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Further development of a model for the production of strange particles in nucleus-nucleus collisions

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*on leave from Rudjer Boskovic Institute, Zagreb, Croatia

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1 Introduction

In ultrarelativistic nucleus-nucleus interactions one can study hadronic systems under extreme conditions of temperature and pressure. The main goal of experiments in this field is the search for exotic states of strongly interacting matter, e.g. a state of deconfined quarks and gluons, the Quark Gluon Plasma (QGP). One of the first predicted signatures of the deconfined phase is an enhancement of the s and $\bar{s}$ quark concentration as compared to that in ordinary hadronic matter. Therefore the production of strange particles is expected to be significantly higher when the produced particle system passes through a QGP phase, than when it stays in the hadronic phase [1]. However, before one can conclude that the QGP has been formed, one must know what to expect if only conventional hadronic processes were at work. For this purpose the simultaneous comparison of hadronic models with the available data on all types of interactions, namely nucleon-nucleon (NN), nucleon-nucleus (NA), and nucleus-nucleus (AB) collisions, is clearly needed. In [2] a parametrization of negative hadron (h^- , mainly pions) and neutral strange particle (K_s^0 , Λ , $\bar{\Lambda}$) production was developed which successfully describes the presently available data on average multiplicities in NN, NA and AB collisions at 200 GeV per nucleon incident energy. It was found that the average multiplicities of negative hadrons are proportional to the number of wounded nucleons, calculated according to the Glauber model [3], while the average multiplicities of neutral strange particles are proportional to the number of wounded quarks, calculated according to the Additive Quark Model (AQM) [4]. The success of the model in describing all available data on negative hadron and neutral strange particle multiplicities in NN, NA and AB collisions may indicate that configurations of different spatial size and different interaction cross section, existing in the hadrons [5], are responsible for negative hadron and neutral strange particle production.

Following the ideas developed in [2] this paper presents calculations of average multiplicities and of lab rapidity (y) and transverse momentum (p_T) spectra of K_s^0 , Λ and $\bar{\Lambda}$ particles produced in heavy ion collisions at 200 GeV per nucleon. The results of the model will be compared with the data from central SS collisions [6], and the model predictions for central PbPb collisions will be presented and discussed in some detail.

2 Calculation of the p_T and y distributions for K_s^0 , Λ and $\bar{\Lambda}$ particles

In the AQM [4] particle production in inelastic nucleon-nucleus collisions is determined basically by the mean number $\bar{W}_1^q(A)$ of wounded quarks in the projectile,

$$\bar{W}_1^q(A) = \sum_{i=1}^3 w_i(A) \cdot i. \quad (1)$$

Here A is the atomic number of the target and w_1, w_2, w_3 are the probabilities of collisions with inelastic interactions of one, two and three constituent quarks of the projectile [4], satisfying the condition $\sum_{i=1}^3 w_i(A) = 1$. Consider first the simple system which consists of one projectile (p) and one target (t) nucleon. Without specifying the details of the particle production mechanism, one can write for the number of produced K_s^0 , Λ or $\bar{\Lambda}$ particles, at the nucleon-nucleon c.m.s. rapidity y^* ($y^* = y - 3.0$ at 200 GeV per nucleon) and transverse momentum p_T , the following ansatz:

$$\begin{aligned} n(p_T, y^*) &= w_1(1) \cdot (n_{wss}^t(p_T, y^*) + n_{wss}^p(p_T, y^*)) \\ &+ w_2(1) \cdot (n_{wws}^t(p_T, y^*) + n_{wws}^p(p_T, y^*)) \\ &+ w_3(1) \cdot (n_{www}^t(p_T, y^*) + n_{www}^p(p_T, y^*)) \end{aligned} \quad (2)$$

with $n_{wss}^{t,p}$, $n_{wws}^{t,p}$, $n_{www}^{t,p}$ denoting the number of produced particles from the target or the projectile nucleon, with one wounded and two spectator, two wounded and one spectator, and with three wounded quarks. The number of produced particles at given y^* and p_T , $n(p_T, y^*) = d^2n/dp_T dy^*$, is normalized such that

$$\int_{p_T} \int_{y^*} n(p_T, y^*) dy^* dp_T = \int_{p_T} \frac{dn}{dp_T} dp_T = \langle n_x \rangle. \quad (3)$$

Here $\langle n_x \rangle = \langle n_x \rangle$ denotes the average multiplicity of produced particles of kind $x = (K_s^0, \Lambda, \bar{\Lambda})$. Since in nucleon-nucleon collisions the probabilities for inelastic interactions of two and three quarks are very small, one has to a good approximation $w_2(1) = w_3(1) = 0$, and consequently

$$n(p_T, y^*) = n_{wss}^p(p_T, y^*) + n_{wss}^t(p_T, y^*). \quad (4)$$

Similarly, in calculating the number of produced particles n_{NA} in nucleon-nucleus collisions, one can assume that the probability of wounding one target nucleon more than once is very small. It then follows that

$$\begin{aligned} n_{NA}(p_T, y^*) &= \bar{W}_1^q(A) \cdot n_{wss}^t(p_T, y^*) + n_C^A(p_T, y^*) \\ &+ w_1(A) \cdot n_{wss}^p(p_T, y^*) + w_2(A) \cdot n_{wws}^p(p_T, y^*) + w_3(A) \cdot n_{www}^p(p_T, y^*). \end{aligned} \quad (5)$$

The term $n_C^A(p_T, y^*)$ describes the contribution to the total multiplicity $n_{NA}(p_T, y^*)$ from the reinteractions of secondary produced particles inside the target nucleus (cascading).

In analogy with (5) the expression for the number of produced particles in a nucleus-nucleon (AN) collision (where now A is the projectile and N the target) can be written as

$$\begin{aligned} n_{AN}(p_T, y^*) &= \bar{W}_1^q(A) \cdot n_{wss}^p(p_T, y^*) + n_C^A(p_T, -y^*) \\ &+ w_1(A) \cdot n_{wss}^t(p_T, y^*) + w_2(A) \cdot n_{wws}^t(p_T, y^*) + w_3(A) \cdot n_{www}^t(p_T, y^*). \end{aligned} \quad (6)$$

Taking into account the symmetry about $y^* = 0$ it follows that

$$n_{NA}(p_T, y^*) = n_{AN}(p_T, -y^*). \quad (7)$$

To extend the model to nucleus-nucleus collisions, a few assumptions are required regarding the particle production from cascading. As in [2] it will be assumed that cascading is fully developed only in the overlapping regions of two colliding nuclei, defined by the impact parameter and the resulting numbers of nucleons A' and B' in the overlap regions of A and B (see Fig. 1). These two regions are assumed to be separated in rapidity, so that they can contribute independently to the particle production. Furthermore, the amount of cascading in the overlapping regions of A and B is assumed to be proportional to the incoherent superposition of the cascading from NA' and NB' collisions, respectively. With these assumptions the expression for the strange particle multiplicities produced in AB collisions becomes:

$$\begin{aligned}
n_{AB}(p_T, y^*) = & A'_q \cdot [w_1(A', B') \cdot n_{wss}^p(p_T, y^*) + w_2(A', B') \cdot n_{wws}^p(p_T, y^*) \\
& + w_3(A', B') \cdot n_{www}^p(p_T, y^*)] + A' \cdot n_C^{B'}(p_T, y^*) \quad (8) \\
& + B'_q \cdot [w_1(B', A') \cdot n_{wss}^t(p_T, y^*) + w_2(B', A') \cdot n_{wws}^t(p_T, y^*) \\
& + w_3(B', A') \cdot n_{www}^t(p_T, y^*)] + B' \cdot n_C^{A'}(p_T, -y^*).
\end{aligned}$$

With A'_q and B'_q we denote the number of nucleons with at least one wounded quark (afterwards wounded nucleons) in the overlapping regions of A and B, respectively. It is found [2] that except for very peripheral collisions one can take $A'_q = A'$ and $B'_q = B'$, i.e. that each nucleon in the overlap region interacts. The mean number of wounded quarks per wounded projectile nucleon $\overline{W}_{A'}^q(B')$ in the collision of projectile A' with the target B' is defined as

$$\overline{W}_{A'}^q(B') = \sum_{i=1}^3 w_i(A', B') \cdot i. \quad (9)$$

Here, $w_i(A', B')$ is the probability to have i ($= 1, 2, 3$) wounded quarks per wounded projectile nucleon in $A'B'$ collisions. Since each collision results in one wounded quark each in a projectile and a target nucleon and since according to the AQM the number of wounded quarks in a nucleon does not exceed three, $\overline{W}^q$ satisfies the identity:

$$A'_q \cdot \overline{W}_{A'}^q(B') = B'_q \cdot \overline{W}_{B'}^q(A'). \quad (10)$$

We see from (8) that the two mechanisms which contribute to the particle production in AB collisions, namely rescattering of the "wounded projectile objects", and cascading of secondary produced particles, are likewise present in NA collisions (see (5) and (6)). Therefore NA interactions provide a link between NN and AB collisions. This can be demonstrated more explicitly for the multiplicities of the neutral strange particles produced in symmetric ($A = B$) and asymmetric ($A \ll B$) nucleus-nucleus collisions by expressing the results of (8) in terms of (4) to (6). Note that one should use pA data for which the number of wounded quarks in the projectile is approximately equal to the mean number of wounded quarks per wounded projectile nucleon in the AA or AB case.

For the collisions of equal mass nuclei one may then approximate:

$$w_i(A', A') = w_i(A'). \quad (11)$$

With these assumptions the results from (5) and (6) can be inserted into (8) and one obtains, using also (4) and (7), the following formula for $d^2n/dp_T dy^*$ of strange particle production in AA collisions:

$$n_{AA}(p_T, y^*) = A' \cdot [n_{NA'}(p_T, y^*) + n_{NA'}(p_T, -y^*) - \overline{W}_1^q(A') \cdot n(p_T, y^*)]. \quad (12)$$

This formula shows that the production of K_s^0 , Λ and $\overline{\Lambda}$ particles in the collisions of symmetric nuclei can be described by the corresponding results from nucleon-nucleon and nucleon-nucleus collisions. By integrating (12) over p_T and y^* we obtain the average multiplicity $\langle n \rangle_{AA}$ of the neutral strange particles produced in AA collisions:

$$\langle n \rangle_{AA} = A' \cdot [2 \cdot \langle n \rangle_{NA'} - \overline{W}_1^q(A') \cdot \langle n \rangle]. \quad (13)$$

For an asymmetric system $A \ll B$, one can assume that the probability of wounding one target nucleon more than once is very small, i.e.

$$w_i(B', A') = \delta_{i1}. \quad (14)$$

Again, in analogy to (11), the following equality approximately hold :

$$w_i(A', B') = w_i(B'). \quad (15)$$

Using (9), (10) and (14), (8) can thus be written in the form :

$$n_{AB}(p_T, y^*) = A' \cdot n_{NB'}(p_T, y^*) + B' \cdot n_C^{A'}(p_T, -y^*). \quad (16)$$

After integrating (16) over p_T and y^* we obtain the expression for the average multiplicity of produced particles in AB collisions:

$$\langle n \rangle_{AB} = A' \cdot \langle n \rangle_{NB'} + B' \cdot n_C^{A'}. \quad (17)$$

The last term accounts for the contribution to the particle multiplicity from cascading in the overlapping volume of the projectile nucleus A.

3 Comparison with experimental results at 200 GeV per nucleon

In calculating the average multiplicities of K_s^0 , Λ and $\overline{\Lambda}$ particles in central SS collisions, the experimental values for the corresponding multiplicities in NN and pS collisions [6] are used as input values in (13). For central SS collisions, the number of nucleons participating in the collision is found to be $A' = 27$ [7] and the mean number of wounded quarks per wounded nucleon is

Reaction	K_s^0	Λ	$\bar{\Lambda}$
NN	0.20 ± 0.03	0.096 ± 0.015	0.013 ± 0.005
pS	0.38 ± 0.05	0.28 ± 0.03	0.049 ± 0.006
SS _{exp}	10.5 ± 1.7	9.4 ± 1.0	2.2 ± 0.4
SS _{mod}	11.3	10.7	2.1

Table 1: The experimental data on the average K_s^0 , Λ and $\bar{\Lambda}$ multiplicities in NN, pS and central SS collisions from [6], together with the model predictions from (13) for central SS collisions.

calculated to be $\bar{W}_{A'}^q(A') = 1.7$ [2]. From the K_s^0 multiplicity in the pS data (charged particle multiplicity $n_{ch} > 5$) one derives a similar mean number of wounded quarks in the projectile nucleon, i.e. $\bar{W}_1^q(A') \approx 1.7$. This justifies the use of the pS data as an input into (13). The experimental data on the average K_s^0 , Λ and $\bar{\Lambda}$ multiplicities in NN, pS and central SS collisions [6], together with the model predictions for central SS collisions from (13), are given in Table 1. Good agreement between the model and the experimental results is obtained. The model predictions differ somewhat from those given in [2] since here they are obtained by using pS data directly as input into the calculation. Note also that the experimental results for pS and SS collisions from [6], used in this paper, have changed as compared to [8] on which the calculation in [2] was based.

It is interesting to note the strong correlation between particle production in AA and the corresponding pA collisions. To demonstrate this qualitatively, consider the predictions of (13) in more detail. Namely, if the number of produced strange particles in pA collisions is proportional to the number of wounded quarks,

$$\langle n_x \rangle_{pA} = \bar{W}_1^q(A) \cdot \langle n_x \rangle, \quad (18)$$

then according to (13) one obtains for AA collisions:

$$\langle n_x \rangle_{AA} = A \cdot \langle n_x \rangle_{pA} \quad (19)$$

with $x = (K_s^0, \Lambda, \bar{\Lambda})$. On the other hand, if the production of strange particles in pA collisions is enhanced relative to (18), then

$$\langle n_x \rangle_{pA} > \bar{W}_1^q(A) \cdot \langle n_x \rangle. \quad (20)$$

From (13) one then finds

$$\langle n_x \rangle_{AA} > A \cdot \langle n_x \rangle_{pA}, \quad (21)$$

i.e. an enhancement of strange particle production in AA collisions relative to (19). From Table 1 we see that the first case is true for K_s^0 production ((18) and (19)), and the second case for Λ and $\bar{\Lambda}$ production ((20) and (21)), which was found to show a large cascading contribution [2].

The analysis of neutral strange particle production in collisions of two unequal mass nuclei ($A < B$) shows that the production is sensitive to the asymmetry of the nuclear systems involved. In the backward hemisphere ($y^* < 0$), the contribution of the second term (cascading in A) in (17) can be neglected, i.e.

$$\langle n_x \rangle_{AB} \approx A \cdot \langle n_x \rangle_{pB}. \quad (22)$$

In contrast to the central SS collisions ((18) to (21)), the relation (22) should then be simultaneously valid for K_s^0 , Λ and $\bar{\Lambda}$ particles. This was indeed found by the NA35 Collaboration [9], which measured the rates of strange particle production in central OAu collisions to be about a factor of 16 higher than in pAu collisions, when compared in the (same) backward phase space region.

Equations (12) and (16), derived in the previous chapter, can in principle be used for calculating the y^* and p_T distributions of strange particles produced in nucleus-nucleus collisions. Assuming that there is no correlation between the rapidity and transverse momentum distributions, i.e.

$$n(p_T, y^*) = [n(p_T) \cdot n(y^*)] / \langle n \rangle, \quad (23)$$

one derives from (12) the following y^* and p_T distributions of K_s^0 , Λ and $\bar{\Lambda}$ produced in the collisions of two symmetric nuclei:

$$n_{AA}(y^*) = A' \cdot [n_{NA'}(y^*) + n_{NA'}(-y^*) - \bar{W}_1^q(A') \cdot n(y^*)]. \quad (24)$$

$$n_{AA}(p_T) = A' \cdot [2 \cdot n_{NA'}(p_T) - \bar{W}_1^q(A') \cdot n(p_T)]. \quad (25)$$

As an example, these two equations are used to calculate the y^* and p_T distributions of K_s^0 , Λ and $\bar{\Lambda}$ particles produced in central SS collisions.

Fig. 2 shows the rapidity distributions of K_s^0 , Λ and $\bar{\Lambda}$ particles in pS collisions from [6]. The data extrapolated to the full rapidity range and parametrized as shown by the full lines are used as input into (24). The parametrization of the rapidity distributions of K_s^0 , Λ and $\bar{\Lambda}$ particles in NN collisions from [10] was taken as the second input into (24). The resulting predictions (24) for the rapidity distributions of K_s^0 , Λ and $\bar{\Lambda}$ particles in central SS collisions are shown by the full lines in Fig. 3 which also exhibits the NA35 data [6]. The dashed line in Fig. 3b corresponds to a slightly different parametrization of the Λ rapidity distribution for pS collisions, represented by the dotted curve in Fig. 2b. Good agreement between the model predictions and the SS data is observed in Fig. 3.

For calculating the transverse momentum distributions of K_s^0 , Λ and $\bar{\Lambda}$ particles produced in the central SS collisions, (25) is used. The corresponding data for the NN and pS transverse momentum distributions, used as input into (25), are parametrized by the exponential functions proposed in [10] for NN and in [6] for pS collisions; they are shown in Fig. 4 by dotted and dashed lines, respectively. The transverse momentum distributions of neutral strange particles produced in central SS collisions, shown in Fig. 5,

were measured in the restricted rapidity acceptances $0.5 < y < 3.5$ for K_s^0 , $0.5 < y < 3$ for Λ , and $0.5 < y < 3$ for $\bar{\Lambda}$ [6]. The model predictions $n_{SS}^{acc}(p_T)$ in the corresponding phase space region are obtained by rescaling the results from (25) using the expression

$$n_{SS}^{acc}(p_T) = n_{SS}(p_T) \cdot \frac{\langle n_x \rangle_{SS}^{acc}}{\langle n_x \rangle_{SS}}. \quad (26)$$

The values for the average multiplicities $\langle n_x \rangle_{SS}^{acc}$ of particle kind $x = (K_s^0, \Lambda, \bar{\Lambda})$, produced in the restricted rapidity region, and $\langle n_x \rangle_{SS}$, produced in full phase space, are taken from [6]. The predicted transverse momentum distributions of neutral strange particles produced in central SS collisions are shown in Figs. 4 and 5 by the full lines. Again, good agreement with the measured data is obtained in Fig. 5. Since the function proposed in [6] does not describe the data on $\bar{\Lambda}$ production in pS collisions well enough, especially in the high- p_T region, the experimental data points from pS collisions are used as input into (25), as an alternative. Better agreement with the SS data is then obtained as shown by the open circles in Fig. 5c. It is interesting to note that the slopes of the p_T distributions of K_s^0 , Λ and $\bar{\Lambda}$ particles in pS collisions are similar to the corresponding slopes in SS collisions (compare dashed and full lines in Fig. 4). At the same time, the p_T distributions of neutral strange particles in NN and SS collisions differ significantly. This suggests the presence of similar strange particle production mechanisms in pS and SS collisions.

4 Predictions for PbPb collisions at 200 Gev per nucleon

Encouraged by the success of the model in describing strange particle production in SS collisions, the model predictions will now be extrapolated to the total average multiplicities and the rapidity distributions of neutral strange particles produced in central PbPb collisions.

The rapidity distributions of K_s^0 , Λ and $\bar{\Lambda}$ produced in minimum bias pPb collisions [11] together with the corresponding rapidity distributions for pAu collisions [9] are used to construct the input for (24). Since the data cover only the p_T range $0.1 < p_T < 2$ GeV/c, they had to be extrapolated to the full p_T range. The results are shown in Fig. 6 by dots and open squares for pAu [9] and pPb [11] collisions respectively. The extrapolations to the full rapidity range are shown by the full curves in Fig. 6. With $A' = B' = 200$ one obtains $\bar{W}_{A'}^q(A') = 2$ for PbPb collisions. In minimum bias pAu or pPb reactions, the average number of wounded quarks $\bar{W}_1^q(A')$ in the projectile proton is similar to this $\bar{W}_{A'}^q(A')$ value. Using the curves of Fig. 6 as input to (24) one obtains the predictions for central PbPb collisions shown in Fig. 7. It will be interesting to check in the forthcoming PbPb experiments at the CERN-SPS, whether the rapidity distributions of neutral strange particles are really

dominated by the shapes of the corresponding nucleon-nucleus distributions as assumed in the model and presented in Fig. 6, or whether collective effects will dominate and substantially change these distributions. From the model one expects that the p_T distributions of neutral strange particles produced in the central PbPb collisions will be similar to the corresponding p_T distributions in pPb collisions.

Using the data and extrapolations presented in Fig. 6 one can estimate the average multiplicities of K_s^0 , Λ and $\bar{\Lambda}$ particles produced in pPb collisions. The values were used as input into (13) for calculating the average multiplicities of neutral strange particles produced in central PbPb collisions. The following results were obtained: $\langle n_{K_s^0} \rangle_{PbPb} = 122$, $\langle n_{\Lambda} \rangle_{PbPb} = 163$ and $\langle n_{\bar{\Lambda}} \rangle_{PbPb} = 20$. The prediction for $\langle n_{K_s^0} \rangle_{PbPb}$ is somewhat larger than the value calculated in [2]. This is due to using the actual value of $\langle n_{K_s^0} \rangle_{pPb}$ in (13) and not the more restrictive relation (3) of [2].

5 Conclusion

In this paper a parametrization of neutral strange particle production [2], based on the Additive Quark Model, is further developed. The model for nucleon-nucleon and nucleon-nucleus collisions is extended to nucleus-nucleus collisions assuming that cascading is fully developed only in the overlapping regions of the two colliding nuclei, and that the amount of cascading in these regions is proportional to the incoherent superposition of cascading from the corresponding nucleon-nucleus collisions. With these assumptions, it is shown how the production of neutral strange particles in nucleus-nucleus collisions can be derived from the nucleon-nucleon and appropriate nucleon-nucleus data. The average multiplicities and the rapidity and transverse momentum distributions of neutral strange particles in central SS collisions at 200 GeV per nucleon were calculated from the NN and pS experimental data. The agreement between the model results and the experimental SS data suggests the presence of similar strange particle production mechanisms in pS and SS collisions.

Finally the model predictions for the average multiplicities and the rapidity distributions of neutral strange particles were calculated for central PbPb collisions at 200 GeV per nucleon, using extrapolations of the available pAu and pPb experimental data.

In order to perform more stringent tests of the underlying hypothesis that production mechanisms already present in NN and pA collisions can also describe strange particle production in AB reactions, one clearly needs more comprehensive and precise pp and pA experimental data.

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Figure Captions

Fig. 1

Schematic diagram of a collision of two nuclei with mass numbers A and B at impact parameter b . A' and B' (dashed areas) are the numbers of nucleons participating in the collision.

Fig. 2

Rapidity distributions of K_s^0 (a), Λ (b) and $\bar{\Lambda}$ (c) particles in pS collisions at 200 GeV from [6] (dots). The parametrized extrapolations to the full rapidity range are shown by the full lines. A slightly different parametrization for the Λ particles is shown by the dashed curve.

Fig. 3

Rapidity distributions of K_s^0 (a), Λ (b) and $\bar{\Lambda}$ (c) particles in central SS collisions at 200 GeV per nucleon from [6] (dots). The model predictions are shown by the full lines. The dashed line in (b) corresponds to a parametrization of the Λ rapidity distribution in pS collisions as represented by the dashed line in Fig. 2b.

Fig. 4

The parametrizations for the transverse momentum distributions of K_s^0 (a), Λ (b) and $\bar{\Lambda}$ (c) in NN collisions (dotted curves) and pS collisions (dashed curves) at 200 GeV. The model predictions for central SS collisions at 200 GeV per nucleon are shown by the solid curves. The results for NN and pS collisions are normalized to the SS results at $p_T = 100$ MeV/c.

Fig. 5

Transverse momentum distributions of K_s^0 (a), Λ (b) and $\bar{\Lambda}$ (c) particles in central SS collisions at 200 GeV per nucleon from [6] (dots). The model predictions are shown by the full lines. Open circles in (c) show the model prediction for the $\bar{\Lambda}$ particles when experimental data points from pS collisions are used as input into (25).

Fig. 6

Rapidity distributions of K_s^0 (a), Λ (b) and $\bar{\Lambda}$ (c) particles produced in pAu collisions (dots) from [9] and pPb collisions (open squares) at 200 GeV from [11]. The parametrized extrapolations to the full rapidity range are shown by the full lines.

Fig. 7

The model predictions for the rapidity distributions of K_s^0 (a), Λ (b) and $\bar{\Lambda}$ (c) particles produced in central PbPb collisions at 200 GeV per nucleon.

Fig. 1

Fig. 2

Fig. 3

Fig. 4

Fig. 5

Fig. 6

Fig. 7