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Residual Third-body Coulomb Effect on Identical Charged Pion Correlations in Au+Au Collisions at STAR

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STAR Collaboration

Outline

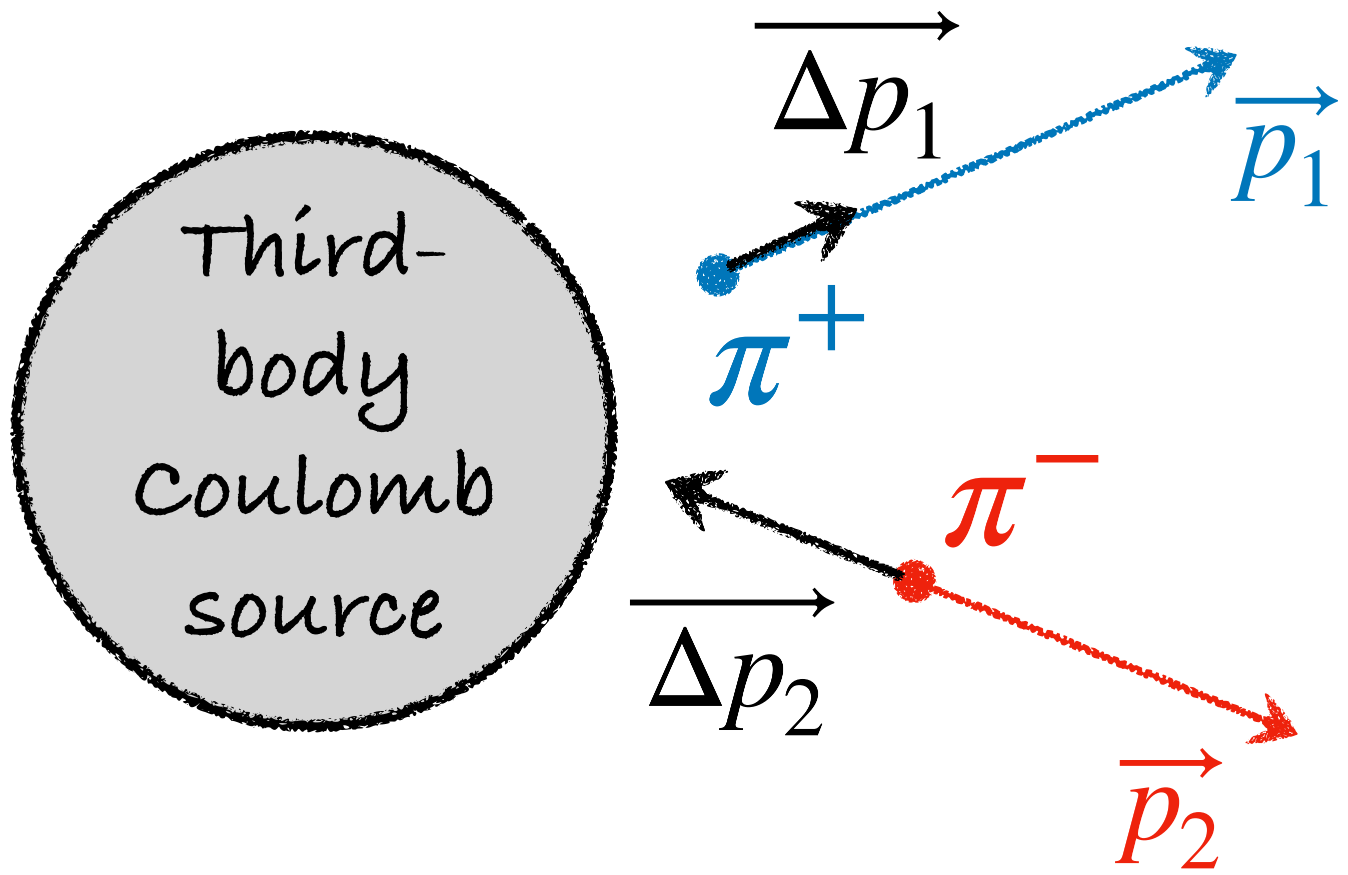
- Motivation
- The STAR experiment and Fixed-Target program
- Femtoscopic correlations technique
- Results from Au+Au $\sqrt{s_{\mathrm{NN}}}$ = 3.0–7.7 GeV:
  - Measured $\pi^{\pm}\pi^{\pm}$ correlation functions
  - $\sqrt{s_{\mathrm{NN}}}$-dependence of radii
  - $\sqrt{s_{\mathrm{NN}}}$ and centrality dependence of $\pi^{-}\pi^{-}/\pi^{+}\pi^{+}$ radii ratio
  - Third-body Coulomb corrected $\pi^{-}\pi^{-}/\pi^{+}\pi^{+}$ radii ratio
- Summary

Motivation

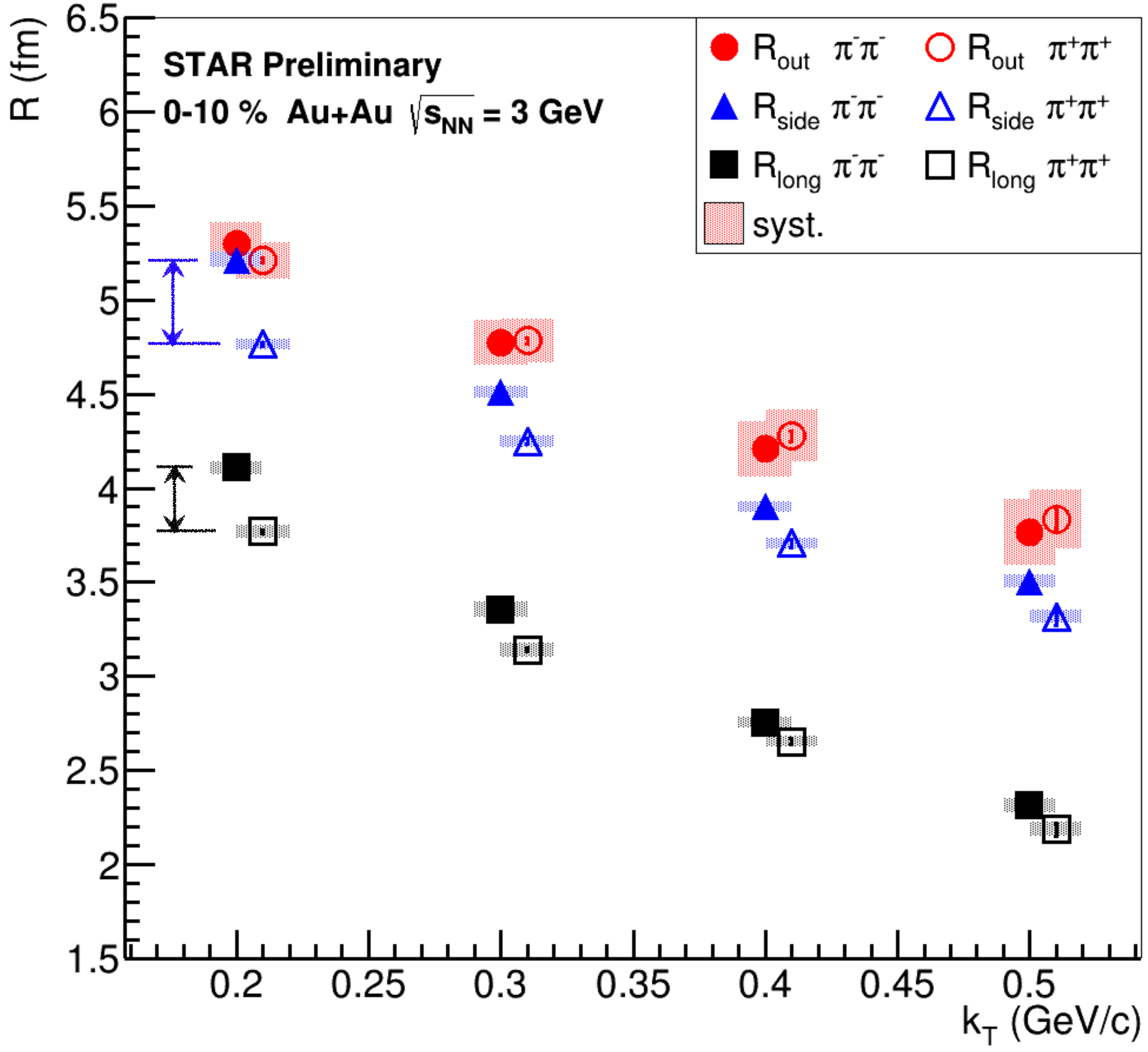
- Clear difference in R_{side} and R_{long} radii between $\pi^+\pi^+$ and $\pi^-\pi^-$ at small pair transverse momentum (k_T)
- Possible effects causing the difference:
  - Third-body Coulomb effect
  - Isospin effect

$$pp \rightarrow pn\pi^+$$
$$nn \rightarrow pn\pi^-$$

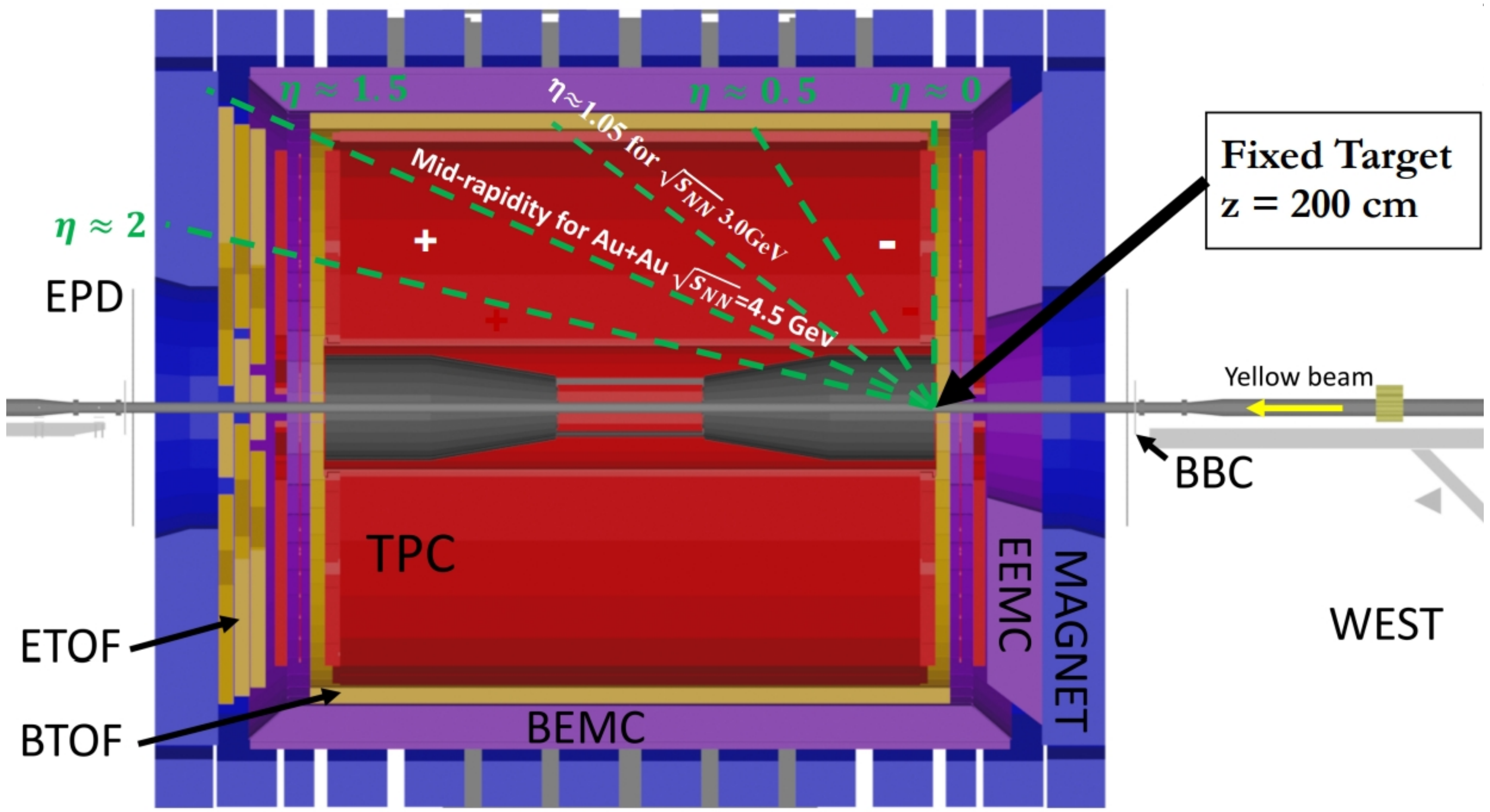
Isospin effect

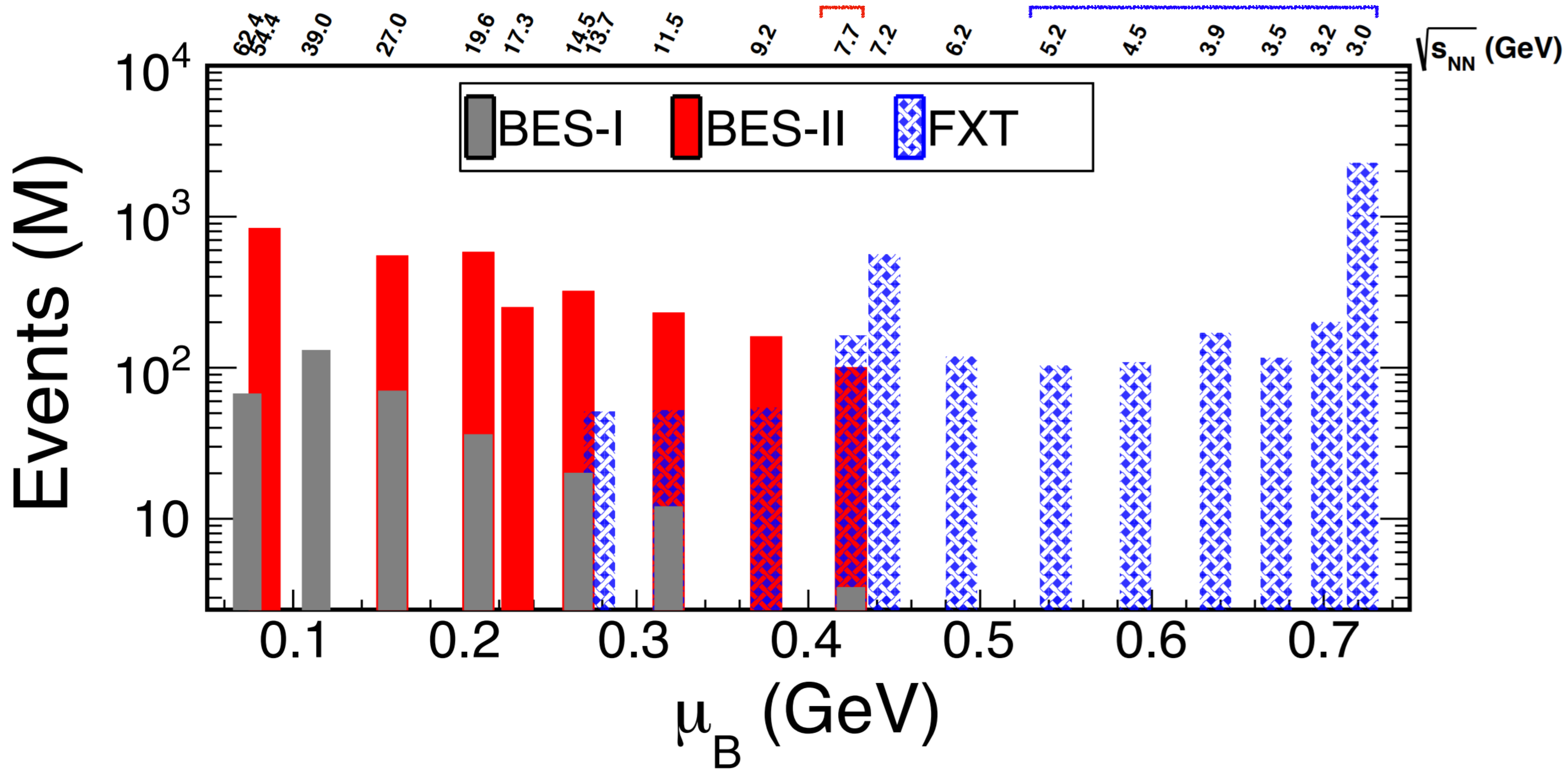


Third-body Coulomb effect



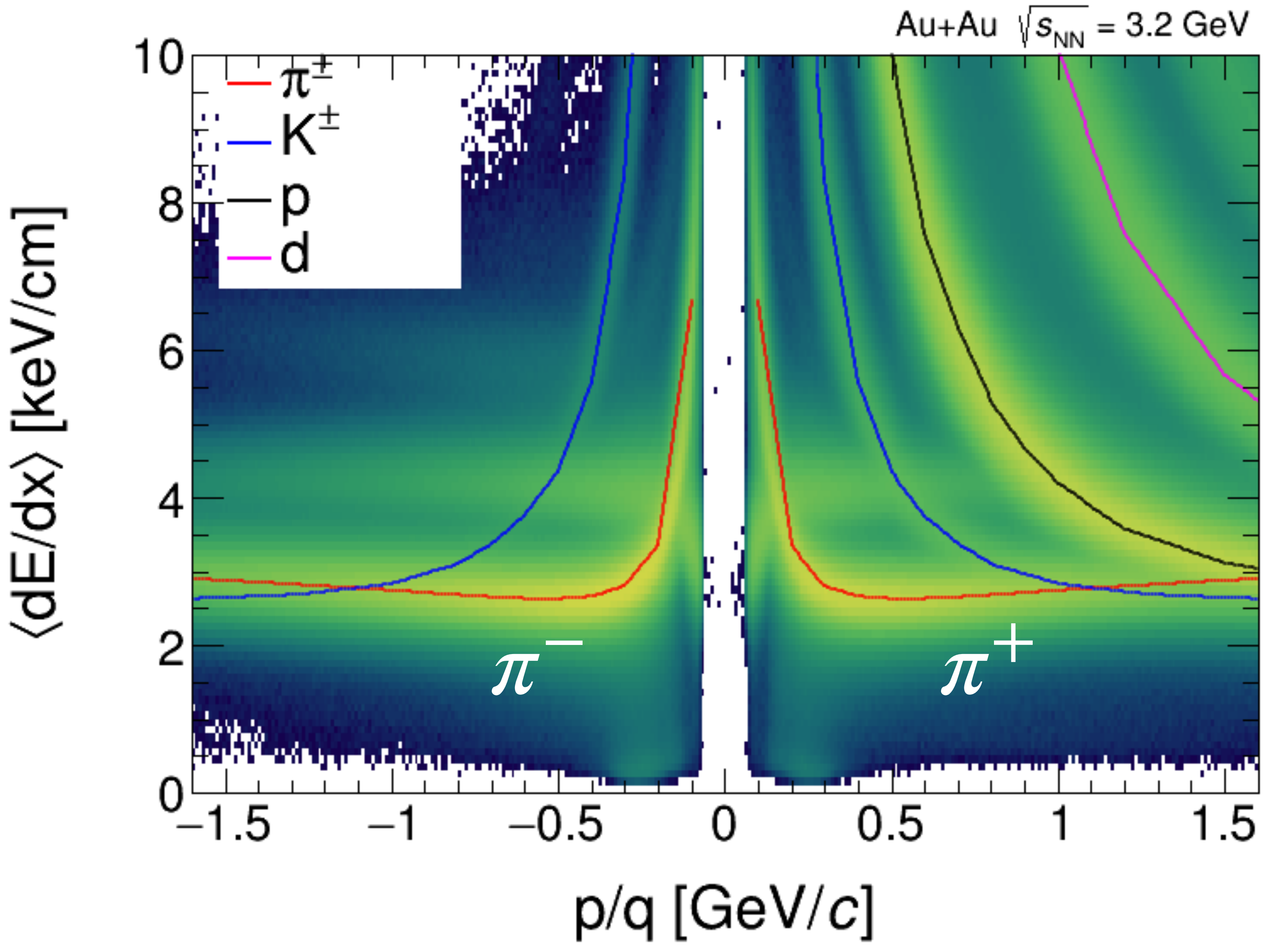
The STAR detector & Fixed-Target Program

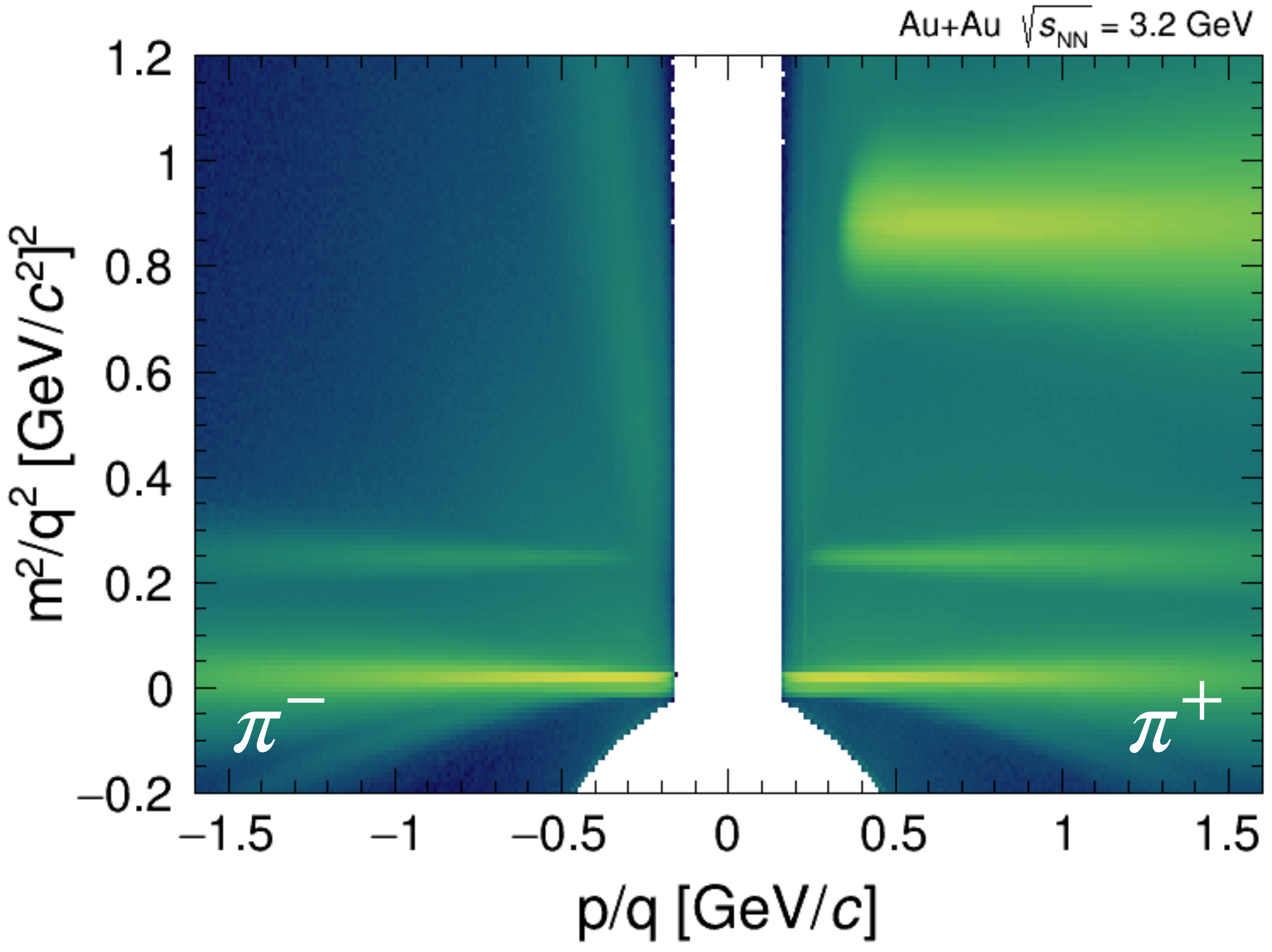


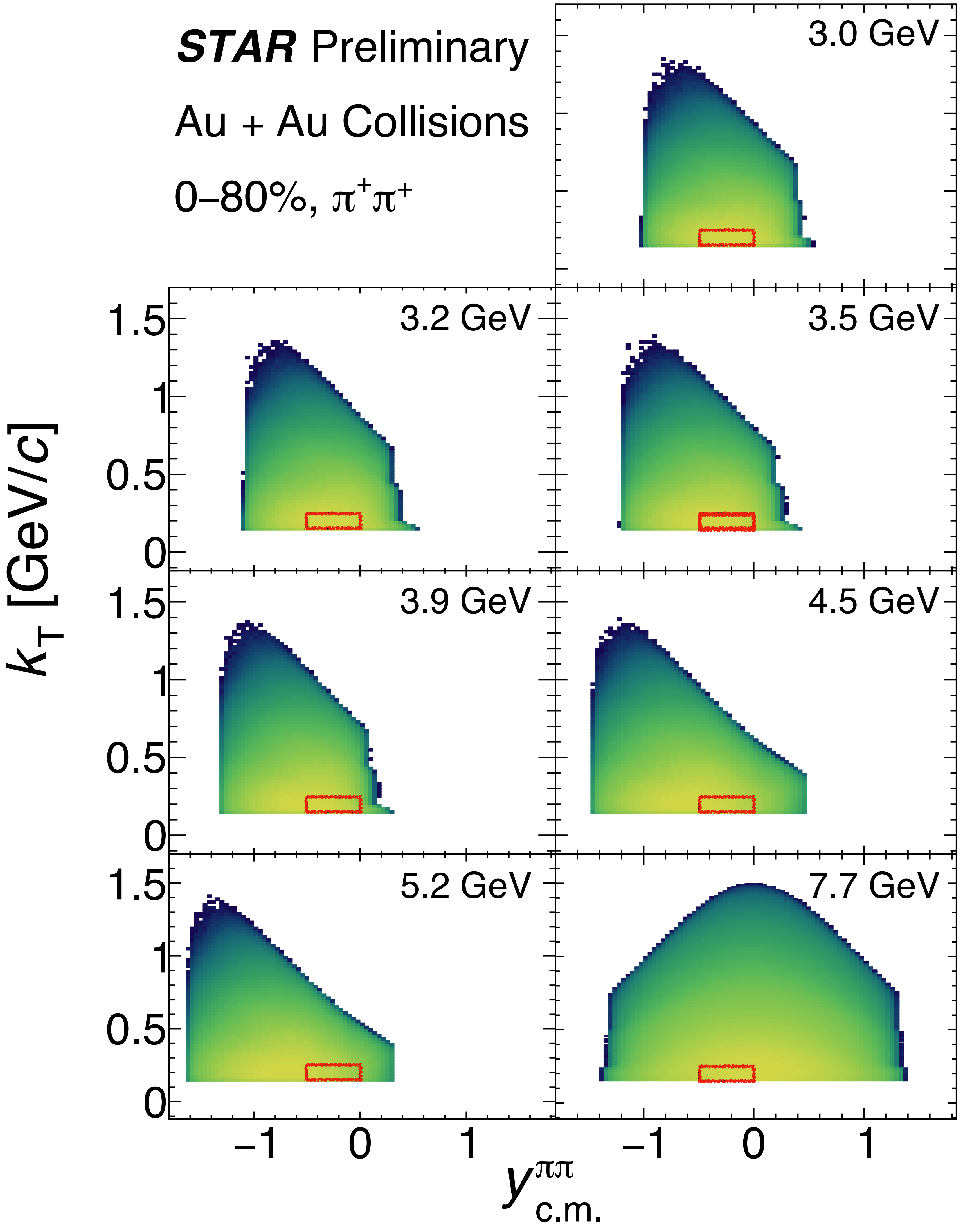


- Fixed-target (FXT) program: Au + Au collsions at $\sqrt{s_{\mathrm{NN}}}$ = 3.0–13.7 GeV
- Identical charged pion correlations are measured for Au + Au collisions at:
  - $\sqrt{s_{\mathrm{NN}}}$ = 3.0, 3.2, 3.5, 3.9, 4.5, 5.2 GeV (FXT mode)
  - $\sqrt{s_{\mathrm{NN}}}$ = 7.7 GeV (BES-II, collider mode)

Pion identification

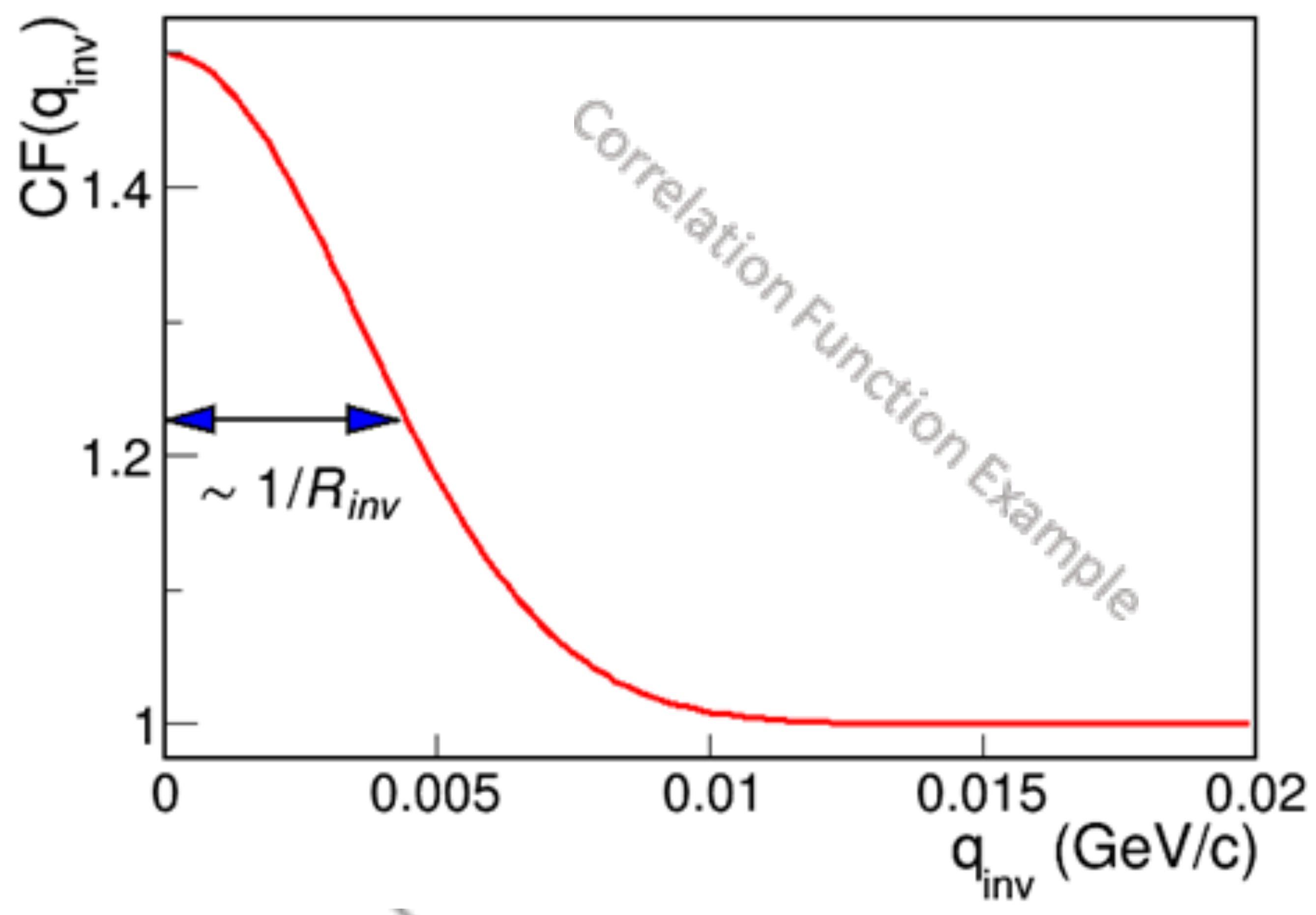


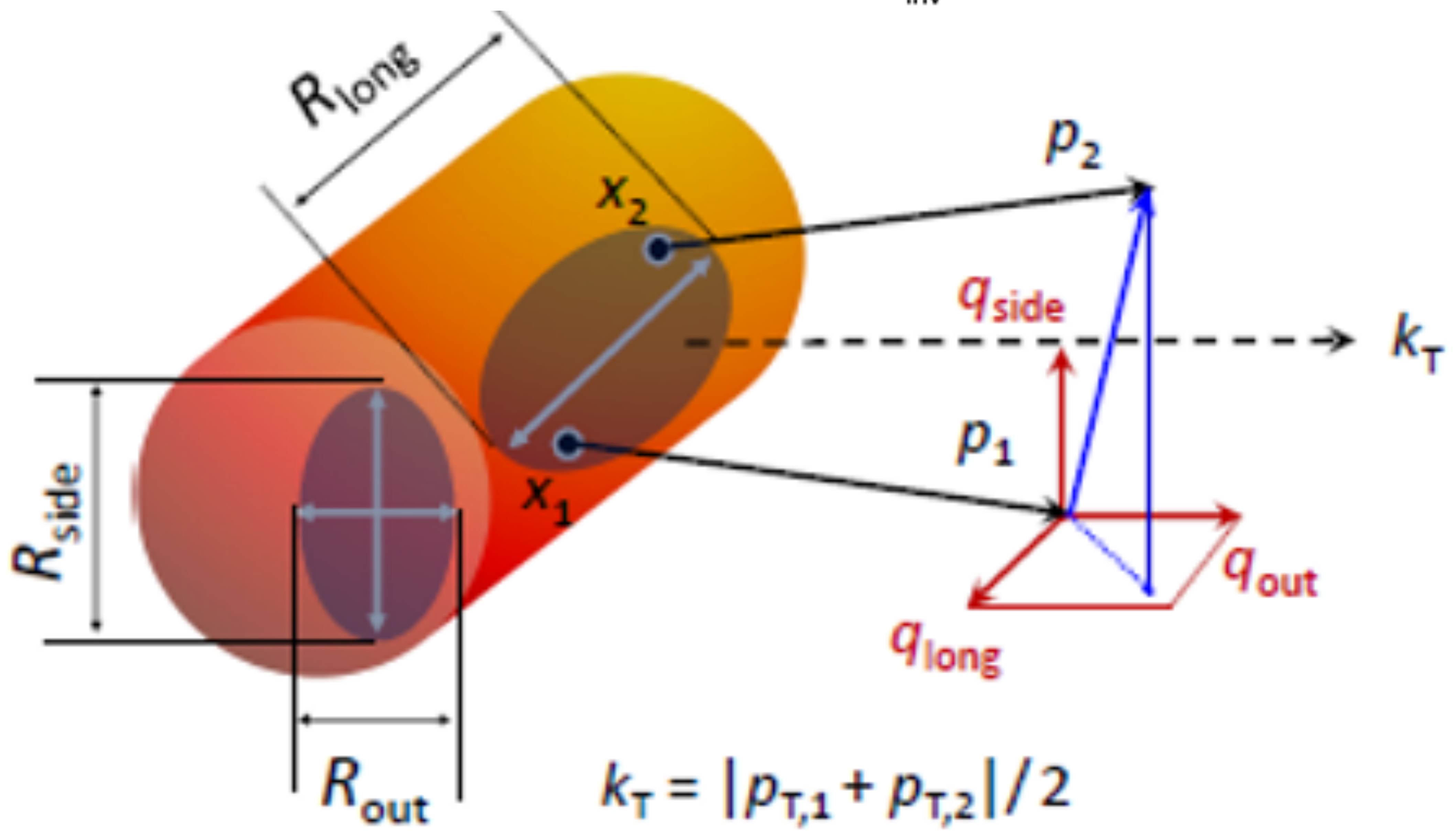




- Good particle identification capability:
  - $0.15 < p < 0.55$ GeV/*c*: TPC identification
  - $0.55 < p < 1.5$ GeV/*c*: TPC+TOF identification
- Pairs with $0.15 < k_{\mathrm{T}} < 0.25$ GeV/*c*, $-0.5 < y^{\pi\pi}_{\mathrm{c.m.}} < 0$ are selected to study the third-body Coulomb effect

Measuring two-particle correlation function





- Experimentally, correlation function: $C(\vec{q}) = A(\vec{q})/B(\vec{q})$
  - Relative momentum: $\vec{q} = \vec{p_1} - \vec{p_2}$
  - $A(\vec{q})$: measured distribution of $\vec{q}$ within the same event, containing quantum statistic (QS) correlation and final state interactions
  - $B(\vec{q})$: background distribution of $\vec{q}$ of two tracks from different events, where physical correlations are absent
- Projection of $\vec{q}$ onto Bertsch-Pratt longitudinal co-moving system (LCMS):
  - q_{out}: along pair transverse momentum (k_{T})
  - q_{long}: along beam direction
  - q_{side}: perpendicular to the other two axes

S. Pratt, PRD **33**, 1314 (1986)
G. Bertsch, M. Gong, M. Tohyama, PRC **37**, 1896 (1988)

Fitting the correlation function

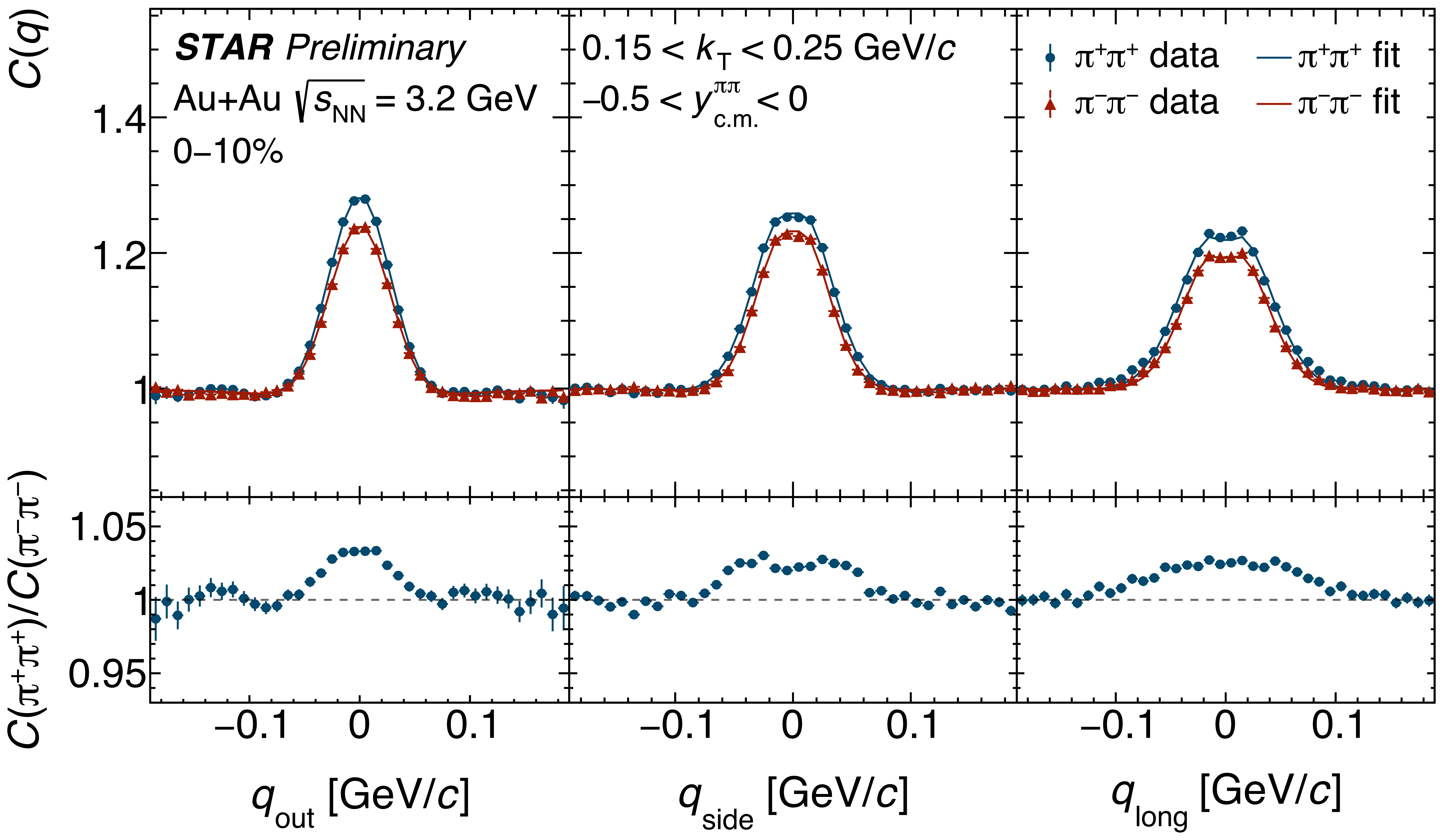
- Bowler—Sinyukov procedure: $C(\vec{q}) = N\left[(1-\lambda) + \lambda K_{\mathrm{Coul}}(q_{\mathrm{inv}})(1+G(\vec{q}))\right]$

$$G(\vec{q}) = \exp(-q_o^2 R_o^2 - q_s^2 R_s^2 - q_l^2 R_l^2 - 2 q_o q_l R_{ol}^2)$$

  - N: normalization factor, λ: correlation strength factor
  - K_{Coul}: two-pion Coulomb correlation function
  - $R_{\mathrm{out}} \propto$ geometrical size and emission duration
  - $R_{\mathrm{side}} \propto$ geometrical size
  - $R_{\mathrm{long}} \propto$ source lifetime
  - $R^2_{\mathrm{out\text{-}long}} \propto$ tilt of the correlation functions in the $(q_{\mathrm{out}}, q_{\mathrm{long}})$ plane, depending on the degree of asymmetry of the rapidity acceptance w.r.t. midrapidity

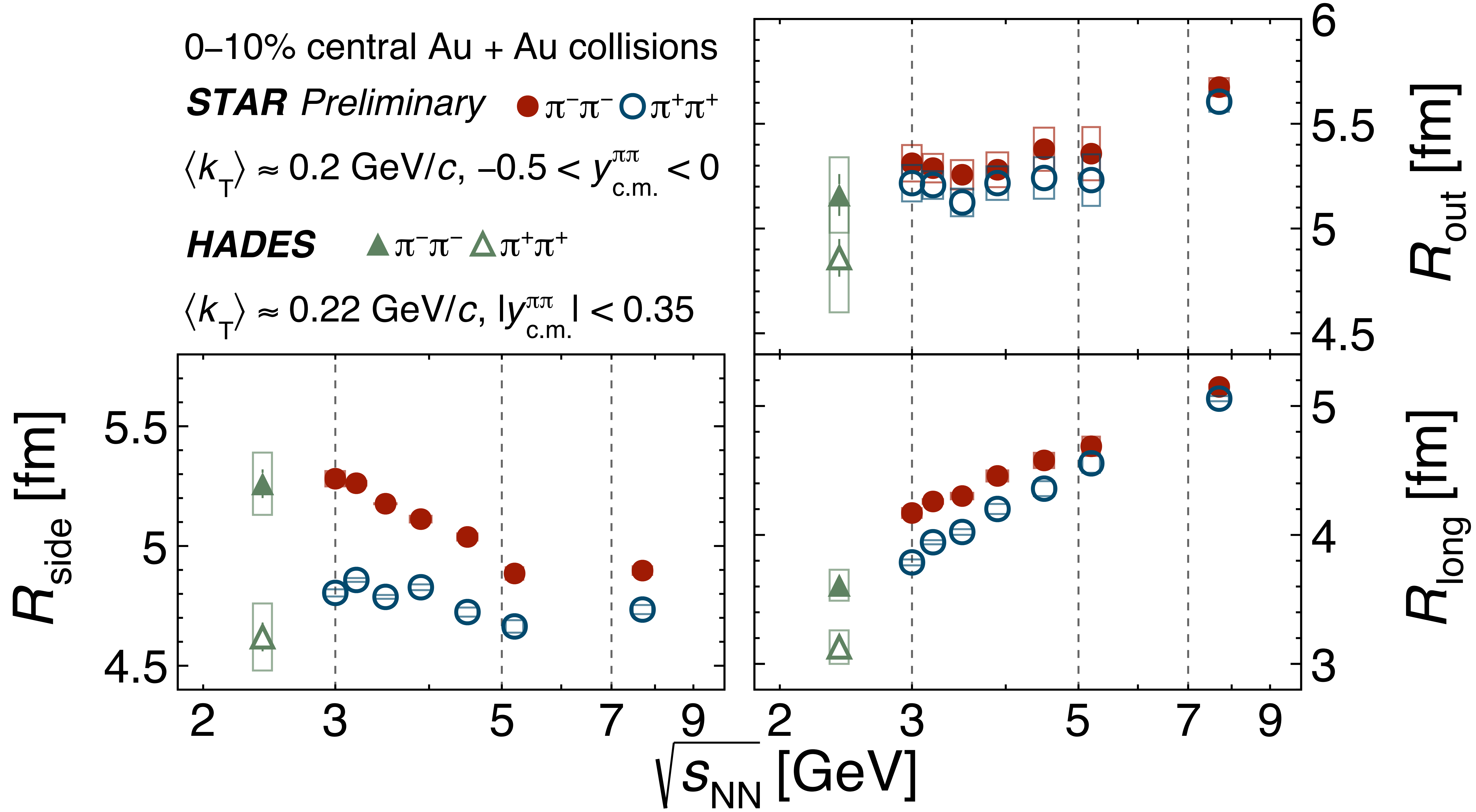
M.G. Bowler, PLB **270**, 69 (1991)
Yu.M. Sinyukov, et. al., PLB **432**, 248 (1998)

Charged pion correlation function



- About 3% difference between $C(\pi^+\pi^+)$ and $C(\pi^-\pi^-)$
  - Likely due to the third-body Coulomb and isospin effects

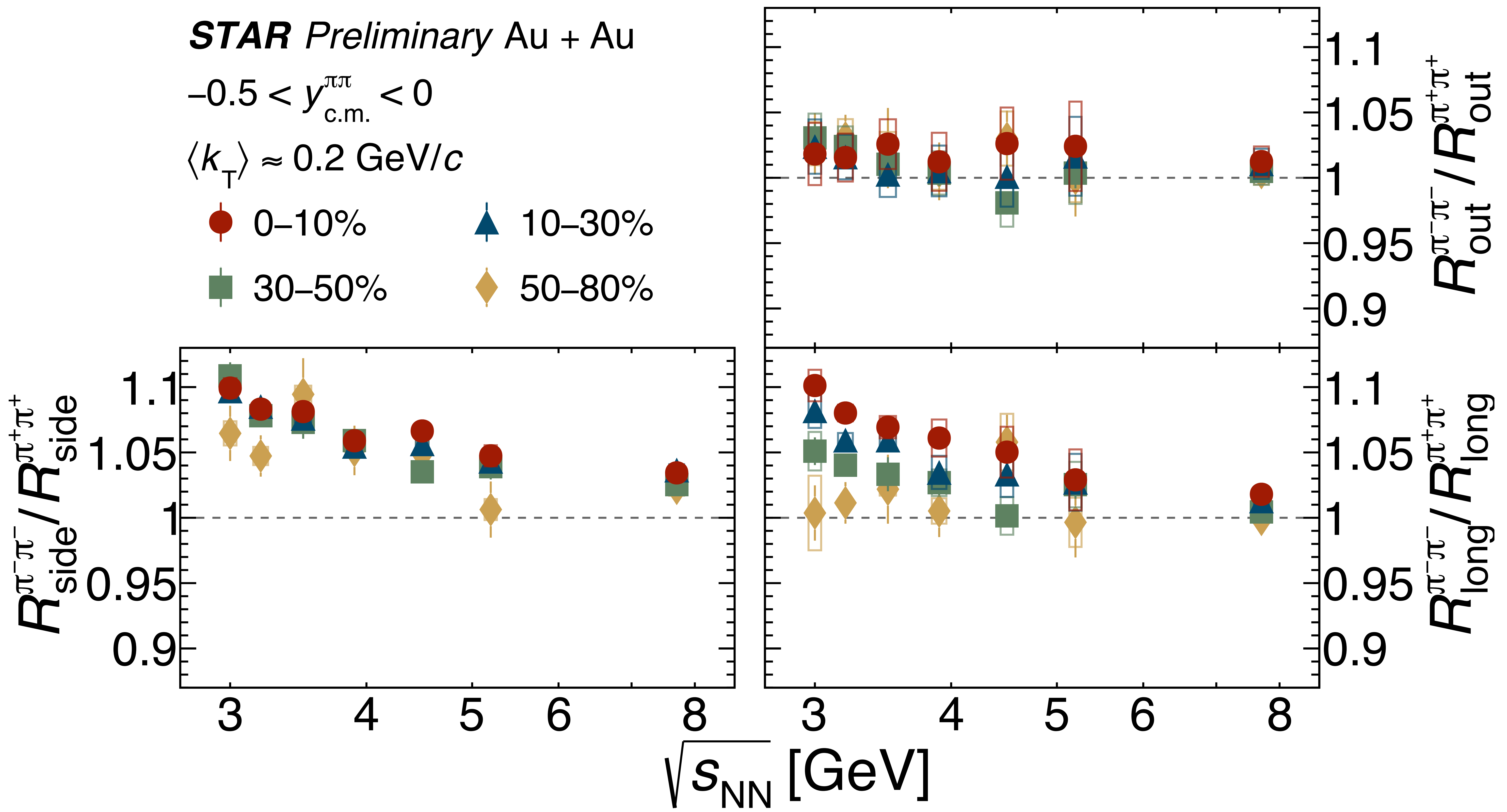
Collision energy dependence of radii



- $R_{\rm out}^{\pi^+\pi^+}$ and $R_{\rm out}^{\pi^-\pi^-}$ agree within uncertainties
- Difference between $\pi^+\pi^+$ and $\pi^-\pi^-$ decreases with increasing $\sqrt{s_{\rm NN}}$ for $R_{\rm side}$ and $R_{\rm long}$

HADES, EPJA **56**, 140 (2020)

$\pi^-\pi^-/\pi^+\pi^+$ radii ratio



- $\sqrt{s_{\mathrm{NN}}}$ **-dependence of charge difference:**
  - weak for R_{out}
  - decreases as $\sqrt{s_{\mathrm{NN}}}$ increases for R_{side}, R_{long}
- **Centrality dependence of charge difference:**
  - weak for R_{out} and R_{side}
  - visible for R_{long}

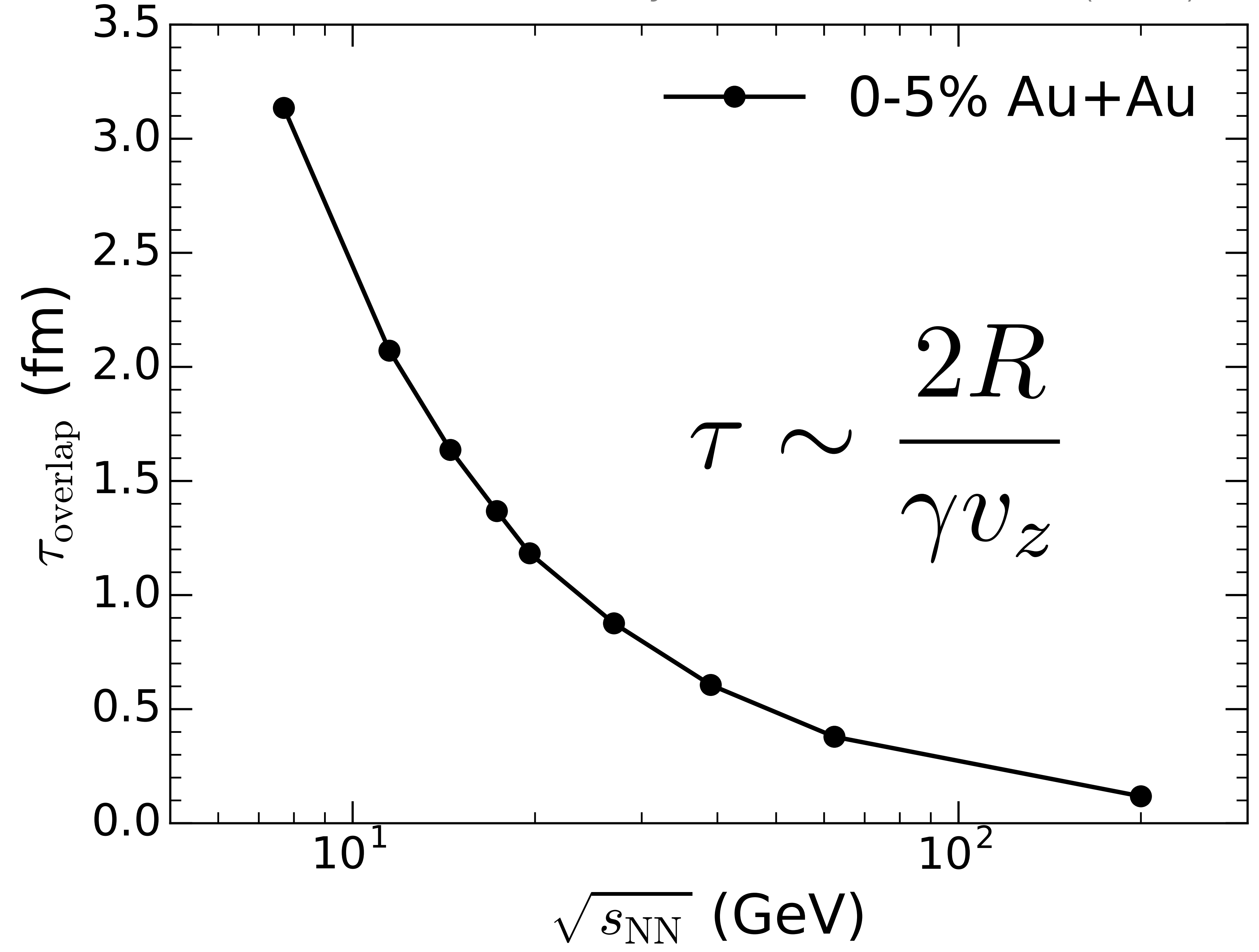
Third-body Coulomb correction

Estimation of effective third-body charge

- **<u>Step 1</u>:** Estimate effective third-body charge $Z^{\text{eff}}_{\text{res.ch.}}$:
  - At $\sqrt{s_{\text{NN}}}$ = 3.0 GeV: extract $Z^{\text{eff}}_{\text{res.ch.}}$ from π^-/π^+ p_{T}-spectra ratio by comparing data with UrQMD + third-body
  - At $\sqrt{s_{\text{NN}}}$ = 3.2–7.7 GeV: $Z^{\text{eff}}_{\text{res.ch.}}$ are scaled by passing time τ_{overlap} (assuming $Z^{\text{eff}}_{\text{res.ch.}} \propto \tau_{\text{overlap}}$)

$\sqrt{s_{\text{NN}}}$ (GeV)	3.0	3.2	3.5	3.9	4.5	5.2	7.7
τ_{overlap} (fm/c)	10.11	9.14	8.02	6.94	5.80	4.90	3.18
$Z^{\text{eff}}_{\text{res.ch.}}$	50	45	40	34	29	24	16

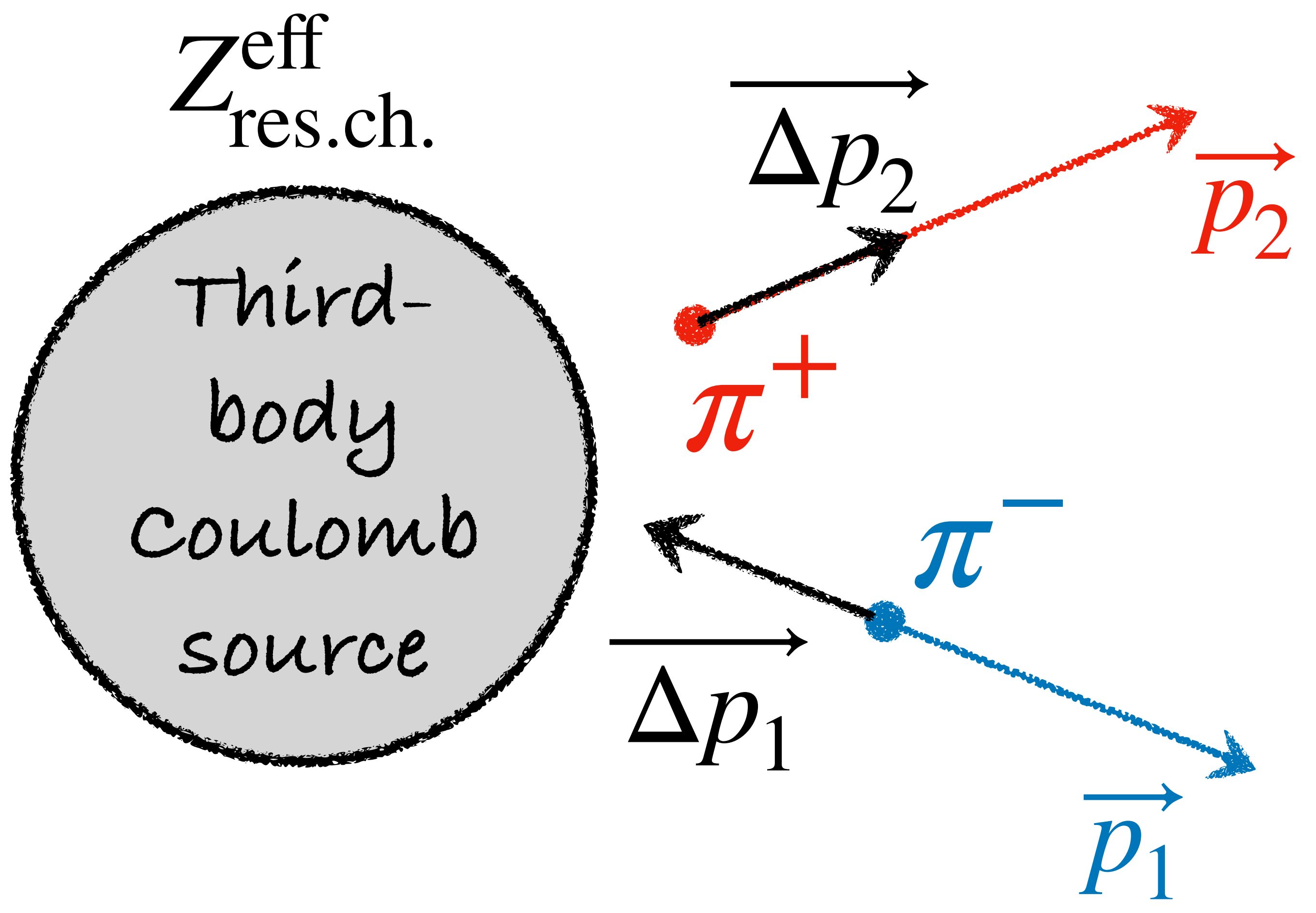
C. Shen, B. Schenke, *Phys. Rev. C* **97**, 024907 (2018)



See Youquan Qi's poster for more details (ID: <u>605</u>)

Third-body Coulomb correction

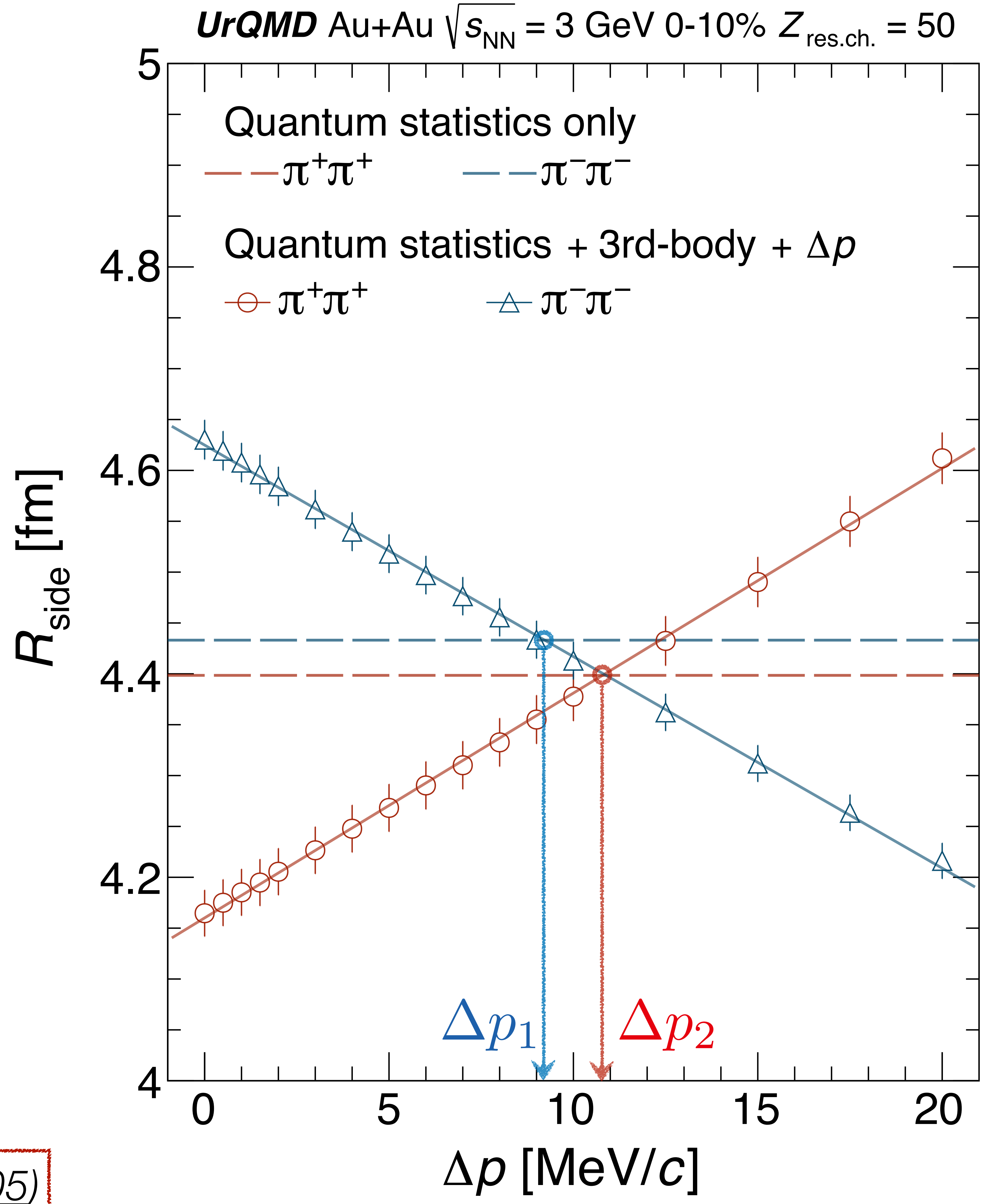
Estimation of momentum shift Δp



Correct momenta of single-$\pi^\pm$ for third-body Coulomb effect:

- Push π^- outward: $p'_1 = p_1 + \Delta p_1$
- Pull π^+ inward: $p'_2 = p_2 - \Delta p_2$
- $\Delta\vec{p} \parallel \vec{p}$

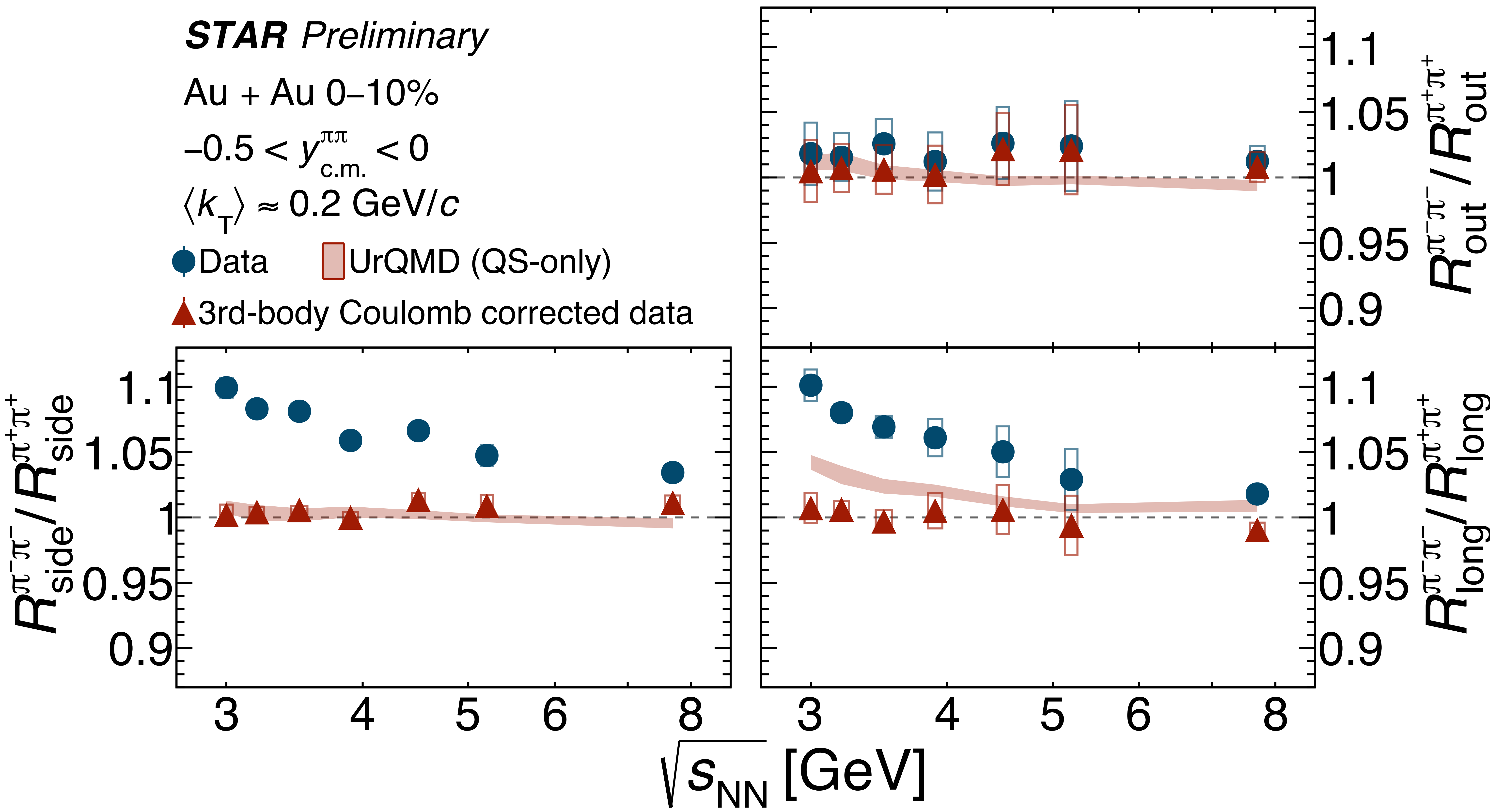
- **Step 2:** Estimate the momentum shift Δp needed for correction:
  - Add third-body Coulomb into UrQMD using a quantum relativistic approach* with the determined $Z^{\rm eff}_{\rm res.ch.}$ values
  - Find Δp such that the $R_{\rm side}$ without third-body are restored
- **Step 3:** Apply Δp values to experimental data and construct correlation functions with corrected momenta



*R. Lednický, Phys. Part. Nucl. **40**, 307 (2009)

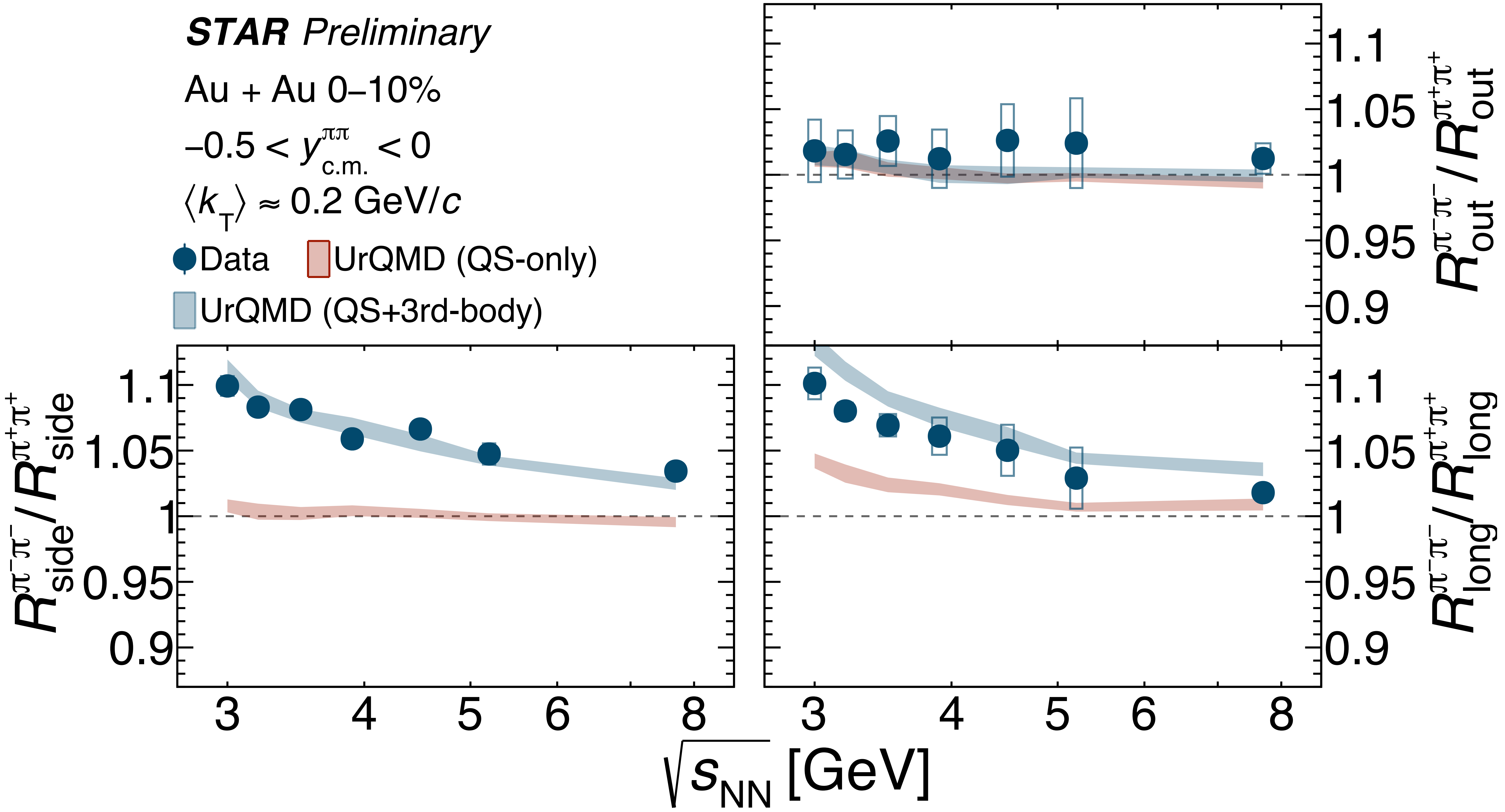
See Youquan Qi's poster for more details (ID: 605)

Third-body Coulomb corrected radii



- **Data corrected for the third-body Coulomb:**
  - small difference between $\pi^+\pi^+$ and $\pi^-\pi^-$ radii → small isospin effect, if any
- **UrQMD predictions:**
  - isospin effect is mostly pronounced in R_{long}
  - overpredicts R_{long} ratio

Data vs. UrQMD (QS + third-body)

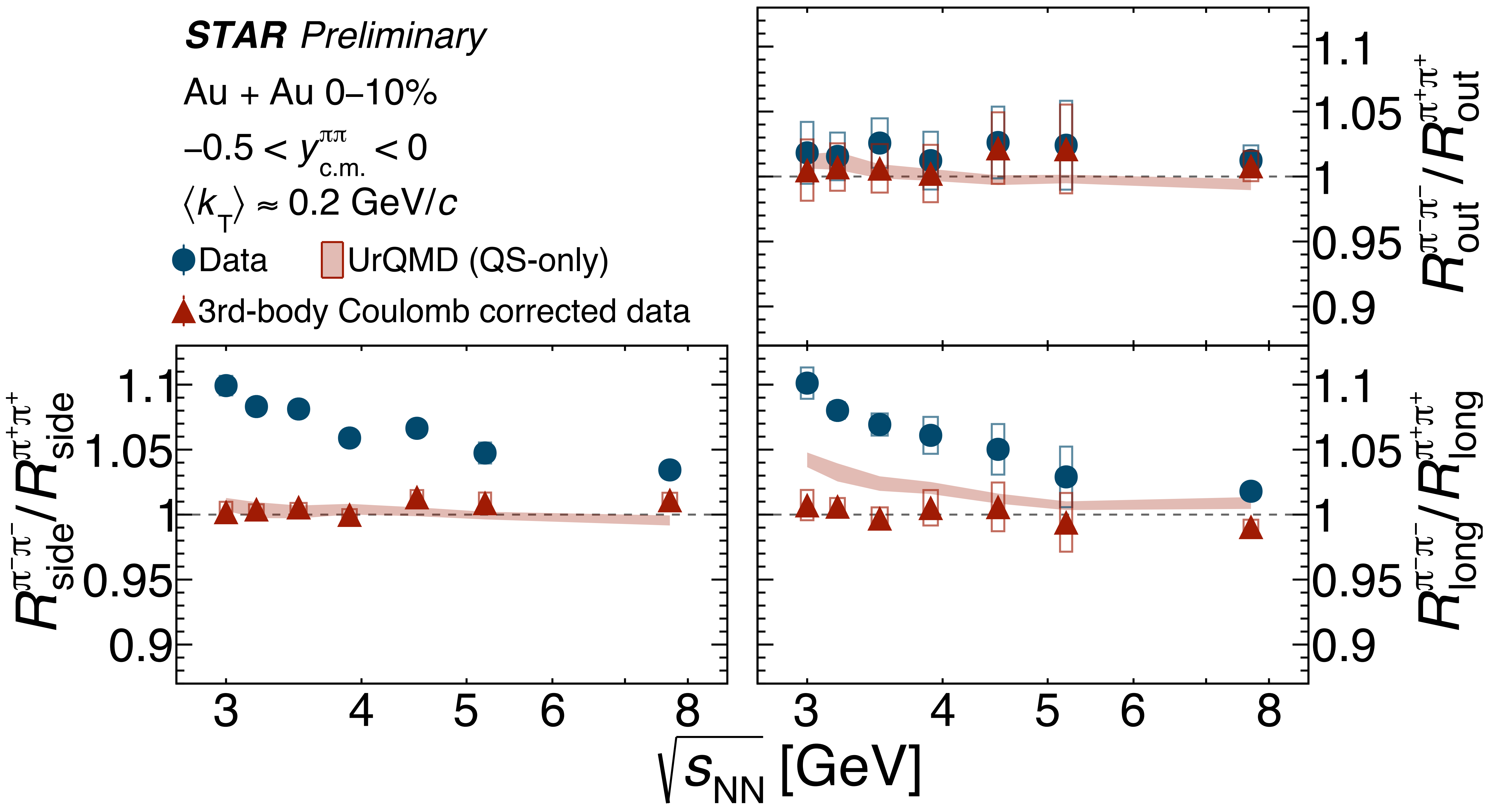


- As a closure test, add third-body* to UrQMD with the same $Z^{\text{eff}}_{\text{res.ch.}}$ used for the data correction
- UrQMD (QS+third-body) vs. data w/o third-body correction:
  - reproduces $R^{\pi^-\pi^-}_{\text{side}}/R^{\pi^+\pi^+}_{\text{side}}$
  - slightly overestimates $R^{\pi^-\pi^-}_{\text{long}}/R^{\pi^+\pi^+}_{\text{long}}$

*R. Lednický, Phys. Part. Nucl. **40**, 307 (2009)

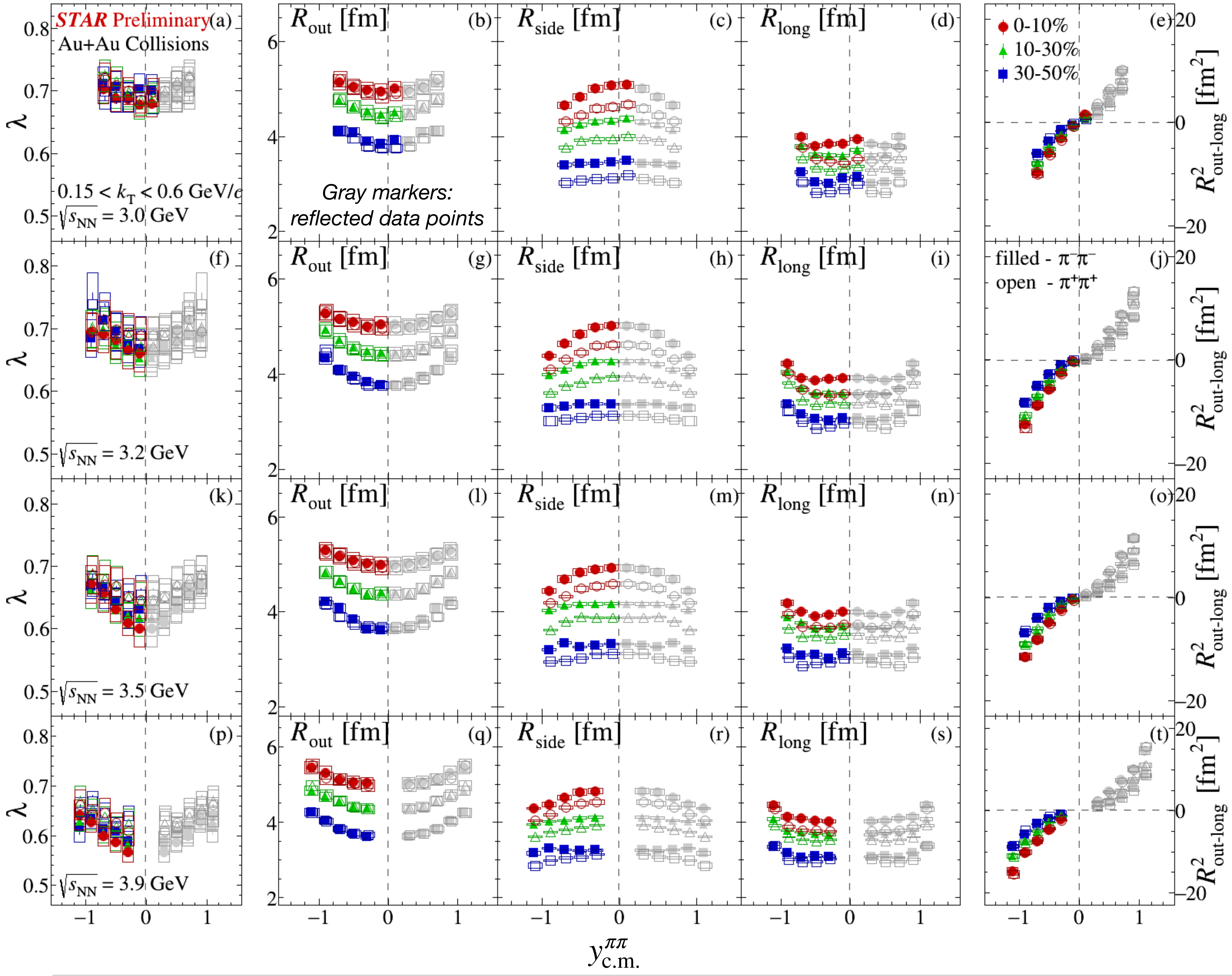
Summary

- We reported identical charged pion femtoscopy measurements in Au+Au collisions from STAR at $\sqrt{s_{NN}}$ = 3.0–7.7 GeV
- Difference between $R(\pi^+\pi^+)$ and $R(\pi^-\pi^-)$ radii:
  - decreases as $\sqrt{s_{NN}}$ increases for R_{side} and R_{long}; no difference within uncertainties for R_{out}
  - can be largely described by the third-body Coulomb effect; isospin effect is small within the following assumptions:
    - Point-like third-body Coulomb source
    - $Z^{eff}_{res.ch.} \propto \tau_{overlap}$
    - Model dependence of $Z^{eff}_{res.ch.}$ estimation at $\sqrt{s_{NN}}$ = 3.0 GeV



Backup slides

Rapidity dependence of femtoscopic parameters



- The difference of R_{side} and R_{long} between positive and negative pion is observed
- R_{side} decreases as $|y^{\pi\pi}_{c.m.}|$ increases
  - Hint on boost-invariance breaking
- $|R^2_{out-long}|$ is larger for larger $|y^{\pi\pi}_{c.m.}|$