Update on charge balance function analysis

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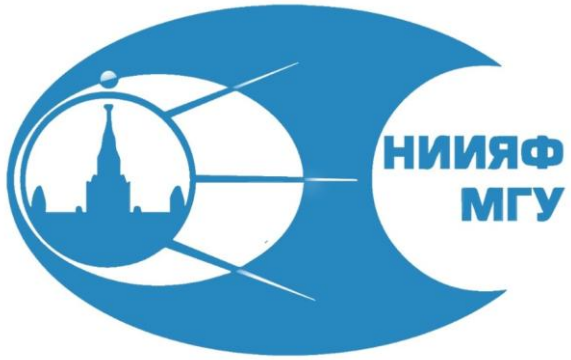


Charge balance functions of oppositely charged particles

$$B(\Delta y, \Delta\varphi) = \frac{1}{2}\left\{\frac{\langle N^{+-}(\Delta y, \Delta\varphi)\rangle - \langle N^{++}(\Delta y, \Delta\varphi)\rangle}{\langle N^{+}\rangle} + \frac{\langle N^{-+}(\Delta y, \Delta\varphi)\rangle - \langle N^{--}(\Delta y, \Delta\varphi)\rangle}{\langle N^{-}\rangle}\right\},$$

where N^{+-} is number of pairs of oppositely charged particles whose rapidities y_1 and y_2 satisfy the condition $|y_1 - y_2| = \Delta y$, and similarly, for $\Delta\varphi$. N^{+} and N^{-} are the multiplicities of positively and negatively charged particles respectively. **The balance function (CBF) is the probability density that oppositely charged particles are separated by certain intervals of (pseudo-)rapidity and azimuthal angle. The CBF is characterized by rapidity and azimuthal widths.**

$$\langle \Delta\eta \rangle = \frac{\sum_i B_i \Delta\eta_i}{\sum_i B_i} \qquad \langle \Delta\varphi \rangle = \frac{\sum_i B_i \Delta\varphi_i}{\sum_i B_i}$$

The CBF is sensitive to the time of electric charge separation during the evolution of the system – **information about spatiotemporal characteristics of the particle emission region, including the presence and type of the quark-hadron phase transition.**

Long-range charge correlations (wide distribution) → early charge separation
Short-range charge correlations (narrow distribution) → late charge separation

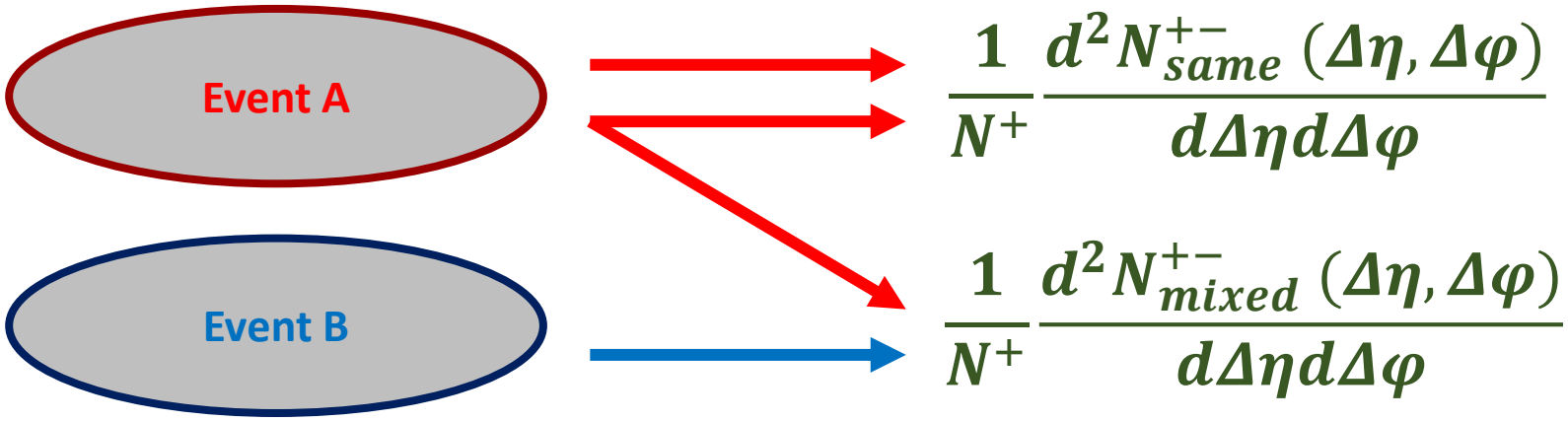
CBFs were measured in heavy-ion experiments at the SPS, RHIC, and LHC accelerators.

Modern theoretical models struggle to describe CBFs → unaccounted correlation mechanisms?

Calculation and correction of Charge Balance Functions

$$\frac{P^{+-}}{P^{+}} = \frac{P^{+-}(\Delta\eta, \Delta\varphi)}{P^{+}} \longrightarrow \frac{1}{N^{+}} \frac{d^2N^{+-}(\Delta\eta, \Delta\varphi)}{d\Delta\eta d\Delta\varphi}$$

Here N^{+} is number of positive hadrons, $d^2N^{+-}/d\Delta\eta d\Delta\varphi$ is the distribution of positive-negative hadron pairs by relative pseudorapidity and azimuthal angle.



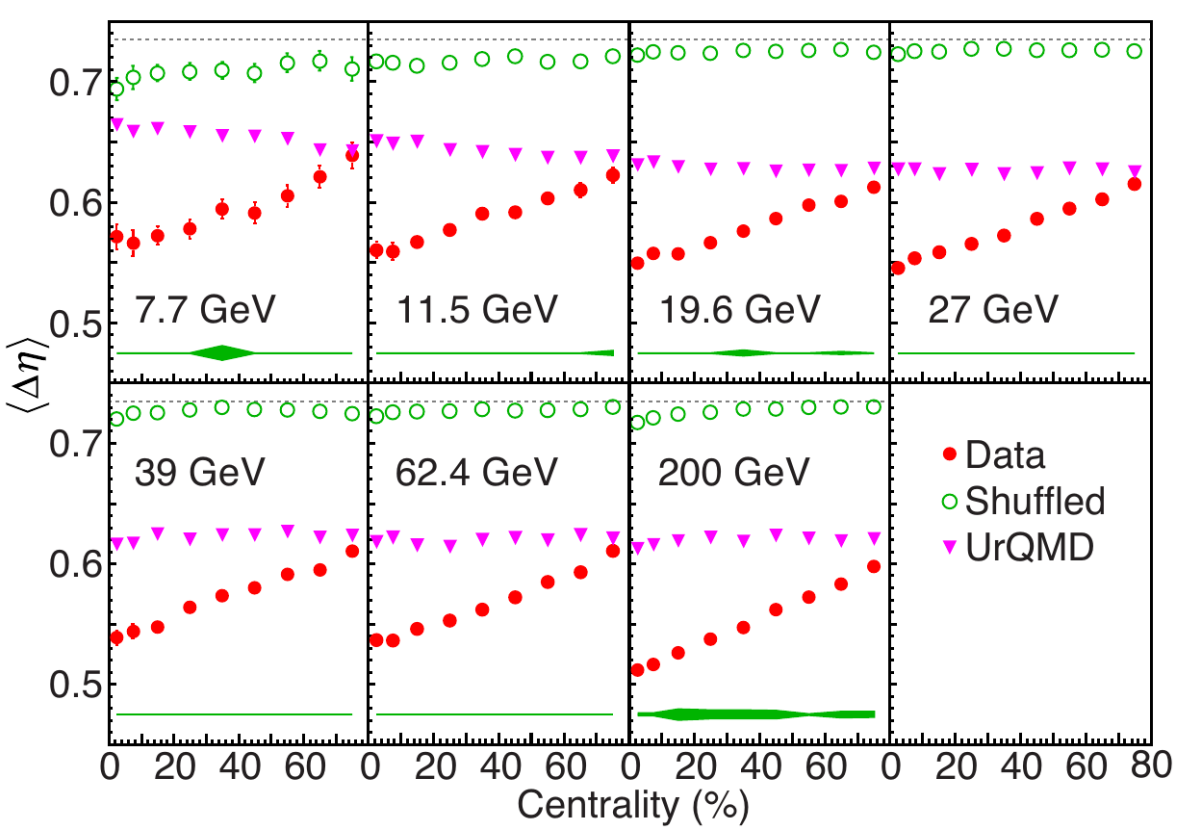
In case of excess positive charge (NICA/RHIC) to suppress distortion, the CBFs should be corrected according to the formula below:

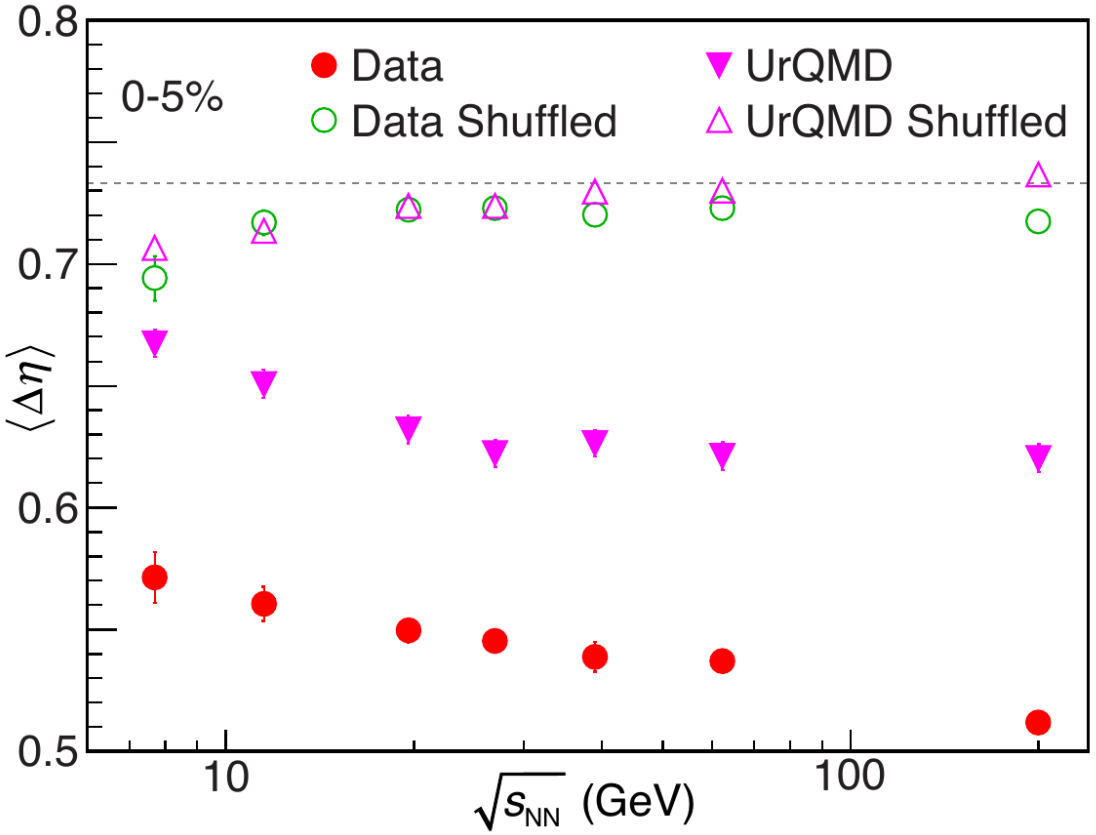
$$\frac{1}{N^{+}} \frac{d^2N^{+-}(\Delta\eta, \Delta\varphi)}{d\Delta\eta d\Delta\varphi} = \frac{1}{N^{+}} \frac{d^2N^{+-}_{same}(\Delta\eta, \Delta\varphi)}{d\Delta\eta d\Delta\varphi} - \frac{1}{N^{+}} \frac{d^2N^{+-}_{mixed}(\Delta\eta, \Delta\varphi)}{d\Delta\eta d\Delta\varphi}$$

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.**

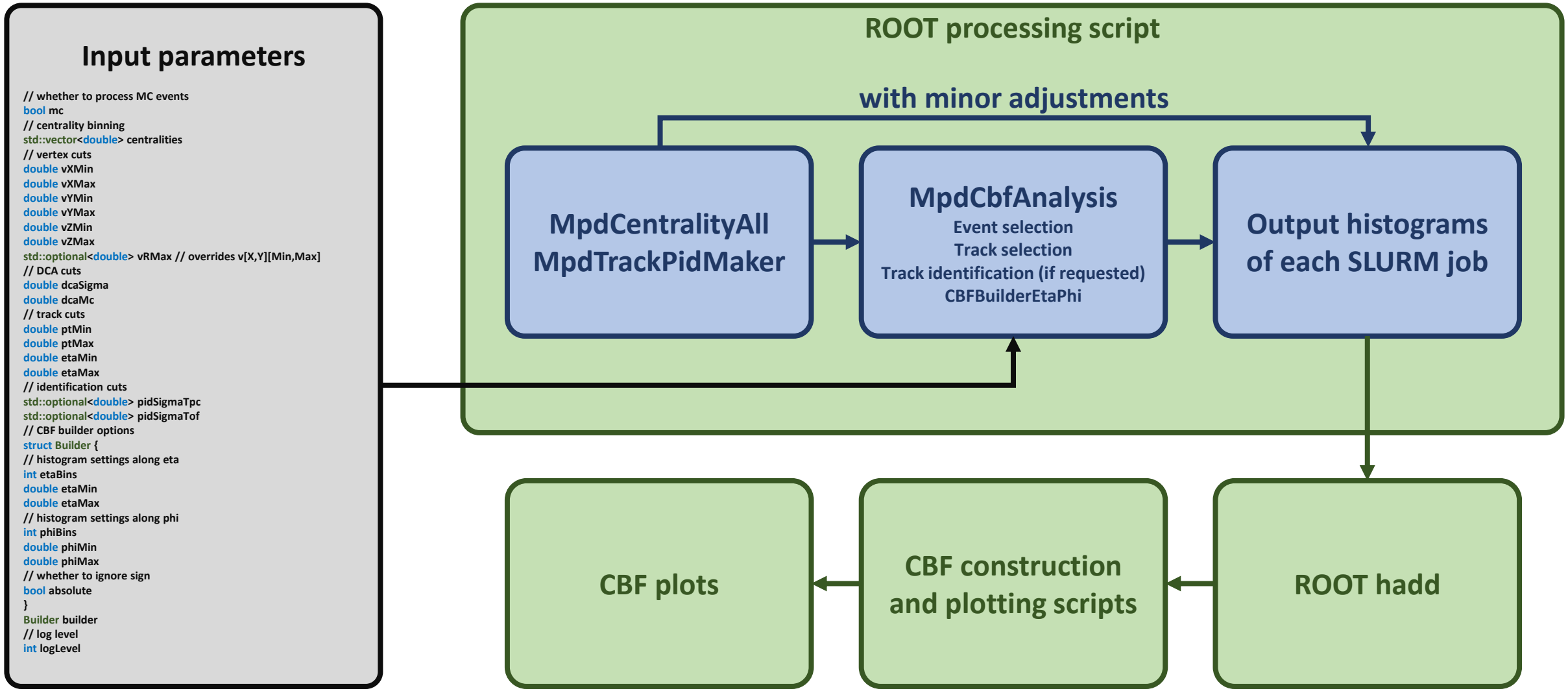




Energy dependence of CBF widths compared with the widths of CBFs calculated using events with shuffled charges (on the left). **CBF widths for the most central events (0-5%)** compared with CBF widths calculated using events with shuffled charges (on the right) [Phys.Rev.C 94 (2), 024909 (2016)].

CBF analysis MpdRoot integration

MpdCbfAnalysis Wagon has been developed and integrated into MpdRoot. It can (though not necessarily) use ***MpdCentralitryAll*** and ***MpdTrackPidMaker*** Wagons for centrality estimation and track identification.



Previous results on CBF reconstruction in MPD/NICA experiment

Request 25 events were used in this analysis (50 million events):
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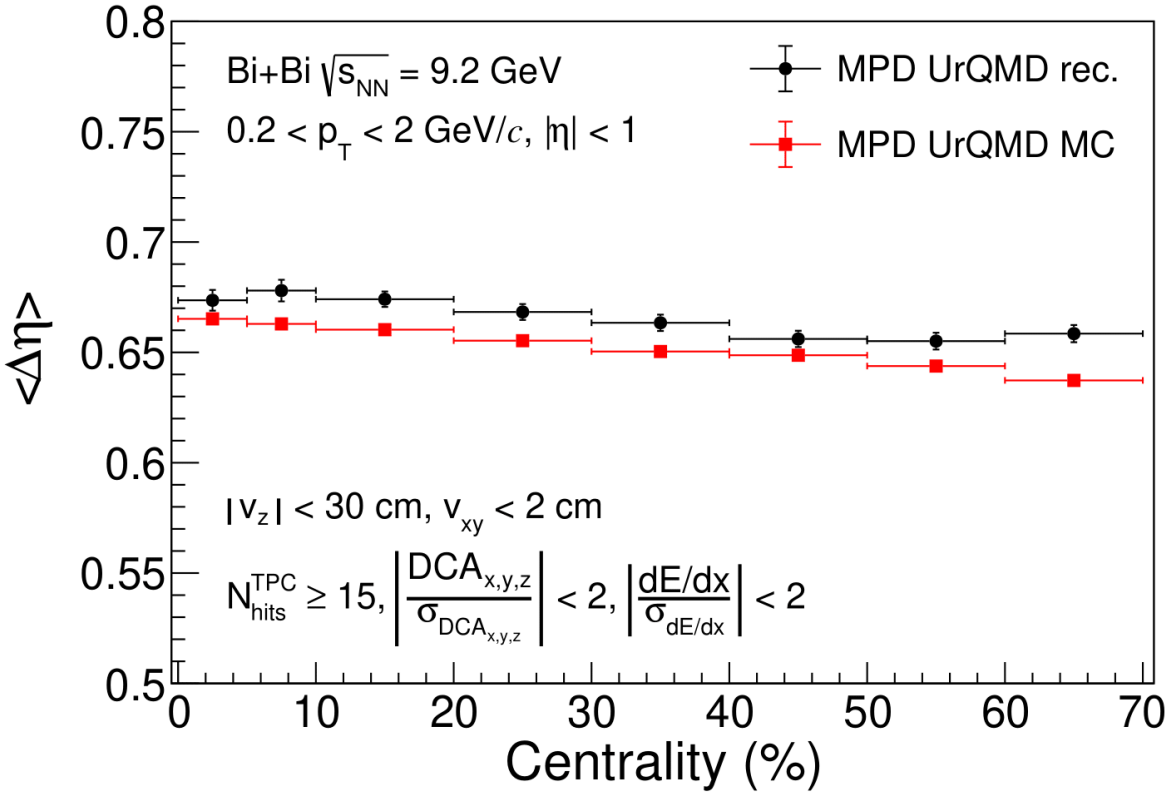

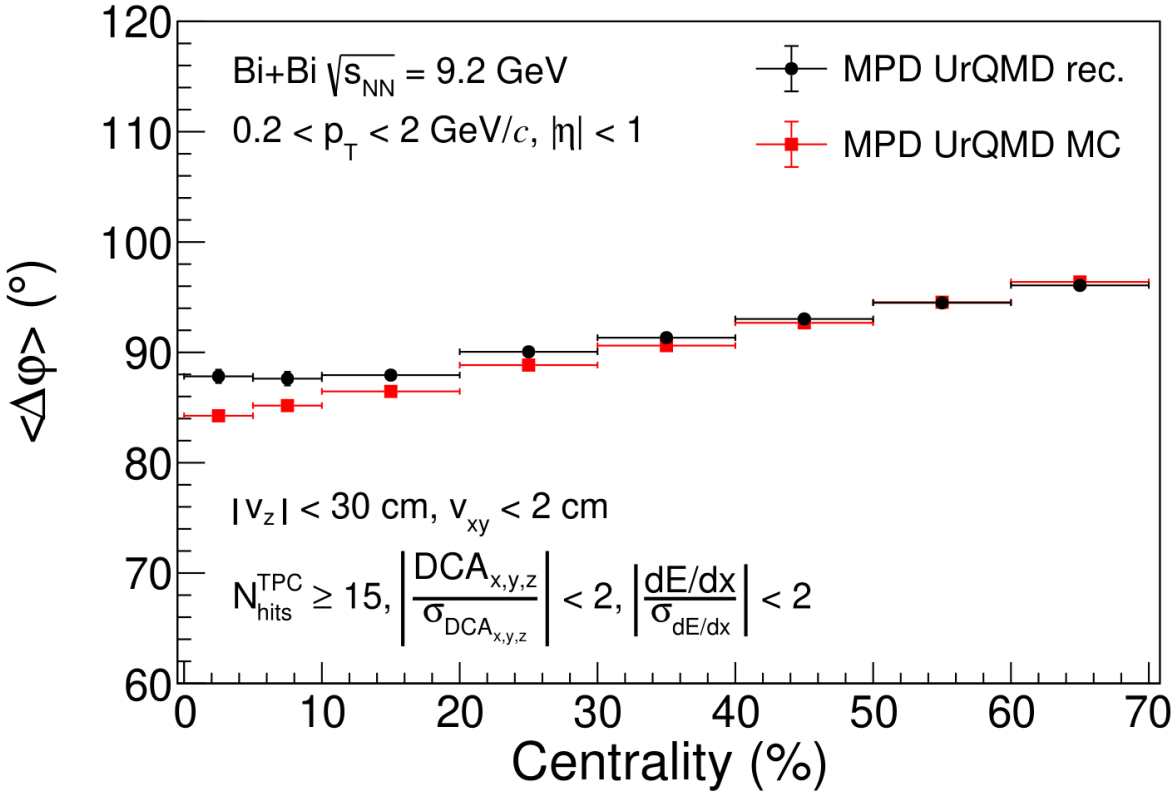

MPD Cross-PWG Meeting, 17 June 2025

Both rapidity and azimuthal reconstructed widths are close to MC widths, however, some systematic overestimation of RECO widths within 5% is observed.

Previous results on CBF reconstruction in MPD/NICA experiment

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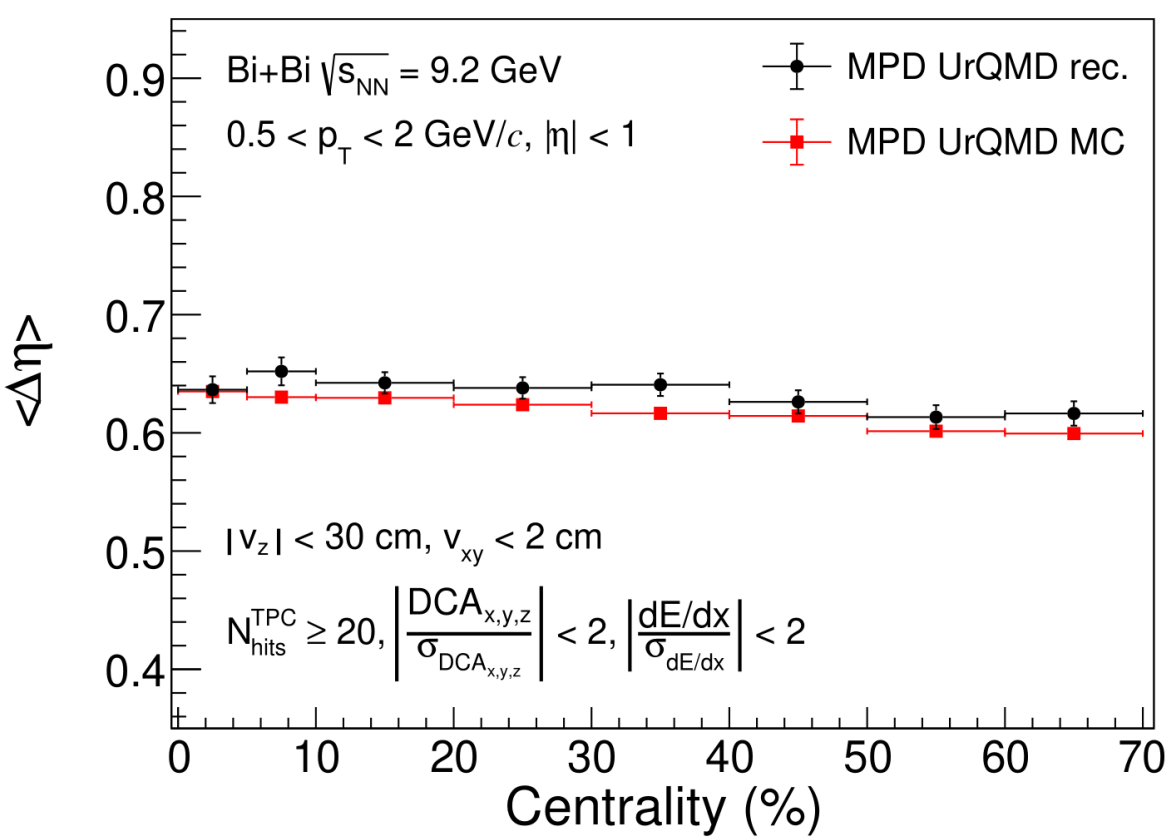
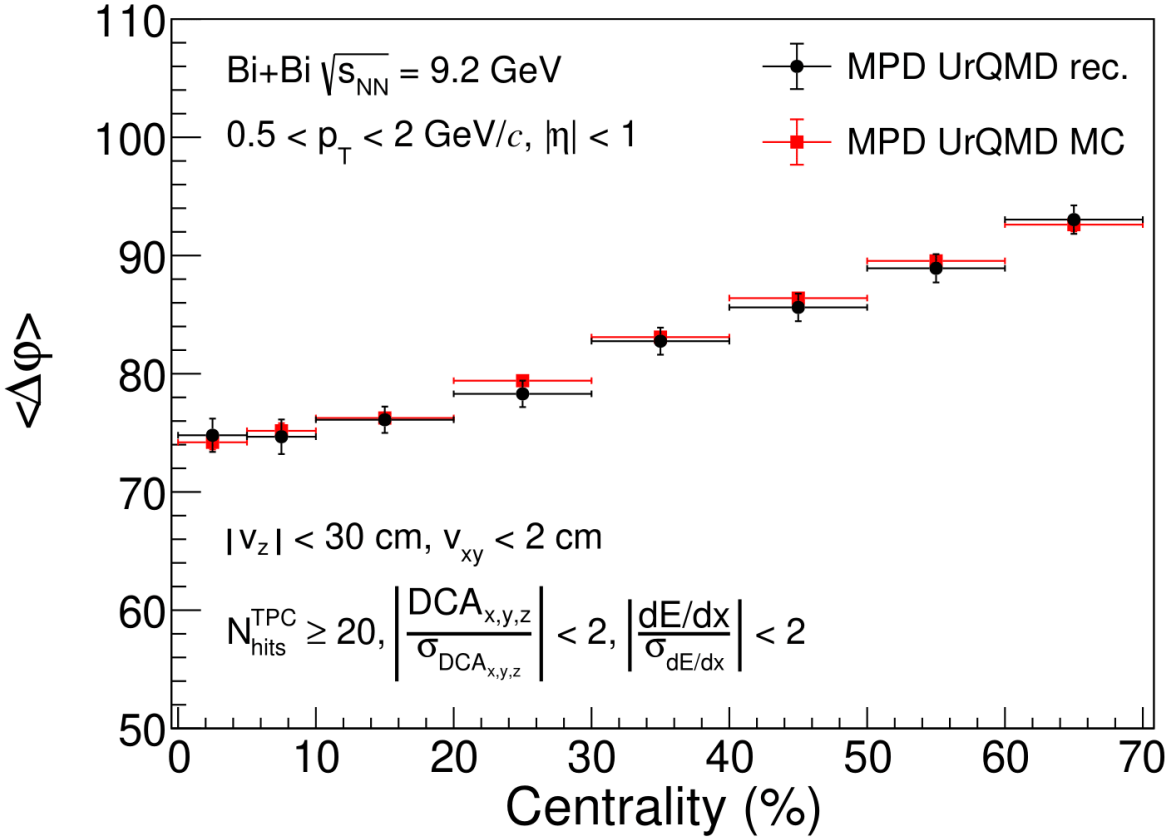
/eos/nica/mpd/sim/data/exp/dst-BiBi-09.2GeV-mp07-22-500ev-req25/BiBi/09.2GeV-mb/urqmd/BiBi-09.2GeV-mp07-22-500ev-req25



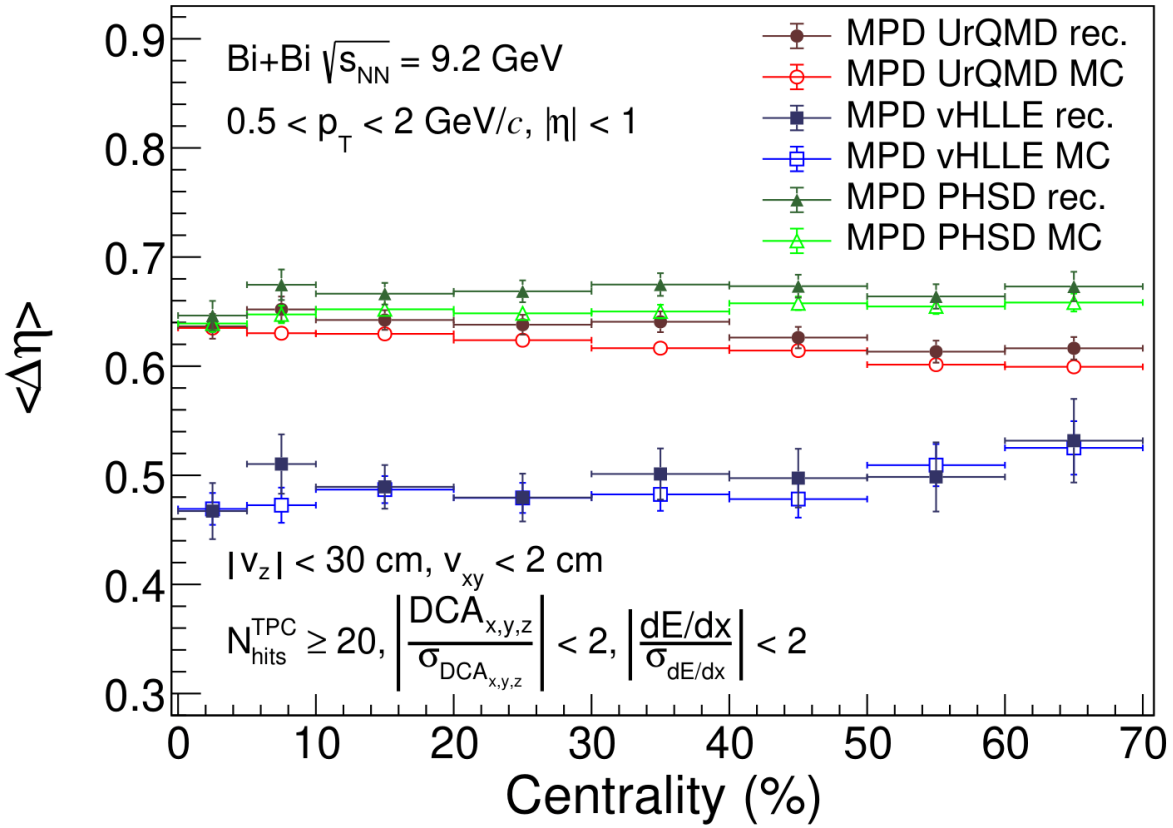


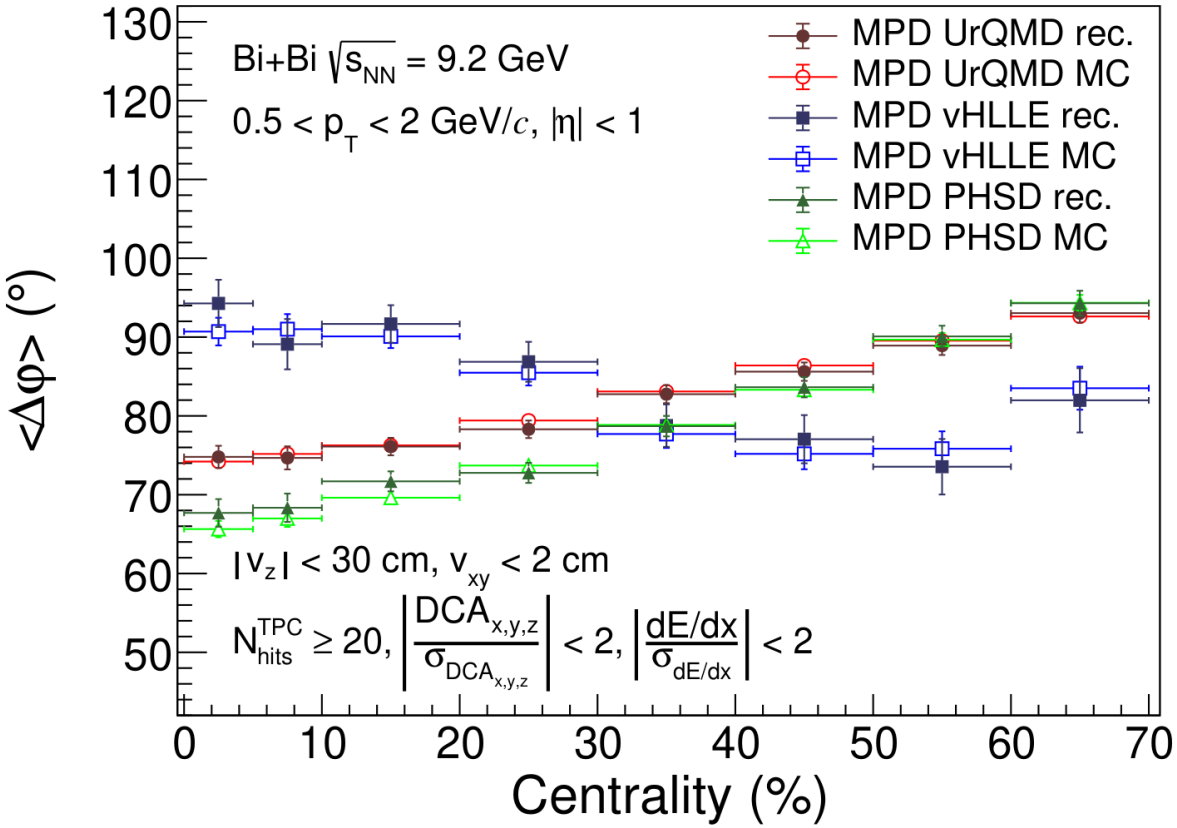
MPD Cross-PWG Meeting, 21 October 2025

Both rapidity and azimuthal reconstructed widths are close to MC widths

Current state of CBF reconstruction in MPD/NICA experiment

Request 25 https://mpdforum.jinr.ru/t/request-25-general-purpose-50m-urqmd-bibi-9-2-second-collaboration-paper/455
Request 30 https://mpdforum.jinr.ru/t/request-30-general-purpose-hyperon-polarization-15m-phsd-bibi-9-2-second-collaboration-paper/481
Request 32 https://mpdforum.jinr.ru/t/request-32-flow-vhlle-urqmd-23m-bibi-9-2-gev/540

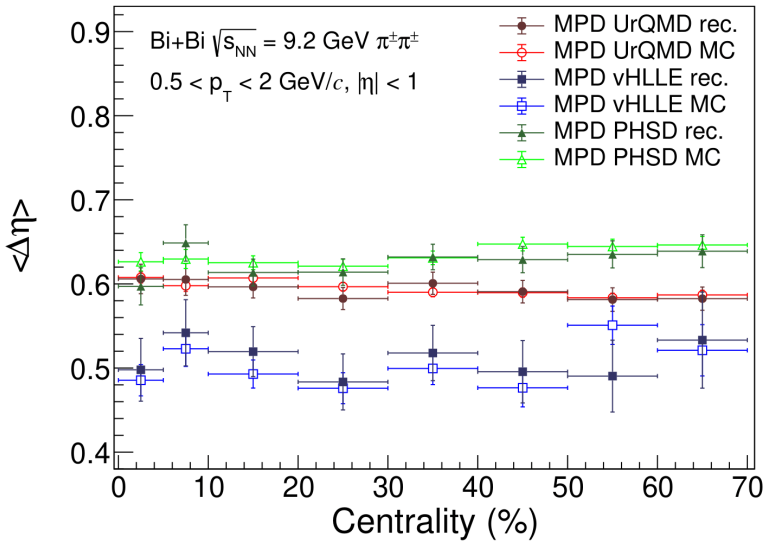


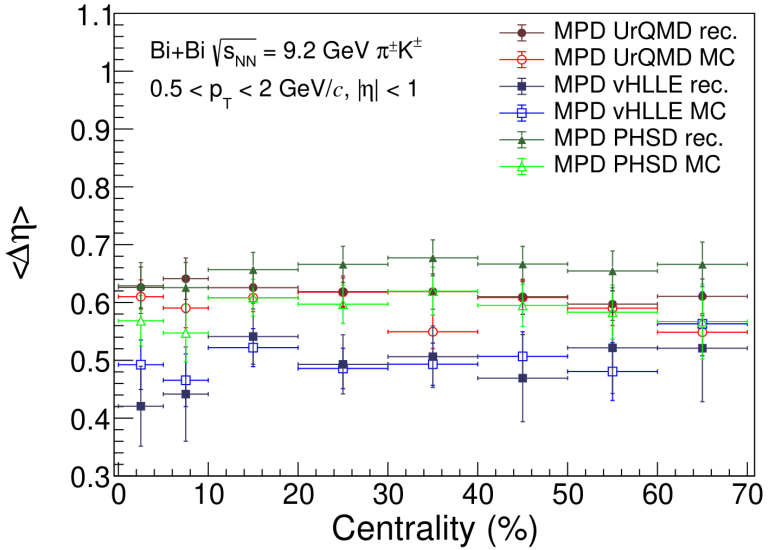


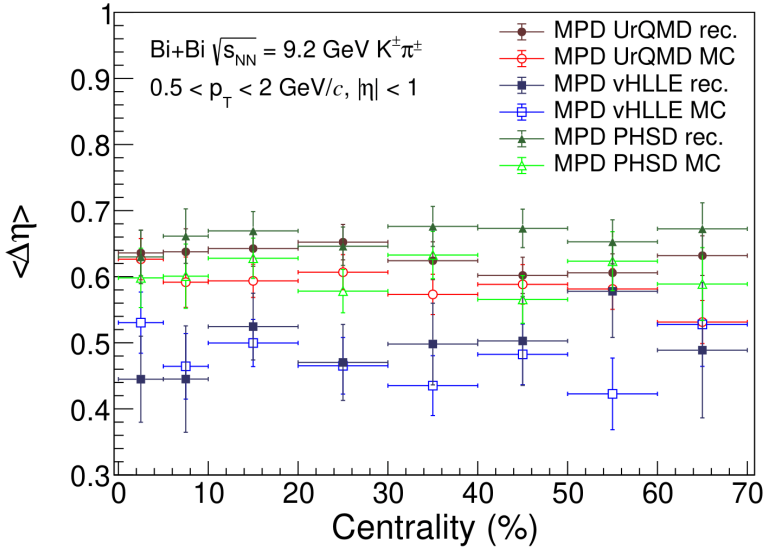
MPD Cross-PWG Meeting, 7 April 2026

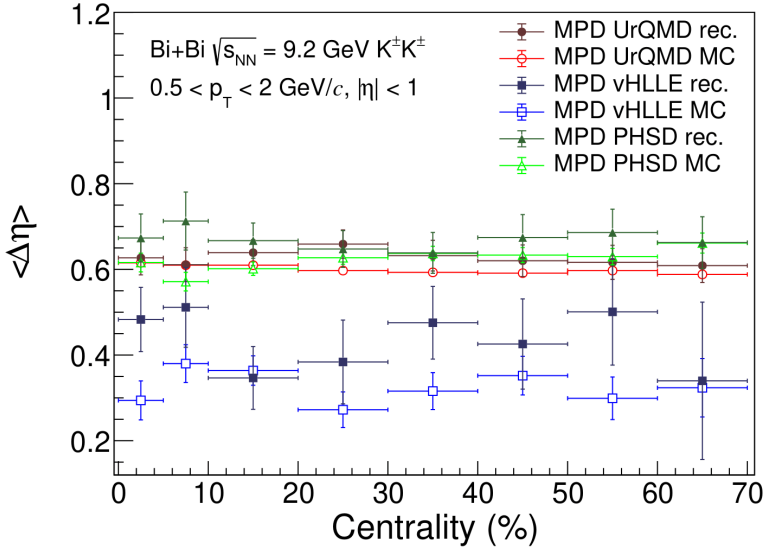
Both rapidity and azimuthal reconstructed widths are close to MC widths. It seems that reconstruction efficiency is enough to distinguish predictions of different models.

Reconstruction of partial CBFs in the MPD/NICA experiment





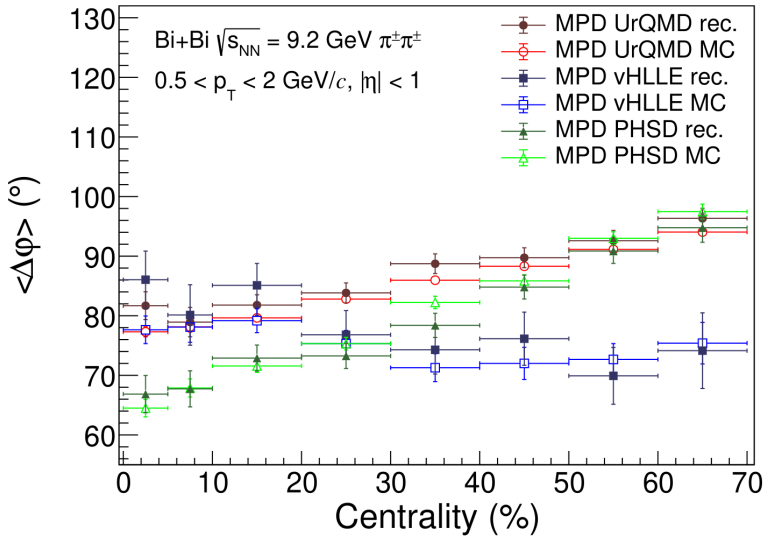


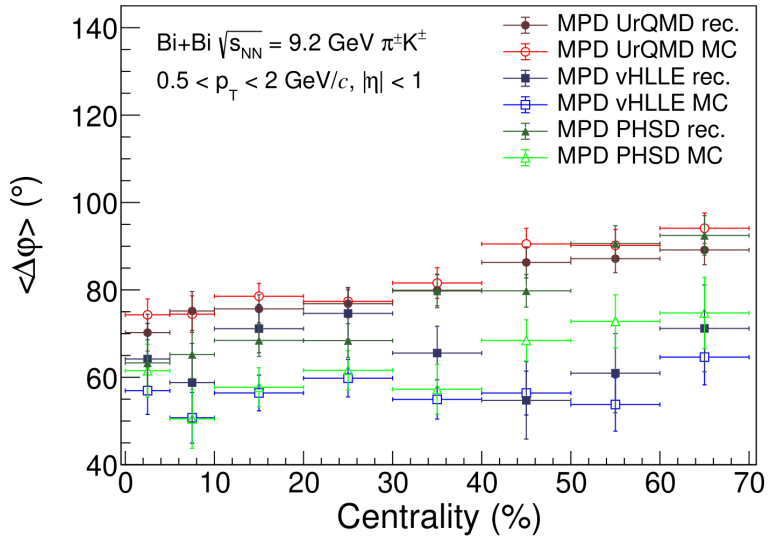


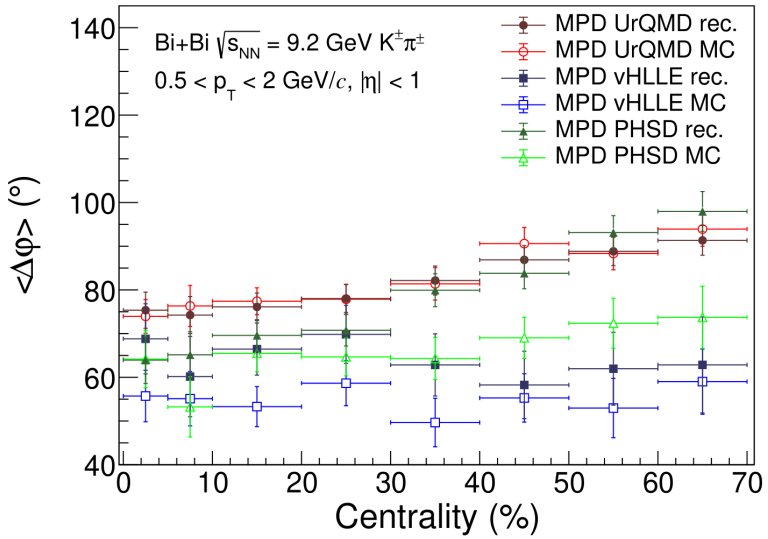
Reconstructed pion-pion rapidity widths are in fair agreement with generator level widths in all productions.

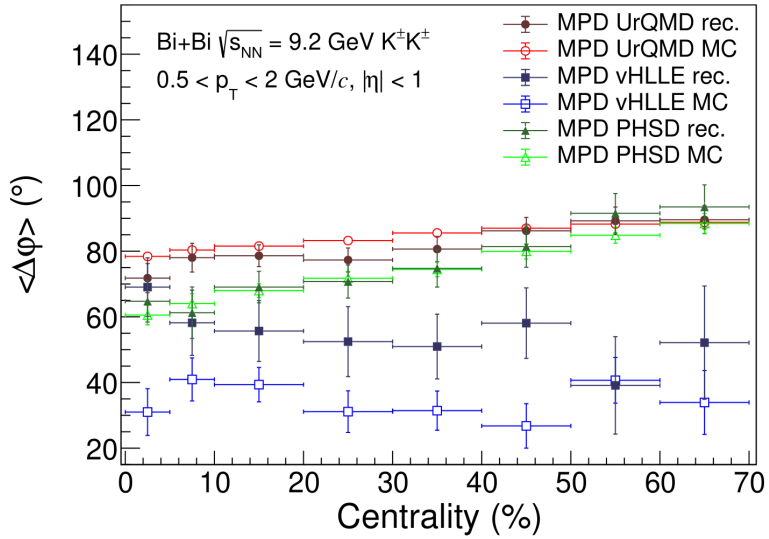
Meanwhile, there are noticeable differences in pion-kaon (PHSD, req. 30) and kaon-kaon (VHLLE, req. 32) widths.

Reconstruction of partial CBFs in the MPD/NICA experiment





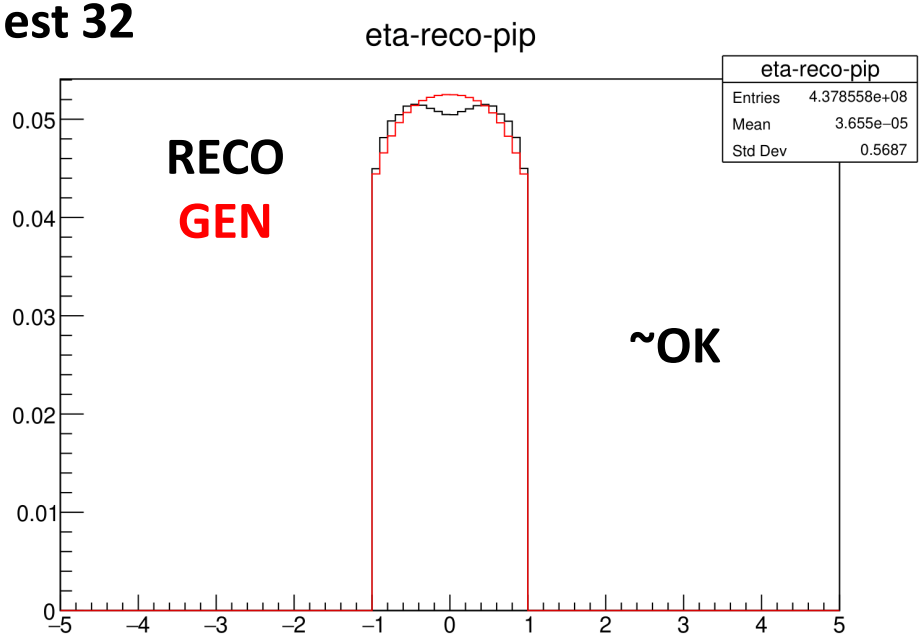


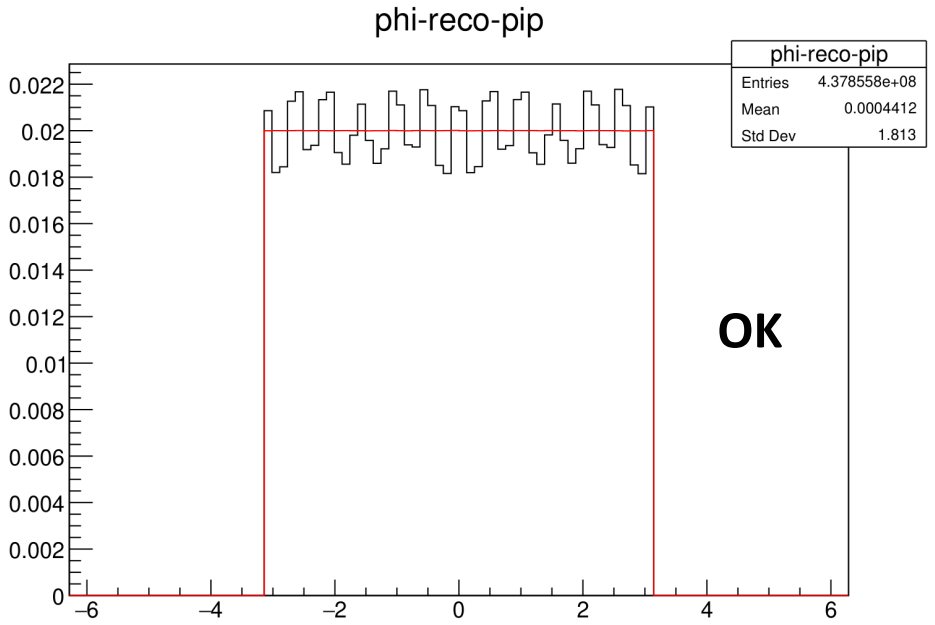


Reconstructed pion-pion rapidity widths are in fair agreement with generator level widths in all productions.

However, there are noticeable differences in pion-kaon (PHSD, req. 30) and kaon-kaon (VHLLE, req. 32) widths.

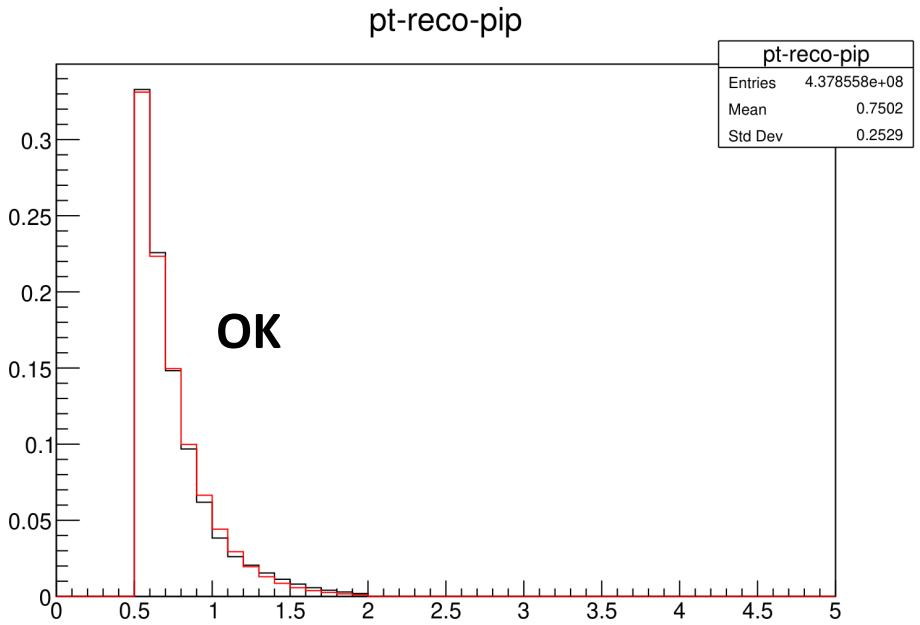
Request 32



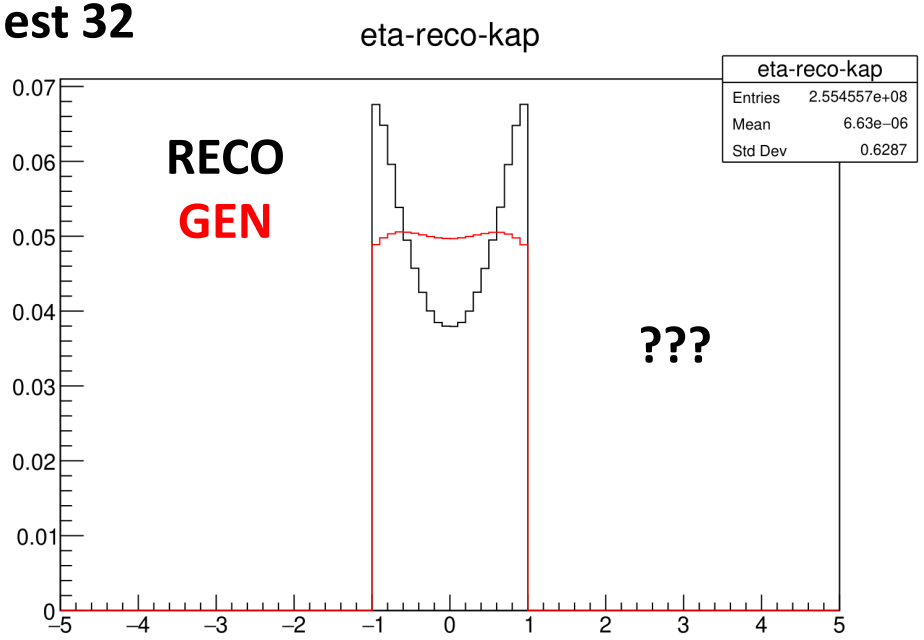


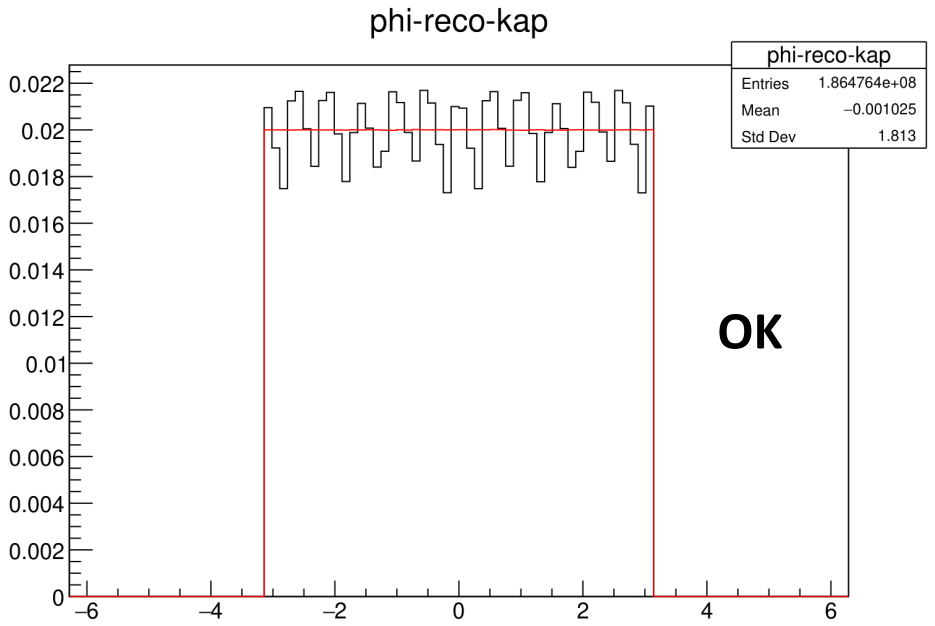
Charged pions

RECO vs GEN



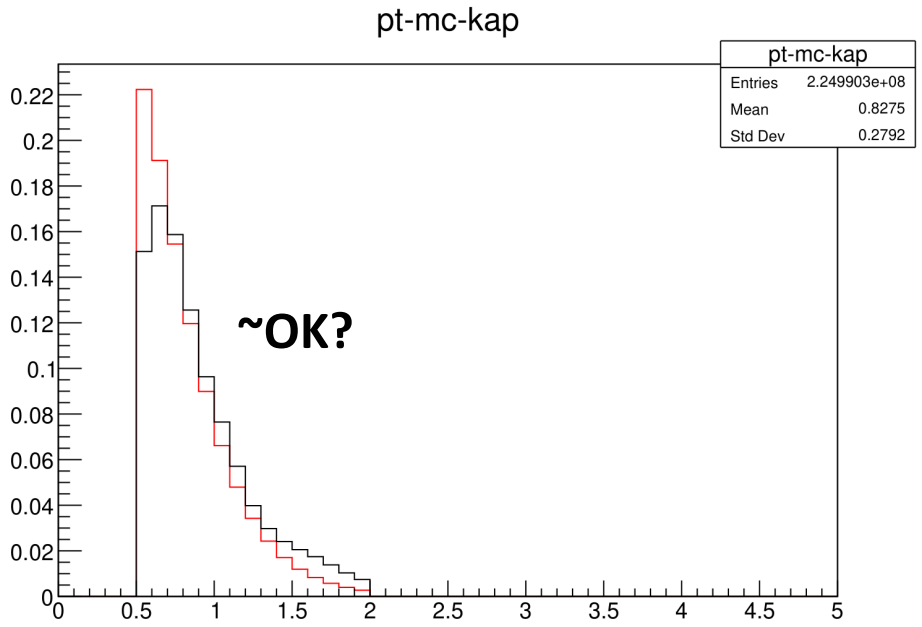
Request 32



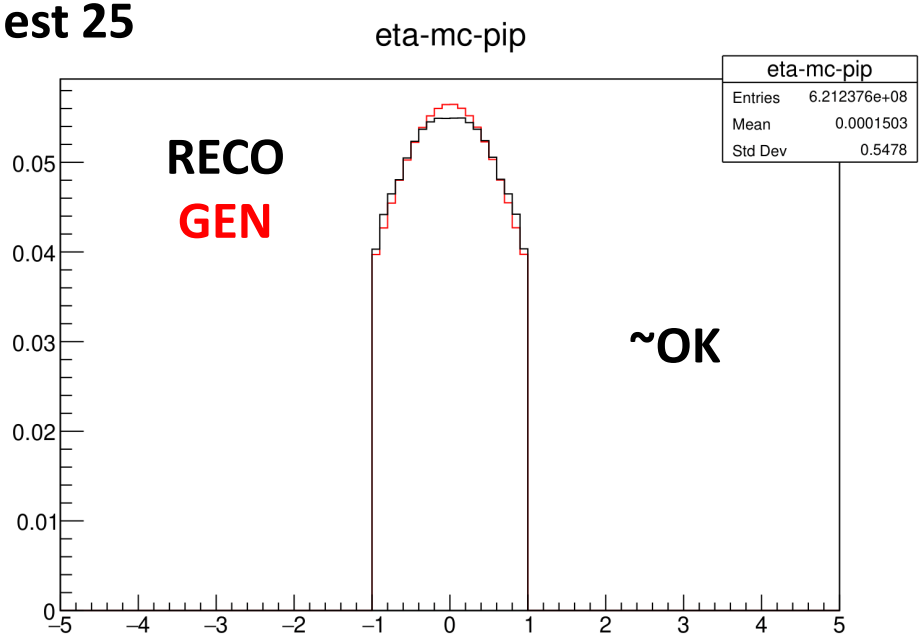


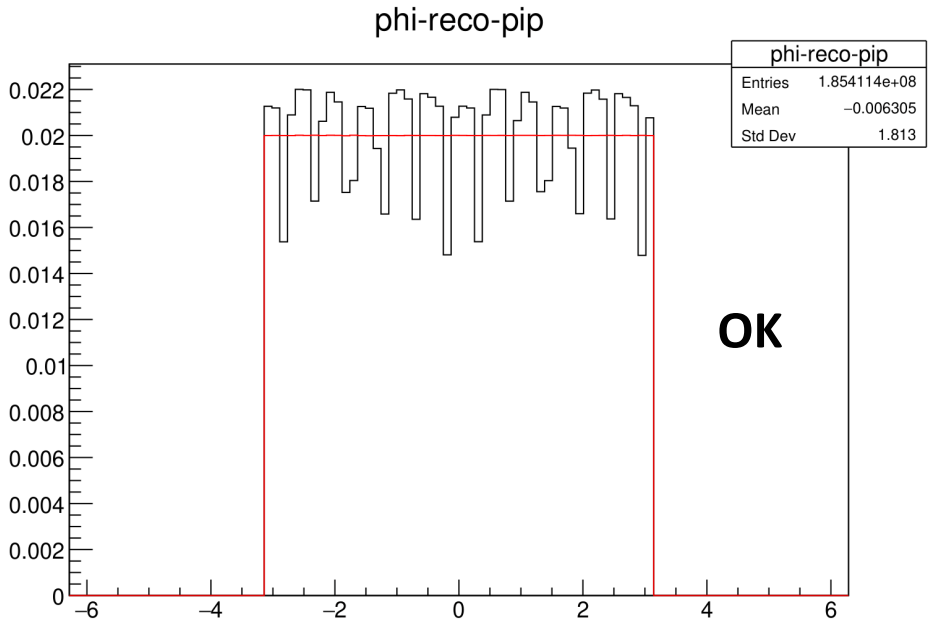
Charged kaons

RECO vs GEN



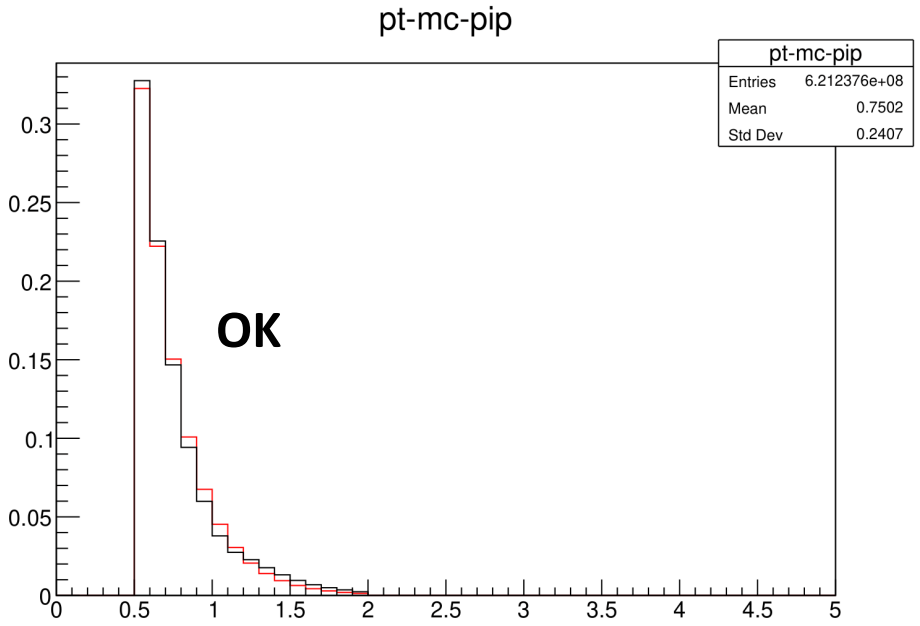
Request 25



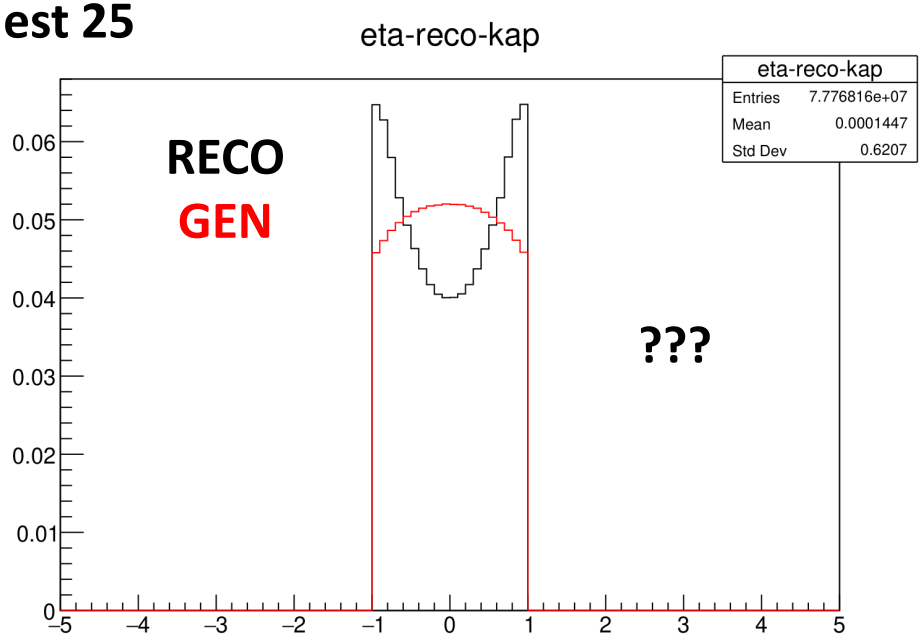


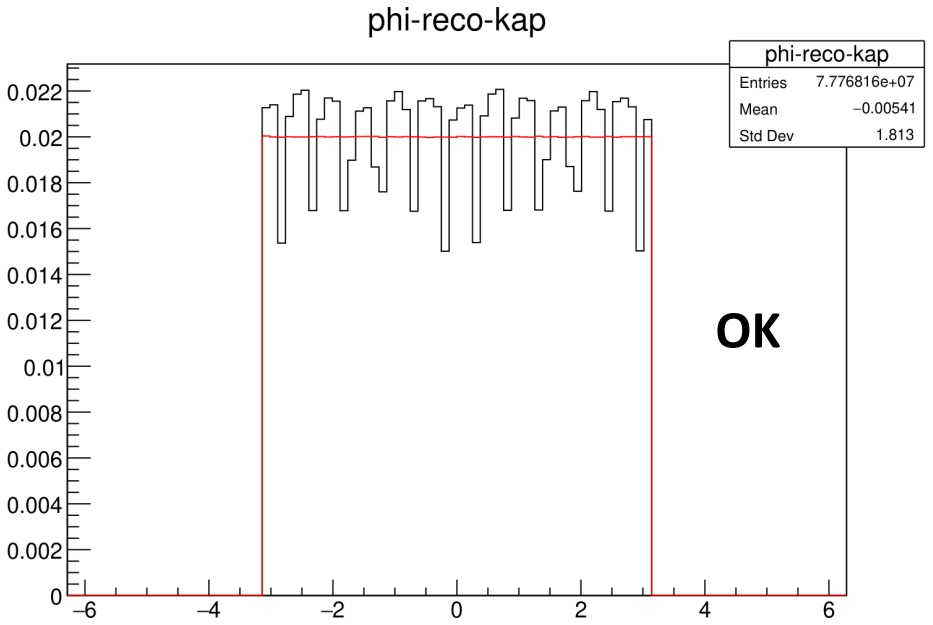
Charged pions

RECO vs GEN



Request 25





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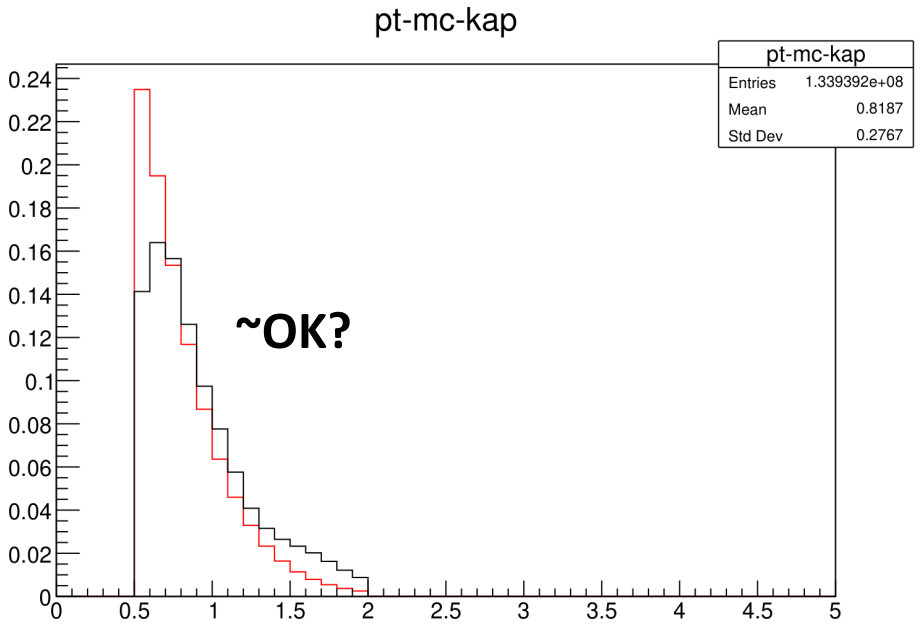
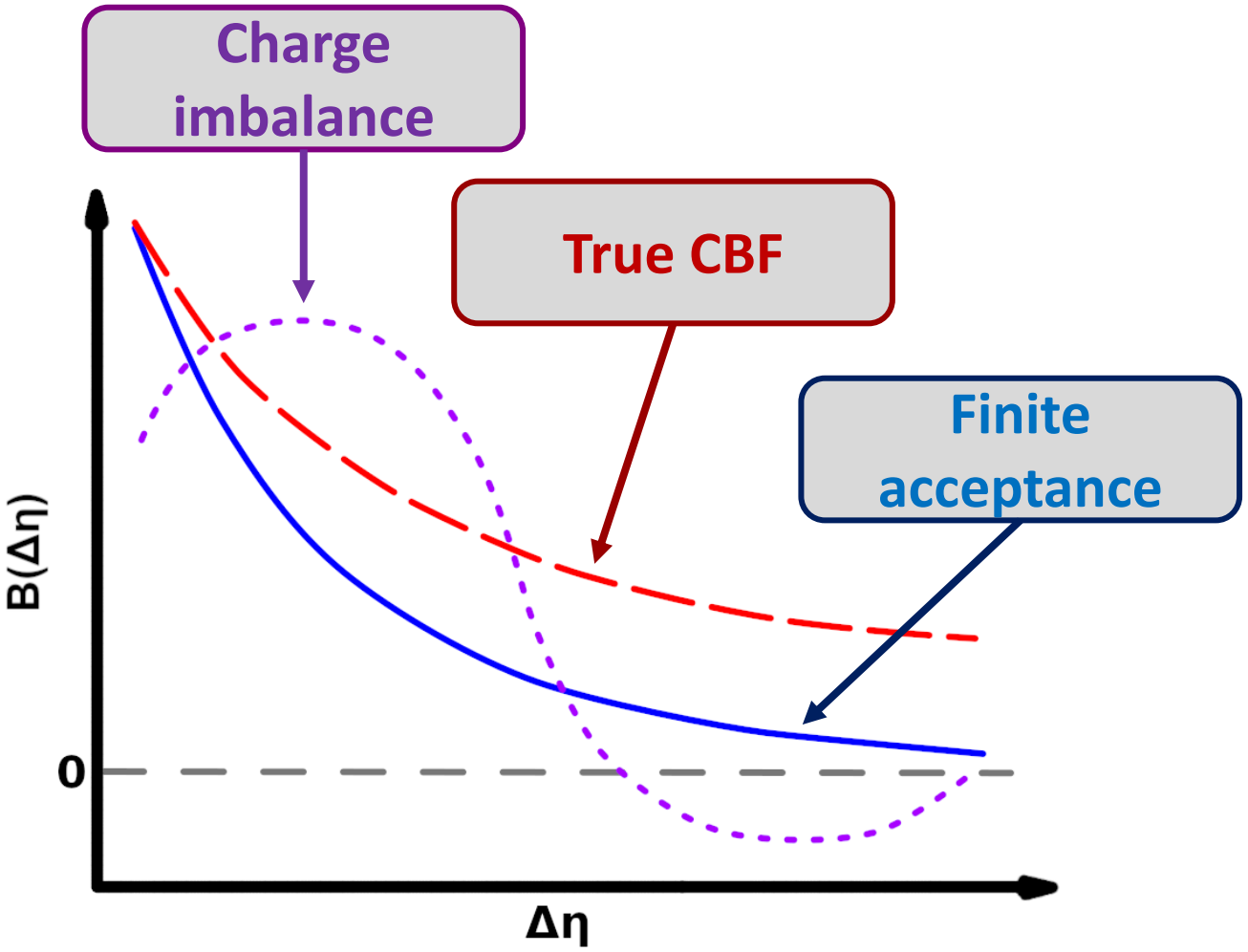


Conclusions

- ✓ **MpdCbfAnalysis “wagon” functionality is extended with more QA histograms.**
- ✓ **Reconstructed CBF widths of inclusive hadrons are close to generator widths in several productions (req. 25 – UrQMD, req. 30 – PHSD, req. 32 – VHLLE). Reconstruction efficiency is enough to distinguish predictions of different models.**
- ✓ **Reconstructed partial CBF widths are close to GEN widths in some productions (pion-pion widths in requests 25, 30, 32). However, in some productions partial widths are not close enough (pion-kaon widths in req. 30 and kaon-kaon widths in req. 32).**

Additional slides

Calculation and correction of Charge Balance Functions



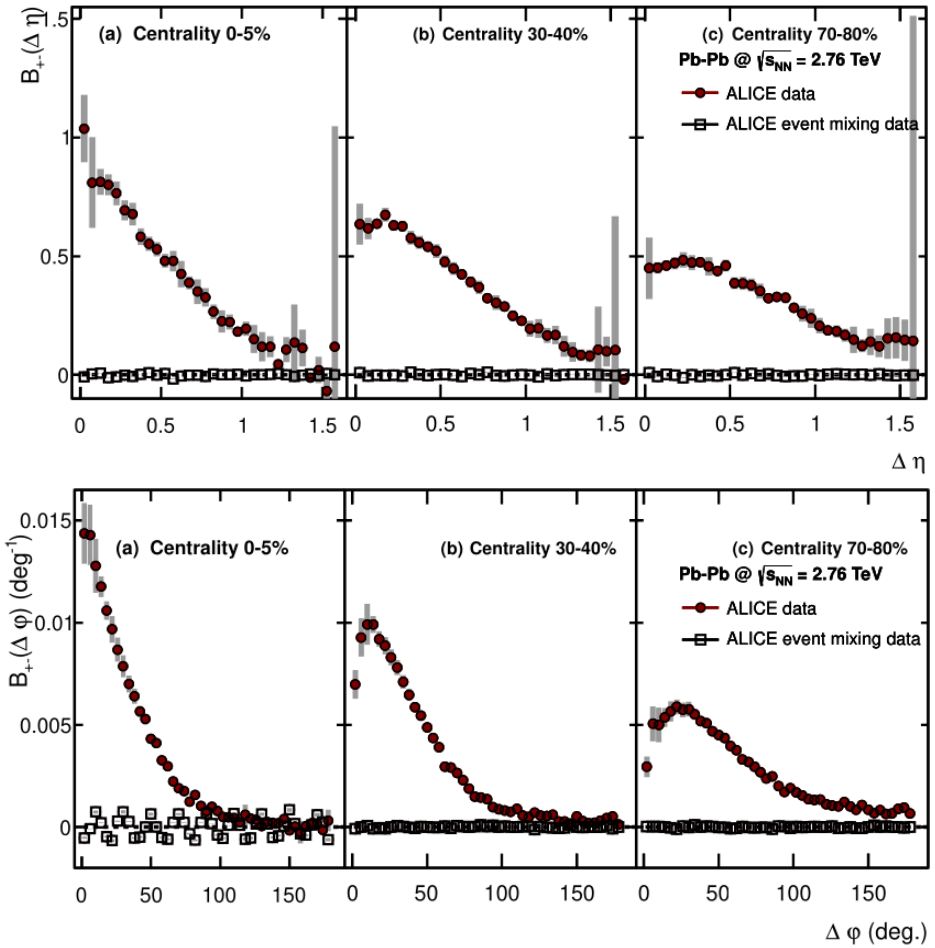
To take into account the influence of the finite angular acceptance of the detector of modeling and experimental analysis, the method described in **[STAR Coll., Phys. Rev. C 94 (2) 024909 (2016)]** is used, in which the charge imbalance-corrected CBF is multiplied by weighting factors:

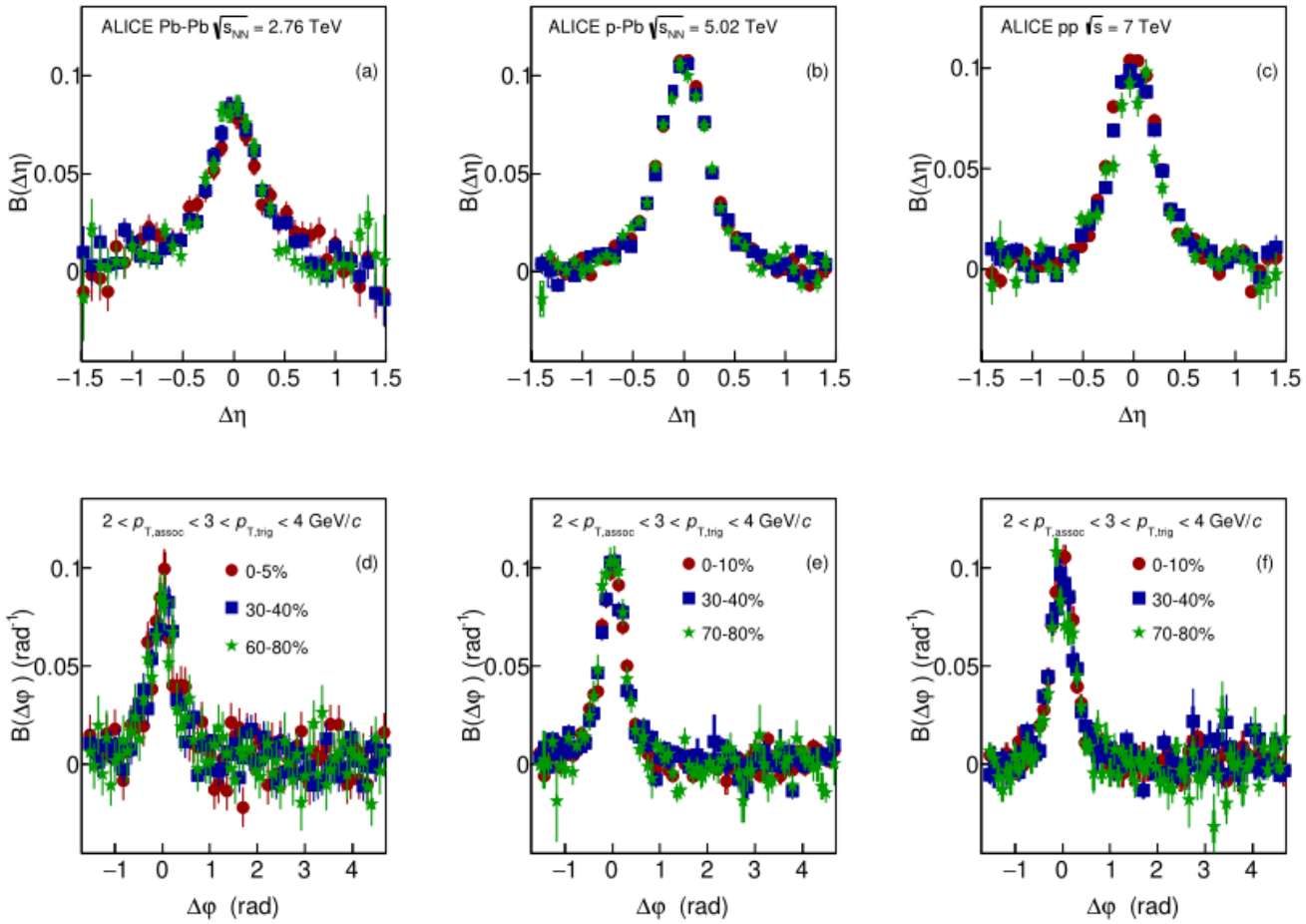
$$B(\Delta\eta|\infty) = \frac{B(\Delta\eta|\Delta\eta_{max})}{\left(1 - \frac{\Delta\eta}{\Delta\eta_{max}}\right)}$$

In case of azimuthal hermiticity of the detector, correction of the azimuthal CBF is not required.

Experimental status of CBFs at LHC (ALICE)

An extensive experimental analysis of CBFs was performed at the LHC by the 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)].**

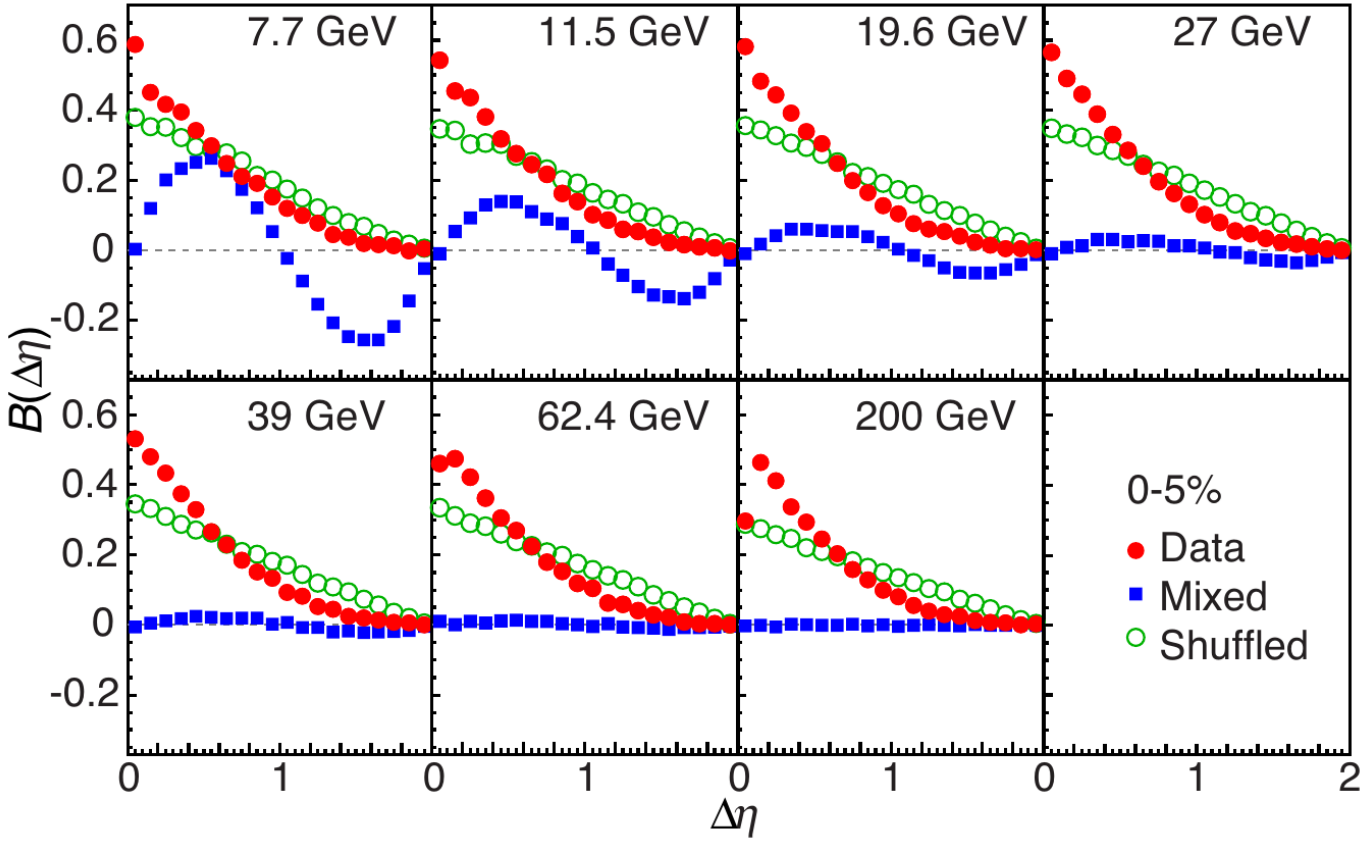




CBFs as a function of *Δη* in different centrality classes: 0-5%, 30-40%, and 70-80% (on the left). CBFs for charged particles as a function of *Δη* (upper row) and *Δφ* (lower row) in different multiplicity classes (on the right).

Experimental status of CBFs at RHIC BES energies

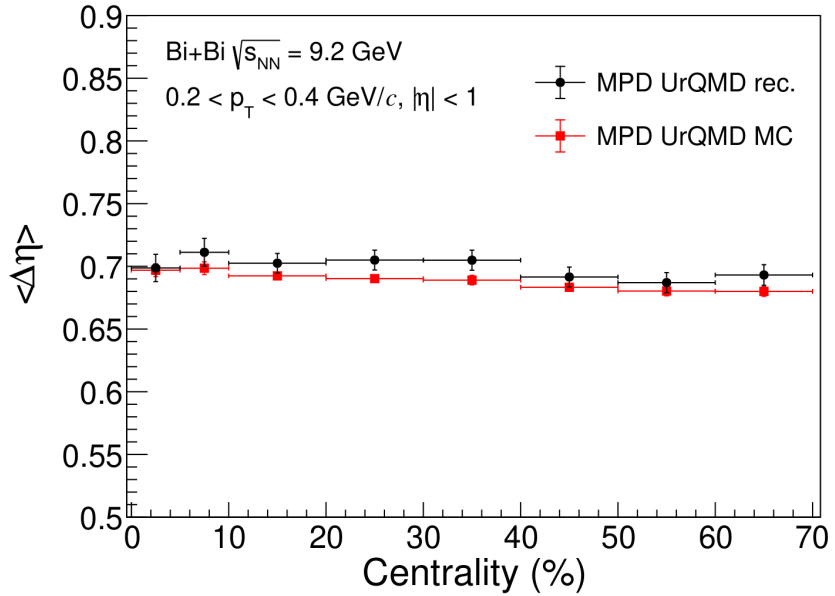
Meanwhile, only inclusive rapidity CBFs were measured at RHIC BES energies. Azimuthal and partial CBFs are still to be measured in order to provide better insight on charge generation mechanisms and consequent correlations of charged particles.

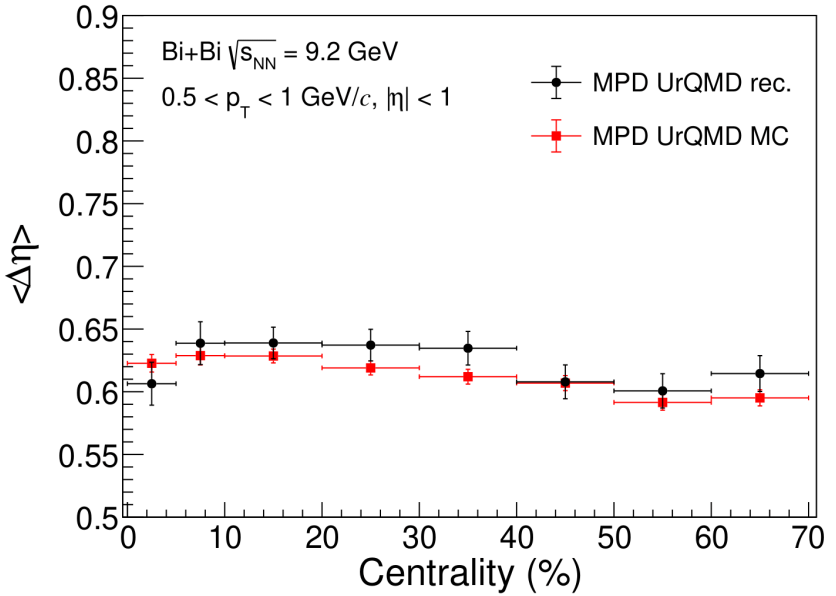


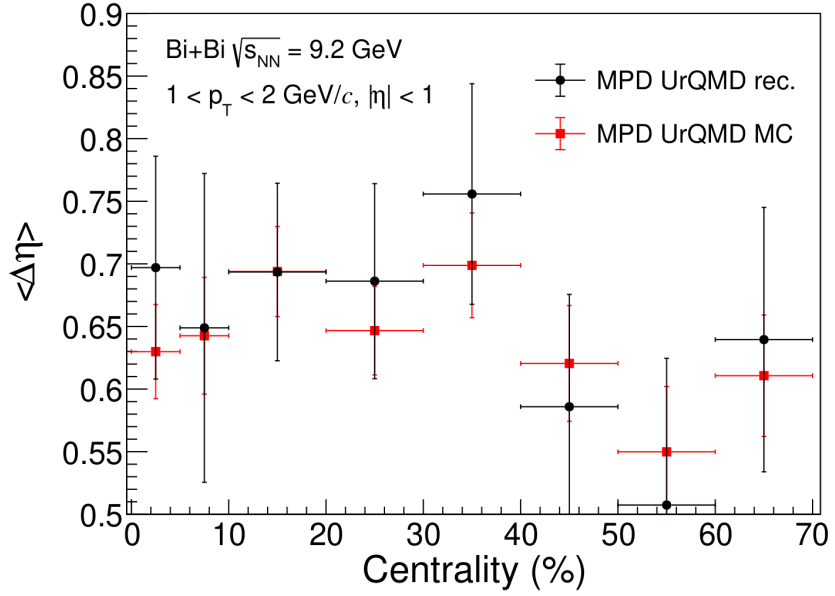
B(Δϕ) = ?

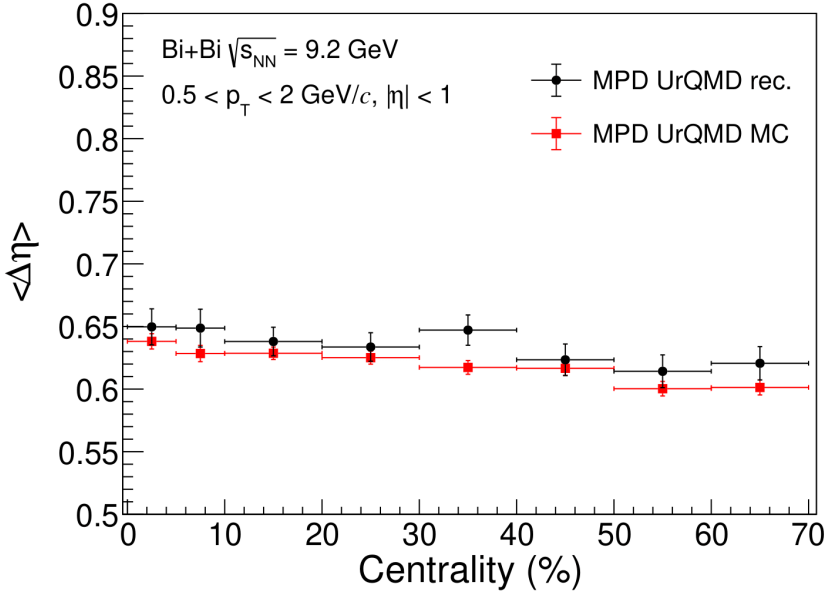
Rapidity CBFs of all charged particles with $0.2 < p_T < 2$ GeV/c in central Au+Au collisions (0-5%) at $\sqrt{s_{NN}}$ from 7.7 to 200 GeV. Mixed CFBs are constructed from mixed events, shuffled CBFs are constructed from tracks with shuffled charges within single event **[Phys.Rev.C 94 (2), 024909 (2016)].**

CBF widths in different p_T intervals

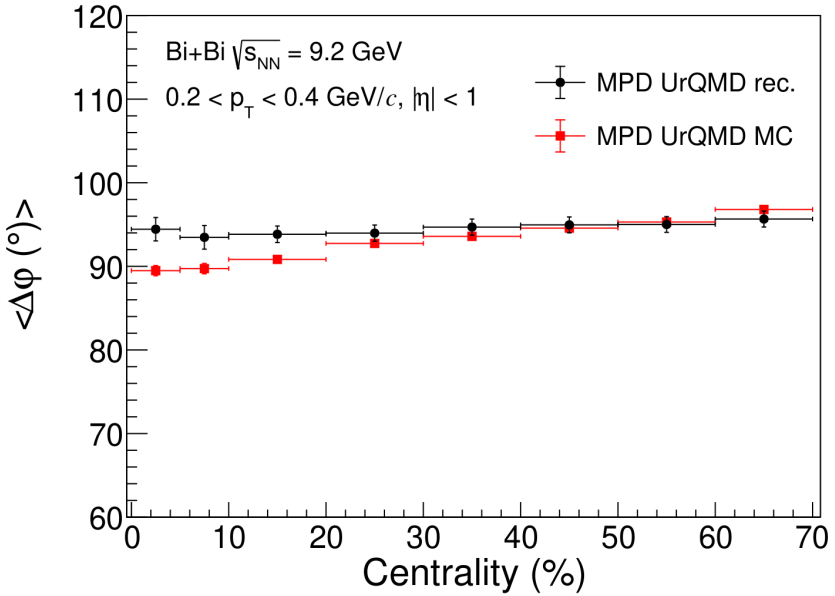


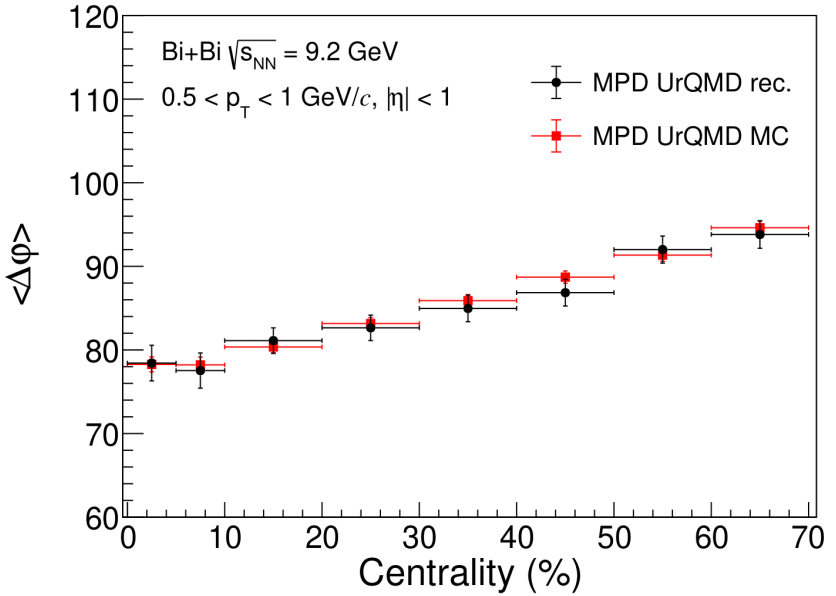


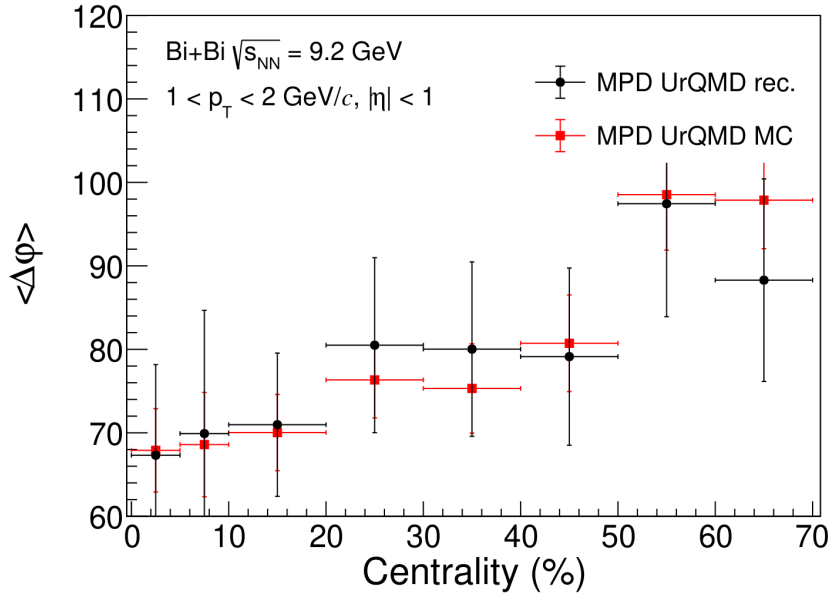


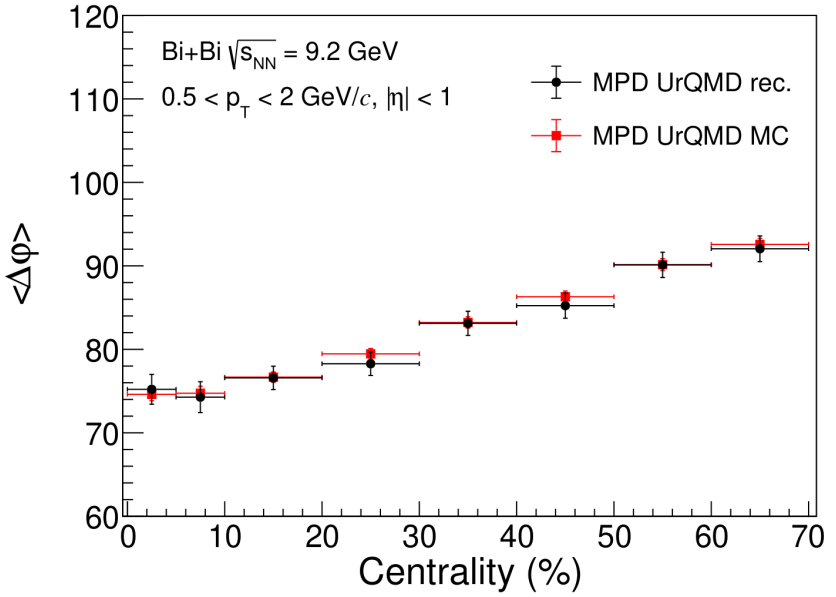


CBF widths in different p_T intervals









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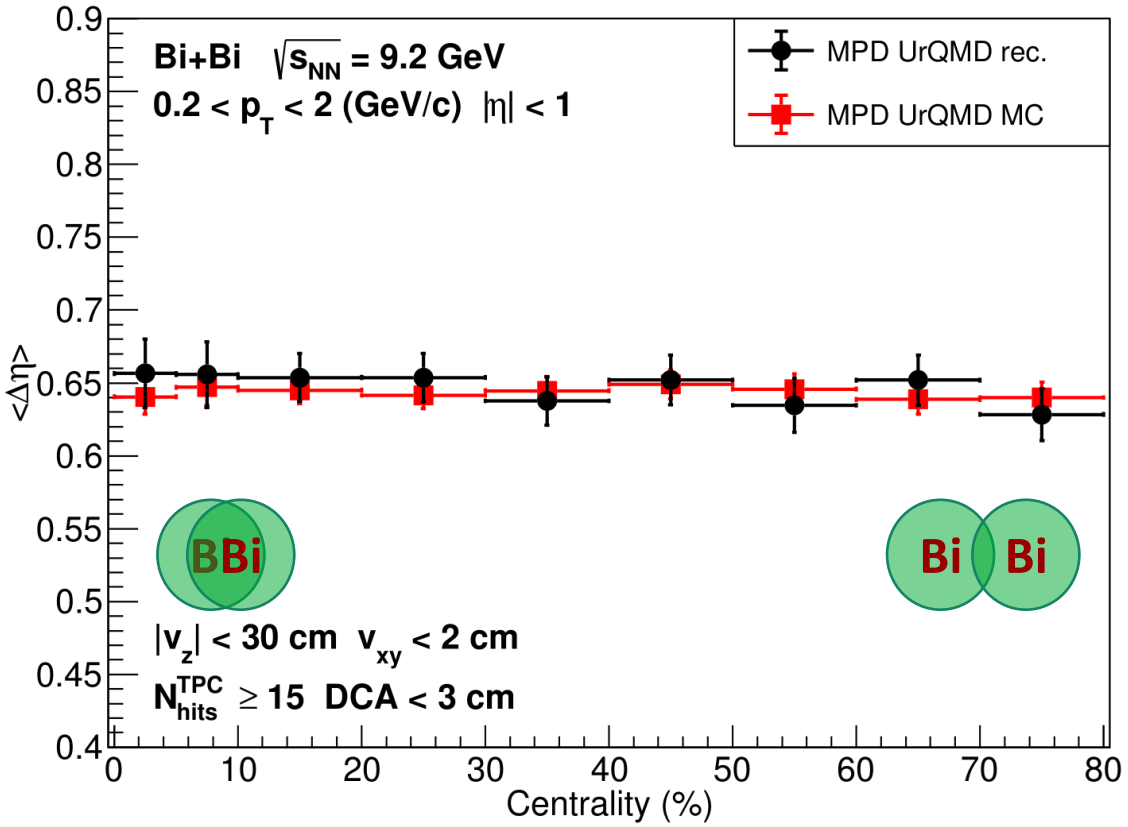
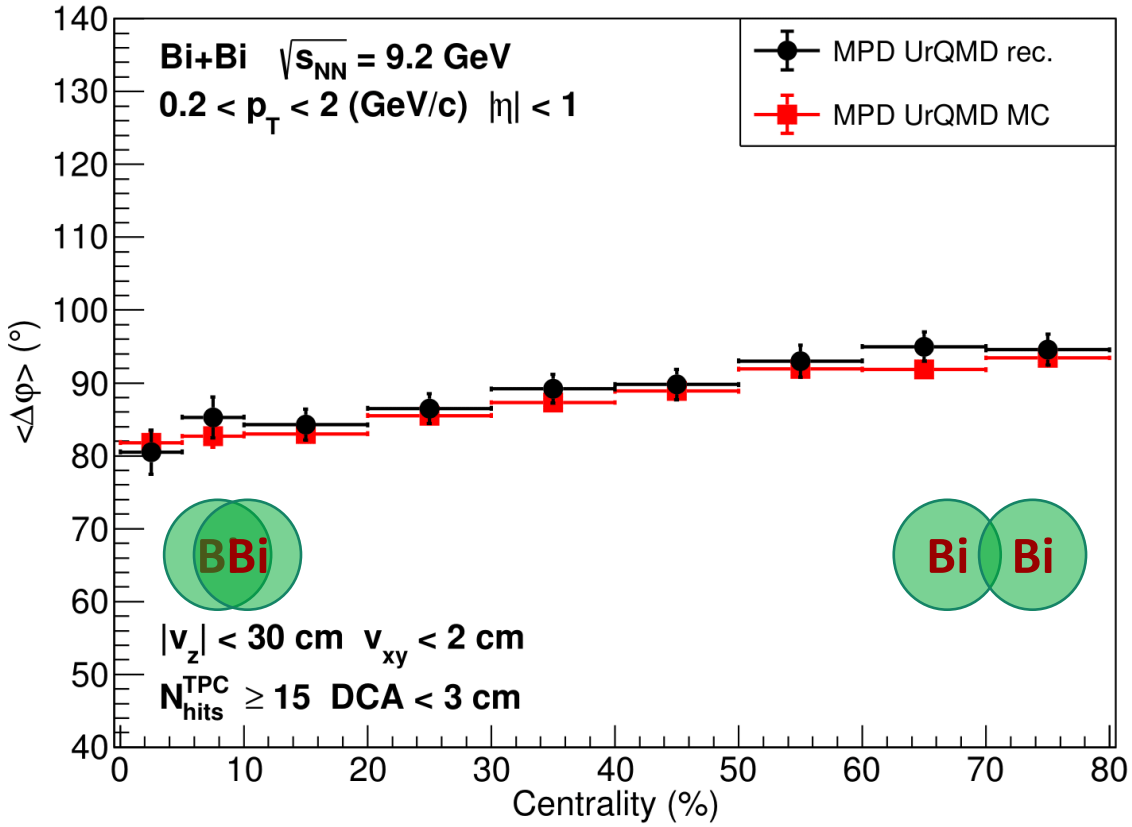
/eos/nica/mpd/sim/data/exp/dst-BiBi-09.2GeV-mp07-22-500ev-req25/BiBi/09.2GeV-mb/urqmd/BiBi-09.2GeV-mp07-22-500ev-req25



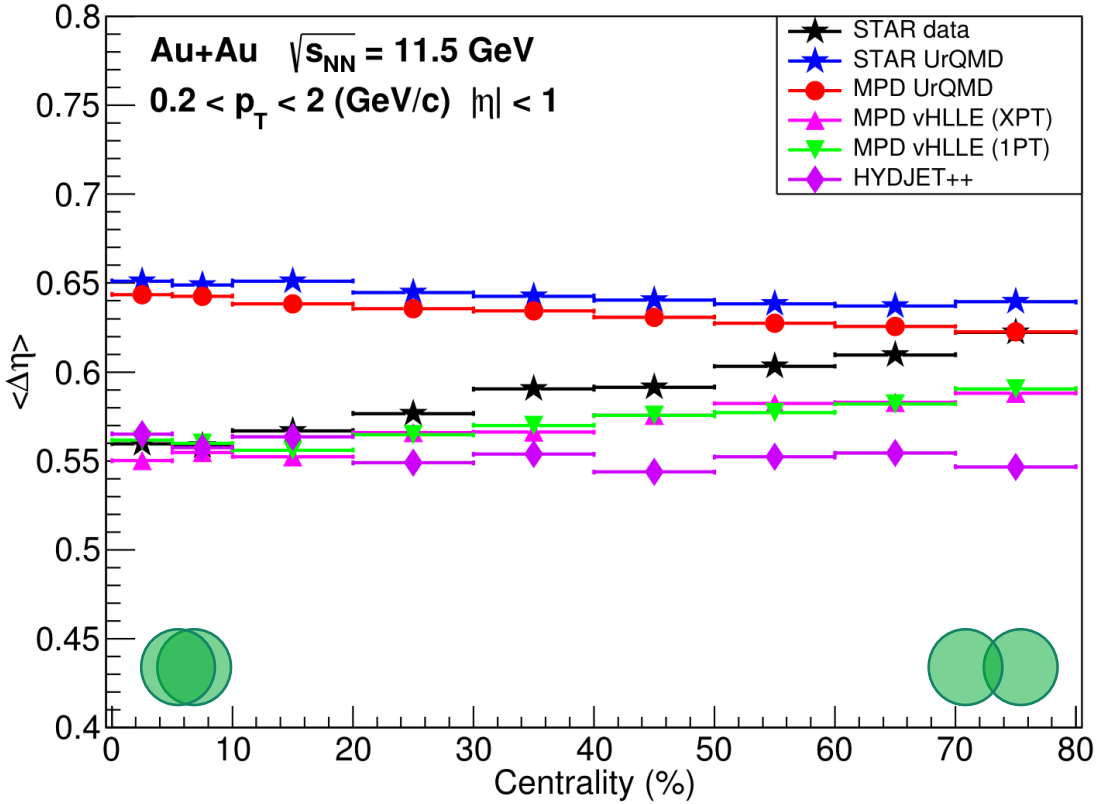


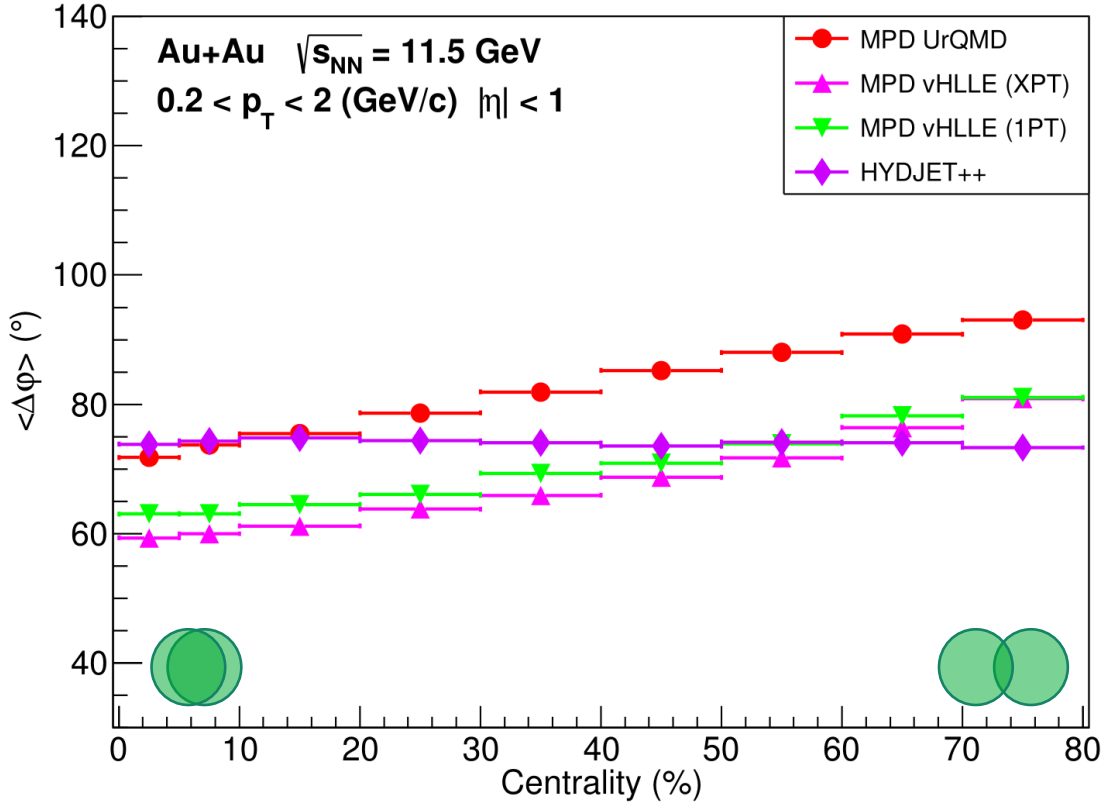
MPD Cross-PWG Meeting, 13 June 2023

Included into the 2nd Collaboration paper, http://dx.doi.org/10.31349/RevMexFis.71.041201

The widths of the charge balance functions reconstructed in the MPD experimental conditions are close to the generator widths in the UrQMD model.

Charge balance function of oppositely charged hadrons (RHIC/NICA)



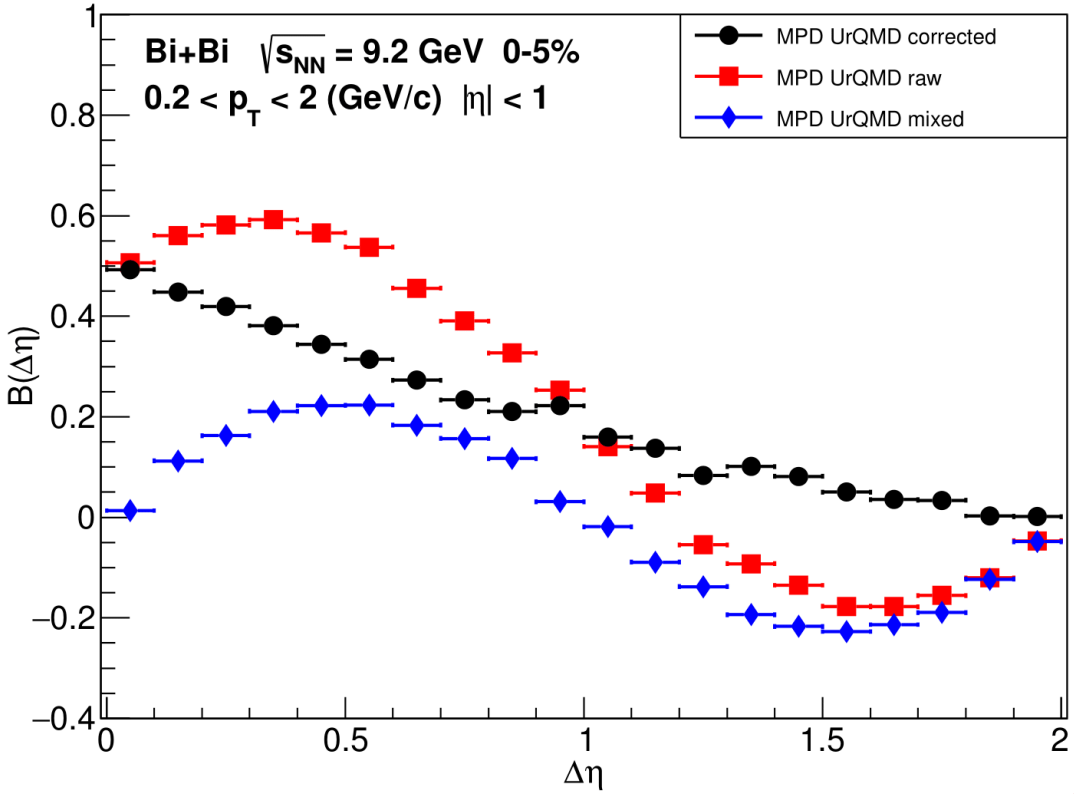


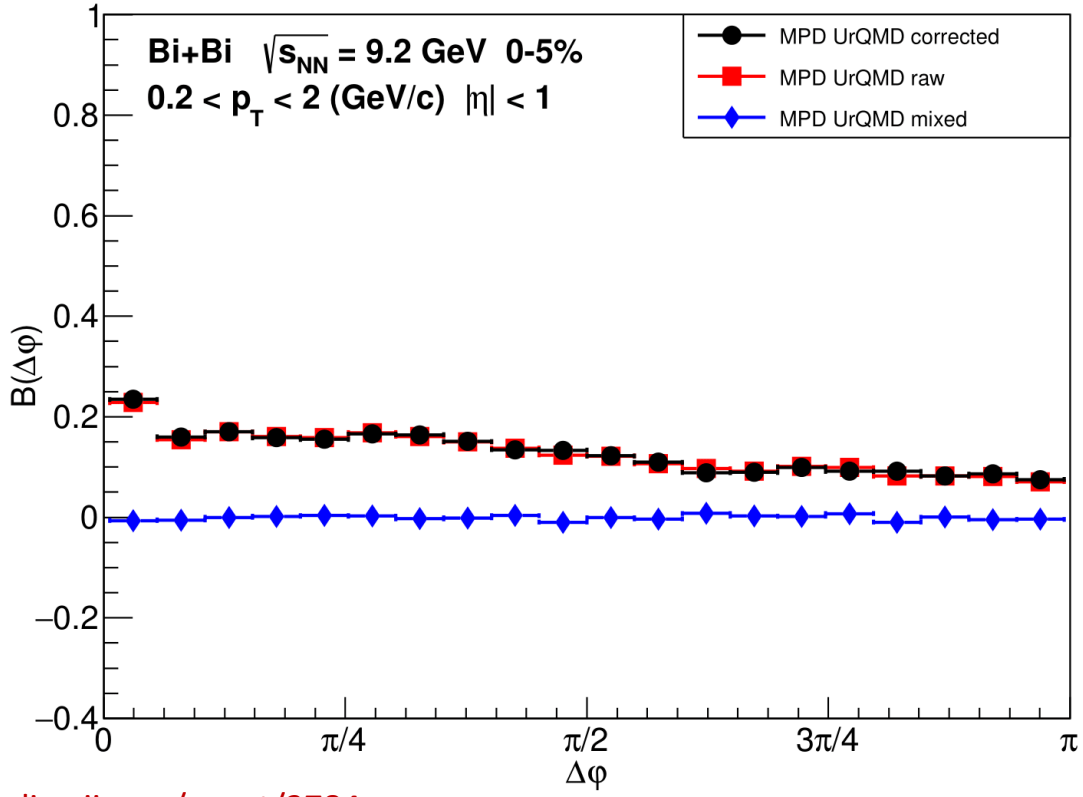
A model study of the CBF with different event generators at energies of 7.7 and 11.5 GeV per nucleon pair was carried out *(MPD Cross-PWG https://indico.jinr.ru/event/3784):*

- **the vHLLE and HYDJET++ models reproduce the STAR/RHIC data on the rapidity CBF widths in central collisions, the UrQMD model – in peripheral collisions;**
- none of the models describes dependency of the rapidity CBF width on the centrality of interactions – ***unaccounted mechanisms of particle charge correlations in these models?***

The code for constructing the CBF (including corrections for charge imbalance and acceptance) is built into MpdRoot for analyzing simulated events taking into account the detector responses.

Reconstruction of Charge Balance Functions under MPD experimental conditions



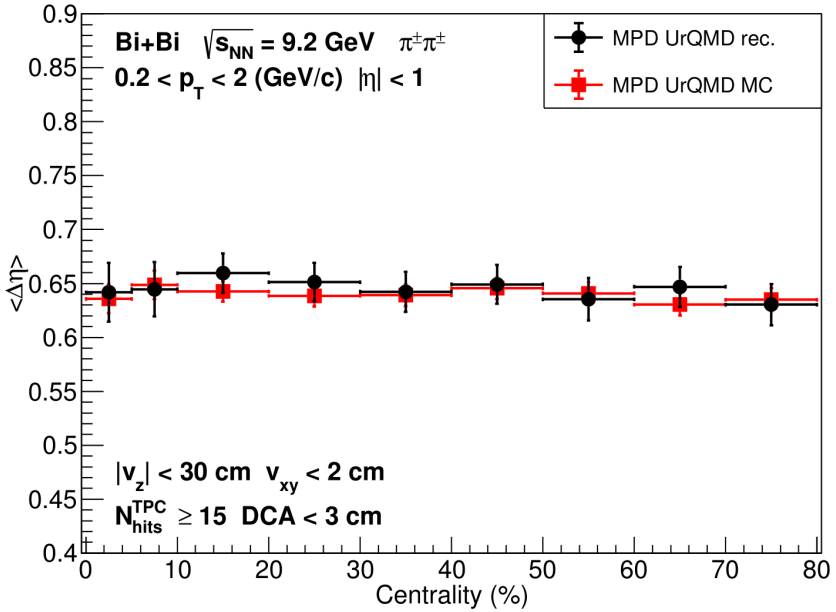


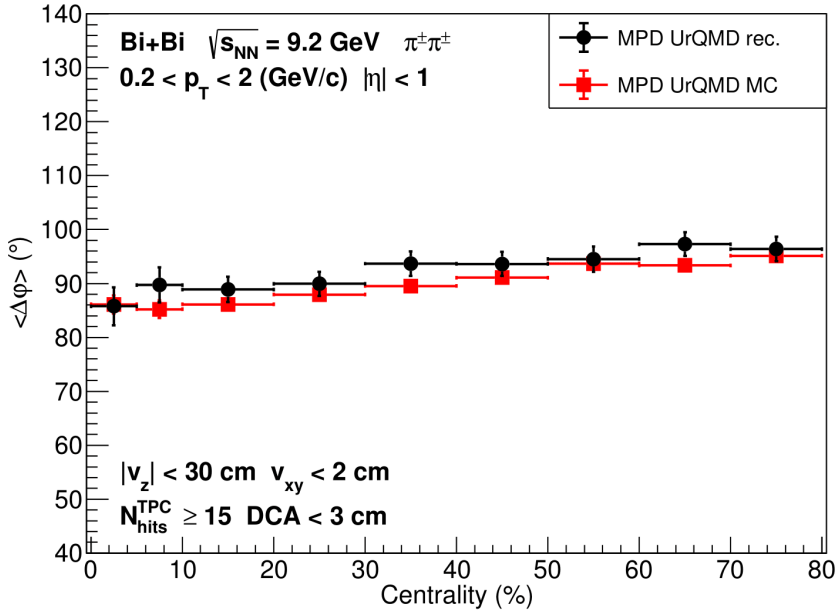
MPD Cross-PWG https://indico.jinr.ru/event/3784

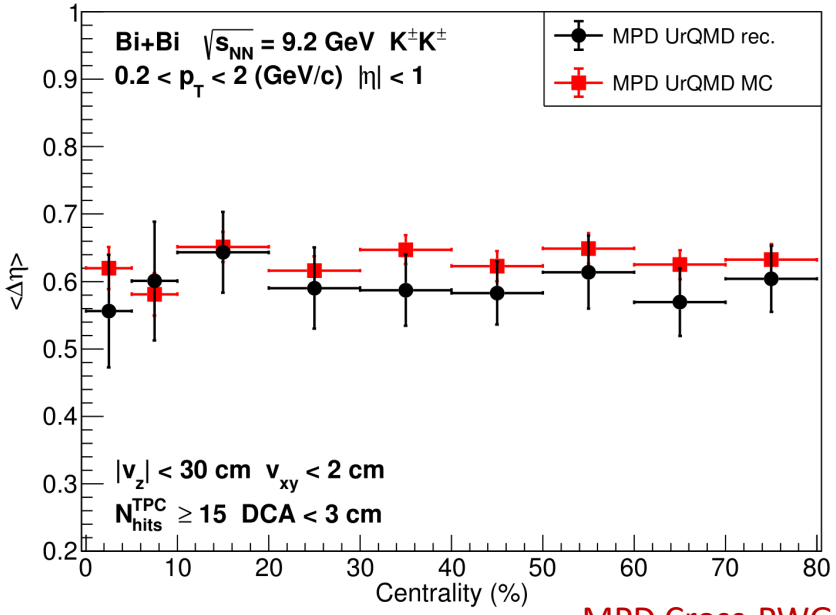
Correction procedure for generator CBFs in the UrQMD model in Bi+Bi collisions at NICA $\sqrt{s_{NN}}$ = 9.2 GeV. Blue diamonds are the uncorrected CBF, black dots are the corrected function, red squares are the balance function constructed from mixed events.

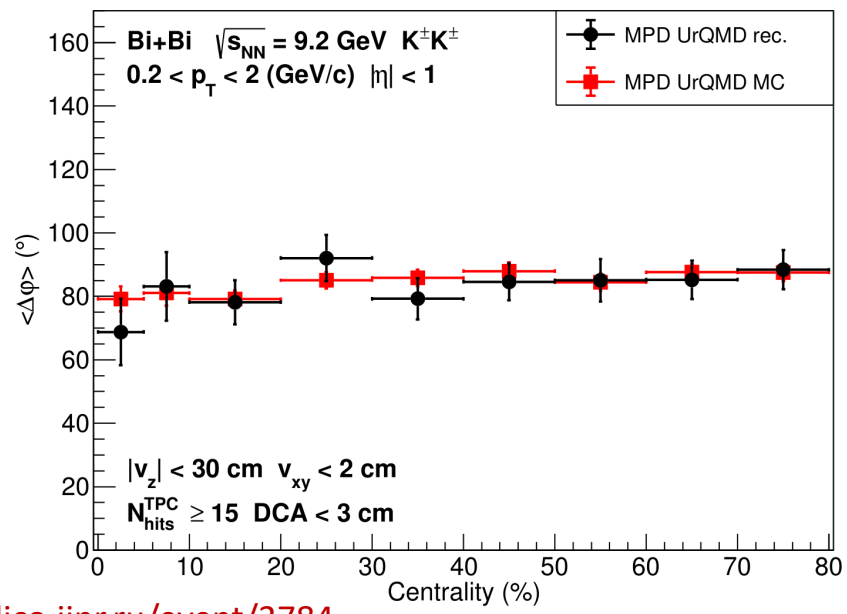
The effect of the unbalanced positive charge (from protons) at NICA energy distorts the charge balance function. To suppress this effect, the balance function constructed from mixed events is subtracted from the distorted balance function.

Reconstruction of the CBF in the MPD/NICA experiment ($\pi^+\pi^-$, K^+K^-)



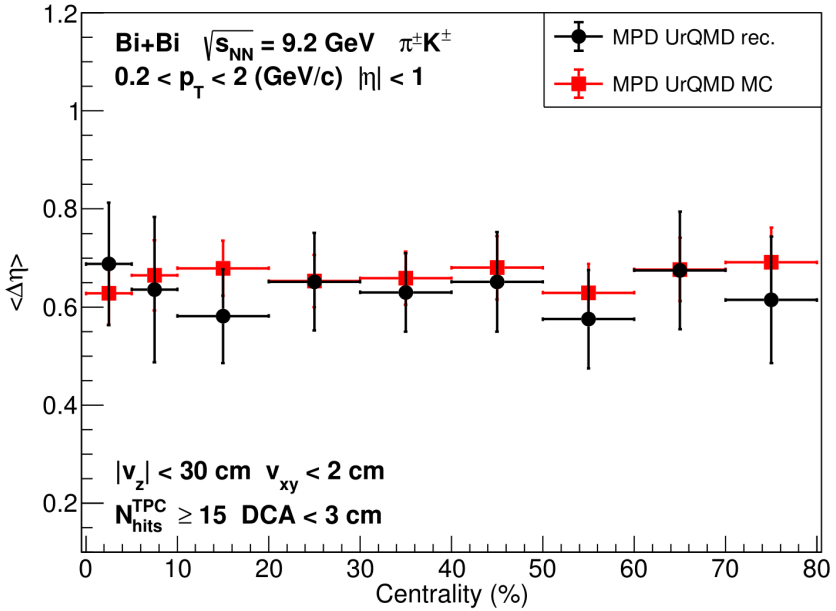


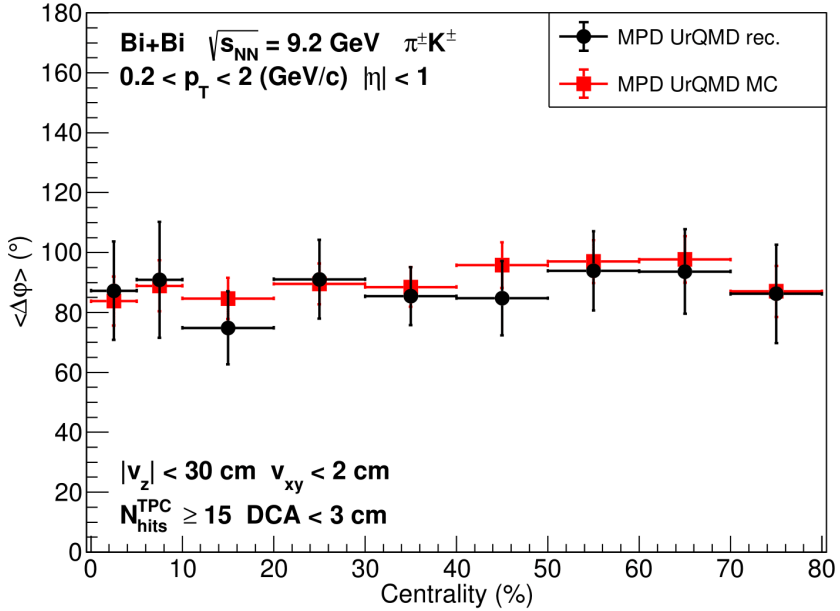


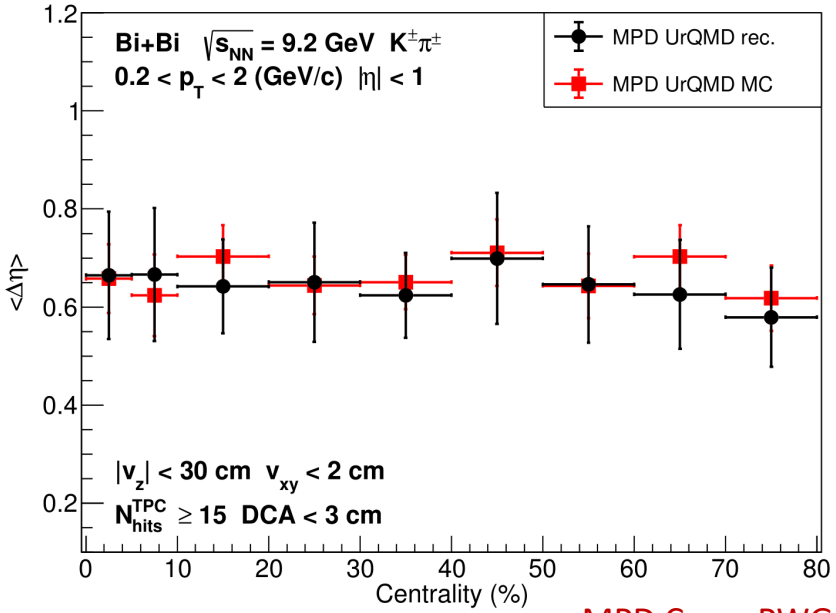


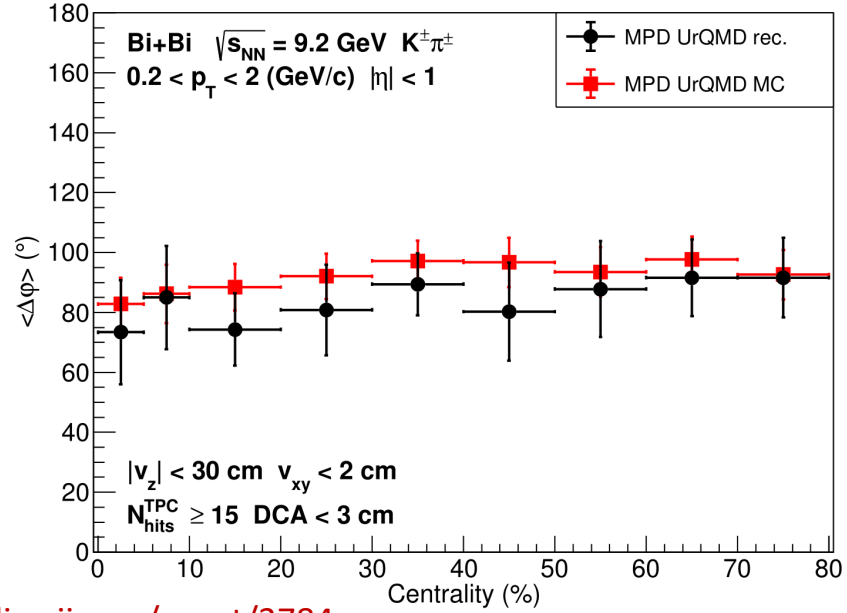
MPD Cross-PWG https://indico.jinr.ru/event/3784

Reconstruction of the CBF in the MPD/NICA experiment (π^+K^-, $K^+\pi^-$)



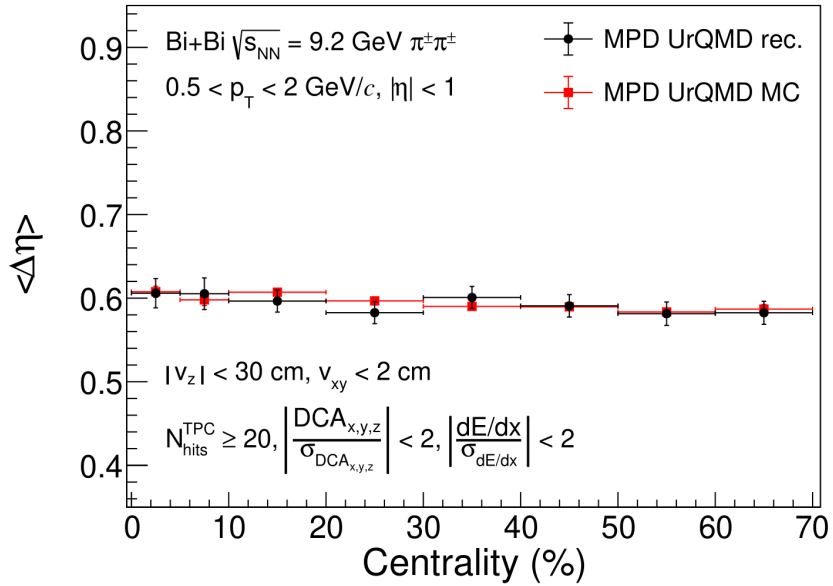


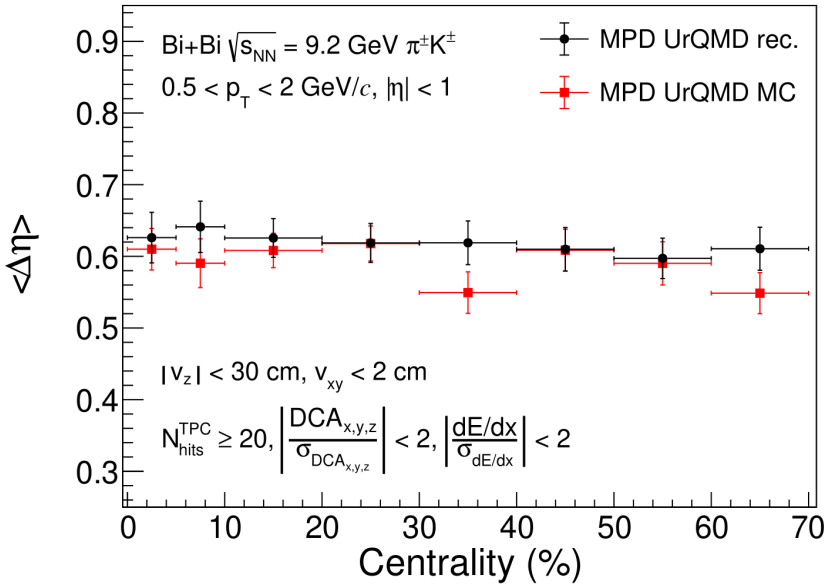


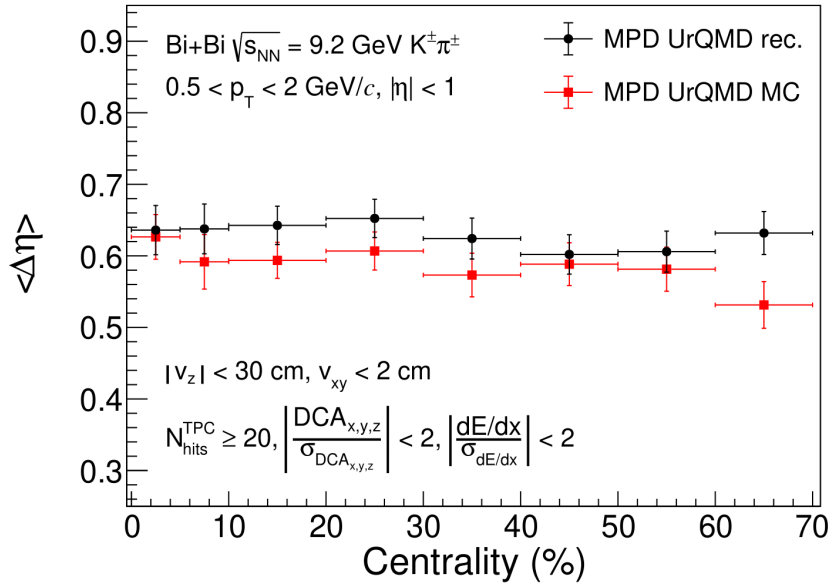


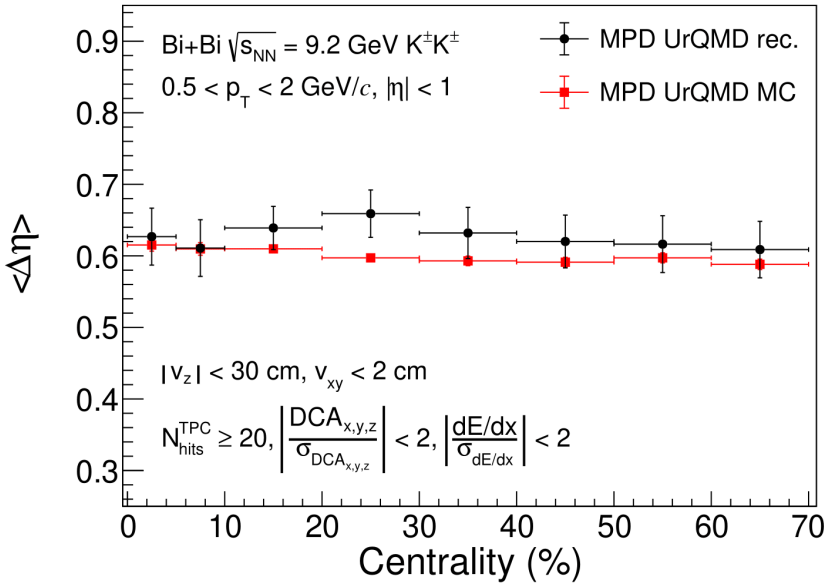
MPD Cross-PWG https://indico.jinr.ru/event/3784

Reconstruction of partial CBFs in the MPD/NICA experiment









Reconstruction of partial CBFs in the MPD/NICA experiment

