



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

Vinh Luong (梁霸荣)

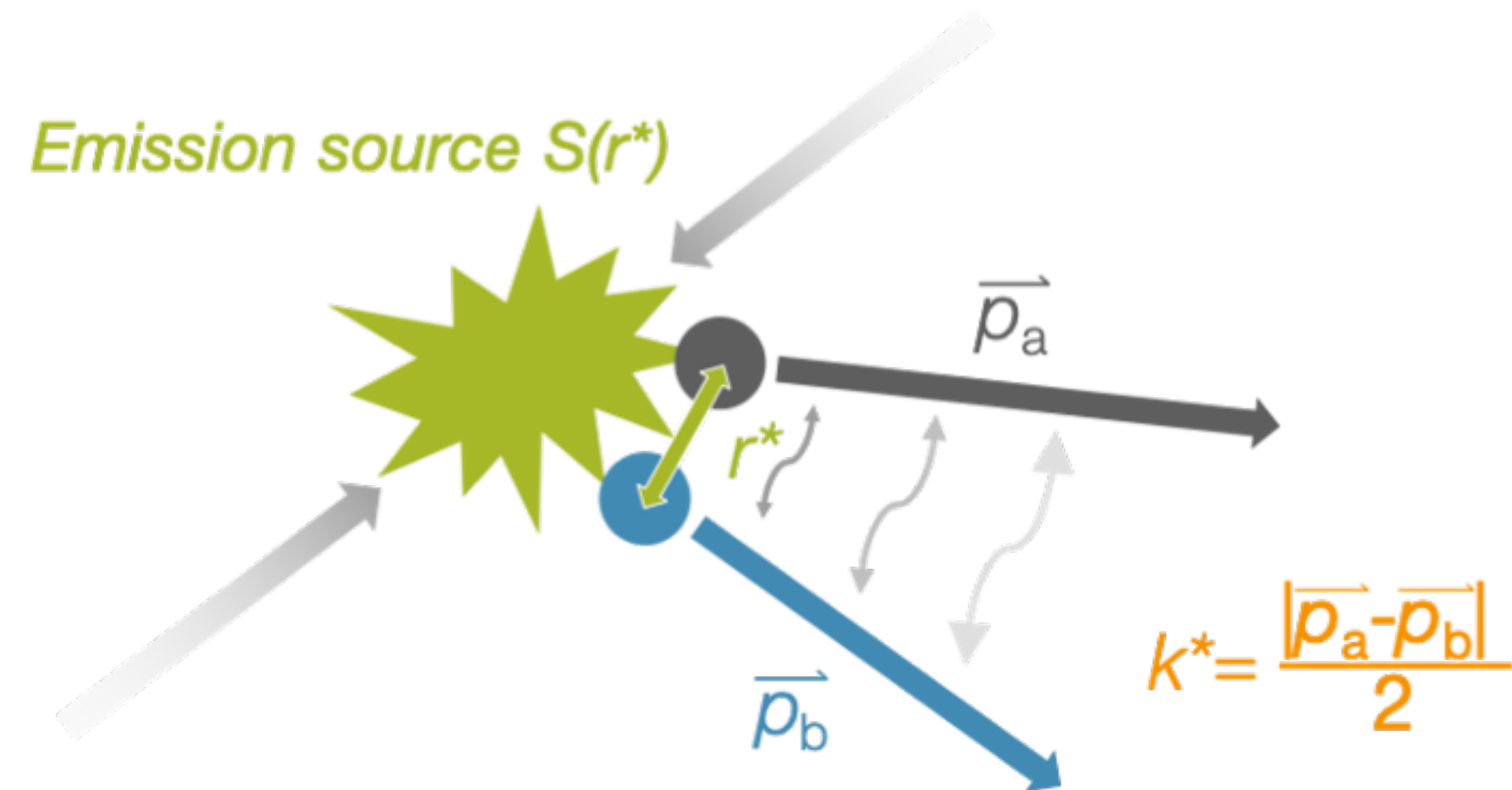
Joint Institute for Nuclear Research

The 2nd International Workshop on Physics at High Baryon Density
16–18 Oct. 2025, CCNU, Wuhan, China

Outline

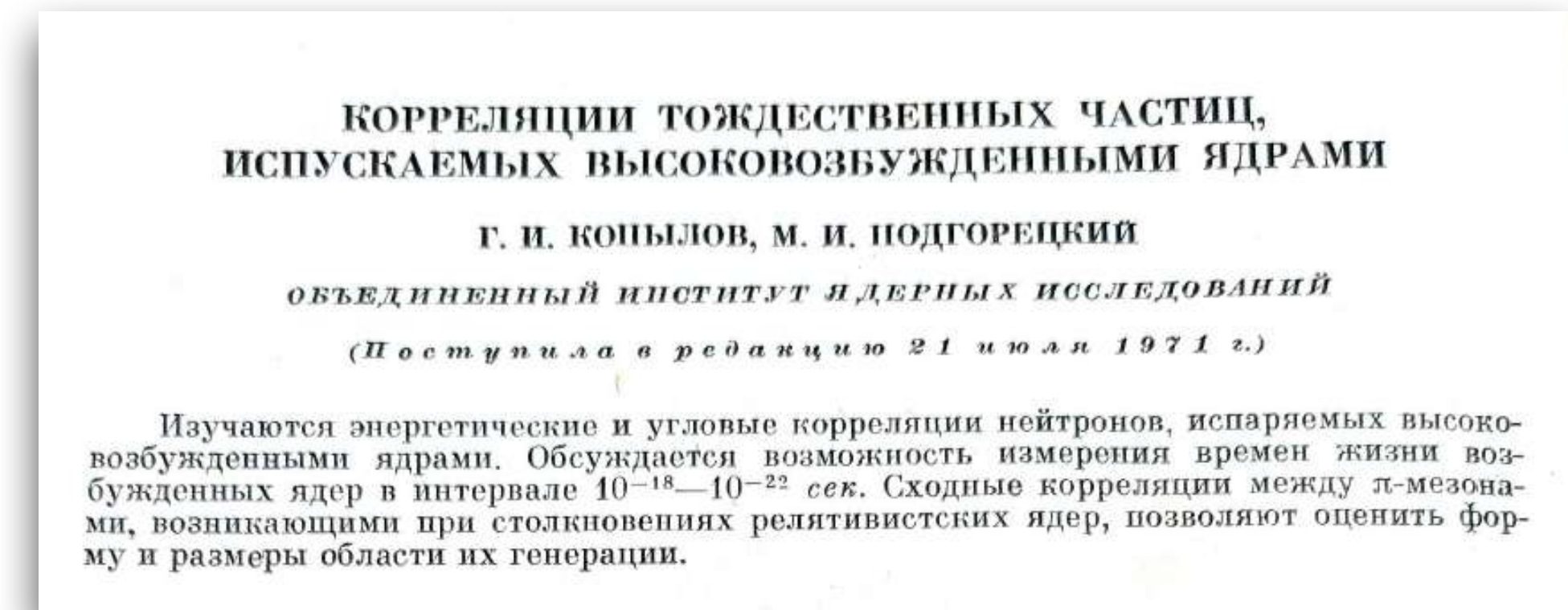
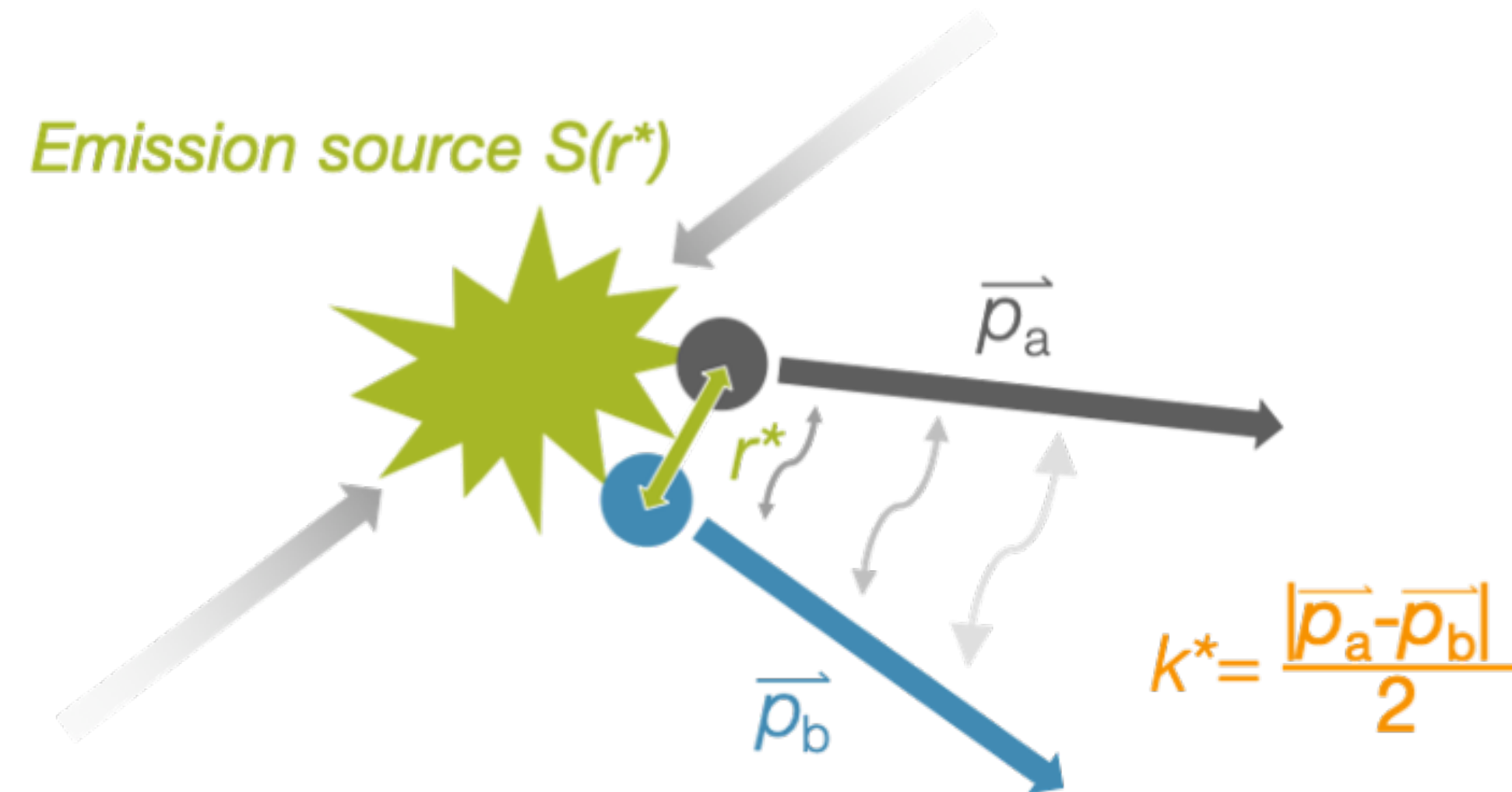
- ◉ Femtoscopy technique
- ◉ The STAR experiment and Fixed-Target program
- ◉ Results from Au+Au $\sqrt{s_{\text{NN}}} = 3.0\text{--}7.7$ GeV:
 - ▶ Measured $\pi^{\pm}\pi^{\pm}$ correlation functions
 - ▶ $\sqrt{s_{\text{NN}}}$ -dependence of radii
 - ▶ $\sqrt{s_{\text{NN}}}$ and centrality dependence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

Femtoscopy technique



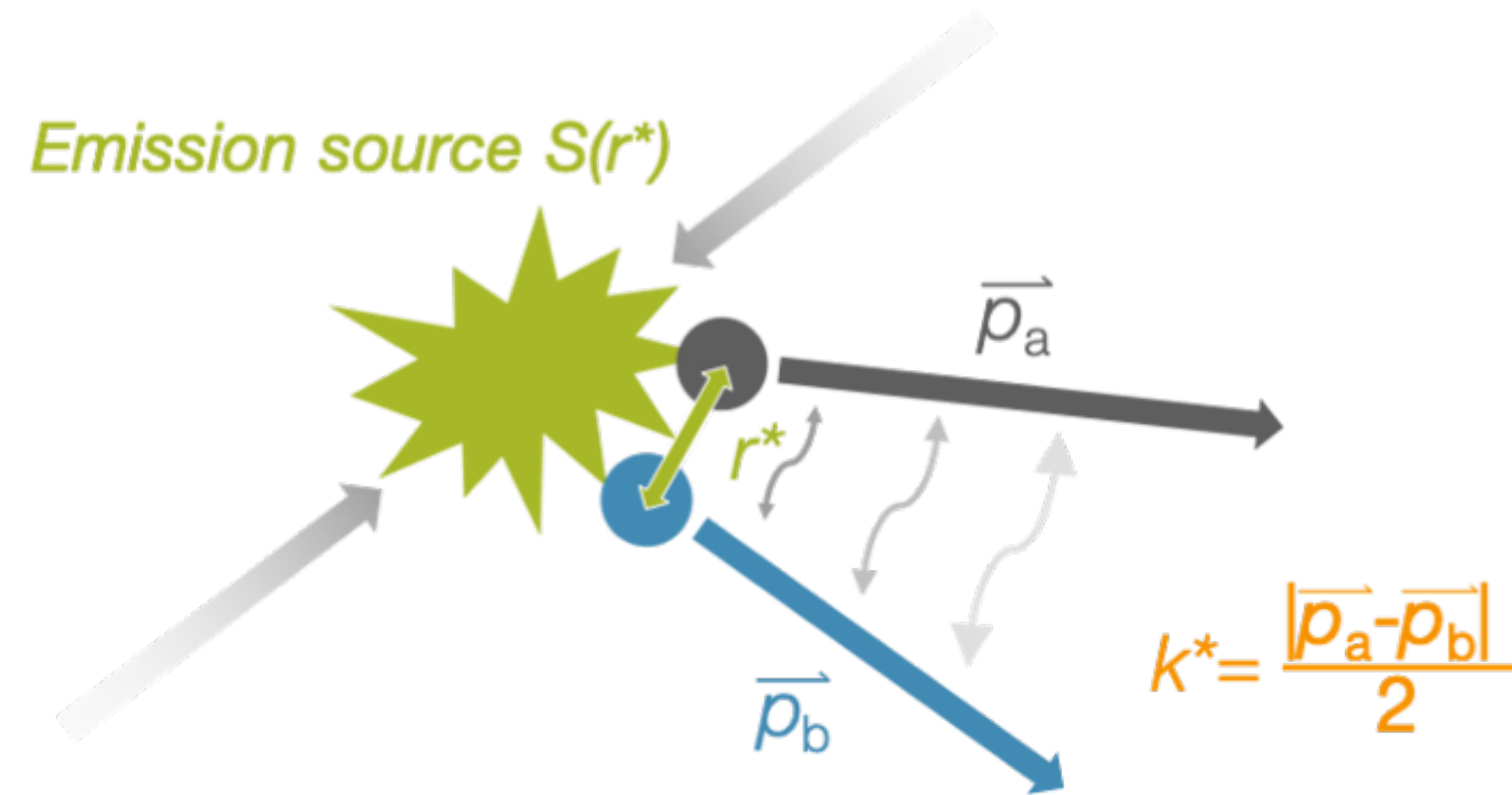
- *Femtoscopy* is a powerful technique to study characteristics of particle-emitting source in relativistic heavy-ion collisions:

Femtoscscopy technique

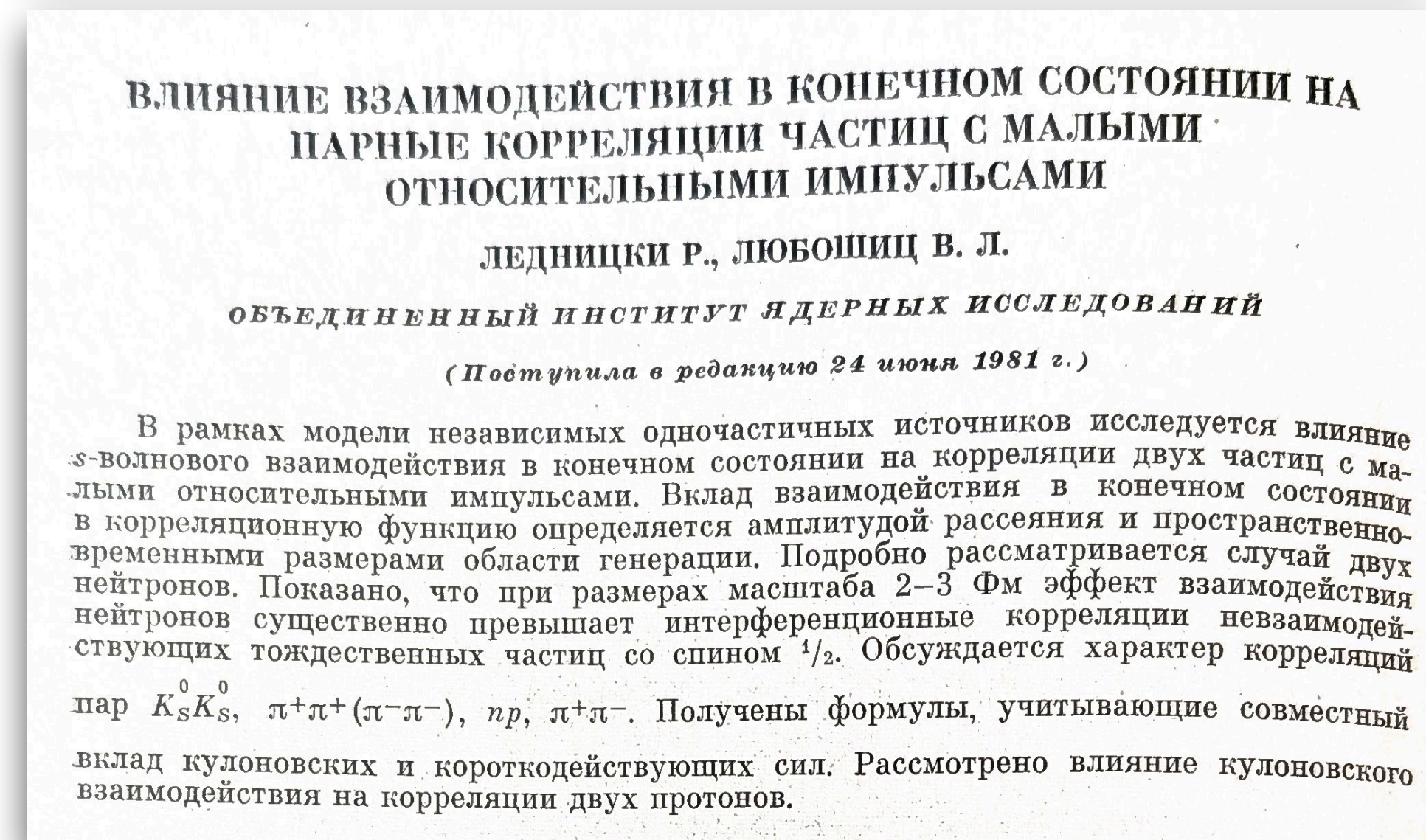
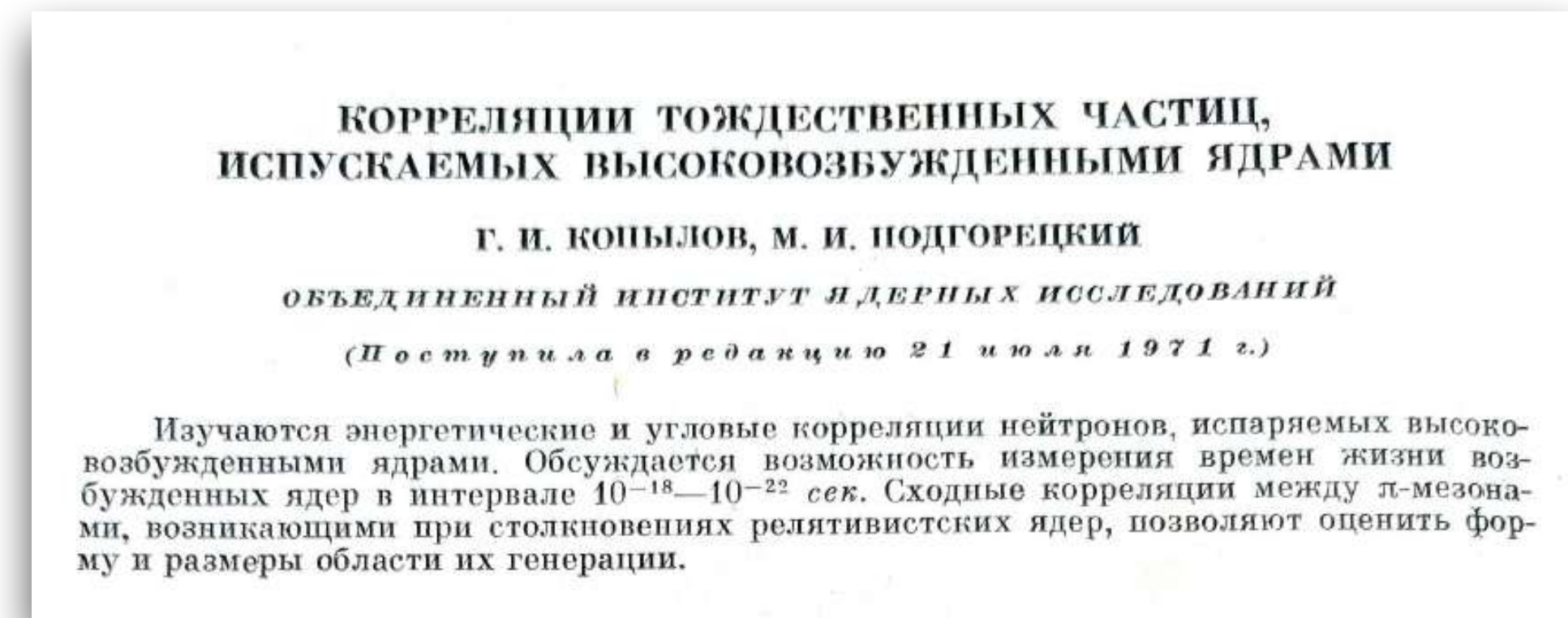


- *Femtoscscopy* is a powerful technique to study characteristics of particle-emitting source in relativistic heavy-ion collisions:
 - ▶ access to spatial and temporal properties (Kopylov, Podgoretsky 1971)

Femtoscscopy technique

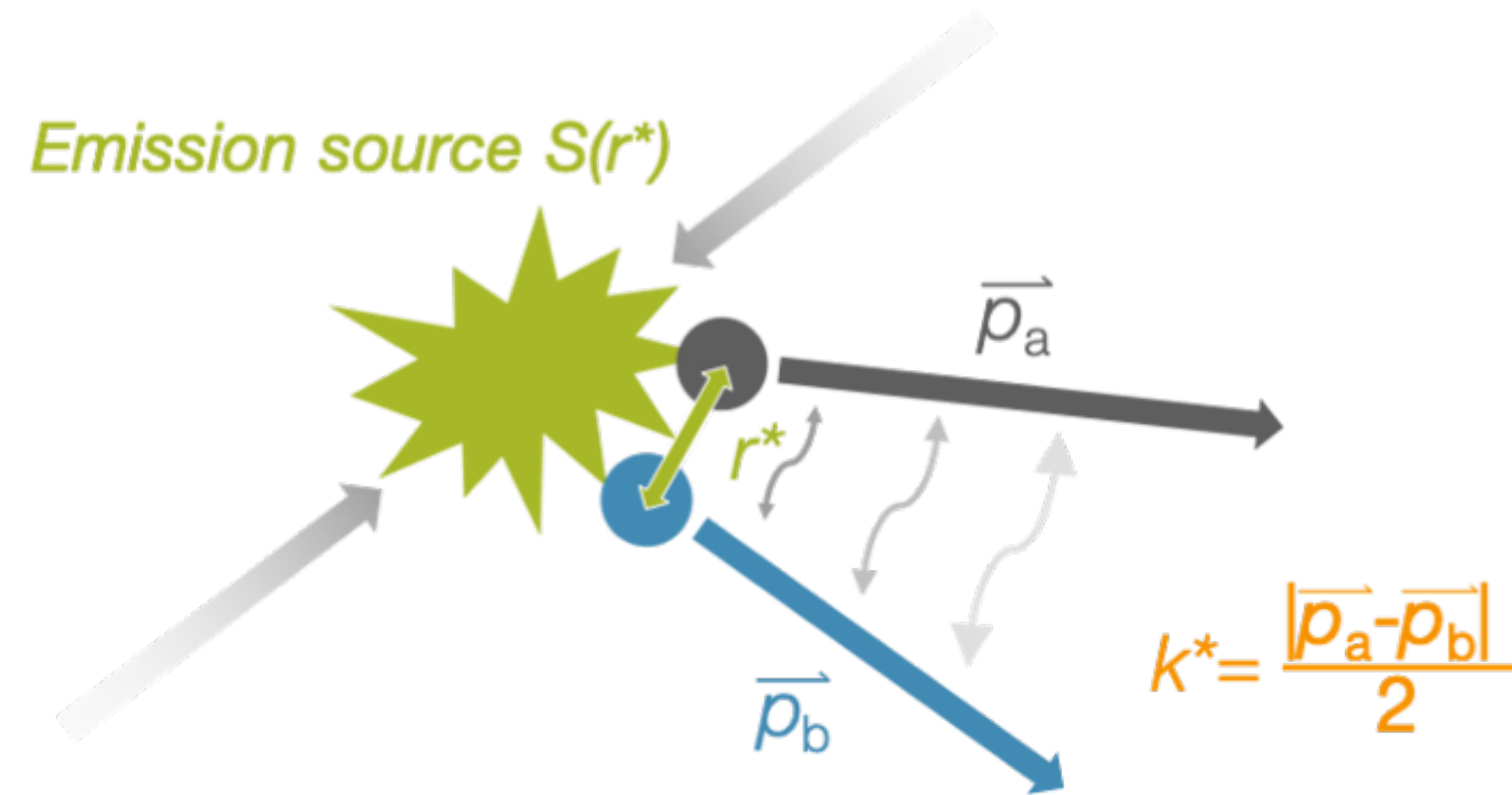


- *Femtoscscopy* is a powerful technique to study characteristics of particle-emitting source in relativistic heavy-ion collisions:
 - ▶ access to spatial and temporal properties (Kopylov, Podgoretsky 1971)
 - ▶ study final state interactions (Lednický, Lyuboshits 1981)



> 50 years of femtoscopy

Femtoscscopy technique



Correlation functions:

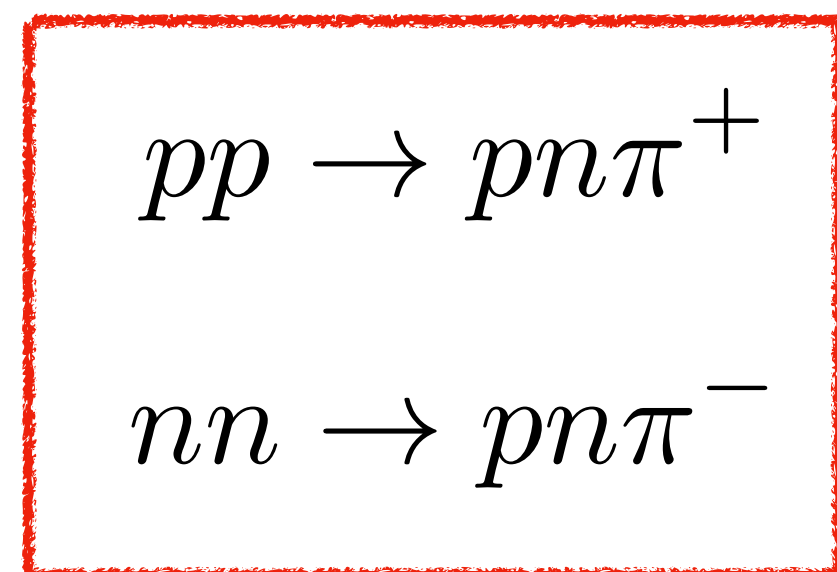
$$C(k^*) = \underbrace{\int S(r^*) \left| \Psi(k^*, r^*) \right|^2 d^3 r^*}_{\text{Model}} = \underbrace{\frac{A(k^*)}{B(k^*)}}_{\text{Measurement}}$$

- *Femtoscscopy* is a powerful technique to study characteristics of particle-emitting source in relativistic heavy-ion collisions:
 - ▶ access to spatial and temporal properties (Kopylov, Podgoretsky 1971)
 - ▶ study final state interactions (Lednický, Lyuboshits 1981)

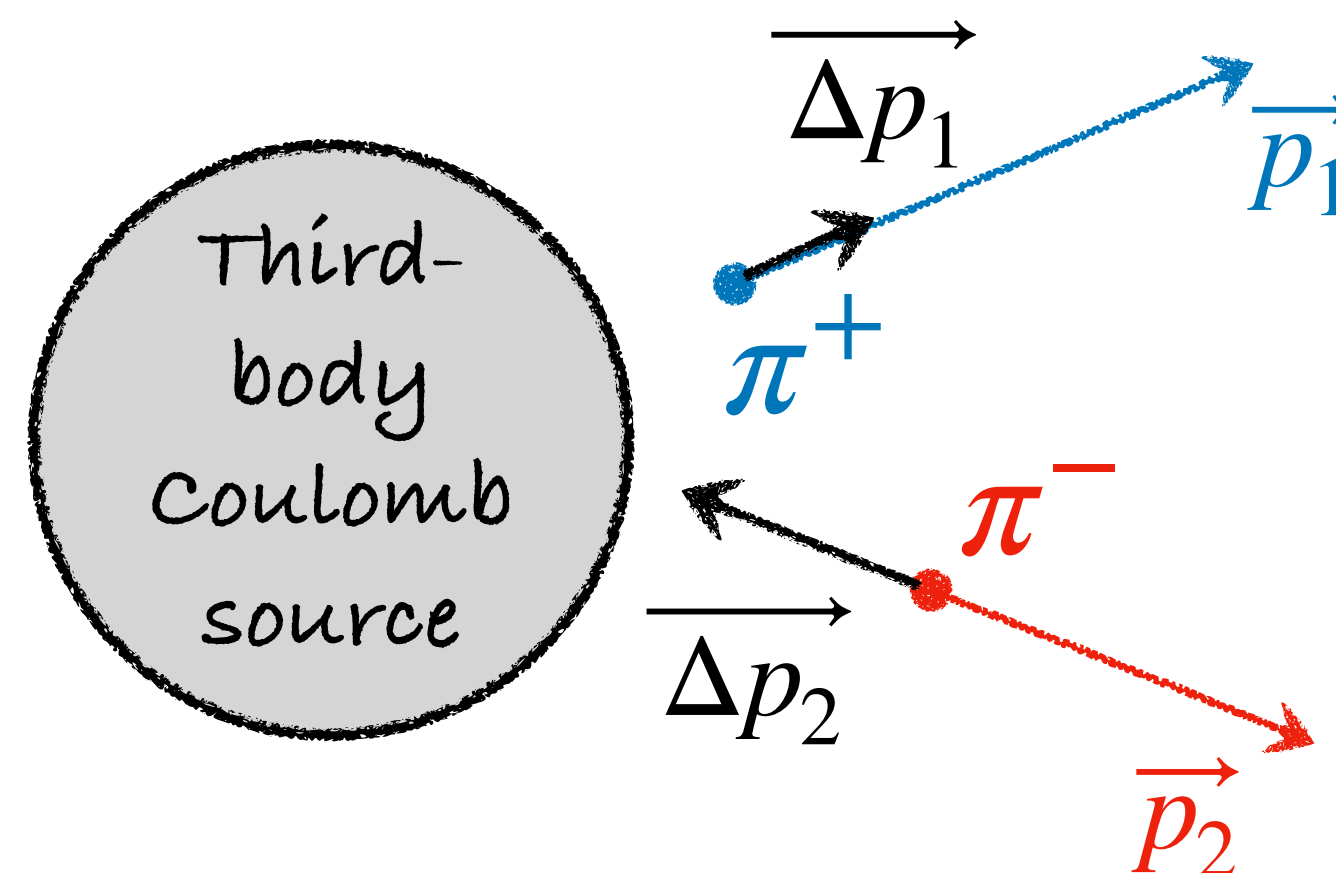
r^* : relative distance, k^* : relative momentum,
 $S(r^*)$: source function, $\Psi(k^*, r^*)$: two-particle wave function
 $A(k^*)$: distribution of pairs from same event, containing quantum statistical (QS) correlations, final state interactions (FSI) (Coulomb, strong)
 $B(k^*)$: distribution of pairs from mixed events, served as background

Motivation

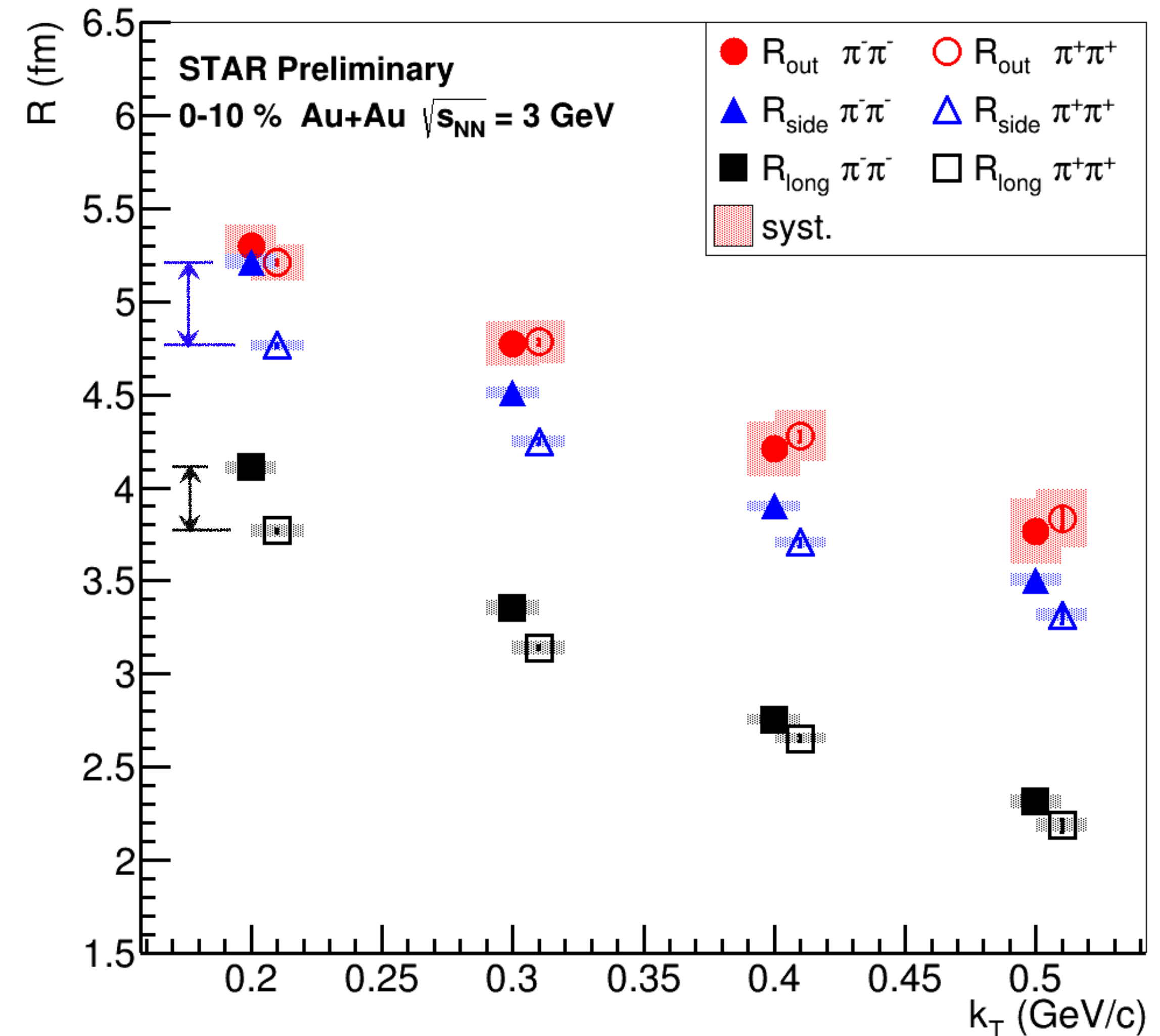
- Clear difference in R_{side} and R_{long} radii between $\pi^+\pi^+$ and $\pi^-\pi^-$ at small pair transverse momentum (k_T)
- Possible effects causing the difference:
 - Third-body Coulomb effect
 - Isospin effect



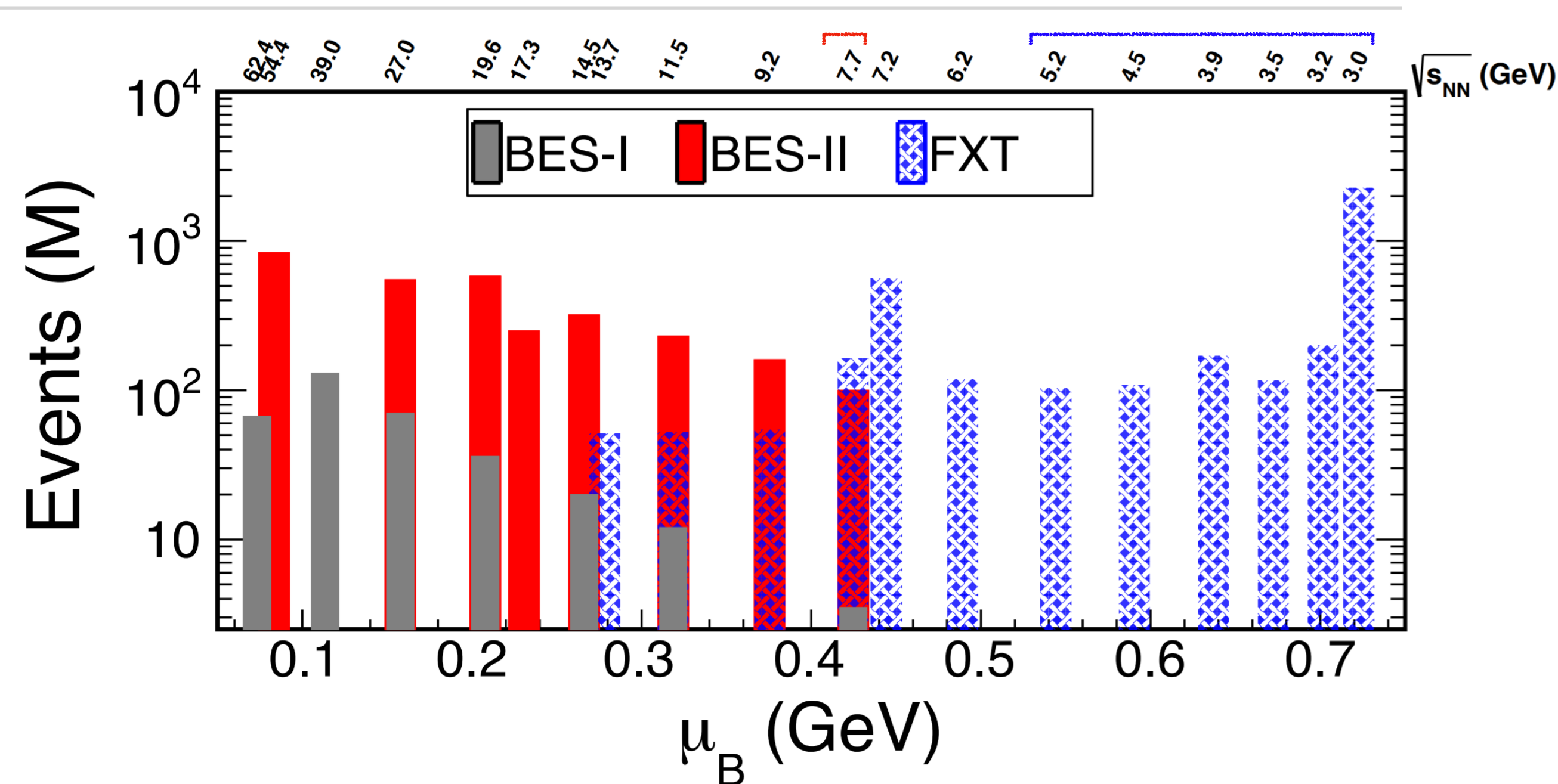
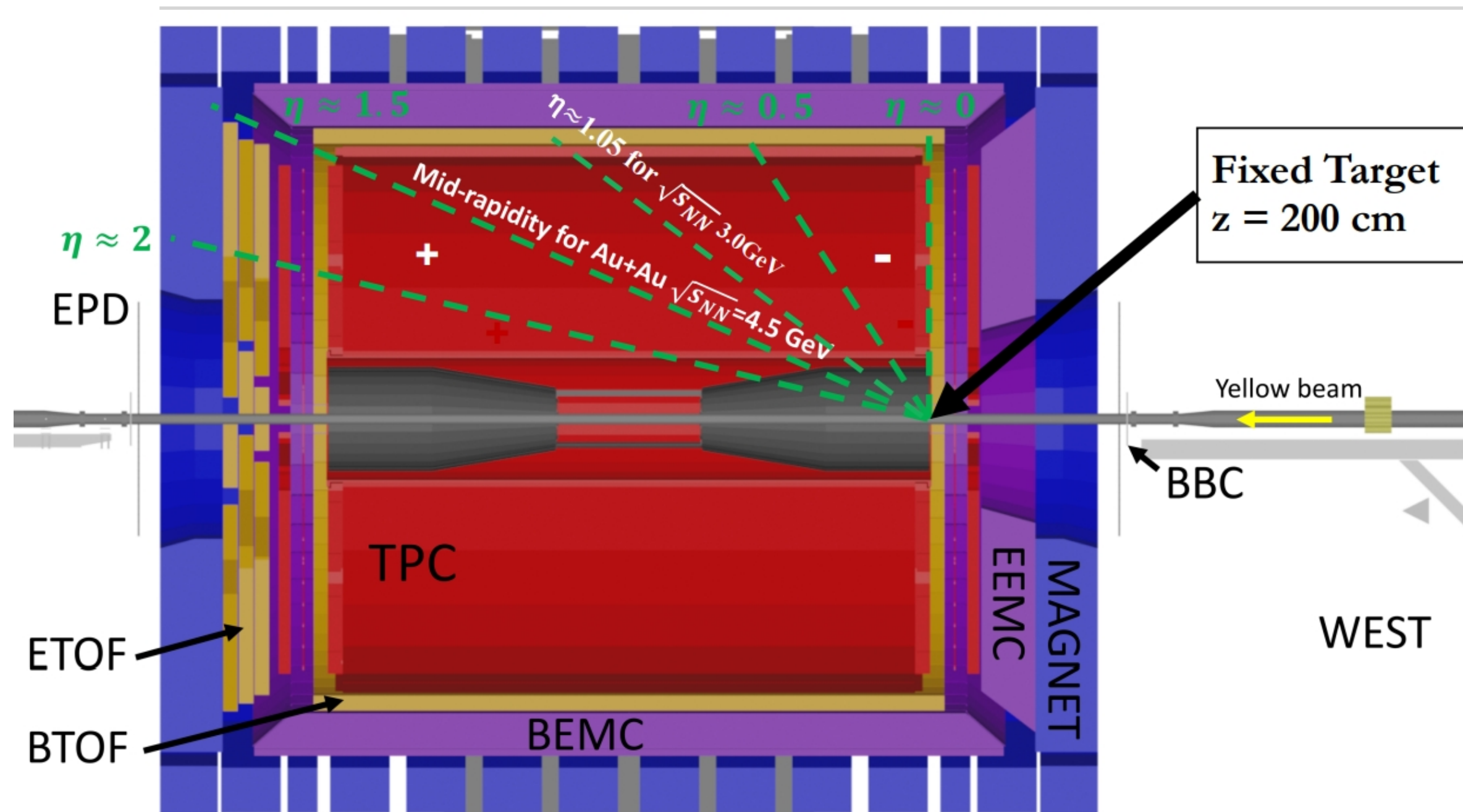
Isospin effect



Third-body Coulomb effect

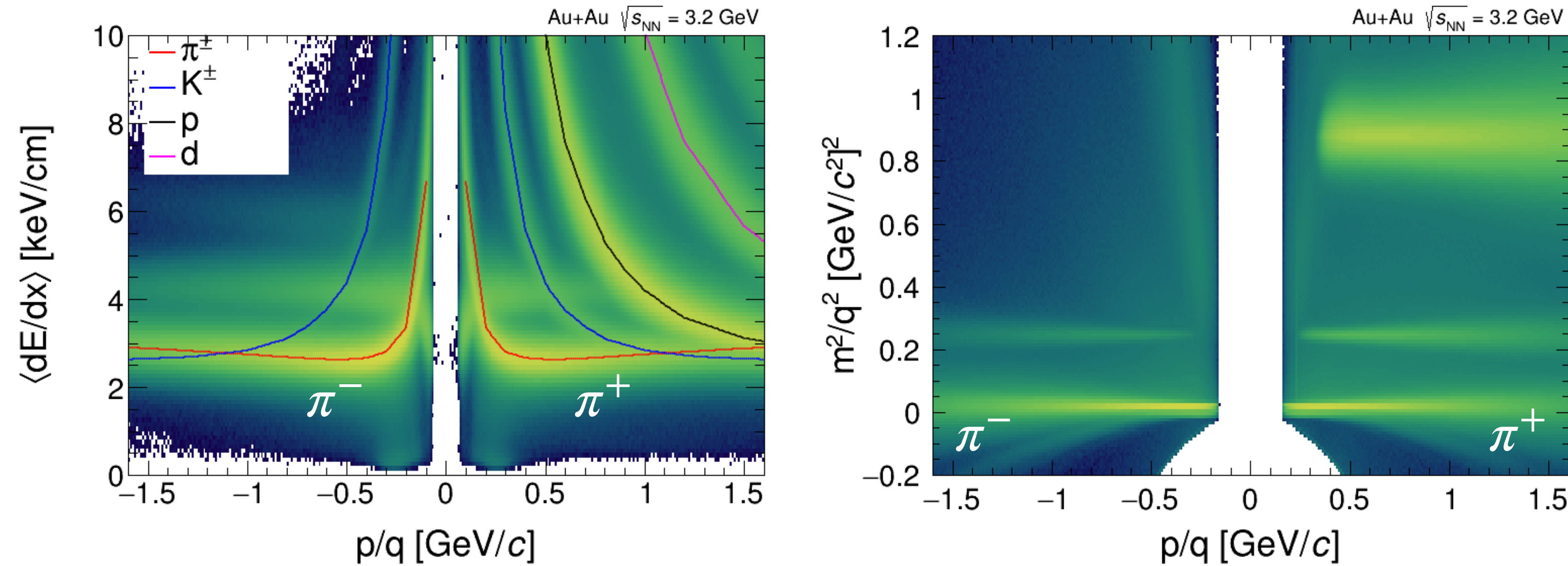


The STAR detector & Fixed-Target Program

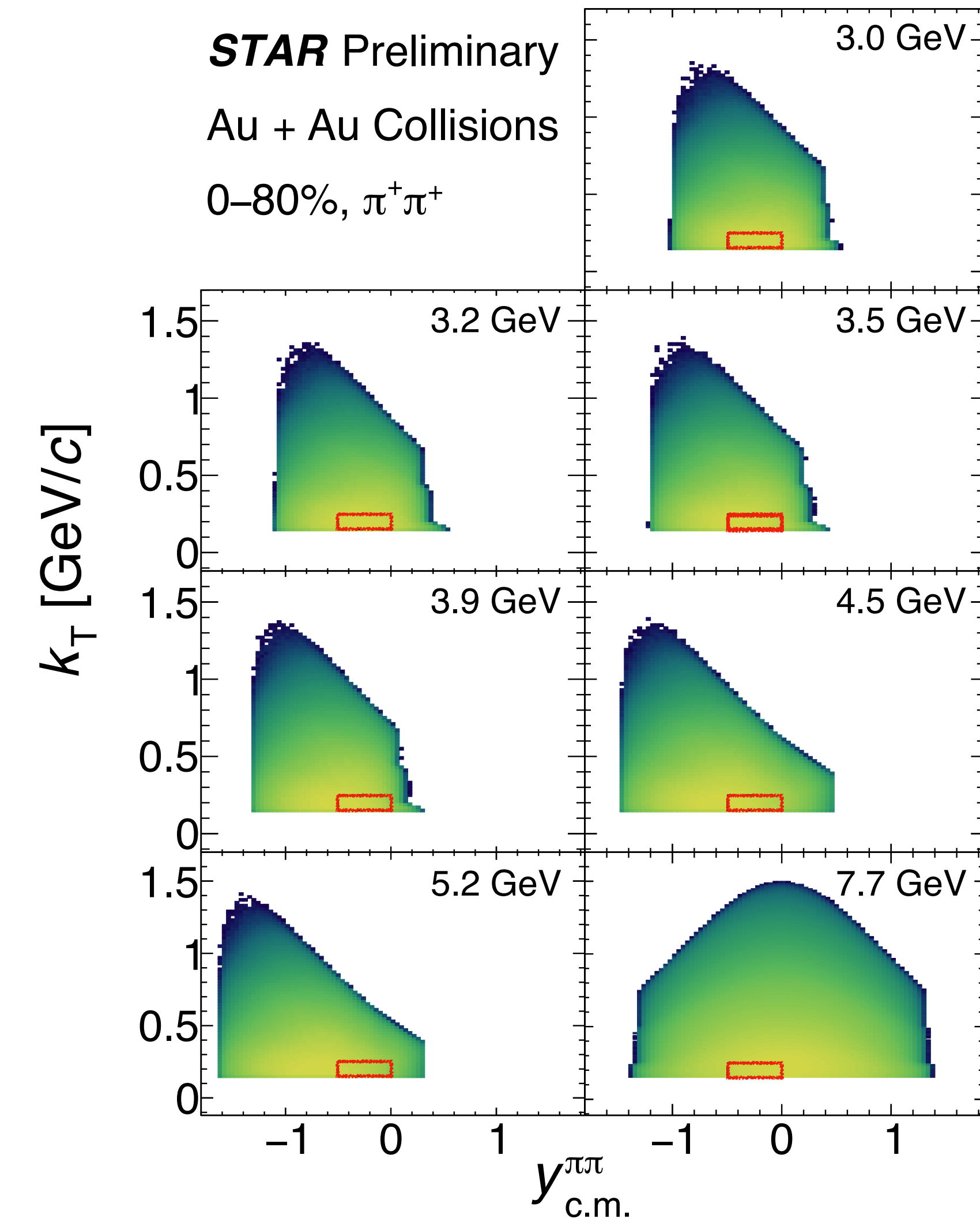


- ◉ Fixed-target (FXT) program: Au + Au collisions at $\sqrt{s_{NN}} = 3.0\text{--}13.7$ GeV
- ◉ Identical charged pion correlations are measured for Au + Au collisions at:
 - ▶ $\sqrt{s_{NN}} = 3.0, 3.2, 3.5, 3.9, 4.5, 5.2$ GeV (FXT mode)
 - ▶ $\sqrt{s_{NN}} = 7.7$ GeV (BES-II, collider mode)

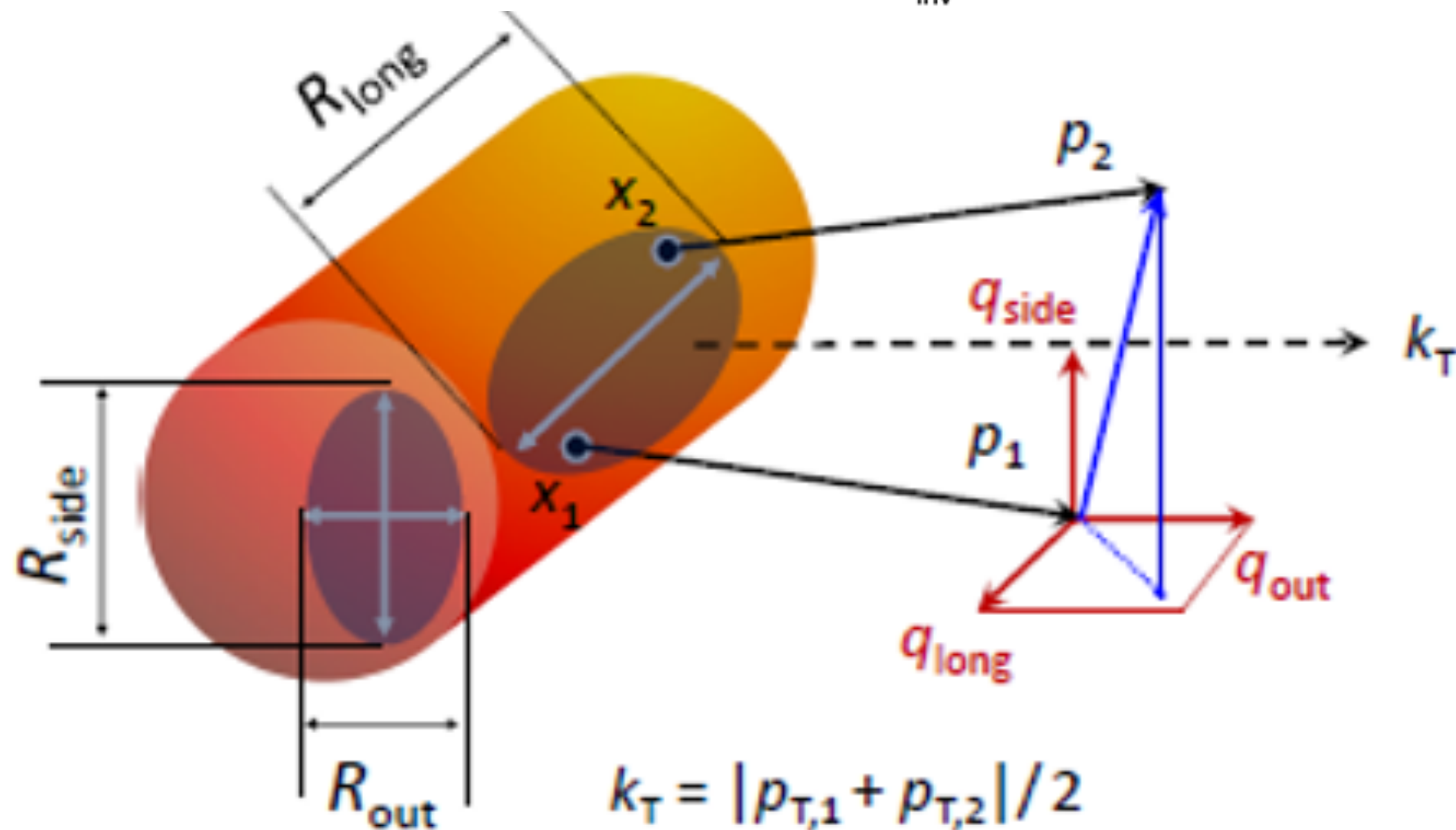
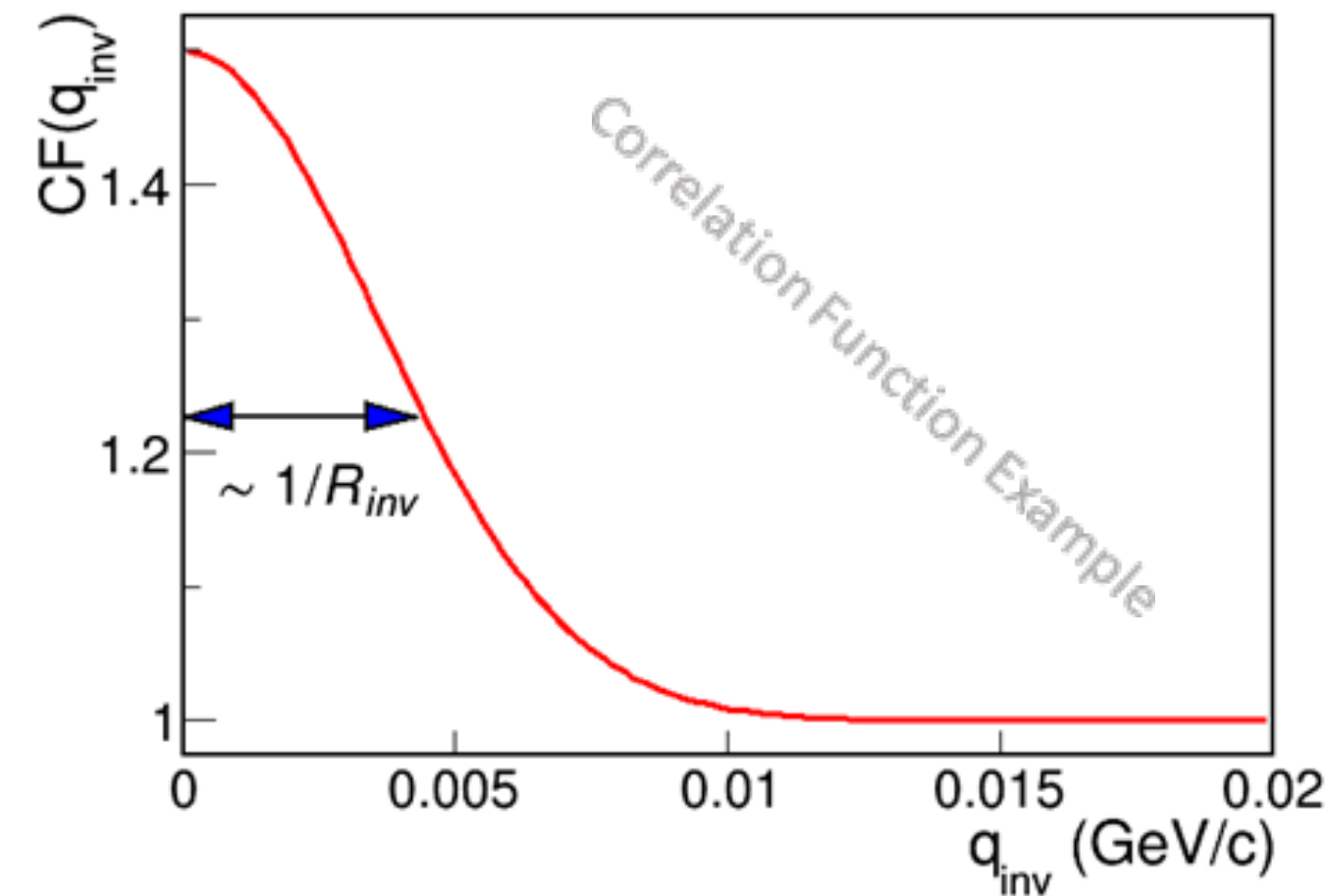
Pion identification



- 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 $0.15 < k_T < 0.25$ GeV/c, $-0.5 < y_{c.m.}^{\pi\pi} < 0$ 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
 - $B(\vec{q})$: background distribution of $\vec{q}$ of two tracks from different events
- 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)

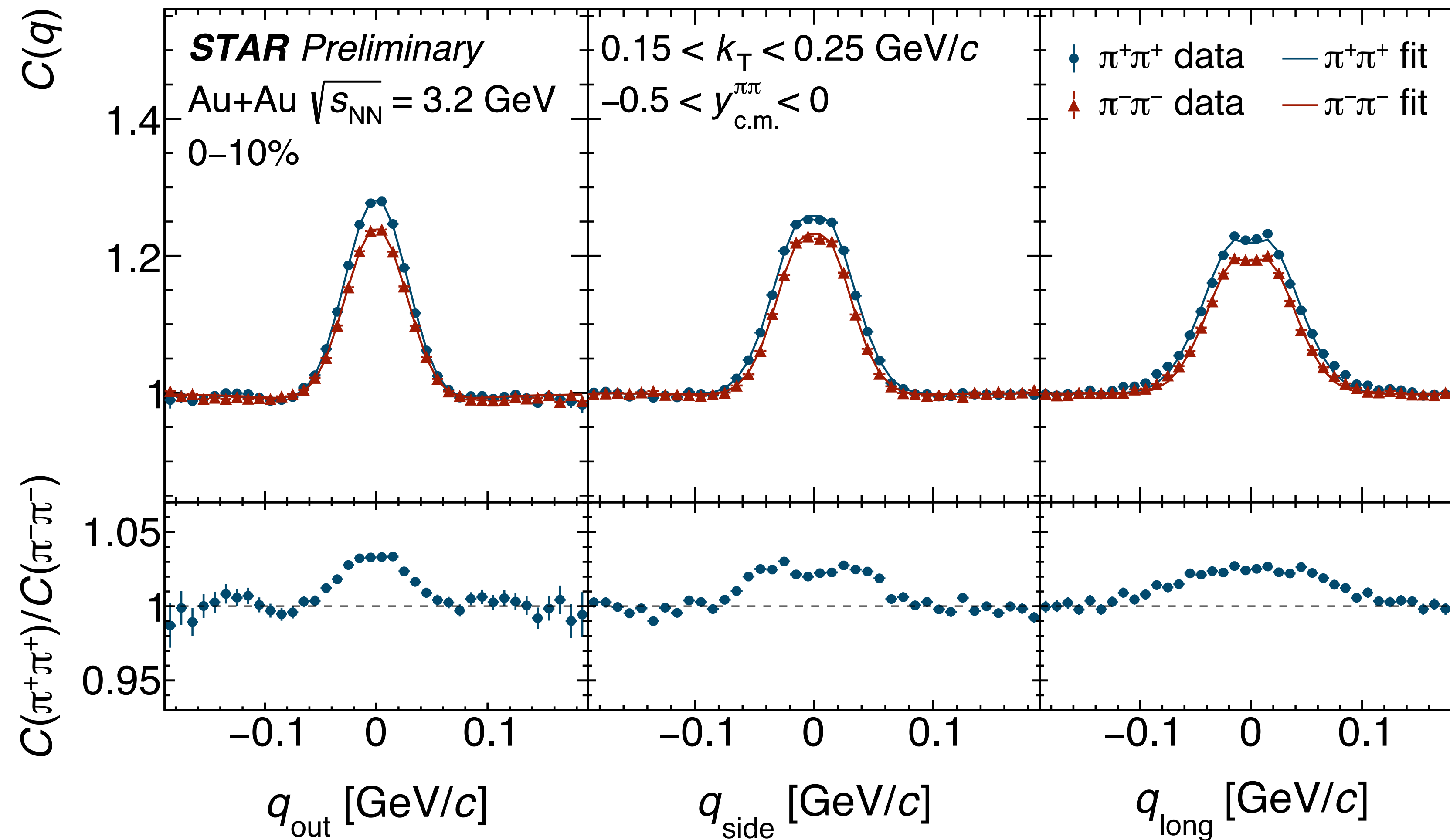
Fitting the correlation function

- Bowler—Sinyukov procedure: $C(\vec{q}) = N [(1 - \lambda) + \lambda K_{\text{Coul}}(q_{\text{inv}})(1 + G(\vec{q}))]$
$$G(\vec{q}) = \exp(-q_o^2 R_o^2 - q_s^2 R_s^2 - q_l^2 R_l^2 - 2q_o q_l R_{ol}^2)$$
 - ▶ N : normalization factor, λ : correlation strength factor
 - ▶ K_{Coul} : two-pion Coulomb correlation function
 - ▶ $R_{\text{out}} \propto$ geometrical size and emission duration
 - ▶ $R_{\text{side}} \propto$ geometrical size
 - ▶ $R_{\text{long}} \propto$ source lifetime
 - ▶ $R_{\text{out-long}}^2 \propto$ tilt of the correlation functions in the $(q_{\text{out}}, q_{\text{long}})$ plane, depending on the degree of asymmetry of the rapidity acceptance w.r.t. midrapidity

M.G. Bowler, PLB **270**, 69 (1991)

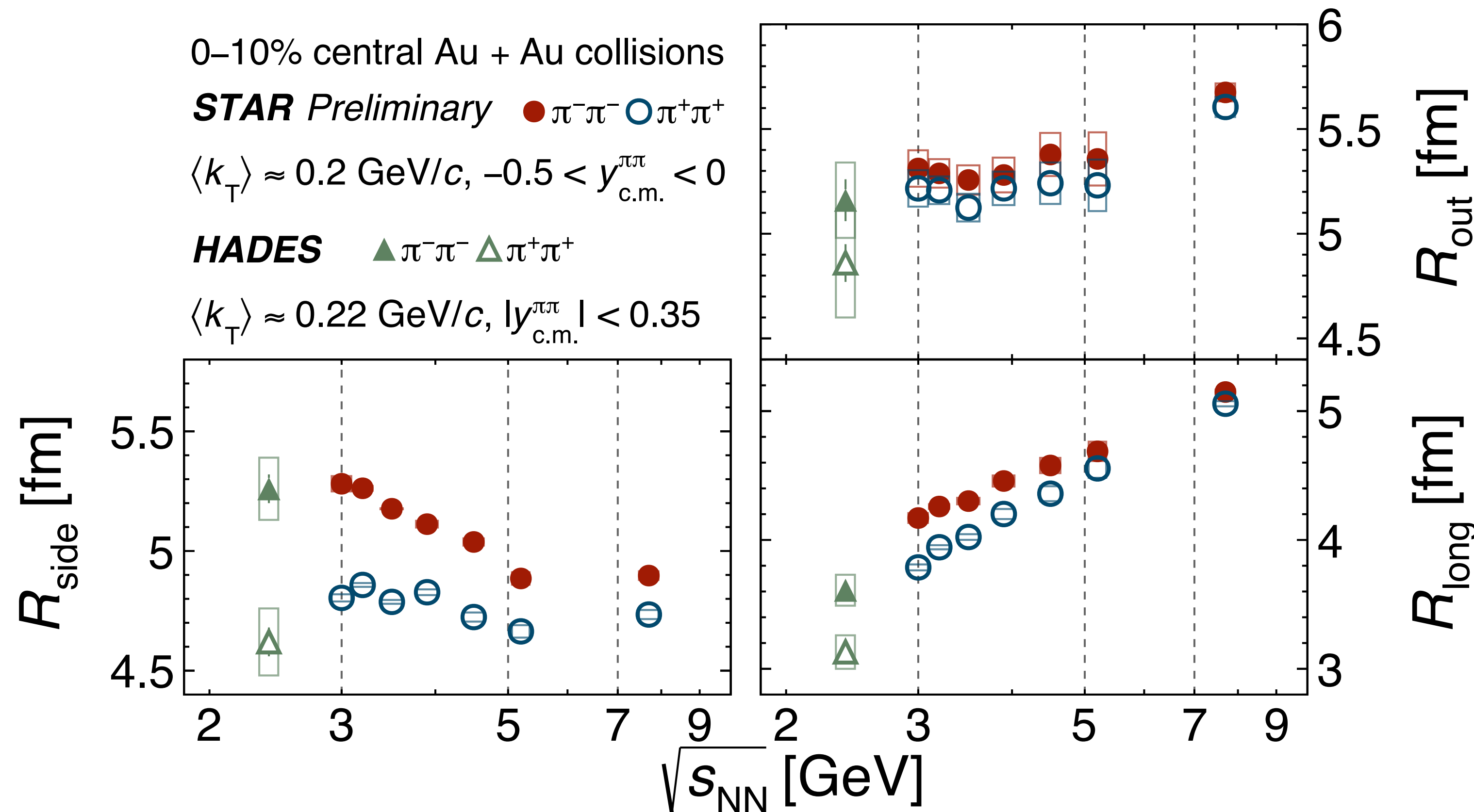
Yu.M. Sinyukov, et. al., PLB **432**, 248 (1998)

Charged pion correlation function



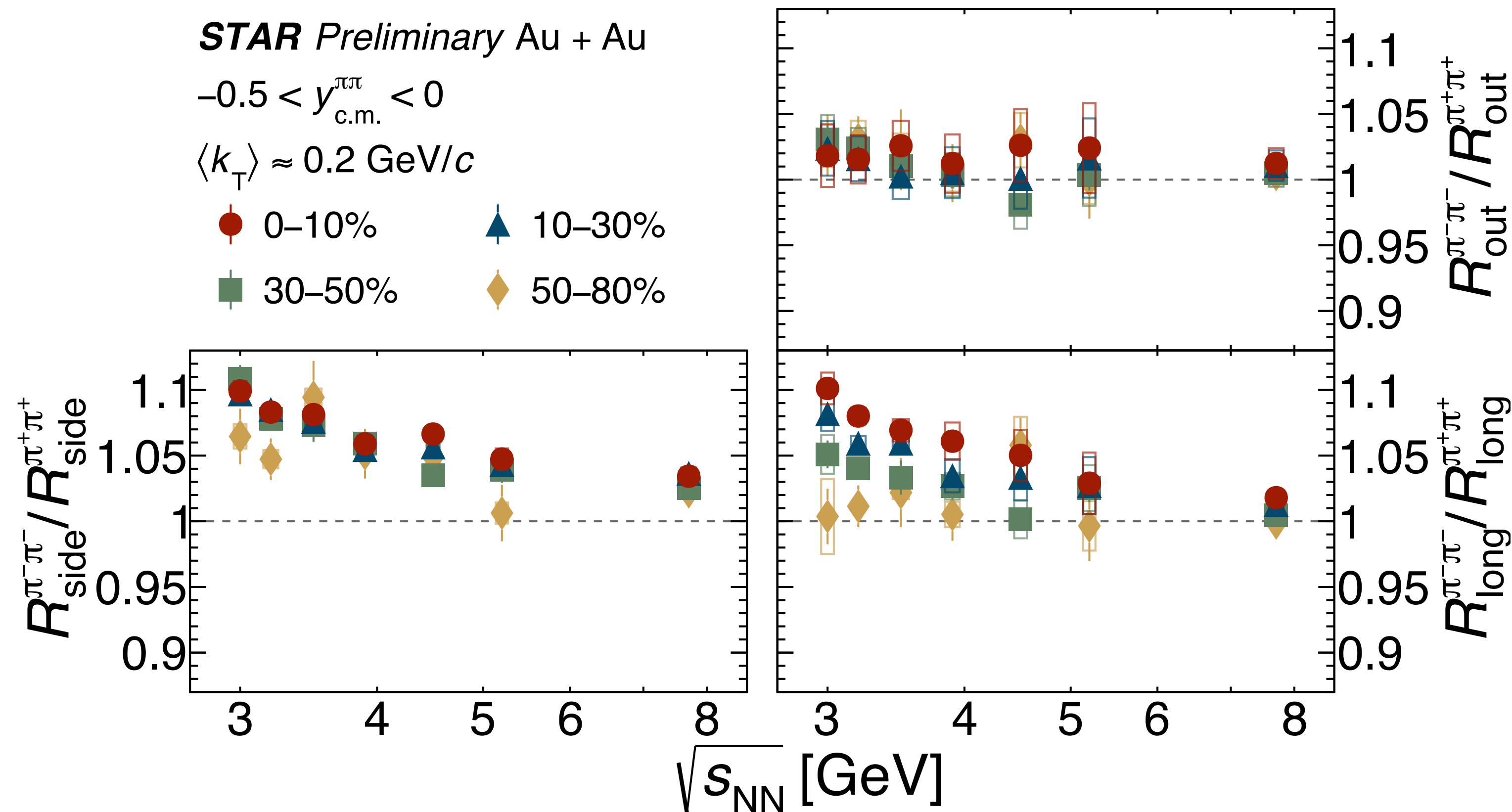
- About 3% difference between $C(\pi^+\pi^+)$ and $C(\pi^-\pi^-)$
- Likely due to the third-body Coulomb and isospin effects

Collision energy dependence of radii



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

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



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

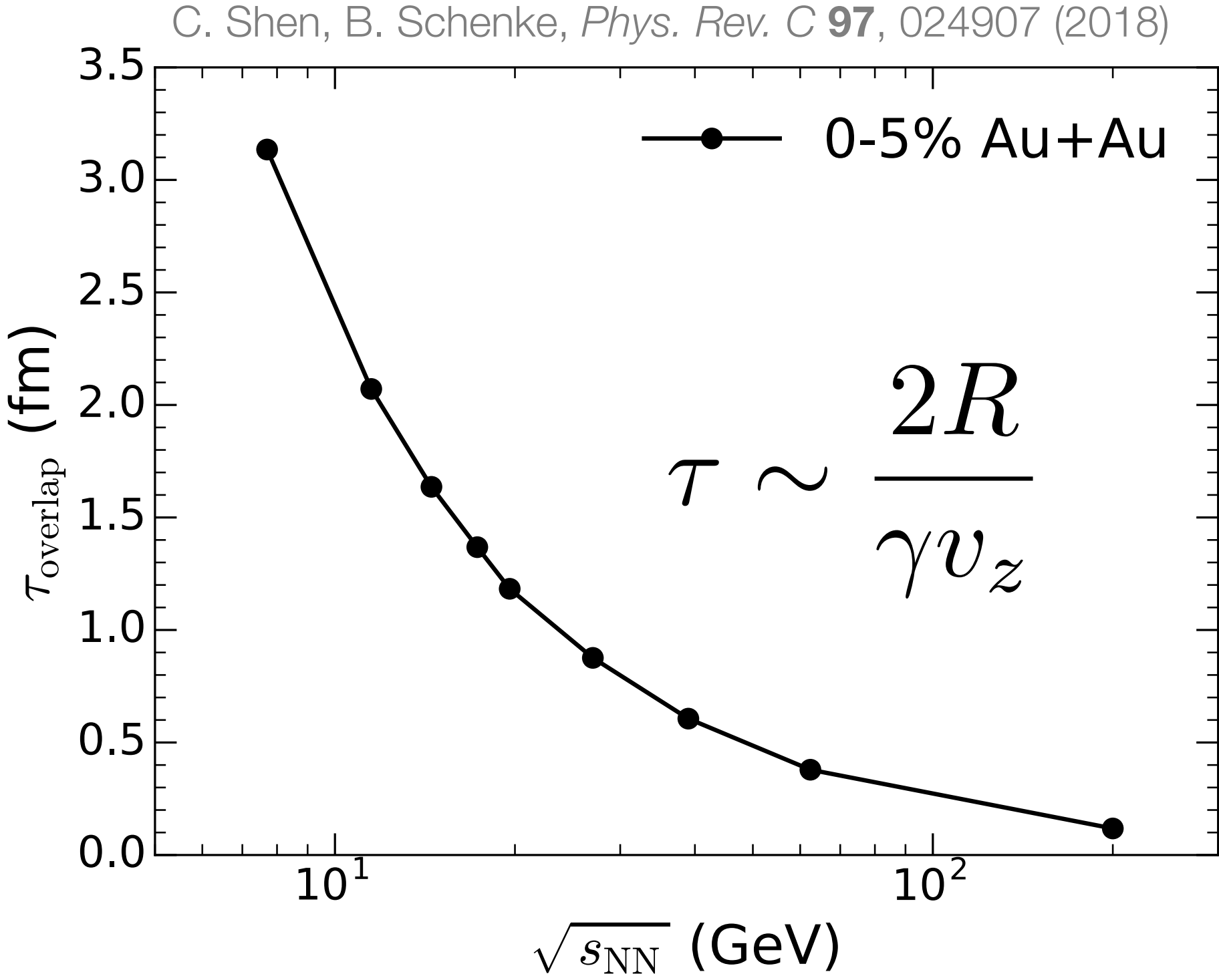
Third-body Coulomb correction

Estimation of effective third-body charge

◉ **Step 1:** Estimate effective third-body charge $Z_{\text{res.ch.}}^{\text{eff}}$:

- ▶ At $\sqrt{s_{\text{NN}}} = 3.0$ GeV: extract $Z_{\text{res.ch.}}^{\text{eff}}$ from π^-/π^+ p_{T} -spectra ratio by comparing data with UrQMD + third-body
- ▶ At $\sqrt{s_{\text{NN}}} = 3.2\text{--}7.7$ GeV: $Z_{\text{res.ch.}}^{\text{eff}}$ are scaled by passing time τ_{overlap} (assuming $Z_{\text{res.ch.}}^{\text{eff}} \propto \tau_{\text{overlap}}$)

$\sqrt{s_{\text{NN}}}$ (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
$Z_{\text{res.ch.}}^{\text{eff}}$	50	45	40	34	29	24	16

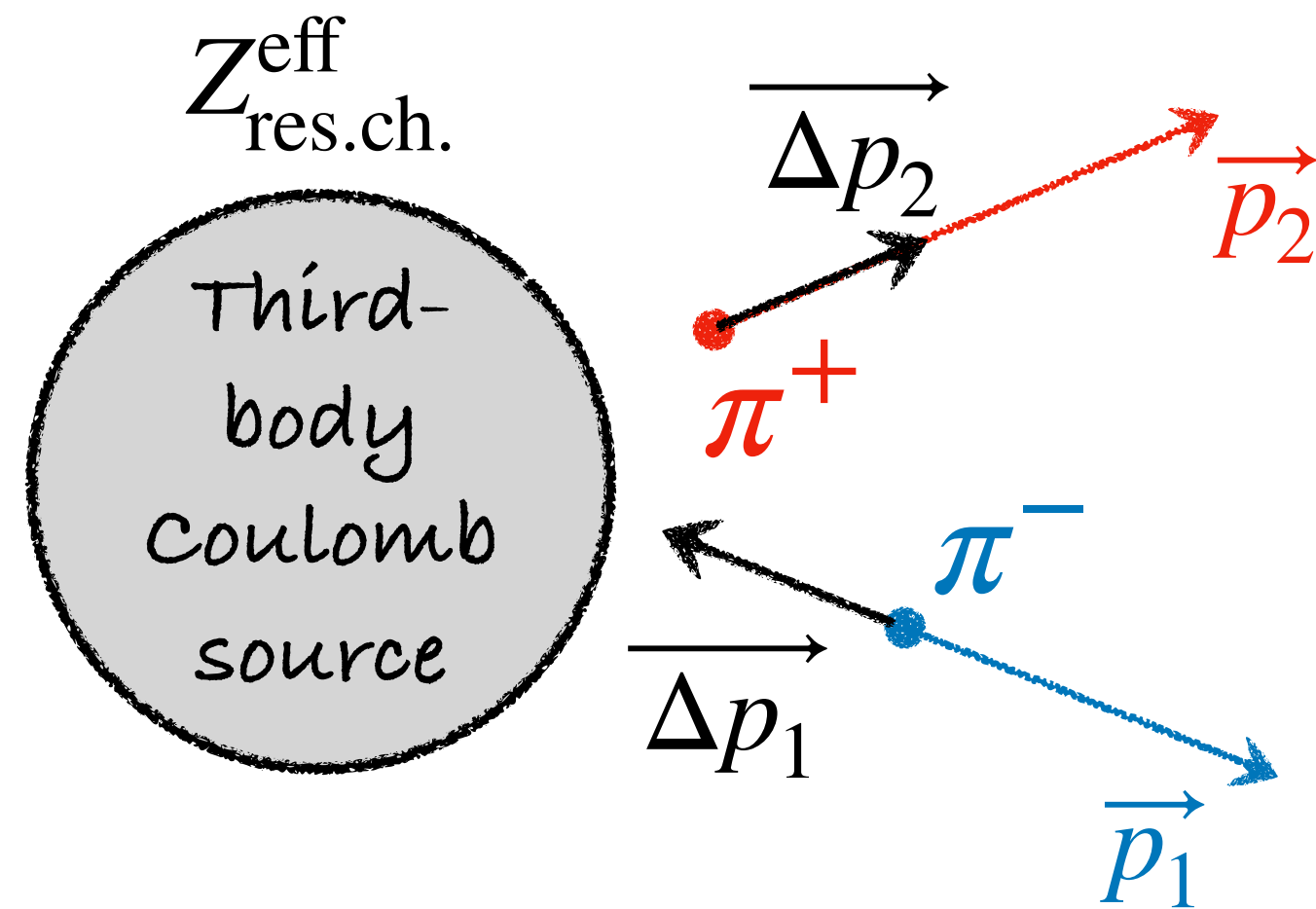


Third-body Coulomb correction

Estimation of momentum shift Δp

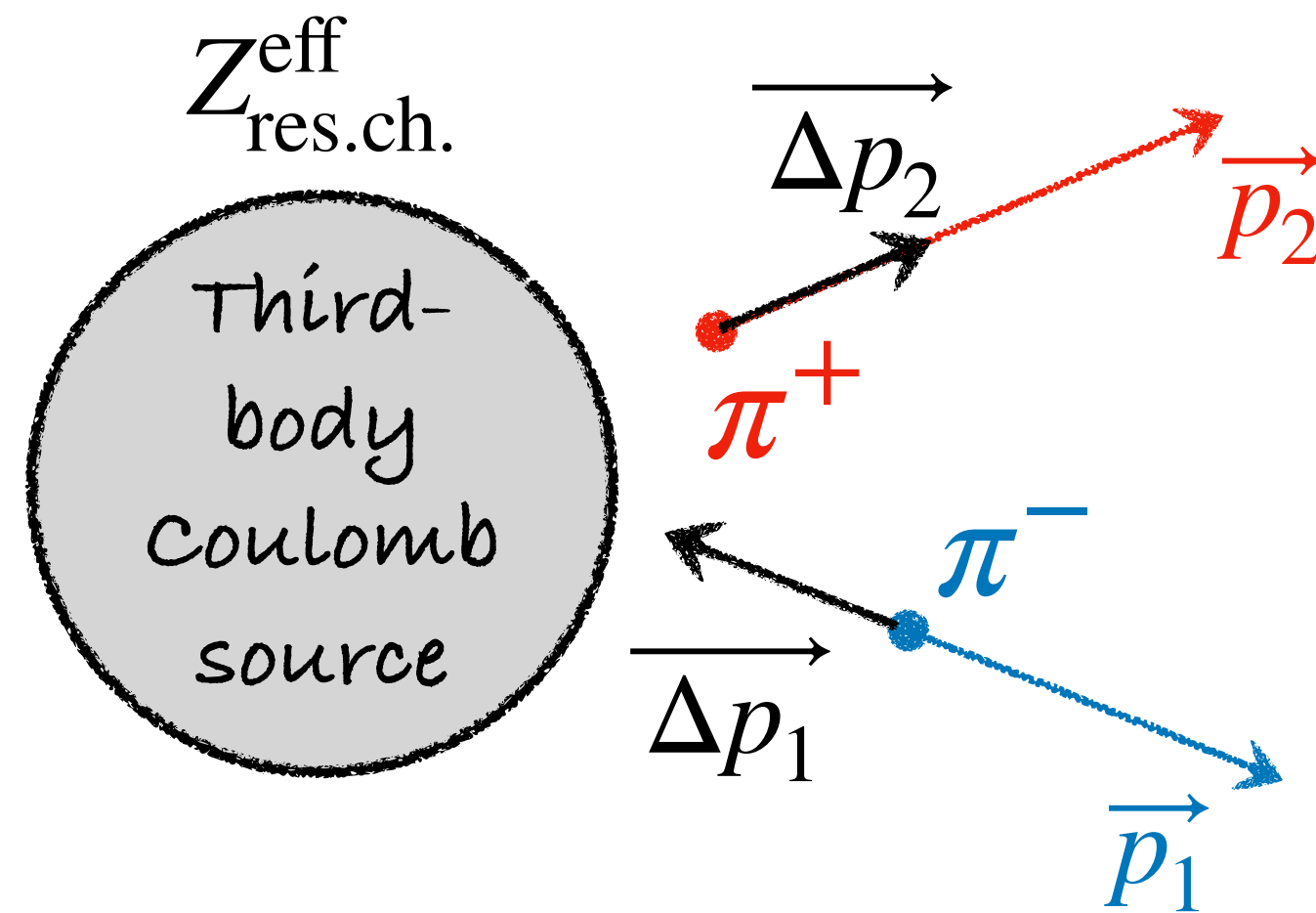
Third-body Coulomb correction

Estimation of momentum shift Δp



Third-body Coulomb correction

Estimation of momentum shift Δp

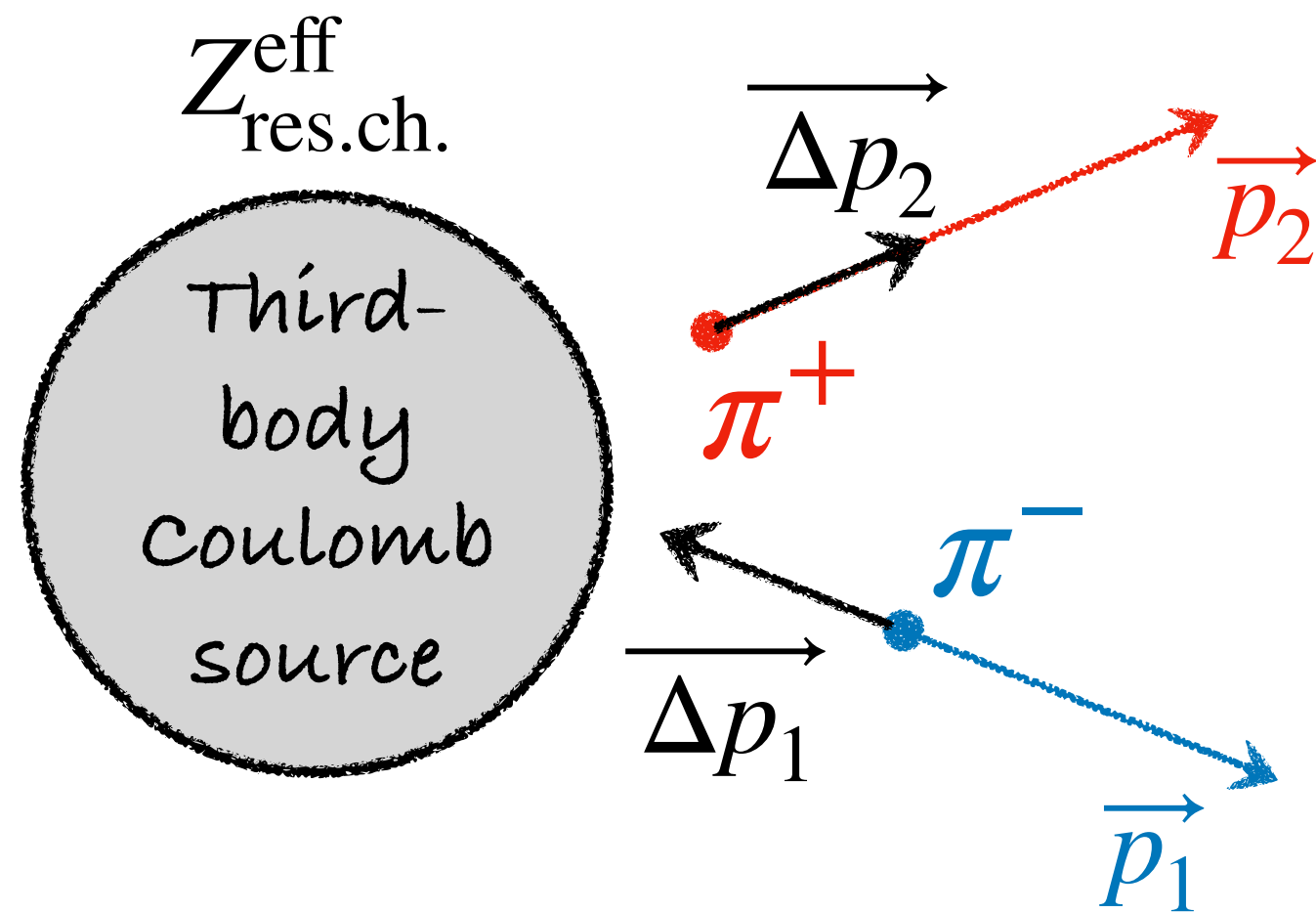


Correct momenta of single- $\pi^\pm$ for third-body Coulomb effect:

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

Third-body Coulomb correction

Estimation of momentum shift Δp



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

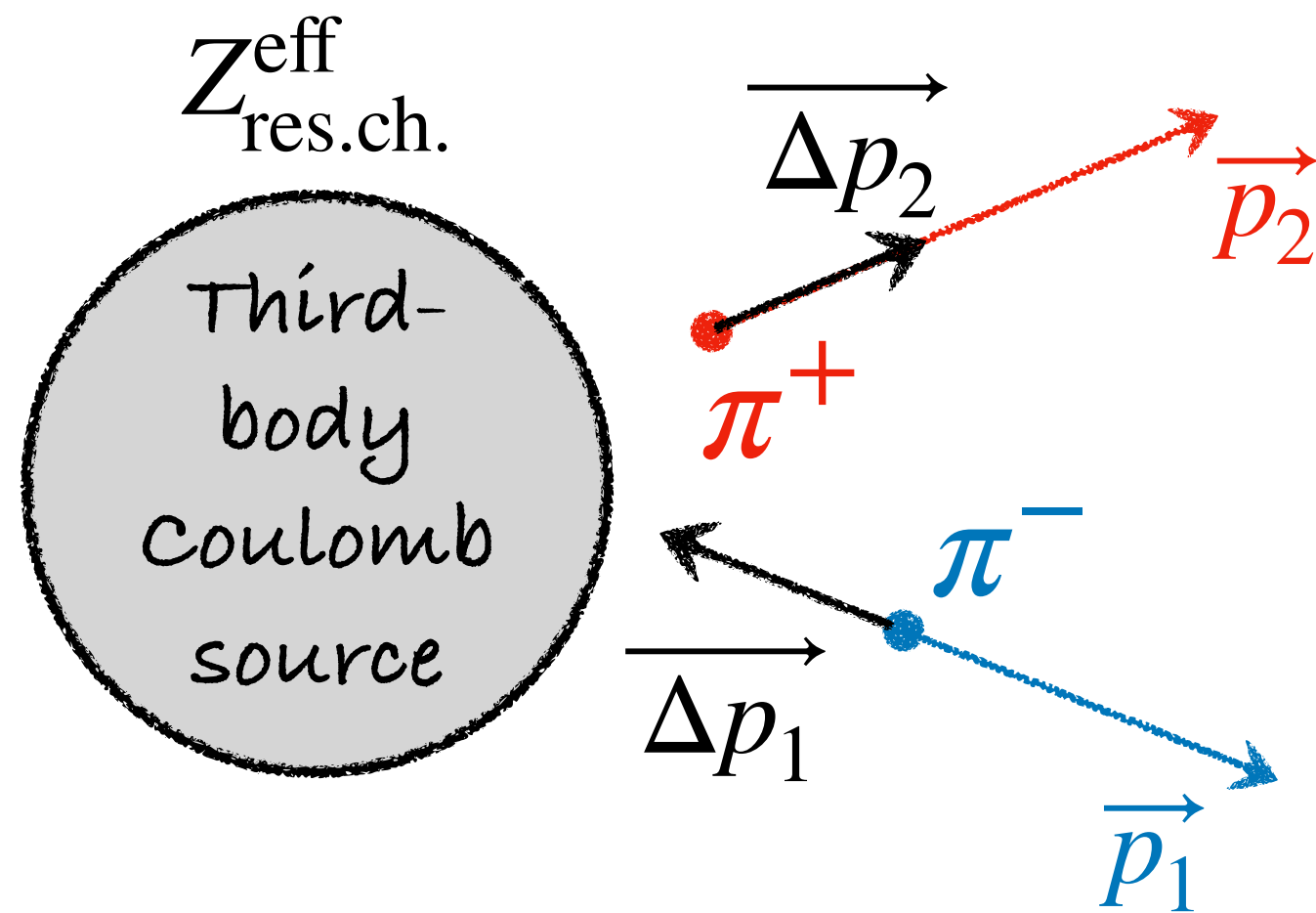
- Push π^- outward: $p'_1 = p_1 + \Delta p_1$
- Pull π^+ inward: $p'_2 = p_2 - \Delta p_2$
- $\Delta \vec{p} \parallel \vec{p}$

- **Step 2:** Estimate the momentum shift Δp needed for correction:
 - ▶ Add third-body Coulomb into UrQMD using a quantum relativistic approach* with the determined $Z^{\text{eff}}_{\text{res.ch.}}$ values
 - ▶ Find Δp such that the R_{side} without third-body are restored

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

Third-body Coulomb correction

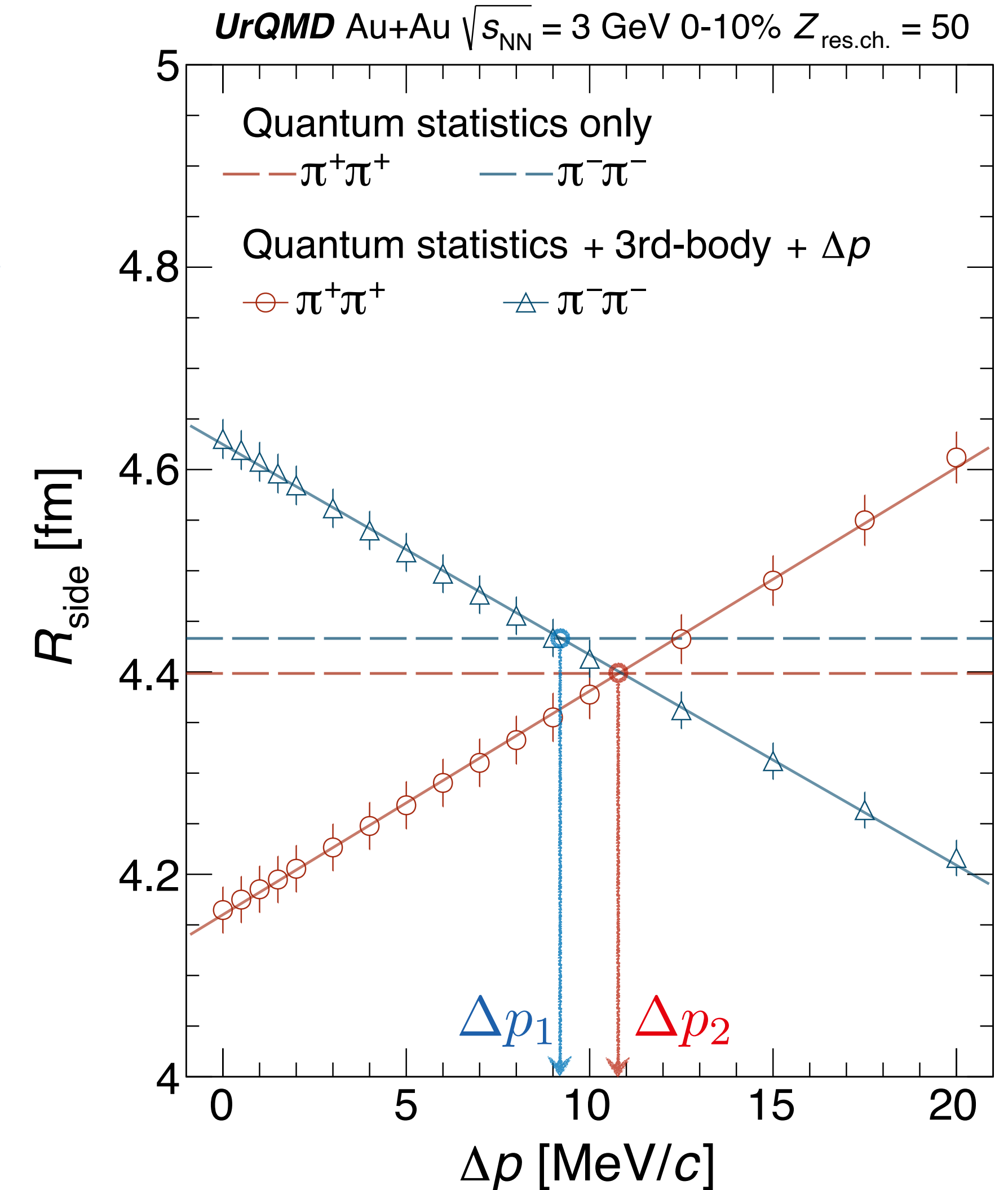
Estimation of momentum shift Δp



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

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

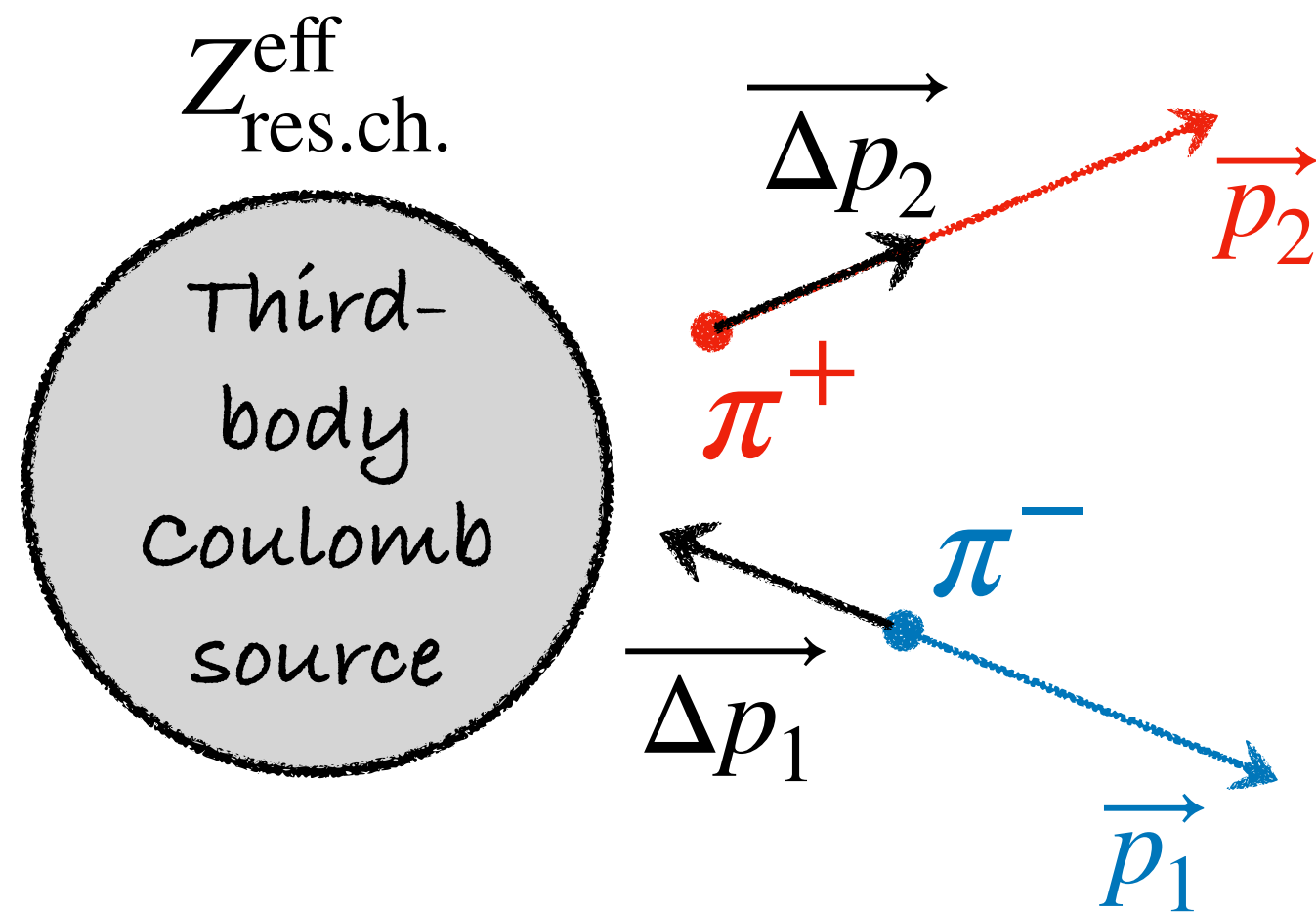
- **Step 2:** Estimate the momentum shift Δp needed for correction:
 - ▶ Add third-body Coulomb into UrQMD using a quantum relativistic approach* with the determined $Z^{\text{eff}}_{\text{res.ch.}}$ values
 - ▶ Find Δp such that the R_{side} without third-body are restored



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

Third-body Coulomb correction

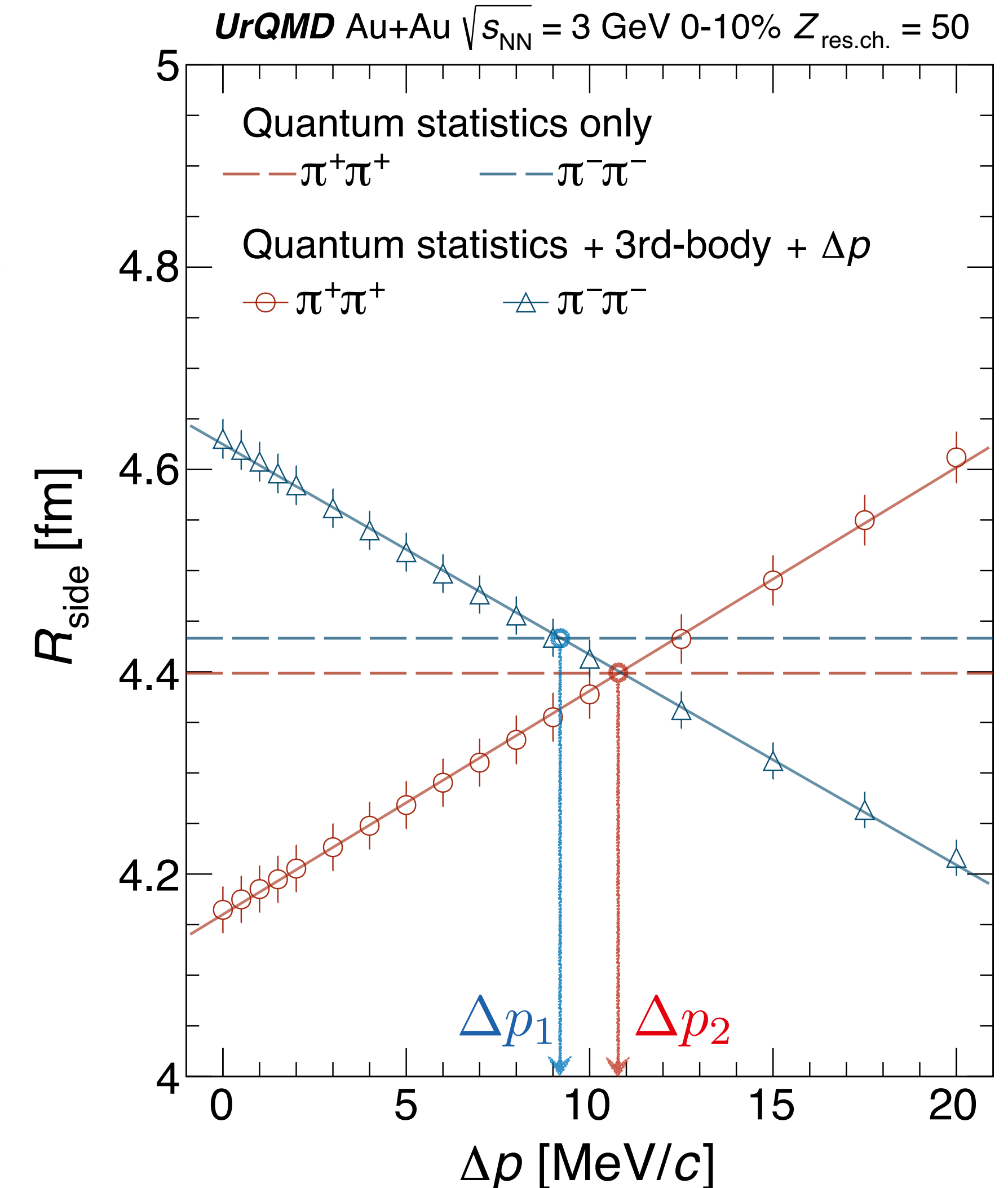
Estimation of momentum shift Δp



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

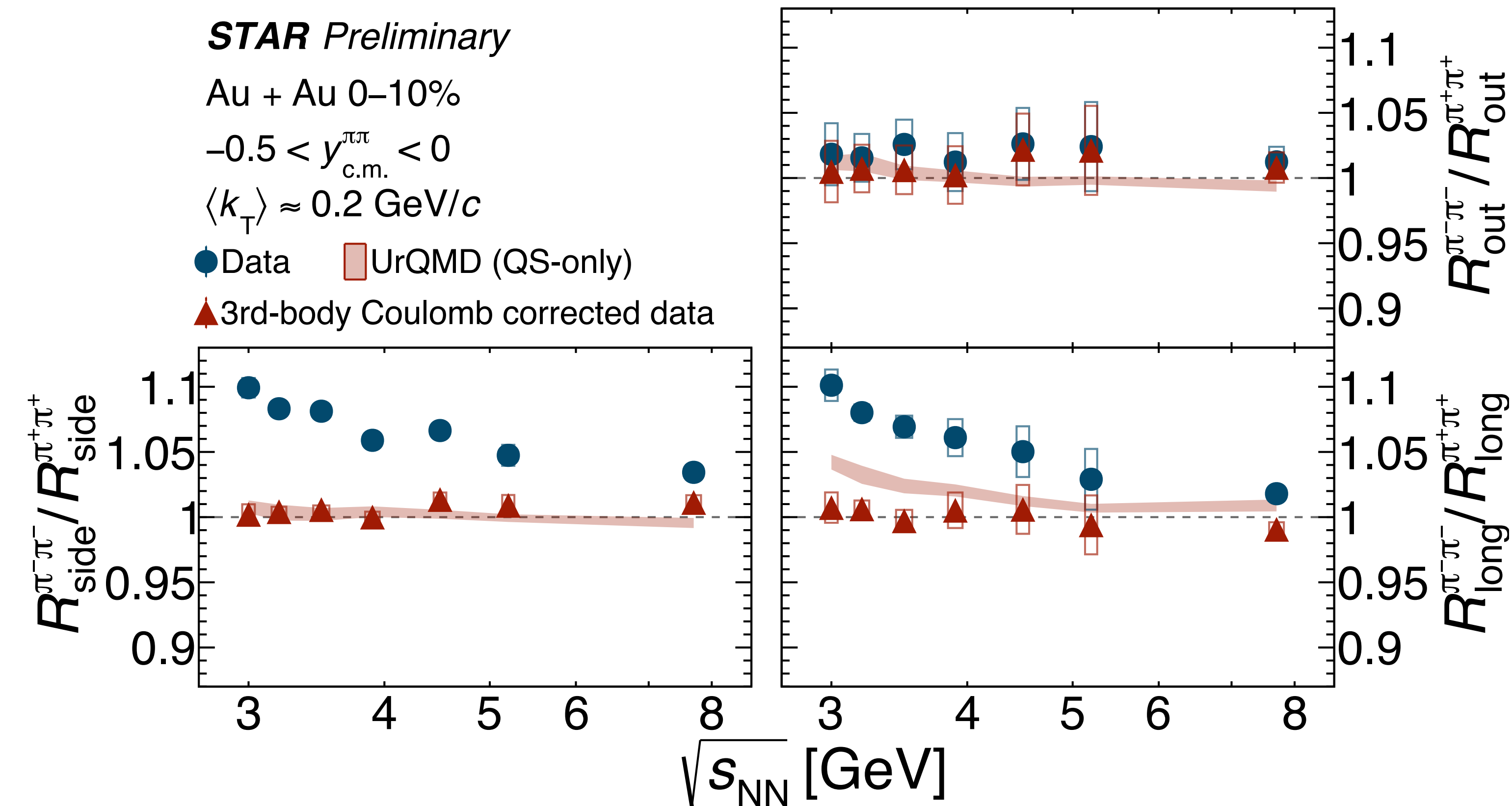
- Push π^- outward: $p'_1 = p_1 + \Delta p_1$
- Pull π^+ inward: $p'_2 = p_2 - \Delta p_2$
- $\Delta \vec{p} \parallel \vec{p}$

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



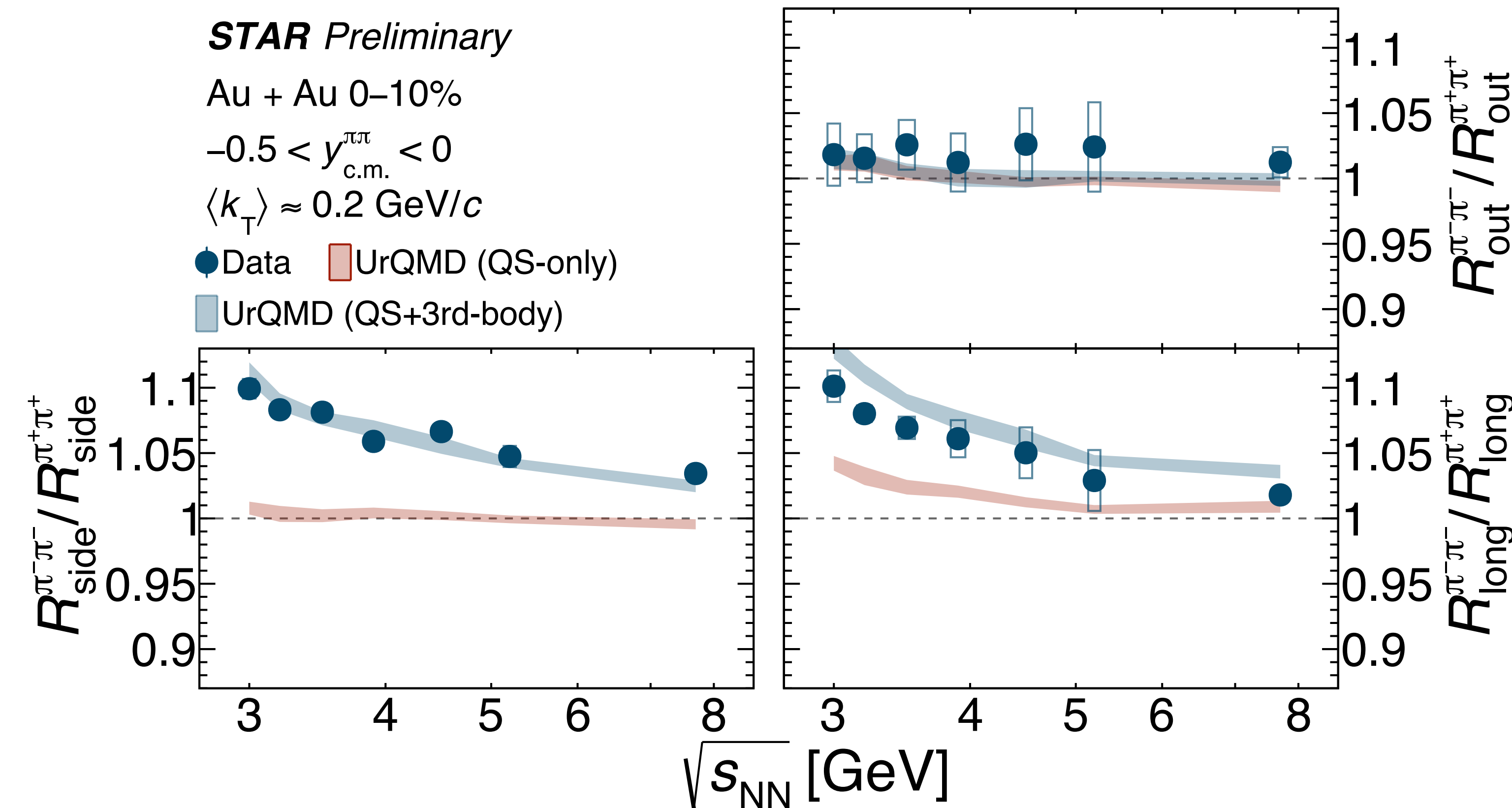
*R. Lednický, Phys. Part. Nucl. **40**, 307 (2009)

Third-body Coulomb corrected radii



- **Data corrected for the third-body Coulomb:**
 - ▶ small difference between $\pi^+ \pi^+$ and $\pi^- \pi^-$ radii $\rightarrow$ 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 $Z_{\text{res.ch.}}^{\text{eff}}$ used for the data correction

- UrQMD (QS+third-body) vs. data w/o third-body correction:

- reproduces $R_{\text{side}}^{\pi^- \pi^-} / R_{\text{side}}^{\pi^+ \pi^+}$
- slightly overestimates

$$R_{\text{long}}^{\pi^- \pi^-} / R_{\text{long}}^{\pi^+ \pi^+}$$

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

Summary

- ◉ We reported identical charged pion femtoscopy measurements in Au+Au collisions from STAR at $\sqrt{s_{\text{NN}}} = 3.0\text{--}7.7$ GeV
- ◉ Difference between $R(\pi^+\pi^+)$ and $R(\pi^-\pi^-)$ radii:
 - ▶ decreases as $\sqrt{s_{\text{NN}}}$ 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
 - $Z_{\text{res.ch.}}^{\text{eff}} \propto \tau_{\text{overlap}}$
 - Model dependence of $Z_{\text{res.ch.}}^{\text{eff}}$ estimation at $\sqrt{s_{\text{NN}}} = 3.0$ GeV

