CPOD 2024 - 15th Workshop on Critical Point and Onset of Deconfinement

Kaon Femtoscopy at High Baryon Density Region

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for the STAR Collaboration

Central China Normal University

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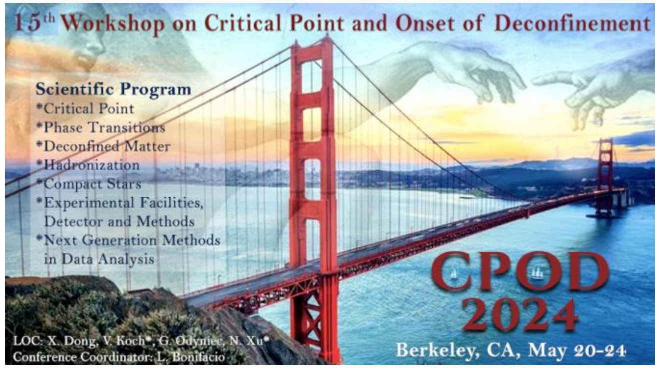


15th Workshop on Critical Point and Onset of Deconfinement

Scientific Program
- *Critical Point
- *Phase Transitions
- *Deconfined Matter
- *Hadronization
- *Compact Stars
- *Experimental Facilities, Detector and Methods
- *Next Generation Methods in Data Analysis

CPOD 2024

Berkeley, CA, May 20-24

LOC: X. Dong, V. Koch*, G. Odyniec, N. Xu*
Conference Coordinator: L. Bonifacio

Outline

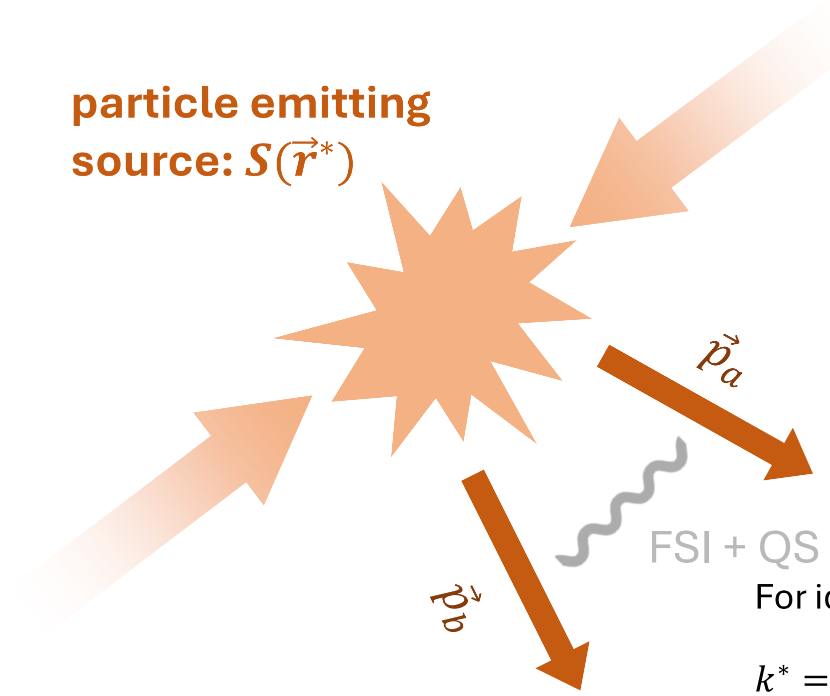
1. Motivation

2. STAR Fixed Target Setup and Analysis Technique

3. Kaon Femtoscopy in Au + Au Collisions at $\sqrt{s_{\mathrm{NN}}}$ = 3.0, 3.2, 3.5, 3.9 and 4.5 GeV
   ① Correlation Functions
   ② Particle Emitting Source Parameters and the m_{T} - scaling
   ③ Strangeness Abundance Asymmetry in Kaon

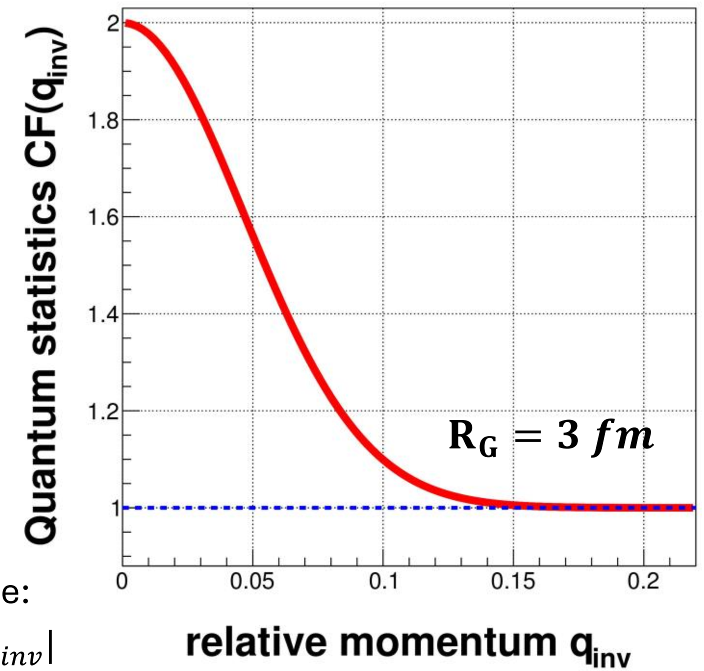
4. Summary

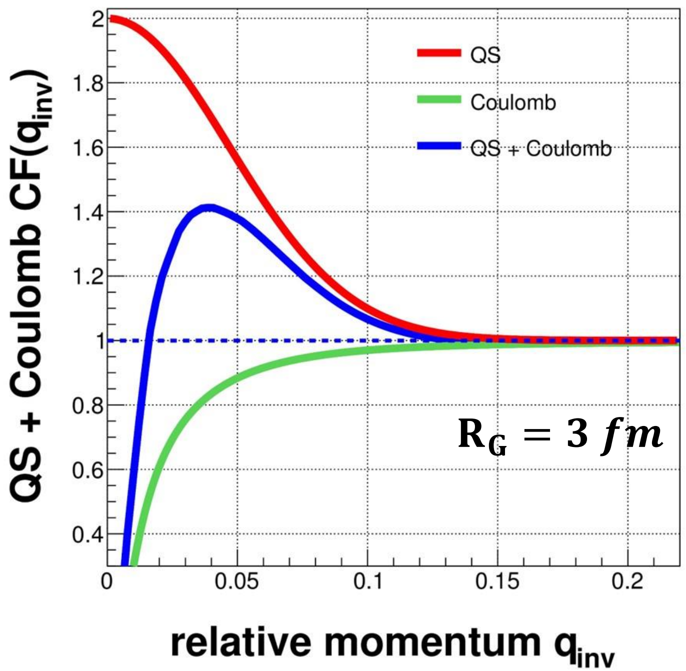
Motivation – Femtoscopy



For identical particle:

$$k^* = \frac{|\vec{p}_a^* - \vec{p}_b^*|}{2} = \frac{|q_{inv}|}{2}$$





$$C(k^*) = \int S(\vec{r}^*)\left|\Psi(\vec{k}^*,\vec{r}^*)\right|^2 d^3\vec{r}^* = \frac{\mathcal{P}(\vec{p}_a,\vec{p}_b)}{\mathcal{P}(\vec{p}_a)\mathcal{P}(\vec{p}_b)} = \mathcal{N}\frac{N_{same}(k^*)}{N_{mixed}(k^*)}$$

Theory:
$S(\vec{r}^*)$: particles emitting source function
$\Psi(\vec{k}^*,\vec{r}^*)$: Two-particle wave function

Statistical:
$\mathcal{P}(\vec{p})$: probability of measuring the particle with momentum $\vec{p}$
$\mathcal{P}(\vec{p}_a,\vec{p}_b)$: probability of observing particles a and b with given momenta independently
$\mathcal{P}(\vec{p}_a)\mathcal{P}(\vec{p}_b)$: probability of observing particles a and b with given momenta simultaneously

Experimental:
$N_{same}(k^*)$: correlated
$N_{mixed}(k^*)$: uncorrelated

- Quantum statistics (QS): Bose-Einstein condensation for both K^+-K^+ and K_S^0-K_S^0:
  - Particle emitting source size (Gaussian assumption): R_G
  - Correlation strength: λ
- Study the Final State Interaction (FSI)
  - Coulomb interaction (K^+-K^+)
  - Strong interaction (K_S^0-K_S^0)

star marker(*) represent the pair rest frame

Motivation – Methodology

Assumptions:

- Equal-time approximation
  - Pair wave function: $\Psi\left(\vec{k}^*,\vec{r}^*,t\right) \to \Psi\left(\vec{k}^*,\vec{r}^*\right)$
- Gaussian source assumption
  - Single particle source: $s(x_i,p_i) = \delta(t)e^{-\frac{\vec{r}^2}{2r_0^2}}$
  - Pair source (radius R_G): $S_G(\vec{r}^*) = e^{-\frac{\vec{r}^{*2}}{4R_G^2}} \Big/ (4\pi R_G^2)^{3/2}$
- Smoothness approximation for source function

- Sinyukov-Bowler[1] approach used for K^+- K^+ and π^+- π^+ CF

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

Coulomb interaction part **QS part**

- N: normalize factor; λ: correlation strength

- Lednický-Lyuboshitz (L-L)[2] approach used for K_S^0-K_S^0 CF

QS part

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

Strong interaction part

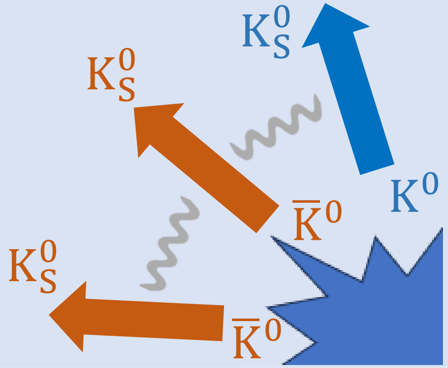
Kaon abundance asymmetry

- $f(k^*)$: scattering amplitude:

$$f(k^*) = \frac{1}{2}[f_0(k^*) + f_1(k^*)],\ f_I(k^*) = \frac{\gamma_r}{m_r - s - i\gamma_r k^* - i\gamma_r' k_r'}$$

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

- K_S^0-K_S^0 state is made up of a combination of K^0-K^0 ($\bar{K}^0$-$\bar{K}^0$) and K^0-$\bar{K}^0$ state
- With K_S^0-K_S^0 CF, Kaon abundance asymmetry can be extracted



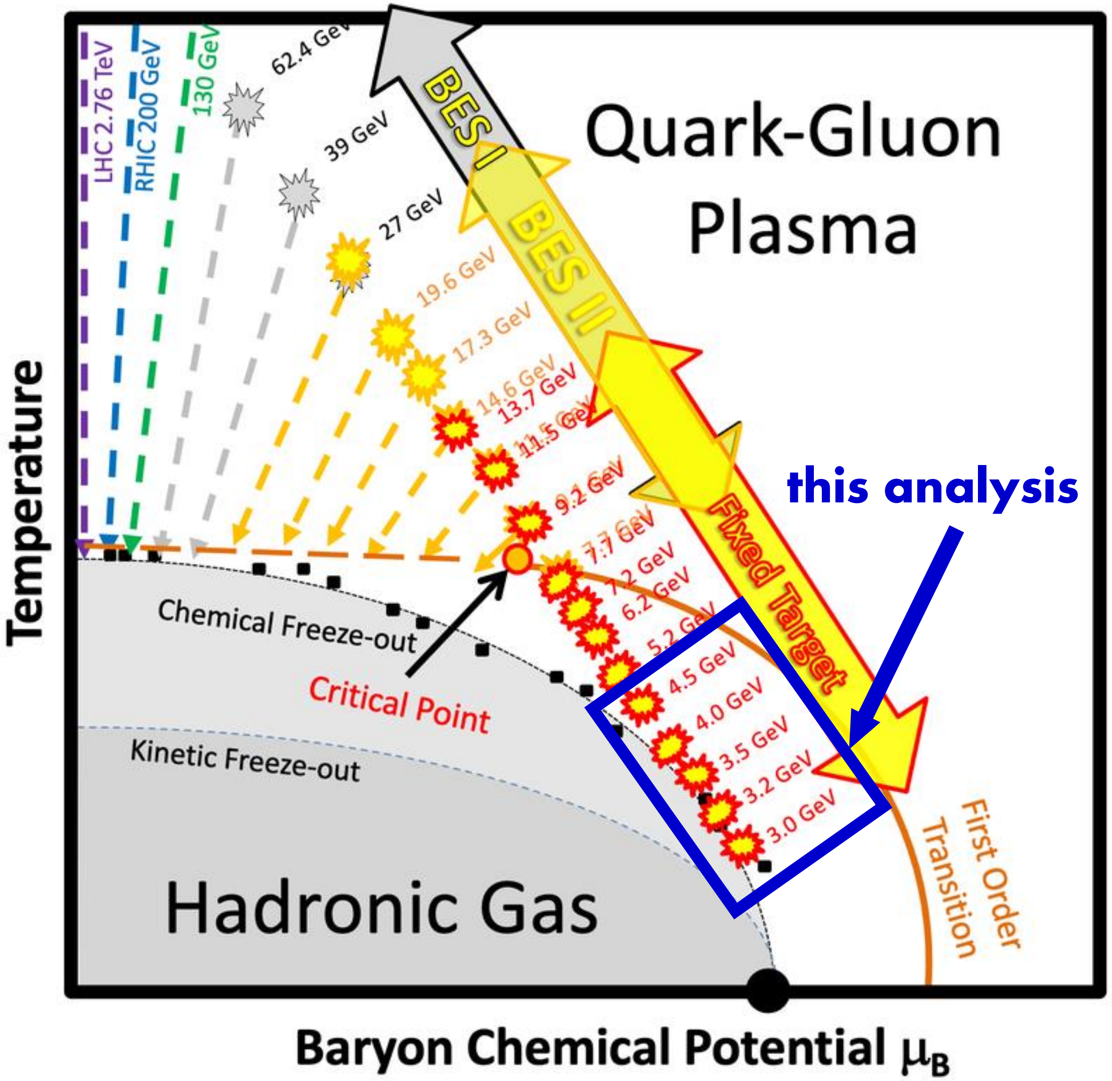
[1] Phys. Lett. B, 432(3-4), 248-257 (1998)

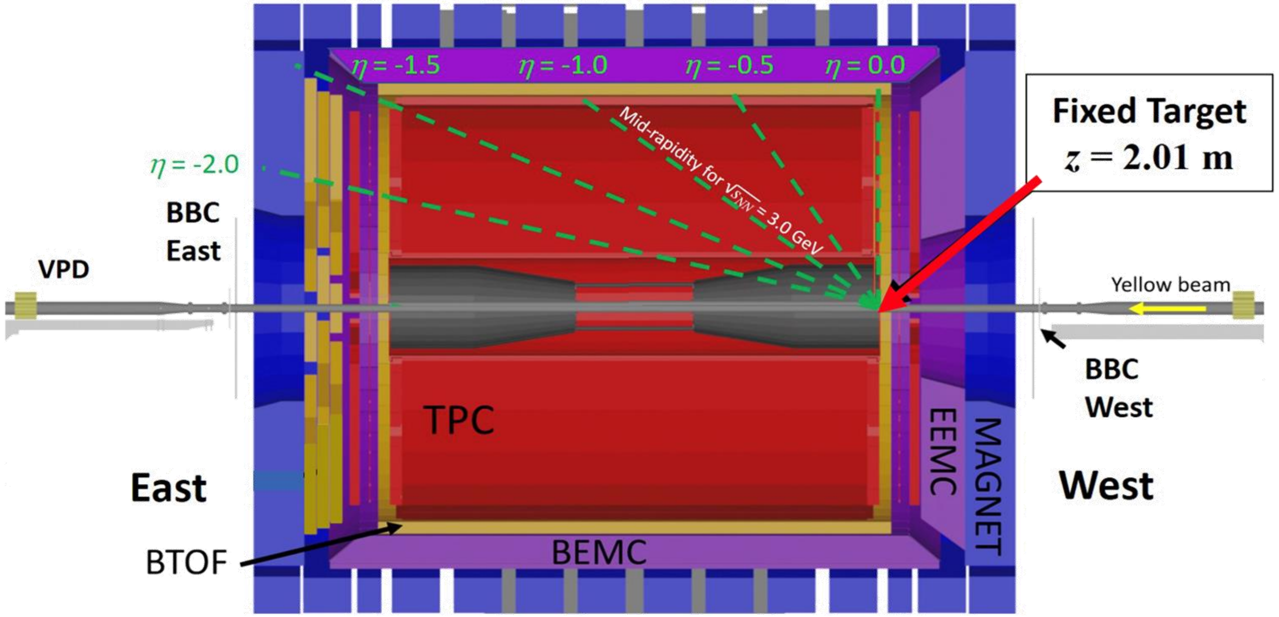
[2] J.Nucl.Phys. 35, 770 (1982)

[3] eConfC020620, THAT06 (2002)

STAR Fixed Target Setup

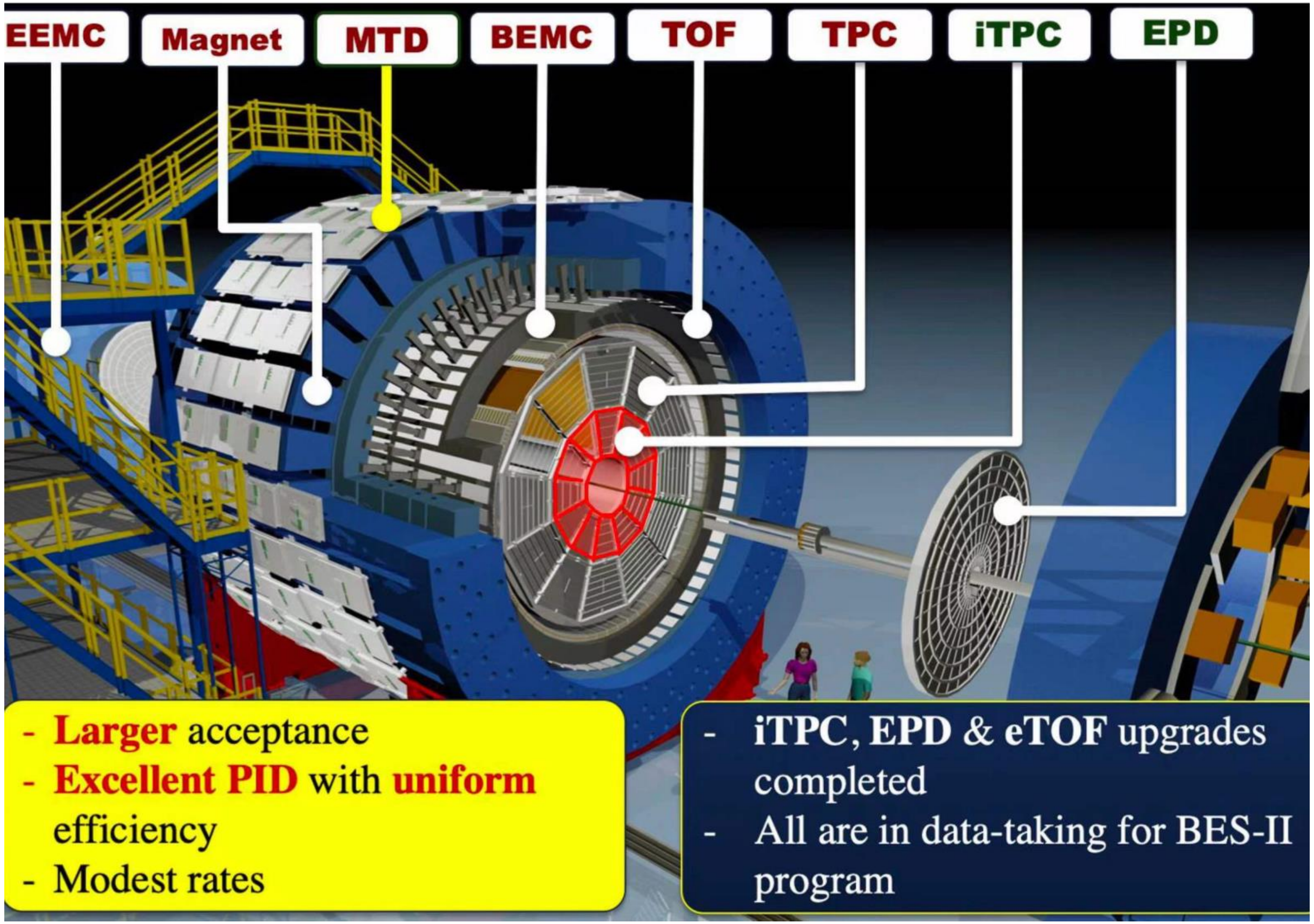
Beam Energy Scan (BES) at STAR





Energy $\sqrt{s_{NN}}$	y_{beam}	μ_B	Events
3.0 GeV	-1.05	750 MeV	260 M
3.2 GeV	-1.13	699 MeV	200 M
3.5 GeV	-1.20	670 MeV	120 M
3.9 GeV	-1.37	633 MeV	120 M
4.5 GeV	-1.52	590 MeV	110 M
......		......	

STAR Detector



- **Larger** acceptance
- **Excellent PID** with **uniform** efficiency
- Modest rates

- **iTPC, EPD & eTOF** upgrades completed
- All are in data-taking for BES-II program

Time Projection Chamber (TPC)

- Charged particle tracking
- Momentum reconstruction
- Particle Identification
- Pseudorapidity coverage $-2.0 < \eta < 0$ (for fix target)

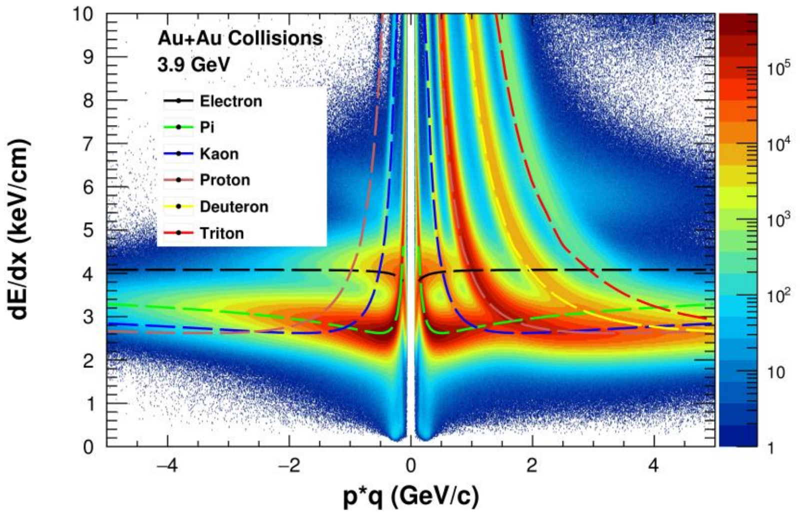
barrel Time-of-Flight (bTOF)

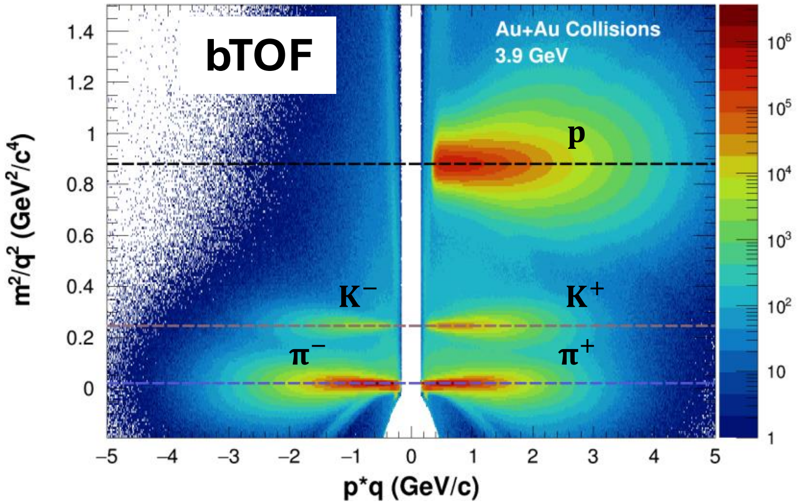
- Particle Identification
- Pseudorapidity coverage $-1.5 < \eta < 0$ (for fix target)

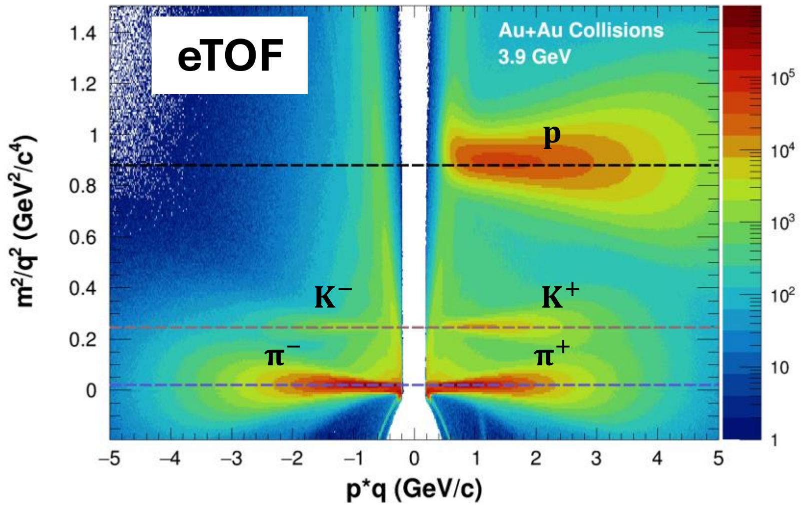
end-cap Time-of-Flight (eTOF)

- Particle Identification
- Pseudorapidity coverage $-2.2 < \eta < -1.5$ (for fix target)

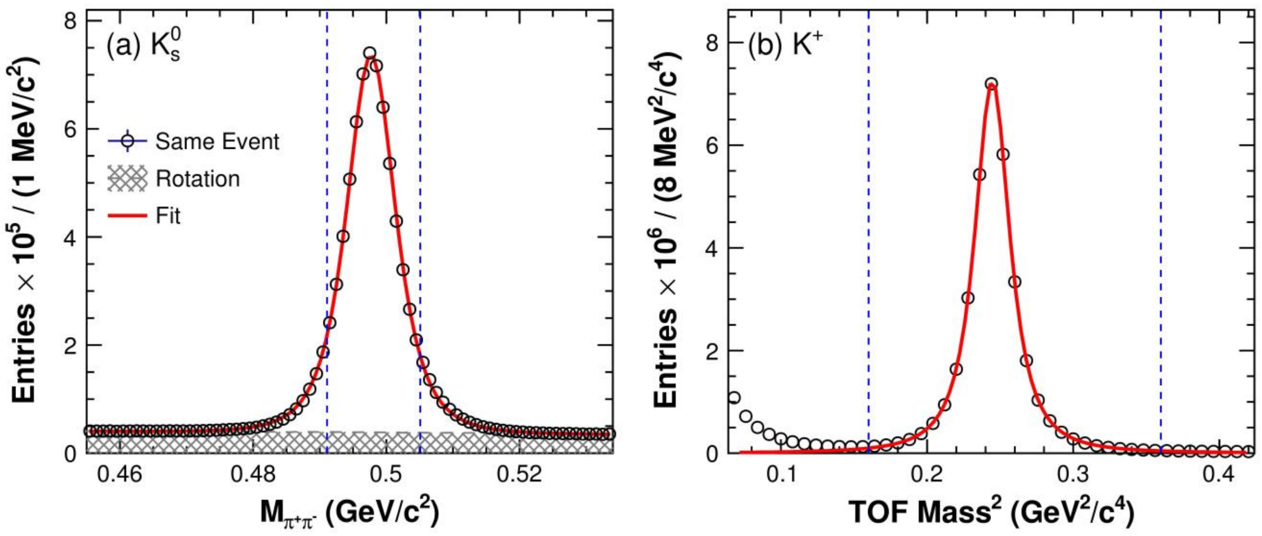
Analysis detail –PID, Reconstruction







3.9 GeV Au + Au Collisions at RHIC



- TPC (dE/dx) and TOF (β) for charged pion and kaon particle identification
  - K^+ PID: TPC+bTOF (+eTOF for $\sqrt{s_{\mathrm{NN}}}$ = 3.5 GeV and above)
  - $\pi^\pm$ PID: TPC (+bTOF for high momentum track)
- $\mathrm{K_S^0}$ hadrons are reconstructed using invariant mass method: $\mathrm{K_S^0} \rightarrow \pi^+\pi^-$
- $\mathrm{K_S^0}$ combinatorial backgrounds are reconstructed by the rotation method

Analysis detail – Correlation Function

CF in statistical and experimental format:

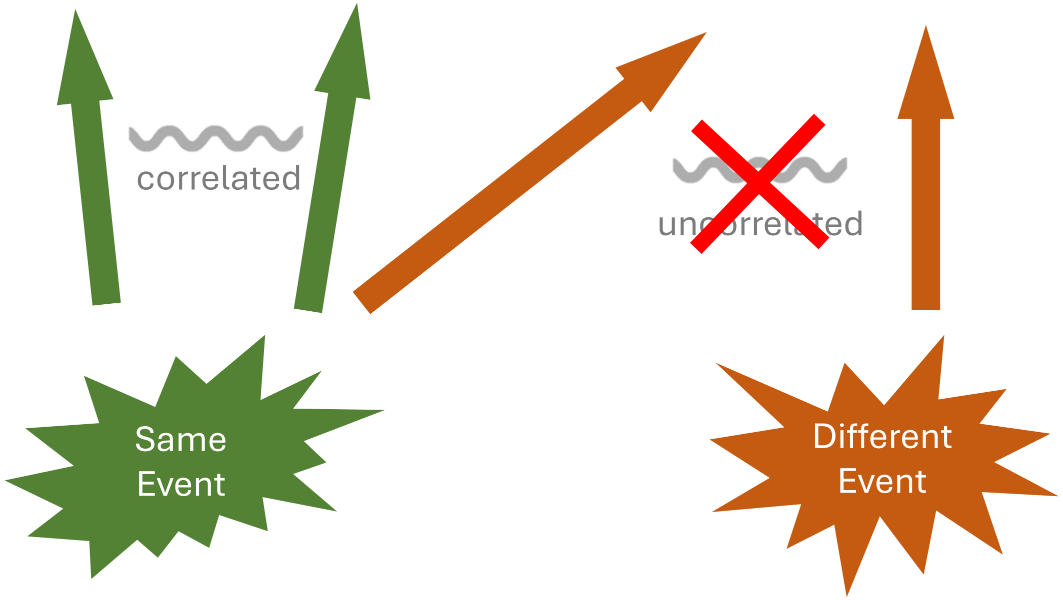
$$C(k^*) = \frac{\mathcal{P}(\vec{p}_a,\vec{p}_b)}{\mathcal{P}(\vec{p}_a)\mathcal{P}(\vec{p}_b)} = \mathcal{N}\frac{N_{same}(k^*)}{N_{mixed}(k^*)}$$

$N_{same}(k^*)$

correlated k^* distribution, corresponding $\mathcal{P}(\vec{p}_a,\vec{p}_b)$ with normalization factor

$N_{mixed}(k^*)$

uncorrelated k^* distribution, corresponding $\mathcal{P}(\vec{p}_a)\mathcal{P}(\vec{p}_b)$ with normalization factor

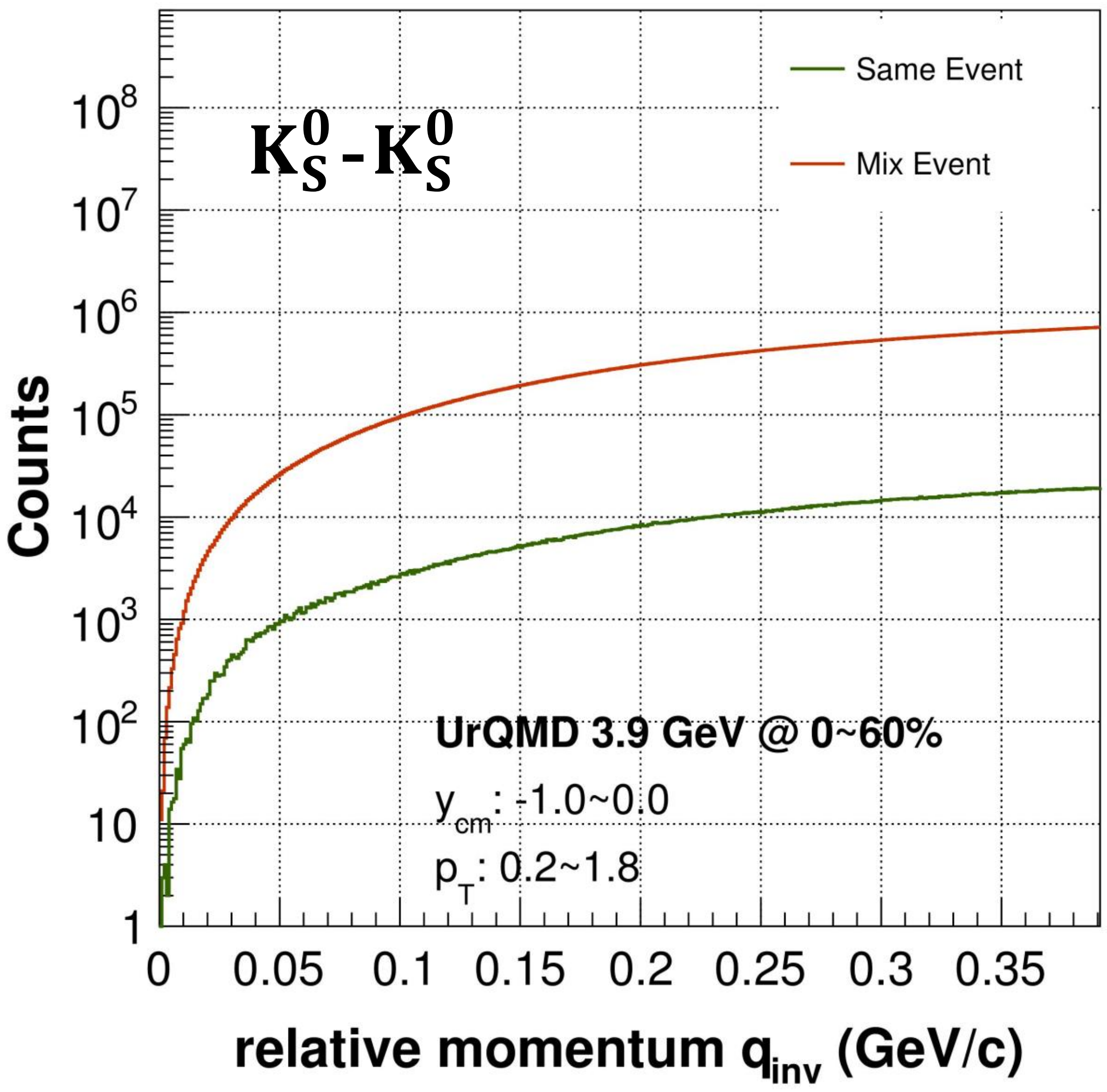


correlated

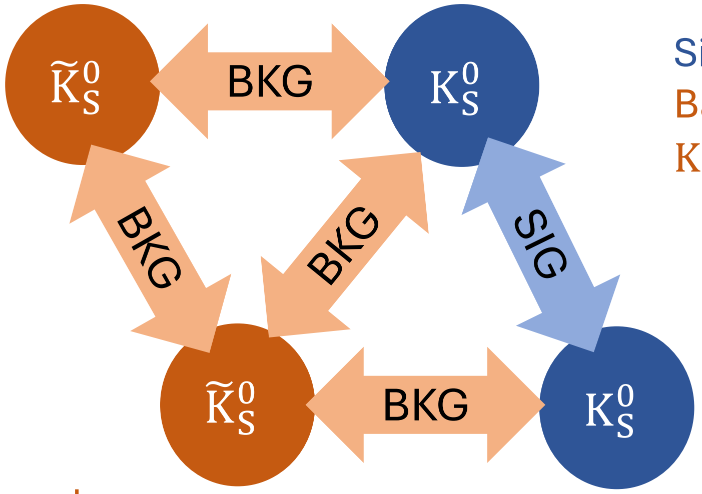
uncorrelated

Same Event

Different Event



Analysis detail – Purity Correction



Signal pair: K^0_S-K^0_S

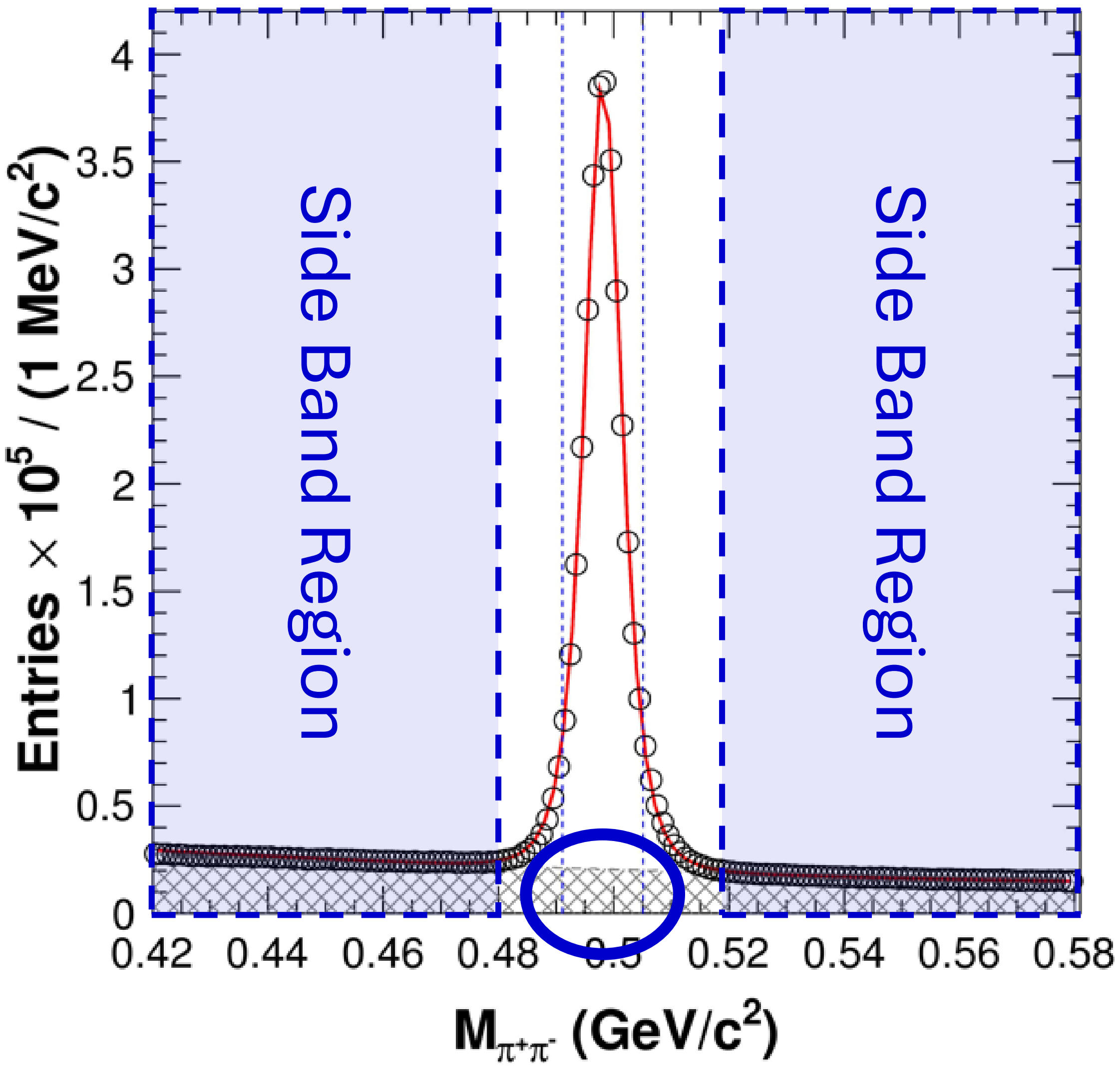
Background pair: K^0_S-$\widetilde{K}^0_S$, $\widetilde{K}^0_S$-$\widetilde{K}^0_S$

K^0_S: Signal

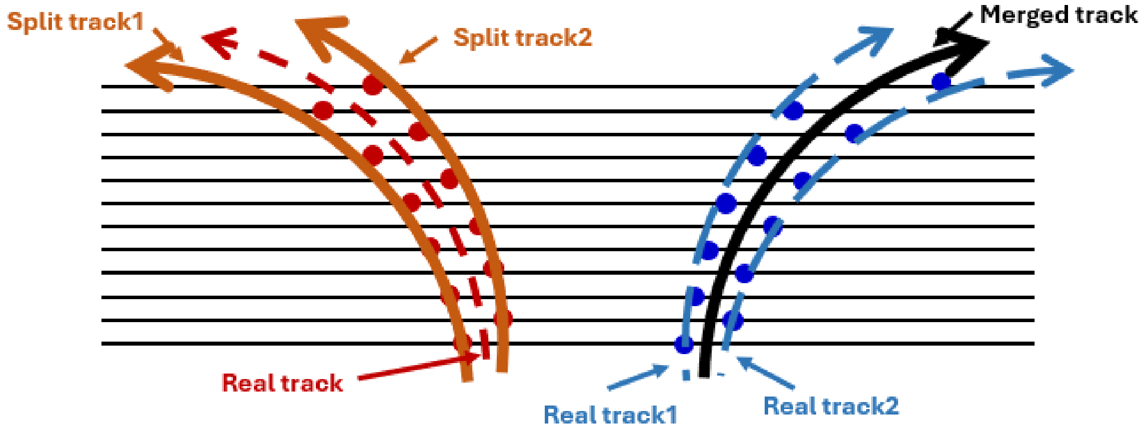
$\widetilde{K}^0_S$: Background

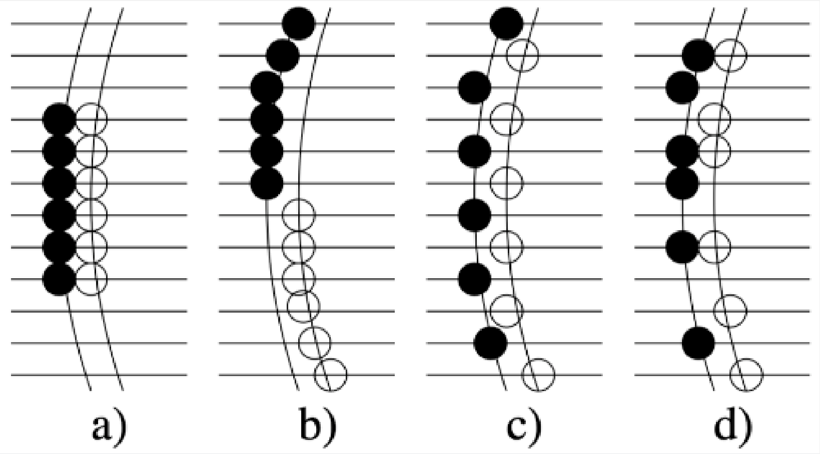
1. Use the side band candidates estimate the background: $\widetilde{K}^0_S$
2. Calculate CF for each component: K^0_S-$\widetilde{K}^0_S$, $\widetilde{K}^0_S$-$\widetilde{K}^0_S$
3. Take average of left and right side band CF
4. Estimate the contribution for each part
    - ① Purity of K^0_S: ~90%
    - ② Pair Purity of K^0_S-K^0_S: ~80%
5. Extract the pure CF

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



Analysis detail – Track Splitting and Merging





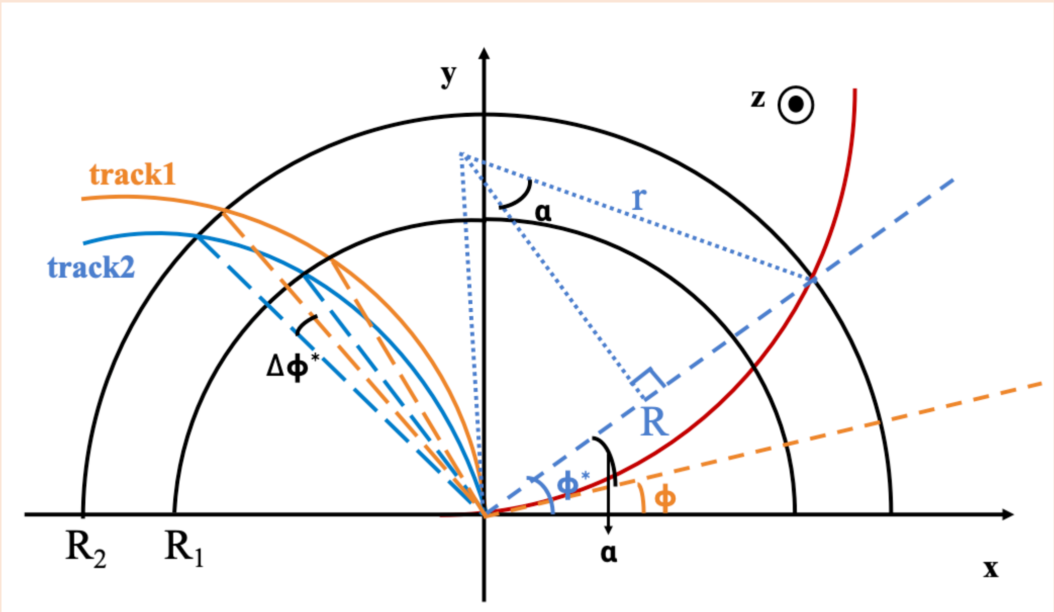
SL = -0.5 SL = 1 SL = 1 SL = 0.25

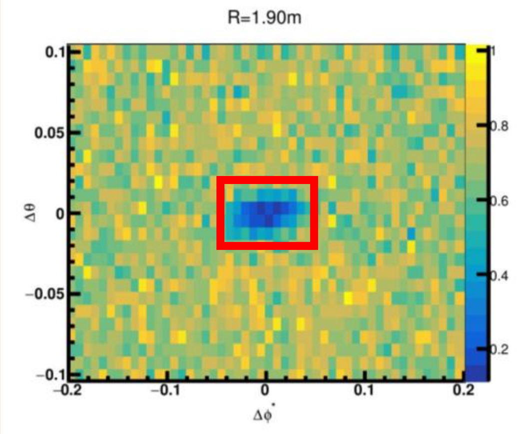
Splitting level[1]

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

-0.5 < SL < 0.6 required

$$\text{Splitting Level (SL)} = \frac{\sum_i S_i}{Nhits_1 + Nhits_2}$$





Merging effect

- Longitudinal angle difference $\Delta\theta$ or $\Delta\eta$
- Azimuth angle difference $\Delta\phi^*$
- 2D cuts for $\Delta\theta$ and $\Delta\phi^*$ to remove merging effect

Kaon:

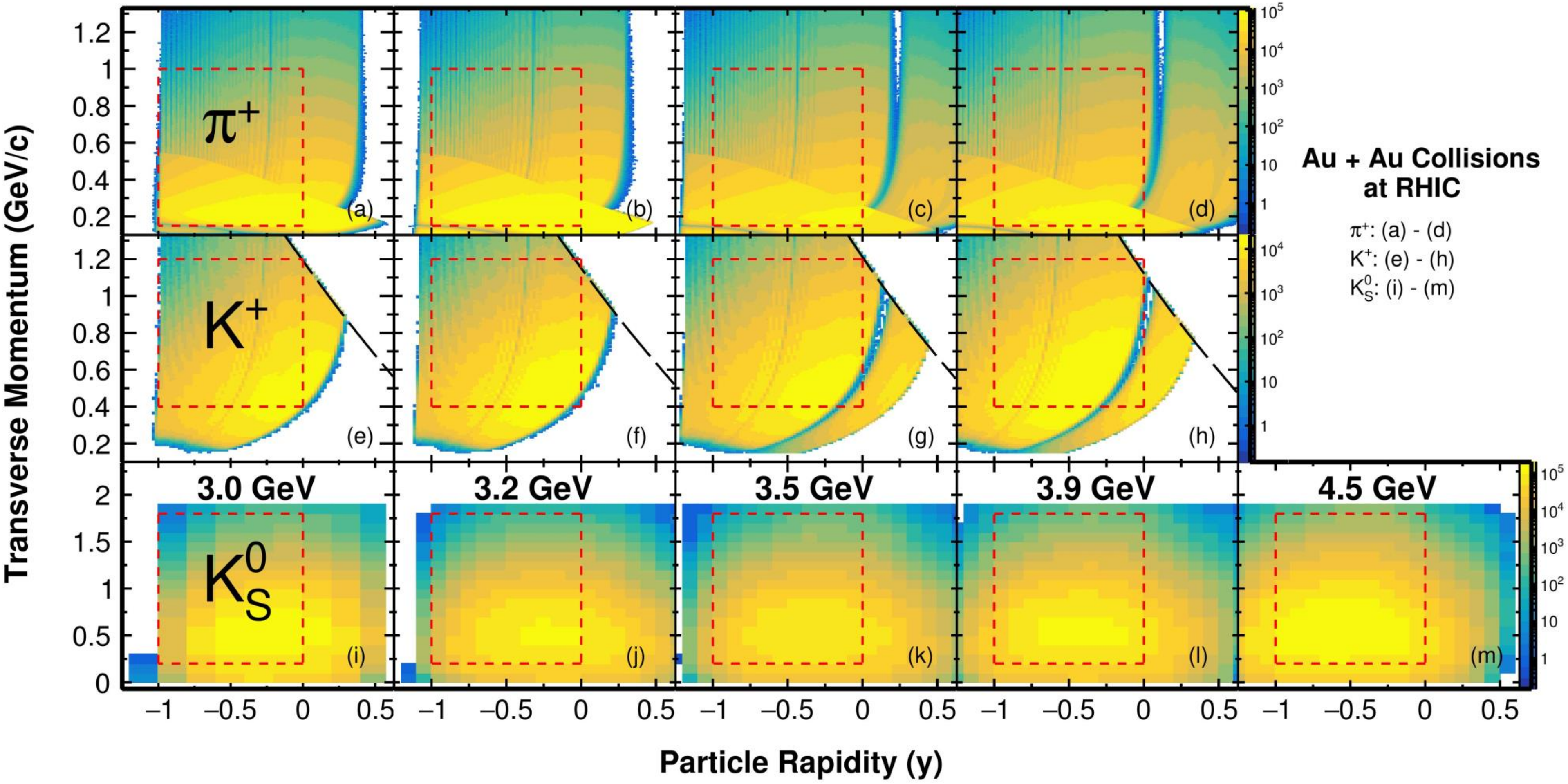
$|\Delta\theta| > 0.02$ or $|\Delta\phi^*| > 0.05$

Pion:

$|\Delta\eta| > 0.04$ or $|\Delta\phi^*| > 0.06$

[1] Phys.Rev.C, 71, 044906 (2005)

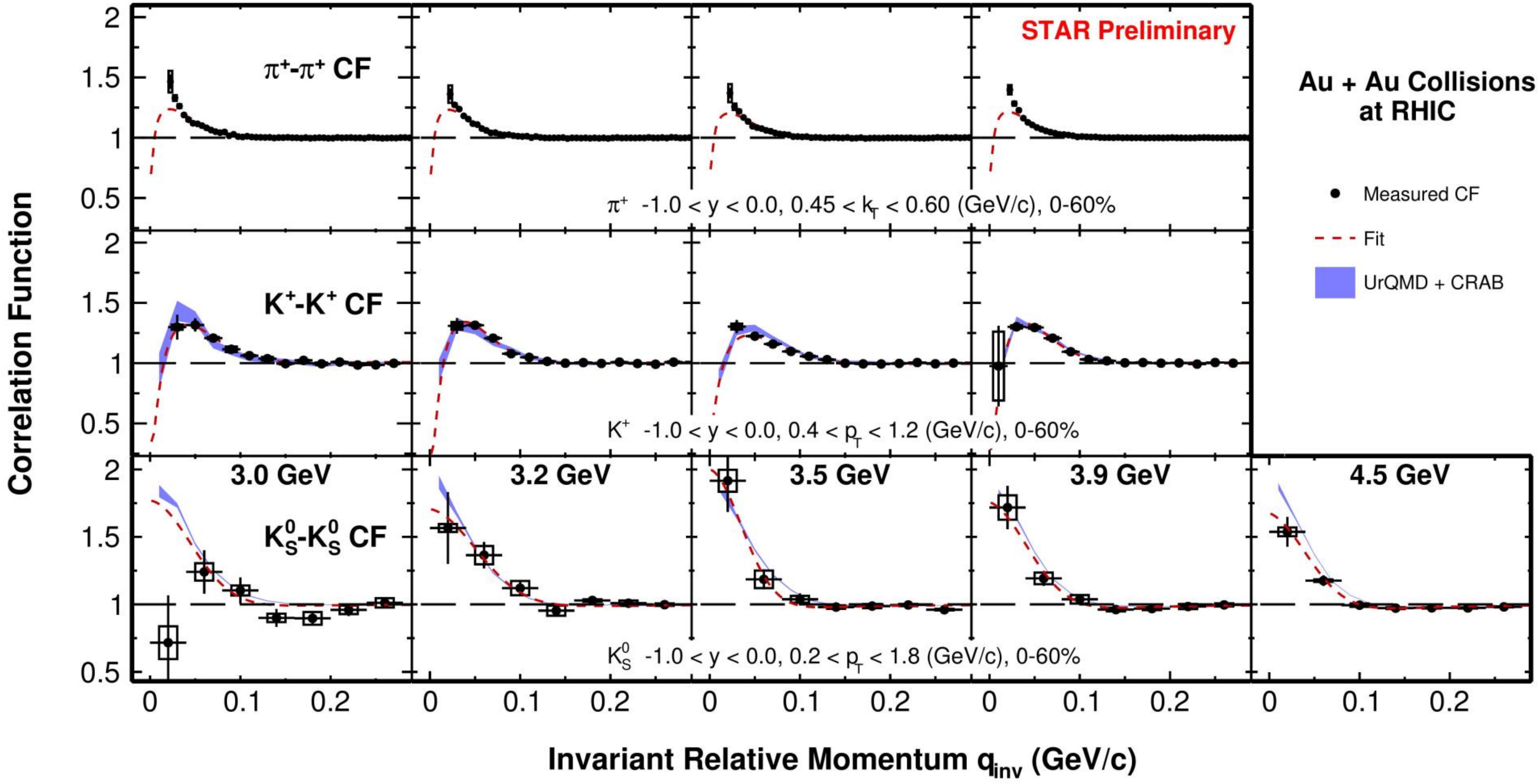
Analysis detail – Acceptance



- KF Particle package is used for the strange hadron for $\mathrm{K_S^0}$ reconstruction
- Good coverage from beam-rapidity to mid-rapidity for $\pi^{\pm}$, K^{+} and $\mathrm{K_S^0}$

- Analysis acceptance window:
  - $\pi^{\pm}$: -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^{+}: -1.0 < y < 0, 0.2 < p_T < 1.8 (GeV/c)

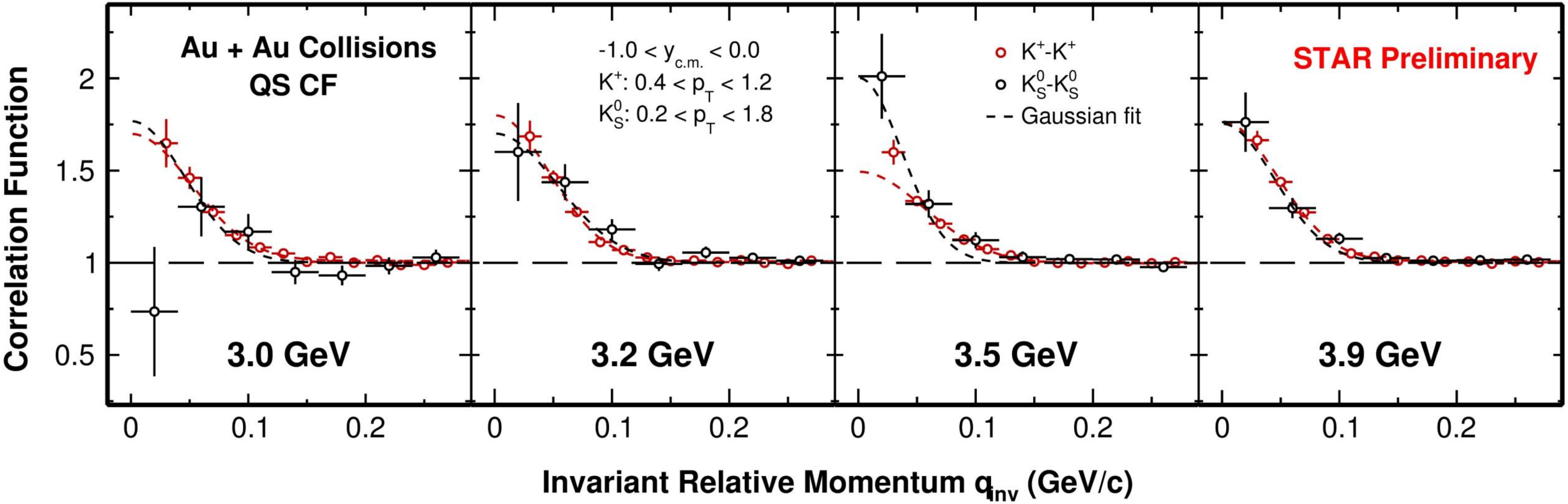
Results – Correlation Functions



- Particle emitting source parameters (R_G, λ) and abundance asymmetry (ϵ) can be extracted
- For K_S^0 L-L model fitting, four difference scattering amplitude parameters[1,2,3,4] compared, and consistent with each other
- UrQMD + CRAB calculation reproduce the results

[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)

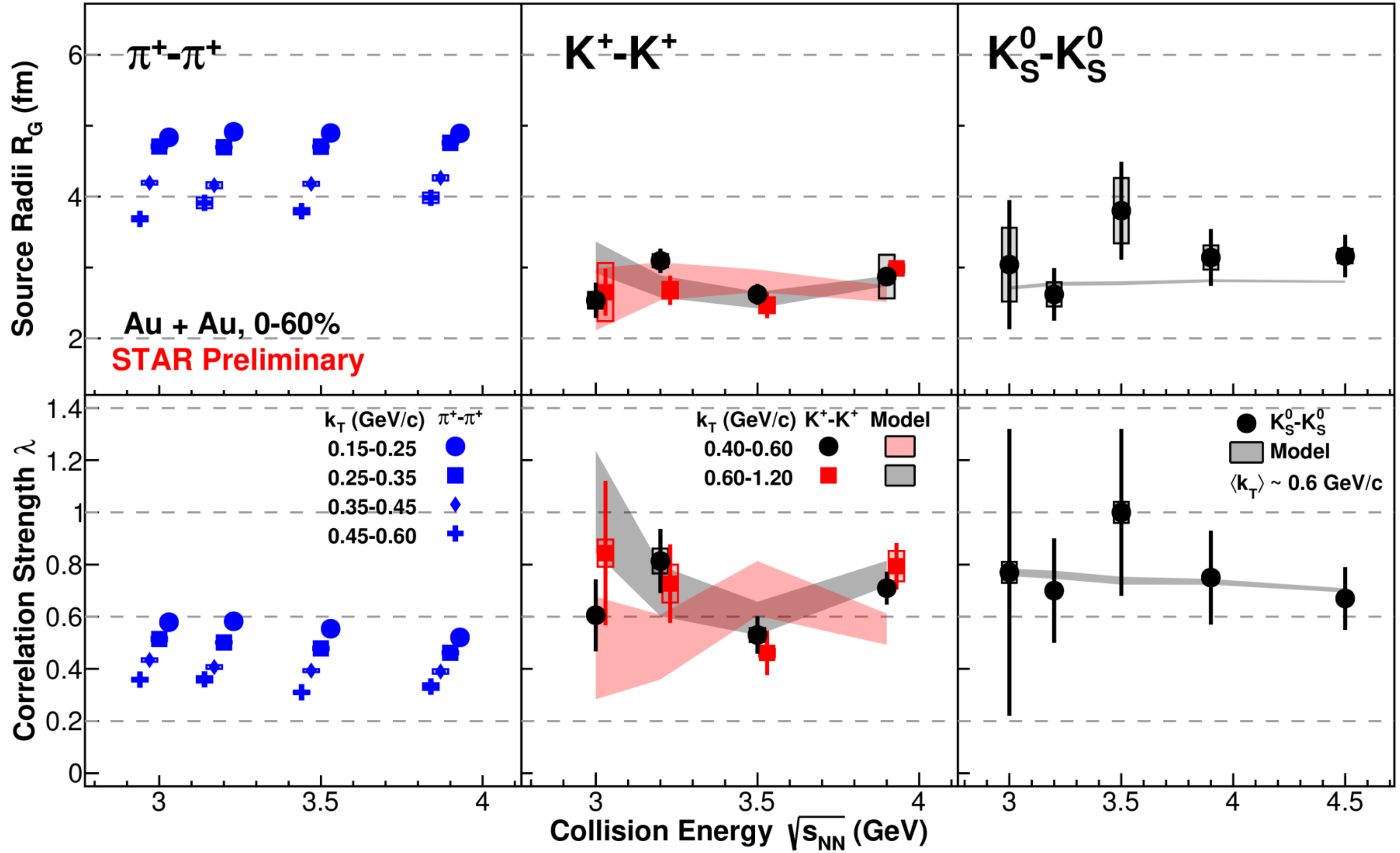
Results – Correlation Functions



- Particle emitting source parameters (R_G, λ) and abundance asymmetry (ϵ) can be extracted
- For K_S^0 L-L model fitting, four difference scattering amplitude parameters[1,2,3,4] compared, and consistent with each other
- Model calculation reproduce the results
- Charged kaon consistent with neutral kaon after subtracting the Coulomb effect

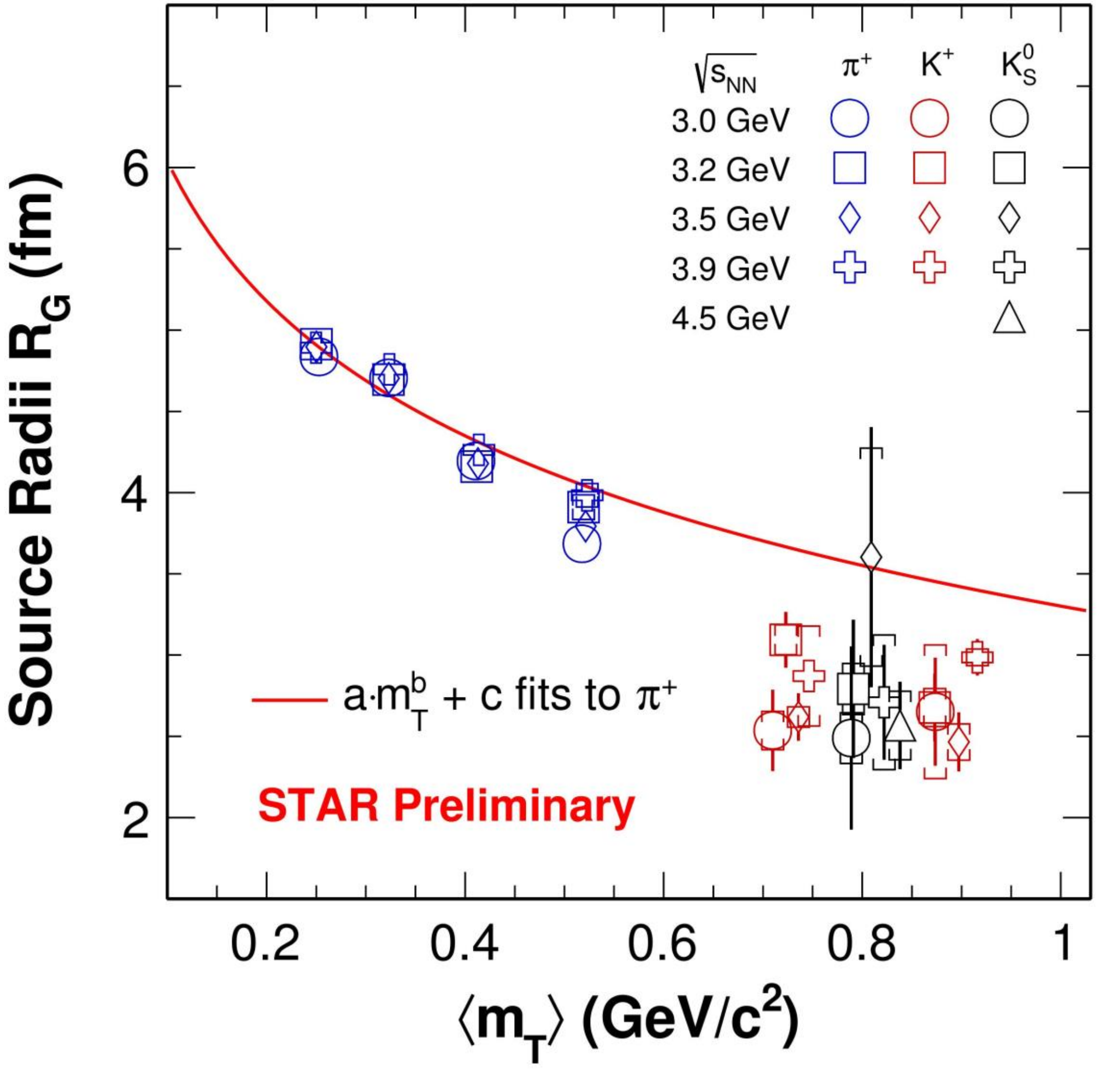
[1] eConfC020620, THAT06 (2002)
[2] Phys. Rev. D 63, 094007 (2001)
[3] Phys. Rev. D 68, 014006 (2003)
[4] Nucl. Phys. B 121, 514–530 (1977)

Results – R_G and λ



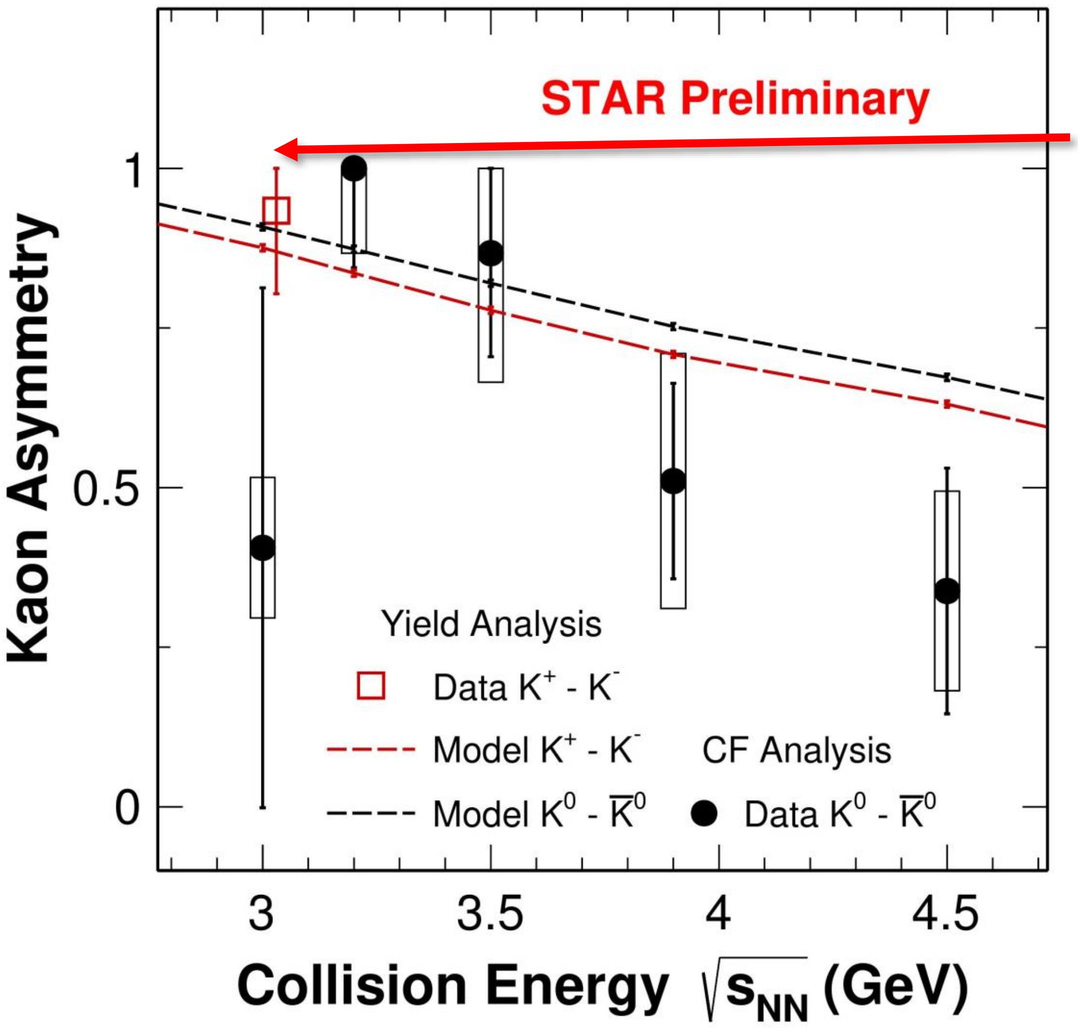
- No clear energy dependence was observed for both source radii and correlation strength, and UrQMD + CRAB calculations reproduce the results
- Kaon correlation strength larger than pion's, implying less impact from resonance decay

Results – m_T Scaling

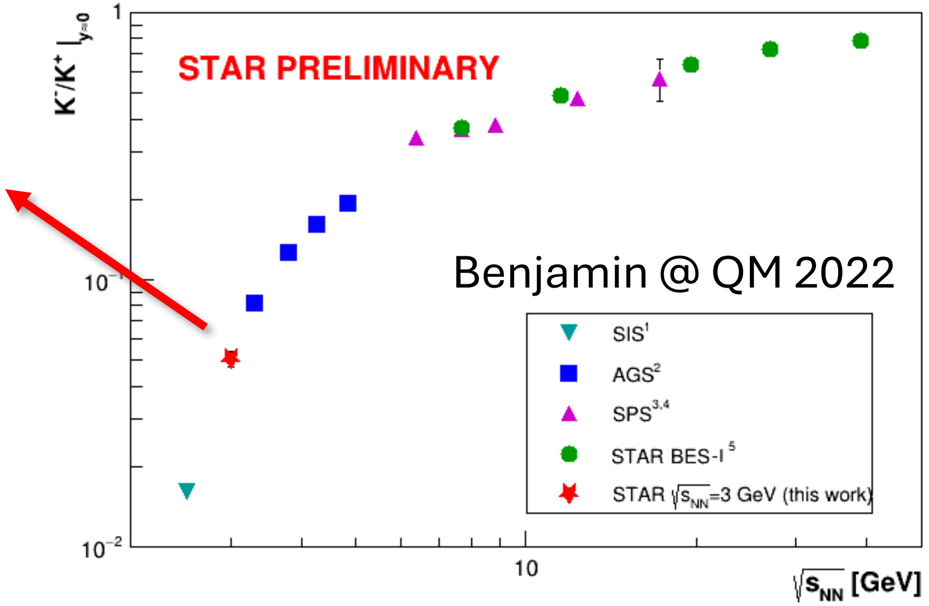


- Source size of kaons don’t follow $\mathrm{m_T}$-scaling of pions’
- Kaon source size smaller than pions’ trend
- Implying no equilibrium amongst pions and kaons at high baryon density region

Results – Abundance Asymmetry



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



Benjamin @ QM 2022

- First measurement of abundance asymmetry of neutral kaon in heavy ion collision
- The kaon abundance asymmetry decreases as the collision energy increases at high baryon density region, UrQMD model yield calculations are consistent with data trend
  1. Associate production dominates at high baryon density region
  2. Pair production becomes more important at higher collision energies

Summary

1) First systematic measurements of kaon correlation functions in Au+Au collisions at high baryon density with STAR detector;
2) Source parameters (source size $\mathrm{R_G}$ and correlation strength λ) are extracted for both charged- and neutral-kaons and they are consistent within uncertainties;
3) Within the energy range $\sqrt{s_{\mathrm{NN}}}$ = 3.0 – 4.5 GeV:
   (i) No clear energy dependence was observed in $\mathrm{R_G}$, while the $\mathrm{K_S^0}$ abundance asymmetry parameter ϵ is close to unity at the lower FXT energies and is decreasing as a function of the collision energy;
   (ii) Kaons' source parameter $\mathrm{R_G}$ do not follow the m_{T}-scaling determined from pions', implying no equilibrium between kaons and pions in the high baryon density medium.

Thanks for your attention !

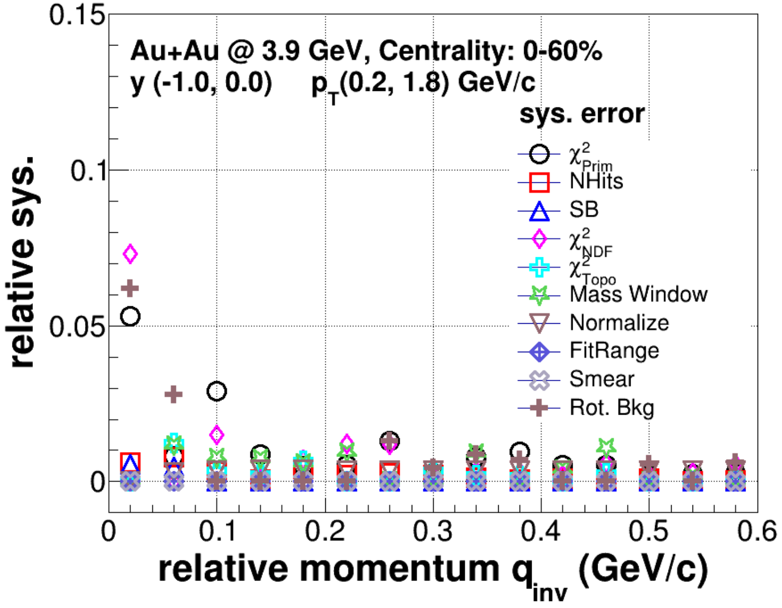
Back up

Analysis detail – Systematics

$K_S^0 - K_S^0$ CF systematic source

1. Track quality: NHitsFit
2. K_S^0 Reconstruction: $\chi^2_{Topo}, \chi^2_{NDF}, \chi^2_{primary}$, mass window
3. Momentum resolution effect (embedding)
4. CF calculation: Side band region, background estimate method, fitting range, normalize range

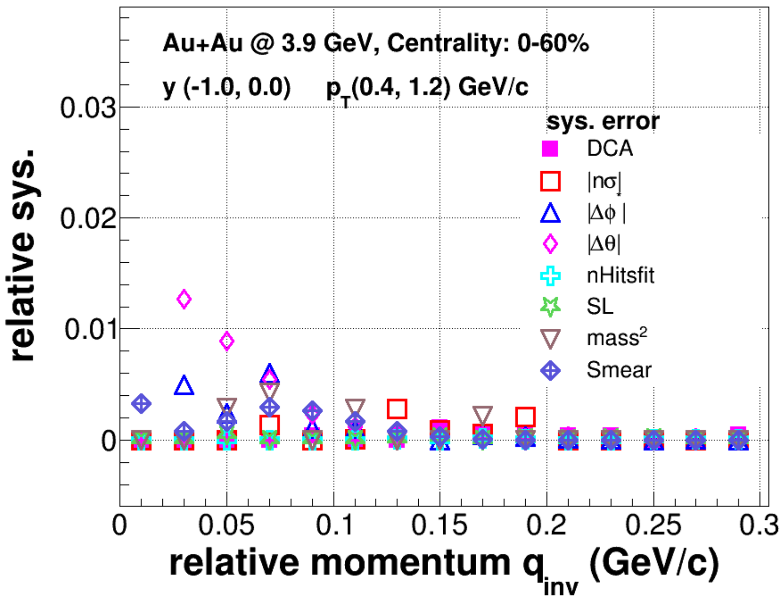
Barlow check[1] to reduce the statistical fluctuation



$K^+ - K^+$ CF systematic source

1. Track quality: NHitsFit, DCA
2. PID: TOF mass square, $n\sigma_K$
3. Track splitting & merging: splitting level, $|\Delta\phi^*|$, $|\Delta\theta|$
4. Momentum resolution effect (embedding)
5. CF calculation: Fitting range

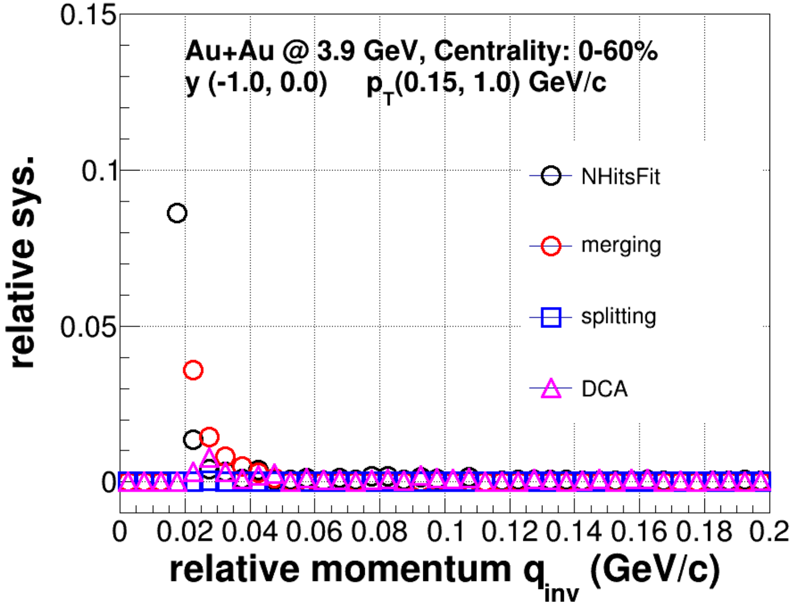
Barlow check[1] to reduce the statistical fluctuation



$\pi^+ - \pi^+$ CF systematic source

1. Track quality: NHitsFit, DCA
2. Track splitting & merging: splitting level, $|\Delta\phi^*|$, $|\Delta\theta|$

Barlow check[1] to reduce the statistical fluctuation



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[1] arXiv:hep-ex/0207026v1