Precision measurements of the jet production at the ATLAS experiment

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Low-x 2021 (Isola d'Elba, Italy)

28/09/2021

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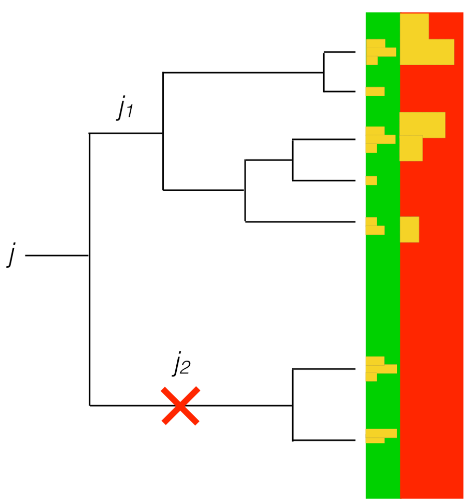
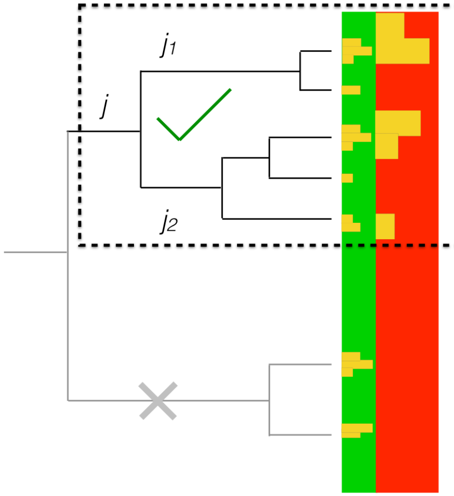
Outline of the talk

- Several measurements of jet fragmentation and substructure recently published by the ATLAS Collaboration:
  - Soft-drop jet observables - Phys. Rev. D 101 (2020) 052007
  - Hadronic event shapes in high-p_T multijet final - JHEP 01 (2021) 188
  - Lund jet plane using charged particles - Phys. Rev. Lett. 124 (2020) 2 22002
  - b-quark fragmentation properties - 2108.11650 (submitted to JHEP)
- Motivation for such measurements:
  - Sensitive to parton shower and fragmentation models in MC simulations
  - Compare to resummed theoretical predictions beyond leading logarithm
  - Gain understanding in quark/gluon jet separation
    - Interesting from the theoretical point of view
    - Experimentally useful to reduce JES uncertainties

Soft-drop jet observables

- Dijet (anti-k_t algorithm, R = 0.8) events with $p_{T,1} / p_{T,2} < 1.5$ are selected
- Two inputs for jet substructure: cluster and tracks (p_T > 500 MeV)
- Jet constituents (tracks, cluster) are resclustered using Cambridge-Aachen (C/A) algorithm
- The last step of clustering is undone, producing subjets 1 and 2
- Subjets 1 and 2 are evaluated using the soft-drop condition: $\frac{\min(p_{T1}, p_{T2})}{p_{T1} + p_{T2}} > z_{\rm cut} \left(\frac{\Delta R_{12}}{R}\right)^{\beta}$
- Remove the lower p_T subjet and iterate until the condition is fulfilled



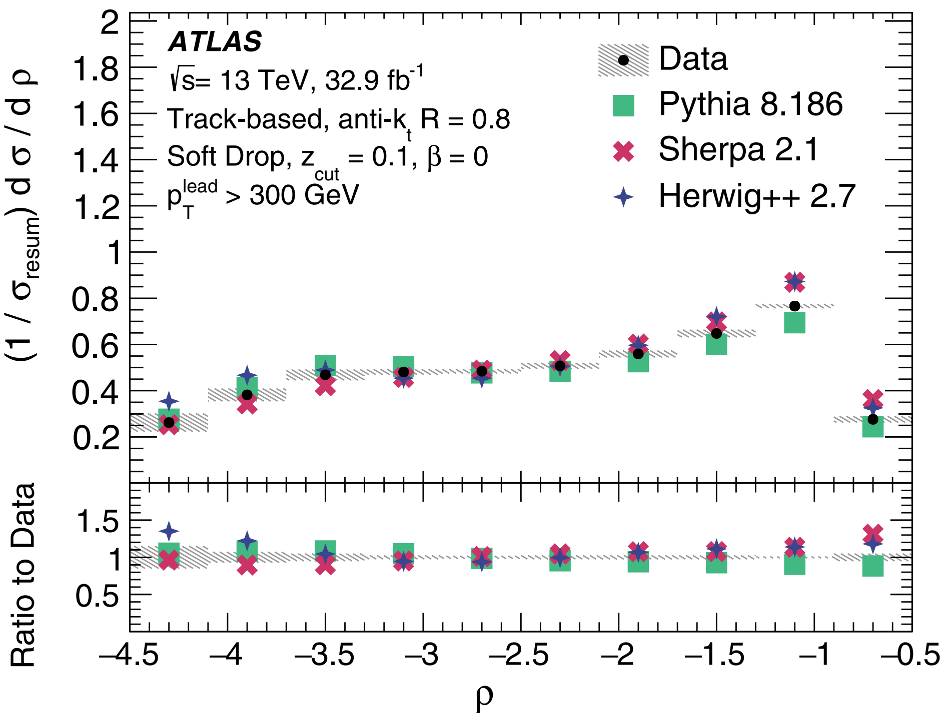


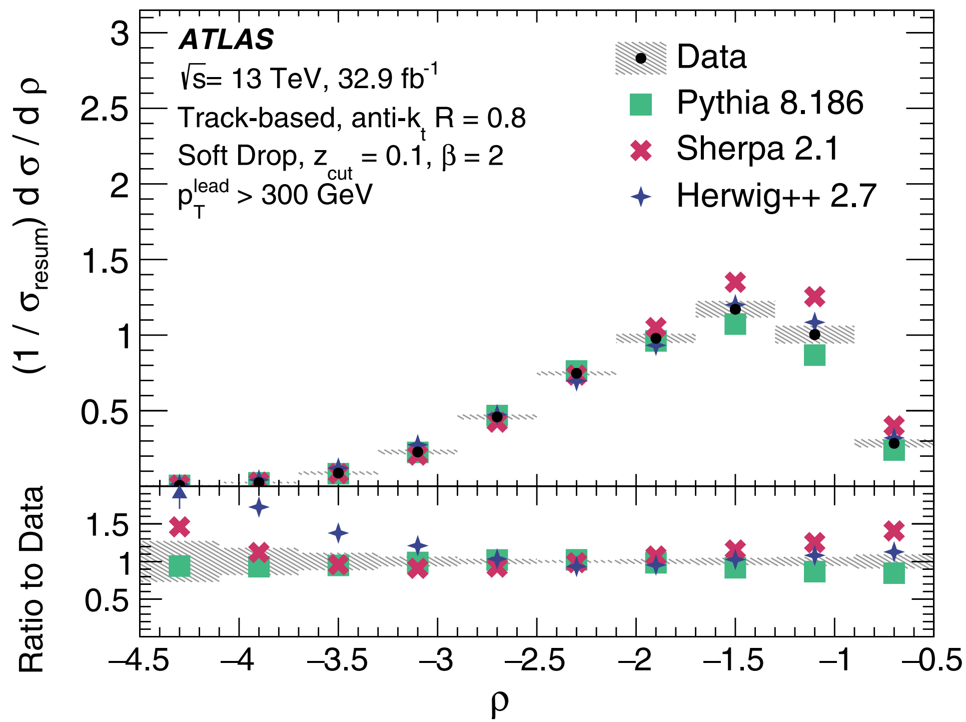
Soft-drop jet observables

- Measurements are performed for z_{cut} = 0.1 and β = 0,1,2

[Phys. Rev. D 101 (2020) 052007](#)

- Higher values of β imply larger non-perturbative (NP) effects
- Dimensionless mass: $\rho = \log\left(\frac{m^2}{p_T^2}\right)$ where $m^2 = \left(\sum_{i=1}^{N} E_i\right)^2 - \left(\sum_{i=1}^{N} \vec{p}_i\right)^2$





- Similar results found for calorimeter-based jets

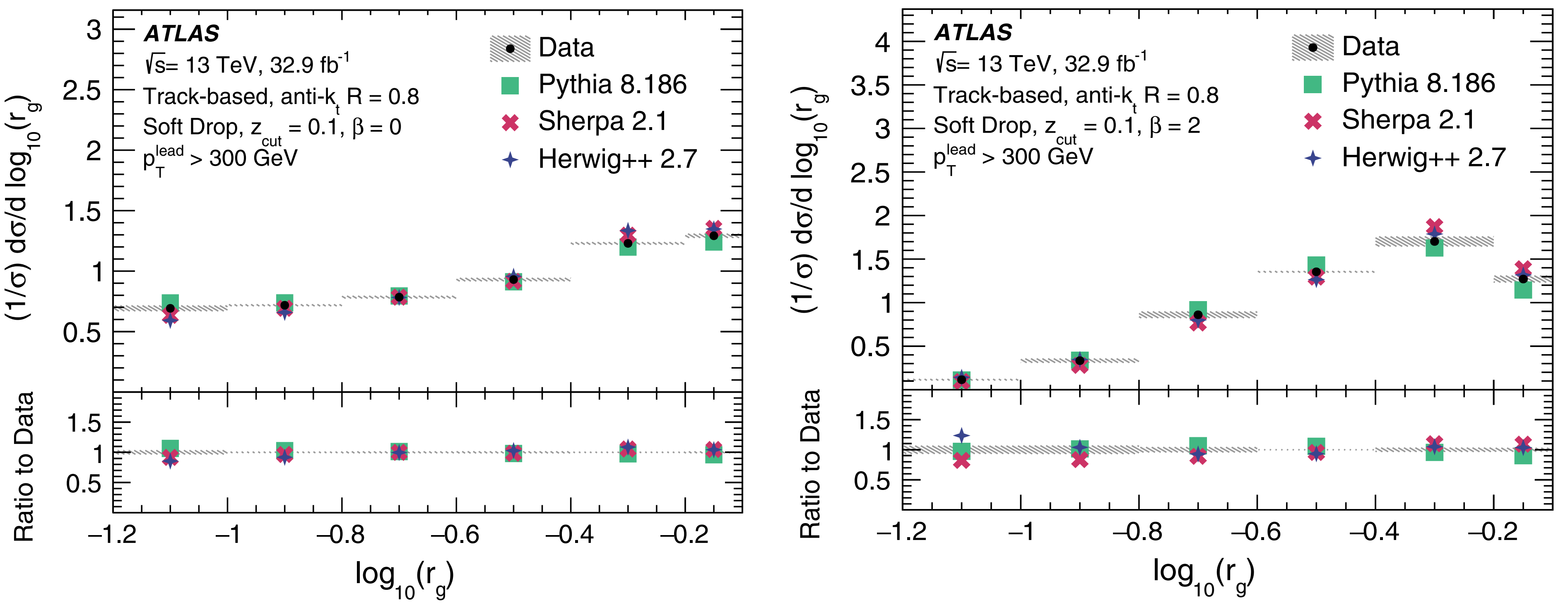
Soft-drop jet observables

- Measurements are performed for z_{cut} = 0.1 and β = 0,1,2

Phys. Rev. D 101 (2020) 052007

- Higher values of β imply larger non-perturbative (NP) effects

- Angular distance for subjet fulfilling soft-drop condition: $r_g = \sqrt{(y_1 - y_2)^2 + (\phi_1 - \phi_2)^2}$



- Similar results found for calorimeter-based jets

Soft-drop jet observables

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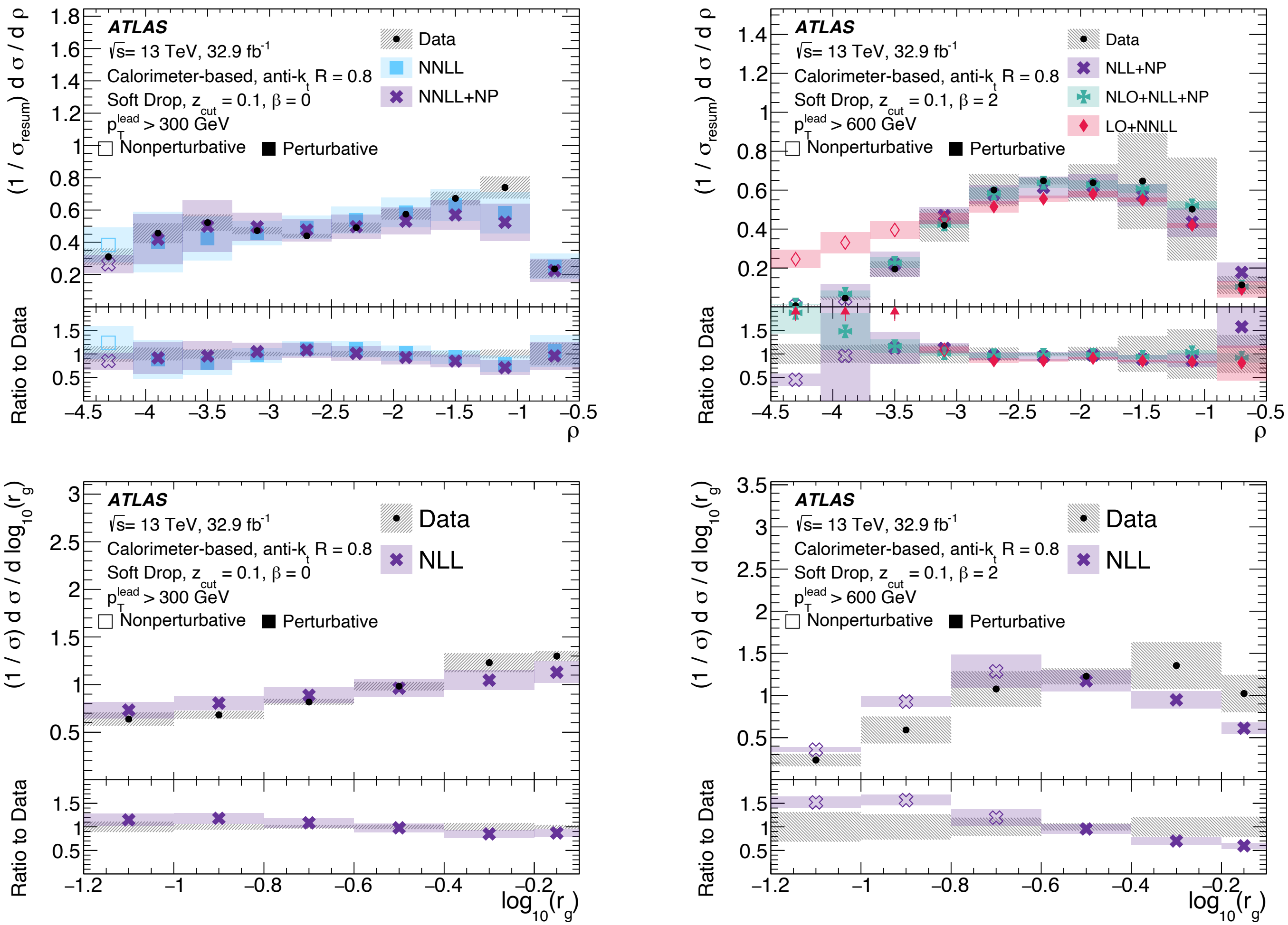
- Comparison with resummed predictions, including NP corrections
  - LO+NNLL (based on SCETlib)
  - NLO+NLL matched to NLOJet++



- **NLO+NLL** provides an accurate model of the data at high ρ
- **LO+NNLL** and **NNLL** calculations do not because fixed-order effects are dominant
- In the region where NP effects are small, data and predictions agree within uncertainties
- In the region where NP effects are large, the prediction is higher than data

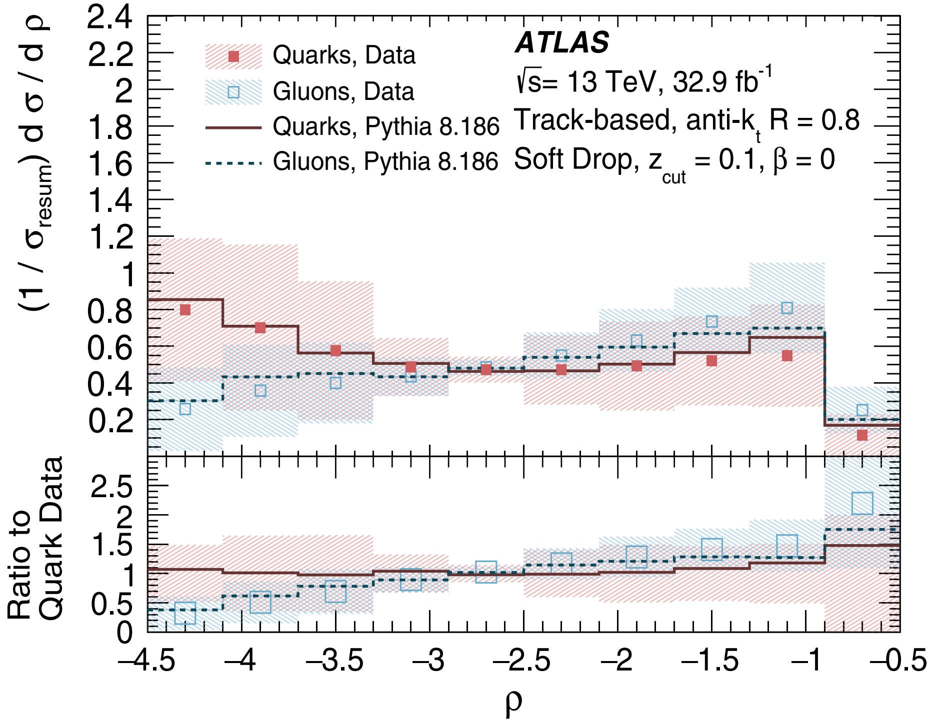
Soft-drop jet observables

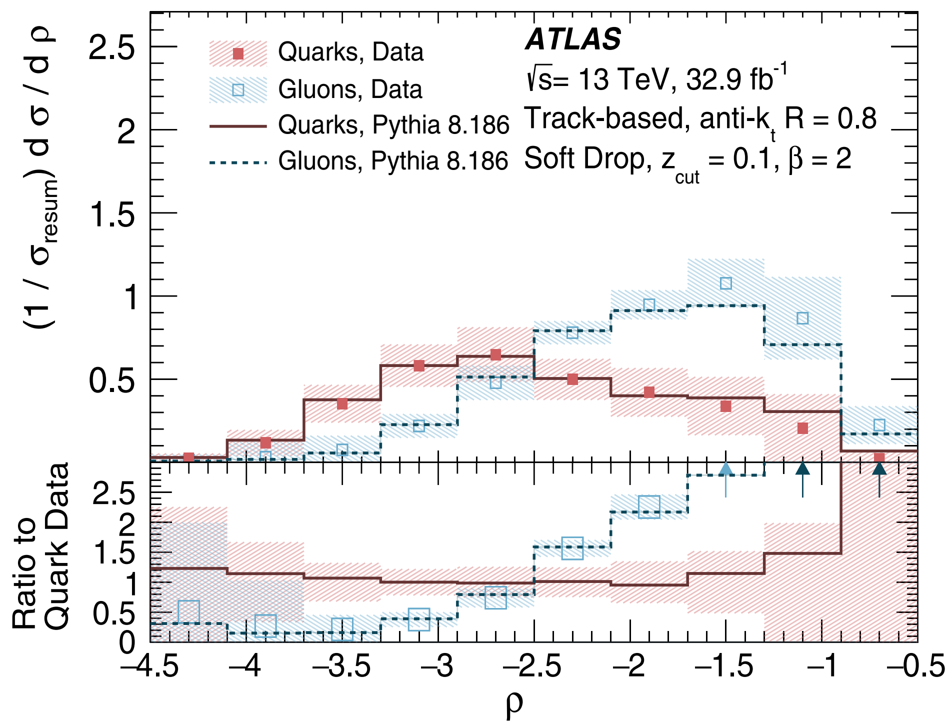
Phys. Rev. D 101 (2020) 052007

- Quark and gluon distributions obtained by solving a per-bin system of equations

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

- As expected, gluon jets are more massive and wider than quark jets





Event shape variables

- Sensitive to the details of the hadronisation process and useful to determine α_S and MC tune parameters and search for new physics phenomena

- Six event-shape variables measured as a function of jet multiplicity in three interval of $H_{T,2}$

- **Thrust major/minor**

$$T_{\perp} = \frac{\sum_i |\vec{p}_{\mathrm{T},i} \cdot \hat{n}_{\mathrm{T}}|}{\sum_i |\vec{p}_{\mathrm{T},i}|}; \qquad T_{\mathrm{m}} = \frac{\sum_i |\vec{p}_{\mathrm{T},i} \times \hat{n}_{\mathrm{T}}|}{\sum_i |\vec{p}_{\mathrm{T},i}|}$$

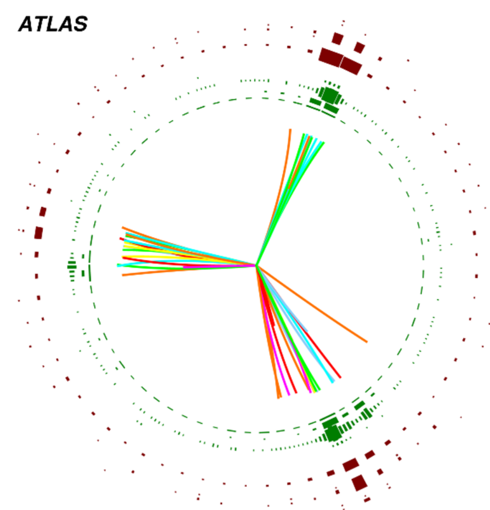
- **Sphericity** and **aplanarity** from linear combinations of the eigenvalues of

$$\mathcal{M}_{xyz} = \frac{1}{\sum_i |\vec{p}_i|} \sum_i \frac{1}{|\vec{p}_i|} \begin{pmatrix} p_{\mathrm{x},i}^2 & p_{\mathrm{x},i}p_{\mathrm{y},i} & p_{\mathrm{x},i}p_{\mathrm{z},i} \\ p_{\mathrm{y},i}p_{\mathrm{x},i} & p_{\mathrm{y},i}^2 & p_{\mathrm{y},i}p_{\mathrm{z},i} \\ p_{\mathrm{z},i}p_{\mathrm{x},i} & p_{\mathrm{z},i}p_{\mathrm{y},i} & p_{\mathrm{z},i}^2 \end{pmatrix}$$

$$S = \frac{3}{2}(\lambda_2 + \lambda_3); \quad A = \frac{3}{2}\lambda_3$$

- **C** and **D** from cubic and quartic combinations

$$C = 3(\lambda_1\lambda_2 + \lambda_1\lambda_3 + \lambda_2\lambda_3),$$
$$D = 27(\lambda_1\lambda_2\lambda_3)$$



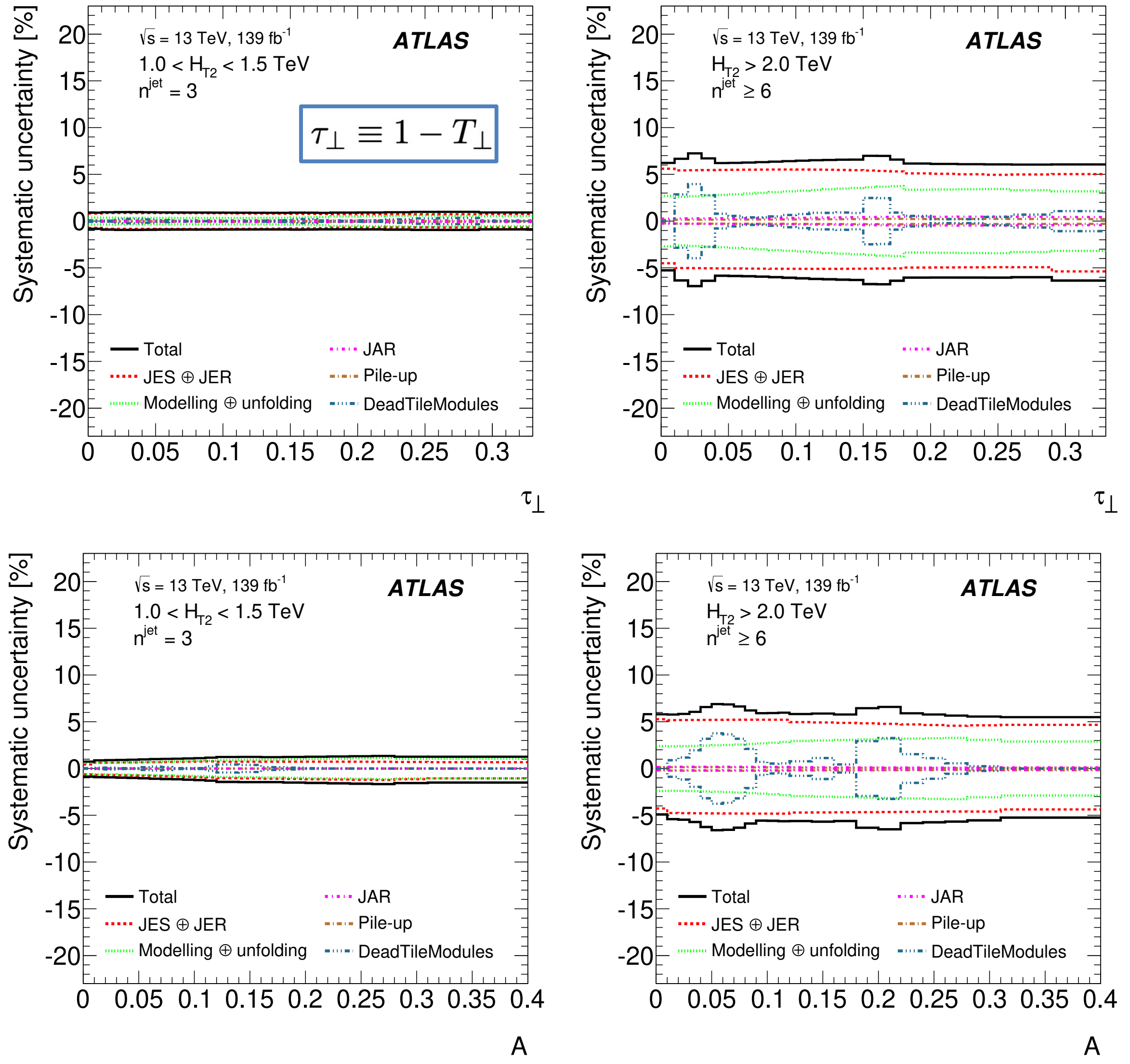
- 3-jets (5-jets) event with high (low) values of $T_{\perp}$ and S

Event shape variables

JHEP 01 (2021) 188

- Jet (anti-k_t algorithm, R = 0.4) with p_T > 100 GeV, $|\eta|$ < 2.4 and $H_{T,2} = (p_{T,jet1} + p_{T,jet2})$ / 2 > 1 TeV are selected

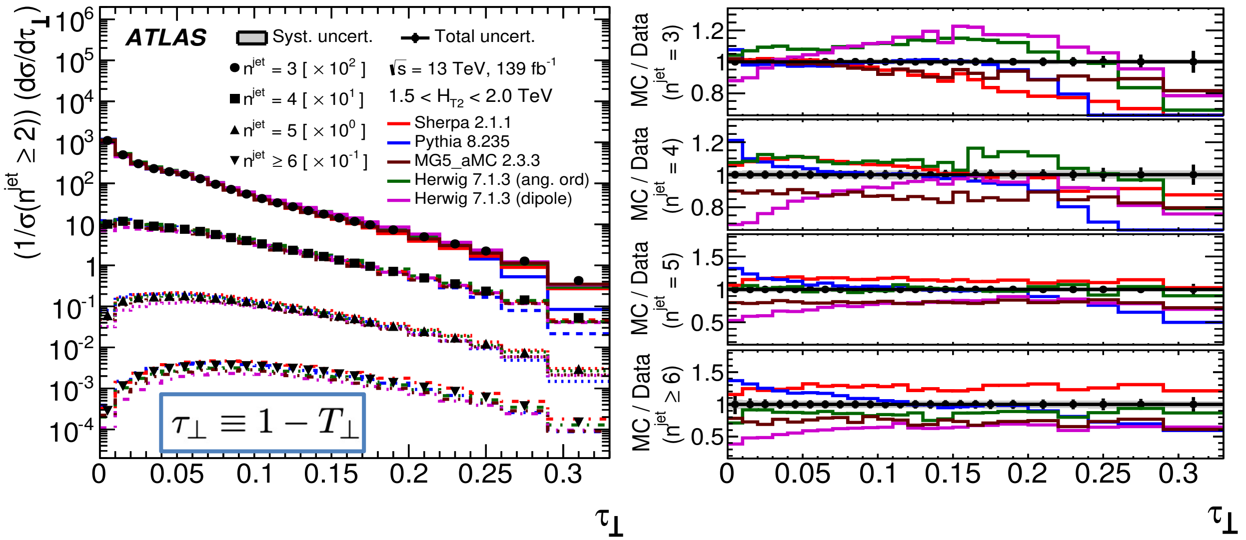
- Dominant systematics:
  - Jet Energy Scale (JES)
  - Jet Energy Resolution (JER)
  - Jet Angular Resolution (JAR)
  - Pileup (vary reweighting)
  - Unfolding (difference when MC reweighted to data)
  - Modelling (change MC reference in unfolding)
  - Luminosity
  - Dead-tiles

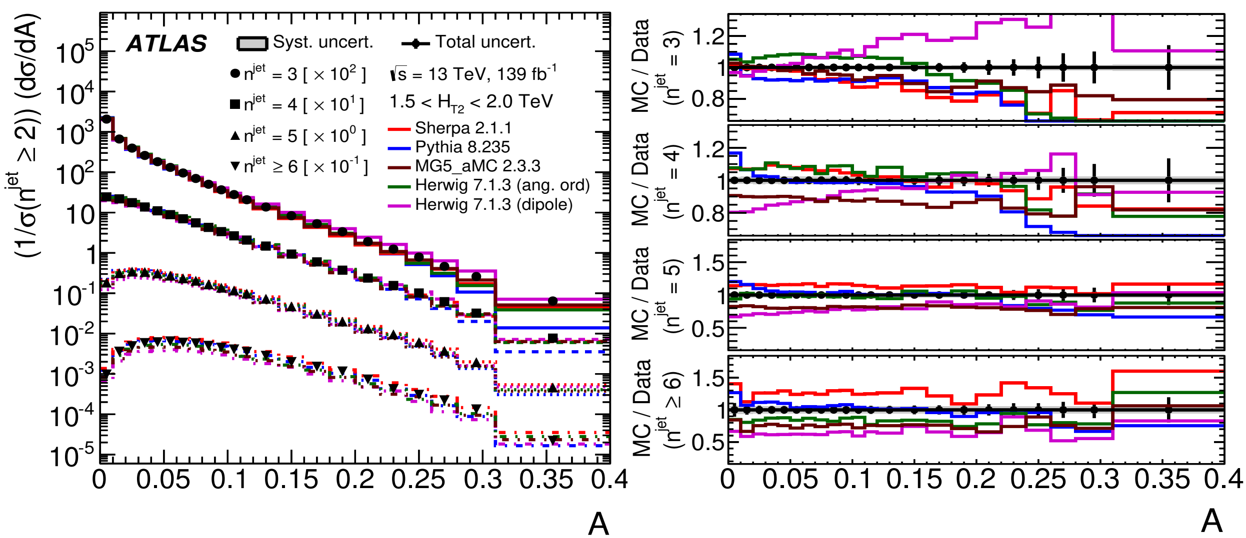


Event shape variables

JHEP 01 (2021) 188

- MC normalised to data in each $H_{T,2}$ bin (Pythia8 xsec +30%, aMC@NLO -35%)
- Sherpa overestimates high multiplicities
- Herwig dipole model underestimates high multiplicities - better when considering Herwig with angular ordered Parton Shower (PS)
- Pythia8 (A14 tune) describes data well for intermediate thrusts only
- aMC@NLO gives the best description - importance of including beyond LO terms in Matrix Element (ME)

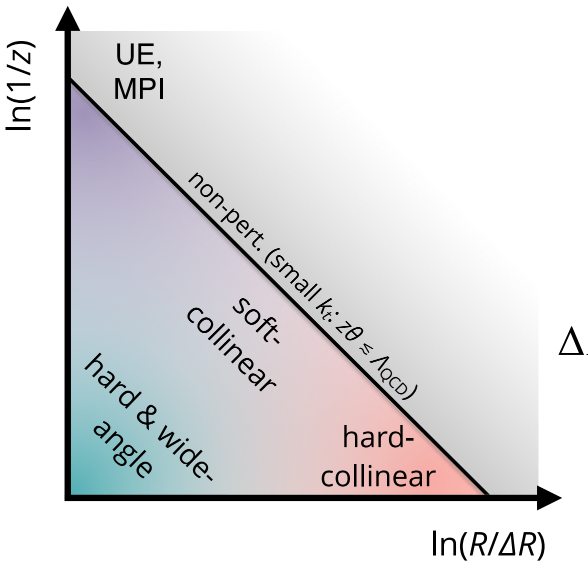




None of the MC provide a good description of the data in all the regions

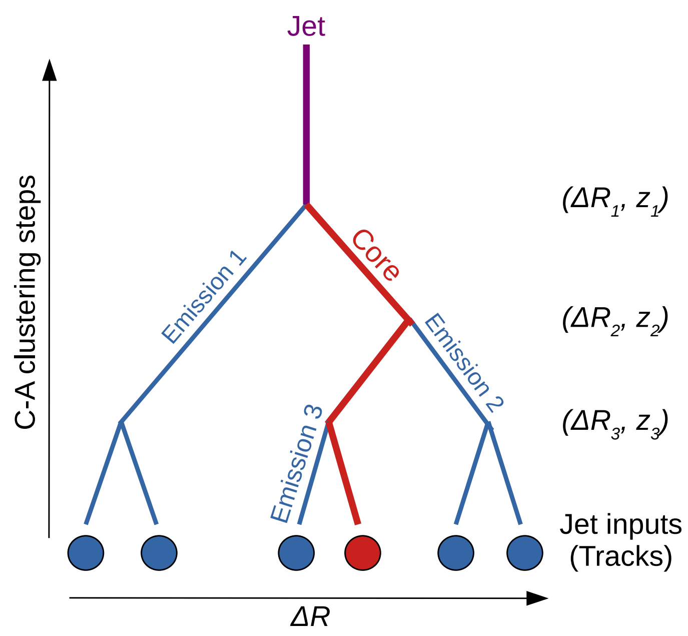
Lund Jet Plane measurement

- The LJP is an abstract description of jet development, with each entry corresponding to the transverse momentum and angle of any given emission with respect to the emitter
- Regions of plane point to various physical processes
- Dijet (anti-k_t algorithm, R = 0.4) events with $p_{T,1}$ / $p_{T,2}$ < 1.5
- Reconstructed by reversing the C/A clustering algorithm
- Only charged tracks in jets with p_T^{jets} > 675 GeV



$$z = \frac{p_T^{\text{emission}}}{p_T^{\text{emission}} + p_T^{\text{core}}}$$

$$\Delta R^2 = (y_{\text{emission}} - y_{\text{core}})^2 + $$
$$+ (\phi_{\text{emission}} - \phi_{\text{core}})^2$$

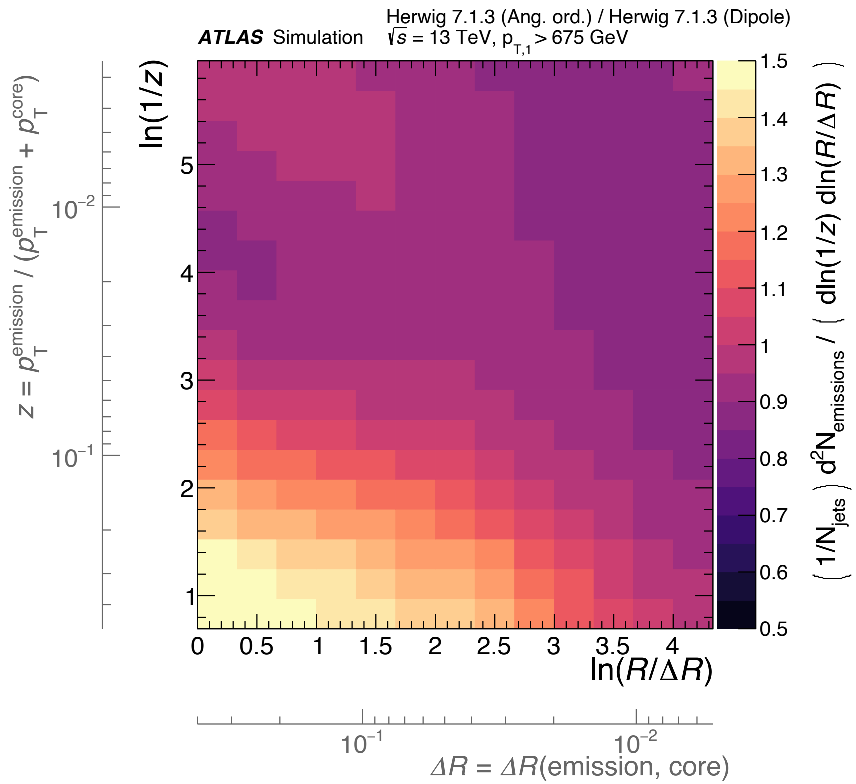


Lund Jet Plane measurement

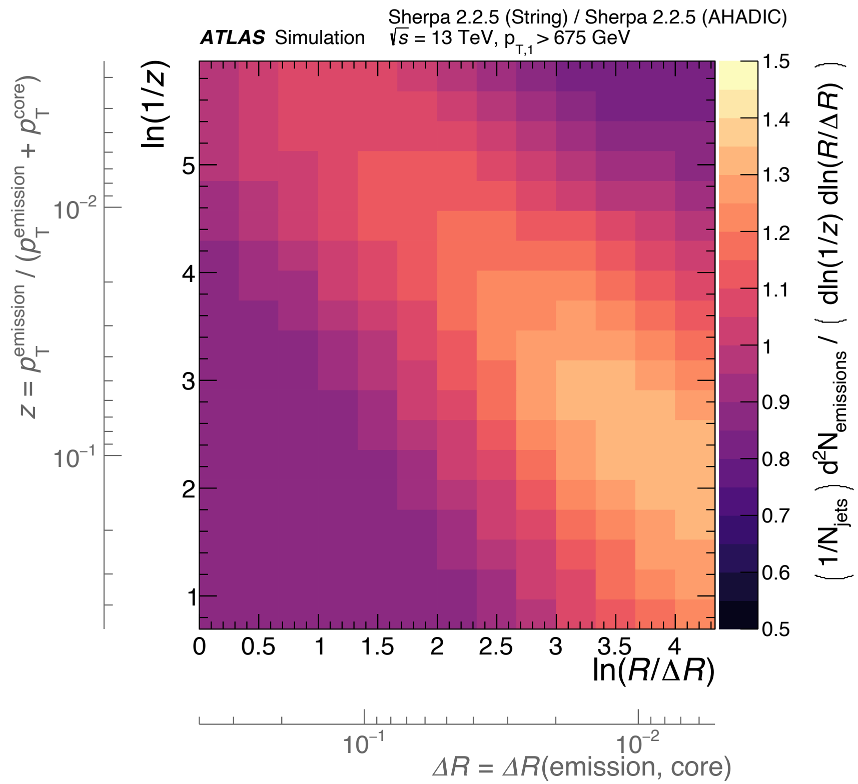
Phys. Rev. Lett. 124 (2020) 2 22002

- Sensitivity to the ME calculation, PS and hadronization models

Parton Shower



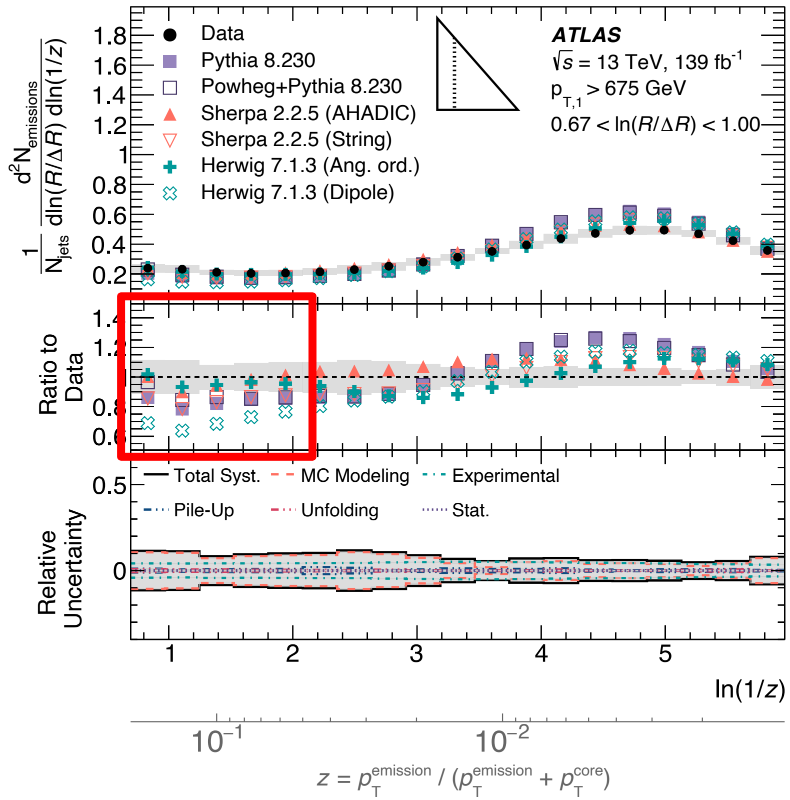
Hadronisation

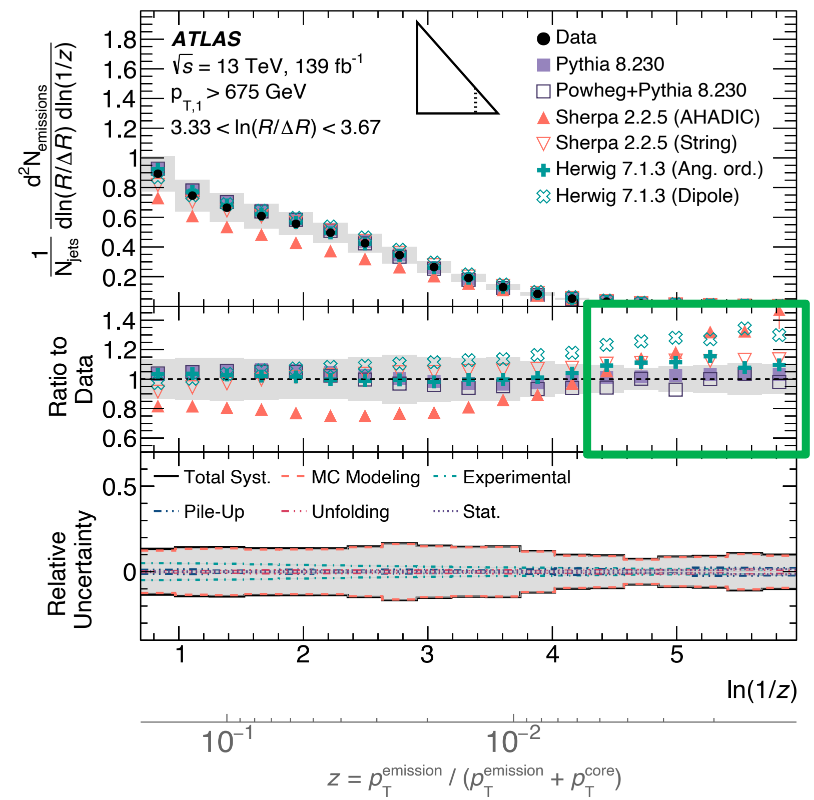


- These plots show the ratios for different shower and hadronization models
- Angle-ordered PS present more hard, wide-angle activity than dipole PS
- String model presents more hard collinear activity than cluster model

Lund Jet Plane measurement

Phys. Rev. Lett. 124 (2020) 2 22002

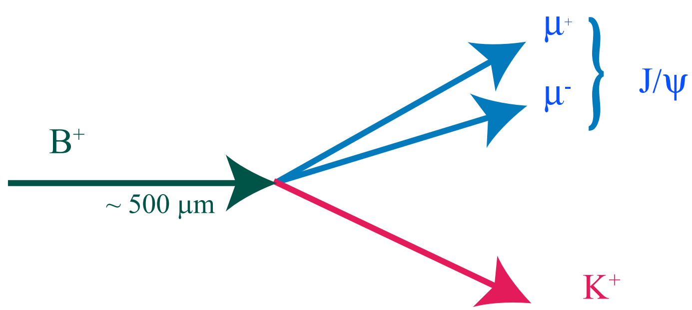




- Probing PS (wide angle, left) to hadronization (collinear, right)
- **Hard wide angle**: differences in PS algorithms in Herwig7, as well as Pythia8 and Sherpa
- **Soft collinear**: different hadronization models in Sherpa
- Most MC good in describing jet core, but fail at small z e.g. large angle emission

b-quark fragmentation properties

- Identify B hadron from $B^{\pm} \rightarrow J/\psi K^{\pm} \rightarrow \mu^{+}\mu^{-}K^{\pm}$



- Associate B meson to jet and compute

$$z = \frac{\vec{p}_B \cdot \vec{p}_j}{|\vec{p}_j|^2}; \quad p_{\mathrm{T}}^{\mathrm{rel}} = \frac{|\vec{p}_B \times \vec{p}_j|}{|\vec{p}_j|}$$

- Unfold at particle level in different bins of z, p_T^{rel} and p_T^j for 50 < p_T^j < 70 GeV, 70 < p_T^j < 100 GeV and p_T^j > 100 GeV

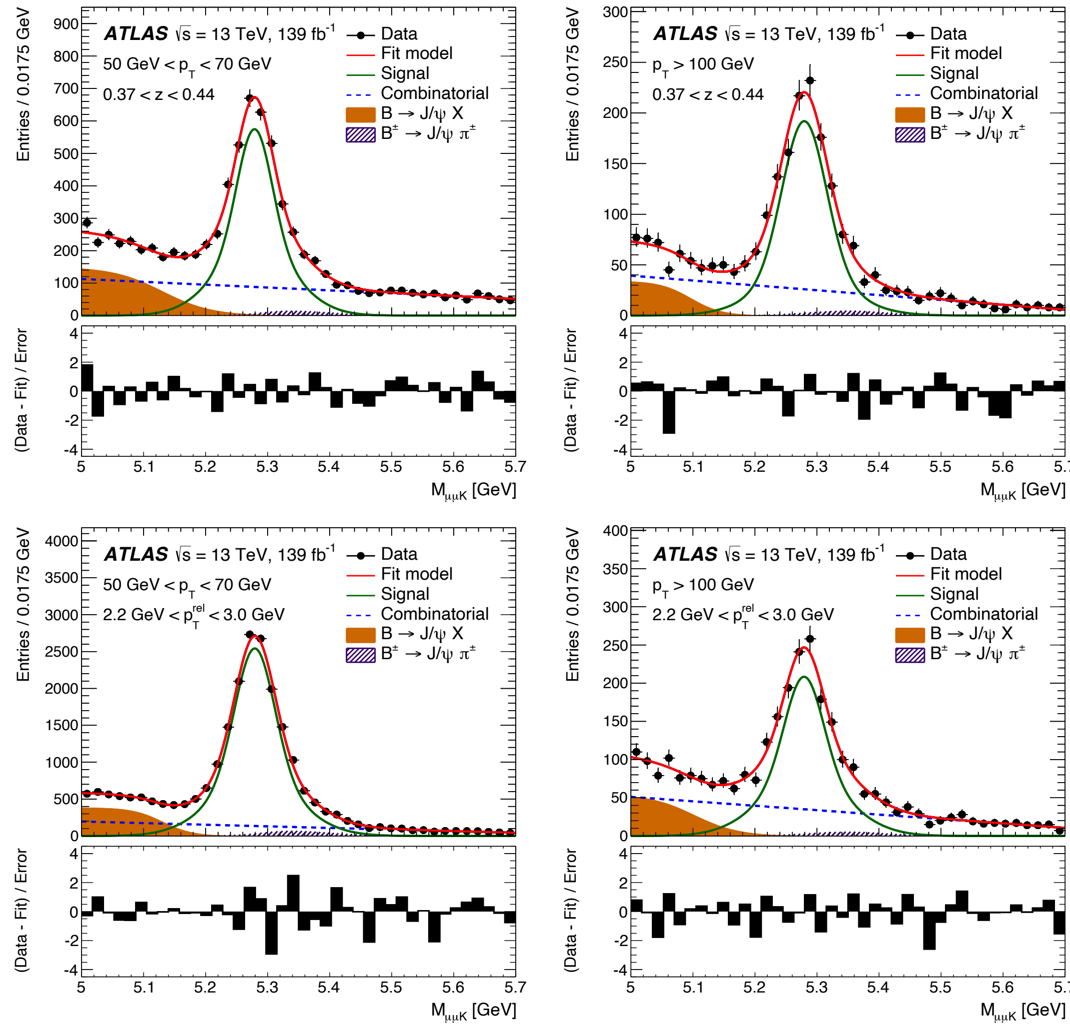
- Measurements using all the Run2 data (139 fb^{-1}) compared to several MC samples

Generator	ME order	Scales μ_r, μ_f	Parton shower	PDF set	Tune	Hadronisation
Pythia 8	$2 \rightarrow 2$ @ LO	$(m_{T3} \cdot m_{T4})^{\frac{1}{2}}$	p_T-ordered	CTEQ6L1	A14 A14-rb	Lund–Bowler Lund–Bowler
				NNPDF2.3	Monash	Lund–Bowler Peterson
Sherpa	$2 \rightarrow 2$ @ LO	$H(s,t,u)$	CSS (dipole)	CT14	–	Cluster model Lund string model
Herwig 7	$2 \rightarrow 2$ @ LO	$\sqrt{\frac{2stu}{s^2+t^2+u^2}}$	Angle-ordered Dipole	MMHT2014	–	Cluster model

b-quark fragmentation properties

2108.11650

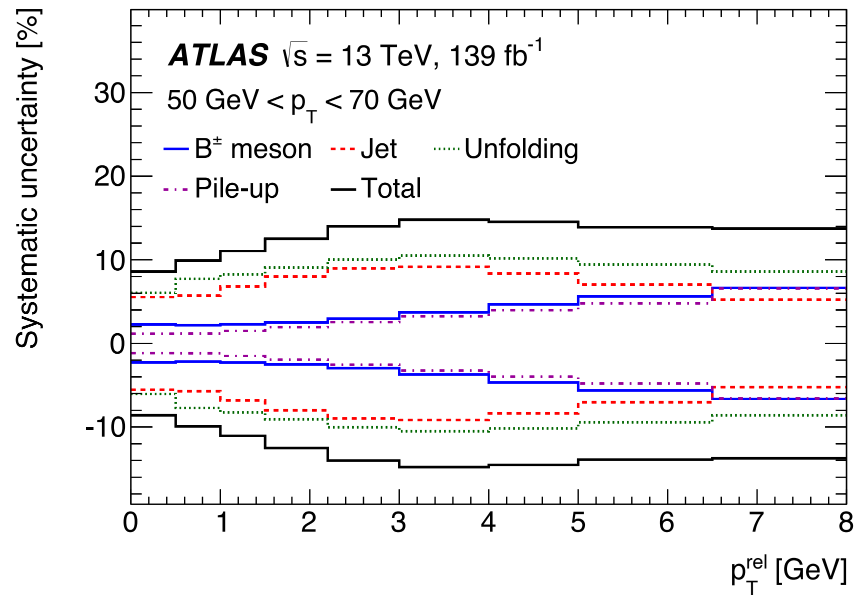
- $\boldsymbol{J/\psi}$: 2 OS μ with p_T > 6 GeV, $|\eta|$ < 2.5 and 2.6 < $m_{\mu\mu}$ < 3.6 GeV (displaced vertex)
- $\boldsymbol{K^{\pm}}$: third track from the same vertex, p_T > 4 GeV, $|\eta|$ < 2.5
- Assume PDG masses for J/ψ and $K^{\pm}$, require 5.0 < $m_{\mu\mu K}$ < 5.7 GeV
- Assuming PDF mass for B-meson, $\tau = m_{\mu\mu K} L_{xy}/p_T$ > 20 ps

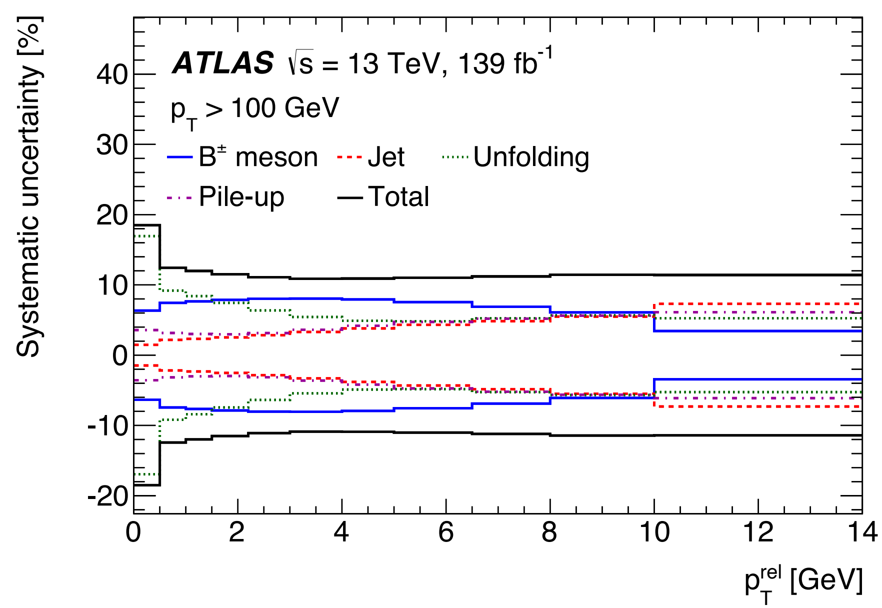


b-quark fragmentation properties

2108.11650

- B meson reconstruction
  - Purity corrections (from different models)
  - Muon momentum scale and resolution
  - Muon identification
  - Trigger and kaon reconstruction
- Jets
  - Jet Energy Scale and Resolution
  - Jet Angular Resolution
  - Jet Vertex Tagger for pileup mitigation
- Unfolding
  - Mismodelling from MC used in unfolding
  - Use of a specific MC model
- Pileup (compare $\mu < 32$ and $\mu \geq 32$)



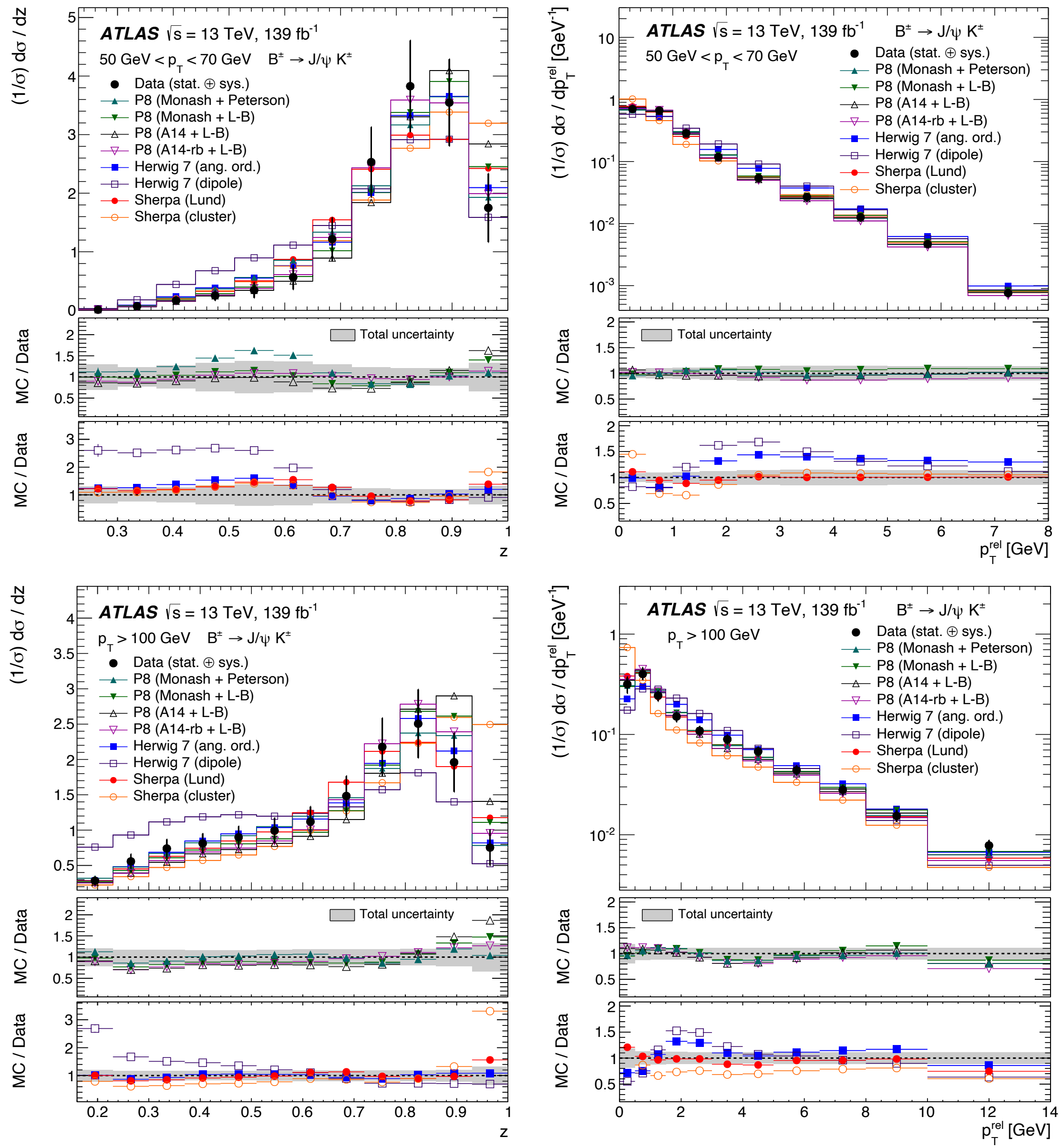


b-quark fragmentation properties

2108.11650

- Disagreement with **Herwig7 dipole PS** due to larger gluon splitting $g \rightarrow b\bar{b}$
- **Sherpa cluster** model disagrees at high z and low p_T^{rel}
- **Herwig7 angle-ordered PS** and **Sherpa Lund** model give similar results for z (not true for p_T^{rel})
- **Pythia8 Monash** overestimates data at middle z and low p_T^{rel}
- Data well described by **Pythia8 A14+$r_b = 1.05$** (value fitted from LEP data)

r_b = Pythia8 tune parameter controlling b-quark fragmentation



Conclusion and outlook

- QCD is an essential ingredient of SM, its apparent formal simplicity covers a very complex phenomenology
- Important to improve precision on other measurements, but a very interesting and intellectually challenging problem/process by itself
- Enormous theory effort to improve precision, now being matched by important measurements in specific regions of phase space
- Comparison with MC predictions over a large phase space
- HepData and Rivet routines are available for the presented measurements
- Despite many improvements, still many divergences exist, and more corners of phase space need to be measured
- Many more clever measurements needed, I just presented some of them
- Stay tuned for more measurements to be released soon!

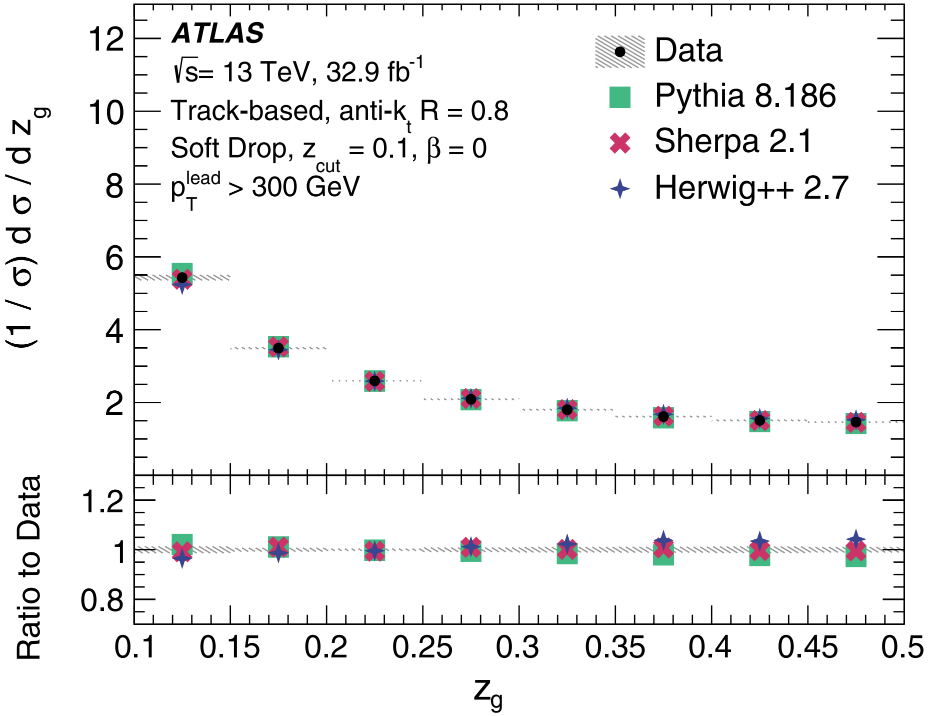
Backup Slides

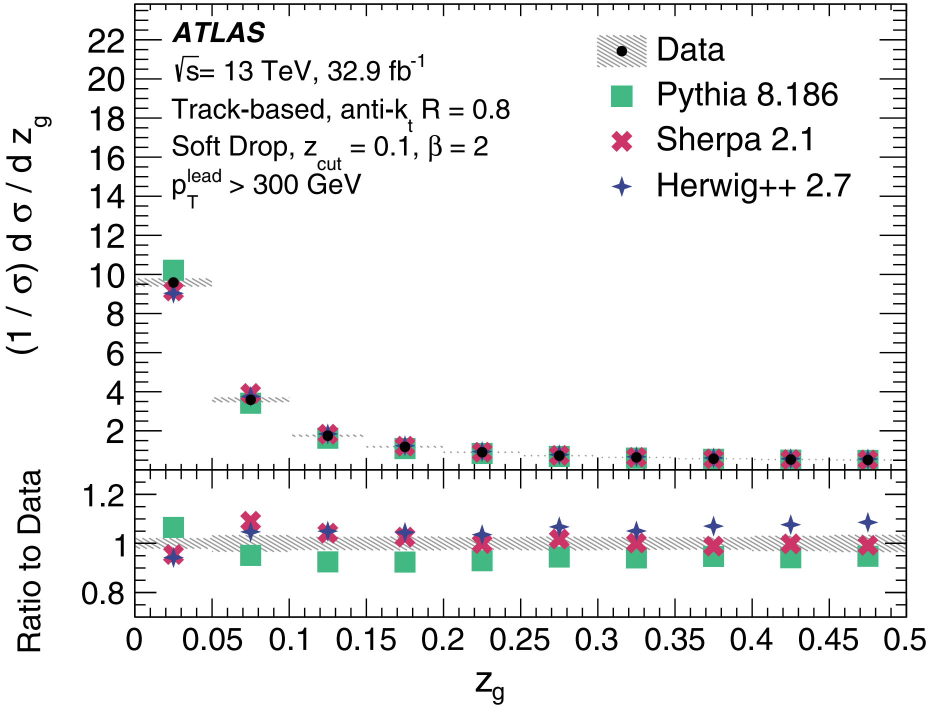
Soft-drop jet observables

- Measurements are performed for z_{cut} = 0.1 and β = 0,1,2

Phys. Rev. D 101 (2020) 052007

- Higher values of β imply larger non-perturbative (NP) effects
- Splitting scale for subjet fulfilling soft-drop condition: $\frac{\min(p_{T1}, p_{T2})}{p_{T1} + p_{T2}}$





- Similar results found for calorimeter-based jets

Soft-drop jet observables

- Comparison between track and cluster observables

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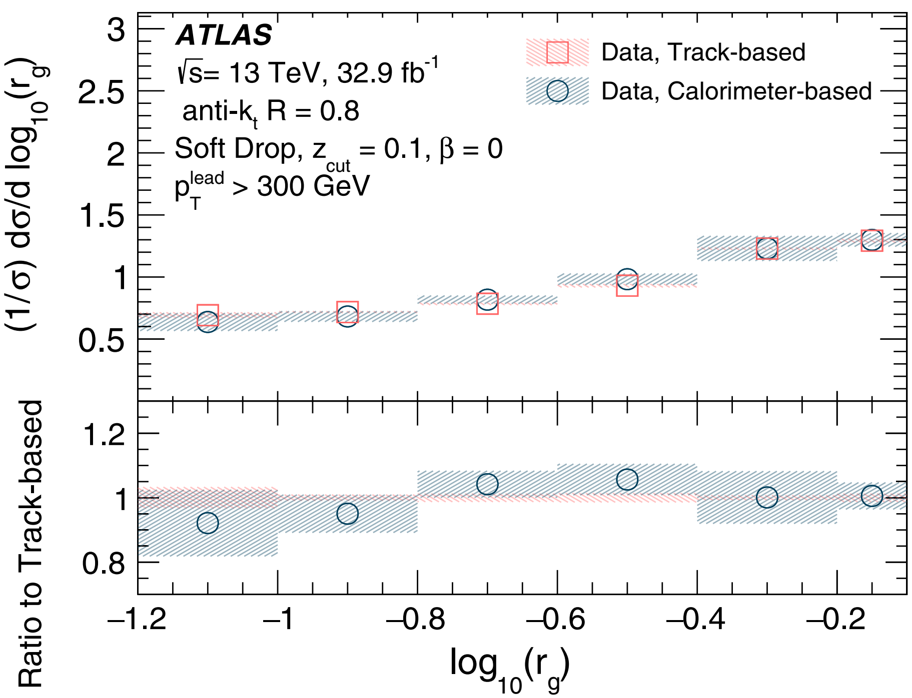
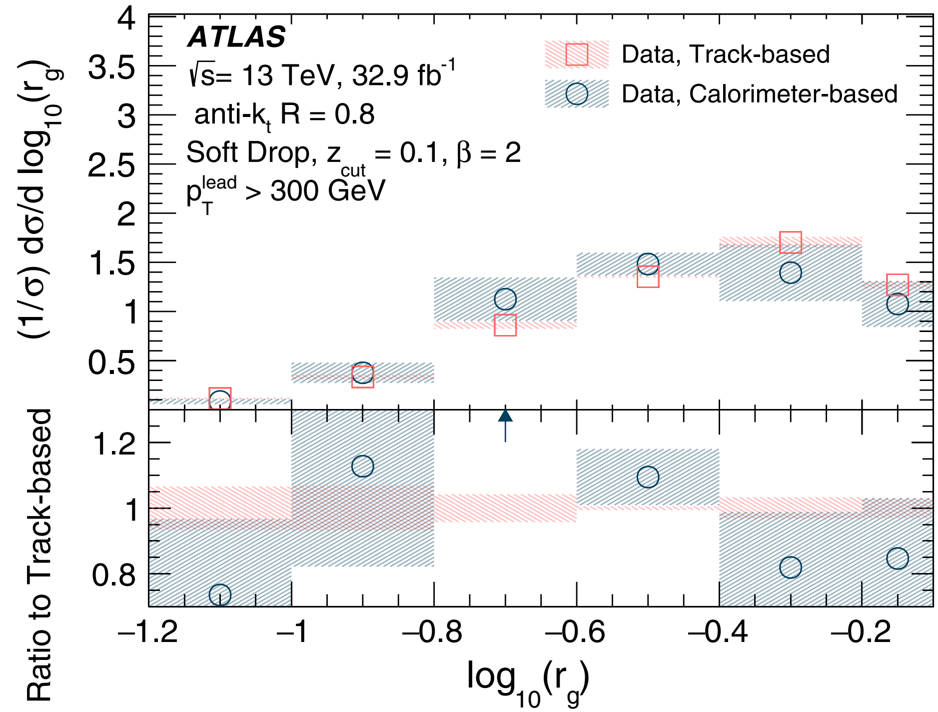
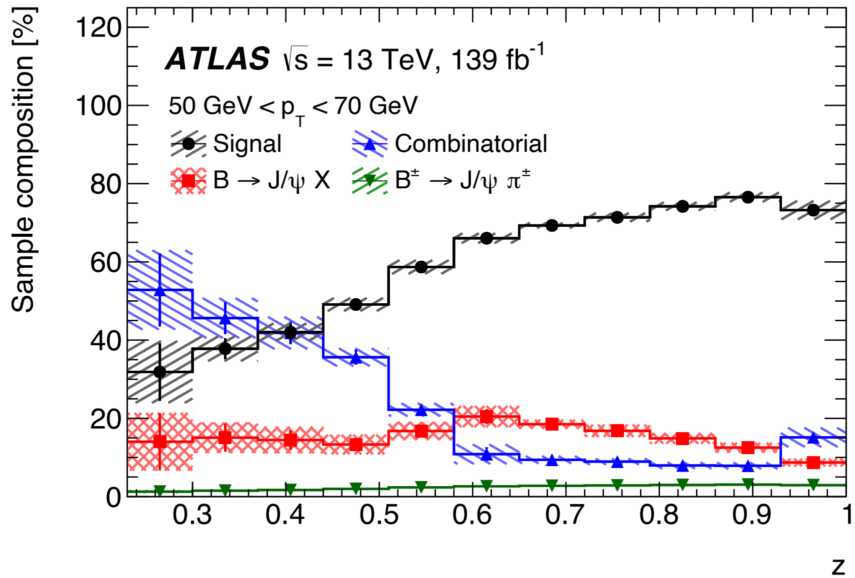
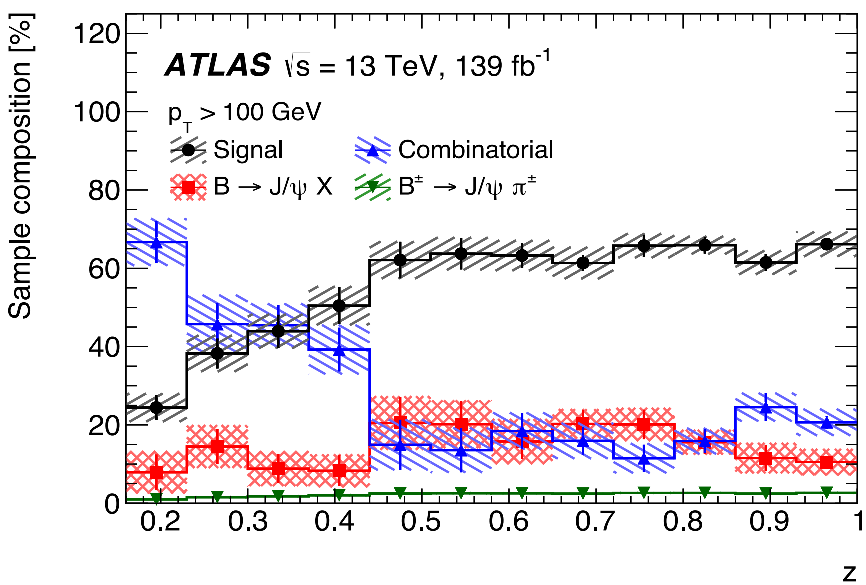
- Distributions for β = 0 and β = 2
- Overall, β = 0 presents a better agreement between both observables





b-quark fragmentation properties





- The B-meson invariant mass is fitted in each z, p_T^{rel} bin using components from MC templates:

$$\mathcal{F}(m) = \lambda_s \mathcal{F}_s(m) + \lambda_{B_x} \mathcal{F}_{B_x}(m) + \lambda_{B_\pi} \mathcal{F}_{B_\pi}(m) + \lambda_c \mathcal{F}_c(m)$$

Probability distribution functions

Relative fractions

- Fits show:
  - Signal purity ~70%
  - Lost pion 15%
  - Combinatorial background 12%
  - $J/\psi\pi$ 3%

- Similar results found as a function of p_T^{rel}

b-quark fragmentation properties

- Large differences in the amount of gluon splitting in the considered models
- Strong correlations between these differences and the observed discrepancies with data on the average values of z, p_T^{rel} VS p_T^{jet}