



Third-body-corrected Two-Pion Femtoscopic Correlations in Au+Au Collisions at High Baryon Density

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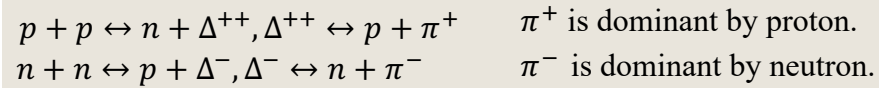
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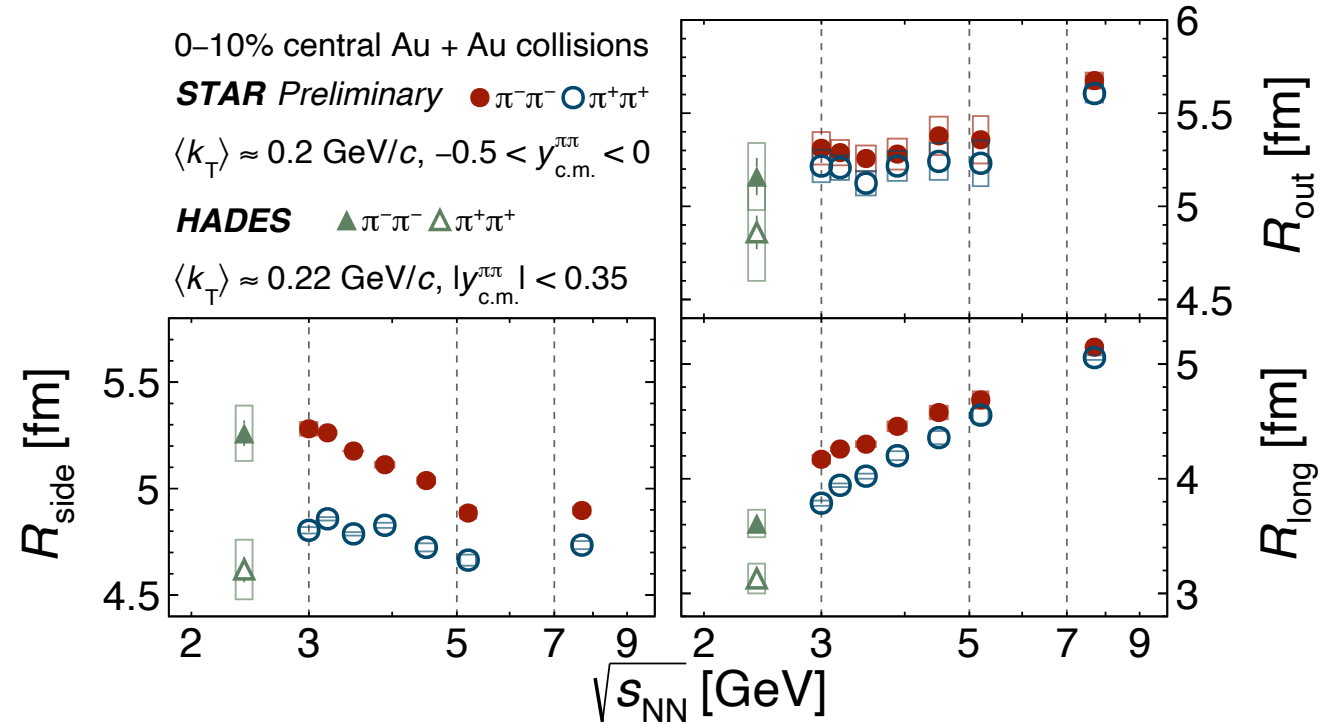
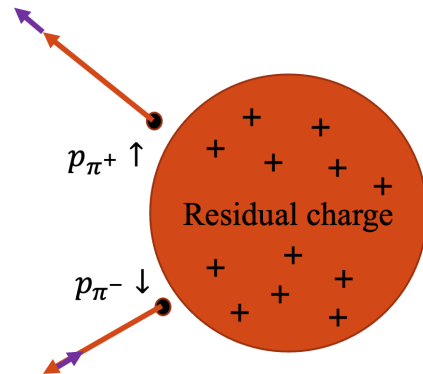
Motivation

- The R_{side} and R_{long} of $\pi^+\pi^+$ are smaller than $\pi^-\pi^-$. The reason may be due to **isospin asymmetry** in the gold nucleus and **residual third-body Coulomb** effect.

1. Initial isospin plays an important role in determining the EoS of the medium in collisions at high baryon density [1].



2. Coulomb interactions among the pair and the net positive charge in the emitting source also affect the final correlation functions[2].

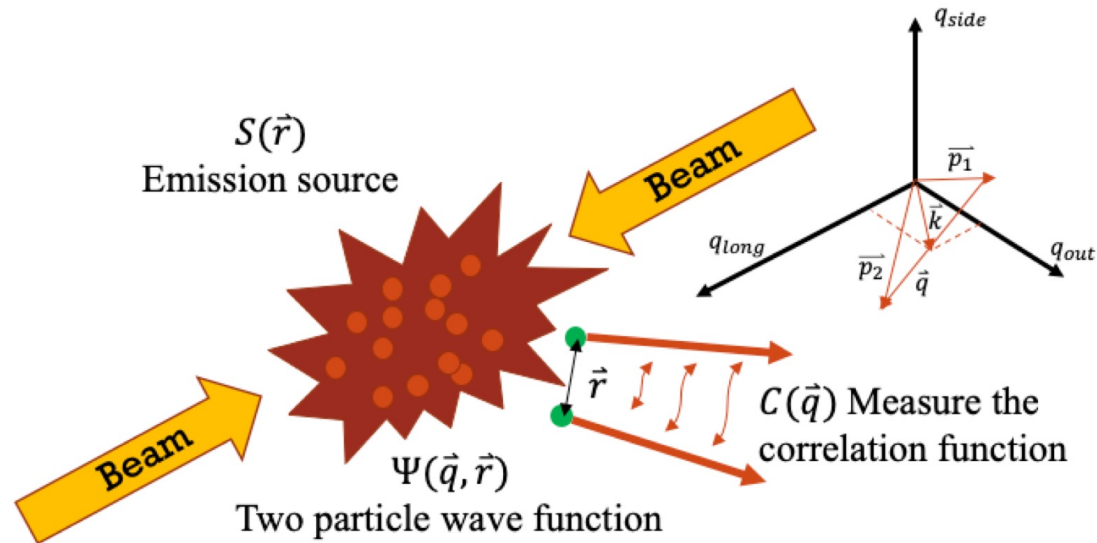


➤ Motivation:

Correct the contribution of the third-body Coulomb to study the isospin effect.

[1] B. A. Li, L. W. Chen, C. M. Ko, Phys. Rept. 464, 13 (2008).
 [2] R. Lednicky, Phys.Part.Nucl. 40, 307-352, (2009).

Femtoscopic Correlations Technique



➤ Definition of the correlation function(CF) [3, 4]:

$$C(\vec{q}) = \frac{\mathcal{P}(\vec{p}_1, \vec{p}_2)}{\mathcal{P}(\vec{p}_1)\mathcal{P}(\vec{p}_2)} = \frac{N_{same}(\vec{q})}{D_{mixed}(\vec{q})}$$

Statistical Experimental

- $\vec{q} = \vec{p}_1 - \vec{p}_2$, relative momentum.
- $\mathcal{P}(\vec{p}_1, \vec{p}_2)$ and $\mathcal{P}(\vec{p}_1)\mathcal{P}(\vec{p}_2)$ are the probability of observing particles 1 and 2 with given momenta simultaneously and independently respectively.
- $N_{same}(\vec{q})$: It contains correlations due to quantum-statistics and final state interactions.
- $D_{mixed}(\vec{q})$: The correlations are absent.

➤ The relative momentum can be projected onto the Bertsch-Pratt, out-side-long system:

- q_o direction is that of the pair transverse momentum.
- q_l direction is parallel to the beam.
- q_s direction is orthogonal to these two.

➤ CF are constructed in Longitudinally Co-Moving System (LCMS), where $\vec{p}_{z1} + \vec{p}_{z2} = 0$.

[3]S. Pratt, Phys.Rev.D 33, 1314-1327 (1986).

[4]G. Bertsch, M. Gong, and M. Tohyama, Phys.Rev.C 37, 1896 (1988).

Femtoscopic Correlations Technique

➤ Extract parameters by Bowler-Sinyukov function [5, 6]:

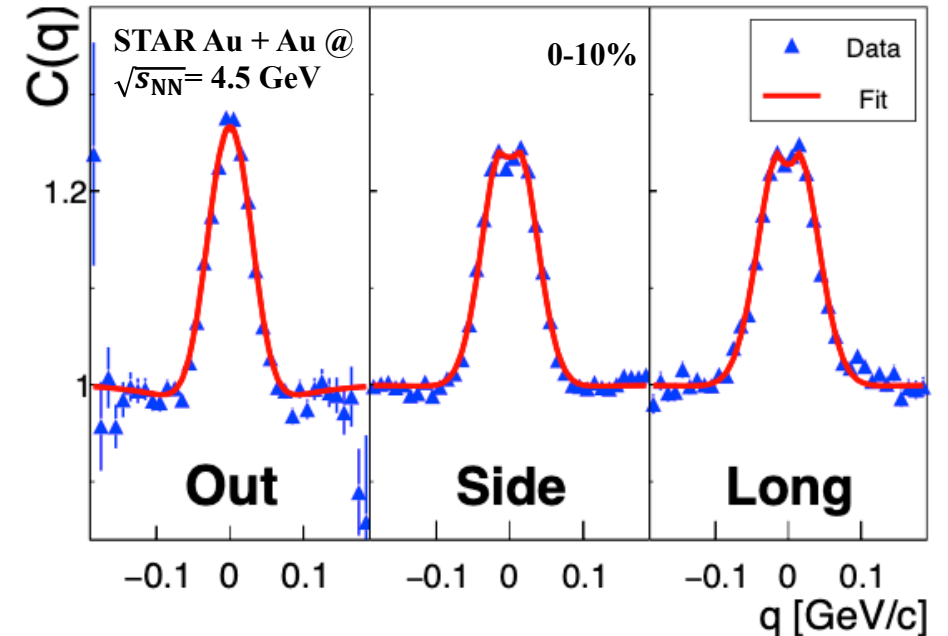
[5] Yu. Sinyukov et al., Phys. Lett. B 432, 248 (1998)

[6] M. Bowler, Phys. Lett. B 270, 69 (1991)

$$C(q_{out}, q_{side}, q_{long}) = N[(1 - \lambda) + \lambda K(q_{inv})(1 + \exp(-R_{out}^2 q_{out}^2 - R_{side}^2 q_{side}^2 - R_{long}^2 q_{long}^2 - 2R_{out-long}^2 q_{out} q_{long}))]$$

- N : Normalization constant.
- λ : Correlation Strength.
- $K(q_{inv}) = \int d^3r \rho(\vec{r}) |\psi_r(\vec{r}, \vec{q})|^2$, Coulomb contribution.
- R_{out} : geometrical size + particle emission duration.
- R_{side} : geometrical size of the system.
- R_{long} : kinetic freeze-out temperature and lifetime.
- $R_{out-long}^2$: tilt of the CF in the $q_{out} - q_{long}$ plane, depending on the degree of asymmetry of the rapidity acceptance w.r.t. midrapidity.

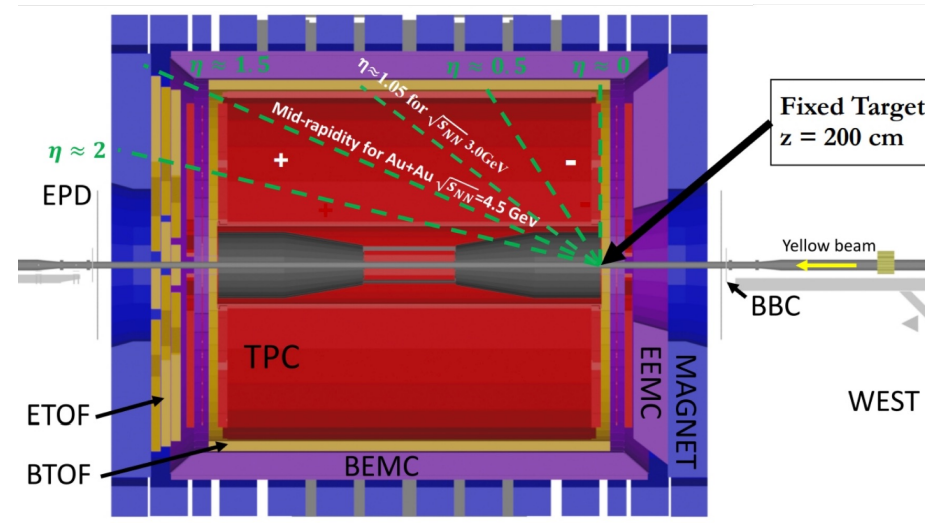
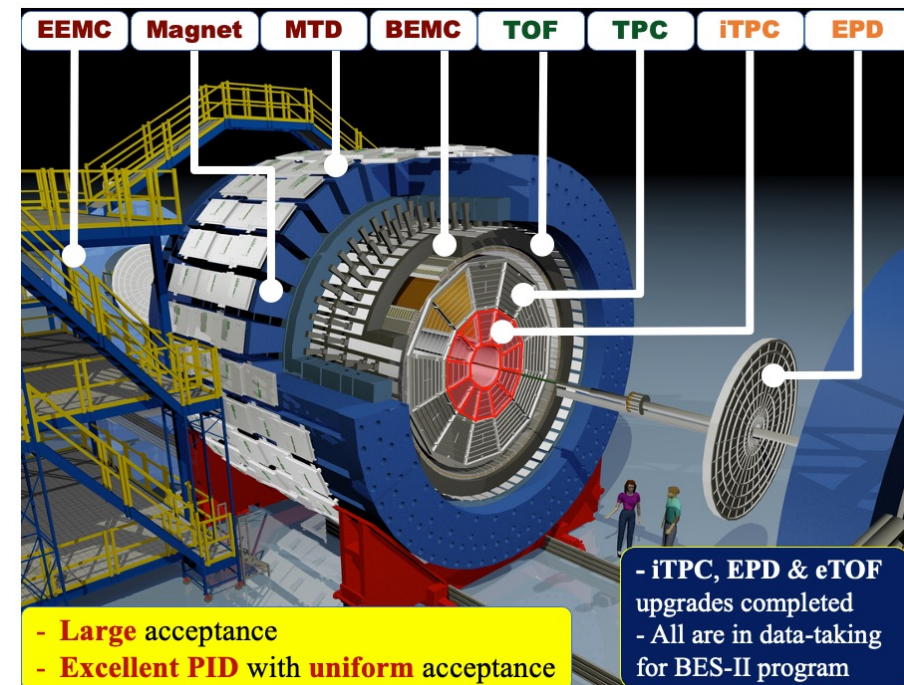
Fitting Example [7]:



[7] STAR Collaboration, Phys.Rev.C 103, 3, 034908 (2021)

The STAR Detector & Fixed-Target Program

➤ STAR Detector System



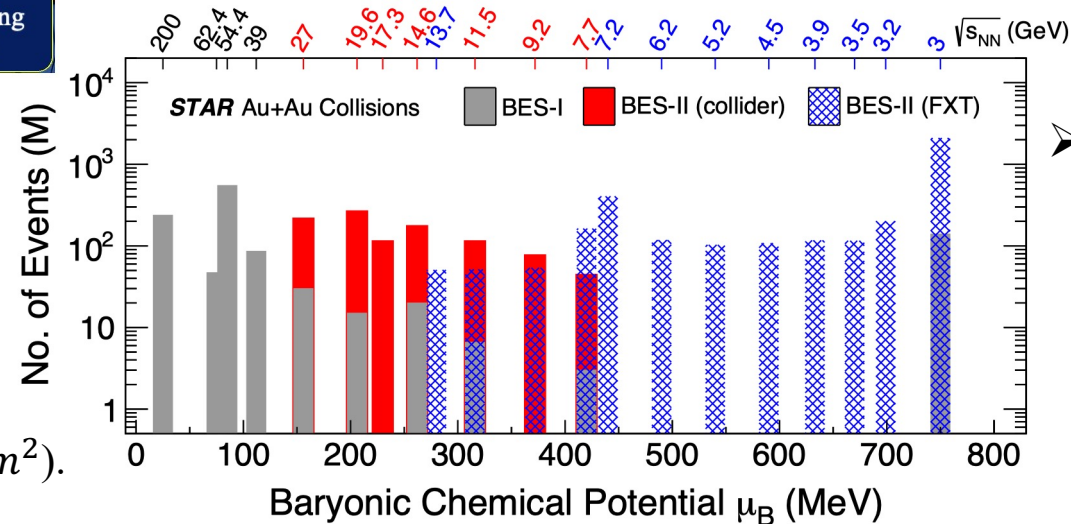
- FXT mode collision energies:
 $\sqrt{s_{NN}} = 3.0 - 13.7$ GeV.
 ➤ Extends the μ_B to ~ 720 MeV.

Time Projection Chamber (TPC)

- Charged particle tracking.
- Momentum reconstruction.
- Particle Identification (by dE/dx).

Time-of-Flight (TOF)

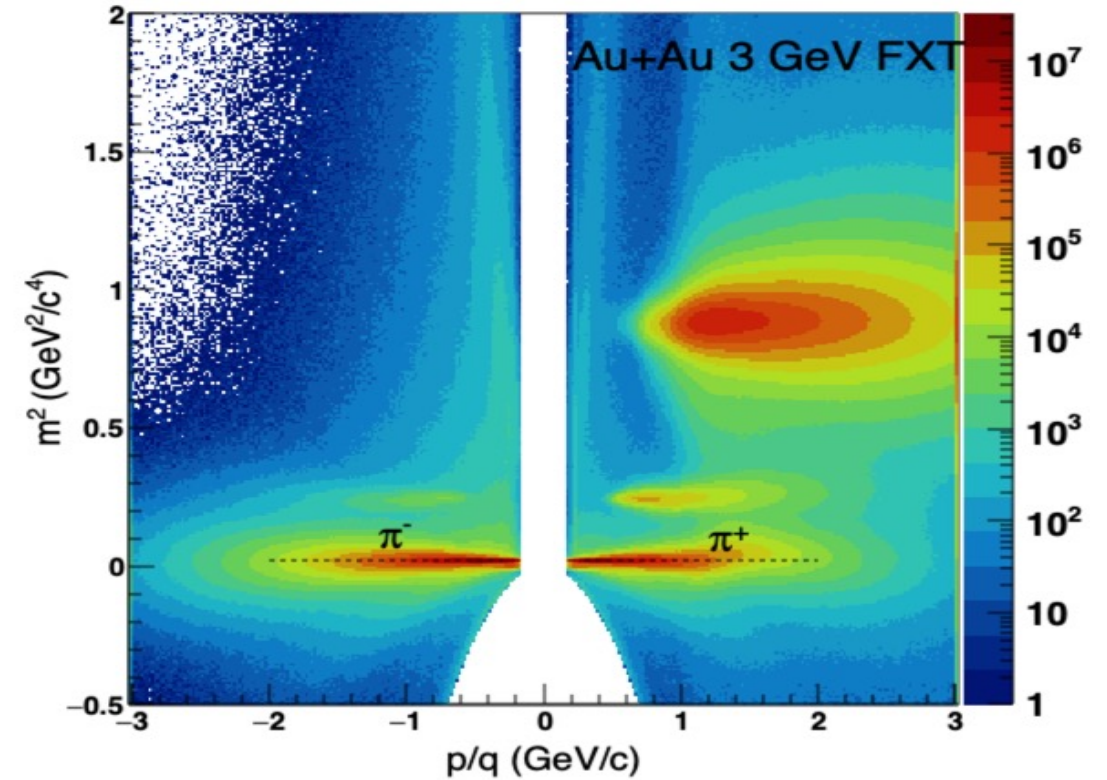
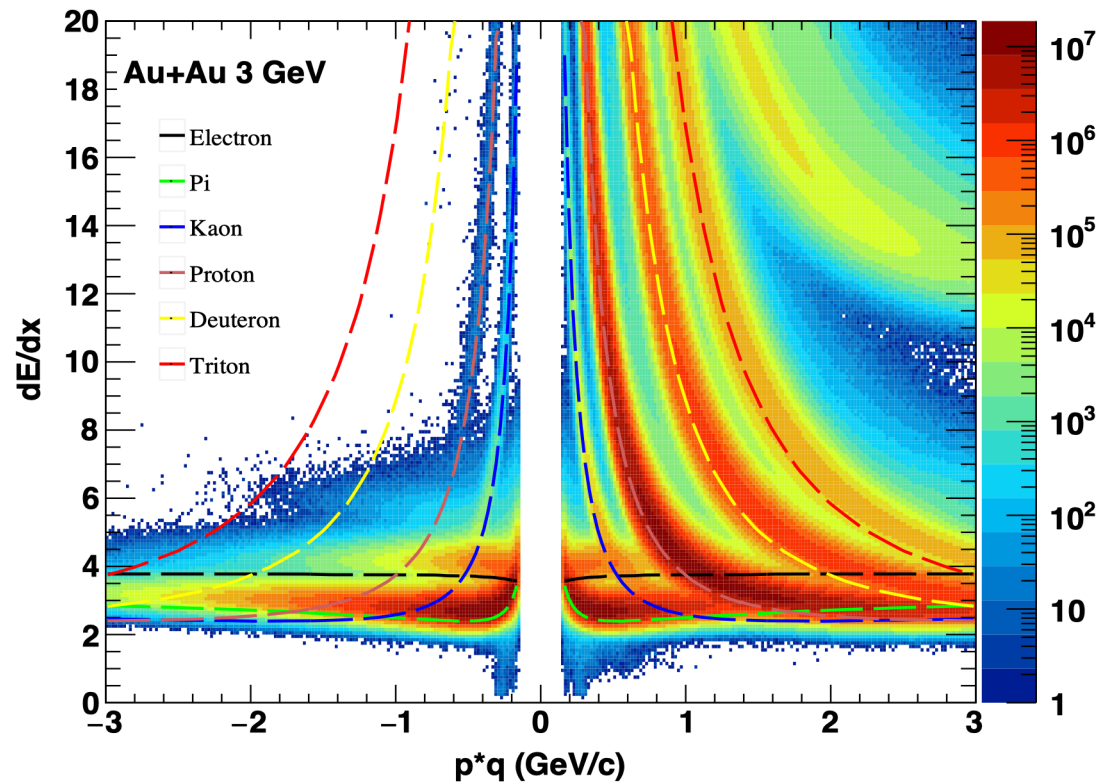
- Particle Identification at high momentum (by m^2).



➤ Data set:

- $\sqrt{s_{NN}} = 3.0, 3.2, 3.5, 3.9, 4.5$ GeV (BES-II, FXT mode).
- $\sqrt{s_{NN}} = 7.7$ GeV (BES-II, collider mode).

Pion Selection



➤ Good particle identification capability:

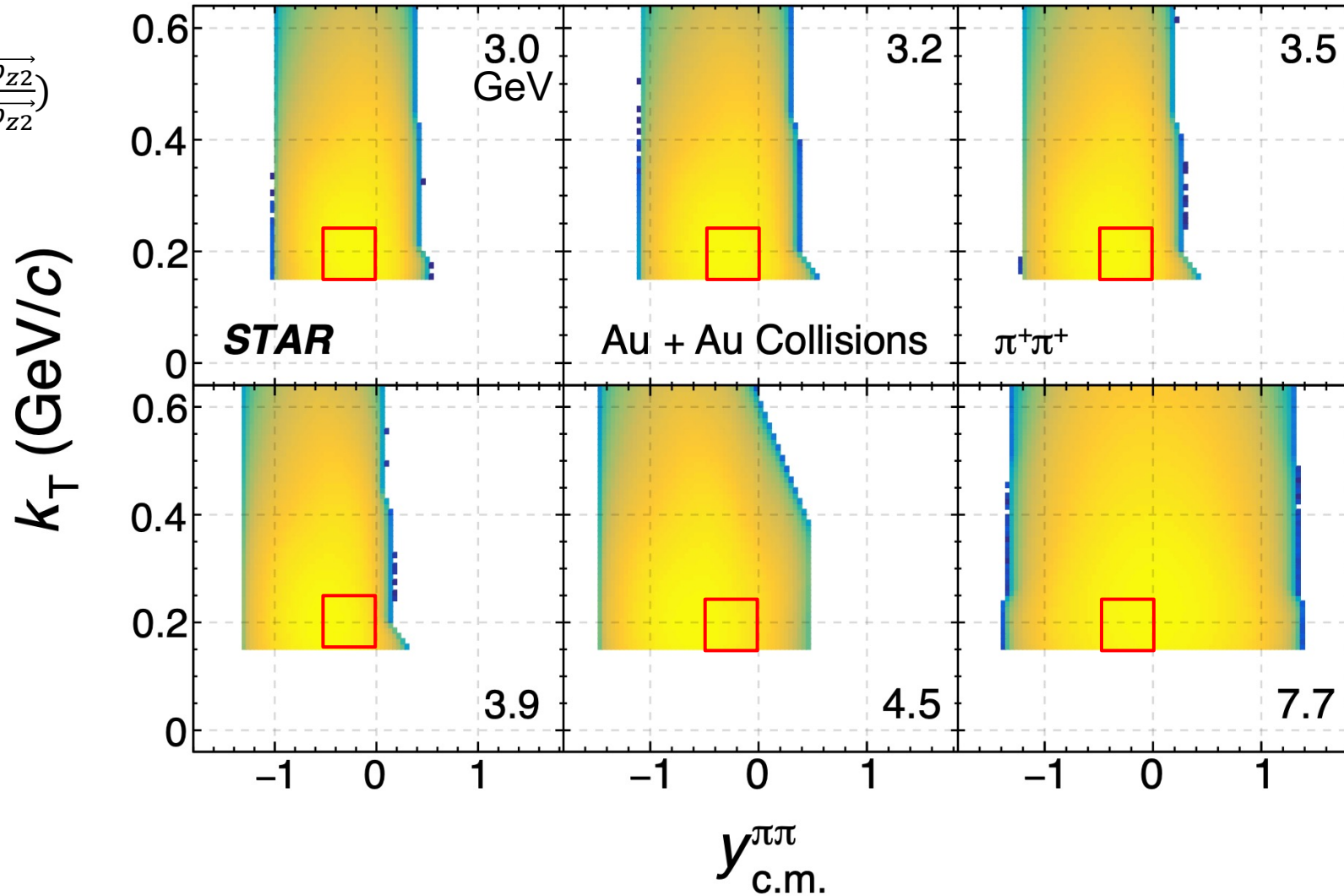
- $0.15 < p < 0.55$ GeV/c: TPC identification.

- $0.55 < p < 1.50$ GeV/c: TPC+TOF identification.

Pion Pair Acceptance

$$k_T = \frac{1}{2} |\vec{p}_{T1} + \vec{p}_{T2}|$$

$$y_{c.m.}^{pair} = \frac{1}{2} \ln \left(\frac{E_1 + E_2 + \vec{p}_{z1} + \vec{p}_{z2}}{E_1 + E_2 - \vec{p}_{z1} - \vec{p}_{z2}} \right)$$



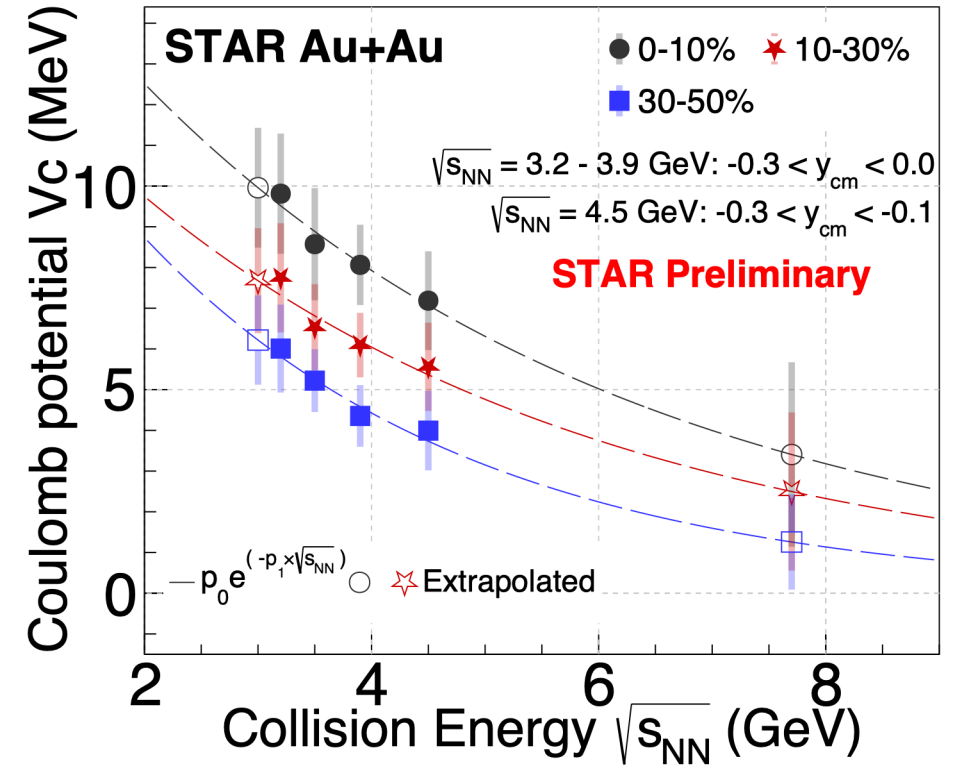
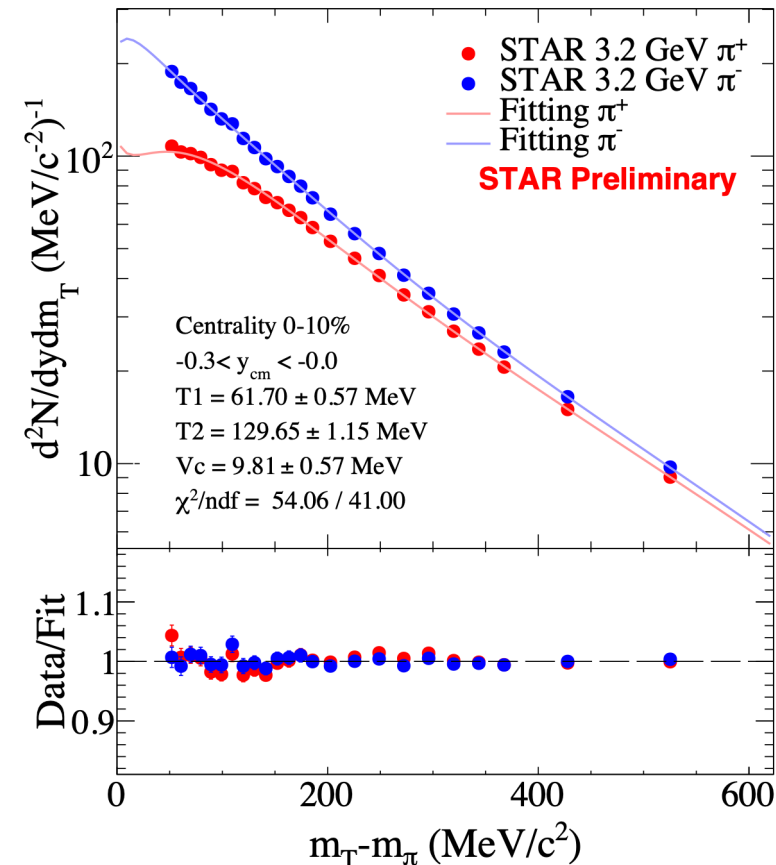
- Pairs with $0.15 < k_T < 0.25$ GeV/c, $-0.5 < y_{c.m.}^{\pi\pi} < 0$ are selected to study the third-body Coulomb and isospin effect.

Third-body Coulomb Correction (Experimental Method)

Step1: Fit the p_T spectra of π^- and π^+ simultaneously to extract Coulomb potential [8].

$$\frac{d^2N^\pm}{dydm_T} = A^\pm m_T^2 J^\pm J_{eff}^\pm [f_\pm e^{-\frac{E_f \mp V_{eff}}{T_1}} + (1 - f_\pm) e^{-\frac{E_f \mp V_{eff}}{T_2}}]$$

[8] HADES, Eur. Phys. J. A 58, 166 (2022)



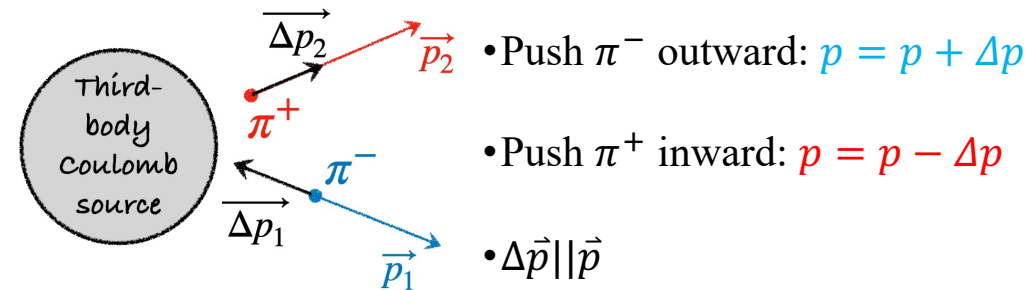
Step2: Calculate Δp from V_c .

$$V_{eff} = V_c (Erf(x) - (2/\sqrt{\pi}) x e^{-x^2})$$

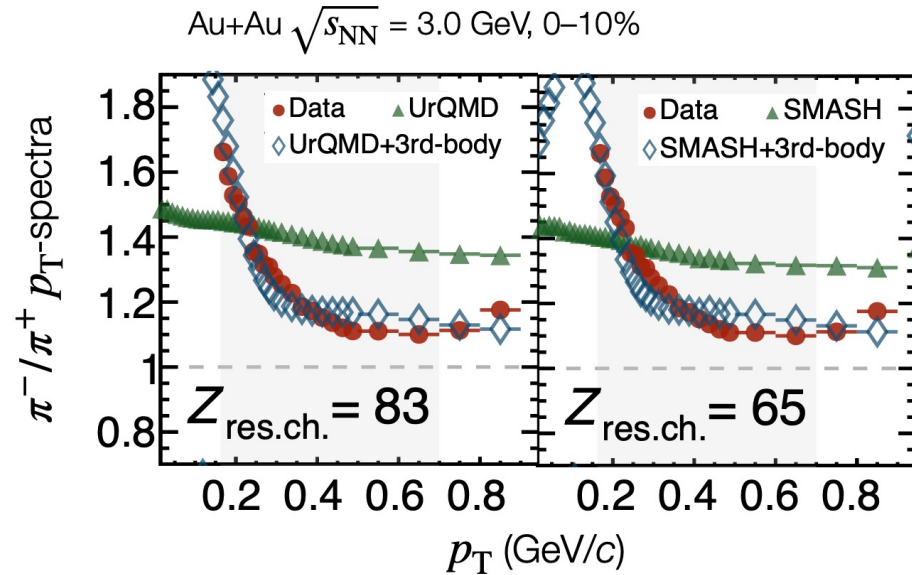
$$x = \sqrt{\left(\frac{E_\pi}{m_\pi} - 1\right) m_p / T_p}$$

$$\Delta E = V_{eff}$$

$$\Delta p = p' - p = \sqrt{(E + \Delta E)^2 - m^2} - \sqrt{E^2 - m^2} = \sqrt{(E + V_{eff})^2 - m^2} - \sqrt{E^2 - m^2}$$



Third-body Coulomb Correction (Transport Model Method)



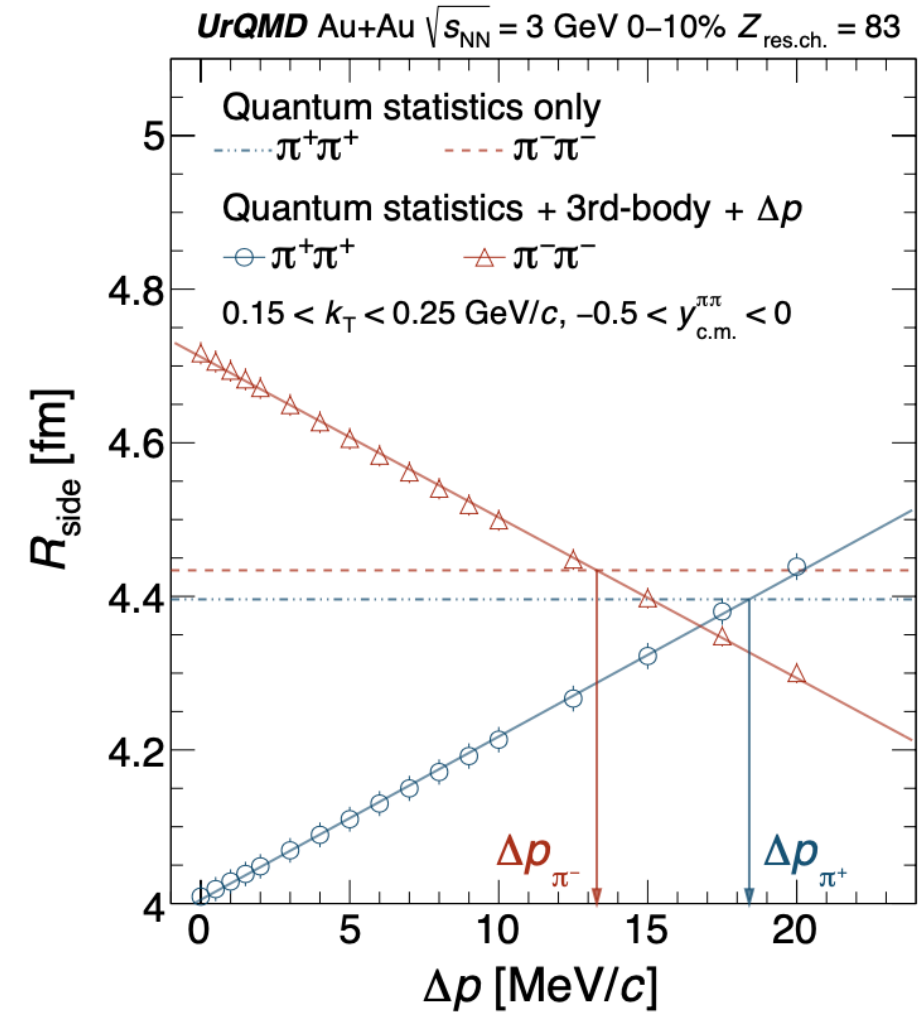
Step1: Add third-body Coulomb effect to UrQMD/SMASH using electrostatic potential energy.

$$V = \frac{1}{4\pi\epsilon_0} \frac{Z_{res.ch.} Z_\pi}{r_{f.o.}}$$

Step2: From $\pi^-/\pi^+ p_T$ -spectra ratio, find $Z_{res.ch.}$ that matches data best.

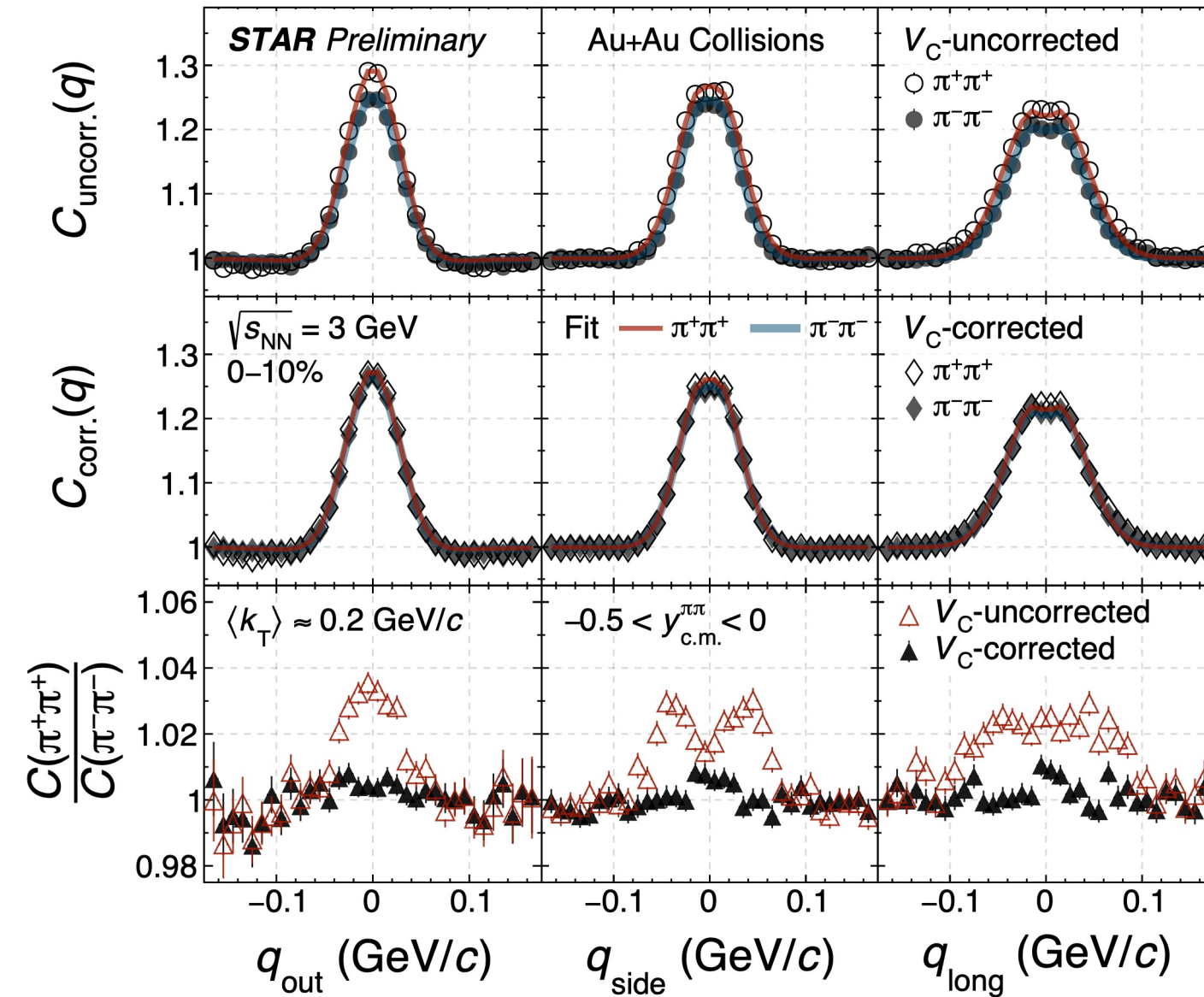
Step3: Add third-body Coulomb effect into UrQMD/SMASH using a quantum relativistic approach with the determined $Z_{res.ch.}$ [2]

Step4: Find Δp that the R_{side} without third-body Coulomb are restored.



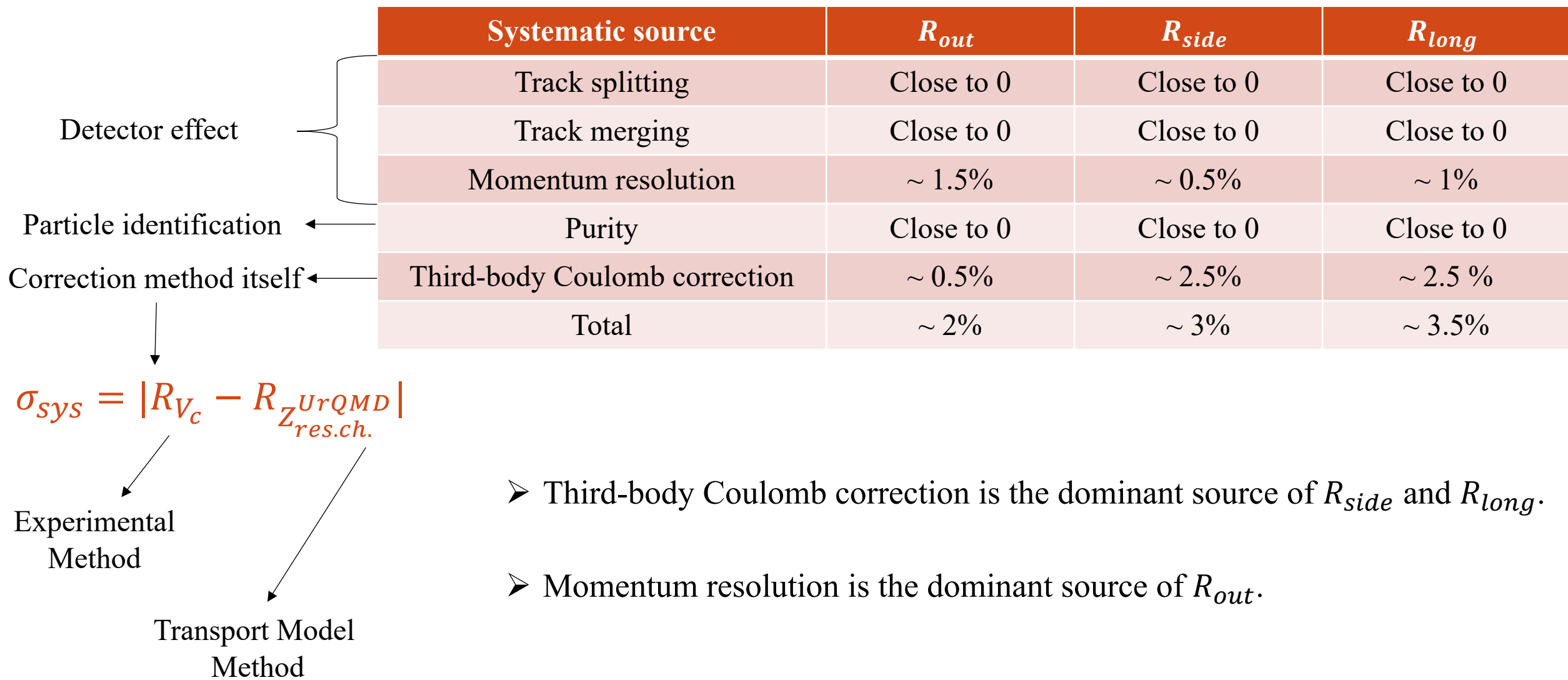
[2] R. Lednicky., Phys.Part.Nucl.40, 307-352, (2009).

Correlation Function



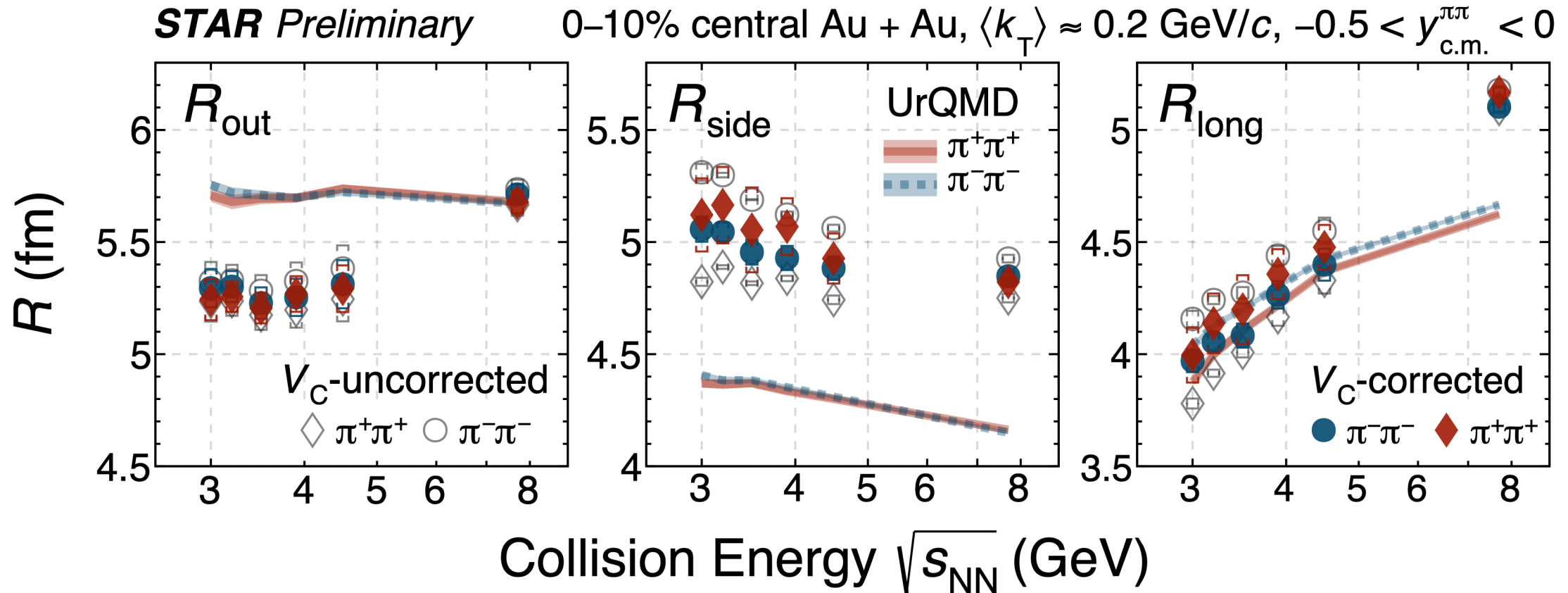
- Before third-body Coulomb corrections, the difference between $C(\pi^-\pi^-)$ and $C(\pi^+\pi^+)$ is about 4%.
- After third-body Coulomb corrections, the CF difference between $C(\pi^-\pi^-)$ and $C(\pi^+\pi^+)$ is about 1%.
- No room for Isospin effect?

Estimation of Systematic Error



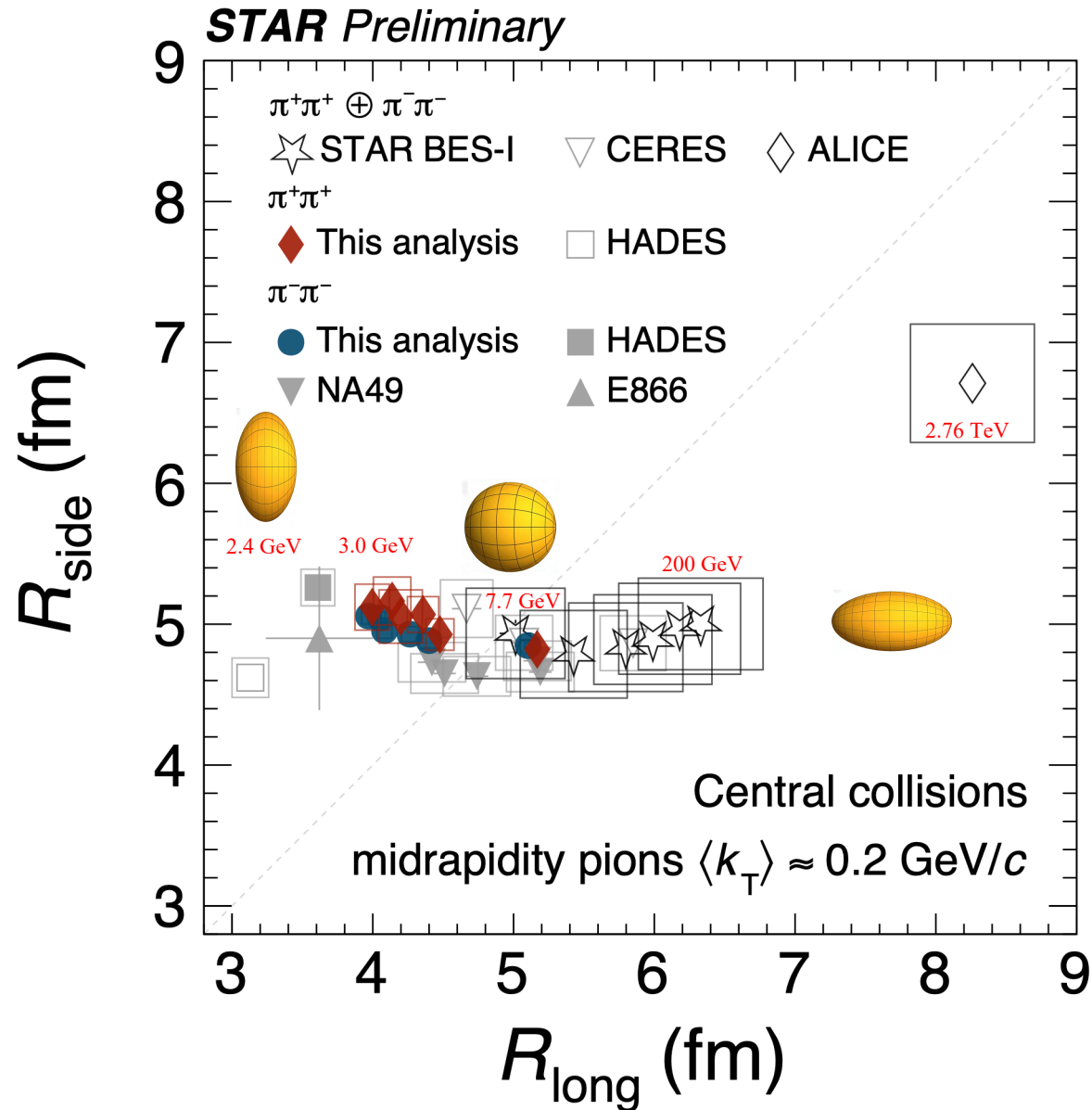
- Third-body Coulomb correction is the dominant source of R_{side} and R_{long} .
- Momentum resolution is the dominant source of R_{out} .

Energy Dependence of HBT Radius at Mid-rapidity



1. After third-body Coulomb correction, all HBT radius show insignificant difference between $\pi^-\pi^-$ and $\pi^+\pi^+$ pairs within uncertainties.
2. Third-body Coulomb is the dominant source causing the charge splitting. Initial isospin asymmetry, if any, contributes $< 5\%$ (95% CL) to the pion correlation.
3. R_{out} is not sensitive to third-body Coulomb effect.
4. For the $\sqrt{s_{\text{NN}}}$ from 3.0 to 7.7 GeV:
 - R_{out} and R_{side} change only slightly.
 - R_{long} rises by 20%, implying the increase of the source lifetime.

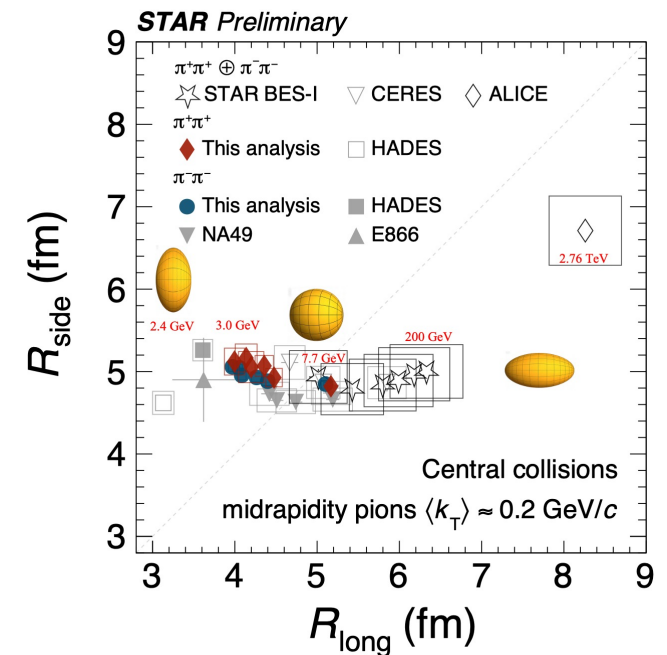
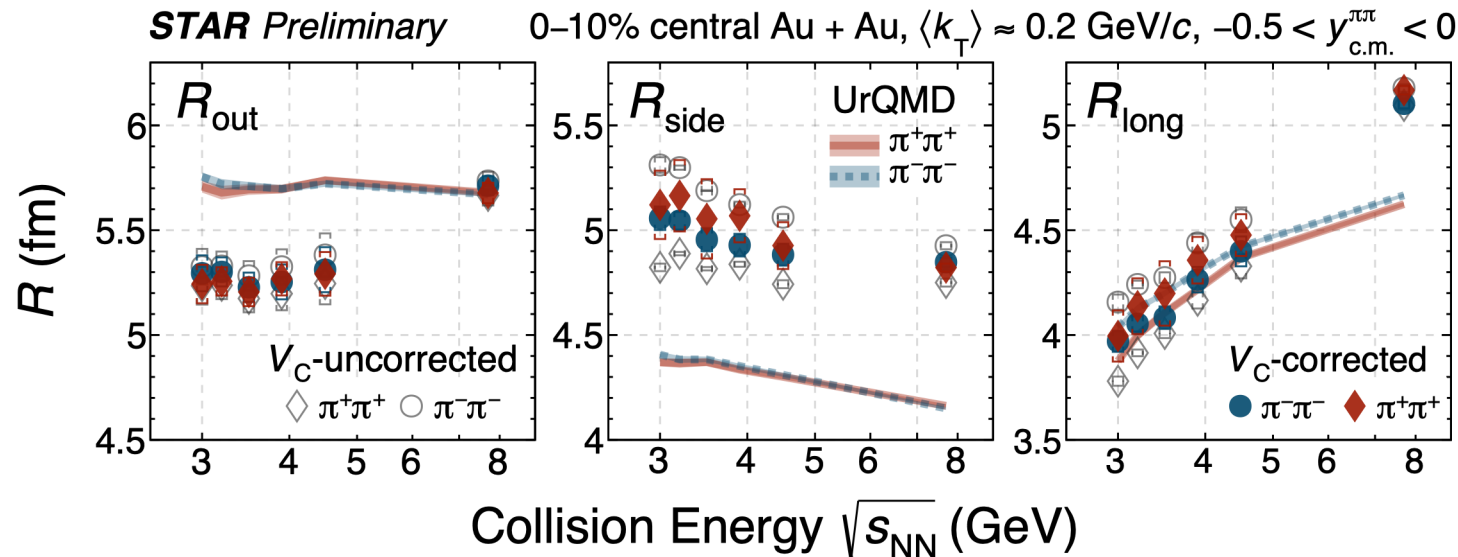
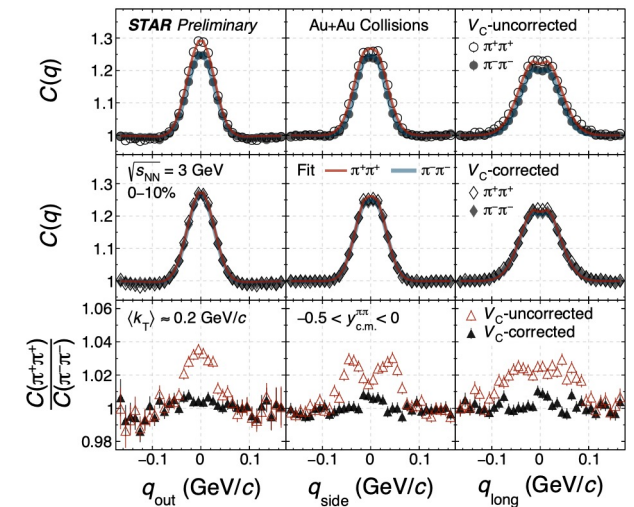
Energy Dependence of R_{side} vs. R_{long} at Mid-rapidity



- Lower energy collisions generally produce more oblate systems.
- Higher energy collisions generally produce more prolate systems.
- At approximately 5 GeV, the shape of the system changes from oblate to prolate.

Summary

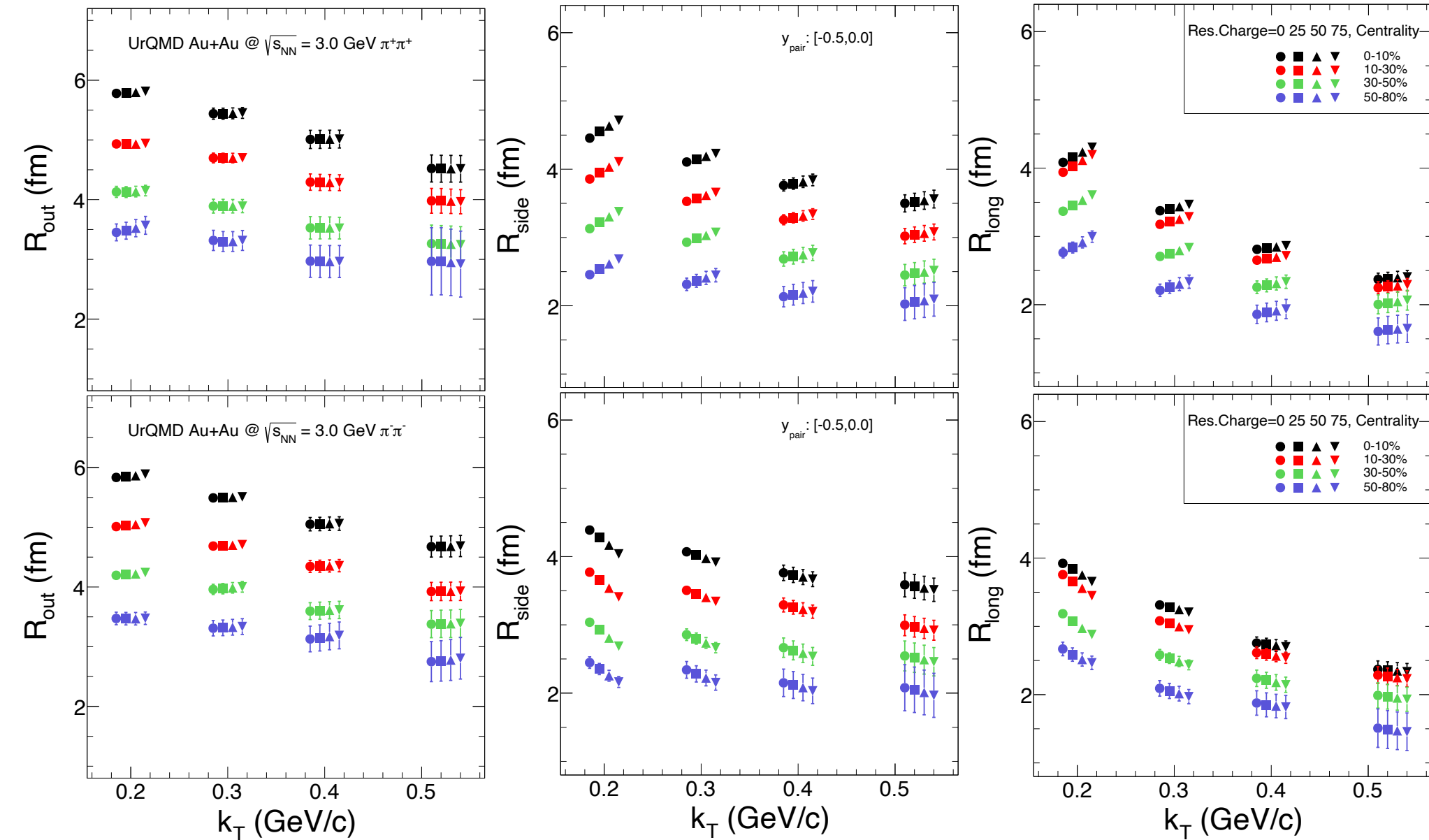
1. First time address third-body Coulomb effect in pion femtoscopy in Au + Au collisions at $\sqrt{s_{NN}} = 3.0 - 7.7$ GeV
2. Third-body Coulomb is the dominant source causing the charge splitting. Initial isospin asymmetry, if any, contributes $< 5\%$ (95% CL) to the pion correlation
3. At approximately 5 GeV, the shape of the system changes from oblate to prolate



Thanks for your attention !

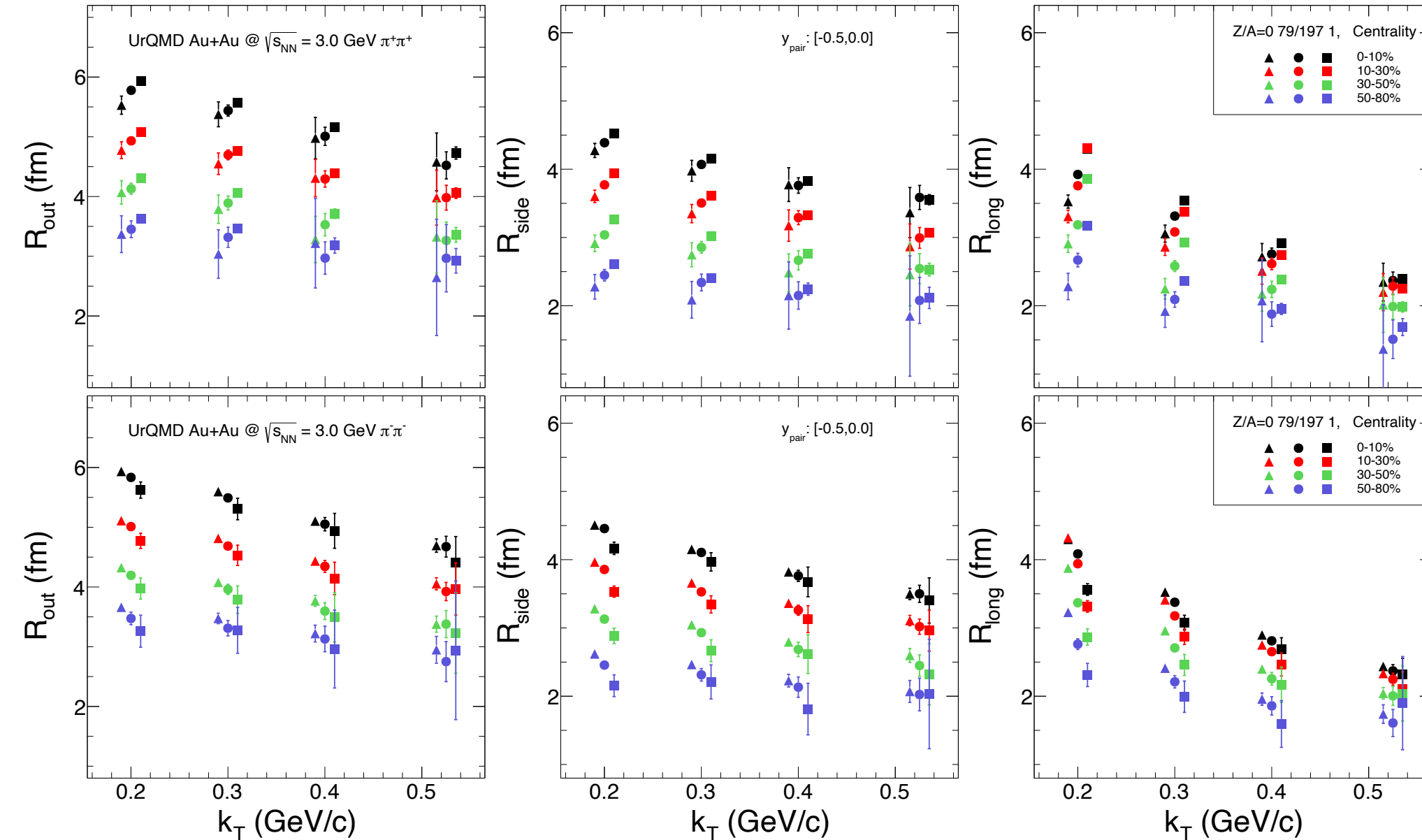
Backup

Third-body Coulomb Effect



As the number of residual charge increases, the R_{side} and R_{long} of $\pi^+\pi^+$ will decrease and $\pi^-\pi^-$ will increase.

Isospin Effect



One may expect the initial isospin effect is absent for $Z = N$ nuclei. For the case of Au nuclei, $Z < N$, which gives $R(\pi^+\pi^+) < R(\pi^-\pi^-)$.