Femtoscopy observables within NICA/MPD

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on behalf of the MPD collaboration

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Outline

- The NICA complex
- Feasibility of femtoscopy studies @ NICA
- MPDROOT::FEMTOMPD and its application to the TTE-estimation.
- Conclusions

NICA Complex

General characteristics:

Beams - p, d ... $^{197}Au^{79+}$

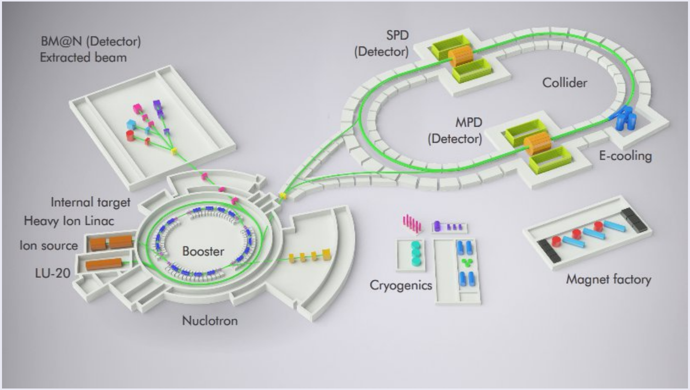
Collision energy:

$\sqrt{s_{NN}}$ = **4 - 11 GeV** E_{lab} = **1 - 6 AGeV**

Luminosity: $10^{27}\ cm^{-2}s^{-1}$ **(Au)**, 10^{32} **(p)**

Experiments:

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

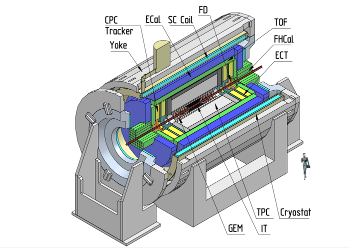


The general contractor is STRABAG (Bodostal-3 & PCJ are the sub-contactors)

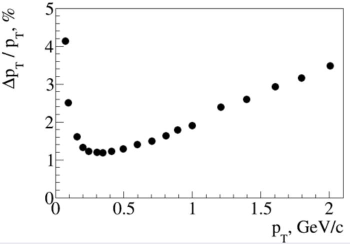
- **2017: extracted beams of heavy ions are available within the BM@N experiment**
- **2019: a first configuration of the MPD setup available.**
- **2023: commissioning of the fully designed NICA-complex is foreseen.**

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

Layout:



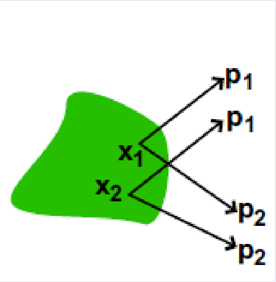
Momentum resolution:



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 = ZDC) (centrality determination, reaction plane ...)
- Fast timing and triggering (FFD)
- Low material budget
- High event rate (up to 7 kHz)

Femtoscopy formalism



Correlation femtoscopy:

Measurement of space-time characteristics R, c_τ (fm) 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:

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

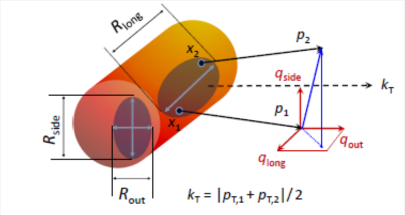
1d-analysis is sensitive only to the system size averaged over all directions.

3D CF:

$$C(q) = 1 + \lambda e^{-R^2_{out} q^2_{out} - R^2_{side} q^2_{side} - R^2_{long} q^2_{long}}$$

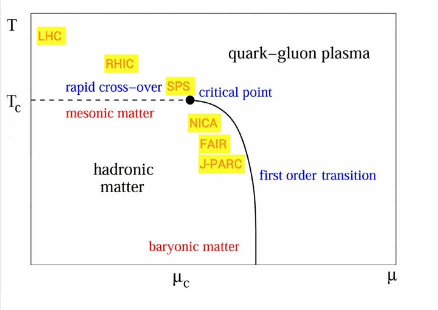
3d-analysis gives an access to the three system sizes in three directions separately.

Definition of femtoscopy radii:



Motivation

Crossover transition to QGP occurs at RHIC & LHC



Questions to be answered:

- What femtoscopy observables are the most sensitive to this difference?
- At what energies do the hydro models with a first order phase transition (1PT) describe femtoscopy observables better than those with crossover?

Femtoscopy: from high to low energies...

RHIC: $\sqrt{s_{NN}} = 62$ to 200 GeV

large T & small μ_B

Smooth, rapid crossover

BES @ RHIC: $\sqrt{s_{NN}} = 7.7$, 11.5, 19.6, 27, 39 GeV

small T & large μ_B

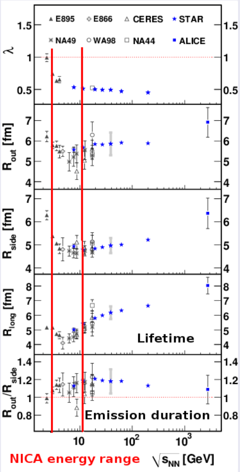
search for "critical point"

NICA: $\sqrt{s_{NN}} = 4$ to 11 GeV

small T & large μ_B

What do the modern hydrodynamic (hybrid) models expect?

STAR, Phys.Rev. C92 (2015) 1, 014904



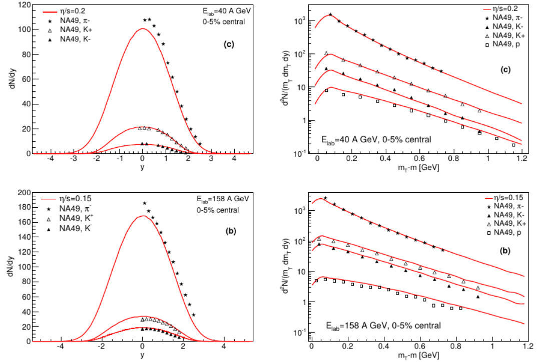
vHLLE + UrQMD model

Iu. Karpenko, P. Huovinen, H.Petersen, M. Bleicher, Phys.Rev. C 91, 064901 (2015)
vHLLE code: free and open source, https://github.com/yukarpenko/vhlle

Pre-thermal phase → hydrodynamic phase → hadronic cascade

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

40 + 158 A GeV PbPb SPS ($\sqrt{s} = 8.8$ and 17.3 GeV)



Chiral EoS - crossover
J. Steinheimer et al, J. Phys. G 38, 035001 (2011)

HadronGas + Bag Model - 1PT
P. F. Kolb et al, Phys.Rev. C 62, 054909 (2000)

More details in the report of D. Wielanek (GDRE 2016)

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vHLLE code: free and open source,
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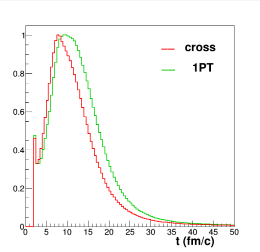
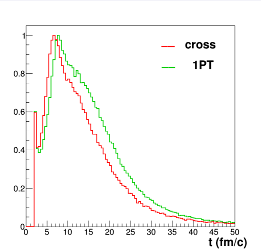
Pre-thermal phase → hydrodynamic phase → hadronic cascade

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

AuAu @ $\sqrt{s_{NN}} = 11.5$ GeV, pions:



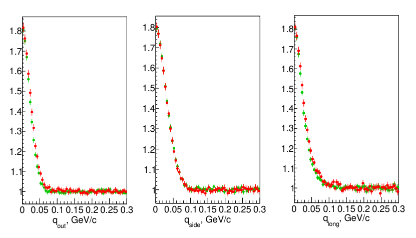
AuAu @ $\sqrt{s_{NN}} = 11.5$ GeV, kaons:



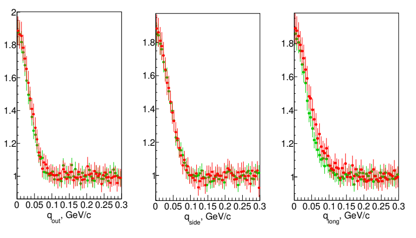
1PT delays emission of particles. Is it possible to see this time difference using the femtoscopy techniques?

Projections of 3D CF in comparison of the two EoS's used

Pions:

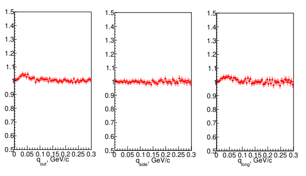


Kaons:

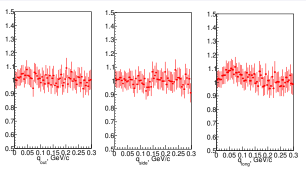


- **Green line –> EoS: 1PT**
  Red line –> EoS: crossover
- **Each projection is extracted while other directions are fixed in the corridor 5 MeV/c for pions and 15 MeV/c for kaons.**

Pions:



Kaons:



Visible difference in out- and long-directions is clearer for kaons.

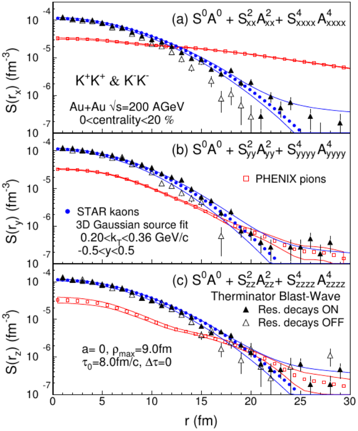
Source Function Technique

$S(r^*)$ is a **source function**, which represents time-integrated distribution of particle emission points separation r^* in the PRF.

$$C(\mathbf{q}) - 1 \equiv R(\mathbf{q}) = \int (|\phi(\mathbf{q}, \mathbf{r})|^2 - 1) S(\mathbf{r})\, d\mathbf{r}$$

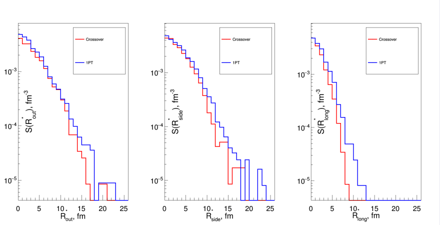
The method is suitable for extracting the $S(r^*)$ directly from the data **without any hypothesis about source shape**.

STAR, Phys.Rev. C88 (2013) 3, 034906

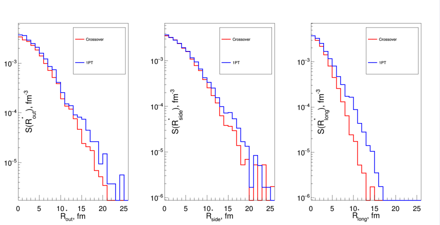


Projections of Source Function, pions (calculated in the PRF)

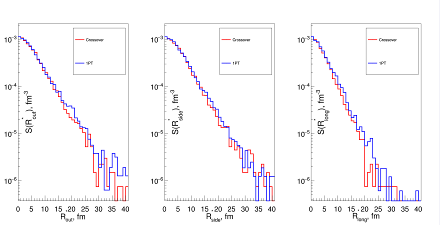
AuAu @ $\sqrt{s_{NN}} = 7.7$ GeV, vHLLE



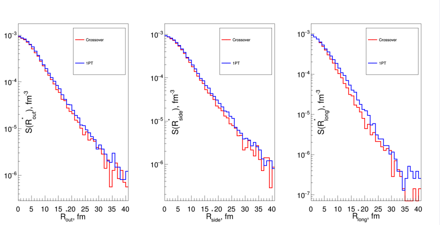
AuAu @ $\sqrt{s_{NN}} = 11.5$ GeV, vHLLE



AuAu @ $\sqrt{s_{NN}} = 7.7$ GeV, vHLLE + UrQMD

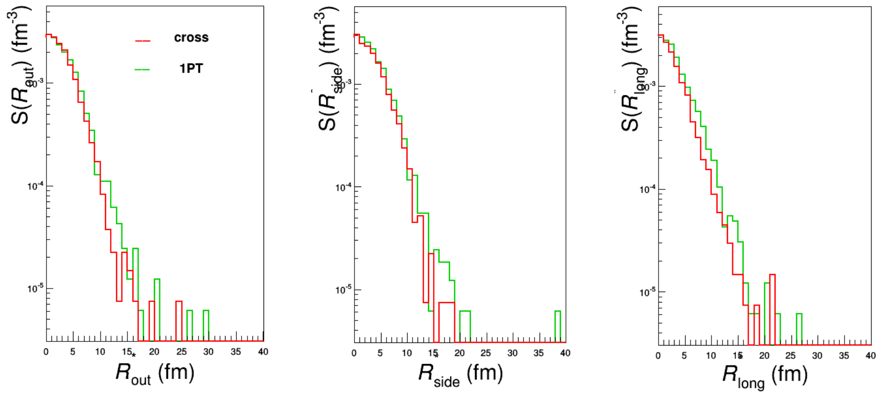


AuAu @ $\sqrt{s_{NN}} = 11.5$ GeV, vHLLE + UrQMD

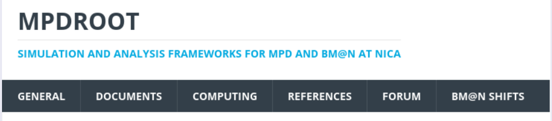


Projections of Source Function, kaons (calculated in the PRF)

AuAu @ $\sqrt{s_{NN}} = 11.5$ GeV, vHLLE + UrQMD



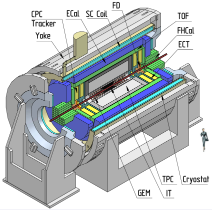
Simulation Framework for MPD (MPDROOT)



MPDROOT home web-page:

http://mpd.jinr.ru

- News
- Software repositories
- Software tests
- Forums
- Database for physics run
- E.t.c.



Physics models to be used:

- UrQMD / Hybrid UrQMD / vHLLE + UrQMD
- QGSM / LAGQSM
- HSD / PHSD
- 3FD

Benefits:

- Inherits basic properties from FairRoot (developed at GSI), C++ classes
- Extended set of event generators for heavy-ion collisions
- Detector composition and geometry; particle propagation by GEANT3/4
- Advanced detector response functions, realistic tracking and PID included
- Event display for Monte-Carlo and experimental data

Femtoscopy within MPDROOT

NICAFEMTO

To be presented in the report of D. Wielanek, GDRE 2016

FEMTOMPD (is still developing)

Alternative software / package to perform femto-analysis within the MPDROOT

Example of macro to use within FEMTOMPD:

```
void femtoAna(...) {
    [ ... ]
    MpdFemto* femto = new MpdFemto(...);
    femto->SetStartEvent(nStartEvent);
    femto->SetEvNumToRead(nEvents);
    femto->SetSourceSize(3.);
    femto->SetPdgCode(211);
    femto->SetEtaCuts(-1.0, 1.0);
    femto->SetPtCuts(0.15, 1.5);
    femto->SetNumMixedEvents(10);
    femto->SetKtCuts(0.15, 1.5);
    femto->SetQinv(Qinv);
    femto->SetMagField(0.5);
    femto->SetRadTpc(1.0);
    femto->SetMinNoHits(20);
    femto->SetZeroSharing(kTRUE);
    // femto->SetQualityPairCut(kTRUE);
    femto->SetQualityMax(-0.4);
    femto->SetSharingMax(0.01);

    // A method to perform 1D-analysis
    femto->MakeCFs_1D();
    [ ... ]
}
```

Benefits of the package:

- totally integrated in the MPDROOT-software and based on the main principles of the MPDROOT (prev. slide)
- flexible due to consists of different modules to be expanded in a simple manner if necessary
- allows one to estimate influence of the two-track effects (TTE) (splitting & merging) in order to avoid distortion of CFs.
-

HowTo:

http://mpd.jinr.ru/howto-install-mpdroot

The MPD femto group:

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- Ludmila Malinina, Ludmila.Malinine@cern.ch
- Konstantin Mikhaylov, Konstantin.Mikhaylov@cern.ch
- Daniel Wielanek, daniel.wielanek@gmail.com
- Pavel Batyuk, pavel.batyuk@jinr.ru

Two Track Effects (TTE)

Track merging

Two tracks that are spatially very close are falsely reconstructed as one. This will show up as an inefficiency of close pairs compared to a sample of unaffected pairs.

Track splitting

One track is falsely reconstructed as two tracks (or more). This will show up as an enhancement of close pairs compared to an uncorrelated sample.

CF could be affected by these effects $\rightarrow$ shape of CF could be distorted

TTE, details of analysis

The statistics used: $\sim$ 25 000 fully reconstructed events
AuAu @ $\sqrt{s_{NN}} = $ 11.5 GeV,
$\pi^+\pi^+$ **pairs,**
k_T **bins** (GeV/c)**: 0.2 - 1.5**

Single Track Cuts

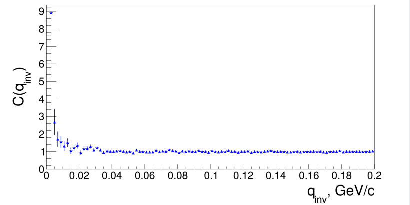
TPC tracks only
$|\eta| <$ **1**
$0.2 < p_T < 1.5$ **GeV/c**
$N_{hits} >$ **10 (maximal number of hits in a padrow per track is equal to 53)**

PID

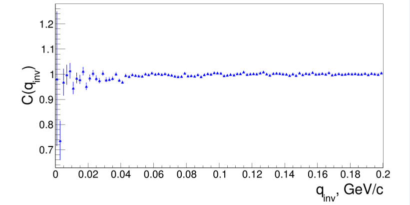
The PID MC was used for the analysis.

Two Track Cuts

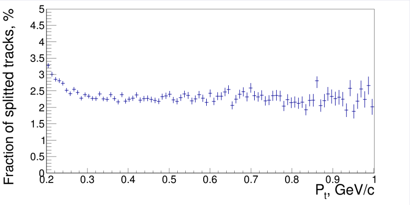
"Original" CF



CF after splitting cut



Fraction of splitting tracks

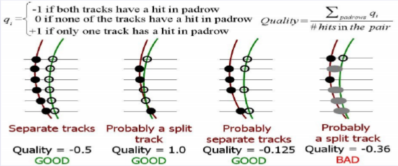


Splitting:

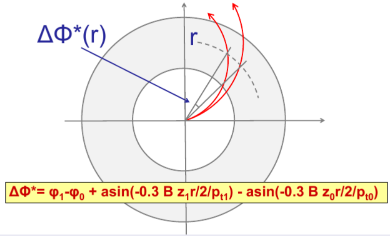
- reveals itself as a wide distribution with an average value of $\approx$ 2% for $P_t = \mathbf{0.3}$ **- 1 GeV/c**
- affects sufficiently CFs
- is excluded nicely by use of (anti-)splitting cut

Two Track Cuts

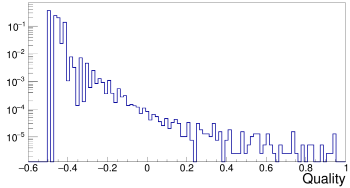
Quality cut



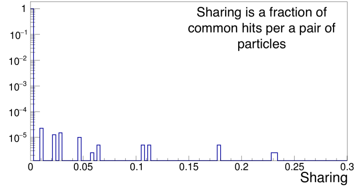
Anti-merging cut



Quality



Sharing

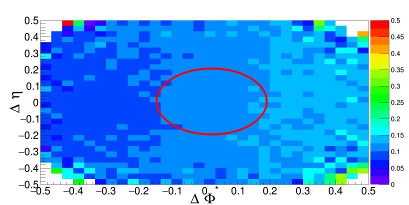


$$\Delta\Phi^*(R) = \phi_1 - \phi_0 + \arcsin\left(-\frac{0.3 B_z Z_1 R}{2P_{T1}}\right) - \arcsin\left(-\frac{0.3 B_z Z_0 R}{2P_{T0}}\right)$$

ϕ_1 and ϕ_0 are azimuthal angles of the tracks at the vertex.
P_{T1} and P_{T0} are their transverse momenta.
B_z indicates the magnetic field in z-direction.
Z_1 and Z_0 are charges of particles forming the track.

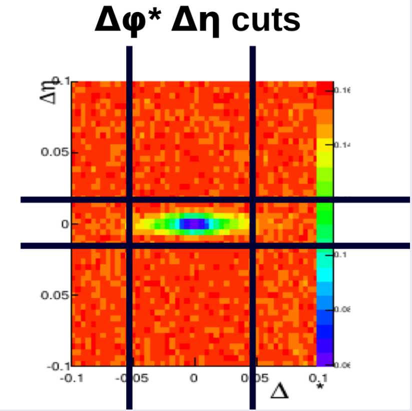
$d\eta d\Phi^*$ as a monitoring of TTE

$d\eta d\Phi^*$ (splitting cut used, no restriction on q, s = 0)



Probably, no merging?

$d\eta d\Phi^*$

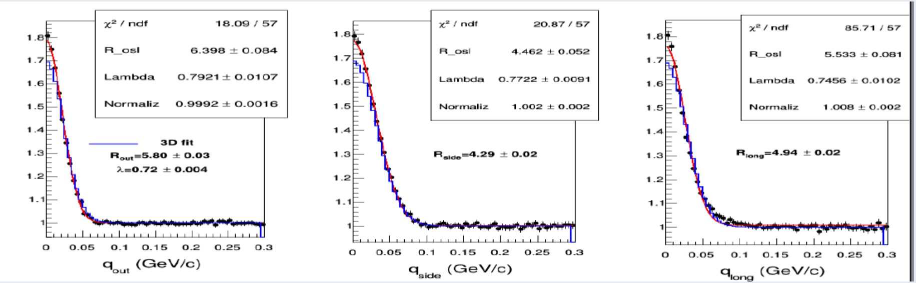


Conclusion & Outline

- **1PT delays particle emission.**
- **Obtained 3D CFs for pions and kaons appear to be sensitive to different EoS's.**
- **We plan to study the non-Gaussian tails of CFs using the Hump parametrization.**
- **Despite hadronic cascade affects strongly the observed source functions, it looks possible to distinguish them within the vHLLE + UrQMD hybrid model.**
- **We plan to continue studies with larger statistics for π- and K-mesons.**
- **A study of TTE within the FEMTOMPD has been done and is planned to be continued.**

BACKUP SLIDES

EoS: 1-st order phase transition (1PT)



- Gaussian fit of the CFs does not describe shape of the CFs at small q.
- A difference observed between the 3D CFs fit and a fit of 1D projections of the 3D CFs leads to a conclusion that the projections look more Gaussian.
- R_{out} and R_{long}, obtained in case of 1PT, are larger than the ones in case of the crossover EoS.

- Difference between the 1PT and crossover EoS's is small. The maximum difference is observed for R_{long}.
- Non-Gaussian fits will be tried.
- CFs for kaons will be studied.