Review and Outlook of the Search for Chiral Effects at STAR

Gang Wang (UCLA)

for the STAR Collaboration

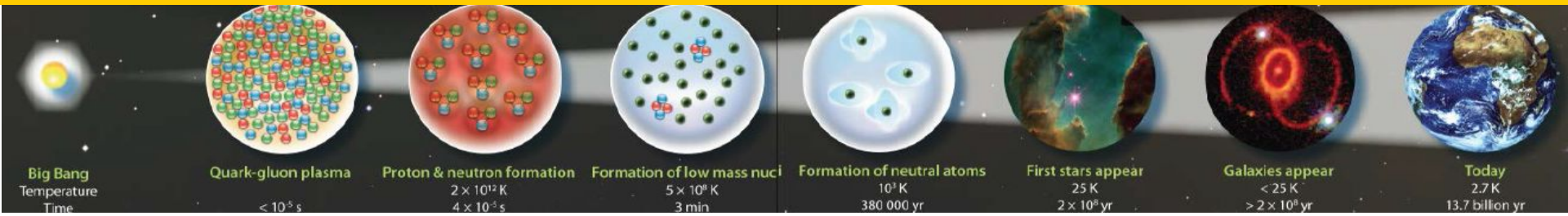
Outline

- Motivation
- STAR Results
  - Chiral Magnetic Effect (CME)
  - Chiral Magnetic Wave (CMW)
  - Chiral Vortical Effect (CVE)
- Outlook

Phys. Rev. Lett. 103(2009)251601:	276
Phys. Rev. C 81(2010)54908:	181
Phys. Rev. C 88(2013)64911:	8
Phys. Rev. C 89(2014)44908:	15
Phys. Rev. Lett 113(2014)052302:	19

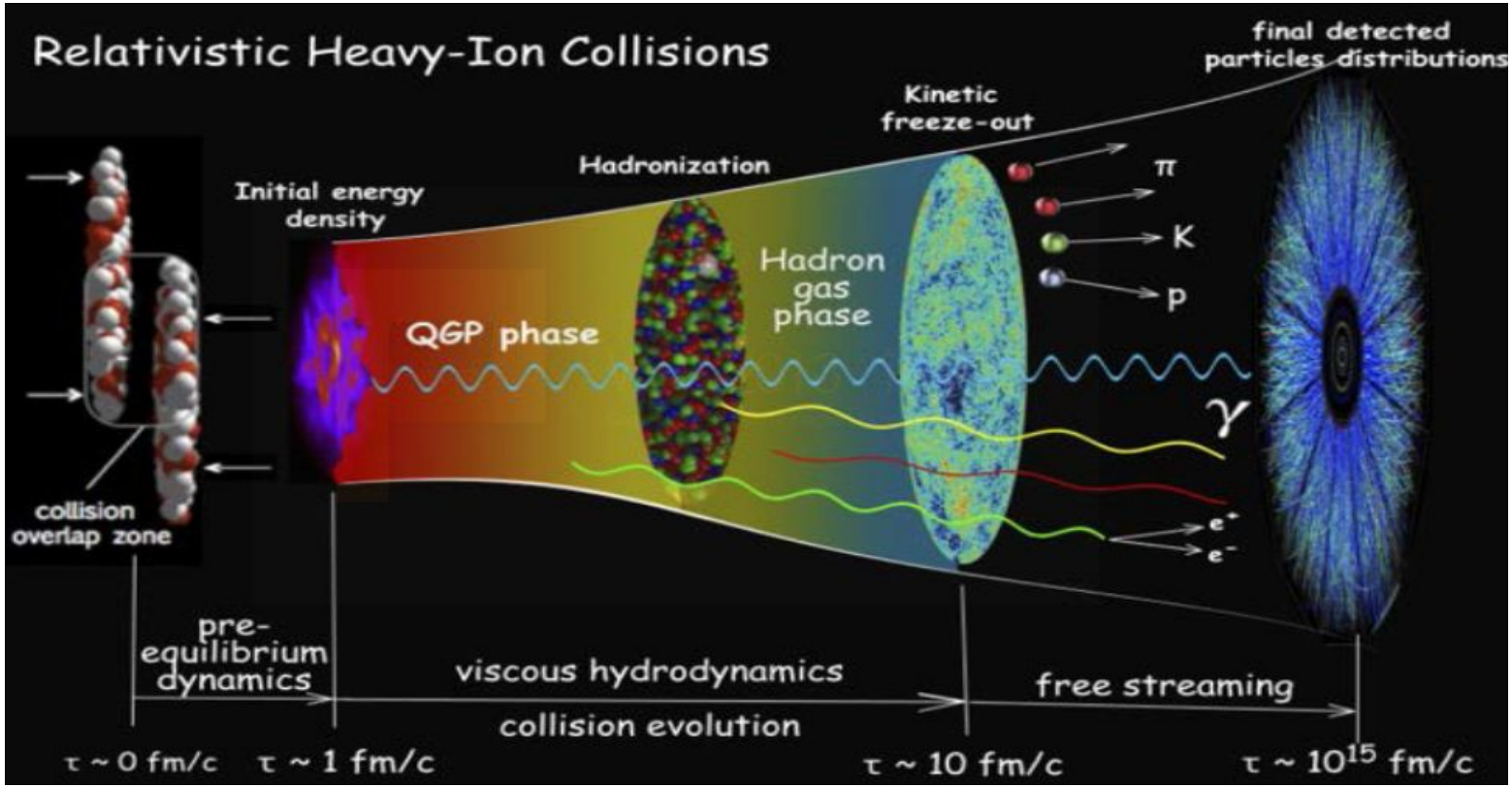
arXiv:1504.02175, accepted by PRL
PRL Editors' Suggestion

Big Bang & Little Bangs

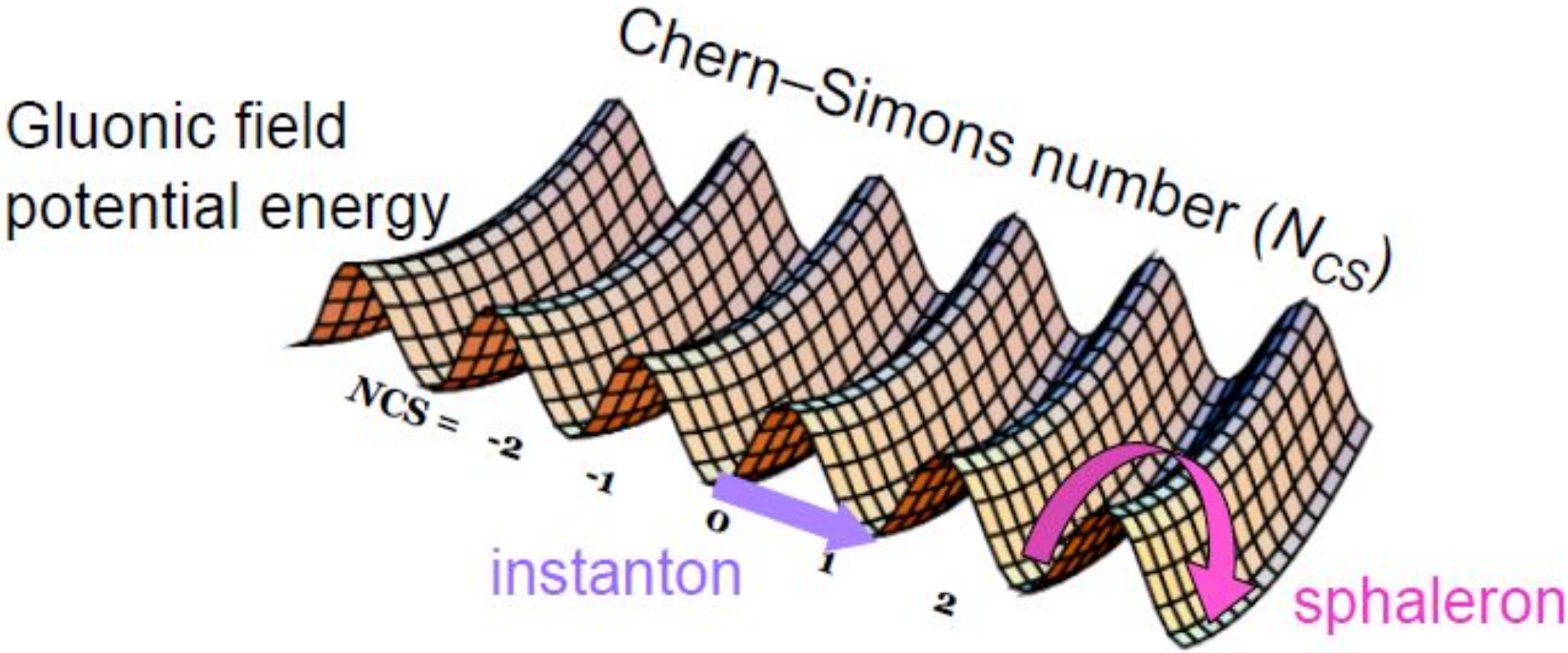


Vacuum transition may occur on a large scale or a small scale.

- we can learn from the Little Bangs



QCD vacuum transition



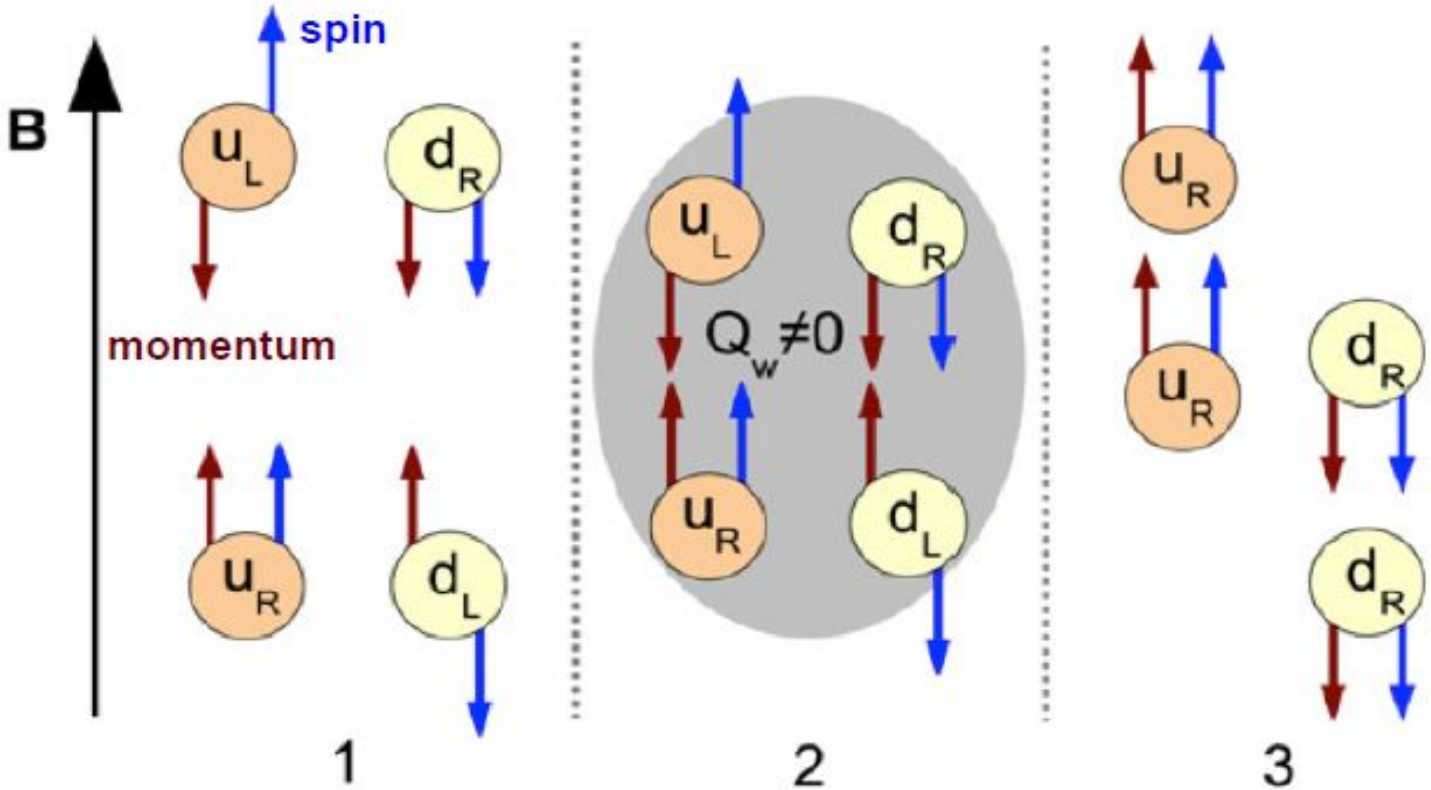
D. Diakonov, Prog. Part. Nucl. Phys. 51, 173 (2003)

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

QCD vacuum transition

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

Chiral Magnetic Effect



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

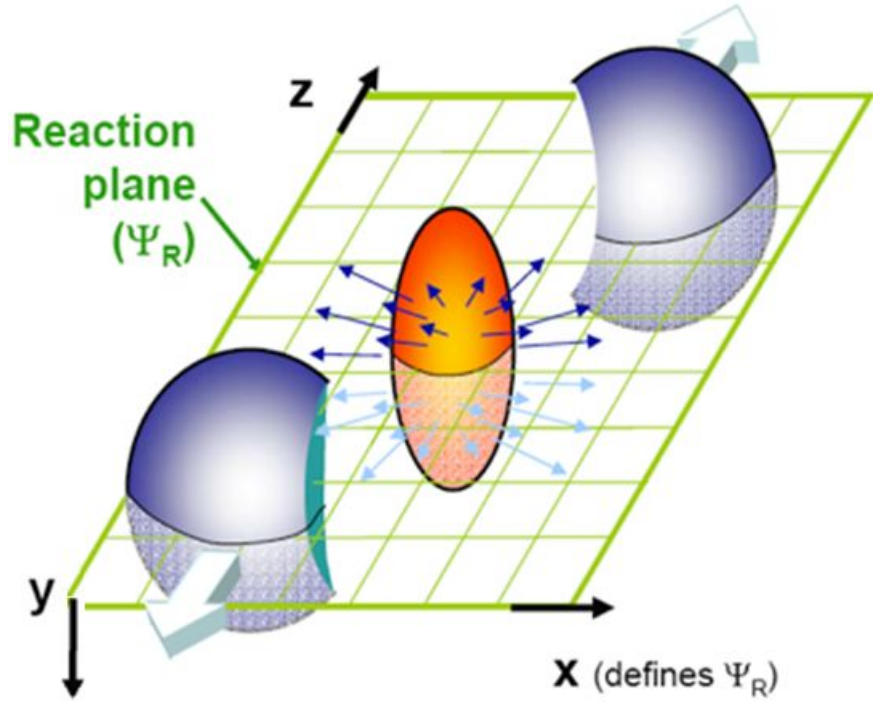
$$j_V = \frac{N_c e}{2\pi^2}\mu_A B$$ ➔ electric charge separation along *B* field

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

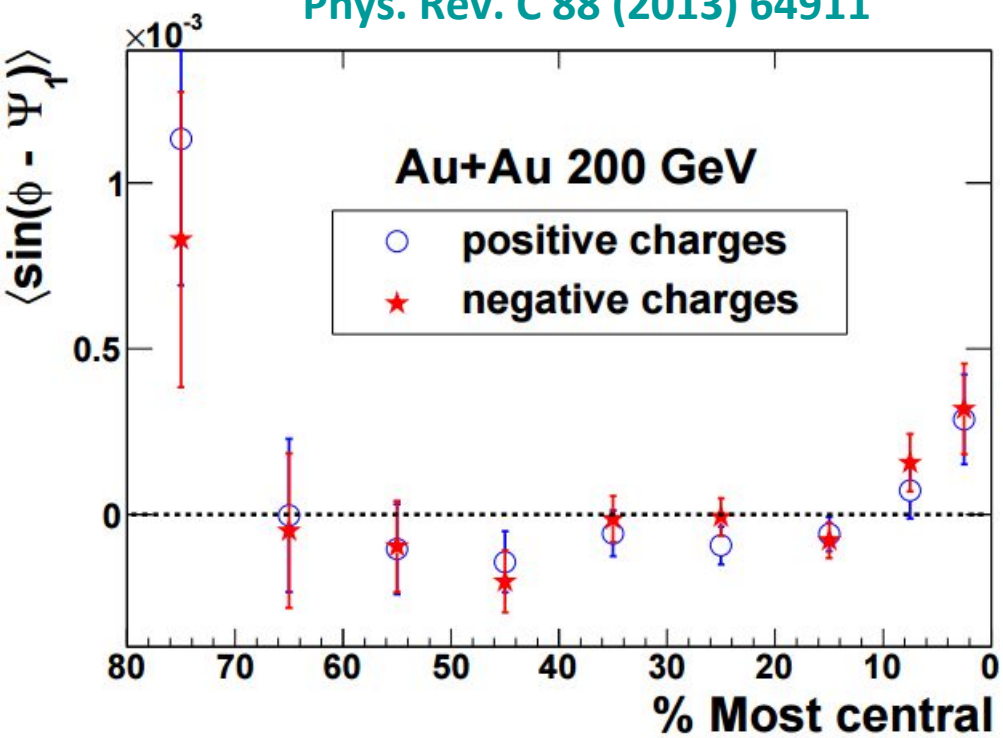
Local Parity Violation + CME

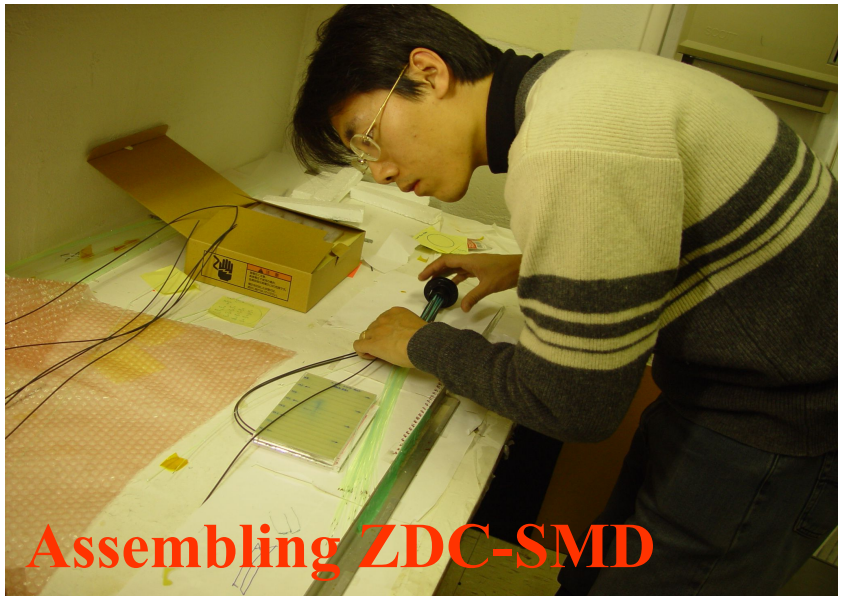
$$\frac{dN_{\pm}}{d\phi} \propto 1 + 2a_{\pm} \cdot \sin\left(\phi^{\pm} - \Psi_{RP}\right)$$

A direct measurement of the *P*-odd quantity *"a"* should yield *zero*.

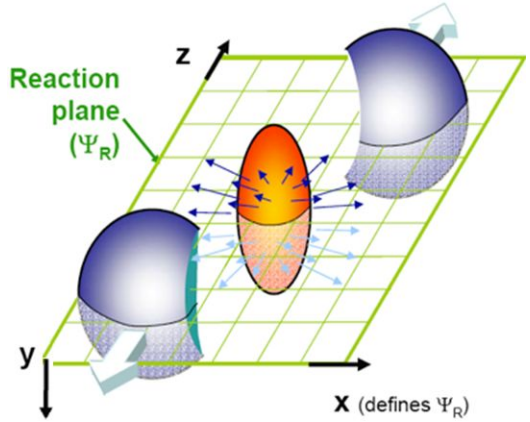


Phys. Rev. C 88 (2013) 64911

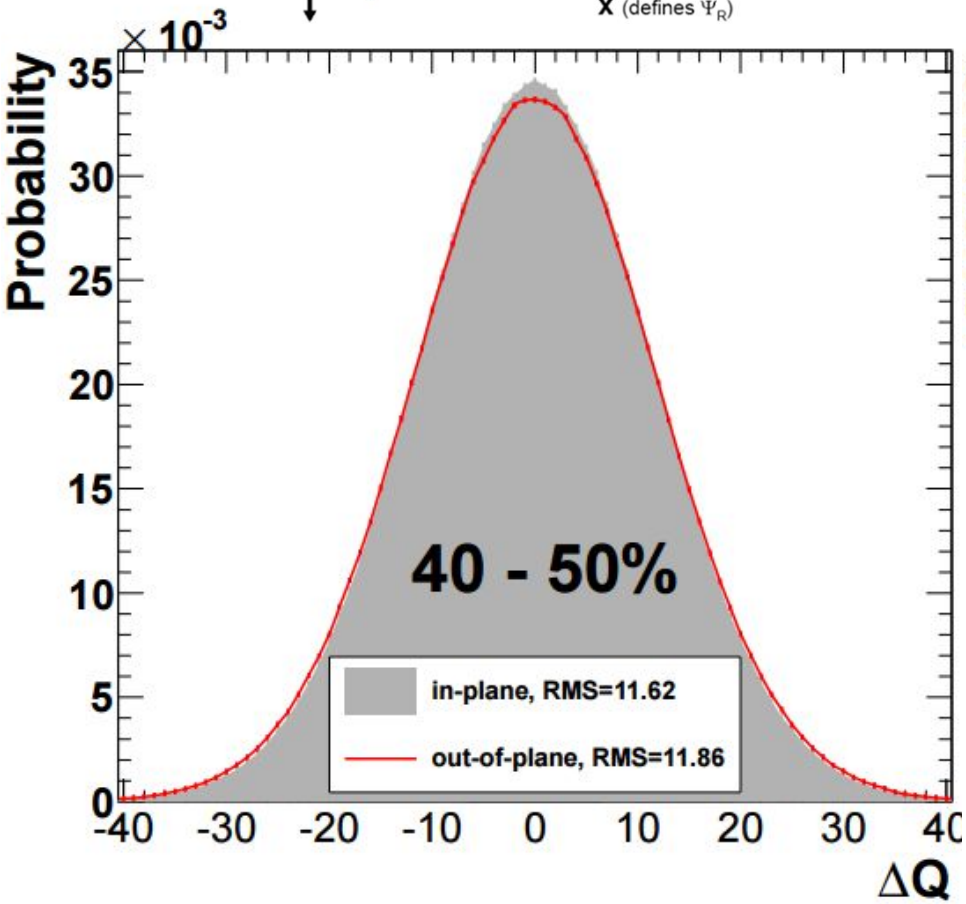


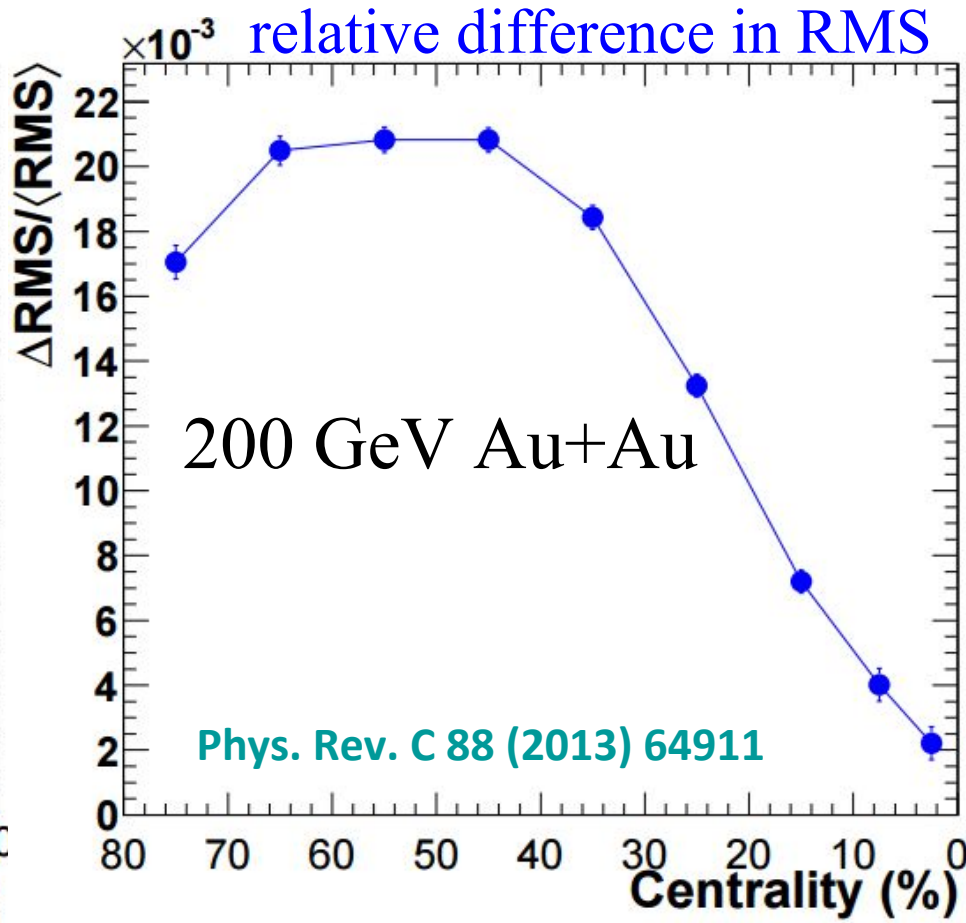


Visual evidence: fluctuation



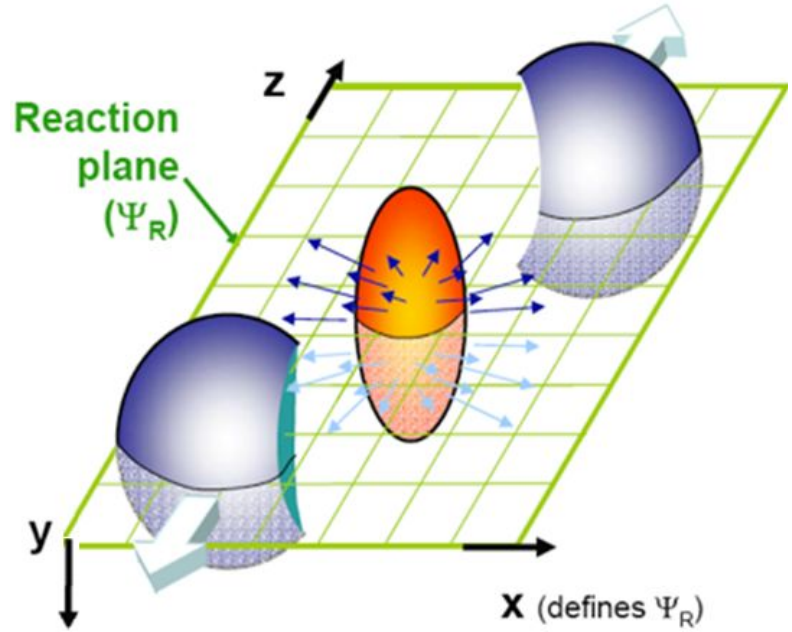
There should be more out-of-plane charge fluctuation than in-plane. *Indeed, we can visualize this effect, which is on percent level!*





γ correlator

A better way to quantify the extra charge fluctuation.



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

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

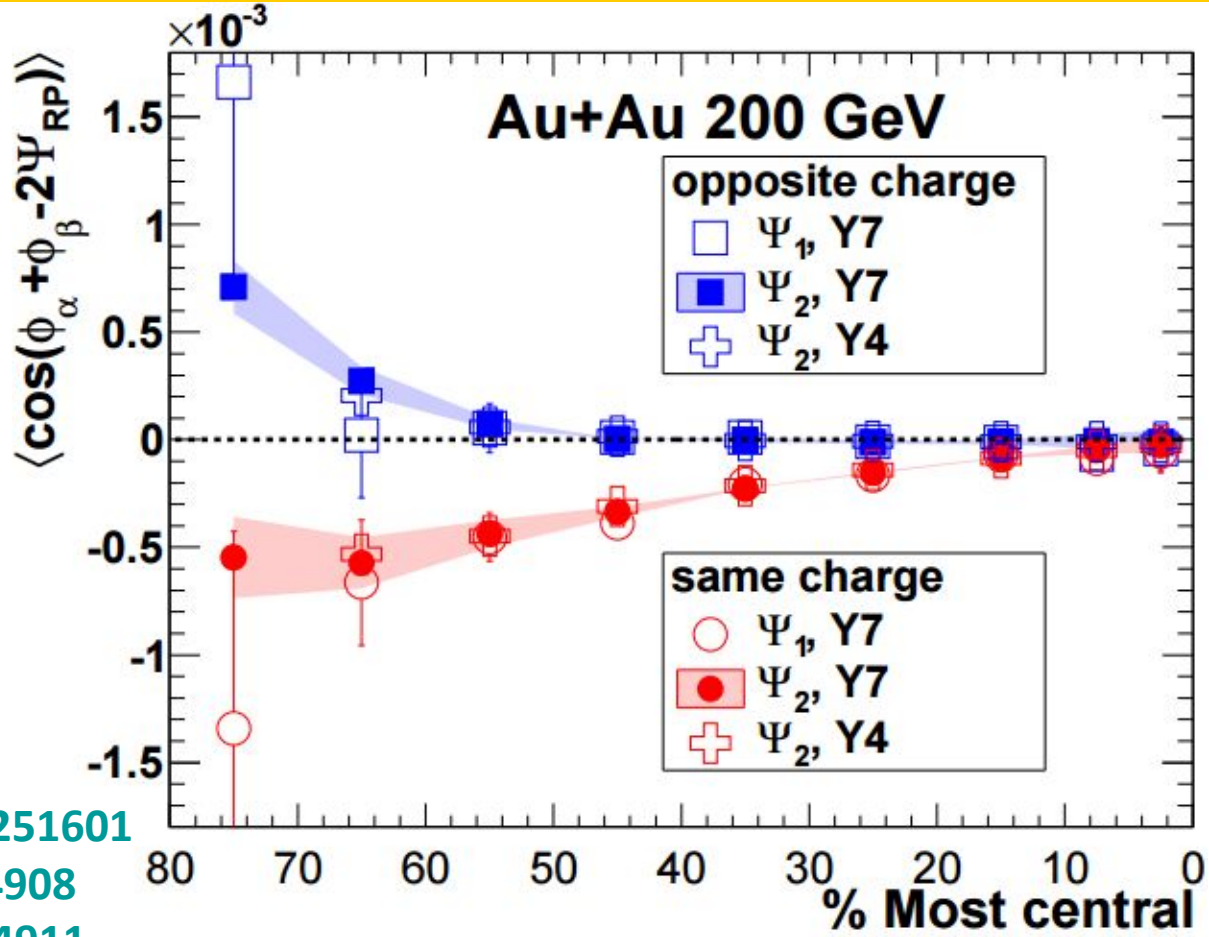
S. Voloshin, PRC 70 (2004) 057901

background effects: largely cancel out

Directed flow: expected to be the same for SS and OS

P-even quantity: still sensitive to charge separation

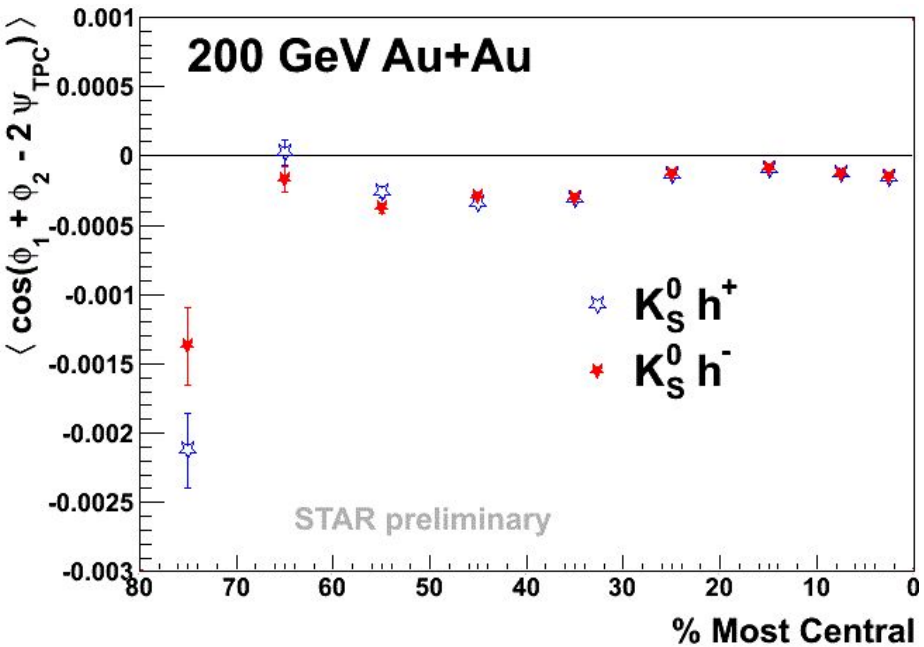
Charge separation signal

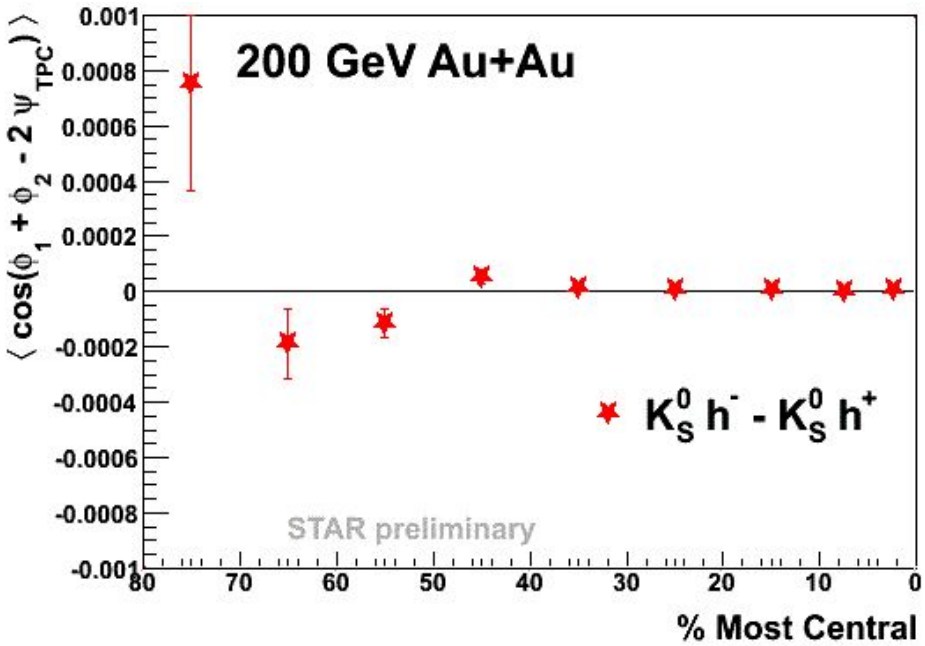


Phys. Rev. Lett. 103(2009)251601
Phys. Rev. C 81(2010)54908
Phys. Rev. C 88 (2013) 64911

- $\gamma_{os} > \gamma_{ss}$, 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

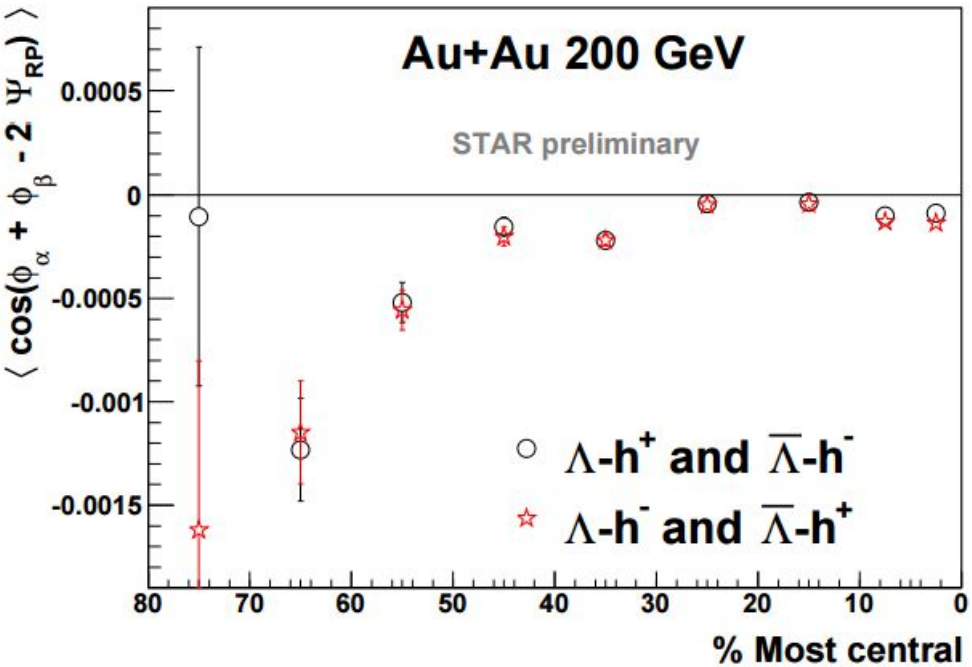
K^0_S-hadron correlation

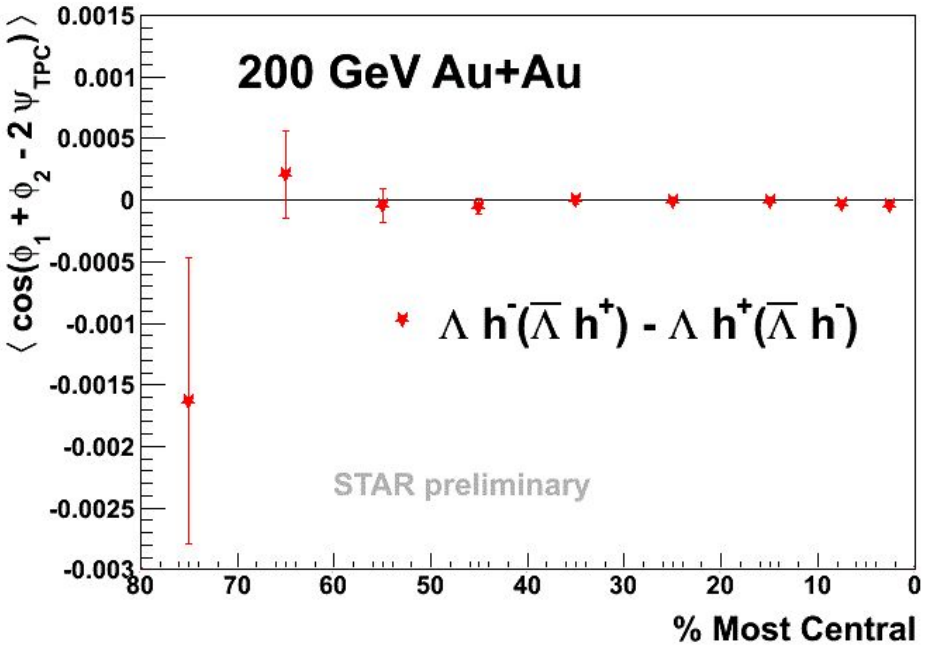




- Correlations of K^0_S-h^- and K^0_S-h^+ consistent with each other: no charge-dependent separation

Λ-hadron correlation





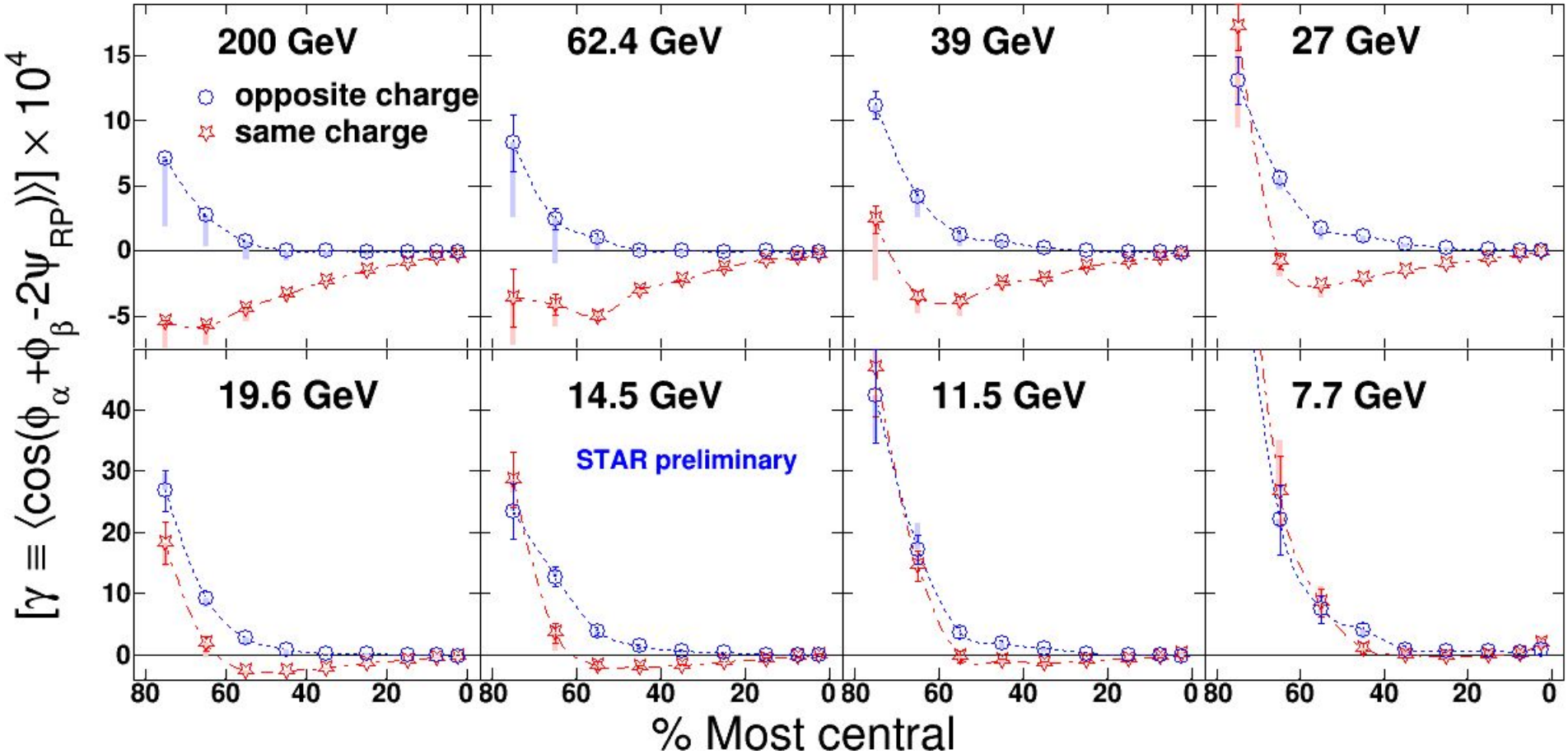
- Correlations of Λ-$h^{\pm}$ also show no charge-dependent separation (protons and antiprotons have been excluded from $h^{\pm}$)

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

- s quarks participate in the chiral dynamics in a similar way as u/d

Beam Energy Scan

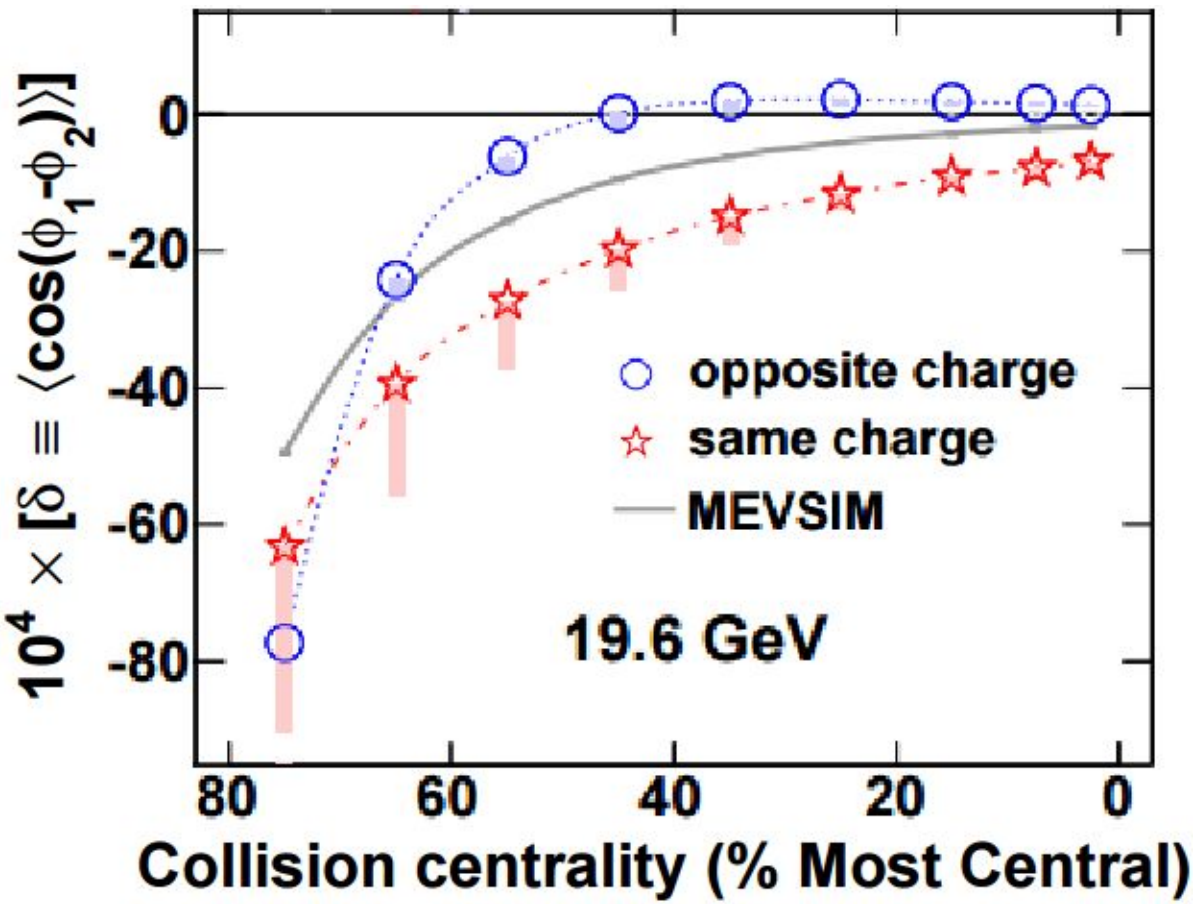
Phys. Rev. Lett 113 (2014) 052302



At lower beam energies, charge separation starts to diminish.

Flow-related background

Phys. Rev. Lett 113 (2014) 052302



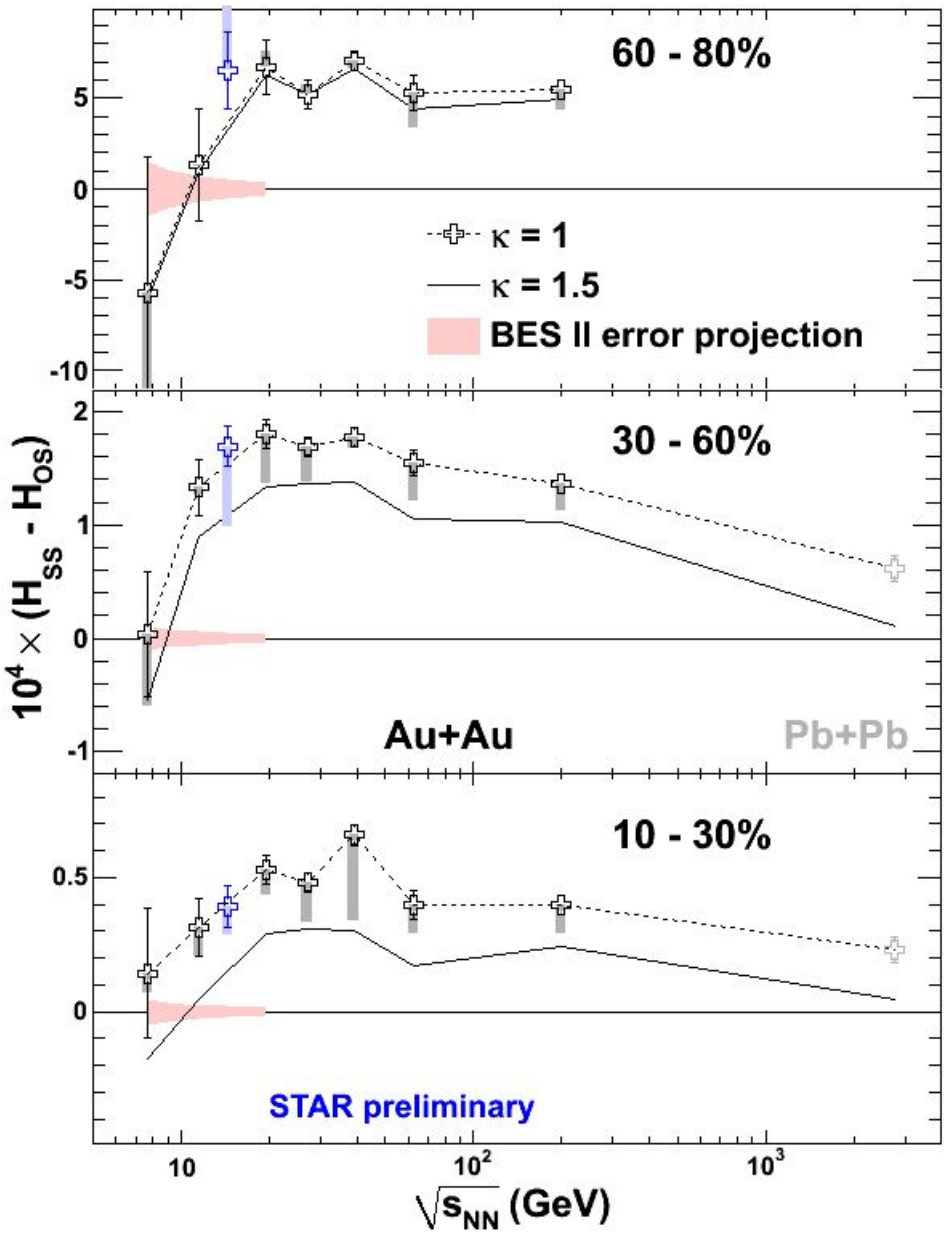
- Against CME expectation, $\delta_{OS} > \delta_{SS}$
- Indicate overwhelming background, larger than any possible CME effect.
- Try combining information from γ and δ to retrieve the CME contribution, *H*

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

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

CME contribution

Phys. Rev. Lett 113 (2014) 052302

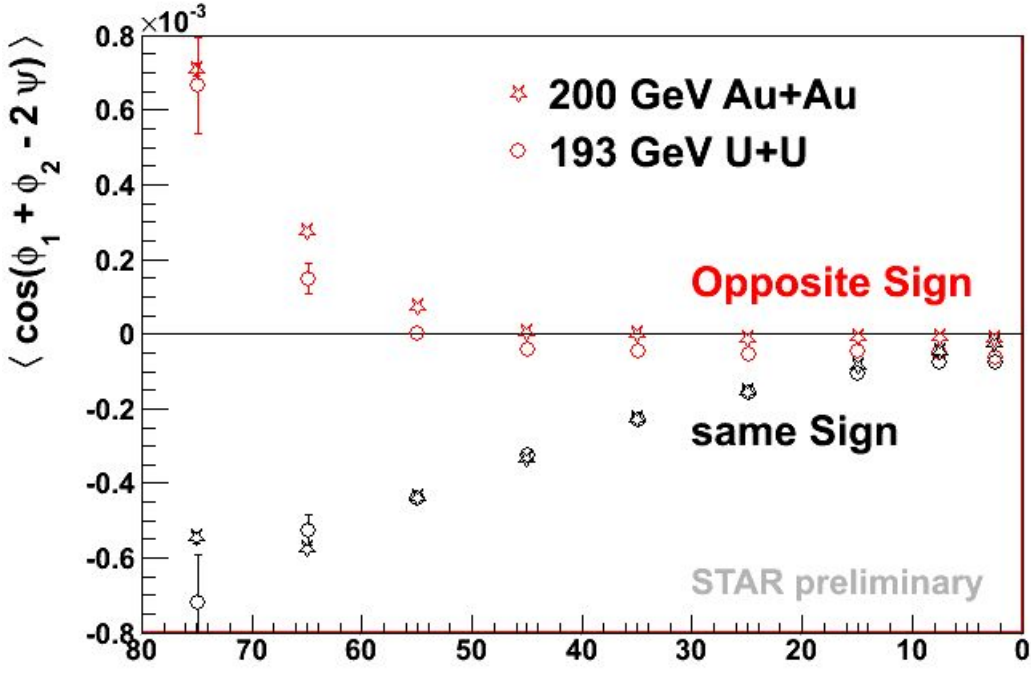


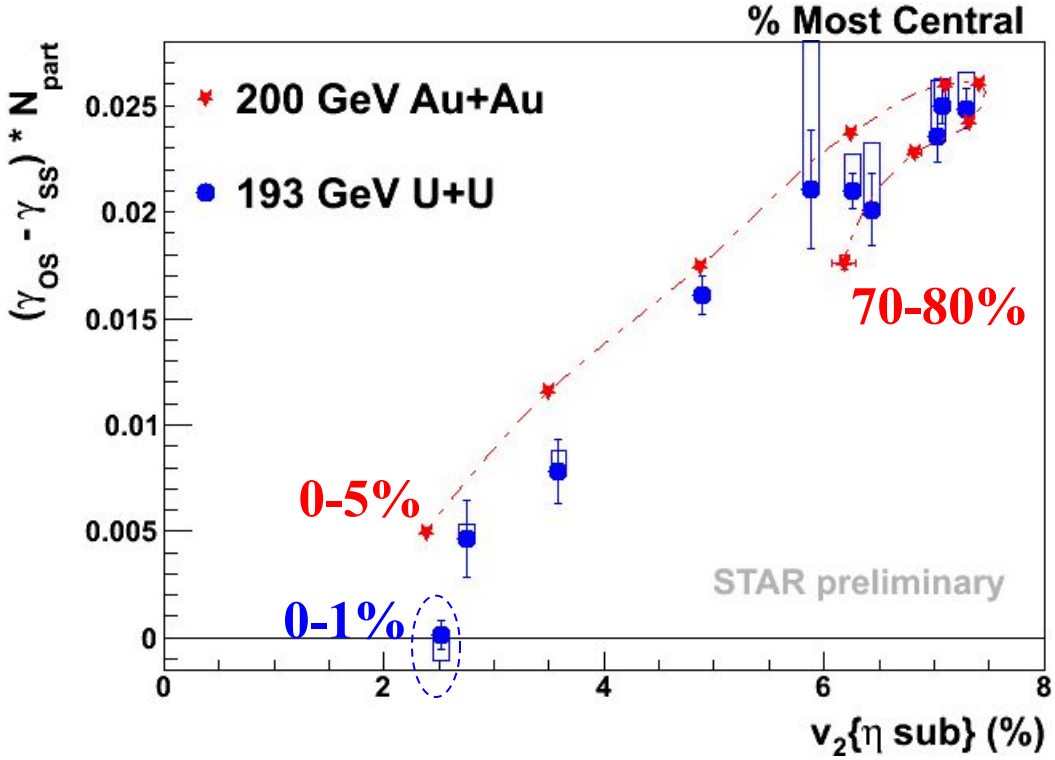
$$H^{\kappa} = (\kappa v_2 \delta - \gamma)/(1 + \kappa v_2)$$

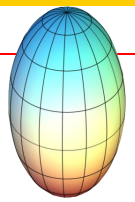
A. Bzdak, V. Koch and J. Liao, Lect. Notes Phys. 871, 503 (2013).

- $\kappa \approx 2 - v_{2,F}/v_{2,\Omega} \approx 1.2$: F and Ω denote full phase space and finite detector acceptance, respectively
- CME signal (ΔH) decreases to 0 from 19.6 to 7.7 GeV
- Probable domination of hadronic interactions over partonic ones
- Need better estimate of κ and more statistics

Deformed nuclei: U+U







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

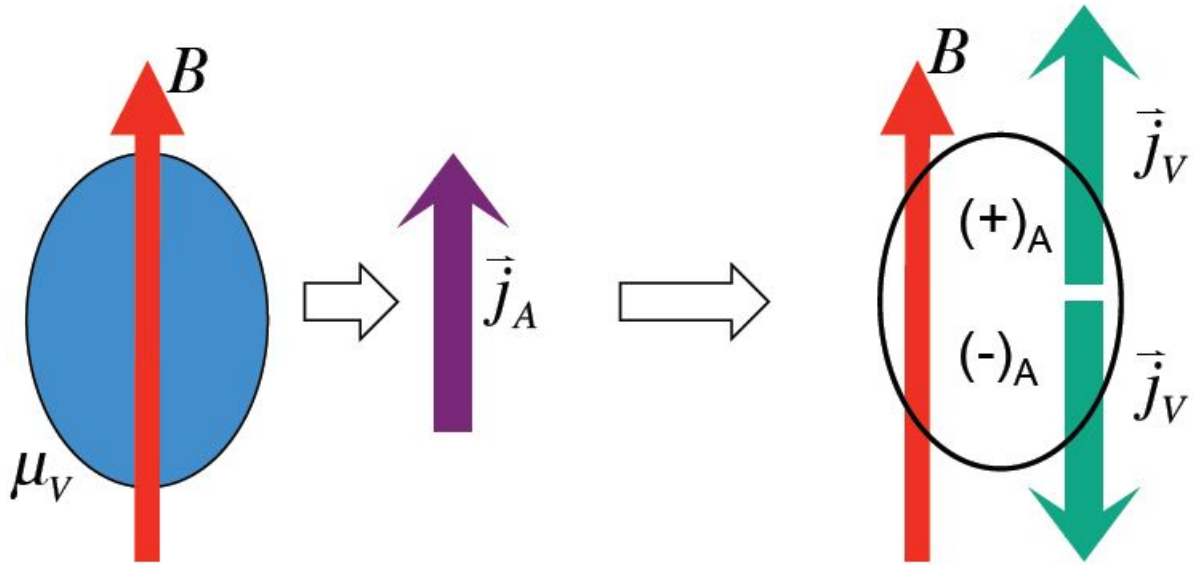
- A dedicated trigger for events with 0-1% spectator neutrons
- With magnetic field suppressed, the charge separation signal (mostly background) disappears, while v_2 is still ~2.5%

Extrapolate to intermediate centrality?

Isobar collisions may work better.

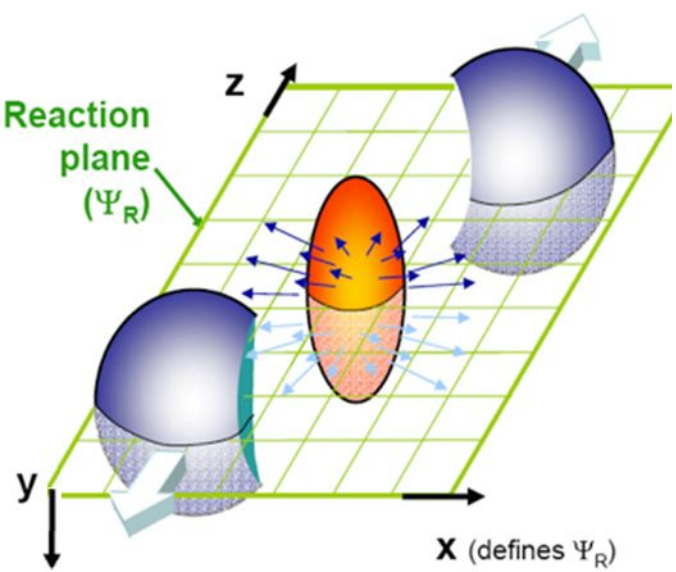
CMW

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



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

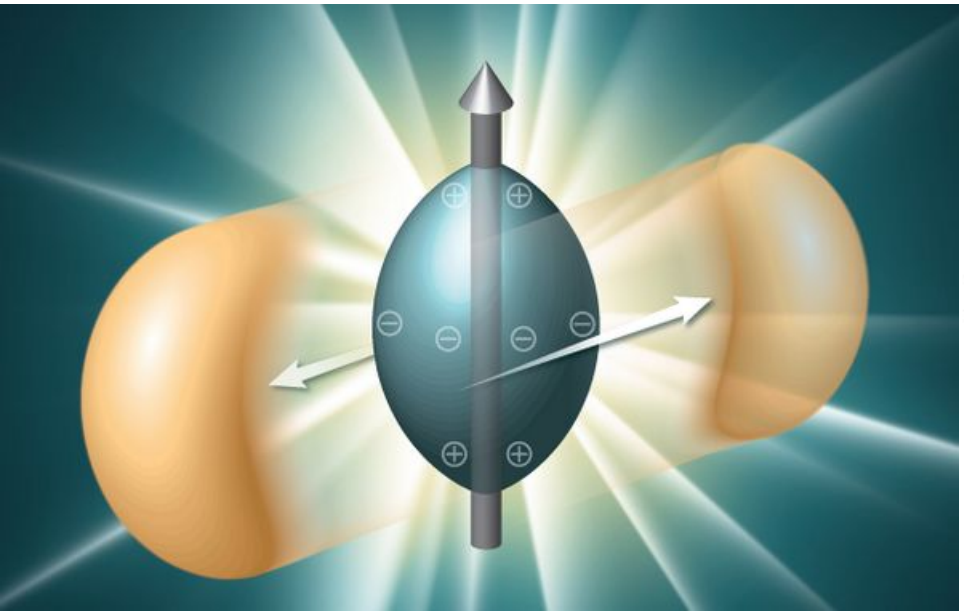
Chiral Separation Effect | Chiral Magnetic Effect



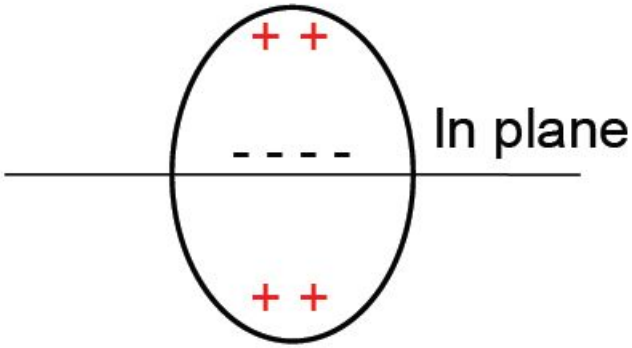
CSE + CME → Chiral Magnetic Wave:

- collective excitation
- signature of chiral symmetry restoration

Observable



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



quadrupole moment

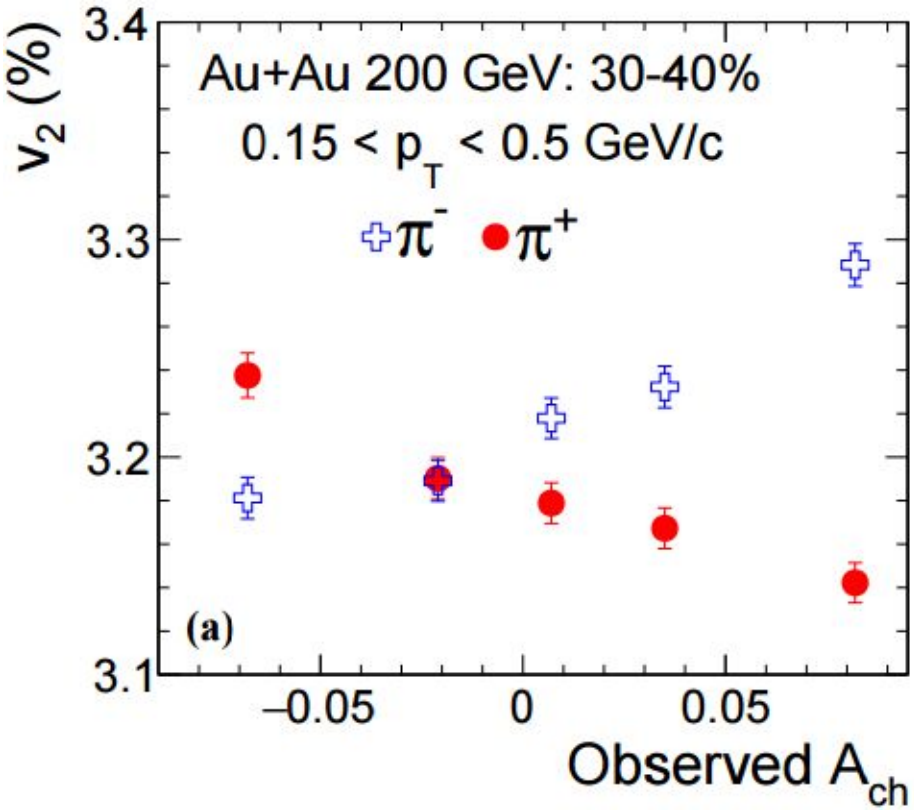
Formation of electric quadrupole: $v_2^{\pm} = v_2^{\text{base}} \mp \left(\frac{q_e}{\bar{\rho}_e} \right) A_{\text{ch}}$,

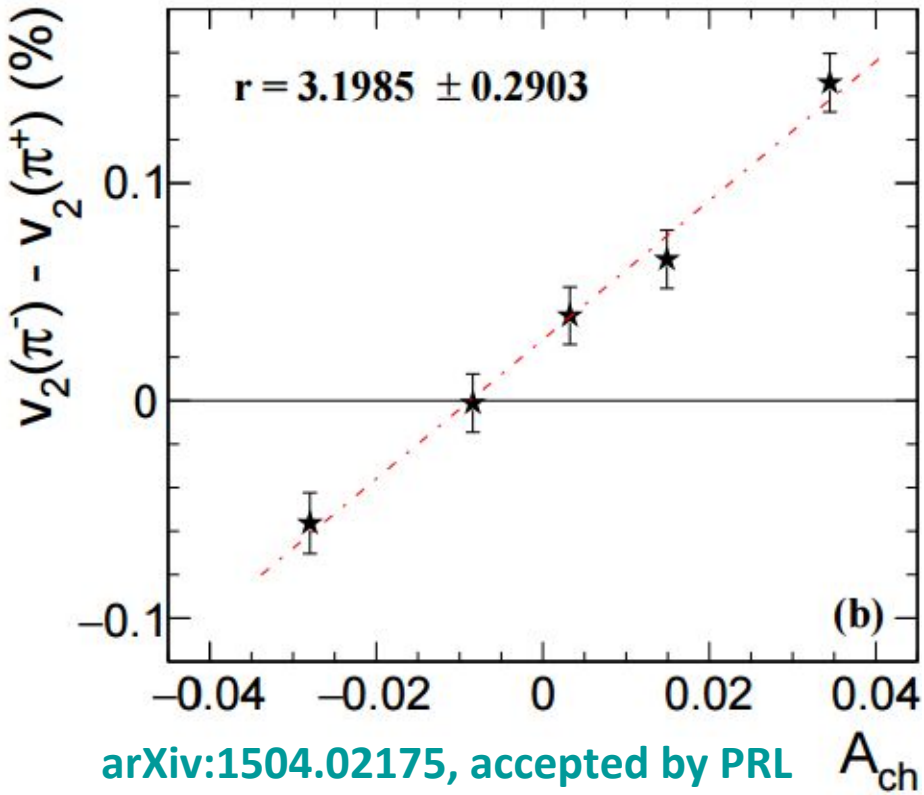
net charge density

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}





arXiv:1504.02175, accepted by PRL

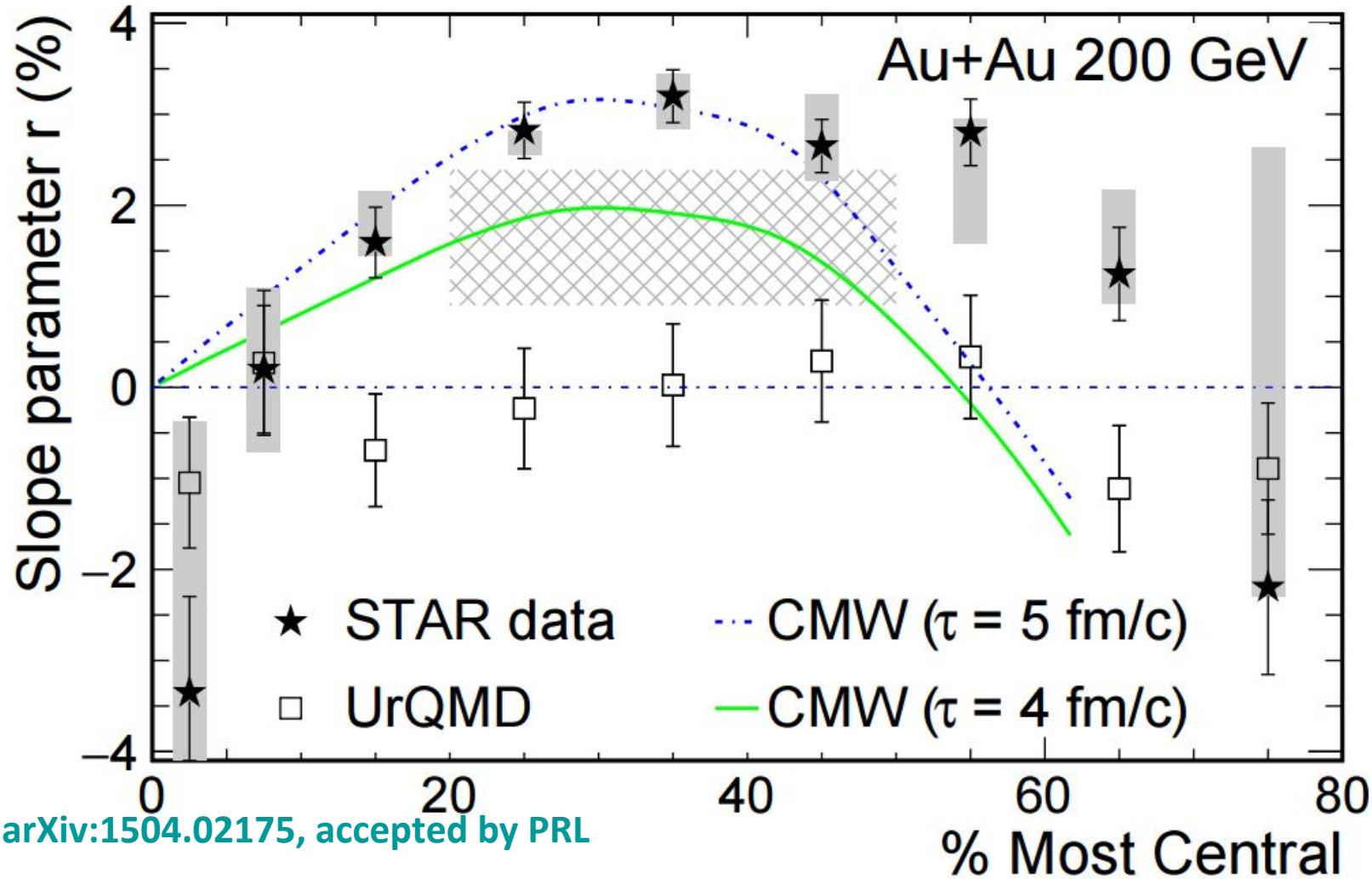
- Clear A_{ch} dependence of $v_2\{2\}$
- $v_2(A_{ch})$ slopes for $\pi^{\pm}$:
  - opposite sign
  - similar magnitude

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

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

Slope vs centrality

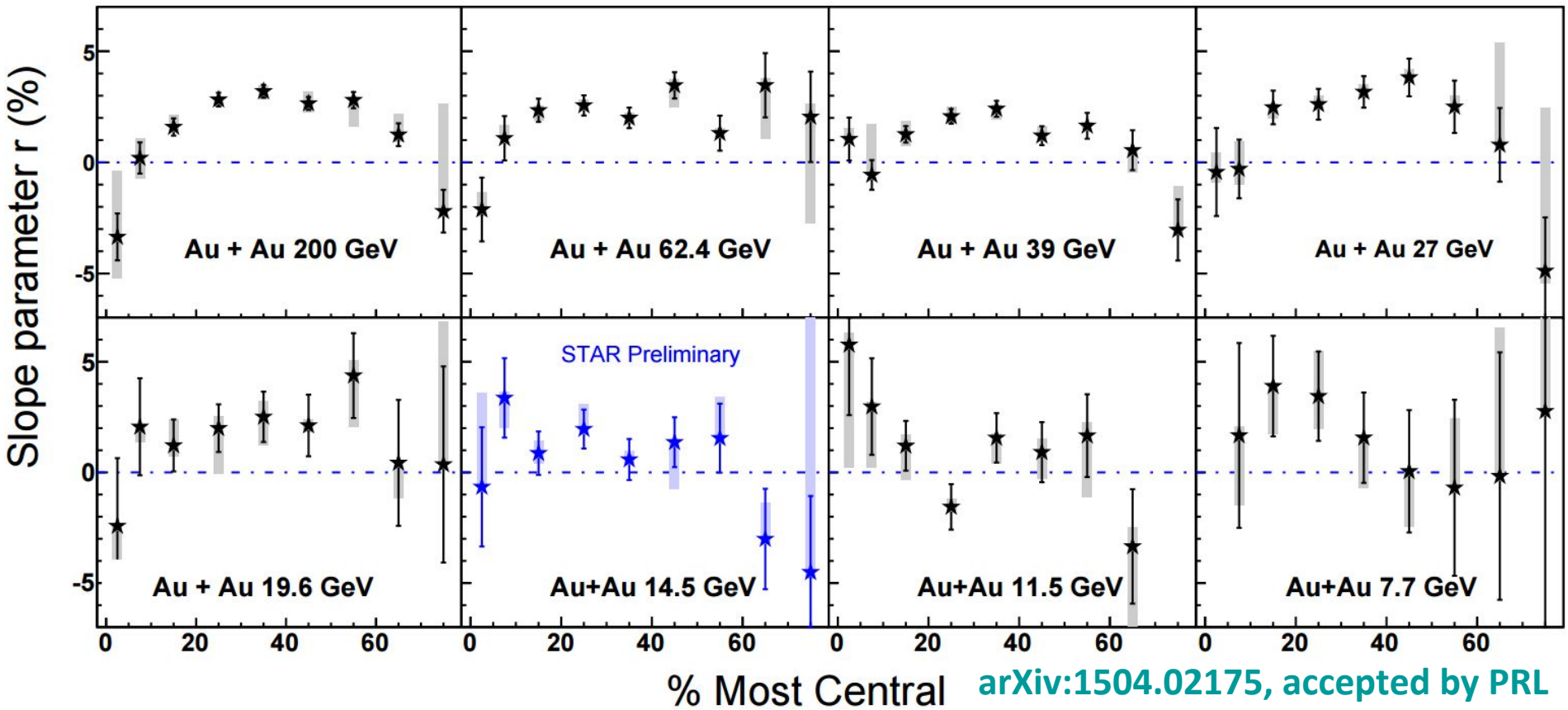
Y. Burnier, D. E. Kharzeev, J. Liao and H-U Yee, arXiv:1208.2537v1 [hep-ph].



arXiv:1504.02175, accepted by PRL

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

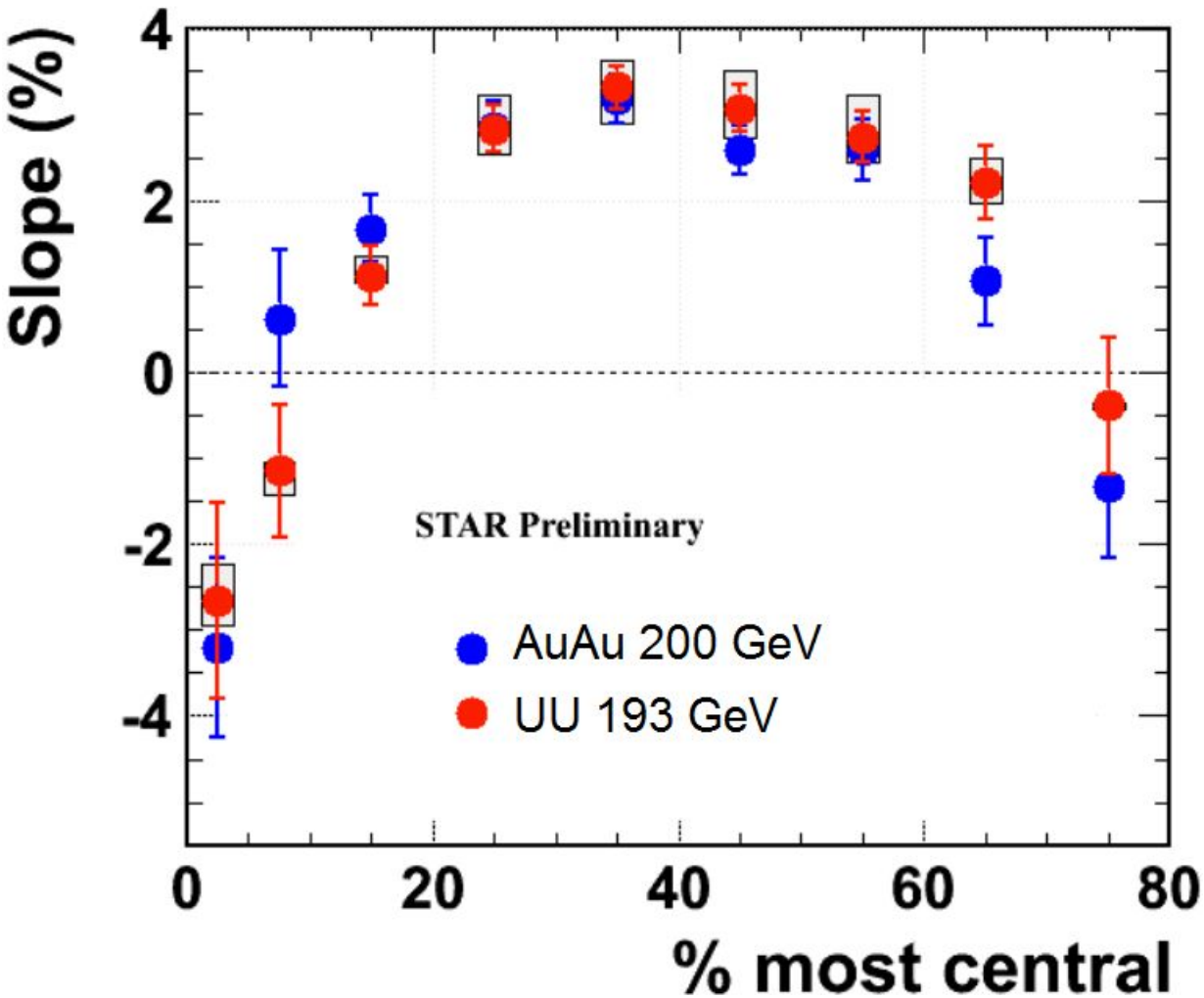
Beam Energy Scan



arXiv:1504.02175, accepted by PRL

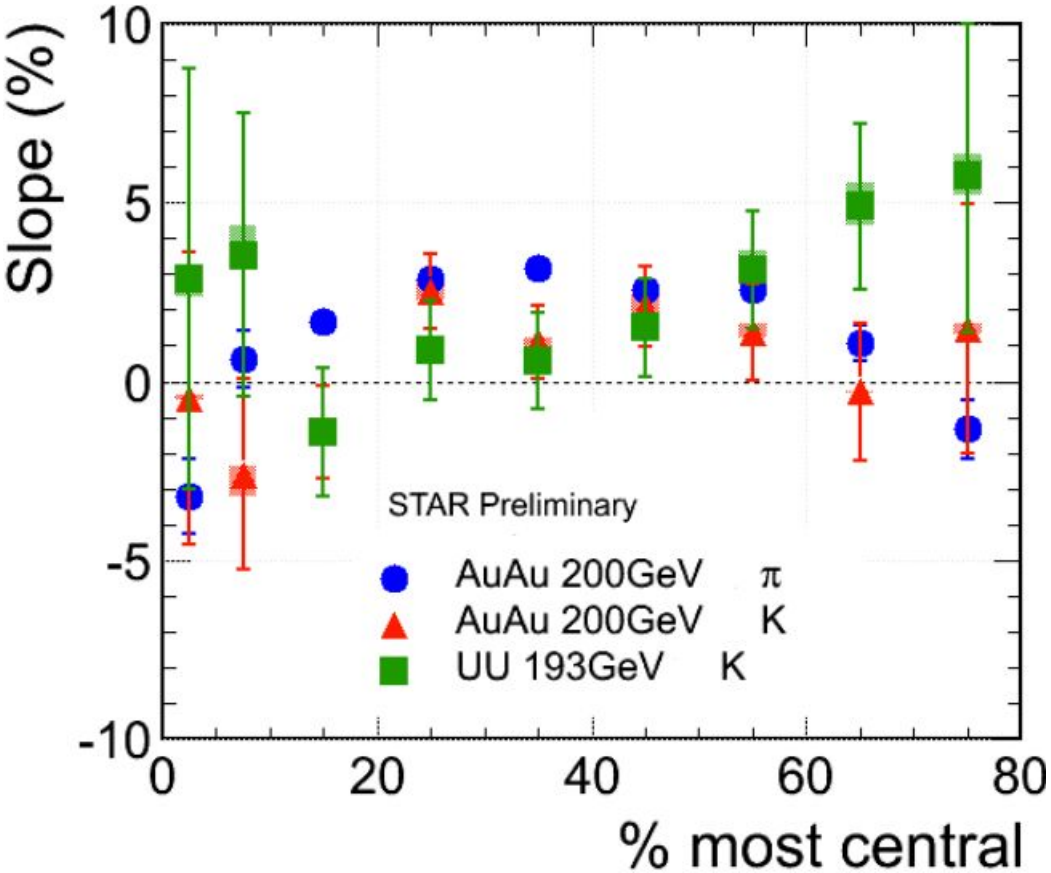
Similar trends are observed for different beam energies down to 19.6 GeV. Below 19.6 GeV, more statistics are needed.

U+U

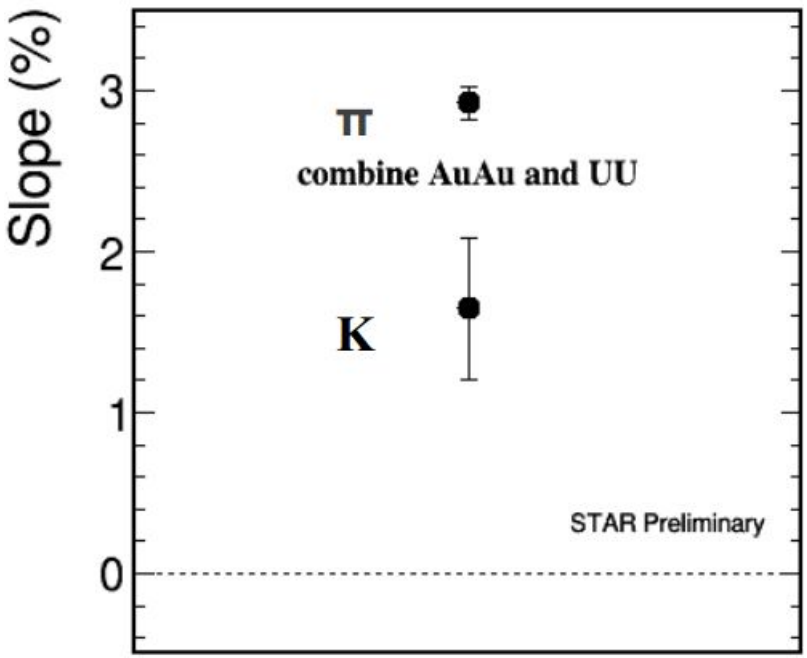


Similar pattern and magnitude seen in U+U collisions.

Kaon



20-60% collisions



With the same electric quadruple of QGP upon chemical freezeout, one expects to see a weaker effect for kaons (Y. Burnier, D. Kharzeev, J.g Liao, and H. Yee, PRL 107 052303)

Chiral Vortical Effect

Chiral Magnetic Effect vs **Chiral Vortical Effect**

Chirality Imbalance (μ_A)

Magnetic Field ($\omega\ \mu_e$) ↓ Electric Charge (j_e)

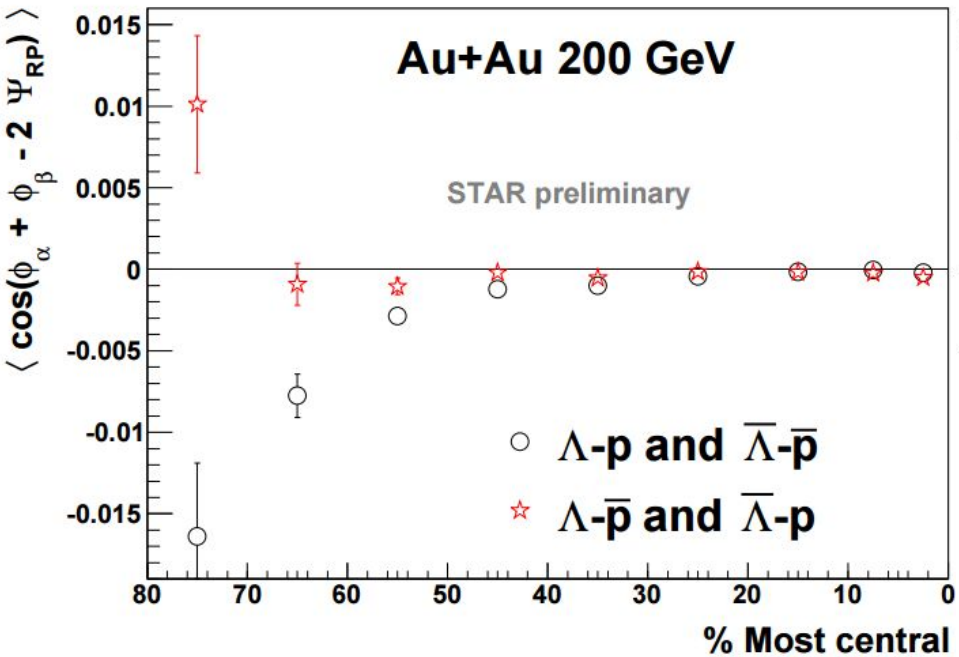
Fluid Vorticity ($\omega\ \mu_B$) ↓ Baryon Number (j_B)

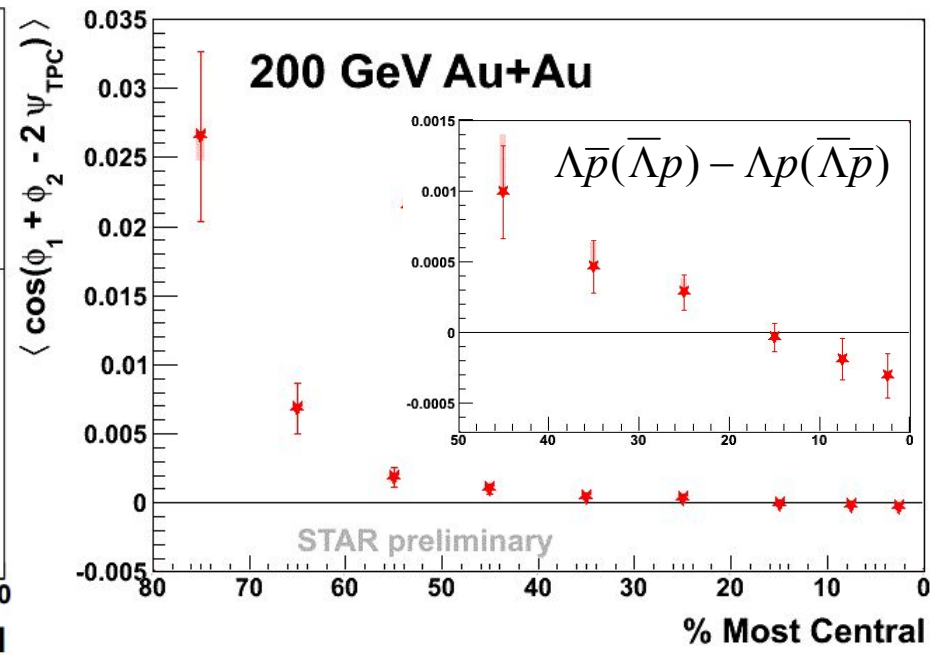
D. Kharzeev, D. T. Son, PRL 106 (2011) 062301

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

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.

What we learned so far

- signal of charge separation w.r.t RP
  - comfirmed with different EP types (1st- and 2nd-order)
  - remain in Au+Au, Cu+Cu, Pb+Pb and U+U
  - persist from 19.6 GeV to 2.76 TeV
  - repeated with reduced correlators (not shown here)
  - robust when suppressing HBT+Coulomb (not shown here)

- signal seems to disappear when
  - one of $h^{\pm}$ is replaced with a neutral strange particle
  - the collision energy is down to ~7.7 GeV
  - B field from spectators is supressed (v_2 is still sizable)

- we also showed
  - CMW signal: finite $\Delta v_2(A_{ch})$ slopes
  - CVE signal: baryon-number separation w.r.t. RP

Outlook: Isobars

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

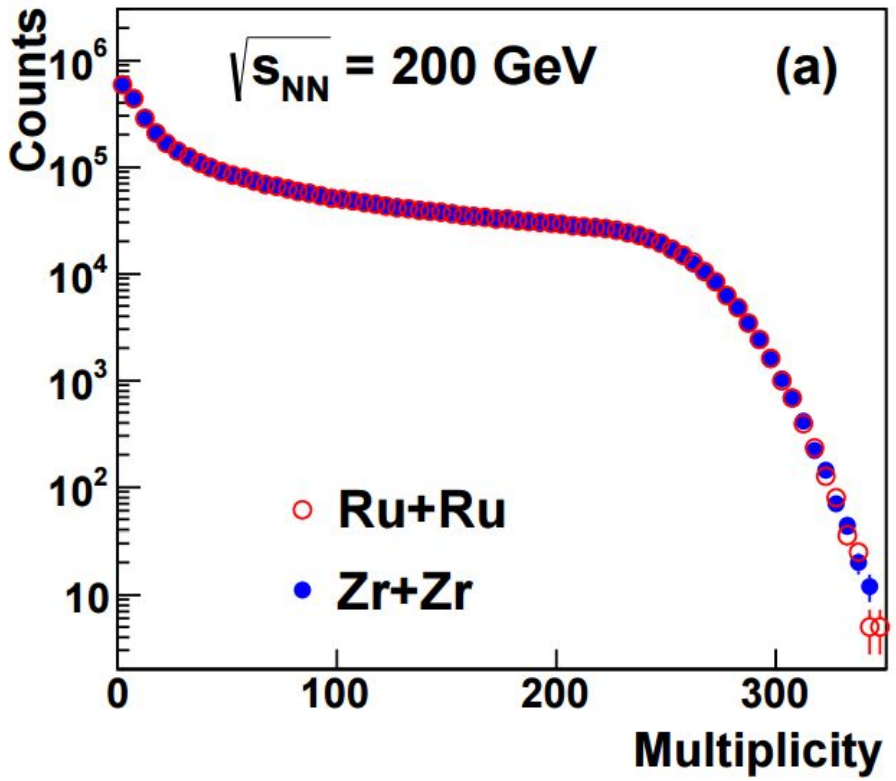
For example, $^{96}_{44}$Ruthenium and $^{96}_{40}$Zirconium:

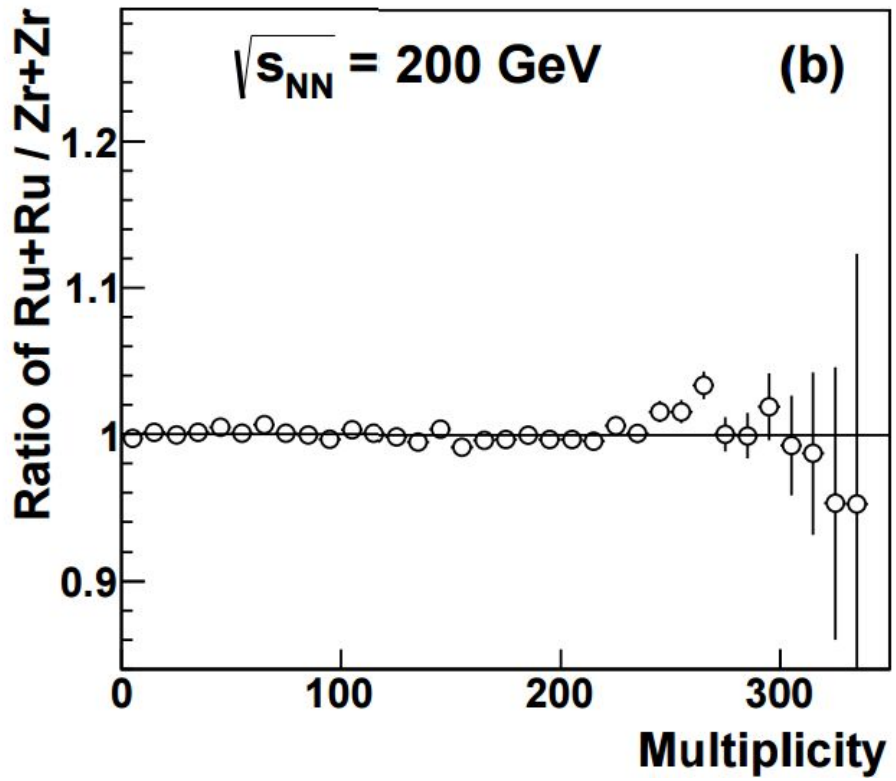
Up to 10% variation in B field

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

Isobars: multiplicity

- Almost identical distributions of multiplicity (MC Glauber)
- The ratio is close to 1 except for 0-10% most central events
- Zr is a little deformed (β_2=0.2), and Ru is spherical (β_2=0.05)

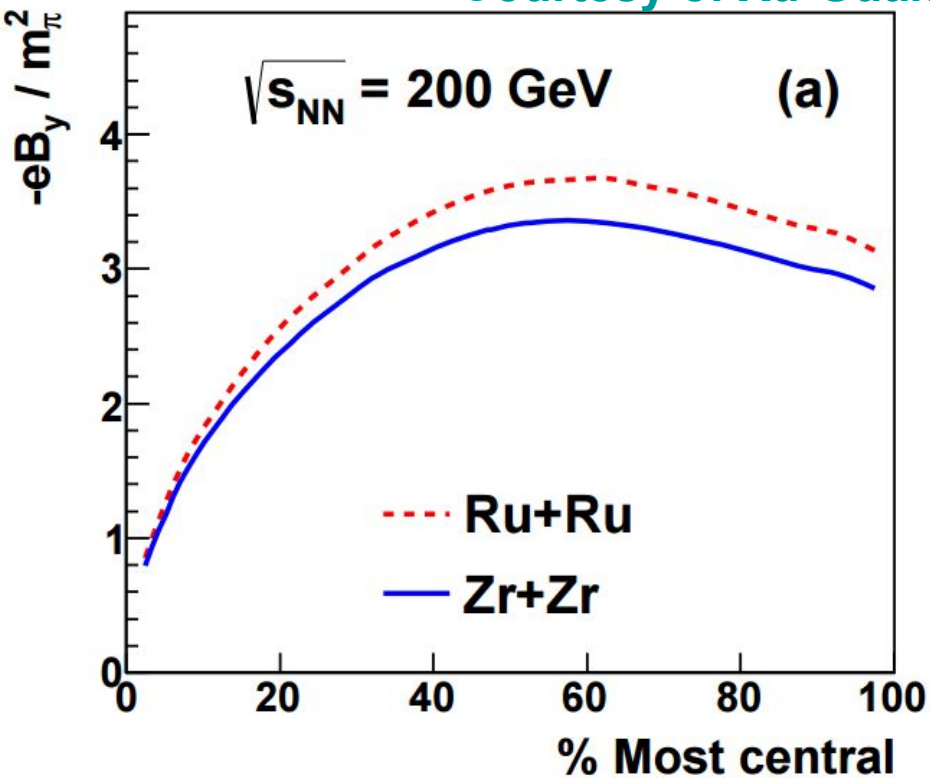


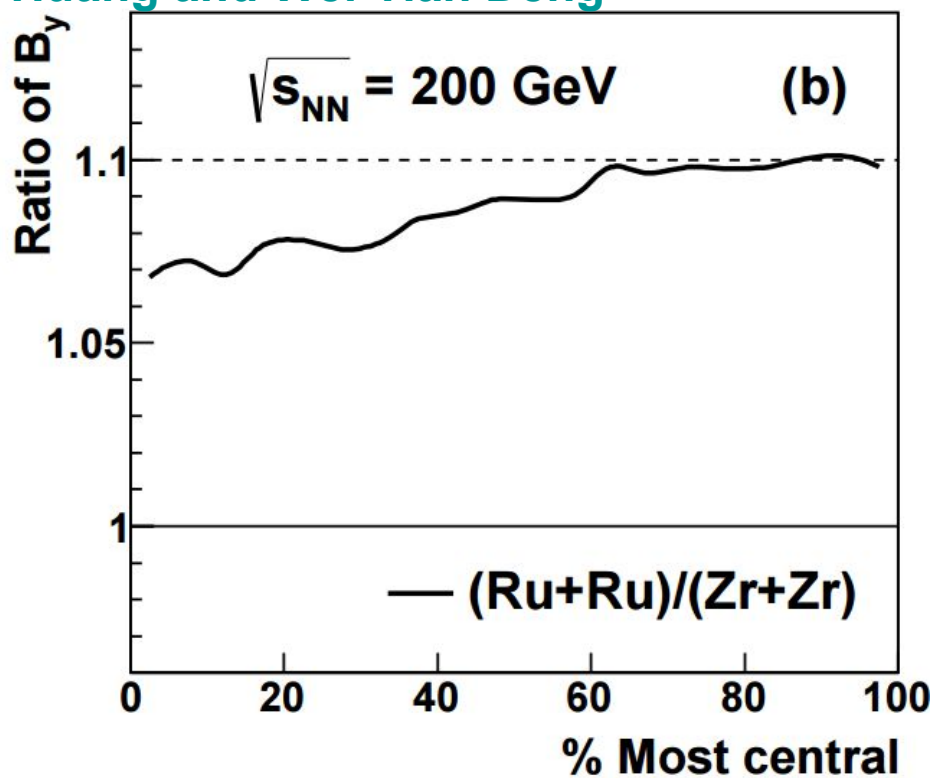


Isobars: B field

- Clear difference in the B field for the same centrality
- The ratio is close to 1.1 for peripheral events
- Reduces to 1.07 for central events

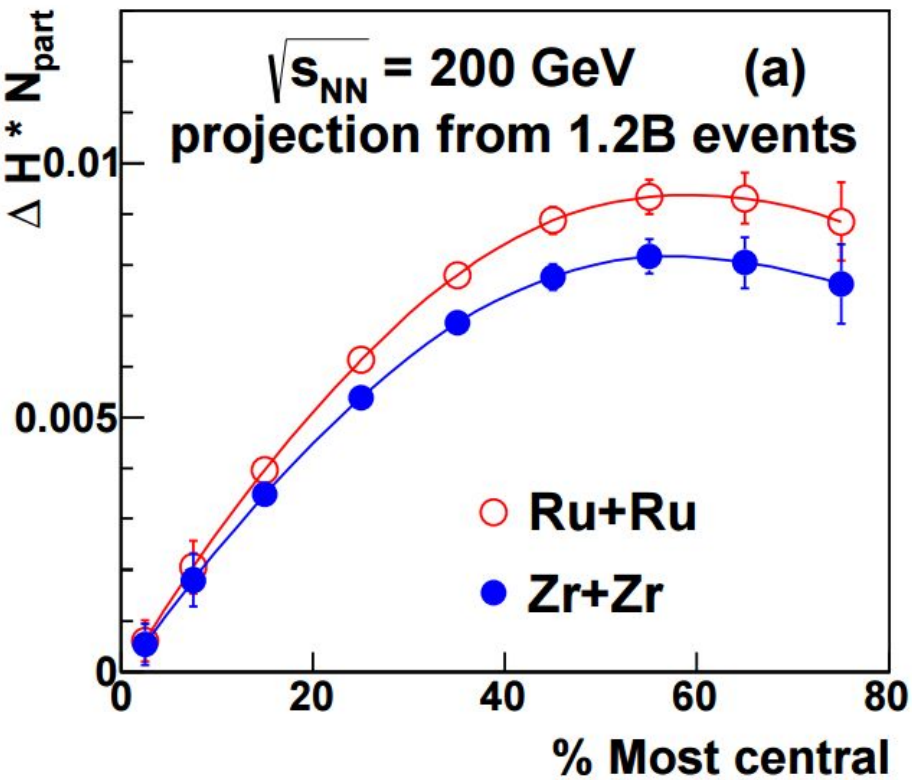
Courtesy of Xu-Guang Huang and Wei-Tian Deng

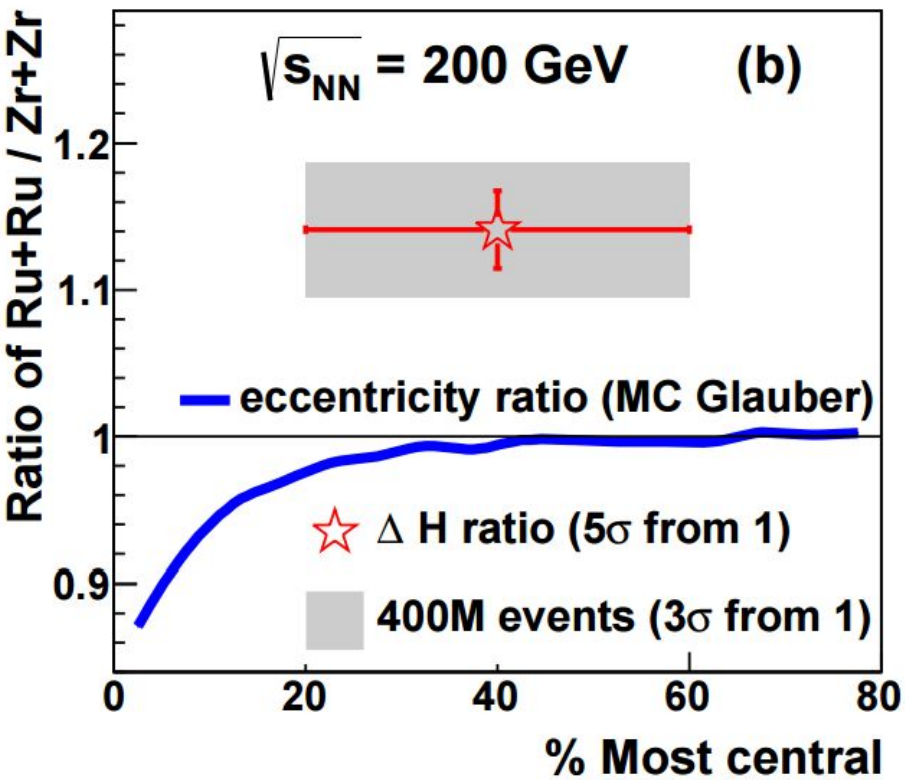




Isobars: charge separation

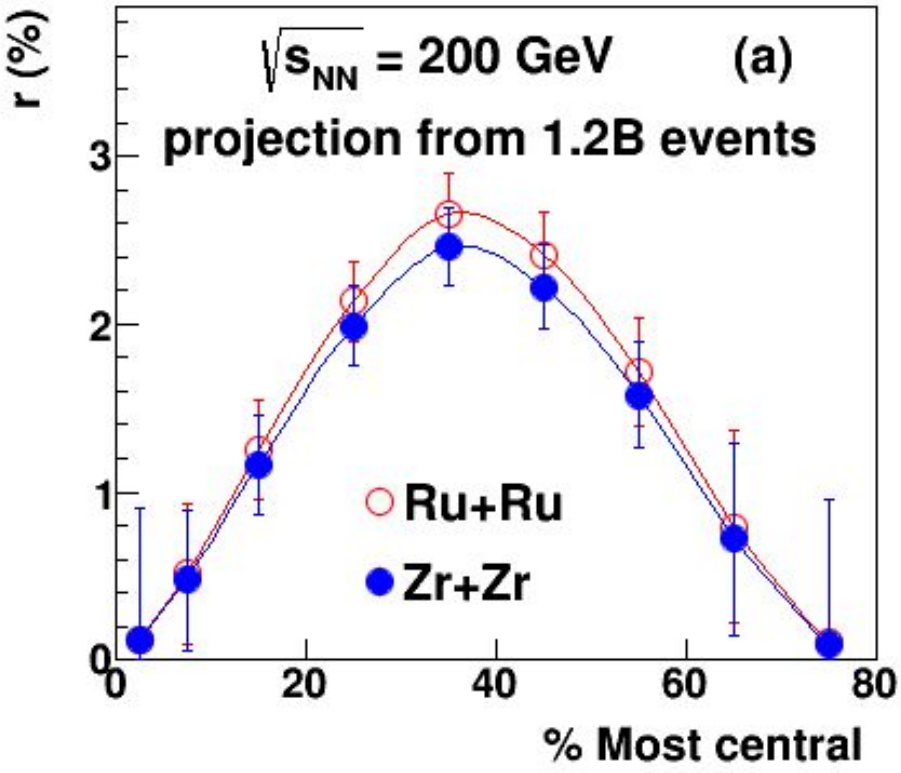
- Projection from 1.2B events shows difference in ΔH
- The ratio is 5σ above 1 (3σ with 400M events)
- If it's v_2-driven, the ratio will follow eccentricity (be 1 or below 1)

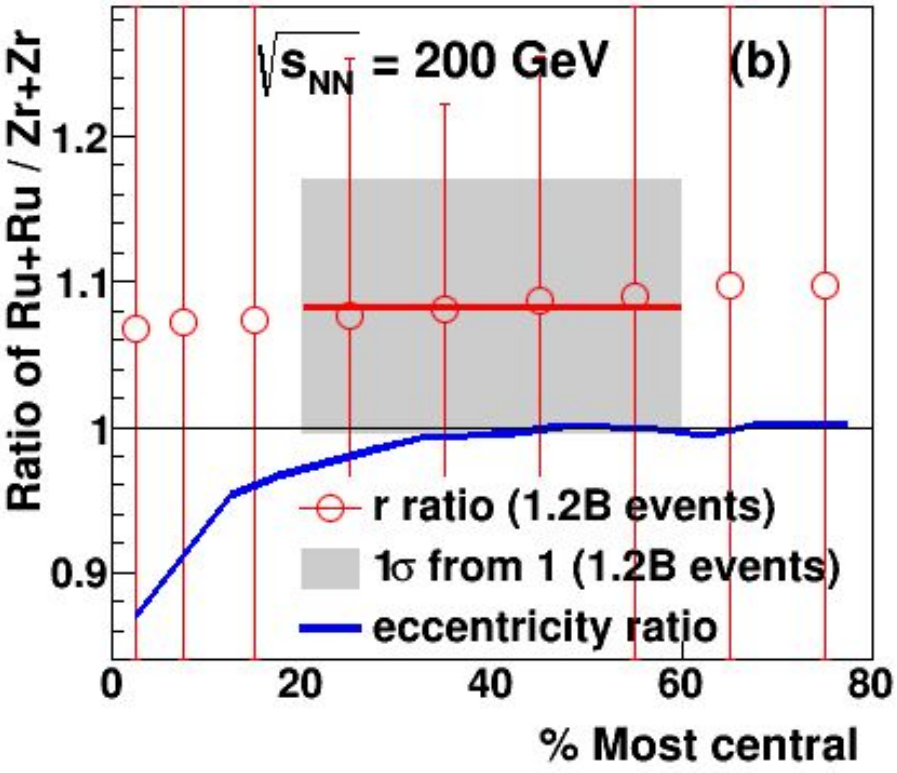




Isobars: $\Delta v_2(A_{ch})$ slope

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

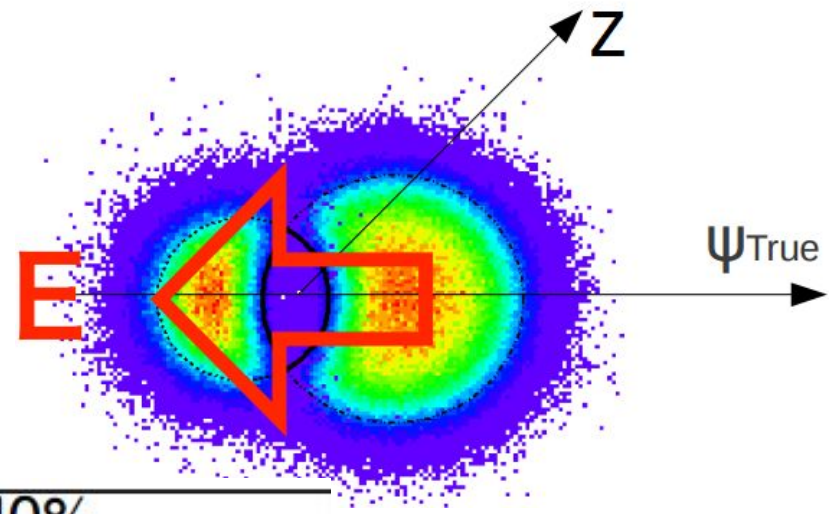


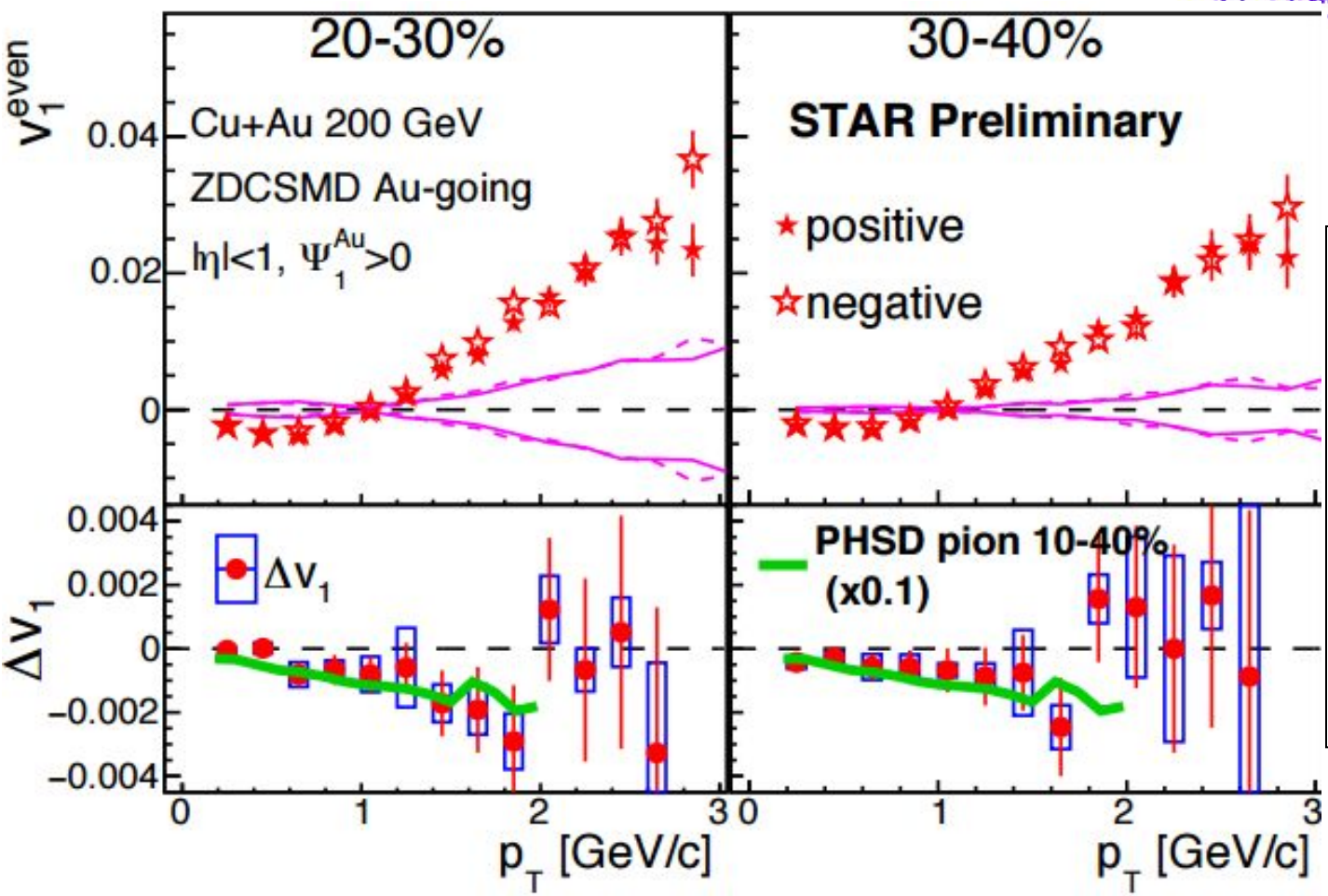


Outlook: Cu+Au

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).

Outlook: Cu+Au

Ohm's Law

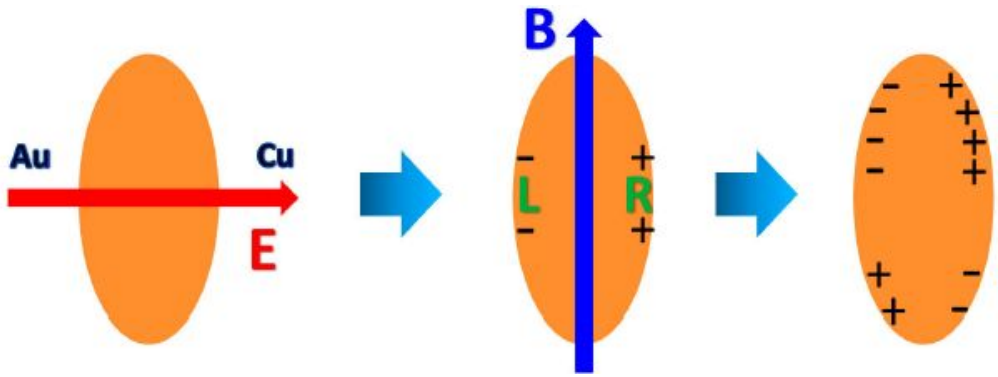
Chiral Magnetic Effect

	E	B
J_V	σ	$(e/2\pi^2)\mu_A$
J_A	$\propto \sigma\mu_V\mu_A/T^2$	$(e/2\pi^2)\mu_V$

Chiral Electric Separation Effect

Chiral Separation Effect

Y. Jiang, X.-G. Huang, J. Liao, arXiv:1409.6395



in-plane charge separation

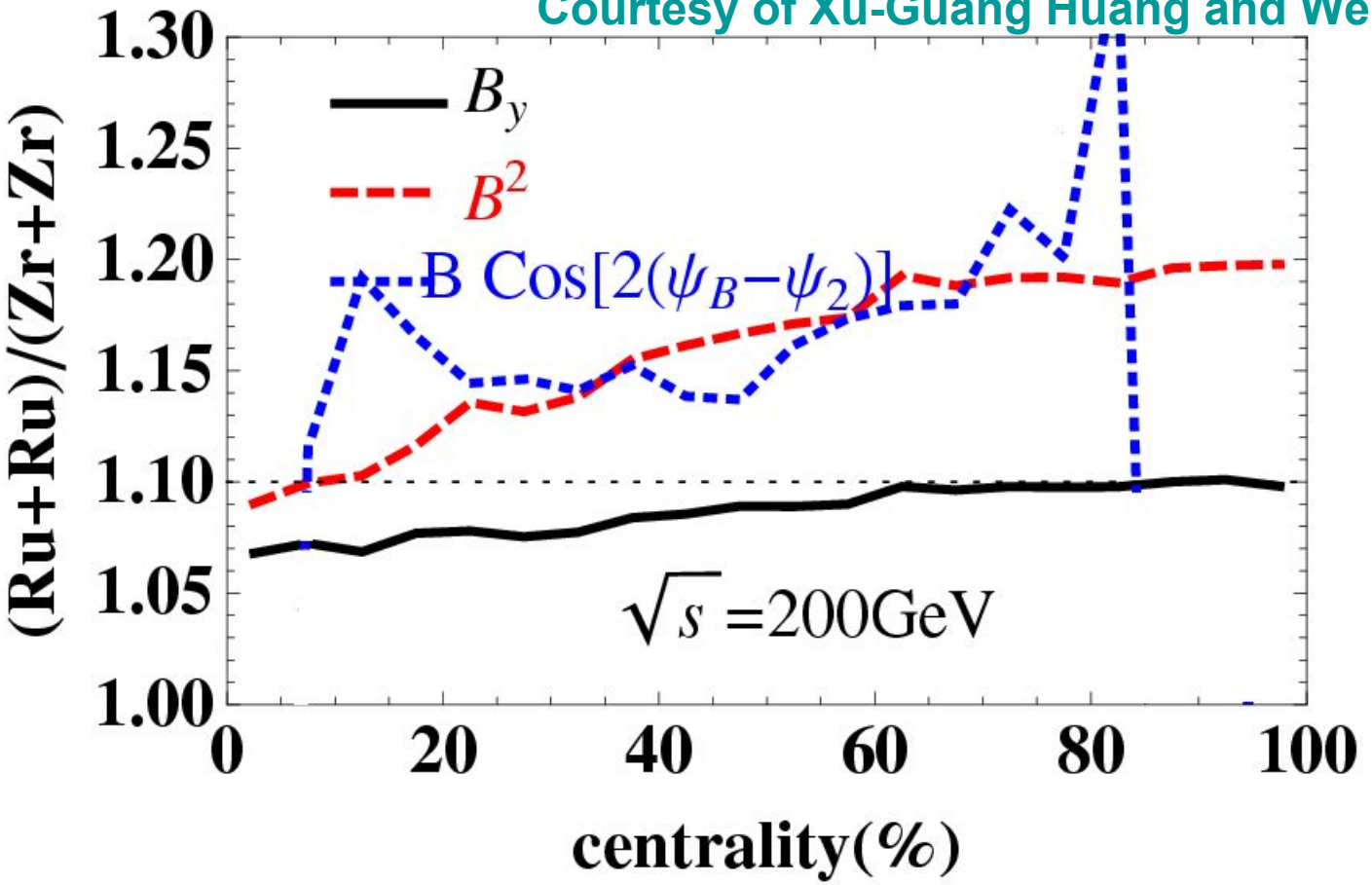
Suppressed γ signal of charge separation in Cu+Au collisions?

Backup slides

Isobars: B field

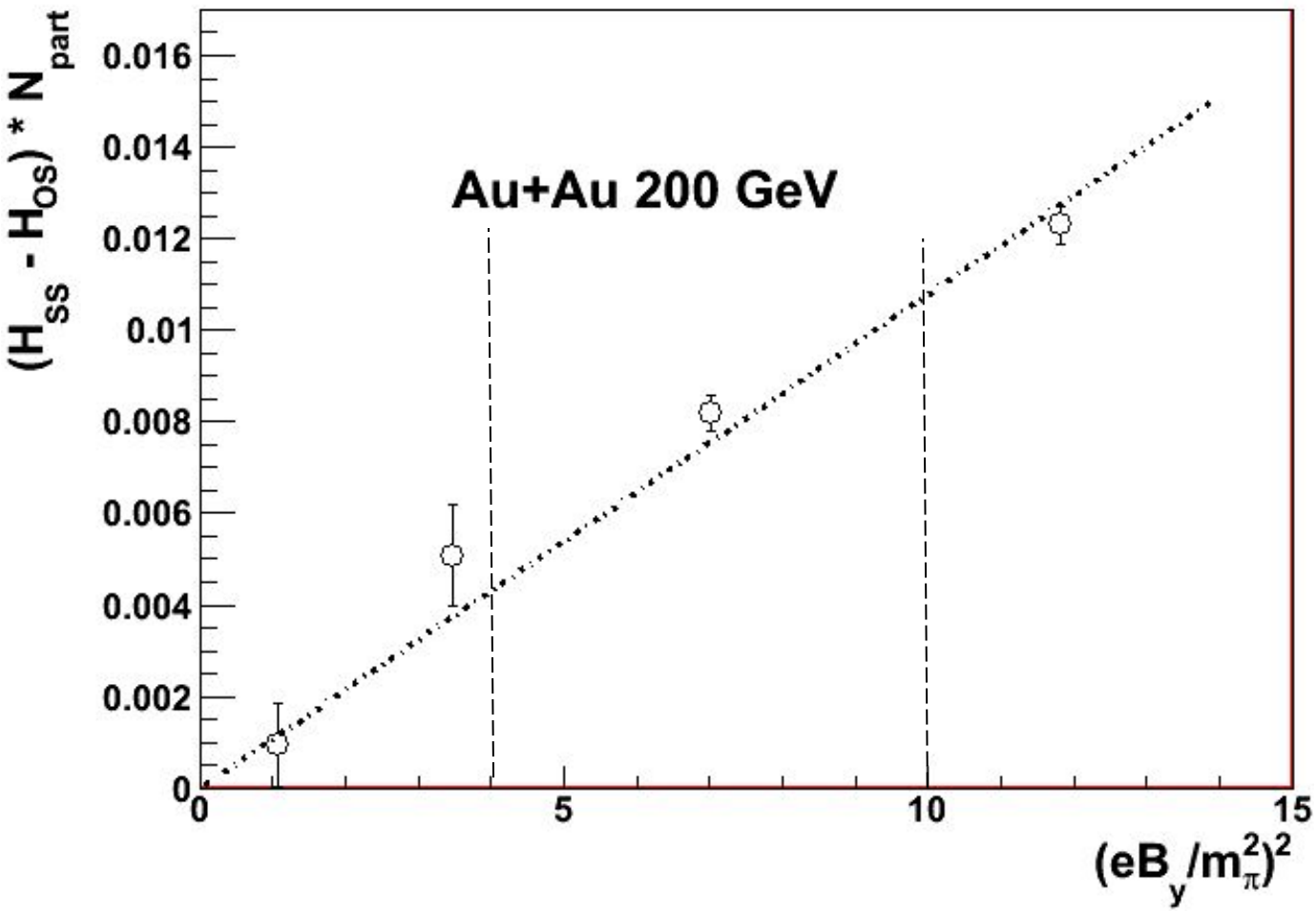
- Which B quantity is sensitive to the charge separation?
- The ratio is similar in term of ~ B^2 for 20-60% collisions
- $B \cdot \cos(2\Delta\varphi)$ may be more realistic, with a bigger difference
- We use B_y for simplicity

Courtesy of Xu-Guang Huang and Wei-Tian Deng

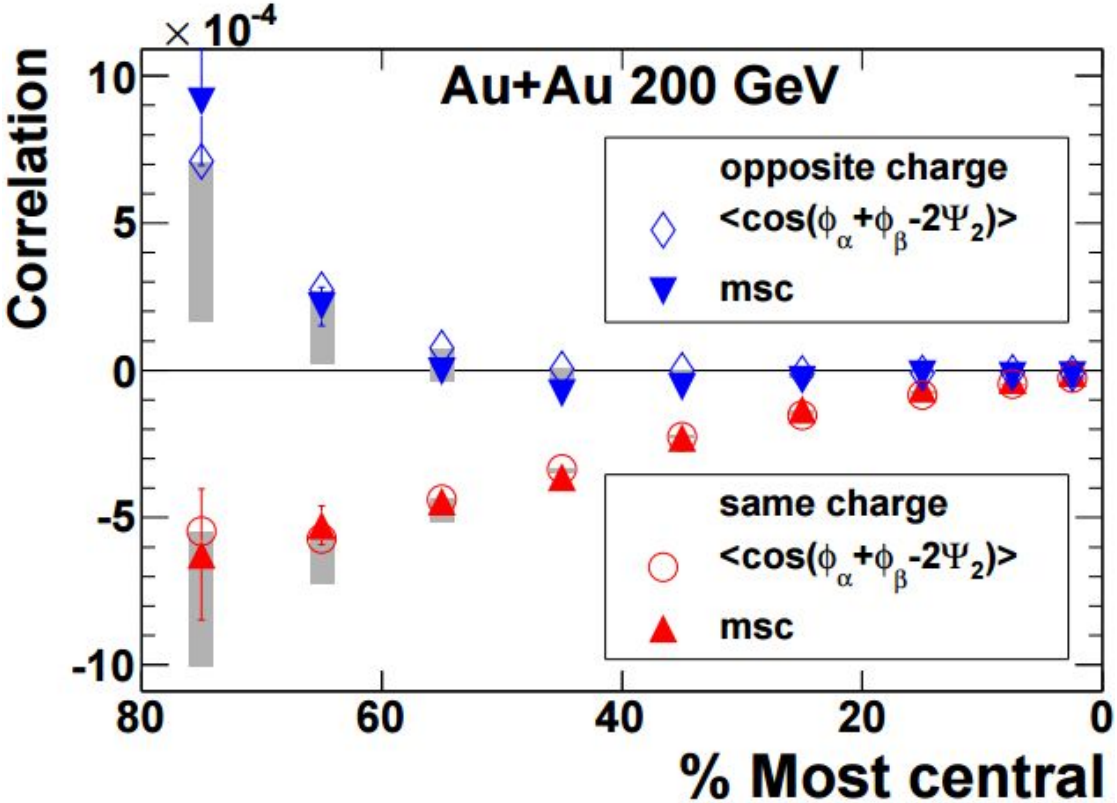


Au+Au 200 GeV

- $\Delta H \cdot N_{part}$ is a roughly linear function of B^2 for Au+Au 200 GeV.
- The 20-60% isobar collisions covers [4, 10] in the x axis.



Modulated sign correlator (msc)



$$\langle \cos(\varphi_\alpha + \varphi_\beta - 2\Psi_{\mathrm{RP}}) \rangle$$
$$= \langle \cos(\Delta\varphi_\alpha)\cos(\Delta\varphi_\beta) - \sin(\Delta\varphi_\alpha)\sin(\Delta\varphi_\beta) \rangle$$
$$= \langle (M_\alpha M_\beta S_\alpha S_\beta)_{\mathrm{IN}} \rangle - \langle (M_\alpha M_\beta S_\alpha S_\beta)_{\mathrm{OUT}} \rangle$$

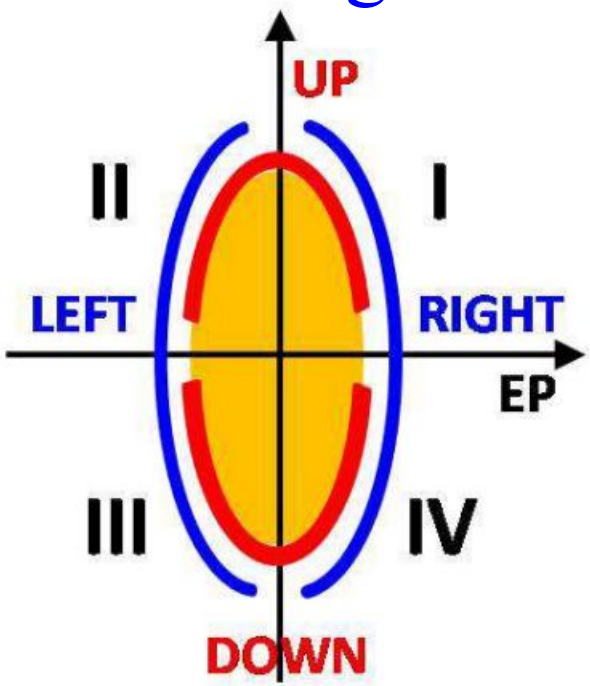
$$\mathrm{msc} \equiv \left(\frac{\pi}{4}\right)^2 \left(\langle S_\alpha S_\beta \rangle_{\mathrm{IN}} - \langle S_\alpha S_\beta \rangle_{\mathrm{OUT}} \right)$$

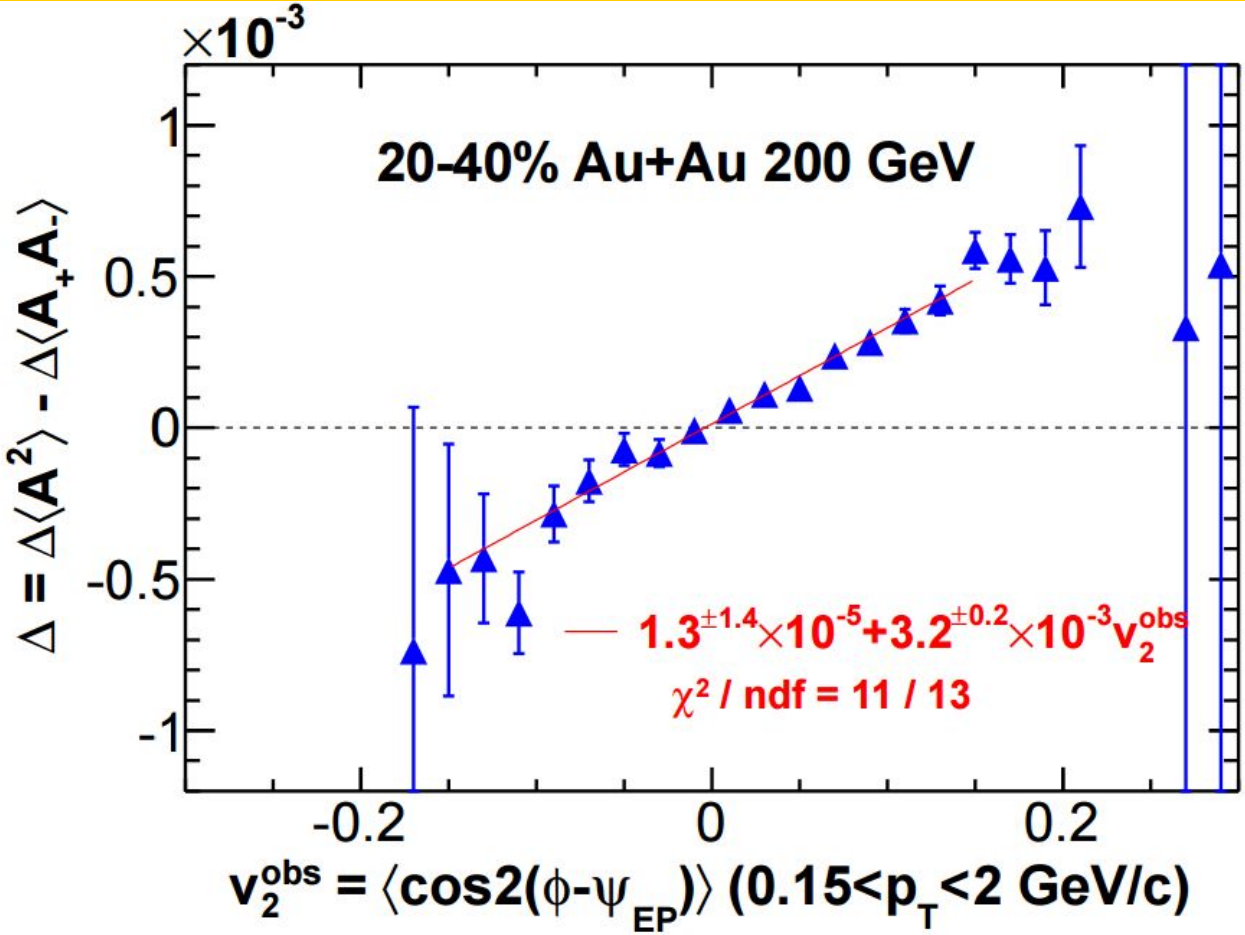
- robust after removing HBT+Coulomb effects with kinematic cuts ($\Delta\eta$ and Δp_T)
- γ weights different azimuthal regions of charge separation differently
- Modify γ such that all azimuthal regions are weighted equally
- γ is reduced to modulated sign correlator (msc)
- The charge separation signal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

Phys. Rev. C 88 (2013) 64911

Charge multiplicity asymmetry correlator

count the charges of 4 regions

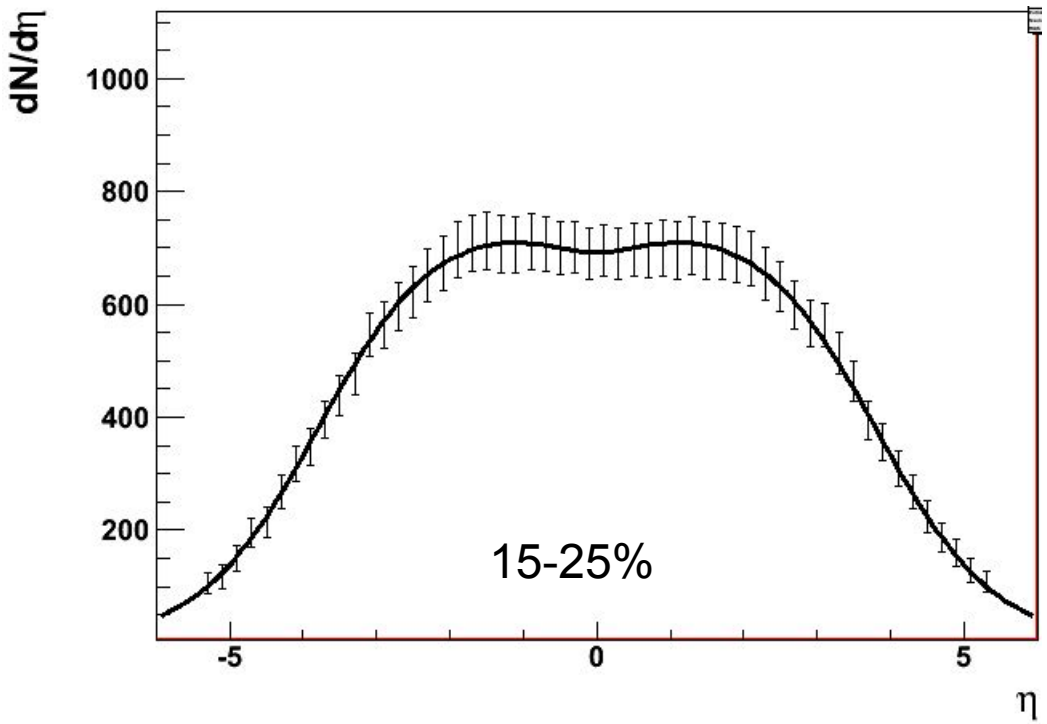


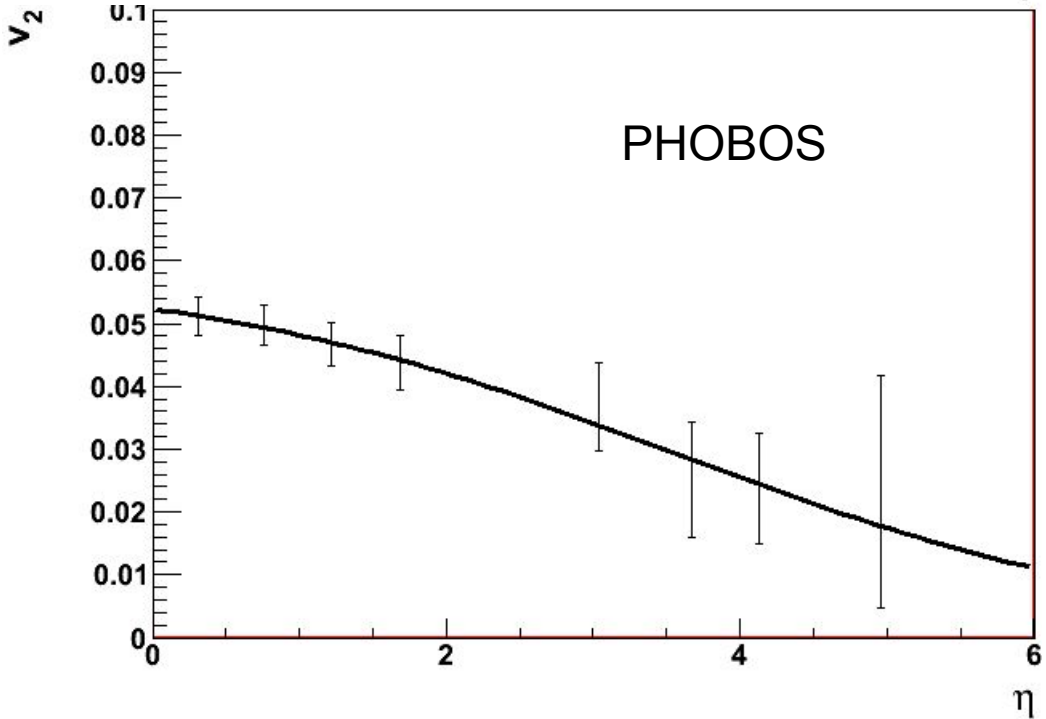


- A similarly reduced correlator, observes a similar charge separation.
- Previously, when "v_2^{obs}"=0, the signal was consistent with zero!

Phys. Rev. C 89 (2014) 44908

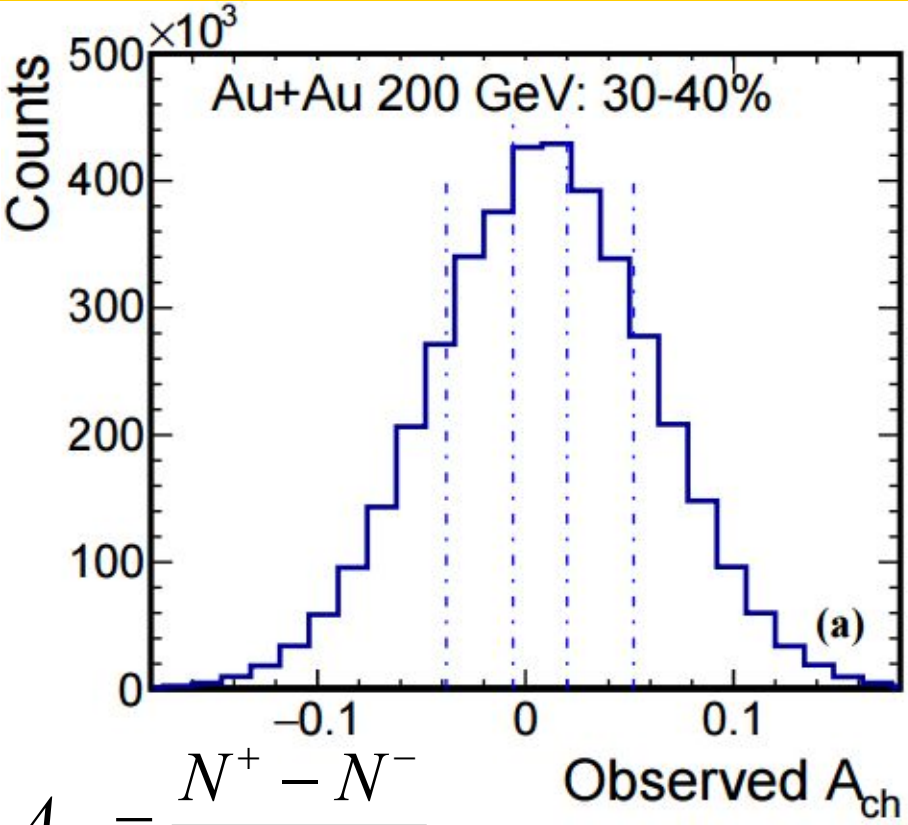
- Now, new measurements with higher statistics report non-zero signal!
- Beam energy dependence also looks similar to that of γ.

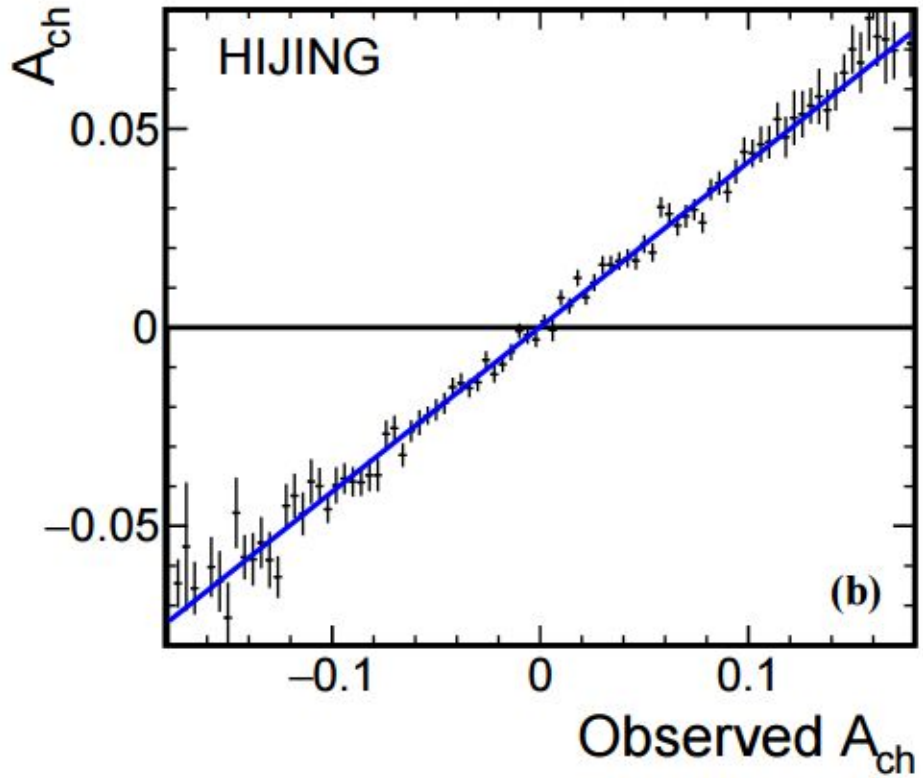




$v_2^{\Omega} = 0.0504$,
and $v_2^{F} = 0.0397$
$\kappa \approx 2 - v_2^{F} / v_2^{\Omega} \approx 1.2$

Observed charge asymmetry

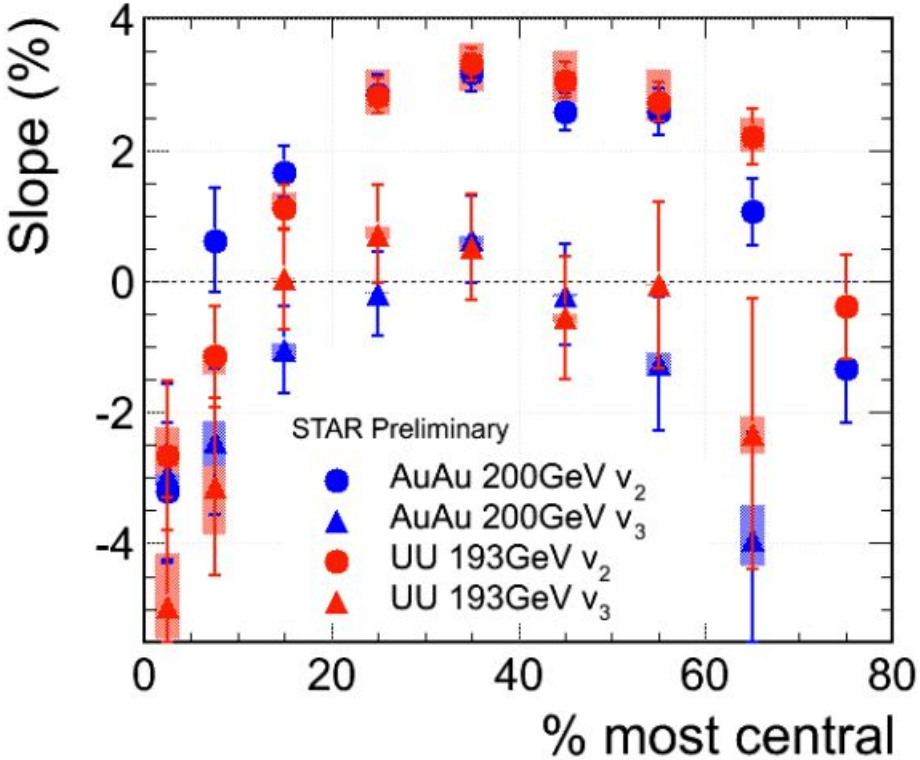


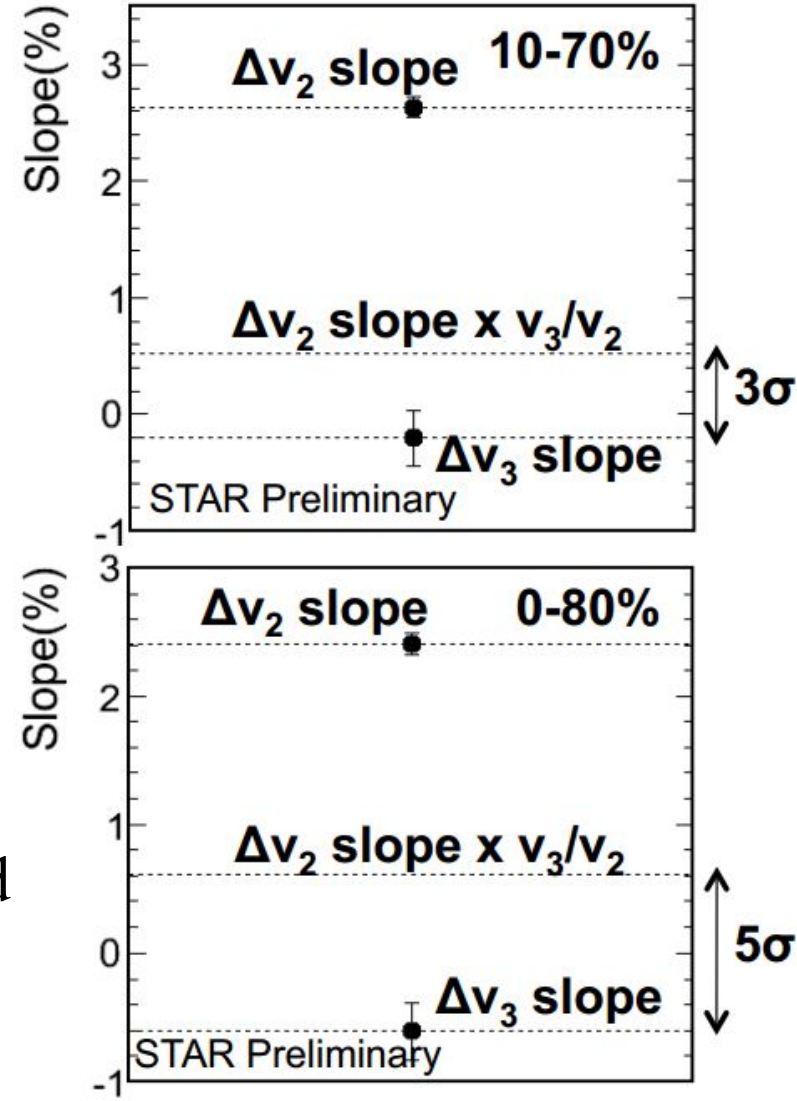


$$A_{ch} = \frac{N^+ - N^-}{N^+ + N^-}$$

- N^+ (N^-) is the number of positive (negative) particles within $|\eta|<1$.
- The distribution was divided into 5 bins, with roughly equal counts.
- Tracking efficiency was corrected with help of HIIJNG.

Δv_3 slope

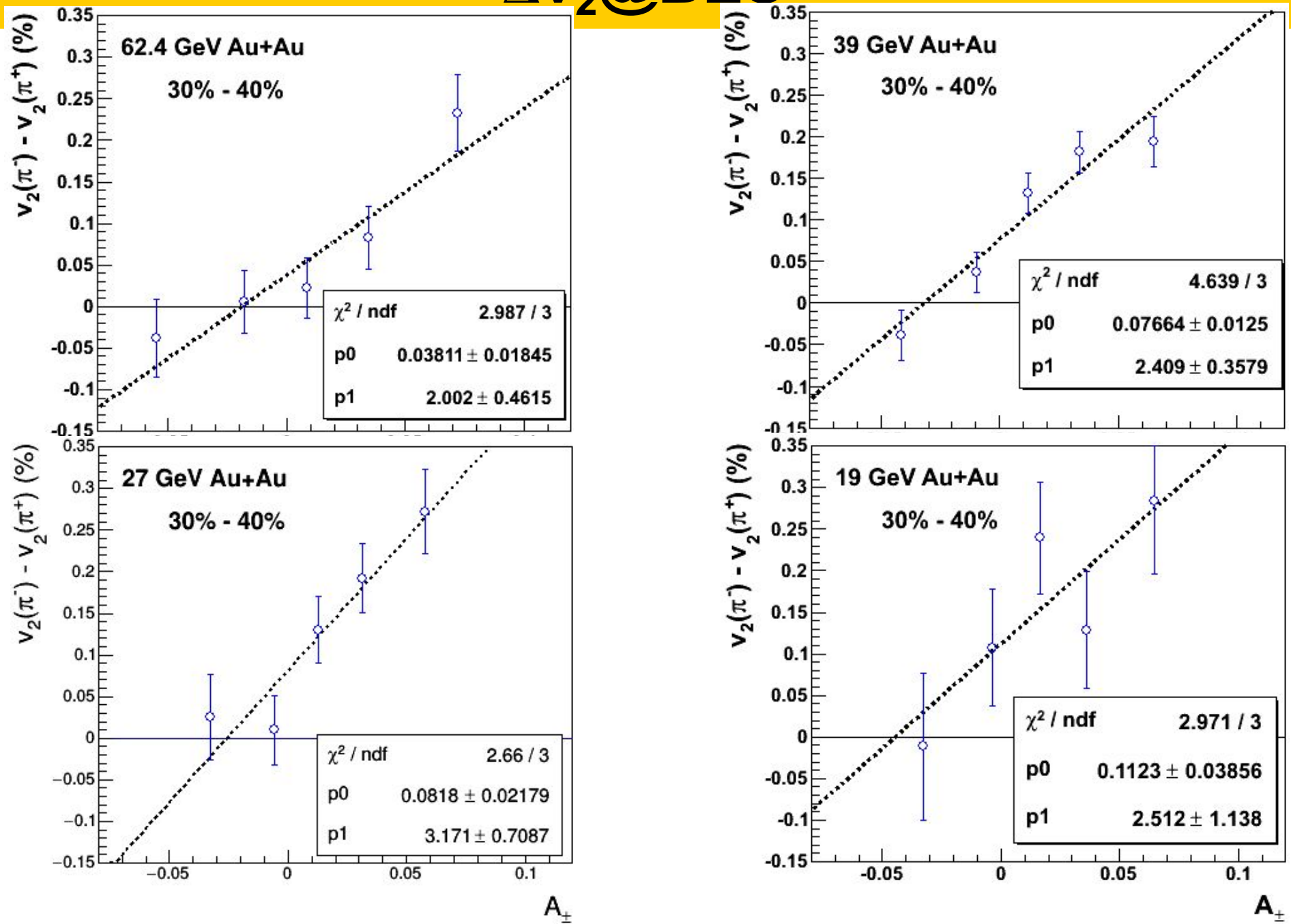




Local charge conservation may introduce A_{ch} dependence of $\Delta v_2(\pi)$. Then one should see **slope-for-Δv_3 / slope-for-Δv_2 ~ v_3/v_2** (Bzak & Bozek PLB 726 239 (2013)).

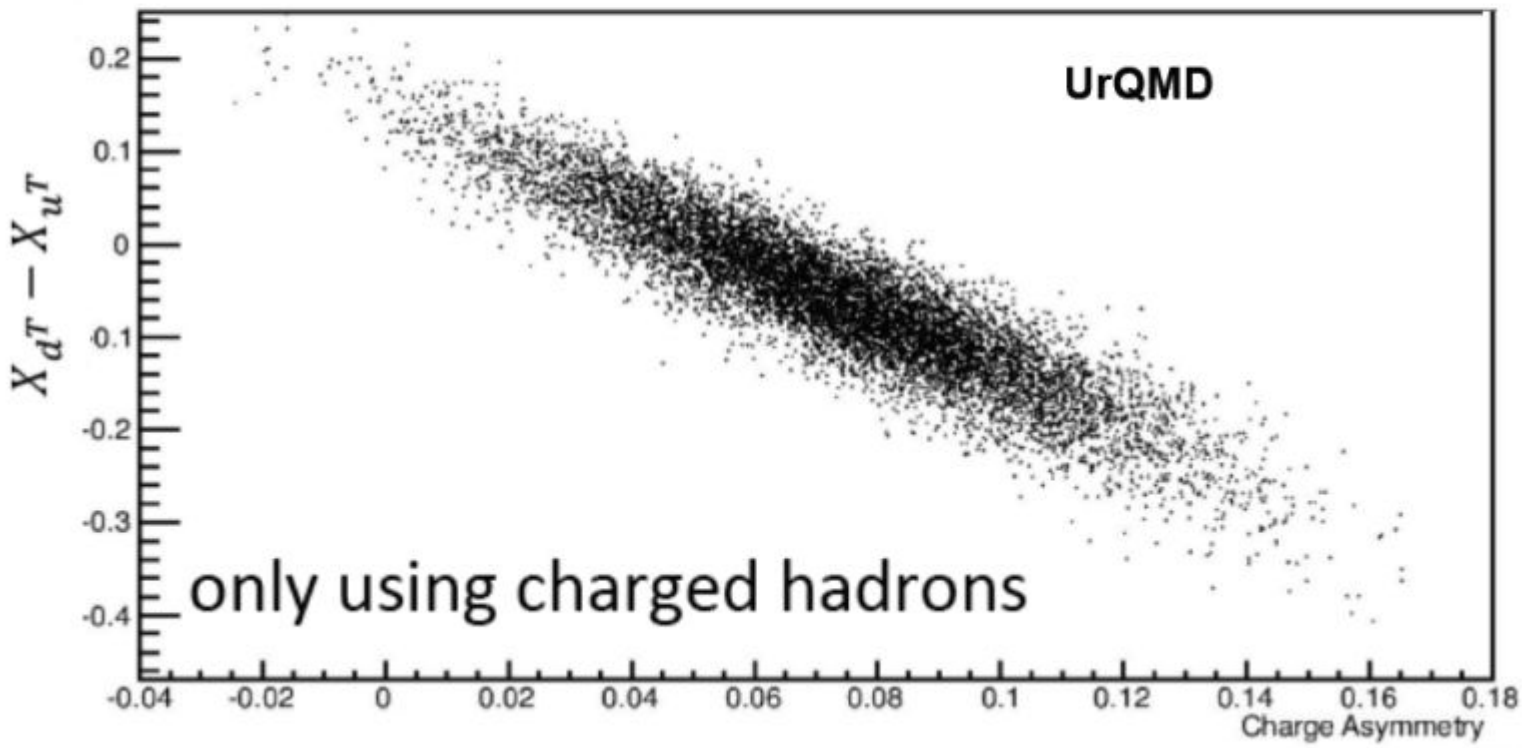
Our measurement for Δv_3 indicates that such mechanism alone cannot explain data.

Δv_2@BES


62.4 GeV Au+Au
30% - 40%
χ² / ndf 2.987 / 3
p0 0.03811 ± 0.01845
p1 2.002 ± 0.4615
39 GeV Au+Au
30% - 40%
χ² / ndf 4.639 / 3
p0 0.07664 ± 0.0125
p1 2.409 ± 0.3579
27 GeV Au+Au
30% - 40%
χ² / ndf 2.66 / 3
p0 0.0818 ± 0.02179
p1 3.171 ± 0.7087
19 GeV Au+Au
30% - 40%
χ² / ndf 2.971 / 3
p0 0.1123 ± 0.03856
p1 2.512 ± 1.138
v2(π⁻) - v2(π⁺) (%)
A±

Multi-component Coalescence (MCC) + Quark Transport

$X_{d^T} - X_{u^T}$ vs Charge Asymmetry



Pearson coefficient : -0.92 → Strong negative correlation

$$\Delta v_2{}^{\pi} \equiv v_2{}^{\pi^-} - v_2{}^{\pi^+} = \boxed{(X_{d^T} - X_{u^T})}(v_2{}^{T} - v_2{}^{P})$$

John Campbell's poster.