# Elliptic flow of $\phi$ mesons at intermediate $p_T$: Influence of mass versus quark number

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We have studied elliptic flow ($v_2$) of $\phi$ mesons in the framework of a multiphase transport (AMPT) model at CERN Large Hadron Collider (LHC) energy. In the realms of AMPT model we observe that $\phi$ mesons at intermediate transverse momentum ($p_T$) deviate from the previously observed [at the BNL Relativistic Heavy Ion Collider (RHIC)] particle type grouping of $v_2$ according to the number of quark content, i.e, baryons and mesons. Recent results from the ALICE Collaboration have shown that $\phi$ meson and proton $v_2$ has a similar trend, possibly indicating that particle type grouping might be due to the mass of the particles and not the quark content. A stronger radial boost at LHC compared to RHIC seems to offer a consistent explanation to such observation. However, recalling that $\phi$ mesons decouple from the hadronic medium before additional radial flow is built up in the hadronic phase, a similar pattern in $\phi$ meson and proton $v_2$ may not be due to radial flow alone. Our study reveals that models incorporating $\phi$-meson production from $K\bar{K}$ fusion in the hadronic rescattering phase also predict a comparable magnitude of $\phi$ meson and proton $v_2$ particularly in the intermediate region of $p_T$. Whereas, $v_2$ of $\phi$ mesons created in the partonic phase is in agreement with quark-coalescence motivated baryon-meson grouping of hadron $v_2$. This observation seems to provide a plausible alternative interpretation for the apparent mass-like behavior of $\phi$-meson $v_2$. We have also observed a violation of hydrodynamical mass ordering between proton and $\phi$ meson $v_2$ further supporting that $\phi$ mesons are negligibly affected by the collective radial flow in the hadronic phase due to the small in-medium hadronic interaction cross sections.

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## I. INTRODUCTION

The primary objective of heavy ion collisions at ultrarelativistic energy is to create and characterize a novel form of QCD matter consisting of strongly interacting and deconfined state of quarks and gluons, the quark gluon plasma (QGP) [1,2]. Dedicated experiments were designed at the BNL Relativistic Heavy Ion Collider (RHIC) and CERN Large Hadron Collider (LHC) to search for evidences that ensure formation of such a new state of matter and study its properties. One of the key observables, particularly sensitive to the early stage dynamics of the collision and hence to the formation of QGP is the elliptic flow coefficient $v_2 = \langle \cos[2(\varphi - \Psi_{\rm RP})]\rangle$ [3–5]. It quantifies event and particle averaged anisotropy in the azimuthal ($\phi$) distribution of the particles relative to reaction plane angle ($\Psi_{RP}$) [6].

It is generally perceived that in noncentral collisions, the anisotropic emission of final state particles results from the difference in the pressure gradient in a spatially anisotropic but locally thermalized system of quarks and gluons. Below $p_T < 2\,\mathrm{GeV}/c$ where the majority of particles are produced, this azimuthal anisotropy has been described as a hydrodynamical evolution of strongly interacting QGP with a nominal shear viscosity to the entropy density ratio [7–9] ($\eta/s$ extracted is close to Anti-de Sitter/Conformal Field Theory lower bound of $1/4\pi$).

Results from RHIC and LHC have revealed that $v_2$ measured for different particles as a function of $p_T$ exhibits a characteristic mass ordering up to $p_T \sim 3\,\mathrm{GeV}/c$. That is, massive particles has less $v_2$ and vice versa at fixed $p_T$. Whereas at intermediate $p_T$, $3 \leqslant p_T \leqslant 6\,\mathrm{GeV}/c$, $v_2(p_T)$ exhibits a flavor ordering, i.e., baryon and meson $v_2$ bifurcates [10,11,13]. The observed baryon-meson splitting of identified particles $v_2$ was found to be compatible with the models invoking hadronization of a collectively expanding partonic medium via a mechanism of quark recombination or coalescence [14–17]. This was further supported by the observation of constituent quark number scaling (NCQ) of hadron $v_2$, providing a strong indication towards the onset of the partonic collectivity and the dominance of quark degrees of freedom at the time of hadronization [18].

At RHIC energies, baryon-meson difference in $v_2$ and NCQ scaling was taken as a confirmation of quark coalescence being a plausible mechanism of hadronization at intermediate values of $p_T$. But at LHC, scaling violation at a level of $\pm$10–20 % and comparable magnitude of $v_2$ of $\phi$ mesons and protons in central collisions tend to disfavor coalescence as a relevant particle production mechanism at this range [11]. In hybrid model calculations where partonic and hadronic evolution is modelled by hydrodynamics and hadronic cascade, respectively [19,20], baryon and meson grouping of $v_2$, i.e., $v_2^{\rm baryons} > v_2^{\rm mesons}$ at intermediate $p_T$ may be understood as a manifestation of increase in the mean transverse momentum $\langle p_T\rangle$ and hence the $p_T$-integrated $v_2$ values of particles as a function of hadron mass. Some of these hybrid models also predict up to 30% increase in the $p_T$-averaged $v_2$ due to expected rise in the radial boost at LHC when compared to Au-Au collisions at top RHIC energy [4,19–22,24,25]. This increase in total transverse boost could be due to the build-up of additional radial flow in the hadronic phase that boosts massive hadrons to higher $p_T$. As the effect is more pronounced for high mass particles, observed

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similarity in $\phi$ meson and proton $v_2$ appears to be consistent with the increased radial flow in central $A$-$A$ collisions at LHC relative to RHIC. Further studies on the spectral shapes of proton and $\phi$ meson have revealed that in central collisions the $(p + \bar{p})/\phi$ ratio is independent of $p_T$ up to 3–4 GeV/$c$. The flat $p_T$ dependence of the $p/\phi$ ratio is seen to be in agreement with hydrodynamical calculations, suggesting the significance of mass over quark number in determining the shape of $p_T$ distributions up to intermediate values of $p_T$ [12]. Thus, the baryon-meson grouping seems to be congruous with the mass of the particles rather than the number of quark content [11].

Generally, those particles which suffer less interactions in the hadronic phase are often termed as better probes of partonic phase of heavy ion collisions and may also be sensitive to the particle production mechanism. The hadronic interaction cross section of $\phi$ mesons with nonstrange hadrons because of the OZI-suppression rule is rather small [26,27]. Consequently, $\phi$ mesons are not expected to undergo substantial rescattering in the late hadronic phase and decouple from the medium earlier than their nonstrange counterparts [28,29]. The fact that the $\phi$ mesons are weakly coupled to the medium, radial boost developed during hadronic evolution has a less-significant effect on $\phi$ mesons compared to other hadrons of similar masses. Thus, the elliptic flow of $\phi$ mesons are expected to be more sensitive to the partonic stages of collision and shown to have negligibly affected by hadronic interactions [30–32].

In contrast, recent measurements by the ALICE Collaboration have shown a progressive shift in $\phi$-meson $v_2$ from meson to baryon band with increasing centrality and interpreted it as a consequence of pick-up of some additional radial flow in the posthadronization phase [11]. However, considering that $\phi$ mesons decouple prior to the build-up of radial flow in the hadronic phase, it seems unlikely to be an effect of radial flow only. It was shown in [33] that the models incorporating $\phi$-meson production in the hadronic rescattering stage via $K\bar{K}$ fusion predict a higher value of $\phi$-meson $v_2$ relative to other mesons. It would be therefore interesting to test the effect of hadronic interactions on the elliptic flow of $\phi$ mesons which in turn may be useful in resolving the ambiguity over the origin baryon-meson grouping of $v_2$ at LHC.

Here, using the string melting (SM) version of a multiphase transport model (AMPT) [34] we have calculated $v_2$ of some selected species of hadrons including $\phi$ mesons for Pb-Pb collisions at 2.76 TeV. To demonstrate the effect hadronic rescatterings on $v_2$, model simulation has been performed by varying the time of hadronic cascade. While discussing our results, emphasis has been given to $v_2$ of $\phi$ mesons as they are equally as massive as protons and $\Lambda$s but of different quark content. We have also investigated whether the $v_2$ of $\phi$ mesons developed at the partonic phase is modified by additional contributions from the hadronic interactions like, $K\bar{K} \rightarrow \phi$-meson production.

The presentation of this paper is as follows. In Sec. II, we briefly discuss about the AMPT model and processes of $\phi$-meson production at the partonic and hadronic stage. Results from the model calculation illustrating $v_2(p_T)$ of $\phi$ mesons and other hadrons for different hadronic evolution time are shown in Sec. III and finally we summarize our work in Sec. IV.

## II. THE AMPT MODEL

### A. Brief description of the model

AMPT is a hybrid transport model that describes different stages of a heavy ion collision at relativistic energies. This model has four major steps: the initial conditions, the partonic evolution, the hadronization, and finally the hadronic interactions. As initial conditions, AMPT uses spatial and momentum distributions of minijet partons and excited soft strings as implemented in the HIJING event generator [35]. Then Zhang's parton cascade (ZPC) [36] is used to model the partonic evolution characterized by two-body parton-parton elastic scattering with parton interaction cross section obtained from pQCD calculations as $\sigma_p \simeq 9\pi\alpha_s^2/2\mu^2$, where $\alpha_s$ is the QCD coupling constant for strong interactions and $\mu$ is the Debye screening mass of gluons in the QGP medium. At the end of the partonic evolution, a spatial quark coalescence method is implemented to achieve quark-hadron phase transition in the SM version of AMPT. In this method, spatially closed quark-antiquark pairs or triplets are recombined to form mesons and baryons, respectively. Finally, the hadronic interactions are modelled by a relativistic transport (ART) calculations [37].

In this study, the SM version of AMPT has been used to simulate Pb-Pb collisions with parton scattering cross sections of 1.5 mb and 3 mb by keeping the strong coupling constant, $\alpha_s$, fixed at 0.33 and tuning the Debye screening mass ($\mu$) to 3.22 fm$^{-1}$ and 2.265 fm$^{-1}$, respectively. The parameters for the Lund string fragmentation function, i.e.,

$$f(z) \propto (1-z)^a \exp\left(-bm_T^2/z\right), \tag{1}$$

where $z$ denotes the light cone momentum fraction, are kept the same as that of the default HIJING values corresponding to smaller string tension, i.e., $a = 0.5$ and $b = 0.9\,\text{GeV}^{-2}$.

### B. Production and interactions of $\phi$ mesons

In the SM version of AMPT $\phi$-mesons are dominantly produced in the partonic stage by coalescence of a strange ($s$) and an antistrange ($\bar{s}$) quark. During the hadronic evolutions, $\phi$ mesons are also generated from baryon-baryon interaction channels BB $\rightarrow \phi NN$ and baryon-meson interaction channels $(\pi,\rho)$B $\leftrightarrow$ $\phi$B, where B $= N, \Delta, N^*$ [34]. Hadronically, $\phi$ mesons are also produced by kaon-antikaon fusion, $K\bar{K} \rightarrow \phi$, and the production cross section is obtained from the standard Breit-Wigner form [38].

In hadronic rescatterings, $\phi$ mesons also scatter elastically with nucleons and other mesons $(\pi, K, \rho)$. In this model, elastic scattering cross section for $\phi$ mesons with nucleons and other mesons are set to 8 mb and 5 mb, respectively [34].

## III. RESULTS

Model calculations based on the SM version of AMPT have shown that at top RHIC energy the elliptic flow of $\phi$ mesons are negligibly affected by the hadronic interactions. While proton $v_2$ was found to decrease with the increase in hadronic rescattering time, $v_2$ of $\phi$ mesons remain almost unaltered [19,23,30,32,39]. Thus at $p_T < 1$–$1.5$ GeV/$c$,

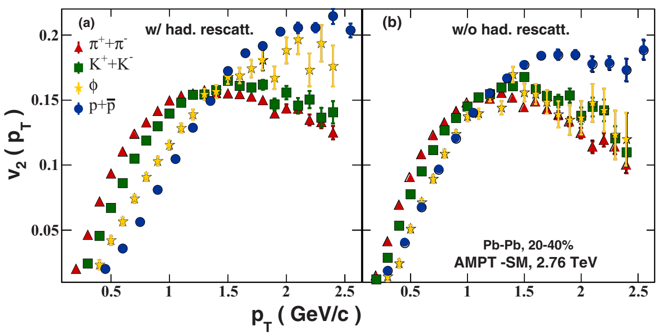


FIG. 1. Elliptic flow parameter $v_2$ for pions ($\pi^+ + \pi^-$), kaons ($K^+ + K^-$), phi mesons ($\phi$), and protons ($p + \bar{p}$) as a function of transverse momentum calculated from the SM version of AMPT (a) with hadronic rescattering (b) without hadronic rescattering in 20–40 % Pb-Pb collisions at $\sqrt{s_{NN}} = 2.76$ TeV.

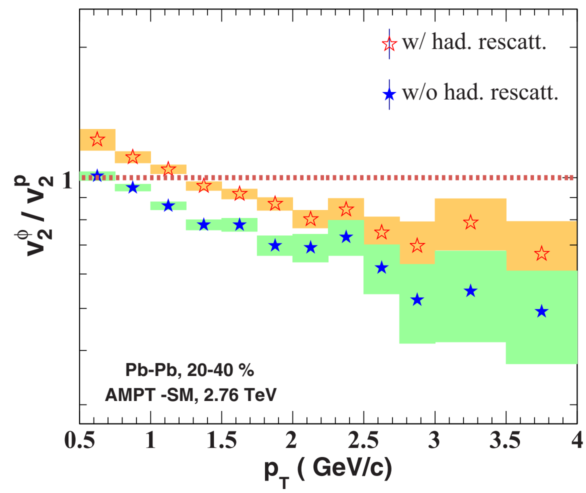


FIG. 2. Ratio of $v_2^\phi(p_T)/v_2^p(p_T)$ as a function of transverse momentum calculated from the SM version of AMPT with hadronic rescattering (open star) and without hadronic rescattering (solid star) in 20–40 % Pb-Pb collisions at $\sqrt{s_{NN}} = 2.76$ TeV. Filled boxes represent statistical uncertainties.

$v_2^{\text{proton}} < v_2^\phi$ although $m_\phi > m_{\text{proton}}$, implying a violation in the hydrodynamically expected mass ordering. The predicted breaking of the hydro-inspired mass-ordering was corroborated by the recent high-statistics measurements of identified particle $v_2$ at RHIC [13].

But a striking difference was noticed at LHC where $v_2$ of $\phi$ mesons at intermediate $p_T$ differs from the well-known baryon-meson hierarchy as mentioned in the earlier section. The different trend of $\phi$-meson $v_2$ was argued to be an effect stronger radial flow in Pb-Pb collisions at $\sqrt{s_{NN}} = 2.76$ TeV. Since the earlier measurements at top RHIC energy have shown that $v_2$ of $\phi$ mesons remain almost unaffected because of a lower interaction rate in the hadronic medium, we, therefore reinvestigate the effect of hadronic rescatterings on the elliptic flow of $\phi$ mesons at LHC energy by varying the hadronic evolution (cascade) time from 0.6 to 30 fm/$c$. Higher time for hadronic cascade corresponds to larger hadronic rescattering. In the figures, the hadronic cascade time of 30 and 0.6 fm/$c$ are referred to as "w/ had. rescatt." and "w/o had. rescatt.", respectively.

In Fig. 1(a) and 1(b) we have shown the transverse momentum dependence of elliptic flow coefficient [$v_2(p_T)$] for pions, kaons, $\phi$ mesons, and protons in 20–40 % Pb-Pb collisions at $\sqrt{s_{NN}} = 2.76$ TeV from the SM version of AMPT. The elliptic flow coefficient or $v_2$ is obtained by calculating the second-order Fourier coefficient of azimuthal ($\varphi$) distributions of final state particles with respect to reaction plane angle ($\Psi_{RP}$), i.e., $v_2 = \langle\cos 2(\varphi - \Psi_{\text{RP}})\rangle$. The angular bracket, $\langle\cdots\rangle$, stands for average over many particles over many events. For all particles including $\phi$ mesons (decay turned-off), particle identification is done based on their respective PID or particle identification number in AMPT. At this point it is worth mentioning that in experiments identification of $\phi$ mesons and its $v_2$ determination differs from the approach presented here. First $\phi$ mesons are identified from the invariant mass distribution of their decay daughters ($\phi \to K^+ + K^-$) by choosing pairs within the $3\sigma$ of $\phi$ mass, followed by $v_2$ determination using the invariant mass method [40], etc. By recalculating our observable, i.e., $v_2(p_T)$, using a different technique (scalar product method), we have checked further whether the choice of a particular method biases the final conclusion. We found that results obtained from both these methods are consistent within statistical error. Having established that results are independent of the method followed, we now proceed to discuss their physics implications.

Figure 1(a) represents flow coefficient calculated with hadronic rescatterings and Fig. 1(b) shows the same without hadronic rescatterings. These results show that without hadronic rescatterings [Fig. 1(b)] the elliptic flow coefficients [$v_2(p_T)$] exhibit a characteristic mass ordering, i.e., $v_2^\pi(p_T) > v_2^K(p_T) > v_2^p(p_T) > v_2^\phi(p_T)$ for $m_\pi < m_K < m_p < m_\phi$ at low $p_T$ but the mass splitting is small. On the other hand, as shown in Fig. 1(a) the mass splitting increases as hadronic rescatterings are switched on and a violation of mass ordering between protons and $\phi$-mesons [$v_2^p(p_T) < v_2^\phi(p_T)$ albeit, $m_p < m_\phi$] below $p_T$ 1.5 GeV/$c$ is also observed. This violation has been interpreted as an effect of different hadronic interaction cross sections for protons and $\phi$ mesons. As the interaction cross section of $\phi$ mesons are much smaller than protons, they decouple from the medium earlier and hence $\phi$-mesons are negligibly affected by the collective expansion in the hadronic phase. In contrary, because of significant hadronic interactions, $v_2$ for protons becomes smaller than that of the $\phi$ mesons which eventually leads to the breaking of hydrodynamical mass ordering. A more clear picture of this behavior can be obtained by studying the ratio of $v_2^\phi(p_T)$ to $v_2^p(p_T)$ as a function transverse momentum.

It is evident from Fig. 2 that as the hadronic interaction time is increased from 0.6 fm/$c$ to 30 fm/$c$ (allowing more hadronic rescatterings) the ratio of $v_2^\phi(p_T)/v_2^p(p_T)$ exceeds unity below 1.5 GeV/$c$ implying breakdown of mass ordering.

Having observed that AMPT-SM with hadronic rescattering has a qualitative agreement with other model calculations [19,39] that reasonably describes the identified particles $v_2$ at low $p_T$, we now focus on the description of elliptic flow coefficients at the intermediate $p_T$ region. At RHIC, it was observed that particle production by quark recombination manifests itself in an unique particle type grouping of $v_2$ according to the number of quark content in the intermediate $p_T$ region, i.e., baryon and meson $v_2$ are grouped into two separate branches.

However, at LHC, the latest ALICE results show $v_2$ of $\phi$ mesons exhibit a different trend from the particle type grouping. Instead of following the baryon-meson hierarchy, $v_2$ values of $\phi$s seem to shifted towards the baryon band [11]. Our model calculation also reveals that $\phi$-meson $v_2$ follow a similar trend as reported by the ALICE Collaboration. As shown in Fig. 1, $v_2$ of $\phi$ mesons appear to follow the proton (baryon) in presence hadronic rescatterings but falls back on the meson band when hadronic interactions are turned off. A similar observation was also reported in this ALICE publication [11], where it was interpreted as a consequence of strong radial flow that boosts massive hadrons to higher $p_T$. As $\phi$ mesons and protons have similar masses, they are expected to be boosted equally.

Such observations tend to indicate that baryon-meson grouping could be due to the mass of the particles rather than the number of constituent quarks. However, recalling that $\phi$ mesons are weakly coupled to the hadronic medium because of small interaction cross sections and decouples prior to the build-up of additional radial flow in the hadronic phase, it seems unlikely to be an effect of radial flow alone. It was shown in [33] that the models with $\phi$-meson production in the hadronic rescattering stage via $K\bar{K}$ fusion predict a higher value of $\phi$-meson $v_2$ relative to other mesons. It would be therefore interesting to test the effect of such processes on the elliptic flow of $\phi$ mesons.

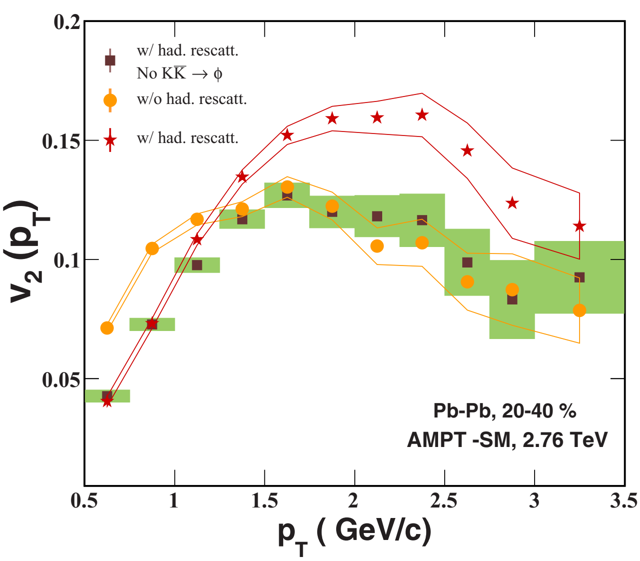


FIG. 3. Transverse momentum dependence $v_2$ of $\phi$ mesons calculated from the SM version of AMPT with hadronic rescattering (solid star), without hadronic rescattering (solid circle), and with hadronic rescattering but $K\bar{K} \rightarrow \phi$ forbidden (solid square) in 20–40 % Pb-Pb collisions at $\sqrt{s_{NN}} = 2.76$ TeV. Filled boxes and the bands represent statistical uncertainties

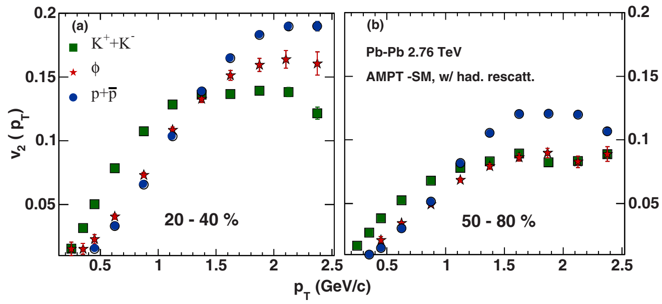


FIG. 4. Elliptic flow parameter $v_2$ for kaons $(K^+ + K^-)$, phi mesons $(\phi)$, and protons $(p + \bar{p})$ as a function of transverse momentum calculated from AMPT SM with hadronic rescattering in (a) 20–40 % and (b) 50–80 % centrality classes of Pb-Pb collisions at $\sqrt{s_{NN}} = 2.76$ TeV.

In this work we have also analyzed $\phi$-meson $v_2$ by turning-off $K\bar{K}$ coalescence in the hadronic phase. In Fig. 3 solid star represents $v_2$ of inclusive $\phi$ mesons (all $\phi$ mesons produced in partonic and hadronic phase) and solid square represents $v_2$ of $\phi$ mesons excluding those from the $K\bar{K}$ fusion process (here we call it *primordial* $\phi$s). It is interesting to observe that at the end of hadronic rescattering for 30 fm/$c$, $v_2$ of *primordial* $\phi$ mesons show no change rather it values at intermediate $p_T >$ 1.5 GeV/$c$ coincides with the results obtained from the model calculation with hadronic rescatterings turned off. Therefore it indicates that $\phi$ mesons regenerated hadronically by $K\bar{K}$ fusion in the late hadronic stage may be responsible for the observed increase in $v_2$ at moderate $p_T$. But *primordial* $\phi$ mesons which are dominantly produced in the partonic phase are least affected by hadronic interactions and follow quark-recombination expected baryon-meson grouping. In fact, in peripheral collisions, as shown in Fig. 4(b), even with hadronic rescattering turned on, inclusive $\phi$-meson $v_2$ is seen to follow meson $v_2$ instead of baryon.

This could be because of relatively lesser number of regenerated $\phi$ mesons in peripheral collisions than in central or midcentral collisions at the same $\sqrt{s_{NN}}$. Thus, the apparent mass-like behavior of $\phi$-meson $v_2$ may also be understood as a consequence of $\phi$-meson regeneration from $K\bar{K}$ fusion.

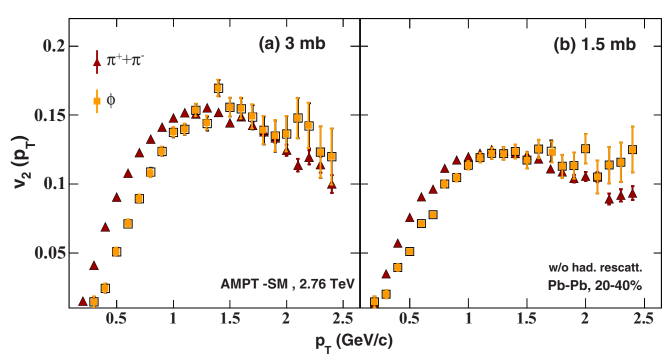


FIG. 5. Transverse momentum dependence of $\phi$-meson and pion $v_2$ for 20–40 % Pb-Pb collisions at $\sqrt{s_{NN}} = 2.76$ TeV. Results obtained from SM version of AMPT model for parton scattering cross section of (a) 3 mb and (b) 1.5 mb without hadronic rescatterings.

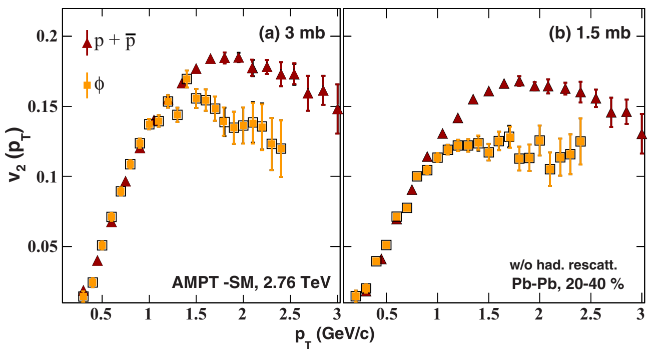


FIG. 6. Transverse momentum dependence of $\phi$-meson and proton $v_2$ for 20–40 % Pb-Pb collisions at $\sqrt{s_{NN}} = 2.76$ TeV. Results obtained from SM version of AMPT model for parton scattering cross section of (a) 3 mb and (b) 1.5 mb without hadronic rescatterings.

To further substantiate that $\phi$-meson $v_2$ in AMPT is consistent with quark number and not mass, we compare $v_2$ of *primordial* $\phi$ mesons with pions and protons. Results presented in Figs. 5 and 6 clearly show, despite the mass of $\phi$ meson being comparable to that of the proton (baryon), $\phi$-meson $v_2(p_T)$ at intermediate $p_T$ region exhibit similar flow pattern as that of the lighter mesons irrespective of parton scattering cross section. Further confirming that in AMPT particle species, dependence of the $v_2(p_T)$ is a baryon-meson effect and not because of the mass of the particle. However, any deviation from the observed pattern may be attributed to the modification in the spectral shape and/or $v_2$ itself by hadronic interactions in the later stages of collision.

## IV. DISCUSSION

In summary, we have studied elliptic flow of $\phi$ mesons at low and intermediate ranges of transverse momentum for 20–40 % Pb-Pb collisions at 2.76 TeV using a hybrid transport model AMPT. $\phi$-meson $v_2$ has generated a lot of interest at LHC since it was observed to deviate from particle type dependent flow pattern at intermediate $p_T$. This observation led to an interpretation of baryon-meson ordering of $v_2$ as a mass effect rather the quark number. As separate flow patterns for baryons and mesons are naturally accounted by the hadronization models where hadrons are formed by coalescing quark from a collectively expanding partonic medium, mass-like flow pattern for $\phi$ mesons would suggest that baryon-meson ordering is simply an interplay between particle mass and radial flow, which can be explained in the hydrodynamical framework without requiring different hadronization schemes such as recombination.

However, our model calculation shows that regeneration of $\phi$ during the hadronic phase through hadronic interactions of $K/\bar{K}$ fusion could be responsible for this apparent mass-like behavior. Whereas those created in the partonic phase by $s$-$\bar{s}$ coalescence perfectly follow the baryon-meson grouping. In spite of having mass comparable to that of a proton, similarity in the $v_2(p_T)$ of $\phi$ and other lighter mesons $(\pi, K)$ further supports that elliptic flow developed at the partonic phase is inherited by the hadrons via a mechanism of quark recombination.

At low $p_T$, a violation in the traditional hydrodynamic mass ordering between proton and $\phi$-meson $v_2$ is observed. This is attributed to a small interaction cross section of $\phi$ mesons compared to protons resulting in a decrease in proton $v_2$ keeping $\phi$-meson $v_2$ almost unaffected during hadronic rescatterings. This observation is supported by RHIC data for Au-Au collisions at 200 GeV but could not be verified at LHC due to lack of data below 0.9 GeV/$c$ in $p_T$.

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