Charge Asymmetry Dependence of Pion Azimuthal Anisotropy in Au + Au Collisions at STAR

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CME & CSE

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

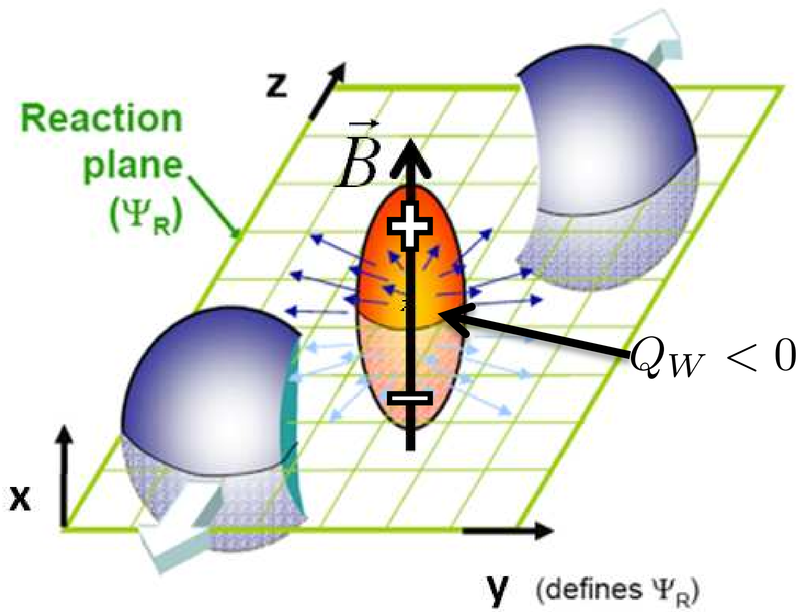
$$\boldsymbol{j}_V = \frac{N_c e}{2\pi^2}\mu_A \boldsymbol{B}$$ ➔ electric charge separation along B field

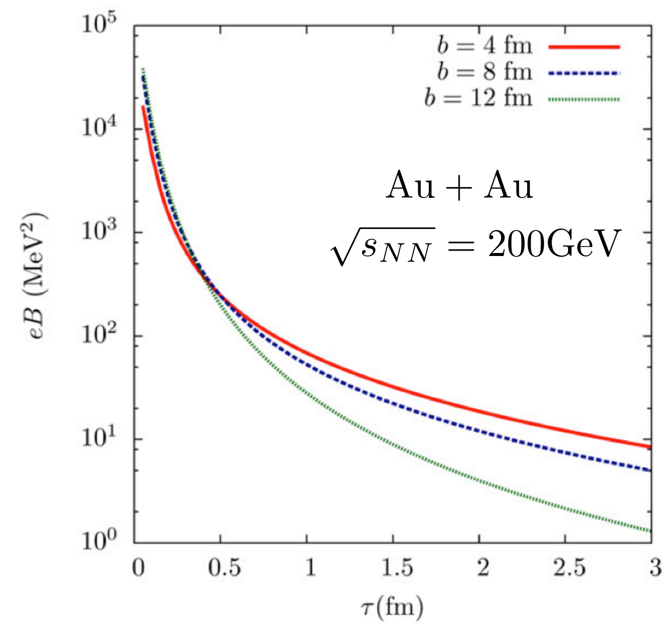
- Chiral Separation Effect (CSE): nonzero vector charge density induces an axial current along external magnetic field.

$$\boldsymbol{j}_A = \frac{N_c e}{2\pi^2}\mu_V \boldsymbol{B}$$ ➔ 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)

CME in Heavy Ion Collisions

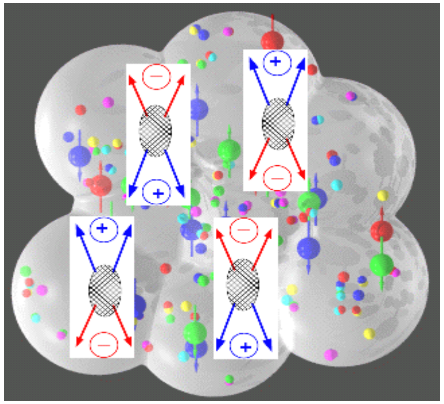


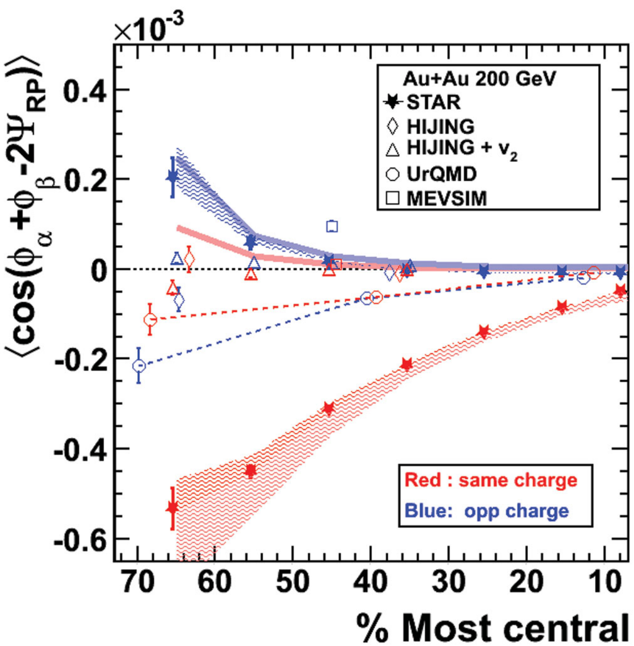


Nuclear Physics A **803**, 227 (2008).

- QCD vacuum transition in heavy ion collision → $Q_w \neq 0$
- Extremely strong magnetic field created in heavy ion collision
- 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





- Charge particle azimuthal angle distribution
  - $$\frac{dN_\alpha}{d\phi} \propto 1 + 2v_{1,\alpha}\cos(\Delta\phi) + 2v_{2,\alpha}\cos(2\Delta\phi) + \cdots + 2a_{1,\alpha}\sin(\Delta\phi) + 2a_{2,\alpha}\sin(2\Delta\phi) + \cdots$$
  - Correlations $\langle a_\alpha a_\beta \rangle$ can be measured
  - $\alpha, \beta = +, -$

- The three-particle correlations are directly sensitive to predicted local *P*-violation in heavy-ion collisions.

$$\langle \cos(\phi_\alpha + \phi_\beta - 2\Psi_{RP}) \rangle$$

- Out-of-plane charge separation
  same charge correlation < 0
  opposite charge correlation > 0

- The observed signal cannot be described by models (HIJING, HIJING + v_2, URQMD, MEVSIM)

S. A. Voloshin, Phys. Rev. C **70**, 057901 (2004)
STAR Phys. Rev. Lett. **103**, 251601 (2009), Phys. Rev. C **81**, 054908 (2010)

Chiral Magnetic Wave

Chiral Magnetic Effect

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

important at high beam energy: enough energy for "jumping" over barriers to create initial axial charge density

Chiral Separation Effect

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

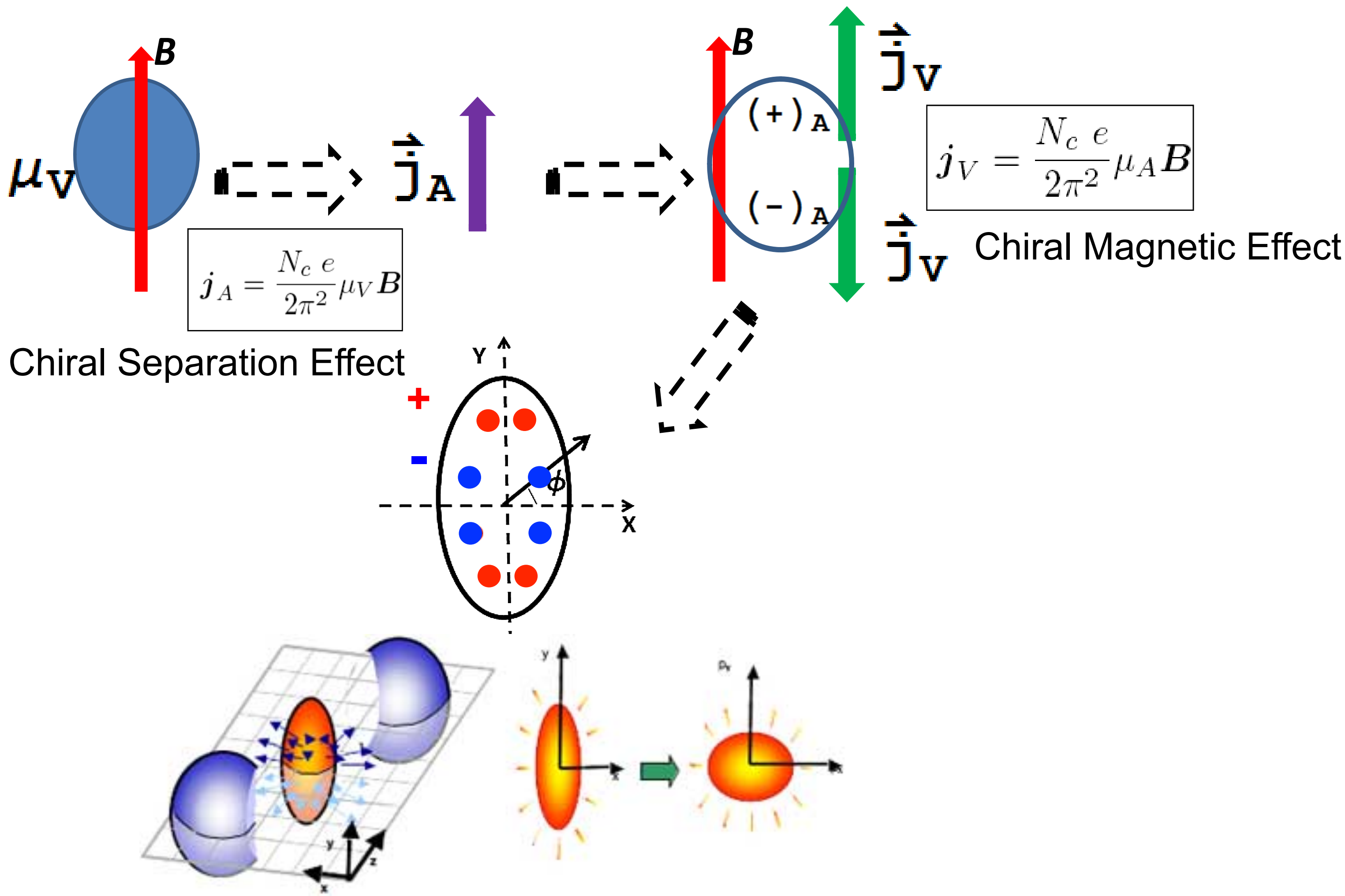
important at low beam energy: there is sizable initial vector charge density to set off chiral magnetic waves

Chiral Magnetic Wave: coupling two effects

$$\left(\partial_0 \mp \frac{N_c e B \alpha}{2\pi^2}\partial_1 - D_L \partial_1^2\right) j^0_{L,R} = 0$$

D. Kharzeev and H.-U. Yee, Physical Review D **83**, 085007 (2011)

Chiral Magnetic Wave



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

Observable for Chiral Magnetic Wave

$$\frac{dN_{\pm}}{d\phi} = N_{\pm}\left[1 + 2v_2\cos(2\phi)\right]$$

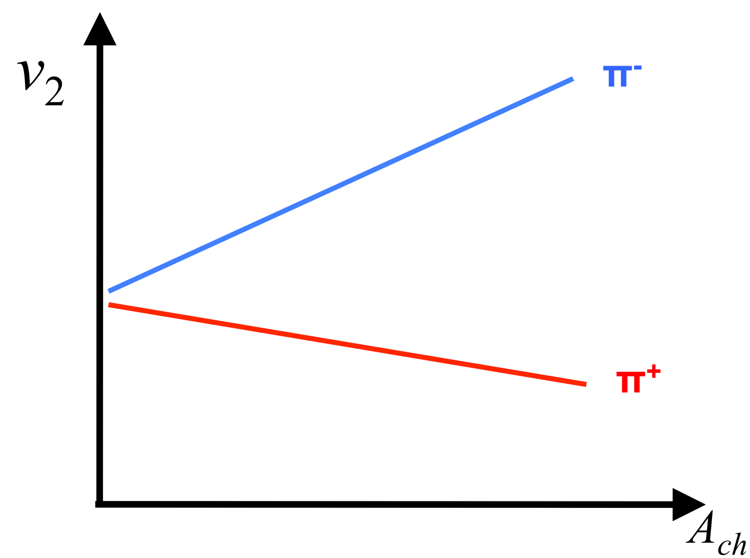
$$\approx \bar{N_{\pm}}\left[1 + 2v_2\cos(2\phi) \mp A_{ch} r \cos(2\phi)\right]$$

$$A_{ch} = \frac{N_+ - N_-}{N_+ + N_-}$$

$$r = 2\left(\frac{q_e}{\bar{\rho}_e}\right)$$

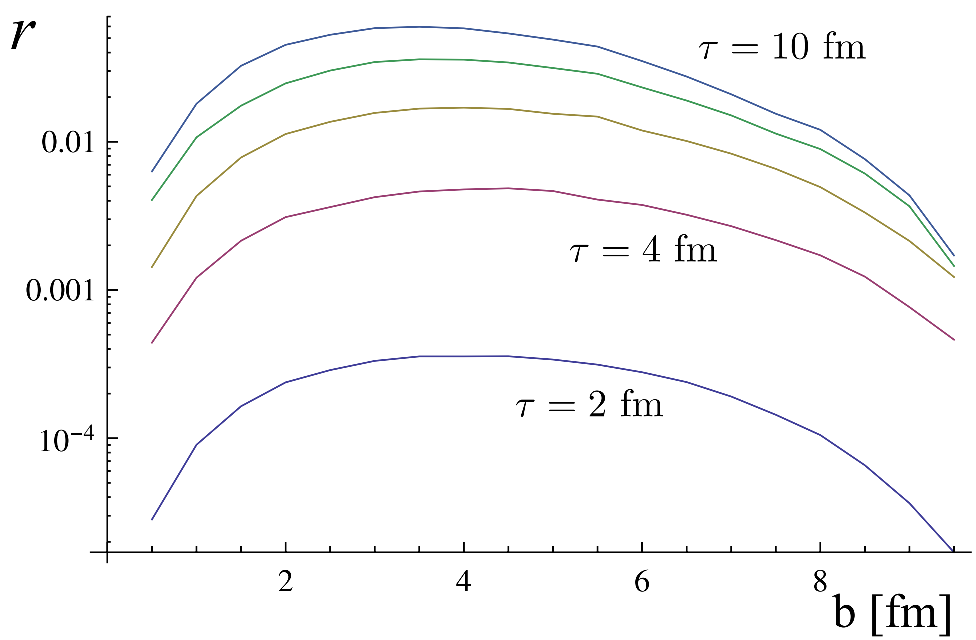
$$v_2^{\pm} = v_2 \mp \left(\frac{q_e}{\bar{\rho}_e}\right) A_{ch}$$

- $v_2(\pi^-) > v_2(\pi^+)$
- $v_2(\pi^-)$ and $v_2(\pi^+)$ have opposite trend as a function of A_{ch}
- difference between $v_2(\pi^-)$ and $v_2(\pi^+)$ has a linear relationship with A_{ch}



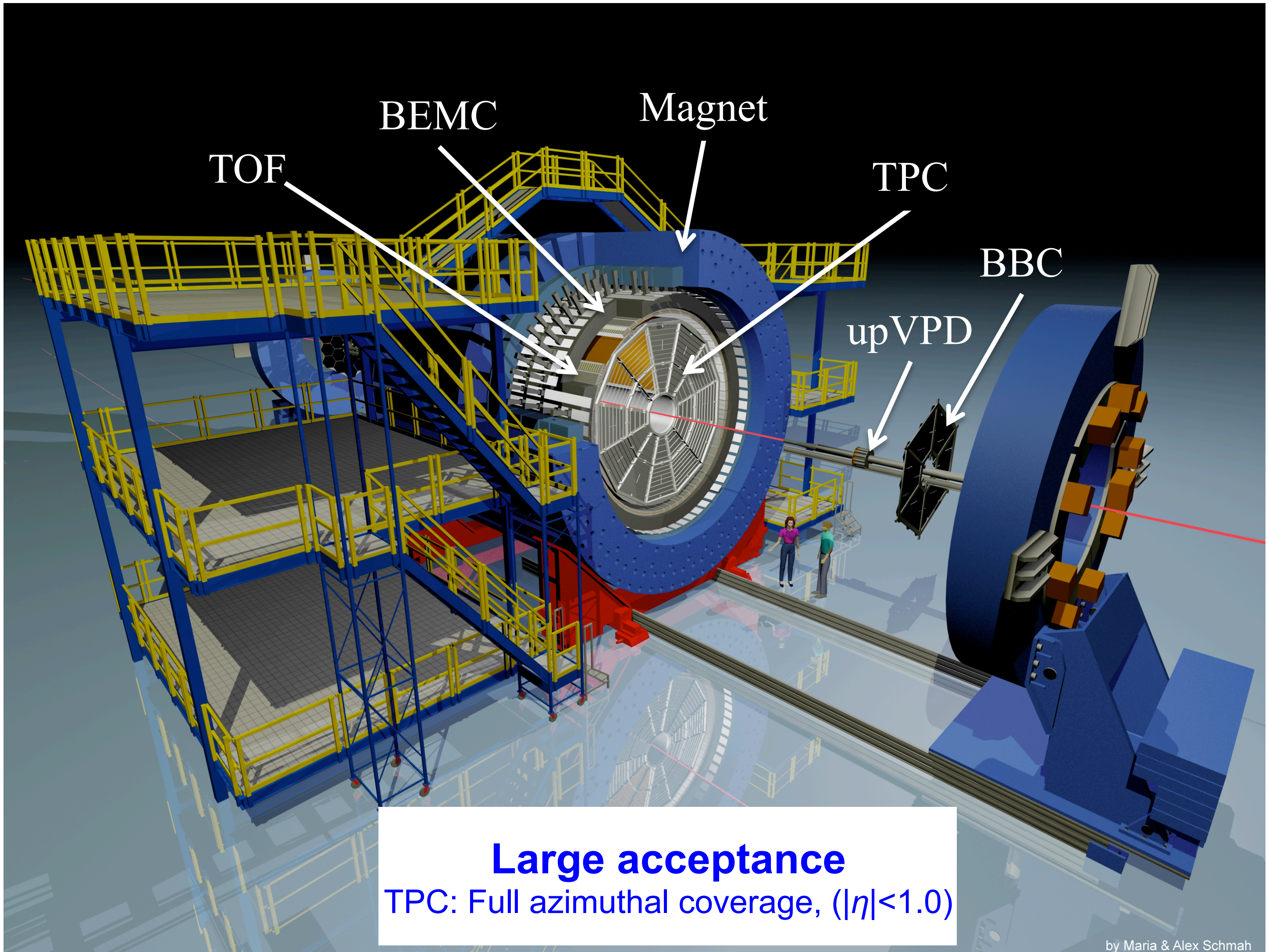
Observable for Chiral Magnetic Wave

$$v_2^- - v_2^+ = 2\left(\frac{q_e}{\bar{\rho}_e}\right) A_{ch} \qquad r = 2q_e/\bar{\rho}_e$$



Y. Burnier, D. E. Kharzeev, J. Liao and H-U Yee, Phys. Rev. Lett. **107**, 052303 (2011) and arXiv: 1208.2537

STAR Experiment

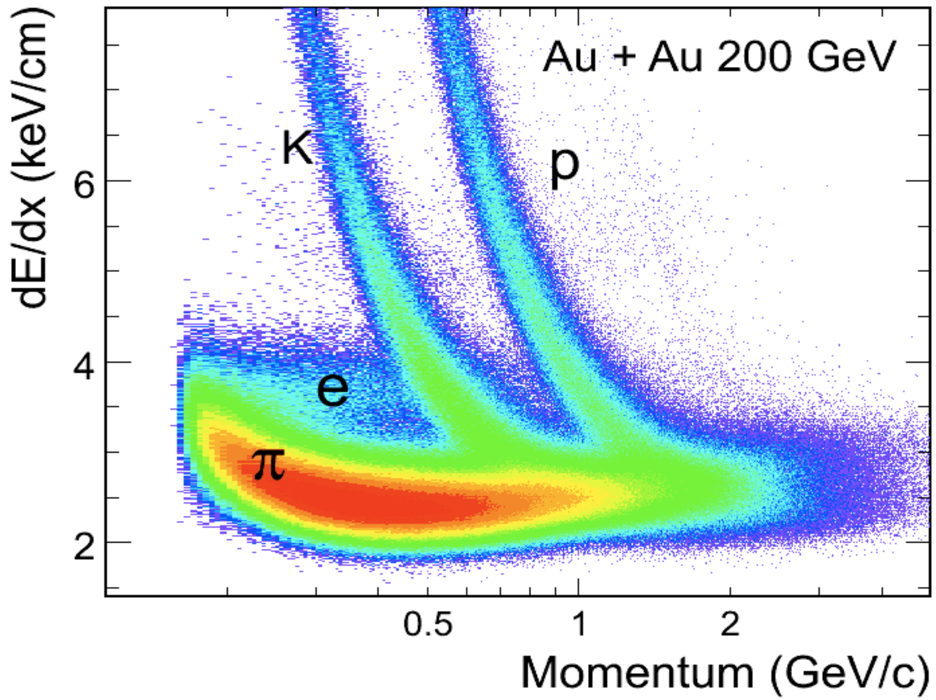


Large acceptance

TPC: Full azimuthal coverage, ($|\eta|$<1.0)

Particle identification at STAR

Ionization energy loss in the Time Projection Chamber



$$n\sigma_{\pi} = \frac{1}{R}\log\frac{dE/dx_{measured}}{\langle dE/dx\rangle_{\pi}}$$

d*E*/dx Particle Identification:
(π, K): $p \sim 0.6$ GeV/c; (π/K, p): $p \sim 1.0$ GeV/c

Analysis Details

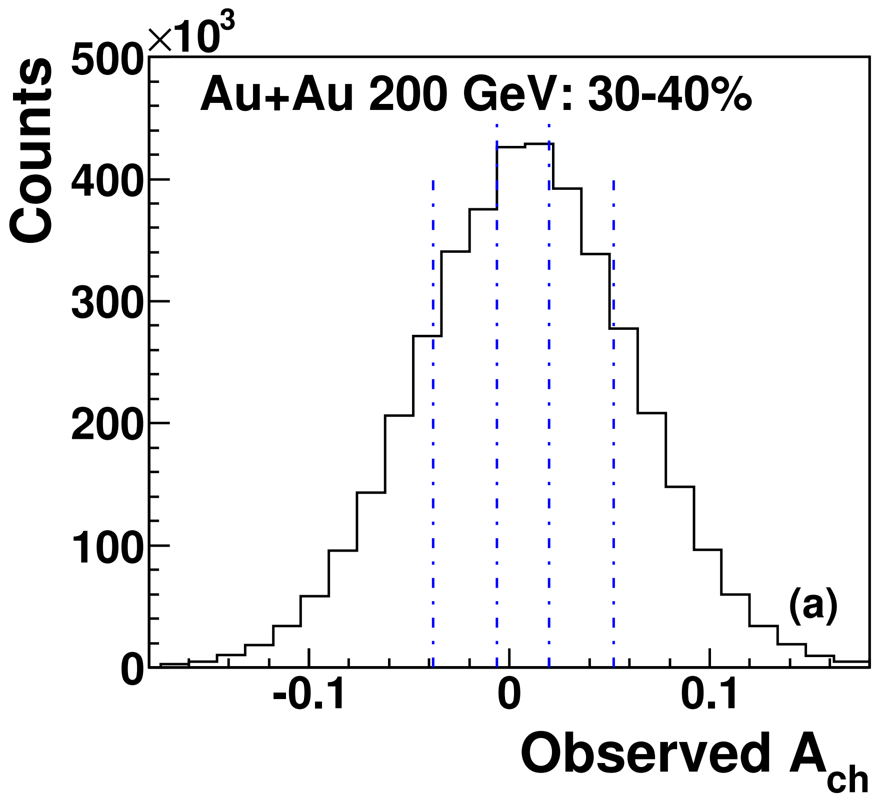
- Data Set
  - Au + Au
  - Minimum Bias trigger
  - 0 – 80% centrality

$\sqrt{s_{NN}}$ (GeV)	Events (M)
200	238
62.4	63
39	104
27	46
19.6	23
11.5	10
7.7	4

- Pion Selection
  - PID: $|n\sigma_\pi| < 2$
  - $0.15 < p_T < 0.5$ GeV/c
  - $|\eta| < 1.0$

- Particles for charge asymmetry
  - charged particle
  - $0.15 < p_T < 12$ GeV/c
  - $|\eta| < 1.0$
  - exclude (anti-)protons with $p_T < 0.4$ GeV/c

Observed Charge Asymmetry

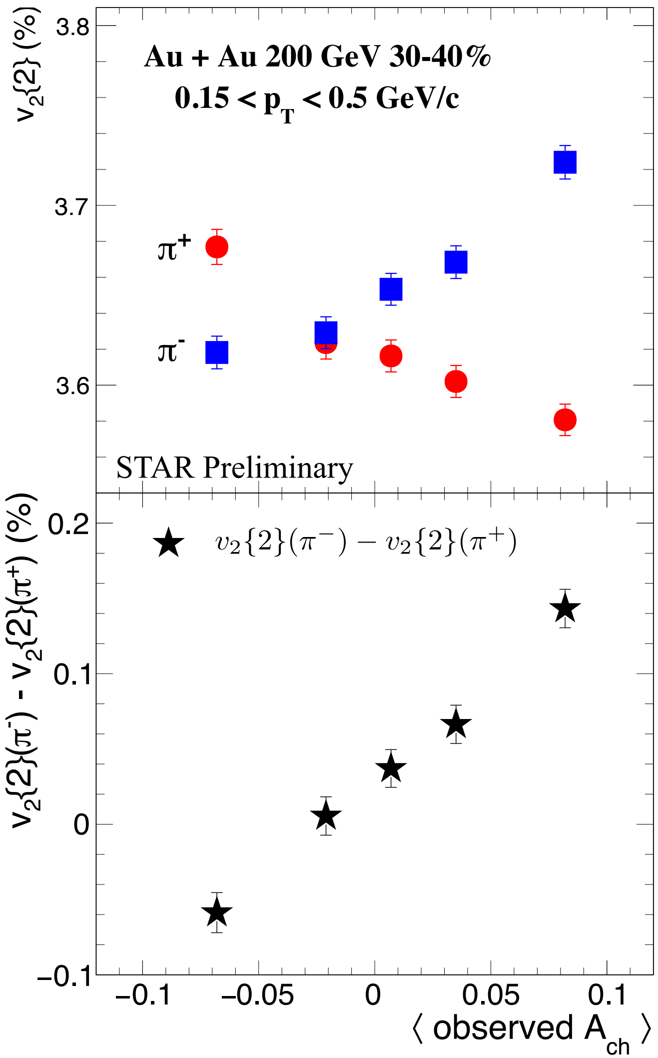


- N_+ and N_- : number of positive and negative particles
- observed A_{ch}

$$A_{ch} = \frac{N_+ - N_-}{N_+ + N_-}$$

- Each bin has roughly the same number of events

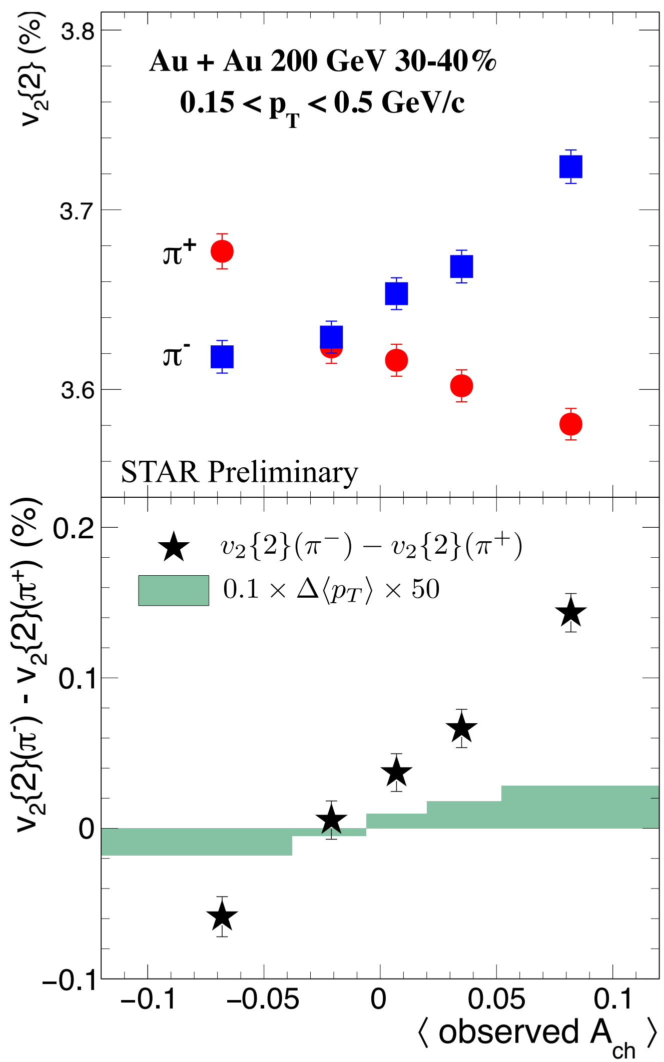
Integrated Elliptic Flow



- $v_2(\pi^+)/v_2(\pi^-)$ integrated over 0.15 $< p_T <$ 0.5 GeV/c
- $v_2(\pi^-) > v_2(\pi^+)$
- $v_2(\pi^-)$ and $v_2(\pi^+)$ have opposite trend as a function of A_{ch}
- difference between $v_2(\pi^-)$ and $v_2(\pi^+)$ has a linear relationship with A_{ch}

All of the above are consistent with calculation based on Chiral Magnetic Wave

Integrated Elliptic Flow



- $v_2(\pi^+)/v_2(\pi^-)$ integrated over $0.15 < p_T < 0.5$ GeV/c
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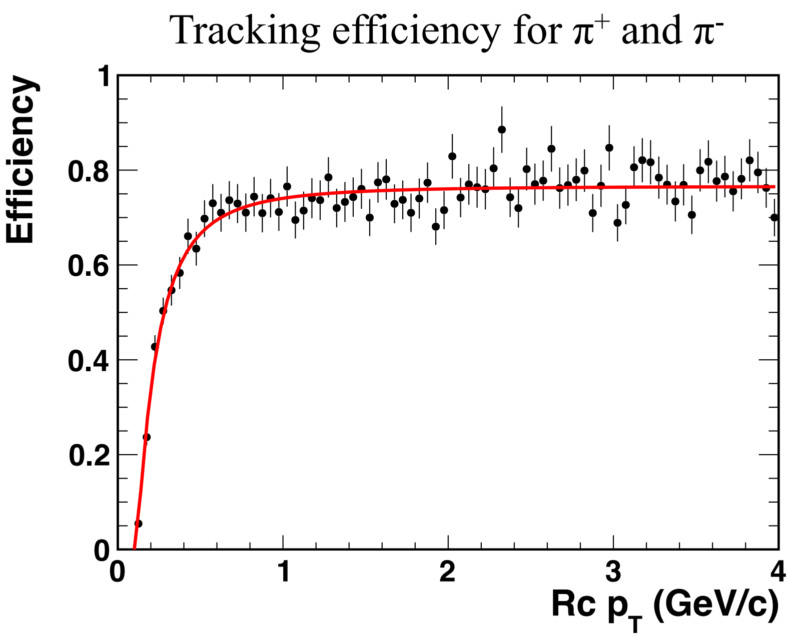
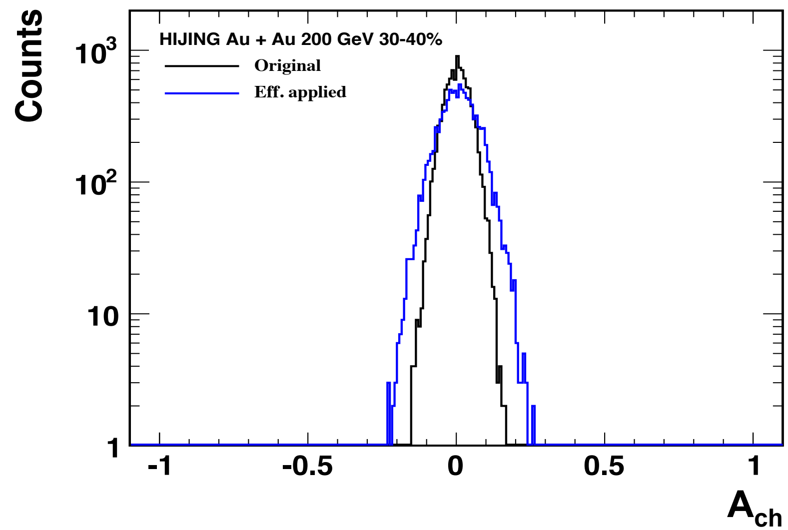
All of the above are consistent with calculation based on Chiral Magnetic Wave

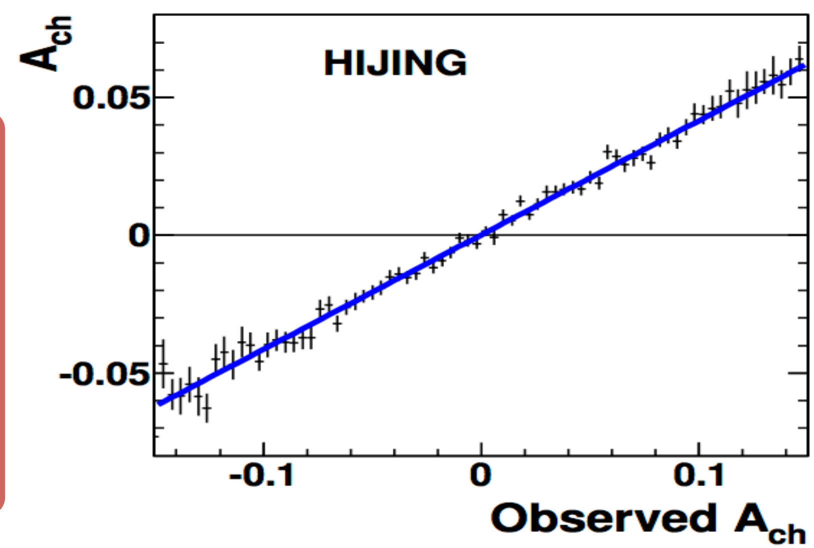
- $v_2 \approx 0.1 \times p_T$ with $p_T < 1$GeV/c
- Mean p_T difference between π^- and π^+ gives about 1% of the observed v_2 difference

Detector inefficiency Correction on A_{ch}

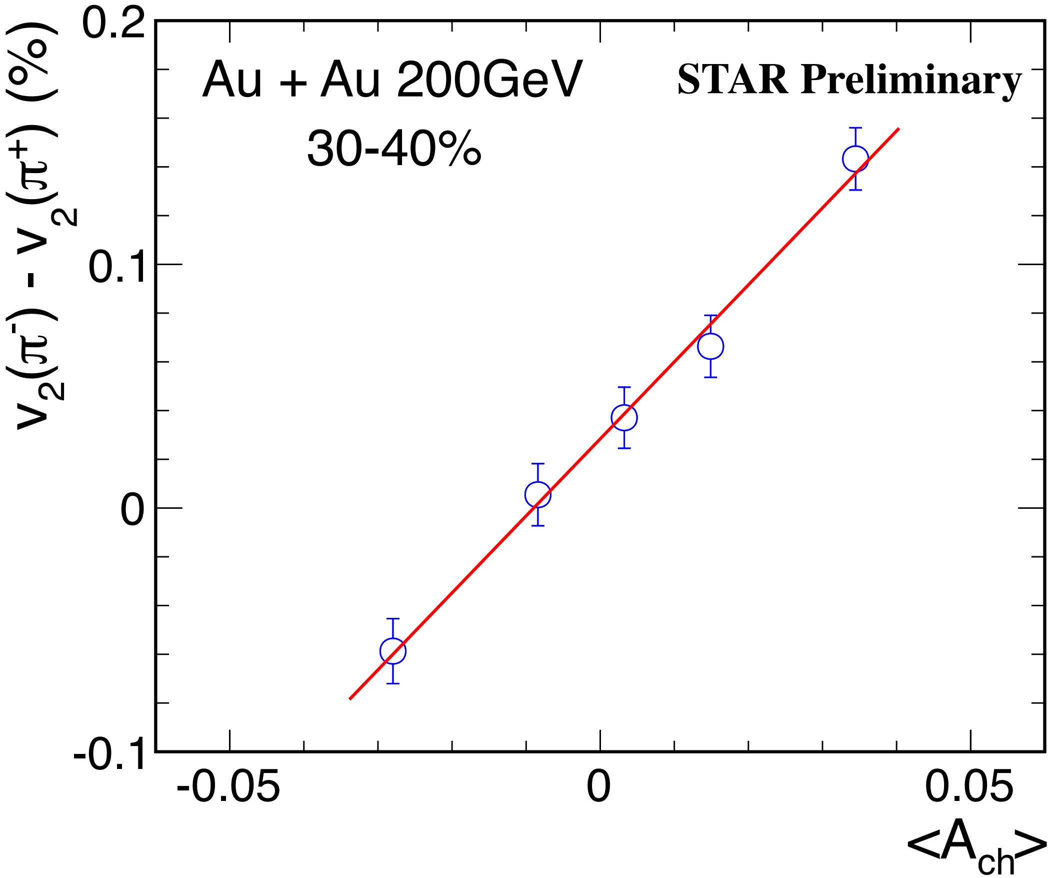




- use pion tracking efficiency as charged particle tracking efficiency
- apply same cuts to calculate A_{ch} for Monte-Carlo and real data



Fit the Slope Parameter

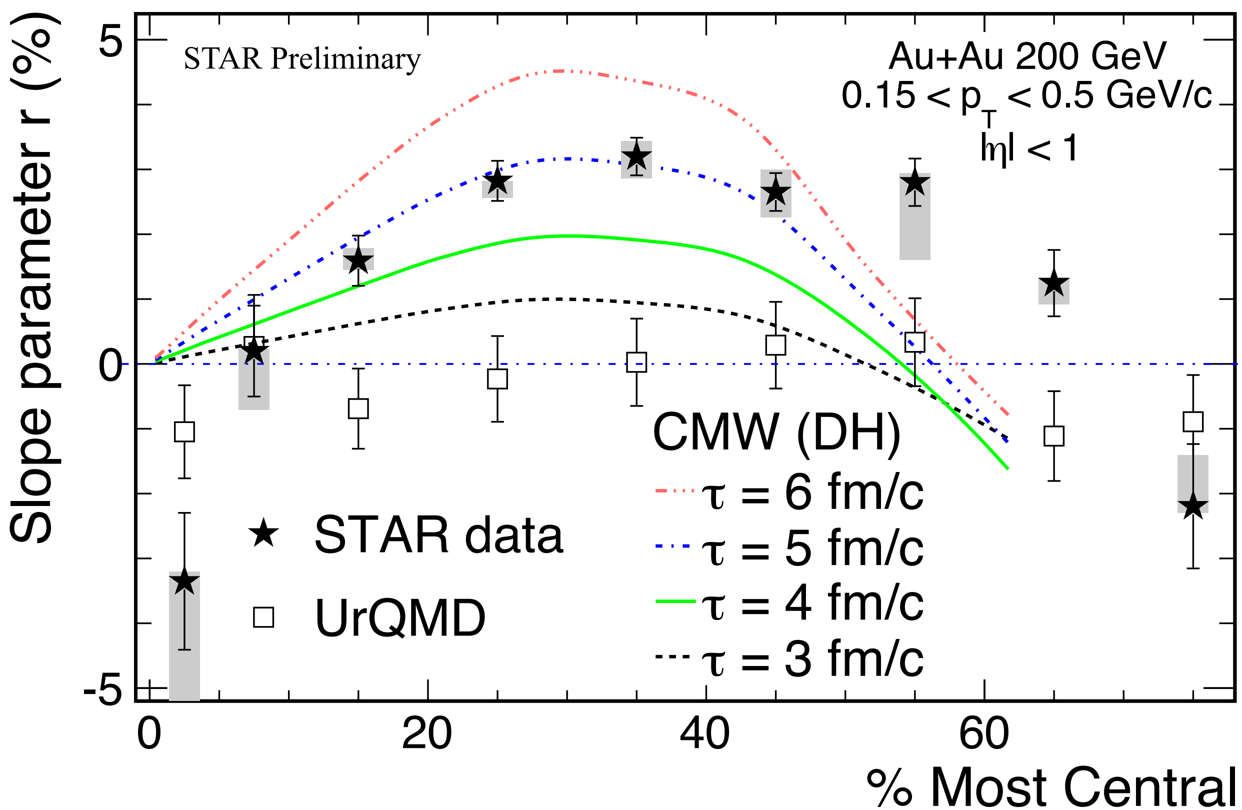


- Prediction based on CMW

$$v_2^- - v_2^+ = 2\left(\frac{q_e}{\bar{\rho}_e}\right) A_{ch} + C_0$$

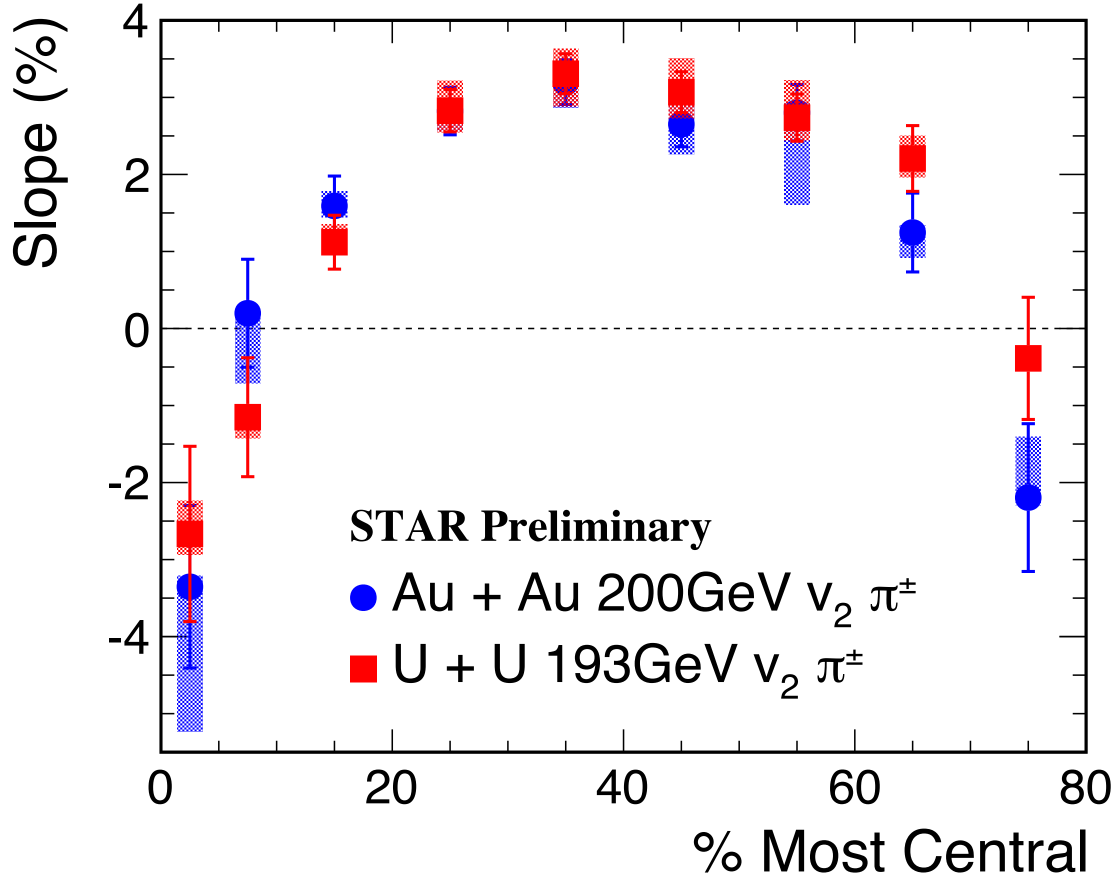
- Fit $v_2(\pi^-) - v_2(\pi^+)$ vs. $\langle A_{ch} \rangle$ to a straight line
- The slope parameter will be extracted for all centralities

Slope vs. Centrality



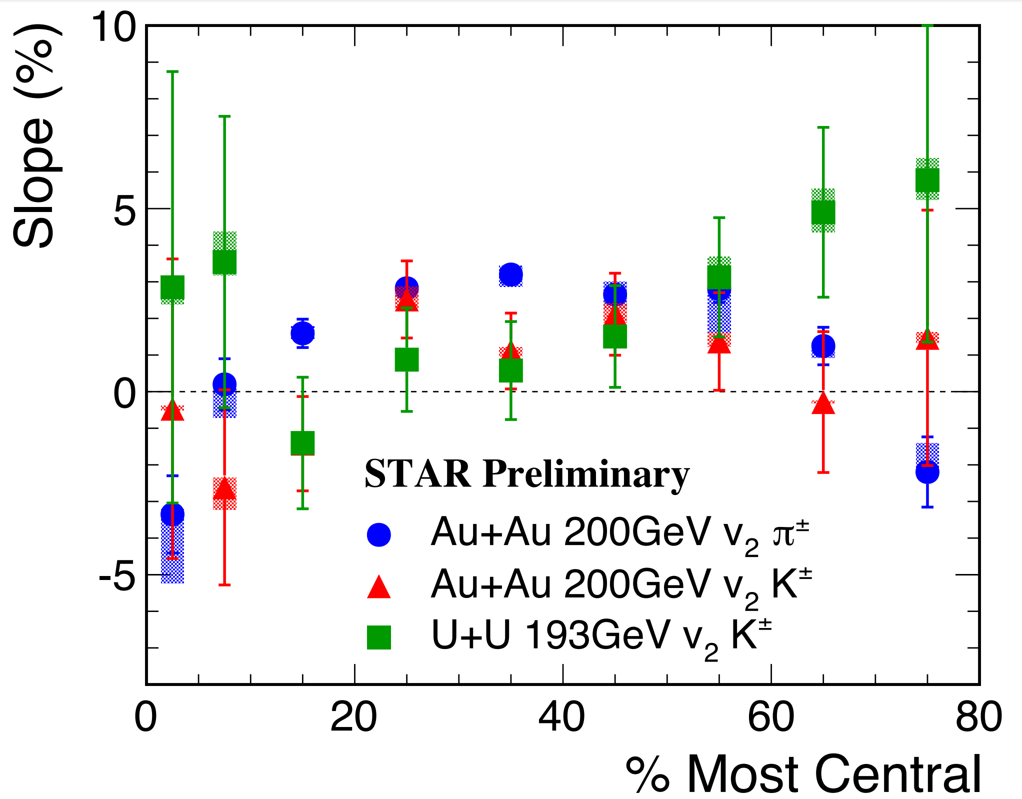
- Similar trends between data and theoretical calculations with CMW, which use different magnetic field calculations, i.e. DH and BS(not shown here), in arXiv: 1208.2537.
- There is no specific beam energy input for the theoretical calculation.
- UrQMD cannot reproduce the slopes at $\sqrt{s_{NN}}$ = 200 GeV.

Slope vs. Centrality in U+U Collisions



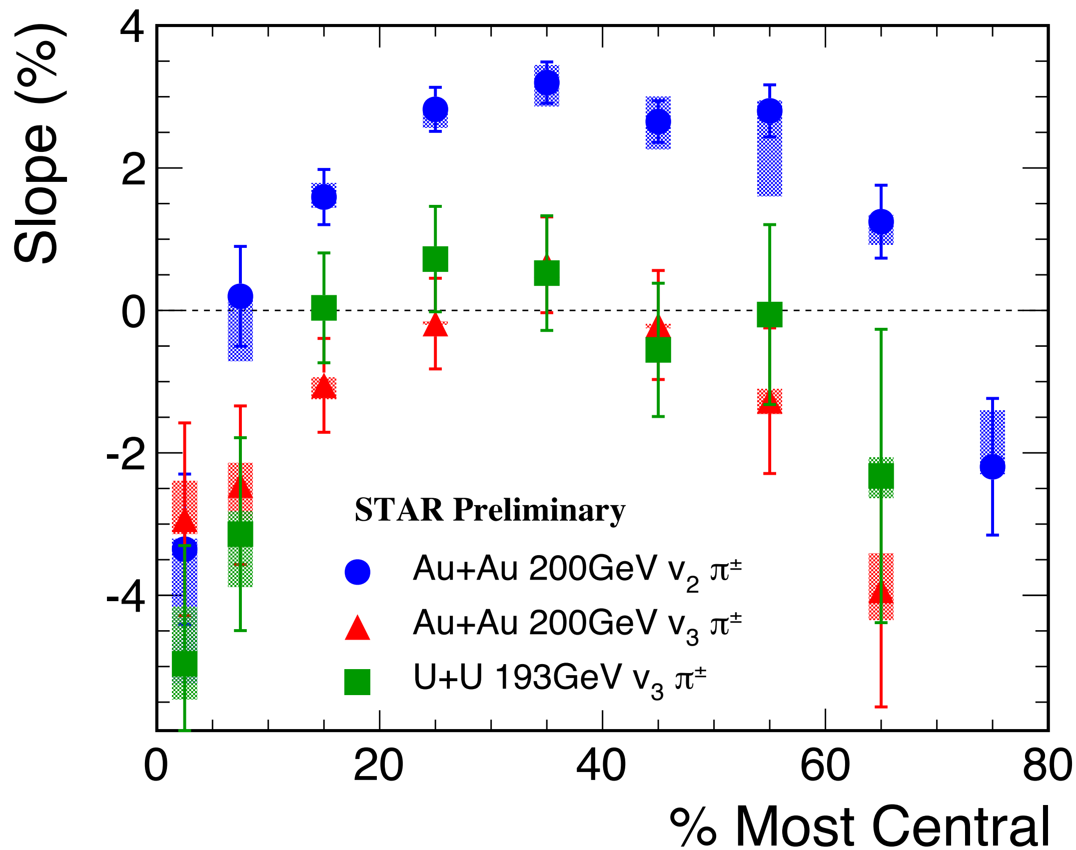
- A similar centrality dependence of the slope parameter has been seen in U + U collisions at $\sqrt{s_{NN}}$ = 193 GeV

Slope vs. Centrality for v_2 of $K^{\pm}$



- Theoretical calculations suggest the slope of $v_2(A_{ch})$ for K can be different from that of π
- The slopes for $v_2(A_{ch})$ for K have the same magnitude as that from π in the middle centralities with large error bars. More experimental data are needed to make the measurements of K conclusive.

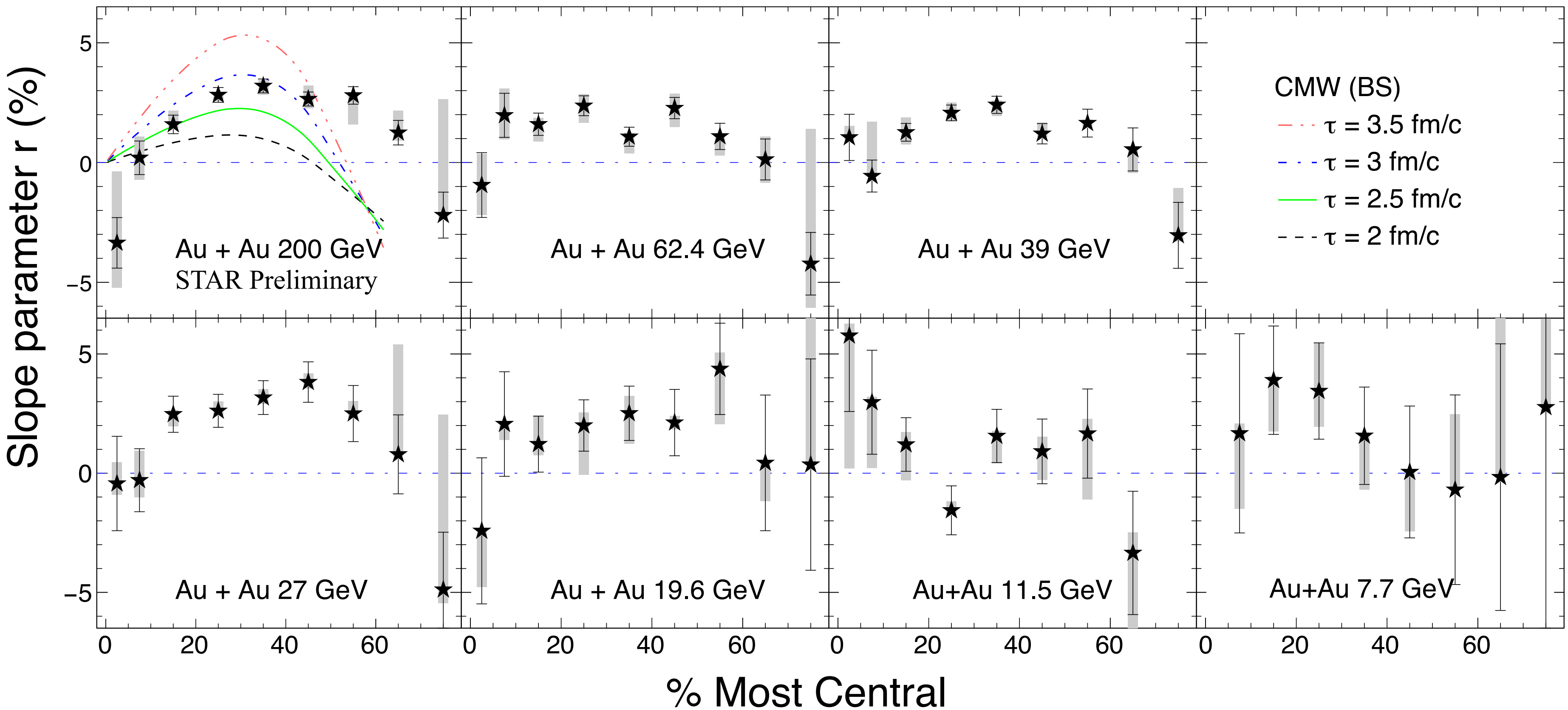
Slope vs. Centrality from v_3 of $\pi^{\pm}$



- The trend of $\Delta v_3(\pi)$ slope is similar to that of $\Delta v_2(\pi)$, which needs more study to understand
- The $\Delta v_3(\pi)$ slope is consistent with zero in mid-central collisions in contrast to finite values

A. Bzdak and P. Bozek, Physics Letters B **726** (2013) 239

Energy Dependence



- The slope parameter *r* shows a rise and fall feature from central to peripheral collisions
- Slope as a function of centrality shows weak energy dependence down to 27GeV
- Similar trend to the theoretical calculations with CMW

Y. Burnier *et al.*, arXiv:1208.2537 [hep-ph]

Summary

- The difference between $v_2(\pi^-)$ and $v_2(\pi^+)$ shows a linear dependence on charge asymmetry in Au + Au collisions at $\sqrt{s_{NN}}$ = 200, 62.4, 39 and 27 GeV and in U + U collisions at $\sqrt{s_{NN}}$ = 193 GeV. The UrQMD model calculations cannot reproduce this feature in Au + Au collisions at $\sqrt{s_{NN}}$ = 200 GeV.

- As a function of collision centrality, the slope parameter r for $\pi^\pm$ shows a rise and fall feature from central to peripheral collisions and the energy dependence seems weak from 200 to 27 GeV.

- The centrality dependence of the $\Delta v_2(\pi)$ slope shows a similar trend of the calculations based on Chiral Magnetic Wave at 200GeV. However, model calculations do not reproduce the centrality dependence exactly.

- The $v_3(\pi^\pm)$ as a function of A_{ch} has also been studied in Au + Au and U + U collisions. The centrality dependence of $\Delta v_3(\pi)$ slope is similar to that of $\Delta v_2(\pi)$ slope. However, the $\Delta v_3(\pi)$ slope is consistent with zero in mid-centrality collisions.

- At low energies, i.e. $\sqrt{s_{NN}}$ = 19.6, 11.5 and 7.7 GeV, the slopes are consistent with zero with large bar errors.