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Novel tools and challenges for jet physics in heavy-ion collisions at the LHC

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Jet measurements in heavy-ion collisions have a unique challenge due to the large fluctuating background from the underlying event. Recent advances in background subtraction techniques will be discussed that have allowed inclusive jet measurements to be made to lower jet transverse momentum and larger jet resolution parameters than ever before at the LHC. Additionally, it can be challenging to find observables that are sensitive to the particular in-medium effects in which we are interested in order to study the quark-gluon plasma. Recent applications of novel jet substructure tools for heavy-ion collisions will be discussed that are shown to be sensitive to jet quenching effects along with improvements in background subtraction techniques for these jet substructure measurements. These new tools allow jet measurements in heavy-ion collisions at the LHC to be unfolded for detector and background effects such that they can be compared to various theoretical predictions to help us better understand jet quenching.

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1. Introduction

Jets are used as a probe of the quark-gluon plasma (QGP) produced in heavy-ion collisions (HICs). As jets move through the medium they interact leading to jet energy loss and substructure modification, a phenomena called jet quenching [1, 2, 3]. Jet quenching is interesting to study over a large range of scales, including the jet transverse momentum p_{T} and resolution parameter R, where in-medium effects are expected to vary [4, 5, 6, 7]. Measuring jets in HICs can be challenging because of the large background from the underlying event (UE) of flowing particles underneath the jet that produces fluctuations on the order of the jet p_{T} itself [8]. Upward fluctuations in the UE can be taken as jets, called fakes, which sometimes prevent unfolding especially at lower jet p_{T} and larger R, regions of the phase space where the physics is of interest. Additionally, it can be challenging to find observables that are sensitive to in-medium effects, especially those that can be compared to first principle calculations to help constrain models.

In this proceeding, recent progress at the LHC in addressing these challenges will be discussed. For dealing with the large background new background subtraction techniques have been developed, which include machine learning techniques. In addition, new jet substructure tools are being utilized to isolate in-medium effects and constrain models to better understand the QGP.

2. Overcoming the heavy-ion background

Jet measurements in HICs at the LHC already cover a large jet p_{T} range, which can be illustrated using the nuclear modification factor R_{AA}. Since jets are expected to lose energy in the QGP, the jet yield should be suppressed at a fixed value of p_{T} in HI compared to pp collisions where no medium is produced. This suppression is quantified using the R_{AA}, which compares the yield in HICs to the cross section in pp collisions with a scale factor to account for the nuclear geometry. The ATLAS and CMS experiments focus on measuring jets at very high p_{T} with high precision [9, 10, 11], where for example ATLAS measured inclusive jet suppression out to a TeV in jet p_{T} [9]. The ALICE experiment focuses on measuring jets at lower p_{T} taking advantage of precise tracking in the TPC, where inclusive jet suppression was measured over a range of 60–140 GeV$/c$ [12]. Therefore, we see jet suppression over a large range in jet p_{T} but we would like to push these limits, particularly to lower jet p_{T} and larger R.

2.0.1 ALICE machine learning technique

A new method of background removal has been developed using a ML approach [13]. Recently ALICE implemented this method to measure inclusive jets to lower p_{T}. The standard area-based (AB) method [8] used by ALICE effectively subtracts the average background but residual fluctuations remain large, leading to a large fake contribution. Previously when measuring inclusive jets, a leading track p_{T} cut was applied to remove fakes, which introduced a bias [12]. This new method uses ML techniques to correct the jet p_{T} by learning the difference between signal PYTHIA [14] jets and the background from properties of the jet including its constituents. This leads to a decrease in residual fluctuations, but introduces a fragmentation bias because PYTHIA jets in pp collisions have different fragmentation patterns than quenched jets in HICs [15, 16].

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In ALICE, this new method has been applied to both charged particle and full jets, which contain charged tracks and neutral clusters [17, 18]. The performance of this method for full jets is shown in left panel of Figure 1 compared to the AB method. The performance is evaluated using the $\delta p_{\mathrm{T}} = p_{\mathrm{T,rec}} - p_{\mathrm{T,det}}$, where $p_{\mathrm{T,rec}}$ is the ML corrected p_{T}, and $p_{\mathrm{T,det}}$ is the PYTHIA detector level jet p_{T}, which is narrower for smaller residual fluctuations. The ML method shows a significant improvement over the AB method, allowing us to unfold to lower jet p_{T}. This method has been applied to ALICE data in Ref. [18] and the fragmentation bias has been quantified, allowing full jets to be measured down to 40 GeV/c with reduced systematic uncertainties.

2.0.2 CMS large-R jets

CMS has the ability to measure jets at very high p_{T} where the background effects are smaller. The jet-by-jet constituent subtraction method [19] that was originally developed for pp collisions to remove pile-up helps improve the jet energy resolution (JER) when used for HI jets in CMS [11]. The method works by estimating the background energy density inside each jet (with an UE modulation from flow) and adding infinitesimal small "ghosts" to the jets whose transverse momentum is negative. The ghosts and particles are then combined based on how close they are to each other, then particles and ghosts with less than zero total momentum are removed from the jet. The right panel of Figure 1 shows the JER for jets with different R. The JER is shown to improve substantially with increasing jet p_{T}, especially for larger $R = 1.0$ jets. This allowed CMS to measure the R_{AA} for $R = 1.0$ jets for the first time in HICs in Ref. [11].

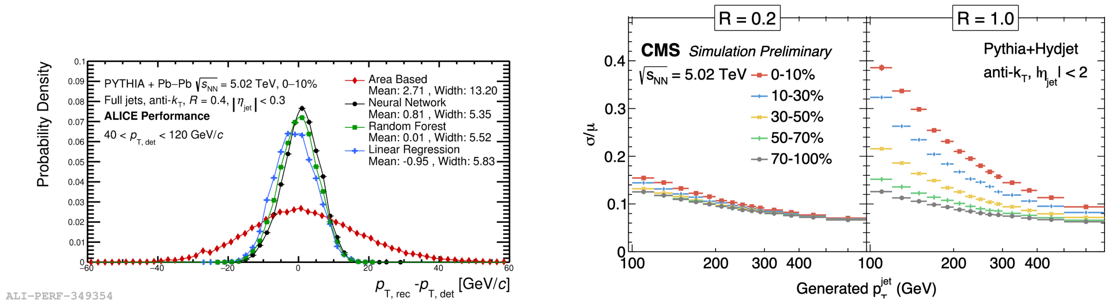

Figure 1: Left: The $\delta p_{\mathrm{T}} = p_{\mathrm{T,rec}} - p_{\mathrm{T,det}}$ distributions for $R = 0.4$ jets in central collisions (0–10%) with ALICE [18]. Right: The JER distributions for $R = 0.2$ and $R = 1.0$ central jets in CMS [11].

3. Novel jet substructure tools

There are many examples of jet substructure measurements at the LHC. This includes the jet mass which appears insensitive to medium modification possibly due to a cancellation of in-medium effects [20, 21, 22]. The high energy physics community has developed tools in pp collisions to access hard splittings inside a jet by removing the soft background contribution. Recently, these tools were found to be useful when applied to HICs because they help to remove the soft background and some of the soft signal, which can separate out medium effects that might cancel in other observables. These variables are also directly calculable in pQCD, allowing for comparisons to theoretical predictions. ALICE uses Soft Drop (SD) [23] grooming where jets are reclustered with the Cambridge-Aachen (C/A) [24] algorithm and a condition is placed on the shared momentum fraction between the splittings. ATLAS reclusters smaller R jets into larger R jets using the anti-k_{T} algorithm [24] with a cut on the smaller R jet p_{T}.

Jet splitting measurements in HICs are challenging because background particles can be picked up as a subjet in a splitting over the real subjet. This leads to incorrect splittings that cause large off-diagonal contributions in the response matrix, making unfolding impossible. The LHC experiments have come up with solutions to this by measuring in regions of phase space where the background is suppressed. ALICE uses smaller $R = 0.2$ jets in central (0–10%) and larger $R = 0.4$ jets in semi-central (30–50%) collisions for charged-particle jets between 60–80 GeV/c [25]. ATLAS uses higher $p_{\mathrm{T}} > 250$ GeV/c $R = 1.0$ jets from clustered $R = 0.2$ jets [26]. Both experiments additionally require more symmetric splittings to further suppress the background, with ALICE using a stronger grooming condition and ATLAS restricting the $R = 0.2$ jets to have $p_{\mathrm{T}} > 35$ GeV/c.

In addition to the phase space restrictions, ALICE uses the event-by-event constituent subtraction method instead of the jet-by-jet (described in Section 2.0.2) [19, 27]. The left panel of Figure 2 shows the groomed jet radius R_{g} distribution for PYTHIA jets embedded in real Pb–Pb data, where a secondary peak from the background splittings at large values is seen [25]. The event-by-event method is shown to reduce this contribution significantly. The center panel of Figure 2 also shows that the peak is again significantly reduced when a stronger grooming condition is used ($z_{\mathrm{cut}} = 0.1$ to 0.2). In ATLAS, combining the smaller $R = 0.2$ jets into larger $R = 1.0$ jets allows these measurements to take advantage of the precise background subtraction for smaller $R = 0.2$ jets [26]. The JER for these reclustered $R = 1.0$ jets is shown in the right panel of Figure 2, where it is only 10% for jets above 200 GeV/c in central collisions. These techniques are used to measure the unfolded R_{g} in ALICE and the unfolded k_{T} splitting scaling in ATLAS as discussed in Refs. [25] and [26], respectively. Both are the first measurements of their kind and demonstrate a significant modification in HICs, successfully isolating in-medium effects.

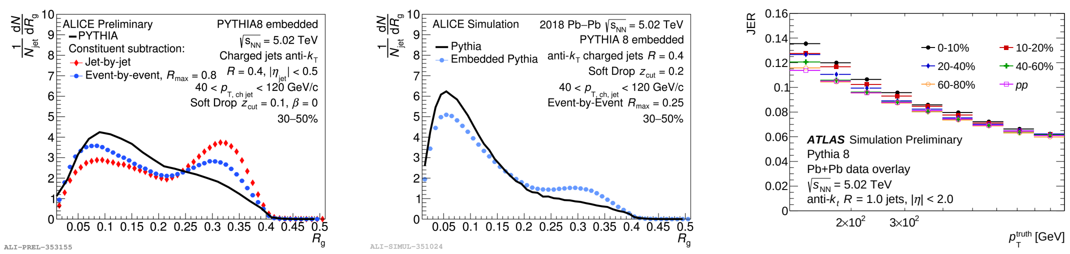

Figure 2: Left: The R_{g} distribution ($z_{\mathrm{cut}} = 0.1$) for embedded PYTHIA and PYTHIA for the event-by-event and jet-by-jet subtraction method in ALICE [25]. Center: The embedded R_{g} distributions for $z_{\mathrm{cut}} = 0.2$. Right: The JER for the reclustered $R = 1.0$ jets for different centralities in ATLAS [26].

4. Conclusion

New background subtraction techniques at the LHC have allow for jet measurements at lower p_{T} and larger R than ever before. Additionally, jet substructure tools applied to HICs seem to be sensitive to jet quenching effects. In general, improving jet measurement tools allow for direct comparison of unfolded results to theoretical calculations to help constrain jet quenching models.

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