Influence of methodological effects on femtoscopy in MPD within the RFBR Mega Grant # 18-02-40044

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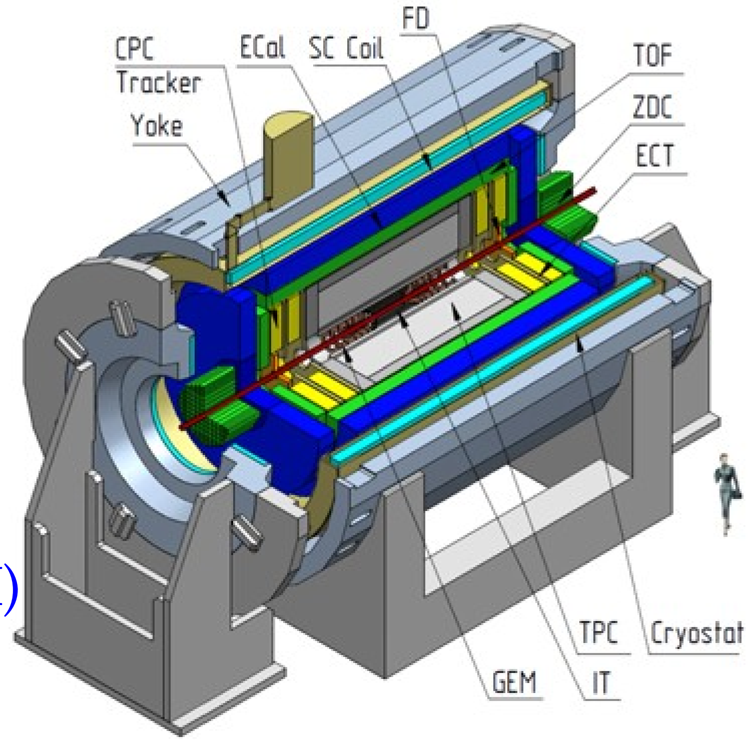
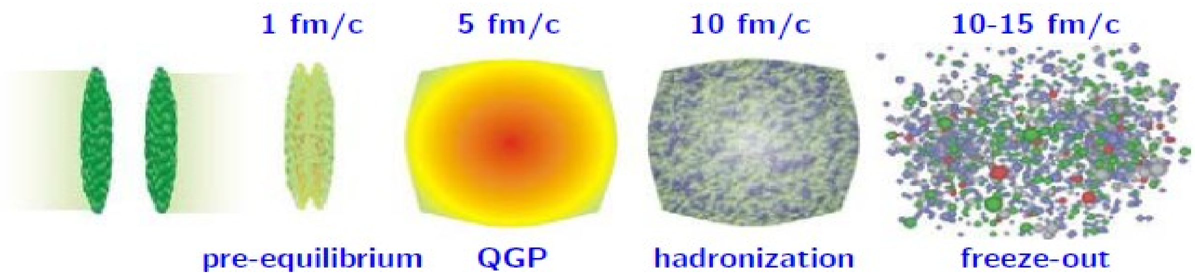


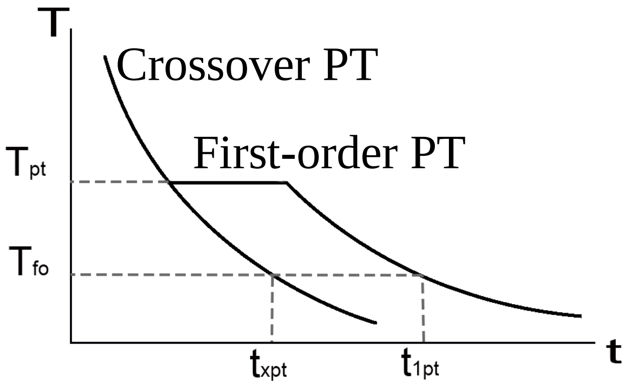
Outline

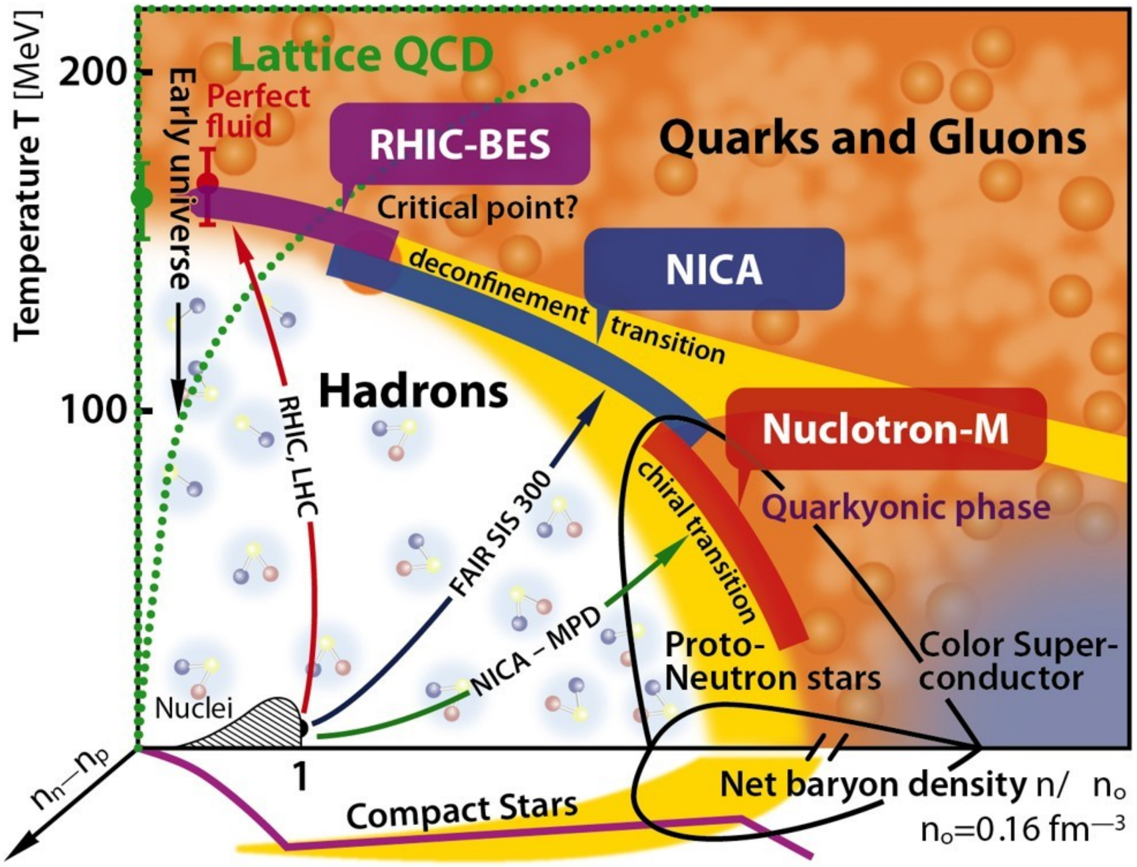
- Femtoscopy & Motivation
- Analysis details
- Influence of single- and two-track resolution on Correlation Functions (Cfs)
- PID study
- Momentum resolution studies
- Two-tracks effects studies

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 (?)



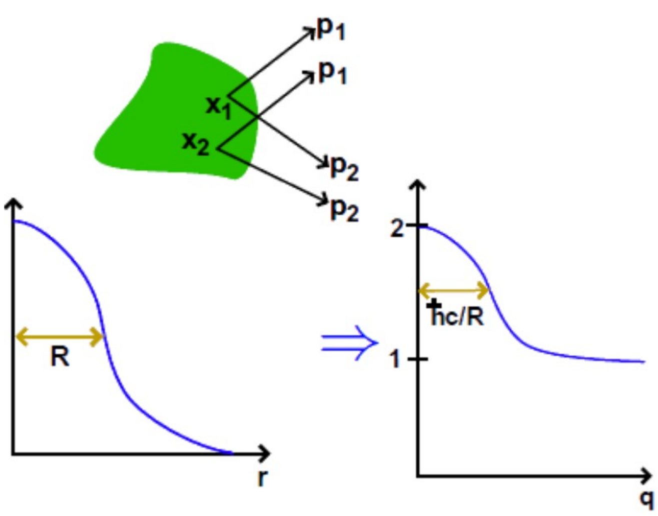




It is important to extract space-time information -> femtoscopy

- BES RHIC ($\sqrt{s_{NN}}$= 3-39 GeV)
- BES-II + FXT ($\sqrt{s_{NN}}$ = 3-27 ГэВ)
- 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:

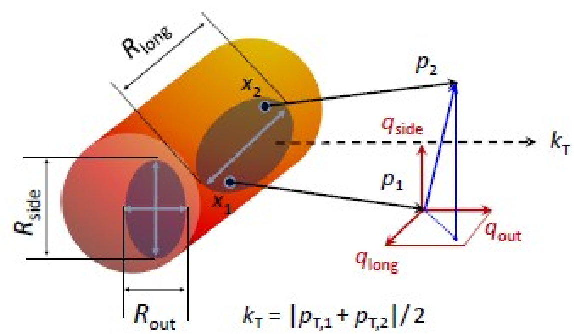
theory: $$C(q)=\frac{N_2(p_1,p_2)}{N_1(p_1)\cdot N_2(p_1)},\ C(\infty)=1$$

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

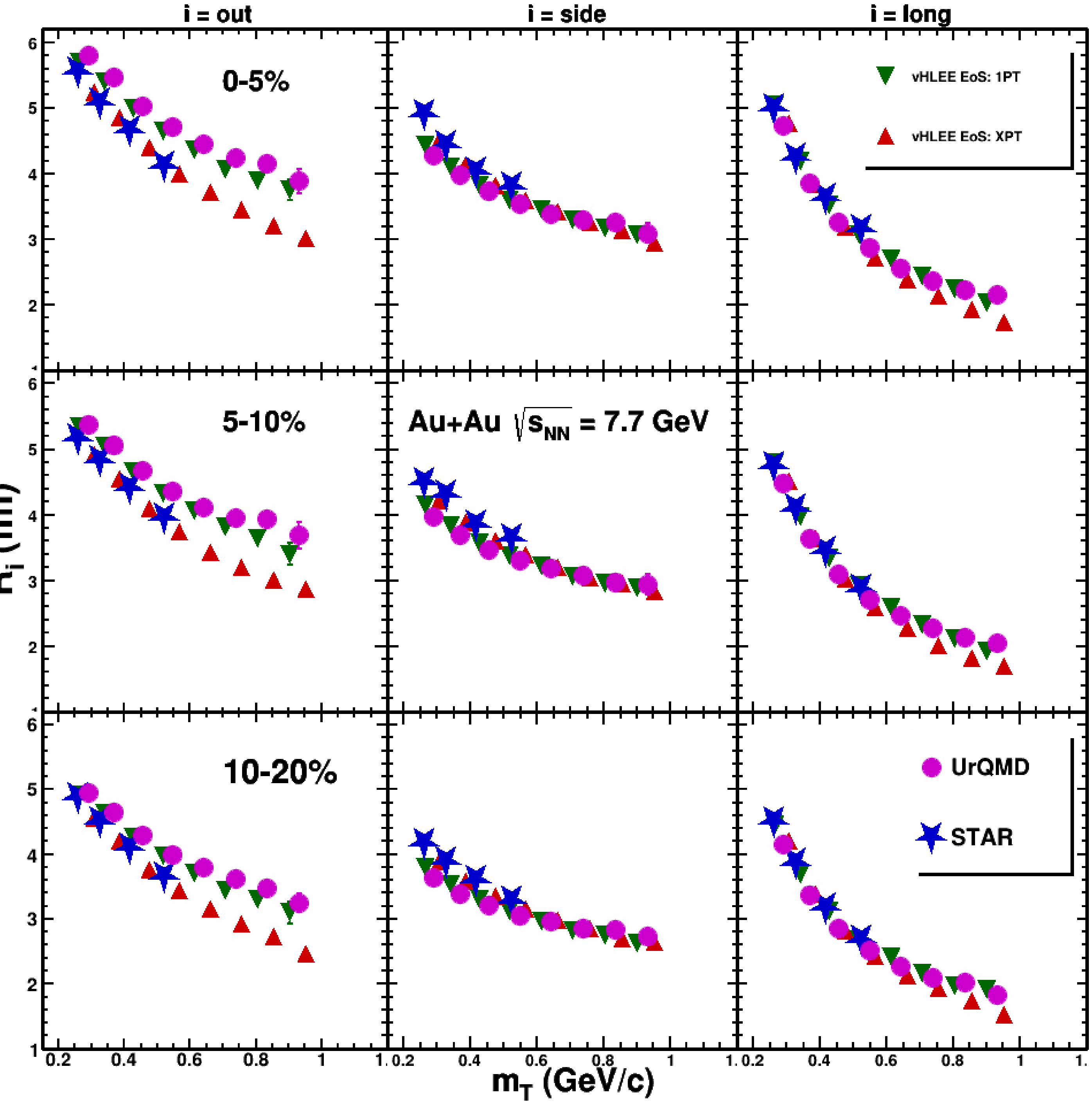
3D analysis:

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

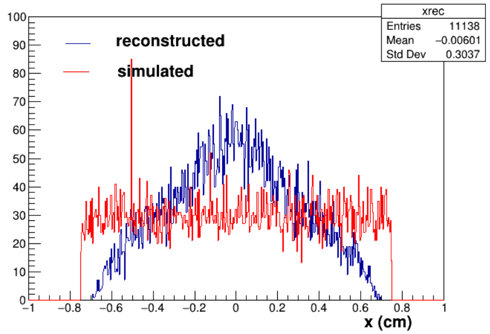


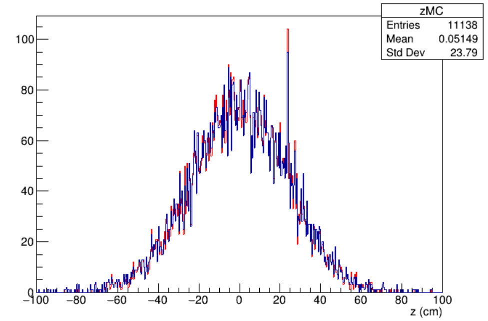
- Au+Au, $\sqrt{s_{NN}}$ = 7.7 GeV
- **It is important to study femtoscopic radii dependence in the broad $k_T(m_T)$ range**
- **Difference between different models demonstrates it self more clearly.**
- **$k_T(m_T)$-dependence allows to study evolutioon of the system**
- Radii decrease with m_T → radial 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

Analysis of reconstructed data in MPD

Details of 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/

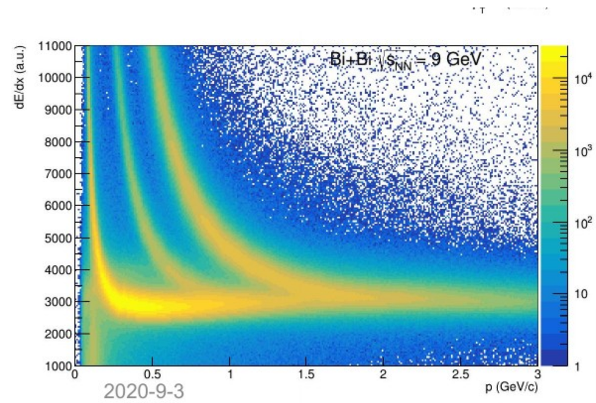


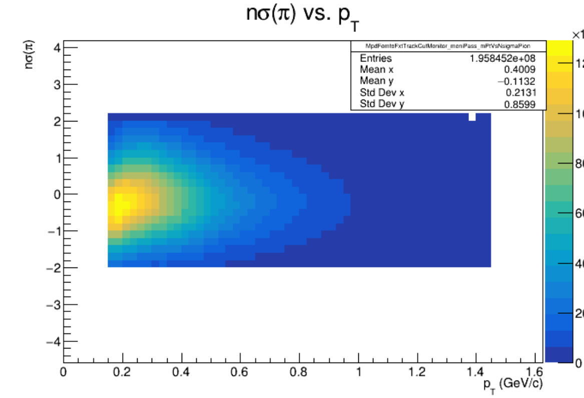


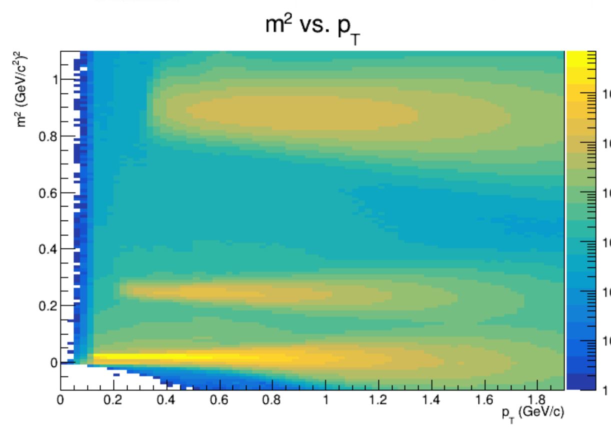
- **Track Cuts:**
  0.15 < pT < 1.5 GeV/c
  |η|<1.0
  Nhits(TPC) > 15
  DCA < 5 cm

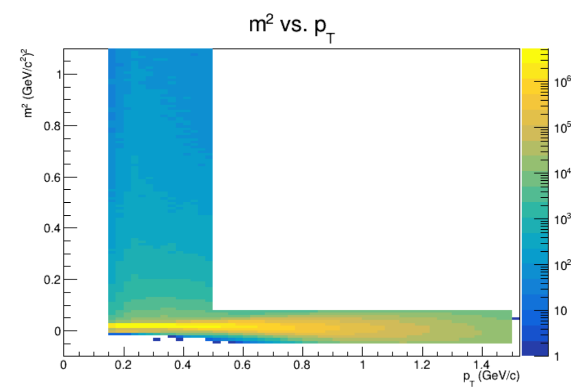
- **PID**
  TPC+TOF,
  - TOF starts at p > 0.5 GeV/c
  - Pion nSigma for TPC+TOF identification (details will be shown)

Pions: 2*2.0 · 10^8









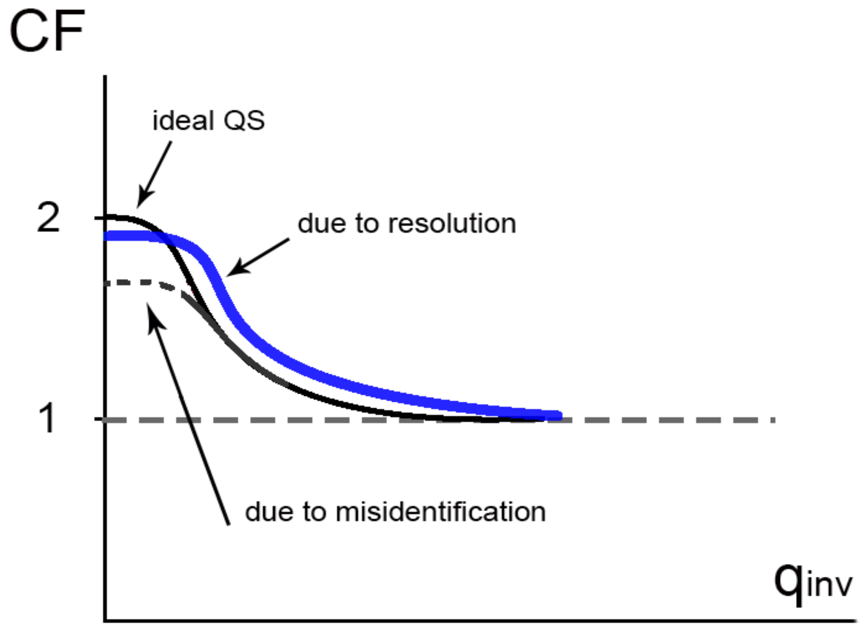
Influence of track reconstruction on CF

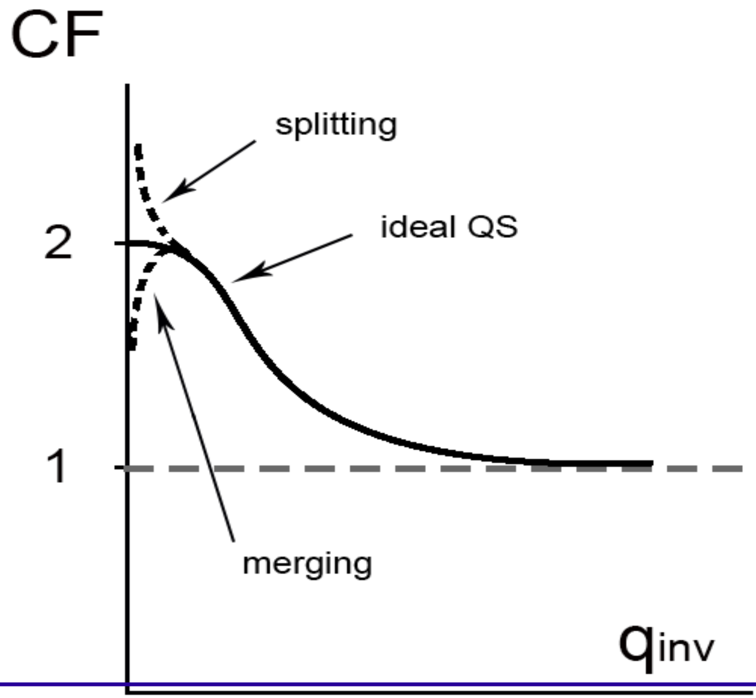
Track reconstruction influences the shape of CF

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

- Particle misidentification:
  - Influences only λ parameter of CF, radii do not change
  - CF should be corrected by pair purity. Pair purity is obtained from particle 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 specific pair cuts that will be applied in the femtoscopic analysis

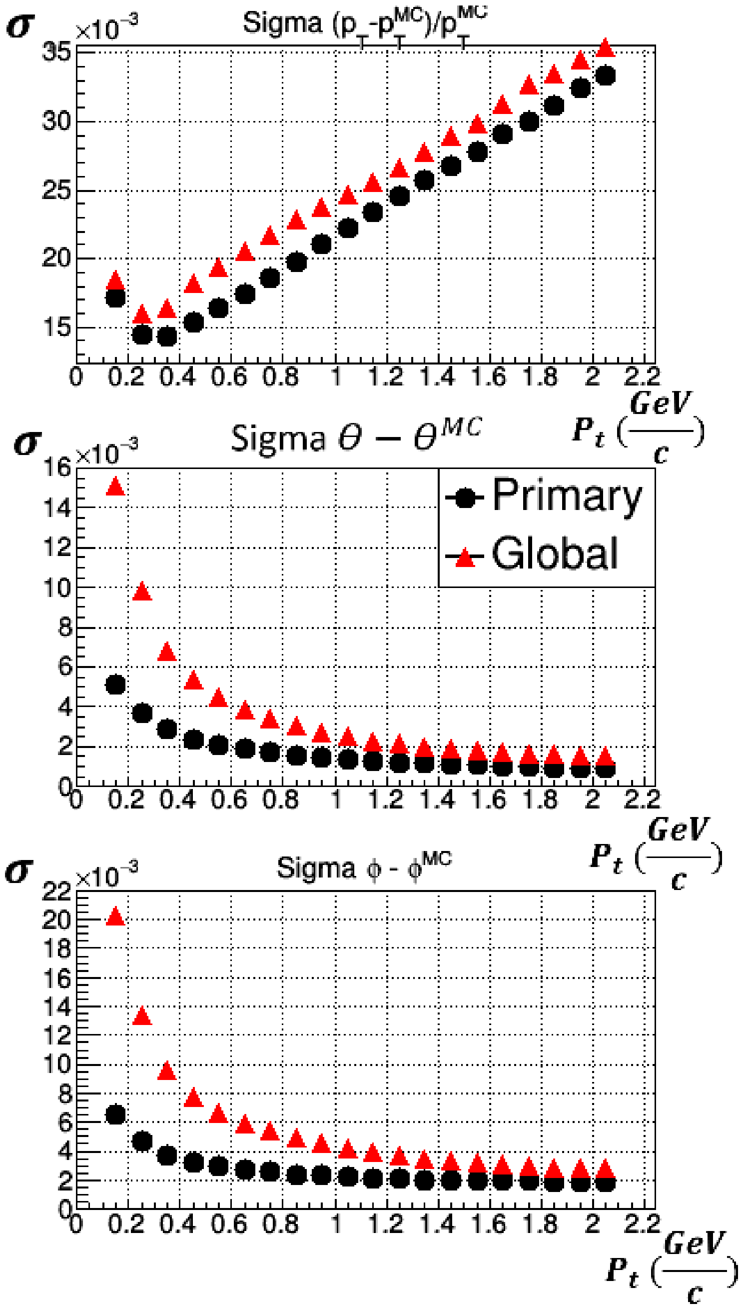




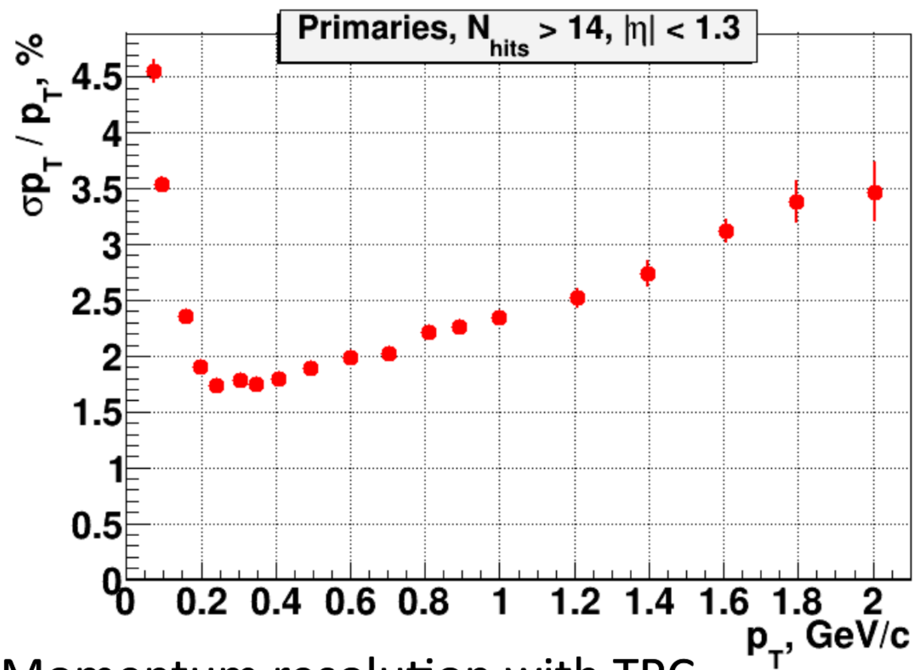
Single-track effects in femtoscopy

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

Momentum resolution for primary and global tracks



|η| < 1
Nhits > 15



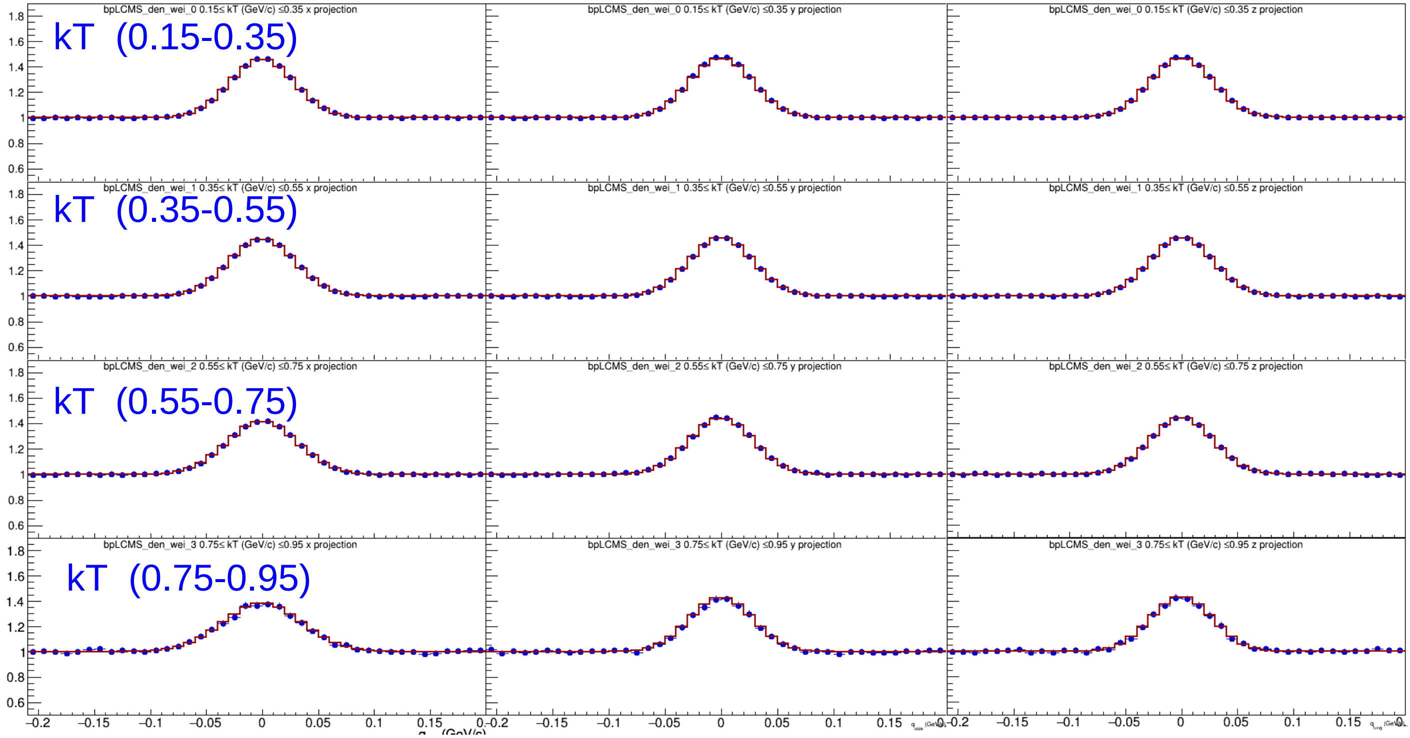
Momentum resolution with TPC

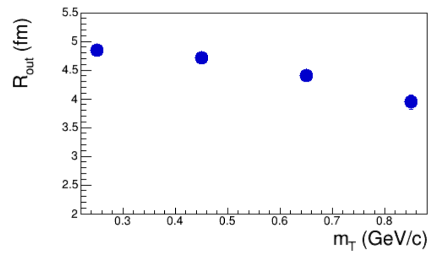
Egor Alpatov (student, NRNU MEPhI)

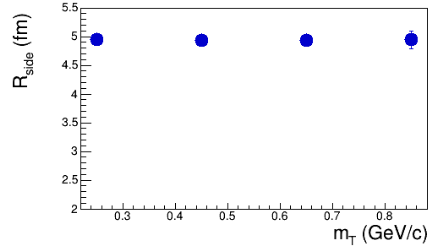
For tracks with vertex constrain (Primary tracks) momentum resolution is better

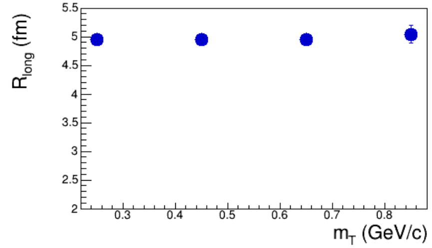
Influence of momentum resolution on 3D CFs in LCMS

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



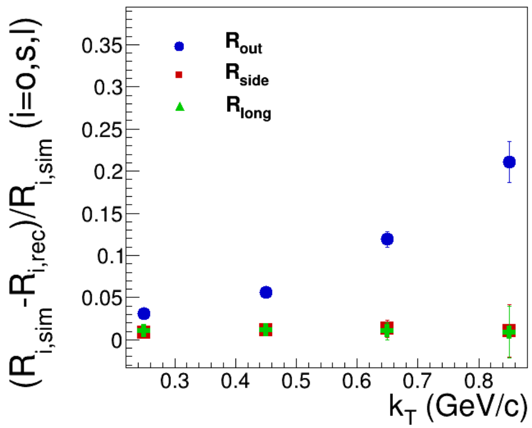






CFs become wider with increasing k_T
Resolution effect on Rout is strong at large k_T

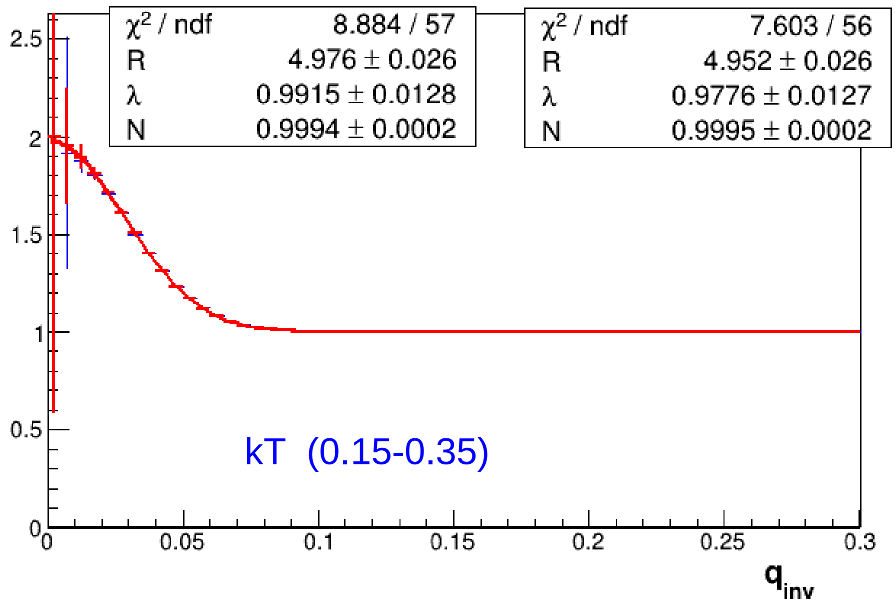
Calculations were performed for each (Ro,Rs,Rl) combination. When projecting on one axis the other two components were required to be within **(-0.04,0.04)** GeV/c.



Influence of momentum resolution on 1D/3D CFs

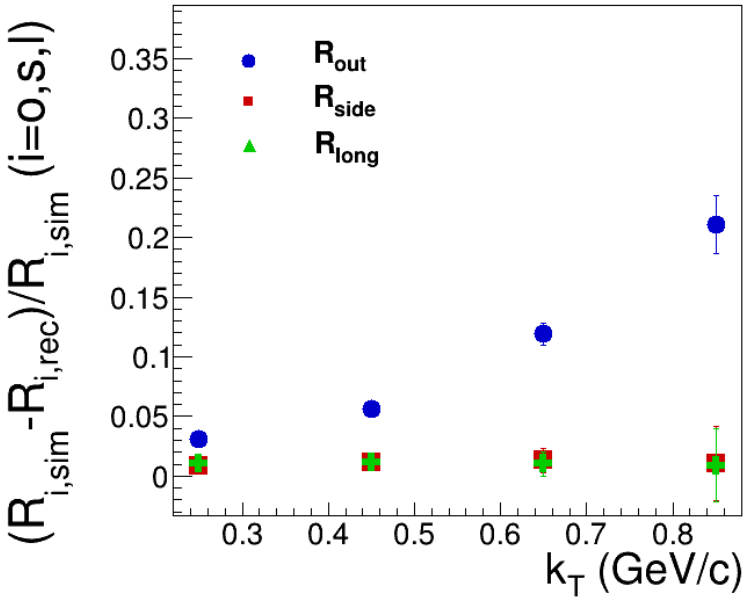
1D Gauss in PRF **Rinv = 5 fm**
k_T (0.15-0.95) GeV/c & 4 k_T bins

CF = (Dmixed, weight=QS)/ Dmixed



- 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)

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

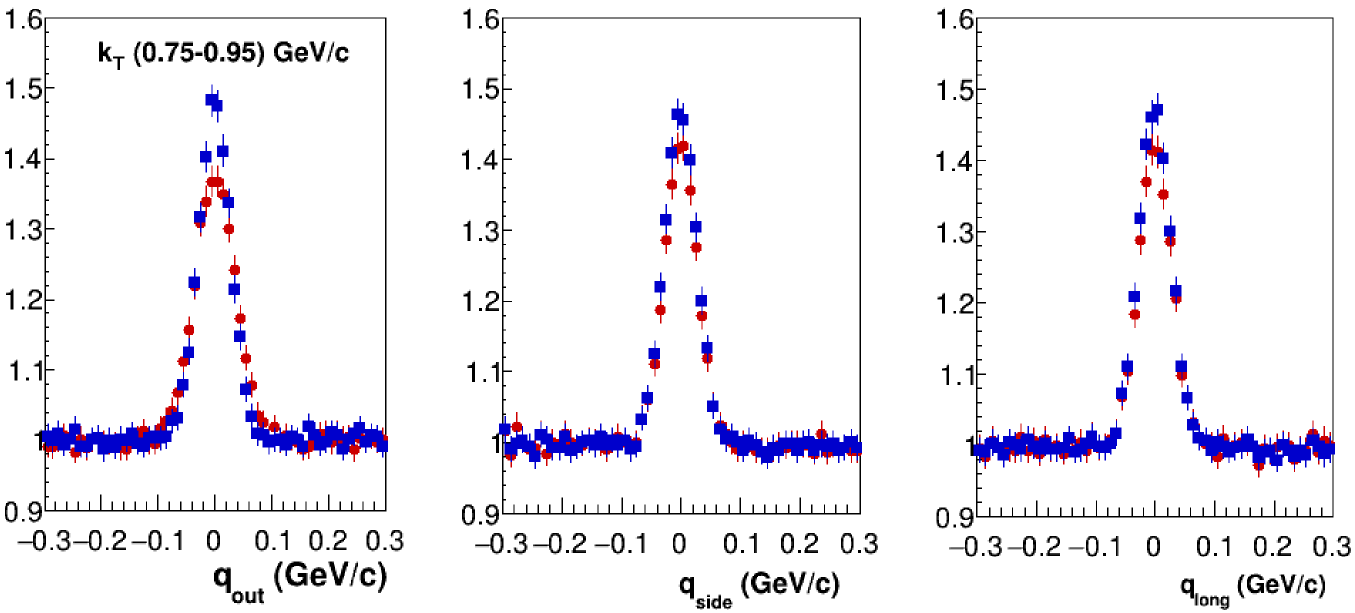
(a)

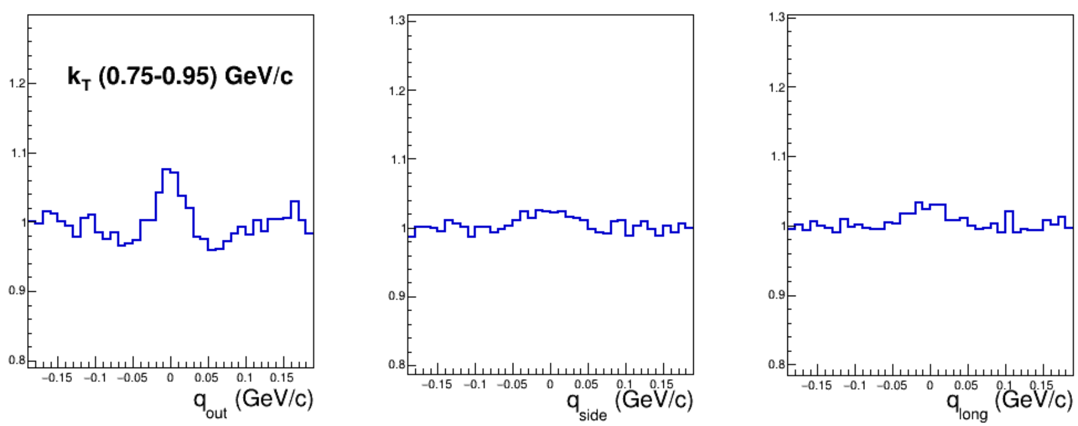
Momentum resolution correction for 3D CFs in LCMS

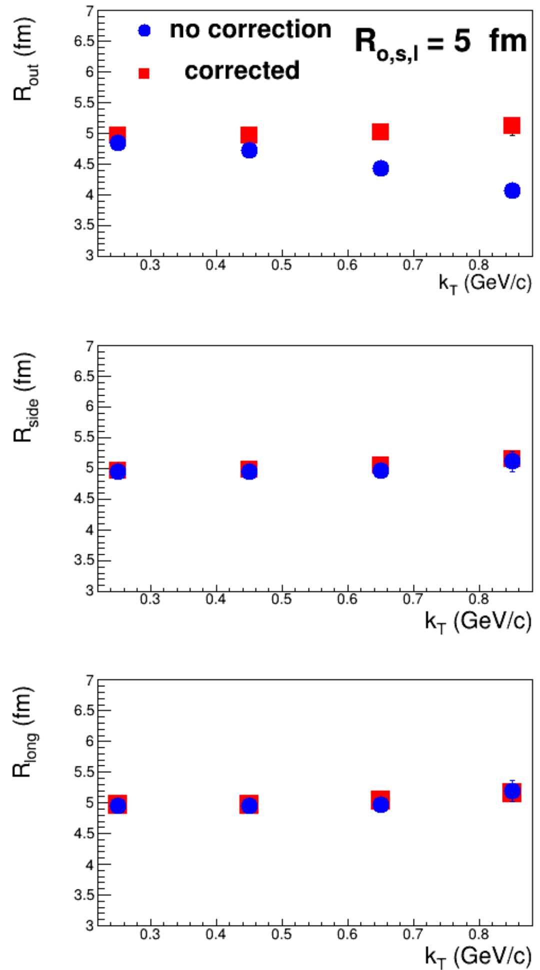
3D Gauss in LCMS **Rosl = 5 fm** ; **CF = (Dmixed, weight=QS) / Dmixed**

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

Single-track effects in femtoscopy

– n-Sigma method was tested and applied
(Alexei Chernishov (MSU student))

-- Particle misidentification
Influences only λ parameter of CF, radii do not change
CF should be corrected by pair purity, determined using single particle purity

n_σ in TPC

Measured distribution		Extracted parameter		Applied cut
$\frac{dE/dx_{TPC} - \langle dE/dx \rangle}{\sigma_E}$	→	Mean μ_E	→	$\left| \frac{dE/dx_{TPC} - \langle dE/dx \rangle}{\sigma_E} - \mu_E \right| < n_\sigma$

Since sigma-based cut is applied, it is denoted as ***n*$_\sigma$ in TPC**.

NB. *Mean value μ_E is meant to correct some systematic errors, if they are present. Otherwise it equals zero.*

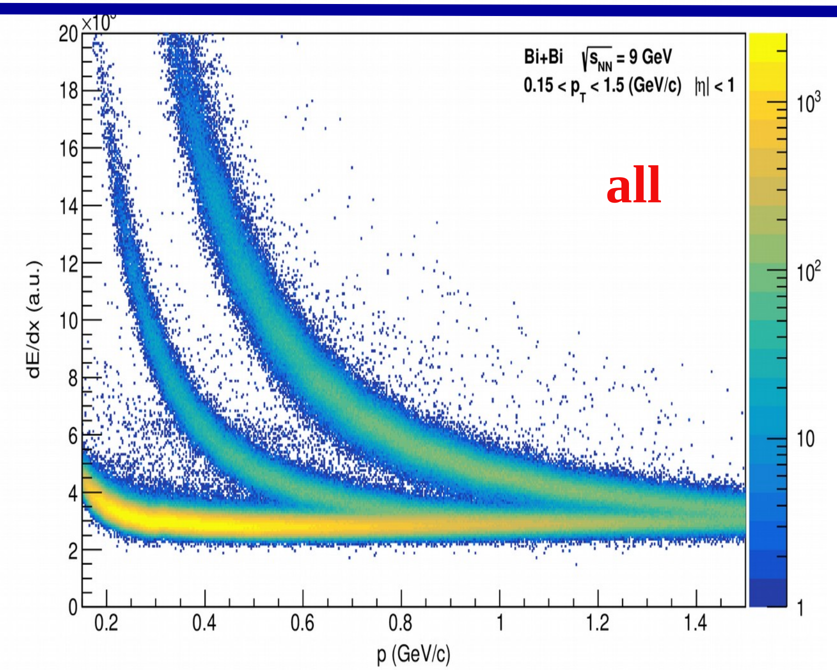
n_σ in TOF

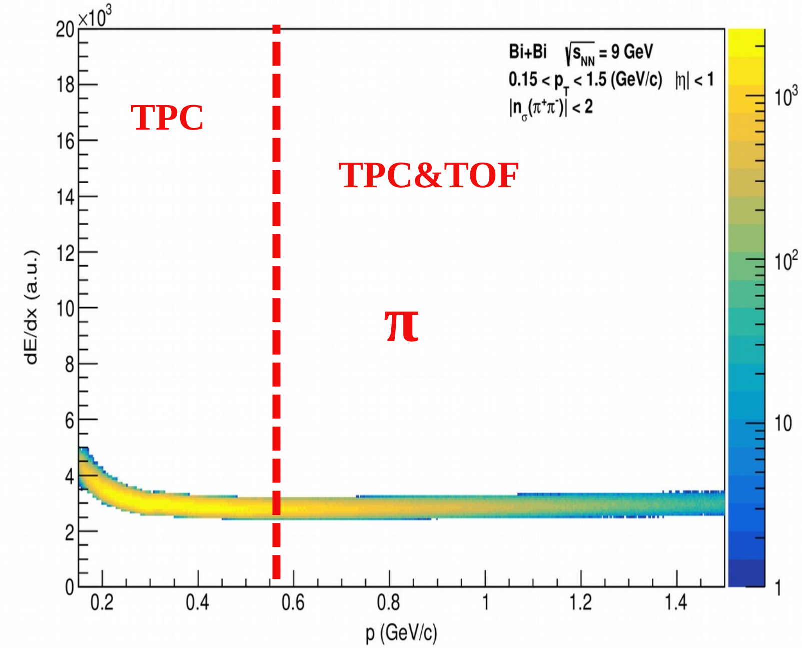
Measured distribution		Extracted parameters		Applied cut
$\frac{1/\beta_{TOF} - 1/\beta}{1/\beta}$	→	Mean μ_β Std. dev. σ_β	→	$\left\lvert \frac{1/\beta_{TOF} - 1/\beta}{1/\beta} - \mu_\beta \right\rvert < n_\sigma \sigma_\beta$
$\frac{m_{TOF}^2 - m^2}{m^2}$	→	Mean μ_m Std. dev. σ_m	→	$\left\lvert \frac{m_{TOF}^2 - m^2}{m^2} - \mu_m \right\rvert < n_\sigma \sigma_m$

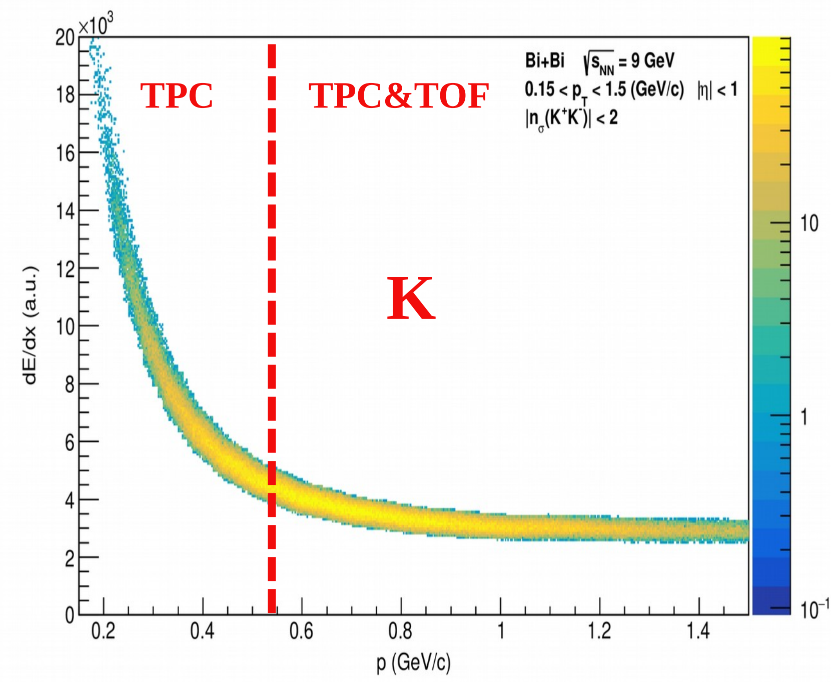
Since sigma-based cut is applied, it is denoted as $\boldsymbol{n_\sigma}$ **in TOF**.

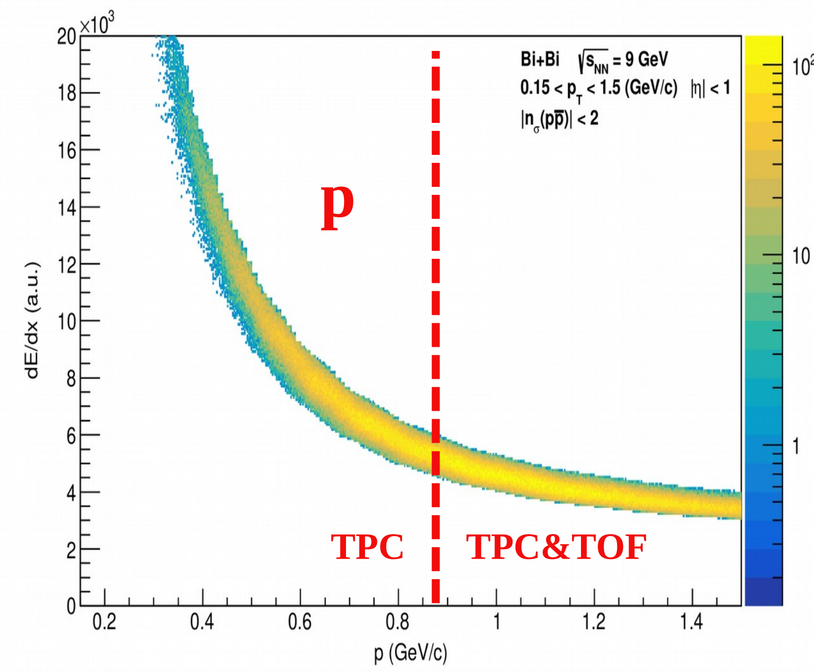
NB. *Mean values μ_β and μ_m are meant to correct some systematic errors, if they are present. Otherwise they equal zero.*

Particle selection by TPC dE/dx(p)

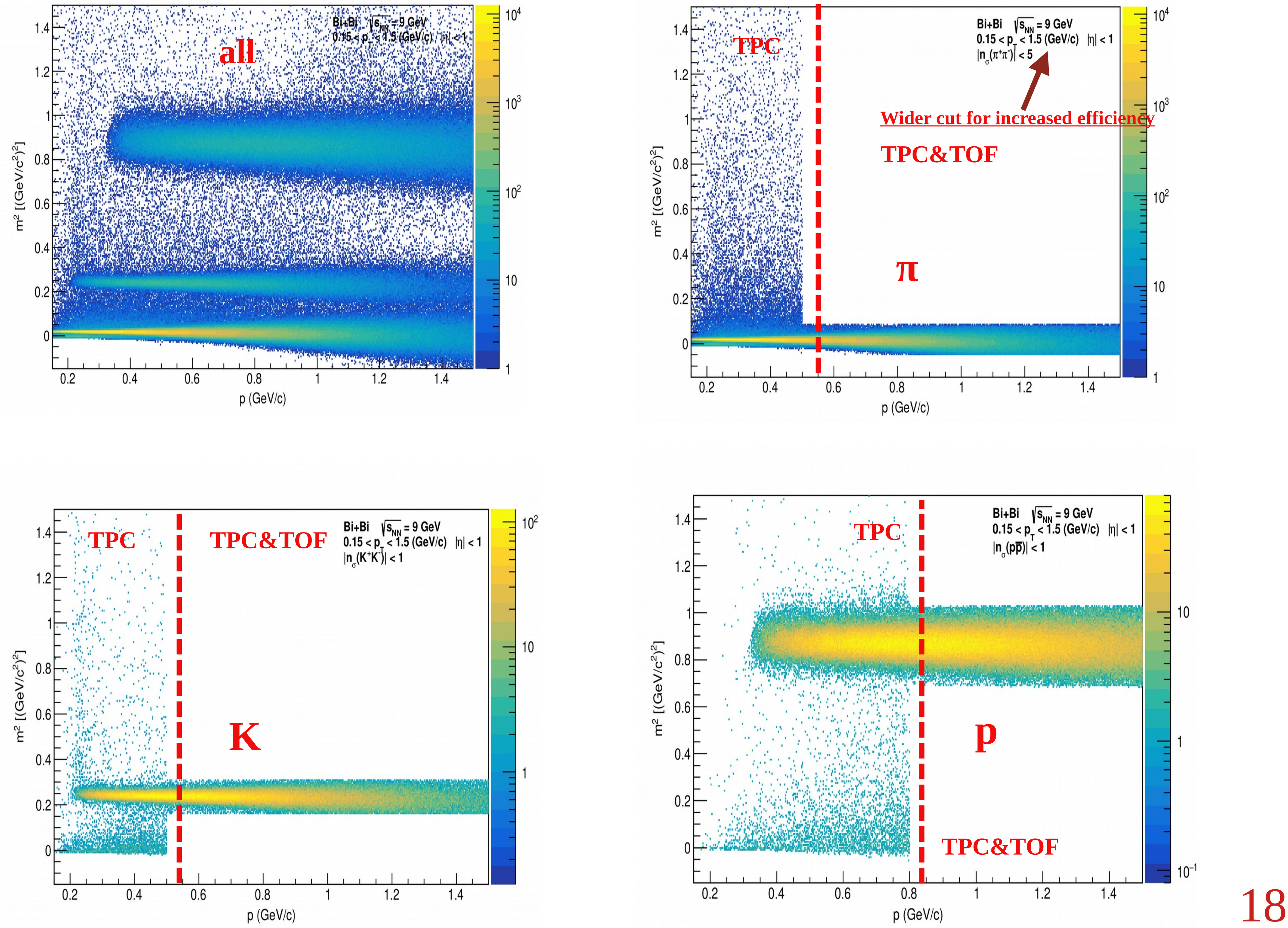








Particle selection by TOF $m^2(p)$



Efficiency & Purity & Contamination

$$\epsilon_i = \frac{dN_{ii}^{meas}/dp}{dN_i/dp} \quad - \quad efficiency$$

$$f_i(p) = \frac{dN_{ii}^{true}/dp}{dN_i^{meas}/dp} \quad - \quad purity$$

$$cont_{ij}(p) = \frac{dN_j^{false}/dp}{dN^{meas}/dp} \quad - \quad contamination$$

N_i: *all generated particles of specie i*

N_{ii}^{meas}: *particles identified as specie i* $(within\ N_i)$

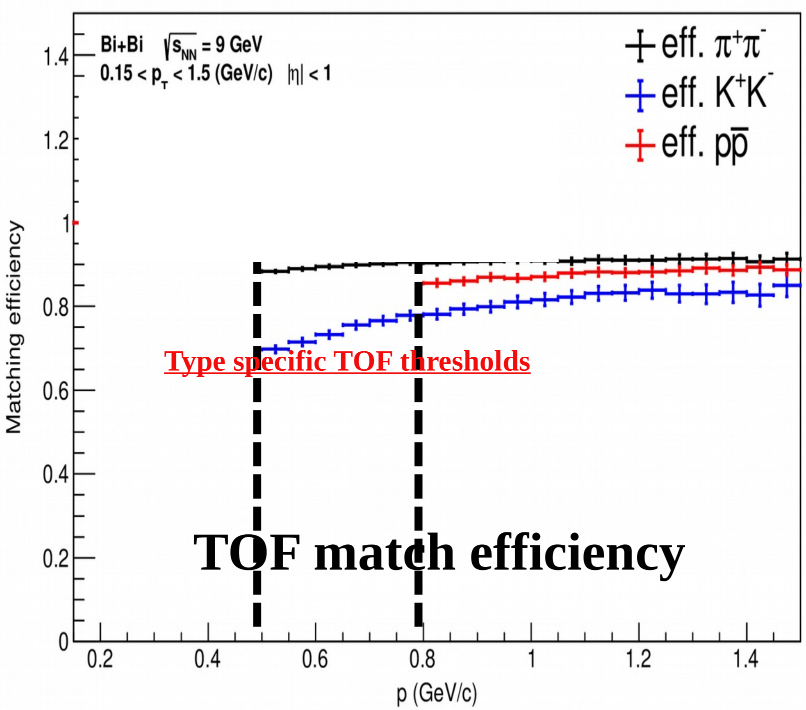
N_i^{meas}: *all particles identified as specie i*

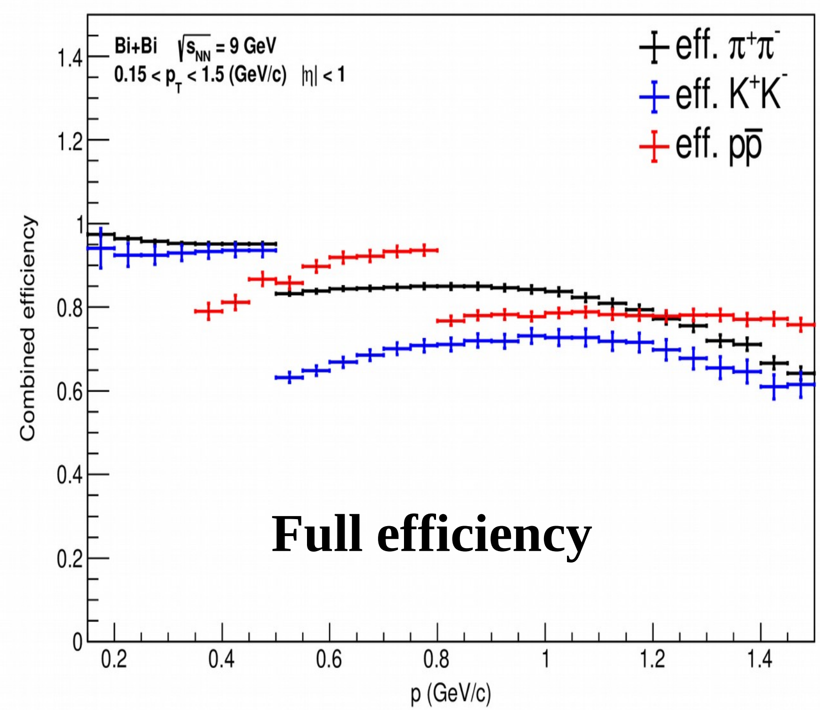
N_{ii}^{true}: *particles identified as specie i, are actually i* $(within\ N_i^{meas})$

N_i^{false}: *particles misidentified as specie j*

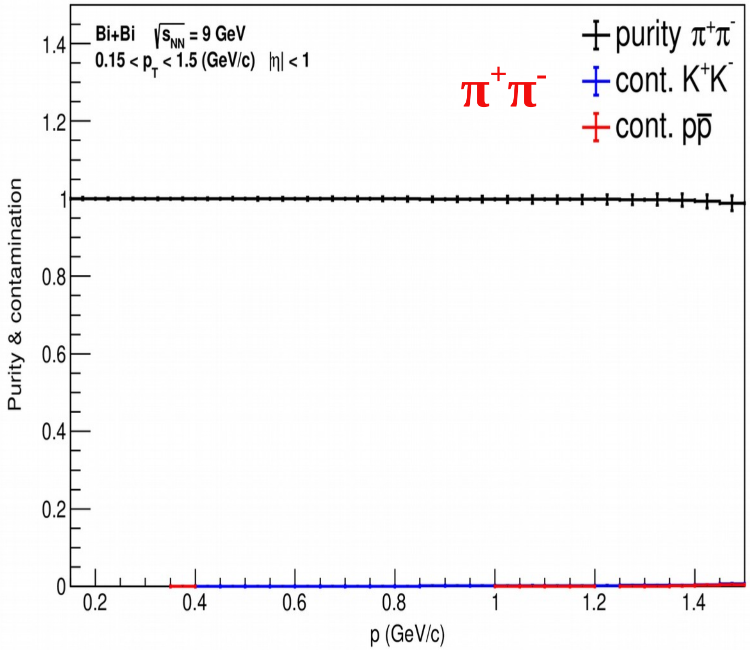
N_{ii}^{meas}: *all particles identified as specie i*

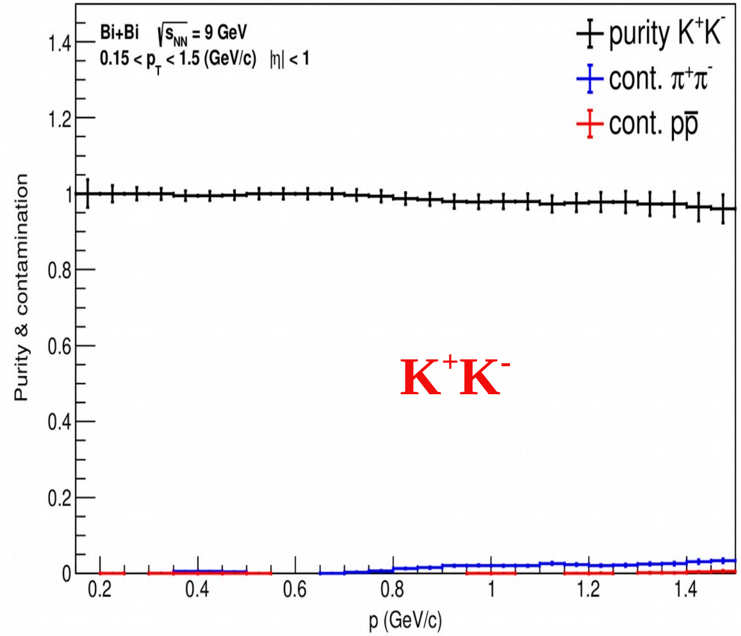
Tracks are required to match TOF hit for track with momentum greater than the threshold.

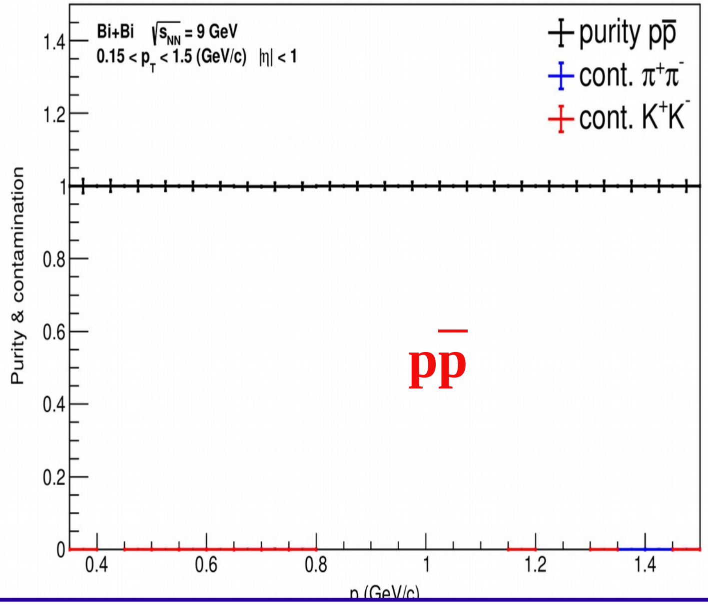




Purity & contamination







- n-Sigma method (used by ALICE & STAR) was successfully tested;
- Obtained small particle misidentifications are non-realistic;
- But n-sigma procedure can be applied for any realistic simulations;
- CF can be corrected by pair purity, determined using single particle purity

Two-track effects in femtoscopy

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

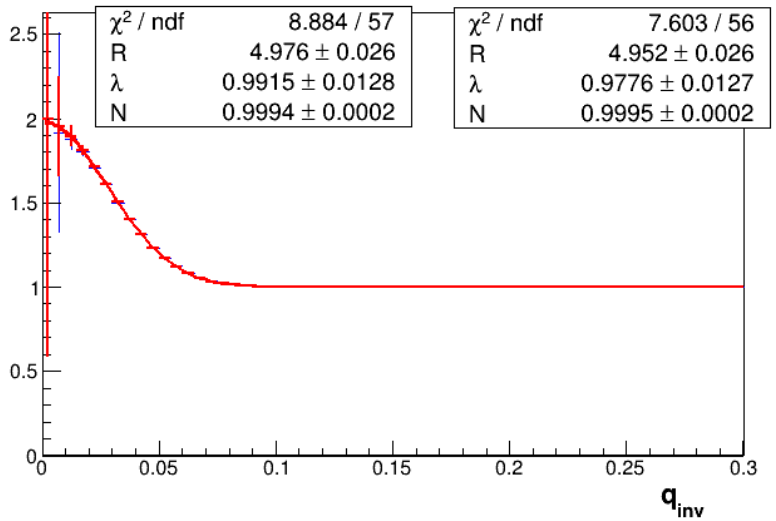
Communication with tracking group is ongoing
(many thanks to Alexander Zinchenko !)

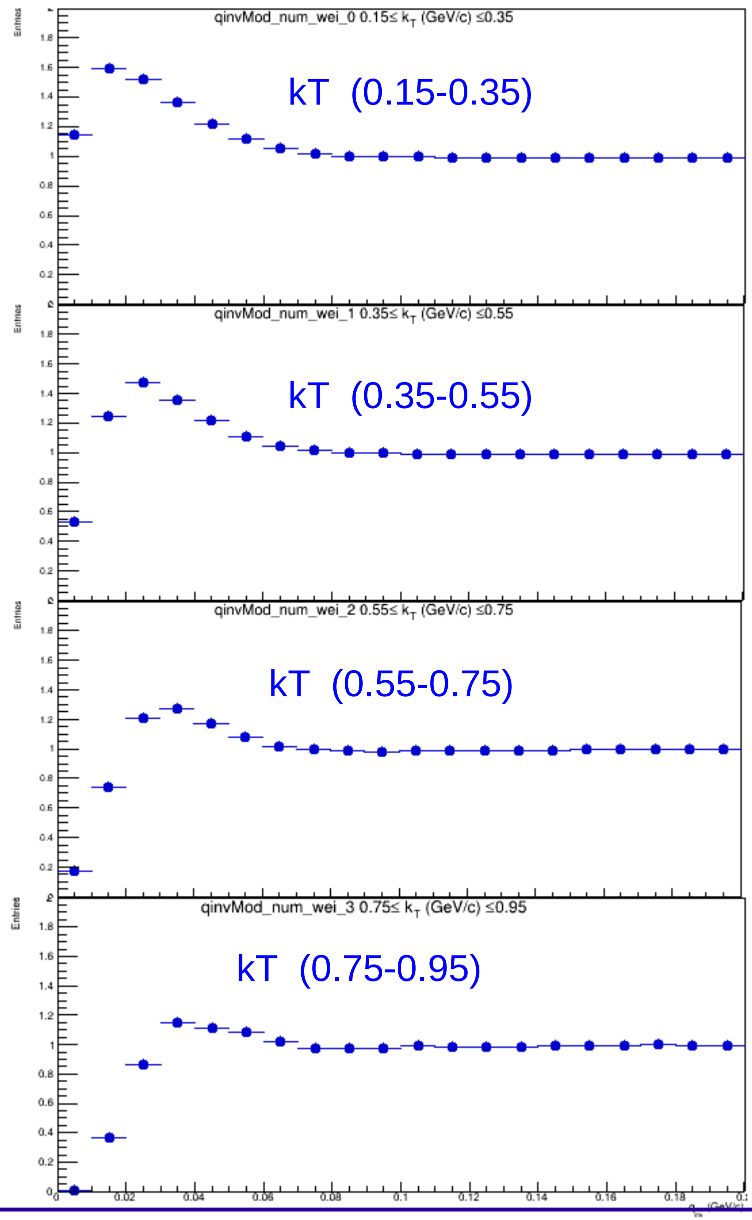
1D Correlation Function CF(q_{inv})

Simulated : Gauss in PRF, R_{inv} = 5 fm

Reconstructed

CF = (Nsame, weight=QS)/ Dmixed



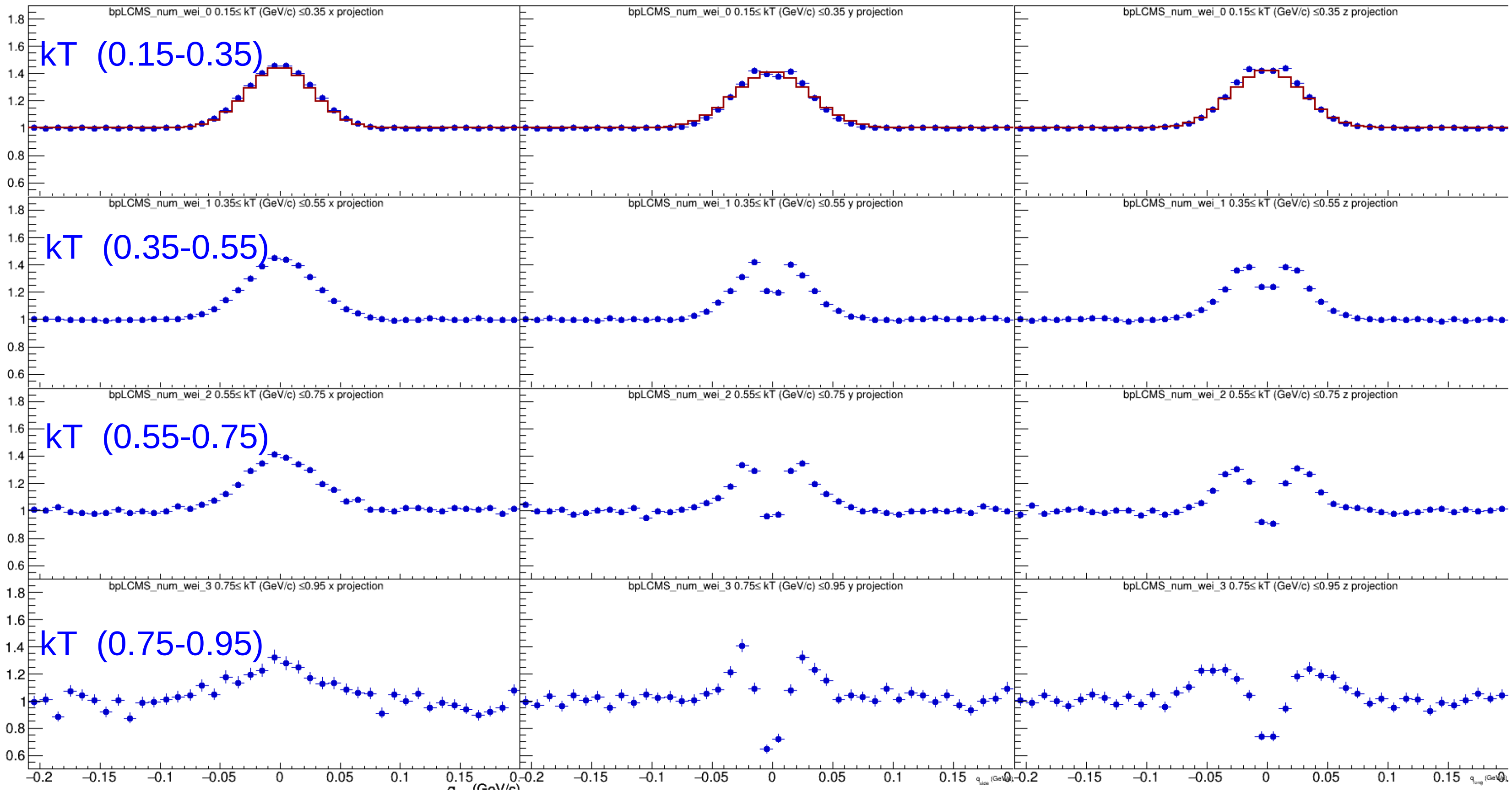


- The deep in CF due to the track-merging effect increases with k_T
- Influence of the track-merging effect is extremely strong (especially at k_T>0.55 GeV/c)

3D Correlation Function

Simulated : Gauss in LCMS, $R_{iout} = R_{side} = R_{ilong} = 5$ fm

CF = (Nsame, weight=QS)/ Dmixed

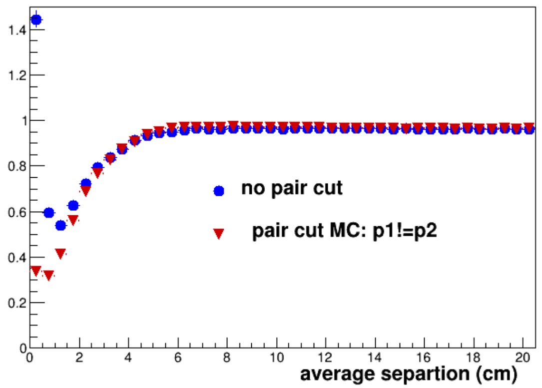


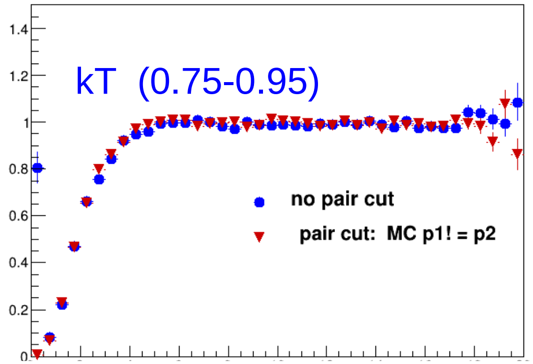
Projections of the three-dimensional ππ−correlation functions. When projecting on one axis the other two components were required to be within (-0.04,0.04) GeV/c.

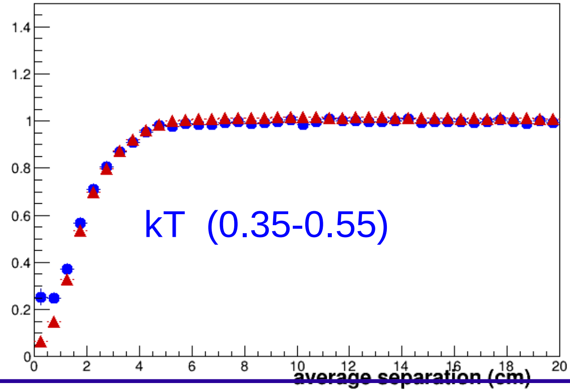
- Strong "merging-like" effect increases with k_T

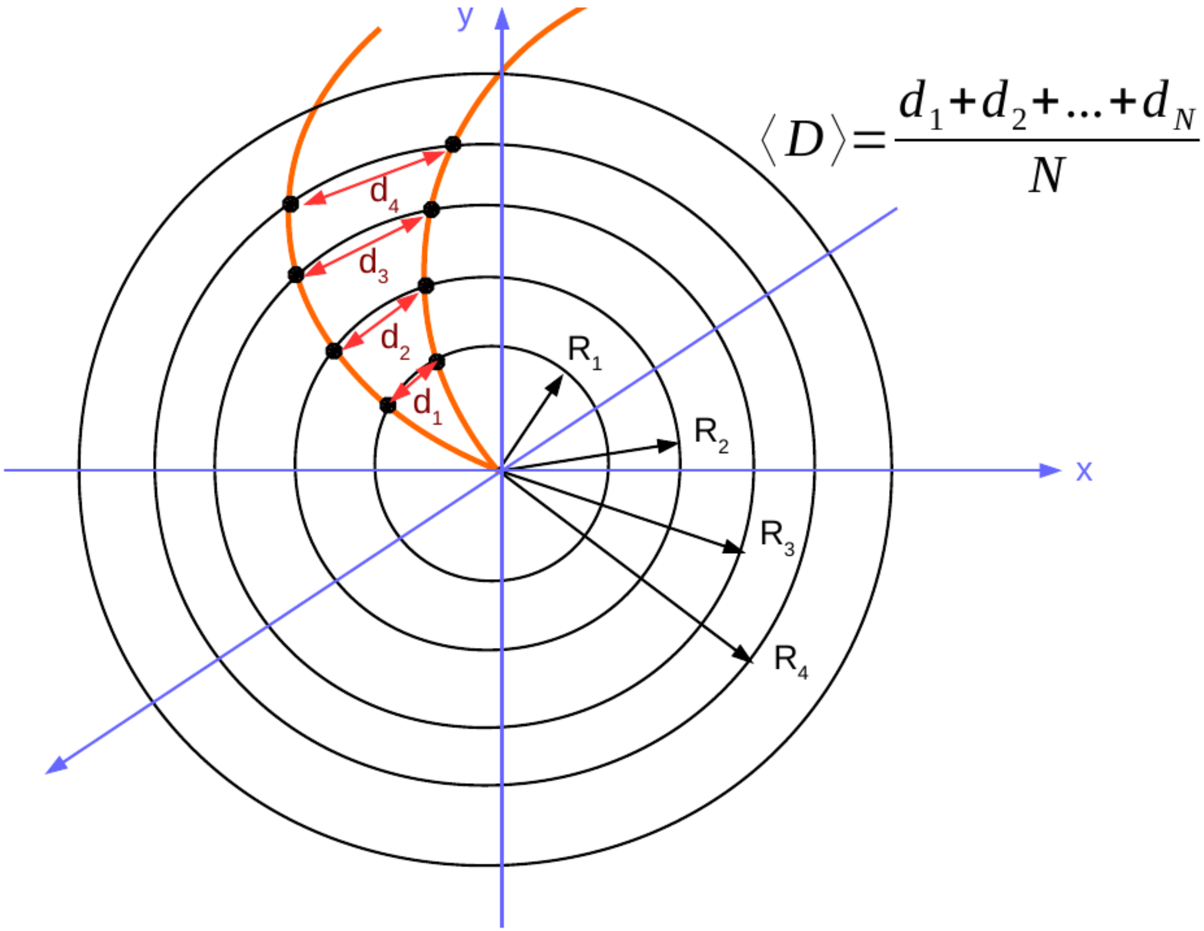
Average separation in TPC

CF = Nsame/ Dmixed







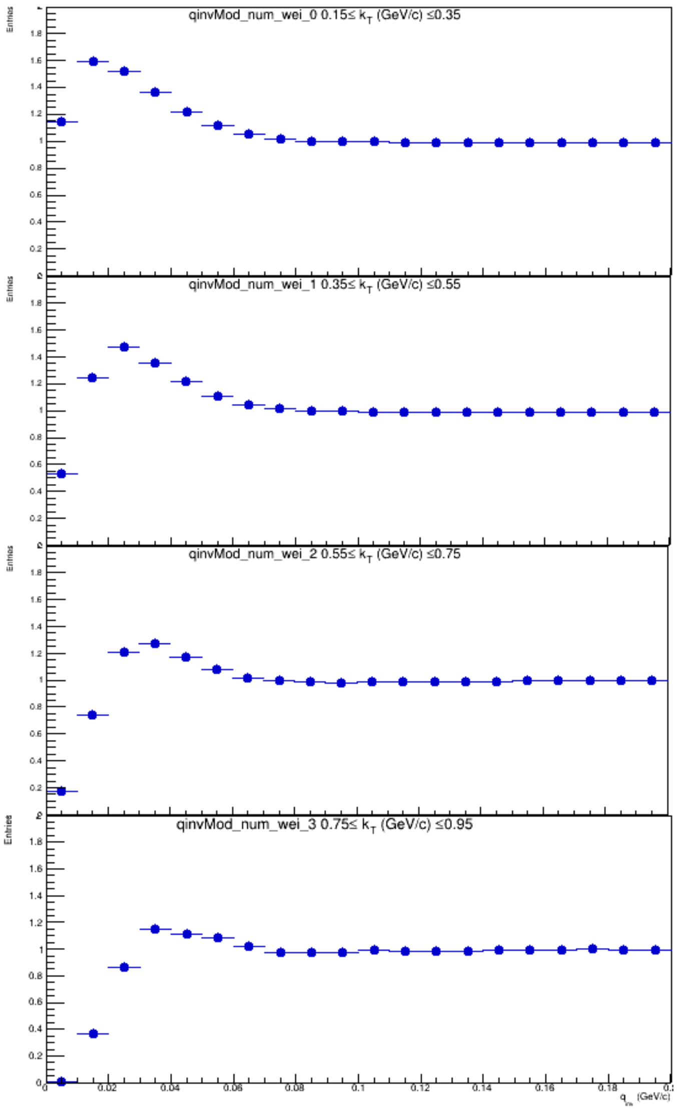


- average separation cut (>6 cm) was chosen for all k_T intervals

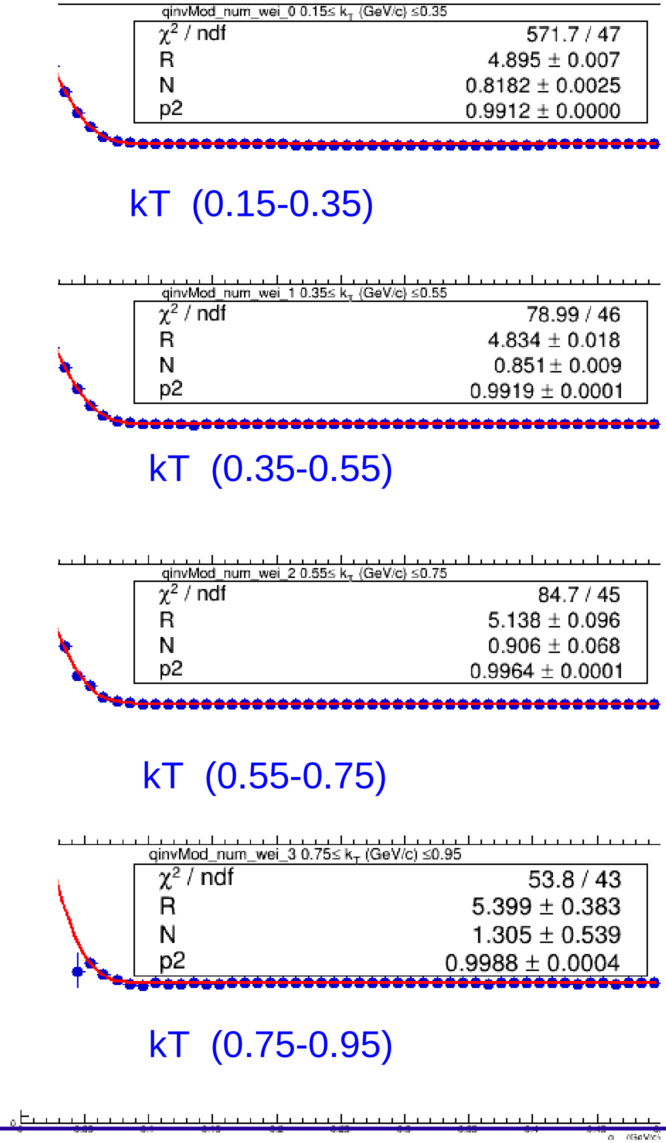
1D CF(q_{inv}) with two-track spatial average separation cut

CF = (Nsame, weight=QS)/ Dmixed Gauss in PRF Rinv = 5 fm

No two-track cuts (No TTC)



Average separation > 6 cm



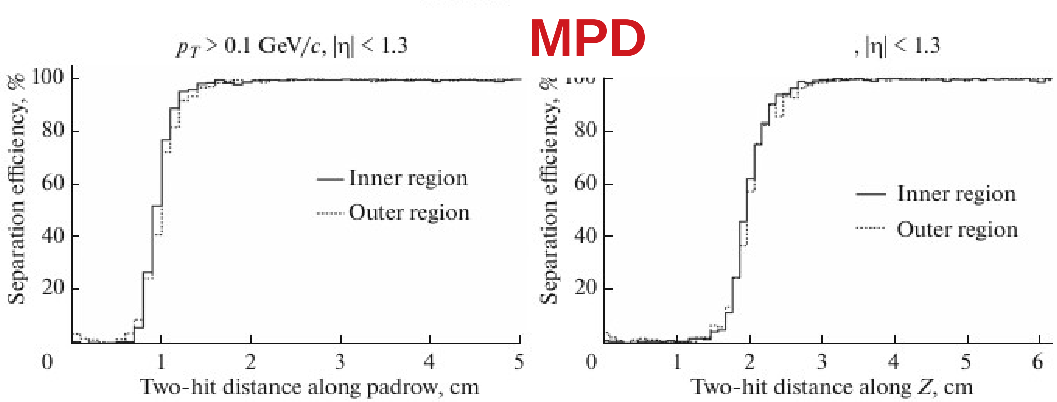
- Influence of the track-merging effect is extremely strong (especially at k_T>0.55 GeV/c)
- Average separation cut significantly removes pairs at small q_{inv} especially at k_T> 0.55 GeV/c
- For a moment impossibility to perform even 1D femtoscopic analysis at k_T> 0.55 GeV/c

Why ?

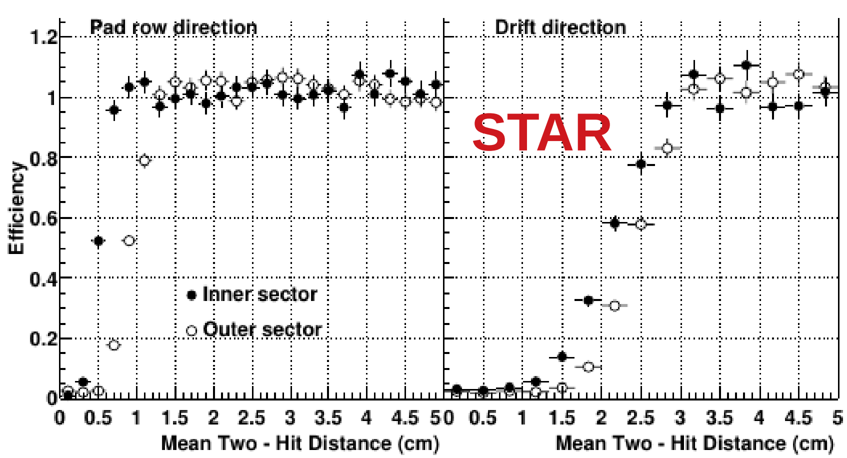
- two-hit resolution (comparable with STAR)
- two-track resolution ?

Two Hits Separation Efficiency (STAR / MPD)

Parameter	MPD	STAR
Magnetic field	0.5 T	same
Drift gas	P10 (90% Argon + 10% Methane)	same
Drift velocity	5.45 cm/μs	same
Transverse diffusion	(σT) 185 μm/ cm	230 μm/ cm
Longitudinal diffusion	(σL) 320 μm/ cm	360 μm/ cm
Pad size	5 × 12 mm2 (27 rows) + 5 × 18 mm2 (26 rows)	2.85 x 11:5 mm2 (13 rows) +6.20 x 19.5 mm2 (32)
Outer radius of the drift volume	133 cm	200 cm
Inner radius the drift volume	34 cm	50 cm
Length of drift volume	170 cm (each half)	210 cm (each half)



"Towards of a Realistic Monte Carlo Simulation the MPD Detector at NICA"
V. Kolesnikov, A. Mudrokh, V. Vasendina, and A. Zinchenko
Physics of Particles and Nuclei Letters, 2019, Vol. 16, No. 1, pp. 6



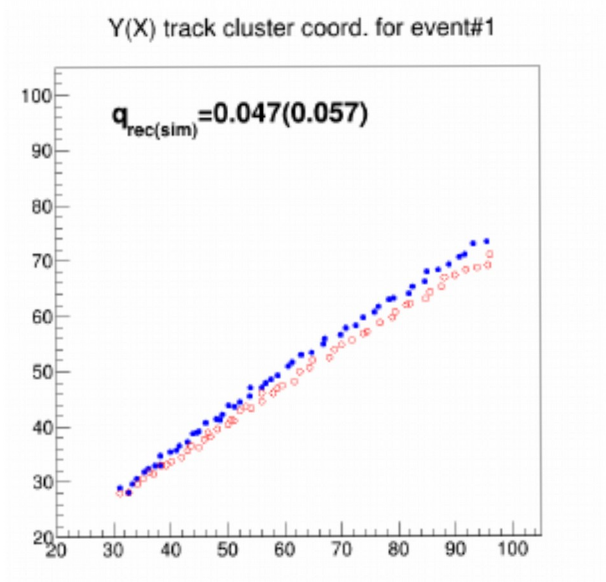
"The STAR time projection chamber: a unique tool for studying high multiplicity events at RHIC"
Nuclear Instruments and Methods in Physics Research A 499 (2003) 659–678

Characteristics of MPD TPC are comparable with STAR TPC → two hits resolutions are comparable

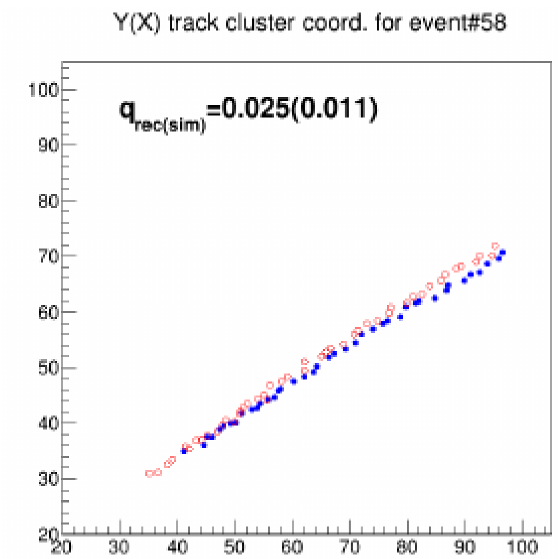
Two-track efficiency with pair of isolated tracks

- Box generator was used to simulate $\pi\pi$ pair with close momenta
- Efficiency of two-pair reconstruction strongly decrease with pair pT
  - Global tracks (no vertex constrains)
  - Primary (vertex constrained tracks)

Well reconstructed as 2 tracks

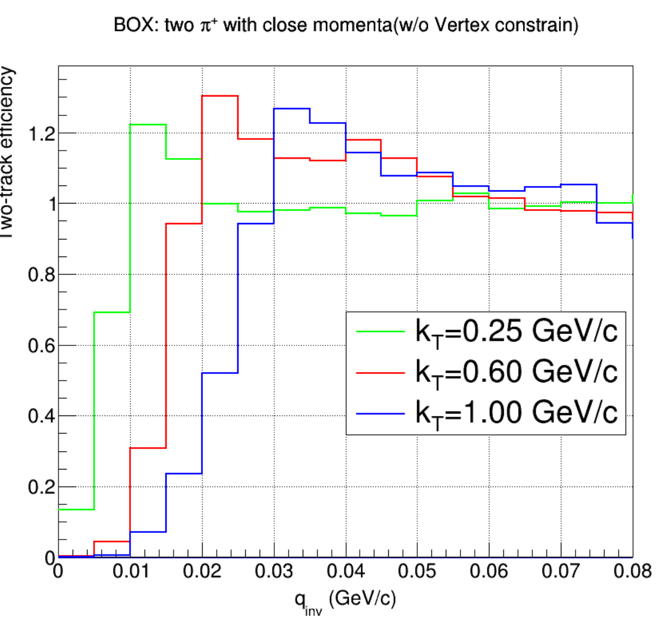


Still reconstructed as 2 tracks

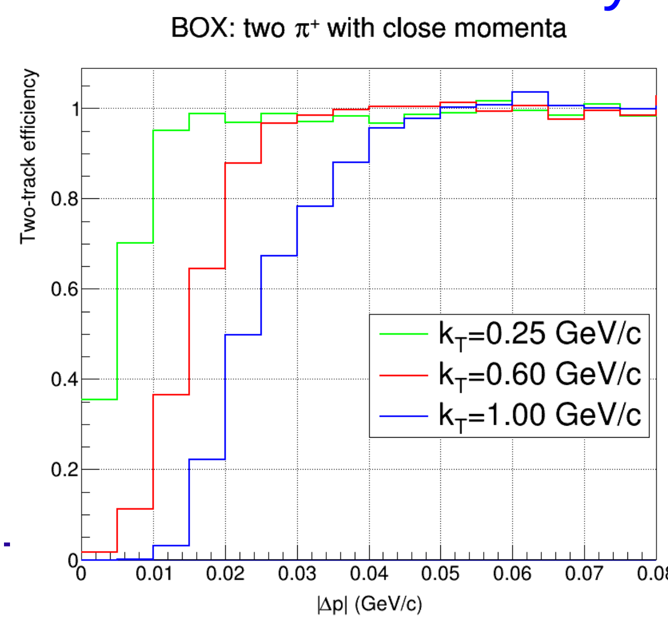


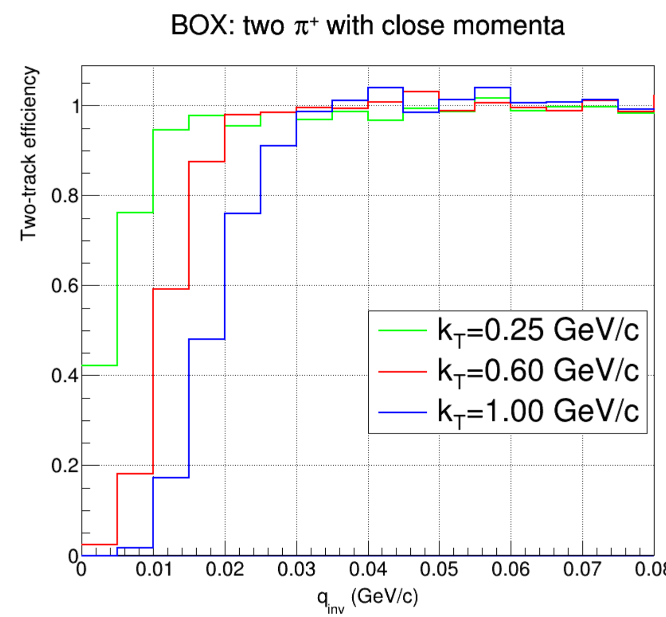
Efficiency of two-tracks reconstruction with:

Global tracks



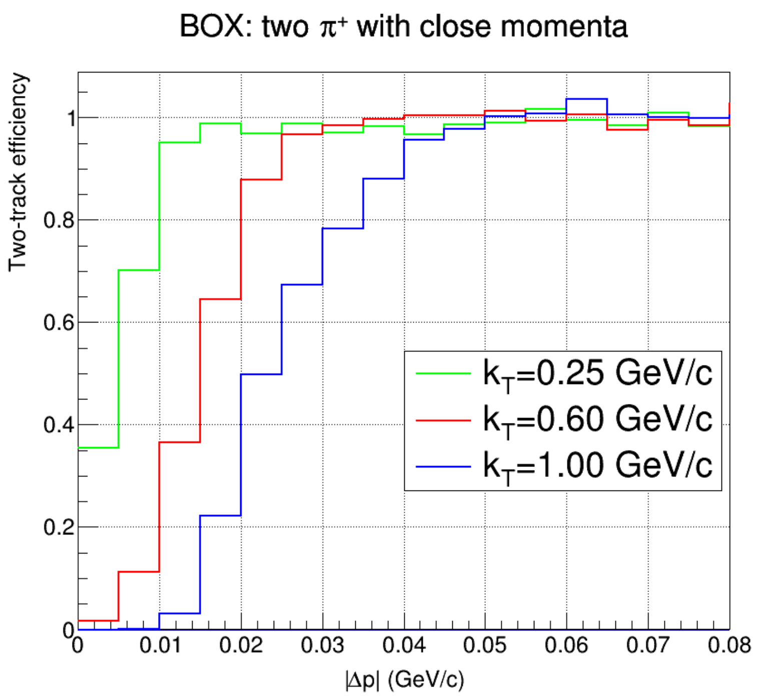
Primary tracks



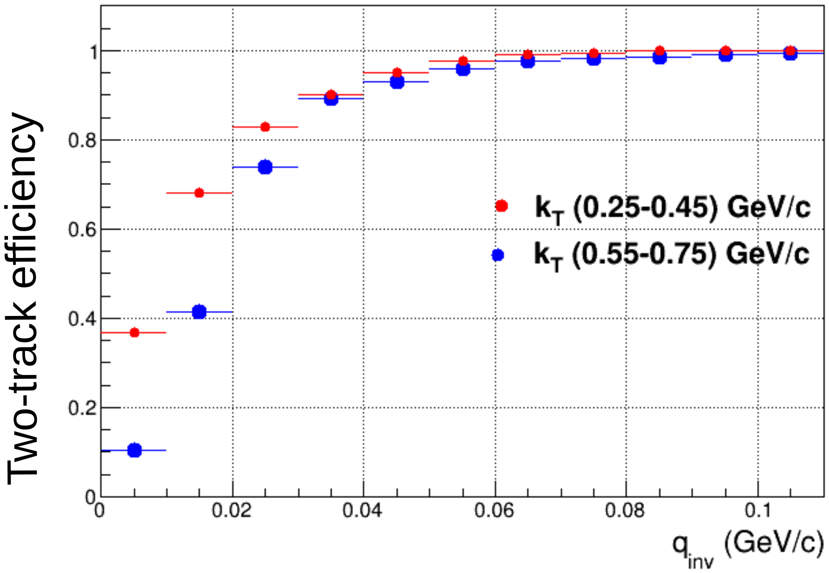


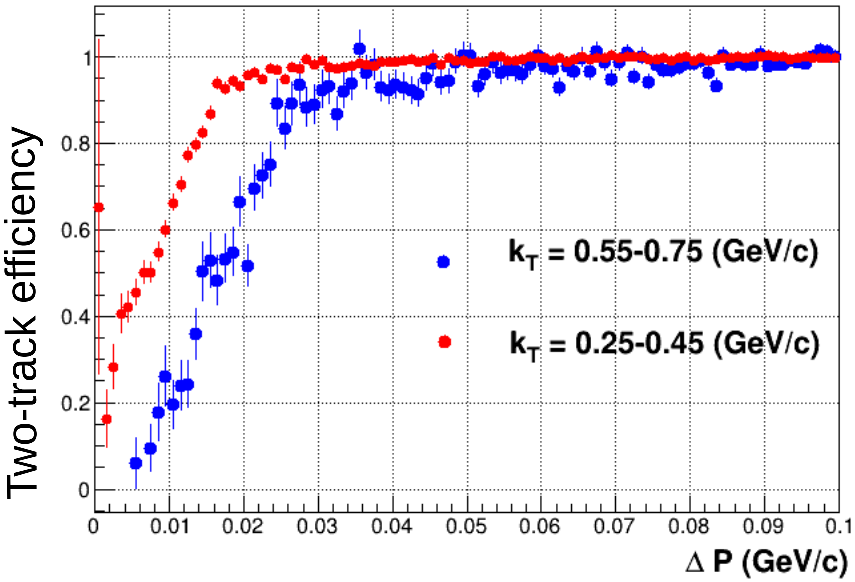
Two-track efficiency in AuAu (BiBi)

- UrQMD generator was used
- Efficiency of two-track reconstruction strongly decrease with pair pT
- Efficiency of two-track reconstruction only slightly depends on colliding system, but is mainly determined by the efficiency of reconstruction of two isolated tracks



Efficiency of two-tracks reconstruction





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

- Misidentification
  - n-Sigma PID method was succesfully tested
  - CF can be corrected by pair purity, determined using single particle purity

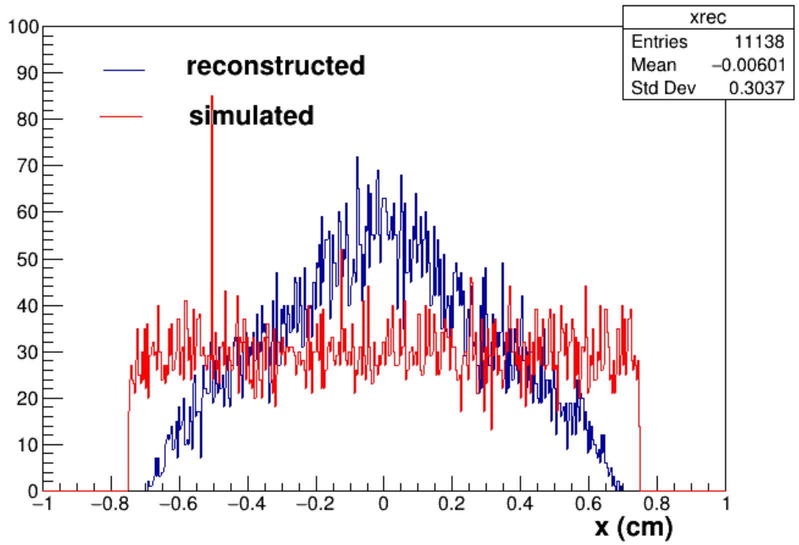
- One track is reconstructed as two (track splitting):
  - Observed at small relative momentum
- Two tracks reconstructed as one (track merging):
  - Strong effect & Depends on k_T of the pair
  - To study femtoscopic correlation for pions at k_T> 0.55 GeV/c the modification of tracking procedure for close tracks is needed

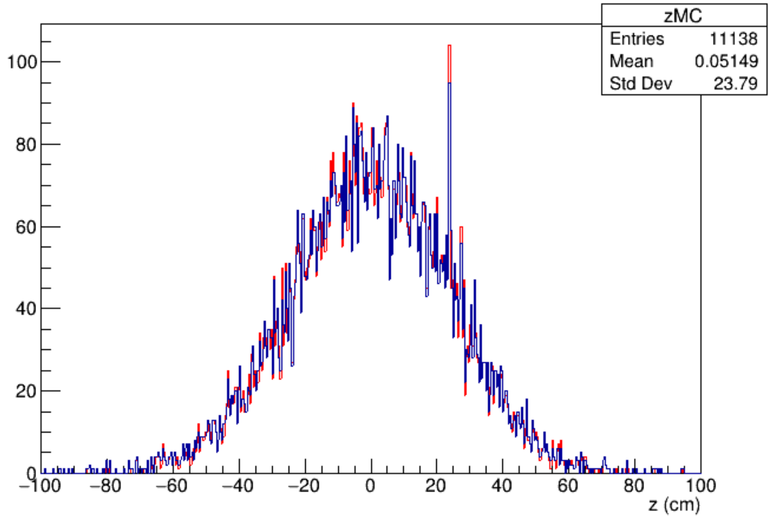
    Communication with tracking group is ongoing many thanks to Alexander Zinchenko !

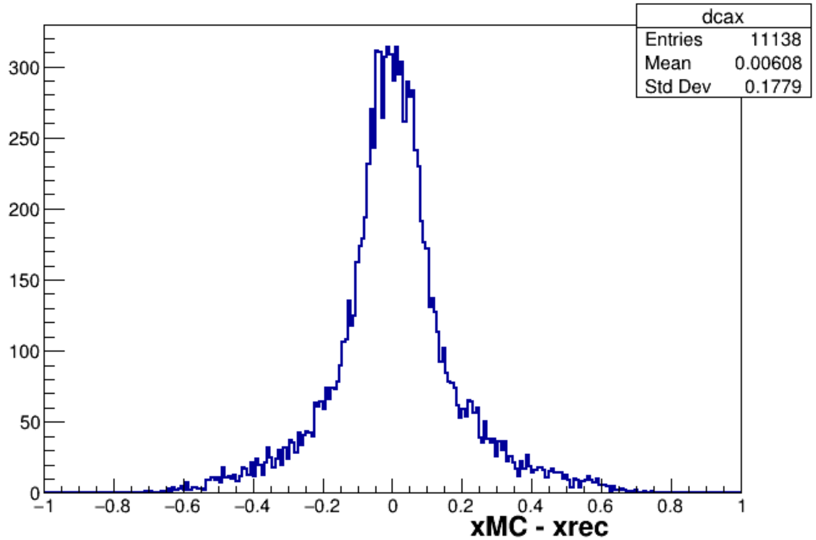
MPD provides a good opportunity to study sophisticated femtoscopic observables: e.g. rare particle pairs more sensitive to EoS

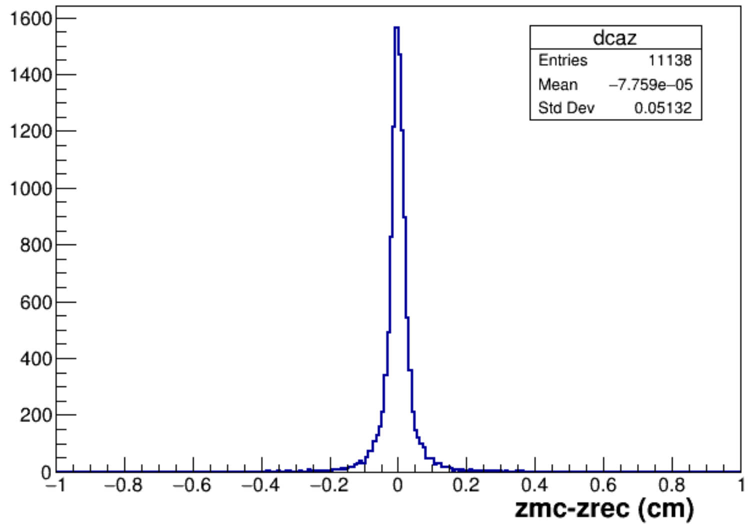
Additional slides

Vertex {X,Y,Z} – distributions



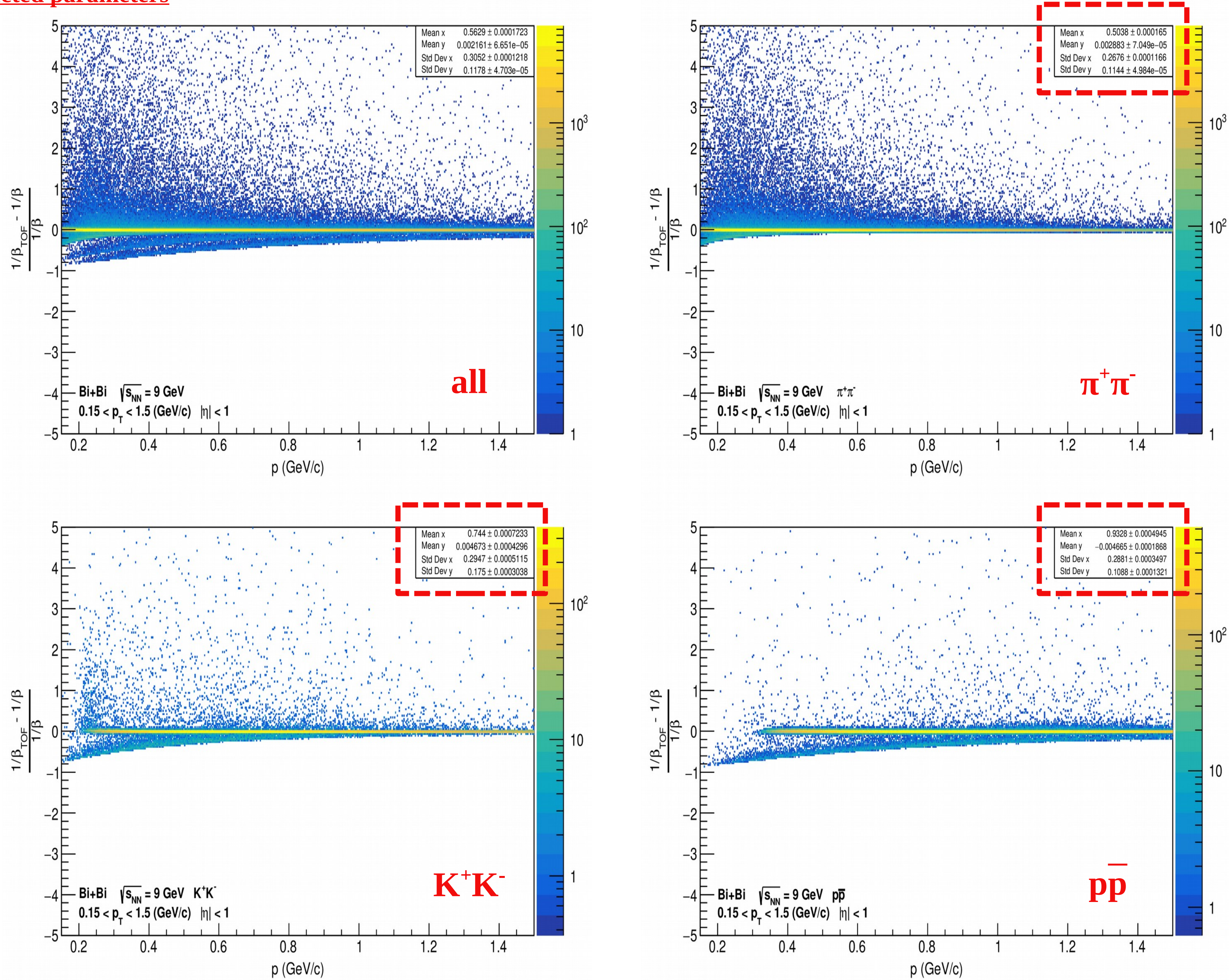


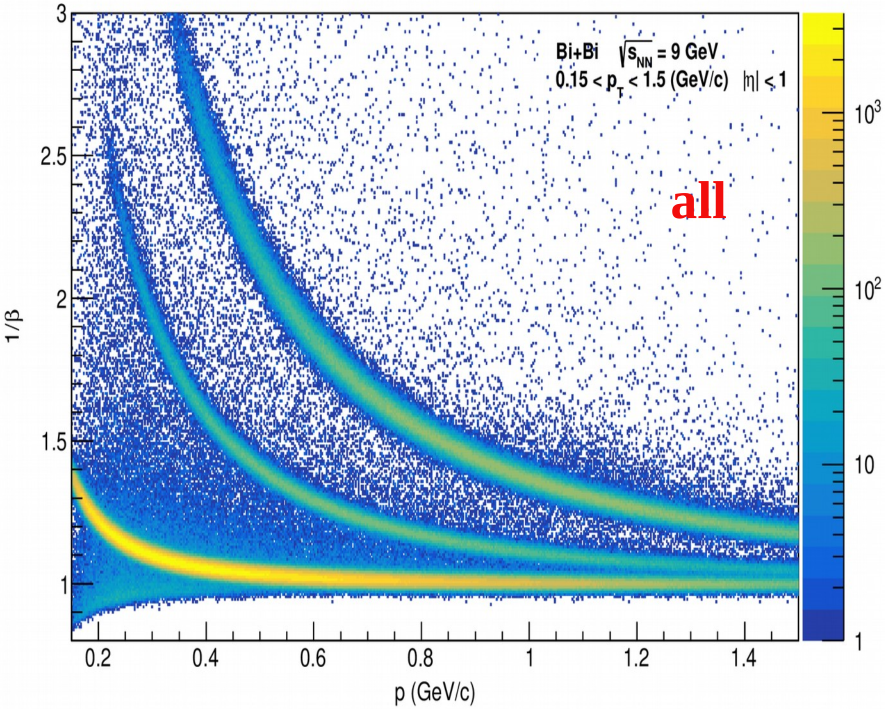


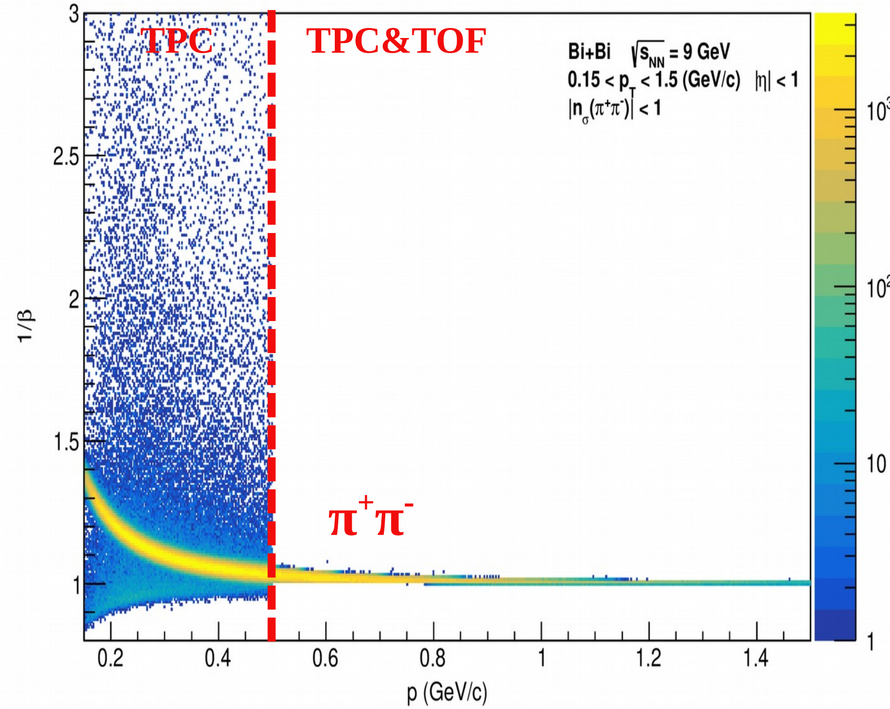


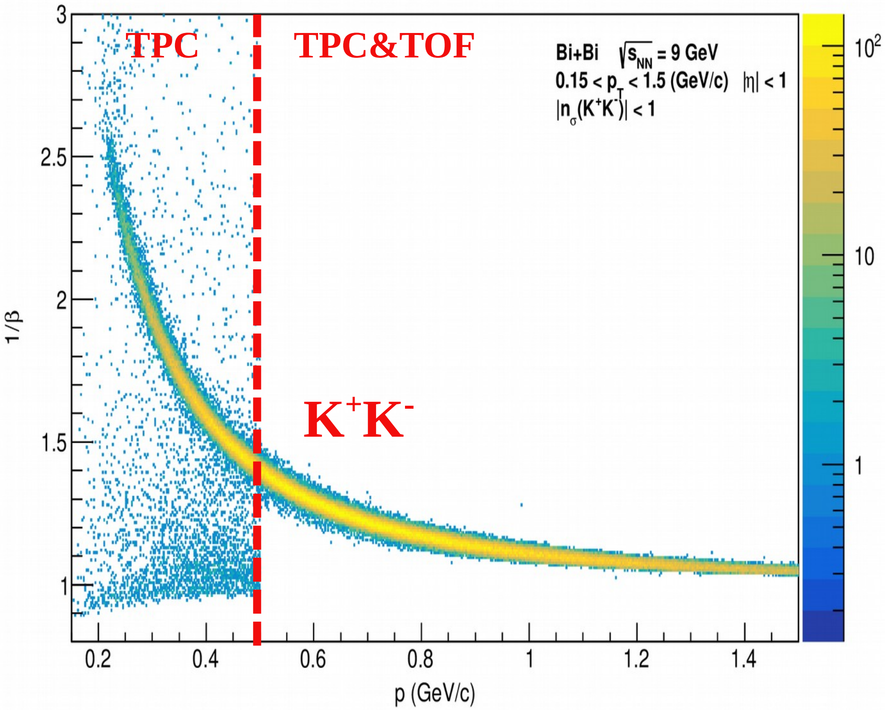
- The same effect is seen for y-coordinate of primary vertex.

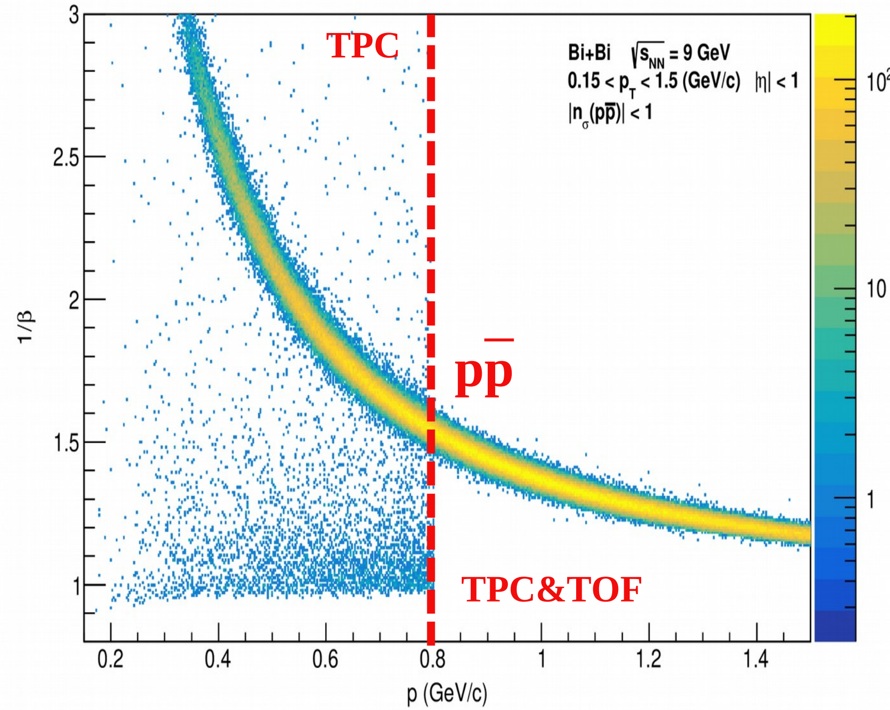
Extracted parameters




Bi+Bi $\sqrt{s_{NN}}$ = 9 GeV
0.15 < p_T < 1.5 (GeV/c) |η| < 1
all
1/β
p (GeV/c)

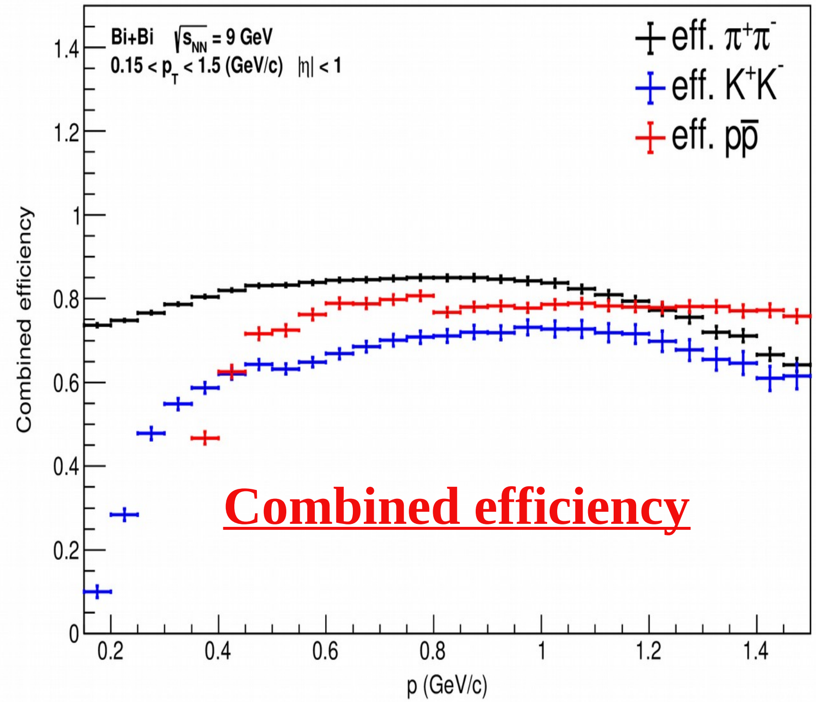

TPC
TPC&TOF
Bi+Bi $\sqrt{s_{NN}}$ = 9 GeV
0.15 < p_T < 1.5 (GeV/c) |η| < 1
$|n_\sigma(\pi^+\pi^-)| < 1$
$\pi^+\pi^-$
1/β
p (GeV/c)

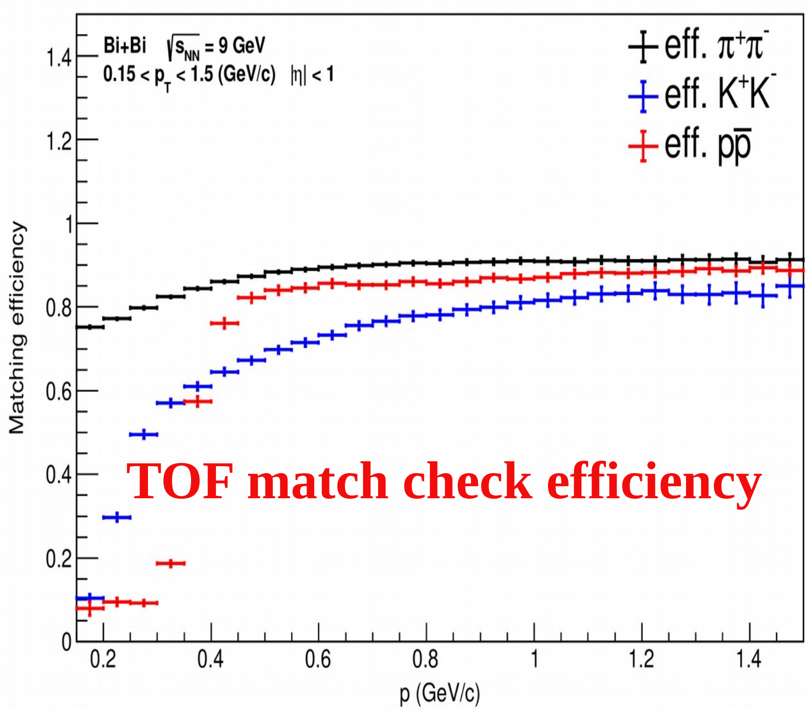

TPC
TPC&TOF
Bi+Bi $\sqrt{s_{NN}}$ = 9 GeV
0.15 < p_T < 1.5 (GeV/c) |η| < 1
$|n_\sigma(K^+K^-)| < 1$
K^+K^-
1/β
p (GeV/c)

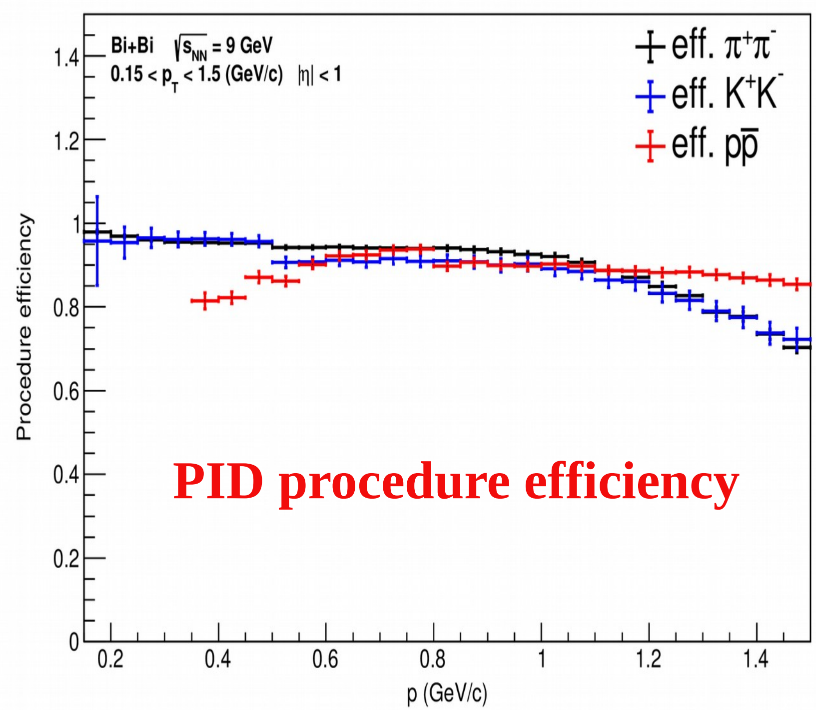

TPC
TPC&TOF
Bi+Bi $\sqrt{s_{NN}}$ = 9 GeV
0.15 < p_T < 1.5 (GeV/c) |η| < 1
$|n_\sigma(p\bar{p})| < 1$
$p\bar{p}$
1/β
p (GeV/c)

«Crude» TOF match check

All tracks are required to have a TOF match – significantly decreases combined efficiency at low momenta, **not preferred.**

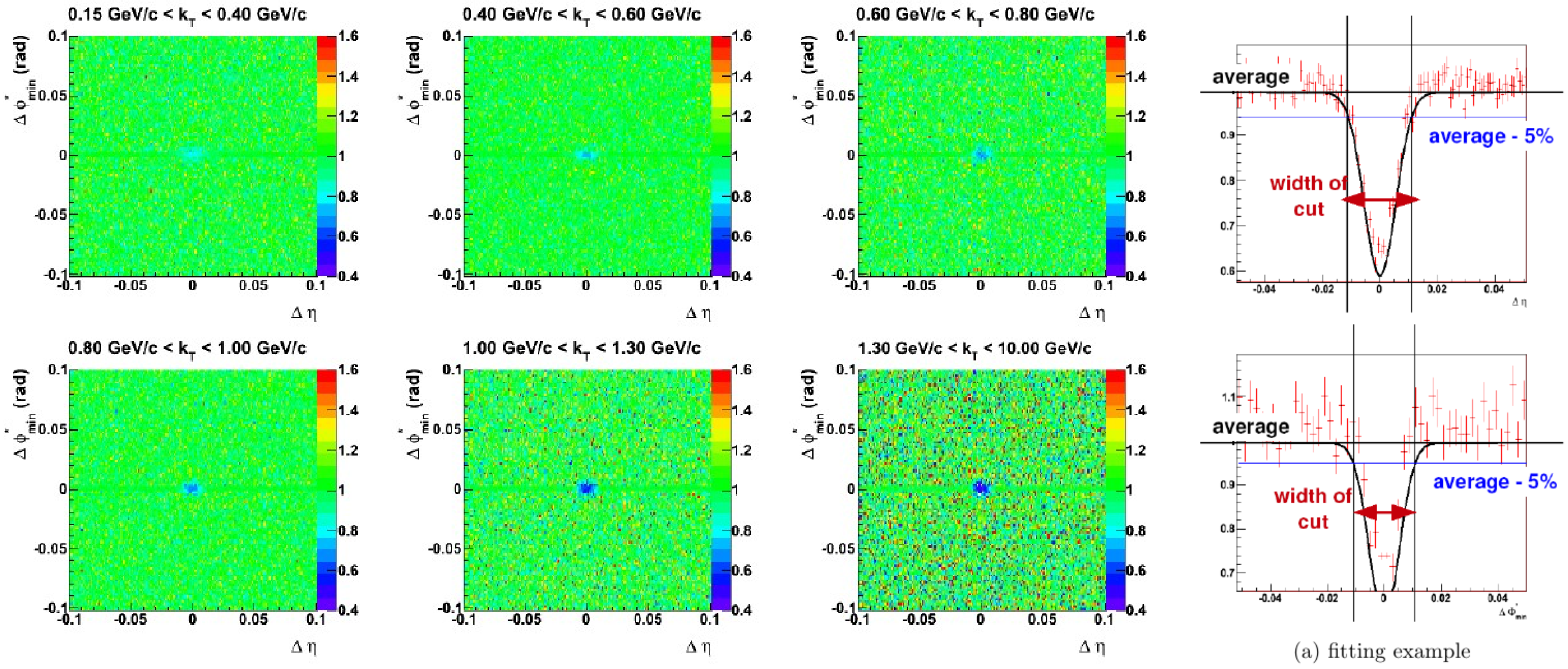






ALICE ΔηΔφ* min – distributions

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)

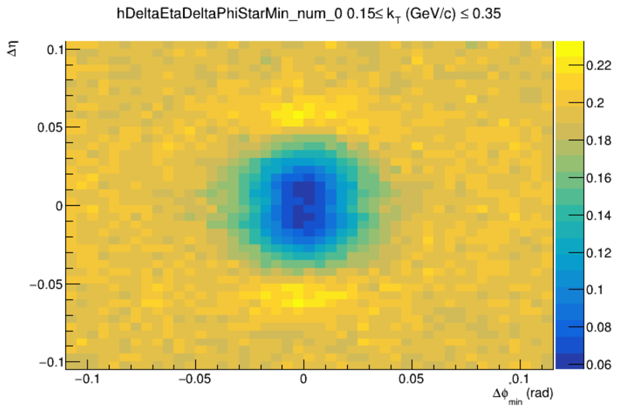
Δη-Δφ* with MPD reconstructed tracks

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

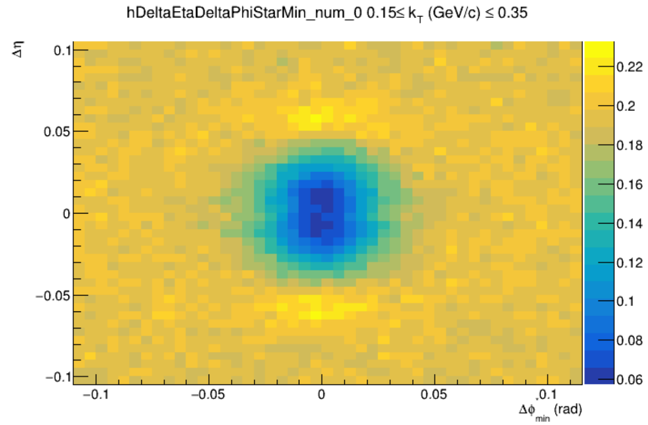
R is a given cylindrical radius

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

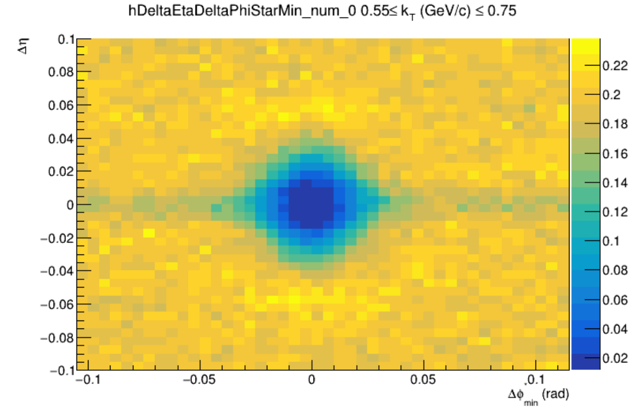
kT (0.15-0.35) GeV/c, R=0.65 m



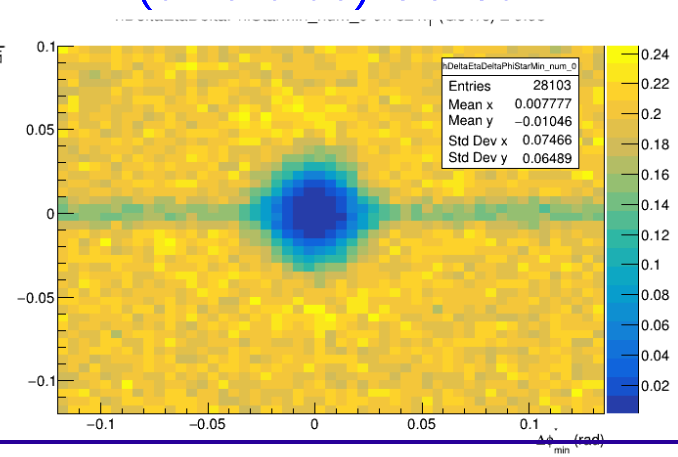
kT (0.15-0.35) GeV/c

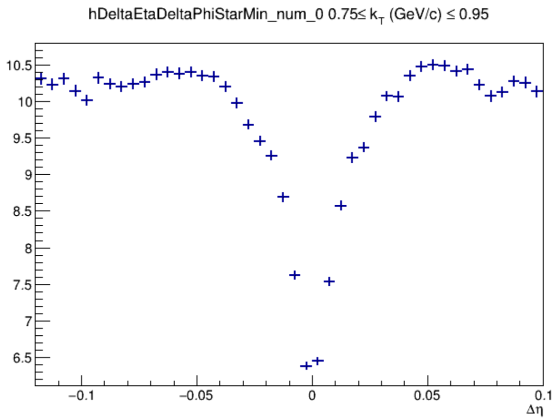


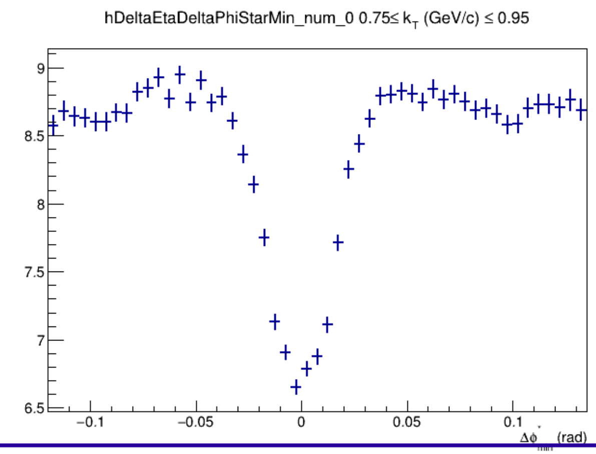
kT (0.55-0.75) GeV/c



kT (0.75-0.95) GeV/c







No TTC : ΔηΔφ* distributions (TPC+pdg)

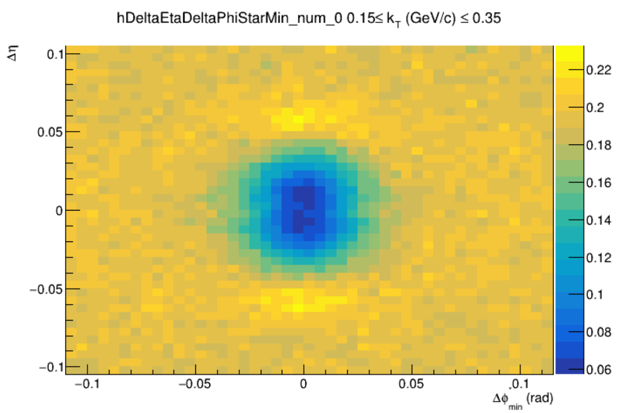
Δη-Δφ* with MPD reconstructed tracks

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

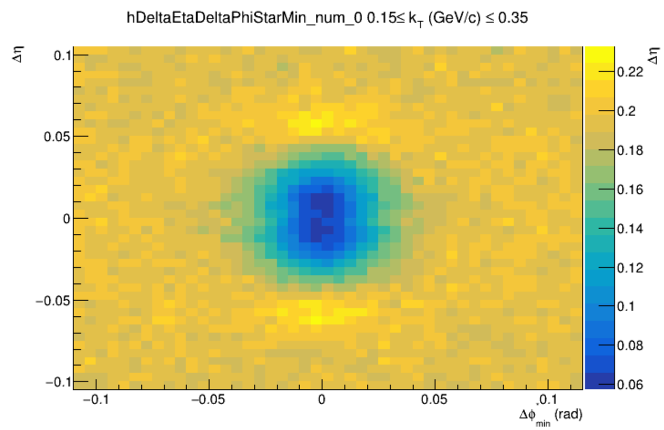
R is a given cylindrical radius

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

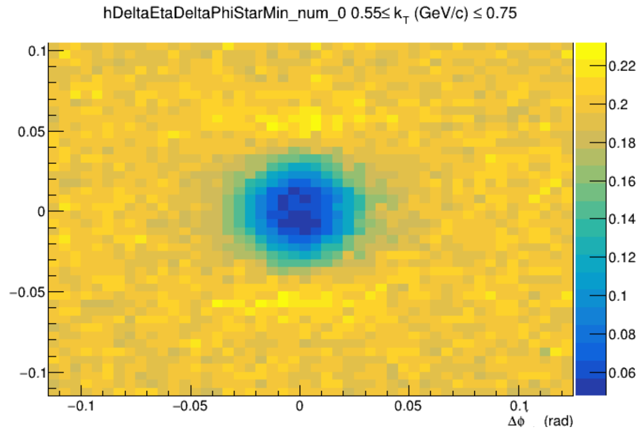
kT (0.15-0.35) GeV/c, R=0.65 m



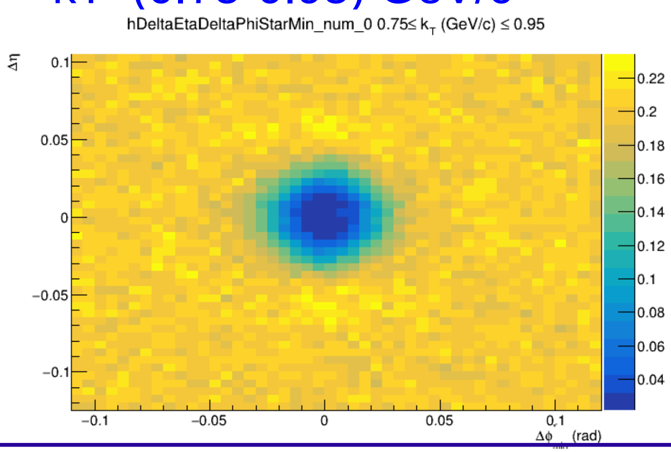
kT (0.15-0.35) GeV/c

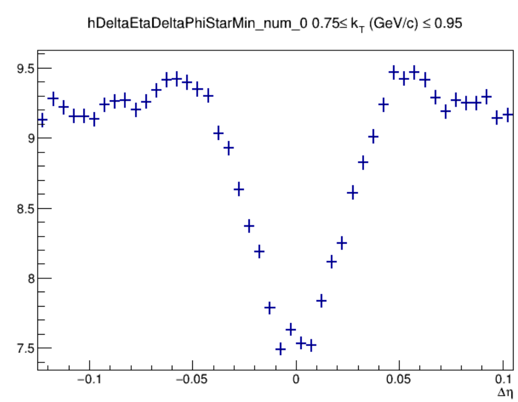


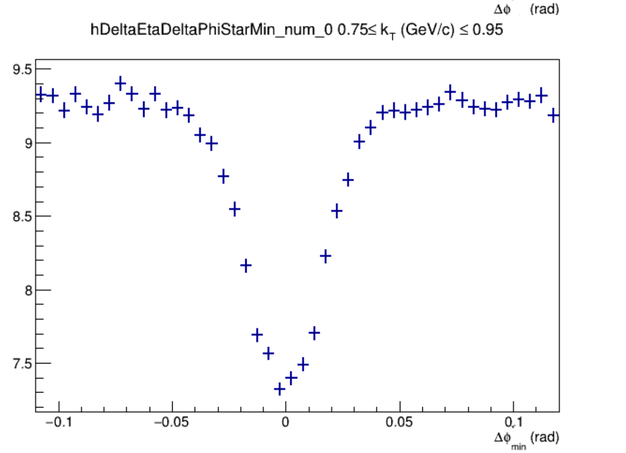
kT (0.55-0.75) GeV/c



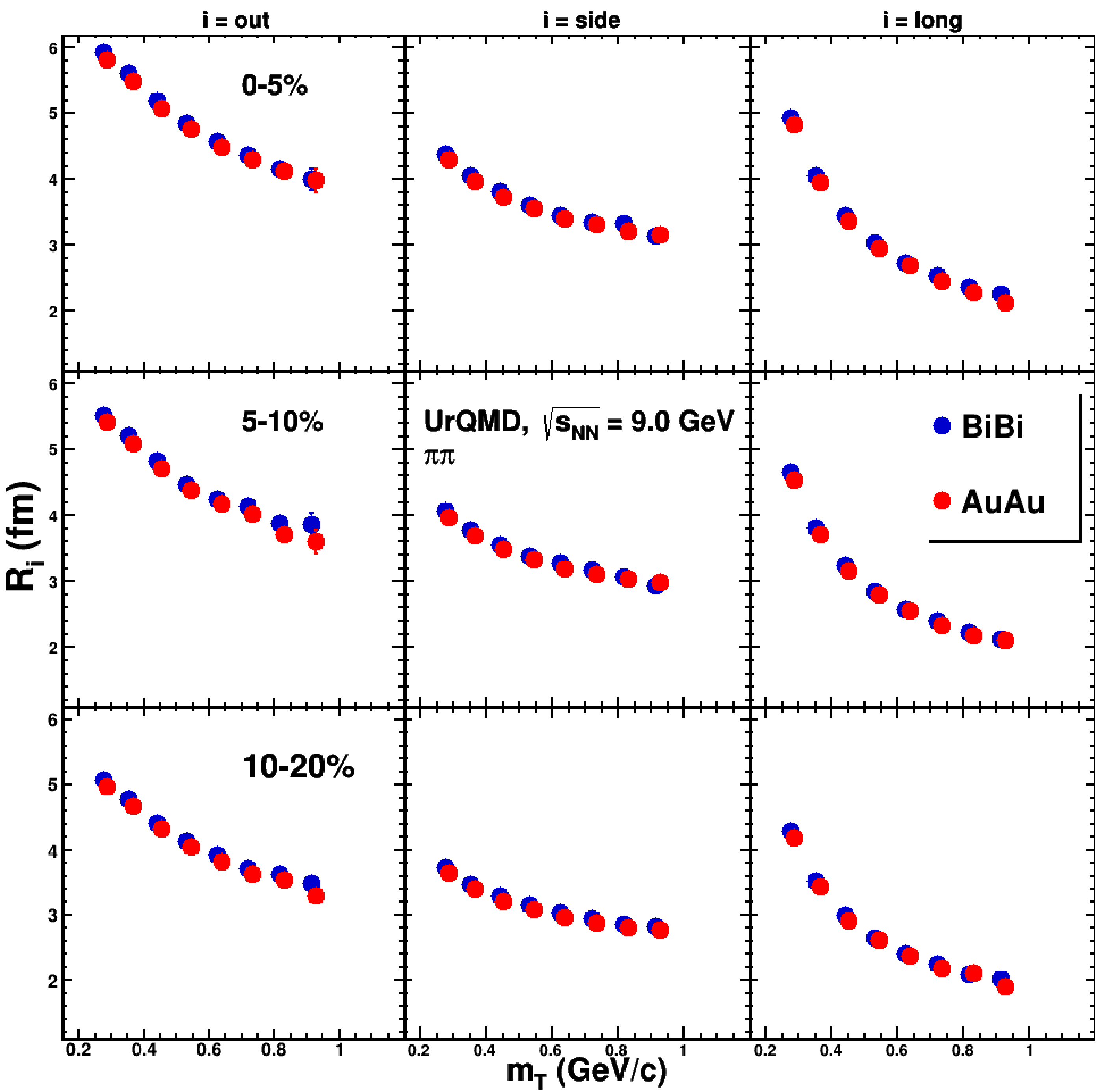
kT (0.75-0.95) GeV/c





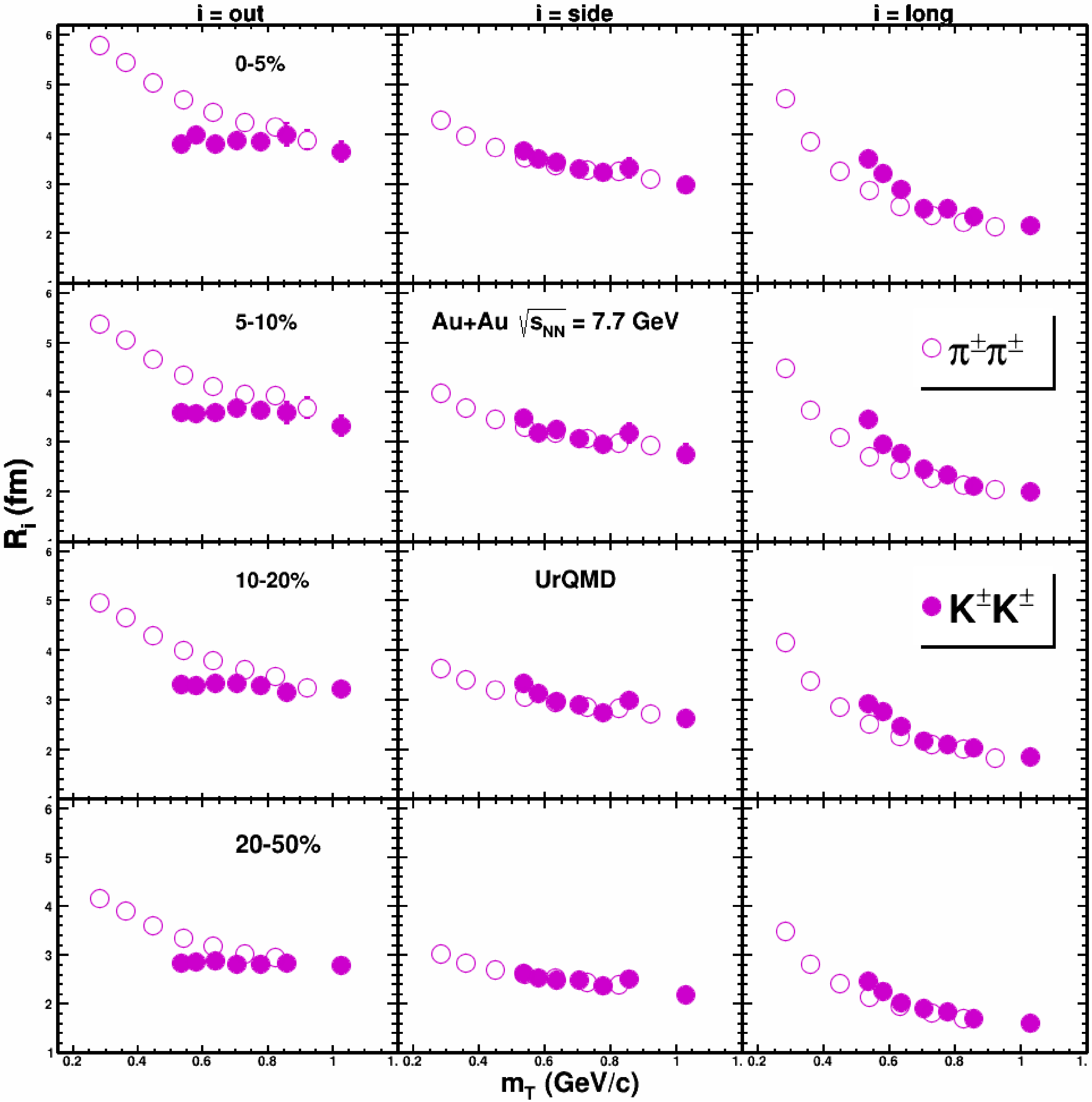


Comparison of AuAu and BiBi (UrQMD)



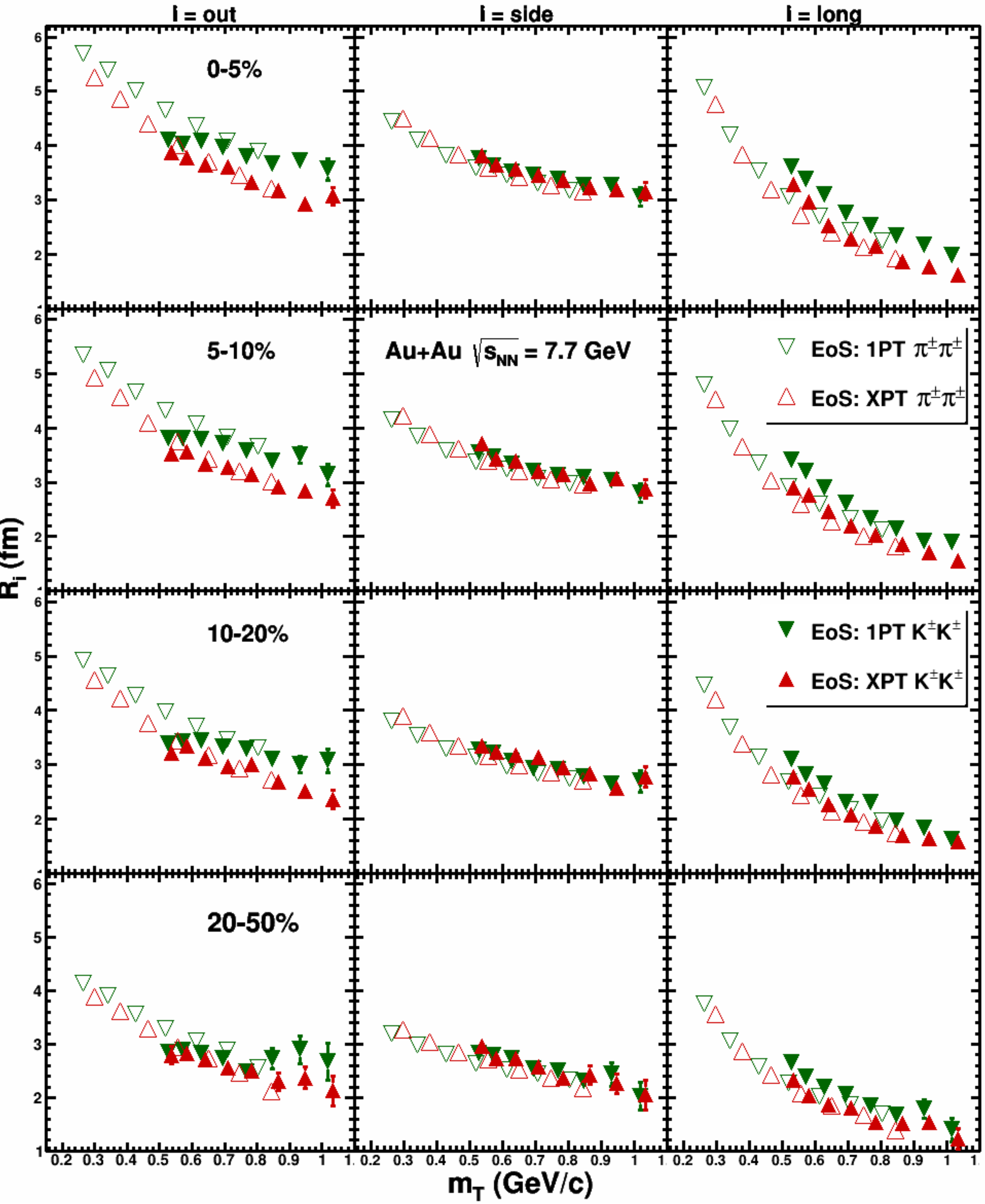
- Au+Au, and Bi+Bi at $\sqrt{s_{NN}}$ = 9 GeV
- Pion femtoscopic radii of Bi+Bi are larger than Au+Au ones by ~2-6%

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

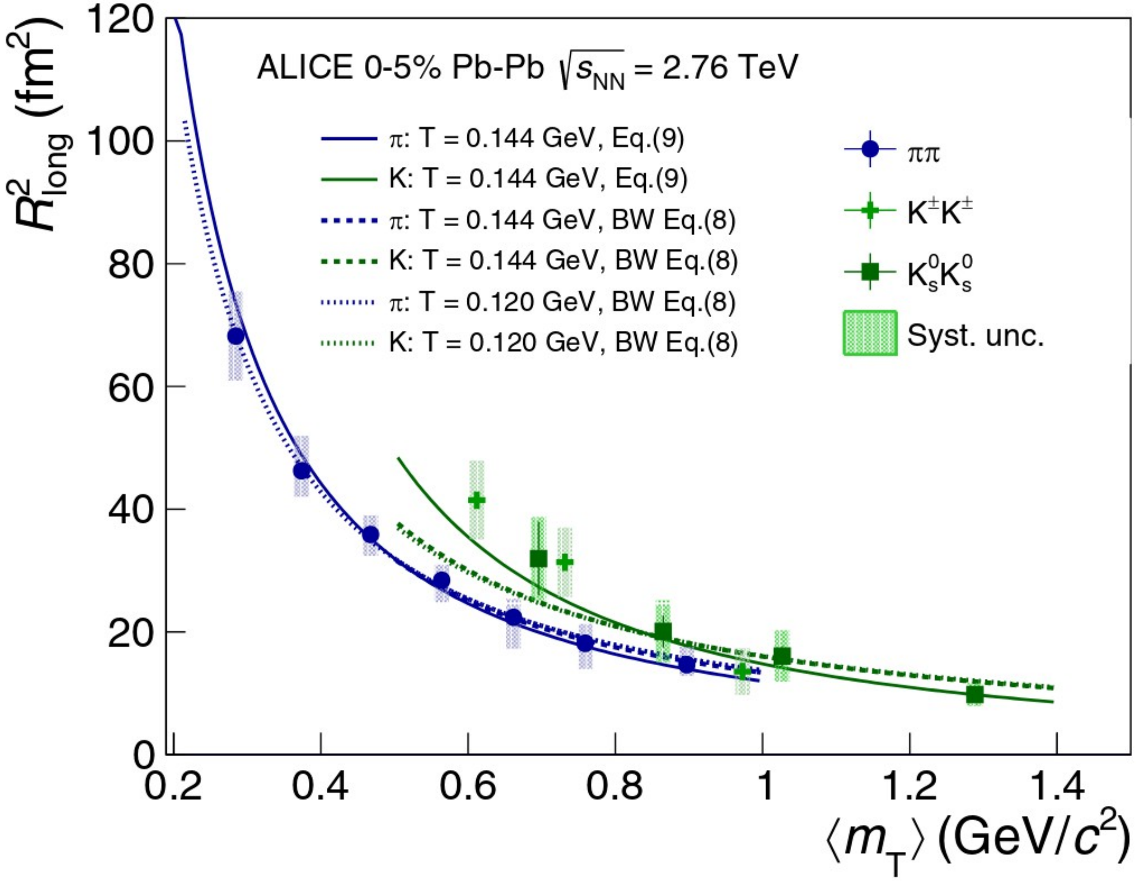
Pion and kaon radii with vHLLE model



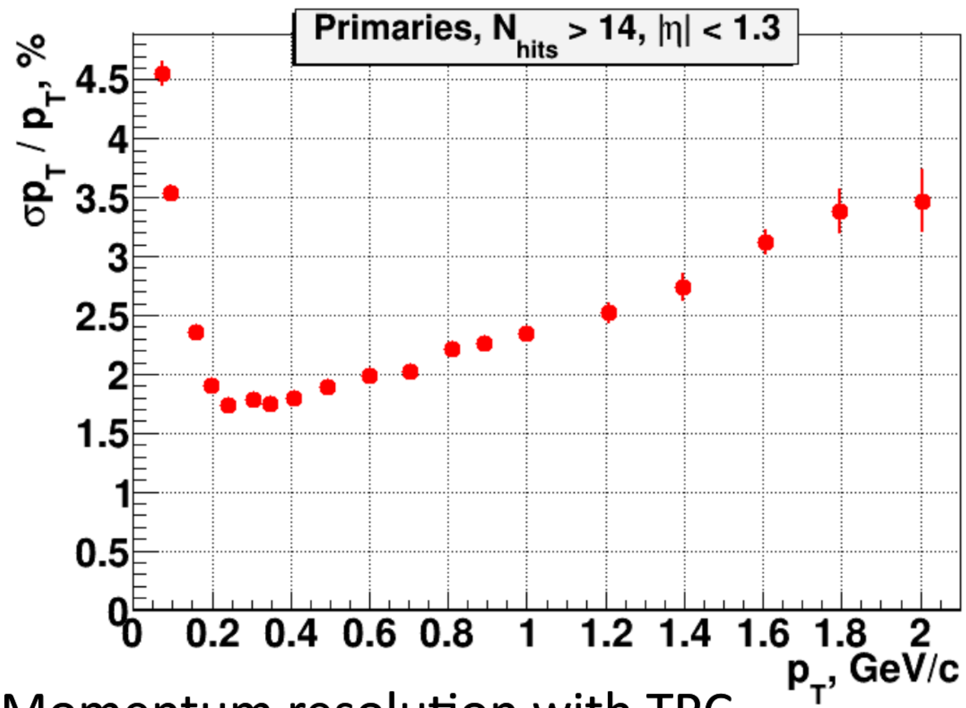
- Au+Au, $\sqrt{s_{NN}}$ = 7.7 GeV
- Approximate m_T scaling for R_{side}
- Similarly to pions : kaon radii decrease with m_T → radial flow ;
- **for 1PT EoS almost flat dependence R_{out} (m_T) is observed → weaker flow**
- **$R_{out,long}$ (1PT) > $R_{out,long}$ (XPT)**
- R_{long} kaon radii for XPT > 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

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



Single-track momentum resolution in MPD



Momentum resolution with TPC