IXth MPD Collaboration meeting
25-27 April 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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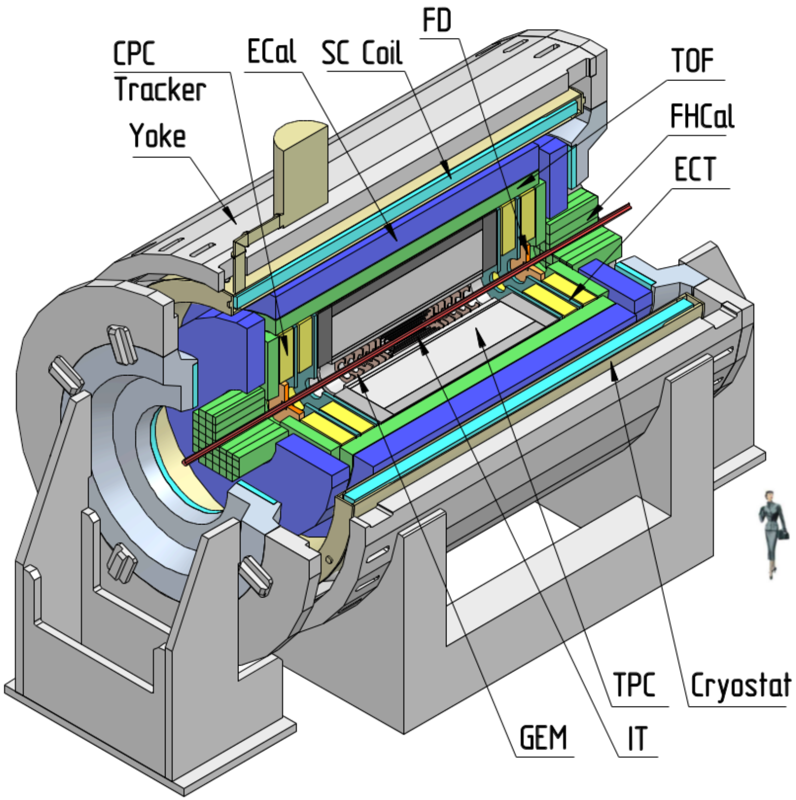
Outline

- Activities
- Femtoscopy
- Femtoscopy and methodical aspect
- Charge balance function
- Factorial moments
- Conclusions



PWG3 activities in 2019-2022

- Three Master and 2 PhD student in Femto group

- PWG3 Femto Meetings: over 50 events (2019-2022) → https://indico.jinr.ru/category/346/

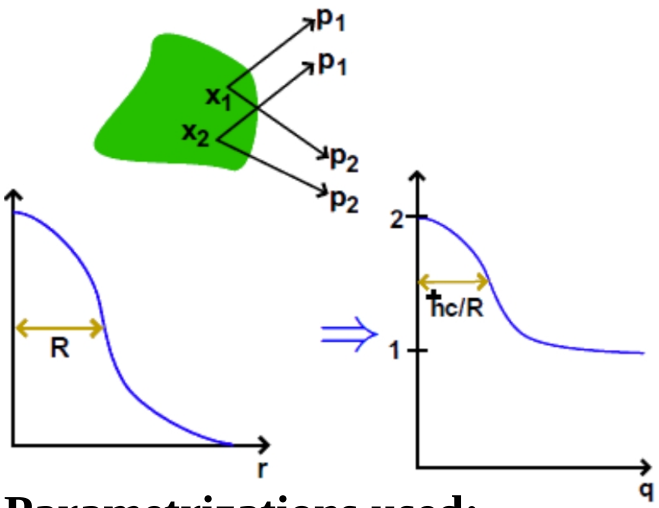
- MPD Physics Seminars: 6 seminars

- Conferences(2019-2022):
  over 10 talks at different conferences

- Publications (most important):

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

Femtoscopy



Parametrizations used:

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

R – Gaussian radius in PRF,

λ – correlation strength parameter

3D CF: $C(q_{out}, q_{side}, q_{long}) = 1 + \lambda\, e^{-R_{out}^2 q_{out}^2 - R_{side}^2 q_{side}^2 - R_{long}^2 q_{long}^2}$

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

long || beam; out || transverse pair velocity v_T; side normal to out,long

Correlation femtoscopy :

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

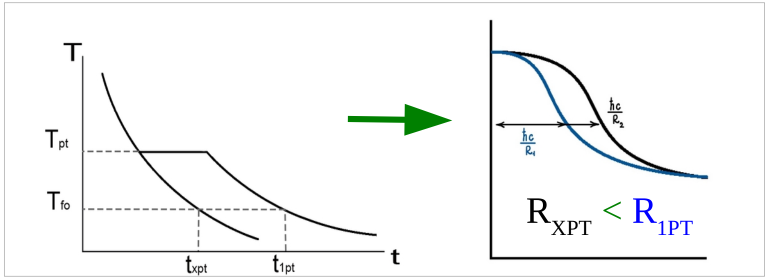
Two-particle correlation function:

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

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

S(*q*) – distribution of pair momentum difference from same event

B(*q*) – reference distribution built by mixing different events



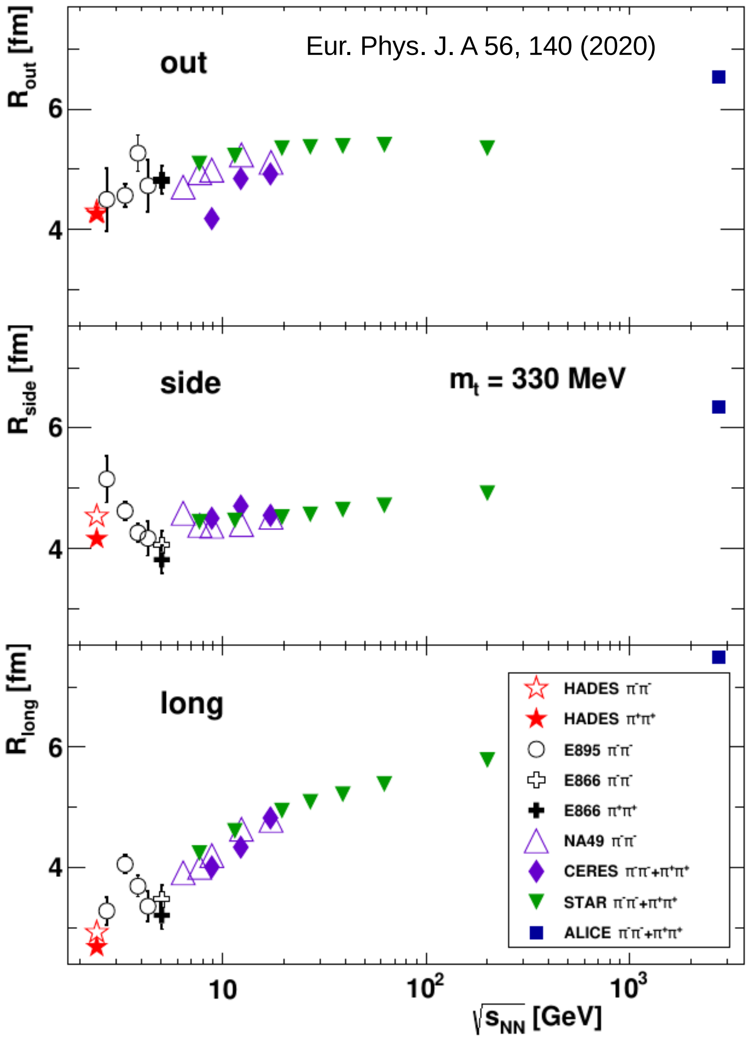
Motivation

- **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,II):
  $\sqrt{s_{NN}}$ = 7.7, 11.5, 19.6, 27, 39 GeV; 3 to 7 and 7.7 to 19 GeV
  - The search for the onset of a first-order phase transition in Au + Au collisions
  - Measured pion and kaon femtoscopic parameters:
    m_T -dependence of radii,
    flow-induced $x - p$ correlations

- NICA energy range: $\sqrt{s_{NN}}$ = 4 – 11 GeV
  - first collider measurements below 7.7 GeV
    - including K and heavier



Femtoscopy with vHLLE

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

Pre-thermal phase → Hydrodynamic phase → Hadronic cascade

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

vHLLE

(3+1)-D viscous hydrodynamics

<u>EoS to be used in the model</u>

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

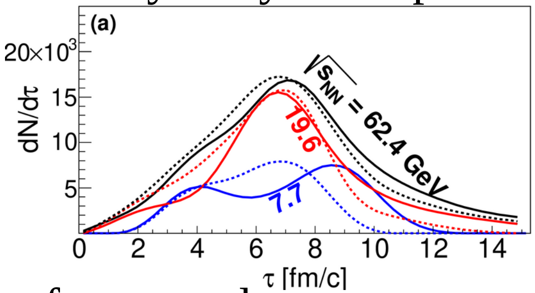
Hydrodynamic phase lasts longer with 1PT, especially at lower energies but cascade smears this difference.

**update planned*

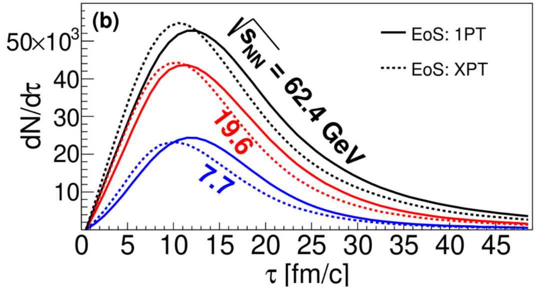
UrQMD

<u>Pion emission time</u>

after hydrodynamic phase

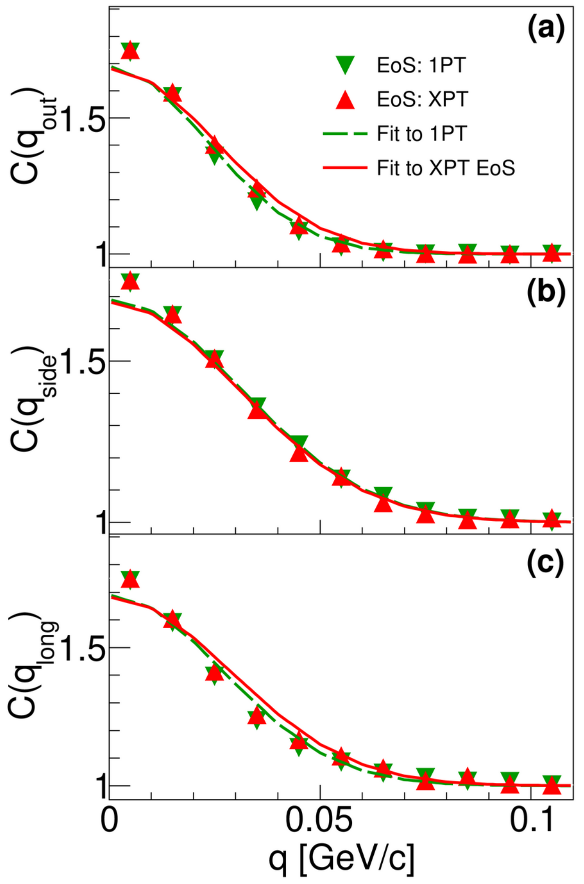


after cascade

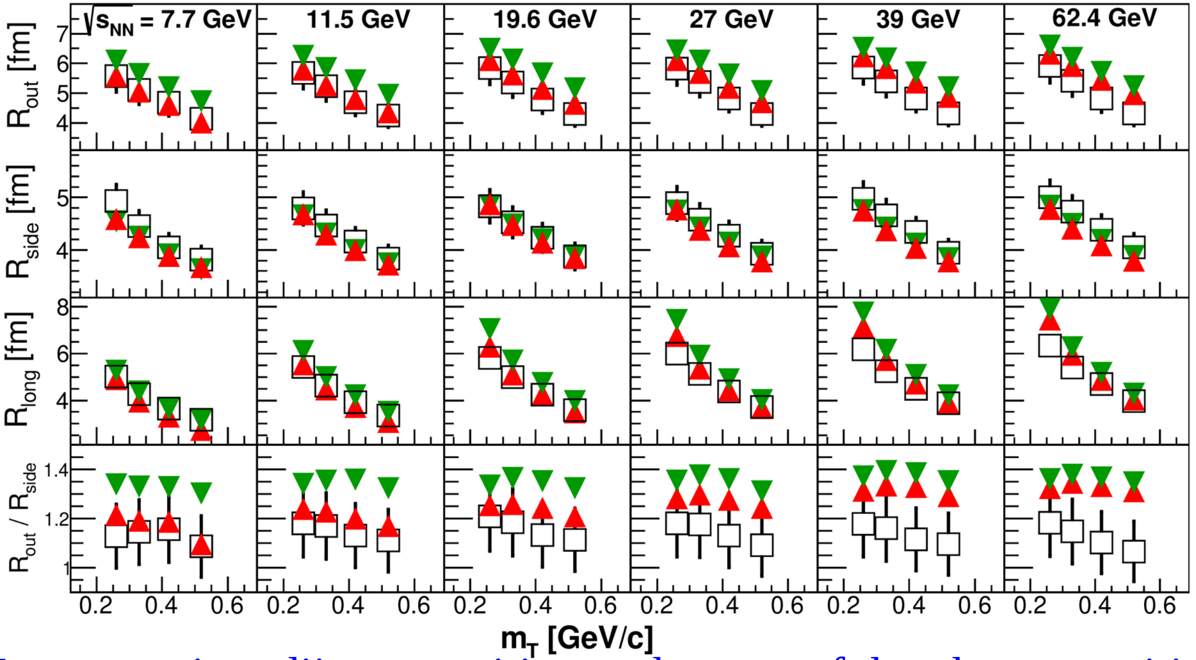


3D Pion radii versus m_T with vHLLE

Model CF



Comparison of extracted radii with the STAR data[PRC 96, 024911(2017)]



- Femtoscopic radii are sensitive to the type of the phase transition
- Crossover EoS does better job at 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 ~1-2 fm.

Correlation Functions from vHLLE

- Examples of the correlation functions of pions and kaons obtained for Au+Au collisions at $\sqrt{s_{NN}}$=11.5 GeV (vHLLE)
- Correlation functions were fitted with:

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

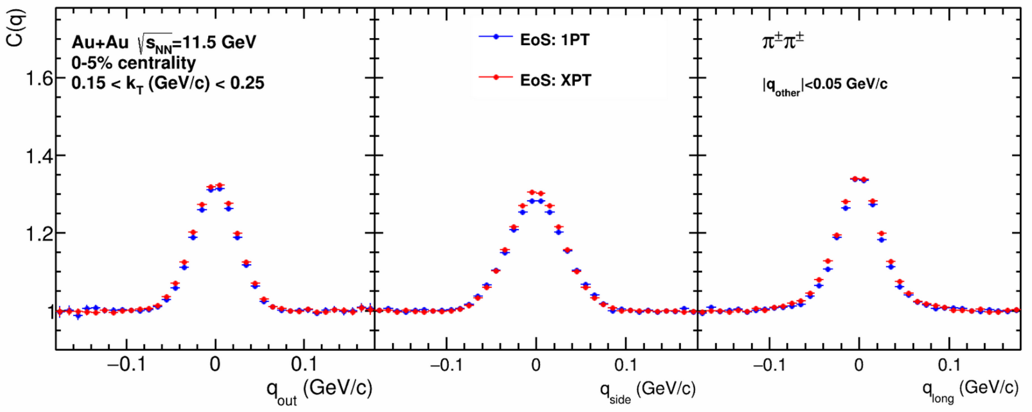
where:

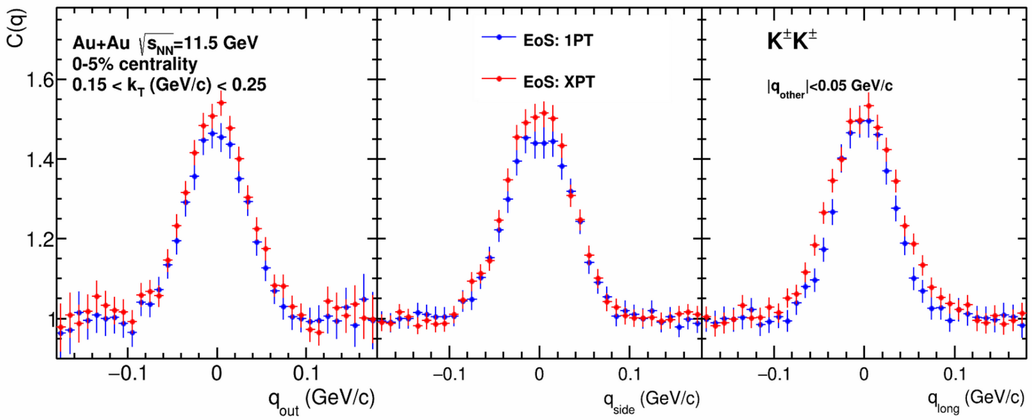
R_{side} – size of the emission region

R_{out} – sensitive to the emission duration

R_{long} – proportional to the system lifetime

- Both K and π CF XPT wide than 1PT
  → XPT size smaller than 1PT





Femtoscopic Radii of Pions and Kaons from vHLLE

- AuAu $\sqrt{s_{NN}}$ = 11.5 GeV
- Pion and kaon results for the cross over (XPT) and 1st-order (1PT) phase transitions

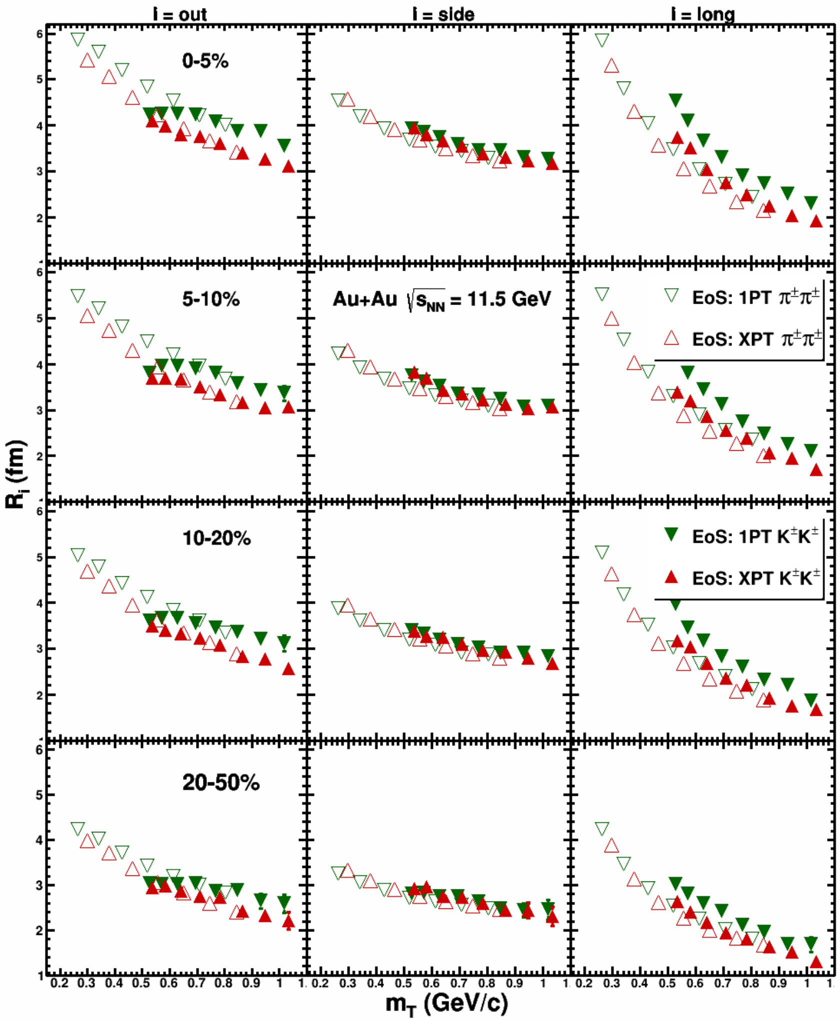
- Femtoscopic radii of π and K decrease with increasing transverse mass → Influence of radial flow

- R_{side} values for π and K are similar
  → Similar size of the particle-emitting region

- R_{out} for both π and K show similar behavior
  → Similar particle emission duration

- R_{long} for K is generally larger than that for π at the same m_T
  → Influence of resonances, K*

- *We have to study femtoscopy in very wide pair transverse momentum region to see all above!*

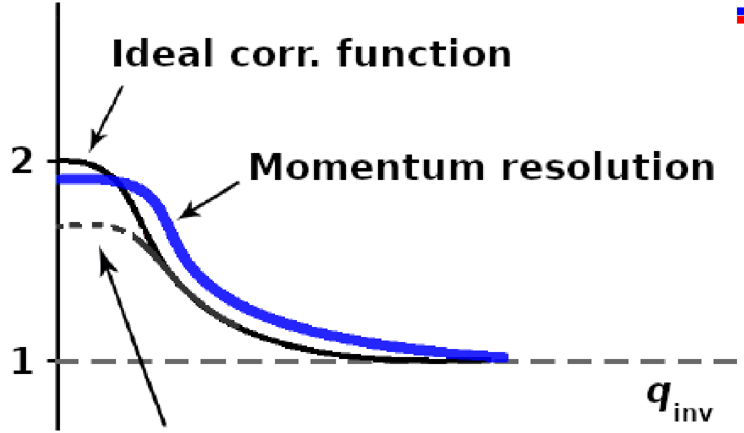


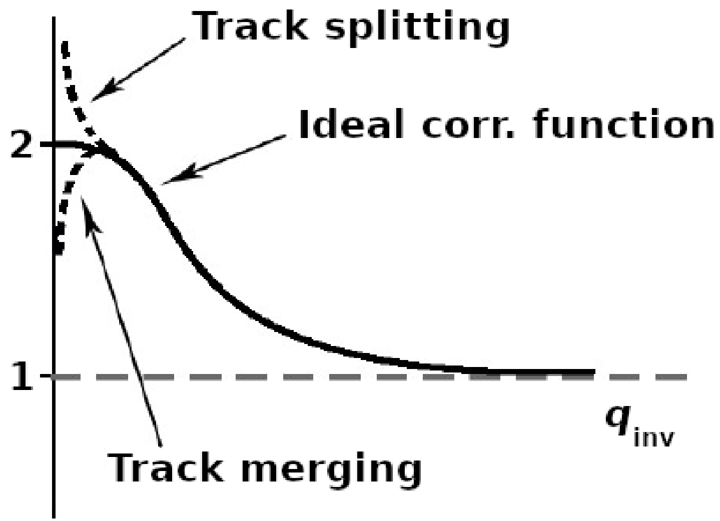
Detector effects affecting the correlation function

- 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.

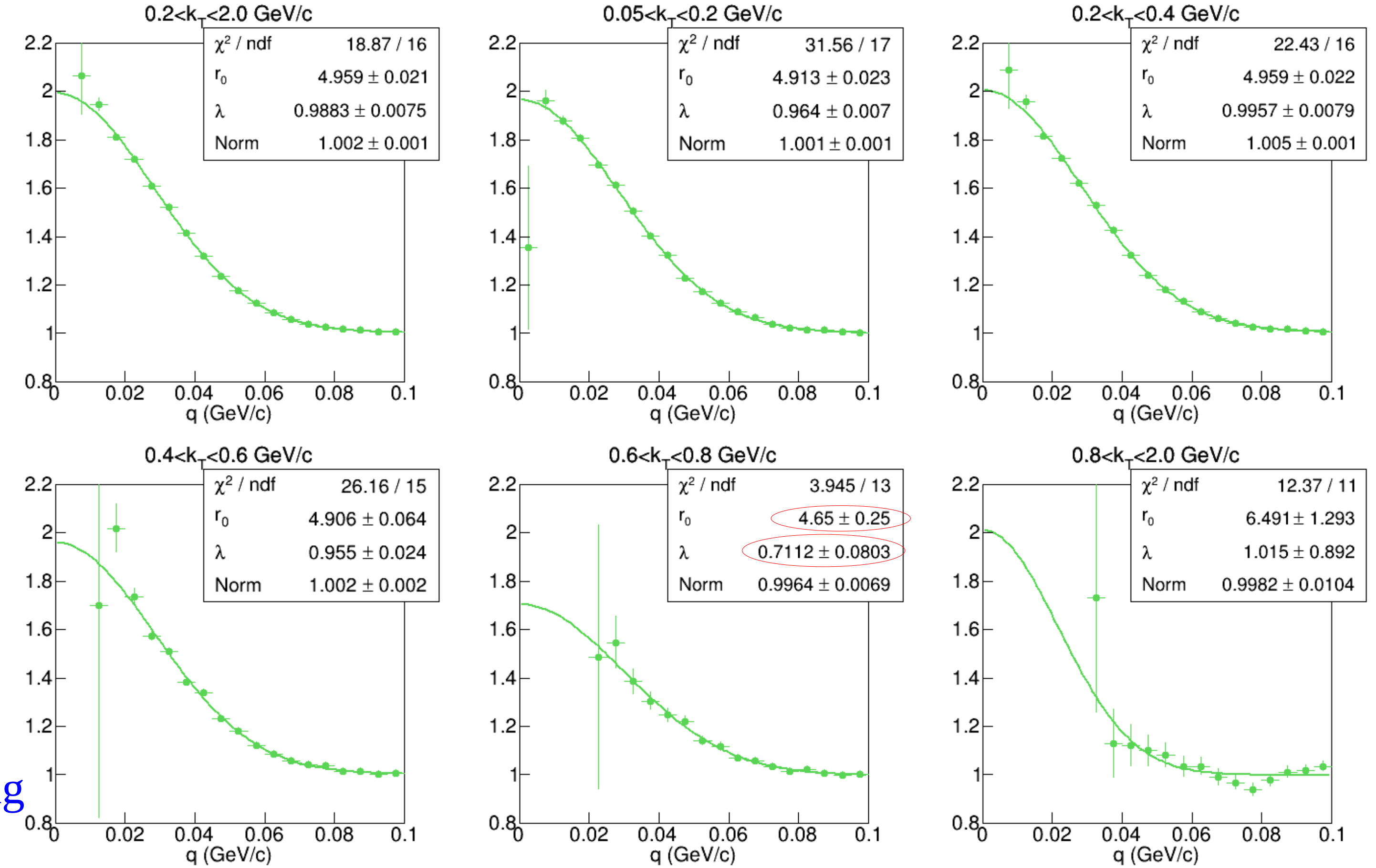
- Two track effects:
  → track splitting (one track is reconstructed as two)
  → track merging (two tracks are reconstructed as one)
  These effects are studied and the special pair selection are used in the analysis.





Parameters R and λ from fitting function (#hits>30)

- Fit QS: $N[1+\lambda\cdot\exp(-q^2 r^2_0)]$
- We should get
  $\lambda=1$ and $r_0=5$ fm
- k_T inclusive CF looks good
- The track-spitting effect is small as compared to the track merging
- Width of merging increases with increasing of k_T
- Unfortunately, we can't study high k_T region for now
- We hope the tracking will be improved in the future
- To be tested new cluster finding (see talk A.Zinchenko)



Charged balance function

A.Chernyshov, I.Lokhtin

Charged 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

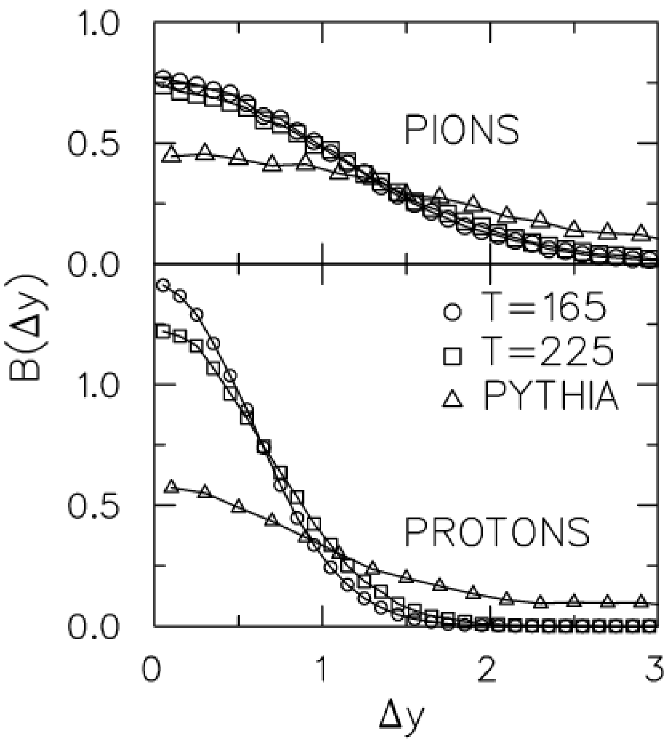
$$B(p_2|p_1) \equiv \frac{1}{2}\{\rho(b,p_2|a,p_1) - \rho(b,p_2|b,p_1) + \rho(a,p_2|b,p_1) - \rho(a,p_2|a,p_1)\}$$

$\rho(b, p_2|a, p_1)$ 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.

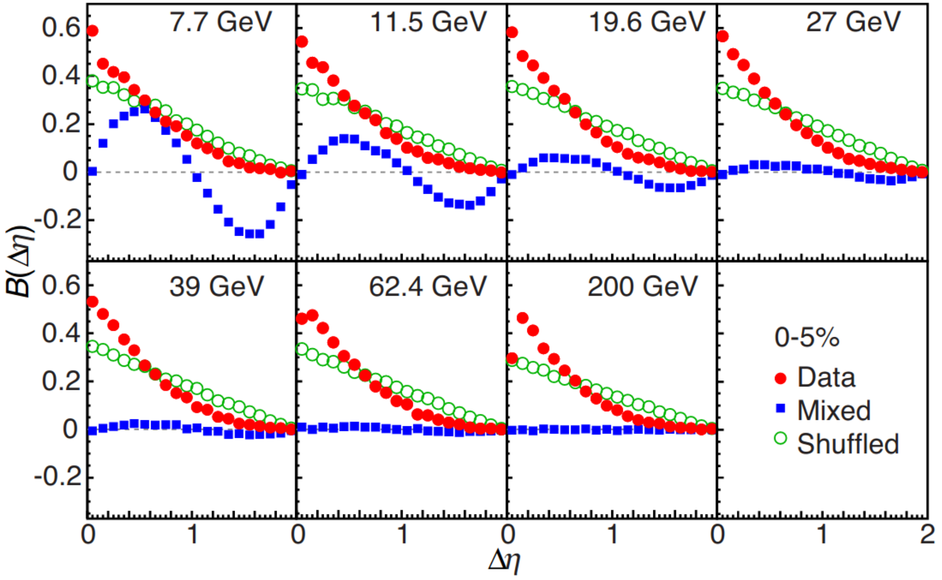


STAR: Charged balance function

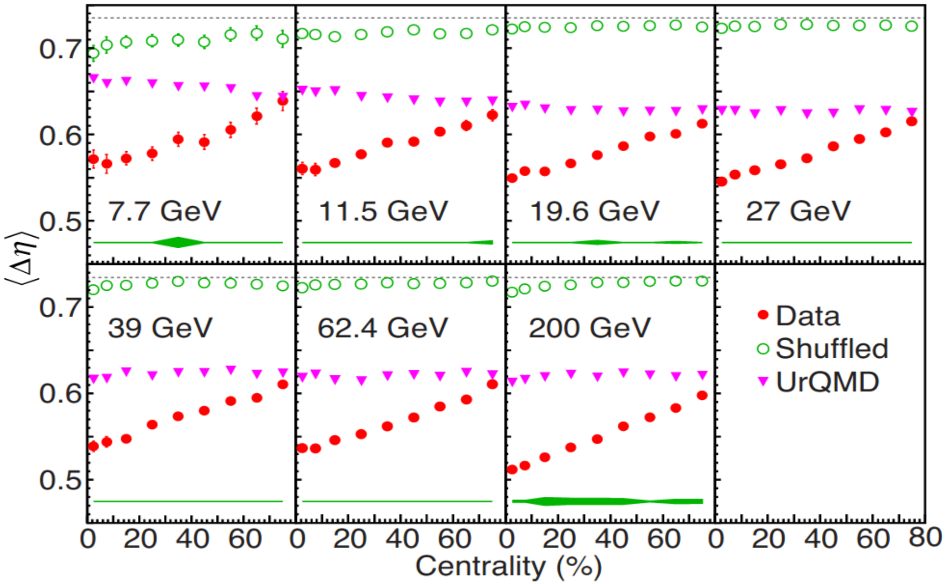
STAR: Beam-Energy Dependence of Charge Balance Functions from Au+Au Collisions at RHIC [Phys.Rev.C 94 (2016) 2, 024909]

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

- $B(\Delta\eta)$ 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

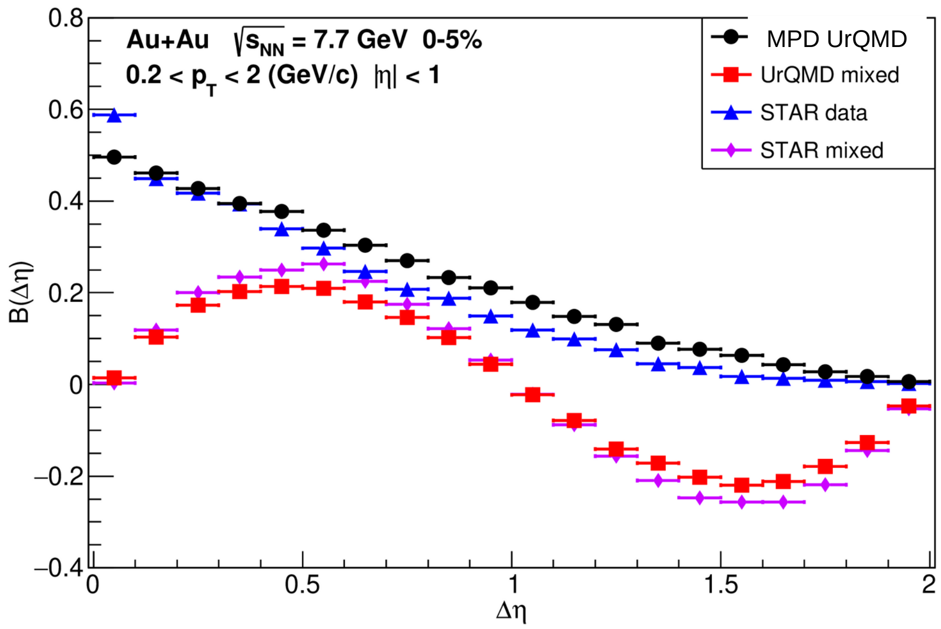


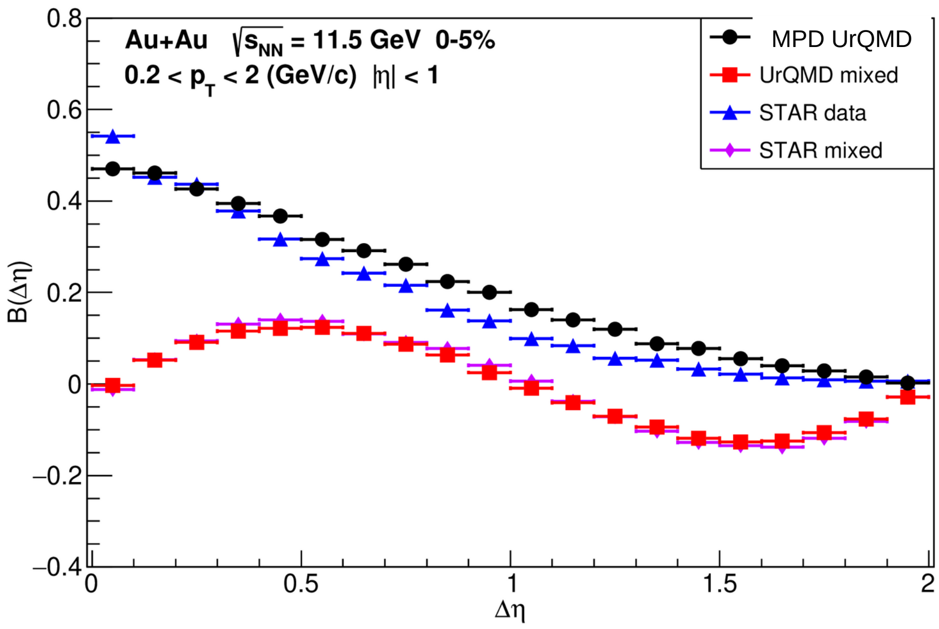
- CBF widths AuAu $\sqrt{s_{NN}}$=7.7...200 GeV(9 centrality)
- Data: decreasing widths with energy and more central events
- UrQMD: almost flat at energy >20 GeV



Charged balance function with MPD (UrQMD Au–Au)

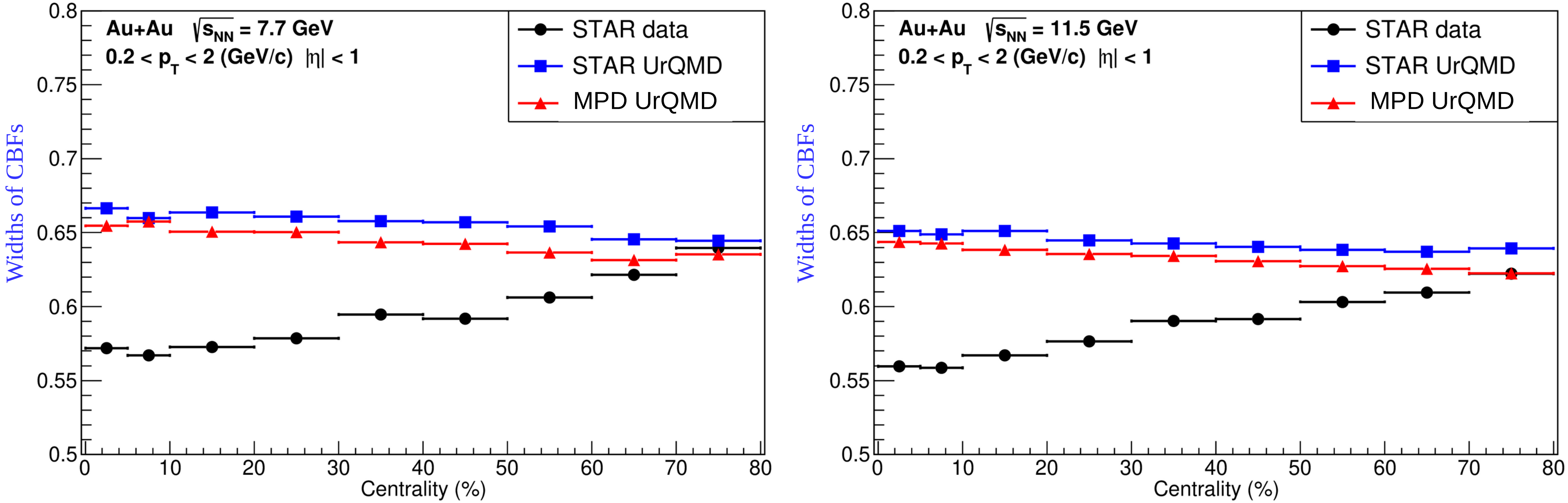
- CBF construction code was developed within the MpdRoot (including <Δη> and <Δφ> CBF widths calculation).
- The developed code was utilized to compute CBFs of Au+Au collisions on UrQMD events at $\sqrt{s_{NN}}$ = 7.7 and 11.5 GeV
- Examples of CBFs calculation using UrQMD events (same and mixed) for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





Widths of CBFs with MPD package

- Widths of the CBF using UrQMD events calculated with new MpdRoot package
- The UrQMD widths from MpdRoot and from STAR paper are in agreement
- Both do not reproduce STAR data except peripheral events
- All above for two energies $\sqrt{s_{NN}}$ = 7.7 and 11.5 GeV



Factorial moments

M. Cheremnova, O. Kodolova

Factorial moments

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

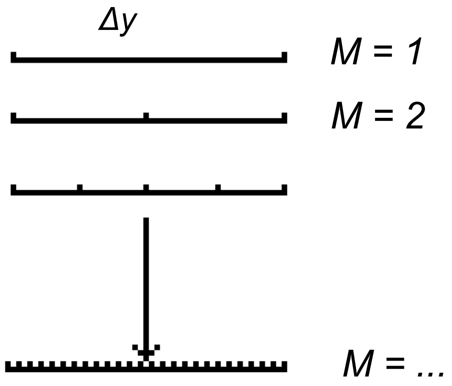
It was proposed by A. Bialas and R. Peschanski (Nucl. Phys. B 273 (1986) 703) to study the dependence of the normalized factorial moments of the rapidity distribution on the bin size δ*y*:

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

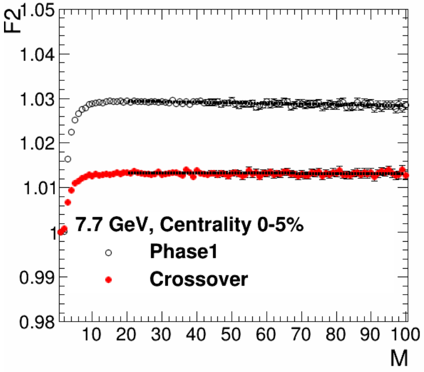
$\delta y = \Delta y / M$
M — number of bins
Δy — size of mid rapidity window
N — number of particles in Δy
k_j-the number of particles in bin j

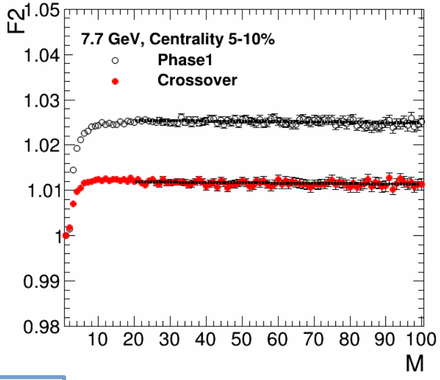
Note: there is a set of definitions of moments and cumulants.



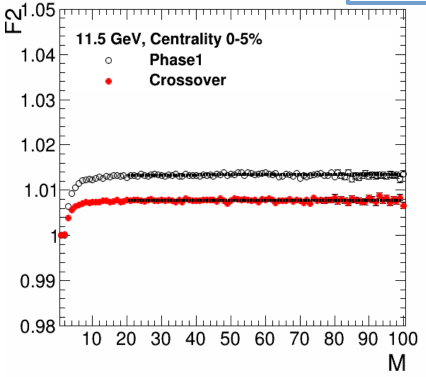
Au-Au, vHLLE: generator information

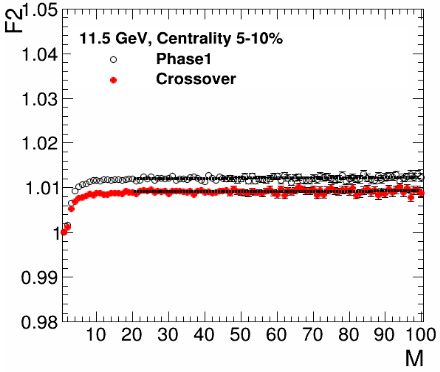
7.7 GeV

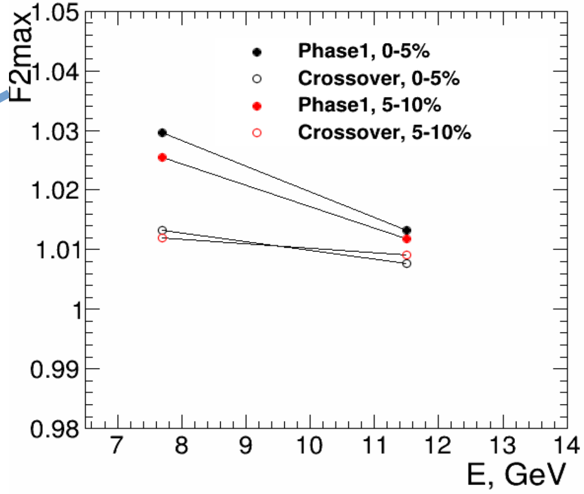




11.5 GeV

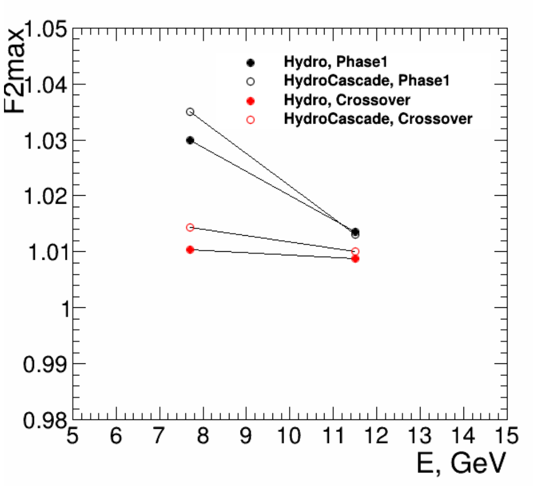


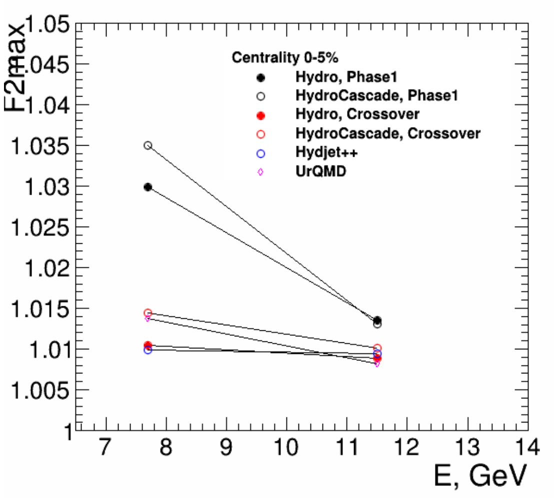


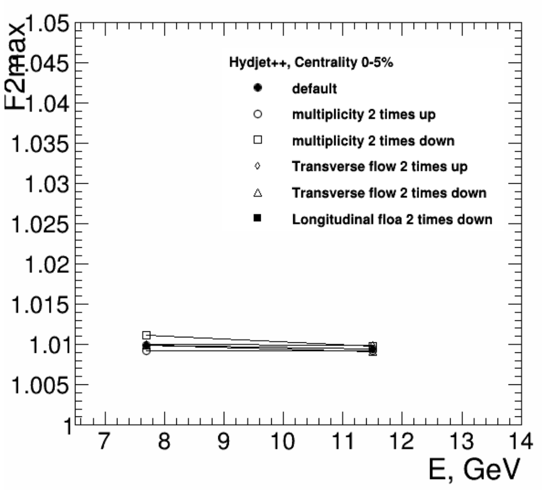


- Different energy dependence is expected for Crossover and 1st order phase transition
- There is a mild dependence on centrality for 1st order phase transition

Factorial moments for different event generators







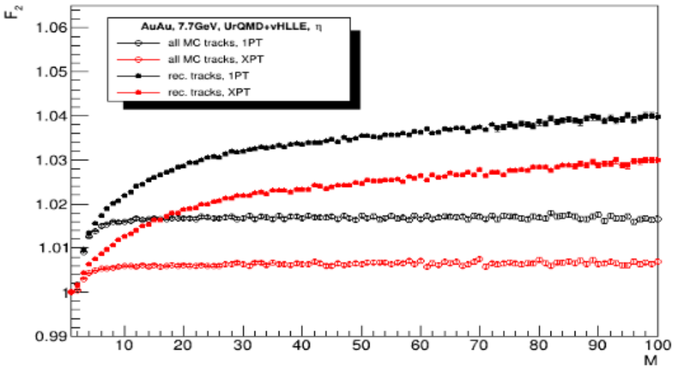
The maximum of the F2(M) as a function of collision energy for Au+Au interactions produced with vHLLE with cascade on/off (left, middle), UrQMD (middle), HYDJET++ with multiplicity up/down, transverse and longitudinal volume size up/down (right).

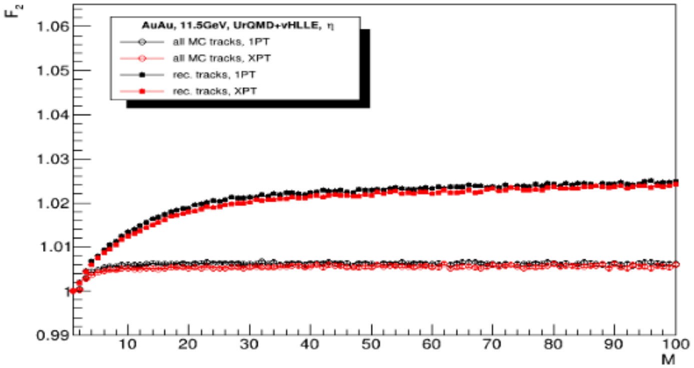
The switching on/off cascade on top of hydrodynamical evolution has a mild effect on the dependence of F2(M) maximum value.

UrQMD, vHLLE and HYDJET++ indicates that phase transition of the crossover type and no-phase transition (UrQMD, HYDJET++) do not reveal any changes of the F2(M) maximum value.

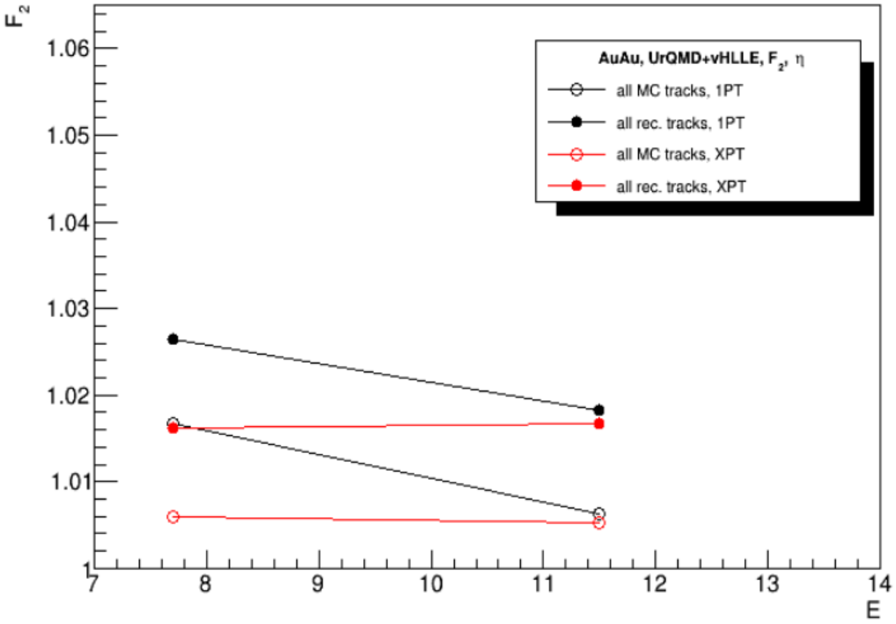
Changing conditions in pure hydrodynamical model (increase and decrease of multiplicity, transverse and longitudinal flow) HYDJET++ do not show any essential difference in F2(M) with respect to crossover produced with vHLLE.

Factorial moments: pseudorapidity instead of rapidity





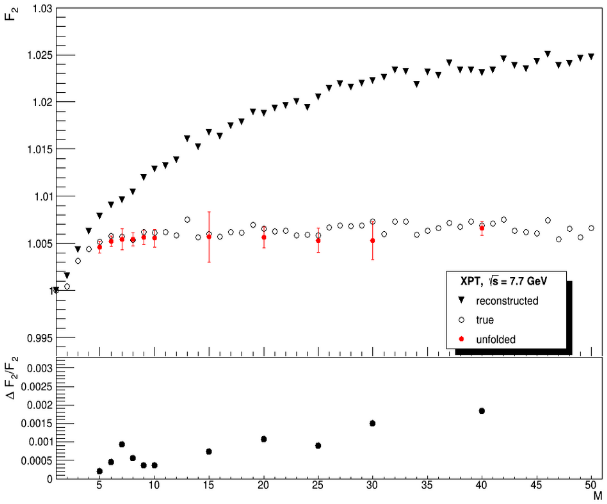
Factorial moments: generated vs reconstructed tracks

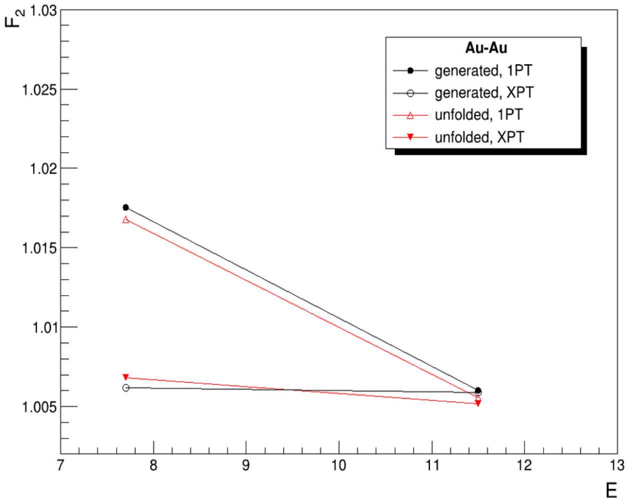


Factorial moments of multiplicity distribution in the ***pseudorapidity*** interval [-1,1]

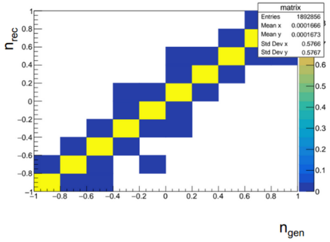
Unfolding of F2(M)

- Use ROOUNFOLD (current) or TUnfold (future) to unfold F2(M) distribution at each binning (M).





Central events
b<3.3 fm



Response matrix is calculated using 25000 of minbias events
Errors are calculated using N samples of 25000 of minbias events

Conclusions and outlooks

- The model shows that it is necessary to explore a wide range of the pair's transverse momentum
- Since the femtoscopy signal is found at small relative momenta, it is necessary to study in detail the two-track effects (to be tested a new procedure of cluster finding)
- The perspectives of charge balance function analysis at MPD are under investigation
  - CBF construction code was developed within the MpdRoot (Femto package)
  - The code was used to calculate CBFs of Au+Au on UrQMD events at $\sqrt{s_{NN}}$ = 7.7 and 11.5 GeV
  - The UrQMD widths from MpdRoot and from STAR paper are in agreement
- Factorial moments:
  - The pseudorapidy instead of rapidity helps with identification problem
  - Unfolding procedure does a great job

Thank you for your attention!