III NICA DAYS 2019
International scientific and engineering conference associated with the
IVth MPD Collaboration Meeting
and
V Slow Control Warsaw 2019

21- 25 October 2019

Ministry of Science and Higher Education
Republic of Poland

Warsaw University of Technology

Correlation femtoscopy and factorial moments at the NICA energies

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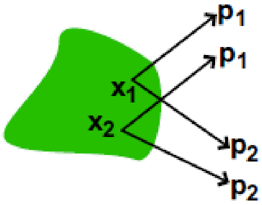
on behalf of PWG3 (Correlations and Fluctuations)

October 22, 2019

Outline:

- Femtoscopy and Motivation
- Hybrid vHLLE+UrQMD model
- Comparison with STAR BES
- First look at factorial moments with vHLLE+UrQMD
- Probing some tests with the reconstructed MPD tracks
- Other activities we are responsible for

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:

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

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

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.

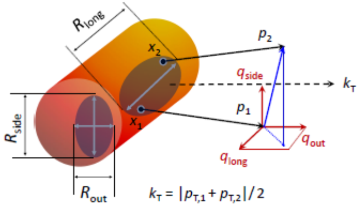
3D CF:

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

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:



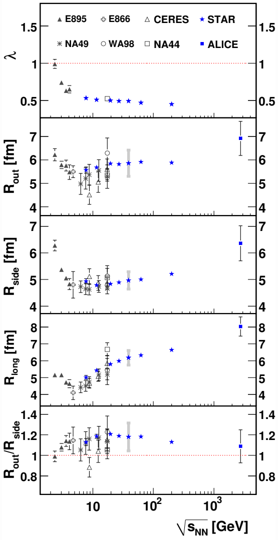
S. Pratt. Phys. Rev. D 33 (1986) 1314

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

Motivation

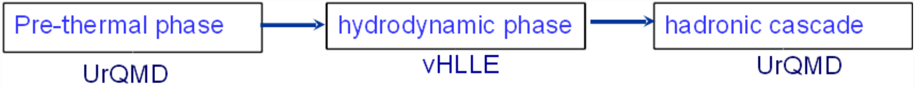
- **Femtoscopy allows one:**
  - **To obtain spatial and temporal information on particle-emitting source at kinetic freeze-out**
  - **To study collision dynamics depending on EoS**
- **RHIC Beam Energy Scan program (BES-I): $\sqrt{s_{NN}} = 7.7$, 11.5, 19.6, 27, 39 GeV Measured pion and kaon femtoscopic 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



Femtoscopy with vHLLE+UrQMD

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



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

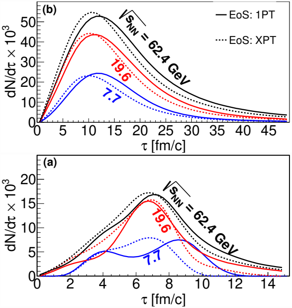
- Chiral EoS - crossover transition
  J. Steinheimer et al., J. Phys. G 38, 035001 (2011)
- Hadron Gas + Bag Model
  1-st order phase transition
  P. F. Kolb et al., Phys.Rev. C 62, 054909 (2000)

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

Pion emission time

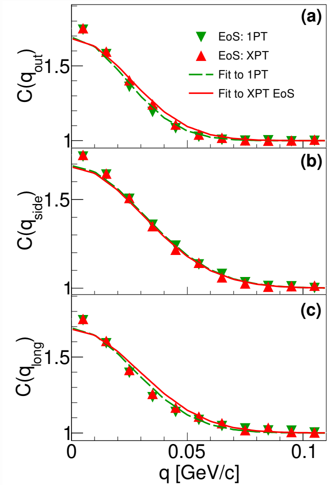
(a) - after hydrodynamic phase

(b) - after cascade

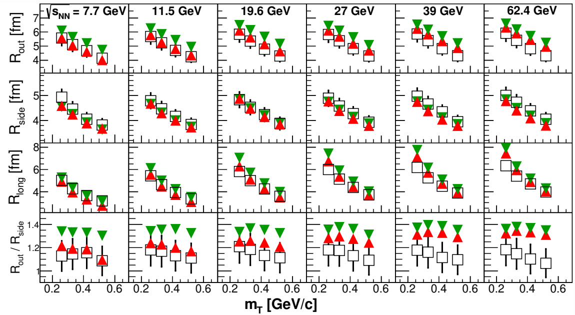


3D Pion radii versus m_T with vHLLE+UrQMD

Phys. Rev. C 96, 024911 (2017)



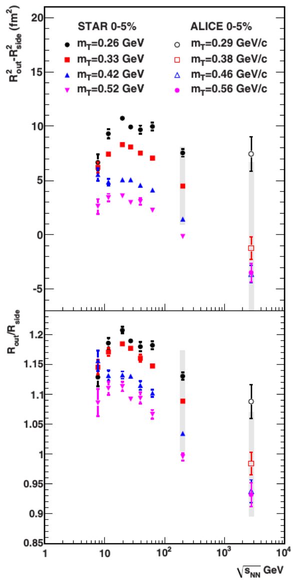
Comparison of extracted radii with the STAR data



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.**

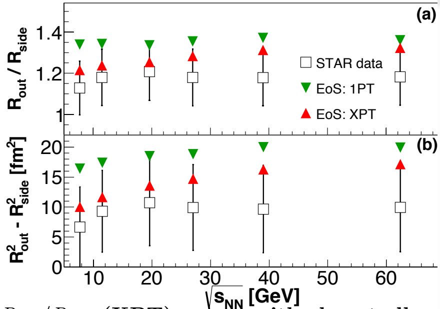
R_{out}/R_{side} with vHLLE + UrQMD model



Exp. data:

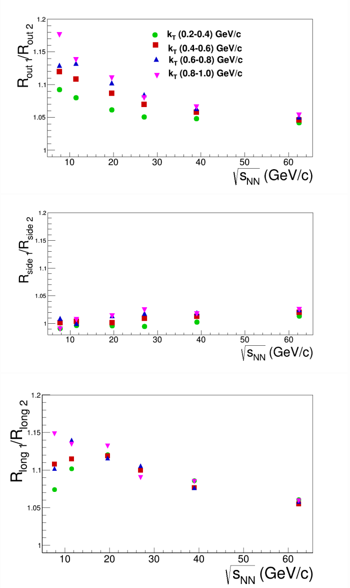
R_{out}/R_{side} and $R^2_{out} - R^2_{side}$ as a function of $\sqrt{s_{NN}}$ at a fixed m_T demonstrate a wide maximum near $\sqrt{s_{NN}} \approx 20$ GeV

Our calculations (performed at $m_T =$ 0.26 GeV, 0-5%):



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. $\sqrt{s_{NN}}$

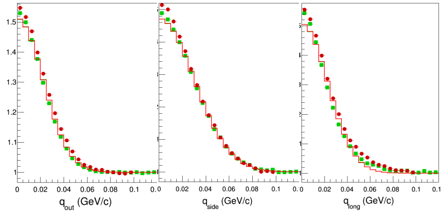


- R_{side} **practically coincide for both scenarios**
- R_{out} **and** R_{long} **for 1PT EoS are greater than for XPT EoS demonstrating a strong** k_T**-dependence**

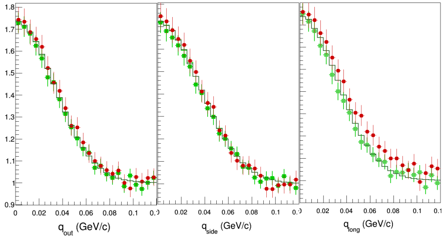
Why?

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:

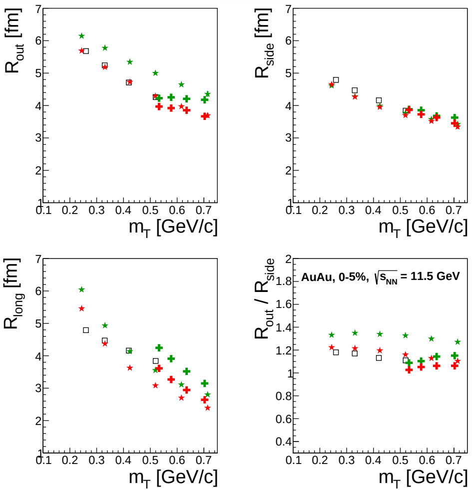


Analysis:

- **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 and kaon radii vs. m_T with vHLLE+UrQMD



- As well as for pions kaon out and long radii are greater for 1PT than for XPT
- Approximate m_T-scaling for pions and kaons observed only for side radii
- Out almost flat for 1PT
- R_{long}(kaons) is greater than R_{long}(pions) due to larger average time emission
- R_{out} / R_{side} for kaons is less than for pions
- Approximately the same result is for AuAu $\sqrt{s_{NN}} = 7.7$ GeV

Important to measure both kaon and pion radii!

Factorial moments with vHLLE+UrQMD

Proposed by A. Bialas and R. Peschanski (Nucl. Phys. B 273 (1986) 703) to study the dependence of the normalized factorial moments of the rapidity distribution on the size of the resolution

Set of definitions of moments and cumulants

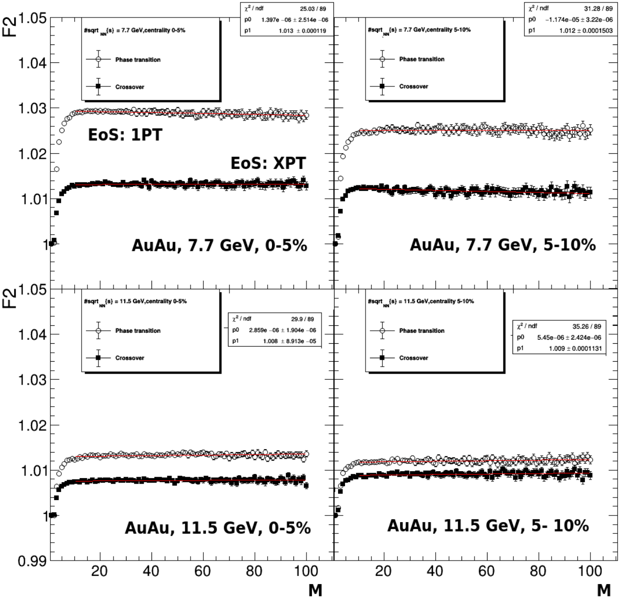
$$F_i = M^{i-1} \cdot \left\langle \frac{\sum_{j=1}^{M} k_j \cdot (k_j - 1) \cdot \ldots \cdot (k_j - i + 1)}{N \cdot (N-1) \cdot \ldots \cdot (N - i + 1)} \right\rangle$$

M is the number of bins
δy is the size of mid-rapidity window

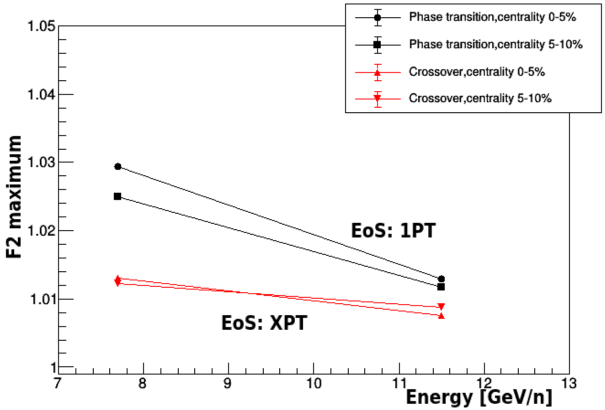
- **No variation of moments δy expected if fluctuations are purely statistical**
- **Observation of variations indicates the presence of physics origin fluctuations**

Intermittency (fluctuations of many different sizes in 1D, 2D and 3D space) has been studied at LEP, Tevatron, Protvino in ee, hh, hA, AA interactions at various energies.

Factorial moments with vHLLE+UrQMD



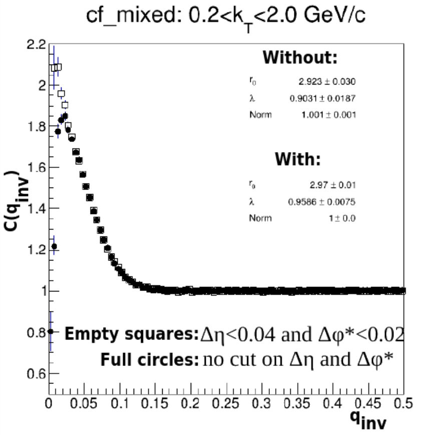
Factorial moments with vHLLE+UrQMD

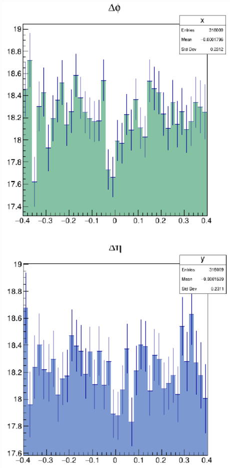


Different energy dependence is expected for XPT and 1PT EoS

Probing $\Delta\eta$-$\Delta\phi^*$ with MPD reconstructed tracks

$$\Delta\phi^* = \phi_1 - \phi_2 + \arcsin\left(\frac{z \cdot e \cdot B_z \cdot R}{2p_{T1}}\right) - \arcsin\left(\frac{z \cdot e \cdot B_z \cdot R}{2p_{T2}}\right)$$





Other activities we do (Supported by the RFBR grant 18-02-40044 for a period of 2019-2021)

vHLLE+UrQMD interface software

How to get?

```
1. git clone https://github.com/pbatyuk/vHLLE_package.git
2. git checkout 1.1.2
```

How to compile and use?

- **vHLLE_package/README.md (very detailed description on how to ...)**

Aim of the project:

- **To collect all components (model + interface) in one place.**
- **To start simulations locally or remotely in a common way.**
- **To avoid a huge messy in the start configure scripts.**
- **Possibility to use the model for its adjustment (pre-hydro + hydro phase) as planned.**

Main macro: vHLLE_package/macro/vHLLE.C

```
void vHLLE() {
VHLLE* gen = new VHLLE();
gen->SetSourceROOT(""); // Set ROOT-environment if not set yet and necessary to be set
// gen->SetExtendedFileName(kTRUE); // Set use of extended output filename ...
gen->SetUseBatch(kFALSE); // False value (default) means calculations at your locale machine ...
gen->SetBatchCluster("ncx"); // Possible values are: ncx, govorun, basov and gsi

// Parameters below (6) are considered as those to be set obligatory
gen->SetPathToTheModel(""); // Absolute(!) path to the root folder of the model
gen->SetOutputDirectory(""); // Directory where output data stored
gen->SetEnergy(7.7); // Set collision energy [GeV], possible energies are 7.7 GeV ...
gen->SetImpact(0., 3.3); // Set impact range (min, max) [fm]
gen->SetEoS("XPT"); // Set EoS to be used (1PT - first order phase transition, XPT - crossover)
gen->SetNsamples(100); // nEvents to be sampled in hadronic cascade from one hydro-evolution

gen->SetParameters(); // Set parameters for urqmd, hydro and hadronic cascade given by ...

// Modifiers to redefine almost all parameters given by the author for urqmd, hydro ...
// See $VHLLE/vhlle.h to get more if needed
// N. B.: Redefinition, if needed, can be done after gen->SetParameters() called !!!
/*
gen->SetTau0(3.2);
gen->SetEtaS(0.2);
gen->SetRg(1.4);
gen->SetRgz(0.5);
gen->SetNsamples(100);
*/

gen->PrintBasicParams();
gen->CheckParamsValidity(); // It checks whether the params defined are consistent
gen->GenerateStartScript(); // It produces a script to be executed
delete gen;
}
```

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

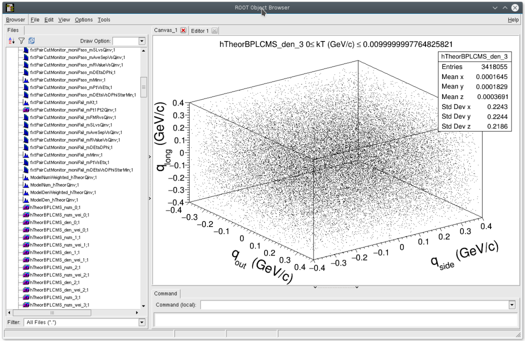
Data formats (DST)

- General-purpose data format for Monte Carlo generators - McDst
- 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)

Needed raw information from generator on momentum and coordinates!

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);
}
```

MiniDST, current status

How to get?

```
1. git clone --recursive https://git.jinr.ru/nica/mpdroot.git
2. git checkout miniDST_toBeTested
```

Source codes in MpdRoot:

- **MiniDST source codes:**
  $VMCWORKDIR/mpddst/MpdMiniEvent/MpdMini*.h(cxx) -
- **Converter to the format:**
  $VMCWORKDIR/mpddst/MpdMiniDstFillTask.h(cxx)

Use in reco.C:

```
...
// Task to be included
MpdMiniDstFillTask* miniDst = new MpdMiniDstFillTask("miniDST.root");
// miniDst->isUseTpc(kFALSE);
// miniDst->isUseTof(kFALSE);
// miniDst->isUseEcal(kTRUE);
miniDst->isUseMcTracks(kTRUE);
fRun->AddTask(miniDst);
...
```

MiniDST, current status

Already done:

- Output data format derived from STAR has been incorporated to MpdRoot.
- Converter to be used for filling the format, written in a "canonical way" via the FairRoot task mechanism, has been incorporated to MpdRoot.
- Some data members of the format have been already filled.
- The task has been added to the main reco macro.
- The task allows one to include / exclude detectors (data types - MC or reco) to be written to output.

Planned to be done a.s.a.p.:

- To fill remaining data members of the format (A discussion required ...).
- To decide whether we need to add new or remove existing data members or not to be adopted better to MPD.
- To extend the format by specific detectors to be used in MPD.
- ...
- As done and extensively tested, to finish transition to the format as the main output from reco. (Right now a standard DST and the current one co-exist together)

Thank you for attention!