Searches for penta-quark particles and study of proton-kaon correlation in Au+Au collisions at $\sqrt{s_{NN}}$ = 200 GeV at RHIC/STAR

Runze Zhao(UCLA), *for the STAR Collaboration*

Abstract

The proton-kaon (p-K$^+$, p-K$^-$, $\bar{p}$ -K$^+$ and $\bar{p}$ -K$^-$) correlations can be sensitive to several physics topics in heavy-ion collisions. The same-charge p-K correlation could be sensitive to a possible formation of penta-quark candidates with quark contents (uudu-sbar). The opposite-charge p-K correlation measurement could be sensitive to the formation of Λ(1520) and Λ(1405). In particular, the Λ(1405) was suggested by recent Lattice QCD calculations [1] as a molecular proton-kaon state. The mass of Λ(1405) is below the p-K threshold, and its possible coalescence formation from p-K could deplete the p-K correlation at small two-particle relative momenta.

Introduction

- Penta-quark Candidate: $\Theta^{++}(uuud\bar{s})$

Invert decay mode to get distribution of invariant mass of the decay parent. If the penta-quark particle Θ^{++} exists, we expect to see a signal around 1.5 GeV/c^2.

Decay Mode: $\Theta^{++} \to K^+ + p$, $\Theta^{--} \to K^- + \bar{p}$ (anti-particle)

Special Relativity: $m_\Theta = \sqrt{E_\Theta^2 - \vec{p}_\Theta^2} = \sqrt{(E_K + E_p)^2 - (\vec{p}_K + \vec{p}_p)^2}$ (c = 1)

Background Method:

1. Rotational Background:

Accumulate collision events with symmetric insert angles (multiple of 60° in this case).This method can reduce all possible correlation dependence on insert angles.

2. Mixed-Event Background:

Pair decay daughters from different collision events to eliminate possible correlation dependence.

- Λ(1405) and Λ(1520) (same methods as Θ^{++})

Decay Mode: $\Lambda \to K^+ + \bar{p}$ / $\Lambda \to K^- + p$

- p-K Momentum Correlation:

Investigate the momentum of decay daughters in center-of-mass frame $|k^*|$, and the distribution of its correlation function. Lorentz transformation is used.

Correlation Function:

$$CF = \frac{Q_{FG}(|\vec{k}^*|)}{Q_{BG}(|\vec{k}^*|)}$$

$Q_{FG}(|\vec{k}^*|)$: Distribution of $|k^*|$ in real collisions, i.e. foreground.

$Q_{FG}(|\vec{k}^*|)$: Distribution of $|k^*|$ in simulated collisions, i.e. background (Mixed-Event Background).

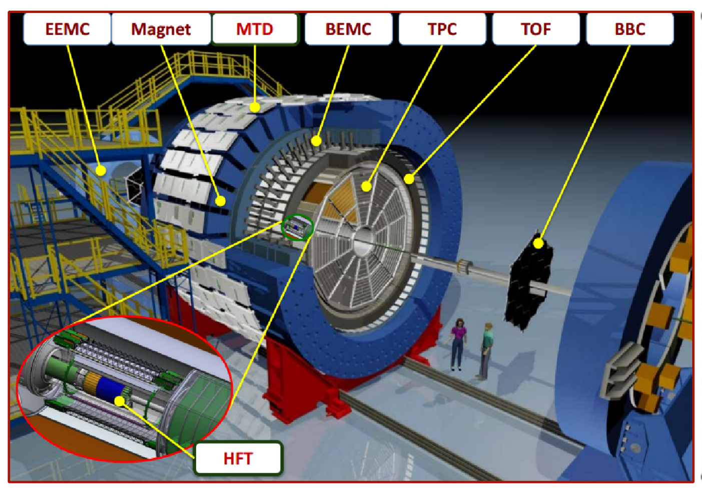
Calculation:

$$|k^*| = \sqrt{\frac{(m_\Lambda^2 + m_K^2 - m_P^2)^2}{4m_\Lambda^2} - m_K^2} \quad (1)$$

Direct Result:

for Λ(1520): $|k^*| \approx 0.243$ GeV/c

for Λ(1405): the formation is below K-p threshold → No direct signal for Λ(1405).



Experiment:

Data of Au+Au at 200GeV were collected by STAR detector in RHIC run 2011.

Particle Identification:

TPC(Time Projection Chamber) dE/dx and TOF are used for proton/pion/kaon identification;

Results I – Invariant Mass

Θ^{++}:

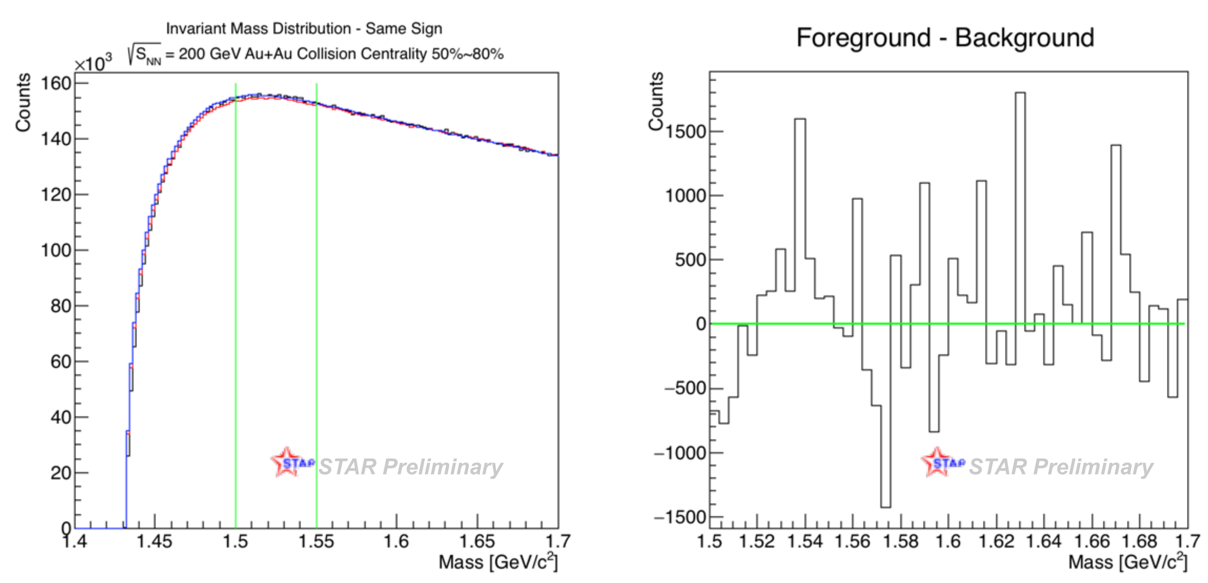


Figure 1. Invariant mass distribution of same sign particles (K$^+$-p and K$^-$-$\bar{p}$). The histogram on the left side indicates invariant mass distribution in foreground and backgrounds using two methods. The black line represents foreground; the red line is rotational background; the blue line is mixed-event background. The histogram on the right side is the foreground subtracted by Mixed-Event background. The histogram of foreground subtracted by Rotational background is similar.

Figure 1 shows that there is no clear signal observed in both background methods. The expected range for signal is from 1.5 GeV/c^2 to 1.55 GeV/c^2, indicated between the two vertical green lines in left side.

Λ(1520):

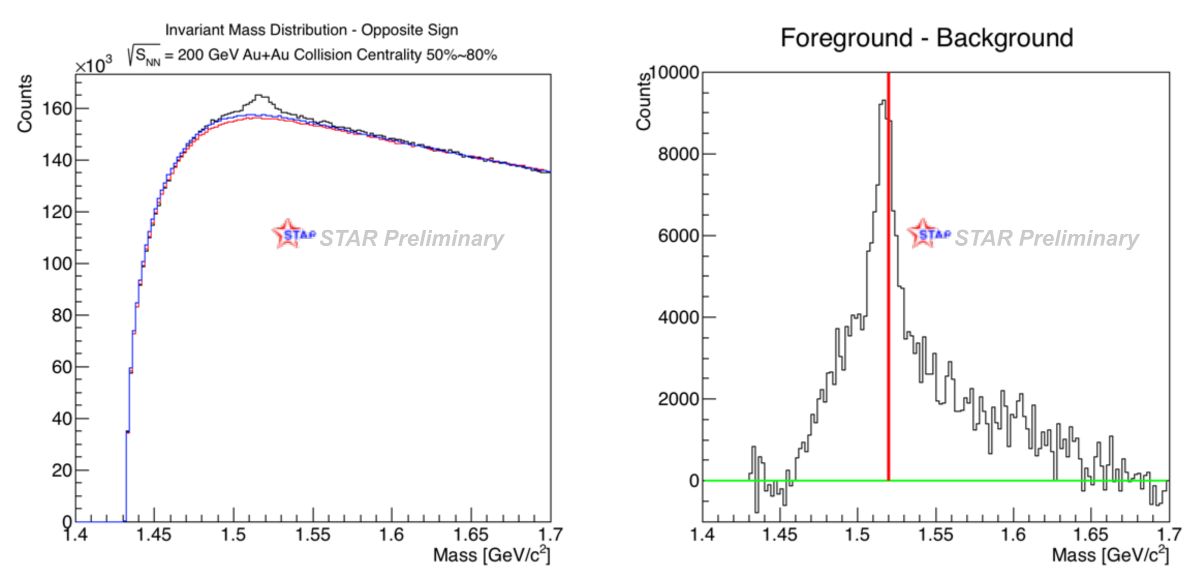


Figure 2. Invariant mass distribution of opposite sign particles (K$^-$-p and K$^+$-$\bar{p}$). The histogram on the left side are foreground and backgrounds created through either Mixed-Event method and Rotational background method. The color correspondence is the same as in Figure1. The histogram at right side is the foreground subtracted by Rotational background. The histogram of foreground subtracted by Mixed-Event background is similar.

Figure 2 shows a clear signal at 1.52 GeV/c^2, indicated by the vertical red line in histogram at right side. The result shows a solid evidence of formation of Λ(1520) particle.

Results II – Momentum Correlation Function

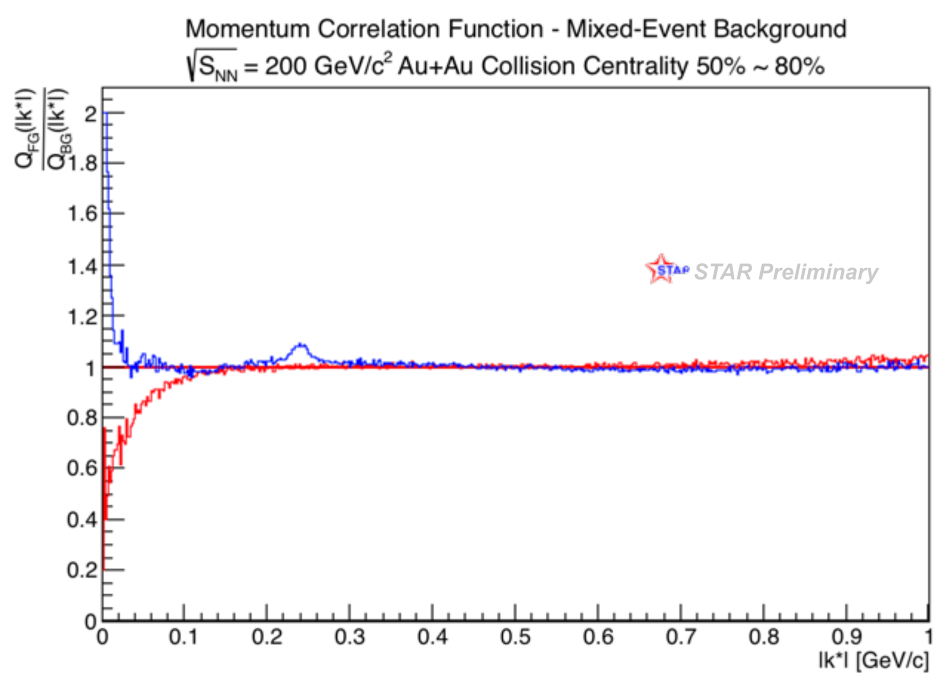


Figure 3. Correlation function of momentum |k*| of decay daughters (K and p) in center of mass frame. ***The Y-axis is the ratio of foreground entries Q_{FG} to background entries Q_{BG} for each bin of histograms.*** The blue line represents the correlation function of opposite sign particles, and the red line represents that of same sign particles.

Figure 3 shows the momentum correlation functions of both same sign pair and opposite sign pair. At the low momentum range the ratio for opposite sign pair increases and the ratio for same sign pair decreases. This result is consistent with coulomb effect as particles of the same charge tends to repel each other and therefore reduce the possibility at low relative momenta. (Vice versa for particles of opposite charges.)

However, a sink below 0.5 GeV/c on the correlation function of opposite sign pair is observed. This non-symmetry could be due to a depletion effect of formation of Λ(1405) particle. This nontrivial phenomenon needs further investigation and could be used to study the inner structure of Λ(1405). A theoretical study [1] shows that the Λ(1405) could actually be a molecule structure of proton-kaon state. It predicts an observable effect on momentum correlation function, which is one of future work of this study.

A signal around 0.25 GeV/c is also observed on correlation function of opposite sign pair, as shown in Figure 4. According to equation (1), the formation of Λ(1520) will result in a signal at about 0.243 GeV/c (Mass of proton and kaon used: m_p = 0.938272 GeV/c^2 and m_K = 0.493667 GeV/c^2), which is indicated by the vertical red line. The green line at the ratio of 1 indicates the equal counts in foreground and Mixed-Ev ent background.

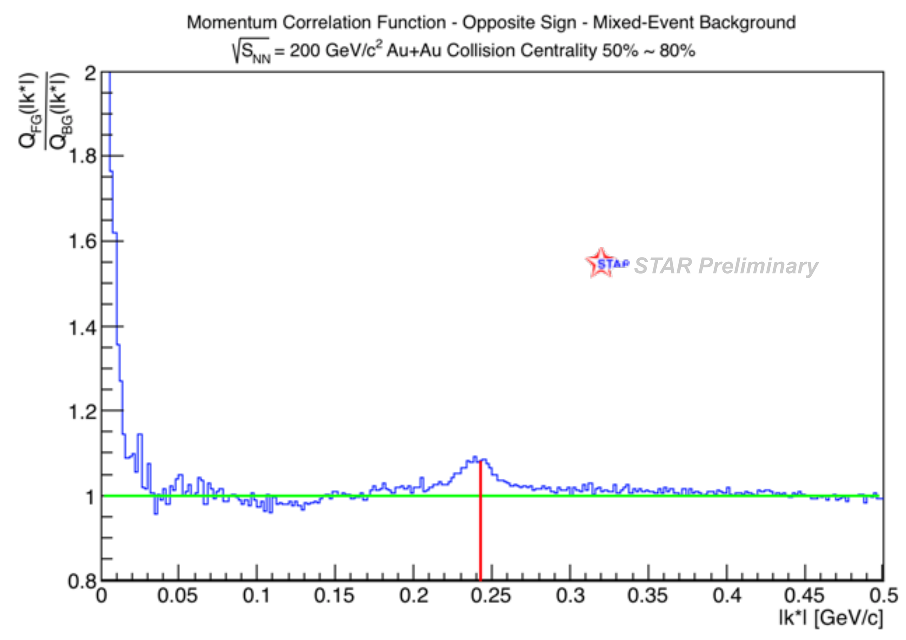


Figure 4. Signal of momentum correlation function for opposite sign particles.

Summary and Future Work

- No signal is observed for penta-quark candidate Θ^{++} from the p+K channel.
- Formation of Λ(1520) is observed in both mass distribution and momentum correlation.
- Investigation on momentum correlation function at low energy range will be done in future work, especially for study on the structure of Λ(1405) particle.

Reference

[1]. J. M.M. Hall et al, Phys Rev Lett. 114(2015)132002

Acknowledgement

Thanks to Prof. Huan Z. Huang for mentorship and to Dr. Gang Wang and the STAR collaboration for guidance and insight. Thanks to Brian Zhu, Liwen Li, Feng Zhao, Yuxi Pan, Neha Shah and Roli Esha for patient help on solving my coding and other problems.

Office of Science
U.S. DEPARTMENT OF ENERGY