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A Brief Review on Possibility of Smallest Collisions at the Large Hadron Collider Probing the Signals from Early Universe

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Abstract: The little bangs of heavy-ions made in collider experiments like Large Hadron Collider (LHC) reproduce the conditions happened during the fraction of a second after the Big-Bang. Recent measurements of high multiplicity proton-proton collisions at LHC energies have revealed that these systems exhibit features similar to quark-gluon plasma, traditionally believed to be only achievable in heavy nucleus-nucleus collisions at ultra-relativistic energy. To pinpoint the origin of these phenomena and to bring all collision systems in equal footings, several event shape observables have been used extensively in experiments as well as in the phenomenological front. In this contribution, a brief review on the QGP signatures and QGP-like effects in small systems in shown. Two of the key event shape observables are also highlighted which could shed light in understanding the QGP- like effects in small systems.

1. Introduction

To understand infancy of or Universe and its evolution, the little bangs of heavy-ions are made in collider experiments like Large Hardon Collider (LHC) at CERN, Switzerland, which reproduces the conditions happened during the fraction of a second after the Big-Bang. The collision process two nuclei products a hot and dense system of deconfined quarks and gluons for a short time. This deconfined state of quarks and gluons are often referred as quark gluon plasma (QGP). Due to very short time scale, it is impossible to measure QGP directly, however, several indirect signatures are proposed such as presence of strangeness enhancement, jet quenching and collective flow; which validates the presence of QGP. Recent experimental measurements [1] show a smooth evolution of strange to non-strange particle ratios across different colliding systems (pp, p-Pb, and Pb-Pb) as a function of charged-particle multiplicities, which may point towards a common underlying physics mechanism across collision systems. Collective flow-like effects have also been seen in small collision systems, but so far, no jet quenching signatures have been reported in small collision systems [2]. Such behaviours are quite challenging for currently popular event generators with relevant and contrasting physics models, like PYTHIA 8 [3] and EPOS-LHC [4], to reproduce all the observed behaviours simultaneously for small collision systems. Event shape observable such as transverse spherocity (S_0) and the relative transverse activity classifier (R_T) can be exploited to understand the origins of these phenomena, and separate collisions dominated by hard and soft particles. Here, a brief review on the QGP signature and QGP- like effects in small systems is shown. Two of the key event shape observables are also highlighted which could shed light in understanding the QGP-like effects in small systems.

2. Quark gluon plasma and its signatures

2.1 Strangeness Enhancement

The enhanced production of strange particle with respect to particles with light quarks could signal to the formation of QGP, as the strange quarks are absent in the colliding matter [5]. One needs to compare the abundance of strangeness between QGP and the phase after the QGP (called as hadron gas phase) as the strange particle production rates are different in a hadron gas as compared to QGP medium to quantify the strangeness enhancement. The formation of strange anti-strange quark in QGP from the $g\bar{g} \to s\bar{s}$ channels dominate over $q\bar{q} \to s\bar{s}$ channel due to higher gluon density, where q represents the light quark. However, in proton-proton (pp) collisions, where QGP medium formation was not expected traditionally, annihilation of light quarks to strange quark is the only channel for the production of strangeness. The strangeness enhancement factor (E) for heavy-ion collisions is given as,

$$E = \frac{2}{\langle N_{part} \rangle} \left[\frac{\frac{dN^{AA}}{dy}|y=0}{\frac{dN^{pp}}{dy}|y=0} \right]. \tag{1}$$

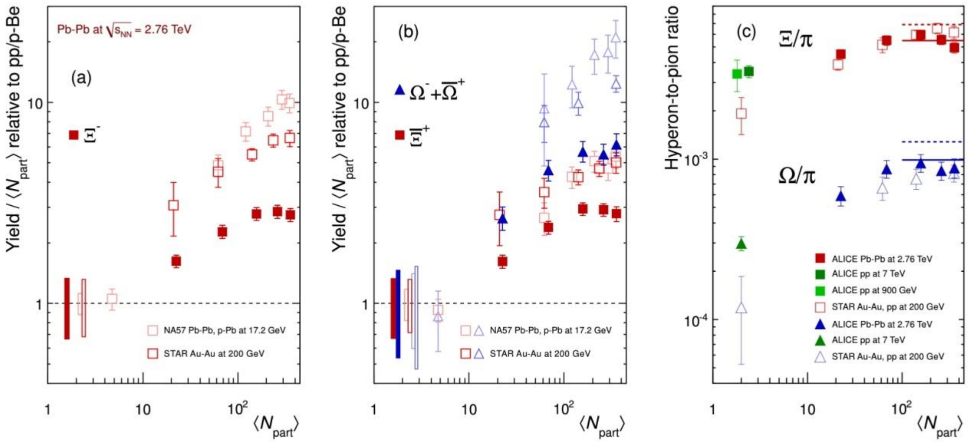

Fig. 1: Yield of multi-strange hadrons in Pb-Pb collisions relative to small collision systems measured in ALICE, NA5 and STAR experiments as function of average number of participants [6-8]

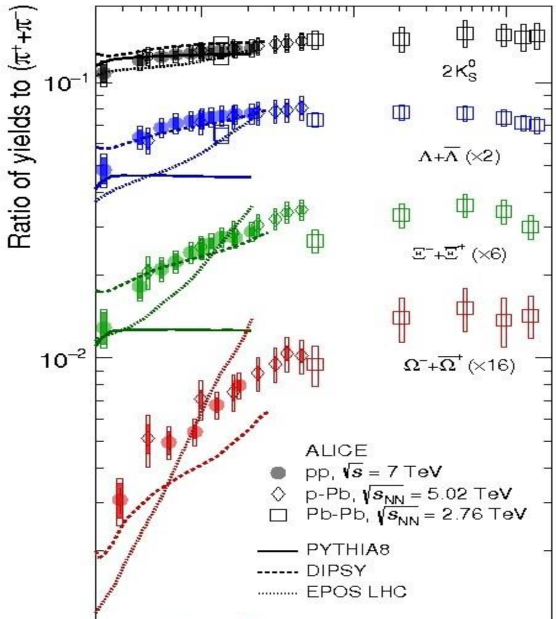

Fig. 2: Strangeness enhancement as function of charged particle multiplicities of different collision systems at the LHC [9].

Here (N_{part}) is the number of participants of heavy-ion collisions, $\frac{dN^{pp}}{dy}|y=0$ and $\frac{dN^{AA}}{dy}|y=0$ are the integrated yields in pp and heavy-ions collisions, respectively. Figure 1 shows the yield of strange and multi-strange enhancement factor (E) as a function of number of participants [6–8]. The enhanced production of strange particle in Pb-Pb collisions with respect to small collision systems indicate the formation of deconfined state of quarks and gluon i.e. QGP in the LHC energies. It is also observed that the enhancement factor is increases with increase in the number of strange quarks i.e. $E(\Lambda) < E(\Xi) < E(\Omega)$ [6-8]. Surprisingly, the measurements reported recently by ALICE experiment at the LHC in 2017 [1] provide one of the key signals to validate that QGP-like conditions are also created in pp collisions. This is shown in Fig. 2. ALICE has observed strangeness enhancement pp collisions, which was historically considered to be one of the baselines of QGP formation [1]. The ratio of strange particles to pions in high-multiplicity pp collisions show a similar value as found in heavy-ion collisions and this enhancement is higher for particles with higher strangeness content. So far, there is no concrete understanding available in literature whether this behaviour arises from fluid-like behaviour or purely microscopic in nature.

2.2 Anisotropic flow

Anisotropic flow is an observable that helps in understanding the collective behaviour of the system and also its probes the initial state of the system. The expansion of matter created in semi-peripheral ultra-relativistic heavy-ion collisions results in anisotropy of the initial density profile in space which results in final state momentum anisotropy due to the pressure gradients during expansion. This phenomenon leads to anisotropic flow. This is quantified via the azimuthal anisotropy in momentum. It is defined as the fourier expansion in the azimuthal angle ϕ as [11,12],

$$\frac{dN}{p_T dp_T d\phi dy} = \frac{dN}{2\pi p_T dp_T d\phi dy}\left[1 + 2\sum_{1}^{\infty} V_n \cos[n(\phi - \psi R)]\right]. \tag{2}$$

Here v_n's are n^{th} order of flow harmonics, v_2 represents the elliptic flow and ... is the event plane angle. The elliptic flow of charged particles comparison presented in Fig. 3 indicates that, medial produced at RHIC and LHC experiments are of similar nature. The higher value v_2 at LHC is due to availability of larger re-scattering among partons at the LHC experiments compared to RHIC experiments. A finite anisotropic flow has also been observed for pp and p-Pb collisions in ALICE Experiment at the LHC [13].

2.3 Jet quenching

The suppression in the production of high transverse momentum (p_T) mesons in heavy-ions collisions is one of the key observables which provides a hint of QGP medium formation. In heavy-ion collisions, high p_T partons fly off to all possible directions from the collision point after production and finally fragment into narrow cones of hadrons, called as jets. When these jets traverse through the thermalized QGP medium, they go through the interactions with particles in the medium. They loose energies and eventually their transverse momenta before hadronisation.

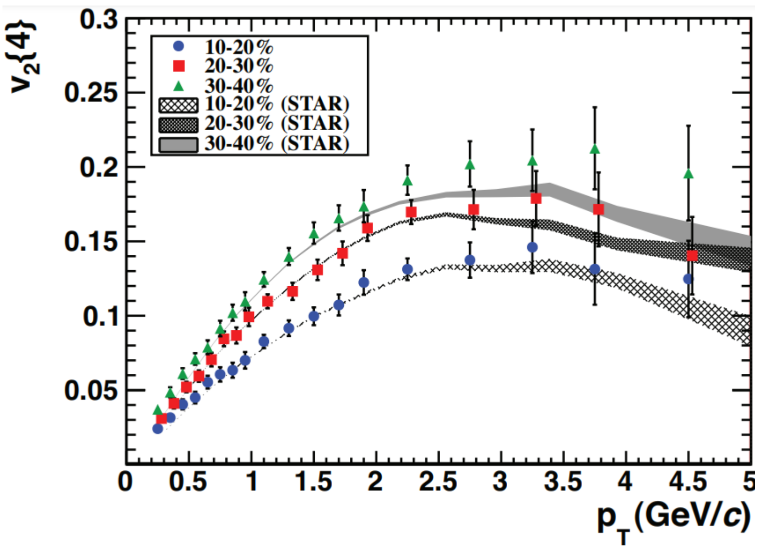

Fig. 3: Elliptic flow of charged particles in Pb-Pb collisions at $\sqrt{S_{NN}} = 2.76$ TeV measured by ALICE experiment compared to Au+Au collisions measured by STAR experiment at $\sqrt{S_{NN}} = 200$ GeV [10].

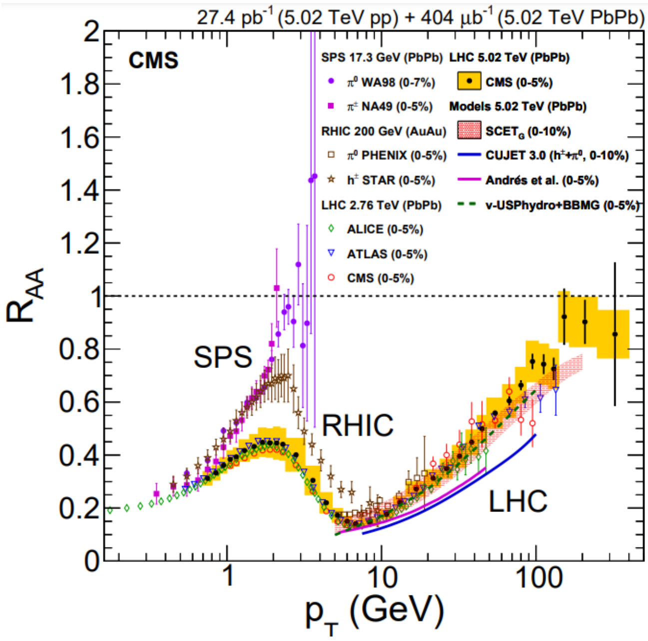

Fig. 4: R_{AA} for charged hadrons and neutral pions in central heavy-ion collisions at SPS, RHIC and the LHC experiments [10].

Thus, a significant suppression is observed in heavy-ion collisions compared to corresponding data from minimum-bias pp collisions scaled with the number of binary collisions [14, 15] This effects is called as the jet quenching. The suppression of particles in heavy-ion collisions are usually expressed in terms of the nuclear modification factor (R_{AA}),

$$R_{AA}(p_T) = \frac{1}{\langle T_{AA} \rangle} \times \left[\frac{\left(\frac{d^2N}{dp_T dy} \right)_{AA}}{\left(\frac{d^2N}{dp_T dy} \right)_{pp}} \right]. \tag{3}$$

where R_{AA} is the ratio between the yield of particles in heavy-ion collisions to that of minimum-bias pp collisions scaled with the average nuclear overlap function, $\langle T_{AA} \rangle = \langle N_{coll} \rangle / \sigma_{inel}$. Here, $\langle N_{coll} \rangle$ and σ_{inel} are number of binary collisions and inelastic pp cross section, respectively. The condition R_{AA}=1 suggests that the heavy-ion collisions would be simply a linear superposition of pp collisions and thus the absence QGP medium formation. However, value below the unity value is an indication of quenching in the QGP medium. Fig. 4

shows the results of R_{AA} for charged hadrons and neutral pions in Au-Au and Pb-Pb collisions. The high transverse momentum suppression of hadron in QGP medium could be seen in experiments from both RHIC and LHC energies.

As highlighted in the previous sub-sections, the observed strangeness enhancement and anisotropic flow in high-multiplicity pp collisions are similar to that of heavy-ion collisions. However, so far there is no observation of jet quenching in small collision systems. Thus, it is important to understand the origin of the QGP-like effects, whether it is driven by hydrodynamics or microscopic in nature. In this direction, event shape engineering could shed some light via disentangling the events based on its geometrical shapes.

3. Event shape engineering to understand QGP-like effects in small collision systems

Event shape observables have the capability to separate events with back-to-back jet structures from events dominated by soft scatterings.

3.1 Transverse spherocity (S_0)

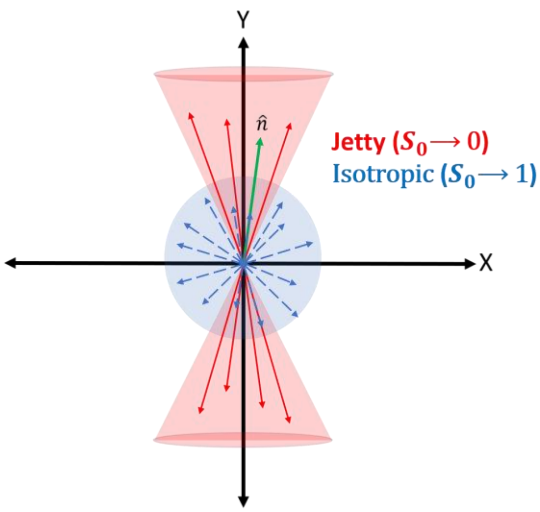

Fig. 5: Depiction of isotropic and jetty events based on the transverse spherocity selection [19]

Transverse spherocity is defined for a unit vector $\hat{n}(n_T, 0)$ which follows a minimization criteria as the following ratio [16-19]

$$S_0 = \frac{\pi^2}{4}\left(\frac{\sum_i \vec{p}_{T_i} \times \hat{n}}{\sum_i p_{T\,i}}\right)^2 . \tag{4}$$

S_0 is usually calculated using charged-particle tracks that have $p_T > 0.15\,\mathrm{GeV}/c$ with more than 5 charged particle tracks in an event to ensure a statistically meaningful concept of a topology. The charged-particles are usually selected within the pseudorapidity interval $|\eta| < 0.8$. By construction, the S_0 estimator varies in the range of 0 to 1. The two extreme limits of spherocity correspond to the two different limits on topology. Events $S_0 \to 0$ consists of single back to back jets, while events with $S_0 \to 1$ are isotropic particle production dominated events. The different limits are depicted in Fig. 5. The events located in the bottom 10% of the spherocity distribution are referred as jetty events while the top 10% of the spherocity distribution are referred as isotropic events.

3.2 Relative transverse activity classifier (R_T)

The final-state particle production can be studied as a function varying underlying events using the relative transverse activity classifier (R_T). To ensure that a hard scattering took place in an collision, analysed collisions are required to have a leading trigger particle above a certain p_T. An collision can be classified into three different azimuthal regions, relative to the trigger particle. Assuming ϕ_{trig}. as the azimuthal angle for the leading trigger particle with highest transverse momentum and ϕ_{assoc}. as the azimuthal angle of the associated particles, the regions are classified as the following.

- Toward region : $|\phi_{trig.} - \phi_{assoc}| < \frac{\pi}{3}$
- Away region : $|\phi_{trig.} - \phi_{assoc}| > \frac{2\pi}{3}$
- Transverse region : $\frac{\pi}{3} \leq |\phi_{trig.} - \phi_{assoc}| \leq \frac{2\pi}{3}$

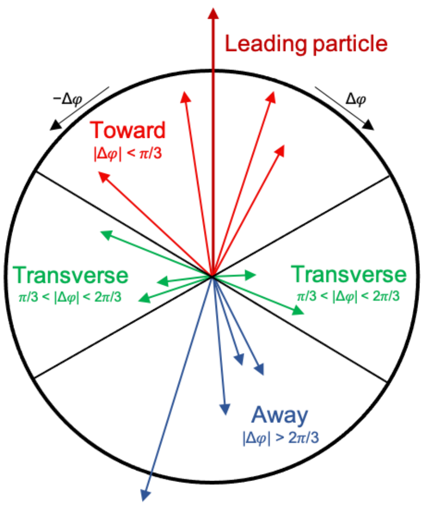

Fig. 6: Depiction of transverse, away and towards regions with respect to the leading particle in a collision [23]

Particle production in the toward region is dominated by jet fragmentation while the away region consists of some of the back-scattered jets. The transverse region is mostly dominated by particles dominated by the underlying event. The leading- p_T selection of usually > 5 GeV/c ensures that the charged particle density in the transverse region remains almost independent of leading particle transverse momentum [20]. R_T is given as [21, 22],

$$R_T = \frac{N_{ch}^T}{\langle N_{ch}^T \rangle}. \tag{5}$$

where N_{ch}^T is the charged particle multiplicity in the transverse region and the events with $R_T \rightarrow 0$ are the events with no underlying event, thus, they are expected to be dominated by jet fragmentation.

4. Summary

Recent measurements of high multiplicity proton-proton collisions at LHC energies have revealed that these systems exhibit features similar to quark-gluon plasma, traditionally believed to be only achievable in heavy nucleus-nucleus collision at ultra-relativistic energy. To pinpoint the origin of these phenomena and to bring all collision systems in equal footings, several event shape observables have been used extensively in experiments as well as in the phenomenological front. Here, a brief review on the QGP signature and QGP-like effects in small systems is shown. Two of the key shape observables are also highlighted which could shed light in understanding the QGP-like effects in small systems.

References

[1] J. Adam et al. [ALICE Collaboration], *Nature Phys.* **13**, 535 (2017).

[2] J. L. Nagle and W. A. Zajc, *Ann. Rev. Nucl. Part. Sci.* **68**, 211 (2018).

[3] T. Sjostrand et. al., *Comput. Phys. Commu.* **191**, 159 (2015).

[4] T. Pierog, et. al., *Phys. Rev. C* **92**, 034906 (2015).

[5] P. Koch, B. Muller. J. Rafelski, *Phys. Rep.* **142**, 167-262 (1986).

[6] B. Abelev et al. (ALICE Collaboration), *Phys. Lett. B* **728**, 216 (2013).

[7] (STAR Collaboration) G. Agakishiev et al., *Phys. Rev. Lett.* **108**, 072301 (2012).

[8] (NA57 Collaboration) K. F. Hetland et al. *J. Phys. G* **28** (2002).

[9] J. Adam et al., (ALICE Collaboration), *Nature Phys.* **13**, 535 (2017).

[10] R. Pasechnik and M. Sumbera, *Universe* **3**, 7 (2017).

[11] S. Voloshin, Y. Zhang, Z. *Phys. Rev. C* **70**, 665 (1996).

[12] A. M. Poskanzer, S. A. Voloshin, *Phys. Rev. C* **58**, 1671-1678 (1998).

[13] S. Acharya et al. (ALICE), *Phys. Rev. Lett.* **123**, 142301 (2019).

[14] S. S. Adler et al. (PHENIX Collaboration), *Phys. Rev. Lett.* **91**, 072301 (2003).

[15] B. B. Back et al. (PHOBOS Collaboration), *Phys. Rev. Lett.* **91**, 072302 (2003).

[16] E. Cuautle, R. Jimenez, I. Maldonado, A. Ortiz, G. Paic and E. Perez, *arXiv: 1404.2372 [hep-ph]*.

[17] A. Ortiz, G. Paic and E. Cuautle, *Nucl. Phys. A* **941**, 78 (2015)

[18] A. Ortiz, *arXiv: 1705.02056 [hep-ex]*.

[19] A. Khuntia, S. Tripathy, A Bisht and R. Sahoo, *J. Phys. G* **48**, 035102 (2021).

[20] S. Acharya et al. (ALICE Collaboration), *JHEP* **04**, 192 (2020).

[21] T. Martin, P. Skands and S. Farrington, *Eur. Phys. J. C* **76**, 299 (2016).

[22] A. Ortiz and L.Valencia Palomo, *Phys. Rev. D.* **96**, 114019 (2017).

[23] (ALICE), *Phys. Lett. B* **843**, 137649 (2023)