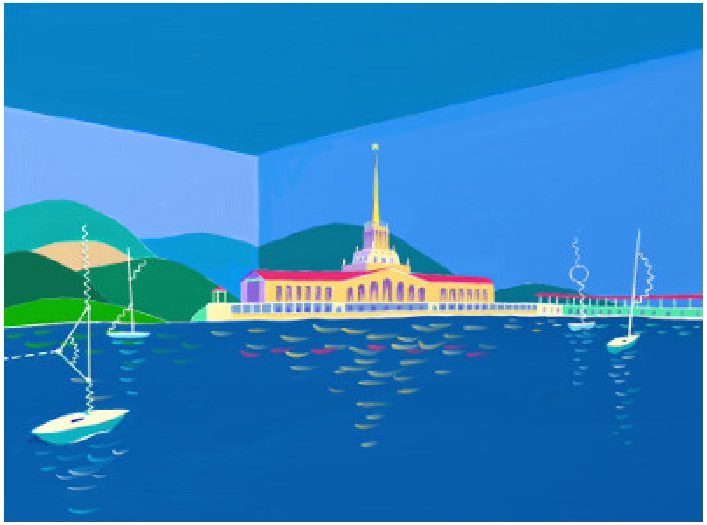

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Sochi, Russia

Correlation femtoscopy at NICA energies

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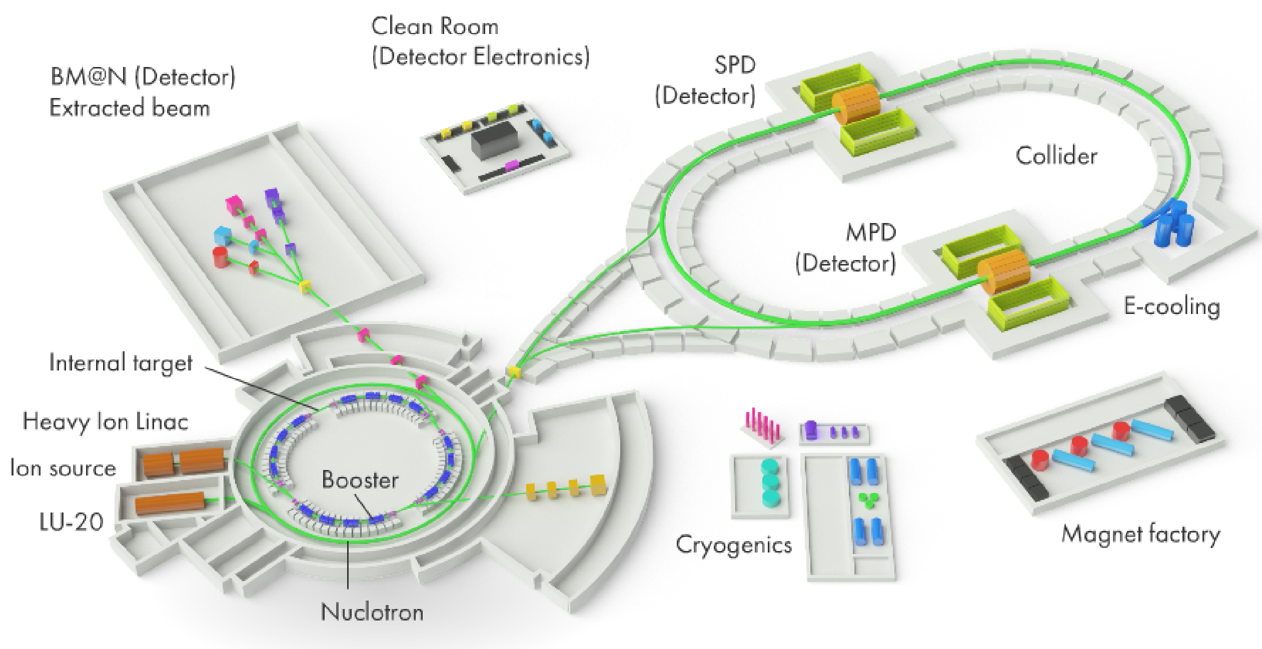
Outline

- NICA
- Femtoscopy and Motivation
- Hybrid vHLLE+UrQMD model
- Comparison with STAR BES
  - pions
  - first results with kaons
- Conclusion

NICA complex



Beams - p, d ... ^{197} Au^{79+}
Collision energy:
$\sqrt{s_{NN}}$ = 4 - 11 GeV E_{lab} = 1 - 6 AGeV
Luminosity: 10^{27} cm^{-2}s^{-1} (Au),
10^{32} (p)

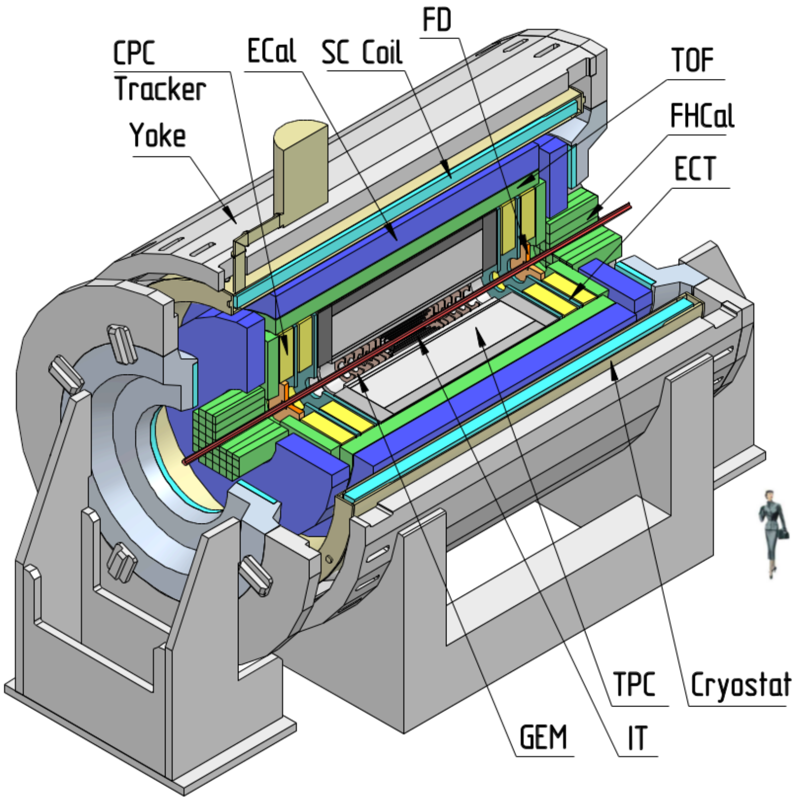
- 2 interaction points - MPD and SPD
- Fixed target experiment - BM@N

Specific scope elements of the project NICA/MPD facility are expected to include:

- Injection complex,
- New superconducting Booster synchrotron,
- The existing superconducting heavy ion synchrotron Nuclotron,
- Collider having two new superconducting storage rings,
- New beam transfer channels.

- 2018: extracted beams of heavy ions (Ar, Kr) are available within the BM@N experiment
- 2020-2021: a first configuration of the MPD setup available.
- 2023: commissioning of the fully designed NICA-complex is foreseen.

MultiPurpose Detector (MPD) for A+A collisions @ NICA



Benefits:

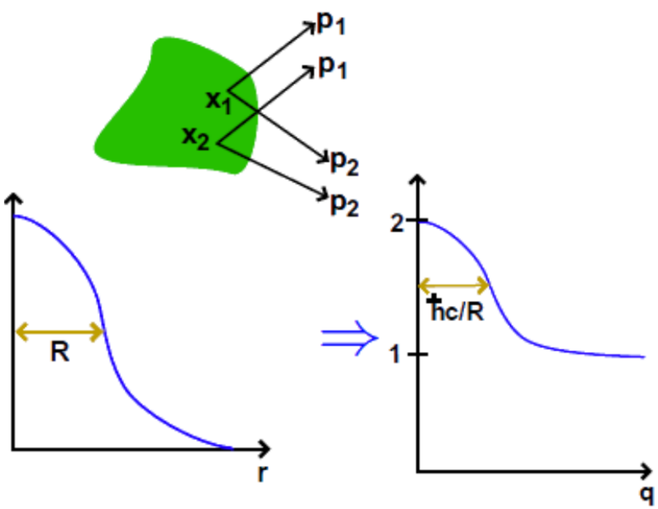
- Hermeticity, 2π-acceptance in azimuth
- 3D-tracking (TPC, ECT)

- Vertex high-resolution (IT)
- Powerful PID (TPC, TOF, ECAL)
  - π, K up to 1.5 GeV/c
  - K, p up to 3 GeV/c
  - γ, e from 0.1 GeV/c up to 3 GeV/c
- Precise event characterization (FHCAL)
- Fast timing and triggering (FFD)
- Low material budget
- High event rate (up to 7 kHz)

Realization progress:

- TDR - completed
- Detector mass production is on going
- First stage - 2021 (ready for cosmics - end of 2020)
- Second stage and full commissioning (IT + end-cups) - 2023

Femtoscopy



Correlation femtoscopy :

Measurement of space-time characteristics **R, cτ** of particle production using particle correlations due to the effects of quantum statistics (QS) and final state interactions (FSI)

Two-particle correlation function:

theory: $$C(q)=\frac{N_2(p_1,p_2)}{N_1(p_1)\cdot N_2(p_1)}, C(\infty)=1$$

experiment: $$C(q)=\frac{S(q)}{B(q)}, q=p_1-p_2$$

$S(q)$ – distribution of pair momentum difference from same event
$B(q)$ – reference distribution built by mixing different events

Parametrizations used:

1D CF: $$C(q_{inv})=1+\lambda e^{-R^2 q_{inv}^2}$$

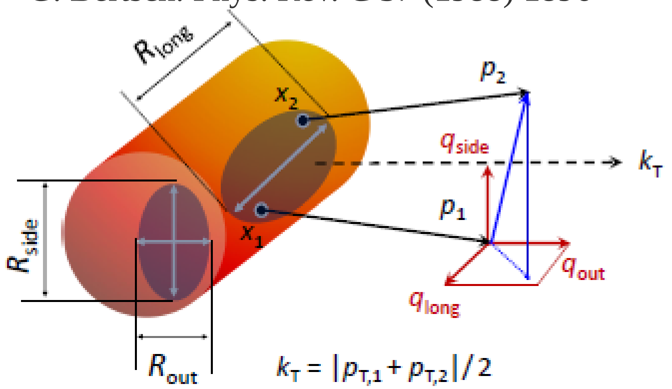
R – Gaussian radius in PRF,
λ – correlation strength parameter

3D CF: $$C(q_{out},q_{side},q_{long})=1+\lambda e^{-R_{out}^2 q_{out}^2-R_{side}^2 q_{side}^2-R_{long}^2 q_{long}^2}$$

R and q are in Longitudinally Co-Moving Frame (**LCMS**)
long || beam; out || transverse pair velocity $\boldsymbol{v}_T$; side normal to out,long

LCMS decomposition:

S. Pratt. Phys. Rev. D 33 (1986) 1314
G. Bertsch. Phys. Rev. C 37 (1988) 1896

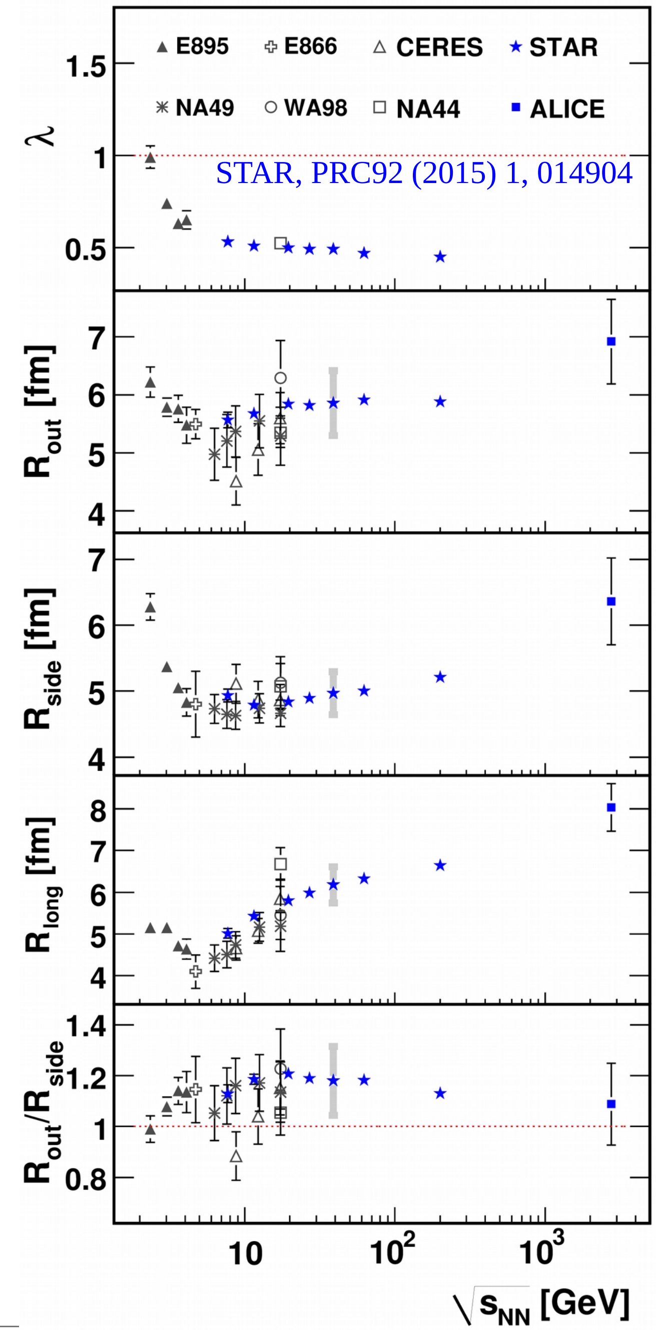


Motivation

- **<u>Femtoscopy allows one:</u>**
  - To obtain spatial and temporal information on particle-emitting source at kinetic freeze-out
  - To study collision dynamics depending on EoS

- RHIC Beam Energy Scan program (BES-I):
  $\sqrt{s_{NN}}$ = 7.7, 11.5, 19.6, 27, 39 GeV
  - The search for the onset of a first-order phase transition in Au + Au collisions
  - Measured pion and kaon femtoscopic parameters: m_T -dependence of radii, flow-induced $x - p$ correlations

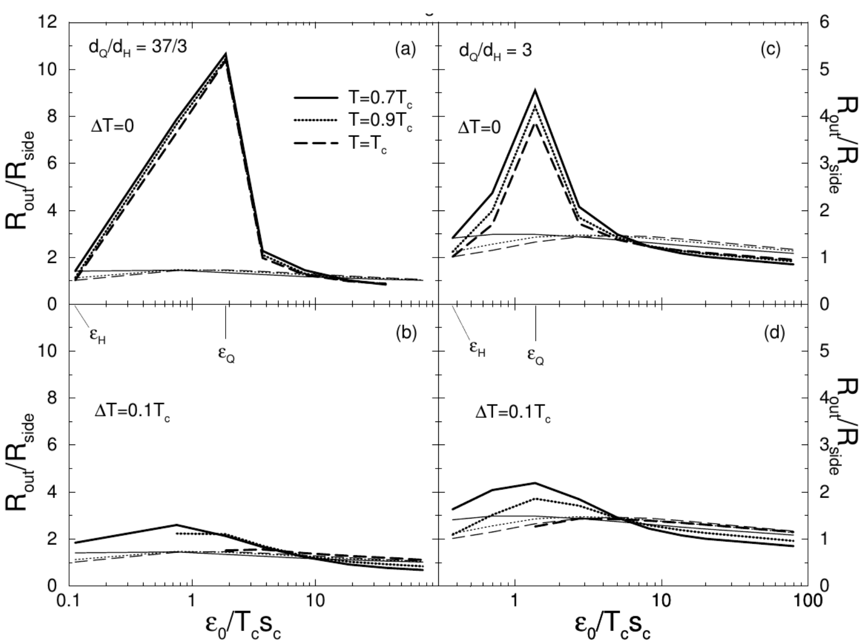
- NICA energy range: $\sqrt{s_{NN}}$ = 4 – 11 GeV measurements with great accuracy

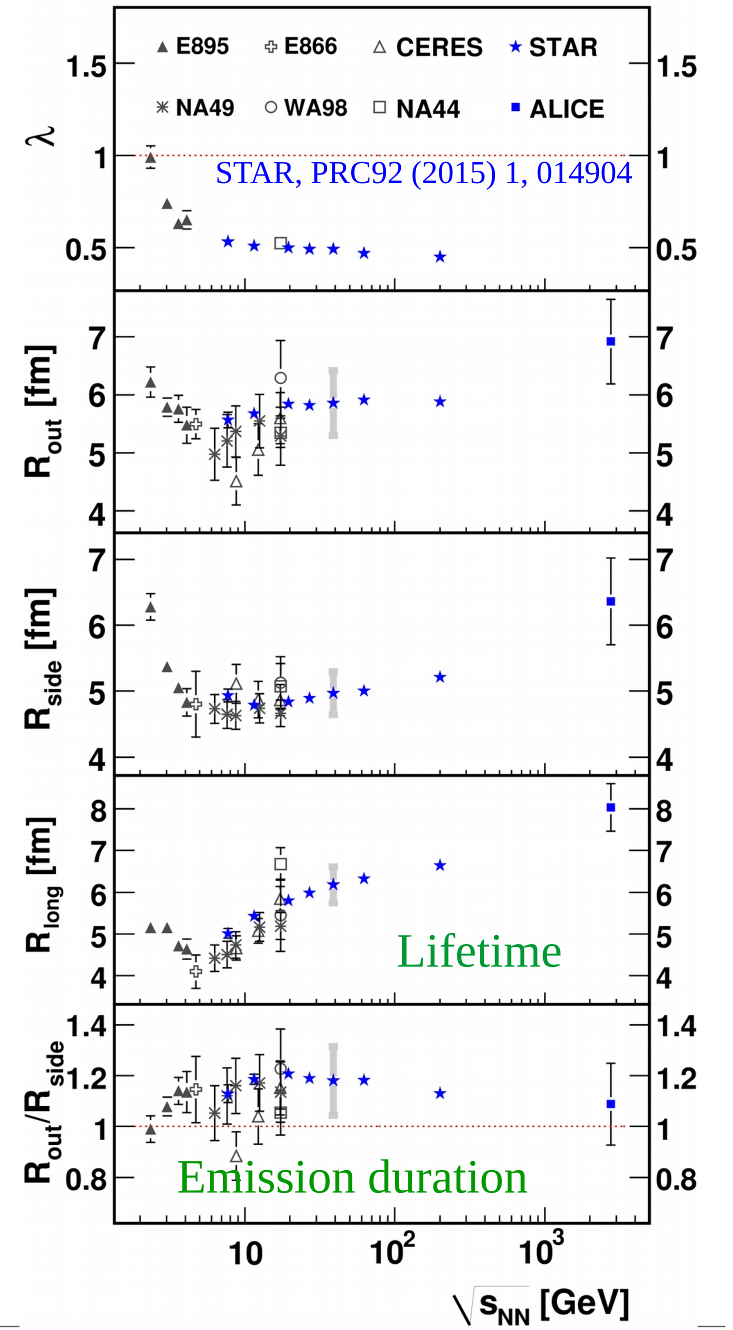


Expected features of first-order phase transition (1PT)

- It was predicted for first-order phase transition R_{out}/R_{side} » 1 and larger R_{long} due to emission stalling during phase transition.
  S. Pratt, Phys. Rev. D 33 (1986) 1314.G. Bertsch, M. Gong, M. Tohyama, Phys. Rev. C 37 (1988) 1896

D. H. Rischke, M. Gyulassy, Nucl. Phys. A608, 479 (1996):





- But space-time correlations in expanding source reduce the observed R_{out} → R_{out}/R_{side}
- Study of femtoscopy observables allows to perform tune of the models to describe correctly collision dynamics

Femtoscopy with vHLLE+UrQMD

Iu. Karpenko, P. Huovinen, H.Petersen, M. Bleicher, Phys.Rev. C 91, 064901 (2015)

Pre-thermal phase → Hydrodynamic phase → Hadronic cascade

UrQMD | vHLLE (3+1)-D viscous hydrodynamics | UrQMD

Pion emission time
(a) - after hydrodynamic phase
(b) - after cascade

Parameters τ_0 , $R_\perp$, R_η and η/s adjusted using basic observables in the RHIC BES-I region.

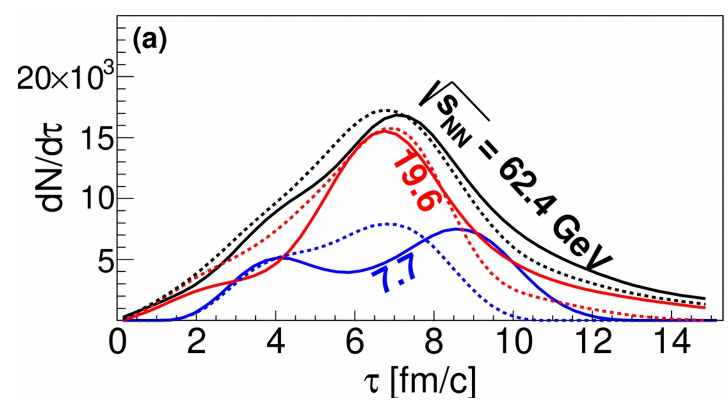
$\sqrt{s_{NN}}$ [GeV]	τ_0 [fm/c]	$R_\perp$ [fm]	R_η [fm]	η/s
7.7	3.2	1.4	0.5	0.2
8.8 (SPS)	2.83	1.4	0.5	0.2
11.5	2.1	1.4	0.5	0.2
17.3 (SPS)	1.42	1.4	0.5	0.15
19.6	1.22	1.4	0.5	0.15
27	1.0	1.2	0.5	0.12
39	0.9	1.0	0.7	0.08
62.4	0.7	1.0	0.7	0.08
200	0.4	1.0	1.0	0.08

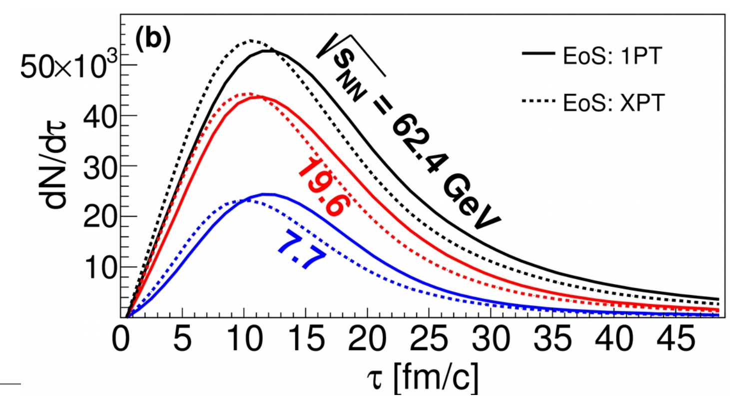
Model tuned by matching with existing experimental data from SPS and BES-I RHIC

EoS to be used in the model

- Chiral EoS - crossover transition
  J. Steinheimer et al., J. Phys. G 38, 035001 (2011)
- Hadron Gas + Bag Model 1st-order phase transition
  P. F. Kolb et al., Phys.Rev. C 62, 054909 (2000)

Hydrodynamic phase lasts longer with 1PT, especially at lower energies but cascade smears this difference.

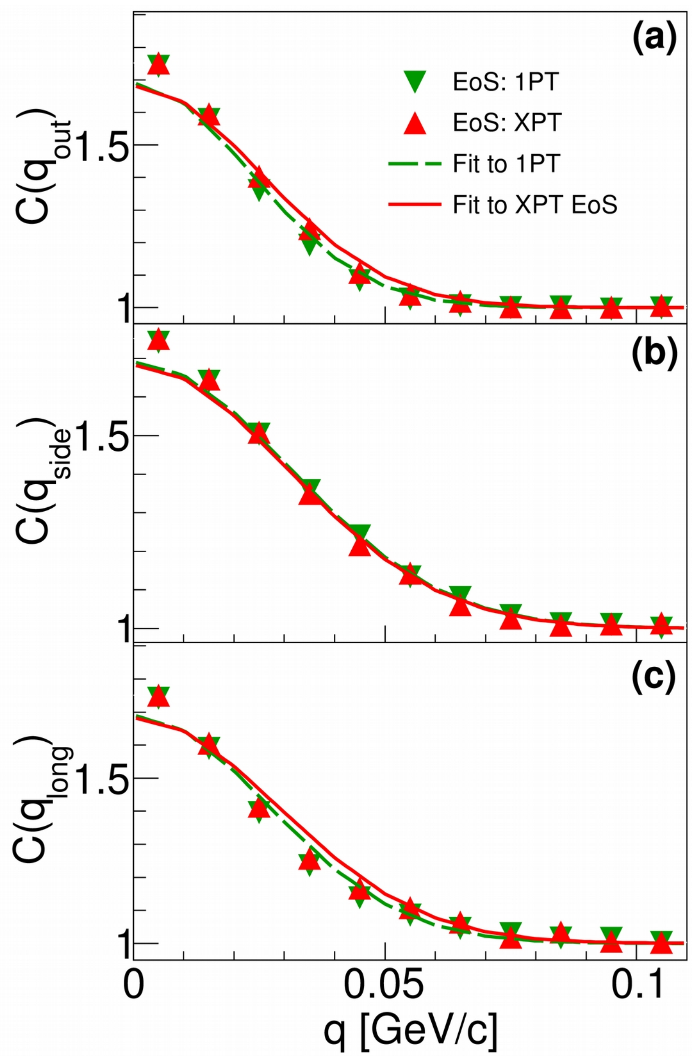


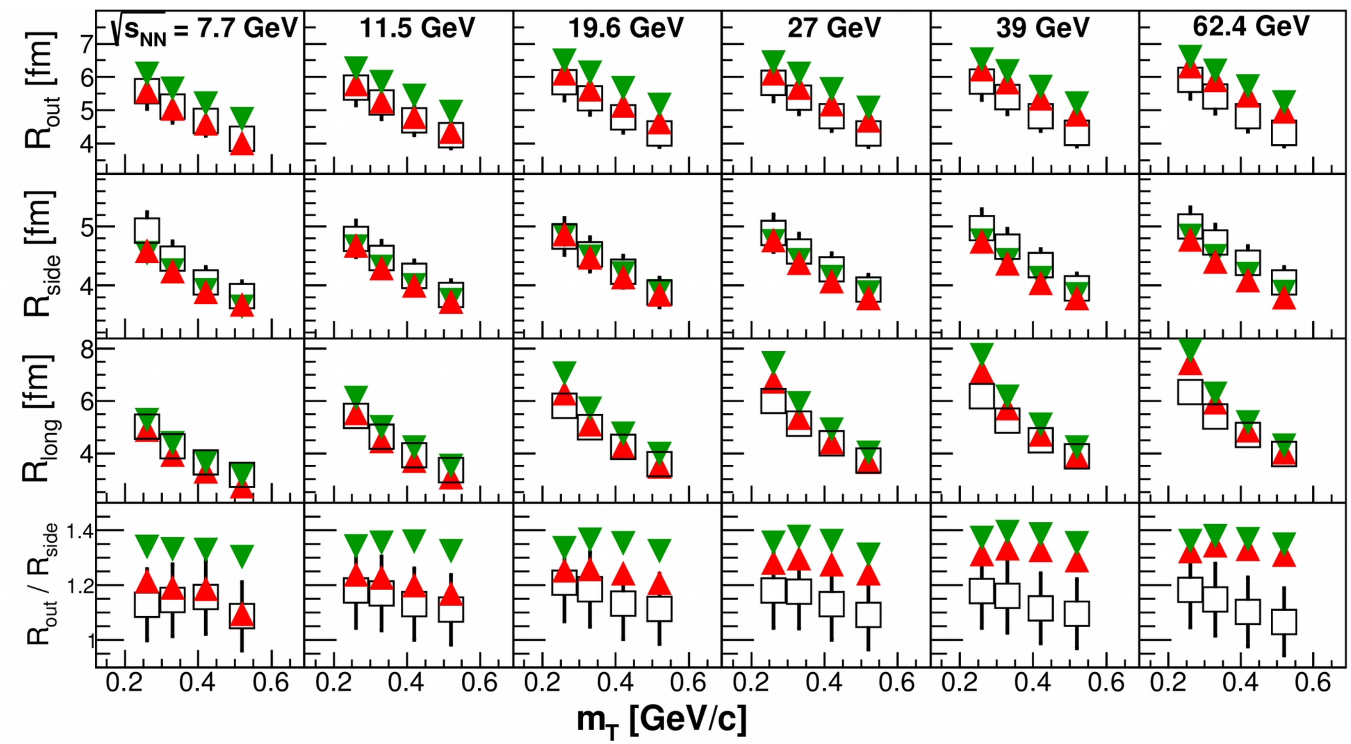


3D Pion radii versus m_T with vHLLE+UrQMD

Comparison of extracted radii with the STAR data[PRC 96, 024911(2017)]

Model CF

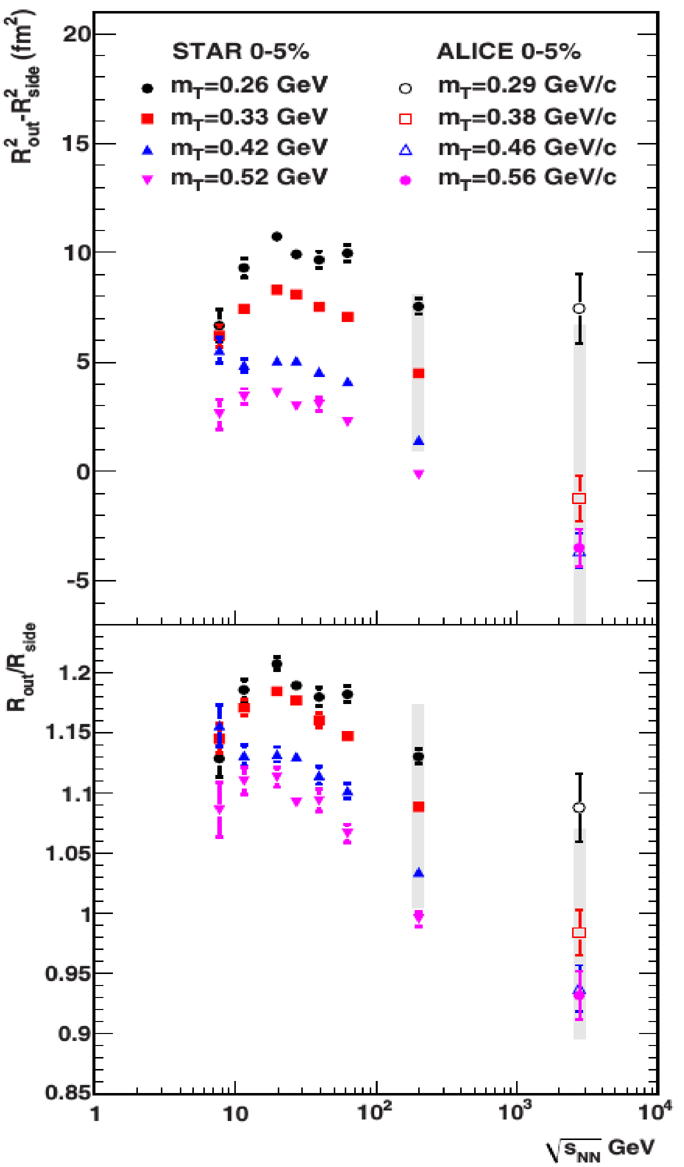




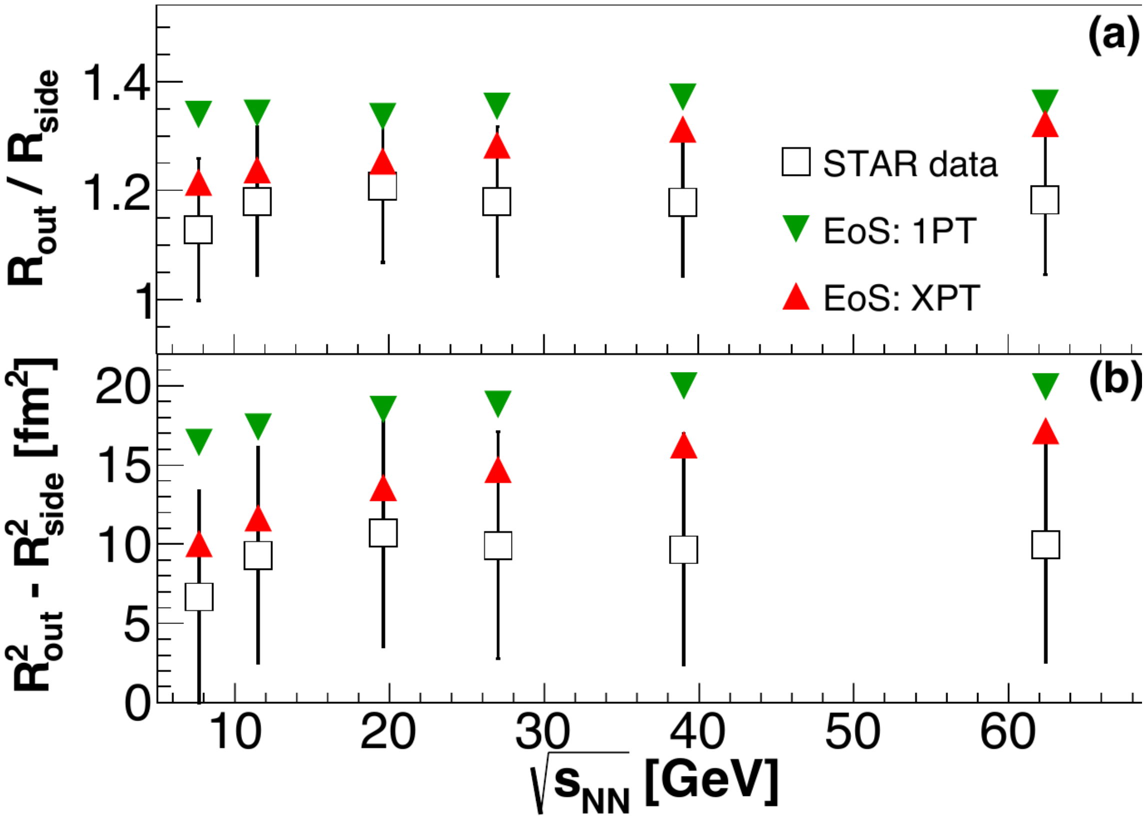
- Femtoscopic radii are sensitive to the type of the phase transition
- Crossover EoS does better job at lowest collision energies.
- R_{out} (XPT) at high energies and R_{out} (1PT) at all energies are slightly overestimated
- $R_{\mathrm{out,long}}$ (1PT) > $R_{\mathrm{out,long}}$ (XPT) by value of ∼1-2 fm.

R_{out} /R_{side} with vHLLE + UrQMD model

Exp. data: R_{out} /R_{side} and R^2_{out} - R^2_{side} as a function of $\sqrt{s_{NN}}$ at a fixed m_T demonstrate a wide maximum near $\sqrt{s_{NN}} \approx 20$ GeV

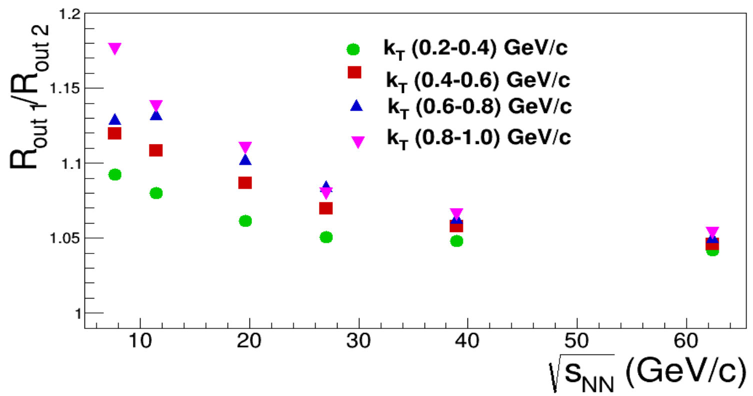


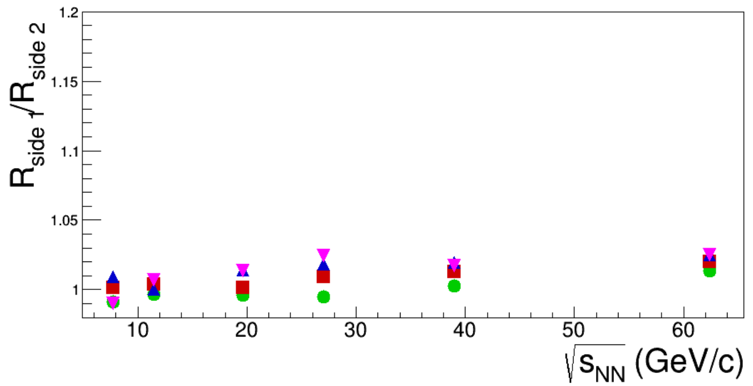
Present vHLLE+UrQMD calculations:

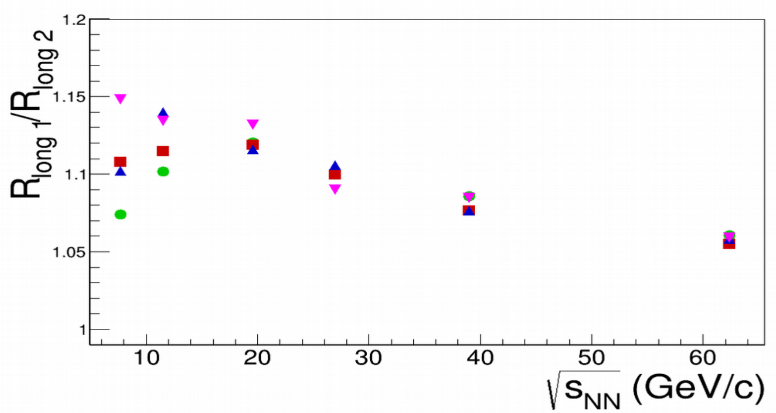


- R_{out} /R_{side} (XPT) agrees with almost all STAR data points within rather large systematic errors, while R_{out} /R_{side} (1PT) overestimates the data.
- XPT – a monotonic increase in both quantities

Ratio of $R_{out,side,long}$(1PT)/$R_{out,side,long}$ (XPT) vs. $\sqrt{s_{NN}}$







- Pion k_T divided into 4 bins
- R_{side} ratio practically coincide for both scenarios
- R_{out} and R_{long} ratios for 1PT EoS are greater than for XPT EoS and demonstrating a strong k_T -dependence at low energy

- The difference comes from a weaker transverse flow developed in the fluid phase with 1PT EoS as compared to XPT EoS and its longer lifetime in 1PT EoS

Kaon correlation functions with vHLLE+UrQMD (NEW!)

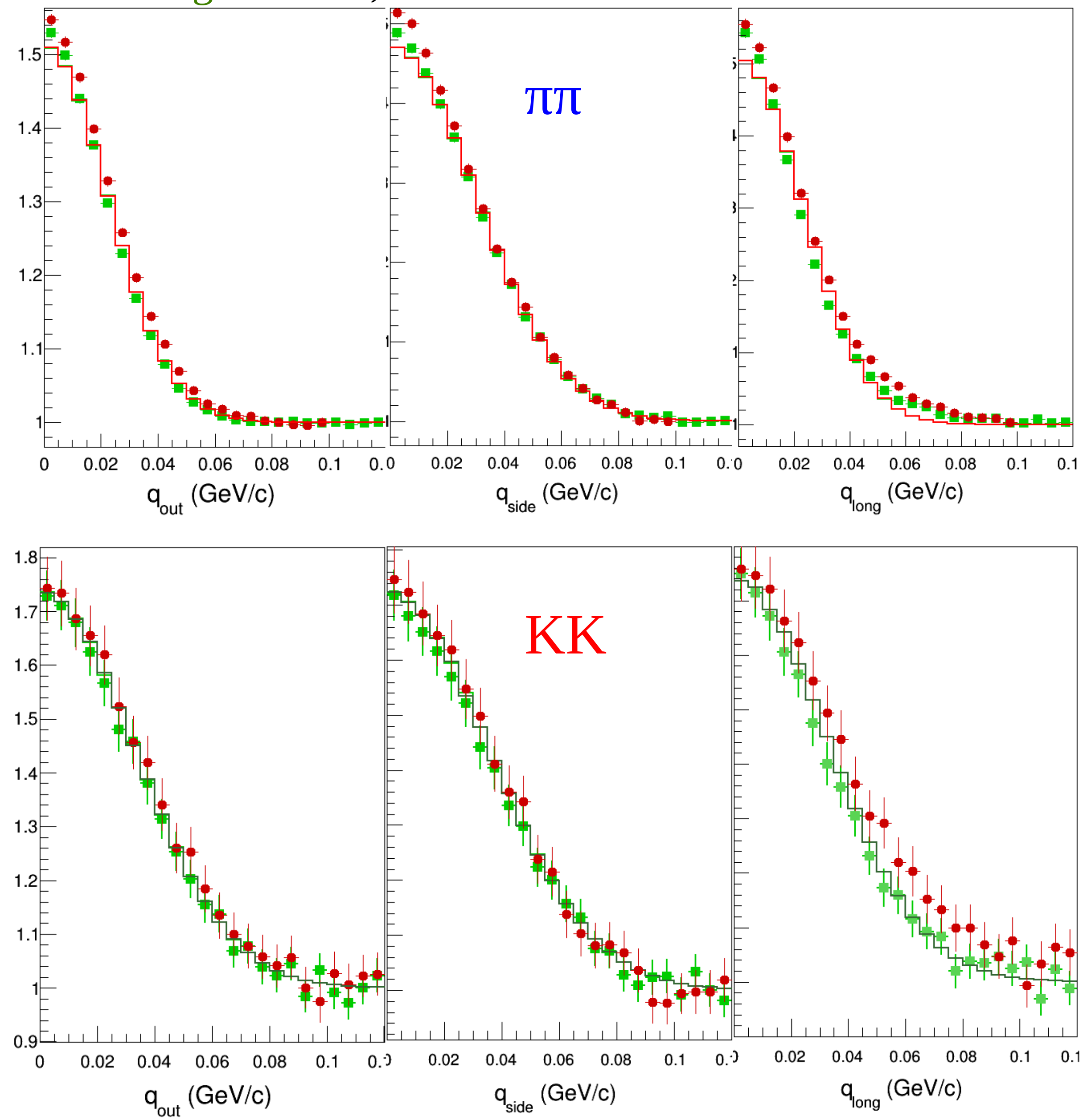
Analysis:

- Au+Au, $\sqrt{s_{NN}}$ = 11.5 GeV
- $N_{events} \approx 4 \cdot 10^5$
- Standard 3D Gaussian fit used
- Our, side, long projections

- Projections of 3D kaon correlation functions on out-side-long directions are more Gaussian

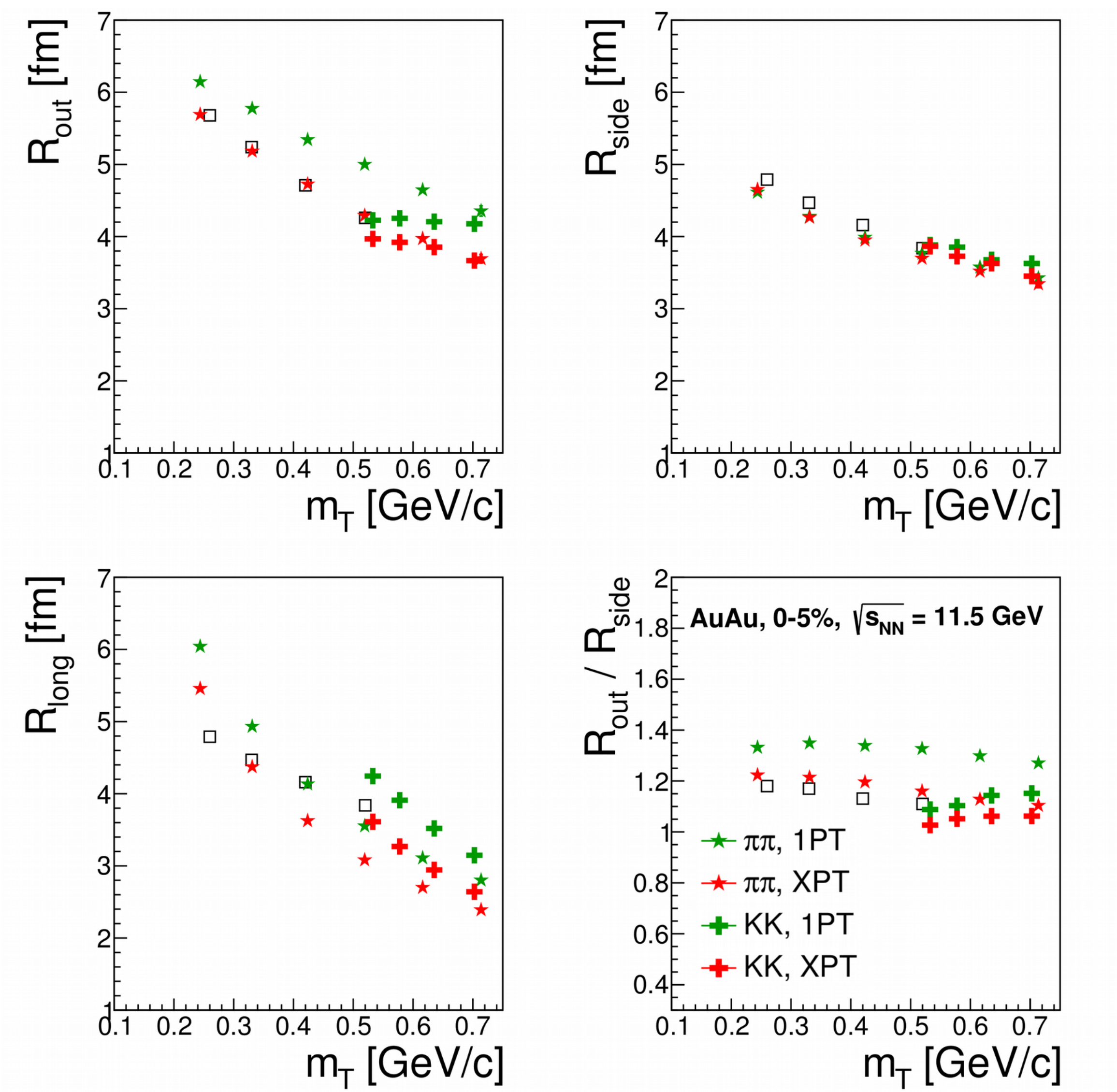
- XPT CF projections on long direction are visibly wider than 1PT especially for kaons

1PT -green dots; XPT – red dots



Radii π and K vs. mT with vHLLE+UrQMD

1PT -green dots; XPT – red dots



- Au+Au, $\sqrt{s_{NN}}$ = 11.5 GeV
- As well as for π, kaon out and long radii greater for 1PT than for XPT
- Approximate m_T-scaling for pions and kaons observed only for "side" radii
- R_{out} almost flat for 1PT
- R_{long}(KK) is greater than R_{long}(ππ) kaons on average emitted later than pions
- Rout/Rside(KK) for kaons is less than for pions
- Approximately the same result is for Au+Au $\sqrt{s_{NN}}$ = 7.7 GeV
- It is important to measure both kaons and pions

Conclusions

- Hydro phase lasts longer with 1PT.
- vHLLE+UrQMD with XPT-scenario describes BES-I
  STAR femtoscopy radii at $\sqrt{s_{NN}}$ = 7.7, 11.5 GeV better than the 1PT-scenario.
- R_{long} for 1PT is greater than for XPT.
- R_{out}/R_{side} for 1PT also is greater than for XPT.
- First results with kaon femtoscopy look promising and this study is planned to be continued.

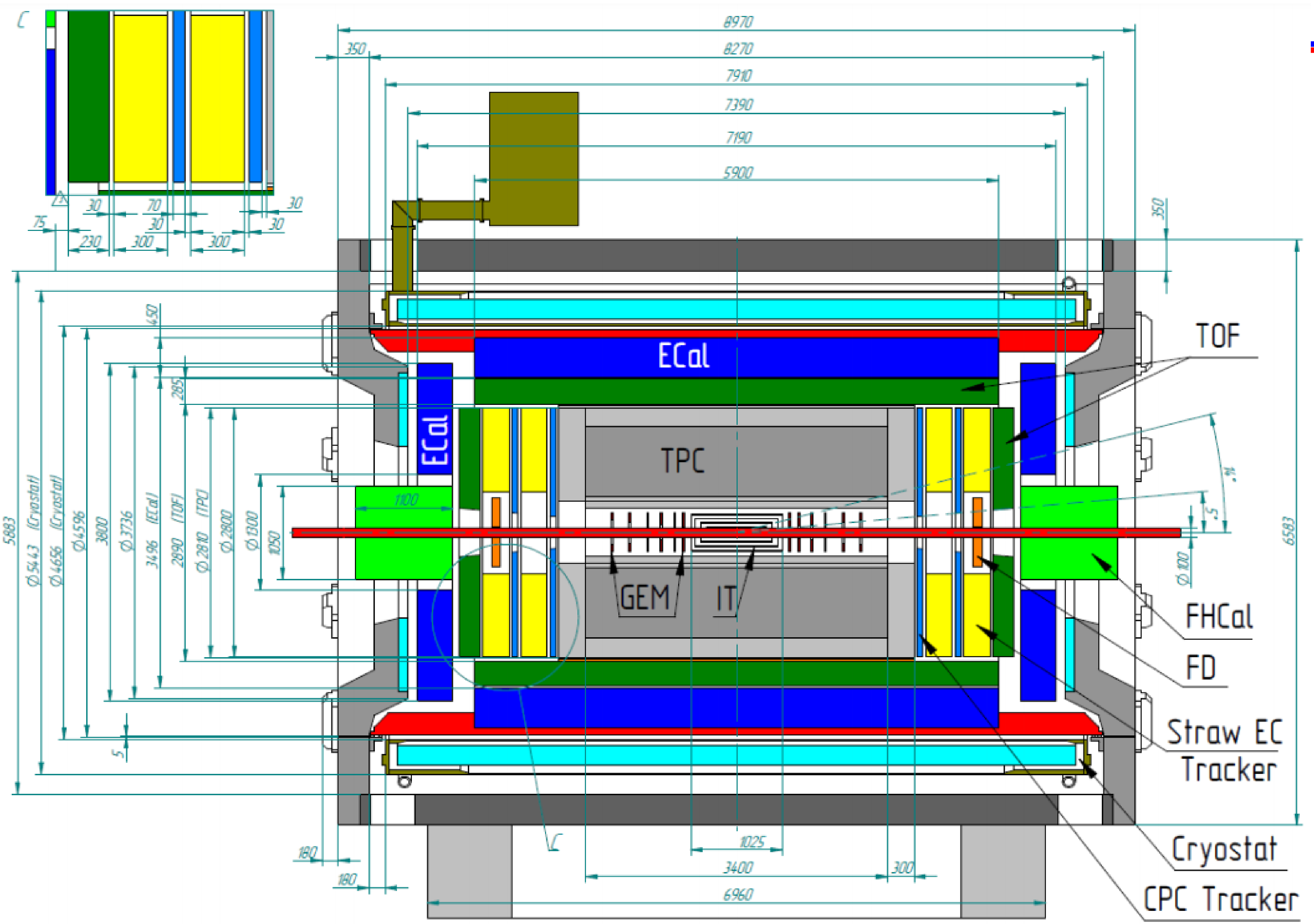
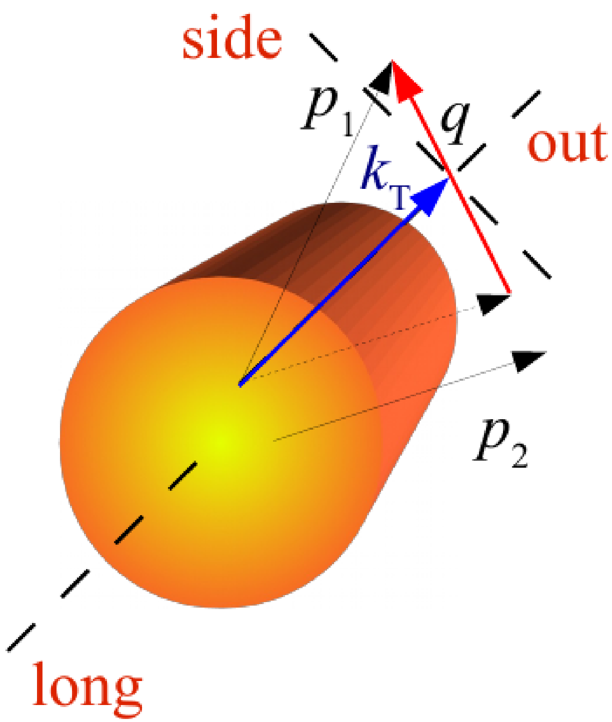


Fig. 2: Side view of the MPD experiment with indicated subsystem dimensions.

LCMS reference frame



$$m_T = \sqrt{k_T^2 + m_\pi^2}$$

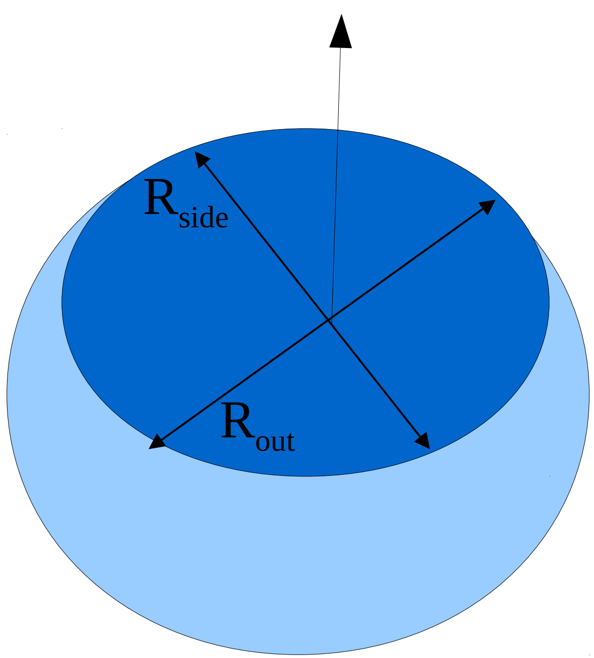
Longitudinally Co-Moving System (LCMS):
$p_{1,long} = -p_{2,long}$

- For charged pions measurement in 3 dimensions, giving 3 independent sizes in Longitudinally Co-Moving System
- The Bertsch-Pratt decomposition of q:
  - Long along the beam: sensitive to longitudinal dynamics and evolution time
  - Out along k_T: sensitive to geometrical size, emission time and space-time correlation
  - Side perpendicular to Long and Out: sensitive to geometrical size
- For statistically challenged analyses, measurement in one dimension (giving only one size) in Pair Rest Frame

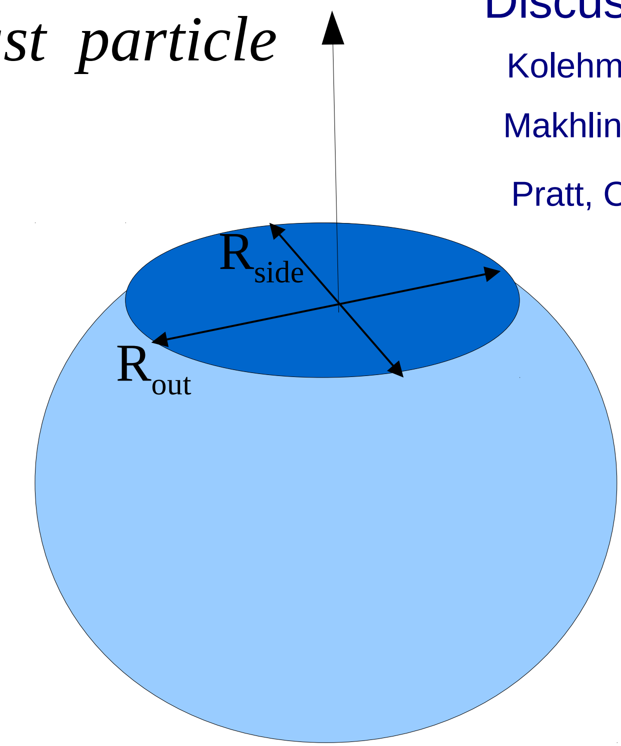
Femtoscopy with expanding source → m_T-dependence

- **x-p** correlations → interference dominated by particles from nearby emitters.
- Interference probes only parts of the source at close momenta – **homogeneity regions.**
- Longitudinal and transverse expansion of the source -> significant reduction of the radii with increasing pair velocity, consequently with k_T (or $m_T=(m^2+k_T^2)^{1/2}$)

Slow particle



Fast particle



Discussed in e.g.:

Kolehmainen, Gyulassy'86

Makhlin-Sinyukov'87

Pratt, Csörgö, Zimanyi'90

$$R_{side} \sim R/(1+m_T\beta_T^2/T)^{1/2}$$

β_T collective transverse flow

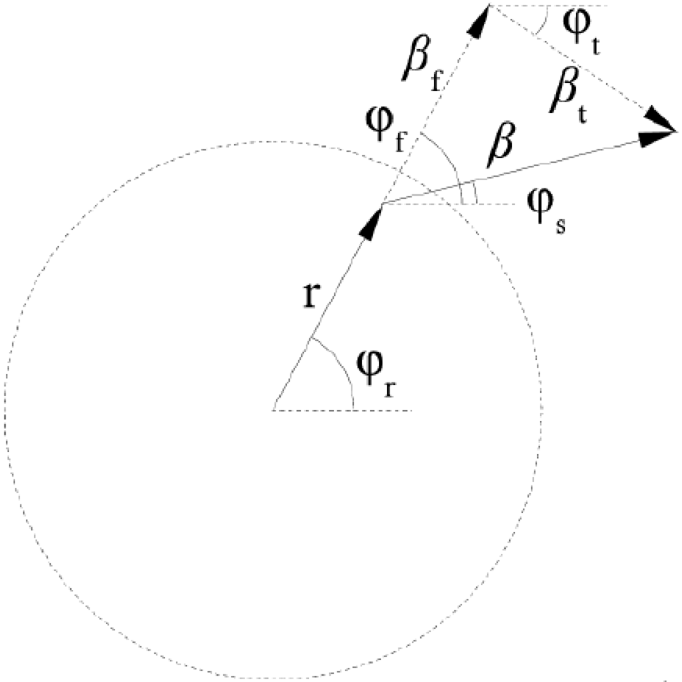
$$R_{long} = \tau\,(T/m_T)^{1/2}$$

assuming a longitudinal boost invariant expansion

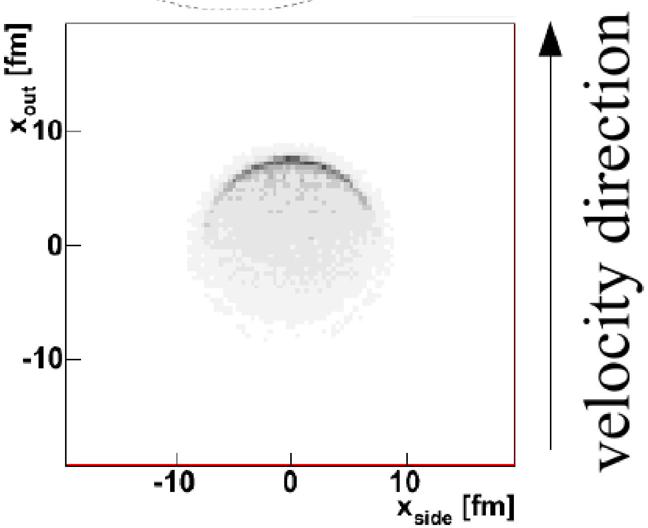
$$R^2_{out} \sim R^2_{side} + 1/2(T/m_T)^2\beta_T^2\tau^2$$

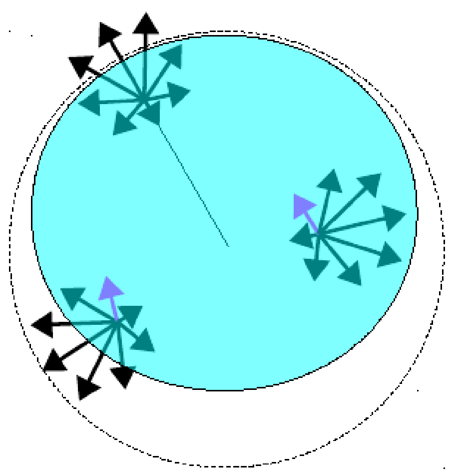
Expanding source

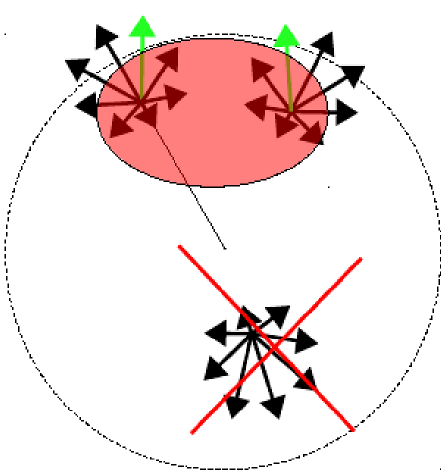
Interference probes only parts of the source at close momenta – **homogeneity regions.**
[Yu.M. Sinyukov, Nucl. Phys. A 566, 589 (1994);]



- A particle emitted from a medium will have a collective velocity β_f and a thermal (random) one β_t
- As observed p_T grows, the region from where pairs with small relative momentum can be emitted gets smaller and shifted to the outside of the source



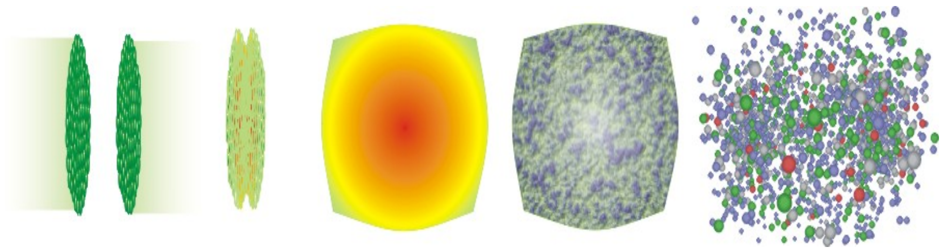


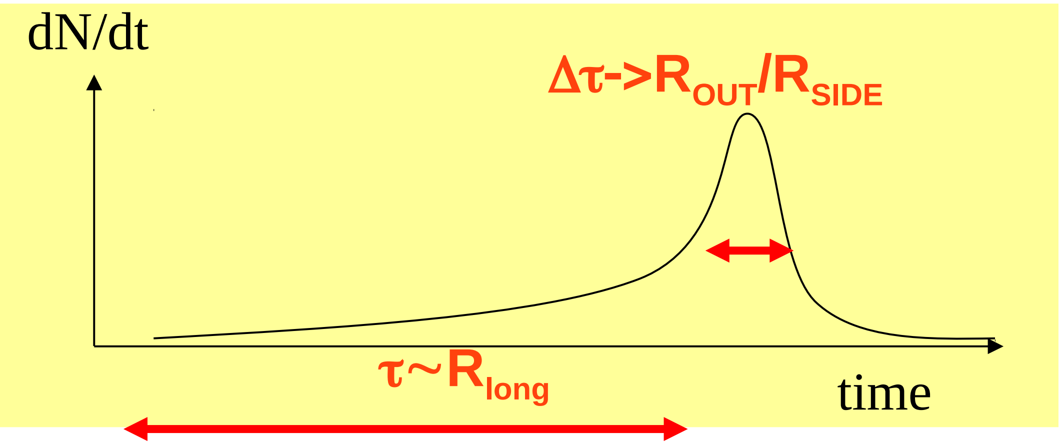


Femtoscopy: physics motivation

HI collisions

• Measure the size of the homogeneity region from which the volume of the QGP can be inferred
• Study of radii dependence on transverse momentum -> manifestation of collective motion of matter
• Study of transverse mass dependence for different particle types (π, K, p, ...)- additional confirmation of the hydrodynamic type of expansion: m_T scaling & asymmetries
• Study of source shape at freeze-out: az-femtoscopy





pp collisions

• Study space-time characteristics of particle production in “elementary process”
• Multiplicities, comparable to peripheral AA collisions: collectivity in pp as in AA ?

Constraints on model parameters.

D. H. Rischke, M. Gyulassy, Nucl. Phys. A608, 479 (1996)

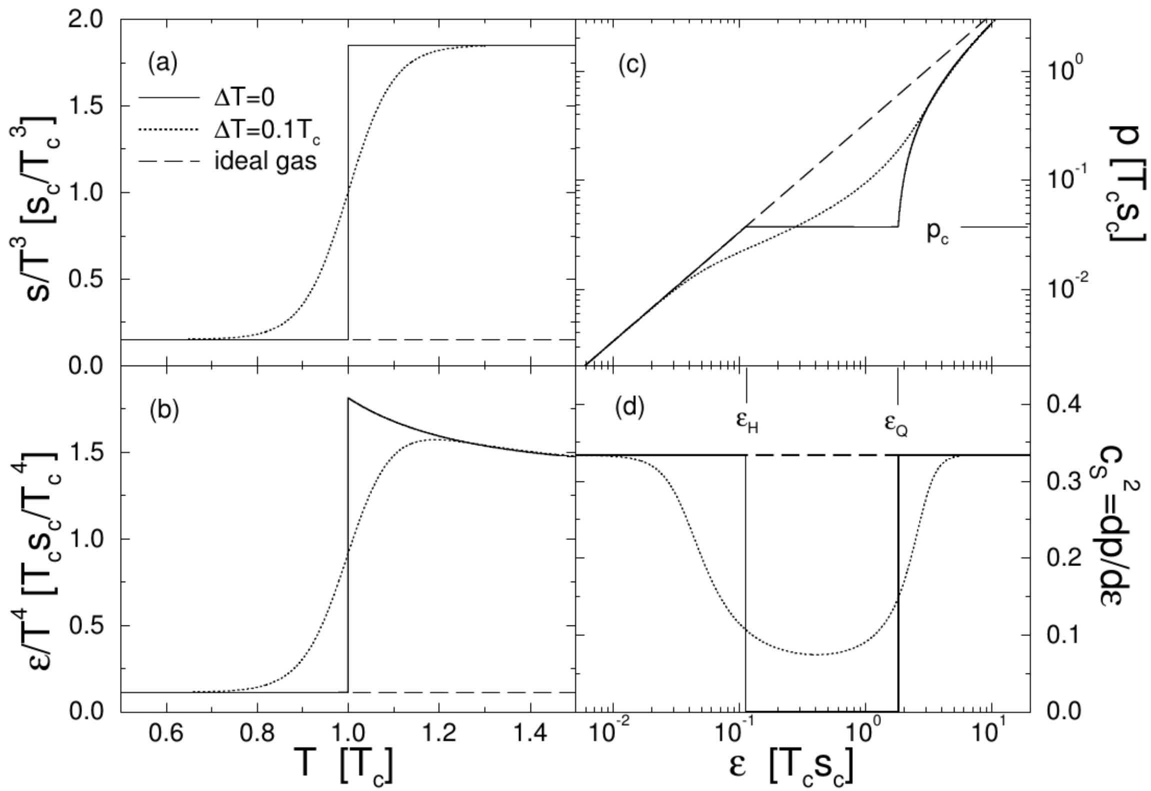


Fig. 1: (a) the entropy density divided by T^3 (in units of $s_c/T_c^{\,3}$), (b) the energy density divided by T^4 (in units of $T_c\ s_c/T_c^{\,4}$) as functions of temperature (in units of T_c), (c) the pressure (in units of $T_c s_c$), (d) the square of the velocity of sound as functions of energy density (in units of $T_c s_c$). The solid lines correspond to $\Delta T = 0$, the dotted curves$\Delta T = 0.1\ T_c$. Quantities for the ideal gas equation of state (with dH degrees of freedom) are represented by dashed lines. The ratio of degrees of freedom in the QGP to those in the hadronic phase is $d_Q/d_H = 37/3$. The critical enthalpy density is $T_c\ s_c$ ~=0.75 GeV fm^{-3} for $\simeq$the case $d_Q = 37$, $d_H = 3$.

vHLLE

$$\tau_0 = 2R/\sqrt{(\sqrt{s_{\mathrm{NN}}}/2m_N)^2 - 1},$$

Minimal time of starting hydrodynamic evolution: average time for the two colliding nuclei to completely pass through each other.

At $\tau = \tau_0$ energy, momentum and baryon/electric charges of hadrons are distributed to fluid cells ijk around each hadron's position according to Gaussian profiles:

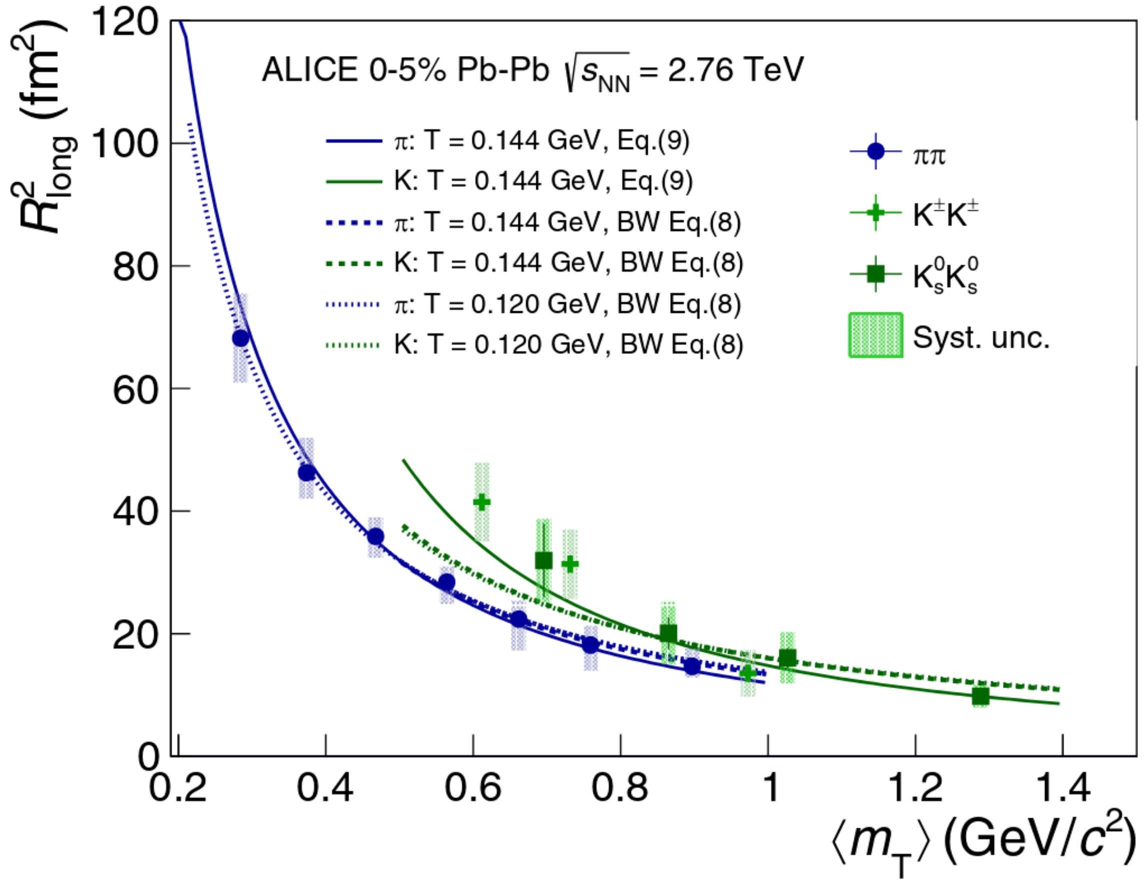
$$\Delta P^{\alpha}_{ijk} = P^{\alpha} \cdot C \cdot \exp\left(-\frac{\Delta x_i^2 + \Delta y_j^2}{R_\perp^2} - \frac{\Delta \eta_k^2}{R_\eta^2}\gamma_\eta^2\tau_0^2\right) \quad (2)$$

$$\Delta N^{0}_{ijk} = N^{0} \cdot C \cdot \exp\left(-\frac{\Delta x_i^2 + \Delta y_j^2}{R_\perp^2} - \frac{\Delta \eta_k^2}{R_\eta^2}\gamma_\eta^2\tau_0^2\right), \quad (3)$$

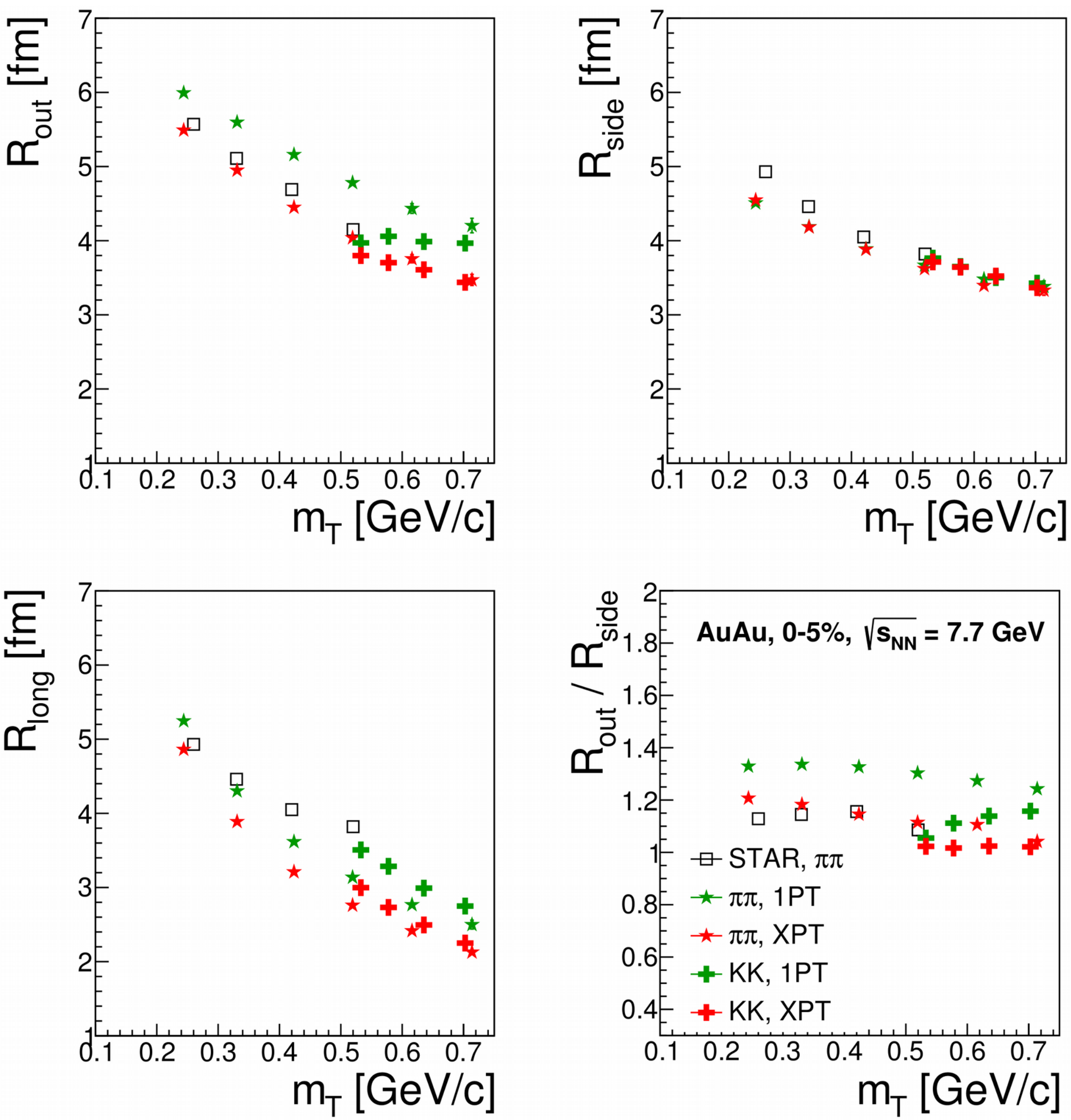
where P^α and N^0 are 4-momentum and charge of a hadron, $\{\Delta x_i, \Delta y_j, \Delta \eta_k\}$ are the distances between hadron's position and center of a hydro cell ijk in each direction, $\gamma_\eta = \cosh(y_p - \eta)$ is the longitudinal Lorentz factor of the hadron as seen in a frame moving with the rapidity η, and C is a normalization constant. The normalization constant C is calculated so that the discrete sum of energy depositions to the hydrodynamic cells equals to the energy of the hadron. The width parameters $R_\perp$ and R_η control granularity of the produced initial state.

Emission delay in ALICE data

- ALICE kaon data in hydro-based parameterization: kaons emitted on average later than pions.
- It comes from rescattering via K* resonance
- $R_{long} \sim \tau / \sqrt{m_T}$
- Measured values: τ_π=9.5±0.2 fm/c
  τ_K=11.6±0.1 fm/c



Radii π and K vs. mT with vHLLE+UrQMD (7.7GeV)



- AuAu, $\sqrt{s_{NN}}$ = 7.7 GeV
- As well as for π kaon out and long radii greater for 1PT than for XPT
- Approximate m_T scaling for pions and kaons observed only for "side" radii