Search for the Chiral Magnetic Wave at STAR with Isobar (Ru+Ru and Zr+Zr) and Au+Au collisions

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STAR Collaboration

Outline

- ☑ Introduction

- ☑ What's new in experimental results: Investigations to separate CMW signals from backgrounds.
  - BES - II data: Exploring low-energy regime where CMW prerequisites could be changing.
  - 200 GeV Au+Au: Comparing $v_n - A_{ch}$ correlators for v_2 (signal + bkg.) and v_3 (bkg. only).
  - Isobar data: Looking for an enhanced CMW signal (~B) in Ru+Ru due to 5–9% higher B than Zr+Zr.

- ☑ Summary

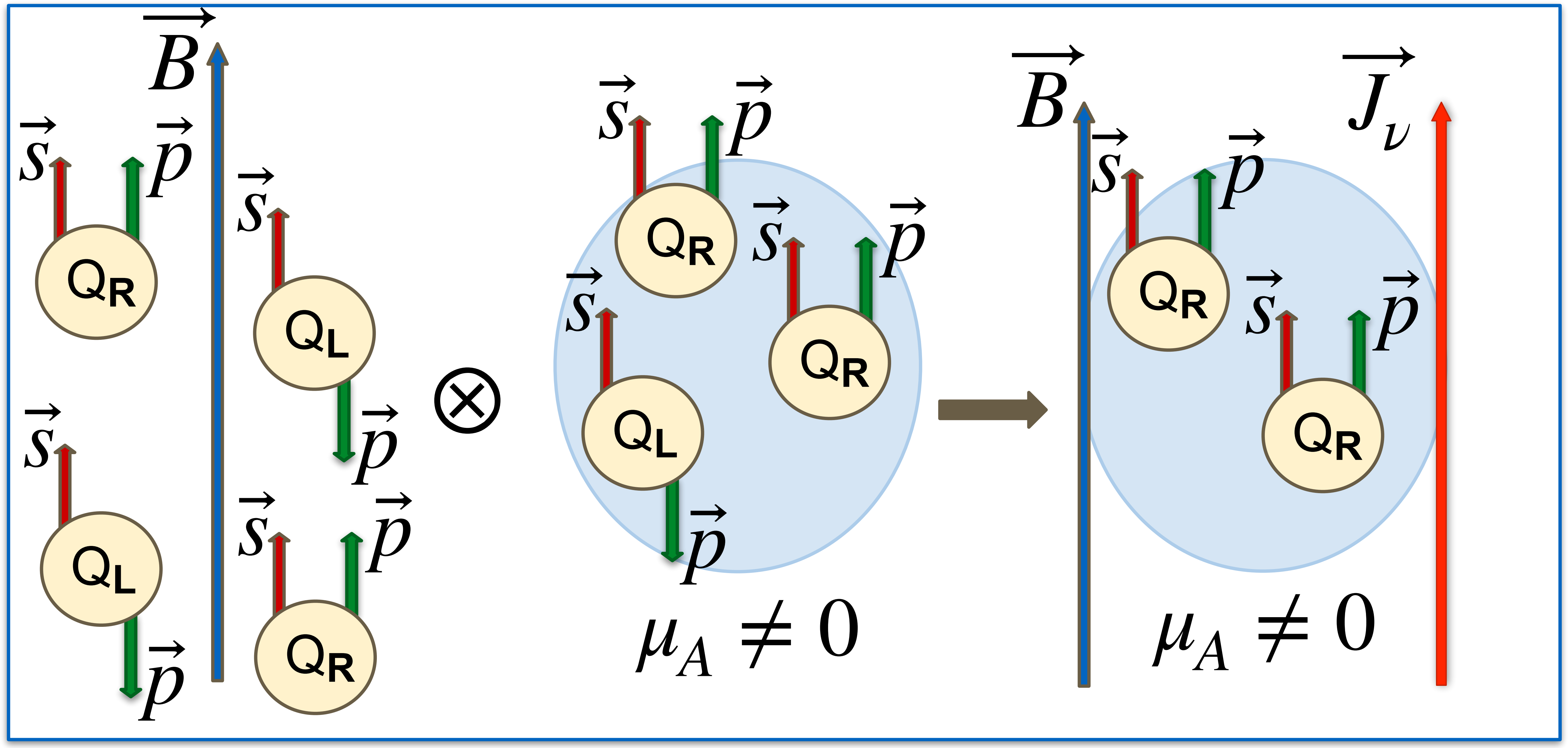
Introduction

CME + CSE → CMW

Chiral Magnetic Wave

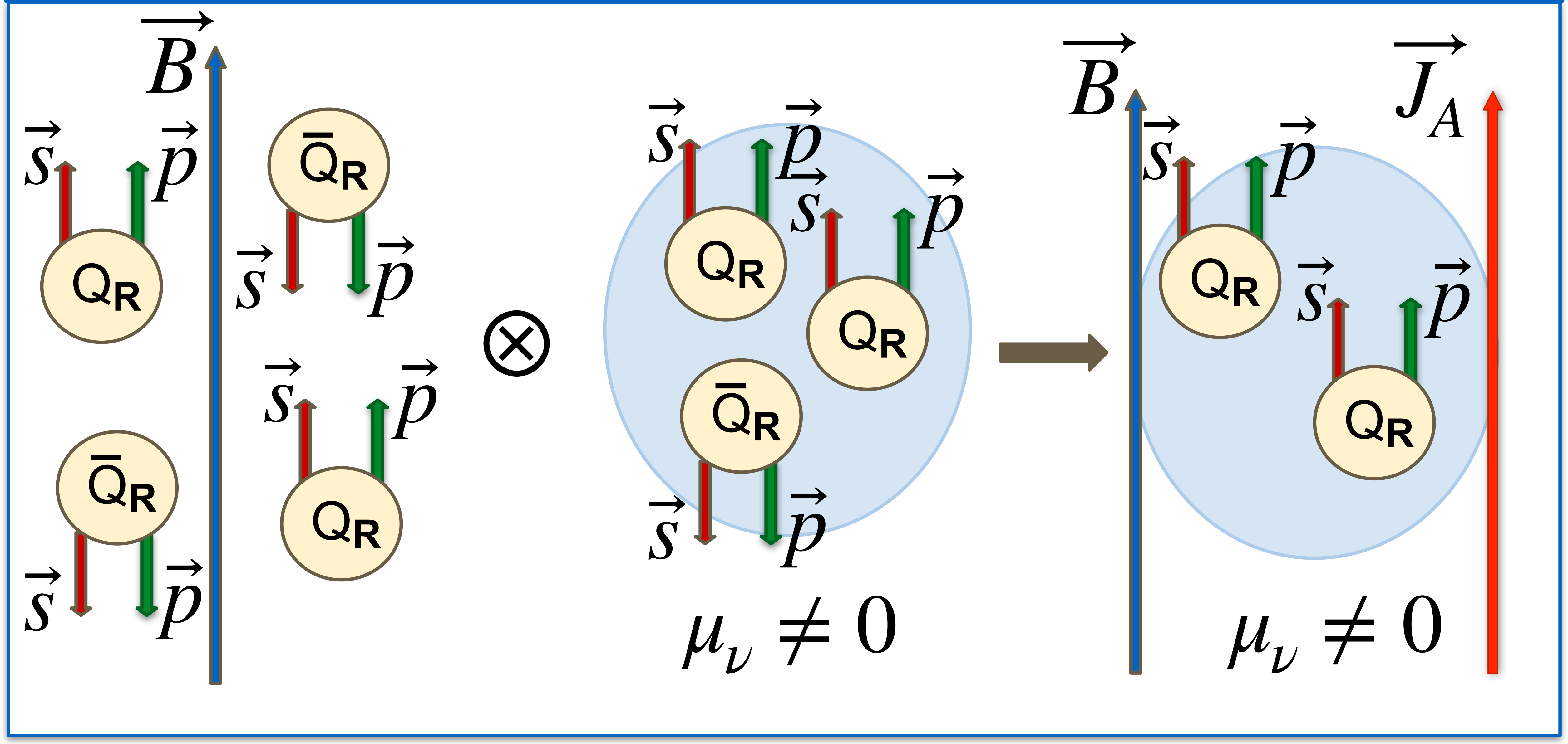
Chiral Magnetic Effect (CME)

With chirality imbalance, net electric charge current emerges in response to external B field.



Chiral Separation Effect (CSE)

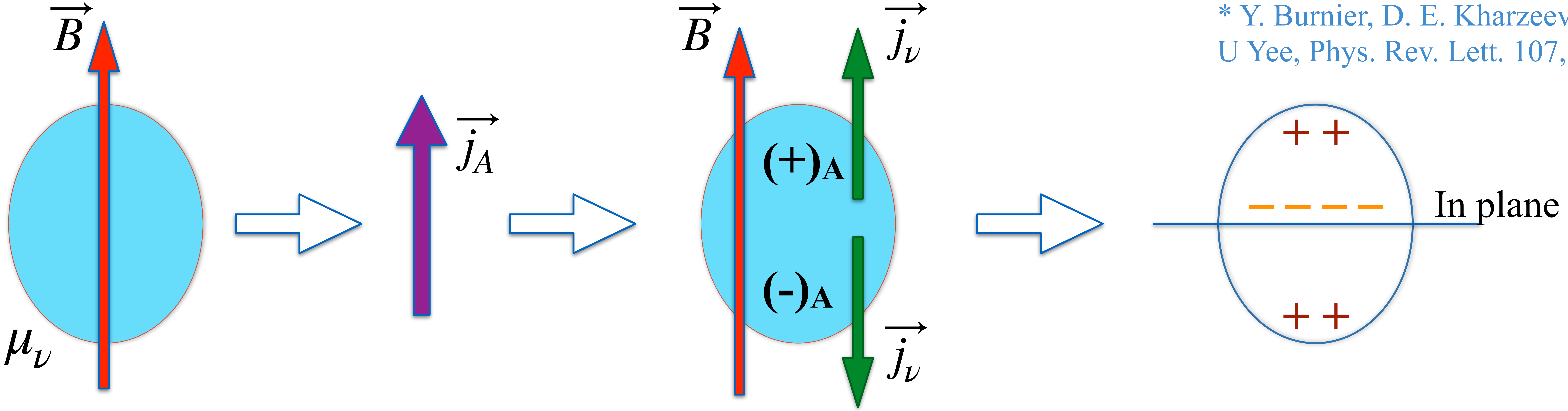
In presence of finite charge density, net axial current emerges along the axis of external B field.



Chiral Magnetic Wave (CMW)

- The coupling of CME and CSE leads to the propagation of electric and axial charge densities in the quark-gluon plasma under the influence of an external magnetic field, forming a collective excitation known as the CMW.

* Y. Burnier, D. E. Kharzeev, J. Liao and H-U Yee, Phys. Rev. Lett. 107, (2011) 052303



quadrupole moment   slope parameter

$$v_2^{\pm} = v_2^{base} \mp \left(\frac{q_e}{\bar{\rho}_e}\right)A_{ch} = v_2^{base} \mp \frac{r_2 A_{ch}}{2} \rightarrow \Delta v_2 = v_2^{-} - v_2^{+} \approx r_2 A_{ch}$$

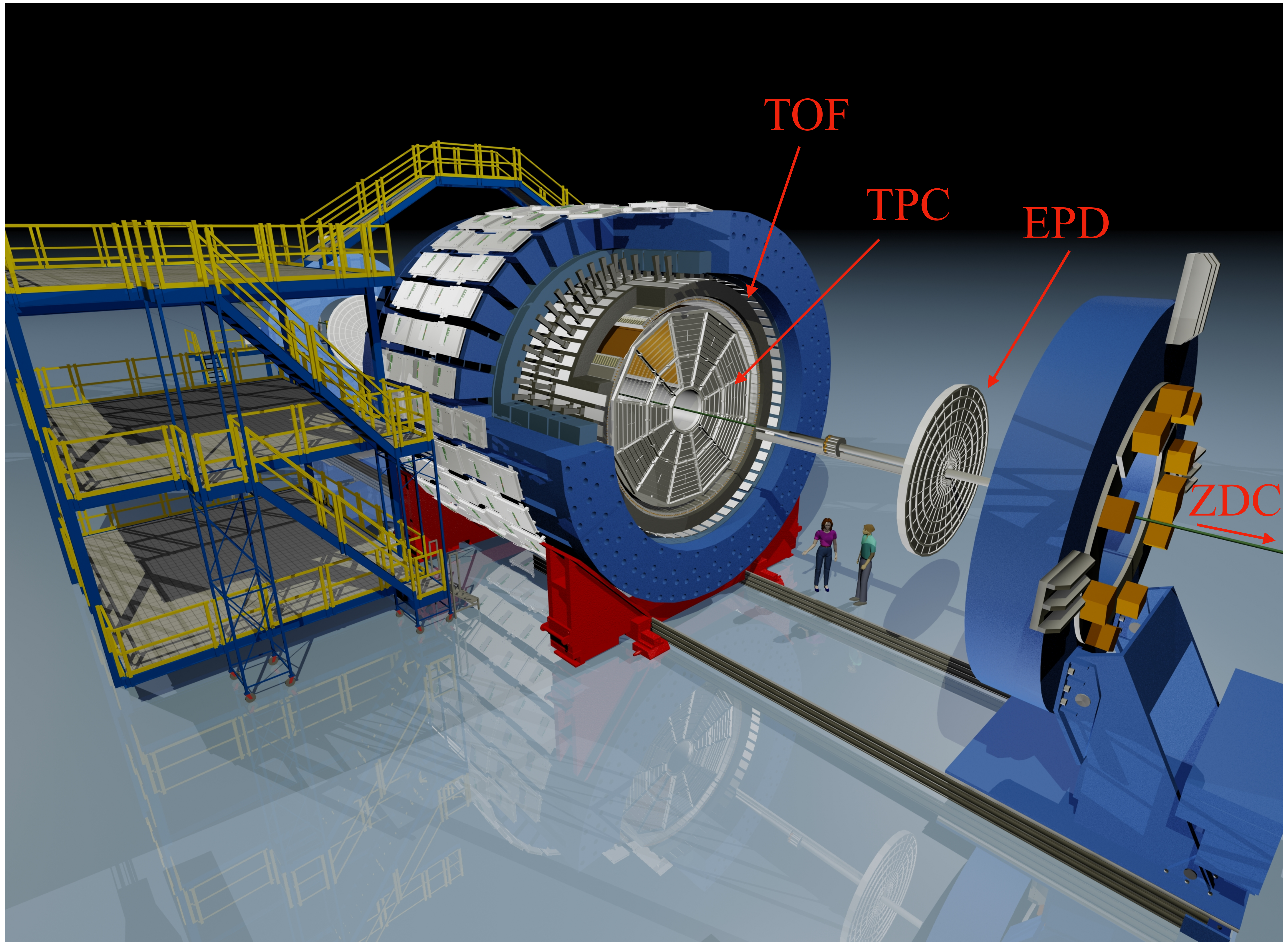
net charge density

$$A_{ch} \equiv \frac{N_+ - N_-}{N_+ + N_-}$$

Charge asymmetry

- ☑ The slope parameter r_2 quantifies the CMW signal strength.
- ☑ CMW signal strength is proportional to the B field.

STAR Detector at RHIC



- **T**ime **P**rojection **C**hamber (TPC)
  - Tracking - momentum
  - Particle identification - Ionization energy loss (dE/dx)
- **T**ime **O**f **F**light detector (TOF)
  - Particle identification improvement
  - Pile-up rejection
- **E**vent **P**lane **D**etector (EPD) ($2.1 < |\eta| < 5.1$), **Z**ero **D**egree **C**alorimeter (ZDC) ($|\eta| > 6.3$) are used for event plane determination.
- Datasets analyzed:
  - Au+Au collisions at 7.7, 19.6, 27 GeV BES II
  - Au+Au collisions at 200 GeV
  - Zr+Zr & Ru+Ru collisions at 200 GeV

Event Plane determination

- Different detectors (TPC, EPD and ZDC) are used to determine event plane using spectators or participants.

$\sqrt{s_{NN}}$	7.7 GeV	19.6 GeV	27 GeV	200 GeV
EP^{2nd} {TPC}	TPC sub event plane with η gap = 0.3			
EP^{2nd} {EPD}	—	|η|<3.0	|η|<3.4	—
EP^{1st} {EPD}	|η|>2.3	|η|>3.2	|η|>3.8	—
EP^{1st} {ZDC}	—	—	—	|η|>6.3

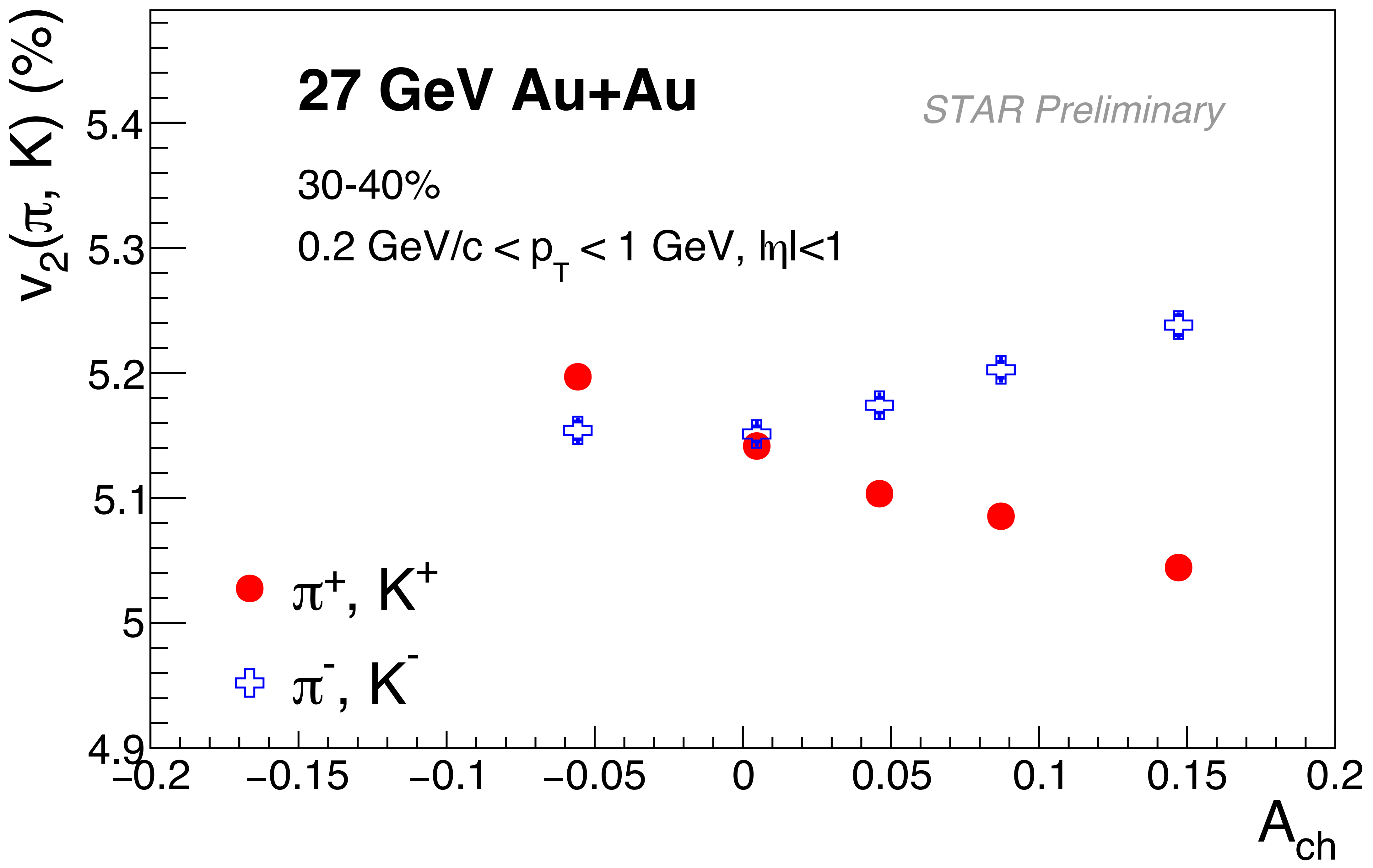
Participant dominated (EP^{2nd} {TPC}, EP^{2nd} {EPD})

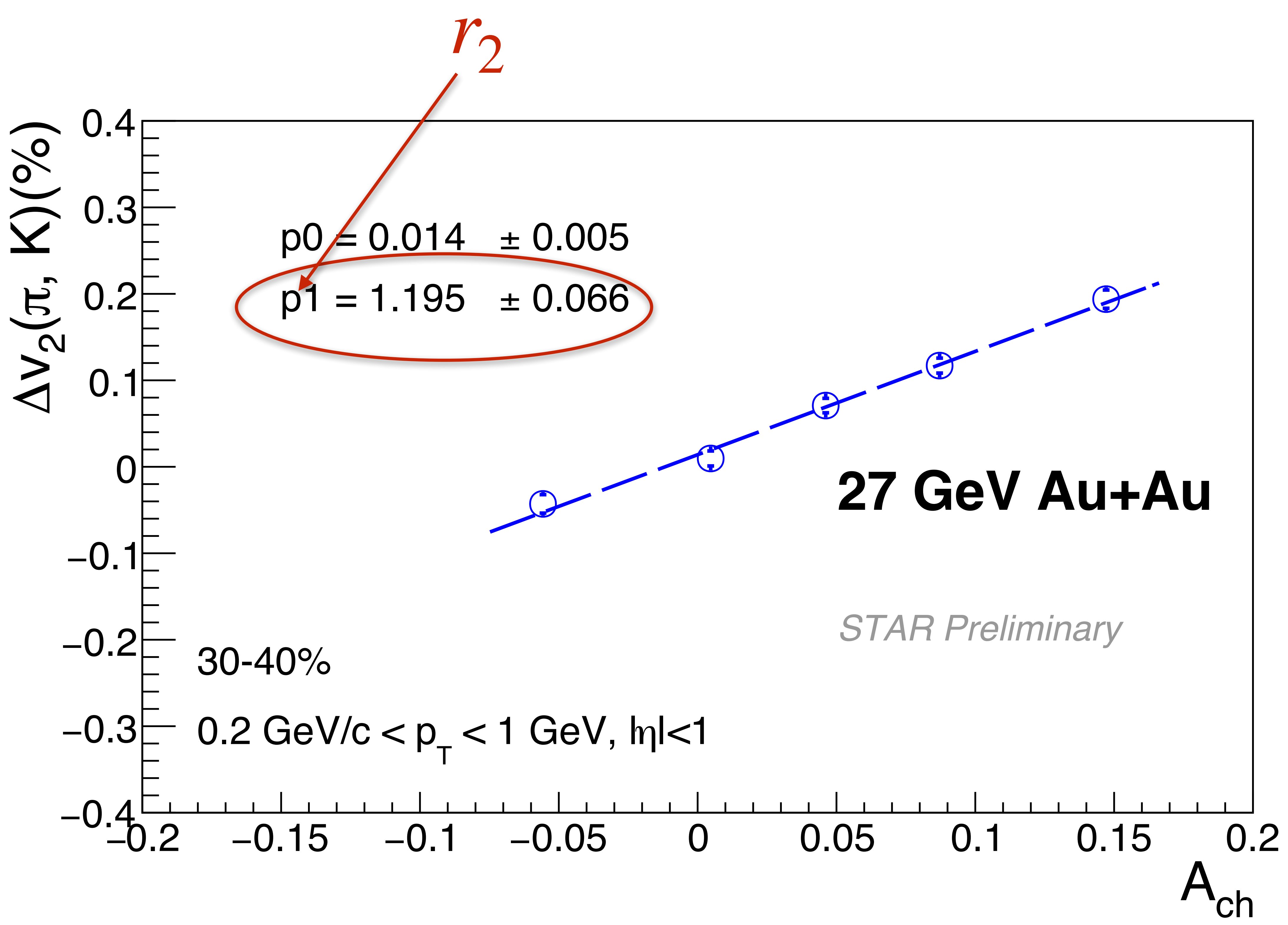
Spectator dominated (EP^{1st} {EPD}, EP^{1st} {ZDC})

- ☑ Enhanced statistics of BES-II data and Au+Au 200 GeV in 2016 provide an opportunity to significantly reduce uncertainties in the measurement of r_2.
- ☑ Event Plane (EP) calculated using spectators, has stronger correlation with B-field and minimizes non-flow in r_2.

Dependence of v_2 and Δv_2 on A_{ch}

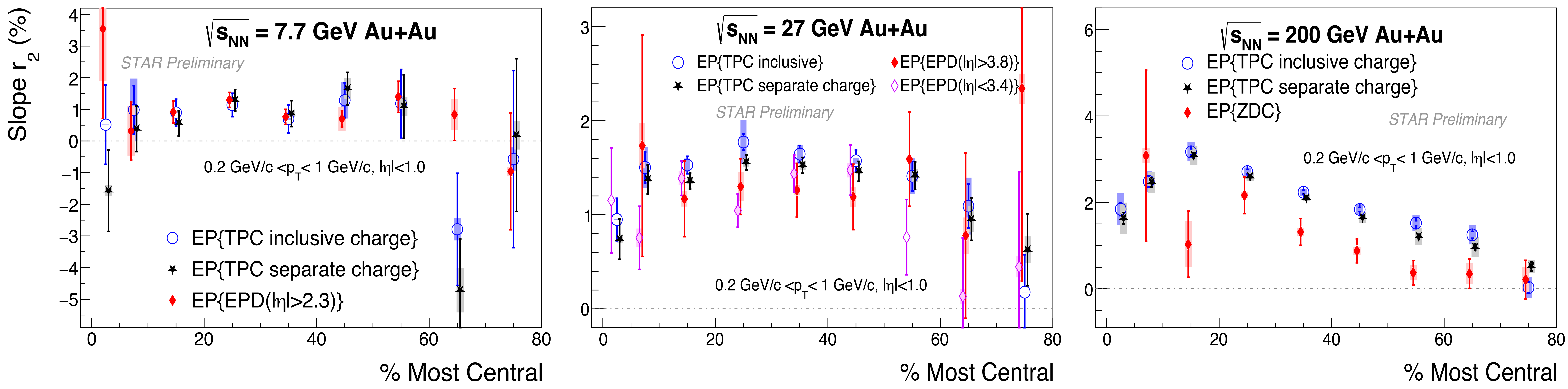
η gap of 0.3 is taken between particles of interest (POI) and EP{TPC}





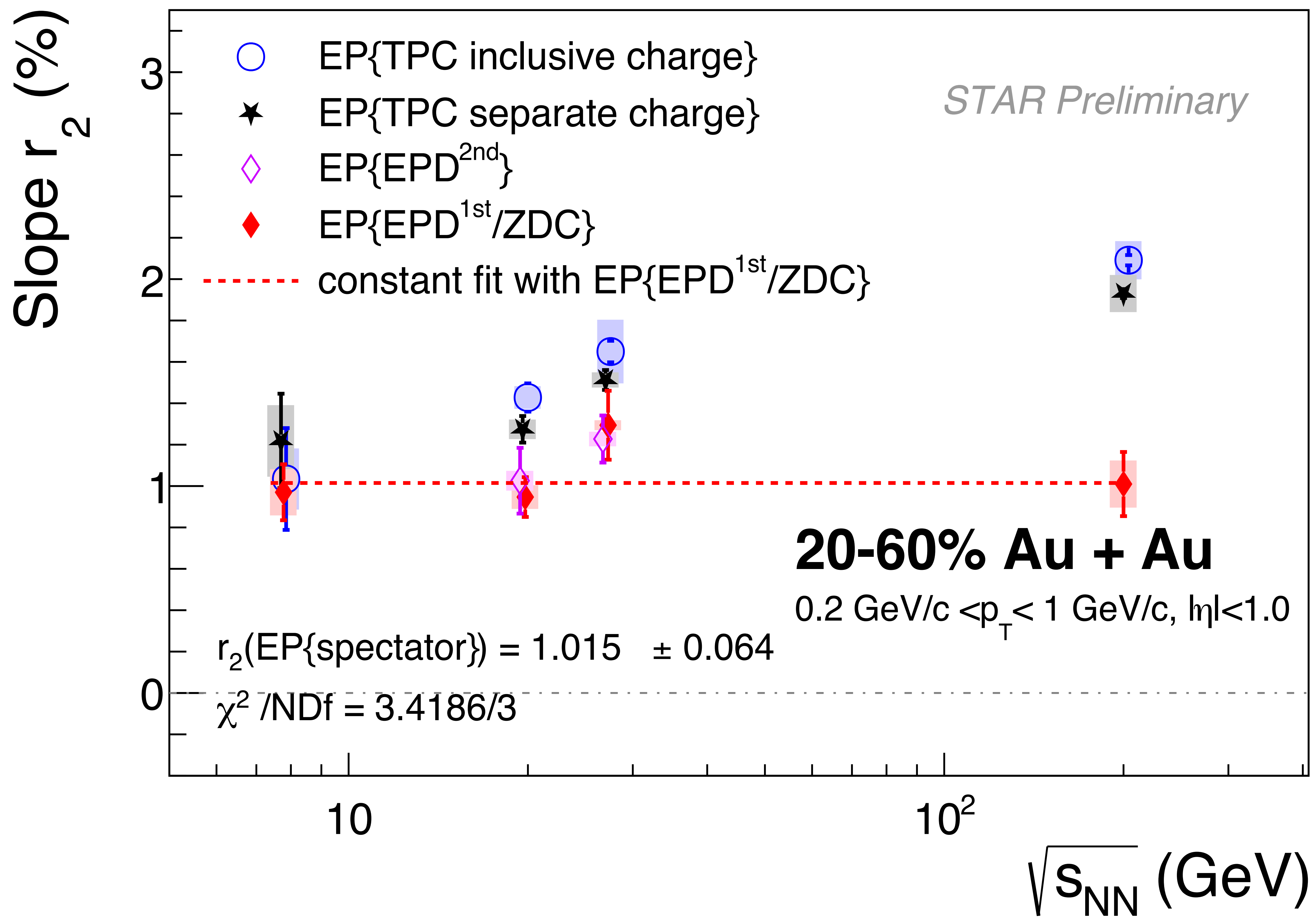
- ☑ v_2 of positively and negatively charged particles, as well as their difference $\Delta v_2 = (v_2^- - v_2^+)$ varies linearly with A_{ch}
- ☑ The slope (r_2) of Δv_2 versus A_{ch}, represents CMW signal strength.

Slope parameter r_2 vs. Centrality:



- ☑ r_2 is measured using spectator and participant planes.
- ☑ No increase in signal is observed when spectator plane is used.
- ☑ Cross check with separate charge event plane to constrain size of ‘trivial’ autocorrelation.

Slope parameter r_2 as a function of energy



- ☑ Spectator plane signal shows no clear energy dependence, even at 7.7GeV where partonic interactions are expected to dominate.
- ☑ Comparison between spectator and participant plane results allows tuning of signal and background sensitivity.
- ☑ No larger r_2 values seen with spectator plane measurements. Suggests background contributions are large.

Comparing normalized CMW strengths in Au+Au at 200 GeV for v_2 and v_3

- Another observable studied is integral correlator (IC) : covariance of $v_2^{\pm}$ and A_{ch}

$$IC = \langle v_2^{\pm} A_{ch} \rangle - \langle A_{ch} \rangle \langle v_2^{\pm} \rangle \approx \mp r(\langle A_{ch}^2 \rangle - \langle A_{ch} \rangle^2)/2 \approx \mp r\sigma_{A_{ch}}^2/2$$

- Δ Integral Correlator :

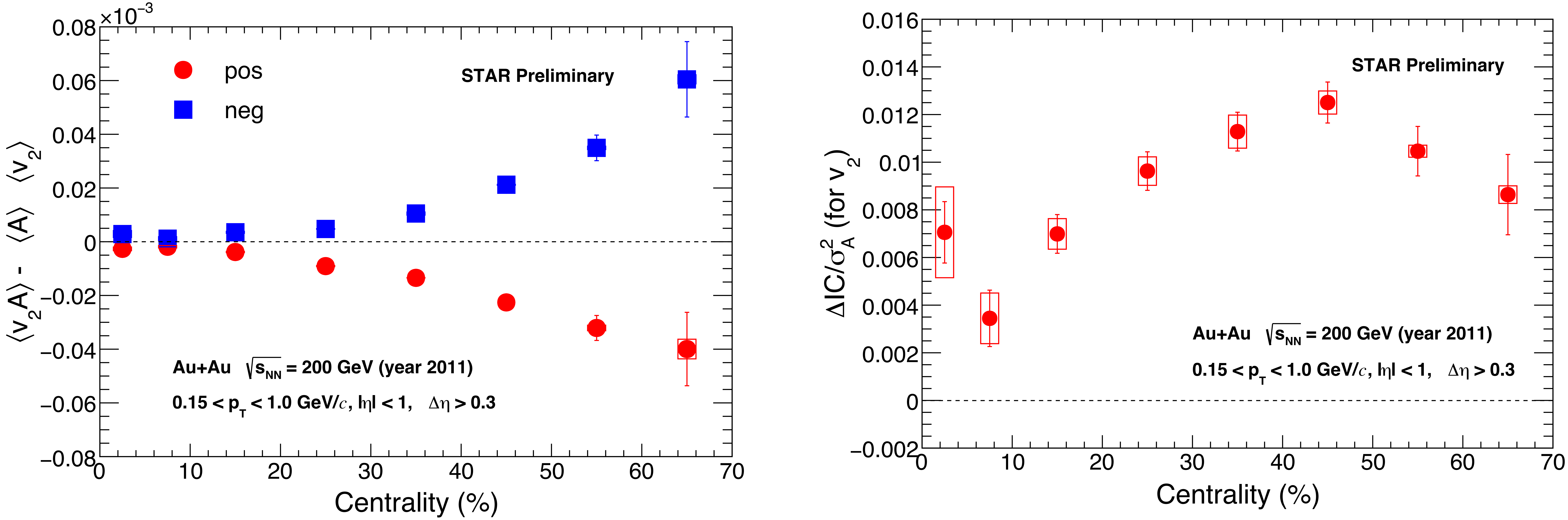
$$\Delta IC = (\langle v_2^{-} A_{ch} \rangle - \langle A_{ch} \rangle \langle v_2^{-} \rangle) - (\langle v_2^{+} A_{ch} \rangle - \langle A_{ch} \rangle \langle v_2^{+} \rangle)$$

- Advantage of covariance method:
  - Reduce statistical fluctuations as no need to divide each sub sample of v_2 into A_{ch} intervals.
  - More robust against the detector acceptance and reconstruction efficiency of charged hadrons.

* J. Adam *et al.* (ALICE Collaboration) Phys. Rev. C 93 (2016) 044903

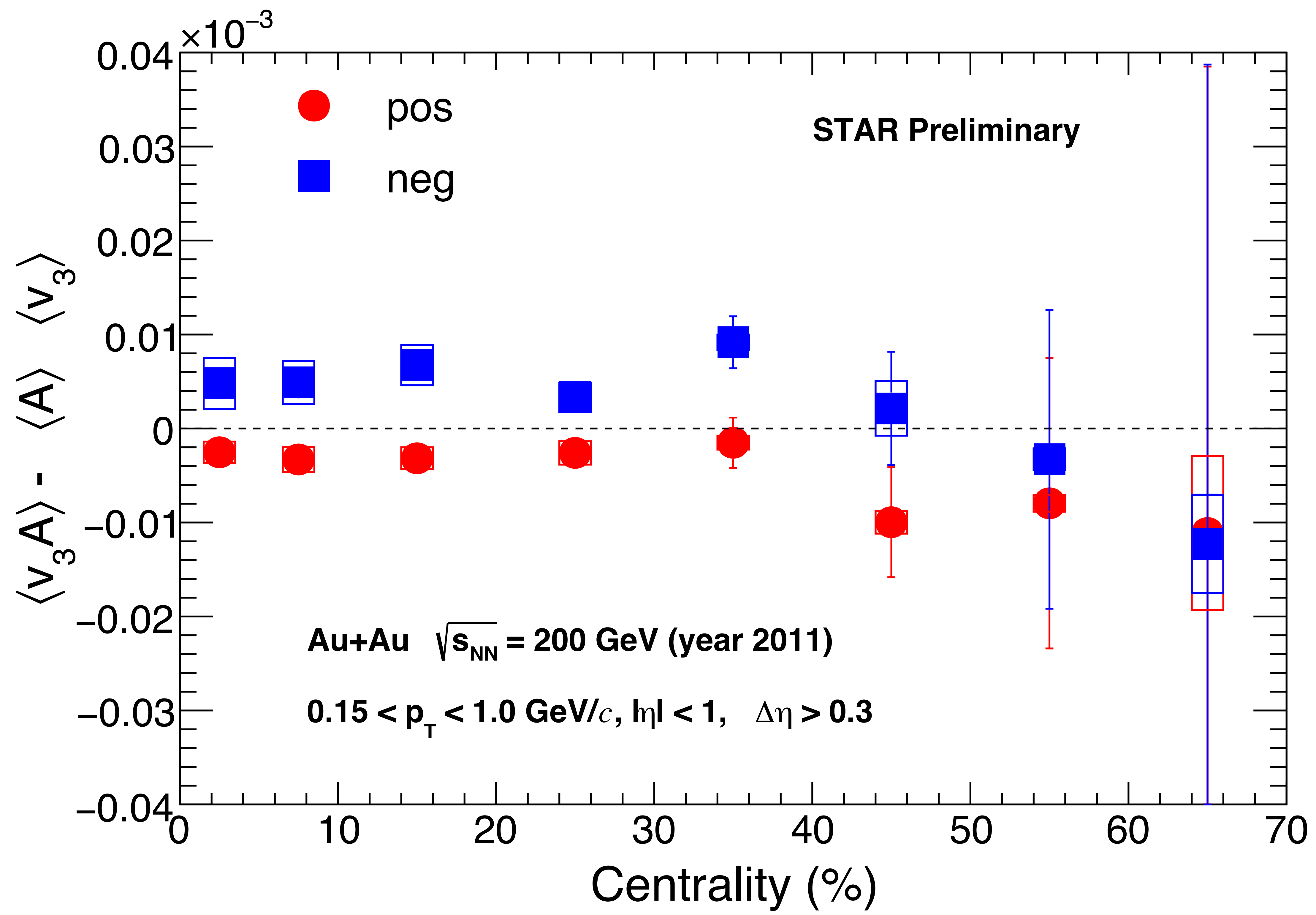
- We don't expect CMW signal in the case of v_3. Normalized CMW signal for v_2 and v_3 are expected to be same if dominated by backgrounds such as LCC.

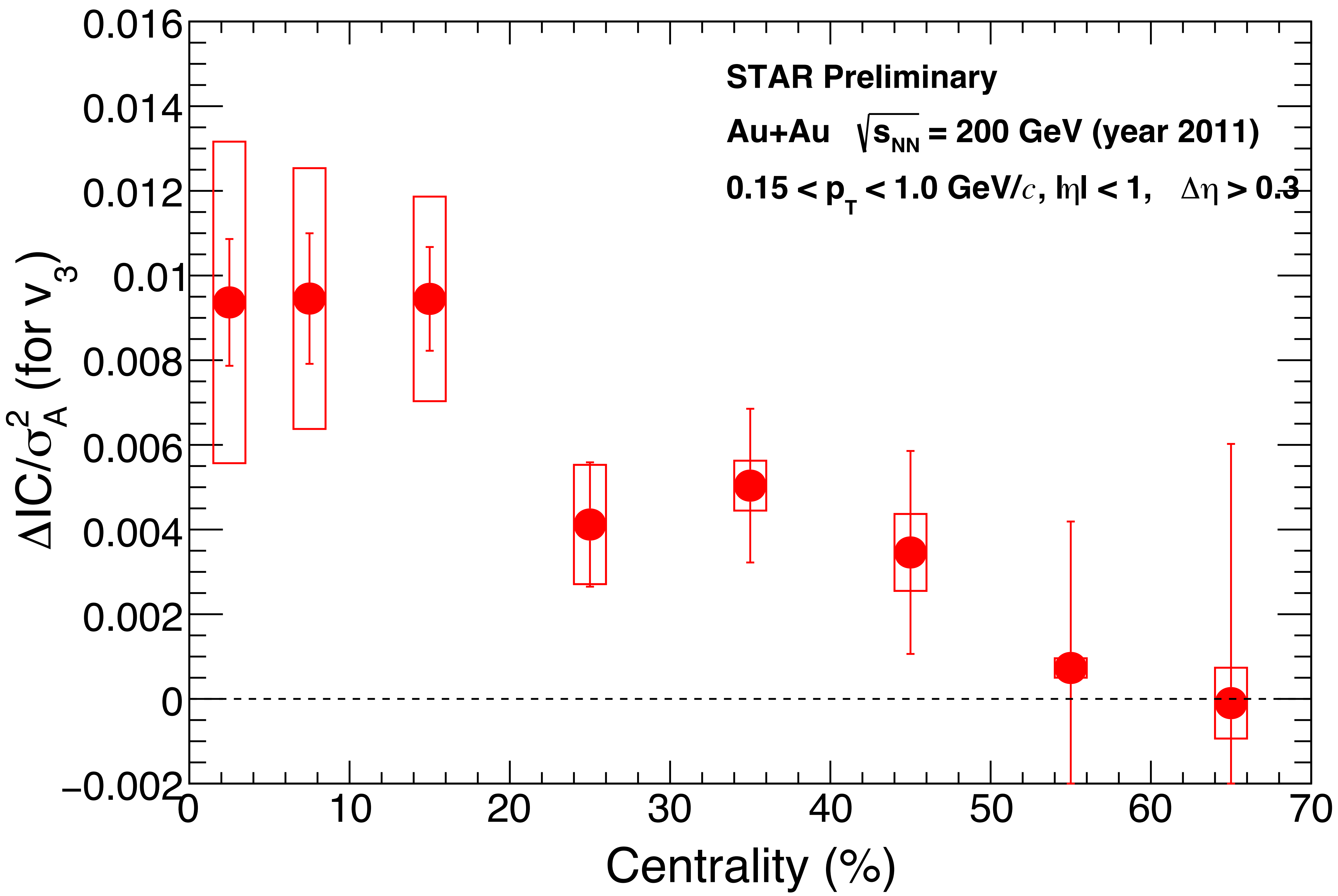
Covariance of v_2 and A_{ch} in Au+Au at 200 GeV



- Covariance of v_2 and A_{ch} increases from central to peripheral collisions for both positive and negative particles. ΔIC also increases from central to peripheral collisions.

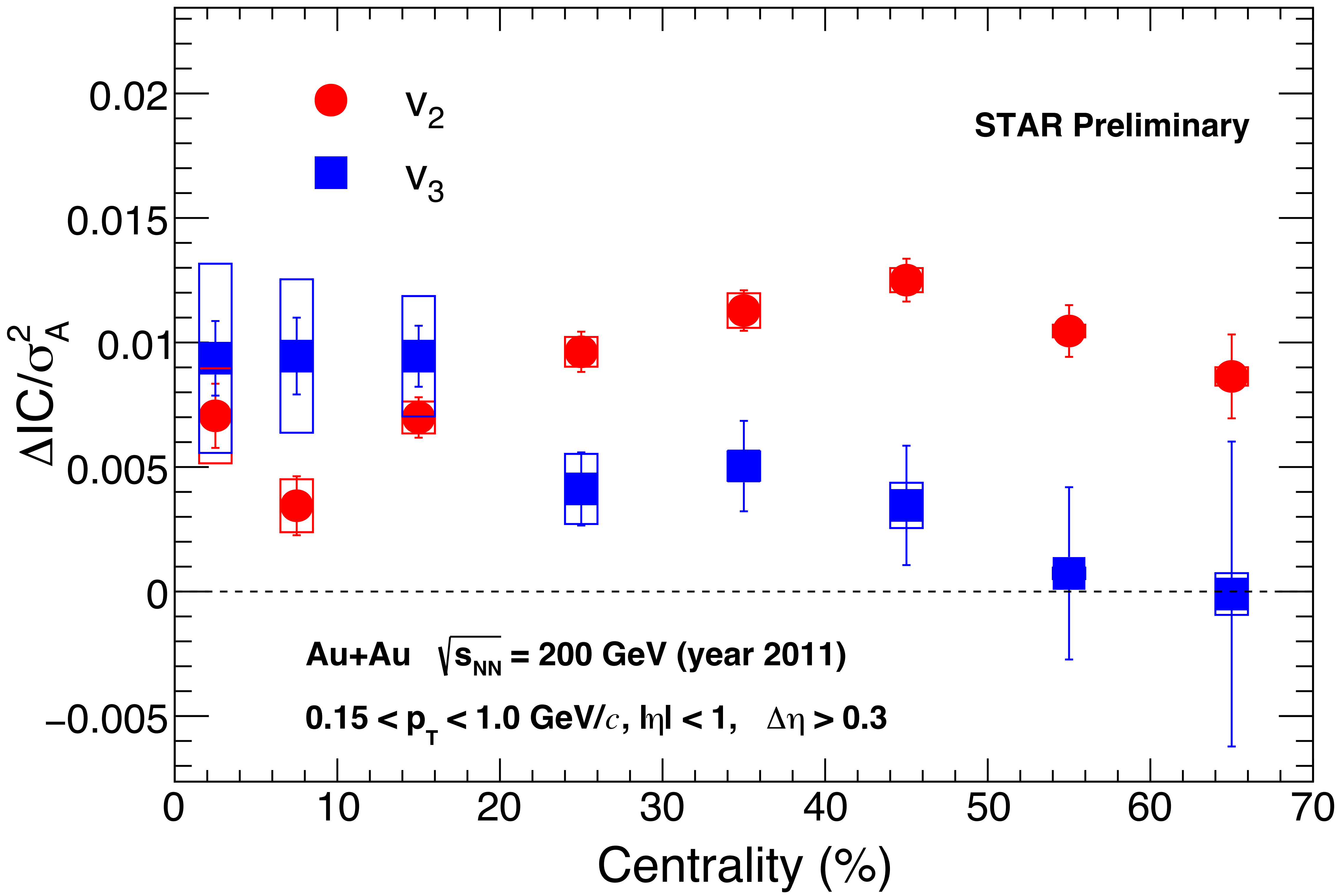
Covariance of v_3 and A_{ch}

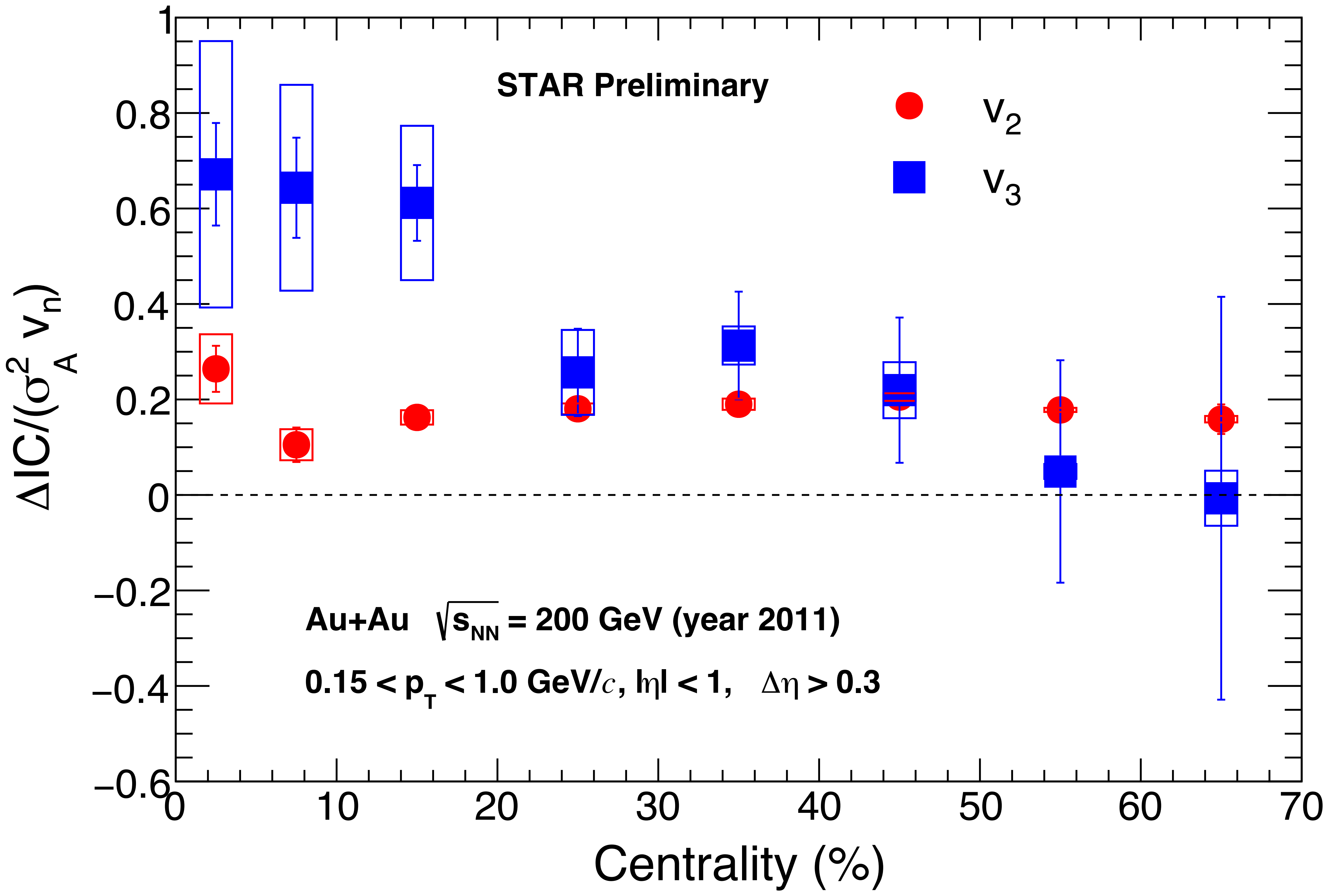




☑ Covariance of v_3 and A_{ch} for positive and negative particles is approximately independent of centrality.

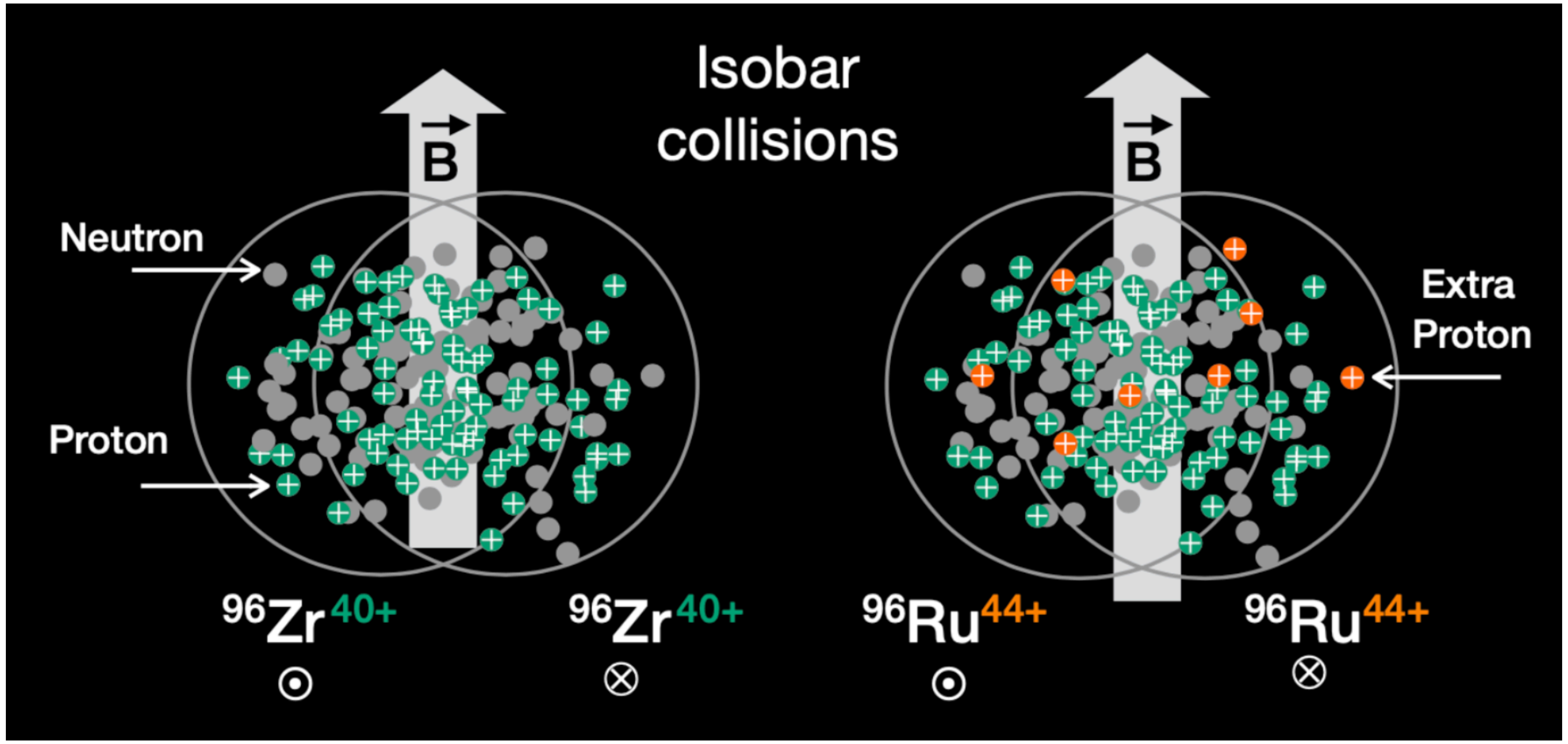
$\Delta IC/\sigma_A^2$ normalized by v_2 and v_3





☑ No difference between the values of normalized $\Delta IC/\sigma_A^2$ by v_2 and v_3, respectively, within uncertainties, for 20-70% centralities indicating no evidence for a CMW signal from this study.

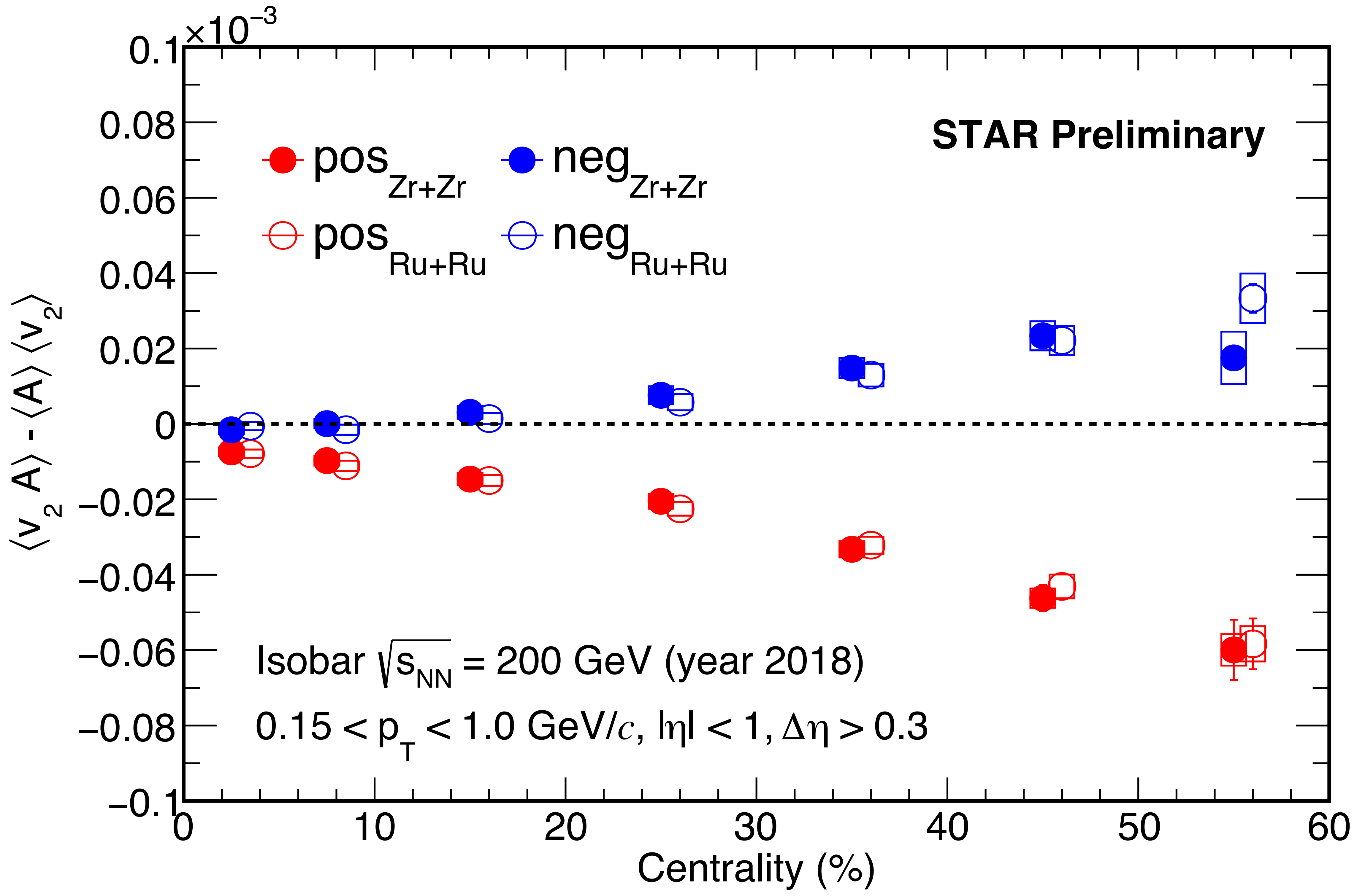
Searching expected enhanced CMW signal in Ru+Ru over Zr+Zr collisions

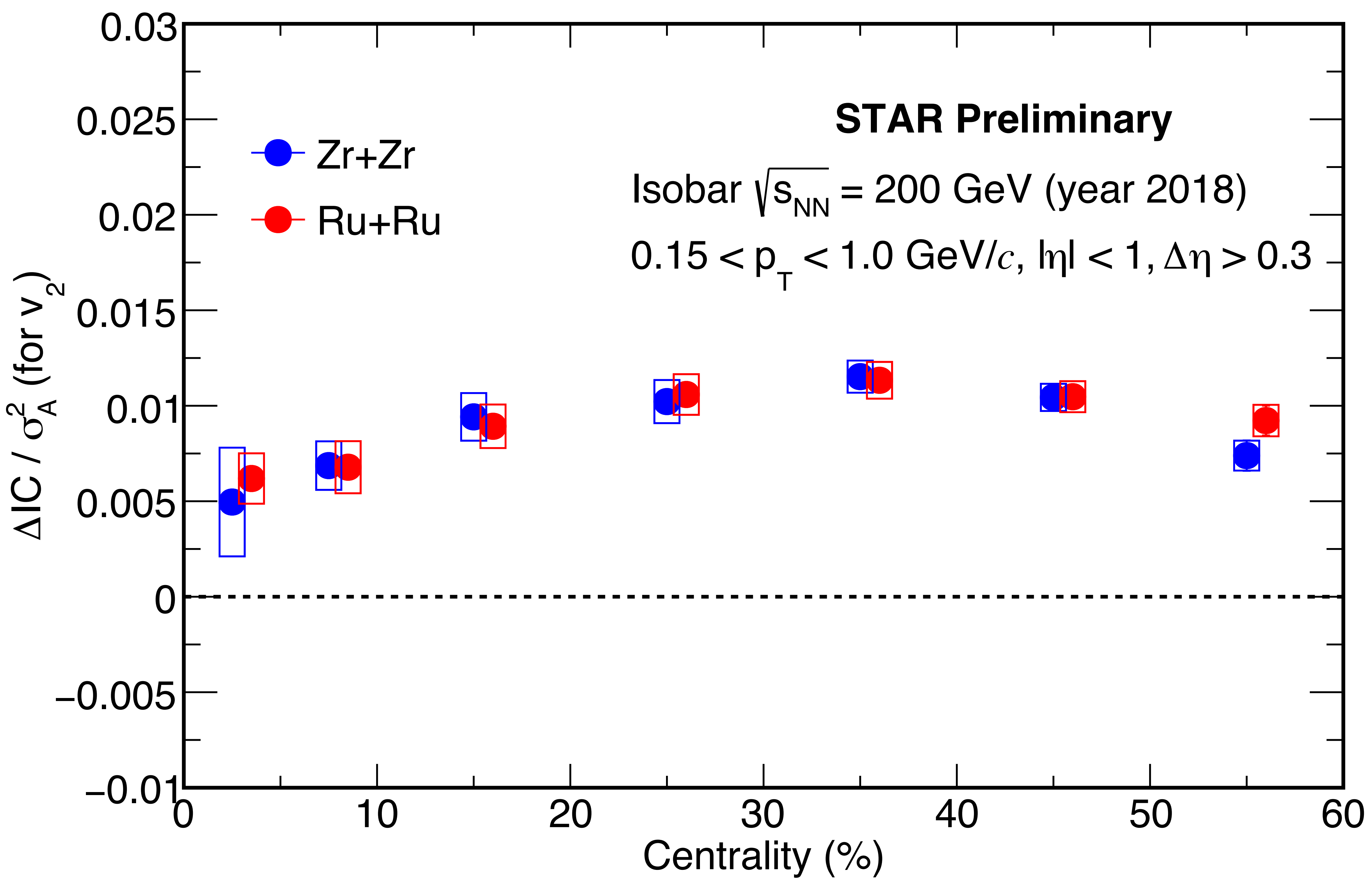


P. Tribedy

- Enhanced magnetic fields in Ru+Ru collisions are expected to give rise to a larger CMW signal in Ru+Ru, with a 5–9% increase in B, while both systems have similar backgrounds.
- $\frac{CMW_{(Ru+Ru)}}{CMW_{(Zr+Zr)}} \rightarrow \frac{B_{(Ru+Ru)}}{B_{(Zr+Zr)}} \rightarrow 1.05 - 1.09$

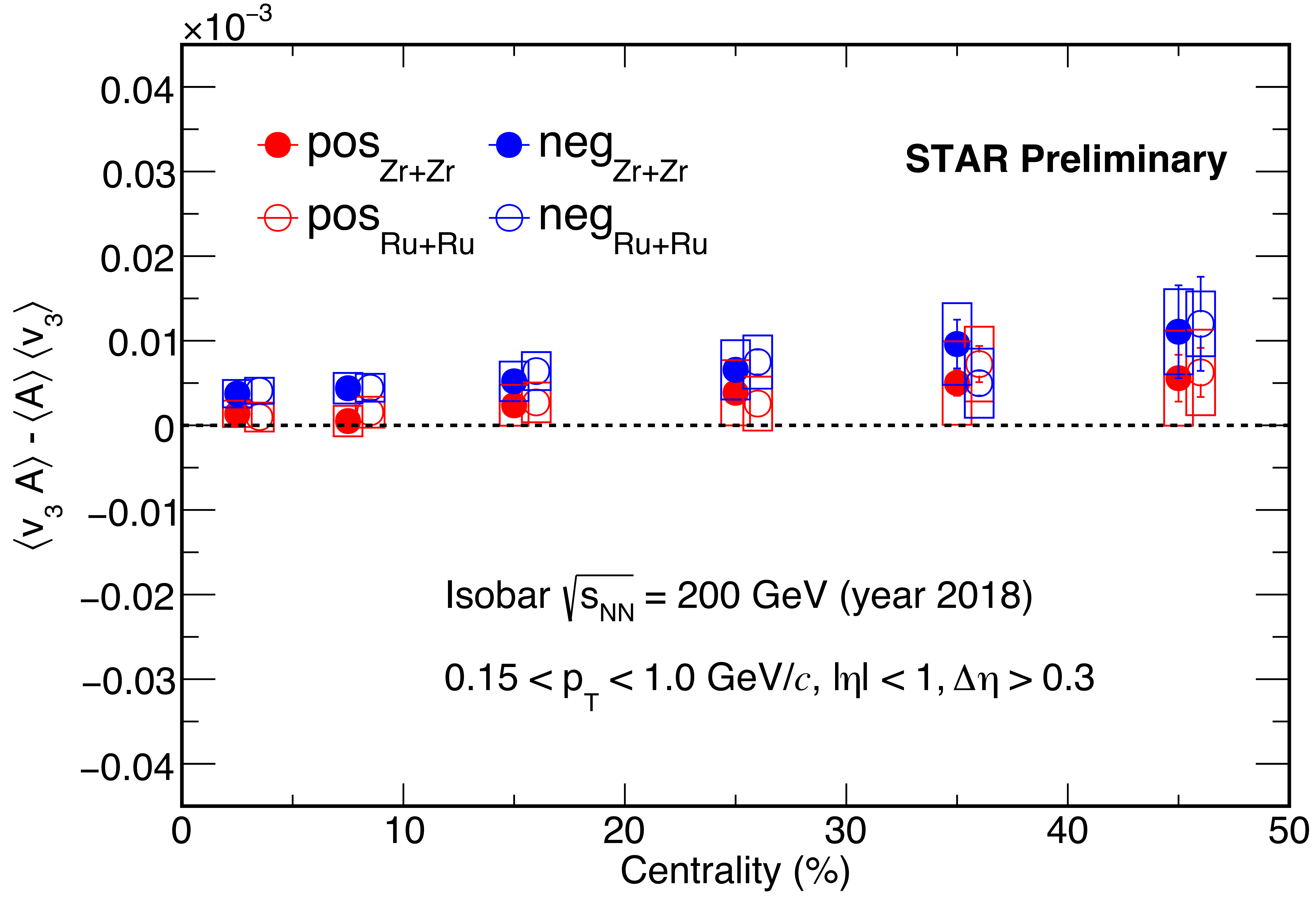
Covariance of v_2 and A_{ch} in Isobars at 200 GeV

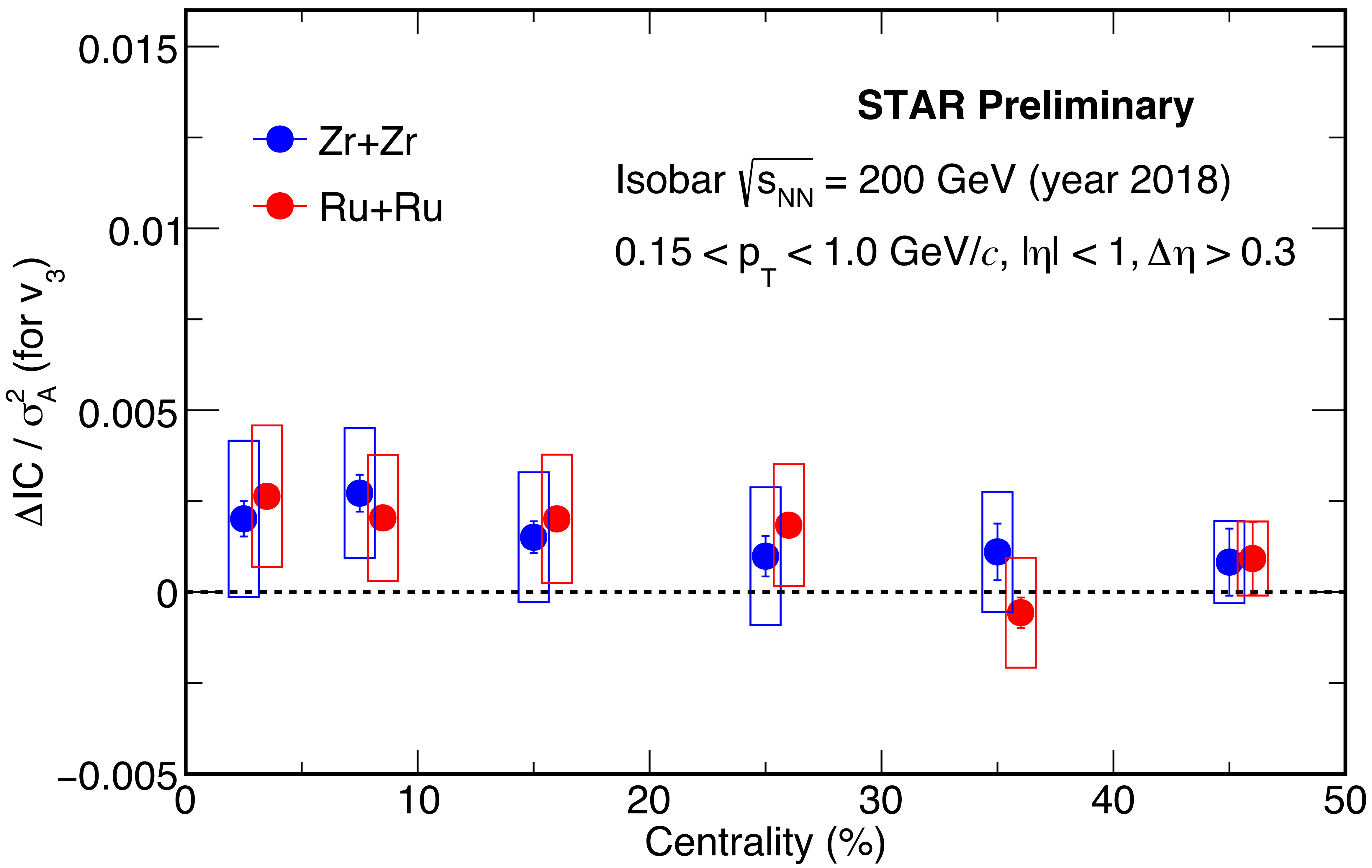




- ☑ Both Ru+Ru and Zr+Zr show charge-dependent splitting of covariance of v_2 and A_{ch}.
- ☑ $\Delta IC/\sigma_A^2$ (for v_2) values for both collision systems are same within errors.

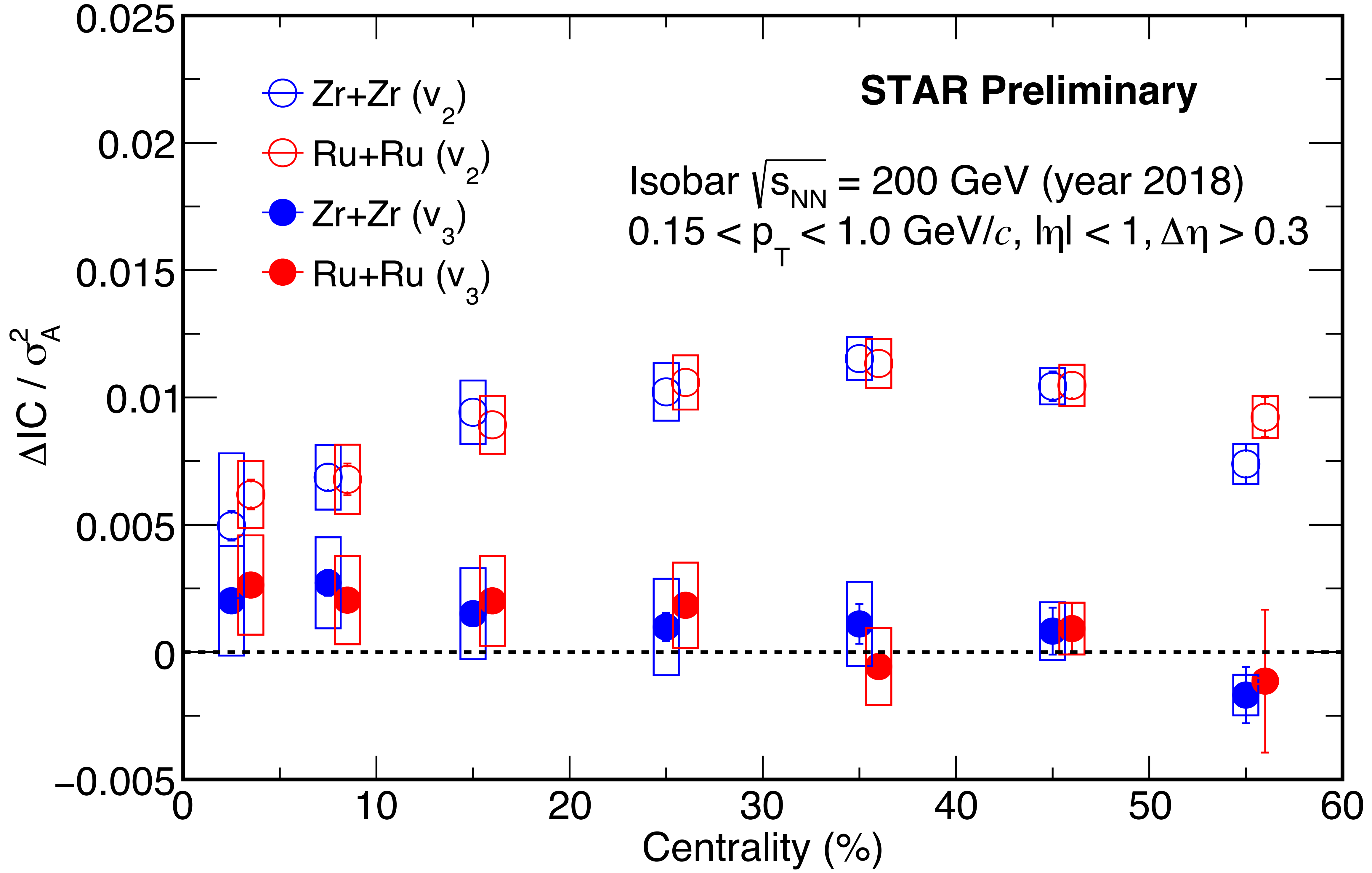
Covariance of v_3 and A_{ch} in Isobars at 200 GeV

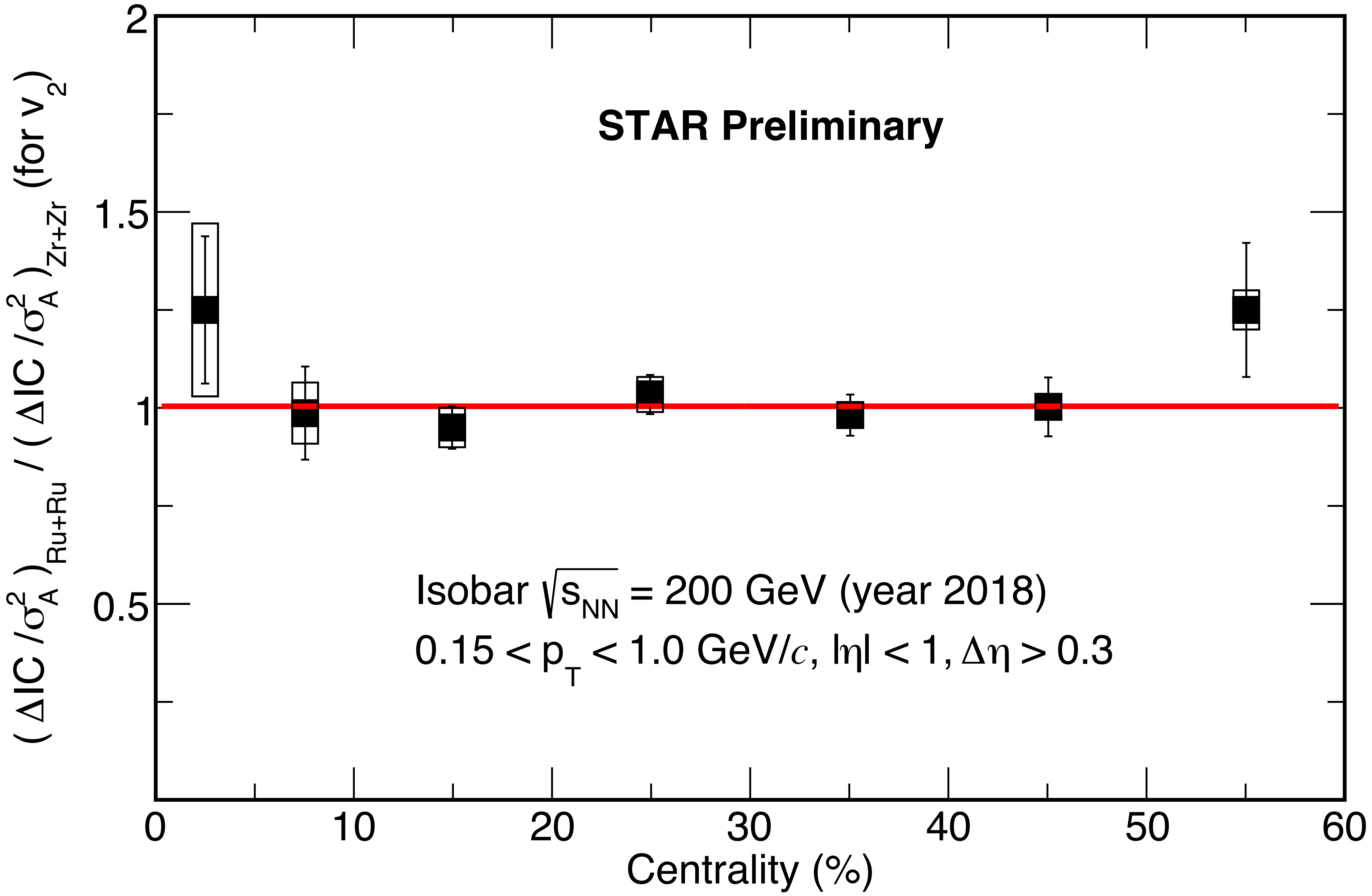




- Both Ru+Ru and Zr+Zr show no charge-dependent splitting of covariance of v_3 and A_{ch}.
- The values of $\Delta IC/\sigma_A^2$ (for v_3) are same for both collision systems within the uncertainties.

Ratio





- ☑ A constant (pol0) fit yields 1.004 ± 0.03
- ☑ The CMW-sensitive parameter $\Delta IC/\sigma_A^2$ for Ru+Ru and Zr+Zr is consistent within 3% precision, tight constraints on possible B-field–driven enhancement.

Summary

- BES-II CMW search: Slopes, r_2, measured with participant and spectator planes, provide sensitivity to disentangle signal from background; results suggest sizeable background contributions.

- Normalized signal sensitive $v_2 - A_{ch}$ vs. background-driven $v_3 - A_{ch}$ correlation in 20–70% centralities are consistent, largely constrain CMW signal in Au+Au collisions at 200 GeV.

- CMW-sensitive measurements in Ru+Ru are found to be consistent with Zr+Zr within uncertainties, constraining B-field–driven enhancement.

Outlook:

- To separate CMW signal from background by using event shape engineering technique which helps to investigate variation of CMW observables with v_2.

Thank you for your kind attention!