Studies of jet cross-sections and production properties with the ATLAS and CMS detectors

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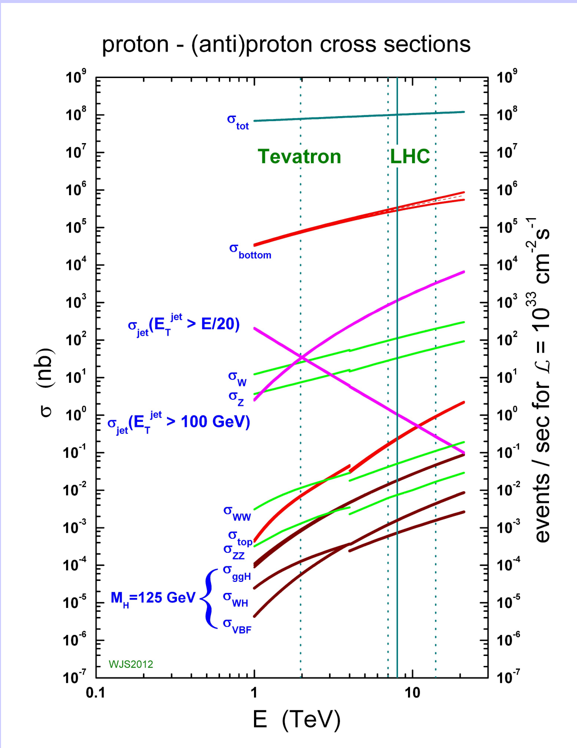
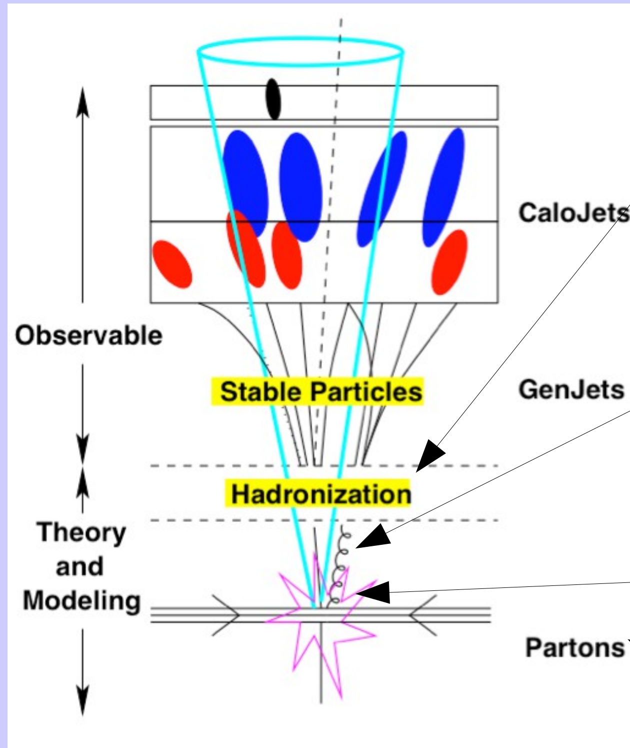
Outline

- Motivation
- Jet Performance
- Event Shapes
- Di-jet Azimuthal De-correlation
- 3-jet Cross-sections
- 4-jet Cross-sections
- Multi-jet Topologies
- Jet Charge
- Transverse Energy-Energy Correlation
- Conclusion

Motivation

- Jets: narrow collimated clusters of stable particles (mainly hadrons) produced by the fragmentation of a hard parton → experimental signature of quarks and gluons.





Parton fragmentation:
- **Phenomenological models** (PYTHIA, HERWIG).
- Matching to fixed order.

Parton shower:
- Soft- and collinear **approximations**.
- Mismatch between kinematics of virtual and real corrections: soft-gluon resummation.

Hard acattering: **pQCD** predictions at fixed orders, LO, NLO, NNLO.

Initial State: **PDFs.**

- Jet production: dominant high-p_T process in pp collisions.
- Jets: signatures and also background for (B)SM processes.
- Understanding jet production: pre-condition for many measurements and searches.

- Probe parton substructure: test QCD through wide energy range.
- Probe highest p_T transfers: best handles on searches for new physics.

- In this talk: focus on experimental insights onto modeling parton showers and hadronization.

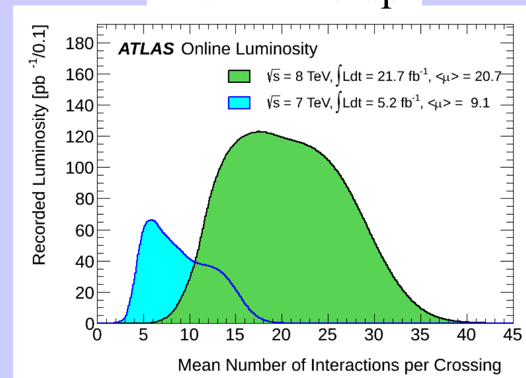
Jet Performance

- Jets: extended objects, reconstructed using algorithms.
- Require **calibration**, corrections for **pile-up** and **detector effects.**

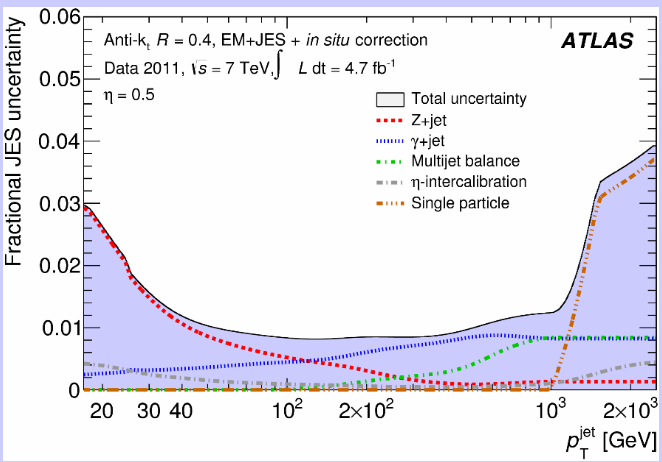
$$d_{ij} = min\left(k_{ti}^{2p}, k_{tj}^{2p}\right)\frac{\delta_{ij}^2}{R^2}$$

- **Anti-k_T** recombination jet algorithm: collinear and infrared safe (ATLAS and CMS).
- Inputs for jet building: **topological** calorimeter **clusters** (ALTAS), particle candidates identified with **particle flow** algorithm (CMS).
- Distance parameter R: 0.4 and 0.6 (ATLAS); 0.5 and 0.7 (CMS)
- Jet calibration; Factorized, with corrections for **pile-up** and **jet energy scale** (ATLAS and CMS).

Run 1 Pile-up

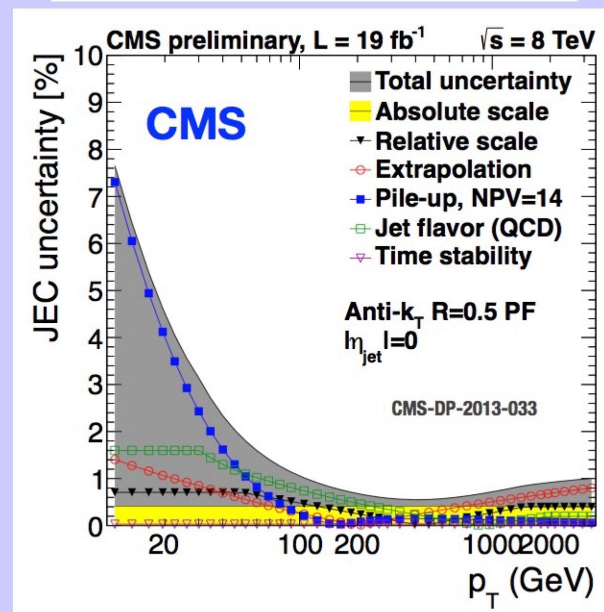


ATLAS: EPJ C75 (2015) 17



Jet energy scale: calibrated to about 1% (in the most precise region) in Run-1.

CMS: DP-2013-033



- Both ATLAS and CMS correct to "particle level": remove detector effects, allow **comparison with theory.**
- Measurements are **unfolded** to particle level with a variety of methods (Bayesian, IDS, SVD, bin-by-bin).
- pQCD predictions corrected for non-perturbative effects such as fragmentation and hadronization, underlying event.

Event Shapes

Hadronic Event-Shape Variables in Multijet Final States
CMS, 5/fb @ 7TeV, 2011 data, JHEP 10 (2014) 087

Event Shapes: combinations of **hadron momenta** in a number related to event **geometry** → indirect probes of **multi-jet topolology**

$$T_{\perp,\mathcal{C}} \equiv \max_{\hat{n}_T} \frac{\sum_i |\vec{p}_{\perp i} \cdot \hat{n}_T|}{\sum_i p_{\perp i}}, \quad \tau_{\perp,\mathcal{C}} \equiv 1 - T_{\perp,\mathcal{C}},$$

Central Transverse Thrust

Sensitive to **modelling of two-jet and multijet topologies**. For a perfectly balanced two jet event it is *zero,* while in isotropic multi-jet events it is $(1-2/\pi)$.

Jet Broadenings

$$B_{X,\mathcal{C}} \equiv \frac{1}{2\,P_\perp} \sum_{i \in \mathcal{C}_X} p_{\perp i} \sqrt{(\eta_i - \eta_X)^2 + (\phi_i - \phi_X)^2},$$

Insensitive to contributions from **underlying event** and **hadronization.** **Sensitive** to **color coherence effects**.

Jet Masses

$$\rho_X \equiv \frac{1}{Q^2} \left(\sum_{i \in \mathcal{C}_X} q_i \right)^2,$$

Q: scalar sum of momenta of all jet constituents. S**ame behavior and dependence** as **jet broadenings** but **more sensitive to (initial state) forward radiation.**

$$y_{23,\mathcal{C}} \equiv \frac{\min(R^2 \times p_{T,3}^2, \min(p_{T,i}, p_{T,j})^2 \times \Delta R_{ij}^2)}{P_{12}^2},$$

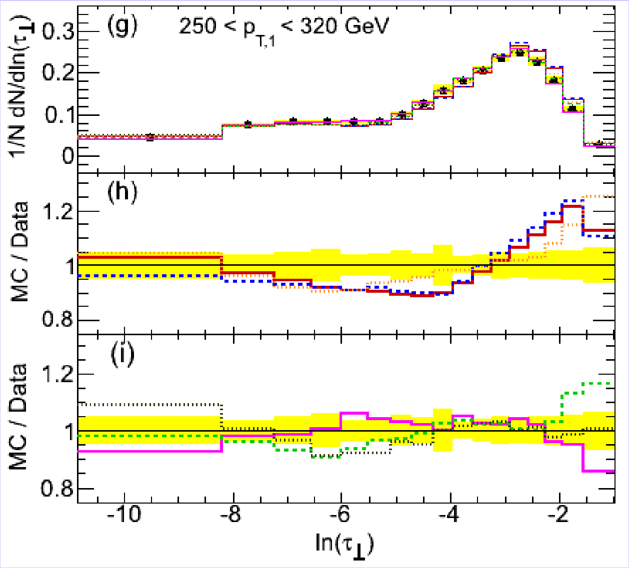
Third-jet Resolution Parameter

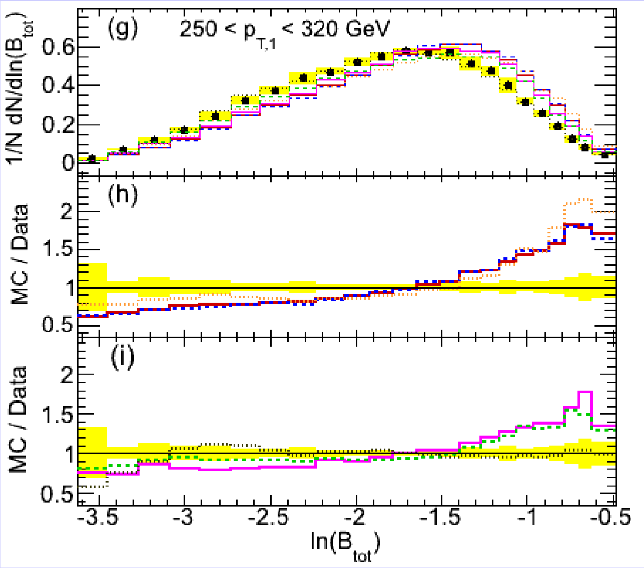
Estimates relative strength of a third jet p_T with respect to other two jets.

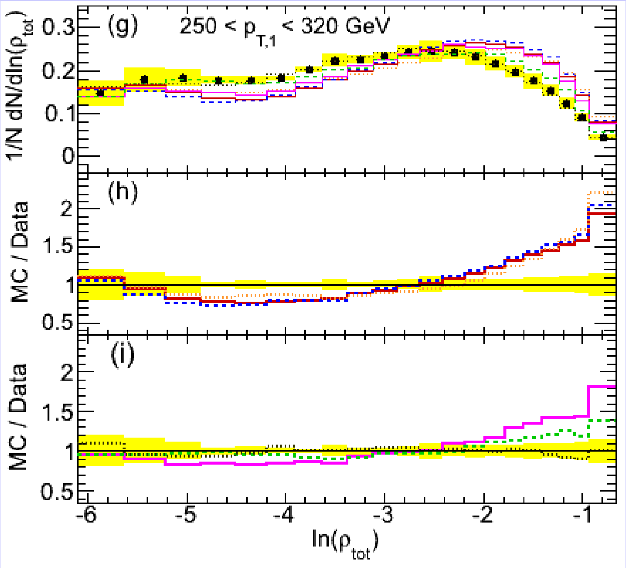
Zero for two-jet events, non-zero value indicates presence of hard parton emission. Sensitive to parton showering modelling.

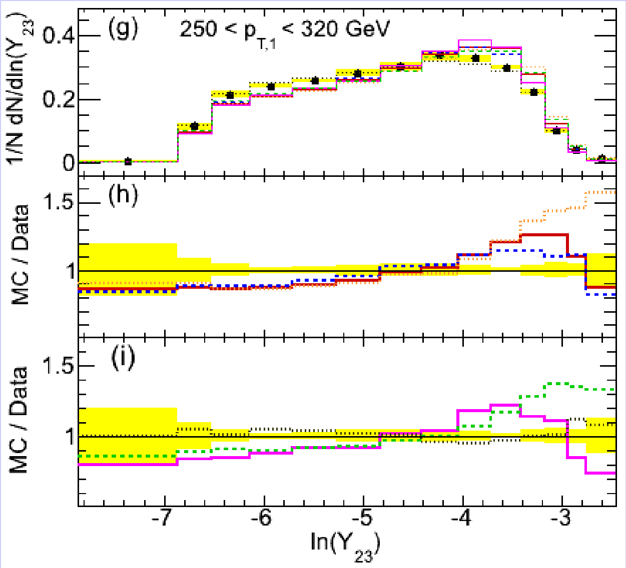
Event Shapes

CMS, 5/fb @ 7TeV, 2011 data, JHEP 10 (2014) 087

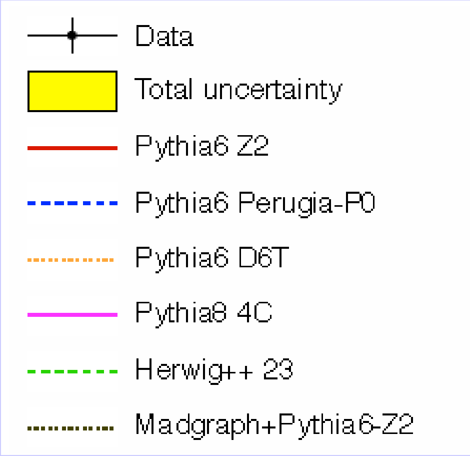






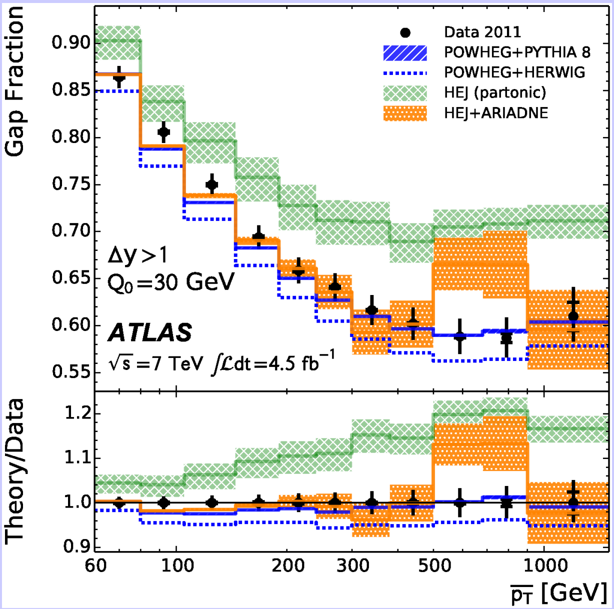


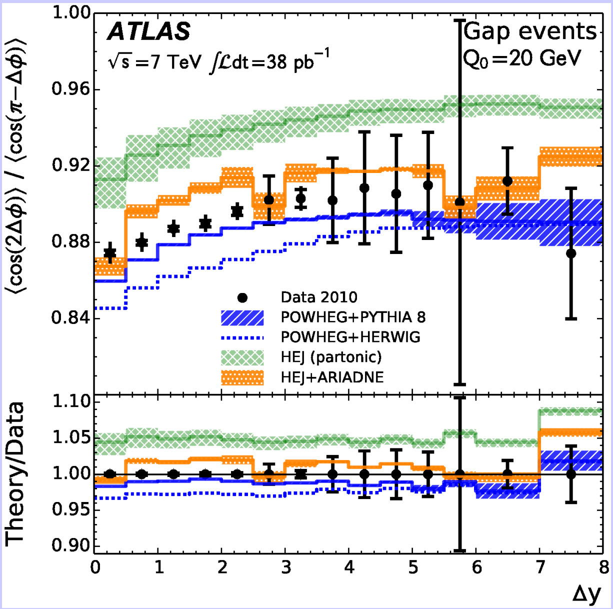
- **Central thrust**: generators show overall agreement with data to within 20%.
- Variables sensitive to **longitudinal energy flow** show larger disagreement between data and theory.

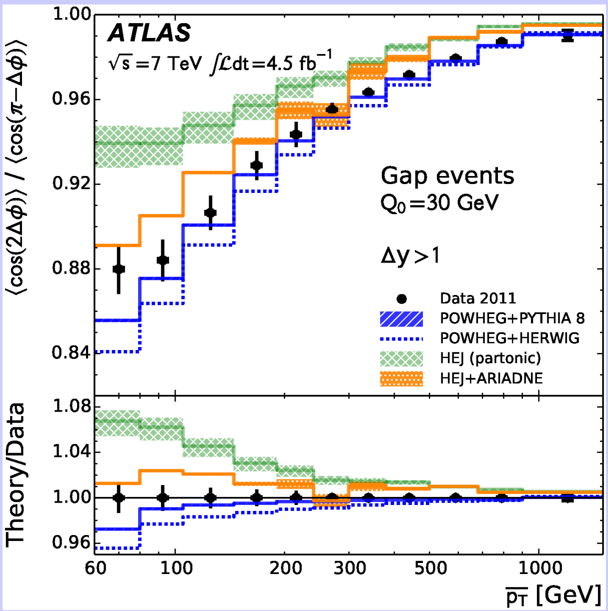


Di-jet azimuthal de-correlation

Jet Vetoes and Azimuthal Decorrelations in Dijet Events
ATLAS, 36/pb+4.5/fb @ 7TeV, 2010+2011 data, EPJ C74 (2014) 3117

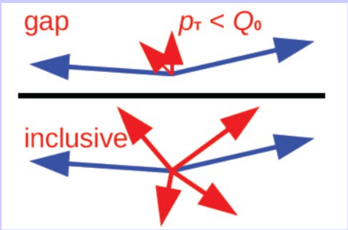


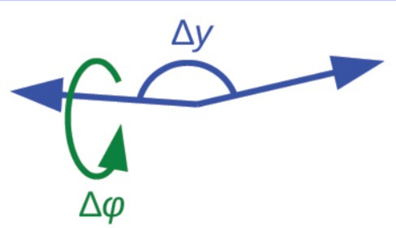




- Probe **parton evolution** using **large-y separated di-jets** along with **veto on a third** in-between jet.
- The **ratio** of the 1st and 2nd **moments** of the **cosine** of the **ϕ separation** of the di-jets is particularly sensitive to **BFKL** effects.
- POWHEG+PYTHIA 8 and HEJ+ARIADNE provide best agreement with data
- POWHEG (BFKL-like) underestimates whereas HEJ (DGLAP-like) overestimates ϕ correlation.

Gap fraction: $f(Q_0) = \sigma_{jj}(Q_0) / \sigma_{jj}$





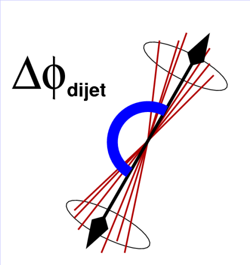
Angular moments: $\langle \cos(n(\pi-\Delta\varphi)) \rangle$, n = 1, 2

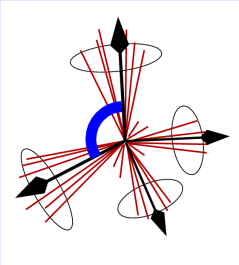
Di-jet azimuthal de-correlation

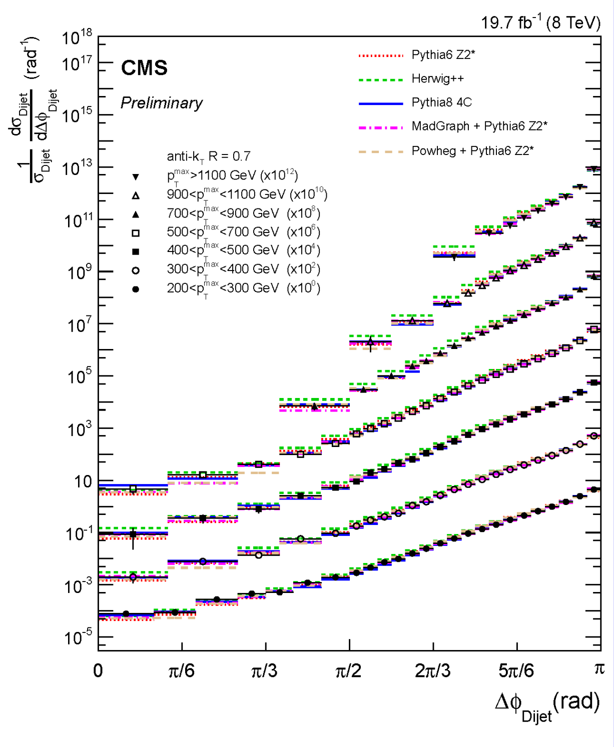
Measurement of dijet azimuthal decorrelations
CMS, 19.7/fb @ 8TeV, 2012 data, CMS-PAS-SMP-14-015

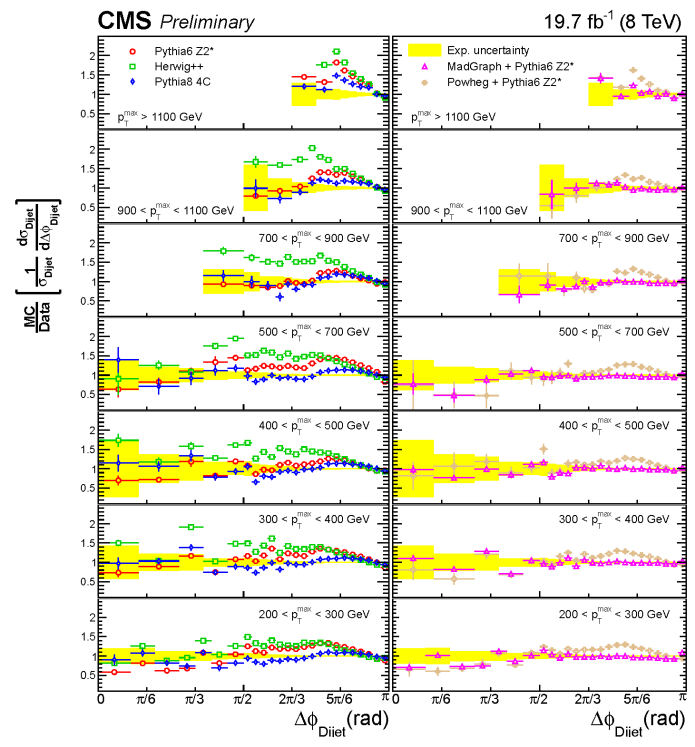
$\Delta\phi$:

- sensitive to **radiation of additional jets**,
- probes dynamics of **multi-jet production**.









Two leading jets $\Delta\phi$ for 7 regions of jet p_T up to 2.2 TeV.

(LO+PS)/Data (NLO+PS)/Data

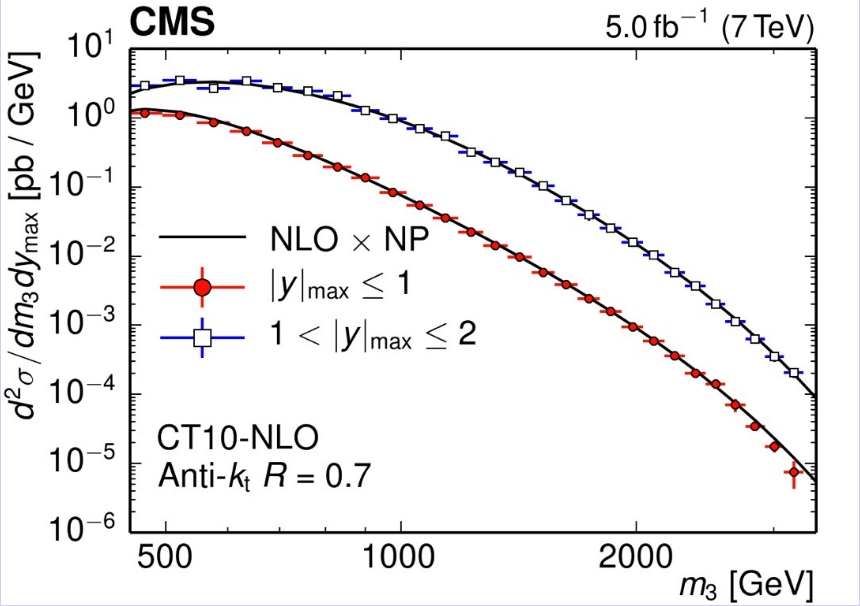
- Multi-jet 2→4 MC (Madgraph +Pythia6) agrees with data throughout whole $\Delta\varphi_{Dijet}$ region.
- LO MCs HERWIG++, PYTHIA8 and POWHEG overestimate data for $\pi/2<\Delta\varphi_{Dijet}<\pi$.
- PYTHIA6 and HERWIG++ systematically overshoot data, in particular around $\Delta\varphi_{Dijet} = 5\pi/6$.

3-Jet cross-section

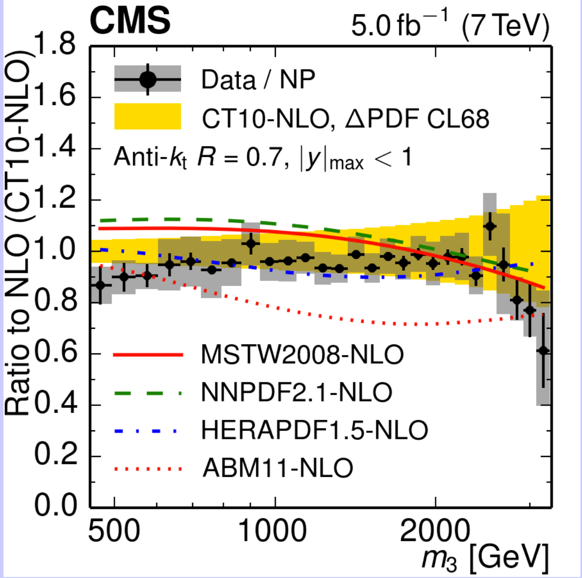
Inclusive 3-jet Production Differential Cross Section
CMS, 5/fb @ 7TeV, 2011 data, EPJ C75 (2015) 186

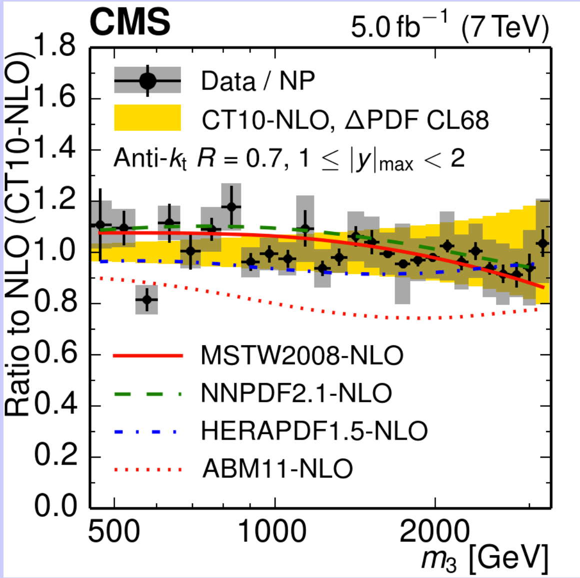
- Measurement of double differential cross section: $\dfrac{d^2\sigma}{dm_3\, dy_{max}}$

  $m_3^2 = (p_1 + p_2 + p_3)^2$ $\quad |y|_{max} = \max(|y_1|, |y_2|, |y_3|)$
- Sensitive to **PDFs** and **α_s** **(see dedicated talks)**
- Require jet $p_T > 100$ GeV
- **Two rapidity bins**: $|y|_{max} < 1$ and $1 < |y|_{max} < 2$
- Scale choice: $\mu_R = \mu_F = m_3/2$
- Good agreement with pQCD at NLO.



- Best agreement with CT10-NLO PDF.



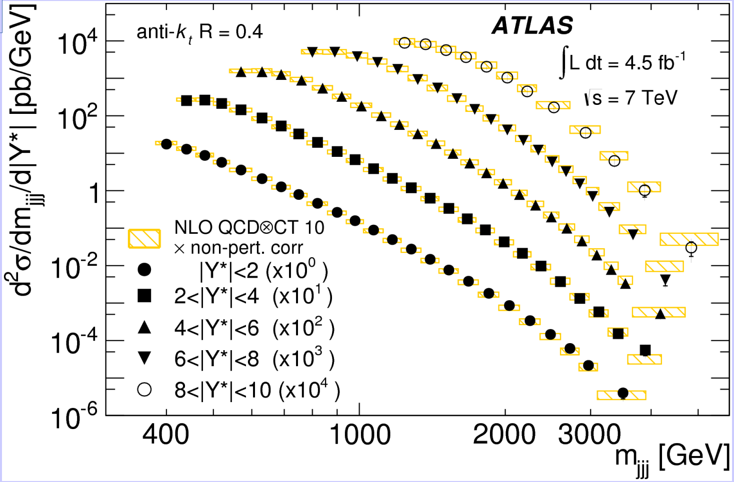


3-Jet cross-section

Measurement of Three-jet Production Cross-sections ATLAS, 4.5/fb @ 7TeV, 2011 data, EPJ C75 (2015) 228

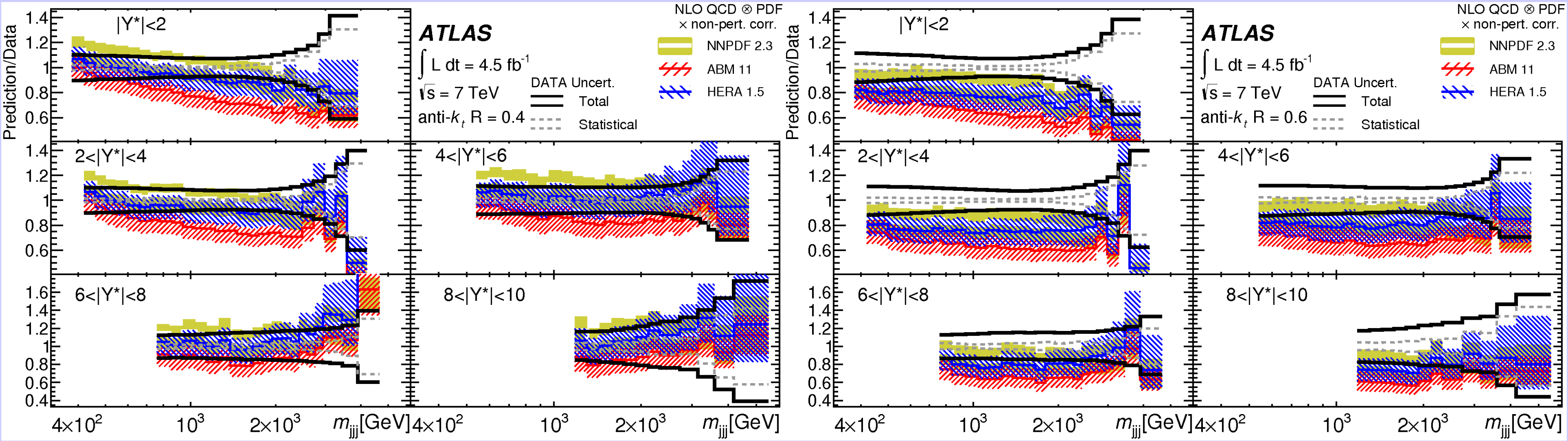
- 3 leading jets with pT>150, 100, 50 GeV respectively in rapidity region |y|<3.
- Double differential cross section as function of $\mathbf{m_{jjj} = \sqrt{((p_1+p_2+p_3)^2)}}$ in slices of $\mathbf{|Y^*| = |y_1-y_2|+|y_2-y_3|+|y_1-y_3|}$
- Scale: $\mu_R = \mu_F = m_{jjj}$.
- Two distinct jet radius parameters.

- Good agreement from 0.4 to 5 TeV



- Good agreement for R=0.4.
- ABM11 PDF yield systematically lower predictions, in particular in low rapidity region.

- Prediction/data ratio for R=0.6 is shifted towards lower values.

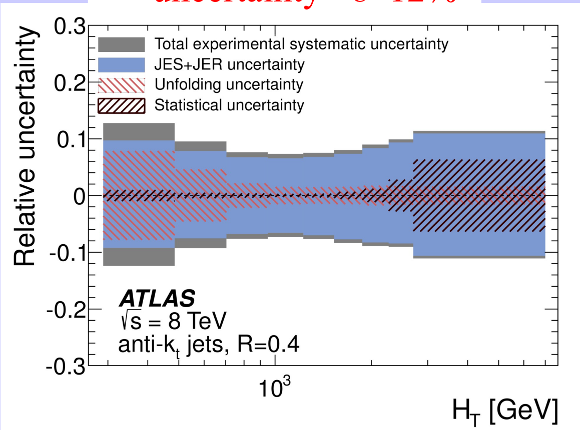


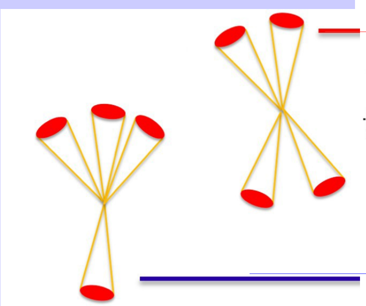
4-Jet cross-section

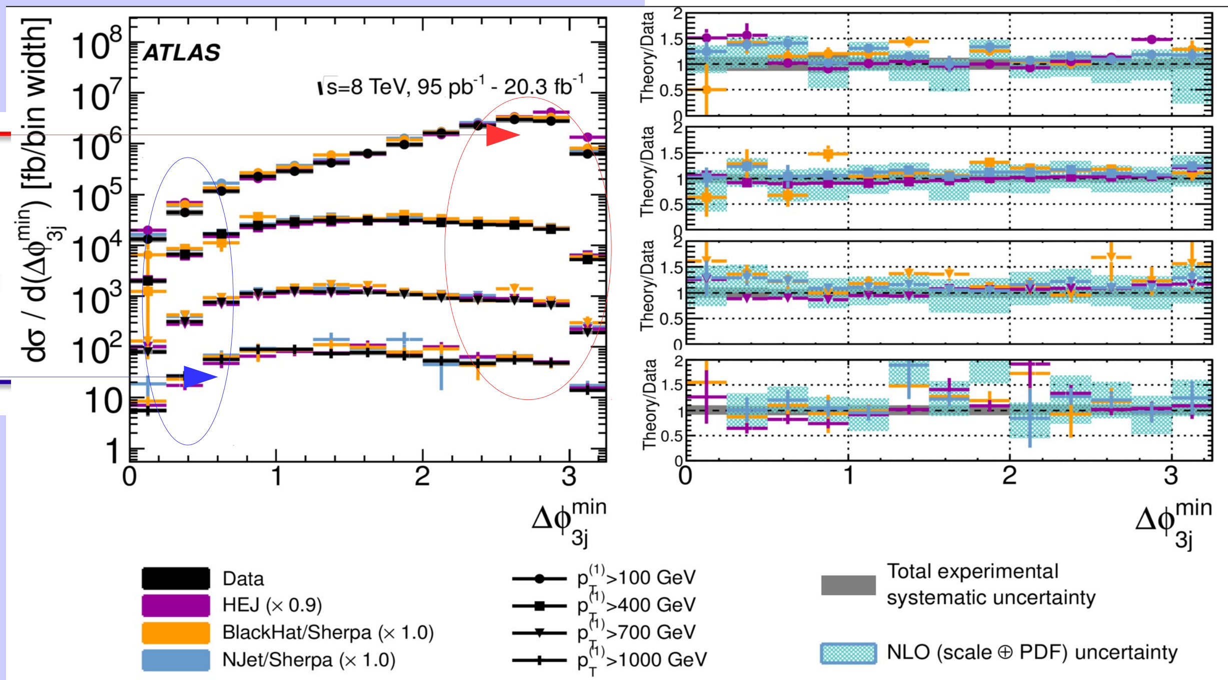
Measurement of Four-jet Differential Cross-sections
ATLAS, 20.3/fb @ 8TeV, 2012 data, CERN-PH-EP-2015-181

- Detailed study of **four-jet topologies: differential measurements** in several variables depending on the **jet momenta** and **angular distributions**.
- Unfolded measurements compared to various MC generators and fixed order predictions.
- Measurements test QCD predictions up to scale H_T ~7 TeV with p_{T1} reaching 3 TeV, p_{T2}~2.5 TeV, p_{T3}~2 TeV, p_{T4}~1.5 TeV.

Total experimental uncertainty ~8–12%







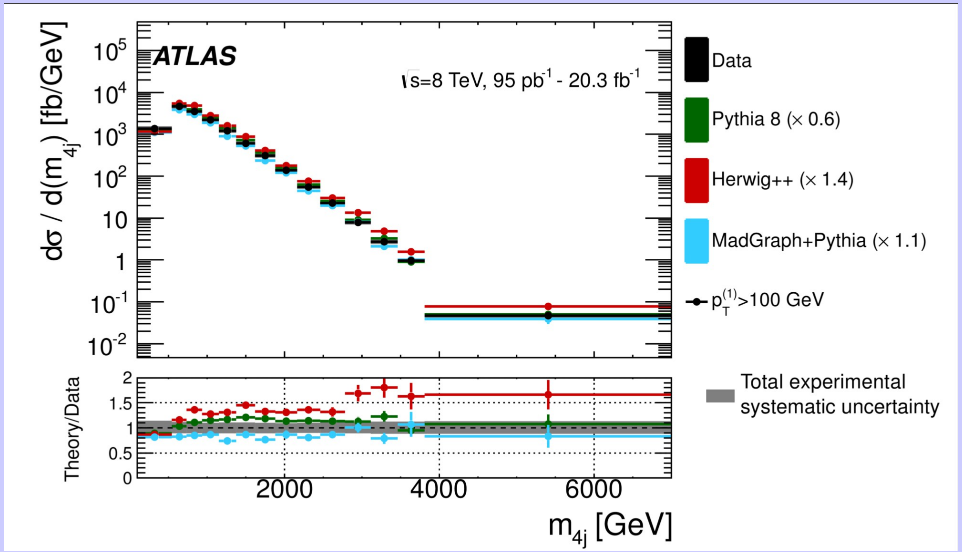
$$\Delta\phi_{ijk}^{min} = min_{\substack{i,j,k\in[1,4] \\ i\neq j\neq k}} \left(|\Delta\phi_{ij}| + |\Delta\phi_{jk}|\right)$$

- Δφ very sensitive to soft emissions.
- Good overall agreement between data and MC.

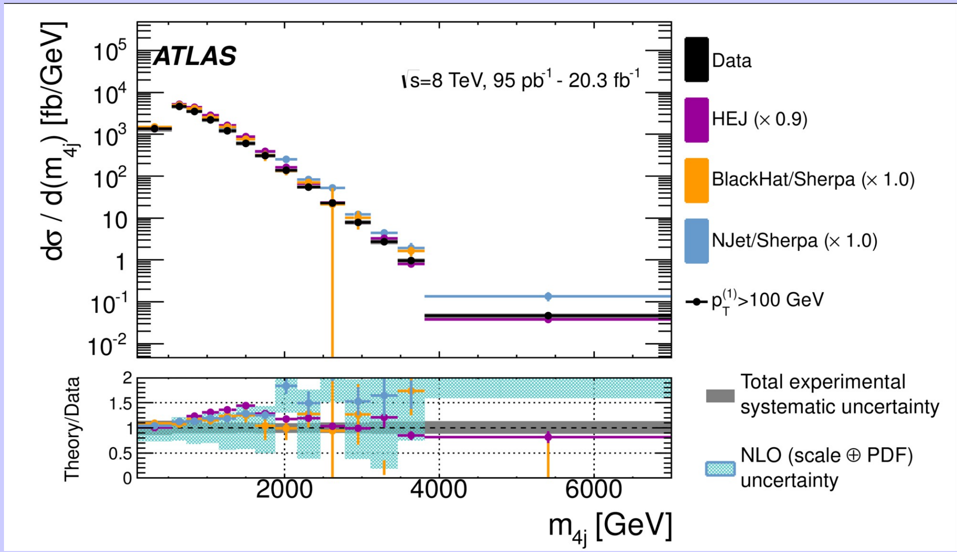
4-Jet cross-section

ATLAS, 20.3/fb @ 8TeV, 2012 data, CERN-PH-EP-2015-181

Jets are reconstructed with anti-k_t R=0.4.



(LO+PS)/Data



(NLO+PS)/Data

- **LO MC**: PYTHIA, HERWIG and MADGRAPH+PYTHIA.
- **NLO pQCD**: Blackhat/Sherpa and NJet/Sherpa.
- **HEJ** also used: Fully exclusive MC generator.
  Approximates matrix element to all orders for **jet multiplicities of two or greater**.
  Approximation **exact for large separation in rapidity** between partons.

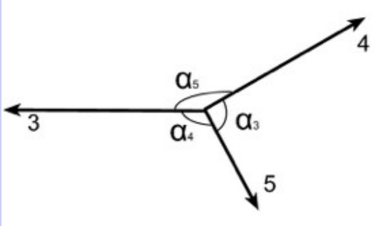
- **m4j** well described by NLO up to 3 TeV and by HEJ at high masses.
- NLO uncertainties relatively large, O(30%) at low momenta.

Multi-Jet Topologies

Topological observables in inclusive three- and four-jet events
CMS, 5/fb @ 7TeV, 2011 data, EPJ C75 (2015) 302

Three-jet Variables

Event plane angles

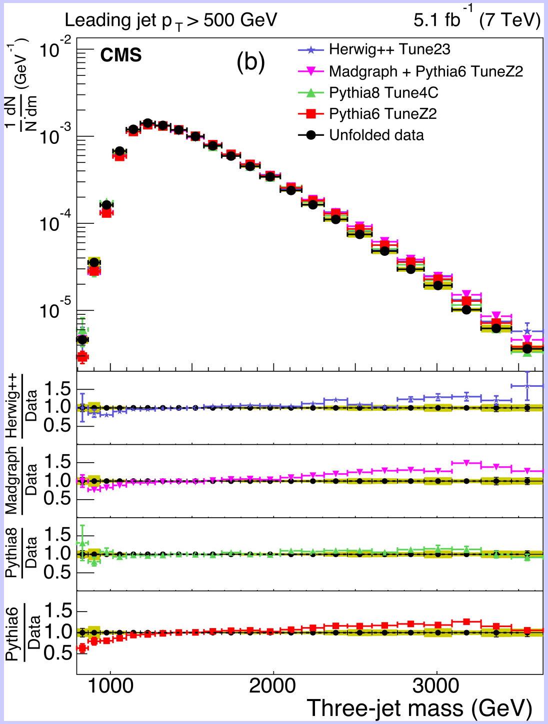


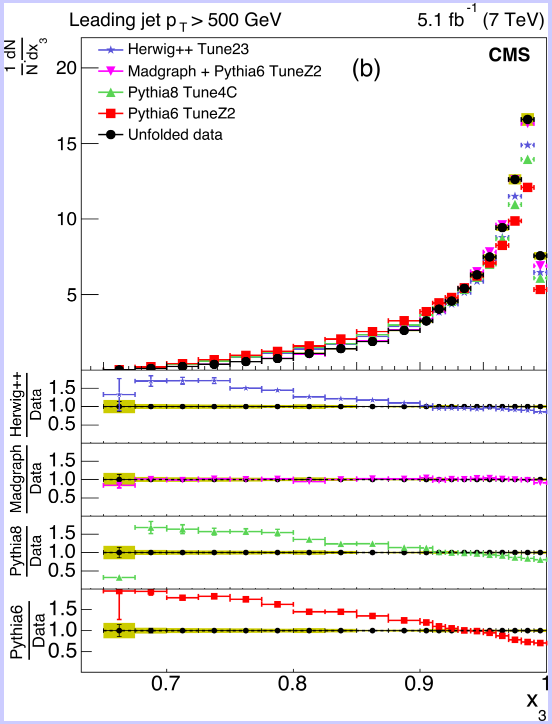
three-jet mass

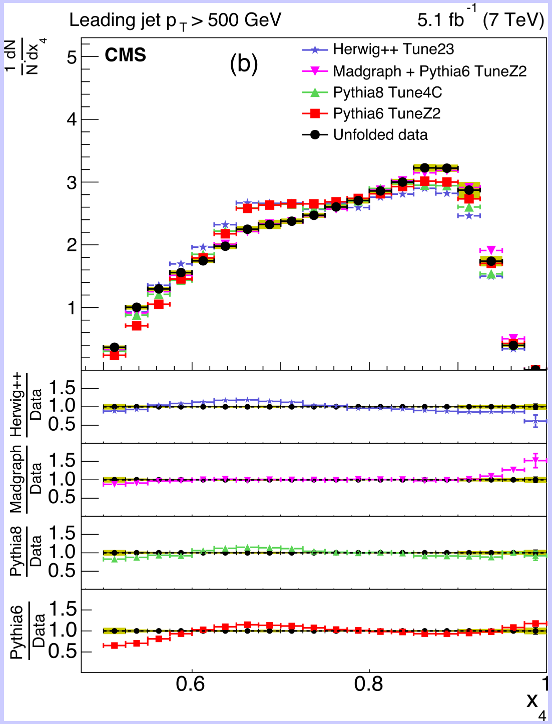
$$E_{CM} = \sqrt{\hat{s}_{345}}$$

$$x_i = 2E/\sqrt{\hat{s}_{345}}$$

Topological variables sensitive to QCD color factors, gluon spin structure, and hadronization models.







- Best descriptions: Pythia8 (3-jet mass), Madgraph (x_3, x_4).
- Data-MC differences possibly due to missing higher multiplicities.

Multi-Jet Topologies

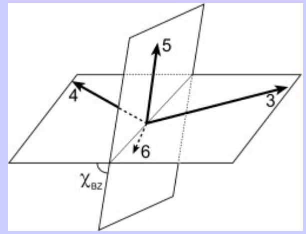
CMS, 5/fb @ 7TeV, 2011 data, EPJ C75 (2015) 302

Four-jet Variables

four-jet mass

$$E_{CM} = \sqrt{\hat{s}_{3456}}$$

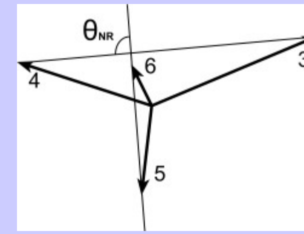
Bengtsson–Zerwas angle

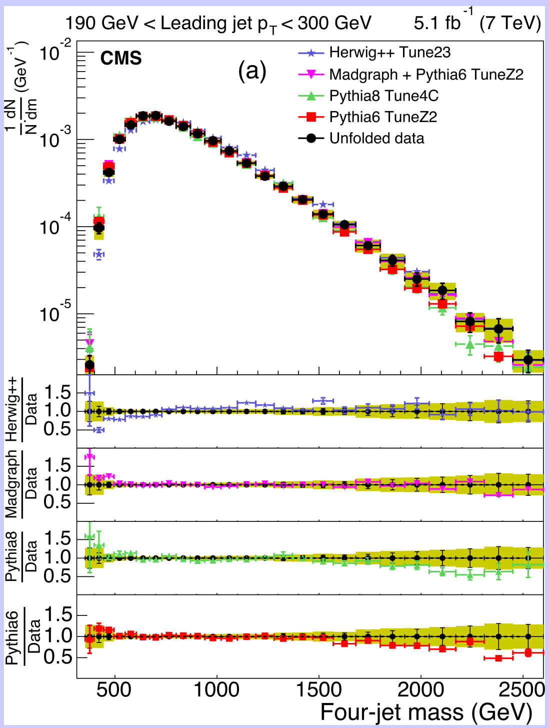


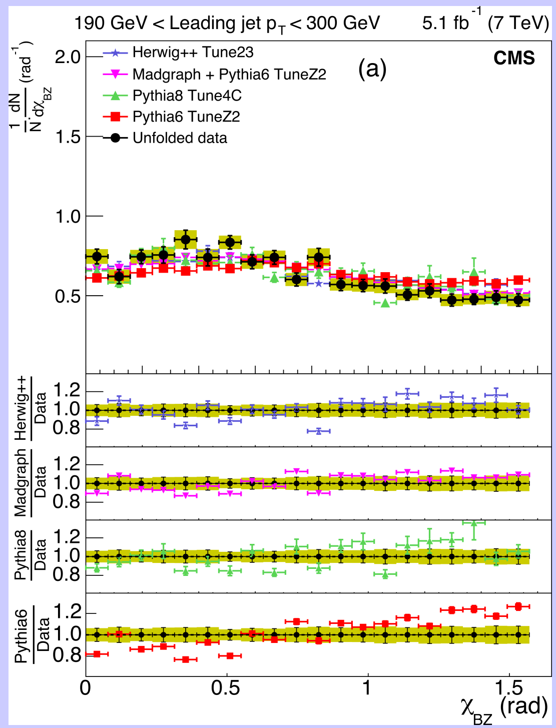
$$\cos\chi_{\mathrm{BZ}} = \frac{(\vec{p}_3 \times \vec{p}_4)\cdot(\vec{p}_5 \times \vec{p}_6)}{|\vec{p}_3 \times \vec{p}_4||\vec{p}_5 \times \vec{p}_6|}$$

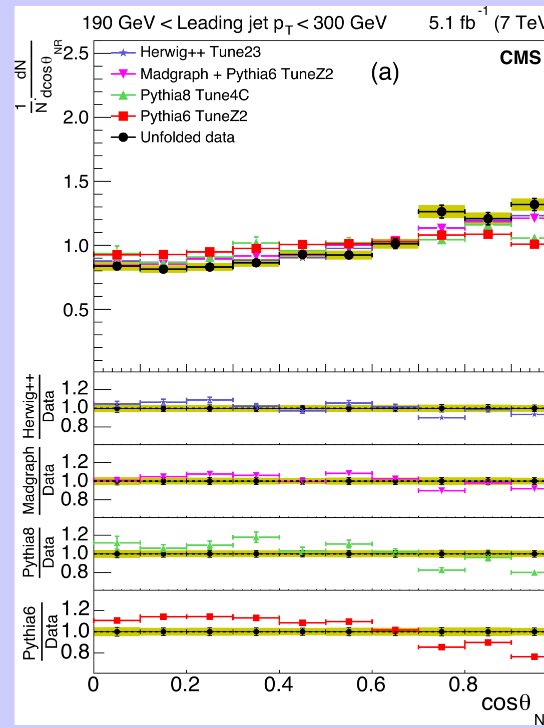
Nachtmann–Reiter angle

$$\cos\theta_{\mathrm{NR}} = \frac{(\vec{p}_3 - \vec{p}_4)\cdot(\vec{p}_5 - \vec{p}_6)}{|\vec{p}_3 - \vec{p}_4||\vec{p}_5 - \vec{p}_6|}$$









- Good overall data-MC agreement.
- Specific regions have less good agreement or large uncertainties.

Jet Charge

Measurement of jet charge in dijet events
ATLAS, 20.3/fb @ 8TeV, 2012 data, CERN-PH-EP-2015-207

Jet charge: momentum-weighted sum of the **charges of tracks** associated to a jet.

- sensitive to charge of initiating quark or gluon.
- depends on jet flavor, energy-dependence of PDFs and fragmentation functions.
- can provide constraint on models of jet formation.

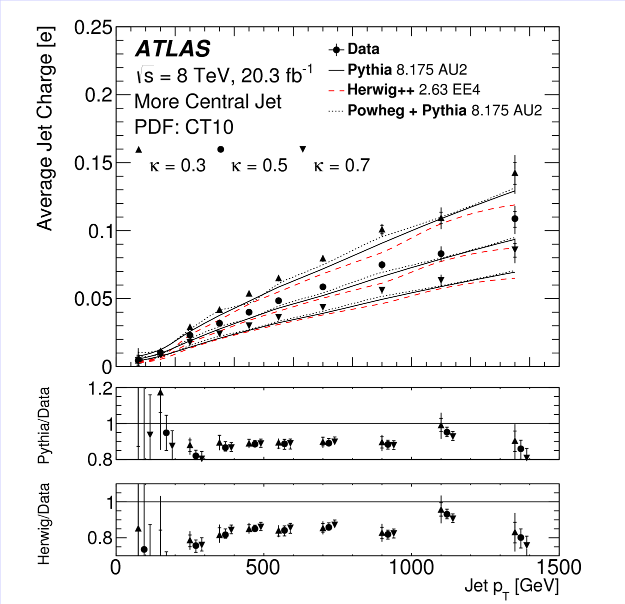
Average charge expected to increase with jet p_T (increase in up-flavor jets).

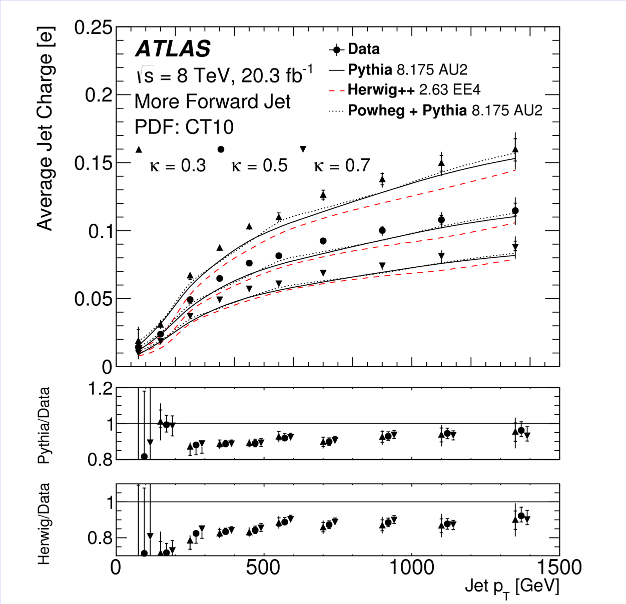
κ regulates sensitivity to soft radiation (0.3, 0.5 and 0.7 considered)

$$Q_J = \frac{1}{(p_{\mathrm{T}\,J})^{\kappa}} \sum_{i \in Tracks} q_i \times (p_{\mathrm{T,i}})^{\kappa}$$

Dijets events:

- Jet $p_T > 50$ GeV, $p_{T1}/p_{T2} < 1.5$,
- $|\eta_{jet}| < 2.1$
- Tracks for reco-jet +charged particles for particle-jets.
- Track multiplicity and JES are the major systematics.



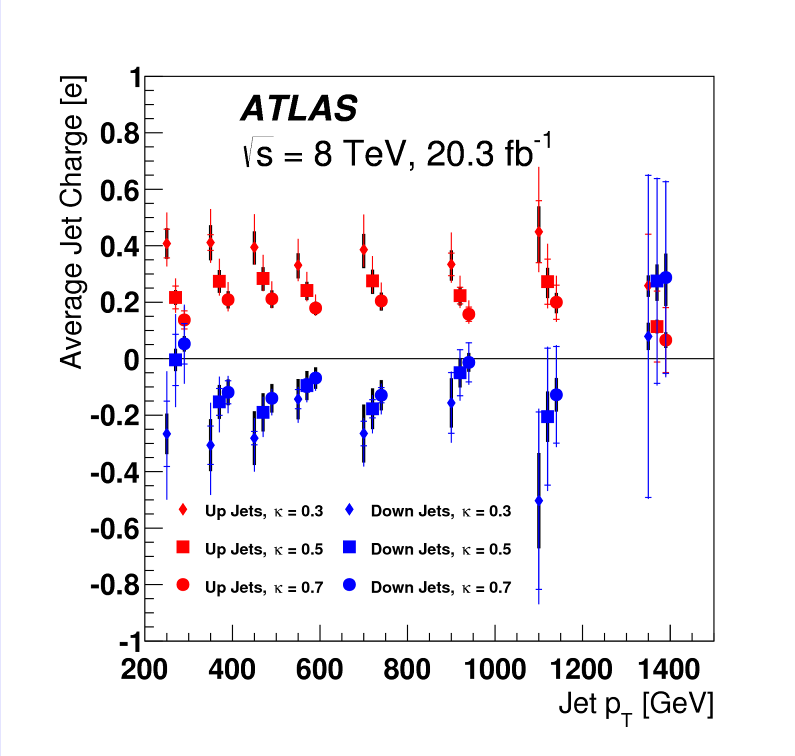


- Comparison with NLO/LO MCs for more central (left) and forward (right) jets.
- Data consistently above predictions, possibly due to fragmentation modelling (not PDFs alone).

Jet Charge

ATLAS, 20.3/fb @ 8TeV, 2012 data, CERN-PH-EP-2015-207

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



Scale violation parameter can be defined as function of κ:

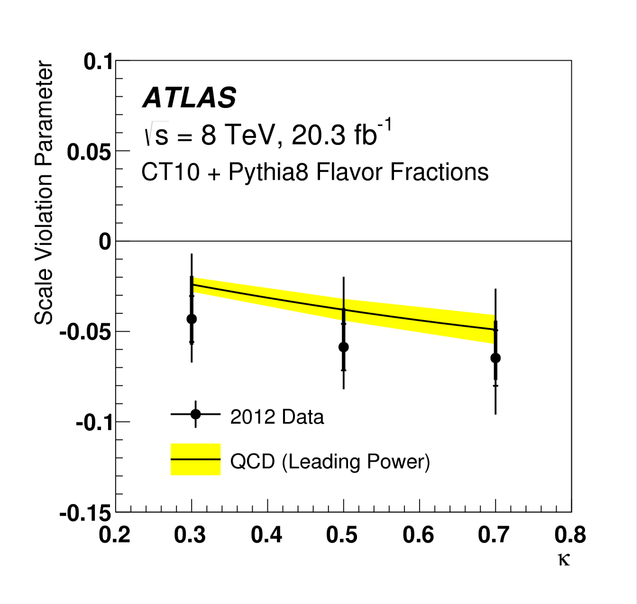
$$\frac{p_T}{<Q_\kappa>}\frac{d}{dp_T} < Q_\kappa > = \frac{\alpha_s}{\pi} P_{qq}(\kappa) = c_\kappa$$

c_κ can then be extracted from data using:

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

$\alpha_{f,i}$: flavour fraction in the i-th p_T bin

Q_f :mean charge at fixed p_T = 700GeV



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

Transverse Energy-energy Correlations

Transverse energy–energy correlations in multi-jet events
ATLAS, 158/pb @ 7TeV, 2011 data, CERN-PH-EP-2015-177

Transverse energy-energy correlation (TEEC):

- Event shape used in e^+e^-, adapted to pp.
- Exhibits quadratic dependence on α_s.

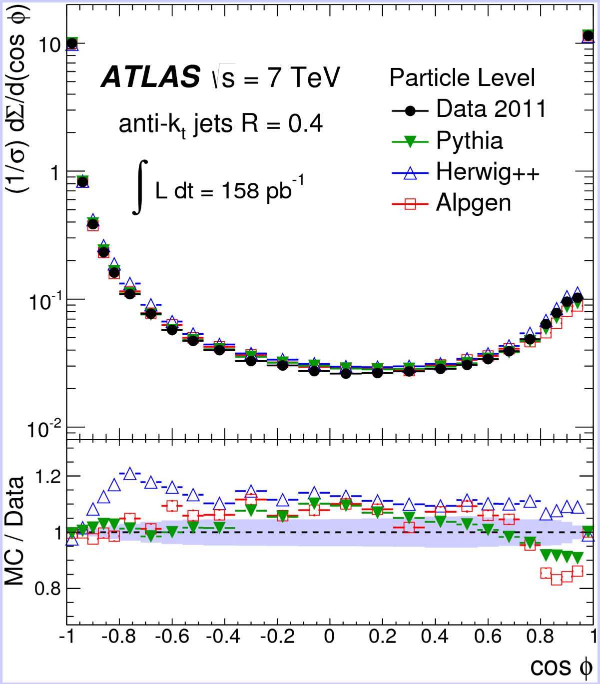
$$\frac{d\Sigma}{\sigma\, d\cos\phi} = \frac{1}{N\Delta\cos\phi} \sum^{N_{events}} \sum_{ij}^{N_{jets}} \frac{E_T^i E_T^j}{\left(\sum_k^{N_{jets}} E_T^k\right)^2} \delta(\cos\phi - \cos\phi_{ij})$$

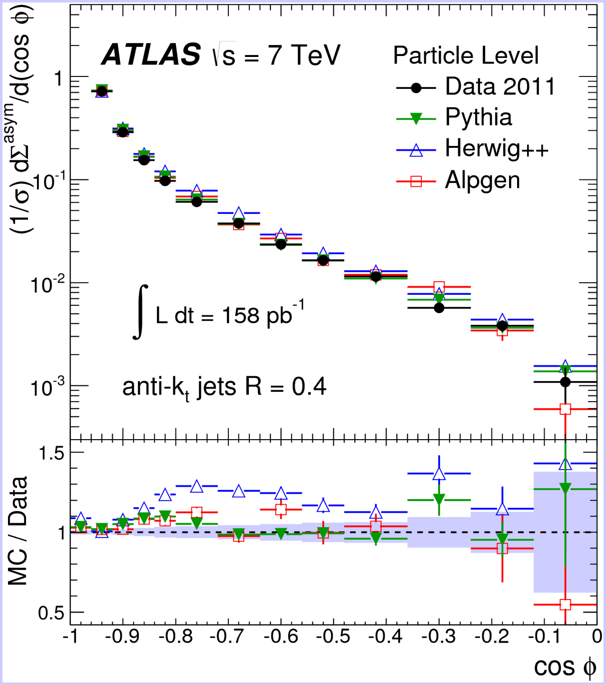
Measures angular distributions of jet pairs weighted by $E_T^1\, E_T^2 / (\Sigma E_T)^2$

- Its asymmetry (ATEEC) is also studied.

- At least two jets with $p_T > 50$ GeV
- $p_{T1} + p_{T2} > 500$ GeV
- $|y_{jet}| < 2.5$

Total uncertainty ~ 5%, dominated by jet energy scale, pileup and MC parton-shower modelling.

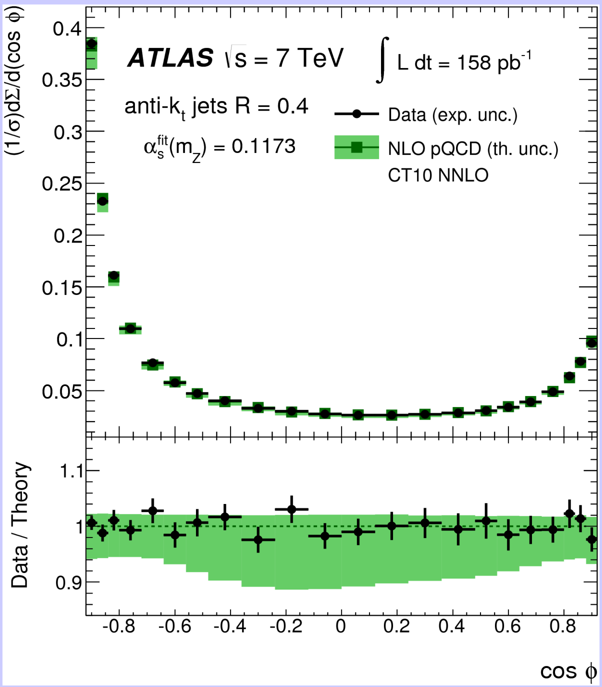




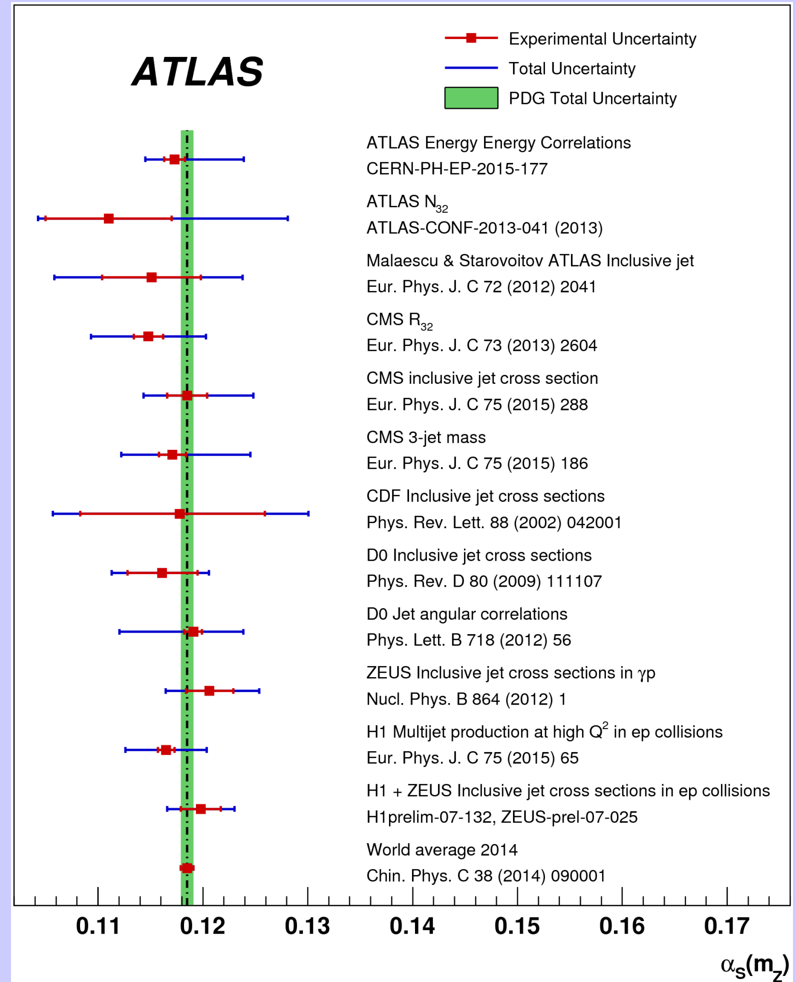
Comparisons with LO MCs:
Pythia/Alpgen predictions agree reasonably well with data, Herwig++ deviates from data by up to 20%.

ATLAS, 158/pb @ 7TeV, 2011 data, CERN-PH-EP-2015-177

Good agreement with NLO pQCD calculations including non perturbative corrections.



- Small sensitivity to non-perturbative effects.
- Very good experimental precision.
- Theoretical scale uncertainty dominate over experimental uncertainties.



$\alpha_s(m_Z)$ extraction: χ^2 fit of NLO predictions to data.

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

Excellent compatibility with World average.

Conclusion

- Jets are the most abundant high p_T final state in hadron colliders.
- Understanding jet production essencial to physics at the LHC.
- Perturbative QCD predictions, parton shower approximations and hadronization models need to be extensively tested.
- Performance of LHC detectors allows for precision jet physics.

- Studies of event shapes, 3- and 4-jet cross sections and topological distributions in multijet events allow extensive testing of MC simulation.
- Overall good data-MC agreement, Pythia8 does well at LO.
- NLO simulation: generally best performance, but scale uncertainties an issue.

- Azimuthal Decorrelations with Jet Vetoes show potential to probe BFKL effects.
- Jet charge measurements can correlate to charge of original partons.
- TEEC allow precise extraction of strong coupling constant.

- Run 1 analysis still ongoing, Run 2 data arriving fast.
- Meanwhile, look for more QCD results in other talks:
  - Overview of QCD measurements at high pT
  - The 2015 World Summary of alpha_s
  - Early Run 2 Hard QCD Results from the ATLAS Collaboration