Supported in part by U.S. DEPARTMENT OF ENERGY | Office of Science

Investigating the CME in isobaric ($^{96}_{44}Ru +^{96}_{44} Ru$ and $^{96}_{40}Zr +^{96}_{40} Zr$) collisions at $\sqrt{s_{NN}}$ = 200 GeV using Sliding Dumbbell Method with the STAR detector at RHIC

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The STAR Collaboration
https://drupal.star.bnl.gov/STAR/presentations

03/09/2024

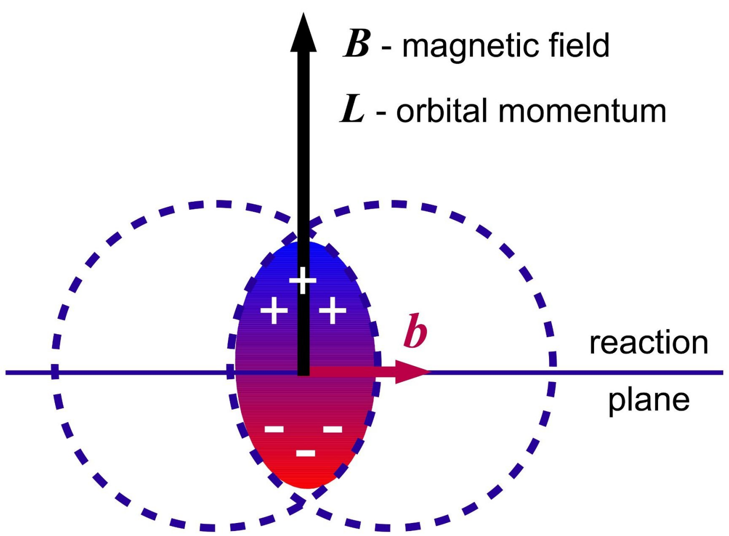
Outline

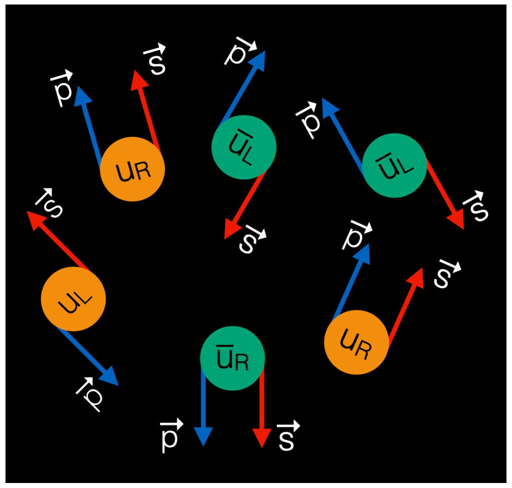
- Introduction
- STAR Experiment
- Analysis Details
- Results
- Summary

Introduction

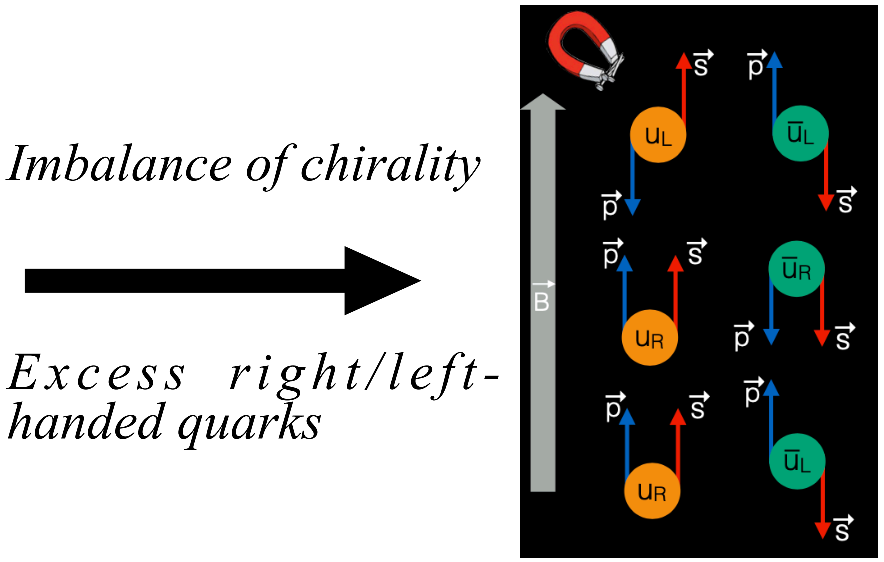
Chiral Magnetic Effect?

- Strong magnetic field created by the fast-moving spectator protons and chirality imbalance causes the charge separation perpendicular to the reaction plane, known as the CME [1].





- *Imbalance of chirality*
- *Excess right/left-handed quarks*

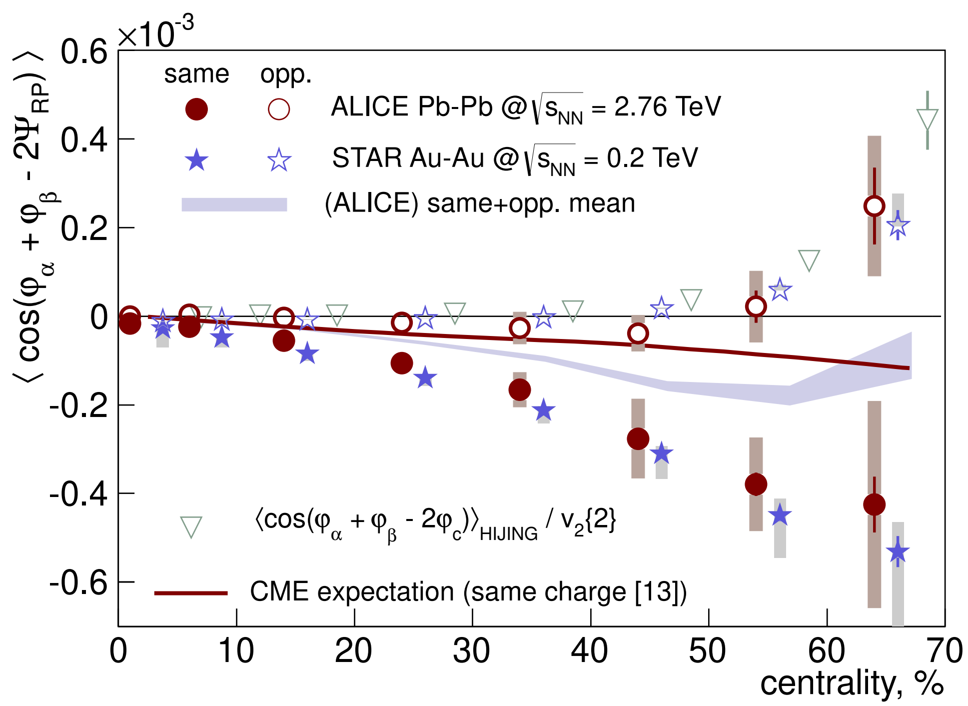


Massless Quarks produced in the system will have random spin orientations

Strong B-field will align the spin of the quarks due to magnetic polarization

P. Tribedy, Free meson seminar, TIFR, Oct 7th, 2021

- The STAR at RHIC and the ALICE at the LHC have studied the CME by measuring the γ -correlator ($\gamma = \langle cos(\phi_a + \phi_b - 2\Psi_{RP}) \rangle$) [2].

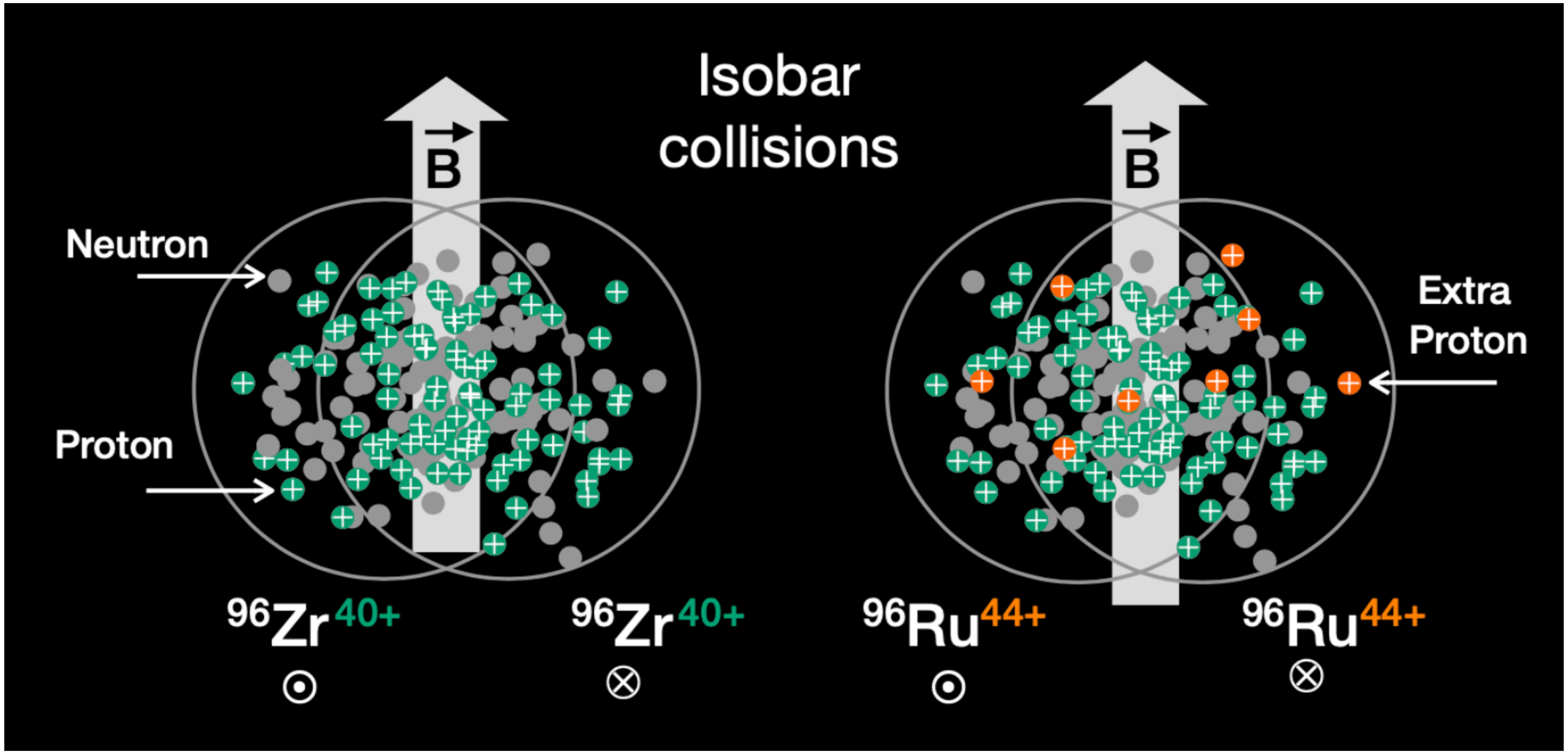


B. Abelev et al., (ALICE Collaboration), Phys. Rev. Lett. 110, 012301 (2013).

[1] K. Fukushima, D. E. Kharzeev and H. J. Warringa, Phys. Rev. D 78, 074033 (2008).
[2] S. Voloshin, Phys. Rev. C 70, 057901 (2004).

Isobar Collisions

- The magnetic field is ~10-18% larger in Ru+Ru collisions
- Expect enhanced CME effect in Ru+Ru collisions than Zr+Zr collisions.



P. Tribedy, Free meson seminar, TIFR, Oct 7th, 2021

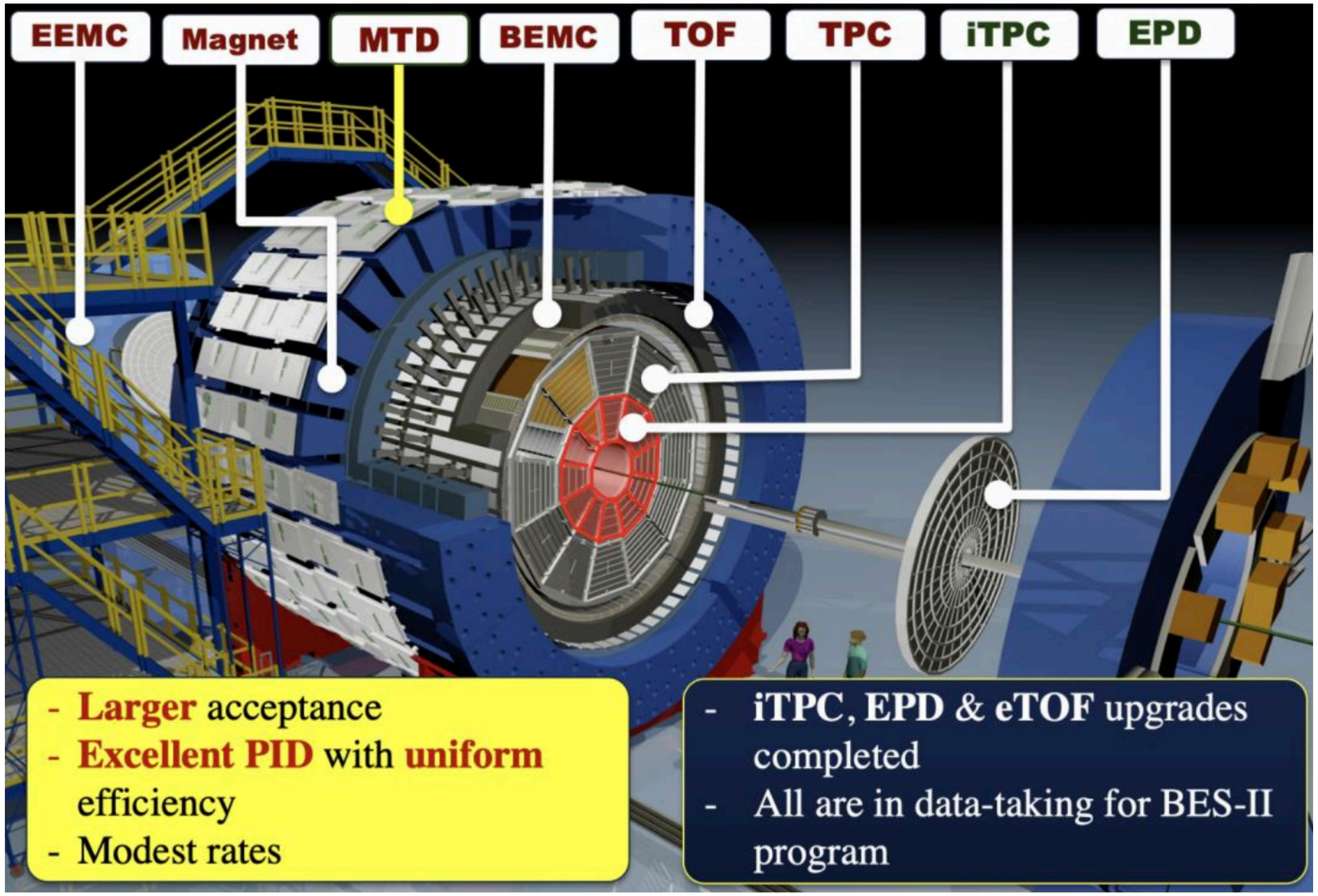
Phys. Rev. C 105, 014901 (2022)

Two main detectors used in STAR for particle identification:

- **Time Projection Chamber (TPC)**
- **Time of Flight (TOF)**

The main characteristics of the STAR:

- Large coverage i.e., $\phi(0, 2\pi)$ and $\eta(-1, 1)$
- Excellent particle identification at low p_T using TPC and at intermediate p_T using TOF



STAR (Solenoidal Tracker at RHIC)

Data Set: Isobaric collisions (Ru+Ru & Zr+Zr) at 200 GeV (~1.7B each).

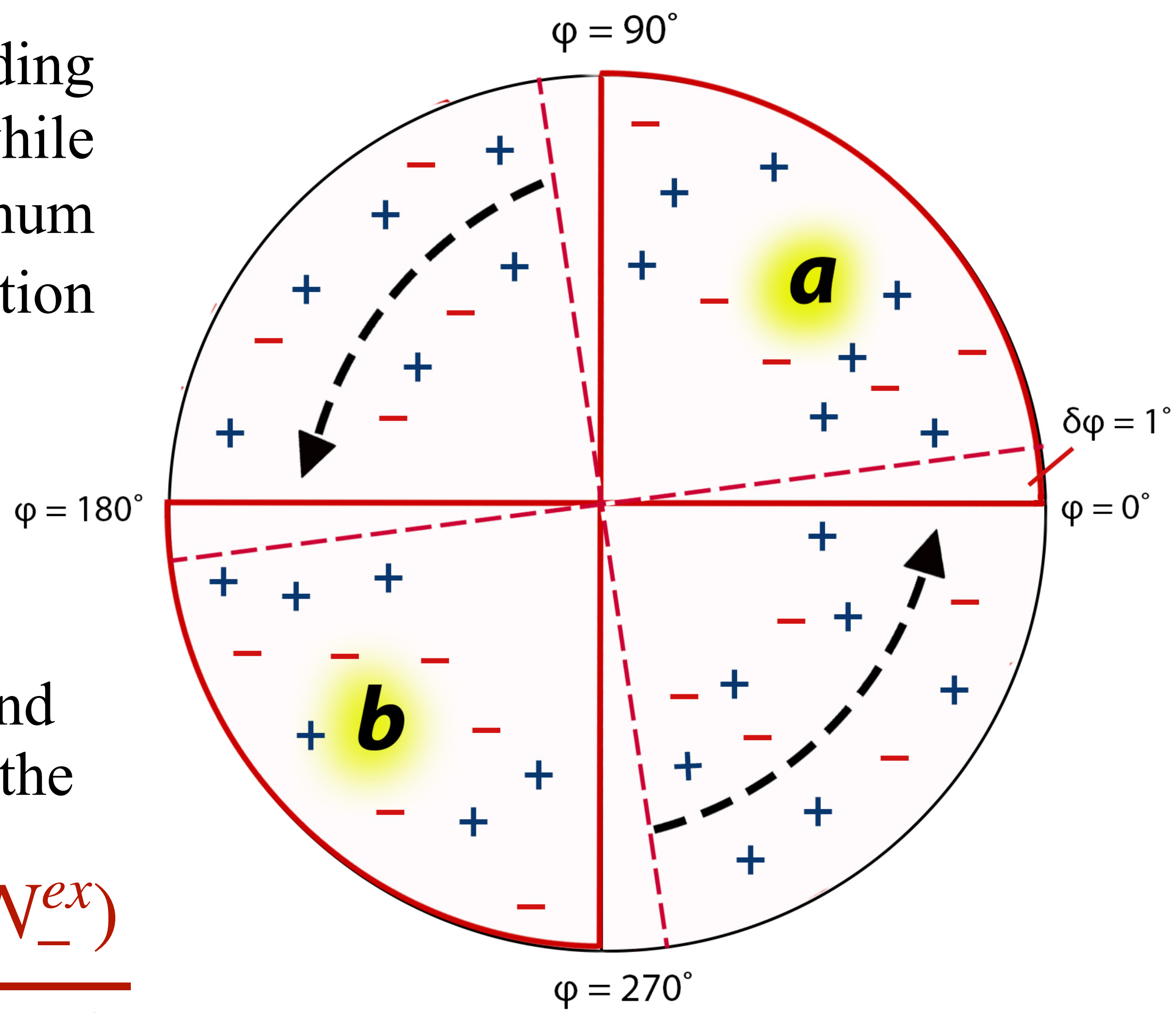
Event and track selection cuts:

- $-35 < V_z < 25$ cm
- $|\eta| < 1$
- $0.2 < p_t < 2.0\ GeV/c$
- DCA < 3 cm

Analysis Details

Sliding Dumbbell Method

- The azimuthal plane in each event is scanned by sliding the dumbbell of $\Delta\phi = 90^\circ$ in steps of $\delta\phi = 1^\circ$ while calculating, Db_{+-} for each region to obtain maximum values of Db_{+-} (Db_{+-}^{max}) in each event with a condition that $Db_{asy} < 0.25$.



$$Db_{+-} = \frac{n_+^a}{(n_+^a + n_-^a)} + \frac{n_-^b}{(n_+^b + n_-^b)}$$

n_+^a *and* n_-^a (n_+^b *and* n_-^b), the number of positive and negative charged particles on the "a" ("b") side of the dumbbell.

- Db_{asy} can be defined as:

$$Db_{asy} = \frac{(N_+^{ex} - N_-^{ex})}{(N_+^{ex} + N_-^{ex})}$$

N_+^{ex} ($= n_+^a - n_-^a$) is positive charge excess and N_-^{ex} ($= n_-^b - n_+^b$) is negative charge excess.

- Fractional Charge separation (f_{DbCS}) across the dumbbell with $Db_{asy} < 0.25$ in each event is defined as :

$$f_{DbCS} = Db_{+-}^{max} - 1$$

- f_{DbCS} distributions are obtained for different collision centralities and divided into 10-percentile bins.

M.M. Aggarwal et al., Pramana - J Phys ***98****, 117 (2024)*

Background Estimation

- **Charge Shuffle (ChS):** The charges of particles in each event are shuffled randomly to destroy the charge-dependent correlations amongst charged particles but keeping θ and ϕ of each particle unchanged in an event. This is termed as γ_{ChS}.

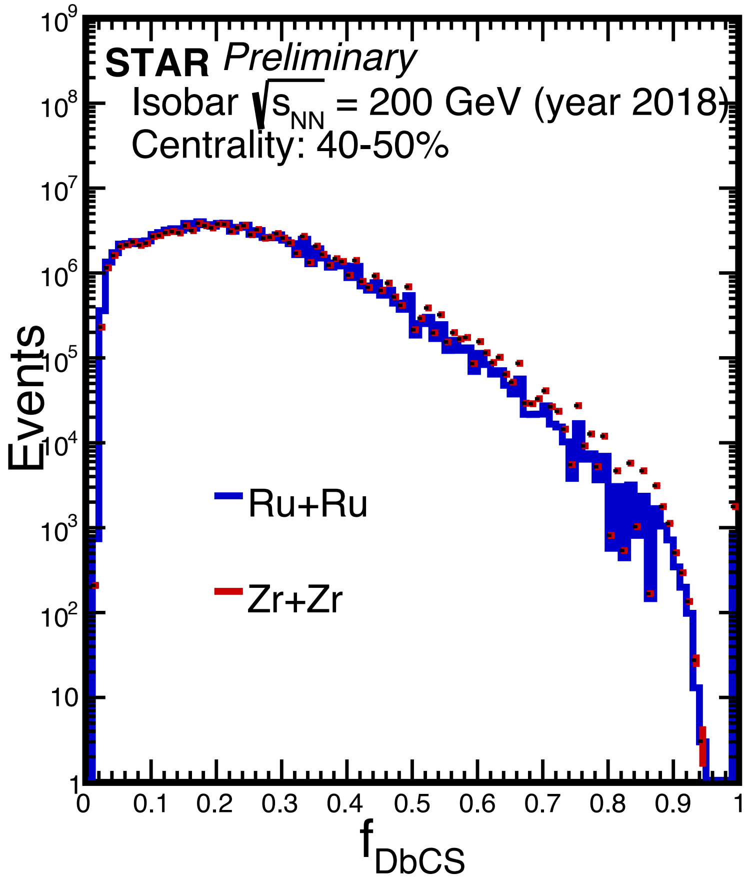
- **Correlated (Corr.) Background**: The shuffling of charges of particles in an event keeping the flow in, kills not only the CME-like correlations but also correlations amongst produced particles in an event. To restore the correlations among particles, which were destroyed during charge shuffling, the γ correlator is calculated from the corresponding events in the original events' sample for the sliced f_{DbCS} bin of ChS events. This is termed as γ_{Corr}. Since γ_{Corr} is derived from the original events themselves, it encompasses all types of correlations.

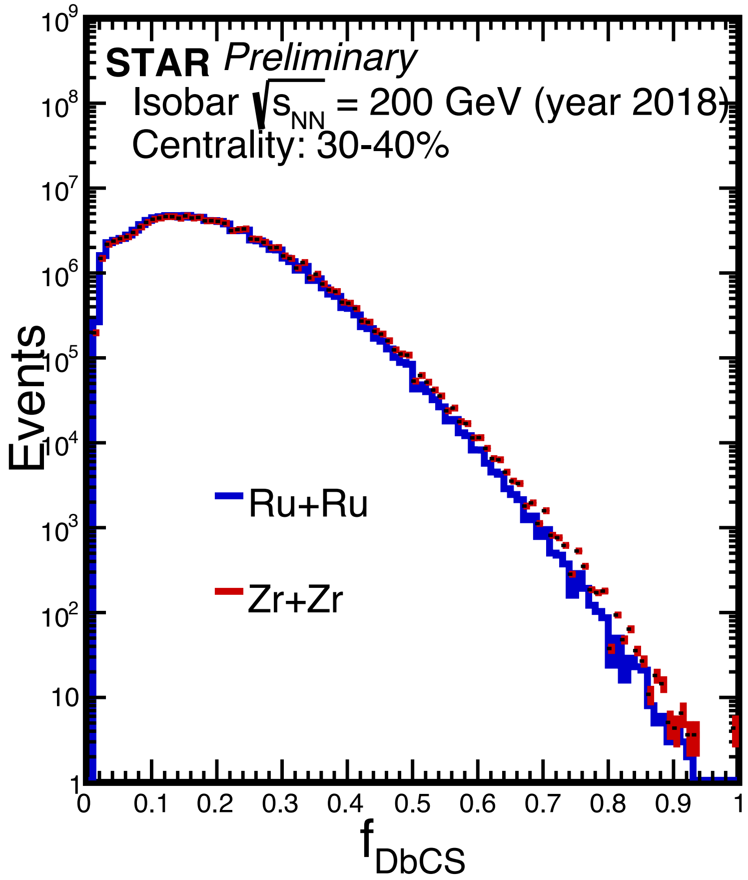
The background contribution (γ_{Bkg}) to γ is estimated as the sum of and γ_{Corr}:

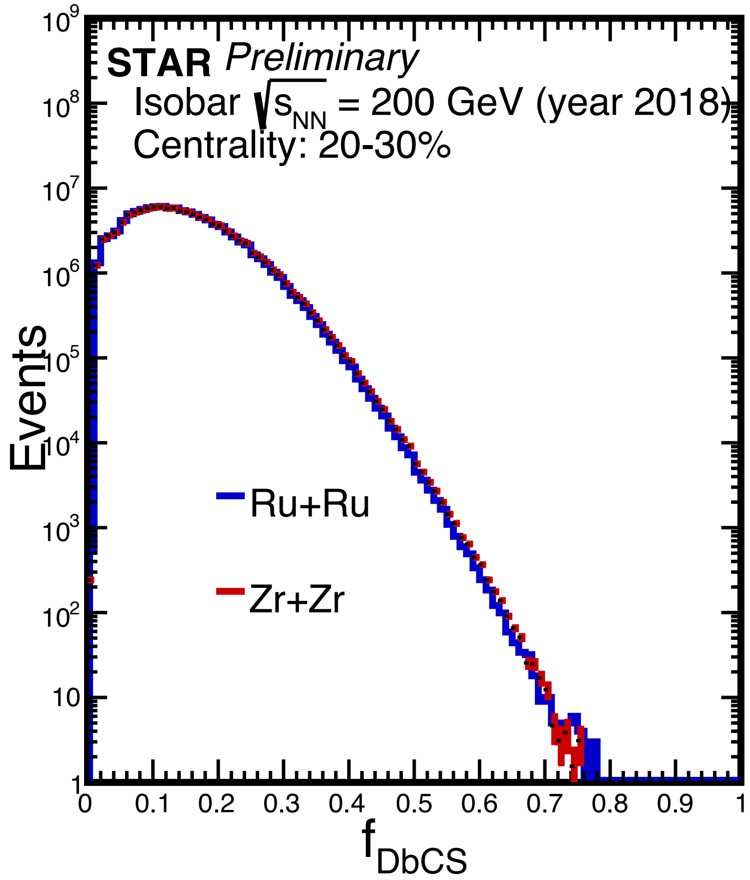
$$\gamma_{Bkg} = \gamma_{ChS} + \gamma_{Corr}$$

1. *M.M. Aggarwal et al., Pramana - J Phys **98**, 117 (2024).*
2. *J. Singh (for the STAR Collaboration), Springer Proc.Phys.* 304, 464-468 (2024).

f_{DbCS} distributions for Ru+Ru and Zr+Zr collisions

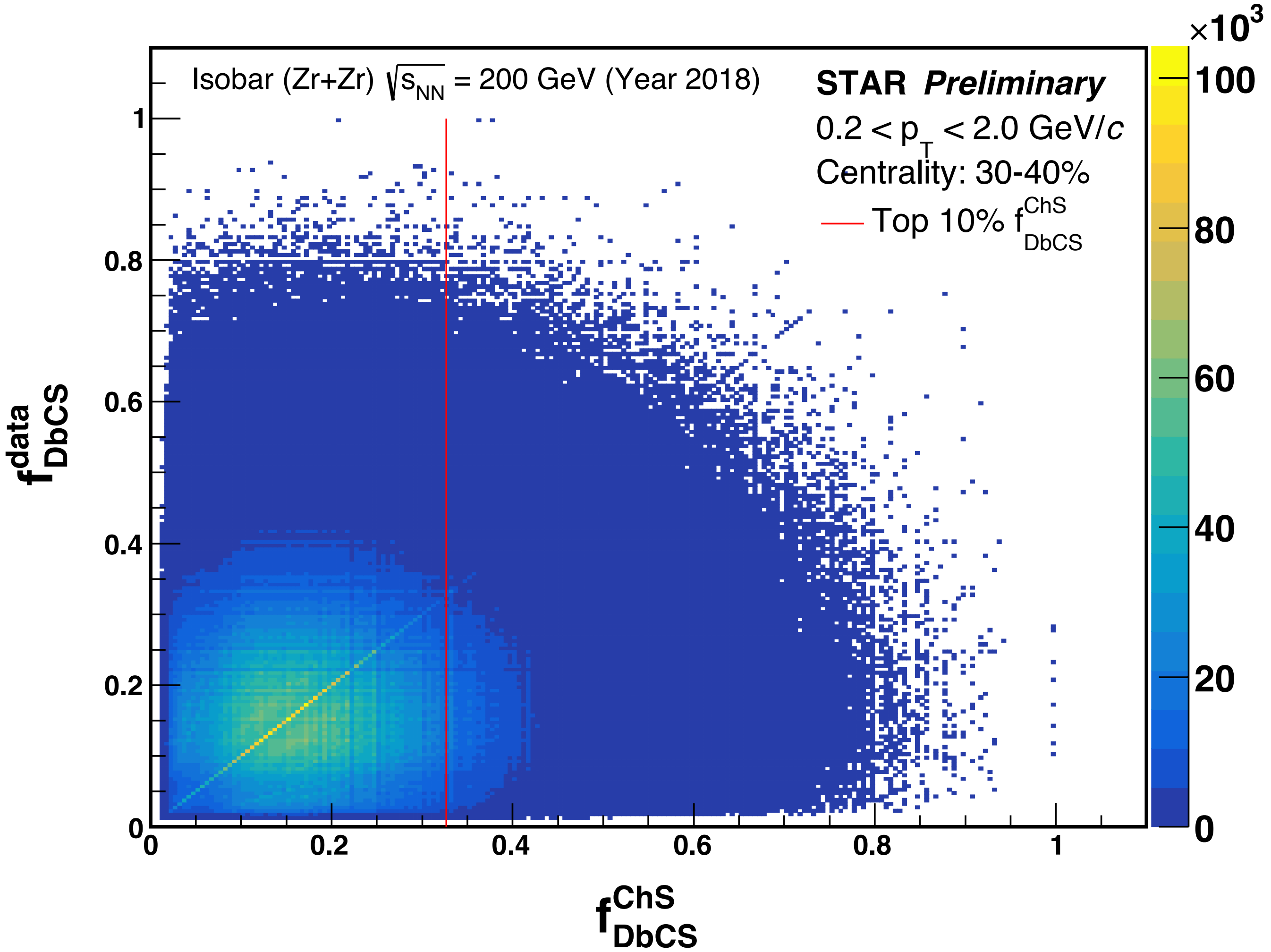


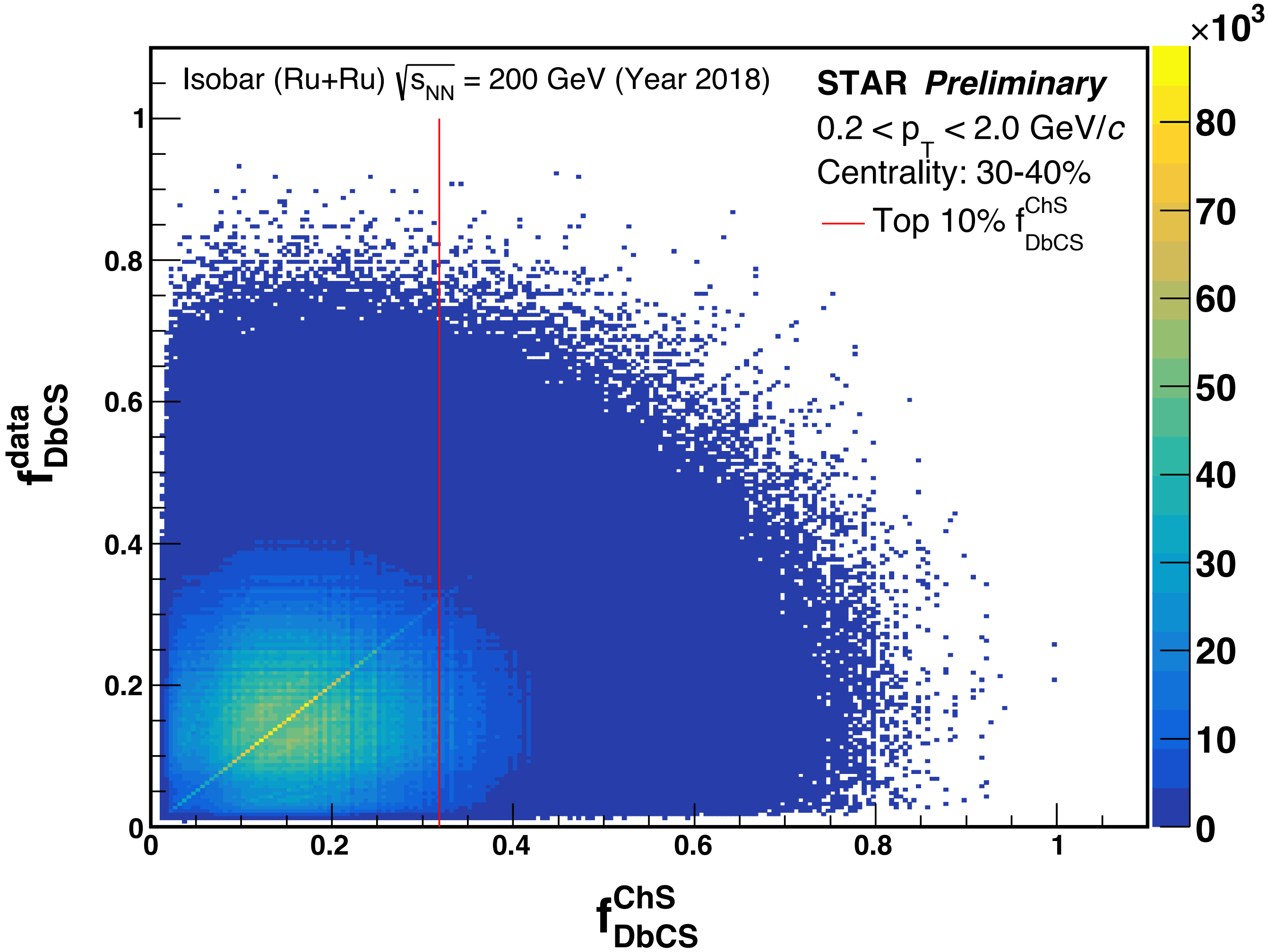




- Charge separation (f_{DbCS}) distributions extend towards higher f_{DbCS} values with decreasing collision centrality.

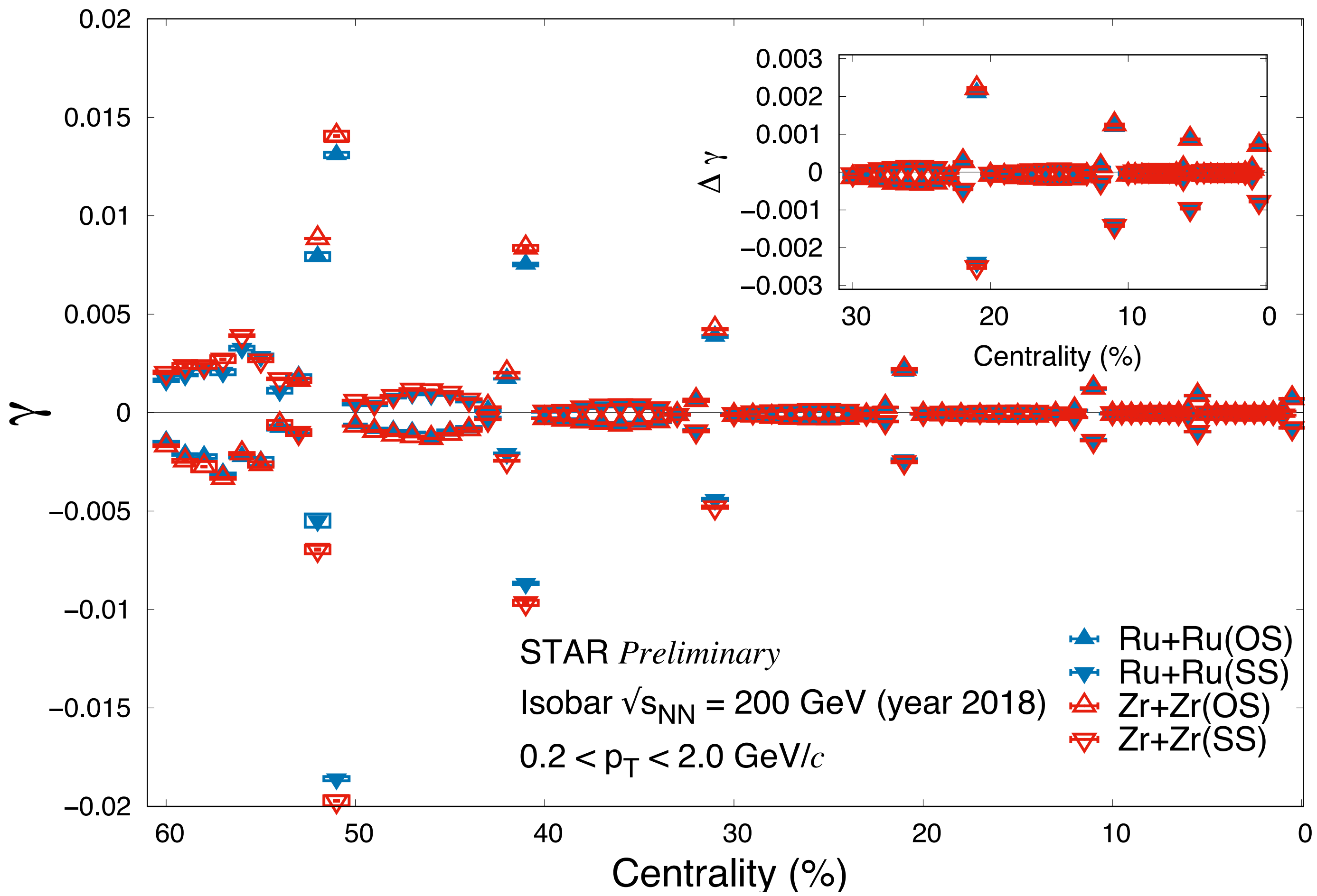
Scatter plots of f_{DbCS}^{ChS} vs f_{DbCS}^{data}





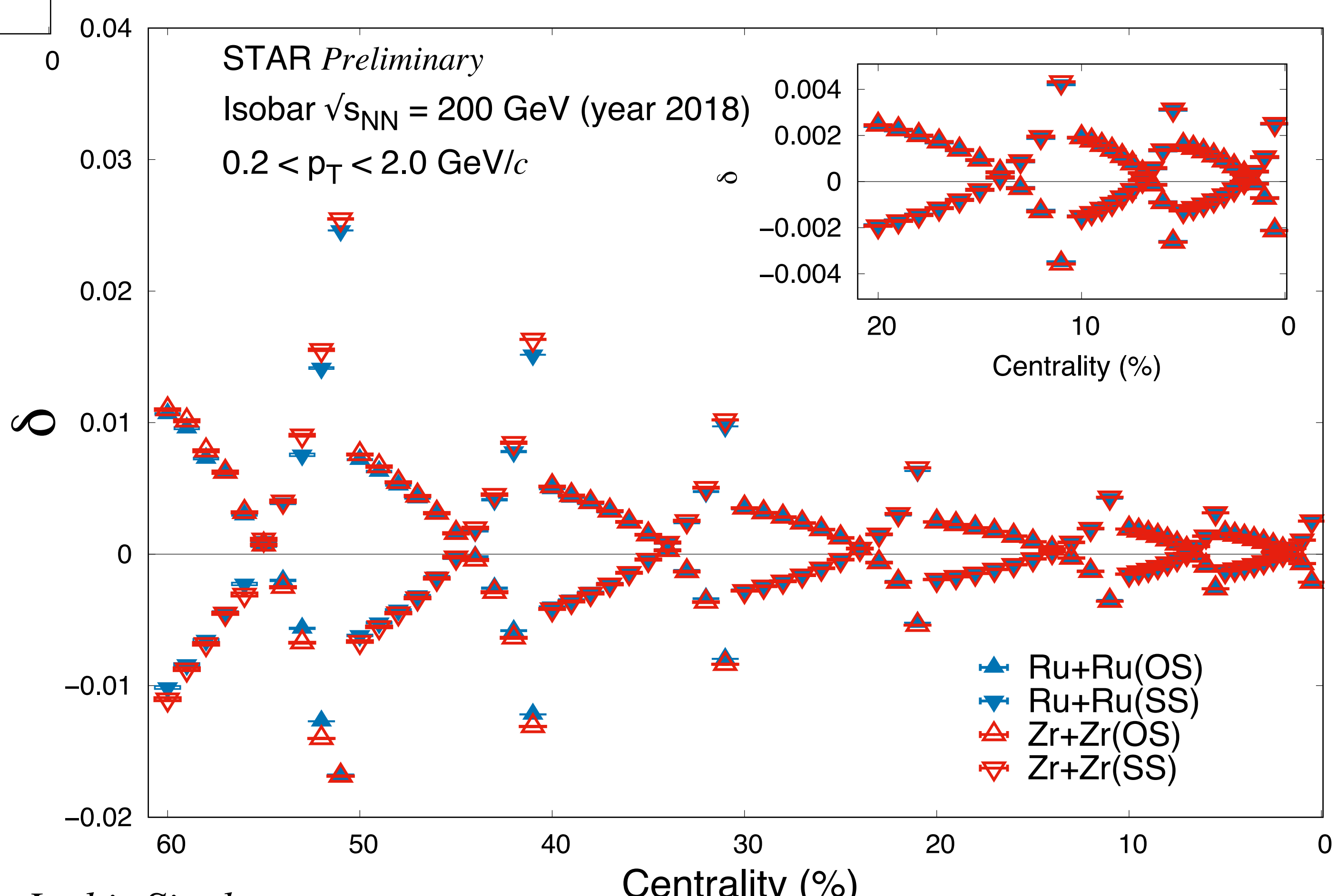
- There seems to be no correlation between f_{DbCS} of the charge shuffled event and the f_{DbCS} of the real event.

γ and δ correlators' dependences on centrality and f_{DbCS}

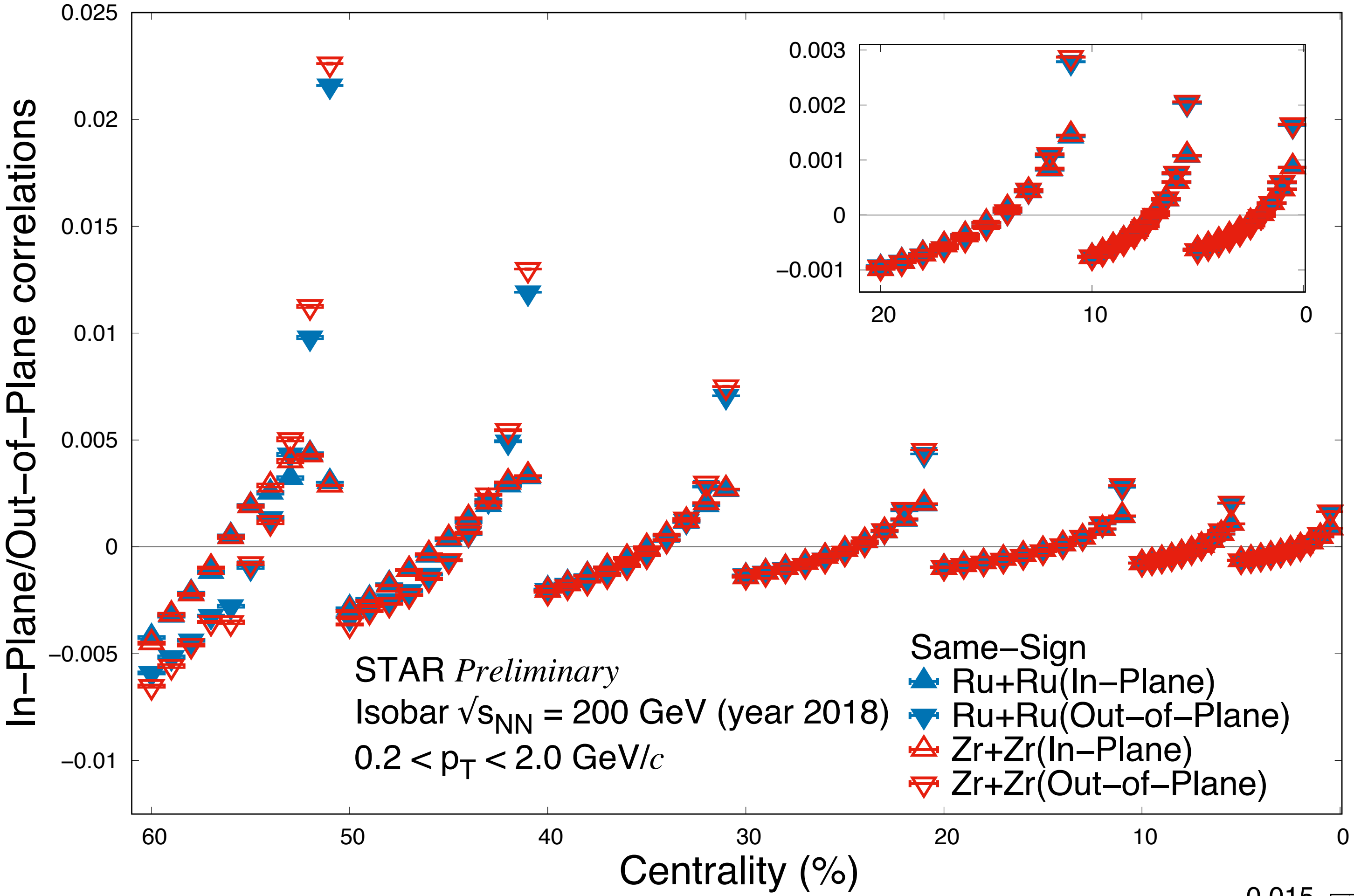


- For γ-correlator ($= \langle cos(\phi_a + \phi_b - 2\Psi_{RP})\rangle$), top f_{DbCS} bins (i.e., 0-20% / 0-30%) shows $\gamma_{OS} > 0$ *and* $\gamma_{SS} < 0$.

- For δ-correlator ($= \langle cos(\phi_a - \phi_b)\rangle$, i.e., 2-particle correlater), top f_{DbCS} bins (0-20% / 0-30%) shows $\delta_{SS} > 0$ *and* $\delta_{OS} < 0$.



In- and Out-of-plane correlations for different charge combinations



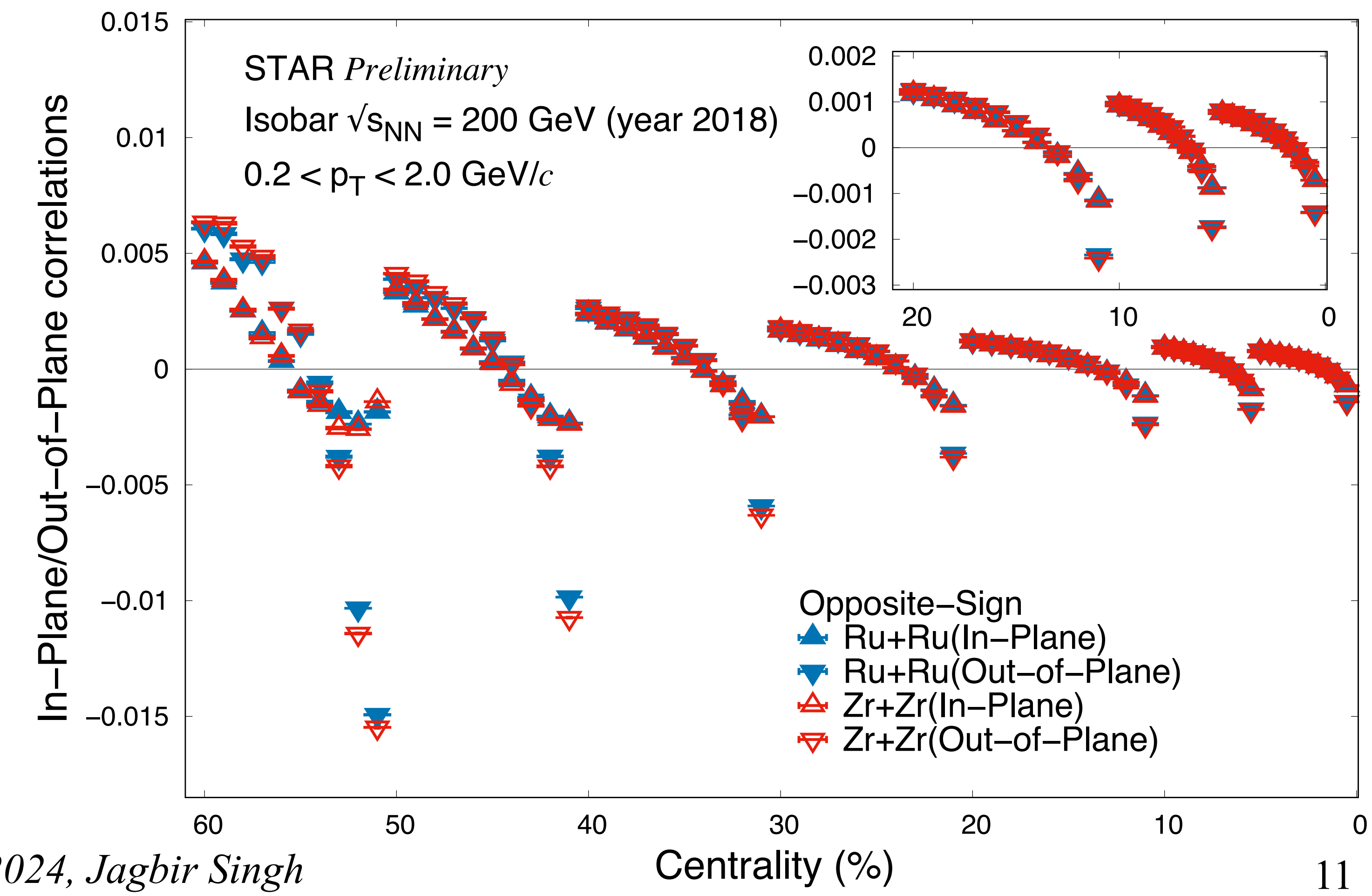
$$\gamma = \langle \cos(\phi_i)\cos(\phi_j) \rangle - \langle \sin(\phi_i)\sin(\phi_j) \rangle$$

$$\delta = \langle \cos(\phi_i)\cos(\phi_j) \rangle + \langle \sin(\phi_i)\sin(\phi_j) \rangle$$

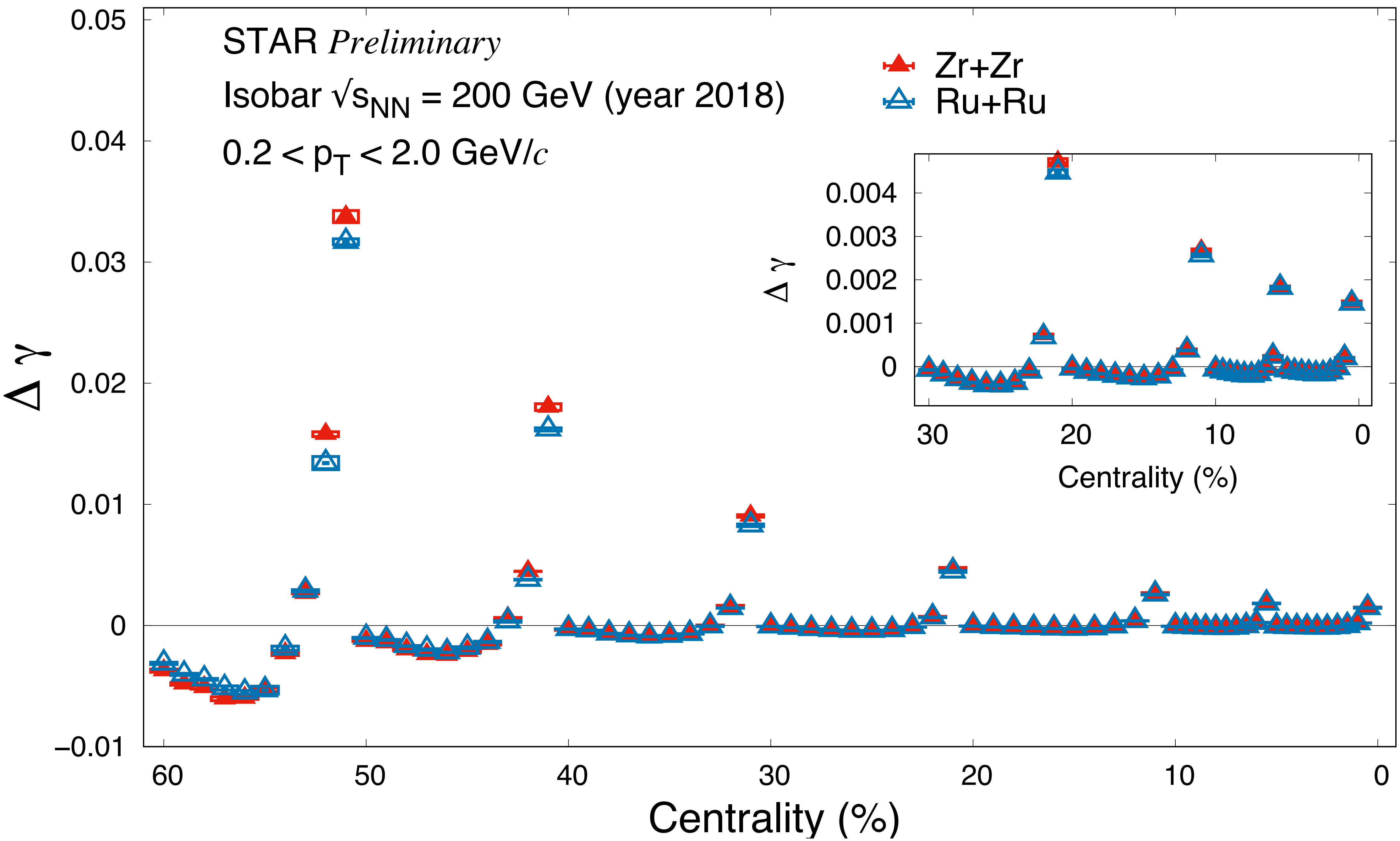
$$\langle \sin(\phi_i)\sin(\phi_j) \rangle = \frac{\delta - \gamma}{2}(Out - of - Plane)$$

$$\langle \cos(\phi_i)\cos(\phi_j) \rangle = \frac{\delta + \gamma}{2}(In - Plane)$$

- Stronger correlations are seen in out-of-plane for both same-sign and opposite-sign charge pairs due to out-of-plane charge separation for both Ru+Ru and Zr+Zr collisions for top f_{DbCS} bins.

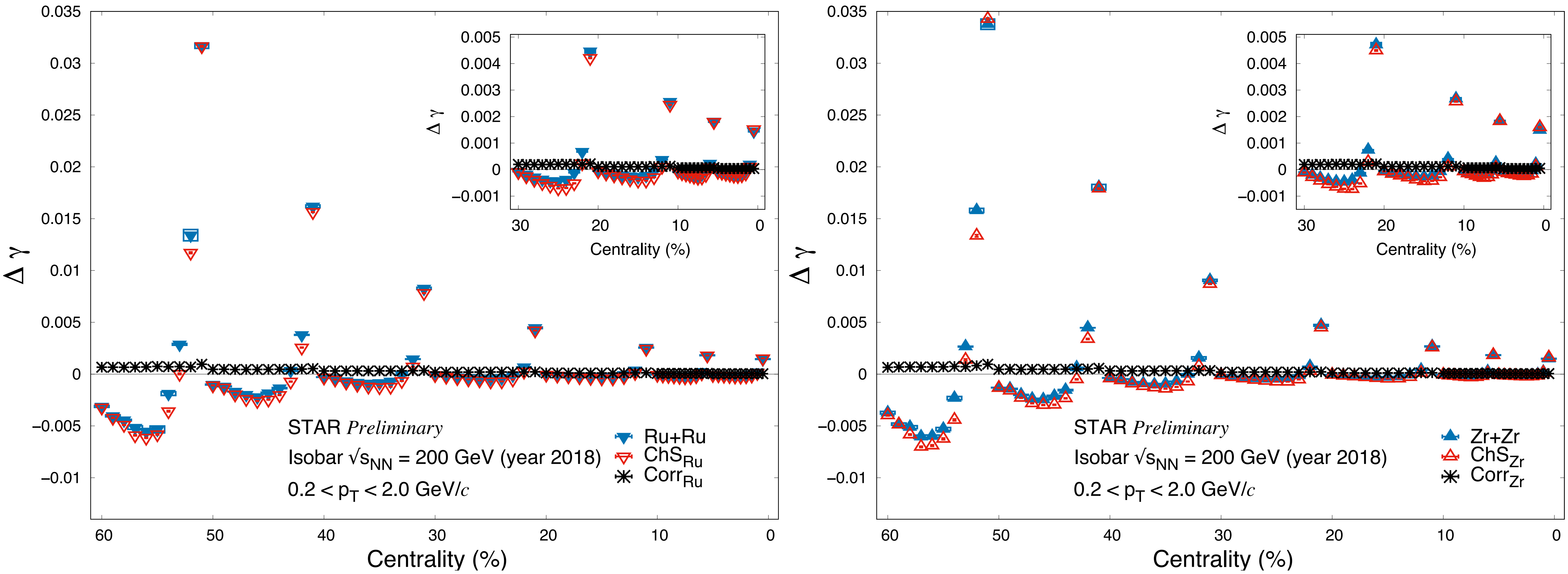


$\Delta\gamma$ dependence on centrality and f_{DbCS}

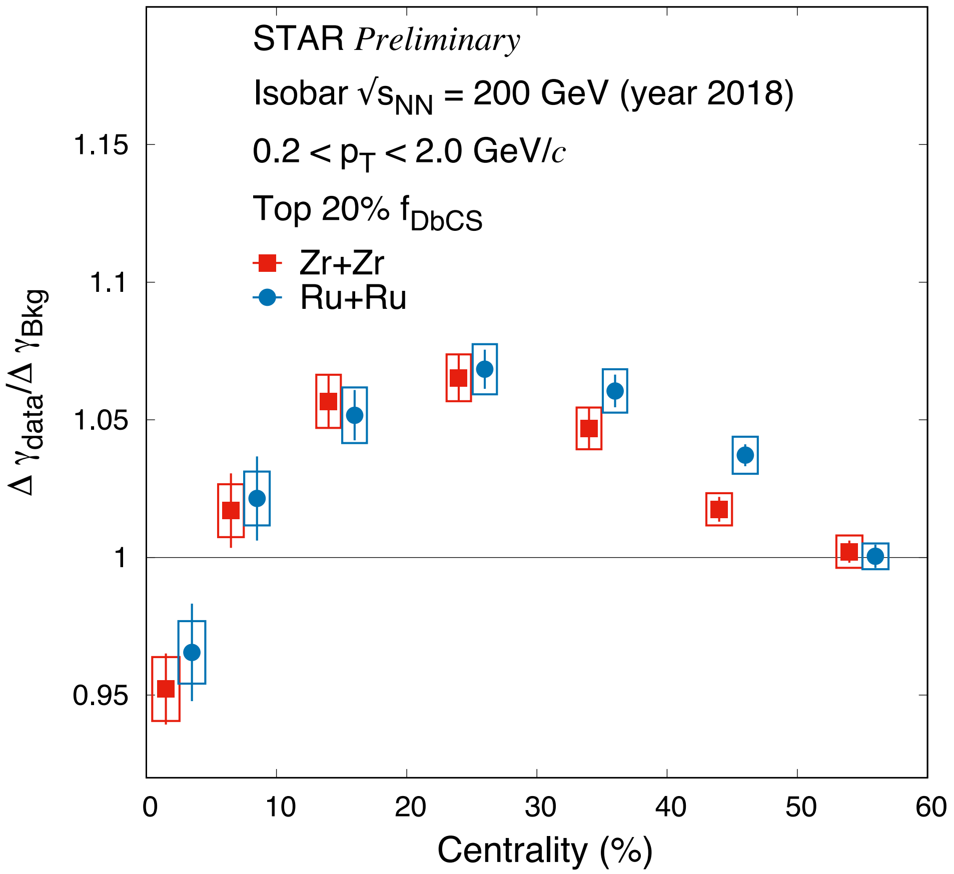


- $\Delta\gamma\ (=\gamma_{OS}-\gamma_{SS})$ is positive for the top 20% (30%) f_{DbCS} bins for 0-40% (40-60%) centralities.
- $\Delta\gamma$ is smaller for Ru+Ru than those of Zr+Zr collisions in top f_{DbCS} bins.

Comparison of $\Delta\gamma$ with respective backgrounds for each f_{DbCS} bin



- The data points for the top 20% or 30% f_{DbCS} bins look higher than the total background ($\gamma_{Bkg} = \gamma_{ChS} + \gamma_{Corr}$) for the 20-50% collision centralities.
- γ_{Corr} is derived from the original events themselves using f_{DbCS} bins of ChS events, it encompasses all types of correlations.

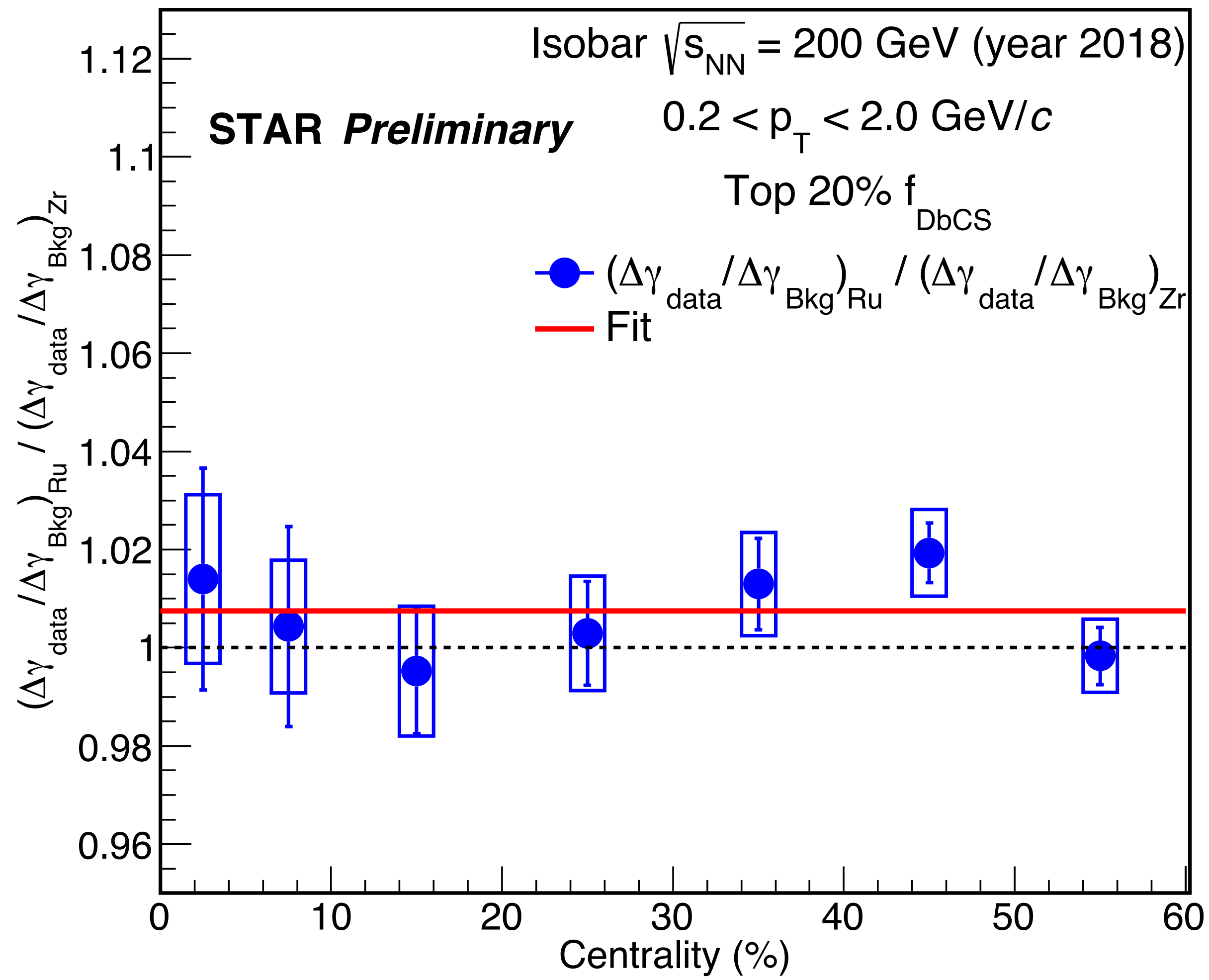


- $\Delta\gamma_{data}/\Delta\gamma_{Bkg_{Ru+Ru}}$ seem to agree within errors those of $\Delta\gamma_{data}/\Delta\gamma_{Bkg_{Zr+Zr}}$ for the top 20% f_{DbCS}.

- The double ratio is calculated as:

$$Double\ ratio = \frac{(\Delta\gamma_{Data}/\Delta\gamma_{Bkg})_{Ru}}{(\Delta\gamma_{Data}/\Delta\gamma_{Bkg})_{Zr}}$$

$$\Delta\gamma_{bkg.} = \Delta\gamma_{ChS} + \Delta\gamma_{Corr}$$



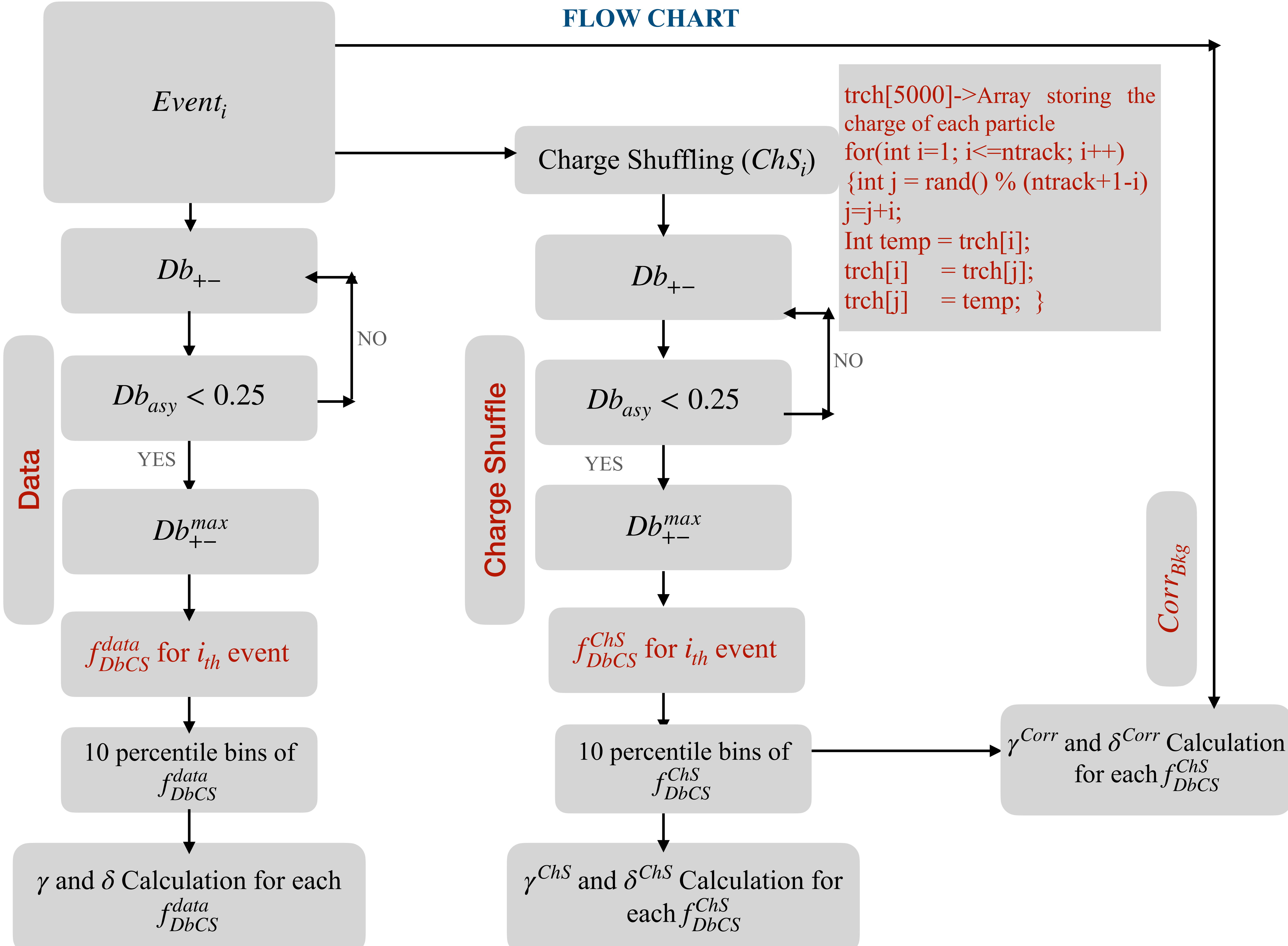
- The double ratio is 1.007±0.003 (pol0 Fit) for 0-60% centralities.

Summary

- The charge separation (f_{DbCS}) distribution extends towards higher f_{DbCS} values with decreasing collision centrality. There seems to be no correlation between f_{DbCS}^{ChS} and the f_{DbCS}^{data}.
- It is seen that $\gamma_{OS} > 0$ *and* $\gamma_{SS} < 0$ for the top 20% (30%) f_{DbCS} bins for 0-40% (40-60%) centralities. For 2-particle correlation, $\delta_{SS} > 0$ *and* $\delta_{OS} < 0$ in top f_{DbCS} bins (0-20%).
- Stronger correlations are seen in out-of-plane for both same-sign and opposite-sign charge pairs due to out-of-plane charge separation for top f_{DbCS} bins.
- It can be seen that $\Delta\gamma$ are smaller for Ru than those of Zr for the top 10% (top 20%) f_{DbCS} bins for 20-40% (40-60%) centralities.
- We do not observe any enhancement in the background scaled $\Delta\gamma$ (i.e., $\Delta\gamma_{data}/\Delta\gamma_{Bkg}$) of Ru+Ru over Zr+Zr for the top 20% f_{DbCS} contrary to the expectation in isobar collisions and the double ratio is 1.007±0.003 for 0-60% centralities.

Thank you for your attention!!

FLOW CHART


$Event_i$
Charge Shuffling (ChS_i)
trch[5000]->Array storing the charge of each particle
for(int i=1; i<=ntrack; i++)
{int j = rand() % (ntrack+1-i)
j=j+i;
Int temp = trch[i];
trch[i] = trch[j];
trch[j] = temp; }
Data
Db_{+-}
$Db_{asy} < 0.25$
NO
YES
Db_{+-}^{max}
f_{DbCS}^{data} for i_{th} event
10 percentile bins of f_{DbCS}^{data}
γ and δ Calculation for each f_{DbCS}^{data}
Charge Shuffle
Db_{+-}
$Db_{asy} < 0.25$
NO
YES
Db_{+-}^{max}
f_{DbCS}^{ChS} for i_{th} event
10 percentile bins of f_{DbCS}^{ChS}
γ^{ChS} and δ^{ChS} Calculation for each f_{DbCS}^{ChS}
$Corr_{Bkg}$
γ^{Corr} and δ^{Corr} Calculation for each f_{DbCS}^{ChS}

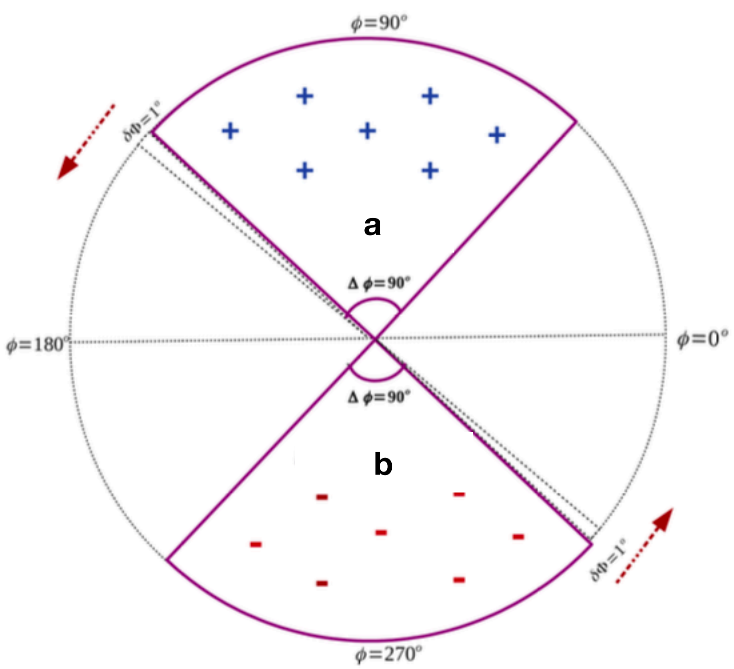
Different asymmetry of the dumbbell

Why do we chose $Db_{asy} < 0.25$?

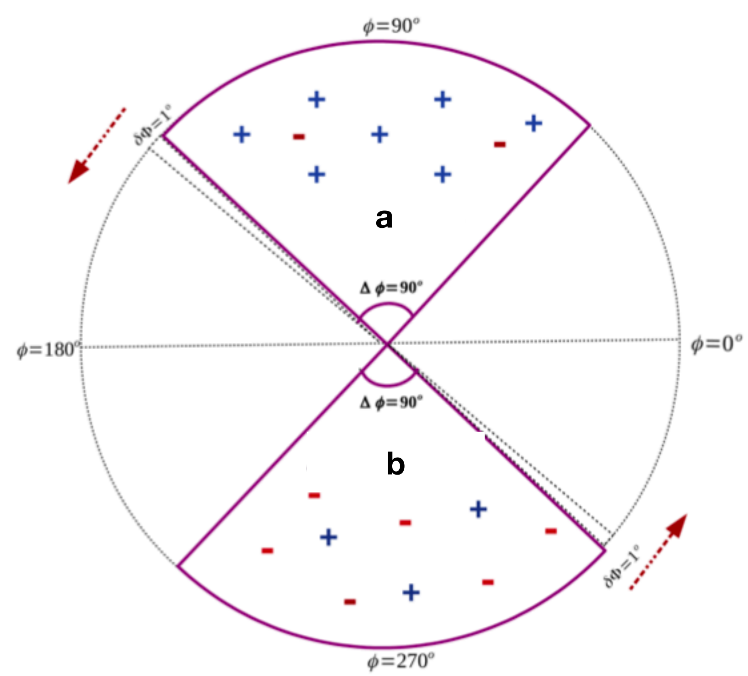
$$Db_{asy} = \frac{(N_{+}^{ex} - N_{-}^{ex})}{(N_{+}^{ex} + N_{-}^{ex})}$$

$N_{+}^{ex} = n_{+}^{a} - n_{-}^{a}$ = Positively charged particle excess on side "a" of the dumbbell

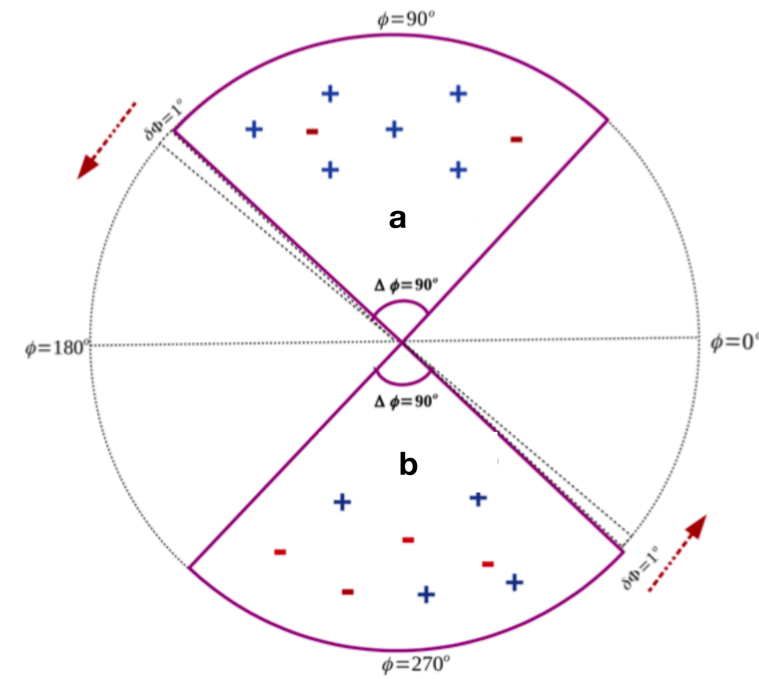
$N_{-}^{ex} = n_{-}^{b} - n_{+}^{b}$ = Negatively charged particle excess on side "b" of the dumbbell



Db_{asy}=0, Pos_{ex} = Neg_{ex}
Ideal CME Case



Db_{asy}=0.25,
Pos_{ex} = 5, Neg_{ex} = 3



Db_{asy}=1, Neg_{ex} = 0

- $Db_{asy} = 1$ gives one side charge excess of positive/negative charge particles