Measurement of jet fragmentation at ATLAS

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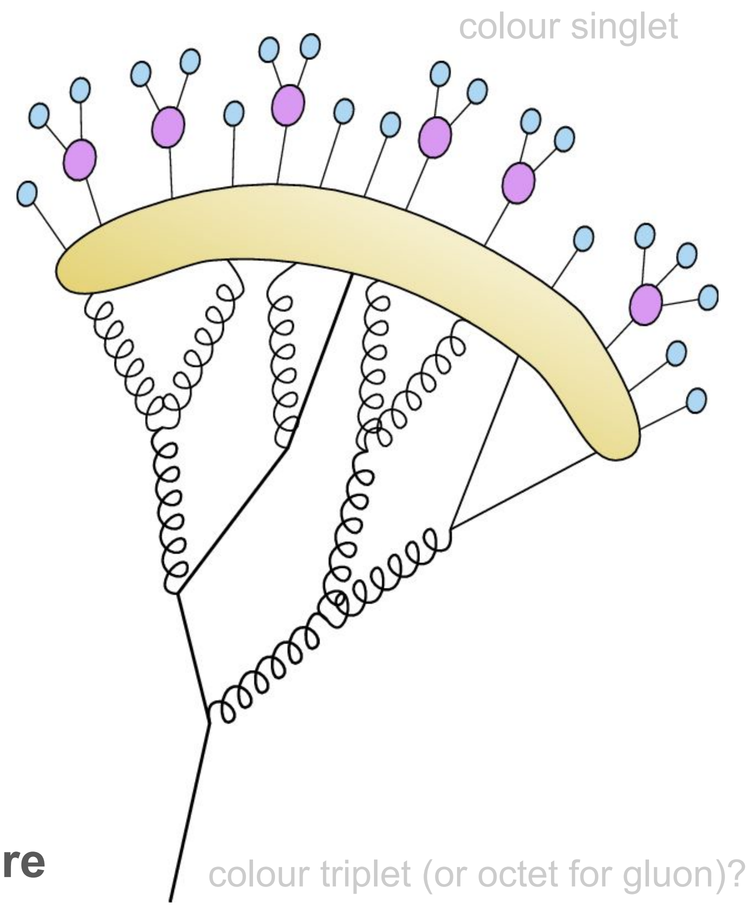
Jet fragmentation

In leading-order QCD, well-separated jets and partons are exactly equivalent

Broken by evolution from fixed-order to “real” jets: a multi-scale phenomenon including both perturbative QCD radiation and non-perturbative hadronisation

Collectively this process can be considered as the *fragmentation* of a parton into the multi-hadron spray of a particle-level jet

Measuring jet fragmentation means understanding the emergence of jet structure



ATLAS jet fragmentation measurements

Previous ATLAS measurements of jet fragmentation:

Eur. Phys. J. C 76 (2016) 322 — Measurement of the charged-particle multiplicity inside jets from $\sqrt{s}$ = 8 TeV pp collisions with the ATLAS detector arXiv:1602.00988

Phys. Rev. D 93 (2016) 052003 — Measurement of jet charge in dijet events from $\sqrt{s}$=8 TeV pp collisions with the ATLAS detector, arXiv:1509.05190

Eur. Phys. J. C 71 (2011) 1795 — Measurement of the jet fragmentation function and transverse profile in proton-proton collisions at a center-of-mass energy of 7 TeV with the ATLAS detector, arXiv:1109.5816

+ 2011 jet shapes arXiv:1101.0070 and **2018 $g \rightarrow bb$ jet properties** arXiv:1812.09283

Today: presentation of new ATLAS jet fragmentation measurement at 13 TeV

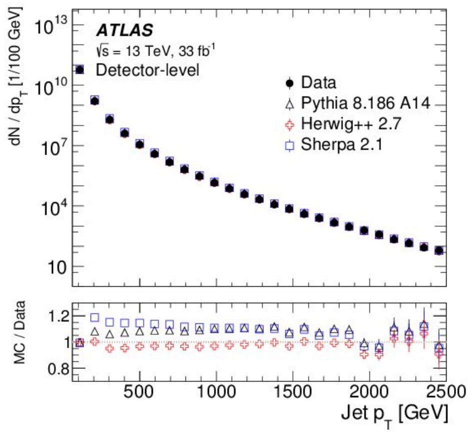
ATLAS jet fragmentation at 13 TeV — arXiv:1906.09254

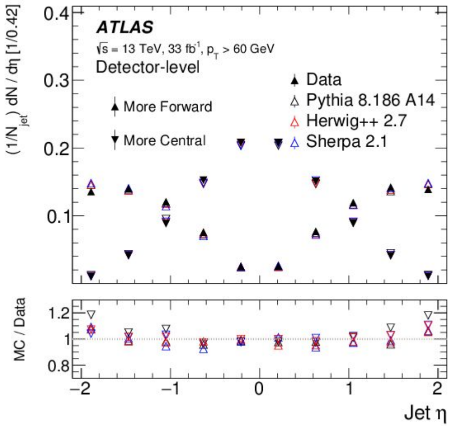
Uses 33 fb^{-1} dataset of 13 TeV pp collisions from 2016

- Increased phase space & jet p_T reach wrt 7, 8 TeV
- Makes use of Run 2 tracker upgrades, e.g. IBL
- Dense-environment tracking, for $\langle\mu\rangle \approx 25$

At least two jets with $|\eta| < 2.1$, and $p_T > 60$ GeV

- $|\eta|$ requirement for full containment in tracker
- $p_{T1}/p_{T2} < 1.5$ balance to simplify interpretation
- $p_T > 100$ GeV at fiducial level
- Charged tracks ghost-associated to calo jets





Observables

Fragmentation function *D* defined as p_T fraction of hadron *h* wrt its containing jet p_T, from parton *p*.
⇒ DGLAP pQCD evolution; mirror image of PDFs

$$\mu \frac{\partial}{\partial \mu} D_p^h(\zeta, \mu) = \sum_{p'} \int_\zeta^1 \frac{d\zeta'}{\zeta'} \frac{\alpha_S(\mu) P_{p' \leftarrow p}(\zeta', \mu)}{\pi} D_{p'}^h\left(\frac{\zeta}{\zeta'}, \mu\right)$$

This paper uses charged hadrons, but full (calo) jet
⇒ $\langle n_{ch} \rangle$ and differential $1/N_{jet}\, dN_{jet}/d\langle n_{ch} \rangle$

$$\langle n_{ch} \rangle (p_T^{jet}) = \sum_p f_p(p_T^{jet}) \sum_{h \text{ charged}} \int_{\text{threshold}/p_T^{jet}}^1 d\zeta\, D_p^h(\zeta, p_T^{jet})$$

- **summed fragmentation function:**
  differential in p_T fraction ζ *and* jet p_T ⇒ extract partial fractions, moments & weighted sums

$$F(\zeta, p_T^{jet}) = \sum_p f_p(p_T^{jet}) \sum_{h \text{ charged}} D_p^h(\zeta, p_T^{jet})$$

- Relative transverse momentum
  Radial profile (non-p_T-weighted)

$$p_T^{rel} \equiv p_T^{\text{charged particle}} \sin \Delta\phi$$

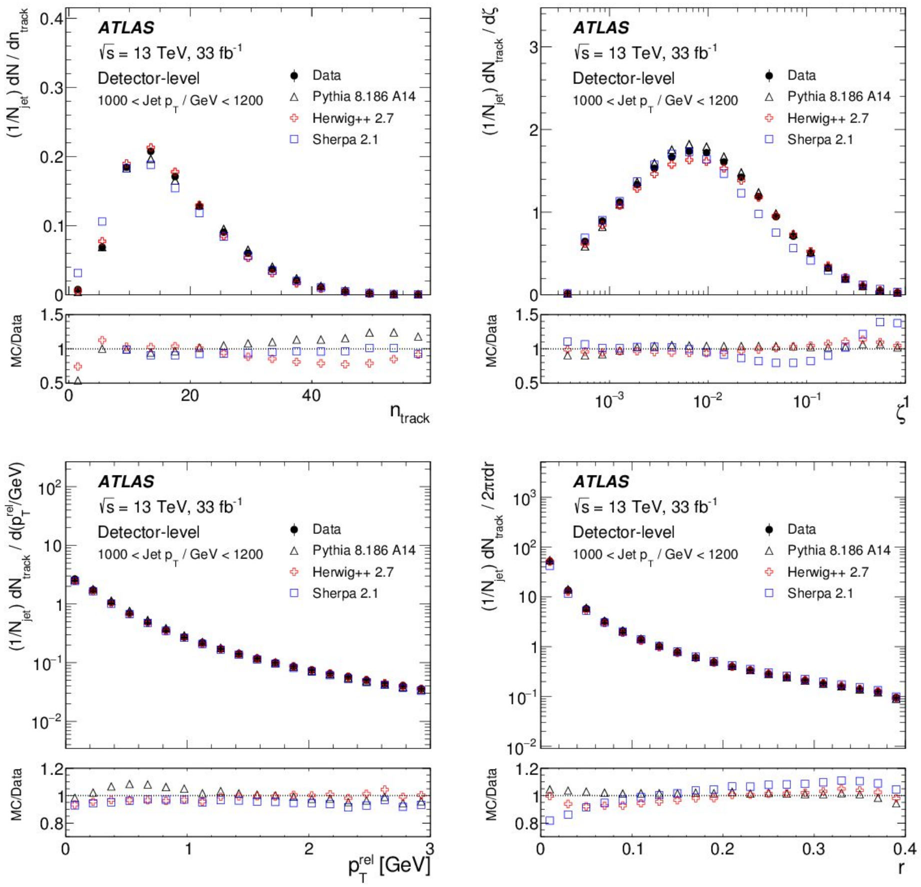
$$\rho_{ch}(r, p_T^{jet}) = (1/N_{jet}) dn_{ch}/2\pi r dr$$

Detector-level variables

Raw distributions of n_{trk}, track momentum fraction, track $p_{T,rel}$, and track radial profile

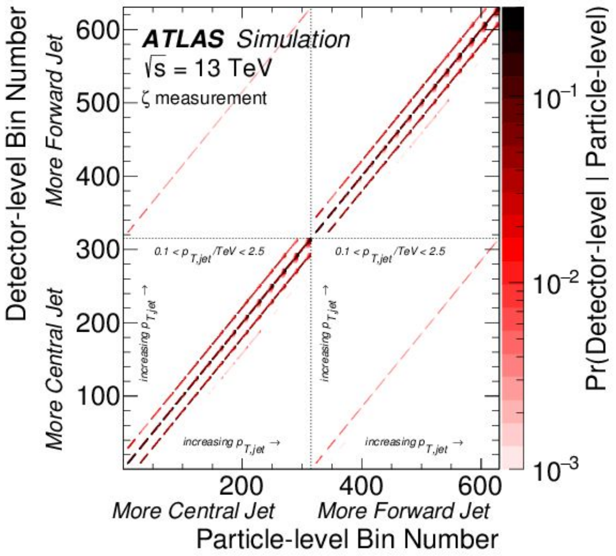
For a 1 TeV jet, most probable n_{trk} is ~15, and most probable momentum fraction ~1%

Track $p_{T,rel}$ and r (radial profile) distributions peak at zero since radiation dominantly collinear



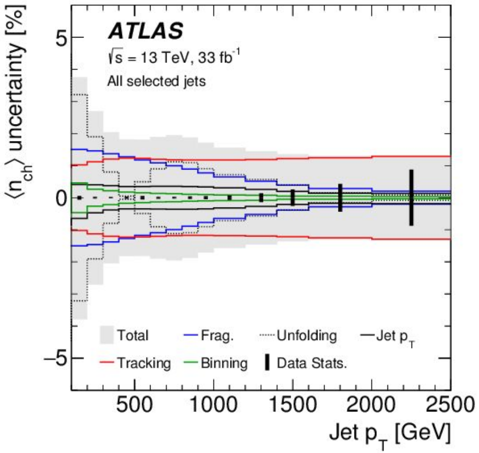
Detector correction & uncertainties

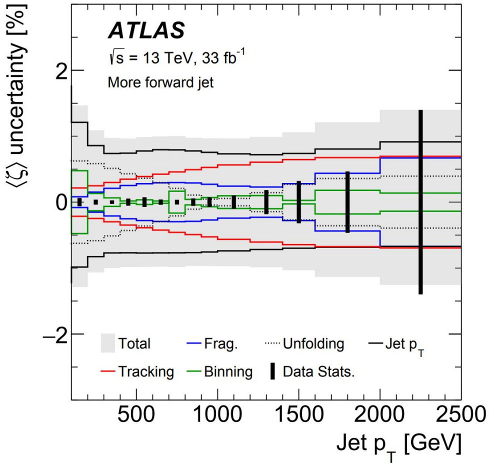
Unfolding from detector obs to fiducial phase space:
particle-level tracks & jets from particles with
$c\tau_0$ > 10 mm; muons and neutrinos excluded from jets



Unfolding by 2D iterative Bayes method (1 iter) sandwiched by explicit in/out migration corrs.

Main uncertainties:
tracking, jet scale, binning & unfolding, depending on observable

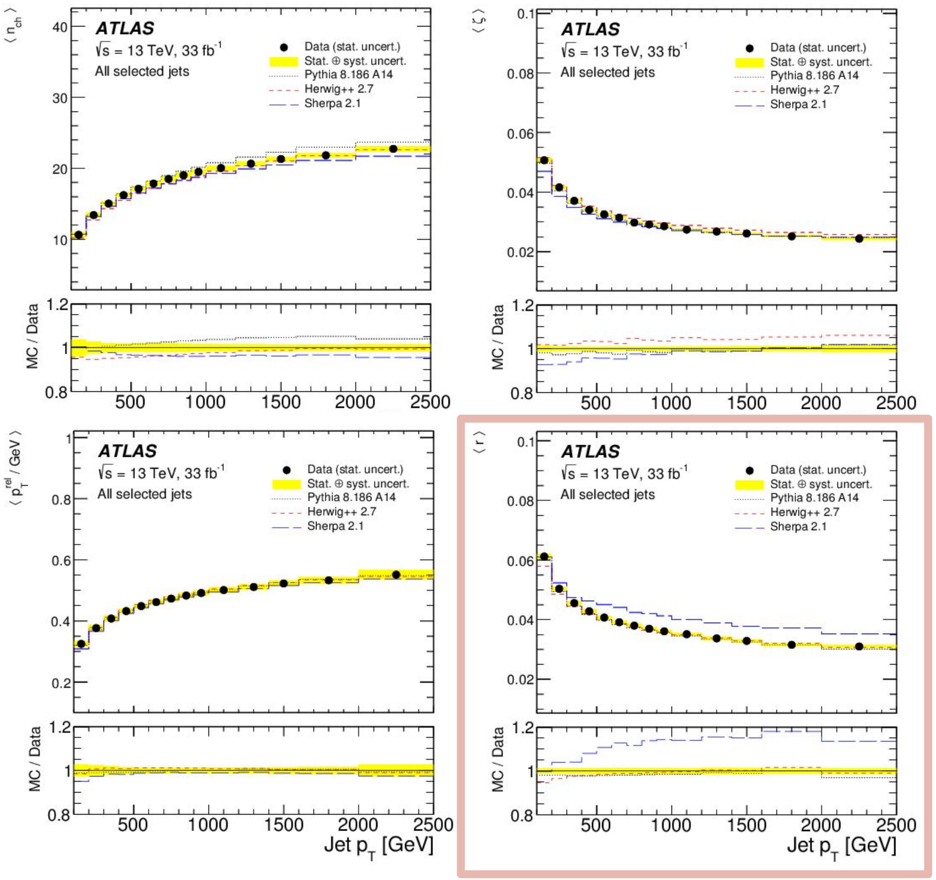




Unfolded average observables

Average observables vs p_T generally well-described by main shower MC codes (Pythia8, Herwig++ and Sherpa)

Hints of deviation from Sherpa, particularly in radial profiles — these are a standard component of MC tuning since 7 TeV jet-shape paper… but only for jet pT < 500 GeV!



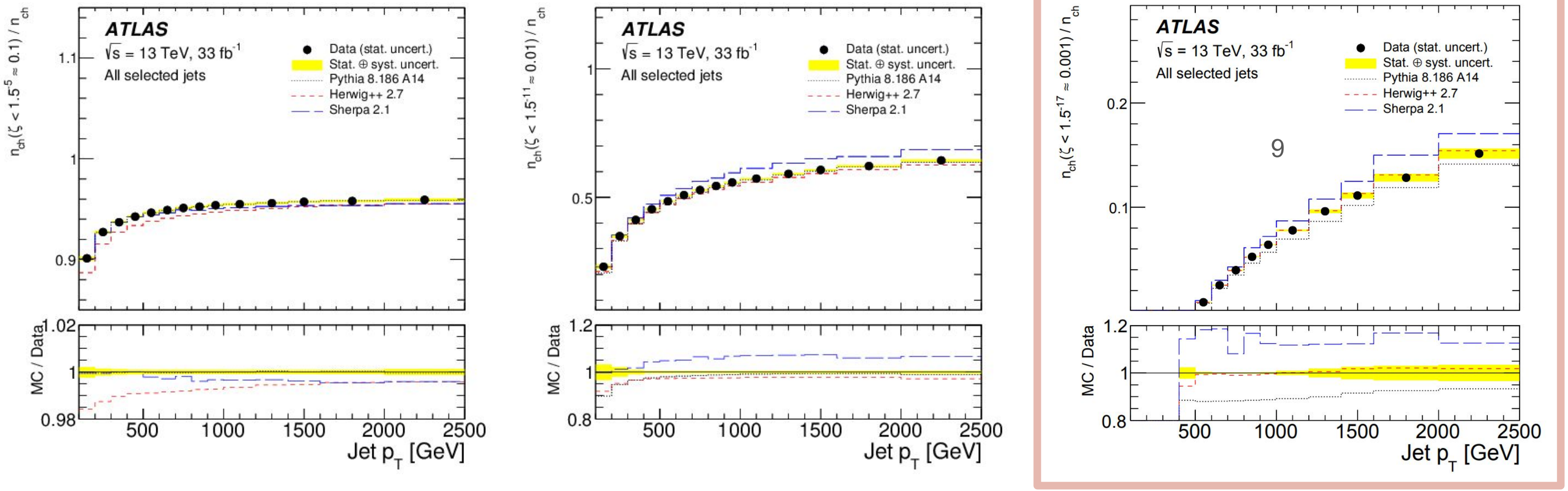
Unfolded partial sums: $n_{\rm ch}$ fraction in bins of ζ

$$\int_0^X F(\zeta)d\zeta \, / \int F(\zeta)d\zeta = n_{\rm ch}(\zeta < X)/n_{\rm ch}$$

Fractions of charged particles with $\zeta \lesssim$ 10%, 1%, and 0.1% vs jet p_T

Fraction of small-fraction particles increases with jet p_T, cf. hadronisation scale

Small mismodelling of 10% by Herwig; with Sherpa & Py8 in less inclusive bins



Unfolded observable moments & weighted sums

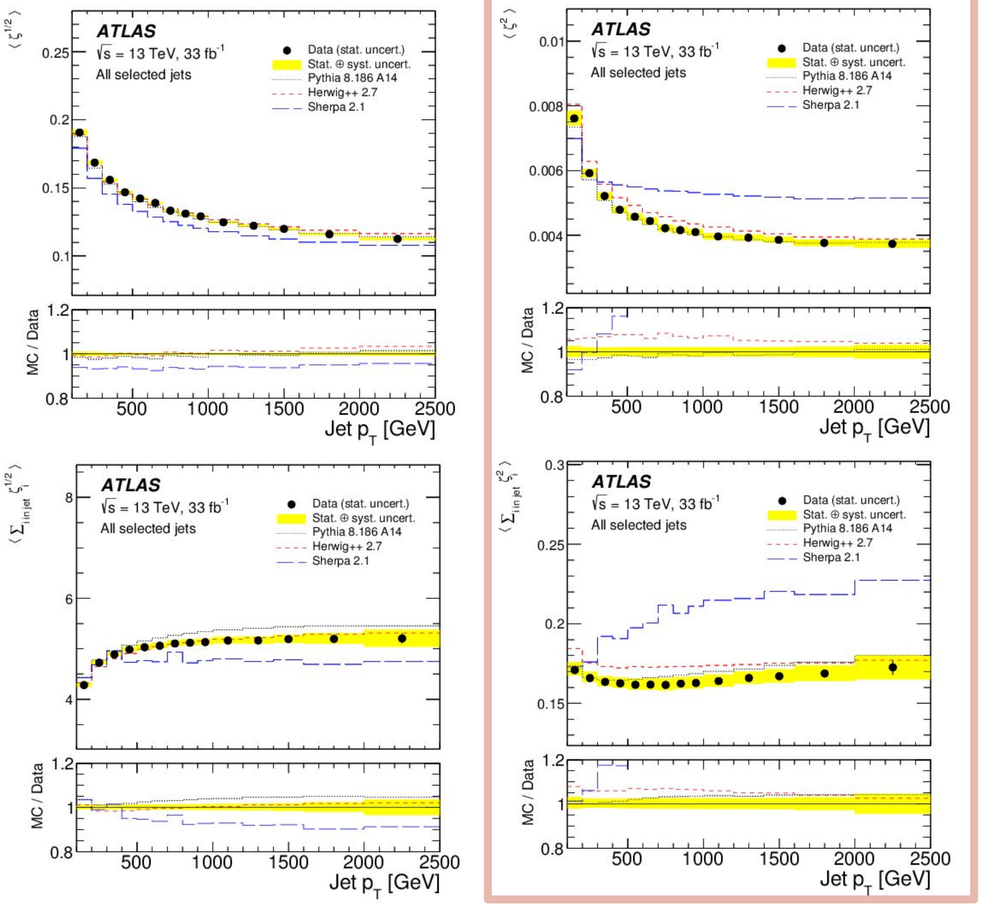
Also observables computed as moments and weighted sums with the p_T fraction ζ raised to powers $\kappa = 0.5$ and $\kappa = 2$:

$$\langle \zeta^{\kappa} \rangle = \int \zeta^{\kappa} F(\zeta) d\zeta \,/ \int F(\zeta) d\zeta$$

$$\langle \textstyle\sum_{i \in \mathrm{jet}} \zeta_i^{\kappa} \rangle = \int \zeta^{\kappa} F(\zeta) d\zeta$$

Pythia 8 and Herwig++ mostly well-behaved; major discrepancies seen for Sherpa, esp. for κ = 2

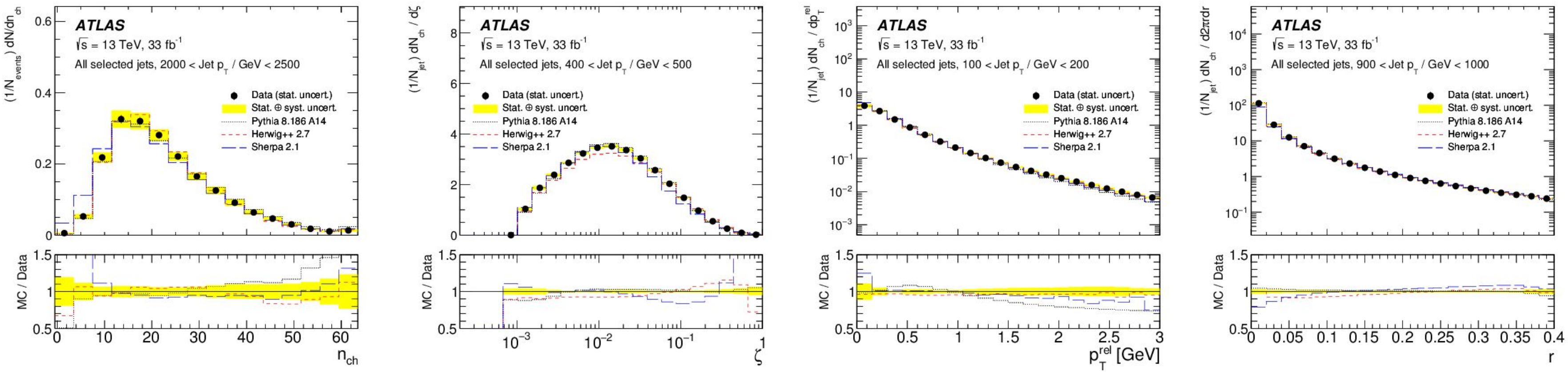
[effectively a var(ζ) measurement]



And more!

Differential distributions of every core variable in bins of jet p_T

A treasure-trove of data for jet modelling & resummation studies!



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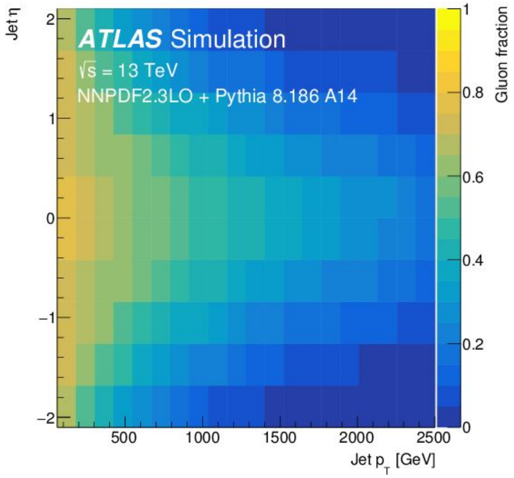
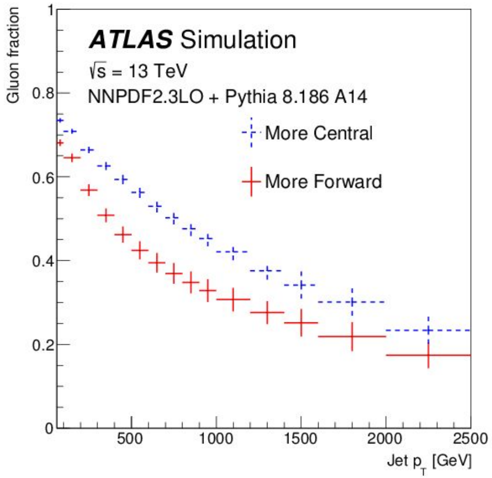
Quark/gluon jet discrimination

An important application of jet structure data is development of methods to extract information about quark/gluon jet origins

Ideally in a well-defined, QCD-aware way!

- **Central/forward jet:** roughly, central and low-p_T jets are more likely to be gluon-initiated
- ⇒ Extract q/g components with an MC-template procedure
- **New:** model-independent q/g extraction by data-driven “topic” modelling





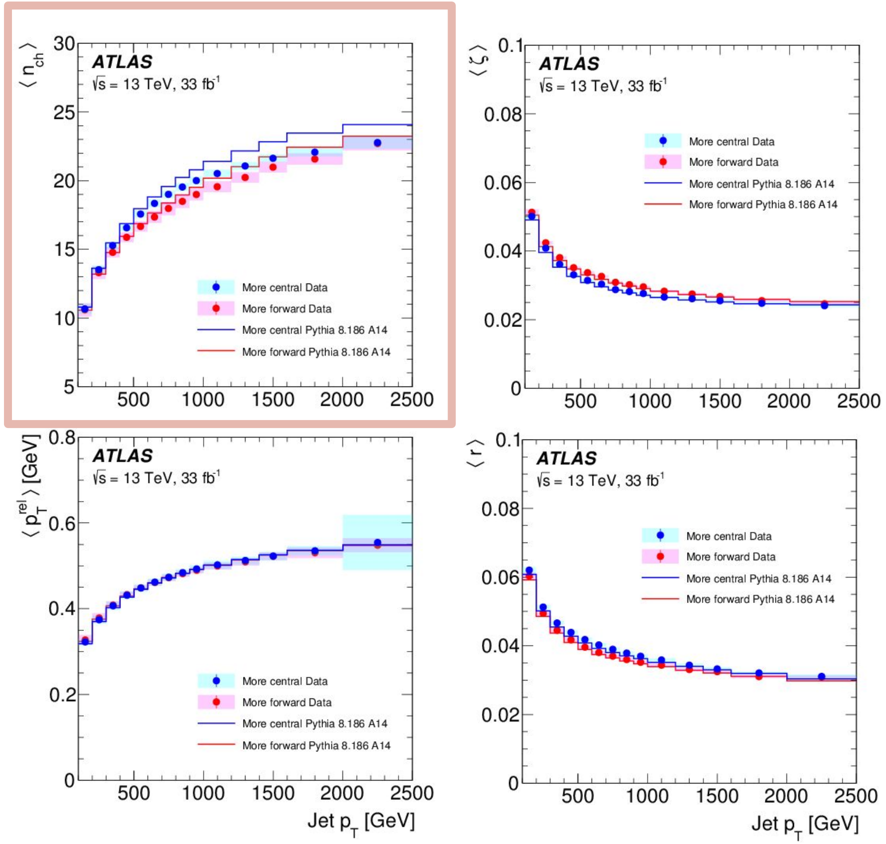
Mean observables with central/forward-jet split

Aim of central/forward jet distinction is to bias quark or gluon jet origin

Biases allow extraction of separate q/g-like fragmentation functions by comparison of forward and central jet ones

Note Pythia mismodelling of split n_{ch} distributions, unlike inclusive.

Most c/f-split mean observables are well-described



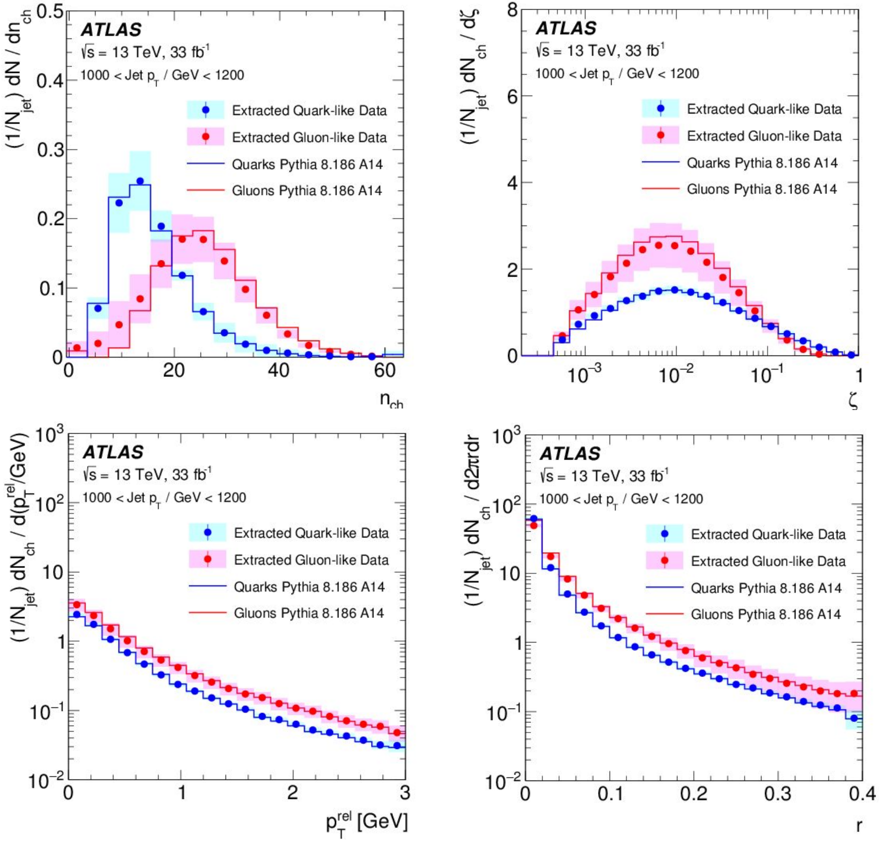
Model-dependent quark/gluon jet characterisation

q/g extraction by use of MC flavour fractions *f*, nominally from Pythia:

$$h_i^f = f_q^f h_i^q + (1 - f_q^f) h_i^g$$
$$h_i^c = f_q^c h_i^q + (1 - f_q^c) h_i^g$$

Jet flavour defined by hardest parton geometrically associated to the jet: many theory issues, and potential sources of uncertainty

Extracted q/g-like fragmentation observables fit expectations:



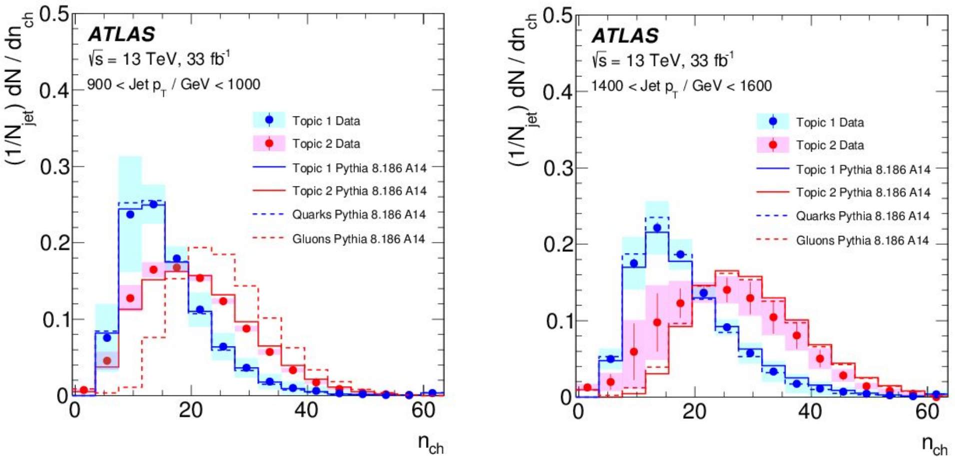
Model-independent quark/gluon jet characterisation

Novel approach is to use "topic modeling" extraction.

The categories are defined by data rather than MC internals:

$$h_i^{T_1} = \frac{h_i^f - \left(\min_j\{h_j^f/h_j^c\}\right) \times h_i^c}{1 - \min_j h_j^f/h_j^c}$$

$$h_i^{T_2} = \frac{h_i^c - \left(\min_j\{h_j^c/h_j^f\}\right) \times h_i^f}{1 - \min_j h_j^c/h_j^f}$$

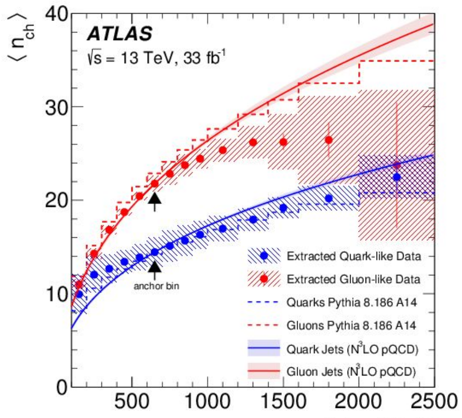


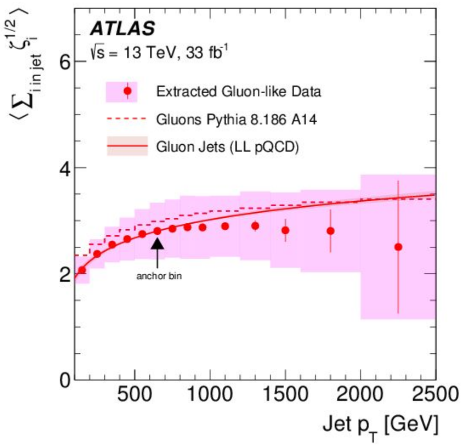
Interesting new approach. Limitation: alignment of topics to q and g template ideas relies on the existence of bins dominated by q or g: applies to n_{ch} distribution only

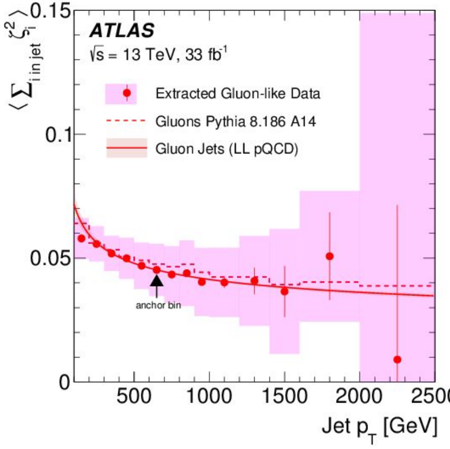
Comparing quark/gluon jet characterisations

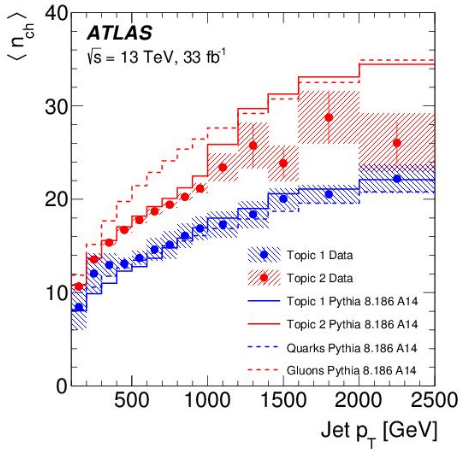
Pythia-based vs topic modeling: good description by Pythia for quarks in both; less good for gluons. "Quark" topic also aligns well with quarks, worse for gluons.

pQCD normalization-anchored, since can't handle non-perturbative physics: compares well to q/g extractions









Conclusions

- **New ATLAS measurement of jet fragmentation observables**
- Very comprehensive study of charged jet constituent distributions, unfolded to fiducial phase-space for MC comparisons
- Inclusive / averaged observables generally described well by popular SHG MC generators; differential and weighted/moment observables reveal issues. Breakdowns in MC shower tuning to lower-p_T jet moment observables?
- Extraction of quark/gluon fragmentation function components by model-dependent and new model-independent means. Both perform well for quarks, gluons more difficult. Comparisons with pQCD look consistent
- **All data public on HepData for MC/pQCD development & tuning**

ATLAS g→bb fragmentation — arXiv:1812.09283

Super-quick summary: b-tagged track subjets in boosted jets

Fiducial differential cross-sections in b-subjet separation, mass, p_T balance, and polarisation angle

Key: flavour fit via signed impact param