Probing properties of pion- and kaon-emitting sources at NICA energies

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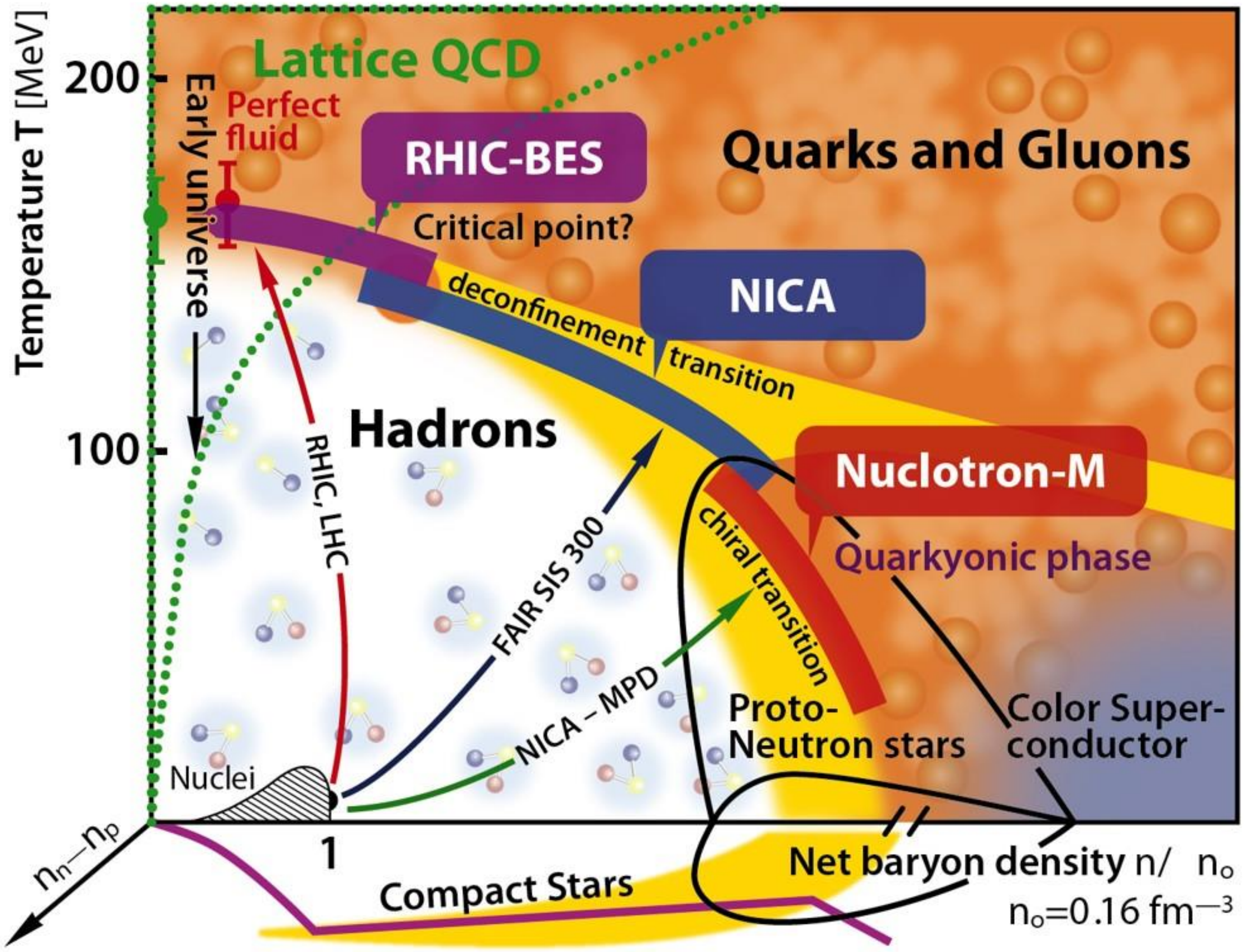
The QCD Phase Diagram



Main goals

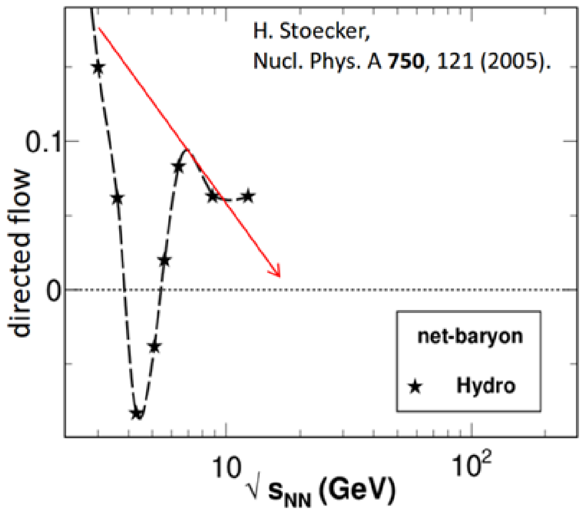
- Explore QCD phase diagram, study the Equation of State (EoS) and transport properties of the medium
- Search for the 1st-order phase transition and critical point
- Study turn-on and turn-off signatures of sQGP

How to study

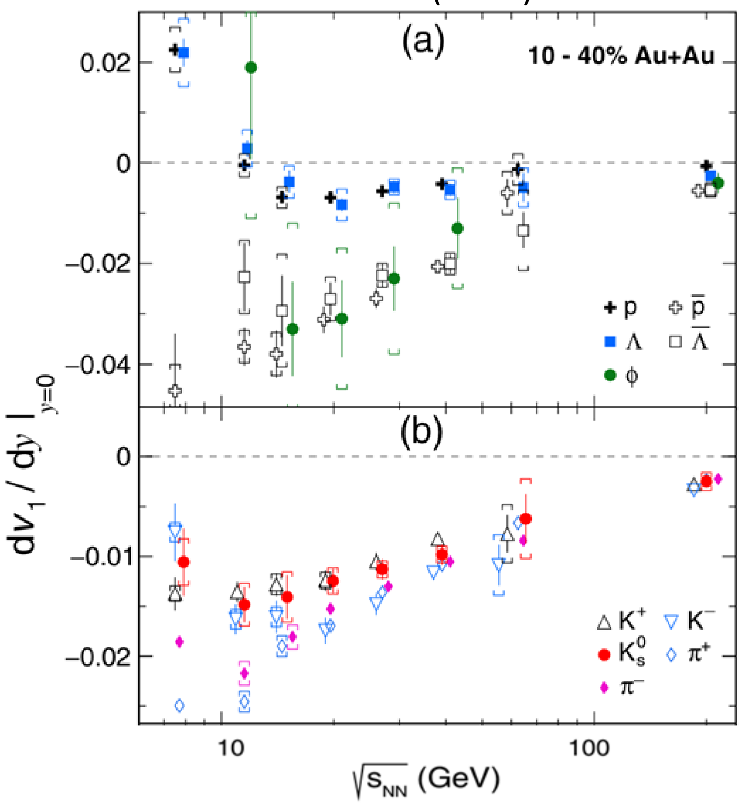
- Collisions of ions at various energies
    - BES-I and BES-II programs at RHIC
    - MPD and BM@N experiments at NICA
    - NA61/SHINE experiment at SPS

Searches for the First-order Phase Transition

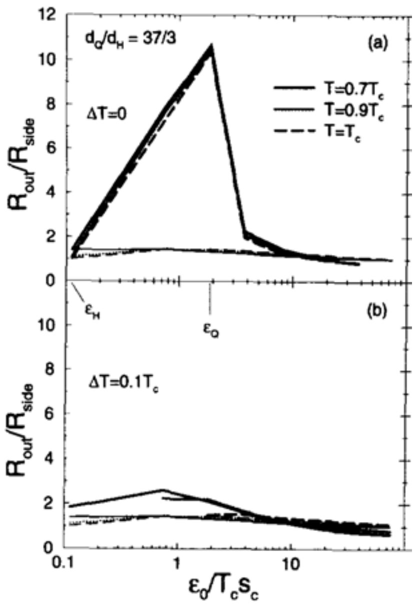
- Softening of the EoS
  - Could be observed in the dv_1/dy slope
  - Strong softening: consistent with the 1st-order phase transition
  - Weaker softening: likely due to crossover



STAR. PRL 120 (2018) 062301



- Time delays of the particle emission
  - Could be observed using femtoscopy techinique



D.H. Rischke, M. Gyulassy. NPA 608 (1996) 479

Correlation Femtoscopy

- Two-particle correlation function (CF):

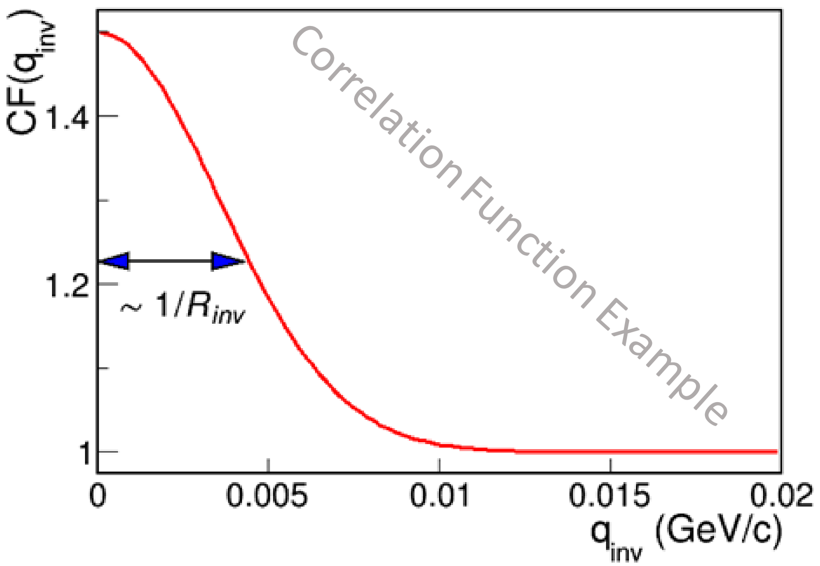
$$CF(p_1, p_2)=\int d^4r\, S(r, k)\, |\Psi_{1,2}(r, k)|^2$$

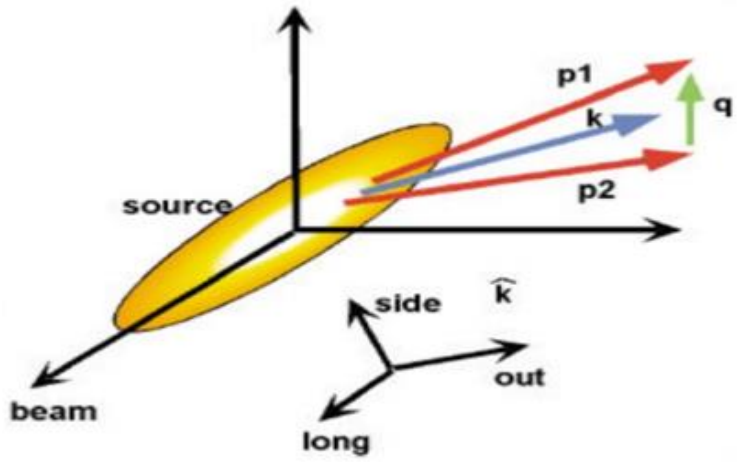
$$r=x_1-x_2 \text{ and } q\equiv q_{inv}= p_1 - p_2$$

- Experimentally:

$$CF(q) = A(q)/B(q)$$

  - A(q) – contain quantum statistical (QS) correlations and final state interactions (FSI)
  - B(q) – obtained via mixing technique (does not contain QS and FSI)





S. Pratt. PRD 33 (1986) 1314
G. Bertsch. PRC 37 (1988) 1896

The relative pair momentum can be projected onto the Bertsch-Pratt, out-side-long system:

q_{long} – along the beam direction
q_{out} – along the transverse momentum of the pair
q_{side} – perpendicular to longitudinal and outward directions

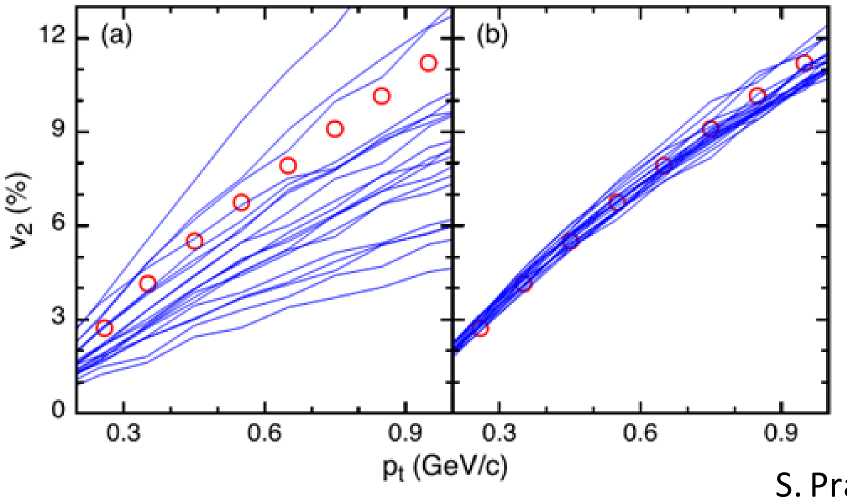
Correlation functions are constructed in Longitudinally Co-Moving System (LCMS), where $p_{1z}+p_{2z}=0$

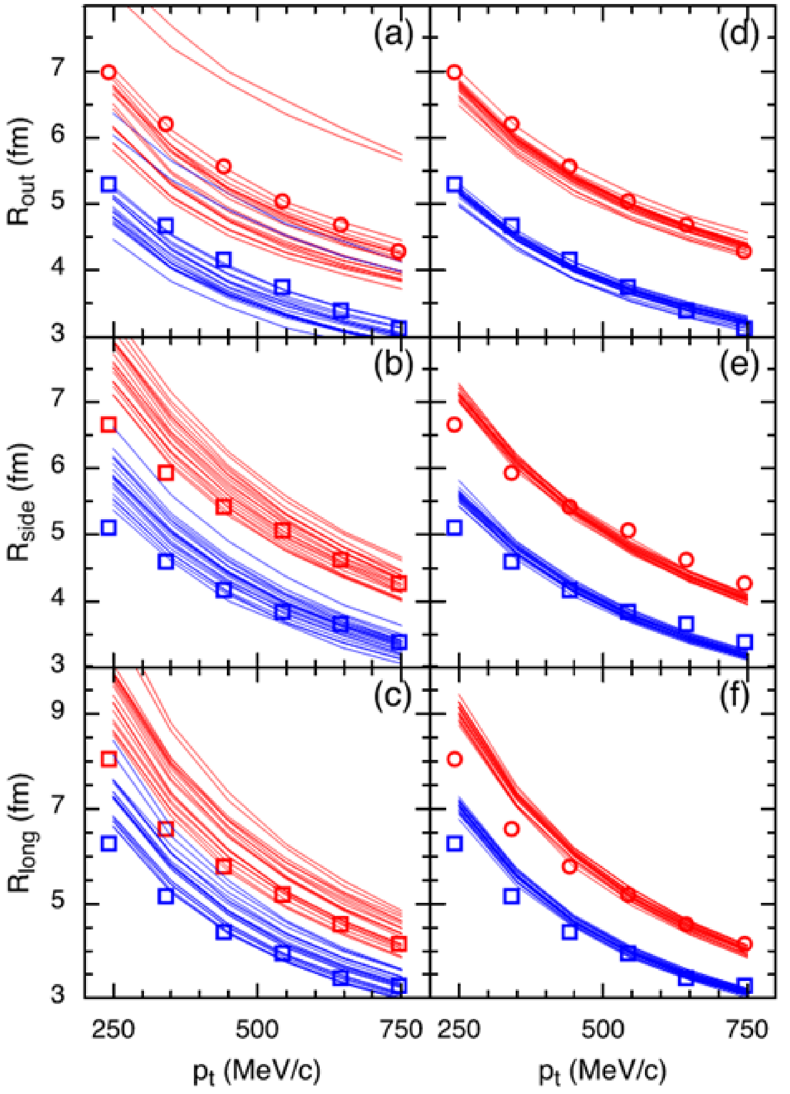
Why Correlation Femtoscopy?

- Access to the spatial and temporal information about a particle-emitting source at kinetic freeze-out
- Different particle species are sensitive to various effects (Final State Interactions (FSI), transport properties, asymmetries, etc…)

V.M. Shapoval et al. NPA 968 (2017) 391
M.A. Lisa et al. Ann. Rev. Nucl. Part. Sci. 55 (2005) 357
D.H. Rischke, M. Gyulassy. NPA 608 (1996) 479
R. Lednicky et al. Phys. Lett. B 373 (1996) 30

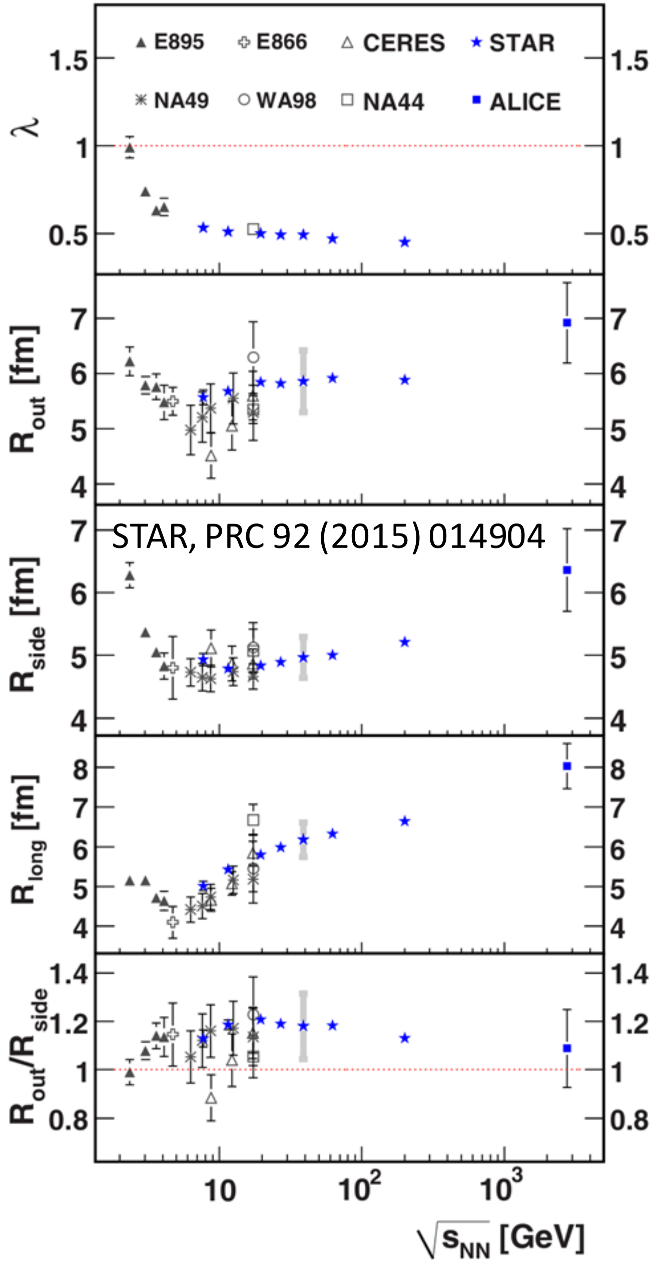
- Strong model constraints





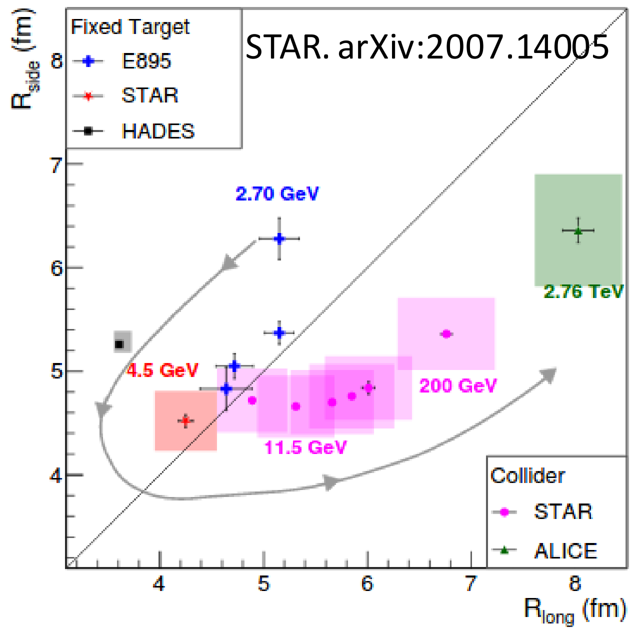
S. Pratt et al. PRL 114 (2015) 202301

Femtoscopy: World Systematics



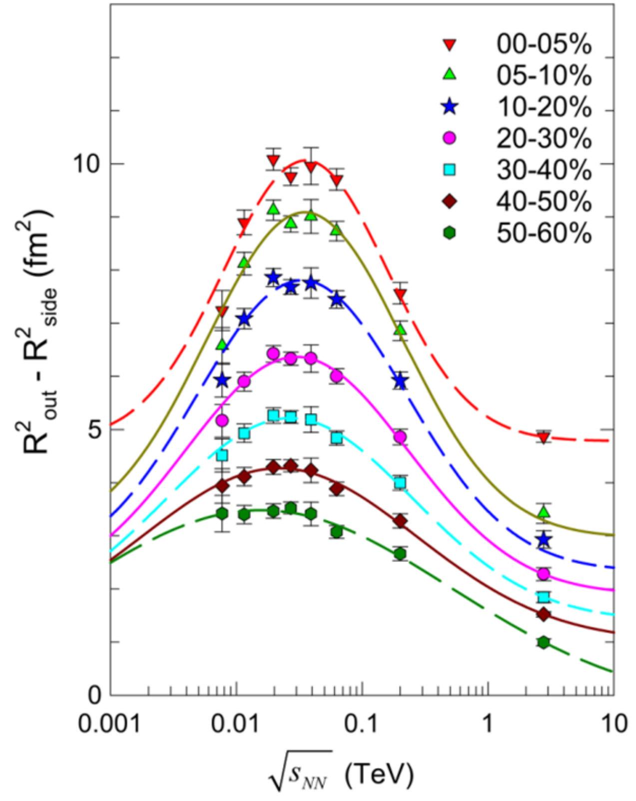
STAR, PRC 92 (2015) 014904

- Precise measurements in a broad energy range (from 7.7 GeV to 2.76 TeV)
- Need more high-statistics measurements at low energies
- Precise measurements exist only with pions
  - Need heavier particles



STAR. arXiv:2007.14005

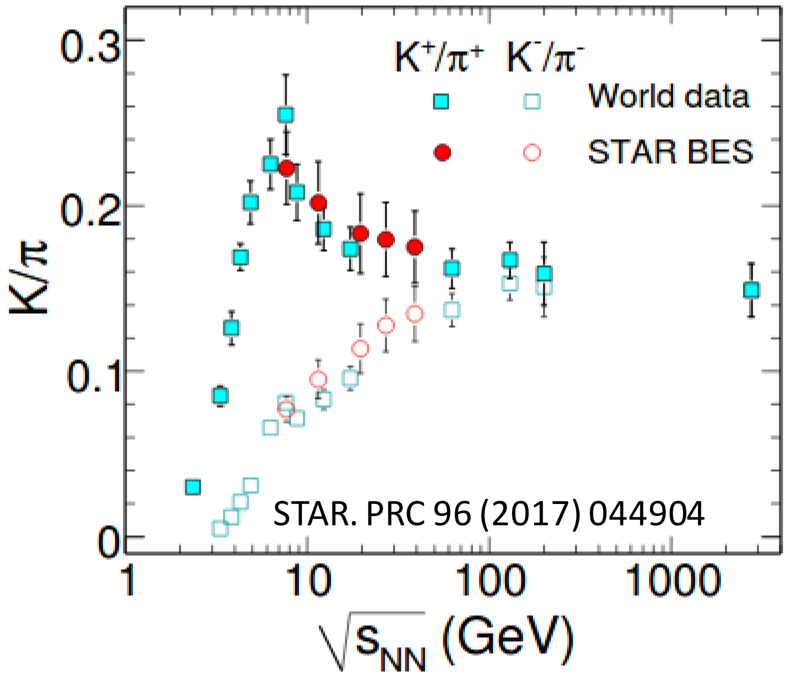
R. Lacey. PRL 114 (2015) 142301



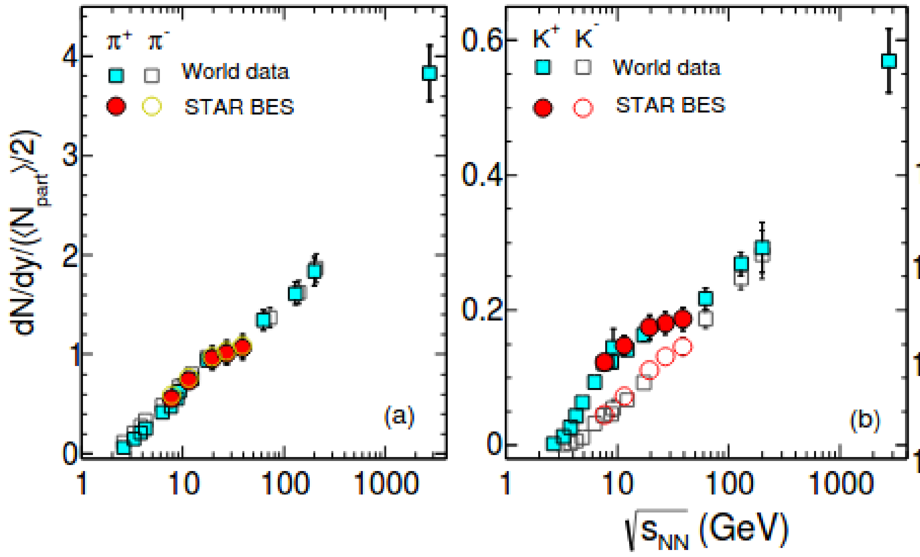
Femtoscopy with Strange Particles

- Contain strange (anti)quark
- Enhancement of strange particle yields was one of the first suggested signatures of QGP

J. Rafelski and B. Muller. PRL 48 (1982) 1066
P. Koch, B. Muller and J. Rafelski. Phys. Rept. 142 (1986) 167



- Interesting behaviour was observed in K/π ratios at NICA energies
- Could be sensitive to different production mechanisms at low collision energies



We would like to explore the quark-gluon matter at NICA/FAIR/RHIC energies using femtoscopy technique

This talk is dedicated to the study with the UrQMD (micr. descr.) **and**

S.A. Bass et al. Prog. Part. Nucl. Phys. 41 (1998) 225
M. Bleicher et al. J. Phys. G: Nucl. Part. Phys. 25 (1999) 1859

VHLLE (viscous hydrodynamics + resc.) **models**

Iu. Karpenko et al. Phys.Rev. C 91 (2015) 064901

Correlation Functions from UrQMD

- Examples of the correlation functions of pions and kaons obtained for Au+Au collisions at $\sqrt{s_{NN}}$=11.5 GeV
- Correlation functions were fitted with:

$$C(q_{out}, q_{side}, q_{long}) = 1 + \lambda e^{-R_{out}^2 q_{out}^2 - R_{side}^2 q_{side}^2 - R_{long}^2 q_{long}^2}$$

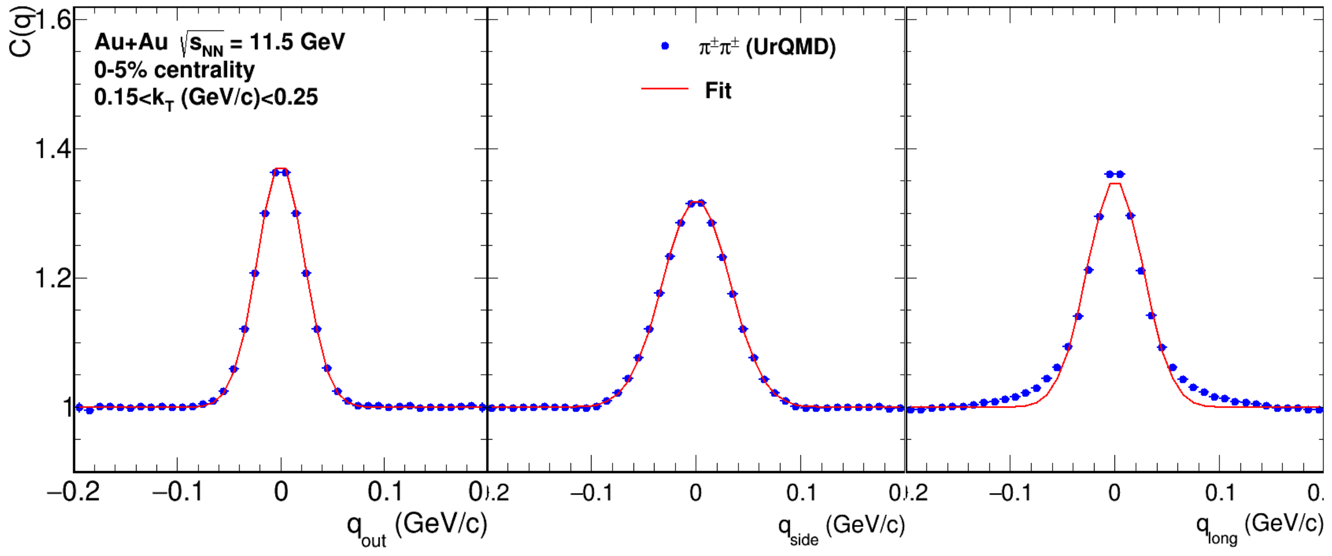
Where:

R_{side} – size of the emission region

R_{out} – sensitive to the emission duration

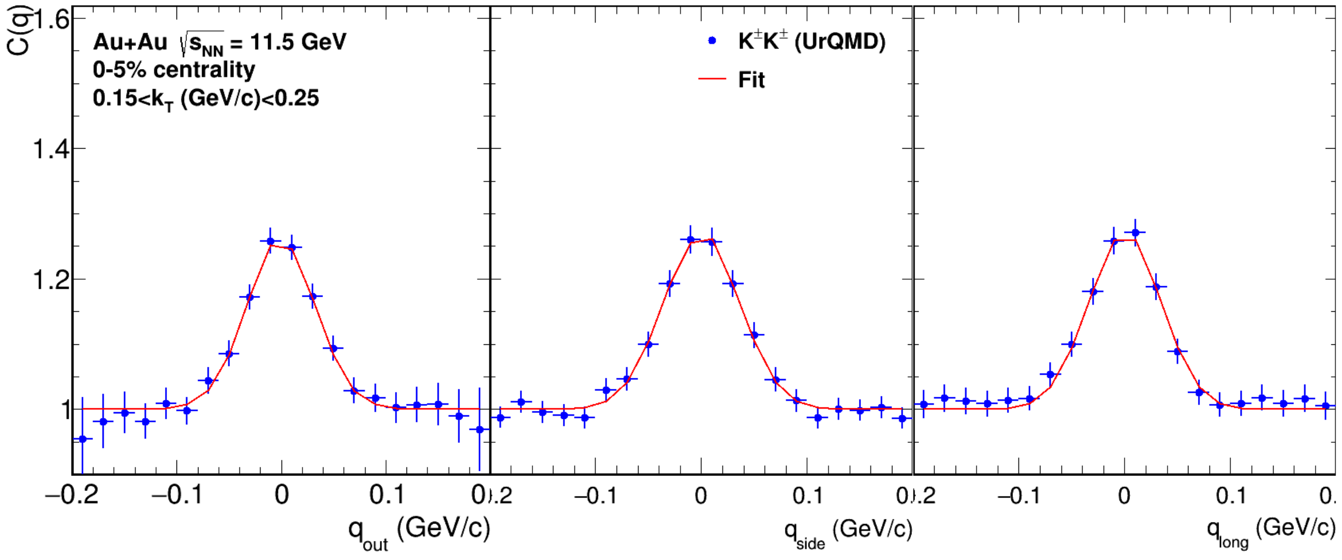
R_{long} – proportional to the system lifetime

Pions



$|q_{other}|$<0.05 GeV/c

Kaons



Correlation Functions from vHLLE

- Examples of the correlation functions for of pions obtained for Au+Au collisions at $\sqrt{s_{NN}}$=11.5 GeV obtained for two equations of state:
  - XPT – cross over
  - 1PT – first-order phase transition
- Correlation functions were fitted with: STAR, PRC 92 (2015) 014904

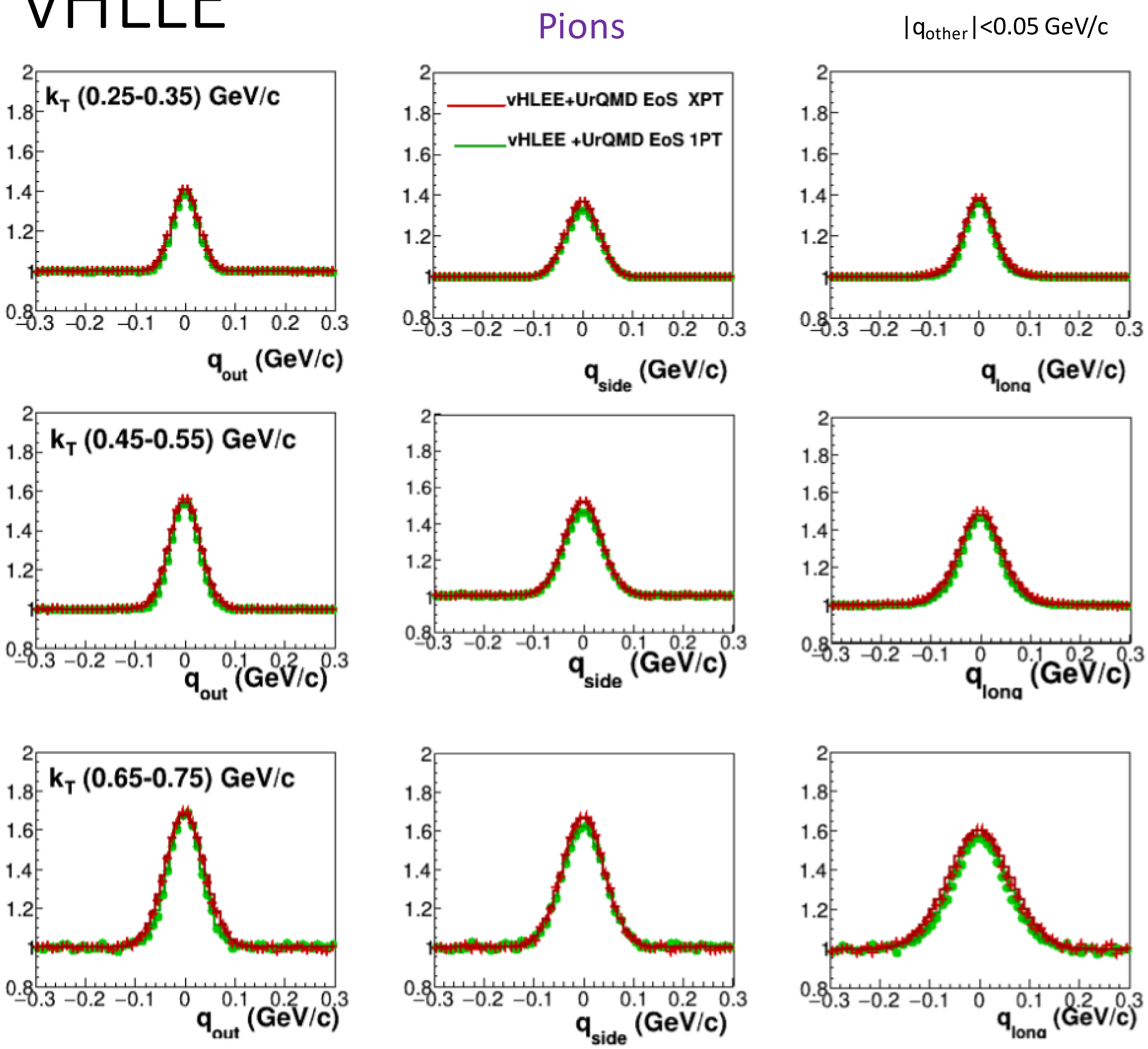
$$C(q_{out}, q_{side}, q_{long}) = 1 + \lambda e^{-R_{out}^2 q_{out}^2 - R_{side}^2 q_{side}^2 - R_{long}^2 q_{long}^2}$$

Where:

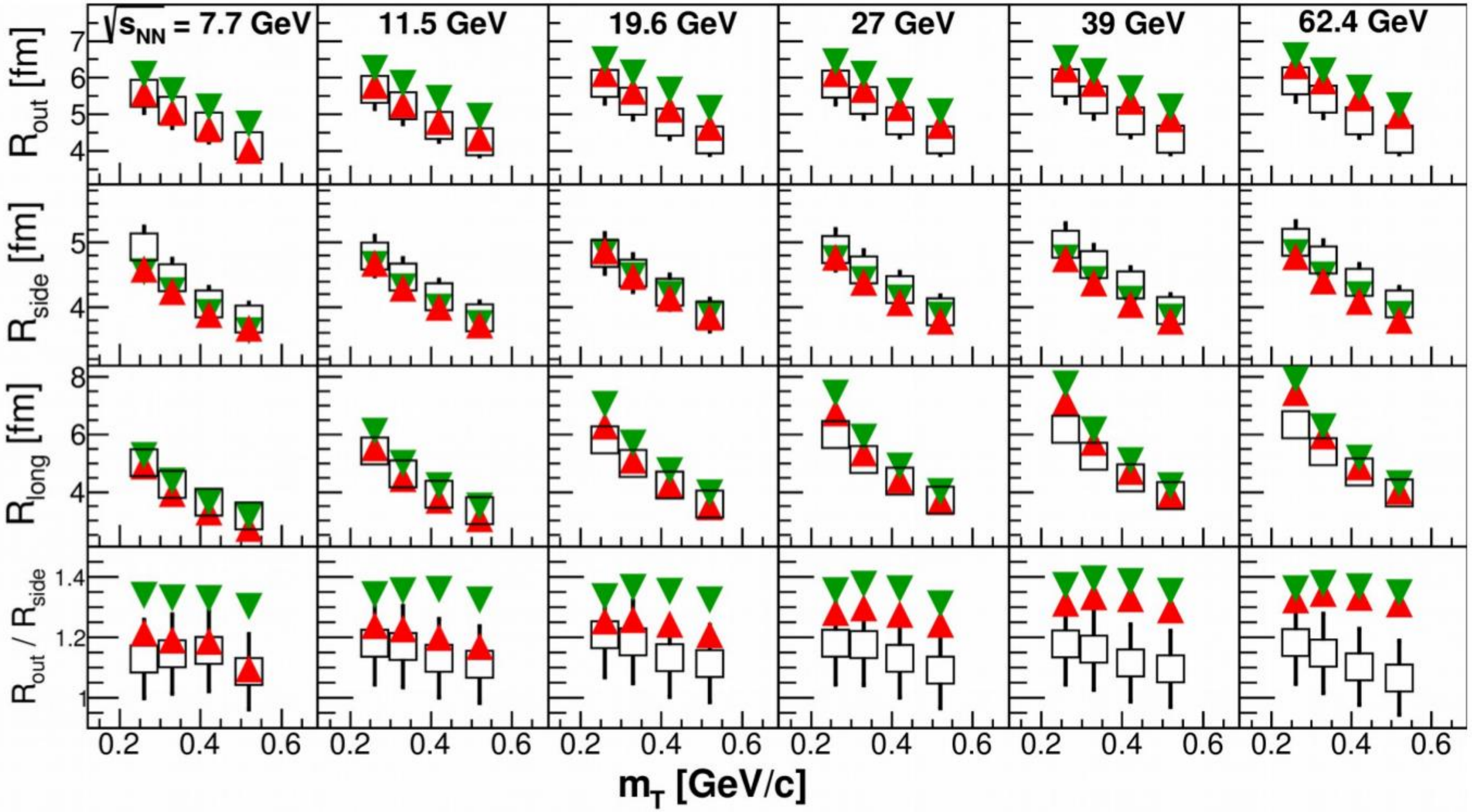
R_{side} – size of the emission region

R_{out} – sensitive to the emission duration

R_{long} – proportional to the system lifetime



Pion Results from vHLLE and STAR Data

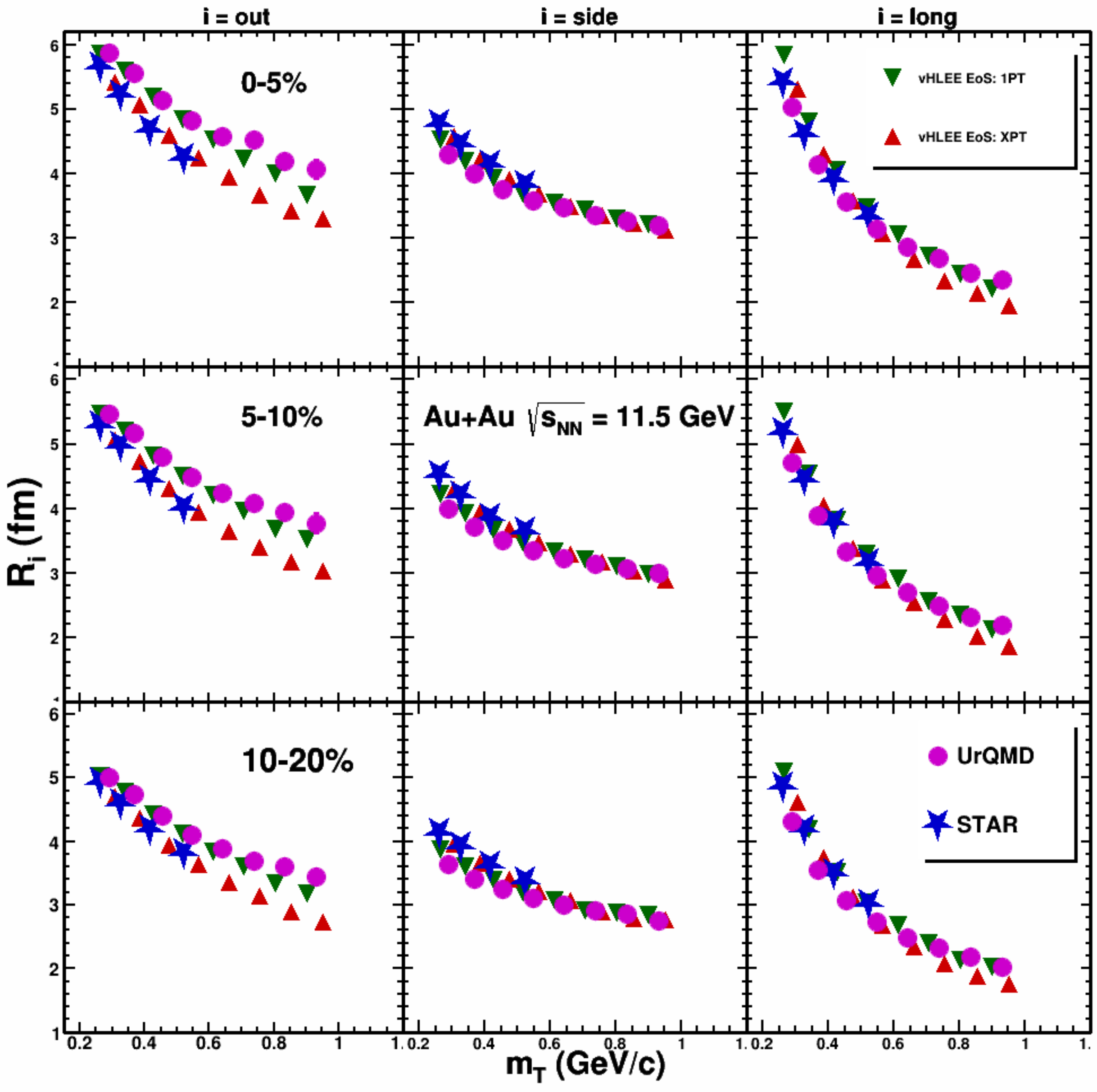


P. Batyuk et al. Phys.Rev. C96 (2017) 024911

STAR, PRC 92 (2015) 014904

- Femtoscopic radii are sensitive to the type of the phase transition
- Cross over EoS reasonably describes femtoscopic radii measued
- R_{out}/R_{side}(XPT) agrees with STAR data points at 7.7 and 11.5 GeV but then increases with increasing collision energy

Femtoscopic Radii of Pions from UrQMD and vHLLE



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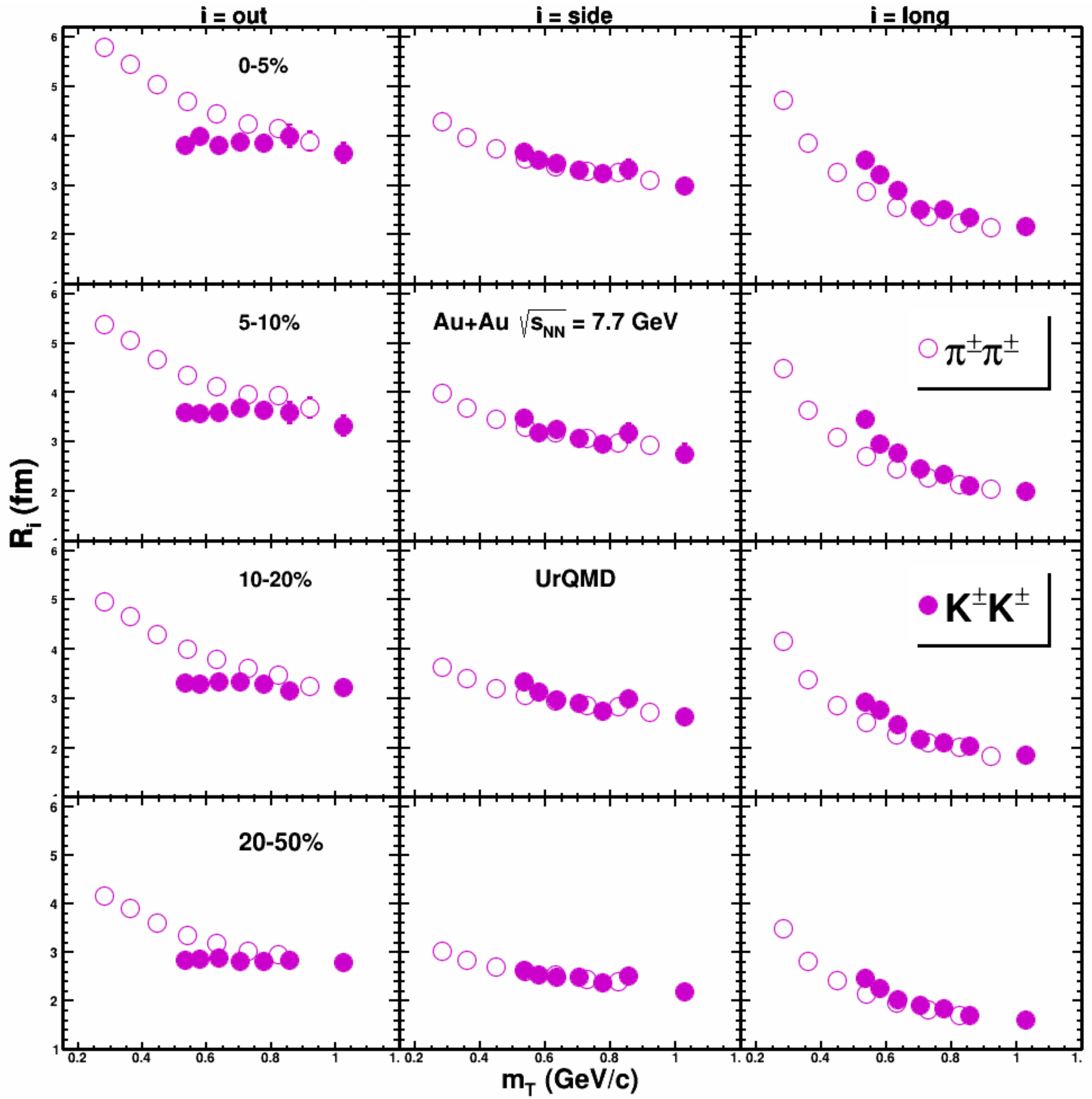
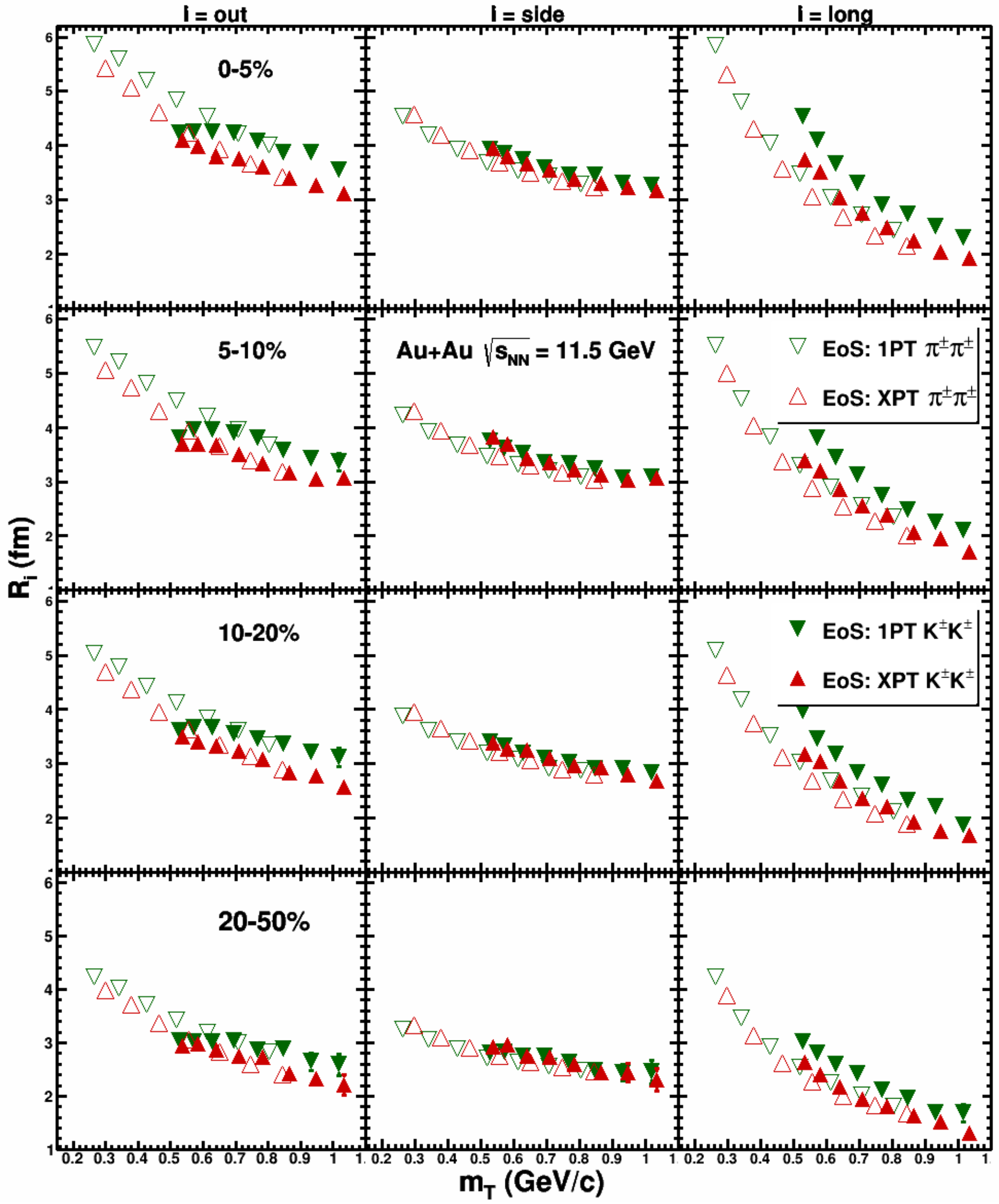
- Femtoscopic radii of pions decrease with increasing transverse mass
  - Influence of radial flow
- R_{side} increases going from peripheral to central collisions
  - Geometrical picture of ion-ion collision
- UrQMD shows similar results to vHLLE with 1PT
- vHLLE with XPT reasonably describe STAR data

Femtoscopic Radii of Pions and Kaons from UrQMD



- Femtoscopic radii of pions decrease with increasing transverse mass
  - Influence of radial flow
- R_{side} values for pions and kaons are similar
  - Similar size of the particle-emitting region
- R_{long} for kaons is generally larger than that for pions at the same m_T
  - Influence of resonances?
- R_{out} pions and kaons behave differently
  - Different emission duration?
  - Change of the production mechanism?

Femtoscopic Radii of Pions and Kaons from vHLLE



- Pion and kaon results for the cross over (XPT) and 1st-order (1PT) phase transitions
- Femtoscopic radii of pions decrease with increasing transverse mass
  - Influence of radial flow
- R_{side} values for pions and kaons are similar
  - Similar size of the particle-emitting region
- R_{out} for both pions and kaons show similar behaviour
  - Similar particle emission duration?
- R_{long} for kaons is generally larger than that for pions at the same m_T
  - Influence of resonances?

Energy dependence of femtoscopic radii

- Estimated radii for NICA energy range ($\sqrt{s_{NN}}$= 4-11 GeV)
- Pion radii slightly increase with increasing collision energy
- Excitation function of R_{long} suggests a slight increase of the system lifetime with increasing $\sqrt{s_{NN}}$

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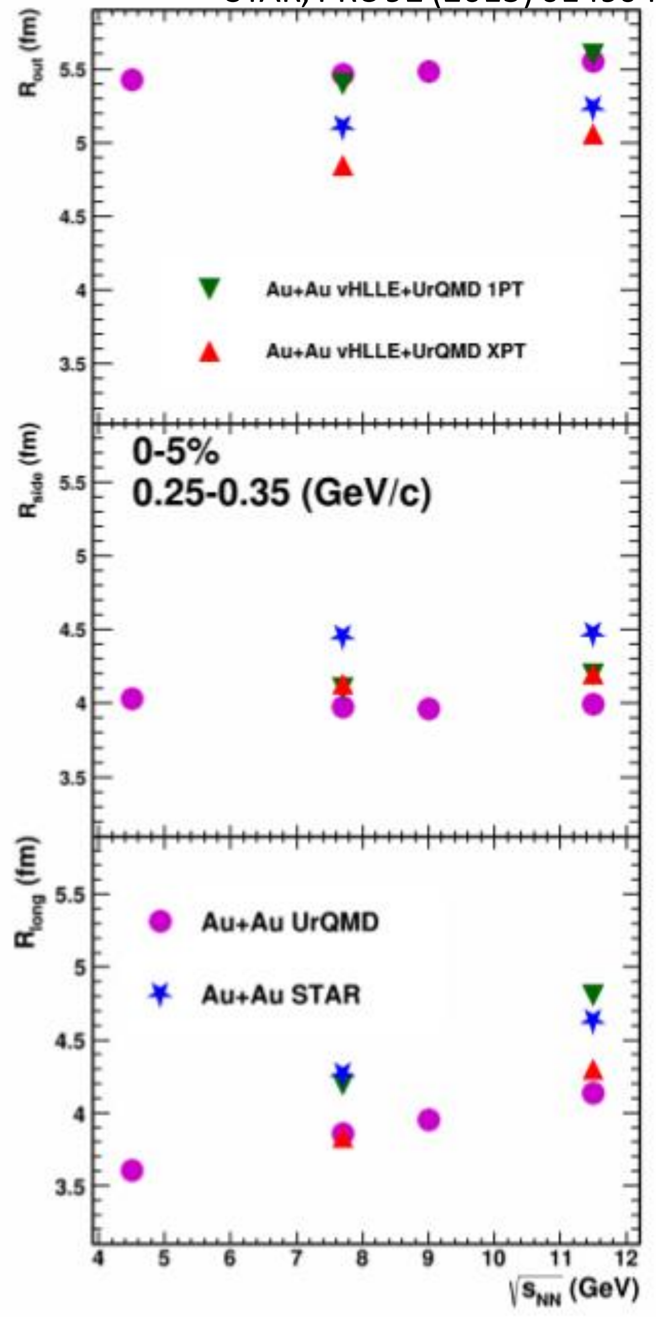

Summary

- We performed the first model estimation of kaons femtoscopic radii using the UrQMD and vHLLE models
- Pion femtoscopic radii decrease with increasing transverse momentum
- Experimental pion radii can be reasonably described by vHLLE with XPT
- Kaon radii dependence as a function of transverse mass shows:
  - R_{side} values for pions and kaons are similar for vHLLE and behaviour is different for UrQMD
  - R_{long} for kaons is generally larger than that for pions
- Energy dependence of R_{long} for both pions and kaons at NICA energies suggests a slight increase of the system lifetime