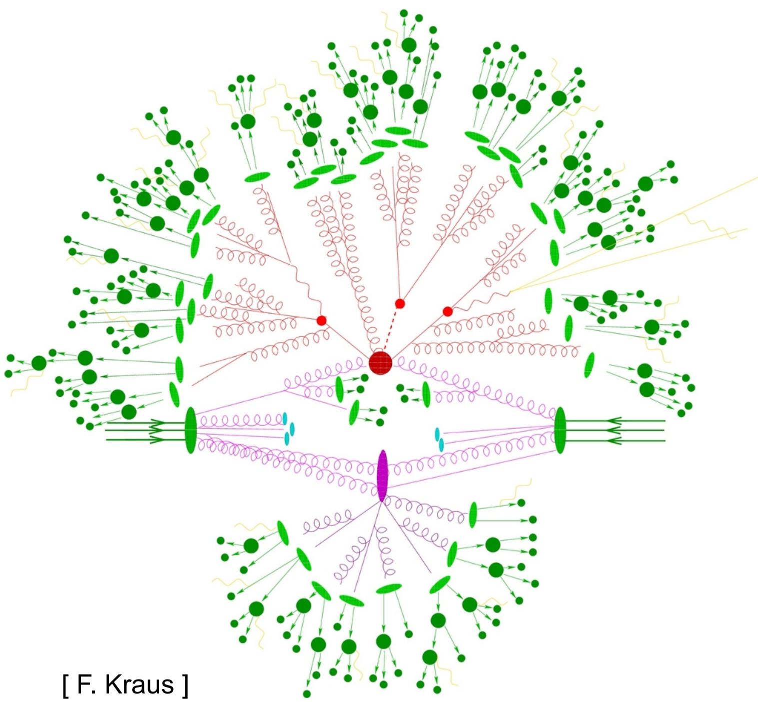
Jet measurements, and subjet structure for boosted hadronic objects

Bertrand Chapleau
on behalf of the ATLAS collaboration

McGill
Montréal, Canada

Motivation

- Jet production at the LHC is the dominant high transverse-momentum process
  - Testing ground for our understanding of perturbative QCD in a new kinematic regime.
  - Hard QCD processes are a background for many new physics model → including boosted heavy objects.



[F. Kraus]

- A jet is a composite object; more information available than only its 4-vector.
- Internal structure of jets provides crucial discrimination against backgrounds for searches involving boosted massive particles.

Jet Reconstruction

- 3D noise suppressed clusters of calorimeter cells, fed as input to jet algorithms :

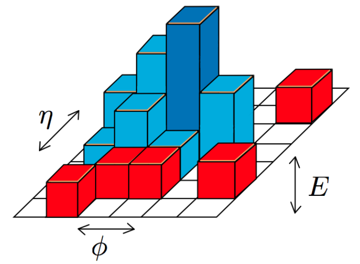
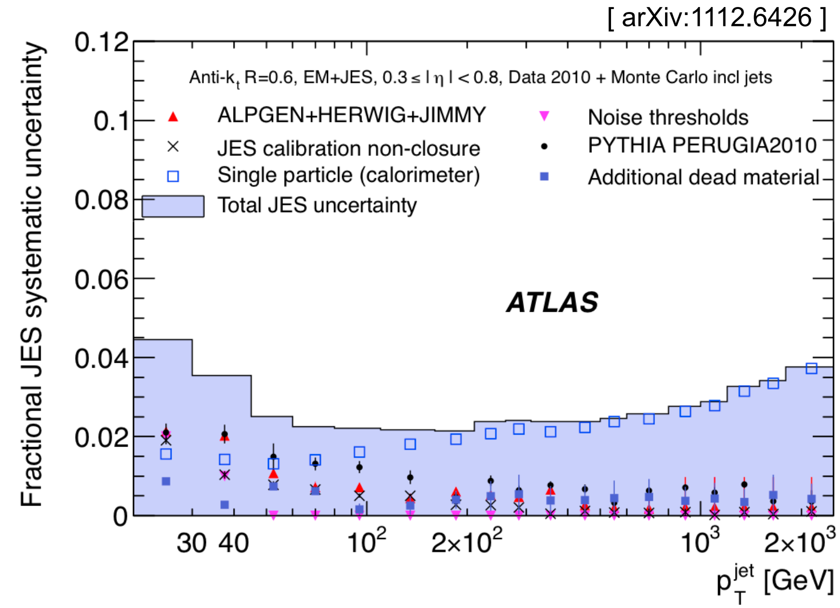


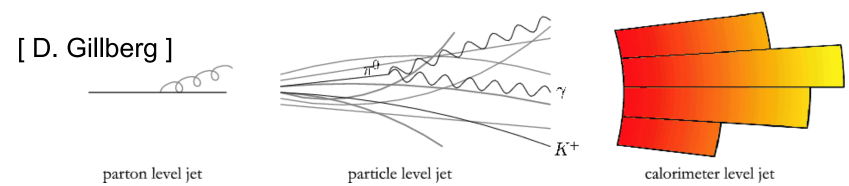
Illustration of a topological cluster:
dark blue seed cell
light blue selected adjoint and neighboring cells
red rejected cells

→ **anti-k_t** R=0.4, 0.6
→ Cambridge-Aachen **R=1.2**, anti-k_t **R=1.0** for substructure studies (*large-R* jets)

- Jet calibration restores the measured jet energy to the particle-level jet energy scale (JES), on average. Main source of uncertainty for many measurements.

- Reduced uncertainty in 2011 thanks to in-situ measurements (Z+jet: ATLAS-CONF-2012-053)

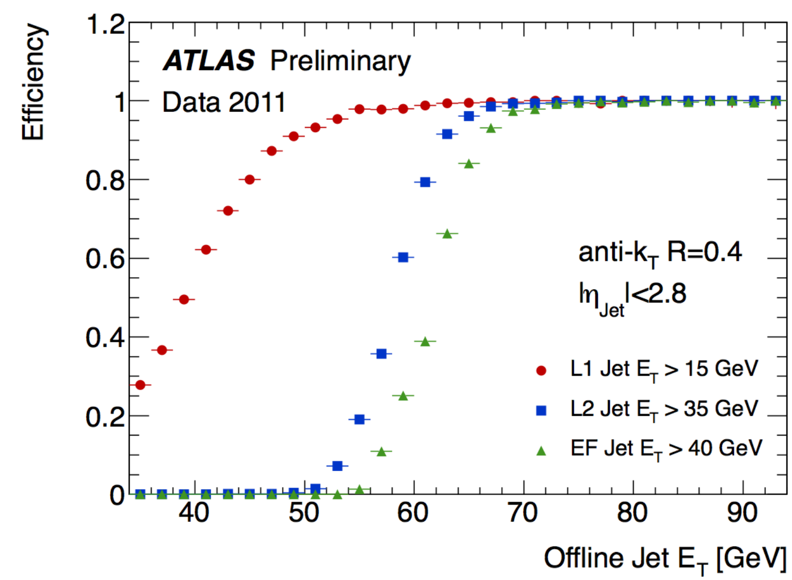




Jet Trigger

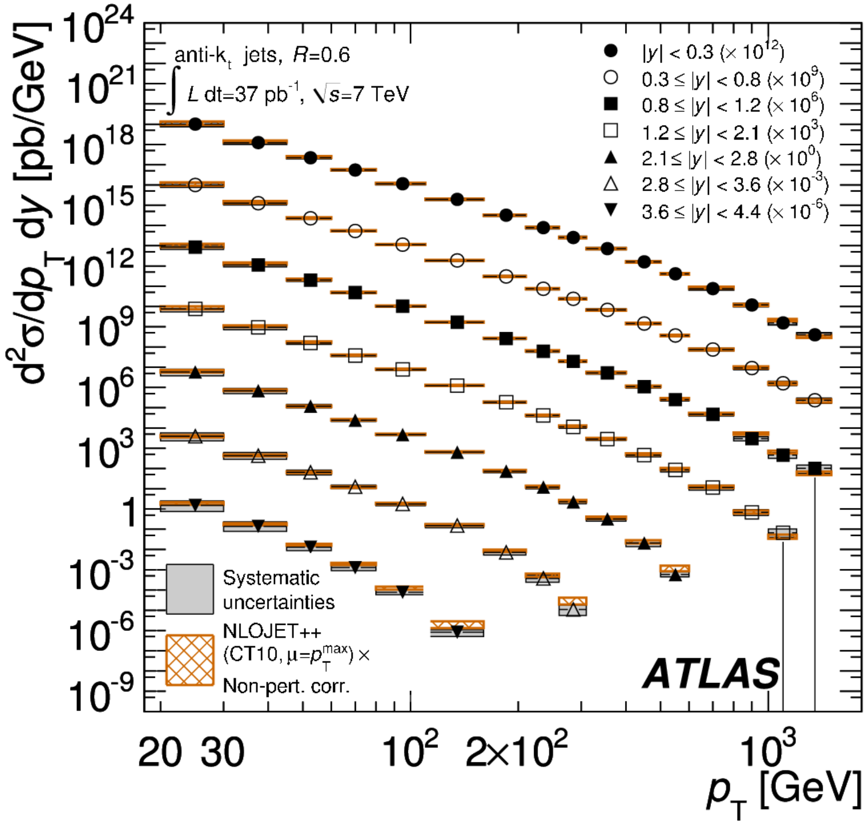
- ATLAS trigger selects jets using the anti-k_t algorithm (as of 2011)

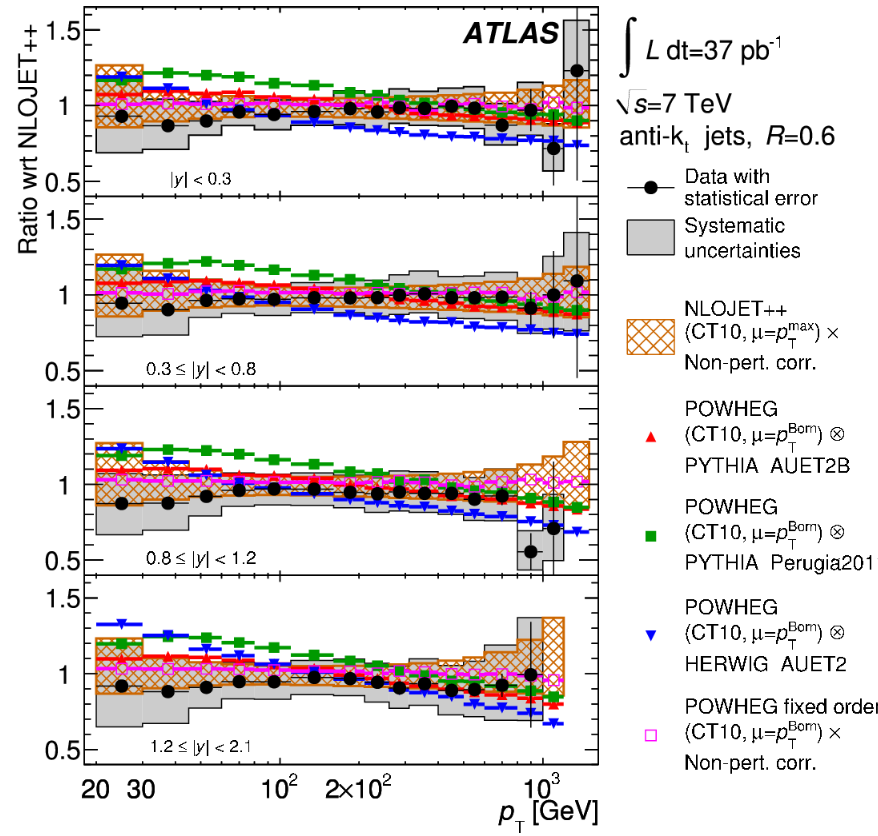
- 3 successive levels to cope with the large data input rate



arXiv:1112.6297

Inclusive jet cross section



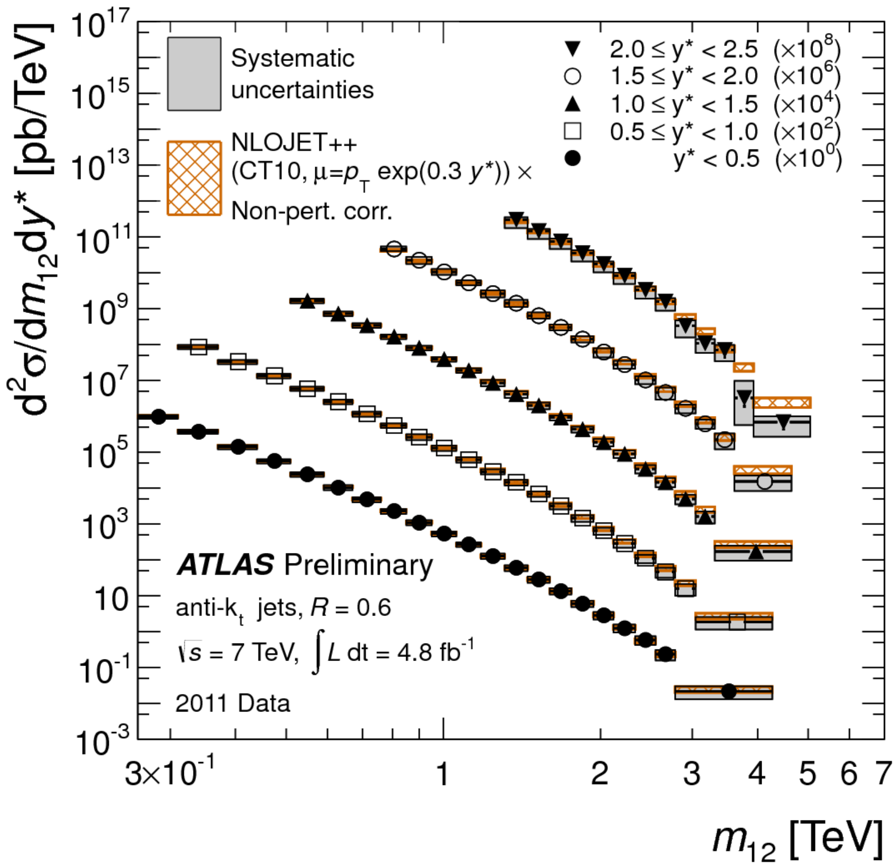


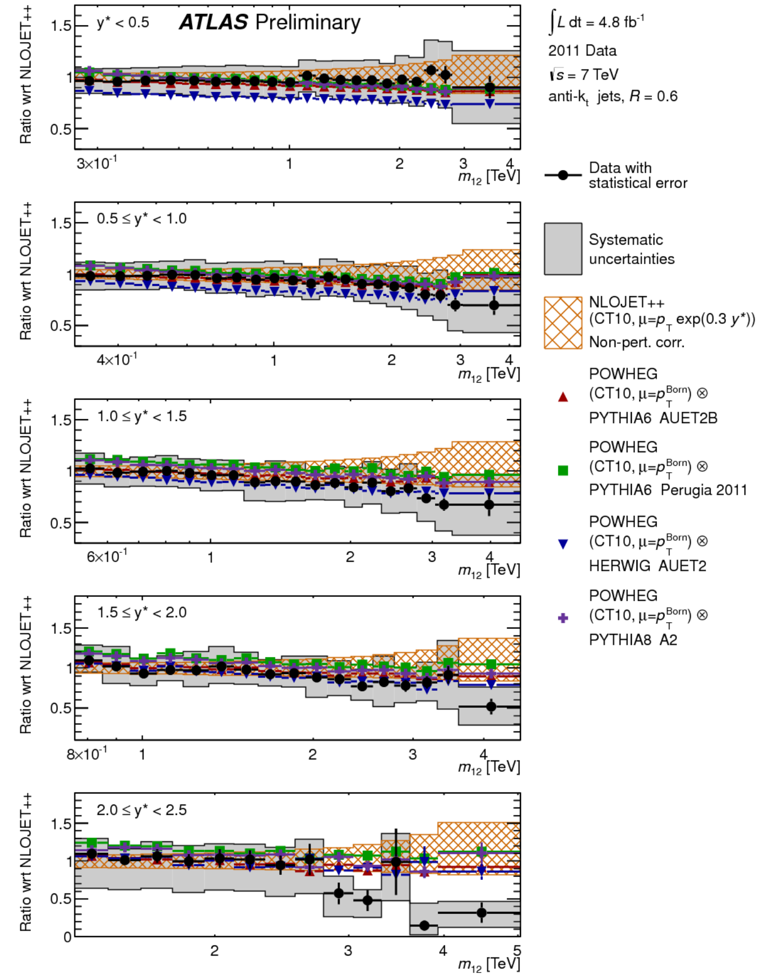
- 2010 data. Spans jet p_T from 20 GeV to 1.5 TeV, wide rapidity coverage of $|y| < 4.4$
  Anti-k_t jet R=0.4 and R=0.6

- Good agreement with NLO fixed order calculations (with non perturbative corrections)
- POWHEG interfaced to different parton showers (PS) MC shows some deviations
  - indication of some uncertainty coming from different PS approximations.

ATLAS-CONF-2012-021

High mass dijet cross section



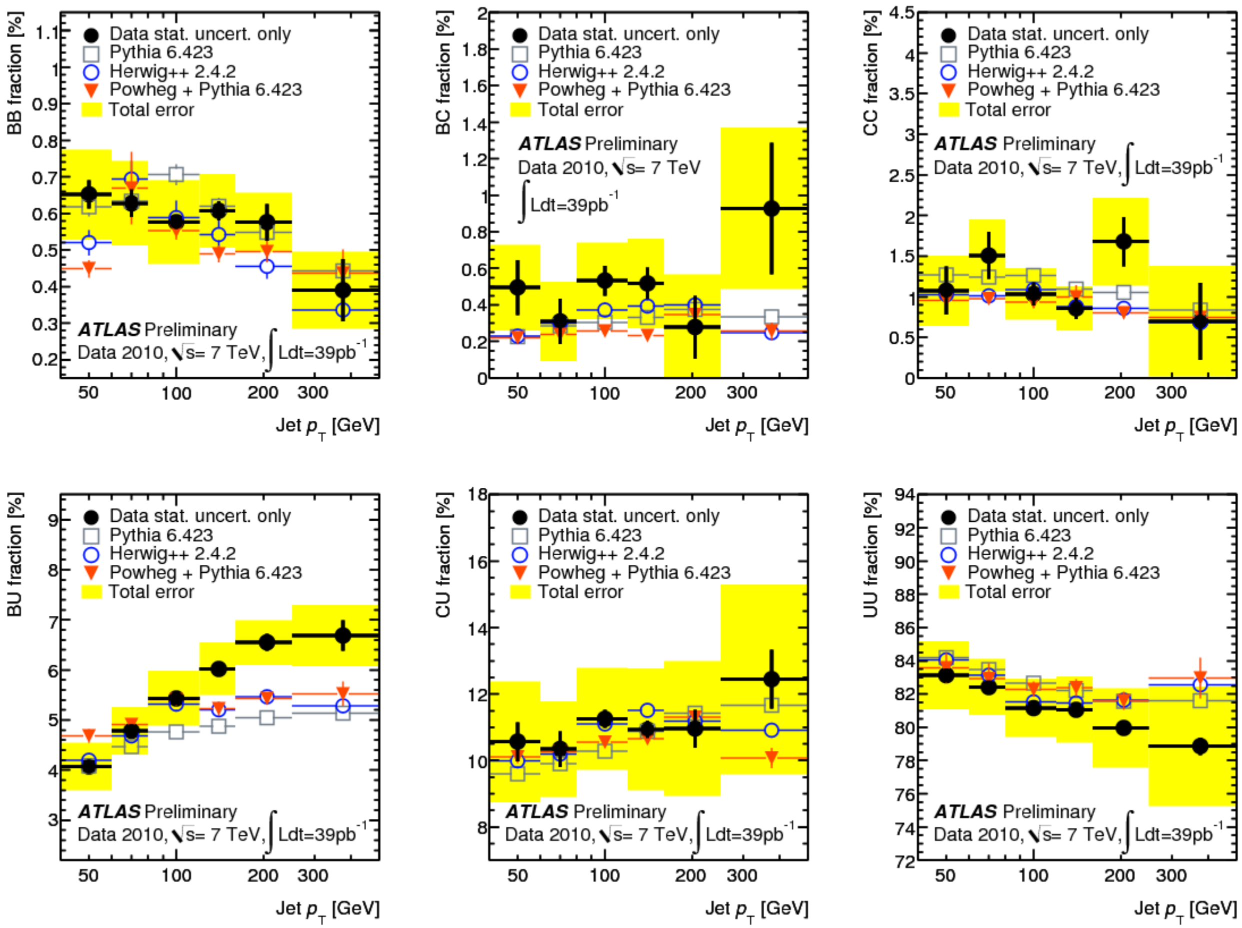


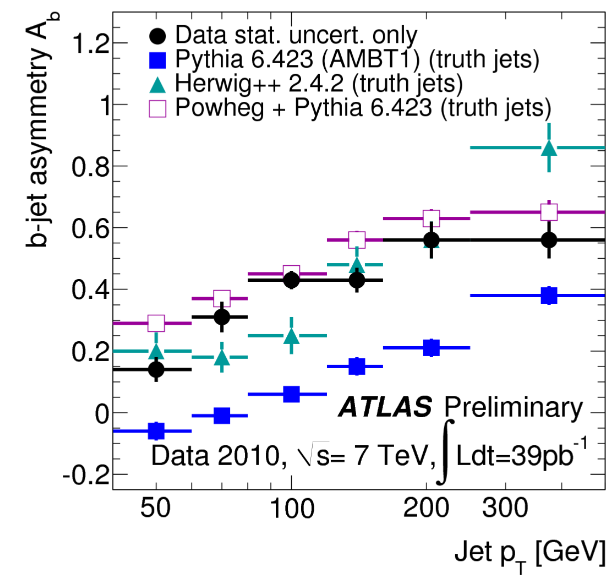
- Full 2011 dataset : 4.8 fb^{-1}
- Spans dijet system mass from 260 GeV to 4.6 TeV, $y^* = |y_1 - y_2|/2 < 2.5$

- Overall good agreement with both NLOJET++ and POWHEG + PS
- Largest disagreement at very high m_{12} and y^*

ATLAS-CONF-2012-081

Flavour composition of dijet events





- **Asymmetry** in the number of leading and subleading beauty jets: $A_b = N^{SL}_b/N^{L}_b - 1$
  Poor description by Pythia.

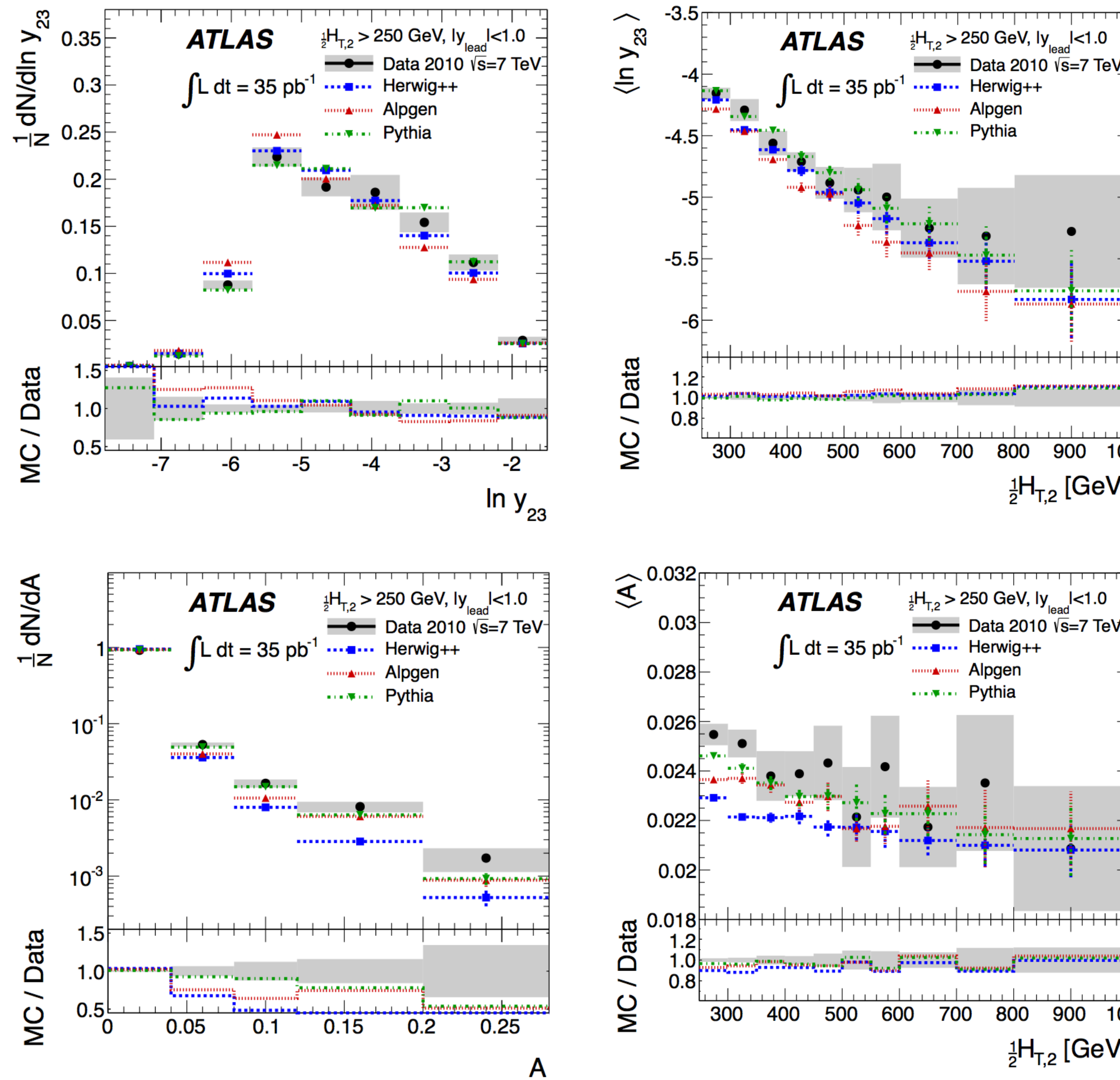
- Two flavour discriminating variables constructed from kinematic properties of secondary vertices found in jets → MC based template for light, charm and beauty flavour state of jets.
  - Flavour dijet fractions extracted from a multidimensional fit to the data.

- Predictions for light-beauty fraction lower than measured value at high p_T

arXiv:1206.2135

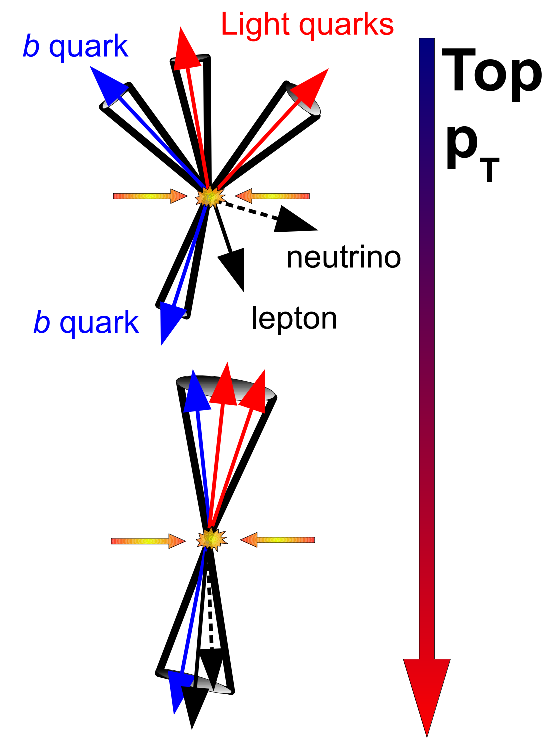
Event shapes at large momentum transfer

- Event shapes characterize the event energy flow → probes and tests the multi-jet topologies through the use of hadronic jets.
- Selected events are required to have ½ $H_{T,2}$ = ½ ($p_{T,jet\ 1}$ + $p_{T,jet\ 2}$) > 250 GeV
- Six observables studied, fully unfolded back to particle level. Shown here :
  - **y_{23}** = $p_{T,jet\ 3}{}^2/H_{T,2}{}^2$
  - **Aplanarity** (~ amount of transverse momentum w.r.t. the plane formed by the two hardest jets)
- y_{23} well described by 2 → 2 MC (Pythia, Herwig++)
- Herwig++ predicts more planar events



Boosted Hadronic Objects

- **Boosted production of heavy particles** (e.g. : top, Higgs, W) → collimated decay products at high p_T
  Decay is best captured by a single **large-R jet** (anti-k_t R=1.0, Cambridge-Aachen R=1.2)

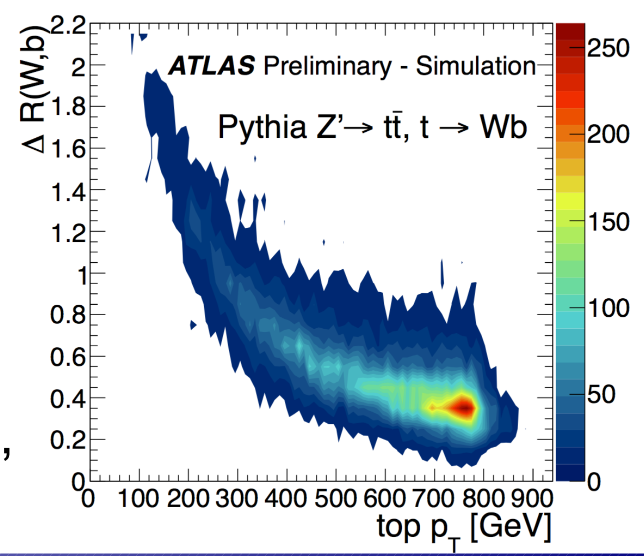


- QCD jets (induced by a single light quark/gluon) are an important background for searches involving boosted objects
  - Extensively studied with 2010 data :
    Jet mass and substructure of inclusive jets, arXiv:1203.4606, JHEP.
    Jet fragmentation and transverse profile: arXiv:1109.5816, EPJC.

- Wide variety of new jet substructure techniques studied with 2011 data and compared to LO and NLO+PS predictions at the reconstructed level

  - **Jet grooming techniques** : **Trimming**, Mass-drop filtering, pruning

  - **Substructure observables** : **Mass, k_t splitting scales**, N-subjettiness

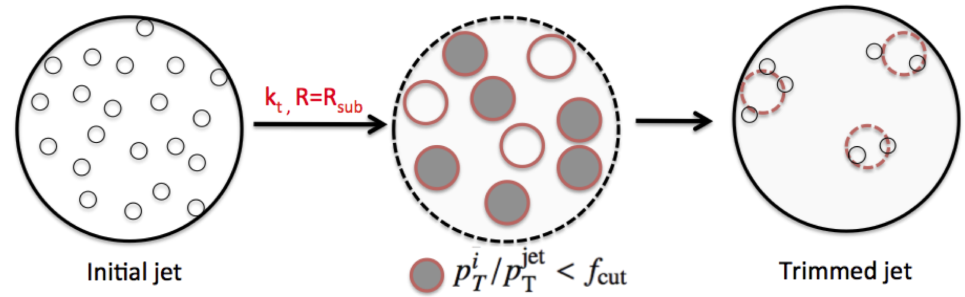


ATLAS-CONF-2012-065/066

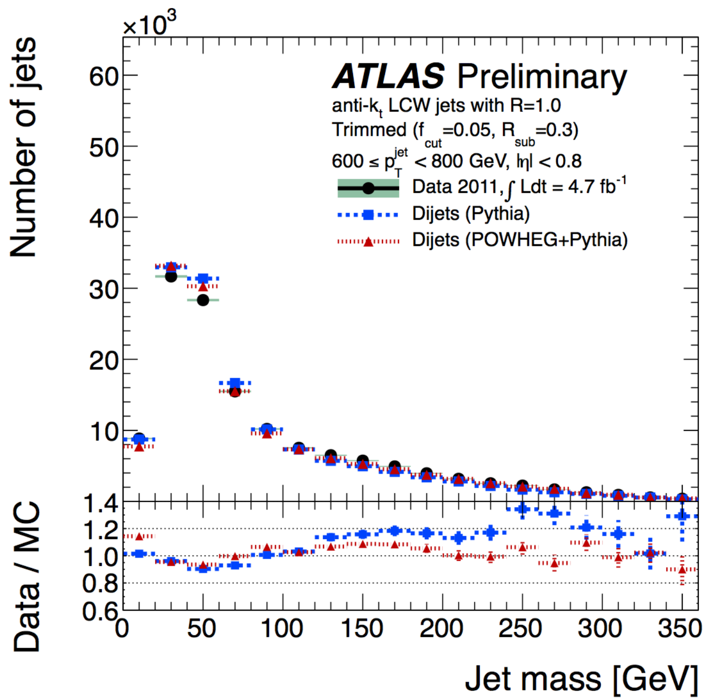
Large-R jets performance

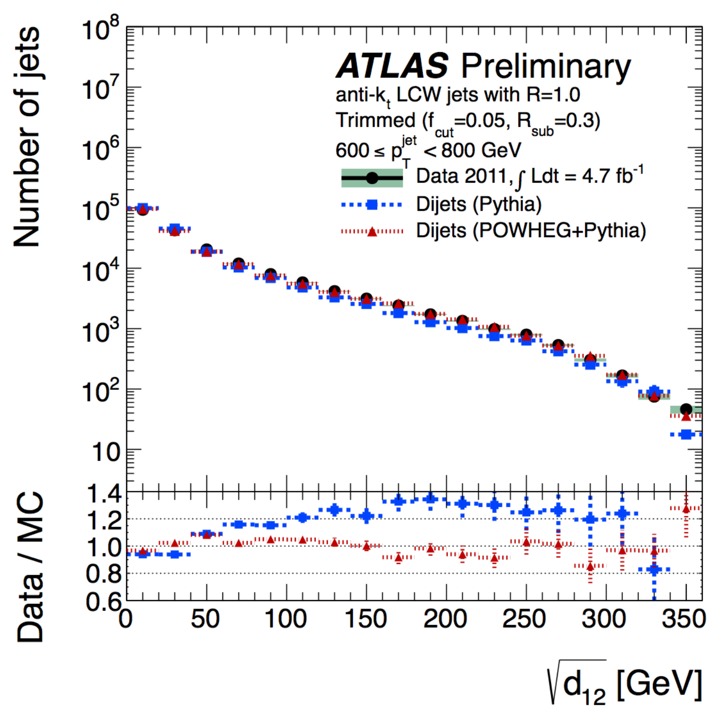
- **Jet grooming** algorithms remove extraneous constituents in a jet
→ reveals the jet internal hard structure.

- An asset for large-R jets : mitigates the underlying event and pile up contributions (see ATLAS-CONF-2012-066).



Trimming in action. D. Krohn, J. Thaler, and L.-T. Wang, Jet trimming, JHEP 2010, arXiv:0912.1342 [hep-ph]





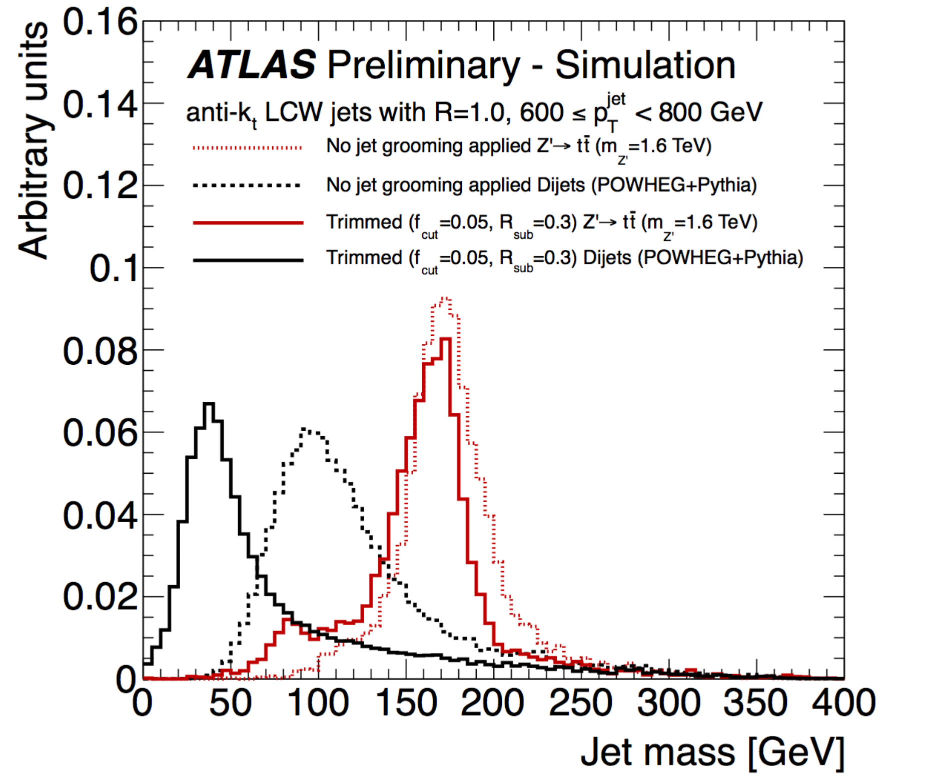
Jet mass (left) and first **k_t splitting scale** (right) for anti-k_t R=1.0 jets with trimming applied, in inclusive QCD dijet events.

Good description by POWHEG in both cases, even in the tails.

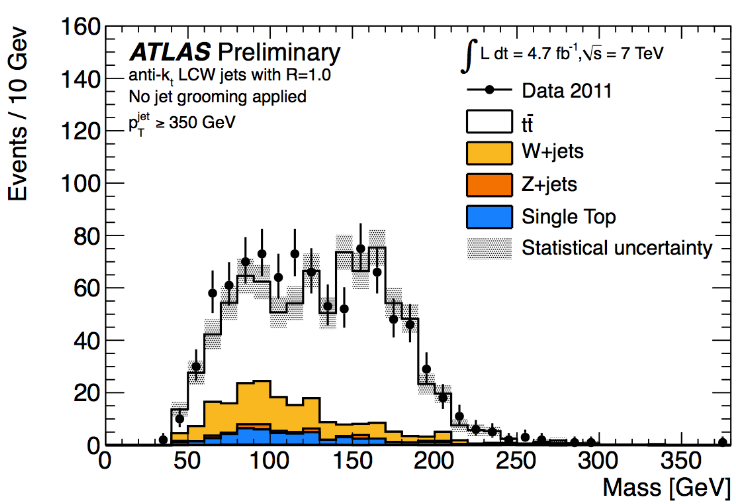
ATLAS-CONF-2012-065/066

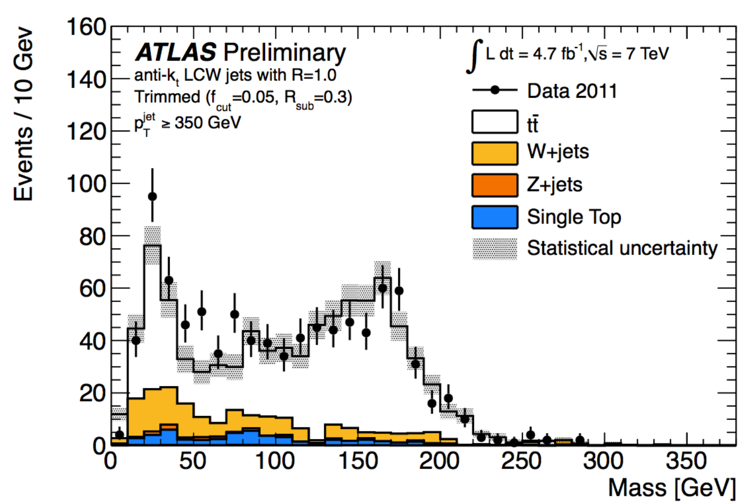
Large-R jets performance

- Grooming preserves jet mass for jets with real hard substructure (e.g. boosted hadronic top decay)
  → enhanced signal discrimination



- Qualitative effect of trimming **in $t\bar{t}$ events**, in data. Standard (resolved) semi-leptonic $t\bar{t}$ selection. **Jet mass** for the leading-p_T anti-k_t **R=1.0** jet (with p_T > 350 GeV)





Well contained boosted tops better resolved with trimmed jets. Increased discrimination between jets encompassing one, two or three partons.

arXiv:1206.5369

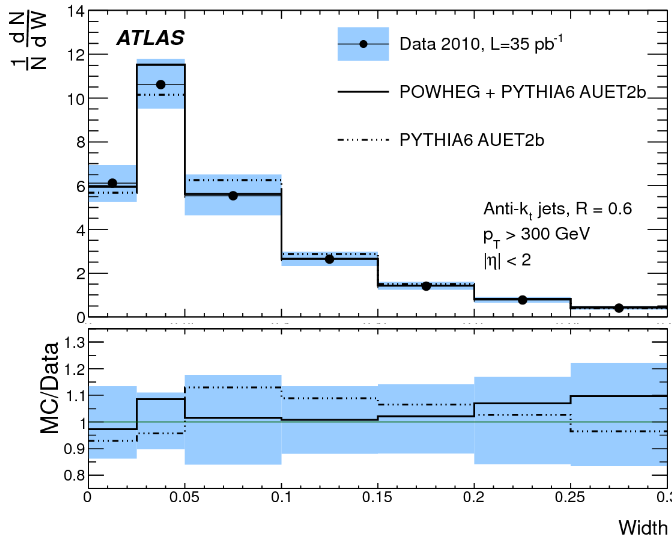
Properties of boosted jets

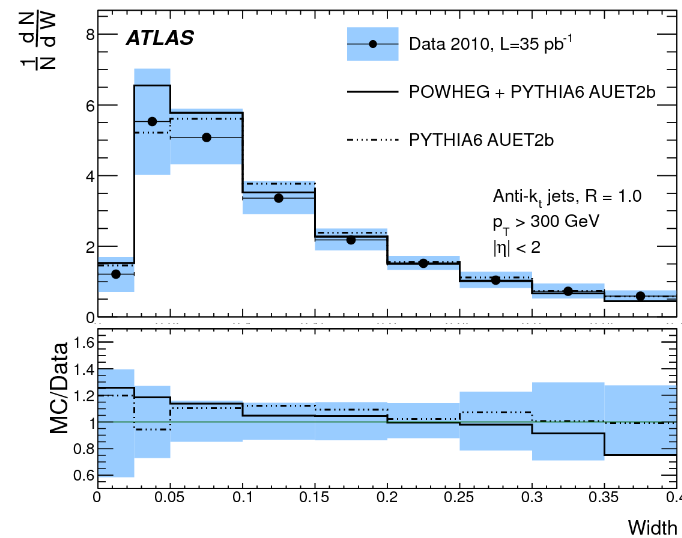
- Analysis performed using the 2010 dataset using high p_T standard (R=0.6) and large-R (R=1.0) anti-k_t jets.

- Several jet shapes measured and unfolded back to particle level. Shown here :

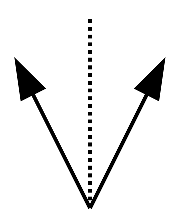
  - **Width** (p_T weighted average of the distances between the jet's constituents and its axis)

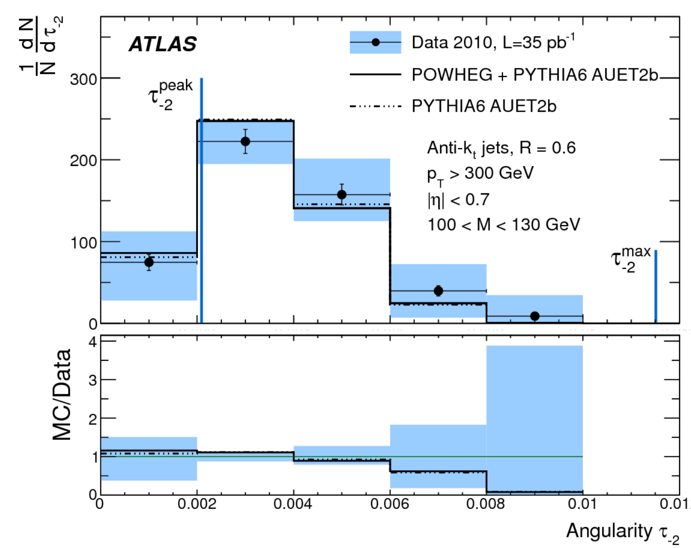
  - **Angularity**, for massive R=0.6 jets (measure of the symmetry in the energy flow inside a jet)
    Peak and maximum value positions from direct calculations



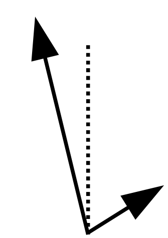


low angularity

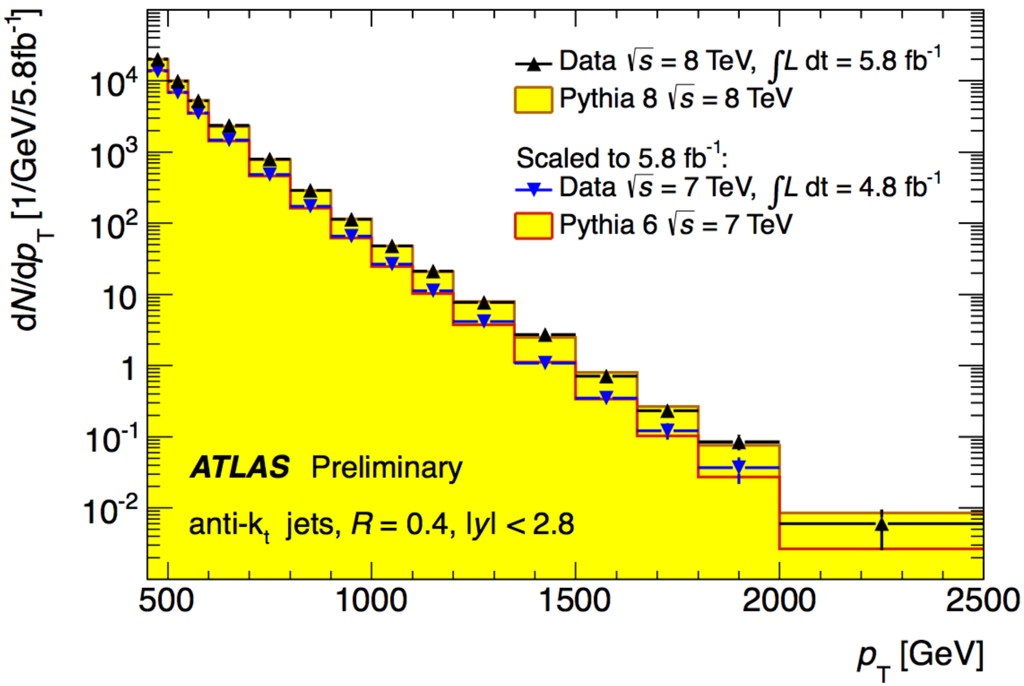


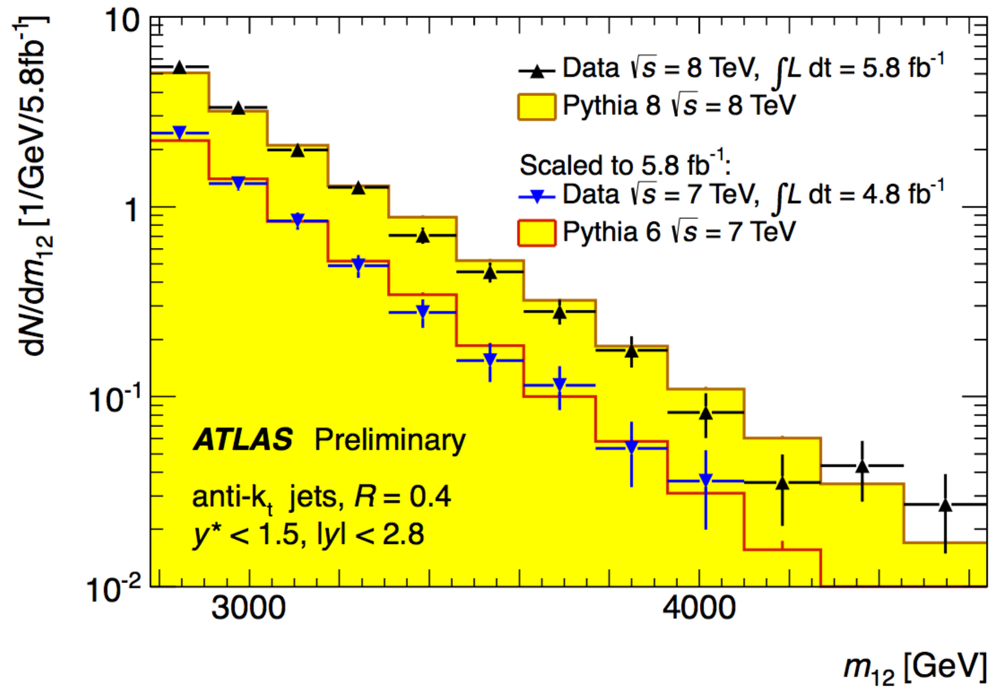


high angularity



Jets @ √s = 8 TeV





- Inclusive jet pT (left) and dijet mass (right) spectrum for *pp* collisions at √s = 8 TeV for anti-k_t R=0.4 jets.

- Comparison with √s = 7 TeV 2011 data and to Pythia 6 (Pythia 8) MC predictions at √s = 7 TeV (√s = 8 TeV).

→ lower center of mass energy in 2011; therefore, lower cross section.

Conclusion

- ATLAS has performed many precision measurements to test perturbative QCD predictions in a previously unexplored kinematic regime. Discussed here :
  - Inclusive jet and dijet differential cross sections
  - Flavour composition of dijet events
  - Event shapes at high momentum transfer

  → overall good data/theory agreement

- Gaining confidence in our understanding of jet substructure techniques with the ATLAS detector
  - Jet mass, shapes, substructure observables measured in 2010 and 2011 data.
  - Exhaustive number of new jet *grooming* algorithms tested.

  → Already used in current searches involving boosted particles production. Will become a key handle on background processes for many searches in 2012 and beyond.

Backup Slides

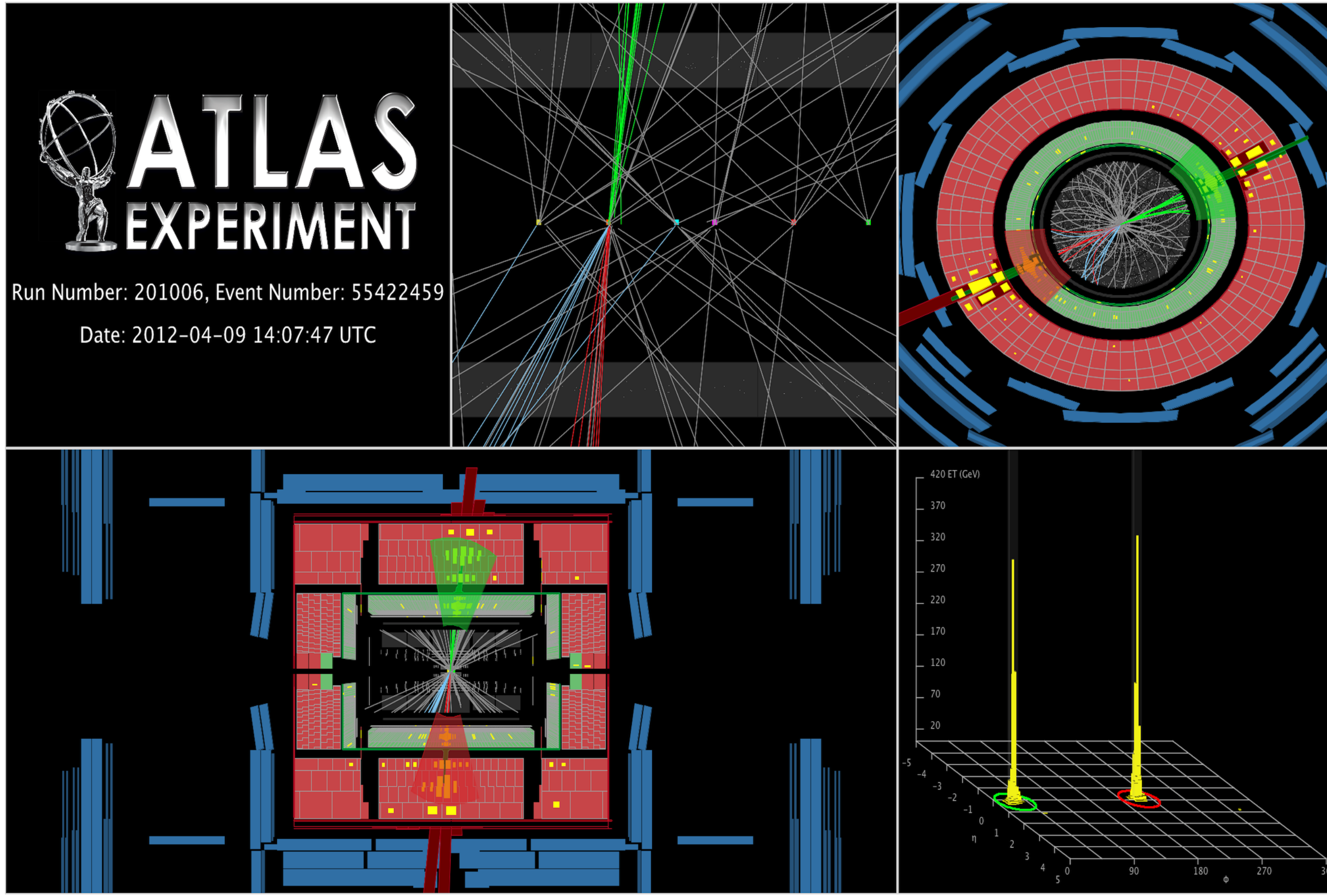
Jets @ $\sqrt{s}$ = 8 TeV

Jet 1 :
p_T = 1.96 TeV
eta = -0.07, phi = -2.68

Jet 2 :
p_T = 1.65 TeV
eta = 0.17, phi = 0.48

Missing E_T = 318 GeV,
phi = 0.43

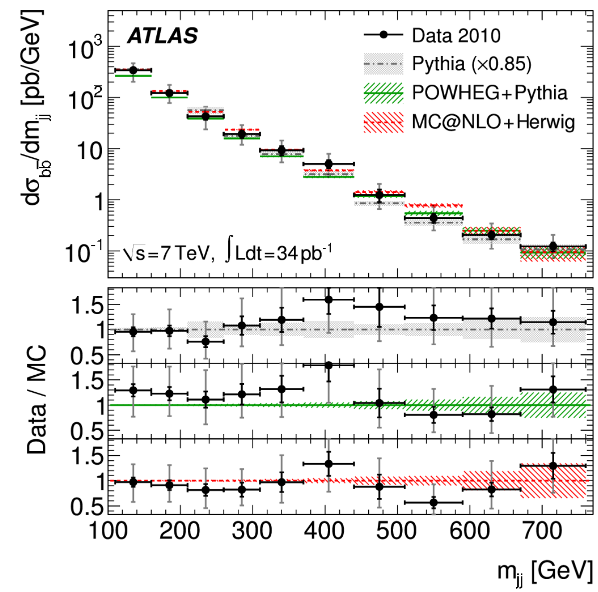
Sum E_T = 3.81 TeV



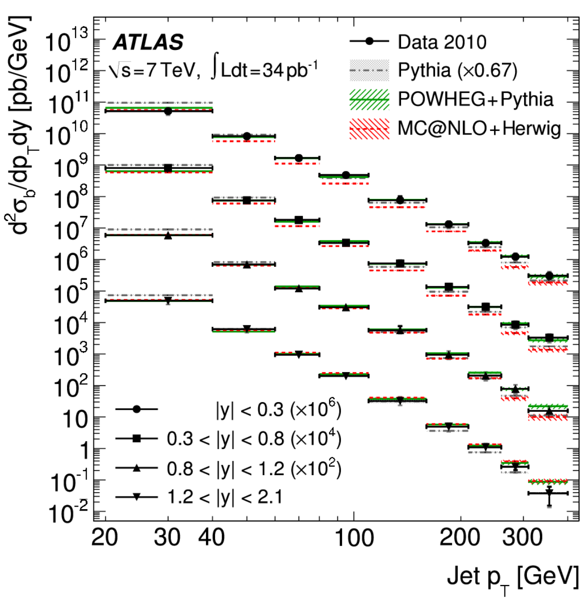
- High mass central dijet event collected in April 2012. Invariant dijet mass of 3.62 TeV arXiv:1109.6833, EPJC

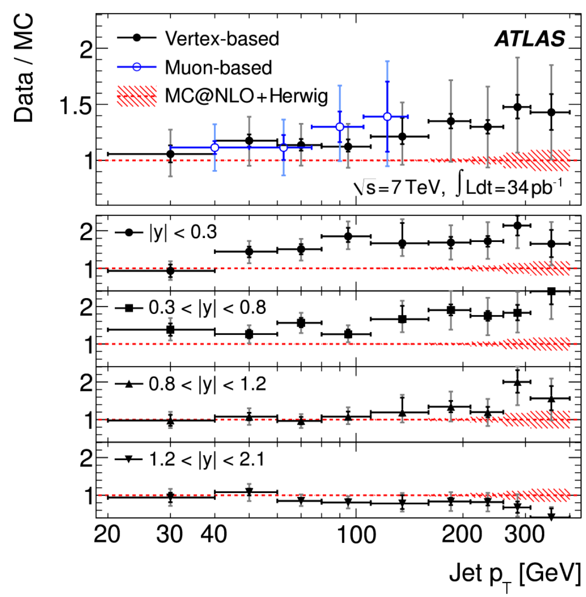
Inclusive and dijet cross sections of *b*-jets

- Measurement of jets containing a *b*-hadron, in 2010 data. Comparison with pQCD predictions.
- Cross check between two experimental methods for *b*-tagging in the inclusive measurement : displaced vertices and muon tagging in jets.
- *b*-JES and *b*-jet tagging efficiency are the main sources of systematic uncertainty



$b\bar{b}$ dijet cross section agrees with NLO predictions. Statistically more limited.



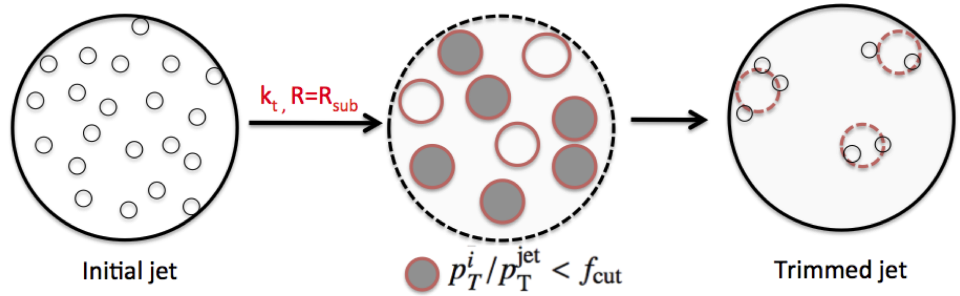


Good agreement of POWHEG for the double differential inclusive cross section. Some deviations observed for MC@NLO predictions.

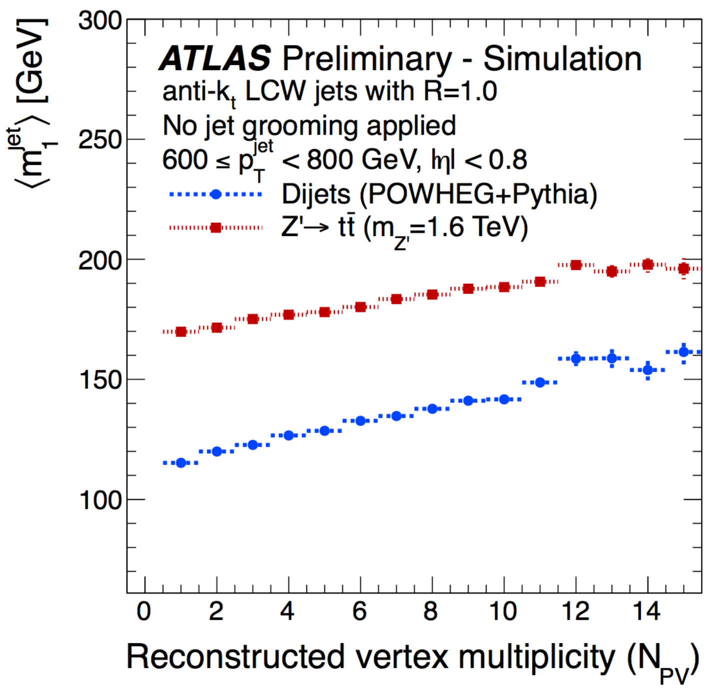
ATLAS-CONF-2012-065/066

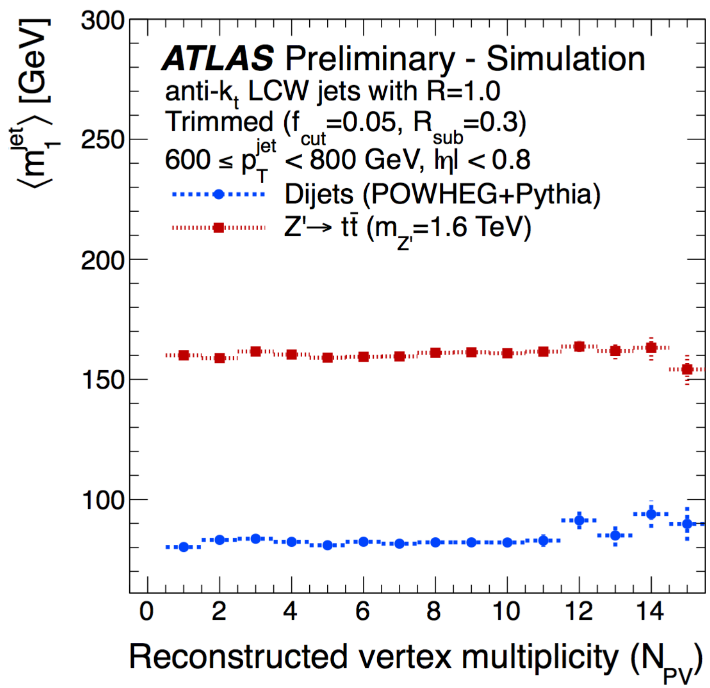
Large-R jets performance

- Jet grooming algorithms removes extraneous constituents in a jet → reveals the jet internal hard structure.
- An asset for large-R jets : mitigates the underlying event and pile up contributions.



Trimming [1] in action. [1] D. Krohn, J. Thaler, and L.-T. Wang, Jet trimming, JHEP 2010, arXiv:0912.1342 [hep-ph]

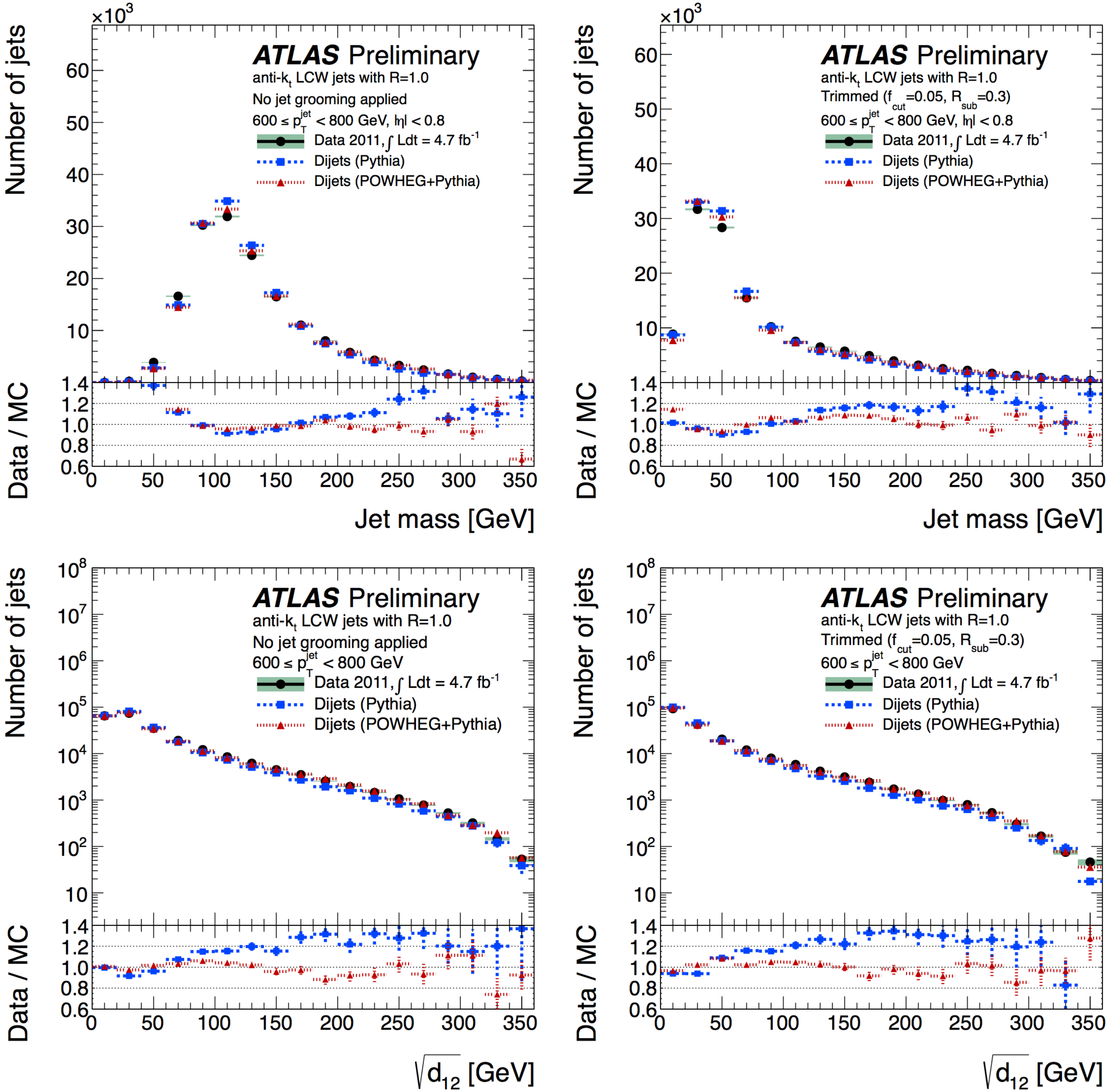




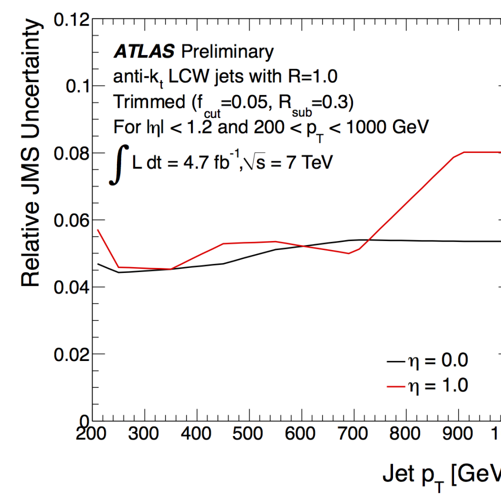
- Average jet mass as a function of the number of reconstructed vertices in fully simulated events for jets emanating from light quarks and boosted top quarks.
- Much reduced pile up dependence after trimming.
- Increased separation power.

Large-R jets performance

ATLAS-CONF-2012-065/066

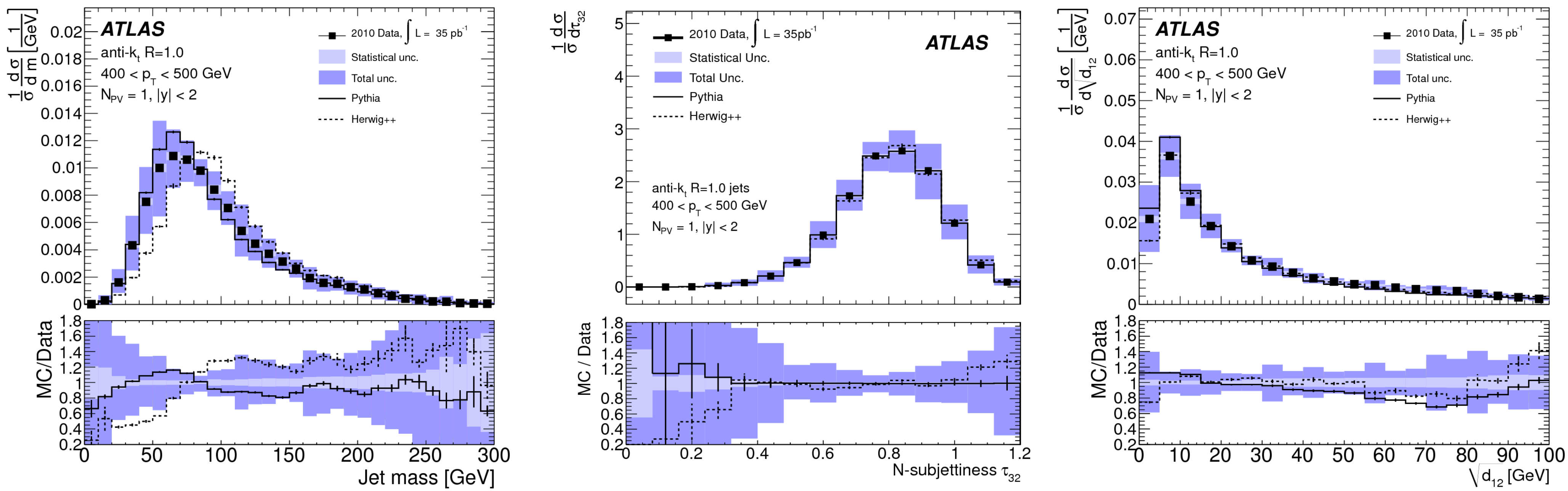


- Jet mass (upper row) and first k_t splitting scale (bottom row) for anti-k_t R=1.0 jets with and without trimming applied, in inclusive QCD dijet events.
- Good description by POWHEG in both cases, even in the tails.
- Jet mass scale validated in situ by comparing to jets built out of tracks from the inner detector. Systematic uncertainty estimated at ~ 4%-8%



Jet mass and substructure

arXiv:1203.4606, JHEP 1205 (2012) 128



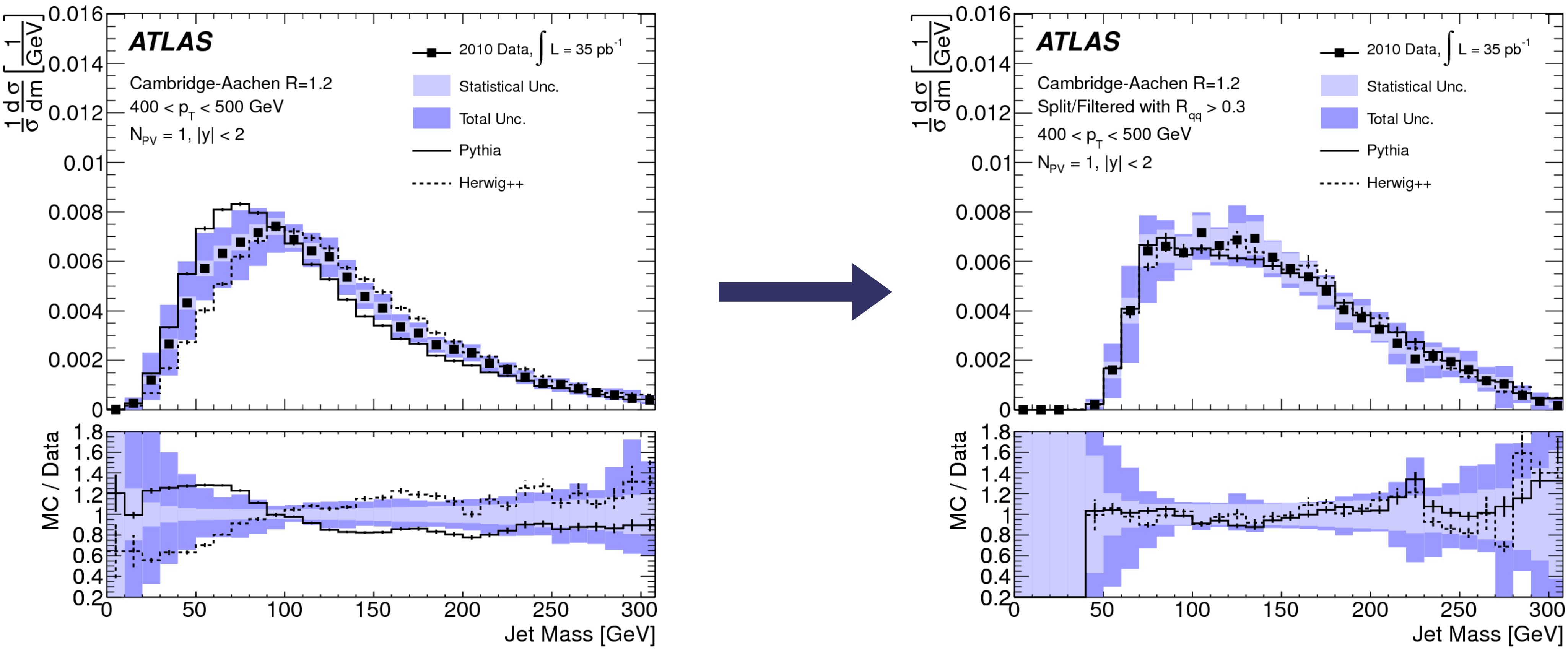
N-subjettiness measures the degree of resemblance of a jet with an N subjet configuration. $\sqrt{d_{12}}$ is the first k_t splitting scale; measures the hard substructure inside a jet.

- Analysis performed using 2010 dataset using high p_T *large-R* jets. Only one primary reconstructed vertex was allowed → no pile-up

- Jet mass shapes relatively well modelled
  - Pythia predictions → softer spectrum
  - Herwig++ predictions → harder spectrum
- Substructure variables are better reproduced by MC predictions than mass.

Jet mass and substructure

arXiv:1203.4606, JHEP 1205 (2012) 128



- Analysis performed using 2010 dataset using high p_T *large-R* jets. Only one primary reconstructed vertex was allowed → no pile-up

- *Split & Filtering* procedure identifies hard splittings in a jet's clustering history and filters out the remaining soft components
  - improves significantly the MC/Data agreement.