Probing bottom quark mass effects in jet substructure with CMS using a novel technique to cluster the b-hadron decays

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Abstract. The study of jet substructure has given rise to a new era of precision quantum-chromodynamics (QCD) measurements related to the evolution of the parton shower. In order to better understand the role of the quark mass, the decay kinematics of the heavy flavor hadrons need to be isolated from the QCD branchings. This talk presents new CMS results on the groomed jet radius $\boldsymbol{R}_\mathrm{g}$ and momentum balance $\boldsymbol{z}_\mathrm{g}$ of bottom quark jets (**b** jets) in proton-proton collisions by employing a novel technique that partially reconstructs the **b** hadron from its charged-particle decay daughters. This approach provides direct access to the dead cone of the **b** quark for the first time. The jet fragmentation function, defined as the fraction of the charged-particle component of the transverse momentum of the jet held by the partially reconstructed **b** hadron is also presented. The results are compared to predictions from two Monte-Carlo generators, which show varying degrees of agreement.

1 Introduction

Jets originating from a heavy flavor bottom (b jets) or charm (c jets) quark are a fundamental object in the understanding of the effect of the quark mass in the formation of the parton shower. The heavy flavor quark mass enters the evolution equations, giving rise to a rich phenomenology in the context of quantum chromodynamics (QCD). One such property is the presence of a *dead cone* around the direction of motion of the heavy flavor quark, inside of which gluon emissions are suppressed [1]. The dead cone angle is proportional to the mass of the quark and inversely proportional to its energy ($\theta_0 = m_\mathrm{Q}/E_\mathrm{Q}$), such that the cone is the largest for b quarks. However, as of recently, a direct observation of this effect has only been possible for the c quark, in the measurement of D^0 tagged jets by the ALICE Collaboration [2].

The reconstruction of the b hadron through its exclusive decay channels yields statistically limited results, making a comprehensive study of the b jet substructure challenging. The identification of the flavor of the jet based on the presence of displaced tracks and reconstructed secondary vertices from heavy flavor hadron decays, also known as *tagging*, offers a larger collection of signal events than the full reconstruction of the hadrons. Nevertheless, the presence of the heavy flavor hadron decay daughters in the jet constituents

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complicates the study of the jet substructure, as the QCD parton shower and electroweak decay kinematics remain intertwined.

In these proceedings, new b jet substructure results, sensitive to the b quark dead cone, are presented, utilizing a novel technique for the partial reconstruction of the b hadron. The b hadron charged-particle decay daughters are identified via a multivariate analysis, independent of the decay channel. Their four-momenta are then summed, and the reconstructed particle replaces them in the jet constituents, disentangling the decay kinematics from the parton shower evolution and making it possible to study the jet substructure.

The analysis is performed on 301 pb^{-1} of proton-proton collision data collected by the CMS experiment [3] in 2017 at $\sqrt{s} = 5.02$ TeV. Jets are reconstructed using the anti-k_{T} algorithm, with a clustering parameter of $R = 0.4$, and are selected to have a transverse momentum (p_{T}) between 100 GeV and 120 GeV. The narrow p_{T} range helps to constrain the size of the b quark dead cone. The jets are further required to be within the pseudorapidity $|\eta| < 2$, where the b jet identification in CMS is highly performant [4]. The measured distributions are corrected to the charged-particle level. The background contributions in the b jet sample are reduced via a template fit of the partially reconstructed b hadron mass, so that the resulting sample consists of jets containing exactly one b hadron. Corrections related to the b tagging efficiency are applied. A sample of inclusive jets, also corrected to the charged-particle level, is used as a reference. The distributions are compared to predictions from two Monte-Carlo generators, namely PYTHIA8 and HERWIG7, that implement different parton shower models. More details about the measurement can be found in Ref. [5].

2 Groomed jet radius and momentum balance

Groomed observables allow to look at the internal structure of the jet by isolating energy clusters, also referred to as subjets. Soft drop [6] aims at removing low-energy, wide-angle radiation and reducing the jet into two subjets. The algorithm sequentially recombines the jet constituents based on their distance on the rapidity-azimuth plane, from smaller to larger angles, forming a clustering tree. The clustering steps are then reversed so that low-energy splittings at larger angles are discarded, until the soft-drop condition is met:

$$\frac{\min(p_{\mathrm{T},1}, p_{\mathrm{T},2})}{p_{\mathrm{T},1} + p_{\mathrm{T},2}} > z_{\mathrm{cut}} \left(\frac{\Delta R_{1,2}}{R} \right)^{\beta}, \tag{1}$$

where $p_{\mathrm{T,i}}$ are the transverse momenta of the two subjets at each declustering step and $\Delta R^2_{1,2} = \Delta y^2_{1,2} + \Delta\phi^2_{1,2}$ is their angular distance. The parameter R is the jet clustering distance parameter, and z_{cut} and β are tunable grooming parameters, here taking the values 0.1 and 0, respectively. The selected subjet system may be considered as a proxy for the b quark and a gluon emission off of it. The two observables of interest are the groomed jet radius, corresponding to the opening angle between the two subjets, $R_{\mathrm{g}} = \Delta R_{1,2}$, and the momentum balance, $z_{\mathrm{g}} = p_{\mathrm{T},2}/(p_{\mathrm{T},1} + p_{\mathrm{T},2})$, where $p_{\mathrm{T},2} < p_{\mathrm{T},1}$. Both observables are sensitive to quark mass effects.

The fully corrected R_{g} and z_{g} distributions are presented in Figs. 1 and 2 for inclusive jets and b jets, respectively. In the inclusive jet case, HERWIG7 agrees with the data better than PYTHIA8 for the two observables. Looking at the b jet distributions, both generators capture the z_{g} shape, but struggle to describe R_{g}. The ratio of the b over inclusive jets is presented in Fig. 3, with R_{g} on the left and z_{g} on the right panel. Focusing on R_{g}, one observes the suppression b jet emissions in the small angle region, which is a direct consequence of the presence of the dead cone around the b quark. The b jets also seem to favor the lower z_{g}

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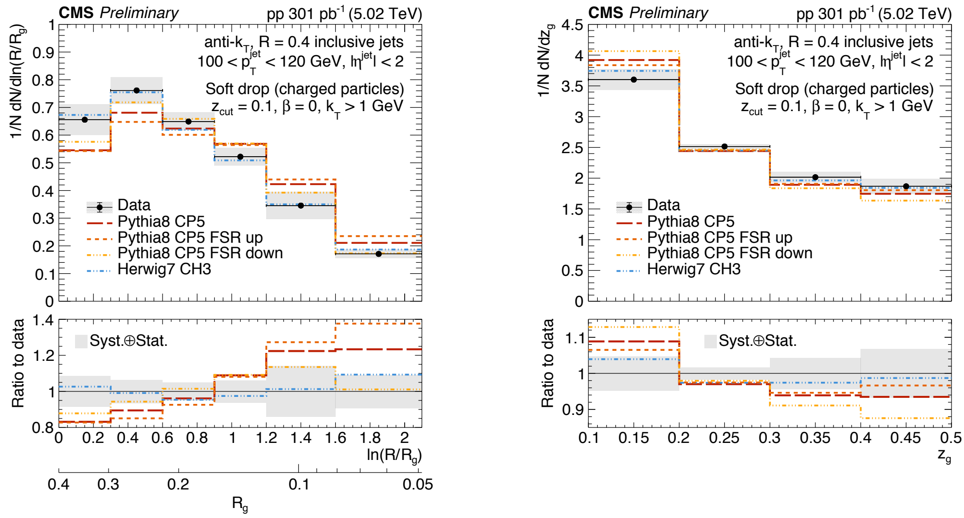

Figure 1. The groomed jet radius R_g (left) and the momentum balance z_g (right) distributions of inclusive jets. The data is compared to predictions from two Monte-Carlo generators. The ratio of simulation to data is presented in the bottom panels. Figures from Ref. [5].

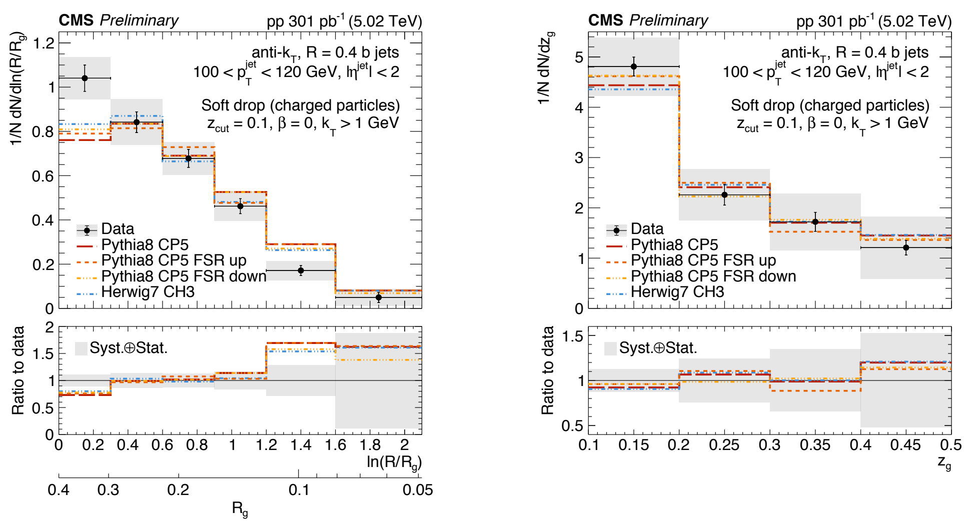

Figure 2. The groomed jet radius R_g (left) and the momentum balance z_g (right) distributions of b jets. The data is compared to predictions from two Monte-Carlo generators. The ratio of simulation to data is presented in the bottom panels. Figures from Ref. [5].

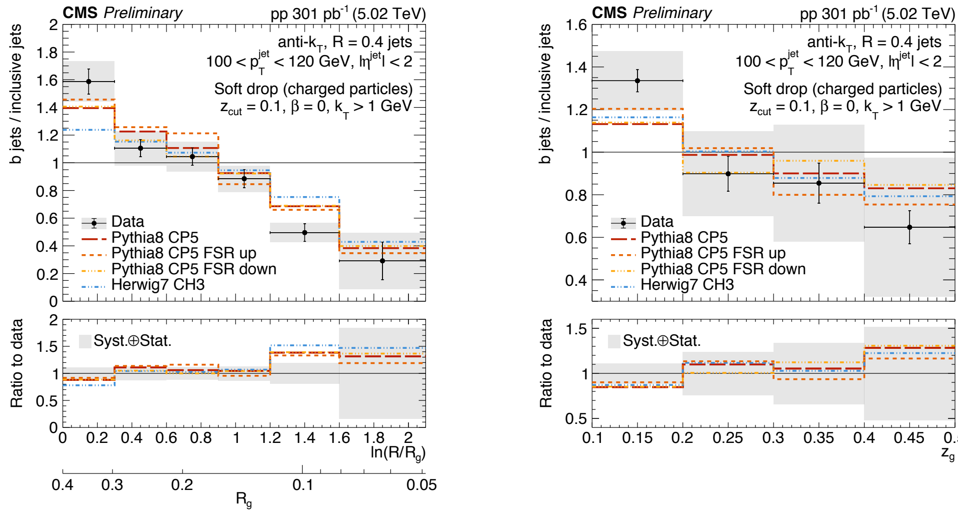

Figure 3. The ratio of b jets to inclusive jets of the groomed jet radius R_g (left) and momentum balance z_g (right). The data is compared to predictions from two Monte-Carlo generators. The ratio of simulation to data is presented in the bottom panels. Figures from Ref. [5].

values, meaning that the b quark holds more of the transverse momentum of the system at each splitting. The PYTHIA8 generator describes the R_g ratio better than HERWIG7, but both simulations agree with the z_g data.

3 Jet fragmentation function

A jet fragmentation function is also measured, defined as the fraction of the charged-particle p_T component of the jet held by the partially reconstructed b hadron, $z_{b,ch} \equiv p_T^{b,ch}/p_T^{jet,ch}$. This observable is complementary to the groomed substructure measurements, as the jets that do not satisfy the soft-drop condition are included. The $z_{b,ch}$ results are presented in Fig. 4. The distribution peaks near 1, meaning that the b hadron holds most of the jet transverse momentum. Predictions from the two different Monte-Carlo generators show good agreement with data.

4 Prospects in PbPb

Heavy flavor jets are an important probe of the quark-gluon plasma (QGP) created in PbPb collisions. As the search for color coherence effects, *i.e.*, the ability of the QGP to resolve two color charges, is still underway, the dead cone angle of heavy flavor quarks can act as a reference for the color decoherence angle. The dead cone, now identified in the the vacuum both for b [5] and c jets [7], may act as a region to isolate medium induced radiation [8]. Exploring whether each of the b and c quark dead cones is populated with emissions in PbPb collisions can help to narrow down the range of the color decoherence angle.

5 Conclusions

The CMS Collaboration has measured b jet substructure observables in proton-proton collisions by partially reconstructing the b hadron for the first time. This novel technique has

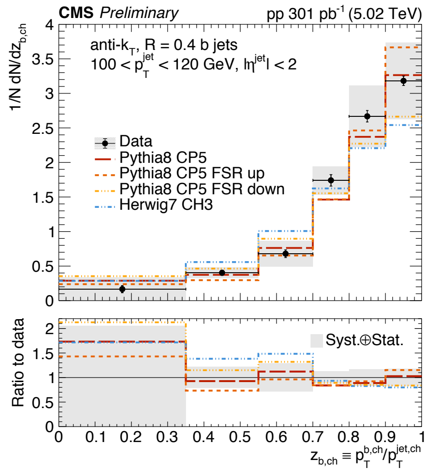

Figure 4. The jet fragmentation function of the partially reconstructed b hadron. The data is compared to predictions from two Monte-Carlo generators. The ratio of simulation to data is presented in the bottom panel. Figure from Ref. [5].

allowed to unveil the b quark dead cone, offering new insights into the role of the quark mass in the parton shower evolution. This measurement serves as a reference for a future analysis in PbPb collisions, where the relation between the dead cone and the color decoherence angle will be explored.

References

[1] Y. L. Dokshitzer, V. A. Khoze and S. I. Troian, JPhysG **17**, 1602 (1991)
[2] ALICE Collaboration, Nature **605**, 440 (2022) [erratum: Nature **607**, E22 (2022)]
[3] CMS Collaboration, JINST **3**, S08004 (2008)
[4] CMS Collaboration, JINST **13**, P05011 (2018)
[5] CMS Collaboration, CMS-PAS-HIN-24-005 (2024)
[6] A. J. Larkoski, S. Marzani, G. Soyez and J. Thaler, JHEP **05**, 146 (2014)
[7] CMS Collaboration, CMS-PAS-HIN-24-007 (2024)
[8] L. Cunqueiro, D. Napoletano and A. Soto-Ontoso, PRD **107**, 094008 (2023)