Testing of coalescence mechanism in high energy heavy ion collisions using two-particle correlations with identified particle trigger

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In central Au-Au collisions at top RHIC energy, two particle correlation measurements with identified hadron trigger have shown attenuation of near side proton triggered jet-like yield at intermediate transverse momentum \( p_T \), \( 2 < p_T < 6 \text{ GeV}/c \). The attenuation has been attributed to the anomalous baryon enhancement observed in the single inclusive measurements at the same \( p_T \) range. The enhancement has been found to be in agreement with the models invoking coalescence of quarks as a mechanism of hadronization. Baryon enhancement has also been observed at LHC in the single inclusive spectra. We study the consequence of such an enhancement on two particle correlations at LHC energy within the framework of A Multi Phase Transport (AMPT) model that implements quark coalescence as a mode of hadronization. In this paper we have calculated the proton over pion ratio and the near side per trigger yield associated to pion and proton triggers at intermediate \( p_T \) from String Melting (SM) version of AMPT. Results obtained are contrasted with the AMPT Default (Def.) which does not include coalescence. Baryon enhancement has been observed in AMPT SM at intermediate \( p_T \). Near side jet-like correlated yield associated to baryon (proton) trigger in the momentum region where baryon generation is enhanced is found to be suppressed as compared to the corresponding yields for the meson (pion) trigger in most central Pb-Pb events. No such effect has been found in the Default version of AMPT.

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I. INTRODUCTION

Temperature and energy density attained in ultrarelativistic heavy ion collisions at RHIC and LHC are compatible with the lattice quantum chromodynamics (lQCD) thresholds for phase transition from hadronic to a de-confined state of quarks and gluons [1-3]. The Hot and dense matter thus formed, known as quark-gluon plasma (QGP), cools down in the process of evolution, re-confines to hadrons and streams freely to detectors [4]. This gives us a unique opportunity to study the mechanism of particle production under extreme conditions. The \( p_T \) spectra of the final state particles give an insight on their production mechanism and of interactions at various stages of evolution [4-6]. Various theoretical models have been proposed but no unique prescription is available to explain the \( p_T \) spectra over the entire experimentally measured range. Particle production below \( p_T \approx 2 \text{ GeV}/c \), referred to as the bulk region can be reproduced with the hydro-inspired models [8, 10]. For \( p_T > 6 \text{ GeV}/c \), hadronization is primarily through fragmentation of high \( p_T \) partons to a collimated shower of hadrons (jets). This process involves parton scattering with large momentum transfer and can be convincingly described by perturbative QCD calculations [11, 12].

However, none of these approaches could account for particle production at the intermediate \( p_T (2 < p_T < 6 \text{ GeV}/c) \). The observations like the anomalous enhancement of inclusive baryon over meson yield, particle species dependence of the nuclear modification factor \( R_{AA}, R_{CP} \) and baryon-meson ordering of elliptic flow coefficient \( v_2 \) were found to be at odds with either of these formalisms [6, 13]. Plausible explanations to enhanced baryon/meson or nuclear modifications were achieved from the models either incorporating recombination of quarks [14, 15, 17, 18] or boost from a radially expanding medium pushing massive hadrons to higher \( p_T \) (Hydrodynamics) [8, 10]. In principle, both the approaches attempt to generate high \( p_T \) baryons from soft processes as opposed to mesons.

Another explanation could be in terms of energy loss of partons in the medium. The independent fragmentation of energetic partons based on pQCD calculations gives baryon/meson \( \sim 0.1 \) both in light and strange flavor sectors [15]. This is in contradiction to the experimental results. However, jet fragmentations are strongly influenced by the dense medium leading to an alteration of the fragmentation function [19, 20]. It has been argued that the medium modified fragmentation can also be a potential source of enhanced baryon generation [21]. Jet-like peak structure observed in the correlation measurements between baryons and charged hadrons at intermediate \( p_T \) reported by the PHENIX and STAR Collaborations may be an indication that the baryon enhancement is associated to the medium induced jet modification [22, 23].

The high density environment achieved in heavy-ion collisions may be conducive for hadron formation through coalescence of quarks. In simple coalescence approach, quark and anti-quark pairs close in phase space recombine into mesons and three quarks to (anti-)baryons. Thus at the same \( p_T \), baryons and mesons are formed...
from the quarks with momenta $\sim p_T/3$ and $\sim p_T/2$ respectively. Different approaches of quark recombination have been suggested and adopted by various groups. Each of them particularly differ in the way high $p_T$ partons from the initial hard-scatterings and the thermalized soft partons are treated. While some consider coalescence of only soft partons and hard partons to hadronize by fragmentation only \cite{14,15}, others allow coalescence of both soft and hard minijet partons \cite{18}. Since the $p_T$ spectra of these hard partons show a power-law behaviour, an exponential thermal spectrum of soft partons is therefore imperative for large baryon to meson enhancement. All these implementations with proper tuning of parameters describe the basic features at intermediate $p_T$ e.g., $p_T$ spectra, $v_2$-scaling reasonably well at RHIC energy. At LHC, scaling violation of $v_2$ is somewhat larger than that at RHIC and may be naturally explained within soft-hard recombination formalism \cite{24}. Additionally, the near-side peak structure observed in the measurements of azimuthal correlations triggered by identified particles at intermediate $p_T$ at RHIC energy have been reasonably explained with the inclusion of mini-jet partons or partons from hard scatterings in the coalescence formalism. Thus an alternative way to look for the source of baryon anomaly at intermediate $p_T$ is to study the baryon-charged hadron correlations. The angular correlation measurements are likely to be more sensitive to probe the contribution of hard scattering towards hadron production. In this paper we have studied the sensitivity of di-hadron correlation measurements to the coalescence mechanisms when measured by itaking identified mesons ($\pi$) and baryons ($p/\bar{p}$) at intermediate $p_T$ as leading hadrons.

The two-particle azimuthal correlation functions triggered by leading hadrons encode the characteristic of the production mechanism of the trigger and associated particles. The correlation measurements with high $p_T$ trigger particles ($>4-6$ GeV/c) in $p-p$ collisions manifest itself as di-jet peaks in azimuth, an imprint of the QCD fragmentation of back to back hard scattered partons \cite{25}. At intermediate $p_T$, hadronization through recombination would lead to “trigger dilution” in central heavy ion collisions \cite{22,23}. Trigger particles originating from recombination or coalescence of thermal quarks from the dense partonic medium would lack correlated hadrons at small angular region (jet-like correlation). This would effectively dilute (reduce) per trigger associated yield. Furthermore, dilution is expected to be prominent for baryon trigger than meson trigger as the baryon production is more favourable through coalescence of quarks.

In this work, the sensitivity of the near side yields of proton and pion triggered azimuthal correlation functions to the coalescence mechanism have been tested using two versions of the AMPT model \cite{24}. While the partonic version (SM) of the AMPT model produces particles by the coalescence of quarks, the default version has only minijets and strings fragmenting to hadrons. We have built triggered correlation functions from the events generated from either version of the AMPT model for Pb-Pb collision at $\sqrt{s_{NN}} = 2.76$ TeV and extracted near side yield as final observable.

The paper is organised as follows. In the next section we have given a brief introduction to the AMPT model and the implementation of coalescence mechanism. The method of extraction of background subtracted correlation function is discussed in section 3. The results and discussions are performed in sections 4 and 5 respectively.

II. THE AMPT MODEL

The AMPT model has been extensively studied at RHIC and LHC energies. Free parameters of the model have been constrained by a wide range of experimental data. If broadly classified, model has two modes: Default (minijets and strings) and String Melting (replicate QGP allowing strings to melt into partons) \cite{27}. The spatial and momentum distributions of minijet partons and excited soft strings, obtained from the HIJING model \cite{28} are used as initial conditions for subsequent modeling of partonic evolution. In the default version, minijet partons are evolved via a parton cascade model (ZPC) \cite{29} which basically includes 2-body elastic scatterings among the partons with a medium dependent scattering cross-section represented as $\sigma_T \simeq 9\alpha_s^2 / 2\mu^2$ where $\alpha_s$ is the QCD coupling constant for strong interactions and $\mu$ is the Debye screening mass of gluons in QGP medium. Although, it is a function of temperature and density of the partonic medium but in ZPC it is parameterised to fix the magnitude of scattering cross-section. At the end of evolution, these minijet partons are recombined with their parent strings and are eventually hadronized by the Lund string fragmentation \cite{30}. The post hadronization stage is modeled by A Relativistic Transport model (ART) \cite{31,32}, which guides the hadronic interactions till freeze-out.

To emulate the conditions similar to the de-confined QGP, AMPT has been extended to perform melting of excited strings. Taking initial conditions from HIJING, strings are first fragmented to hadrons followed by conversion of these hadrons to valance quarks/antiquarks preserving their flavor and spin quanta. Now the system comprises both minijet and string melted partons, which are further scattered through ZPC. Once the interaction ceases, partons are re-confined to hadrons via an implementation of coalescence formalism that combines two or three partons nearest in coordinate space to mesons and/or (anti-)baryons respectively. Mass and flavor of hadrons are determined from the invariant mass and respective flavors of the coalescing partons. Therefore a quark-antiquark pair will be recombined to pions provided di-quark invariant mass is in the proximity of pion mass. Present approach of coalescence is therefore not exactly similar to those discussed in \cite{14,17,18}. Here it allows coalescence of partons with a relatively large momentum difference. To account for the hadronic inter-
actions prior to freeze-out, final state hadrons are then transported through ART model.

AMPT in SM mode with partonic cross section of 6-10 mb provides a good fit to the flow observables at top RHIC energy. While at LHC, with increased beam energy and high initial temperature, data seem to be better reproduced with the choice of a lower parton scattering cross section. In this study we have set scattering cross section to 1.5 mb by tuning \( \alpha_s = 0.33 \) and \( \mu = 3.22 \, fm^{-1} \) keeping in mind that this particular choice simultaneously reproduces charged particle multiplicity density and flow coefficients at LHC energy. The parameters for Lund string fragmentation are kept same as that of the default HIJING values corresponding to smaller string tension.

### III. ANALYSIS METHOD

In the present analysis, events generated from the AMPT model for Pb-Pb collisions at \( \sqrt{s} = 2.76 \, TeV \) have been analyzed to calculate inclusive \( p/\pi \) ratio and di-hadron correlation functions between two sets of particles classified as *trigger* and *associated*. The \( p_T \) ranges of trigger and associated particles are \( 1.8 < p_T < 3.0 \, GeV/c \) and \( 1.0 < p_T < 1.8 \, GeV/c \) respectively and the pseudo-rapidity range of all particles has been restricted within \(-1 < \eta < 1\). The *trigger* \( p_T \) range has been chosen in such a way that it contains the region where \( p/\pi \) ratio reaches its maximum. A Two dimensional (2D) correlation function has been obtained as a function of the difference in azimuthal angle \( \Delta \phi = \phi_{\text{trigger}} - \phi_{\text{associated}} \) and pseudo-rapidity \( \Delta \eta = \eta_{\text{trigger}} - \eta_{\text{associated}} \). The per trigger yield of the associated particles in \( \Delta \eta \) and \( \Delta \phi \) has been defined as

\[
\frac{dN}{d\Delta \eta d\Delta \phi} = \frac{N_{\text{asso}}}{N_{\text{same}}}
\]

where \( N_{\text{asso}} \) is the number of particles associated to the triggers particles \( (N_{\text{trigger}}) \) on event by event basis.

The correlation function introduced above has been corrected for finite acceptance of trigger and associated particles. The acceptance corrected 2D correlation function has been obtained by dividing the raw correlations by a correction factor represented as \( B(\Delta \eta) = 1 - |\Delta \eta|/2\eta_{\text{max}} \). The correction factor has a triangular shape arising out of the limited acceptance in pseudo-rapidity. Uniform \( 2\pi \) acceptance in azimuth ensures that no correction is required on \( \Delta \phi \). Fig. 1(a) shows a corrected 2D correlation function for unidentified particles containing a near side jet-like peak sitting over a flow modulated background.

To obtain the near side jet like yield, the acceptance corrected correlation structure is projected on to the \( \Delta \phi \) axis for \( |\Delta \eta| < 1.2 \). The particles from jet fragments are most likely to be confined in a small angular region provided the width does not get broadened with centrality. To isolate the contribution for near side jet-like correlations, we need to subtract the modulation in \( \Delta \phi \) arising out of the correlation with the event plane as represented by \( v_2, v_3 \) or higher harmonics. Flow coefficients can be extracted by fitting the \( \Delta \phi \) projection of the bulk region (large \( \Delta \eta \)) with \( 1 + 2\sum_n v_n^{\text{trig}} v_n^{\text{asso}} \cos(n \Delta \phi) \) where \( v_n^{\text{trig}}, v_n^{\text{asso}} \) represent the magnitude of \( n^{th} \) harmonic of flow coefficients for the trigger and associated particles respectively. The Background lying beneath the jet-like peak is modulated by flow correlations dominated by elliptic flow \( (v_2) \). We have checked that contributions from higher order flow harmonics \( (v_3, v_4) \) are insignificant. In the present analysis instead of calculating different orders of flow harmonics and subtracting separately, we have

![Fig. 1](image-url)
subtracted the projected $\Delta \phi$ distributions at larger $\Delta \eta$ region ($1.2 < |\Delta \eta| < 1.7$) from the short-range region. The bulk subtraction by the $\eta$-gap method as stated above assumes that the correlations other than jet-like are $\eta$ independent \cite{35}. 1D $\Delta \phi$ correlation functions for the regions $|\Delta \eta| < 1.2$ and $1.2 < |\Delta \eta| < 1.7$ are shown in Fig. 1(b) and result from the difference of these two distribution has been plotted in Fig. 1(c). The near side peak centered around $\Delta \phi = 0$ mainly represents jet-like correlations and the strength of the correlation (per trigger yield) has been calculated integrating the $\Delta \phi$ distribution over a range of $|\Delta \phi| < \pi/2$.

IV. RESULTS

As a first step to test the features of coalescence in the SM version of AMPT, we have compared the $p_T$ dependence of the $p/\pi$ ratio from both the versions of AMPT in Fig. 2. We find a clear centrality dependence in $p/\pi$ enhancement from the SM version of AMPT. Enhancement is found to reach maximum in 0-5% most central collisions at $\approx 2$ GeV/$c$. In contrast, the default version shows an initial rise followed by a flat distribution of the ratio.

![FIG. 2:](image1)

**FIG. 2:** [Color online] The ratio of the yields of proton to pion from two versions of AMPT in Pb-Pb collisions at $\sqrt{s} = 2.76$ TeV. The ratio in SM version (a) shows a clear peak around 2 GeV/$c$ as opposed to the default version (b) which does not show any such peak.

Having established the best-known feature of the coalescence in AMPT SM model, we obtain two-particle correlations taking leading hadrons as $\pi$ and $p/\bar{p}$ in the region where $p/\pi$ excess has been observed ($1.8 \leq p_T \leq 3.0$ GeV/$c$). We have extracted the two-particle correlation in $\Delta \eta$-$\Delta \phi$ for 5 centrality classes selecting trigger and associated particles in the range $1.8 \leq p_T \leq 3.0$ GeV/$c$ and $1.0 \leq p_T \leq 1.8$ GeV/$c$ respectively. Fig. 3 shows the 2D $\Delta \eta$-$\Delta \phi$ correlations for (anti-)proton and pion as triggers. The per-trigger correlation functions show features typical to the presence of several effects like jet-peaks, harmonic coefficients among others \cite{39}. Near-side jet-like yield associated with pion and (anti-)proton triggered near-side yields exhibit initial rise with centrality till $N_{part} < 200$. Beyond that,
per trigger yield for pion seems to attain saturation but corresponding yields for (anti-)protons undergo suppression. In Fig. 4 the ratio of the yields associated with (anti-)proton and pion triggers ($Y_p/\bar{Y}_\pi$) as a function $N_{part}$ have been presented for two different transverse momentum regions. In high $p_T$ region ($3.0 \leq p_T \leq 8.0$ GeV/$c$), ratios of yields are consistent with unity and independent of centrality. However, in the $p_T$ region $1.8 \leq p_T \leq 3.0$ GeV/$c$, ratio dips showing the anticipated dilution. Similar analysis on events generated by the SM version of AMPT for Au-Au collisions at 200 GeV and comparison with results from correlation measurements by the PHENIX Collaboration is represented in Fig. 6. It is clearly seen that the model explains dilution trend of the data qualitatively.

**V. DISCUSSION**

We have measured per-trigger yield of jet-like correlations associated with pion and proton triggers at mid-rapidity over a wide range of centrality in Pb-Pb and Au-Au collisions at $\sqrt{s}_{NN} = 2760$ GeV and 200 GeV respectively, in the momentum range where baryons are generated in excess of mesons. We have observed a significant enhancement in the jet-like yield associated with leading pions compared to protons. In central A-A collisions, pion trigger yield is much higher than peripheral, while the proton trigger yield exhibits a suppression. The relative enhancement in pion triggered yield could be due to the energy dissipation of minijet partons and its re-distribution via parton cascade resulting copious production of softer hadrons aligned to the jet-direction.

However, suppression in proton triggered yield may be attributed to the combined effect of competing processes that involve parton energy loss and quark recombination. If protons are produced dominantly from the recombination of thermal quarks, suppression in proton triggered yield could be naturally expected since hadrons created by recombination of thermal partons are unlikely to have correlated partners in small angular region. This would cause a suppression of proton trigger correlation as function of centrality as baryon generation at intermediate
The ratio of yields in Fig.5 shows a clear dilution in proton triggered correlation from peripheral to central events when trigger particles are chosen from the $p_T$ region where inclusive $p/\pi$ ratio has shown enhancement, but no such effect has been observed when trigger particles are chosen from higher $p_T$ region indicating that contributions from thermal recombination falls-off rapidly at larger $p_T$.

It is interesting to note that jet-like yield calculated from the default version of AMPT has no or negligible dependence on the choice of trigger species and almost remain unchanged with centrality. A possible reason could be that the initial partonic density in default operation is much less than that in SM version as strings are kept intact. Thus the minijet partons during partonic evolution suffers less interaction resulting in negligible energy dissipation. Lack of any significant energy loss may possibly lead to no additional increase in jet-like yield.

Our study therefore indicates that the difference in jet yield of baryon-hadron and meson-hadron correlation is an effect of competition between jet-medium interplay and dilution of jet-like yield due to quark recombination. Comparison of our result with data would interesting as inelastic processes of energy loss are still missing in AMPT.

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[1] A. Adare et al. (PHENIX Collaboration), Phys. Rev. Lett. 104 (2010) 132301 .
[2] M. Wilde (ALICE Collaboration), Nucl. Phys. A 904 - 905 (2013) 573c .
[3] F. Karsch, Nucl. Phys. A 698 (2002) 199 .
[4] M. Kliemant, et al.: Global Properties of Nucleus-Nucleus Collisions. Lect Notes Phys.(2010) 785, 23-103, and references therein.
[5] J.L. Klay et al. (STAR Collaboration), Nucl. Phys. A (2003) 715 733 .
[6] S.S. Adler et al. (PHENIX Collaboration), Phys. Rev. C 69 (2004) 034909.
[7] B. Ablev et al. (ALICE Collaboration), Phys. Rev. C 88 (2013) 044910.
[8] S. A. Bass and A. Dumitru, Phys. Rev. C 61 (2000) 064909 .
[9] D. Teaney, J. Lauret and E. V. Shuryak, Phys. Rev. Lett. 86 (2001) 4783.
[10] T. Hirano et al. Phys. Rev. C 77 (2008) 044909.
[11] F. Arleo, Eur. Phys. J. C 61 (2009) 603-627.
[12] D. d’Enterria and B. Betz, High-$p_T$ Hadron Suppression and Jet Quenching. Lect. Notes Phys. 785, 285-339 (2010).
[13] A. Adare et al., Phys. Rev. Lett. 98 (2007) 162301.
[14] R. Fries, B. Muller, C. Nonaka, and S. Bass, Phys. Rev. Lett. 90 (2003) 202303.
[15] R. J. Fries, B. Muller, C. Nonaka and S. A. Bass , Phys. Rev. C 68 (2003) 044902 .
[16] R. J. Fries, S. A. Bass and B. Muller Phys. Rev. Lett.94. (2005) 122301.
[17] V. Greco, C. Ko, and P. Levai, Phys. Rev. Lett. 90 (2003) 202302.
[18] R. Hwa and C. B. Yang, Phys. Rev. C 70 (2004) 024904.
[19] C. Adler et al. (PHENIX Collaboration) Phys. Rev. Lett. 90 (2003) 082302.
[20] K. Aamodt et al. (ALICE Collaboration) Phys. Rev. Lett. 108 (2012) 092301.
[21] S. Sapeta and U. A. Wiedemann, Eur. Phys. J. C 55 (2008) 293-302.
[22] S.S. Adler et. al (PHENIX Collaboration) Phys. Rev. C 71 (2005) 051902.
[23] N. M. Abdelwahab et. al (STAR Collaboration) *arXiv:1410.3524* [nucl-ex].
[24] C. B. Chiu, R. C. Hwa, and C. B. Yang, Phys. Rev. C 78 (2008) 044903.
[25] J. Adams et. al (STAR Collaboration) Phys. Rev. Lett. 95 (2005) 152301.
[26] Zi-Wei Lin et. al , Phys. Rev.C 72 (2005) 064901.
[27] Z. W. Lin and C. M. Ko , Phys. Rev. C 65 (2002) 034904. .
[28] X. N. Wang and M. Gyulassy, Phys. Rev. D 44 (1991) 3501.
[29] B. Zhang, Comput. Phys. Commun. 109 (1998) 193 .
[30] T. Sjostrand, Comput. Phys. Commun. 82( 1994) 74 .
[31] B. A. Li and C. M. Ko, Phys. Rev. C 52 (1995) 2037 .
[32] B. A. Li, A. T. Sustich, B. Zhang and C. M. Ko, Int. Jour. Phys. E 10 (2001) 267-352.
[33] S. A. Voloshin, Nucl.Phys. A715 (2003) 379-388.
[34] Subrata Pal and Marcus Bleicher, Phys. Lett. B 709 (2012) 82-86.
[35] E. Abbas et. al (ALICE Collaboration), Phys. Lett. B 726 (2013) 610-622.
[36] J. Xu and C .M. Ko , Phys. Rev. C 83 (2011) 034904.
[37] B. Ablev (ALICE Collaboration) Physics Letters B 741 (2015) 3850.
[38] X. Zhu ( ALICE Collaboration ), *arXiv:1311.2394* [hep-ex].
[39] G.L. Ma et. al, Phys. Lett. B 641 (2006) 362-367.