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Tracking Lost Jet Energy in Individual Collisions: New Insights to Quark-Gluon Plasma Study

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Abstract. The investigation of jet energy loss in high-energy proton-proton (pp) collisions offers crucial insights into the properties of Quark-Gluon Plasma (QGP) and strongly interacting matter. In this study, we simulate 10,000 pp collision events using the *Pythia* event generator, followed by jet clustering via the longitudinally invariant anti-k_t algorithm implemented in *Fastjet*. The analysis focuses on examining missing transverse momentum (MET) and jet momentum imbalances to identify a mechanisms behind the potential energy loss on an event-by-event basis. Our results reveal a significant correlation between large MET values and low p_T2/p_T1 ratios, indicative of pronounced momentum imbalance between the leading and sub-leading jets. These findings suggest a substantial jet energy loss. Which is likely due to the medium interactions with implications for studying jet quenching phenomena in QGP. This work introduces a refined methodology for assessing jet quenching at a level of individual events, providing a detailed characterization of jet-medium interactions and contributing to the broader understanding of energy loss in high-energy nuclear collisions.

Keywords: High Energy Particle Physics, Quark-Gluon Plasma, Particle Collision Simulations, Jet Quenching

1. Introduction

The study of high-energy nuclear collisions offers a unique window into understanding the early universe, as conditions mirrored those just microseconds after the Big Bang. Under these extreme conditions, ordinary hadronic matter is believed to undergo a phase transition into a state known as Quark-Gluon Plasma (QGP), where quarks and gluons, typically confined within protons and neutrons, are liberated into a hot, dense medium. The properties of QGP has been a primary target of heavy-ion physics studies, with the phenomenon of jet quenching serving as a crucial observable for probing this exotic state of matter.

Jets, defined as collimated sprays of particles resulting from the fragmentation of high-energy quarks and gluons, play a pivotal role in QGP studies. As these high-energy partons traverse the QGP, they lose energy through a variety of mechanisms, including medium-induced gluon radiation and collisional energy loss. This energy loss, or jet quenching, alters the momentum and structure of the jets, providing valuable information about the properties of the medium they traverse. Theoretical foundations laid by researchers such as Yuri L. Dokshitzer have been instrumental in developing models that describe the behavior of jets in Quantum Chromodynamics (QCD), the theory governing strong interactions [1]. These models predict that the amount of energy lost by a jet is directly related to the properties of the QGP, making jet quenching a sensitive probe of the medium's density and temperature.

Experimental evidence for jet quenching has been well-documented in a variety of studies. Notably, the CMS Collaboration observed significant suppression of high-energy jets in PbPb collisions at $\sqrt{s_{NN}} = 2.76$ TeV at the Large Hadron Collider (LHC), consistent with theoretical predictions of QGP formation [2]. These observations, however, are generally derived from data averaged over many collision events, which, while statistically powerful, can obscure the rich event-by-event fluctuations that are crucial for a deeper understanding of the underlying physics. As pointed out by Wang and Yin [3], such averaging can mask the complexity of individual collision events, where variations in initial conditions, such as the geometry of the collision or the density of the medium, can lead to significant differences in energy loss.[4]

This paper aims to address this gap by focusing on the analysis of jet quenching at the level of individual collision events, leveraging the capabilities of modern simulation tools like ROOT [5] and open data from the LHC [6]. The use of *Fastjet*, a software package designed for jet clustering in high-energy physics, allows for precise reconstruction of jet properties from experimental data [7]. Coupled with *Pythia*[8], a widely-used event generator that simulates the outcomes of high-energy collisions, this study seeks to replicate the conditions under which jets interact with the QGP and lose energy. By compiling and modifying C++ code to integrate external modules into *Pythia*, this research endeavors to create a simulation environment capable of capturing the nuanced behavior of jets in single events. Proposing a novel approach to jet quenching analysis by shifting the focus from averaged data to single-event analysis. By integrating advanced simulation tools and leveraging open data, it aims to provide new insights into the mechanisms of energy loss in high-energy nuclear collisions, thereby contributing to the broader understanding of QGP and the strong force that governs the behavior of quarks and gluons.

This paper is organized as follows. Section 2 introduces data preparation and analysis methods using *Pythia* and *Fastjet*. The results are presented in Section 3, followed by conclusions and discussions in Section 4.

2. Data and Methodology

2.1. Data Preparation Using *Pythia*

In order to investigate jet energy loss in proton-proton (pp) collisions, events were generated using the *Pythia* 8 event generator. *Pythia* is widely utilized in high-energy physics for simulating the interactions and final state particles from proton-proton collisions, reproducing various QCD processes. For this study, *Pythia* was configured to generate hard QCD interactions, which are ideal for producing high-energy jets. A total of 10,000 events were simulated using the following configuration:

- **Center-of-mass energy**: 5360 GeV (`Beams:eCM = 5360.`)
- **Hard QCD processes**: Enabled (`HardQCD:all = on`)
- **Minimum transverse momentum for partons**: 500 GeV/c (`PhaseSpace:pTHatMin = 500.`)
- **Random seed for reproducibility**: Set with (`Random:setSeed = on`)

This setup produced datasets that included detailed information about the particles created in each event, such as their momentum components (p_x, p_y, p_z), energy, mass, particle ID, and event-specific indices.

2.1.1. Filtering Intermediate Particles

The output from *Pythia* includes both final-state particles (those that can be detected experimentally) and intermediate particles (transient particles that decay into other particles and are not directly observed). *Pythia* assigns a *status flag* to each particle, where particles with a *negative status* represent these intermediate states.

For this analysis, only final-state particles with a *positive status* were considered, as they are physically detectable in experiments. All particles with a negative status (i.e., those representing intermediate states) were filtered out. This ensures that the dataset reflects only the observable particles produced in the collision events.

2.1.2. Removal of Neutrinos

Neutrinos, which interact only via the weak force, are difficult to detect and do not significantly contribute to the energy measurements in particle detectors. Therefore, they were removed from the dataset to avoid distorting the energy analysis.

Neutrinos were identified by their particle IDs and excluded from the final dataset:

- **Electron neutrino** (ν_e): Particle ID 12
- **Muon neutrino** (ν_μ): Particle ID 14
- **Tau neutrino** (ν_τ): Particle ID 16

This exclusion step ensures that only detectable particles (hadrons, leptons, photons) contribute to the energy and momentum calculations in subsequent analyses.

2.1.3. Structuring the Data for Analysis

After filtering out intermediate particles and removing neutrinos, the remaining dataset consisted of stable particles such as hadrons, photons, and leptons. The following attributes were retained for each particle:

- **Particle ID**: Identifies the type of particle (e.g., 211 for π^+, 321 for K^+).
- **Momentum components**: The particle's momentum along the x, y, and z axes, denoted as p_x, p_y, and p_z.
- **Energy** (e): The total energy of the particle, which is important for reconstructing the event's overall energy distribution.
- **Mass** (m): The rest mass of the particle, which aids in identifying specific particles and validating the results.
- **Event index**: This indicates the event number, allowing for tracking individual particles across different events and enabling event-by-event analysis.

The final prepared dataset was structured for input into the subsequent stages of analysis, which involve clustering the particles into jets and examining the energy loss across different events.

2.1.4. Data Validation

Before proceeding to the analysis phase, a validation step was conducted to ensure the accuracy of the data preparation:

- **Particle count verification**: After filtering out intermediate particles and removing neutrinos, the number of particles per event was checked to ensure consistency with expectations.
- **Energy conservation check**: To ensure energy consistency after filtering, the total energy of the final-state particles was verified. This step confirmed that energy conservation was maintained within the observable particle set, providing a reliable dataset for further study.

Following these data preparation steps, the dataset was ready for use in jet clustering and energy loss analyses, which form the core of the study.

2.2. Jet Clustering with *Fastjet*

After the data preparation and filtering steps, the next phase in the analysis involved clustering the final-state particles into jets. For this purpose, the *Fastjet* software package was employed. *Fastjet* is a highly efficient and accurate tool used in high-energy physics for jet clustering. It applies a variety of algorithms designed to identify and reconstruct jets from the momenta of particles produced in collision events.

2.2.1. Choice of Jet Clustering Algorithm

The *longitudinally invariant anti-k_t algorithm* was selected for jet clustering. The anti-k_t algorithm is widely regarded as the gold standard for jet clustering in high-energy physics experiments due to its desirable properties, such as:

- **Infrared and collinear safety**: Ensures the algorithm is insensitive to soft radiation and collinear splitting of partons.
- **Circular jets**: Produces jets that are approximately circular in the transverse plane (η-ϕ space), closely mirroring the shape of jets observed in real experimental conditions.

The jet clustering algorithm relies on a distance parameter, R, which controls the size of the jets. A radius parameter of $R = 0.4$ was chosen for this study, which provides a balance between capturing small jets and avoiding the merger of large, distant clusters of particles. This choice is consistent with the parameters used in collider experiments like those conducted at the LHC.

2.2.2. Recombination Scheme

The *E-scheme recombination* was utilized for combining the four-momenta of particles during the jet clustering process. In this scheme, the momentum of a clustered jet is the sum of the four-momenta of its constituent particles. This method preserves energy-momentum conservation and ensures that the final jets have physically meaningful energy and momentum values, which is critical when studying energy loss.

2.2.3. Input Data Organization

To facilitate smooth and consistent data handling throughout the analysis, the raw output from *Pythia* was structured into a unified format that is compatible with *Fastjet*'s input requirements. Each particle in the final-state dataset was represented by:

Transverse momentum (p_T): The momentum component perpendicular to the beam axis.
Rapidity (y): A relativistic measure of velocity along the beam axis.
Azimuthal angle (ϕ): The angle of the particle in the transverse plane.
Event index: A unique identifier for each event, allowing event-by-event jet analysis.

The particles were fed into *Fastjet* as input for each individual event, where they were clustered into jets based on their relative momentum and spatial distribution in η-ϕ space.

2.2.4. Jet Reconstruction Procedure

For each simulated collision event, *Fastjet* grouped the final-state particles into jets using the anti-k_t algorithm. The algorithm works by calculating a distance measure between particles, prioritizing those closest to each other in momentum space, and clustering them together to form jets. Specifically:

- The algorithm assigns each particle a "distance" measure, dependent on the transverse momentum (p_T) and the angular distance in η-ϕ space.
- Particles that are close together in this space are successively merged into jets.
- The merging continues until no nearby particles or clusters remain within the radius R, and a final set of jets is produced for each event.

The reconstructed jets are characterized by their collective properties:

- **Transverse momentum** (p_T): The total momentum of the jet in the transverse plane, which is a key observable in studies of jet quenching and energy loss.
- **Rapidity** (y): The jet's rapidity along the beam axis, giving insight into the spatial distribution of energy loss.
- **Azimuthal angle** (ϕ): The angle of the jet in the transverse plane, which helps in understanding the angular spread of energy and momentum in the event.

2.2.5. Jet Constituents

In addition to the overall properties of each jet, *Fastjet* also provides detailed information about the *constituents* that make up each jet. For every jet, the following data were recorded:

- **Constituent** p_T: The transverse momentum of each individual particle within the jet.
- **Constituent** y: The rapidity of each particle within the jet.
- **Constituent** ϕ: The azimuthal angle of each particle within the jet.

By analyzing the constituents of the jets, we gain a deeper understanding of the internal structure of the jets and the energy flow within them. This information is crucial for identifying which particles contribute most significantly to the overall jet properties and for studying how energy is distributed across the jet.

2.2.6. Output Format and Interpretation

For each event, *Fastjet* produced an output containing the following:

- A list of all jets identified in the event.
- For each jet, the key properties such as its p_T, y, and ϕ.
- For each jet, the list of constituent particles and their corresponding p_T, y, and ϕ.

An example of the jet clustering output for a given event is shown below:

$$\text{Jet 0: } p_T = 618.387\,\text{GeV},\ y = 0.814425,\ \phi = 2.30356$$

Constituents of Jet 0:

- Constituent 0: $p_T = 0.178\,\text{GeV},\ y = 0.757253,\ \phi = 2.68799$

- Constituent 1: $p_T = 0.469879\,\text{GeV},\ y = 0.517493,\ \phi = 2.5164$
- Constituent 2: $p_T = 0.98072\,\text{GeV},\ y = 0.627865,\ \phi = 2.58753$
- …

This detailed output was stored and organized to allow for further analysis, such as comparing jet properties between different events and investigating the effects of jet energy loss in a Quark-Gluon Plasma environment. The ability to study the composition of each jet, down to the individual particle level, provides insights into how energy is distributed within the jets and enables a deeper understanding of the mechanisms of jet quenching.

2.2.7. Application to Energy Loss Analysis

The clustered jets and their constituent information form the foundation for studying jet quenching and energy loss. By analyzing the p_T spectra of jets across multiple events, variations in energy loss due to medium effects can be identified. Specifically, jets in events where Quark-Gluon Plasma formation is expected may exhibit reduced transverse momentum, indicating significant energy loss.

The comparison between jets from different events—especially those from events with and without QGP formation—will provide insights into the behavior of high-energy jets as they traverse the QGP medium. Additionally, by analyzing the angular distribution and internal structure of the jets, it may be possible to infer the energy loss mechanisms at play.

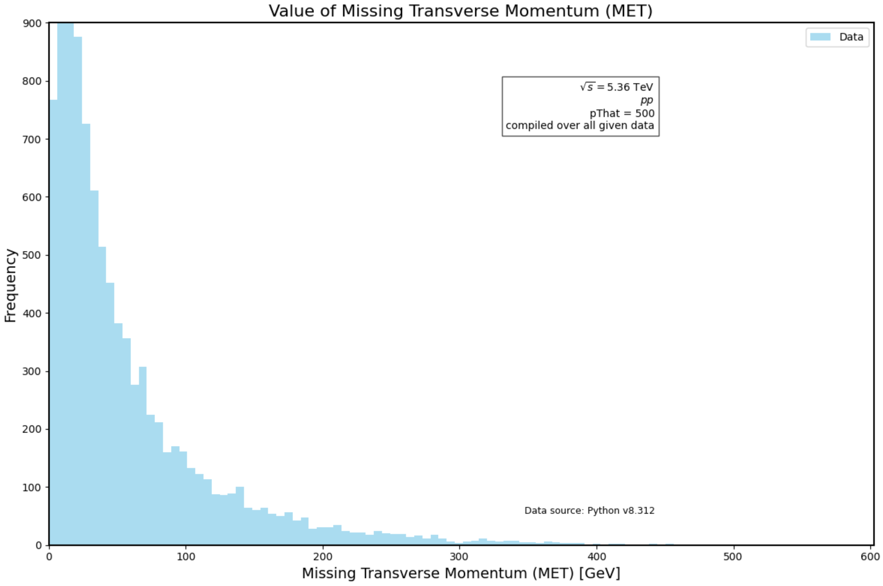

Figure 1: Distribution of Missing Transverse Momentum (MET) for all events. The majority of events show small MET values, with a peak around 50 GeV.

3. Results

3.1. Missing Transverse Momentum (MET) Distribution

To begin our analysis, we examined the distribution of missing transverse momentum (MET) for all proton-proton (pp) collision events. MET is an important observable in high-energy physics because it reflects the momentum imbalance in the transverse plane, potentially indicating the presence of undetected particles or significant energy loss. Figure 1 shows the distribution of MET values across all simulated events, with a peak occurring at low MET values, typically below 100 GeV.

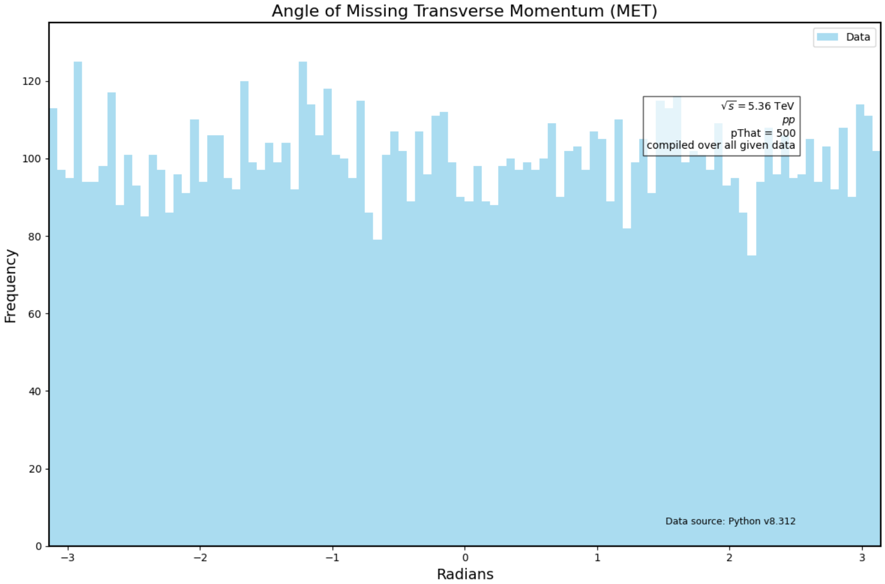

Figure 2: Angular distribution of MET (ϕ) for all events. The uniform distribution indicates no preferential direction for missing energy in the transverse plane.

The prevalence of small MET values is consistent with the detector's pseudorapidity coverage of $|\eta| < 2.5$. Since our detector does not capture particles outside this range, a significant portion of the total event energy is not accounted for, leading to relatively low MET values. In contrast, high-MET events, which are of particular interest for studying jet quenching and energy loss mechanisms, occur much less frequently.

The uniform distribution of MET in the azimuthal plane (Figure 2) further confirms that there is no preferential direction for missing energy, indicating that the energy imbalance occurs randomly across different events. This is expected for pp collisions, where jets and other final-state particles are distributed isotropically in the transverse plane.

The small MET values observed in the majority of events suggest that most collisions involve well-balanced momentum distributions, with only a small fraction of events exhibiting large momentum imbalances. These high-MET events are the focus of the subsequent sections, where we apply additional selection criteria to isolate events of interest.

To explore the relationship between jet momentum imbalance and MET, we analyzed the ratio of the transverse momentum of the second jet (p_T2) to the leading jet (p_T1), comparing it to the MET for events with MET > 200 GeV (Figure 3). This analysis is particularly relevant for studying jet quenching and energy loss, as events with a large imbalance between the leading and sub-leading jets may indicate significant energy loss due to medium interactions.

The plot reveals a clear correlation between low p_T2/p_T1 values and large MET. Specifically, events where the second jet has significantly less transverse momentum than the leading jet ($p_T2/p_T1 \ll 1$) tend to exhibit higher missing transverse momentum. This suggests that the large momentum im-

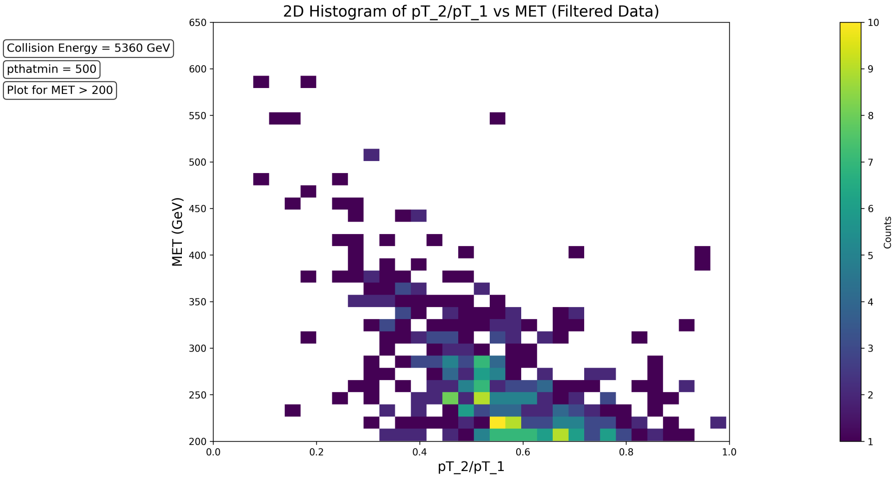

Figure 3: 2D histogram of p_T2/p_T1 vs MET for events with MET $>$ 200 GeV. Events with lower p_T2/p_T1 ratios are correlated with higher MET values.

balance between the leading and sub-leading jets is a potential source of the missing energy in these events.

Physically, this may indicate that energy carried by the second jet is lost or undetected, possibly due to interactions with the Quark-Gluon Plasma (QGP) or other medium effects. The strong correlation between large MET and jet momentum imbalance supports the hypothesis that significant energy loss occurs in these events, and that MET is a useful observable for identifying such events.

3.2. Event Selection and Data Refinement

To further refine our dataset and focus on events with significant missing transverse momentum and high-energy jets, we applied several event selection criteria based on established methods from high-energy physics analyses [9]. The goal of these selections was to isolate events that exhibit potential jet quenching or other energy loss mechanisms, which are typically characterized by high MET and the presence of energetic jets.

The following selection criteria were applied:

- **MET $>$ 200 GeV**: This ensures that only events with significant missing energy are considered, filtering out the majority of low-MET events.
- **Leading jet transverse momentum** $p_T(j1) > 110$ **GeV**: A requirement for the leading jet to have substantial momentum, focusing on events with high-energy jets.
- **Leading jet pseudorapidity** $|\eta(j1)| < 2.4$: Ensures that the leading jet is within the detector's pseudorapidity coverage, preventing jets that are outside the detector's range from skewing the results.

Figure 4 shows the effect of these selection criteria on the MET distribution. The selection of MET ¿ 200 GeV (orange) significantly reduces the number of events, while the additional cuts on the leading jet's p_T and $|\eta|$ (green and red, respectively) have minimal impact. This suggests that most events with large MET already have a leading jet that satisfies these criteria.

This result is consistent with expectations, as events with large MET tend to feature high-energy jets and are within the detector's pseudorapidity range. The additional selections based on tau-lepton decays and dijet events (purple and brown, respectively) further refine the dataset, though they do not

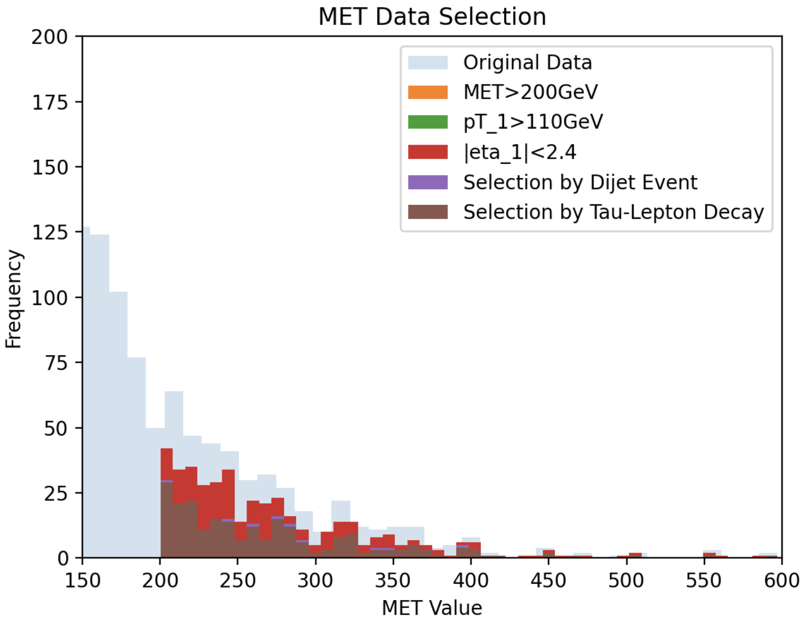

Figure 4: Effect of different selection criteria on the MET distribution. The application of MET ¿ 200 GeV significantly reduces the dataset, while the additional leading jet cuts do not change the dataset significantly.

drastically reduce the number of events, indicating that these selections filter out only a small subset of the data.

4. Analysis and Discussion

4.1. Momentum Conservation in the Transverse Plane

To verify momentum conservation in the transverse plane, we analyzed the azimuthal angle (ϕ) of the leading jet and compared it to the negated azimuthal angle of the MET vector. In a perfectly balanced event, the MET vector should point in the opposite direction to the leading jet, reflecting momentum conservation. Figure 5 shows the 2D histogram of the leading jet's ϕ versus the negated ϕ of the MET vector.

The plot shows a strong anti-correlation, where the majority of events lie along a diagonal line, indicating that the MET vector recoils in the opposite direction to the leading jet. This is consistent with the principle of momentum conservation in the transverse plane and suggests that the MET is primarily due to particles or energy that are not detected, rather than an imbalance caused by misreconstructed jets or background noise.

This result confirms that the events selected for this analysis exhibit good momentum conservation, further validating the accuracy of the selection criteria and the overall quality of the dataset.

4.2. Leading Jet Transverse Momentum Distribution

The distribution of the leading jet transverse momentum (p_T) is shown in Figure 6. This distribution is central to understanding the energy scale of the events we are analyzing, as the leading jet typically carries a significant portion of the total event energy.

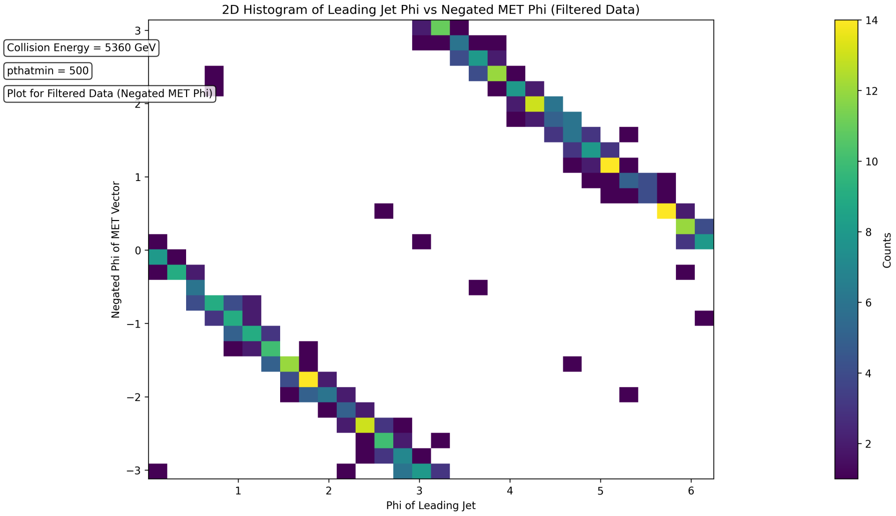

Figure 5: 2D histogram of the leading jet ϕ vs the negated ϕ of the MET vector. The strong anti-correlation demonstrates momentum conservation in the transverse plane.

The histogram reveals that the majority of events feature leading jets with p_T values centered around 600 GeV, with the distribution ranging from 200 GeV to 1200 GeV. This indicates that the dataset primarily contains high-energy jets, which are crucial for probing medium effects like jet quenching in Quark-Gluon Plasma (QGP) environments.

Figure 7 shows the distribution of the transverse momentum ratio between the second and leading jets (p_T2/p_T1). This observable provides insight into the momentum imbalance between the two highest-energy jets in each event, which is a key feature for understanding energy loss mechanisms and MET.The (p_T2/p_T1) ratio distribution peaks near 1, meaning that, in most events, the second jet has a momentum close to that of the leading jet. However, there is a noticeable tail extending towards smaller values of (p_T2/p_T1) , which corresponds to events where the second jet carries significantly less momentum than the leading jet. This tail is particularly relevant for high-MET events, as low (p_T2/p_T1) ratios are correlated with large MET, as demonstrated in Section 4.3.

4.3. Visualizing a Dijet Event with *Fastjet*

In addition to the statistical analyses presented, we provided a visualization of a specific dijet event to illustrate the spatial structure and momentum distribution of jets in a single event. This visualization is generated using *Fastjet*'s anti-k_t algorithm with a resolution parameter $R = 1$. It recorded jets based on their transverse momentum (p_T) and spatial distribution in y-ϕ space.

Figure 8 shows two primary jets, where the taller jet corresponds to a higher p_T, signifying that this jet carries a significant amount of the total event energy. The second jet, though smaller, still contributes notably to the overall event structure. This plot exemplifies how *Fastjet* clusters particles into jets based on their momentum and spatial properties, helping us identify high-energy jet pairs in dijet events. The observed imbalance between the two jets, combined with missing transverse momentum, suggests a potential energy loss mechanisms in play.

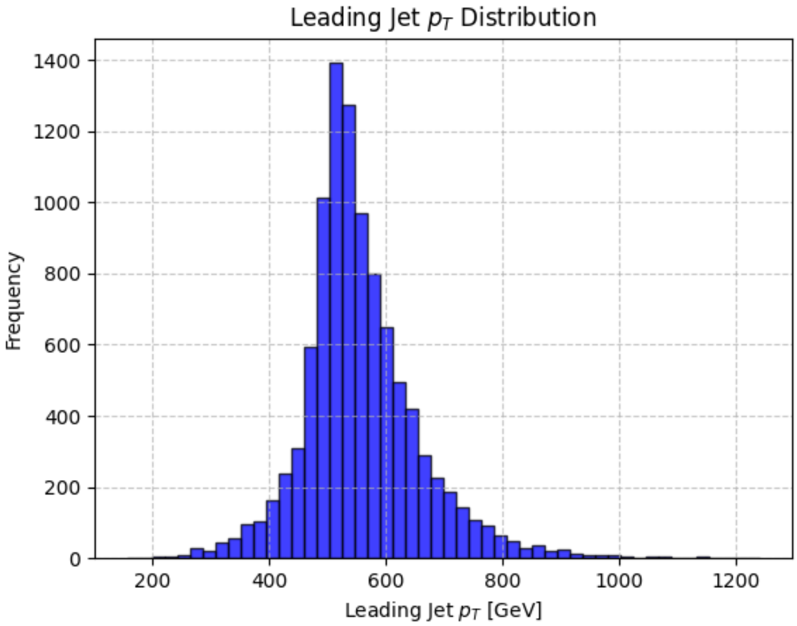

Figure 6: Distribution of leading jet transverse momentum (p_T) for all events. The distribution peaks at around 600 GeV, indicating that the majority of leading jets in this dataset are highly energetic.

4.4. Interpretation: Comparison with ATLAS Monojet Dark Matter Searches

To contextualize our analysis within a broader high-energy physics framework, which includes various experimental searches at hadron colliders [10], we specifically refer to the ATLAS monojet dark matter search discussed in the press release by the ATLAS Collaboration [11] and in their detailed study [12]. In this research, ATLAS physicists investigated events characterized by high missing transverse momentum (MET) and a single high-energy jet (monojet), searching for signatures of dark matter. In these events, the MET is produced by unseen particles recoiling against a visible jet, providing indirect evidence of dark matter.

The ATLAS study is particularly relevant to our work in understanding MET and its relationship with visible jets. Although our analysis focuses on dijet events and jet quenching in Quark-Gluon Plasma (QGP), the principle of using MET to infer missing energy or undetected particles is analogous. Both the ATLAS monojet search and our dijet analysis rely on momentum conservation in the transverse plane, where visible jets recoil against invisible energy or particles (such as neutrinos in ATLAS or undetected energy loss in our study).

In both cases, MET is a key observable used to identify interesting physics processes. While the ATLAS experiment focuses on new physics searches like dark matter, our study seeks to explore the dynamics of energy loss in the QGP by analyzing jet momentum imbalances and MET.

The ATLAS monojet analysis uses high-energy monojet events and MET to search for dark matter. The visible jet recoiling against MET is seen as a signature of particles escaping the detector, possibly dark matter. In contrast, our study investigates dijet events, focusing on the energy loss mechanisms within the QGP. Large MET values, combined with momentum imbalance between the leading and second jets, suggest that energy is being lost, possibly due to jet-medium interactions.

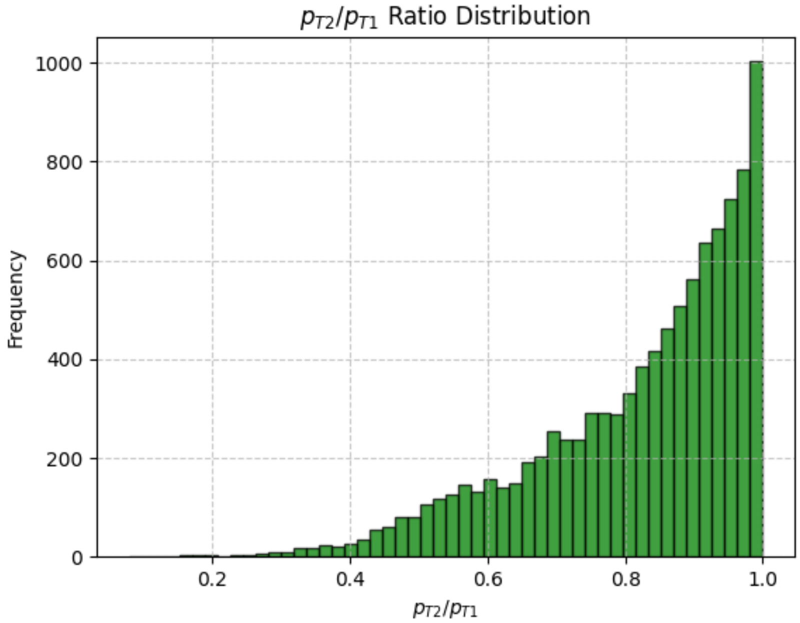

Figure 7: Distribution of p_T2/p_T1 ratio for all events. The ratio peaks near 1, indicating that in most events, the second jet has a similar momentum to the leading jet, though a significant tail exists for events with a lower p_T2/p_T1 ratio.

5. Conclusion

The exploration of jet energy loss in Quark-Gluon Plasma (QGP) is a vital aspect of understanding strongly interacting matter at extreme energy densities, and this study has made important contributions to that effort by focusing on the missing transverse momentum (MET) and jet momentum imbalances in proton-proton (pp) collisions. By generating a substantial dataset using *Pythia* and analyzing the results with *Fastjet*, this research has provided a detailed picture of how jets lose energy and how MET can serve as a tool to quantify such losses in single-event analyses.

Key findings of this study include the following:

(1) **MET Distribution and Event Selection**: The majority of events show small MET values, consistent with a well-balanced transverse momentum distribution. However, a small fraction of events exhibit large MET values, indicative of significant momentum imbalance. By applying refined selection criteria—MET > 200 GeV, $p_T(j1) > 110$ GeV, and $|\eta(j1)| < 2.4$—we successfully isolated events of interest that exhibit potential energy loss, thereby filtering out background and focusing on the most relevant subset of the data.

(2) **Correlation Between Jet Momentum Imbalance and MET**: A strong correlation was observed between low p_T2/p_T1 values (momentum imbalance between the leading and sub-leading jets) and high MET values. This suggests that in high-MET events, a significant portion of the jet's energy is lost, possibly due to jet-medium interactions in the QGP. The momentum imbalance in these events further supports the hypothesis that energy loss is responsible for the missing energy.

(3) **Momentum Conservation**: Through the analysis of azimuthal angle correlations, we confirmed that MET vectors consistently recoil in the opposite direction of the leading jets, verifying mo-

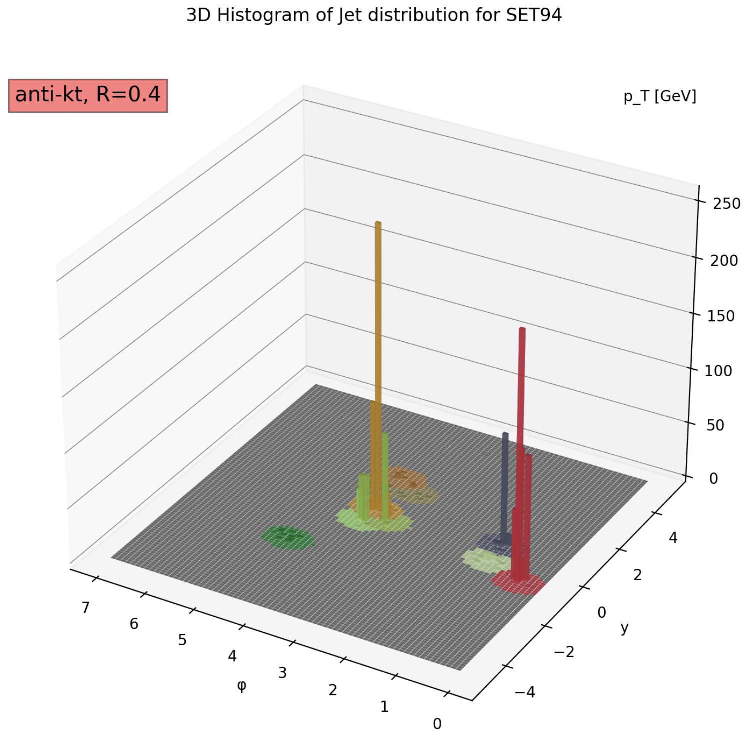

Figure 8: 3D plot of a dijet event from *Fastjet*, visualizing the jets in terms of transverse momentum (p_T), rapidity (y), and azimuthal angle (ϕ). The height of each jet indicates the jet p_T, while the base represents its position in y-ϕ space.

mentum conservation in the transverse plane. This ensures the reliability of the observed MET values and the overall accuracy of the dataset.

(4) **Visualization of Dijet Events**: A 3D visualization of a dijet event revealed the spatial distribution and momentum structure of jets in a single event. The visualization demonstrated how *Fastjet* clusters particles into jets and illustrated the momentum imbalance between jets, suggesting potential energy loss. This visualization complements the statistical analyses and provides an intuitive understanding of individual collision events.

(5) **Contextualization with ATLAS Monojet Searches**: The comparison with the ATLAS Collaboration's monojet search for dark matter provides an insightful context for our study. While ATLAS focuses on the MET produced by undetected dark matter particles, our work uses MET as a proxy for undetected energy loss in the QGP. Both studies demonstrate a critical role of MET in uncovering physics processes that are otherwise invisible from direct detection.

This study presents a novel methodology for examining jet energy loss on a single-event basis, rather than relying on averaged data from multiple events. By doing so, it opens the door to more precise characterizations of energy loss mechanisms in the QGP, allowing for the detection of subtle, event-by-event variations that would otherwise be masked by averaging techniques. These findings not only enhance our understanding of jet-medium interactions but also provide a new framework for future analyses of high-energy collision events.

Moving forward, this work can be extended to heavy-ion collisions, where the presence of a fully formed QGP is more pronounced, offering a clearer environment for studying jet quenching. Additionally, further refinements in jet selection techniques and MET analysis may yield even more detailed insights into the dynamics of energy loss in extreme environments.

In conclusion, this study has provided key insights into the dynamics of jet energy loss and MET in high-energy pp collisions, leveraging state-of-the-art tools like *Pythia* and *Fastjet*, and laying the groundwork for future investigations into the microscopic nature of QGP.

Acknowledgments

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Appendix: List of Physics Values and Units

Table 1: List of physics values and their units.

Symbol	Description	Unit
ϕ	Azimuthal angle	radians
η	Pseudorapidity	dimensionless
y	Rapidity	dimensionless
θ	Polar angle	radians
MET	Missing transverse energy	GeV