Selected Overview of Searches for Chiral Magnetic Effect in Heavy Ion Collisions -- Lessons I learned

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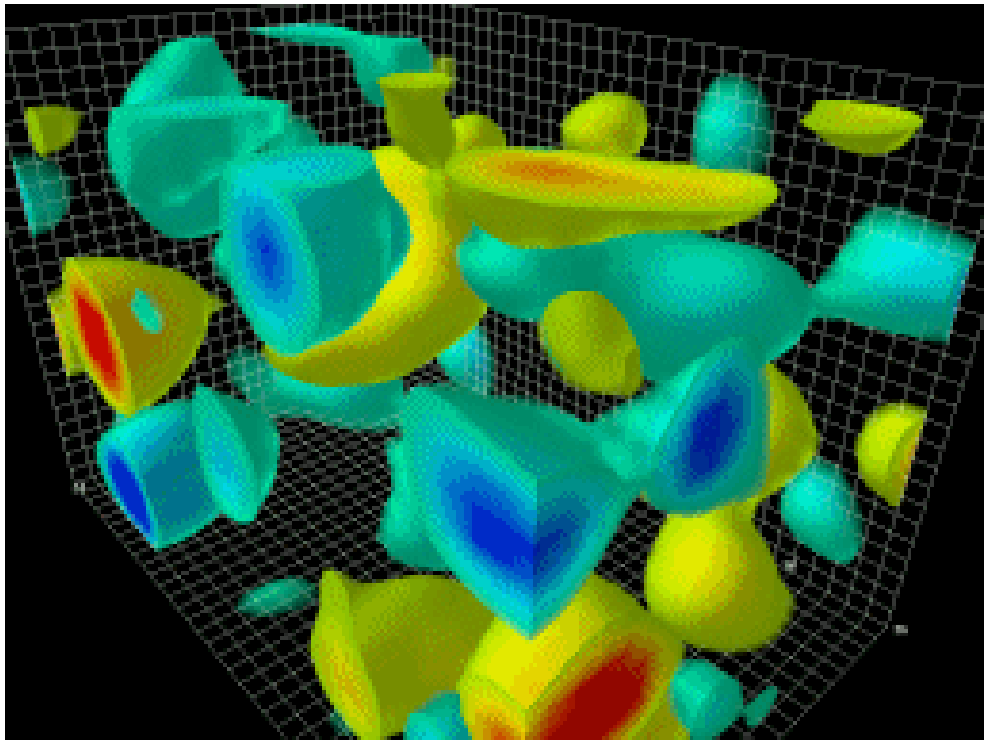
QCD Domain Formation



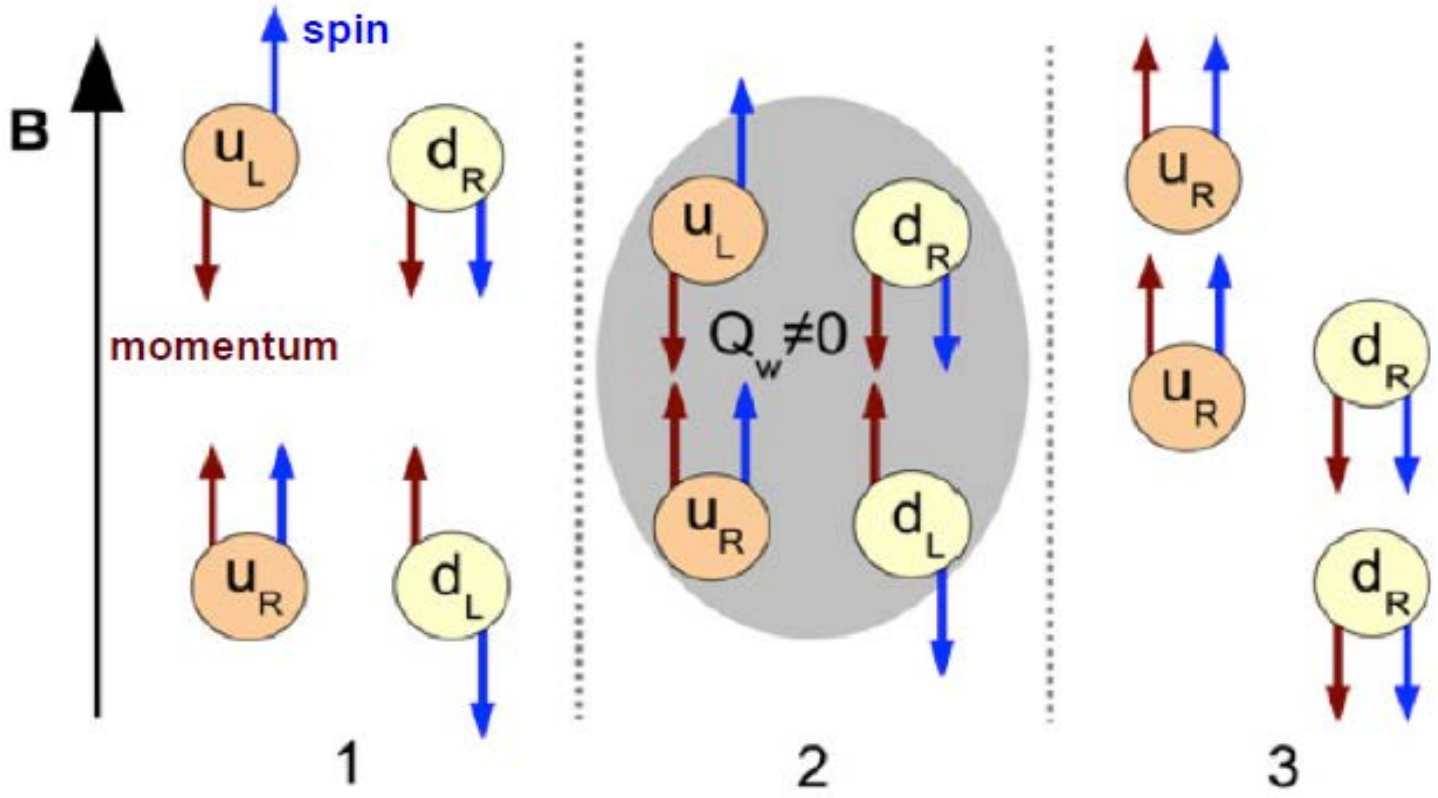
The volume of the box is 2.4 by 2.4 by 3.6 fm.
The topological charge density
Animation by *Derek Leinweber*

Non-Abelian Gauge Theory
Dynamical by nature !

Extraordinary discovery requires extraordinary evidence !

Ruling out a possibility takes more than hand-waving arguments and crude extrapolation of background !

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)

OUTLINE

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

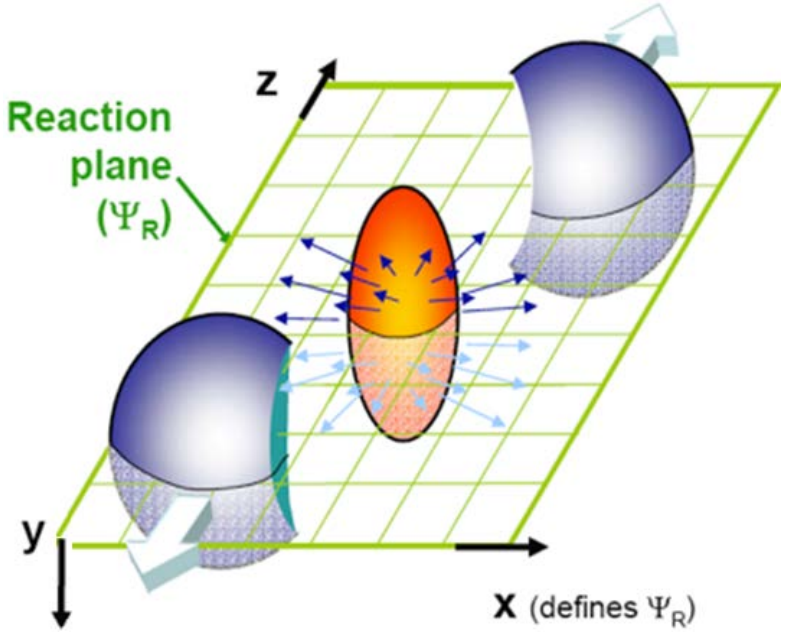
2) **LHC vs RHIC Energy**

3) **Correlating Various Chirality Effects**

4) **Lessons and Future Perspective**

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

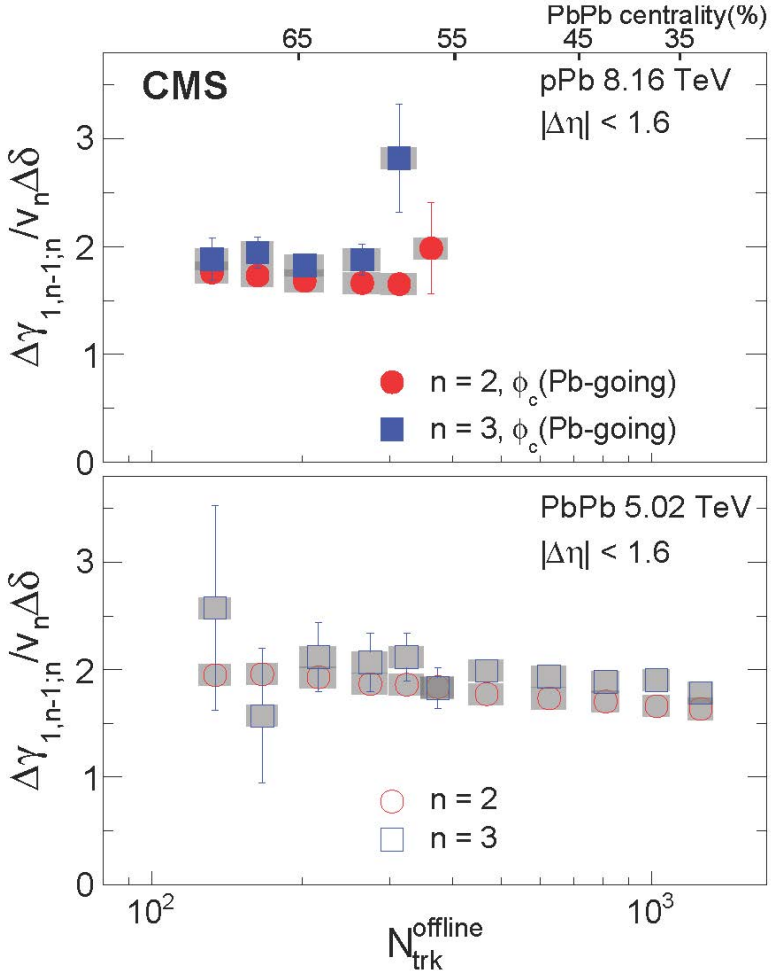
Directed flow

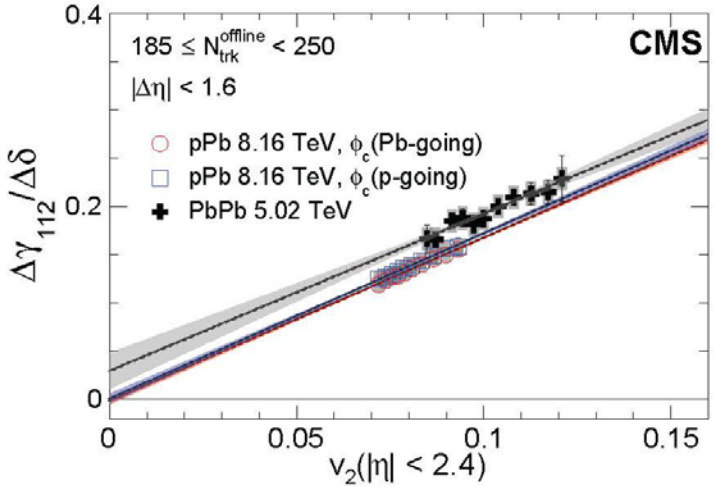
background effects

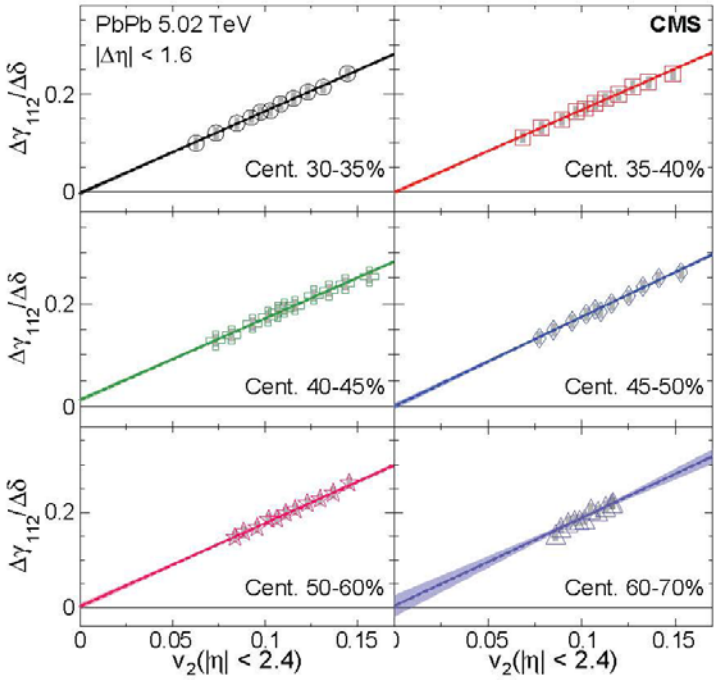
P-even quantity: sensitive to charge separation fluctuation

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

CMS Quantitative Approach to CME







Pb+Pb at 5.02 TeV v_2 Independent CME < 3.8%

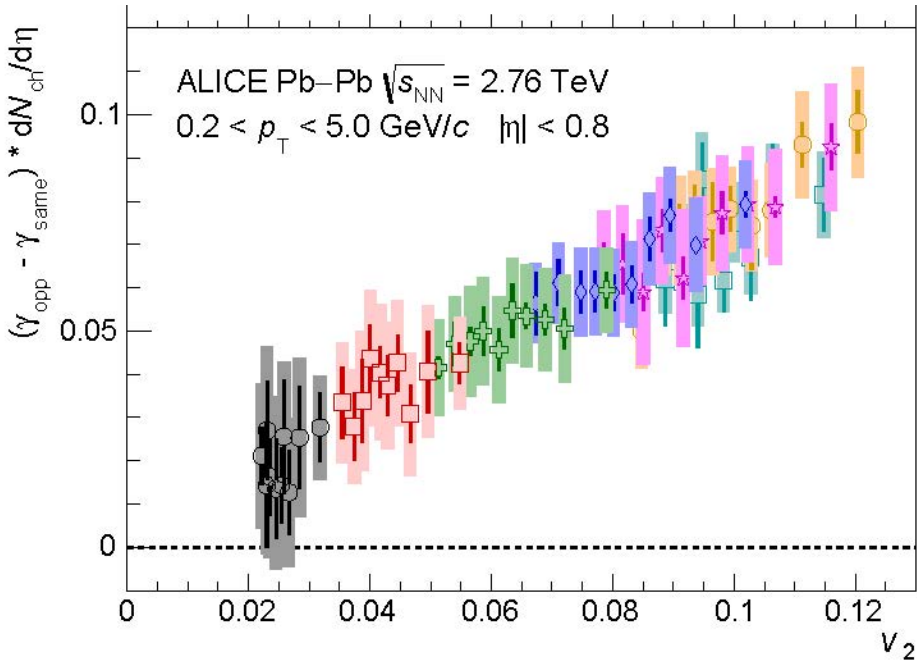
P+Pb at 8.16 TeV CME < 6.6%

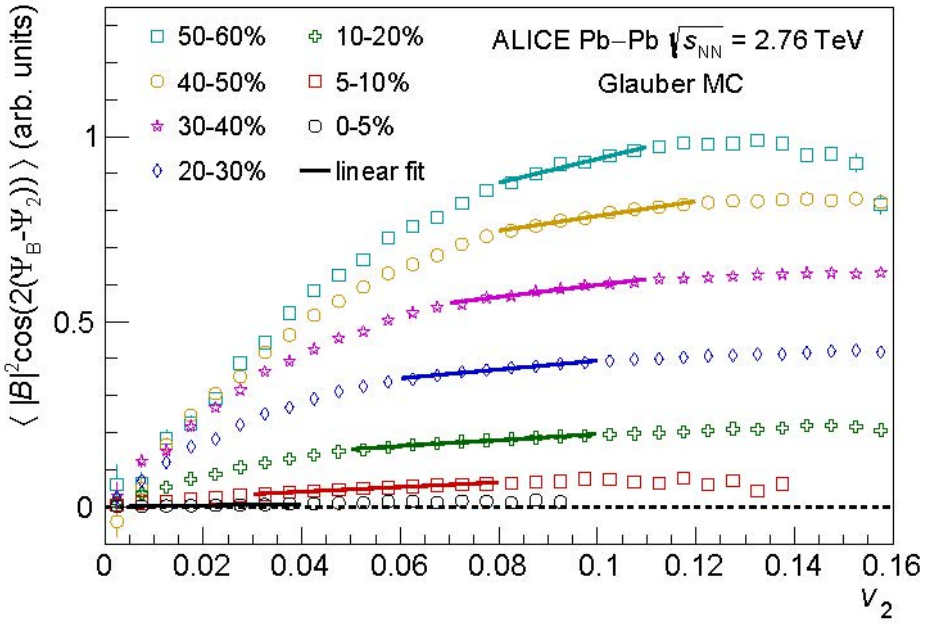
All at 95% C.L.

Event-Shape Selected Analysis

ALICE Quantitative Approach to CME

Event-Shape Selected Analysis





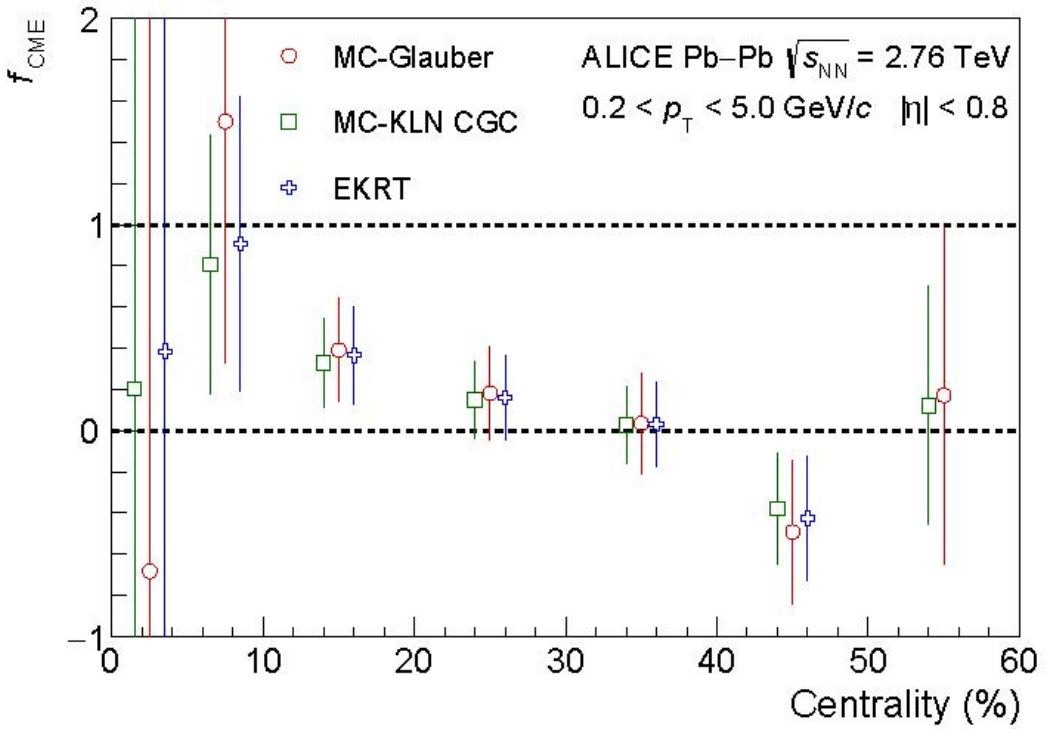
Background – linear dependence on v_2

CME – also dependent on v_2

Measurement – combination of background and CME

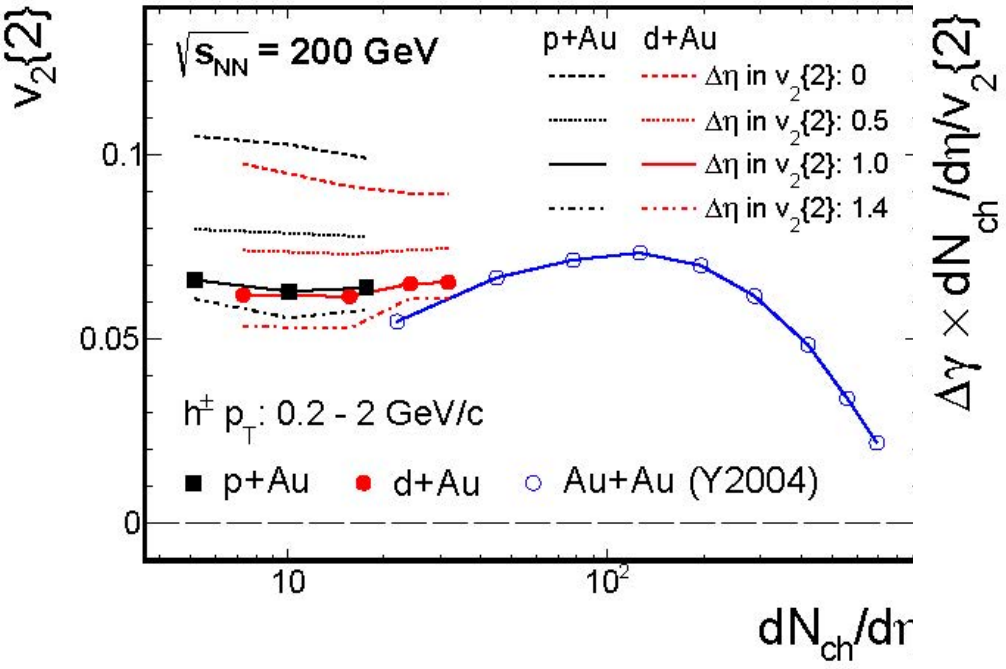
→ fraction of CME contributions

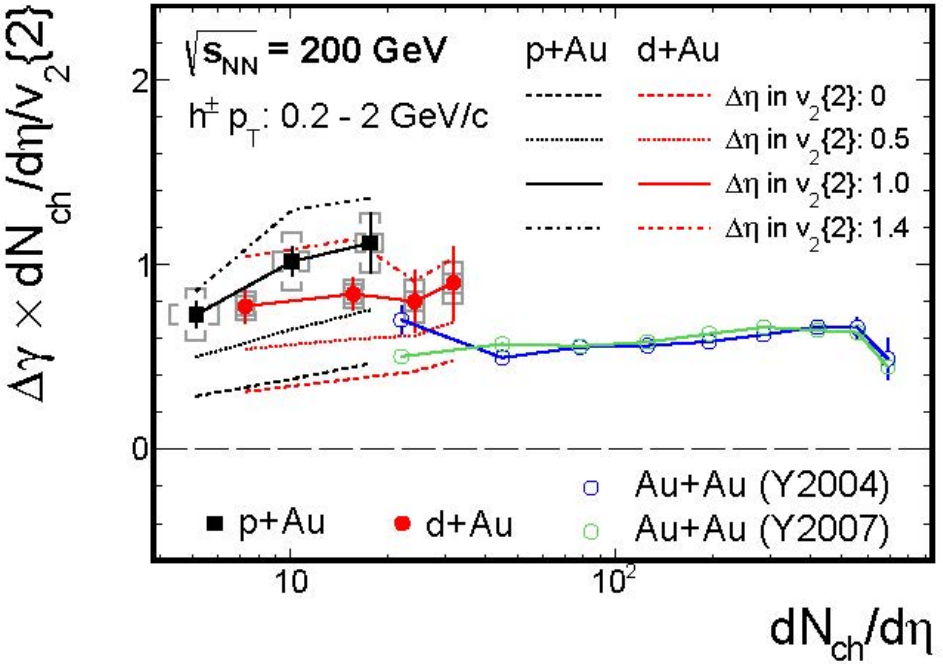
ALICE Quantitative Approach to CME



(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 !

Small System not Relevant for CME
Insufficient data at RHIC to conclusive





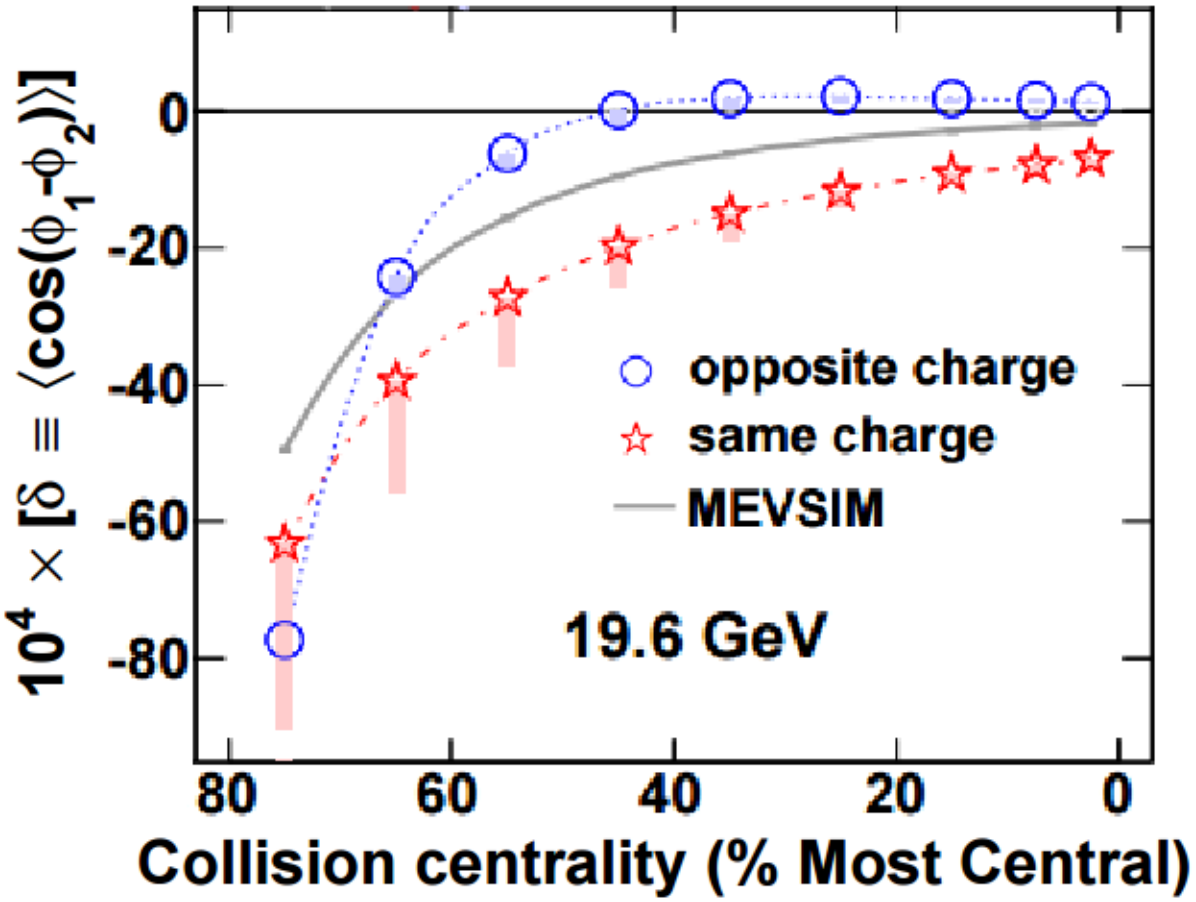
Background not as simple as we expect !

Though the background in AA may arise from v_2 related background , the background in small systems are unlikely related to the hydro-flow v_2 Alone.

(Non-Flow effect very large !)

H Measure

Phys. Rev. Lett 113 (2014) 052302



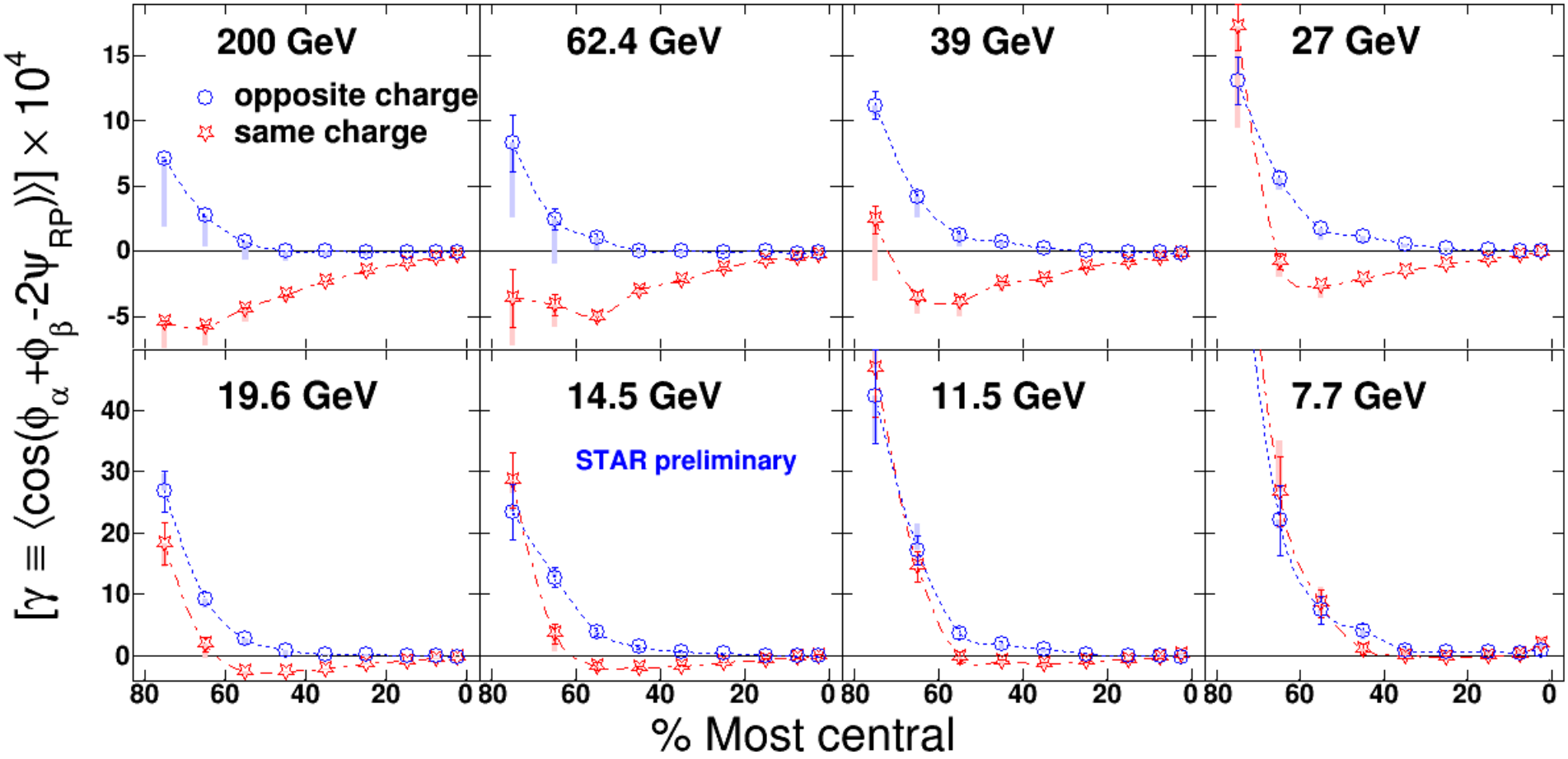
- Against CME expectation, $\delta_{OS} > \delta_{SS}$
- Indicate overwhelming background, larger than any possible CME effect.
- Try combining information from γ and δ to retrieve the CME contribution, *H*

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

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

Beam Energy Scan

Phys. Rev. Lett 113 (2014) 052302

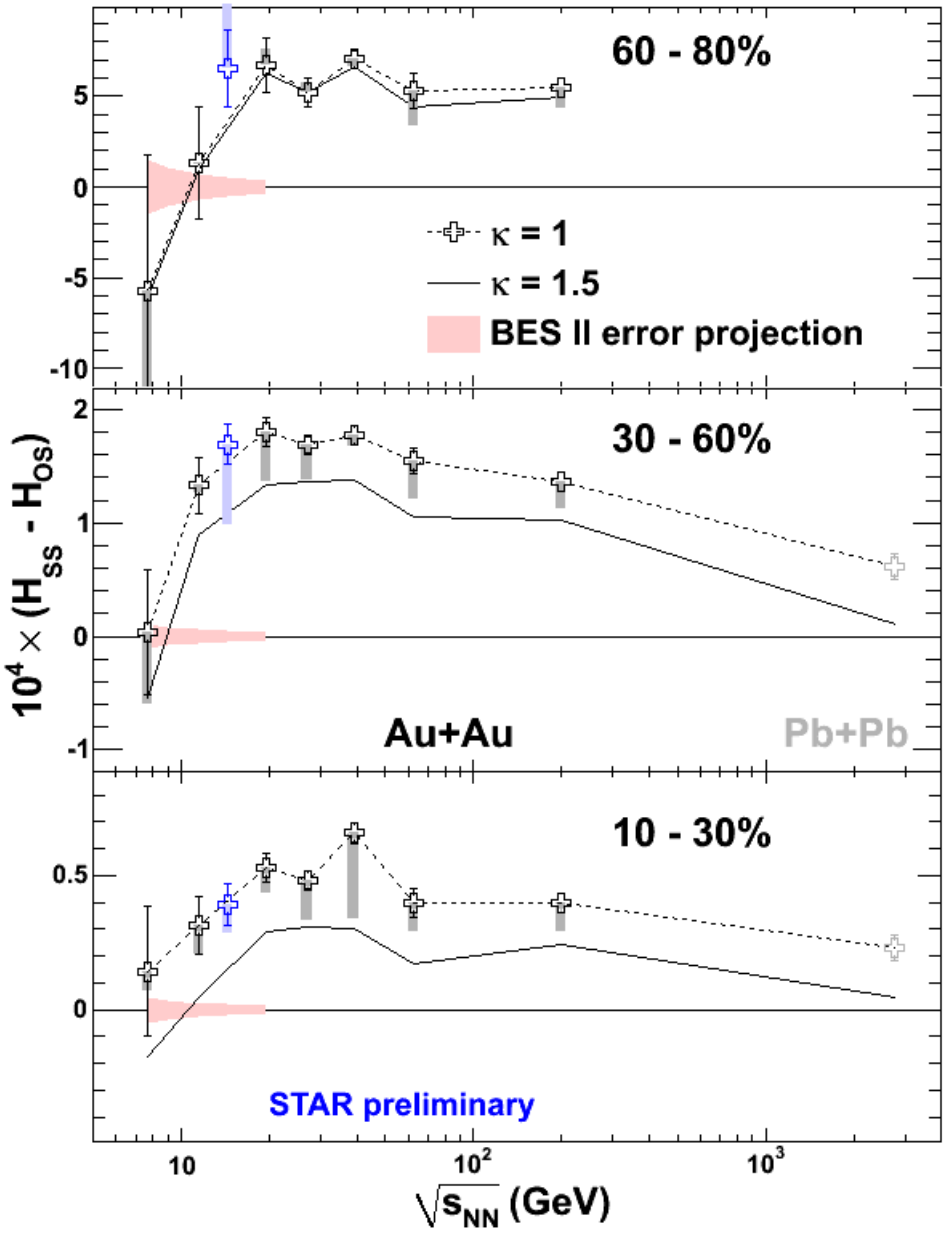


At lower beam energies, charge separation starts to diminish.

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



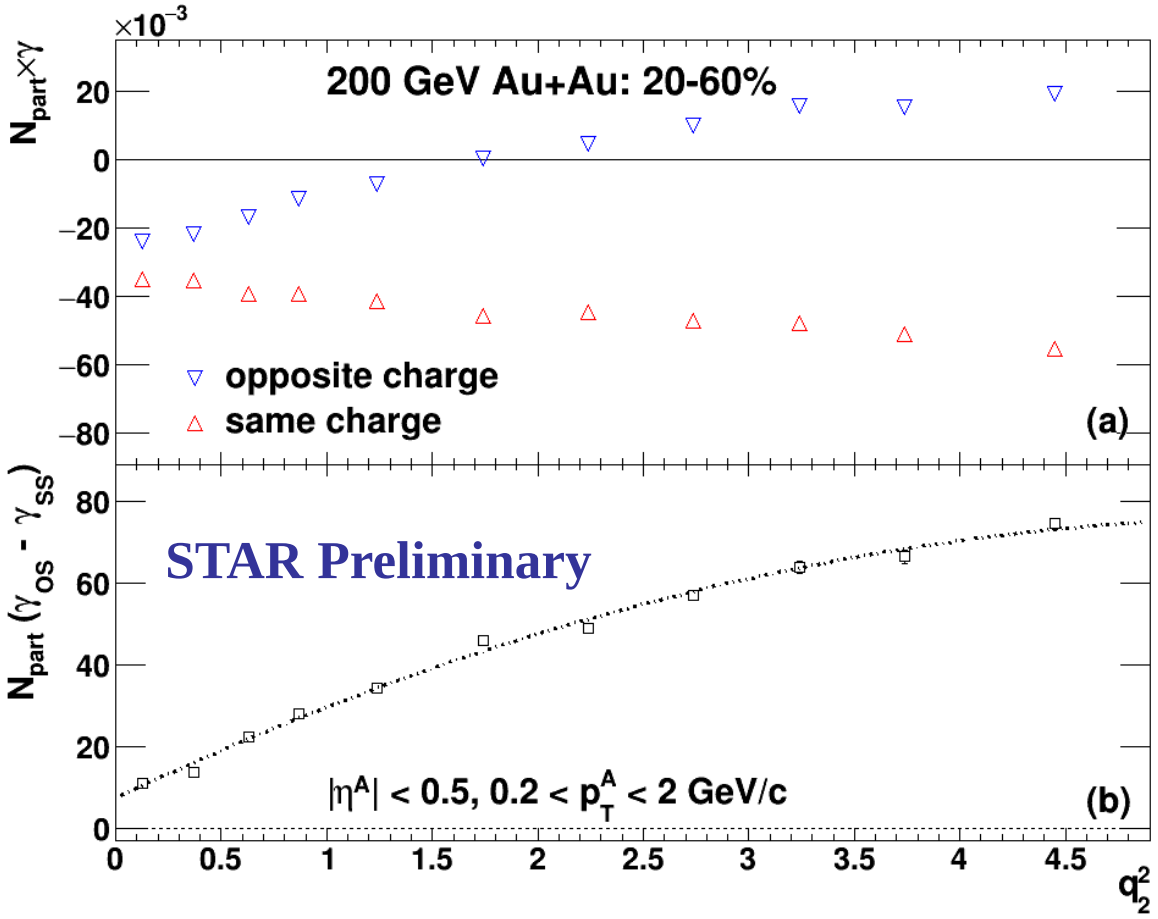
$$H^{\kappa} = (\kappa v_2 \delta - \gamma)/(1 + \kappa v_2)$$

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

Optimal Beam Energy: 15-50 GeV

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

Event Shape Selection Analysis



$$\vec{q} = (q_x, q_y)$$

$$q_x \equiv \frac{1}{\sqrt{N}} \sum_i^N \cos(2\phi_i)$$

$$q_y \equiv \frac{1}{\sqrt{N}} \sum_i^N \sin(2\phi_i).$$

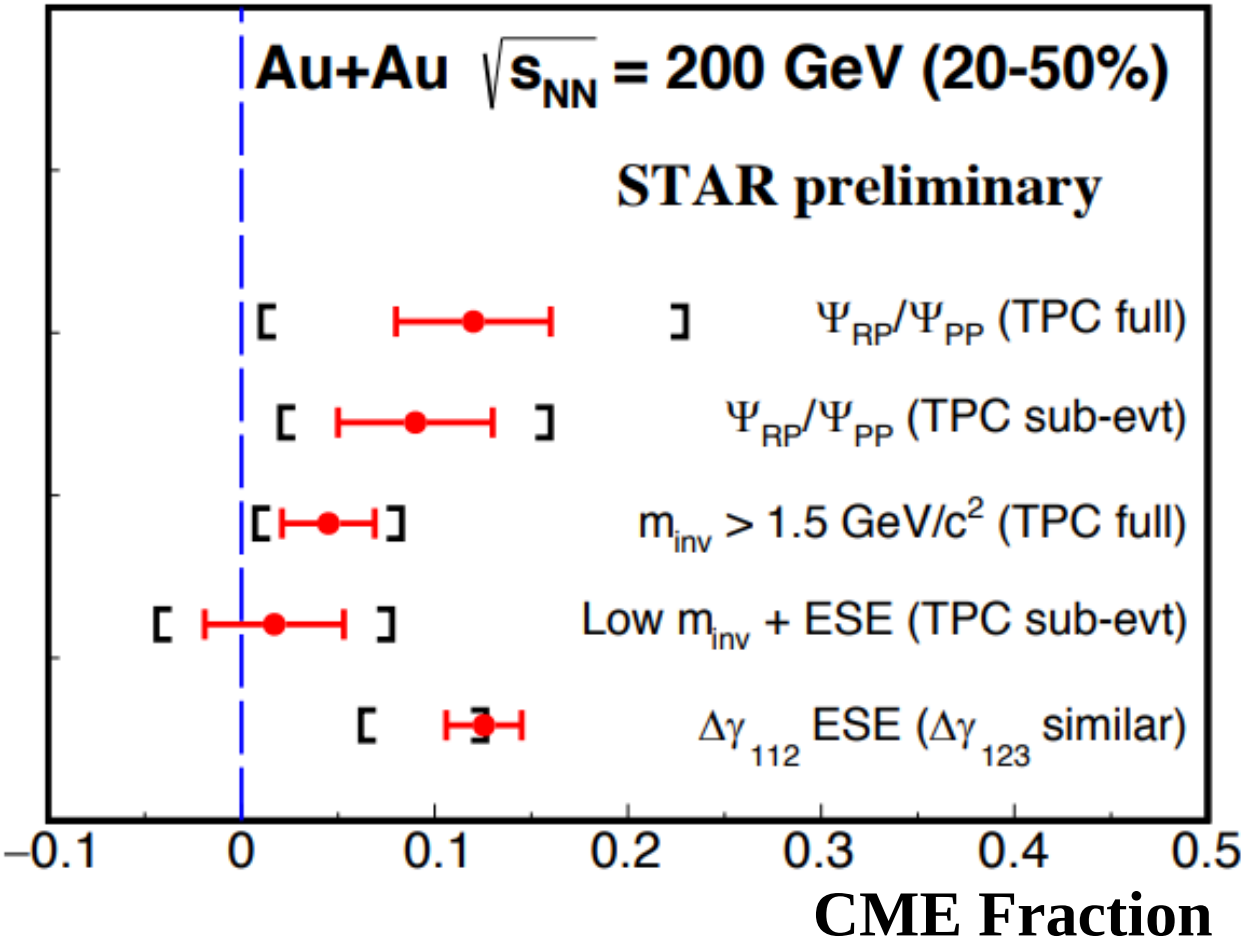
- OS and SS approach each other at small q.
- When q^2 is extrapolated to 0, there is a finite intercept: $(7.51 \pm 0.75)*10^{-3}$
- If this is due to the CME, then a_1 is on ~ 1% level.

<N_{part}> for 20-60% collisions ~ 98.

Should the background depend on v_2 only?

Need Time to Reconcile Various Event Shape Selection Analyses

@QM2018



Improve sensitivity !

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

Intriguing Observation from CMS:

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

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

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

$$\rightarrow \kappa_2 < \cos(\varphi_\alpha - \varphi_\beta)><\cos 2(\varphi_\beta - \Psi_2)>$$

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

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

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

$$\rightarrow \kappa_3 < \cos(\varphi_\alpha - \varphi_\beta)><\cos 3(\varphi_\beta - \Psi_3)>$$

Why are κ_2 and κ_3 almost the same?

No CME? Unknown Correlations?

$\Delta\gamma_{112}$ and $\Delta\gamma_{123}$ and $\Delta\gamma_{132}$

The decomposition very sensitive to correlations:

$$=\langle\cos(\varphi_\alpha-\varphi_\beta)\cos2(\varphi_\beta-\Psi_2)\rangle - \langle\sin()\sin()\rangle$$

$$\rightarrow\ \kappa_2 < \cos(\varphi_\alpha-\varphi_\beta)\rangle\langle\cos2(\varphi_\beta-\Psi_2)\rangle$$

The decomposition is not unique or exact !

Will $\kappa_2 \sim \kappa_3$ still allow for a small CME signal $\langle a_1 a_1\rangle$?

CME or not CME in HIC

The current analyses are inclusive

There must be significant background in the gamma correlations

Features of measurements cannot be explained by background model alone, and there may be energy dependent

Background in pA and AA collisions may arise from different sources !

Chiral Vortical Effect

Chiral Magnetic Effect vs Chiral Vortical Effect

Chirality Imbalance (μ_A)

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

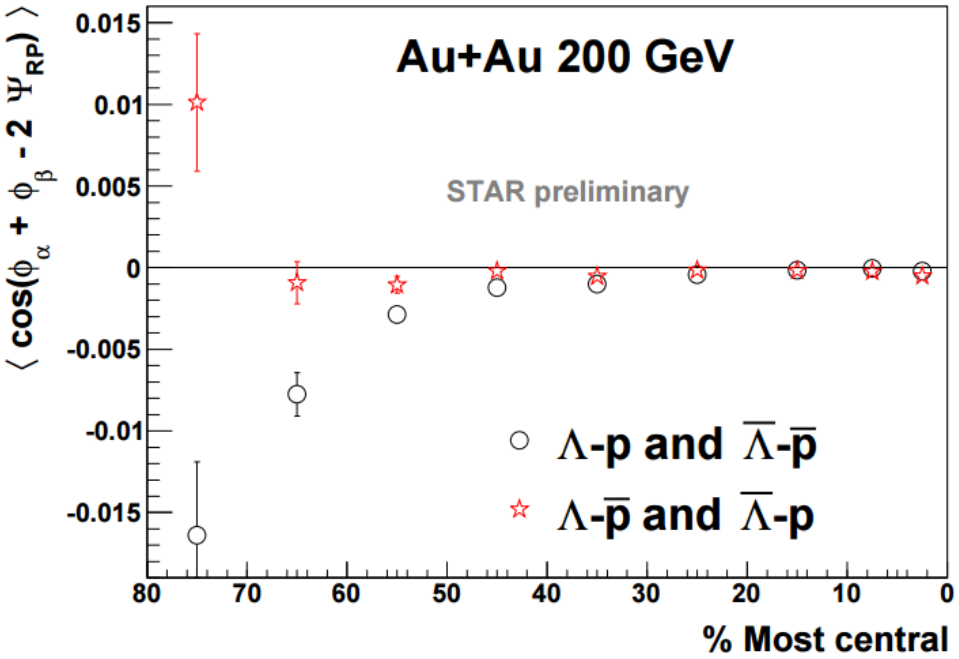
Fluid Vorticity ($\omega\ \mu_B$) → Baryon Number (j_B)

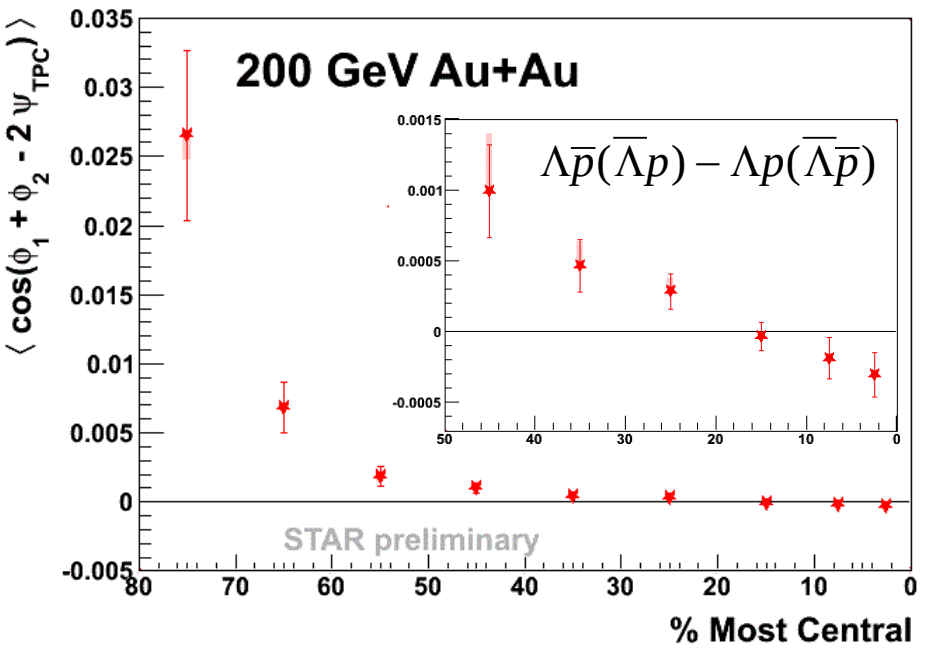
D. Kharzeev, D. T. Son, PRL 106 (2011) 062301

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

correlate Λ–p to search for the Chiral Vortical Effect

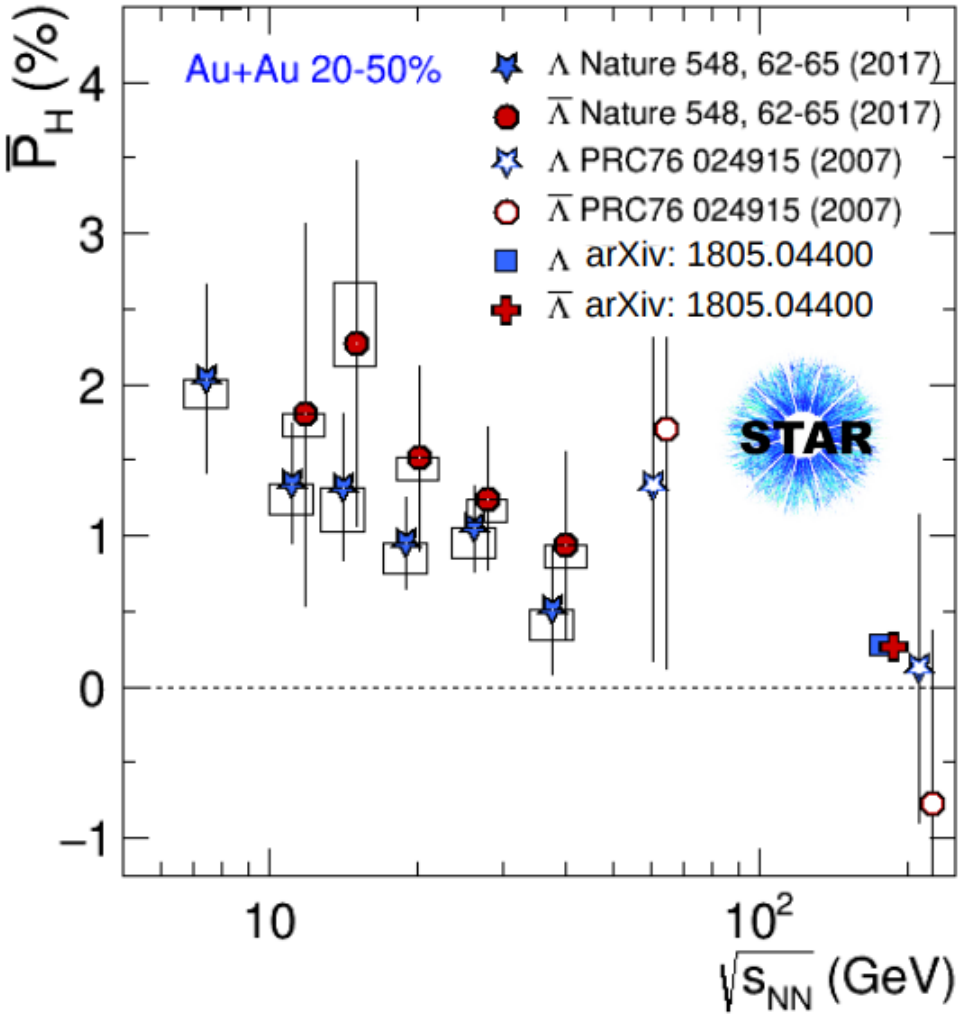
Λ-proton Correlation





- 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.

STAR Measurement for Lambda Polarization WRT the Reaction Plane



Vortical Quantum Fluid at RHIC !

Another way to establish B field!

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 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

Observables for CME

$\Delta\gamma_{112}$ is not perfect – sensitive to background

hydro-v_2 related background

-- event shape selection analysis

resonance decays

-- STAR, ALICE and many other

background -- short-range background

Prithwish Tribedy et al.

Jet – can have long-range non-flow correlations (back-to-back partons)

pA-AA centrality dependent extrapolation from pA to AA – non-trivial

Exploration of new observables –

Roy Lacey et al, Fuqiang Wang et al, ……

Guidance from Dynamical Models

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

H may be a better representation –

κ – theoretical guidance

-- hydro-v_2 related background

Remove non-flow effect as much as possible

Works better for low energy data where jet production is reduced/small

AMPT/AVFD (Anomalous Viscous Fluid Dynamics) provided essential guidance on dynamical background sources and magnitude of the background

there are other backgrounds not in these models

What Constituents a Discovery of CME in Heavy Ion Collisions

1) Need to establish a B field effect (5 sigma)

2) Relating to charge separation effect

3) Establish a beam energy dependence

OR

Ruled out with quantitative analyses !

There are enough confusions, illusions around
let us stick to what data represent
not all data would deepen our understanding

Experimental Window of Opportunity

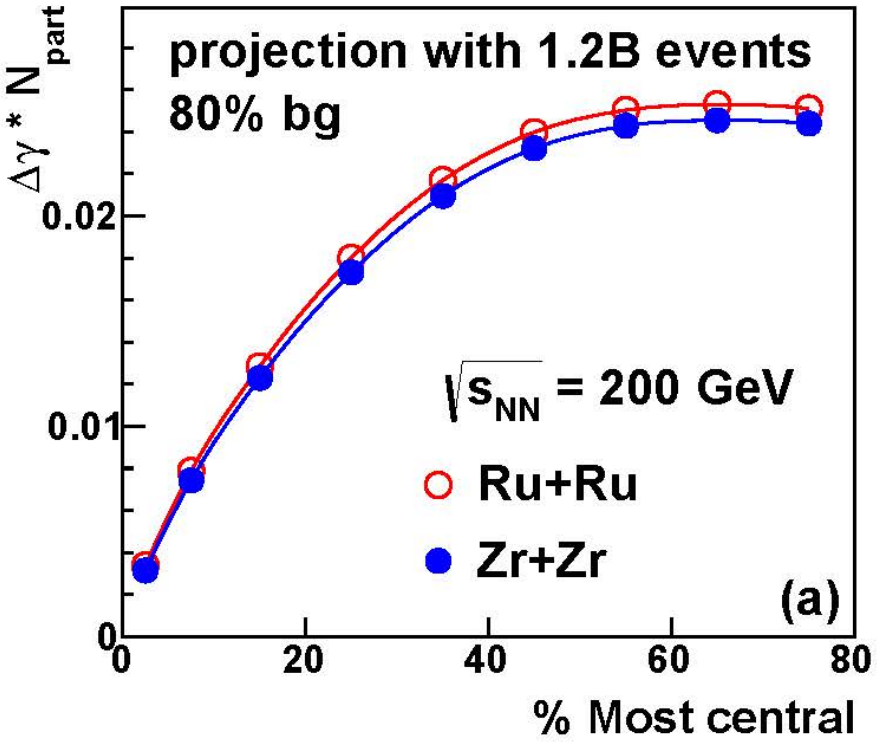
1) Isobaric running to see B field effect
   Successful Run 2018 @200 GeV
2) Au+Au data from low RHIC energies
   to observe B magnitude and life-time
   difference 2018 +
3) If promising, another run for isobaric
   system would be needed

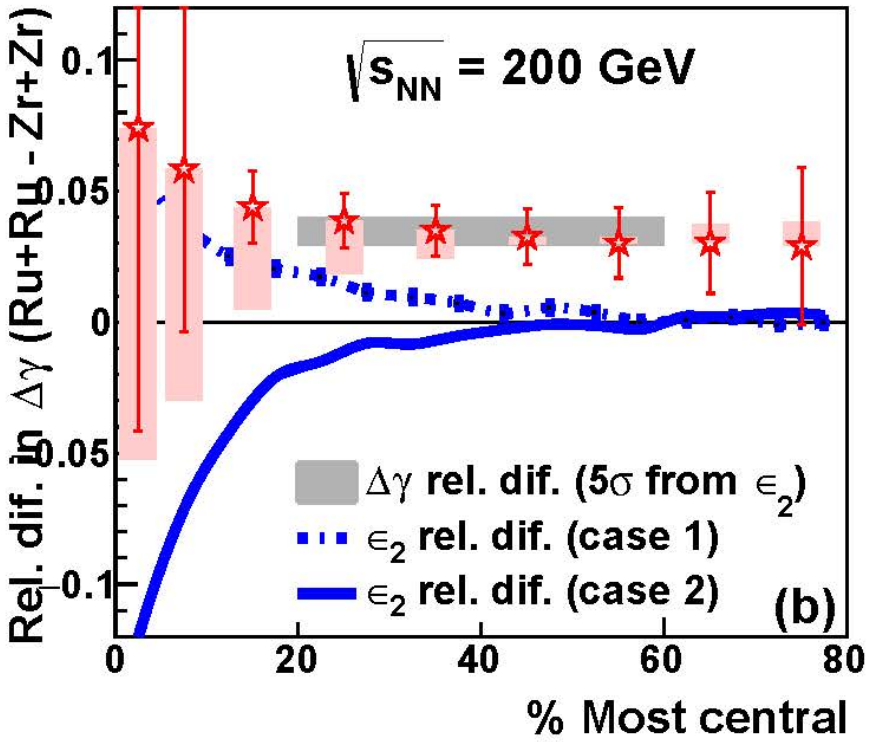
There must be some background –
yet no satisfactory background model can
explain all features in data –
any room for CME/CMW? Definitive Answer?

THE END

Isobars: charge separation

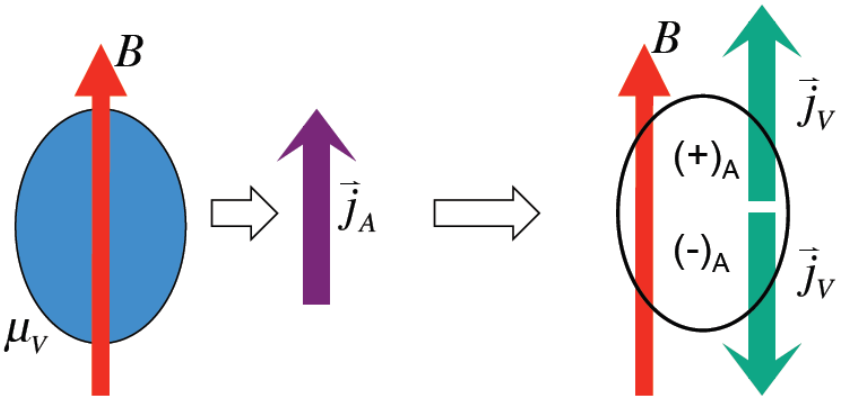
- Projection from 1.2B events shows difference in ΔH
- The ratio is 5σ above 1 (3σ with 400M events)
- If it's v_2-driven, the ratio will follow eccentricity (be 1 or below 1)

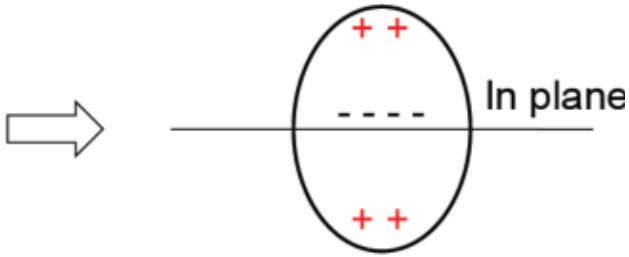




Very Successful RHIC Run in 2018 !

Chiral Magnetic Wave





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

Chiral Separation Effect

Chiral Magnetic Effect

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

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

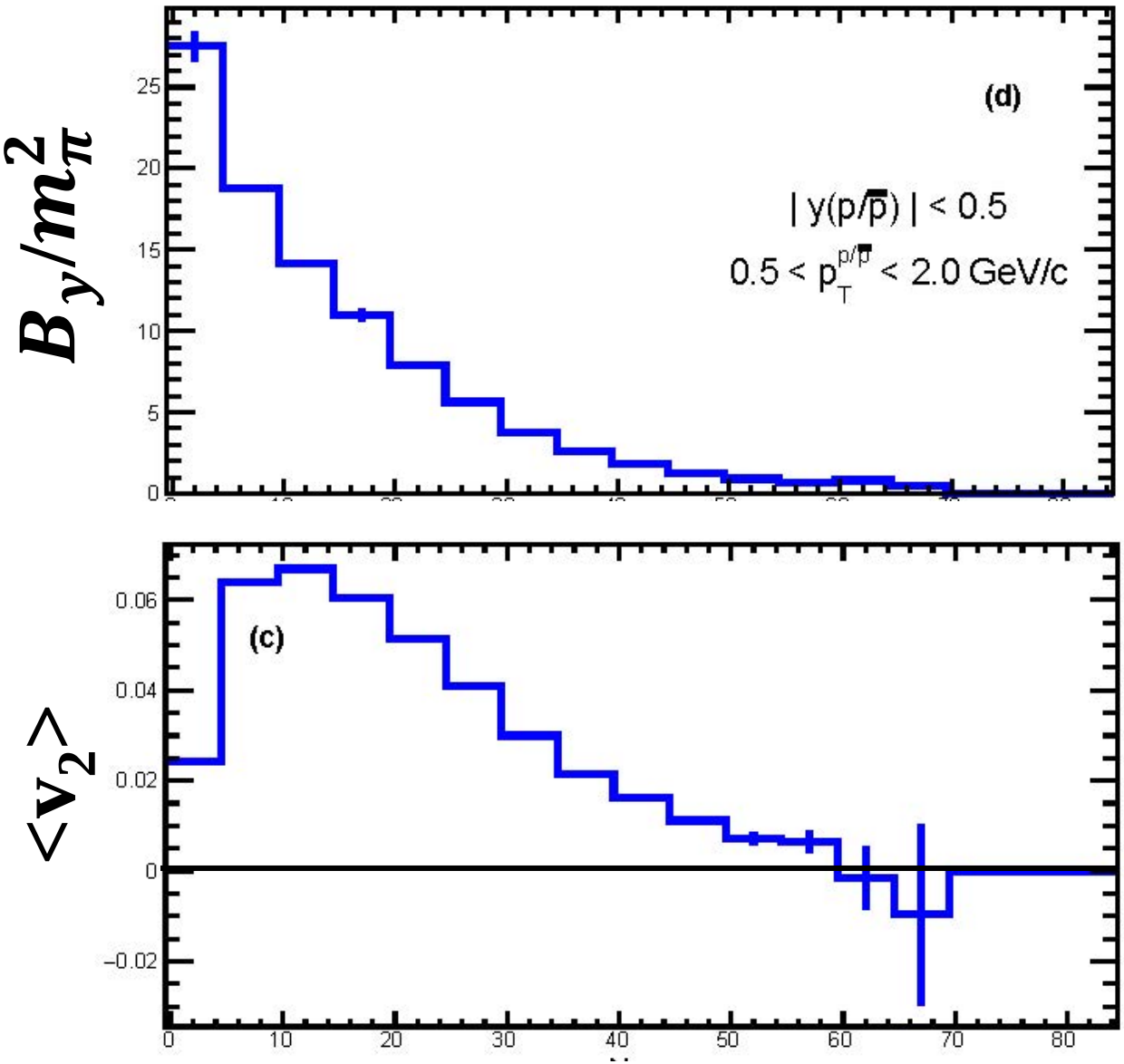
quadrupole moment

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.

Event Selection Technique Sensitive to B_y



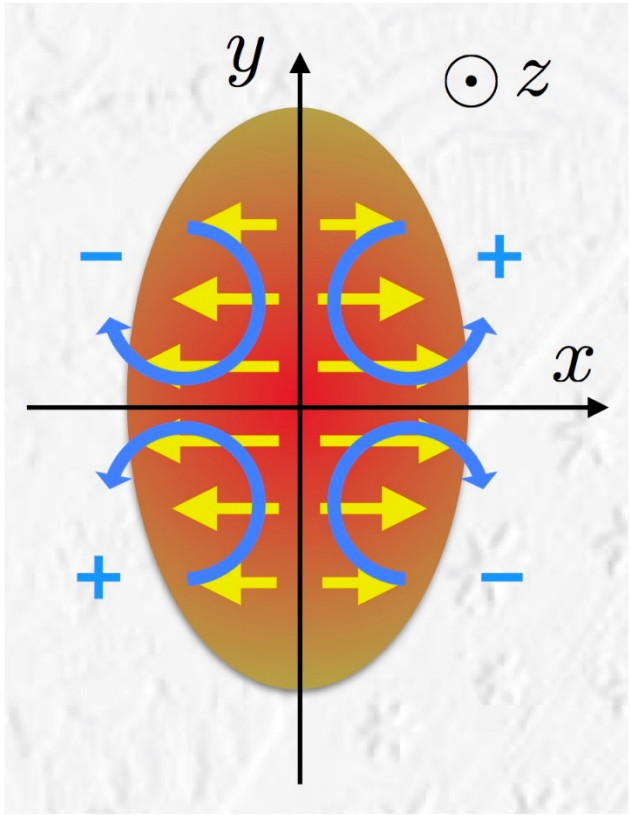
Au+Au @ 27 GeV

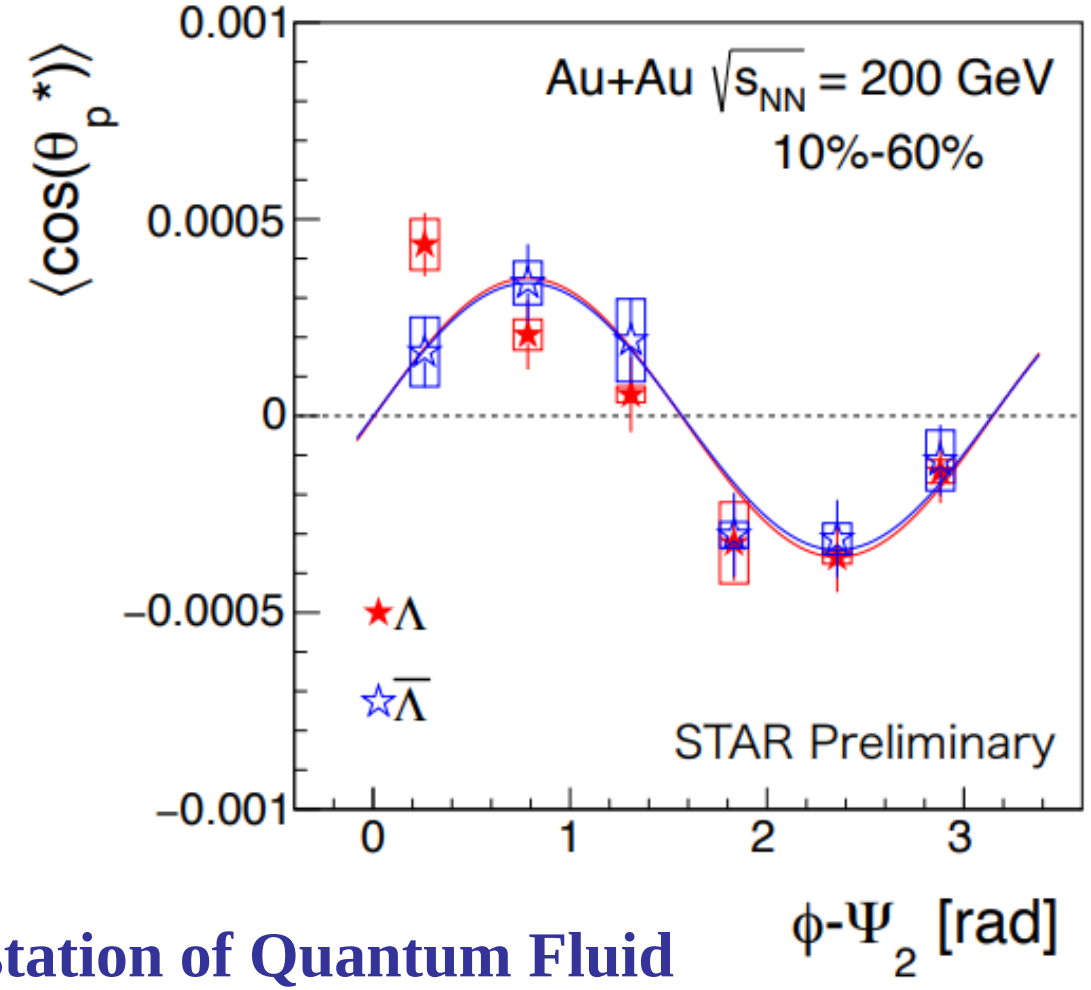
Net-protons
Another handle
for event selection

Net-protons

Subikash Choudhury
Fudan University

Longitudinal Polarization of Lambda





Polarization – Manifestation of Quantum Fluid not yet established theoretically!

S. Voloshin, EPJ Web Conf. 17 (2018) 10700
F. Becattini and I. Karpenko, PRL120, 012302 (2018)