VIIIth MPD Collaboration meeting
12-14 October 2021, JINR, Dubna

Femtoscopy correlations with MPD at NICA

on behalf of PWG3 (Correlations and Fluctuations)

Supported by the RFBR grant 18-02-40044

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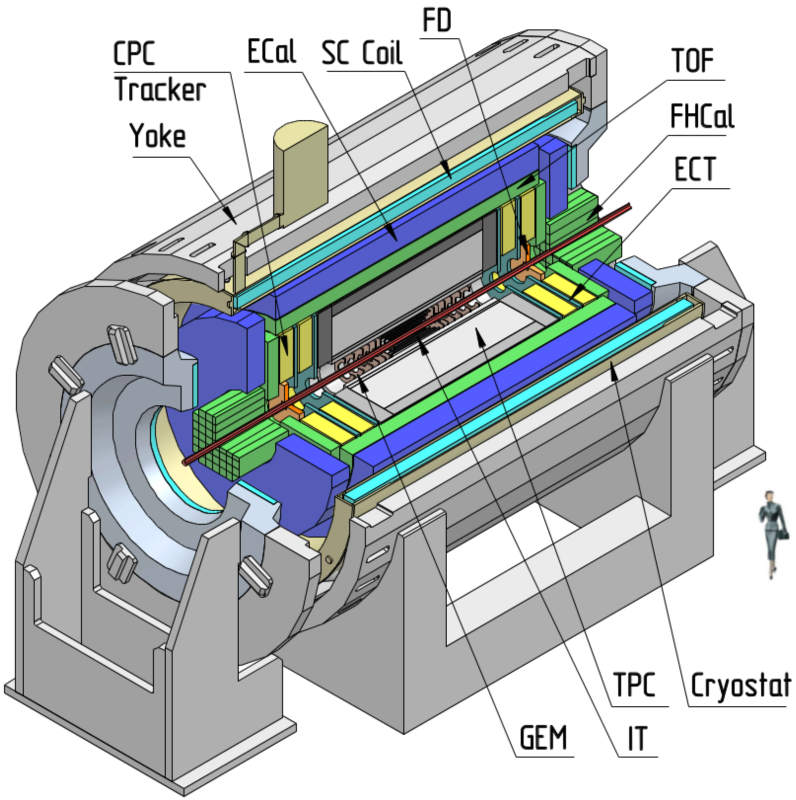
Outline

- Activities
- Femtoscopy
- Femtoscopy and methodical aspects
- Two-track effects
- Momentum resolution and n-sigma PID
- Factorial moments status
- Conclusions



Activities within RFBR grant 18-02-40044

- Three Master and 2 PhD student in Femto group

- PWG3 Femto Meetings: over 50 events (2019-2021) →   https://indico.jinr.ru/category/346/

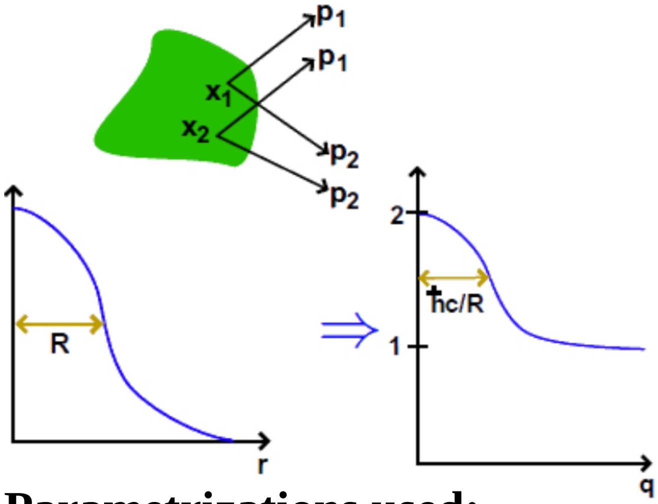
- MPD Physics Seminars(+5 in 2019,2020): 6 seminars

- Conferences(2019-2021):
  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



Correlation femtoscopy :

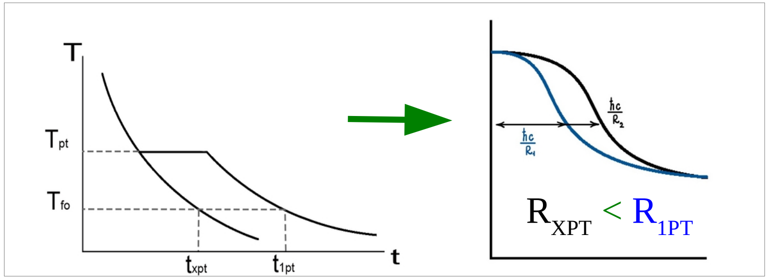
Measurement of space-time characteristics **R**, **cτ** of particle production using particle correlations due to the effects of quantum statistics (QS) and final state interactions (FSI)

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



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 $\boldsymbol{v}_T$; side normal to out,long

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

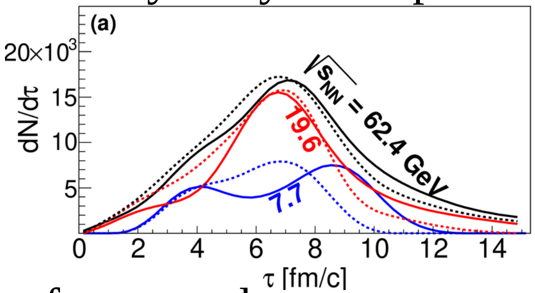
EoS to be used in the model

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

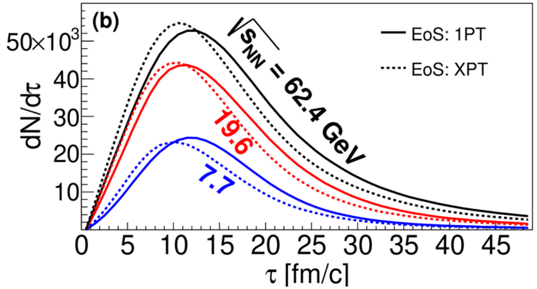
Hydrodynamic phase lasts longer with 1PT, especially at lower energies but cascade smears this difference.

Pion emission time

after hydrodynamic phase



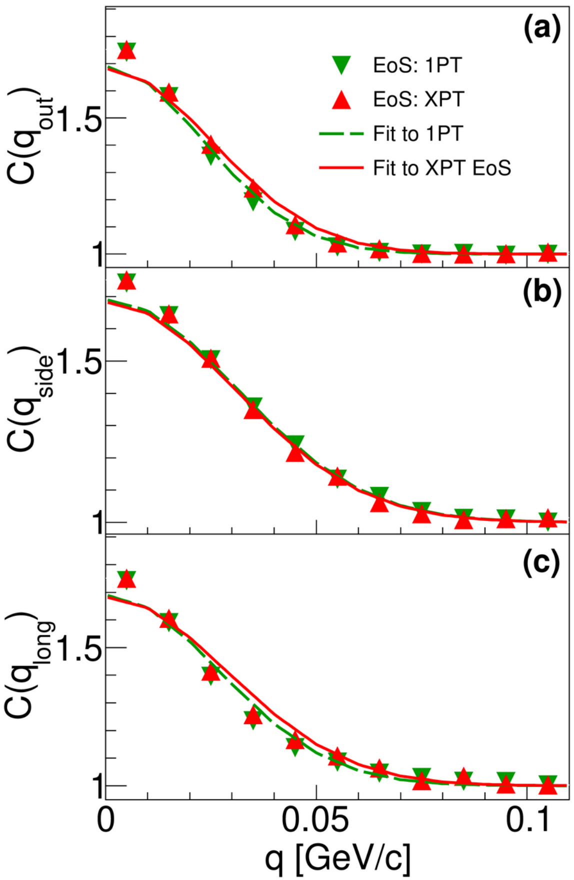
after cascade



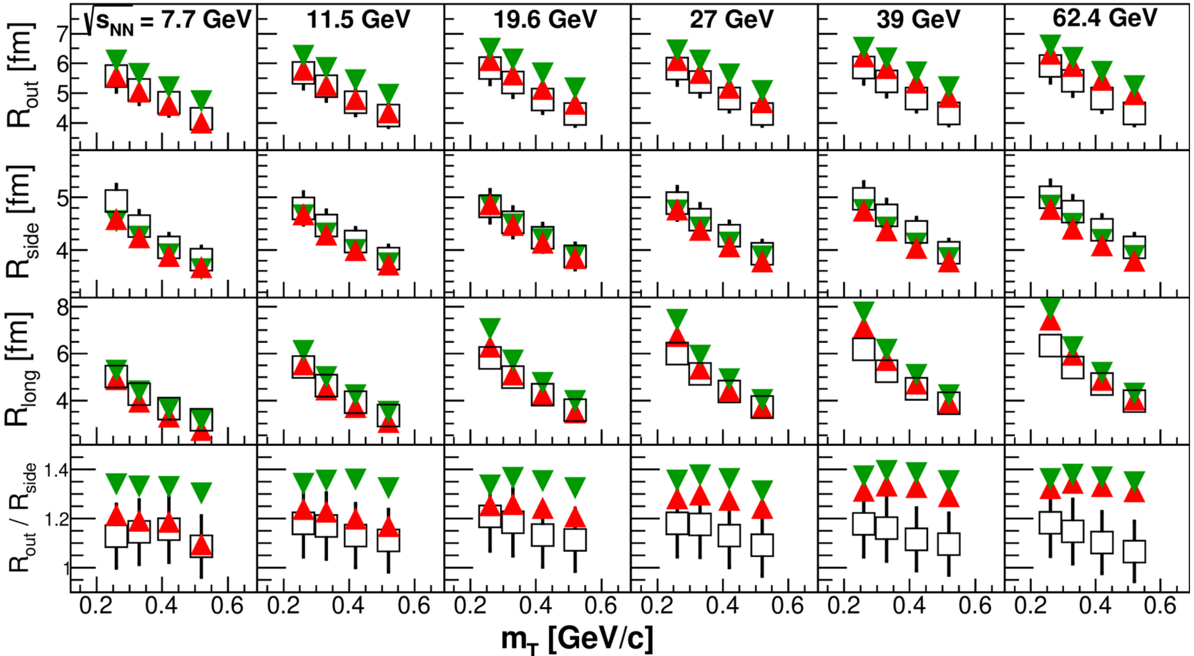
*update planned

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.

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

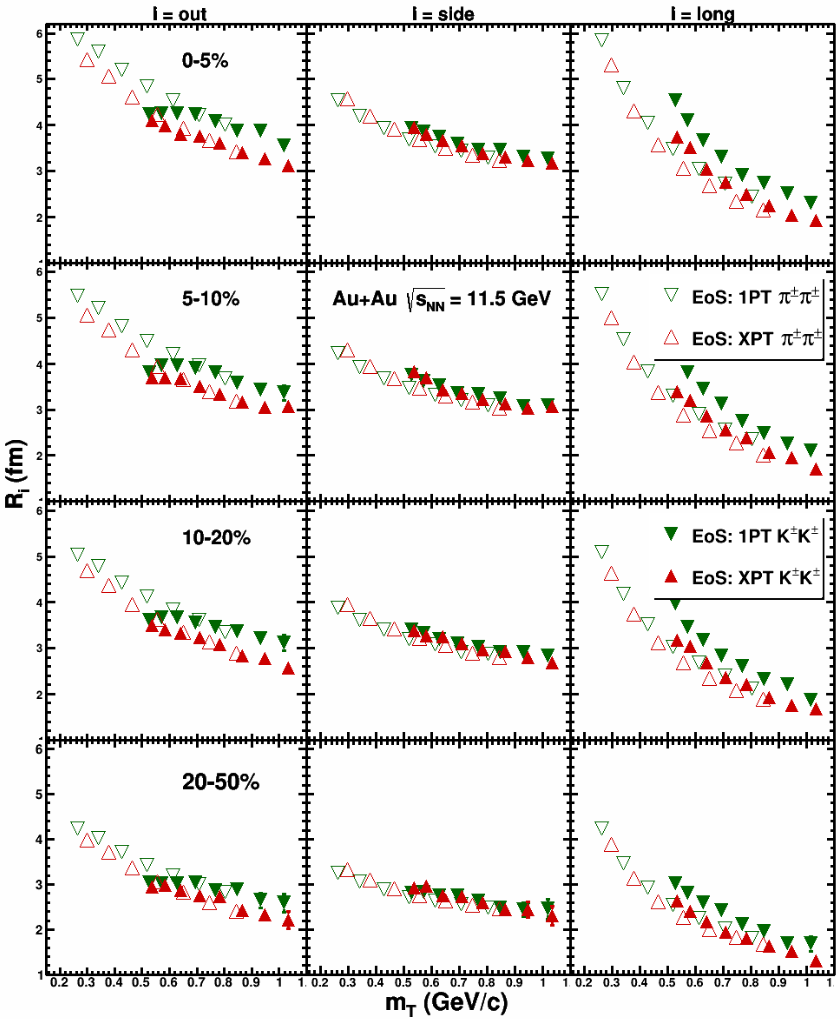
- Femtoscopic radii of π and K decrease with increasing transverse mass → Influence of radial flow

- 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

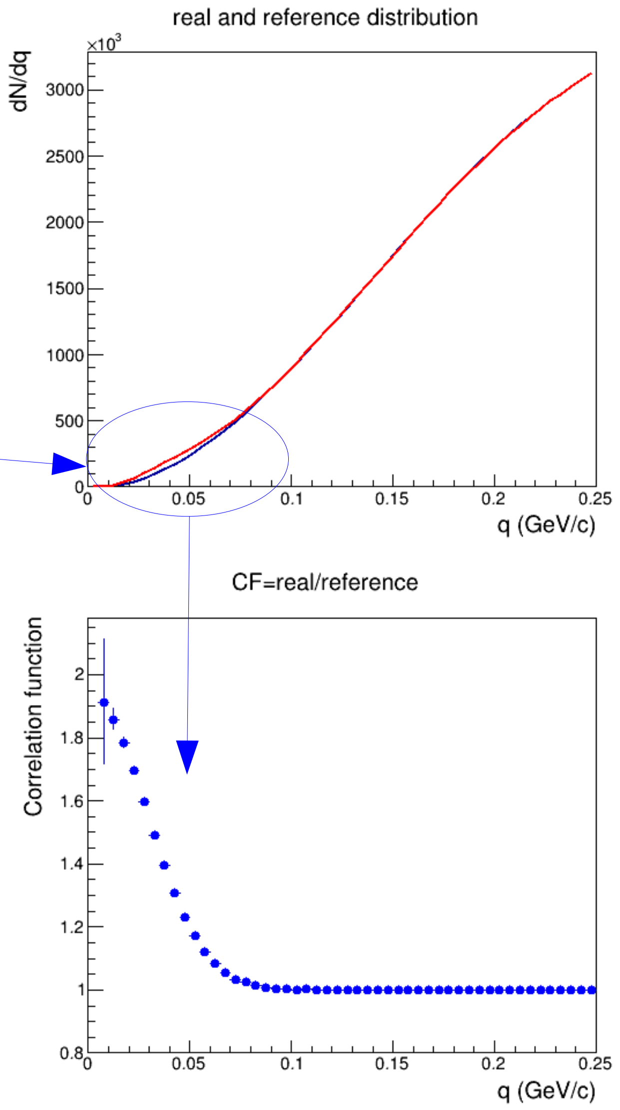
- R_{long} for K is generally larger than that for π at the same m_T
  → Influence of resonances, K*

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



Features of reconstruction for femtoscopy

- The signal is in small phase space (small $\Delta p=|\mathbf{p}_1-\mathbf{p}_2|$)
- Close track reconstruction is very important
- Momentum resolution
- Particle identification in pair (e.g. e+e- could destroy K+K-)

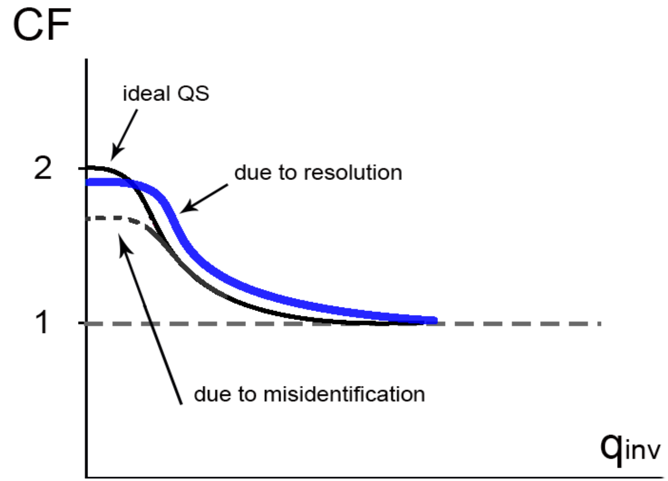


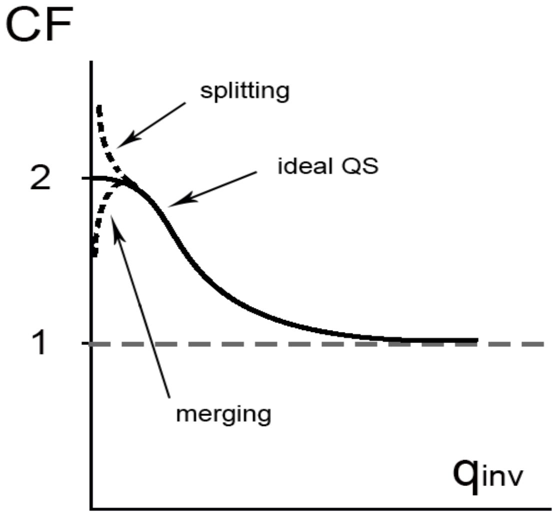
Detector effects affecting the correlation function *

- 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.

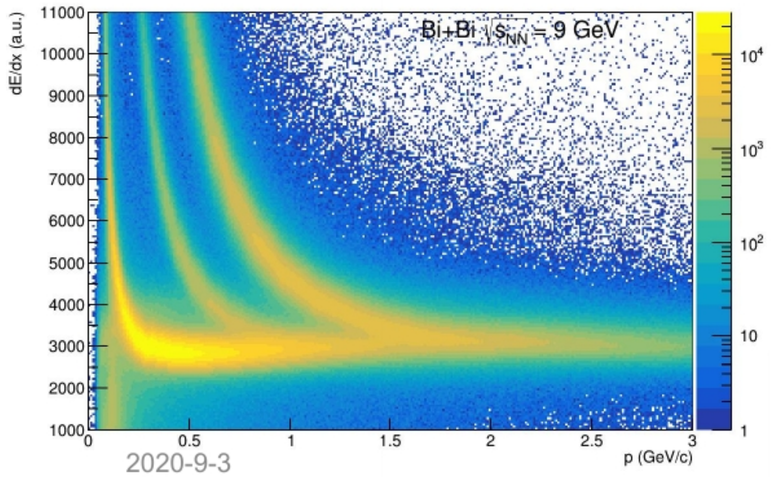




* *see Ludmila's talk today*

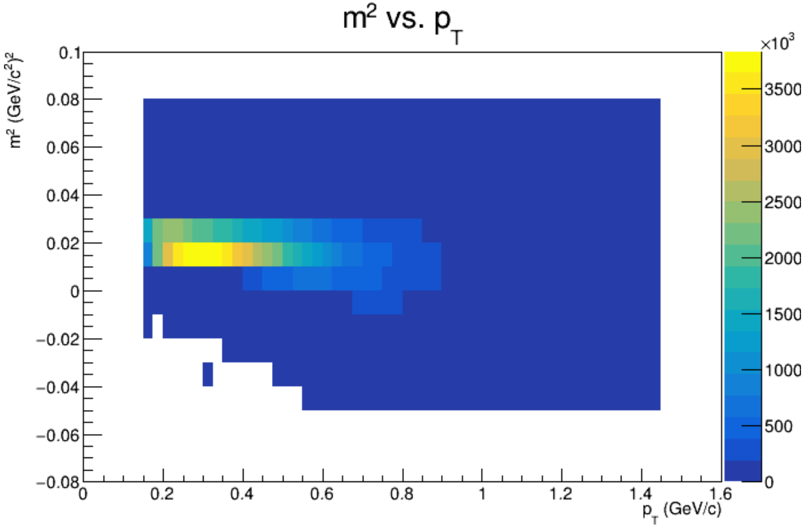
Monte-Carlo data

- Monte Carlo simulation request
- UrQMD Minimal Bias 10 million evens
- BiBi at $\sqrt{s_{NN}}$=9 GeV
- MiniDst format



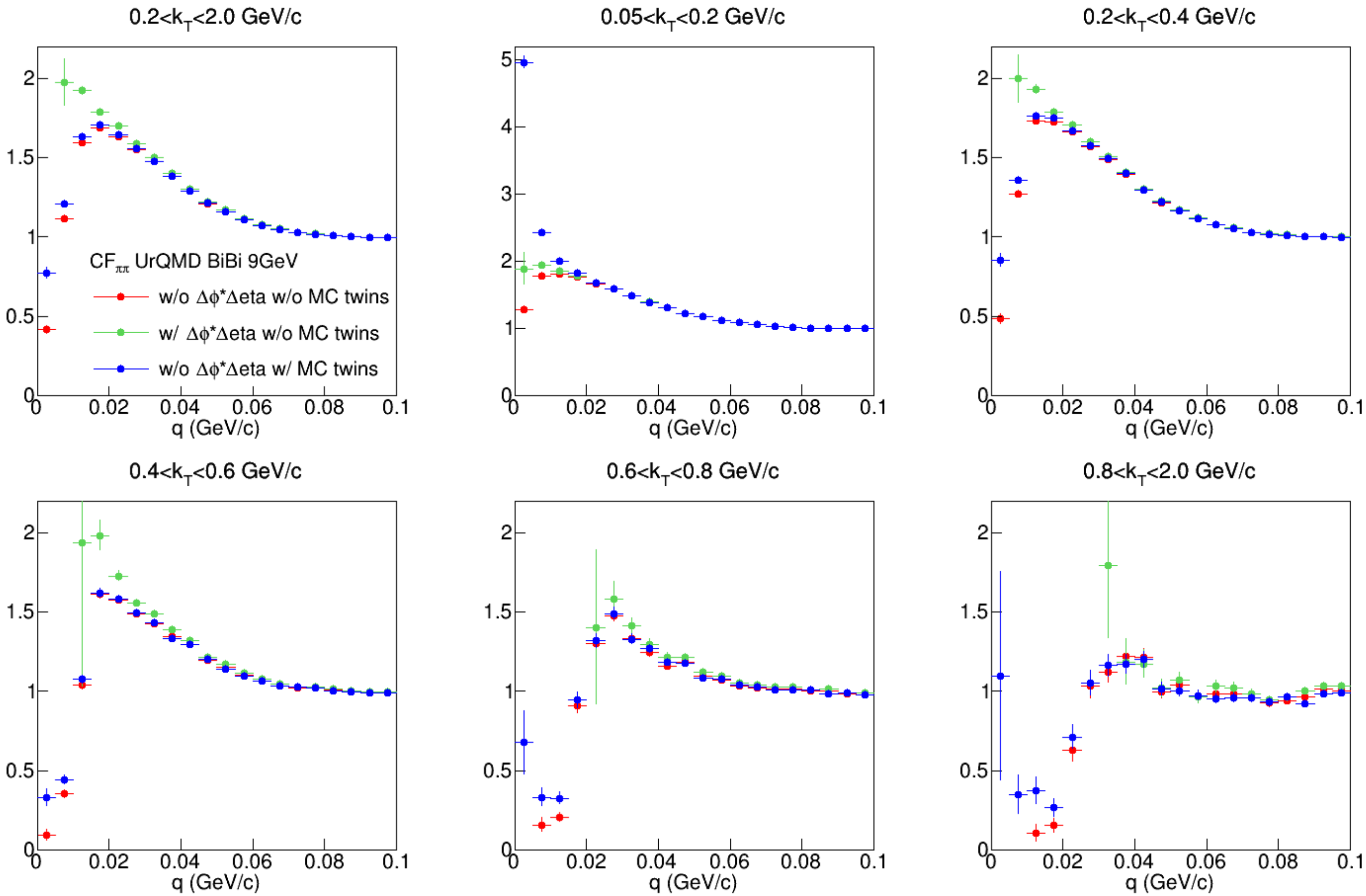
- Kinematic conditions for pions
  $0.05<p_T<2$ GeV/c
  |eta|<1.0

- Nhits TPC > 15
  DCA < 3 cm
  |VertexZ| < 75
  PID : Select poin track by PDG code (tests)
  (Nsigma for pion selections in TPC & TOF = 2)



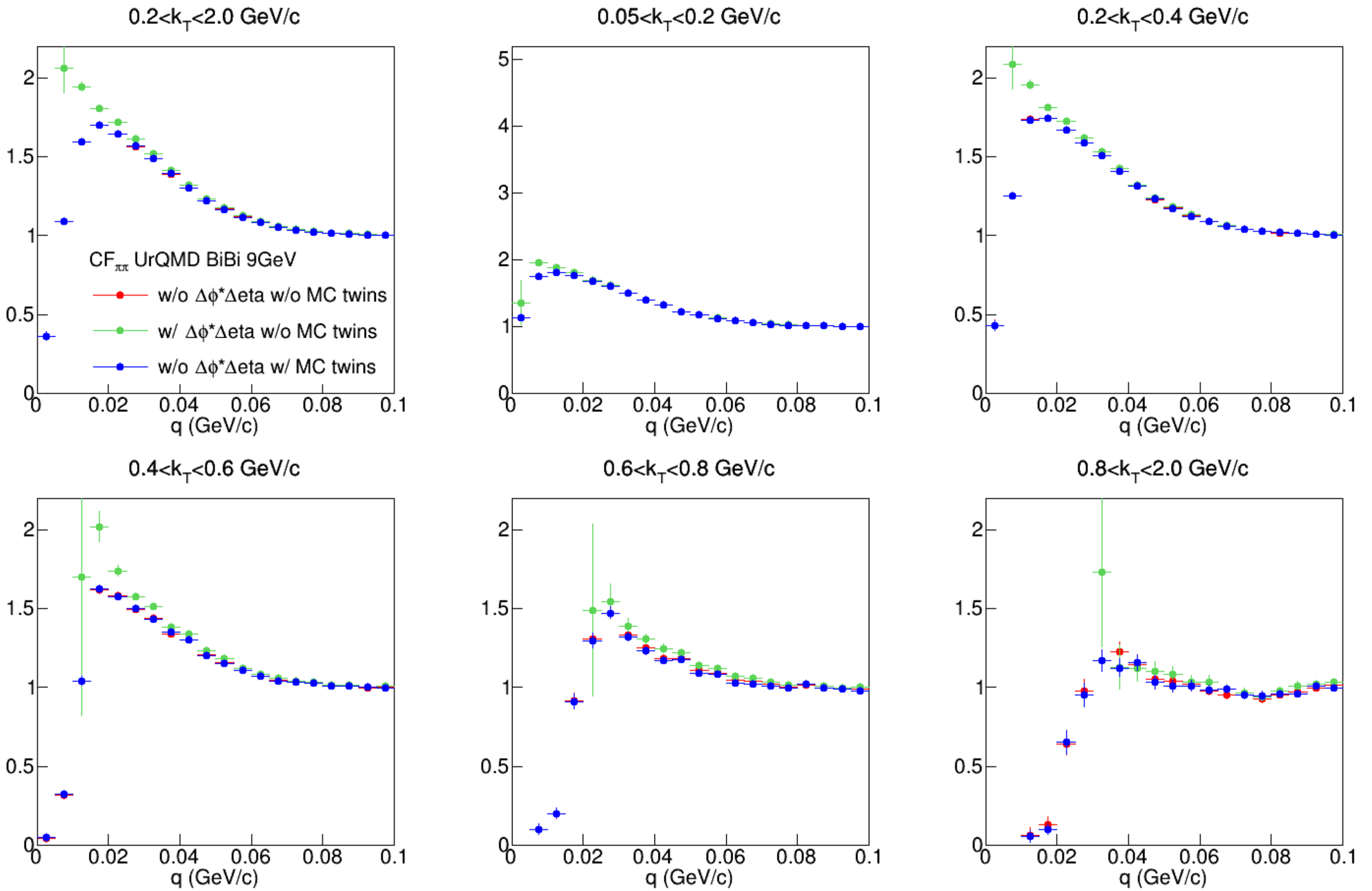
Two-pion CFs versus kT (#hits>15)

- UrQMD BiBi @ $\sqrt{s_{NN}}$=9 GeV
- 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 measure k_T-dependence due to the track-merging effect coming from reconstruction



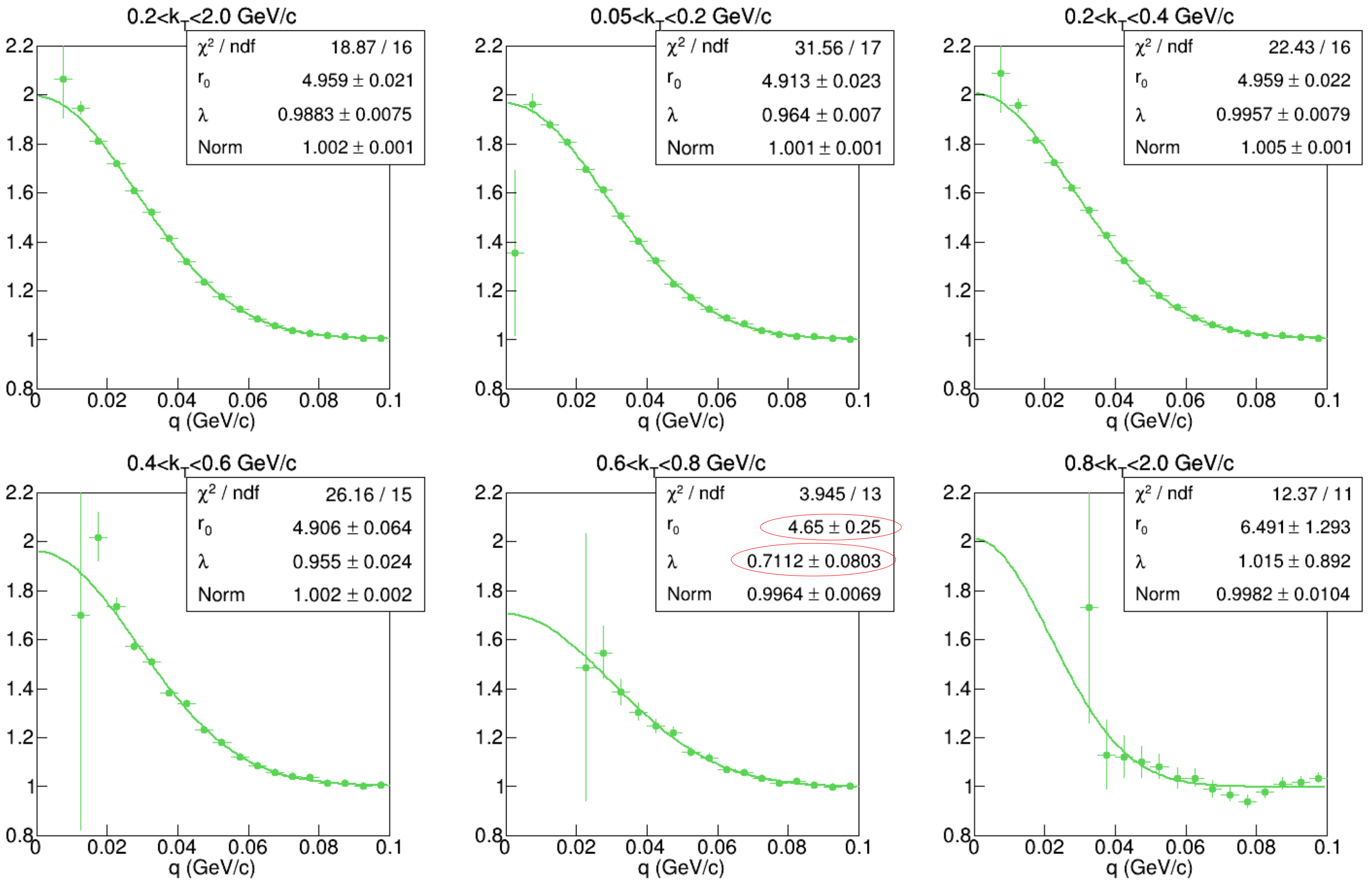
Two pion CFs vs kT (#hits>30)

- Good news: splitting effect disappears starting from number of hits per track is higher 30
- Undesirable two-track effects lead to a dip at low q



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

- Fit QS: $N[1+\lambda\cdot\exp(-q^2r^2_0)]$
- We should get
  $\lambda=1$ and $r_0=5$ fm
- Unfortunately, we can't study high k_T region for now

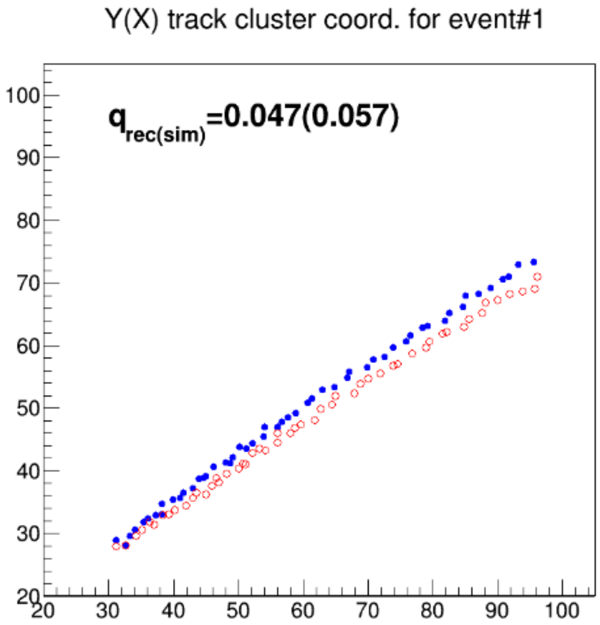


Two-track resolution with BOX generator

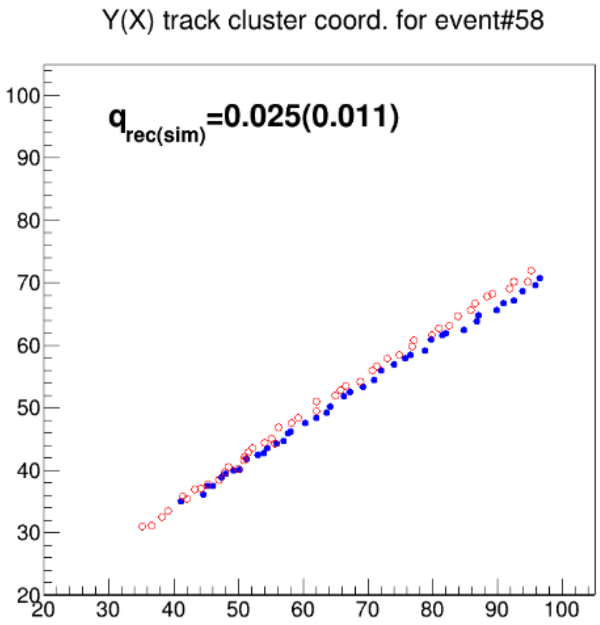
- Look at the simplest case → two π+ tracks with BOX generator:
- FairBoxGenerator* boxGen = new FairBoxGenerator(211, 2);
- boxGen->SetPtRange(0.6, 0.6);//pT=0.25, 0.6, 1.0 GeV/c
- boxGen->SetPhiRange(40, 50);//depends on pT
- boxGen->SetEtaRange(0.,0.); //center of detector theta=90
- // smearing of beam interaction point
- primGen->SetBeam(0.0,0.0,0.1,0.1);//XYcm 1cm 1cm 0.1, 0.1 - standard
- primGen->SetTarget(0.0,24.0);
- primGen->SmearGausVertexZ(kTRUE);
- primGen->SmearVertexXY(kTRUE);

Example of reconstructed global tracks

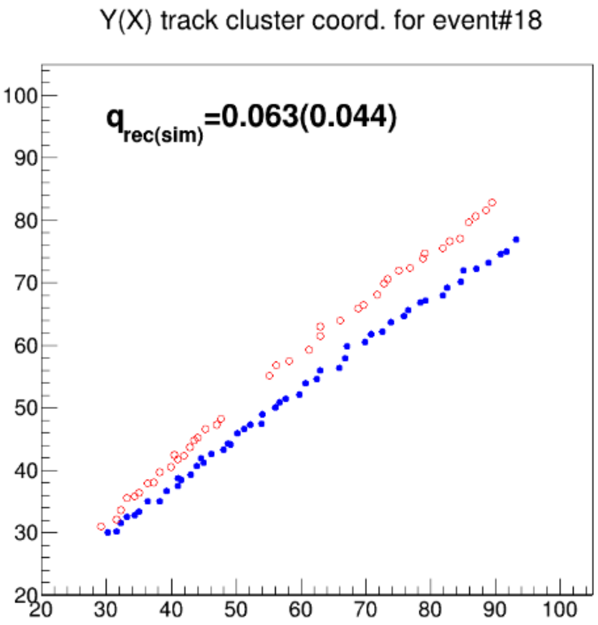
About 50%



About 30%

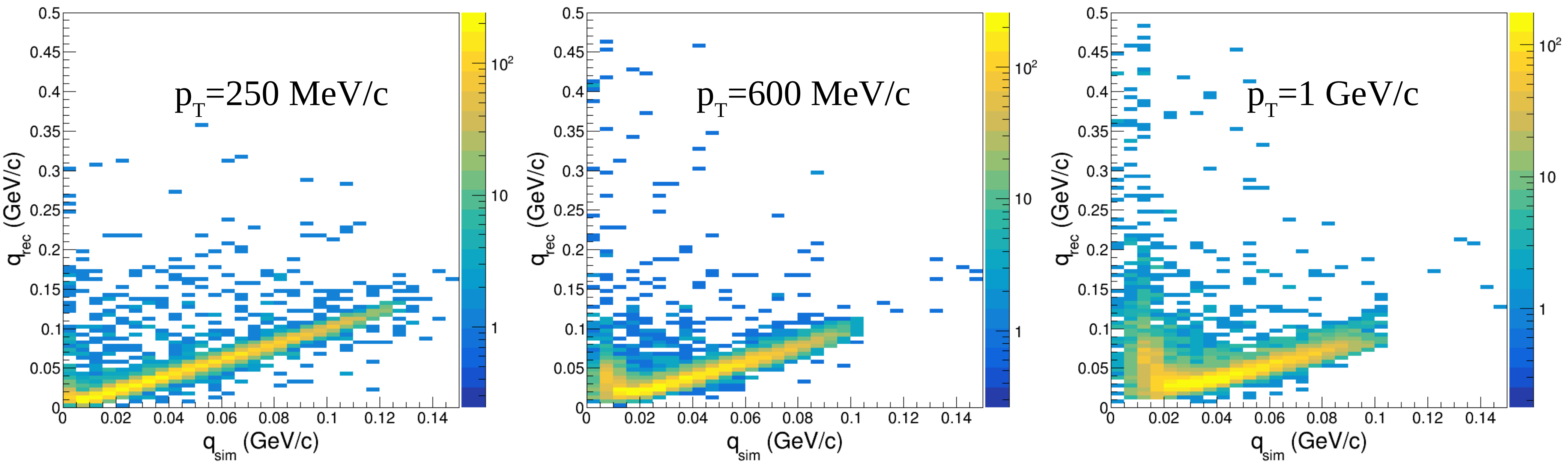


A few %



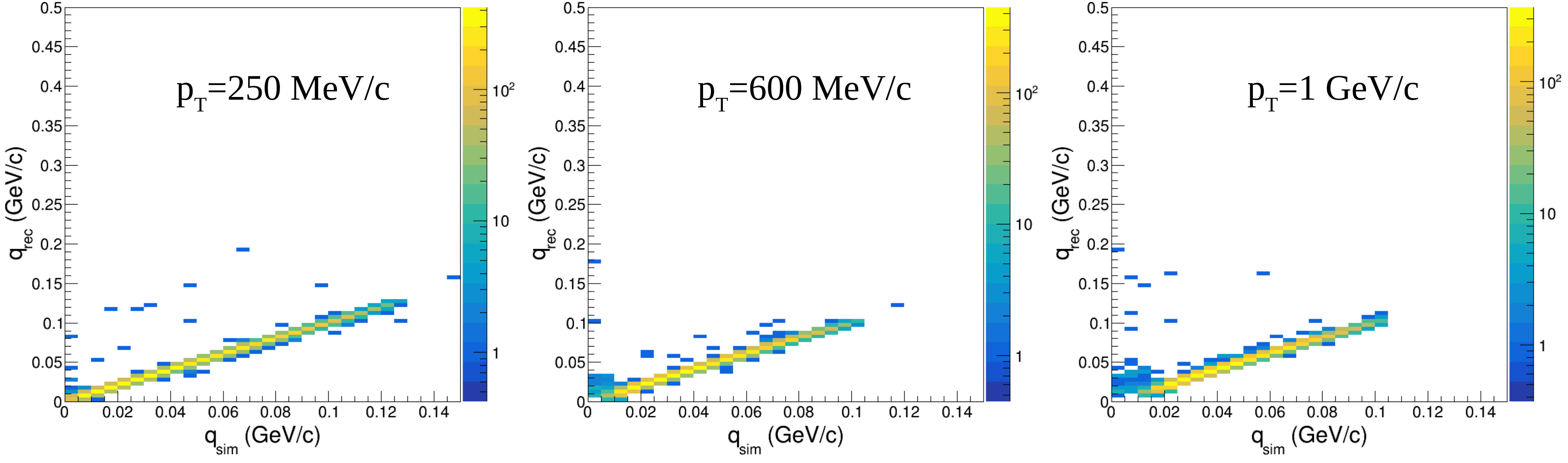
- About 80% of reconstructed track pairs

q_{inv}: reconstructed versus generated (global tracks)



- Global tracks: q_{sim} ~10 MeV/c → q_{rec} ~ 30 MeV/c

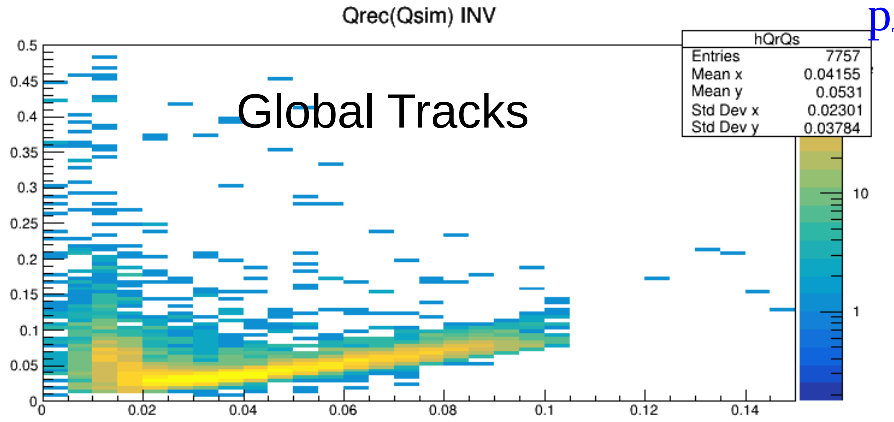
q_{inv}: reconstructed versus generated (primary tracks)

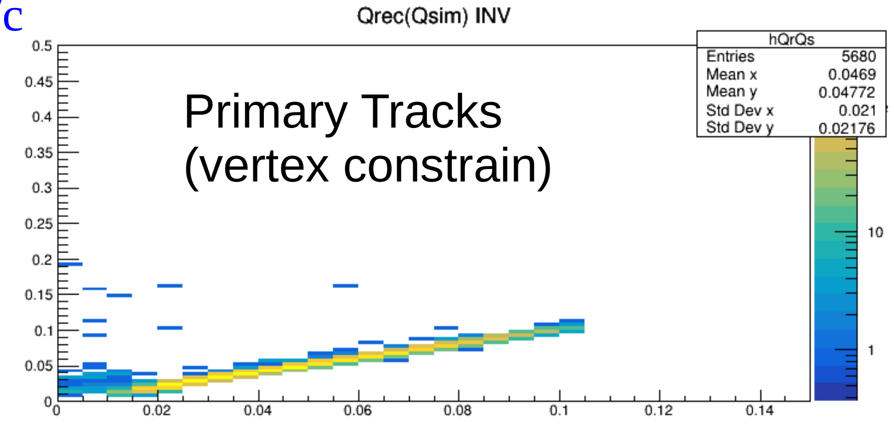


- Primary tracks: q_{sim} ~ 10-20 MeV/c → not reconstructed

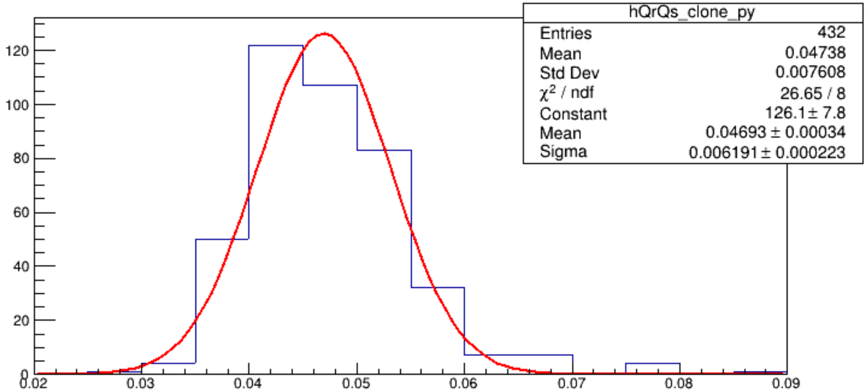
Qinv: reconstructed versus generated (global&primary tracks)

p_T=1 GeV/c

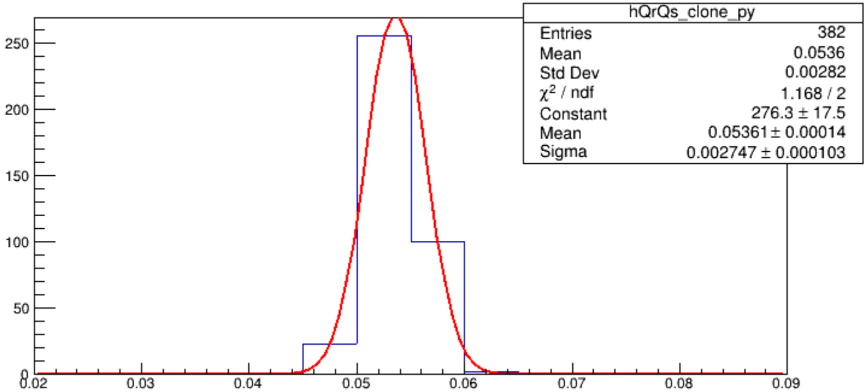




$0.05<Q_{sim}<0.055$ GeV/c

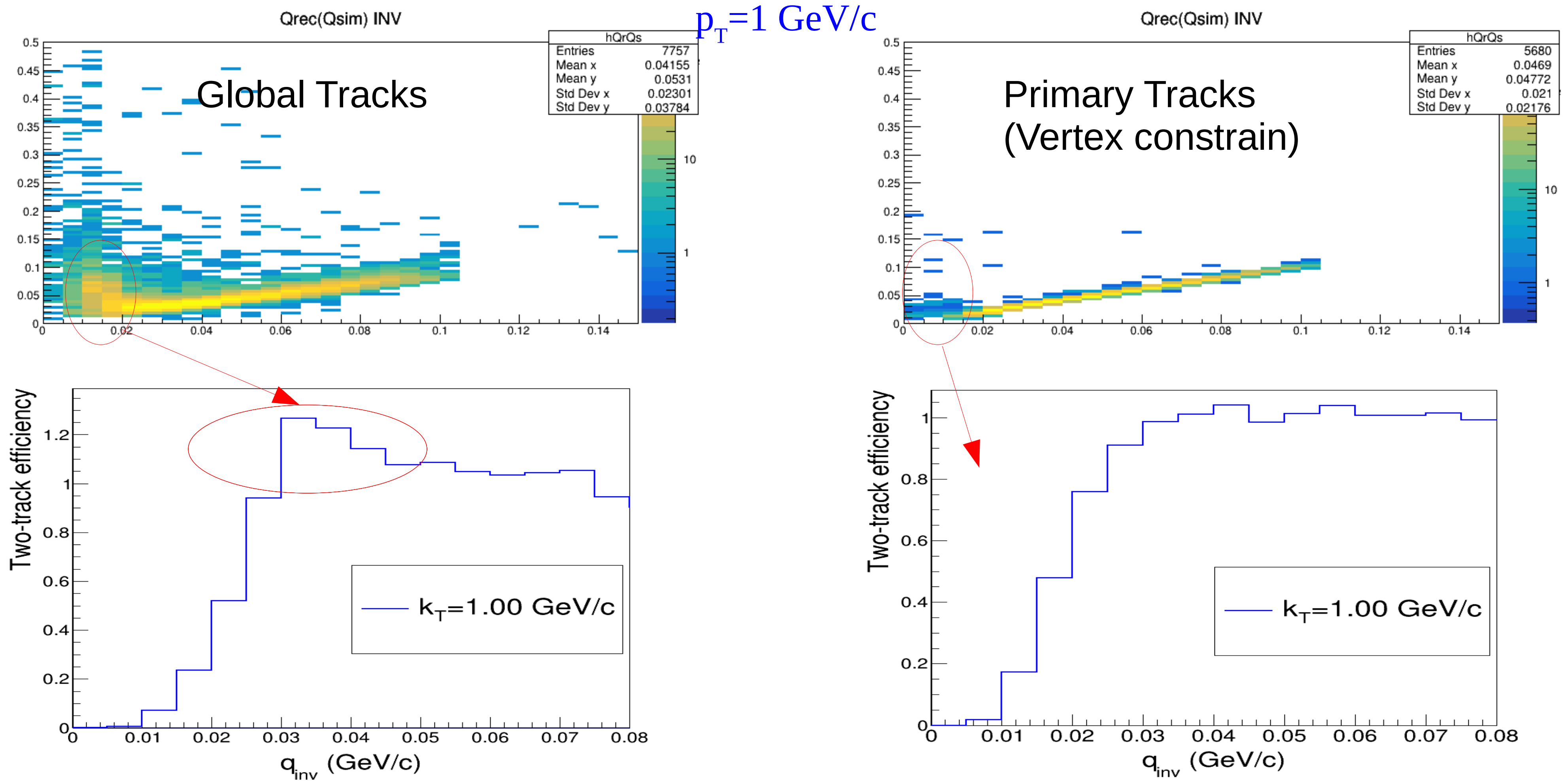


$0.05<Q_{sim}<0.055$ GeV/c

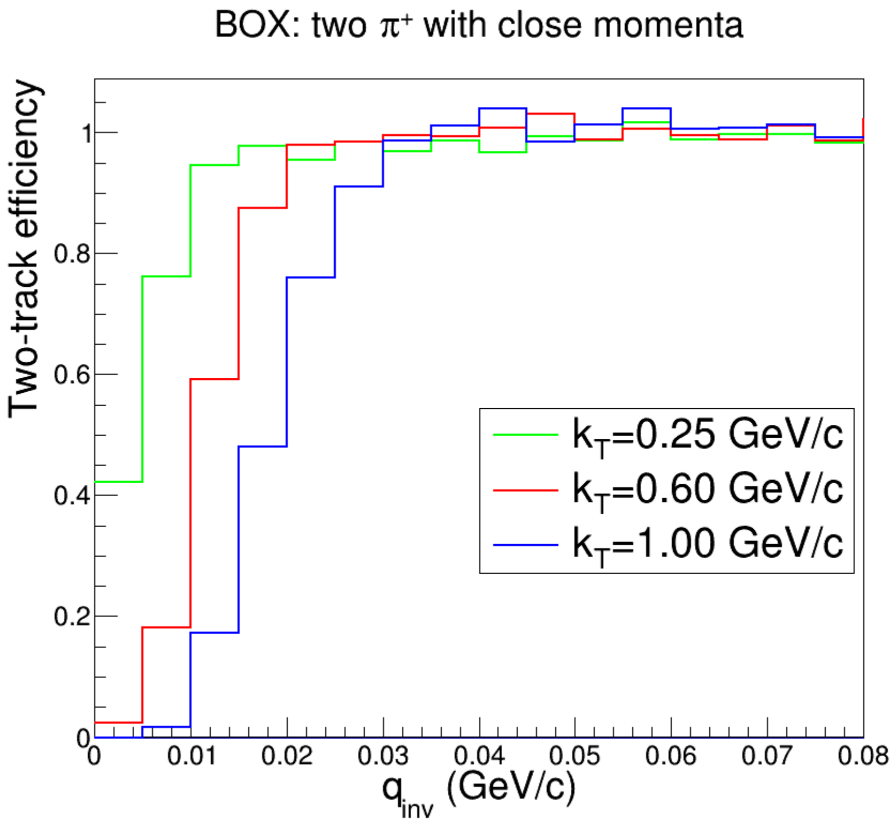


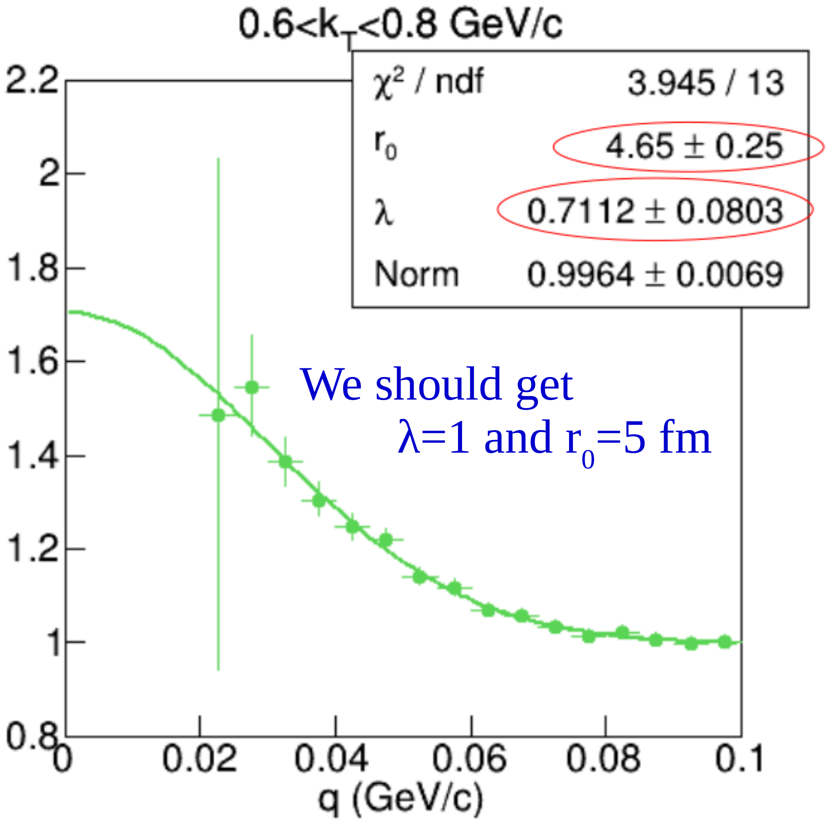
The q-resolution of primary tracks is approximately two times better that than for globals

Qinv: reconstructed versus generated (global&primary tracks)



Two-track resolution efficiency and CF at high k_T





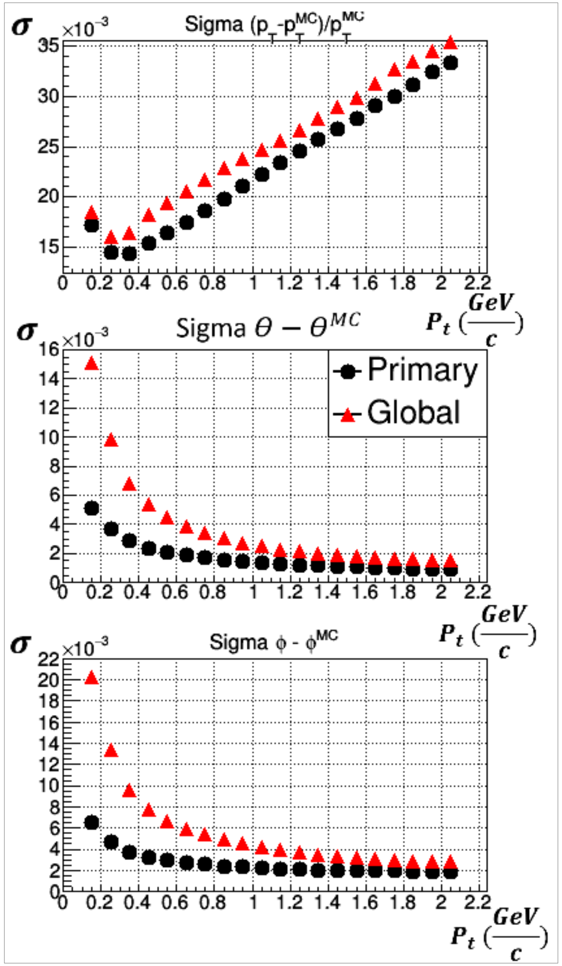
We should get
$\lambda=1$ and $r_0=5$ fm

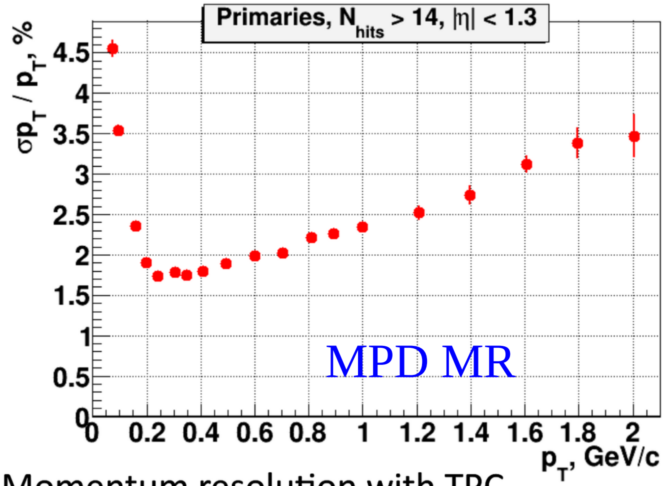
Momentum resolution for primary and global tracks (Egor Alpatov)

- Bi+Bi @ 9 GeV
  UrQMD

- $|\eta| < 1$
  $N_{hits} > 15$

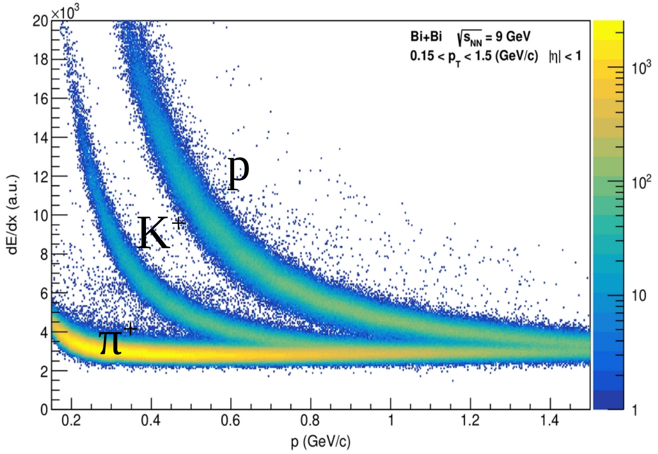
- MR is better with
  vertex constrain

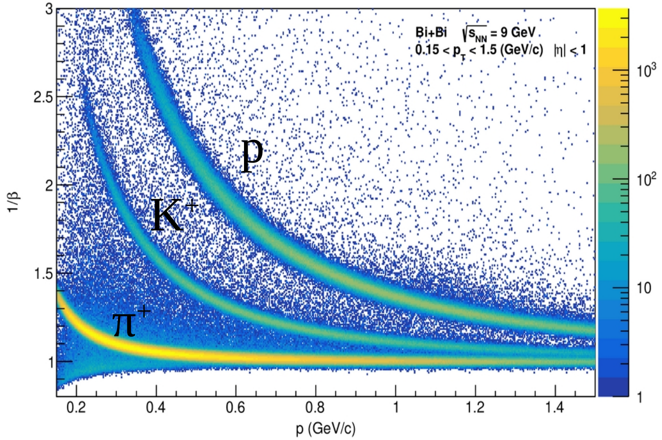


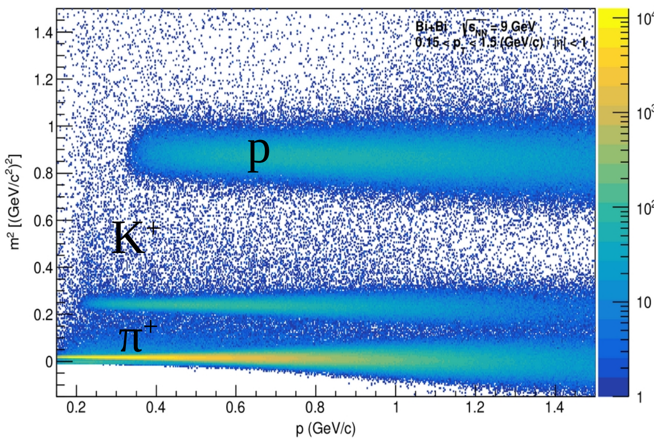


Momentum resolution with TPC

N-sigma PID tests: Aleksey Chernyshov (see Ludmila talk)



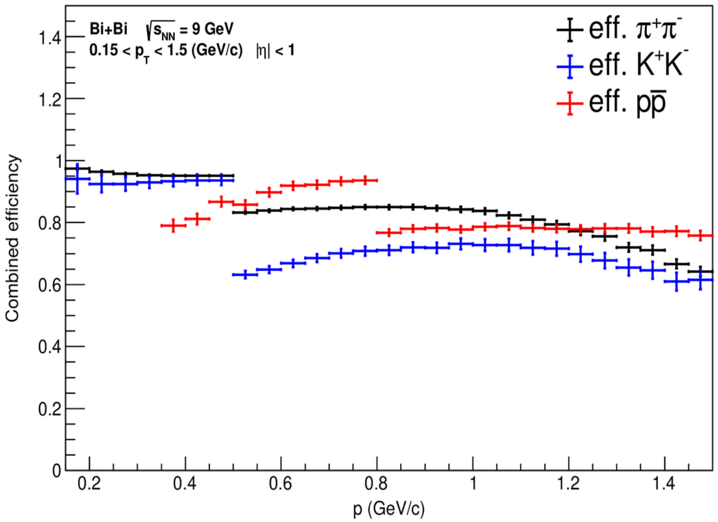




$$\left|\frac{dE/dx_{TPC} - \langle dE/dx \rangle}{\sigma_E} - \mu_E\right| < n_\sigma$$

$$\left|\frac{1/\beta_{TOF} - 1/\beta}{1/\beta} - \mu_\beta\right| < n_\sigma \sigma_\beta$$

$$\left|\frac{m^2_{TOF} - m^2}{m^2} - \mu_m\right| < n_\sigma \sigma_m$$



Factorial moments*

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

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

$\delta y = \Delta y / M$

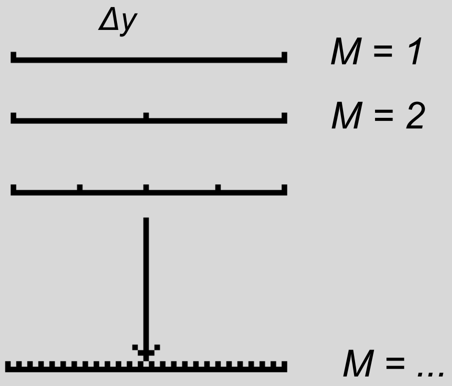
M — number of bins

Δy — size of mid rapidity window

N — number of particles in Δy

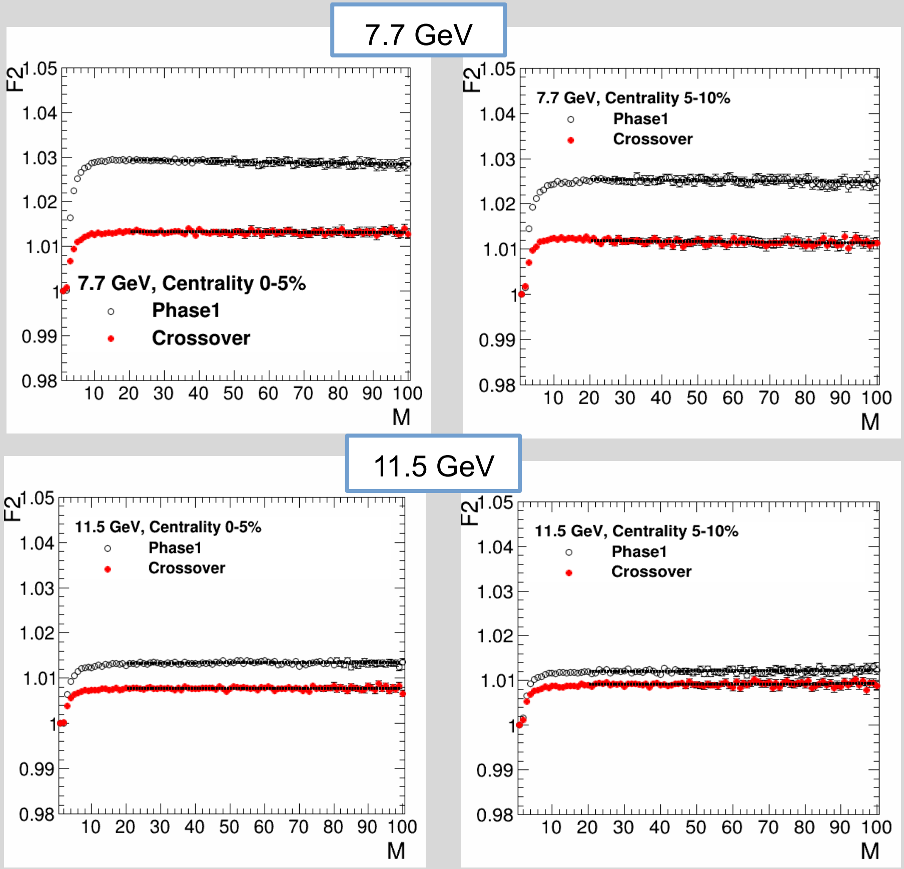
k_j-the number of particles in bin j

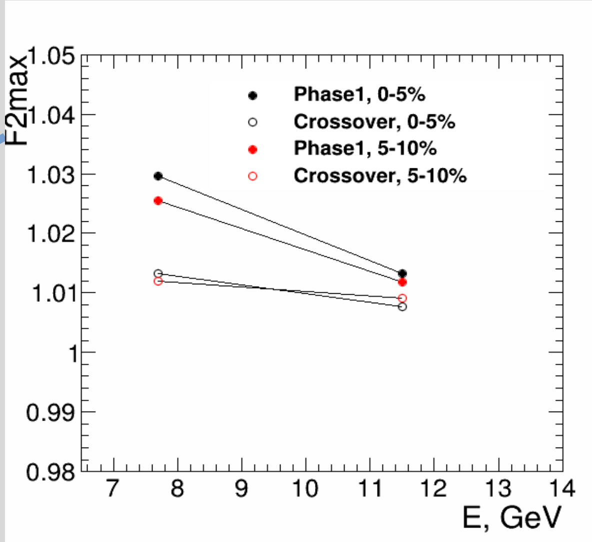
<u>*Note:*</u> there is a set of definitions of moments and cumulants.



* Olga Kodolova and Maria Cheremnova

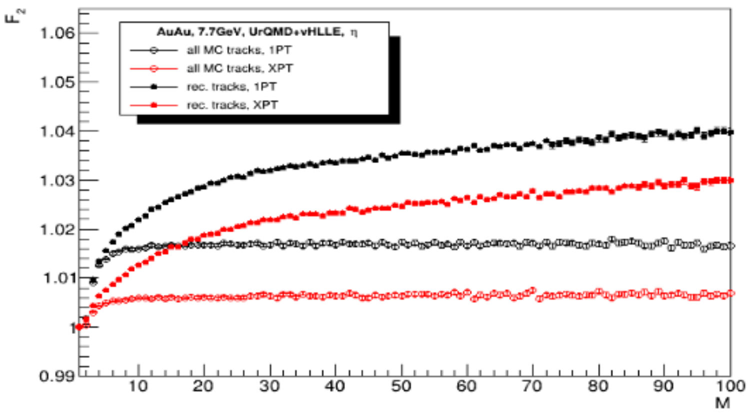
Au-Au, UrQMD+vHLLE: generator information

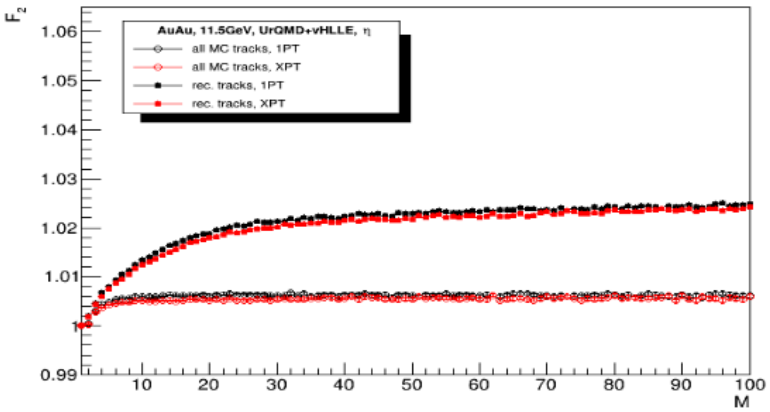




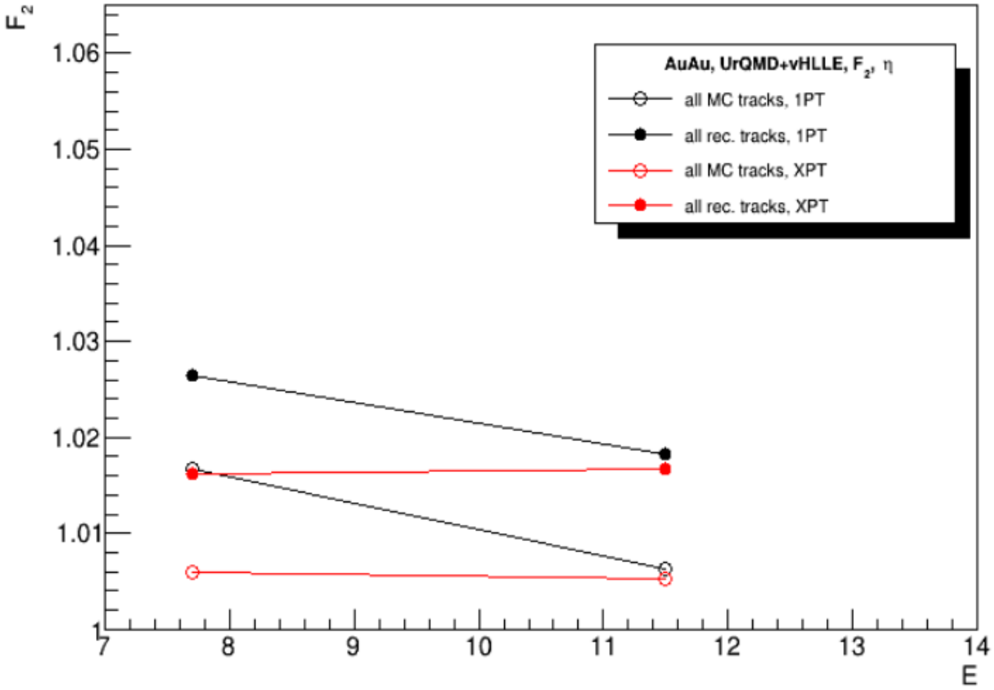
- Different energy dependence is expected for Crossover and 1st order phase transition
- There is a mild dependence on centrality for 1st order phase transition

Factorial moments: pseudorapidity instead of rapidity





Factorial moments: generated vs reconstructed tracks



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

Conclusions

- The vHLLE model shows that it is necessary to explore a wide range of the pair's transverse momentum
- Since the femtoscopy signal is located at small relative momenta,

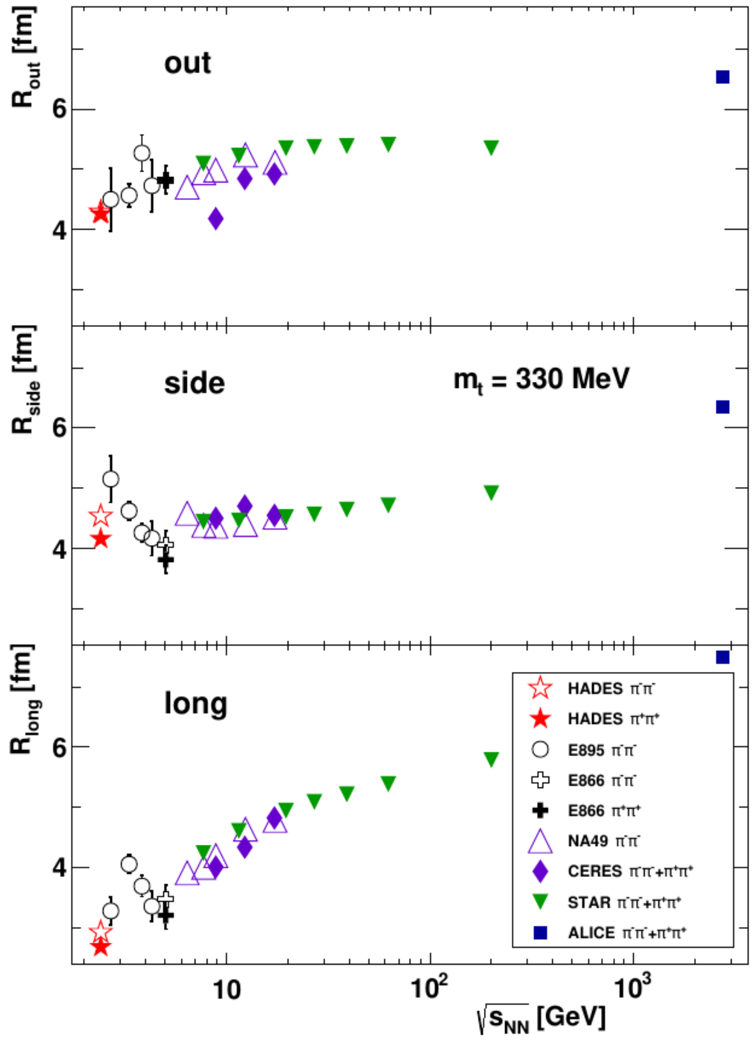
  it is necessary to study the two-track effects in detail
- Global tracks change the shape of the CF → primary tracks should be used instead of global ones
- Two-track inefficiency effect at high kT of pairs is seen with simple BOX generator
- The momentum resolution is better for tracks with vertex constrain as well as the two-track efficiency
- The n-sigma PID method is under study. Results look promising.
- Factorial moments: the pseudorapidy instead of rapidity helps with identification problem
- Please, see Ludmila and Maria talks for details

Thank you for your attention!

Backup

Motivation

- **<u>Femtoscopy allows one:</u>**
  - 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
  - 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



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:

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

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 1XP
  → XPT size smaller than 1XP