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Overview of femtoscopic correlation measurements in the STAR experiment at RHIC

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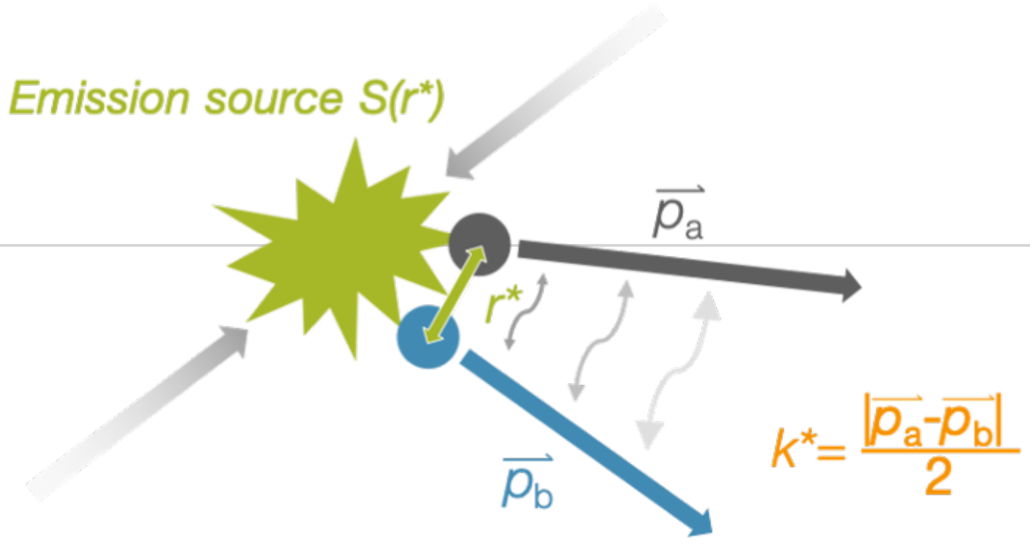
Outline

- Introduction
  - Femtoscopy technique
  - STAR experiment
- Extracting source geometry and dynamics
  - $\pi^{\pm}\pi^{\pm}$, $K^{\pm}K^{\pm}$ correlations
- Extracting final state interactions
  - $\bar{p}\bar{p}$, pd, dd, $d\Lambda$, $p\Xi^{-}$, $p\Omega^{-}$ correlations

Disclaimer: Not all STAR femtoscopy results could be covered in this talk

Femtoscopy



Correlation functions:

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

Model — Measurement

r^*: relative distance, k^*: relative momentum

$S(r^*)$: source function

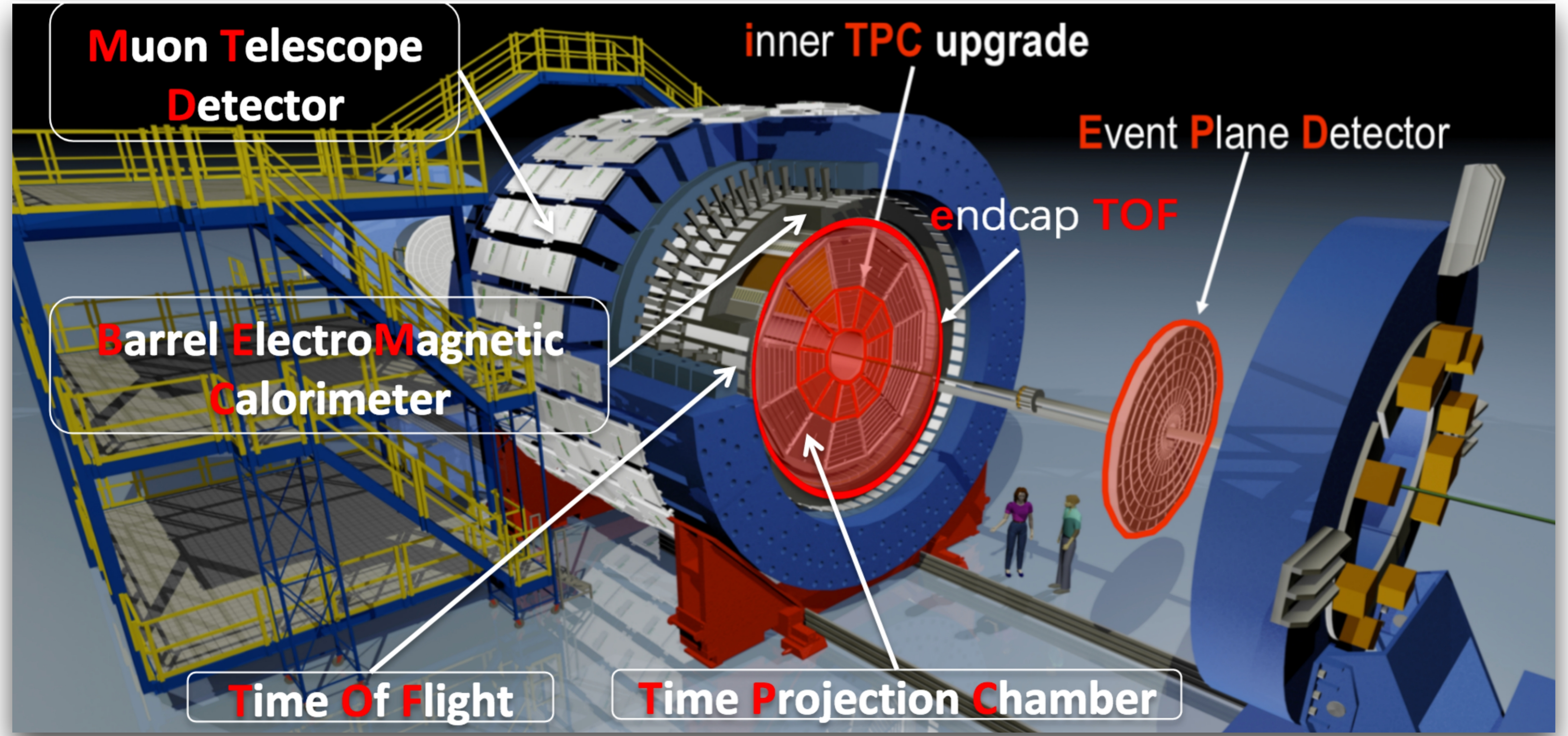
$\Psi(k^*, r^*)$: two-particle wave function

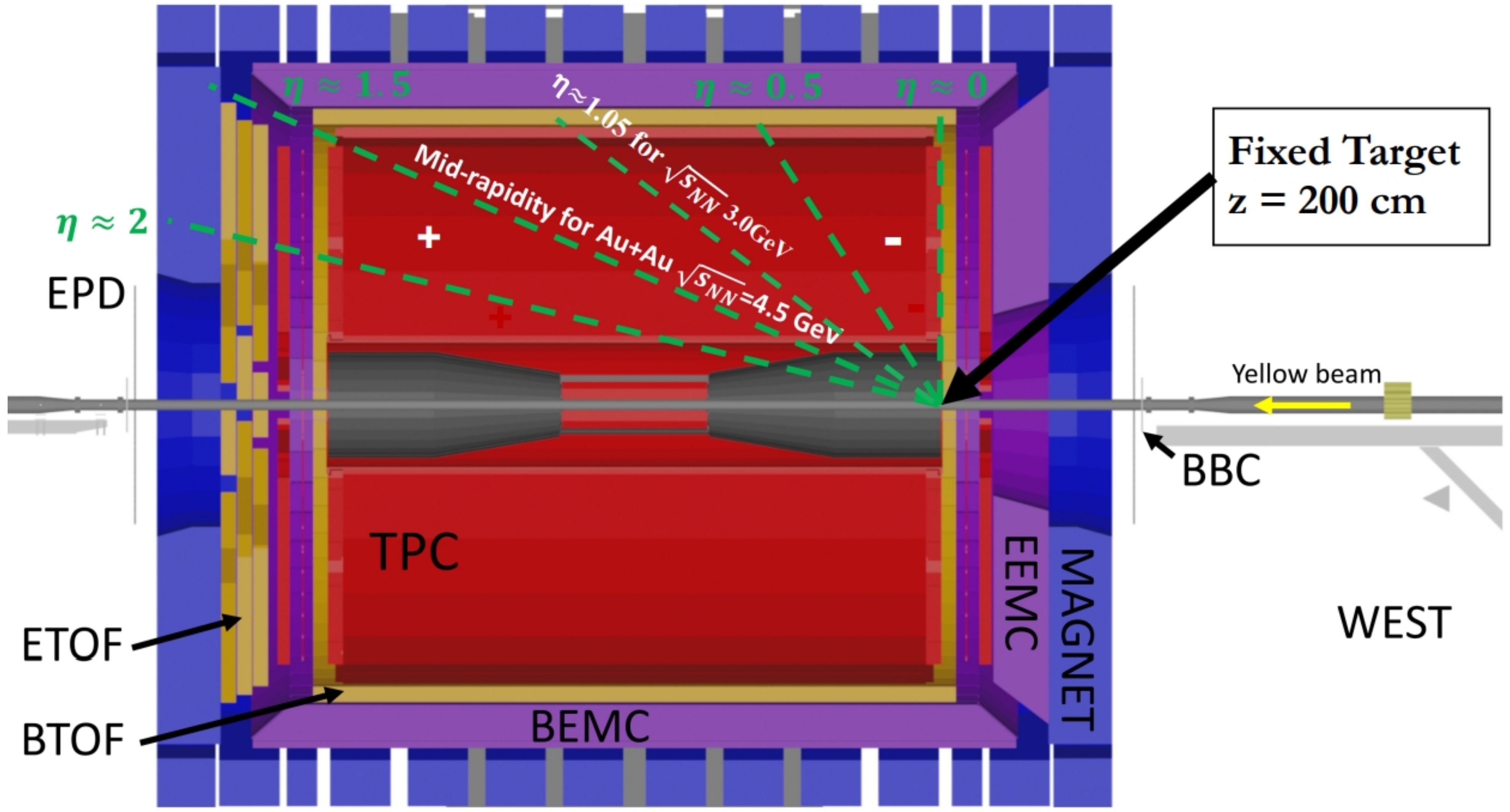
$A(k^*)$: distribution of pairs from same event, containing quantum statistical (QS) correlations, final state interactions (FSI) (Coulomb, strong)

$B(k^*)$: distribution of pairs from mixed events, served as background

- *Femtoscopy* is a powerful technique to study characteristics of systems of femtometer scale at kinetic freeze-out
- Extracting emitting source:
  - If $\Psi(k^*, r^*)$ is assumed, then geometric and dynamic properties of the source can be measured
- Extracting final state interactions (FSI):
  - Lednický–Lyuboshitz analytical model is widely used to extract strong FSI parameters

STAR detector



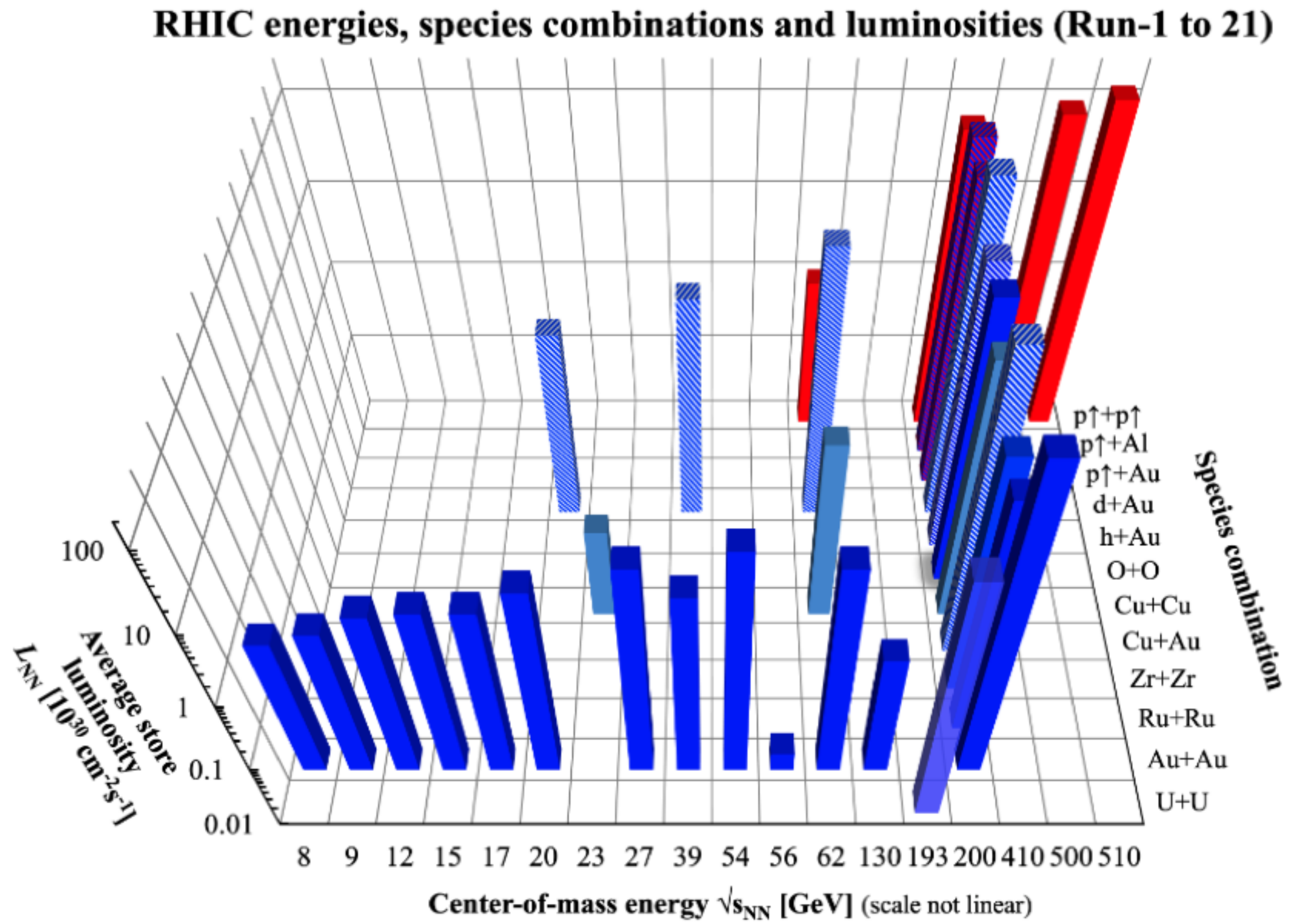


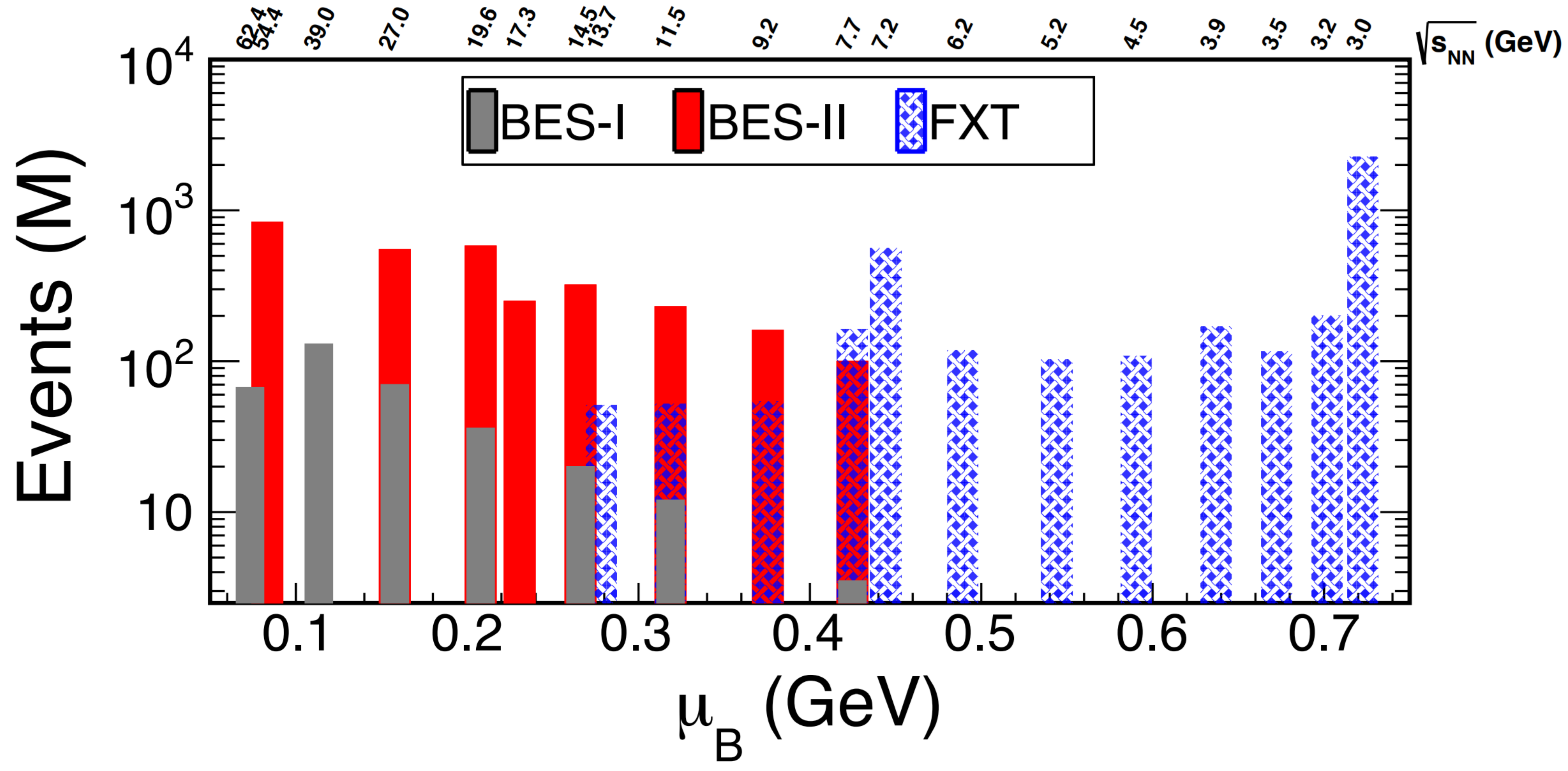
- Beam energy scan II (BES-II) upgrades
  - iTPC (2019+): extended η acceptance and improved tracking, dE/dx resolution
  - eTOF (2019+): extended PID coverage
  - EPD (2018+): EP determination away from mid-rapidity, improved EP resolution compared to BBC

- Fixed-target (FXT) setup extends energy down to $\sqrt{s_{NN}}$ = 3.0 GeV

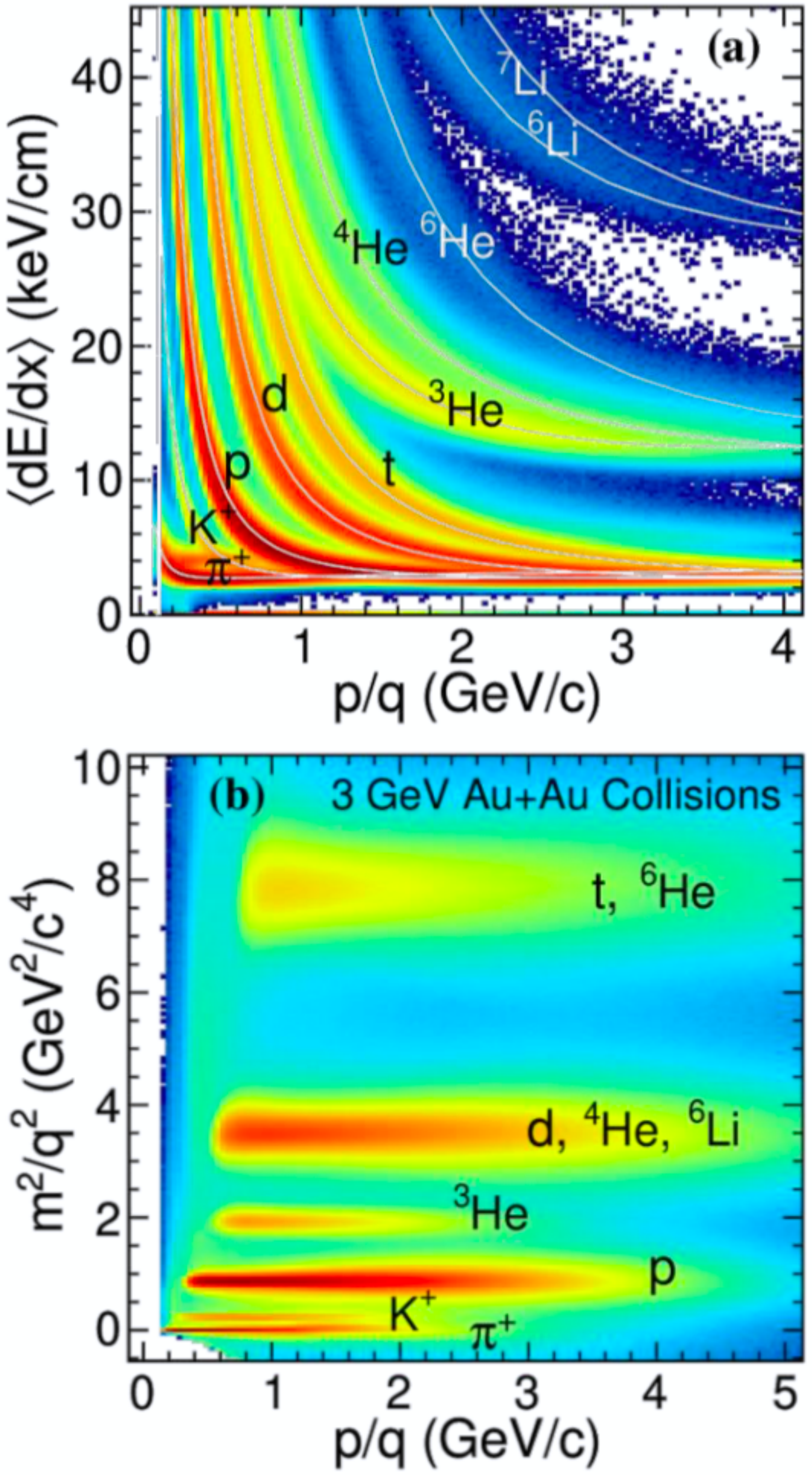
Collision systems and energies at STAR

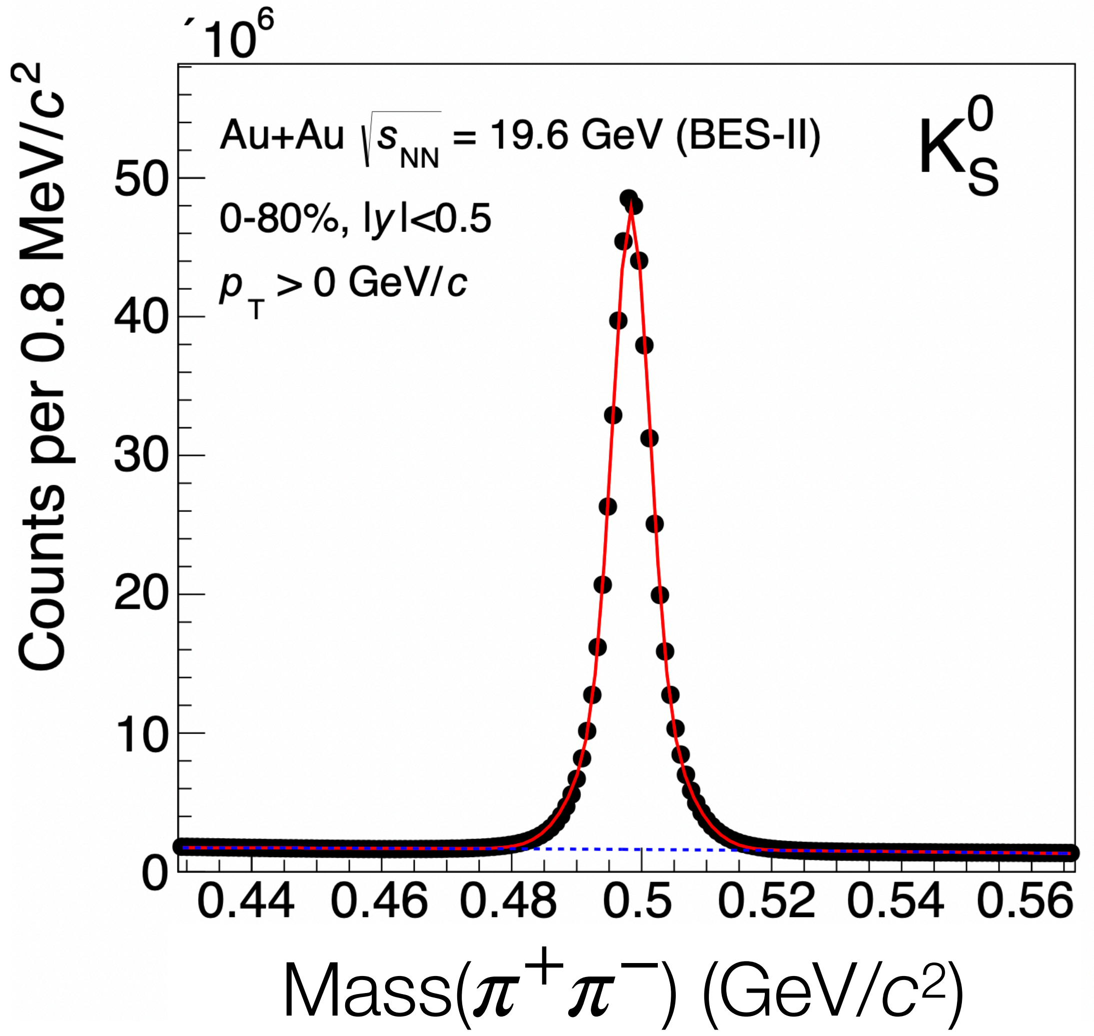
- BES-II and FXT program: Au+Au collisions at $\sqrt{s_{NN}}$ = 3.0 — 54.4 GeV
- Top RHIC energy $\sqrt{s_{NN}}$ = 200 GeV: Au+Au, Zr+Zr, Ru+Ru, p+Au, d+Au, ^{3}He+Au, O+O, U+U, etc.

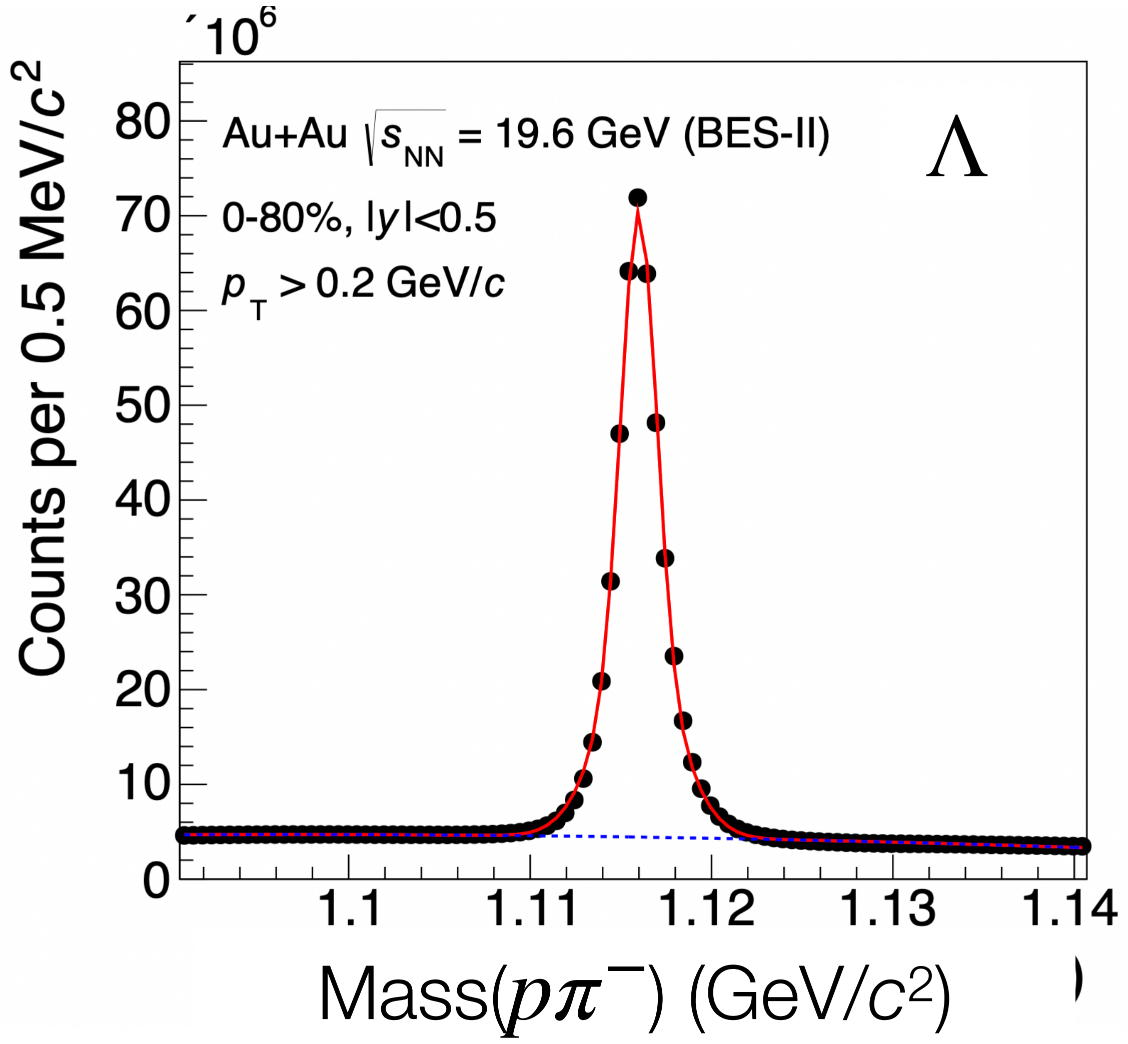


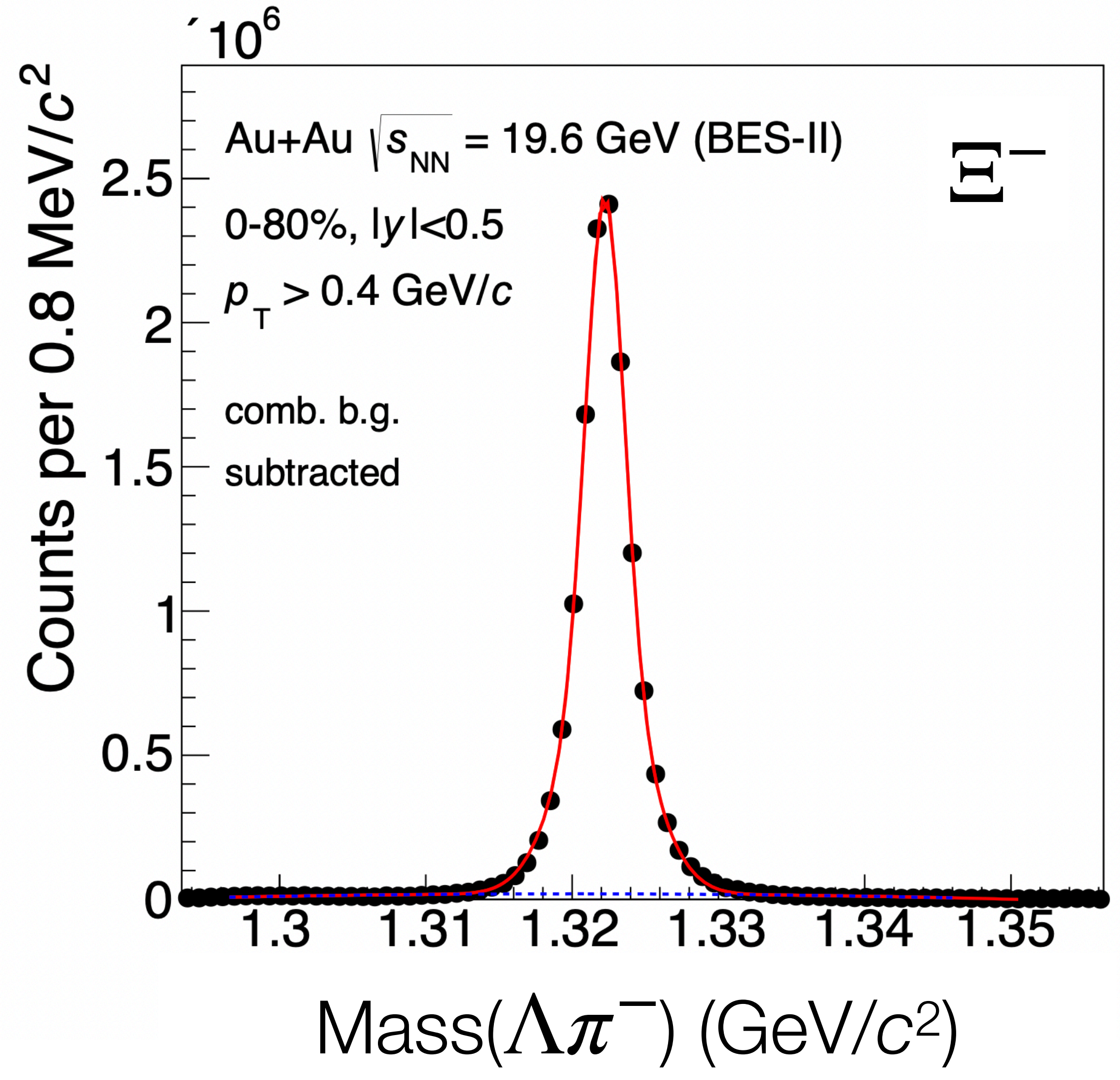


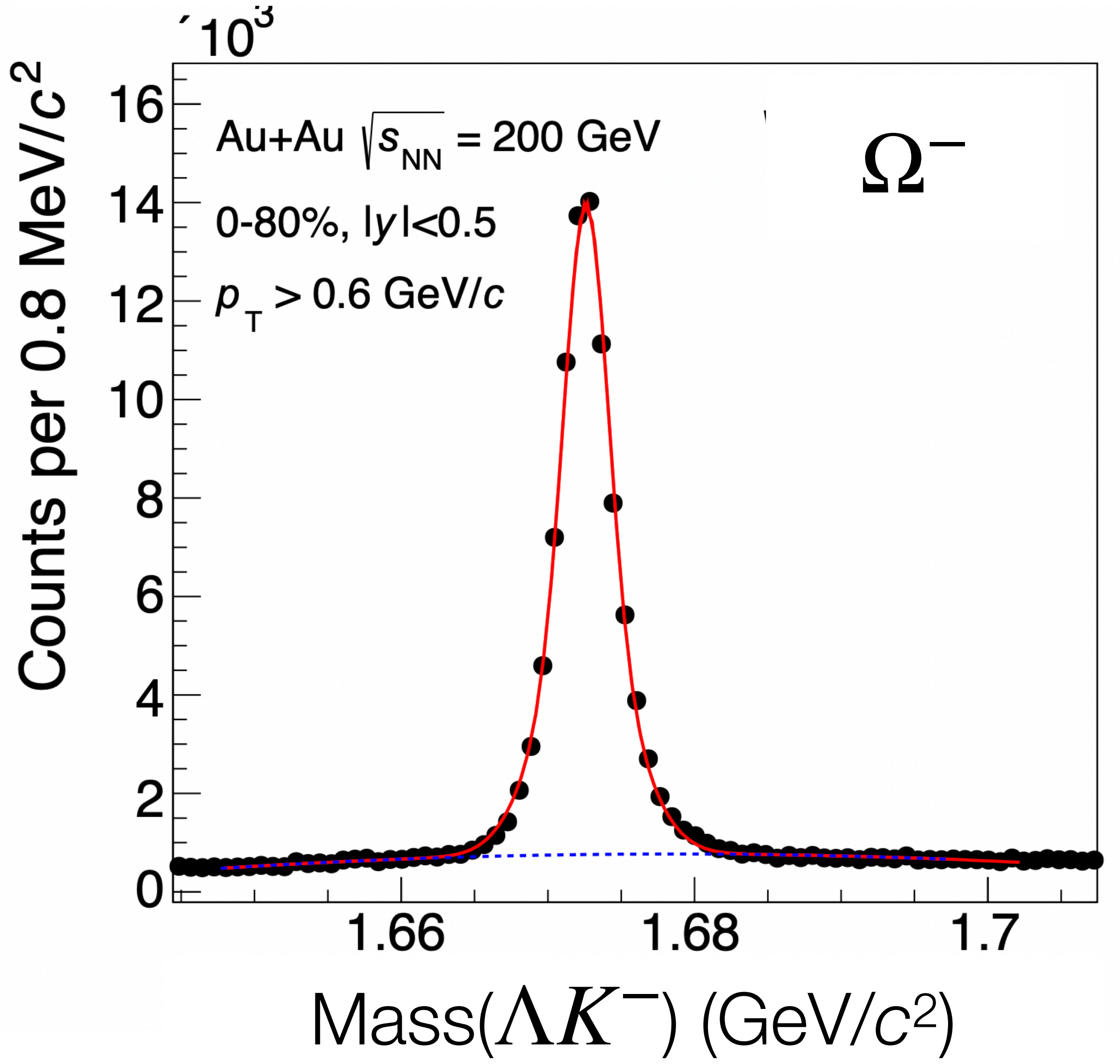
Particle identification & reconstruction





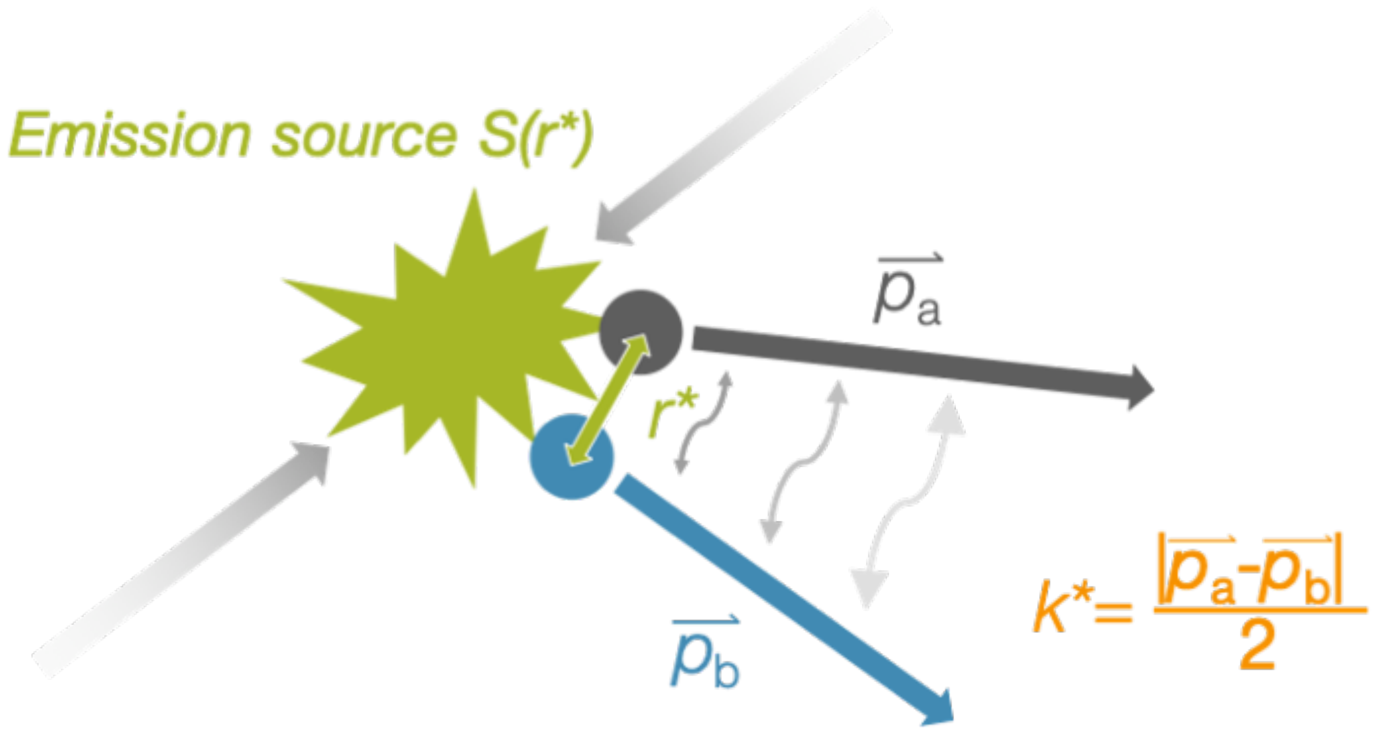






- Particle identification by TPC dE/dx and TOF m^2
- Reconstruction of short-lived particles via their decay channels
- Good particle identification and reconstruction capability

Extraction of geometric and dynamic properties of the source



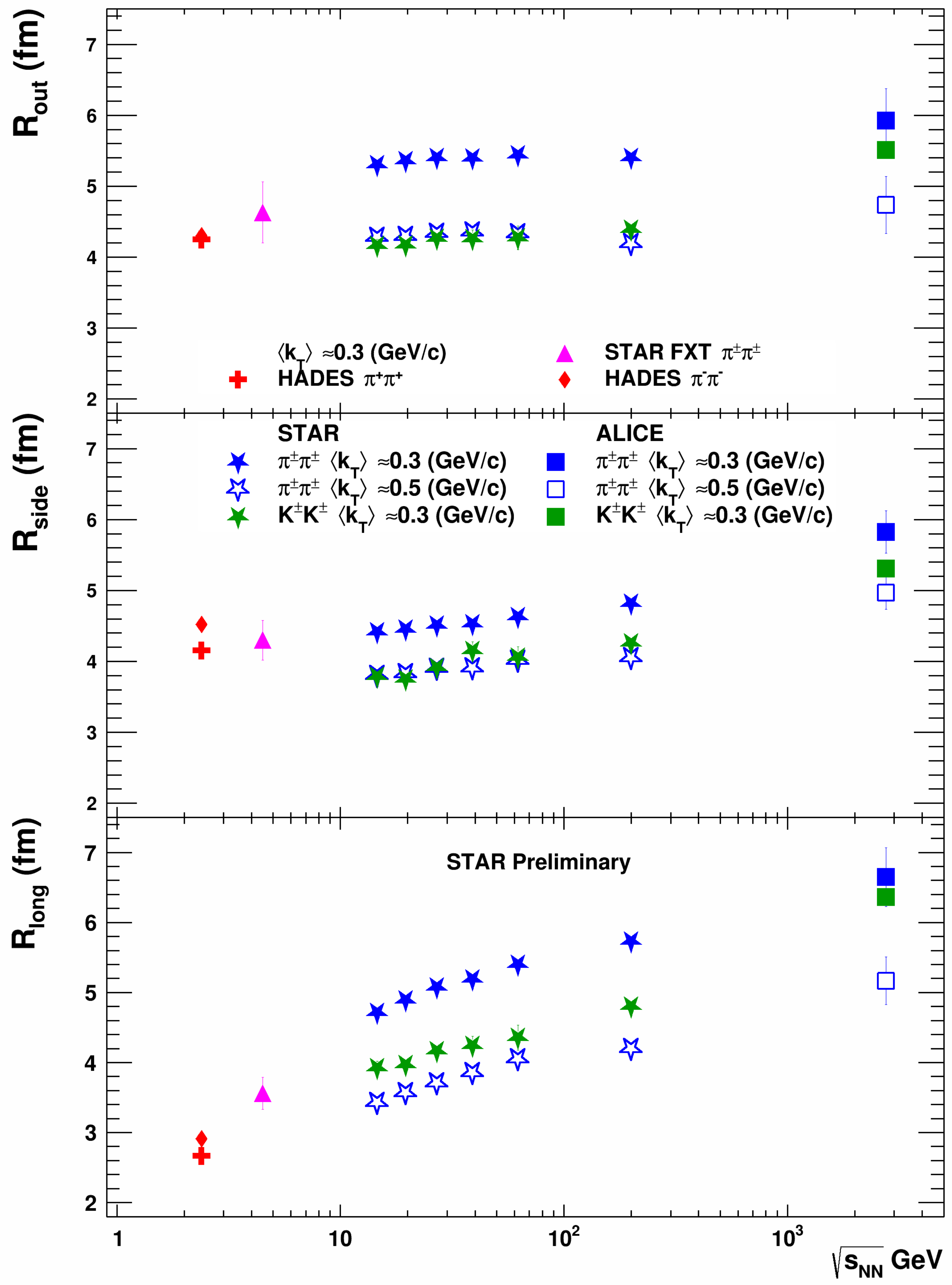
Object of study

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

Model

Measurement

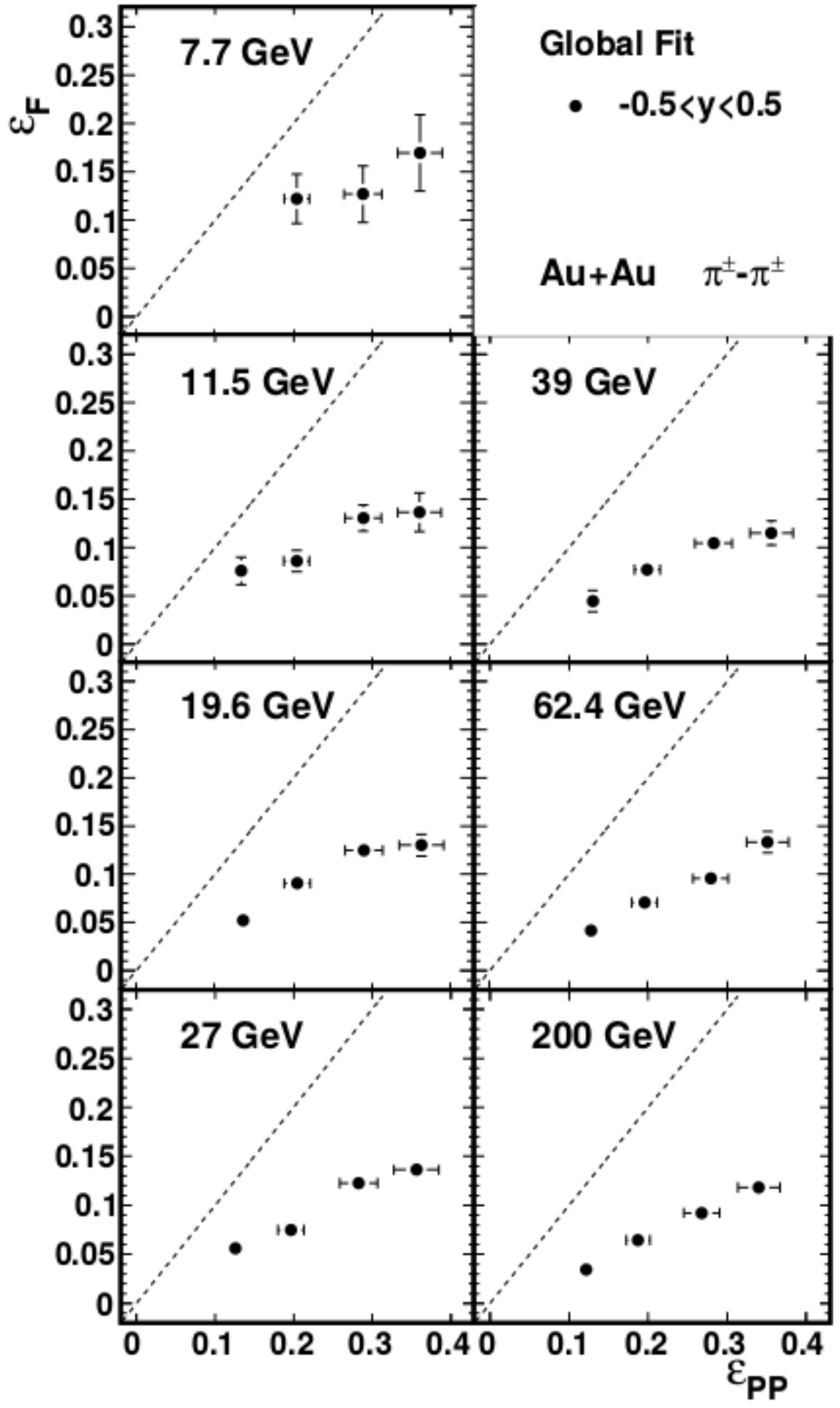
$\pi^{\pm}\pi^{\pm}$, $K^{\pm}K^{\pm}$ correlations

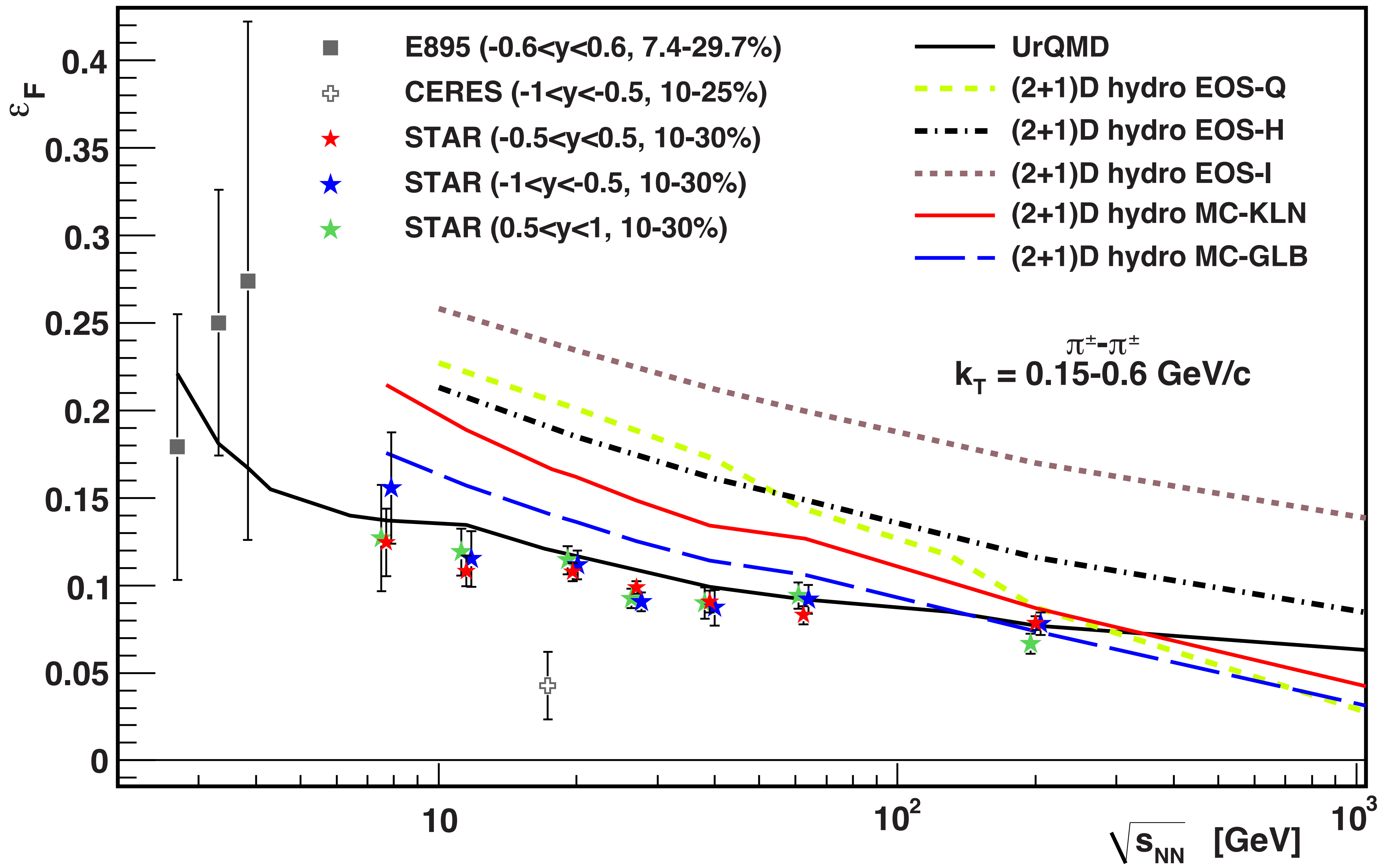


- $C(\vec{q}) = (1-\lambda) + \lambda K_{\mathrm{Coul}}(q_{\mathrm{inv}})\left(1 + e^{-q_o^2R_o^2 - q_s^2R_s^2 - q_l^2R_l^2}\right)$, where
  - $\lambda \propto$ fraction of correlated pairs
  - $R_{\mathrm{out}} \propto$ geometrical size, emission duration, and transverse flow
  - $R_{\mathrm{side}} \propto$ geometrical size
  - $R_{\mathrm{long}} \propto$ longitudinal flow, evolution time
- Femtoscopic parameters are extracted over a wide range of collision energies
- Extracted radii increase with increasing collision energy
- Extracted radii decrease with increasing transverse mass

$\pi^{\pm}\pi^{\pm}$ correlations

Kinetic freeze-out eccentricity ε_F





- Azimuthal-sensitive femtoscopy analysis:

$$R_\mu^2(\Phi) = R_{\mu,0}^2 + 2 \sum_{n=2,4,6,\ldots} R_{\mu,n}^2 \cos(n\Phi),\ \mu = \mathrm{o, s, l, ol}$$

$$R_\mu^2(\Phi) = R_{\mu,0}^2 + 2 \sum_{n=2,4,6,\ldots} R_{\mu,n}^2 \sin(n\Phi),\ \mu = \mathrm{os}$$

- Kinetic freeze-out eccentricity:

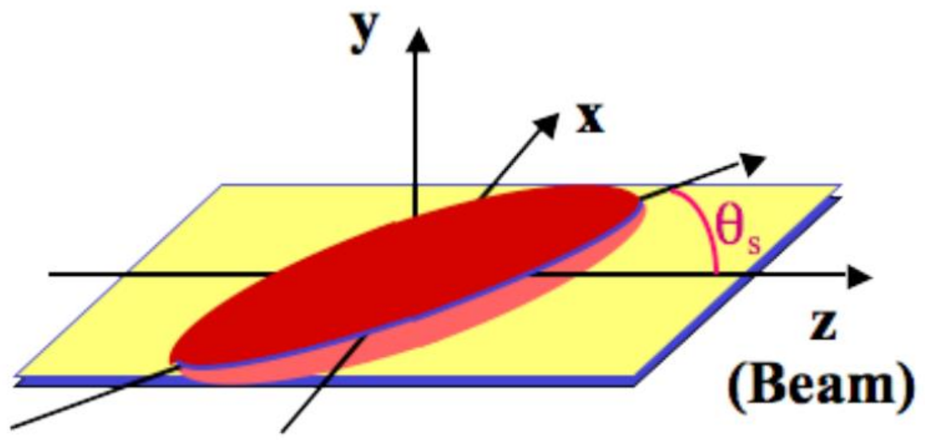
$$\varepsilon_F = \frac{\sigma_y'^2 - \sigma_x'^2}{\sigma_y'^2 + \sigma_x'^2} \approx 2\frac{R_{s,2}^2}{R_{s,0}^2}$$

- ε_F decreases with beam energy
  - Consistent with expectation at higher energies: increased flow and/or increased lifetime
- The freeze-out shape remains an out-of-plane extended ellipse ($\varepsilon_F > 0$)

STAR, Phys. Rev. C **92** (2015) 014904

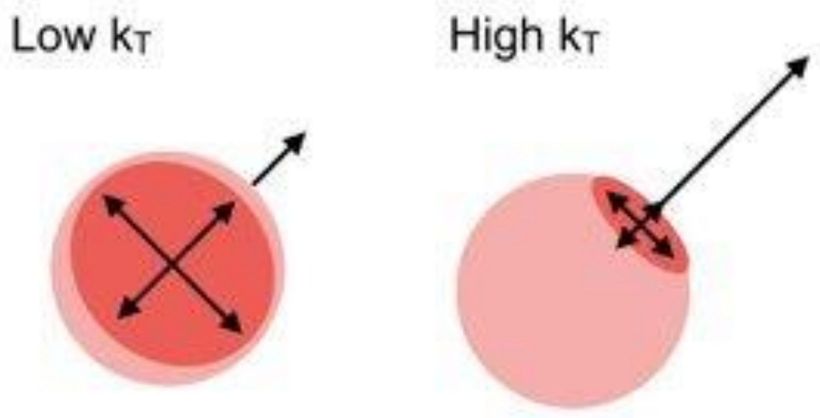
$\pi^{\pm}\pi^{\pm}$ correlations

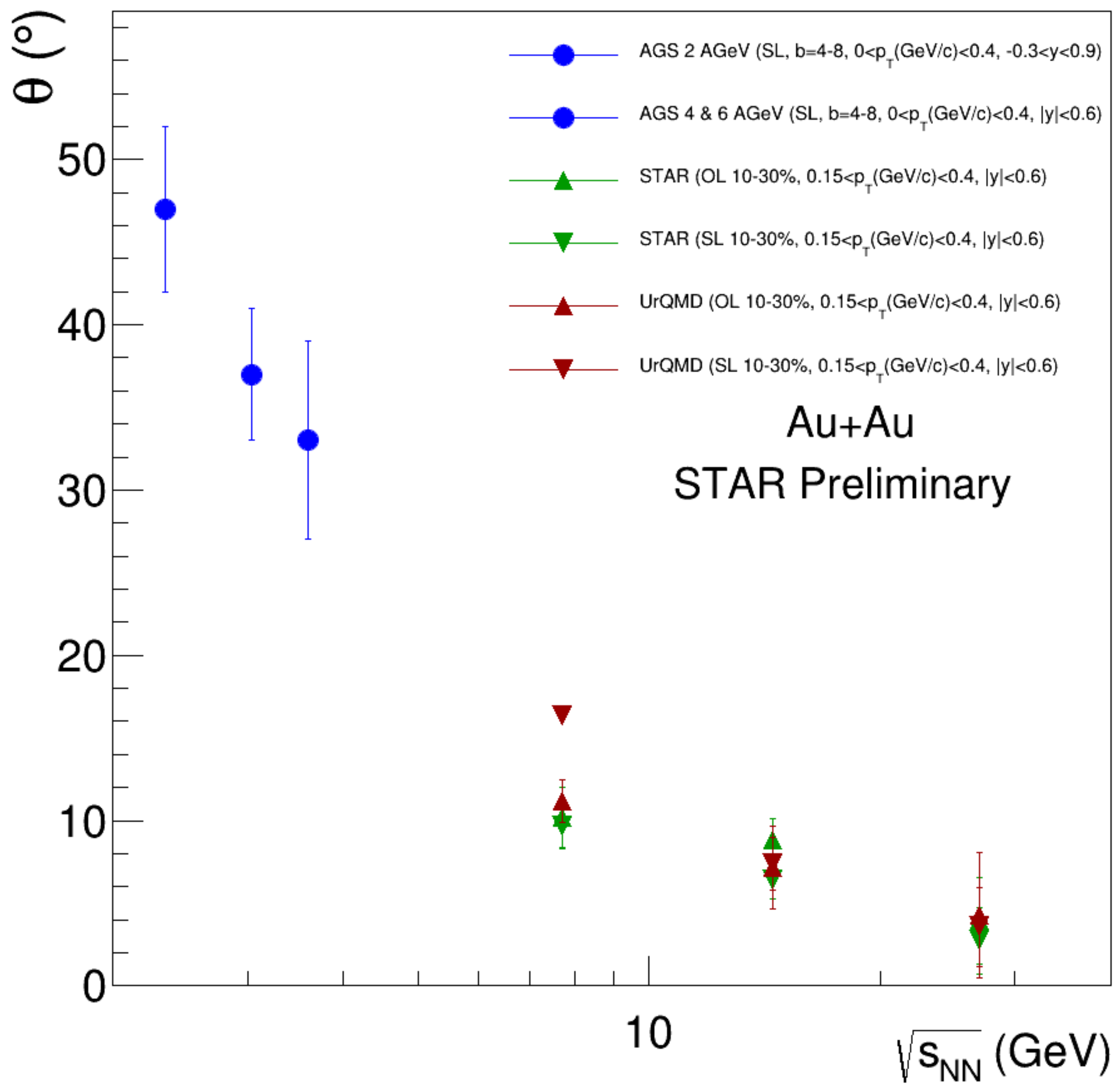
Source tilt angle at freeze-out

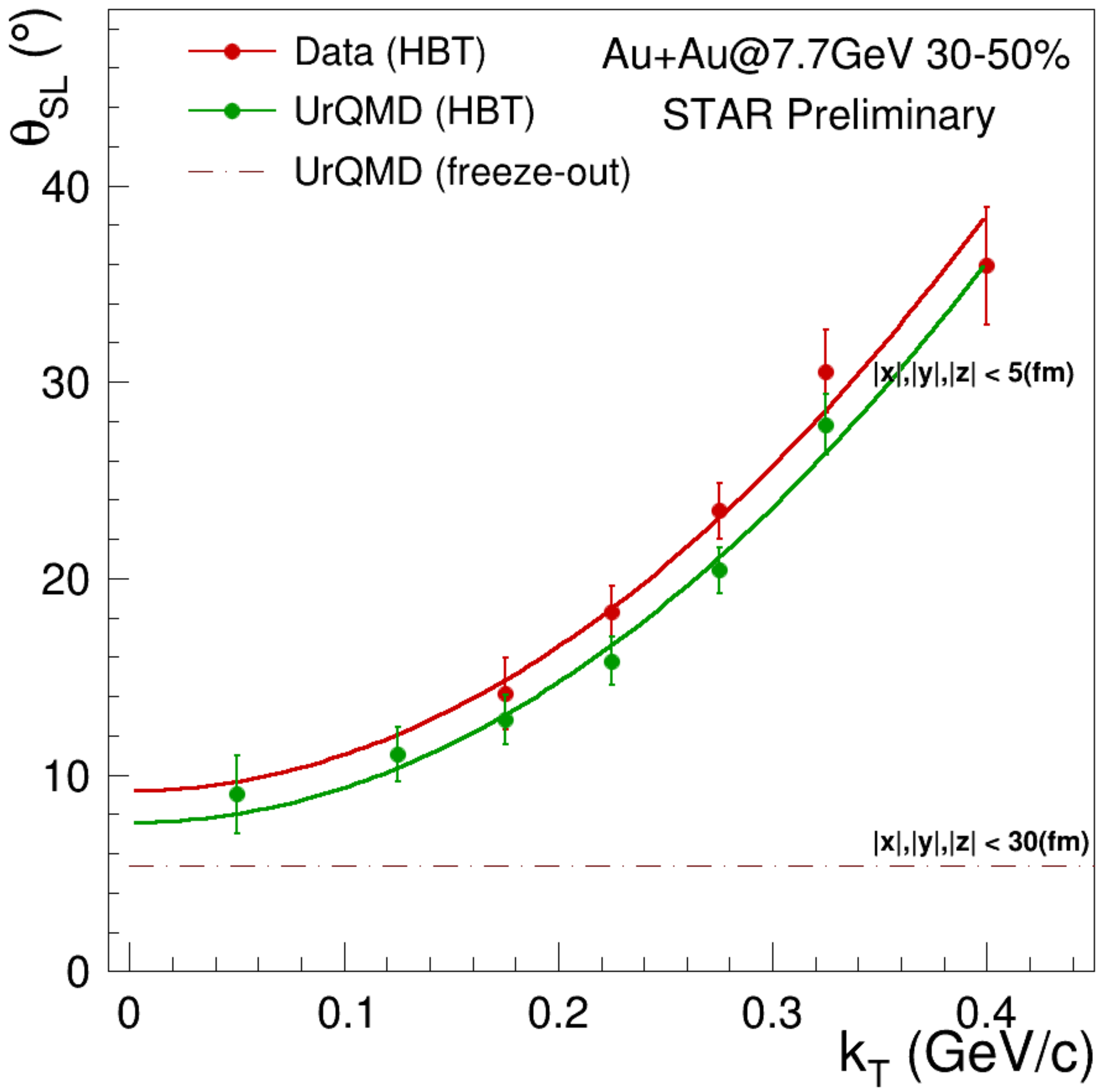


$$\theta_{\mathrm{sl}} = \frac{1}{2}\tan^{-1}\left(\frac{-R^2_{sl,1}}{R^2_{l,0} - R^2_{s,0} + 2R^2_{s,2}}\right)$$

$$\theta_{\mathrm{ol}} = \frac{1}{2}\tan^{-1}\left(\frac{-R^2_{ol,1}}{R^2_{l,0} - R^2_{s,0} + 2R^2_{s,2}}\right)$$



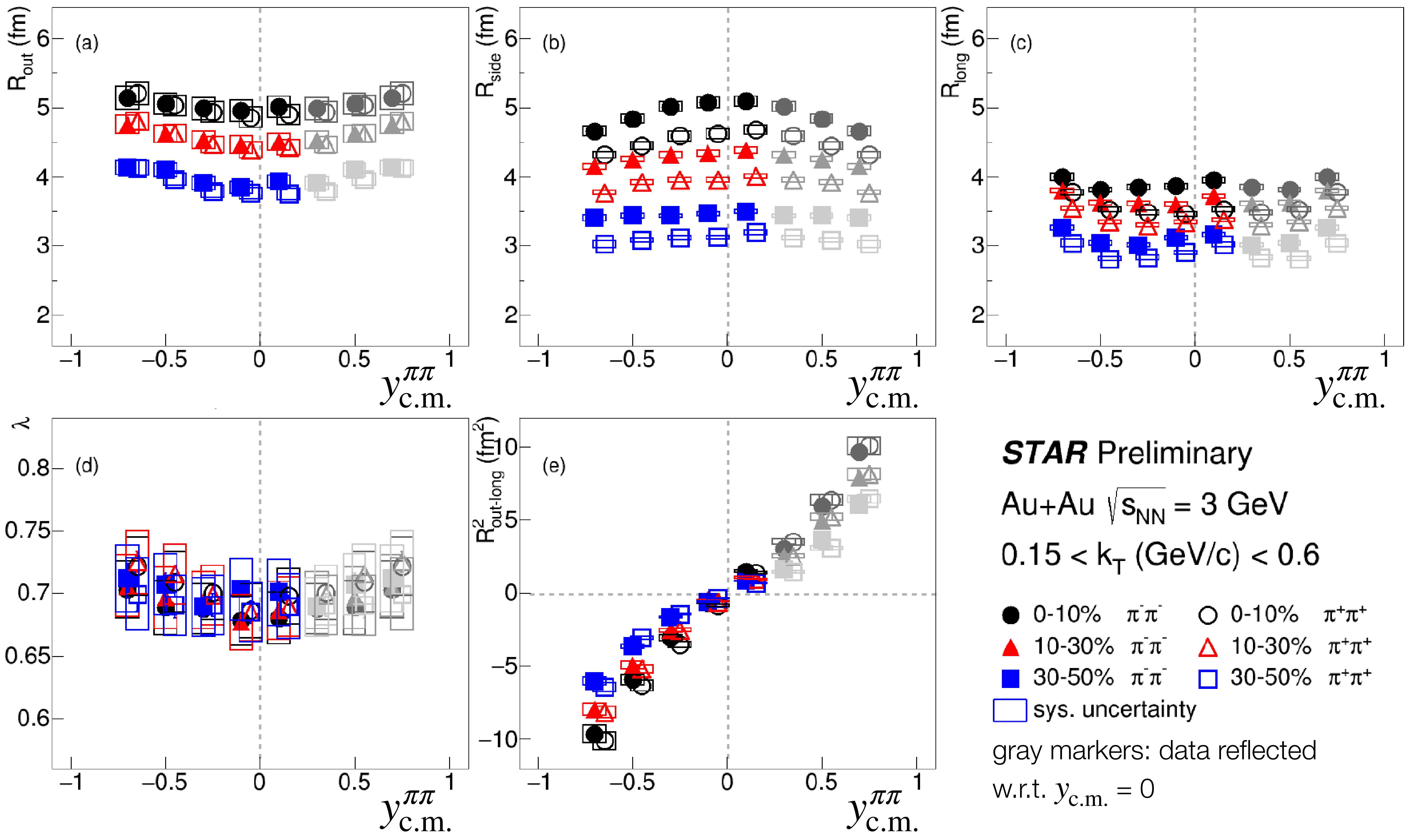




- The source tilt is sensitive to the dynamical response of the strongly-interacting matter under extreme conditions
- UrQMD model quantitatively describes the results
- $\sqrt{s_{\mathrm{NN}}}$-dependence
  - In trend with AGS data
- k_{T}-dependence
  - The tilt is extrapolated to $k_{\mathrm{T}} = 0$
  - Good agreement between $\theta_{k_{\mathrm{T}}=0}$ from femtoscopy and the tilt extracted from freeze-out coordinates in UrQMD

$\pi^{\pm}\pi^{\pm}$ correlations

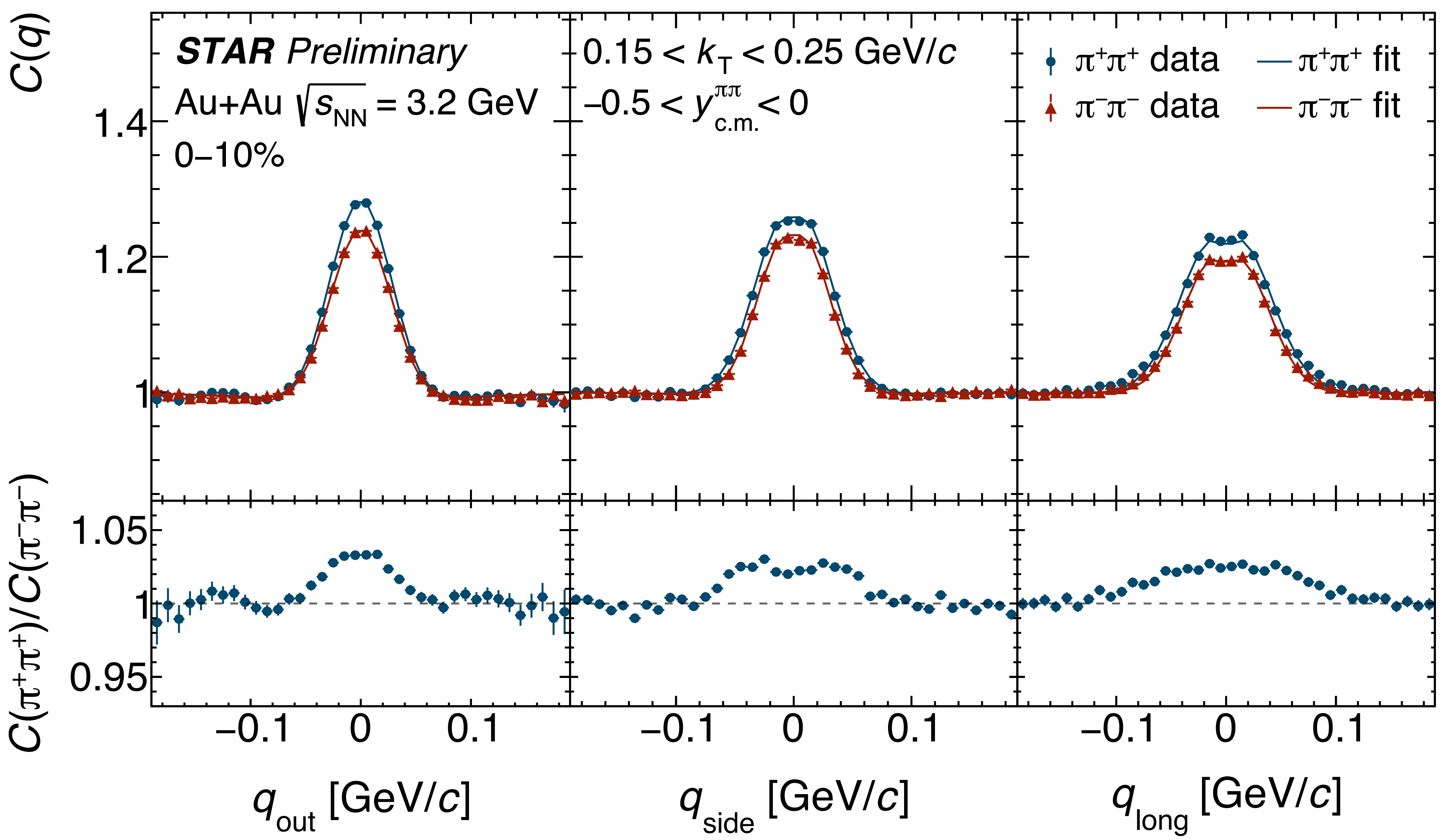
Rapidity dependence

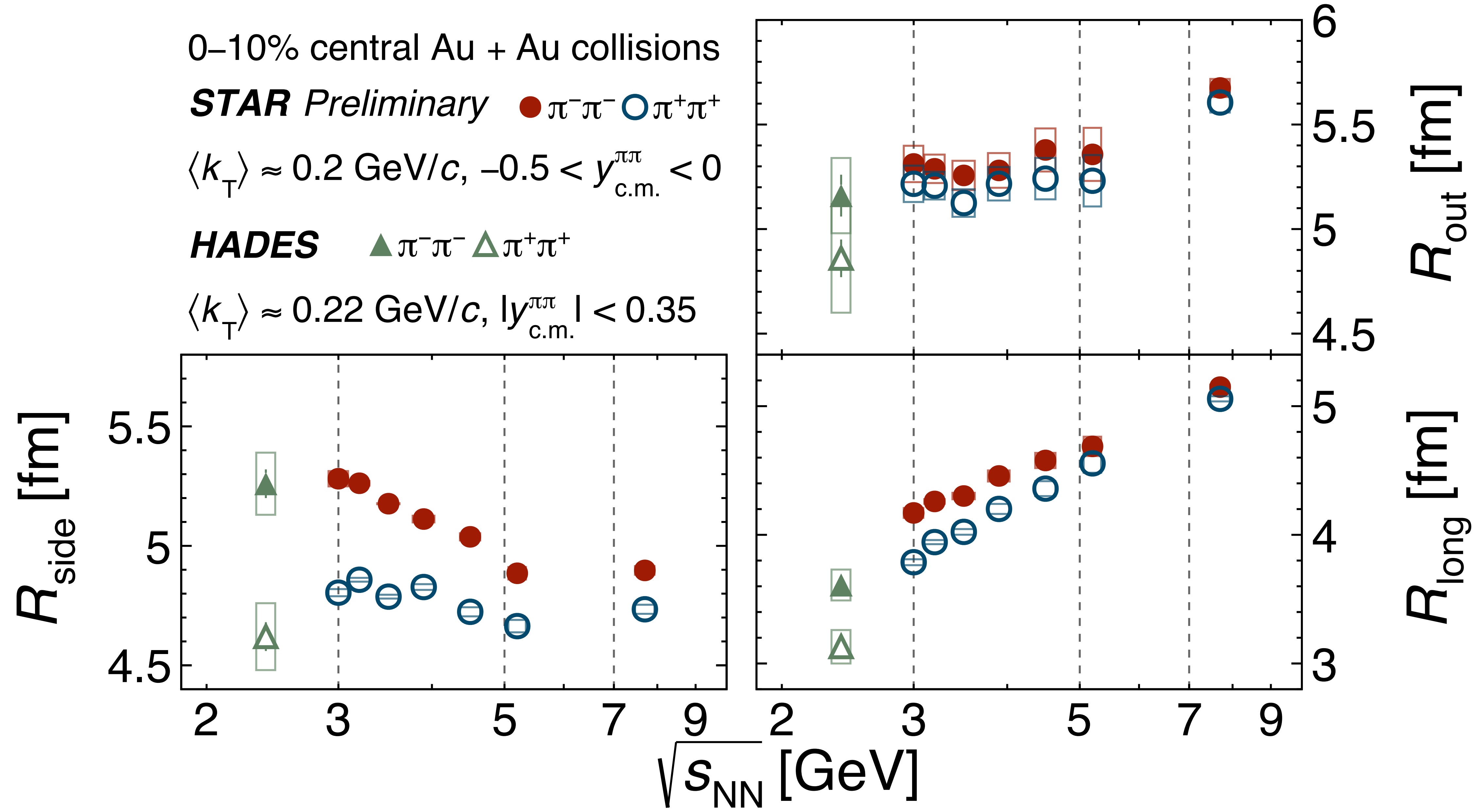


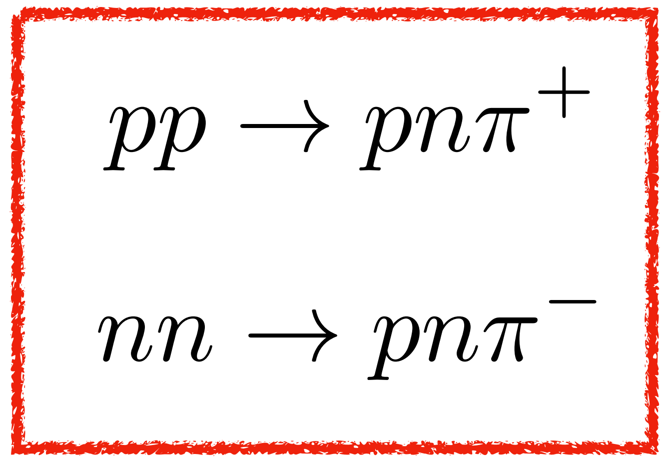
- Clear rapidity dependence of extracted femtoscopic parameters at $\sqrt{s_{NN}}$ = 3.0 GeV
- Decrease of R_{side} from midrapidity to backward rapidity; non-vanishing $R^2_{out-long}$ cross-term
  - Hint of boost-invariance breaking at low $\sqrt{s_{NN}}$

$\pi^{\pm}\pi^{\pm}$ correlations

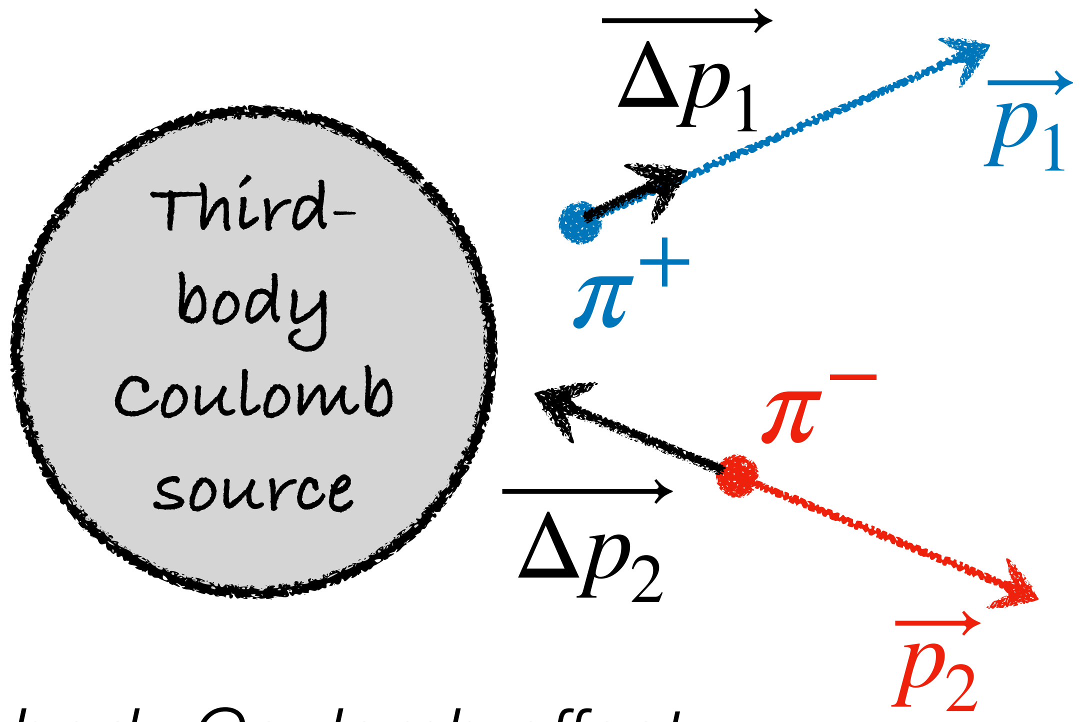
Charge splitting: $\pi^+\pi^+$ vs. $\pi^-\pi^-$







Isospin effect

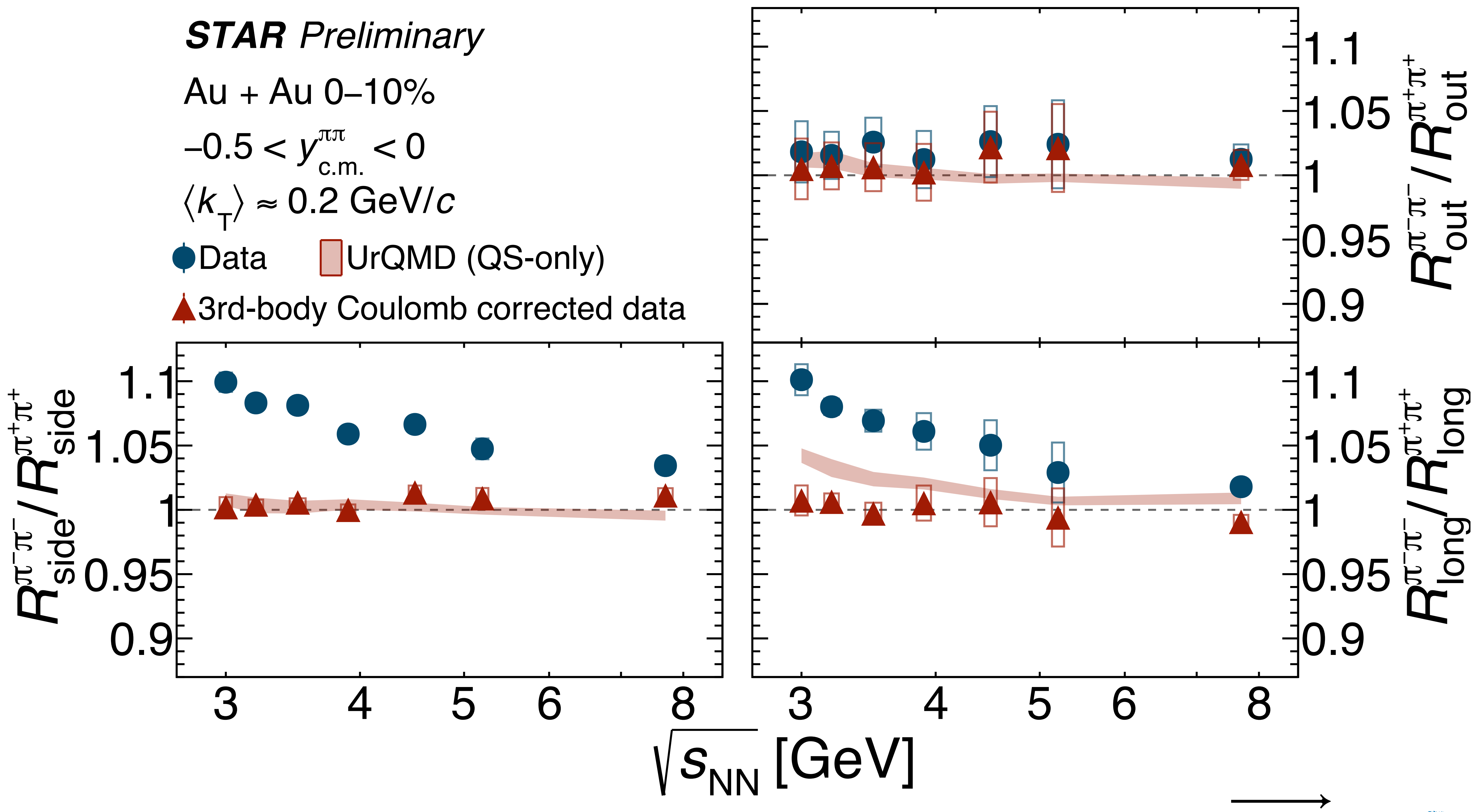


Third-body Coulomb effect

- Difference between $\pi^+\pi^+$ and $\pi^-\pi^-$ decreases with increasing $\sqrt{s_{NN}}$
- Two possible effects:
  - Residual 3rd-body Coulomb
  - Isospin of initial colliding nuclei

$\pi^{\pm}\pi^{\pm}$ correlations

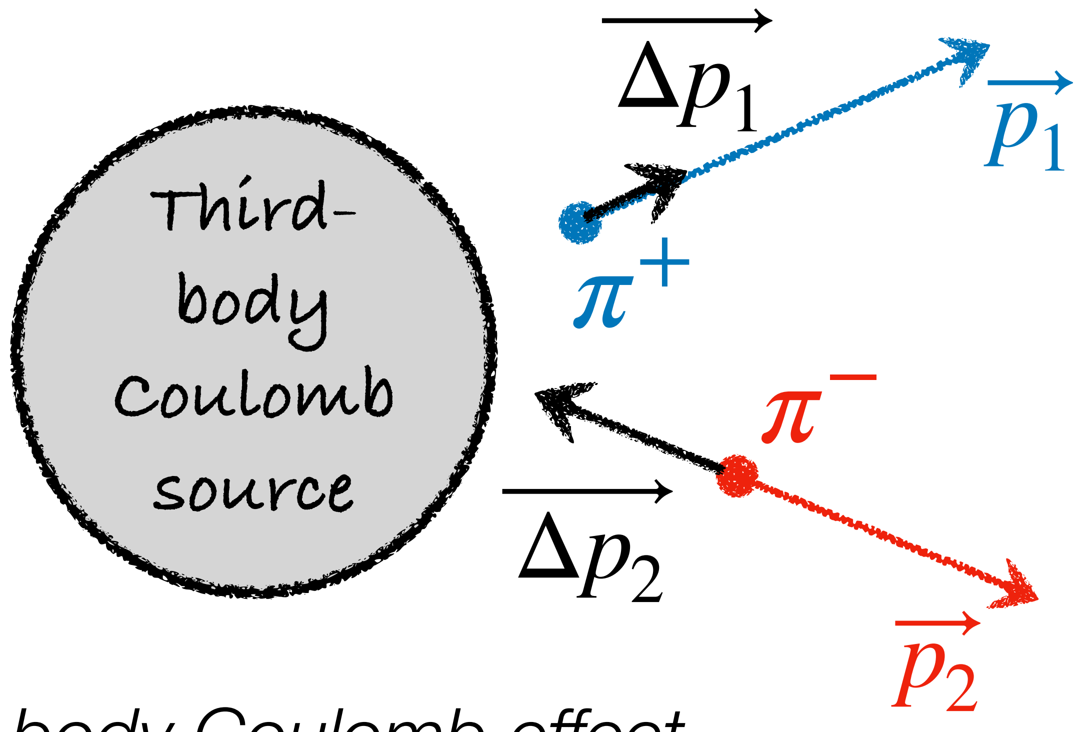
Charge splitting: $\pi^{+}\pi^{+}$ vs. $\pi^{-}\pi^{-}$



$$pp \to pn\pi^{+}$$

$$nn \to pn\pi^{-}$$

Isospin effect



Third-body Coulomb effect

- Radii ratios corrected for 3rd-body Coulomb are consistent with unity, indicating that:
  - The charge difference can be largely described by the residual 3rd-body Coulomb
  - Effect of isospin of initial colliding nuclei is small

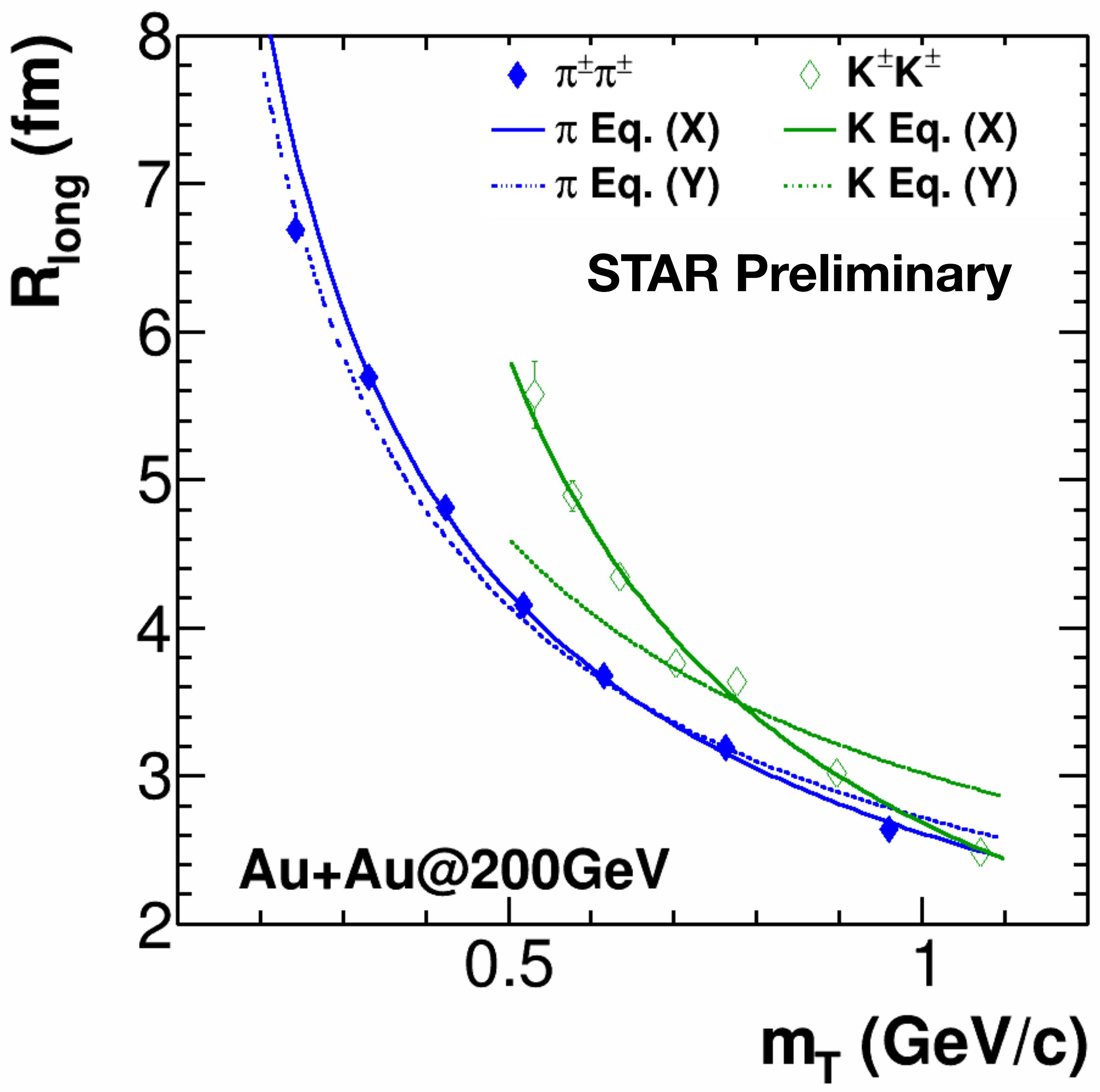
$K^{\pm}K^{\pm}$ correlations

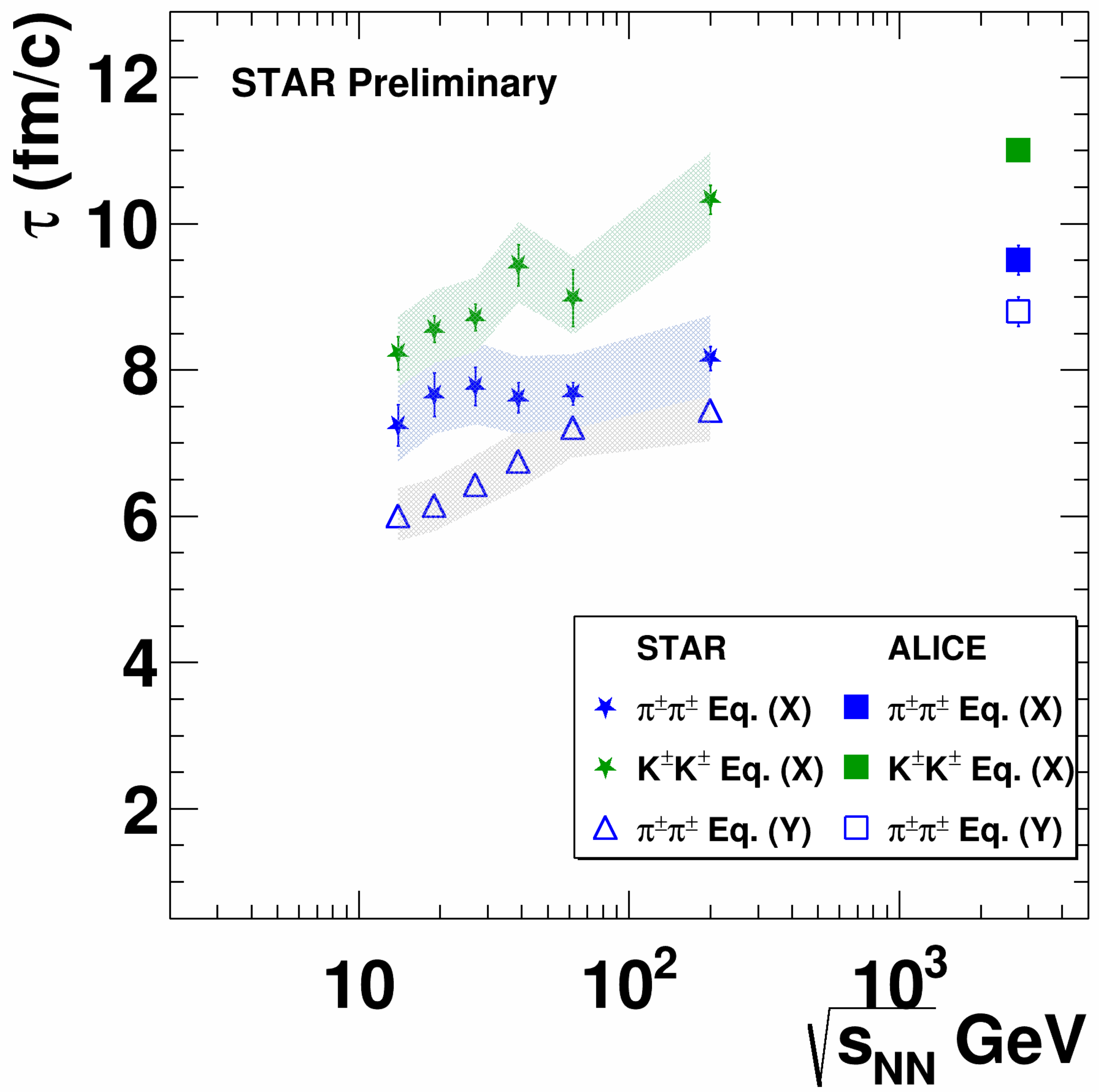
Emission time

- Femtoscopy of kaons is complementary to one of pions
  - less contribution from resonances decay
  - smaller rescattering cross-section

Eq. (Y): $R_{\rm long} = \tau\sqrt{\frac{T}{m_{\rm T}}\frac{K_2(m_{\rm T}/T)}{K_1(m_{\rm T}/T)}}$

Eq. (X): $R^2_{\rm long} = \tau^2_{\rm max}\frac{T_{\rm max}}{m_{\rm T}\cosh y_{\rm T}}\left(1+\frac{3T_{\rm max}}{2m_{\rm T}\cosh y_{\rm T}}\right)$

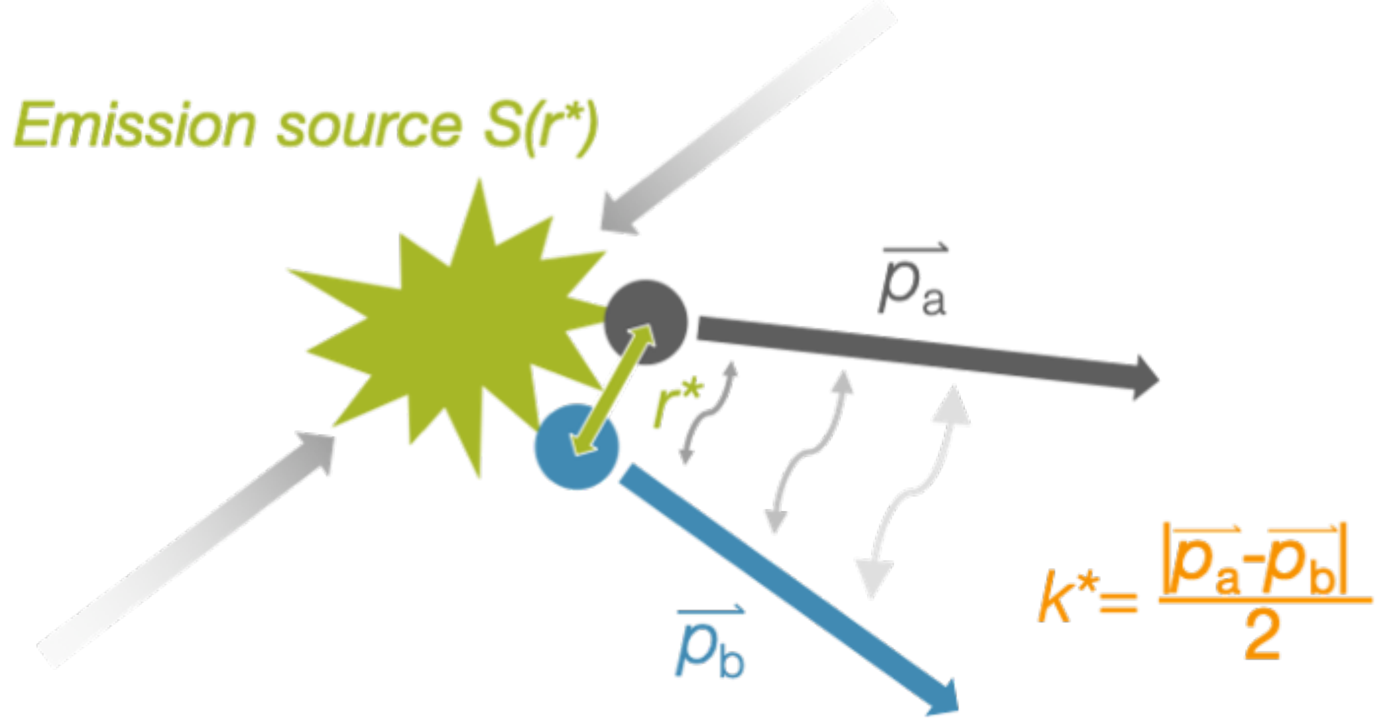




- For kaons, Eq. (Y), where transverse flow is absent, fails to describe $R_{\rm long}$
- Emission time increases with increasing $\sqrt{s_{\rm NN}}$
- Kaons are emitted later than pions → influence from K^{*} resonance decay

Shapoval, Sinyukov, Nucl. Phys. A **1016** (2021) 122322

Extraction of final state interactions



Object of study

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

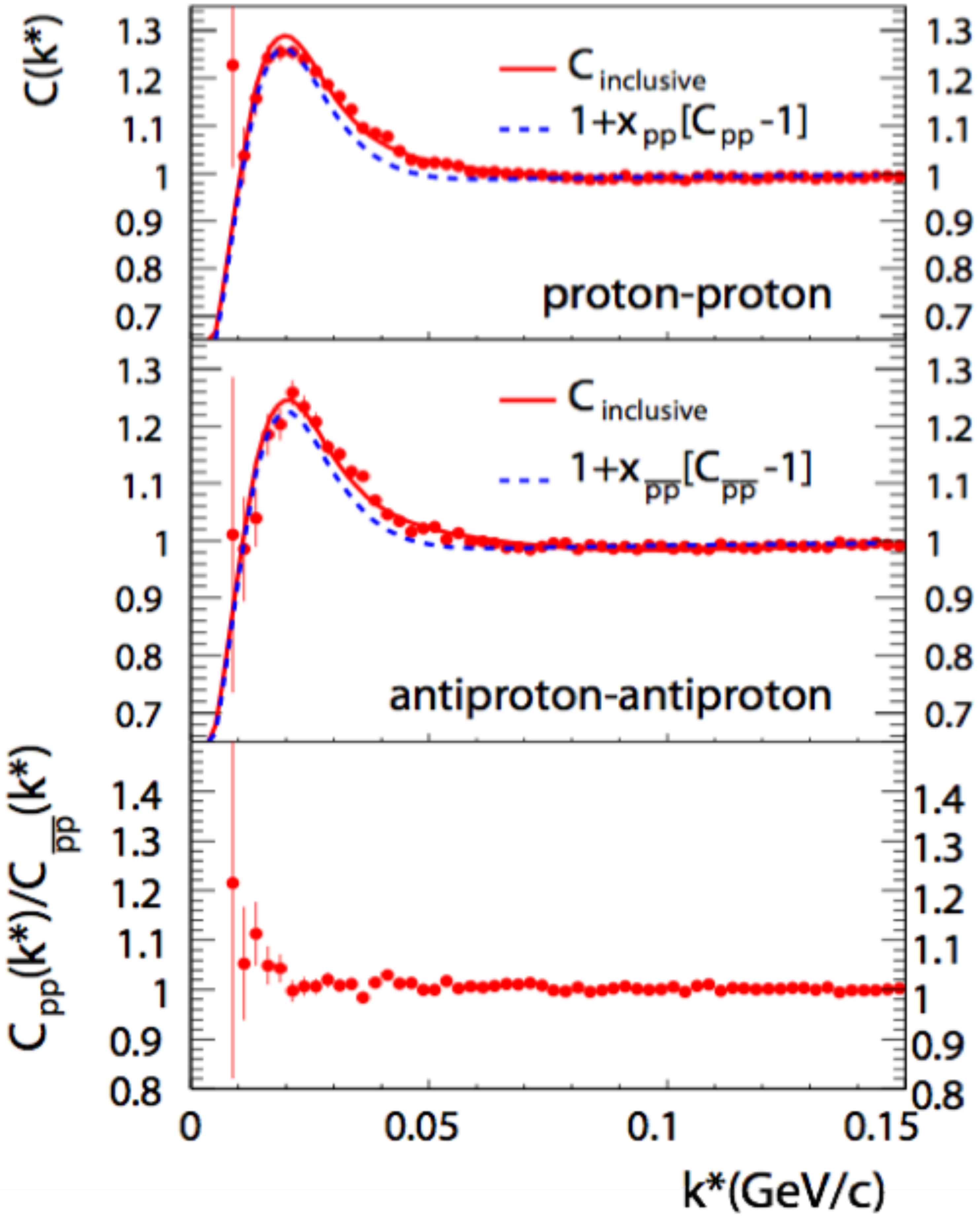
Model

Measurement

$\bar{p}$-$\bar{p}$ correlations

Reduced Bethe–Salpeter amplitude:

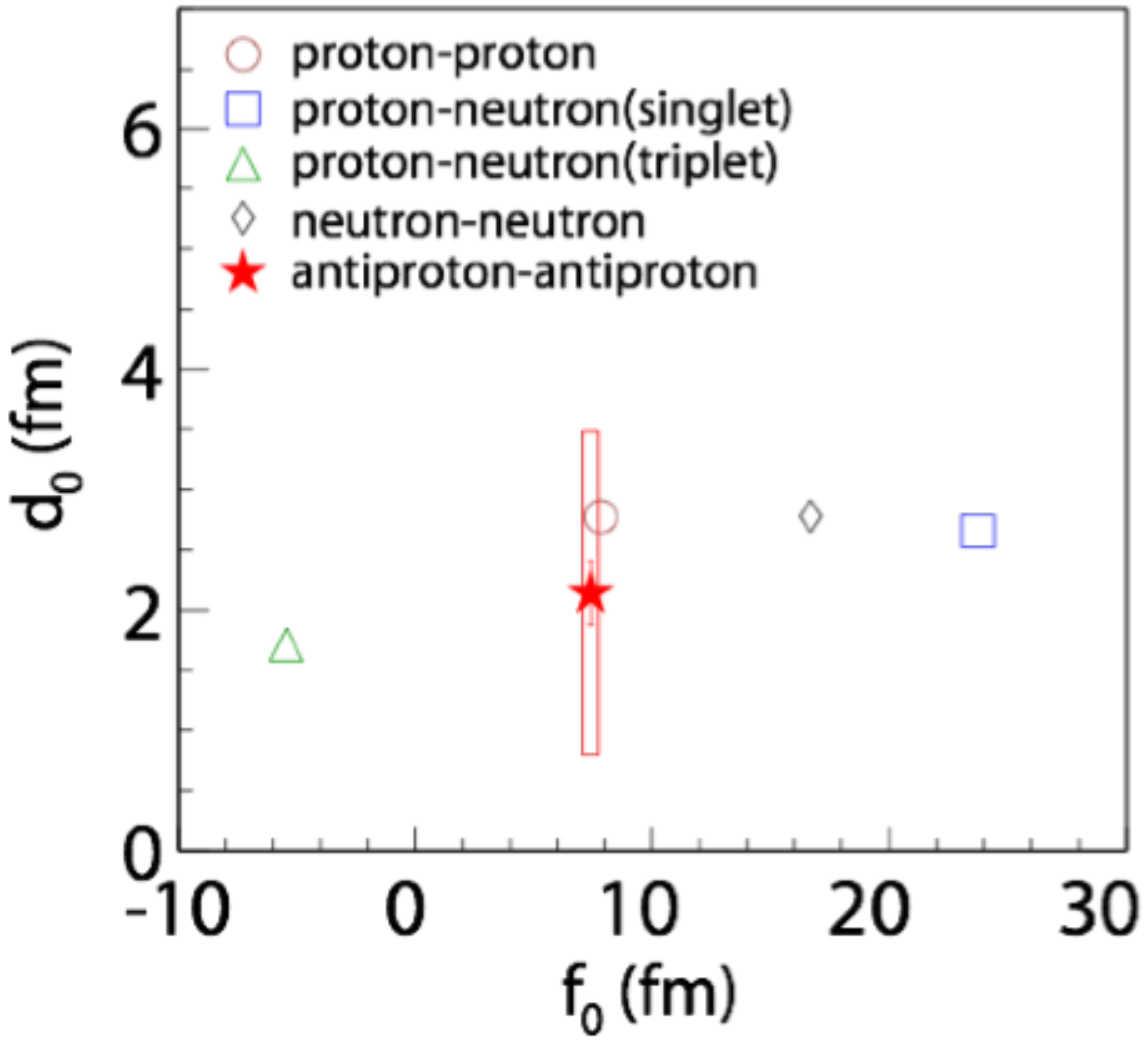
$$\Psi_{-\mathbf{k}^*}(\mathbf{r}^*) = e^{i\delta_c}\sqrt{A_c(\eta)}\left[e^{-i\mathbf{k}^*\mathbf{r}^*}F(-i\eta,1,i\xi) + f_c(k^*)\frac{\tilde{G}(\rho,\eta)}{r^*}\right],$$



s-wave scattering amplitude renormalized by Coulomb interaction:

$$f_c(k^*) = \left[\frac{1}{f_0} + \frac{1}{2}d_0 k^{*2} - \frac{2}{a_c}h(\eta) - ik^* A_c(\eta)\right]^{-1}$$

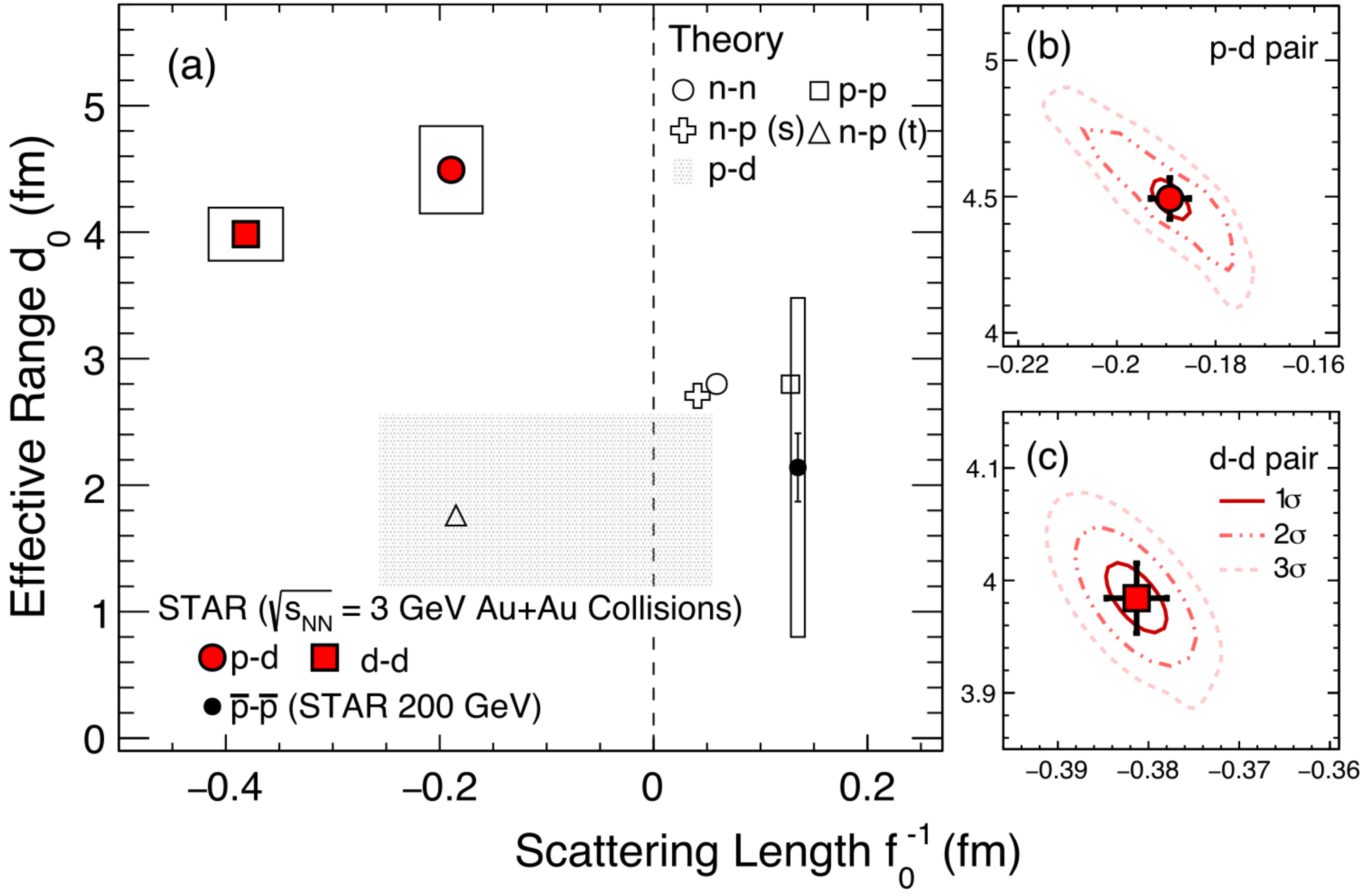
f_0: scattering length, d_0: effective range



- First measurement of $\bar{p}\bar{p}$ strong interaction parameters
- f_0 and d_0 extracted from fit of correlation functions using Lednický–Lyuboshitz (LL) model for the $\bar{p}\bar{p}$ interaction is consistent with parameters for the pp interaction
  - A quantitative verification of matter-antimatter symmetry in context of the forces responsible for the binding of (anti)nuclei

R. Lednický, V.L. Lyuboshitz, Sov. J. Nucl. Phys. **35** (1982) 770
STAR, Nature **527** (2015) 345

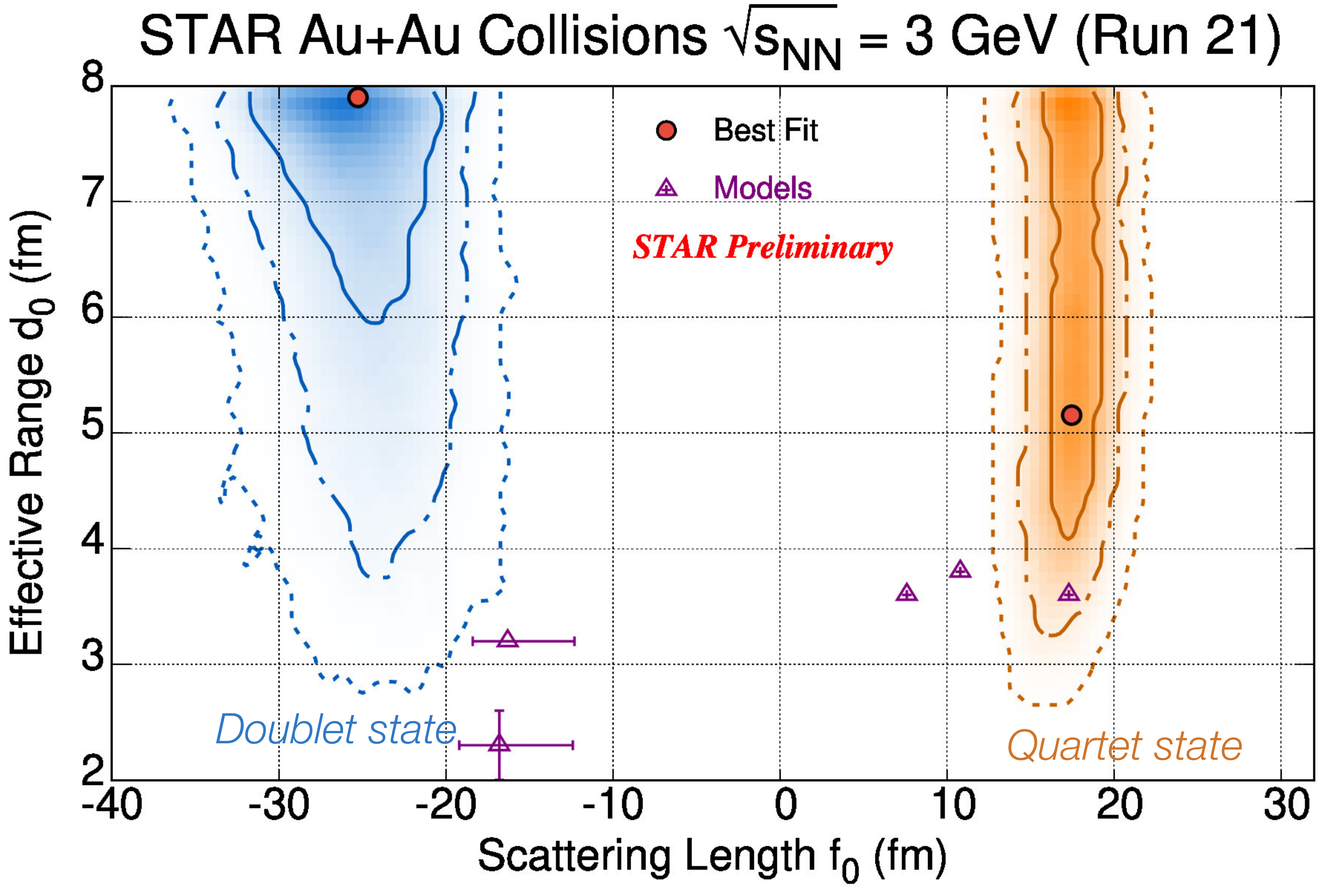
p-d, d-d correlations

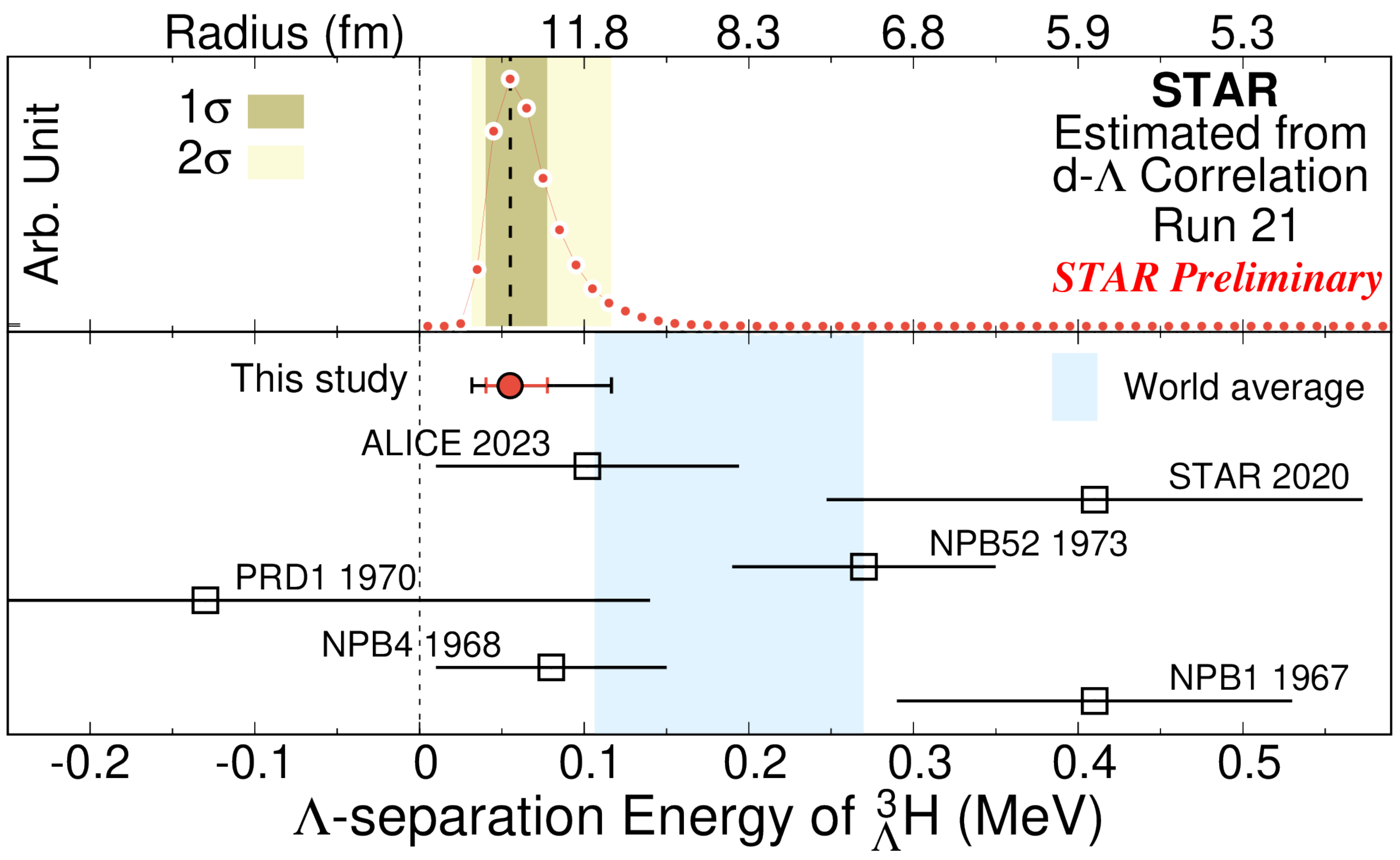


- For both p-d and d-d interaction, the spin-averaged f_0 is negative
  - Combination of repulsive interactions in quartet (quintet) spin state for p-d (d-d) along with the presence of bound states (^{3}He for p-d and ^{4}He for d-d)
- For p-d interaction, the extracted f_0 is consistent with theory calculation

STAR, PLB **864** (2025) 139412

d-Λ correlations





${}^{3}_{\Lambda}\mathrm{H}$ binding energy (B_Λ): Bethe formula from Effective Range Expansion

$$B_\Lambda = \frac{\gamma^2}{2\mu_{d\Lambda}},$$

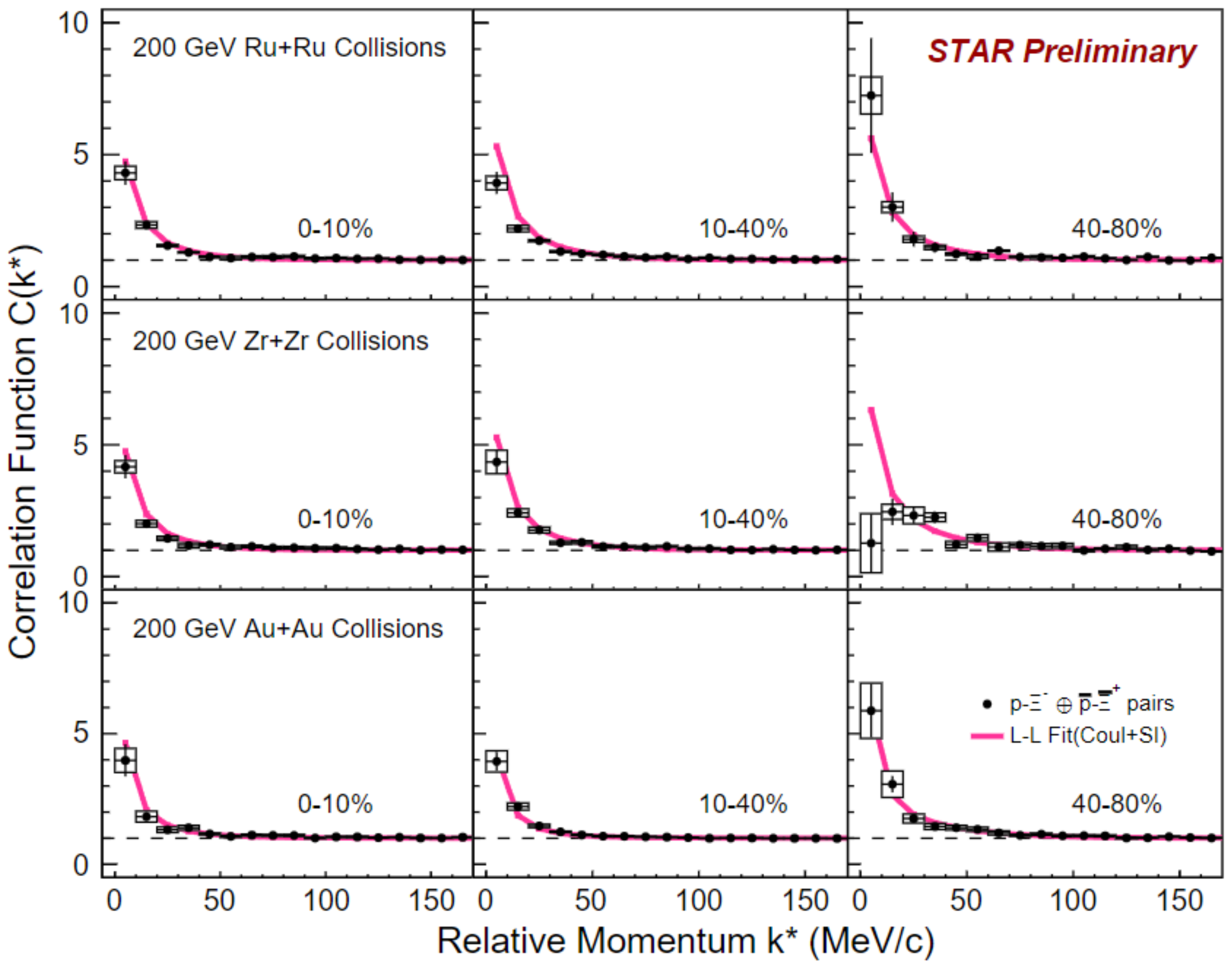
$$\frac{1}{-f_0} = \gamma - \frac{1}{2} d_0 \gamma^2$$

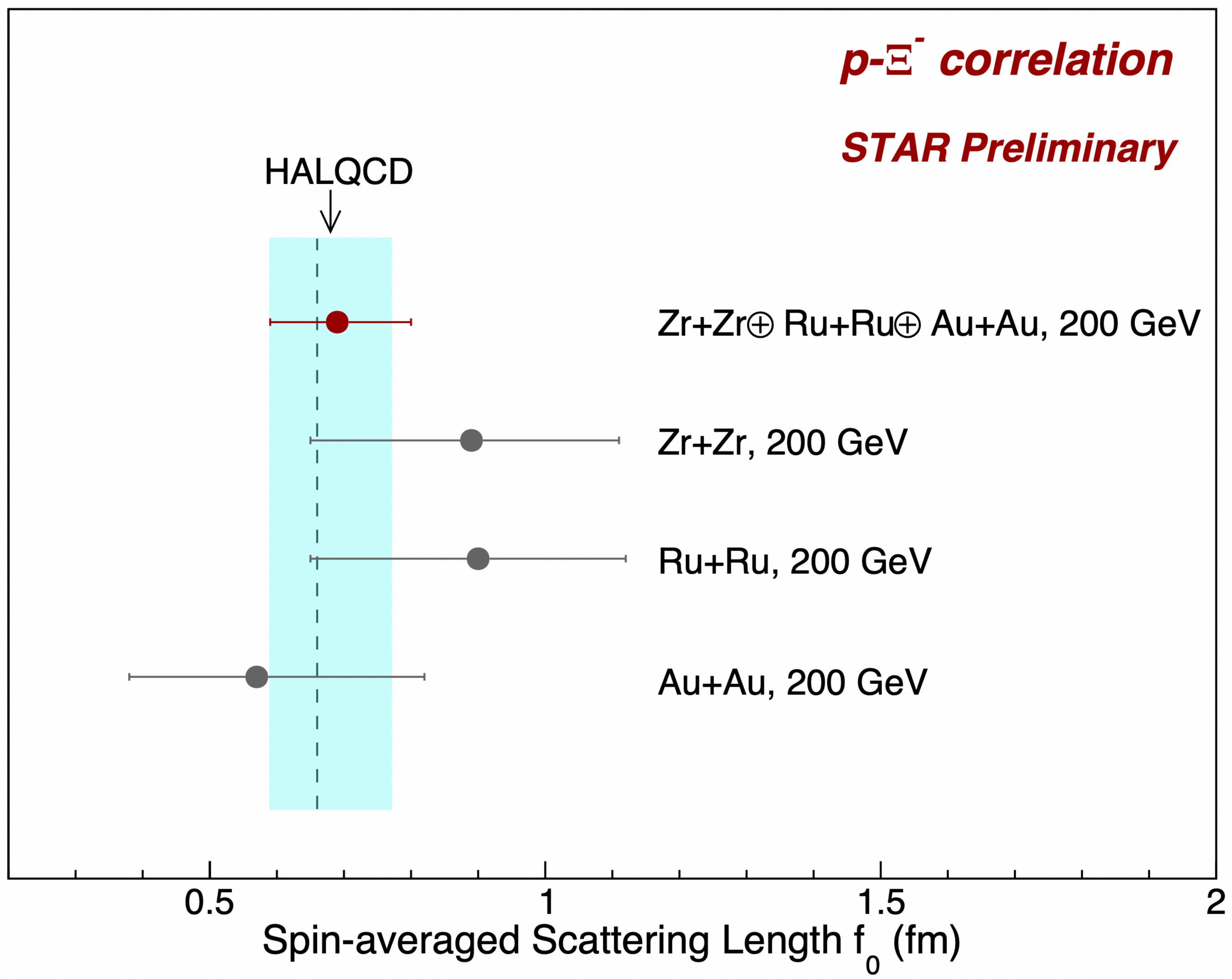
$\mu_{d\Lambda}$: reduced mass,
γ: binding momentum

- Successfully separate two spin components in d-Λ correlation functions using L–L approach:
  - $f_0(D) = -25.3 \pm 3.3$ fm → ${}^{3}_{\Lambda}\mathrm{H}$ bound state
  - $f_0(Q) = 17.5 \pm 1.6$ fm → attractive interaction

- ${}^{3}_{\Lambda}\mathrm{H}\ B_\Lambda = 0.06^{+0.06}_{-0.02}$ MeV (95% CL)
  - Consistent with world average
  - New way to constrain ${}^{3}_{\Lambda}\mathrm{H}$ properties

p-Ξ^- correlations





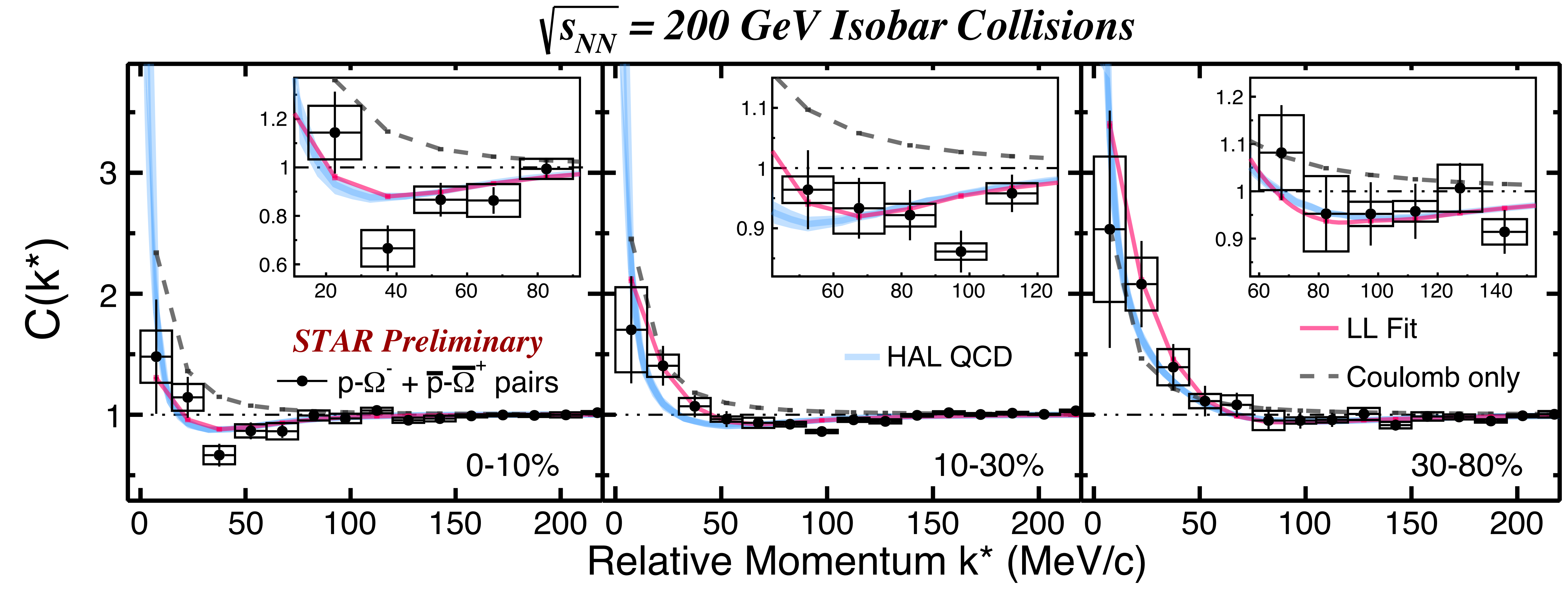
- Enhancement at small k^*
  - Due to Coulomb attraction and strong interactions

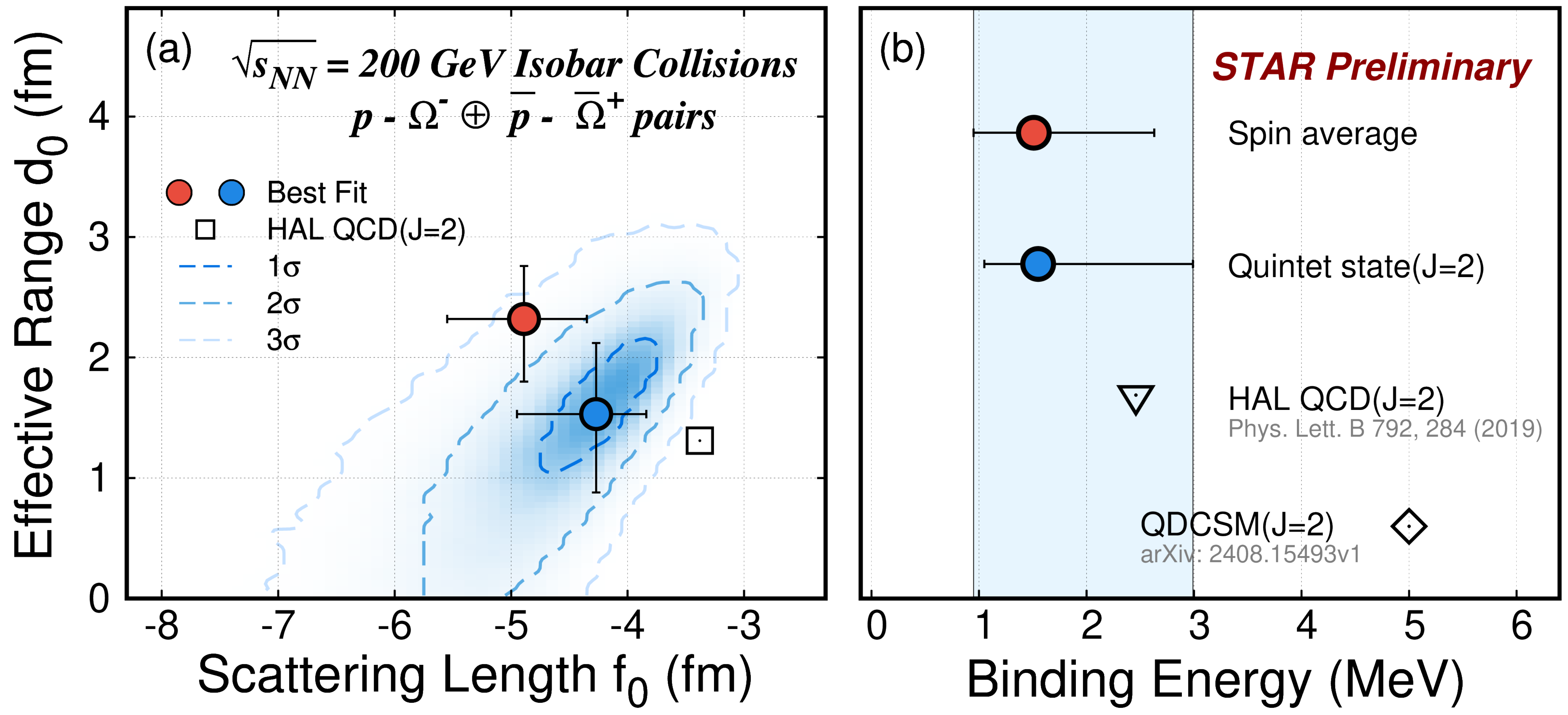
- First measurement of strong interaction parameters of p-Ξ^-:

$$f_0 = 0.7 \pm 0.1 \text{ fm}$$

  - Shallow attractive interaction
  - Consistent with HAL QCD prediction

p-Ω^- correlations





- Depletion in $C(k^*)$ around $k^* \sim$ 30–100 MeV/c → indication of bound state
- Strong interaction parameters from LL model fit to p-Ω correlation functions:
  - Negative f_0 extracted
  - Calculated binding energy consistent with HAL QCD prediction
  - First experimental evidence for strange di-baryon bound state

Summary

- Extraction of emitting source parameters using femtoscopy:
  - Femtoscopic source size is measured over a wide range of collision energy
  - Dynamic properties of the source: emission time, source tilt angle, freeze-out eccentricity, space-time emission asymmetry, are determined
- Extraction of final state interaction using femtoscopy:
  - Powerful tool to measure parameters of strong interactions, complement to scattering experiments
  - Extraction of parameters of strong interation of $\bar{p}$-$\bar{p}$, p-d, d-d, d-Λ, p-Ξ^-, p-Ω^-
  - First experimental evidence for strange di-baryon bound state for p-Ω^-