

Hard And Soft QCD Physics In ATLAS

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on behalf of the ATLAS collaboration

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QCD Measurements in ATLAS

- at LHC every kind of new physics will begin with a QCD process
- QCD processes are an important background to new physics

Soft QCD

- low momentum transfer
- inelastic interactions at LHC are dominated by soft processes
- pQCD breaks down → phenomenological models

→ this talk: minimum bias and underlying event measurements of soft QCD observables

Hard QCD

- large momentum transfer
- test LO and NLO pQCD prescriptions

→ this talk: jet cross-section measurements, results on jet substructure studies

There is more than just a pair of interacting partons...

Minimum Bias:

- events passing a minimum set of requirements making sure an inelastic interaction has occurred
- dominated by soft multiple scattering
- pile-up events (=overlay of multiple proton-proton interactions per bunch-crossing) are minimum bias like
- measurements of minimum bias observables: charged particle distributions [New J. Phys. 13 (2011) 053033] and correlations [arXiv:1203.3549], [arXiv:1203.3100], [arXiv:1203.0419]

Underlying Event:

- additional parton interactions in hard processes due to beam remnants and rest of the proton constituents
- measurements of underlying event characteristics using tracks [Phys. Rev. D83 (2011) 112001], calorimeter clusters [Eur.Phys.J. C71 (2011) 1636], track jets

Soft QCD Measurements in ATLAS

- datasets recorded at three different center of mass energies:

\sqrt{s}	int. Luminosity	inelastic interactions
7 TeV	$190 \mu\text{b}^{-1}$	$> 10 \times 10^6$
2.36 TeV	$0.1 \mu\text{b}^{-1}$	6×10^3
0.9 TeV	$7 \mu\text{b}^{-1}$	$> 3 \times 10^5$

- use of Minimum Bias Trigger Scintillator disks (16 counters on each side of ATLAS)
 - sensitive to charged particles
 - make sure inelastic interaction has occurred
- data are only corrected for detector efficiencies and resolution – no model dependent corrections
- use different phase space regions with varying contribution from different effects (diffractive events, hadronisation,...)

Minimum Bias: Charged-Particle Distributions

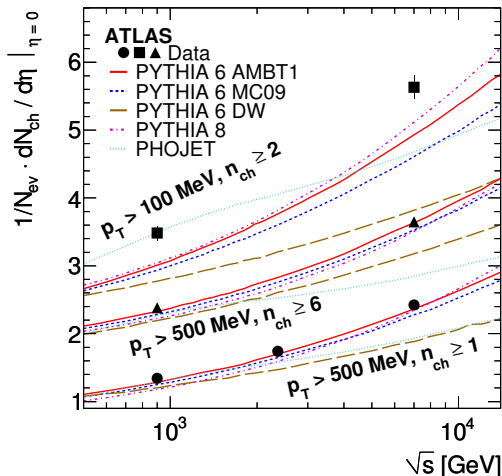
Study kinematic properties of charged particles in minimum bias events.

→ average charged-particle multiplicity per unit of rapidity for $\eta = 0$ as a function of the centre-of-mass energy
[New J. Phys. 13 (2011) 053033]

⇒ data tend to show higher particle multiplicities than predicted by the Monte Carlo models

⇒ however, except for AMBT1 the data/MC comparison only includes pre-LHC tunes

⇒ better agreement between the models in phase-space regions with higher cut on minimum p_T (less contribution from diffractive processes)



Minimum Bias: Forward-Backward Correlations

Soft processes tend to produce lower particle multiplicities with weaker correlations over a wider pseudorapidity distance.

Test the strength of soft and hard contributions by studying the

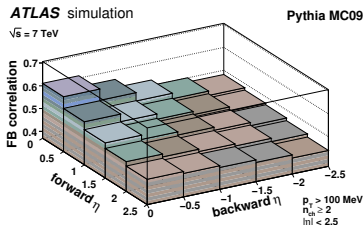
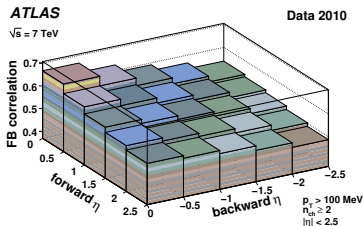
particle multiplicity correlation

$$\rho_{fb}^n = \frac{\langle (n_f - \langle n_f \rangle) (n_b - \langle n_b \rangle) \rangle}{\sqrt{\langle (n_f - \langle n_f \rangle)^2 \rangle \langle (n_b - \langle n_b \rangle)^2 \rangle}}$$

p_T correlation

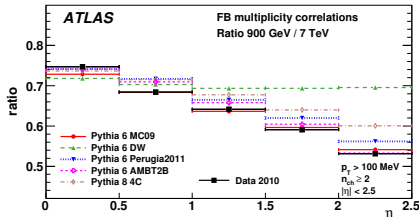
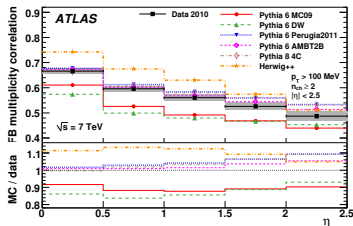
$$\rho_{fb}^{p_T} = \frac{\langle (\sum^f p_T - \langle \sum^f p_T \rangle) (\sum^b p_T - \langle \sum^b p_T \rangle) \rangle}{\sqrt{\langle (\sum^f p_T - \langle \sum^f p_T \rangle)^2 \rangle \langle (\sum^b p_T - \langle \sum^b p_T \rangle)^2 \rangle}}$$

of charged particles in different pseudorapidity bins in the forward and backward region [arXiv:1203.3100].



Minimum Bias: (Forward-Backward) Correlations

→ forward-backward multiplicity correlation in symmetrically opposite η intervals / ratio of the 900 GeV results to 7 TeV results [arXiv:1203.3100]



- ⇒ MC description of shapes in general good, however there are discrepancies w.r.t. strength of correlation between data and MC (up to 15% for some tunes at 7 TeV)
- ⇒ long-range correlation considerably higher at 7 TeV w.r.t. 900 GeV

Further minimum bias related correlation studies in ATLAS:

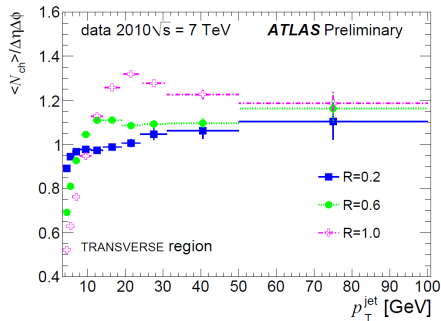
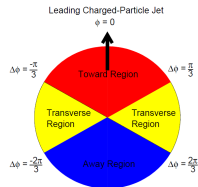
- Two-particle angular correlations [arXiv:1203.3549]
- Azimuthal ordering of charged hadrons [arXiv:1203.0419]

Underlying Event Measurements in ATLAS

study observables sensitive to UE activity in transverse region ($60^\circ < |\phi^{particle} - \phi^{jet}| < 120^\circ$ w.r.t. leading object)

various studies in ATLAS using

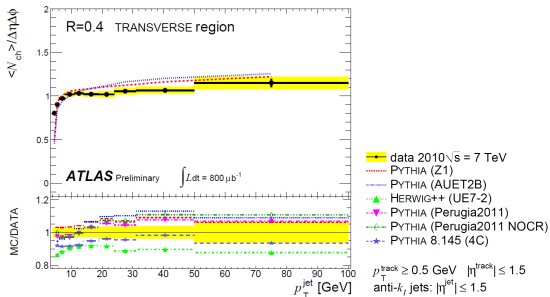
- tracks [Phys. Rev. D83 (2011) 112001]
- calorimeter clusters [Eur.Phys.J. C71 (2011) 1636]
- track jets [to be submitted to Phys.Rev. D.]



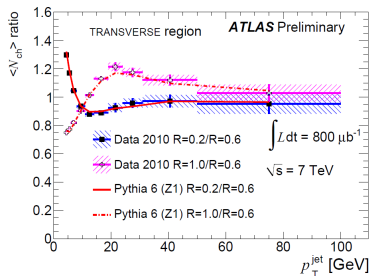
→ study of charged particle distributions in the transverse and away region as a function of the leading jet p_T^{jet} using track jets

→ in addition the R-dependence of these observables has been studied
⇒ sensitive to fluctuations in UE activity

Underlying Event Measurements in ATLAS



→ mean value of N_{ch}
 and its ratio for various
 R-values in the
 transverse region as a
 function of the leading
 jet p_T^{jet} using track jets



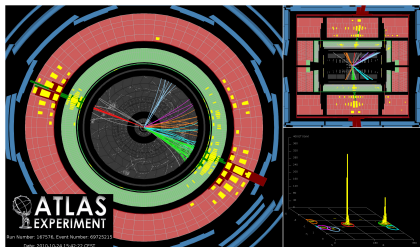
→ reasonable data/MC agreement for
 mean UE activity and fluctuations

Hard QCD Physics in ATLAS

- testing the Standard Model at the shortest distance scales
- large number of studies/publications in ATLAS, this talk: cross-section measurements, studies on jet substructure

further QCD measurements with jets in ATLAS:

- $D^{*+/-}$ meson production in jets [Phys. Rev. D85 (2012) 052005]
- properties of jets measured from tracks [Phys.Rev. D84 (2011) 054001]
- dijet production with a veto on additional central jet activity [JHEP 1109 (2011) 053]
- dijet azimuthal decorrelations [Phys.Rev.Lett. 106 (2011) 172002]



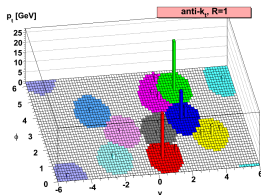
Jet Reconstruction in ATLAS

Combination of 3 dimensional, noise-suppressed calorimeter clusters according to anti- k_t clustering algorithm.

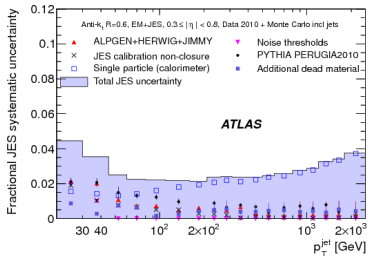
- based on $\min(p_i^{-2}, p_j^{-2})$ scaled distance
 $\Delta_{ij}^2 = (y_i - y_j)^2 + (\phi_i - \phi_j)^2$ measurement
- combine hardest objects first until all objects are separated by $\Delta R_{ij} > R$
- infrared and collinear safe
- standard jet reconstruction algorithm in ATLAS with $R=0.4/0.6$

Apply calibration constants to restore the JES.

- correct for non-compensating calorimeters, inactive material, out-of-cone effects and pile-up
- 2010 uncertainty [ATLAS-CONF-2011-032]:
<2.5% for central jets ($p_T = 100$ GeV),
<9 (14)% in endcap (forward) region
- 2011 uncertainty: reduced uncertainty thanks to in-situ measurements



[Cacciari, Salam, Soyez, JHEP 0804:063,2008]



Inclusive And Dijet Cross-Section

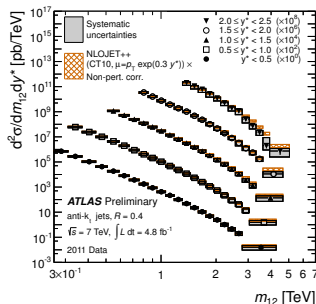
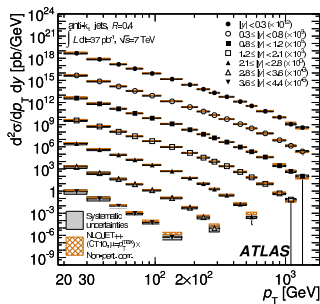
Probe NLO perturbative QCD in a large, new kinematic regime...

- using full 2010 dataset: $L=37 \text{ pb}^{-1}$ [arXiv 1112.6297, to be published by PRD]
- dijet cross section measurement redone for full 2011 dataset: $L=4.8 \text{ fb}^{-1}$ [ATLAS CONF-2012-021]

Covering a large kinematic Range:

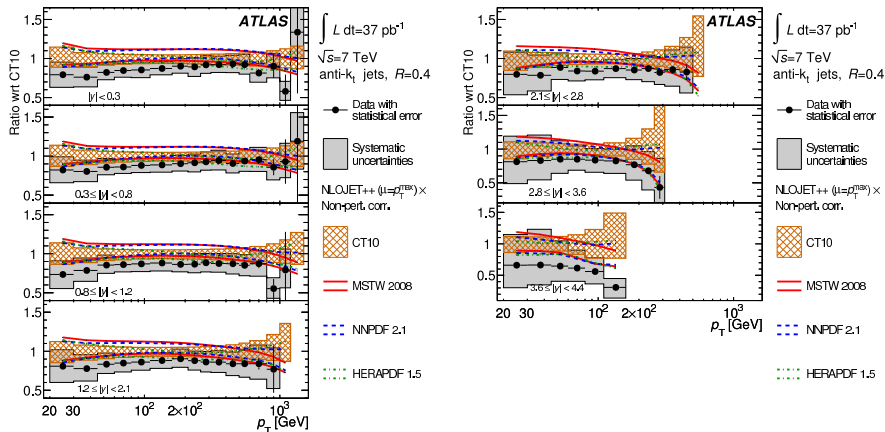
- inclusive: $p_T = 20 \text{ GeV} - 1.5 \text{ TeV}$ and $|y| < 4.4$
- m_{12} up to 5 TeV and $y^* = |y_1 - y_2|/2 < 4.4$

⇒ dominant experimental systematic uncertainties from jet energy scale



Inclusive and Dijet Cross-Section

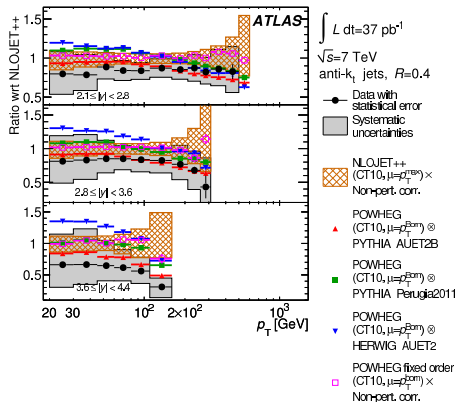
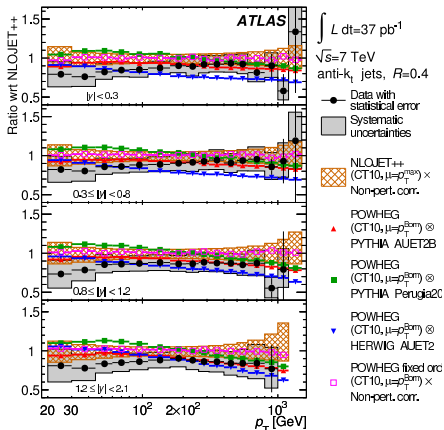
⇒ comparison to theoretical NLOJET++ predictions (with CT10, MTSW 2008, NNPDF 2.1, and HERAPDF 1.5)



⇒ good data/MC agreement in central region, some overall shifts in forward region

Inclusive and Dijet Cross-Section

⇒ comparison to PowHeg



⇒ good agreement between data and Monte-Carlo, deviations between data and PowHeg interfaced to Herwig

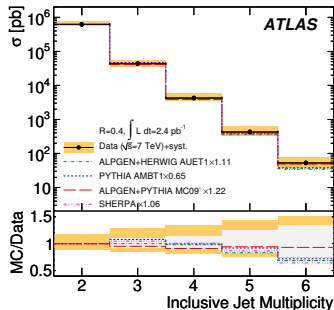
Multi-Jet Cross-Section

important background in searches for new physics: constrain uncertainty on multi-jet cross-section

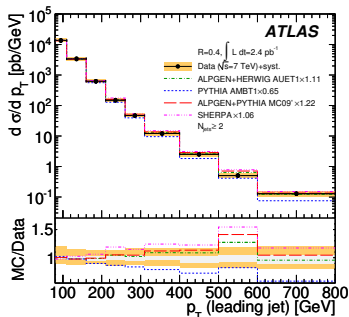
⇒ JES dominant source of experimental systematic uncertainty

cross-section vs. inclusive jet multiplicity

differential cross-section vs. leading jet p_T



⇒ data/MC agreement over the full multiplicity spectrum



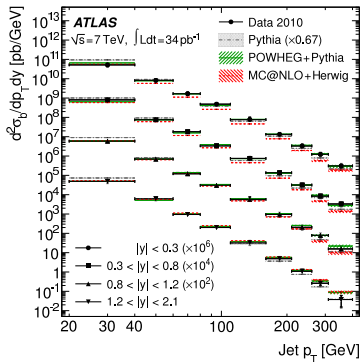
⇒ differences between data and LO Monte-Carlo
[Eur.Phys.J. C71 (2011) 1763]

Inclusive and Dijet Cross-Section of b-jets

b-jets represent substantial backgrounds in many searches for new physics.

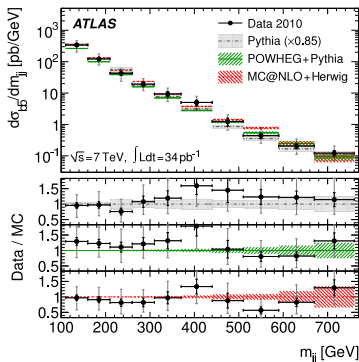
⇒ b-JES and b-jet tagging efficiency/purity dominant sources of experimental systematic uncertainty

double differential inclusive cross-section



⇒ good agreement with PowHeg+Pythia
 ⇒ discrepancies with MC@NLO+Herwig

dijet cross-section



⇒ good agreement with PowHeg+Pythia,
 MC@NLO+Herwig

[Eur.Phys.J.C 71 (2011) 1846]

Jet Substructure

- Decay products of **heavily boosted objects** tend to be collimated in a small area and can thus be **clustered into a single jet**.
- Jets from two- or three body decays show a **different substructure** w.r.t. quark and gluon initiated jets.

⇒ Jet substructure studies thus provide a useful tool to suppress background from QCD jets when searching for new physics (Higgs).

⇒ They also provide a test of non-perturbative effects like fragmentation and hadronisation.

ATLAS results on jet substructure:

- Jet shapes [Phys.Rev. D83 (2011) 052003]
- Jet fragmentation [Eur.Phys.J.C 71 (2011) 1795]
- Jet mass and substructure variables [JHEP 1205 (2012) 128]
- Jets properties for boosted objects [ATLAS-CONF-2012-044]

Jet Substructure

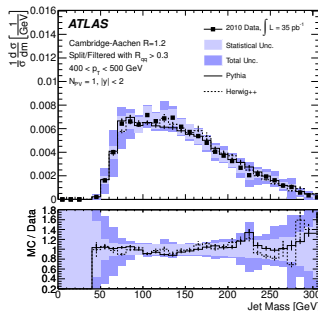
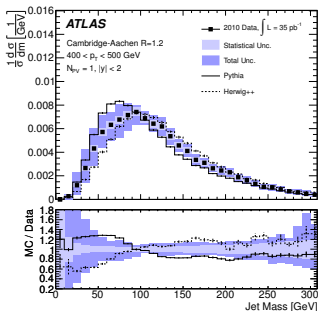
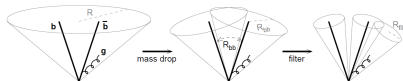
Cambridge/Aachen Filtering

- reverse the clustering of large Cambridge-Aachen jets ($R=1.2$) in an iterative procedure by looking for hard (large mass drop) and symmetric splittings
- recluster remaining constituents with smaller R
- suitable for identification of two-body decays ($H \rightarrow b\bar{b}$)

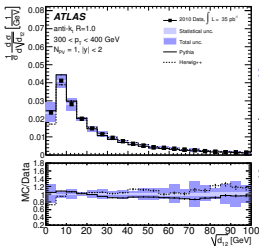
→ normalized cross section as a function of mass [JHEP 1205 (2012) 128]

→ better data/MC agreement after C/A filtering (right plot)

[Phys. Rev. Lett. 100, 242001 (2008)]

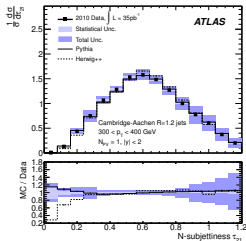


Jet Substructure - Some Further Variables...

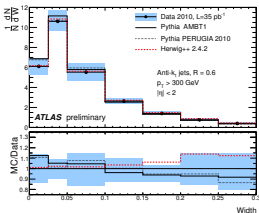


splitting scale:
kinematic
threshold for
breaking jet into
subjets

[JHEP 1205 (2012) 128]



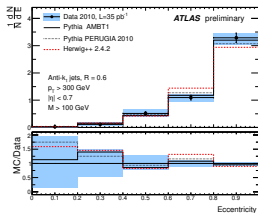
N-subjettiness:
how well can the
jet be described
by n subjets



width:
 p_T -weighted
distance of
constituents to
jet axis

[ATLAS-CONF-2012-044]

⇒ variables show reasonable data/MC agreement



eccentricity:
deviation of jet
profile from circle

Conclusions

Modelling of Soft Processes:

- several observables sensitive to minimum bias/underlying event activity have been investigated
- these studies have been carried out for different center of mass energies, in different phase space regions
- data/MC comparison shows there is still need to improve on the modelling of soft QCD processes

Cross-Section:

- test pQCD in new kinematic regime
- very good agreement between data and NLO pQCD calculations

Jet Substructure:

- exploit the substructure of jets to reduce background from quark-/gluon initiated jets in searches for new physics
- several discriminating variables have been tested in recent studies: reasonable data/MC agreement

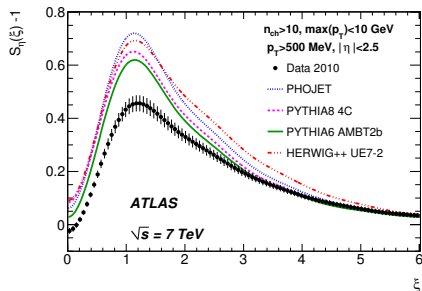
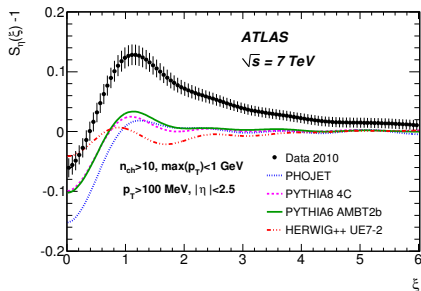
Backup: Azimuthal Ordering of Charged Hadrons

Modified Lund String Model: Formation of a helix-like structured gluon field at the end of the parton cascade leads to observable effects in the azimuthal ordering of direct hadrons.

The azimuthal ordering of hadrons should be observable with the help of a power spectrum defined according to the expected structure of the helix field:

$$S_\eta(\xi) = \frac{1}{N_{ev}} \sum_{event} \frac{1}{n_{ch}} \left| \sum_j^{n_{ch}} \exp(i(\xi\eta_j - \phi_j)) \right|^2$$
$$S_E(\omega) = \frac{1}{N_{ev}} \sum_{event} \frac{1}{n_{ch}} \left| \sum_j^{n_{ch}} \exp(i(\omega X_j - \phi_j)) \right|^2 \quad X_j = 0.5E_j + \sum_{k=0}^{k<j} E_k$$

Backup: Azimuthal Ordering of Charged Hadrons



- phase space is dominated by the production of low p_T particle \rightarrow hadronisation effects more evident
- MC predicts too little correlation

- low p_T depleted sample \rightarrow non-diffractive processes suppressed
- MC overestimates correlations

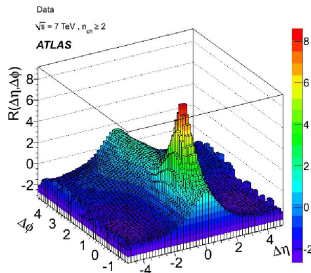
[arXiv:1203.0419]

Backup: Two-Particle Angular Correlations

Correlations between final-state particles can indicate a common mechanism of particle production.

- foreground distribution $F(n_{ch}, \Delta\eta, \Delta\phi)$: particle pairs from same event
- background correlation $B(n_{ch}, \Delta\eta, \Delta\phi)$: particle pairs from different events
- two-particle angular correlation function:

$$R(\Delta\eta, \Delta\phi) = \frac{\langle (n_{ch} - 1) F(n_{ch}, \Delta\eta, \Delta\phi) \rangle_{ch}}{B(n_{ch}, \Delta\eta, \Delta\phi)} - \langle n_{ch} - 1 \rangle_{ch}$$

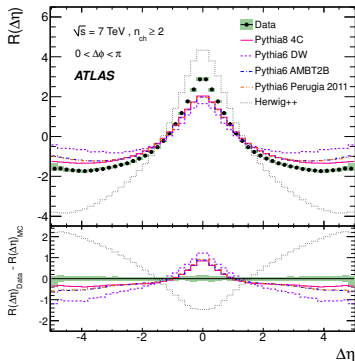


⇒ complex structure, various components reflect the contributions from different underlying processes

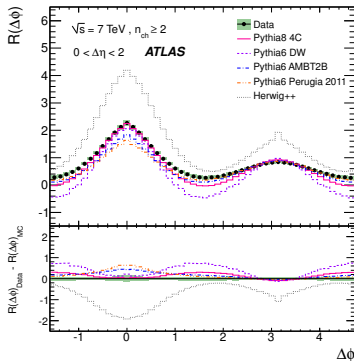
[arXiv:1203.3549]

Backup: Two-Particle Angular Correlations

$R(\Delta\eta)$ two-particle correlation function obtained by integrating the foreground and background distributions over $\Delta\phi$ between 0 and π



$R(\Delta\phi)$ two-particle correlation function obtained by integrating the foreground and background distributions over $\Delta\eta$ between 0 and 2



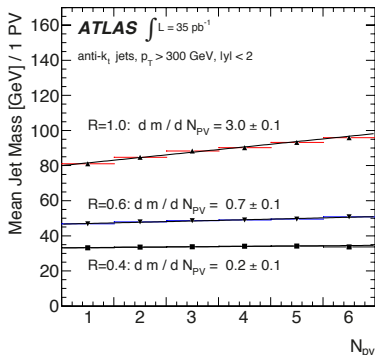
→ many of the Monte Carlo tunes reproduce the general features of the two-particle correlation function

→ none of them provide a good quantitative description of the strength of the correlations [arXiv:1203.3549]

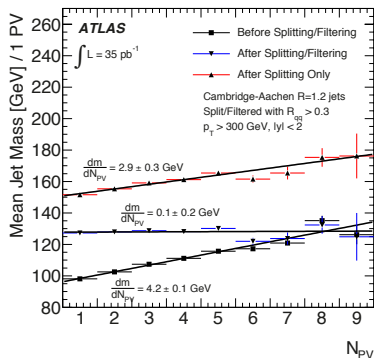
Backup: Cambridge/Aachen Filtering + Pile-Up

Splitting and filtering procedure reduces the effective area of large jets and is therefore expected to reduce sensitivity to pile-up.

impact of pile-up for anti-k_T jets as a function of R



impact of pile-up for C/A jets R=1.2, before and after filtering



[JHEP 1205 (2012) 128]