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

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Outline

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2. Event Reconstruction and Selection
3. Cross-section definition
4. Predictions
5. Results
6. Conclusion

Introduction and Motivation

Test of 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 theoretical predictions describe:

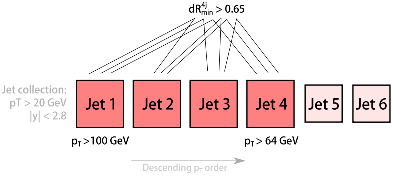
- inclusive variables,
- angular variables,
- the range of energy scales within an event,
- regimes sensitive to NLO effects,
- low-x (large Δy) distributions.

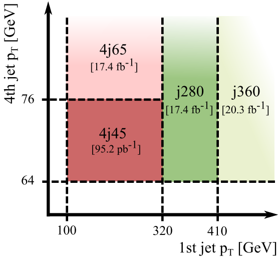
Study of QCD background: several new physics searches have many jets in the final state;
it is thus crucial to understand the QCD contribution to this kind of events.

Event Reconstruction and Selection

Jets:

- reconstructed using the anti-k_t algorithm, with radius parameter R=0.4
- calibrated using 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.

Cross-section definitions

Probed multijet topologies by measuring the distributions of event variables:

Momentum

- $p_{\mathrm{T}}^{(i)}$: p_{T} of the i-th jet, $i = 1, 2, 3, 4$
- H_{T}: scalar sum of the p_{T} of the 4 jets
- $\Sigma p_{\mathrm{T}}^{\mathrm{central}}$: scalar sum of the p_{T} of the 2 central jets

Mass

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

Angular

- $\Delta y_{2\mathrm{j}}^{\mathrm{min}}$, $\Delta\phi_{2\mathrm{j}}^{\mathrm{min}}$: minimum angular separation between 2 jets
- $\Delta y_{3\mathrm{j}}^{\mathrm{min}}$, $\Delta\phi_{3\mathrm{j}}^{\mathrm{min}}$: minimum angular separation between 3 jets
- $\Delta y_{2\mathrm{j}}^{\mathrm{max}}$: 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.
- 4 examples shown today; all results can be found in JHEP 12(2015)105.

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

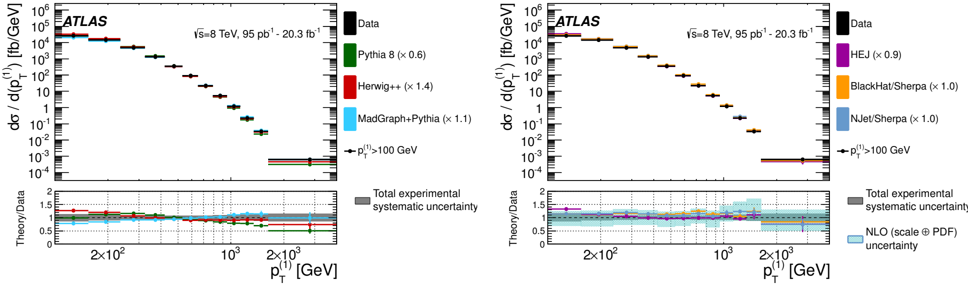
(†) The HEJ sample is based on an approximation to all orders in α_s.

- 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.

Results: Momentum Variables

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

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

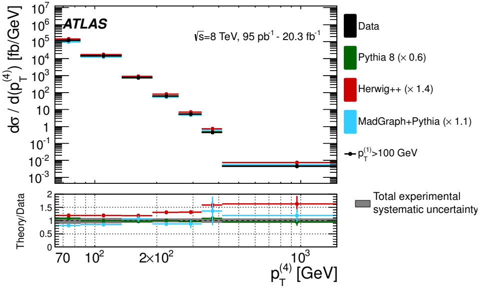


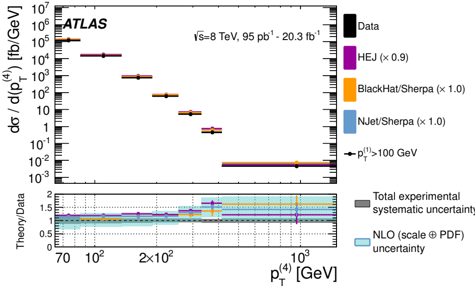
- All LO generators show a slope with respect to data, `Madgraph` being the only one with a positive slope in $p_T^{(1)}$.
- `NJet` and `HEJ` do well in the leading jet spectrum, but might benefit from matching to PS in the $p_T^{(4)}$ case.
- `Pythia` is better in $p_T^{(4)}$. `Madgraph` does reasonably well in all.

Results: Momentum Variables

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

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

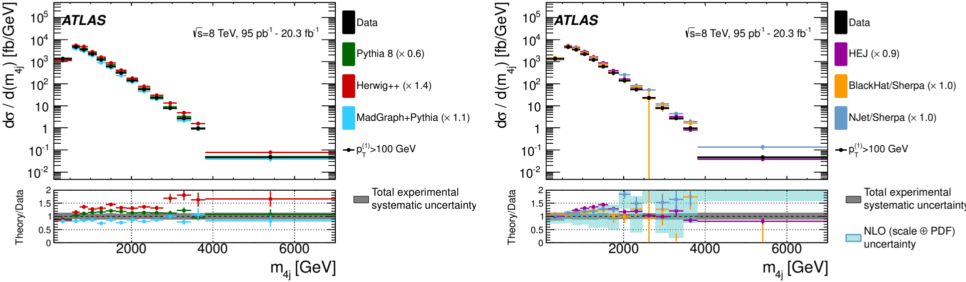




- All LO generators show a slope with respect to data, Madgraph being the only one with a positive slope in $p_T^{(1)}$.
- NJet and HEJ do well in the leading jet spectrum, but might benefit from matching to PS in the $p_T^{(4)}$ case.
- Pythia is better in $p_T^{(4)}$. Madgraph does reasonably well in all.

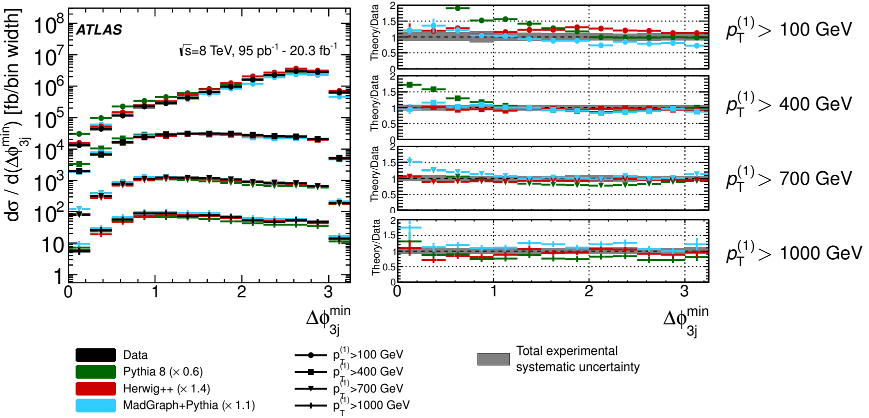
Results: Mass Variables

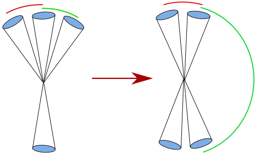
Invariant Mass of the 4 leading jets (m_{4j}).
Data compared to LO (left) and NLO and HEJ (right) predictions.



- 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.

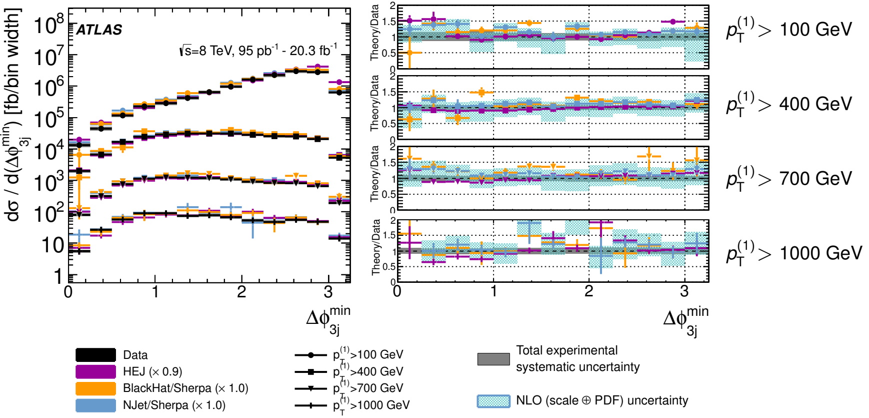
Results: Angular Variables - LO





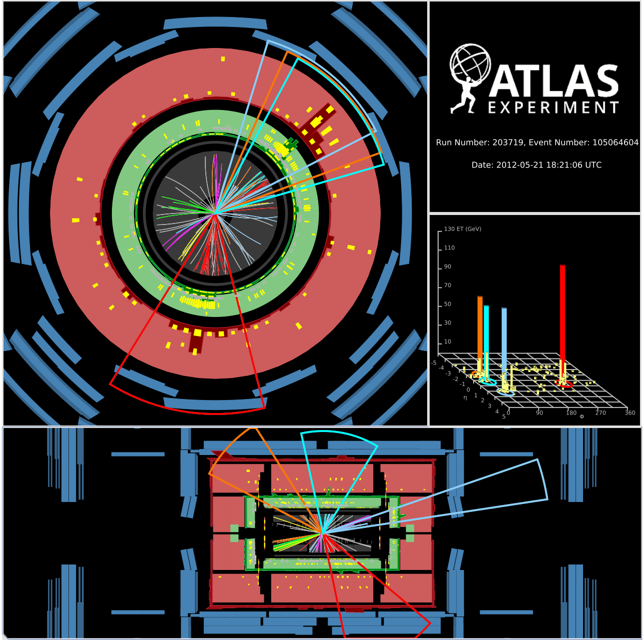
$$\Delta\phi_{ijk}^{min} = min_{\substack{i,j,k\in[1,4] \\ i\neq j\neq k}} \left(|\Delta\phi_{ij}| + |\Delta\phi_{jk}|\right)$$

Results: Angular Variables - NLO and HEJ

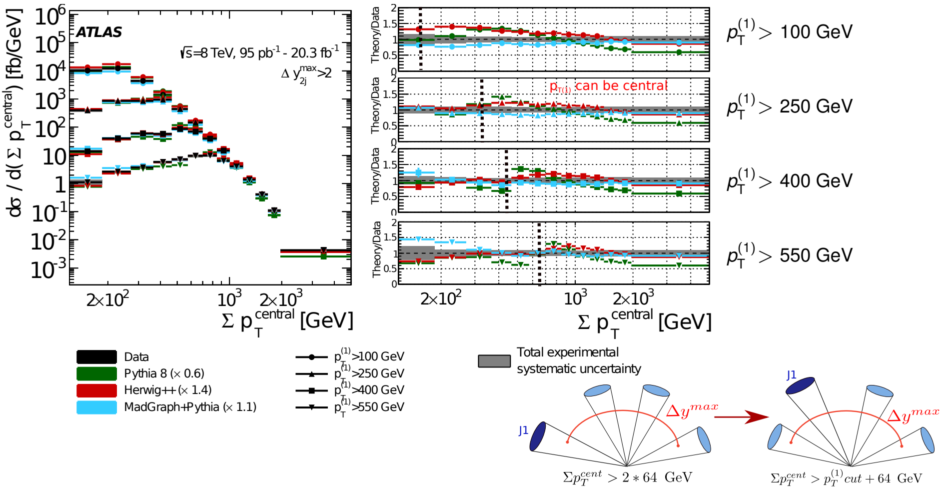


- `HEJ` provides a good description of all angular variables for $p_T^{(1)} > 400$ GeV, but shows significant discrepancies in all variables for lower $p_T^{(1)}$ values.
- `NJet` describes the data well within uncertainties.

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

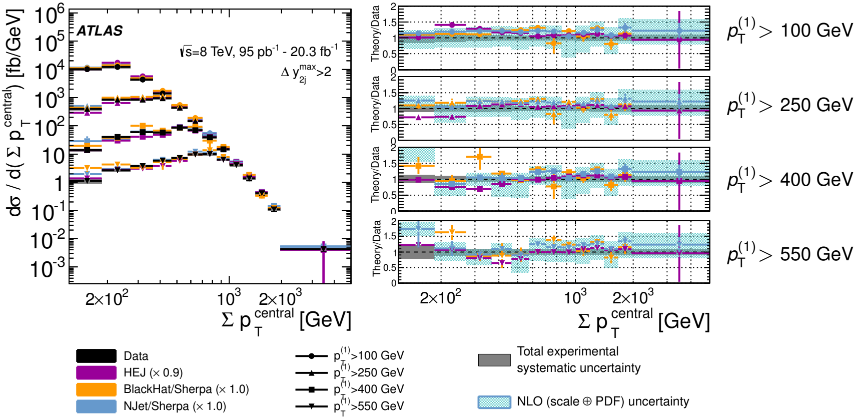


Results: $\Sigma p_T^{\rm central}$ for $\Delta y_{2j}^{\max} > 2$ - LO



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

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



- 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 $\Sigma p_T^{\text{central}}$ region, the lower part shows more shape differences.
- NJet overestimates the values for low $\Sigma p_T^{\text{central}}$ 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 $2 \to 2$ plus parton shower predictions in a variety of scenarios and highlight the importance of the more sophisticated calculations.

Thank you!

BACK UP SLIDES

Cross-section definitions

Momentum

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

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

Angular

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

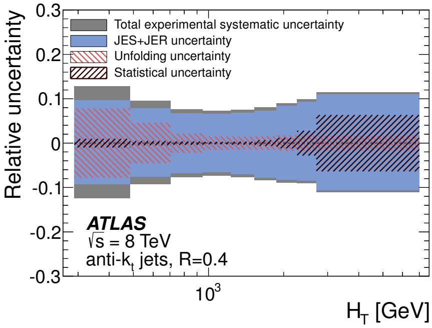
Uncertainties

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.)



Unfolding Method

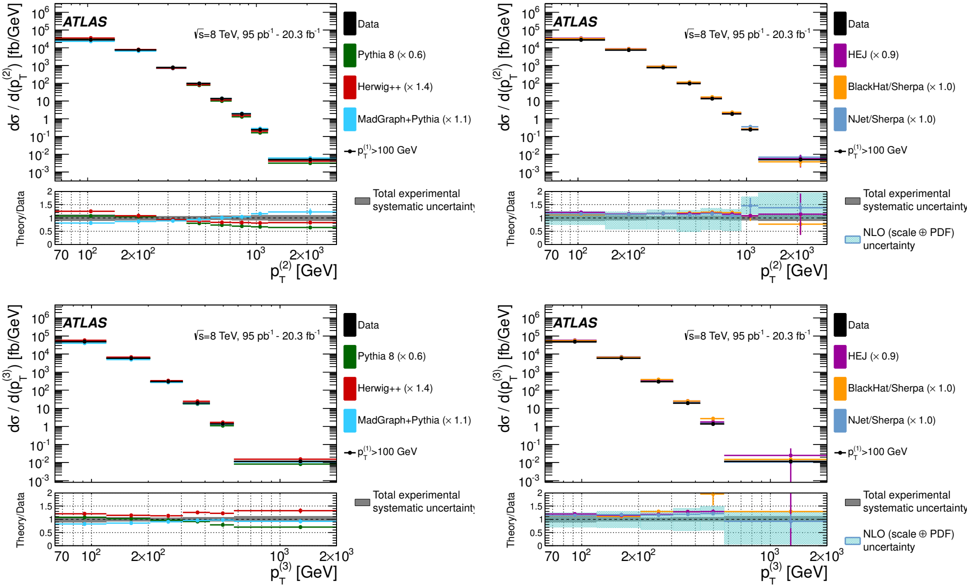
Bayesian Iterative method is used, using 2 iterations. This method corrects for:

- migrations between bins
- background events
- detector inefficiencies

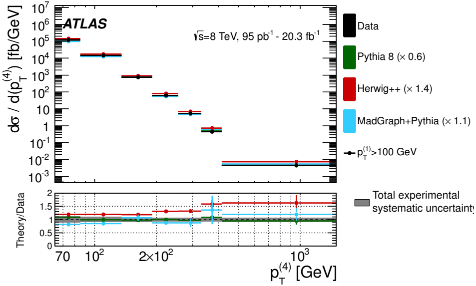
Unfolding matrix built with `Pythia`, with event by event reco-level and particle-level matching. No jet-by-jet spatial matching is applied.

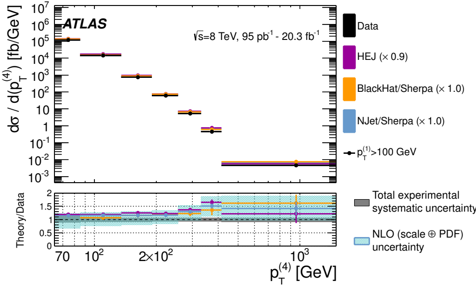
Binning was determined to get a bin by bin purity between 70 and 90%, and a statistical uncertainty in data below 10%

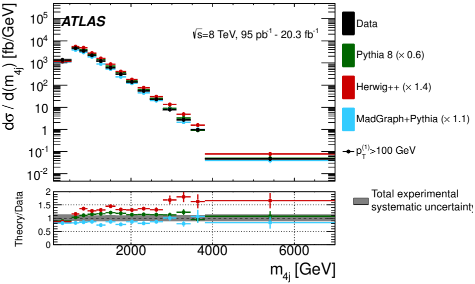
Results: $p_T^{(2)}$ and $p_T^{(3)}$

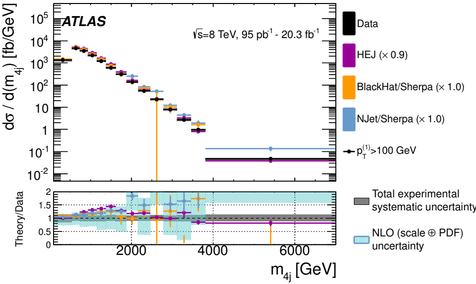


Results: $p_T^{(4)}$ and m_{4j}



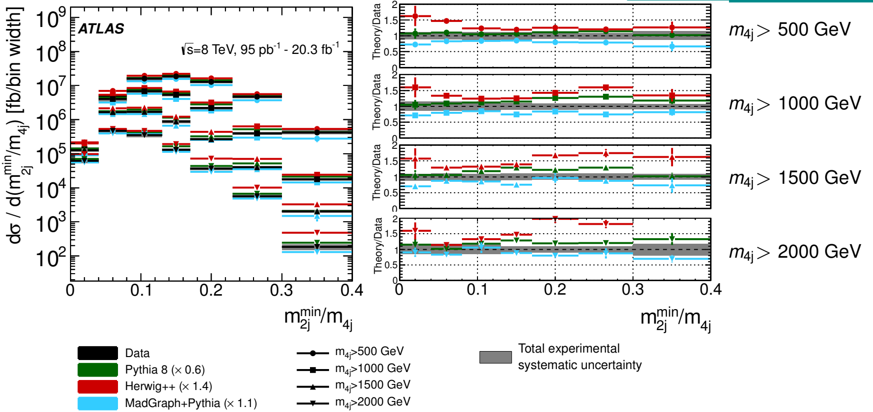






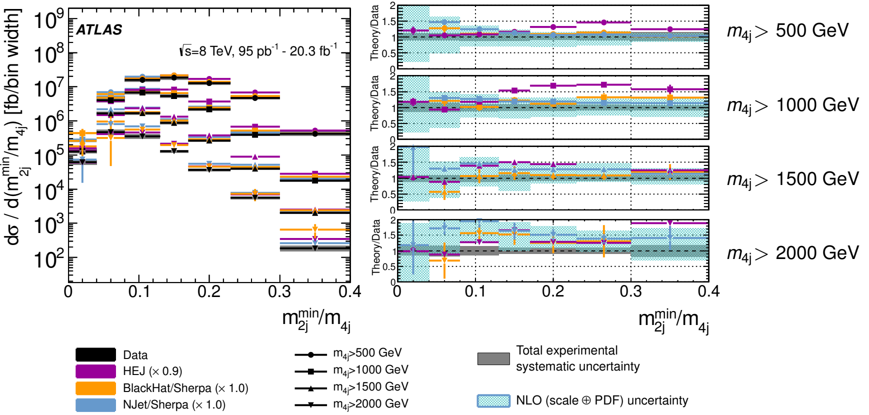
Results: Mass Variables - LO

$$\frac{m_{2j}^{min}}{m_{4j}} = \frac{\text{minimum 2 jet mass}}{m_{4j}}$$



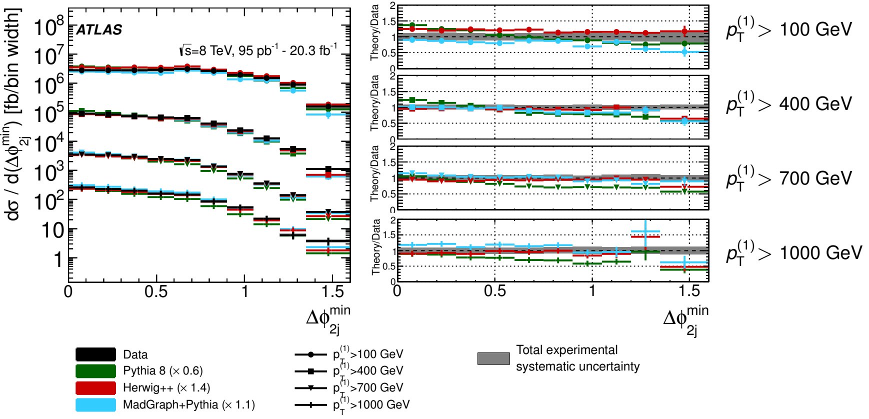
- Mass variables are sensitive to the separation between the jets
- $m_{4j} > 1$ TeV is well described by the LO predictions, particularly `Madgraph`, but normalisation is off by 20-40%.
- `Pythia` and `Herwig` overestimate the events for low m_{2j}^{min}/m_{4j}, worse for higher m_{4j}.
- m_{2j}^{min}/m_{4j}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

Results: Mass Variables - NLO and HEJ

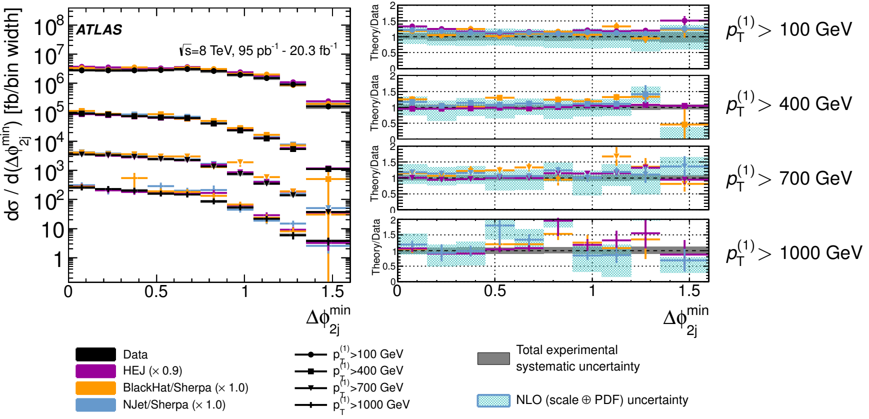


- m_{4j} is well described by `HEJ` and `NJet`, though presenting a bump structure.
- m_{2j}^{min}/m_{4j} is well described by `HEJ` at low m_{4j}, differences are covered by the large theoretical uncertainties.
- `NJet` overestimates the first bin values, but otherwise agrees with data within uncertainties

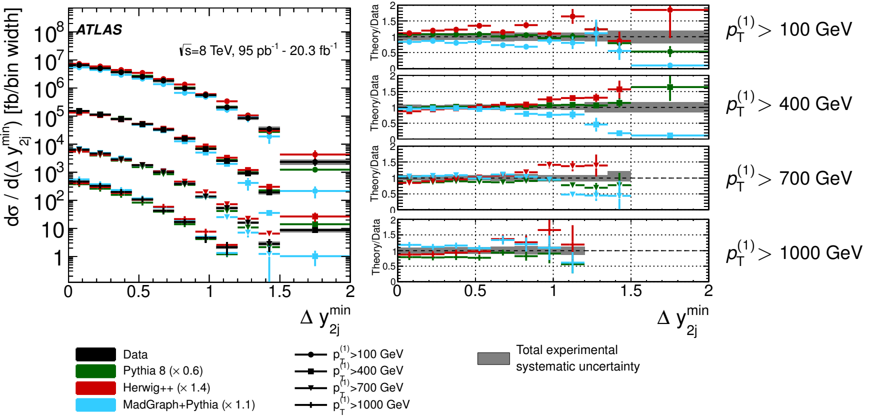
Results: $\Delta\phi_{2j}^{min}$- LO predictions



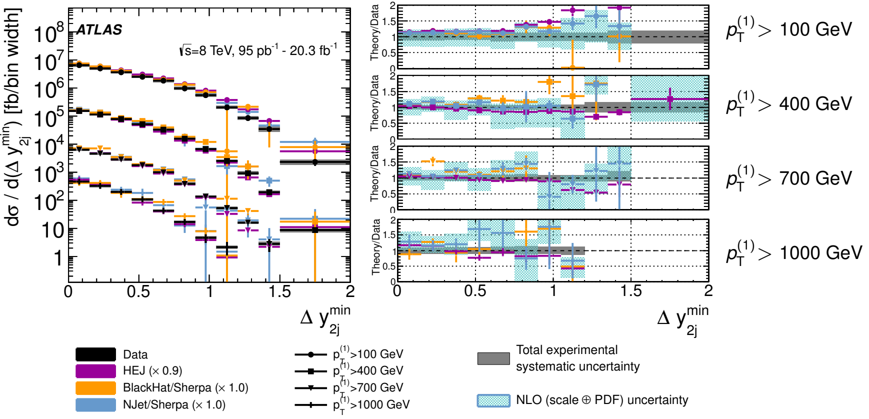
Results: $\Delta\phi_{2j}^{min}$- NLO and HEJ



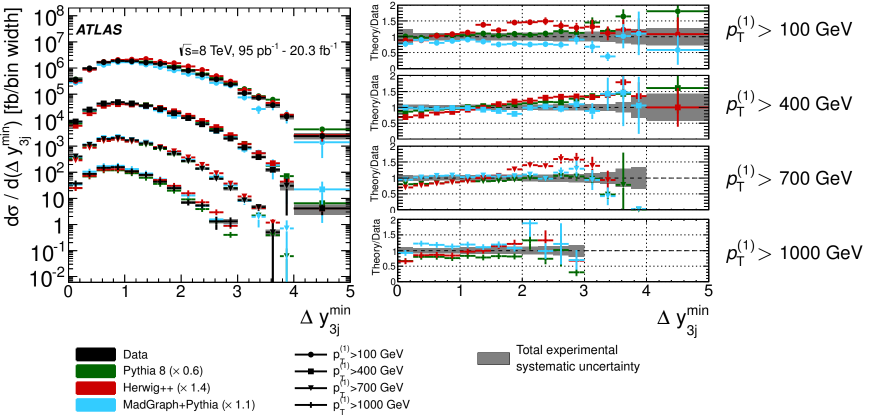
Results: Δy_{2j}^{min}- LO predictions



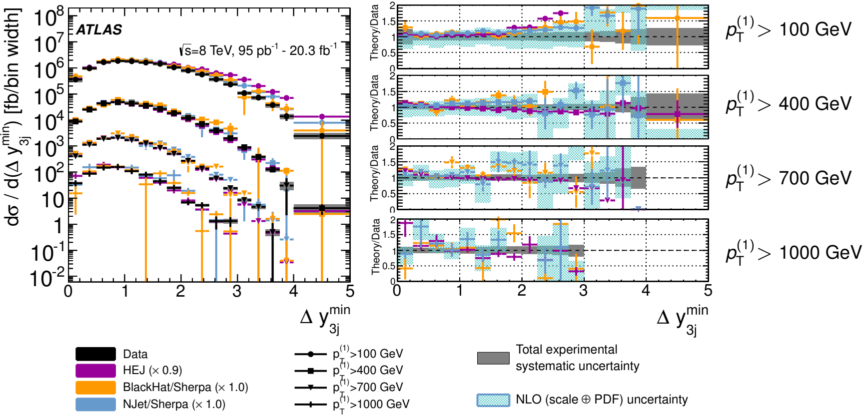
Results: Δy_{2j}^{min}- NLO and HEJ



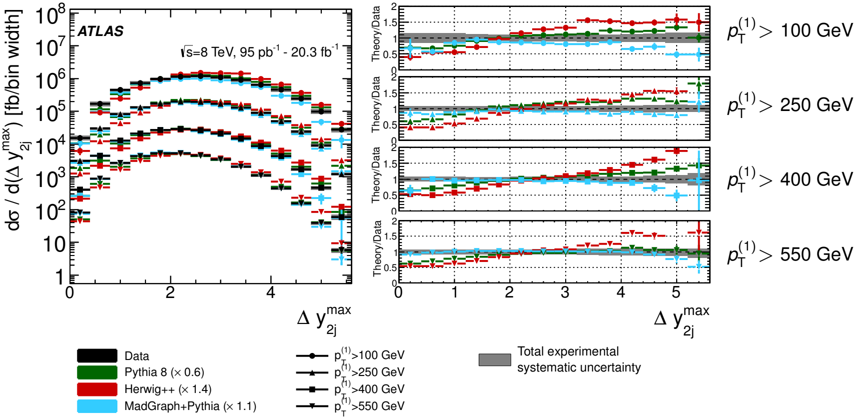
Results: Δy_{3j}^{min}- LO predictions



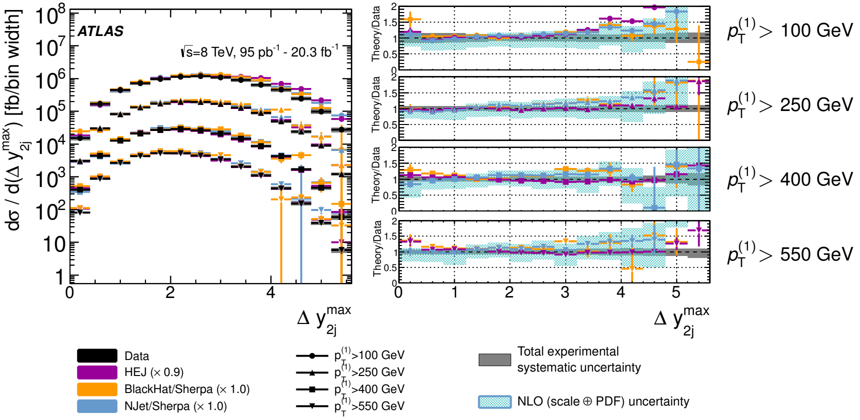
Results: Δy_{3j}^{min}- NLO and HEJ



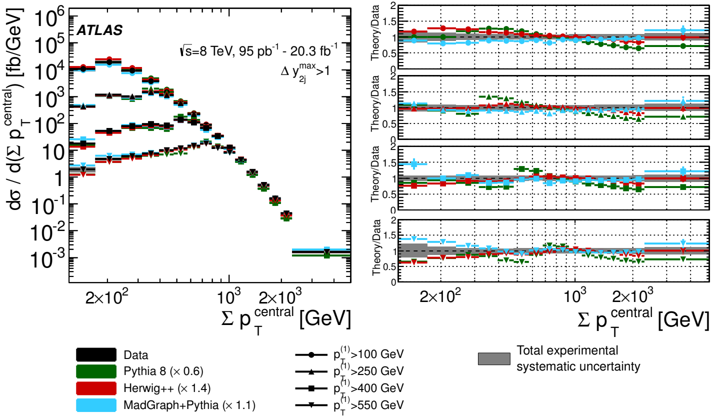
Results: Δy_{2j}^{max}



Results: Δy_{2j}^{max}- NLO and HEJ



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



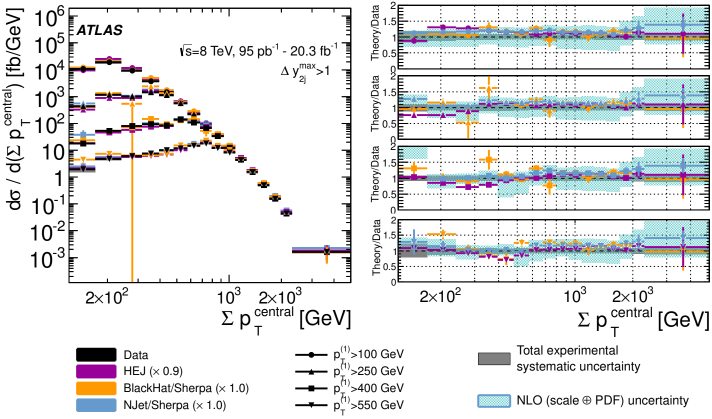
$p_T^{(1)} > 100$ GeV

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

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

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

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



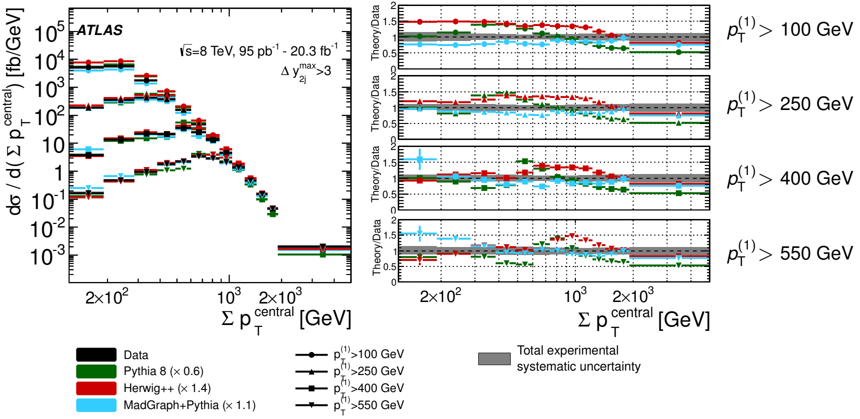
$p_T^{(1)} > 100$ GeV

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

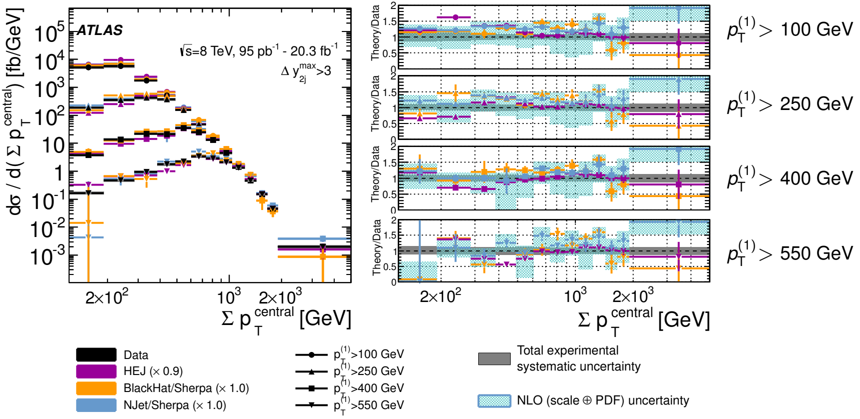
$p_T^{(1)} > 400$ GeV

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

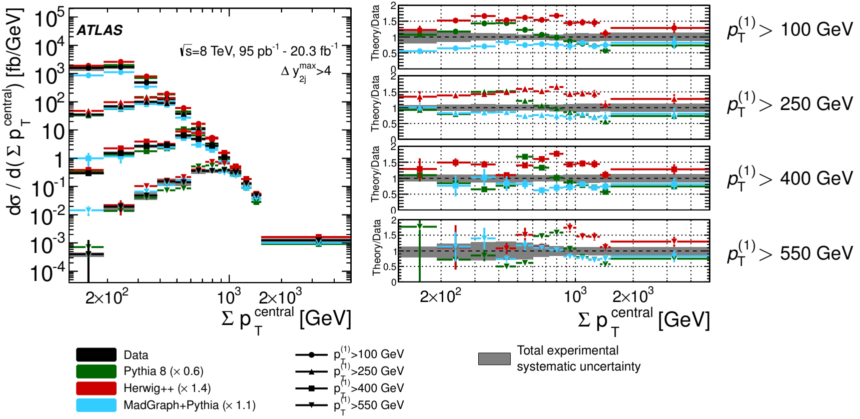
Results: $\Sigma p_T^{central}$ for $\Delta y_{2j}^{max} > 3$ - LO predictions



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



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



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