Experimental Searches for Chirality and Vorticity Effects in Heavy Ion Collisions

HUAN ZHONG HUANG (黄焕中）

University of California, Los Angeles

&

Fudan University

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OUTLINE

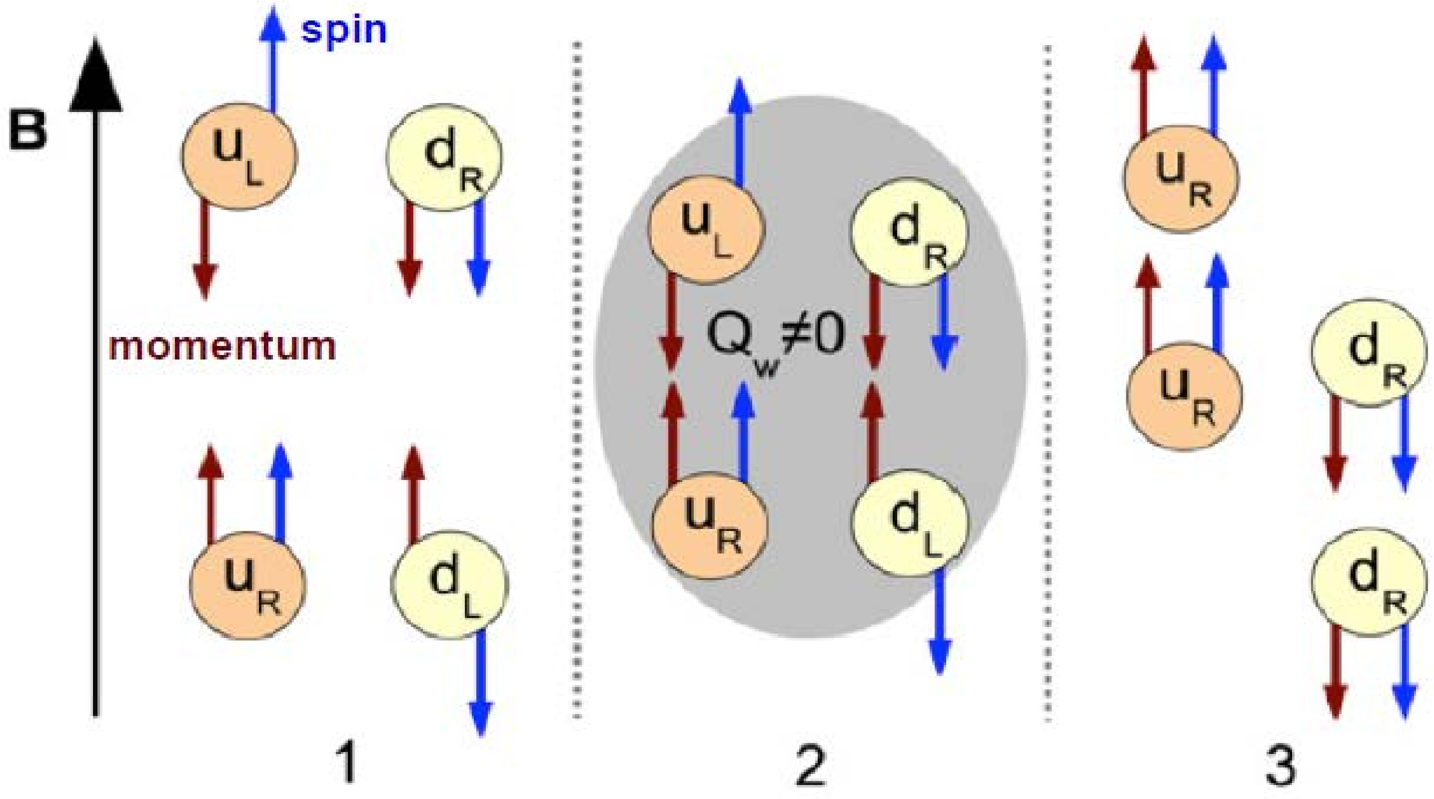
1) CME and Charge Separation Across the RP

2) CMW and Background Flow Effect

3) Search for Chiral Vortical Effect

4) Future Perspective

Chiral Magnetic Effect → Charge Separation

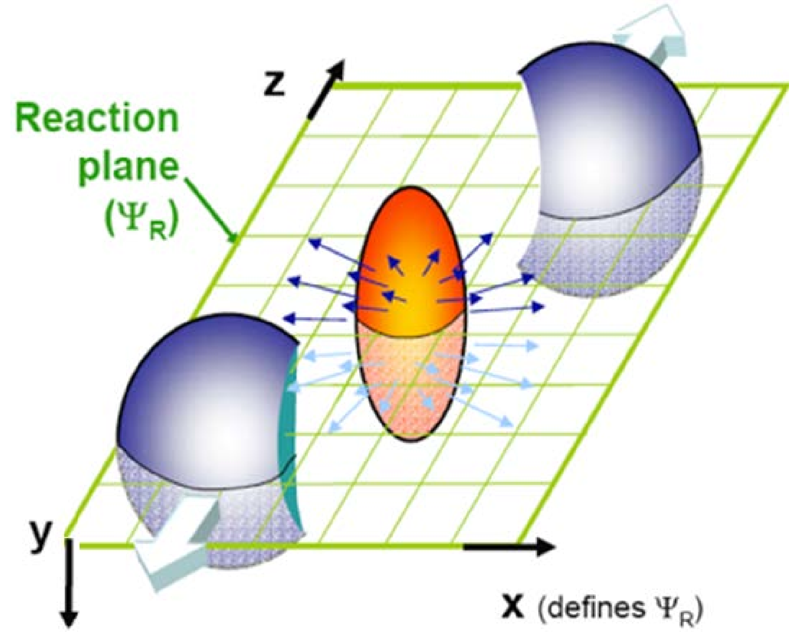


Chiral Magnetic Effect **(CME):** finite chiral charge density induces an electric current along external magnetic field.

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

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

γ correlator



A quantitative measure for extra charge fluctuation.

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

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

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

S. Voloshin, PRC 70 (2004) 057901

Directed flow

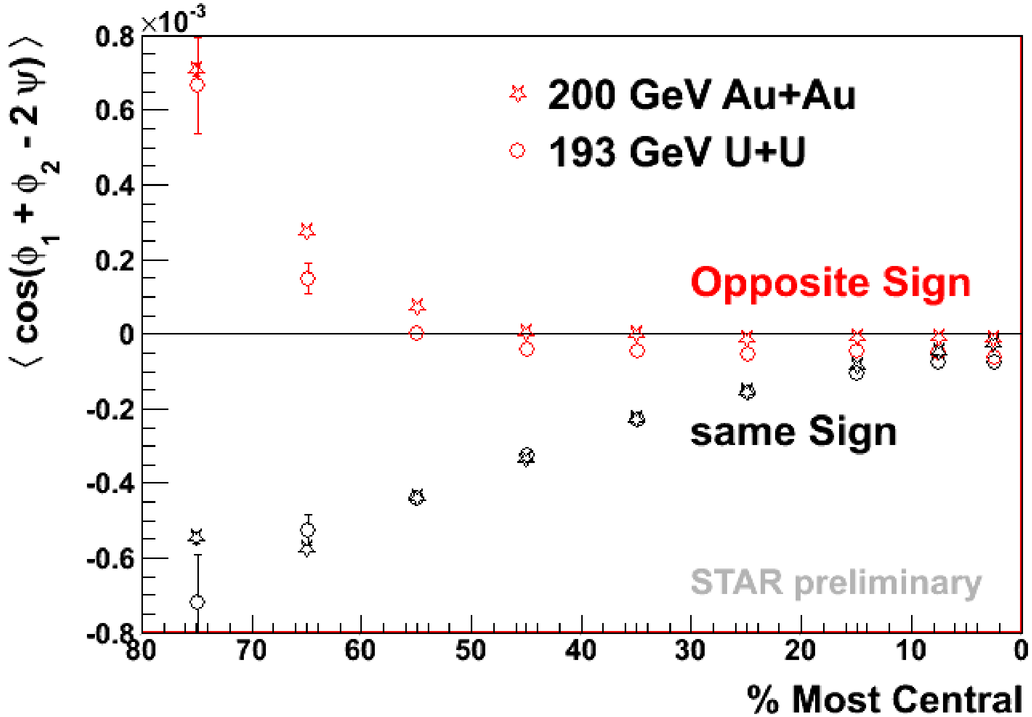
background effects

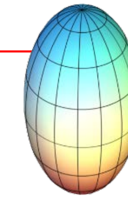
P-even quantity: sensitive to charge separation fluctuation

Background does not cancel !

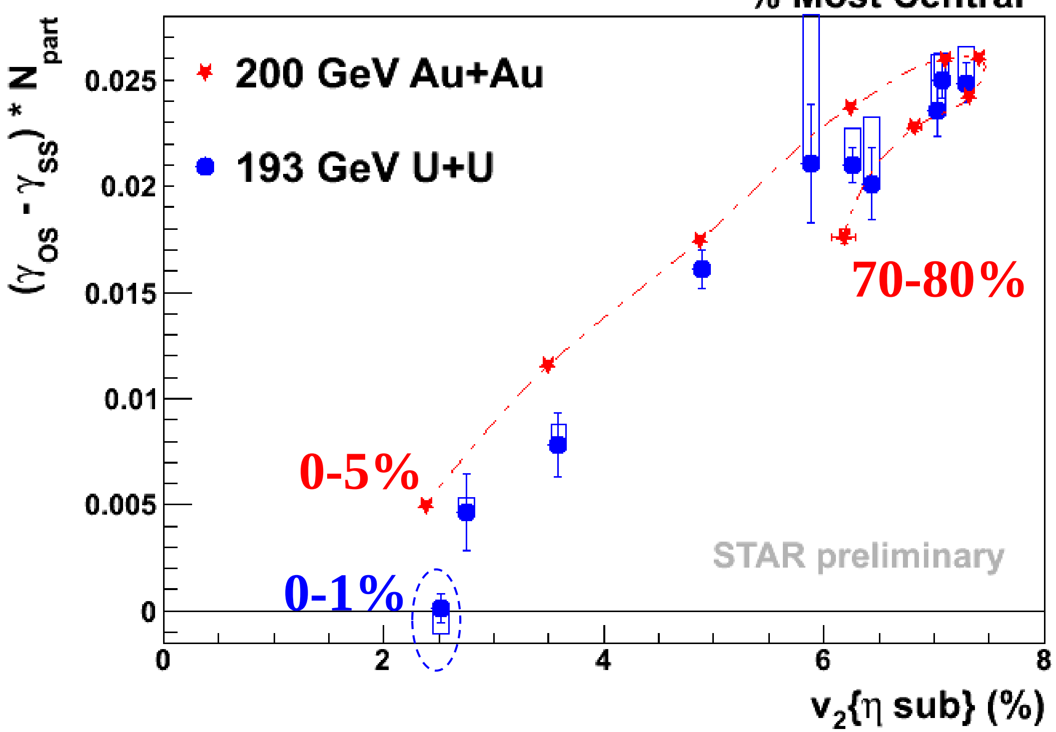
OS-SS subtraction !

Deformed nuclei: U+U





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

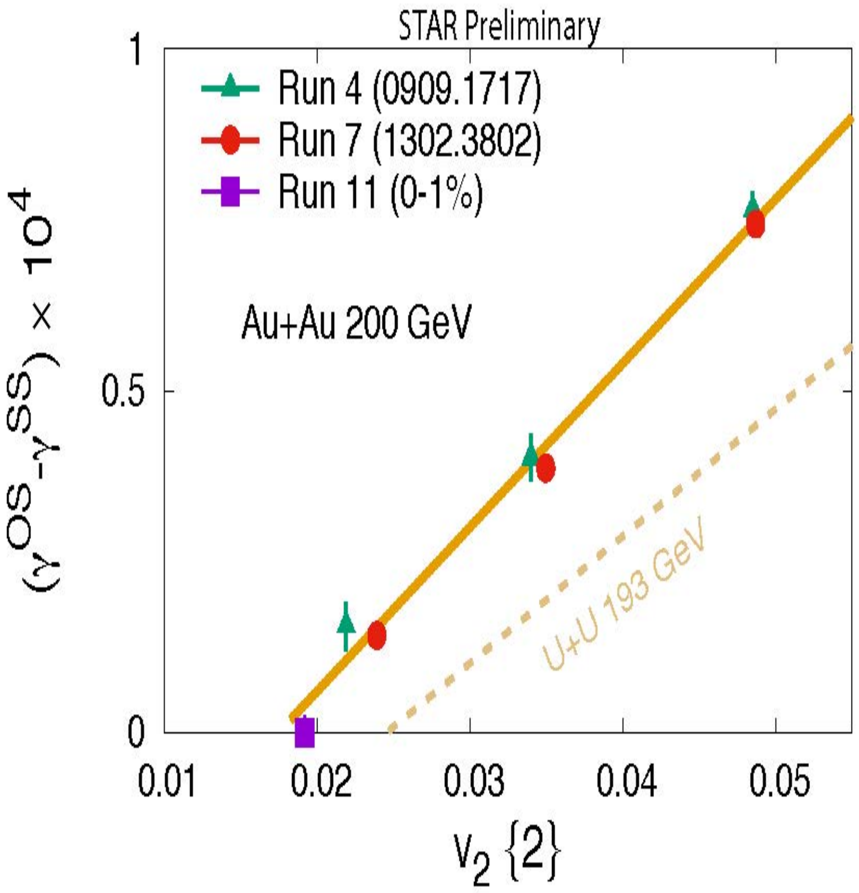


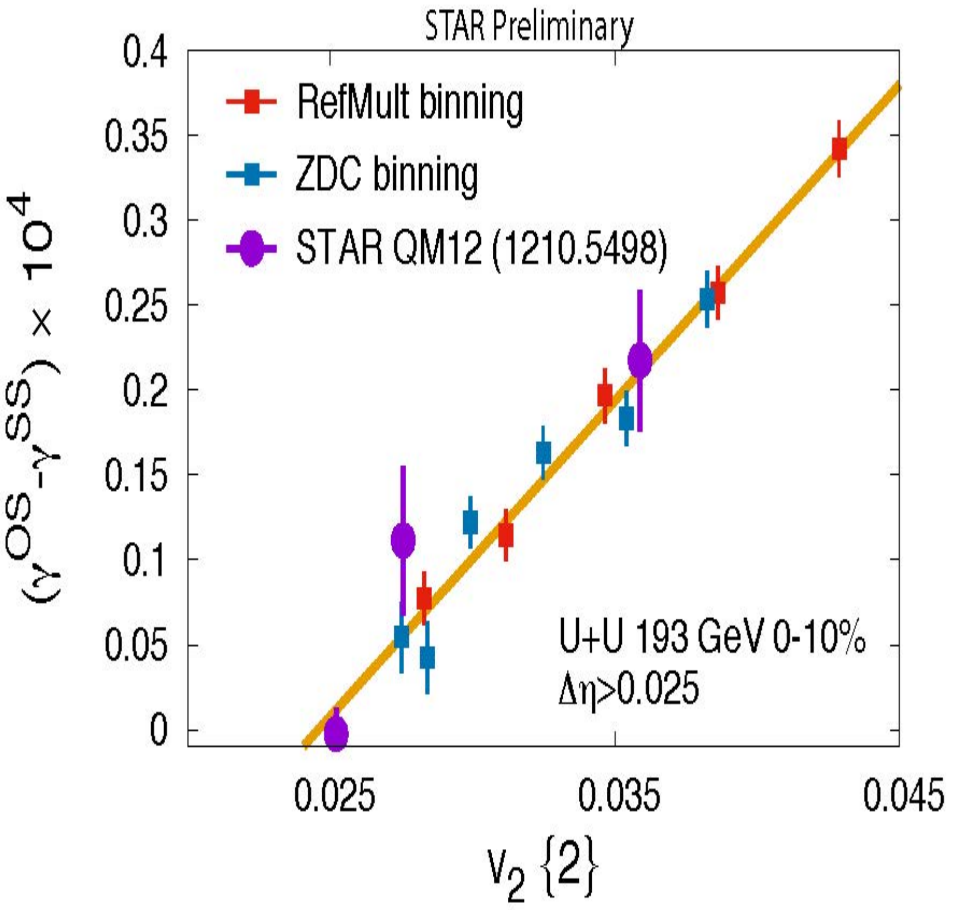
- A dedicated trigger for events with 0-1% spectator neutrons
- With magnetic field suppressed, the charge separation signal (mostly background) disappears, while v_2 is still ~2.5%

Extrapolate to intermediate centrality?

Isobar collisions may work better.

Details of Au+Au and U+U Comparison

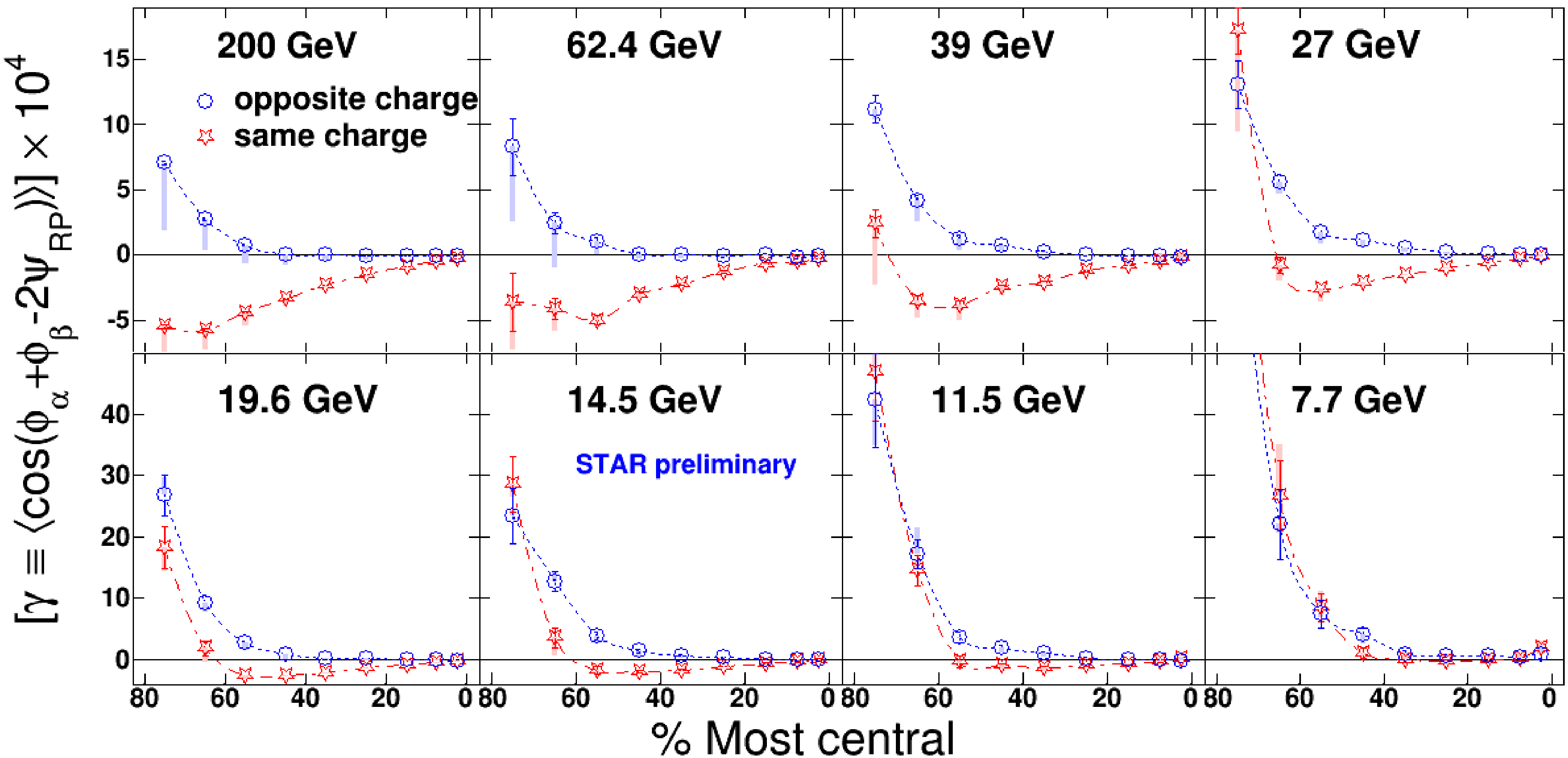




What/Where is Pratt v_2 induced background?

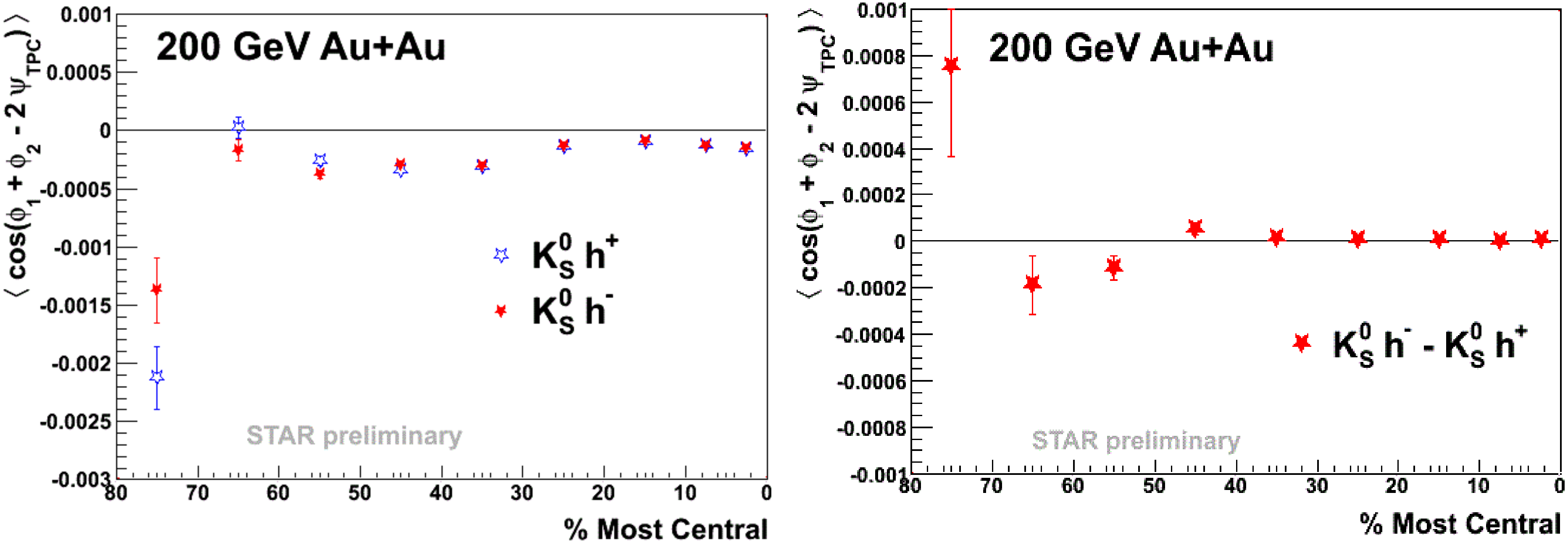
Beam Energy Scan

Phys. Rev. Lett 113 (2014) 052302



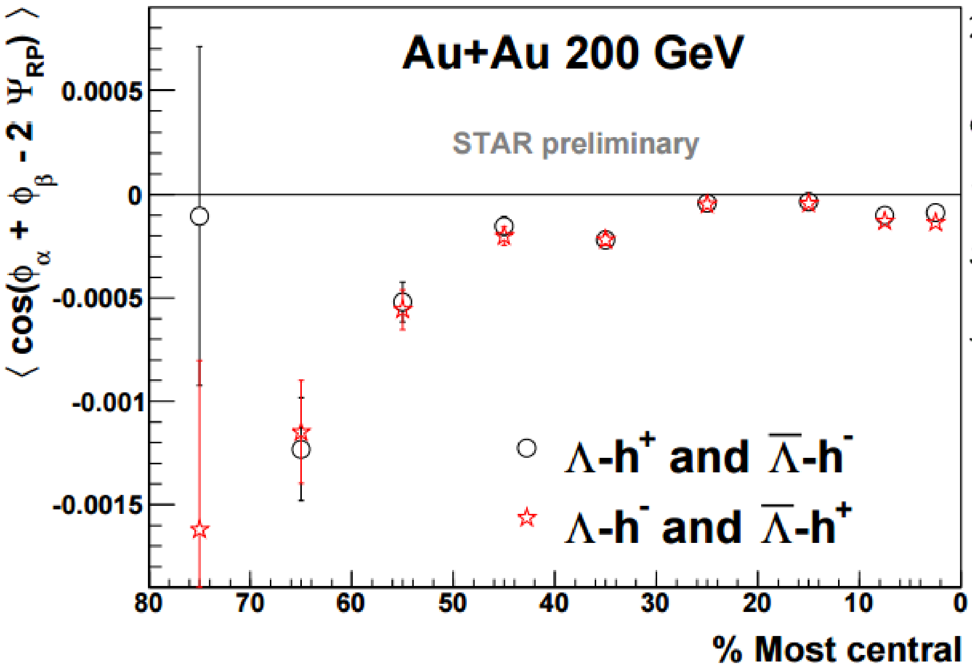
At lower beam energies, charge separation starts to diminish. Note v_2 is finite for charged hadrons at 7.7 GeV beam energy!

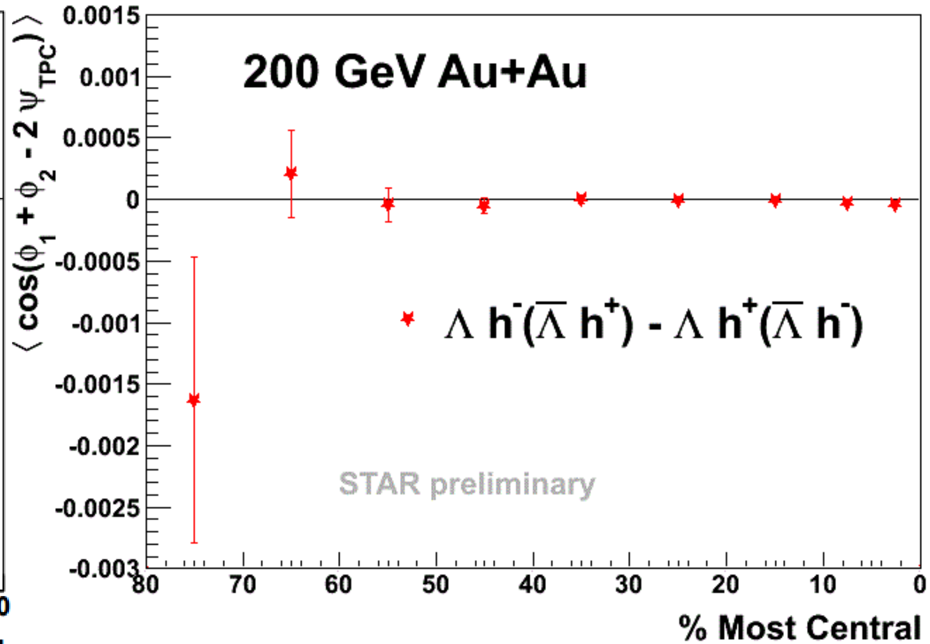
K^0_S-hadron correlation



- 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





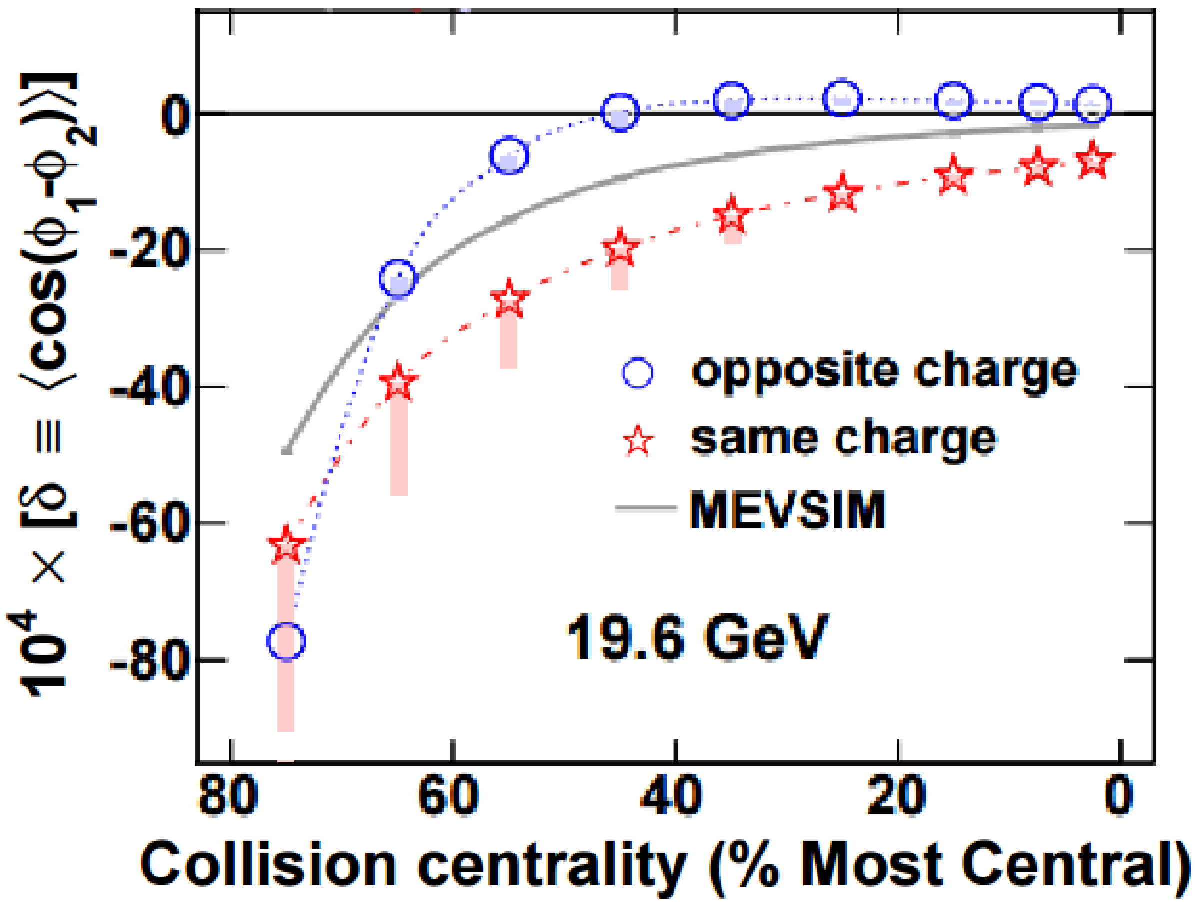
- Correlations of Λ-$h^{\pm}$ also show no charge-dependent separation (protons and antiprotons have been excluded from $h^{\pm}$)

- 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



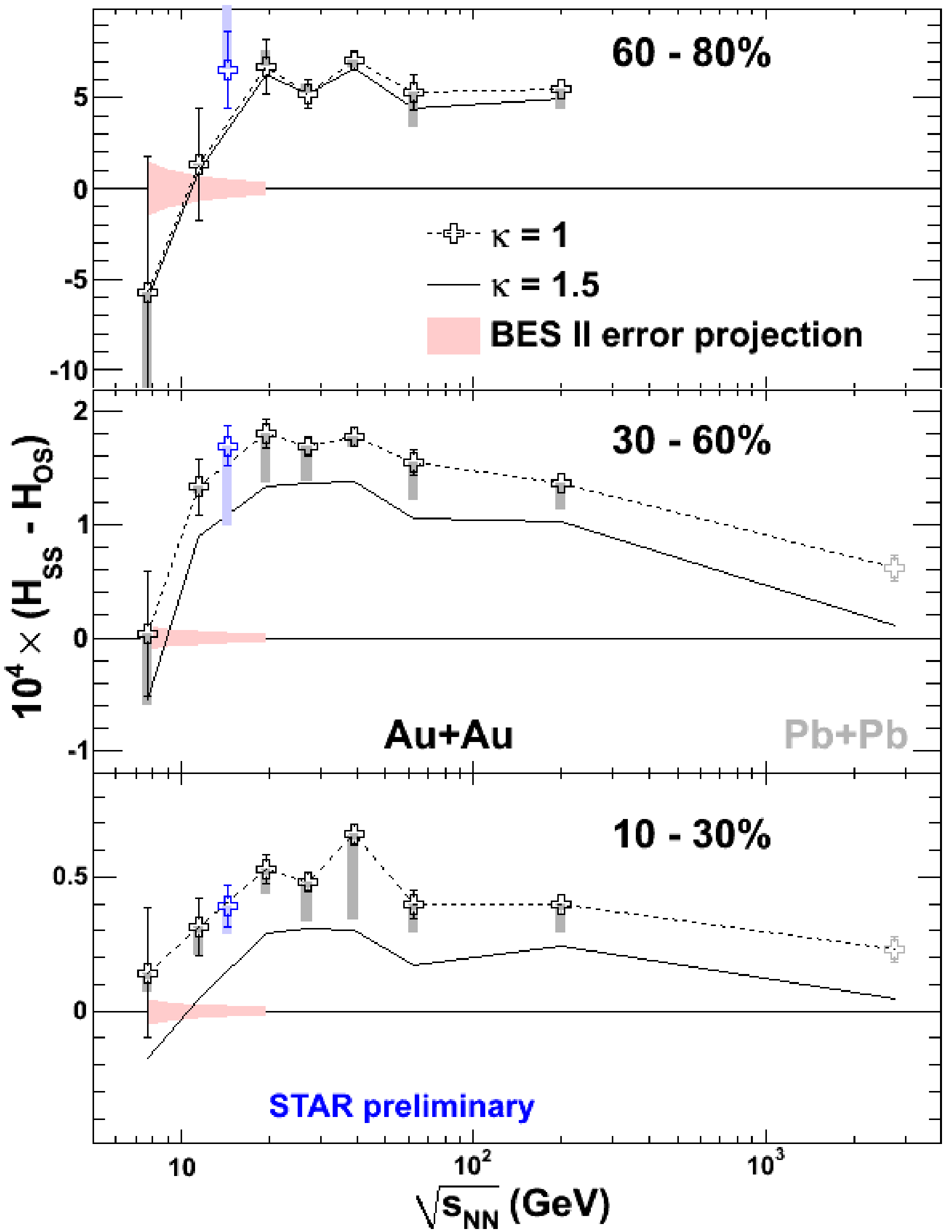
- Against CME expectation, $\delta_{OS} > \delta_{SS}$
- Indicate overwhelming background, larger than any possible CME effect.
- Try combining information from γ and δ to retrieve the CME contribution, *H*

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

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 (Δ*H*) decreases to 0 from 19.6 to 7.7 GeV
- The decomposition of γ into F and H is not unique

Summary on γ Measure

Sensitive to charge separation w.r.t RP

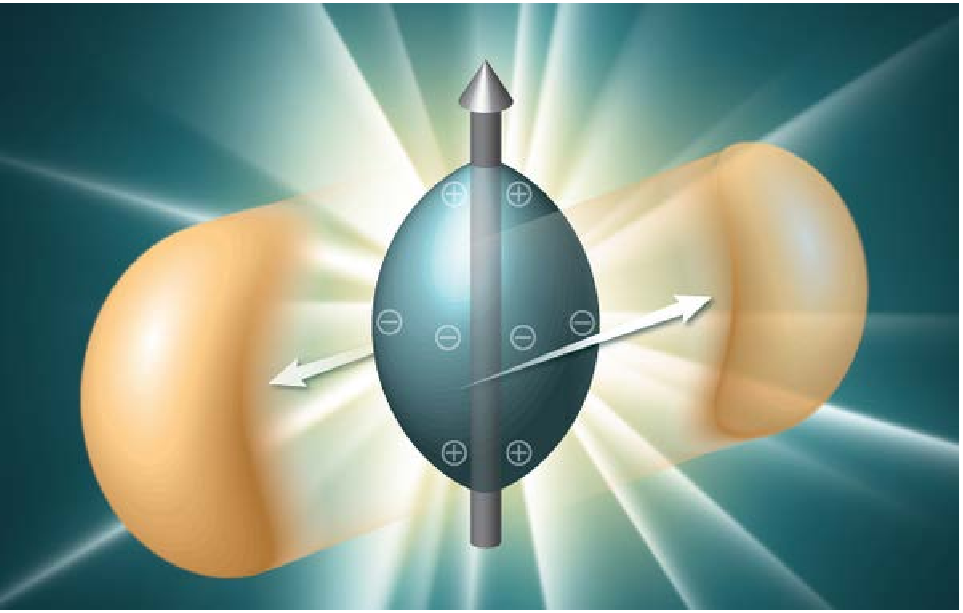
- comfirmed with different EP types (1st- and 2nd-order)
- observed in Au+Au, Cu+Cu, Pb+Pb and U+U collisions
- persist from 19.6 GeV to 2.76 TeV
- robust when suppressing HBT+Coulomb (not shown here)

The measured γ magnitude cannot be entirely due to v_2 induced background (e.g. Pratt model)

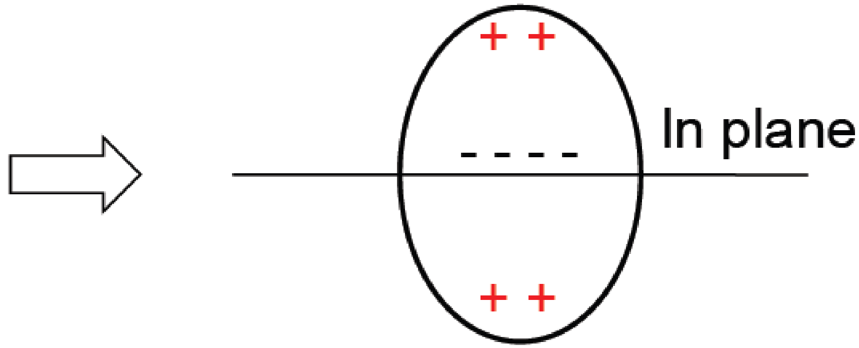
γ seems to disappear when

- 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

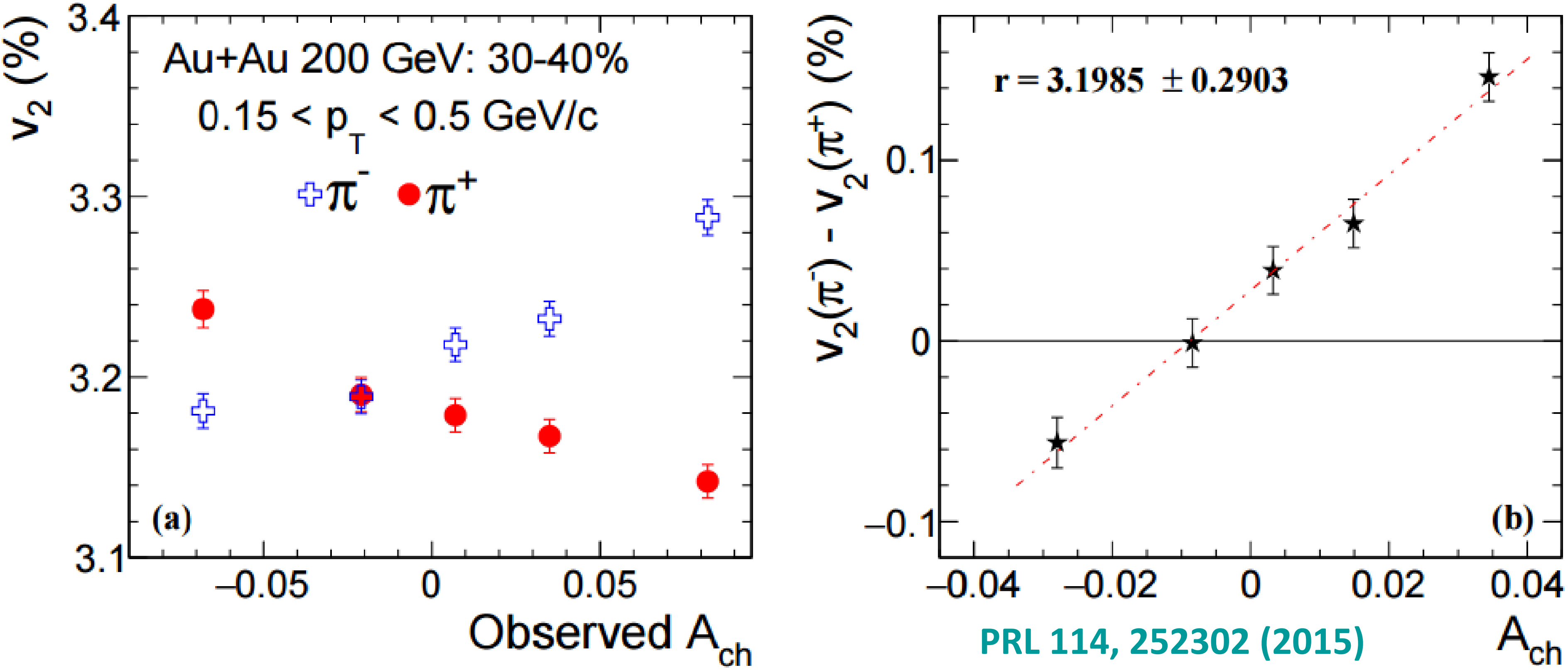
Formation of electric quadrupole: $v_2^{\pm} = v_2^{\text{base}\pm} \mp \left(\frac{q_e}{\bar{\rho}_e}\right) A_{\text{ch}}$,

net charge density

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

Then π^- v_2 should have a positive slope as a function of A_{ch}, and π^+ 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 $v_2\{2\}$

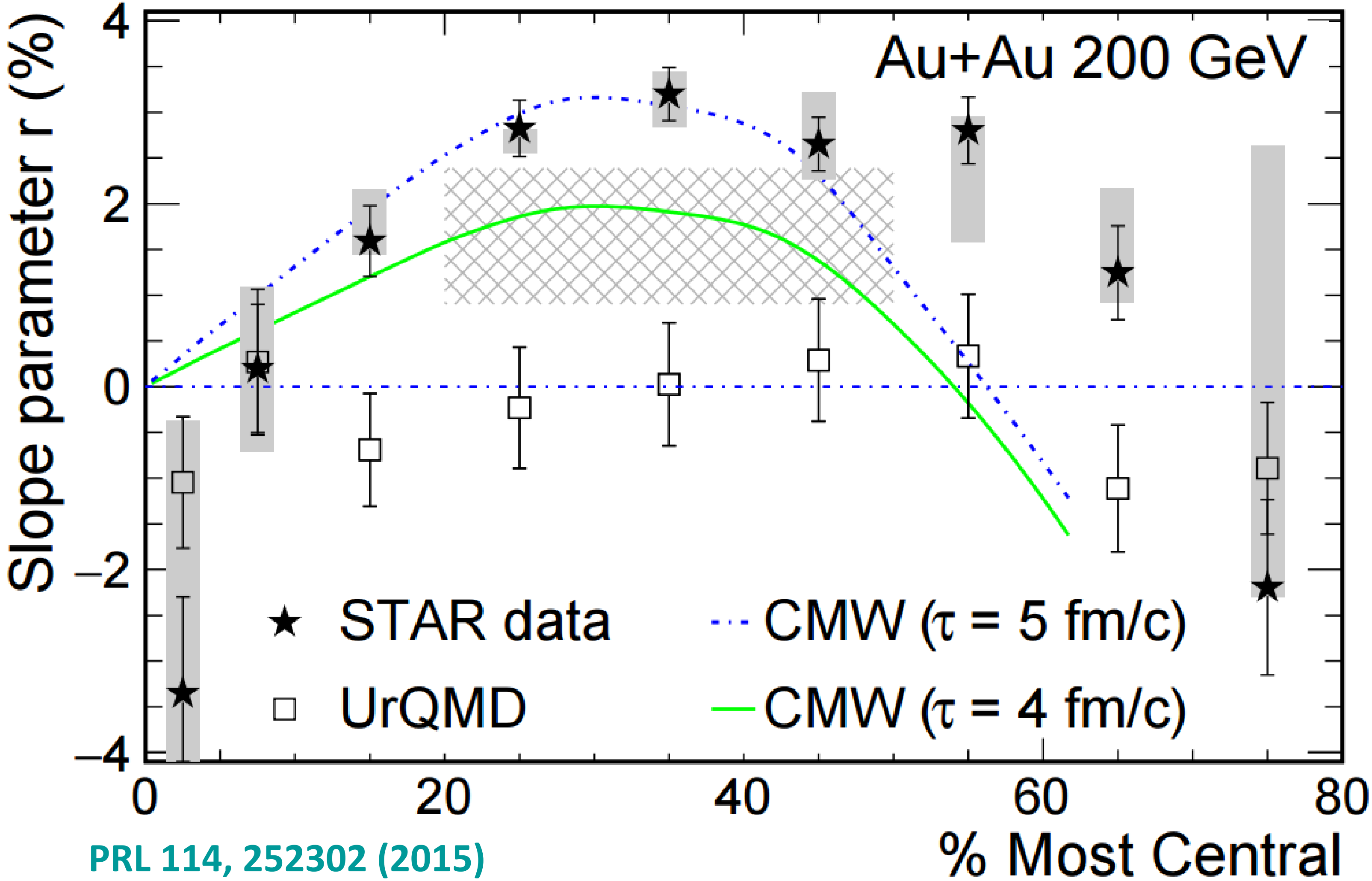
- $v_2(A_{ch})$ slopes for $\pi^{\pm}$:
  - opposite sign
  - similar magnitude

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

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

Slope vs centrality

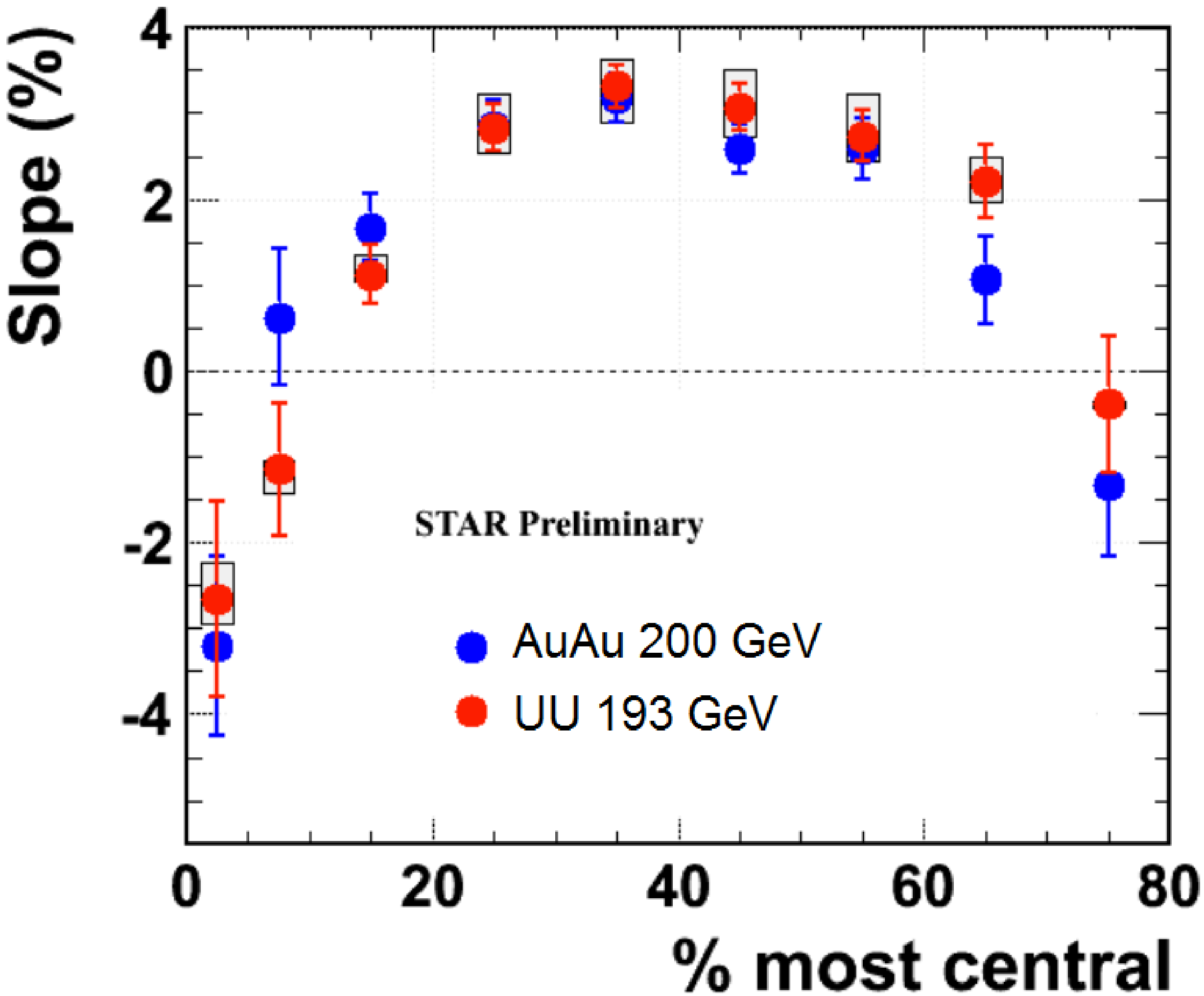
Y. Burnier, D. E. Kharzeev, J. Liao and H-U Yee, arXiv:1208.2537v1 [hep-ph].



PRL 114, 252302 (2015)

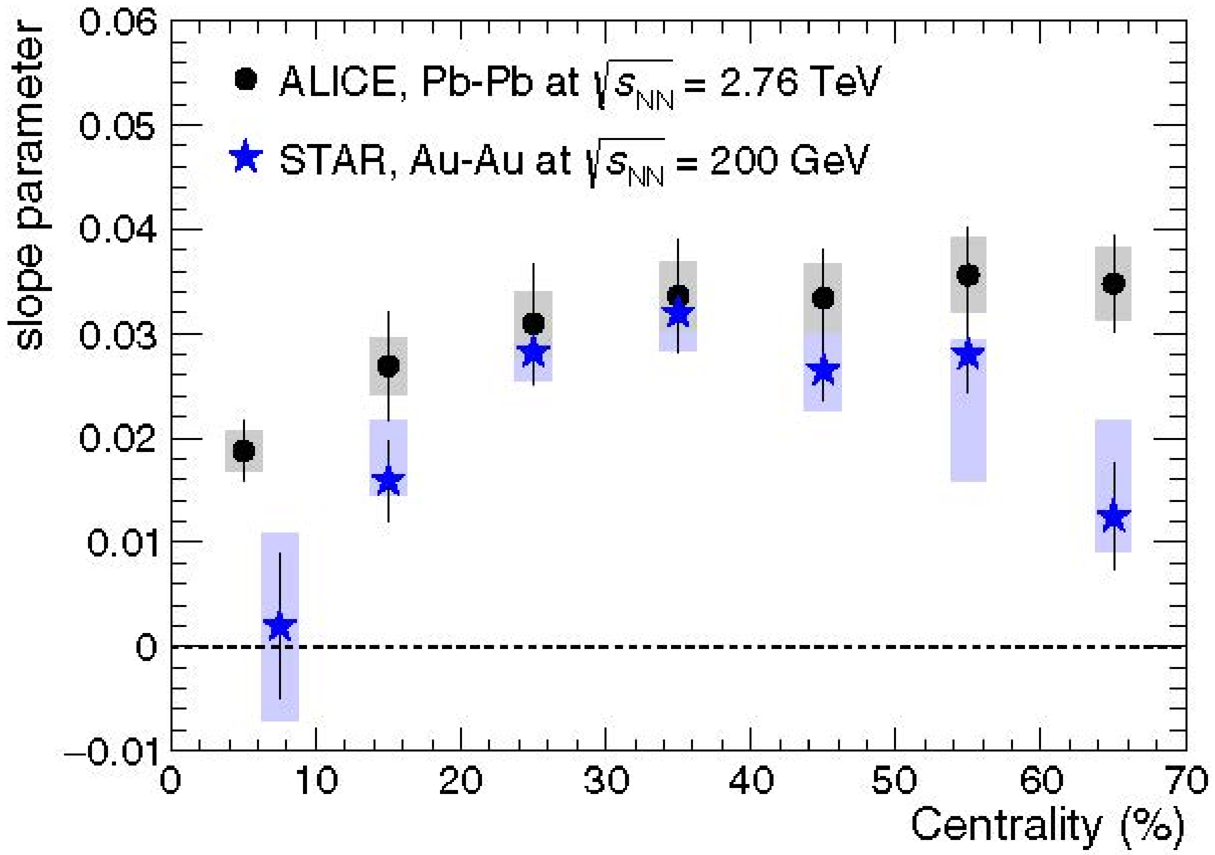
Similar trends between data and theoretical calculations with CMW.
UrQMD can not reproduce the slopes.

U+U and Au+Au



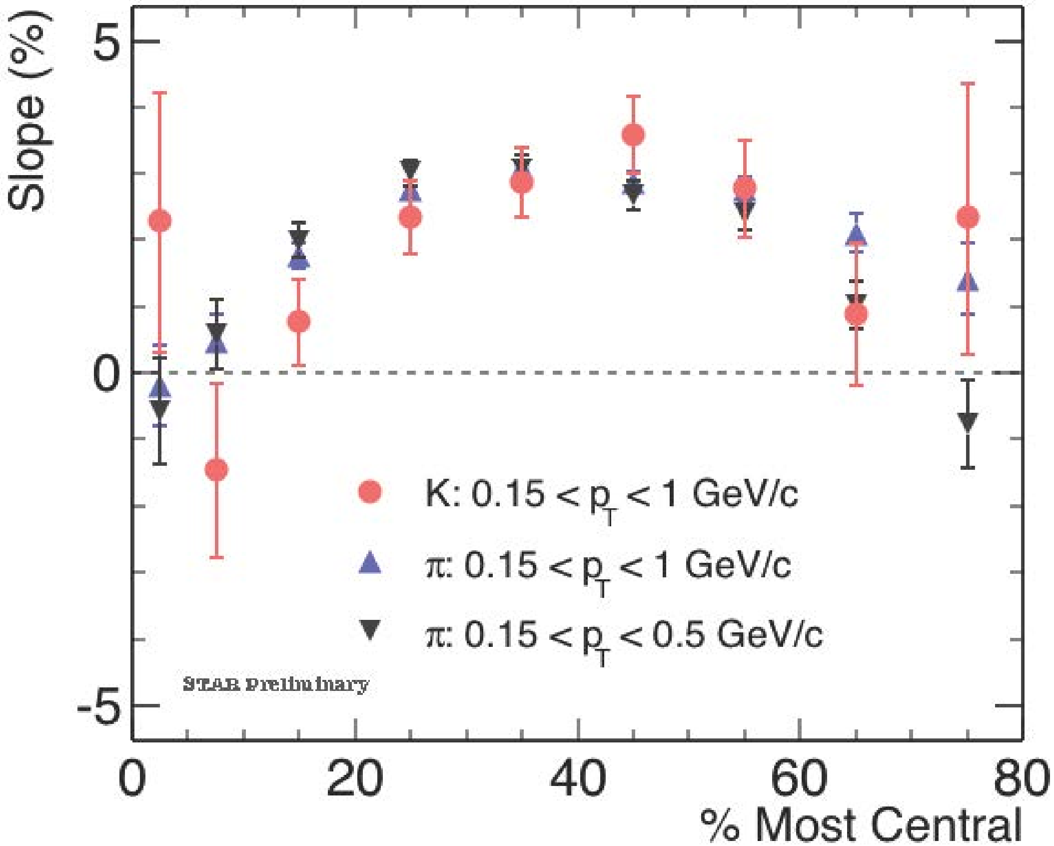
Similar pattern and magnitude seen in U+U collisions.

Similar Slope Parameters from ALICE and STAR



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

Kaon



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

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

Chiral Vortical Effect

Chiral Magnetic Effect vs **Chiral Vortical Effect**

Chirality Imbalance (μ_A)

Magnetic Field (ω μ_e) | Fluid Vorticity (ω μ_B)

↓ | ↓

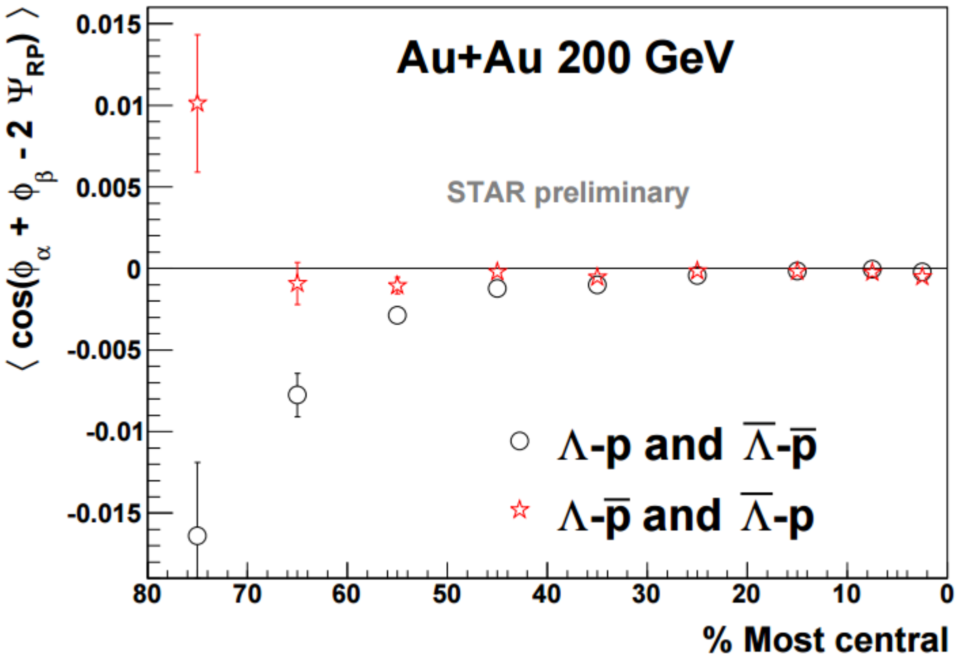
Electric Charge (j_e) | Baryon Number (j_B)

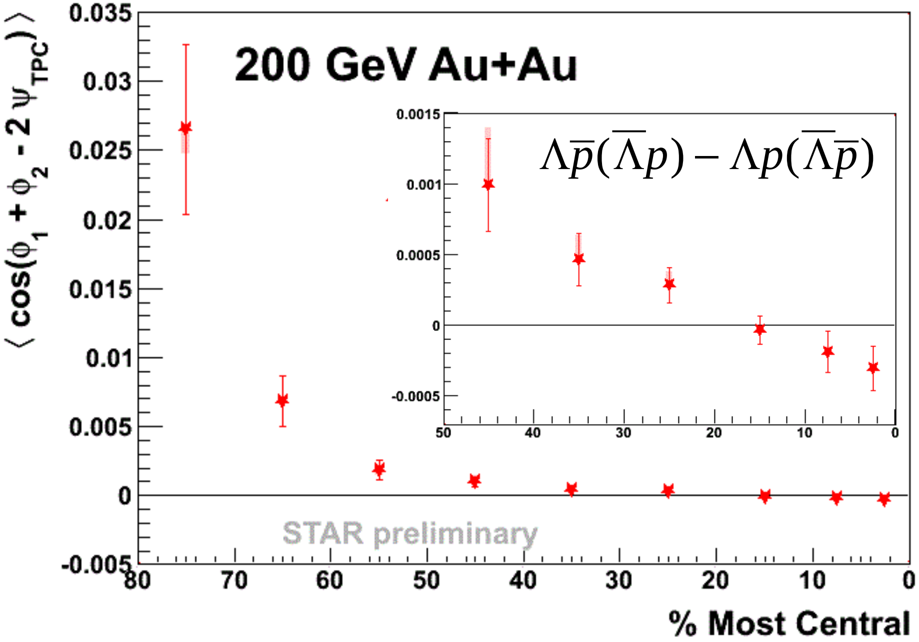
D. Kharzeev, D. T. Son, PRL 106 (2011) 062301

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

correlate Λ–p to search for the Chiral Vortical Effect

Λ-proton correlation



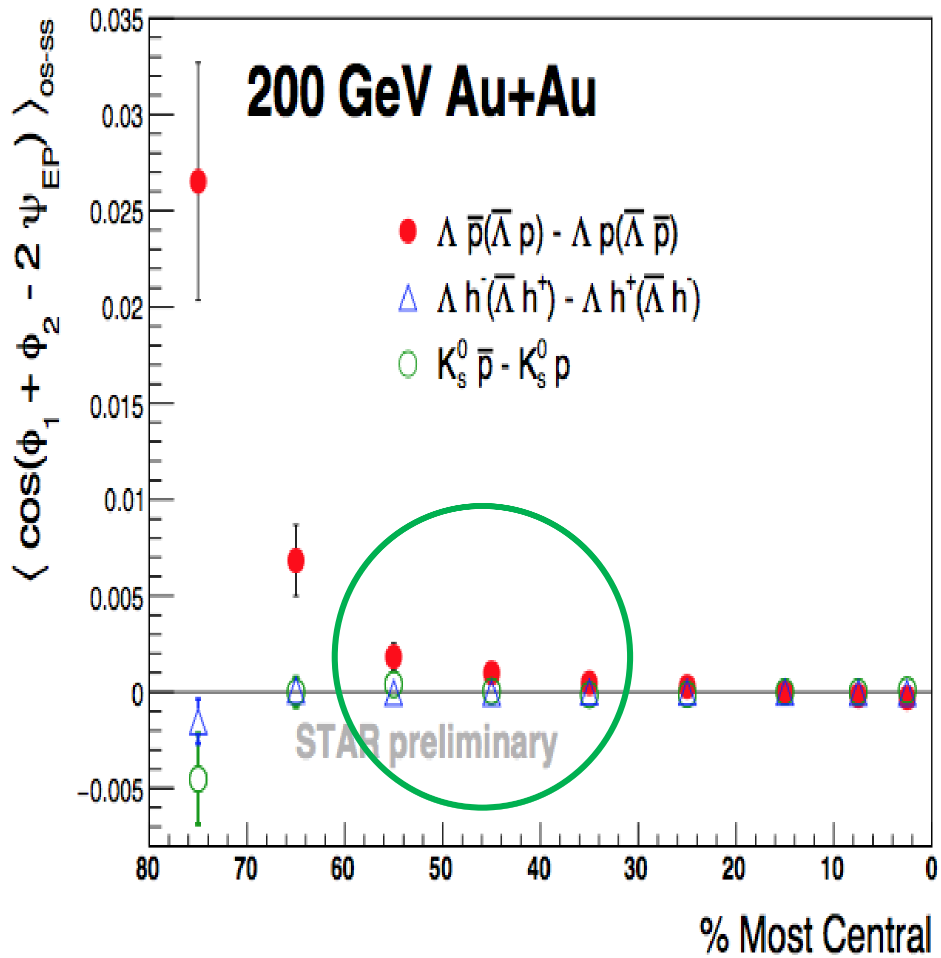


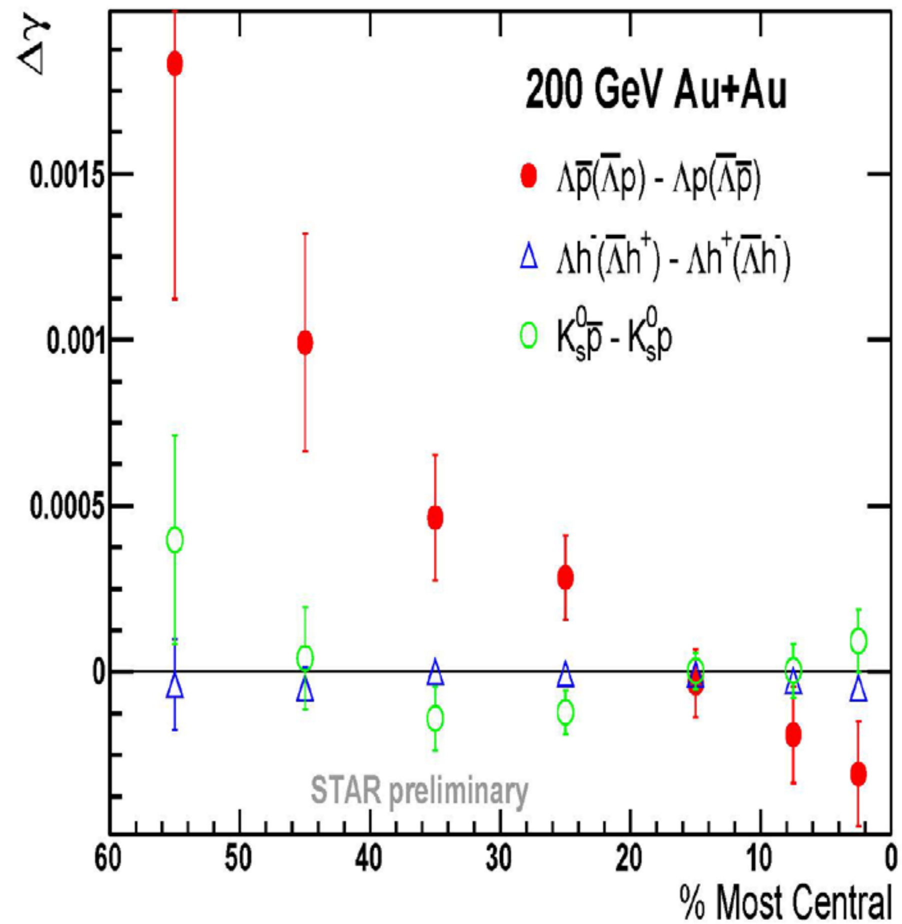
❖ same baryon number: Λp and $\bar{\Lambda}\bar{p}$

❖ 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



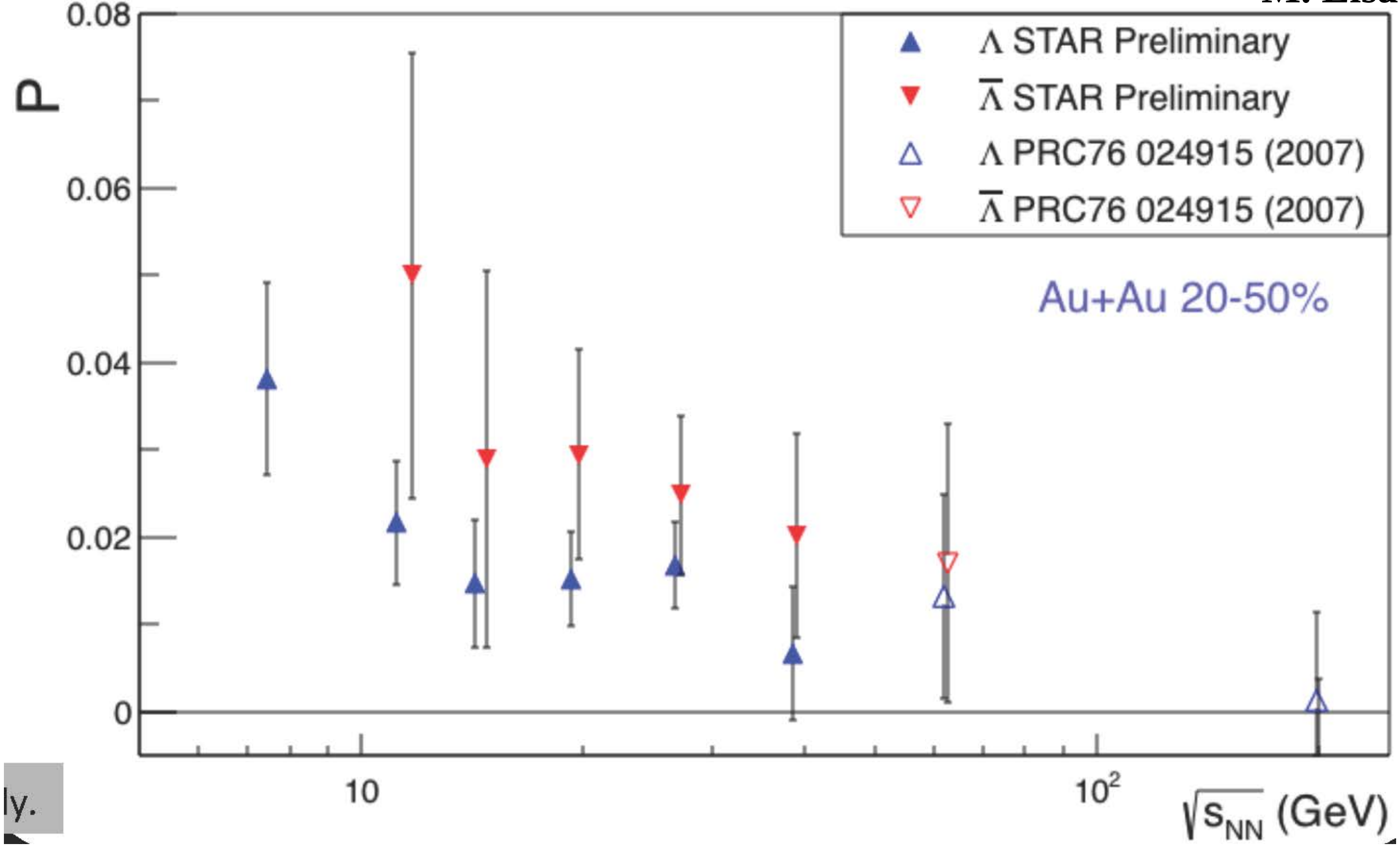


Λ-p correlation – different from Λ-h and K_S-p?

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:

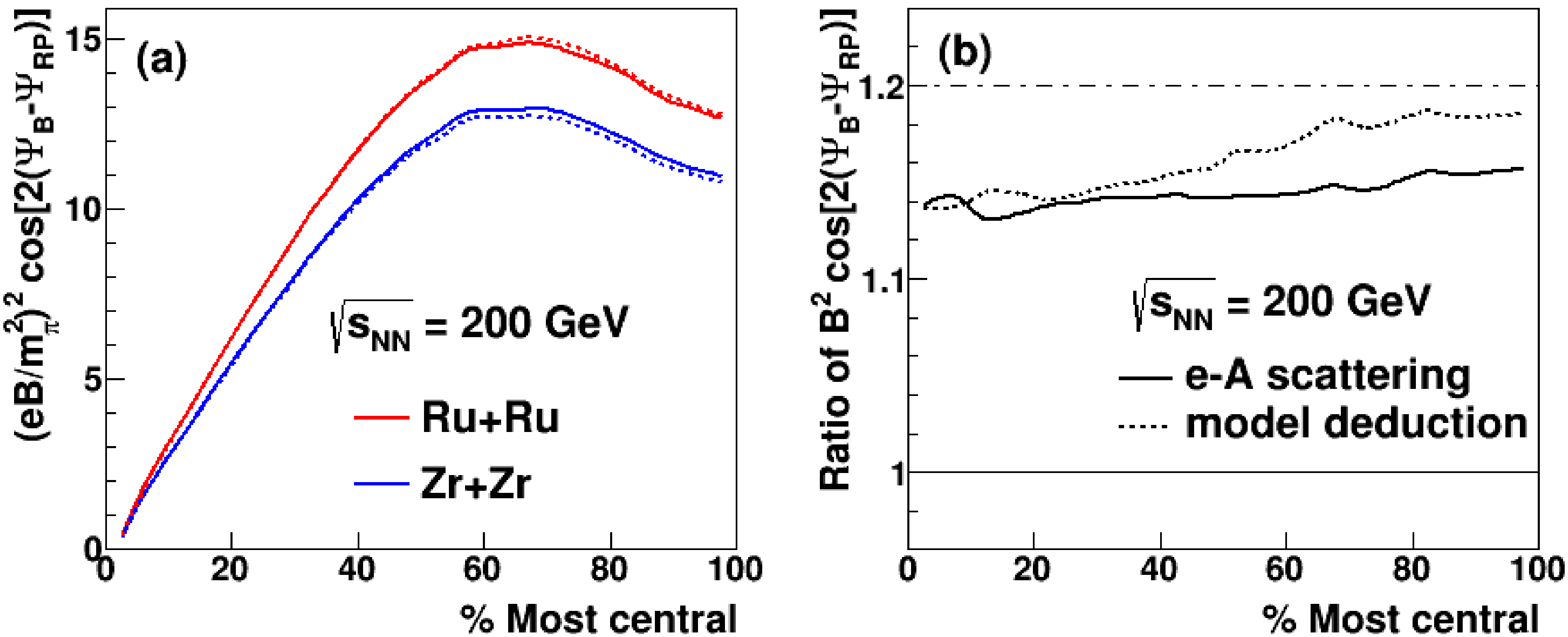
Up to 10% variation in B field

	$^{96}_{44}Ru+^{96}_{44}Ru$ 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 β_2
- The ratio in B^2 is close to 1.2 for peripheral events
- Reduces to 1.14 for central events

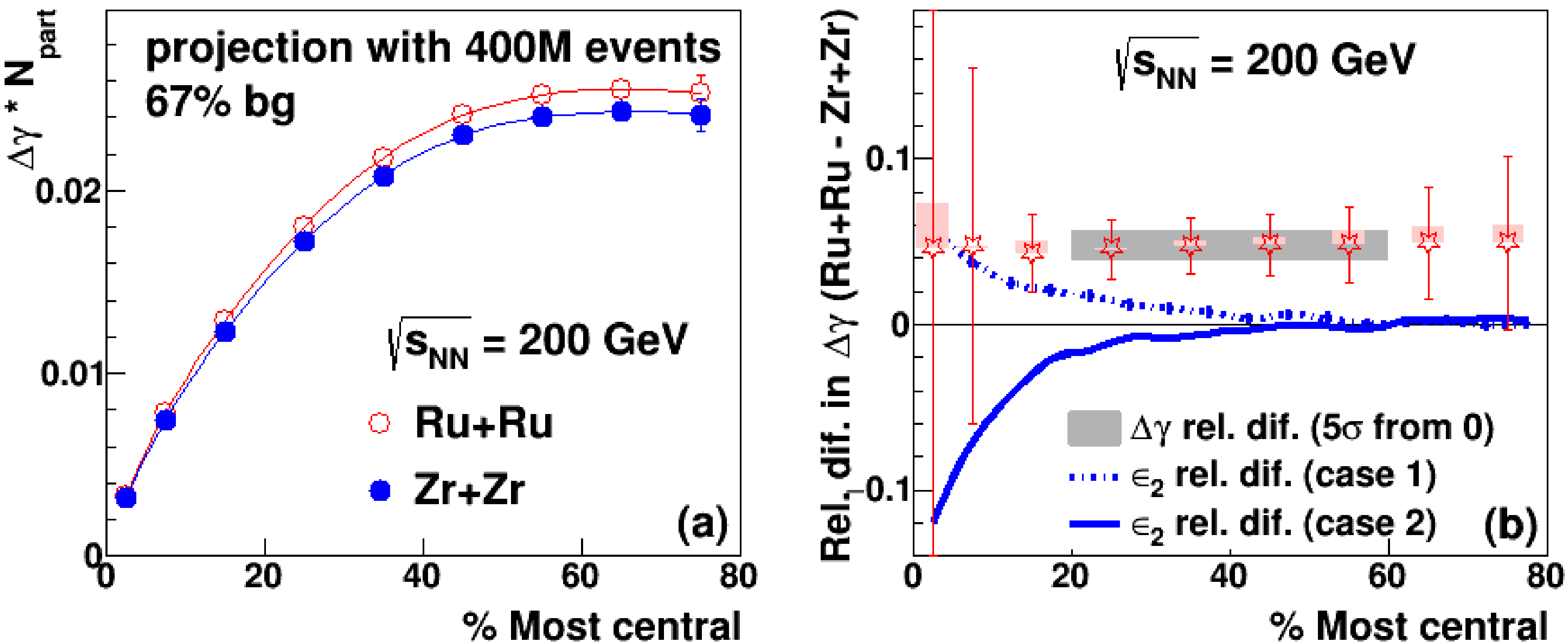
Courtesy of Xu-Guang Huang and Wei-Tian Deng



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

Future Perspectives:

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