Search for Chiral Effects in STAR@RHIC

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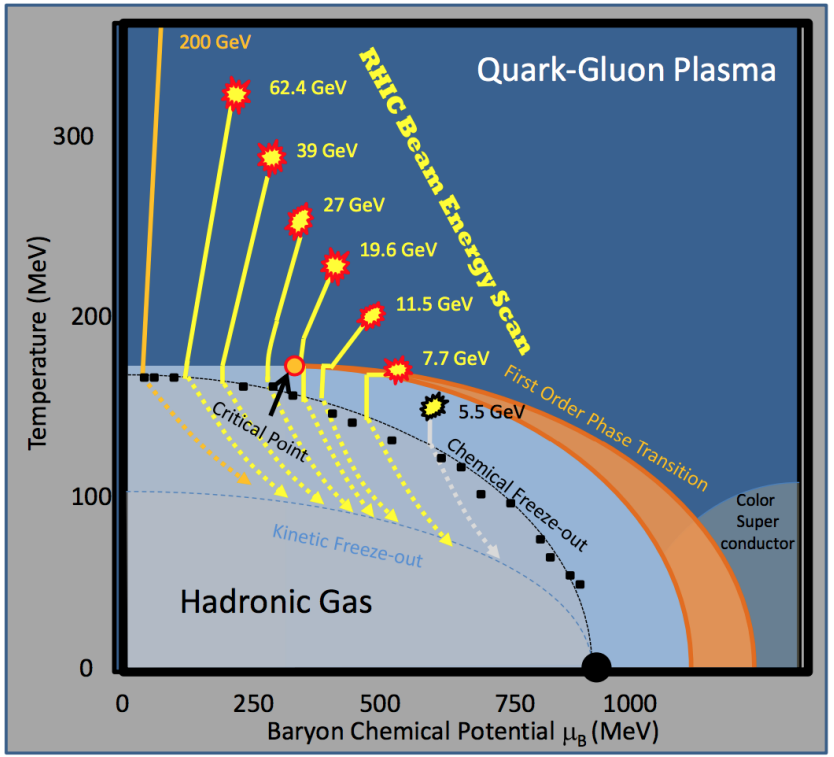
2015 RHIC & AGS Annual Users' Meeting

Outline

1. Introduction
2. Chiral Magnetic Effect(CME)
3. Chiral Magnetic Wave(CMW)
4. Chiral Vortical Effect(CVE)
5. Summary
6. Outlook

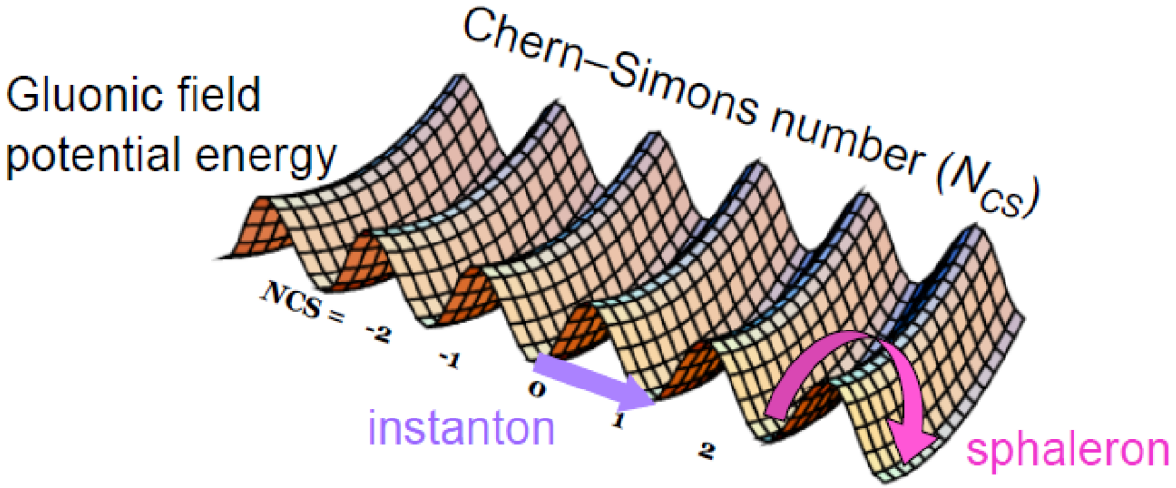
Search for the Turn-off of QGP



Three Goals:

1. Search for the turn-off of QGP signatures;
2. Search for first-order phase transition.
3. Search for the evidence of critical fluctuations in the vicinity of Critical Point;

QCD Vacuum Transition



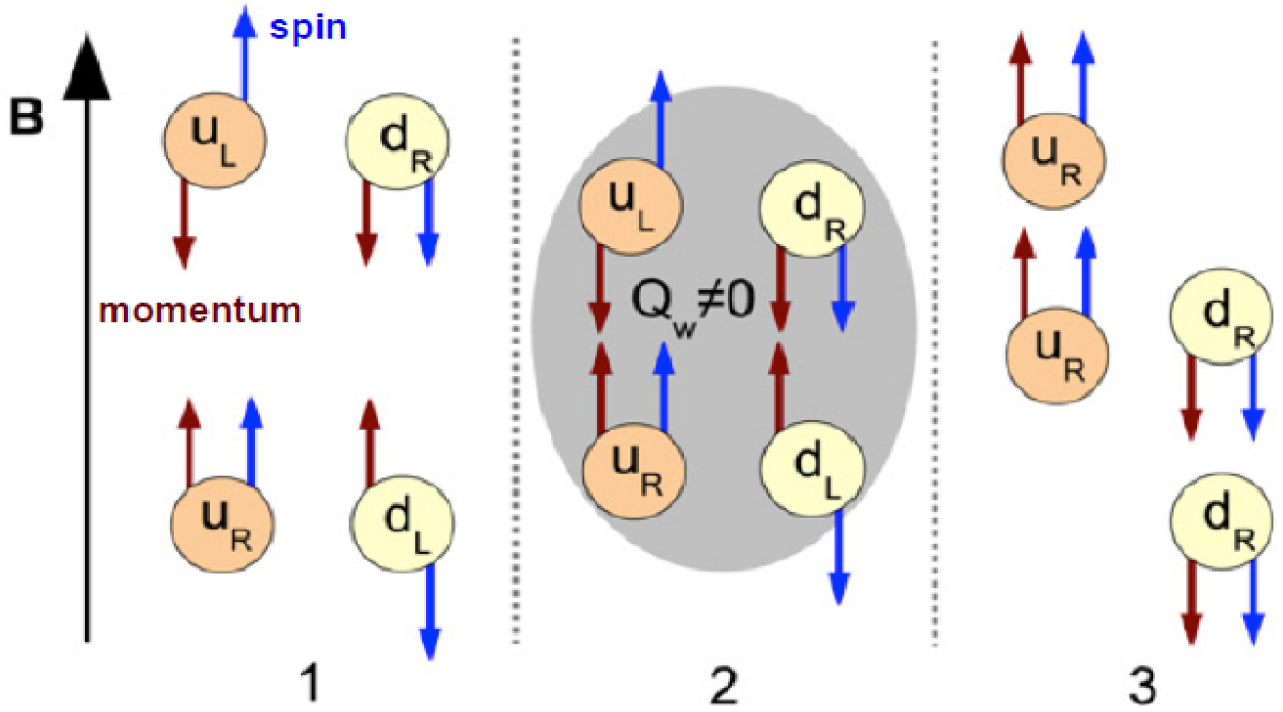
QCD vacuum state transition:

1. Nonzero topological charge
2. Chirality imbalance

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

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

Chiral Magnetic Effect



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

▷ Finite chiral charge density induces an elec trical current along the B field direction, which finally leads to electric charge separation along B field.

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

Observable γ correlator

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

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

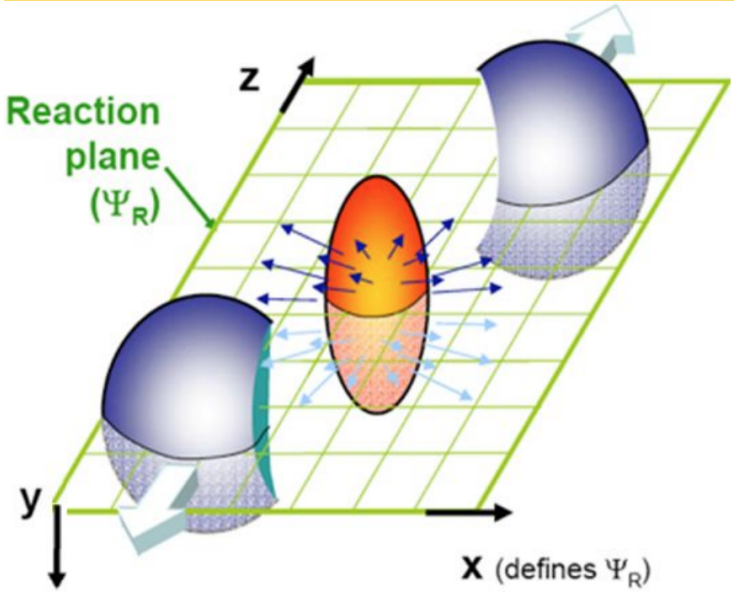
$$\gamma = \left\langle \cos(\phi_\alpha + \phi_\beta - 2\psi_{RP}) \right\rangle$$

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

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

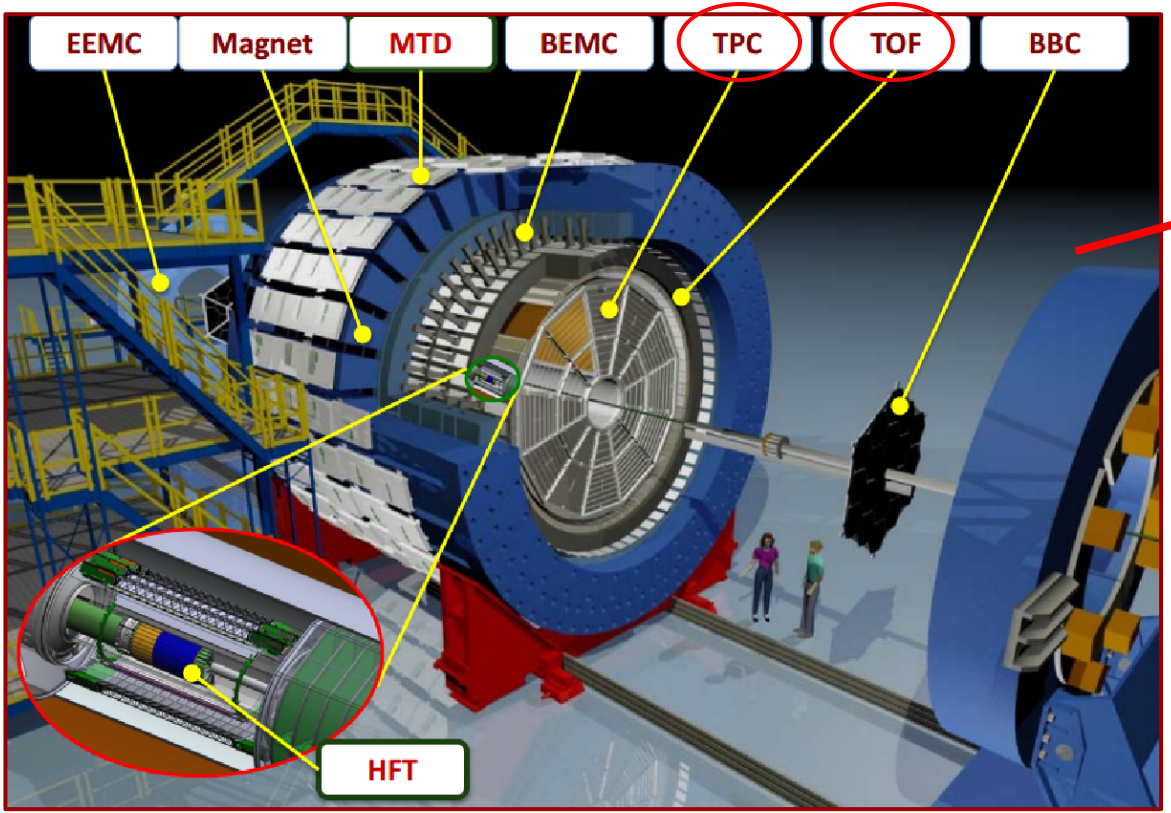
background effects: largely cancel out

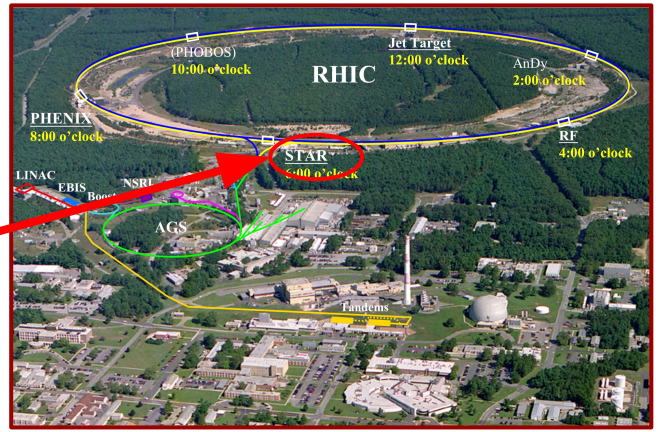
P-even quantity: still sensitive to charge separation

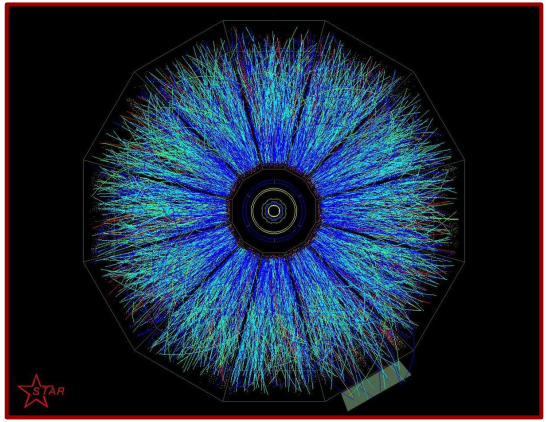


S. Voloshin, PRC 70 (2004) 057901

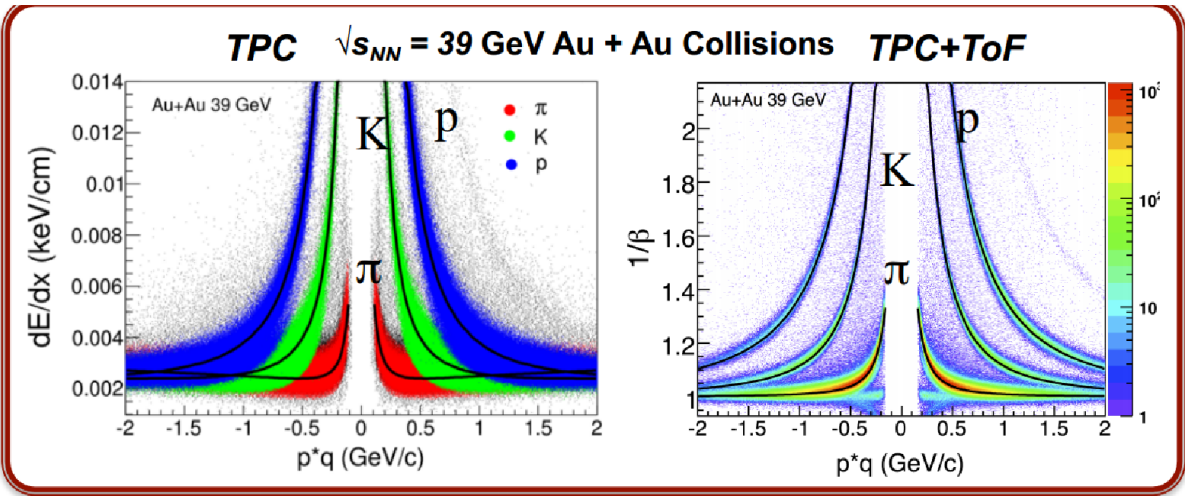
Solenoidal Tracker At RHIC

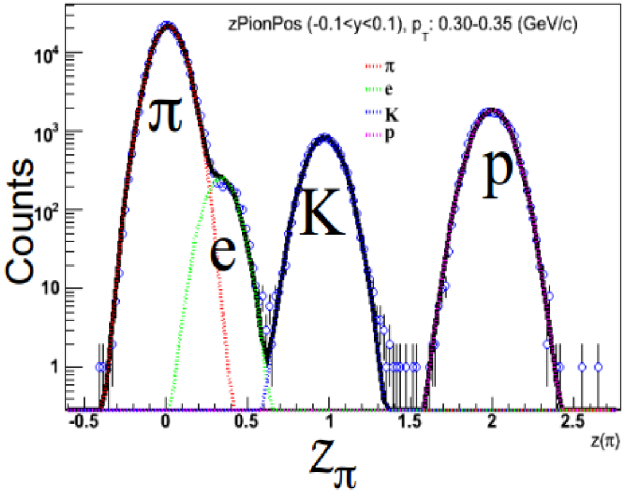






Particle Identification@STAR



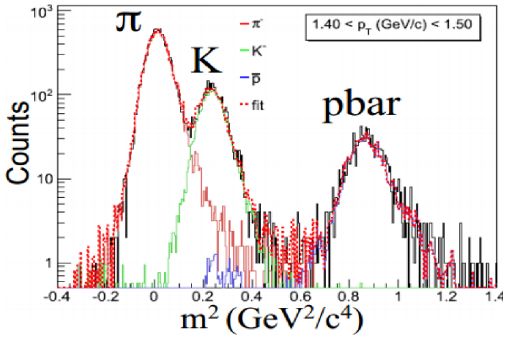


$$z = \log\left(\frac{(dE/dx)_{meas.}}{(dE/dx)_{theory}}\right)$$

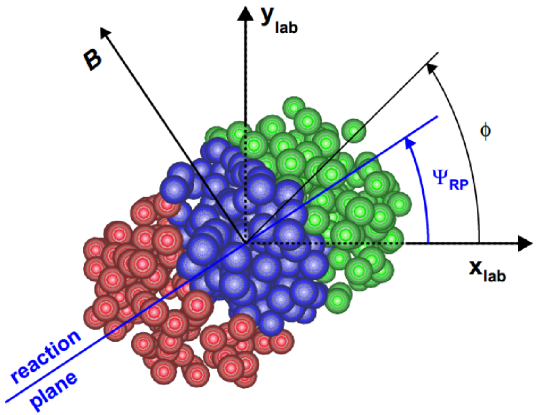
H. Bichsel, NIM A. 562 (2006) 154

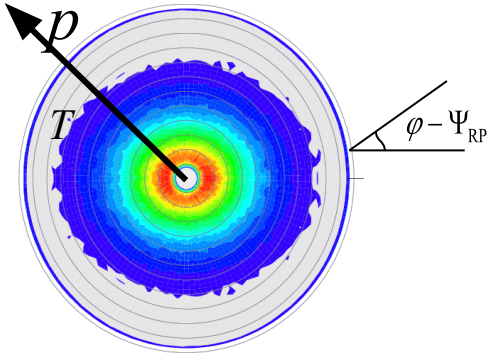
$$m^2 = p^2\left(\frac{c^2t^2}{L^2} - 1\right)$$

c=velocity of light,
L=path length



Event Plane Determination





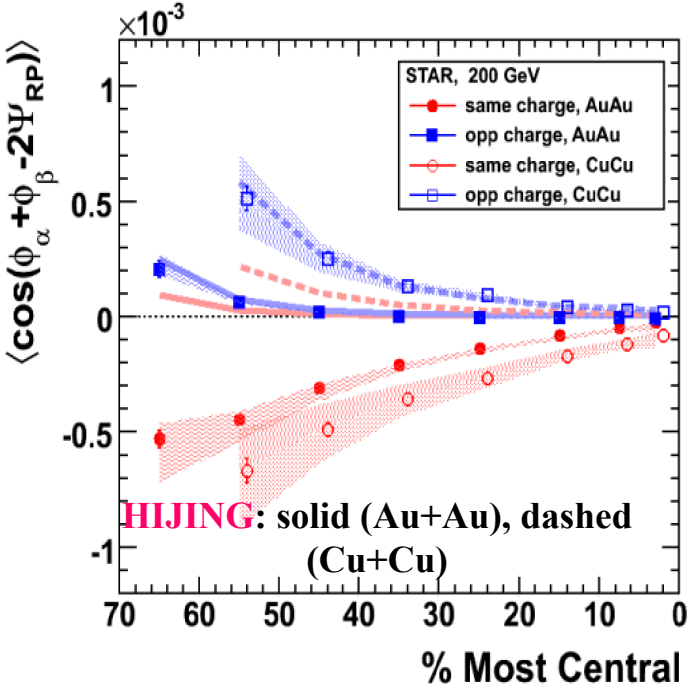
$$Q_n \cos(n\Psi_n) = Q_x = \sum_i w_i \cos(n\phi_i)$$

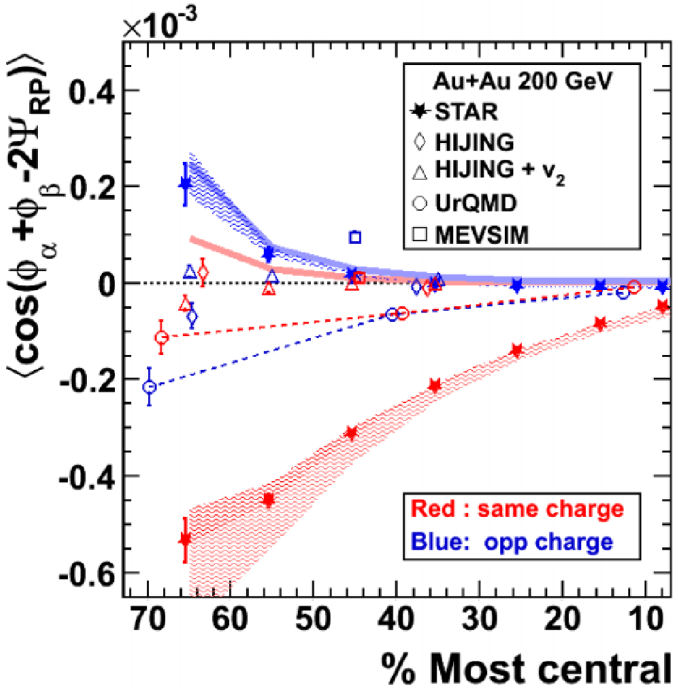
$$Q_n \sin(n\Psi_n) = Q_y = \sum_i w_i \sin(n\phi_i)$$

$$\Psi_n = \left(\tan^{-1} \frac{Q_y}{Q_x} \right) / n$$

▷ We use the large anisotropic particle flow in heavy ion collisions to estimate the event plane orientation.

Electric Charge Separation

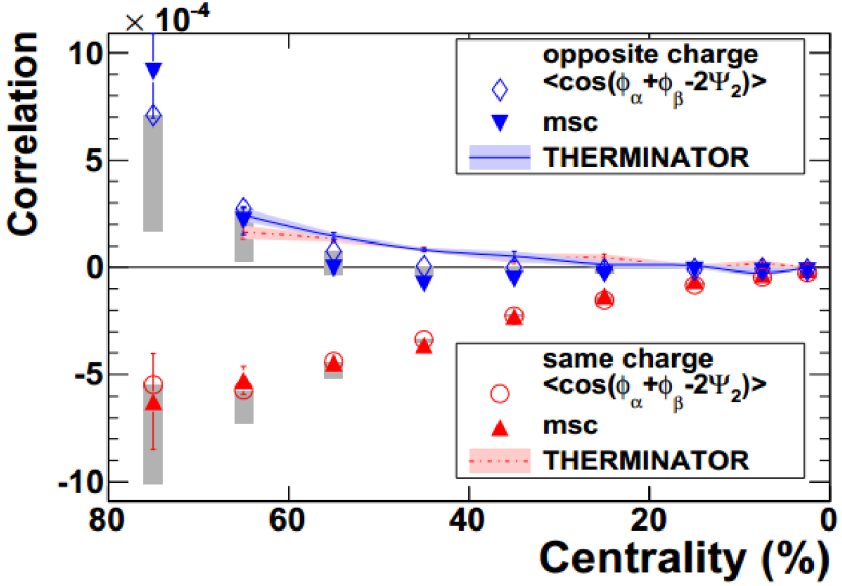




- Different γ_{os} and γ_{ss}, consistent with the CME expectation: both AuAu and CuCu
- Not explained by known event generators

Phys. Rev. Lett. 103 (2009) 251601; Phys. Rev. C 81 (2010) 54908

Modulated Sign Correlator(MSC)

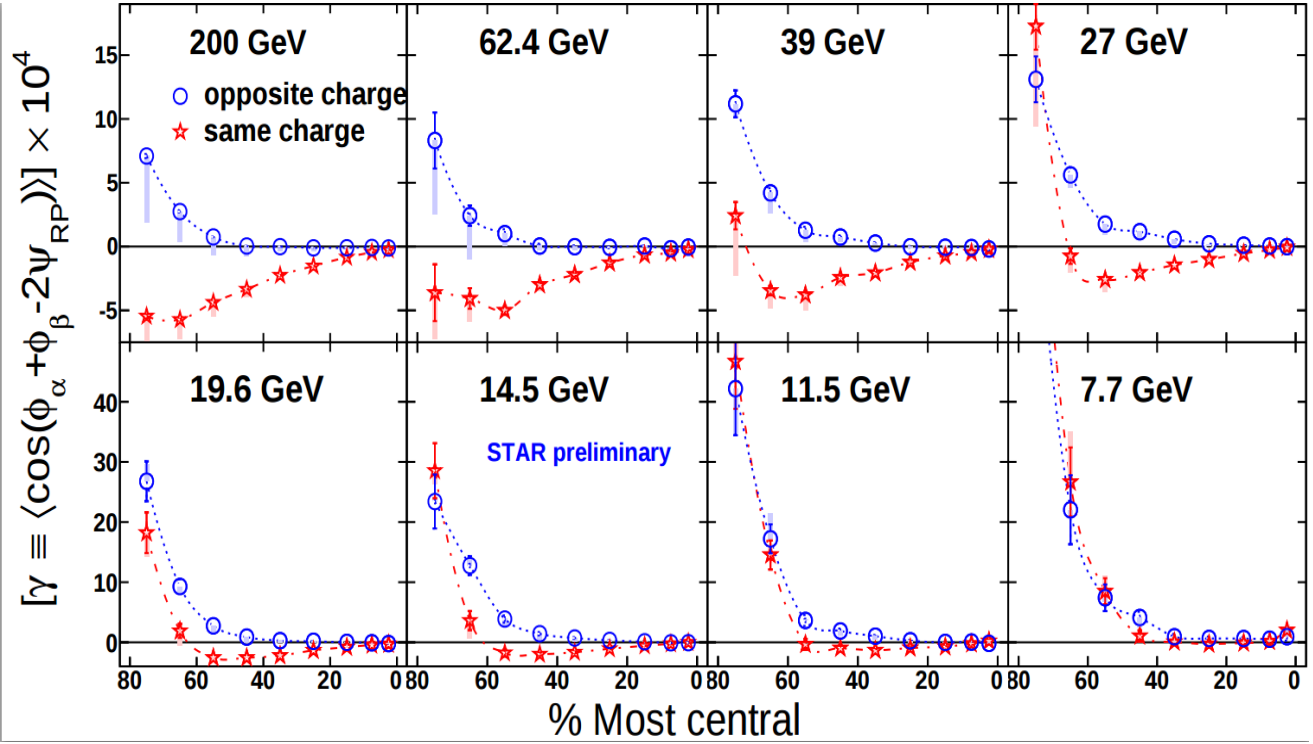


$$\mathrm{msc} \equiv \left(\frac{\pi}{4}\right)^2 \left(\langle S_\alpha S_\beta \rangle_{\mathrm{IN}} - \langle S_\alpha S_\beta \rangle_{\mathrm{OUT}}\right)$$

Phys. Rev. C 88 (2013) 64911

- Signal is robust after removing HBT+Coulomb effects
- γ weighs different azimuthal regions of charge separation differently
- Modify γ such that all azimuthal regions are weighted identically
- γ is reduced to modulated sign correlator (msc)
- the charge separation signal is robust with msc

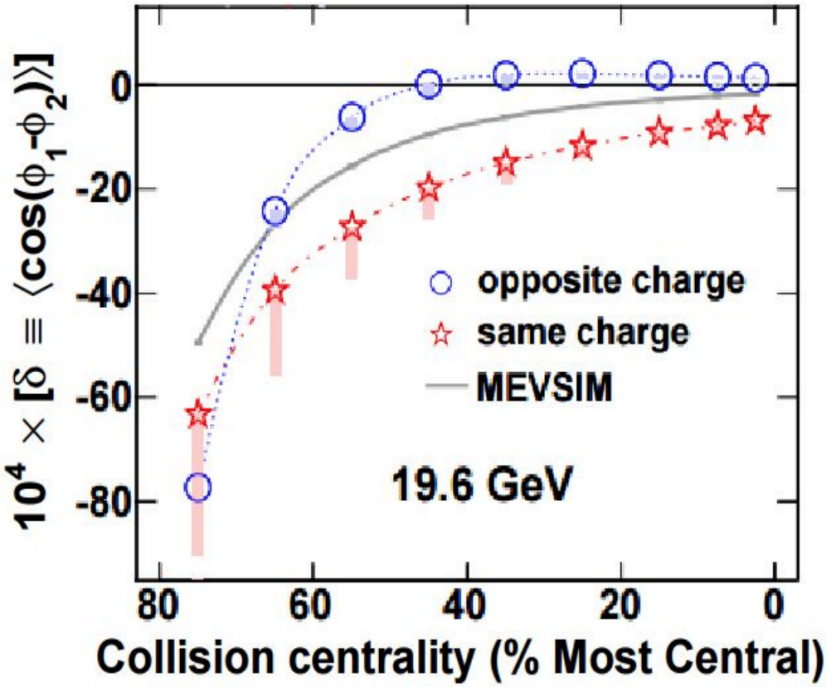
CME.BES



▷ BES results shows charge separation starts to diminish at lower energies.

ALICE, Phys. Rev. Lett. 110 (2013)012301; STAR, Phys. Rev. Lett 113 (2014) 052302

CME: Flow Related Background



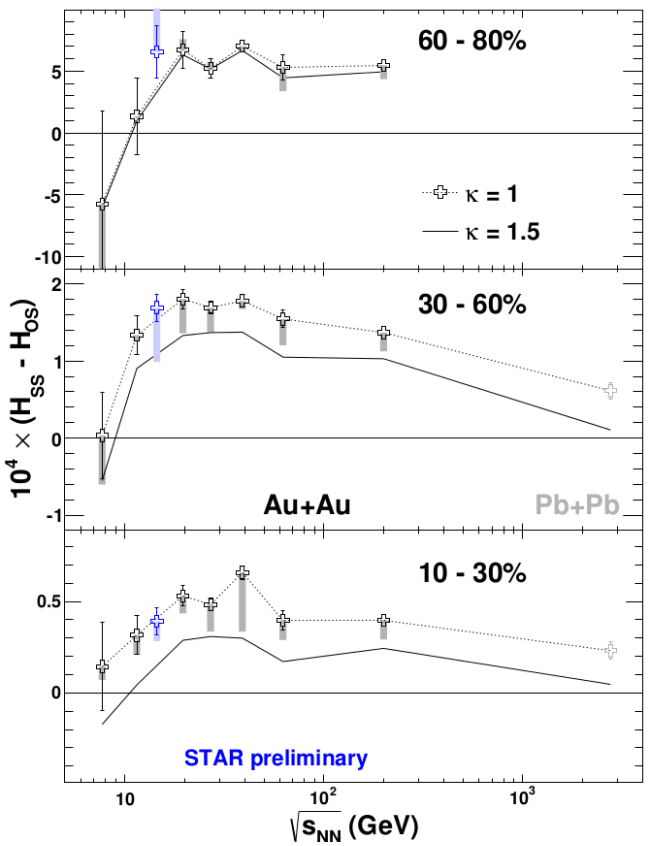
STAR, Phys. Rev. Lett 113 (2014) 052302

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

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

- Against CME expectation, δ_{OS} is above δ_{SS}
- indicate overwhelming background larger than any possible CME effect.
- try to combine information from γ and δ to retrieve the CME contribution, H

CME Contribution(H correlator)



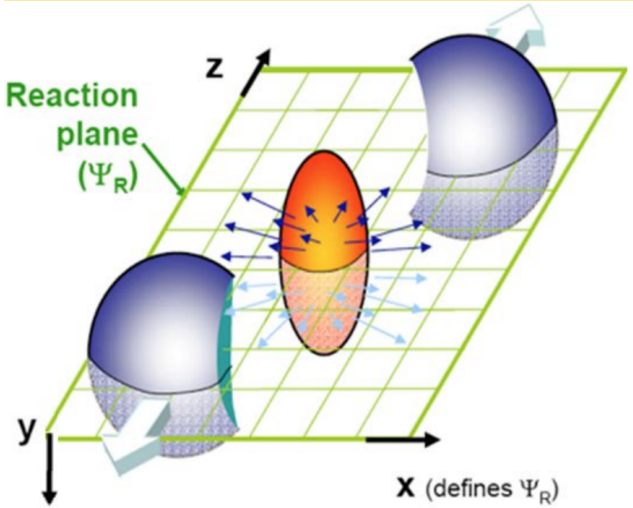
$$H^{\kappa} = (\kappa v_2 \delta - \gamma)/(1 + \kappa v_2)$$

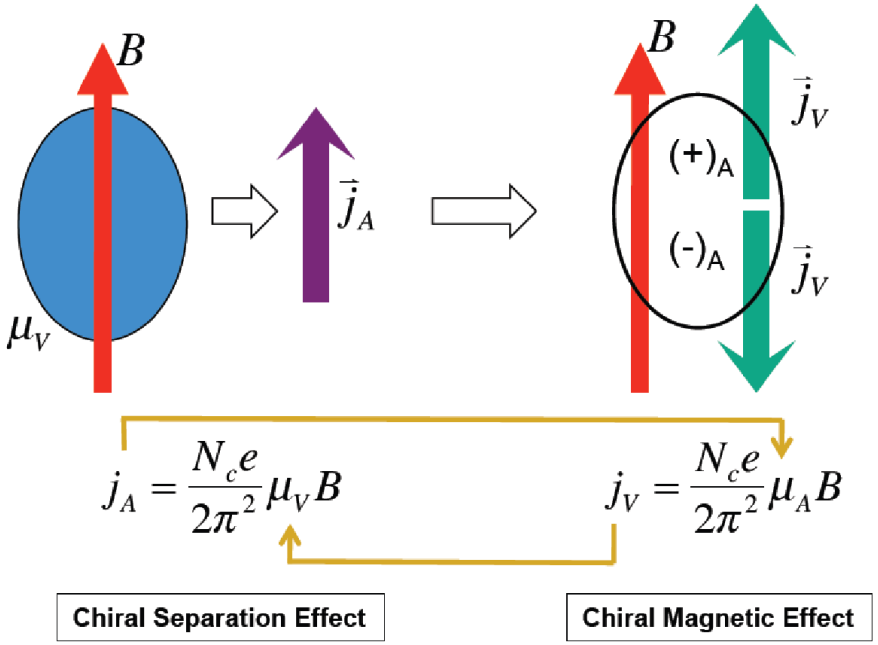
- ▷ κ could deviate from 1 due to a finite detector acceptance and theoretical uncertainties
- ▷ the CME signal decreases to zero in the interval between 19.6 and 7.7 GeV
- ▷ probable domination of hadronic interactions over partonic ones
- ▷ need better theoretical estimate of κ and better statistics

STAR, Phys. Rev. Lett 113 (2014) 052302

Chiral Magnetic Wave

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



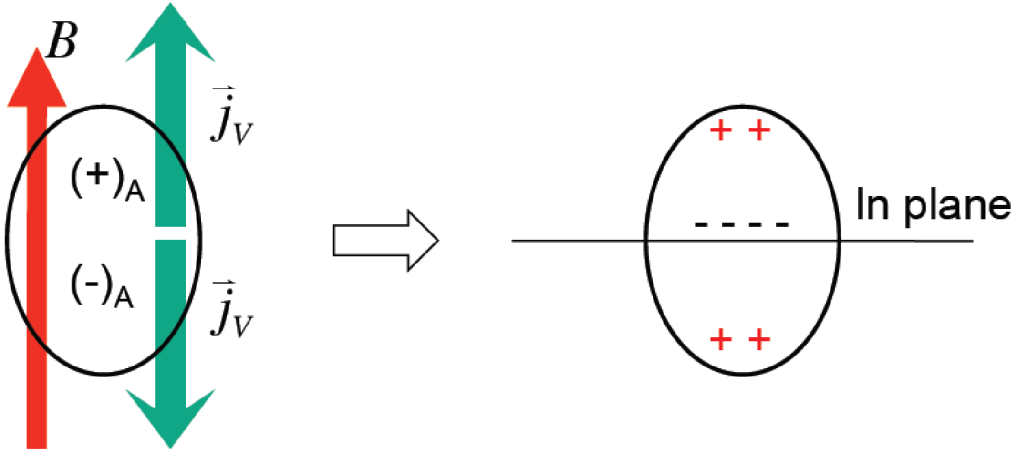


CSE + CME → Chiral Magnetic Wave:

- collective excitation
- signature of chiral symmetry restoration

CMW.Observable

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



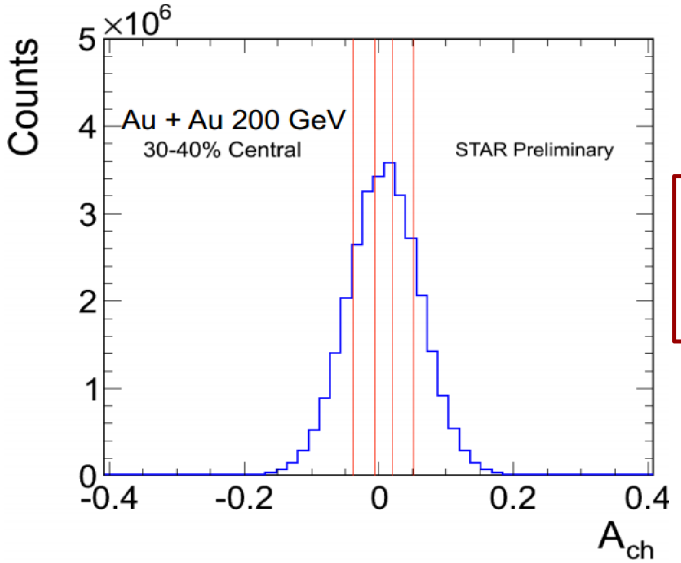
$$v_2^{\pm} = v_2^{base} \pm \left(\frac{q_e}{\bar{\rho}_e}\right) A_{ch}$$

where the charge asymmetry is defined as:

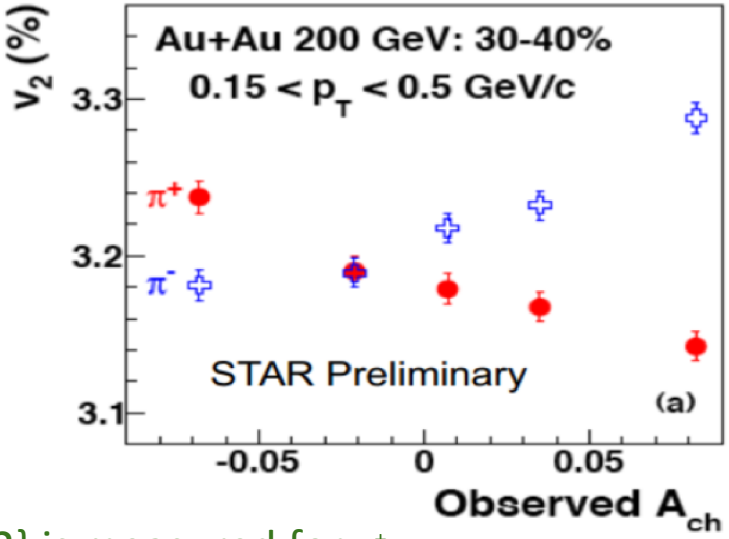
$$A_{ch} = \frac{N^+ - N^-}{N^+ + N^-}$$

- π^- v_2 should have a positive slope as a function of A_{ch}
- π^+ v_2 should have a negative slope with the same magnitude

CMW.Measurement



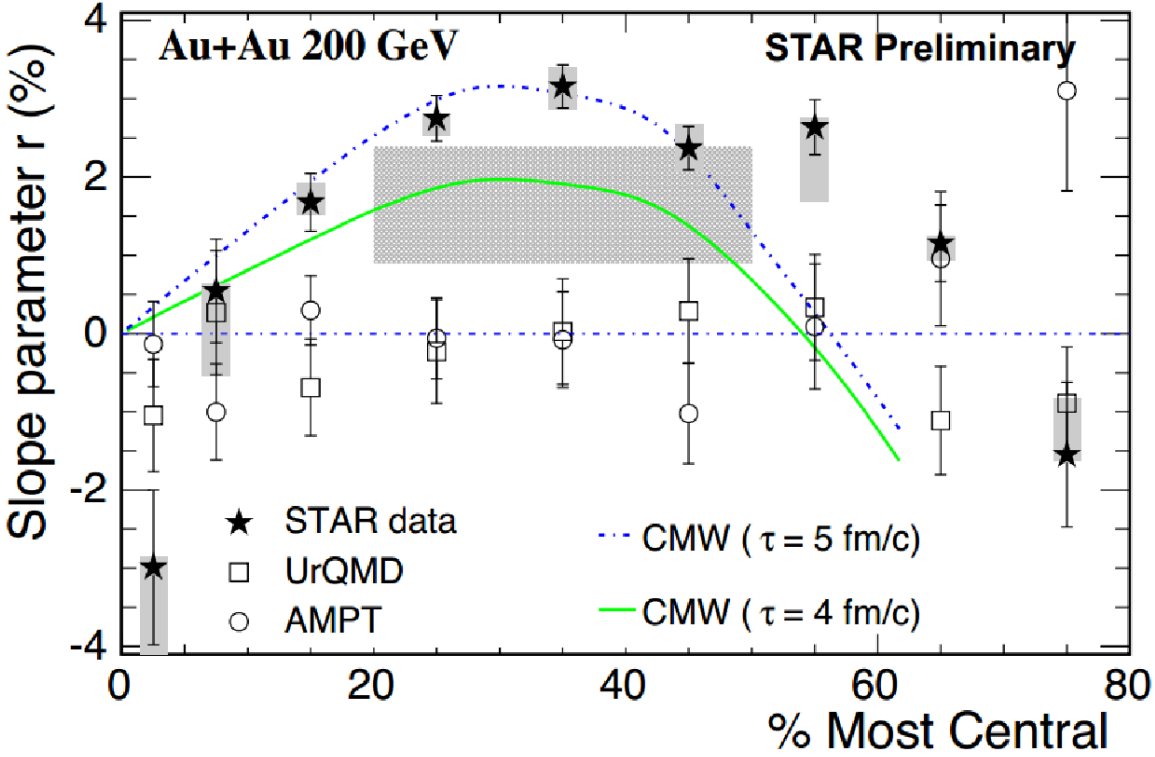
$$A_{ch} = \frac{N^+ - N^-}{N^+ + N^-}$$



- $N^+(N^-)$ is the number of positive charged particles within $|\eta| < 1$
- Ach dist. is divided into 5 bins with roughly equal events number

- $v_2\{2\}$ is measured for $\pi^{\pm}$
- v_2 vs. A_{ch} shows clear linear relation
- v_2 (A_{ch}) slopes for $\pi^{\pm}$:
  1. opposite sign
  2. similar magnitude

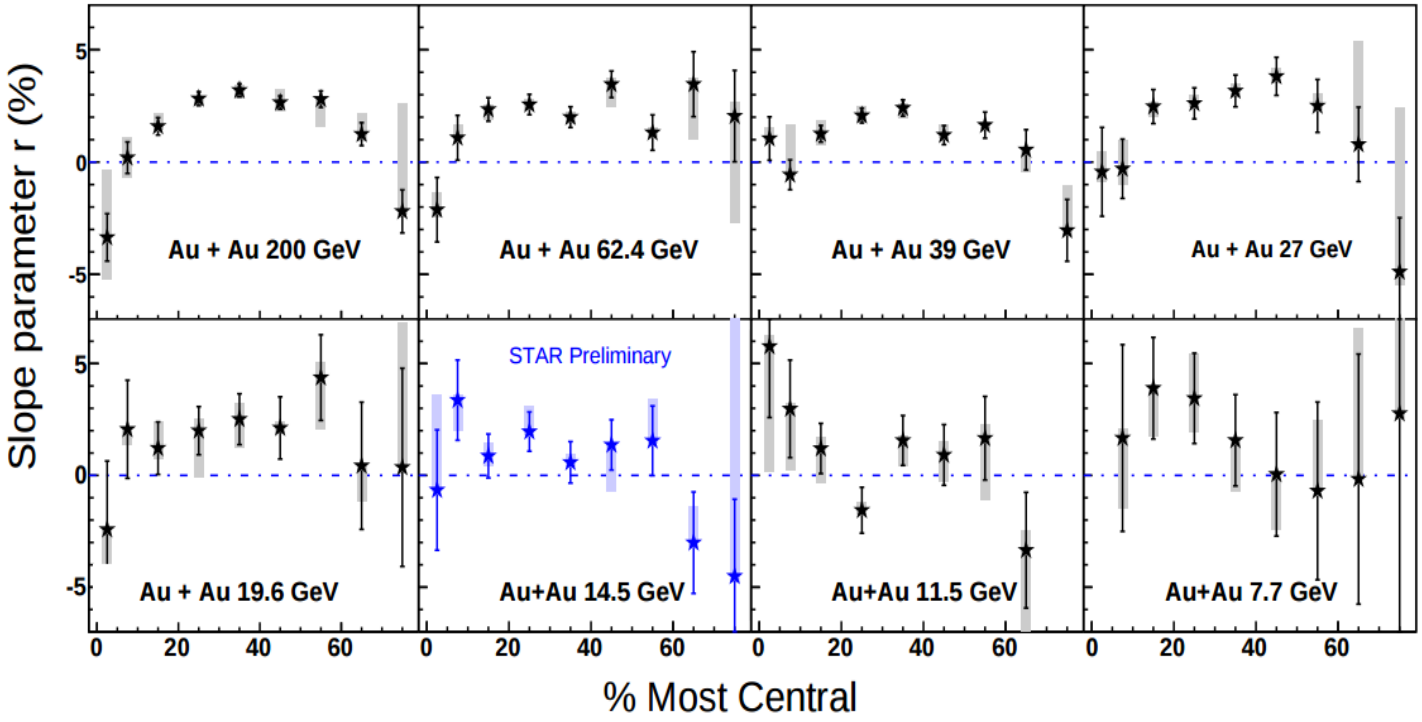
CMW.Slope



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

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

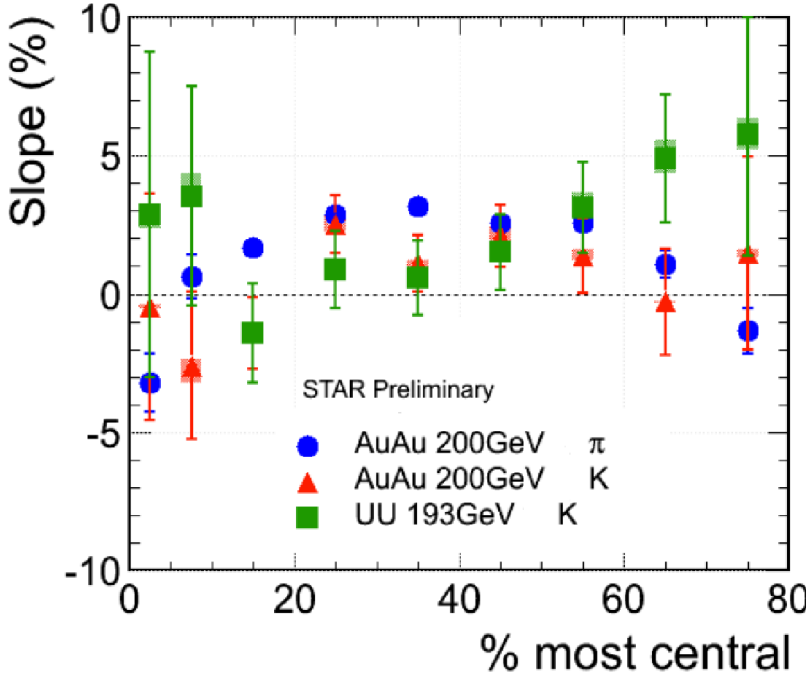
CMW.BES

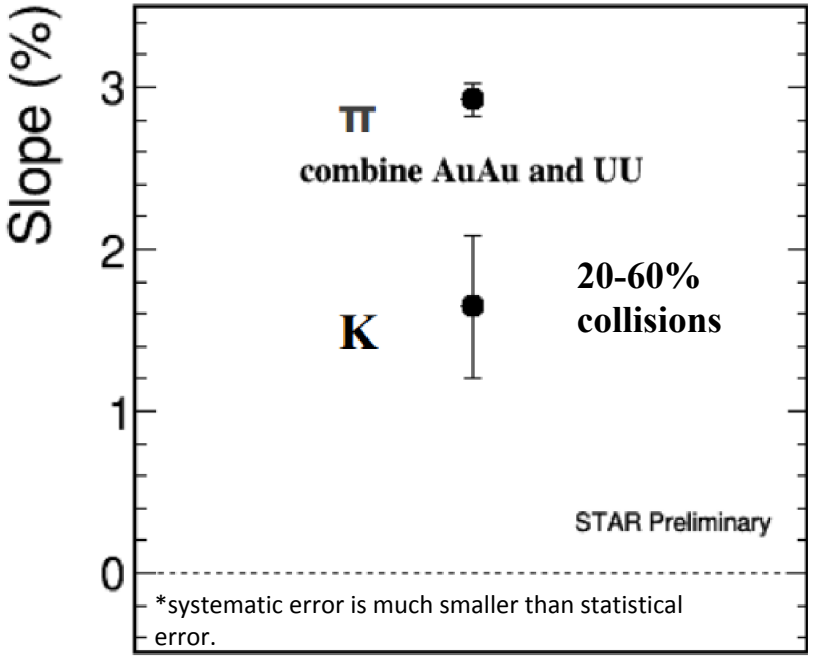


▷ Similar trends pattern can be observed in different collision energies down to 19.6 GeV.

Y. Burnier, D. E. Kharzeev, J. Liao and H-U Yee, arXiv:1208.2537v1 [hep-ph]; Wei-Tian Deng and Xu-Guang Huang, PRC 85 (2012) 044907

CMW.Kaon





Y. Burnier, D. E. Kharzeev, J. Liao, and H. Yee, PRL 107 052303

▽ We observed weaker **CMW** effect on kaons, which is consistent with theoretical expectation.

Chiral Vortical Effect

Chiral Magnetic Effect

Chirality Imbalance(μ_A)

Magnetic Field(ω μ_e)

Electric Charge Separation(j_e)

Chiral Vortical Effect

Chirality Imbalance(μ_A)

Fluid Vorticity(ω μ_B)

Baryon Number Separation(j_B)

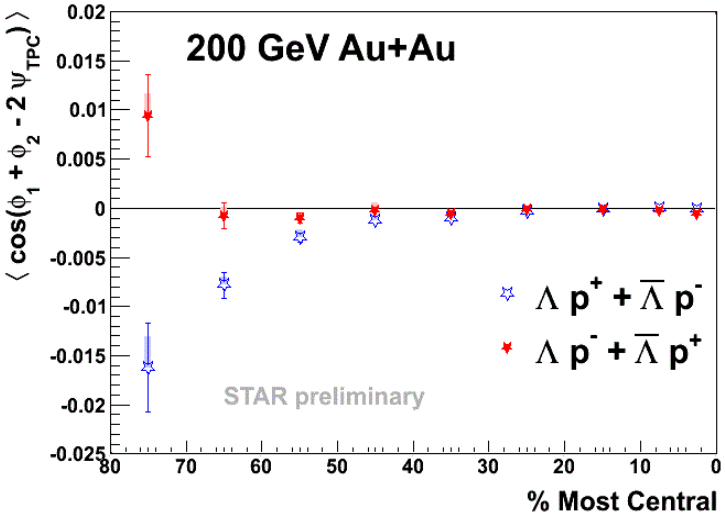
Observable:

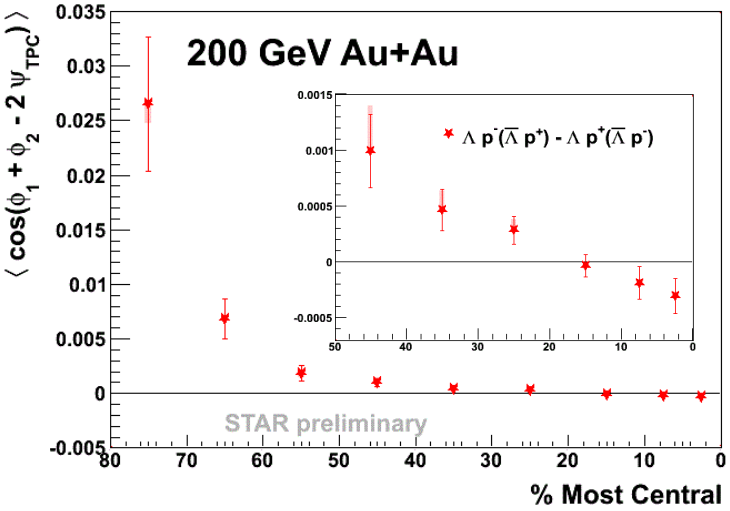
$$\langle \cos(\phi_\Lambda + \phi_p - 2\Psi_{RP}) \rangle$$

▷ Λ–P correlation measurement can be used to search for the Chiral Vortical Effect

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

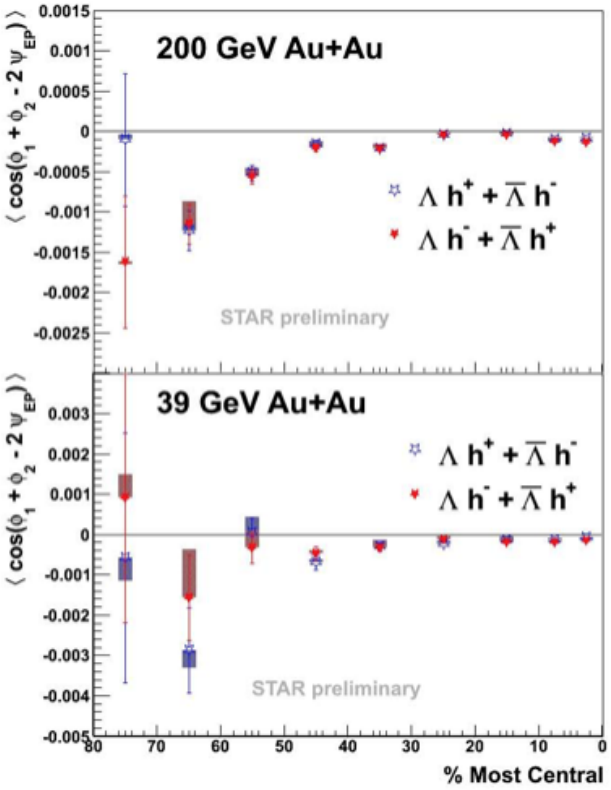
CVE: Λ-p Correlation

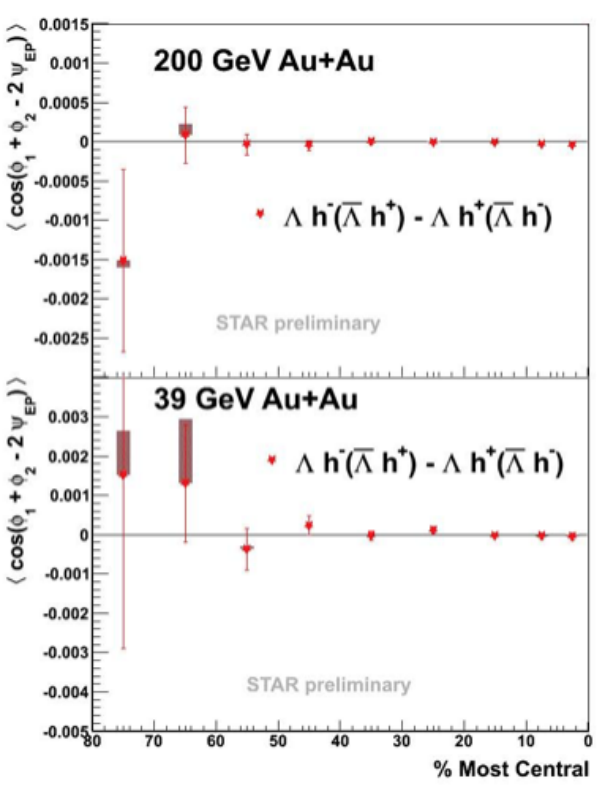




- Λ-p(Λ-antip) and antiΛ-antip(antiΛ-p)(same baryon number / oppo baryon number) show similar behaviors and their results are compared;
- "same B" is systematically lower than "oppo B" in the mid-central and peripheral collisions.

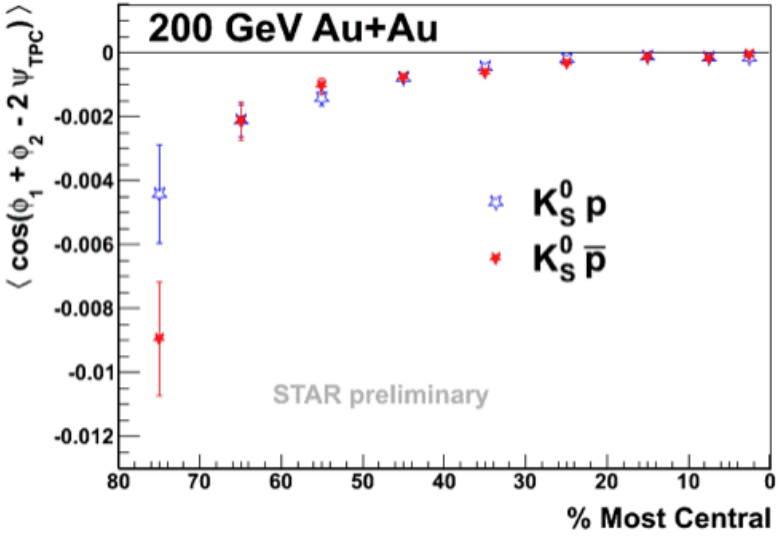
CVE: Λ-h Correlation

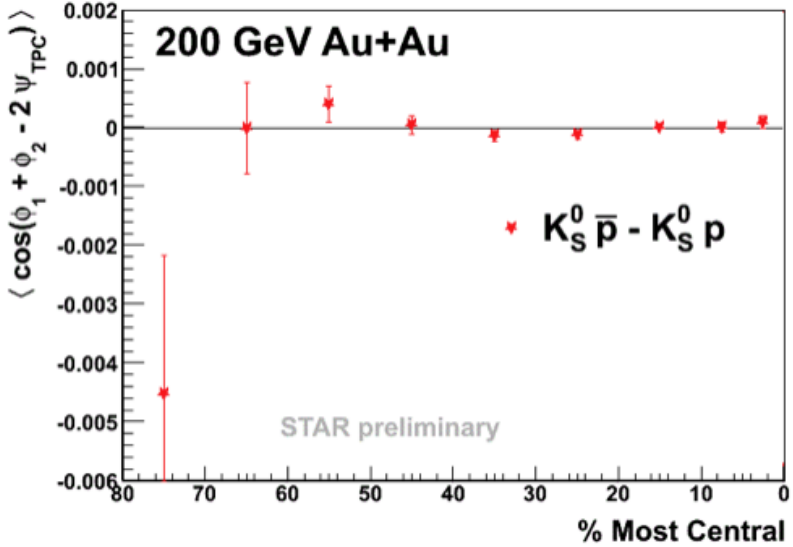




- Replace proton with charged hadron.
- As expected, difference between "same baryon number" and "oppo baryon number" is consistent with ZERO.

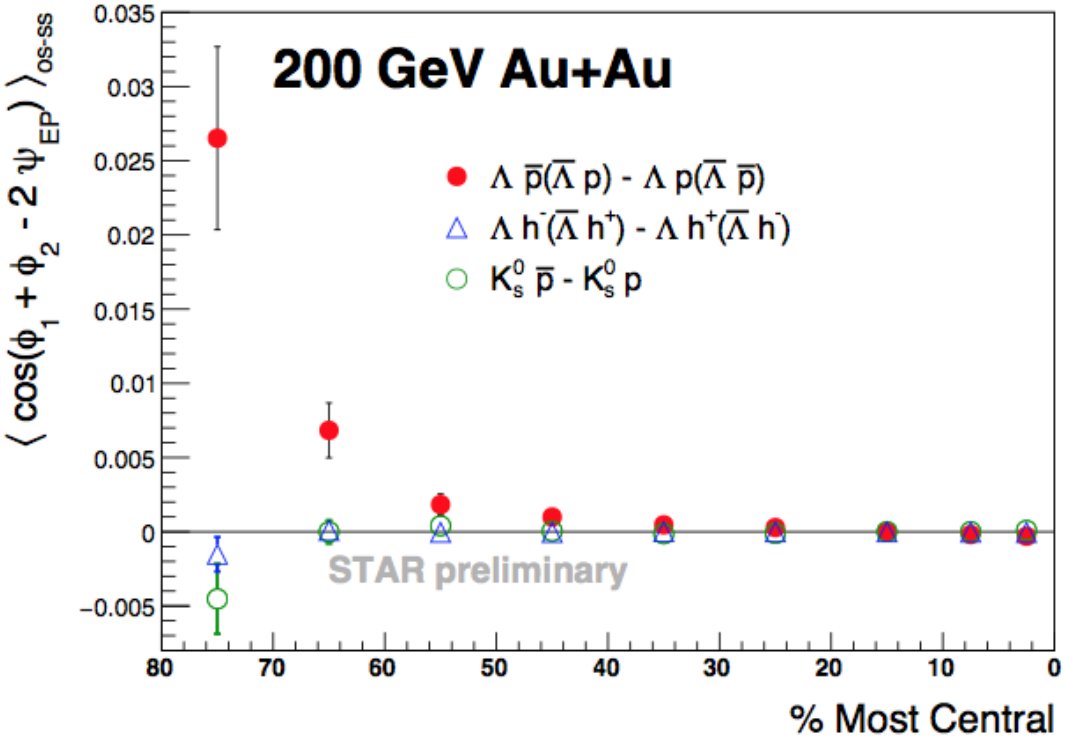
CVE: Ks-p Correlation





▷ Replace Lambda with Ks0(no baryon charge). As CVE predicted, no significant separation signal observed.

Chiral Vortical Effect



▷Put our results together, we can see separation effect is baryon number dependent.

Summary

Chiral Magnetic Effect:

- Electric Charge Separation w.r.t EP is observed through three point correlator measurement;
- Signal is robust after eliminating HBT and Coulomb effect;
- Signal is robust with modulated sign correlator(msc);
- BES shows charge separation exists down to 19.6GeV;

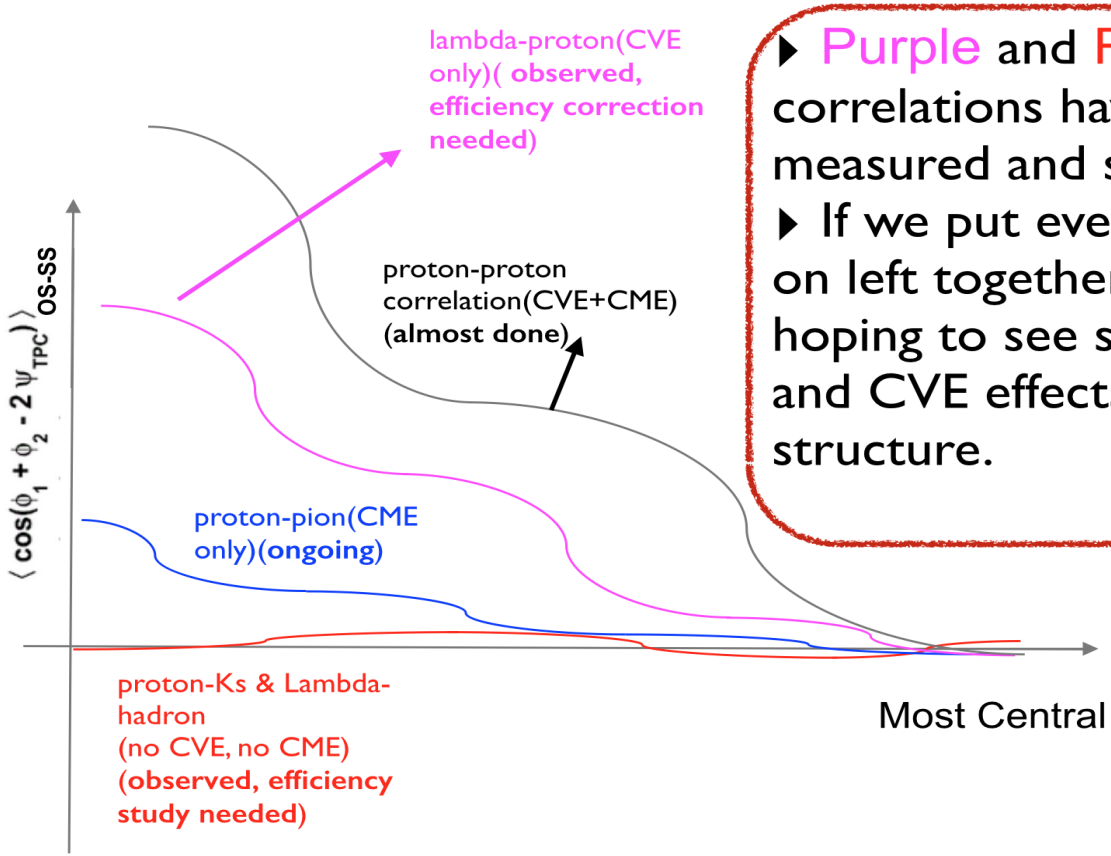
Chiral Magnetic Wave:

- Charge asymmetry dependence of pion v_2 has been observed;
- UrQMD and AMPT cannot reproduce centrality dependence of v_2 slope;
- BES shows robust v_2 slope trend down to 19.6GeV;
- Weaker CMW effect is observed in Kaon measurement as expected;

Chiral Vortical Effect:

- Baryon-charge separation across event plane is observed in Λ-p correlation measurement from 39GeV and 200GeV AuAu collisions.

Outlook: CME and CVE Manifestation in Correlation Hierarchy

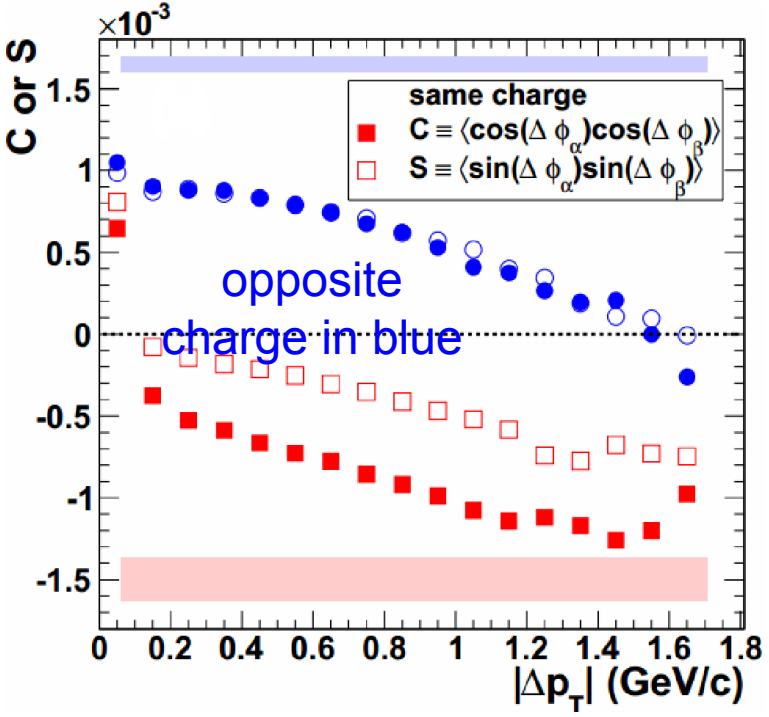


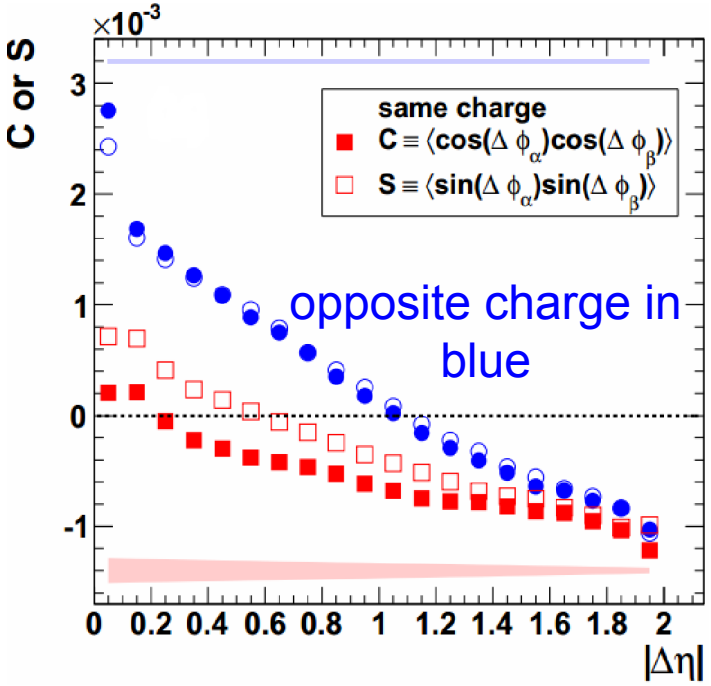
- Purple and Red correlations have been measured and shown today.
- If we put everything listed on left together, we are hoping to see such a CME and CVE effects hierarchical structure.

Backup Slides

HBT and Coulomb

200 GeV Au+Au: 40 - 60%





- Short-range correlations exist
- probably due to HBT + Coulomb