Net Charge Asymmetry Dependency of π^+/π^- Elliptic Flow in Au + Au Collisions at $\sqrt{s_{NN}} = 200$ GeV

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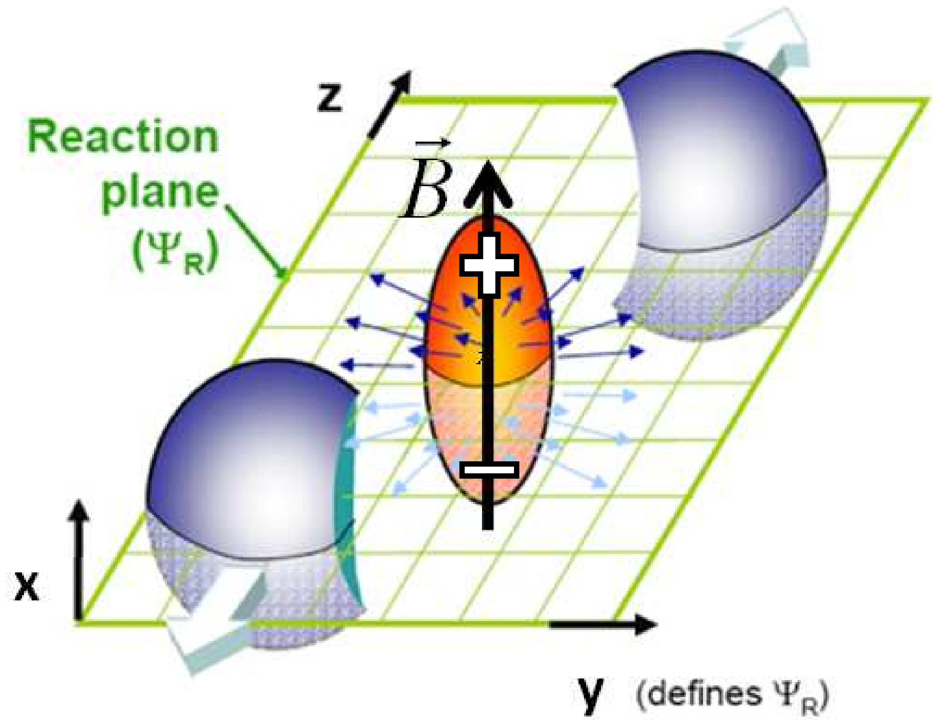
Outline

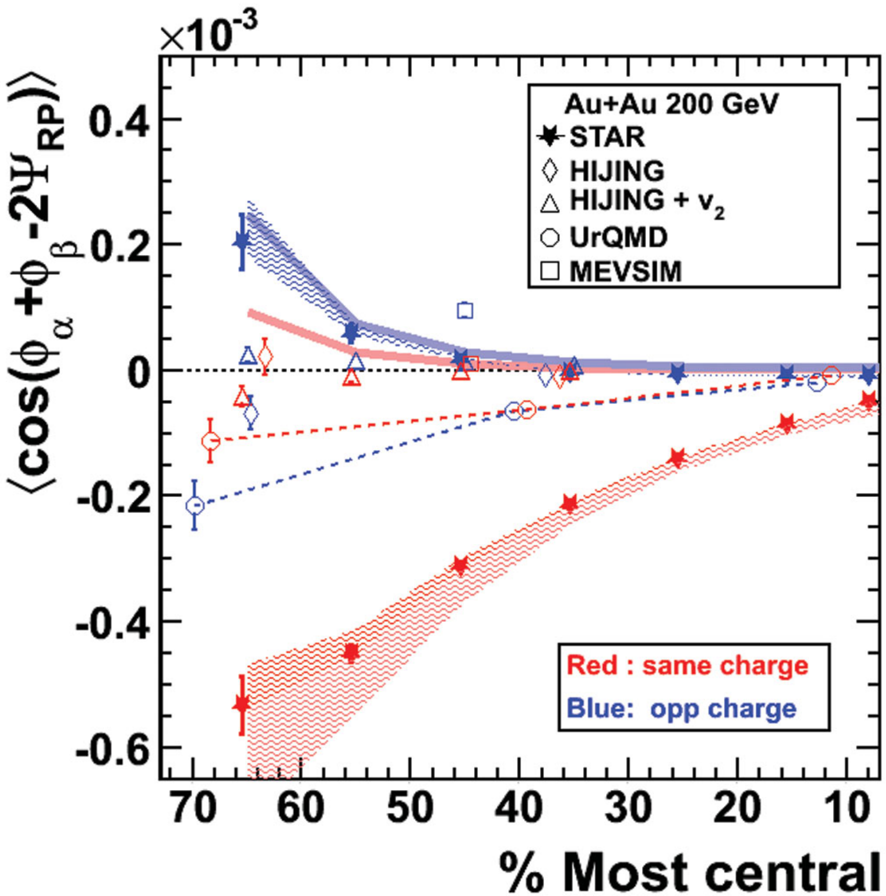
- Motivation
- STAR Experiment
- Results
  - Elliptic flow measurement, $v_2(\pi^+)$ and $v_2(\pi^-)$
  - Net charge asymmetry, $A_\pm$
  - Difference between $v_2(\pi^+)$ and $v_2(\pi^-)$ as a function of $A_\pm$
- Summary and outlook

Motivation



- Elliptic flow
  Coordinate-space anisotropy
  $$\varepsilon = \frac{\langle y^2 - x^2 \rangle}{\langle y^2 + x^2 \rangle}$$
  Momentum-space anisotropy
  $$v_2 = \langle \cos 2\varphi \rangle, \varphi = \tan^{-1}\left(\frac{p_y}{p_x}\right)$$
- Moving spectators consists electric current, which produces a magnetic field at the center of collision region.
- Peak magnetic field ~10^{15} *Tesla* !
  D.E. Kharzeev et al., Nucl. Phys. A **803** (2008) 227
- Vacuum fluctuates, chirality asymmetry
  $$N_L - N_R = 2n_f Q$$

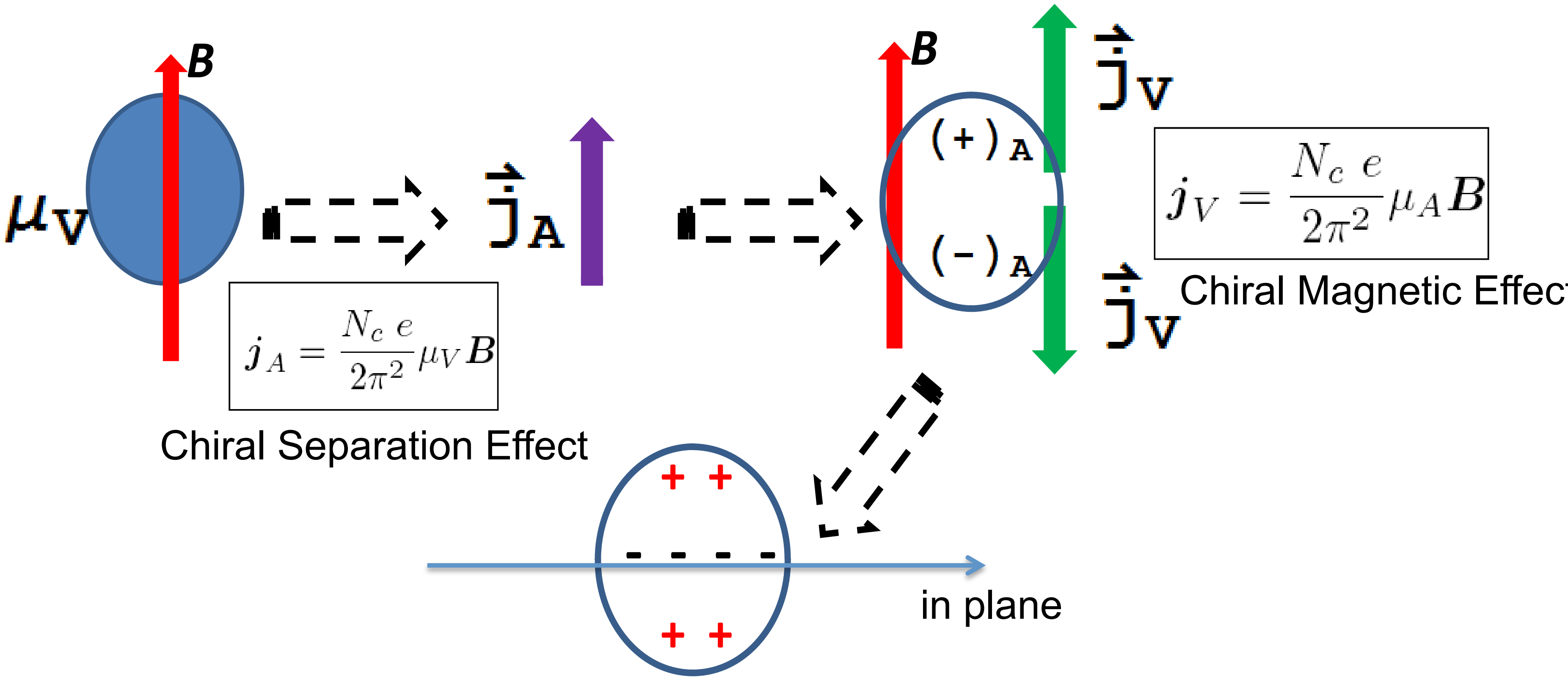
Motivation



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

- The three-particle correlations are directly sensitive to predicted local *P*-violation in heavy-ion collisions.
- Out-of-plane charge separation
  same charge < 0
  opposite charge > 0
- The observed signal cannot be described by models (HIJING, HIJING + v_2, URQMD, MEVSIM)

Motivation



The QGP acquires a

electric quadruple deformation

due to the Chiral Magnetic Wave at finite baryon density!

- Y. Burnier, D. E. Kharzeev, J. Liao and H-U Yee, Phys. Rev. Lett. **107**, 052303 (2011)
- Jinfeng Liao's talk at STAR analysis meeting, Mar. 2011.

Motivation

$$A_{\pm} = \frac{\bar{N}_{+} - \bar{N}_{-}}{\bar{N}_{+} + \bar{N}_{-}}$$

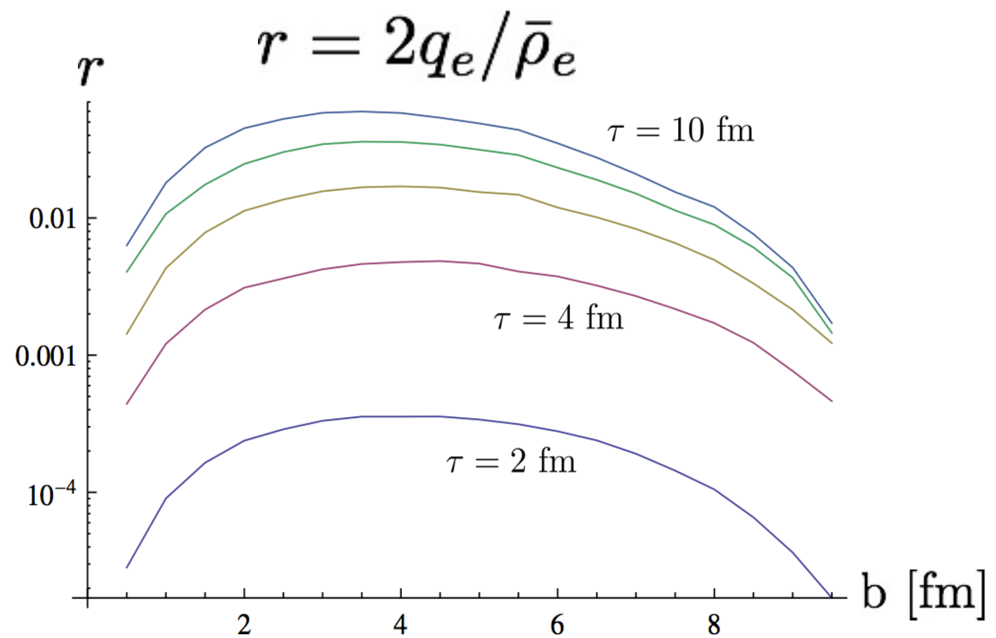
- $A_{\pm}$: net charge asymmetry
- $\bar{N}_{+}(\bar{N}_{-})$: number of positive (negative) particle

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

$$\approx \bar{N}_{\pm}[1 + 2v_2\cos(2\phi) \mp A_{\pm} r\cos(2\phi)].$$

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

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



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

Motivation

Quark transport

- Quark coalesce
- In mid-rapidity range, *u* and *d* quarks are transported from the entrance channel
- Transported quarks have stronger flow than produced quarks
- More transported *d* quarks than transported *u* quarks

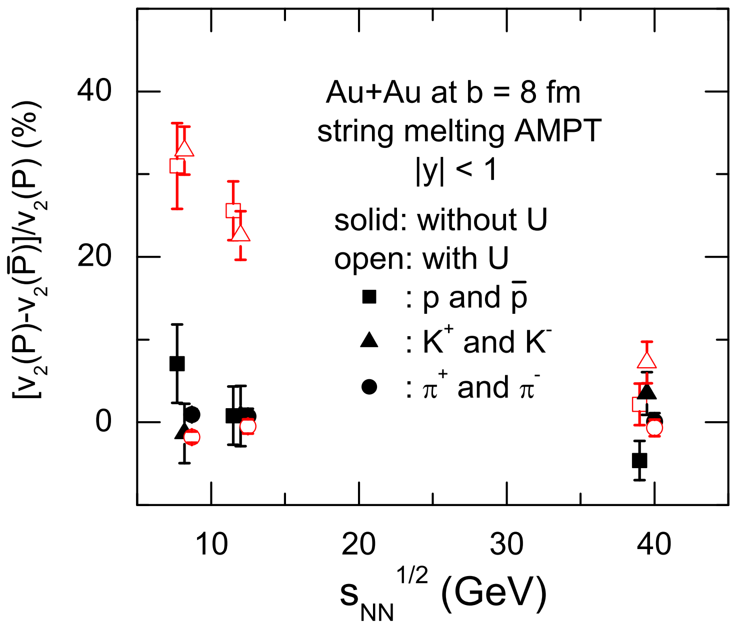
Conclusions:

- $v_2[\pi^- = d\bar{u}] > v_2[\pi^+ = u\bar{d}]$
  $v_2[K^+ = u\bar{s}] > v_2[K^- = \bar{u}s]$
  $v_2[p = uud] > v_2[\bar{p} = \bar{u}\bar{u}\bar{d}]$
  $v_2[\Lambda = uds] > v_2[\bar{\Lambda} = \bar{u}\bar{d}\bar{s}]$
- Net Charge Asymmetry dependency of v_2 difference needs further study

J. C. Dunlop, M. A. Lisa, and P. Sorensen, Phys. Rev. C **84,** 044914 (2011)

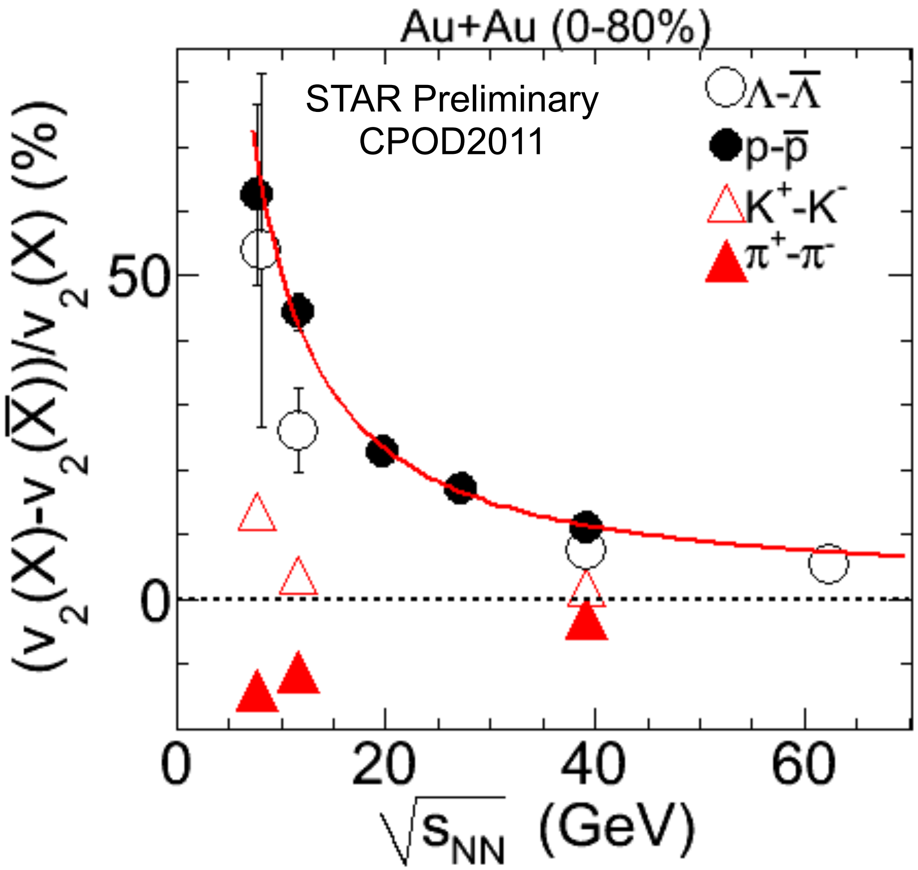
AMPT + Mean-field potentials

- Mean-field potentials lead different elliptic flow of particles and anti-particles
- Elliptic flow difference is smaller at higher energy



J. Xu, L-W Chen, C. M. Ko, and Z-W Lin, Phys. Rev. C **85**, 041901 (2012)

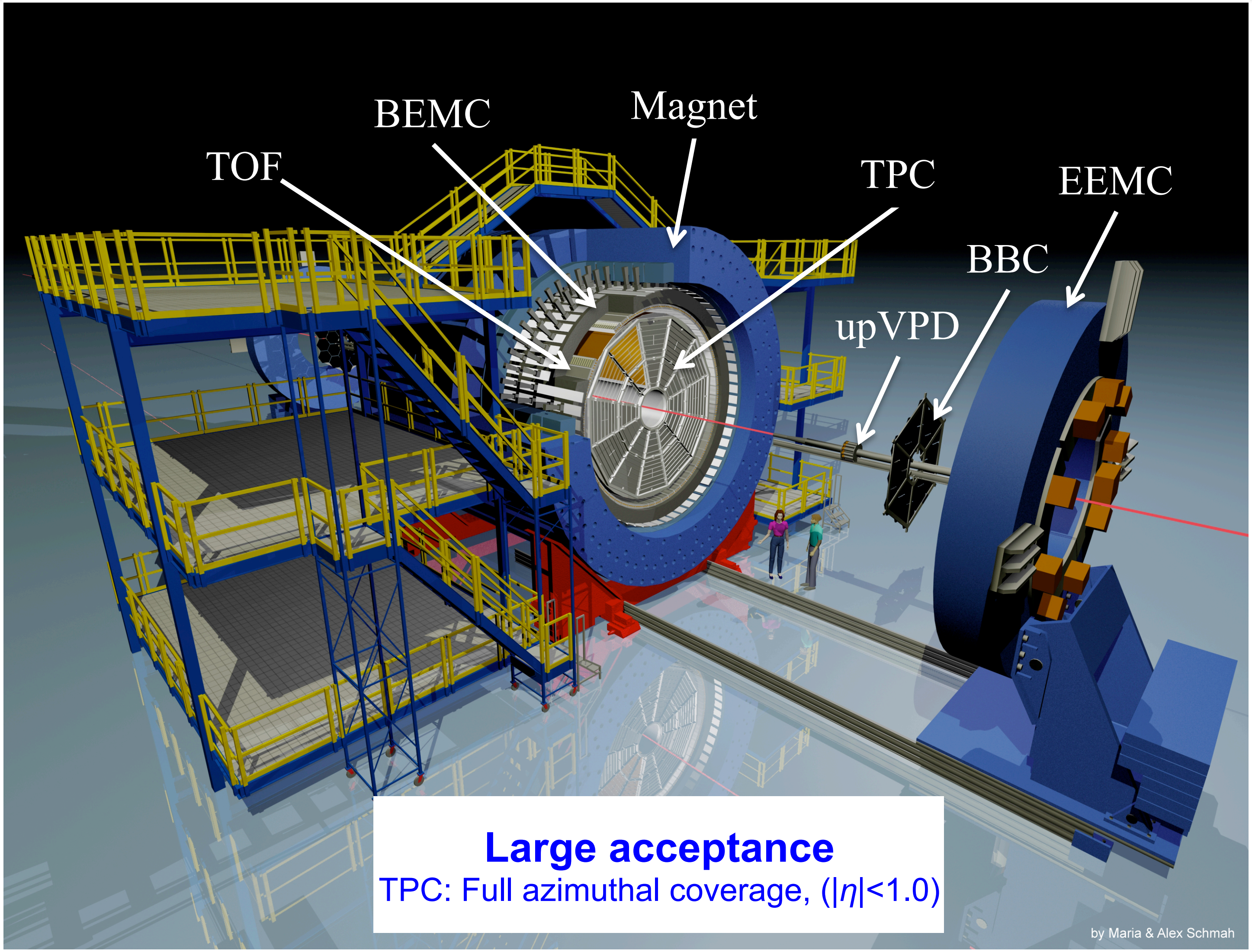
Motivation



- Different elliptic flow of particle and anti-particle is observed
- $v_2(\Lambda) > v_2(\bar{\Lambda})$
  $v_2(p) > v_2(\bar{p})$
  $v_2(K^+) > v_2(K^-)$
  $v_2(\pi^+) < v_2(\pi^-)$

The sign of the difference in integrated v_2 agrees with predictions.
What about the net charge asymmetry ($A_{\pm}$) dependency?

STAR Experiment

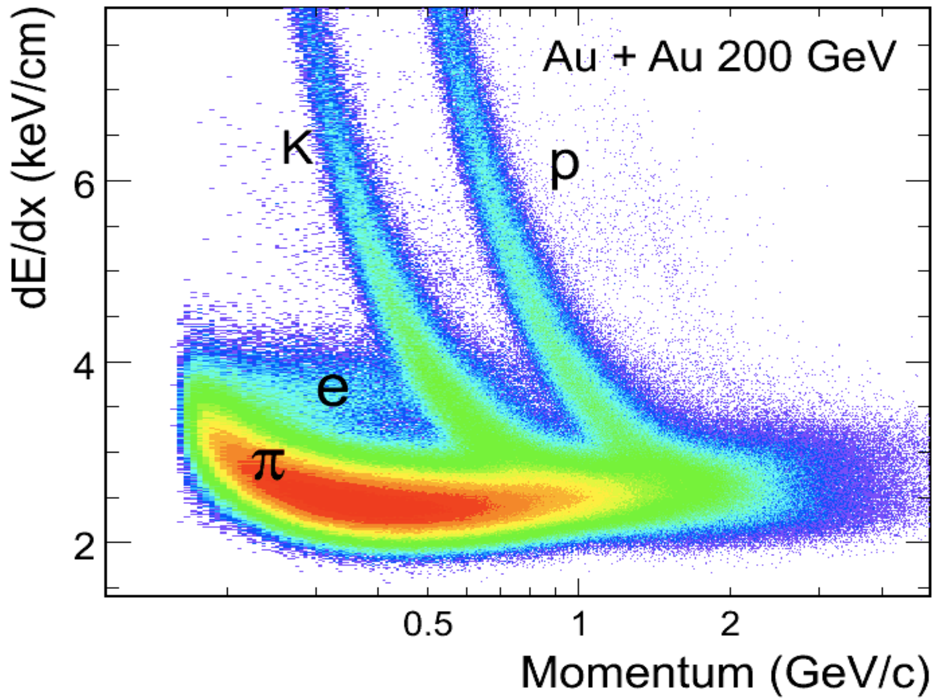


Large acceptance

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

Particle identification at STAR

STAR Time Projection Chamber Ionization energy loss



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

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 200 GeV, MiniBias, 0 – 80%, ~238M events
- Pion Selection
  - PID: $|n\sigma_\pi| < 2$
  - $0.15 < p_T < 0.5$ GeV/c
  - $|\eta| < 1.0$
- Particles for net charge asymmetry
  - charged particle
  - $0.15 < p_T < 12$ GeV/c
  - $|\eta| < 1.0$
  - exclude (anti)protons with $p_T < 0.4$ GeV/c

Q-Cumulants Method

1. Flow vectors:

Reference Particle (RP): $Q_n \equiv \sum_{i=1}^{M} e^{in\phi_i}$

Particle of Interest (POI): $p_n \equiv \sum_{i=1}^{m_p} e^{in\psi_i}$

RF & POI: $q_n \equiv \sum_{i=1}^{m_q} e^{in\psi_i}$

2. Two-particle Correlations:

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

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

3. Cumulants:

$$c_n\{2\} = \langle\langle 2 \rangle\rangle$$

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

4. Flow estimation:

Reference flow: $v_n\{2\} = \sqrt{c_n\{2\}}$

Differential flow: $v_n'\{2\} = \frac{d_n\{2\}}{\sqrt{c_n\{2\}}}$

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)

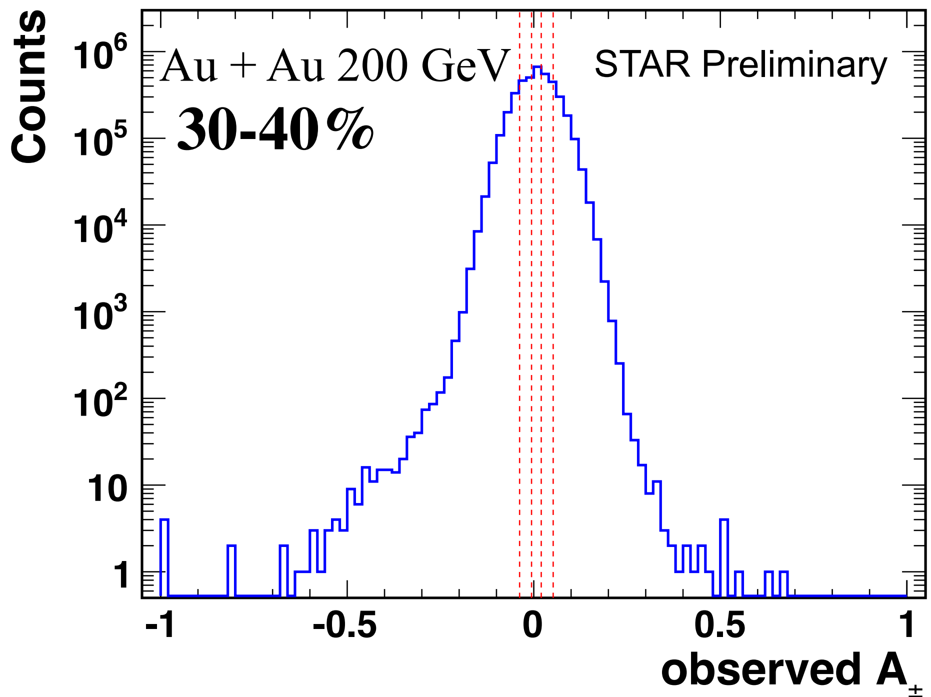
Q-Cumulants Method

	RP	POI
Sub-event *a* (Q^{a}, p^{a})	Basic track cuts $0.15 < p_{T} < 2.0$ GeV/c, $-1 < \eta < -0.3$	π^{+}/π^{-} $0 < \eta < 1$
Sub-event *b* (Q^{b}, p^{b})	Basic track cuts $0.15 < p_{T} < 2.0$ GeV/c, $0.3 < \eta < 1$	π^{+}/π^{-} $-1 < \eta < 0$

$$\langle 2 \rangle = \frac{Q_n^a \cdot Q_n^{b\,*}}{M_a M_b} \qquad \langle 2' \rangle = \frac{p_n^a \cdot Q_n^{b\,*}}{m_p^a M_b}$$

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

Observed Net Charge Asymmetry

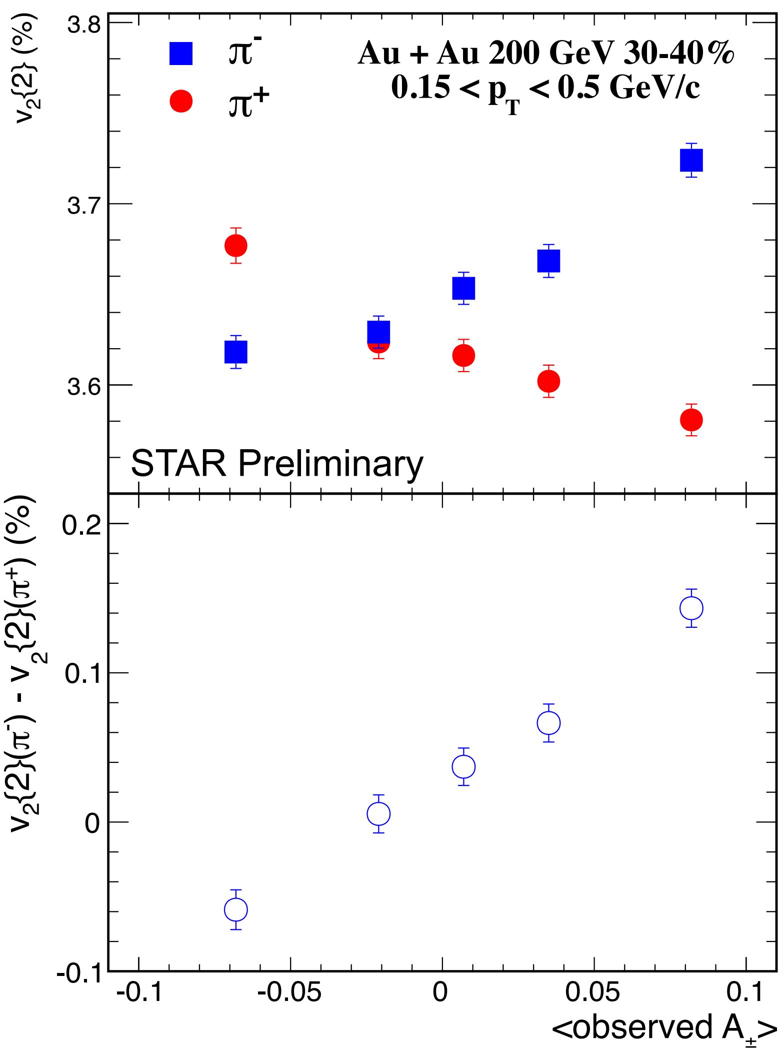


- $\bar{N}_+$ and $\bar{N}_-$: number of positive and negative particles
- observed $A_{\pm}$

$$A_{\pm} = \frac{\bar{N}_+ - \bar{N}_-}{\bar{N}_+ + \bar{N}_-}$$

- Each bin has roughly the same number of events

Integrated Elliptic Flow

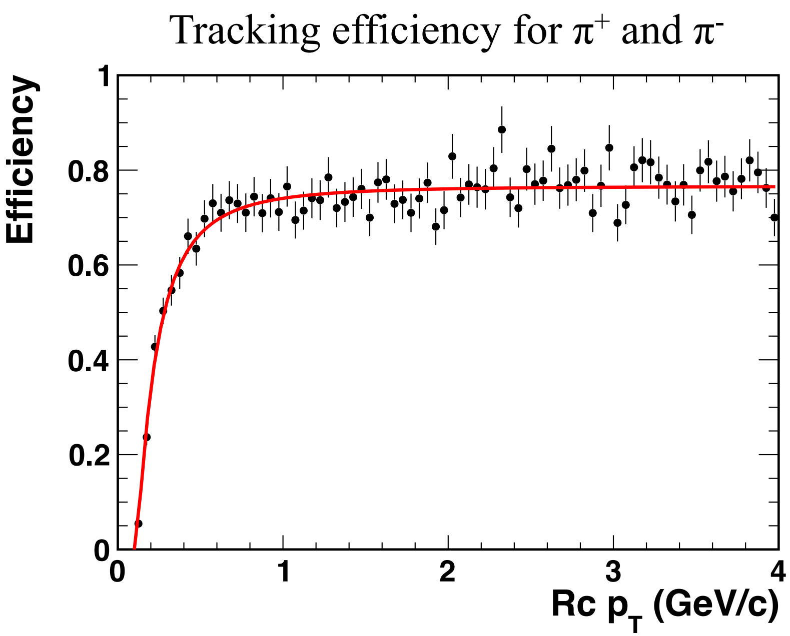


- π^+/π^- v_2 integrated over $0.15 < p_T < 0.5$ GeV/c
- bin mean
  <observed $A_\pm$>

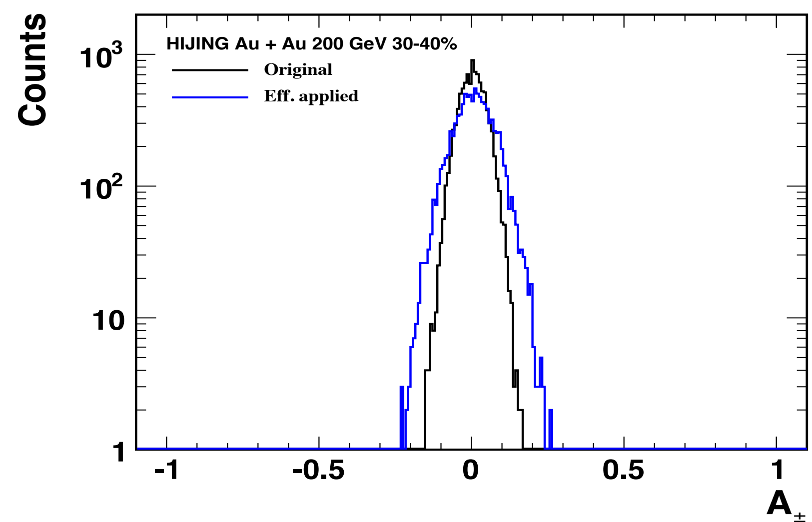
- $v_2(\pi^-) > v_2(\pi^+)$
- $v_2(\pi^-)$ and $v_2(\pi^+)$ have opposite trend as a function of $A_\pm$
- difference between $v_2(\pi^-)$ and $v_2(\pi^+)$ has a linear relationship with $A_\pm$

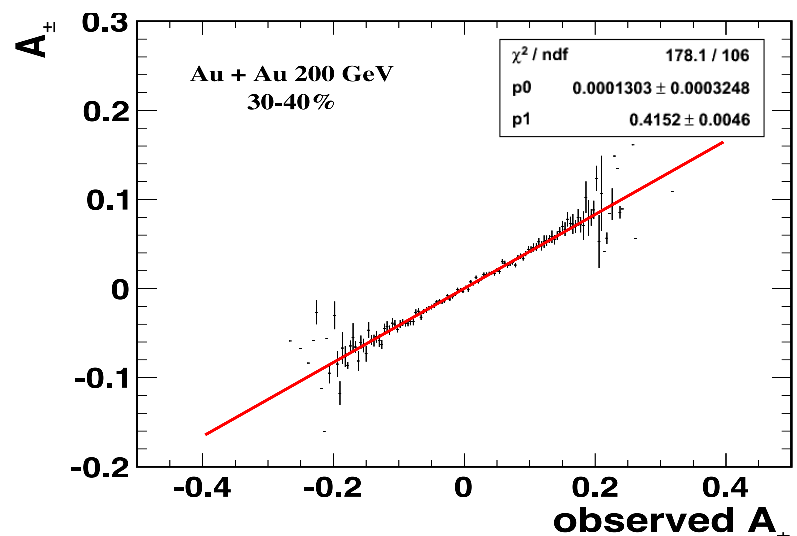
All of the furthers above are consistent with predictions made in Phys. Rev. Lett. **107**, 052303 (2011)

Detector inefficiency Correction on $A_\pm$

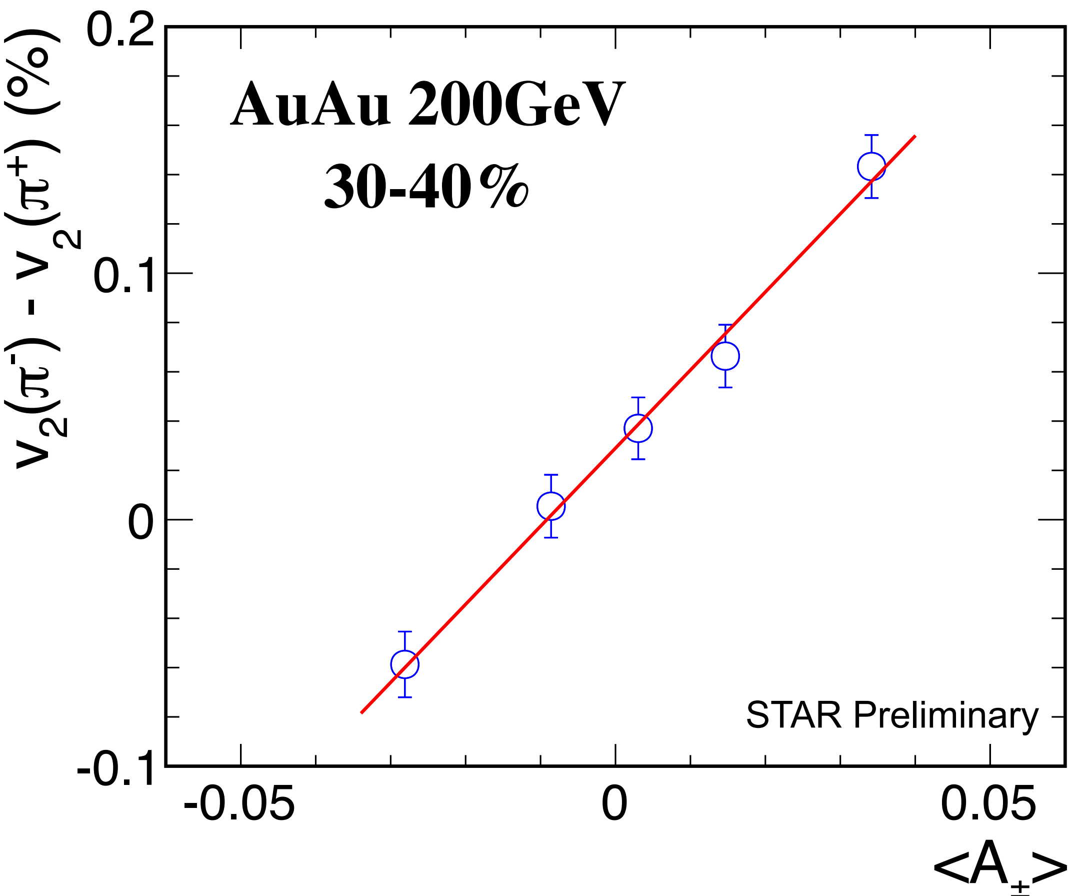


- use pion tracking efficiency as charged particle tracking efficiency
- apply same cuts to calculate $A_\pm$ for Monte-Carlo and real data





Fit the Slope Parameter



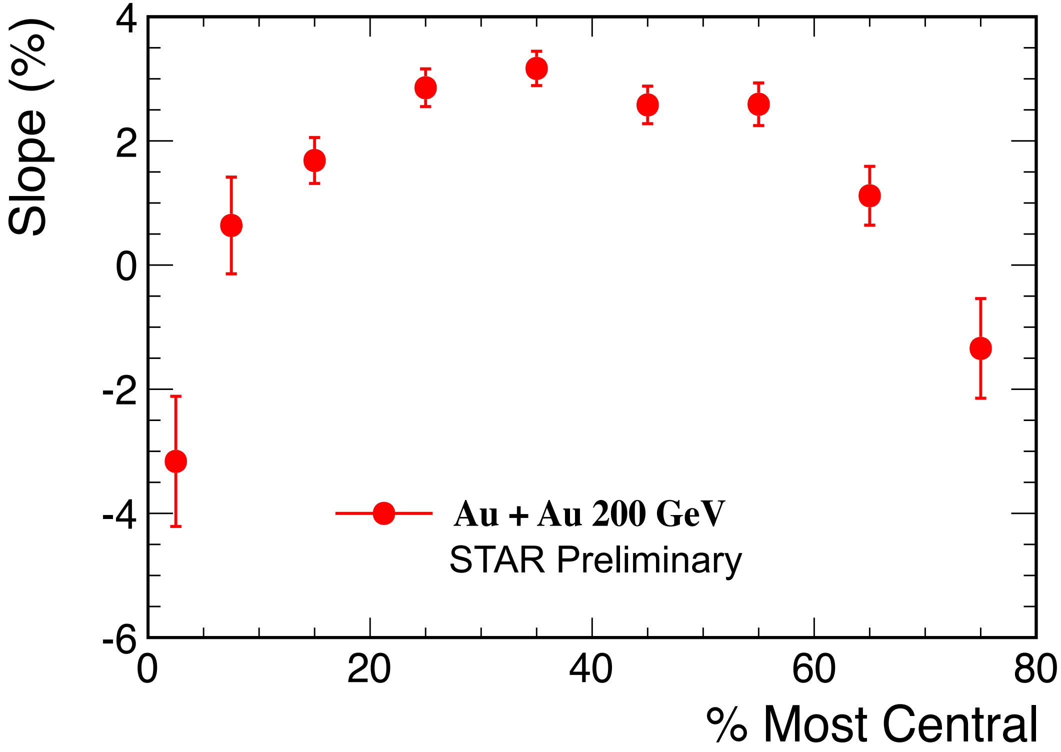
- Prediction based on CMW

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

- Fit $v_2(\pi^-) - v_2(\pi^+)$ vs. $\langle A_\pm \rangle$ to a straight line

- The slope parameter will be extracted for all centralities

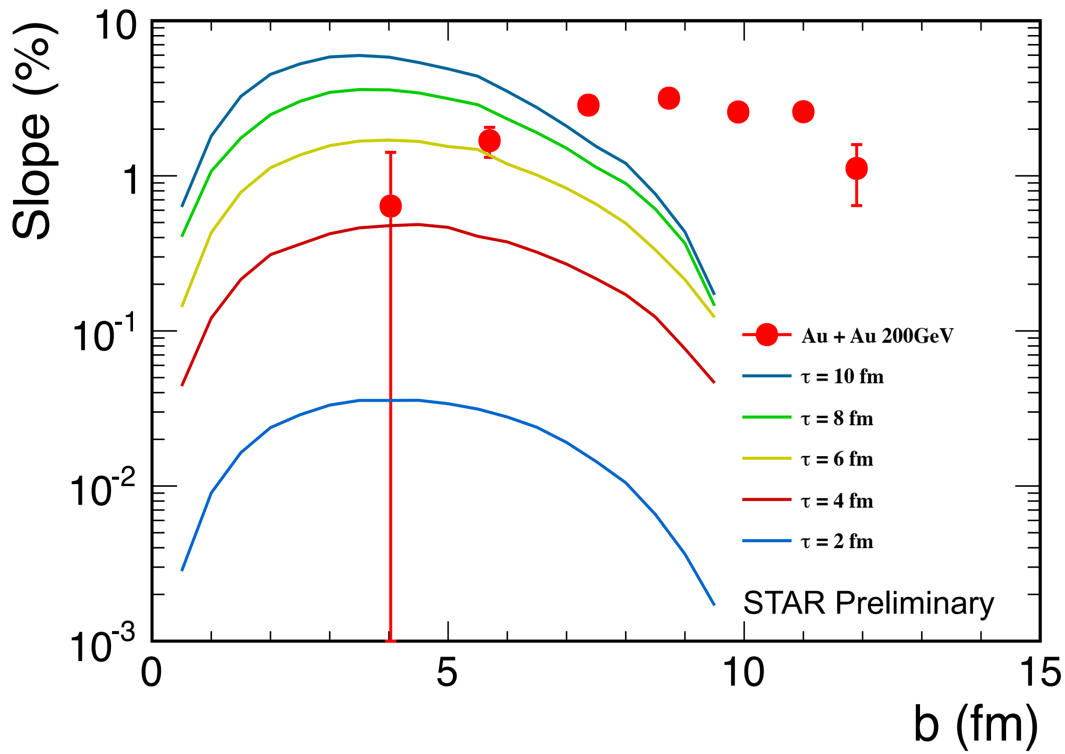
Slope vs. Centrality



- Only statistical uncertainties are shown

Slope vs. Centrality

Compare to the theoretical predictions based on Chiral Magnetic Wave (CMW), which are shown by solid lines.



- Centrality-b relation comes from STAR Phys. Rev. C **79,** 034909 (2009)

- Only statistical uncertainties are shown
- The slope parameters have the same order of magnitude as theoretical prediction based on Chiral Magnetic Wave
- Centrality dependency of slope parameter is different from prediction based on CMW

Summary & Outlook

- The difference between $v_2(\pi^-)$ and $v_2(\pi^+)$ shows a linear dependency on net charge asymmetry in Au + Au collisions at $\sqrt{s_{NN}} = 200$ GeV, as predicted based on Chiral Magnetic Wave.

- Slope parameters have the same order of magnitude as predicted based on CMW, but the centrality dependency is different.

- Outlook
  - Systematic uncertainties
  - Lower energies