# Experimental Searches for Chirality and Vorticity Effects in Heavy Ion Collisions

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**&**

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# OUTLINE

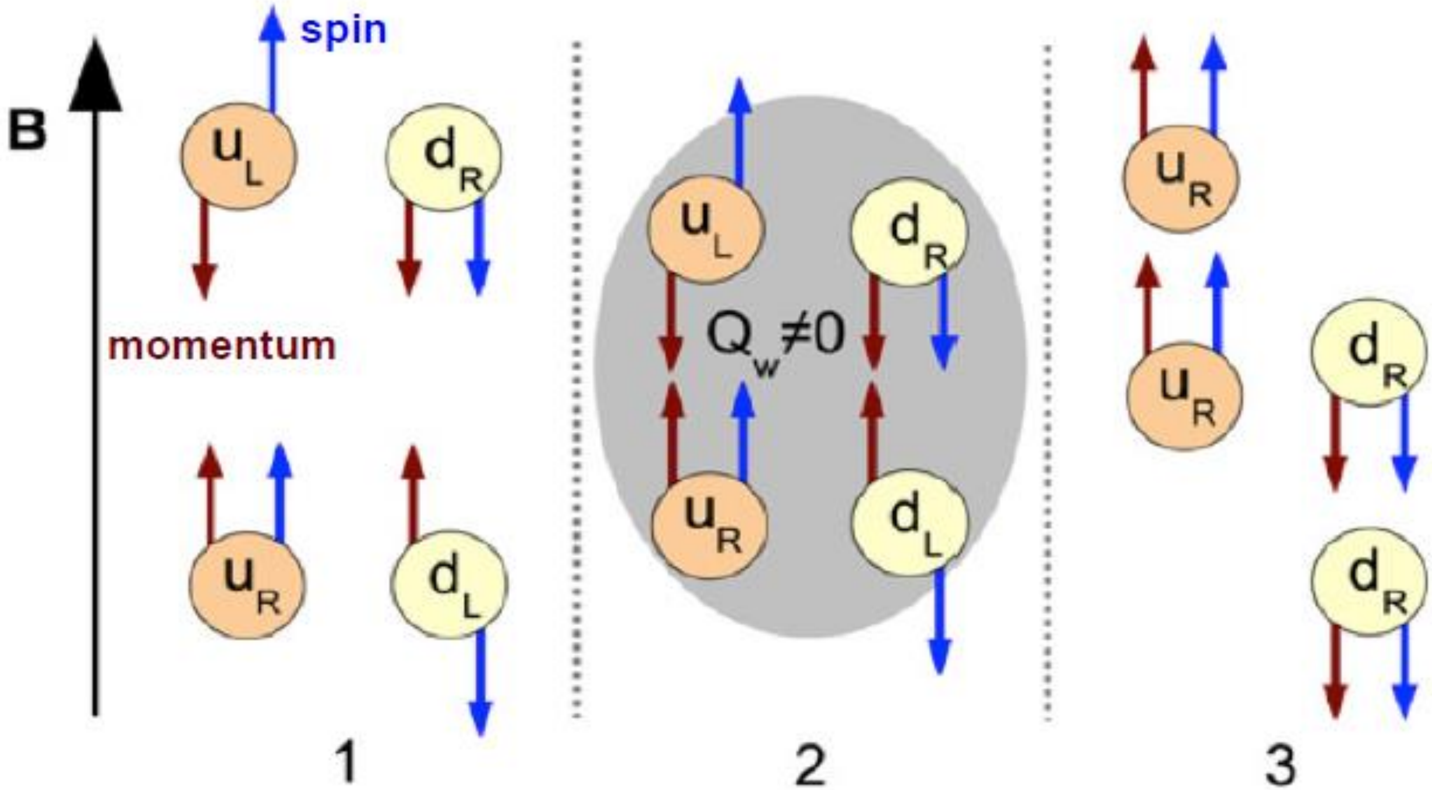
1) **CME and Charge Separation Across the RP**

2) **CMW and Background Flow Effect**

3) **Search for Chiral Vortical Effect**

4) **Future Perspective**

# Chiral Magnetic Effect → Charge Separation



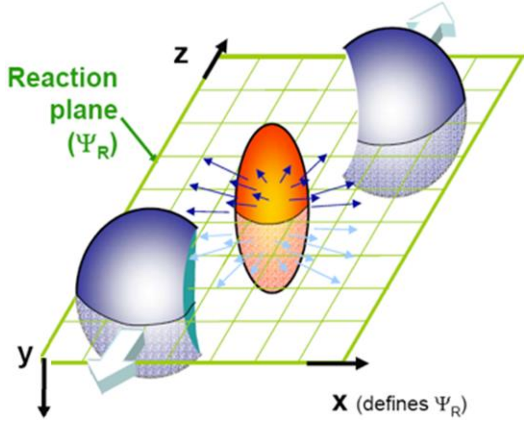

Chiral Magnetic Effect **(CME):** finite chiral charge density induces an electric current along external magnetic field.

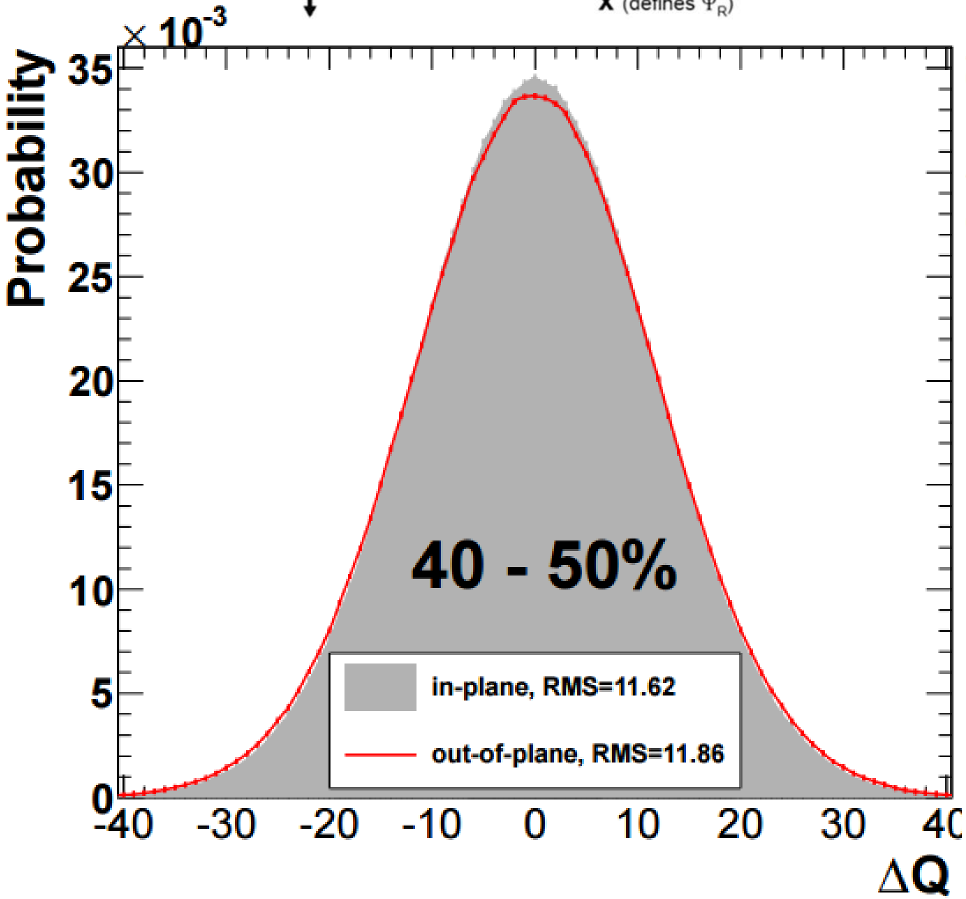
$$j_V = \frac{N_c e}{2\pi^2}\mu_A B$$ ➔ electric charge separation along *B* field

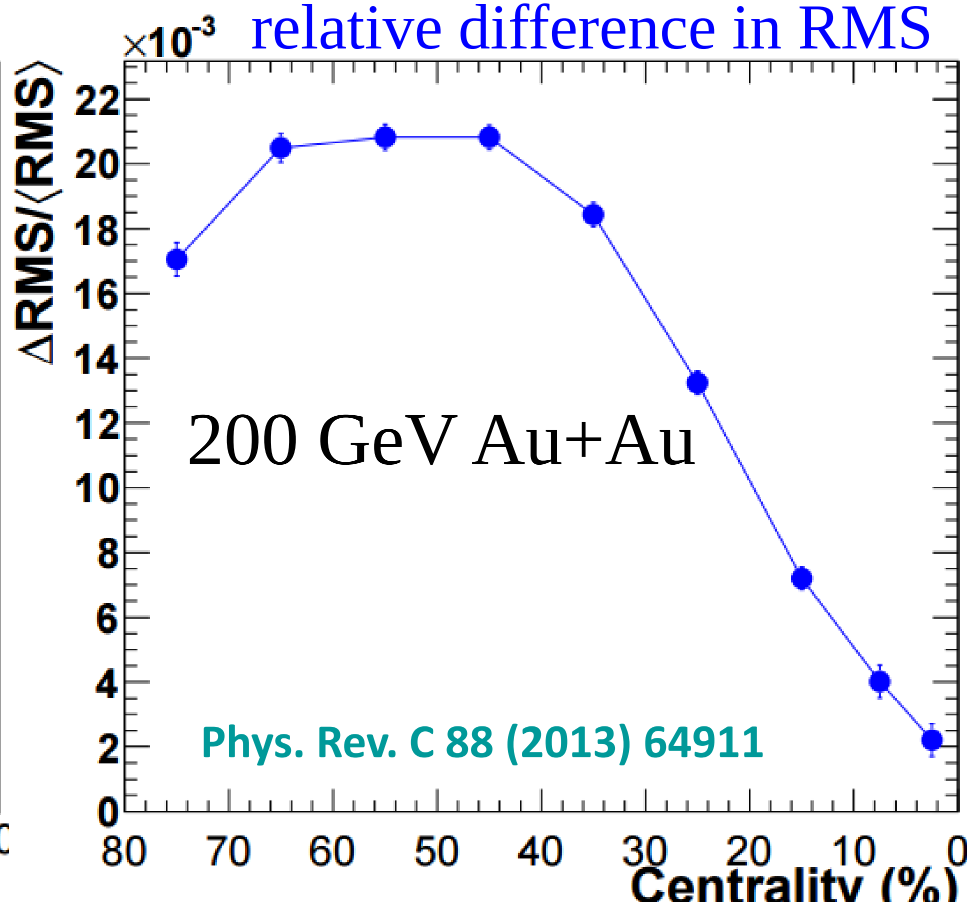
D. E. Kharzeev, L. D. McLerran, and H. J. Warringa, Nuclear Physics A 803, 227 (2008)

# Charge Separation Out-of vs. In RP

There should be more out-of-plane charge fluctuation than in-plane.
*Indeed, we can visualize this effect, which is on percent level!*

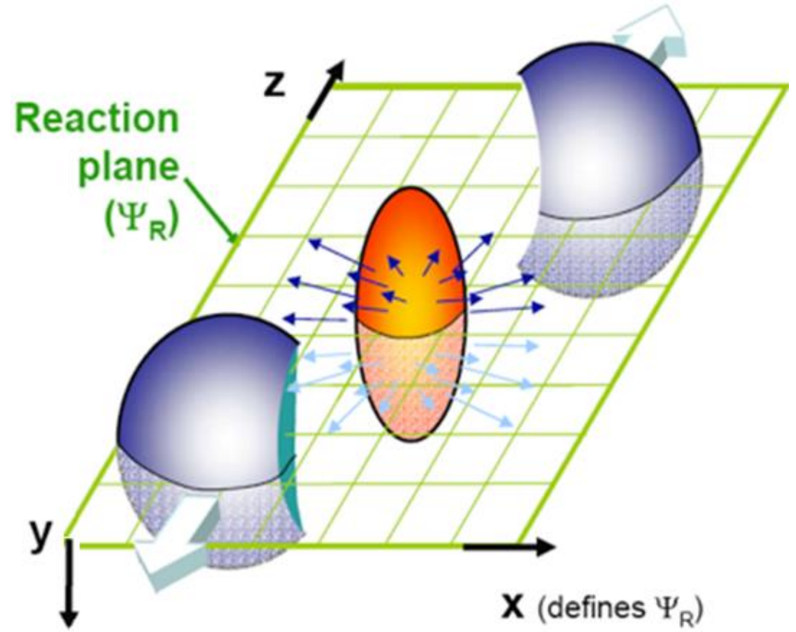


# γ correlator

**A quantitative measure for extra charge fluctuation.**




$$\gamma = \langle \cos(\phi_\alpha + \phi_\beta - 2\psi_{RP}) \rangle$$

$$= < \cos()\cos() > - < \sin()\sin() >$$

$$\cong \left[ \langle v_{1,\alpha} v_{1,\beta} \rangle + B_{in} \right] - \left[ \langle a_\alpha a_\beta \rangle + B_{out} \right]$$

S. Voloshin, PRC 70 (2004) 057901

*Directed flow*

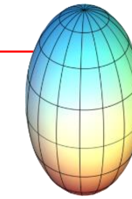
*background effects*

*P-even quantity: sensitive to charge separation fluctuation*

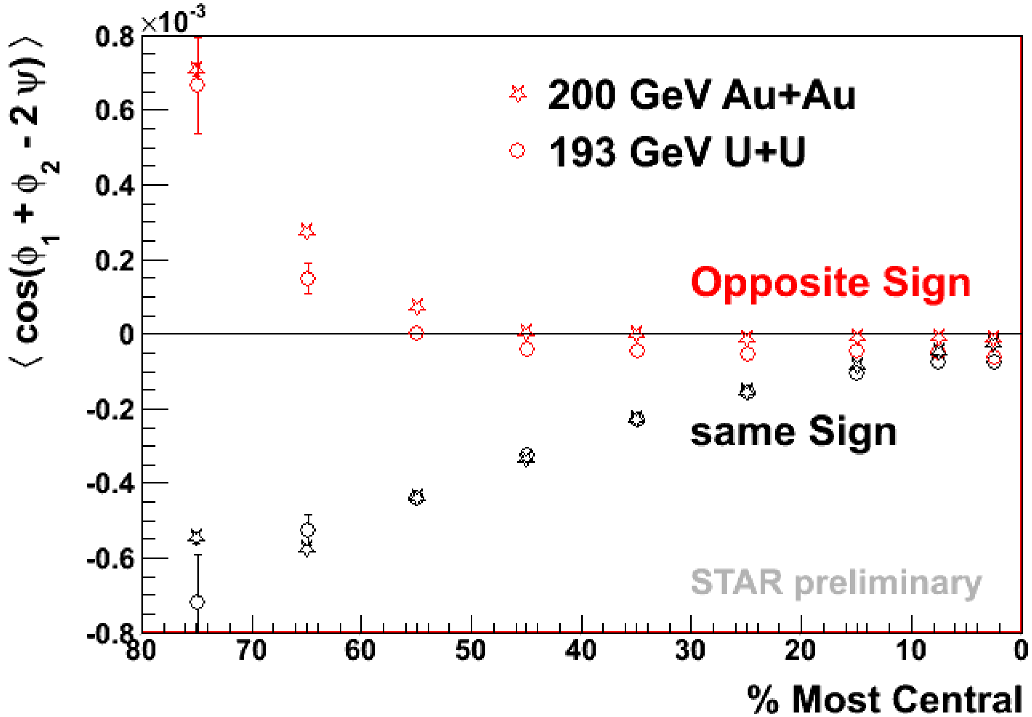
**Background does not cancel !**

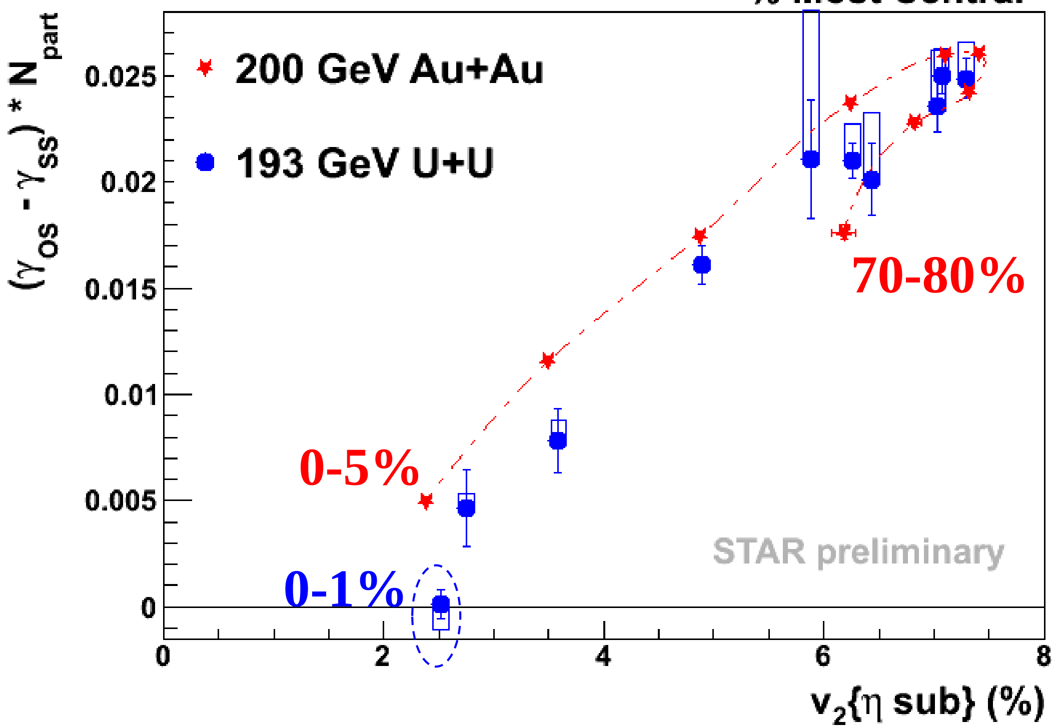
**OS-SS subtraction !**

# Deformed nuclei: U+U



- Similar signals in U+U
- Use $\gamma_{OS}$-$\gamma_{SS}$ to quantify the signal
- $N_{part}$ accounts for dilution effects



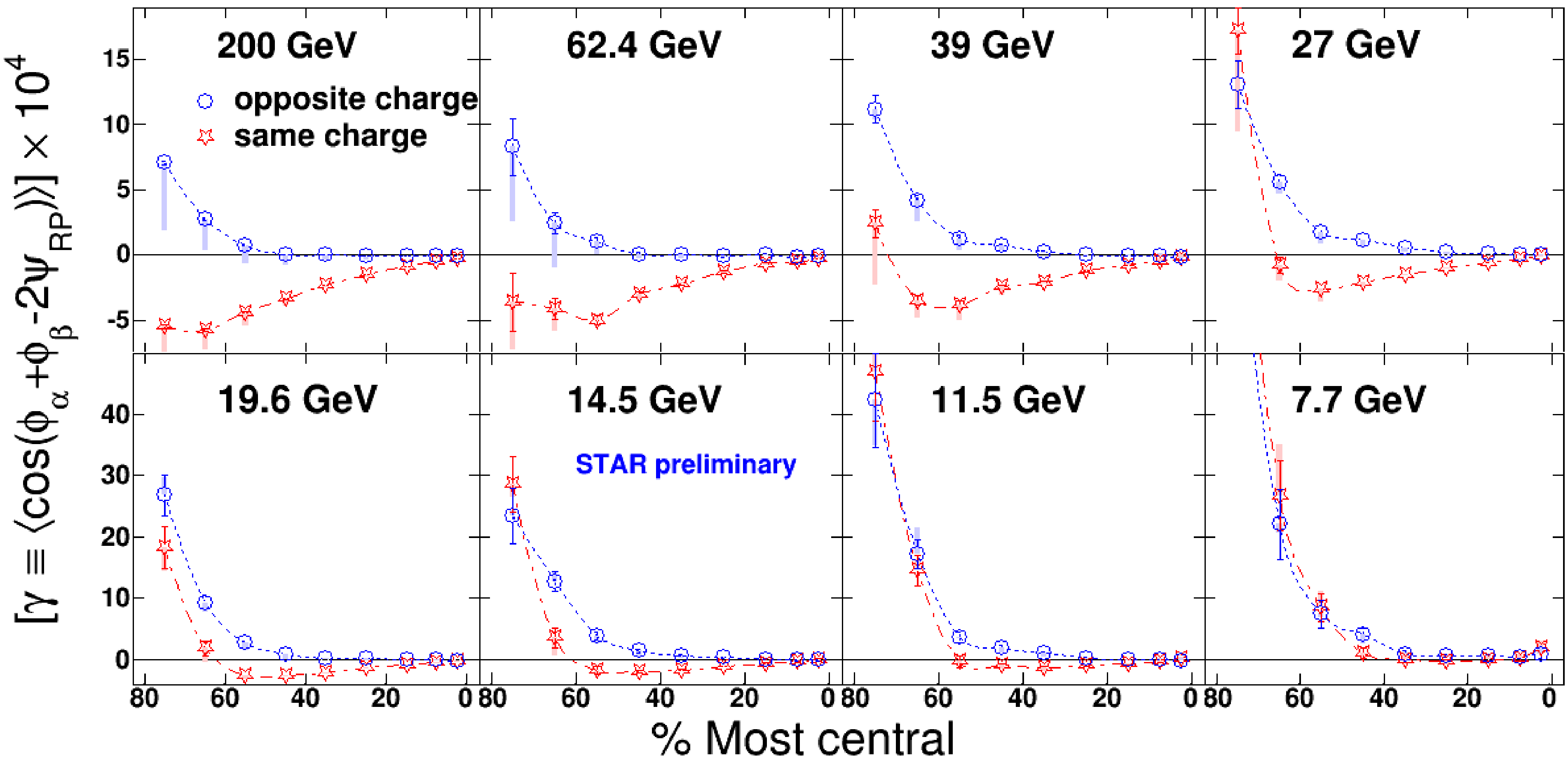

- A dedicated trigger for events with 0-1% spectator neutrons
- With magnetic field suppressed, the charge separation signal (mostly background) disappears, while $v_2$ is still ~2.5%

Extrapolate to intermediate centrality?

**Isobar collisions may work better.**

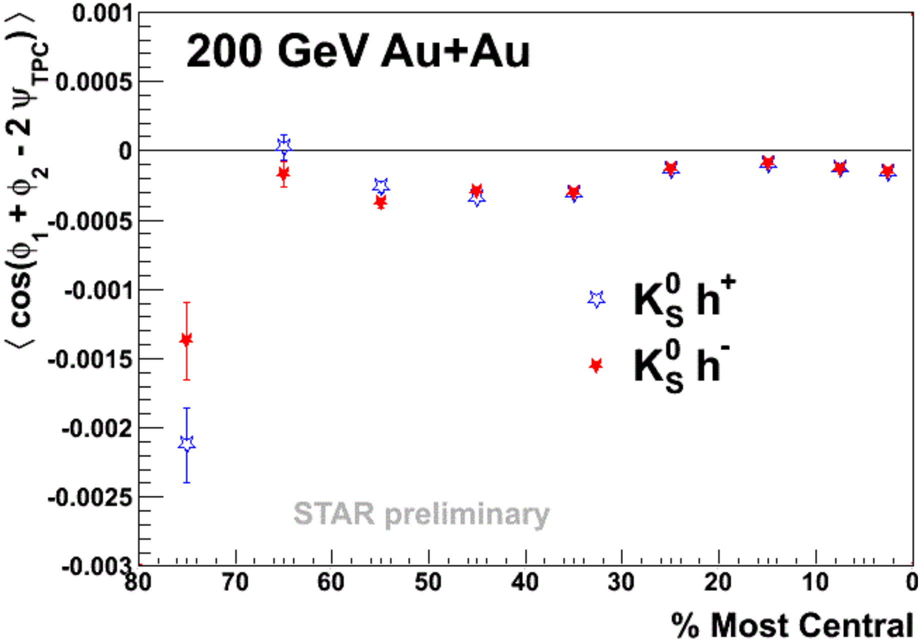
# Beam Energy Scan

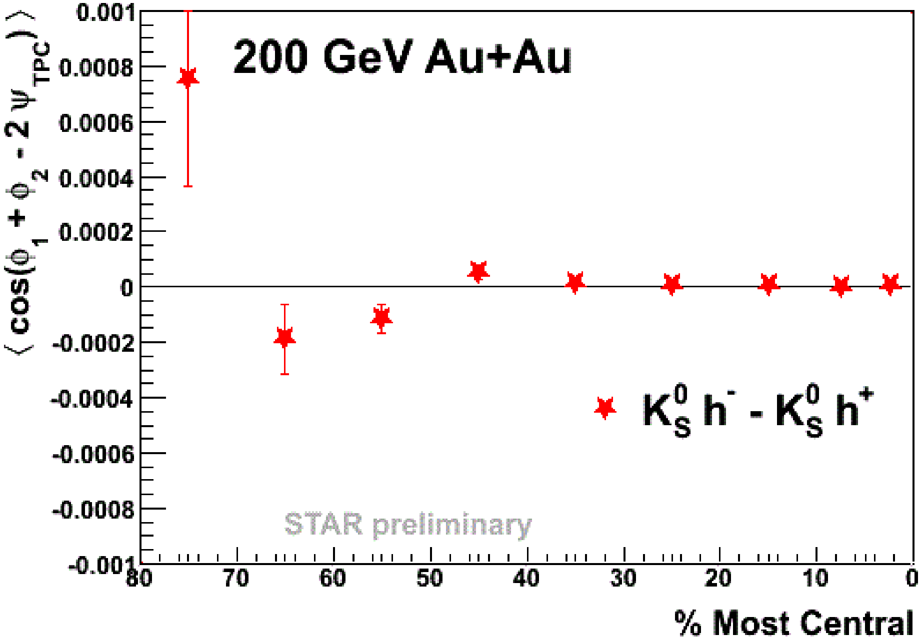
Phys. Rev. Lett 113 (2014) 052302




**At lower beam energies, charge separation starts to diminish. Note $v_2$ is finite for charged hadrons at 7.7 GeV beam energy!**

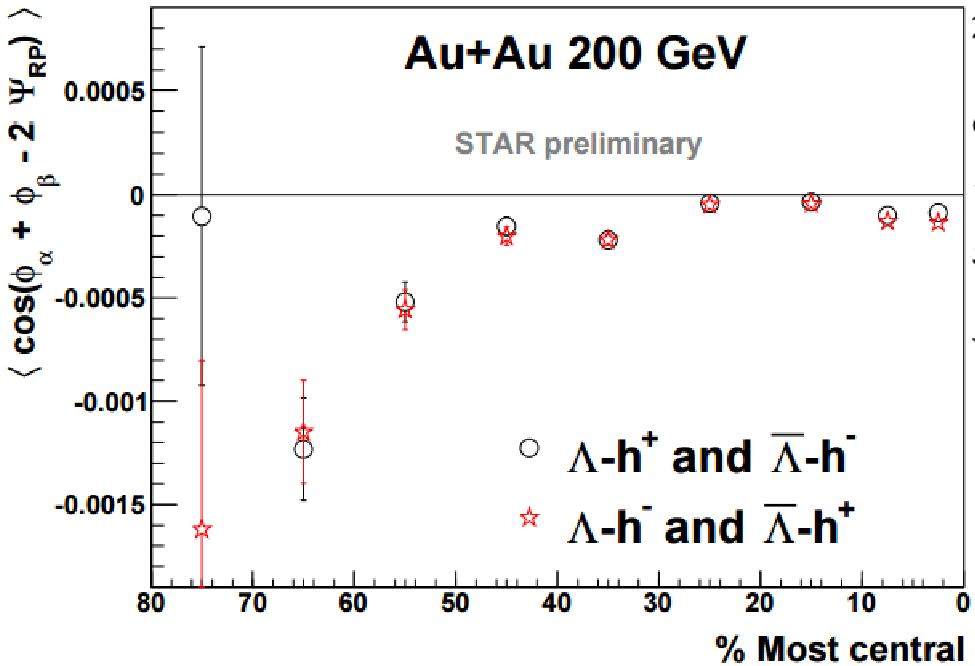
# $K^0_S$-hadron correlation

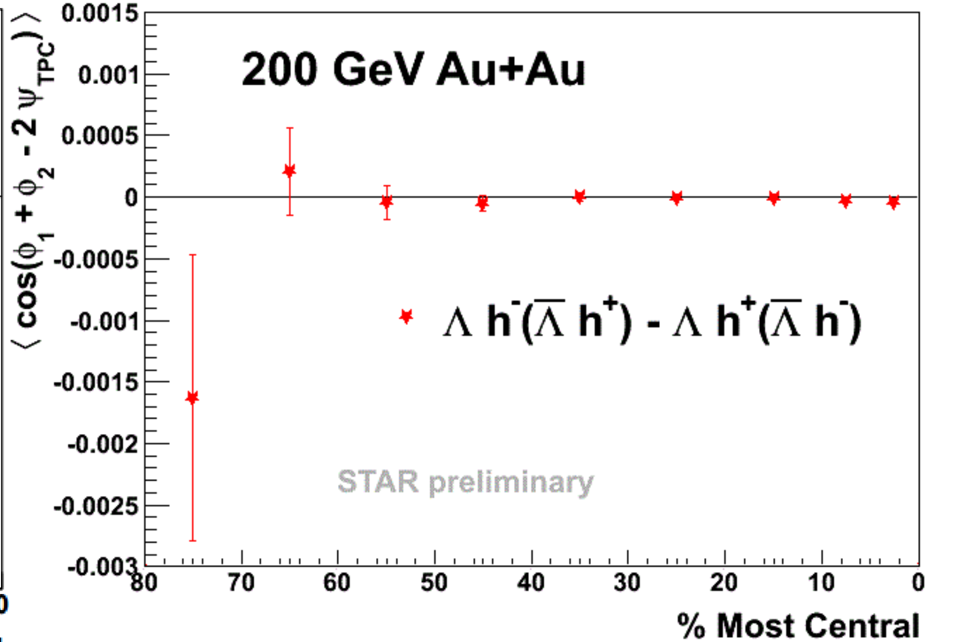



- Correlations of $K^0_S$-$h^-$ and $K^0_S$-$h^+$ consistent with each other within current statistical error: no obvious charge-dependent separation

# Λ-hadron correlation



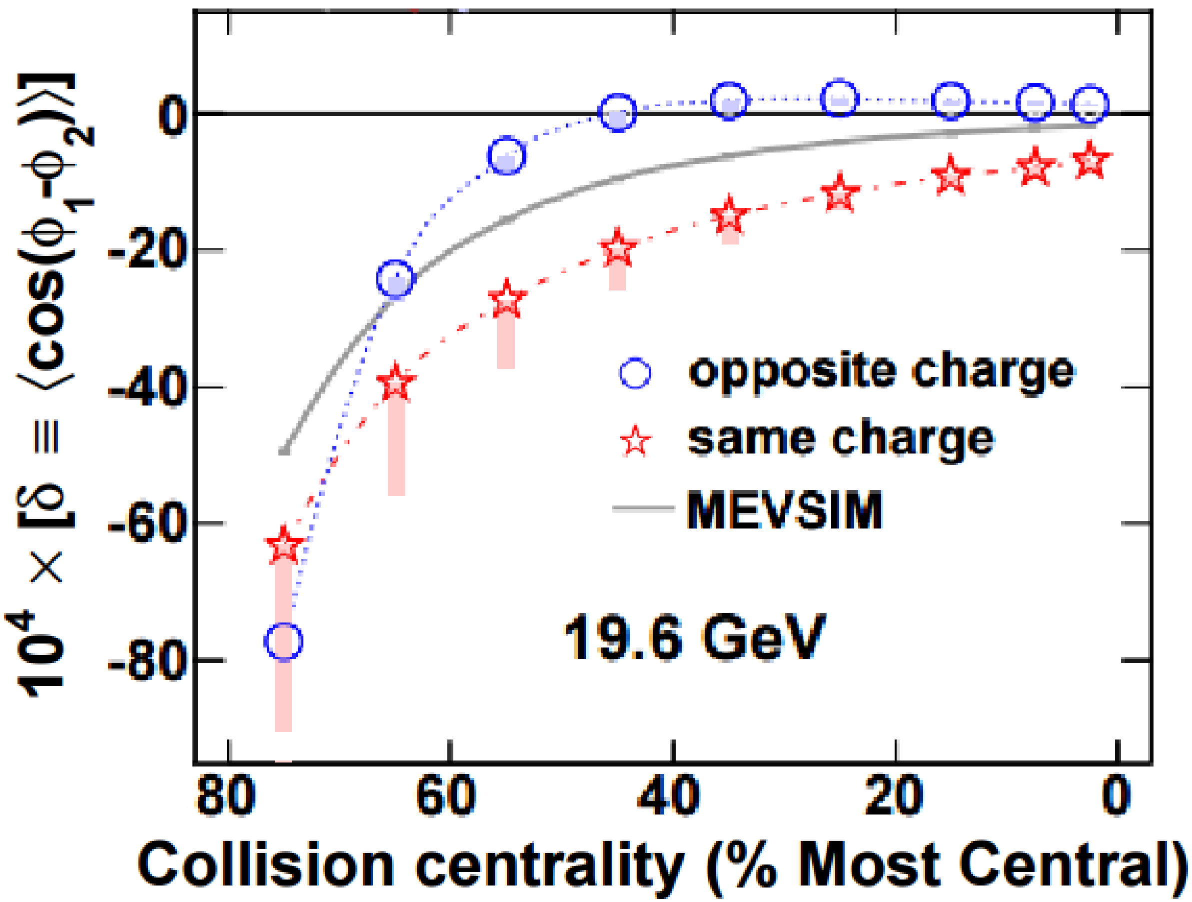

- Correlations of $\Lambda$-$h^{\pm}$ also show no charge-dependent separation (protons and antiprotons have been excluded from $h^{\pm}$)

- Separation observed for $h^{\pm}$-$h^{\pm}$ is due to electric charge

- Need efficiency correction (Λ reconstruction favors high pT)

# H Measure

Phys. Rev. Lett 113 (2014) 052302




- Against CME expectation, $\delta_{OS} > \delta_{SS}$
- Indicate overwhelming background, larger than any possible CME effect.
- Try combining information from γ and δ to retrieve the CME contribution, *H*

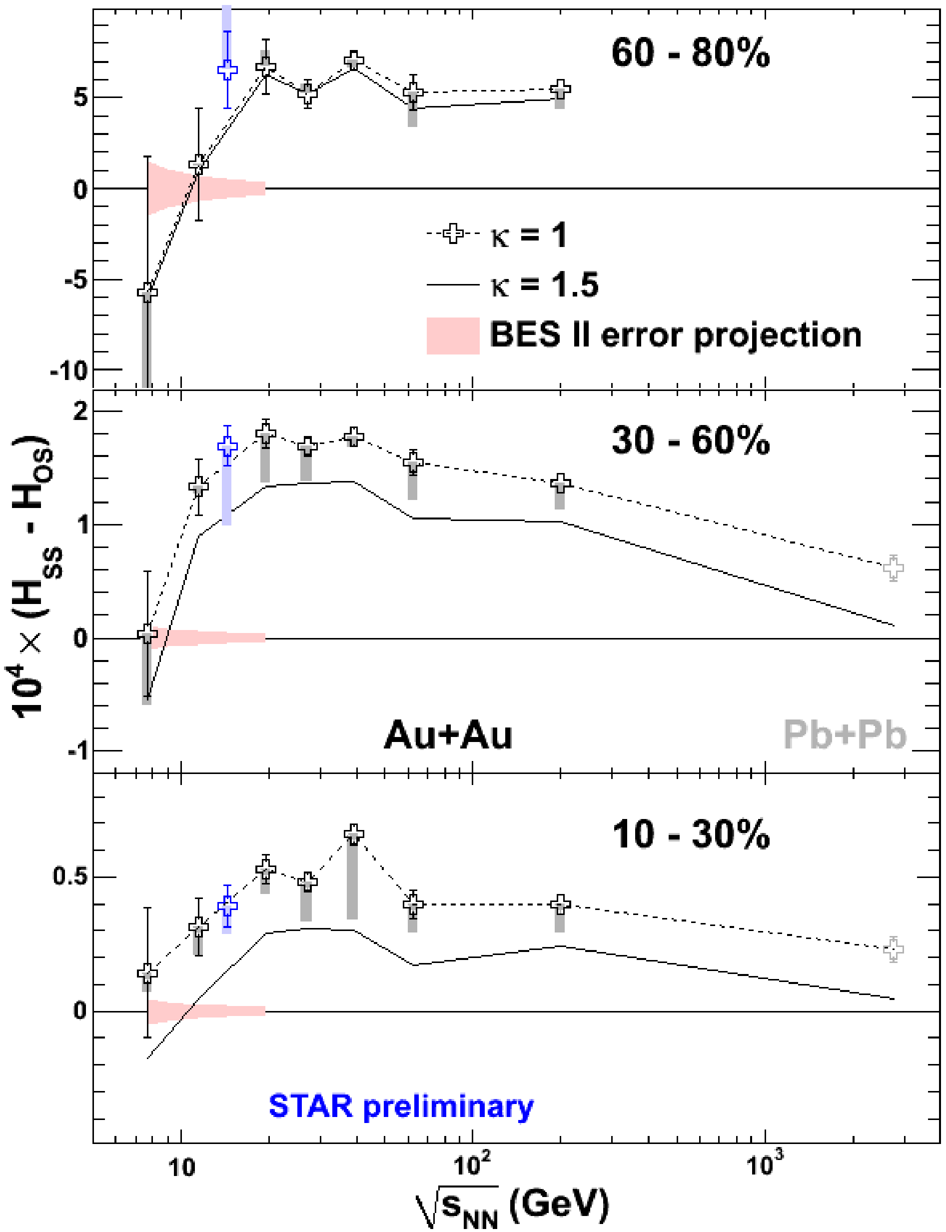
$$\gamma \equiv \langle\cos(\phi_1 + \phi_2 - 2\Psi_{RP})\rangle = \kappa v_2 F - H$$

$$\delta \equiv \langle\cos(\phi_1 - \phi_2)\rangle = F + H,$$

A. Bzdak, V. Koch and J. Liao, Lect. Notes Phys. 871, 503 (2013).

# Difficult to Remove Charge Separation

Phys. Rev. Lett 113 (2014) 052302




$$H^{\kappa} = (\kappa v_2 \delta - \gamma)/(1 + \kappa v_2)$$

A. Bzdak, V. Koch and J. Liao, Lect. Notes Phys. 871, 503 (2013).

- $\kappa \approx 2 - v_{2,F}/v_{2,\Omega} \approx 1.2$:
F and Ω denote full phase space and finite detector acceptance, respectively

- CME signal ($\Delta H$) decreases to 0 from 19.6 to 7.7 GeV

- The decomposition of $\gamma$ into F and H is not unique

# Summary on $\gamma$ Measure

**Sensitive to charge separation w.r.t RP**

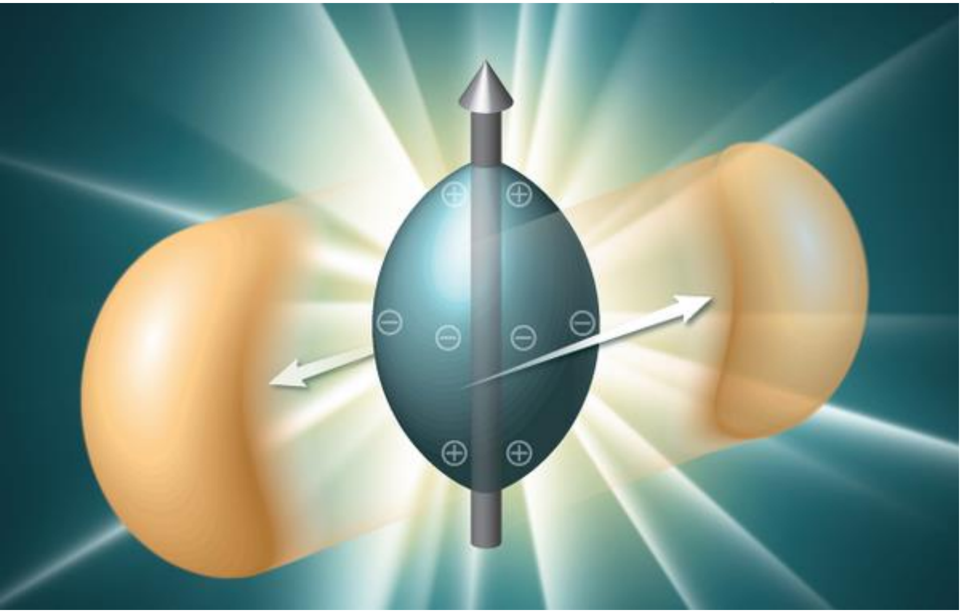
- comfirmed with different EP types (1st- and 2nd-order)
- observed in Au+Au, Cu+Cu, Pb+Pb and U+U collisions
- persist from 19.6 GeV to 2.76 TeV
- robust when suppressing HBT+Coulomb (not shown here)

**The measured $\gamma$ magnitude cannot be entirely due to $v_2$ induced background (e.g. Pratt model)**

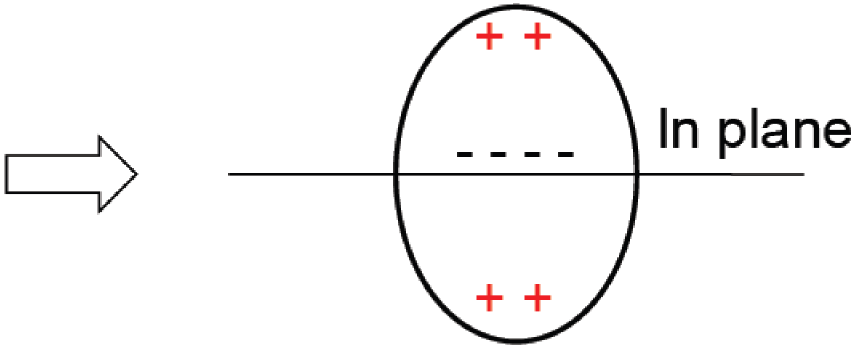
**$\gamma$ seems to disappear when**

- one of $h^{\pm}$ is replaced with a neutral strange particle
- the collision energy is below ~7.7 GeV
- in most central collisions (B field small and $v_2$ finite)

# Chiral Magnetic Wave Observable



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




quadrupole moment

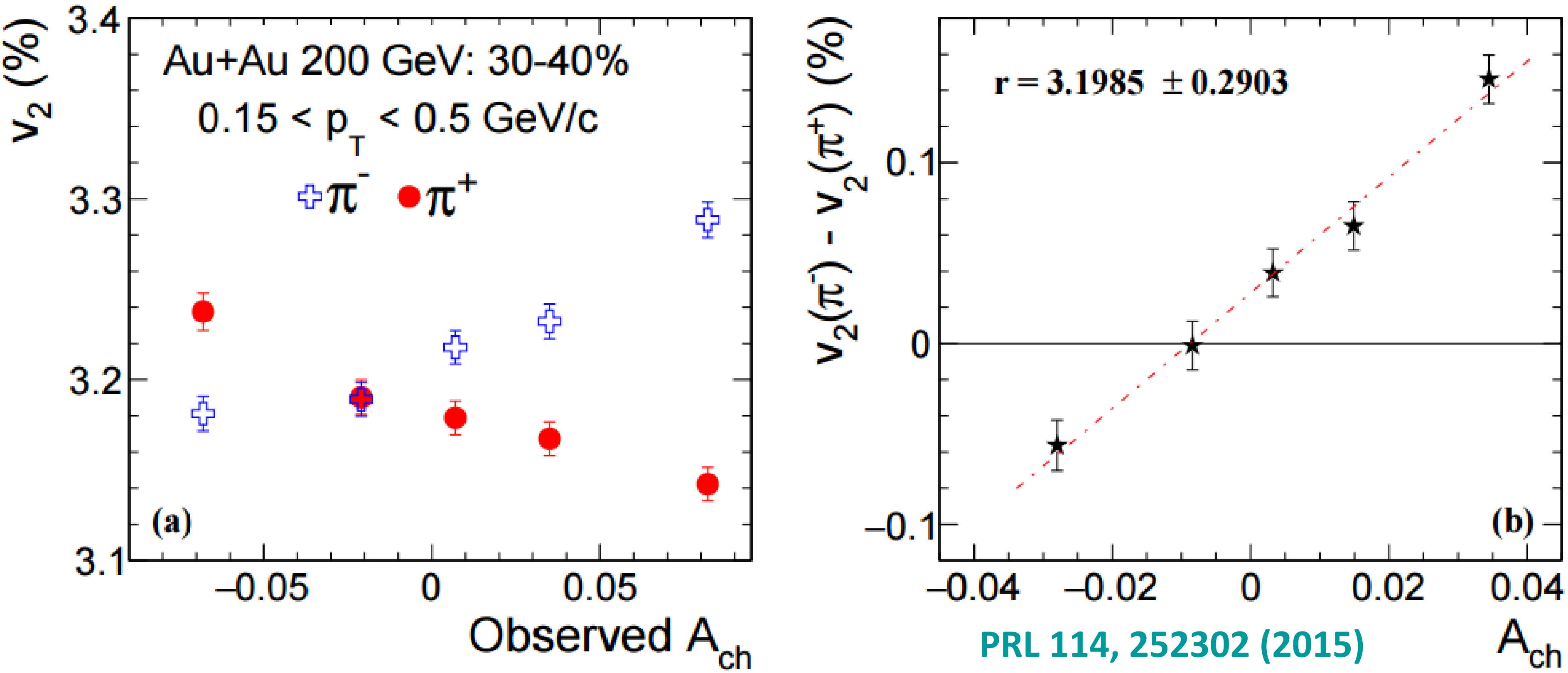
Formation of electric quadrupole: $v_2^{\pm} = v_2^{\text{base}\pm} \mp \left( \frac{q_e}{\bar{\rho}_e} \right) A_{\text{ch}}$ ,

net charge density

where charge asymmetry is defined as $A_{\text{ch}} = \frac{N^+ - N^-}{N^+ + N^-}$ .

Then $\pi^-$ $v_2$ should have a positive slope as a function of $A_{\text{ch}}$,
and $\pi^+$ $v_2$ should have a negative slope with the same magnitude.

# $v_2$ vs $A_{ch}$




PRL 114, 252302 (2015)

- Clear $A_{ch}$ dependence of $v_2\{2\}$

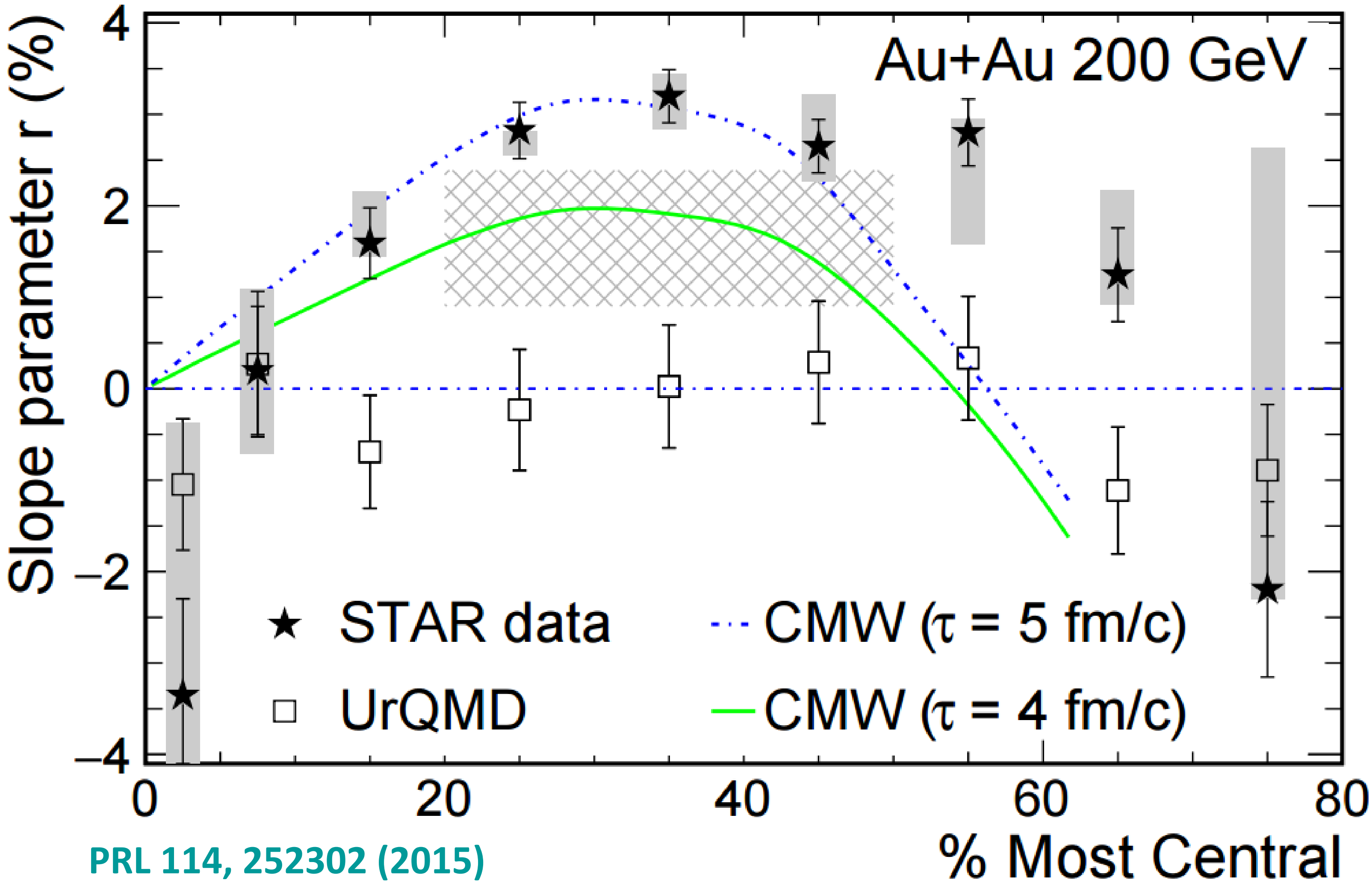
- $v_2(A_{ch})$ slopes for $\pi^{\pm}$:
  - opposite sign
  - similar magnitude

$$v_2^{\pm} = v_2^{\mathrm{base}\pm} \mp \left(\frac{q_e}{\bar{\rho}_e}\right) A_{ch}$$

- $v_2$ difference vs $A_{ch}$ may have a non-zero intercept: other physics?

# Slope vs centrality

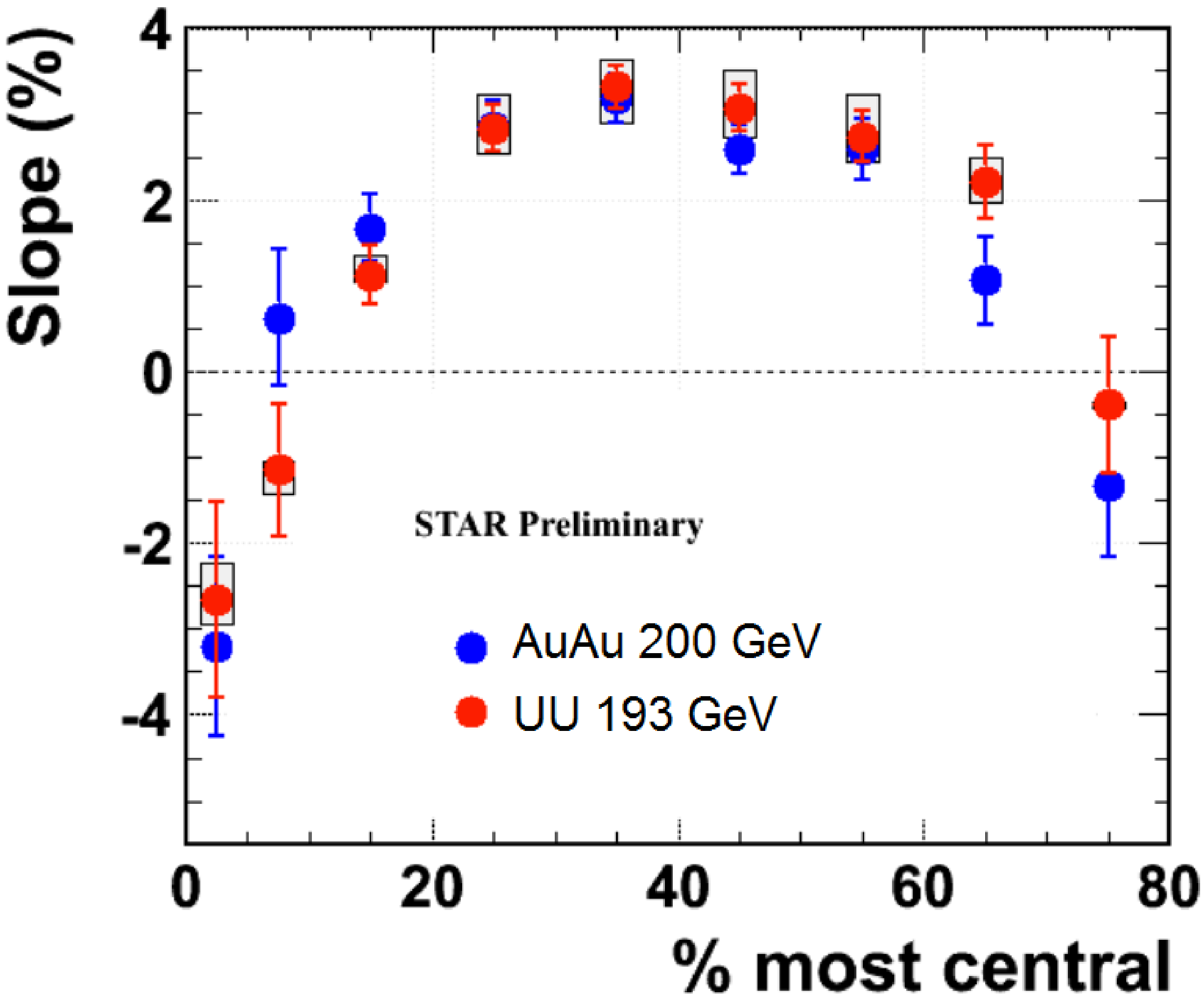
Y. Burnier, D. E. Kharzeev, J. Liao and H-U Yee, arXiv:1208.2537v1 [hep-ph].




PRL 114, 252302 (2015)

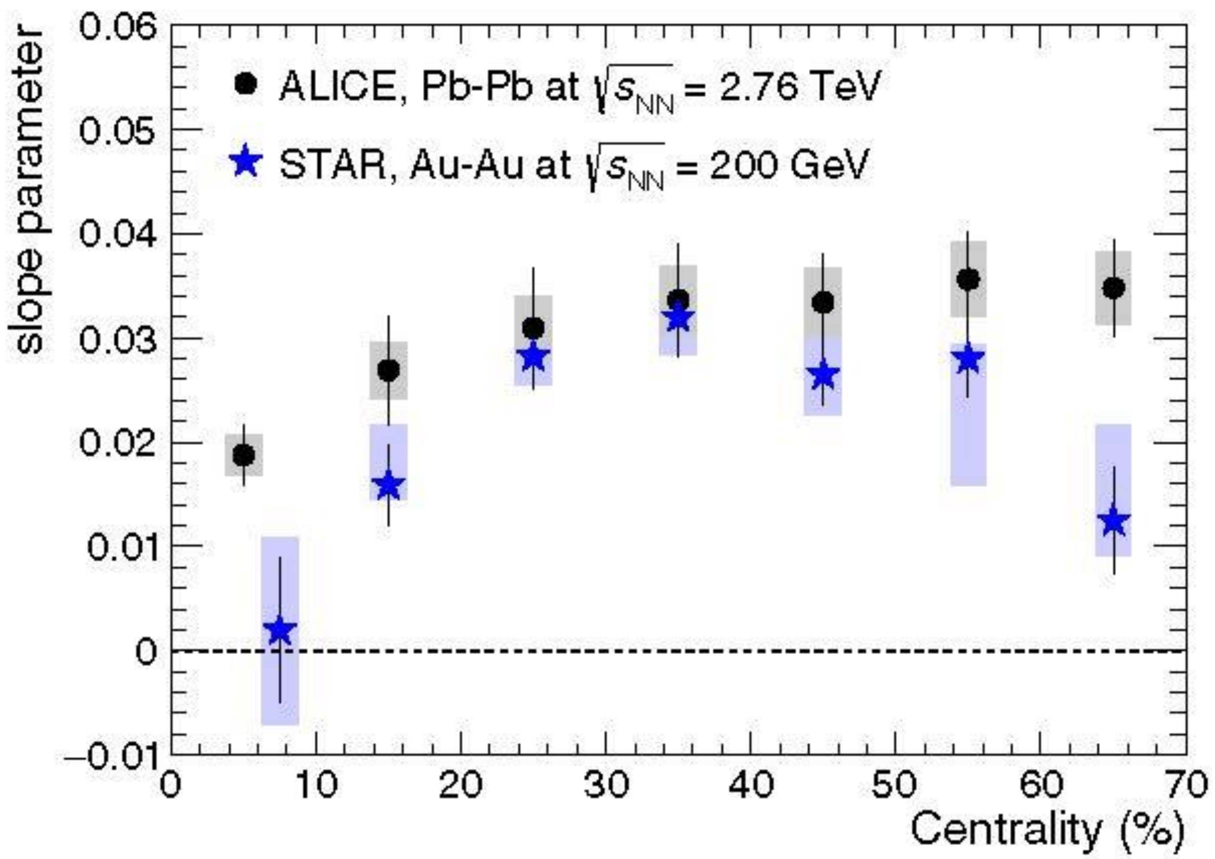
Similar trends between data and theoretical calculations with CMW.
UrQMD can not reproduce the slopes.

# U+U and Au+Au



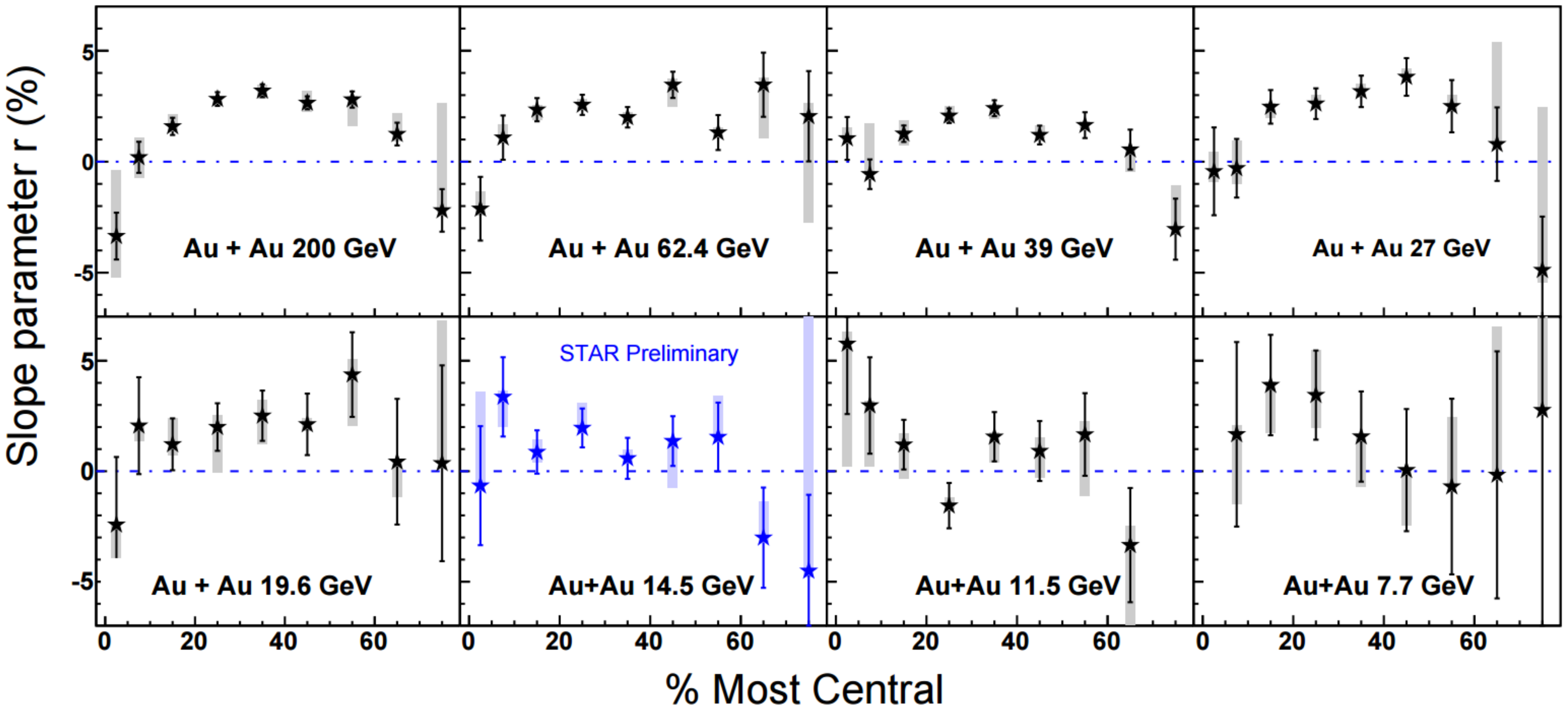

**Similar pattern and magnitude seen in U+U collisions.**

# Similar Slope Parameters from ALICE and STAR




**Things (background level?) in central and pheripheral collisions are clearly different at LHC and RHIC !**

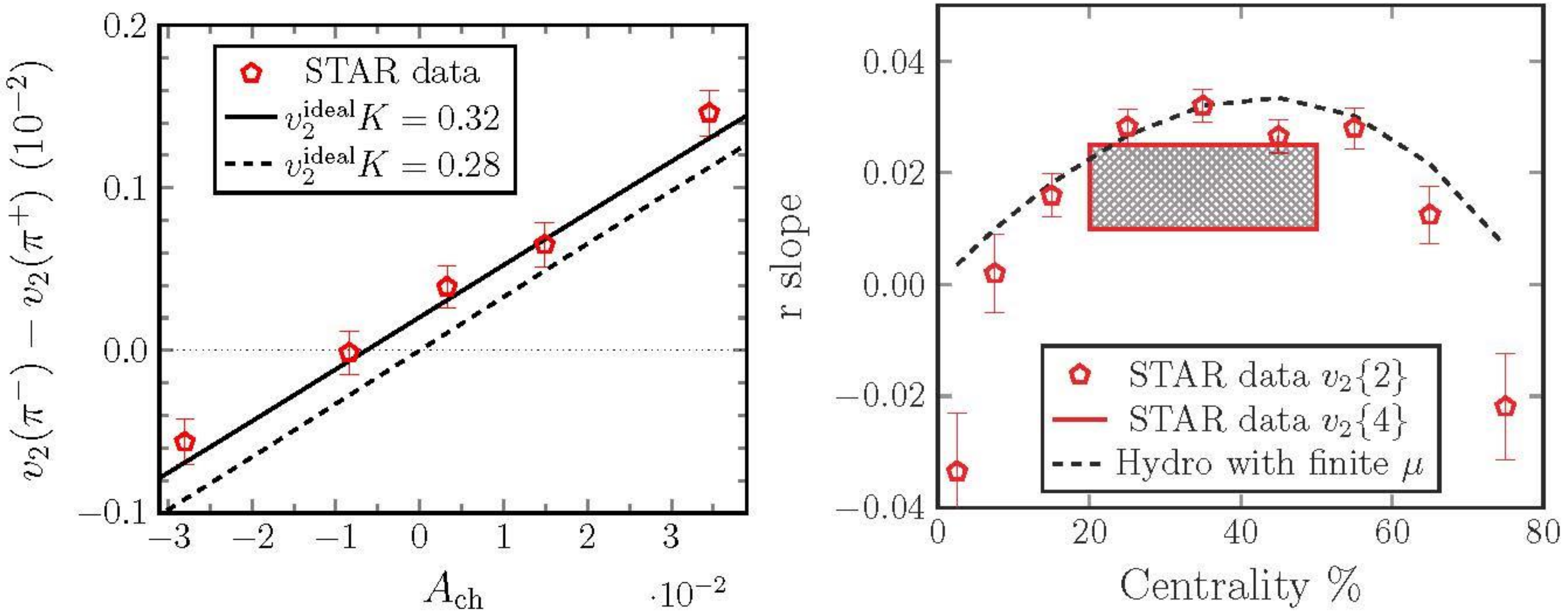
# Beam Energy Scan




**Similar trends are observed for different beam energies down to 19.6 GeV.**

**Below 19.6 GeV, more statistics are needed.**

# Background Model
# Viscos Hydro with Isospin μ

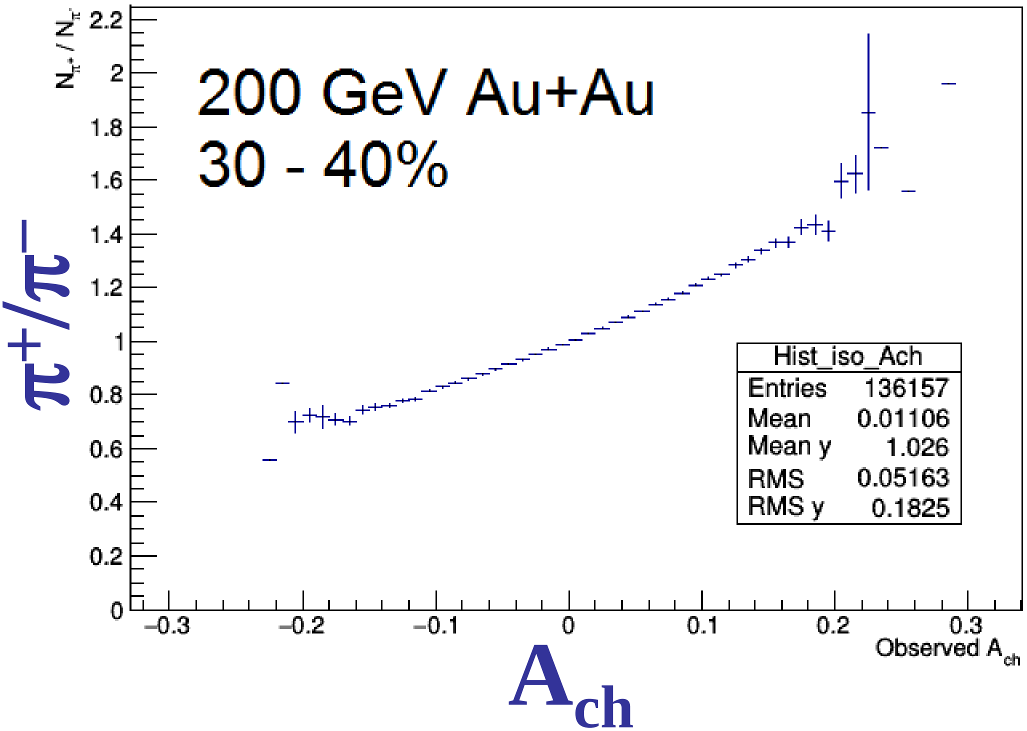


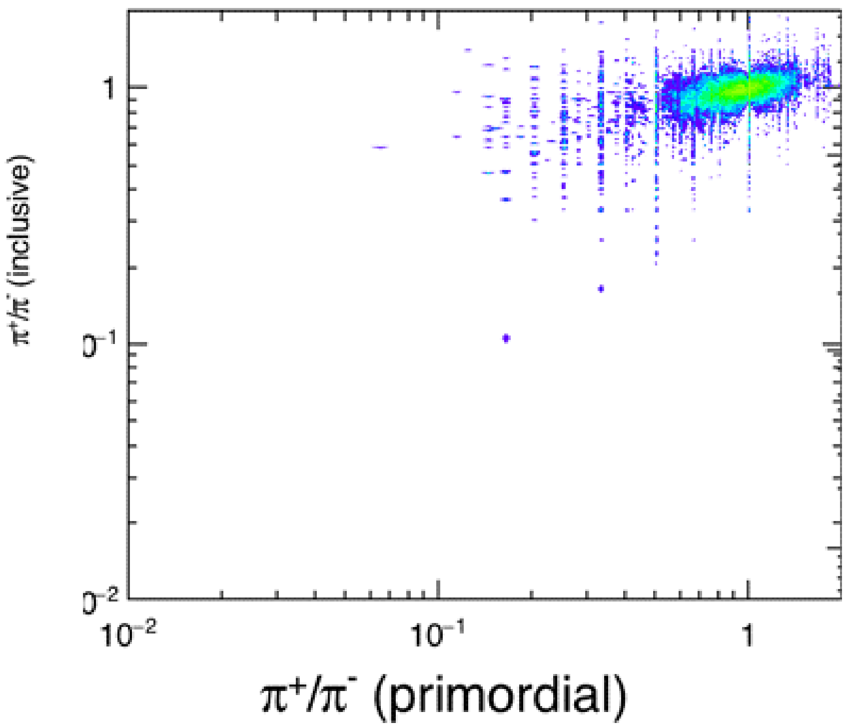

**Hatta, Monnai and Xiao 1507.04690**

# Correlation from Data

**STAR Data**

**AMPT**

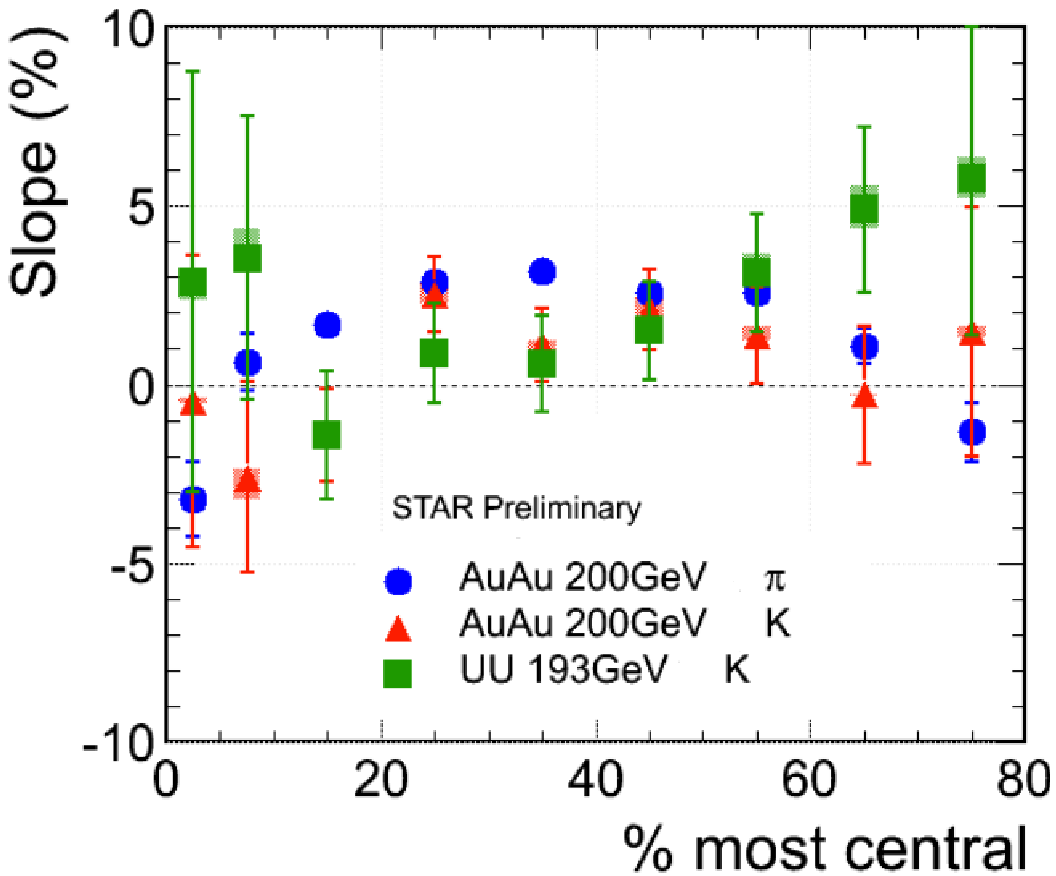


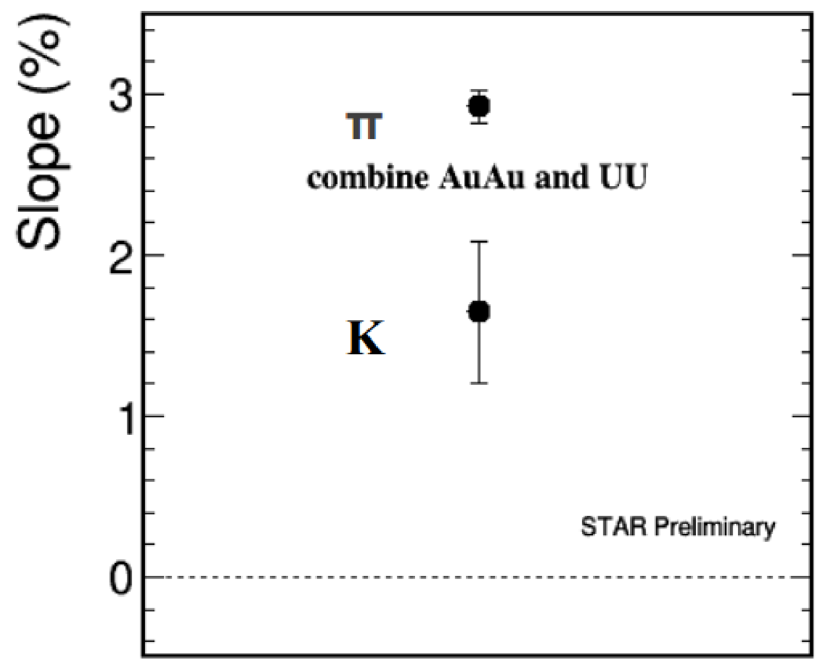




**$\pi^+/\pi^-$ ratio vs $A_{ch}$ different from Hatta et al expectation**

# Kaon

## 20-60% collisions




**With the same electric quadruple of QGP upon chemical freezeout, one expects a smaller effect for kaons (Y. Burnier et al, PRL 107 052303)**

**Hydro background model predicts opposite sign slopes between Kaon and pions**

$$v_2^{\pm} = v_2^{\text{base}\pm} \mp \left(\frac{q_e}{\bar{\rho}_e}\right) A_{ch}$$

**More statistics needed**

# Chiral Vortical Effect

## Chiral Magnetic Effect vs Chiral Vortical Effect

Chirality Imbalance ($\mu_A$)

Magnetic Field ($\omega$ $\mu_e$) Fluid Vorticity ($\omega$ $\mu_B$)

↓ ↓

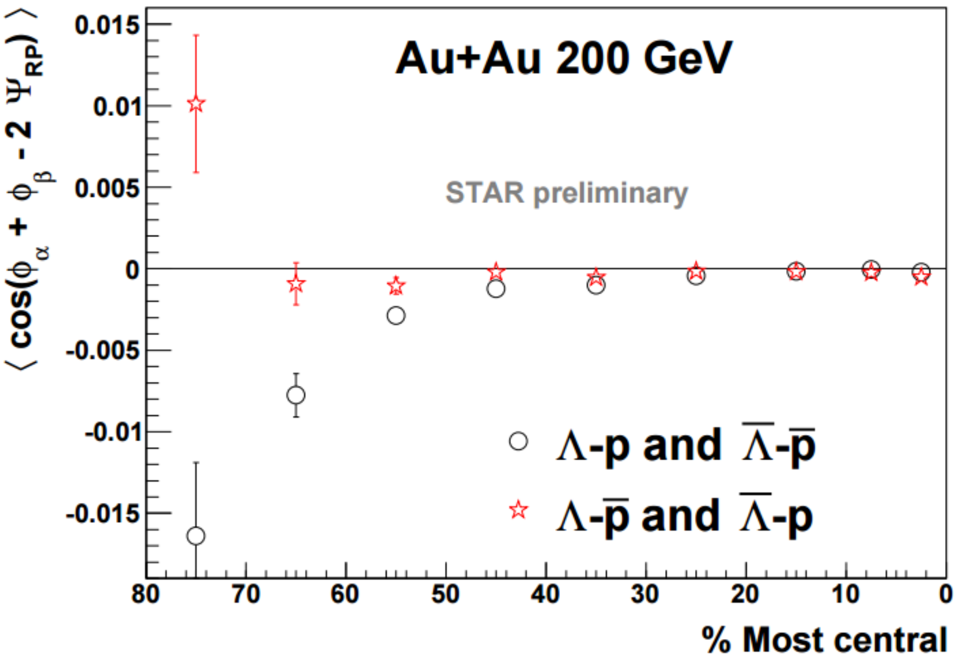
Electric Charge ($j_e$) Baryon Number ($j_B$)

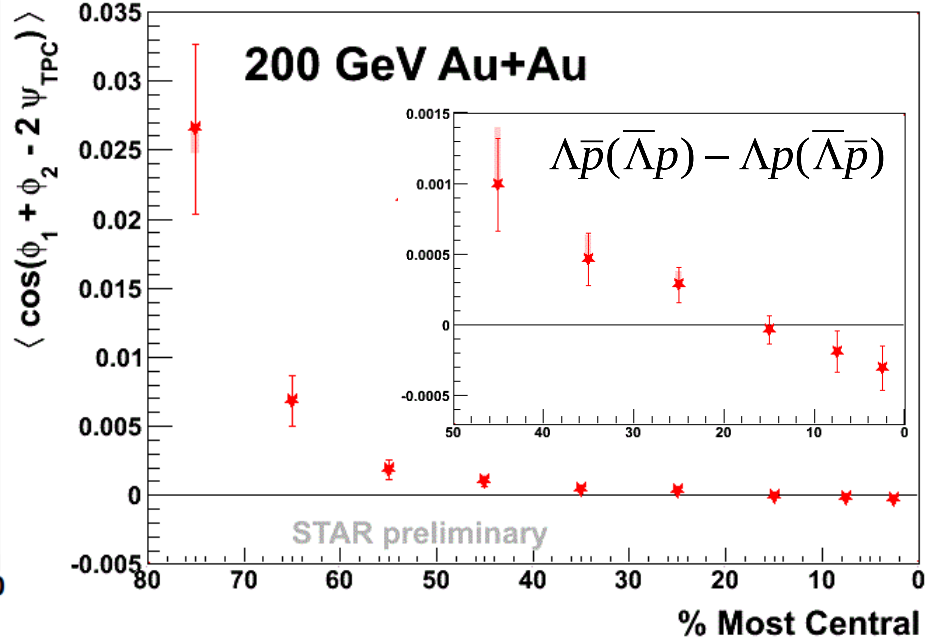
D. Kharzeev, D. T. Son, PRL 106 (2011) 062301

$$\langle \cos(\phi_\Lambda + \phi_p - 2\Psi_{RP}) \rangle$$

correlate Λ–p to search for the Chiral Vortical Effect

# Λ-proton correlation



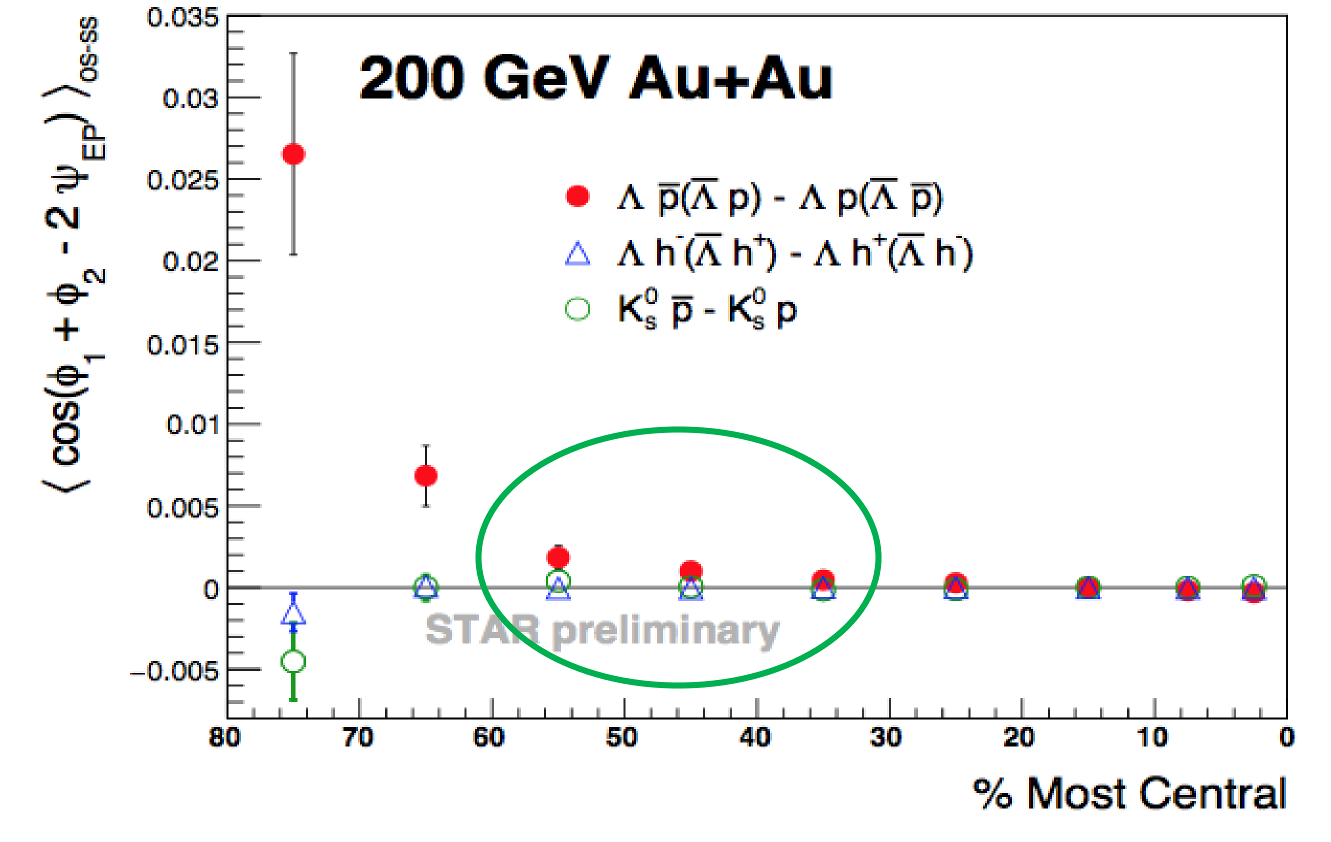




- same baryon number: $\Lambda p$ and $\bar{\Lambda}\bar{p}$

- opposite baryon number: $\Lambda\bar{p}$ and $\bar{\Lambda}p$

- "same B" is systematically lower than "oppo B" in the mid-central and peripheral collisions, consistent with the CVE expectation.

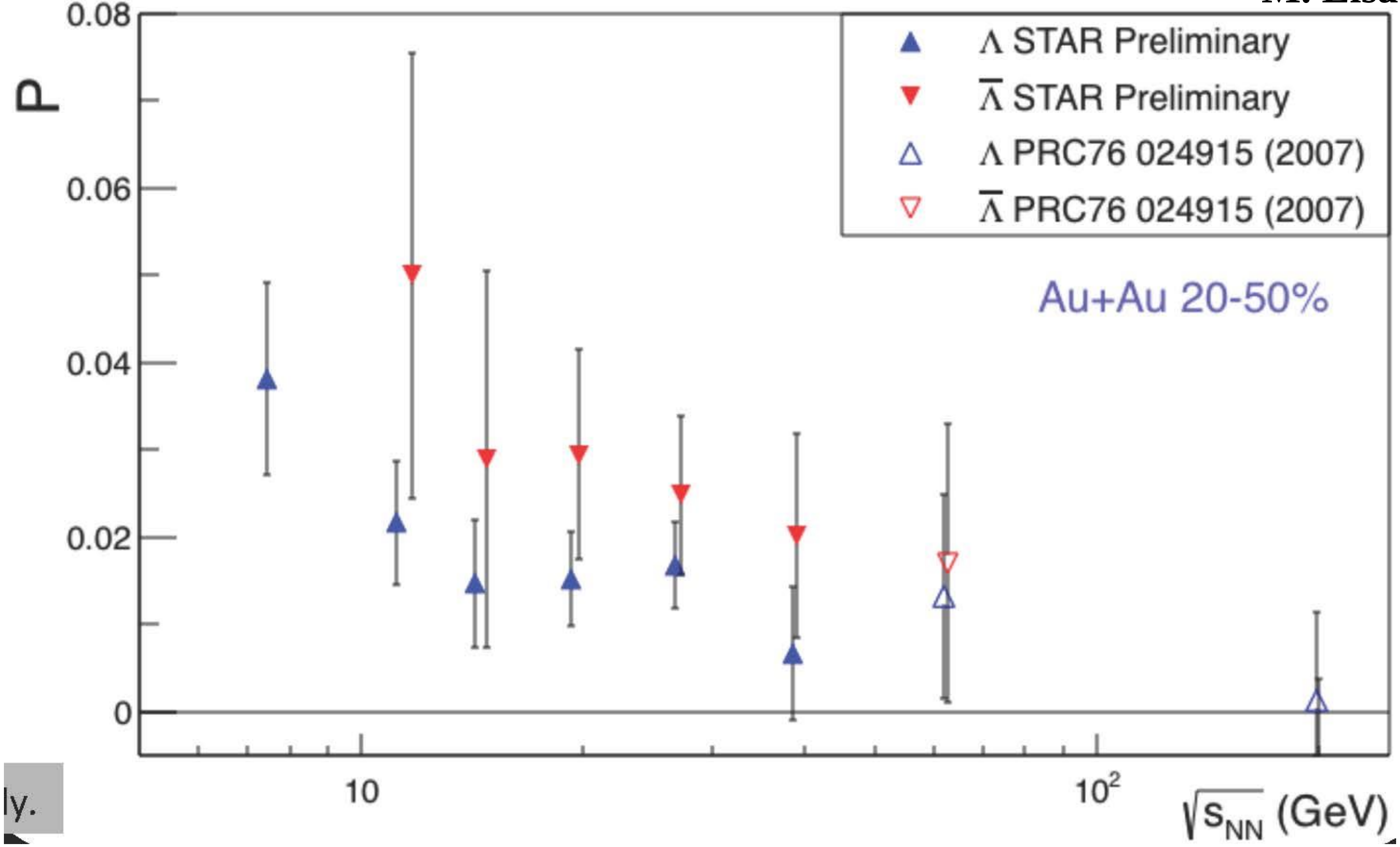
# Baryon-Baryon Correlation




**$\Lambda$-p correlation – different from $\Lambda$-h and $K_S$-p?**
**Only mid-centrality meaningful! More data !!**

# STAR Measurement for Lambda Polarization WRT the Reaction Plane

M. Lisa et al




1) Larger effect at lower beam energy ?
2) Difference between Lambda and Anti-Lambda?

# Discovery Yet ?

**There is a charge separation effect**

**-- separate CME and background ?!**

**There is an extra-$v_2$ due to charge asymmetry**

**-- electric quadrupole due to CMW or ?**

**There is a baryon-baryon separation effect**

**-- CVE or ?**

**More insight and towards a definitive answer:**

**-- establish B field and its consequence**

**-- correlating CME/CVE/CMW effects**

# Outlook: Isobars

Isobars are atoms (nuclides) of different chemical elements that have the same number of nucleons.

For example, $^{96}_{44}$Ruthenium and $^{96}_{40}$Zirconium:

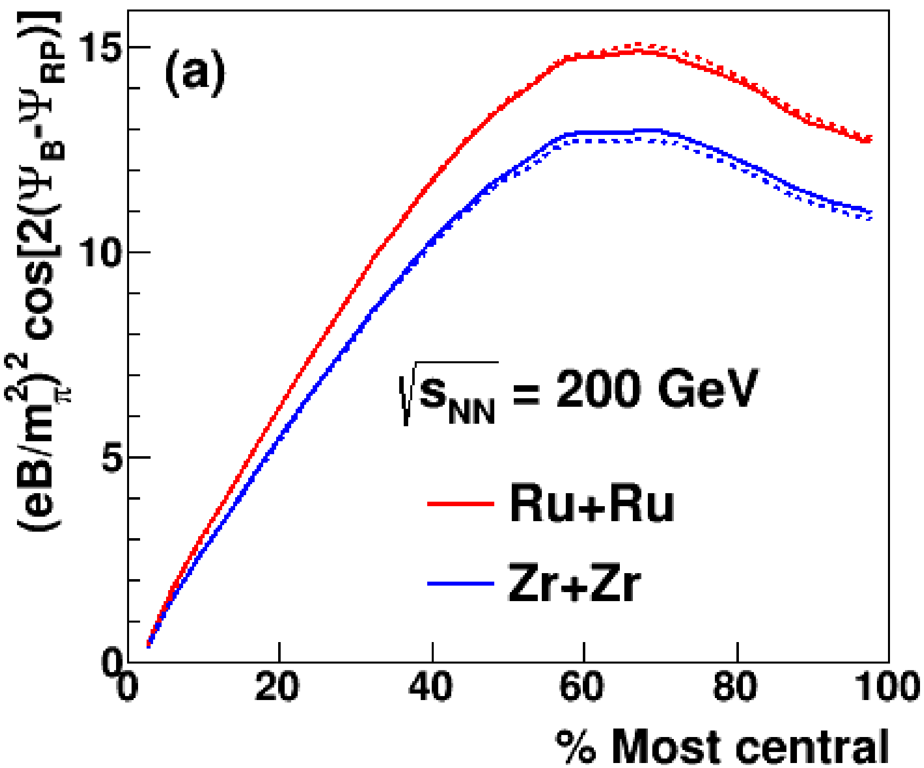
Up to 10% variation in B field

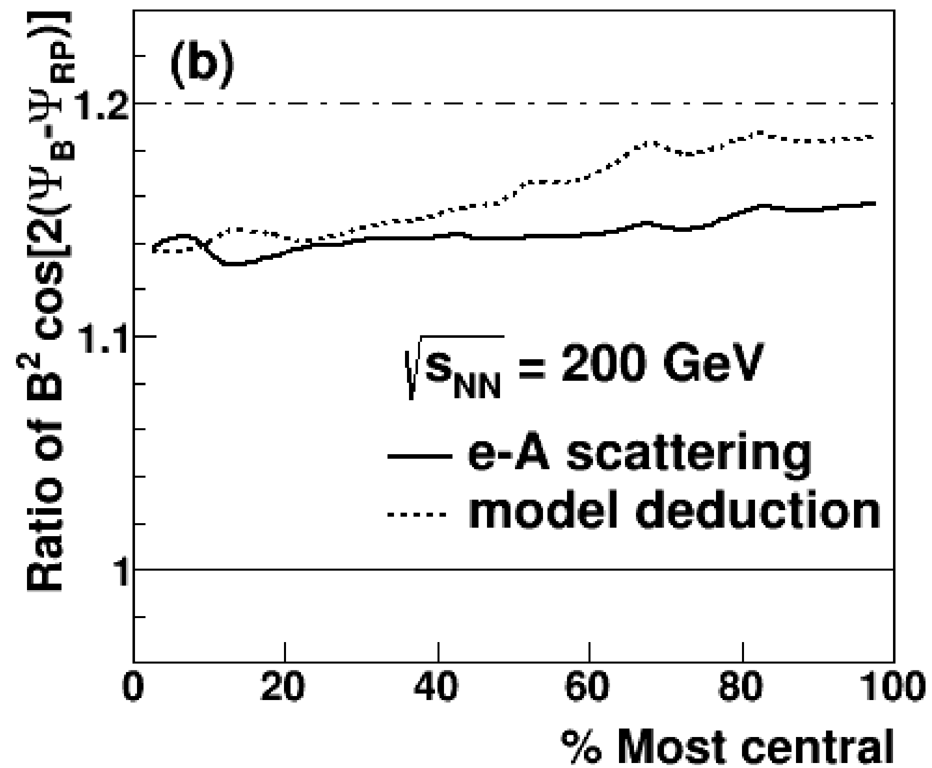
| | $^{96}_{44}Ru+^{96}_{44}Ru$ vs $^{96}_{40}Zr+^{96}_{40}Zr$ |
|---|---|
| Flow | ≤ |
| CMW | > |
| CME | > |
| CVE | = |

# B field

- B calculated at t=0, at one point (center of mass of participants)
- B field slightly affected by $\beta_2$
- The ratio in $B^2$ is close to 1.2 for peripheral events
- Reduces to 1.14 for central events

Courtesy of Xu-Guang Huang and Wei-Tian Deng

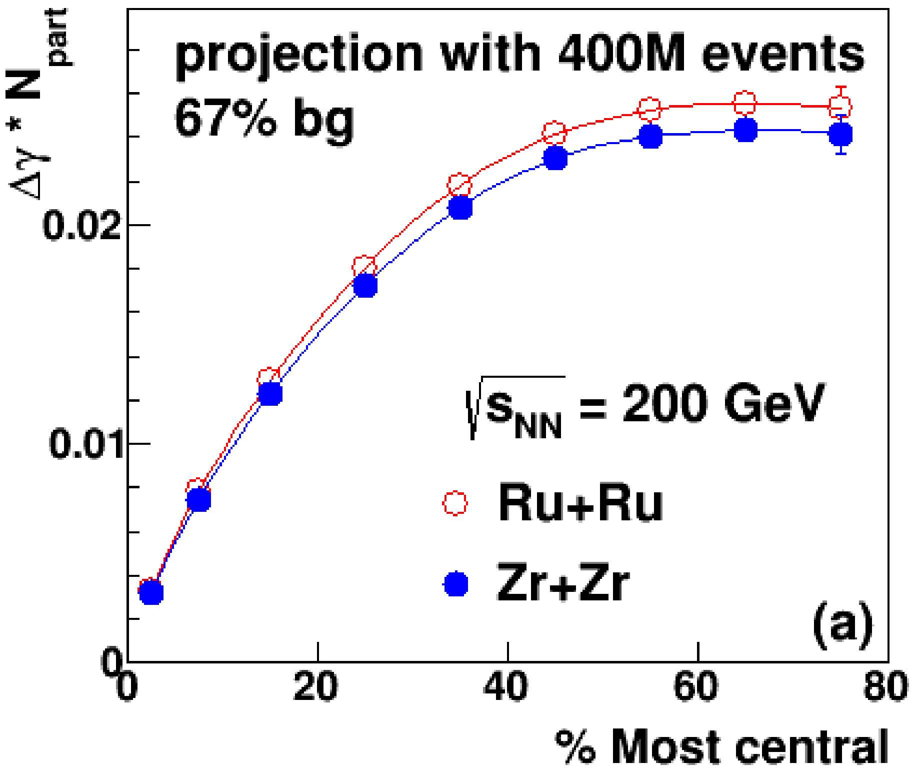


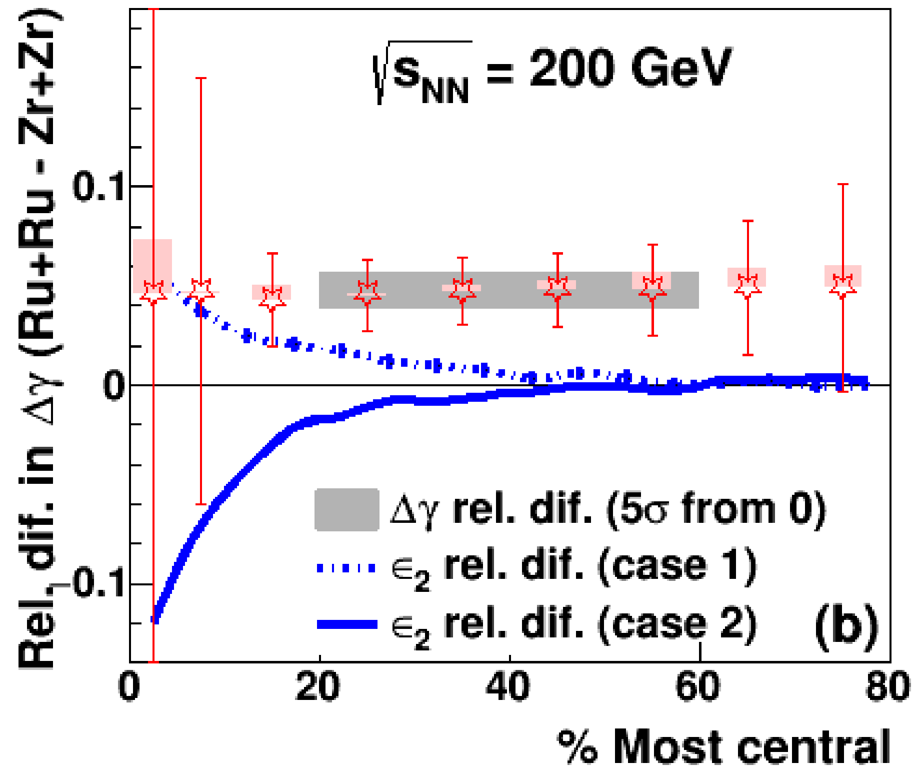




W. -T. Deng and X. -G. Huang, Phys. Rev. C 85 (2012) 044907; Phys. Lett. B 742 (2015)296

# charge separation: γ (67% bg)

- Projection with 400M events from each collision type
- If it's $v_2$-driven, rel. dif. will follow eccentricity (~0 for 20-60%)
- If it's 1/3 CME-driven, the difference in Δγ is 5σ above 0,




red star: case 1; pink box: case 2

# Experimental Window of Opportunity

1) **Isobaric running to see B field effect**
2) **Isobaric running at two beam energies to observe B magnitude and life-time difference**

**Run 2018 ~ 10 weeks**

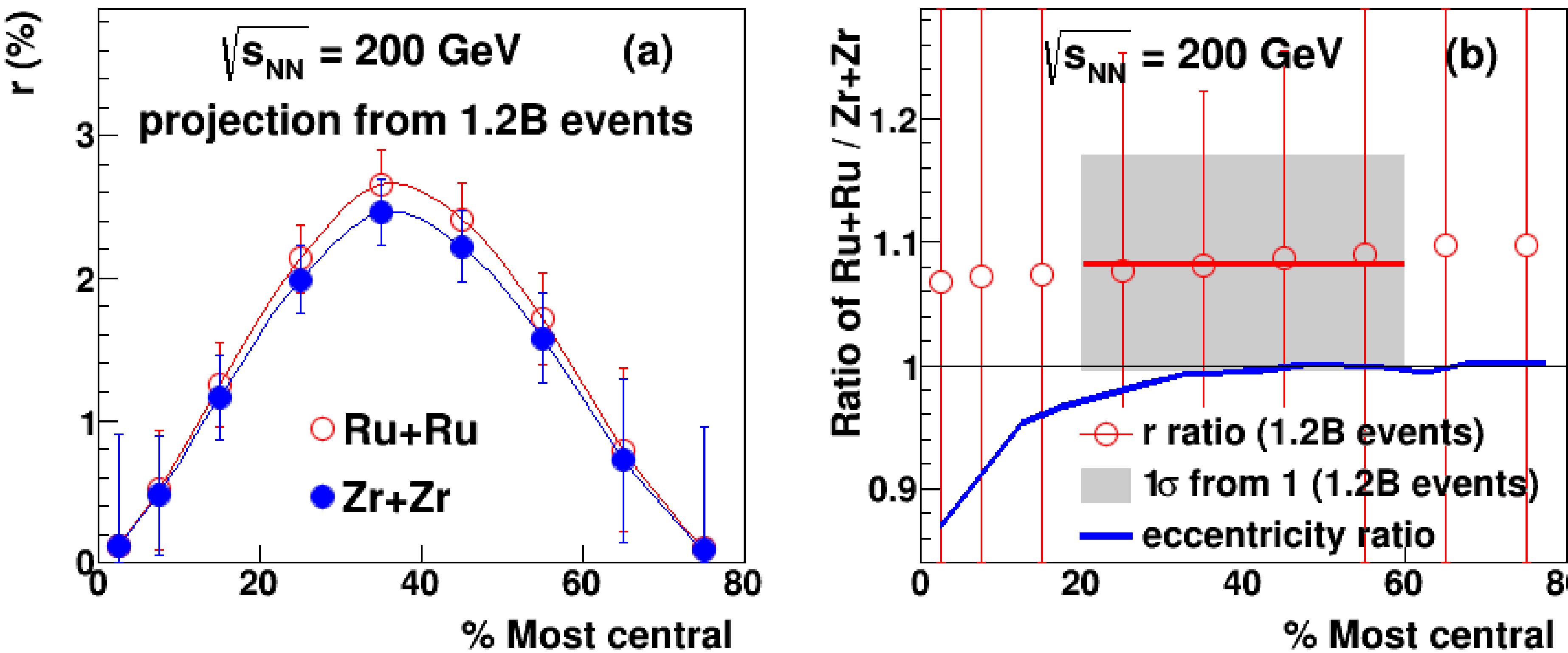
## Help from the BEST people

1) **Reliable separation of signal and background (constrain Pratt model from UU and BES)**
2) **CMW calculation – Ach dependence on eta**
3) **Prediction for isobaric data, 200 and 27 GeV**
4) **Correlations in CME, CMW and CVE**

# THE END

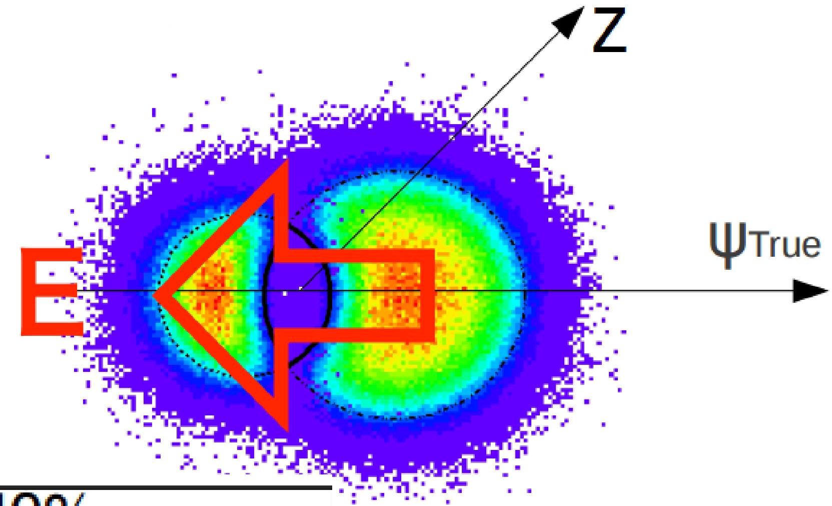
# Isobars: $\Delta v_2(A_{ch})$ slope

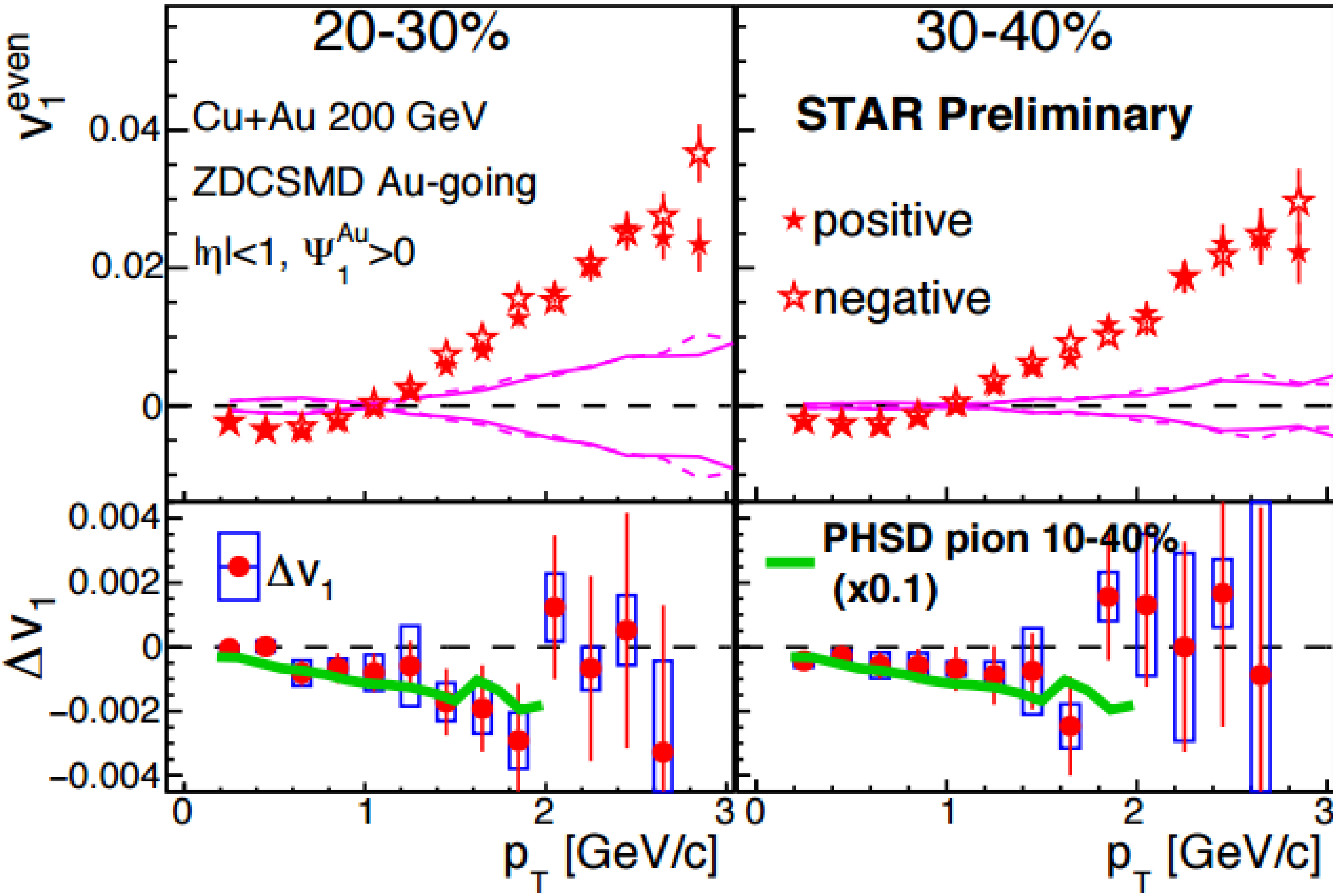
- The slope parameter is also expected to differ
- With 1.2B events, the ratio is 1σ above 1
- Need more statistics



# Outlook: Cu+Au

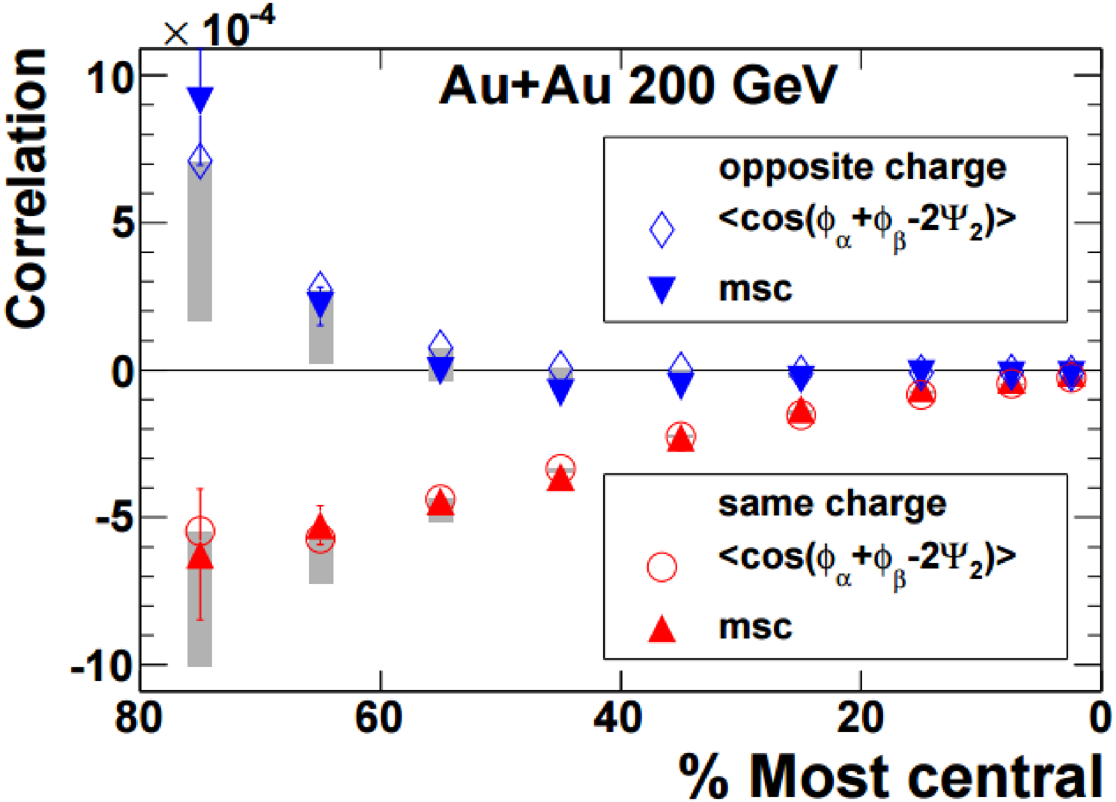
Expect charge-dependence of directed flow due to a dipole deformation
Y. Hirono, M. Hongo and T. Hirano, PRC 90, 021903(R)




A possible direct evidence of the strong initial E field? (comparable to the strong initial B field).

# Modulated sign correlator (msc)




$$\langle \cos(\varphi_\alpha + \varphi_\beta - 2\Psi_{RP}) \rangle$$

$$= \langle \cos(\Delta\varphi_\alpha)\cos(\Delta\varphi_\beta) - \sin(\Delta\varphi_\alpha)\sin(\Delta\varphi_\beta) \rangle$$

$$= \langle (M_\alpha M_\beta S_\alpha S_\beta)_{IN} \rangle - \langle (M_\alpha M_\beta S_\alpha S_\beta)_{OUT} \rangle$$

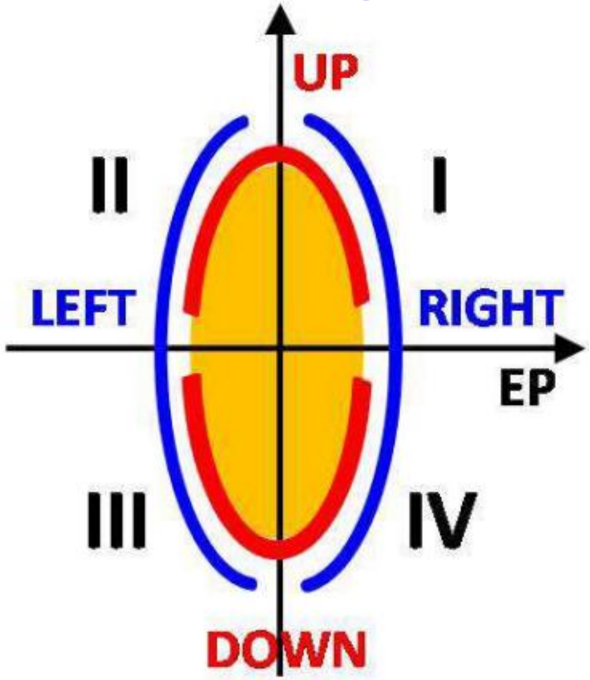
$$\text{msc} \equiv \left(\frac{\pi}{4}\right)^2 \left( \langle S_\alpha S_\beta \rangle_{IN} - \langle S_\alpha S_\beta \rangle_{OUT} \right)$$

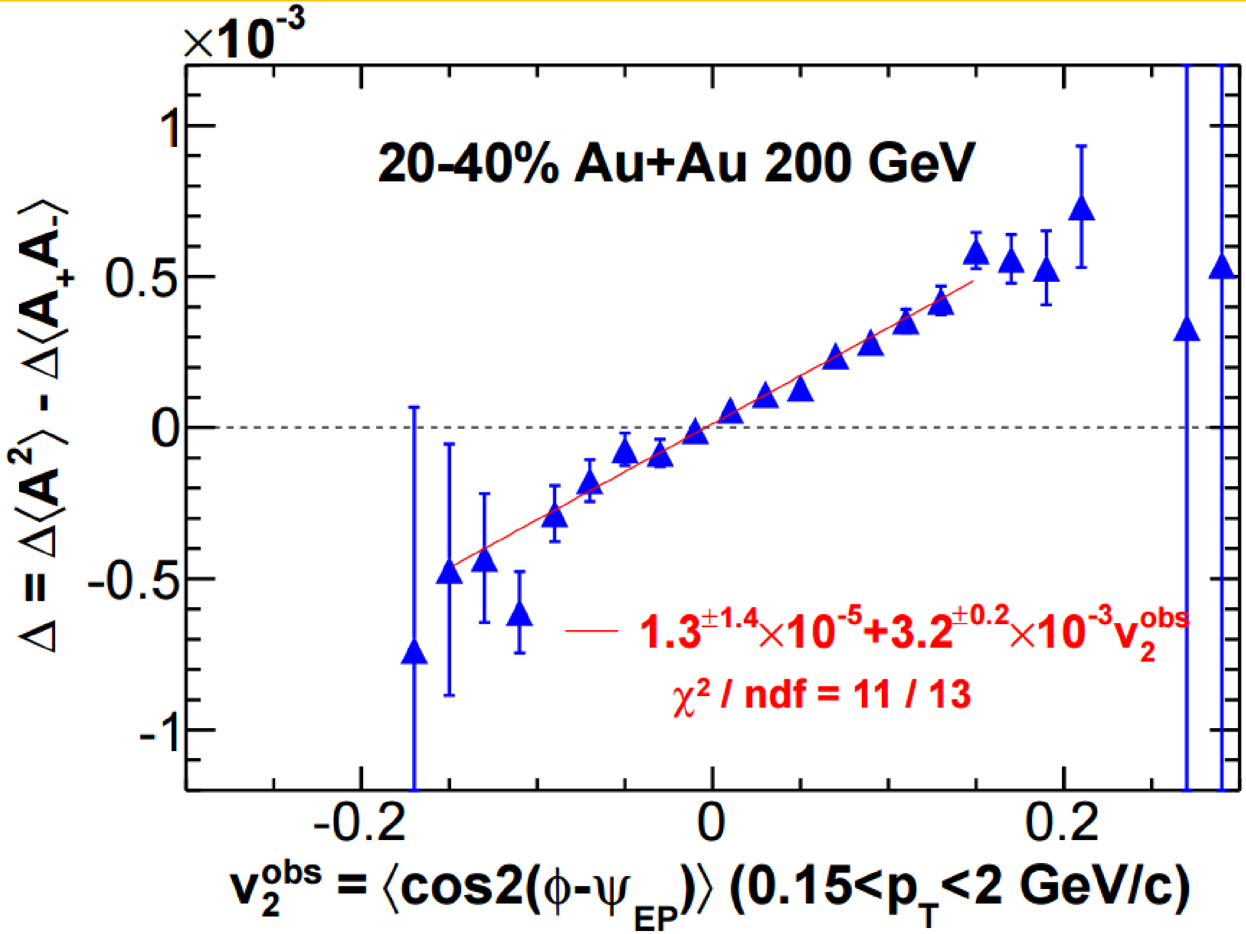
- robust after removing HBT+Coulomb effects with kinematic cuts (Δη and $\Delta p_T$)
- γ weights different azimuthal regions of charge separation differently
- Modify γ such that all azimuthal regions are weighted equally
- γ is reduced to modulated sign correlator (msc)
- The charge separation signal is confirmed with msc

Phys. Rev. C 88 (2013) 64911

# Charge multiplicity asymmetry correlator

count the charges of 4 regions



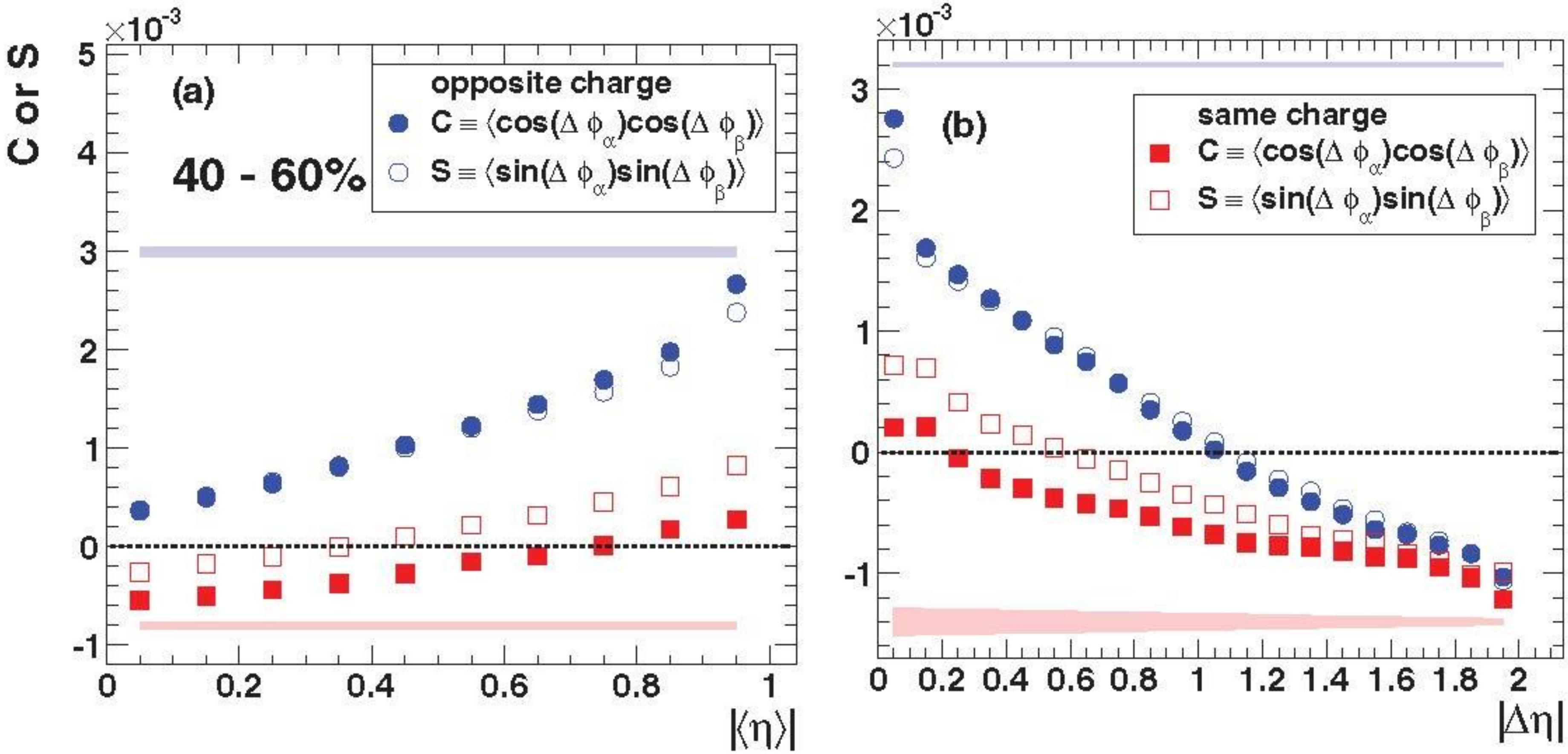




- A similarly reduced correlator, observes a similar charge separation.
- Previously, when "$v_2^{obs}$"=0, the signal was consistent with zero!

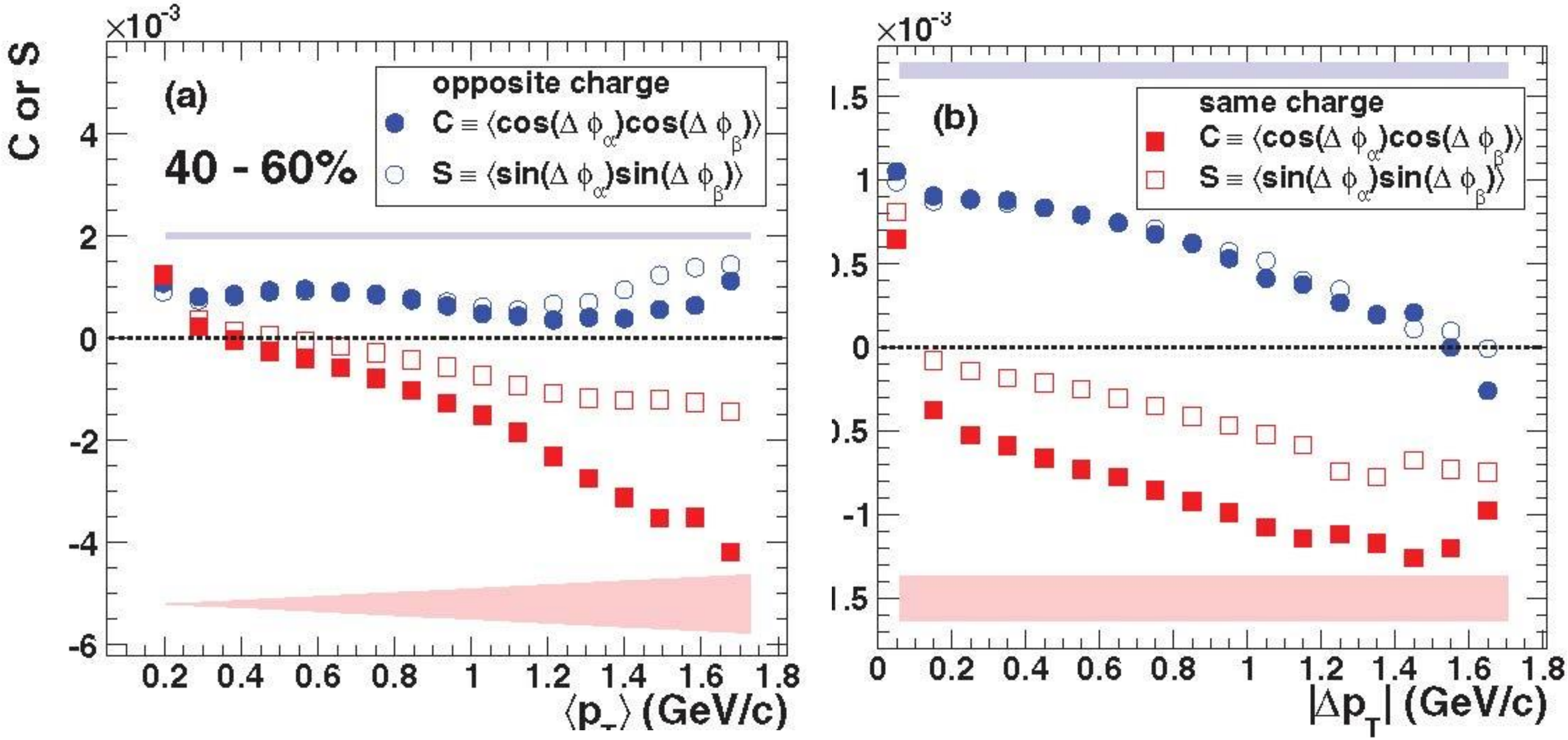
Phys. Rev. C 89 (2014) 44908

- Now, new measurements with higher statistics report non-zero signal!
- Beam energy dependence also looks similar to that of $\gamma$.

# Differential C and S Correlations

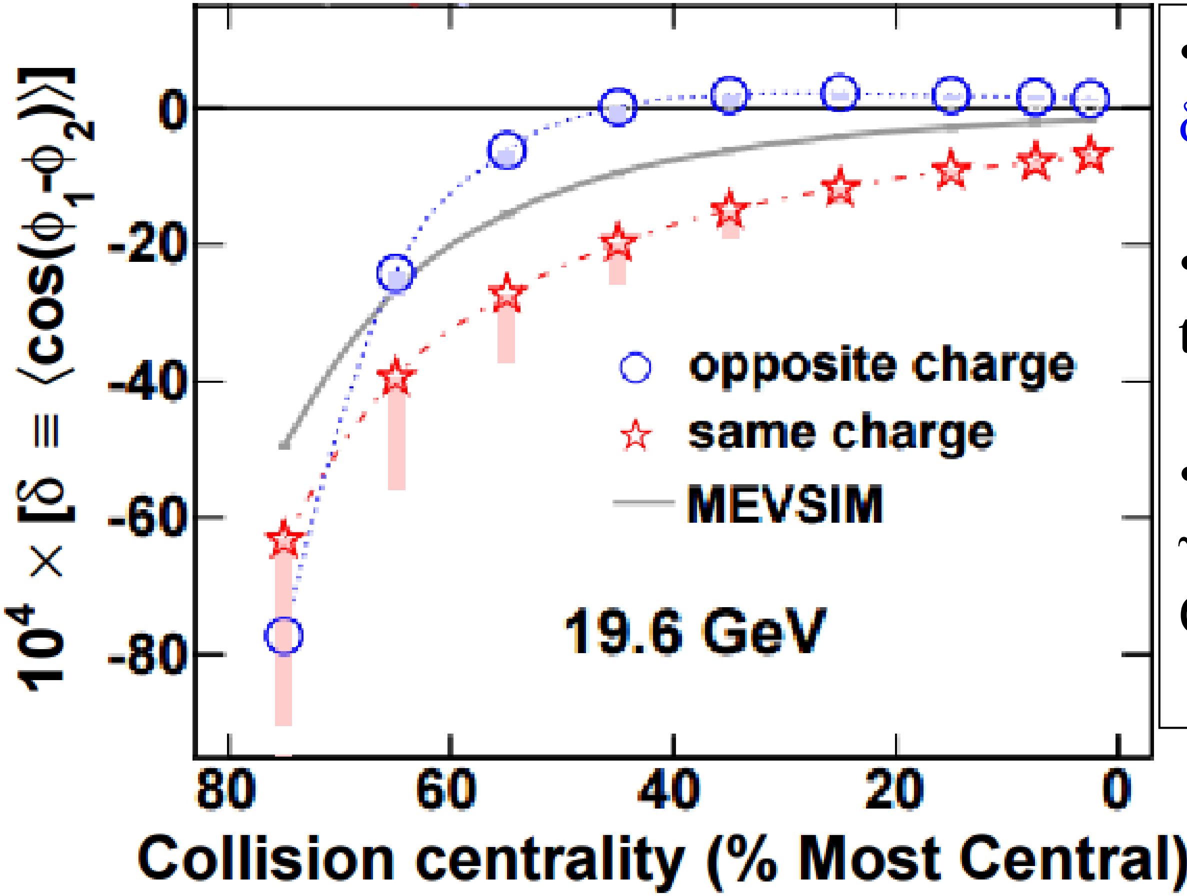


# Differential C and S Correlations



# $v_2$-related background

Phys. Rev. Lett 113 (2014) 052302

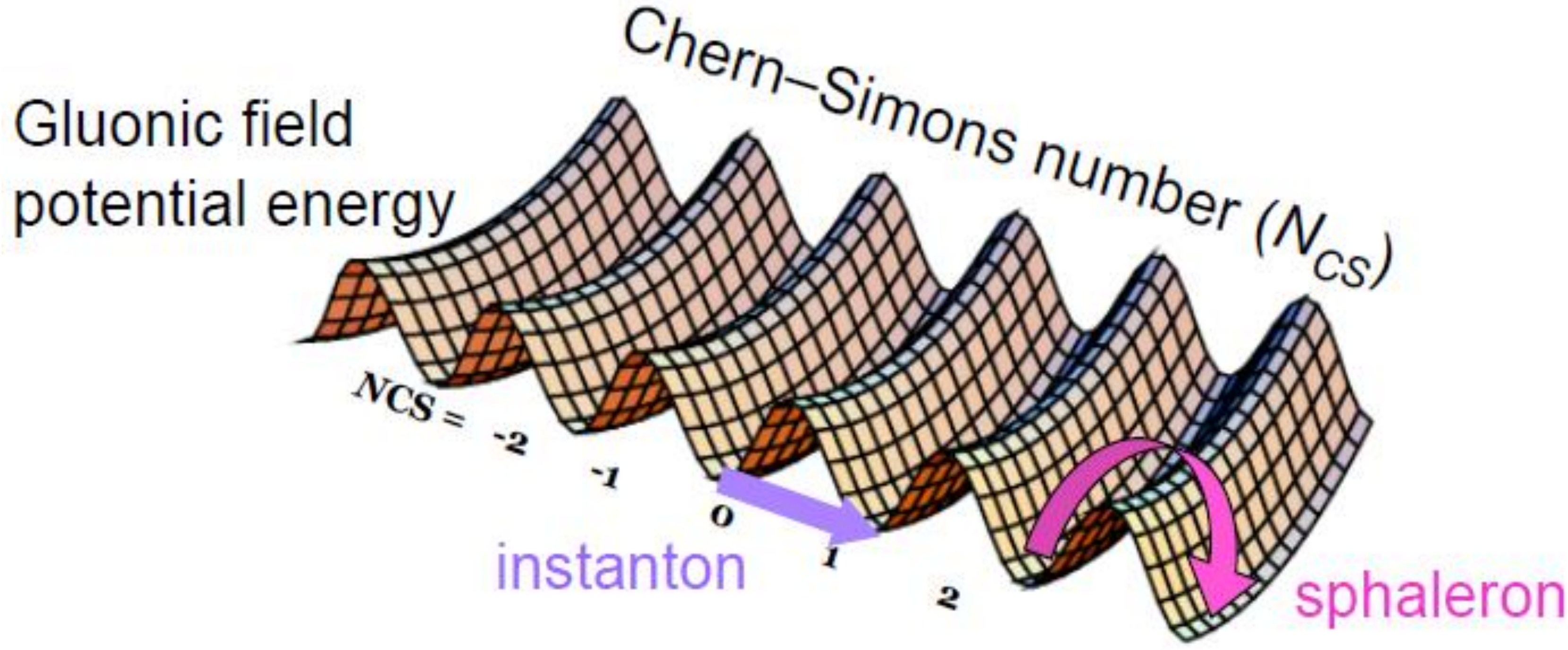



- Against CME expectation, $\delta_{OS} > \delta_{SS}$
- Overwhelming bg, larger than any CME effect.
- Combine information from $\gamma$ and $\delta$, and retrieve the CME contribution, *H*

$$\gamma \equiv \langle\cos(\phi_1 + \phi_2 - 2\Psi_{RP})\rangle = \kappa v_2 F - H$$
$$\delta \equiv \langle\cos(\phi_1 - \phi_2)\rangle = F + H,$$

A. Bzdak, V. Koch and J. Liao, Lect. Notes Phys. 871, 503 (2013).

# QCD vacuum transition

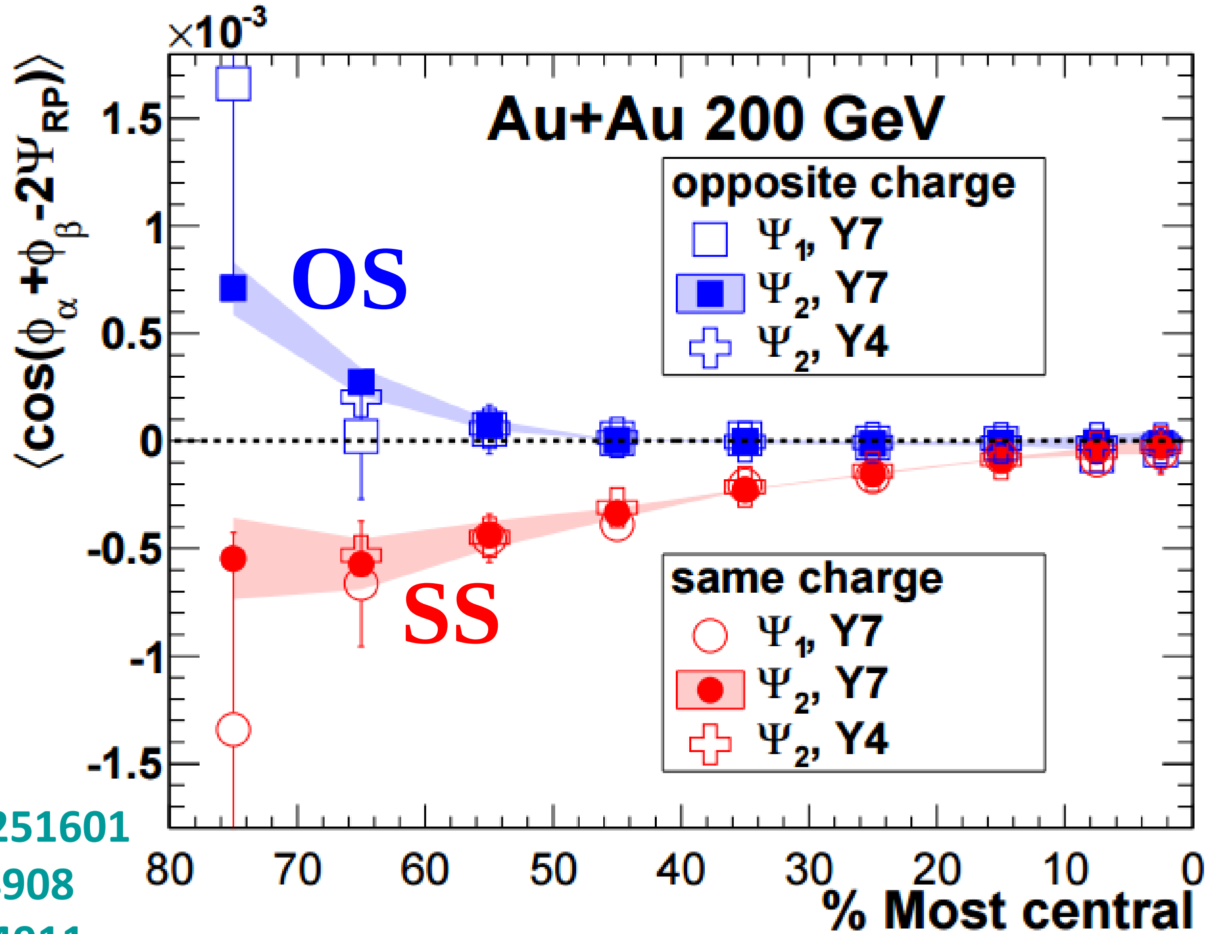



D. Diakonov, Prog. Part. Nucl. Phys. 51, 173 (2003)

$$N_L^f - N_R^f = 2Q_W\,,\ Q_W \neq 0 \rightarrow \mu_A \neq 0$$

**QCD vacuum transition**
- **nonzero topological charge**
- **chirality imbalance (local parity violation)**

# Charge Dependent γ Measure




Phys. Rev. Lett. 103(2009)251601
Phys. Rev. C 81(2010)54908
Phys. Rev. C 88 (2013) 64911

- $\gamma_{OS} > \gamma_{SS}$, consistent with CME expectation
- Consistent between different years (2004 and 2007)
- Confirmed with 1st-order EP (from spectator neutron $v_1$)
- Not explained by known event generators

# Conventional Explanation ?

## Blast Wave Parameterization = Charge Correlation + Radial + Elliptic Flow

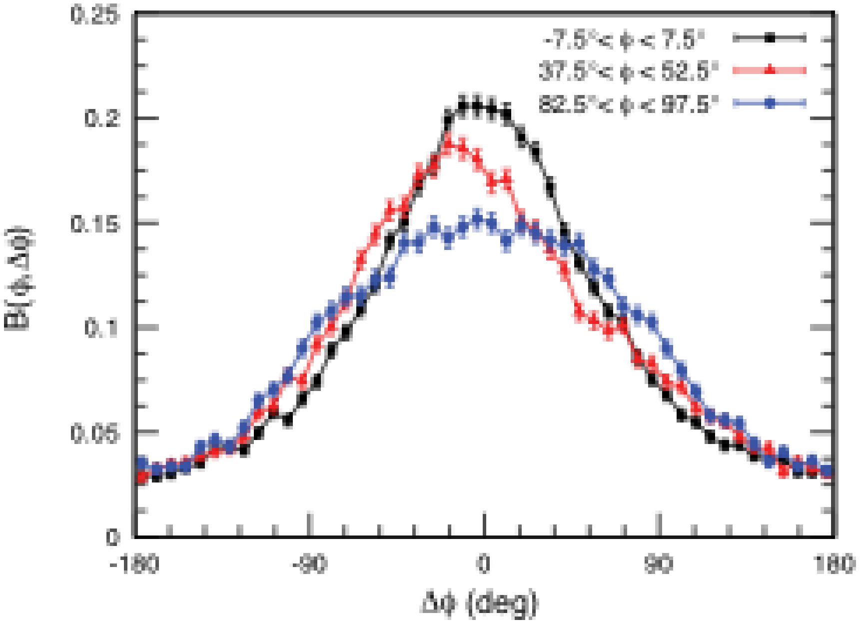
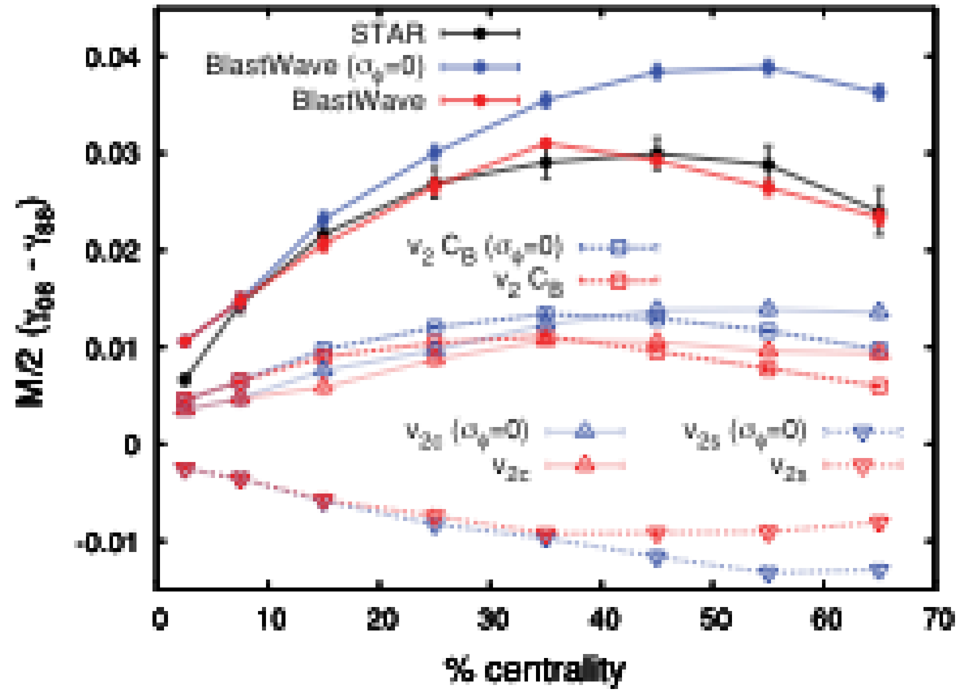



FIG. 7. (Color online) Balance function $B(\phi, \Delta\phi)$ for 40–50% centrality as function of the relative angle included by balancing partners for $\phi = 0^\circ$ (black squares), 45° (red triangles), and 90° (blue circles). The balance function is narrower for in-plane pairs than for out-of-plane pairs. For intermediate angles, the balance function is biased toward negative angles.



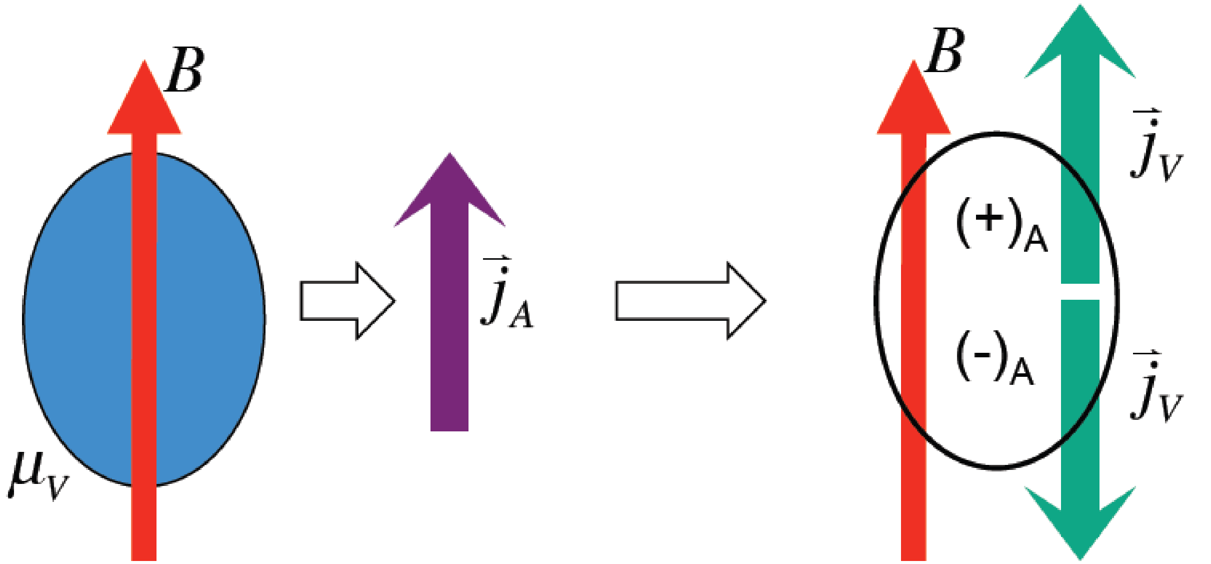

$$\frac{\langle M^2\gamma_P\rangle}{\langle M\rangle} = \frac{2}{\langle M\rangle}\int d\phi\, d\Delta\phi \langle\frac{dM}{d\phi}\rangle\, B(\phi,\Delta\phi) \times [\cos(2\phi)\cos(\Delta\phi) - \sin(2\phi)\sin(\Delta\phi)],$$

- With some "adjustments" can describe the data (diff "OS" - "SS").
- Note that the correlator is inversely proportional to multiplicity

Schlichting and Pratt, PRC83 014913 (2011)

# CMW

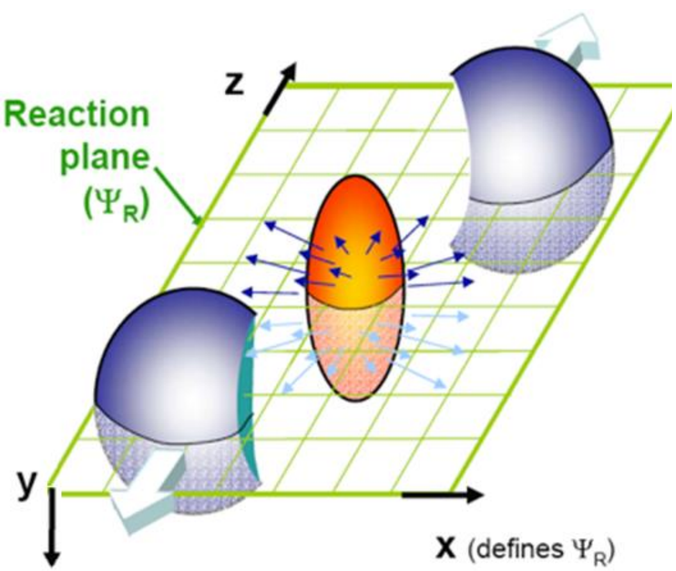
Peak magnetic field ~
**$10^{15}$ Tesla !**
(Kharzeev et al. NPA 803 (2008) 227)




$$j_A = \frac{N_c e}{2\pi^2} \mu_V B \qquad j_V = \frac{N_c e}{2\pi^2} \mu_A B$$

Chiral Separation Effect

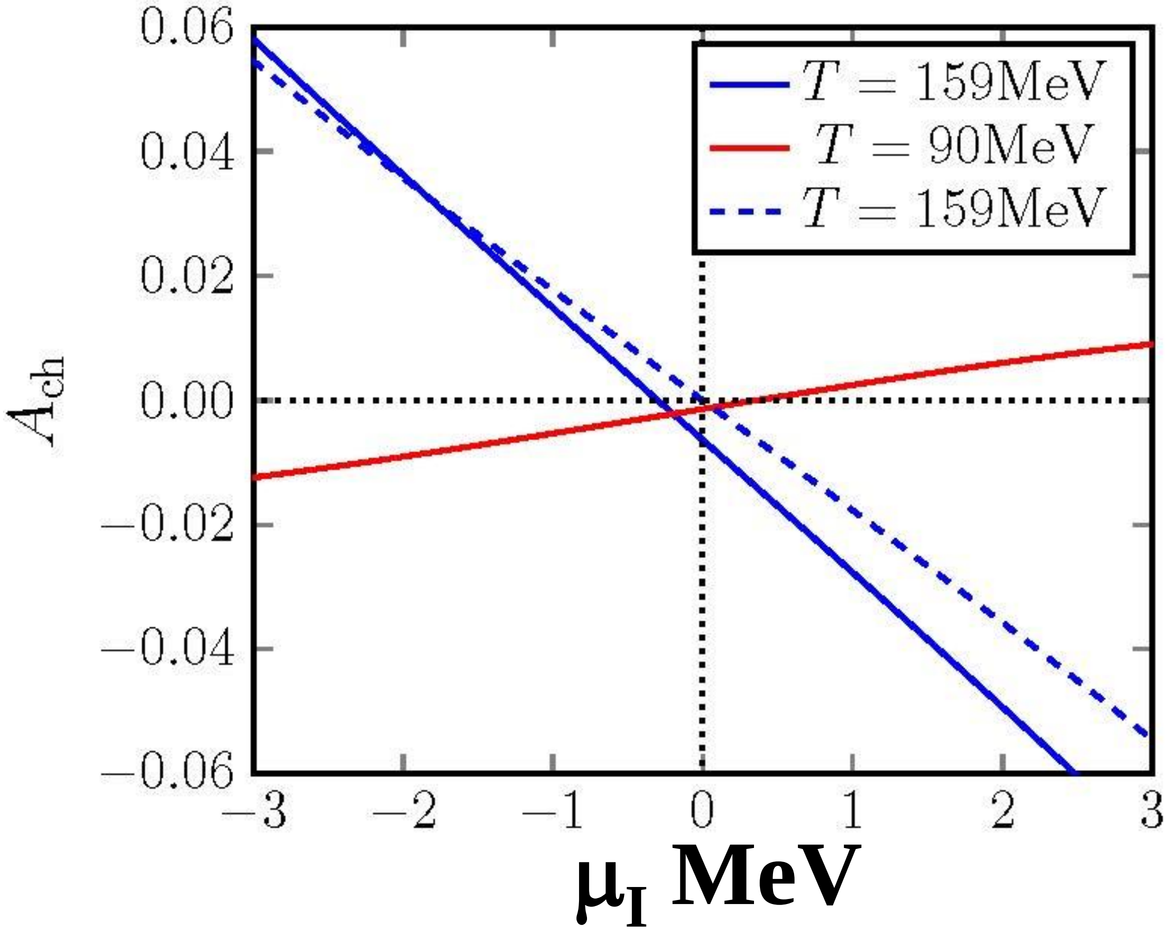
Chiral Magnetic Effect



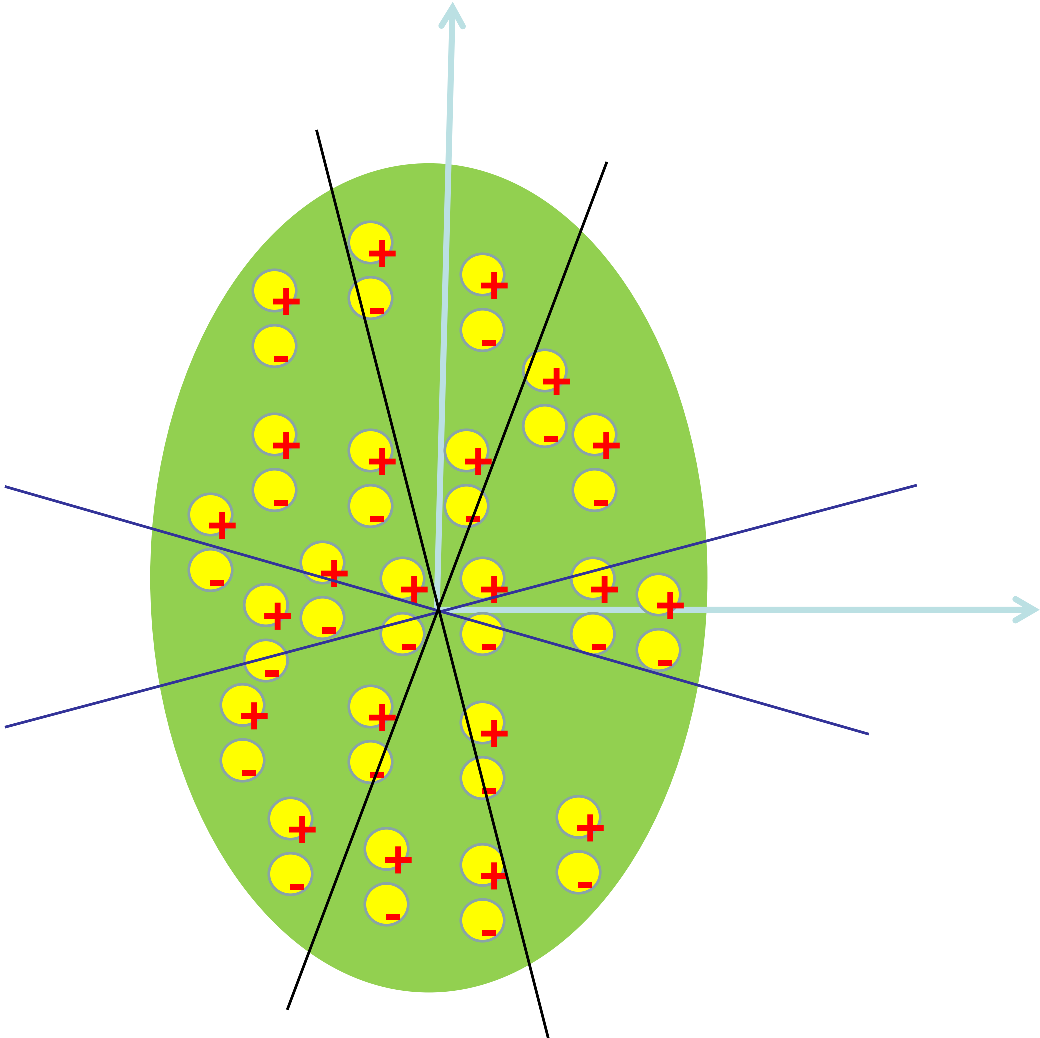

CSE + CME → Chiral Magnetic Wave:

- collective excitation
- signature of chiral symmetry restoration

# Correlation in the Hydro Model



# γ more sensitive to in-plane direction




**Sensitivity to in-plane back-to-back correlation could be an artifact due to γ definition**