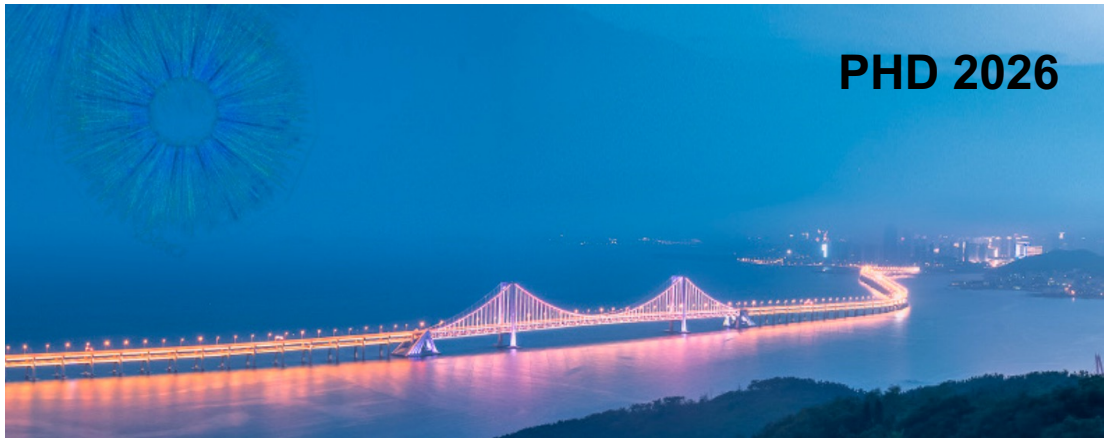


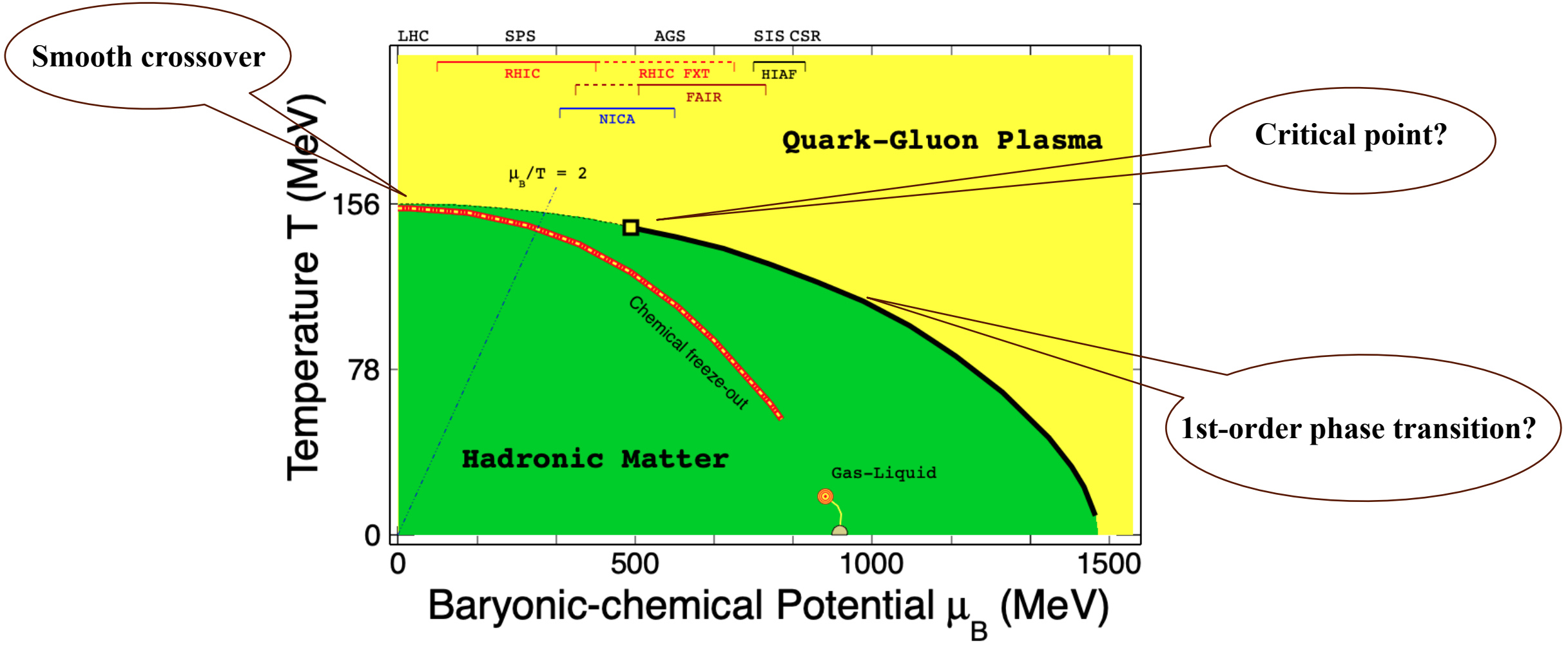
Pion HBT at High Baryon Density

Youquan Qi (*for the STAR Collaboration*)
Central China Normal University

Outline

1. Introduction
2. The STAR Detector & Fixed-Target Program
3. Femtoscopic Correlations Technique
4. Result and Discussions
5. Summary and Outlook

Introduction: QCD Phase Diagram



STAR Beam Energy Scan (BES):

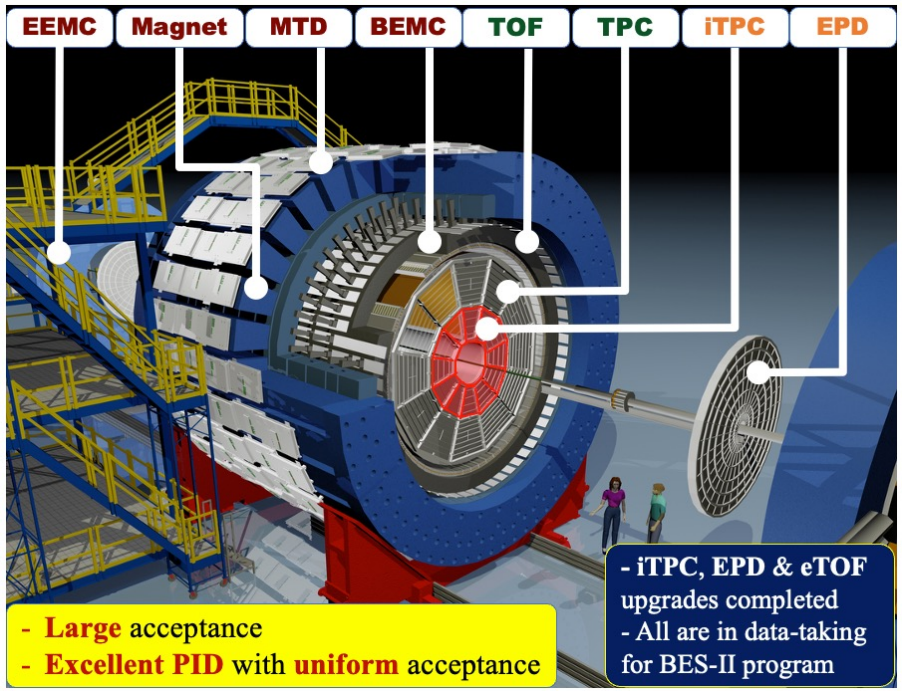
Vary T, μ_B by varying collision energy to scan phase diagram.

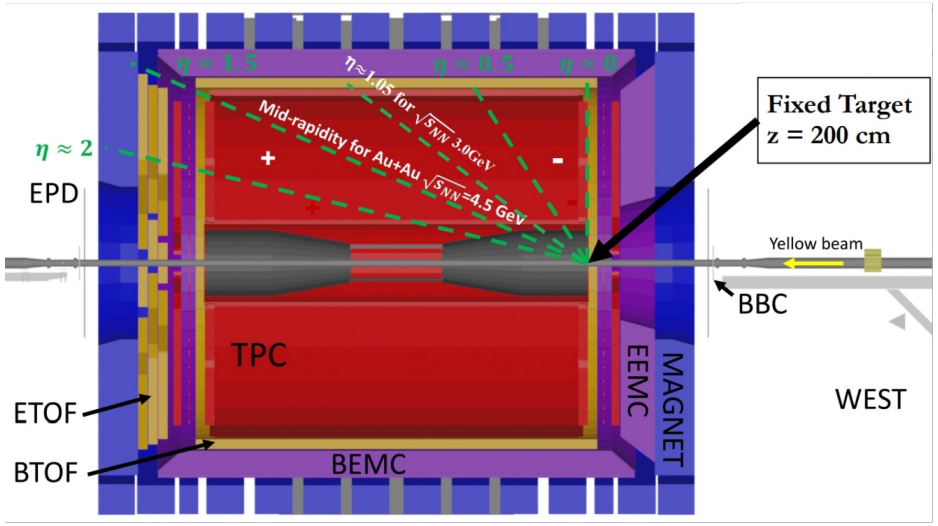
Y. Aoki et al, Nature 443, 675(2006)
H.T. Ding, F. Karsch, S. Mukherjee, Int. J. Mod. Phys. E 24 (2015) 10, 1530007
X. Luo, N. Xu, Nucl. Sci. Tech. 28, 112 (2017)

X. Luo, Q. Wang, N. Xu, P. F. Zhuang. Properties of QCD Matter at High Baryon Density. Springer, 2022, doi:10.1007/978-981-19-4441-3
https://drupal.star.bnl.gov/STAR/starnotes/public/sn0598

The STAR Detector & Fixed-Target Program

➢ STAR Detector System





➢ FXT mode collision energies: $\sqrt{s_{NN}}$ = 3.0 – 13.7 GeV.

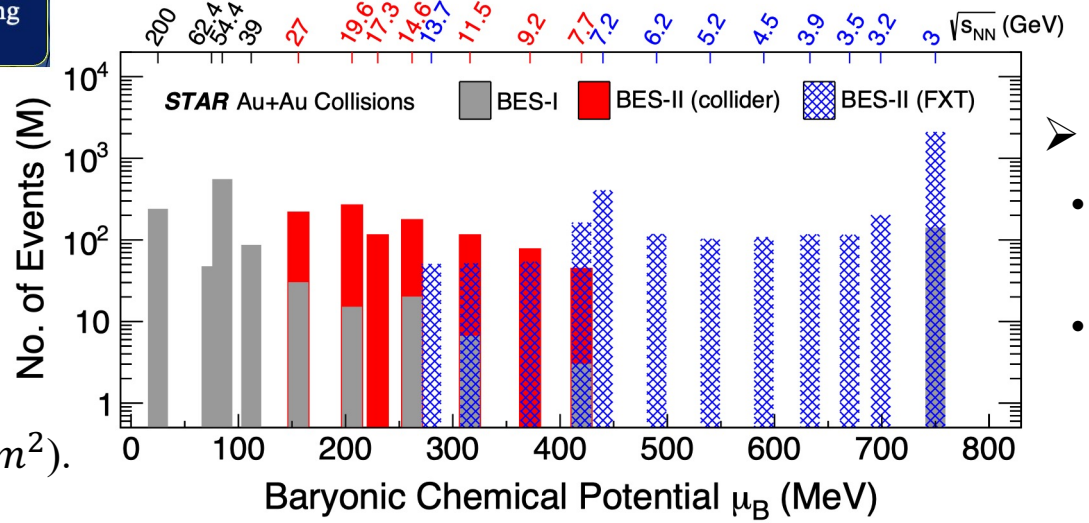
➢ Extends the μ_B to ~ 720 MeV.

Time Projection Chamber (TPC)

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

Time-of-Flight (TOF)

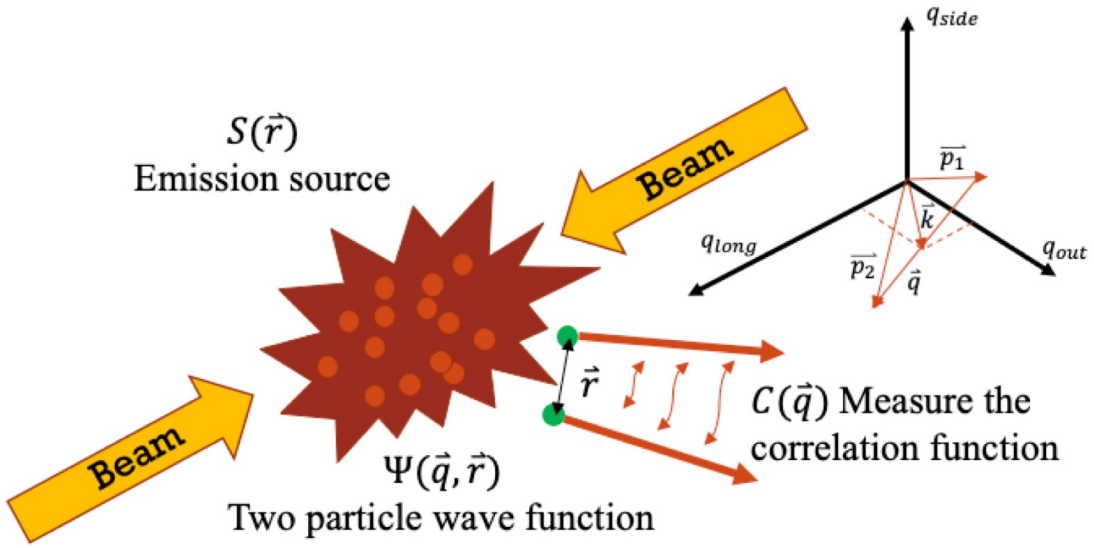
- Particle Identification at high momentum (by m^2).



➢ 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).

Femtoscopic Correlations Technique



- Definition of the correlation function (CF):

$$C(\vec{q}) = \int d^3r\, S(\vec{r})|\Psi(\vec{q},\vec{r})|^2 = \frac{N_{same}(\vec{q})}{D_{mixed}(\vec{q})}$$

Theory | Experimental

Source

1.Quantum statistics
2.Coulomb
3.Strong interaction

- The relative momentum can be projected onto the Bertsch-Pratt, out-side-long system:
  - q_{out} direction is that of the pair transverse momentum.
  - q_{long} direction is parallel to the beam.
  - q_{side} direction is orthogonal to these two.
- CF are constructed in Longitudinally Co-Moving System (LCMS), where $\overrightarrow{p_{z1}} + \overrightarrow{p_{z2}} = 0$.

- $\vec{q} = \overrightarrow{p_1} - \overrightarrow{p_2}$, relative momentum.
- $N_{same}(\vec{q})$: It contains correlations due to quantum-statistics and final state interactions.
- $D_{mixed}(\vec{q})$: The correlations are absent.

S. Pratt, Phys.Rev.D 33, 1314-1327 (1986).
G. Bertsch, M. Gong, and M. Tohyama, Phys.Rev.C 37, 1896 (1988).

Femtoscopic Correlations Technique

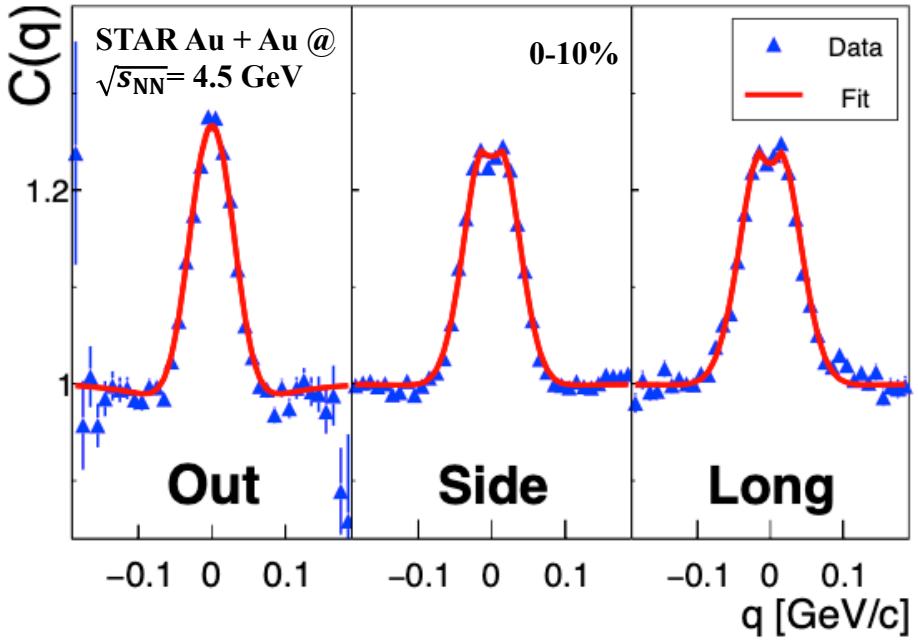
➢ Extract parameters by Bowler-Sinyukov function:

Yu. Sinyukov et al., Phys. Lett. B 432, 248 (1998)
M. Bowler, Phys. Lett. B 270, 69 (1991)

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

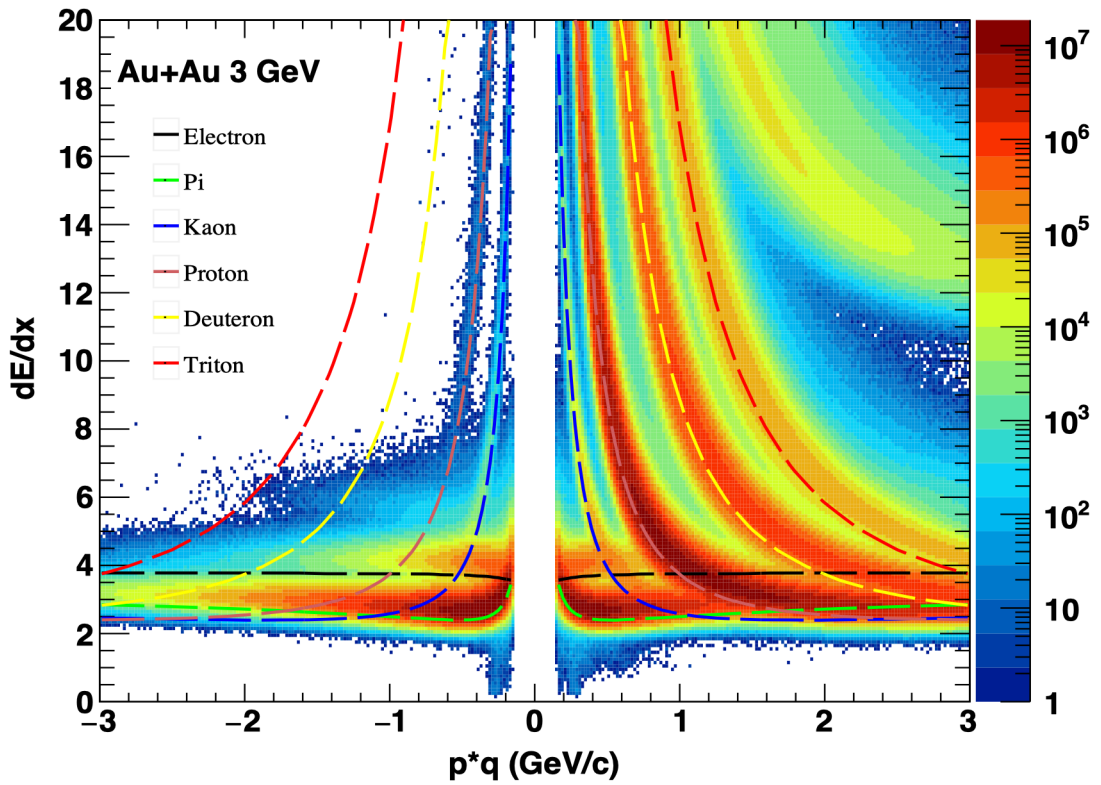
- N: Normalization constant.
- λ: Correlation Strength.
- $K(q_{inv}) = \int d^3r \rho(\vec{r}) |\psi_r(\vec{r}, \vec{q})|^2$, Coulomb contribution.
- R_{out}: geometrical size + particle emission duration.
- R_{side}: geometrical size of the system.
- R_{long}: kinetic freeze-out temperature and lifetime.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

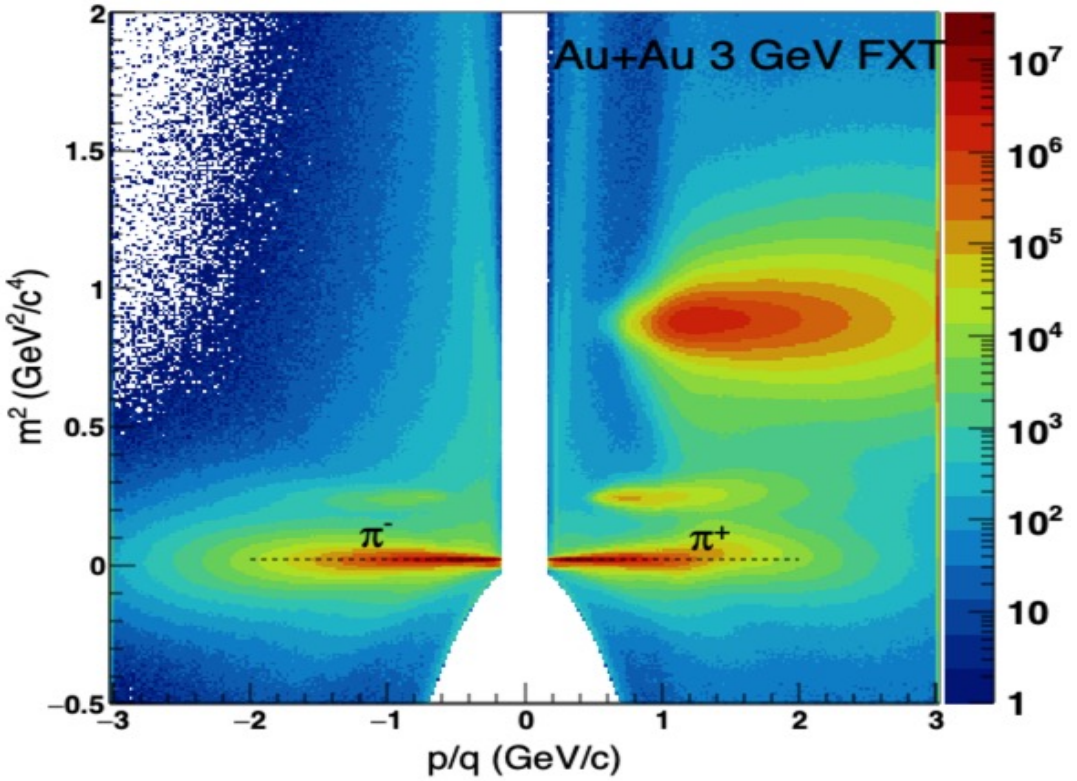
Fitting Example:



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

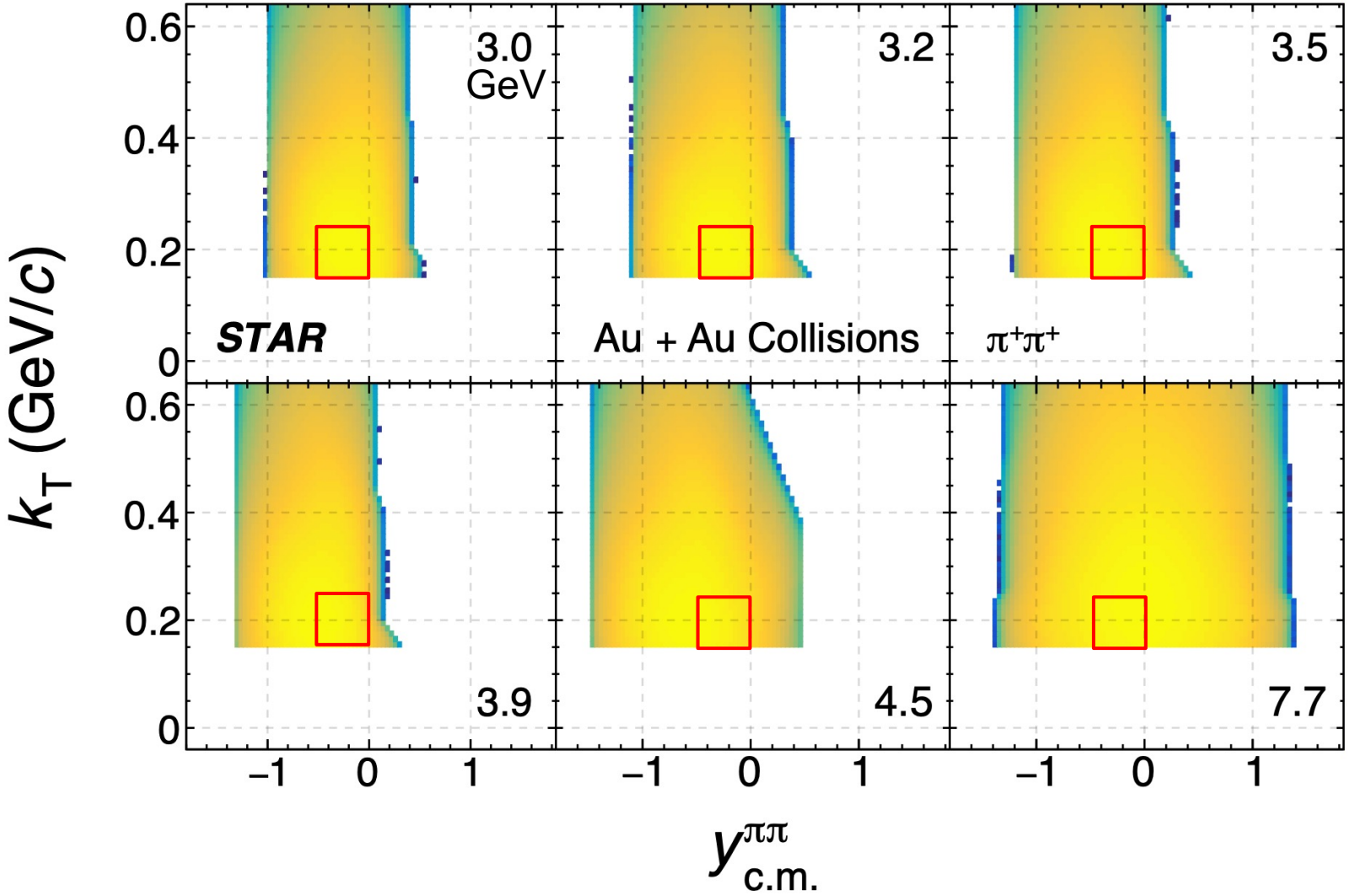
Pion Selection





- Good particle identification capability (purity~99.9%):
  - $0.15 < p < 0.55$ GeV/c: TPC identification.
  - $0.55 < p < 1.50$ GeV/c: TPC+TOF identification.

Pion Pair Acceptance

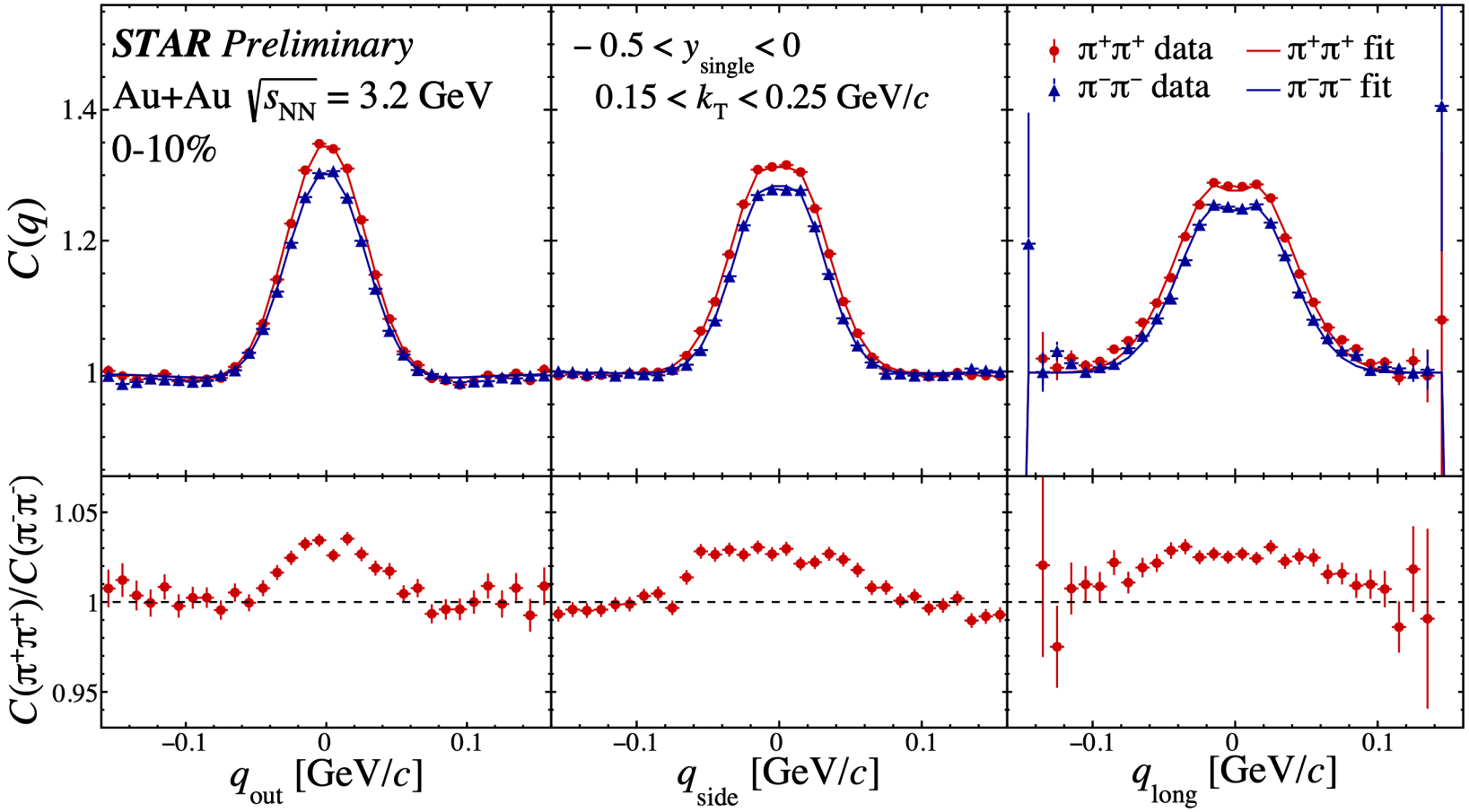


$$k_T = \frac{1}{2}|\overrightarrow{p_{T1}} + \overrightarrow{p_{T2}}|$$

$$y_{c.m.}^{pair} = \frac{1}{2}\ln\left(\frac{E_1+E2+\overrightarrow{p_{z1}}+\overrightarrow{p_{z2}}}{E_1+E2-\overrightarrow{p_{z1}}-\overrightarrow{p_{z2}}}\right)$$

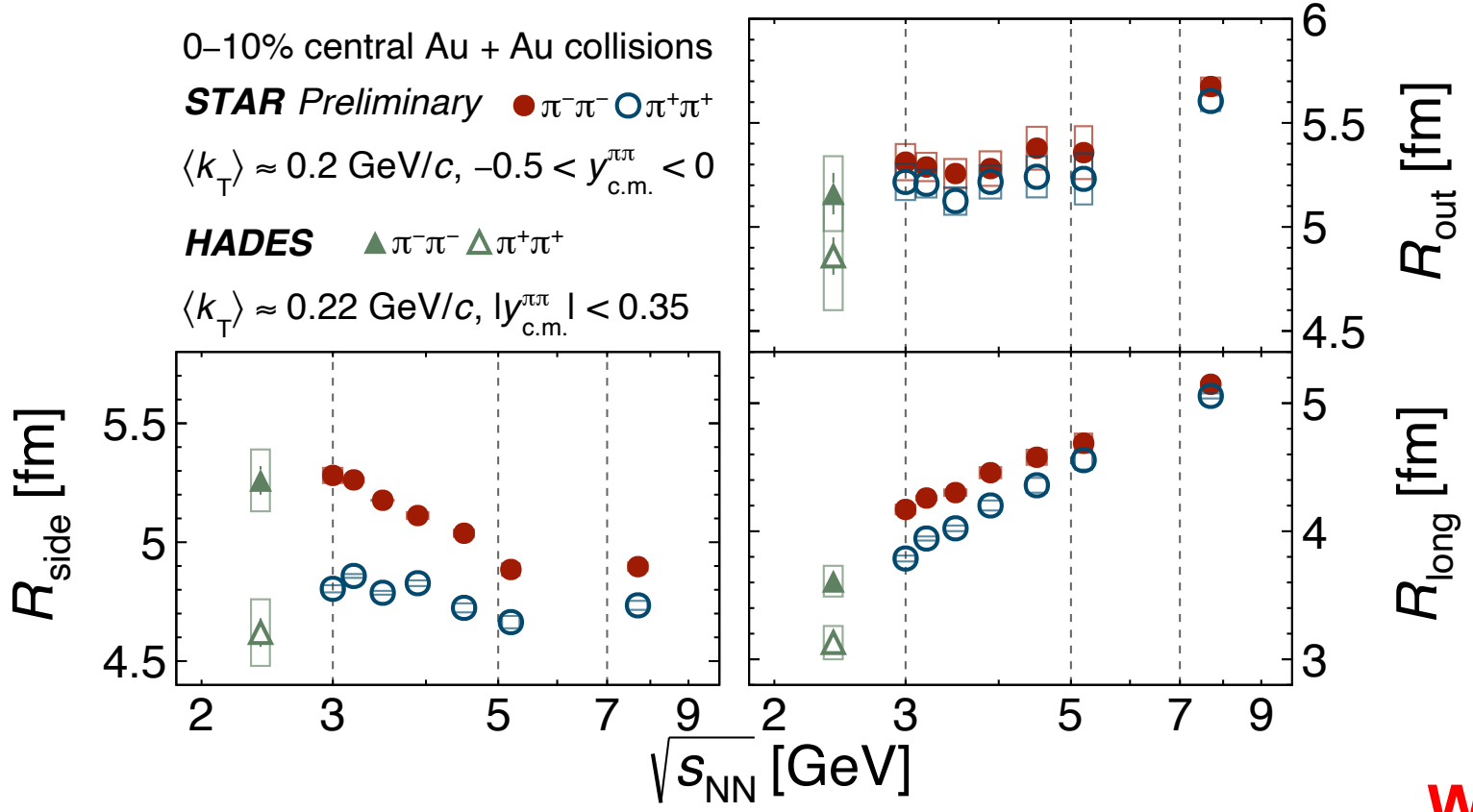
- $0.15 < k_T < 0.25$ GeV/c,
  $-0.5 < y^{\pi\pi}_{c.m.} < 0$.

Correlation Function



- The correlation function is enhanced at low q due to Bose–Einstein quantum statistical effects.
- Clear differences in π correlation functions: $C(\pi^+\pi^+) > C(\pi^-\pi^-)$.

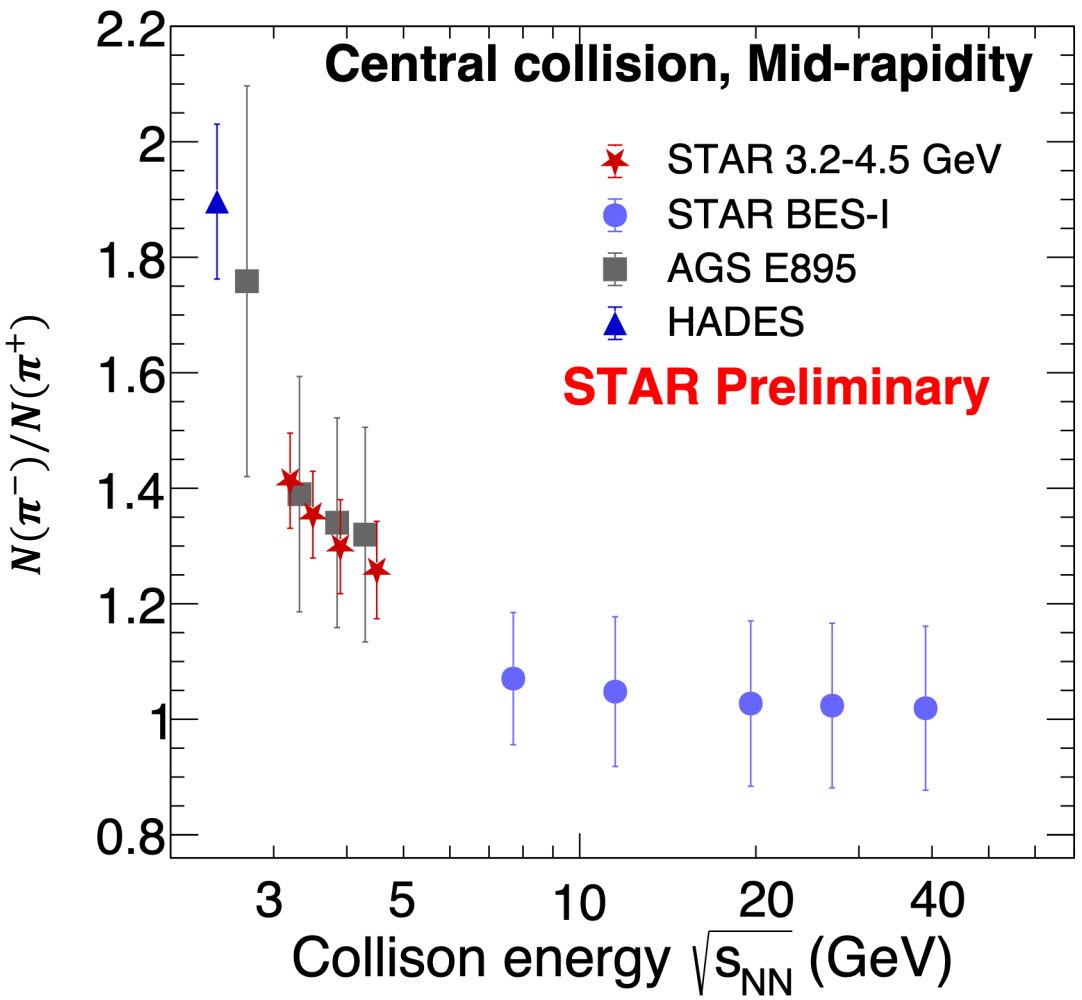
Energy Dependence of HBT Radii



What caused this charge splitting?

- **Clear charge splitting is seen in pion radii.**
- **$R(\pi^-) > R(\pi^+)$ (especially for R_{side} and R_{long}).**
- **The lower the collision energy, the larger the baryon density, the larger the splitting.**

Pion Yield Ratio:



^{197}Au Nuclear Isospin Asymmetry:

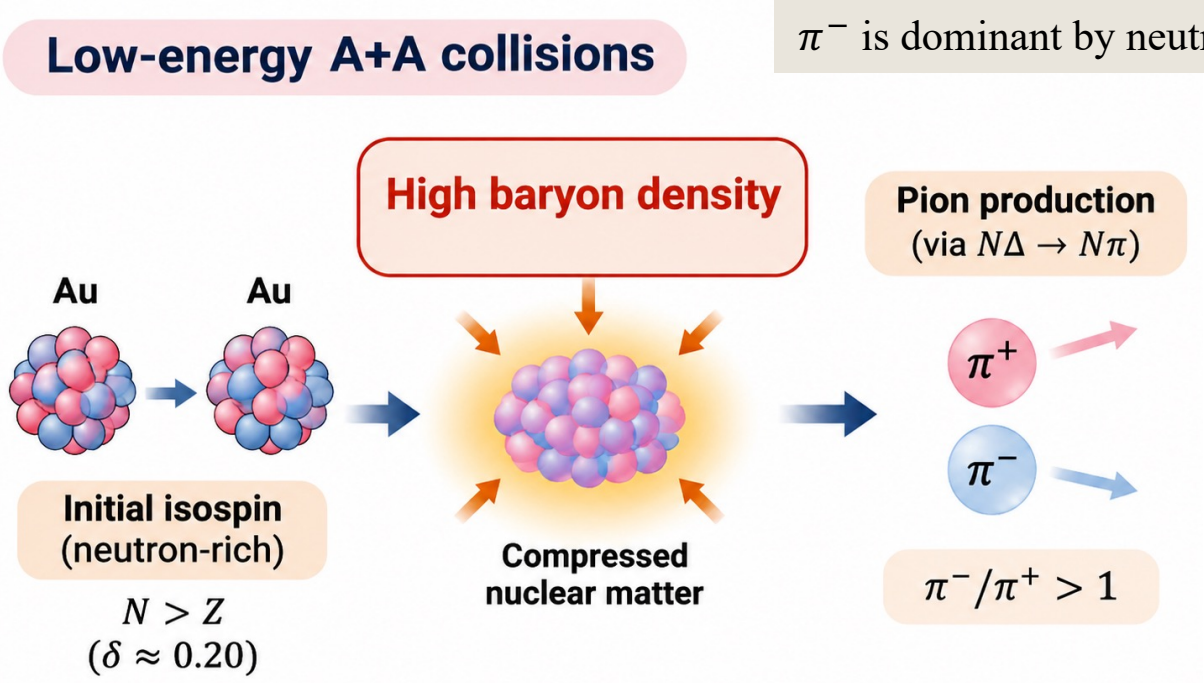
$$\frac{N-Z}{N+Z} = \frac{118-79}{197} \approx 0.198$$

$p + p \leftrightarrow n + \Delta^{++}, \Delta^{++} \leftrightarrow p + \pi^+$

$n + n \leftrightarrow p + \Delta^-, \Delta^- \leftrightarrow n + \pi^-$

π^+ is dominant by proton.

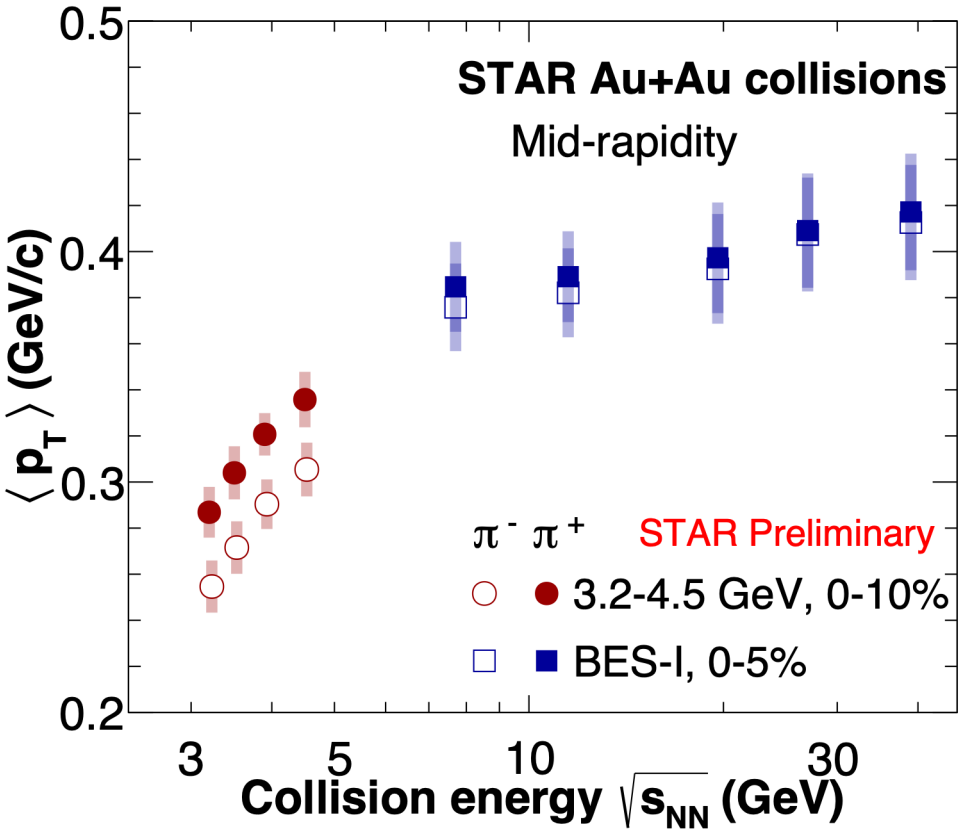
π^- is dominant by neutron.



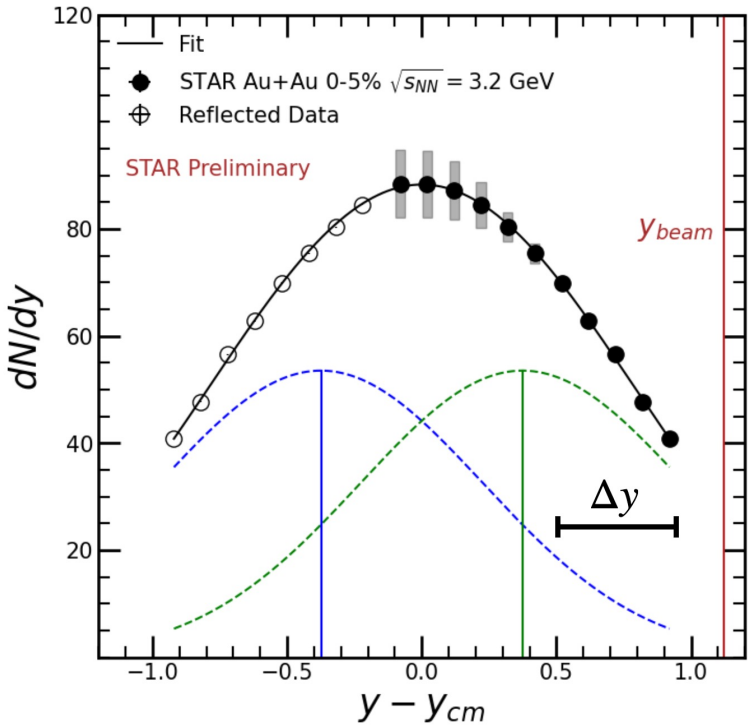
Isospin effect?

➢ **The lower the collision energy, the larger the baryon density, the larger the $\frac{N(\pi^-)}{N(\pi^+)}$.**

Pion $\langle p_T \rangle$:



Proton dN/dy

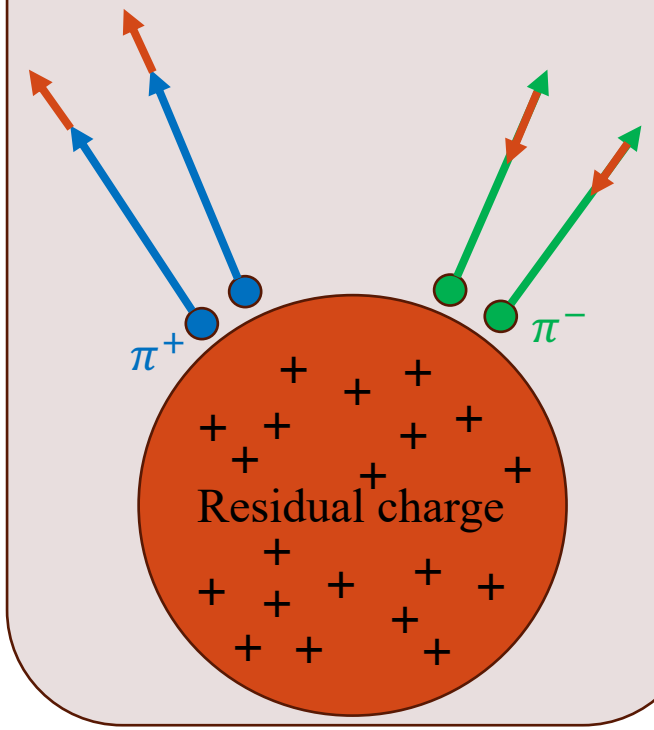


Baryon stopping

Third-body Coulomb effect?

$\pi^+: p = p_{real} + \Delta p$

$\pi^-: p = p_{real} - \Delta p$

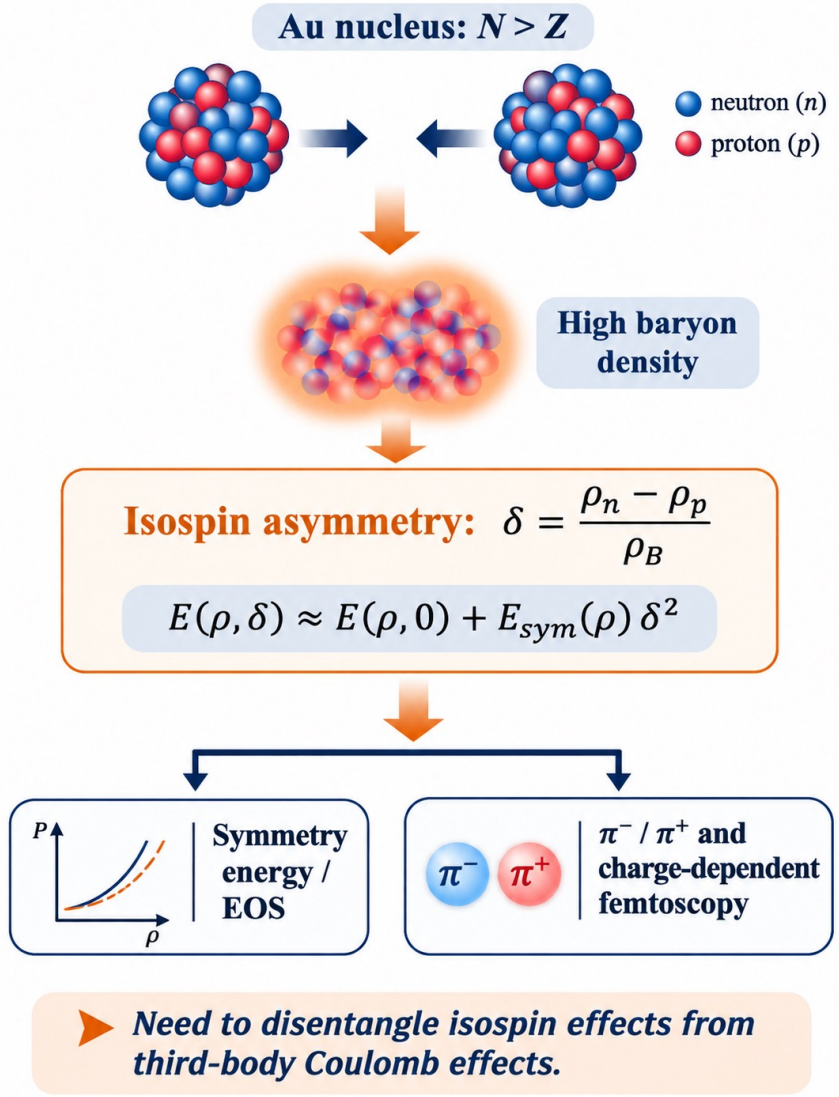


- **Clear charge splitting is also seen in pion $\langle p_T \rangle$.**
- **$\langle p_T(\pi^+) \rangle > \langle p_T(\pi^-) \rangle$.**
- **The lower the collision energy, the larger the baryon density, the larger the splitting.**

Initial Isospin → EOS

✔ **Initial isospin plays an important role in determining the EoS of the medium in collisions at high baryon density.**

✘ **Third-body Coulomb distort the final correlation functions.**



➢ Motivation:

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

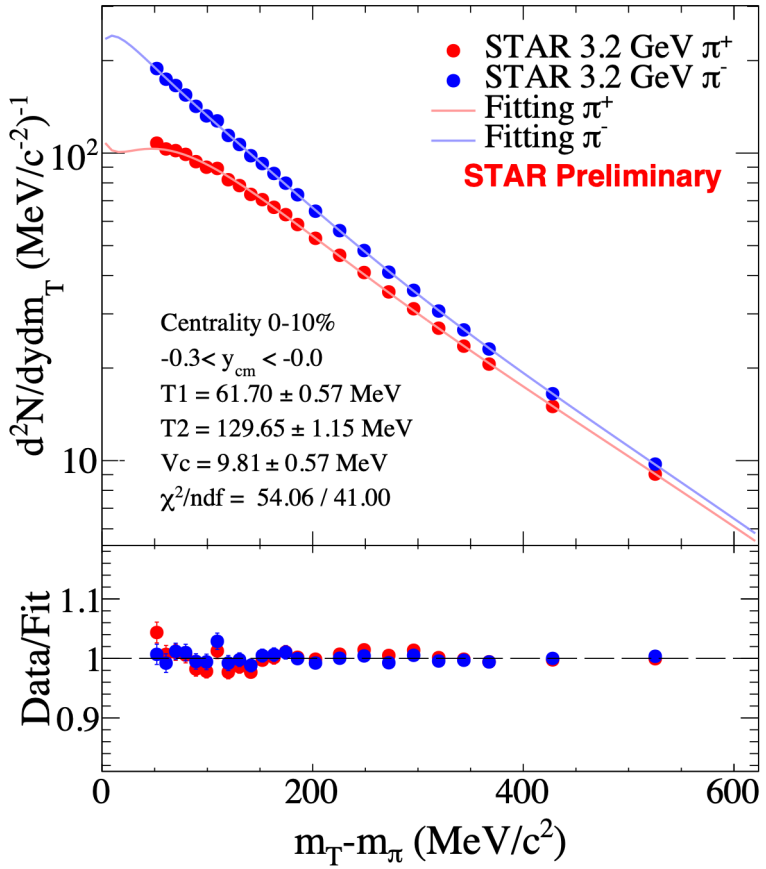
B. A. Li, L. W. Chen, C. M. Ko, Phys. Rept. 464, 13 (2008).

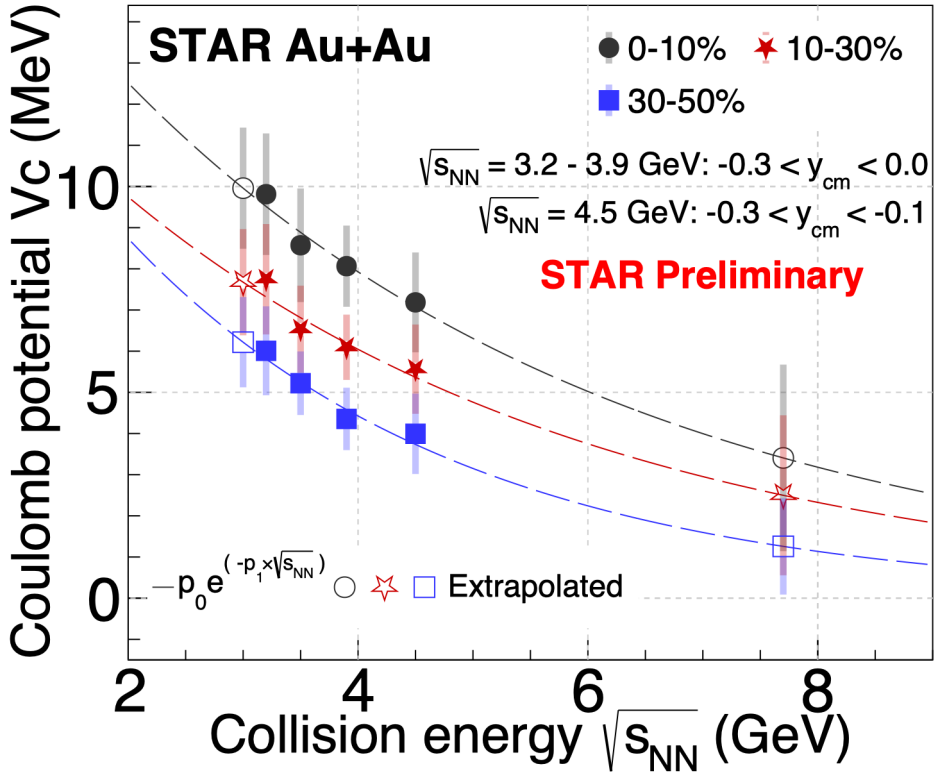
Third-body Coulomb Correction

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

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

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





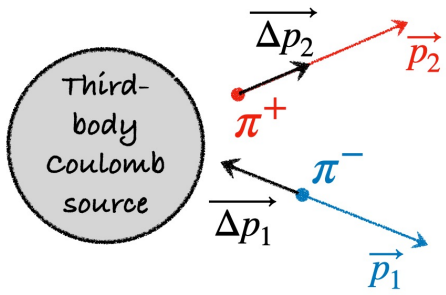
Step2: Calculate Δp form V_c.

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

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

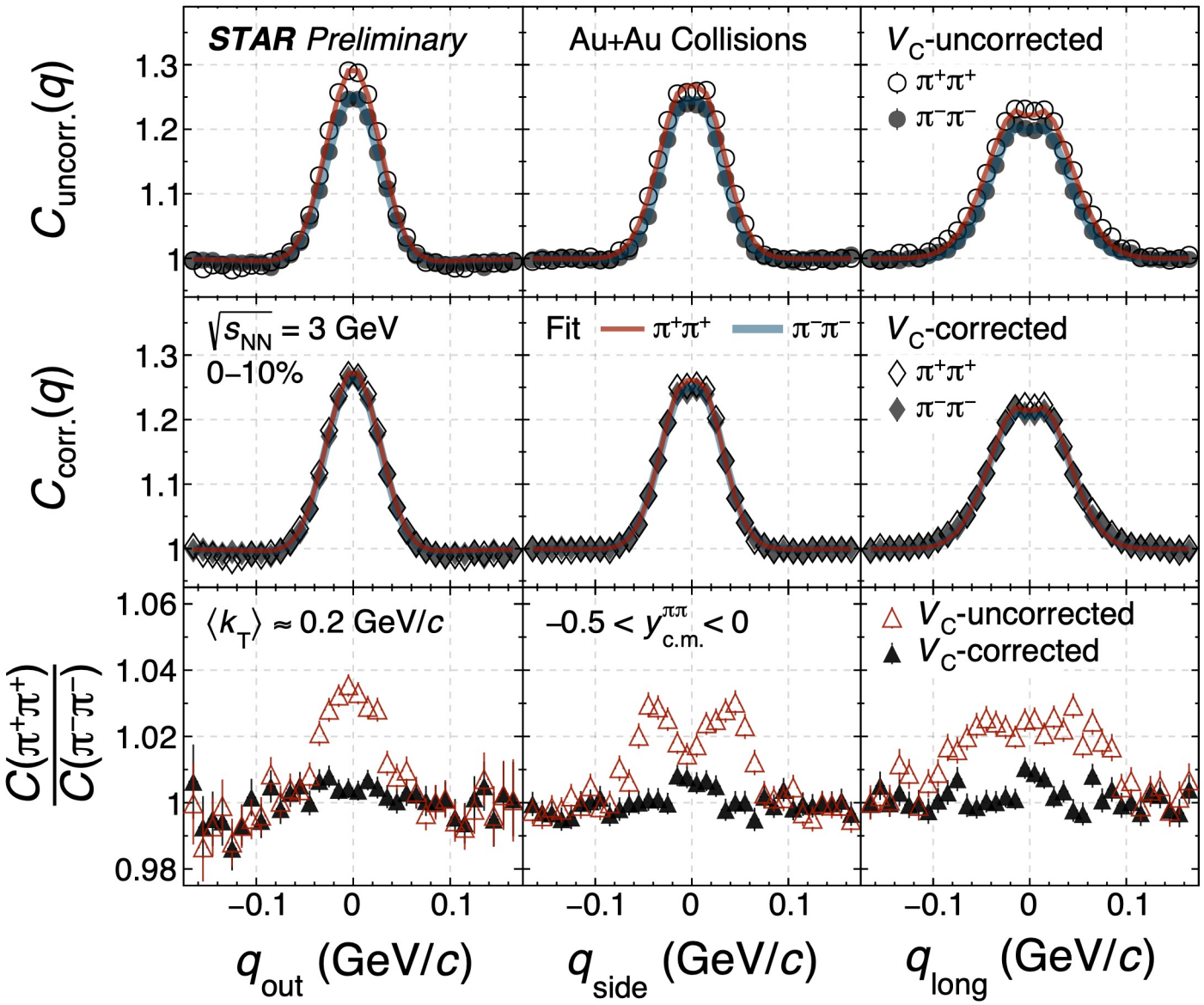
$$\Delta E = V_{eff}$$

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



- Push π^- outward: $p = p + \Delta p$
- Push π^+ inward: $p = p - \Delta p$
- $\Delta\vec{p} || \vec{p}$

Correlation Function



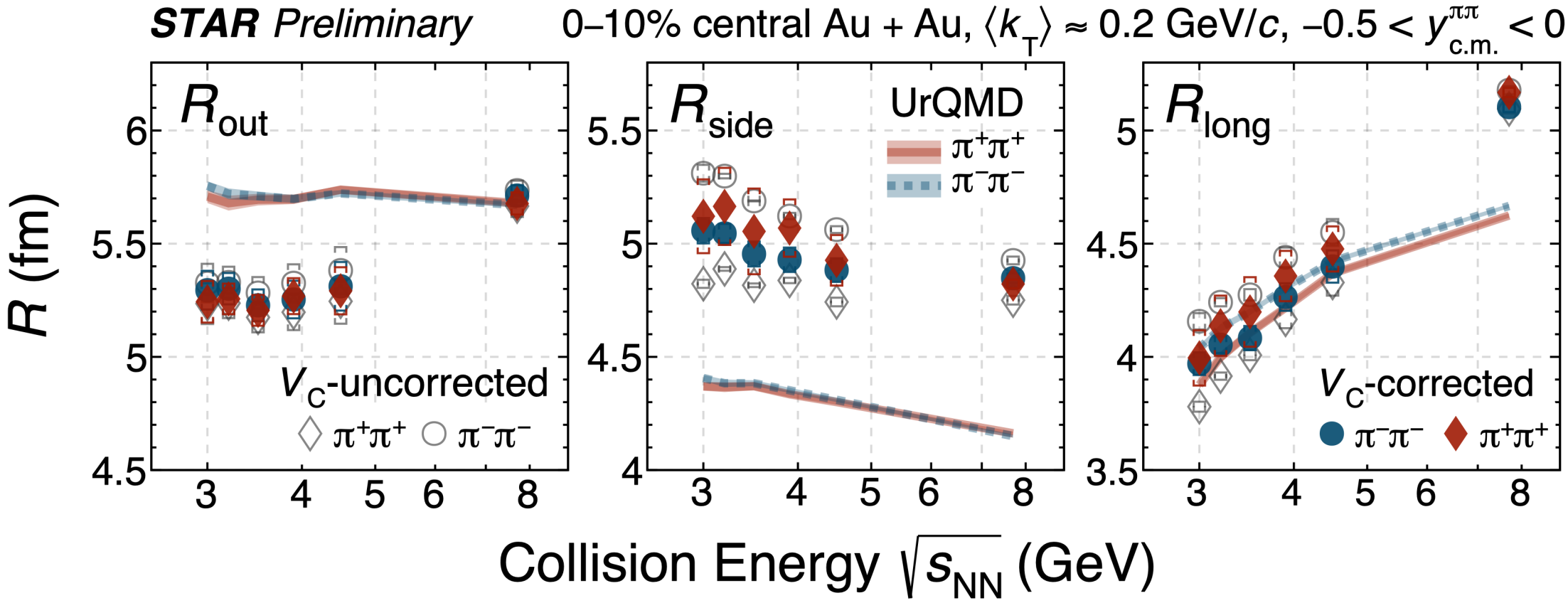
- Before third-body Coulomb corrections, the difference between $C(\pi^-\pi^-)$ and $C(\pi^+\pi^+)$ is about 4%.
- After third-body Coulomb corrections, the CF difference between $C(\pi^-\pi^-)$and $C(\pi^+\pi^+)$ is about 1%.
- No room for Isospin effect?

Estimation of Systematic Error

	Systematic source	R_{out}	R_{side}	R_{long}
Detector effect	Track splitting	~ 0	~ 0	~ 0
	Track merging	~ 0	~ 0	~ 0
	Momentum resolution	~ 1.5%	~ 0.5%	~ 1%
Particle identification	Purity	~ 0	~ 0	~ 0
Correction method	Third-body Coulomb correction	~ 0.5%	~ 2.5%	~ 2.5%
	Total	~ 2%	~ 3%	~ 3.5%

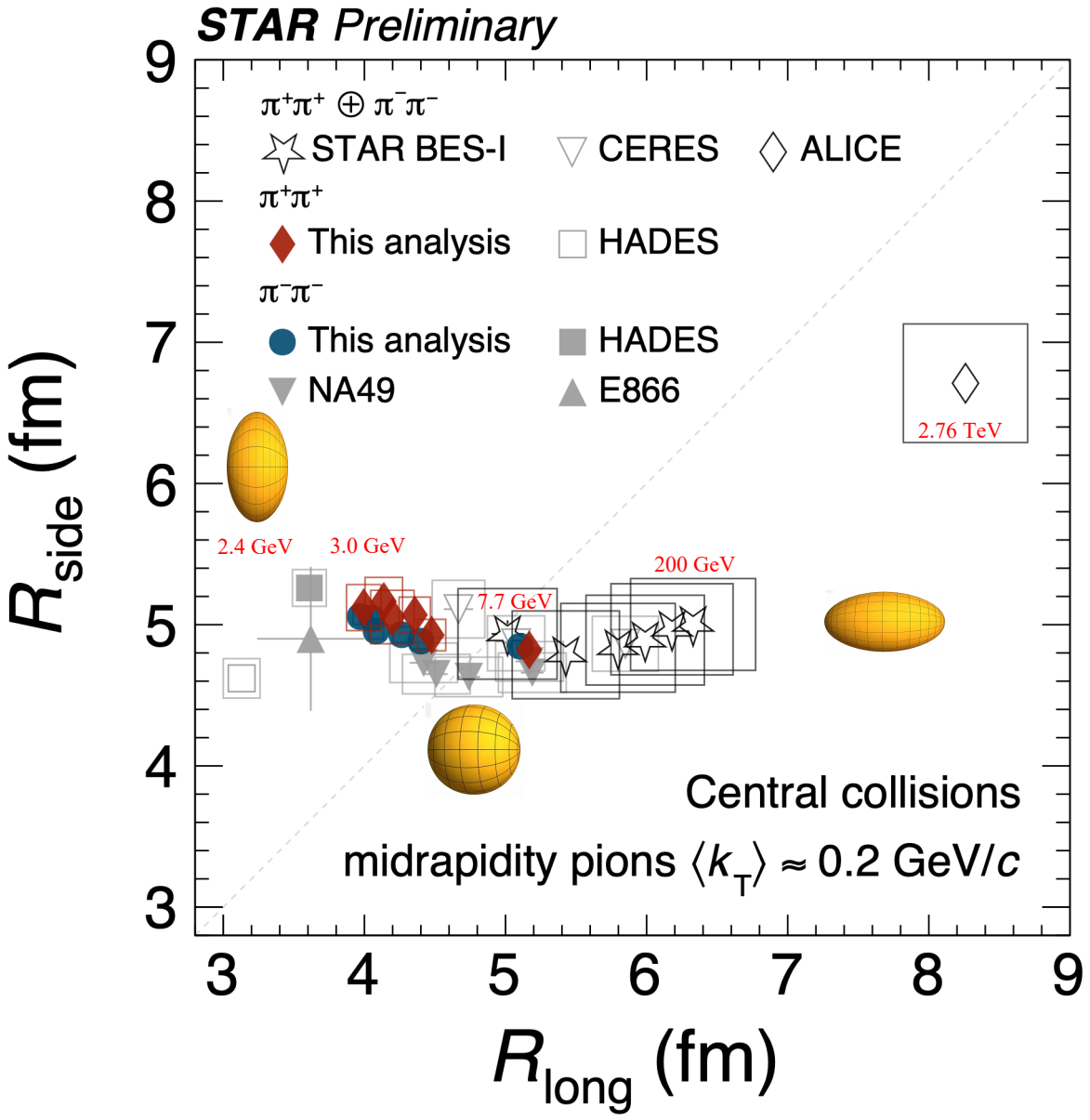
- Third-body Coulomb correction is the dominant source of R_{side} and R_{long}.
- Momentum resolution is the dominant source of R_{out}.

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. UrQMD model simulations only qualitatively reproduced the energy trend.

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

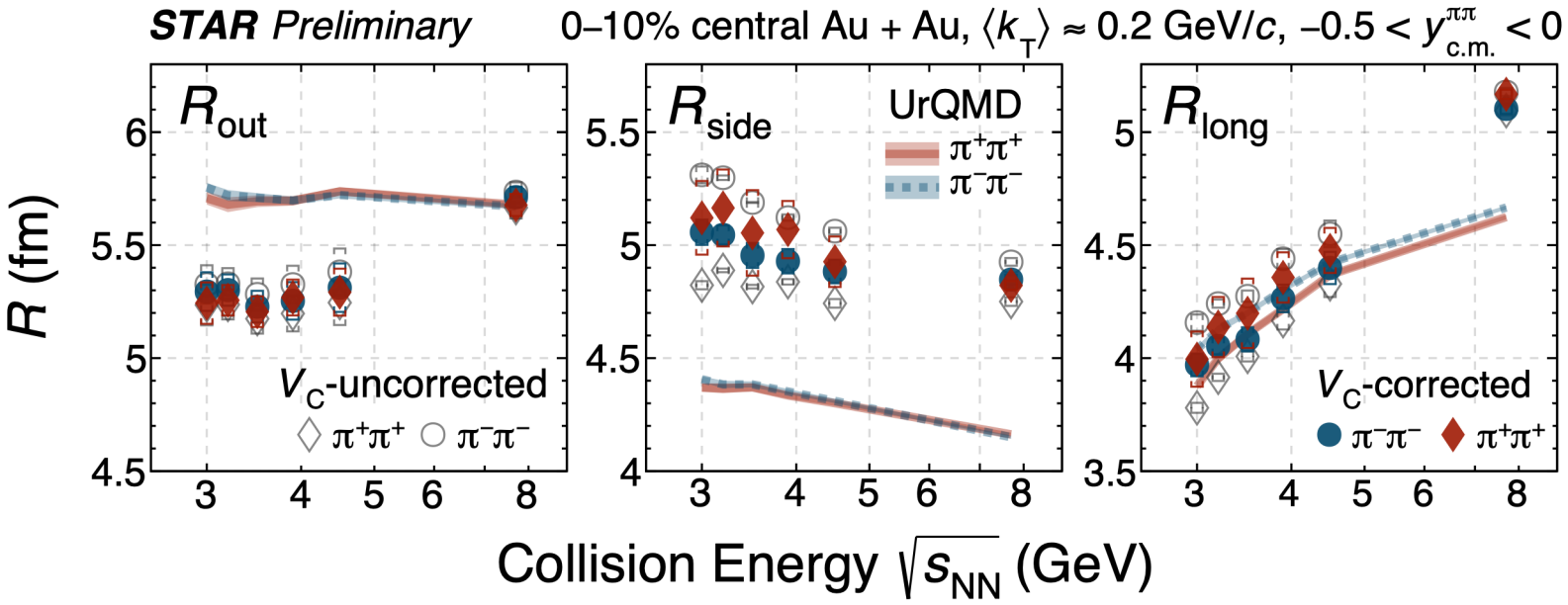


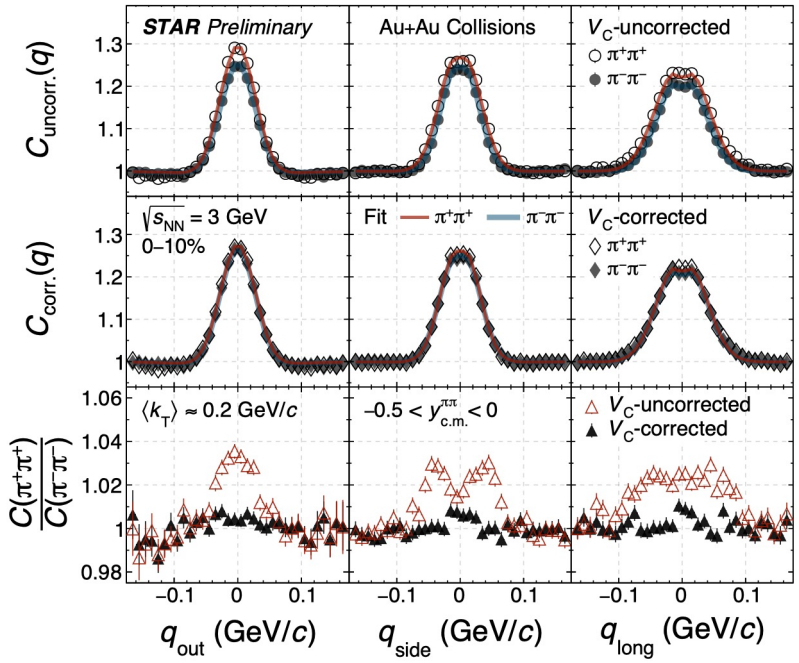
- Lower energy collisions generally produce more oblate systems.
- Higher energy collisions generally produce more prolate systems.
- At approximately 5 GeV, the shape of the system changes from oblate to prolate.

Summary and Outlook

1. Correcting for the 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





Outlook:

1. Centrality dependence
2. Rapidity dependence
3. Transverse momenta dependence

Acknowledgements

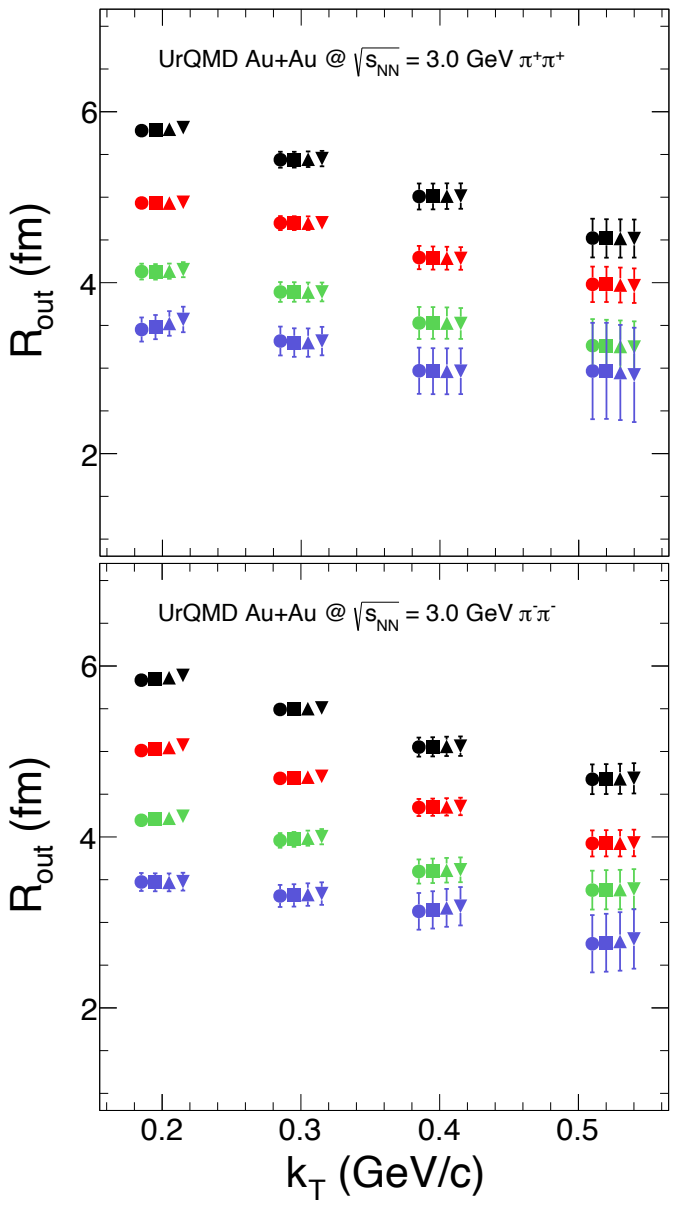
L.B. Chen, A. Kareva, X.F. Luo, V. Luong, R. Lednicky, G. Nigmatkulov, N. Xu

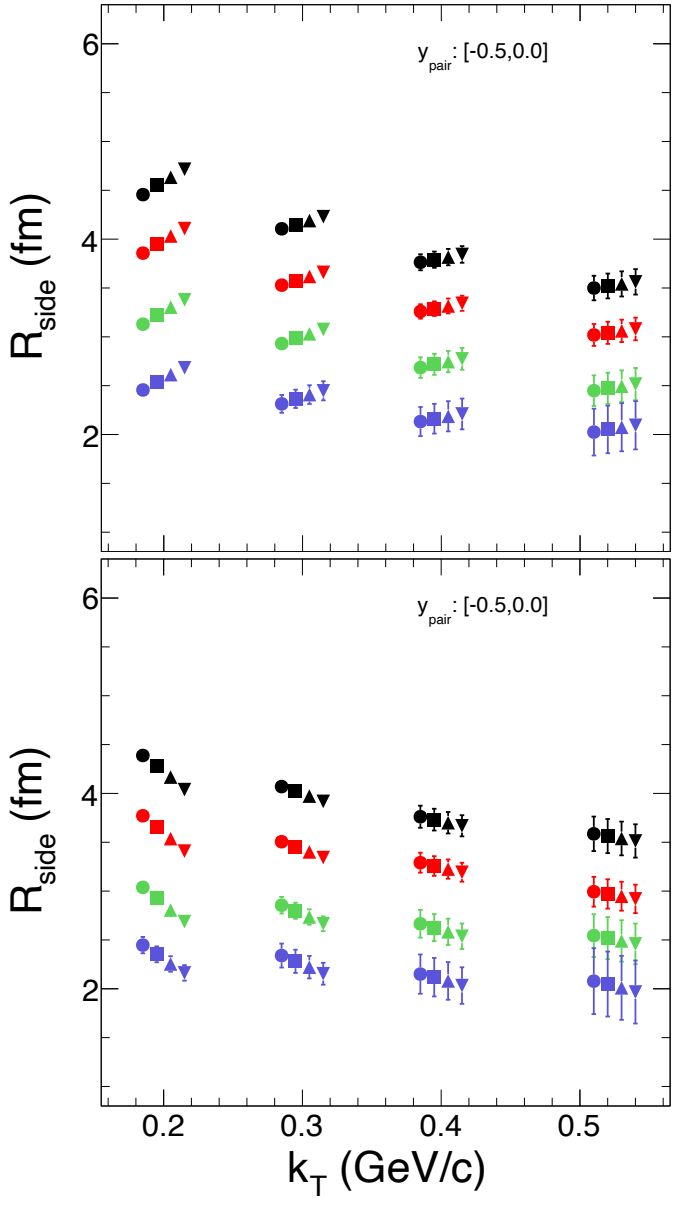
STAR Collaboration, Organizers of PHD meeting

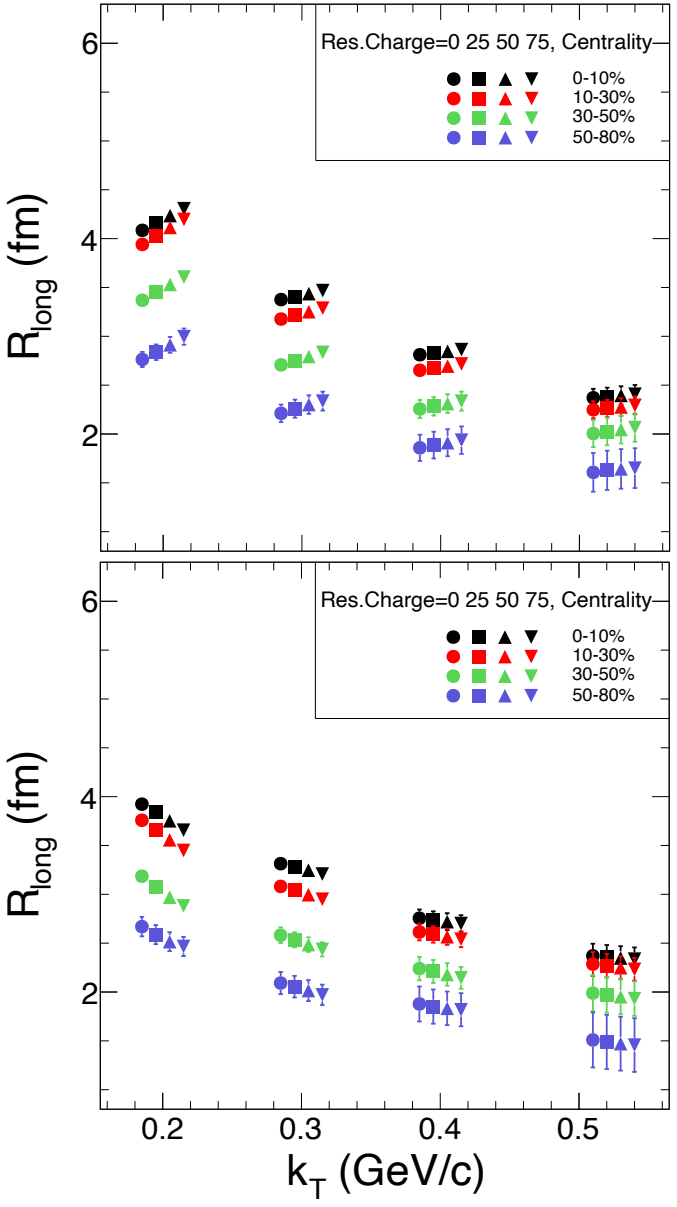
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Backup

Third-body Coulomb Effect

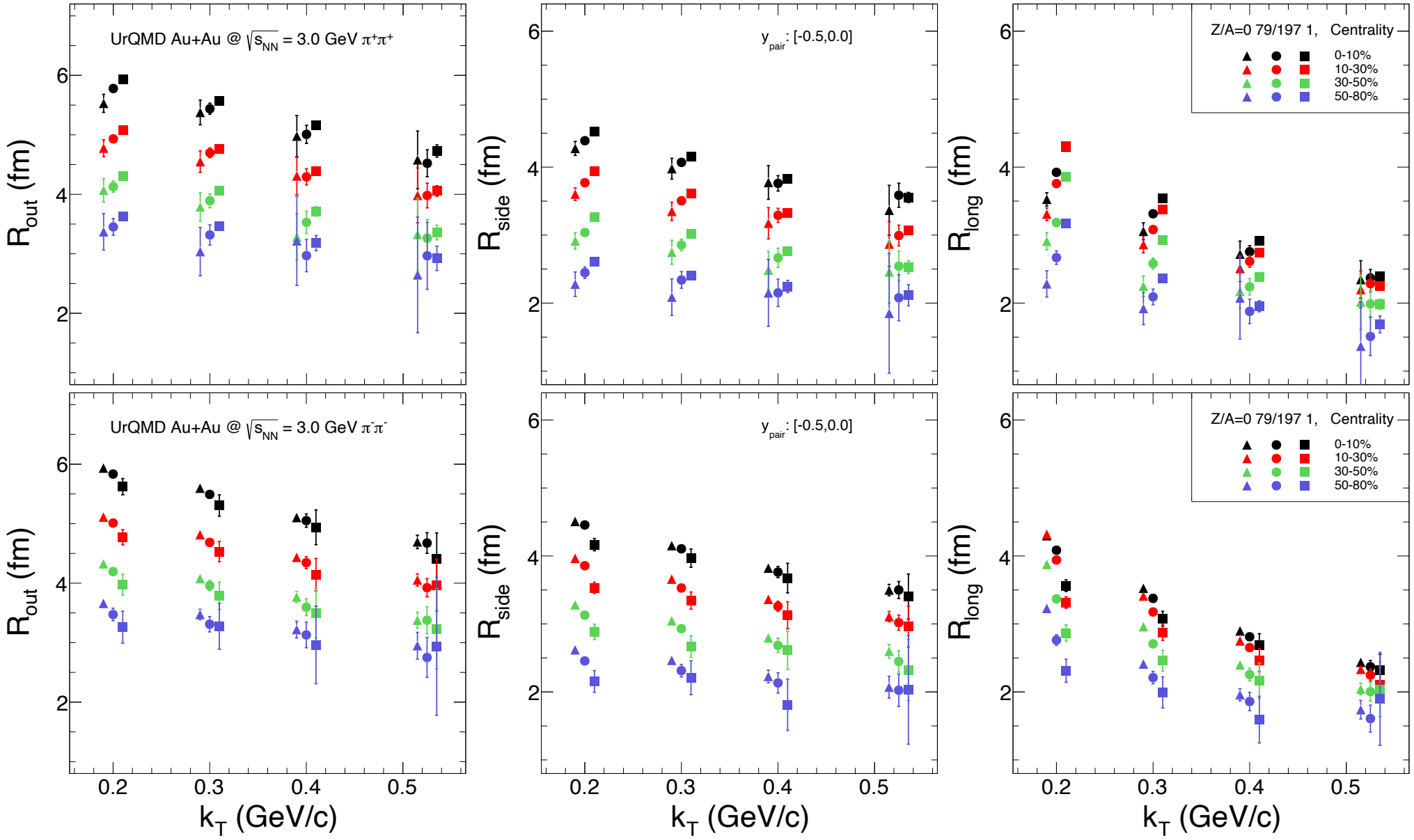






As the number of residual charge increases, the R_{side} and R_{long} of $\pi^+\pi^+$ will decrease and π^- π^- will increase.

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 $R(\pi^+\pi^+) < R(\pi^-\pi^-)$.