
# Femtoscopy with identified particles for NICA/MPD

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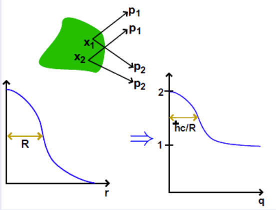
# Outline:

- **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 $R$, $c_\tau$ 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,

$\lambda$ is a correlation strength parameter

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

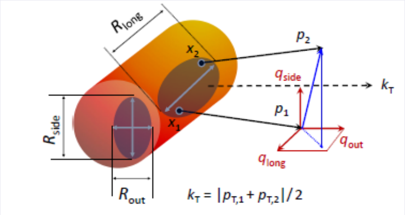
**3D CF:**

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

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:





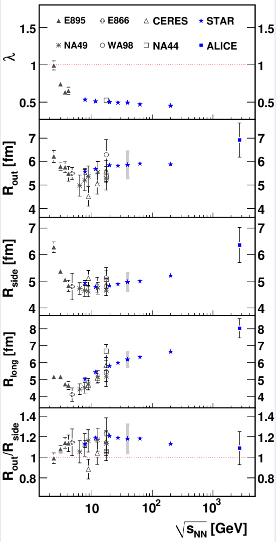
S. Pratt. Phys. Rev. D 33 (1986) 1314

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

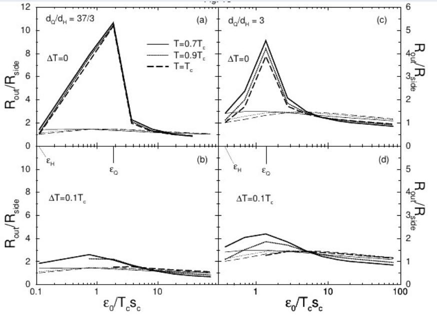


# Expected features of first order phase transition (1PT)

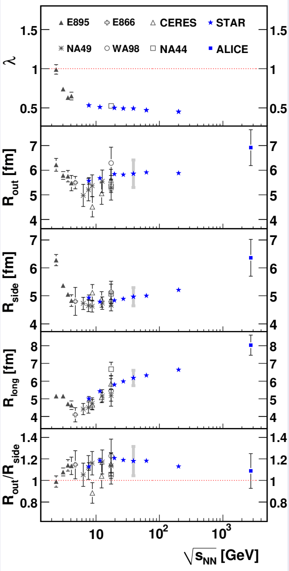
## Predicted:

$\frac{R_{out}}{R_{side}} \gg 1$ & 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 $R_{out} \rightarrow R_{out}/R_{side}$

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 $\tau_0$, $R_\perp$, $R_\eta$ and $\eta/s$ adjusted using basic observables in the RHIC BES-I region.**

| $\sqrt{s_{NN}}$ [GeV] | $\tau_0$ [fm/c] | $R_\perp$ [fm] | $R_\eta$ [fm] | $\eta/s$ |
|---|---|---|---|---|
| 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

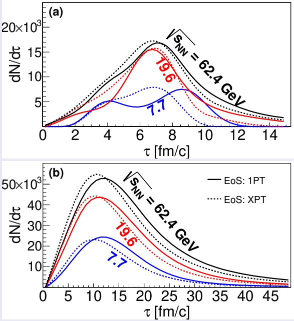
- Chiral EoS - crossover transition
  J. Steinheimer et al., J. Phys. G 38, 035001 (2011)
- Hadron Gas + Bag Model
  1-st order phase transition
  P. F. Kolb et al., Phys.Rev. C 62, 054909 (2000)

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

### Pion emission time

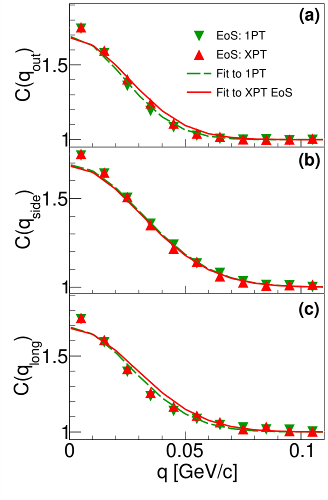
(a) - after hydrodynamic phase

(b) - after cascade

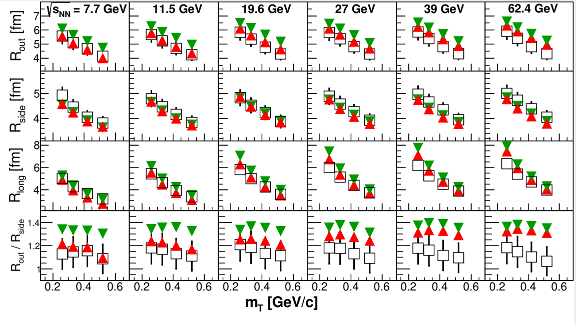


# 3D Pion radii versus $m_T$ with vHLLE+UrQMD

Phys. Rev. C 96, 024911 (2017)



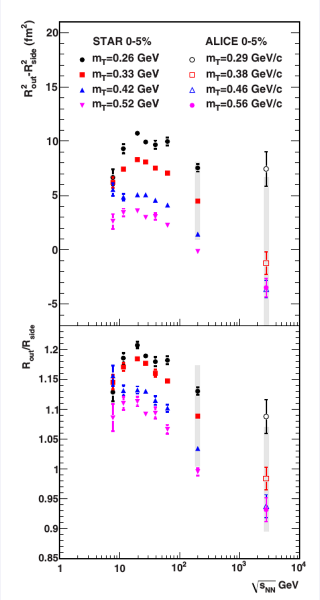

Comparison of extracted radii with the STAR data




**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.

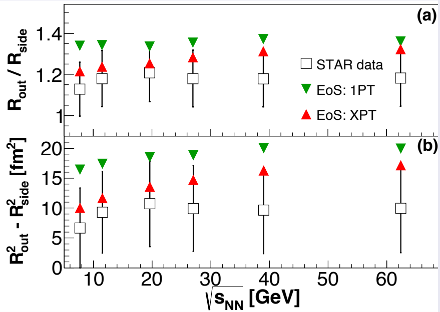
# $R_{out}/R_{side}$ with vHLLE + UrQMD model




## Exp. data:

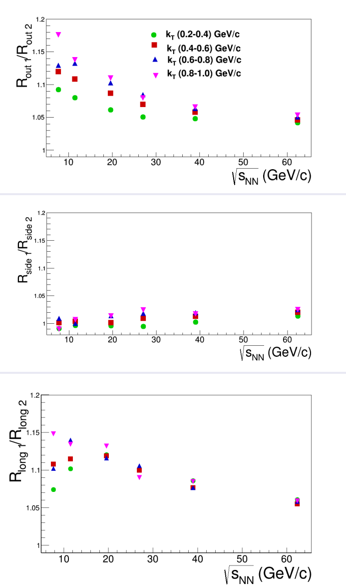
**$R_{out}/R_{side}$ and $R^2_{out} - R^2_{side}$ as a function of $\sqrt{s_{NN}}$ at a fixed $m_T$ demonstrate a wide maximum near $\sqrt{s_{NN}} \approx$ 20 GeV**

## 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. $\sqrt{s_{NN}}$

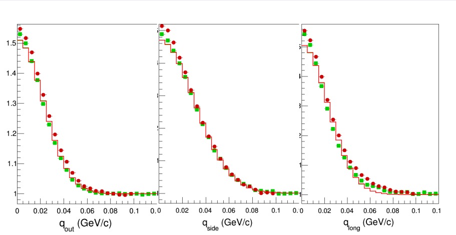



- $R_{side}$ **practically coincide for both scenarios**
- $R_{out}$ **and** $R_{long}$ **for 1PT EoS are greater than for XPT EoS demonstrating a strong** $k_T$**-dependence**

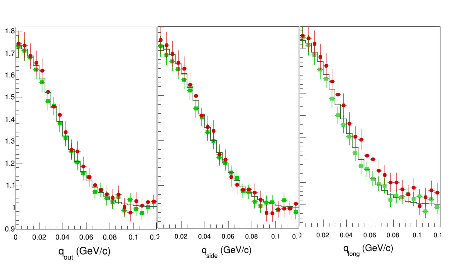
## Why?

**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:

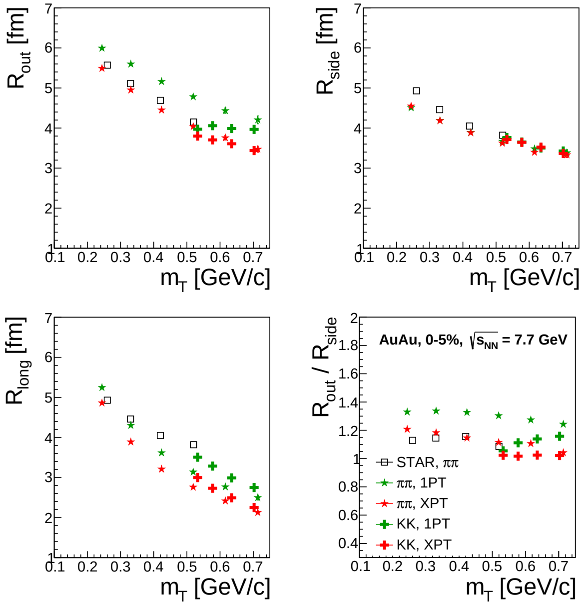



## Analysis:

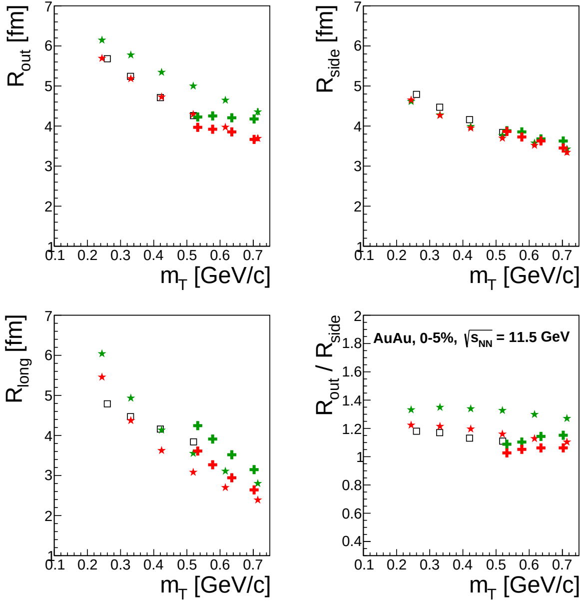
- **AuAu,** $\sqrt{s_{NN}} = 11.5$ **GeV**
- $N_{events} \approx 400000$
- **Standard 3D Gaussian fit used**

- **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

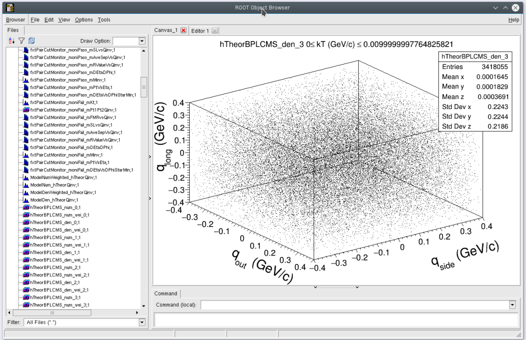
- Inherited from STAR (StHbtMaker) and ALICE (AliFemto)
- Keeps the same hierarchy as in ALICE (PckgName/, PckgNameUser/, macros/)
- Works with ROOT 5 and 6
- Lighter than ancestors:
  - Most of STAR-developed classes replaced with ROOT ones
  - Better compression, smaller sizes
- Implemented running 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:

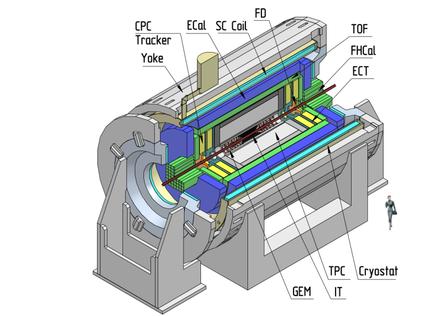
- To set track cuts, particle pair cuts, number of events to be used for mixing ...
- To get 1D and 3D correlation functions for a set of $k_T$-bins
- To switch on / off different physics effects (QS, FSI ...)

## 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, $2\pi$-acceptance in azimuth
- 3D-tracking (TPC, ECT)
- Vertex high-resolution (IT)
- Powerful PID (TPC, TOF, ECAL)
  - $\pi$, $K$ up to 1.5 GeV/c
  - $K$, $p$ up to 3 GeV/c
  - $\gamma$, $e$ 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!