

Simulation-based study of jet substructure of light- and heavy-flavor jets in $p + p$ collisions at 200 GeV

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Jet substructure studies at the CERN Large Hadron Collider have been used to constrain parton distribution functions, test perturbative quantum chromodynamics, measure the strong-coupling constant, and probe the properties of the quark-gluon plasma. We extend these studies to lower collision energies at the BNL Relativistic Heavy Ion Collider (RHIC) and present a feasibility and strategy study for the sPHENIX experiment. In this work, we perform a PYTHIA8 based Monte Carlo study of jet substructure in $p + p$ collisions at $\sqrt{s} = 200$ GeV with selection criteria adapted for a realistic measurement at sPHENIX. We consider jet substructure observables such as jet angularities and the primary Lund plane projection. In particular, we quantify the discriminating power of jet angularities for quark/gluon and light versus heavy flavor jets, and demonstrate how these observables can serve as experimentally accessible proxies for flavor separation at RHIC. We further show that the primary Lund plane exhibits a characteristic suppression pattern consistent with the dead cone effect for heavy quarks, and outline a concrete measurement strategy at sPHENIX based on a combination of heavy-flavor jet tagging and differential substructure observables.

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I. INTRODUCTION

Jets, described as collimated sprays of particles, encode rich information about hard quantum chromodynamics (QCD) processes occurring at spatial scales significantly smaller than the proton radius. The internal structure of jets, often referred to as jet substructure, provides a unique probe into the fundamental properties of strong interactions. Over the past two decades, the field of jet substructure has matured, yielding a wealth of applications in a variety of contexts. In particular, jets are used for precision measurements of the strong coupling constant [1–5], provide constraints on parton distribution functions (PDFs) [6–13], and enable stringent tests of high-precision perturbative QCD calculations [14,15]. Moreover, they play a central role in searches for

heavy hadronically decaying resonances predicted by theories beyond the standard model [16–19] and, in addition, jet substructure has been widely adopted as input for machine learning algorithms [20–22] and is extensively employed for particle tagging [23–32]. Finally, since the formation and evolution of jets are sensitive to the interactions between partons produced via hard scattering process with the dense medium formed in proton-nucleus ($p + A$) or nucleus-nucleus ($A + A$) collisions [33–48], jet substructure has become an important tool for studies of the properties of quark gluon plasma (QGP). More details can be found in dedicated reviews, see [49,50].

While jet substructure at high center-of-mass collision energies has been extensively studied at the CERN Large Hadron Collider (LHC) [51–75], similar investigations at the BNL Relativistic Heavy Ion Collider (RHIC) remain relatively sparse [76–82]. Consequently, jet substructure studies at RHIC offer a crucial platform for testing and refining existing models of nonperturbative QCD as highlighted in [47] and would allow probes of different QCD regimes, in particular to separate contributions from hadronization and the soft background due to the underlying event contribution.

In this study we consider two crucial examples of jet substructure observables, namely jet angularities [83–85] and the primary Lund plane projection [86,87]. Jet angularities are a family of jet substructure observables sensitive to the

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distribution of particles around the jet axis defined as

$$\lambda_\alpha = \sum_{i \in \text{jet}} \left(\frac{p_{T,i}}{\sum_{j \in \text{jet}} p_{T,j}} \right) \left(\frac{\Delta_{i,\text{jet}}}{R} \right)^\alpha, \quad (1)$$

where the sum runs over particles inside the jet, z_i is the fraction of the transverse jet momentum carried by its i th constituent, R is the jet radius, and

$$\Delta_{i,\text{jet}} = \sqrt{(y_i - y_{\text{jet}})^2 + (\phi_i - \phi_{\text{jet}})^2} \quad (2)$$

is the Euclidean azimuth-rapidity distance between the jet axis and the i th jet constituent. The requirement of infrared and collinear safety implies $\alpha > 0$. While values of $0 < \alpha < 1$ are generally more sensitive to soft QCD effects, such as hadronization or underlying event contributions, $\alpha \geq 1$ tend to be less affected by nonperturbative contributions and hence are better suited to test analytical results obtained for partonic degrees of freedom, see, e.g., Refs. [47,88,89].

On the other hand, unlike jet angularities, the primary Lund plane maps emissions within a jet onto a two-dimensional plane, providing insights into the dynamics of parton showers and QCD radiation. It describes correlation between the angle and transverse momentum of an emission with respect to its emitter for each QCD splitting in the jet clustering tree and, therefore, allows for a separate study of soft, collinear, and soft-collinear emissions inside of the jets leading to tests of different QCD regimes, see [90–93].

A major scientific motivation for the sPHENIX experiment is its broad program on jet measurements. The large acceptance, hadronic calorimetry, high-efficiency tracking, and large data-taking rate of the detector will result in an enormous data sample of high- p_T jets, see [94]. These high-statistics measurements will enable precise studies of dijet asymmetry, jet spectra, and jet substructure within QGP, providing critical insights into parton energy loss mechanisms. The sPHENIX results will complement the extensive jet substructure analyses performed at higher energies at the LHC [15,51,63,73], enhancing our understanding of QGP properties across different energy regimes.

Since production of particles in a QCD cascade is predominantly given by soft and collinear QCD emissions, a fundamental property of QCD radiation generally known as a dead cone effect [95,96], i.e., the suppression of QCD radiation around massive quarks, must change the QCD radiation pattern and, therefore, manifest itself in substructure of produced jets. However, despite an extensive theoretical study of the dead cone effect and jet substructure of heavy jets in general, see, e.g., Refs. [97–114], only a handful of measurements of jet substructure observables for jets seeded by heavy quarks is available up to date [115–117]. The first direct observation of dead cone effect was recently reported by the ALICE collaboration [118].¹ A key open question is how

these effects can be translated into experimentally measurable observables at RHIC. In practice, isolating heavy-flavor jets requires dedicated tagging techniques, such as displaced vertex reconstruction or semileptonic decay tagging, which introduce finite efficiencies and purities. Therefore, any realistic measurement of the dead cone effect must rely on statistically robust observables that remain sensitive under imperfect flavor tagging. In this work, we demonstrate that jet angularities and primary Lund plane provide such observables, and we outline how their differential behavior can be exploited in a data-driven measurement strategy at sPHENIX.

II. MONTE CARLO SETUP AND EVENT SELECTION

In this study, jets seeded by massive b and c quarks are compared against jets initiated by light flavors (u , d , s). In addition, quark jets are also compared with gluon jets. The sample of pseudo data using PYTHIA8 [128,129] Monte Carlo event generator with a Detroit tune [130] was generated for $p + p$ collisions at 200 GeV center-of-mass collision energy. The Detroit PYTHIA tune was specifically designed to describe RHIC data and is mainly based upon modified parameters of the multiparton interaction model with a reference transverse momentum scale parameter set to 1.40 GeV, a core radius parameter set to 0.56, and a core fraction set to 0.78. In our simulations, we used the NNPDF3.1 LO PDF set with $\alpha_s(M_Z) = 0.130$ [131] and imposed a PhaseSpaceTHatMin = 20 GeV phase-space cut to accumulate reasonable statistics.

Three different samples of b jets, c jets, and light jets with jets produced via $2 \rightarrow 2$ LO QCD dijet production processes were simulated with each dijet pair required to satisfy the following fiducial cuts: $p_{T1} > 30$ GeV, $p_{T2} > 20$ GeV, and $|\eta_{\text{jet}}| < 0.7$ which is in agreement with sPHENIX acceptance [132]. The transverse momentum difference between leading and subleading jets is inspired by currently available theoretical studies [47,88].² Jet formation is modeled by including initial and final state radiation, multiple parton interactions, and hadronization processes within the simulation. The final-state particles are clustered into jets using anti- k_t algorithm [133] with jet radius parameter $R = 0.4$ and standard E -scheme recombination using the FASTJET [134] library. Two versions of each jet are considered; namely ungroomed (taken as it is), and groomed with the SoftDrop algorithm from the FJCONTRIB package with parameters $z_{\text{cut}} = 0.2$ and $\beta = 0$ [135,136] and the Cambridge-Aachen (C/A) algorithm [137,138] used for the reclustering procedure. The SoftDrop-grooming is an iterative procedure that consists of two steps:

- (1) Recluster the jet into two subjets i and j .
- (2) Check the SoftDrop condition:

$$\frac{\min(p_{Ti}, p_{Tj})}{p_{Ti} + p_{Tj}} > z_{\text{cut}} \left(\frac{\Delta_{ij}}{R} \right)^\beta, \quad (3)$$

¹In the context of b physics, [119] first proposed to use the primary Lund plane to look for the dead-cone effect. For indirect observations of the dead-cone effect, see also Refs. [120–126] and the LHC [91,115,118,127] measurements.

²The transverse momentum imbalance cuts as in Refs. [47,88] were used to avoid large K-factors and associated numerical instabilities.

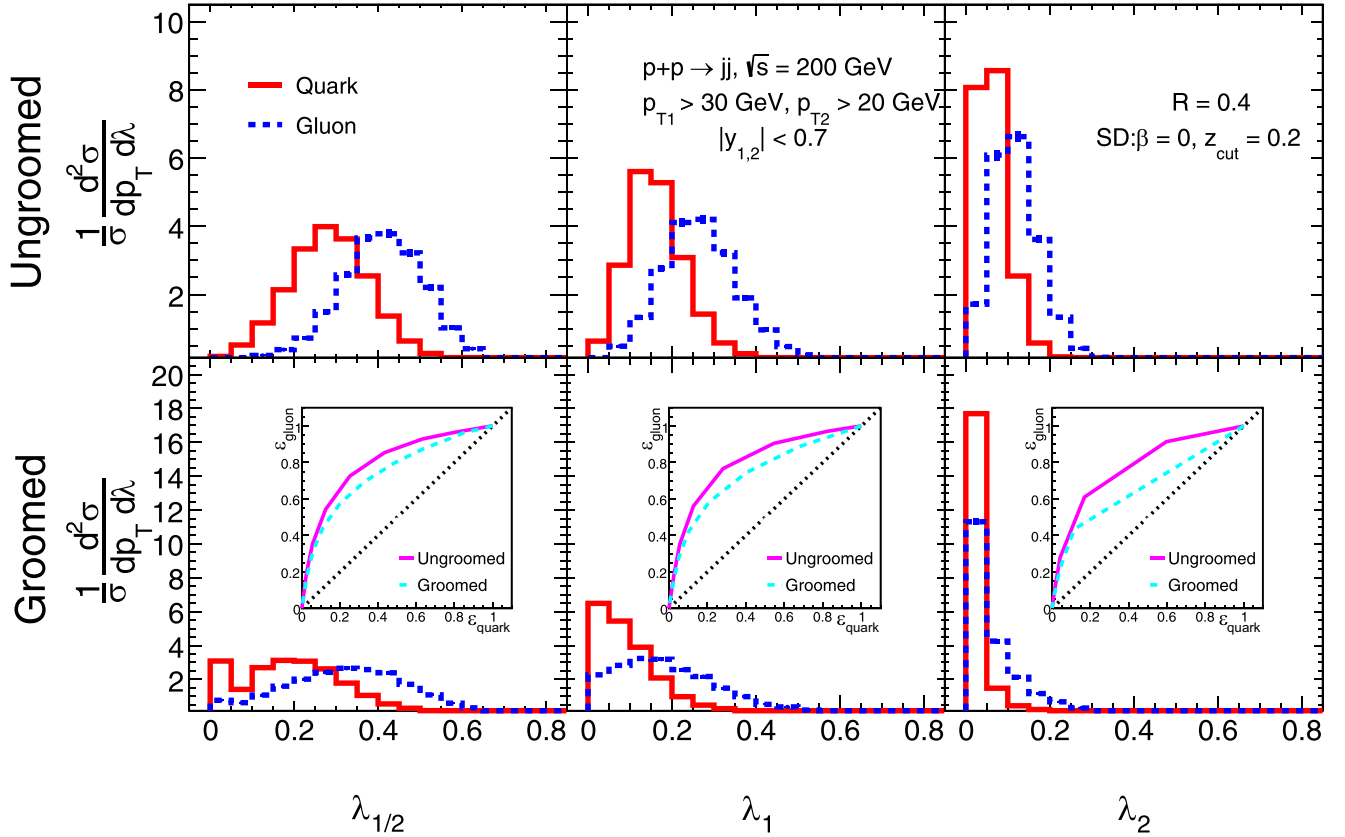


FIG. 1. Comparison of Les Houches ($\lambda_{1/2}$), jet width (λ_1), and jet thrust (λ_2) angularities for ungroomed (top panel) and groomed (bottom panel) quark- and gluon-initiated jets. The inset shows the respective ROC curves for groomed and ungroomed jets.

where

$$\Delta_{ij} = \sqrt{(y_i - y_j)^2 + (\phi_i - \phi_j)^2} \quad (4)$$

is a standard (pseudo)rapidity-azimuth distance between two jet branches and R is a jet radius. If the soft branch carries a fraction of jet p_T smaller than $z_{\text{cut}}(\frac{\Delta_{ij}}{R})^\beta$, discard it and repeat the reclustering procedure. If the SoftDrop condition is met, end the procedure.

The SoftDrop procedure is well defined from a theoretical point of view as it satisfies the concept of infrared and collinear safety and is known to reduce the impact of soft wide-angle radiation on jet substructure which, in turn, makes it less sensitive to the nonperturbative effects such as hadronization and underlying event contribution [135,136].

For each generated event, jet substructure observables are calculated for both the leading and subleading jets. Subsequently, jets are categorized as light quark, charm quark, bottom quark, or gluon jets by matching each jet to initial partons from the hard scattering in the PYTHIA event record, provided that the angular distance, Δ_{ij} between the jet axis and hard parton seeding the jet is smaller than 0.4.

To connect these studies to a realistic experimental environment, it is important to note that heavy-flavor jet identification at sPHENIX may rely on displaced-track and secondary-vertex information, leading to limited tagging efficiencies. Unfolding procedures and data-driven corrections

will therefore be required to account for detector effects and tagging performance. Consequently, the results presented here represent an upper bound on the achievable separation power.

III. JET ANGULARITIES

We start the discussion by considering three commonly used cases of jet angularities corresponding to three different values α in Eq. (1), namely, Les Houches angularity or LHA ($\lambda_{1/2}$), jet width (λ_1), and jet thrust (λ_2) [85,139]. Following the discussion in Refs. [136,140] we use the winner-take-all recombination scheme to define the jet axis [141] for LHA and jet width angularities and the standard E scheme for the jet thrust.

The comparison of angularities for quark and gluon jets is shown in Fig. 1. The top panel shows the distributions for Les Houches, jet width, and jet thrust angularities for ungroomed jets, while the bottom panel shows the same for groomed jets. The quark-initiated jets are represented by solid red lines, whereas gluon-initiated jets are given by blue dashed ones. The peak position of distributions for gluon jets tends to be shifted toward larger values of jet angularities as compared to the quark jets. This behavior is consistent with previous results available in the literature [31,32,49,142–144], and is caused by different emission patterns of quarks and gluons. In order to quantitatively estimate the efficiency of quark-gluon separation for the RHIC setup, the receiver operating charac-

teristic (ROC) curves are presented as insert plots in Fig. 1. Each point on a ROC curve represents a fraction of the signal (in our case gluon) and background (in our case quark) jets selected after triggering on jets with angularity value $\lambda \geq \lambda_{\text{cut}}$:

$$\epsilon_{q/g} = \frac{1}{\sigma} \int_{\lambda_{\text{cut}}}^1 d\lambda_{q/g} \frac{d\sigma}{d\lambda_{q,g}}, \quad (5)$$

where λ_{cut} is varied in between zero and one. The ROC curves for ungroomed jets are presented by solid magenta lines, whereas ROC curves corresponding to SoftDrop jets are given by dashed cyan lines. We found the best tagging efficiency to be $\epsilon_q = 0.43$, $\epsilon_g = 0.85$ which corresponds to $\lambda_{\text{cut}} = 0.3$. The possibility of efficient separation between quark and gluon jets is suggested by the simulation at RHIC energies which, in turn, would allow for testing of existing approaches to perturbative and nonperturbative descriptions of jets produced at collision energies much lower compared to the LHC.

The case for groomed jets is shown in the bottom panel of Fig. 1. As seen, in general, the performance of quark-gluon discrimination for groomed jets is somewhat smaller compared to the ungroomed ones. This is in agreement with the expectations, since SoftDrop grooming reduces the fraction of soft emissions inside the jet, which partially contributes to the difference between quark and gluon jets (quark jets tend to be more collimated, whereas gluon jets have a larger particle spread). It should also be noted that the quark distributions after grooming demonstrate a significant change in their shape: namely, the groomed distributions have peaks around the first bin. This effect is much stronger for the quark jets which can be explained by the fact that quark jets, in general, tend to have fewer constituents compared to gluon jets. Moreover, at RHIC beam energies, quark jets have a much smaller amount of energy available for radiation compared to the LHC. As a consequence, it is more likely to create a quark jet made of a single hard particle and a few soft particles which are eliminated after SoftDrop application. This would lead to quark jets with a single constituent and, therefore, zero angularity value.³

In this analysis, no conditions, other than $|\eta| < 1.0$, on particles that form the jet are applied, thereby, ensuring IRC safety and enabling direct comparison with theoretical predictions with robust qualitative conclusions. Under experimental conditions, typically, transverse momentum thresholds are applied. It is checked that by imposing $p_T \geq 2$ GeV on particles that form the jet, the ROC curves shift by a few percent relative to our main results. The proper dependence of any selection criteria on particles that form the jet must be carefully addressed during the unfolding of the measured data; however, such a study is beyond the scope of this paper.

The presence of non-negligible quark masses for c and b jets leads to nontrivial modification of the QCD emission cascade [95,96,145–149] which, in turn,

changes the shape of the jet substructure observables [97,99,100,103,108,109,112,150–155]. PYTHIA takes into account modifications of the parton shower due to the presence of non-negligible quarks masses [129,156]. Even though, as it was argued in [129], the PYTHIA approach to radiation of heavy quarks [156] does not fully respect the dead-cone effect, it can still be used to obtain a quantitative estimate of jet substructure of heavy jets [109,118]. Therefore, these MC simulations for jet substructure of heavy jets are a good starting point for future jet substructure studies at RHIC. More detailed study would require comparison against other existing MC models and theoretical calculations [97,109,157–160].

The comparison of angularities for jets seeded by light (u , d , s), charm, and bottom quarks is shown in Fig. 2.

The distributions for Les Houches, jet width, and jet thrust angularities for ungroomed jets are given in the top panel, while the bottom panel shows the same for groomed jets. The results for b jets tend to shift towards larger angularity values as compared to the light jets, thereby achieving discrimination efficiency similar to those of angularity-based quark-gluon taggers in Fig. 1. The observed shift of b -jet distributions is caused by two effects of perturbative and non-perturbative nature, correspondingly. The perturbative effect is a suppression of collinear radiation around the massive quarks for observable values smaller or equal to the dead-cone endpoint $m_Q/p_{T,\text{jet}}R$ which implies that the contribution of parton shower to the angularity values with $\lambda \leq m_Q/p_{T,\text{jet}}R$ is suppressed [109]. A second effect is related to decays of produced B hadrons: at RHIC energies, in the case of b jets the probability of producing a jet made of a single b quark is non-negligible. Such parton-level jets after hadronization will often convert into jets containing a single B hadron. In the case of stable B hadrons, the aforementioned events would contribute to a very first angularity bin (events with $\lambda = 0$). However, because B hadrons are unstable their decay products give rise to nontrivial modification of the jet substructure leading to transfer of events from the first angularity bin towards larger angularity bins, contributing to the peak of the distribution [98,109]. Therefore, as it was argued first in [98], the question of B -hadron decays needs to be carefully addressed by both theorists and experimentalists. In this study, perspectives of jet substructure studies for the sPHENIX experiment are addressed, while a detailed discussion of the role of B -hadron decays is left to future investigations.

Finally, it should be noted that, in Fig. 2, the ROC curves obtained for groomed distributions mostly tend to be very similar to the ones obtained for the ungroomed jets. This behavior of the ROC curves is different from the results presented in Fig. 1. However, it can be explained by the fact that both the sources of the differences between heavy and light jets (suppression of radiation and B -hadron decays) affect the collinear region which is not sensitive to SoftDrop grooming, whereas in case of quark-gluon tagging, a significant portion of difference between quark and gluon jets comes from soft emissions which are subtracted by the grooming procedure.

A feasible measurement strategy at sPHENIX would involve measuring inclusive angularity distributions and comparing them to Monte Carlo templates with varying

³Additionally, as it was pointed out in Ref. [47], the low center-of-mass collision energy at RHIC implies significant suppression of uniform soft radiation from beam remnants which, in turn, contributes to the peak creation at low λ values.

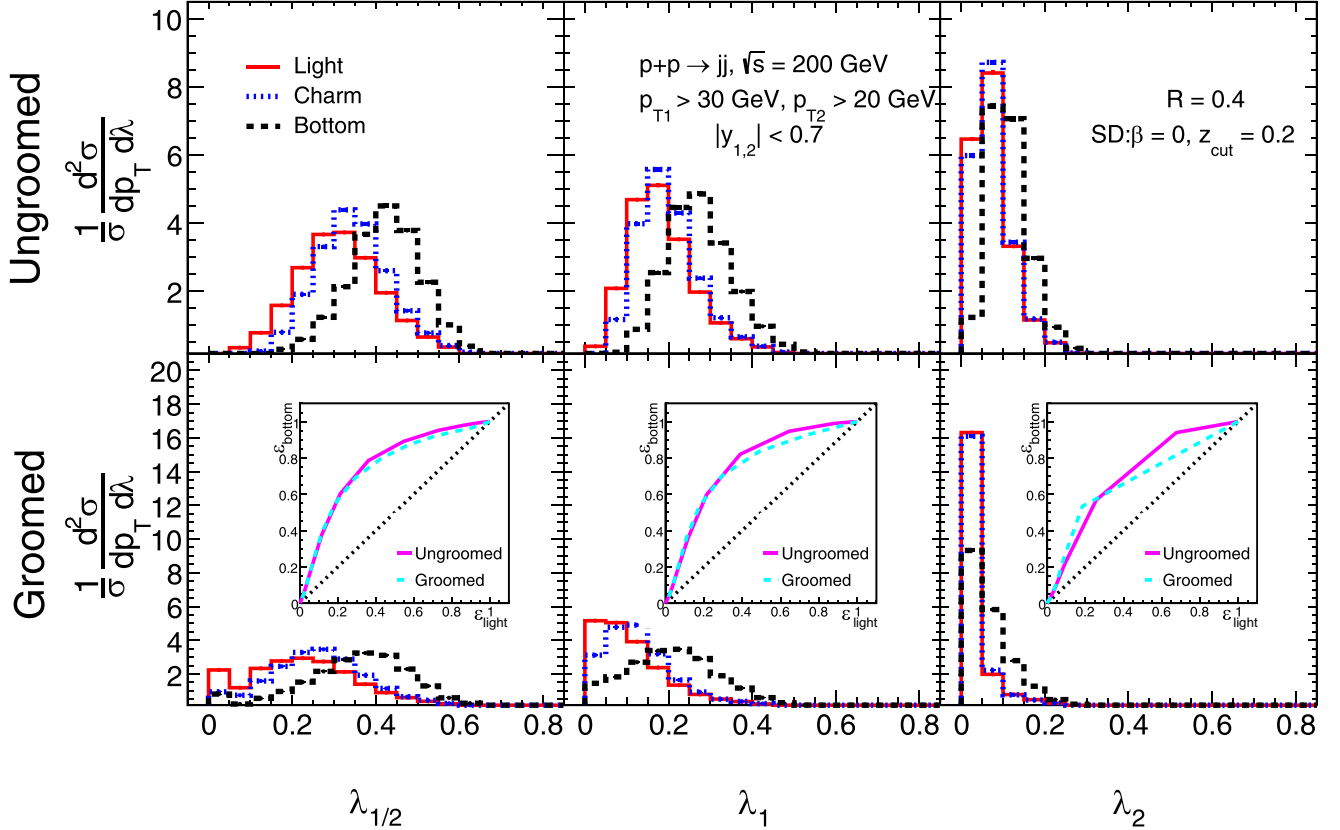


FIG. 2. Comparison of Les Houches ($\lambda_{1/2}$), jet width (λ_1), and jet thrust (λ_2) angularities for ungroomed (top panel) and groomed (bottom panel) jets originating from light, charm, and bottom quarks. The inset shows the respective ROC curves for groomed and ungroomed jets.

heavy-flavor fractions, enabling extraction of heavy-flavor contributions through template fitting or unfolding techniques. In addition, angularity-based selections can be combined with heavy-flavor tagging to enhance the purity of b -jet samples. Selections based on larger angularity values preferentially enhance gluon-like and b -initiated-like radiation patterns, thereby providing an orthogonal handle to traditional tagging approaches. This combined strategy alleviates the limitations of imperfect tagging efficiency and purity by combining inclusive angularity measurements with tagged samples, thereby retaining sensitivity to mass-dependent QCD radiation effects in differential observables.

IV. PRIMARY LUND PLANE

The primary Lund plane is a comprehensive tool that captures the kinematics and dynamics of QCD emissions within jets. It is made with axes that represent the logarithm of the transverse momentum scale, encoding the relative momentum scale of emissions, and the logarithm of the inverse emission angle, representing the angular separation of emissions within the jet. Each emission within a jet is represented as a point on the plane, where its coordinates are determined by its transverse momentum and angular separation relative to the jet axis.

Experimentally, constructing the Lund plane requires high-statistics jet samples and careful control of detector effects. While such measurements are challenging, they have been successfully performed at the LHC [91,118,127]. At RHIC, the lower center-of-mass energy implies reduced phase space for radiation; however, the high luminosity and large acceptance of sPHENIX are expected to provide sufficient statistics for differential measurements in selected kinematic ranges.

The primary Lund plane is constructed by reclustering the selected jet using the Cambridge-Aachen (C/A) jet algorithm. At each declustering stage we obtain two branches i and j such that $p_{Ti} > p_{Tj}$ and calculate

$$k_T = p_{Tj} \Delta_{ij}, \quad (6)$$

where Δ_{ij} is given by Eq. (4). The quantities $\log(1/\Delta_{ij})$ and $\log(k_T/\text{GeV})$ define the x and y coordinates of the primary Lund plane, respectively. This procedure is repeated iteratively until we reach the end of the clustering tree. The obtained set of points in $\log(1/\Delta_{ij})$ and $\log(k_T/\text{GeV})$ coordinates is used to build the primary Lund plane for a given jet. In our analysis we use both leading and subleading jets to construct primary Lund plane for our MC sample.

The primary Lund plane distributions of quark and gluon jets are shown in Fig. 3. The ungroomed distributions for quarks (left) and gluons (right) are compared in the top panel, while the respective groomed distributions are shown in the

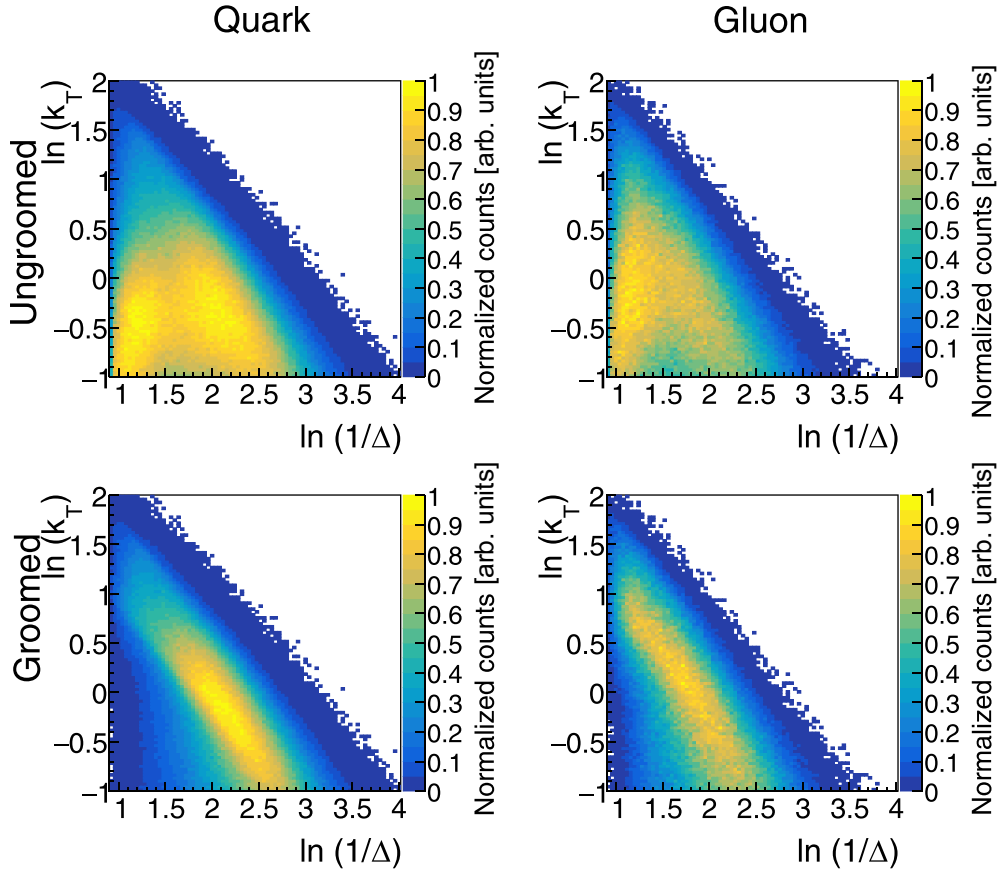


FIG. 3. Primary Lund plane projections for ungroomed (top panel) and groomed (bottom panel) jets originating from quarks (left), and gluons (right).

bottom panel. Looking at the distributions along the x axis, we observe that ungroomed quark jets are more collinear ($\ln(1/\Delta_{ij}) > 2$) than ungroomed gluon jets. That is, for a fixed k_T value, the quark distribution contains a larger number of particles at large $\ln(1/\Delta_{ij})$ values than the gluon distribution, especially at small k_T values. This is very representative of the difference in their radiation patterns. For the groomed primary Lund plane, the difference tends to become milder as the soft emissions are eliminated by SoftDrop.

The dead cone effect is manifested as a suppression of gluon radiation in the vicinity of massive quarks [95,96,145]. This suppression arises because the quark mass introduces an effective angular cutoff, limiting gluon emissions at small angles relative to the trajectory of the heavy quark. In Fig. 4, primary Lund plane distributions for jets initiated by light quarks (left), charm quarks (middle), and bottom (right) quarks, the manifestation of the dead cone effect is shown for ungroomed (top panel) and groomed (bottom panel) jets. Specifically, a significant suppression of collinear radiation within the logarithmic range of $\ln(1/\Delta_{ij}) \approx 2.5$ to 3 for b jets is revealed, a feature markedly less pronounced in jets seeded by lighter quarks. Additionally, this suppression is notably evident at low values of $\ln(k_T)$. The concurrent suppression in both $\ln(1/\Delta_{ij})$ and $\ln(k_T)$ underscores the mass-dependent modification of the radiation pattern inherent to heavy quarks.

A practical approach to observing the dead cone effect at sPHENIX may be to compare Lund plane projections between heavy-flavor-tagged and inclusive jet samples where the dead cone signature would manifest as a relative suppression of emissions in the region of small angles and low transverse momentum.

V. CONCLUSION

In this study, we performed a detailed PYTHIA-based Monte Carlo analysis of heavy-flavor jet substructure for $p + p$ collisions at 200 GeV center-of-mass energy, leveraging the capabilities of the sPHENIX detector. Focusing on jet angularities and the primary Lund plane projection, we identified a suppression of collinear radiation around heavy quarks, consistent with the dead cone effect. Our results reveal distinct differences in the radiation patterns of b jets compared to light and charm jets, as well as between quark and gluon jets, in agreement with theoretical expectations and recent experimental observations. In addition to providing a framework for jet substructure measurements, we establish the feasibility of experimentally observing the dead cone effect at sPHENIX by combining heavy-flavor jet tagging with differential substructure observables such as angularities and Lund plane projections. These results also provide guidance for constructing QCD-motivated observables for the study of tagged jets at RHIC energies.

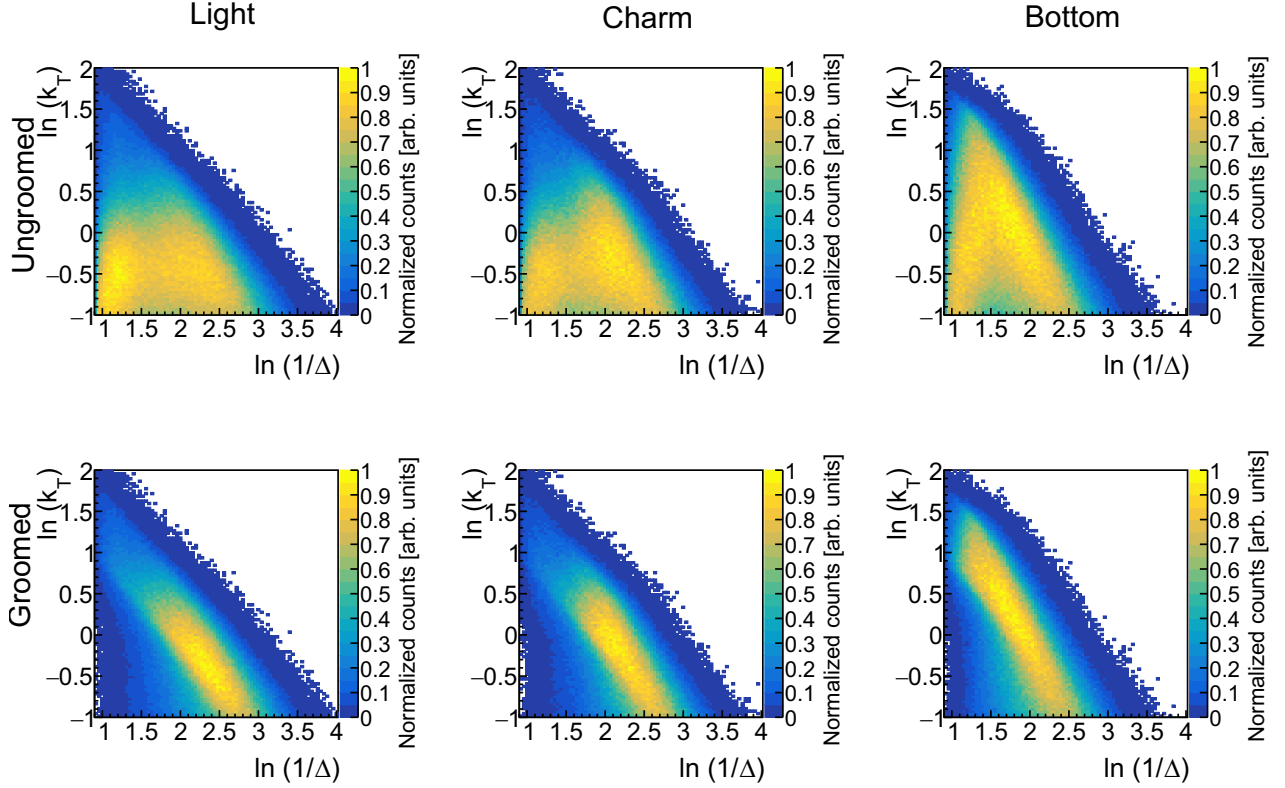


FIG. 4. Primary Lund plane projections for ungroomed (top panel) and groomed (bottom panel) jets originating from light quarks (left), charm quarks (center), and bottom quarks (right).

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DATA AVAILABILITY

There are no publicly available research data or software supporting this manuscript. Requests for further information or data should be sent to the authors.

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