Echoes from the Fireball: What Femtoscopy Reveals at RHIC

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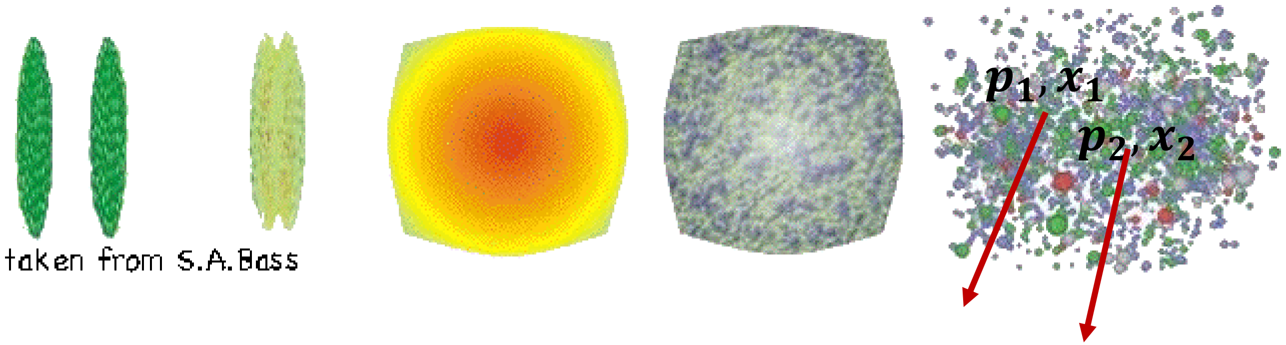
CIPANP 2025

What can we measure?



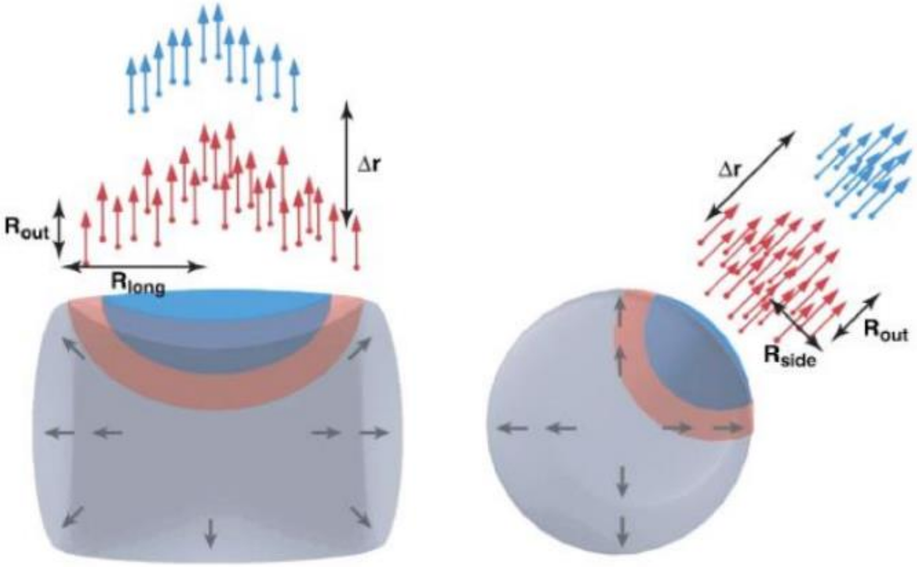
- Size: ~10^{-15} m (~ 1 fm), time: ~ 10^{-23} s
  - impossible to measure directly

Kinetic freeze-out

- Momentum (p) is accessible in experiment

Femtoscopy

- Femtoscopy measures so-called regions of homogeneity (phase space region of outgoing particles with similar velocity vector)
- We can probe different homogeneity regions by varying pairs' transverse momenta

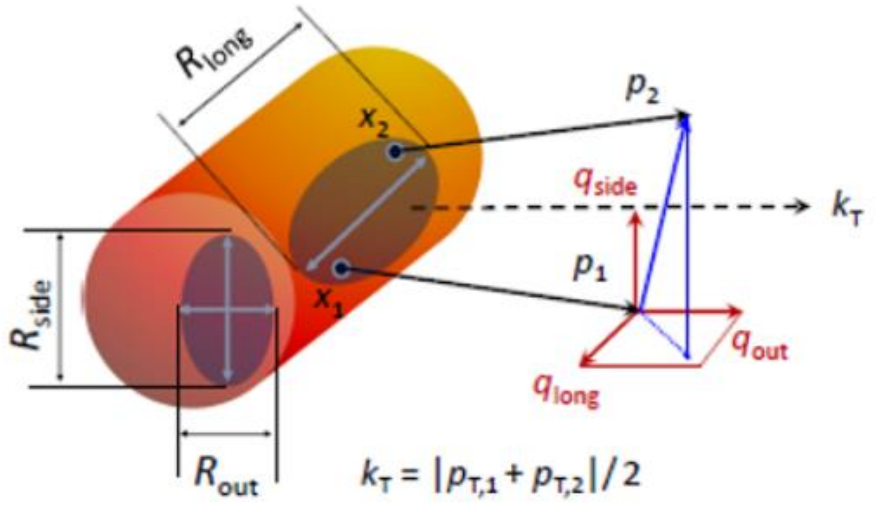


Ann.Rev.Nucl.Part.Sci. 55 (2005) 357-402

- Femtoscopy allows one to explore:
  - ➢Size of the emission source
  - ➢Lifetime of source
  - ➢Emission duration
  - ➢System dynamics
  - ➢Source shape
  - ➢Orientation
  - ➢FSI

Correlation femtoscopy procedure

$$C_{\mathbf{P}}^{ab}(\mathbf{q}) = \frac{A_{\mathbf{P}}^{ab}(\mathbf{q})}{B_{\mathbf{P}}^{ab}(\mathbf{q})}$$ Signal / Background



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

$$C(q) = N[(1-\lambda) + \lambda K(q)(1 + G(q))]$$

$$G(q) = e^{-\sum_{i,j=o,s,l}\left(q_i q_j R_{ij}^2\right)^{\alpha/2}} + FSI$$

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
α = 2 – Gaussian (standard approach in femtoscopy) or free parameter in “Levy-stable source” approach
FSI – final state interaction

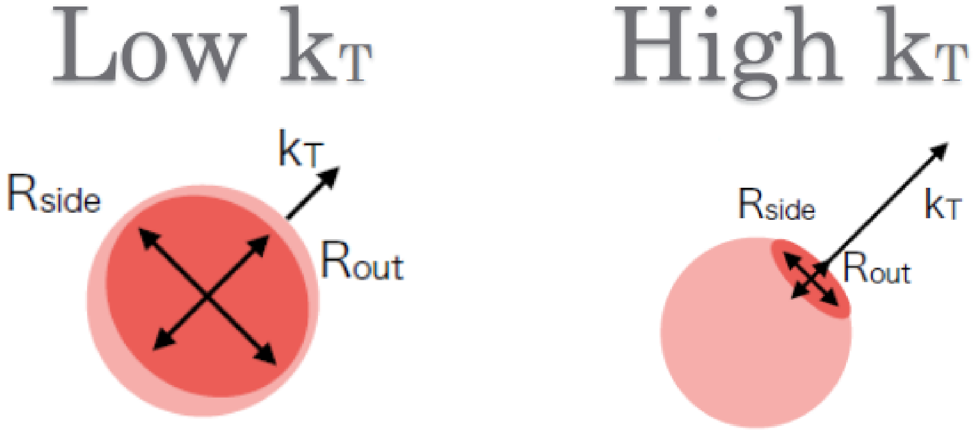
Fit using log-likelihood method

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

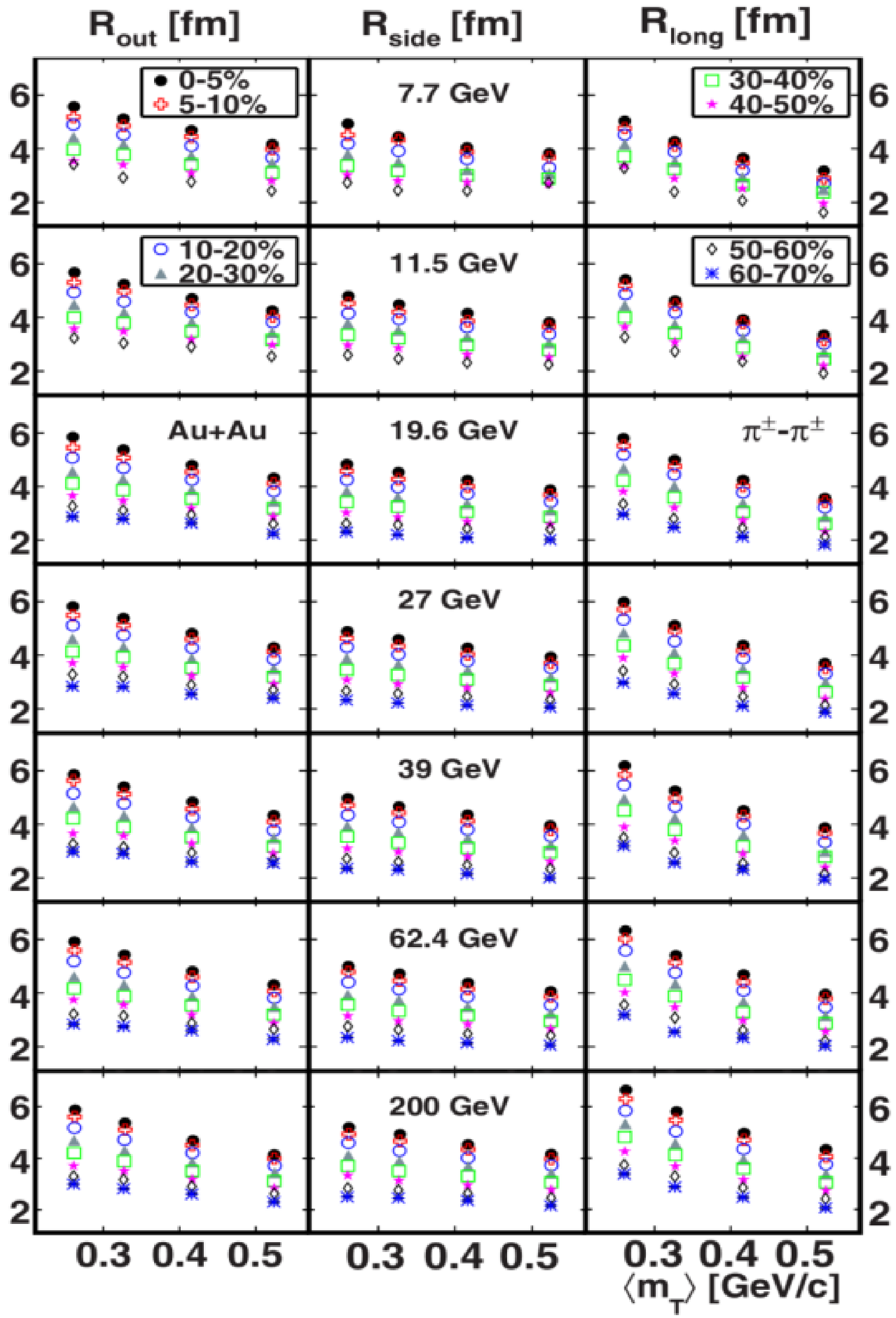
$$C = \frac{A}{B}$$

Pions in BES

- Larger m_T pairs are emitted from smaller emission regions with less correspondence to the size of the entire fireball



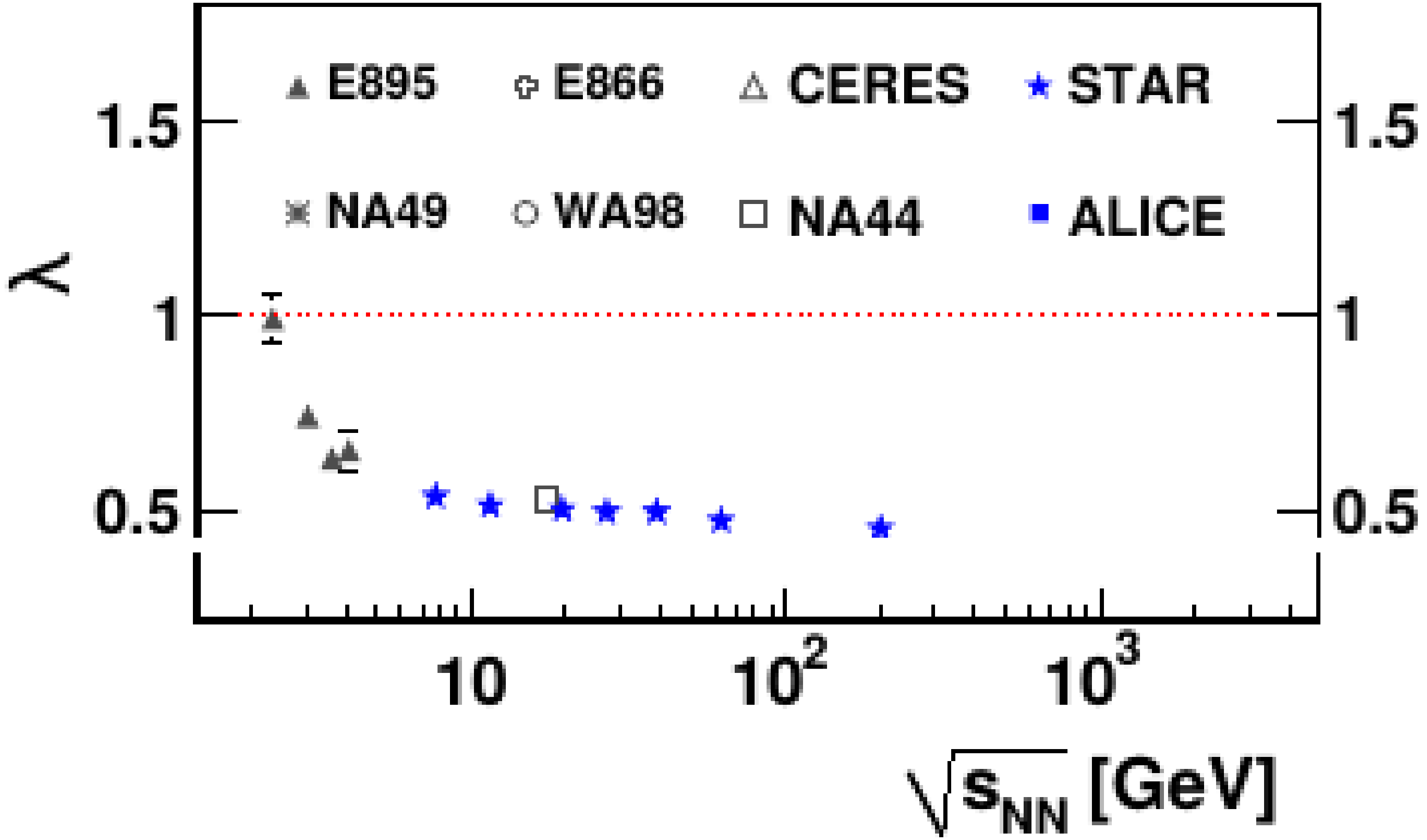
PRC 92 (2015) 014904



Pions in BES

- The λ (fraction of correlated pairs) of pions from long-lived resonances increases at lower energies assuming clearer source to study

PRC 92 (2015) 014904



Pions in BES

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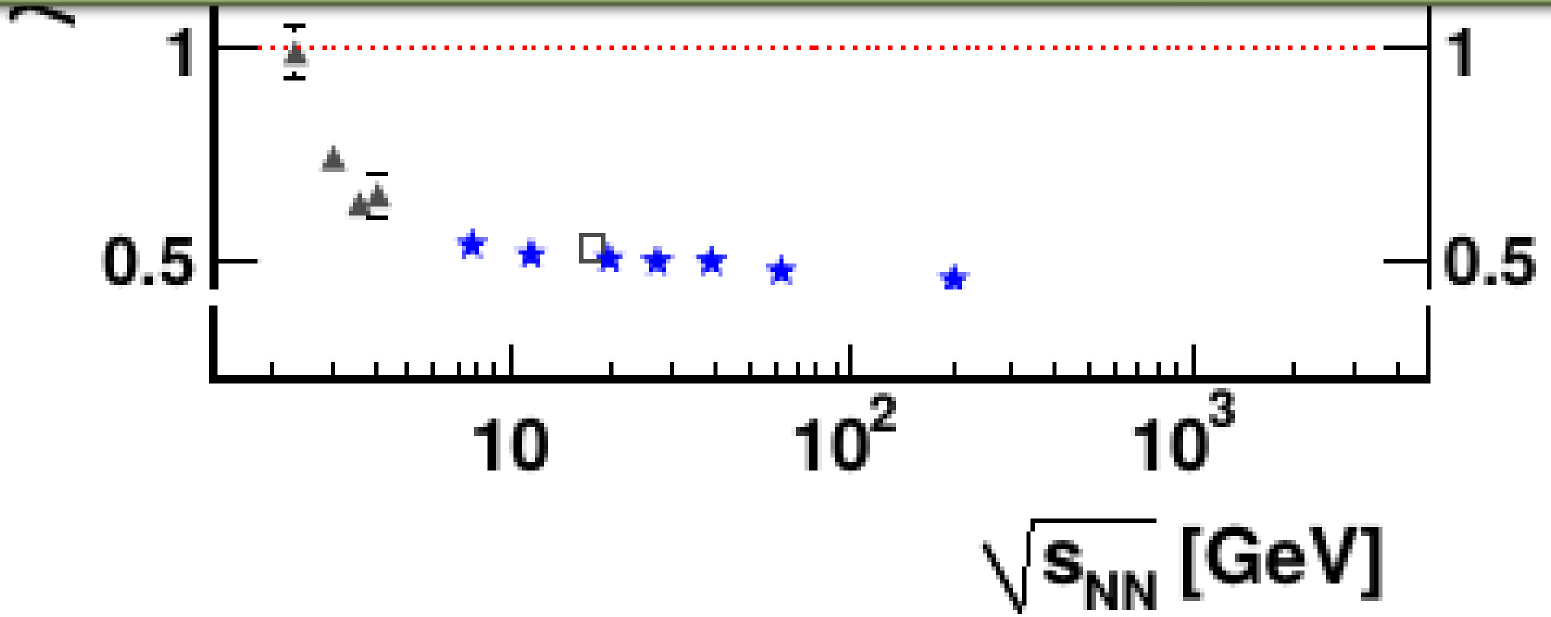
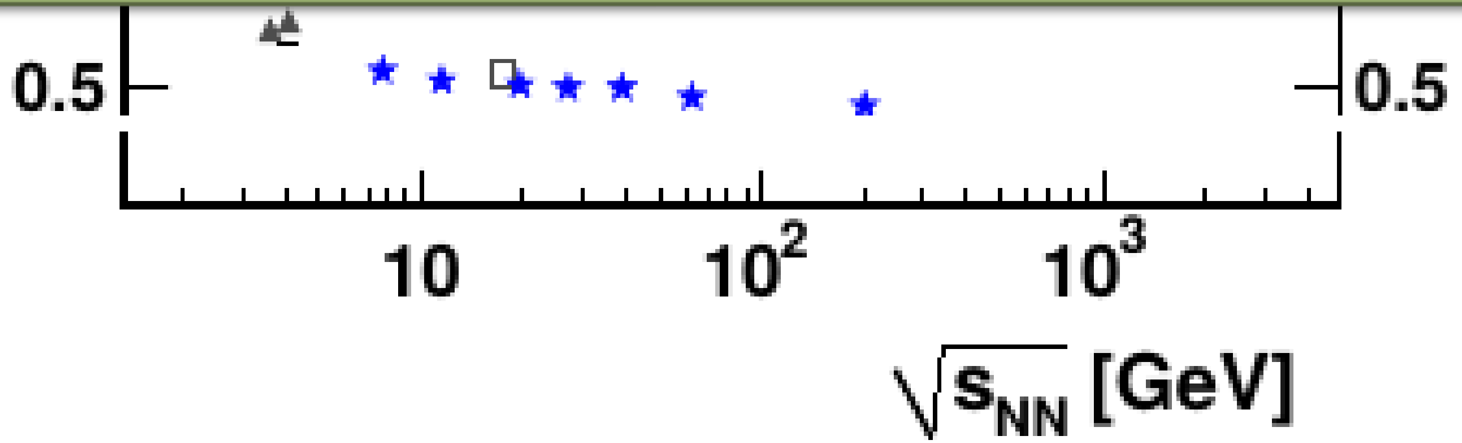
1) Motivation to study source at lower energies



Pions in BES

- The λ (fraction of correlated pairs) of pions from long-lived resonances increases at lower energies assuming clearer source to study

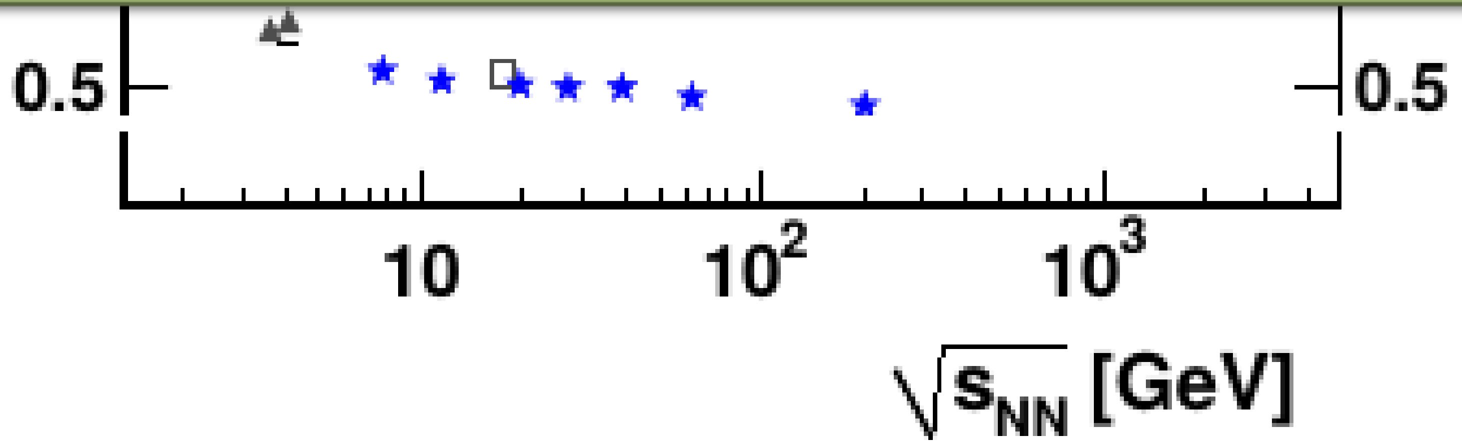
2) Look at the kaons instead of pions (should be less affected by resonances)



Pions in BES

- The λ (fraction of correlated pairs) of pions from long-lived resonances increases at lower energies assuming clearer source to study

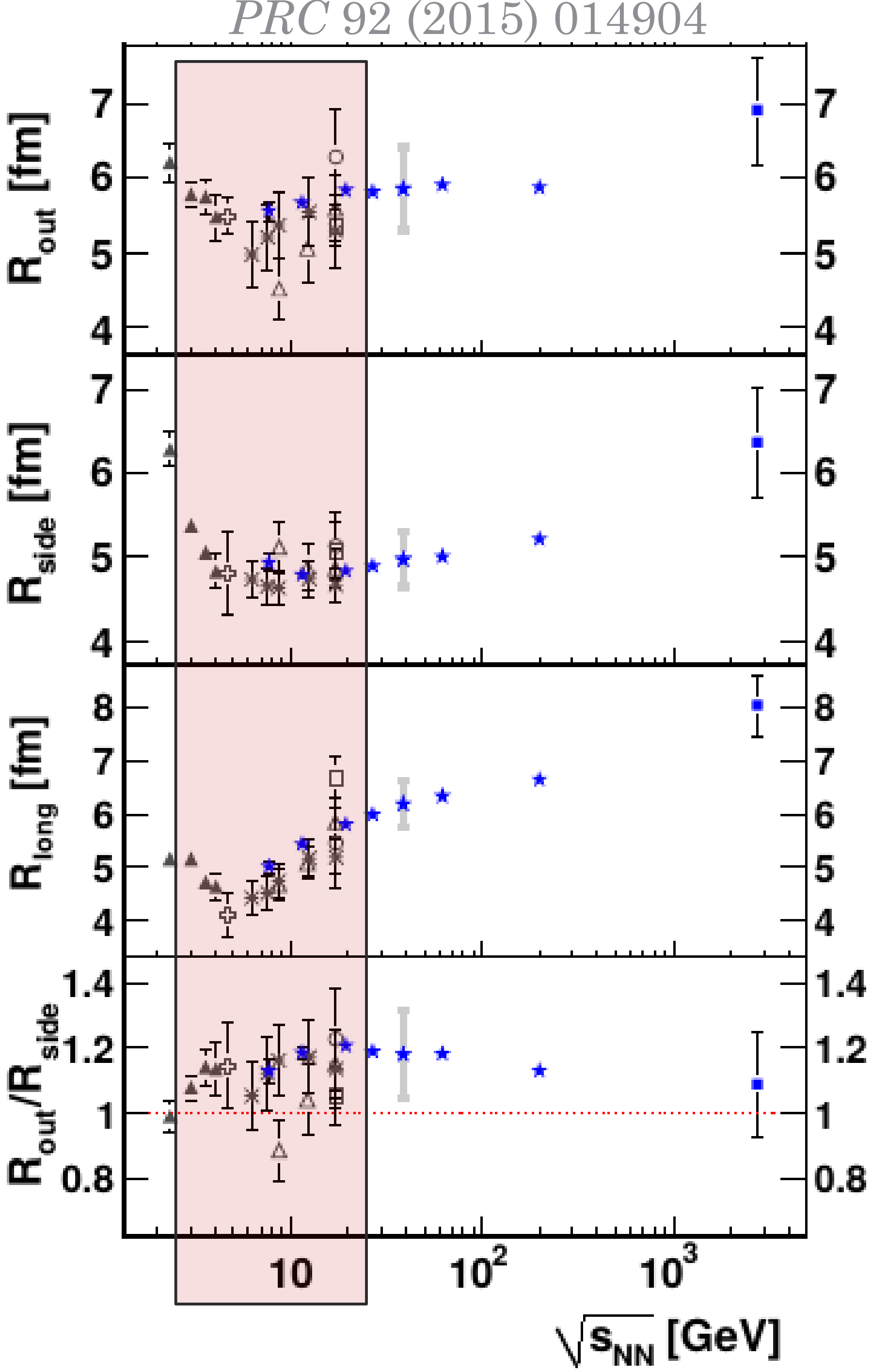
3) Study of non-Gaussian behavior introduced by long-lived resonances?



Pions in BES

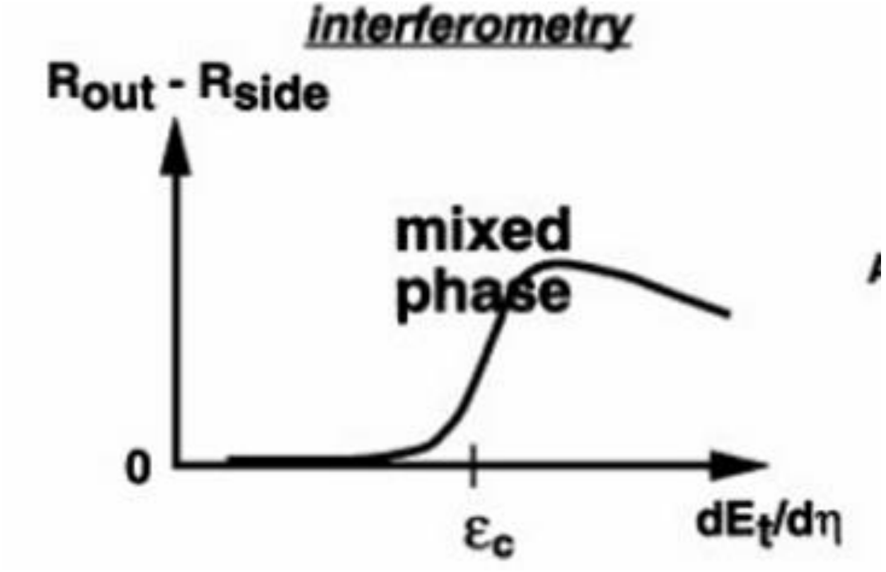
- Big uncertainties in the radii obtained from different experiments

Motivation to study source at lower energies



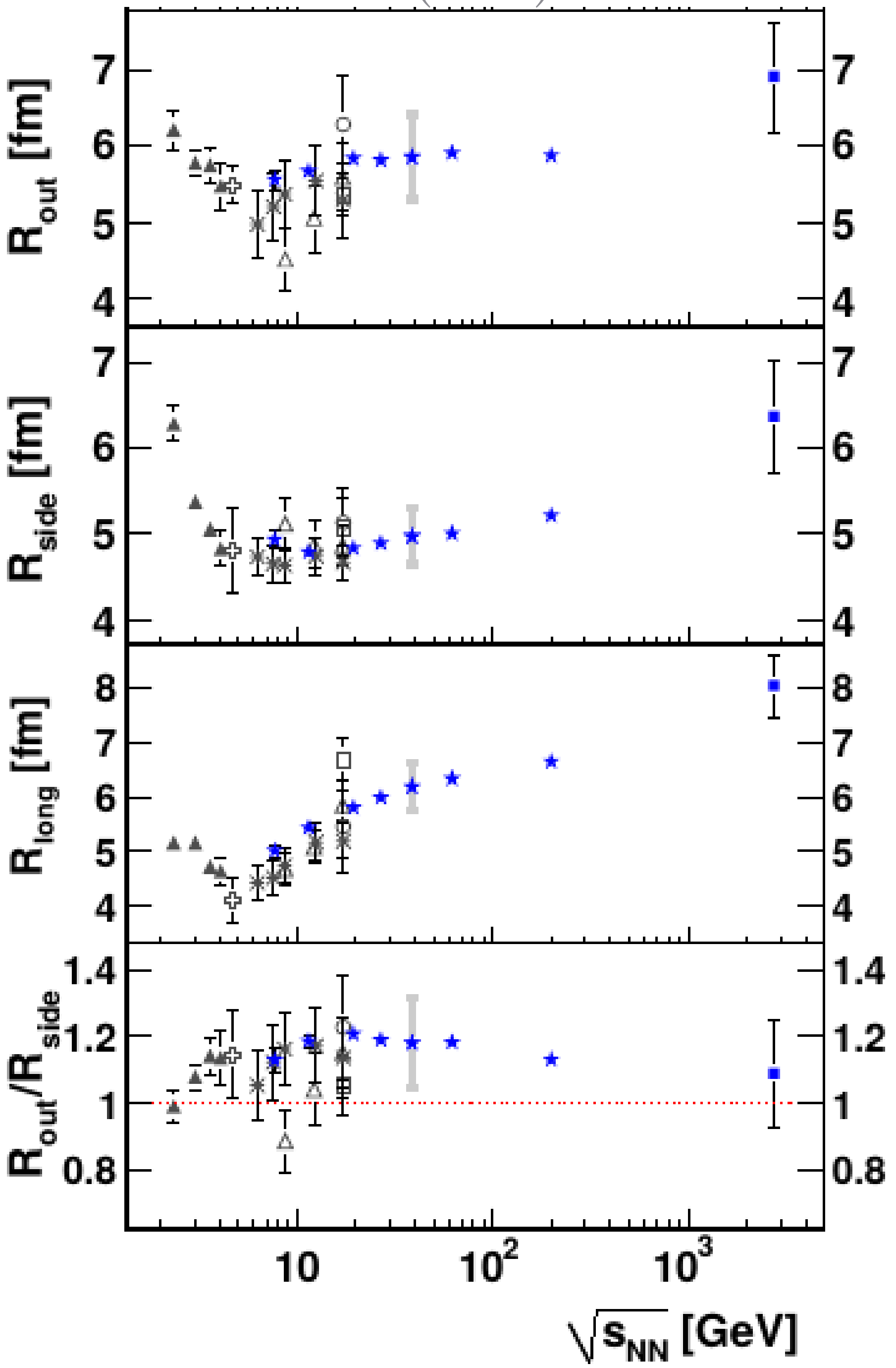
Pions in BES

- The ratio Rout/Rside or their difference as a possible way to search for critical point



Ann. Rev. Nucl. Part. Sci. 46, 71 (1996)

PRC 92 (2015) 014904



Pions in BES

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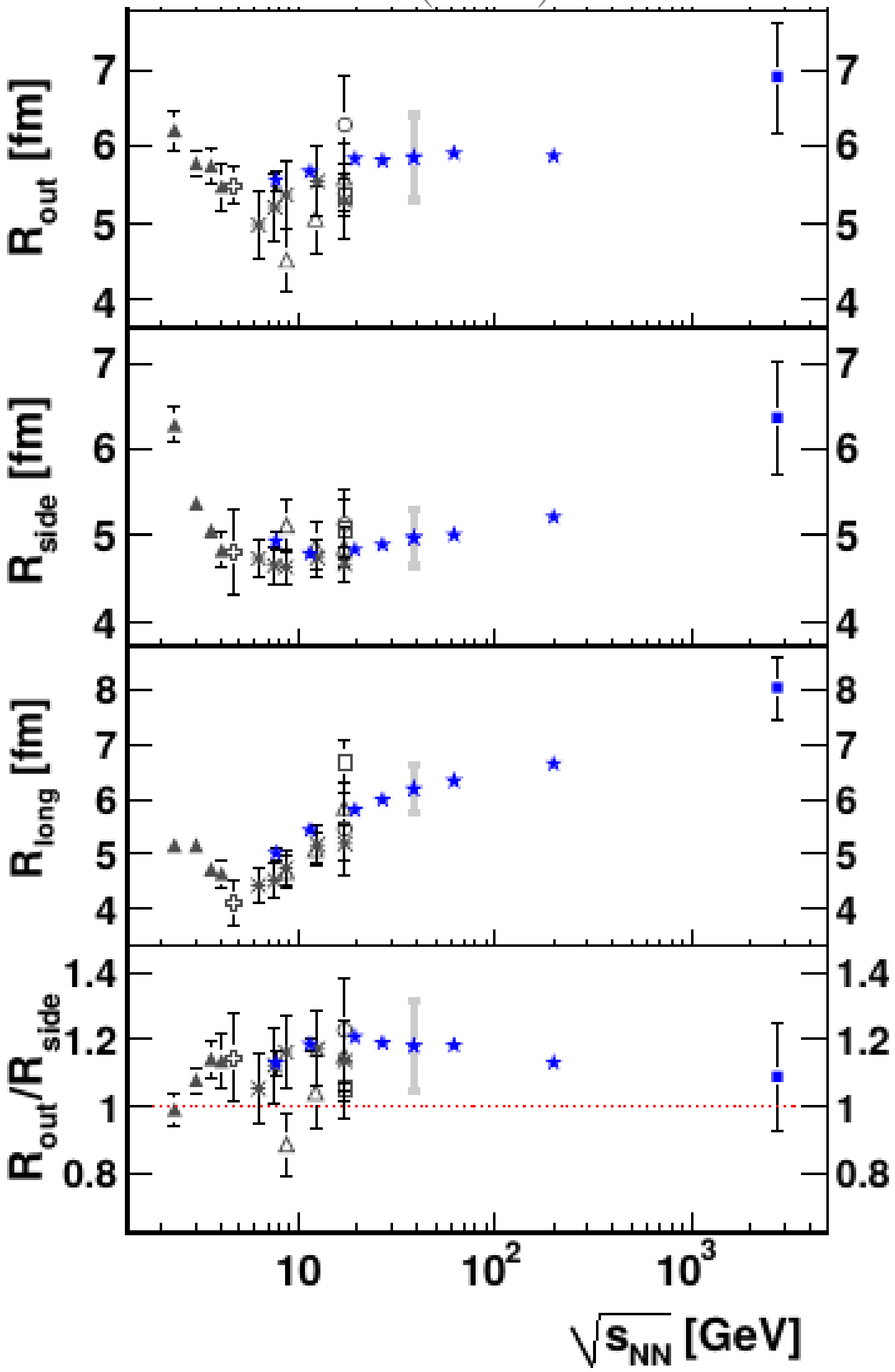
Motivation to study source at lower energies

PRC 92 (2015) 014904



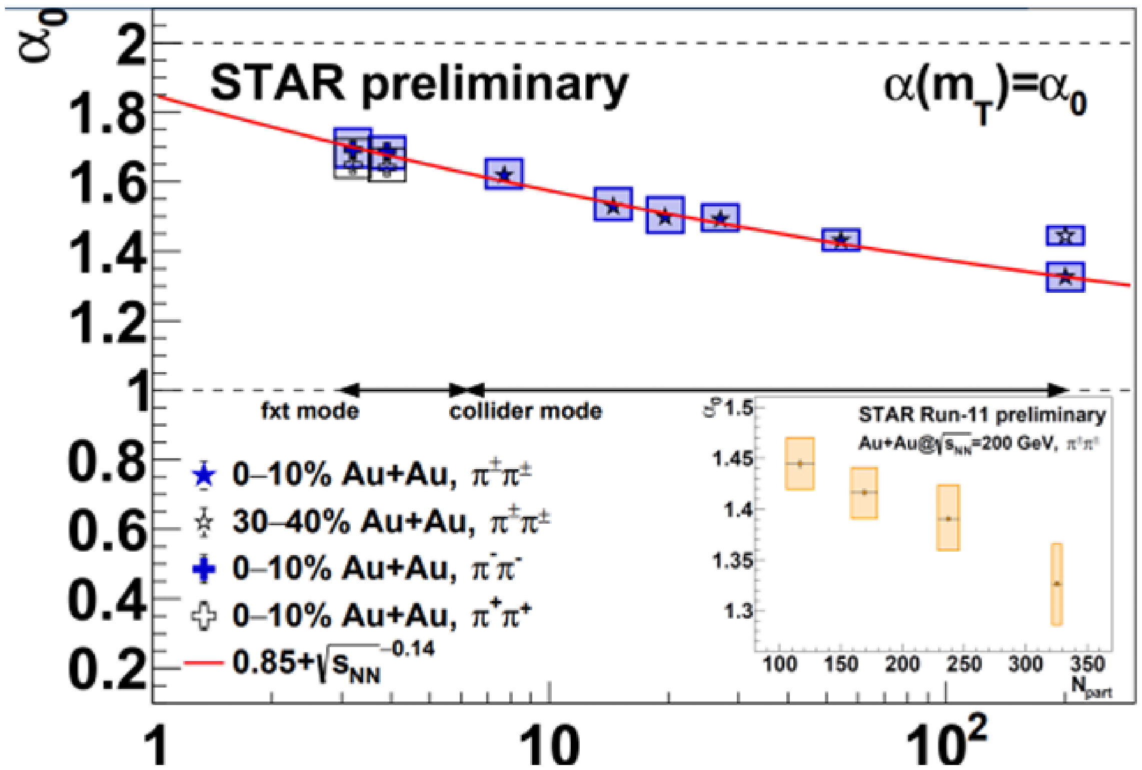
Levy-distributed sources

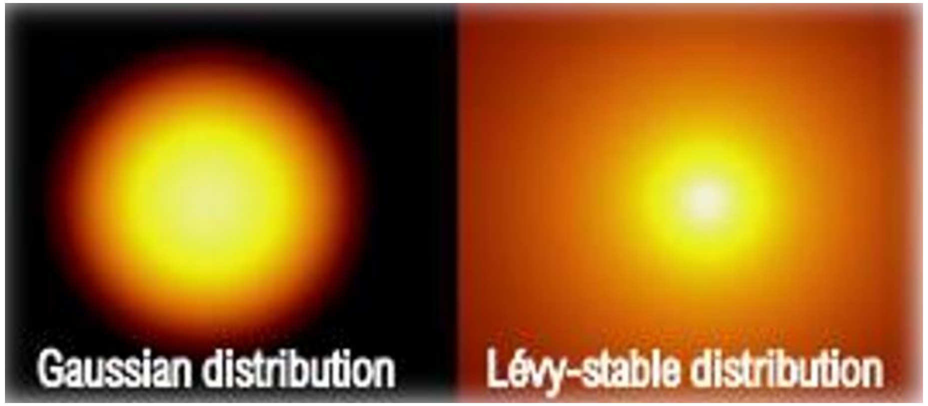
QM2025 Mate Csanad

$$C(q) = N(1-\lambda) + NK(q)\lambda exp\left[-\sum_{i,j=o,s\,l}\left(q_i q_j R_{ij}^2\right)^{\alpha/2}\right]$$

N - normalization factor,
λ - the correlation strength
$K(q)$ accounts for Coulomb effect,
$\alpha = 2$ – Gaussian (standard approach in femtoscopy) or free parameter in "Levy-stable source" approach

QM2025 Mate Csanad



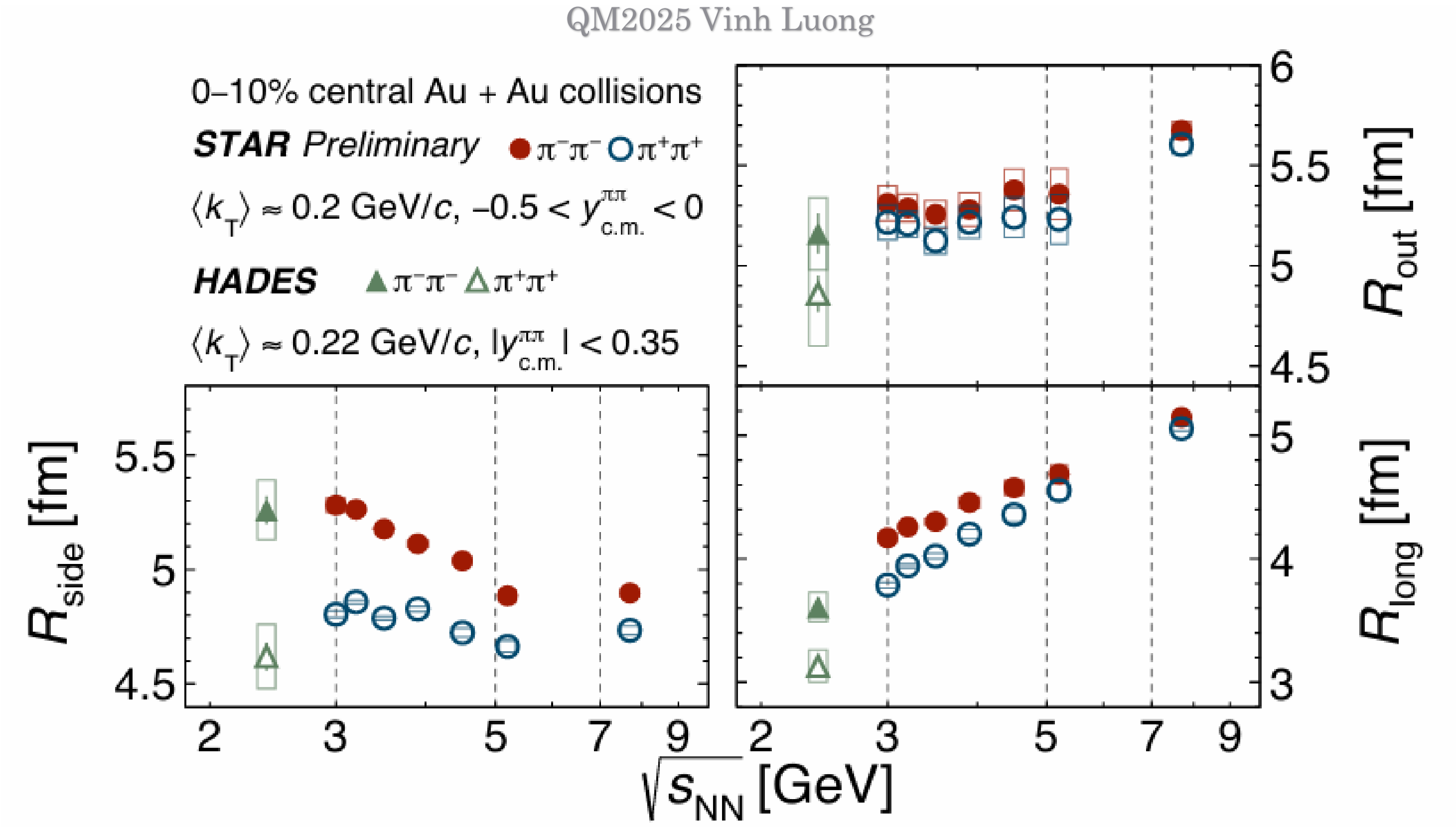


Possible reasons for non-Gaussianity:

- Anomalous diffusion
- Critical behavior
- Jets
- Resonance decays
- Levy-walk

Pions at low energies

- Good statistics – resolves tension between previous data
- Clear difference between π^+ and π^- source



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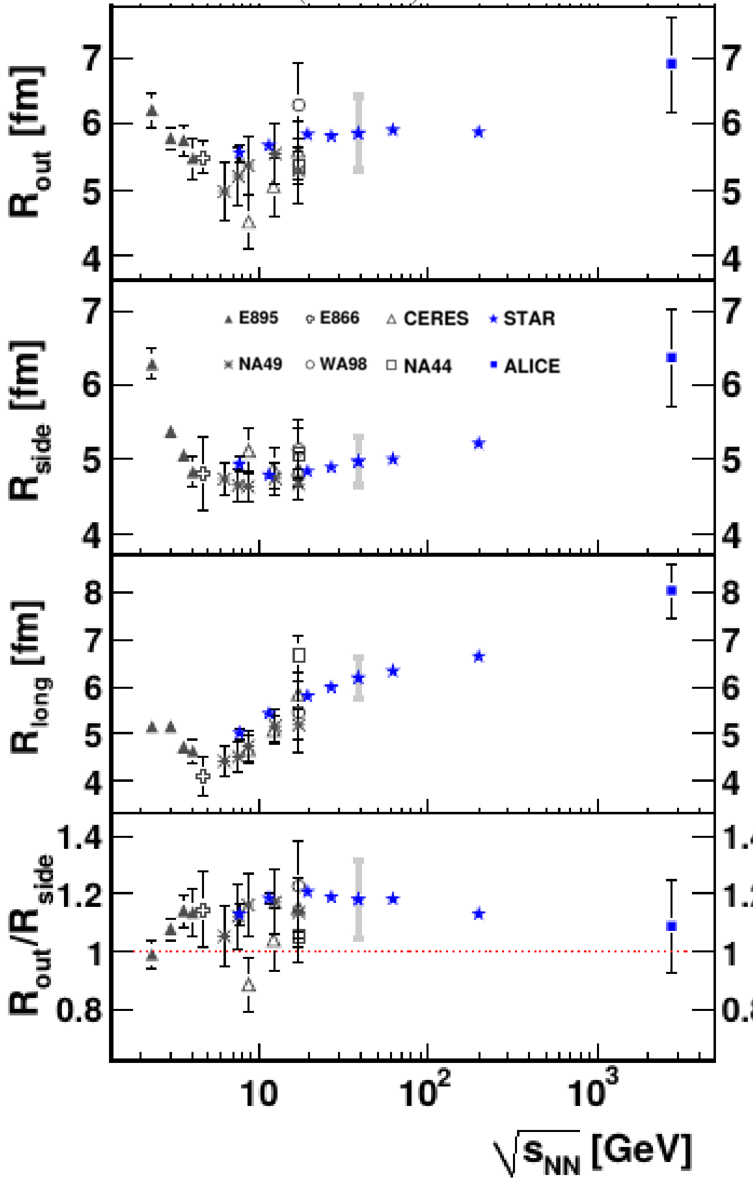

Pions and kaons at ALL energies

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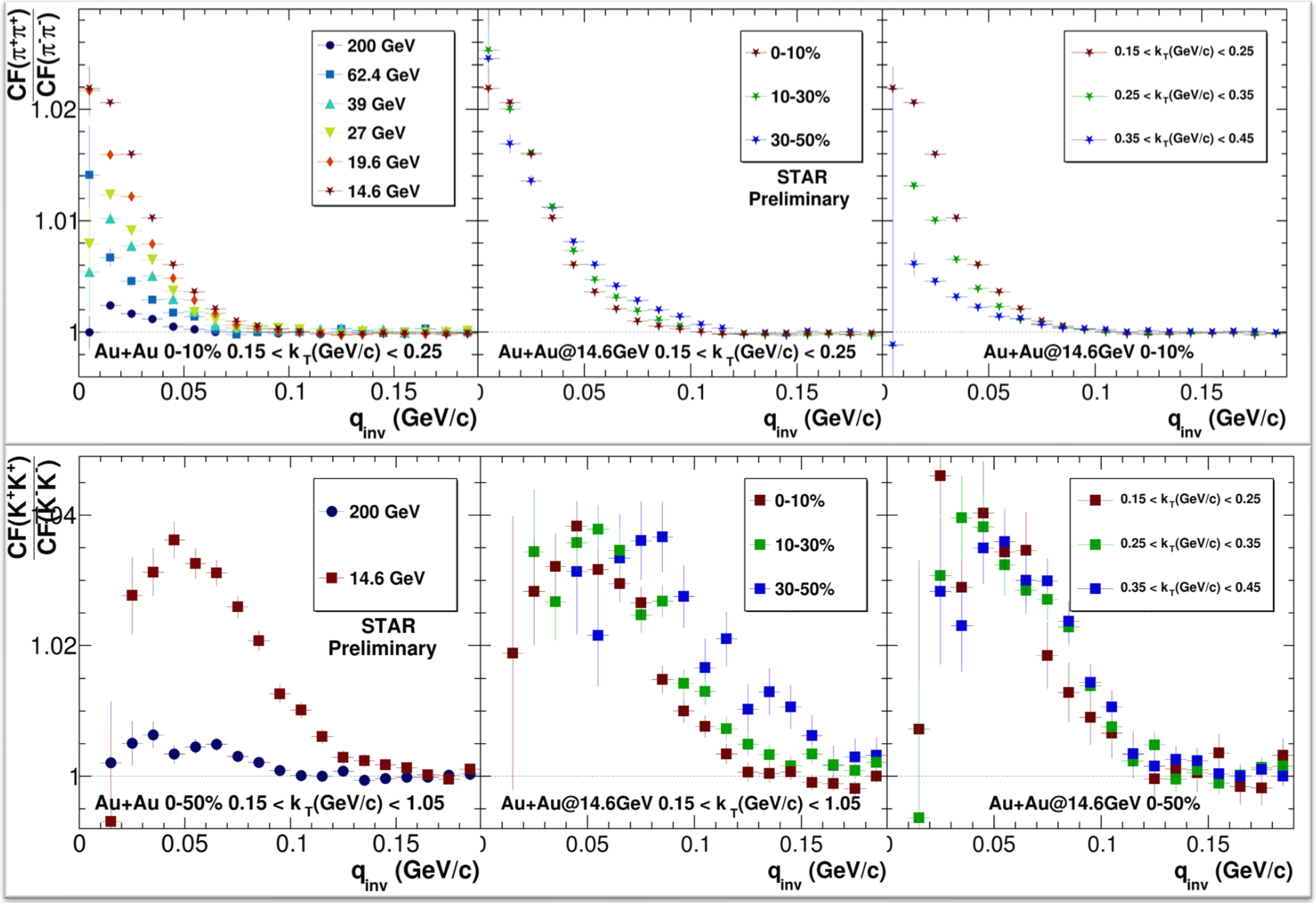

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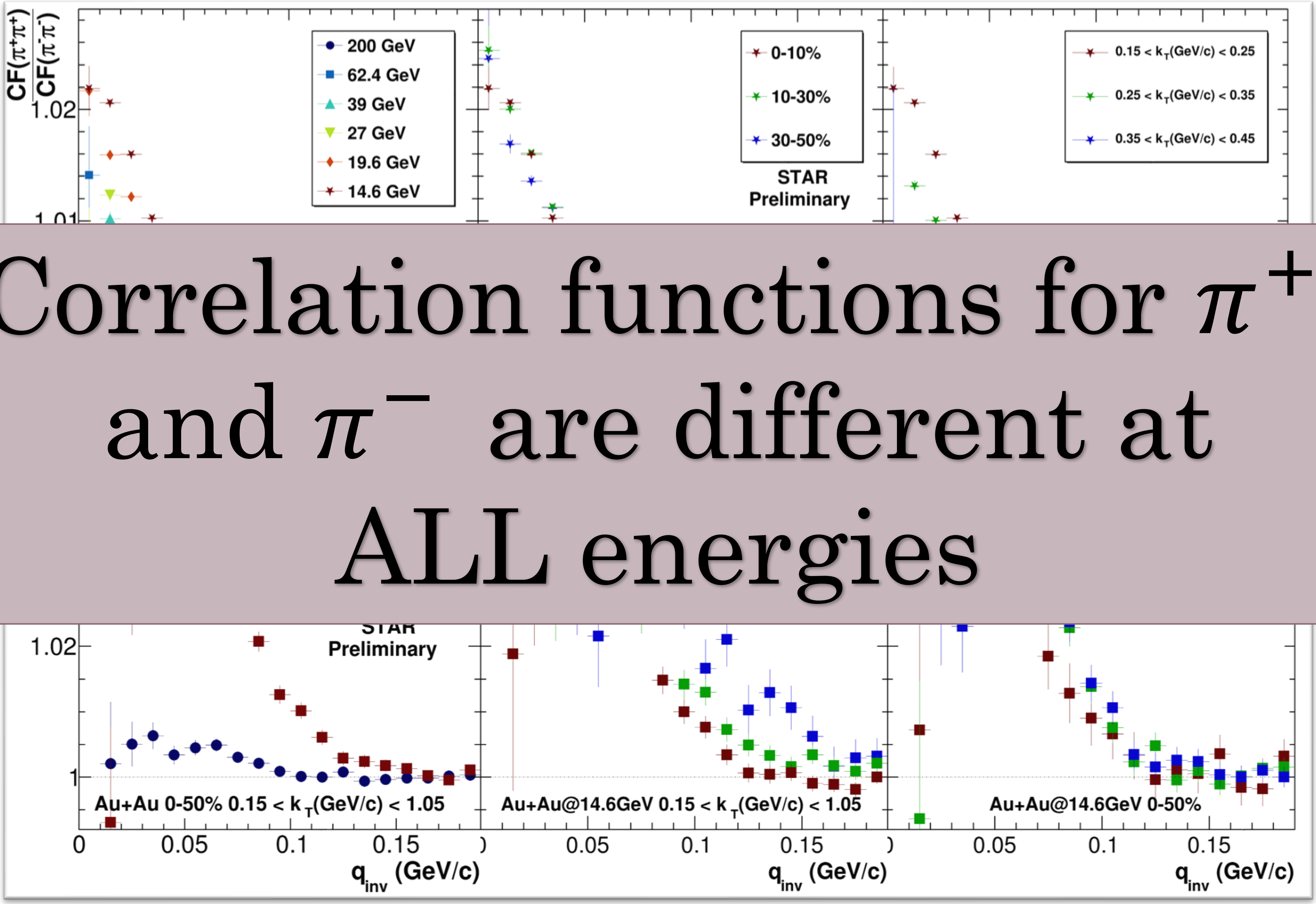
WPCF2023 Yevheniia Khyzhniak

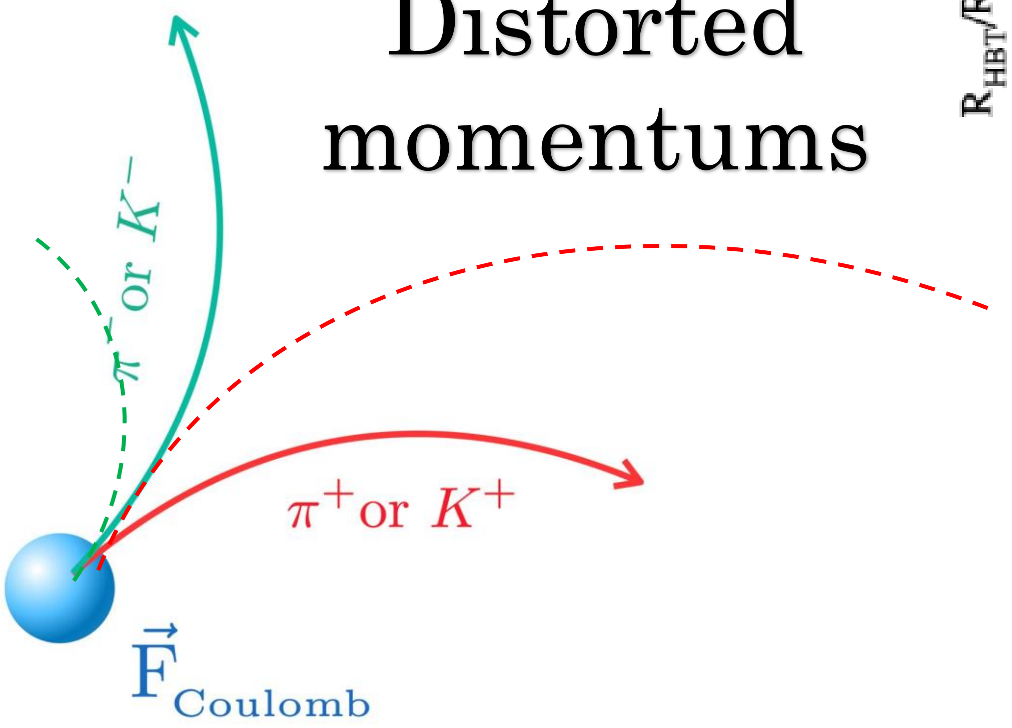


Correlation functions for π^+ and π^- are different at ALL energies

Source of the charge difference

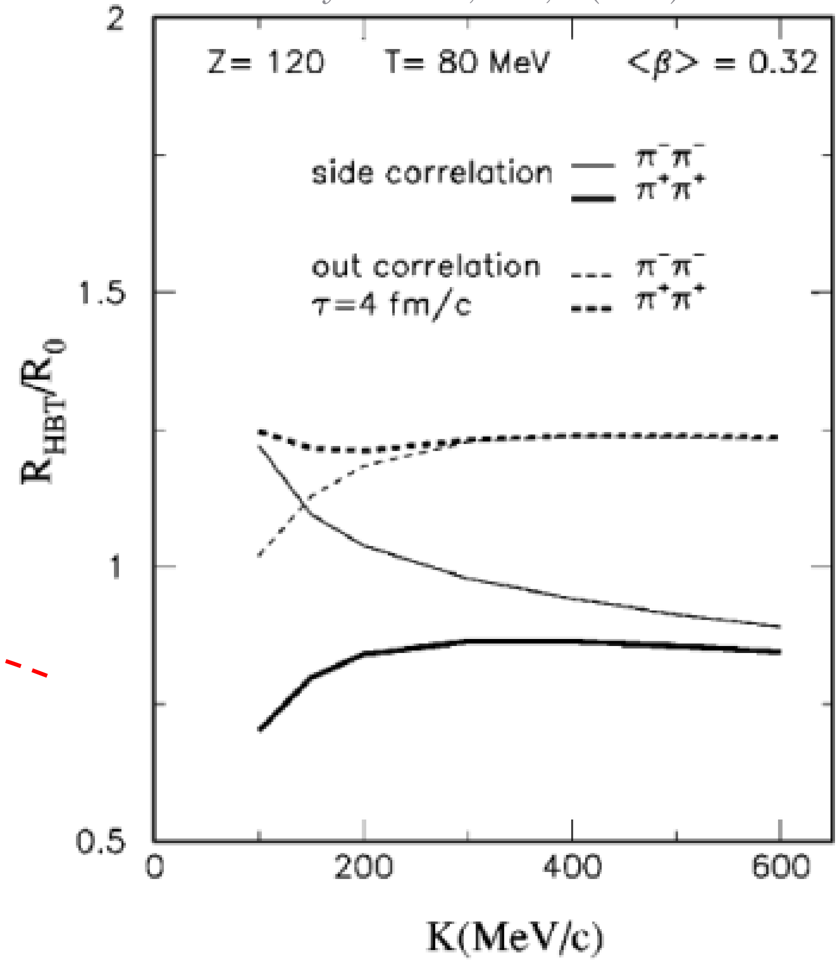
- Coulomb Effect from Residual Source

Distorted momentums



Positively charged source

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



Expected difference between true and distorted by Coulomb effect HBT radii

Source of the charge difference

- 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 -> which gives distinguishing power

➢Isospin effect

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

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

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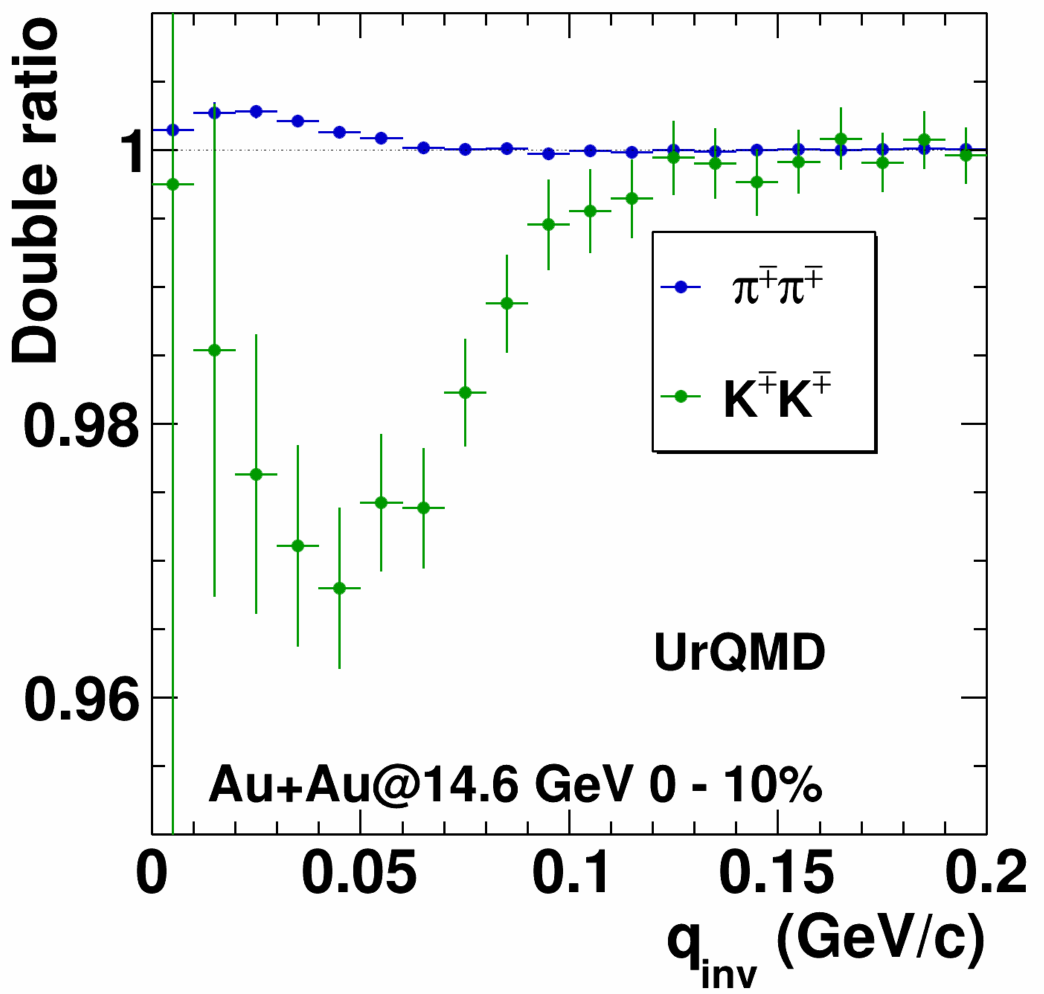
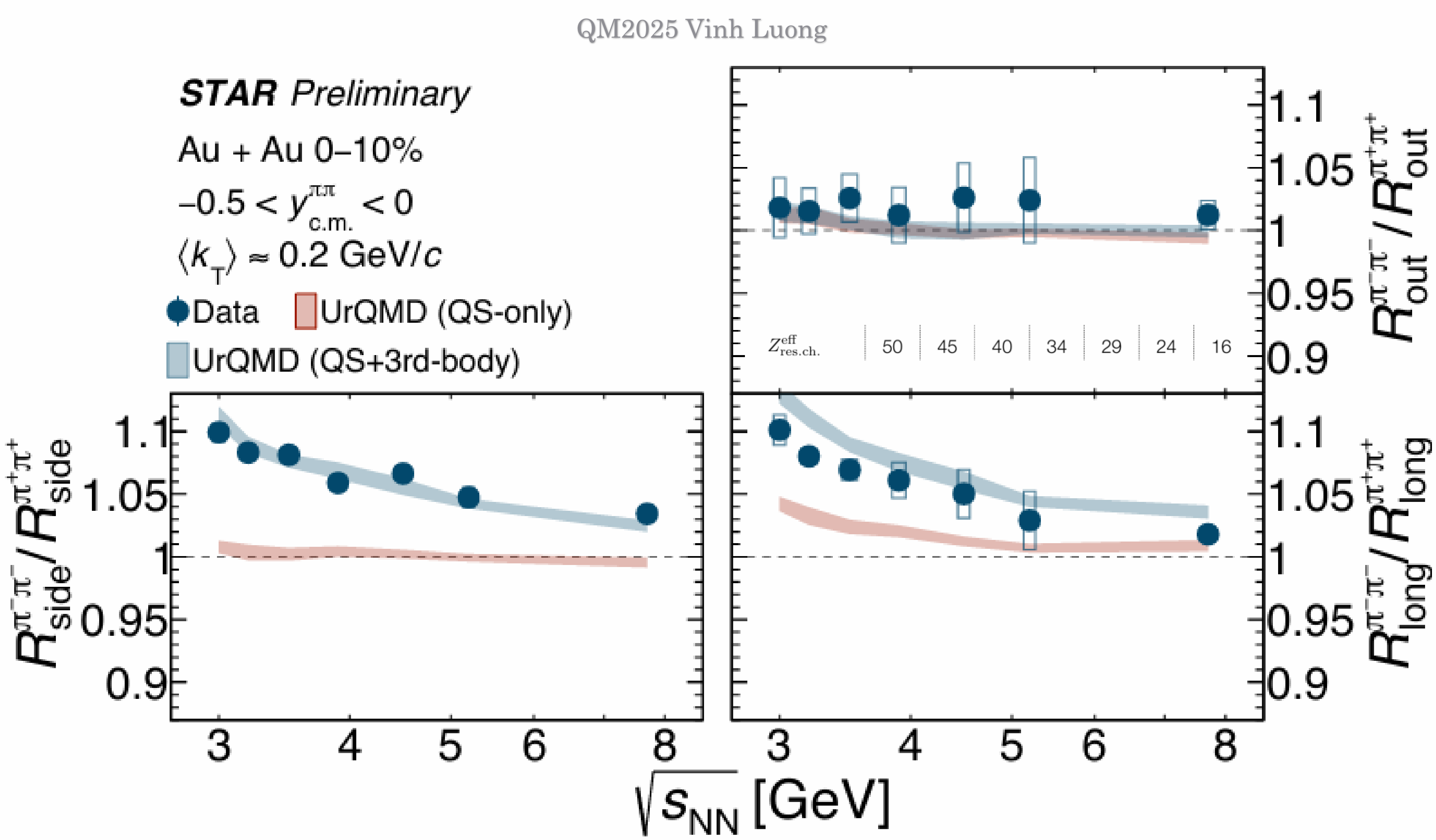


UrQMD Vs Data

- Majority of the effect (at least in the out and side directions) described by the Coulomb effect

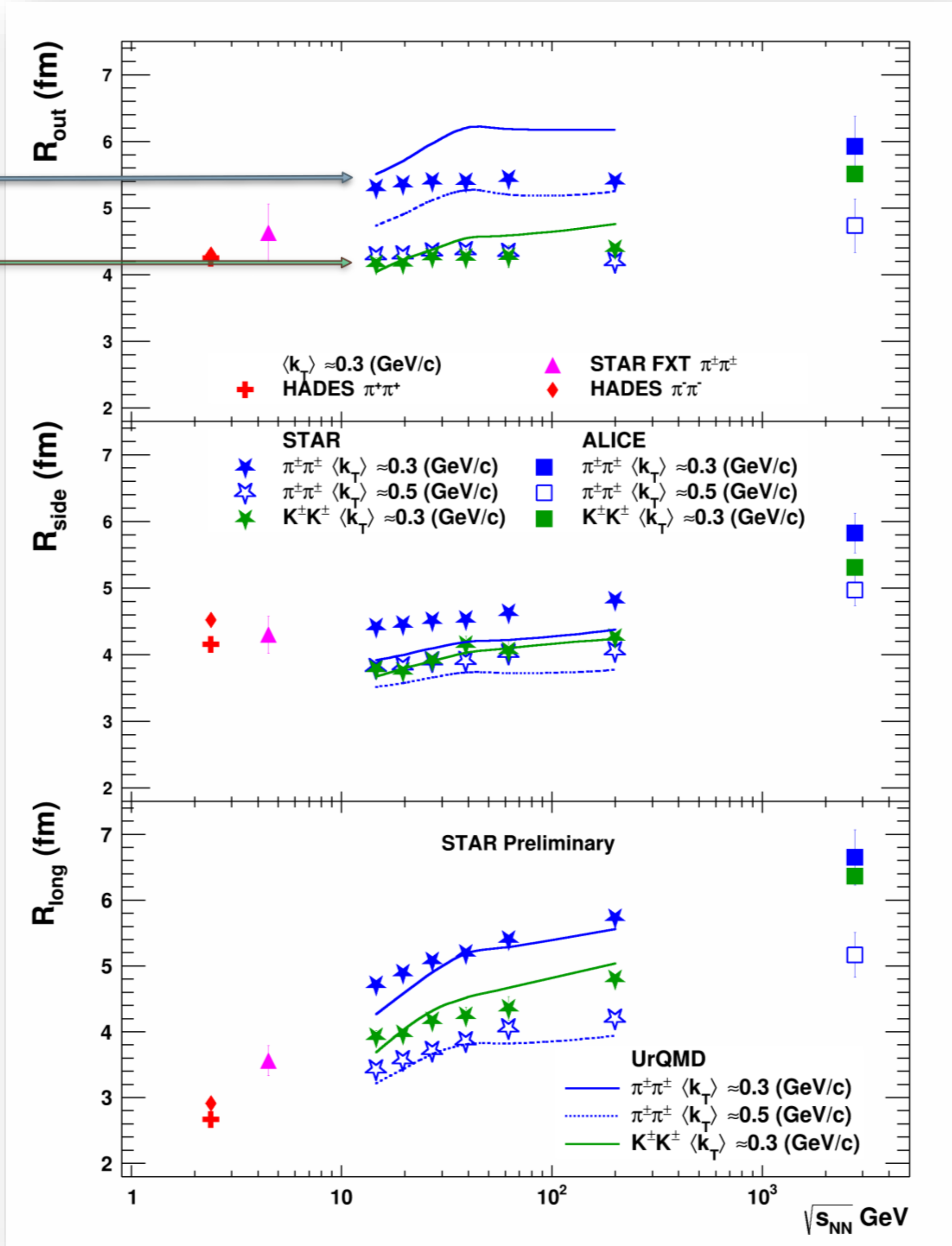


Charged kaons

- 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

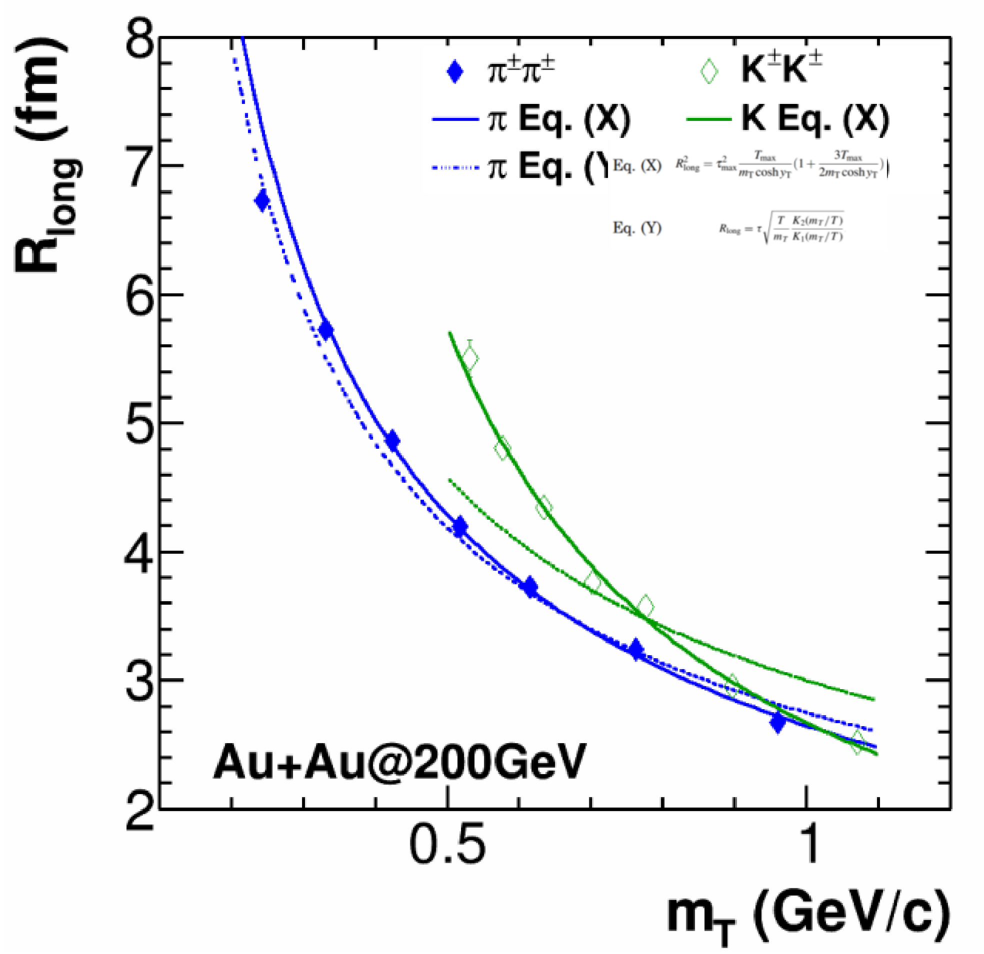
Pions

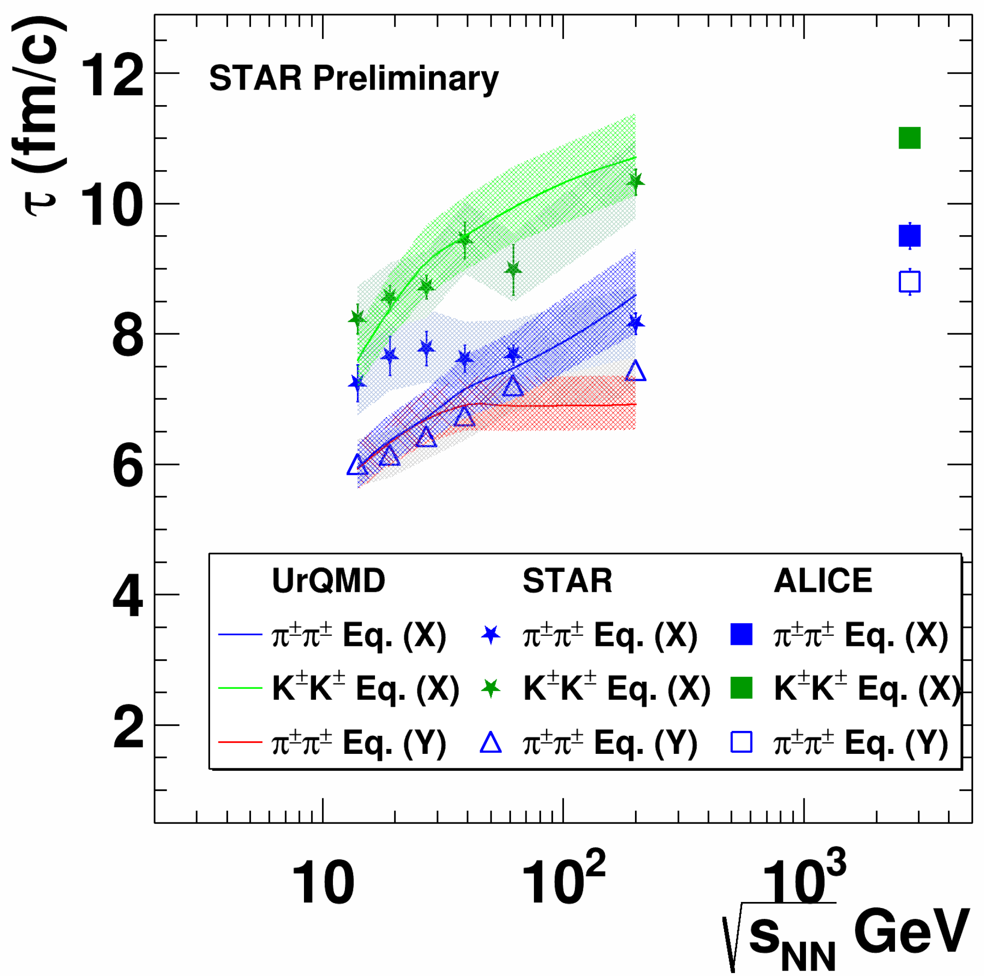
Kaons



Charged kaons

- Kaons are emitted later than pions at all energies!

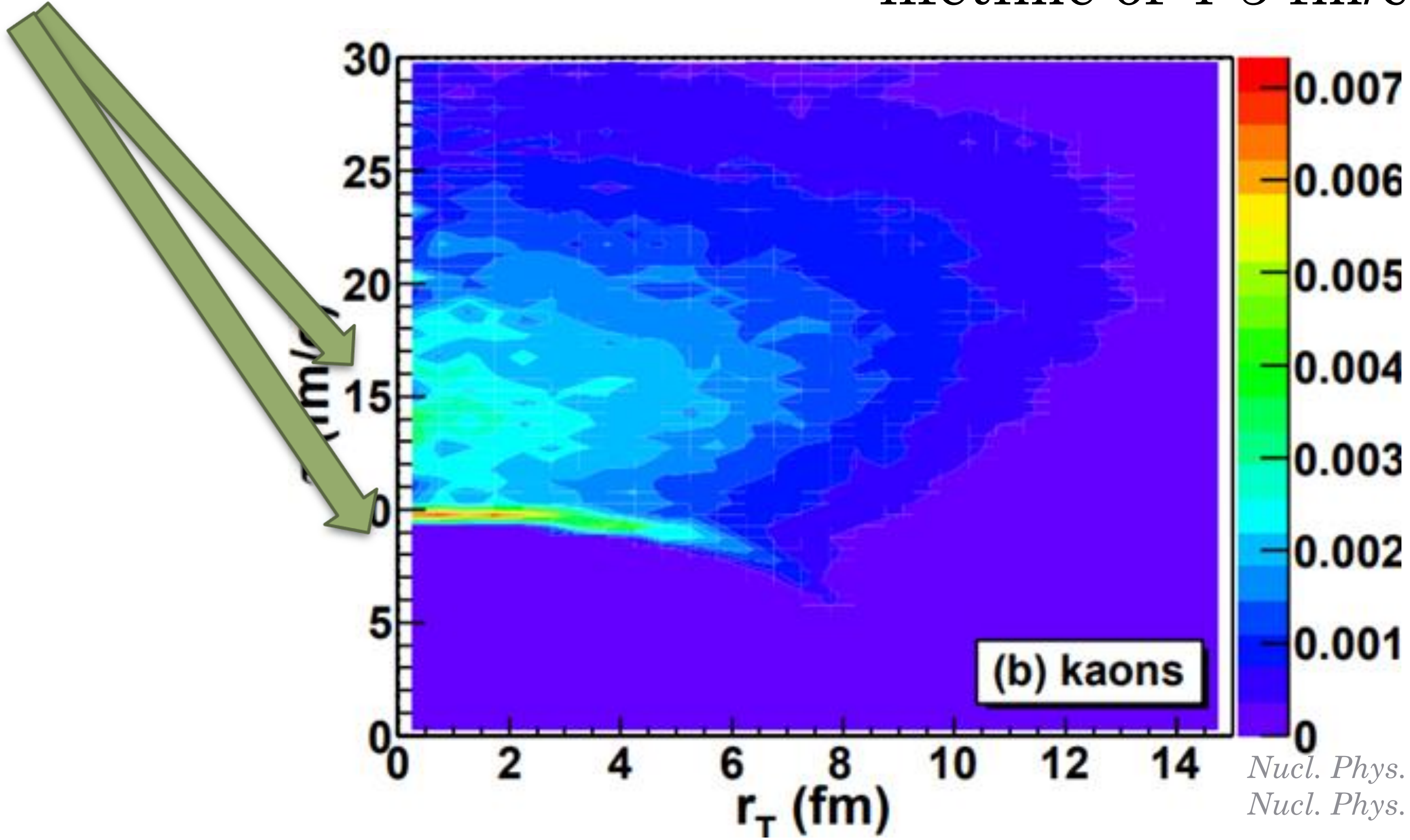




Charged kaons

- Kaon radiation exhibits two maxima

- The second maximum is caused by $K^*(892) \rightarrow \pi + K$ with a lifetime of 4-5 fm/c



Nucl. Phys. A 929 (2014) 1–8
Nucl. Phys. A 946 (2016) 227-239

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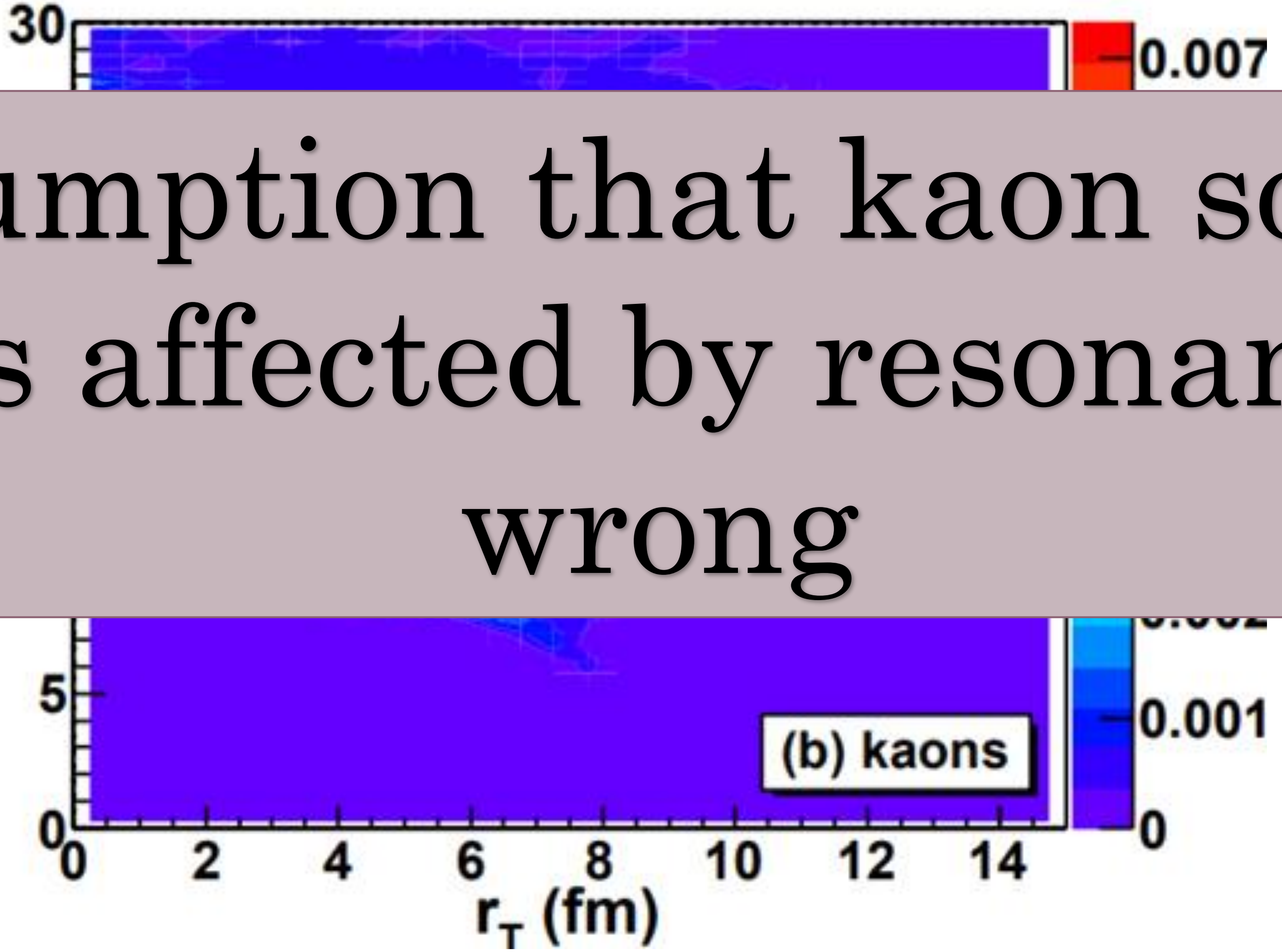
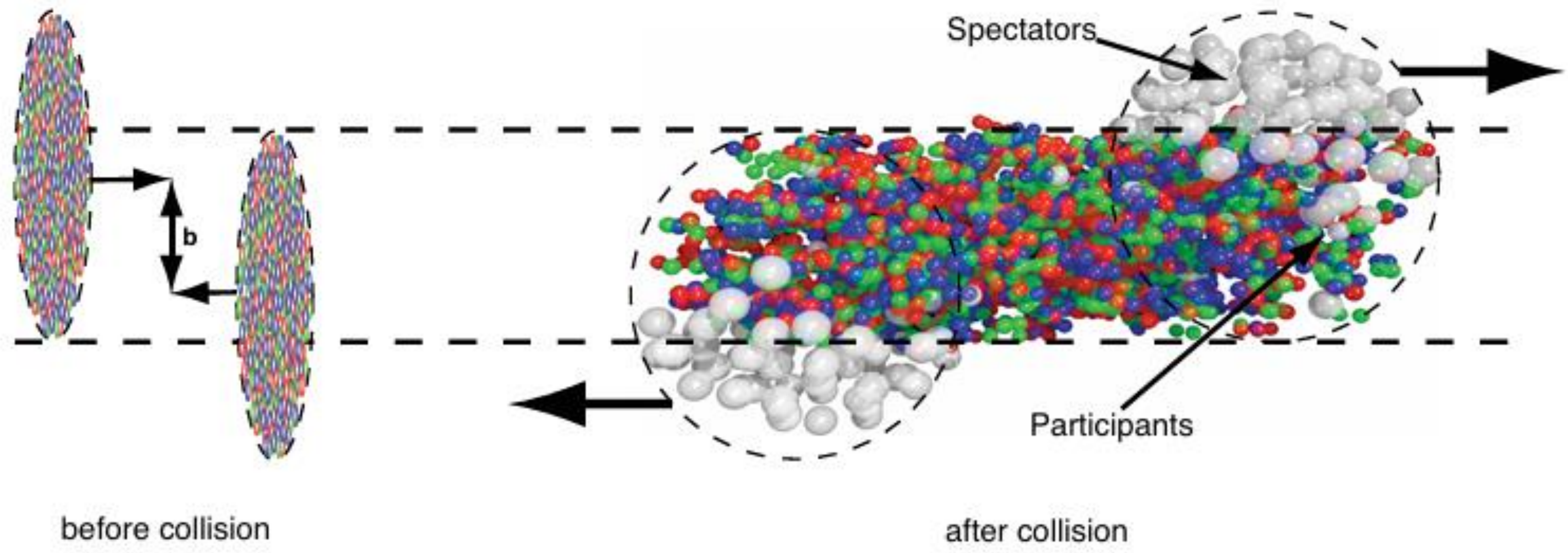


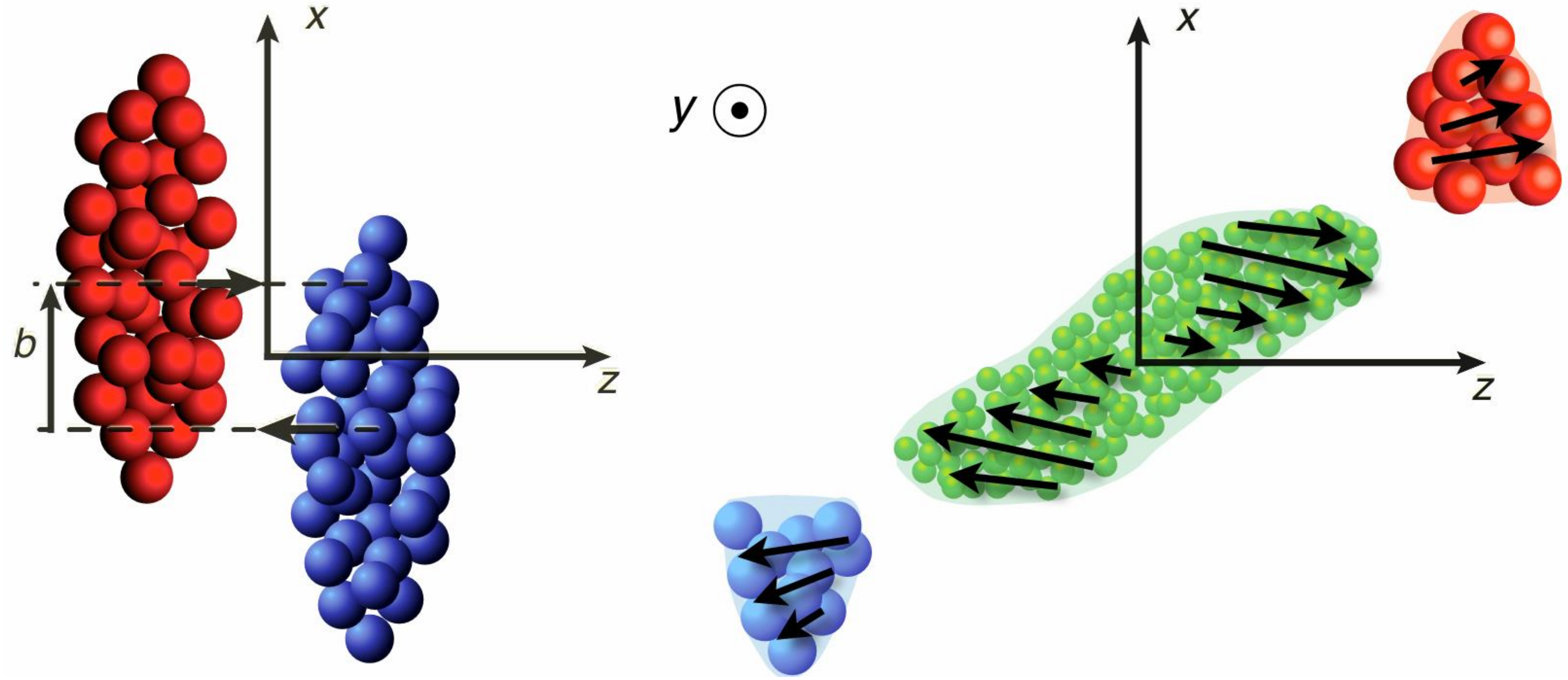
Assumption that kaon source is less affected by resonances is wrong

Emitting source



Usual way of thinking

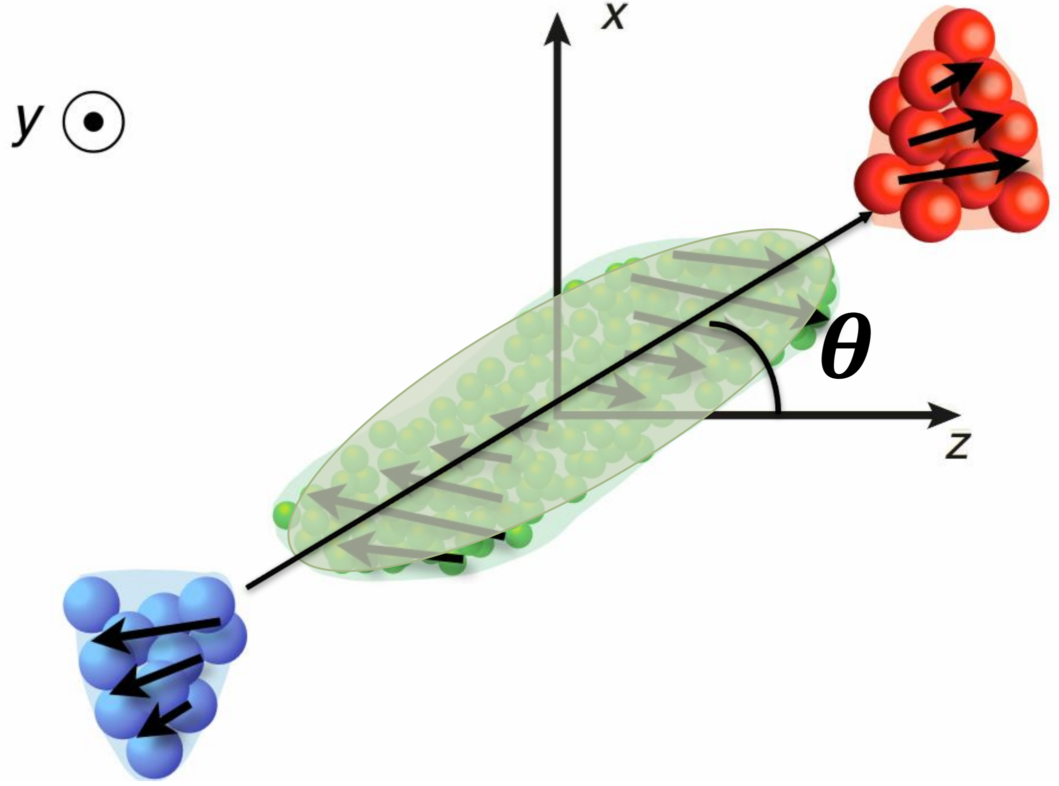
Tilted emitting source



Phys. Rev. C 111, 024902 (2025)

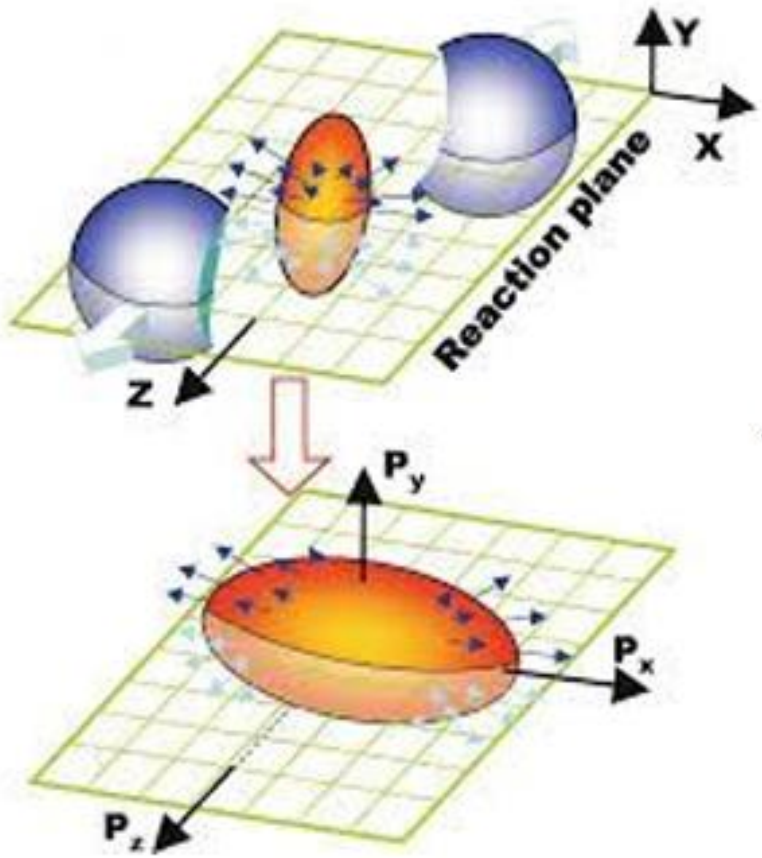
Tilted emitting source

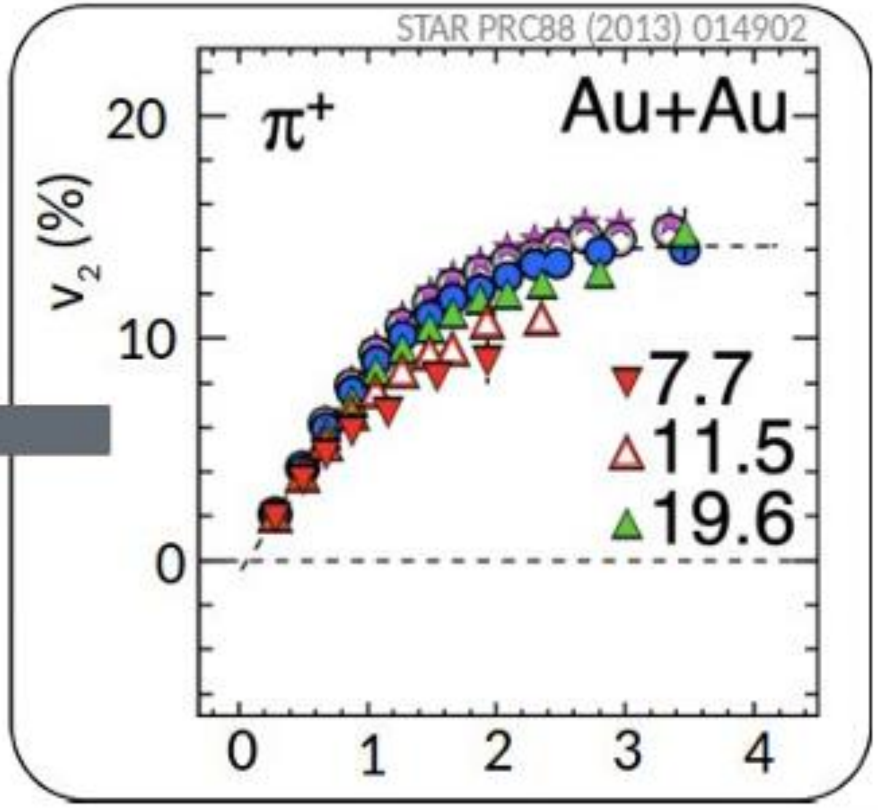
- The 3D initial geometry of a non-central heavy-ion collision breaks the forward-backward symmetry by a "tilt" of the fireball with respect to the reaction plane
  - ➢Azimuthally sensitive femtoscopy allows to measure



Phys. Rev. C 111, 024902 (2025)

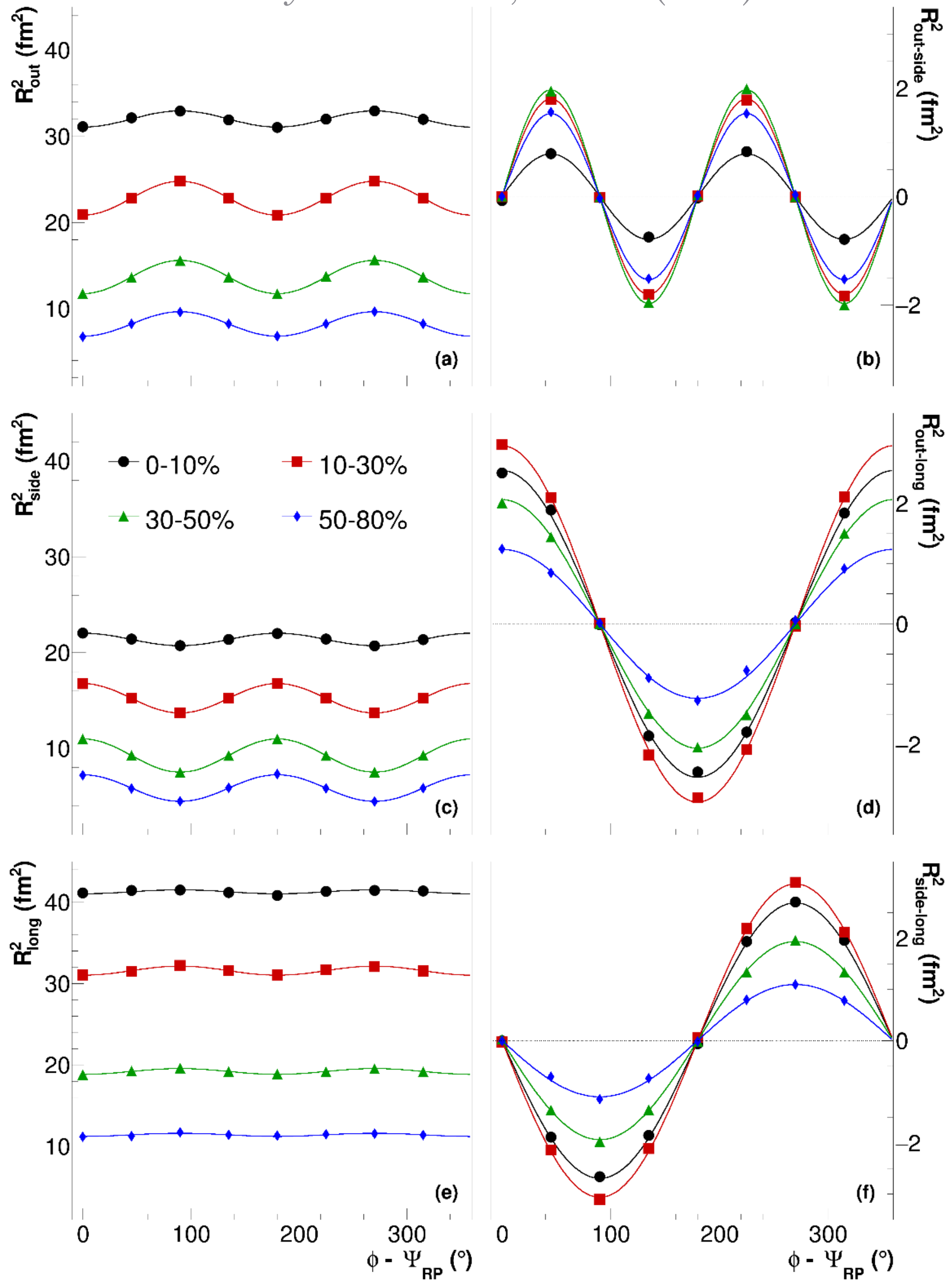
Femtoscopy and elliptic flow

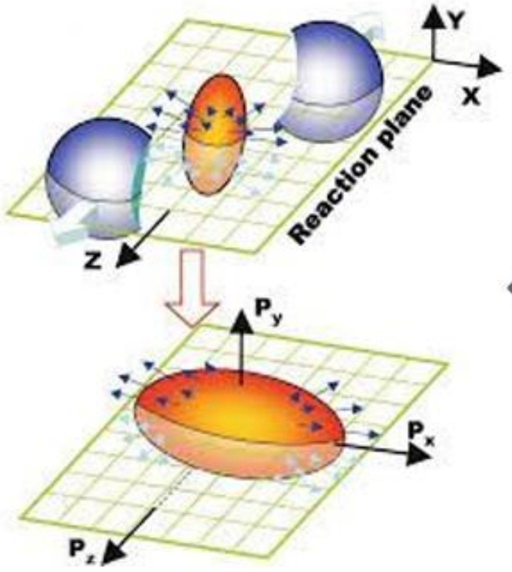


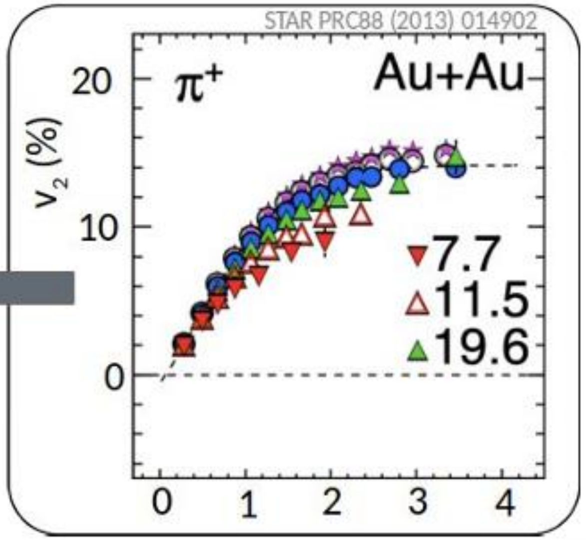


- In momentum space emission source extended in-plane

Phys. Rev. C 111, 024902 (2025)



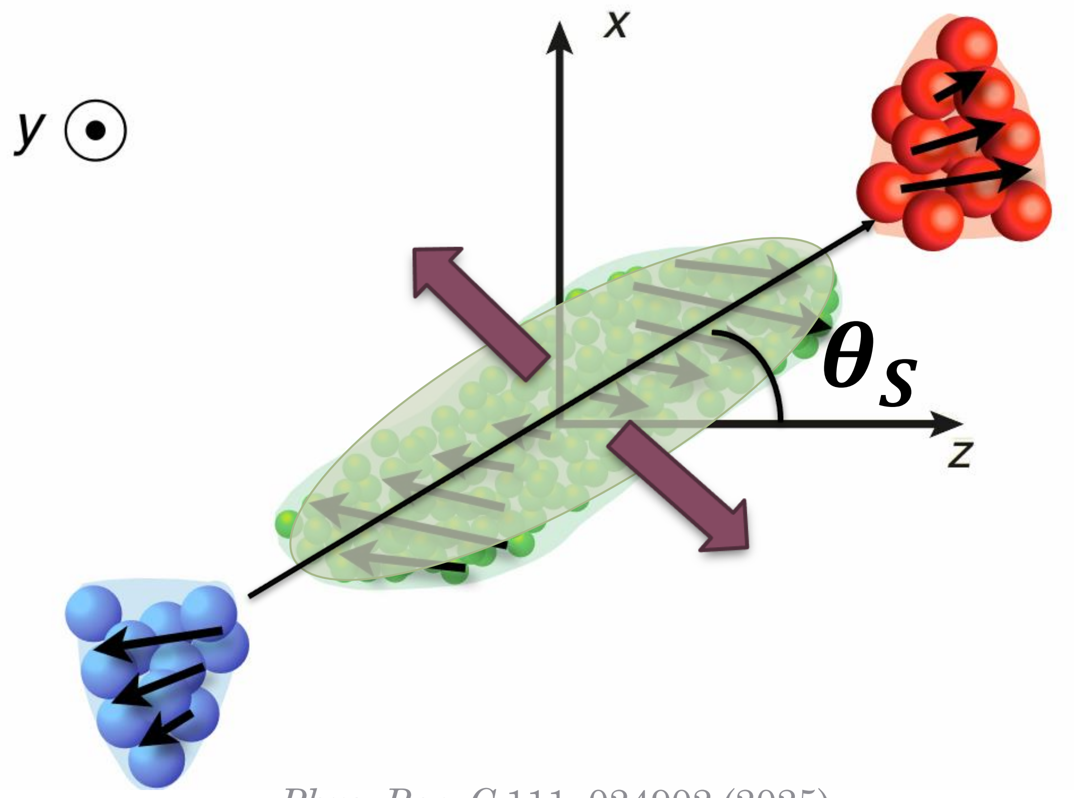




- In momentum space emission source extended in-plane
- Femtoscopy shows out-of-plane extension in the coordinate space -> stronger in-plane pressure gradients -> leading to positive v_2

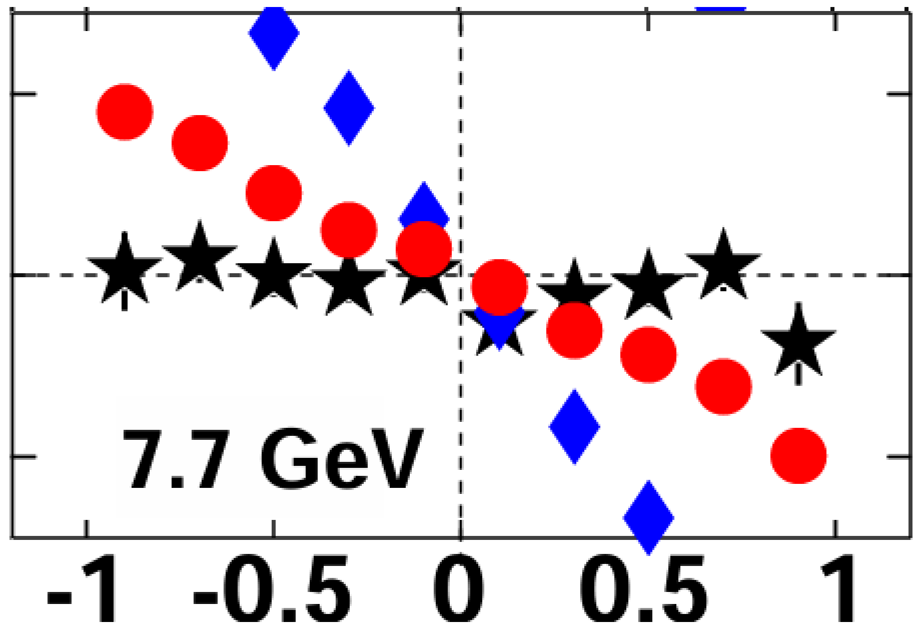
Femtoscopy and directed flow

- Same reasoning for v_1 existence = stronger pressure gradients along shorter axis of the tilted source?



Phys. Rev. C 111, 024902 (2025)

Phys. Rev. Lett. 112, 162301

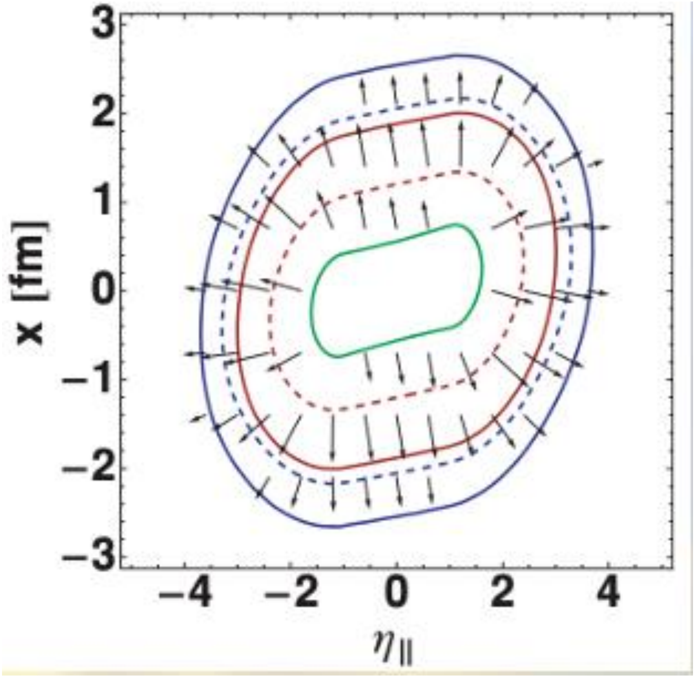


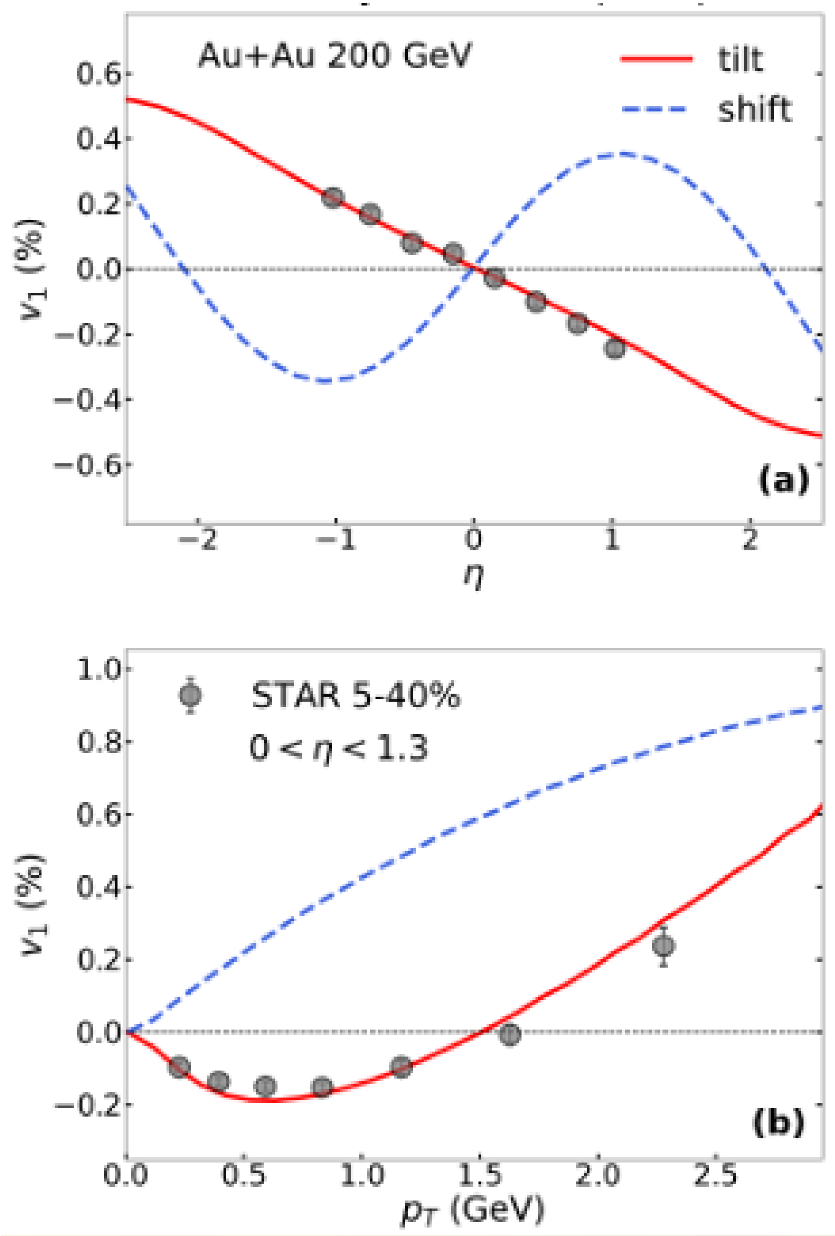
Assuming tilted source

Phys. Rev. C 106 (2022) 044907
EPJC 75, 406 (2015)
J. High Energy Phys. 05 (2021) 279

- Successfully described in models driven by pressure gradients (like v2) from tilted source
- Worse description at higher momenta for heavier species

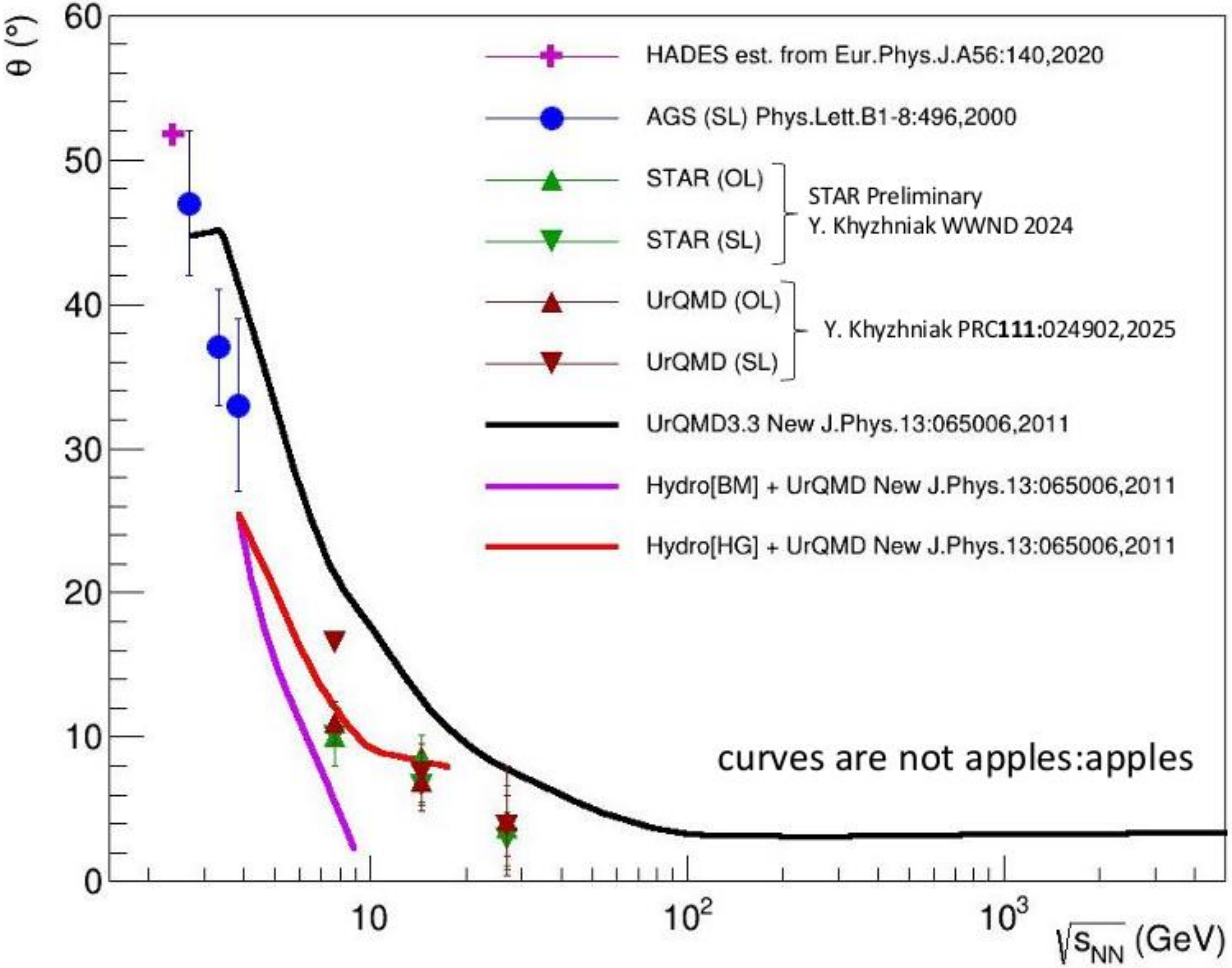
PRC 81, 054902 (2010)

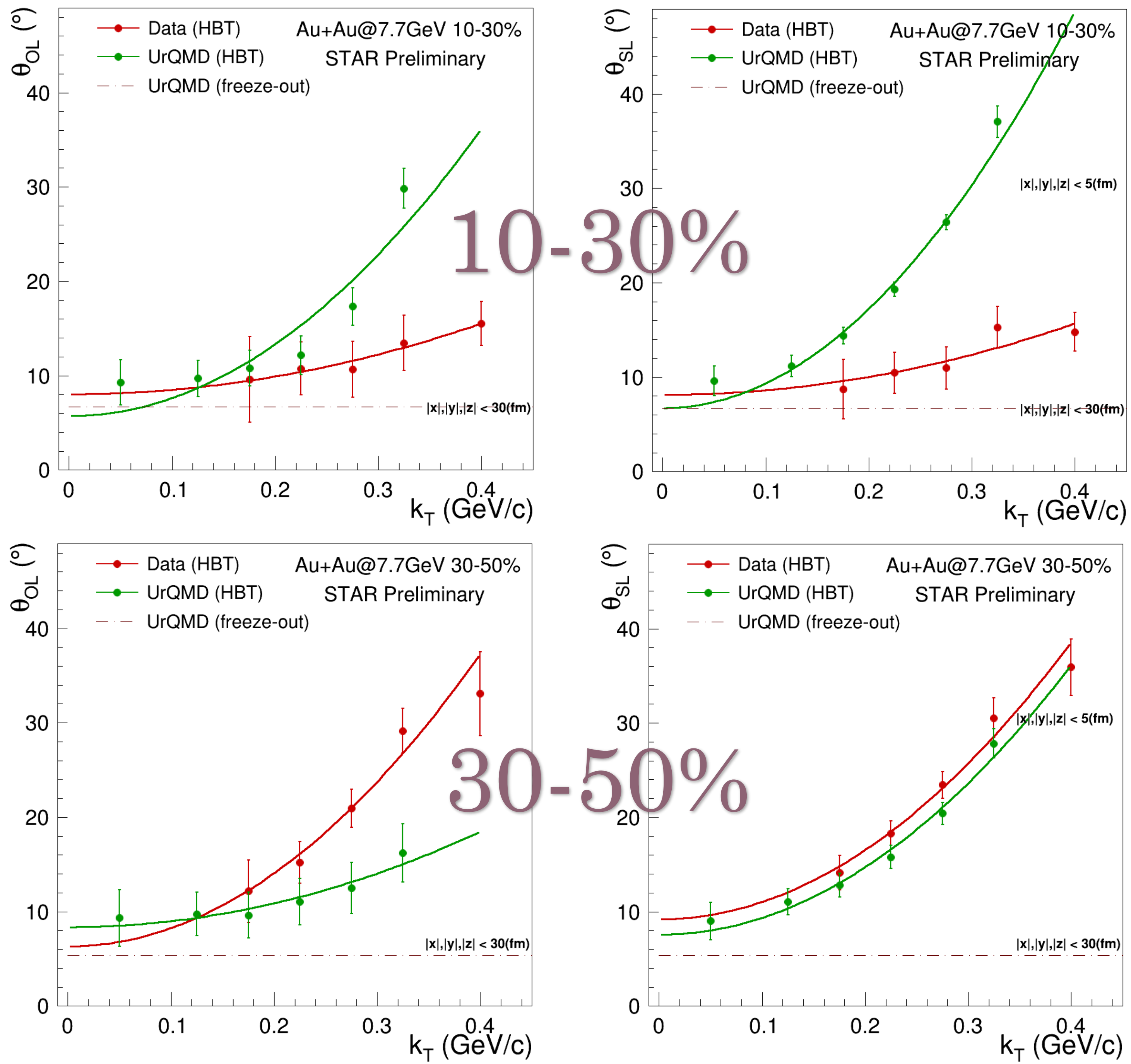




Energy dependence of the tilt

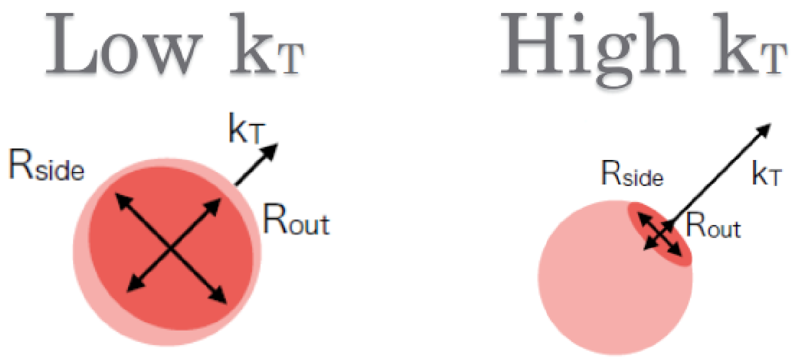
- In trend with AGS and HADES data
- Drops with energy, consistent with the expectation that collisions become increasingly boost invariant
- Good agreement with UrQMD 3.4 (“cascade” mode)
- Slight difference between θ_{SL} and θ_{OL} tilts
- Good distinctive power between models





k_T dependence of the tilt in the experiment and UrQMD

- Larger k_T pairs are emitted from smaller emission regions at earlier times with less correspondence to the size and shape of the entire fireball



Strange Dibaryons

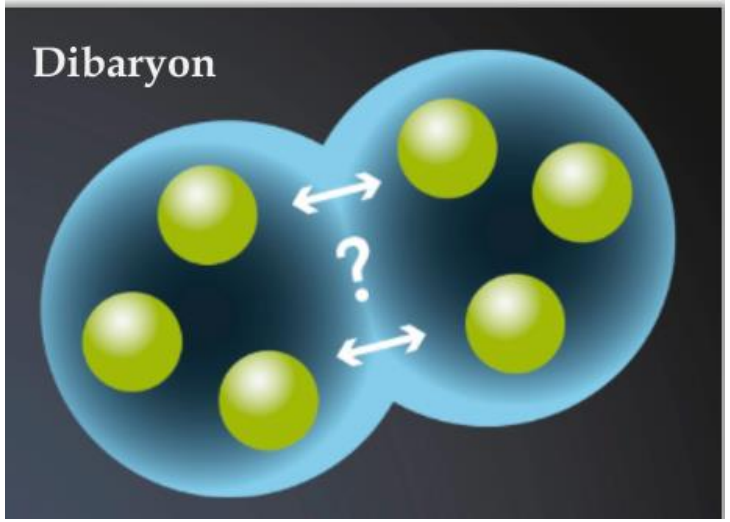
- (Strange) Dibaryons have never been found experimentally
- The possible formation channels:

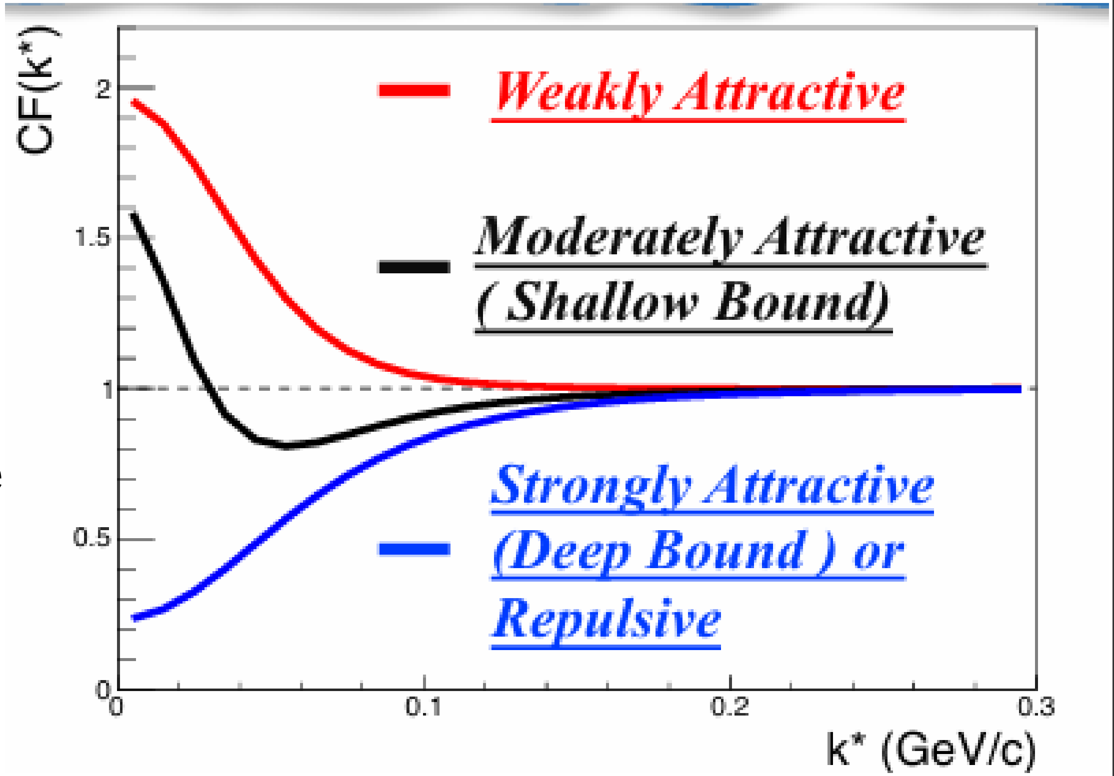
$$(\,|S|=2\,)\text{Dibaryon} \Leftrightarrow p + \Xi^-$$

$$(\,|S|=3\,)\text{Dibaryon} \Leftrightarrow p + \Omega^-$$

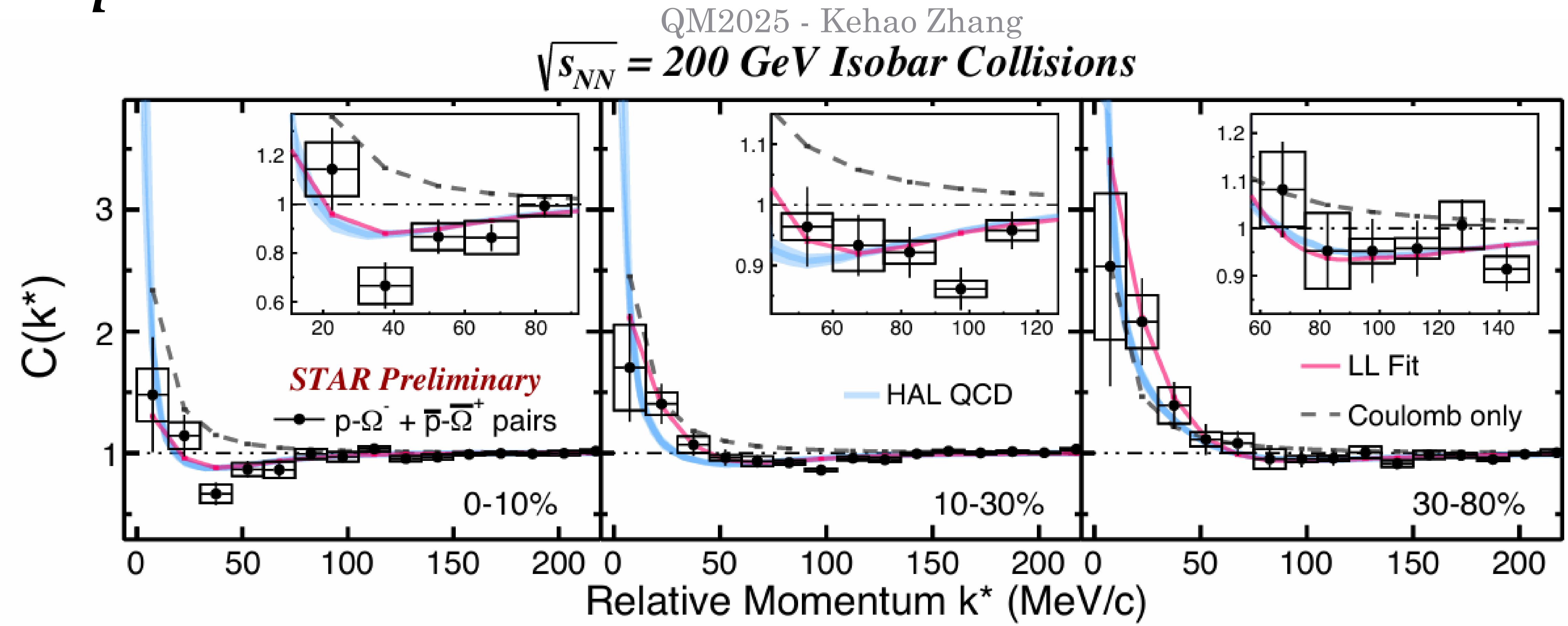
$$(\,|S|=2\,)\text{Dibaryon} \Leftrightarrow \Lambda + \Lambda$$

- Hyperon-Nucleon (Y-N) and Hyperon-Hyperon (Y-Y) interactions provide important information to constrain the Equation-of-State and help to understand the inner structure of compact stars





$p + \Omega^-$



- Data consistent with the model, which assume presence of the shallow bond in $p + \Omega^-$

Ratio of $p + \Omega^-$ at different centralities

Type	f_0 (fm)	d_0 (fm)	BE (MeV)	χ^2/ndf	p-value	
V_I [1]	1.12	1.16	--	48.2/29	0.014	No Bound
V_{II} [2]	-3.38	1.31	2.15	22.2/29	0.812	Shallow Bound
V_{III} [1]	-1.29	0.65	26.9	58.7/29	0.001	Deeply Bound

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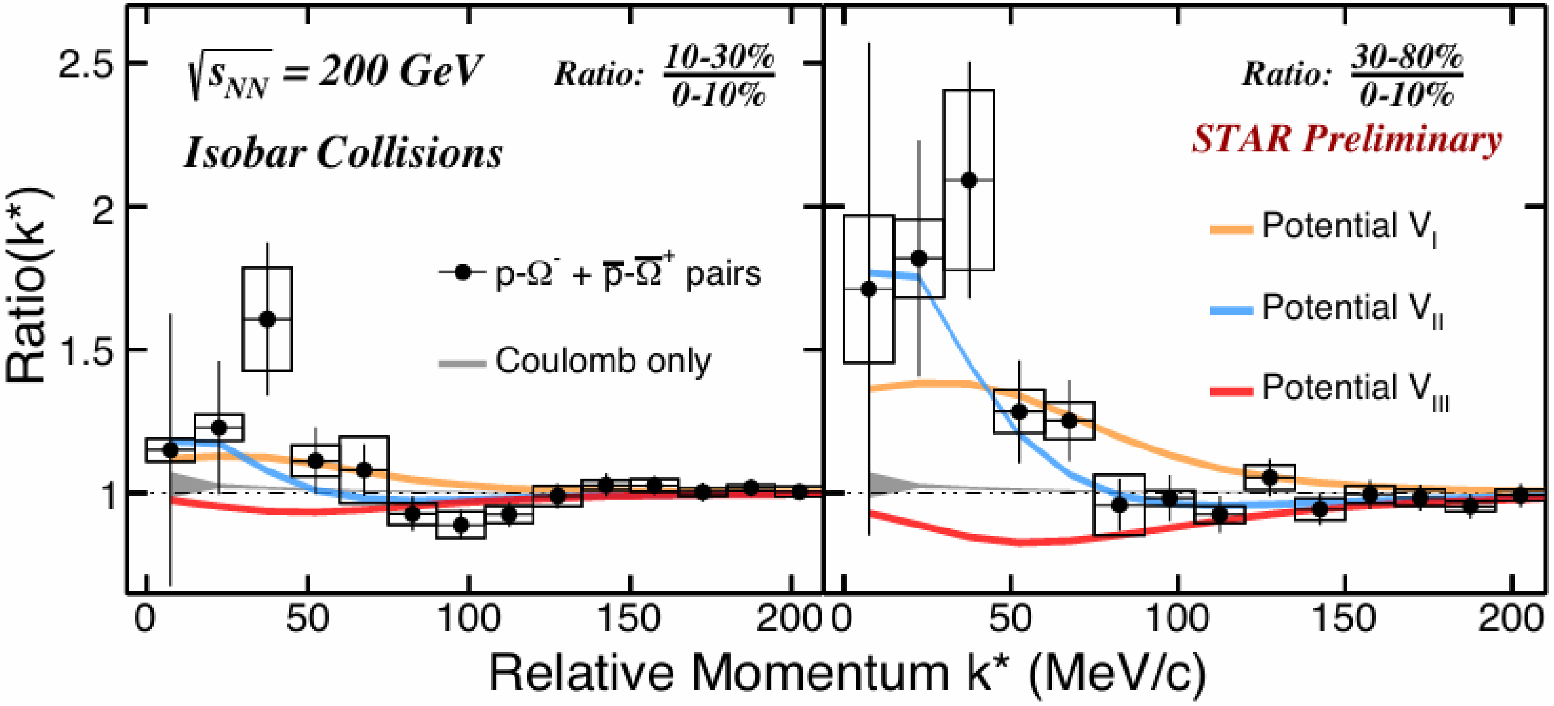


- By taking CF ratio, Coulomb effect can be largely canceled
- CF Ratio shows enhancement at low k* and depletion around k* ~ 100 MeV/c -> Due to the presence of shallow bound state

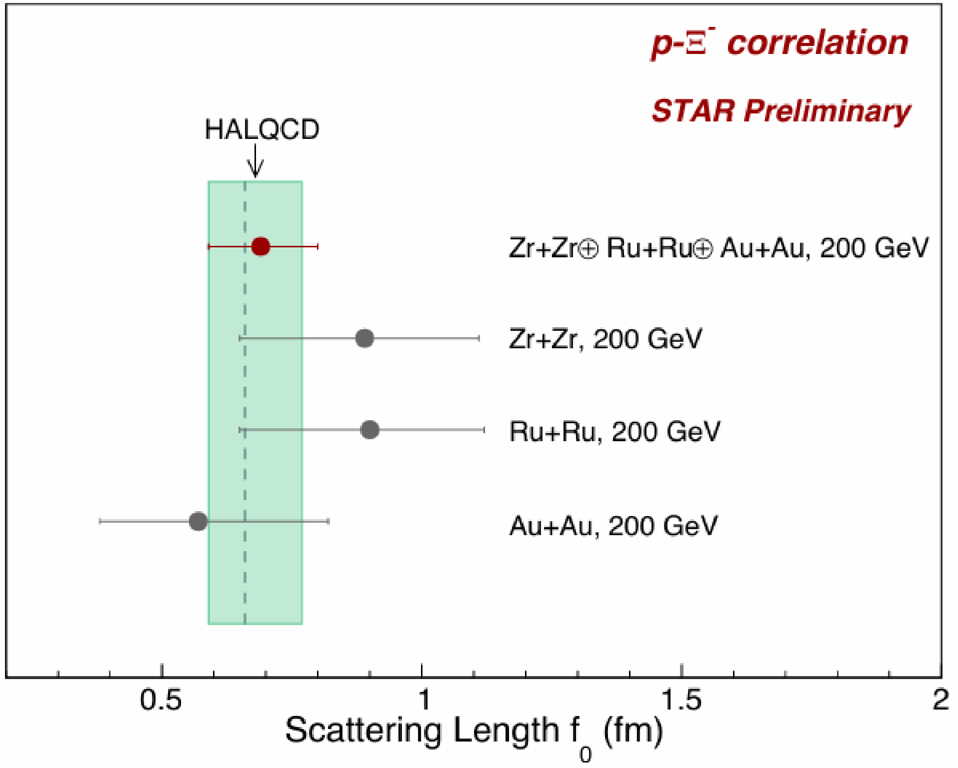
	Spin ave.	Quintet	HAL QCD
f_0 (fm)	$-4.9^{+0.5}_{-0.7}$	$-4.3^{+0.4}_{-0.7}$	-3.4
d_0 (fm)	$2.3^{+0.4}_{-0.5}$	$1.5^{+0.5}_{-0.7}$	1.3
BE (MeV)	$1.5^{+1.1}_{-0.6}$	$1.6^{+1.4}_{-0.5}$	2.3

Kenji Morita, et al., Phys. Rev. C 101, 015201 (2020)

Consistency with the model + negative extracted scattering length and |f0|> 2d0 (effective range) ->
hints on existence of dibaryon

$p + \Xi^-$

- Weakly attractive interaction
- Consistent with HAL QCD prediction



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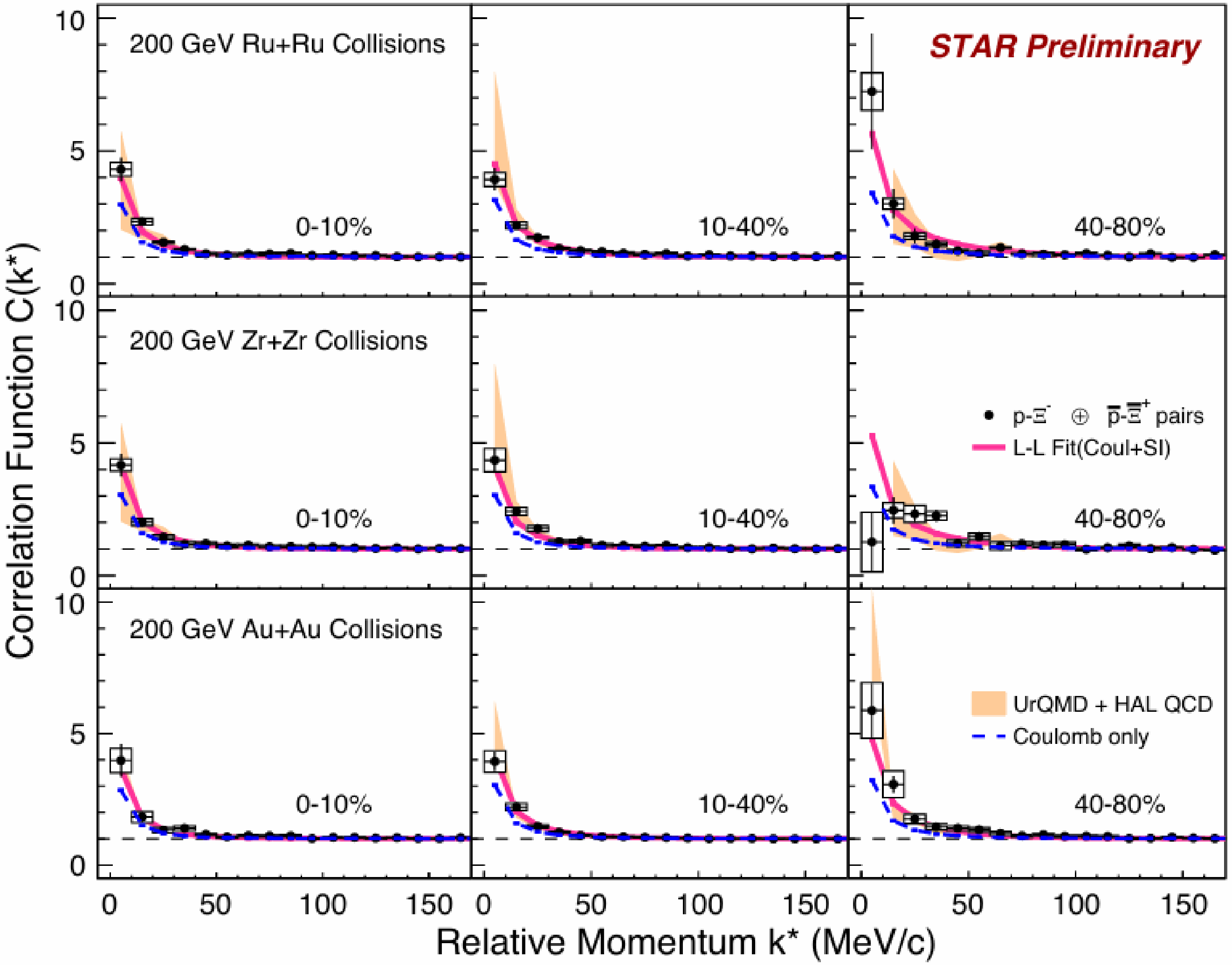

Summary from the recent femtoscopy studies

- Levy source
  - Pion source is non-Gaussian and non-Gaussianity increases with energy
- Gaussian source
  - Positively and negatively charged pions (same for kaons) have different correlations and subsequently different extracted sizes of the source at all energies
    - Driven by Coulomb effect from residual source
    - And, possibly, by isospin effect
  - Kaons are emitted later than pions at all energies!
    - Driven by re-scattering channel: K*
    - Kaon source even more affected by resonances than pions
  - Measurement of the tilt of the source crucial for the reproduction of the directed flow
    - Tilt depend on energy: consistent with the expectation that collisions become increasingly boost invariant at high energies
    - Tilt depends on momentum
- First experimental evidences of the strange dibaryon