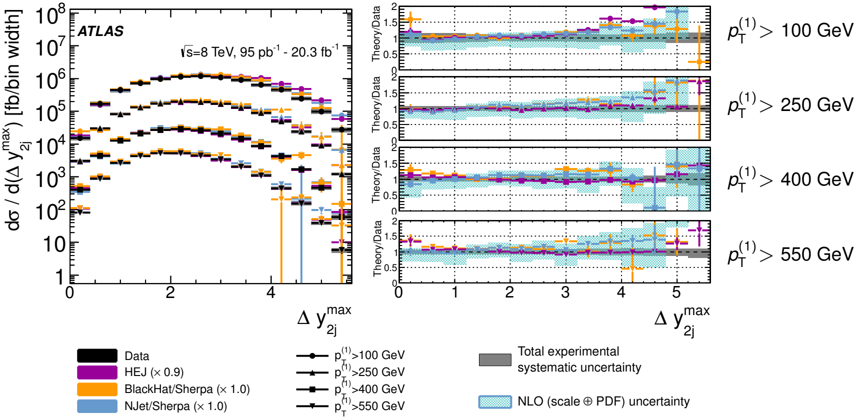
Results: Δy_{3j}^{min}- NLO and HEJ (arXiv:1509.07335)



Results: Δy_{2j}^{max} (arXiv:1509.07335)

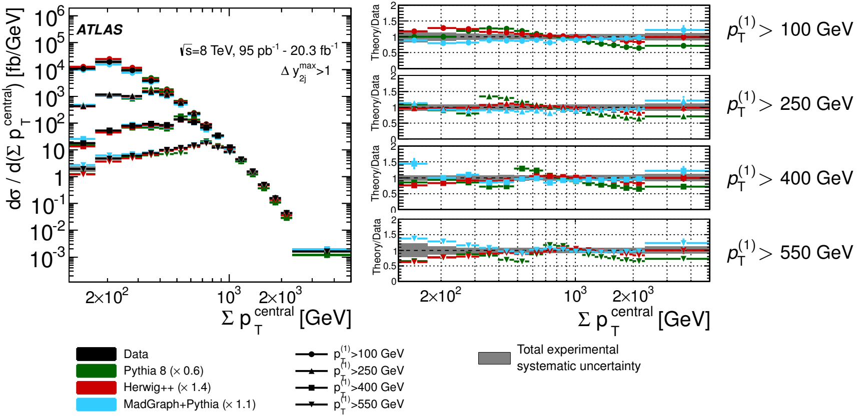


Results: Δy_{2j}^{max} - NLO and HEJ (arXiv:1509.07335)



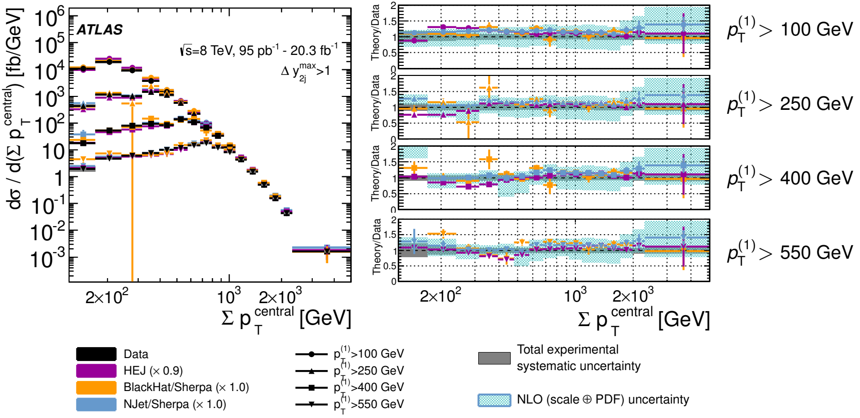
Results: $\Sigma p_T^{central}$ for $\Delta y_{2j}^{max} > 1$ - LO predictions

(arXiv:1509.07335)



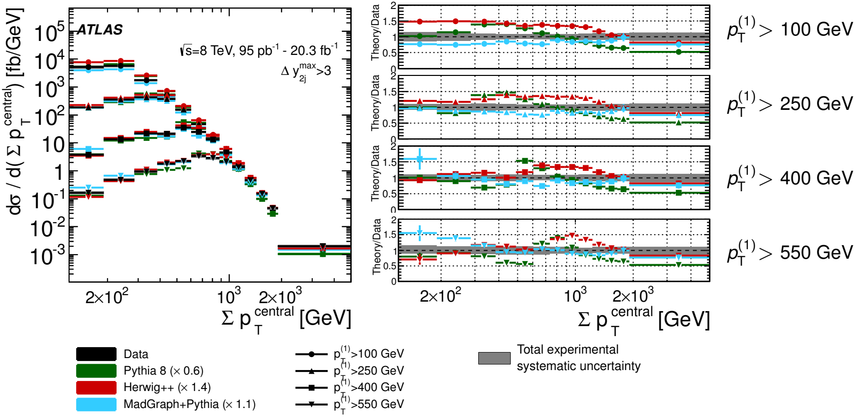
Results: $\Sigma p_T^{central}$ for $\Delta y_{2j}^{max} > 1$ - NLO and HEJ

(arXiv:1509.07335)



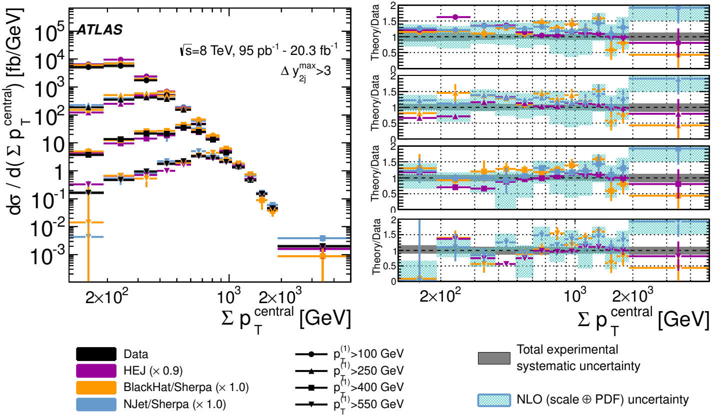
Results: $\Sigma p_{T}^{\text{central}}$ for $\Delta y_{2j}^{\text{max}} > 3$ - LO predictions

(arXiv:1509.07335)



Results: $\Sigma p_T^{\text{central}}$ for $\Delta y_{2j}^{\text{max}} > 3$ - NLO and HEJ

(arXiv:1509.07335)



$p_T^{(1)} > 100$ GeV

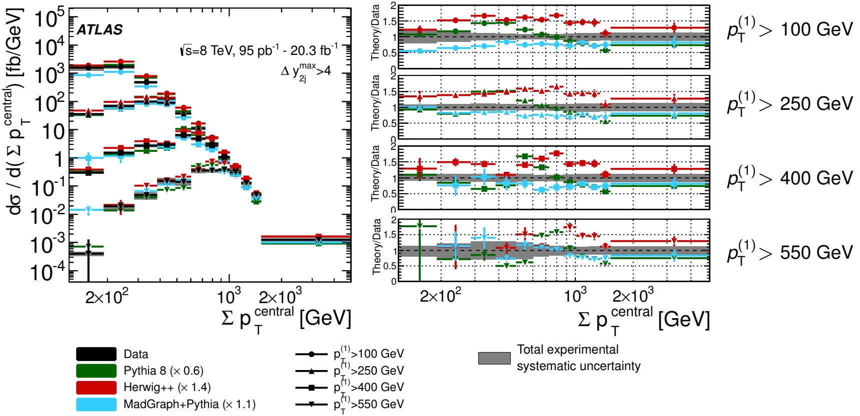
$p_T^{(1)} > 250$ GeV

$p_T^{(1)} > 400$ GeV

$p_T^{(1)} > 550$ GeV

Results: $\Sigma p_T^{central}$ for $\Delta y_{2j}^{max} > 4$ - LO predictions

(arXiv:1509.07335)



Results: $\Sigma p_T^{\text{central}}$ for $\Delta y_{2j}^{\max} > 4$ - NLO and HEJ

(arXiv:1509.07335)