Xth MPD Collaboration meeting
8-10 November 2022, JINR, Dubna

Femtoscopy correlations, factorial moments and charge balance functions with MPD at NICA

on behalf of PWG3 (Correlations and Fluctuations)

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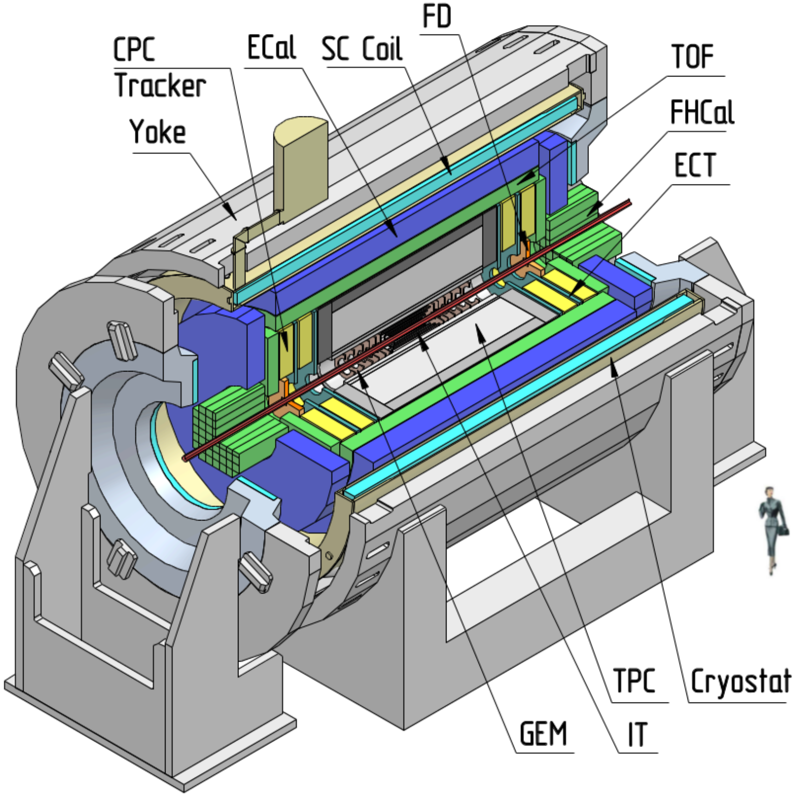
Outline

- Activities
- Publication in Symmetry journal
- Cross PWG meeting
- Charge balance function
- Factorial moments
- Status of MC production
- Conclusions and plans



PWG3 activities in 2019-2022

- *E.Alpatov, P. Batyuk, M. Cheremnova, A.Chernyshov, O. Kodolova, Y. Khyzhniak,*
- *I. Lokhtin, L. Malinina, K.Mikhaylov, G.Nigmatkulov, G. Romanenko, N. Pukhaeva*
- *Alejandro Ayala and young people from his team*
- Three Master and 2 PhD student in Femto group

- PWG3 Femto Meetings: over 50 events (2019-2022) → https://indico.jinr.ru/category/346/
- MPD Physics Seminars: 6 seminars
- Cross-PWG meeting: *Alejandro Ayala (28 June 2022) → https://indico.jinr.ru/event/3108/*
- Conferences (2019-2022): over 10 talks at different conferences

- Publications (most important):

M. Cheremnova *et.al.*, Symmetry 2022, 14(7), 1316; https://doi.org/10.3390/sym14071316
L. Malinina *et. al.* Study of Strongly Interacting Matter Properties at the Energies of the NICA Collider Using the Methods of Femtoscopy. Phys.Part.Nucl. 52 (2021) 4, 624-630
O. Kodolova *et. al.*, Factorial Moments in the NICA/MPD Experiment. Phys.Part.Nucl. 52 (2021) 4, 658-662
G.Nigmatkulov *et. al.*, Measurements of the like-sign pion and kaon femtoscopic correlations at NICA energies. 2020 J. Phys.: Conf. Ser. 1690 012132
G.Nigmatkulov and P. Batyuk, Packages for Data Storage and Femtoscopic Analysis. Phys.Part.Nucl., 2021, v.52 (2021) 4,p.923
P.N. Batyuk *et. al.*, Femtoscopy with Identified Charged Particles for the NICA Energy Range. Phys.Part.Nucl. 51 (2020) 3, 252-257
K. Mikhaylov *et. al.*, Correlation femtoscopy at NICA energies. EPJ Web Conf. 222 (2019) 02004

Publication in Symmetry. Published: 25 June 2022

symmetry

Symmetry **2022**, *14*(7), 1316; https://doi.org/10.3390/sym14071316

MDPI

Article

Particle Multiplicity Fluctuations and Spatiotemporal Properties of Particle-Emitting Source of Strongly Interacting Matter for NICA and RHIC Energies

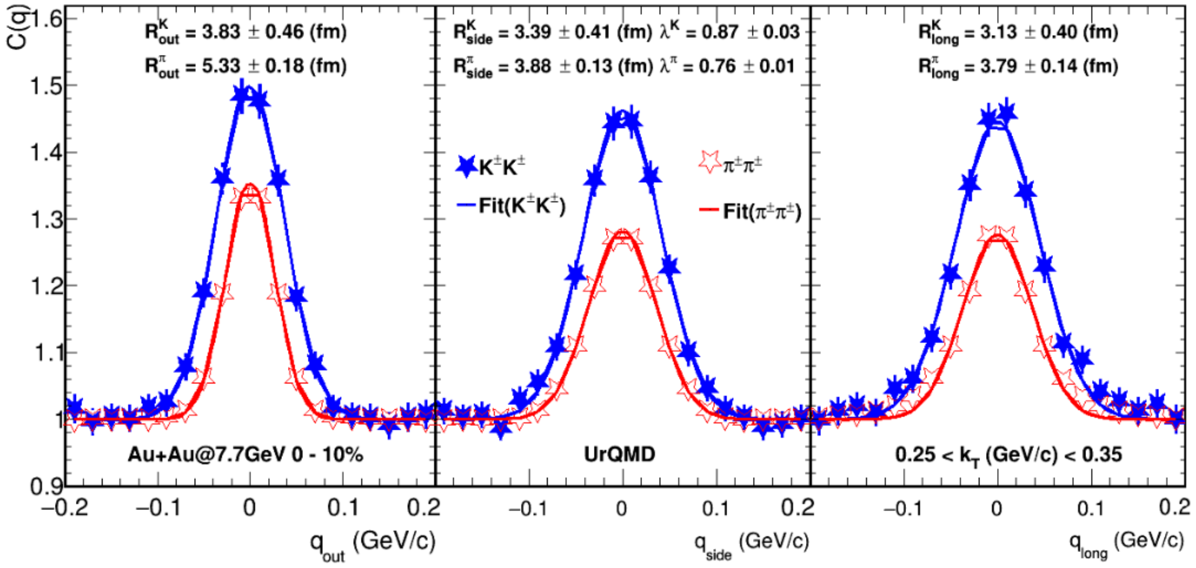
Mariya Cheremnova [1], Alexey Chernyshov [1], Yevheniia Khyzhniak [2], Olga Kodolova [1,*], Valentin Kuzmin [1], Igor Lokhtin [1], Ludmila Malinina [1,3], Konstantin Mikhaylov [3,4] and Grigory Nigmatkulov [2,3]

Abstract: The results of the model analysis of hadron femtoscopic correlations and factorial moments of particle multiplicity in heavy ion collisions for the energy range of the Beam Energy Scan (BES) program at RHIC and future NICA collider are presented. For this purpose, the simulation of Au+Au collisions at center-of-mass energies 7.7 and 11.5 GeV per nucleon pair using the UrQMD, vHLLE+UrQMD (with the crossover and first-order equation of states), and HYDJET++ event generators was performed. The sensitivity of pion and kaon correlation radii and the dependence of the factorial moments on heavy ion beam energy to quark–hadron phase transition details was studied. In addition, the possible influence of some relevant detector effects on the corresponding experimental observables is discussed.

Correlation femtoscopy

Correlation function:

$$C(\vec{p},\vec{q}) = \int \mathrm{d}\vec{r}^{*} S(\vec{p},\vec{r}^{*})|\Psi(\vec{q},\vec{r}^{*})|^{2}$$, S is a source function, Ψ – a two-particle wave function



- Projection of 3d CF
- ππ red open stars
- KK blue solid stars
- 0–10% Au+Au at $\sqrt{s_{NN}}$=7.7GeV
- UrQMD model

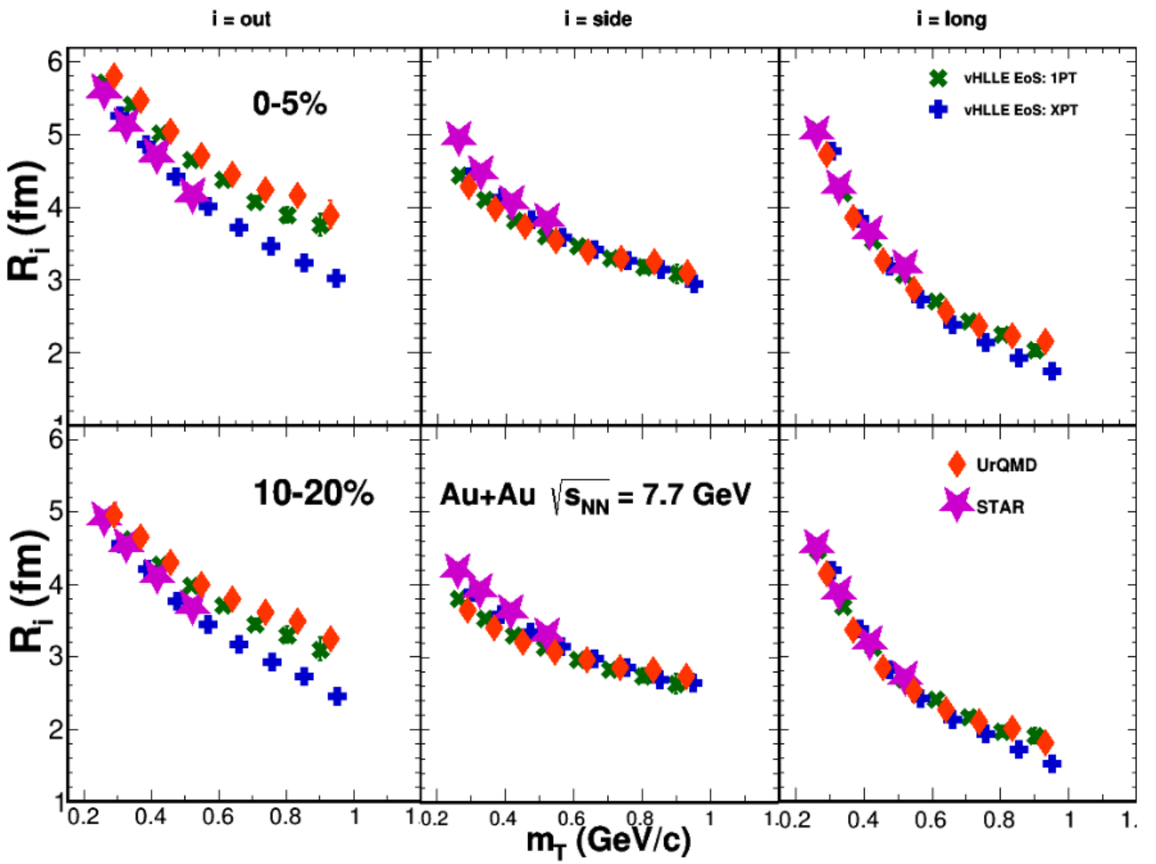
Fit function:

$$C(q_{out}, q_{side}, q_{long}) = \kappa\left(1 + \lambda \exp(-R^2_{out}q^2_{out} - R^2_{side}q^2_{side} - R^2_{long}q^2_{long})\right)$$

Femtoscopic Correlations of Pions in the NICA Energy Range

- 0–5% and 10–20%
- Au+Au at $\sqrt{s_{NN}}$=7.7GeV
- vHLLE+UrQMD with
- Crossover (XPT) EoS
- First-order Phase Transition (1PT) EoS
- UrQMD model
- transverse mass (m_T) dependence of the pion femtoscopic radii R_{out} (left), R_{side} (middle), and R_{long} (right)

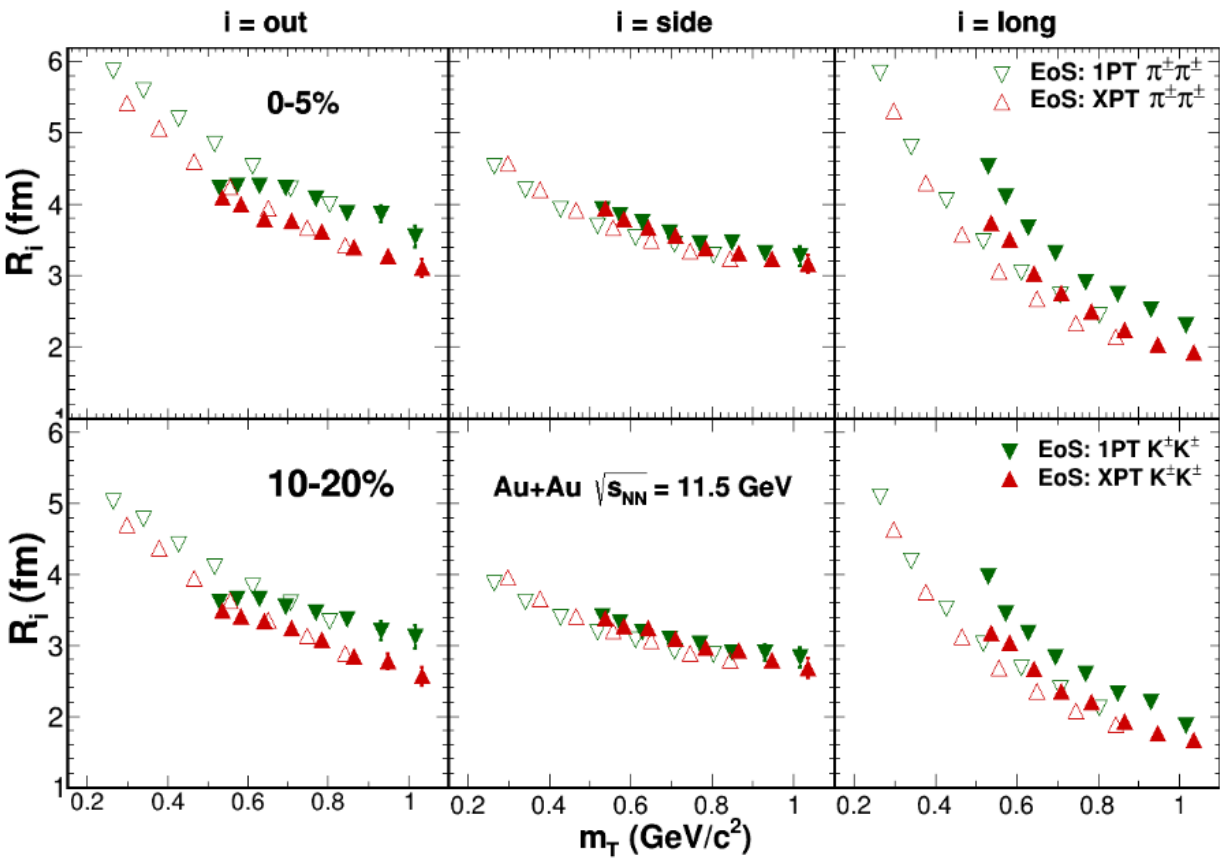
- vHLLE+UrQMD with XPT of EoS showed reasonable agreement to the STAR data



Femtoscopic Correlations of Pions and Kaons in the NICA Energy Range

- 0–5% and 10–20%
- Au+Au at $\sqrt{s_{NN}}$=11.5 GeV
- vHLLE+UrQMD with
- Crossover (XPT) EoS
- First-order Phase Transition (1PT) EoS
- transverse mass (m_T) dependence of the pion and kaon femtoscopic radii R_{out} (left), R_{side} (middle), and R_{long} (right)

- Kaon results make it possible to expand the area of study of m_T-dependence



The chaoticity parameter in two-pion correlation functions

Alejandro Ayala
Instituto de Ciencias Nucleares,
Universidad Nacional Autónoma de México

MPD Cross PWG Meeting
June 28, 2022

Correlation strength

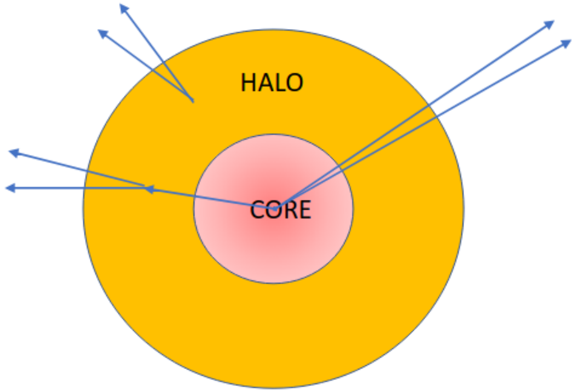
Thus, the correlation function can be expressed as

$$C_2(q, K) = 1 + \left(\frac{N_{\text{core}}(K)}{N_{\text{core}}(K) + N_{\text{halo}}(K)}\right)^2 \frac{\left|\widetilde{S}_{\text{core}}(q, K)\right|^2}{\left|\widetilde{S}_{\text{core}}(0, K)\right|^2}$$

Therefore, **in the core-halo picture**

$$\lambda = \left(\frac{N_{\text{core}}(K)}{N_{\text{core}}(K) + N_{\text{halo}}(K)}\right)^2$$

λ carries indirect information on the decay of long-lived resonances (η, η', ω, K_s^0). In particular of η' that is considered a messenger if $U_A(1)$ symmetry restoration.



- Femtoscopy analyses lend themselves for first physics studies
- The study of the excitation function of the chaoticity parameter (correlation strength) λ is a handle to study chiral symmetry restoration.
- The core-halo picture may be a useful intuitive guide to interpret the results
- **50 million MC events** can provide a good statistics to improve the determination of λ

Charge balance functions

A.Chernyshov, I.Lokhtin

Charge balance function

Clocking Hadronization in Relativistic Heavy-Ion Collisions with Balance Functions.
Steffen A. Bass, Pawel Danielewicz, and Scott Pratt. PRL 85, 2689 (2000)
Charges produced later in the collisions are more tightly correlated in relative (pseudo)rapidity

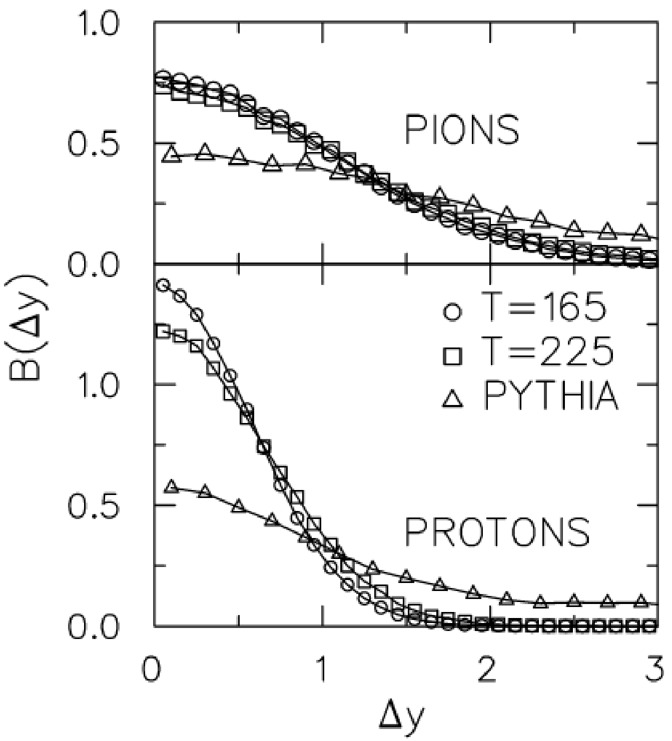
$$B(p_2|p_1) \equiv \frac{1}{2}\{\rho(b,p_2|a,p_1) - \rho(b,p_2|b,p_1) + \rho(a,p_2|b,p_1) - \rho(a,p_2|a,p_1)\}$$

$\rho(b, p_2|a, p_1)$ is the conditional probability of observing a particle of type b in bin p_2 given the existence of a particle of type a in bin p_1. Type a all positive charge, b is a negative. Conditional probability

$$\rho(b,p_2,a,p_1) = \frac{N(b,p_2|a,p_1)}{N(a,p_1)}$$

$p_1 \rightarrow y_1$, $p_2 \rightarrow y_2$ => B(Δy)

Balance functions in a simple Bjorken thermal model for T=225 and 165 MeV. Narrower balance functions might indeed point to thermal production at a lower temperature and thus at later times.

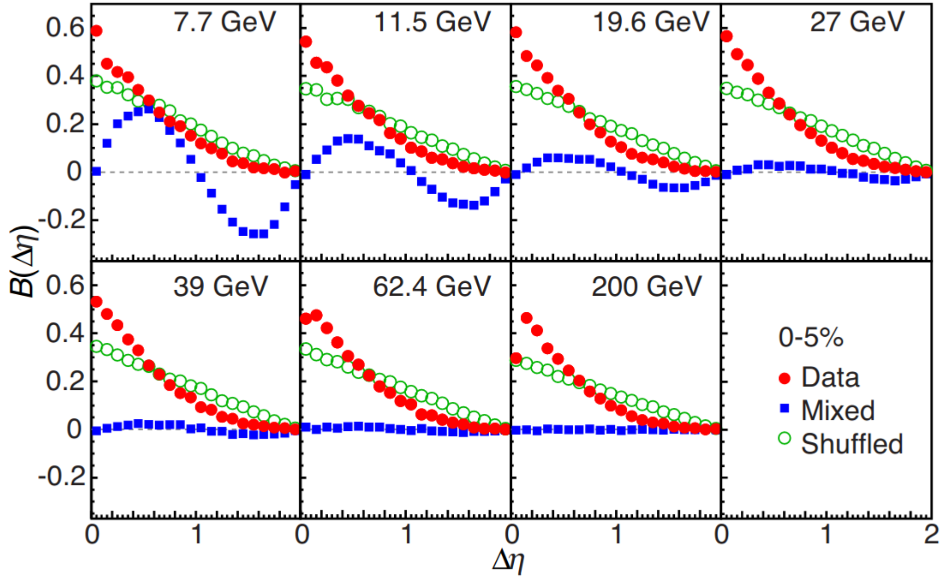


STAR: Charge balance function

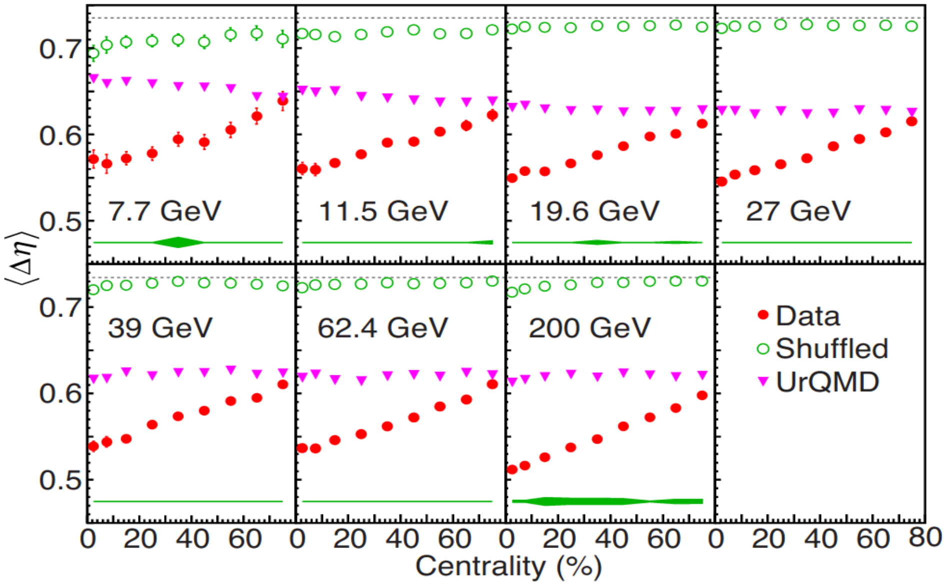
STAR: Beam-Energy Dependence of Charge Balance Functions from Au+Au Collisions at RHIC [Phys.Rev.C 94 (2016) 2, 024909]

The balance functions narrow in central collisions and narrow as the beam energy is increased.

- B(Δη) all charged Au+Au $\sqrt{s_{NN}}$=7.7...200 GeV(0-5%)
- CBFs with mixed and shuffled
- At low energies CBFs(mixed) exhibit oscillatory distribution due to unbalance positive charge

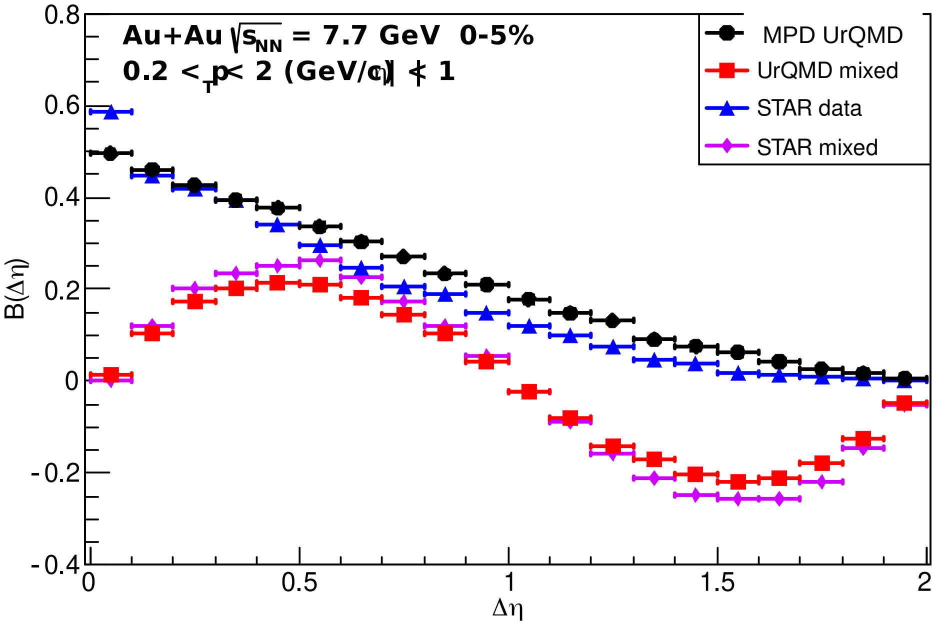


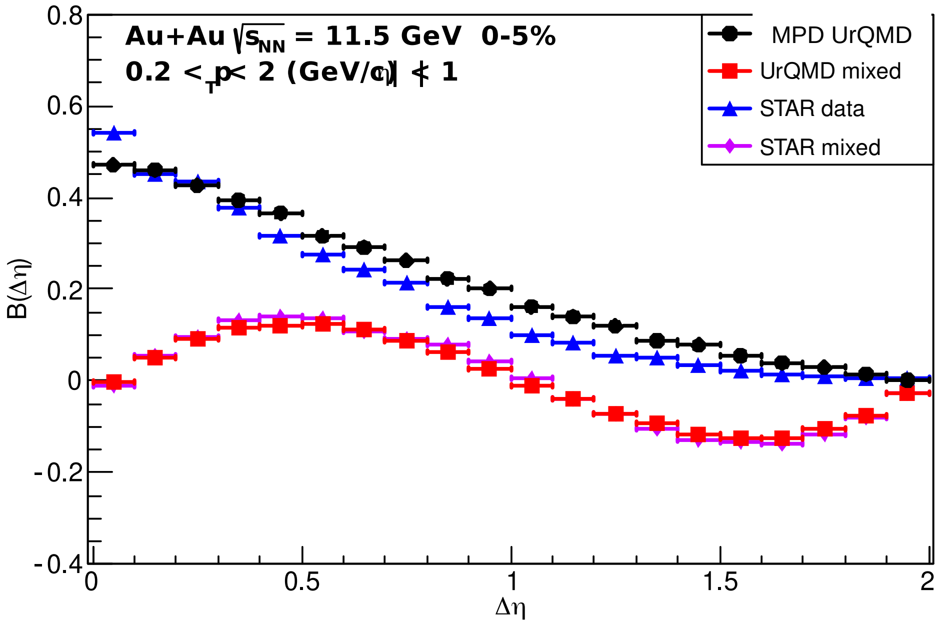
- CBF widths AuAu $\sqrt{s_{NN}}$=7.7...200 GeV(9 centrality)
- Data: decreasing widths with energy and more central events
- UrQMD: almost flat at energy >20 GeV



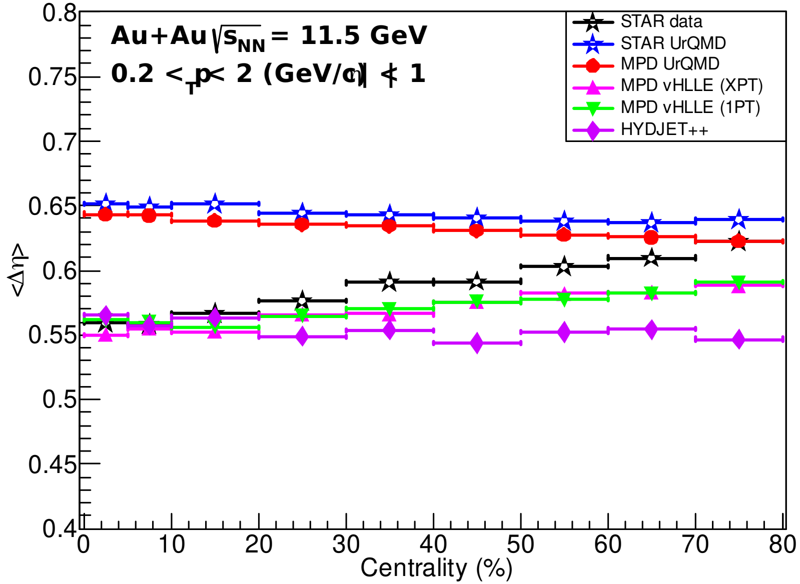
Charge balance function with MPD (UrQMD Au–Au)

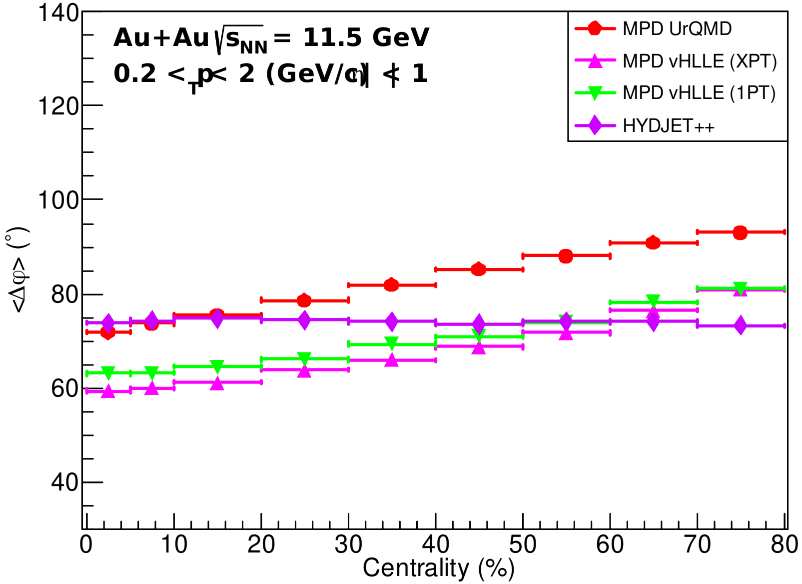
- CBF construction code was developed within the MpdRoot (including <Δη> and <Δφ> CBF widths calculation).
- The developed code was utilized to compute CBFs of Au+Au collisions on UrQMD events at $\sqrt{s_{NN}}$ = 7.7 and 11.5 GeV
- Examples of CBFs calculation using UrQMD events (same and mixed) for 0-5% centrality are shown together with STAR data





CBF Widths with MPD





- MPD UrQMD results are close to those of STAR UrQMD;
- UrQMD describes experimental data in peripheral collisions; vHLLE, HYDJET++ – in central collisions;
- None of the models describes the centrality dependence of experimental widths;
- No dependence on EoS was spotted in the vHLLE model;
- Plan to do simulation for 7.7 GeV to compare with 11.5 GeV results
- to apply CBF construction code for Bi+Bi collisions at 9.2 GeV taking into account MPD detector responses

MC production: Request 31

Request 31: Femtoscopy-purpose, 50 M UrQMD BiBi@9.2 with freeze-out (second collaboration paper)

Monte-Carlo productions

K konstantin.mikhaylov Management of Physics Working Groups 14d

Oct 18

1 / 11
Oct 18

Test/QA production 1e5 events

We make a request for a production to be used for second paper (physics and methodological studies) within our PWG3 in the scope of correlation femtoscopy.

UrQMD + Geant-3 based **femtoscopy**-purpose simulation with freeze-out coordinates project for minbias (b = 0-16 fm) Bi (83/209) +Bi (83/209) collisions at 9.2 GeV, detector configuration for femtoscopy only.

We request to produce a dataset with **100K events** reconstructed for QA.
All necessary macroses:
runMC.C (11.7 KB)
runReco.C (6.4 KB)
Input root DST files at /eos/nica/mpd/users/gnigmat/mcDst/bibi_ecm_9.2

Detector effects affecting the correlation function

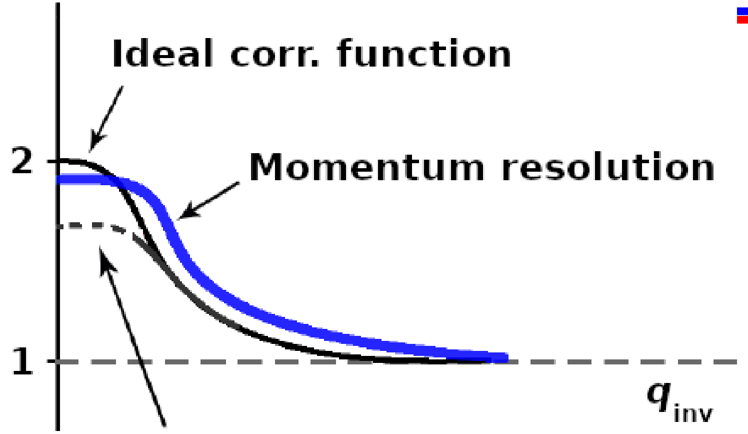
- Single track effects:

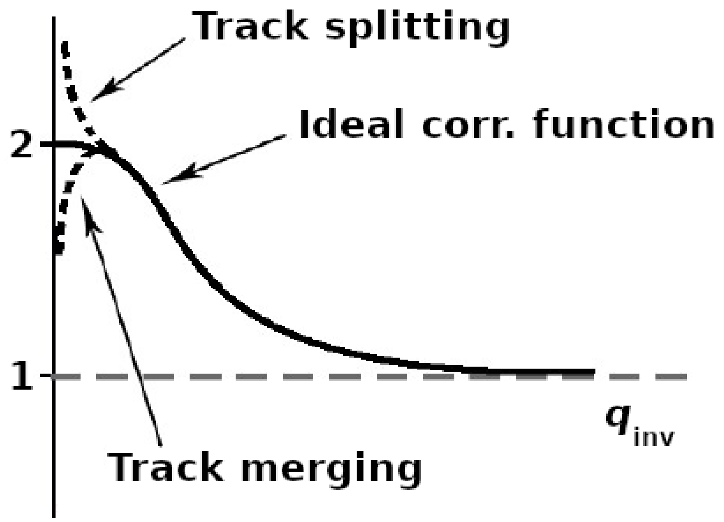
→ the momentum resolution effects smear CF, making it wider and extracted radii smaller
→ CFs should be corrected by resolution

→ the particle misidentification influences only λ-parameter of CF, radii do not change.
→ CF should be corrected by pair purity.

- Two track effects:

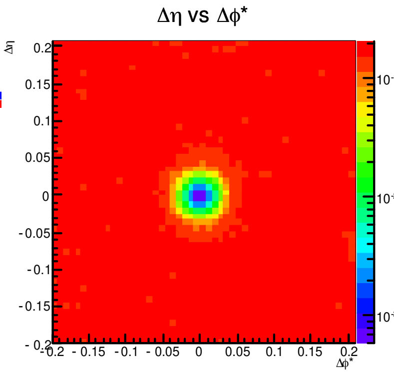
→ track splitting (one track is reconstructed as two)
→ track merging (two tracks are reconstructed as one)
These effects are studied and the special pair selection are used in the analysis.

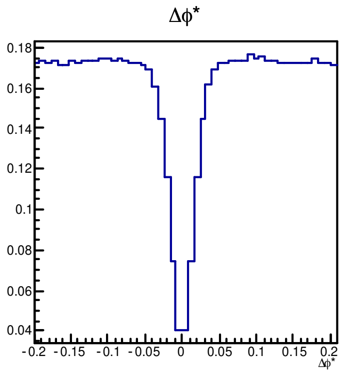


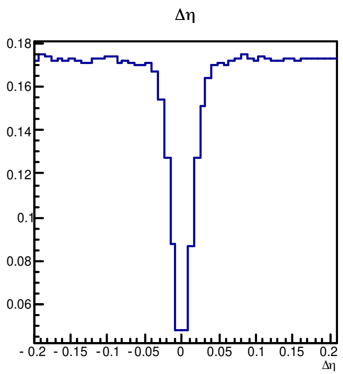


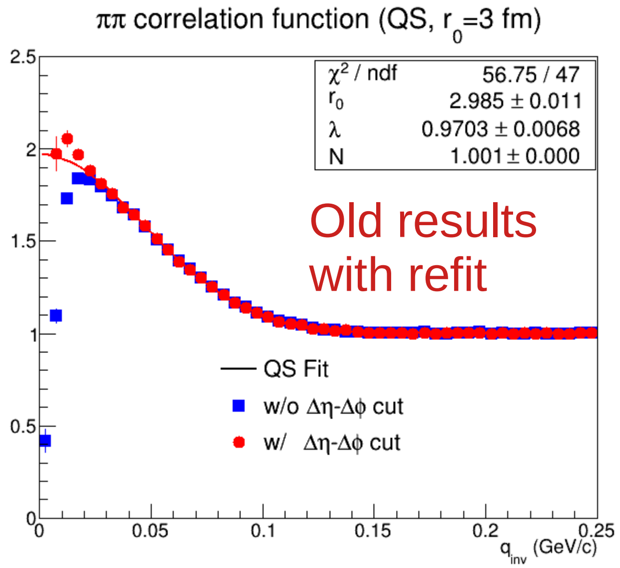
Huge merging effect in QA

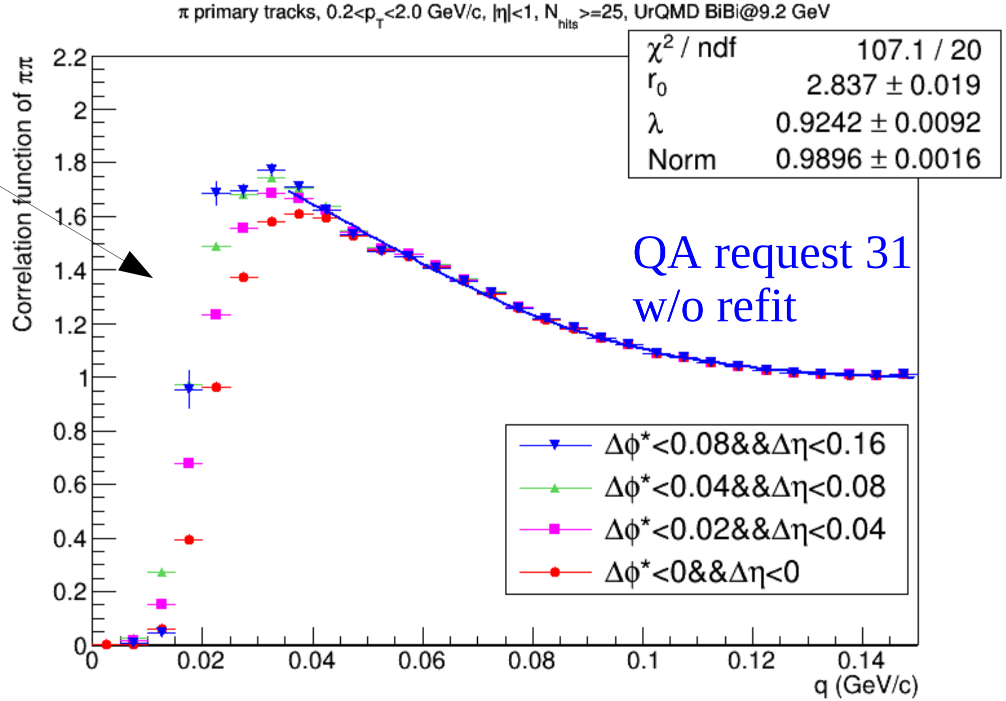
- Tracks reconstructed w/o refit
- Merging effect is larger for global than for primary tracks
- $\Delta\phi^*$-$\Delta\eta$ ct removes the femto effect and do not improve situation











Factorial moments

O. Kodolova

Factorial moments

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

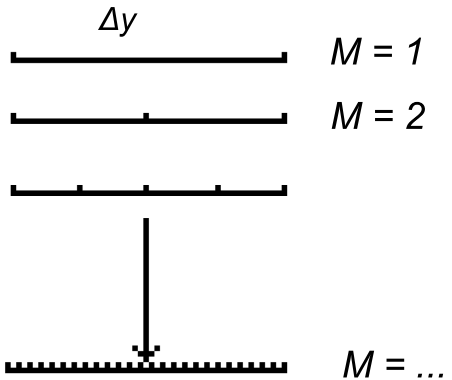
It was proposed by A. Bialas and R. Peschanski (Nucl. Phys. B 273 (1986) 703) to study the dependence of the normalized factorial moments of the rapidity distribution on the bin size δ*y*:

1. if fluctuations are purely statistical no variation of moments as a function of δ*y* is expected

2. observation of variations indicates the presence of physics origin fluctuations

$\delta y = \Delta y / M$
M — number of bins
Δy — size of mid rapidity window
N — number of particles in Δy
k_j-the number of particles in bin j

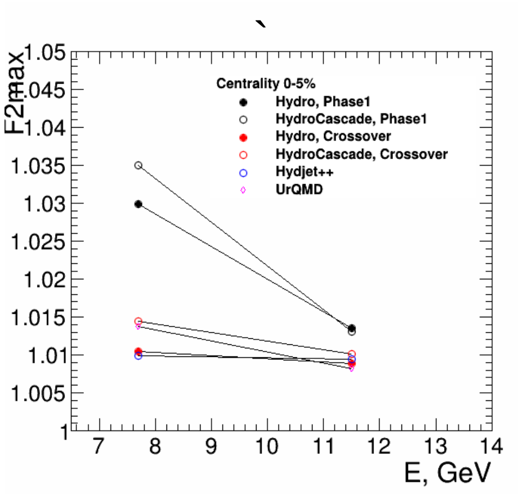
__Note:__ there is a set of definitions of moments and cumulants.

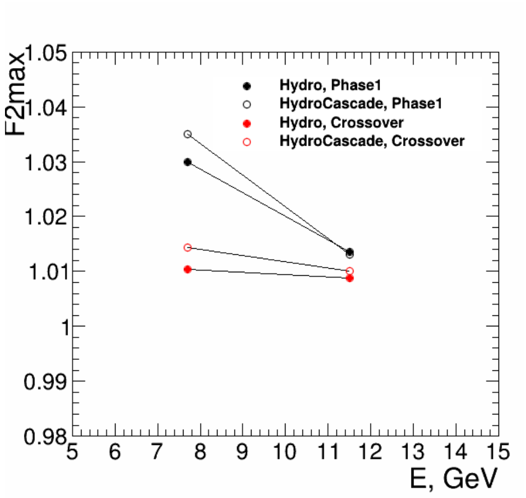


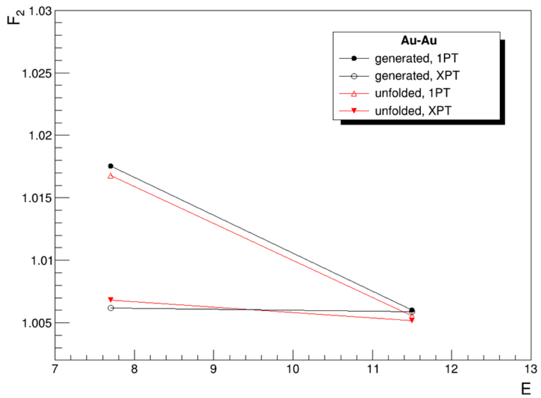
Factorial moments as the method to study dense matter

F2(M) was studied for a set of generators and conditions:
Energy dependence of the F2(M) height is observed for
the 1-st order phase transition as a result of the hydrodynamical
Evolution.

The method to unfold detector F2(M) dependence was designed







Still need to be done in preparation to data taking:

- study another unfolding package and procedures to estimate the method based systematics
- study the method in combination with centrality determination (for the moment central events are selected with generator impact parameter information
- estimate systematic errors due-to track reconstruction efficiency and purity
- study another implementation of the 1st order phase transition (unfortunately, not available yet)

Conclusions and outlooks

- The paper was published in Symmetry journal
- The chaoticity parameter was discussed at the Cross-PWG meeting
- The perspectives of charge balance function analysis at MPD are under investigation
  - CBF construction code was developed within the MpdRoot (Femto package)
  - The package was tested → UrQMD results with MPD package are close to those STAR
  - Description of the experimentally observed centrality dependence of CBF widths is challenging for the theoretical models
- MC production for second physics paper are in progress:
  - First QA test is done
  - More detailed QA is ongoing
- Plans for factorial moments is presented

Thank you for your attention!