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Rapidity distributions of pions in p + p and Pb + Pb collisions at CERN SPS energies

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The centrality and energy dependence of rapidity distributions of pions in Pb + Pb reactions can be understood by imposing local energy-momentum conservation in the longitudinal „fire streaks" of excited matter. With no tuning nor adjustment to the experimental data, the rapidity distribution of pions produced by the fire streak which we obtained from Pb + Pb collisions reproduces the shape of the experimental pion rapidity distribution in $p+p$ interactions, measured by the NA49 Collaboration at the same energy per nucleon. The observed difference in the absolute normalization of this distribution can be explained by the difference in the overall energy balance, induced by baryon stopping and strangeness enhancement phenomena occurring in heavy ion collisions. We estimate the latter effects using a collection of CERN SPS experimental data on $\pi^{\pm}$, $K^{\pm}$, net p, and n production in $p+p$ and Pb + Pb reactions. We discuss the implications of the above findings for the understanding of particle production phenomena in both hadron-hadron and nucleus-nucleus collisions. Our study, originally applied at a collision energy of $\sqrt{s_{NN}} = 17.3$ GeV, is at present extended to the energy regime $7.7 \leq \sqrt{s_{NN}} \leq 17.3$ GeV.

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1. Introduction — fire streaks in Pb + Pb collisions

This work acts mainly as an executive summary of our recent paper [1] complemented with findings of Ref. [2]. Both studies extend the picture of heavy ion collisions at CERN SPS energies presented in Ref. [3], called the fire streaks model. It should be noted, that this picture is similar to the firestreak model of Refs. [4 – 6] but it is used in a different context and it does not invoke a thermal model for particle emission.

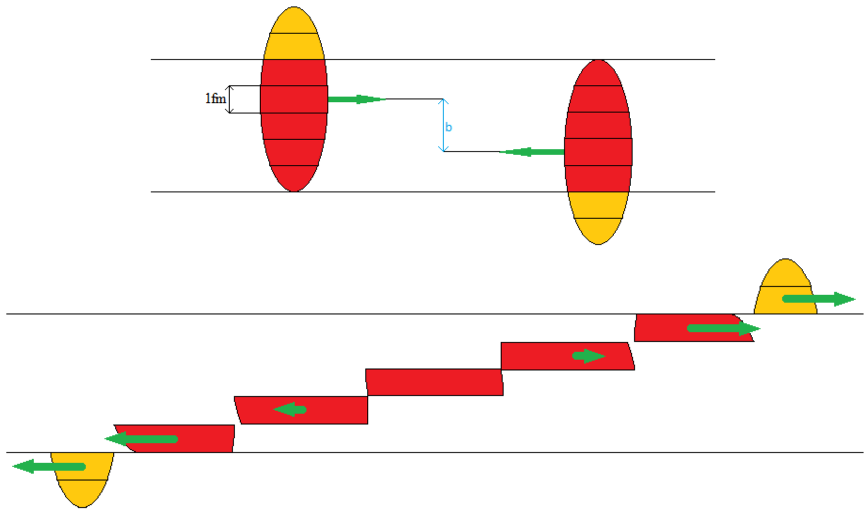


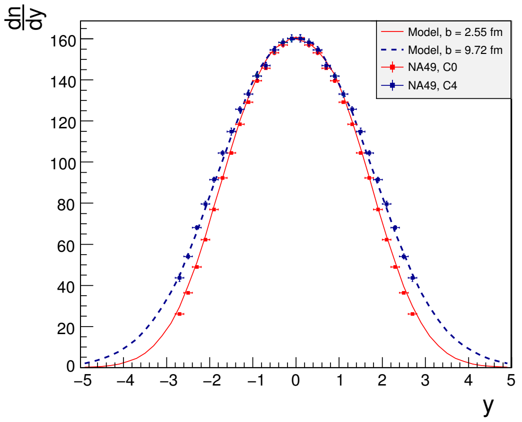
Figure 1: Sketch of the fire streaks model proposed in Ref. [3] to describe Pb + Pb collisions at the CERN SPS energies. The *top* picture illustrates the situation before the collision, while the *bottom* shows the situation after the collision. Green arrows attached to nuclei and fire streaks express longitudinal velocities of respective objects.

The fire streaks model of Ref. [3] considers colliding nuclei as continuous 3D distributions of mass travelling with velocity defined by the energy of the reaction, at the transverse distance (impact parameter) b characterizing the centrality (see Fig. 1, *top*). The transverse space is divided into a 1 fm × 1 fm grid, thus dividing incoming nuclei into bricks of matter with masses given by 3D integrals of initial mass distributions within the bricks. Colliding bricks form fire streaks with kinematical properties given by local energy-momentum conservation (local in the sense that it is satisfied for each pair of colliding bricks separately and not only for the system as a whole). Finally, each fire streak fragments independently into pions with a common rapidity distribution in the fire streak's centre-of-mass system, with total pion yield given by the available energy. Thus the rapidity distribution of produced pions is given by the sum over all fire streaks:

$$\frac{\mathrm{d}n}{\mathrm{dy}} = \sum_{\mathrm{s}} A(E_{\mathrm{s}}^{*} - m_{\mathrm{s}}) \exp\left(- \frac{\left[(\mathrm{y} - \mathrm{y_s})^2 + \varepsilon^2\right]^{\frac{r}{2}}}{r\sigma_{\mathrm{y}}^{r}} \right), \tag{1.1}$$

where E_{s}^{*} is the invariant mass of the fire streak, m_{s} is the sum of masses of incoming bricks and $\mathrm{y_s}$ is fire streak's rapidity. The free parameters A, ε, r and σ are fitted to the experimental data.

As demonstrated in Ref. [3], these free parameters appear to be common for all centralities measured in Ref. [7], meaning that the simple local energy-momentum conservation and collision



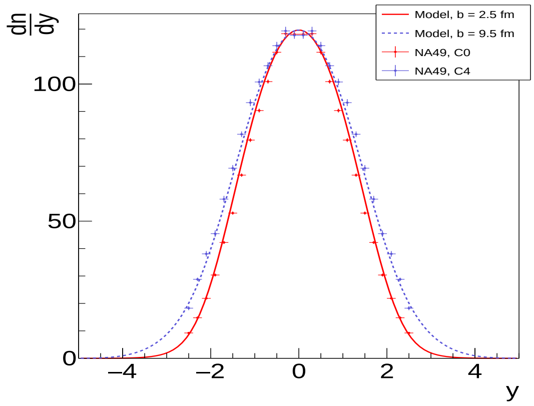


Figure 2: Results of the fire streaks model for Pb + Pb collisions at $\sqrt{s_{NN}} = 17.3\,\mathrm{GeV}$ (*left*; plot from Ref. [3]) and $\sqrt{s_{NN}} = 8.8\,\mathrm{GeV}$ (*right*; plot from Ref. [1]) showing how the model describes the change of width of the π^- rapidity distribution from peripheral to central collisions. The experimental data come from Ref. [7], different centralities are scaled to the same peak height so that visual shape comparison is possible, only statistical uncertainties are shown, data points at negative rapidity values are reflections of those at positive rapidity.

geometry are enough to describe the centrality dependence of pion rapidity distribution in Pb + Pb collisions at $\sqrt{s_{NN}} = 17.3\,\mathrm{GeV}$. The same turns out to be true for $\sqrt{s_{NN}} = 8.8\,\mathrm{GeV}$ [1, 2]. The model describes the centrality dependence of both the shape of the distribution and the total pion yield. The former is illustrated in Fig. 2 for both energies, showing how the π^- rapidity distribution shape changes between the most central and the most peripheral samples.

2. Pion production from one fire streak

Thinking about $p+p$ collisions in the context of the fire streaks model, since the proton size is about the transverse size of a single fire streak in Fig. 1, the simplest is to model each incoming proton as a single brick. In this situation, after the $p+p$ collision, a single fire streak at rest is formed. Pions are emitted according to a single-fire-streak fragmentation function:

$$f(\mathrm{y}) = A(E^*_\mathrm{s} - m_\mathrm{s})\exp\left(-\frac{\left[(\mathrm{y}-\mathrm{y_s})^2+\varepsilon^2\right]^{\frac{r}{2}}}{r\sigma_\mathrm{y}^r}\right), \tag{2.1}$$

with $E^*_\mathrm{s} = \sqrt{s_{NN}}$, $m_\mathrm{s} = 2m_\mathrm{N}$, $\mathrm{y_s} = 0$ (note that contrary to Eq. (1.1) there is no summation over fire streaks). As shown in Fig. 3, taking free parameters values obtained for Pb + Pb collisions, it turns out that the resulting rapidity spectrum *almost* coincides with the measurement [8] for $p+p$ collisions. The shape is reasonably reproduced. The overall yield has a correct order of magnitude (about 100 times smaller than Pb + Pb), but it is different by a factor 0.748 from the $p+p$ data (hence „*almost*" written earlier).

3. Correspondence between Pb + Pb and p + p reactions

The above finding suggests that indeed in a $p+p$ collision a single fire streak is created. The

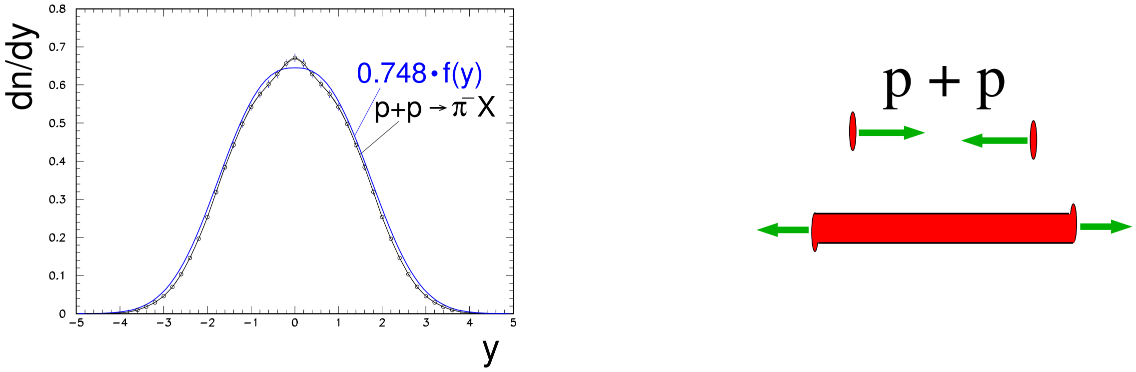


Figure 3: *Left*: π^- rapidity distribution in $p+p$ collisions at $\sqrt{s_{NN}} = 17.3\,\mathrm{GeV}$ measured by NA49 [8] (black lines to guide the eye, only statistical uncertainties, negative rapidity points are reflections of positive rapidity ones) compared to single-fire-streak fragmentation function Eq. (2.1) scaled by 0.748 (plot from Ref. [1]). *Right*: possible picture of a $p+p$ collision, analogous to Fig. 1, with production of a single fire streak.

difference in absolute normalization of the single-fire-streak fragmentation function with parameters take from Pb + Pb collisions and the $p+p$ pion rapidity distribution can be explained as coming from the different energy repartition between $p+p$ and Pb + Pb collisions (*i.e.* how much of the available energy actually is spent on pion production). It should be emphasized, that the fire streaks model says nothing about the longitudinal size, internal structure or internal dynamical properties of fire streaks. This is why we decided to estimate the above-mentioned difference in energy balance in a (nearly) model-independent way. This is what the rest of the paper is devoted to.

3.1 Isospin

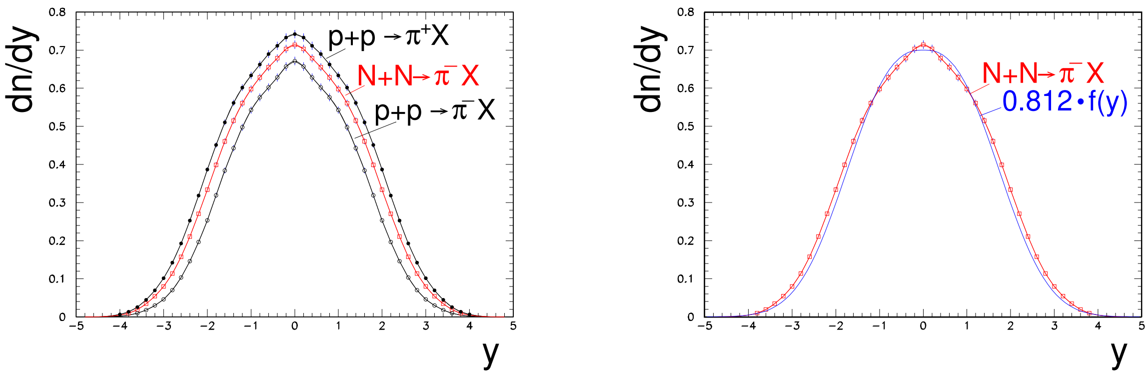


Figure 4: Isospin-averaged π^- rapidity distribution compared to π^- and π^+ distributions measured in $p+p$ collisions [8] from which the average was calculated according to Eq. (3.1) (*left*) and to the Pb + Pb at $\sqrt{s_{NN}} = 17.3\,\mathrm{GeV}$ single-fire-streak fragmentation function Eq. (2.1) scaled by 0.812 (*right*). Plots from Ref. [1].

Before considering really non-trivial (dynamical) issues, an observation needs to be made, that π^- production in $p+p$ collisions cannot be directly compared to that in Pb + Pb collisions due to the different isospin content of the colliding nuclei (Pb nuclei has roughly 40 % protons and

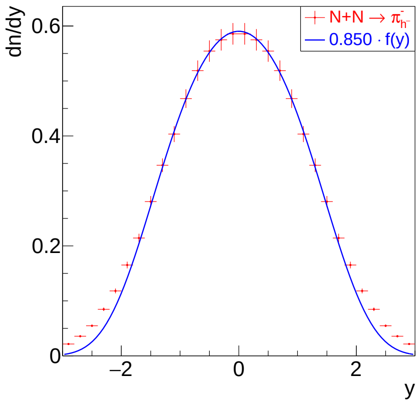


Figure 5: Isospin-averaged π^- rapidity distribution derived from π^- and π^+ measurements in $p+p$ collisions at $\sqrt{s_{NN}} = 8.8\,\text{GeV}$ compared to the Pb+Pb at $\sqrt{s_{NN}} = 8.8\,\text{GeV}$ single-fire-streak fragmentation function Eq. (2.1) scaled by 0.850 [2].

60 % neutrons). Isospin symmetry in pion production for participating protons and neutrons gives $\frac{\mathrm{d}n}{\mathrm{dy}}(n \to \pi^-) = \frac{\mathrm{d}n}{\mathrm{dy}}(p \to \pi^+)$ [9]. From this follows the isospin-averaged π^- rapidity distribution in nucleon-nucleon collisions:

$$\frac{\mathrm{d}n}{\mathrm{dy}}(N+N \to \pi^- X) = \frac{Z}{A} \cdot \frac{\mathrm{d}n}{\mathrm{dy}}(p+p \to \pi^- X) + \left(1 - \frac{Z}{A}\right) \cdot \frac{\mathrm{d}n}{\mathrm{dy}}(p+p \to \pi^+ X), \tag{3.1}$$

which is a better reference for Pb+Pb collisions than the $p+p$ distribution. As is visible in Fig. 4 for $\sqrt{s_{NN}} = 17.3\,\text{GeV}$, the agreement of the single-fire-streak fragmentation function with this new data reference improves (scale factor is closer to 1). An analogous operation is performed for $\sqrt{s_{NN}} = 8.8\,\text{GeV}$, with the result presented in Fig. 5.

3.2 Energy balance

Finally, actual differences in energy repartition between nucleon-nucleon ($N+N$) and lead-lead collisions can be addressed. The fire streak energy is spent on three contributions: baryon emission, strange meson production (at CERN SPS energies approximately equal to kaon production) and non-strange meson production (approximately — pion production). There are two phenomena associated with this, which significantly differentiate the two types of collisions: baryon stopping (baryon inelasticity) and strangeness enhancement. The former defines how much of the incoming baryon energy is spent on non-baryon production (see *e.g.* Refs. [10, 11] for experimental documentation of the phenomenon). The latter is enhancement of the strange over non-strange particles production in heavy ion collisions (see *e.g.* experimental results summary in Ref. [11]).

It turns out that using just the experimental results (*i.e.* model-independently) and few basic assumptions it is possible to estimate the balance of the 3 contributions. The calculation involves averaging with numerical interpolations of the $p+p$ experimental spectra published by NA49 [8, 12, 13]. Energy spent on a particle i (p, $\bar{p}$, $\pi^{\pm}$, $K^{\pm}$) is:

$$\langle E_i \rangle = \frac{\int_0^1 \int_0^{p_T(\max)} E_i(x_F, p_T) \left(\frac{\mathrm{d}^2\sigma}{\mathrm{d}x_F \mathrm{d}p_T}\right)_i \mathrm{d}p_T \, \mathrm{d}x_F}{\int_0^1 \int_0^{p_T(\max)} \left(\frac{\mathrm{d}^2\sigma}{\mathrm{d}x_F \mathrm{d}p_T}\right)_i \mathrm{d}p_T \, \mathrm{d}x_F}, \tag{3.2}$$

where $\left(\frac{\mathrm{d}^2\sigma}{\mathrm{d}x_F \mathrm{d}p_T}\right)_i$ is the interpolation of the measured production cross section for particle i and $E_i(x_F, p_T)$ its energy at given (x_F, p_T).

From this, for $p+p$ collisions at $\sqrt{s_{NN}} = 17.3\,\mathrm{GeV}$, we get energy spent on pions $\langle\pi\rangle \cdot \langle E_\pi\rangle = 6862\,\mathrm{MeV}$ and on kaons $\langle K\rangle \cdot \langle E_K\rangle = 918\,\mathrm{MeV}$, where $\langle i\rangle$ is average number of particles i per event. This yields the ratio of energy spent on kaons to that spent on pions in $p+p$ collisions $R^{p+p}_{K/\pi} = 0.13378$. Similarly baryon inelasticity can be calculated from

$$K = \frac{2E_{\mathrm{inel}}}{\sqrt{s}-2m_p}\,, \qquad E_{\mathrm{inel}} = \frac{\sqrt{s}}{2} - \left\langle E_{\text{net proton}}\right\rangle\,. \tag{3.3}$$

with certain reasonable assumptions [1] about relations of neutron and anti-neutron spectra to that of protons, yielding $K = 0.547$.

For Pb+Pb collisions at $\sqrt{s_{NN}} = 17.3\,\mathrm{GeV}$ the NA49 Collaboration estimated $K \approx 0.78$ [10]. Assuming that the ratio of average energy of one kaon over that of one pion remains constant between $p+p$ and Pb+Pb collisions and knowing the enhancement about 2 times of K/π ratios in Pb+Pb compared to $p+p$ reactions [11], we get the $R^{\mathrm{Pb+Pb}}_{K/\pi} = 2\cdot R^{p+p}_{K/\pi} = 0.26333$.

Thus finally, per unit of total collision energy, the ratio of energy spent on pion production in $p+p$ over Pb+Pb collisions at $\sqrt{s_{NN}} = 17.3\,\mathrm{GeV}$ is

$$\frac{0.547/(1+0.13378)}{0.78/(1+0.26333)} = 0.781\,. \tag{3.4}$$

The above value should be compared with the factor 0.812 in Fig. 4, giving roughly 4 % agreement. Similar reasoning for $\sqrt{s_{NN}} = 8.8\,\mathrm{GeV}$ yields the energy ratio 0.885 [2] to be compared with factor 0.850 in Fig. 5 giving again an agreement on the 4 % level.

The above calculation shows that the scale factors obtained from fire streaks model considerations are understandable on the grounds of changes in energy balance of $p+p$ and relativistic heavy ion collisions. Consequently a correspondence emerges in the framework of the fire streaks model between rapidity spectra in $p+p$ and Pb+Pb collisions, namely that having the rapidity spectrum in $p+p$ collisions, applying correction for isospin, taking into account baryon inelasticity and strangeness enhancement, one obtains a single-fire-streak fragmentation function in Pb+Pb collisions. Then from the latter, the collision geometry and summation over many fire streaks, one obtains the rapidity distribution in Pb+Pb collisions.

4. Summary

The fire streaks model explains the whole centrality dependence of the pion rapidity distribution in Pb+Pb collisions. It is valid in some extended collision energy range — at least from $\sqrt{s_{NN}} = 8.8\,\mathrm{GeV}$ to $\sqrt{s_{NN}} = 17.3\,\mathrm{GeV}$. Furthermore, it turns out that the pion rapidity distribution from one fire streak in Pb+Pb collisions reproduces the pion rapidity spectrum in $p+p$ collisions with a difference in absolute normalization which directly results from the different energy repartition in the two reactions. This can indicate that one fire streak is formed in the $p+p$ collision. As a result, an interesting correspondence emerges between pion distributions in $p+p$ and Pb+Pb reactions.

Acknowledgments

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