



Letter

# First measurement of $b$ -jet mass with and without grooming

LHCb collaboration<sup>1</sup>

## ARTICLE INFO

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## ABSTRACT

The LHCb collaboration presents a novel suite of heavy-flavour jet substructure measurements at forward rapidity in proton-proton collisions at a centre-of-mass energy of  $\sqrt{s} = 13$  TeV. The jet mass is a perturbatively calculable probe of the virtuality of hard-scattered quarks and gluons, connecting small-distance quantum chromodynamics (QCD) with long-distance experimental measurement. The jet mass is dominated by nonperturbative corrections at small values, presenting an excellent test of QCD across a broad range of jet energies. Measuring heavy-flavour jet mass with a theoretically unambiguous flavour definition for the first time probes the gluon splitting mechanism for heavy-flavour production and offers tests of perturbative QCD at new levels of theoretical precision. Utilising the soft drop jet-grooming technique to access the perturbative jet core further enhances constraints on first-principles theory. Measurements of the jet mass for jets containing fully reconstructed  $B^\pm$  hadrons are reported with and without grooming. The unique phase space instrumented by LHCb offers a different quark-gluon fraction than at midrapidity. These results offer unparalleled tests of quark flavour and mass dependence in QCD and provide a baseline for future studies of heavy-flavour jet quenching in heavy-ion collisions.

## 1. Introduction

Collimated sprays of particles called jets are abundantly produced in high-energy particle collisions at the Large Hadron Collider (LHC), via the hard scattering of partons (quarks and gluons) from colliding nuclei. Scattered partons carry away some off-mass-shell virtuality,  $Q \equiv \sqrt{E^2 - p^2}$ , from the four-momentum exchanged in the interaction, the value of which is fundamentally unknown to an observer. However, in the parton shower picture, virtuality is shed by the successive radiation of gluons, forming a jet [1–4]. Studying the final-state jet substructure allows access to the radiation pattern of the scattered parton, and in turn probes its pre-shower kinematics [5,6].

Insomuch as the experimentally reconstructed jet is a proxy for the initiating parton, the jet mass provides a proxy for the parton's virtuality,

$$m_{\text{jet}} = \sqrt{E_{\text{jet}}^2 - p_{\text{jet}}^2} \sim Q_{\text{parton}}, \quad (1)$$

where  $E_{\text{jet}}$  is the jet energy and  $p_{\text{jet}}$  is its total momentum. Measurements of  $m_{\text{jet}}$  as a function of jet transverse momentum  $p_{T,\text{jet}}$  therefore probe the dependence of partonic virtuality versus the momentum scale of the initial scattering. It is useful to study  $m_{\text{jet}}$  normalised by the jet transverse momentum,  $m_{\text{jet}}/p_{T,\text{jet}}$ , which is dimensionless<sup>2</sup> and closely related to the widely studied jet angularities [7–11]. Because higher-virtuality quarks shed their virtuality with more QCD radiation, jets which are broader and contain more gluon emissions will tend to have a higher mass than jets which are narrower and contain less radiation.

Jet substructure calculations are theoretically challenging due to the presence of large non-global logarithms (NGLs) which arise due to the local phase-space constraints of jet observables [12]. Such contributions can be eliminated, however, by utilising *soft drop grooming* to remove soft, wide-angle radiation from the jet [13,14]. Fixed-order calculations of  $m_{\text{jet,gr}}$ , the mass of jets groomed with soft drop, have recently been computed up to next-to-next-to-leading order (N<sup>2</sup>LO) including resummation of large logarithms up to next-to-next-to-next-to-leading logarithmic accuracy (N<sup>3</sup>LL) [15], offering an opportunity to study QCD via jet substructure at unprecedented precision.

Jets initiated by a heavy-flavour (HF) quark,  $c$  or  $b$ , have also become increasingly accessible at the LHC. The substructure of HF jets is modified relative to light-flavour jets due to the QCD “dead cone” effect [16], a perturbatively well-described suppression of gluon radiation at small angles from the hard-scattered HF quark. Heavy-flavour jets also probe nonperturbative effects such as the HF component of the proton wavefunction [17] and HF fragmentation functions [18–25]. However, theoretical interpretation can be limited by traditional jet flavour tagging, as solely requiring a specific HF hadron to be reconstructed inside a jet is not theoretically well-defined past NLO [26]. Reconstructing secondary vertices and using machine learning to tag the jet flavour is also dependent on simulation models, which limits perturbative accuracy.

Recently a variety of algorithms calculable beyond NLO have been proposed to tag jet flavour while maintaining traditional jet kinematics [27–30]. One novel approach is the Winner-Take-All (WTA) flavour-tagging algorithm [31], which is calculable to any perturbative

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<sup>2</sup> Natural units with  $\hbar = c = 1$  are used throughout.

order [32]. At forward rapidity, adding a WTA flavour requirement predominantly removes jets whose HF content arises from in-shower gluon splitting ( $g \rightarrow b\bar{b}$ ) [33]. Gluon splitting contaminates samples of direct HF production; however, it has also been proposed as a probe for studying bulk QCD dynamics in heavy-ion collisions [34,35]. The difference in  $m_{\text{jet}}/p_{\text{T,jet}}$  before and after WTA tagging therefore offers a novel baseline for jet quenching [36–39] via a specific NLO process, useful for probing mass-dependent momentum transfer and quantum coherence effects in quark-gluon plasma [34,35,40].

Previous studies of  $m_{\text{jet}}$  have been performed by the ATLAS [41–44], CMS [45–48], and ALICE [49,50] experiments at the LHC, as well as the STAR [51] experiment at RHIC, but there has been no measurement for jets explicitly tagged with  $b$  flavour. This letter presents new studies of  $m_{\text{jet}}$  for  $b$  jets at forward rapidity in proton-proton ( $pp$ ) collisions at a centre-of-mass energy of  $\sqrt{s} = 13$  TeV with the LHCb detector. Studying  $b$  jets offers enhanced sensitivity to HF mass effects as compared to  $c$ -tagged jets due to the larger  $b$ -quark mass. Jets containing a  $b$  quark are identified using  $B^\pm$  mesons explicitly reconstructed from the  $J/\psi(\rightarrow \mu^+ \mu^-)K^\pm$  final state. Fully reconstructing the  $B^\pm$  meson enables the use of WTA flavour tagging and improves jet momentum resolution as compared to statistical flavour tagging methods. The unique acceptance of LHCb offers a large  $b$ -quark cross-section with significant longitudinal boost, enabling precision identification of secondary vertices from the  $B^\pm$  meson decay. Jets are considered both with/without soft drop grooming [14], and with/without WTA flavour tagging [31], and results are compared to PYTHIA simulations, with direct QCD calculations from the theory community still in preparation.

## 2. Detector and dataset

The LHCb detector [52,53] is a single-arm forward spectrometer covering the pseudorapidity range  $2 < \eta < 5$ , designed for the study of particles containing  $b$  and  $c$  quarks. The detector includes a high-precision tracking system consisting of a silicon-strip vertex detector surrounding the  $pp$  interaction region [54], a large-area silicon-strip detector located upstream of a dipole magnet with a bending power of about 4 T m, and three stations of silicon-strip detectors and straw drift tubes placed downstream of the magnet [55]. The tracking system measures the momentum,  $p$ , of charged particles with a relative uncertainty that varies from 0.5% at low momentum to 1.0% at 200 GeV [53]. The minimum distance of a track to a primary  $pp$  collision vertex, called the impact parameter, is measured with a resolution of  $(15 + 29/p_{\text{T}}) \mu\text{m}$ , where  $p_{\text{T}}$  is in units of GeV. Different types of charged hadrons are distinguished using information from two ring-imaging Cherenkov detectors (RICH) [56]. Photons, electrons and hadrons are identified by a calorimeter system consisting of scintillating-pad and preshower detectors, an electromagnetic and a hadronic calorimeter. Muons are identified by a system composed of alternating layers of iron and multiwire proportional chambers [57].

The data sample used in this analysis corresponds to an integrated luminosity of  $5.4 \text{ fb}^{-1}$  recorded in 2016–2018. The online event selection is performed by a trigger [58] which consists of a hardware stage using information from the calorimeter and muon systems, followed by a software stage which performs the full event and candidate  $B^\pm$  meson reconstruction. The hardware stage selects events with at least one  $\mu^\pm$  candidate with  $p_{\text{T}}(\mu^\pm) > 1.35\text{--}1.80$  GeV, or at least one pair of oppositely charged muons with  $\sqrt{p_{\text{T}}(\mu^+)p_{\text{T}}(\mu^-)} > 1.3\text{--}1.5$  GeV, where the threshold varied during the data taking period [59]. In the software stage, two oppositely charged  $\mu^\pm$  candidates, each with  $p_{\text{T}}(\mu^\pm) > 0.5$  GeV, are required to form a  $J/\psi$  candidate with a mass within  $\pm 100$  MeV of the known value [60] and  $p_{\text{T}} > 2$  GeV. Information from the RICH detectors is used to identify  $K^\pm$  mesons, which reduces contamination from the Cabibbo-suppressed decay  $B^\pm \rightarrow J/\psi(\rightarrow \mu^+ \mu^-)\pi^\pm$ .

Simulation is required to model the effects of the detector response and the imposed selection requirements on the  $J/\psi(\rightarrow \mu^+ \mu^-)K^\pm$  final state. In the simulation,  $pp$  collisions are generated using PYTHIA

8.186 [61] with a specific LHCb configuration [62]. Decays of unstable particles are described by EVTGEN [63], in which final-state radiation is generated using PHOTOS [64]. The interaction of the generated particles with the detector, and its response, are implemented using the GEANT4 toolkit [65,66] as described in Ref. [67]. To improve the simulated response of the RICH detectors, particle identification (PID) variables are corrected using calibration data from  $D^{*+} \rightarrow D^0 \pi^+$  and  $D^0 \rightarrow K^- \pi^+$  decays for  $K^\pm$  and  $\pi^\pm$  mesons, and  $\Lambda_c^+ \rightarrow p K^- \pi^+$  decays for protons [68]. This correction adjusts the variables to match the data distributions, accounting for track kinematics.

## 3. Event reconstruction and jet selection

To minimise uncorrelated in-jet radiation from pileup, events are required to have only one reconstructed primary vertex. Candidate  $J/\psi$  mesons are constrained to the known  $J/\psi$  mass [60] and combined with identified  $K^\pm$  mesons to construct candidate  $B^\pm$  mesons. These candidates are required to have a mass within 130 MeV (below) and 300 MeV (above) the known  $B^\pm$  mass [60]. The asymmetry in the mass window removes the partially reconstructed background coming from  $B^\pm$  and  $B^0$  decays with an additional unreconstructed  $\pi^0$  or  $\pi^\pm$  meson. The reconstructed  $B^\pm$  meson candidates are required to originate from the primary vertex, which improves the signal purity and the mass resolution.

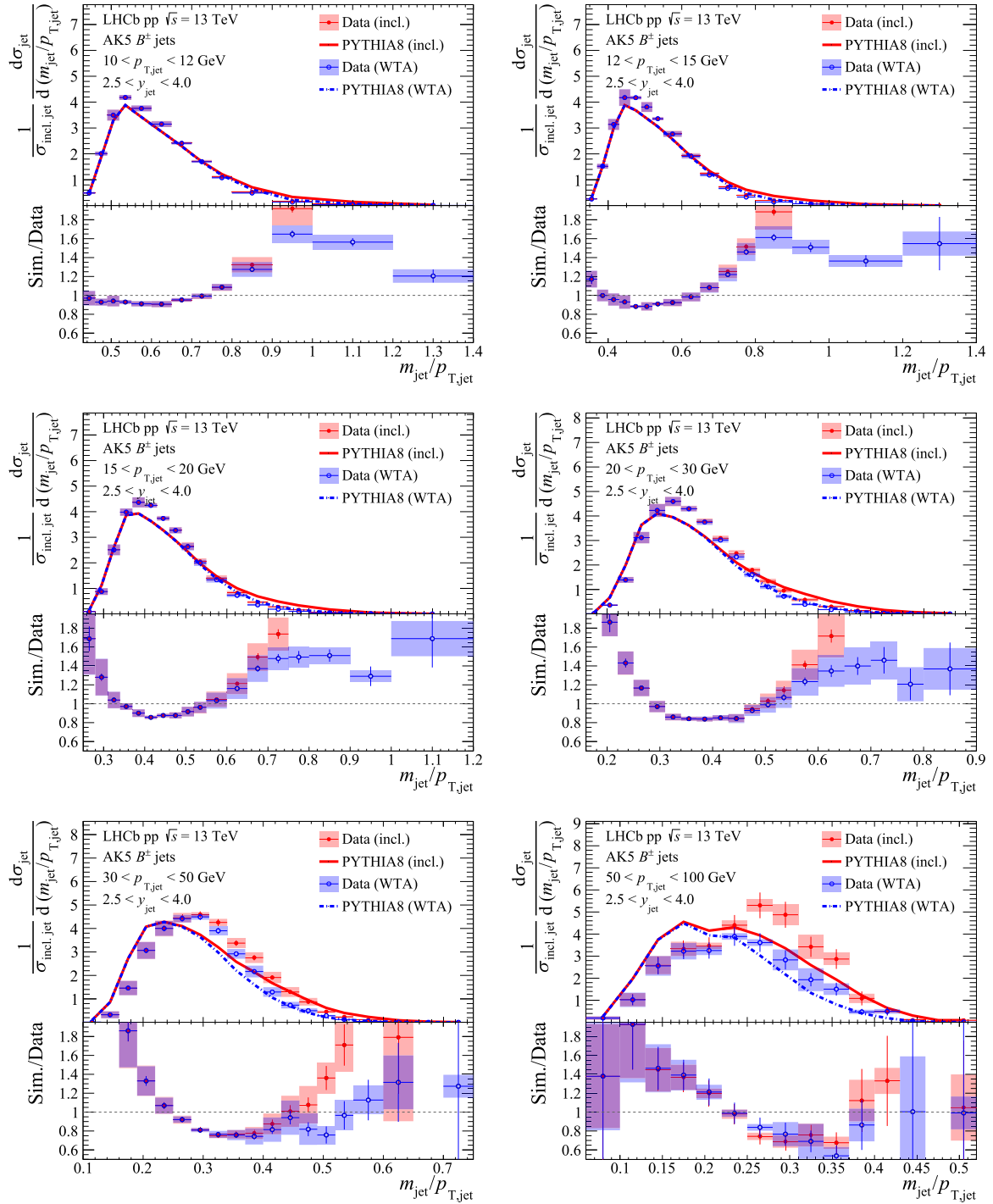
After replacing its decay products with the reconstructed  $B^\pm$  candidate, jets are reconstructed with the FASTJET 3.4.1 package [69] using the anti- $k_{\text{T}}$  algorithm [70] with jet resolution (radius) parameter  $R = 0.5$  and  $E$ -scheme recombination.<sup>3</sup> Particles are assigned the mass [60] of their most likely identity, utilising the excellent PID capabilities of LHCb [71]. Jets that contain the candidate  $B^\pm$  meson are selected. A minimum jet transverse momentum cut of  $p_{\text{T,jet}} > 5$  GeV is applied. The jet rapidity range is restricted to  $2.5 < y_{\text{jet}} < 4.0$  to ensure all particles inside the jet are within the LHCb detector acceptance and have good reconstruction efficiency.

A sample of groomed jets is produced using the soft drop algorithm [14]. The jet is reclustered from its constituents into a tree-like data structure using the Cambridge/Aachen algorithm [72,73], which preferentially clusters together particles nearby in the rapidity ( $y$ ) – azimuth ( $\varphi$ ) plane. This leads to an angular ordering of branches in the tree, reflecting the approximate angular ordering of emissions in QCD [74–76]. Each splitting is then declustered starting from the last (widest-angle) pair, and the relative  $p_{\text{T}}$  fraction of the softer branch,  $z \equiv p_{\text{T,soft}}/(p_{\text{T,soft}} + p_{\text{T,hard}})$ , is calculated. If  $z < z_{\text{cut}}\theta^\beta$ , where  $\theta \equiv (\sqrt{\Delta y^2 + \Delta\varphi^2})/R$ , and  $z_{\text{cut}}$  and  $\beta$  are user-defined grooming parameters, then the softer branch is dropped, and the procedure continues with the next splitting in the remaining branch. If, however,  $z > z_{\text{cut}}\theta^\beta$ , then the procedure is concluded, with all remaining constituents defining the groomed jet. If the jet has no remaining splittings after removing a branch, then the jet is “groomed away” and is removed from the data sample. Because they have no splittings, all single-constituent jets are groomed away. Grooming parameters  $z_{\text{cut}} = 0.1$  and  $\beta = 0$  are used.

Both ungroomed and groomed jets are evaluated using WTA flavour tagging [31]. As with soft drop, the jet is reclustered from its constituent particles using the Cambridge/Aachen algorithm. The WTA axis [77, 78] is determined by evaluating each recombination in the  $p_{\text{T}}$  scheme, whereby the combined axis is set to be along the direction of the higher  $p_{\text{T}}$  branch, and is assigned a magnitude equal to the  $p_{\text{T}}$  sum of the two branches. This continues until all particles are recombined. The WTA flavour tag is then determined by requiring the candidate  $B^\pm$  meson to lie along the WTA axis.

The  $b$ -jet sample contains contamination from combinatorial background which must be statistically subtracted from the  $m_{\text{jet}}/p_{\text{T,jet}}$  distributions. To identify the fraction of signal and background

<sup>3</sup>  $E$ -scheme recombination determines the reconstructed jet energy and momentum by adding the four-vectors of the jet constituents.

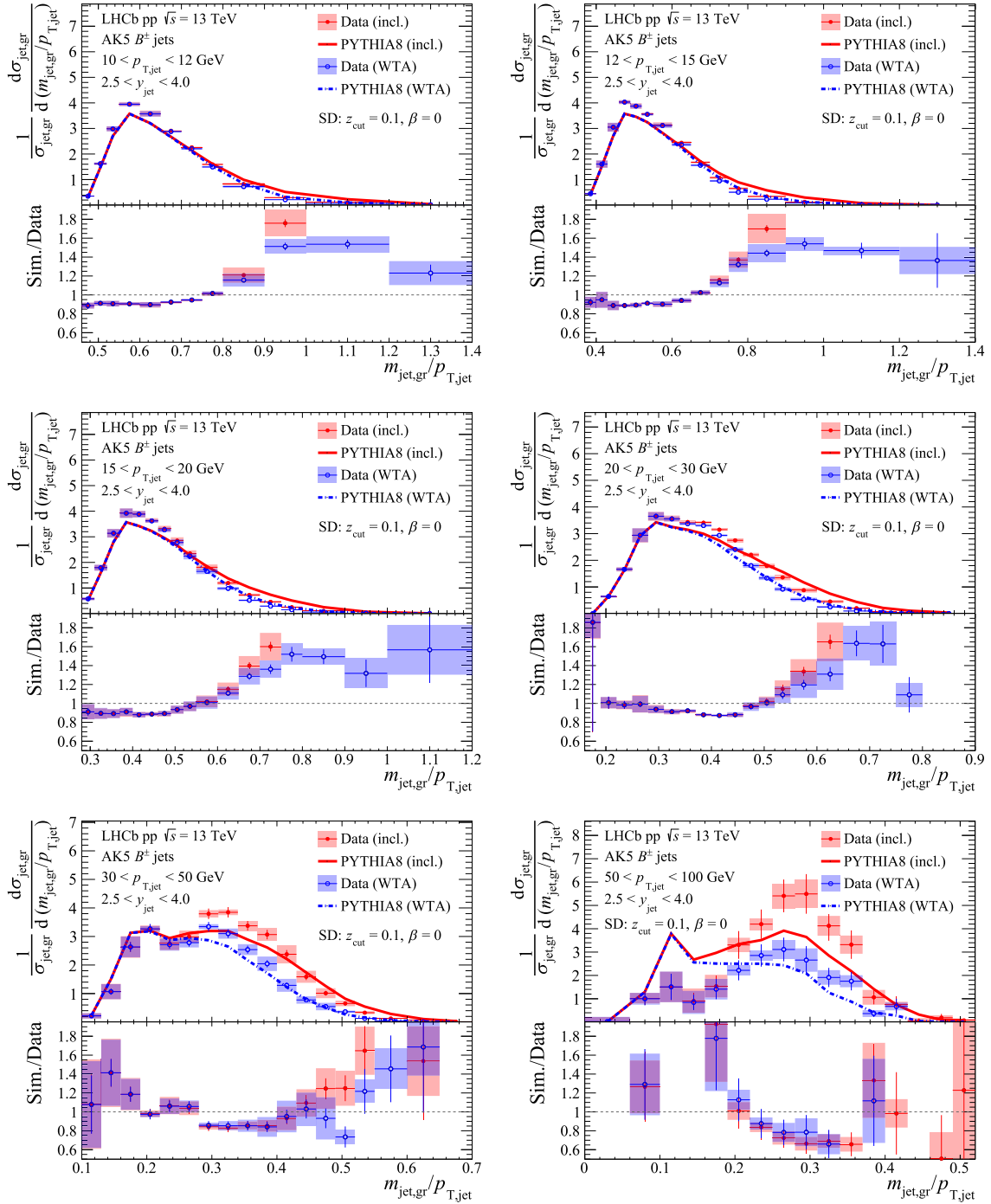


**Fig. 1.** Ungroomed  $m_{\text{jet}}/p_{T,\text{jet}}$  distributions for  $R = 0.5$  anti- $k_T$  jets (AK5) containing a  $B^\pm$  meson with (WTA) and without (incl.) WTA flavour tagging. Results are shown for several bins of  $p_{T,\text{jet}}$ , ranging from 10 to 100 GeV, and are compared to predictions from PYTHIA 8.186 (LHCb tune). The shaded error bands correspond to total systematic uncertainties, while the solid lines correspond to statistical uncertainties. Some points are not displayed in the ratio panel because they are outside the plotted range. Note that the x-axis range changes for each  $p_{T,\text{jet}}$  bin, due to quark-mass effects.

contributions, the candidate  $B^\pm$  mass spectrum is fit using parametric signal and background models as a function of  $B^\pm$  transverse momentum,  $p_{T,\text{HF}}$ . The signal peak is modelled using two double-sided Crystal Ball (DSCB) functions [79,80] with shared peak position and tail parameters, with the latter constrained from fits in simulation. The combinatorial background is modelled by a second-order polynomial function. The distribution of misidentified  $B^\pm$  candidates arising from the Cabibbo-suppressed  $B^\pm \rightarrow J/\psi(\rightarrow \mu^+\mu^-)\pi^\pm$  decay is determined in sim-

ulation and is also modelled using a DSCB function, but this background is found to be negligible due to strong PID requirements on the  $K^\pm$  meson.

“Signal plus background” (S+B) and “pure background” (PB) regions are then defined as a function of candidate  $B^\pm$  mass and  $p_{T,\text{HF}}$ . The S+B region is defined underneath the signal mass peak, with  $p_{T,\text{HF}}$ -dependent edges typically between 5.25 and 5.31 GeV. The fraction of combinatorial background which contaminates this region falls from

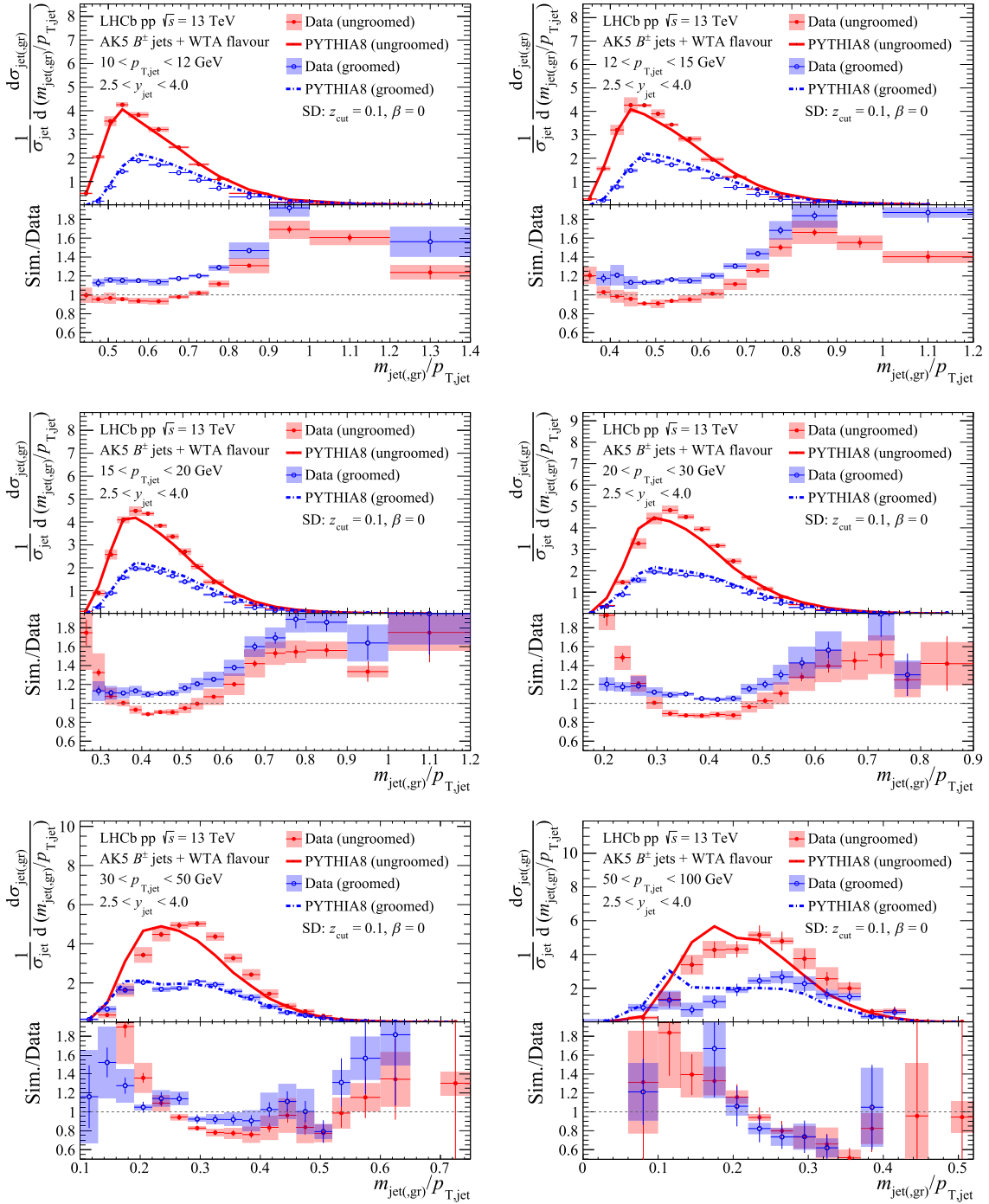


**Fig. 2.** Soft drop groomed  $m_{\text{jet,gr}}/p_{T,\text{jet}}$  distributions for  $R = 0.5$  anti- $k_T$  (AK5) jets containing a  $B^\pm$  meson with (WTA) and without (incl.) WTA flavour tagging. Results are shown for several bins of  $p_{T,\text{jet}}$ , ranging from 10 to 100 GeV, and are compared to predictions from PYTHIA 8.186 (LHCb tune). The shaded error bands correspond to total systematic uncertainties, while the solid lines correspond to statistical uncertainties. Some points are not displayed in the ratio panel because they are outside the plotted range. Note that the x-axis range changes for each  $p_{T,\text{jet}}$  bin, due to quark mass effects.

10% for  $p_{T,\text{HF}} < 4$  GeV to negligible values for  $p_{T,\text{HF}} > 35$  GeV. Two PB regions are then defined using sidebands away from the signal region, typically below 5.22 GeV and above 5.36 GeV. Distributions of  $m_{\text{jet}}/p_{T,\text{jet}}$  are measured using candidate  $b$  jets in each region. The PB distribution is scaled by the ratio of background in the S+B region versus the PB region, and then statistically subtracted from the S+B distributions as a function of  $p_{T,\text{HF}}$  to yield pure signal distributions. See Appendix for an example mass fit distribution.

#### 4. Detector corrections

Effects originating from the imperfect response of the LHCb detector are corrected by applying a suite of detector corrections. In simulation, jets containing a  $B^\pm$  hadron are geometrically matched in  $y$  and  $\phi$  before and after the LHCb detector simulation to estimate such effects. The  $m_{\text{jet}}/p_{T,\text{jet}}$  distribution, binned differentially in  $p_{T,\text{HF}}$  and  $p_{T,\text{jet}}$ , is first corrected for its imperfect purity by removing contribu-

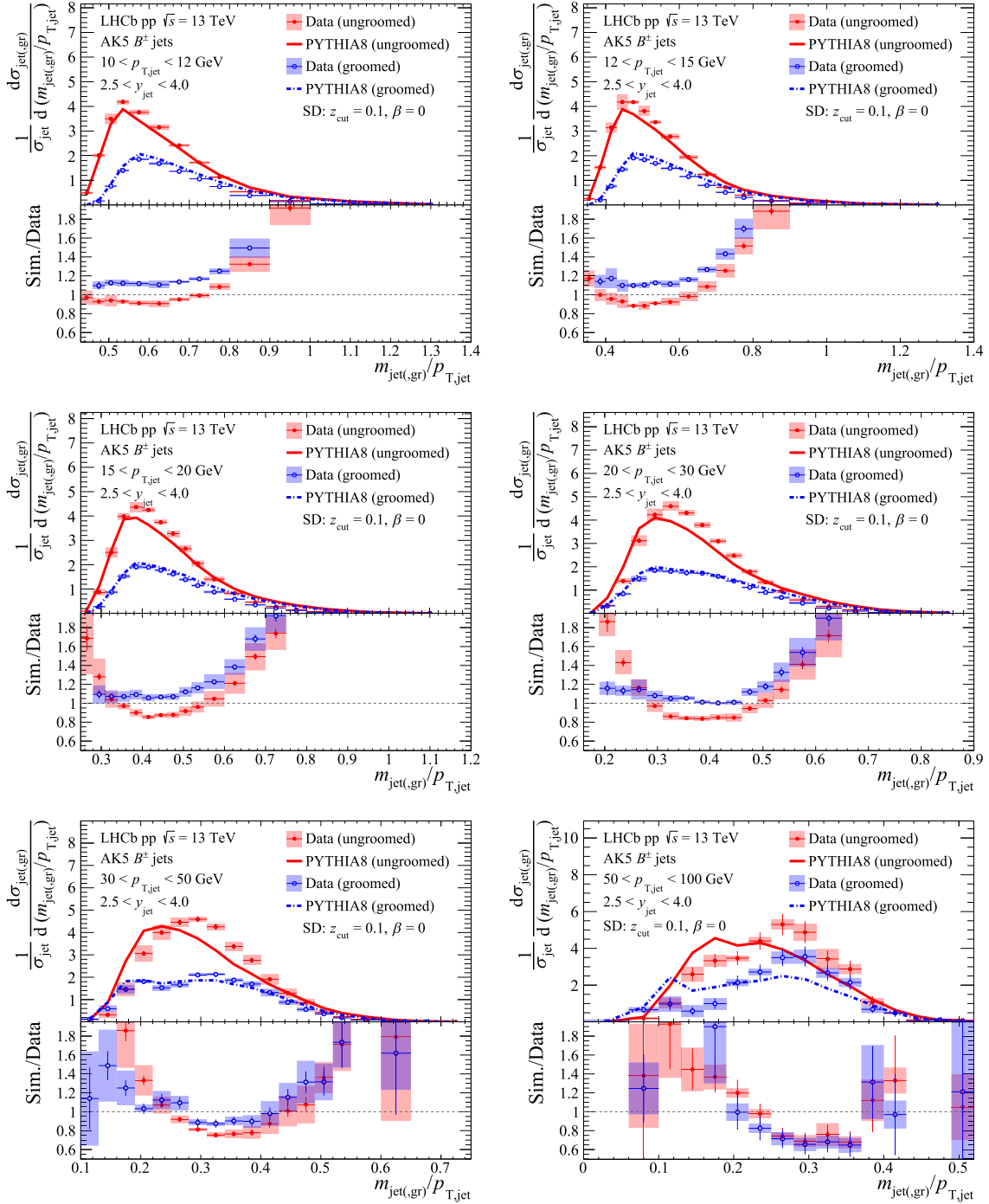


**Fig. 3.** Comparison of ungroomed and soft drop groomed  $m_{\text{jet}(\text{gr})}/p_{T,\text{jet}}$  distributions for  $R = 0.5$  anti- $k_T$  (AK5) jets containing a  $B^\pm$  meson and tagged with WTA flavour tagging. Results are shown for several bins of  $p_{T,\text{jet}}$ , ranging from 10 to 100 GeV, and are compared to predictions from PYTHIA 8.186 (LHCb tune). The shaded error bands correspond to total systematic uncertainties, while the solid lines correspond to statistical uncertainties. Some points are not displayed in the ratio panel because they are outside the plotted range. Note that the  $x$ -axis range changes for each  $p_{T,\text{jet}}$  bin, due to quark mass effects.

tions which originate from fake  $b$  jets (those that do not map to a true  $b$  jet) or  $b$  jets from outside the reported kinematic region. The signal purity rises steeply from around 40–50% (with WTA tagging) or 55–65% (without the WTA requirement) for  $p_{T,\text{HF}} < 3$  GeV to more than 95% for  $p_{T,\text{HF}} > 6$  GeV.

Bin migration effects, which originate from tracking inefficiency, material interactions, and finite momentum and energy resolution in the LHCb detector, are then corrected using a 6D response matrix (RM) that

describes the mapping of  $p_{T,\text{HF}}$ ,  $p_{T,\text{jet}}$ , and  $m_{\text{jet}}/p_{T,\text{jet}}$  before and after detector effects. A 3D unfolding is performed using the iterative Bayesian unfolding algorithm [82], as implemented in ROOUNFOLD [81]. Three iterations are used for all observable configurations, which provides good convergence. Unfolding begins with a prior distribution from simulation before iteratively updating the distribution using Bayes' theorem with the calculated RM and measured data. The bin migration is dominated by a strong diagonal mapping in the RM coupled with a slight



**Fig. 4.** Comparison of ungroomed and soft drop groomed  $m_{\text{jet}(\text{gr})}/p_{T,\text{jet}}$  distributions for  $R = 0.5$  anti- $k_T$  (AK5) jets containing a  $B^\pm$  meson without using WTA flavour tagging. Results are shown for several bins of  $p_{T,\text{jet}}$ , ranging from 10 to 100 GeV, and are compared to predictions from PYTHIA 8.186 (LHCb tune). The shaded error bands correspond to total systematic uncertainties, while the solid lines correspond to statistical uncertainties. Some points are not displayed in the ratio panel because they are outside the plotted range. Note that the  $x$ -axis range changes for each  $p_{T,\text{jet}}$  bin, due to quark mass effects.

smearing along the  $p_{T,\text{jet}}$  and  $m_{\text{jet}}/p_{T,\text{jet}}$  axes, with negligible smearing in  $p_{T,\text{HF}}$ .

The  $m_{\text{jet}}/p_{T,\text{jet}}$  distribution is then corrected for jets which are not reconstructed or selected in data due to kinematic or topological selections, or detector inefficiencies. The total  $b$ -jet reconstruction efficiency is calculated using simulation and adjusted with data-driven methods. Specifically, the efficiency of reconstructing the  $B^\pm$  decay products is calculated using the tag-and-probe method on  $J/\psi \rightarrow \mu^+ \mu^-$  decays [85]. The efficiency of correctly identifying these particles is calculated using

standard calibration samples [83]. The trigger efficiency is calculated using  $J/\psi \rightarrow \mu^+ \mu^-$  decays selected by several hardware triggers [84]. The total efficiency rises from 5% for  $p_{T,\text{HF}} < 4$  GeV to around 20% for  $p_{T,\text{HF}} > 20$  GeV.

## 5. Systematic uncertainties

To probe the dependence of  $m_{\text{jet}}/p_{T,\text{jet}}$  on underlying systematic uncertainties, several procedural variations are performed with the full

analysis repeated. The ratio between these varied results and the baseline one is used to assign a relative systematic uncertainty.

Tighter selection requirements on the  $J/\psi$  and  $B^\pm$  candidates are used to test the robustness of the reconstruction and selection efficiency. The signal and background extraction is varied by replacing the DSCB functions with a Student's  $t$ -distribution. The PB sideband regions are varied by adjusting the lower and upper edges of both sidebands, and the uncertainties arising from these variations are averaged. Uncertainties on the tracking and PID efficiencies for the  $B^\pm$  candidate decay products are propagated from statistical uncertainties on the calibration samples and the uncertainty on the material budget for the  $K^\pm$  meson, which is estimated at  $\pm 1.4\%$  [85]. The uncertainty on the trigger efficiency is estimated by applying the data-driven method in simulation and comparing the result to the true simulated efficiency. Any deviation of this ratio from unity is propagated as a shift in the trigger efficiency.

The uncertainty on the jet energy scale and resolution is determined by studying jets recoiling off a  $Z$  boson, reconstructed via its decay to  $\mu^+\mu^-$ . The relative transverse momentum fraction  $p_{T,\text{jet}}/p_{T,Z}$  is calculated in both data and detector-level simulation, and the simulated distribution is adjusted to fit the data distribution as a function of  $p_{T,\text{jet}}$ . This yields a roughly  $-3\%$  shift on the jet energy scale and  $+12\%$  smearing in the jet energy resolution, which are propagated to the detector-level simulation used to calculate detector corrections. Since  $m_{\text{jet}}$  explicitly depends on  $E_{\text{jet}}$  and  $p_{\text{jet}}$ , this uncertainty tends to be dominant.

Finally, the uncertainty on detector corrections is estimated. The number of iterations through the unfolding procedure is varied by  $\pm 1$  iteration. The dependence on the prior distribution is probed by weighting the RM by the ratio of sideband-subtracted data to detector-level simulation. A series of closure tests is also performed, where detector corrections are applied on a simulated data spectrum smeared by statistical uncertainties in data. Any statistically significant deviations from unity in the closure tests are taken as a bin-by-bin systematic uncertainty. The total unfolding uncertainty is calculated by assuming these underlying variations to be correlated and calculating their standard deviation from zero.

The total systematic uncertainty is then calculated by assuming that each contribution is independent and summing them in quadrature. The systematic uncertainties generally increase with  $p_{T,\text{jet}}$  and are largest in the sparsely populated tails of the  $m_{\text{jet}}/p_{T,\text{jet}}$  distribution, where small changes in the peak position cause the largest effect. Systematic uncertainties are dominant at low and moderate  $p_{T,\text{jet}}$ , whereas statistical uncertainties become more significant in the higher  $p_{T,\text{jet}}$  bins. See Appendix for a summary table of the systematic uncertainties.

## 6. Results

The  $m_{\text{jet}}/p_{T,\text{jet}}$  distributions are reported in six  $p_{T,\text{jet}}$  bins between  $10 < p_{T,\text{jet}} < 100$  GeV. The distributions are normalised per  $p_{T,\text{jet}}$  bin,

$$\frac{1}{N_{\text{jet}}} \frac{dN_{\text{jet}}}{d(m_{\text{jet}}/p_{T,\text{jet}})}, \quad \text{or equivalently} \quad \frac{1}{\sigma_{\text{jet}}} \frac{d\sigma_{\text{jet}}}{d(m_{\text{jet}}/p_{T,\text{jet}})}, \quad (2)$$

where  $N_{\text{jet}}$  is the number of jets in a given  $p_{T,\text{jet}}$  bin, and  $\sigma_{\text{jet}}$  is the corresponding cross-section.

The ungroomed  $m_{\text{jet}}/p_{T,\text{jet}}$  distributions are shown in Fig. 1 for both inclusive and WTA flavour-tagged  $b$  jets, with normalisation set to the inclusive results. The peak of the distribution moves leftward with increasing  $p_{T,\text{jet}}$  due to the reduced contribution of the  $b$ -quark mass to the overall jet mass. There is a long tail on the right side of the distributions, corresponding to rarer, higher-virtuality partons which initiate the  $b$  jet, and a shorter tail on the left side of the distributions, terminating at the kinematic cutoff of  $m_{B^\pm}/p_{T,\text{jet}}$  (a single-particle  $b$  jet). At high  $p_{T,\text{jet}}$ , where the effect of gluon splitting is largest, a two-peak structure emerges, which likely originates from the presence of a second (unreconstructed)  $b$ -hadron in the jet.

The WTA flavour tag changes the shape of the distributions by reducing contributions in the high-mass tail, and these differences become

larger at higher  $p_{T,\text{jet}}$ . This is expected since the WTA flavour tag tends to reject  $b$  jets that originate from gluon splitting, which naturally must have a mass greater than two times the  $b$ -quark mass.

The distributions are compared to PYTHIA 8 predictions [61], where significant deviations are seen. PYTHIA 8 predicts a broader  $m_{\text{jet}}/p_{T,\text{jet}}$  distribution, resulting in significantly more emissions at large  $m_{\text{jet}}/p_{T,\text{jet}}$  than observed in data. It also peaks at lower values, signifying fewer high-virtuality partons than observed in data. Differences are enhanced for inclusive distributions; since WTA tagging predominantly removes  $b$ -jets that arise from gluon splitting [33], this suggests that in-shower contributions to  $b$ -jet production are less constrained than direct (LO)  $b$ -jet production.

The soft drop groomed  $m_{\text{jet,gr}}/p_{T,\text{jet}}$  distributions are shown in Fig. 2 for both inclusive and WTA flavour-tagged  $b$  jets, with normalisation set to results without a WTA flavour requirement. Comparisons between the ungroomed and groomed results are shown in Figs. 3 and 4 with and without WTA flavour tagging, respectively, with normalisation in both cases set to the ungroomed results. The shapes of the groomed distributions are affected by the removal of narrow, low- $m_{\text{jet}}$  jets from the data sample, which are groomed away, pushing the peaks towards higher  $m_{\text{jet}}/p_{T,\text{jet}}$ . The removal of soft, wide-angle radiation from surviving jets simultaneously makes the distributions more strongly peaked and shifted towards lower  $m_{\text{jet}}/p_{T,\text{jet}}$ . The two-peak structure observed only at high  $p_{T,\text{jet}}$  in the ungroomed case emerges at a lower threshold of  $p_{T,\text{jet}} > 20$  GeV. This may suggest that grooming can be used as a tool to better separate quark-initiated  $b$ -jets from gluon-initiated ones. Jets groomed near the kinematic threshold of  $m_{B^\pm}/p_{T,\text{jet}}$  exhibit a large peak, with a tail on the left from the broad  $p_{T,\text{jet}}$  range.

Grooming slightly improves agreement between data and PYTHIA 8, especially in the case of WTA flavour tagging. This is expected since soft, wide-angle radiations are generally less well described perturbatively at fixed order than hard, collinear radiation. However, significant discrepancy remains in the tails of the distributions, with the data having more high- $m_{\text{jet}}$  contributions than simulation, again pointing to a significant difference in high-virtuality direct versus in-shower  $b$ -quark production.

## 7. Conclusion

The LHCb collaboration presents first measurements of  $b$ -jet mass at forward rapidity in  $pp$  collisions at  $\sqrt{s} = 13$  TeV. Winner-Take-All flavour tagging reduces the large- $m_{\text{jet}}$  tail of the distributions by reducing gluon splitting contributions, offering a probe into in-shower production of  $b$  quarks [33]. Comparisons to PYTHIA 8 predictions reveal significant deviations across the  $m_{\text{jet}}/p_{T,\text{jet}}$  distributions with largest discrepancies in the tails of the distributions, which improve with WTA flavour tagging. These effects suggest that  $b$  production models could be refined with improved parton shower prescriptions, such as including NRQCD heavy  $q\bar{q}$  production [86].

Soft drop grooming removes a substantial fraction of candidate  $b$  jets and forms a secondary peak near the single-particle-jet kinematic limit. Agreement with PYTHIA 8 predictions improves with respect to ungroomed  $m_{\text{jet}}$ , especially at low  $m_{\text{jet}}/p_{T,\text{jet}}$  where nonperturbative effects are reduced. These results will enable a comprehensive test of modern QCD calculations with heavy-flavour jets, for which a well-defined path to computation exists and calculations are in development [31,32].

Finally, these results are a baseline and proof-of-principle for future studies in heavy-ion collisions, where gluon splitting accesses the momentum transfer between hard probes and the quark-gluon plasma in a theoretically well-defined way.

### Data availability

The LHCb experiment has agreed to the CERN Open Data policy that is summarised at <https://opendata.cern.ch/docs/about>. The LHCb External Data Access Policy can be downloaded at <https://opendata.cern.ch/record/410>. Data associated to the plots in this publication as well as in supplementary materials are made available on

the CERN Document Server at <https://cds.cern.ch/record/2932487>. This manuscript has associated data in a HEPData repository at <https://www.hepdata.net/record/ins2922449>. An encapsulation of the analysis is provided for measurements in the framework of Rivet at [https://rivet.hepforge.org/analyses/LHCb\\_2025\\_I2922449.html](https://rivet.hepforge.org/analyses/LHCb_2025_I2922449.html).

### Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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### Supplementary material

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### Appendix

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Marin Benito<sup>45</sup>, F. Marks<sup>22</sup>, A.M. Marshall<sup>55</sup>, L. Martel<sup>64</sup>, G. Martelli<sup>34</sup>, G. Martellotti<sup>36</sup>, L. Martinazzoli<sup>49</sup>, M. Martinelli<sup>31,p</sup>, D. Martinez Gomez<sup>80</sup>, D. Martinez Santos<sup>83</sup>, F. Martinez Vidal<sup>48</sup>, A. Martorell i Granollers<sup>46</sup>, A. Massafferri<sup>2</sup>, R. Matev<sup>49</sup>, A. Mathad<sup>49</sup>, V. Matiunin<sup>44</sup>, C. Matteuzzi<sup>69</sup>, K.R. Mattioli<sup>15</sup>, A. Mauri<sup>62</sup>, E. Maurice<sup>15</sup>, J. Mauricio<sup>45</sup>, P. Mayencourt<sup>50</sup>, J. Mazorra de Cos<sup>48</sup>, M. Mazurek<sup>42</sup>, M. McCann<sup>62</sup>, T.H. McGrath<sup>63</sup>, N.T. McHugh<sup>60</sup>, A. McNab<sup>63</sup>, R. McNulty<sup>23</sup>, B. Meadows<sup>66</sup>, G. Meier<sup>19</sup>, D. Melnychuk<sup>42</sup>, F. M. Meng<sup>4,d</sup>, M. Merk<sup>38,81</sup>, A. Merli<sup>50,30</sup>, L. Meyer Garcia<sup>67</sup>, D. 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Ronchetti<sup>50</sup>, T. Rong<sup>6</sup>, M. Rotondo<sup>28</sup>, S. R.

Roy<sup>22</sup>, M.S. Rudolph<sup>69</sup>, M. Ruiz Diaz<sup>22</sup>, R.A. Ruiz Fernandez<sup>47</sup>, J. Ruiz Vidal<sup>81</sup>, J. J. Saavedra-Arias<sup>9</sup>, J.J. Saborido Silva<sup>47</sup>, R. Sadek<sup>15</sup>, N. Sagidova<sup>44</sup>, D. Sahoo<sup>78</sup>, N. Sahoo<sup>54</sup>, B. Saïtta<sup>32</sup>, M. Salomoni<sup>31,49,p</sup>, I. Sanderswood<sup>48</sup>, R. Santacesaria<sup>36</sup>, C. Santamarina Rios<sup>47</sup>, M. Santimaria<sup>28</sup>, L. Santoro<sup>2</sup>, E. Santovetti<sup>37</sup>, A. Saputi<sup>26,49</sup>, D. Saranin<sup>44</sup>, A. Sarnatskiy<sup>80</sup>, G. Sarpis<sup>59</sup>, M. Sarpis<sup>79</sup>, C. Satriano<sup>36,u</sup>, A. Satta<sup>37</sup>, M. Saur<sup>73</sup>, D. Savrina<sup>44</sup>, H. Sazak<sup>17</sup>, F. Sborzacchi<sup>49,28</sup>, A. Scarabotto<sup>19</sup>, S. Schael<sup>17</sup>, S. Scherl<sup>61</sup>, M. Schiller<sup>22</sup>, H. Schindler<sup>49</sup>, M. Schmelling<sup>21</sup>, B. Schmidt<sup>49</sup>, M. Schmitt<sup>17</sup>, H. Schmitz<sup>18</sup>, O. Schneider<sup>50</sup>, A. Schopper<sup>62</sup>, N. Schulte<sup>19</sup>, M.H. Schune<sup>14</sup>, G. Schwering<sup>17</sup>, B. Sciascia<sup>28</sup>, A. Sciuccati<sup>49</sup>, I. Segal<sup>77</sup>, S. Sellam<sup>47</sup>, A. Semennikov<sup>44</sup>, T. Senger<sup>51</sup>, M. Senghi Soares<sup>39</sup>, A. Sergi<sup>29,u</sup>, N. Serra<sup>51</sup>, L. Sestini<sup>27</sup>, A. Seuthe<sup>19</sup>, B. Sevilla Sanjuan<sup>46</sup>, Y. Shang<sup>6</sup>, D.M. Shangase<sup>86</sup>, M. Shapkin<sup>44</sup>, R. S. Sharma<sup>69</sup>, I. Shchemerov<sup>44</sup>, L. Shchutska<sup>50</sup>, T. Shears<sup>61</sup>, L. Shekhtman<sup>44</sup>, Z. Shen<sup>38</sup>, S. Sheng<sup>5,7</sup>, V. Shevchenko<sup>44</sup>, B. Shi<sup>7</sup>, Q. Shi<sup>7</sup>, W. S. Shi<sup>72</sup>, Y. Shimizu<sup>14</sup>, E. Shmanin<sup>25</sup>, R. Shorkin<sup>44</sup>, J.D. Shupperd<sup>69</sup>, R. Silva Coutinho<sup>69</sup>, G. Simi<sup>33,r</sup>, S. Simone<sup>24,t</sup>, M. Singha<sup>78</sup>, N. Skidmore<sup>57</sup>, T. Skwarnicki<sup>69</sup>, M.W. Slater<sup>54</sup>, E. Smith<sup>65</sup>, K. Smith<sup>68</sup>, M. Smith<sup>62</sup>, L. Soares Lavra<sup>59</sup>, M.D. Sokoloff<sup>66</sup>, F.J.P. Soler<sup>60</sup>, A. Solomin<sup>55</sup>, A. Solovev<sup>44</sup>, N. S. Sommerfeld<sup>18</sup>, R. Song<sup>1</sup>, Y. Song<sup>50</sup>, Y. Song<sup>4,d</sup>, Y. S. Song<sup>6</sup>, F.L. Souza De Almeida<sup>69</sup>, B. Souza De Paula<sup>3</sup>, K.M. Sowa<sup>40</sup>, E. Spadaro Norella<sup>29,m</sup>, E. Spedicato<sup>25</sup>, J.G. Speer<sup>19</sup>, E. Spiridenkov<sup>44</sup>, P. Spradlin<sup>60</sup>, V. Sriskaran<sup>49</sup>, F. Stagni<sup>49</sup>, M. Stahl<sup>77</sup>, S. Stahl<sup>49</sup>, S. Stanislaus<sup>64</sup>, M. Stefaniak<sup>87</sup>, E.N. Stein<sup>49</sup>, O. Steinkamp<sup>51</sup>, H. Stevens<sup>19</sup>, D. Strelakina<sup>44</sup>, Y. Su<sup>7</sup>, F. Suljik<sup>64</sup>, J. 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Uwer<sup>22</sup>, V. Vagnoni<sup>25,49</sup>, V. Valcarce Cadenas<sup>47</sup>, G. Valenti<sup>25</sup>, N. Valls Canudas<sup>49</sup>, J. van Eldik<sup>49</sup>, H. Van Hecke<sup>68</sup>, E. van Herwijnen<sup>62</sup>, C.B. Van Hulse<sup>47,aa</sup>, R. Van Laak<sup>50</sup>, M. van Veghel<sup>38</sup>, G. Vasquez<sup>51</sup>, R. Vazquez Gomez<sup>45</sup>, P. Vazquez Regueiro<sup>47</sup>, C. Vázquez Sierra<sup>83</sup>, S. Vecchi<sup>26</sup>, J.J. Velthuis<sup>55</sup>, M. Veltri<sup>27,y</sup>, A. Venkateswaran<sup>50</sup>, M. Verdognia<sup>32</sup>, M. Vesterinen<sup>57</sup>, W. Vetens<sup>69</sup>, D. Vico Benet<sup>64</sup>, P. Vidrier Villalba<sup>45</sup>, M. Vieites Diaz<sup>47</sup>, X. Vilasis-Cardona<sup>46</sup>, E. Vilella Figueras<sup>61</sup>, A. Villa<sup>25</sup>, P. Vincent<sup>16</sup>, B. Vivacqua<sup>3</sup>, F.C. Volle<sup>54</sup>, D. vom Bruch<sup>13</sup>, N. Voropaev<sup>44</sup>, K. Vos<sup>81</sup>, C. Vrahas<sup>59</sup>, J. Wagner<sup>19</sup>, J. 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