Measurement of jet fragmentation using the ATLAS detector

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Outlook

- **Short introduction**

- **Properties of jet fragmentation using charged particles at 13 TeV**

- **Properties of g→bbar at small opening angles at 13 TeV**

What is a jet?

- At short distances quarks and gluons move as quasi-free particles (asymptotic freedom)
- When they are energetic, they produce bremsstrahlung cascades of gluons and qqbar pairs, which then hadronise (via a "fragmentation process")
- We see jets of tightly collimated hadrons
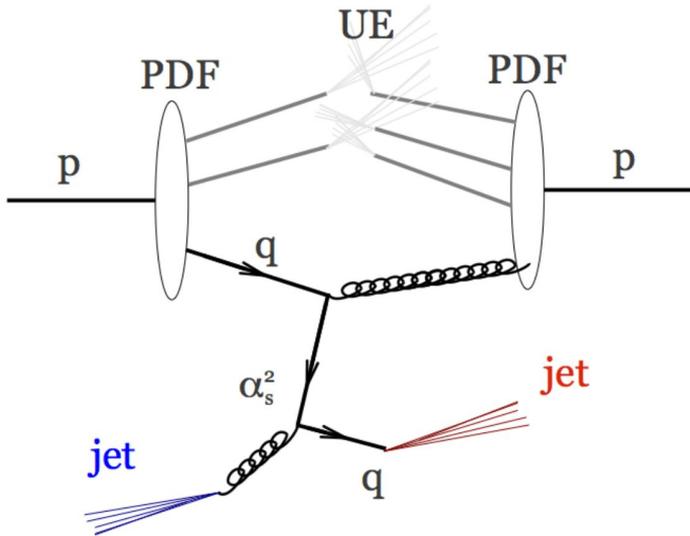
- There are a lot at the LHC! (dominant high p_T process)

- Jet properties reflect those of the quarks and gluons which originated them

- A good handle to test the QCD sector of the SM over many orders of magnitude
    - Proton structure (PDF)
    - Strong coupling constant, α_s
    - Perturbative QCD effects
    - Fragmentation/Hadronization effects

Fragmentation

- The scattering of the proton constituents is well described by perturbative QCD and leads, at lowest order, to final states of gg, gq, and qq
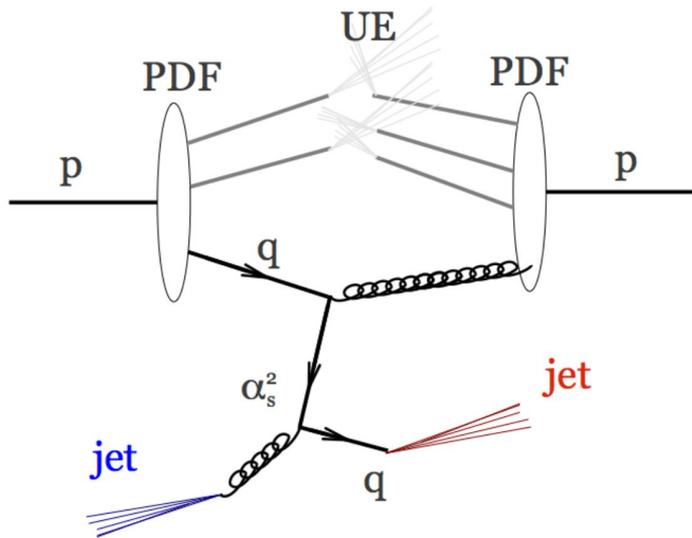

- The fragmentation process is more complex
  - initial parton carries color but the jet consists of colorless hadrons
    - must connect outgoing partons to the rest of the event
  - production of hadrons at an energy scale where the QCD coupling constant is large
    - perturbation theory cannot be used

- Fragmentation is therefore described using a QCD-motivated model with parameters that must be determined from experiment

Properties of jet fragmentation using charged particles measured with the ATLAS at 13 TeV

arXiv:1906.09254 [hep-ex]

Motivation

- Measuring basic quantities related to fragmentation is essential to furthering our understanding of the emergent properties of QCD
  - Tune MC parameters

- Study fragmentation using charged particle tracks is a classic example (SPS: Z. Phys. C 20 (1983) 117)

- This study provides
  - increased jet energy range (due to the larger 13 TeV)
    - probes jets with p_T up to 2.5 TeV

  - improved precision
    - advances in software for tracking in dense environments
    - additional insertable B-layer
    - excellent experimental control
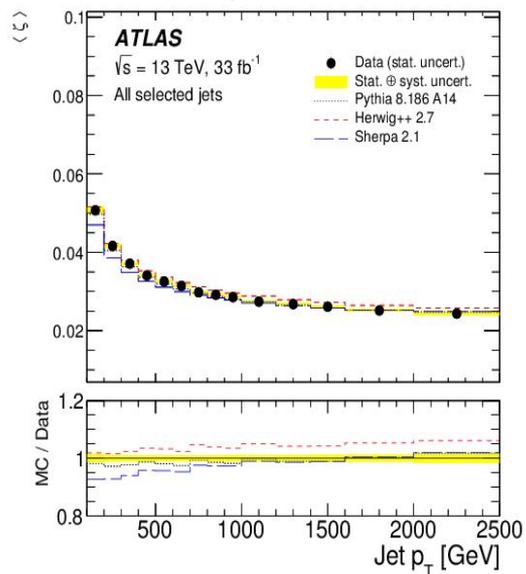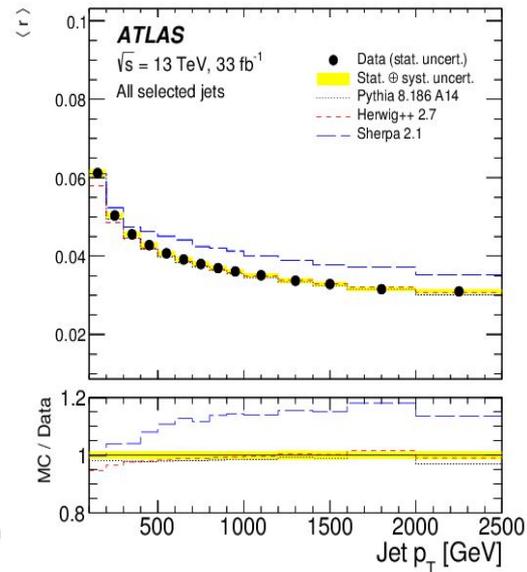   - systematic uncertainties at the level of 1-2%

p_T fraction

charged-particle multiplicity
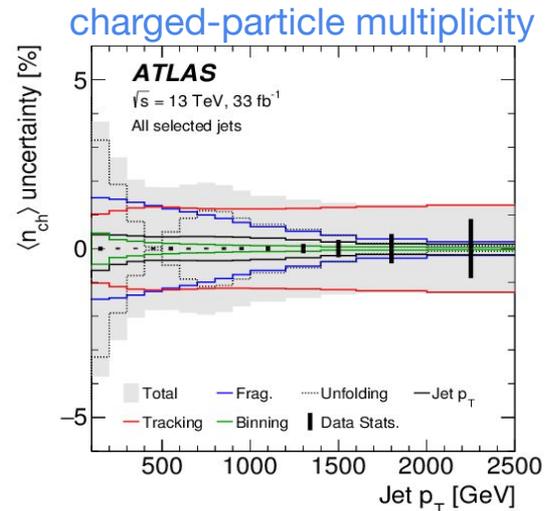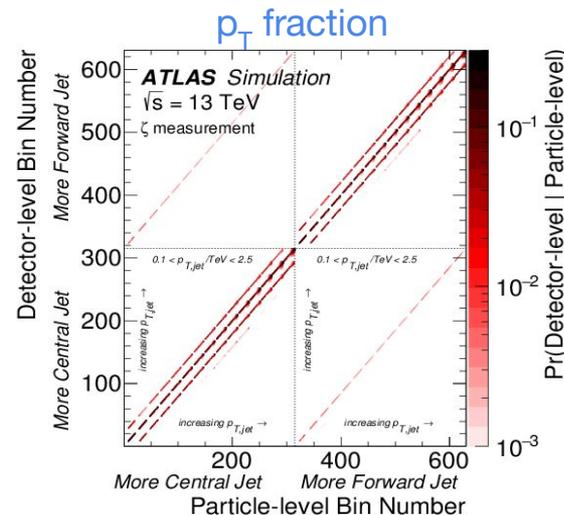
Results
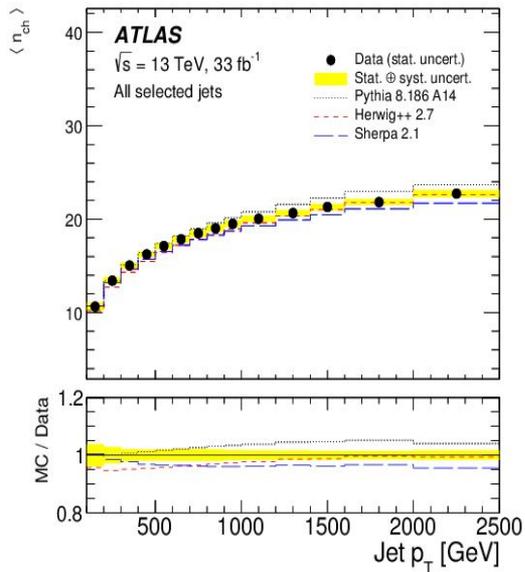
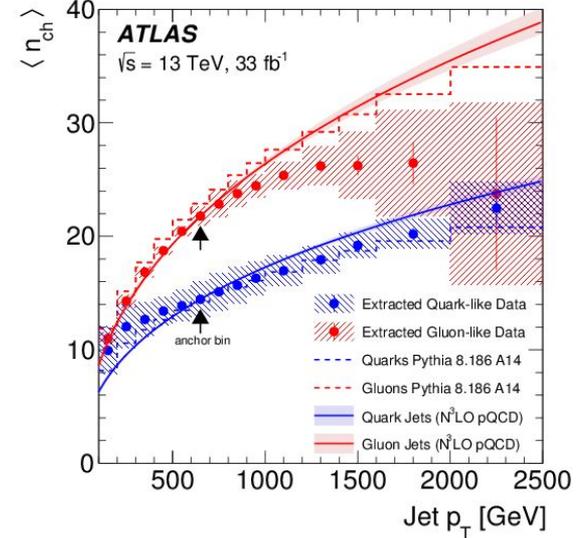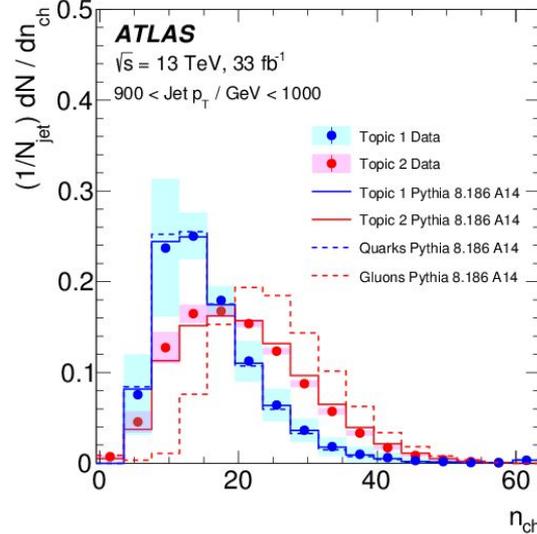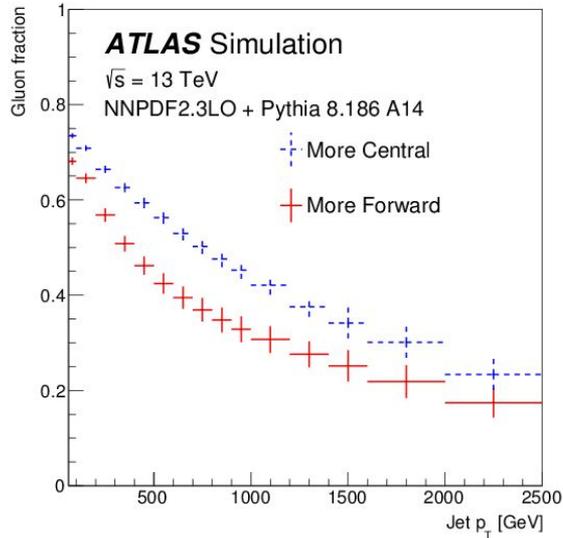charged-particle multiplicity p_T fraction   radial profile

- Pythia and Herwig agree well with data
- Sherpa less so

Results

- Operational hadron-level definition of quark and gluon jets needed
  - most jet-by-jet tagging is highly dependent on PS

- Charged particle multiplicity in forward vs central dijets
 - Rapidity used to isolate quark-like and gluon-like topics

- MCs provide a reasonable description of the quark-like data, but the gluon-like data have systematically fewer charged particles than the simulations

Properties of g→bbar at small opening angles in ATLAS at 13 TeV

Phys. Rev. D 99 (2019) 052004

Motivation

- Critical process for deep understanding of the Standard Model
  - Gluon splitting is a fundamental component of QCD
  - Careful measurement required for understanding Higgs couplings
  - Backgrounds, calibration, b-tagging, jet substructure all come together
  - Also important to constrain difficult backgrounds in BSM searches

- Using b-tagged track jets (R=0.4) associated to a large-R (R=1.0) calorimeter jet
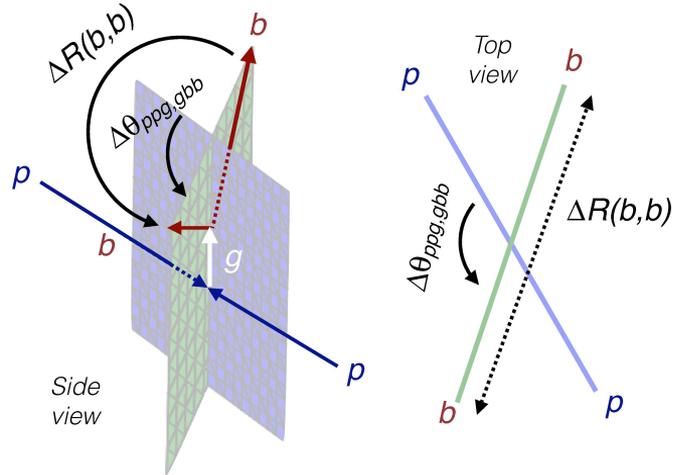
- 4 quantities studied:
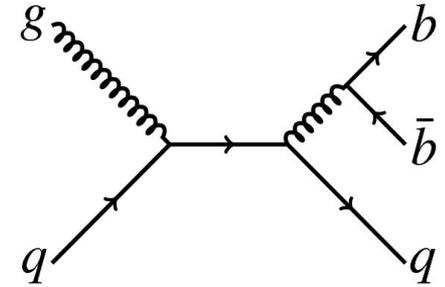
$$\Delta\theta_{\mathrm{ppg,gbb}}$$
$$\log(m_{bb}/p_{\mathrm{T}})$$
$$z(p_{\mathrm{T}}) = p_{\mathrm{T},2}/(p_{\mathrm{T},1}+p_{\mathrm{T},2})$$
$$\Delta R(b,b) = \sqrt{\Delta\phi(b,b)^2 + \Delta\eta(b,b)^2}$$

Systematics

	$\Delta R(b, b)$	$\Delta\theta_{\mathrm{ppg,gbb}}$	$z(p_{\mathrm{T}})$	$\log(m_{bb}/p_{\mathrm{T}})$
Calorimeter jet energy	2–3%	2–3%	2–6%	2–4%
Flavor tagging	<1%	<1%	<1%	<1%
Tracking	1–2%	1–2%	2–4%	1–2%
Background fit	1%	1%	1–2%	2%
Unfolding method	2–3%	2%	2–4%	2–5%
Theoretical modeling	3–10%	2–13%	3–10%	4–11%
Statistical	1%	1%	2%	1%
Total	3–10%	3–10%	3–14%	4–12%

- Measurement dominated by theoretical modeling
- Large-R JES dominates experimental systematics

Results

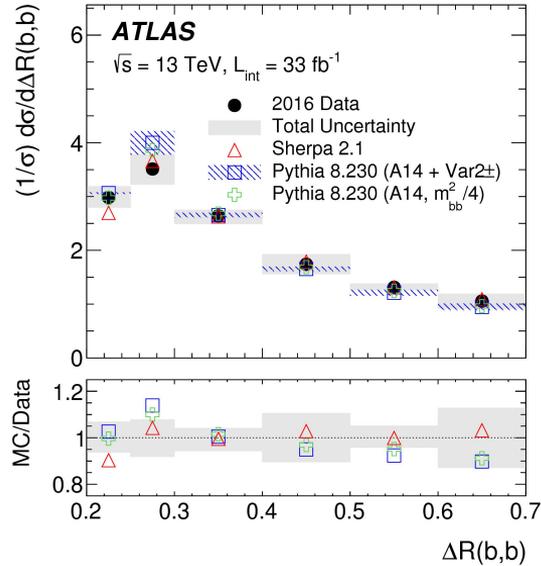- A flavor-fraction fit is used to remove contributions from processes other than g → bbar
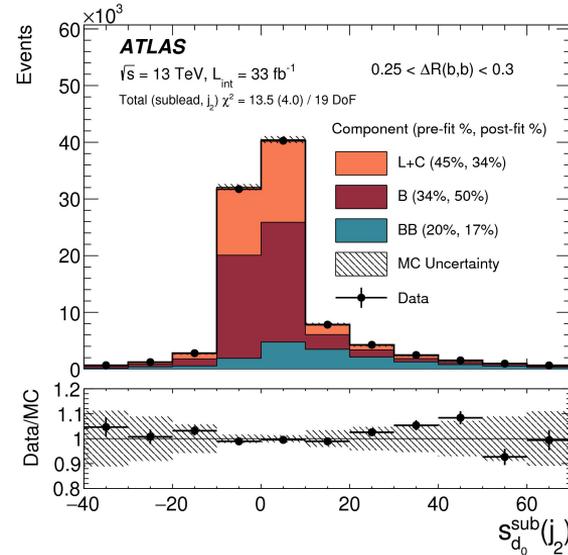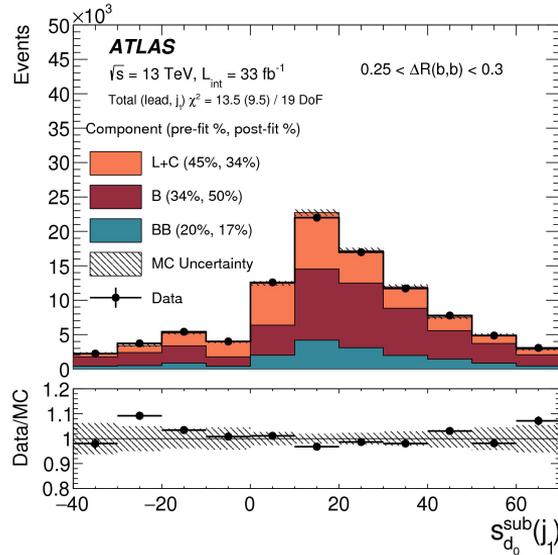
- The fitted fractions significantly disagree with the pre-fit Pythia predictions and suggest that further studies could improve the modeling of analyses sensitive to these fractions.
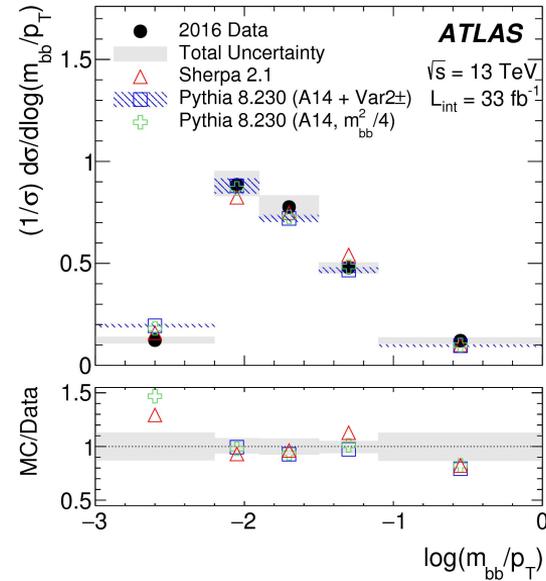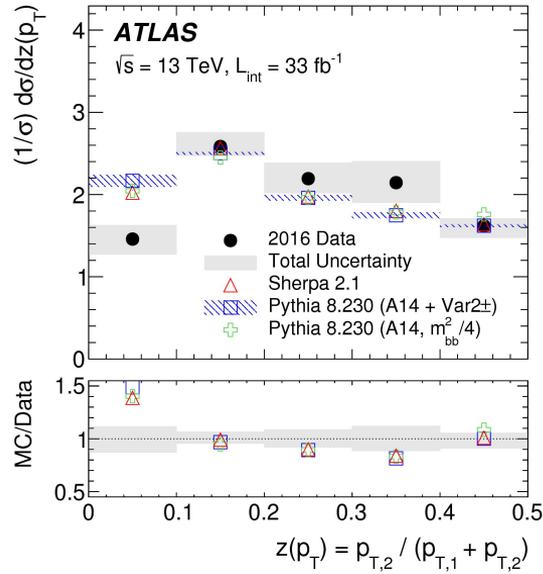
Results

- Differences between MC and data
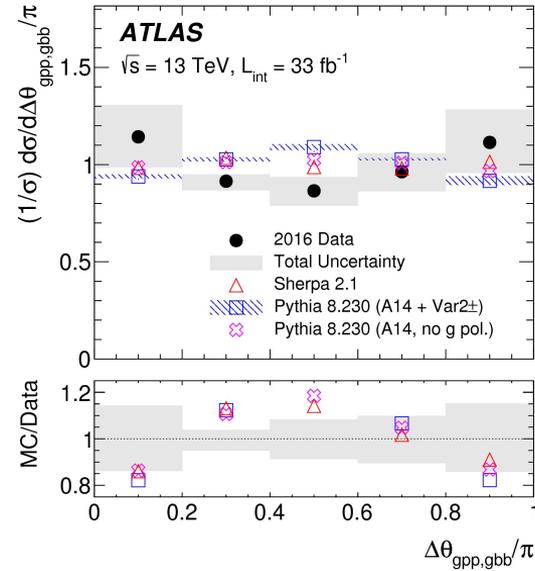
- Basic modelling of ΔR is good
- Decay plane more difficult. Missmodelling of gluon polarization in unpolarized hadrons

Results

- Good modelling of momentum sharing and invariant mass
  - Except at low values

Conclusions

- Fragmentation is described using a QCD-motivated model with parameters that must be determined from experiment

- Presented recent ATLAS measurements of jet fragmentation at 13 TeV

    - **using charged particles** (arXiv:1906.09254)
        - Percent-level uncertainties for pT ~ 1 TeV
        - Pythia and Herwig agree well with data. Sherpa needs better tuning
        - MCs provide a reasonable description of the quark-like data, but the gluon-like data have systematically fewer charged particles than the simulations

    - **g→bbar at small opening angles** (Phys. Rev. D 99 (2019) 052004)
        - Basic modelling is good
        - Angular quantities are modelled somewhat better with Sherpa than Pythia

- Stay tuned for future measurements...

Thanks

Selection

	Particle level	Detector level
Pileup	–	Identify primary vertex
Jet algorithm	Anti-k_t, $R = 0.4$	
Jet requirements	$|\eta| < 2.1$	
Jet constituents	Particles with $c\tau > 10$ mm prior to detector interactions excluding μ and ν	Calorimeter energy clusters
Measurement inputs	Charged jet constituents, $p_{\mathrm{T}} > 500$ MeV and $|\eta| < 2.5$	Ghost-associated tracks, $p_{\mathrm{T}} > 500$ MeV and $|\eta| < 2.5$
Event selection	At least two jets, with the leading two satisfying $p_{\mathrm{T}}^{\mathrm{lead}}/p_{\mathrm{T}}^{\mathrm{sublead}} < 1.5$	
Jet selection	Leading two, separated by η (more forward/central)	