Femtoscopy with identified particles for NICA/MPD

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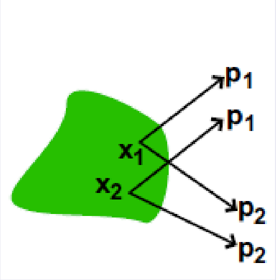
Outline:

- Motivation
- Hybrid vHLLE+UrQMD model
- Comparison with BES-I STAR
  - pions
  - first results with kaons **(NEW!)**
- Package for Femtoscopic Analysis
- Summary

Femtoscopy formalism



Correlation femtoscopy:

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

Two-particle correlation function:

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

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

S(q) is a distribution of pair momentum difference of particles from the same event

B(q) is a reference distribution built by mixing of particles from different events

Parametrizations used:

1D CF:

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

R is a Gaussian radius in PRF,

λ is a correlation strength parameter

1D-analysis is sensitive only to the system size averaged over all directions.

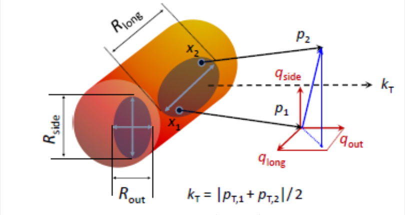
3D CF:

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

Both R and q are in Longitudinally Co-Moving Frame (LCMS)

3D-analysis gives an access to the three system sizes in three directions separately.

Definition of femtoscopy radii:



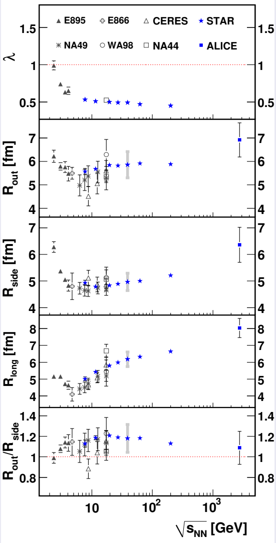
S. Pratt. Phys. Rev. D 33 (1986) 1314

G. Bertsch. Phys. Rev. C37 (1988) 1896

Motivation

- Femtoscopy allows one:
  - 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
  Measured pion and kaon femtoscopic parameters: m_T-dependences of radii, flow-induced $x-p$ correlations
- NICA energy range: $\sqrt{s_{NN}} = 4$ - 11 GeV

Phys. Rev. C92 (2015) 1, 014904

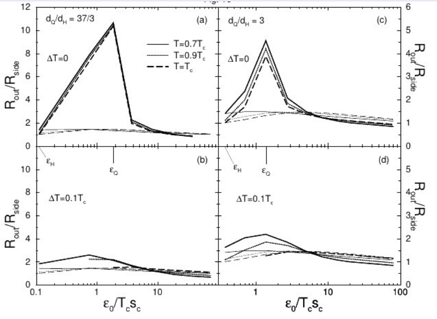


Expected features of first order phase transition (1PT)

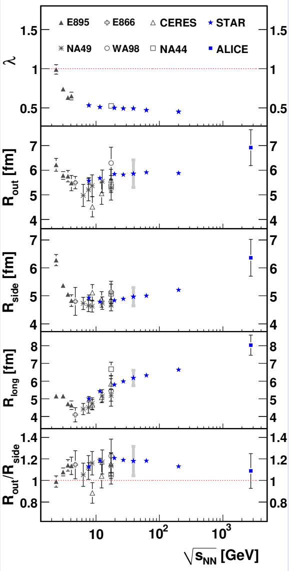
Predicted:

$\frac{R_{out}}{R_{side}} \gg 1$ & Large R_{long} due to emission stalling during phase transition

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



Phys.Rev. C92 (2015) 1, 014904



Observed:

r-t correlations in expanding source reduce R_{out} → R_{out}/R_{side}

Study of femtoscopy observables allows one 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   UrQMD

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

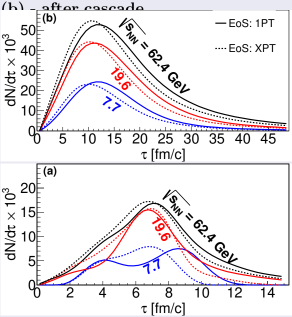
- Chiral EoS - crossover transition
  J. Steinheimer et al., J. Phys. G 38, 035001 (2011)
- Hadron Gas + Bag Model
  1-st order phase transition
  P. F. Kolb et al., Phys.Rev. C 62, 054909 (2000)

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

Pion emission time

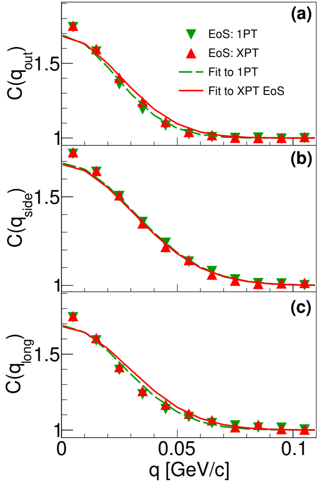
(a) - after hydrodynamic phase

(b) - after cascade

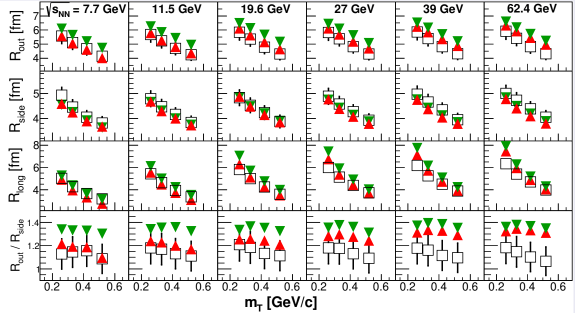


3D Pion radii versus m_T with vHLLE+UrQMD

Phys. Rev. C 96, 024911 (2017)



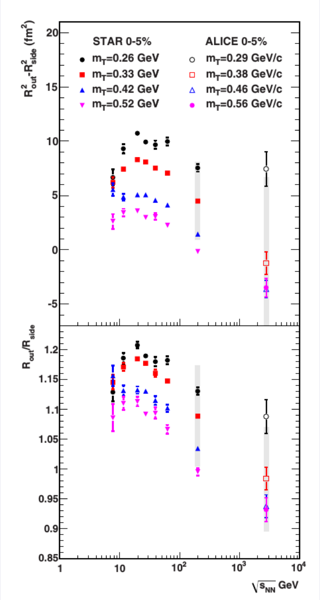
Comparison of extracted radii with the STAR data



Crossover EoS "works" better for lowest collision energies.

- R_{out} (XPT) at high energies and R_{out} (1PT) at all energies are slightly overestimated
- $R_{out,long}$ (1PT) $>$ $R_{out,long}$ (XPT) by value of $\sim$ 1-2 fm.

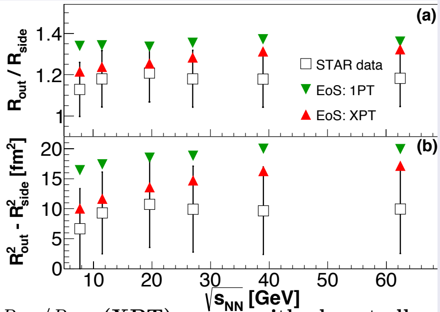
R_{out}/R_{side} with vHLLE + UrQMD model



Exp. data:

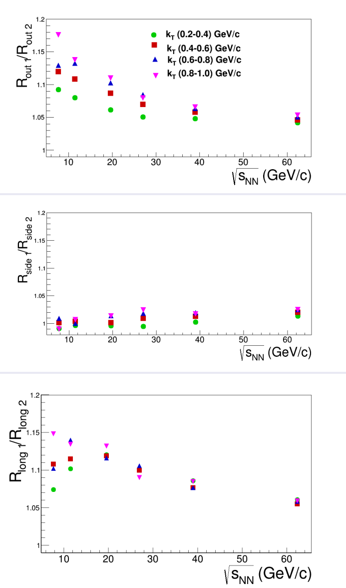
R_{out}/R_{side} and $R^2_{out} - R^2_{side}$ as a function of $\sqrt{s_{NN}}$ at a fixed m_T demonstrate a wide maximum near $\sqrt{s_{NN}} \approx 20$ GeV

Our 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.

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

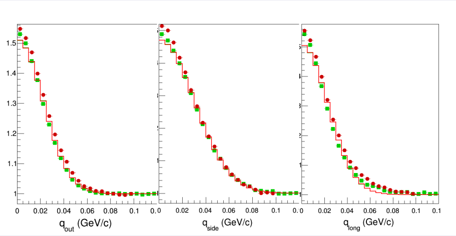


- R_{side} **practically coincide for both scenarios**
- R_{out} **and** R_{long} **for 1PT EoS are greater than for XPT EoS demonstrating a strong** k_T**-dependence**

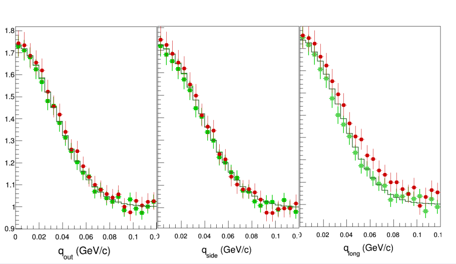
Why?

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

Pions:



Kaons:

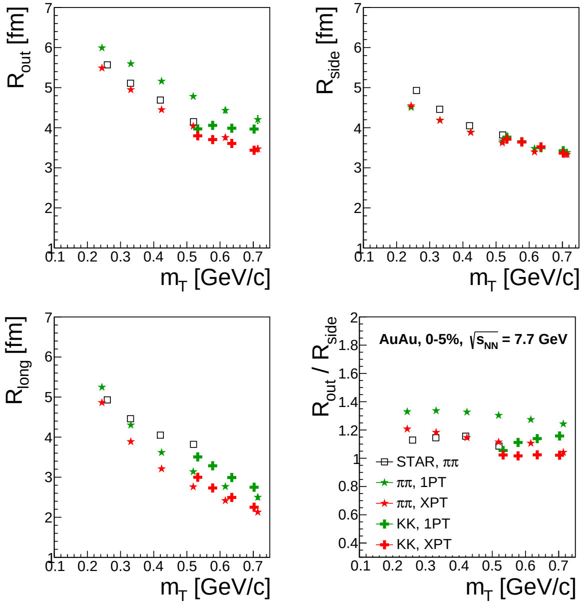


Analysis:

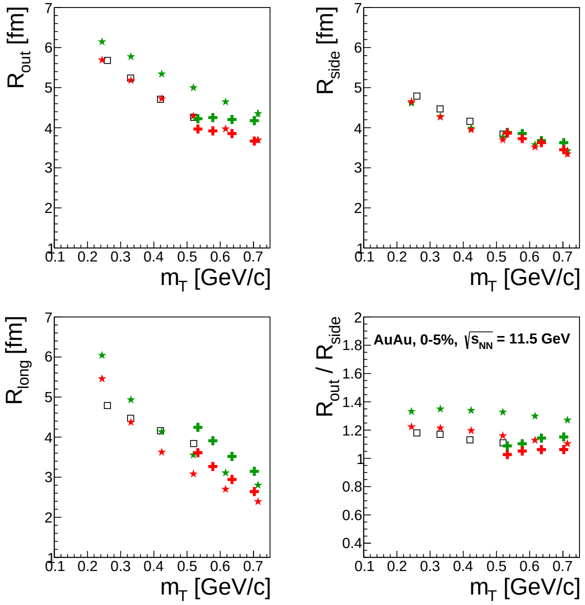
- **AuAu, $\sqrt{s_{NN}} = 11.5$ GeV**
- $N_{events} \approx 400000$
- **Standard 3D Gaussian fit used**

- **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**

Pion & Kaon radii vs. m_T with vHLLE+UrQMD



Pion & Kaon radii vs. m_T with vHLLE+UrQMD



Summarising ...

- **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.**

Package for Femtoscopic Analysis

Femtoscopy

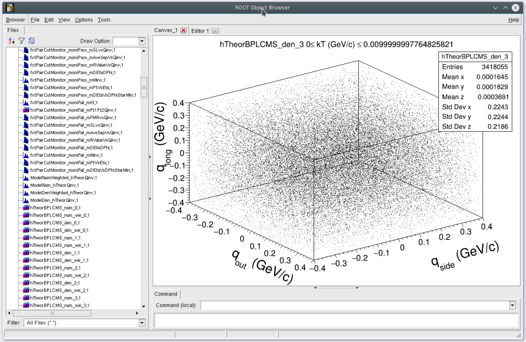
- Inherited from STAR (StHbtMaker) and ALICE (AliFemto)
- Keeps the same hierarchy as in ALICE (PckgName/, PckgNameUser/, macros/)
- Works with ROOT 5 and 6
- Lighter than ancestors:
  - Most of STAR-developed classes replaced with ROOT ones
  - Better compression, smaller sizes
- Implemented running options (INDEPENDENT on experiment-dependent software):
  - Standalone mode – compile with g++ (clang) and run on your "laptop"
  - Maker; Tasks will be also implemented

Data formats (DST)

- General-purpose data format for Monte Carlo generators - McDst `https://github.com/nigmatkulov/McDst`
- Similar to UniGen (developed at GSI)
- Lighter, faster, easy expandable, works with ROOT 5 and 6, g++ (clang)
- Possibility to add converters from other generators: Terminator, EPOS, AMPT ...
- Group has a positive experience on the data format developments:
  - PicoDst format in STAR (standard data format for physics analysis)

Package for Femtoscopic Analysis

Output ROOT tree:



It allows:

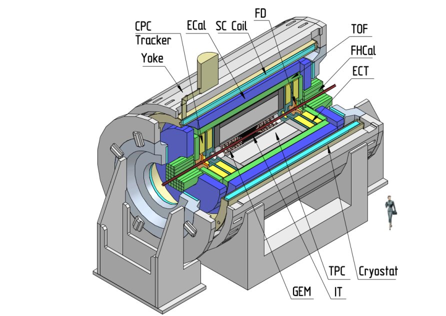
- **To set track cuts, particle pair cuts, number of events to be used for mixing ...**
- **To get 1D and 3D correlation functions for a set of k_T-bins**
- **To switch on / off different physics effects (QS, FSI ...)**

Main macro to define conditions of user's analysis

```
int main(int argc, char* argv[]) {
...
 // Create and set track cut
trackCut->setPdgId(particlePdg);
trackCut->setEta(-1., 1.);
trackCut->setPt(0.15, 1.55);
trackCut->setMass(particleMass);
...
// Set how many events to mix
hbtAnalysis->setNumEventsToMix(10);
...
// Lednicky weight generator
hbtWeight->setPairType(pairType);
hbtWeight->setCoulOn();
hbtWeight->setQuantumOn();
hbtWeight->setStrongOff();
hbtWeight->set3BodyOff();
...
// Create 1D correlation function
// integrated over kT
StHbtModelQinvCorrFctn *oneDim =
new StHbtModelQinvCorrFctn
("hTheorQinv", 40, 0., 0.4);
// Create 3D correlation function
// integrated with kT binning
StHbtModelBPLCMS3DCorrFctnKt *threeDim =
new StHbtModelBPLCMS3DCorrFctnKt
("hTheorBPLCMS", 80, -0.4, 0.4, 4,
0.15, 0.59);
}
```

Where will it be studied?

MPD Layout:



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)

Participants:

- Tsinghua University, Beijing, China
- GSI, Darmstadt, Germany
- WUT, Warsaw, Poland
- MEPhI, Moscow, Russia
- INR, RAS, Russia
- PPC BSU, Minsk, Belarus
- Dubna, JINR, Russia

Realization progress:

- Preparation for / start of mass production
- First stage is planned to be started in 2021
- Second stage and full commissioning (IT + end-cups) - 2023

Activity has been supported by the RFBR grant for a period of three years (2019-2021)

Aim: Study of collective effects and dynamics of quark-hadron phase transitions via femtoscopic correlations of hadrons and factorial moments of particle multiplicity at the NICA energies

Our physics to be studied:

- Development of data analysis methods and software to be integrated in the MPD software environment
- Analysis of simulated events with different event generators (in particular, UrQMD+vHLLE) at the NICA energies
- Understanding dependence of femtoscopic radii and scaled factorial moments of particle multiplicity on the initial conditions and properties of nuclear matter EoS

Our the most future plans:

- Software development for femtoscopic analyses & factorial moments of multiplicity distributions
- Femtoscopic analysis for pions and kaons (correlation functions, source functions ...) for the events simulated (model investigations)
- Study of detector effects on femtoscopic measurements to be taken into account when doing analysis for reco-output from MPD

Thank you for your attention!