THE OHIO STATE UNIVERSITY

Charged kaon and pion femtoscopy in the RHIC Beam Energy Scan at the STAR experiment

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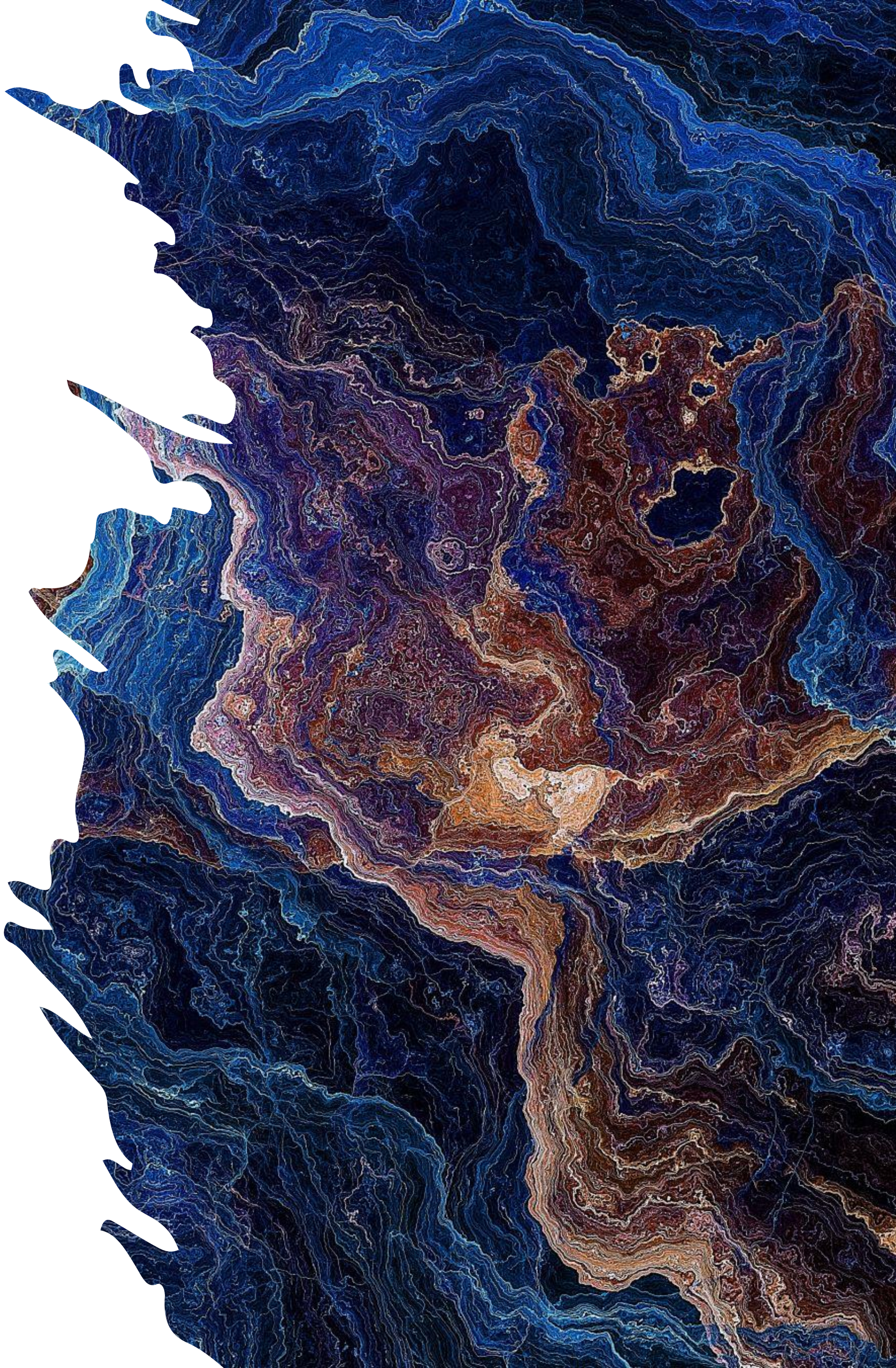
for the STAR Collaboration



STAR
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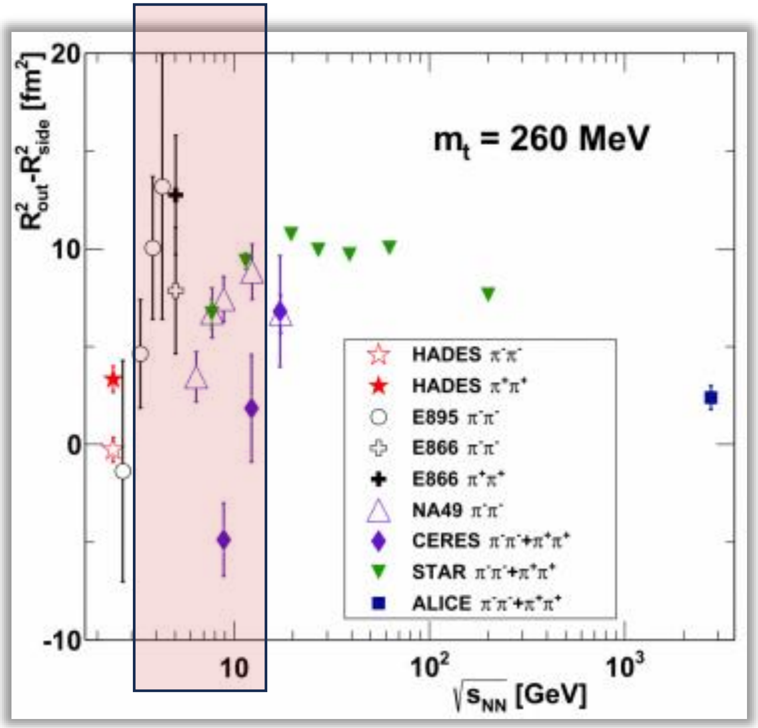
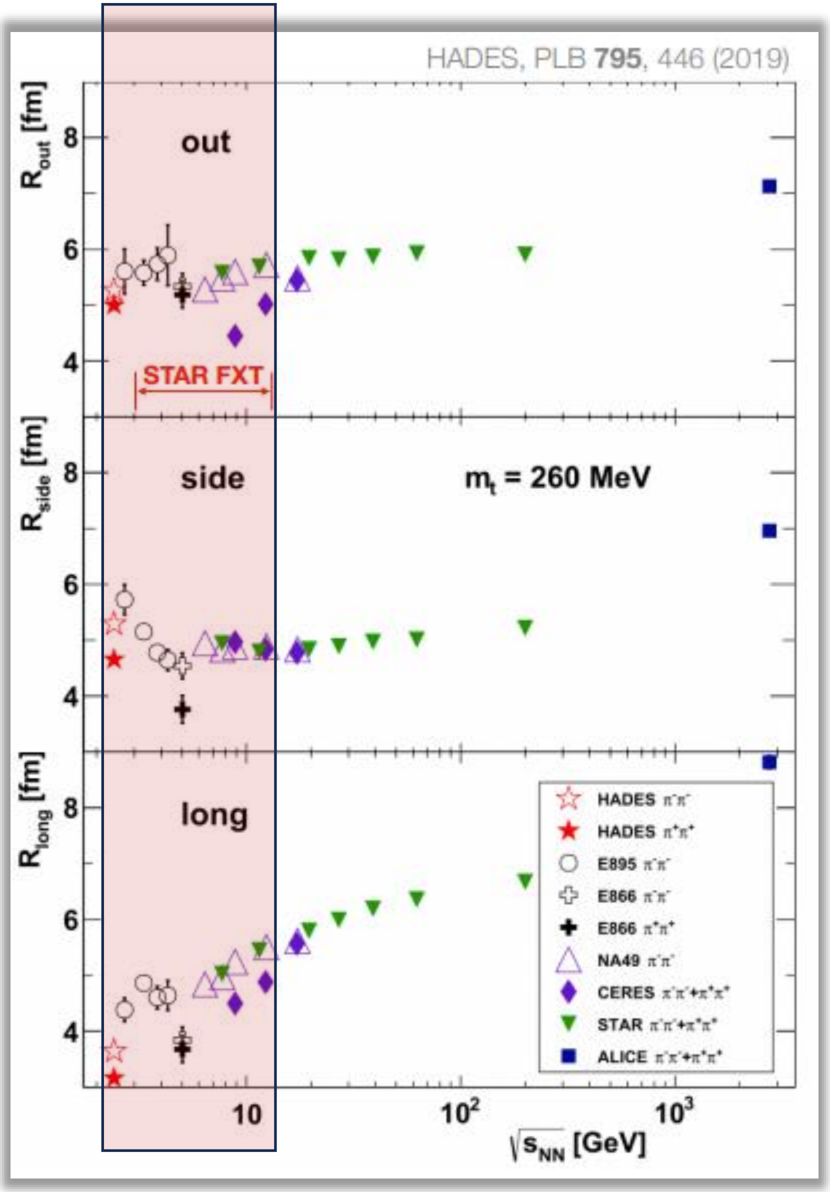
Motivation

- Pions are the most common particles
- Adding strange particles
  - Larger fraction of primarily produced charged kaons as compared to pions
  - More penetrating probe (smaller kaon -nucleon cross -section w.r.t pions)
  - Due to the strange quark content, kaons may carry more information about different collision stage
- Both pions and kaons provide constraints on theoretical models
  - Possibility to distinguish between different model scenarios

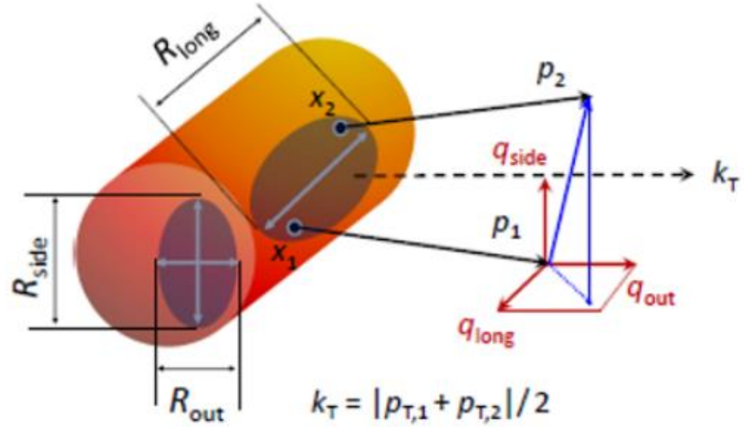
Motivation

- Significant uncertainties and conflicting results exist in the high net-baryon density region





Correlation femtoscopy



Femtoscopic radii are extracted by fitting correlation function with Bowler-Sinyukov

$$CF(q) \text{ or } C(q) = N[(1-\lambda) + \lambda K(q)(1+G(q))]$$

$$G(q) = e^{-q_o^2 R_o^2 - q_s^2 R_s^2 - q_l^2 R_l^2}$$

Phys. Lett. B 270 (1991) 69
Phys. Lett. B 432 (1998) 248

N – normalization factor
λ – correlation strength parameter
$K(q)$ - is a squared like-sign pion pair Coulomb wave-function integrated over a spherical Gaussian source

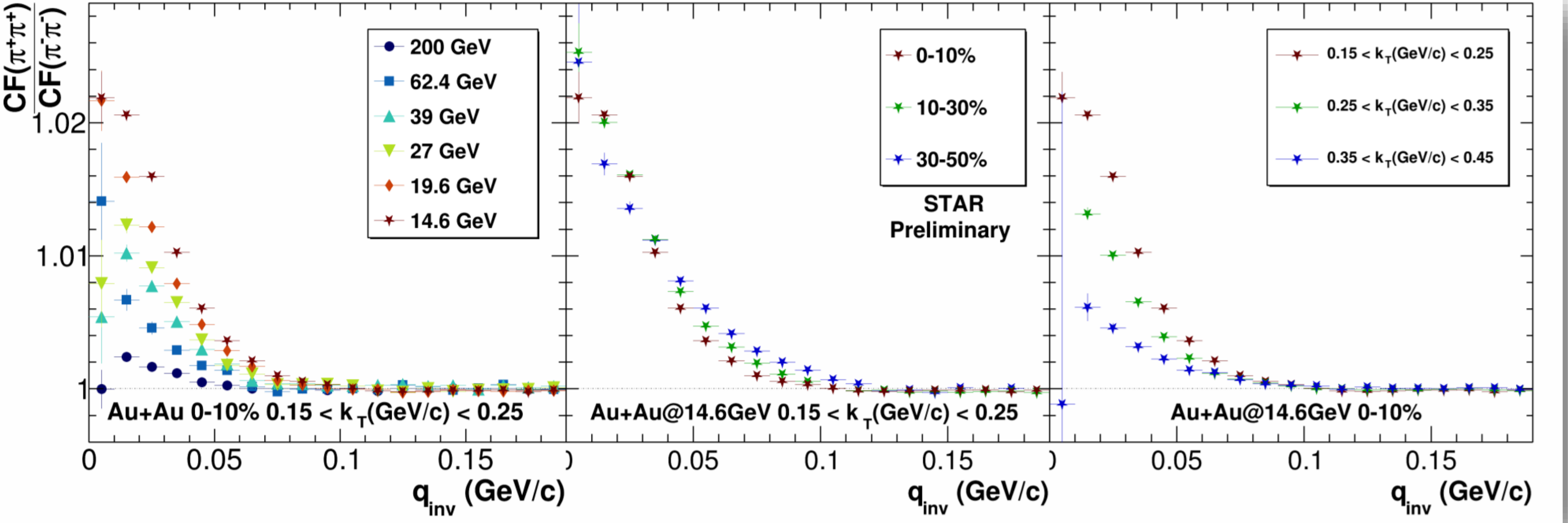
Fit using log-likelihood method

$$\chi^2 = -2\left[A \ln\left(\frac{C(A+B)}{A(C+1)}\right) + B \ln\left(\frac{A+B}{B(C+1)}\right)\right], C = \frac{A}{B}$$

Phys. Rev. C 66 (2002) 054906

Charge-dependent correlations

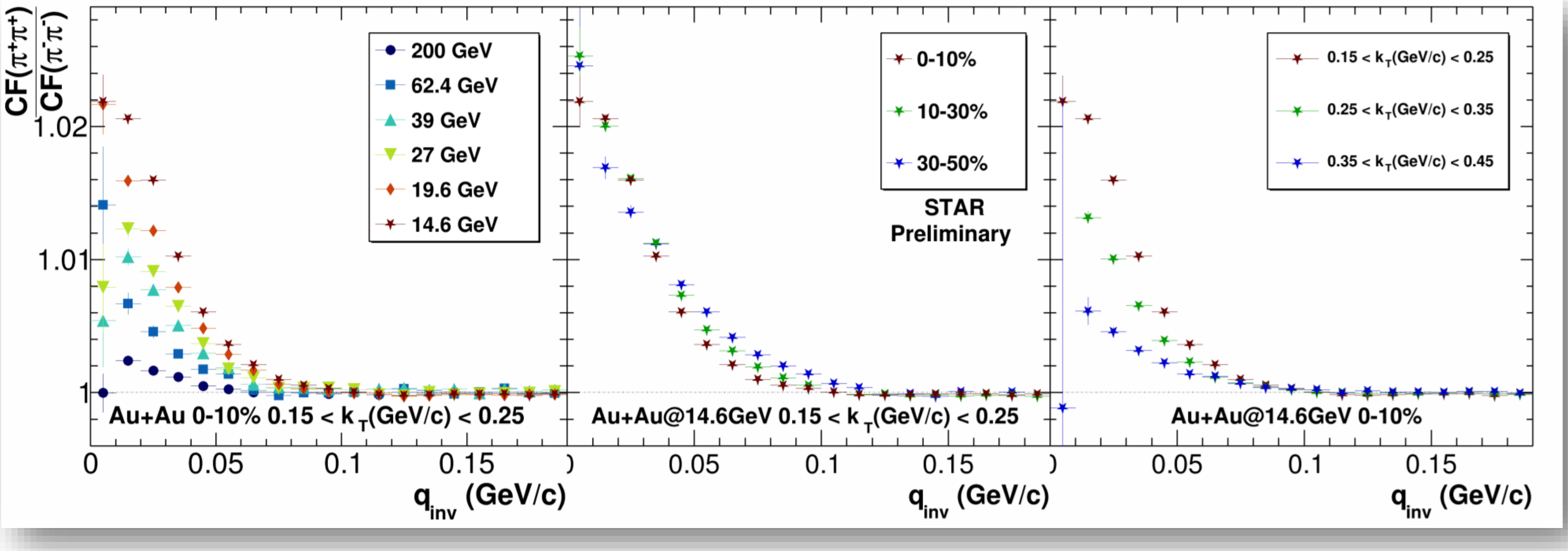
Statistical uncertainties only



- A one-dimensional analysis showed differences in the correlations between positive and negative particles

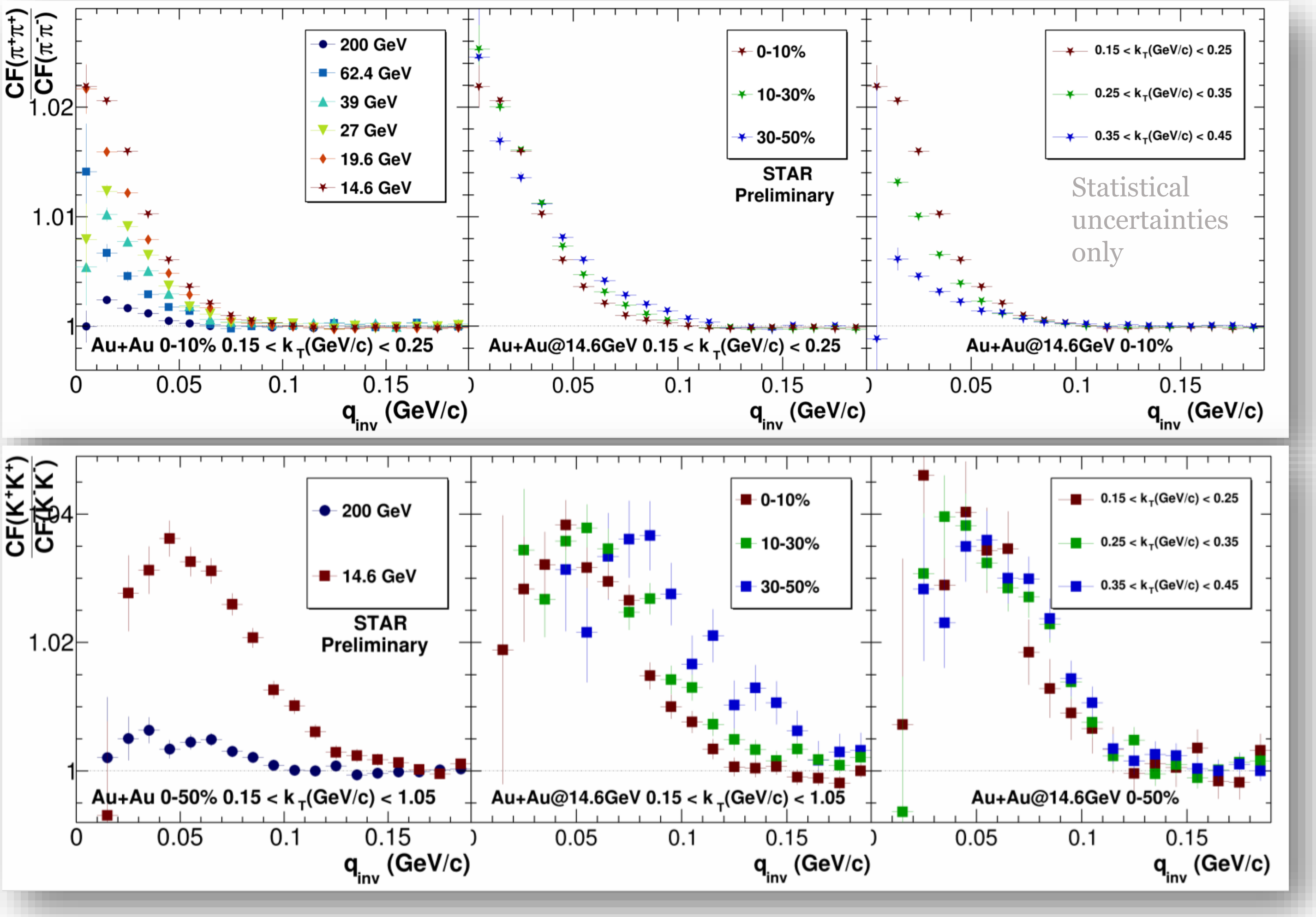
Charge-dependent correlations

Statistical uncertainties only



- The difference increases as the energy decreases
- The difference decreases as the transverse momentum of the pair increases

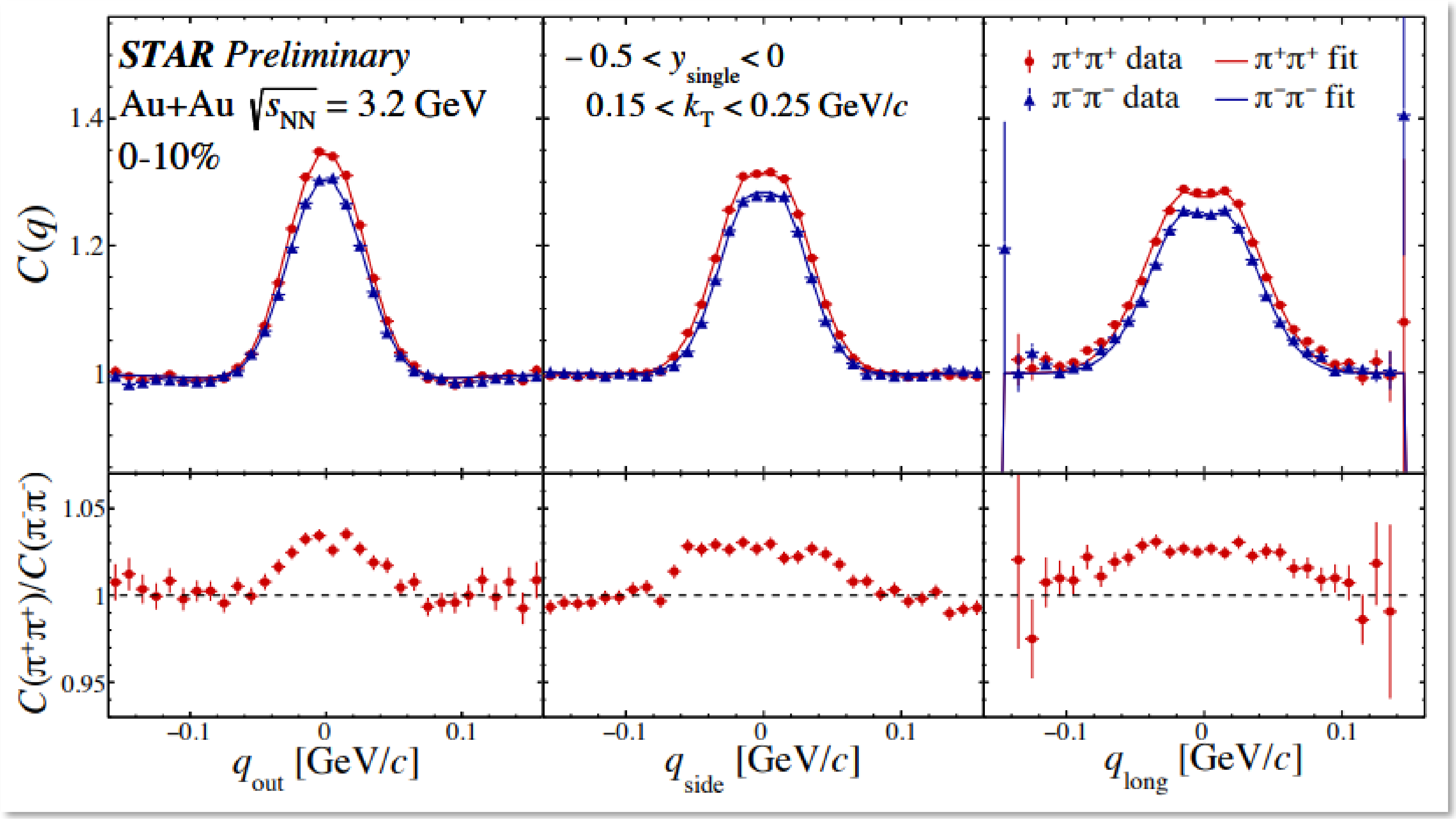
Charge-dependent correlations



- The effect is slightly stronger for kaons than for pions

Charge-dependent correlations: FXT

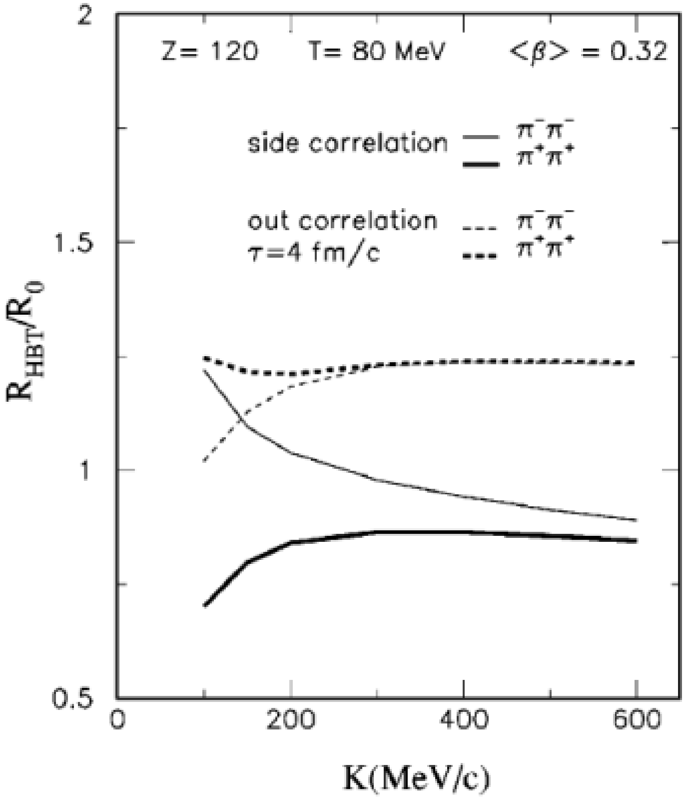
Statistical uncertainties only



- There is a statistically significant difference in correlation functions at FXT energies, even in the 3D case

Possible sources of charge difference

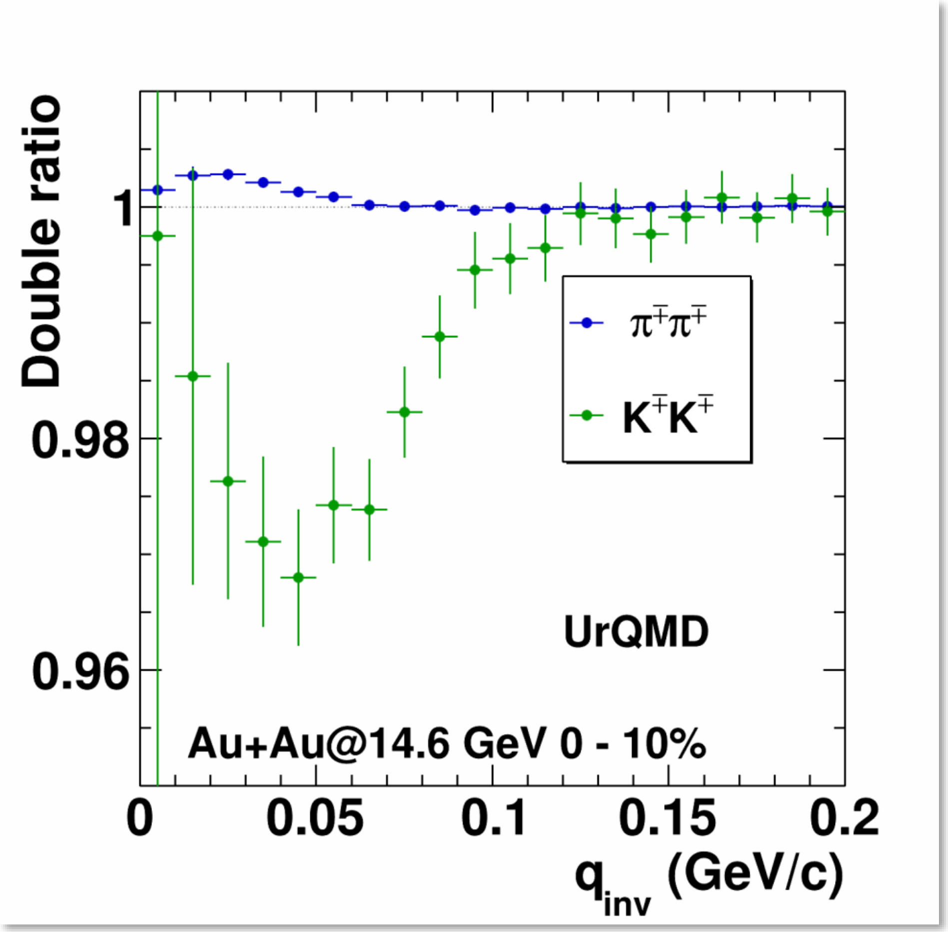
- Coulomb Effect from Residual Source
  - Utilize a toy model that accounts for the influence of the residual source after the collision on the momentum difference distribution.
- Hadronic Scattering Phase
  - Investigate and validate the effect by checking the UrQMD model



Expected difference between true and distorted by Coulomb effect HBT radii

Phys. Rev. C, V59, 4 (1999)

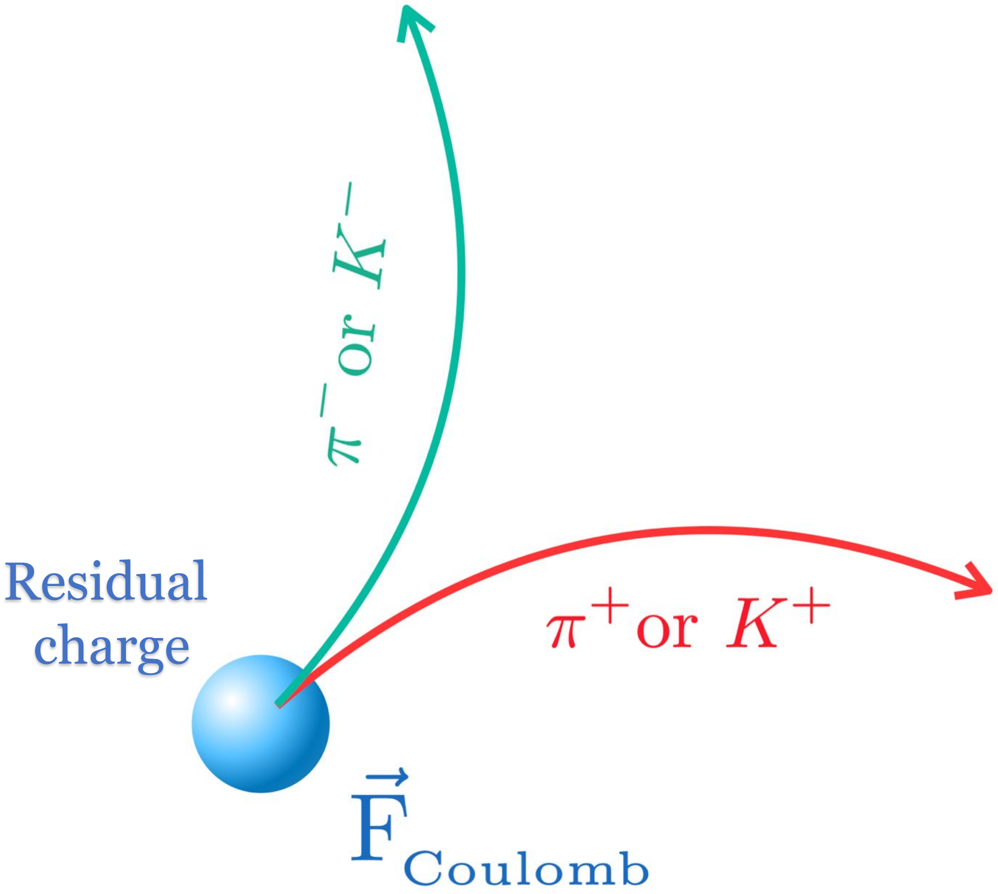
Double ratio from UrQMD



Default UrQMD (Cascade) 3.4

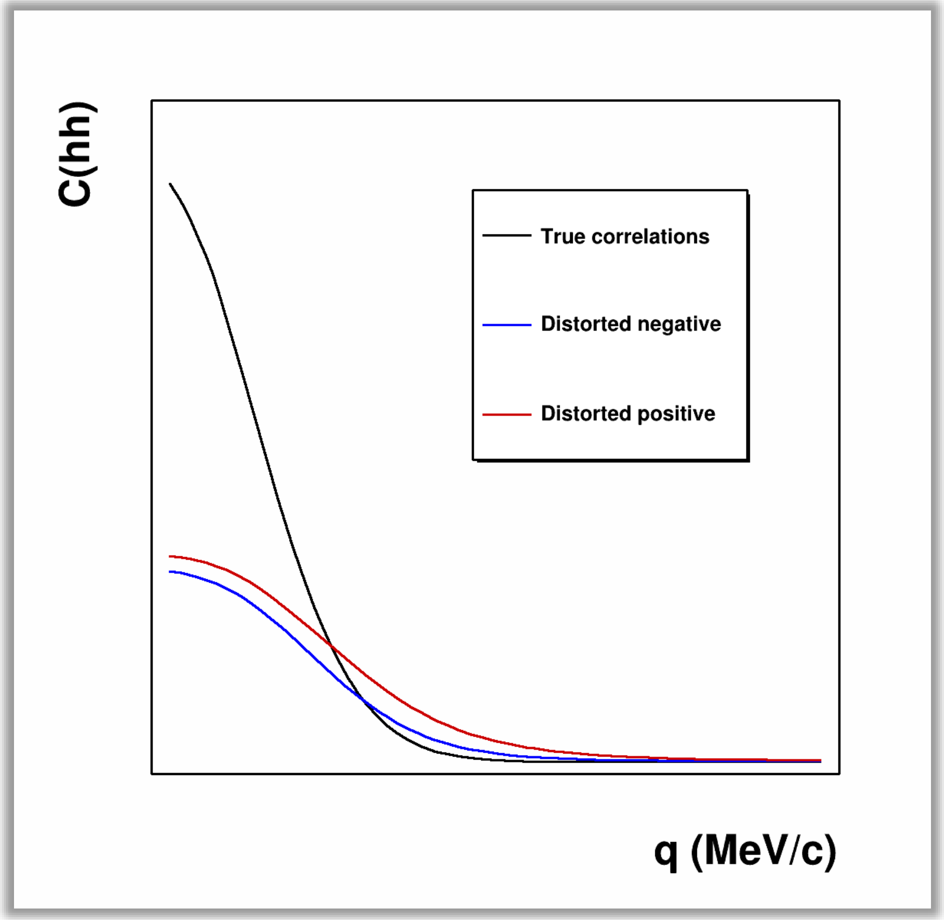
- UrQMD does not contain residual charge influence
- The double ratio of pions and kaons exhibits opposite trends, which is inconsistent with experimental results
- Different production mechanism?

Coulomb effect from residual source



- The Coulomb force distorts momentum and coordinate spectra
- How does the Coulomb force impact the correlation function?

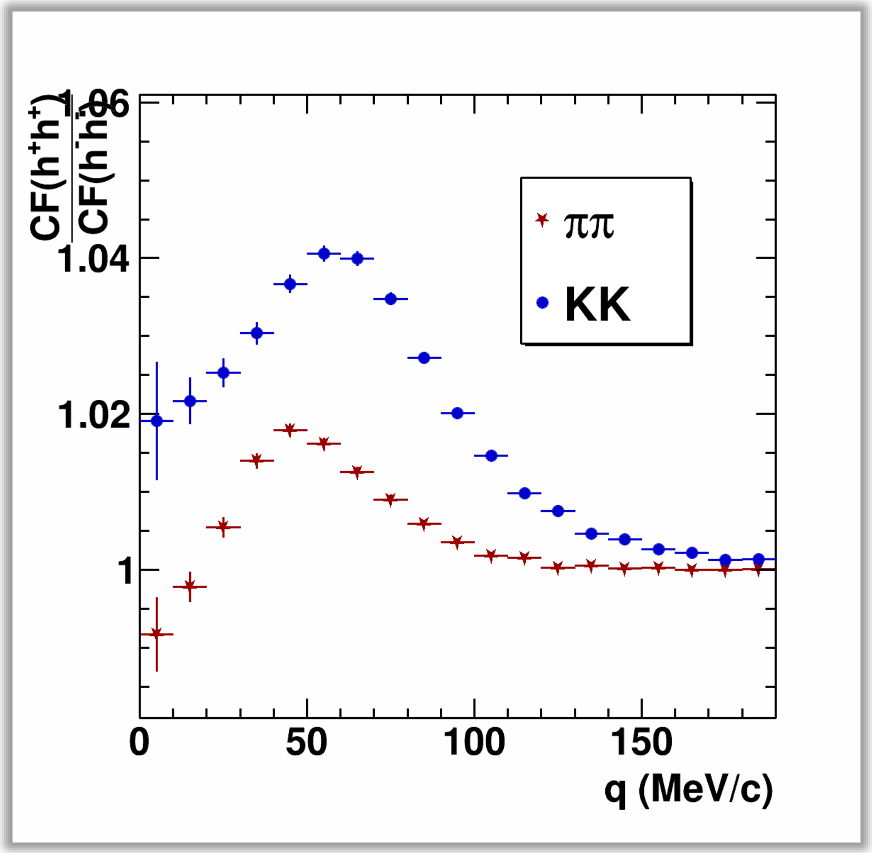
Coulomb effect from residual source

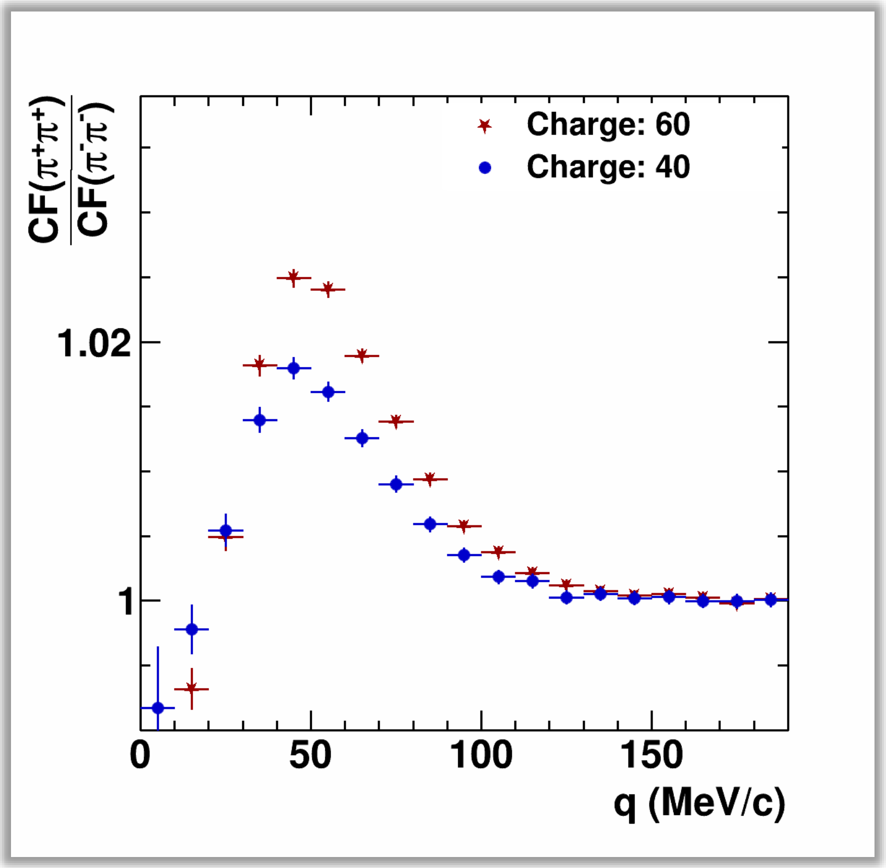


- Creating a toy model with exponentially distributed momentum and Gaussian coordinates for particles

- Constructing 3 correlation functions:
  - True correlations
  - Distorted through the influence of Coulomb force correlations
    - For positive particles
    - For negative particles

Ratio of CF from the toy model



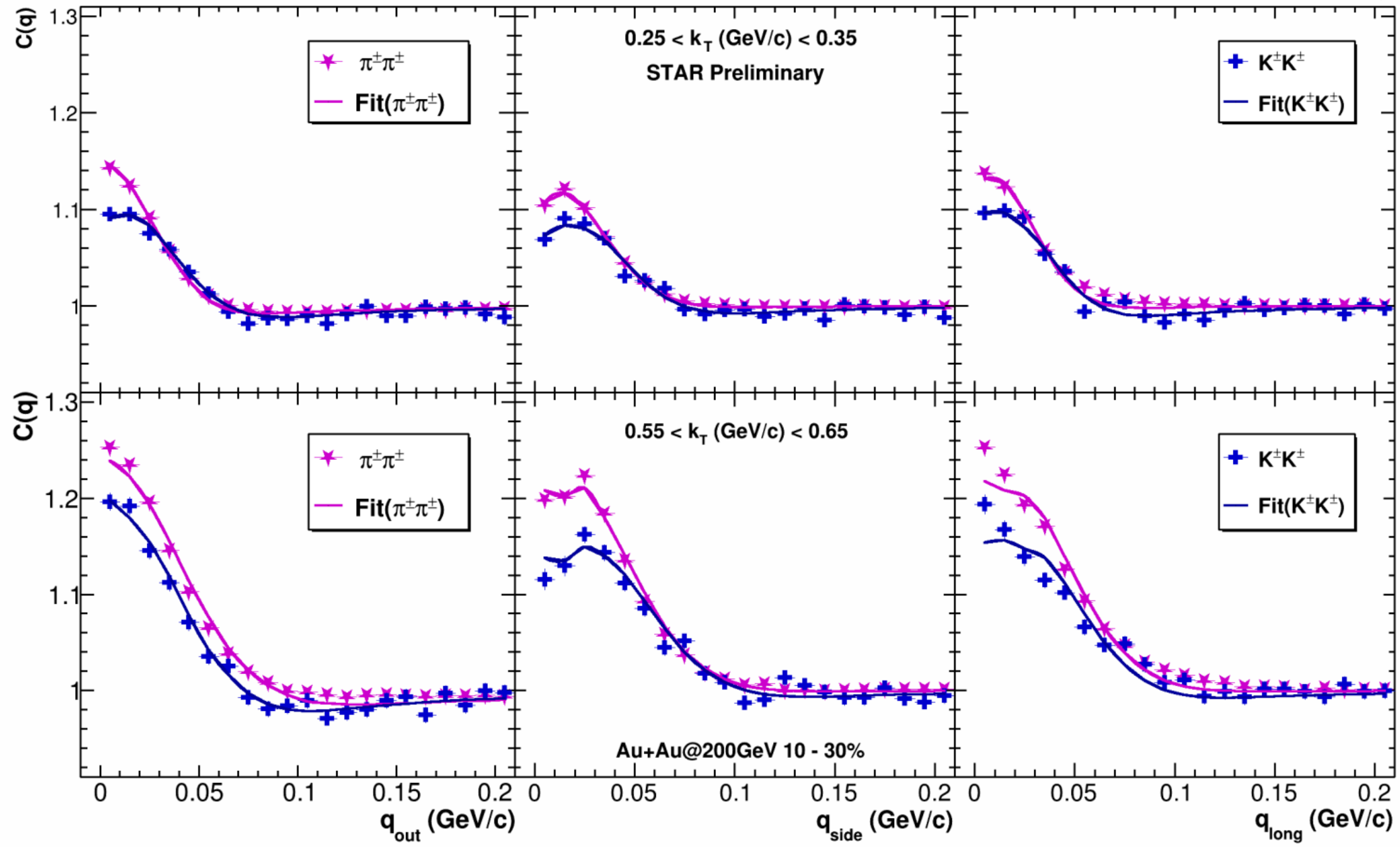


- The toy model exhibits the same trend as the experiment for both pions and kaons

- The varying residual charge simulates energy dependence

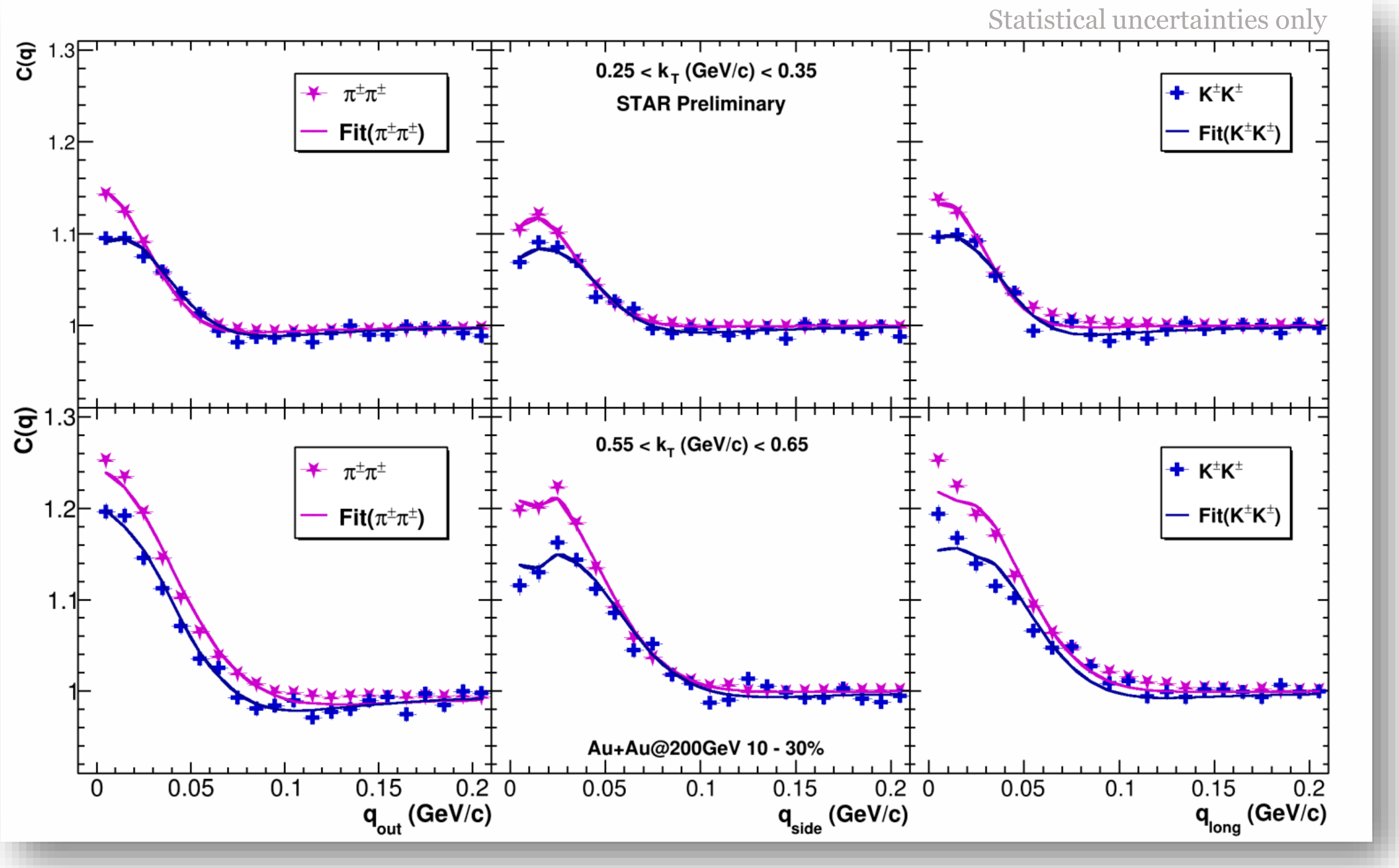
Correlation functions of pions and kaons

Statistical uncertainties only



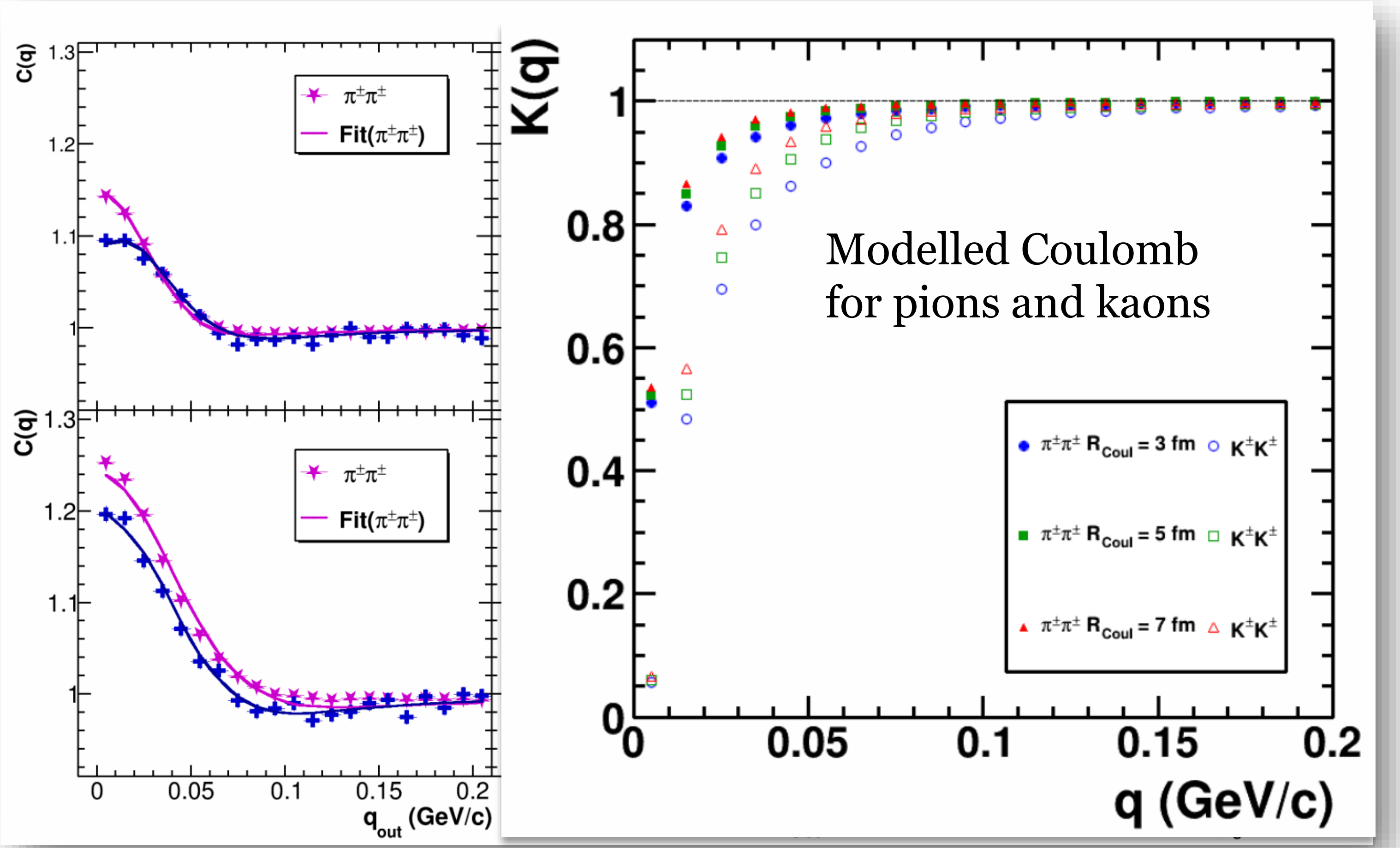
- Kaons are emitted from smaller homogeneity regions compared to pions at the same pair transverse momentum

Correlation functions of pions and kaons



- The Coulomb effect between particle pairs becomes stronger as k_T increases

Correlation functions of pions and kaons



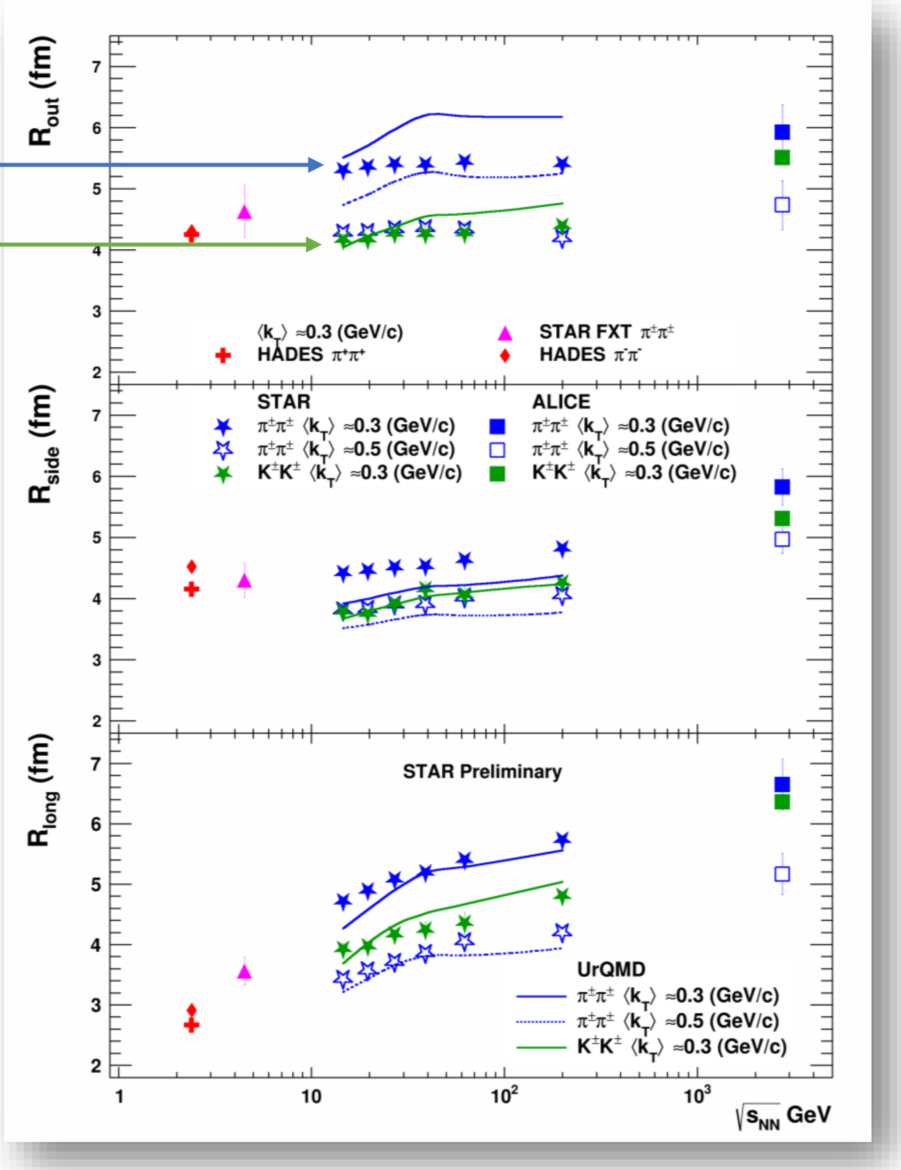
Modelled Coulomb
for pions and kaons

- The Coulomb effect is stronger for kaons than for pions

Energy dependence

Pions

Kaons

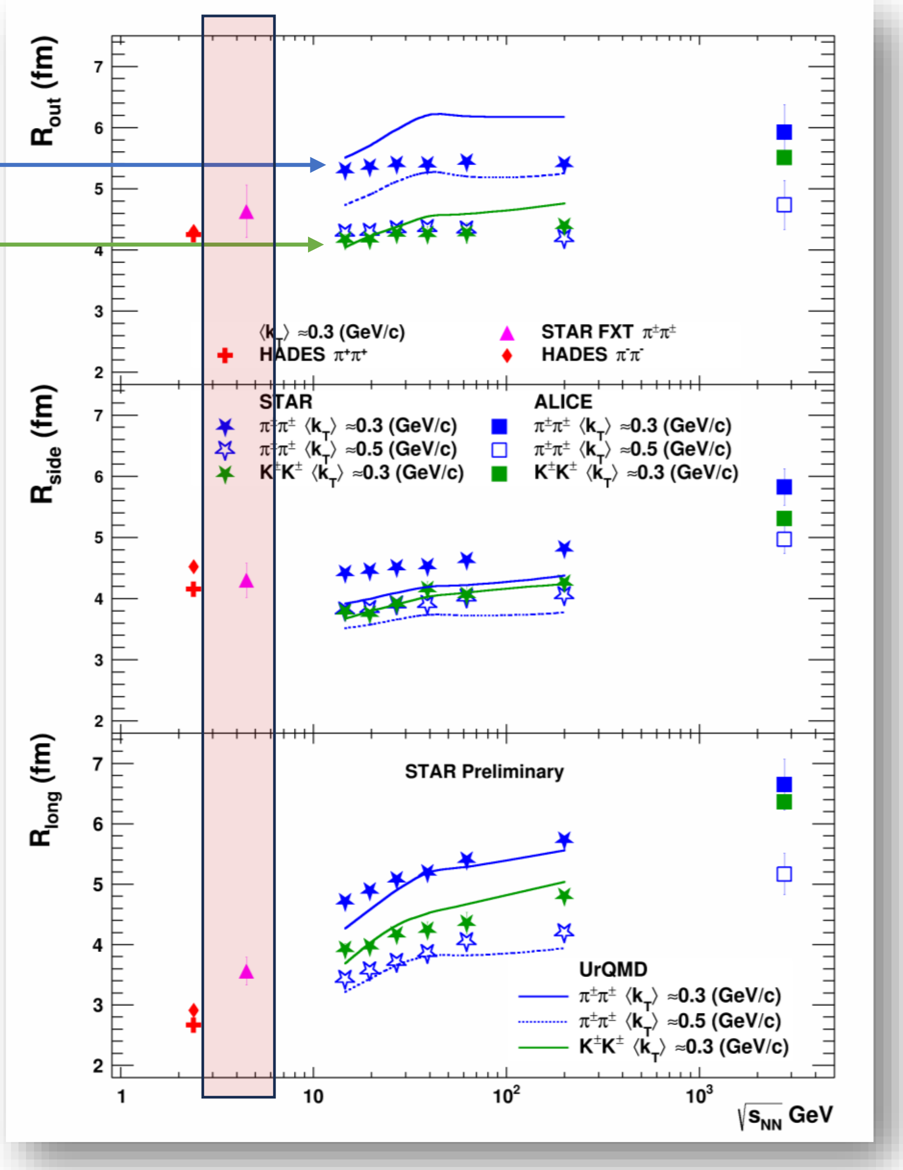


- Three-dimensional femtoscopic analysis reveals:
    - Extracted radii increase with collision energy
    - Decrease with transverse pair momentum
    - Are generally larger for kaons compared to pions under the same conditions
- UrQMD in good qualitative agreement with the data

Energy dependence FXT

Pions

Kaons



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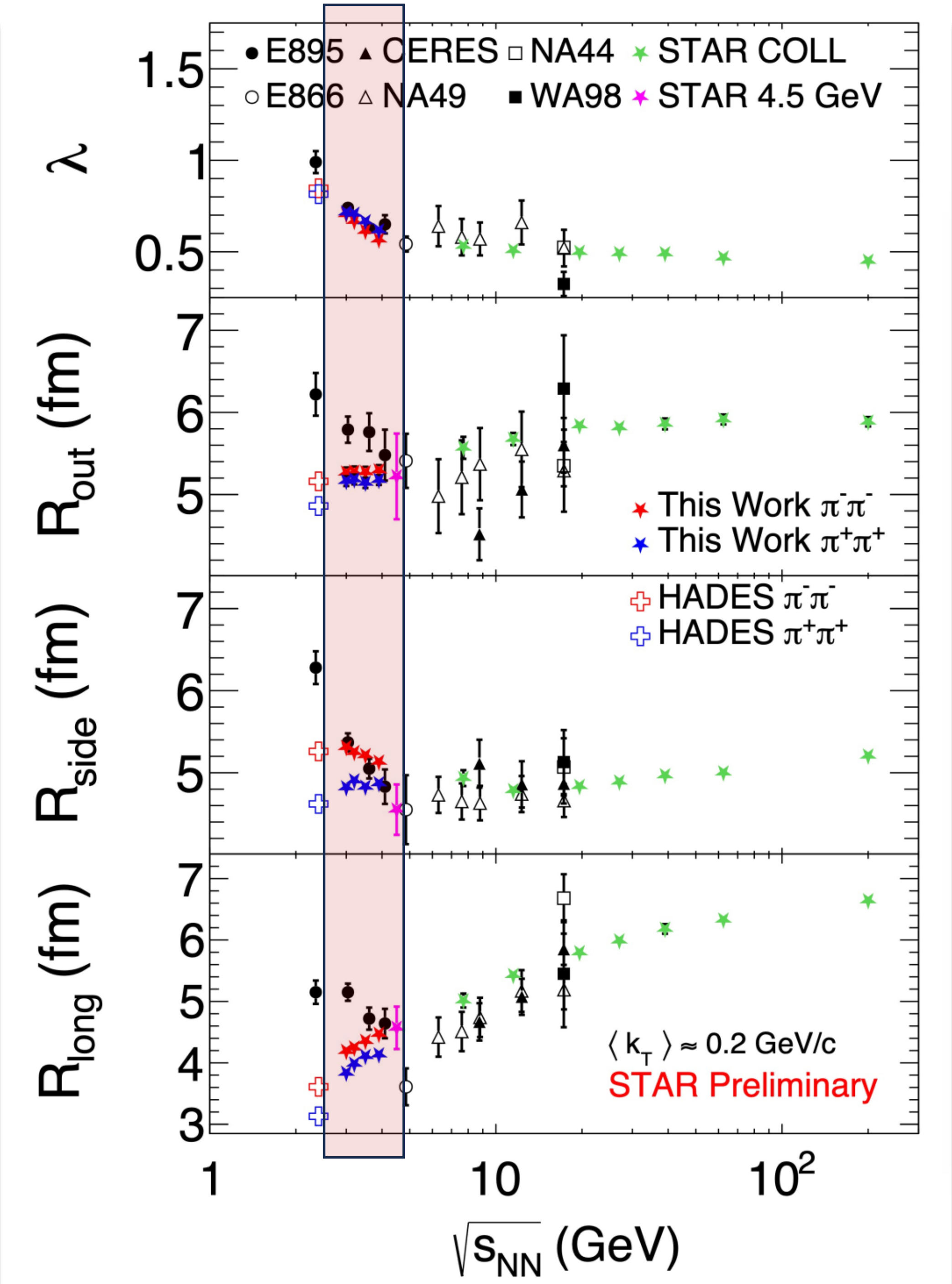
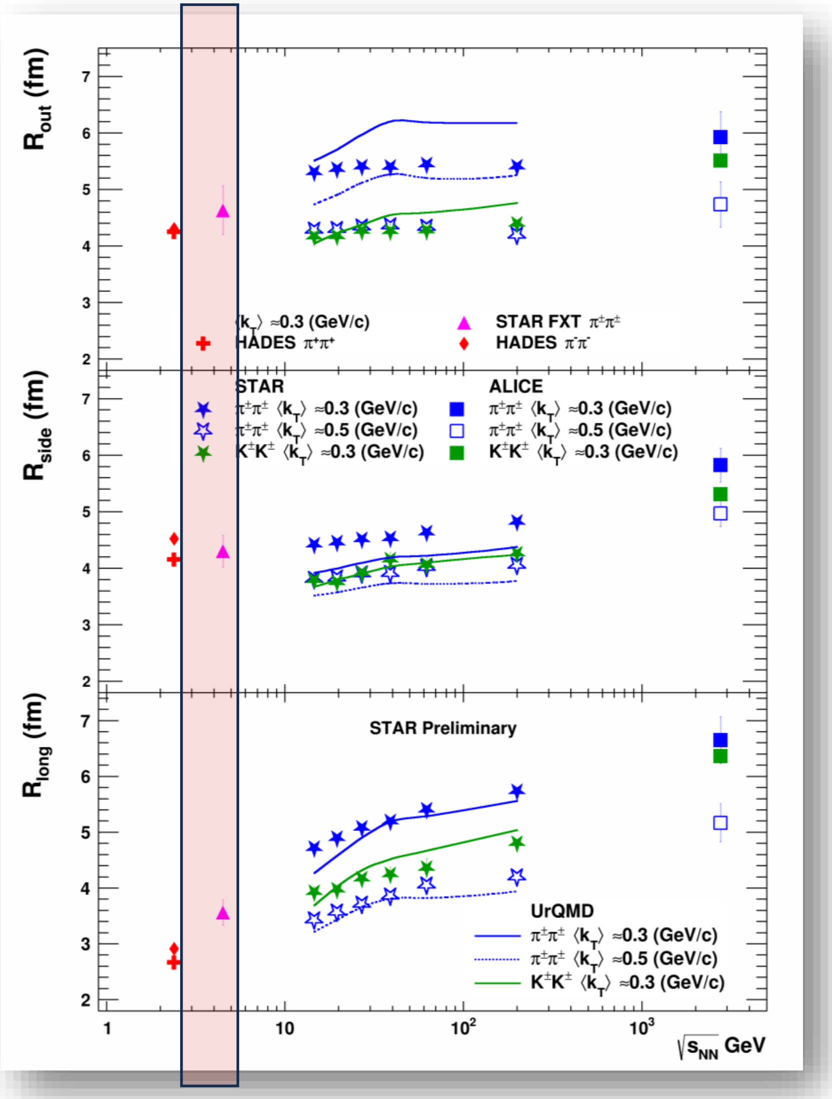
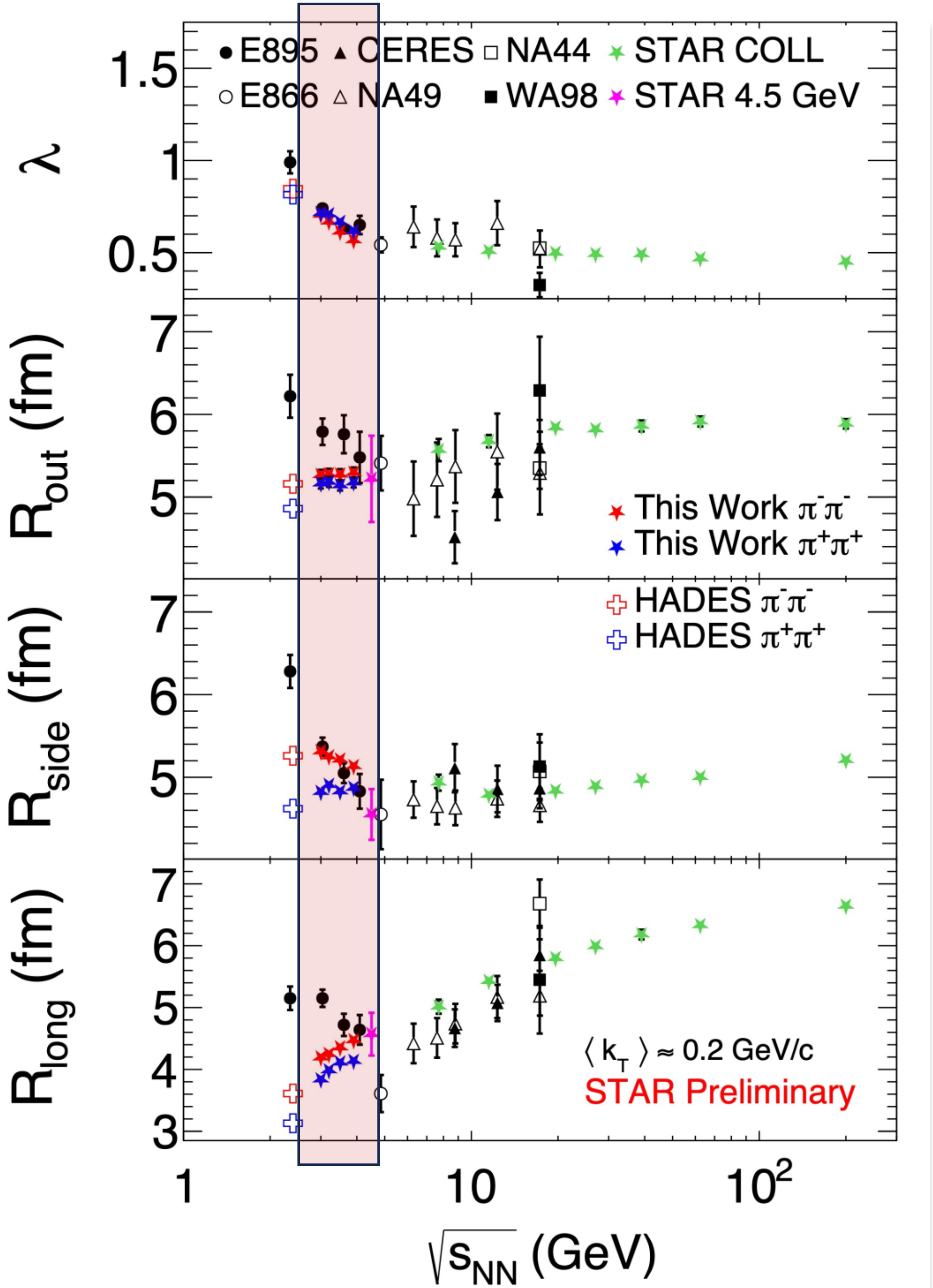
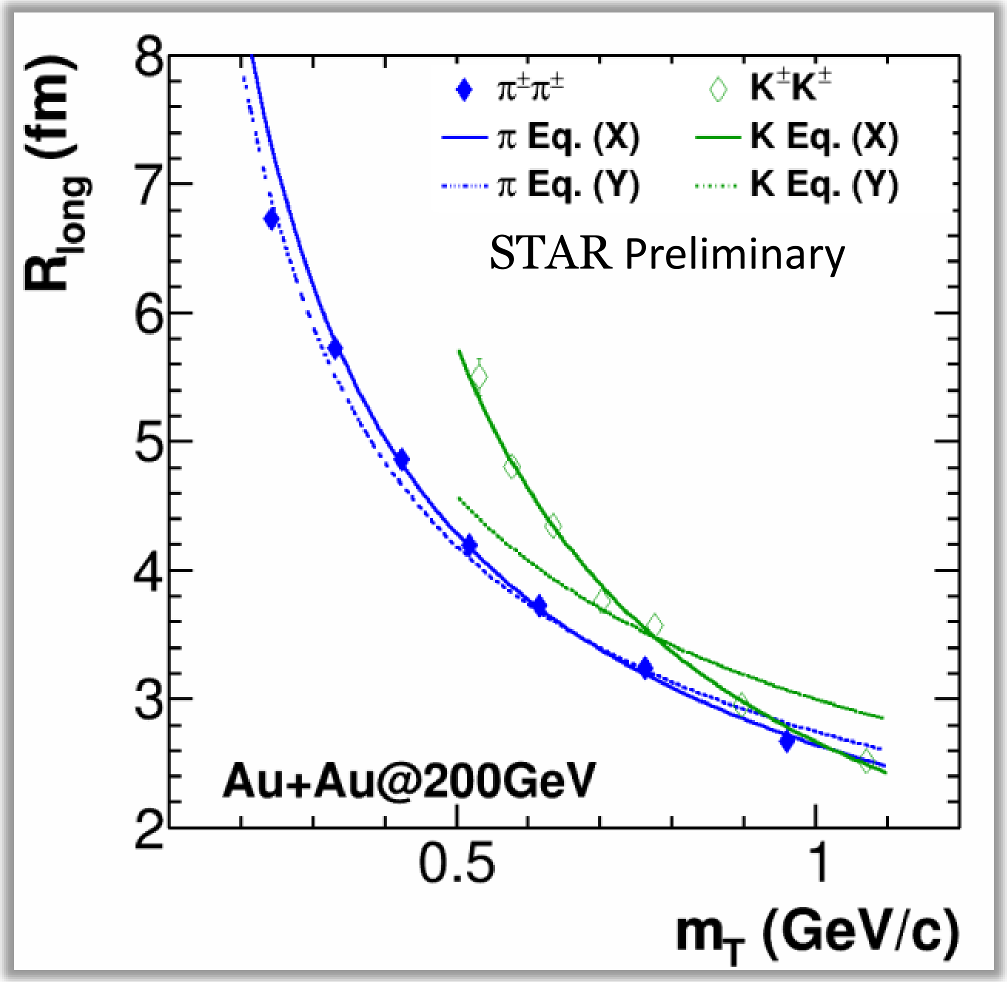

E895
CERES
NA44
STAR COLL
E866
NA49
WA98
STAR 4.5 GeV
λ
1.5
1
0.5
R_{out} (fm)
R_{side} (fm)
R_{long} (fm)
7
6
5
4
3
This Work $\pi^-\pi^-$
This Work $\pi^+\pi^+$
HADES $\pi^-\pi^-$
HADES $\pi^+\pi^+$
$\langle k_T \rangle \approx 0.2$ GeV/c
STAR Preliminary
1
10
10^2
$\sqrt{s_{NN}}$ (GeV)


R_{out} (fm)
R_{side} (fm)
R_{long} (fm)
7
6
5
4
3
2
$\langle k_T \rangle \approx 0.3$ (GeV/c)
HADES $\pi^+\pi^+$
STAR FXT $\pi^\pm\pi^\pm$
HADES $\pi^-\pi^-$
STAR
$\pi^\pm\pi^\pm$ $\langle k_T \rangle \approx 0.3$ (GeV/c)
$\pi^\pm\pi^\pm$ $\langle k_T \rangle \approx 0.5$ (GeV/c)
$K^\pm K^\pm$ $\langle k_T \rangle \approx 0.3$ (GeV/c)
ALICE
$\pi^\pm\pi^\pm$ $\langle k_T \rangle \approx 0.3$ (GeV/c)
$\pi^\pm\pi^\pm$ $\langle k_T \rangle \approx 0.5$ (GeV/c)
$K^\pm K^\pm$ $\langle k_T \rangle \approx 0.3$ (GeV/c)
STAR Preliminary
UrQMD
$\pi^\pm\pi^\pm$ $\langle k_T \rangle \approx 0.3$ (GeV/c)
$\pi^\pm\pi^\pm$ $\langle k_T \rangle \approx 0.5$ (GeV/c)
$K^\pm K^\pm$ $\langle k_T \rangle \approx 0.3$ (GeV/c)
1
10
10^2
10^3
$\sqrt{s_{NN}}$ GeV



- Statistically significant charge difference for radii
  - Importance charge dependent analysis at lower energies
- The beam energy dependence of the radii agrees with other experiments but shows a smoother trend than earlier

Emission time



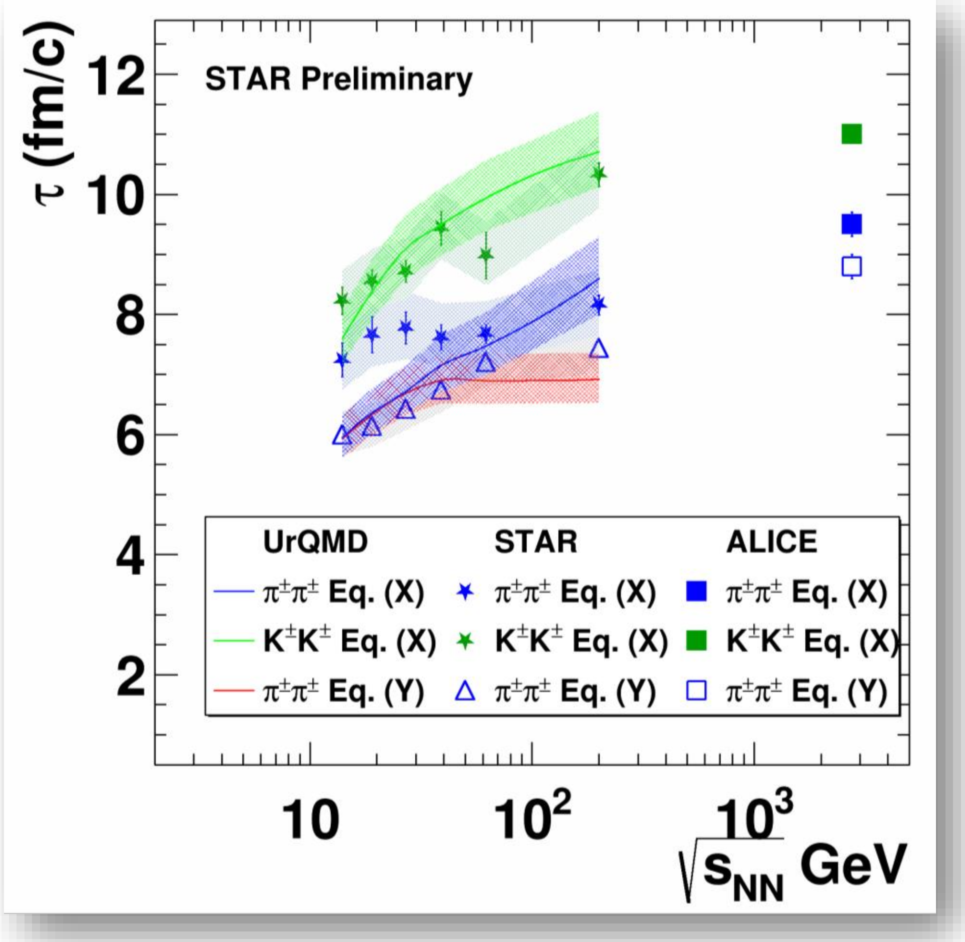
Eq. (X) $$R^2_{\mathrm{long}} = \tau^2_{\mathrm{max}} \frac{T_{\mathrm{max}}}{m_{\mathrm{T}} \cosh y_{\mathrm{T}}} \left(1 + \frac{3T_{\mathrm{max}}}{2m_{\mathrm{T}} \cosh y_{\mathrm{T}}}\right)$$

Eq. (Y) $$R_{\mathrm{long}} = \tau \sqrt{\frac{T}{m_T} \frac{K_2(m_T/T)}{K_1(m_T/T)}}$$

- Kaons cannot be described by Eq. Y
- In the case of longitudinally boost-invariant matter expansion with significant transverse flow, Eq. X should be used instead

Nucl. Phys. A 1016 (2021)

Energy dependence of emission time

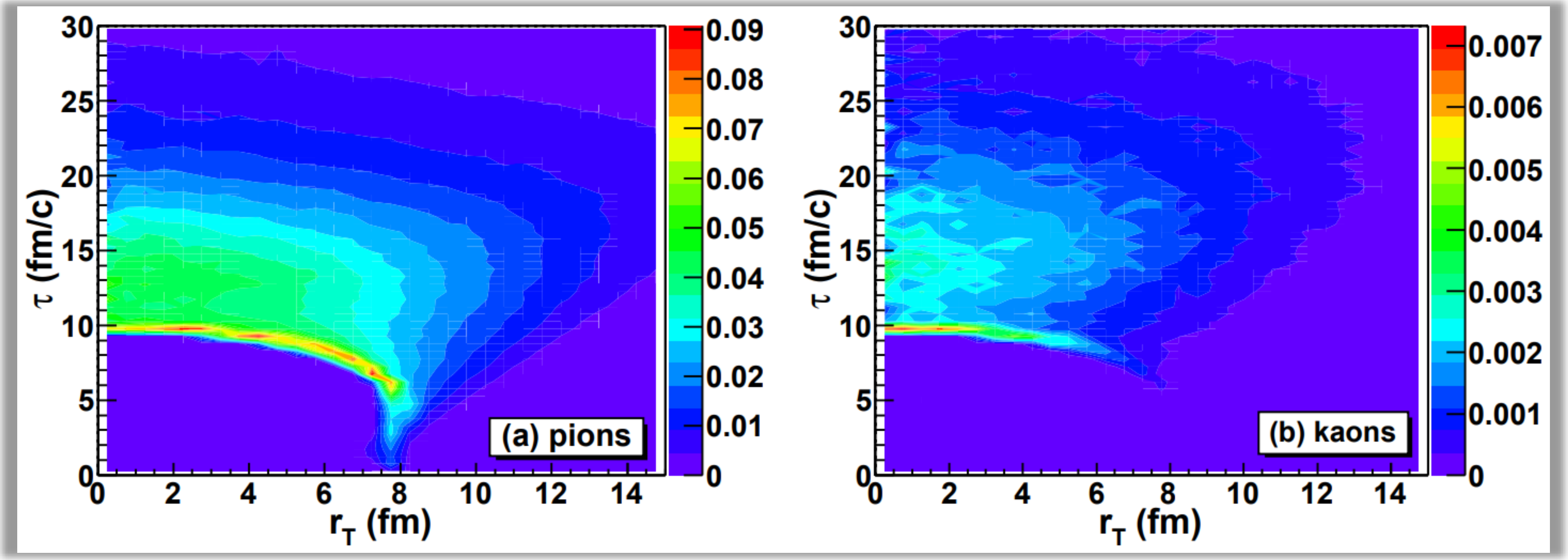


- The emission time of both pions and kaons increases with energy
- UrQMD model agrees with the data
- Kaons are emitted later than pions
  - Influence of resonance (K*) decays

Nucl. Phys. A929 (2014) 1–8

Hydrokinetic model (HKM) insight for emission time

Nucl. Phys. A 946 (2016) 227-239



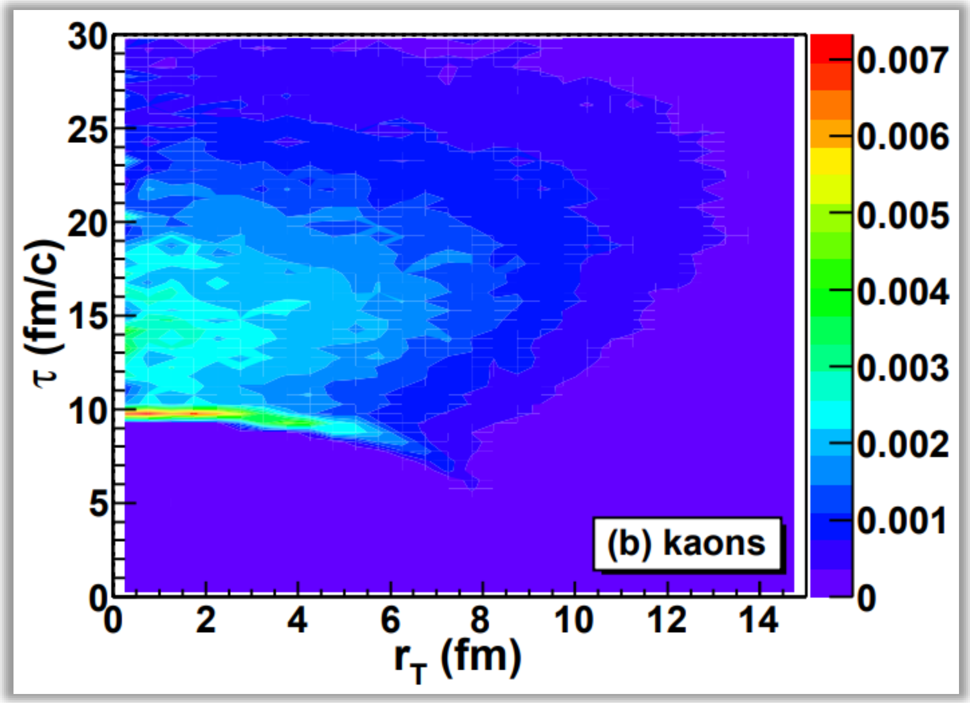
- Kaon radiation exhibits two maxima
- The second maximum is caused by $K^*(892) \rightarrow \pi + K$ with a lifetime of 4-5 fm/c, leading to a mean kaon emission time of approximately 12 fm/c

HKM model insight for emission time

- When only resonance decays are taken into account, the kaon emission time deviates more from the emission time for pions
- Free streaming and decay of fast K* particles create an additional source contributing to non-Gaussian behavior in the correlation function
- Re-scattering of K* particles results in collective motion, linking the time of maximal emission to longitudinal radii

Nucl. Phys. A 946 (2016) 227-239

Nucl. Phys. A 946 (2016) 227-239



Summary

- The difference between correlation functions for positive and negative pairs of pions and kaons was first observed at these energies

- This is consistent with the Coulomb field effect caused by residual charge after the collision

- The double ratio of correlation functions in UrQMD shows an opposite effect for pions and kaons, while experimental data has the same sign for both

Summary

- Extracted radii:
  - Increase with collision energy
  - Decrease with transverse mass
  - Are generally larger for kaons compared to pions under the same conditions

- Emission time:
  - Increases with increasing energy
  - Longer for kaons than for pions
    - Kaons influenced by K* decays

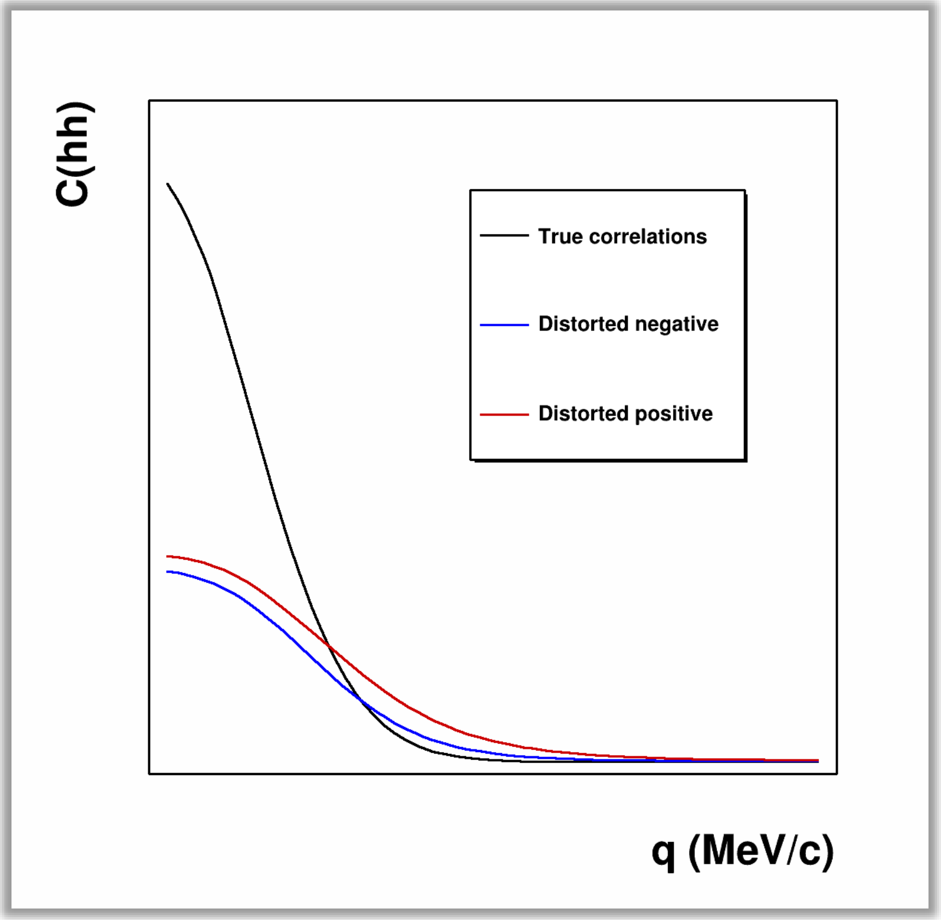
- The UrQMD model agrees with the data

Thank you for the attention!

Back-up

- Pictures with FXT experimental results were taken from Vinh Luong’s talk on ISHEP-2023

Coulomb effect from residual source



- Creating a toy model with exponentially distributed momentum and Gaussian coordinates for particles
- Applying weights to the Δp (particle momentum difference) distribution

$$w = 1 + \cos(\Delta p \Delta x)$$

- Distorting momentum due to the Coulomb force
- Applying same weights to the distorted Δp distribution
- Applying realistic cuts for momentum and pseudorapidity