Selected Overview of Searches for Chiral Effects in Heavy Ion Collisions

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Chirality 2018 Workshop @ Galilei Institute

Thanks to Jinhui Chen, Subikash Choudhury, Wei Li, Jinfeng Liao, Xuguang Huang, Guoliang Ma, Aihong Tang, Gang Wang, Sergei Voloshin….

OUTLINE

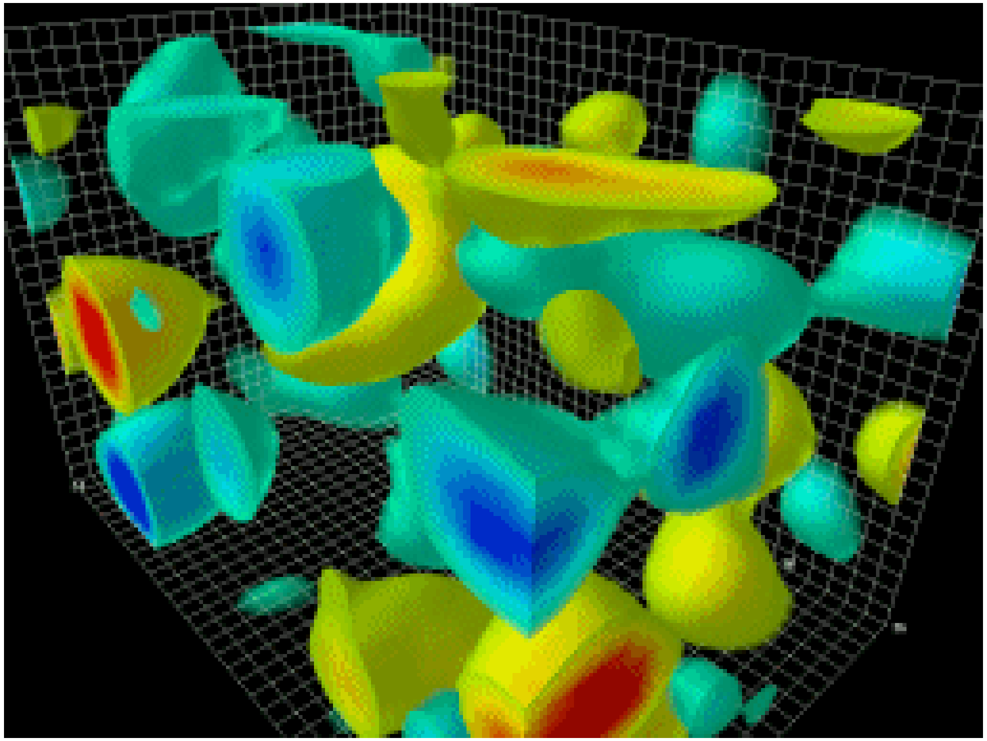
1) CME and Charge Separation Across the RP

2) CMW and Background

3) Search for Chiral Vortical Effect

4) Future Perspective

QCD Domain Formation

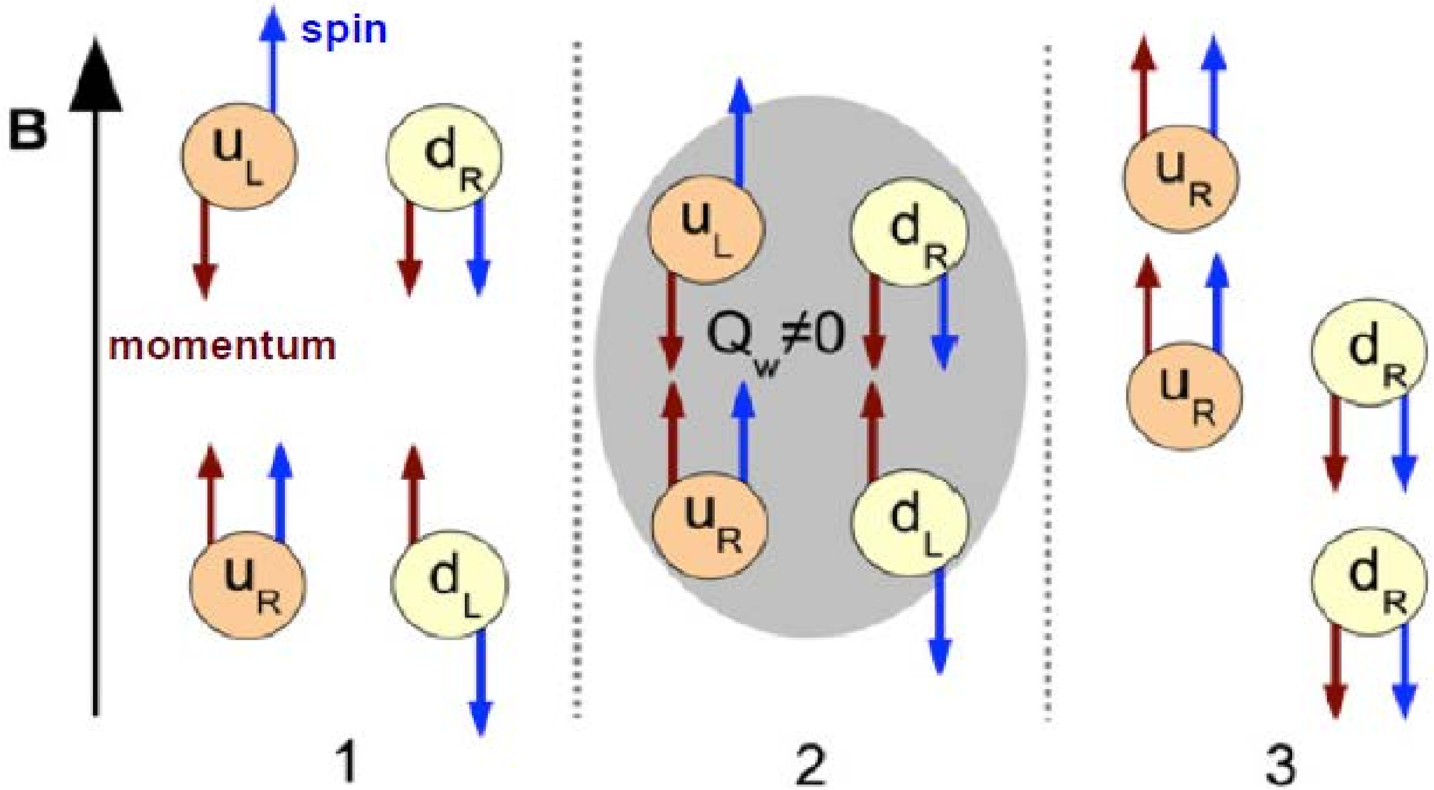


Non-Abelian Gauge Theory

Dynamical by nature

The volume of the box is 2.4 by 2.4 by 3.6 fm.
The topological charge density
Animation by *Derek Leinweber*

Chiral Magnetic Effect → Charge Separation



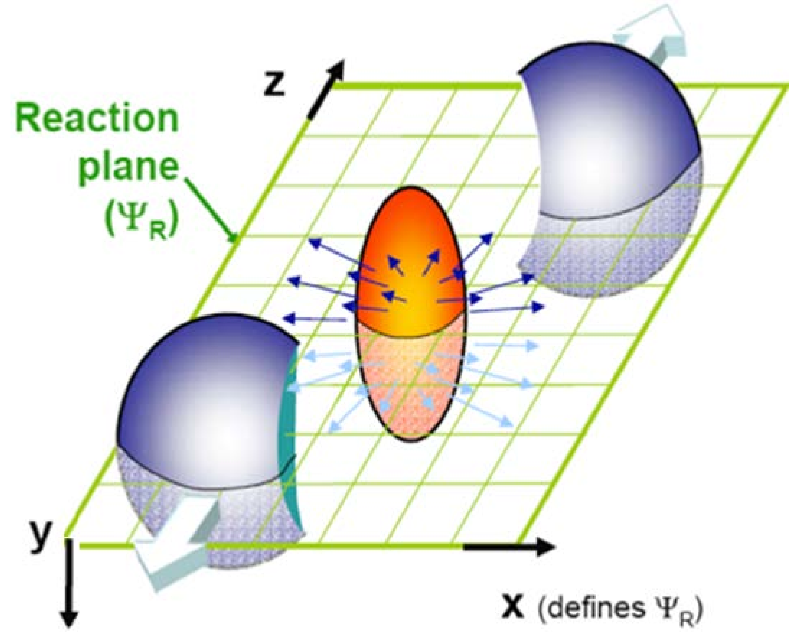
Chiral Magnetic Effect **(CME):** finite chiral charge density induces an electric current along external magnetic field.

$$j_V = \frac{N_c e}{2\pi^2}\mu_A B$$ ➔ 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.



γ_{112}

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

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

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

S. Voloshin, PRC 70 (2004) 057901

background effects

P-even quantity: sensitive to charge separation fluctuation

Directed flow

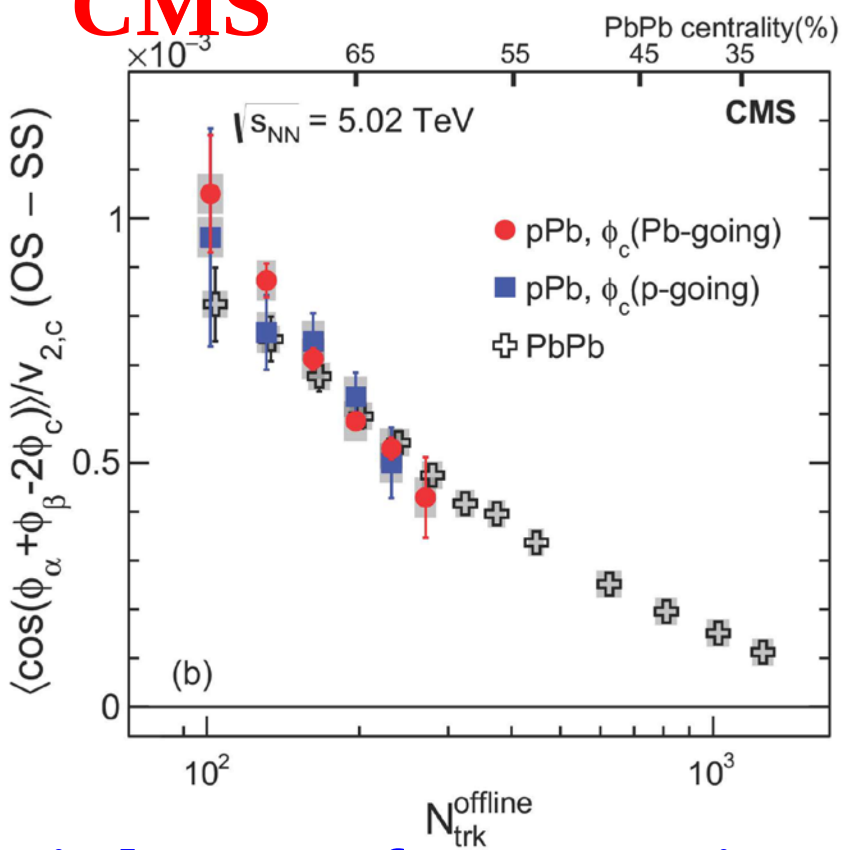
$$\gamma_{123} = <\cos(\phi_\alpha + 2\phi_\beta - 3\psi_3)>$$

pA Data Illuminating!

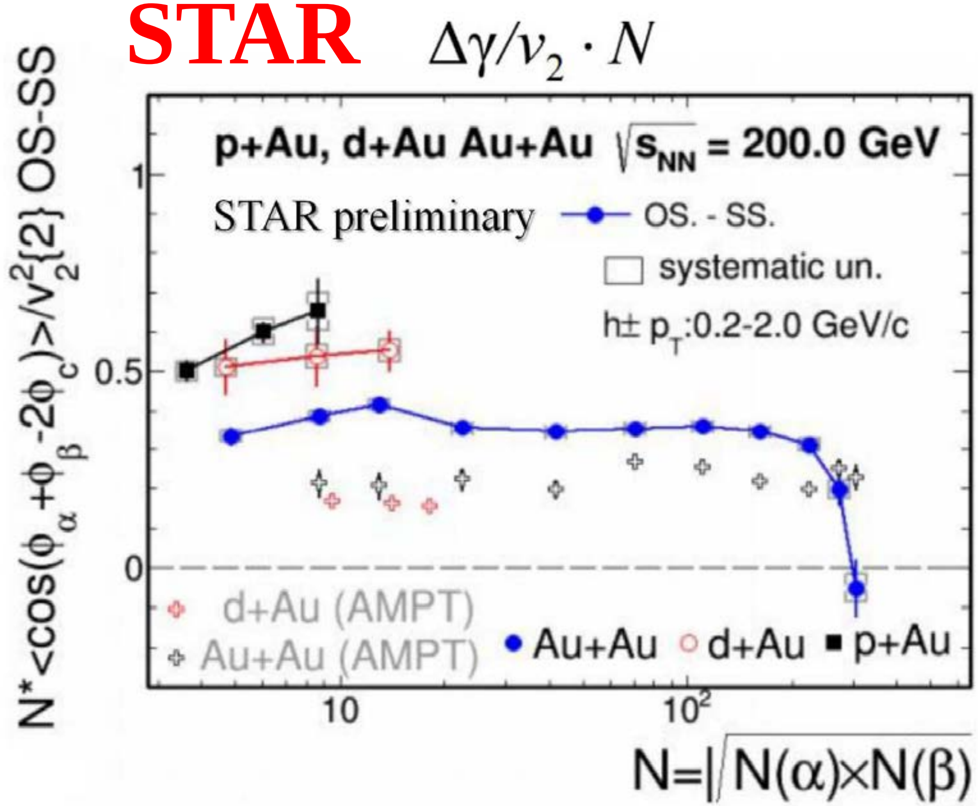
$\Delta\gamma$ correlator in pA – largely background

Many reasons v_2 related background in pA and AA may be different !

CMS

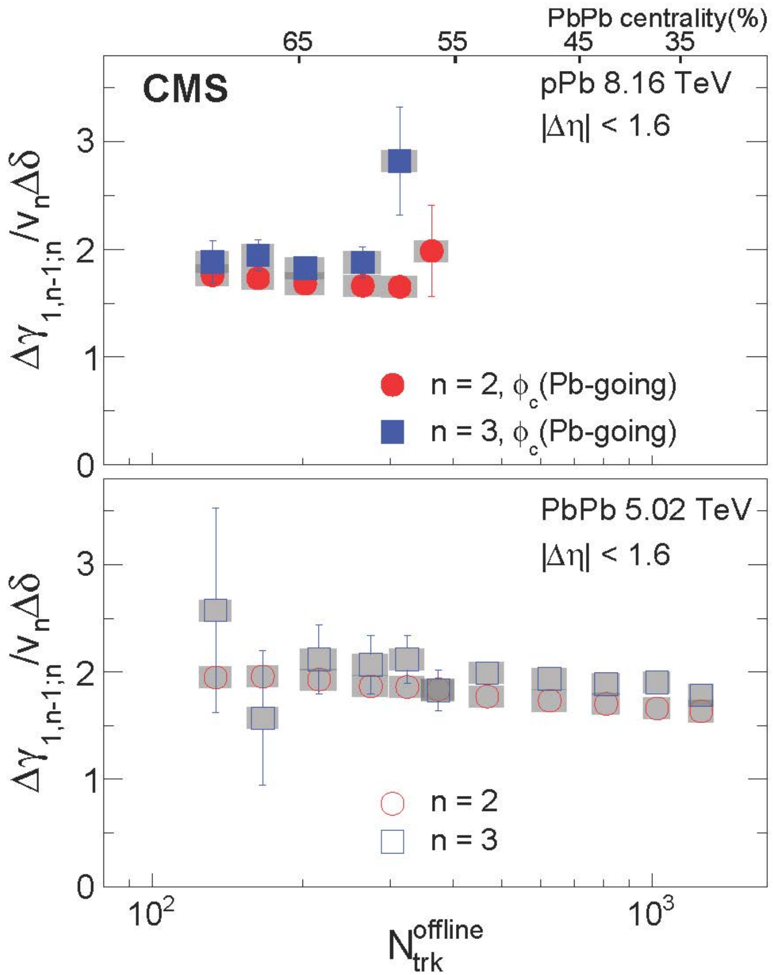


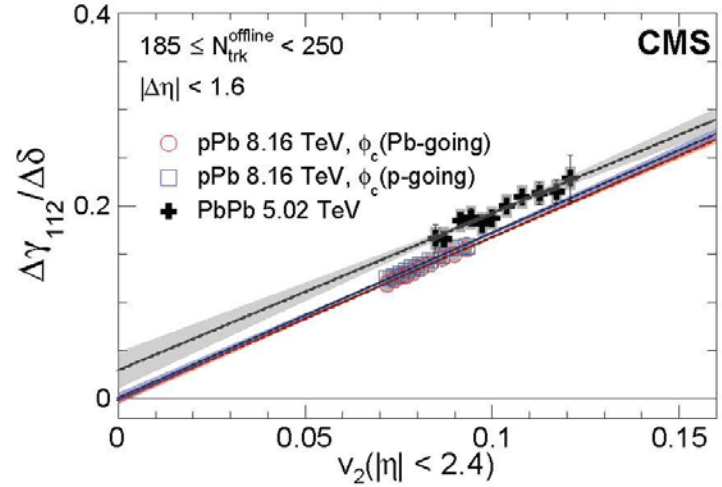
STAR $\Delta\gamma/v_2 \cdot N$

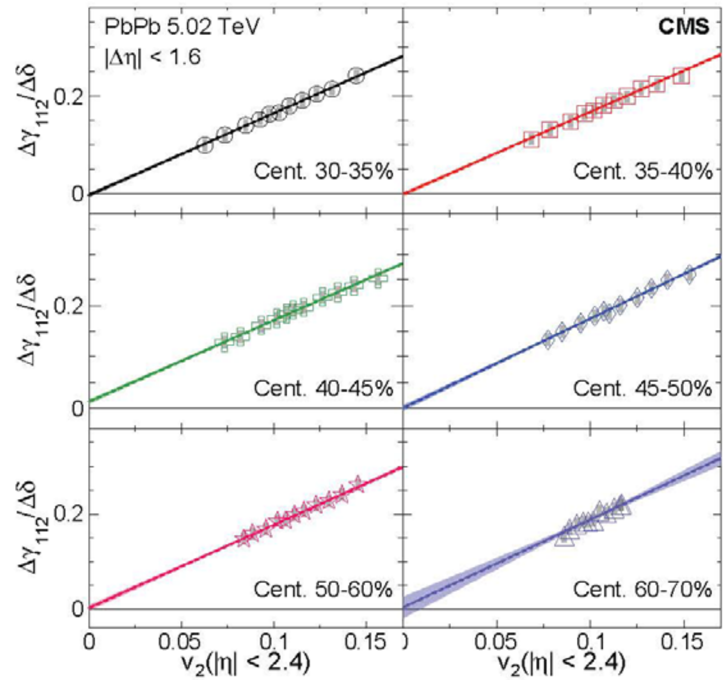


Little room for CME signal in $\Delta\gamma$ at 5.02 TeV from CMS!

CMS Quantitative Approach to CME





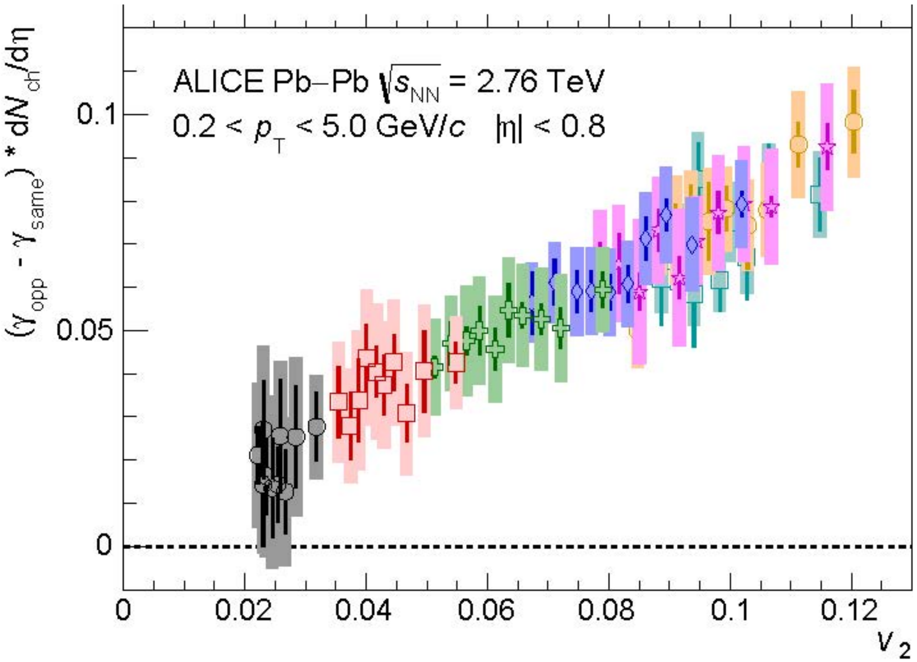


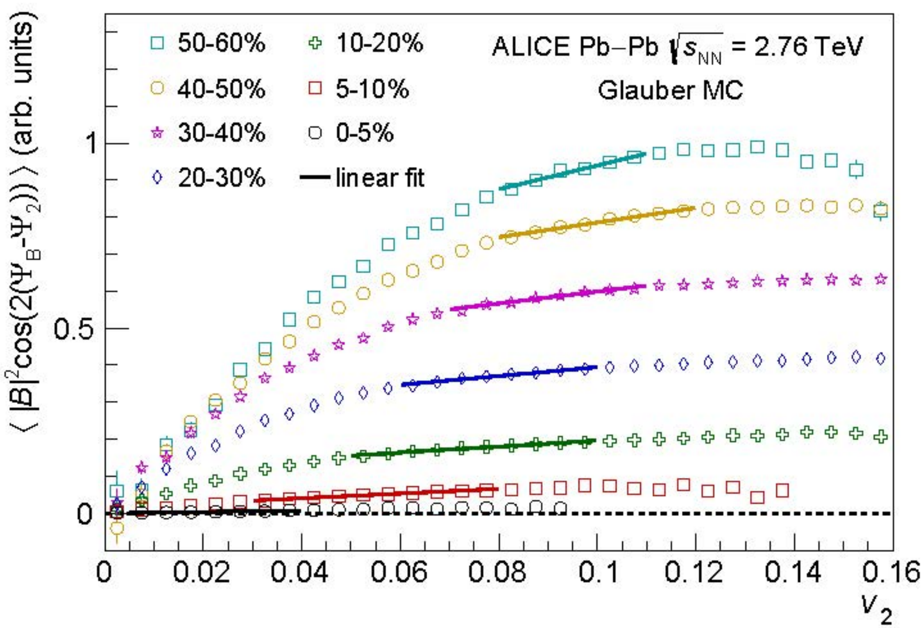
Pb+Pb at 5.02 TeV v_2 Independent
CME < 3.8%
P+Pb at 8.16 TeV
CME < 6.6%
All at 95% C.L. (See Wei Li's talk)

Event-Shape Selected Analysis

ALICE Quantitative Approach to CME

Event-Shape Selected Analysis





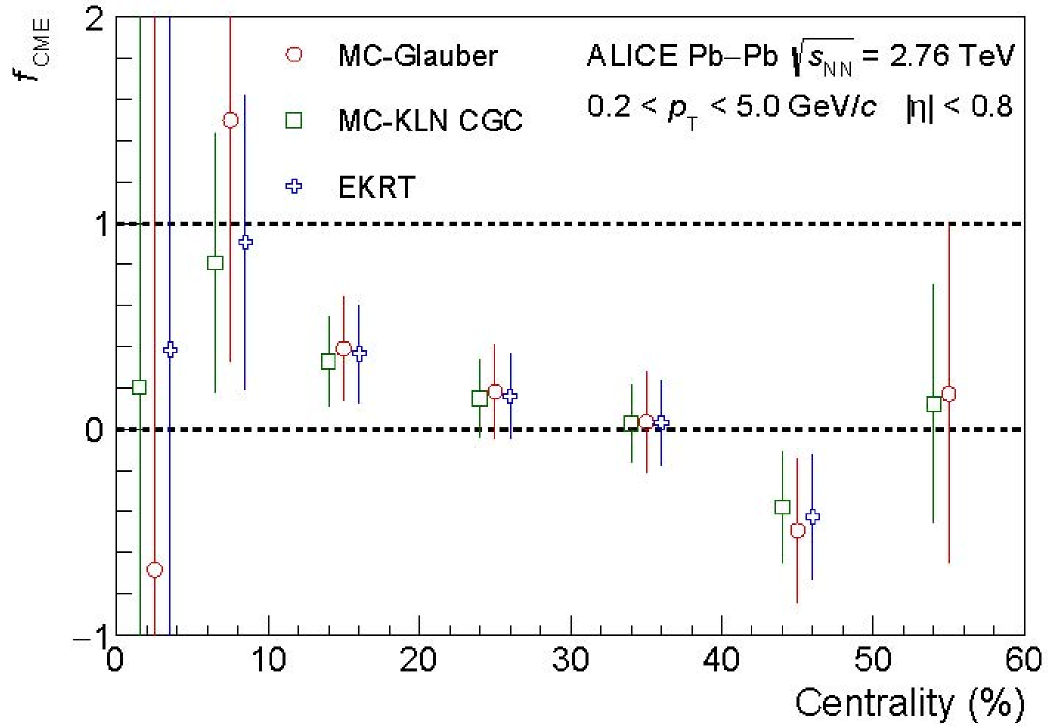
Background – linear dependence on v_2

CME – also dependent on v_2

Measurement – combination of background and CME

→ fraction of CME contributions

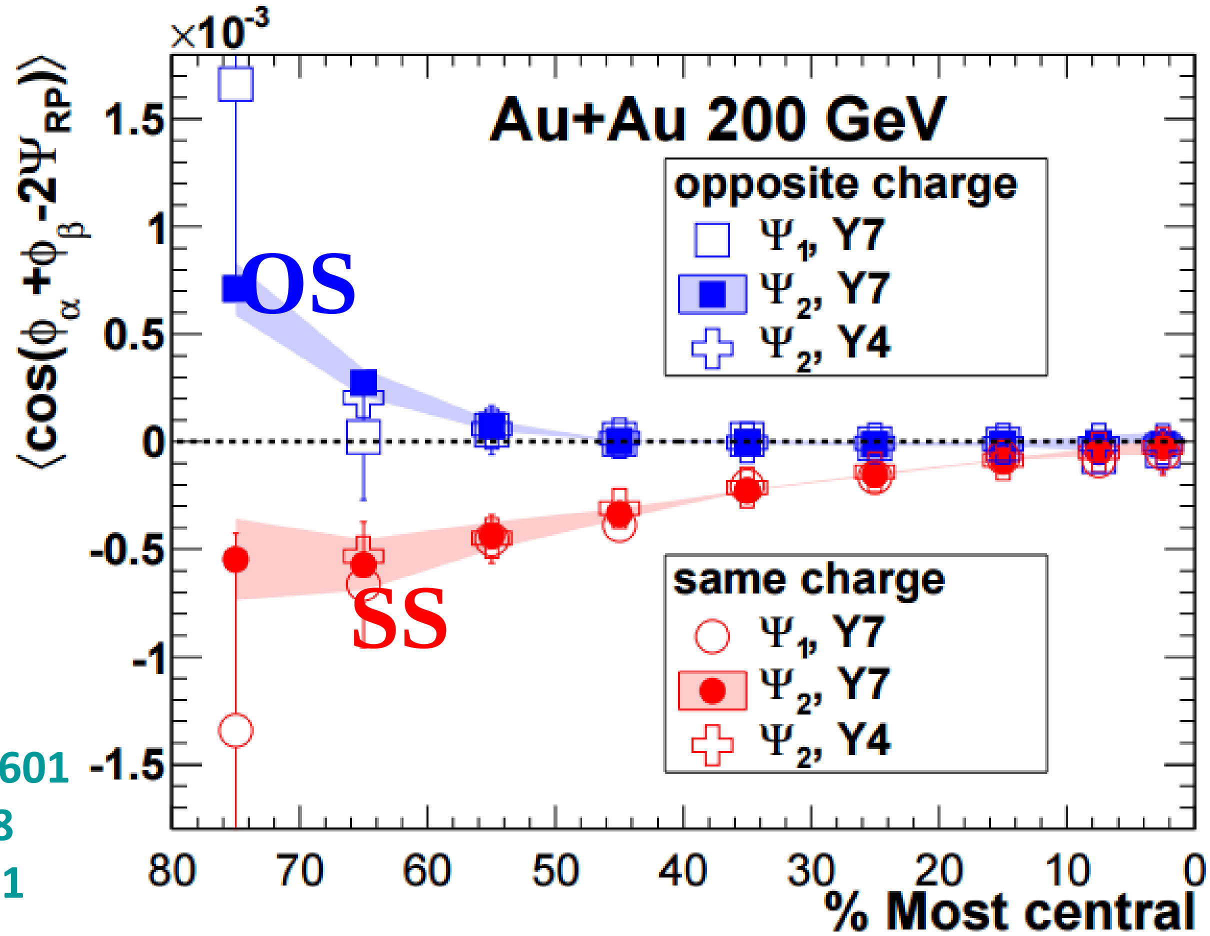
ALICE Quantitative Approach to CME



(10-50)% centrality region: at 2.76 TeV Pb+Pb collisions CME fraction upper limit 26-33% at 95% C.L. depending on models of initial state !

Charge Dependent γ Measure

RHIC data

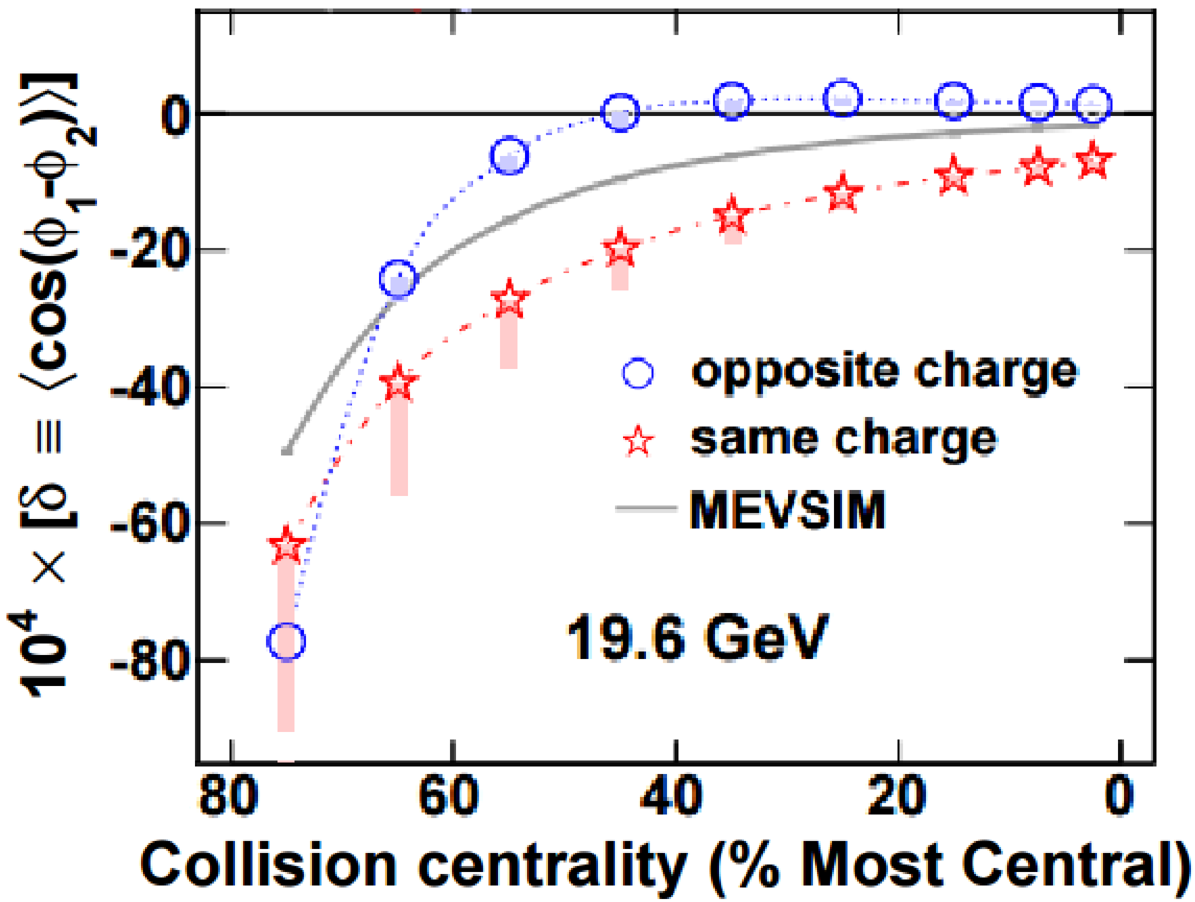


Phys. Rev. Lett. 103(2009)251601
Phys. Rev. C 81(2010)54908
Phys. Rev. C 88 (2013) 64911

- Initial data publication on the topic
- We know better now about the residual background

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*

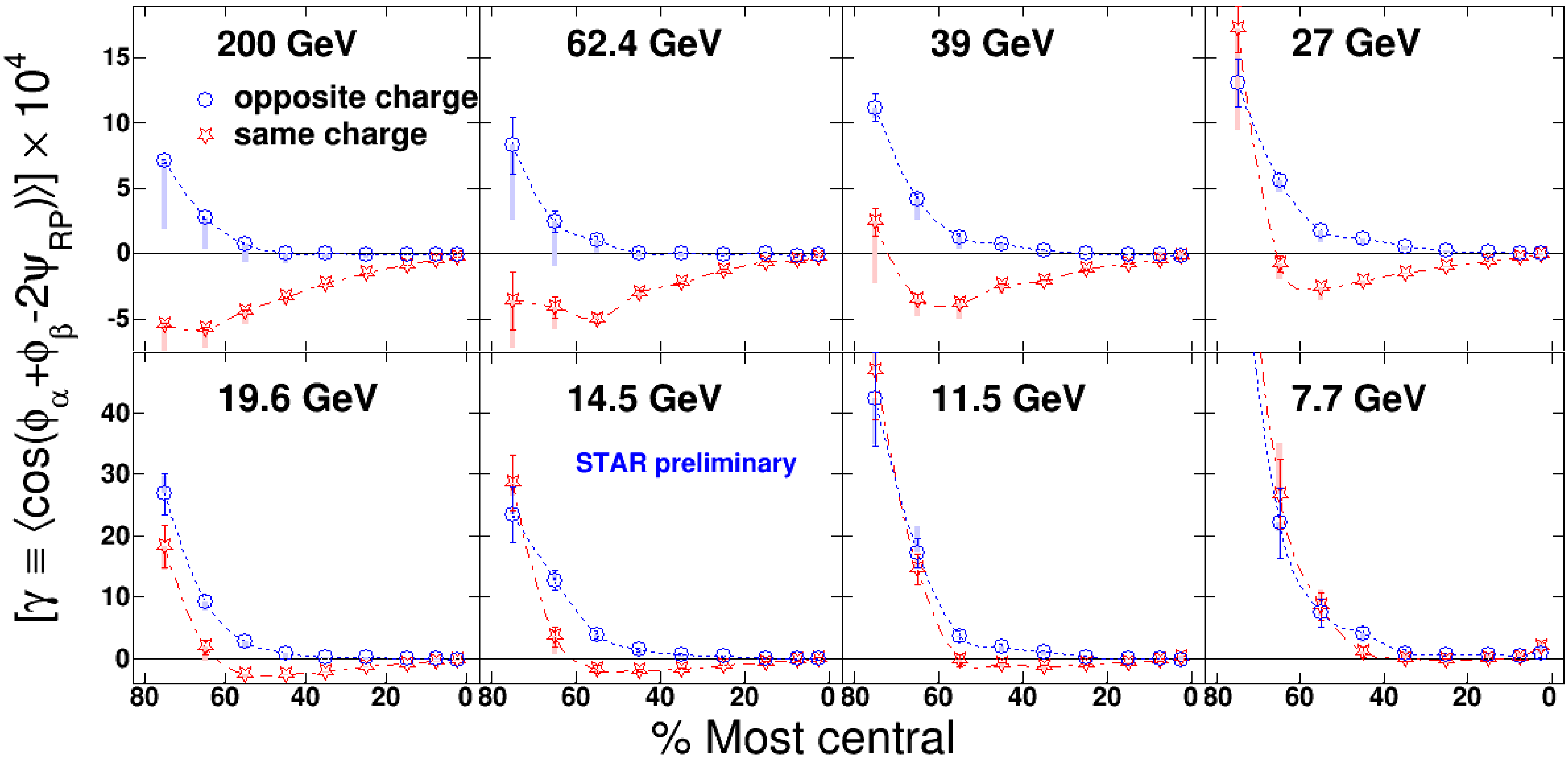
$$\gamma \equiv \langle\cos(\phi_1 + \phi_2 - 2\Psi_{RP})\rangle = \kappa v_2 F - H$$

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

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

Beam Energy Scan

Phys. Rev. Lett 113 (2014) 052302

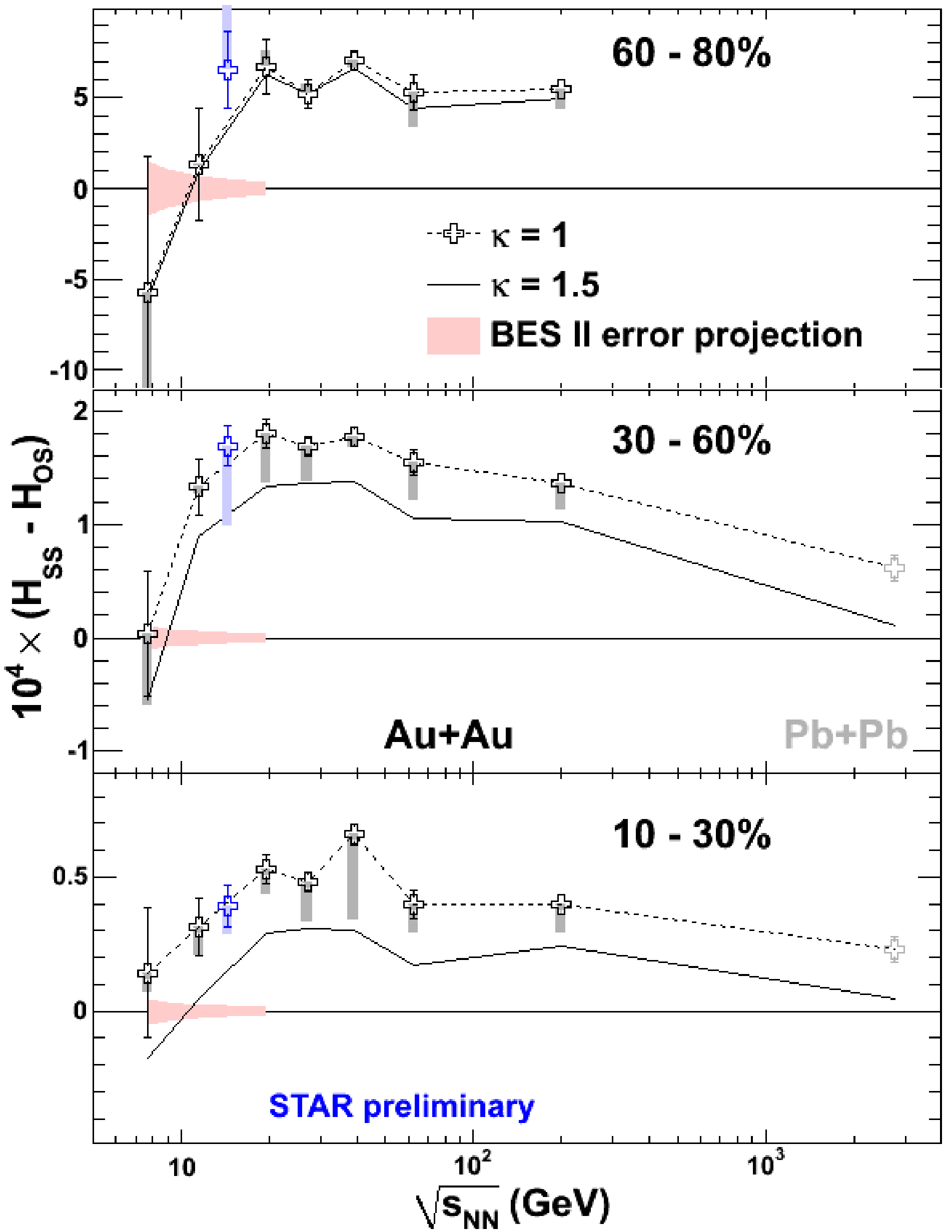


At lower beam energies, charge separation starts to diminish.

If $\Delta\gamma$ is largely background, the background cannot be proportional to v_2 alone as suggested !

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 (ΔH) decreases to 0 from 19.6 to 7.7 GeV and at LHC energies
- The decomposition of γ into F and H is not unique

Agree with CMS Statement !

the magnetic field is fixed. Using an event shape engineering technique, upper limits on the v_2-independent fraction of the three-particle correlator are estimated to be 6.6% for pPb and 3.8% for PbPb collisions at 95% confidence level. The results of this analysis, both the dominance of two-particle correlations as a source of the three-particle results and the similarities seen between PbPb and pPb, provide stringent constraints on the origin of charge-dependent three-particle azimuthal correlations and challenge their interpretation as arising from a chiral magnetic effect in heavy ion collisions.

To be precise, maybe useful to specify "at the 5.02 TeV LHC energy" in the CMS statement!

γ Correlator has major background contribution !
CME contribution can be v_2 dependent as well !
Background cannot be linear to v_2 solely if $\Delta\gamma$ is entirely due to background !

Is there a strong energy dependence in CME & Is there a room for CME at 200 GeV and below?

Please see Gang Wang & Niseem Abdelrahman for STAR update !

Intriguing Observation from CMS:

$$\gamma_{112} = \langle \cos(\varphi_\alpha + \varphi_\beta - 2\Psi_2) \rangle$$

$$= \langle \cos(\varphi_\alpha - \Psi_2)\cos(\varphi_\beta - \Psi_2) \rangle - \langle \sin()\sin() \rangle$$

$$= \langle \cos(\varphi_\alpha - \varphi_\beta)\cos 2(\varphi_\beta - \Psi_2) \rangle - \langle \sin()\sin() \rangle$$

$$\rightarrow \kappa_2 \langle \cos(\varphi_\alpha - \varphi_\beta) \rangle \langle \cos 2(\varphi_\beta - \Psi_2) \rangle$$

$$\gamma_{123} = \langle \cos(\varphi_\alpha + 2\varphi_\beta - 3\Psi_3) \rangle$$

$$= \langle \cos(\varphi_\alpha - \Psi_3)\cos 2(\varphi_\beta - \Psi_3) \rangle - \langle \sin()\sin() \rangle$$

$$= \langle \cos(\varphi_\alpha - \varphi_\beta)\cos 3(\varphi_\beta - \Psi_3) \rangle - \langle \sin()\sin() \rangle$$

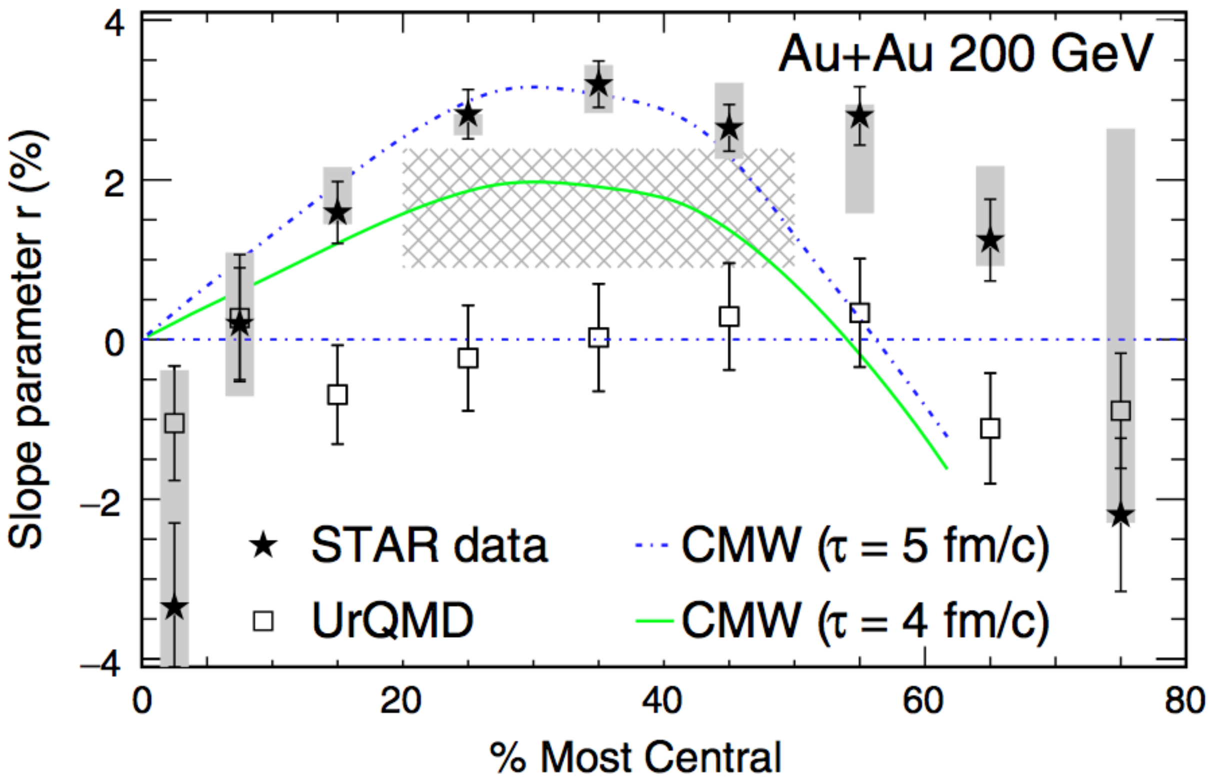
$$\rightarrow \kappa_3 \langle \cos(\varphi_\alpha - \varphi_\beta) \rangle \langle \cos 3(\varphi_\beta - \Psi_3) \rangle$$

Why are κ_2 and κ_3 almost the same?
No CME? Unknown Correlations?

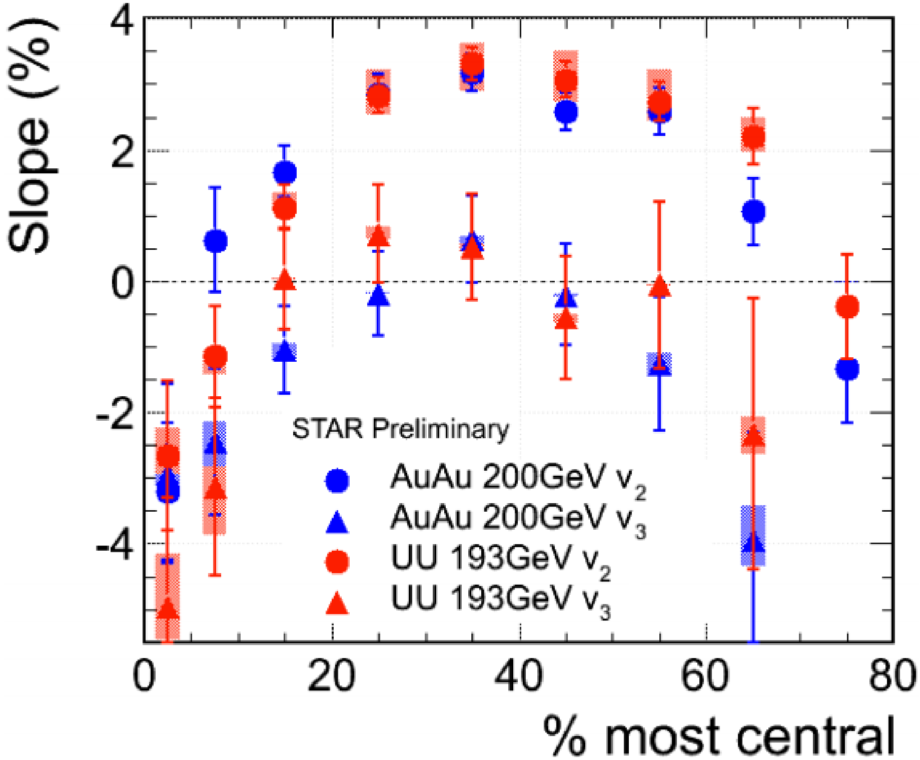
Chiral Magnetic Wave

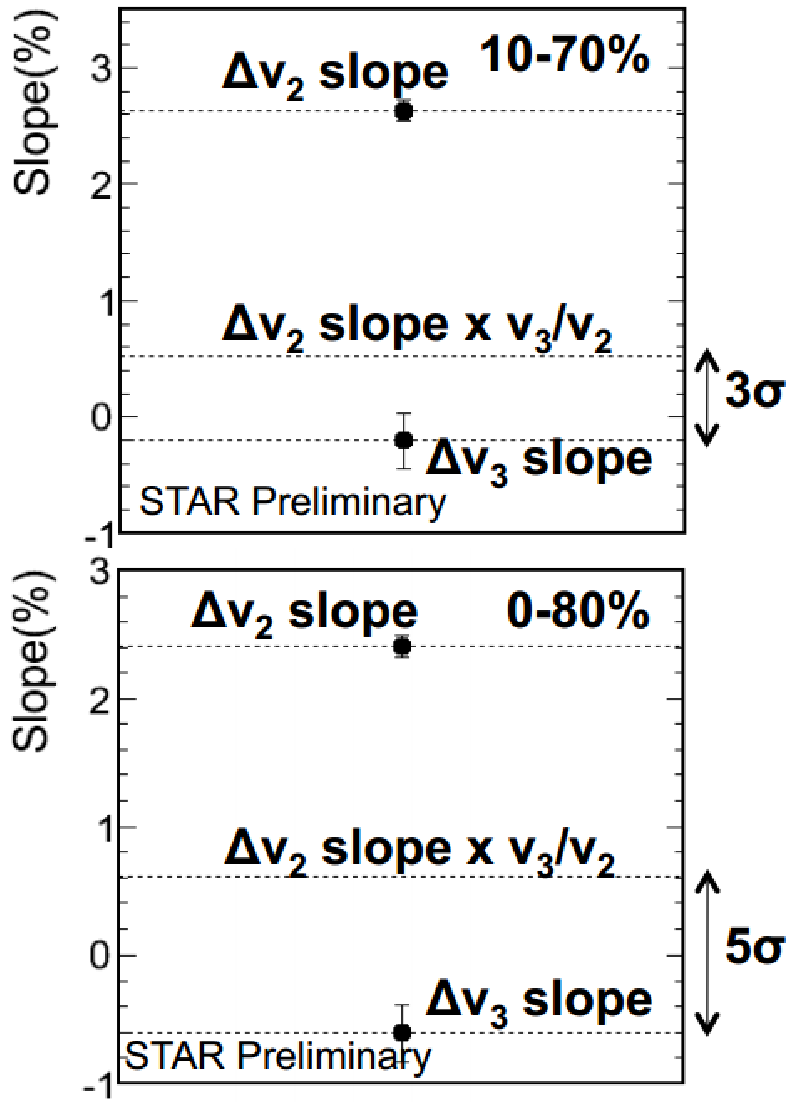
CMW → Electric Quadrupole Moment

$$v_2^{\pm} = v_2 \mp r A_{ch} \qquad A_{ch} = \frac{N^+ - N^-}{N^+ + N^-}$$



Δv_3 slope

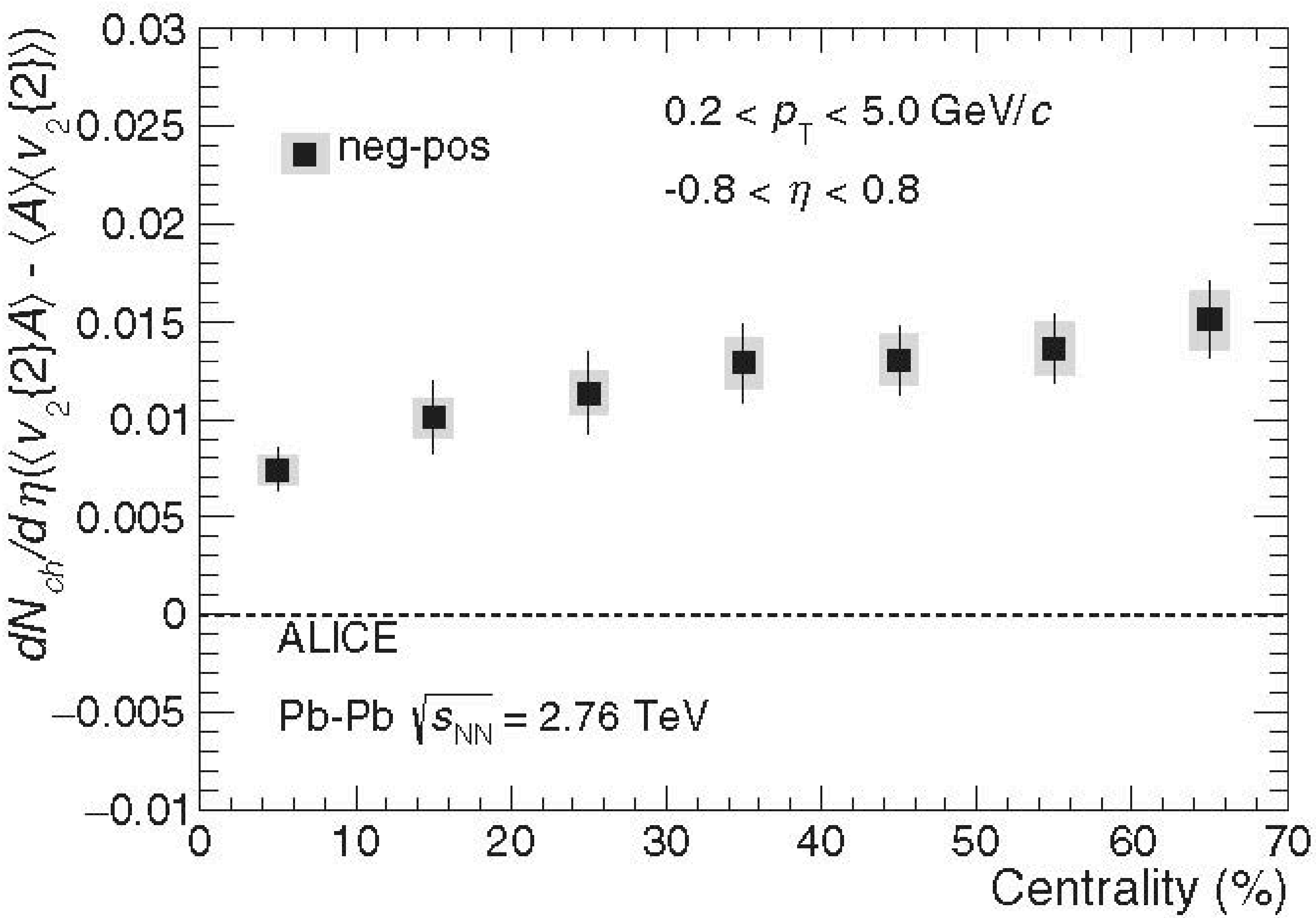




Local charge conservation may introduce A_{ch} dependence of $\Delta v_2(\pi)$. Then one should see **slope-for-Δv_3 / slope-for-Δv_2 ~ v_3/v_2** (Bzak & Bozek PLB 726 239 (2013)).

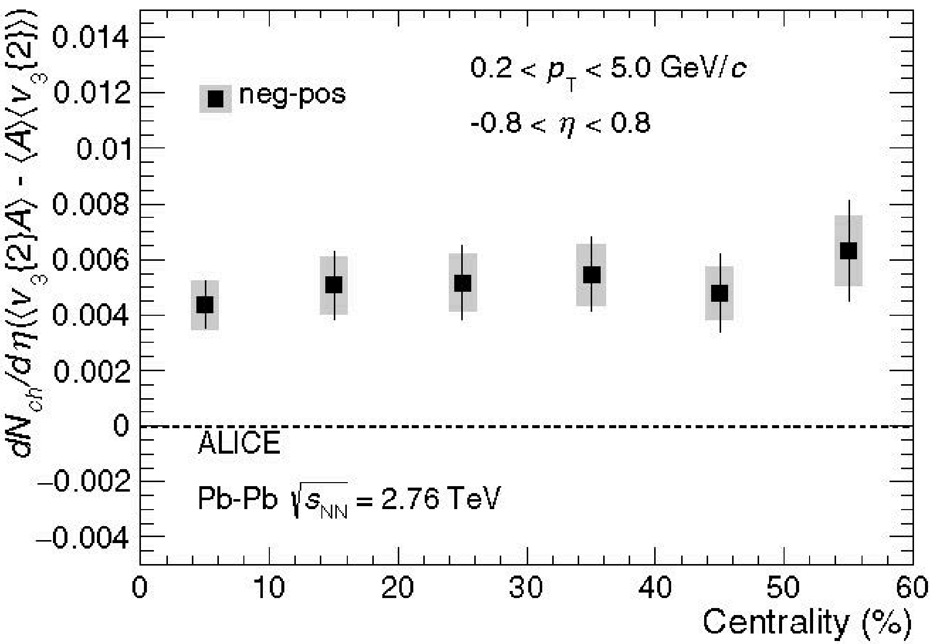
Our measurement for Δv_3 indicates that such mechanism alone cannot explain data.

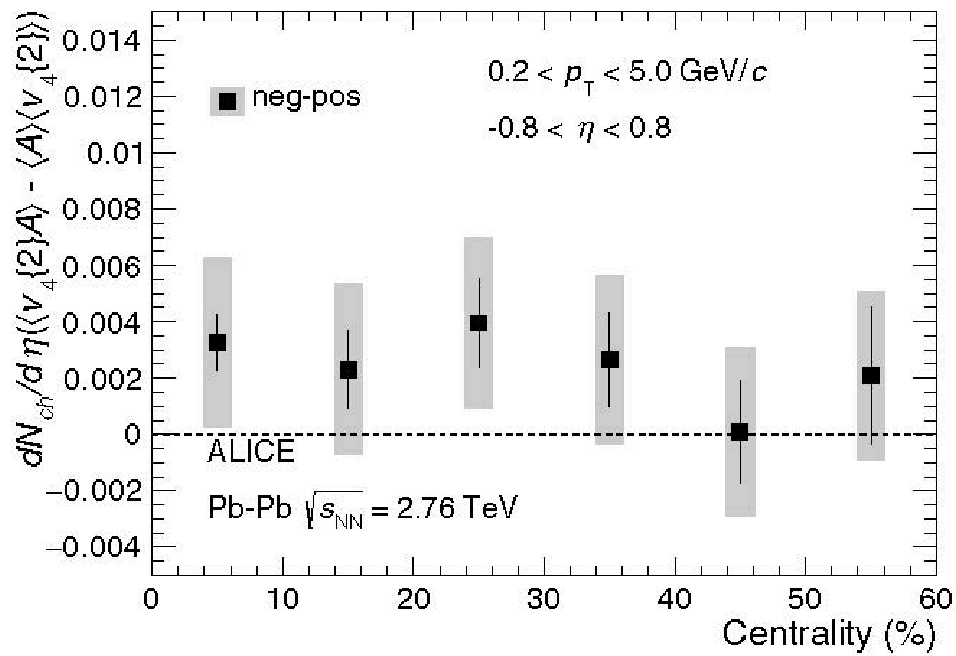
ALICE Improved Approach for Slope



Different centrality dependence from STAR data!

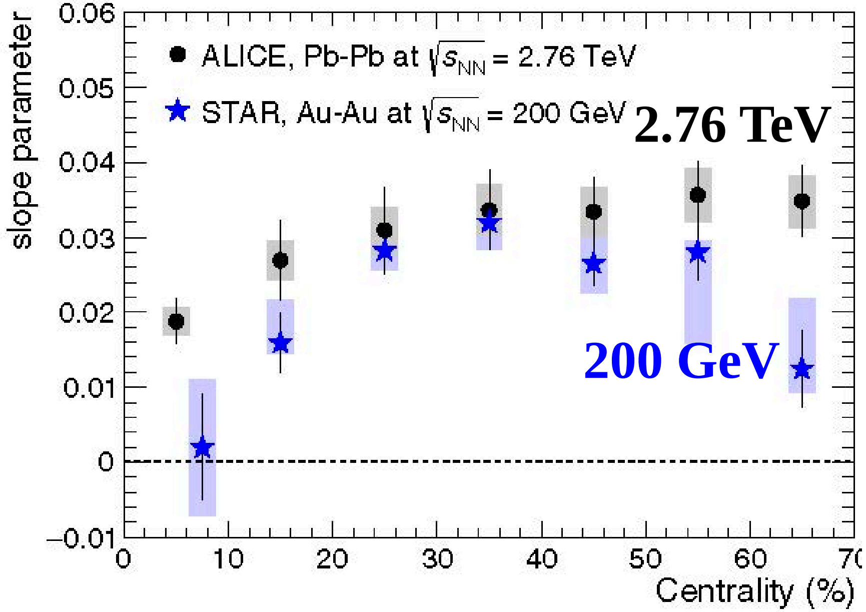
ALICE Slopes for v_3 and v_4

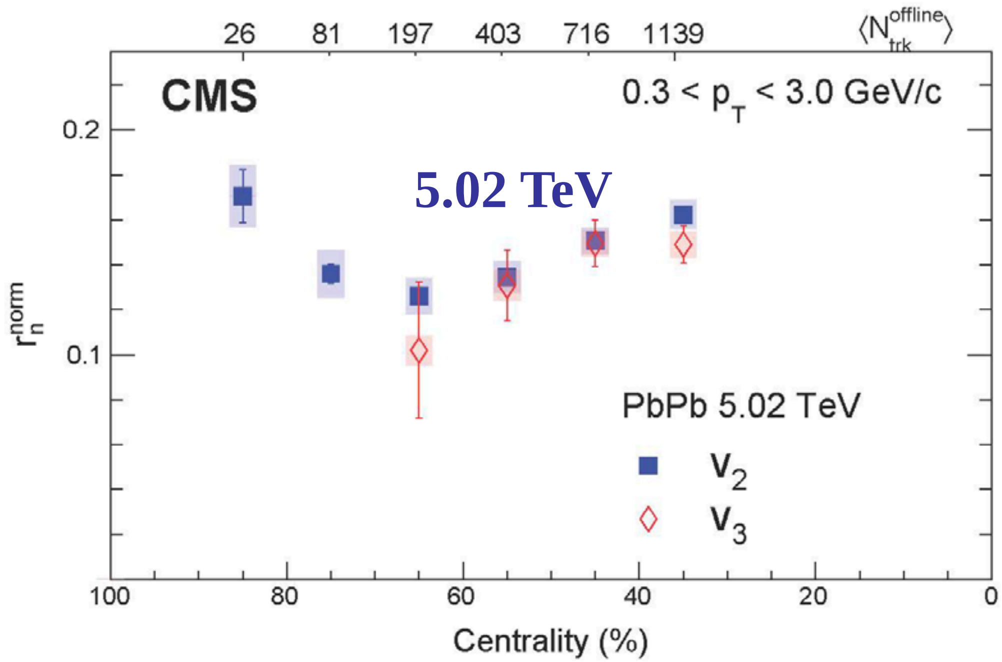




Not exactly the same magnitude as slopes for v_2
Room for CMW signal?
Need good background model !

STAR (0.20 TeV)-ALICE (2.76 TeV)-CMS (5.02 TeV)





Background levels are different !

Little room for CMW signal at 5.02 TeV

Chiral Vortical Effect

Chiral Magnetic Effect **vs** **Chiral Vortical Effect**

Chirality Imbalance (μ_A)

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

$\downarrow$ $\downarrow$

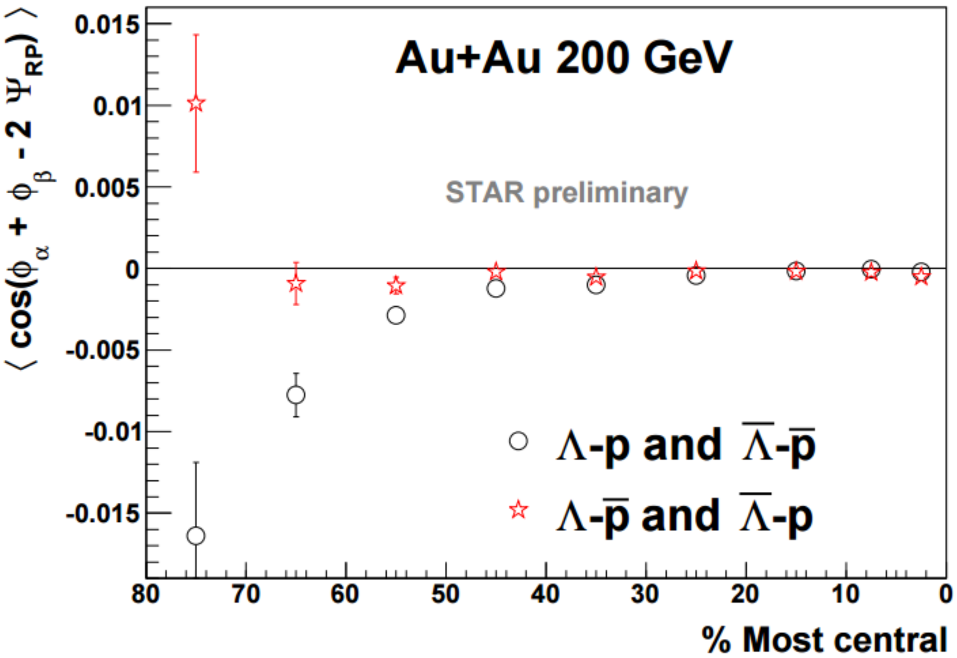
Electric Charge (j_e) Baryon Number (j_B)

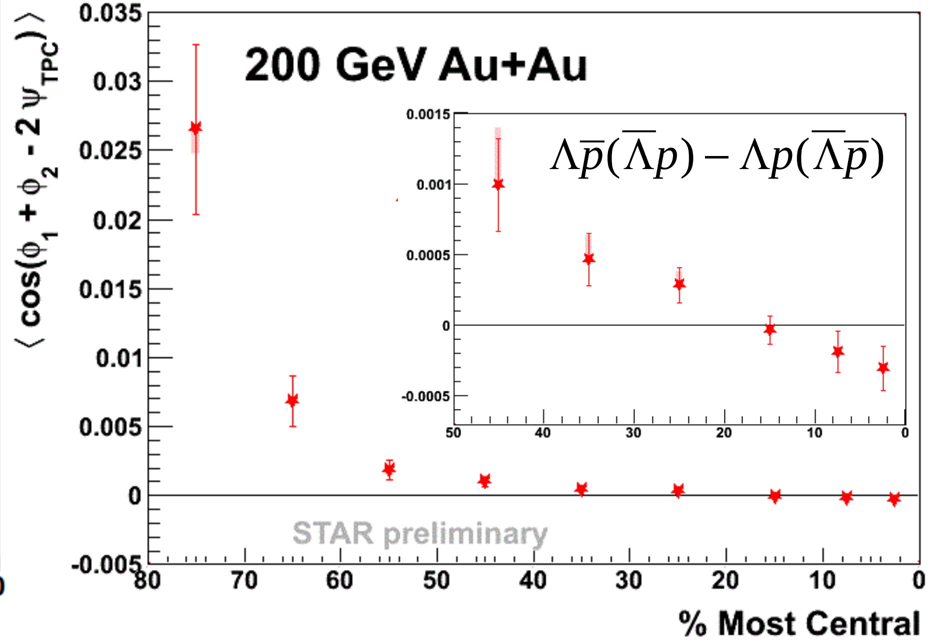
D. Kharzeev, D. T. Son, PRL 106 (2011) 062301

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

correlate Λ–p to search for the Chiral Vortical Effect

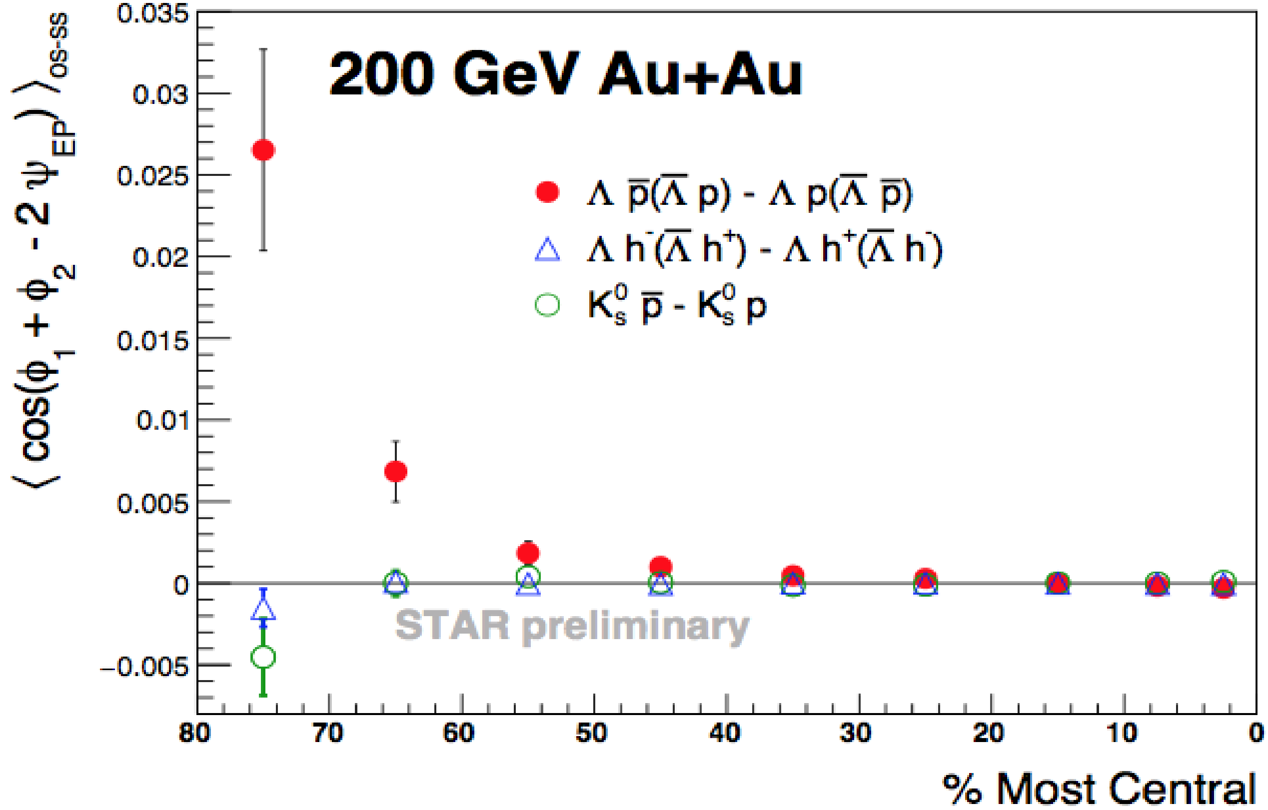
Λ-proton correlation





- same baryon number: Λp and $\overline{\Lambda}\overline{p}$
- opposite baryon number: $\Lambda\overline{p}$ and $\overline{\Lambda}p$
- "same B" is systematically lower than "oppo B" in the mid-central and peripheral collisions, consistent with the CVE expectation.

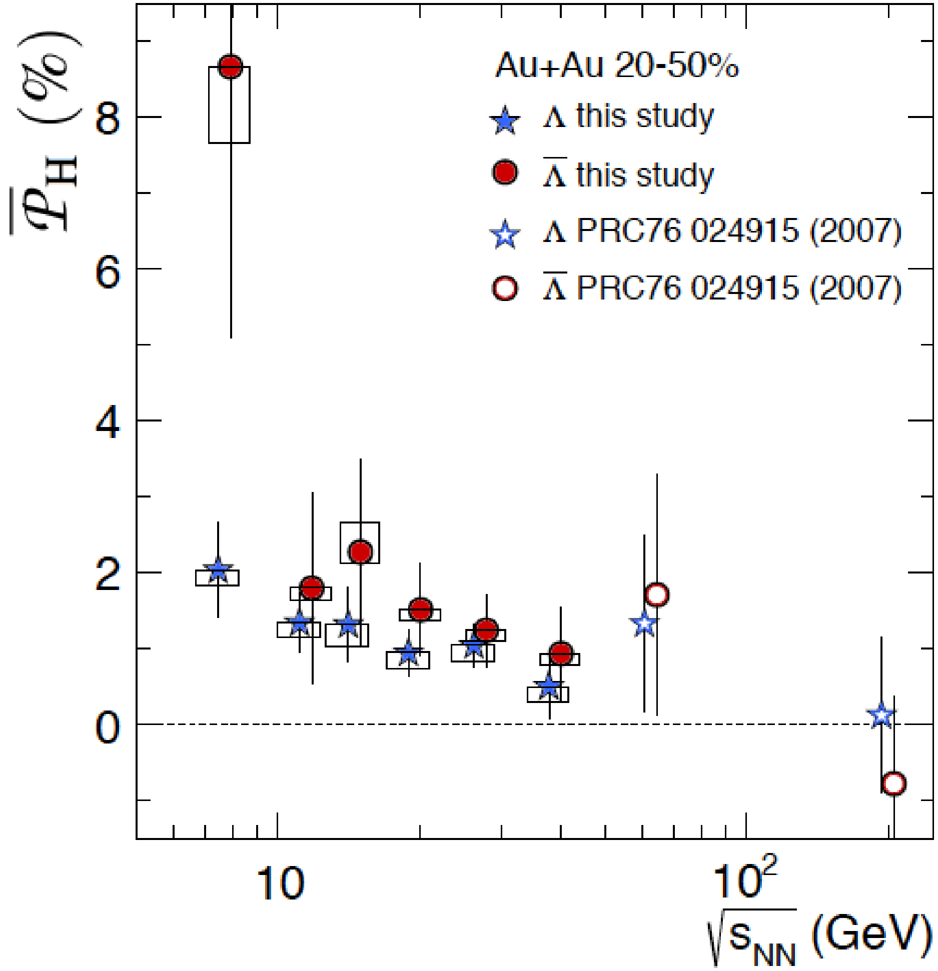
Baryon-Baryon Correlation



Λ-p correlation – different from

Λ-h and K_S-p correlation ! CVE?

STAR Measurement for Lambda Polarization WRT the Reaction Plane



See STAR updates from
Aihong Tang
Takafumi Niida

and talks by
Lisa and Voloshin

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

Intriguing and Puzzling

Energy dependent intriguing observations!

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 ? Vortical Fluidity – Yes!

More insight and towards a definitive answer:

-- establish B field and its consequence

-- effect correlating CME/CVE/CMW

Isobar Collision Running 2018

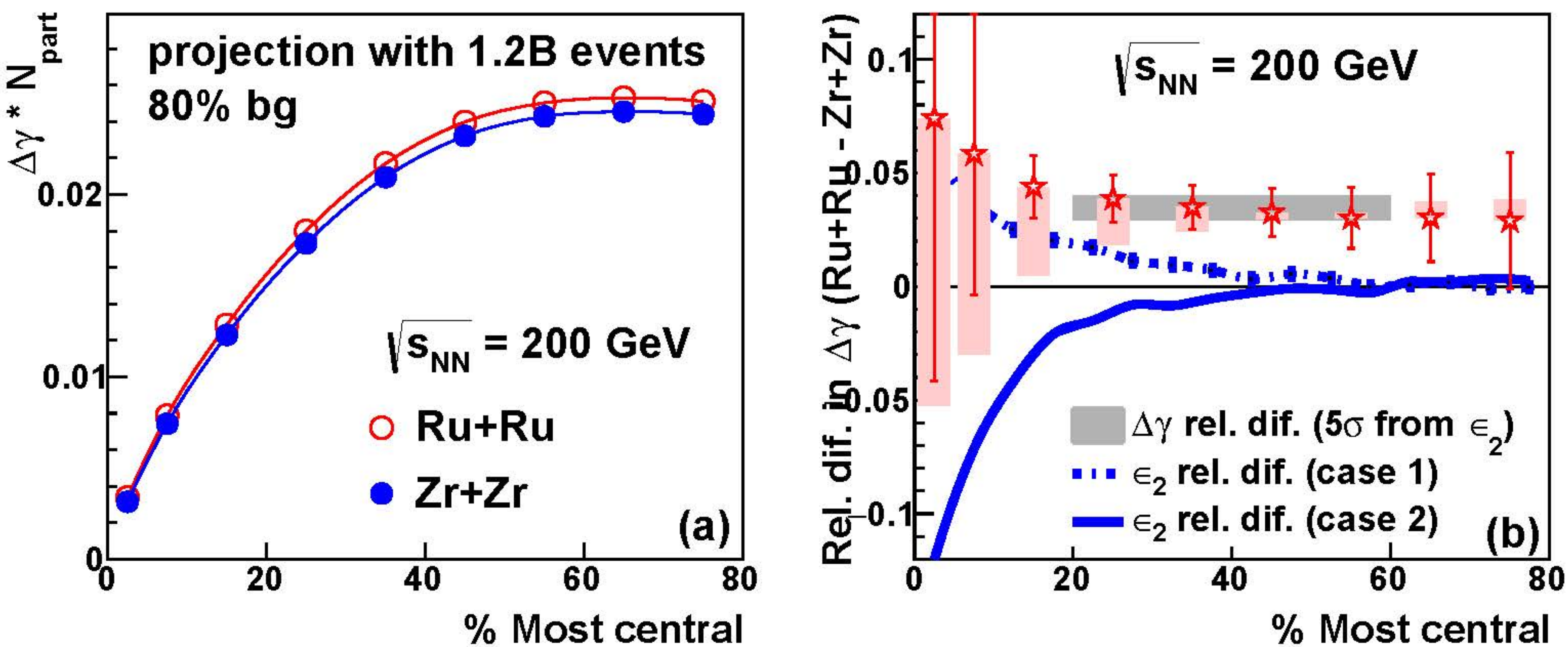
${}^{96}_{44}$Ruthenium and ${}^{96}_{40}$Zirconium:

Up to 10% variation in B field

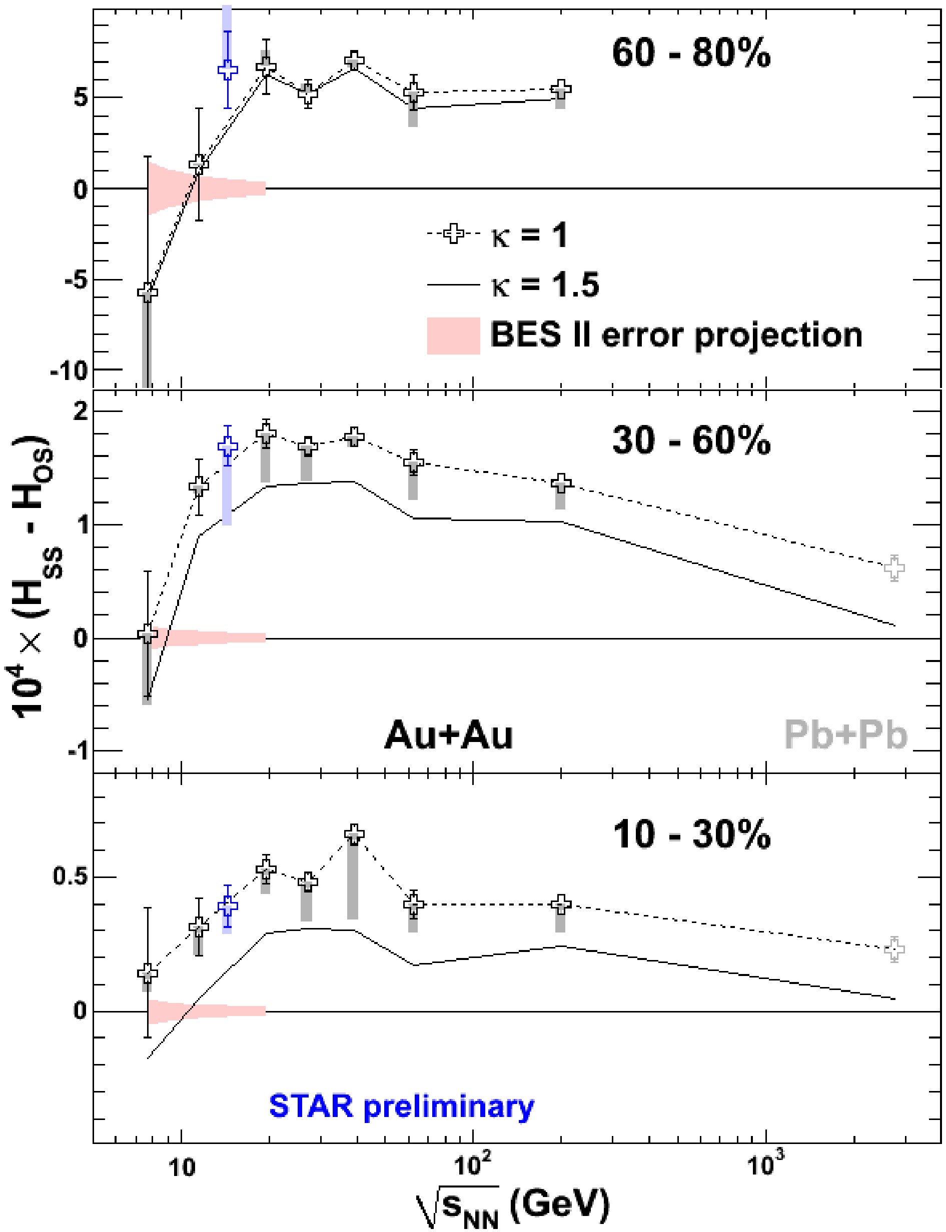
	${}^{96}_{44}Ru+{}^{96}_{44}Ru$ vs ${}^{96}_{40}Zr+{}^{96}_{40}Zr$
Flow	≤
CMW	>
CME	>
CVE	=

Isobars: 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)



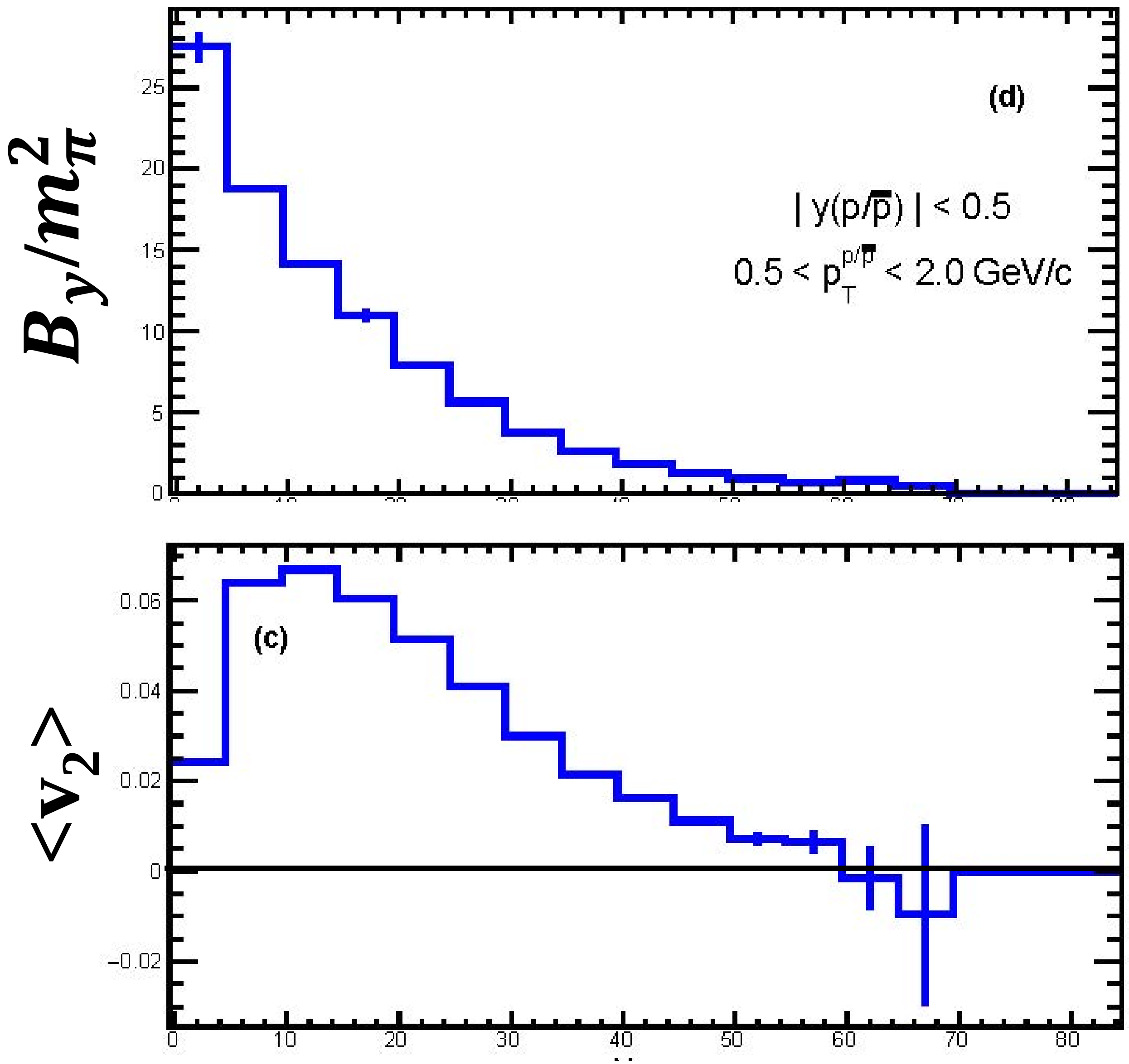
Maybe a Better Beam Energy for Chirality Searches



Optimal Beam Energy: 15-50 GeV

Low beam energy A+A reduces short-range non-flow background!

Event Selection Technique Sensitive to By



Net-protons

Au+Au @ 27 GeV

Net-protons
Another handle for event selection

Subikash Choudhury
Fudan University

Experimental Window of Opportunity

1) Isobaric running to see B field effect @200 GeV in 2018
2) Au+Au data from low RHIC energies to observe B magnitude and life-time difference 2018 +
3) If promising, another run for isobaric system may be proposed

There must be some background – yet no satisfactory background model can explain all features in data – any room for CME/CMW? Definitive Answer?

THE END