B-jet Fragmentation Measurements using the ATLAS Detector

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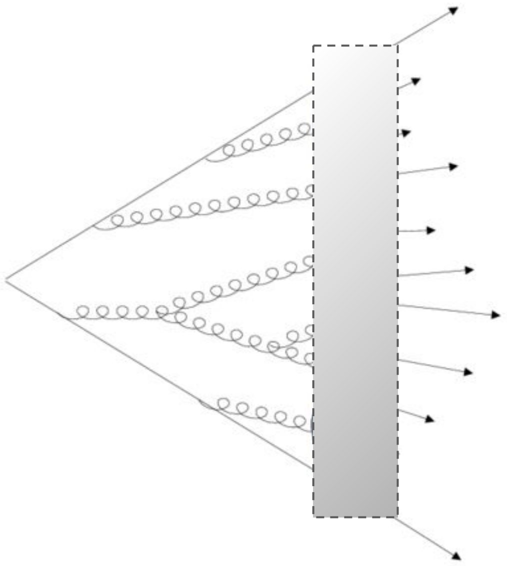
Abstract

Accurate modelling of the *b*-jet fragmentation is a crucial measurements at the LHC

- ⋆ interesting measurement *per se*, testing QCD predictions / MC models
- ⋆ systematics in *b*-jet identification, used by many analyses to select signal events and reject background



Results presented here (13 TeV / 139 fb^{-1})

- ⋆ measurement of fragmentation properties using $B^{\pm} \rightarrow J/\Psi + K^{\pm}$ decays

Measurement of *b*-quark fragmentation properties in jets using the decay $B^{\pm} \rightarrow J/\psi K^{\pm}$ in pp collisions at $\sqrt{s} = 13$ TeV with the ATLAS detector

JHEP 12 (2021) 131
DOI: 10.1007/JHEP12(2021)131

Abstract

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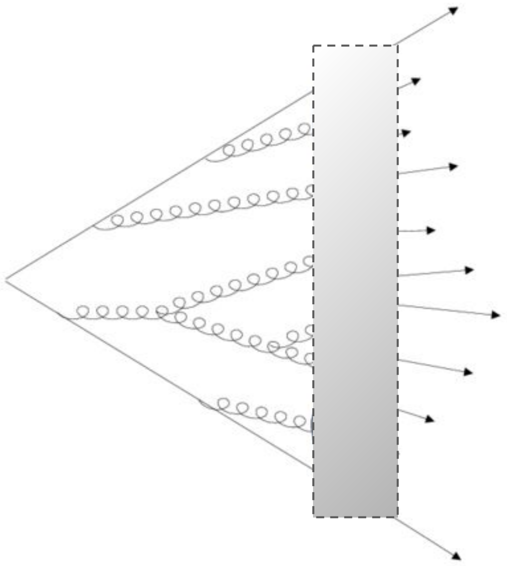


Results presented here (13 TeV / 36 fb^{-1})

- ⋆ charged-particle fragmentation observables measured in events with top quark pairs

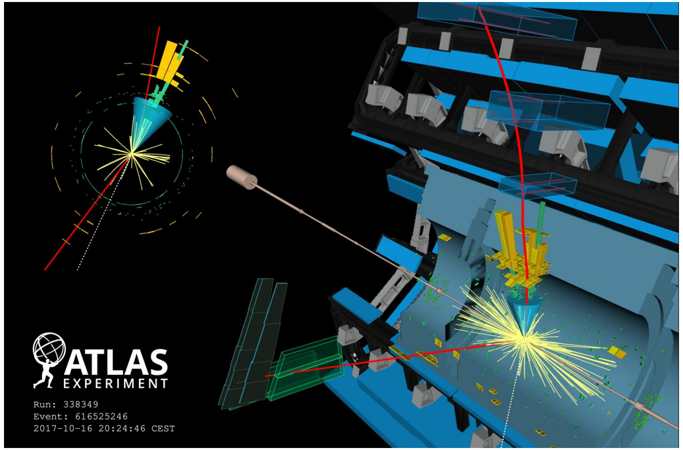
Measurements of jet observables sensitive to *b*-quark fragmentation in $t\bar{t}$ events at the LHC with the ATLAS detector

Phys.Rev.D 106 (2022) 032008
DOI: 10.1103/PhysRevD.106.032008

Physics Analysis point of view

Many physics analyses affected by heavy quark fragmentation modelling

- ⋆ Higgs boson, top quark, their associated production
- ⋆ Uncertainties on modelling can be a limiting factor for precision measurements (top mass)
- ⋆ Extends to future searches, e.g. $HH \rightarrow 4b$



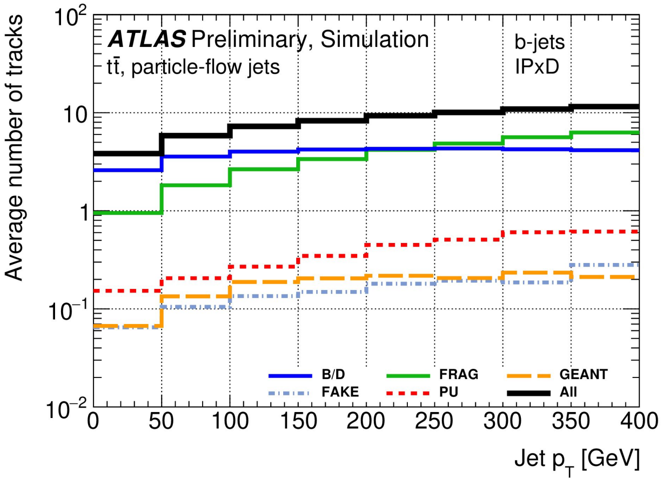
Adapting MC description for LHC

- ⋆ Mostly tuned on **measurements in e^+e^- collisions**
- ⋆ **Differences at LHC**
  - higher center-of-mass energy
  - no well-defined partonic center-of-mass or energy scale (focus on final state)
  - complex color flow in hadron-collider processes affects fragmentation observables

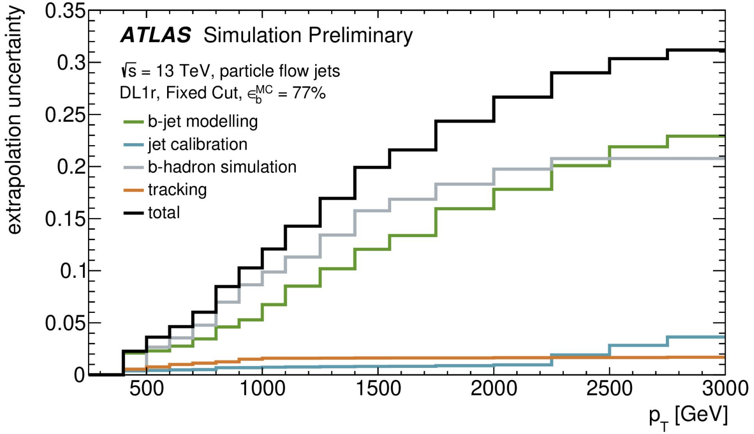
→ **crucial to investigate more with specific LHC measurements**

Flavour Tagging point of view (where my heart beats)

Flavour Tagging identifies jets from heavy quarks



- ★ largely based on charged particle tracks
  → tracks from fragmentation play a key role
- ★ uses discriminants directly tied to fragmentation
  → e.g. fraction of jet energy carried by tracks from *b*



- ★ calibrations required at high p_T (e.g. searches)
  → no data available for direct calibration
  → MC-based extrapolation uncertainty
  → leading contributions from MC modelling
  (fragmentation plays a big role here)

Measuring b-jet fragmentation with $B^{\pm} \rightarrow J/\Psi + K^{\pm}$ decays

The approach

★ reconstruct jets with anti-k_T on PFlow objects and R=0.4 → measure momentum $\boldsymbol{p}_j$

★ find $B^{\pm} \rightarrow J/\Psi(\mu\mu) + K^{\pm}$ candidates in the jets → measure momentum $\boldsymbol{p}_B$

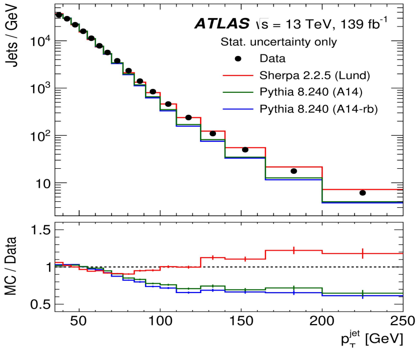
Muons: $p_{\mathrm{T}} > 6$ GeV

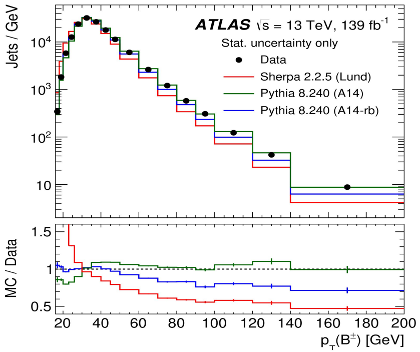
$2 \text{ GeV} < m_{\mu\mu} < 9 \text{ GeV}$

Kaon: $p_{\mathrm{T}} > 4$ GeV

common vertex $\chi^2/N_{\mathrm{dof}} < 2.0$

Cuts on masses and B pseudo-proper lifetime





★ build **longitudinal (z) and transverse (p_T^{rel}) momentum profiles**; compare with MC

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

★ **caveats:** sensitive to fragmentation, but also **other MC choices** (e.g. ME and PS) and presence of **gluon splitting** (not always resolved into two different b-jets)

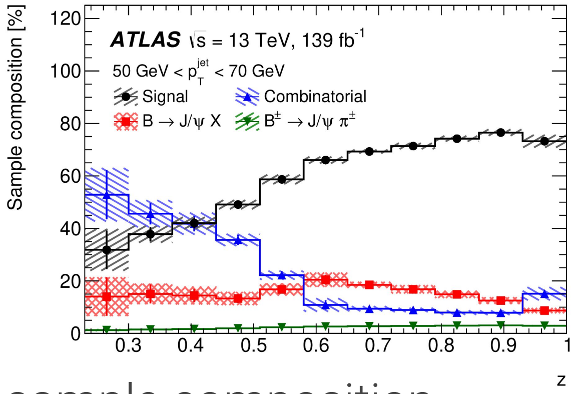
Measuring b-jet fragmentation with $B^{\pm} \to J/\Psi + K^{\pm}$ decays

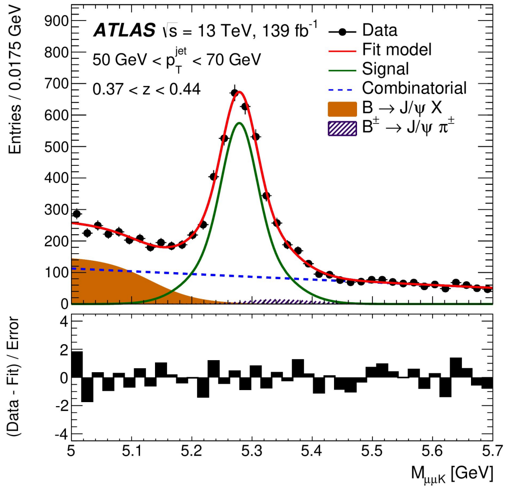
Binning

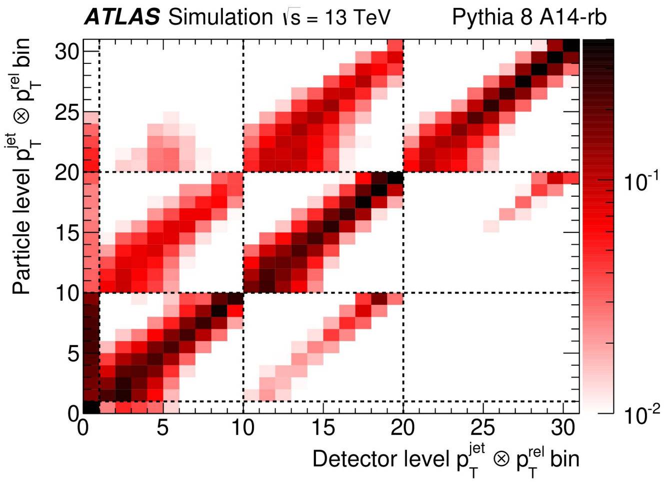
- ★ three jet p_T bins above 50 GeV
- ★ adjusted range / bins for z, p_T^{rel}

Handling backgrounds

- ★ binned ML fit to the invariant mass of $B^{\pm}$ candidates → extract sample composition







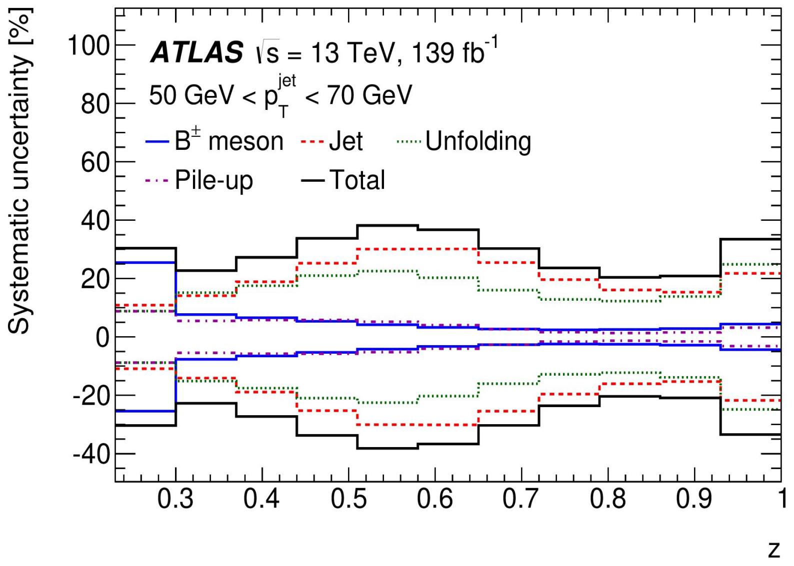
Unfolding $B^{\pm}$ candidates and jets at particle level

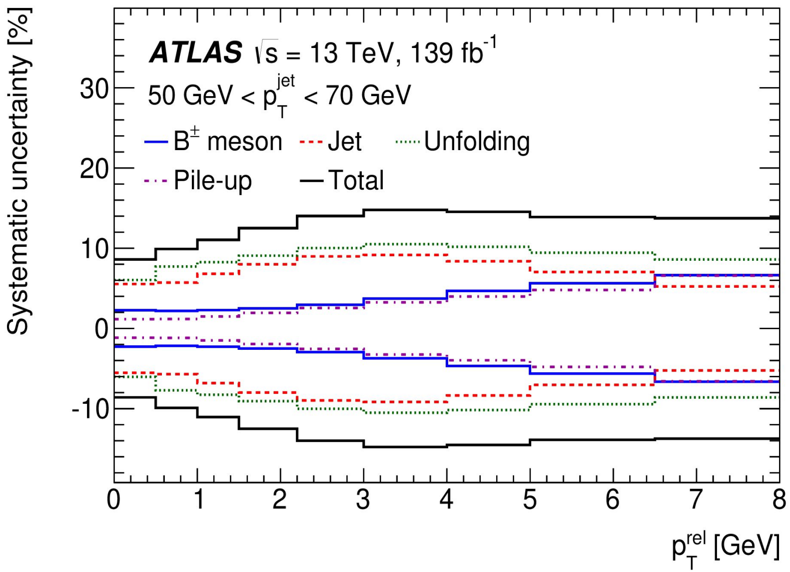
- ★ correct detector inefficiency and resolution
- ★ migration matrix obtained with bayesian unfolding to Pythia 8 samples
- ★ larger migrations observed for p_T^{rel}

Measuring *b*-jet fragmentation with $B^{\pm} \rightarrow J/\Psi + K^{\pm}$ decays

Systematics grouped in four categories

- **identification of $B^{\pm}$ mesons**: includes muon reco calibration and fit for purity
- **jet reconstruction**: includes JES, JER, angular resolution and jet vertex tagging
- **unfolding procedure**: includes uncertainty and mismodelling for the MC reference
- **pile-up**: includes effects due to the MC description of pile-up dependence

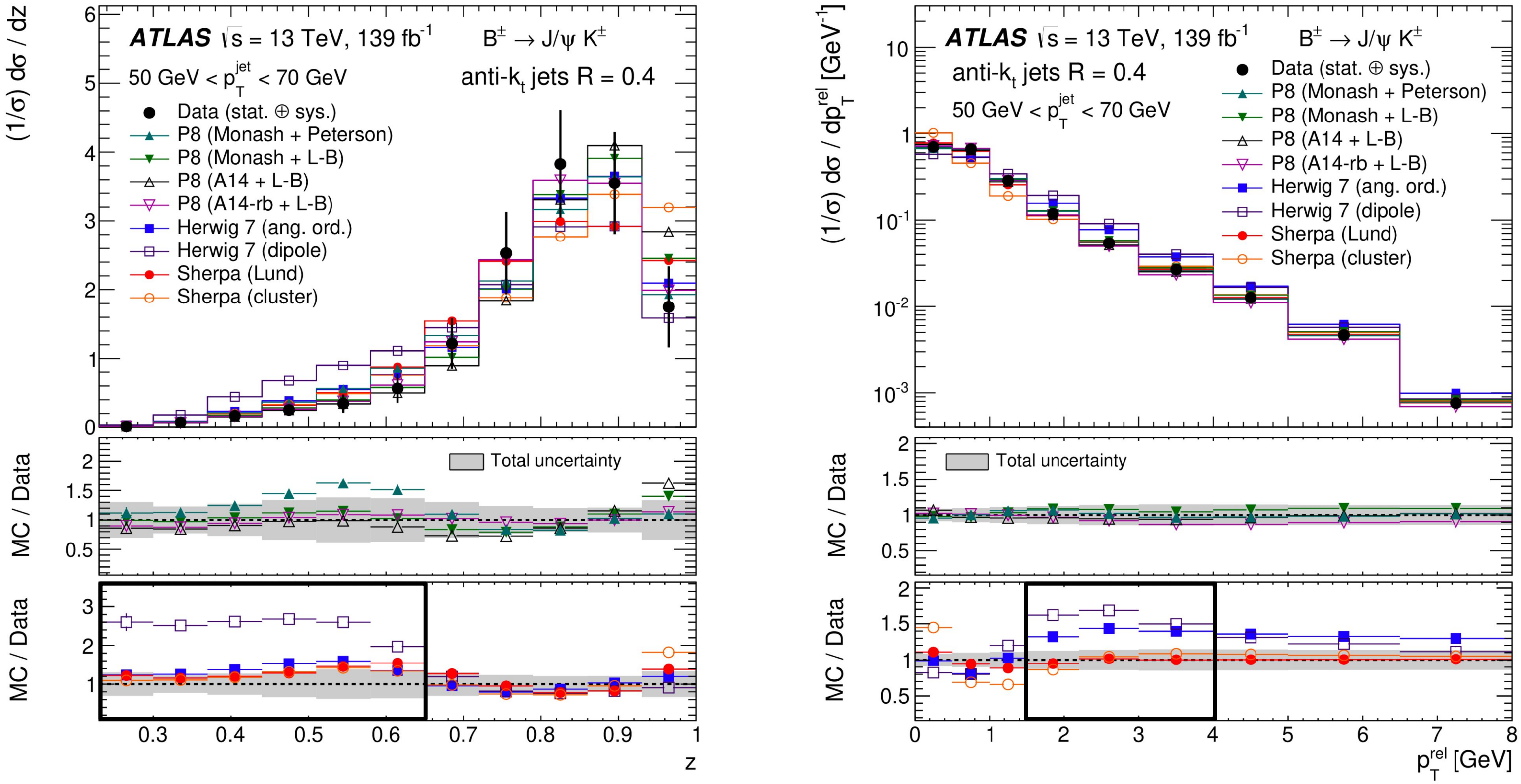




Measuring *b*-jet fragmentation with $B^{\pm} \to J/\Psi + K^{\pm}$ decays

Differential measurements in *z* and p_T^{rel}

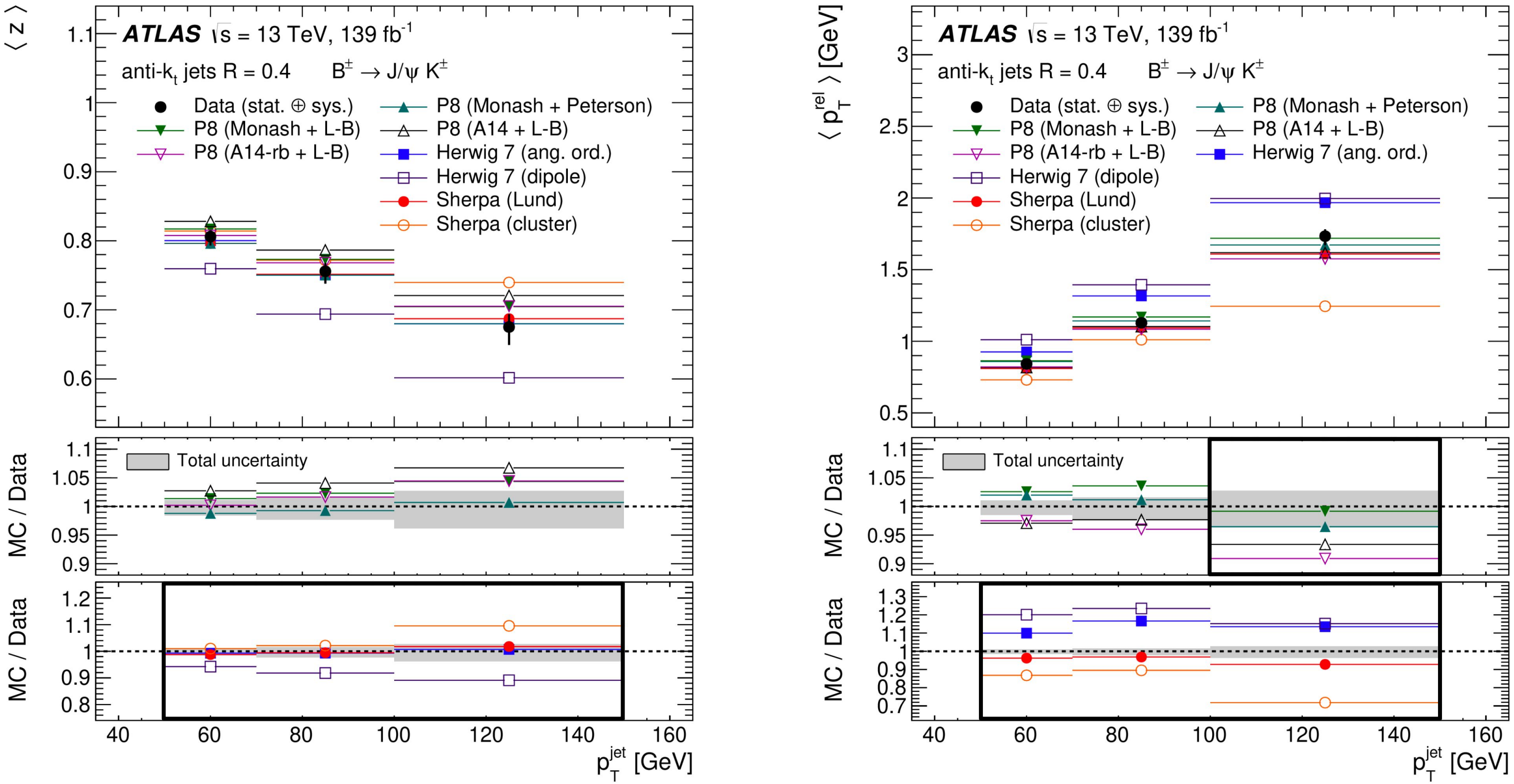
- ★ large deviations from data for Herwig 7 and Sherpa (cluster)



Measuring b-jet fragmentation with $B^{\pm} \rightarrow J/\Psi + K^{\pm}$ decays

Average z and p_T^{rel} values as a function of jet p_T

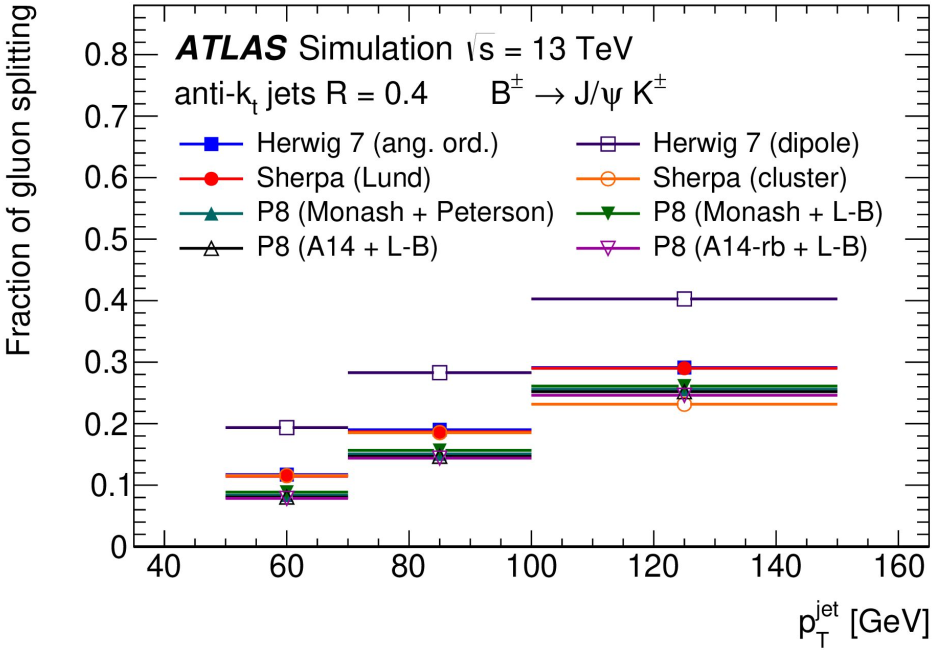
- mismodelling as large as 10% in some bins for all generators, especially at high p_T



Measuring *b*-jet fragmentation with $B^{\pm} \rightarrow J/\Psi + K^{\pm}$ decays

Reminder: measurement affected by the presence of gluon splitting to beauty pairs

- ⋆ fraction of gluon splittings very differently modelled and increasing with jet p_T
- ⋆ this affects fragmentation-sensitive variables, e.g. enhancing low z values
- ⋆ can at least partly explain the observed discrepancies (e.g. for Herwig 7 dipole)



Measuring *b*-jet fragmentation observables in $t\bar{t}$ events

The approach

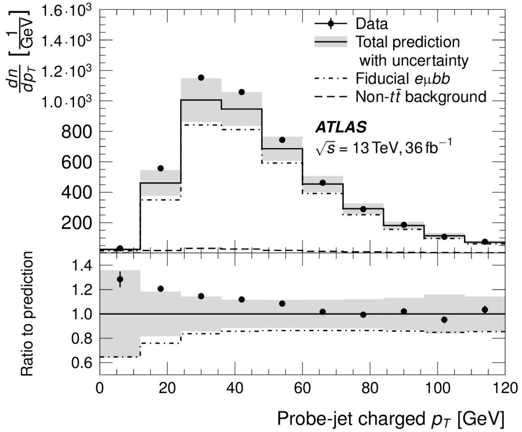
- use *tt* events, large source of *b*-jets → ***b*-tag anti-k_T jets** using calo clusters and R=0.4

> Di-leptonic *tt* events: require **opposite sign μ and e** + **exactly two jets** with $\Delta R > 0.5$
> Two-way **tag-and-probe**: if one jet is *b*-tagged, apply cuts and measure properties on the other

- reconstruct **secondary vertex in probe-jet** → charged-component proxy for *B*-hadron
- build **variable-radius track jet within the probe-jet** → charged-component of the jet
- measure charged momenta of jet and *B*-hadron → **extract fragmentation variables**

$$z^{\mathrm{ch}}_{\mathrm{L},b} = \frac{\vec{p}^{\,\mathrm{ch}}_{b} \cdot \vec{p}^{\,\mathrm{ch}}_{\mathrm{jet}}}{|p^{\mathrm{ch}}_{\mathrm{jet}}|^2}$$

$$z^{\mathrm{ch}}_{\mathrm{T},b} = \frac{p^{\mathrm{ch}}_{\mathrm{T},b}}{p^{\mathrm{ch}}_{\mathrm{T,jet}}}$$



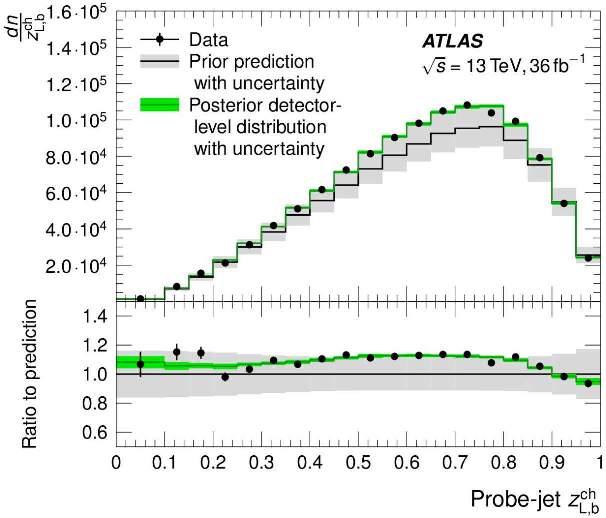
- **compare kinematic of *B*-hadron and *tt* system** (leptons as proxy)
- build variable sensitive to radiation in the top decay

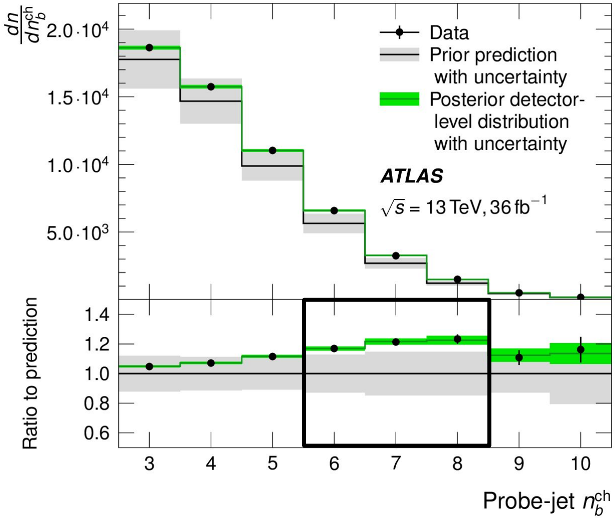
$$\rho = \frac{2p^{\mathrm{ch}}_{\mathrm{T},b}}{p^{e}_{\mathrm{T}} + p^{\mu}_{\mathrm{T}}}$$

Measuring b-jet fragmentation observables in $t\bar{t}$ events

Correcting for detector effects, backgrounds and unfolding to particle level

- all tasks performed in a single pass, using Fully Bayesian Unfolding
- also allows comparison of prior and posterior detector-level simulation w.r.t. data





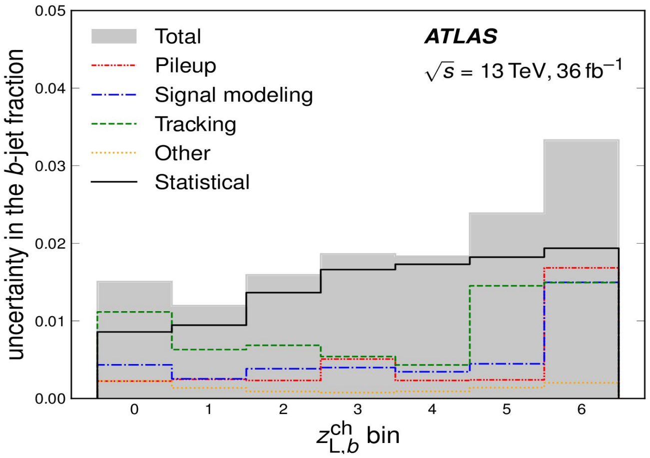
- reasonable agreement between posterior detector-level simulation and data for main variables of interest

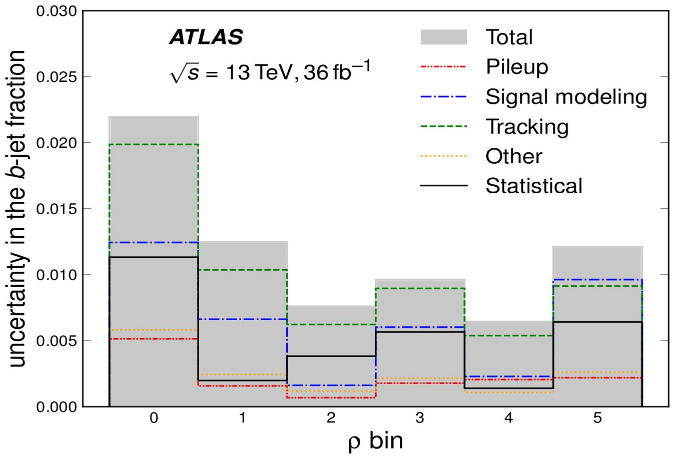
- larger difference for number of tracks at the secondary vertex
- extra syst: reweight n_b^{ch} in MC to data

Measuring *b*-jet fragmentation observables in $t\bar{t}$ events

Systematics grouped in four categories

- ★ **modelling**: variations in PS, ISR, FSR, *B* species, data-MC scalings on jet p_T and n_B^{ch}
- ★ **tracking**: from data-MC differences in alignment, track efficiency, fakes, IP resolution
- ★ **pile-up**: includes effects due to the MC description of pile-up dependence
- ★ **other experimental sources**: includes jet and flavour tagging calibrations



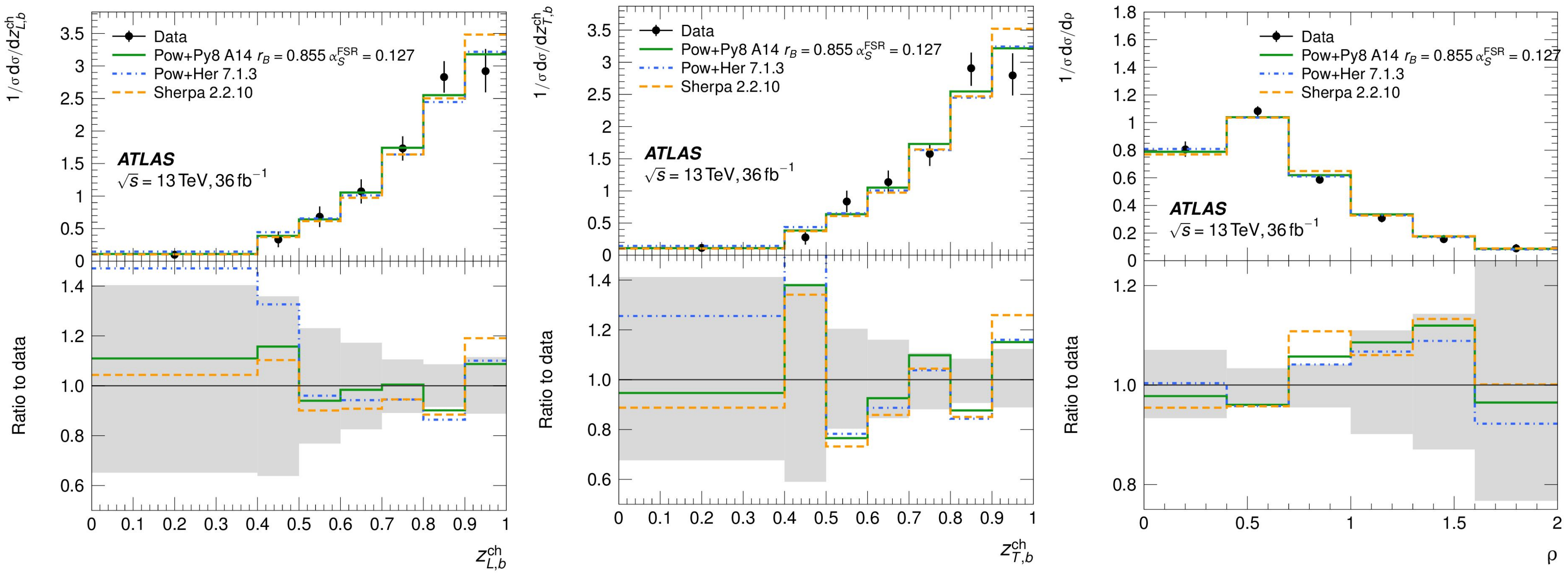


- ★ statistical uncertainty dominates for fragmentation variables
- ★ tracking uncertainty dominates for event-level variables

Measuring b-jet fragmentation observables in $t\bar{t}$ events

Results for widely-used generator configurations

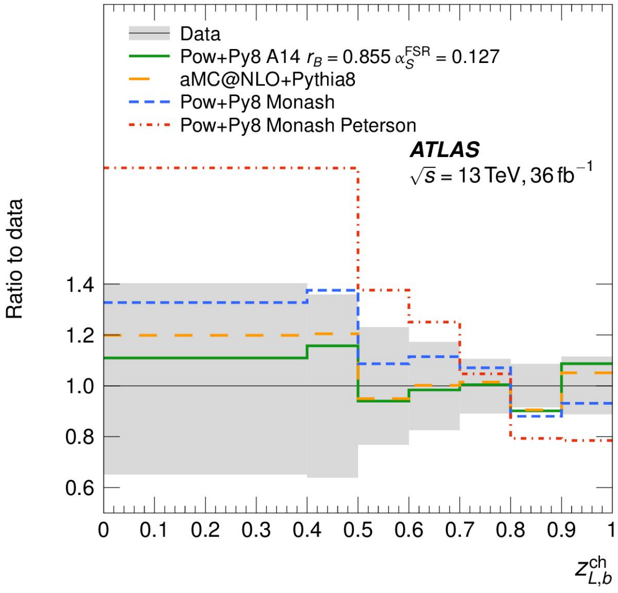
- ★ **good agreement for all models** on fragmentation-related and event-wide variables
- ★ largest (but still small) deviations observed for Powheg+Herwig

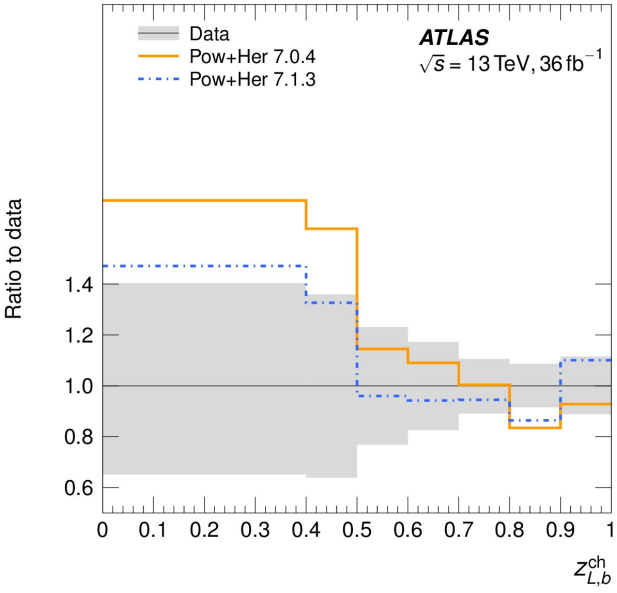


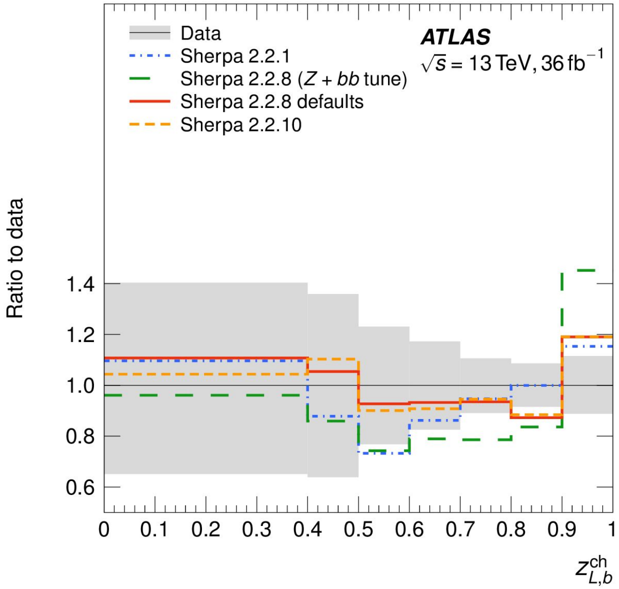
Measuring b-jet fragmentation observables in $t\bar{t}$ events

Results for different generator versions and tunes

- ★ good agreement with data for different Powheg+Pythia configs, except Peterson tune
- ★ general improvements in newer versions for Powheg+Herwig and Sherpa



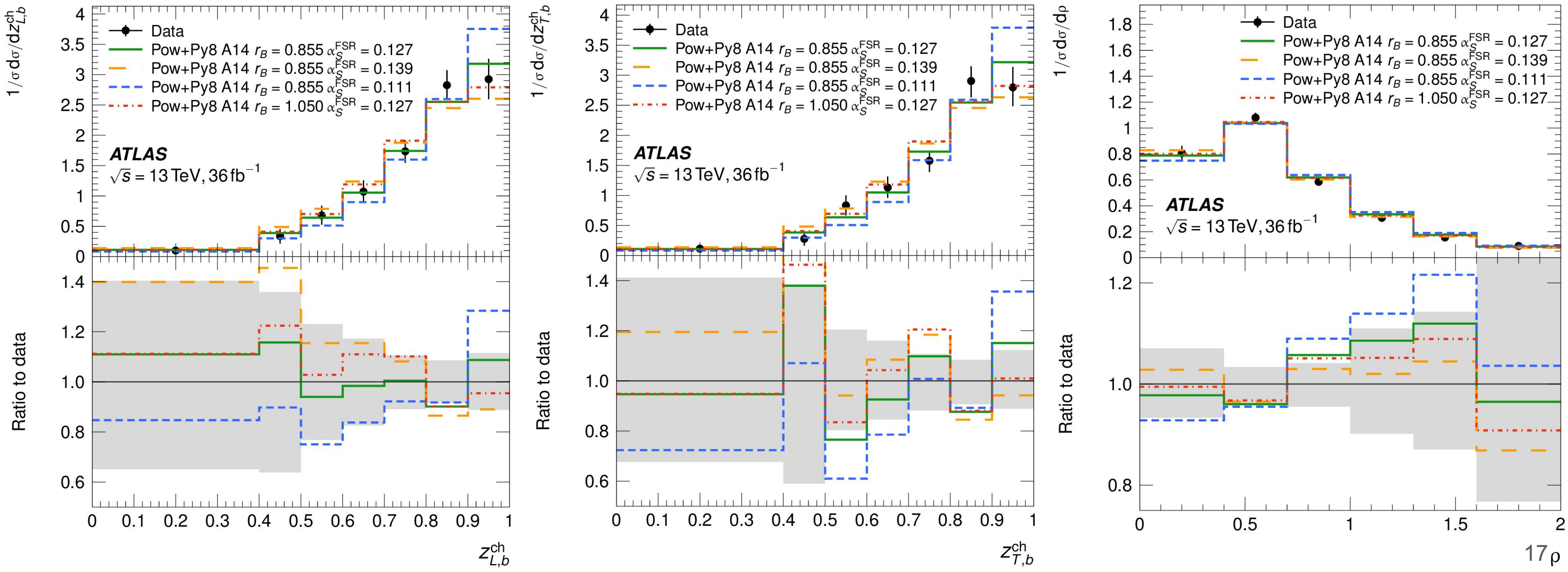




Measuring *b*-jet fragmentation observables in $t\bar{t}$ events

Results for different values of non-perturbative MC parameters in Pythia 8

- ★ test the effect of modifying α_s^{FSR} and *b*-quark mass re-scaling parameter r_B
- ★ A14 Pythia 8 tune variations provide good uncertainty envelope for *b* fragmentation



Summarizing

Exclusive and inclusive studies of fragmentation observables are a powerful tool

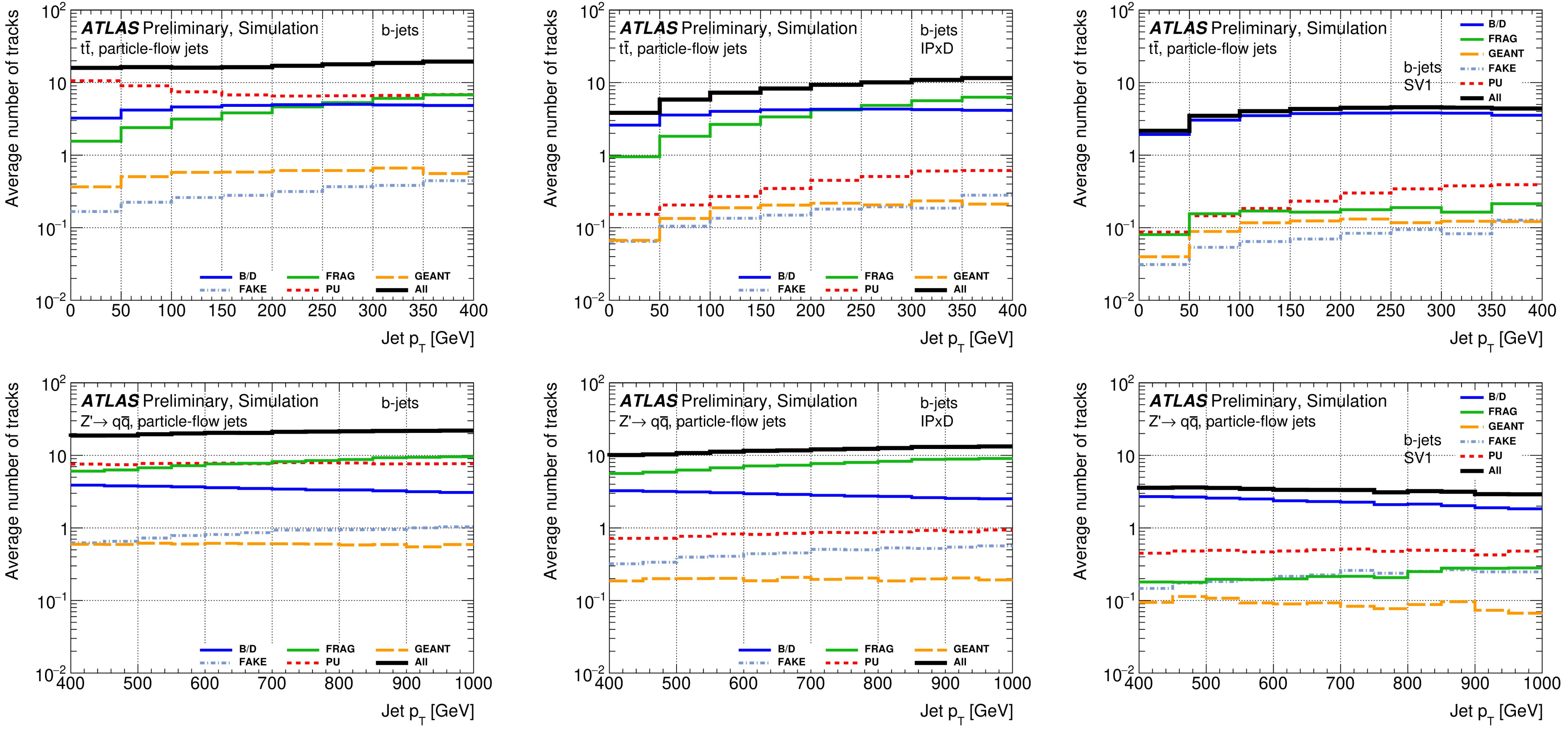
- ★ validate the application of measurements in e^+e^- collisions to LHC
- ★ enable to **spot models** and tunes leading to **large discrepancies** with data
- ★ allow to determine **reasonable tune variations** to build modelling systematics

Feedback welcome

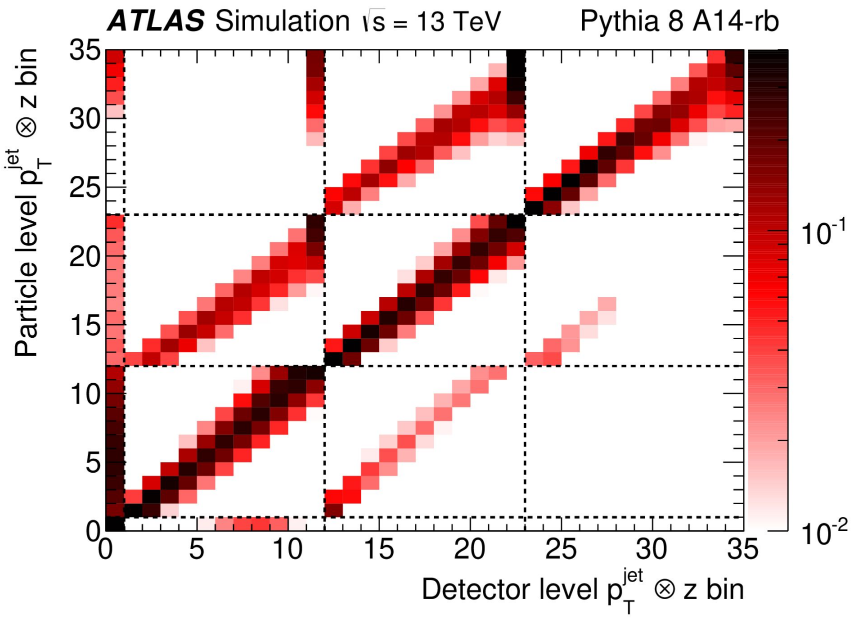
- ★ possibly **more models** to compare with observables measured in data
- ★ new ideas on **building observables** sensitive to fragmentation of heavy quarks

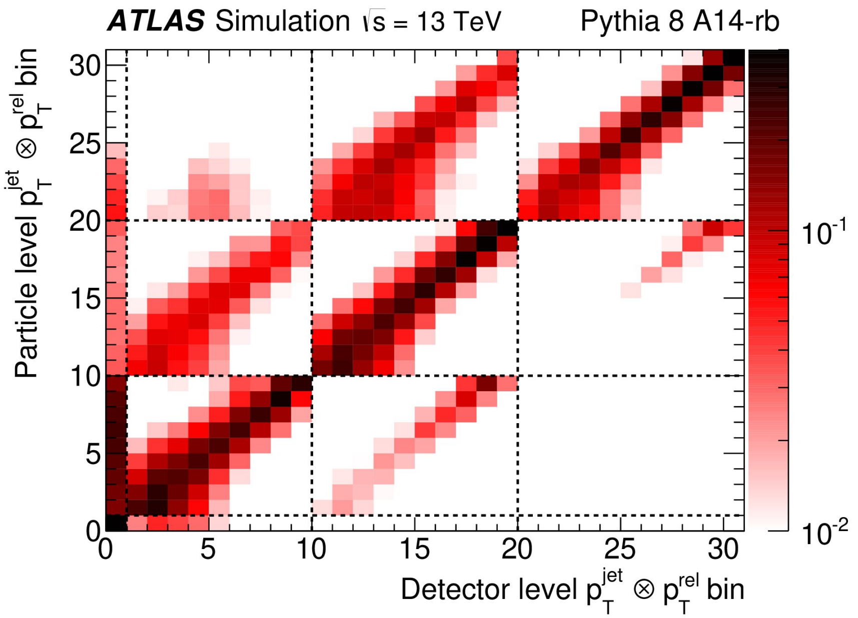
BACKUP

Fragmentation tracks



$B^{\pm} \to J/\Psi + K^{\pm}$ decays





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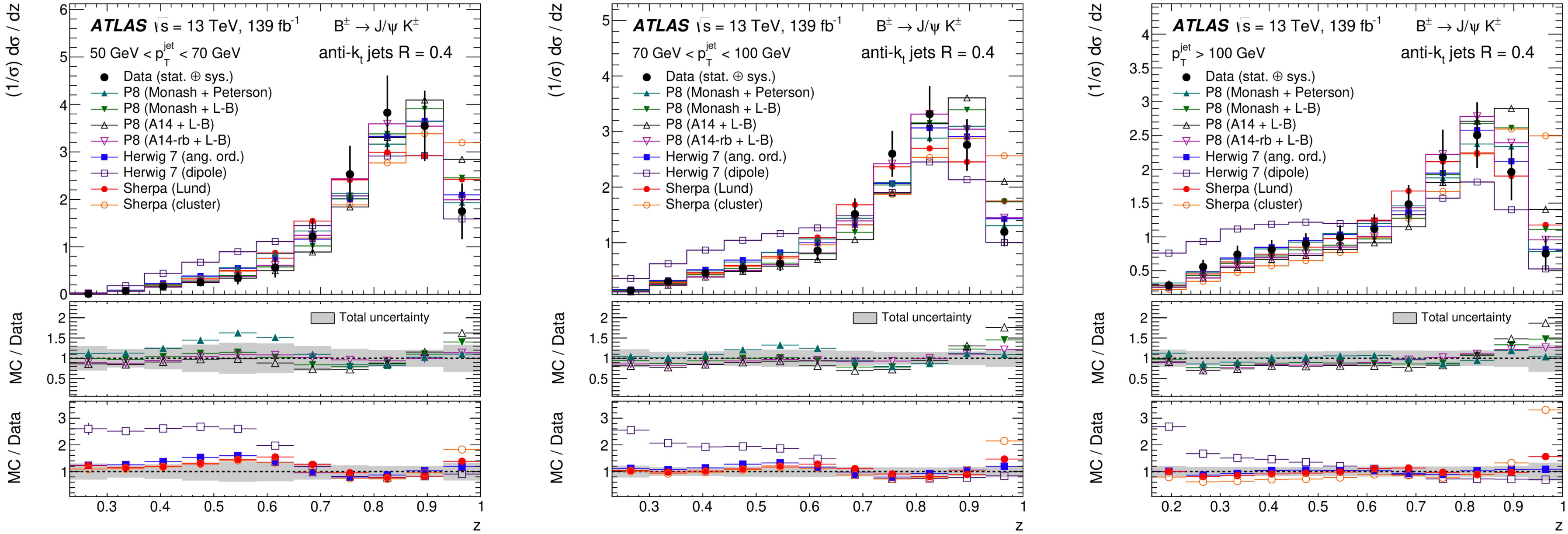

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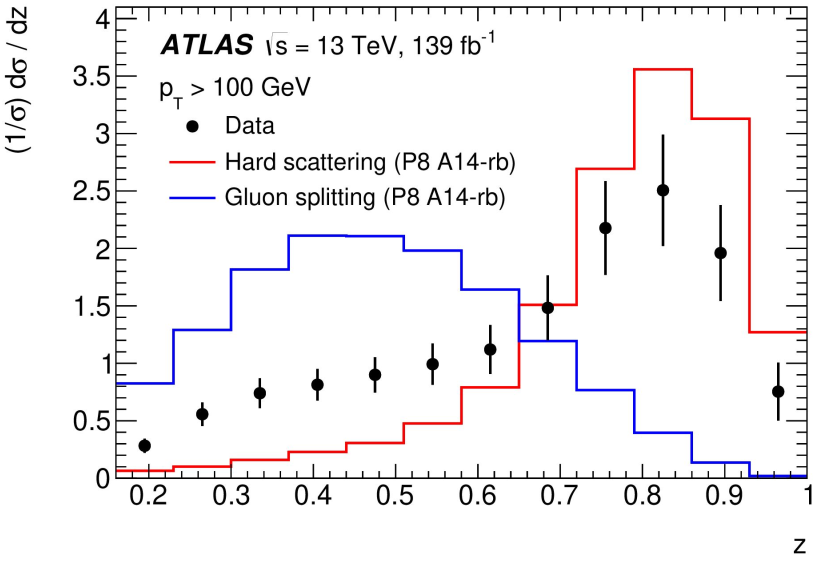

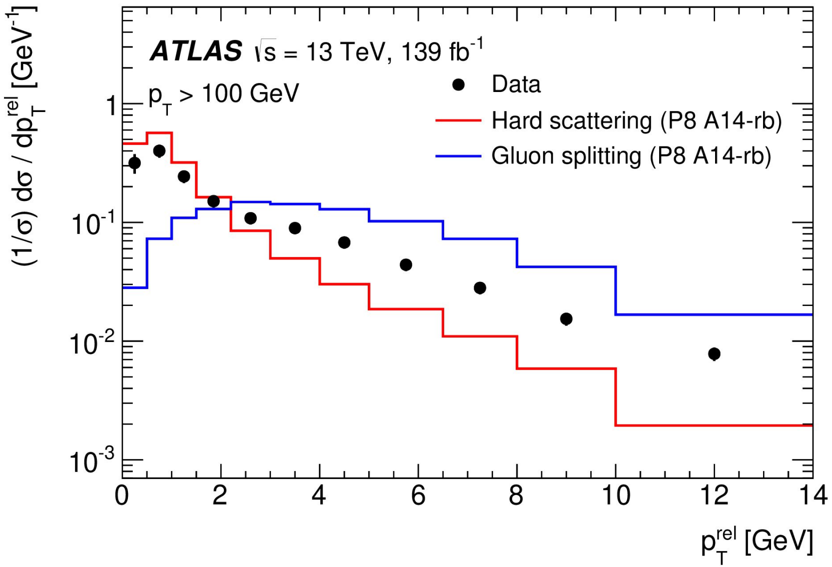

$B^{\pm} \to J/\Psi + K^{\pm}$ decays

Generator	ME order	Scales μ_r, μ_f	Parton shower	PDF set	Tune	Hadronisation
PYTHIA 8	$2 \to 2$ @ 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	$2 \to 2$ @ LO	$H(s,t,u)$	CSS (dipole)	CT14	–	Cluster model Lund string model
HERWIG 7	$2 \to 2$ @ LO	$\sqrt{\frac{2stu}{s^2+t^2+u^2}}$	Angle-ordered Dipole	MMHT2014	–	Cluster model

$t\bar{t}$ events

	Events with $e\mu jj$ ($\geq$ 1 b-tag)	Probe-jets
Process	Predicted yields	
Fiducial $t\bar{t}$	–	44000 ± 9000
Nonfiducial $t\bar{t}$	–	6700 ± 1500
Total $t\bar{t}$	76000 ± 12000	51000 ± 9000
Single top	4400 ± 1500	1580 ± 600
Z+jets	125 ± 45	13.0 ± 5.1
Diboson	90 ± 34	9.7 ± 3.9
Total non-$t\bar{t}$	4600 ± 1600	1600 ± 600
b-jets	–	52000 ± 9000
c-jets	–	180 ± 60
Other jets	–	250 ± 70
Total prediction	81000 ± 13000	53000 ± 9000
	Observed yields	
Data	88511	57476