Multi-jets at the LHC

Hans Van Haevermaet (University of Antwerp)
for the ATLAS and CMS Collaborations

Strong interactions and hadron physics
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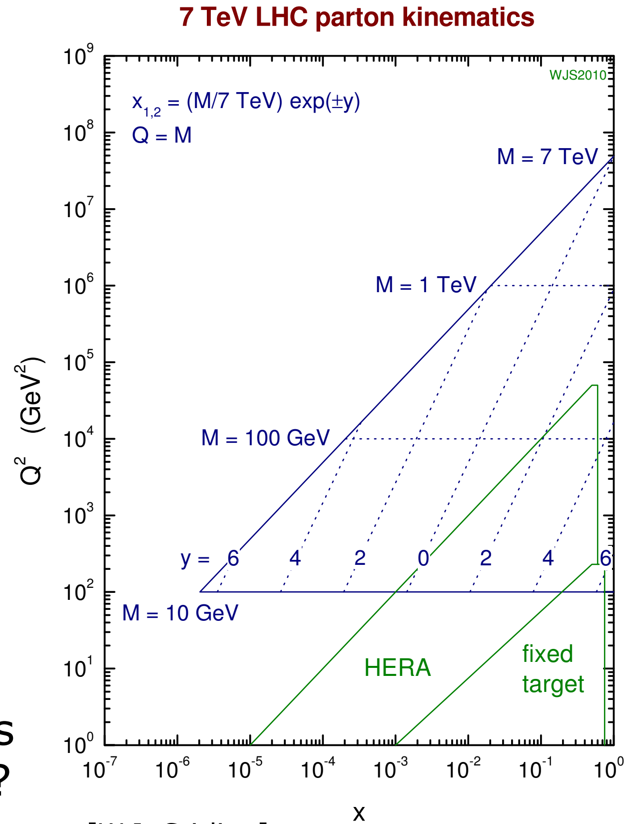
Multi-jets at the LHC

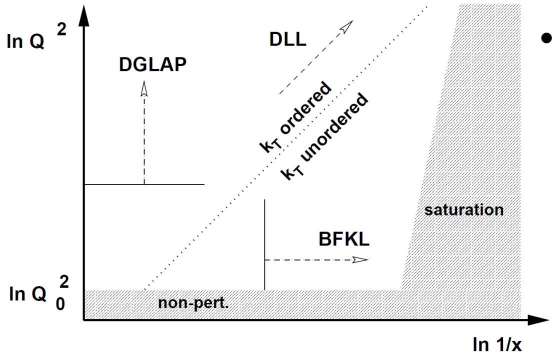
- Ideal tool to study QCD at hadron colliders
- Precision measurements with central high-p_T jets

  ➔ test LO, NLO pQCD calculations, PDF sets
  ➔ challenge 2 → 2 matrix element MC generators with parton showers

- Role of multiple parton interactions (MPI)?
- Double (hard) parton scattering?
- Go to extreme corners of phase space



[W.J. Stirling]



[arXiv:hep-ph/9712505v1]

- Forward low-p_T multi-jets
  ➔ new parton dynamics?

- Very active field in ATLAS and CMS
- Challenging: high pile-up, jet energy scales, …

Four-jet production

- Measure four-jet production in pp collisions at $\sqrt{s}$ = 8 TeV with ATLAS: differential cross sections with momentum, mass and angular variables

- Selection:

  Anti-k_T R=0.4, $N_{jets} \geq 4$, $|y| < 2.8$
  $p_T^{(1)} > 100$ GeV, $p_T^{(2,3,4)} > 64$ GeV
  well separated: $\Delta R_{4j}^{min} > 0.65$

- Observables selected for their sensitivity to differences between MC models

- Probe performance of:
  - all order calc. with HEJ
  - NLO pQCD calc.
  - multi-leg ME + PS
  - 2 → 2 + PS

- Total exp. Uncertainty ~10%, dominated by jet energy scale

Observables:

Name	Definition
$p_{\mathrm{T}}^{(i)}$	Transverse momentum of the ith jet
H_{T}	$\sum_{i=1}^{4} p_{\mathrm{T}}^{(i)}$
$m_{4\mathrm{j}}$	$\left(\left(\sum_{i=1}^{4} E_i\right)^2 - \left(\sum_{i=1}^{4} \mathbf{p}_i\right)^2\right)^{1/2}$
$m_{2\mathrm{j}}^{\min}/m_{4\mathrm{j}}$	$\min_{i,j\in[1,4],\, i\neq j} \left((E_i + E_j)^2 - (\mathbf{p}_i + \mathbf{p}_j)^2\right)^{1/2} \Big/ m_{4\mathrm{j}}$
$\Delta\phi_{2\mathrm{j}}^{\min}$	$\min_{i,j\in[1,4],\, i\neq j} (\lvert\phi_i - \phi_j\rvert)$
$\Delta y_{2\mathrm{j}}^{\min}$	$\min_{i,j\in[1,4],\, i\neq j} (\lvert y_i - y_j\rvert)$
$\Delta\phi_{3\mathrm{j}}^{\min}$	$\min_{i,j,k\in[1,4],\, i\neq j\neq k} (\lvert\phi_i - \phi_j\rvert + \lvert\phi_j - \phi_k\rvert)$
$\Delta y_{3\mathrm{j}}^{\min}$	$\min_{i,j,k\in[1,4],\, i\neq j\neq k} (\lvert y_i - y_j\rvert + \lvert y_j - y_k\rvert)$
$\Delta y_{2\mathrm{j}}^{\max}$	$\Delta y_{ij}^{\max} = \max_{i,j\in[1,4]} (\lvert y_i - y_j\rvert)$
$\Sigma p_{\mathrm{T}}^{\mathrm{central}}$	$\lvert p_{\mathrm{T}}^{c}\rvert + \lvert p_{\mathrm{T}}^{d}\rvert$

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Four-jet production

- Measurements of jet transverse momenta distributions

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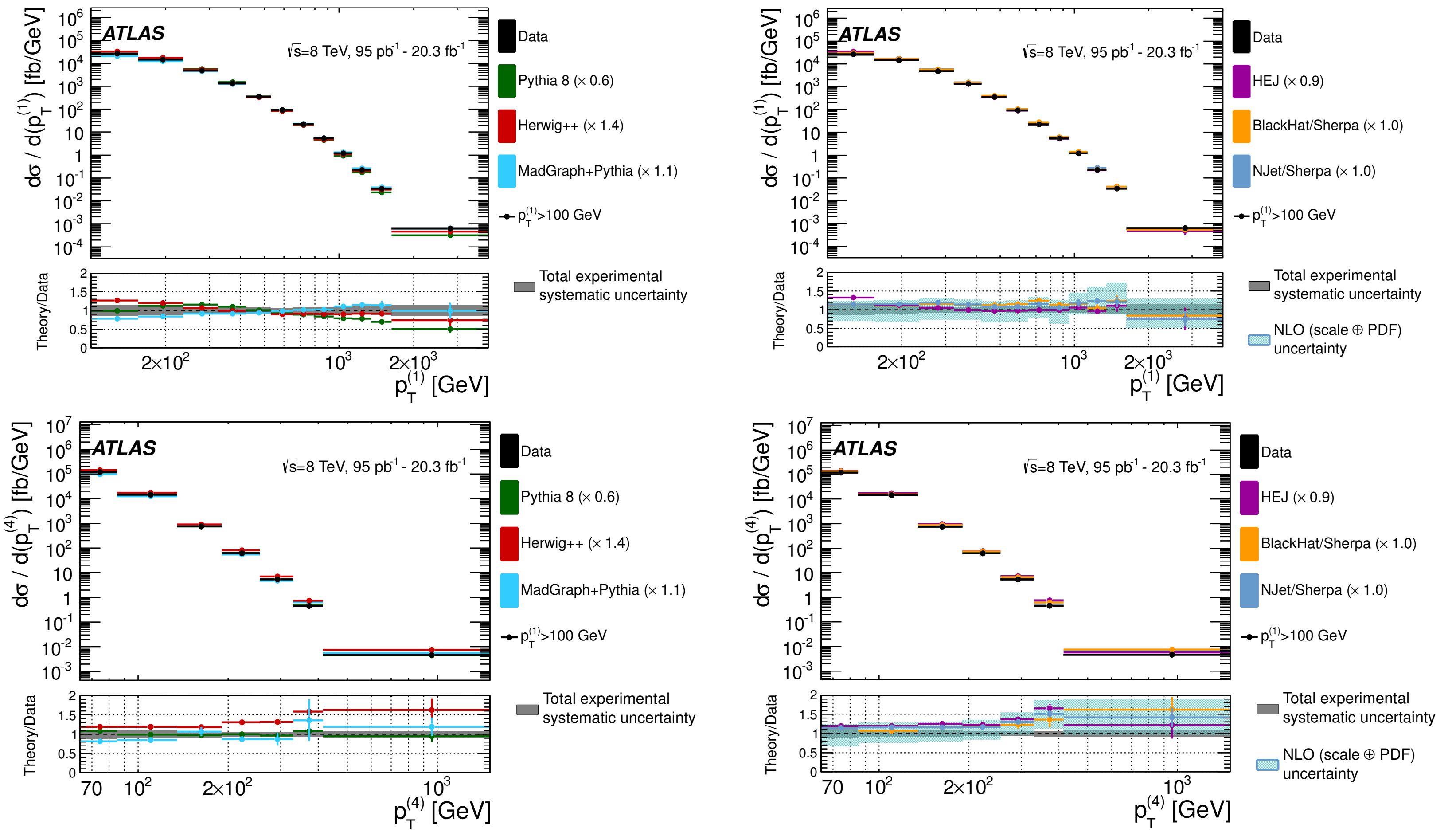


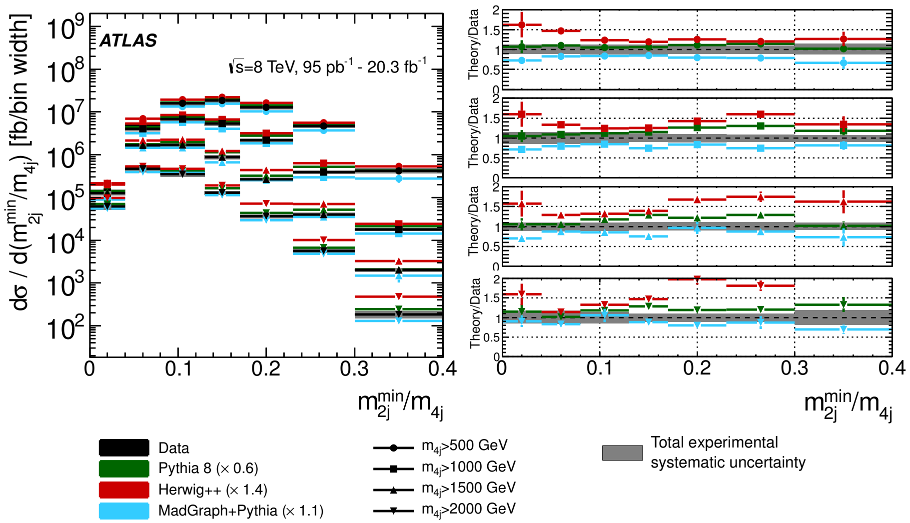
HEJ, NJet/Sherpa and BlackHat/Sherpa: good description of leading jets, but discrepancy for $p_T^{(4)}$ ➔ inverse behaviour for Pythia

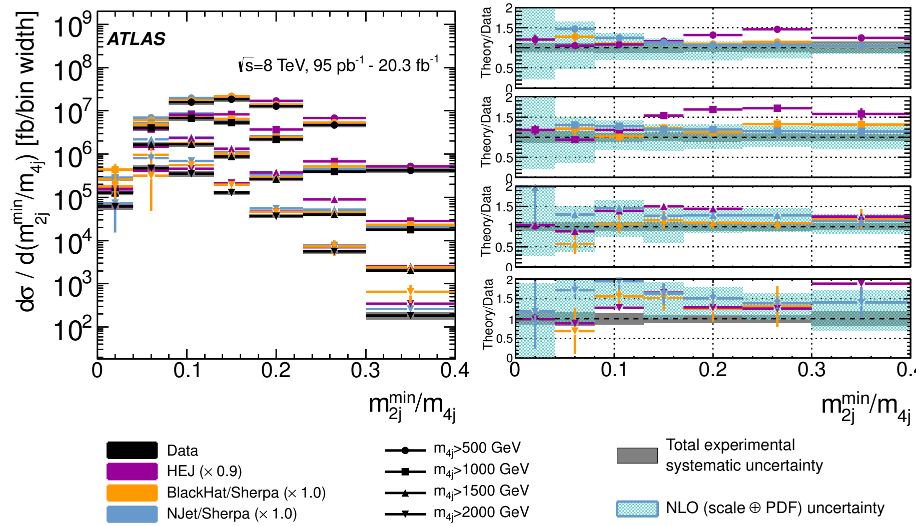
Four-jet production

- Measurements of jet mass and angular variables:

  Information about range of E-scales relevant to QCD calculation.

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





- Multi-leg ME calculations + PS model, Madgraph+Pythia, perform well

- Herwig++ struggles to describe mass scale variables
- In general HEJ provides good description of data

- NLO predictions: compatible with data within theoretical uncertainties

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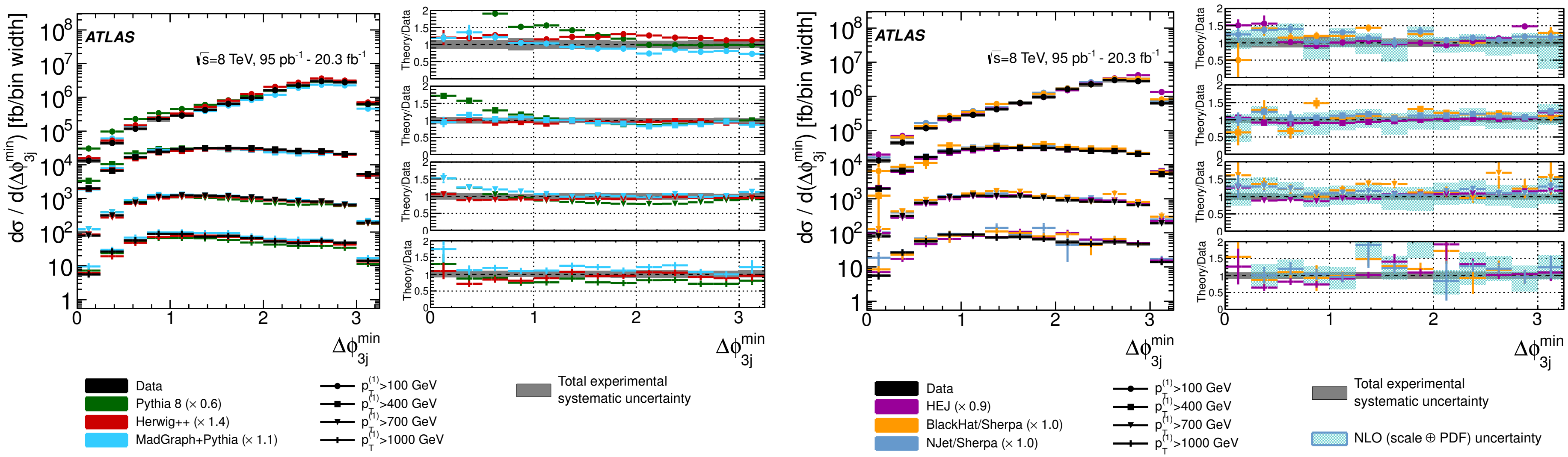
Four-jet production

- Measurements of jet mass and angular variables:

Distinguishes pairs of nearby jets from the recoil of three jets against one

$$\Delta\phi_{3j}^{\min} \quad \Big| \quad \min_{\substack{i,j,k\in[1,4] \\ i\neq j\neq k}} \left(|\phi_i - \phi_j| + |\phi_j - \phi_k|\right)$$



- Herwig++ performs well in the azimuthal angle variables
- Pythia fails at lower leading jet p_T's

- NLO predictions: compatible with data within theoretical uncertainties
- In general: shortcomings of 2 → 2 ME+PS predictions in variety of scenarios

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Transverse energy-energy correlations

- Measurements of energy-weighted angular distributions of hadron pairs
  ➔ proposed in e+e- annihilation as alternative event shape variable
  ➔ by construction not affected by soft divergences

- Significant impact on precision tests of pQCD and determination of α_S

- At hadron colliders:
  transverse energy-energy correlations: (TEEC)

$$\frac{1}{\sigma}\frac{\mathrm{d}\Sigma}{\mathrm{d}(\cos\phi)} = \frac{1}{\sigma}\sum_{ij}\int\frac{\mathrm{d}\sigma}{\mathrm{d}x_{\mathrm{T}i}\mathrm{d}x_{\mathrm{T}j}\mathrm{d}(\cos\phi)}x_{\mathrm{T}i}x_{\mathrm{T}j}\mathrm{d}x_{\mathrm{T}i}\mathrm{d}x_{\mathrm{T}j},$$

Sum over all pairs of jets with:
$\phi = \Delta\varphi_{ij}$ $x_{\mathrm{T}i} = E_{\mathrm{T}i}/E_{\mathrm{T}}$

and its asymmetry: (ATEEC)

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

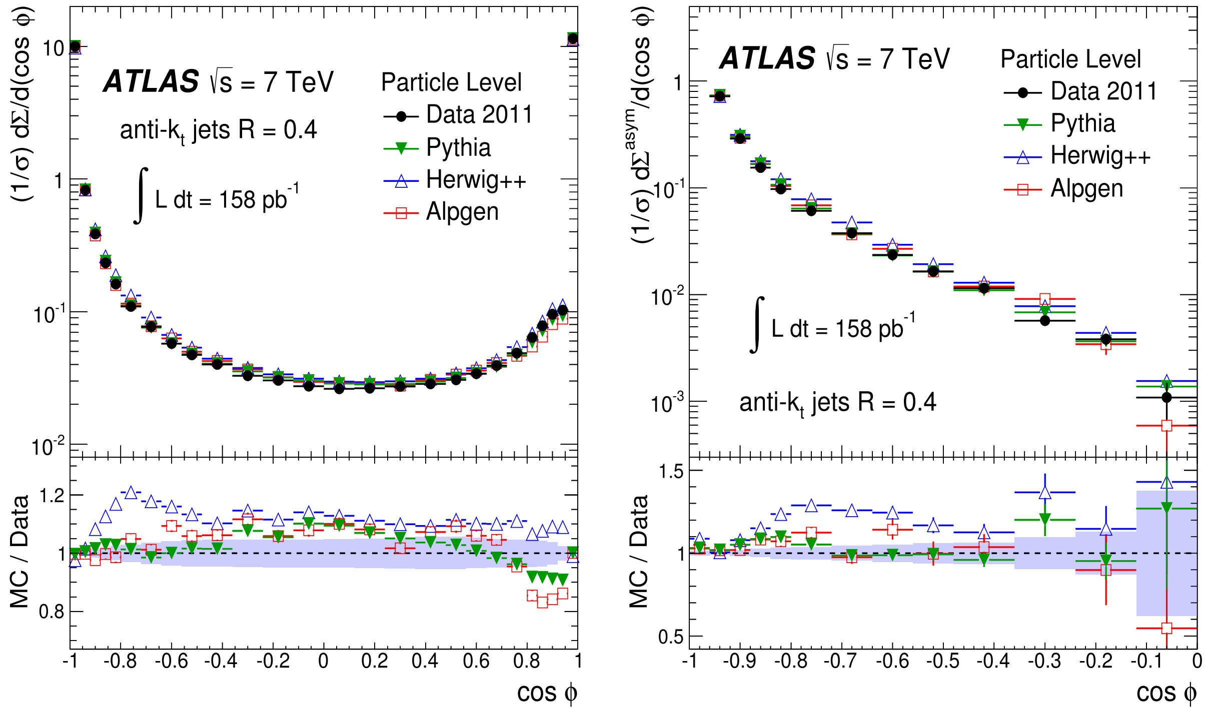
➔ Cancel uncertainties that are constant over cosϕ

- ATLAS measurements in pp collisions at 7 TeV:
  online single-jet trigger: E_T > 135 GeV
  require at least 2 jets (anti-k_T R=0.4) with p_T > 50 GeV and |η| < 2.5
  $p_{T1} + p_{T2}$ > 500 GeV

PLB 750 (2015) 427-447

Transverse energy-energy correlations

- Measure the TEEC and ATEEC distributions:



Well described by Pythia6 and Alpgen

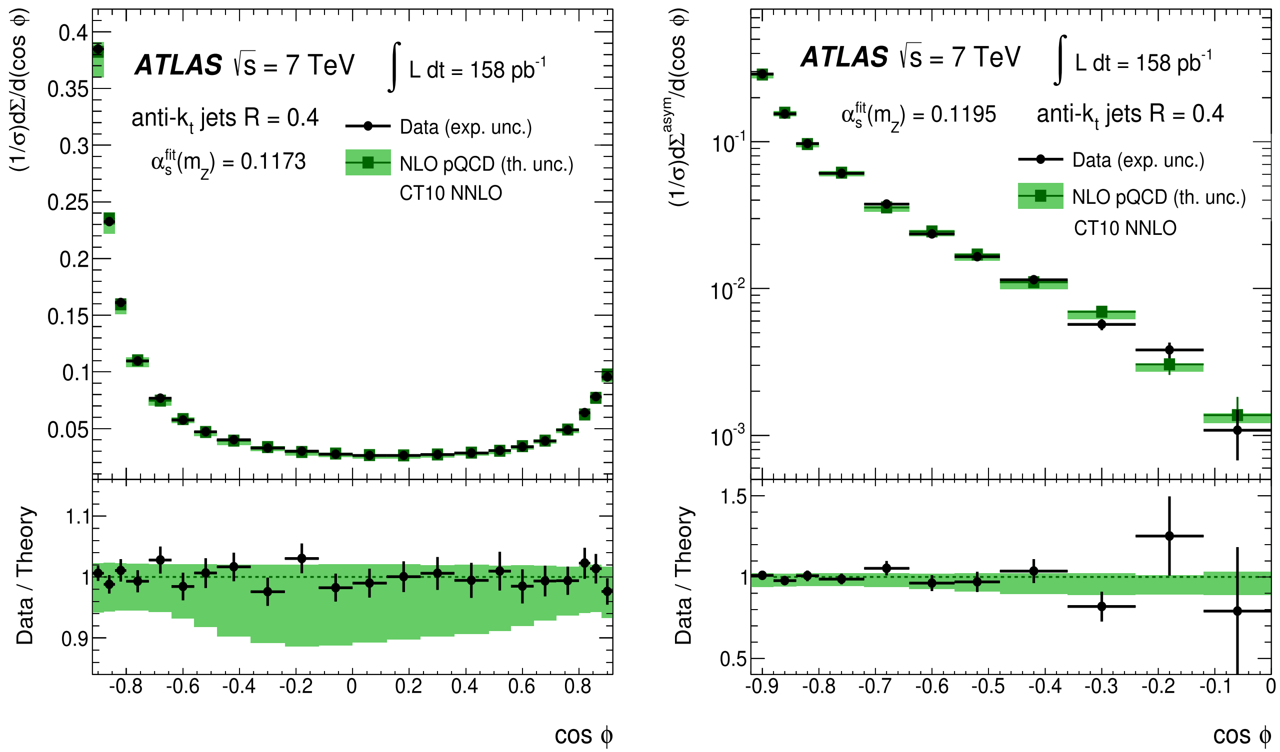
Herwig++: discrepancies up to ~30%

- Both less affected by experimental effects (jet energy scale, pile-up) than absolute cross section measurements

- Similarly, PDF uncertainties in theoretical predictions cancel to large extent ➔ well suited observables to determine α_S

Transverse energy-energy correlations

- Use TEEC and ATEEC to extract value of strong coupling constant:



Compare to NLO pQCD calculations ➔ describe data well

renorm. and fact. scales: $(p_{T1} + p_{T2})/2$

- Data for |cosϕ| < 0.92 fitted to QCD predictions obtained with NLOJET++

- From TEEC fit, using CT10 PDF set, yields:

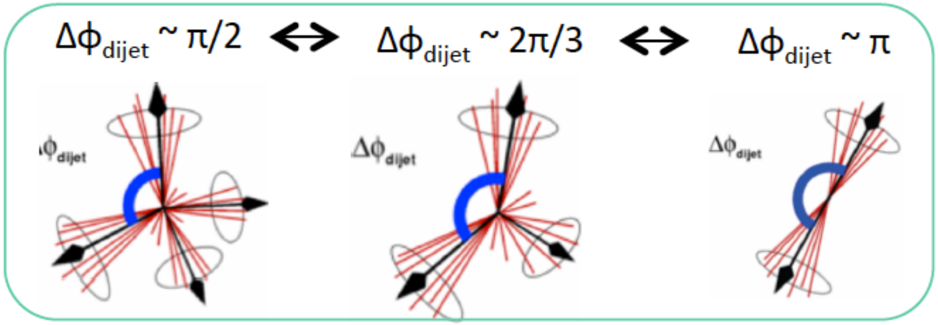
$$\alpha_s(m_Z) = 0.1173 \pm 0.0010\,(\text{exp.})\ {}^{+0.0063}_{-0.0020}\,(\text{scale})\ \pm 0.0017\,(\text{PDF})\ \pm 0.0002\,(\text{NPC}).$$

Di-jet azimuthal decorrelations

- Measure di-jet differential cross section as function of $\Delta\phi$ in pp collisions at 8 TeV with CMS
- With $\Delta\phi_{dijet}=|\phi_{jet1}-\phi_{jet2}|$, $N_{jets} \geq 2$, anti-k_T R=0.7, jets $p_T > 100$ GeV, $|y| < 2.5$
- Reduce the background from ttbar and heavy vector boson production:

$$\not{E}_T / \sum E_T > 0.1$$

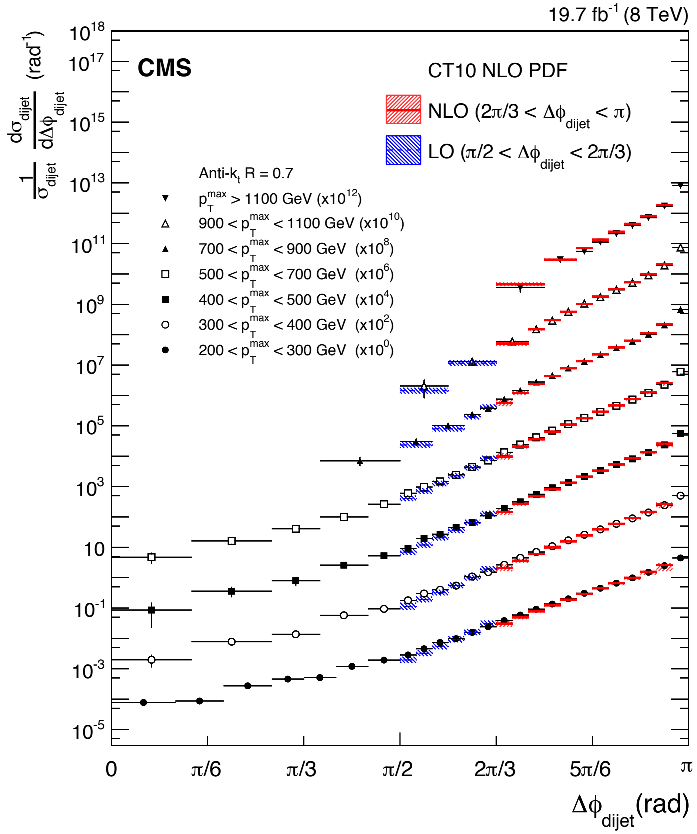
- Normalise to total di-jet cross section: reduce exp. and theo. uncertainties
- Compare to - fixed-order NLO 3-jet predictions, and to NLO and LO di-jets
  - tree-level multi-jet production + PS + MPI + hadronisation
- Interesting tool to probe multi-jet production processes without the need to measure jets beyond the leading two:

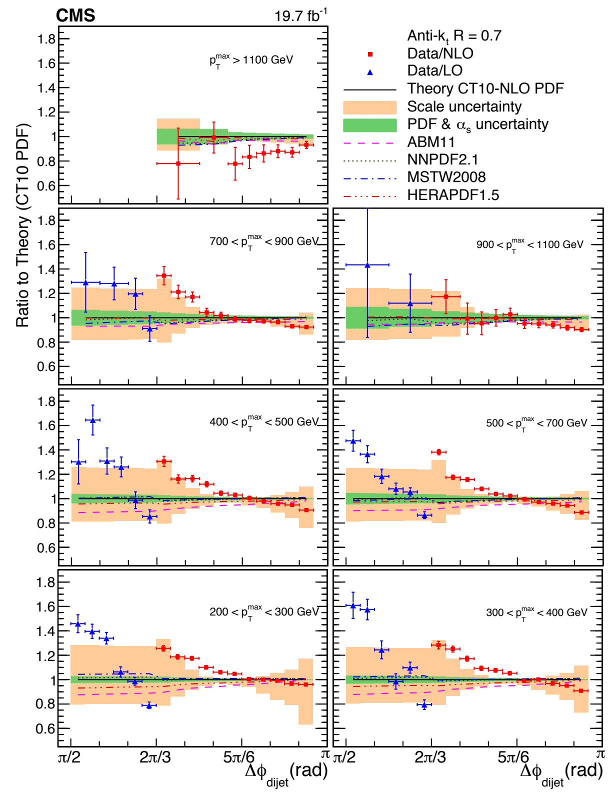


arXiv:1602.04384

Di-jet azimuthal decorrelations

- Compare with fixed order LO and NLO calculations:





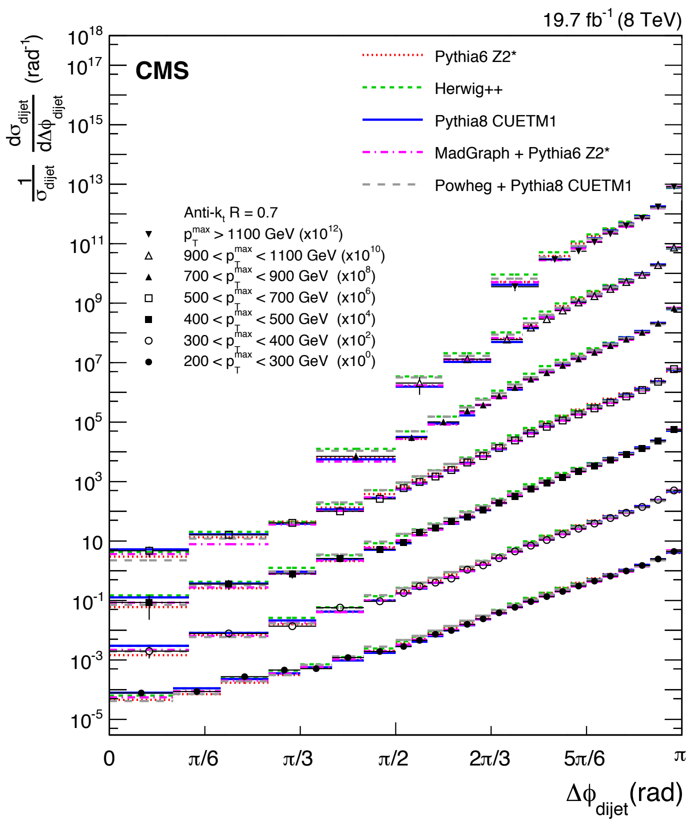
Various PDF sets tested, all agree well

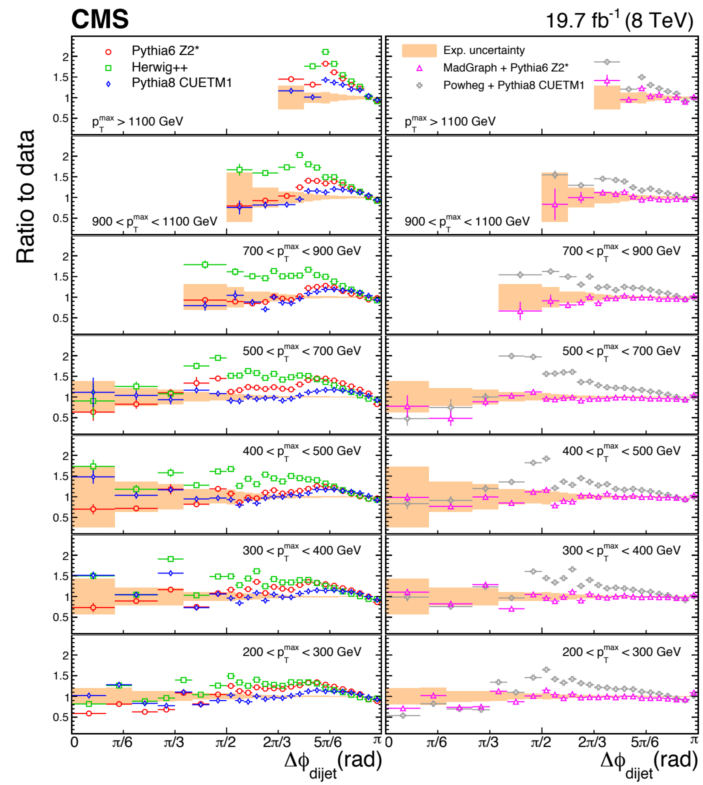
- 3-jet NLO predictions describe data down to values of $\Delta\phi_{dijet} \approx 5\pi/6$
- Deviate when approaching 4-jet region, $\Delta\phi_{dijet} = 2\pi/3$, esp. at low p_T^{max}
- Similar behaviour/deviations at smaller $\Delta\phi$

arXiv:1602.04384

Di-jet azimuthal decorrelations

- Compare with 2 → 2 ME + PS generators and multi-leg predictions:





- PYTHIA8: best agreement. PYTHIA6 and HERWIG++ overshoot data
- Good description provided by tree-level multi-jet generator MADGRAPH
- POWHEG (di-jet NLO) deviates similar to LO dijet MCs

arXiv:1602.04384

Low-p_T jets widely separated in rapidity

- First measurement of azimuthal decorrelation of most-forward and backward jets (Mueller–Navelet di-jets) in pp collisions at 7 TeV with CMS

- Probe rapidity separations up to Δy = 9.4 with low-p_T jets:
  anti-k_T R=0.5, p_T > 35 GeV, |y| < 4.7

- Probe very forward low-p_T phase space of QCD
  ➔ measure (new?) low-x parton dynamics

- Observables include:
  - Δϕ distributions

$$\frac{1}{\sigma}\frac{d\sigma}{d(\Delta\phi)}(\Delta y, p_{\mathrm{Tmin}}) = \frac{1}{2\pi}\left[1 + 2\sum_{n=1}^{\infty} C_n(\Delta y, p_{\mathrm{Tmin}}) \cos(n(\pi - \Delta\phi))\right].$$

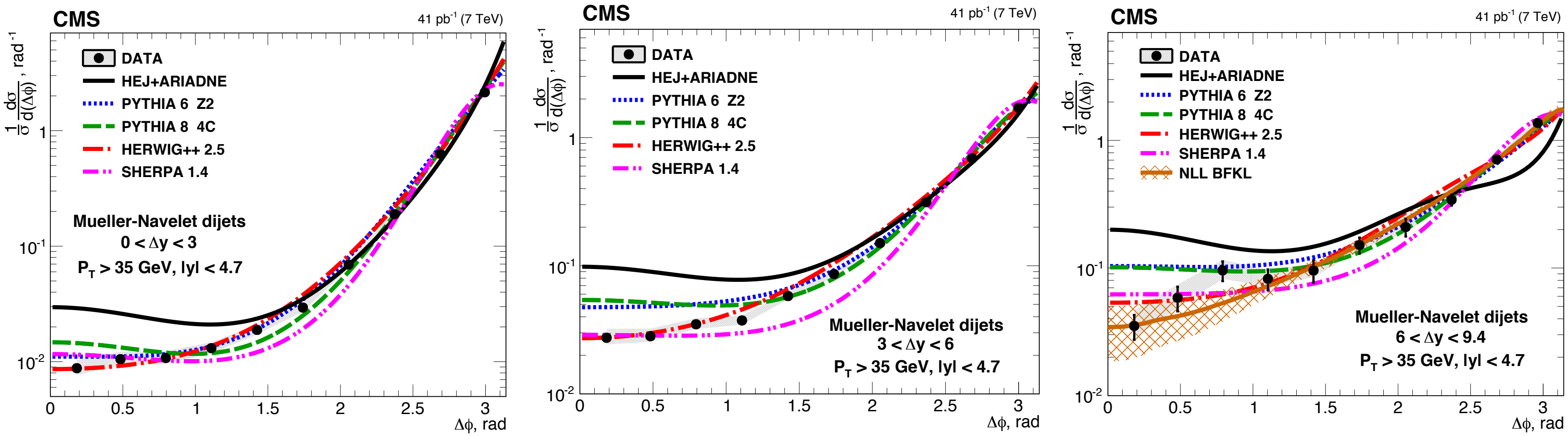
  - moments of average cosines of Δϕ: $C_n(\Delta y, p_{\mathrm{Tmin}}) = \langle\cos(n(\pi - \Delta\phi))\rangle$ for n = 1, 2, 3

  - ratios of these average cosines, as a function of Δy between MN jets.
    ➔ expects suppression of DGLAP contributions in ratios, more sensitive to BFKL effects
    ➔ reduce uncertainties of factorisation and renormalisation scales

arXiv:1601.06713

Low-p_T jets widely separated in rapidity

- Azimuthal decorrelation angle in different bins of rapidity separation:



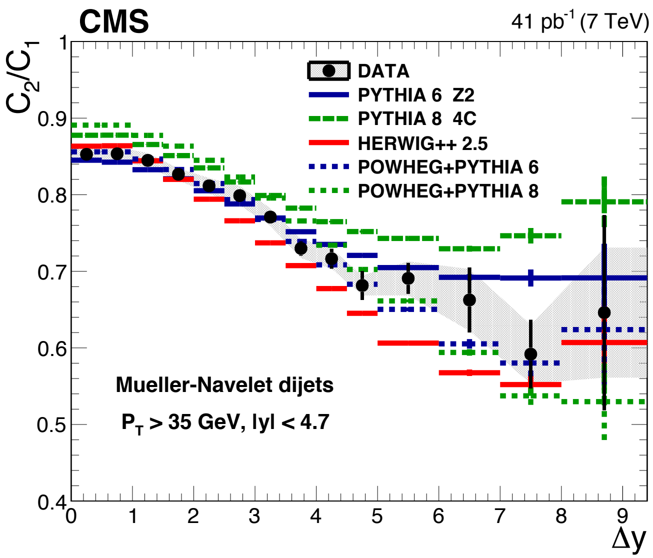
- DGLAP-based HERWIG++ 2.5, with leading-log (LL) parton showers and colour-coherence effects shows best performance
- PYTHIA 6 Z2, PYTHIA8 4C, and SHERPA 1.4 are less accurate

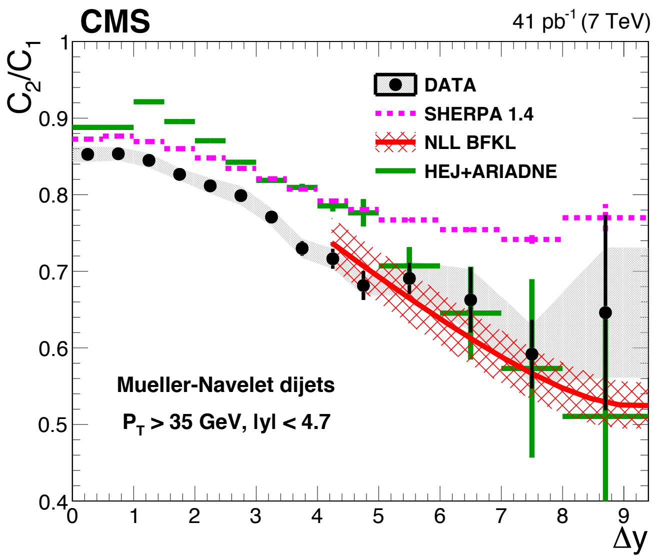
- HEJ: LL BFKL matrix elements combined with ARIADNE (PS + hadr.), predicts stronger decorrelation than in data.
- BFKL calculation at NLL accuracy: satisfactory description of data for large Δy

arXiv:1601.06713

Low-p_T jets widely separated in rapidity

- Ratios of average cosines, as a function of Δy between MN jets:





- DGLAP-based MC generators become less accurate at large Δy
- POWHEG (NLO ME interfaced with LL parton shower of PYTHIA) does not improve overall agreement with data

- BFKL calculation at NLL accuracy: good agreement for Δy > 4
  ➔ current kinematical domain lies in transition between regions described by DGLAP and BFKL approaches

arXiv:1601.06713

Summary

- ATLAS and CMS perform extensive studies in new kinematic regions of QCD available at the LHC , at several centre-of-mass energies
- Multi-jet topologies in pp collisions:
  - ➔ ideal tool to probe QCD dynamics and extract α_S
  - ➔ measure momentum, mass and angle observables
- Precision studies with central high p_T jets:
  - ➔ testing ground for LO, NLO pQCD calculations: perform quite well
  - ➔ 2 → 2 matrix element MC generators with phenomenological parton showers and hadronisation deviate from data
- Measurement of forward low-p_T jets:
  - ➔ probe extreme parton dynamics: kinematical domain in transition between regions described by DGLAP and BFKL approaches
- Latest results from ATLAS and CMS:

  https://twiki.cern.ch/twiki/bin/view/AtlasPublic/StandardModelPublicResults
  http://cms-results.web.cern.ch/cms-results/public-results/publications/SMP/JETS.html
  http://cms-results.web.cern.ch/cms-results/public-results/publications/FSQ/index.html
- More results on inclusive and di-jet measurements in Claire Gwenlan's talk

Backup