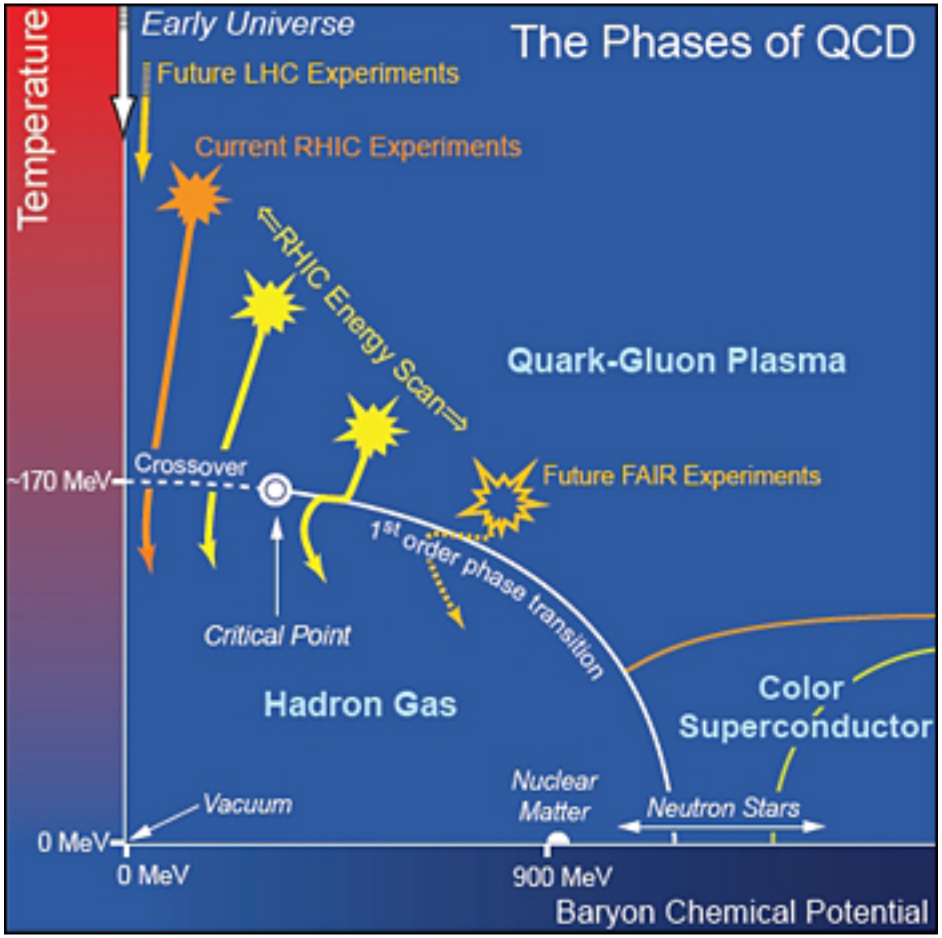
Net Charge Asymmetry Dependence of pion/kaon Anisotropic Flow

- do we see the effect of Chiral Magnetic Wave ?

Aihong Tang for STAR

RHIC as a QCD test ground

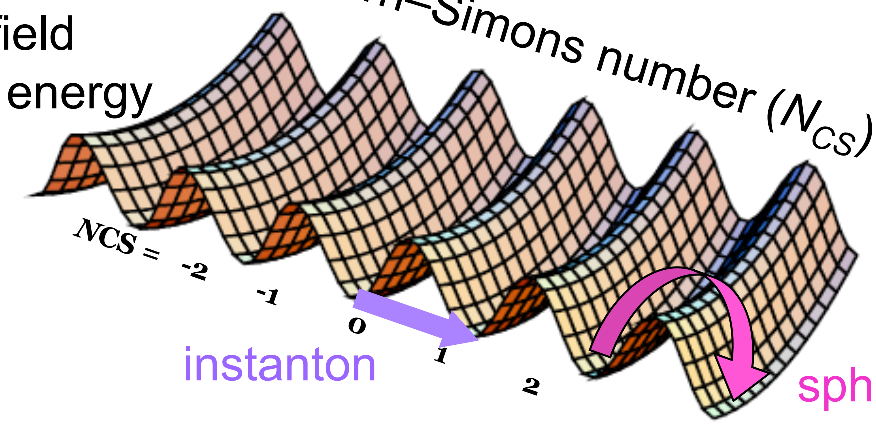


QCD is widely accepted as the theory of strong interactions

Goal of RHIC is to study the properties of QCD matter

This talk addresses phenomena related to a fundamental QCD concept --- the QCD vacuum

QCD Vacuum Transition



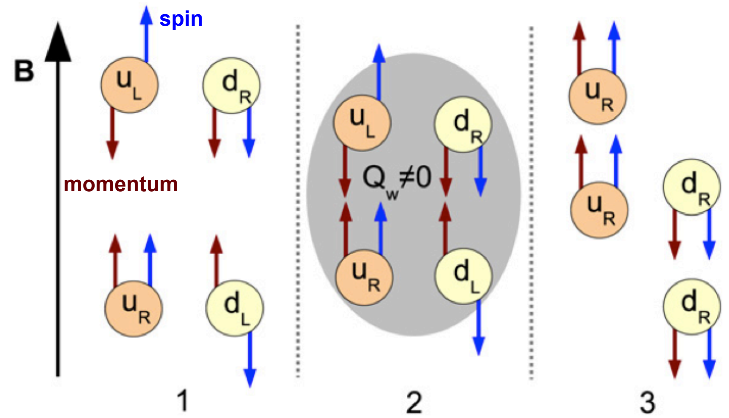
$$N_L^f - N_R^f = 2Q_W,\ Q_W \neq 0 \rightarrow \mu_A \neq 0$$

QCD vacuum transition → nonzero topological charge → chirality imbalance (see more in Ho-Ung Yee's talk)

CME & CSE

- Chiral Magnetic Effect (CME): nonzero axial charge density induces a vector (electric) current along external magnetic field.

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



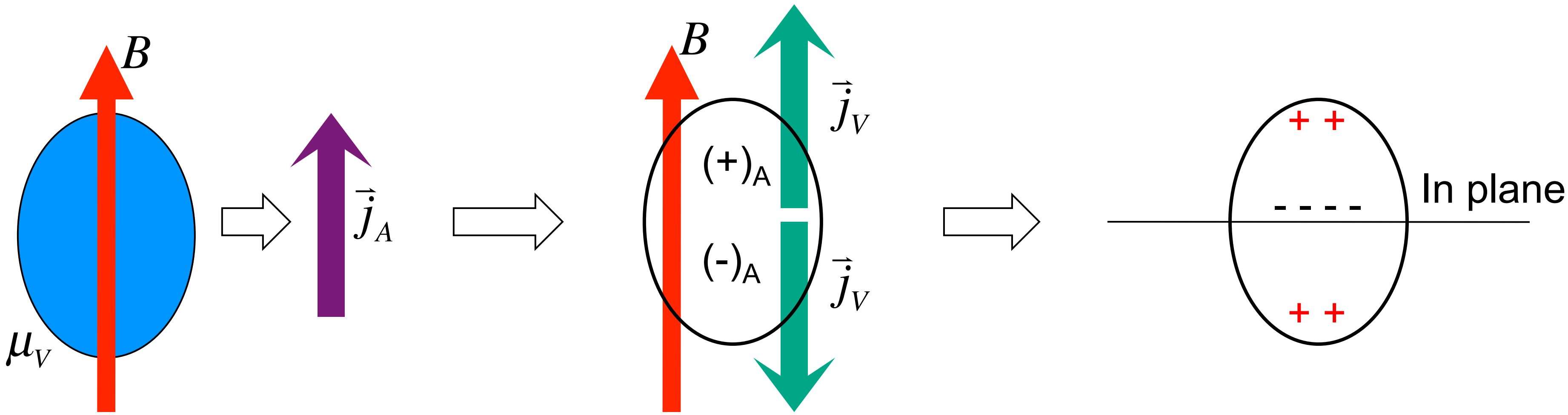
- Chiral Separation Effect (CSE): nonzero vector charge density induces an axial current along external magnetic field.

$$\boldsymbol{j}_A = \frac{N_c e}{2\pi^2}\mu_V \boldsymbol{B}$$ ➔ chiral charge separation along *B* field

D. E. Kharzeev, L. D. McLerran, and H. J. Warringa, Nuclear Physics A 803, 227 (2008)
T. Son, D. and A. R. Zhitnitsky, Phys. Rev. D 70, 074018 (2004)

Chirality imbalance can manifest itself with the help of strong magnetic field

CSE + CME = Chiral Magnetic Wave



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

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

Chiral Separation Effect

Chiral Magnetic Effect

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

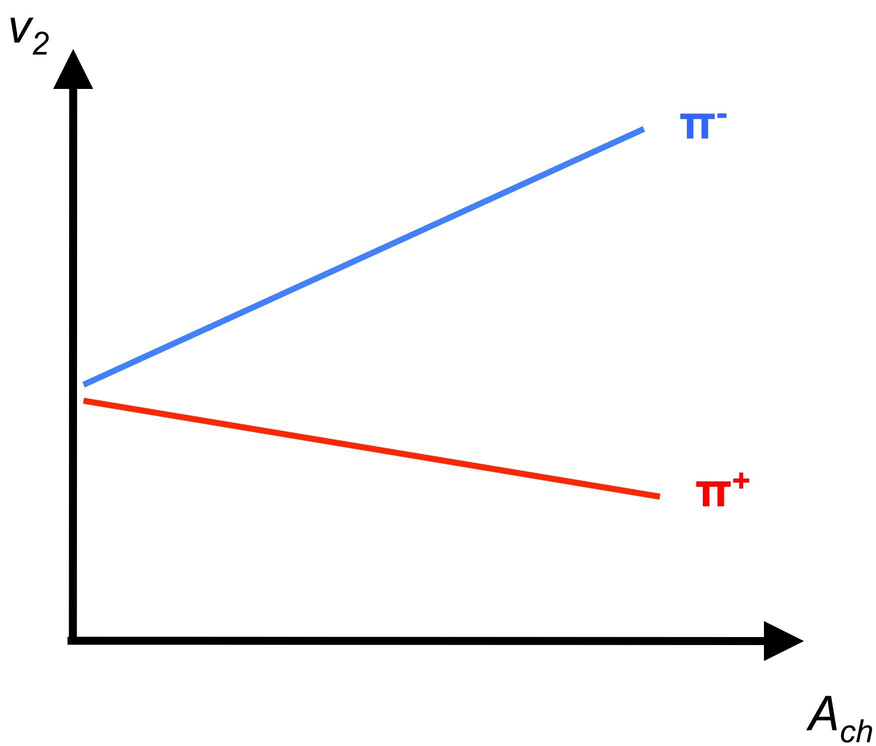
CSE + CME → Chiral Magnetic Wave (CWM). A collective excitation. CMW can cause in-plane π^- enhancement ($v_2(\pi^-) > v_2(\pi^+)$).

CMW : The predicted features

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

A_{ch} : Charge asymmetry $A_{ch} = \frac{\bar{N}_+ - \bar{N}_-}{\bar{N}_+ + \bar{N}_-}$

q_e : quadruple term



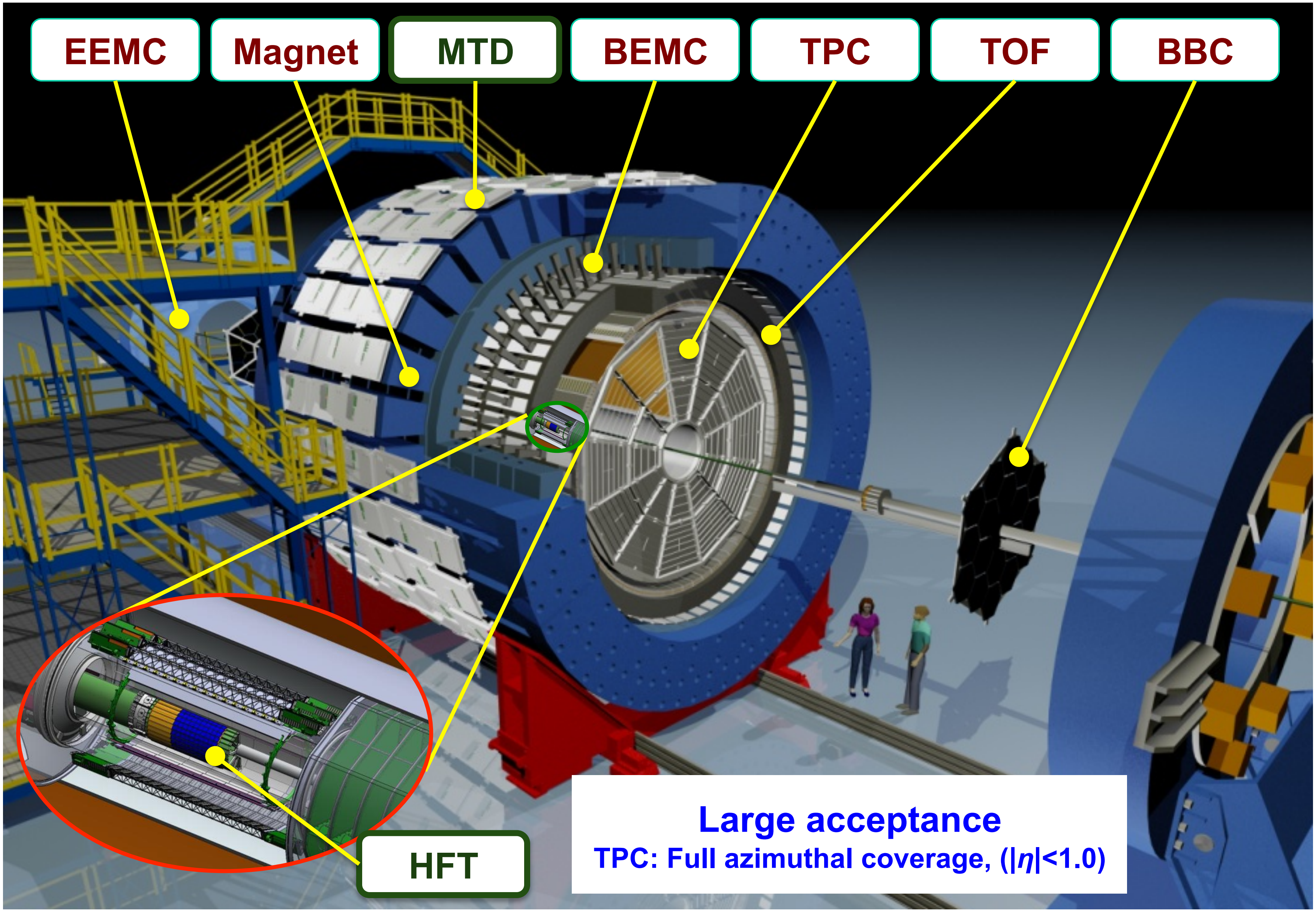
v_2(π-) > v_2(π+) when A_{ch} is large.

v_2(π-) increases with increasing A_{ch}, the trend is opposite for v_2(π+).

The difference of v_2(π-) - v_2(π+) is linearly proportional to A_{ch}.

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

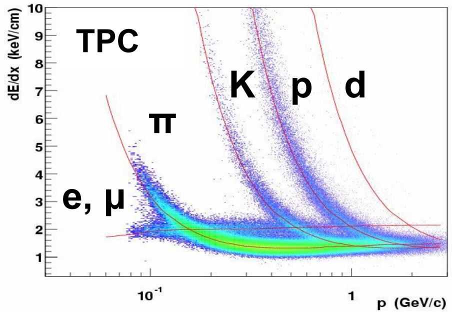
STAR Setup

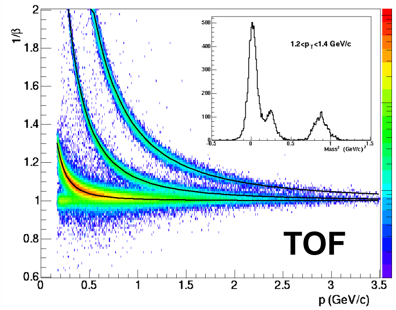


Large acceptance

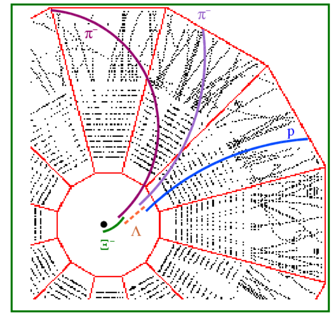
TPC: Full azimuthal coverage, (|η|<1.0)

STAR : Excellent PID and Tracking

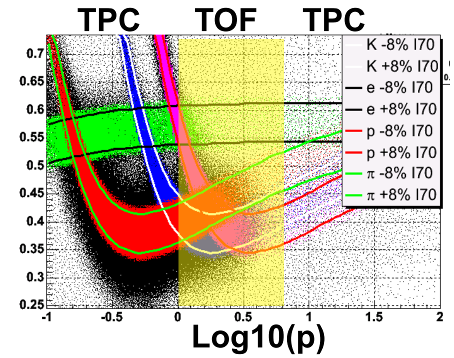


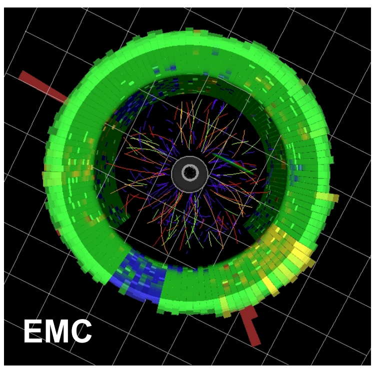


Charged hadrons

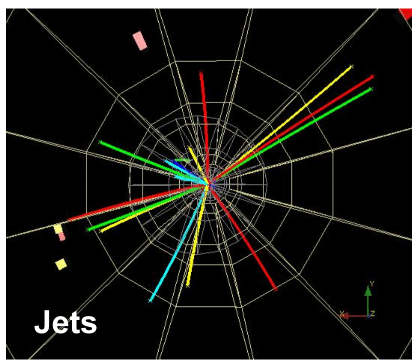


Hyperons & Hyper-nuclei

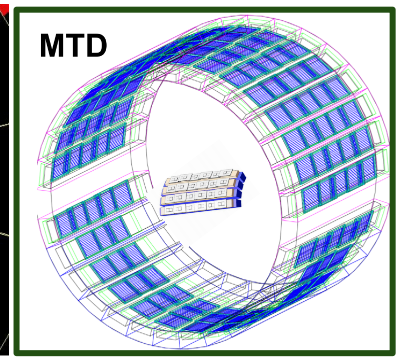




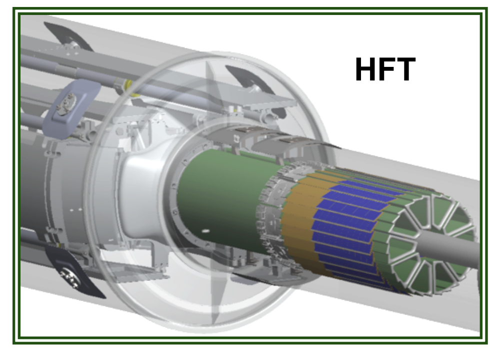
Neutral particles



Jets & Correlations



High pT muons



Heavy-flavor hadrons

Flow Analysis : Q-Cumulant

Reference flow from two-particle correlation

$$\langle 2 \rangle \equiv \langle e^{in(\phi_1-\phi_2)} \rangle \equiv \frac{1}{P_{M,2}} \sum_{i,j}{}' e^{in(\phi_i-\phi_j)}$$

$$W_{\langle 2 \rangle} \equiv M(M-1)$$

$$\langle\langle 2 \rangle\rangle \equiv \langle\langle e^{in(\phi_1-\phi_2)} \rangle\rangle \equiv \frac{\sum_{\text{events}} (W_{\langle 2 \rangle})_i \langle 2 \rangle_i}{\sum_{\text{events}} (W_{\langle 2 \rangle})_i}$$

$$Q_n \equiv \sum_{i=1}^{M} e^{in\phi_i}$$

$$|Q_n|^2 = \sum_{i,j=1}^{M} e^{in(\phi_i-\phi_j)} = M + \sum_{i,j}{}' e^{in(\phi_i-\phi_j)}$$

$$\langle 2 \rangle = \frac{|Q_n|^2 - M}{M(M-1)}$$

$$c_n\{2\} = \langle\langle 2 \rangle\rangle \text{ or } c_n\{2\} = \langle\langle 2 \rangle\rangle - \langle\langle \cos n\phi_1 \rangle\rangle^2 - \langle\langle \sin n\phi_1 \rangle\rangle^2$$

$$v_n\{2\} = \sqrt{c_n\{2\}}$$

$$\langle\langle \cos n\phi_1 \rangle\rangle = \frac{\sum_{i=1}^{N} (\mathrm{Re}[Q_n])_i}{\sum_{i=1}^{N} M_i}$$

$$\langle\langle \sin n\phi_1 \rangle\rangle = \frac{\sum_{i=1}^{N} (\mathrm{Im}[Q_n])_i}{\sum_{i=1}^{N} M_i}$$

Q-Cumulants method improvements:

- **Need only one pass over tracks.**
- **Comprehensive detector inefficiency corrections.**

A. Bilandzic, R. Snellings, and S. Voloshin, Phys. Rev. C 83, 044913 (2011)

Flow Analysis : Q-Cumulant

Differential flow from two-particle correlation

$$\langle 2' \rangle \equiv \langle e^{in(\psi_1 - \phi_2)} \rangle$$

$$\equiv \frac{1}{m_p M - m_q} \sum_{i=1}^{m_p} \sum_{j=1}^{M}{}' e^{in(\psi_i - \phi_j)}$$

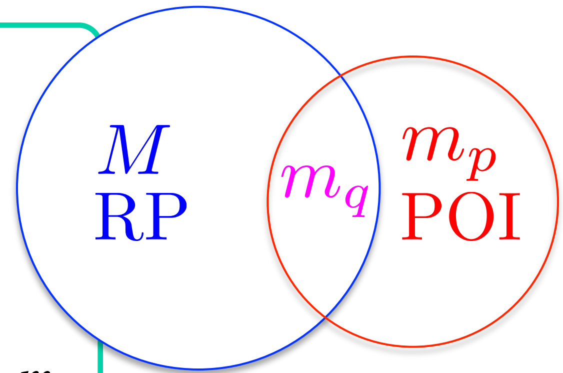
$$w_{\langle 2' \rangle} \equiv m_p M - m_q$$

$$\langle\langle 2' \rangle\rangle \equiv \frac{\sum_{\text{events}} (w_{\langle 2' \rangle})_i \langle 2' \rangle_i}{\sum_{\text{events}} (w_{\langle 2' \rangle})_i}$$

$$p_n \equiv \sum_{i=1}^{m_p} e^{in\psi_i}$$

$$q_n \equiv \sum_{i=1}^{m_q} e^{in\psi_i}$$

$$\langle 2' \rangle = \frac{p_n Q_n^* - m_q}{m_p M - m_q}$$



$$d_n\{2\} = \langle\langle 2' \rangle\rangle \text{ or}$$

$$d_n\{2\} = \langle\langle 2' \rangle\rangle - \langle\langle \cos n\psi_1 \rangle\rangle \langle\langle \cos n\phi_2 \rangle\rangle - \langle\langle \sin n\psi_1 \rangle\rangle \langle\langle \sin n\phi_2 \rangle\rangle$$

$$v'_n\{2\} = \frac{d_n\{2\}}{\sqrt{c_n\{2\}}}$$

$$\langle\langle \cos n\psi_1 \rangle\rangle = \frac{\sum_{i=1}^{N} (\mathrm{Re}[p_n])_i}{\sum_{i=1}^{N} (m_p)_i}$$

$$\langle\langle \sin n\psi_1 \rangle\rangle = \frac{\sum_{i=1}^{N} (\mathrm{Im}[p_n])_i}{\sum_{i=1}^{N} (m_p)_i}$$

Q-Cumulants method improvements:

- **Need only one pass over tracks.**
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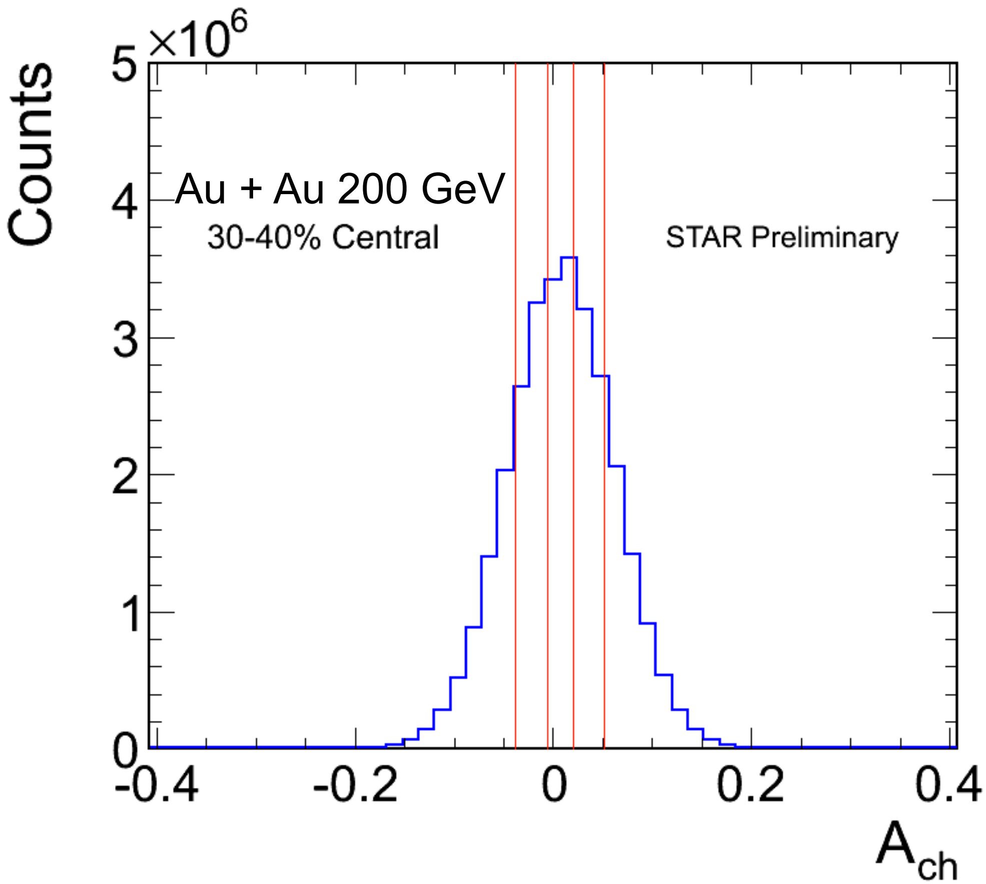
A. Bilandzic, R. Snellings, and S. Voloshin, Phys. Rev. C 83, 044913 (2011)

The Observed Charge Asymmetry

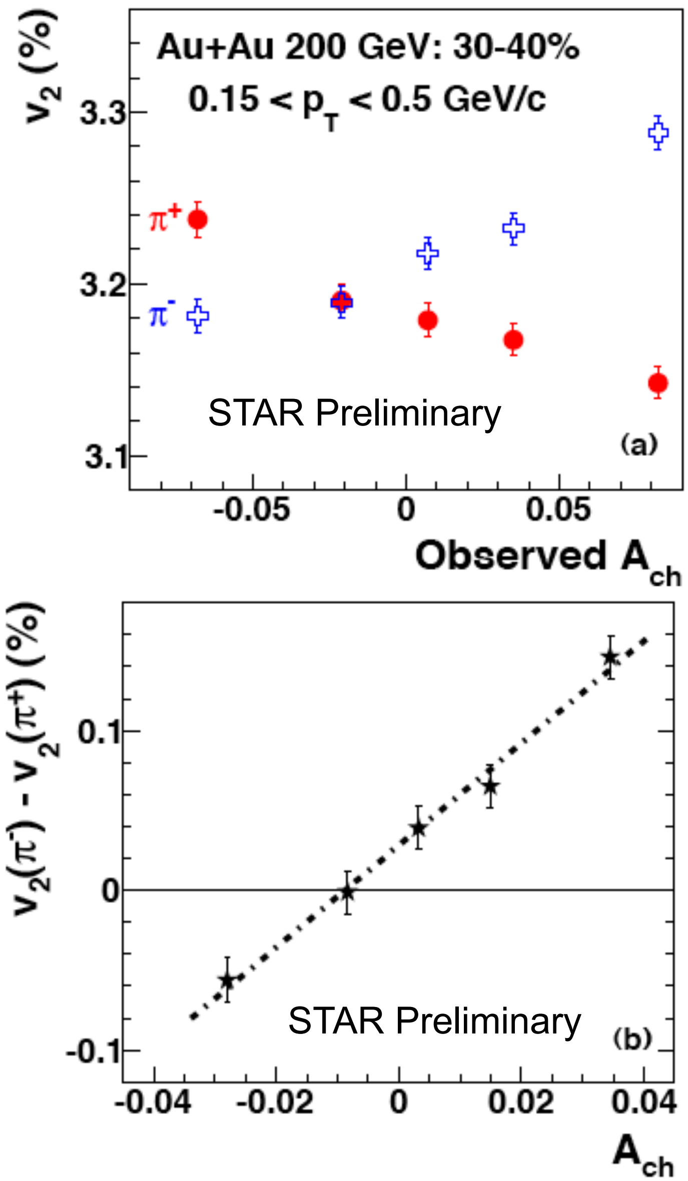


- $\overline{N}_+$ and $\overline{N}_-$: number of positive and negative particles
- observed $A_{\rm ch}$

$$A_{ch} = \frac{\overline{N}_+ - \overline{N}_-}{\overline{N}_+ + \overline{N}_-}$$

- Each bin has roughly the same number of events

The Charge Asymmetry Dependence of $\Delta v_2(\pi)$



$v_2(\pi\text{-}) > v_2(\pi+)$ when A_{ch} is large.

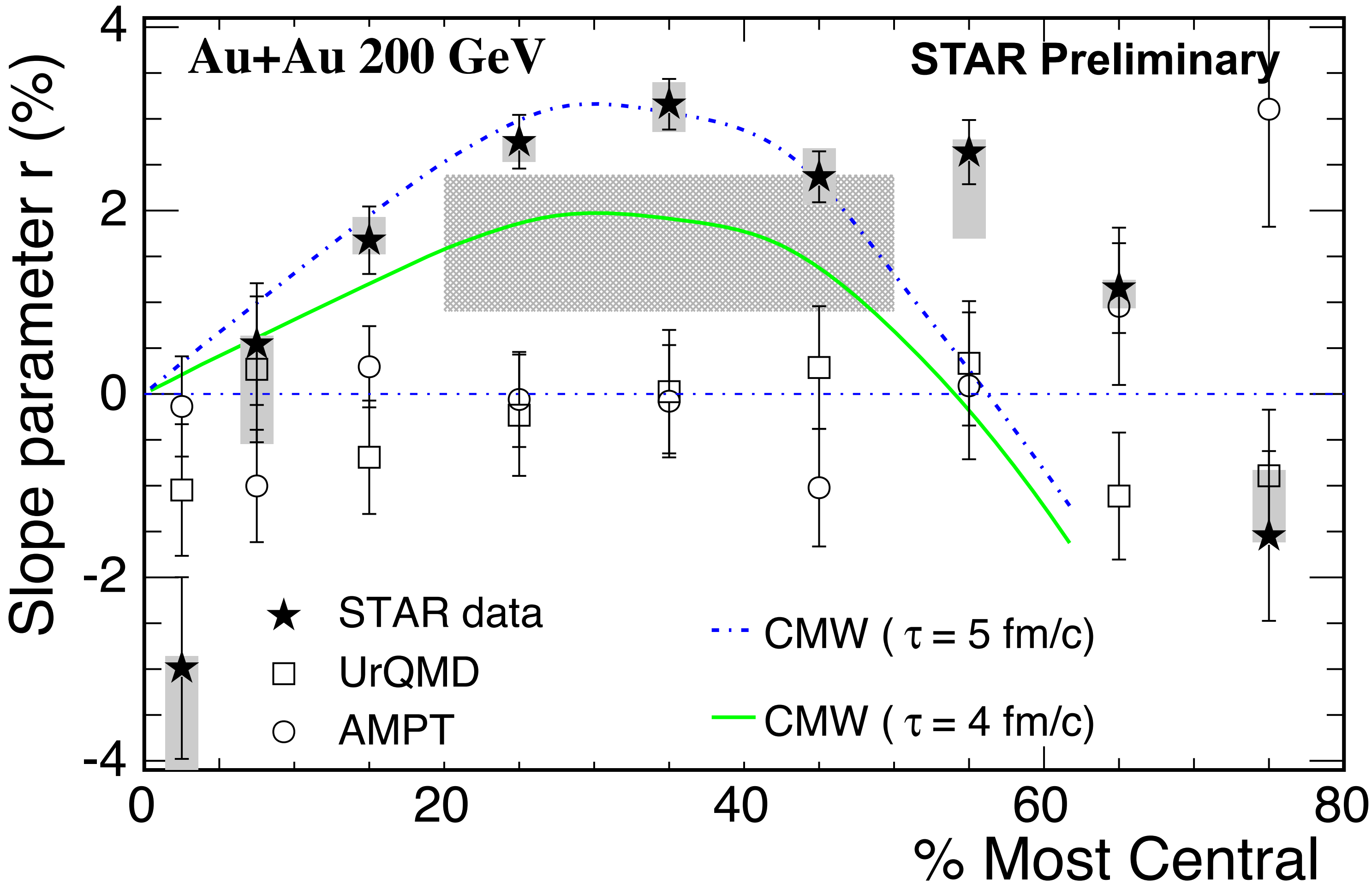
$v_2(\pi\text{-})$ increases with increasing A_{ch}, the trend is opposite for $v_2(\pi+)$.

The difference of $v_2(\pi\text{-})$ - $v_2(\pi+)$ is linearly proportional to A_{ch}.

All features mentioned above are consistent with predictions made in PRL 107, 052303 (2011).

The finite intercept at A_{ch} = 0 could be explained by the electric field in collisions. (Stephanov & Yee, PRC 88 014908 (2013)).

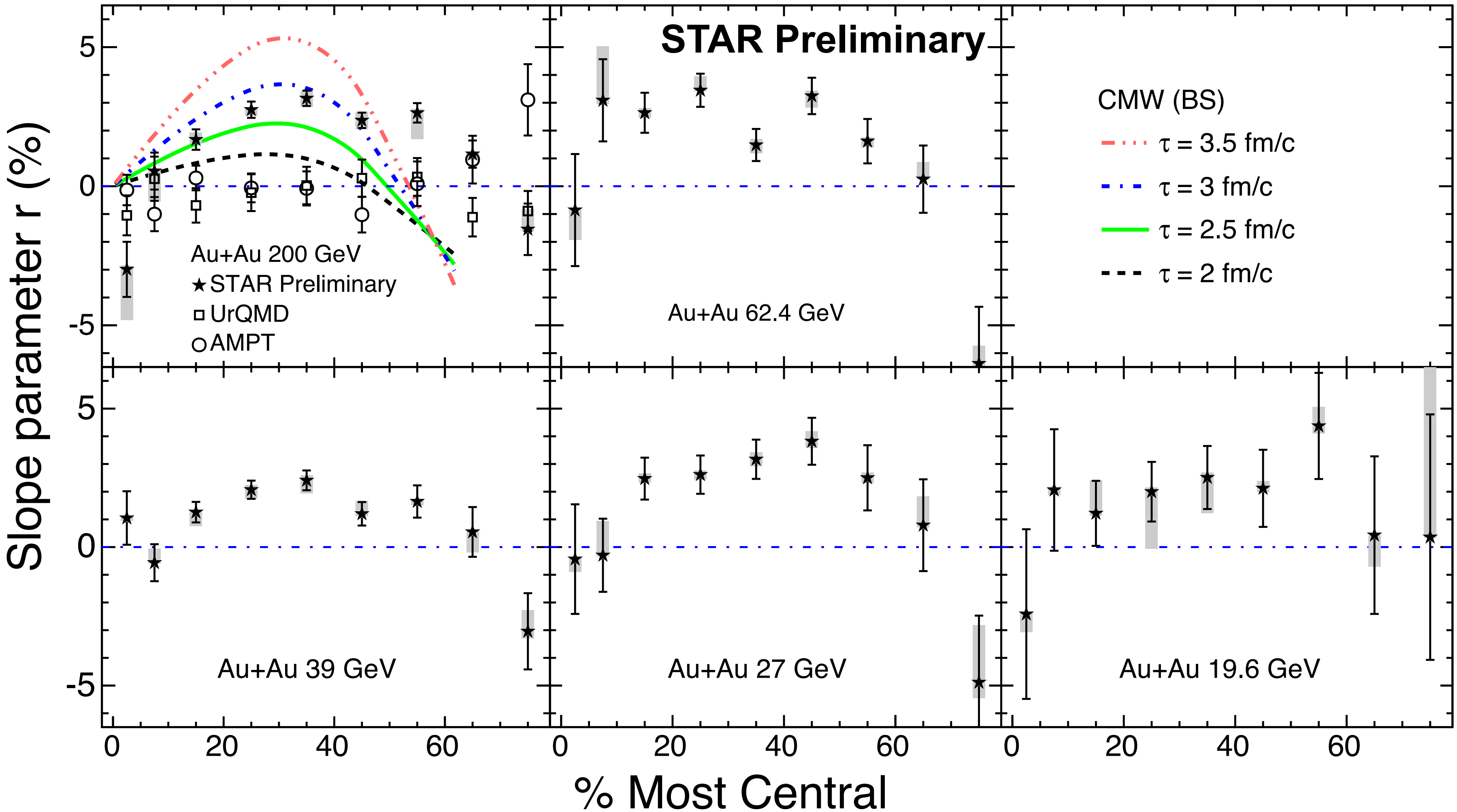
$\Delta v_2(\pi)$ Slope, different centralities



CMW Calculation : Burnier, Kharzeev, Liao and Yee. arXiv: 1208.2537

Magnitude of slope is roughly consistent with CMW prediction.
Slope in UrQMD and AMPT is consistent with zero in most centrality bins.

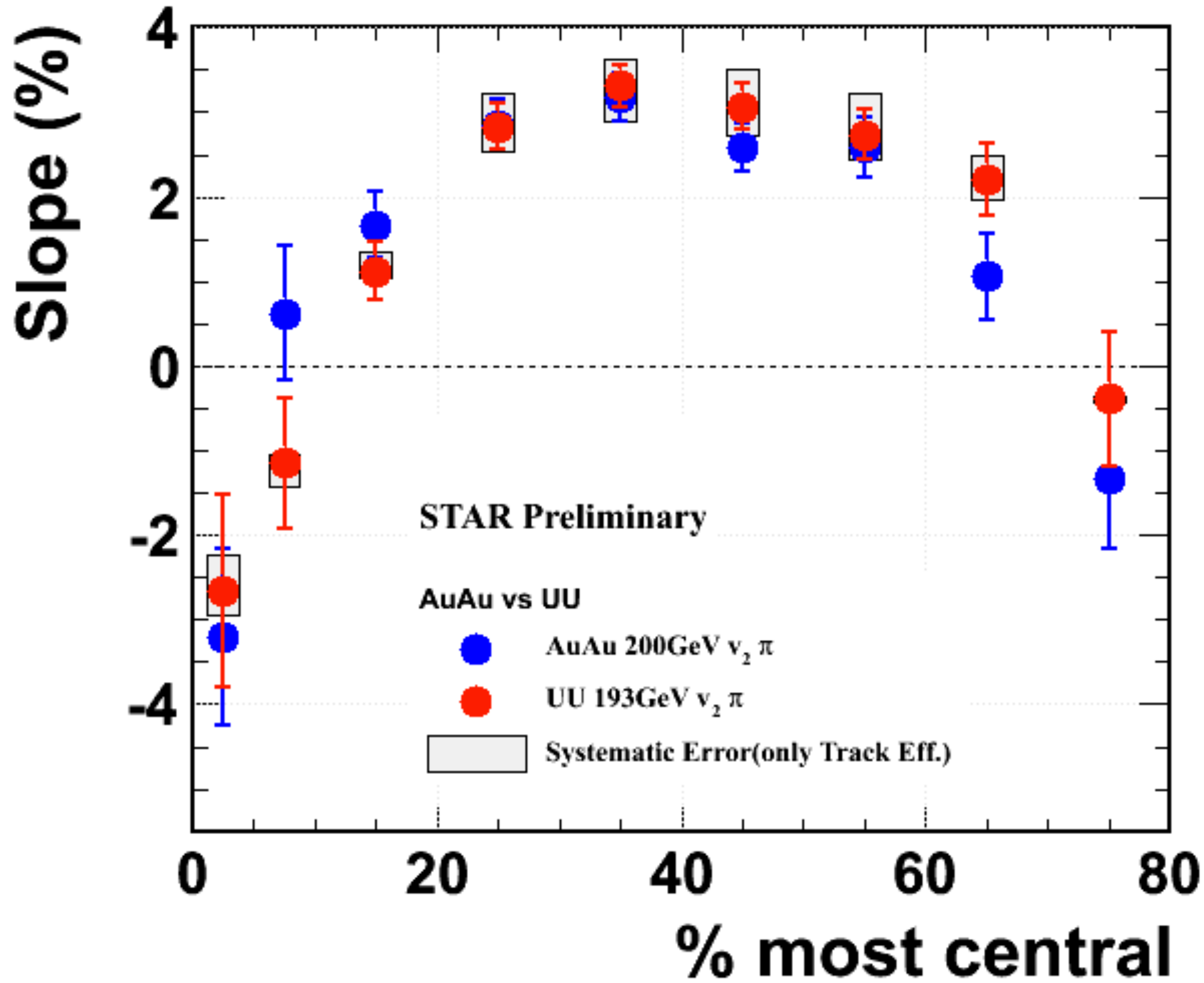
$\Delta v_2(\pi)$ Slope, different energies



CMW Calculation : Burnier, Kharzeev, Liao and Yee. arXiv: 1208.2537

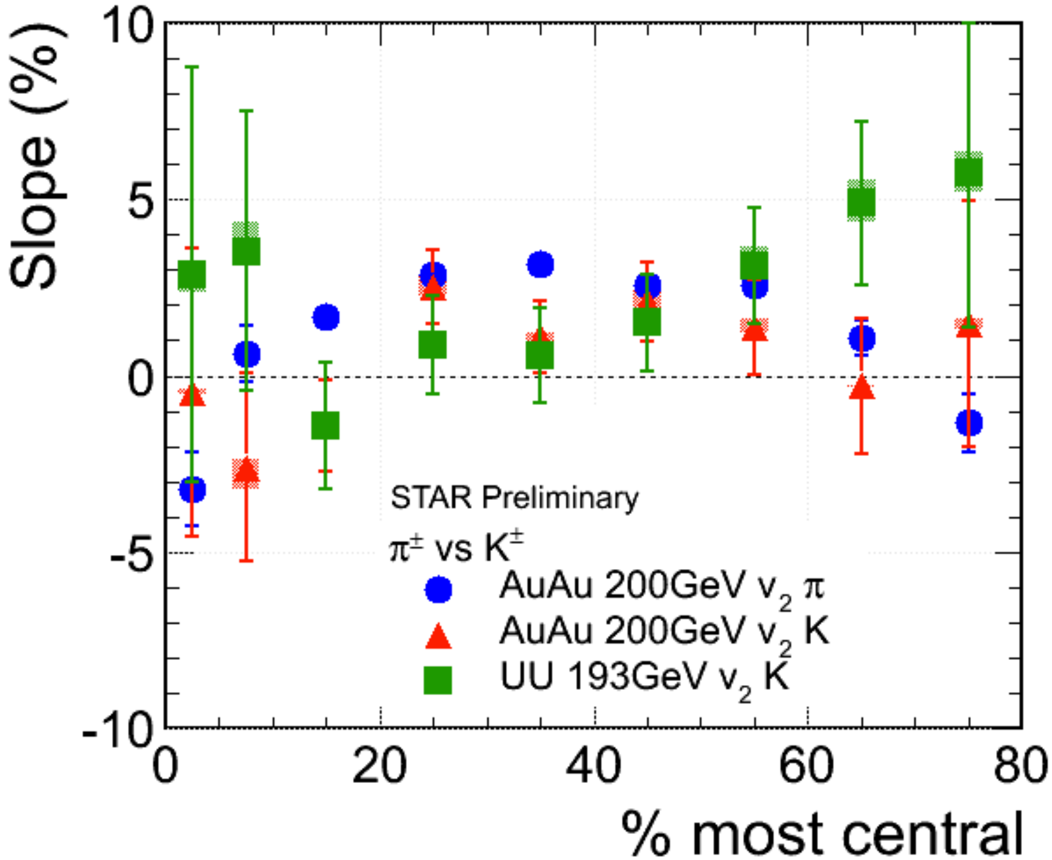
Similar pattern and magnitude is seen at BES energies.

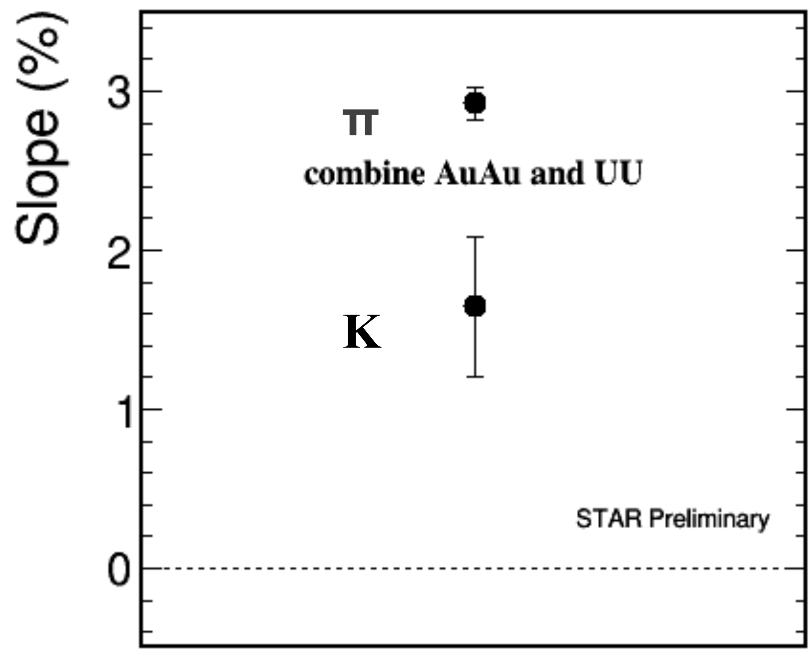
$\Delta v_2(\pi)$ Slope, different systems



Similar pattern and magnitude is also seen in U+U collisions

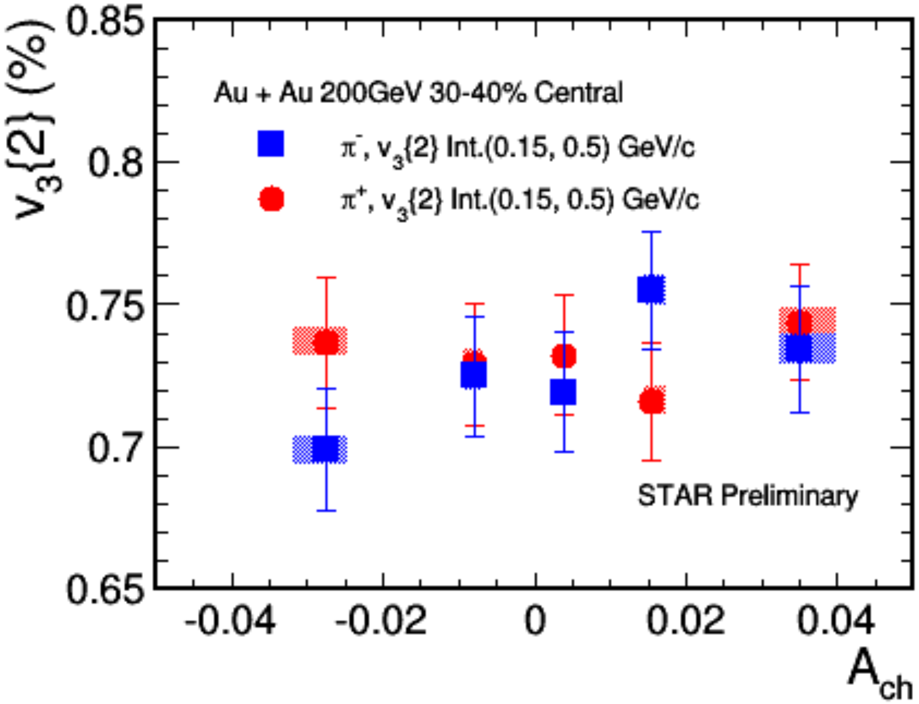
Δv_2 Slope, different PID species

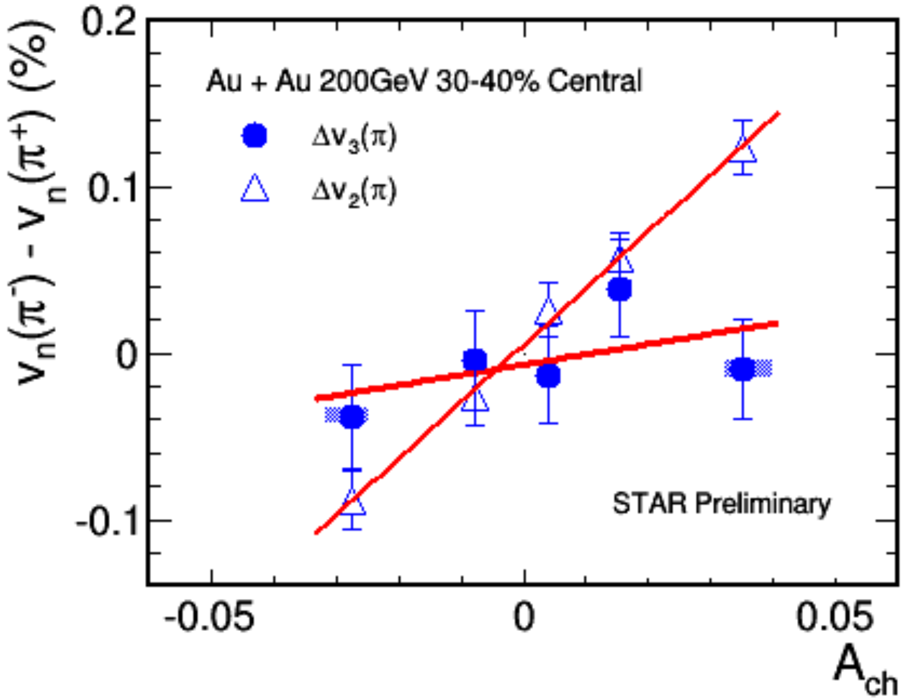




With the same electric quadruple of QGP upon chemical freeze-out, one expects to see a stronger effect on pions than kaons (PRL 107 052303)

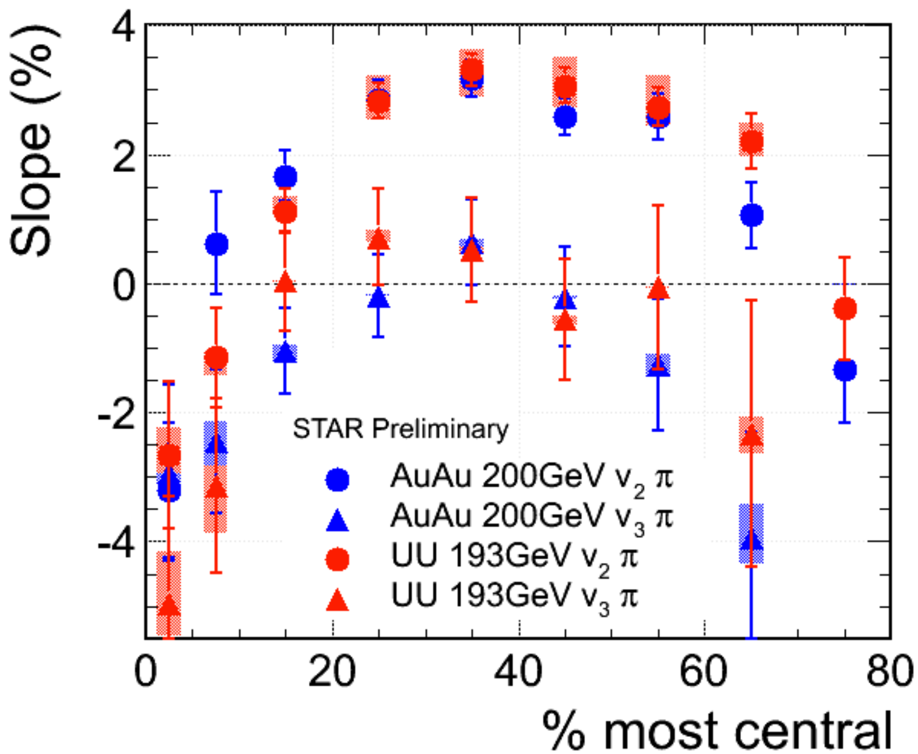
The Charge Asymmetry Dependence of $\Delta v_3(\pi)$

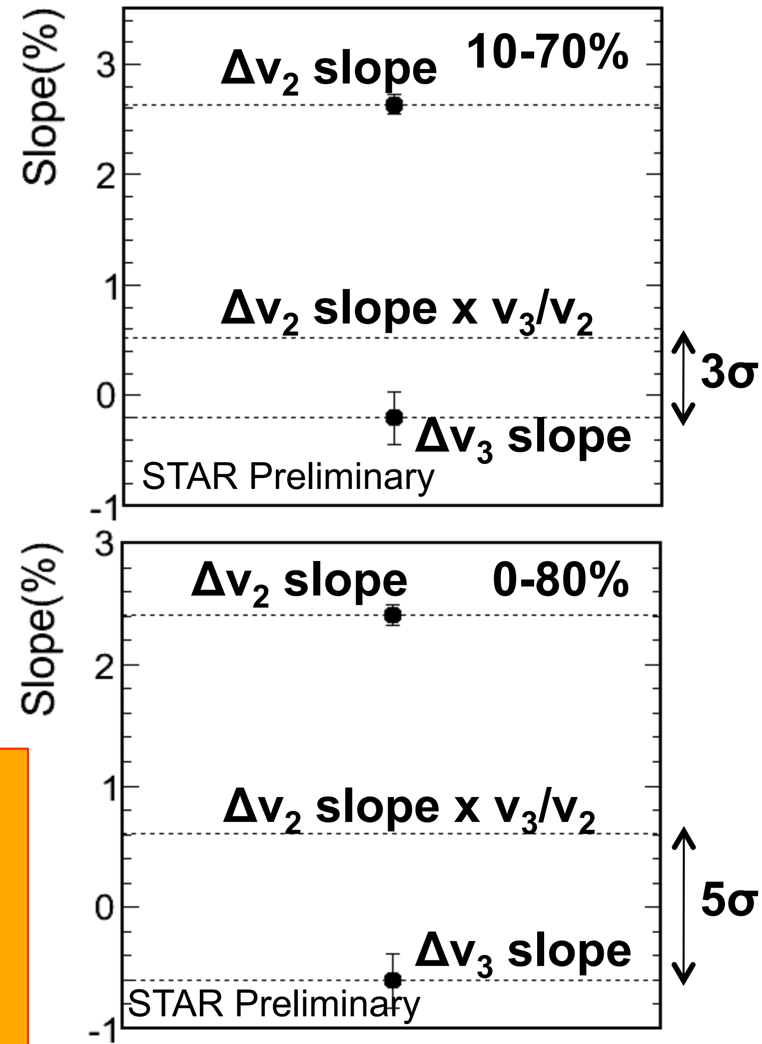




Slope of $\Delta v_3(A_{ch})$ < slope of $\Delta v_2(A_{ch})$
Consistent with zero as expected from CMW.
(Bloczynski, Huang, Zhang and Liao. PLB 718 1529 (2013)).

$\Delta v_2(\pi)$, $\Delta v_3(\pi)$ Slope vs. Centrality, Au+Au and U+U





It was pointed out that local charge conservation at freeze-out may introduce a A_{ch} dependence of $\Delta v_2(\pi)$, which if true, 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.**

Theory Interests on CMW

Local charge conservation at freeze-out + $v_2(\eta)$ and/or $v_2(pt)$ shape (Bzak & Bozek, PLB 726 239 (2013))
Alone unlikely to explain the data

CMW in expanding QCD fluid (Taghavi & Wiedemann e-print arXiv:1310.0193 (2013))
Signal too small, but can be enhanced if initial asymmetry existed.

Anomalous Hydro (Hongo, Hirono & Hirano e-print arXiv:1309.2823 (2013))
Slope is not sensitive to CMW, but the intercept is.

Realistic Implementation of CMW (Yee & Yin, PRC 89 044909 (2014))
Freeze-out important, CMW not small if calculated realistically

For most recent theoretical reviews, see
D. Kharzeev, Progress in Particle and Nuclear Physics, 75, 13 (2014)
J. Liao, arXiv:1401.2500 (2014)

See next talk for more on theory

Summary

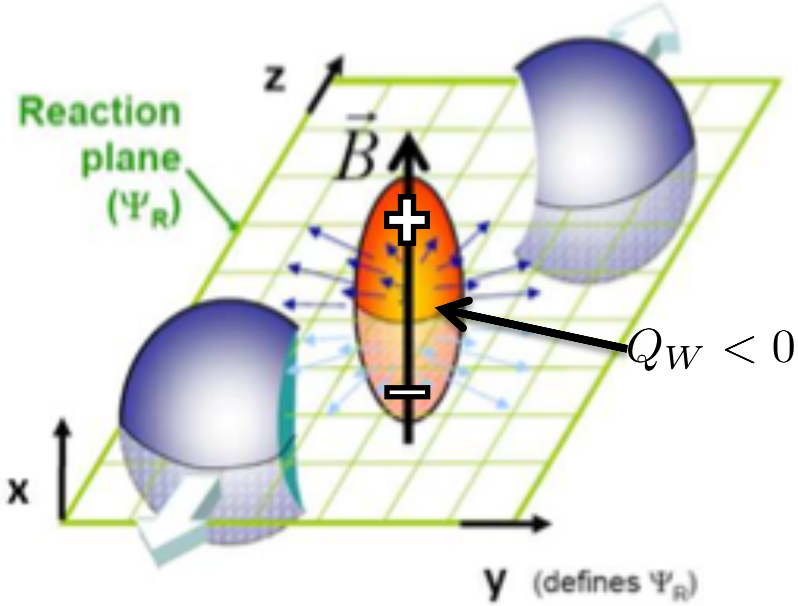
• Separation of charged pion anisotropy as a function of charge asymmetry holds great potential in understanding the property of QCD matter.

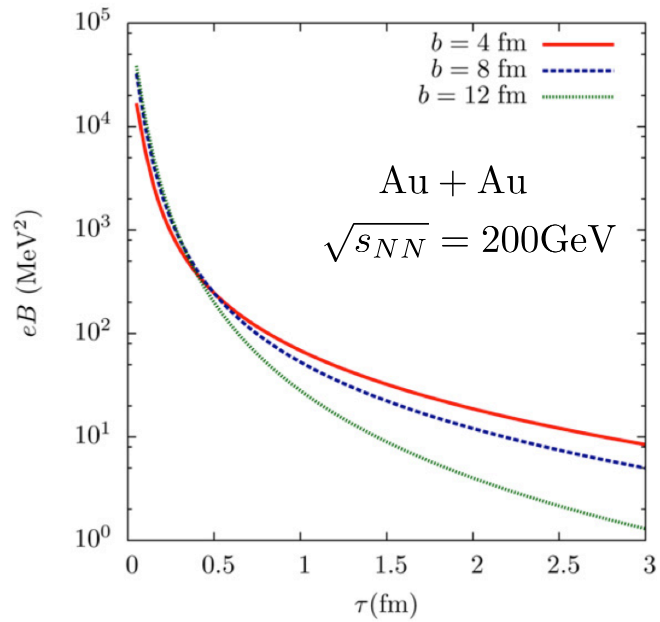
• STAR data is roughly consistent with the prediction made with CMW, in both magnitude and pattern.

• Alternative theoretical explanations are proposed, some are unsuccessful, some are controversial.

Back Up Slides

CME in Heavy Ion Collisions





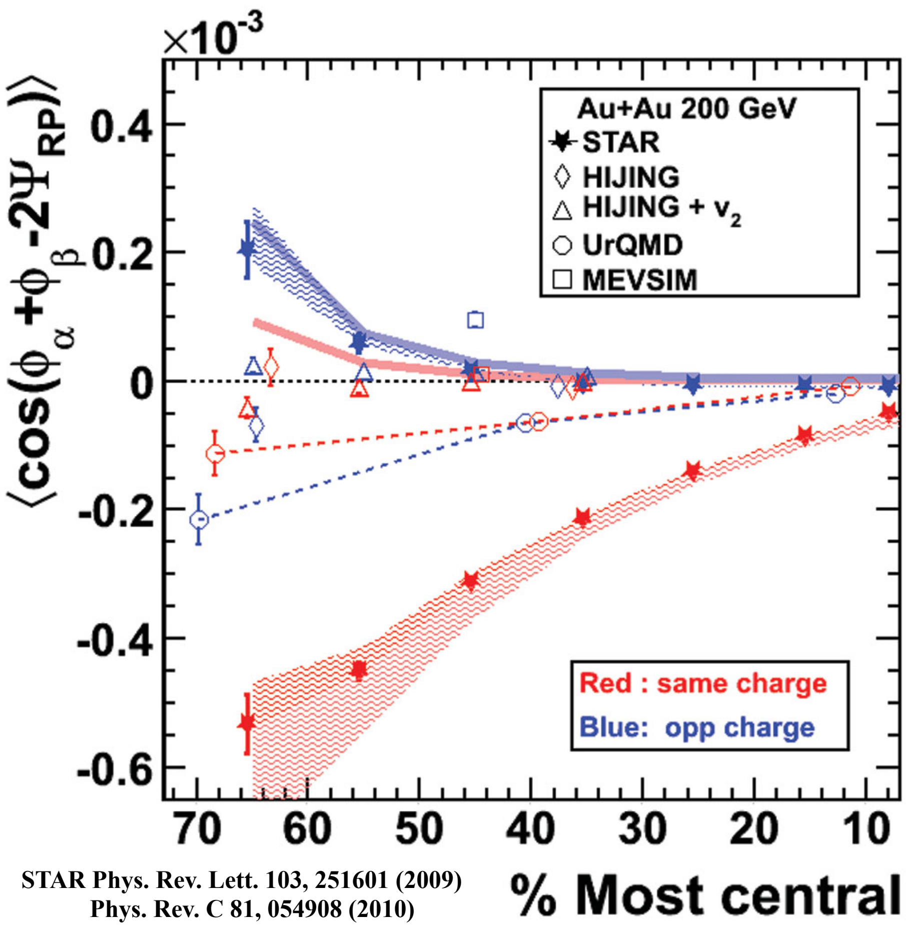
Nuclear Physics A 803, 227 (2008).

Extremely strong magnetic field created in heavy ion collisions, 10^{15} Tesla !

CME causes out-of-plane electric charge separation

Charge asymmetry w.r.t. reaction plane as a signature of LPV

CME in Heavy Ion Collisions

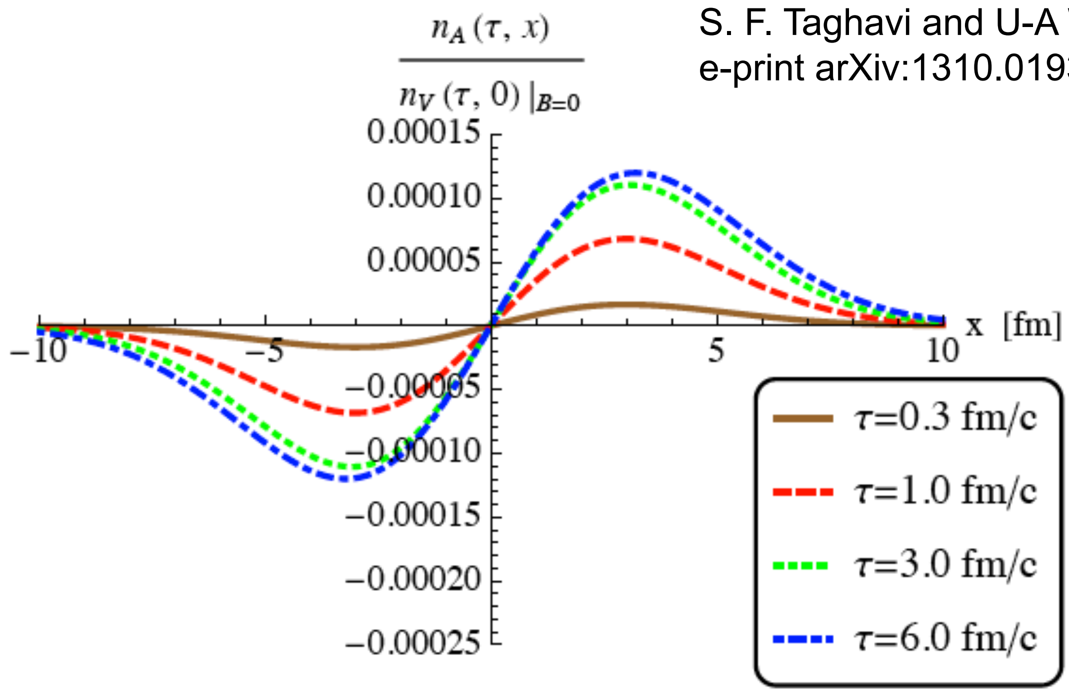


STAR Phys. Rev. Lett. 103, 251601 (2009)
Phys. Rev. C 81, 054908 (2010)

Charge separation has been observed in experiments.

Possible contributions from effects other than CME:
Cluster particle correlation (Wang), In-plane, back-to-back cluster (Bzdak, Koch & Liao), Charge Conservation and/or momentum conservation (Pratt)
……

The Calculation of CMW in an expanding QCD fluid



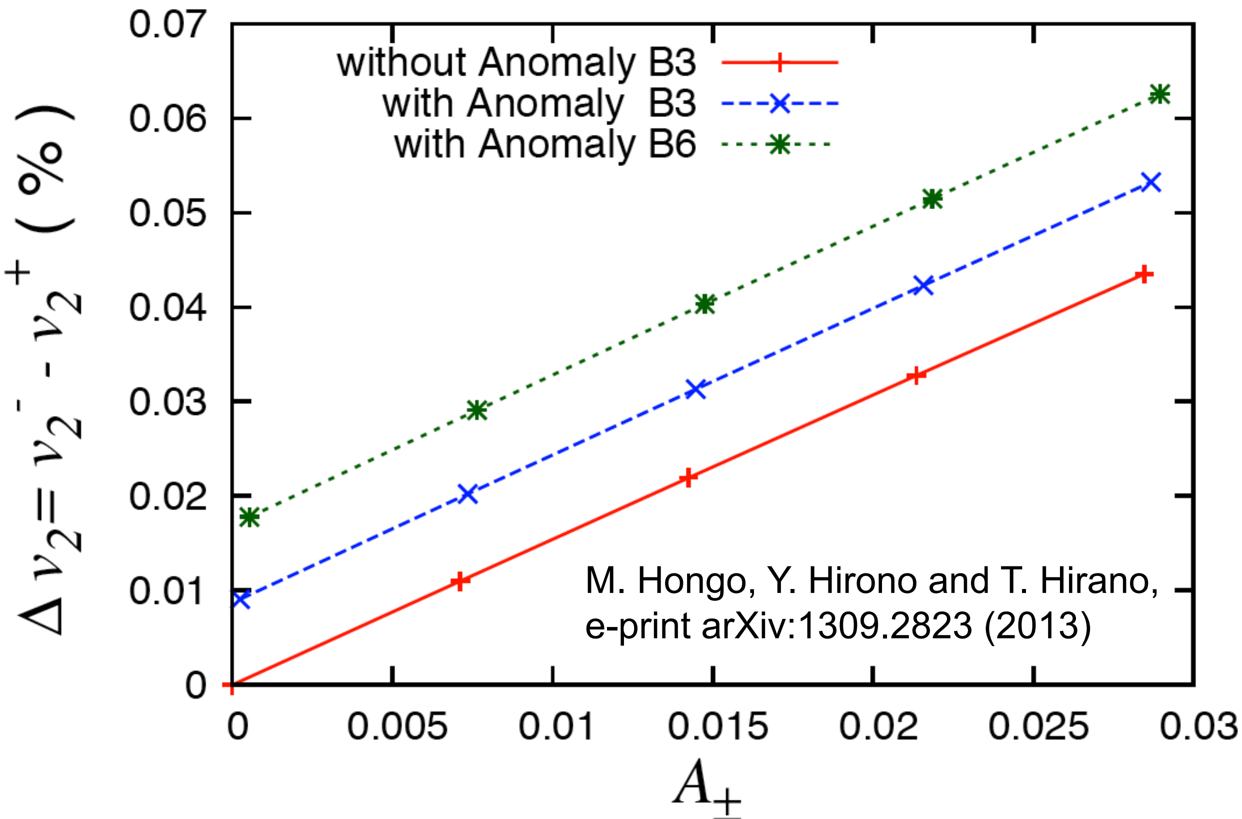
S. F. Taghavi and U-A Wiedemann, e-print arXiv:1310.0193 (2013)

CWM implemented as charge perturbation of top of an expanding Bjorken-type background.

Size smaller by one order of magnitude if compared top RHIC energy data.

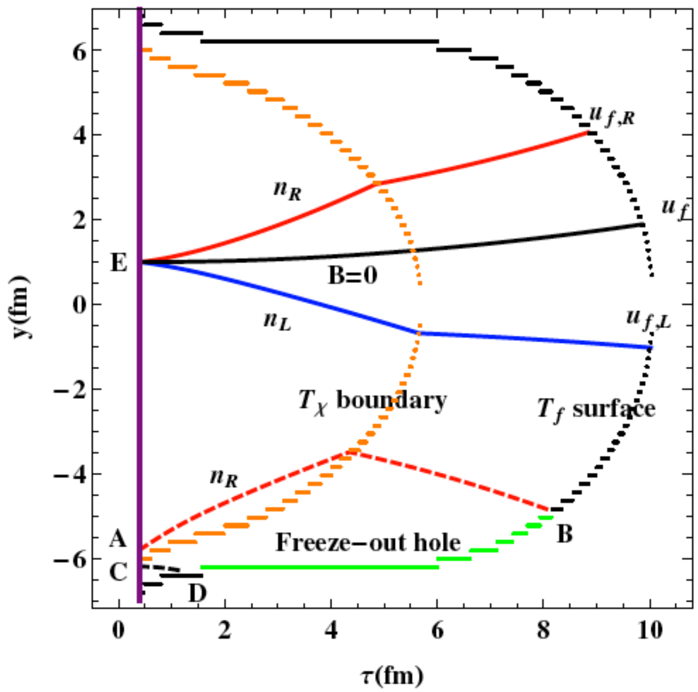
However, if sizable asymmetries in axial charge are present in the early fluid dynamic evolution, the CMW-induced effect can be much enhanced.

The Calculation from Anomalous Hydrodynamics



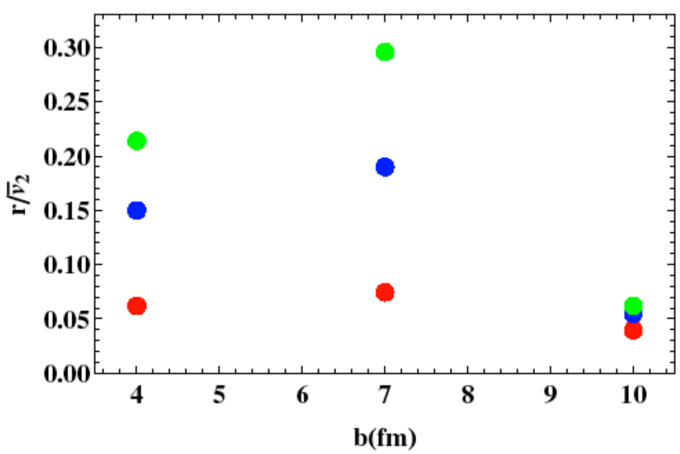
Hydro model with anomaly included.
In this model, the intercept, not the slope, is argued to be sensitive to CMW.
The slope persists even when the anomaly switched off.
Central region emit more positive particles, but contribute less v_2 if compared to outer region, resulting in smaller v2 for π^+

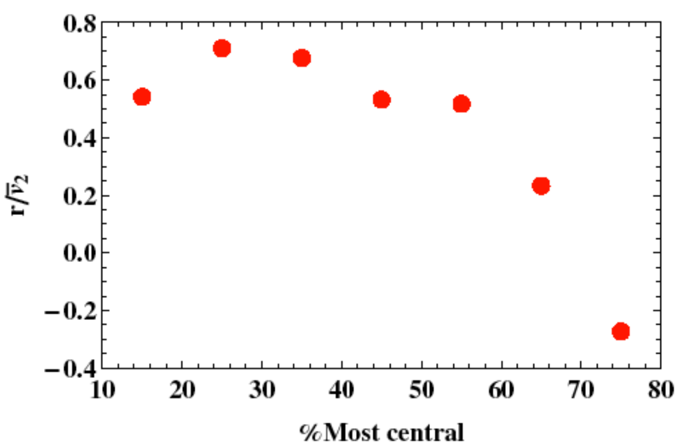
New development from CMW supporters



H-U Yee and Y. Yin
e-print arXiv:1311.2574 (2013)

Claim to be a more realistic calculation.
Freeze-out condition important, no sudden freeze-out.
Conclusion in contrast to anomalous Hydro implemented by Hongo, Hirono and Hirano. (previous slide).





Systematics

- Relative $\langle p_T \rangle$ difference between π^- and π^+ for p_T range [0.15-0.5 GeV/c]: on the order of 10^{-4}.
- Resonance decay
  - Uneven feed down from Lambda at a larger pt : tight dca cut
  - Nonflow : suppressed with same charge correlation.
- p_T selection range [0.15-0.5 GeV/c] : little difference in $v_2(p_T)$ for $p_T > 0.5$ GeV/c.
- PID : negligible for pions as at low p_T most particles are pions.
- Different weighting in A± calculation : negligible.
- … …