First look at Charge Balance Functions in Bi+Bi collisions at 9.2 GeV with MPD

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on behalf of PWG3
(Correlations & Fluctuations)

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Motivation for the analysis

The law of charge conservation establishes strong correlations between charged particles and their momenta. To study these correlations, among other observables, the **Charge Balance Function (CBF)** is proposed. **The function is sensitive to the time the correlation was established and thus provides information on hadronization time point.** In hydrodynamic approach the CBF width is proportional to the inverse strength of the collective flow in the system allowing to estimate collective effects as well. **All that raises a question whether the CBF is dependent on the phase transition type providing great opportunity for the Monte-Carlo study within the MPD.**

General formalism of Charge Balance Functions

Charge is locally conserved in heavy-ion collisions. Correlations between balancing charges (electric charge, baryon number, and strangeness) can be studied by measuring charge balance functions. **They represent the probability, given the observation of a charge *q*, of seeing its balancing charge *-q* at some relative rapidity Δ*y* and relative azimuthal angle Δ*φ*.**

One of the definitions of the charge balance function [Phys.Rev.C 104, 014906 (2021)] is given bellow

$$B(\Delta y, \Delta \varphi) = \frac{1}{2} \int dy_1 d\varphi_1 dy_2 d\varphi_2 \, \delta(y_1 - y_2 - \Delta y) \, \delta(\varphi_1 - \varphi_2 - \Delta \varphi) \left\{ \frac{P_{pn} - P_{pp}}{P_p} + \frac{P_{np} - P_{nn}}{P_n} \right\},$$

$$\frac{P_{pn}}{P_p} = \frac{P_{pn}(y_1, \varphi_1; y_2, \varphi_2)}{P_p(y_1, \varphi_1)}$$

represents the conditional probability density for observing a negative charge at (y_2, φ_2), given a positive charge at (y_1, φ_1) is observed. Other members are defined similarly.

Charge balance function can be characterized by its width defined as follows

$$\langle \Delta \eta \rangle = \frac{\sum_i B_i \Delta \eta_i}{\sum_i B_i}$$ **– rapidity width**

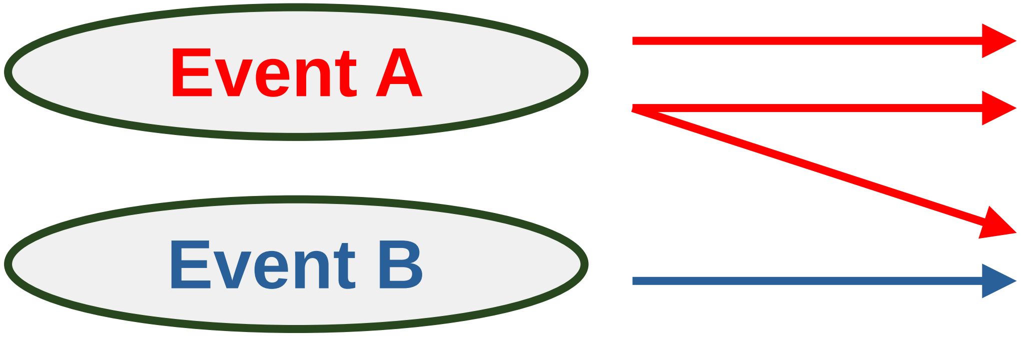
$$\langle \Delta \varphi \rangle = \frac{\sum_i B_i \Delta \varphi_i}{\sum_i B_i}$$ **– azimuthal width**

Charge balance function widths provide information on charge separation time. For instance, long range correlations (wide distribution) display early charge separation, and vice versa late charge separation leads to a narrower distribution, i.e. short range correlations.

Experimental intricacies of CBF calculation

$$B(\Delta\eta,\Delta\varphi)=\frac{1}{2}\left\{\frac{1}{N^{(p)}}\frac{d^2N^{(pn)}(\Delta\eta,\Delta\varphi)}{d\Delta\eta d\Delta\varphi}-\frac{1}{N^{(p)}}\frac{d^2N^{(pp)}(\Delta\eta,\Delta\varphi)}{d\Delta\eta d\Delta\varphi}+\frac{1}{N^{(n)}}\frac{d^2N^{(np)}(\Delta\eta,\Delta\varphi)}{d\Delta\eta d\Delta\varphi}-\frac{1}{N^{(n)}}\frac{d^2N^{(nn)}(\Delta\eta,\Delta\varphi)}{d\Delta\eta d\Delta\varphi}\right\}$$

Here *$N(p)$* is number of positively charged hadrons, *$d^2N^{(pn)}/d\Delta\eta d\Delta\varphi$* — relative rapidity and azimuthal distribution of positive-negative pairs of hadrons.



$$\frac{1}{N^{(p)}}\frac{d^2N^{(pn)}_{same}(\Delta\eta,\Delta\varphi)}{d\Delta\eta d\Delta\varphi}$$

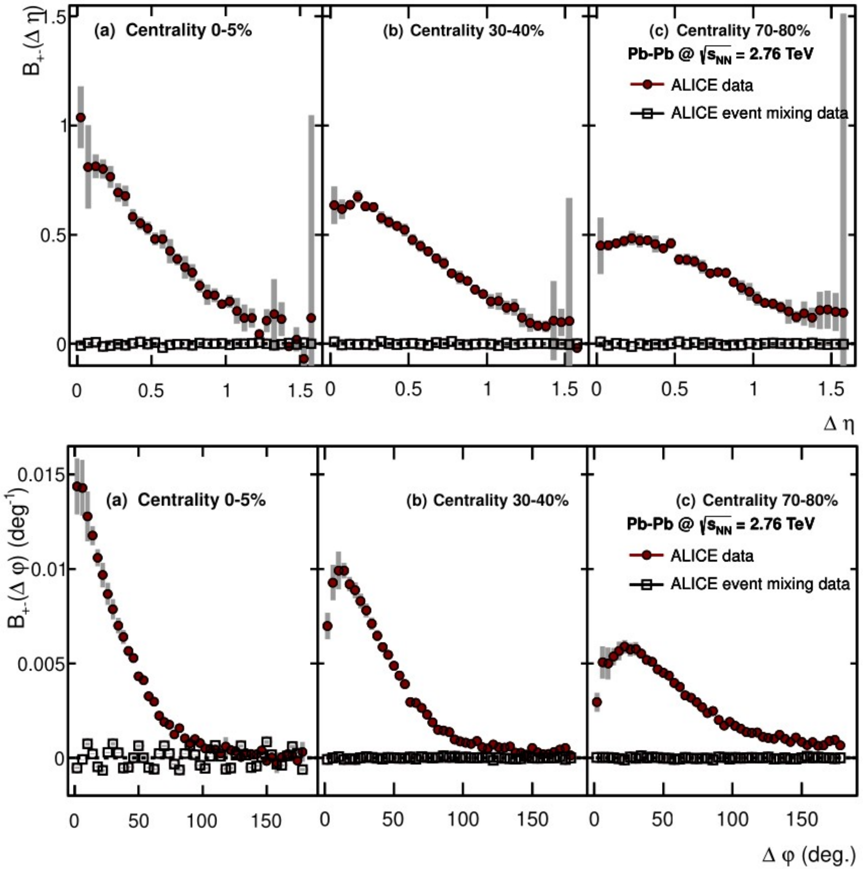
$$\frac{1}{N^{(p)}}\frac{d^2N^{(pn)}_{mixed}(\Delta\eta,\Delta\varphi)}{d\Delta\eta d\Delta\varphi}$$

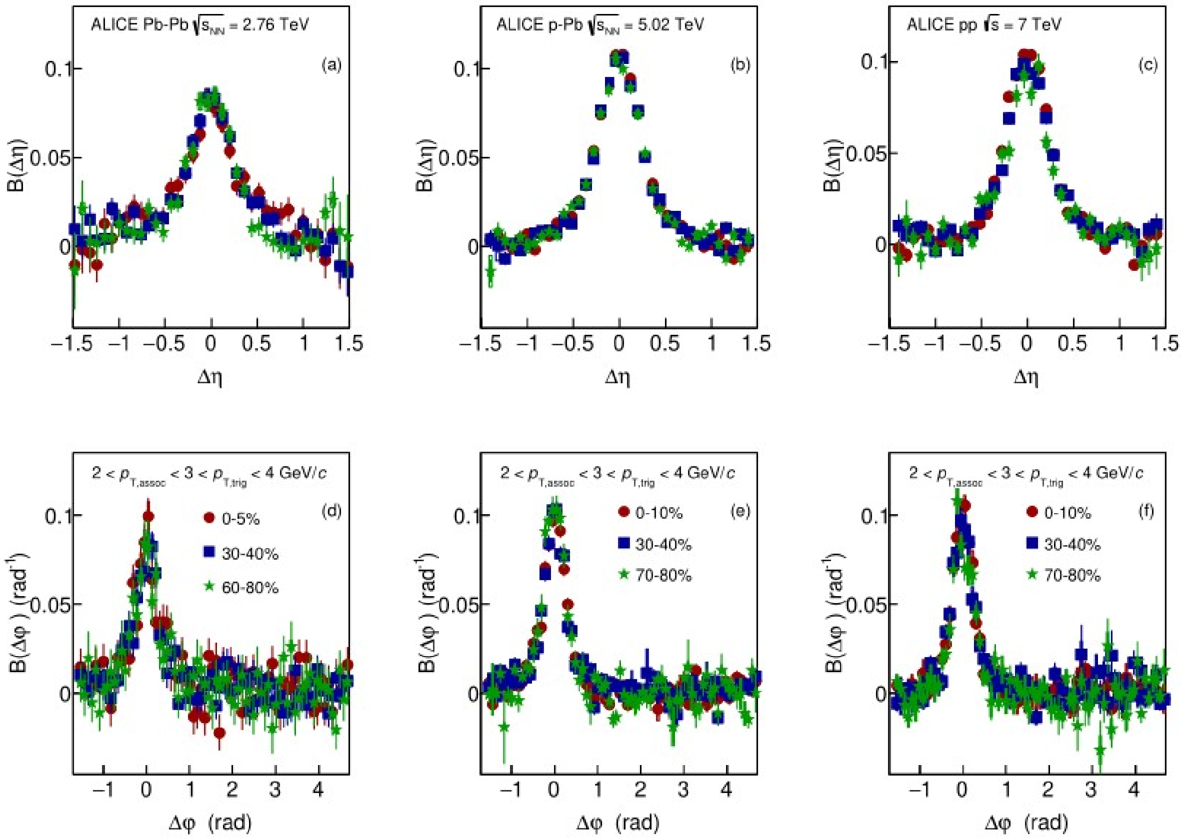
To account for abundance of positive electrical charge (from protons) distributions are to be corrected for charge imbalance at the NICA energies according to the formula bellow:

$$\frac{1}{N^{(p)}}\frac{d^2N^{(pn)}_{data}(\Delta\eta,\Delta\varphi)}{d\Delta\eta d\Delta\varphi}=\frac{1}{N^{(p)}}\frac{d^2N^{(pn)}_{same}(\Delta\eta,\Delta\varphi)}{d\Delta\eta d\Delta\varphi}-\frac{1}{N^{(p)}}\frac{d^2N^{(pn)}_{mixed}(\Delta\eta,\Delta\varphi)}{d\Delta\eta d\Delta\varphi}$$

Experimental status of CBFs at LHC (ALICE)

An extensive experimental analysis of CBFs was performed at LHC by ALICE collaboration **[Phys.Lett.B 723, 267-279 (2013); Phys.Rev.C 100, 044903 (2019); Eur.Phys.J.C 76, 86 (2016); Nucl.Phys.A 982, 315-318 (2019)].**

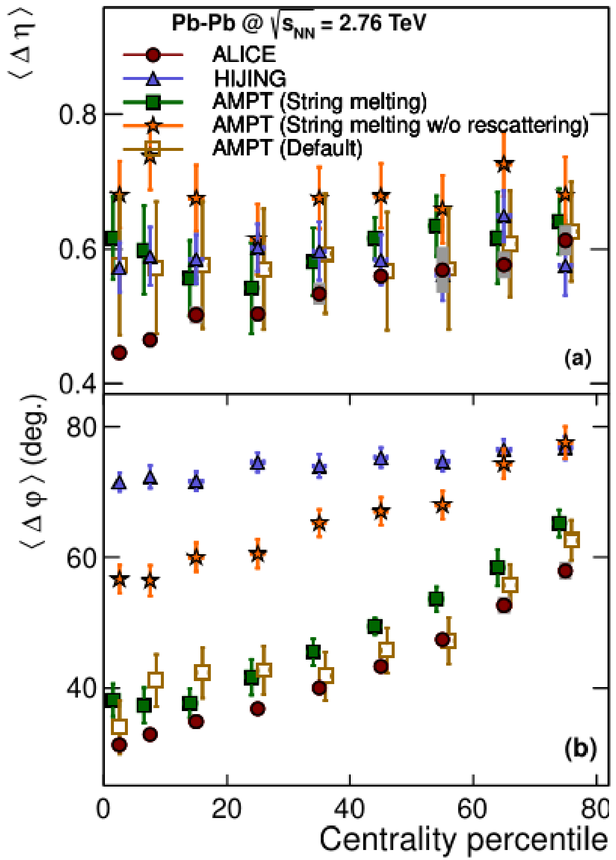


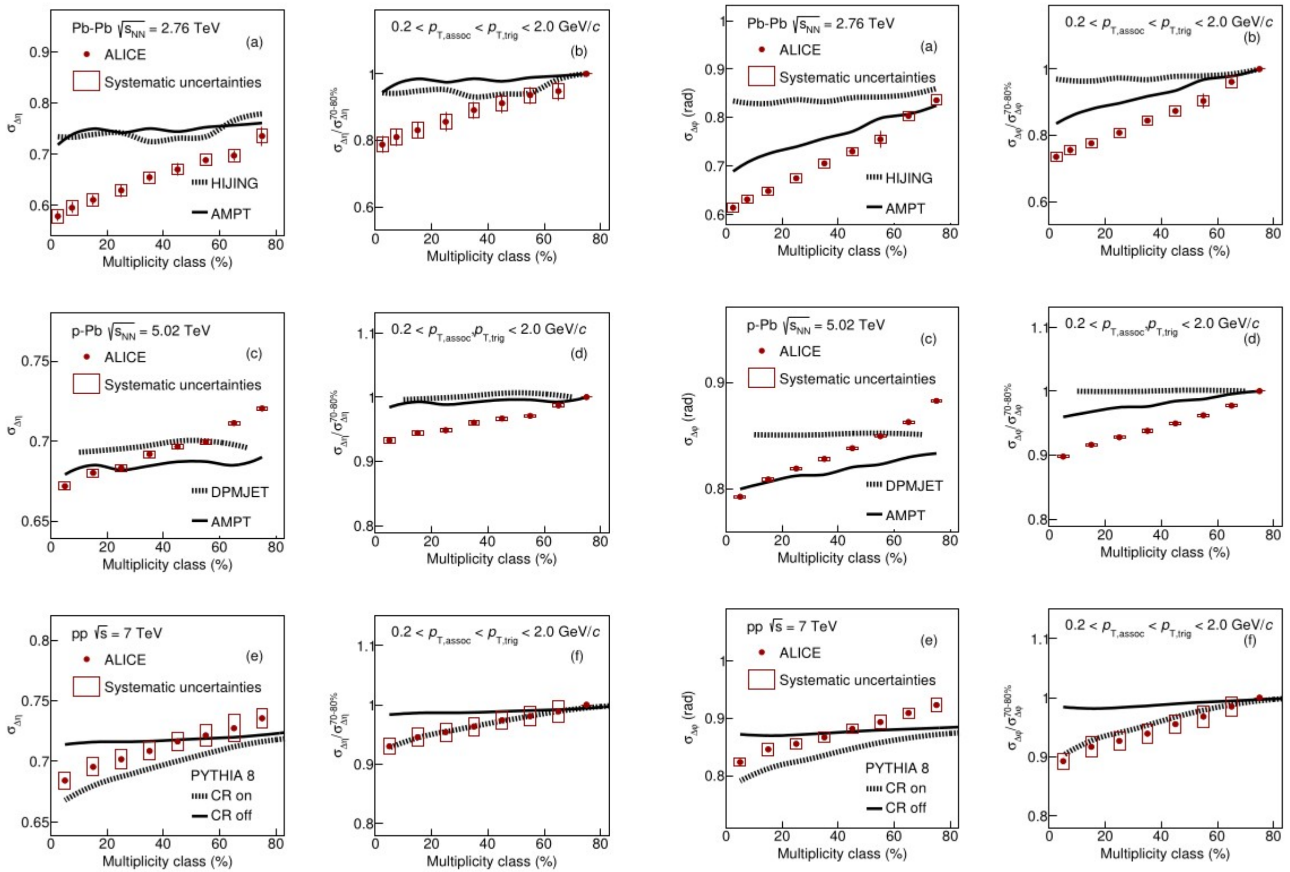


CBFs as a function of Δη for different centrality classes: 0-5%, 30-40%, and 70-80% (on the left). CBFs for charged particles as a function of Δη (upper row) and Δφ (lower row) in different multiplicity classes (on the right).

Experimental status of CBFs at LHC (ALICE)

One can notice that modern models of heavy-ion collisions struggle to reproduce experimental data on CBF widths at both LHC and RHIC BES (see next slides) energies, thus actualizing the area of research and initiating a new series of investigations.

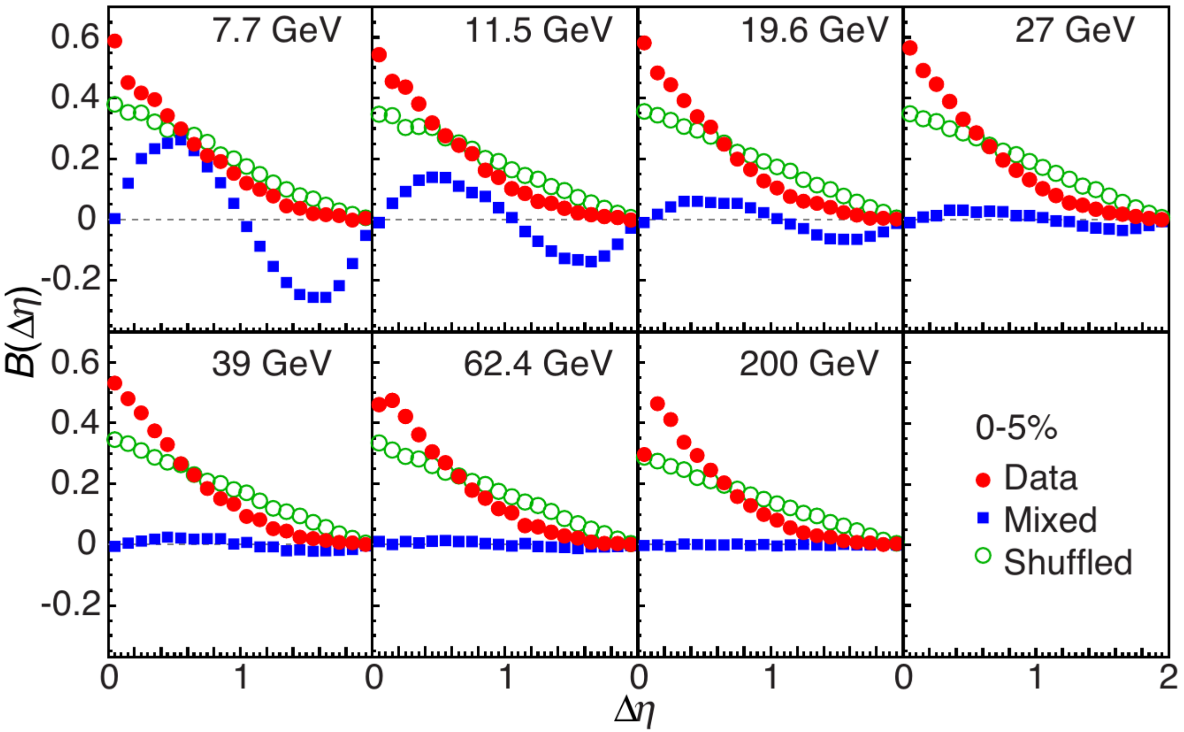




Centrality dependence of the width of the CBF <Δη> and <Δφ>, for the correlations studied in terms of the relative pseudorapidity and the relative azimuthal angle, respectively (on the left). **The multiplicity-class dependence of <Δη>** in PbPb, pPb, and pp collisions at $\sqrt{s_{NN}}$ = 2.76, 5.02, and 7 TeV compared with results from various event generators (in central and right plots).

Experimental status of CBFs at RHIC BES energies

Meanwhile, only inclusive rapidity CBFs were measured at RHIC BES energies. Azimuthal and partial ($\pi^{\pm}\pi^{\pm}$, $K^{\pm}K^{\pm}$, ...) CBFs are still to be measured in order to provide better insight on charge generation mechanisms and consequent correlations of charged particles.



B(Δφ) = ?

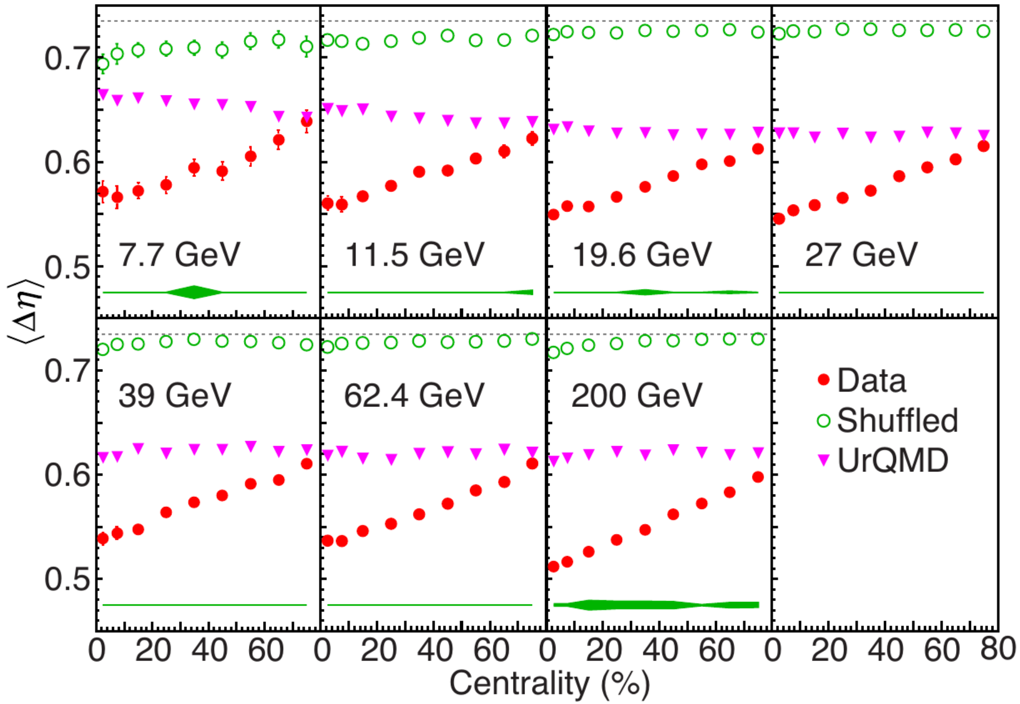
Rapidity CBFs of all charged particles with $0.2 < p_T < 2$ GeV/c in central Au+Au collisions (0-5%) at $\sqrt{s_{NN}}$ from 7.7 to 200 GeV. Mixed CFBs are constructed from mixed events, shuffled CBFs are constructed from tracks with shuffled charges within single event **[Phys.Rev.C 94 (2), 024909 (2016)].**

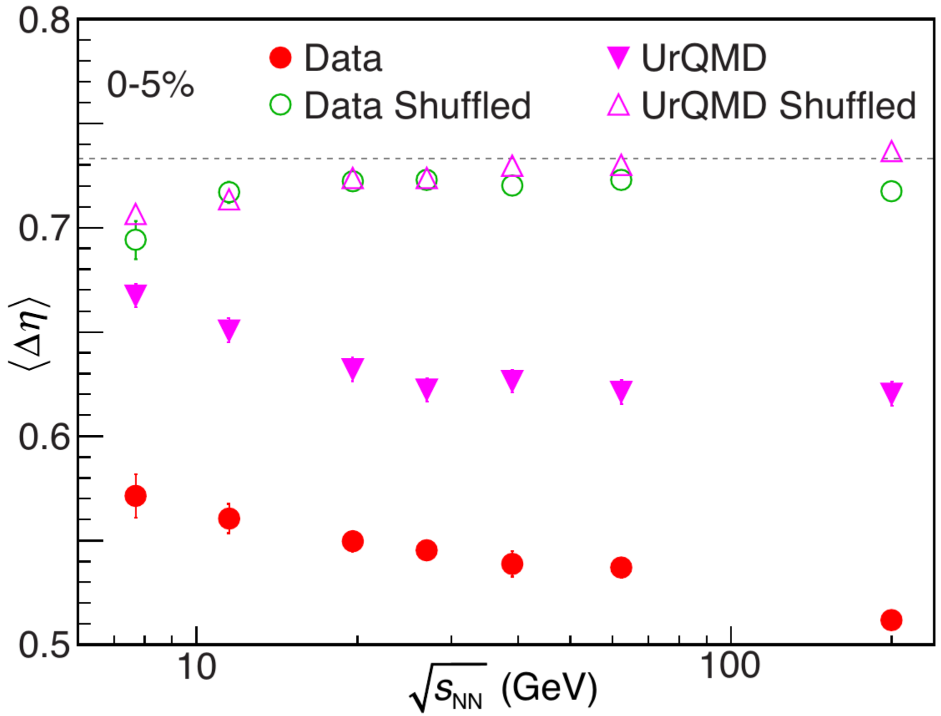
Experimental status of CBFs at RHIC BES energies

There are two experimental observations worth noticing:

✔ **CBF width increases with the increase of the centrality of heavy-ion collisions;**

✔ **CBF width decreases while the energy of the beam increases.**





Energy dependence of CBF widths compared with the widths of CBFs calculated using events with shuffled charges (on the left). **CBF widths for the most central events (0-5%)** compared with CBF widths calculated using events with shuffled charges (on the right) **[Phys.Rev.C 94 (2), 024909 (2016)].**

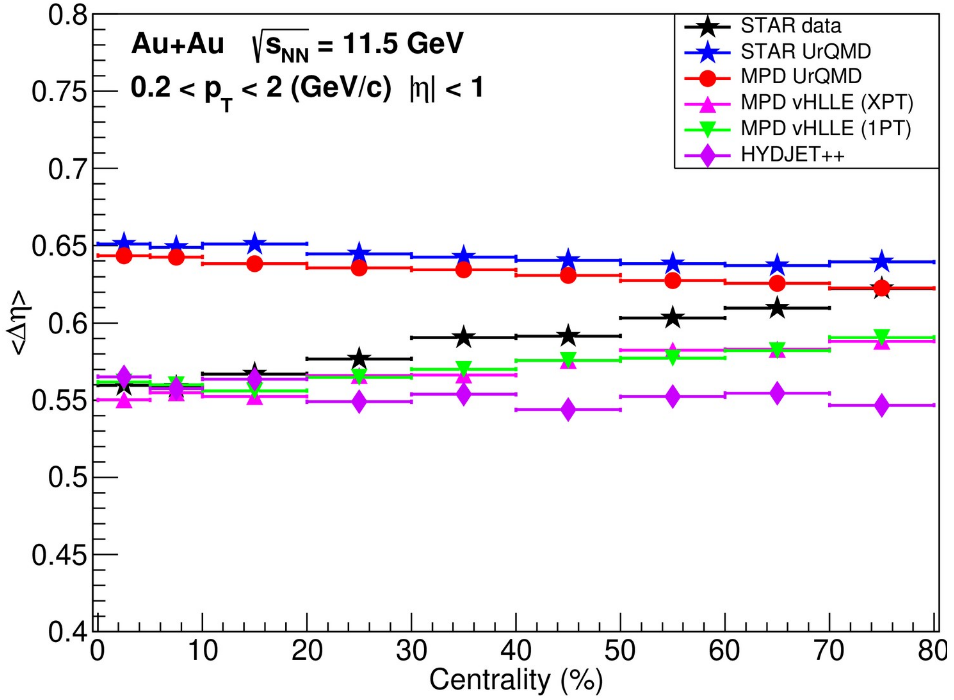
Utilized models

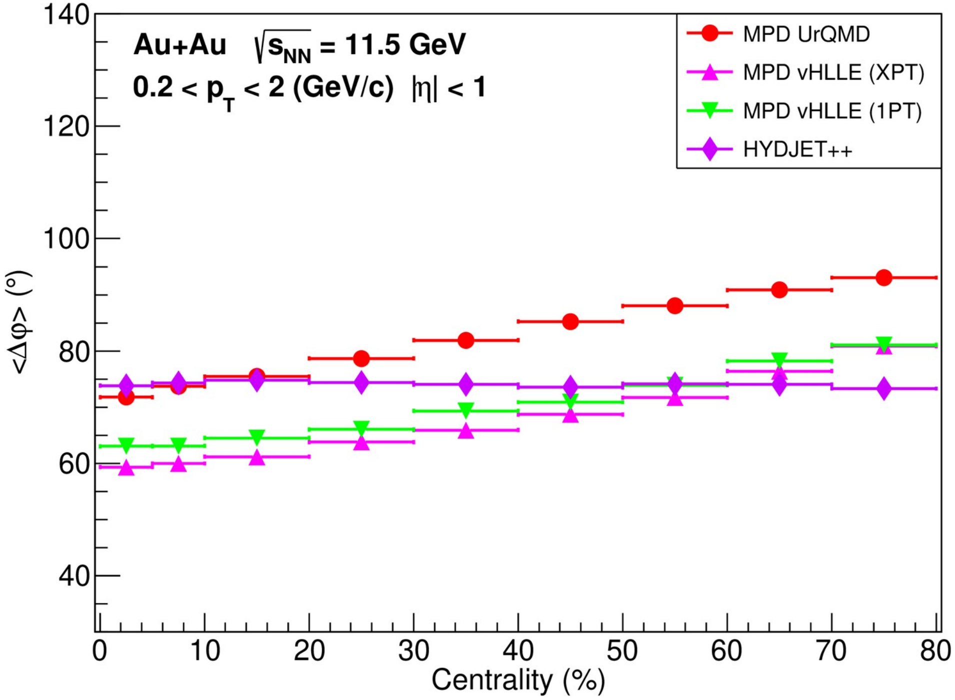
- **HYDJET++** is a Monte-Carlo event generator written in C++ and Fortran for study of various hadron characteristics in relativistic heavy-ion collisions **[Comp.Phys.Com. 180, 779 (2009)]. The final state of the reaction in HYDJET++ is presented as a superposition of two independent components: thermal hadronic state (soft), and multipartonic jet state (hard).**

- **UrQMD** is a microscopic transport model **[Prog.Part.Nucl.Phys. 41 (1998)]** based on covariant propagation of hadrons. **It includes stochastic binary scatterings, formation of color strings, and resonances decay.**

- **vHLLE** is a (3+1) dimensional relativistic viscous hydrodynamic code based on the Godunov method and the relativistic HLLE (Harten, Lax, van Leer, Einfeldt) approximation for the solution of the Riemann problem for its inviscid part **[Comput.Phys.Commun. 185, 3016-3027 (2014)]. Primary application of the code is simulations of the hydrodynamic expansion of QCD matter created in relativistic heavy-ion collisions.**

CBF widths at $\sqrt{s_{NN}}$ = 11.5 GeV (MC generator level)





- ➔ **MPD UrQMD results are close to those of STAR UrQMD;**
- ➔ UrQMD describes experimental data in peripheral collisions; vHLLE, HYDJET++ – in central collisions;
- ➔ None of the models describes experimental data completely;
- ➔ No dependence on EoS was spotted in vHLLE model;
- ➔ **Unaccounted charge correlation mechanisms?**

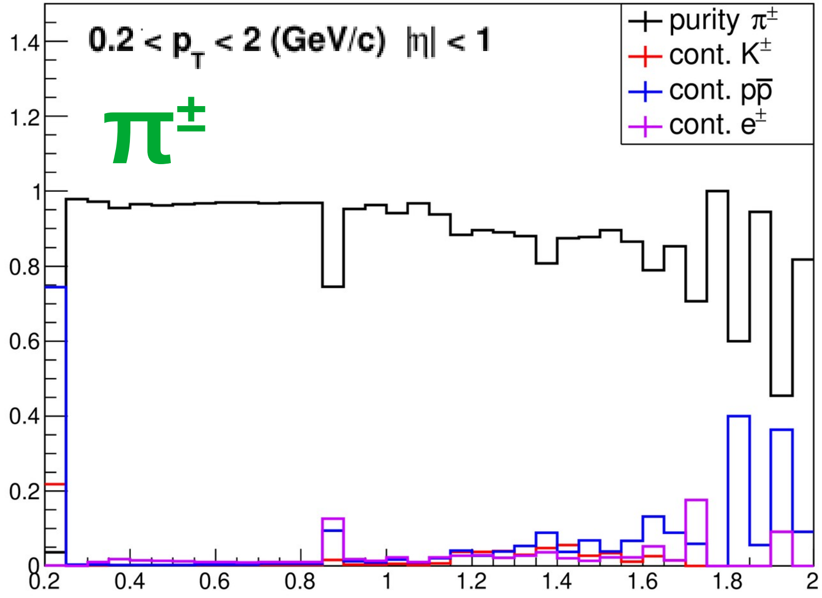
Utilized dataset

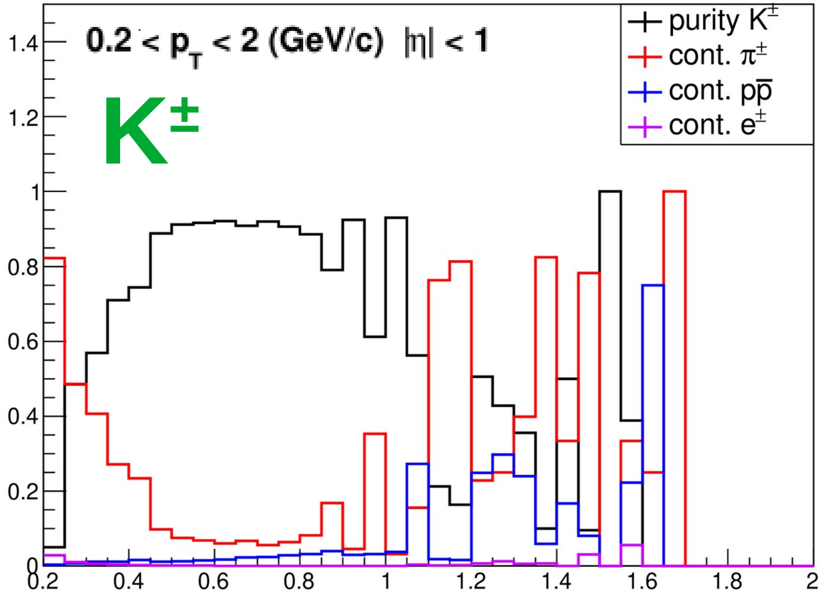
Request № 25 events were used in this analysis (50 million events):
/eos/nica/mpd/sim/data/exp/dst-BiBi-09.2GeV-mp07-22-500ev-req25/BiBi/09.2GeV-mb/urqmd/BiBi-09.2GeV-mp07-22-500ev-req25

Following cuts were applied:
$|v_z| < 30$ cm, $v_{xy} < 2$ cm
$N_{hits} \geq 15$, DCA < 3 cm

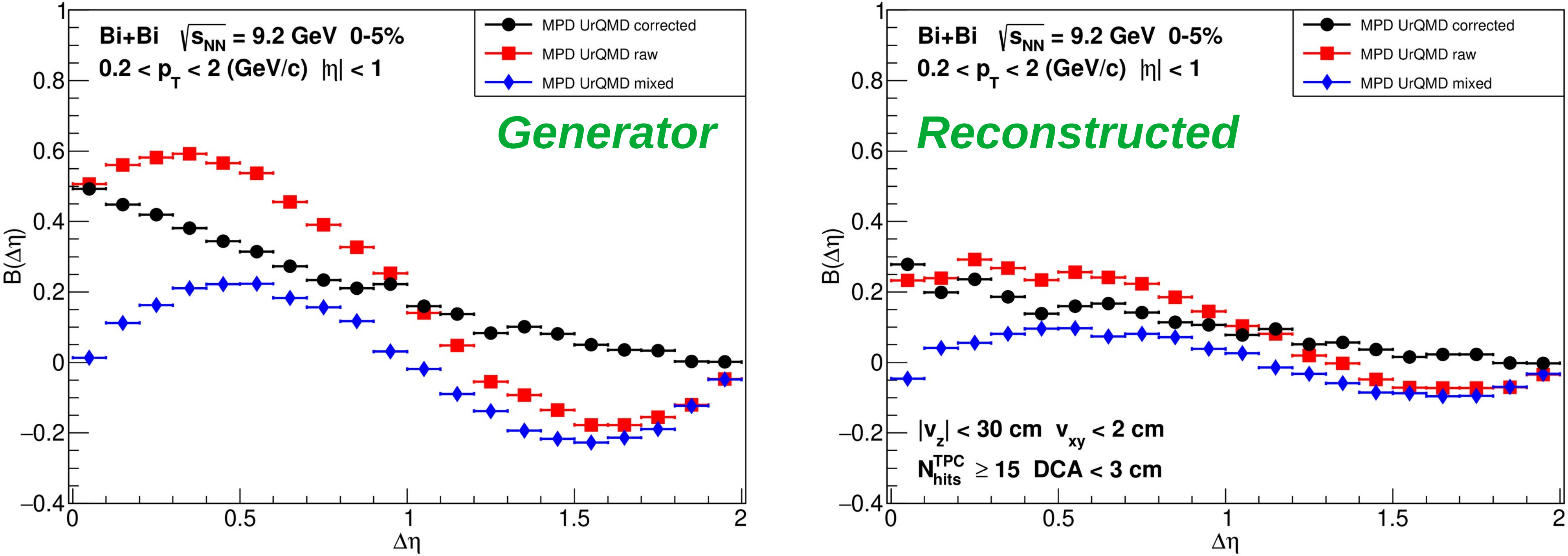
Default PID was used (for example, for pions):
Prob($\pi^{\pm}$) > Prob($K^{\pm}$) > Prob($p\bar{p}$)
Prob($\pi^{\pm}$) > 0.99

Default PID purity & contamination estimations





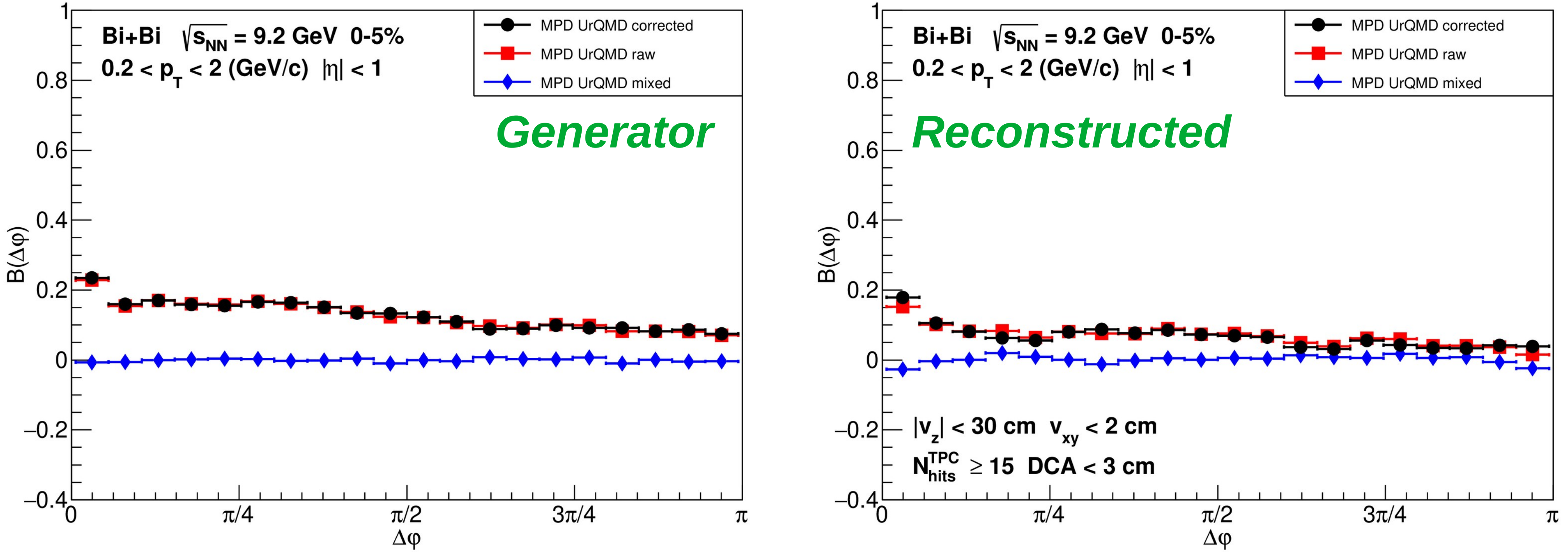
UrQMD rapidity CBF at $\sqrt{s_{NN}}$ = 9.2 GeV (MC generator vs. reconstruction)



Generator and reconstruction level CBFs at $\sqrt{s_{NN}}$ = 9.2 GeV in UrQMD model. Black dots – corrected CBFs, red squares – raw (uncorrected) CBFs, blue diamonds – mixed CBFs.

MC level CBF in the left figure, reconstruction level CBF in the right figure. **Overall, CBF is well reconstructed; however, its amplitude is decreased.** Notably, there are CBF shape distortions, rather small however, that **they do not impact reconstructed CBF widths significantly.**

UrQMD azimuthal CBF at $\sqrt{s_{NN}}$ = 9.2 GeV (MC generator vs. reconstruction)



Generator and reconstruction level CBFs at $\sqrt{s_{NN}}$ = 9.2 GeV in UrQMD model. Black dots – corrected CBFs, red squares – raw (uncorrected) CBFs, blue diamonds – mixed CBFs.

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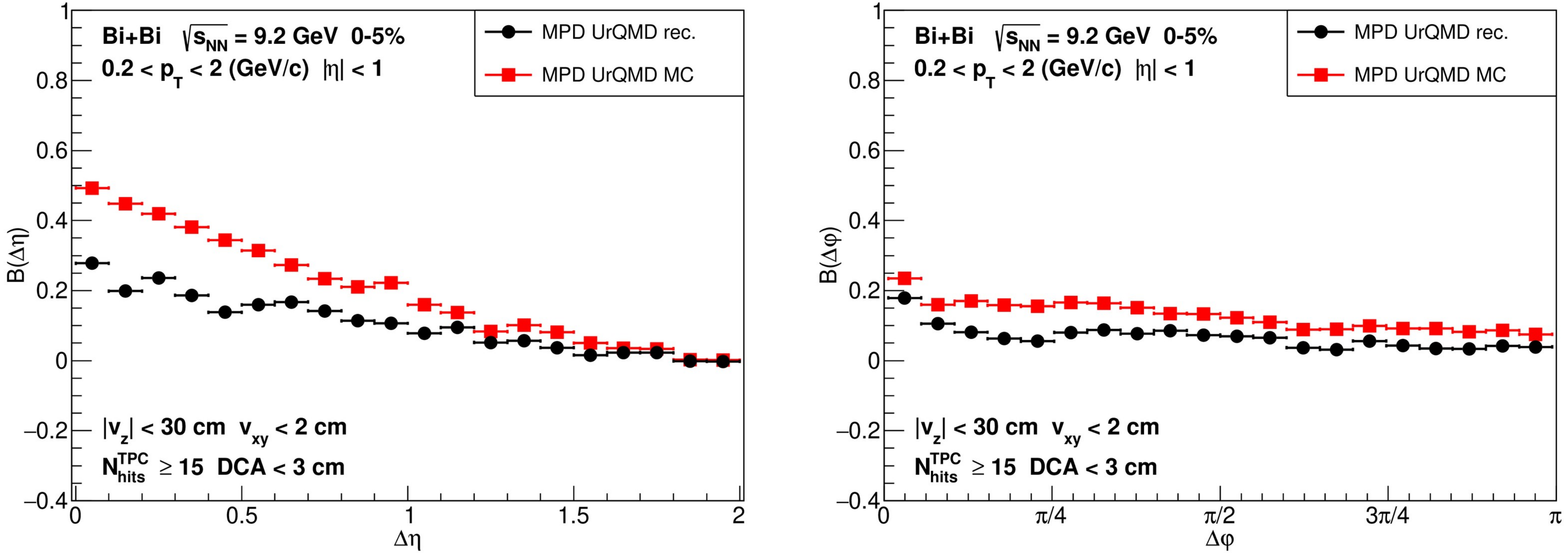
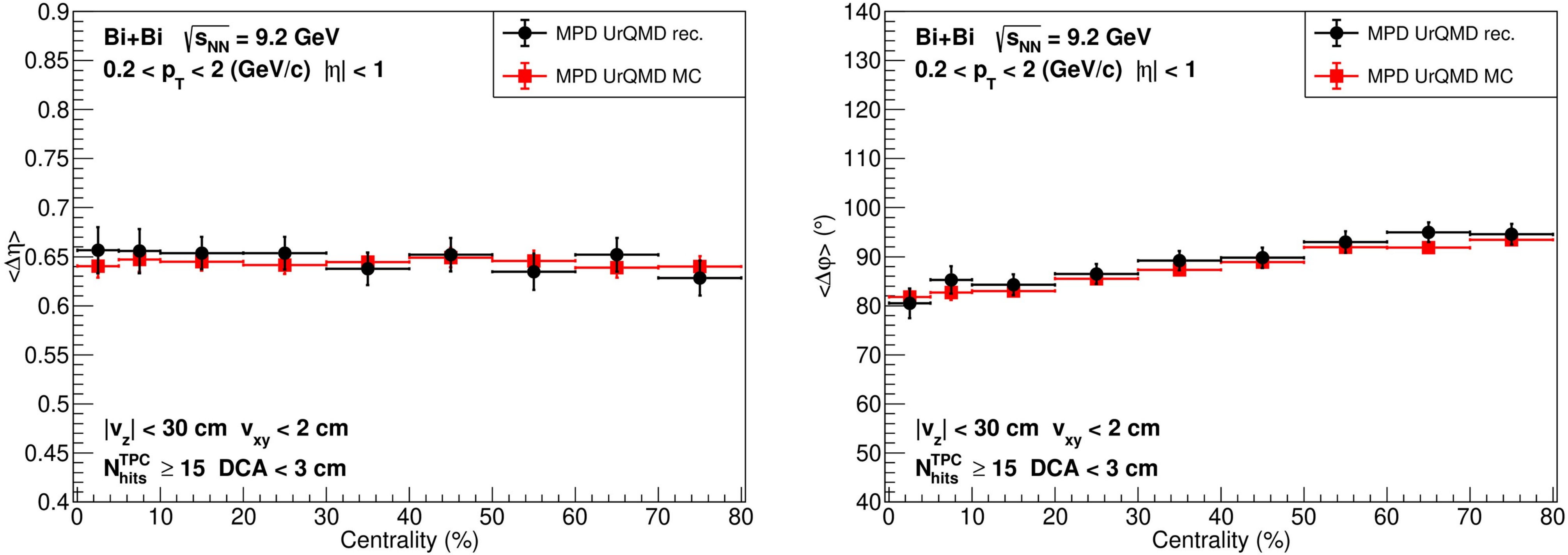
UrQMD CBFs at $\sqrt{s_{NN}}$ = 9.2 GeV (MC generator vs. reconstruction)



Generator and reconstruction level CBFs at $\sqrt{s_{NN}}$ = 9.2 GeV in UrQMD model. Black dots – reconstructed CBFs, red squares – generator level CBFs.

MC generator level and reconstructed CBFs compared. **Overall, CBFs are well reconstructed; however, their amplitudes are decreased.** Notably, there are CBF shape distortions, rather small however, that **they do not impact reconstructed CBF widths significantly.**

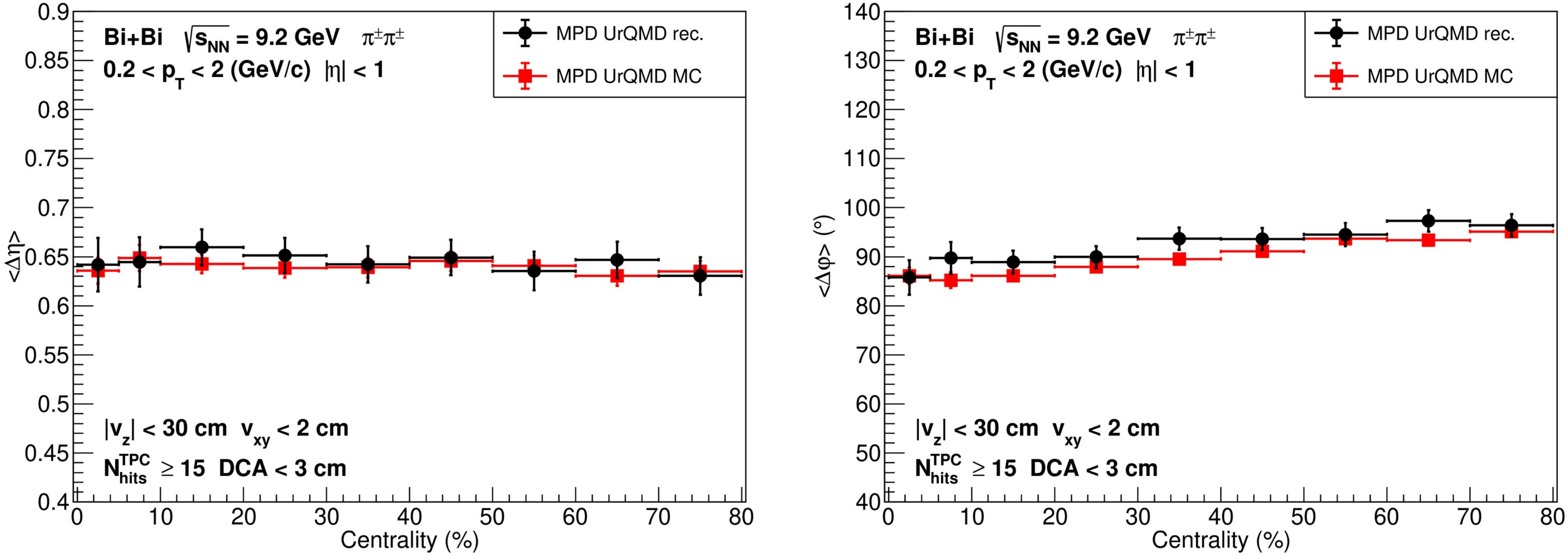
CBF widths reconstruction at $\sqrt{s_{NN}}$ = 9.2 GeV (inclusive CBFs: $\pi^{\pm} + K^{\pm} + p\bar{p}$)



Generator and reconstruction level CBF widths at $\sqrt{s_{NN}}$ = 9.2 GeV in UrQMD model. Black dots – reconstructed CBFs, red squares – generator level CBFs.

MC generator and reconstruction level CBF widths are fairly reconstructed. **Reconstructed rapidity and azimuthal widths are within 3% and 5% correspondingly.**

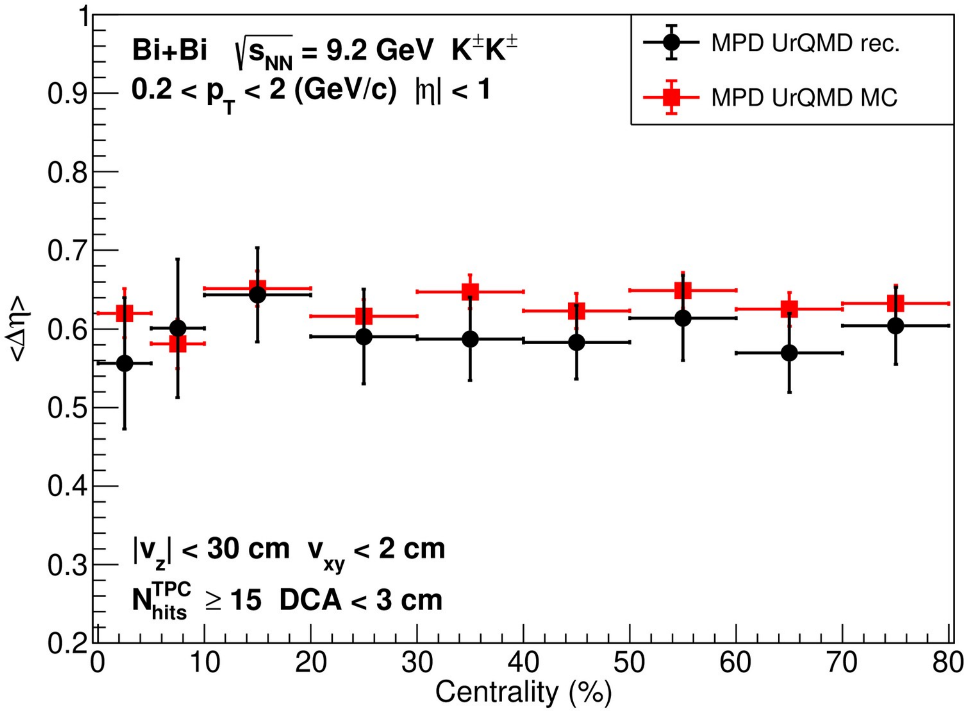
CBF widths reconstruction at $\sqrt{s_{NN}}$ = 9.2 GeV (partial CBFs: $\pi^{\pm}\pi^{\pm}$ pairs)

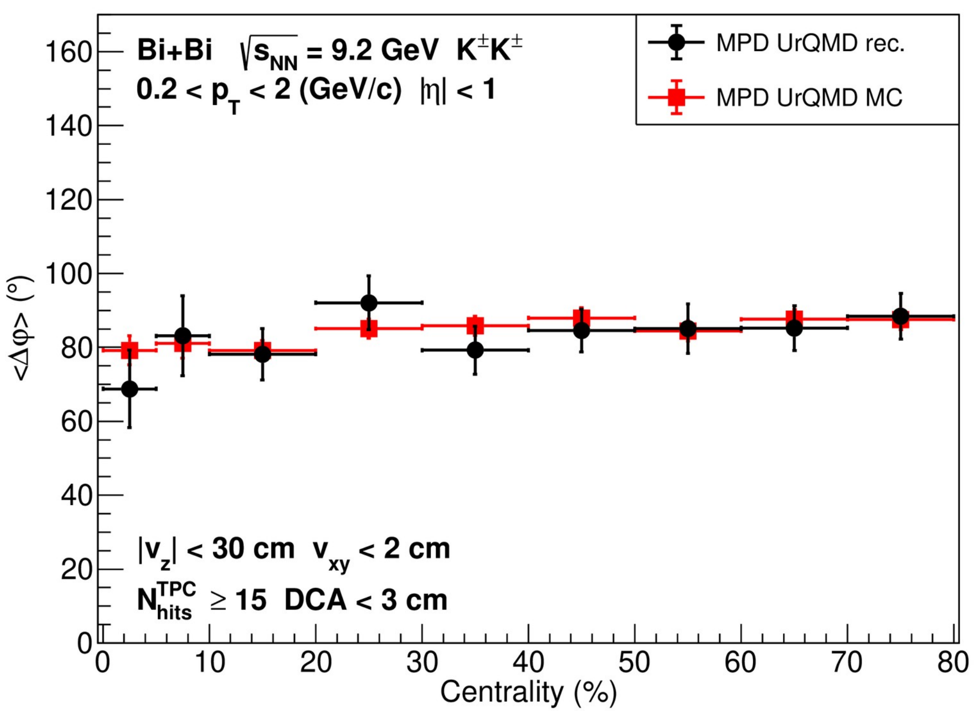


Generator and reconstruction level CBF widths at $\sqrt{s_{NN}}$ = 9.2 GeV in UrQMD model. Black dots – reconstructed CBFs, red squares – generator level CBFs.

MC generator and reconstruction level CBF widths are fairly reconstructed. **Reconstructed rapidity and azimuthal widths are within 8% and 10% correspondingly.**

CBF widths reconstruction at $\sqrt{s_{NN}}$ = 9.2 GeV (partial CBFs: $K^{\pm}K^{\pm}$ pairs)





Generator and reconstruction level CBF widths at $\sqrt{s_{NN}}$ = 9.2 GeV in UrQMD model. Black dots – reconstructed CBFs, red squares – generator level CBFs.

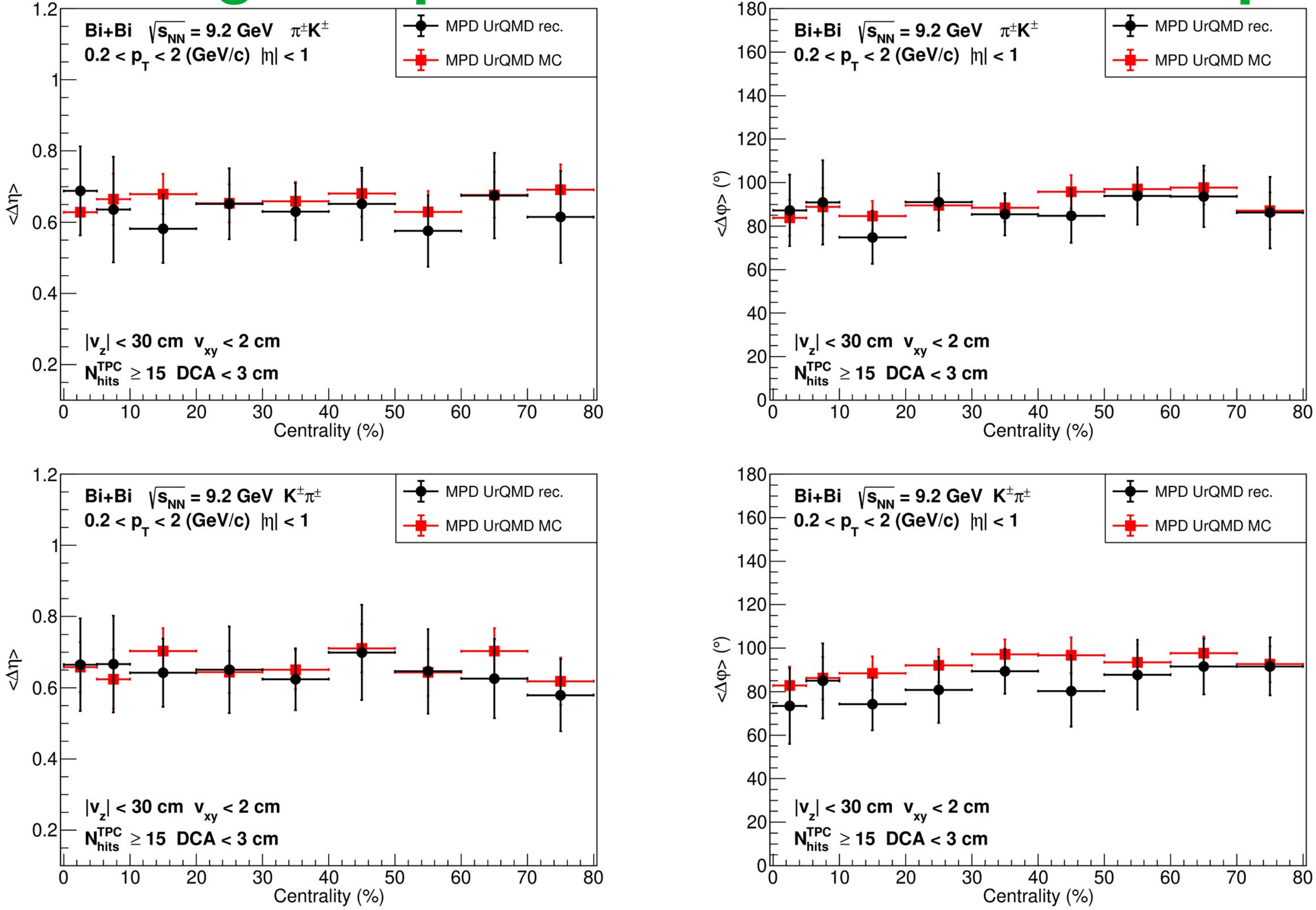
MC generator and reconstruction level CBF widths are fairly reconstructed. **Reconstructed rapidity and azimuthal widths are within 15% and 10% correspondingly.**

Summary & outlook

- ✔ CBFs and their widths were calculated on Request № 25 data. MC generator and reconstruction level results were compared.
- ✔ Inclusive rapidity and azimuthal CBF widths are within 3% and 5% of MC generator widths correspondingly.
- ✔ Overall, CBF widths are fairly reconstructed even with default PID: purity improvement might yield better partial CBF width reconstruction.
- ✔ Further analysis of CBFs with different models is planned in the future.

Supplementary slides

CBF widths reconstruction at $\sqrt{s_{NN}}$ = 9.2 GeV (non-diagonal partial CBFs: $\pi^{\pm}K^{\pm}$ & $K^{\pm}\pi^{\pm}$ pairs)



Track splitting during reconstruction

Track splitting caused dips in CBF due to incorrect reading procedure. In future: separate reading of MC and rec. data if no DIRECT comparison is intended (MC tracks are selected by their IDs in reconstructed tracks).

```
Processing event 7/19140
TRACK 1 index MC 6645       index REC 5
Track 0, mother : 922, Type -321, momentum (0.310328, 0.0295539, 0.219516) GeV
      STS 0, TPC 2, TOF 4, ETOF 0, FFD 0, ECT 0, ECAL 64, NDET 0, CPC 0, BBC 0, ZDC 0, FSA 0
Mass: 0.493677
Energy: 0.623764
TRACK 2 index MC 6645       index REC 412
Track 0, mother : 922, Type -321, momentum (0.310328, 0.0295539, 0.219516) GeV
      STS 0, TPC 2, TOF 4, ETOF 0, FFD 0, ECT 0, ECAL 64, NDET 0, CPC 0, BBC 0, ZDC 0, FSA 0
Mass: 0.493677
Energy: 0.623764


TRACK 1 index MC 8026       index REC 106
Track 0, mother : 714, Type -211, momentum (0.161771, 0.385275, 0.312627) GeV
      STS 0, TPC 2, TOF 4, ETOF 0, FFD 0, ECT 0, ECAL 64, NDET 0, CPC 0, BBC 0, ZDC 0, FSA 0
Mass: 0.13957
Energy: 0.540205
TRACK 2 index MC 8026       index REC 337
Track 0, mother : 714, Type -211, momentum (0.161771, 0.385275, 0.312627) GeV
      STS 0, TPC 2, TOF 4, ETOF 0, FFD 0, ECT 0, ECAL 64, NDET 0, CPC 0, BBC 0, ZDC 0, FSA 0
Mass: 0.13957
Energy: 0.540205


TRACK 1 index MC 1356       index REC 111
Track 0, mother : -1, Type 211, momentum (-0.227688, 0.163272, -0.0967013) GeV
      STS 0, TPC 2, TOF 4, ETOF 0, FFD 0, ECT 0, ECAL 64, NDET 0, CPC 0, BBC 0, ZDC 0, FSA 0
Mass: 0.13957
Energy: 0.327614
TRACK 2 index MC 1356       index REC 360
Track 0, mother : -1, Type 211, momentum (-0.227688, 0.163272, -0.0967013) GeV
      STS 0, TPC 2, TOF 4, ETOF 0, FFD 0, ECT 0, ECAL 64, NDET 0, CPC 0, BBC 0, ZDC 0, FSA 0
Mass: 0.13957
Energy: 0.327614
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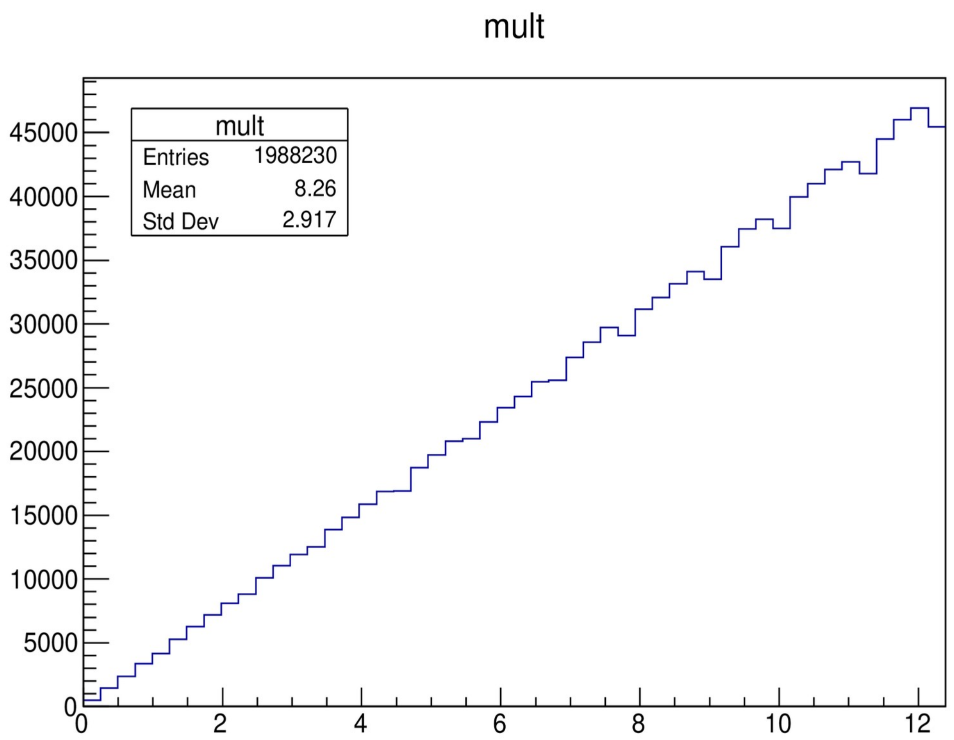
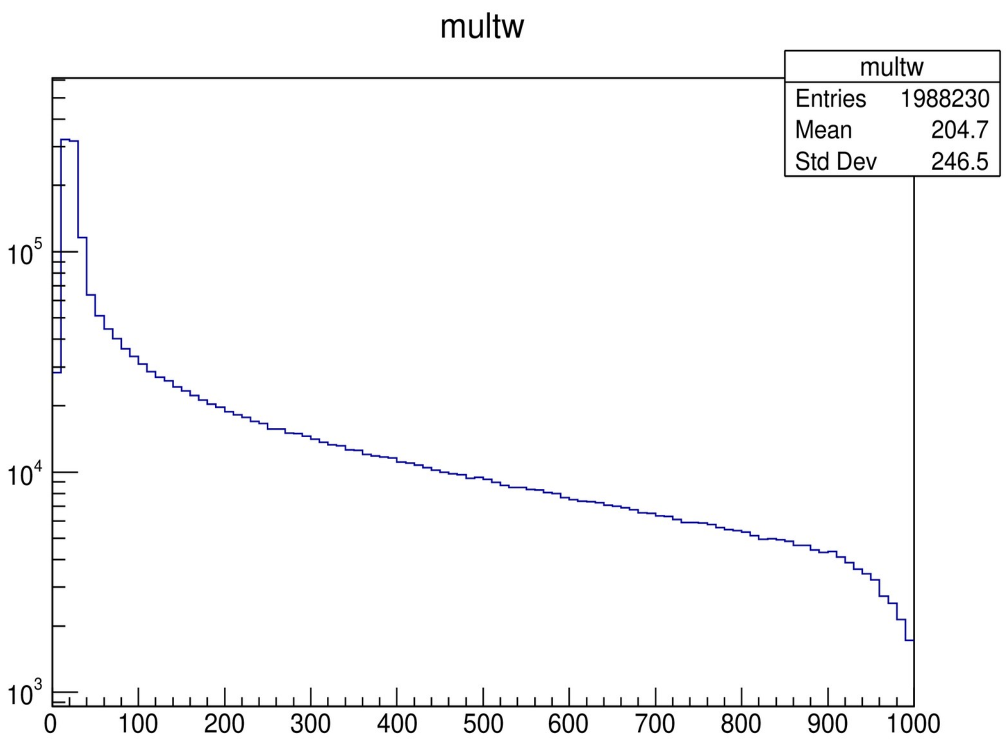
Centrality & multiplicity distributions (MC level)



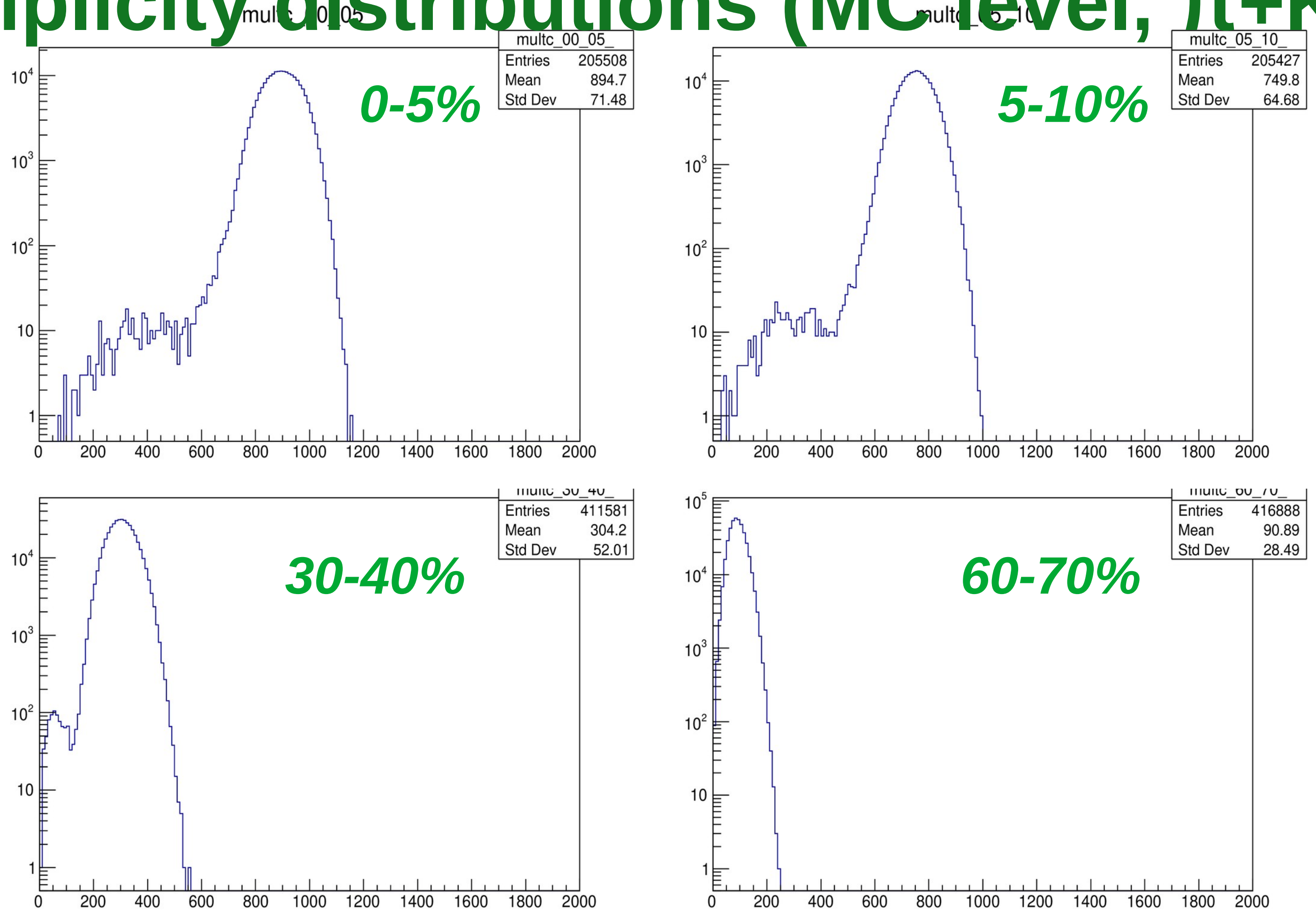
Centrality (fm)



Multiplicity

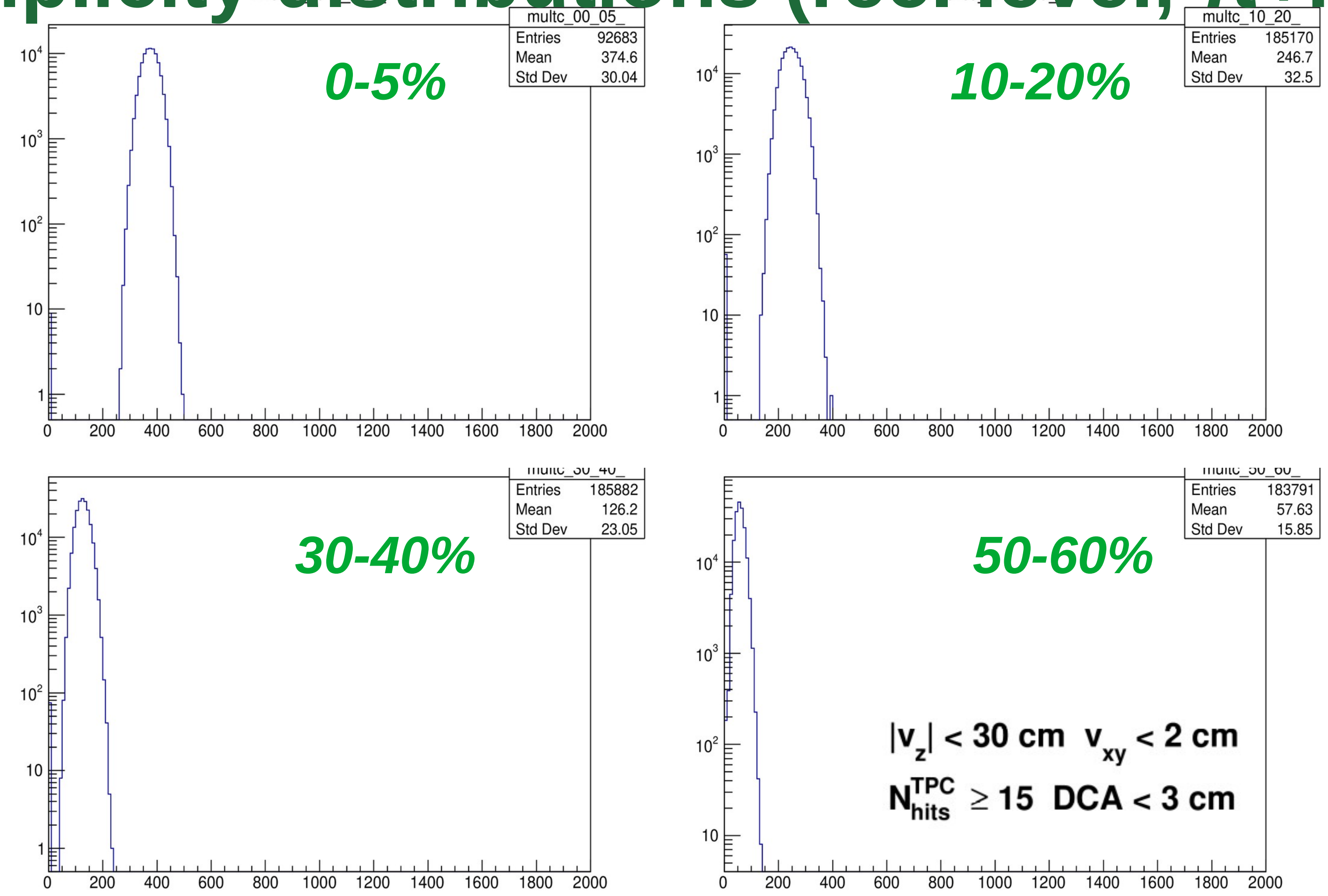
Centrality and multiplicity distributions of MC events seem normal.

Multiplicity distributions (MC level, π+K+p)



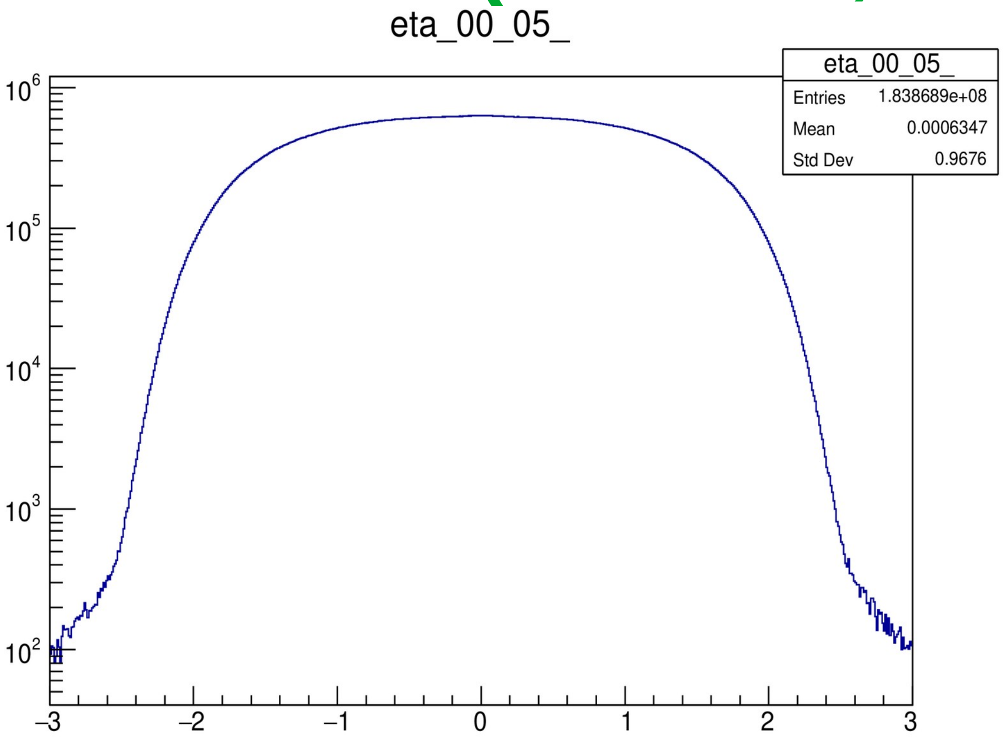
It seems there are events with incomplete multiplicities that are merged with complete multiplicity events in peripheral collisions.

Multiplicity distributions (rec. level, π+K+p)

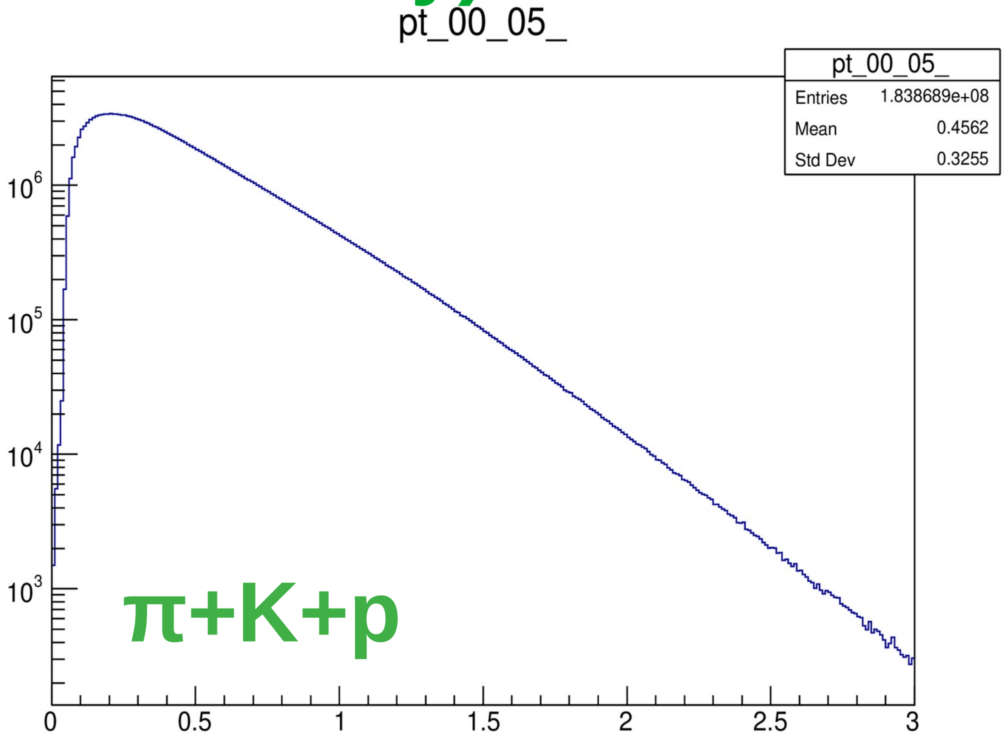


No incomplete multiplicity events are visible at reconstruction level, though multiplicity is decreased compared to MC due to additional track cuts.

Rapidity & transverse momentum distributions (MC level, 0-5% centrality)



η

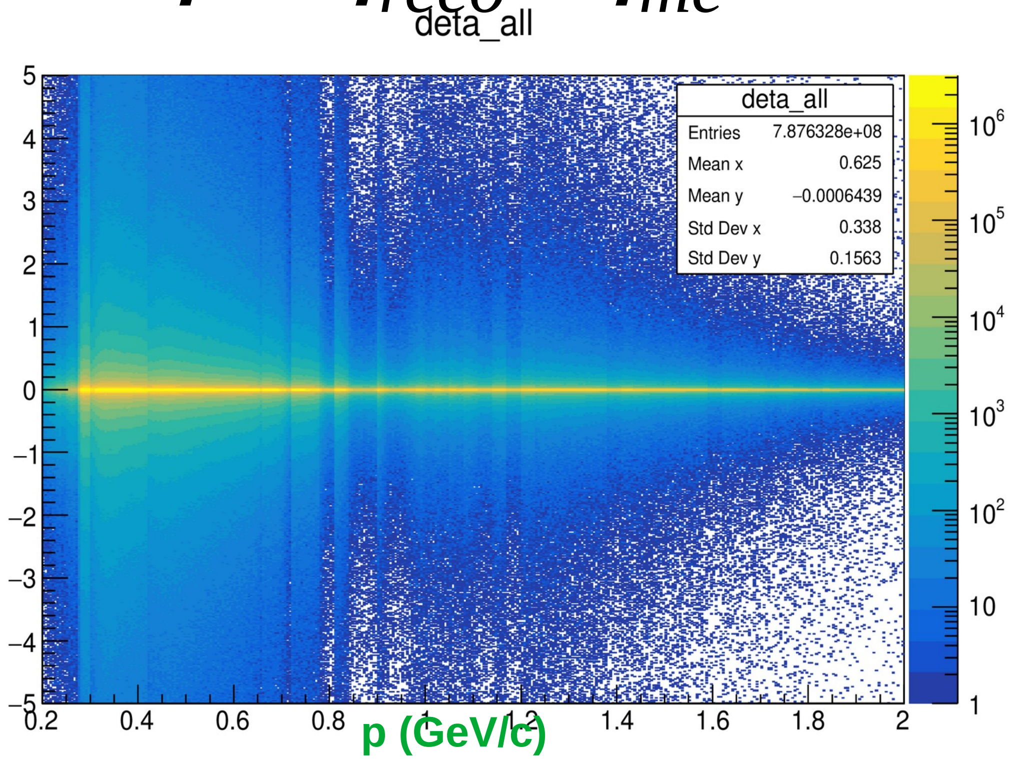


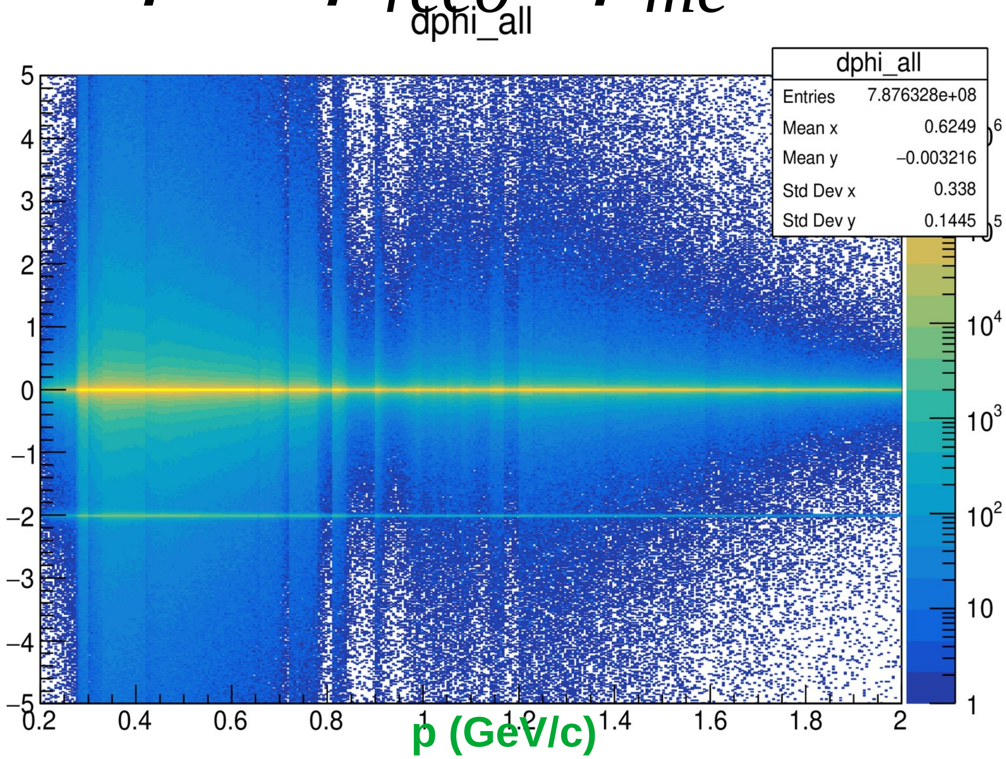
p_T (GeV/c)

Rapidity and momentum distributions of MC events seem normal.

Accuracy of η and φ reconstruction

$$\delta\eta = \eta_{reco}/\eta_{mc} - 1 \qquad \delta\varphi = \varphi_{reco}/\varphi_{mc} - 1$$

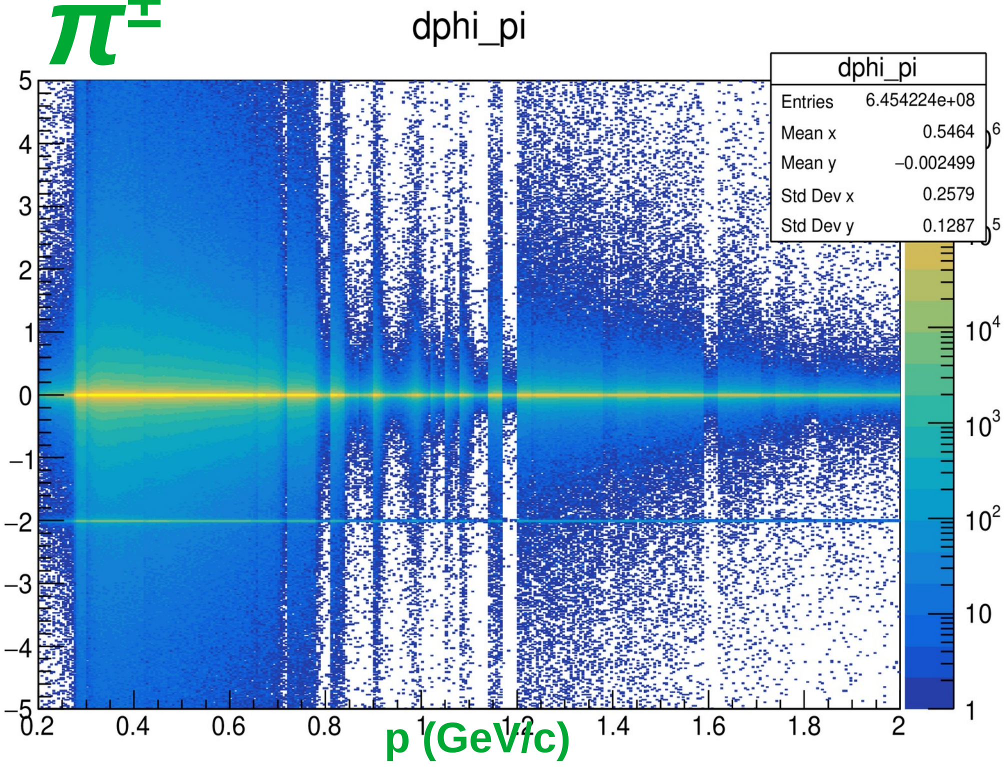




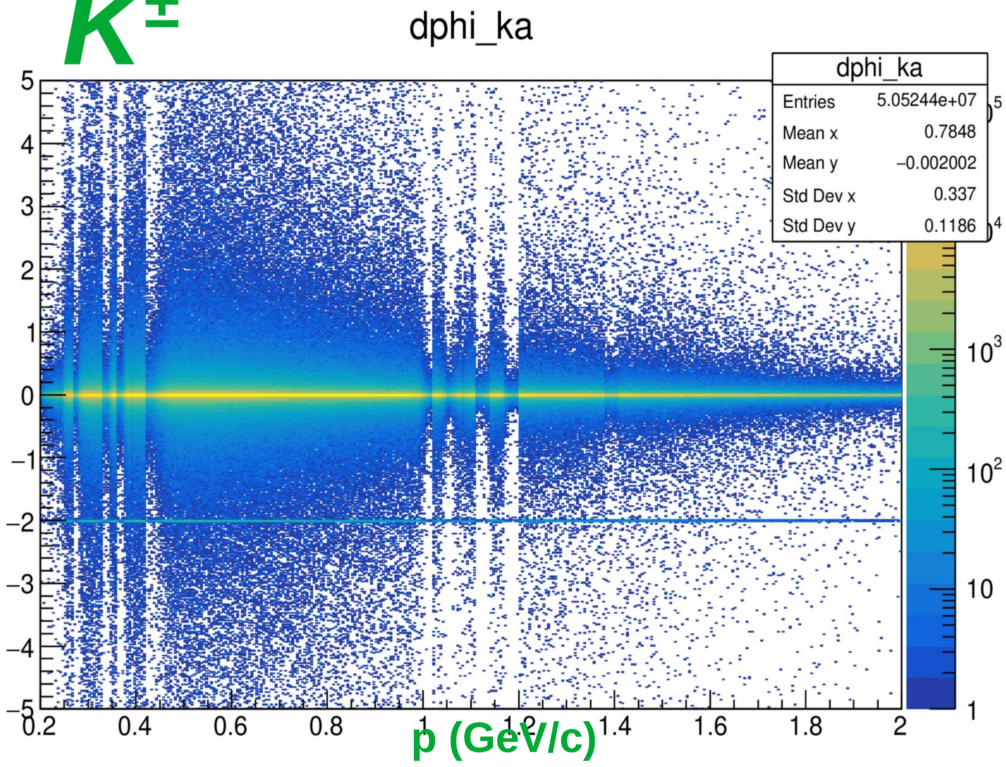
Seem to be fairly reconstructed.

φ reconstruction accuracy of $\pi^{\pm}$ and $K^{\pm}$

$\pi^{\pm}$



$K^{\pm}$



Seem to be fairly reconstructed.