The width of the rapidity distribution in heavy ion collisions

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We have studied the widths of the rapidity distributions of particles produced in nucleus-nucleus collisions at various center of mass energies and as a function of centrality at SPS energies. We show that the width of the rapidity distribution is sensitive to longitudinal flow, velocity of sound in the medium, and rescattering of particles. We explore the possibility of distinguishing the initial hard scattering regime from final state effects by studying the variation in the width of the rapidity distribution of the particles with centrality for various \( p_T \) values.

PACS numbers: 25.75.Ld

The particle production in heavy ion collisions is studied by measuring the particle density in rapidity (\( Y \)) or in pseudorapidity (\( \eta \)). The evolution of the pseudorapidity density at mid rapidity with beam energy and centrality has been one of the main interests of study in heavy ion collisions \(^1\). Its scaling with the number of participating nucleons and/or with the number of collisions is believed to provide information on the dynamics of the particle production \(^1,2\). The pseudorapidity density at mid rapidity is also related to the entropy density \(^3\). However similar importance has not been given to the width of the rapidity distributions of the particles (\( \sigma_Y \)). With the advent of large acceptance detectors such as in RHIC experiments \(^4\) and the energy scan being high on the agenda of the RHIC program, one can study the evolution of the width of the rapidity distribution as a function of beam energy and centrality. The width of the rapidity distribution is believed to be sensitive to the following physics effects:

(a) Final state rescattering \(^5\), hence a \( p_T \) dependence study of the width may help in estimating the value of \( p_T \) that separates the initial hard scattering regime from the later stage in heavy ion collisions which is dominated by rescattering. (b) The width of the rapidity distribution contains the information of longitudinal flow \(^6\). (c) For a given freeze-out temperature, the width of the rapidity distribution in the Landau hydrodynamical model is found to be sensitive to the velocity of sound in the medium \(^7\).

In this brief report, we first make a compilation of the existing data on the widths of the rapidity distributions of the particles as a function of center of mass energy (\( \sqrt{s_{NN}} \)) and centrality. Then we show how longitudinal flow, velocity of sound and rescattering effect the width of rapidity distribution. Qualitatively the variation in width of the rapidity distribution with center of mass energy and centrality can be understood on the basis of above mentioned processes.

In Fig. 1, we have plotted the width of the rapidity distribution, \( \sigma_Y \), for \( \pi^- \), \( K^+ \), and \( K^- \) as a function of \( \sqrt{s_{NN}} \) \(^6,6,9\). The solid curve corresponds to the theoretical prediction from Ref. \(^10\) based on the Landau model, developed for studying the rapidity distribution for pions produced in \( pp \) collisions \(^11\). This model the width of the rapidity distribution is given as \( \sqrt{\ln(\sqrt{s_{NN}}/2m_p)} \). The dashed curve corresponds to the experimentally determined width of the rapidity distribution for pions produced in \( pp \) collisions. Where not provided in the references directly, the widths were obtained by fitting Gaussian distributions with center at \( Y = 0 \) to the rapidity distributions. The following observations can be made from the figure: (a) The width of the rapidity distribution increases with increase in \( \sqrt{s_{NN}} \) for both nucleon-nucleon and nucleus-nucleus collisions. (b) The width of the rapidity distribution for \( pp \) col-
FIG. 2: Variation of the width of the pseudorapidity distribution of charged particles as a function of percentage of cross section for two center of mass energies $\sqrt{s_{NN}} = 17.3$ GeV and 8.76 GeV.

lisions deviates from the predictions based on the Landau model for $\sqrt{s_{NN}} > 25$ GeV. (c) $\sigma_{+} > \sigma_{-}$ in nucleus-nucleus collisions. This reflects their different interaction cross sections with other particles in the medium. (d) The nucleus-nucleus data for pions shows a similar trend as the curve corresponding to $\sqrt{\ln(\sqrt{s_{NN}/2m_p}})$. $\sigma_{\pi}$ values are comparable to $\sigma_{+}$ and they are higher than $\sigma_{-}$ values for SPS and RHIC energies.

In Fig. 2 we have plotted the widths of the pseudorapidity distributions of the charged particles ($\sigma_{ch}$) as a function of % cross section for $\sqrt{s_{NN}} = 8.76$ and 17.3 GeV [12]. We observe that $\sigma_{ch}$ increases as we go from central to peripheral collisions.

To understand the variation in the width of the rapidity and the pseudorapidity distribution in Fig. 1 and Fig. 2 we need to know the various physics processes that effect the width. Here we will qualitatively discuss how the width of the rapidity distribution is effected by (a) longitudinal flow, (b) velocity of sound in medium, and (c) initial and final state rescattering.

The rapidity distribution can be used to study the longitudinal flow [6]. In Fig. 3 we have plotted the rapidity distribution of $\pi^-$ for $\sqrt{s_{NN}} = 8.76$ GeV [8]. Our calculations from a static isotropic thermal emission model where the rapidity density is given as

$$\frac{dN_{th}}{dY} = A T^3 \left[ \frac{m^2}{T^2} + \frac{2}{T \cosh Y} + \frac{2}{\cosh^2 Y} \right] e^{-\left( \frac{m}{T} \cosh Y \right)}$$

is shown by the dashed curve. The temperature $T$ is taken as 120 MeV [12], $m$ is mass of the pion and $A$ is the normalization constant. We observe that the thermal model fails to explain the width of the rapidity distribution. After including the longitudinal flow within the ambit of Bjorken hydrodynamics as discussed in Ref. [6, 7], in the above thermal model, the rapidity distribution of pions is found to be well explained (solid curve). The rapidity distribution is now given as

$$\frac{dN}{dY} = \int_{-\eta_{max}}^{\eta_{max}} \frac{dN_{th}}{dY} (Y - \eta) \ d\eta$$

and the average longitudinal velocity is defined as $\langle \beta_L \rangle = \tanh(\eta_{max}/2)$. $\langle \beta_L \rangle = 0.6$ is found to explain the pion data at $\sqrt{s_{NN}} = 8.76$ GeV as shown by the solid curve in Fig. 3a).
We fitted the rapidity distributions for pions from $\sqrt{s_{NN}} = 2$ to 200 GeV to results from the thermal model with longitudinal flow to obtain the $\langle \beta_L \rangle$. Variation of $\langle \beta_L \rangle$ with $\sqrt{s_{NN}}$ is shown in Fig. 3(b). We find the average longitudinal velocity for pions approach a value of 1 at RHIC from a value of 0.3 at AGS energies. This is indicative of the higher degree of nuclear transparency attained at RHIC compared to SPS or AGS. It is observed that the results in Fig. 3(b) show qualitatively a similar trend with $\sqrt{s_{NN}}$ as seen for the $dY/d\omega$ for pions in Fig. 4. This indicates that the collective behaviour and the final state interactions of the produced particles in nucleus-nucleus collisions play an important role in determining the width of the rapidity distribution.

The width of the rapidity distribution is sensitive to the velocity of sound in the medium formed at freeze-out. Fig. 4 shows the rapidity distribution of pions at $\sqrt{s_{NN}} = 8.76$ GeV compared to rapidity distribution obtained for various values of velocity of sound using Landau hydrodynamics. Within the ambit of Landau hydrodynamics one can show, with certain assumptions, that the rapidity distribution has the form

$$\frac{dN}{dY} \sim Const. \frac{\exp(-\frac{\sigma^2}{2\sigma^2})}{\sqrt{2\pi} \sigma^2}$$

where $\sigma = 2\omega_f/(1 - c_s^2)$, $\omega_f = ln(T_f/T_0)$, $T_f$ is the freeze-out temperature, $T_0$ is the initial temperature, $c_s$ is the velocity of sound in the medium. We observe that for a $T_f = 120$ MeV $c_s^2 = 1/3$, $T_0 = 230$ MeV (obtained from the total multiplicity), $c_s^2 = 1/5$ explains the data very well. A $c_s^2$ value of 1/6 overpredicts the data and a $c_s^2$ value of 1/3 (ideal gas) underpredicts the data. The $\chi^2$ values for the distributions with $c_s^2 = 1/3$, 1/5 and 1/6 are 51, 1, 7 respectively. This shows that the width of the rapidity distribution of data is sensitive to the parameter $c_s^2$ representing the velocity of sound in the medium in the above model. It may be mentioned that the results are sensitive to the choice of initial and freeze-out temperatures also.

Our analysis of the rapidity distributions of pions, kaons and protons at AGS and SPS energies all reveal the same value of $c_s^2$ $\sim 1/5$ which explains the data. This may indicate some kind of universality of the matter formed at the freeze-out stage. It may be mentioned that the value of $c_s^2$ $\sim 1/5$ has been found to be a characteristic value of the speed of sound for a gas of hadrons $c_s^2$ $\sim 1/5$ indicates that the expansion of the system is slower than that in an ideal gas scenario ($c_s^2 = 1/3$). Thus the system formed in heavy ion collisions gets more time to interact and to reach thermal equilibrium.

Sensitivity of the width of the rapidity distribution to rescattering effects is studied here by using A Multi Phase Transport (AMPT) model. The AMPT model includes both initial parton and final hadronic interactions. It uses the input parton distribution from the HIJING model. We found that $c_{sh}$ obtained from the AMPT model increases with $\sqrt{s_{NN}}$. The values at $\sqrt{s_{NN}} = 17.3, 62.4, 130$ and 200 GeV are 1.57, 2.4, 2.6 and 2.8 respectively.
for the impact parameter range from 0 to 3 fm in Au+Au collisions. In Fig. 5 the widths of the rapidity distributions for charged particles is plotted as a function of impact parameter for \( \sqrt{s_{NN}} = 62.4 \text{ GeV} \) for Au on Au collisions using AMPT and HIJING models. We observe that \( \sigma_{ch} \) increases as we go towards higher values of impact parameter for both AMPT and HIJING models. We also observe such a trend at lower and higher center of mass energies. This trend is qualitatively similar to that observed in the data shown in Fig. 2. The variation in the width is smaller for AMPT than for HIJING. This indicates that final state rescattering has an effect on the width of the rapidity distribution.

Also shown in Fig. 4 is the variation of the \( \sigma_{ch} \) from HIJING for the particles with \( p_T > 2 \text{ GeV}/c \) as a function of impact parameter. We observe that for particles having \( p_T > 2 \text{ GeV}/c \), \( \sigma_{ch} \) decreases as we go higher in collision impact parameter. Qualitatively one can think of the following picture, rescattering leads to more isotropic momentum distributions (for example radial flow in a hydrodynamical picture) and hence will lead to narrower rapidity distributions. Particles with very high transverse momentum which are basically coming from the initial state will not exhibit such isotropy in the momentum distribution. The width of their rapidity distribution is expected to show a different variation with centrality. \( p_T > 2 \text{ GeV}/c \) was chosen for this study as RHIC results on elliptic flow show that hydrodynamical calculations agree with the data for \( p_T < 2 \text{ GeV}/c \). Thus studying \( \sigma_{ch} \) as a function of centrality for various \( p_T \) ranges may indicate the possibility of finding a value of transverse momentum at which the initial hard scattering stage can be distinguished from the later final state rescattering.

In summary, we have found that the width of the rapidity distribution of particles increases with increase in \( \sqrt{s_{NN}} \) in heavy ion collisions. \( \sigma_{K^+} > \sigma_{K^-} \) reflects the different interaction cross sections of oppositely charged kaons with other particles in the medium. It has also been observed in the data that the width of the rapidity distribution increases with increase in impact parameter. We have shown that the width of the rapidity distribution can be effected by longitudinal flow, velocity of sound, and rescattering. Longitudinal flow is found to increase with increase in \( \sqrt{s_{NN}} \). Qualitatively the variation of average longitudinal flow velocity with \( \sqrt{s_{NN}} \) shows a similar trend as \( \sigma_T \) for pions with \( \sqrt{s_{NN}} \). For a given freeze-out and initial temperature the width of the rapidity distribution is sensitive to the velocity of sound in the medium. A value of \( c_s^2 \sim 1/5 \) is able to explain the rapidity distribution of particles at AGS and SPS energies. This indicates, the expansion of the system is slower than compared to in an ideal gas scenario (\( c_s^2 = 1/3 \)). Thus the system formed in heavy ion collisions gets more time to interact and to reach thermal equilibrium. The results from a multi-phase transport model qualitatively show a similar dependence of the width of the rapidity distribution on the impact parameter as does the data. We have also studied the possible \( p_T \) dependence of the width of the rapidity distribution of charged particles as a function of impact parameter to get an idea about initial hard scattering and final state effects.

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