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HEAVY ION PHYSICS

Exotic Particle Searches with STAR at RHIC

Sonia Kabana[1,2] for the STAR Collaboration

[1] Yale University, 06520 New Haven, USA and
[2] University of Bern, 3012 Bern, Switzerland

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Abstract. We present preliminary results of the STAR experiment at RHIC on exotic particle searches in minimum bias Au+Au collisions at $\sqrt{s_{NN}} = 200$ GeV. We observe a narrow peak at $1734 \pm 0.5 \pm 5$ MeV in the ΛK_s^0 invariant mass with width consistent with the experimental resolution of about 6 MeV within the errors. The statistical significance can be quantified between 3 and 6 σ depending on cuts and methods. If this peak corresponds to a real particle state it would be a candidate for the N^0 or the Ξ^0 $I = 1/2$ pentaquark states.

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1. Introduction

Hadrons made by 4 quarks and one antiquark, called pentaquarks, were predicted long time ago (e.g. [1]). Pentaquark states have been searched for in the past without success until the recent finding of a candidate for the Θ^+ state first by the LEPS Collaboration [2] and by other experiments [3], motivated by [4]. Candidates for other pentaquarks have been presented recently, in particular for the $\Xi^{--}(1862)$, $\Xi^-(1850)$, $\Xi^0(1864)$ [5] and the $\Theta_c^0(3099)$ [6].

In this article we present preliminary results of the STAR (Solenoidal Tracker At RHIC) experiment at RHIC (Relativistic Heavy Ion Collider) on a search for the Ξ^0 $I = 1/2$ as well as for the N^0 pentaquark states in the decay mode ΛK_s^0. Since there may be many pentaquark multiplets one may expect more than one Ξ^0 and N^0 state to appear.

2. Experimental Setup

This analysis presents results from data of minimum bias Au+Au collisions at $\sqrt{s_{NN}} = 200$ GeV, which were recorded in the 2001 run with the STAR detector at RHIC. A detailed description of the STAR experimental setup can be found

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in Ref. [7]. The present analysis is based on charged particle trajectories measured and identified with the help of a large cylindrical time projection chamber (TPC) [8] with full azimuthal coverage, located inside a 0.5 Tesla solenoidal magnet allowing for momentum reconstruction. The TPC allows for the direct identification of charged particles with small momenta by measuring their ionization energy loss (dE/dx) [8]. Indirect identification of charged or neutral particles decaying at least partly into charged measured particles inside the TPC can be obtained with methods based on the topology of their decay (e.g. Λ, Ξ, Ω, $\mathrm{K}^{\pm}$ etc. decays) [9].

3. Data Analysis Techniques

In the present analysis we investigate the invariant mass of $\Lambda\mathrm{K}^0_s$. We required the Z position (Z is along the beam direction) of the main interaction vertex to be ±25 cm around the center of the TPC. The number of Au+Au events after this cut is 1.65×10^6 and comprise the total available statistics of minimum bias Au+Au data at 200 GeV prior to the 2004 STAR run.

We search for $V0$ topologies which are candidates for the decays $\Lambda \rightarrow \mathrm{p}\,\pi^-$ ($\overline{\Lambda} \rightarrow \overline{\mathrm{p}}\,\pi^+$) and $\mathrm{K}^0_s \rightarrow \pi^+\pi^-$ requiring the finding of a secondary $V0$ vertex, at least 6 cm away from the primary interaction vertex. The Distance of Closest Approach (DCA) between the positive and the negative $V0$ tracks (so-called $V0$ daughters) is required to be less than 0.8 cm. Each of the daughters is required to not originate from the primary interaction vertex (PV). In particular, the DCA of the positive track to PV must be greater than 1 cm for the Λ hypothesis, 2.5 cm for the $\overline{\Lambda}$ hypothesis and 1.3 cm for the K^0_s hypothesis. The DCA of the negative track to PV must be greater than 2.5 cm for the Λ hypothesis, 1 cm for the $\overline{\Lambda}$ hypothesis and 1.3 cm for the K^0_s hypothesis. Since the pentaquarks are expected to decay strongly we require the $V0$'s to point back to the primary vertex, in particular to have a DCA to PV less than 0.4 cm.

We require at least 15 hits (out of maximally 45) for each track. We require that the Λ and K^0_s candidates which are combined to estimate their invariant mass do not share any tracks. The dE/dx of the $V0$ daughters is required to be within 3 σ around the expected dE/dx value for the assumed particle hypothesis. In order to enable the dE/dx identification we restrict the momenta of each track in the region in which a good dE/dx identification is possible [8], namely below 0.7 GeV for (anti)protons and below 0.5 GeV for pions. The latter cut on the momenta of the π coming from the decay of the K^0_s is motivated independently by Monte Carlo results for particles with mass in the range below 2 GeV and above the threshold for decay to $\Lambda\mathrm{K}^0_s$, which show that the momentum of the K^0_s is contained below 1–1.5 GeV, depending on the assumed initial transverse momenta of the parent. We select the K^0_s and Λ candidates within a window of ±35 MeV and ±10 MeV around their mean invariant masses which are shown in Fig. 1 (top panels). We accept only unambiguously identified K^0_s, Λ and $\overline{\Lambda}$ as illustrated in Fig. 1 (bottom panel) for K^0_s and Λ.

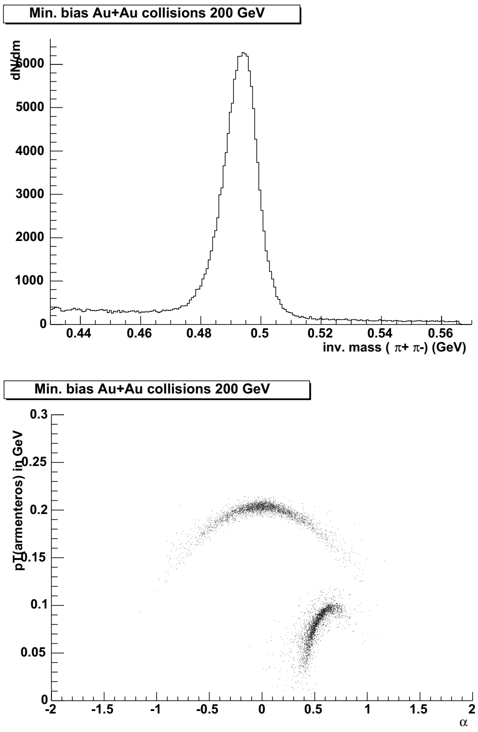

Fig. 1. Top panels, left and right: Invariant masses of $m(\pi^+\pi^-)$ and $m(\mathrm{p}\,\pi^-)$ for the selected K^0_s and Λ candidates. Bottom panel: Armenteros plot for the selected Λ and K^0_s candidates

4. Results

Figure 2 shows the invariant mass of Λ and K^0_s which have been preselected as discussed in the previous section. The data are minimum bias Au+Au collisions at $\sqrt{s_{NN}} = 200$ GeV while the upper ~10% of the $\sigma_{\mathrm{tot,\ Au+Au}}$ has been excluded from the analysis to reduce the background from the highest multiplicity events. The line shows the mixed event background expectation, which has been calculated using Λ and K^0_s originating from different events.

The mixed event distribution has been normalized to the 'signal+background' distribution in the region below 1.7 GeV and between 1.76 and 2 GeV. Other choices of smaller normalization regions did not influence the results significantly. We use bins of 3 MeV. We observe a peak at 1734 MeV. When we fit this peak with a Gaussian distribution restricted to the region of ± 3 MeV around the mean, plus a polynomial function for the background from 1.65 to 1.8 MeV, using 1 MeV bins, we obtain a Gaussian width of 4.6 ± 2.4 MeV and a $\chi^2/\mathrm{DOF} = 1.09$.

We obtain similar results when using a Breit–Wigner distribution and different bin sizes. The width is consistent with the experimental resolution within the errors. The latter has been estimated with Monte Carlo generated particles with

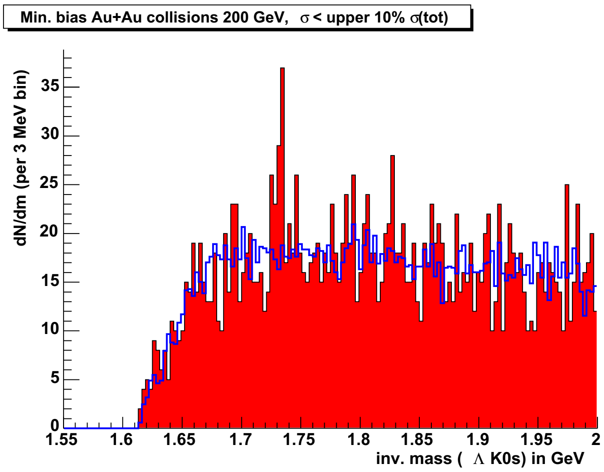

Fig. 2. Invariant mass distribution ΛK_s^0 (in GeV) in min. bias Au+Au collisions at $\sqrt{s_{NN}}$ = 200 GeV measured with the STAR experiment together with the estimated background using the mixed events technique (line). We use 3 MeV bins. The upper ~10% of the $\sigma_{\mathrm{tot,\ Au+Au}}$ has been excluded

mass 1730 MeV, flat dn/dy distribution ±1.5 units around midrapidity, exponential spectrum in m_T with inverse slope 250 MeV and Breit–Wigner width of 1 MeV, decaying into ΛK_s^0, which have been tracked through the Geant STAR simulation and have been embedded in real p+p STAR data. We could reconstruct the initial Monte Carlo particles with a mass of 1729 ± 0.7 MeV and a width of 6.3 ± 1.7 MeV which is dominated by the experimental resolution.

The Gaussian fit to the data described above results in a mass of 1733.6 ± 0.5 MeV with a systematic error of ~5 MeV. The latter has been deduced from the deviation of the K_s^0 mass from the mean K_s^0 mass given by the PDG [10] in the appropriate region of transverse momentum. The values for the mean position of the peak and the width obtained by using Breit–Wigner fits and/or Gaussian fits and/or different binning and/or different analysis cuts were consistent with the above values within the statistical errors. Assuming the mass of 1734 MeV and considering the region of ±1.5 σ around the mean of the mass we obtain a significance of $S/\sqrt{B} = 30.6/\sqrt{35.4} = 5.1$, while a more conservative estimate gives $S/\sqrt{S+B} = 3.8$. The ratio of the signal to its own error is $S/\sigma(S) = S/\sqrt{S+2B}$ $= 3.04$. Furthermore we observe a peak at 1693 ± 0.5 (stat) ±5 (syst) MeV with a significance of $S/\sqrt{B} = 2.92$. The width is similar to the previously discussed peak at 1734 MeV.

Figure 3 shows the same data as Fig. 2, however, with bin size 1.5 MeV, in order to illustrate that the 1734 peak in Fig. 2 is not asymmetric, but the left shoulder seen there is a well separated peak at mass 1726.6 ± 0.5 MeV. Figure 4 shows the same distribution as Fig. 2 but without any restriction on the event centrality. The significance is $S/\sqrt{B} = 40.55/\sqrt{83.45} = 4.44$ in this case. We obtain the best significance of $S/\sqrt{B} = 19.4/\sqrt{10.6} = 5.93$ for semiperipheral events.

In the following we discuss some possible sources of systematic errors. One source of systematic errors especially in high multiplicity events is the fact that the

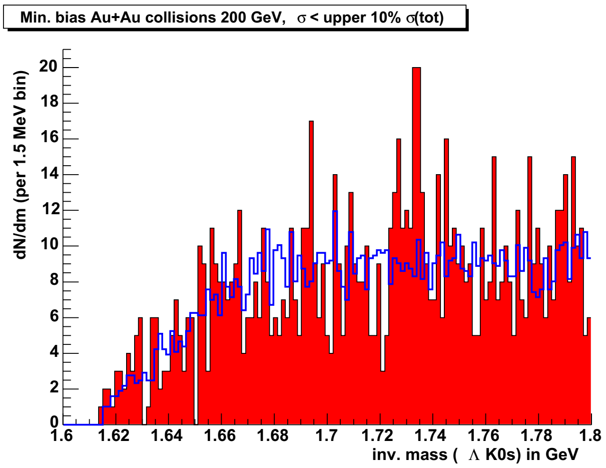

Fig. 3. Invariant mass distribution ΛK_s^0 (in GeV) in min. bias Au+Au collisions at $\sqrt{s_{NN}} = 200$ GeV measured with the STAR experiment together with the estimated background using the mixed events technique (line). The upper ~10% of the $\sigma_{\text{tot, Au+Au}}$ has been excluded. We use 1.5 MeV bins

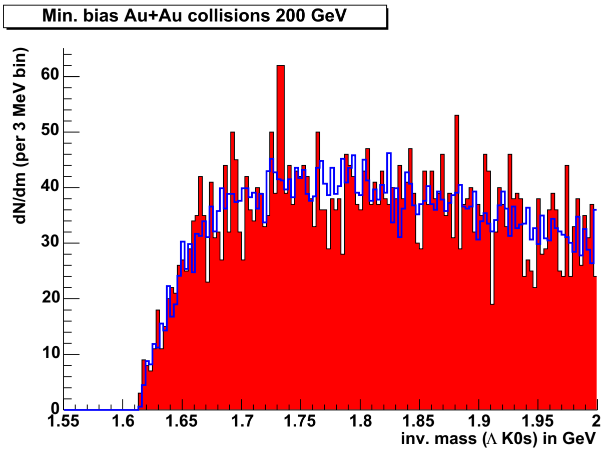

Fig. 4. Invariant mass distribution ΛK_s^0 (in GeV) in min. bias Au+Au collisions at $\sqrt{s_{NN}} = 200$ GeV measured with the STAR experiment (red) together with the estimated background using the mixed events technique (line). We use 3 MeV bins

tracking software may split a real trajectory into two tracks which will have a very similar momentum and can lead to selfcorrelations and to peaks in invariant mass distributions. We excluded split tracks from the analysis by demanding at least 25 hits on each track, as the maximum number of hits is 45. We also studied the effect on the invariant mass ΛK_s^0 if one selects either the same track taken e.g. as pion of the Λ and of the K_s^0 or if one selects only the (same charge) tracks with momentum differences below (respectively above) e.g. 100 MeV. The 100 MeV is well above the expected momentum difference on the basis of the momentum resolution in this momentum range [8]. None of these studies gave a peak near 1734 or 1693 MeV.

Another possible source of systematic errors is the possibility that the proton of the Λ and the π^- of the K_s^0 or the Λ come from a $\Delta(1232)$ decay. As the sum of the

$\Delta(1232)$ mass and the $K_s^0(497.7)$ mass gives 1729.7 MeV this could lead to a peak at 1734 MeV, given the STAR systematic error of about 5 MeV. This possibility has been investigated either by cuting harder on the DCA of all tracks to the PV (as the Δ decays right at the primary vertex) or by cutting out cases giving an invariant mass for $p(\Lambda) + \pi^-(K_s^0)$ outside (respectively inside) a window of ±30 MeV around the $\Delta(1232)$ mass. These studies showed that the peak at 1734 MeV cannot be understood as due to the $\Delta(1232) + K_s^0(497.7)$ mass reflection.

5. Discussion

In this section we discuss the possible assignment of the observed peaks, if they would correspond to real particle states. The already known particles decaying into ΛK_s^0 with mass near 1734 MeV namely the N(1710) and N(1720) (with Breit–Wigner masses in the range up to 1740 MeV) have a width of 100 MeV or greater and are therefore not good candidates for the narrow peak seen here at 1734 MeV. This peak is not a candidate for the decay of the Ξ^0 pentaquark with isospin 3/2, as the latter does not decay into ΛK_s^0 due to isospin violation. It is a possible candidate for two pentaquark states: the N^0 with quark content ($\mathrm{udsd\bar{s}}$, $\mathrm{uddu\bar{u}}$) decaying into ΛK^0 and the Ξ^0 with isospin $I = 1/2$ and quark content $\mathrm{udss\bar{d}}$ decaying into $\Lambda \overline{K^0}$. The N^0 can be from the antidecuplet, from an octet [11] or an 27-plet [12], while the Ξ^0 $I = 1/2$ from an octet. In [12] the best estimate of $m(N)$ is ∼1730 MeV. The mass of the N^0 is expected in the approx. range 1650–1780 MeV [11–13]. The Ξ^0 $I = 1/2$ is expected to be near 1700 [11] or it maybe degenerate with the $\Xi^0(1860)$ $I = 3/2$ [14]. The fact that we do not observe a peak above background near 1850 or 1860 MeV disfavors the latter possibility. However, the branching ratio of a possible $\Xi^0(1850\text{–}1860)$ $I = 1/2$ to ΛK_s^0 may be small and we need more statistics to observe it. The mass of the peak at 1734 MeV is in very good agreement with the N mass of ∼1730 MeV suggested by Arndt et al. [13]. In this paper a modified partial wave analysis allows to search for narrow states and presents two candidate N masses, 1680 and/or 1730 MeV with width below 30 MeV.

We do not yet observe a pronounced peak at 1734 or 1693 MeV in the anti-channel $\overline{\Lambda} K_s^0$. This is work in progress. If pentaquarks would be primarily formed through quark coalescence rather than through hadronic interactions in Au+Au collisions at RHIC, the expected antipentaquark to pentaquark ratio is estimated as follows:

$$\overline{\Xi^0}/\Xi^0 \sim \frac{\mathrm{\bar{u}\bar{d}\bar{s}\bar{s}d}}{\mathrm{udss\bar{d}}} \sim \frac{\bar{\mathrm{q}}}{\mathrm{q}} \cdot \left(\frac{\bar{\mathrm{s}}}{\mathrm{s}}\right)^2 \sim 0.90\,,$$

respectively,

$$\overline{N_s^0}/N_s^0 \sim \frac{\mathrm{\bar{u}\bar{d}\bar{s}\bar{d}s}}{\mathrm{udsd\bar{s}}} \sim \left(\frac{\bar{\mathrm{q}}}{\mathrm{q}}\right)^3 \sim 0.73\,,$$

while we used a ratio of $\overline{\mathrm{p}}/\mathrm{p} = 0.73$ [15] and assumed $\overline{\mathrm{s}}/\mathrm{s} = 1$. These values are at production, while further reduction of the ratios can follow from e.g. absorption of the decay products. Therefore, the non-observation of an antiparticle may favor the N^0 hypothesis.

The possible peak we observe at 1693 ± 0.5 MeV is a candidate for the state $\Xi(1690)$ with mass 1690 ± 10 MeV and width below 30 MeV [10].

6. Conclusions

We present preliminary results of the STAR experiment at RHIC on a search for the N^0 and Ξ^0 $I = 1/2$ pentaquarks in minimum bias Au+Au collisions at 200 GeV through the decay channel $\Lambda\mathrm{K}^0_s$. We observe a peak at a mass of 1733.6 ± 0.5 (stat) ± 5 MeV (syst) and width consistent with the experimental resolution of about 6 MeV within the errors, which gains in significance when restricting the upper ~10% of σ_{tot}. We obtain an estimate of the significance of $S/\sqrt{B} = 30.6/\sqrt{35.4} = 5.1$, $S/\sqrt{S+B} = 3.8$ and $S/\sigma(S) = 3.04$. The best significance of $S/\sqrt{B} = 19.4/\sqrt{10.6} = 5.93$ is obtained for semiperipheral events. Systematic studies suggest that this peak is not due to misidentifications or split tracks or to the decay of $\Delta(1232)$. If this peak corresponds to a real particle state it would be a candidate for the N^0 (octet, antidecuplet or 27-plet) and Ξ^0 $I = 1/2$ (octet) pentaquark states. We do not observe a peak near 1850–1860 MeV, disfavoring the picture of degenerate octet and antidecuplet even though a low branching ratio to $\Lambda\mathrm{K}^0_s$ may prevent us from observing a peak. The non observation of a possible antiparticle, while this is work in progress, may favor the N^0 hypothesis and dominant production through quark coalescence.

The ambiguity between Ξ^0 and N^0 can be resolved by searching for their isospin partners $\mathrm{N}^+ \rightarrow \Lambda\mathrm{K}^+$ and $\Xi^- \rightarrow \Lambda\mathrm{K}^-$. This is work in progress as well as searches for the Θ^+ [16]. Furthermore, new data taken in our 2004 run will enhance the statistics of minimum bias Au+Au events by a factor ~10–15.

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