Measurements of Kaon Femtoscopy in Au+Au Collisions at $\sqrt{s_{\mathrm{NN}}}$ = 3.0 - 4.5 GeV by the STAR Experiment

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Strangeness in Quark Matter

Outline

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- ❖ **STAR Experimental Setup**
- ❖ **Analysis Details**
- ❖ **Results and Discussions**
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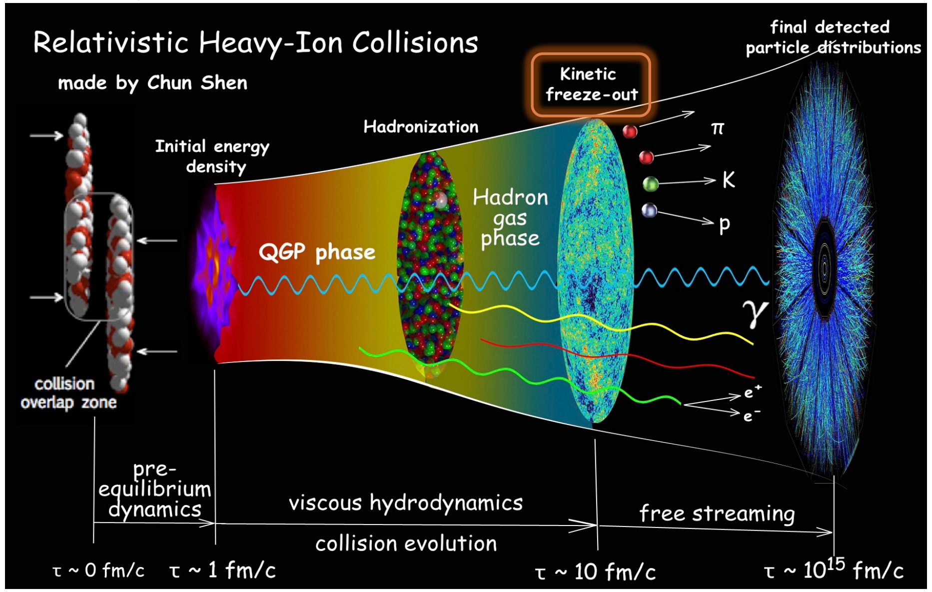
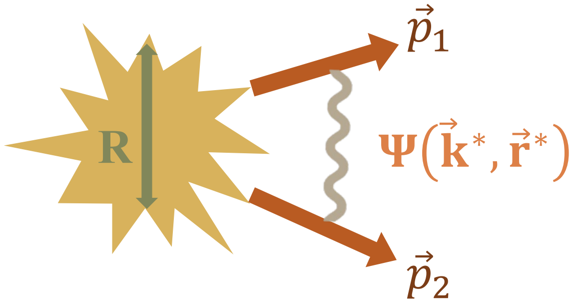
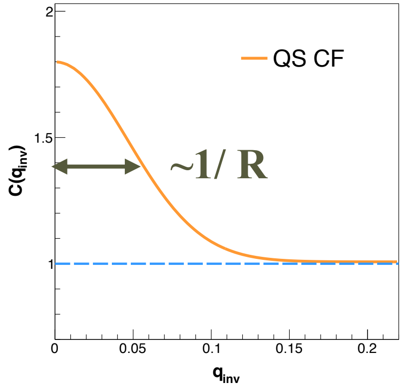
  - **2) Extracted parameters and m_T - scaling**
- ❖ **Summary**

Introduction - femtoscopy

https://u.osu.edu/vishnu/2014/08/06/sketch-of-relativistic-heavy-ion-collisions/







$$C(q_{inv}) = \int S(\vec{r}^*)|\Psi(q_{inv}, \vec{r}^*)|^2 d^3\vec{r}^* = \mathcal{N}\frac{N_{same}(q_{inv})}{N_{mixed}(q_{inv})}$$

Assumed **Determined** **Measured**

- **Decode space and time evolution of source at kinetic freeze-out.**
- **Why study kaons?**
  1) less contribution from resonances decay
  2) smaller rescattering cross-section
- **Two-particle correlations are sensitive to:**
  1) Quantum Statistics (QS);
  2) Final State Interactions (FSI)

- If we assume that we know the **emission function**, the **measured correlation function** can be used to determine **parameters of final state interactions**.

$\vec{r}^*$: relative distance of the emitters in the Pair Rest Frame (PRF: in which frame the total momentum of the pair is zero)

$S(\vec{r}^*)$: emission function

q_{inv}: relative invariant momentum in PRF

$q_{inv} = \sqrt{|\mathbf{q}|^2 - q_0^2}$, where $\mathbf{q} = \mathbf{p_1} - \mathbf{p_2}$, $q_0 = E_1 - E_2$

For identical particles, $q_{inv} = 2k^*$

$\Psi(q_{inv}, \vec{r}^*)$: two-particle wave function

$\mathcal{N}\frac{N_{same}(q_{inv})}{N_{mixed}(q_{inv})}$: measured correlation function

Introduction - Parametrization

❖ **CF including only Quantum Statistical(QS) effect:**

$$CF(q_{inv}) = 1 + \lambda e^{-[R_G^2 q_{inv}^2]}$$

❖ **For K⁺-K⁺ and π^+- π^+, Bowler-Sinyukov[1] method to include FSI(Coulomb effect):**

Coulomb effect QS effect

$$CF(q_{inv}) = N[(1-\lambda) + K_{coul}(q_{inv}, R_G)\lambda\left(e^{-[R_G^2 q_{inv}^2]} + 1\right)]$$

R_G: source radii parameter;
λ: correlation strength;
N: normalization factor;

$$F_1(z) = \int_0^z dx \frac{e^{x^2-z^2}}{z};\ F_2(z) = \frac{1-e^{-z^2}}{z}.$$

scattering amplitude: $f(k^*) = \frac{f_0(k^*)+f_1(k^*)}{2}$

$f_I(k^*) = \frac{\gamma_I}{m_I - s - i\gamma_I k^* - i\gamma_I' k_I'}$, $s = 4(m_K^2 + k^{*2})$

I = 0 or 1 for the f_0 or a_0;

m_I: mass of the resonance;

γ_I and γ_I': couplings of the resonances to their decay channels;

k_I': momentum in the second decay channel.

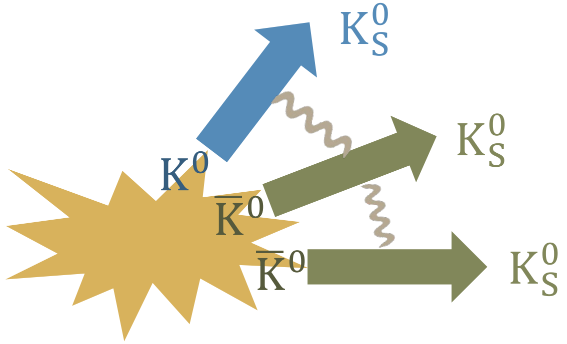
❖ **For K_S^0 - K_S^0, Lednický-Lyuboshitz (L-L)[2] approach to include FSI(Strong interaction):**

QS effect Strong interaction through $f_0(980)$ /$a_0(980)$ resonances

$$CF(q_{inv}) = 1 + \lambda\left(e^{-[R_G^2 q_{inv}^2]} + \frac{1-\epsilon^2}{2}\left[\left|\frac{f(k^*)}{R_G}\right|^2 + \frac{4Re[f(k^*)]}{\sqrt{\pi}R_G}F_1(q_{inv}R_G) - \frac{2Im[f(k^*)]}{R_G}F_2(q_{inv}R_G)\right]\right)$$

abundance asymmetry ϵ

$$\epsilon = \frac{K - \overline{K}}{K + \overline{K}}$$



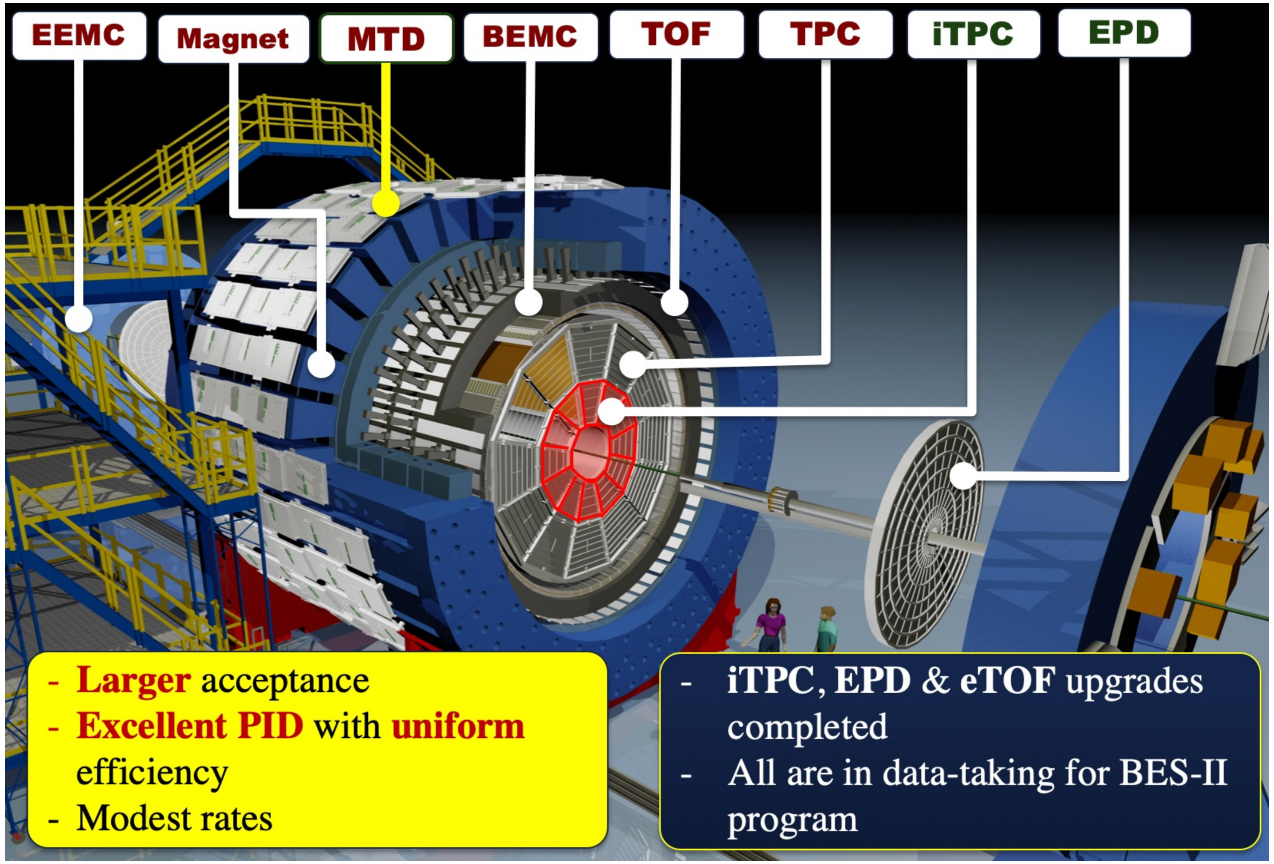
Resonance parameters:

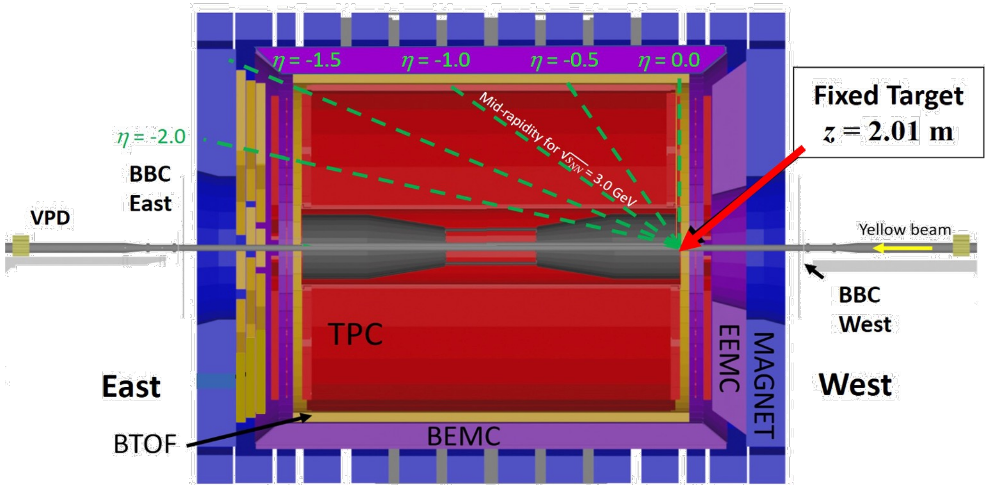
	m_{f_0}	γ_{f_0KK}	$\gamma_{f_0\pi\pi}$	m_{a_0}	γ_{a_0KK}	$\gamma_{a_0\pi\eta}$
Antonelli[3]	0.973	2.763	0.5283	0.985	0.4038	0.3711

- K_S^0-K_S^0 consist of K^0-K^0 ($\overline{K}^0$-$\overline{K}^0$) and K^0-$\overline{K}^0$ states
- Kaon abundance asymmetry can be extracted by K_S^0-K_S^0 CF

[1] Phys. Lett. B, 432(3-4), 248-257 (1998)
[2] J.Nucl.Phys. 35, 770 (1982)
[3] eConfC020620, THAT06 (2002)

STAR Experimental Setup





Main sub-detectors for PID

- ❖ Time Projection Chamber (TPC): Ionization energy loss (dE/dx)
- ❖ Time of Flight (TOF): m^2

BES-II Upgrades

- ❖ Inner-Time Projection Chamber (iTPC)

  Extended eta acceptance and improved tracking and dE/dx resolution
- ❖ Endcap Time of Flight (eTOF)

  Extended PID coverage
- ❖ Event Plane Detector (EPD)

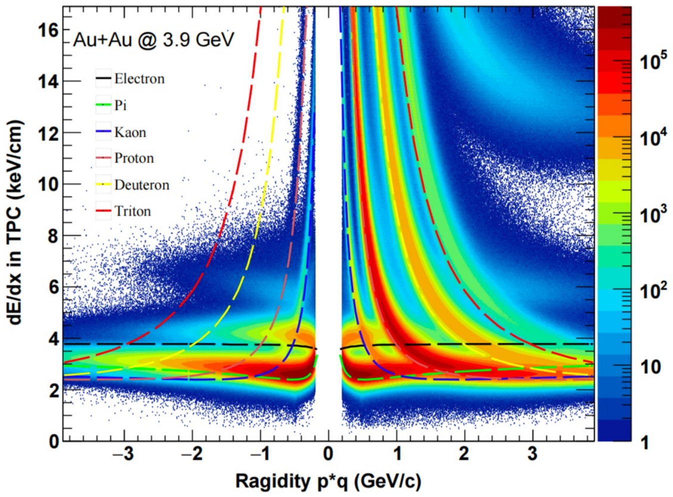
  Improved Event plane resolution

Fixed-Target Experiment

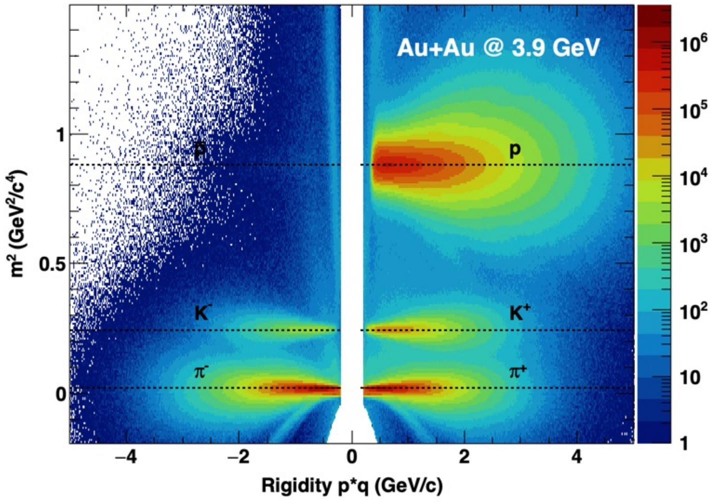
- ❖ FXT extends energy reach down to 3 GeV (μ_B = 750 MeV)

Analysis details – PID, reconstruction

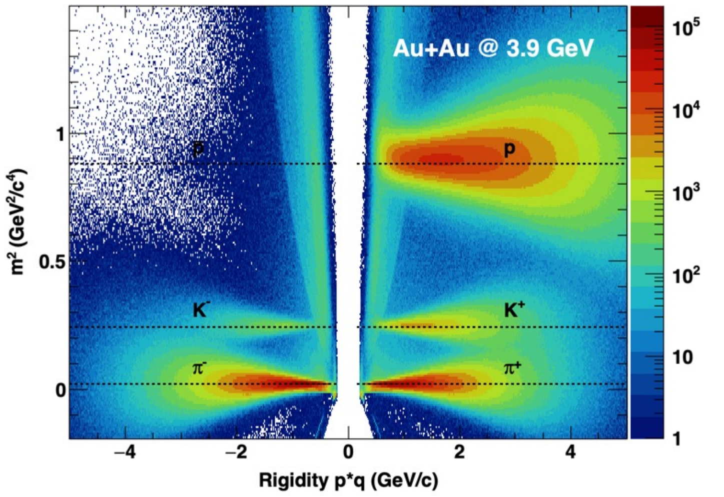
TPC



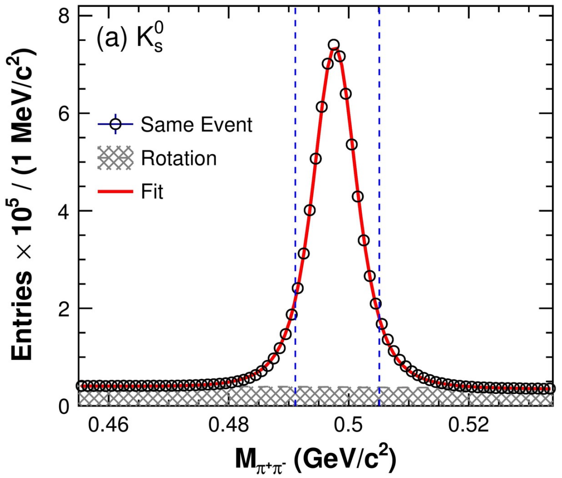
bTOF

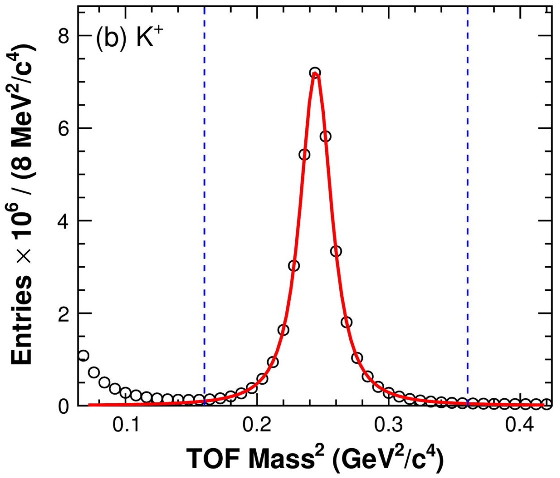


eTOF



3.9 GeV Au + Au Collisions at RHIC

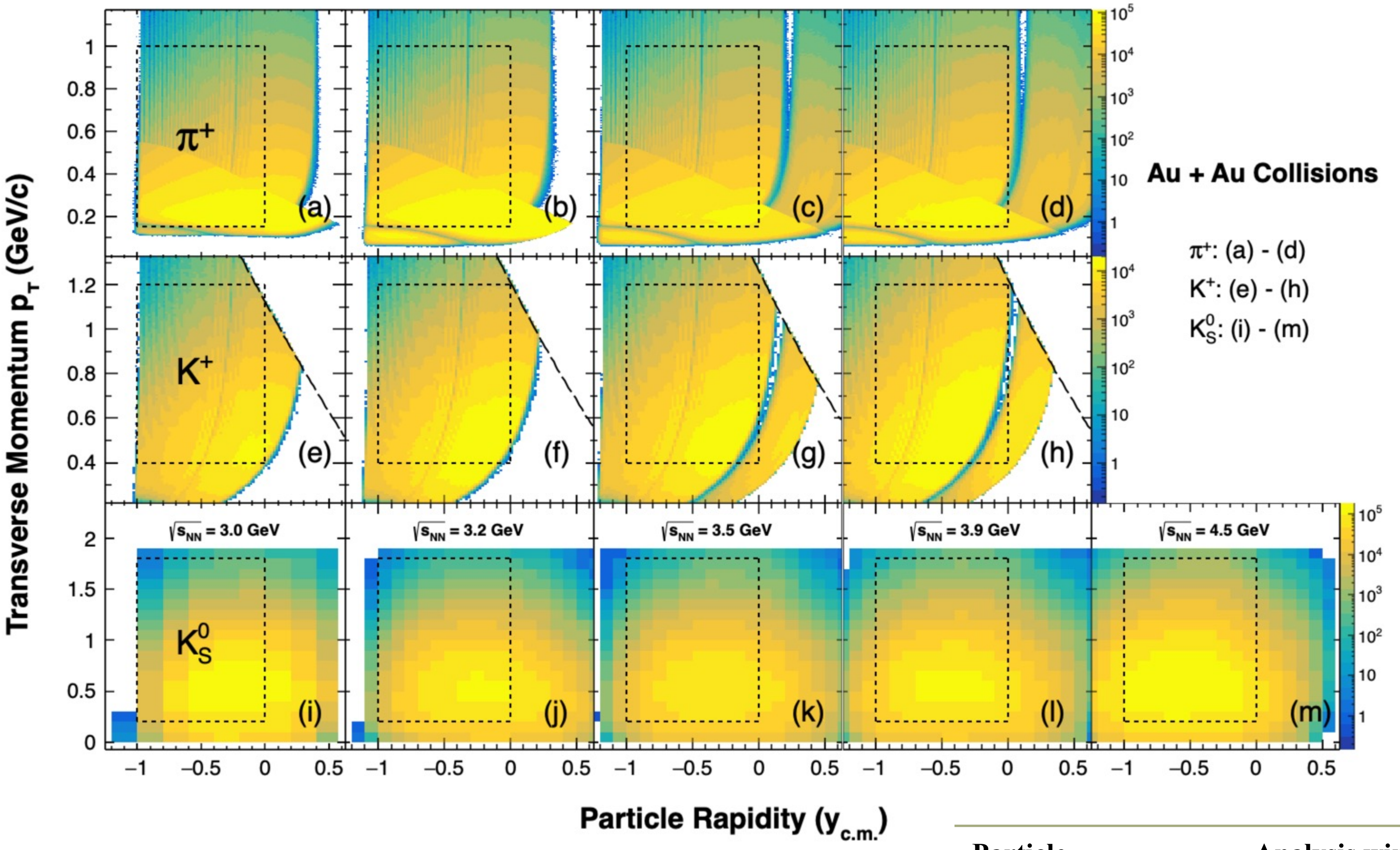




- ❖ π^+ and K^+ particles identified by TPC and TOF
- ❖ K^0_S hadrons reconstructed using invariant mass method:

  $K^0_S \rightarrow \pi^+\pi^-$

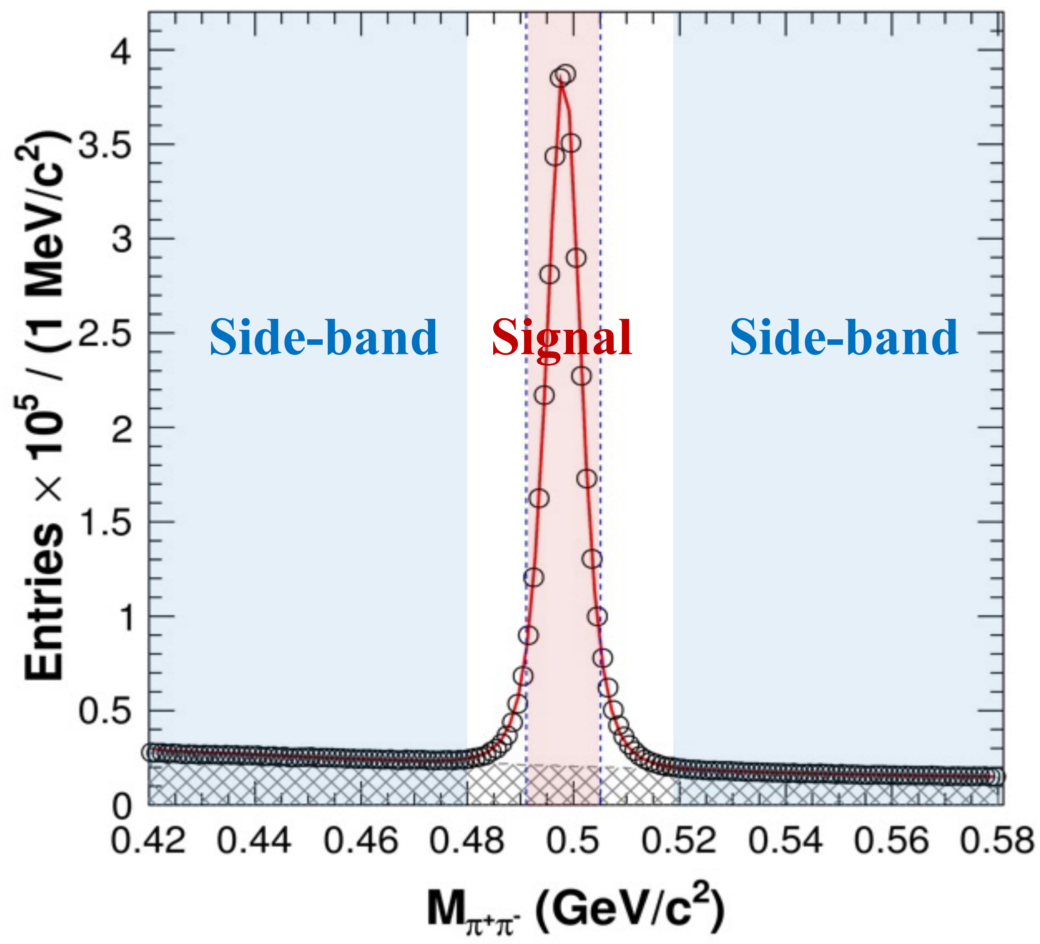
Analysis details – acceptance



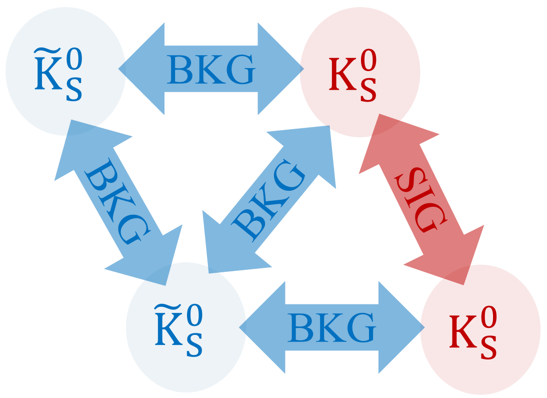
- K^0_S reconstruction: KF Particle package
- Good coverage from beam-rapidity to mid-rapidity

Particle	Analysis window
π^+	$-1.0 < y < 0$, $0.15 < p_T < 1.0$ (GeV/c)
K^+	$-1.0 < y < 0$, $0.4 < p_T < 1.2$ (GeV/c)
K^0_S	$-1.0 < y < 0$, $0.2 < p_T < 1.8$ (GeV/c)

Analysis details – Purity correction



Combinatorial background



K_S^0: Signal

$\widetilde{K}_S^0$: Background

Signal pair: K_S^0-K_S^0

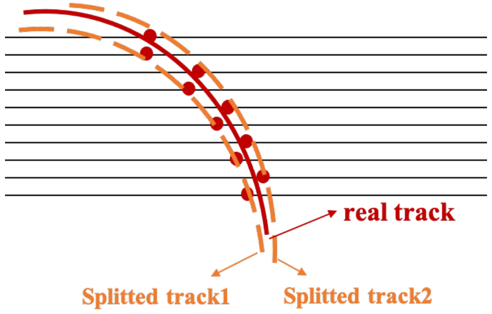
Background pair: K_S^0-$\widetilde{K}_S^0$, $\widetilde{K}_S^0$-$\widetilde{K}_S^0$

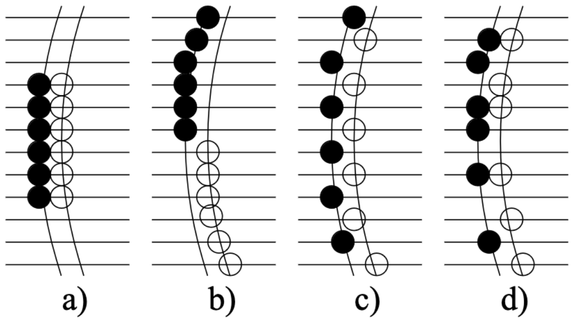
$$C(q_{inv}) - 1 = \omega_{Pair\ Purity}[C_{pure}(q_{inv}) - 1] + (1 - \omega_{Pair\ Purity})[C_{BKG}(q_{inv}) - 1]$$

measured — we want this — background

Analysis details – Pair track correction

Track-splitting effect





SL = -0.5 SL = 1 SL = 1 SL = 0.25

$$\text{Splitting Level (SL)} \equiv \frac{\sum_i S_i}{\text{Nhits}_1 + \text{Nhits}_2}$$

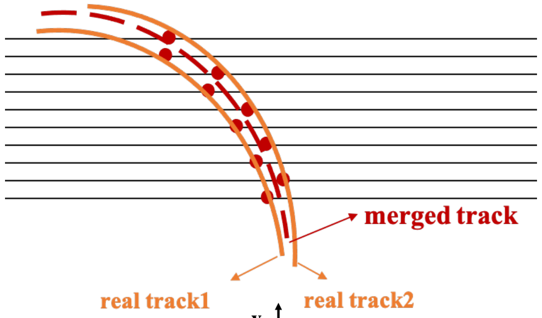
S_i = +1: one hit
S_i = -1: two hits[1]
S_i = 0: no hit

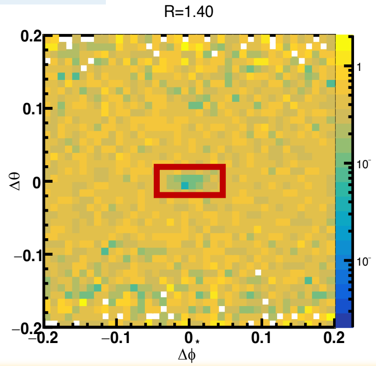
- Results in an increase of pairs, amplifying signal of CF
- Remove: -0.5 < SL < 0.6 used both for Kaon and pion

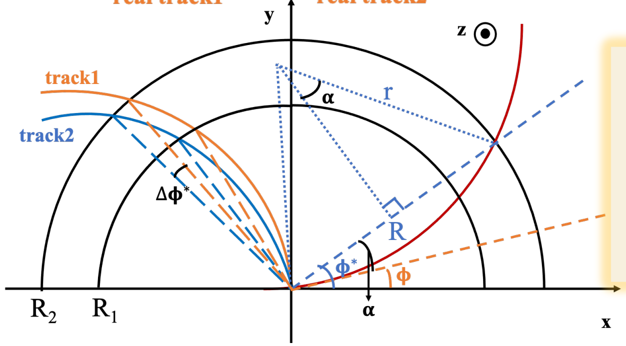
i - the pad-row number
Nhits_1 & Nhits_2 - the total number of hits associated to each track in the pair

[1] arXiv:nul-ex/0411036

Track-merging effect





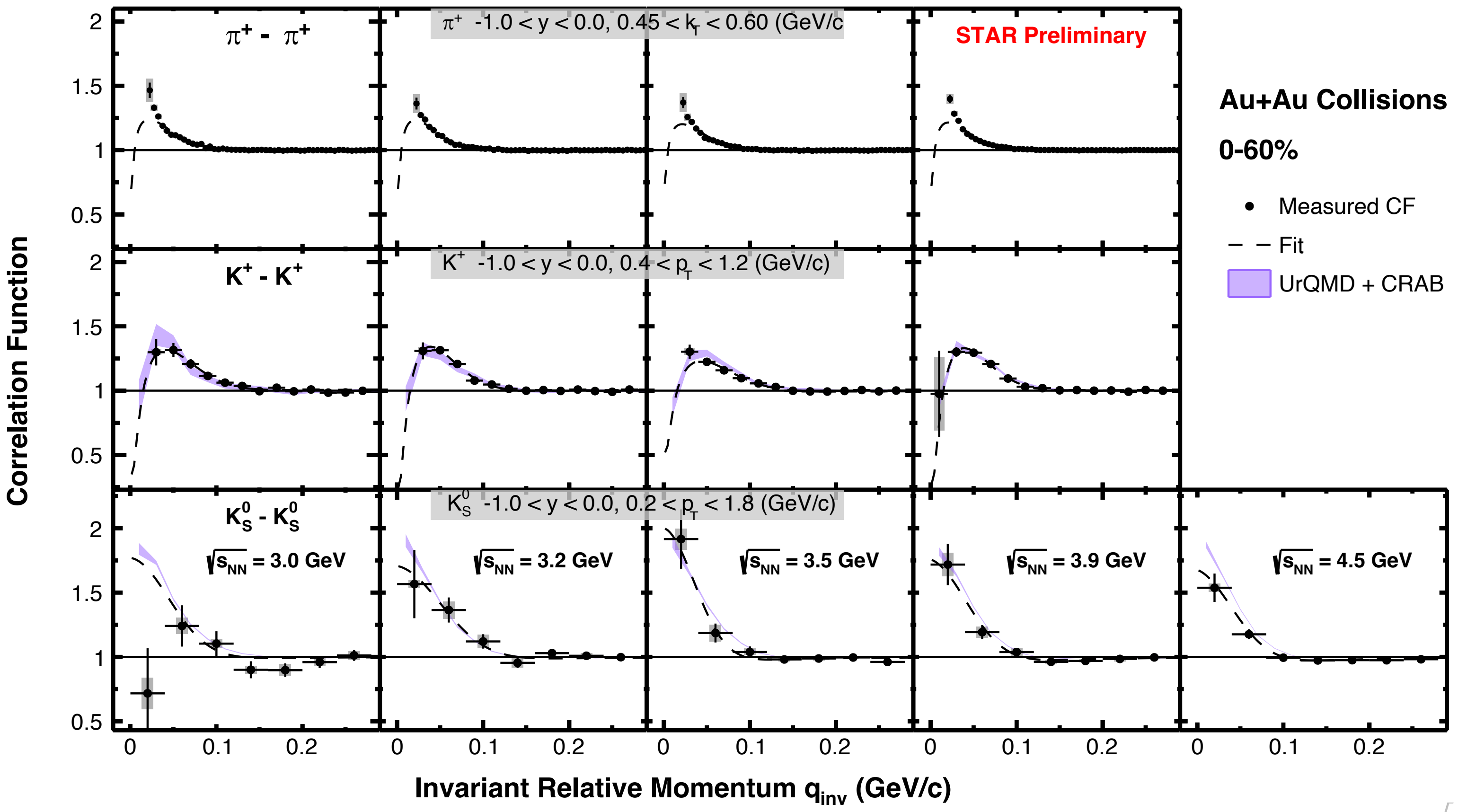


R -The radius of TPC we choose;
r-The radius of the rotation of particle;
B -Magnetic field intensity;
q -The charge of particle;
$\mathbf{p_T}$ -The transverse momentum of particle;

$$\Delta\phi^* = \phi_1^* - \phi_2^* = \Delta\phi + \sin^{-1}\left(\frac{0.15 q_1 BR}{p_{T1}}\right) - \sin^{-1}\left(\frac{0.15 q_2 BR}{p_{T2}}\right)$$

- Results in a reduction of pairs, reducing signal of CF
- Remove: for Kaon, $|\Delta\theta| > 0.02 \;||\; |\Delta\phi^*(R = 1.4m)| > 0.05$
  for pion, $|\Delta\eta| > 0.04 \;||\; |\Delta\phi^*(R = 1.4m)| > 0.06$

Results - Correlation functions



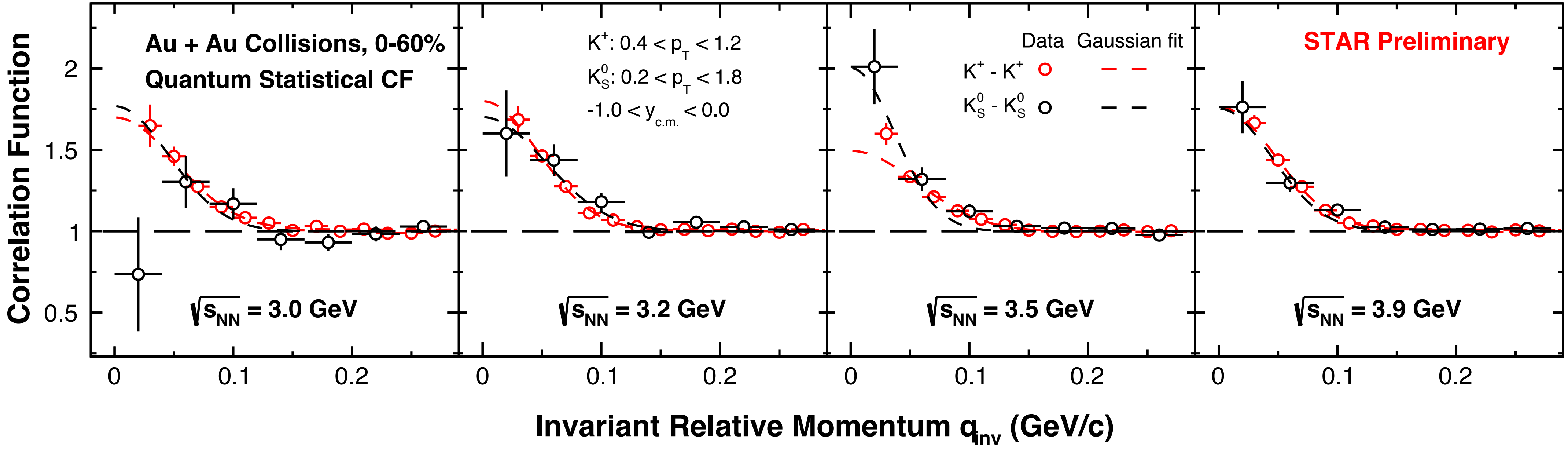
- UrQMD (provide phase space)[5,6]
  Version: 3.4
  Cascade mode
- CRAB (generate correlation: QS, FSI)
  Version: 3.0b

https://web.pa.msu.edu/people/pratts/freecodes/crab/home.html

[1] eConfC020620, THAT06 (2002)
[2] Phys. Rev. D 63, 094007 (2001)
[3] Phys. Rev. D 68, 014006 (2003)
[4] Nucl. Phys. B 121, 514–530 (1977)
[5] S.A.Bass et al., Prog.Part.Nucl.Phys. 41 (1998) 225
[6] M.Bleicher et al., J.Phys. G25 (1999) 1859

- CF of π^+, K^+, and K^0_S with same rapidity range are shown
- Calculations of UrQMD+CRAB consistent with experimental data
- Four different scattering amplitude parameters[1,2,3,4] for K^0_S compared, and consistent with each other

Results - Correlation functions

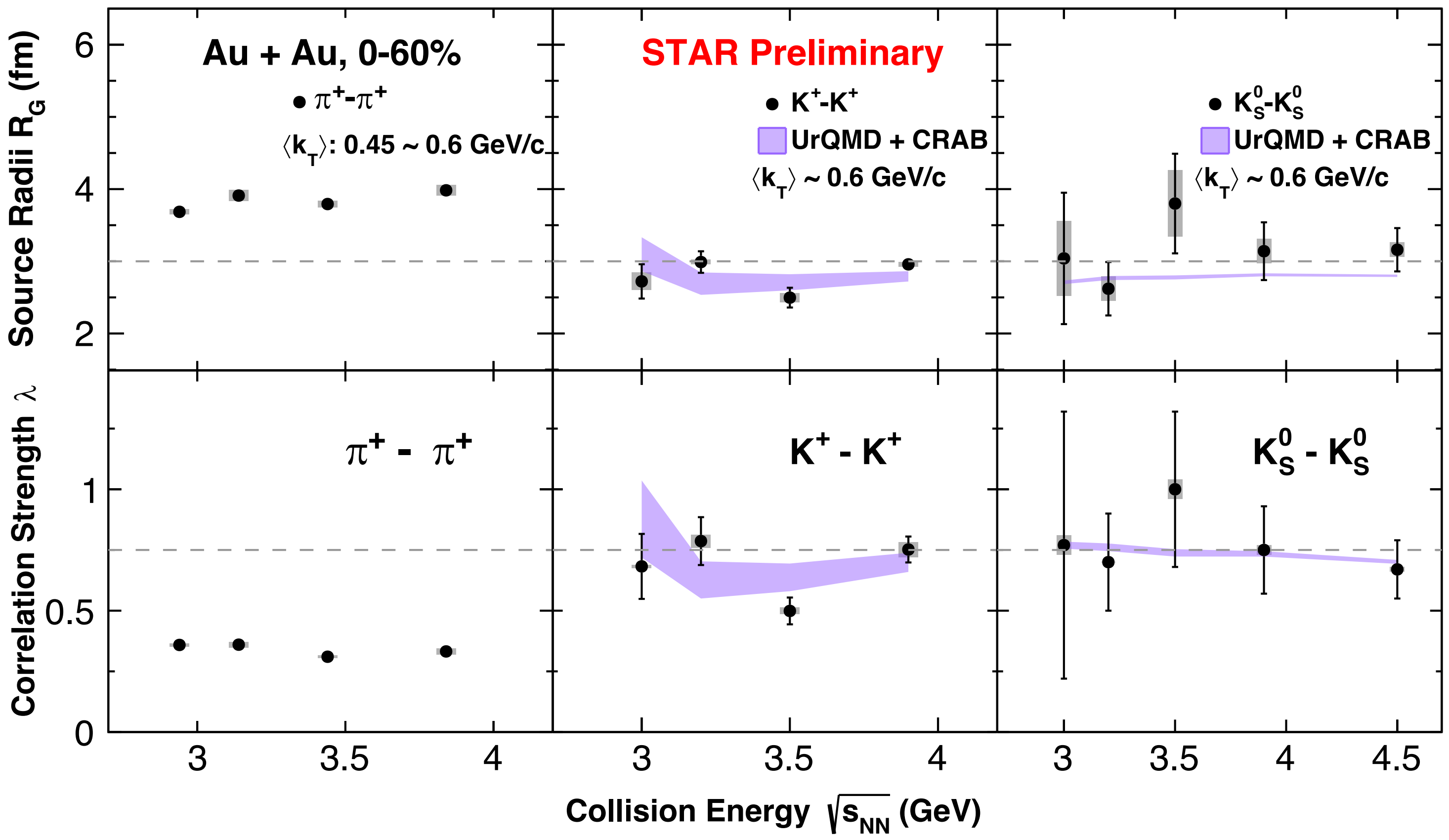


❖ CF of K^+-K^+ after subtracting Coulomb effect consistent with $K_S^0 - K_S^0$ without strong interaction

Extraction of QS correlation function:

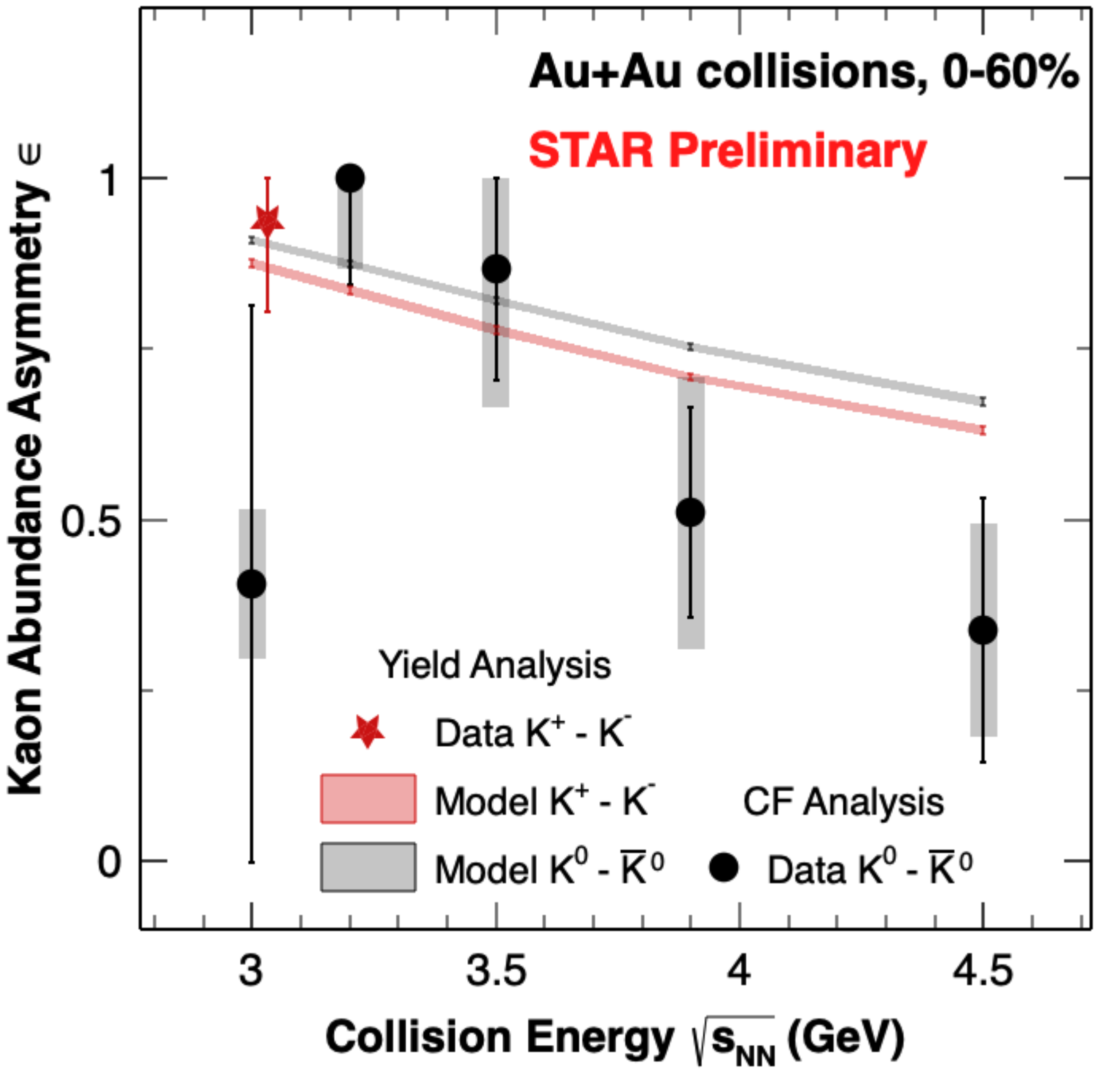
1. Fit the measured correlation function
2. Extract the parameters and get the FSI function
3. Subtract FSI from data points to get the Quantum statistics part contribution

Results - extracted parameters



- ❖ No clear energy dependence for R_G and λ, model consistent with data
- ❖ λ of kaons larger than pions', implying less impact from resonances decay
- ❖ Within uncertainties, R_G and λ of charged kaon correlation data consistent with that from neutral kaon

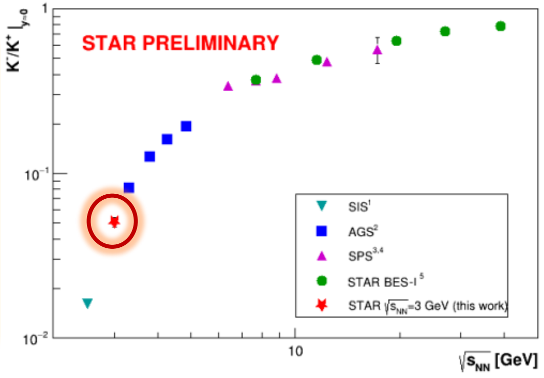
Results – Kaon abundance asymmetry



- **Yield Analysis**: $\epsilon = \frac{K - \bar{K}}{K + \bar{K}}$

  Yield of K^- / K^+ at 3 GeV: STAR Preliminary

- **CF Analysis**: L-L fitting from K^0_S-K^0_S CF

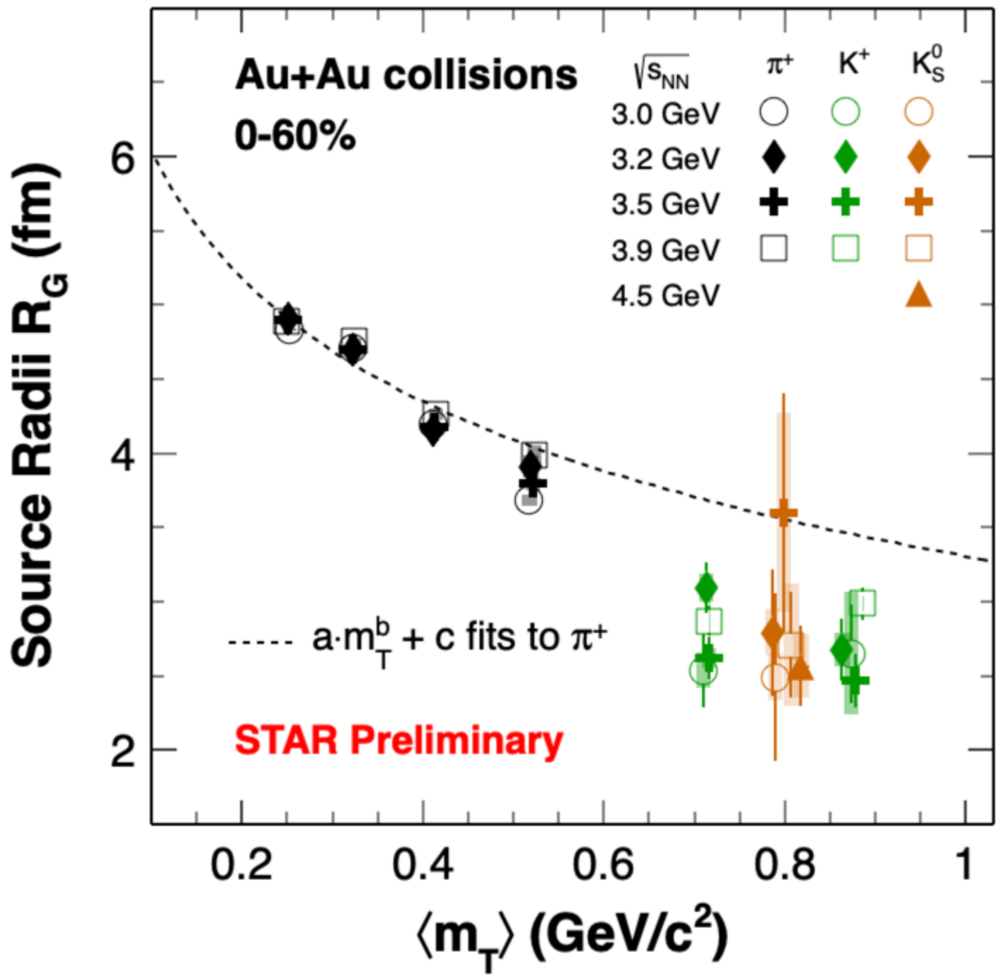


- K^0_S is a mixture of s, $\bar{s}$ quarks, thus can extract ϵ by correlation function
- First measurement of neutral kaon ϵ in heavy ion collisions
- ϵ of kaon decreases with energy, model reproduce trend of data

  1) Associate production dominates at high baryon density

  2) Pair production more important at higher energies

Results - m_T - scaling



- ❖ R_G of kaons smaller than that of pions
- ❖ R_G of kaons do not follow m_T - scaling of pions', implying no equilibrium amongst pions and kaons at high baryon density

Summary

- ❖ **First measurement of kaon and pion femtoscopy at high baryon density**
- ❖ **Within uncertainties, extracted parameters of charged kaon correlation data are consistent with that from neutral kaon**
- ❖ **λ of kaons larger than pions', implying less impact from resonances decay**
- ❖ **For $\sqrt{s_{NN}}$ = 3.0 – 4.5 GeV:**

  1) No clear energy dependence of R_G and λ while ϵ of kaon decreases with energy

  2) R_G of kaons do not follow m_T - scaling of pion's, implying no equilibrium amongst pions and kaons

Thanks for your attention!