Femtoscopy in MPD

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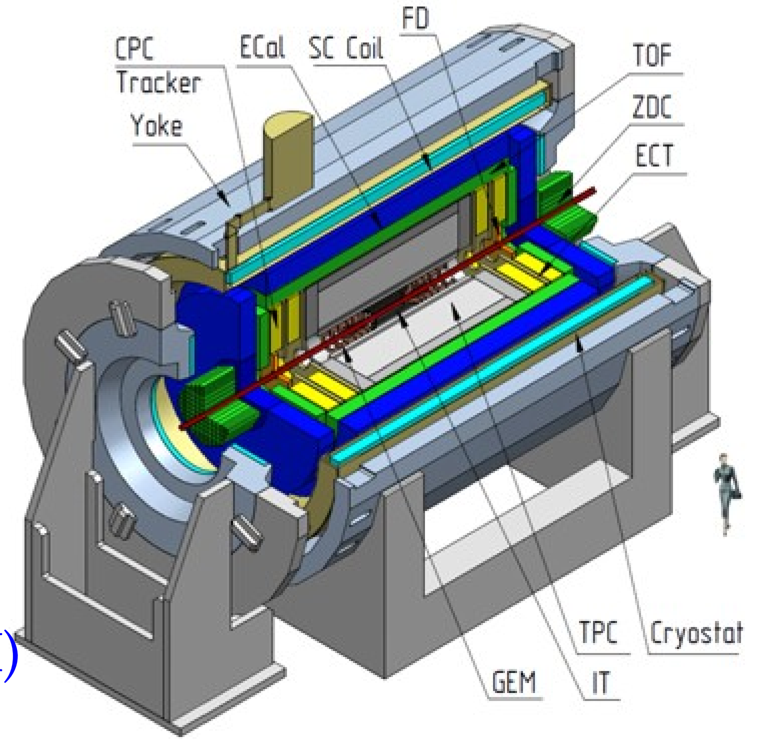
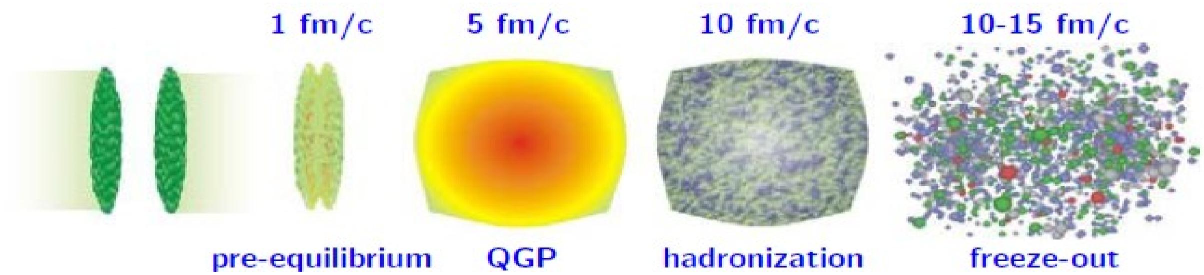


Outline

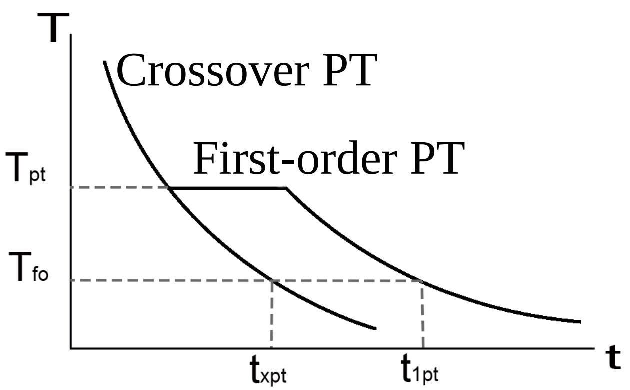
- Femtoscopy & Motivation
- Analysis details
- Influence of single- and two-track resolution on Correlation Functions (CFs)
- Momentum resolution studies
- Two-tracks effects studies

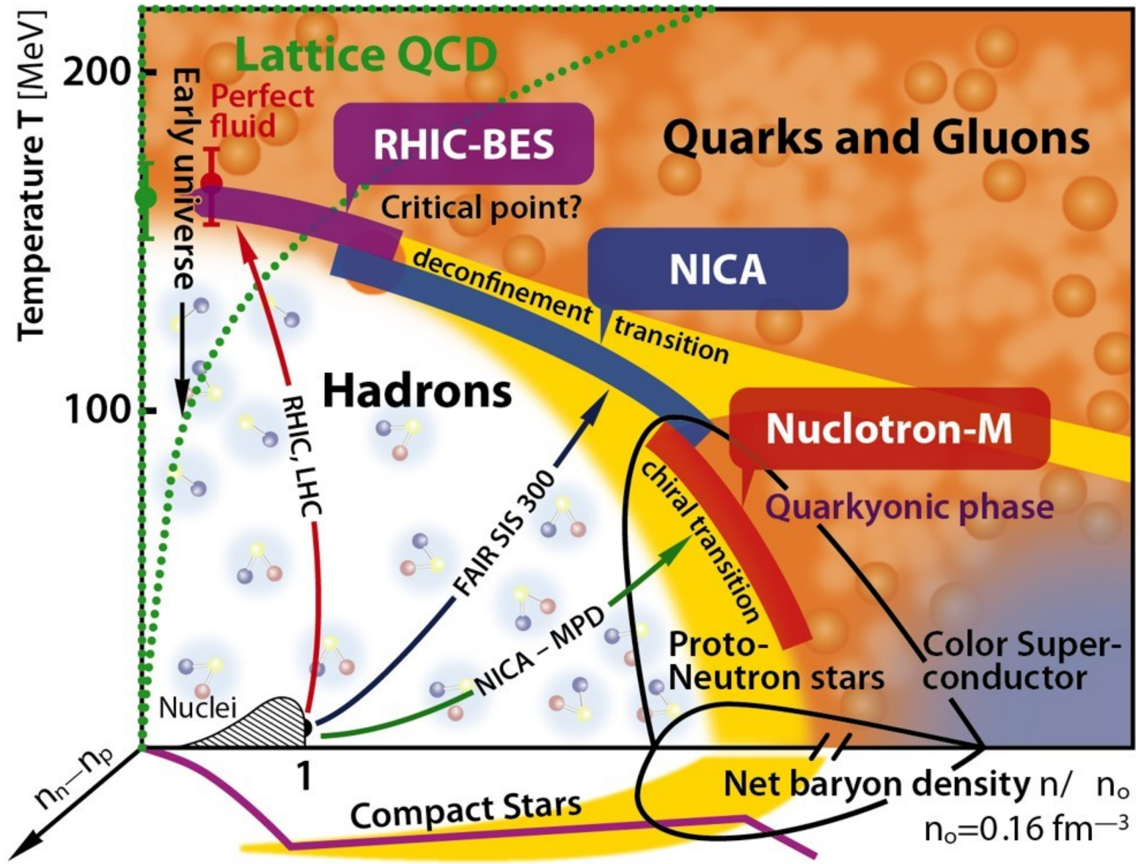
Motivation: Phase diagram QCD

- Crossover phase transition (XPT) to QGP occurs at RHIC & LHC energies



- The 1st-order phase transition (1PT) to QGP occurs at lower energies (?)

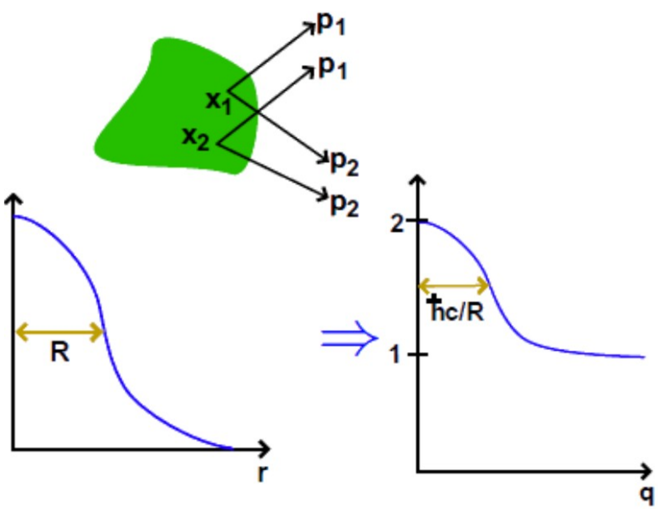




It is important to extract space-time information -> femtoscopy

- BES RHIC ($\sqrt{s_{NN}}$=3-39 GeV)
- NA61@SPS (E_{lab}=10-158 AGeV);
- projects: CBM@FAIR (GSI), **MPD and BM@N @ NICA (JINR)**

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

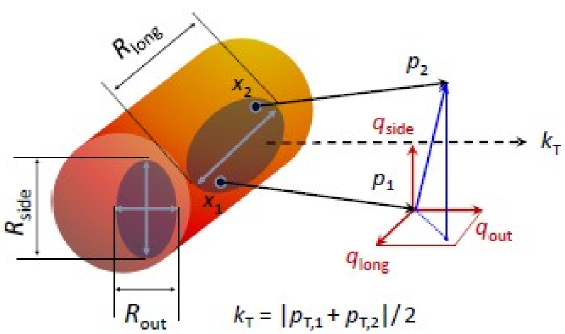
$B(q)$ – reference distribution built by mixing different events

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

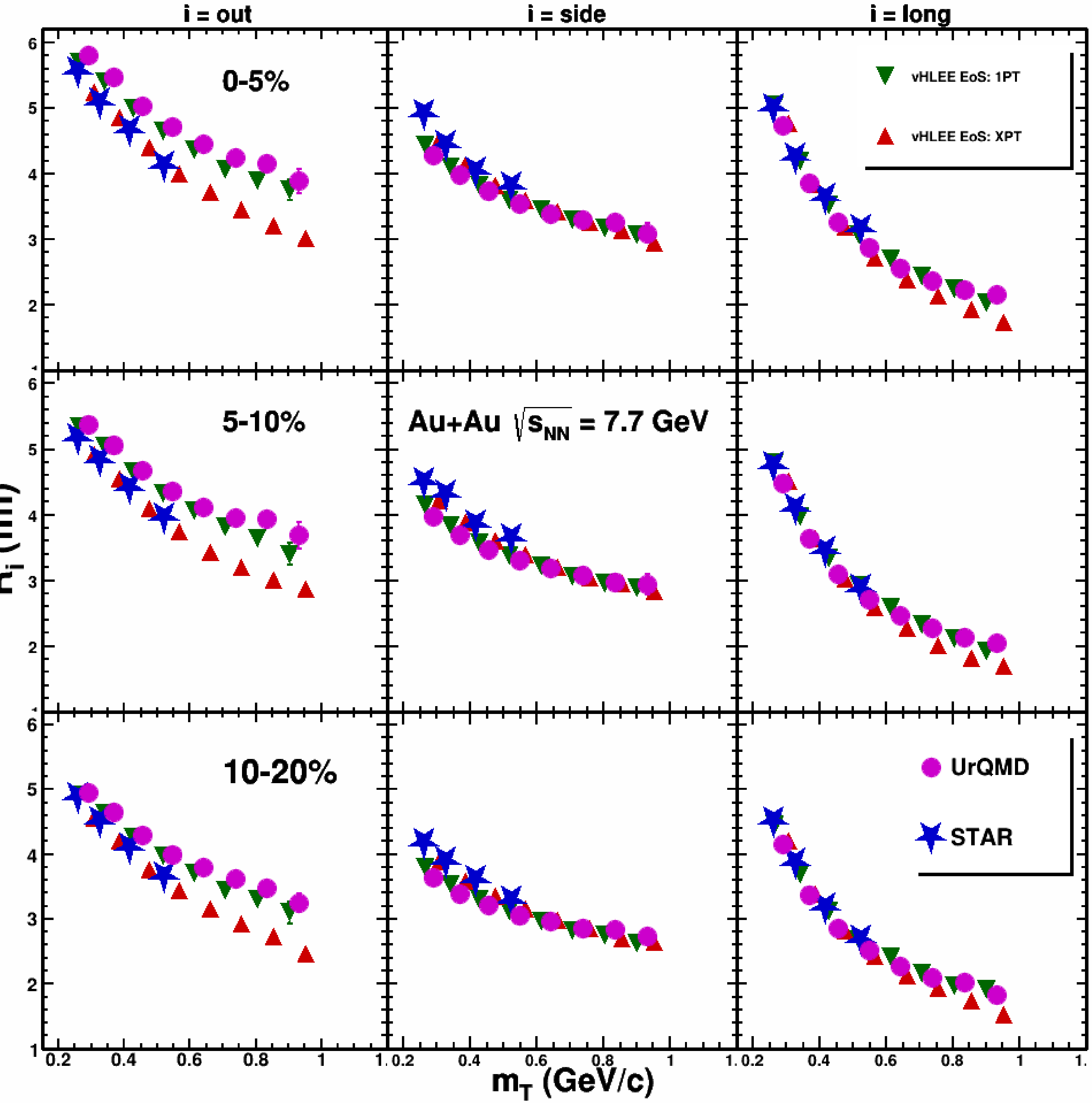
3D analysis:

R_{side} sensitive to geometrical transverse size.

R_{long} sensitive to time of freeze-out.

R_{out} / R_{side} sensitive to emission duration.

Pion radii with the vHLLE and UrQMD models

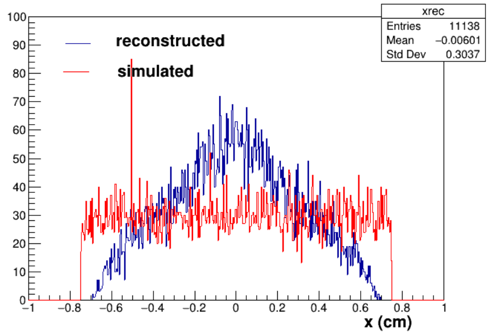


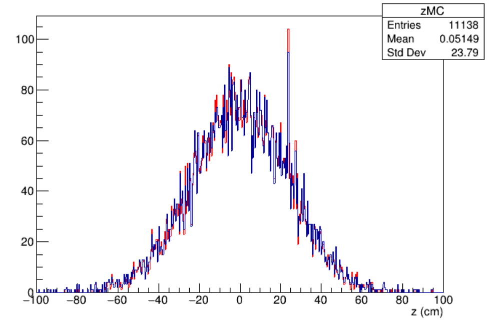
- Au+Au, $\sqrt{s_{NN}}$ = 7.7 GeV
- **It is important to study femtoscopic radii dependence in the broad $k_T(m_T)$ range**
- Radii decrease with m_T → radial flow
- Increase size with increasing centrality → simple geometric picture of collisions
- Cross over EoS describes $R_{out}(m_T)$ better than the 1st-order phase transition
- **$R_{out,long}$ (1PT) > $R_{out,long}$ (XPT)**
- **Radii obtained from UrQMD are close to those from vHLLE with the 1PT**
- The similar trends are observed for Au+Au $\sqrt{s_{NN}}$ = 11.5 GeV

Analysis of reconstructed data in MPD

Details of pion analysis

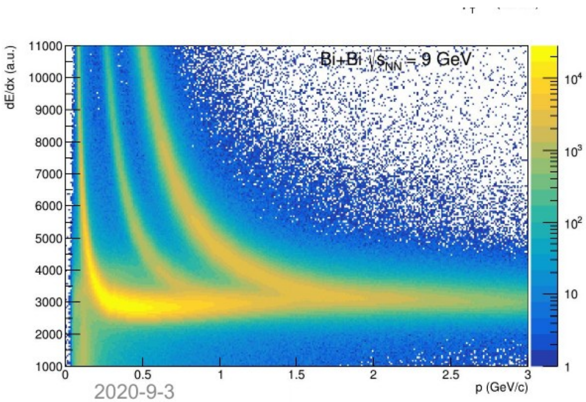
- Dataset (UrQMD → Geant4 → reconstruction) :
  Bi+Bi $\sqrt{s_{NN}}$ = 9 GeV:
  /eos/nica/mpd/sim/data/MiniDst/dst-BiBi-09 GeV-mp07-20-pwg3-250ev/BiBi/ 09.0GeV-0-14fm/UrQMD/

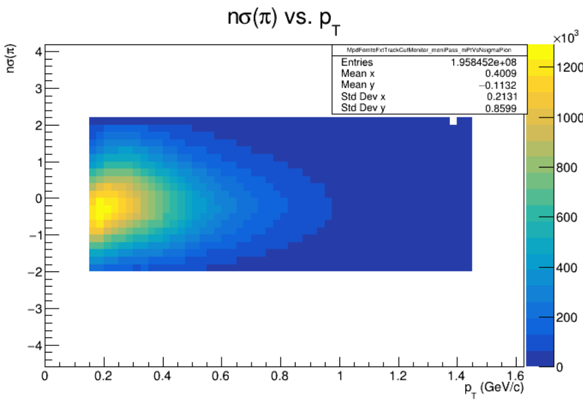




- **Track Cuts:**
  0.15 < pT < 1.5 GeV/c
  |η|<1.0
  Nhits(TPC) > 15
  DCA < 5 cm

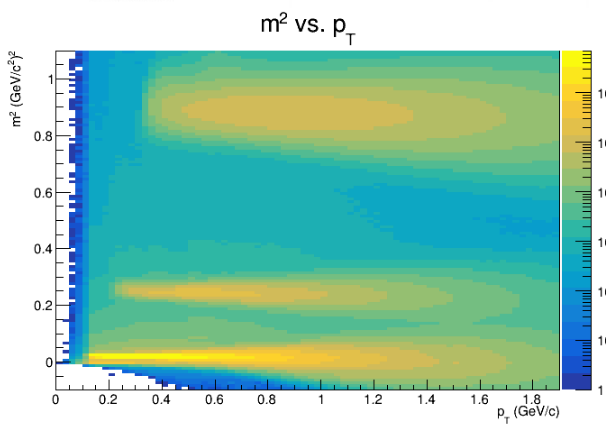
Pions: 2*2.0 · 10^{8}

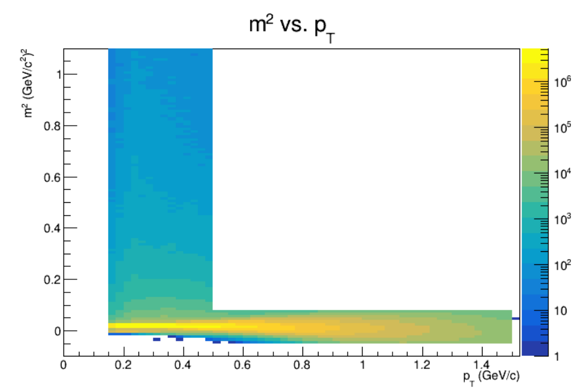




- **PID**
  TPC+TOF,
  - TOF starts at p > 0.5 GeV/c
  - Pion nSigma for TPC+TOF identification **: (-2., 2.)**

  -0.05<M^{2}<0.08 (GeV/c^{2})





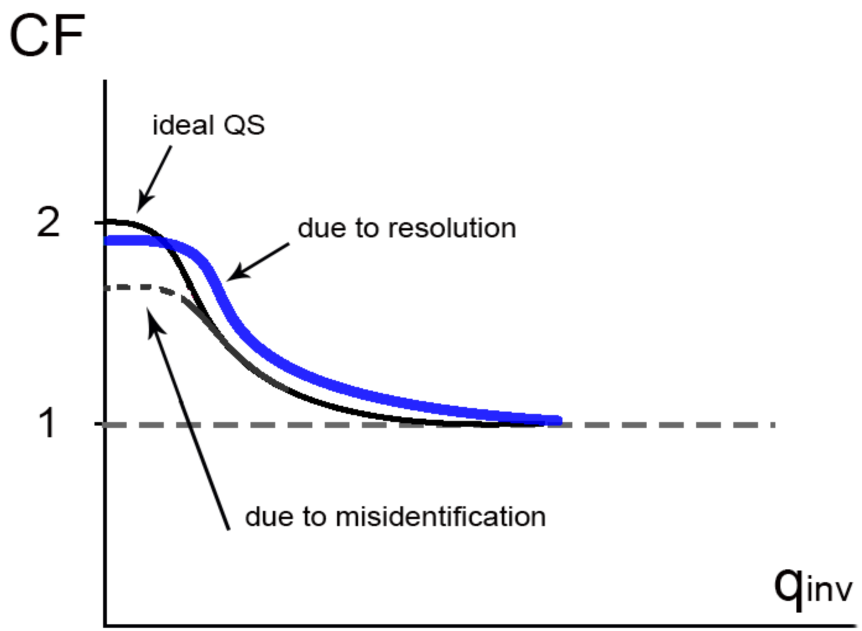
Influence of track reconstruction on CF

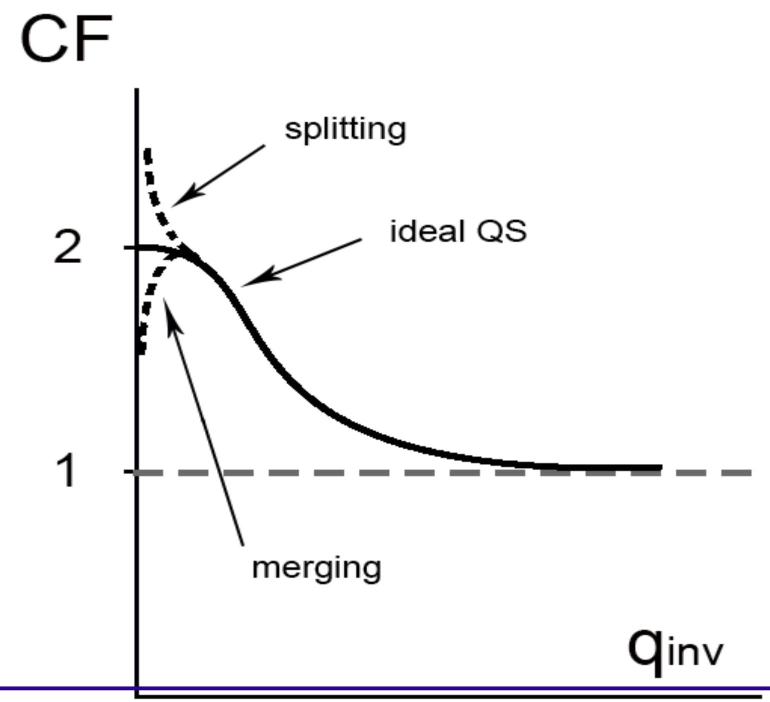
Track reconstruction influences the shape of CF

- <u>Single-track effects</u>:
  - The momentum resolution effect smears CF, making it wider an extracted radii smaller
  - CFs should be corrected for single-track momentum resolution

- <u>Particle misidentification</u>:
  - Influences only λ parameter of CF, radii do not change
  - CF should be corrected by pair purity. Pair purity is obtained from particle purity

- <u>Two-track effects</u>:
  - Track splitting (one track is reconstructed as two)
  - Track merging (two tracks are reconstructed as one)
  - These effects are studied and the specific pair cuts that will be applied in the femtoscopic analysis

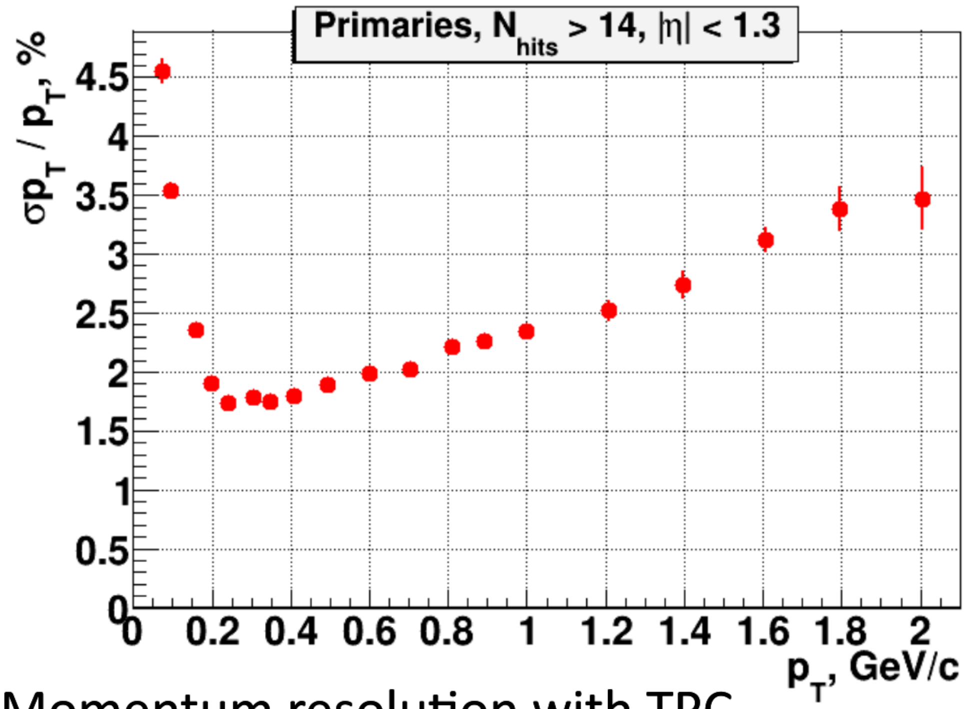




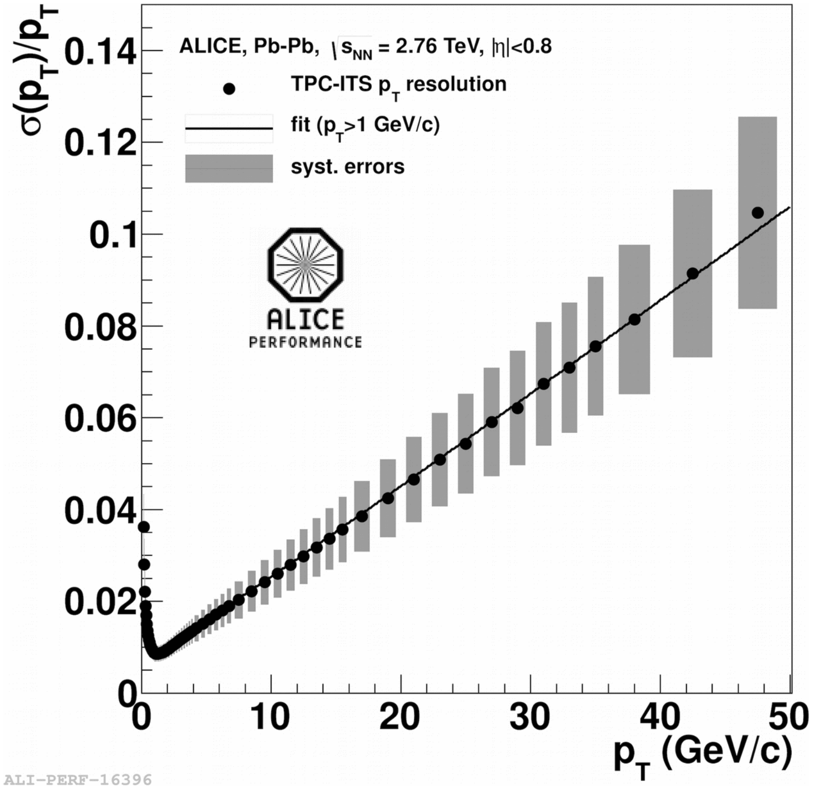
Single-track effects in femtoscopy

– Single-track momentum resolution smears two-particle correlation function

Single-track momentum resolution in MPD



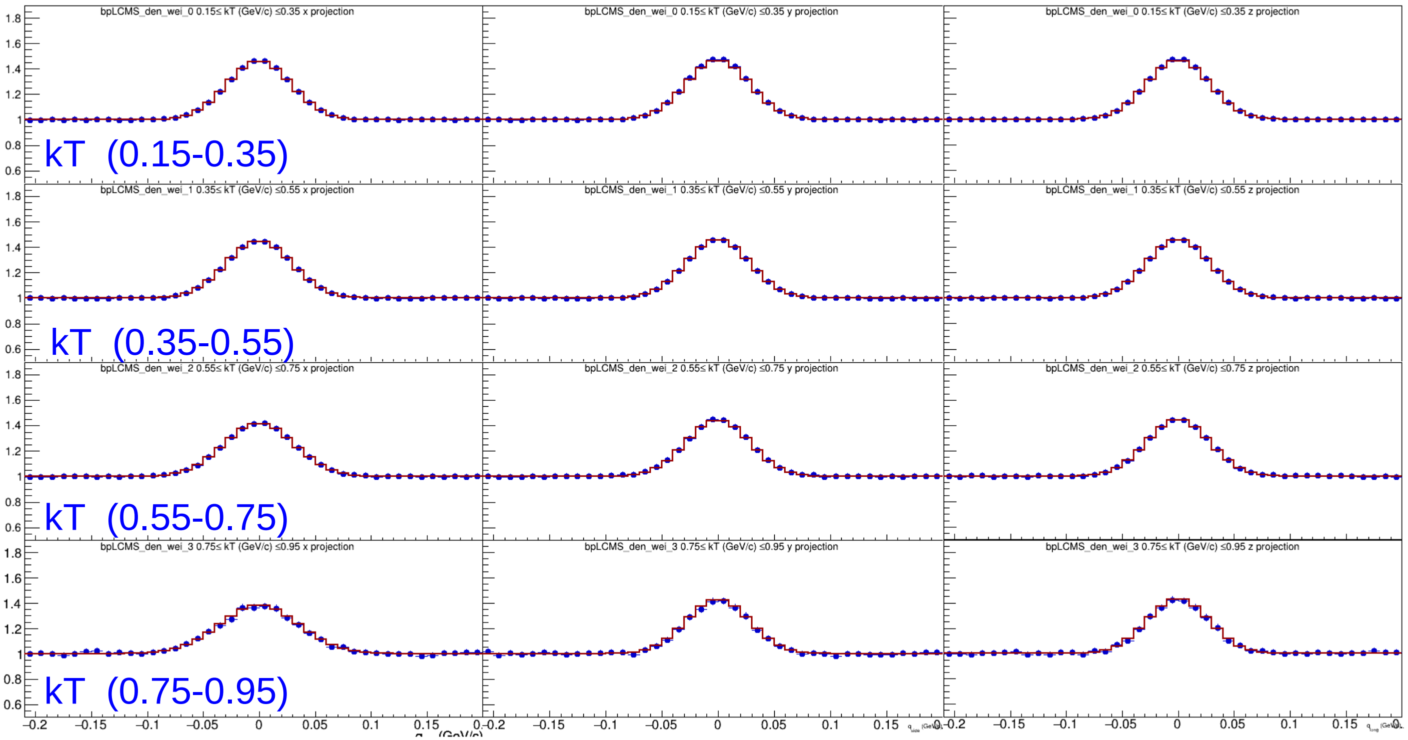
Momentum resolution with TPC

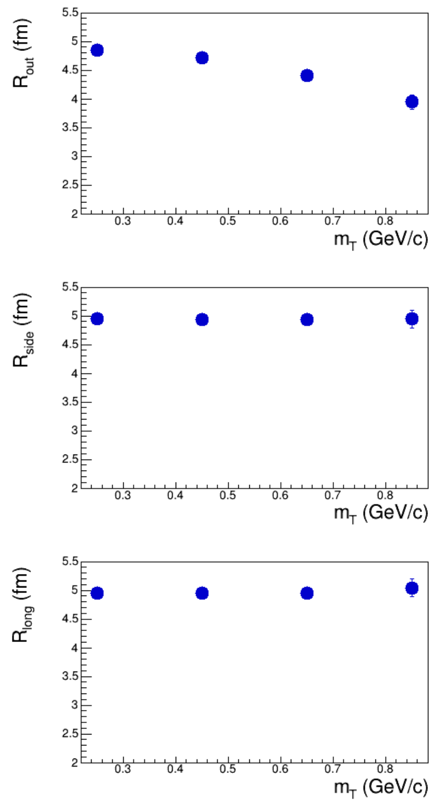


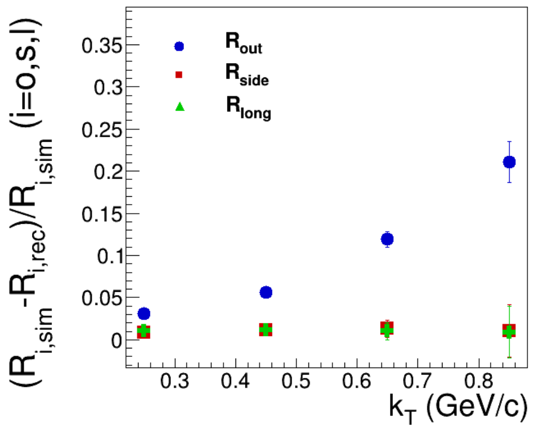
Influence of momentum resolution on 3D CFs in LCMS

3D Gauss in LCMS **Rosl = 5 fm** ; **pdg1=211 & pdg2=211**
k_T (0.15-0.95) GeV/c & 4 k_T bins

CF = (Dmixed, weight=QS)/ Dmixed







CFs become wider with increasing k_T

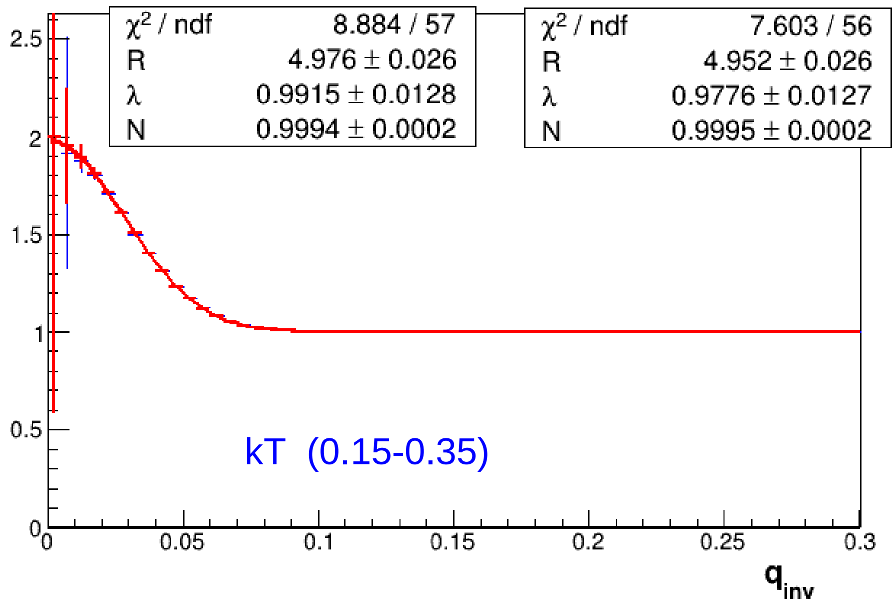
Resolution effect on Rout is strong at large k_T

Calculations were performed for each (Ro,Rs,Rl) combination.When projecting on one axis the other two components were required to be within **(-0.04,0.04)** GeV/c.

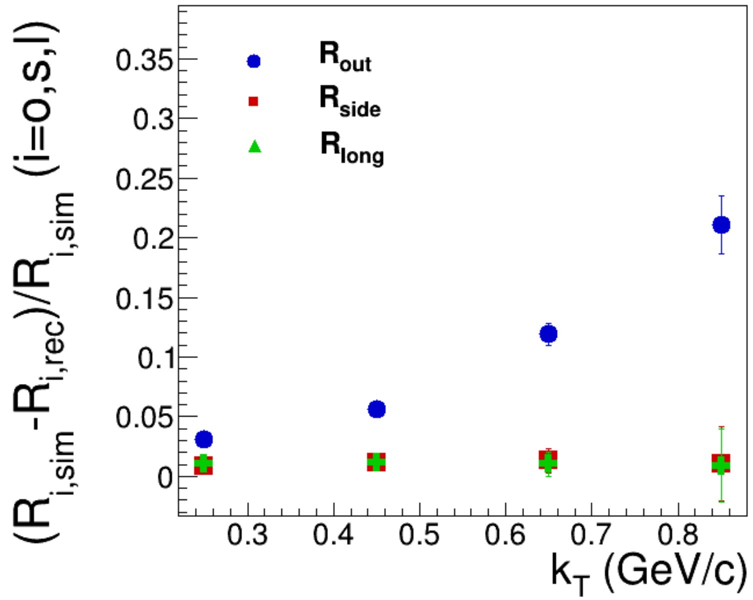
Influence of momentum resolution on 1D/3D CFs

1D Gauss in PRF **Rinv = 5 fm**
k_T (0.15-0.95) GeV/c & 4 k_T bins

CF = (Dmixed, weight=QS)/ Dmixed



MPD



ALICE TDR

K_t range (MeV/c)	Resolution (r.m.s.) (MeV/c)			
	q_{inv}	q_o	q_s	q_l
$100 < p_t < 300$	0.95	2.70	0.34	0.95
$300 < p_t < 600$	0.99	3.62	0.40	1.12
$p_t > 600$	1.17	6.33	0.62	1.42

(a)

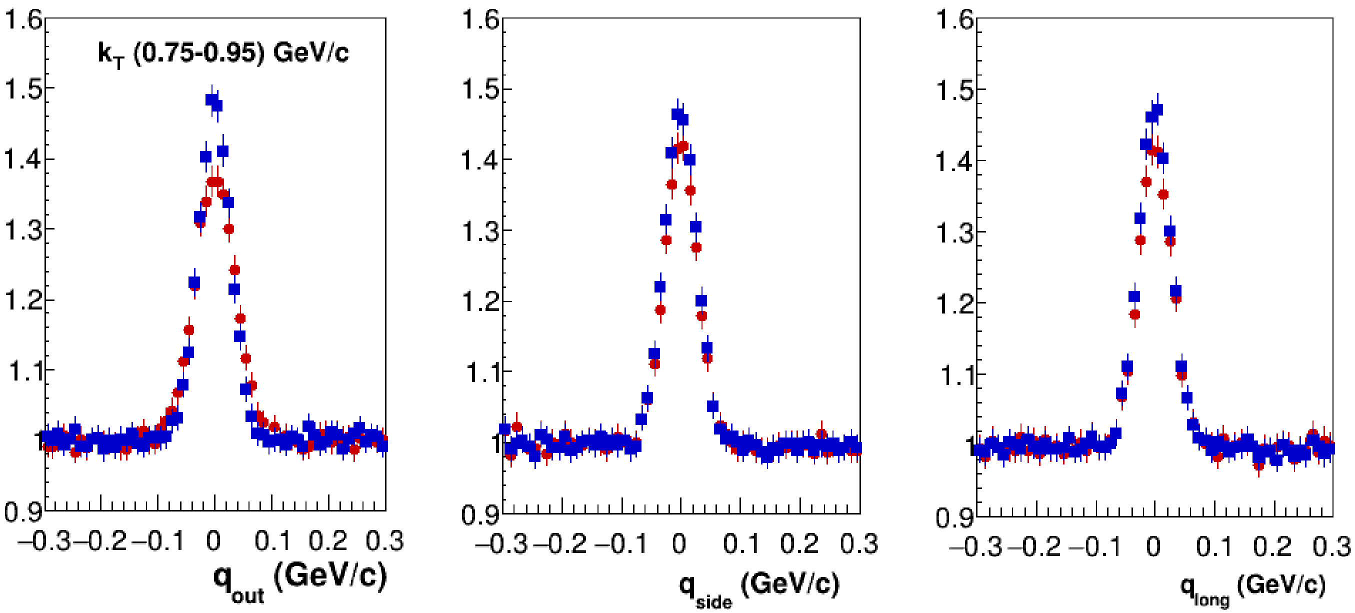
- Resolution effects for Rinv, Rside, Rlong are small
- Resolution effect for Rout increases linearly with k_T.
- It is understandable because "out" component depends linearly on p_T
- Similar effect is observed in ALICE data (effect in MPD ~1.5 times worse than in ALICE)

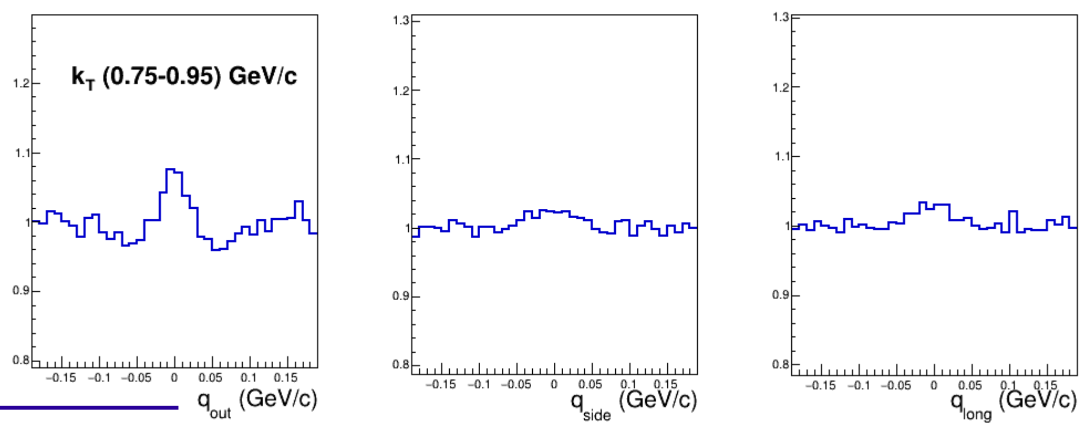
Momentum resolution correction for 3D CFs in LCMS

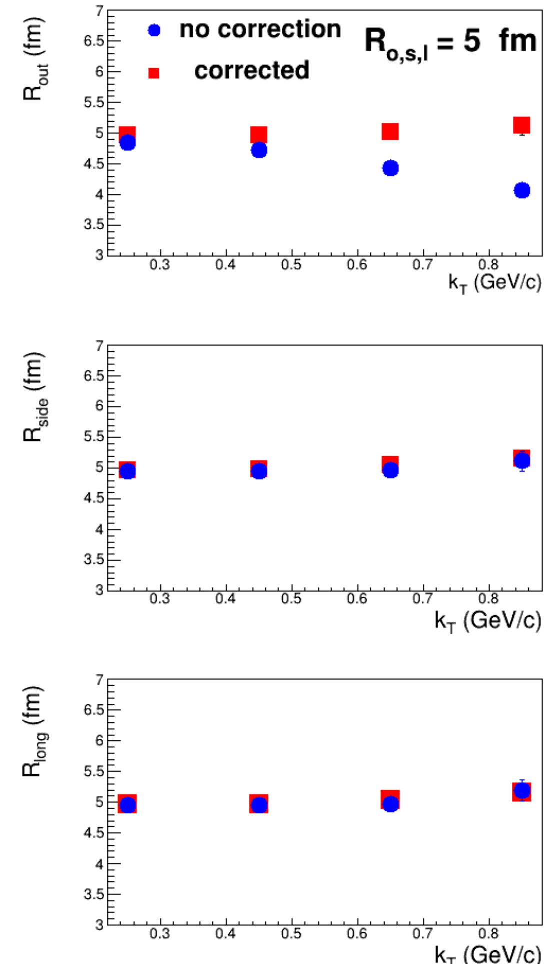
3D Gauss in LCMS **Rosl = 5 fm** ; **CF = (Dmixed, weight=QS) / Dmixed**

Correction factor (q_{osl}) = CF(q_{osl}simulated) / CF(q_{osl}reconstructed)

Example k_T (0.75-0.95) GeV/c







Resolution effect on Rout is strong at large kT, but it is possible to correct CFs by momentum resolution

Two-track effects in femtoscopy

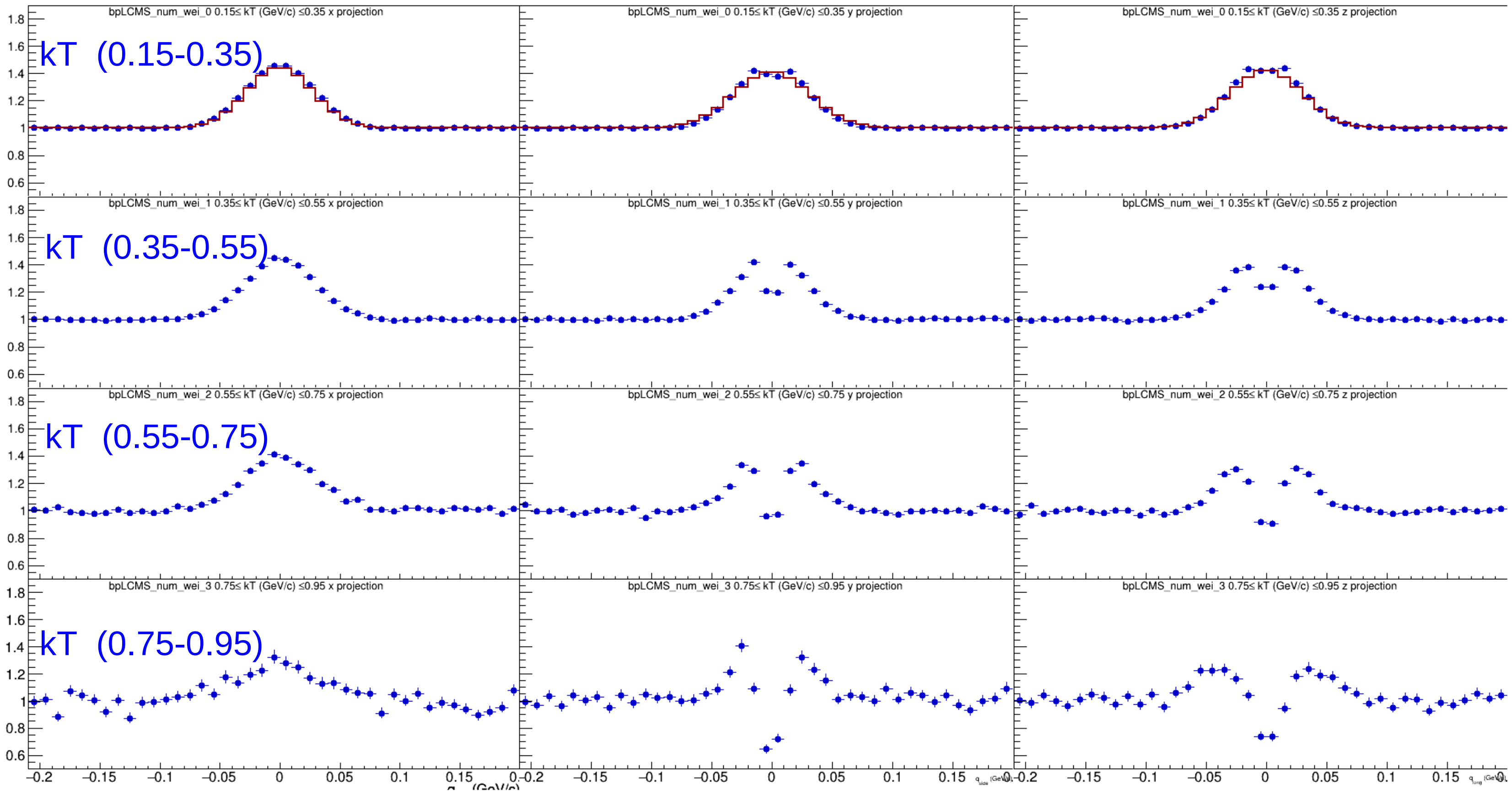
- *Track merging (two tracks are reconstructed as one)*
- *Track splitting (one track is reconstructed as two)*

Two-track effects study 3D CF in LCMS: No TTC

TTC – two-track cuts

Gauss in LCMS : Rosl = 5 fm

k_T (0.15-0.95) GeV/c & 4 k_T bins – **CF = (Nsame, weight=QS)/ Dmixed**

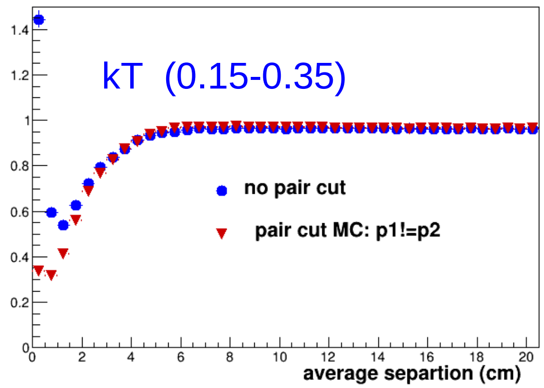


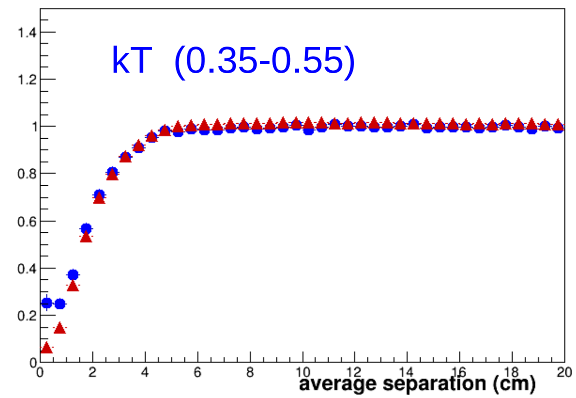
Projections of the three-dimensional ππ−correlation functions. When projecting on one axis the other two components were required to be within (-0.04,0.04) GeV/c.

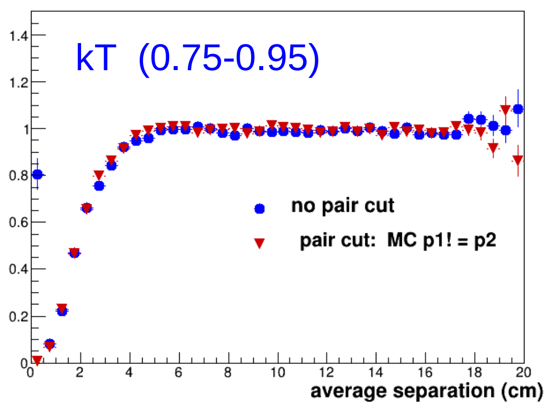
Strong “merging-like” effect increases with k_T

No TTC: average separation CF & CF(q_{inv})

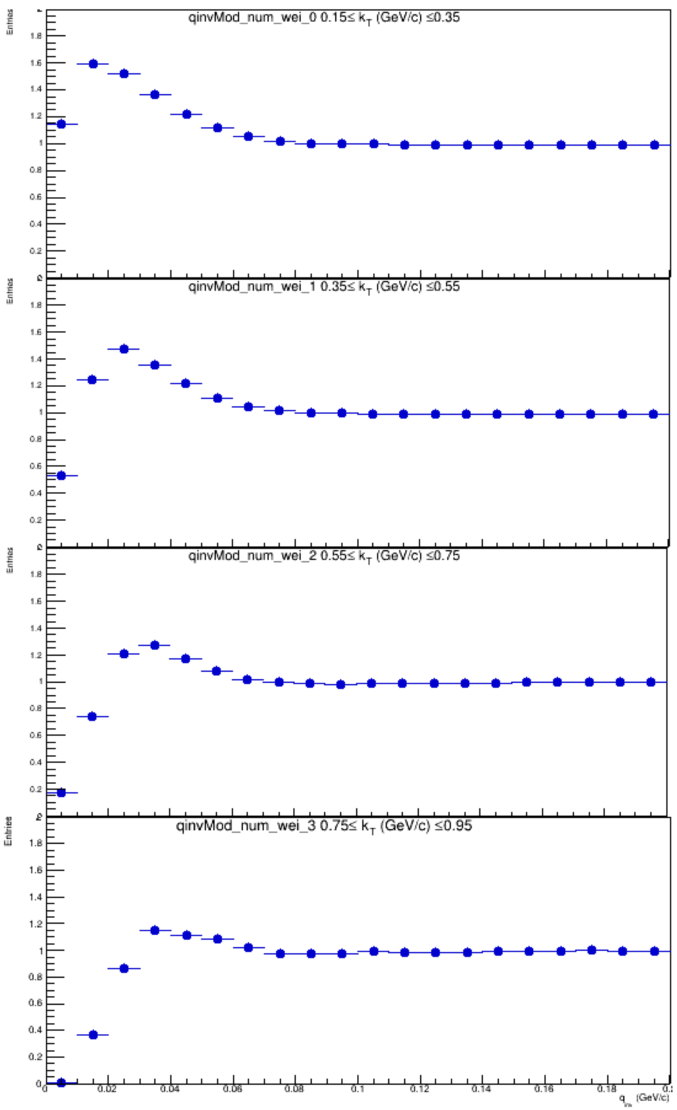
CF = Nsame/ Dmixed







- Combination of two effects: track splitting at small av. separation bins and track merging
- Detailed study of split tracks has shown: 1) doublets of tracks with same id, same pMC and prec 2) one MC track is reconstructed as two (usual splitting)
- If both reasons are excluded by artificial cut MC: p1!=p2 splitting disappears (red triangles).

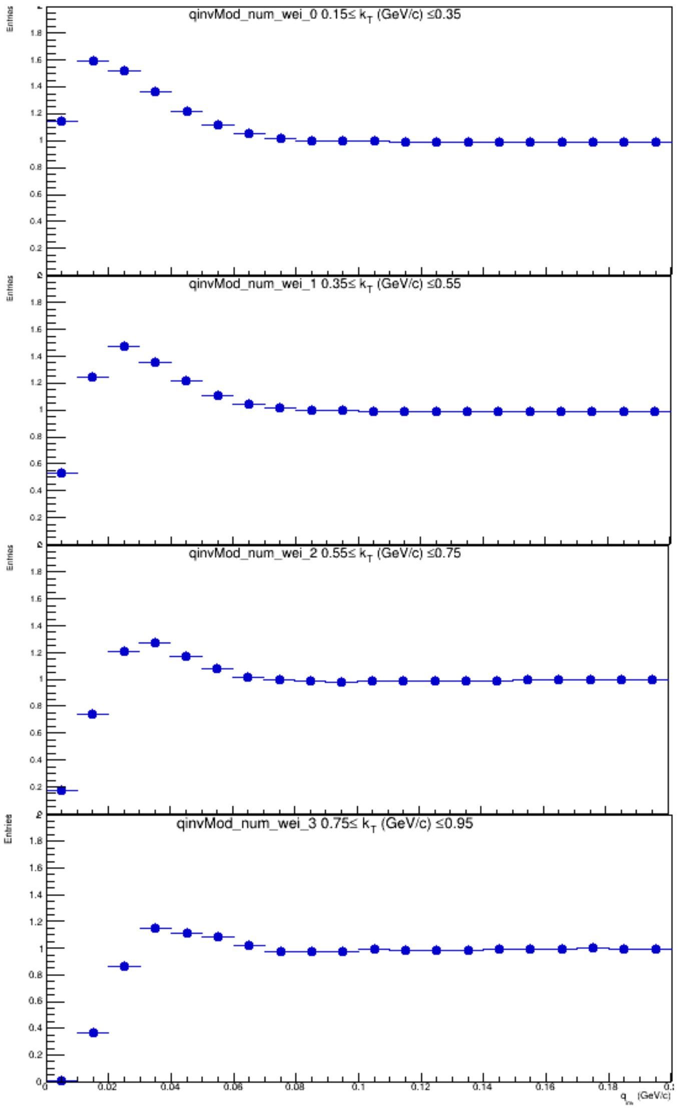


- Looks like the same average separation cut (>6 cm) can be applied for all k_T intervals
- The deep in CF due to the track-merging effect increases with k_T
- **Influence of the track-merging effect is extremely strong (especially at k_T>0.55 GeV/c)**

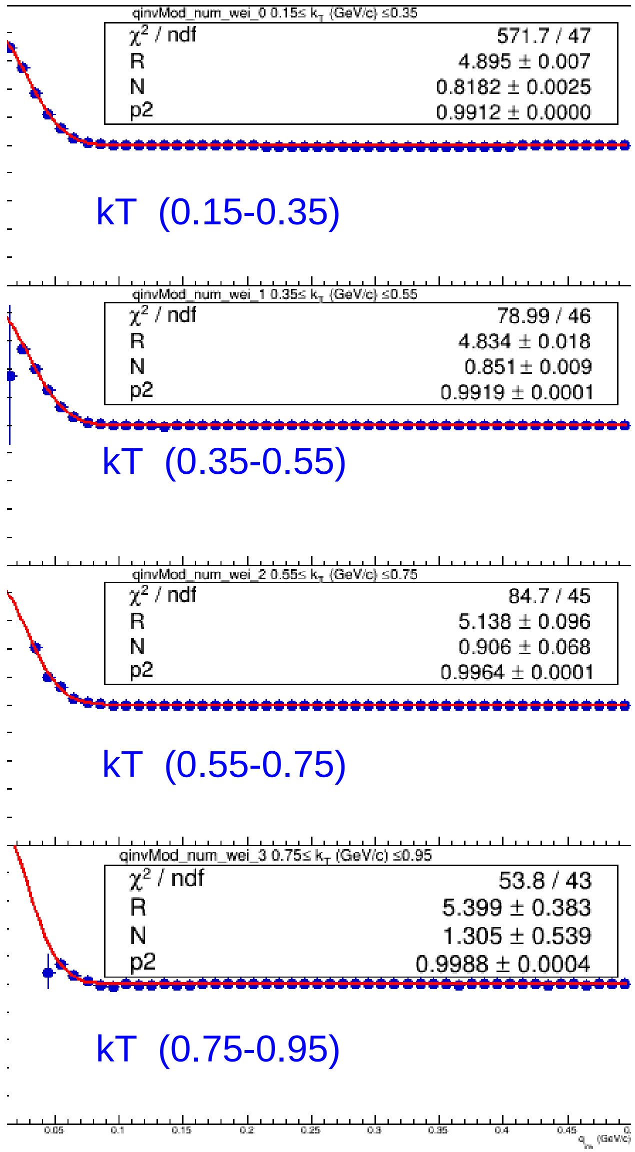
CF(q_{inv}) with two-track spatial average separation cut

Average separation > 6 cm

Gauss in PRF Rinv = 5 fm



CF = (Nsame, weight=QS)/ Dmixed



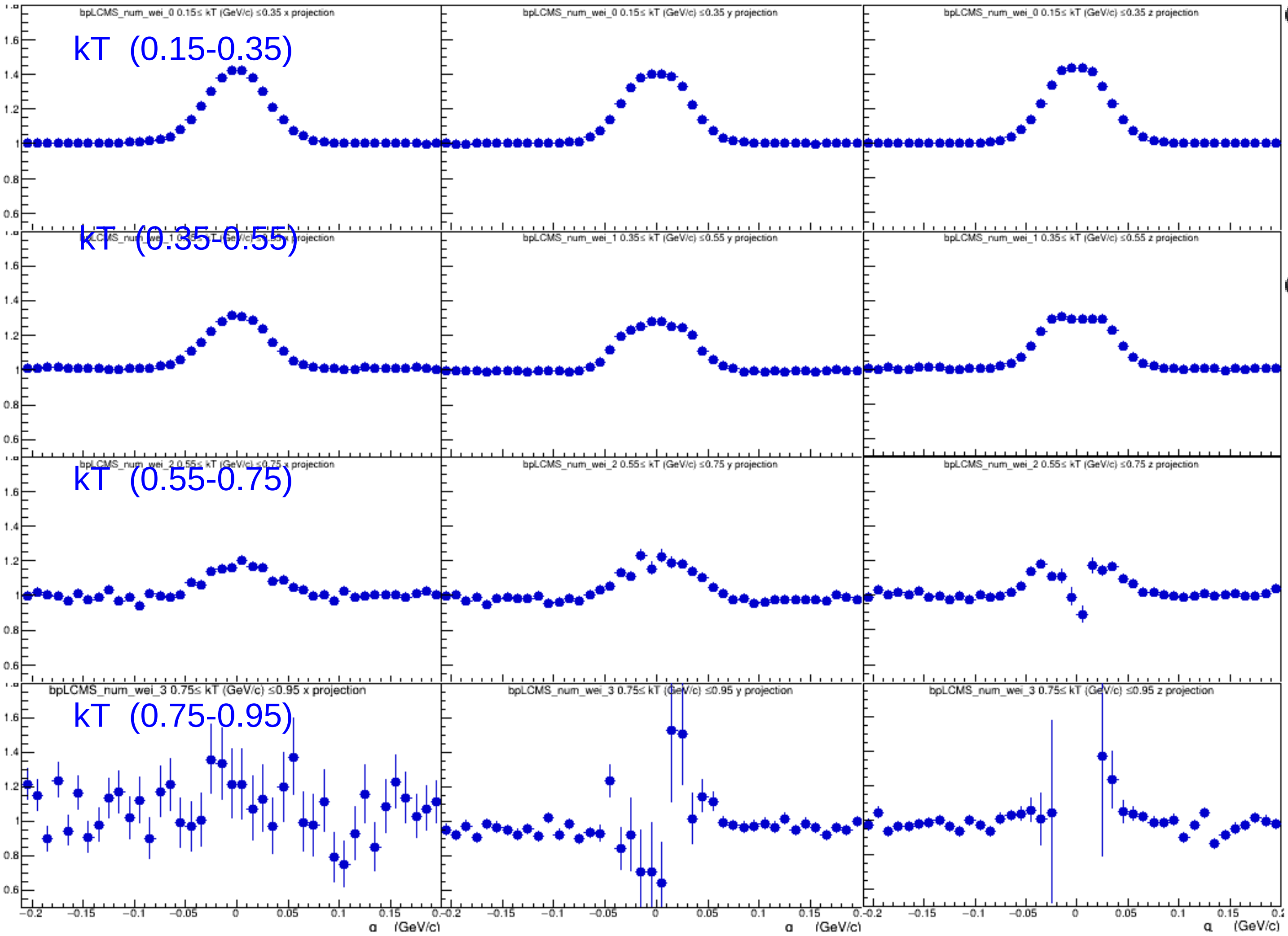
- Average separation cut significantly removes pairs at small q_{inv} especially at k_T> 0.55 GeV/c
- Complicates the 1D analysis

3D CF in LCMS: two-track average separation cut

Average separtion > 6 cm

Gauss in LCMS : Rosl = 5 fm

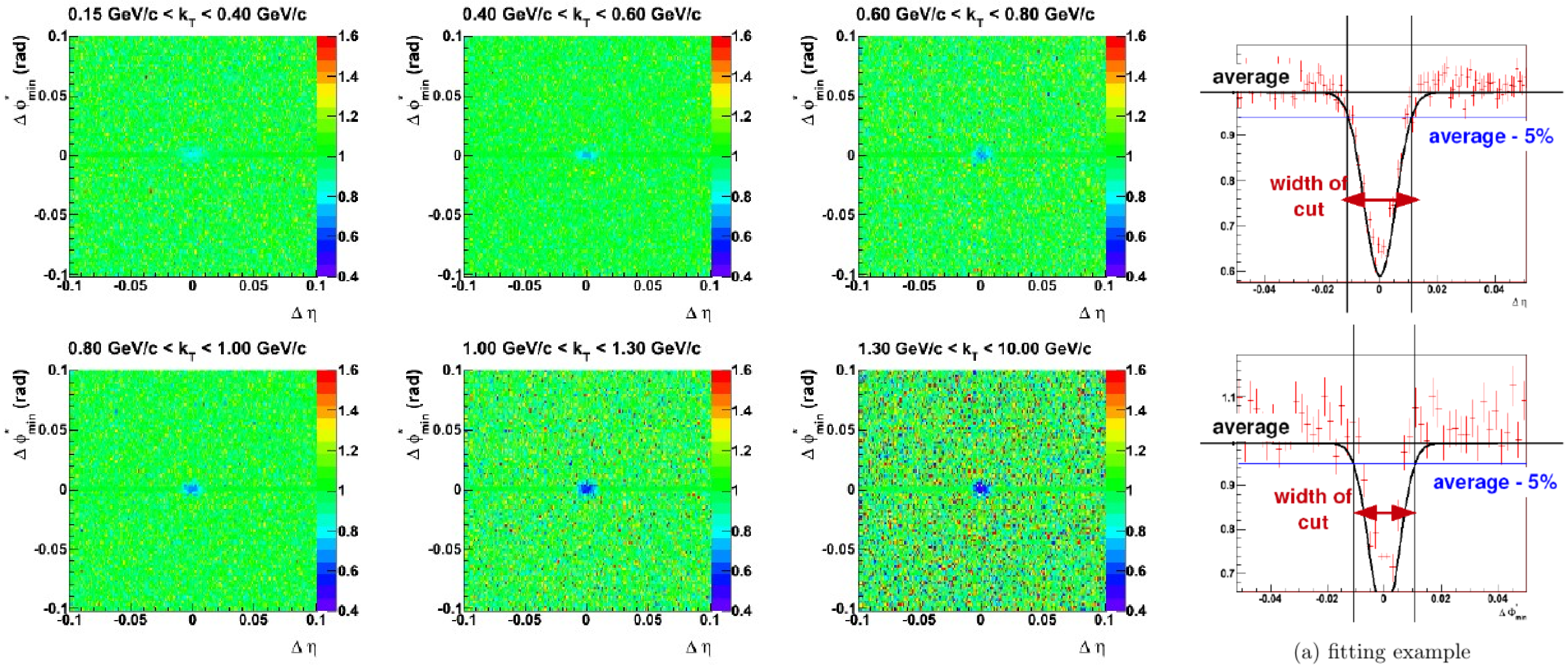
kT (0.15-0.95) GeV/c & 4 kT bins – **CF = (Nsame, weight=QS)/ Dmixed**



- Average separation cut significantly removes pairs at small q_{inv} especially at k_T> 0.55 GeV/c
- Even for kT(0.35, 0.55) GeV/c the shape of CF is strongly deformed

ALICE ΔηΔφ* min – distributions

Diploma Thesis, "Azimuthally Sensitive Hanbury Brown–TwissInterferometry measured with the ALICE Experiment", J.L. Gramling CERN-THESIS-2012-08813/12/20



(a) fitting example

Fig. 7: Two-dimensional ratio in $\Delta\eta$ and $\Delta\phi^*_{min,TPC}$, with the minimum in $\Delta\phi^*$ determined inside the TPC, TPC-only tracks.

No TTC : ΔηΔφ* distributions (TPC+TOF p>0.5GeV/c))

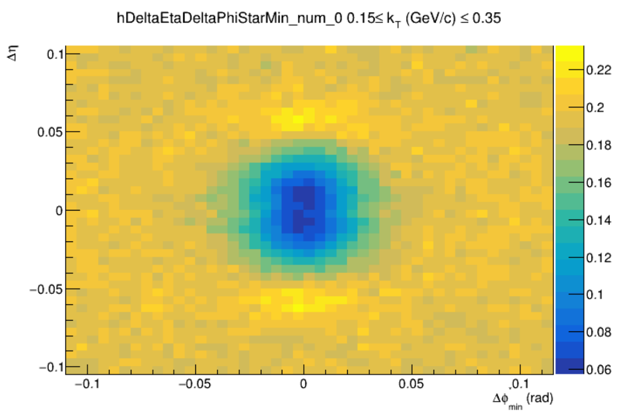
Δη-Δφ* with MPD reconstructed tracks

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

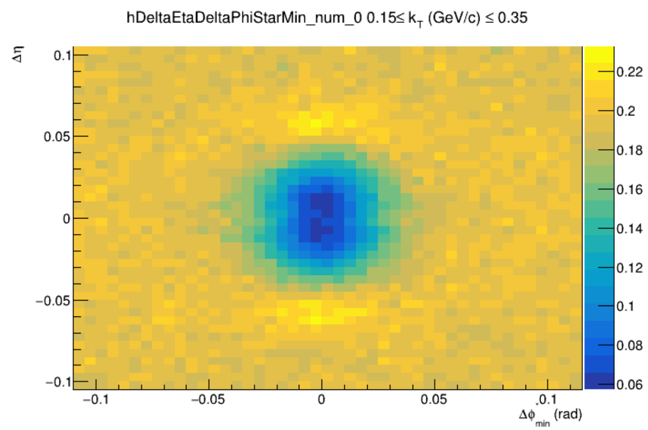
R is a given cylindrical radius

$\Phi_{1,2}$ are azimuthal angles of track at reconstructed vertex

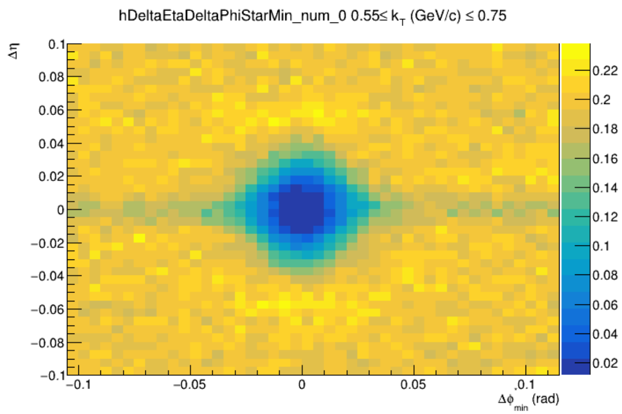
kT (0.15-0.35) GeV/c, R=0.65 m



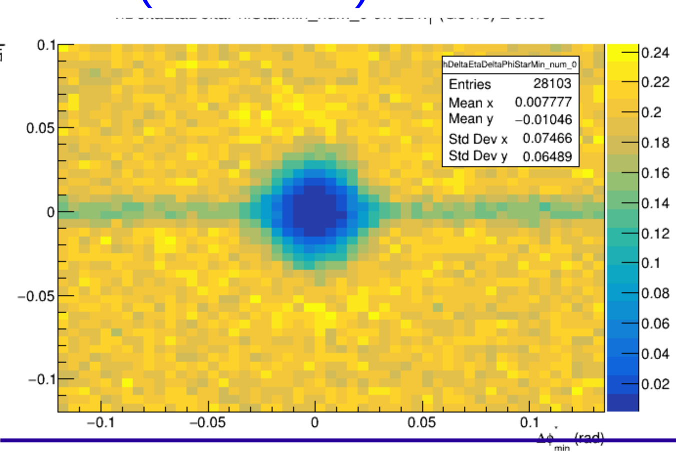
kT (0.15-0.35) GeV/c

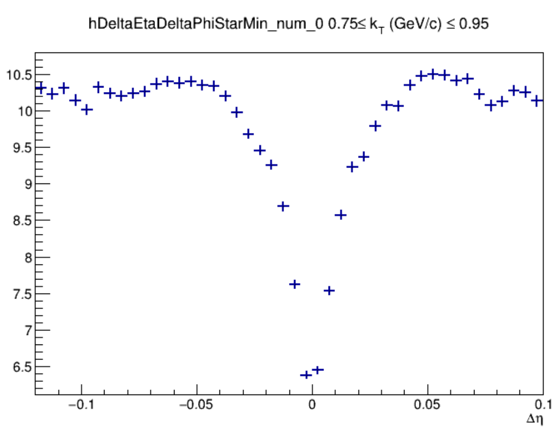


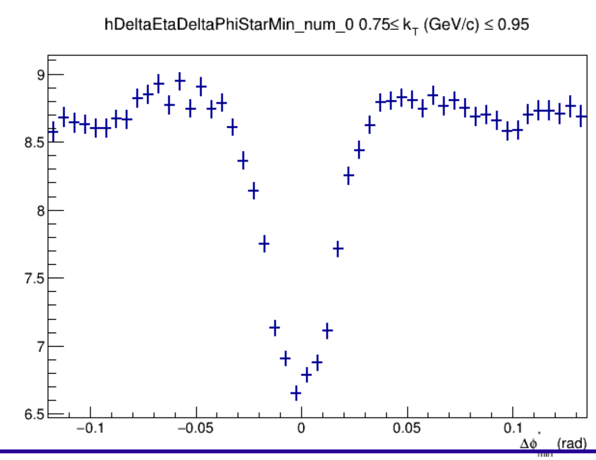
kT (0.55-0.75) GeV/c



kT (0.75-0.95) GeV/c







No TTC : ΔηΔφ* distributions (TPC+pdg)

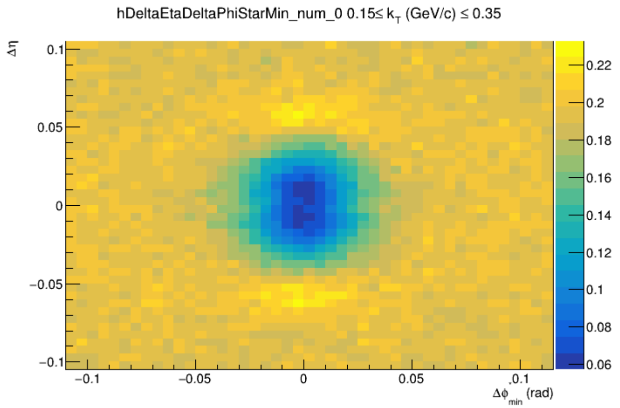
Δη-Δφ* with MPD reconstructed tracks

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

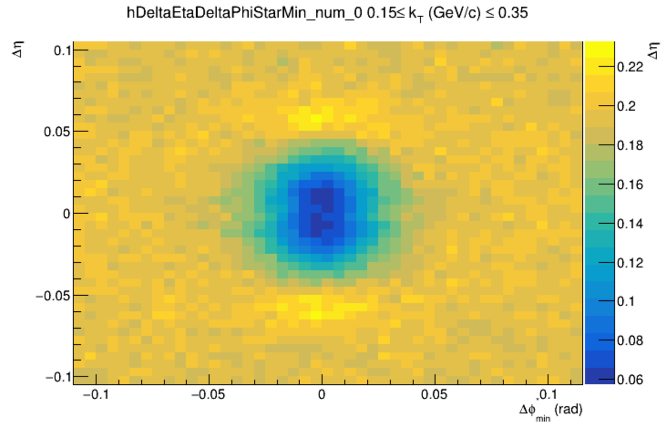
R is a given cylindrical radius

$\Phi_{1,2}$ are azimuthal angles of track at reconstructed vertex

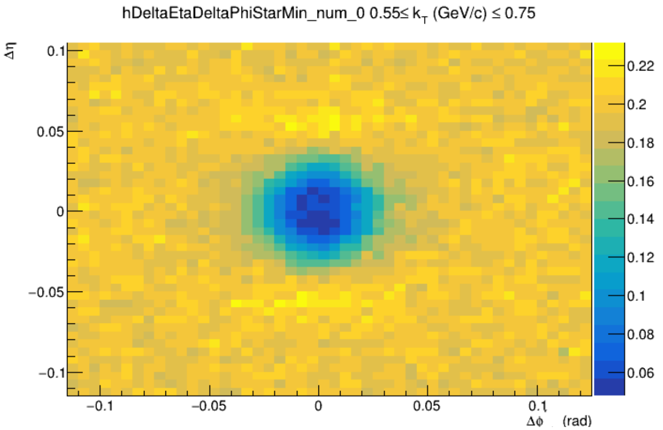
kT (0.15-0.35) GeV/c, R=0.65 m



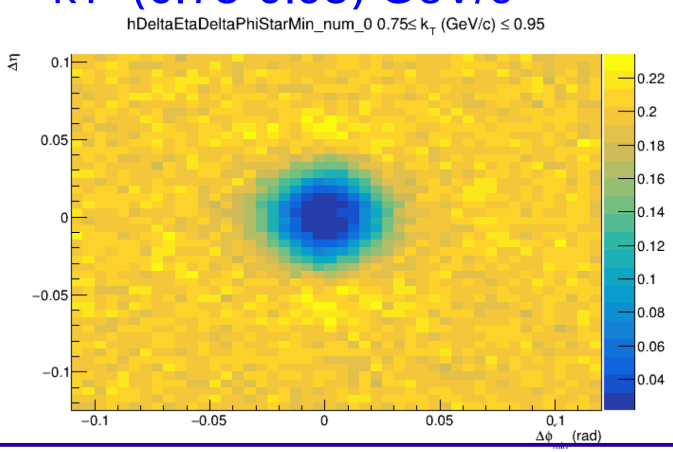
kT (0.15-0.35) GeV/c

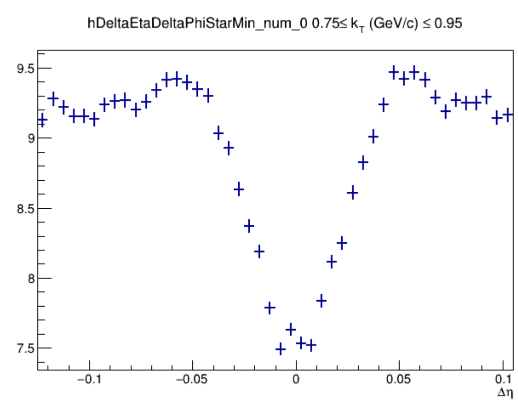


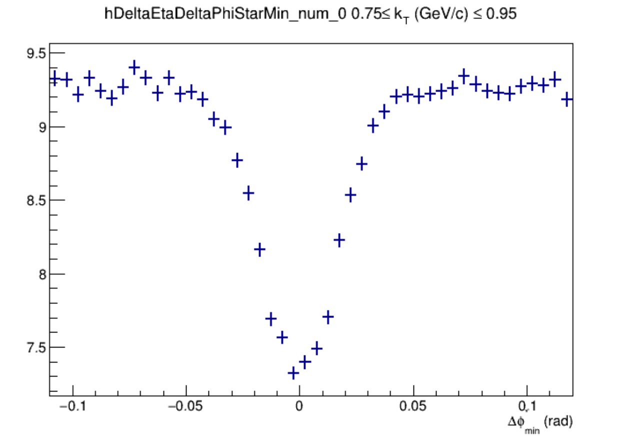
kT (0.55-0.75) GeV/c



kT (0.75-0.95) GeV/c





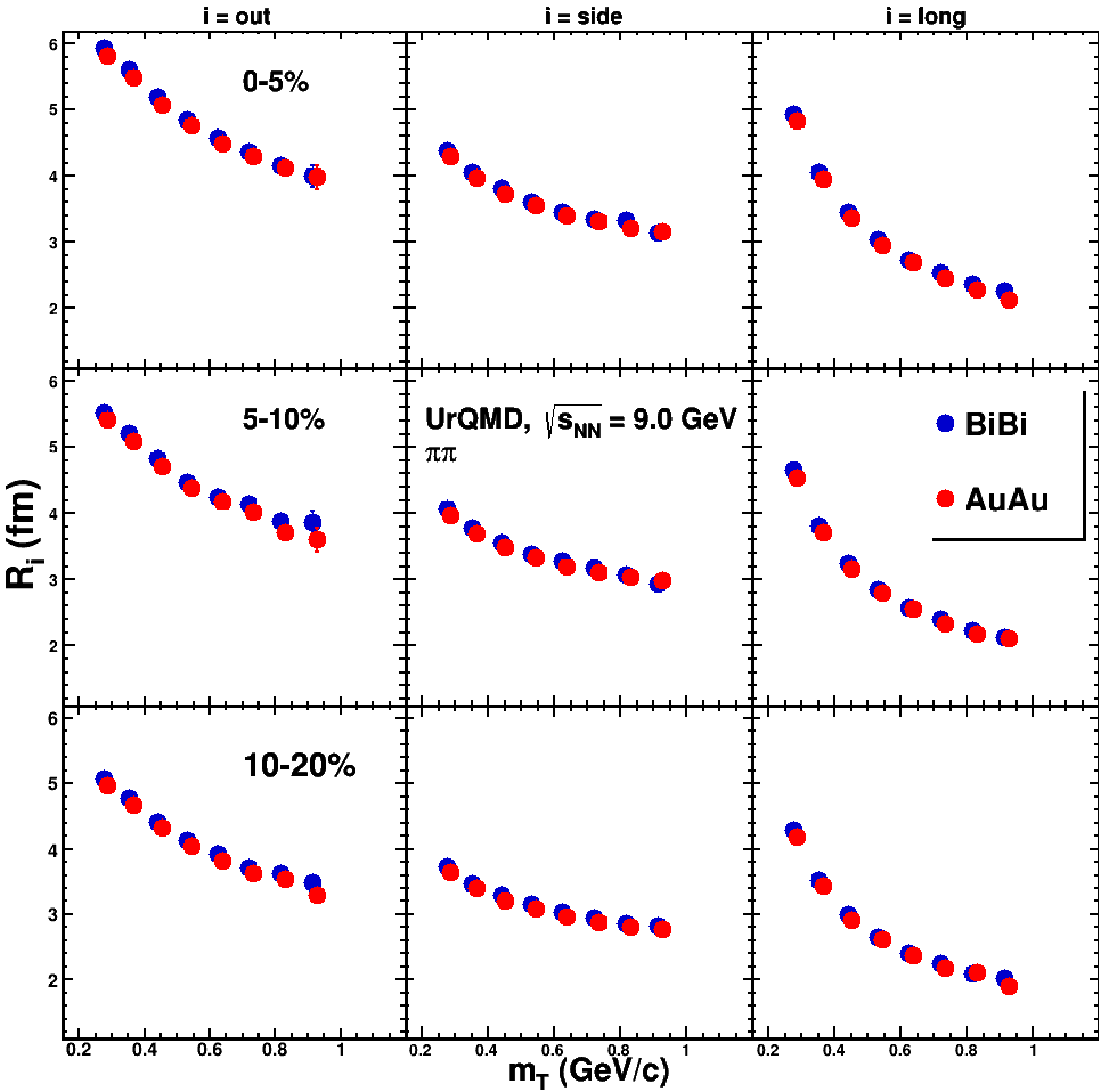


Conclusions

- Single-track momentum resolution:
  - Influence on the femtoscopic correlation function depends on pair transverse momentum
  - Strong influence on outward component, Rout (sensitive to the extraction of the particle emission duration)
  - Effect is strong but can be corrected for
- One track is reconstructed as two (track splitting):
  - Observed at small relative momentum
  - Large effect but can be taken into account using developed two-track selection criteria
- Two tracks reconstructed as one (track merging):
  - Strong effect
  - Two independent methods (two-track spatial and angular separations) show same results
  - Depends on k_T of the pair
  - Makes impossible to study femtoscopic correlation for pions at k_T> 0.55 GeV/c
- Odd reconstruction of the primary vertex position in x and y directions
- Communication with tracking group is necessary
- Tracking improvement is needed

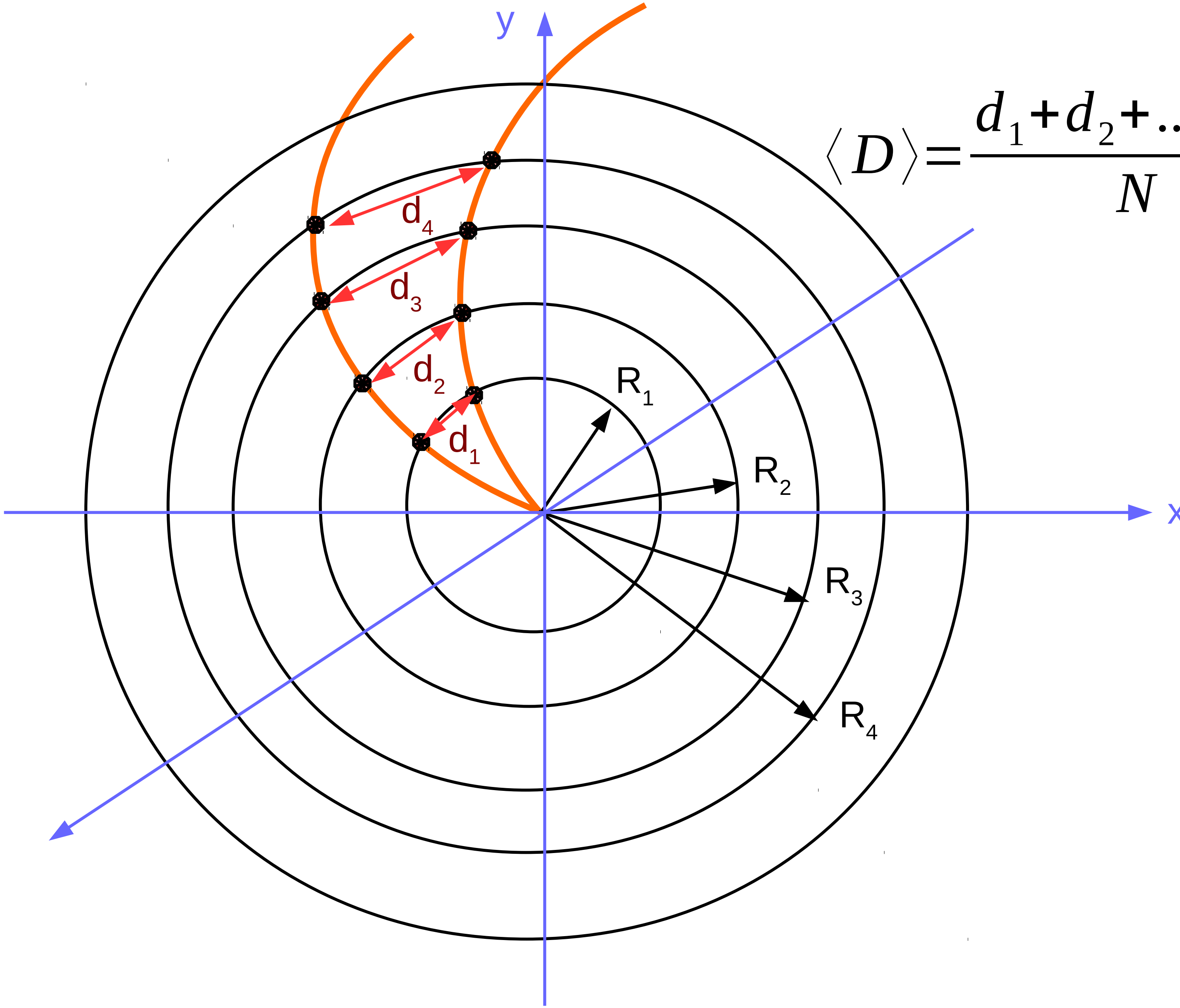
Additional slides

Comparison of AuAu and BiBi (UrQMD)



- Au+Au, and Bi+Bi at $\sqrt{s_{NN}}$ = 9 GeV
- Pion femtoscopic radii of Bi+Bi are larger than Au+Au ones by ~2-6%

Two-track spatial average separation



$$\langle D \rangle = \frac{d_1 + d_2 + \ldots + d_N}{N}$$

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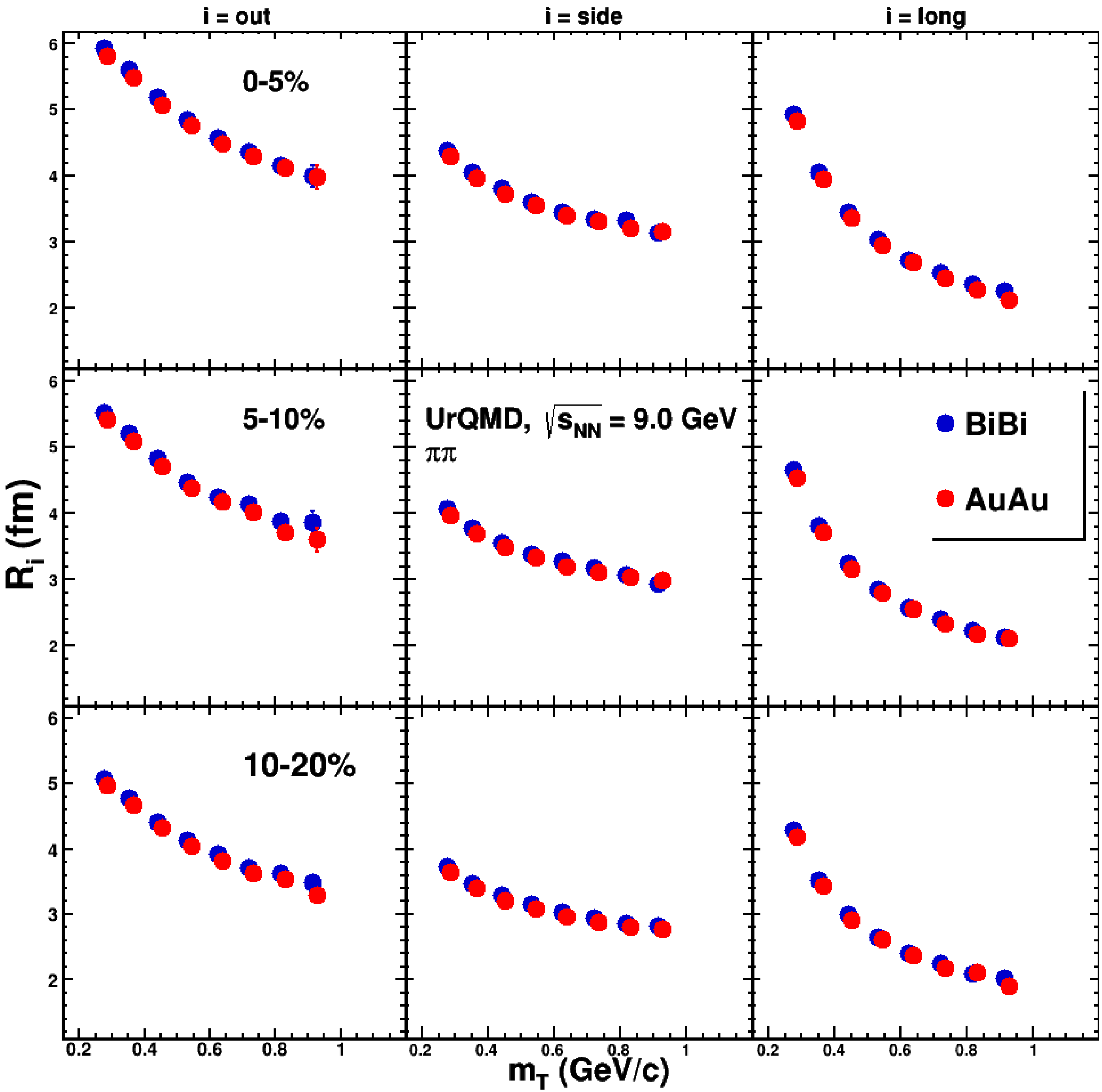

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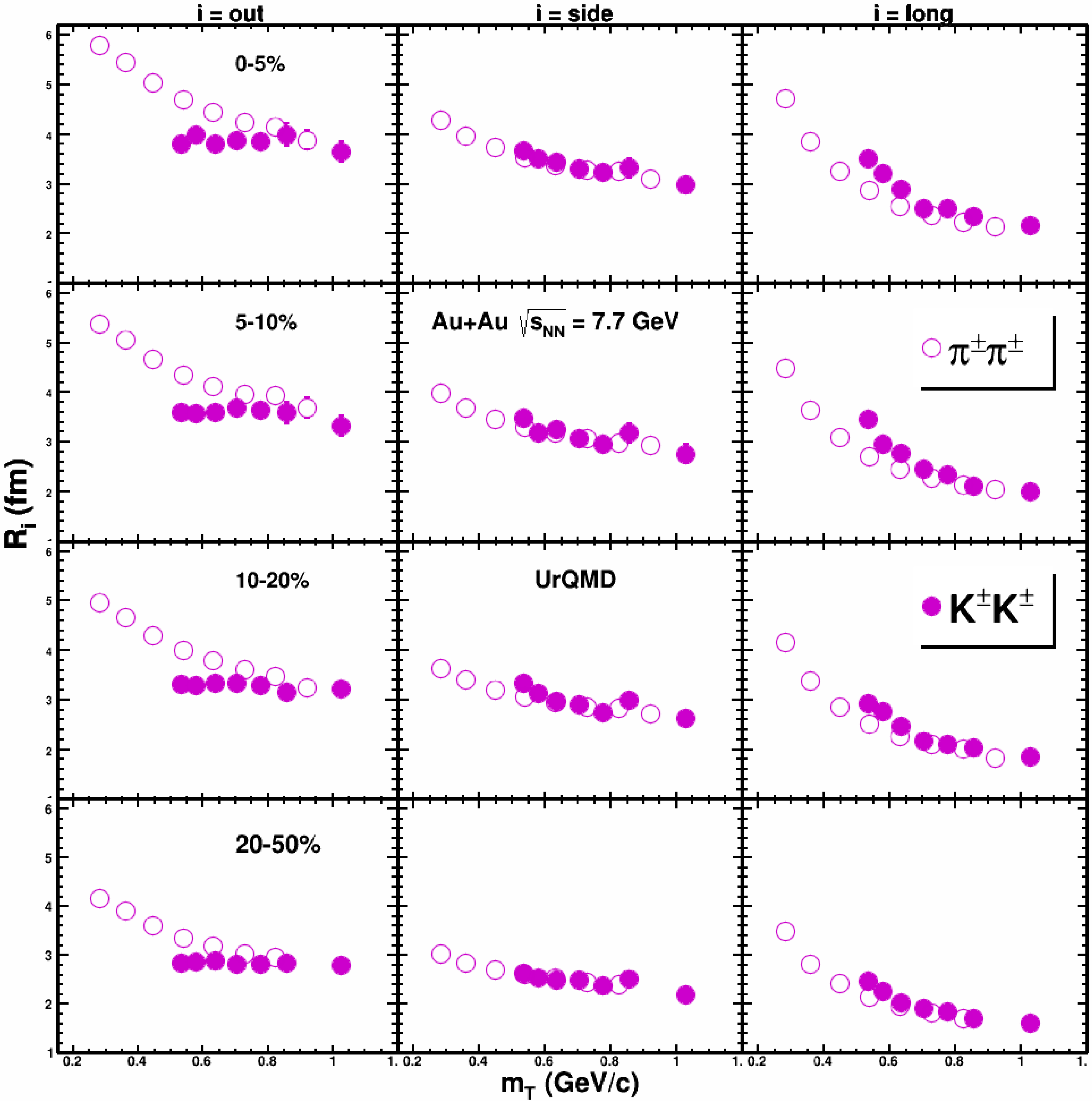
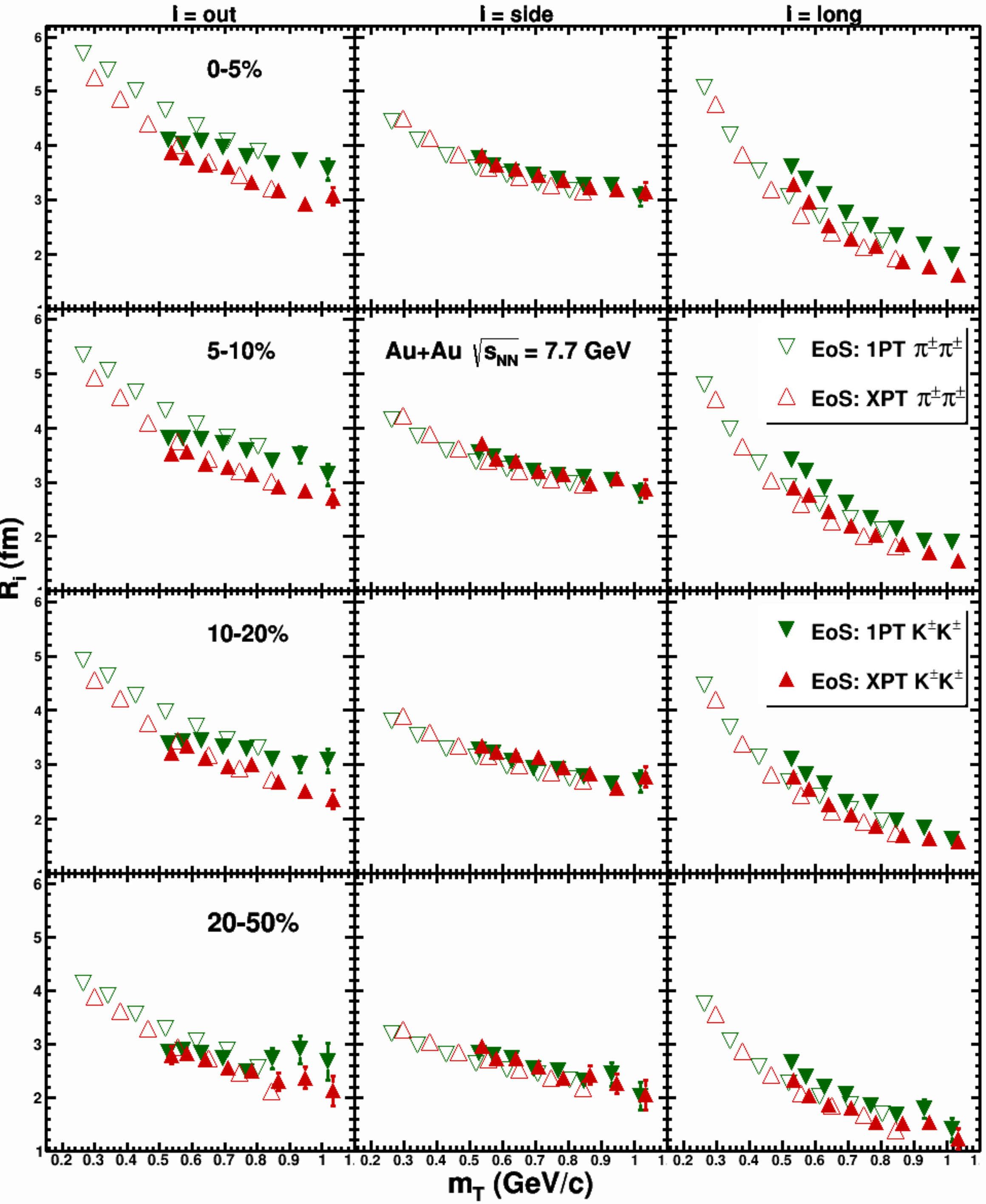
Pion and kaon radii with UrQMD model



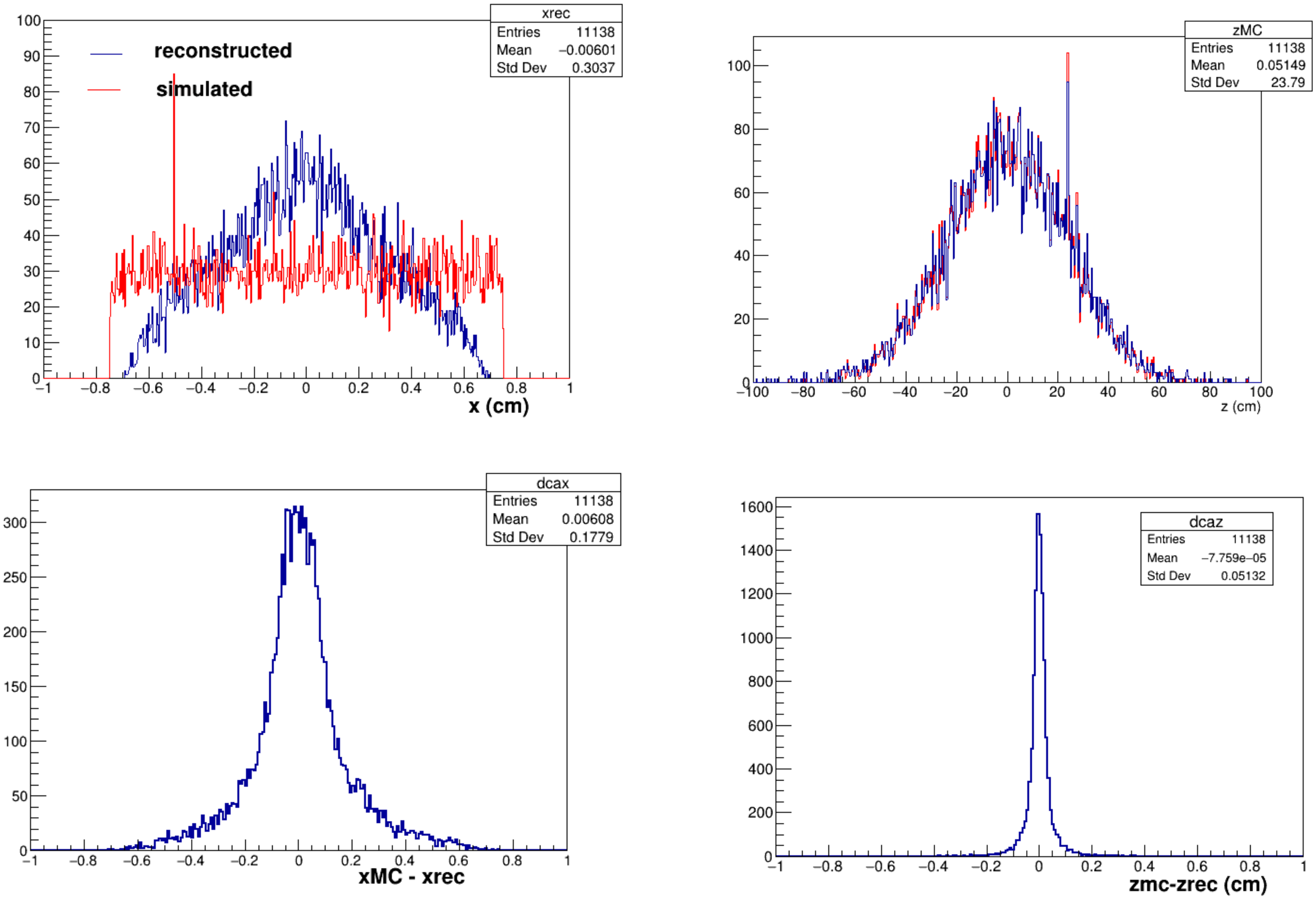
- Au+Au, $\sqrt{s_{NN}}$ = 7.7 GeV
- **kaon radii demonstrate almost flat behavior similarly to vHLEE with the 1PT EoS → weak flow**
- R_{long} kaon radii are larger than pion ones similarly to experiment (LHC & RHIC)
- The similar trend is observed for AuAu 11.5 GeV

Pion and kaon radii with vHLLE model



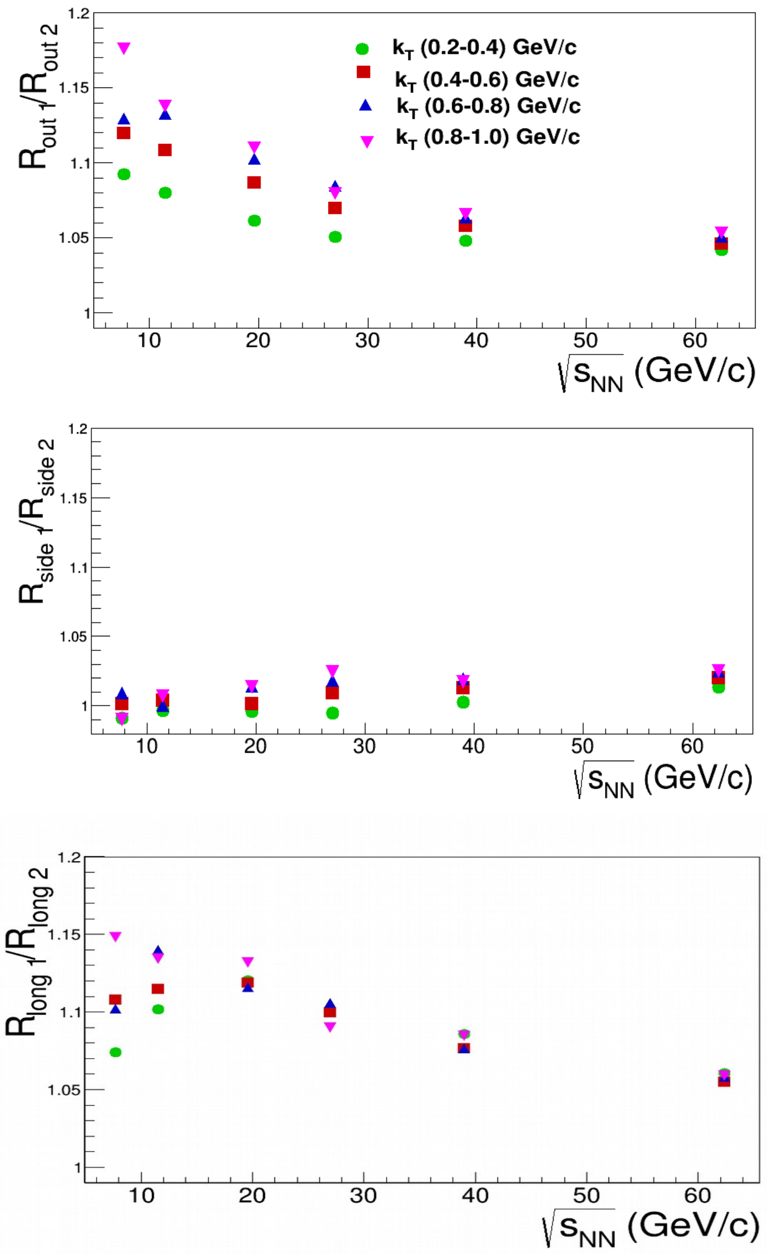
- Au+Au, $\sqrt{s_{NN}}$ = 7.7 GeV
- Approximate m_T scaling for R_{side}
- Similarly to pions : kaon radii decrease with m_T → radial flow ;
- **for 1PT EoS almost flat dependence R_{out} (m_T) is observed → weaker flow**
- **$R_{out,long}$ (1PT) > $R_{out,long}$ (XPT)**
- R_{long} kaon radii for XPT > R_{long} pion similarly to experiment (LHC & RHIC)
- Very different predictions of vHLLE model for different EoS → importance to study heavier than pions particles → kaons
- The similar trend is observed for AuAu 11.5 GeV

Vertex {X,Y,Z} – distributions



- The same effect is seen for y-coordinate of primary vertex.

Ratio of $R_{out,side,long}$(1PT)/$R_{out,side,long}$ (XPT) vs. $\sqrt{s_{NN}}$

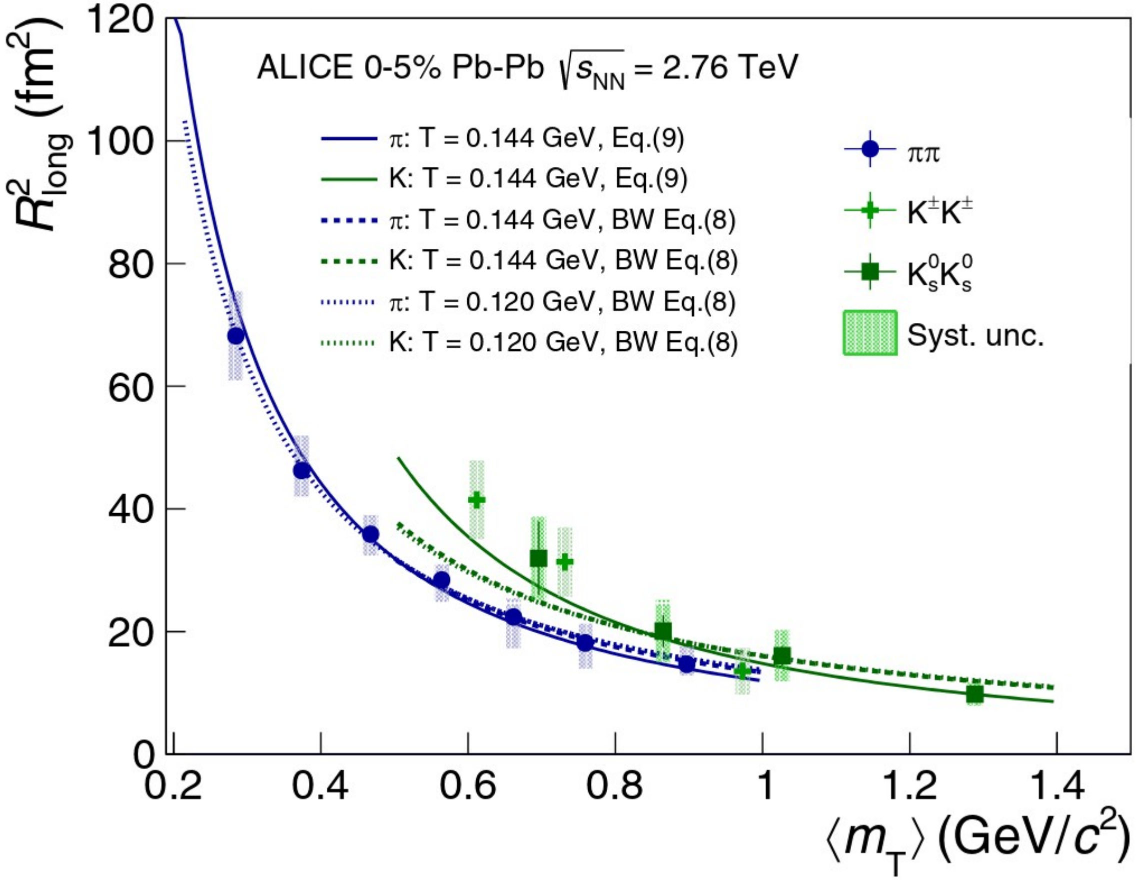


- Pion k_T divided into 4 bins
- R_{side} ratio practically coincide for both scenarios
- R_{out} and R_{long} ratios for 1PT EoS are greater than for XPT EoS and demonstrating a strong k_T -dependence at low energy

- 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

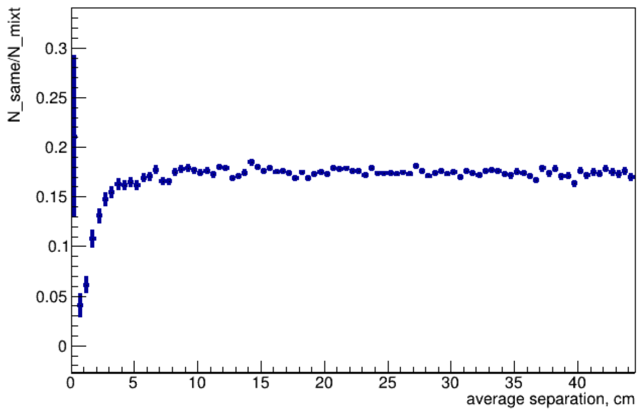
Emission delay in ALICE data

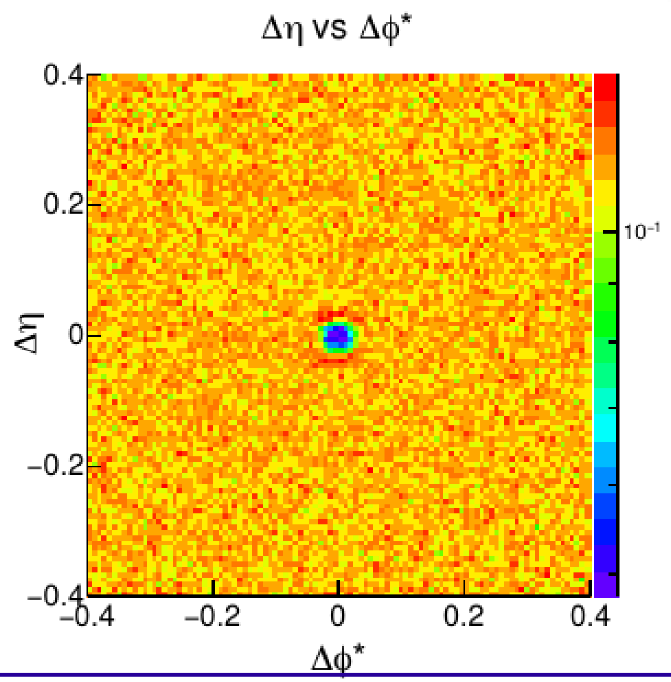
- ALICE kaon data in hydro-based parameterization: kaons emitted on average later than pions.
- It comes from rescattering via K* resonance
- $R_{long} \sim \tau / \sqrt{m_T}$
- Measured values: τ_π=9.5±0.2 fm/c
  τ_K=11.6±0.1 fm/c



Tests with reconstructed data : two-tracks effects

In MPD FEMTO package are implemented different methods for study the two tracks effects which are widely used by STAR and ALICE collaborations.





- The cut on Average Separation between two tracks in TPC was studied and is find to be > 7 cm
- The cut on cylindrial distance between tracks in TPC was tested and is find to be: Δη<0.04 and Δφ*<0.02
- Pion femtoscopic CF can be correctly reconstructed if two-tracks cuts are applied