# Study of the Chiral Magnetic Wave in Au+ Au collisions at $\sqrt{s_{NN}} = 200$ GeV

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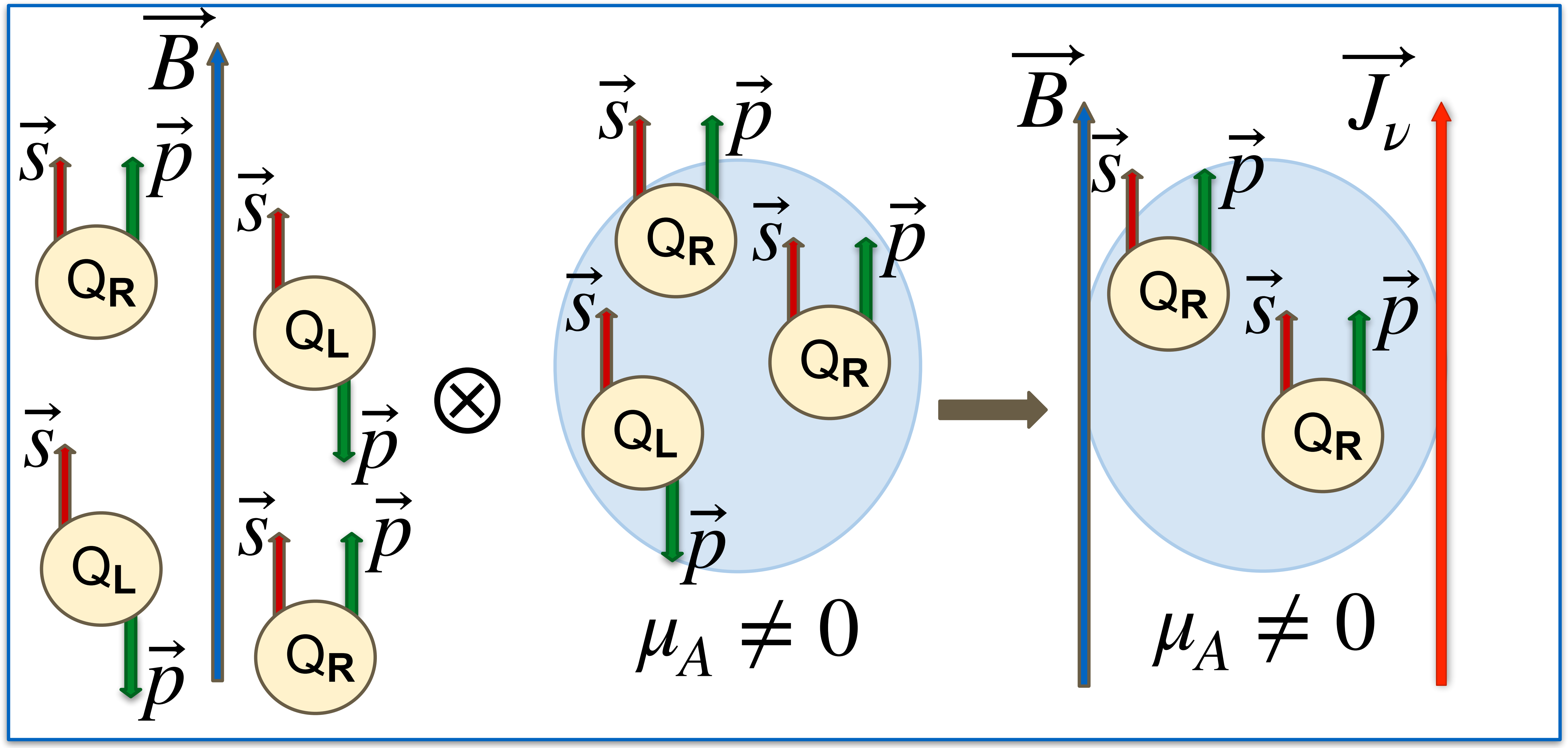
# Introduction

**CME** + **CSE** → **CMW**

**Chiral Magnetic Wave**

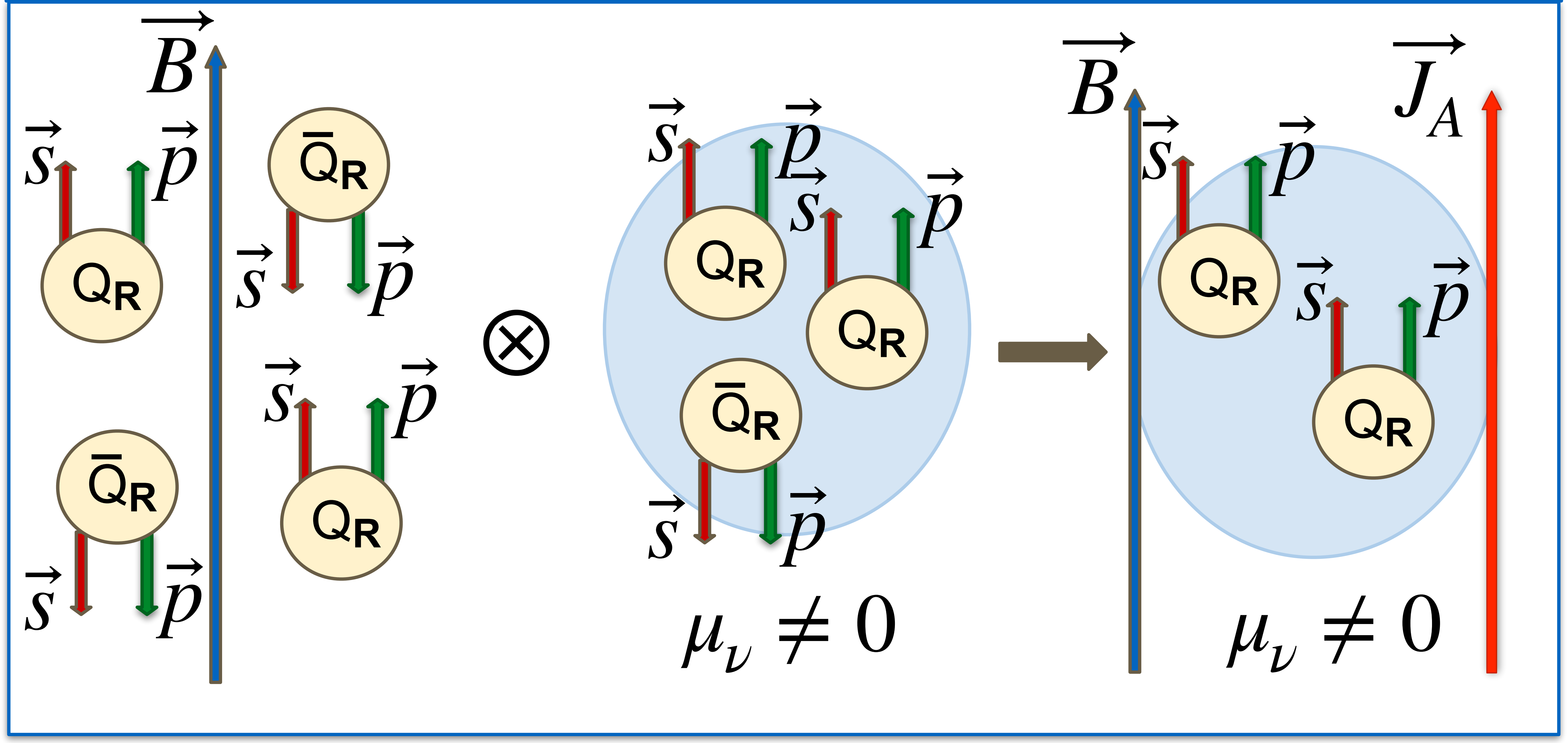
**Chiral Magnetic Effect (CME)**

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



**Chiral Separation Effect (CSE)**

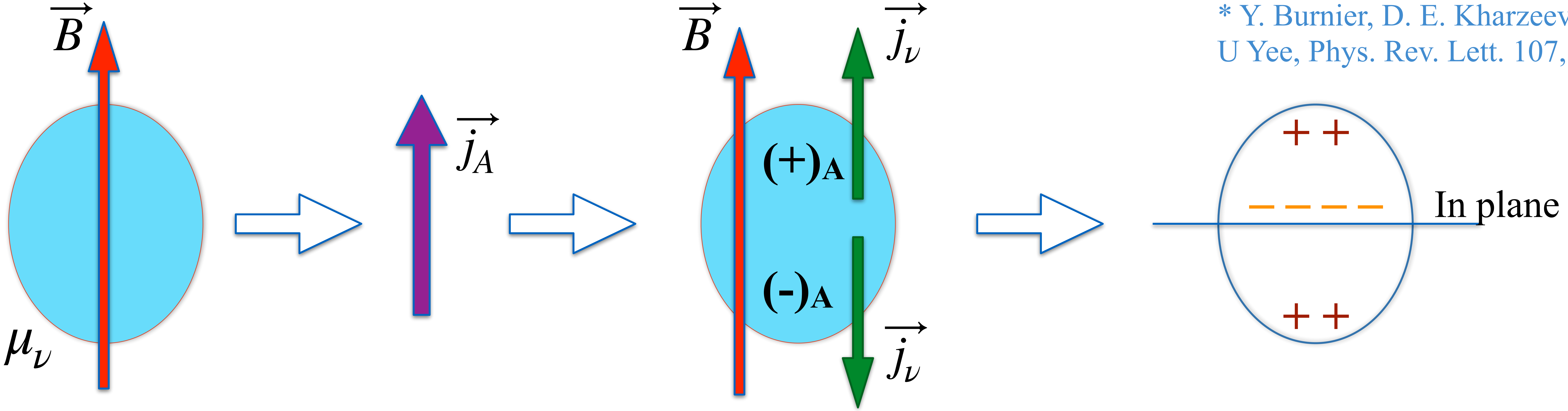
In presence of finite charge density, net axial current emerges along the axis of external B field.



# 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

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

net charge density

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

Charge asymmetry

☑ The slope parameter $r_2$ quantifies the CMW signal strength.

☑ CMW signal strength is proportional to the B field.

# Integral Correlator

☑ Another observable that can be used 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 :

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

* Phys. Rev. C 93 (2016) 044903

☑ 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.

# Anisotropic Flow Calculation

| Sub-Event | REF<br>$p_T < 2.0$ GeV/c | POI<br>$p_T < 0.5$ GeV/c |
|---|---|---|
| A | **$-1 < \eta < -0.3$** | **$0 < \eta < 1$** |
| B | **$0.3 < \eta < 1$** | **$-1 < \eta < 0$** |

☑ The two-particle Q-cumulant method :

$$Q_n = \sum_{j=1}^{M} e^{in\phi_j}, \qquad p_n = \sum_{j=1}^{m_p} e^{in\phi_j}$$

Reference Particles (REF) Particle of Interest (POI)

☑ The reference two particle cumulant is : $C_n\{2\} = \dfrac{Q_n^A \cdot Q_n^{B*}}{M_A\ M_B}$

here $Q_n^A$ and $Q_n^B$ are flow vectors calculated from reference particles for sub-event A and B. $M_A$ and $M_B$ are multiplicities of these two sub-events.

☑ The two-particle cumulant is calculated as $\langle 2' \rangle^A = \dfrac{p_n^A \cdot Q_n^{A*}}{m_p^A\ M_A}$, $\langle 2' \rangle^B = \dfrac{p_n^B \cdot Q_n^{B*}}{m_p^B\ M_B}$, $d_n\{2\} = \langle\langle 2' \rangle\rangle$

☑ With all charged hadrons (h) as REF, the anisotropic flow of $h^\pm$: $v_n^{h^\pm}\{2\} = d_n\{2; h^\pm - REF\}/\sqrt{C_n\{2\}}$

A. Bilandzic, R. Snellings and S. Voloshin, Phys. Rev. C 83, 044913 (2011)

# Trivial Term removal

☑ Including all charged particles (denoted as h) as REF, introduces a trivial term linear in $A_{ch}$.

$$\begin{aligned} d_n\{2;\pi^{\pm}h\} &= \frac{\sum_i q^{\pi^{\pm}}_{n,i} Q^*_{n,i}}{\sum_i m_i M_i} \\ &= \frac{1+A_{\rm ch}}{2}\frac{\sum_i q^{\pi^{\pm}}_{n,i} Q^*_{n+,i}}{\sum_i m_i N_{+,i}} + \frac{1-A_{\rm ch}}{2}\frac{\sum_i q^{\pi^{\pm}}_{n,i} Q^*_{n-,i}}{\sum_i m_i N_{-,i}} \\ &= \frac{d_n\{2;\pi^{\pm}h^{+}\}+d_n\{2;\pi^{\pm}h^{-}\}}{2} + \frac{d_n\{2;\pi^{\pm}h^{+}\}-d_n\{2;\pi^{\pm}h^{-}\}}{2}A_{\rm ch}, \end{aligned}$$

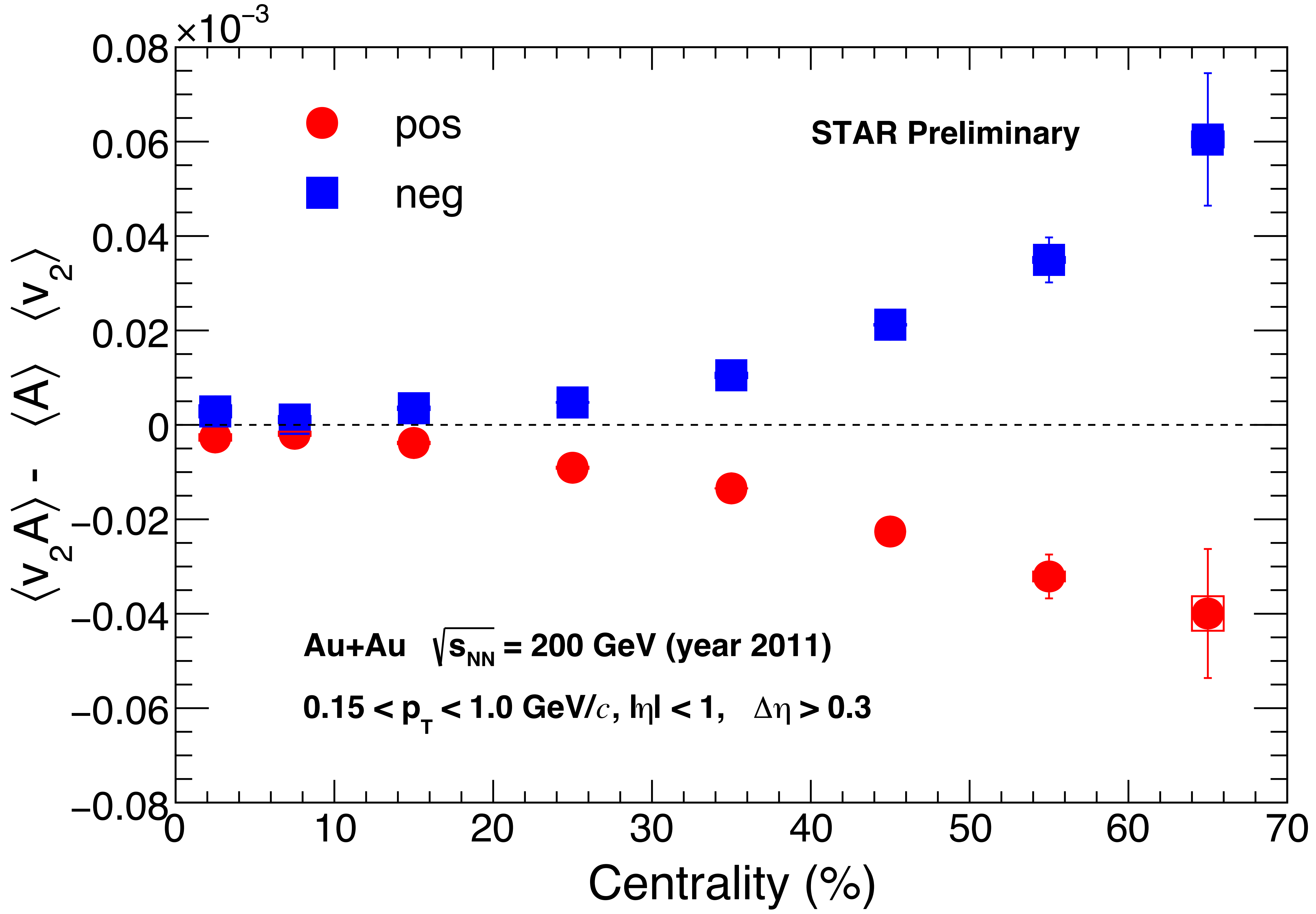
☑ To remove a trivial term linear in $A_{ch}$, mean of $v_2$ is calculated using positive and negative particles as reference in covariance calculation:

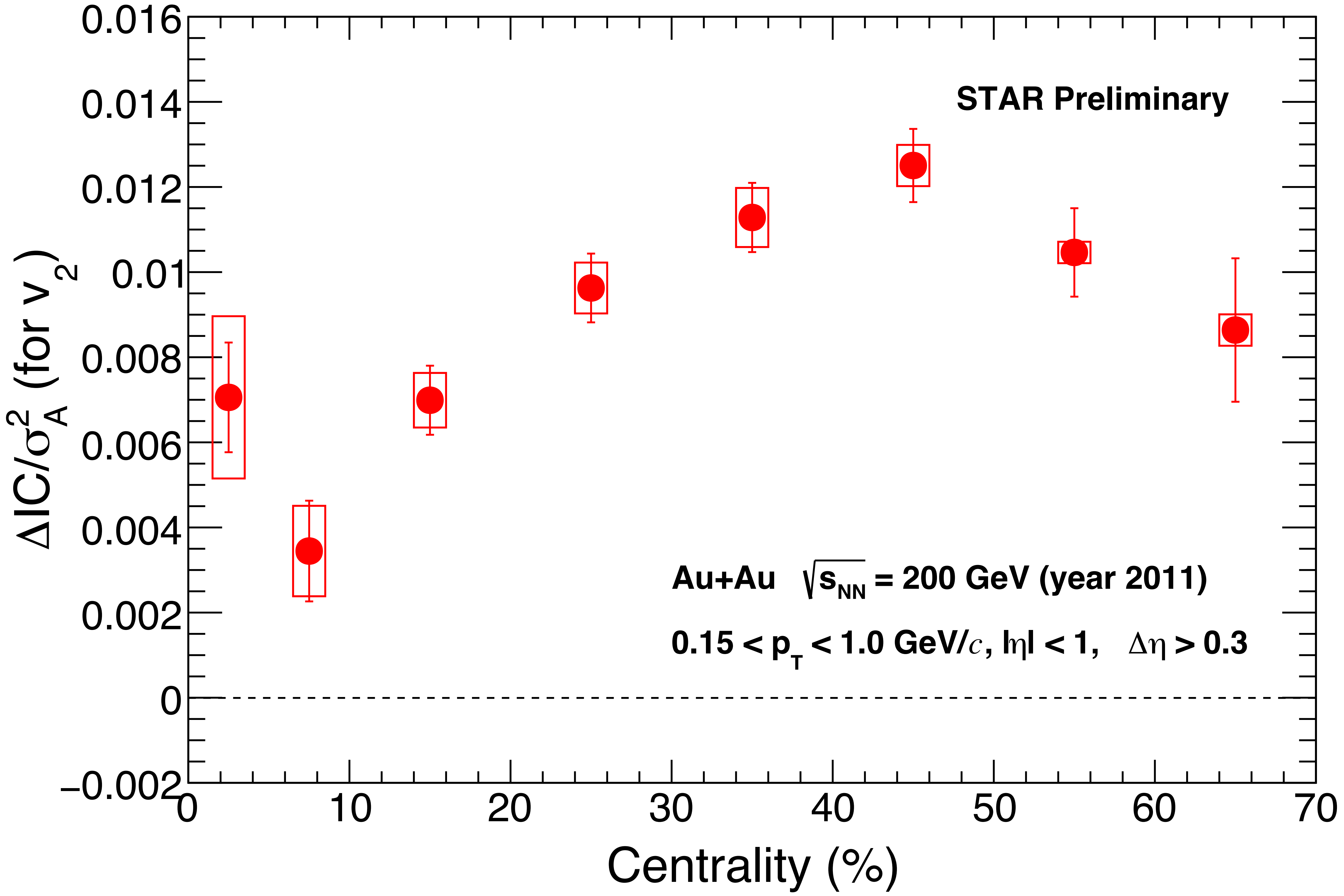
$$\frac{\langle A(d_2\{h^{\pm};h^{+}\}+d_2\{h^{\pm};h^{-}\})/2\rangle - \langle A\rangle\langle(d_2\{h^{\pm};h^{+}\}+d_2\{h^{\pm};h^{-}\})/2\rangle}{\sqrt{C_2}}$$

**POI** **REF**

$$C_2 = \langle\frac{d_2\{h^{\pm};h^{+}\}+d_2\{h^{\pm};h^{-}\}}{2}\rangle$$

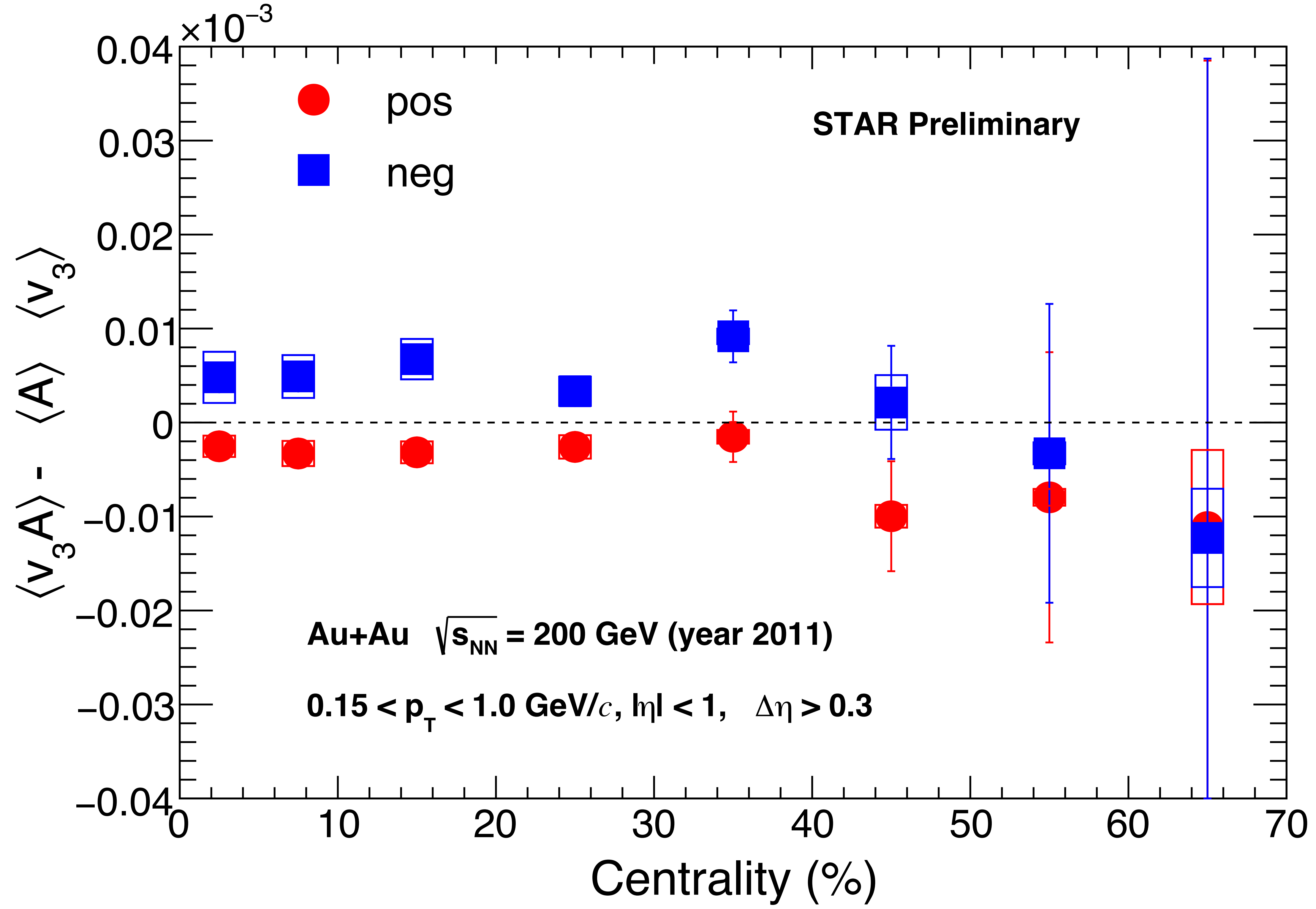
# Covariance of $v_2$ and $A_{ch}$ in Au+Au at 200 GeV

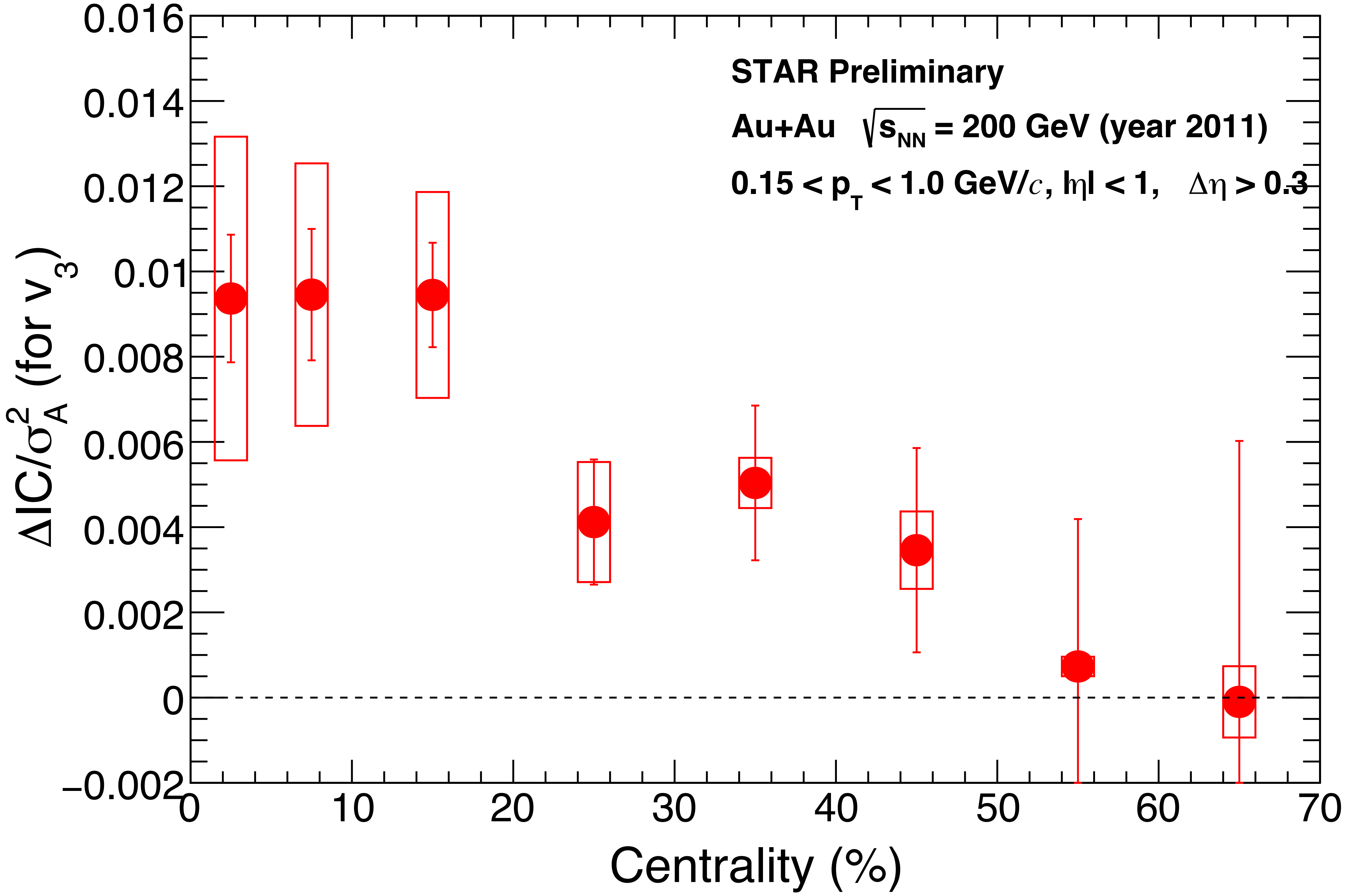




☑ Covariance of $v_2$ and $A_{ch}$ increases from central to peripheral collisions for both positive and negative particles. ΔIC also increases from central to peripheral collisions.

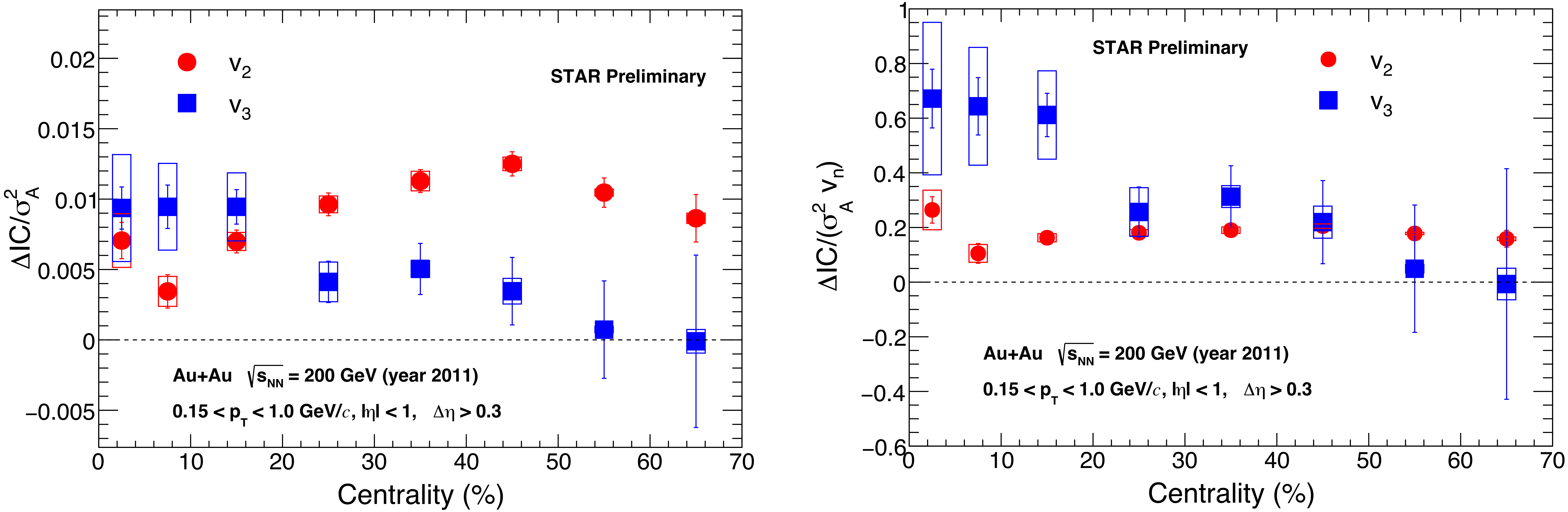
# Covariance of $v_3$ and $A_{ch}$





☑ 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.

# Summary

- ☑ Integral covariance of $v_2$ and $A_{ch}$ shows splitting for positive and negative charged particles which increases from central to peripheral collisions.

- ☑ Integral covariance of $v_3$ and $A_{ch}$ for positive and negative charged particle agrees within errors and is approximately independent of centrality.

- ☑ Normalized $v_2 - A_{ch}$ vs. centrality and $v_3 - A_{ch}$ vs. centrality agrees within errors for 20–70% centralities indicating absence of CMW in Au+Au collisions at 200 GeV.

## Outlook:

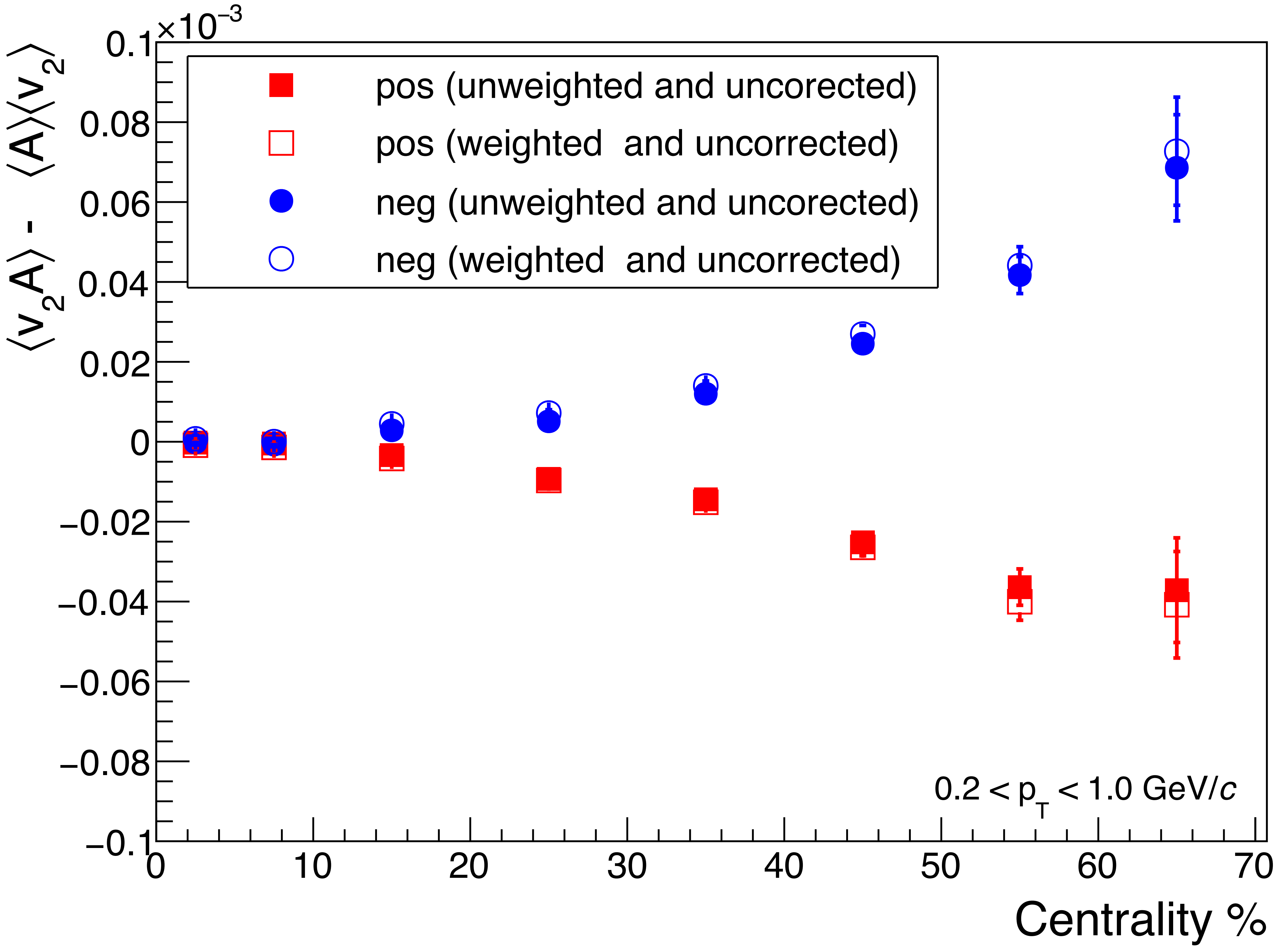
- ☑ Comparison of results with other collision systems (Ru+Ru and Zr+Zr) to study system size dependence.
- ☑ Analyzing Au+Au collisions at 200 GeV (year 2016) to finalize results for $f_{CMW}$ calculated using Event Shape Engineering (ESE) technique.

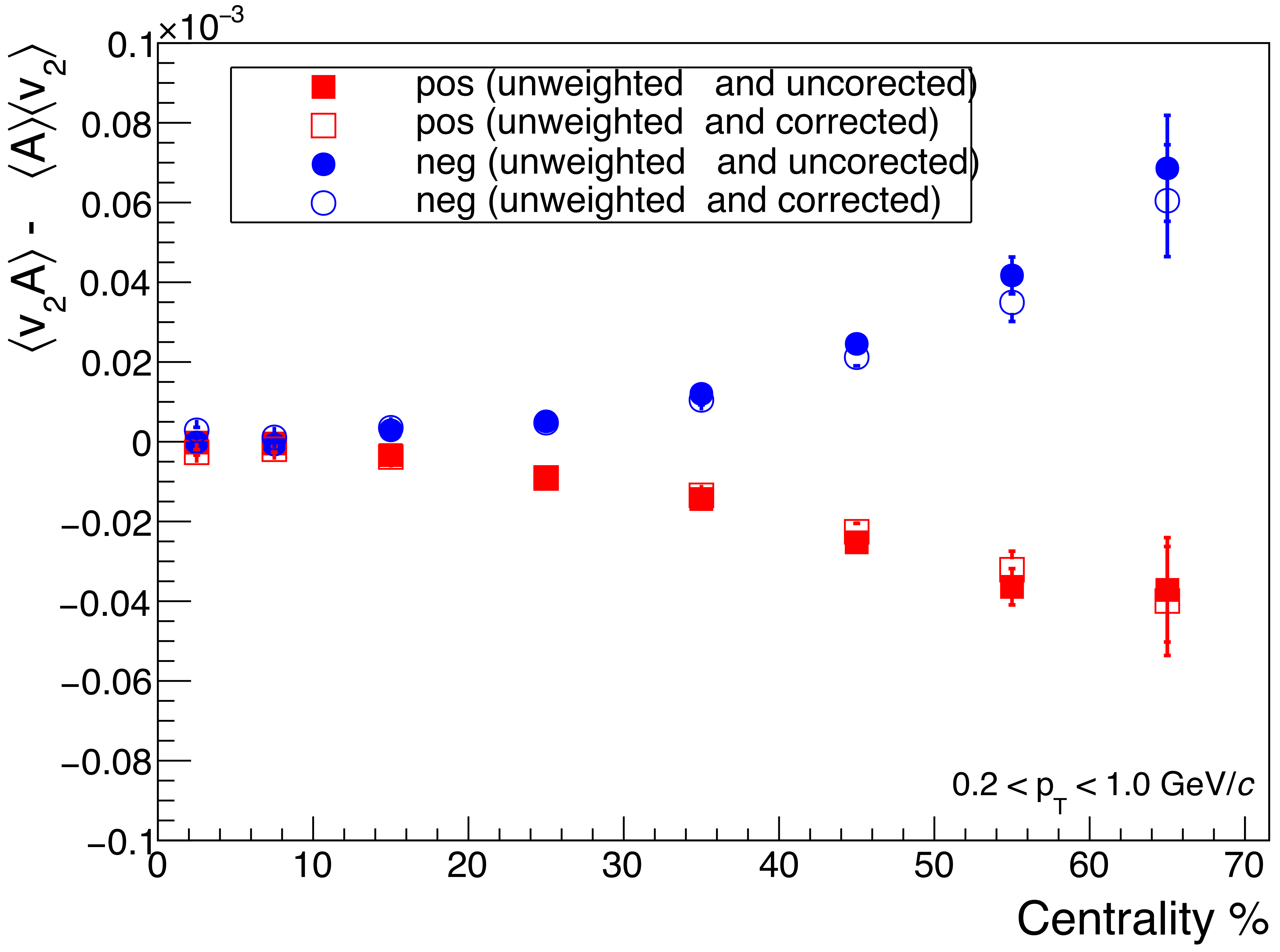
*Thank you for your kind attention!*

# BackUp

# Effect of weight and trivial term correction in covariance of $v_2$ and $A_{ch}$

Weighted: After applying $\eta$-$\phi$ weight
Corrected: After removing trivial term



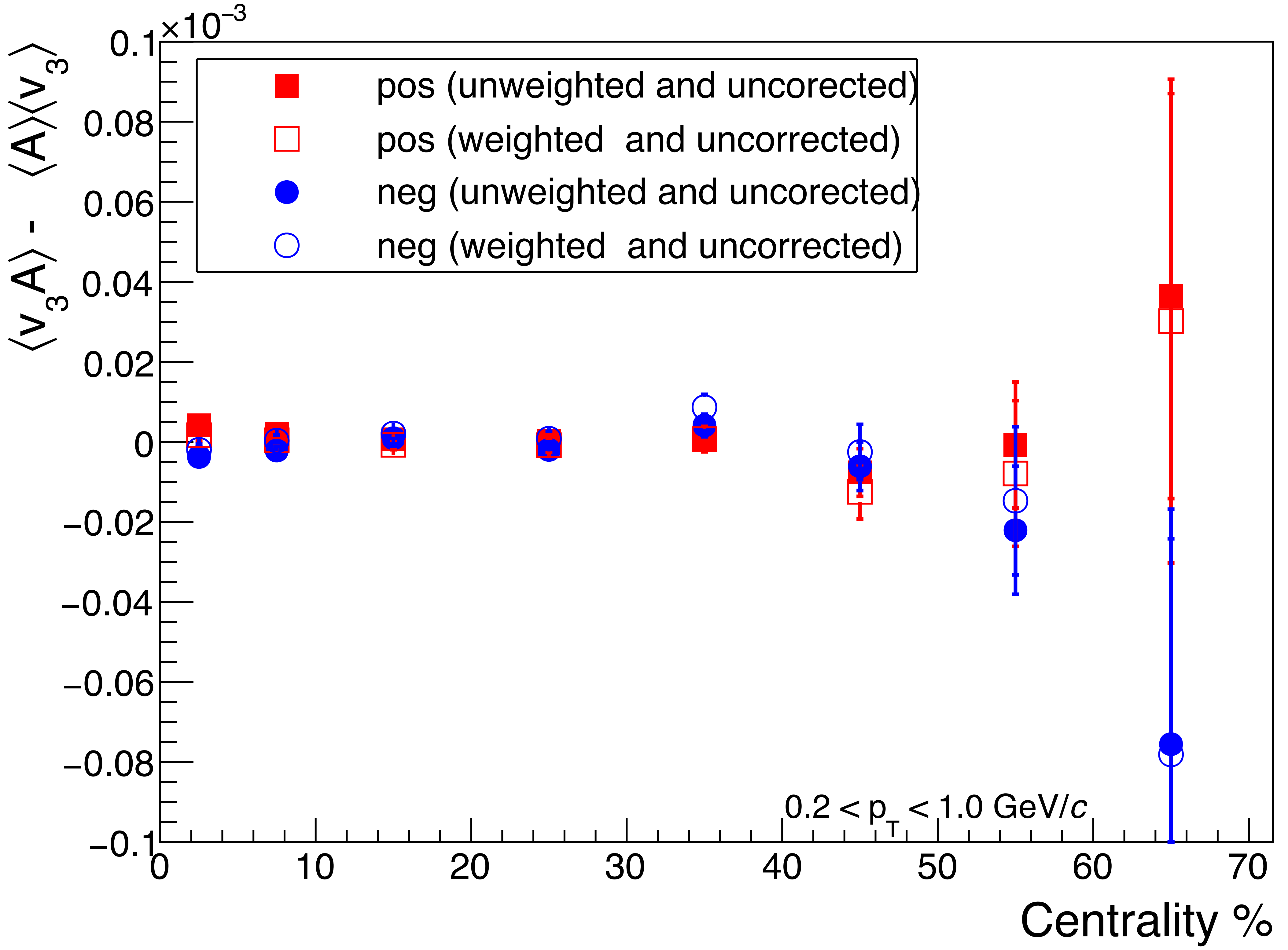


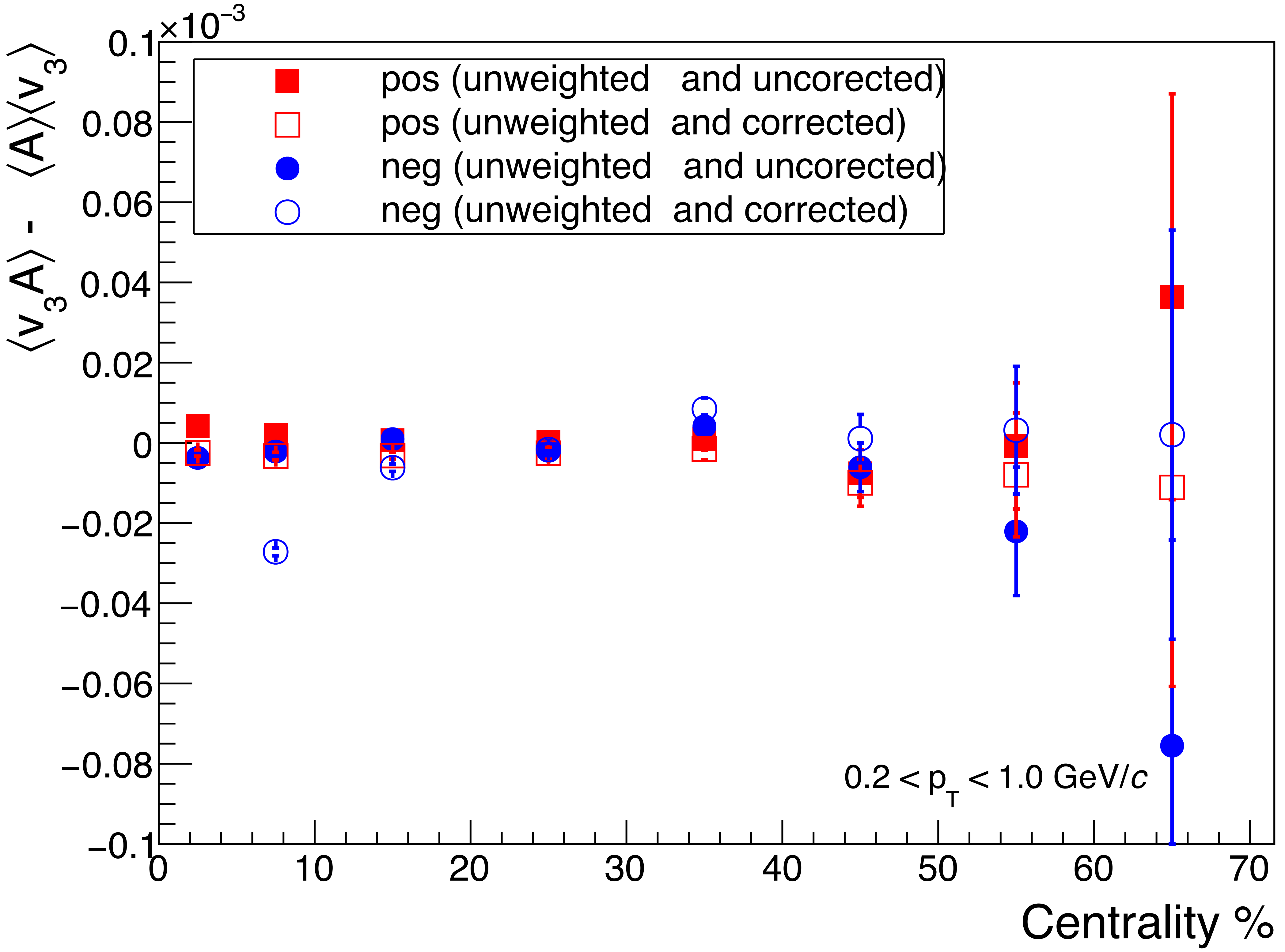
- ☑ Slight increase in covariance values after applying $\eta$-$\phi$ weight in $v_2$.
- ☑ Slight decrease in covariance values after applying trivial term correction in $v_2$.

# Effect of weight and trivial term correction in covariance of $v_3$ and $A_{ch}$

Weighted: After applying $\eta$-$\phi$ weight

Corrected: After removing trivial term



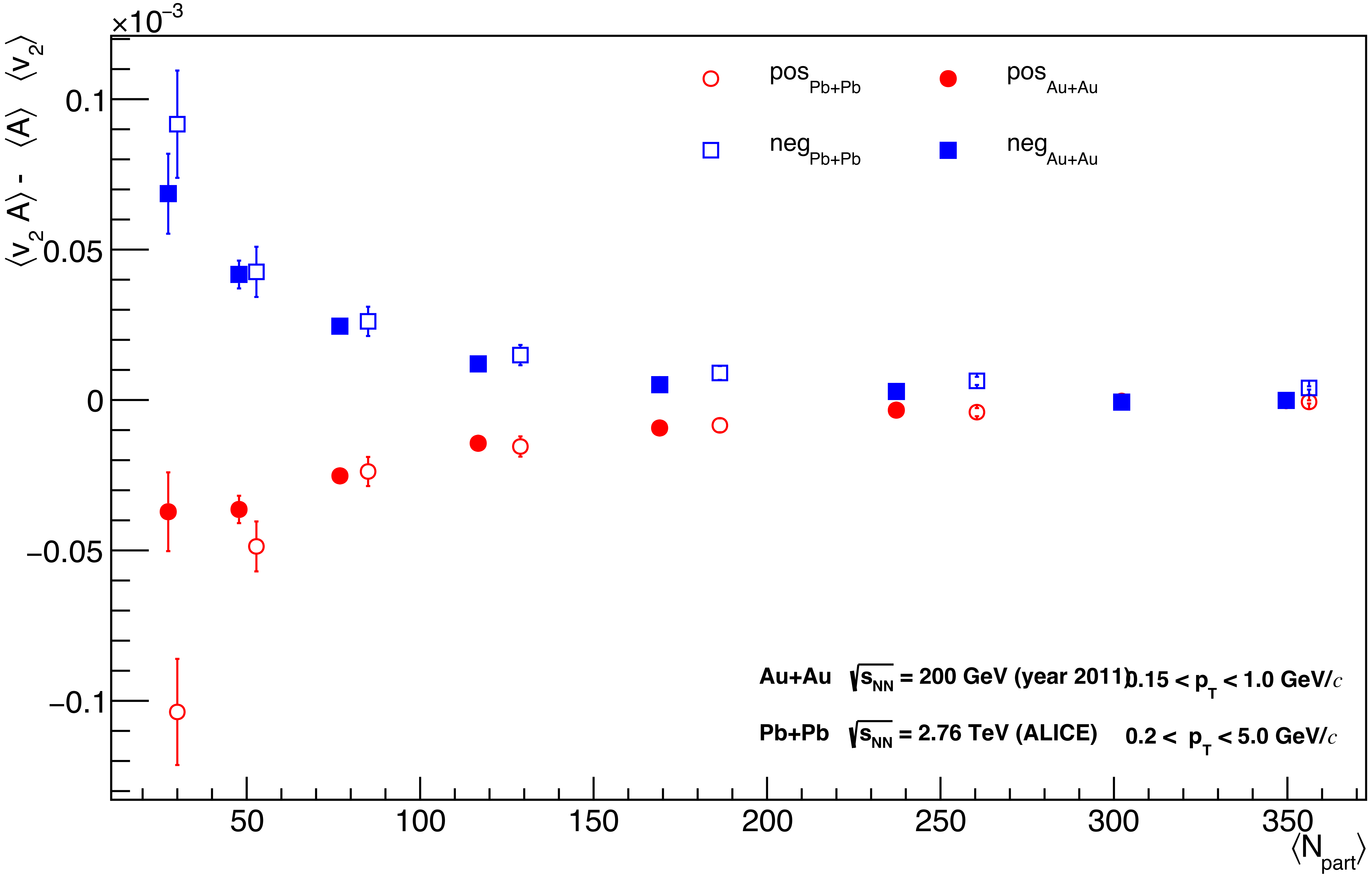


- ☑ Covariance values remain similar after applying $\eta$-$\phi$ weight in $v_3$.

- ☑ Covariance values remain similar after applying trivial term correction in $v_3$.

# Covariance vs. <$N_{part}$>

J. Adam et al.∗. PHYSICAL REVIEW C **93**, 044903 (2016)



☑ Covariance values for Au+Au collisions agree well with those for Pb+Pb collisions within errors, except for the 60-70% centrality range.