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Higher harmonic flow of ϕ meson in STAR at RHIC

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We present the first measurements of ϕ-meson v_3 and v_4 at mid-rapidity ($|y| < 1.0$) in Au+Au collisions at $\sqrt{s_{NN}}$= 200 GeV. Transverse-momentum (p_T) and centrality dependence of $v_3(p_T)$ and $v_4(p_T)$ are shown and compared with corresponding v_2 values. We also present the various higher harmonic ratios and their possible implications.

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1. Introduction

One of the main goals of the STAR experiment at Relativistic Heavy Ion Collider (RHIC) is to study the properties of the QCD (Quantum Chromodynamics) matter at extremely high energy and parton densities, created in the heavy-ion collisions. In the non-central nucleus nucleus collisions, the overlapping area is not spatially isotropic. This initial spatial anisotropy is then transformed into momentum anisotropy because of pressure gradients developed due to the subsequent interactions among the constituents. The flow is a measure of the anisotropy in momentum space. In a picture of the hydrodynamic expansion of the system formed in the collisions, the flow is an early time phenomenon and sensitive to the equation of state of the system formed in the heavy ion collisions [1]. The ϕ-meson which is the bound state of s and $\bar{s}$ quarks has a small interaction cross-section with hadrons [2]. So for the ϕ-meson the v_n effect of later stage hadronic interaction is small. Therefore, the higher harmonics of the ϕ-meson can be used as a clean probe to measure early time collectivity of the system created in heavy-ion collisions.

2. Experimental Setup and Method

This analysis has been carried out with the data taken by the STAR experiment during RHIC run 2011 with a minimum bias trigger. In this analysis we have used the Time Projection Chamber (TPC) and Time of Flight (ToF) detectors. The TPC is capable of tracking charged particles within the pseudo-rapidity interval $|\ \eta\ | < 1.0$ and has full azimuthal coverage [3]. The TPC detector measures the momentum of the charged tracks as well as the specific ionisation energy loss. This energy loss information is then used to identify the individual tracks by comparing them with the theoretical predictions using Bichsel functions [4]. The TOF PID capabilities overlap with TPC

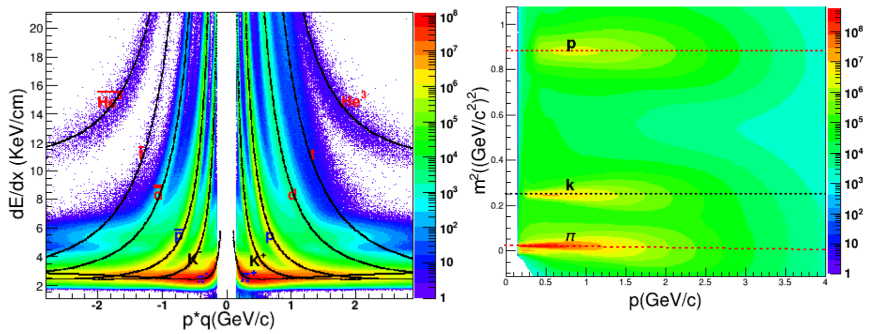

Figure 1: *Left Figure: dE/dx as a function of momentum*charge. Right Figure: The mass squared (m^2) as a function of momentum for minimum bias (0-80%) Au+Au collisions at $\sqrt{s_{NN}}$= 200 GeV.*

dE/dx PID capabilities at low momenta and reach to momenta of ~1.7 GeV/c for pions and kaons and ~3 GeV for protons. A representative plot of dE/dx as a function of (momentum*charge) (Left Figure) and m^2 as a function of particle momentum (Right Figure) is shown in Figure 1, respectively, for a minimum bias (0-80%) Au+Au collisions at $\sqrt{s_{NN}} = 200$ GeV. Theoretical curves are shown by solid black lines. Theoretical values are taken from [4].

Azimuthal anisotropy can be quantified by studying the Fourier expansion of the azimuthal angle (ϕ) distribution of produced particles with respect to the reaction plane angle (ψ_R) and can be written as

$$E\frac{d^3N}{d^3p} = \frac{1}{2\pi}\frac{d^2N}{p_T dp_T dy}(1+\sum_{n=1}^{\infty} 2v_n \cos(n(\phi-\psi_R))) \tag{2.1}$$

where y is rapidity, ϕ is the azimuthal angle of each particle and ψ_R is the event plane. The sine terms in the Fourier expansion vanish due to the reflection symmetry with respect to the reaction plane. The reaction plane ψ_R is not measurable directly so the Fourier coefficients are determined with respect to the estimated event planes

$$v_n^{obs.} = < \cos(n(\phi-\psi_n)) > \tag{2.2}$$

where v_n represent n^{th} order harmonics with n= 2, 3, 4 corresponding to elliptic, triangular and quadrangular flow respectively and ψ_n are the n^{th} order event planes. The v_n measured with respect to the event plane are corrected for the event plane resolution. The η-sub event plane method [5] has been used for the flow analysis. In this method, one defines the event flow vector for each particle based on particles measured in the opposite hemisphere in pseudo-rapidity (η). An η gap of 0.15 between positive and negative pseudo-rapidity sub-events has been introduced to suppress non-flow effects. The invariant mass method [6] has been used to extract the v_n of the ϕ-meson.

3. Results and Discussions

The ϕ-meson v_n as a function of transverse momentum (p_T) for a minimum bias ($0-80\%$), $0-30\%$ and $30-80\%$ centralities in Au+Au collisions at $\sqrt{s_{NN}} = 200$ GeV is presented in Figure 2. The vertical bars in each data point correspond to the statistical error and shaded bands correspond to the systematic error. From the Figure 2, we conclude that all v_n measurement of the ϕ-meson show an increasing trend with increasing p_T i,e $v_n(p_T)$ at 200 GeV increases with transverse momentum and reaches its maximum at intermediate p_t ($\sim$3 GeV/c) after which it decreases again. Further the magnitude of v_2 is greater than v_3 and v_4 ($v_2 > v_3 > v_4$). In this figure, we also observe that v_2 shows strong centrality dependence i.e. the ϕ-meson v_2 values for $30-80\%$ is larger than that of $0-30\%$. This is expected because eccentricity of the initial nuclear overlap area

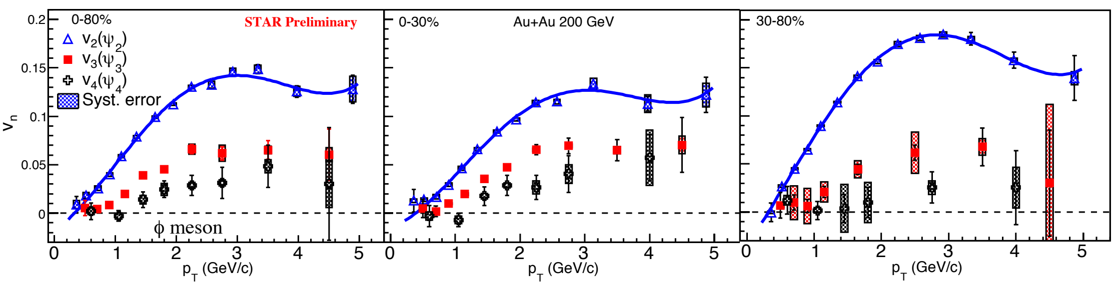

Figure 2: v_n of ϕ-meson as a function of transverse momentum (p_T) in $Au+Au$ at $\sqrt{s_{NN}}$=200 GeV. The line is a 4^{th}-order polynomial fit to the measured ϕ-meson v_2.The vertical bars in each point correspond to the statistical error and shaded bands correspond to the systematic error.

which reflects the initial spatial anisotropy is larger for $30-80\%$(mid central to peripheral) than that for $0-30\%$(central to mid peripheral) collisions. The flow coefficient v_3 exhibits no centrality

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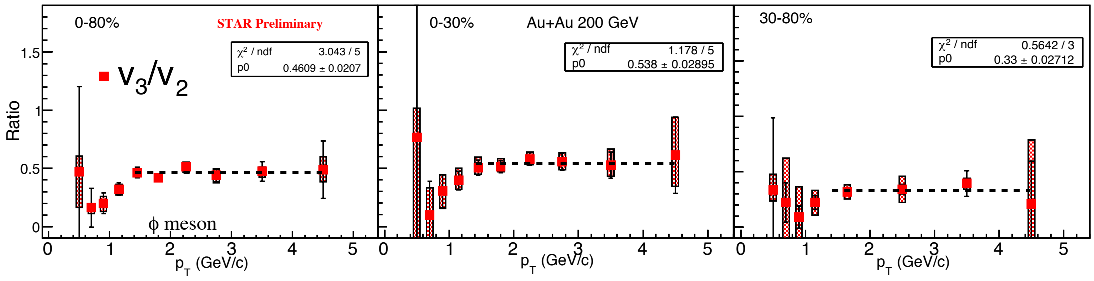

Figure 3: The v_3/v_2 as a function of transverse momentum (p_T) in $Au+Au$ collisions at $\sqrt{s_{NN}}$ =200 GeV. The vertical bars in each point correspond to the statistical error and shaded bands correspond to the systematic error.

dependence which suggests that its origin is entirely from fluctuations of the initial geometry of the system. Similarly the v_4 measured with respect to ψ_4 does not depend strongly on the collision centrality which indicates strong contribution from the flow fluctuations. Figure 3 presents ϕ-meson

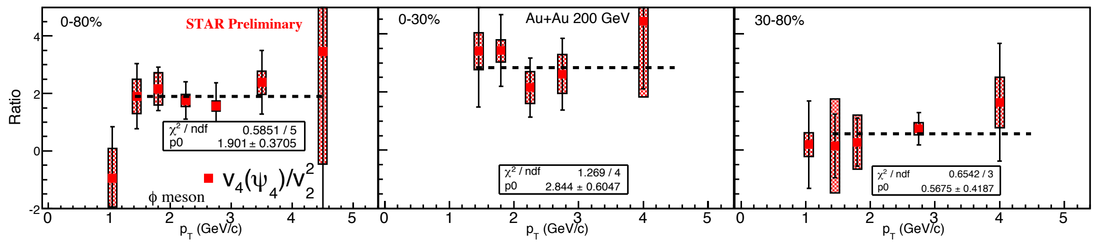

Figure 4: The $v_4(\psi_4)/v_2^2$ ratio as a function of transverse momentum (p_T) in $Au+Au$ collisions at $\sqrt{s_{NN}}$ =200 GeV. The vertical bars in each point correspond to the statistical error and shaded bands correspond to the systematic error.

v_3/v_2 as a function of p_T for a minimum bias $(0-80\%)$, $0-30\%$ and $30-80\%$ centralities in Au+Au collisions at $\sqrt{s_{NN}}$= 200 GeV. From the figure, we can say that the ratio (v_3/v_2) is constant for $p_T > 1.5$ GeV/c and shows a centrality dependence.

Figure 4 shows ϕ-meson $v_4(\psi_4)/v_2^2$ as a function of p_T for a minimum bias $(0-80\%)$, $0-30\%$ and $30-80\%$ centralities in Au+Au collisions at $\sqrt{s_{NN}}$ = 200 GeV. The ratio $v_4(\psi_4)/v_2^2$ is expected to reach 0.5 [7] in ideal hydrodynamics. From the figure, we can see that the ratio is near or larger than one for all the centralities. One explanation is that the interactions among the produced particles are not strong enough to produce local thermal equilibrium, so that the hydrodynamic description breaks down and the resulting value is higher. It is also argued that elliptic flow fluctuations may enhance the value of $v_4(\psi_4)/v_2^2$. As per the calculations of coalescence model the value of the ratio ($v_4(\psi_4)/v_2^2$) is ≈ 0.75 [8], which is also lower than what we have observed in our measurement.

4. Summary

We report the measurement of azimuthal anisotropy v_n for n = 2, 3 and 4 of the ϕ-meson as a function of transverse momentum (p_T) in Au+Au collisions at $\sqrt{s_{NN}}$= 200 GeV. We observe that v_n increases with p_T and has a maximum value at $2-3$ GeV/c. We also observe a strong centrality dependence of $v_2(\psi_2)$ but no centrality dependence for the harmonics $v_3(\psi_3)$ and $v_4(\psi_4)$. We also observe that the ratio v_3/v_2 is constant for $p_T>$ 1.5 GeV and $v_4(\psi_4)/v_2^2$ ratio is higher for central collisions compare to peripheral collisions. The values of the ratio $v_4(\psi_4)/v_2^2$ were found to be greater than 1, well in excess of the value of 0.5 expected from ideal hydrodynamics or the value of $\sim$0.75 expected from coalescence arguments.

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