QCD jet results in ATLAS and CMS

Lene Bryngemark,
for the ATLAS and CMS collaborations

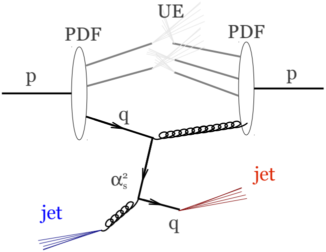
Lund University

Rencontres de Blois, May 29, 2013

Why study jets at the LHC?

Jets are abundant in the final states in the Large Hadron Collider

- a great place to learn about them
- often an important background to physics searches using other final states



We can learn about

- proton structure: parton distribution functions (PDFs)
- the strong coupling constant α_s and perturbative QCD (pQCD)
- non-perturbative effects

But: many steps from signal in detectors back to this picture.

I will pull out a few examples of what we can learn from the many recent studies of *pp* collisions in ATLAS and CMS

Not (by far) a full account!

Links to public results

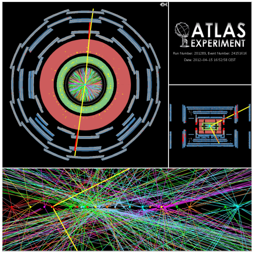
Outline:

Experimental challenge: pile-up

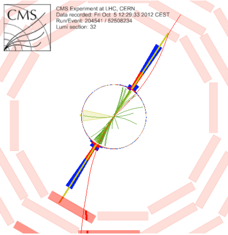
To increase statistics in search for rare phenomena, LHC luminosity is increased.

On average 20 simultaneous collisions in 2012!

$Z \to \mu\mu$ event, 25 primary vertices



- jets are extended objects
  $\Rightarrow$ sensitive to overlaid energy
- pile-up shifts the energy measurement and distorts p_T and angular resolution of jets
- large theory effort as well



ATLAS:

- subtract (pile-up density) $\times$ (jet area) from each jet[a]
- residual correction parametrised in measured number of pile-up events

CMS:

- jets from particle flow (reconstructing particle candidates by matching tracks, vertices, calorimet deposits) already reduces pile-up impact
- subtract (pile-up density) $\times$ (jet area) for neutral component and non-vertex-matched tracks, from each jet

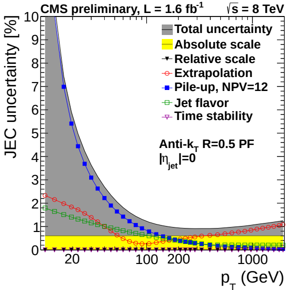
[a] M. Cacciari, G.P Salam

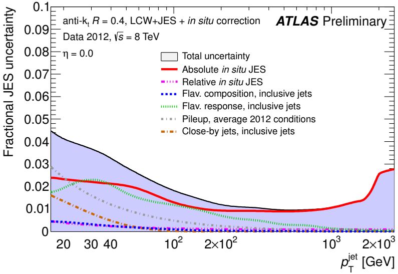
Calibration

Non-compensating calorimeters in both experiments. Sampling of shower particles has different calibration for electromagnetic and hadronic showers.

- jet energy is calibrated from EM to fully hadronic scale

  also compensation for energy lost in material upstream of calorimeter, thresholds (e.g., track p_T thresholds in particle flow), etc
- crucial point of any jet measurement
- based on combinations of test-beam and simulation, with data validation *in situ*, and depends on jet p_T and η
- often the dominant experimental systematic uncertainty!





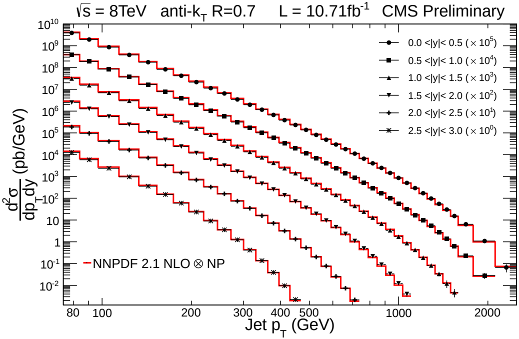
Physics measurements

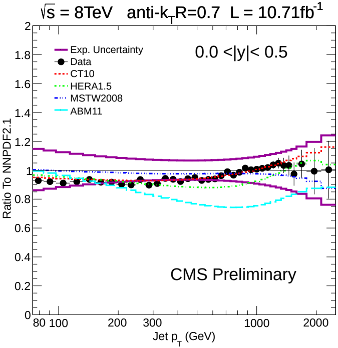
CMS: Inclusive jet cross section

CMS-PAS-SMP-12-012

Inclusive jet cross section can be calculated using pQCD

- can also constrain PDFs
- and determine α_s





- NLO prediction in good agreement with data over many orders of magnitude
- In ratio, most (NLO) PDFs agree with data within uncertainties

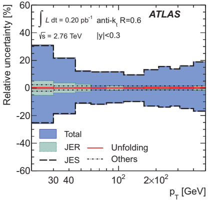
ATLAS: measuring PDFs

arXiv:1304.4739 (submitted to Eur. Phys. J.)

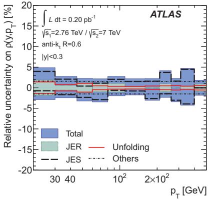
Quark distributions well constrained by HERA measurements over large range of momentum-transfer squared, Q^2, for Bjorken $x \lesssim 0.01$

- larger x gluon momentum distribution not as precisely known
- probed by inclusive jet p_{T} spectrum at low and moderate p_{T} ($\lesssim$ 100 GeV)

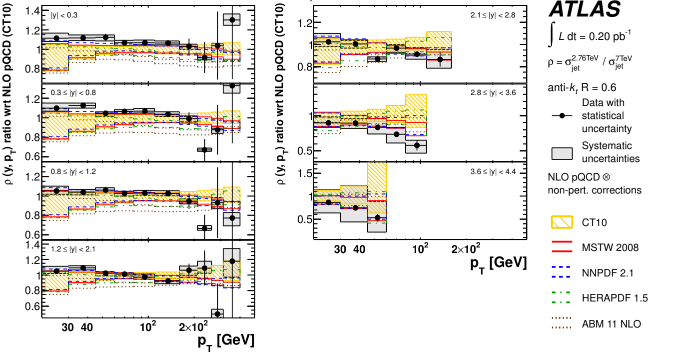
2.76 TeV only



Ratio to 7 TeV



7 TeV: 2010 data, 2.76 TeV: 2011 data

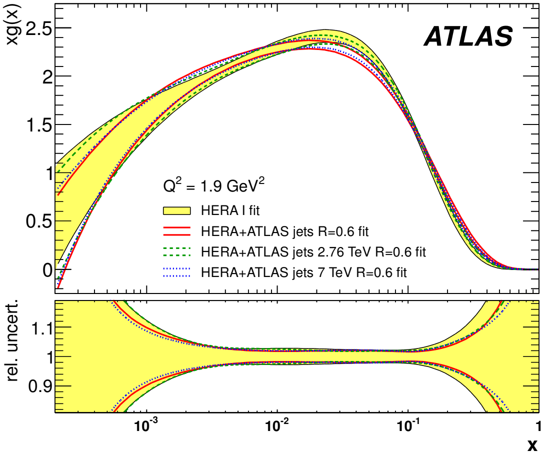


In the ratio of the inclusive jet p_{T} spectra at $\sqrt{s} = 2.76$ and 7 TeV respectively, ATLAS results are sensitive to PDF!

Results using HERAFitter

arXiv:1304.4739

Experimental uncertainties smaller than theoretical – check impact on PDF



- The gluon distribution becomes harder when ATLAS data are included (red solid line compared to yellow).
- See the large impact at $x \gtrsim 0.01$

ATLAS data combined with HERA-I DIS data. Only jets with $p_T > 45$ GeV included, to avoid large non-perturbative corrections and related large uncertainties

Measuring α_s

α_s is predicted to 'run', i.e. depend on the energy scale at which it is probed

- parameter of QCD; not predicted in itself
- has to be experimentally measured as a function of momentum transfer Q
- evolution from a starting point can be predicted via the renormalisation group equation (RGE)
- the LHC provides a new energy regime for testing this!

The probability to radiate an additional parton is proportional to an additional power of $\alpha_s \Rightarrow R_{32} = \frac{\sigma(\mathrm{N_{jets}} \geq 3)}{\sigma(\mathrm{N_{jets}} \geq 2)} \propto \alpha_s$.

In the ratio, many theoretical[1] and experimental uncertainties are reduced $\Rightarrow$ better precision.

[1] choice of renormalisation/factorisation scale, non-perturbative effects, evolution of PDFs to high Q...

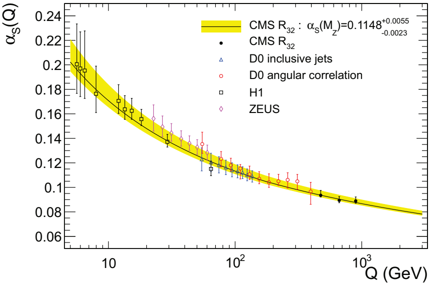
ATLAS and CMS: $\alpha_s(M_Z)$ and for a range of Q

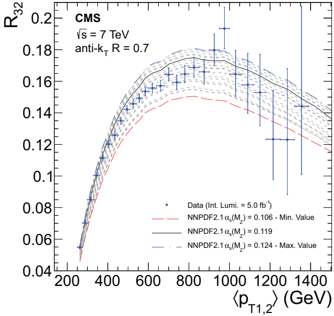
Method:
α_s extracted by comparison to prediction using NLO PDFs, for a range of α_s

ATLAS: $\alpha_s(M_Z) = 0.111 \pm 0.006(\text{exp})^{+0.016}_{-0.003}(\text{theory})$ ('theory' = scale; PDF and non-perturbative uncertainties negligible)

CMS: $\alpha_s(M_Z) = 0.1148 \pm 0.0014(\text{exp}) \pm 0.0018(\text{PDF})^{+0.0050}_{-0.0000}(\text{scale})$

ATLAS ATLAS-CONF-2013-041, 2010 data





Fits: NNPDF2.1; $\alpha_s = (0.106, 0.124)$

Running α_s:

Well described by RGE at this higher momentum range (first measurement at TeV scale)

CMS arXiv:1304.7498, 2011 data

Heavy flavour jets

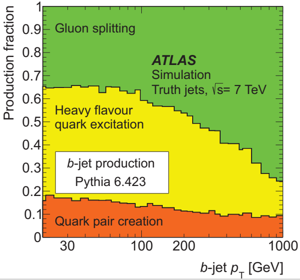
- Higher quark masses (above Λ_{QCD}) – soft (non-perturbative) hadronisation effects shouldn't influence total cross section ⇒ measures pQCD
- some tension in the past (Tevatron, HERA) with theory cross section predictions – what will we see at higher energies?
- at leading order: heavy quarks are pair produced in the hard interaction
  - ⇒ should be back-to-back, symmetric in momentum
  - ⇒ measuring angular correlations probes higher orders of pQCD

This is a good testing ground for your Monte Carlo!

Identification of heavy flavour origin jets: secondary vertices

'Light' jets = gluon and light quark (u, d, s) jets.

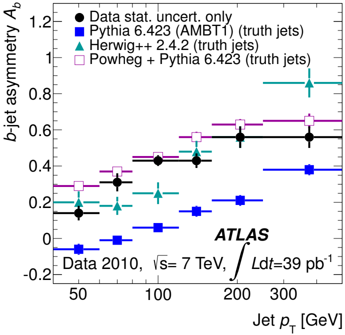
ATLAS: arXiv:1210.0441

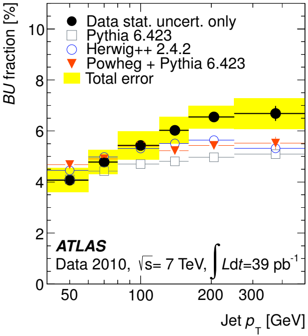


ATLAS: dijet flavour composition

EPJC(2013) 73:2301, 2010 data

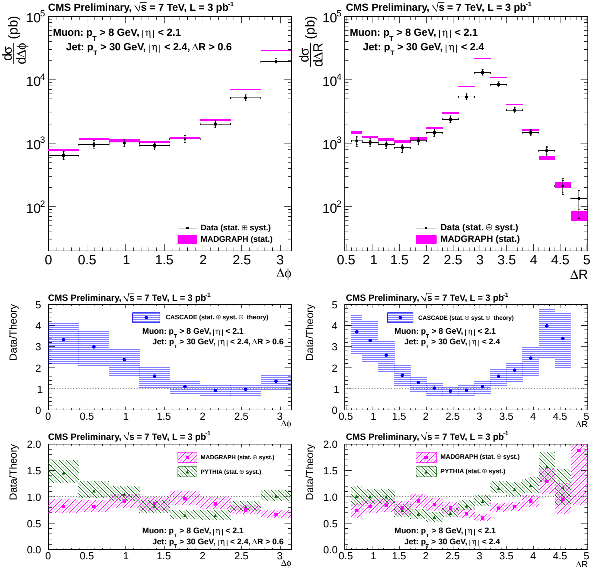
ATLAS measures heavy flavour fractions down to sub-percent level





- b-jet asymmetry: different b-hadron content in leading and sub-leading jets, not well described by PYTHIA6 – NLO accuracy needed
- b + light dijet flavour fraction shows largest deviation of MC from data (both LO and NLO)
- this final state especially probes b quark PDFs (“heavy flavour quark excitation”, sea quarks) and gluon splitting – non-perturbative effects

CMS: angular correlations between *b*-jets CMS PAS-BH-10-019, 2010 data



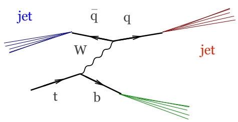
- MC cross sections *not* normalised to data!
- CASCADE and MADGRAPH: different matrix elements, but hadronisation is also using PYTHIA
- PYTHIA gets normalisation right but MADGRAPH predicts shape better

What do we know about jet structure?

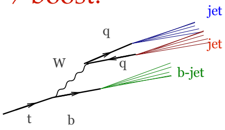
Jets are composite objects. Heavy particle decays (incl from new physics) can lead to substructure in jets, due to Lorentz boost. One example is to discern QCD bremsstrahlung from EW decays

- Several "substructure methods" exist, and could be employed to suppress QCD – given that we know what they do to QCD jets!
- We need to understand the structure of QCD jets
  - how well is jet mass modelled?
  - does ME+PS matching predict internal jet structure?

low-p_T top
$\Rightarrow$ "at rest":



high-p_T top
$\Rightarrow$ boost:



Exploding field: huge effort by many theorists.

Both ATLAS and CMS have published many performance studies on substructure techniques in recent years

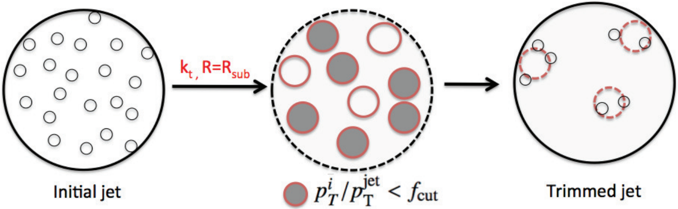
ATLAS results: ATLAS-CONF-2012-065, also see JHEP 1205 (2012) 128 (arXiv:1203.4606)

Recent results in CMS using jet filtering, jet trimming, and jet pruning (arXiv:1303.4811, 2011 data).

Filtering J. M. Butterworth et al., **Trimming** D. Krohn, J. Thaler, and L.-T. Wang; **Pruning** S. D. Ellis, C. K. Vermilion, and J. R.

First: trimming

1. Run a jet algorithm with large distance parameter
2. Rerun another algorithm on the large jets found, with smaller distance parameter
3. Out of the "subjets" found in step 2, keep only those above a certain p_{T} fraction out of the large jet p_{T}

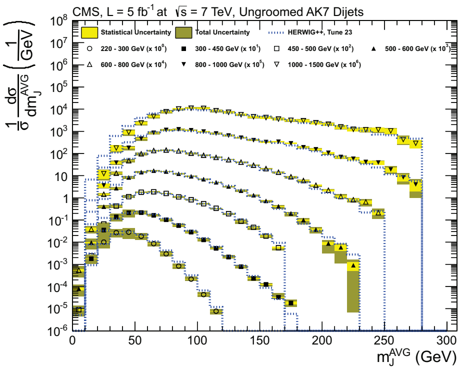


ATLAS graphic: ATLAS-CONF-2012-065

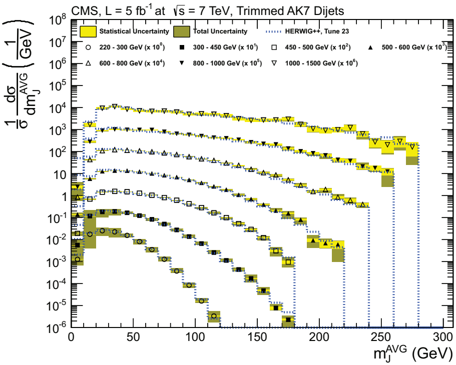
Results

arXiv:1303.4811 (submitted to JHEP)

Standard dijets



After trimming

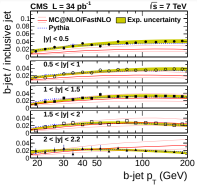


- Trimming shifts mass spectrum down
- Already good data/MC agreement from intermediate out to high-mass tails (where we might look for new physics)
- Trimming improves agreement at low masses (UE + pile-up removed)

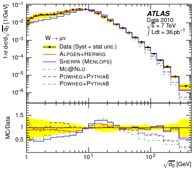
more MC comparisons in backup

Many more jet results

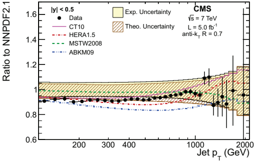
- More on *b*-quark production and fragmentation, LO and NLO comparison
  - CMS inclusive b-jet cross sections, and ratio to inclusive jets
- Precision MC test: resummation shape from parton showers, precision of matching methods
  - ATLAS k_T splitting scales in $W \to \ell\nu$ events
- Dijet mass spectra and further MC and PDF constraints
  - CMS inclusive jet and dijet cross sections
  - ATLAS high mass dijet production
- ATLAS Jet shapes in $t\bar{t}$, shown at DIS2013
- ...



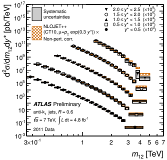
ATLAS arXiv:1302.1415 (submitted to EPJC)



CMS arXiv:1212.6660 (accepted by Phy.s Rev. D)



ATLAS ATLAS-CONF-2012-021



What did we learn?

What did we learn from jet measurements?

Jet measurements are precision measurements, providing valuable input for theory!

- α_s is measured in a new energy regime, and runs as expected
- Consideration of correlation between two jet measurements in ATLAS gives increased sensitivity to PDFs
- Heavy flavour jets reveal some discrepancies to in particular LO generators in jet bottom hadron content, and very small flavour fractions can be measured
- Jet substructure is increasingly well understood $\Rightarrow$ paves the way for new physics searches with jets

None of this would have been possible without an excellent understanding of our detectors, jet algorithms and experimental conditions.

Please consult the publications and backup for more detail.

Further publications can be found on the web at

ATLAS

Standard model results

CMS

Physics results
and in particular, Standard Model results with a jet result link:
Standard model (jet) results

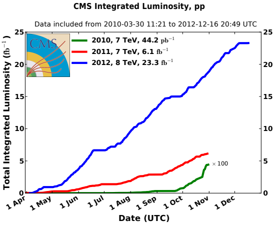
Backup

LHC

Collides *pp*, *pPb*, *PbPb*

pp energies 0.9, 2.36, 2.76, 7, 8 TeV

Delivered 23 fb^{-1} in 2012



The 2.76 TeV *pp* run serves as a reference for HI collisions at this $\sqrt{s_{NN}}$

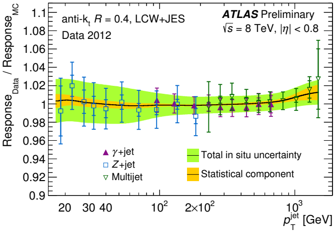
ATLAS and CMS

Multi-purpose detectors with hermetic energy coverage in azimuth

Pseudorapidity coverage $|\eta| \lesssim 5$

Jet energy scale uncertainty evolved from $5 - 10\%$ to typically $1 - 3\%$ over past few years

In situ methods exploit p_{T} balance between jets and other objects

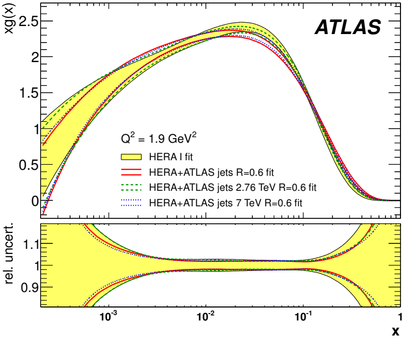


Results using HERAFitter

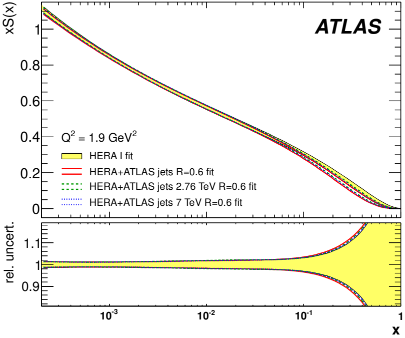
arXiv:1304.4739

- The gluon (sea quark) distribution becomes harder (softer) when ATLAS data are included (red solid line compared to yellow).
- DGLAP evolution from initial scale $Q_0^2 = 1.9\ \text{GeV}^2$

Gluon distribution



Sea quark distribution

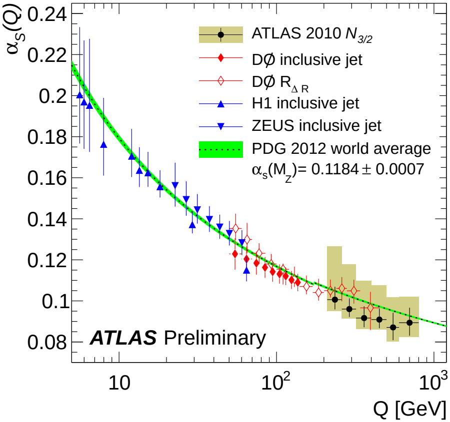


ATLAS data combined with HERA-I DIS data. Only jets with $p_{\text{T}} > 45$ GeV included, to avoid large non-perturbative corrections and related large uncertainties

α_s: ATLAS

- $Q = \sum_{jets} p_T$
- $N_{3/2}(p_T^{\text{all jets}}) = \frac{\sum_i^{N_{jet}} \left(d\sigma_{N_{jet} \geq 3} / dp_{T,i} \right)}{\sum_i^{N_{jet}} \left(d\sigma_{N_{jet} \geq 2} / dp_{T,i} \right)}$
- This definition was found to be less sensitive to scale choices than R_{32}
- α_s determined by comparing to NLOJet++ with MSTW 2008 NLO PDFs, for a range of α_s
- Comparison to four PDF sets; all results compatible within uncertainties
- Running α_s: evolve $\alpha_s(M_Z)$ from individual $p_T^{\text{all jets}}$ bins to bin average p_T using 2-loop solution to RGE

ATLAS ATLAS-CONF-2013-041



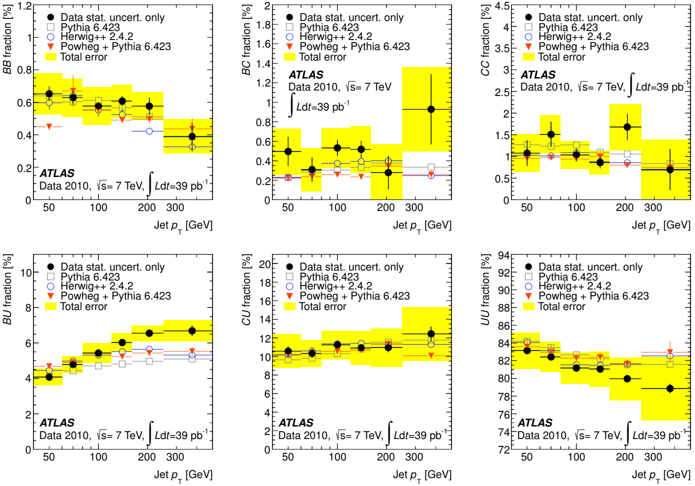
Line: evolution from PDG value
2010 data

Asymmetric errors from scale uncertainties

α_s: CMS

- $Q = \langle p_{T1,2} \rangle = \frac{p_{T1}+p_{T2}}{2}$
- $R_{32} = \frac{d\sigma_{3+}/dQ}{d\sigma_{2+}/dQ}$
- Comparison to four PDF sets; impact of NLO vs NNLO on measured quantity found to be negligible (even though impact on individual cross sections large – cancellation); AMB11 PDFs found to not describe data well however
- Running α_s: evolve $\alpha_s(M_Z)$ using 3-loop solution to RGE from NNPDF2.1

Heavy flavours



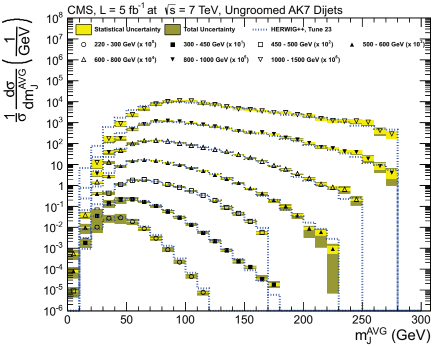
Flavour not individually determined, but using template fits exploiting different kinematic properties of the secondary vertices inside jets

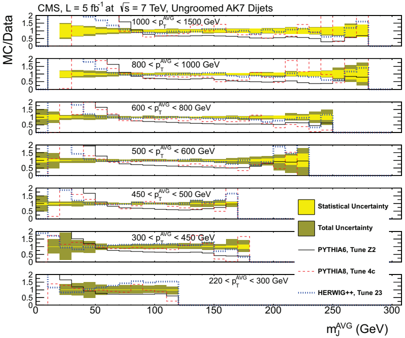
Light quark ("U") vertices mostly due to K_S^0 and Λ decay, or to fake vertices (notably for subleading jets) or interactions in material – increase at high p_T

Good agreement with MC for most flavour compositions

Standard dijets

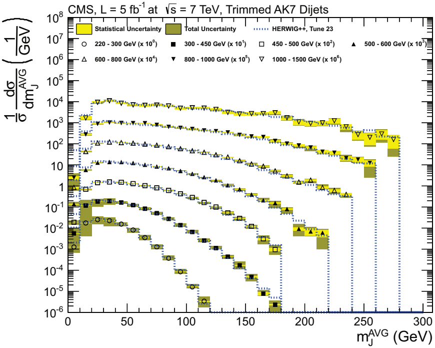
arXiv:1303.4811 (submitted to JHEP)

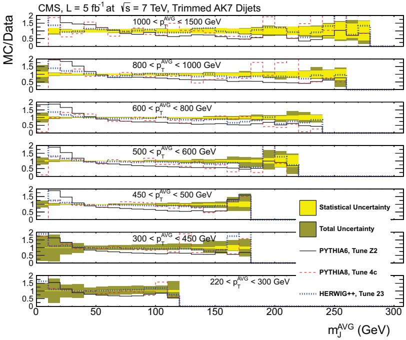




After trimming

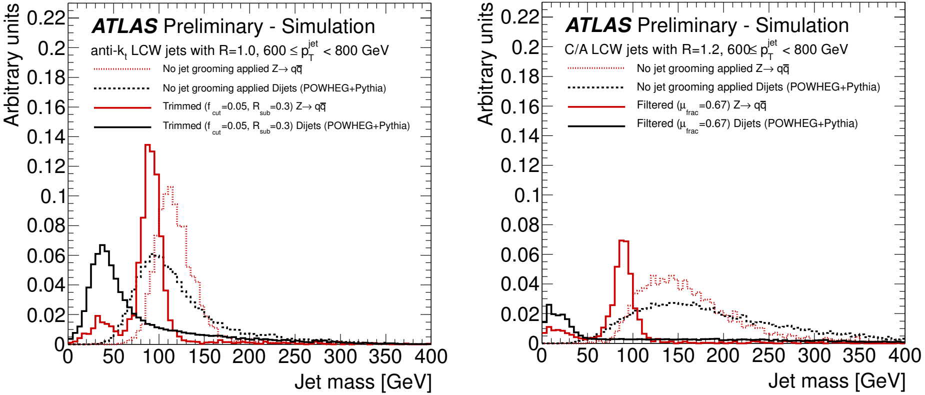
arXiv:1303.4811 (submitted to JHEP)





More jet grooming algorthms shown in the article

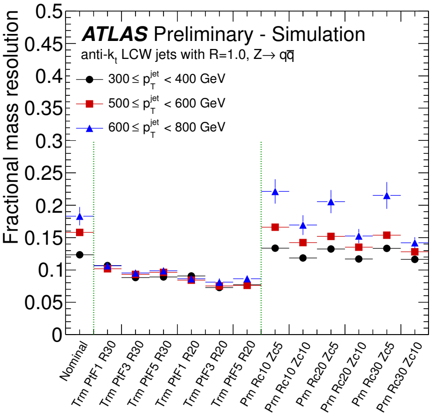
ATLAS-CONF-2012-065 (also see JHEP 1205 (2012) 128 (arXiv:1203.4606))

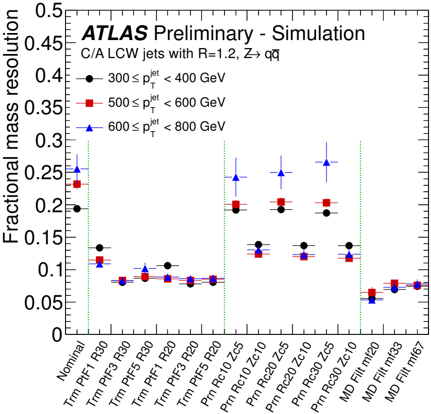


Solid lines: Trimming (anti-k$_t$) and filtering (Cambridge/Aachen) pulls out the Z peak, compared to ungroomed (dotted lines)

ATLAS jet substructure results

ATLAS-CONF-2012-065 (also see JHEP 1205 (2012) 128 (arXiv:1203.4606))





Trimming and pruning, and for Cam/Aach also Mass drop/filtering. Comparison of different parameter settings. Nominal means non-groomed.

Further publications can be found on the web at

ATLAS

Standard model results

CMS

Physics results
and in particular, Standard Model results with a jet result link:
Standard model (jet) results

back