QCD vacuum and matter under strong magnetic field II

中国科学院高能物理研究所
Institute of High Energy Physics Chinese Academy of Sciences

Search for Chiral Effects in High-energy Nuclear Collisions at STAR

Gang Wang (UCLA)

for STAR Collaboration

STAR

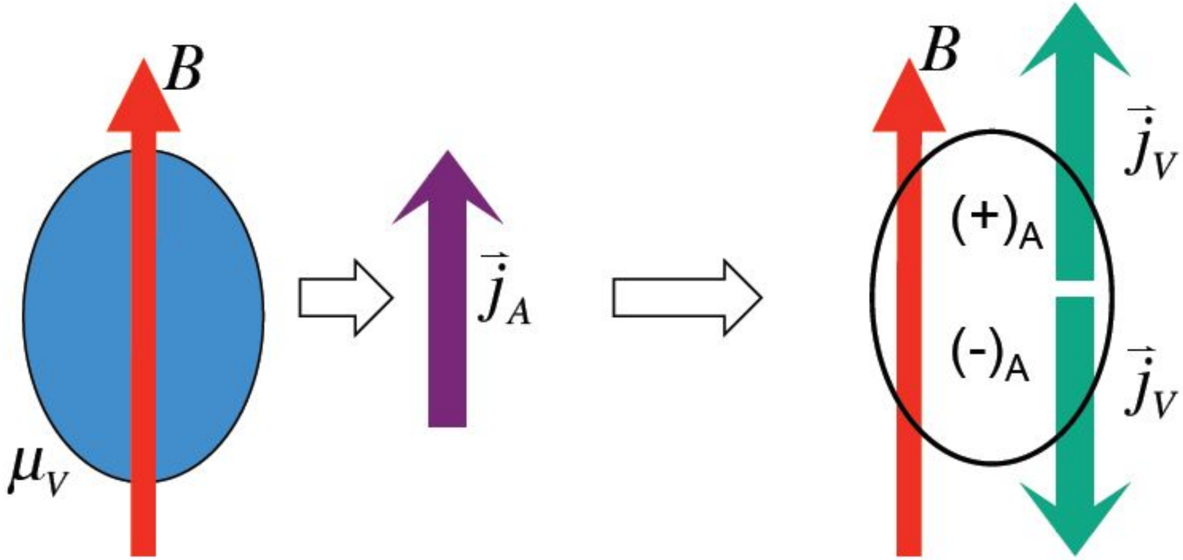
UCLA BRUINS

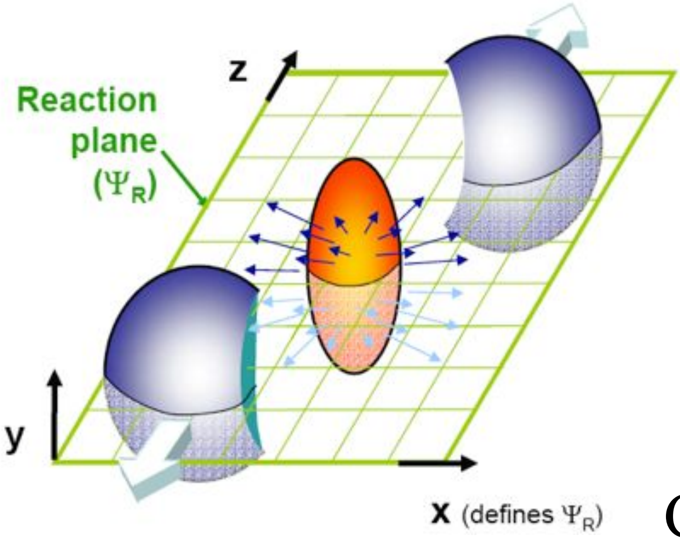
Outline

- ❖ Motivation
- ❖ STAR Experiment
- ❖ Chiral Magnetic Wave (CMW)
- ❖ Chiral Magnetic Effect (CME)
  and Chiral Vortical Effect (CVE)
- ❖ Outlook

Motivation

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





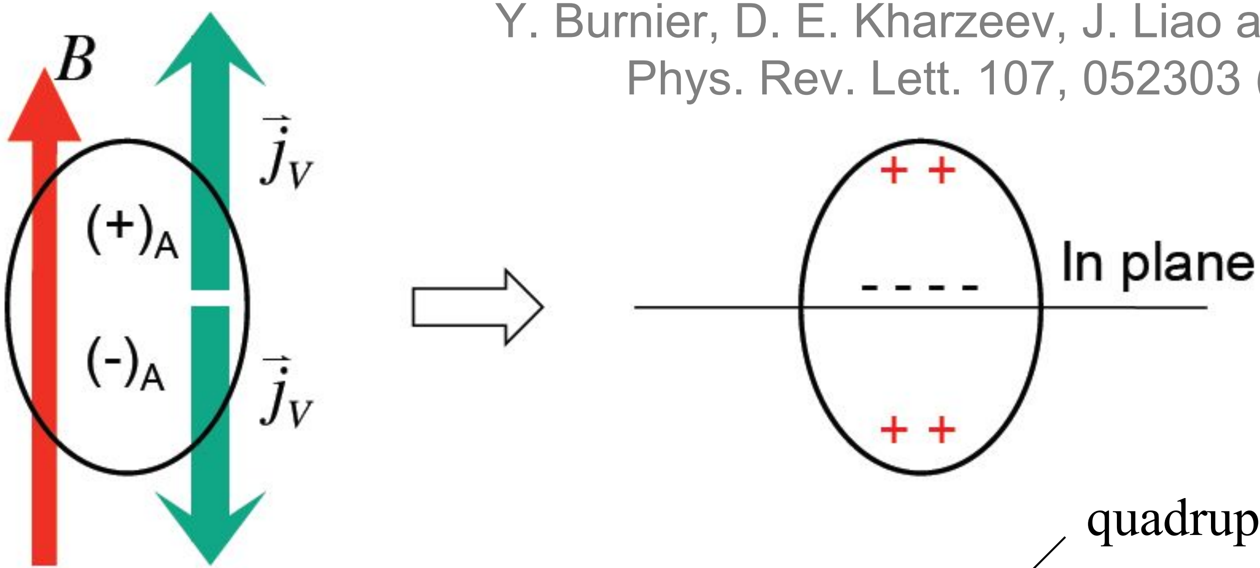
$$j_A = \frac{N_c e}{2\pi^2}\mu_V B \qquad j_V = \frac{N_c e}{2\pi^2}\mu_A B$$

Chiral Separation Effect | **Chiral Magnetic Effect**

CSE + CME ➔ Chiral Magnetic Wave:
- collective excitation
- signature of chiral symmetry restoration

Observable I

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



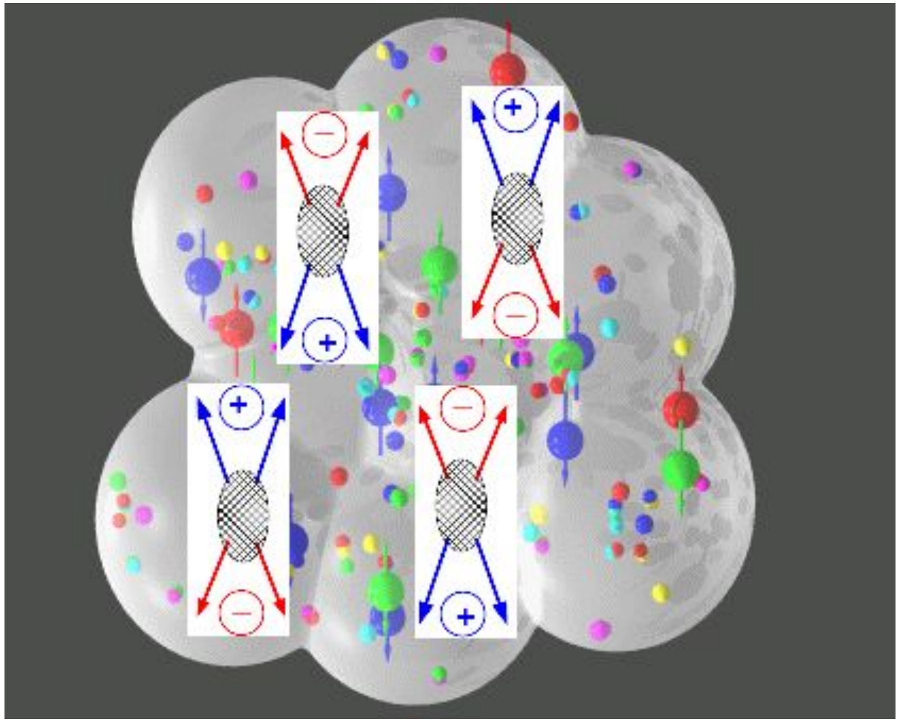
Formation of electric quadrupole: $v_2^{\pm} = v_2^{\text{base}} \mp \left(\frac{q_e}{\bar{\rho}_e}\right) A_{ch}$,

quadrupole moment (q_e); net charge density ($\bar{\rho}_e$)

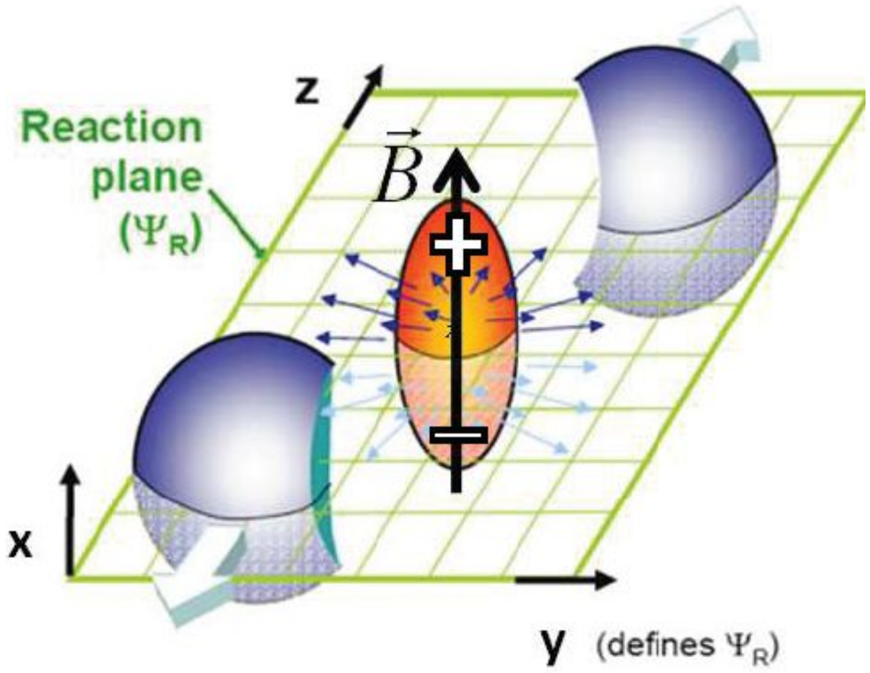
where charge asymmetry is defined as $A_{ch} = \frac{N^+ - N^-}{N^+ + N^-}$.

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.

Observable II



CME => charge separation across RP



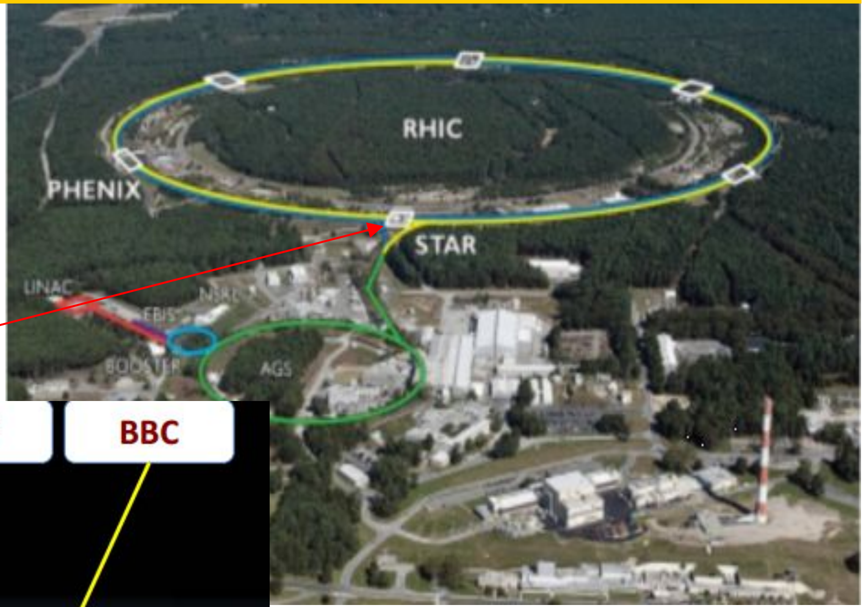
$$\frac{dN_{\pm}}{d\phi} \propto 1 + 2a_{\pm} \cdot \sin\left(\phi^{\pm} - \Psi_{RP}\right)$$

charge separation effect beyond conventional physics background

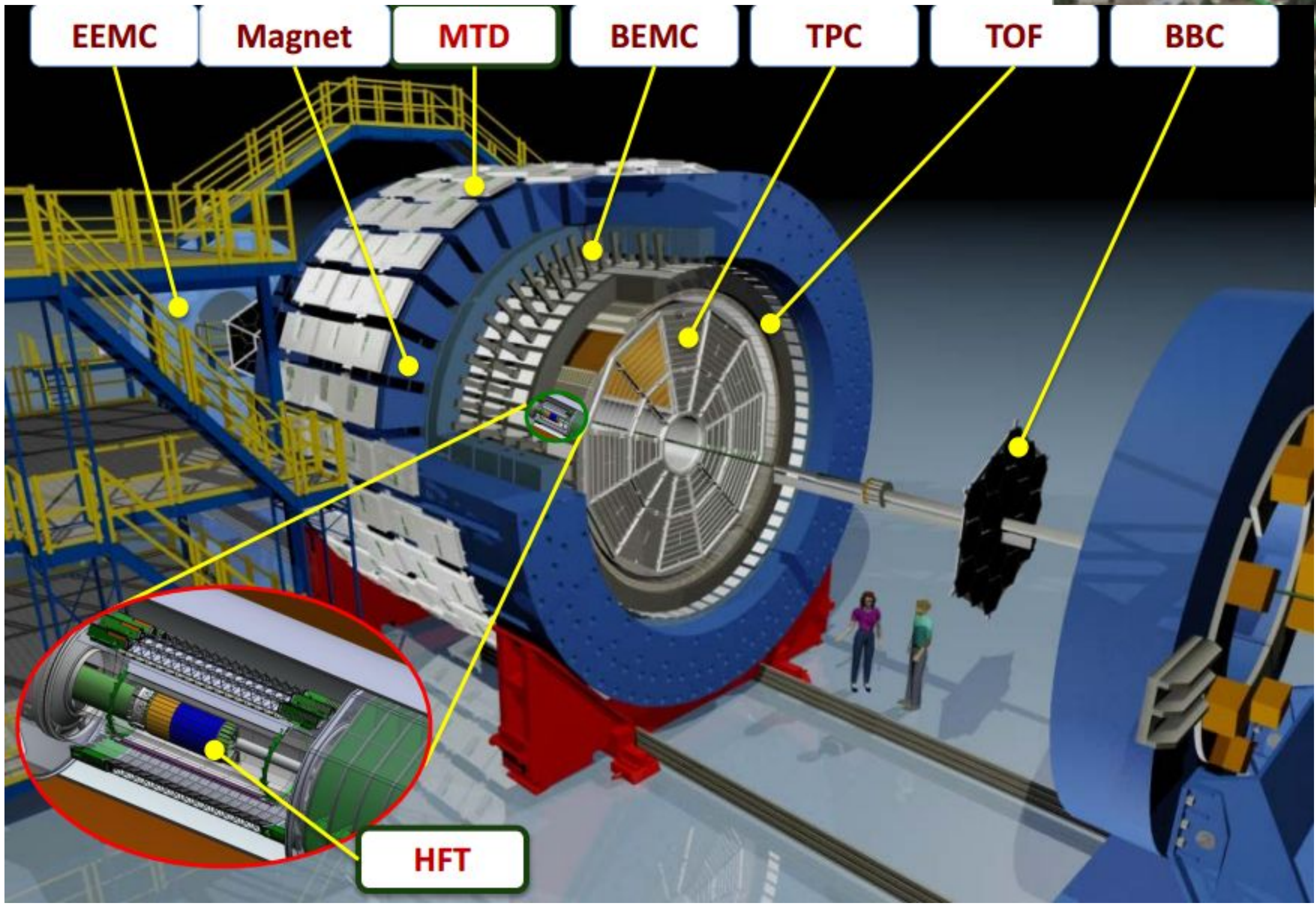
S. Voloshin, PRC 70 (2004) 057901,
Kharzeev, PLB633:260 (2006)
Kharzeev, McLerran, Warringa, NPA803:227 (2008)

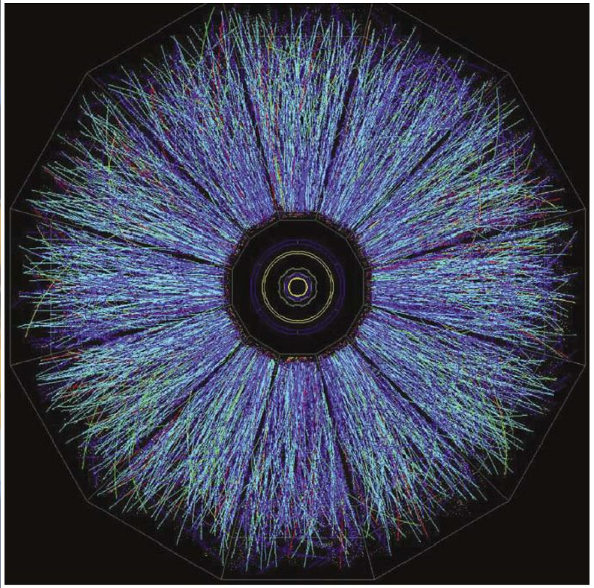
STAR experiment

Relativistic Heavy Ion Collider (RHIC)

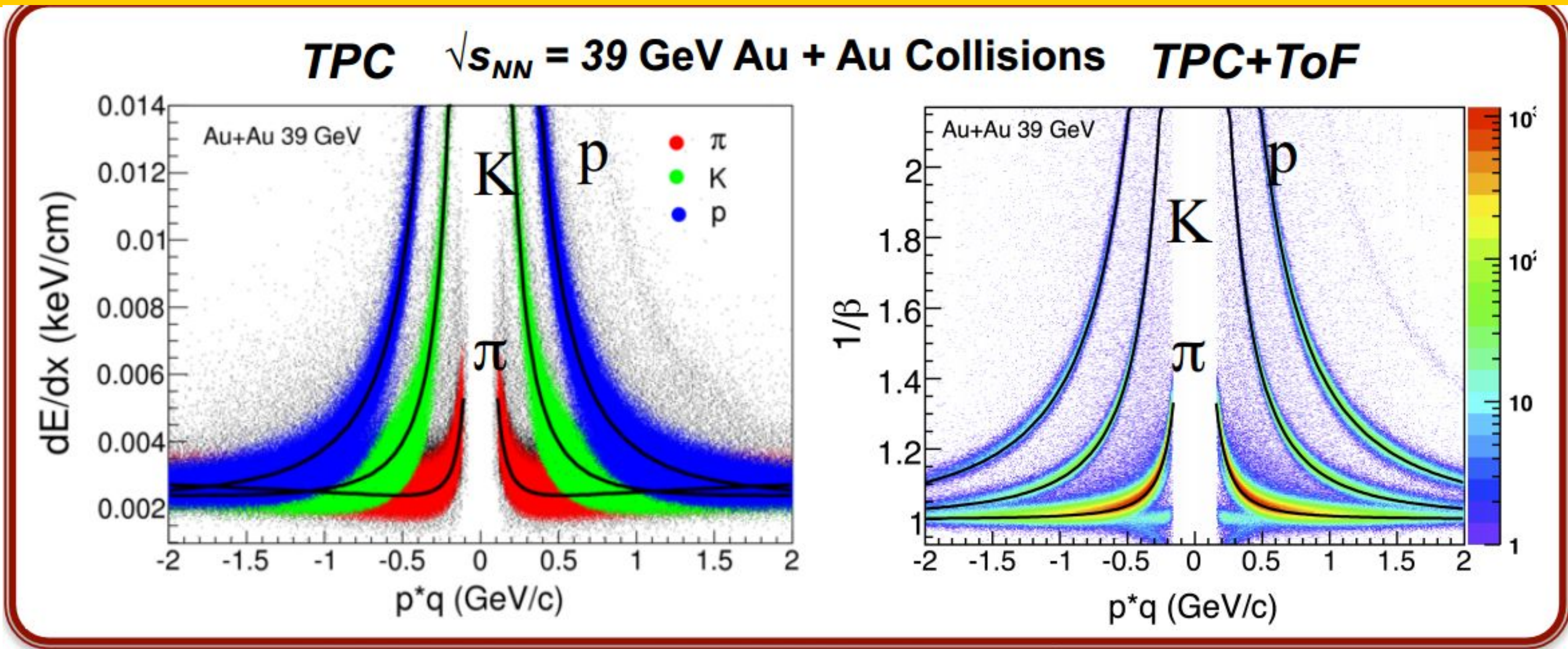


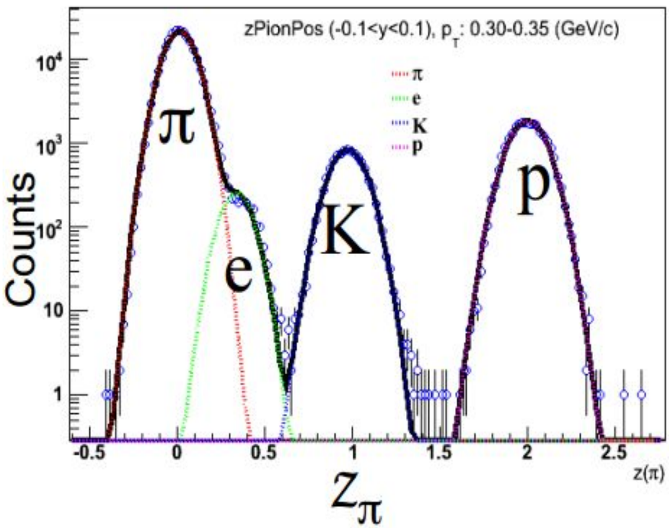
Solenoidal Tracker at RHIC (STAR)





Particle identification



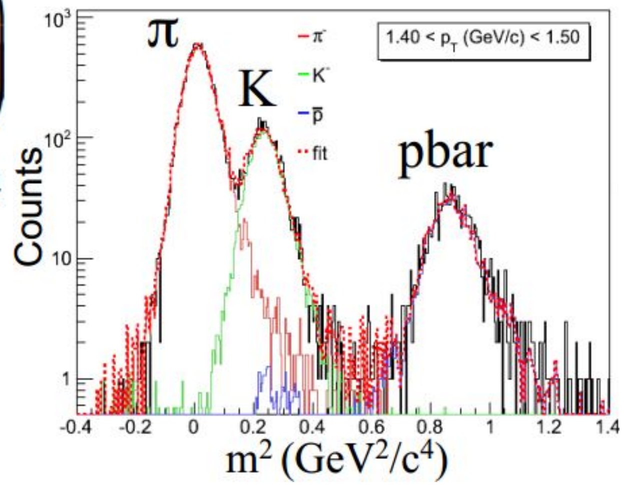


$$z = \log\left(\frac{(dE/dx)_{meas.}}{(dE/dx)_{theory}}\right)$$

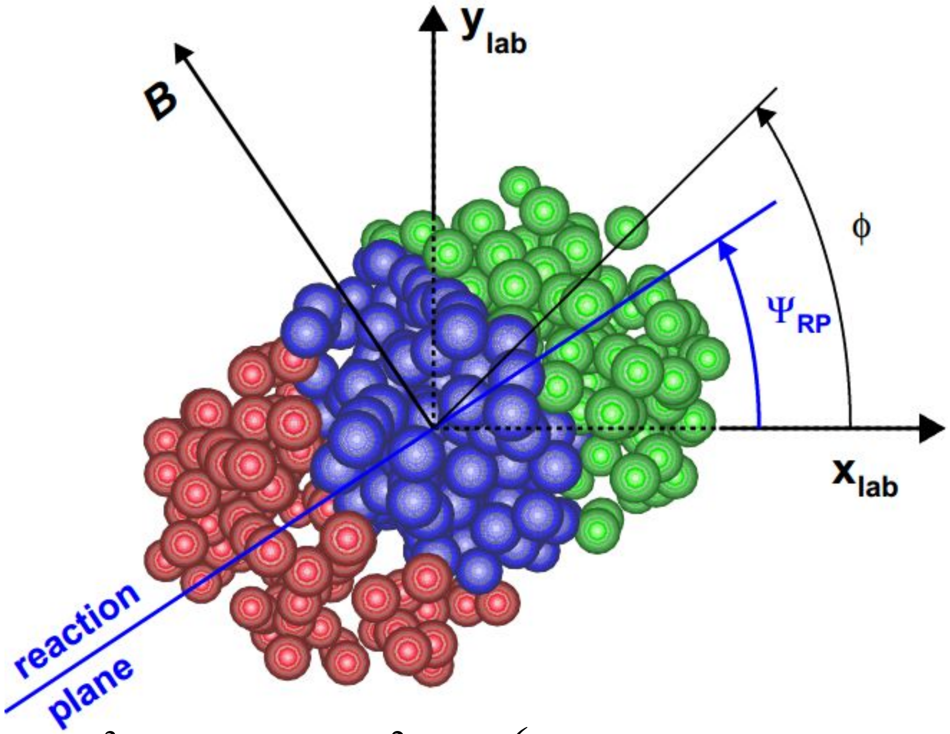
H. Bichsel, NIM A. 562 (2006) 154

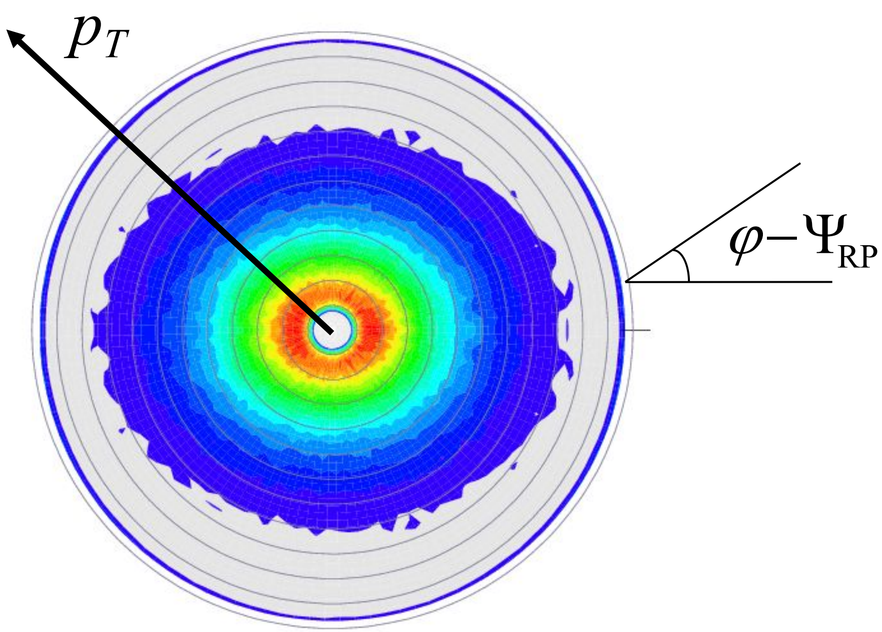
$$m^2 = p^2\left(\frac{c^2t^2}{L^2} - 1\right)$$

c=velocity of light,
L=path length



Azimuthal anisotropy





$$E\frac{d^3N}{d^3p}=\frac{1}{2\pi}\frac{d^2N}{p_t dp_t dy}\left(1+\sum_{n=1}^{\infty}2v_n\cos[n(\varphi-\Psi_{RP})]\right)$$

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

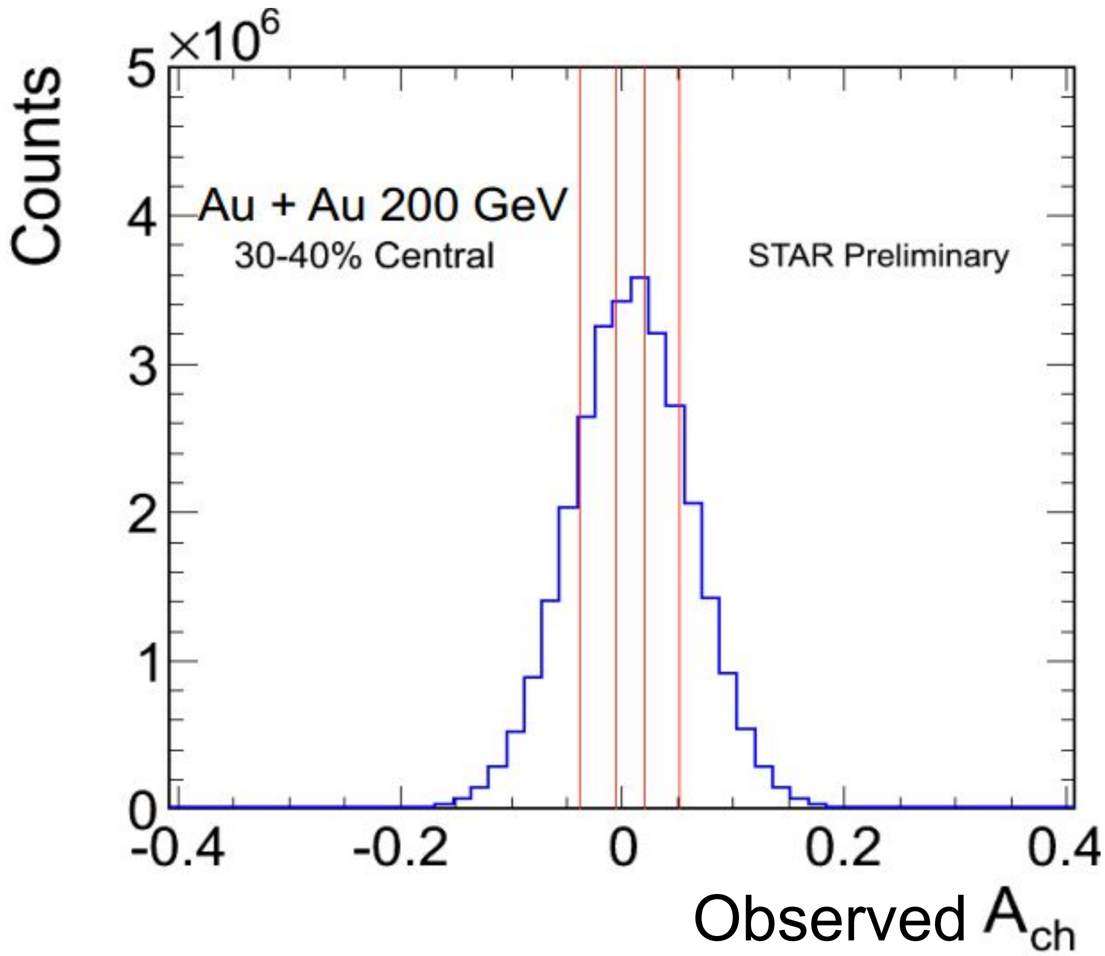
$$Q_n\sin(n\Psi_n)=Q_y=\sum_i w_i\sin(n\phi_i)$$

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

$$v_n=\langle\cos[n(\varphi-\Psi_{RP})]\rangle$$

The estimated reaction plane is called the event plane.

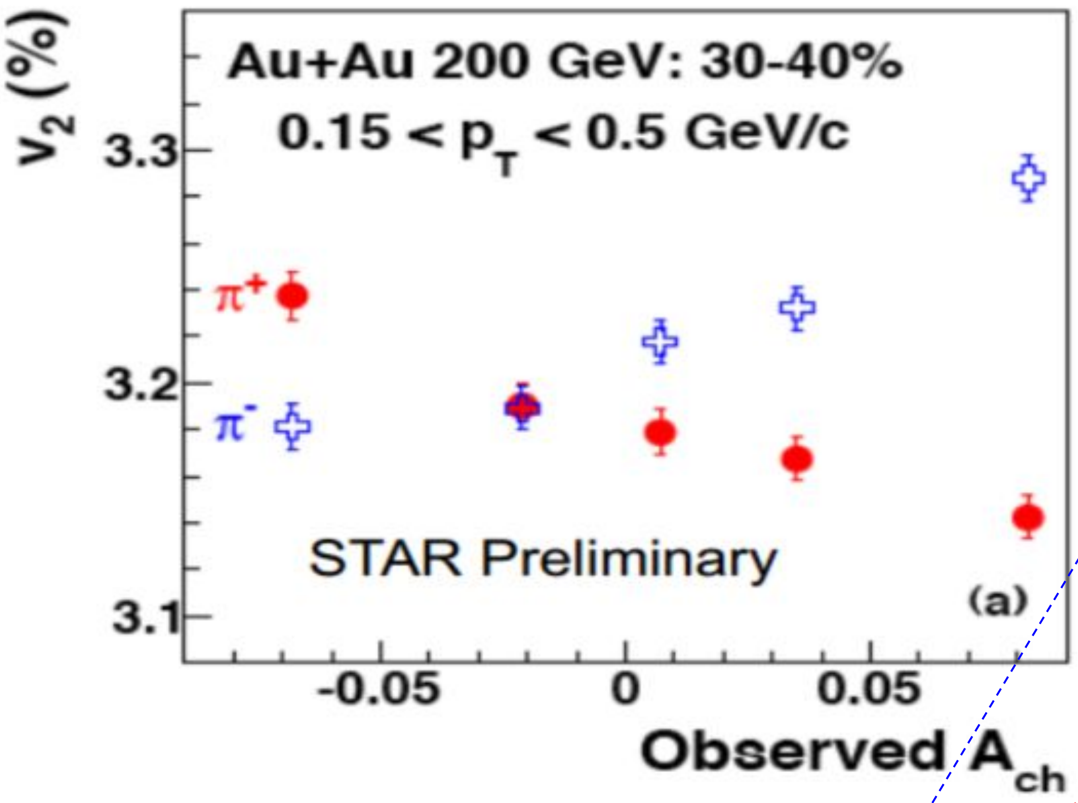
Observed charge asymmetry



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

- N^+ (N^-) is the number of positive (negative) particles within $|\eta|<1$.
- The distribution was divided into 5 bins, with roughly equal counts.
- Tracking efficiency was corrected later.

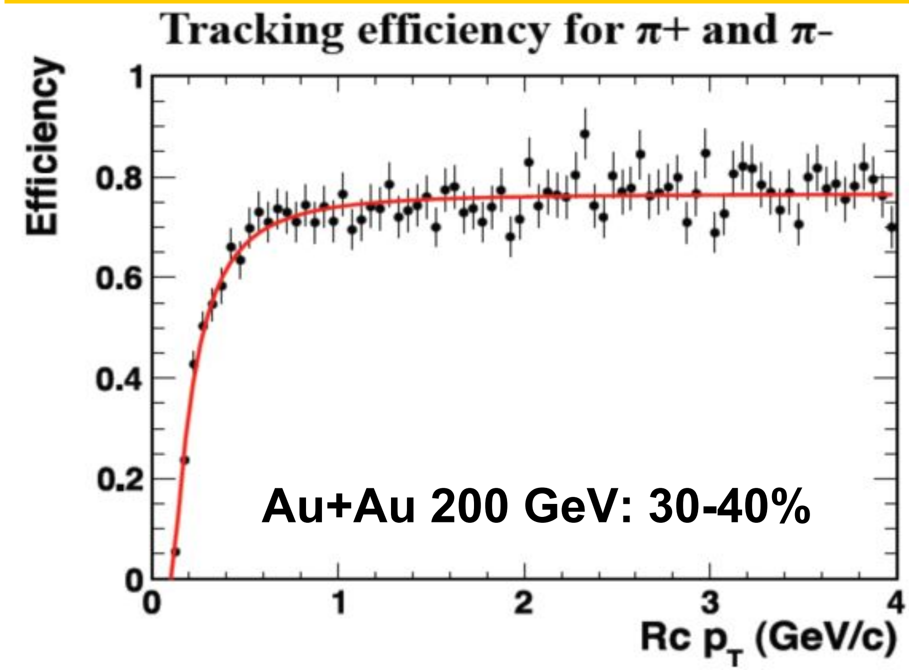
Charge asymmetry dependence

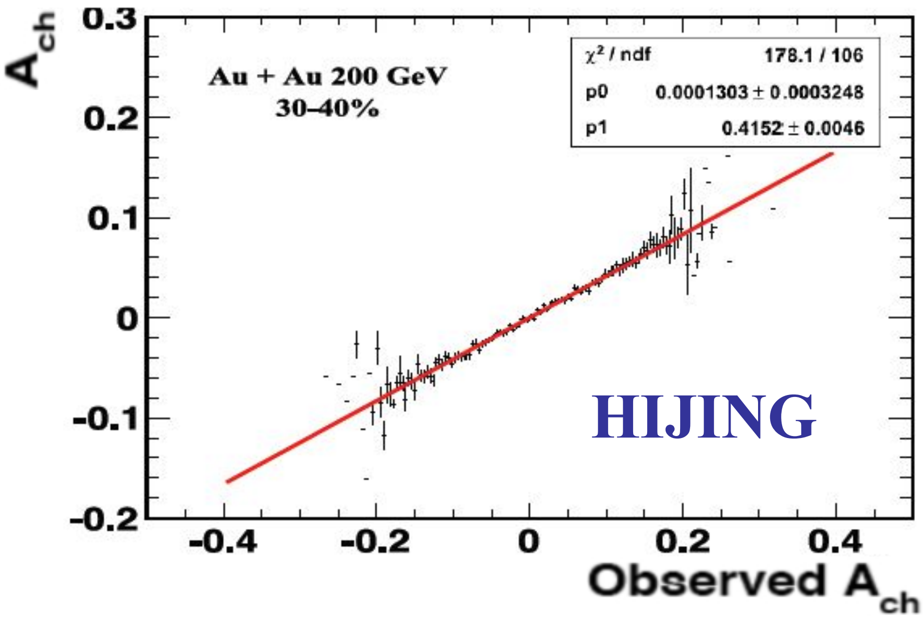


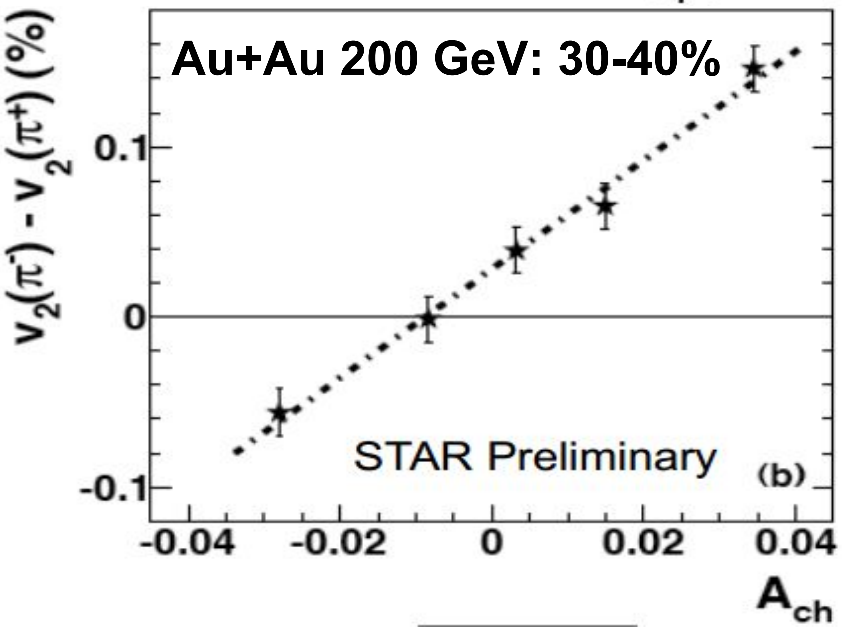
- $v_2\{2\}$ was measured
- Clear A_{ch} dependence
- $v_2(A_{ch})$ slopes for $\pi^{\pm}$:
  - opposite sign
  - similar magnitude
- v_2 difference vs A_{ch} may have a non-zero intercept: other physics?

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

Correction for tracking efficiency







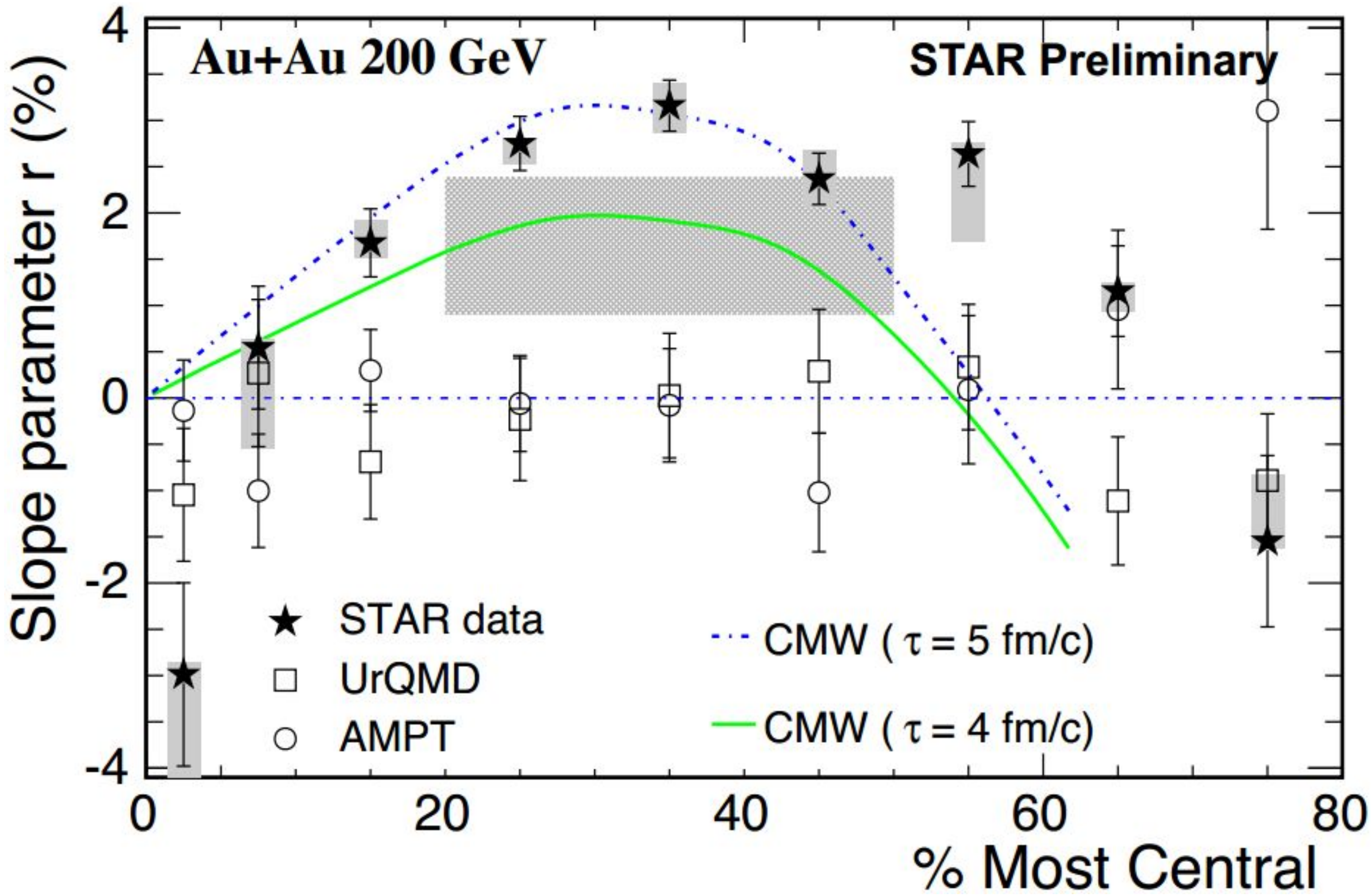
$$v_2^{\pm} = v_2^{\text{base}} \mp \left(\frac{q_e}{\bar{\rho}_e}\right) A_{ch}$$

- Fit with a straight line to extract the slope $r = 2\frac{q_e}{\bar{\rho}_e}$.

- Do the same for all centralities

Slope vs centrality

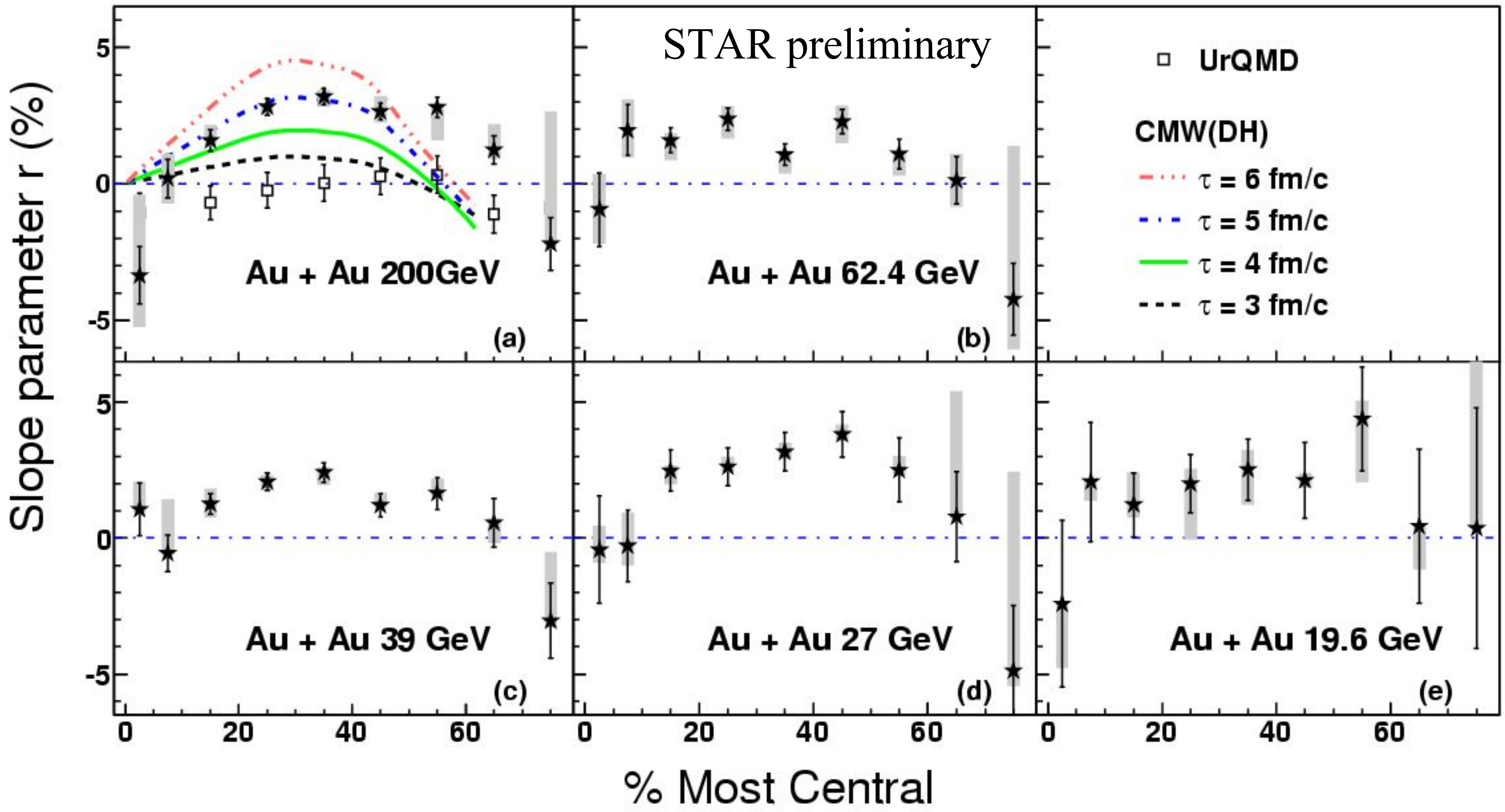
Y. Burnier, D. E. Kharzeev, J. Liao and H-U Yee, arXiv:1208.2537v1 [hep-ph].



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

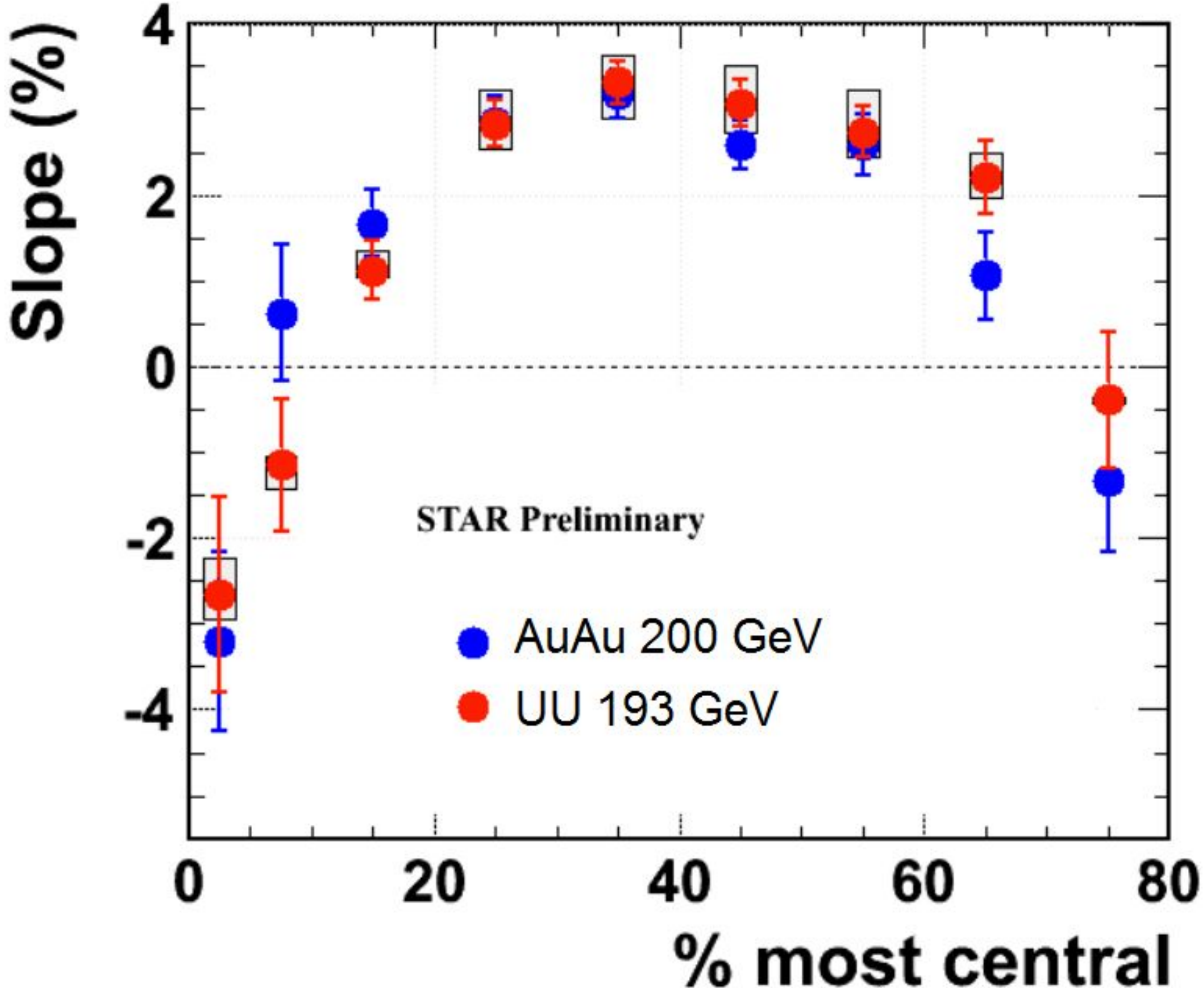
Beam Energy Scan

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



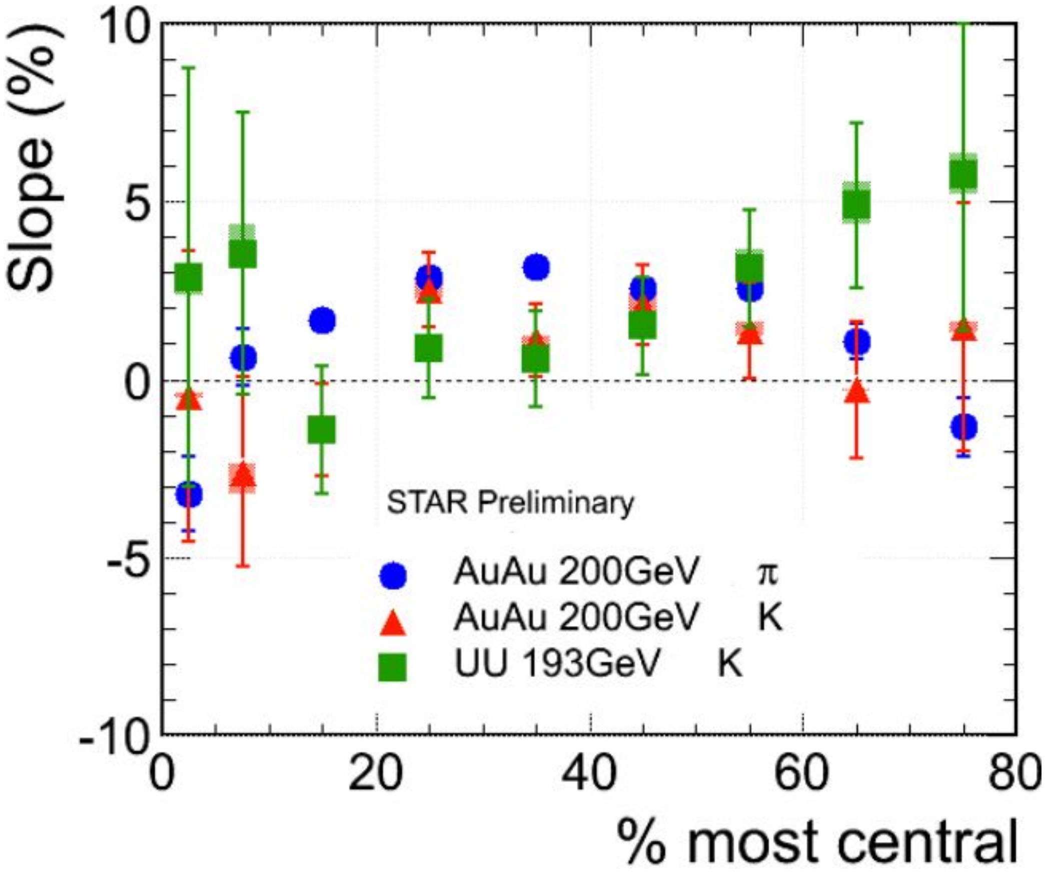
Similar trends are observed for different beam energies down to 19.6 GeV.

U+U

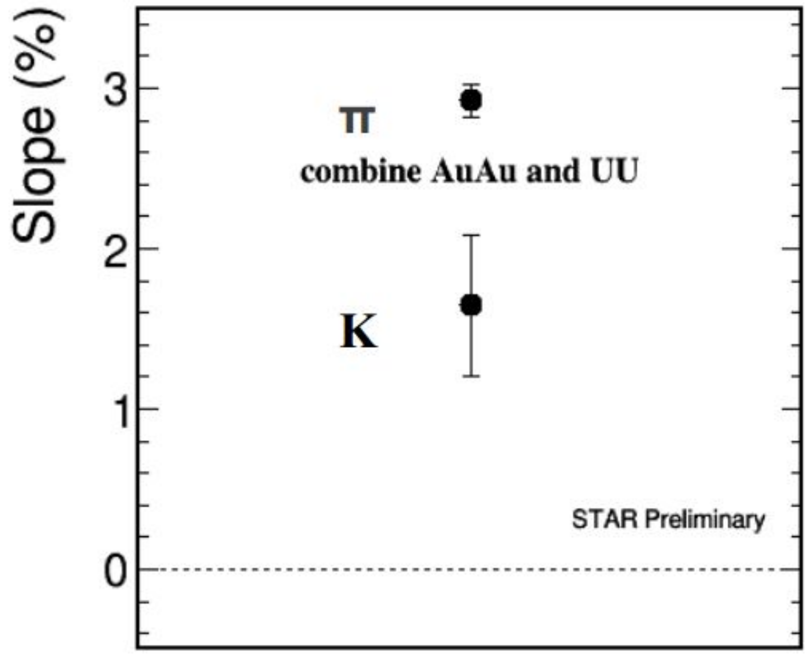


Similar pattern and magnitude seen in U+U collisions.

Kaon

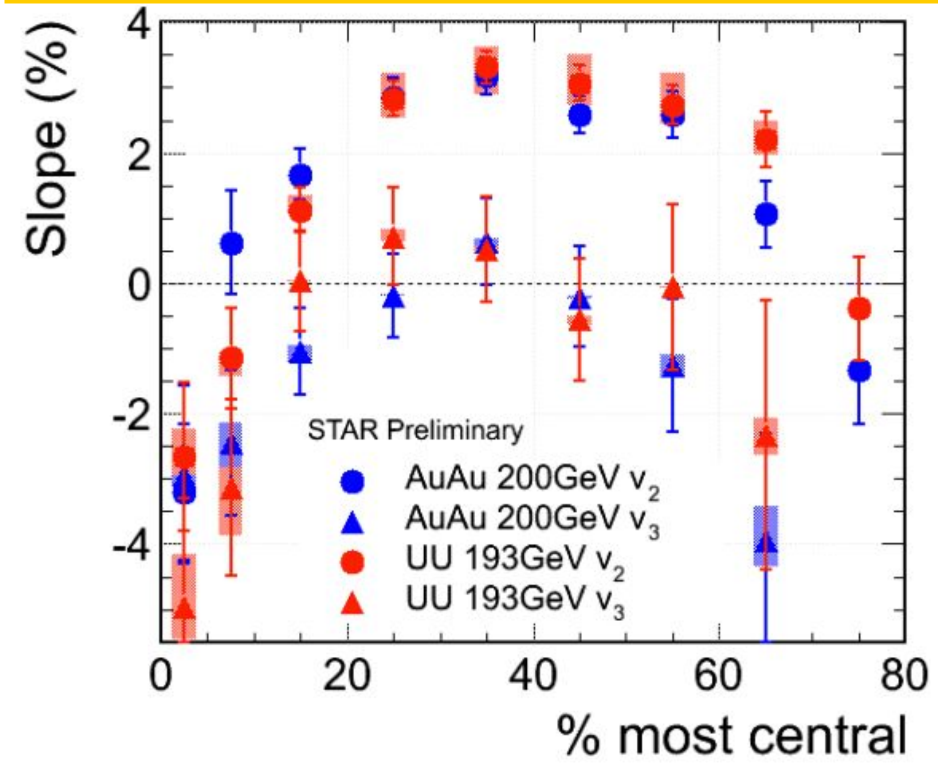


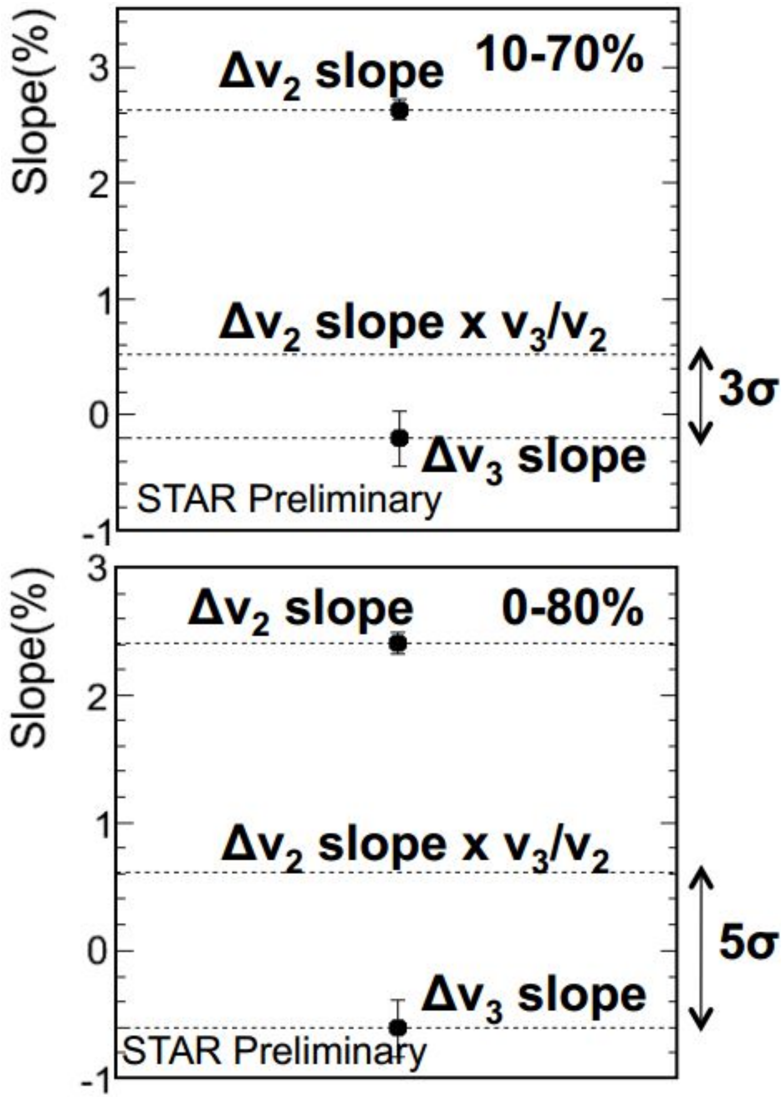
20-60% collisions



With the same electric quadruple of QGP upon chemical freezeout, one expects to see a weaker effect for kaons (Yannis Burnier, Dmitri E. Kharzeev, Jinfeng Liao, and Ho-Ung Yee, PRL 107 052303)

Δv_3 slope





Local charge conservation may introduce A_{ch} dependence of $\Delta v_2(\pi)$. Then 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.

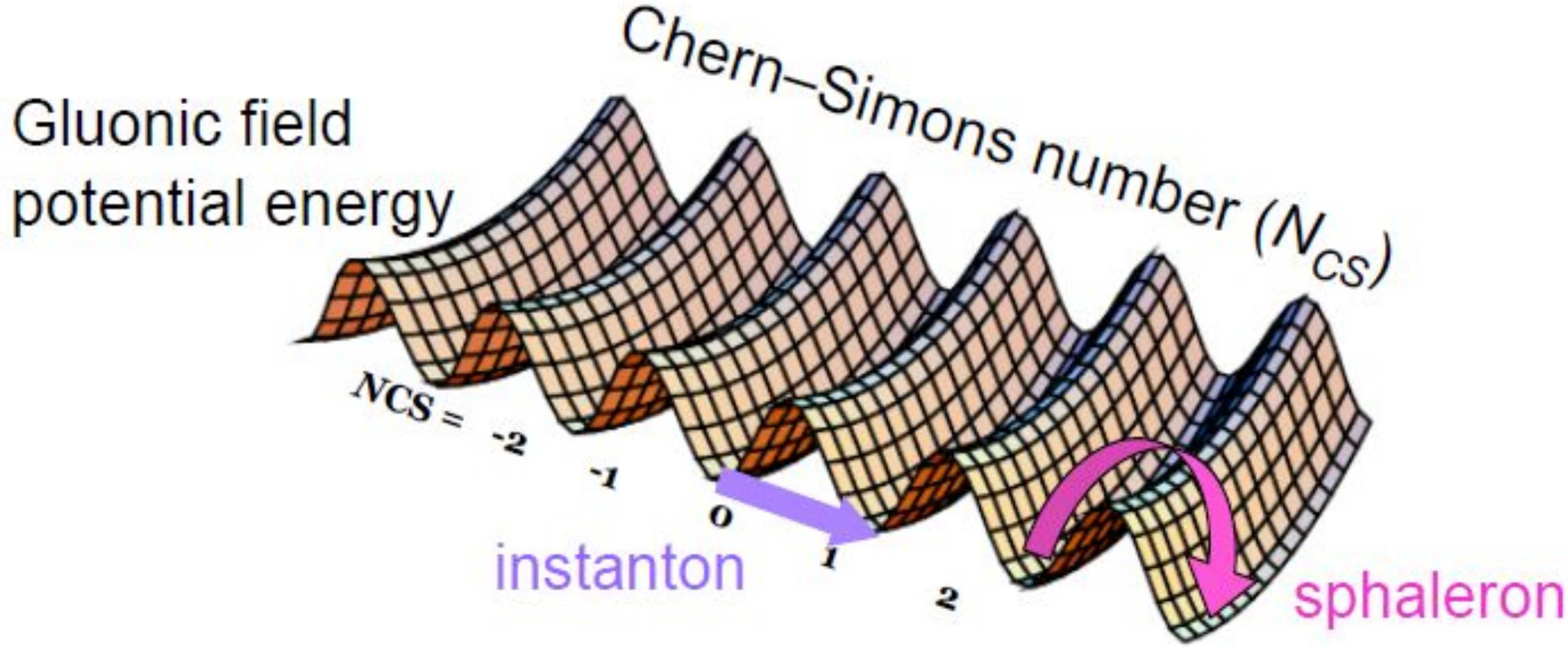
Summary I

- Charge asymmetry dependece of pion v_2 has been observed.
  - $v_2(A_{ch})$ showed opposite slopes for π^+ and π^-
  - similarity between data and calculations with CMW
  - similar centrality dependence from 200 GeV down to 19.6 GeV
  - confirmed with UU
  - finite slopes for kaons, with smaller magnitudes

- On the other hand
  - UrQMD and AMPT (w/o CMW) showed no such effects
  - Δv_3 results consistent with zero

- Further systematic checks to do
  - lower energies like 11.5 and 7.7 GeV
  - acceptance effect

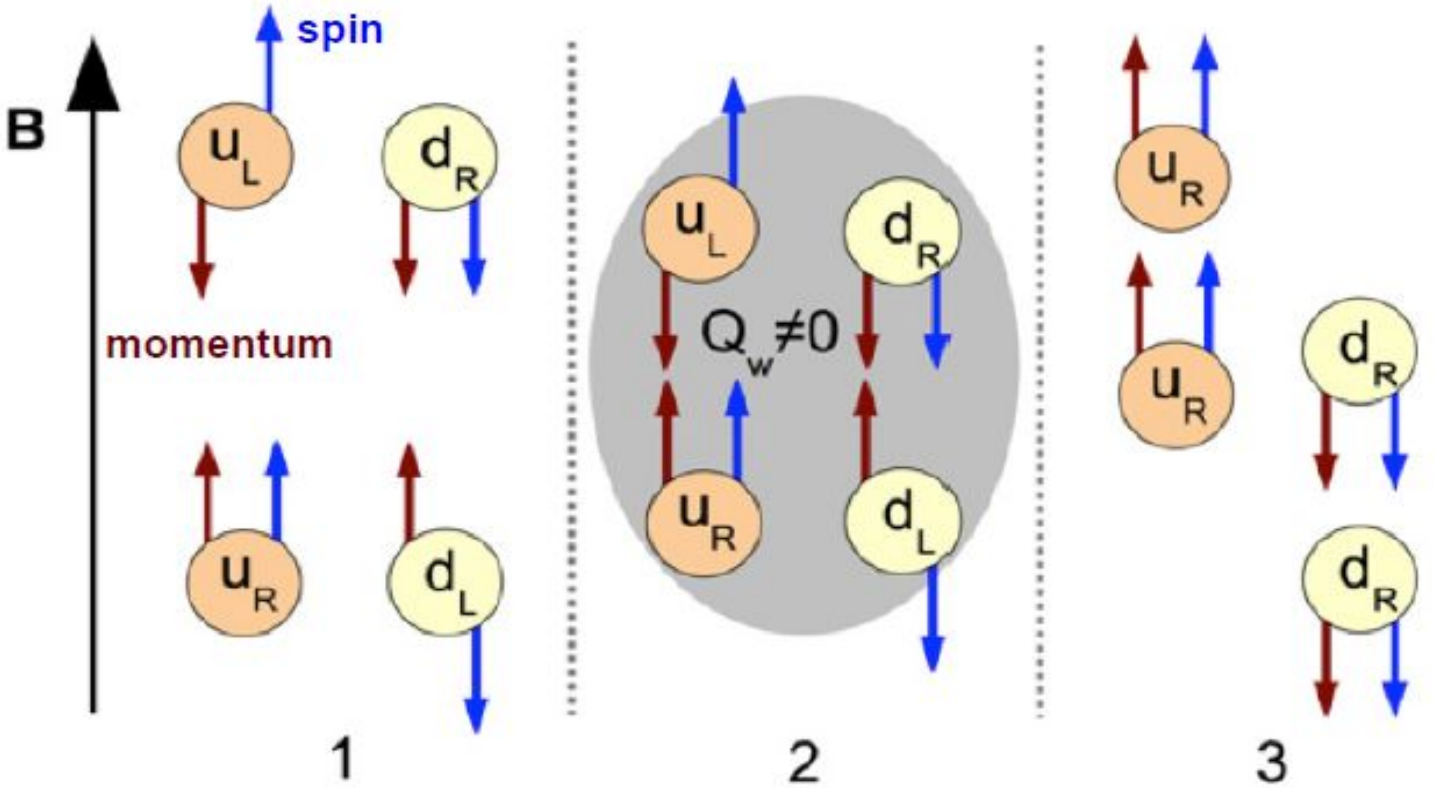
QCD vacuum transition



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

QCD vacuum transition
➔ nonzero topological charge
➔ chirality imbalance (local parity violation)

Chiral Magnetic Effect



Chiral Magnetic Effect **(CME):** finite chiral charge density induces an electric current along external magnetic field.

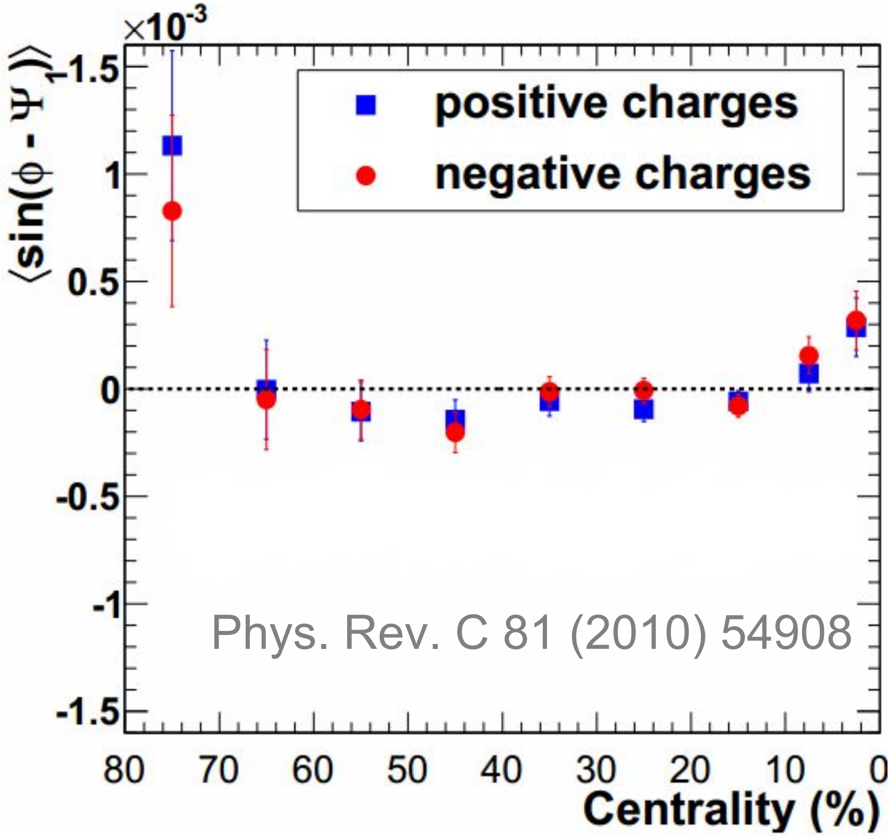
$$j_V = \frac{N_c e}{2\pi^2} \mu_A B$$ ➔ electric charge separation along *B* field

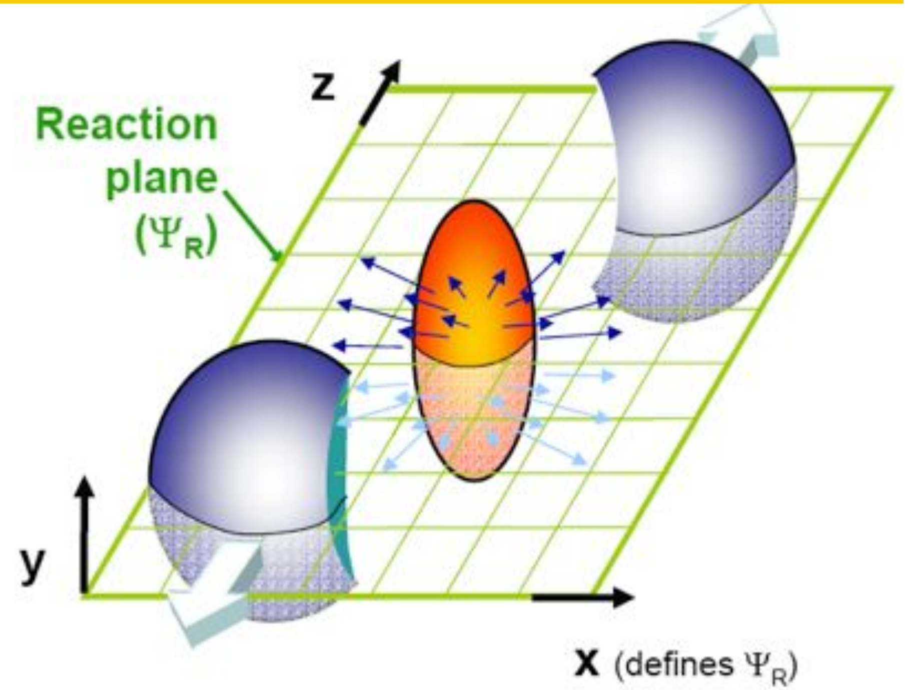
D. E. Kharzeev, L. D. McLerran, and H. J. Warringa, Nuclear Physics A 803, 227 (2008)

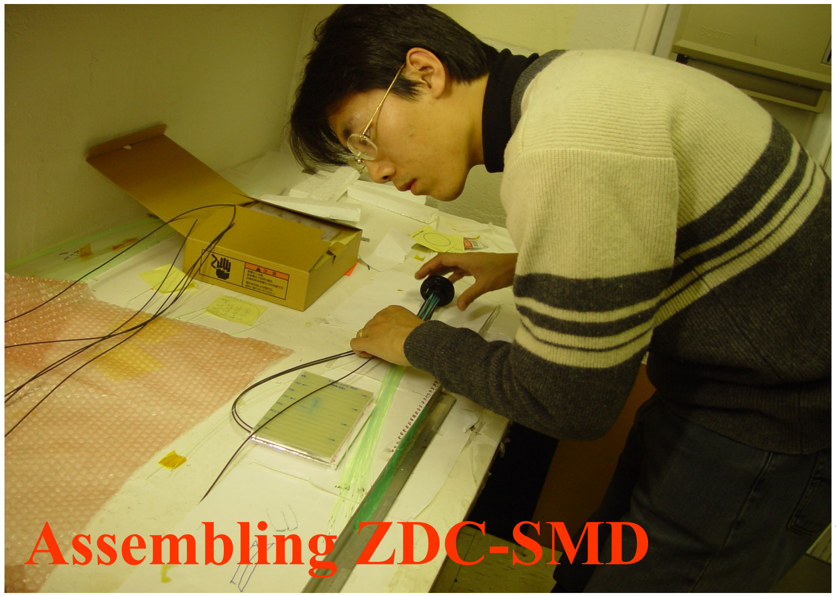
CME + Local Parity Violation

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

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



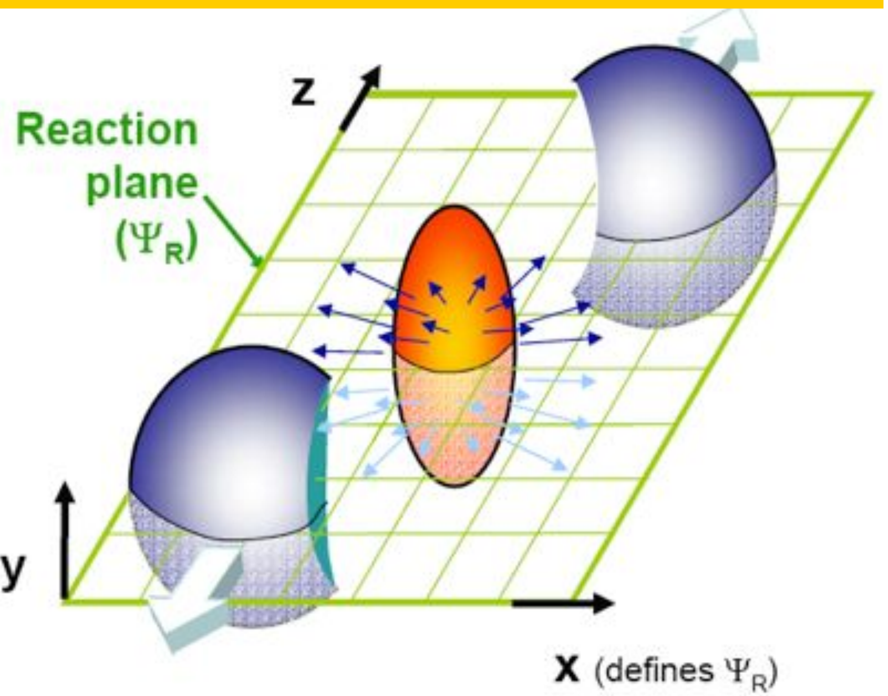




γ correlator

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

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



S. Voloshin, PRC 70 (2004) 057901

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

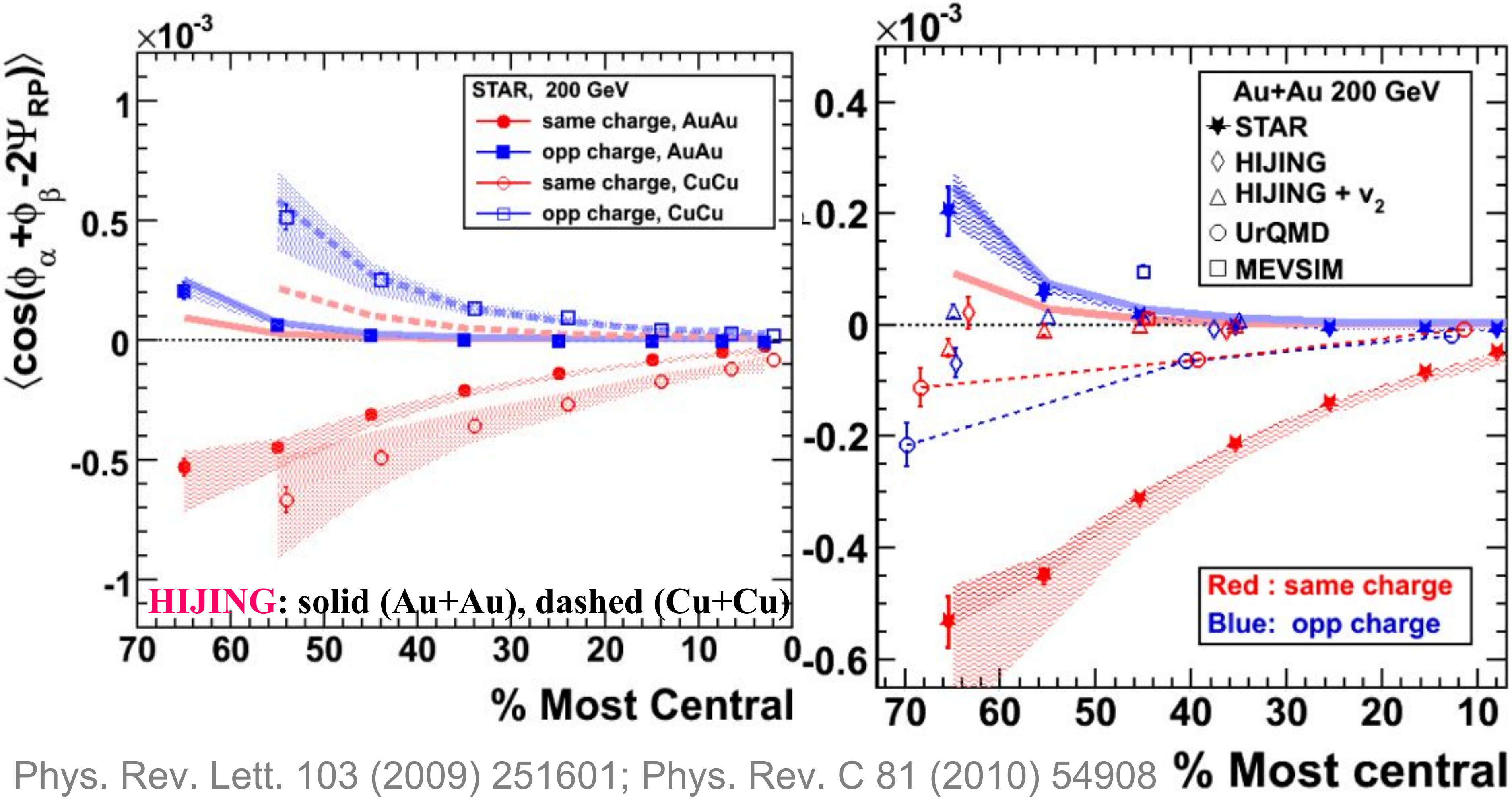
$$= \left[\left\langle v_{1,\alpha} v_{1,\beta} \right\rangle + B_{in}\right] - \left[\left\langle a_\alpha a_\beta \right\rangle + B_{out}\right]$$

background effects: largely cancel out

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

P-even quantity: still sensitive to charge separation

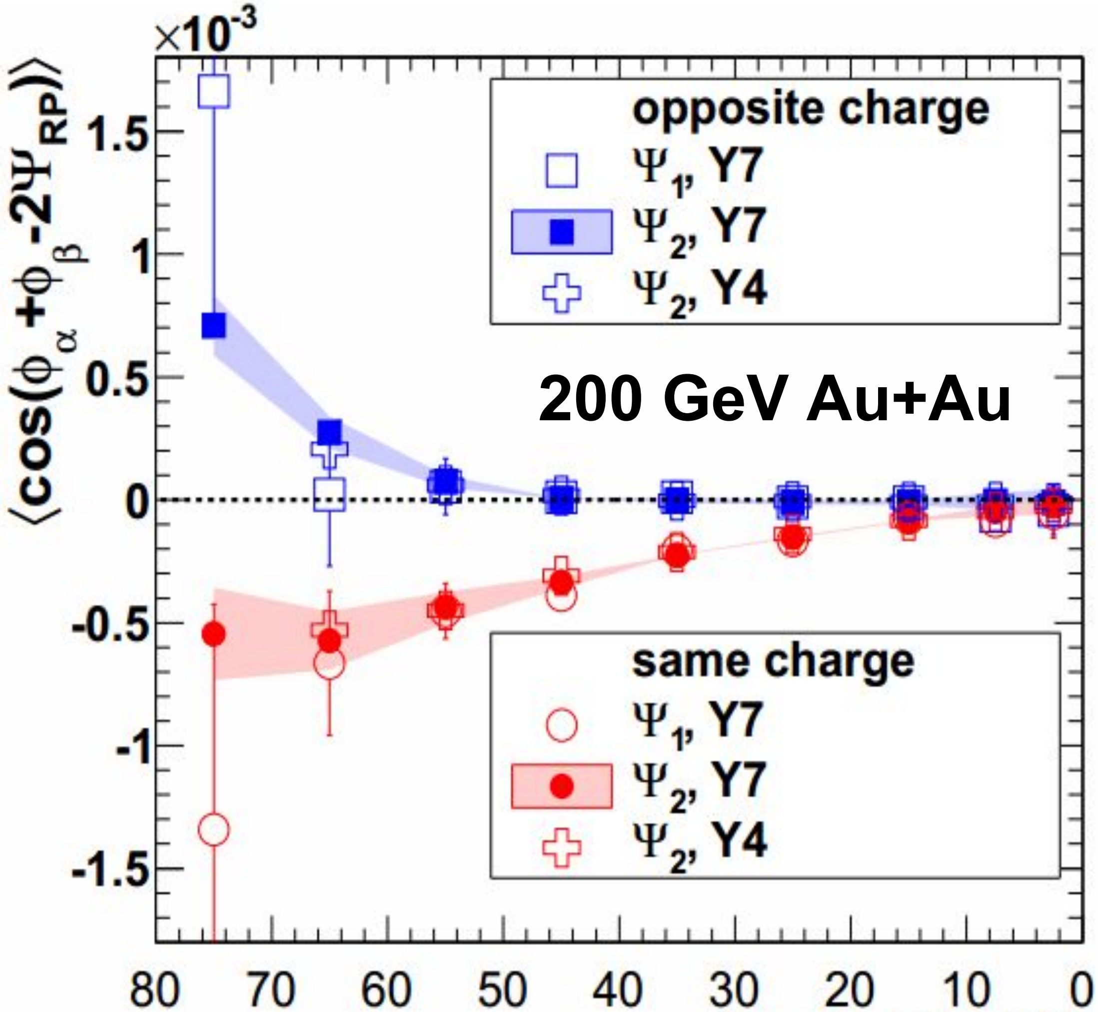
γ at 200 GeV



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

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

1st-order EP

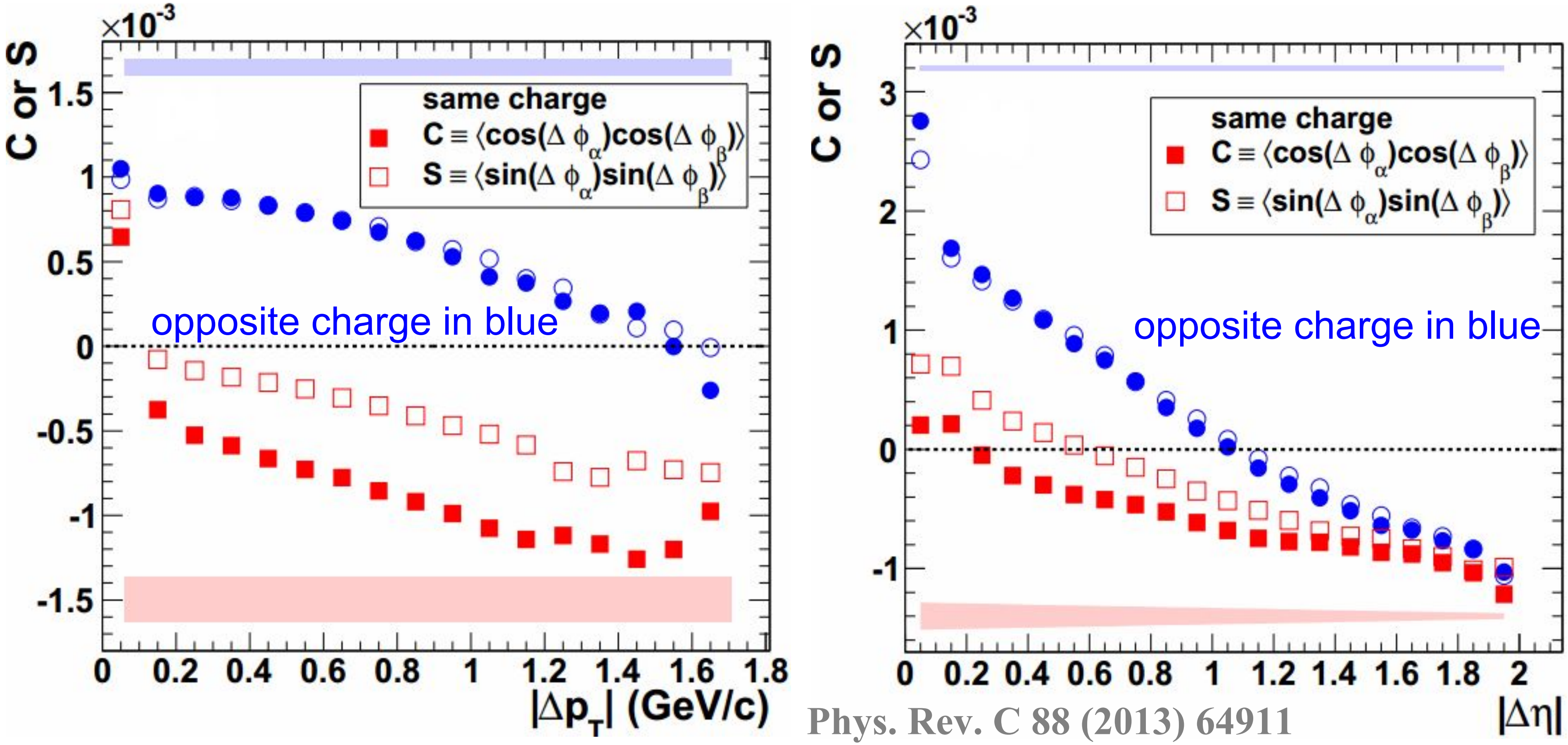


Phys. Rev. C 88 (2013) 64911

- Consistent between different years
- Confirmed with 1st-order EP from spectator neutrons

HBT+Coulomb

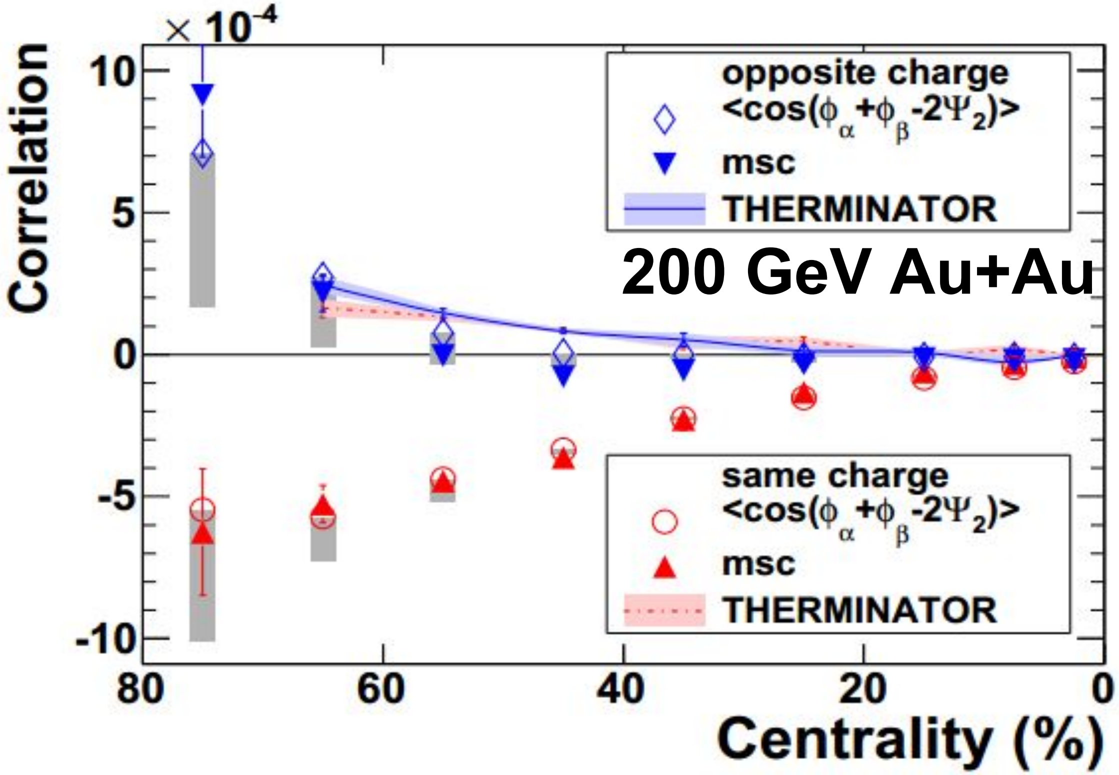
200 GeV Au+Au: 40 - 60%



Phys. Rev. C 88 (2013) 64911

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

Modulated sign correlator (msc)



$$\left\langle \cos(\varphi_\alpha + \varphi_\beta - 2\Psi_{\mathrm{RP}}) \right\rangle$$

$$= \left\langle \cos(\Delta\varphi_\alpha)\cos(\Delta\varphi_\beta) - \sin(\Delta\varphi_\alpha)\sin(\Delta\varphi_\beta) \right\rangle$$

$$= \left\langle (M_\alpha M_\beta S_\alpha S_\beta)_{\mathrm{IN}} \right\rangle - \left\langle (M_\alpha M_\beta S_\alpha S_\beta)_{\mathrm{OUT}} \right\rangle$$

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

- robust after removing HBT+Coulomb effects
- γ weights 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

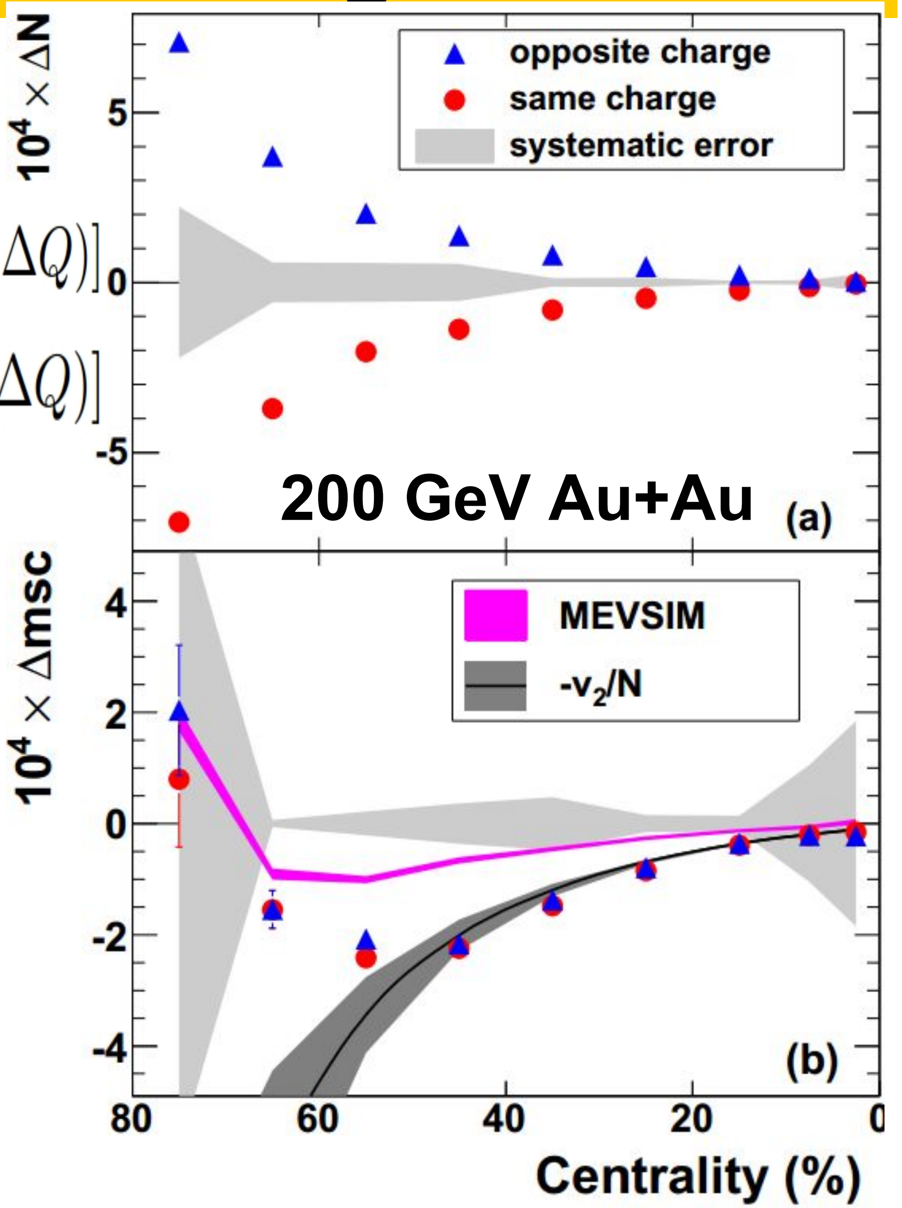
Phys. Rev. C 88 (2013) 64911

Charge-independent background

$$\mathrm{msc} = \Delta\mathrm{msc} + \Delta N$$

$$\Delta\mathrm{msc} = \frac{1}{N_E}\sum_{\Delta Q}\langle N(\Delta Q)\rangle\,[\mathrm{msc}_{\mathrm{IN}}(\Delta Q) - \mathrm{msc}_{\mathrm{OUT}}(\Delta Q)]$$

$$\Delta N = \frac{1}{N_E}\sum_{\Delta Q}\langle \mathrm{msc}(\Delta Q)\rangle\,[N_{\mathrm{IN}}(\Delta Q) - N_{\mathrm{OUT}}(\Delta Q)]$$



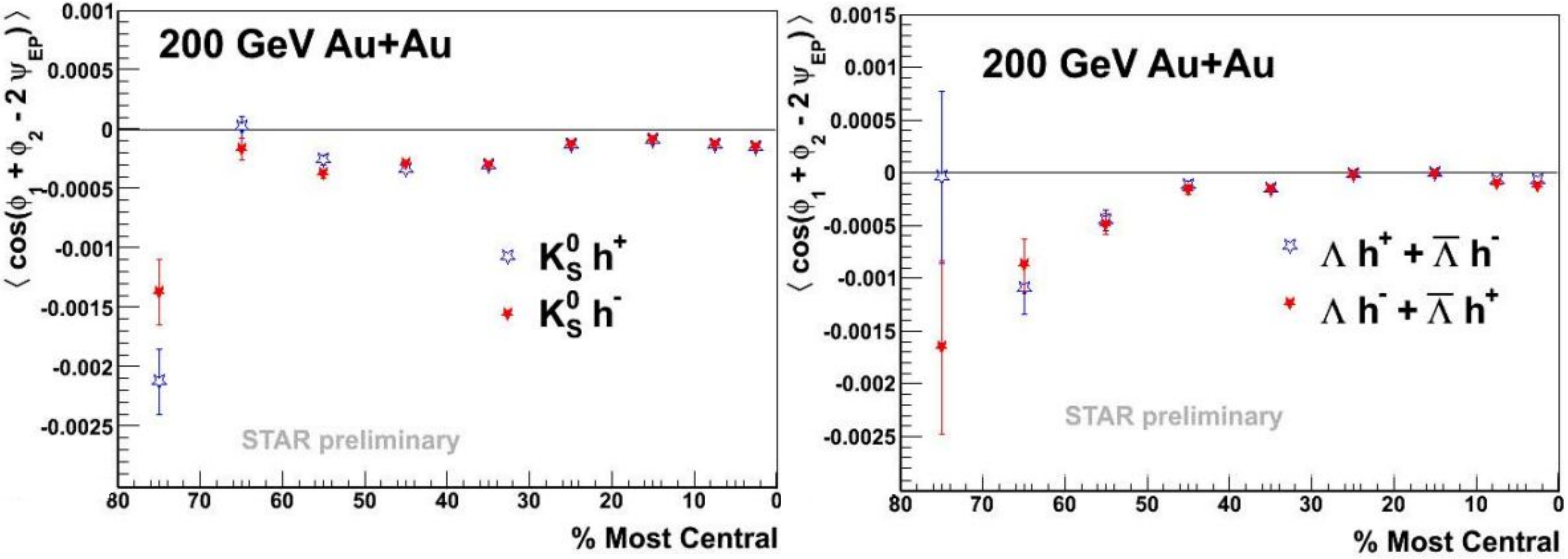
- msc was split to study bg

- $N_{IN}(\Delta Q)$ stands for the number of events with ΔQ units of in-plane charge separation, and $msc_{IN}(\Delta Q)$ stands for the <msc> in those events.

- MEVSIM and $-v_2/N$ tell us that the CI bg is likely due to momentum conservation + v_2

Phys. Rev. C 88 (2013) 64911

Neutral-charged correlation



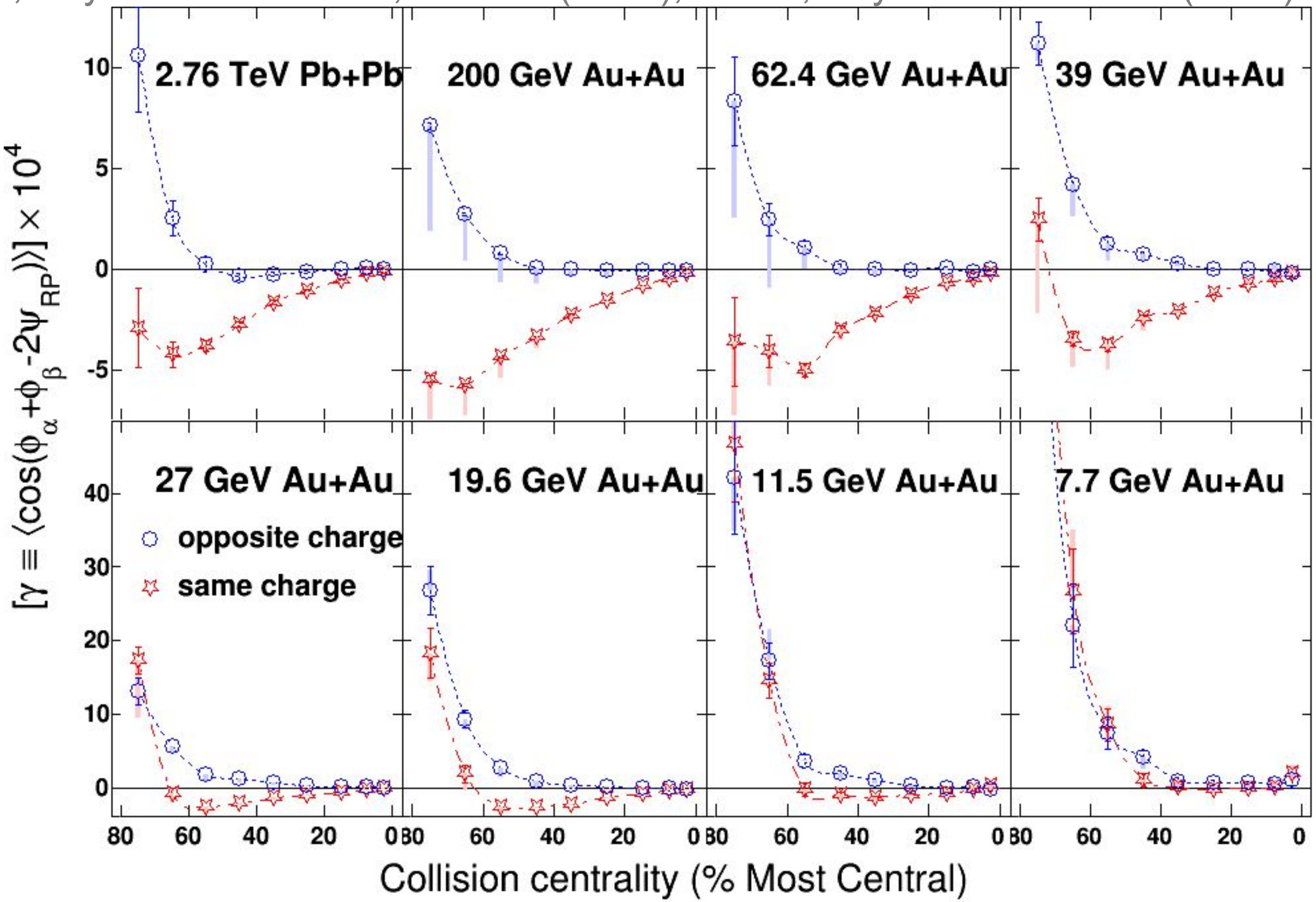
- correlations between neutral strange hadrons and charged hadrons show no charge separation

- separation observed for two charged hadrons is sensitive to electric charge

- strange quarks participate in the chiral dynamics in the same way as u and d

Beam Energy Scan

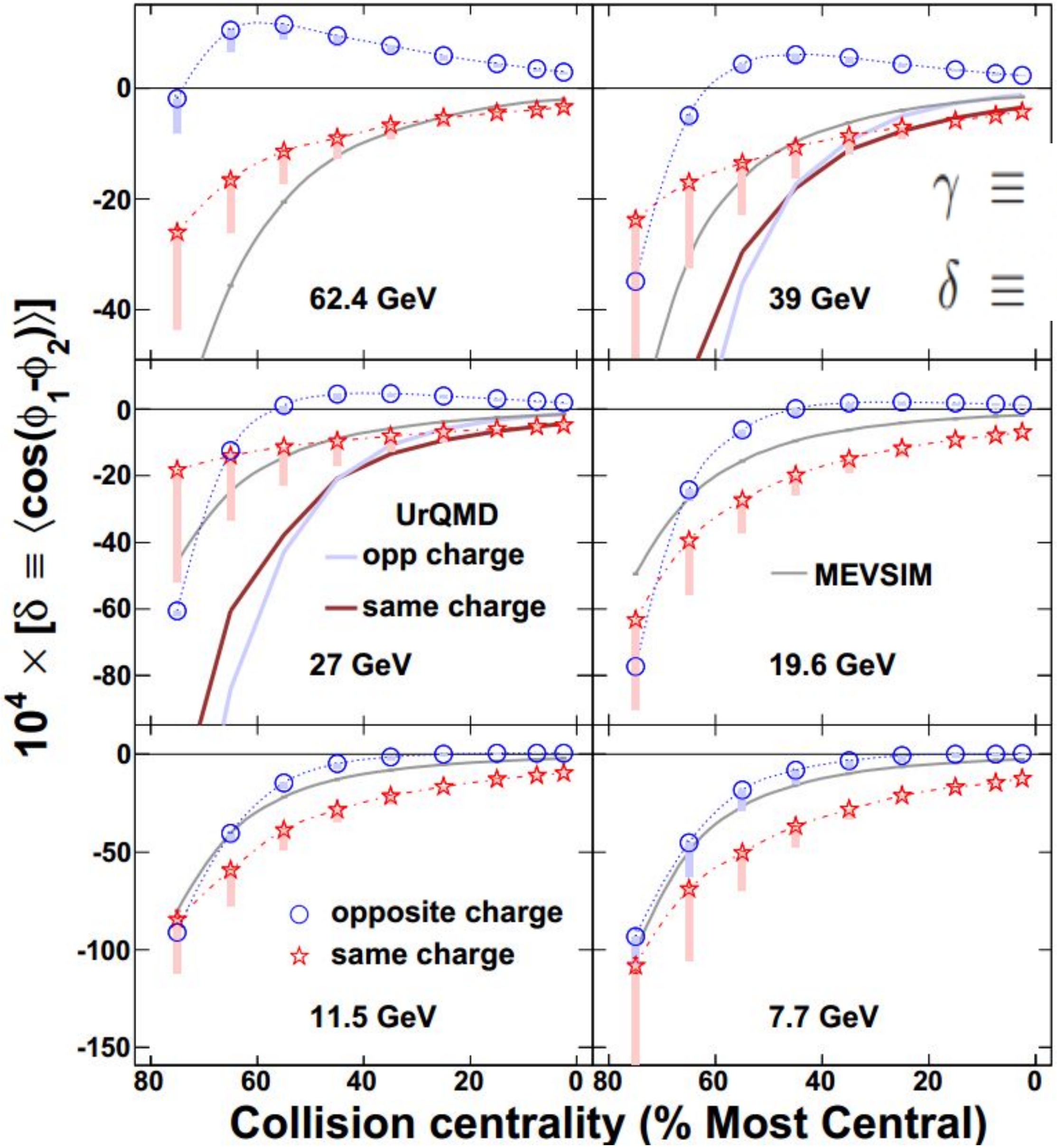
ALICE, Phys. Rev. Lett. 110, 012301 (2013); STAR, Phys. Rev. Lett 113 (2014) 052302



At lower beam energies, charge separation starts to diminish.

Flow-related background

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



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

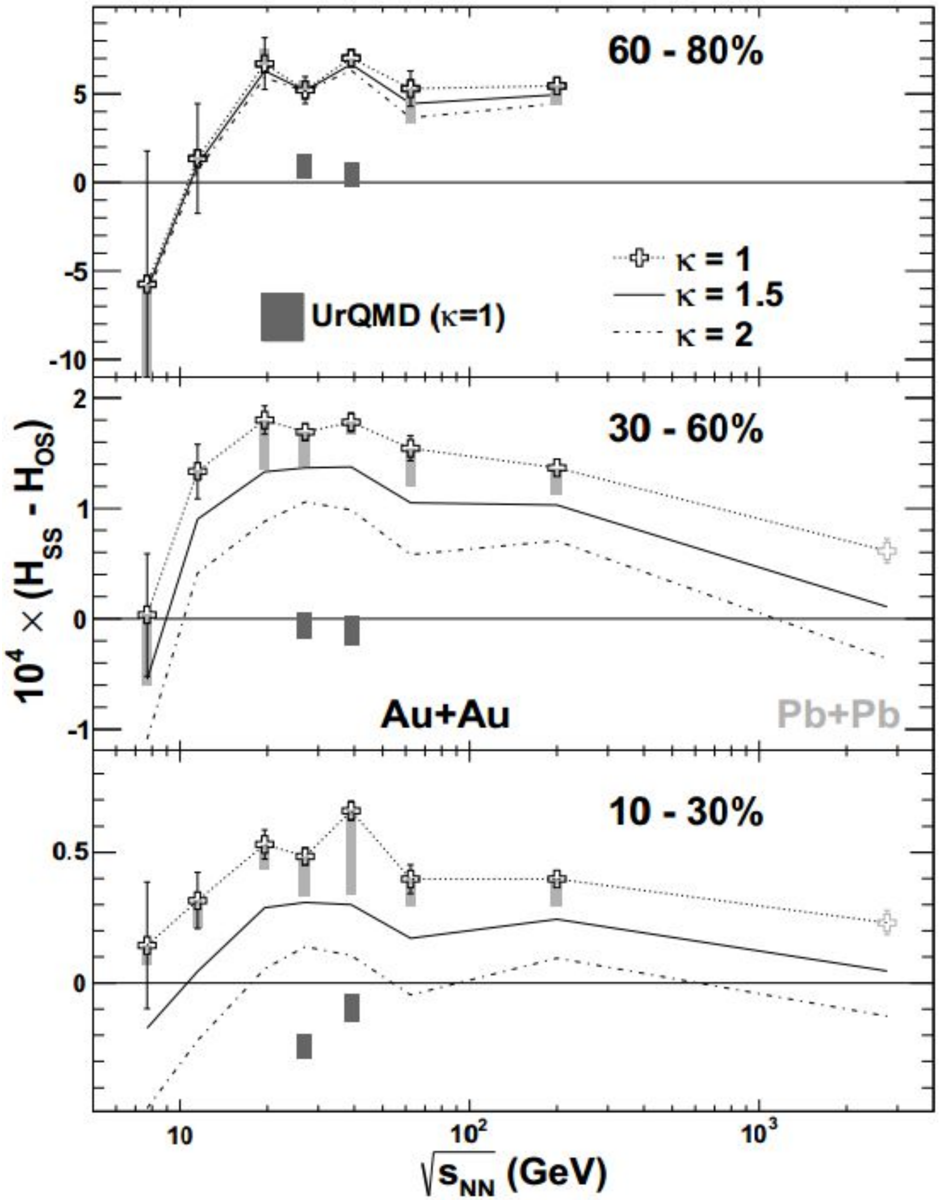
$$\gamma \equiv \langle \cos(\phi_1+\phi_2-2\Psi_{RP})\rangle = \kappa v_2 F - H$$

$$\delta \equiv \langle \cos(\phi_1-\phi_2)\rangle = F + H,$$

- 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

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



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

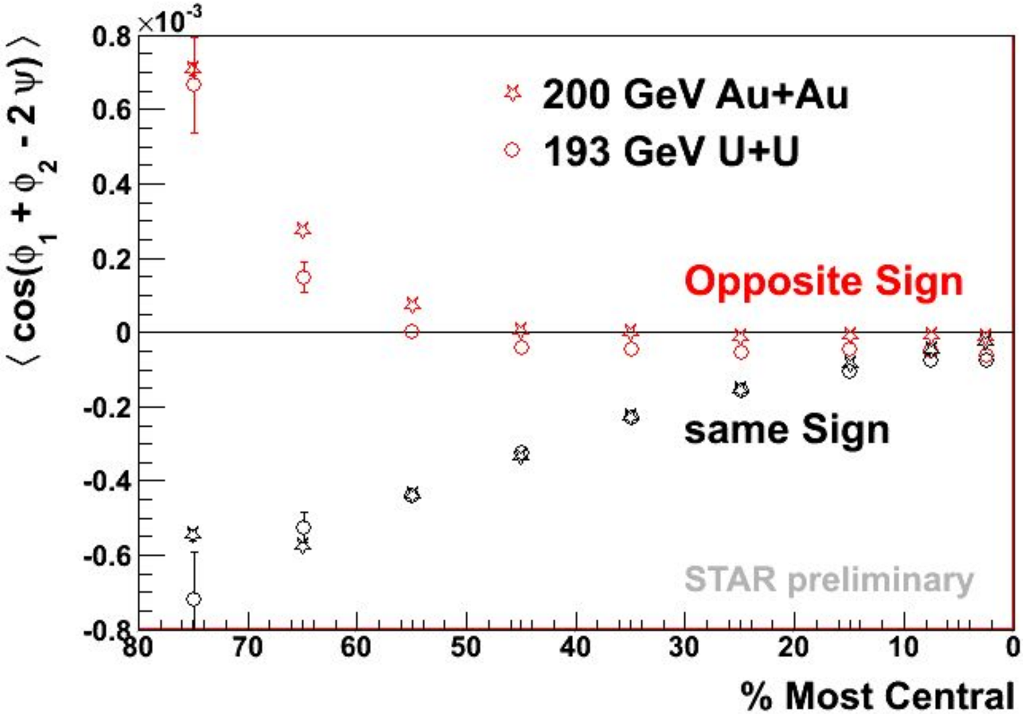
- κ could deviate from 1 due to a finite detector acceptance and theoretical uncertainties

- the CME signal decreases to zero in the interval between 19.6 and 7.7 GeV

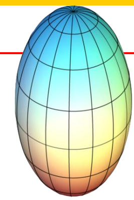
- probable domination of hadronic interactions over partonic ones

- need better theoretical estimate of κ and better statistics

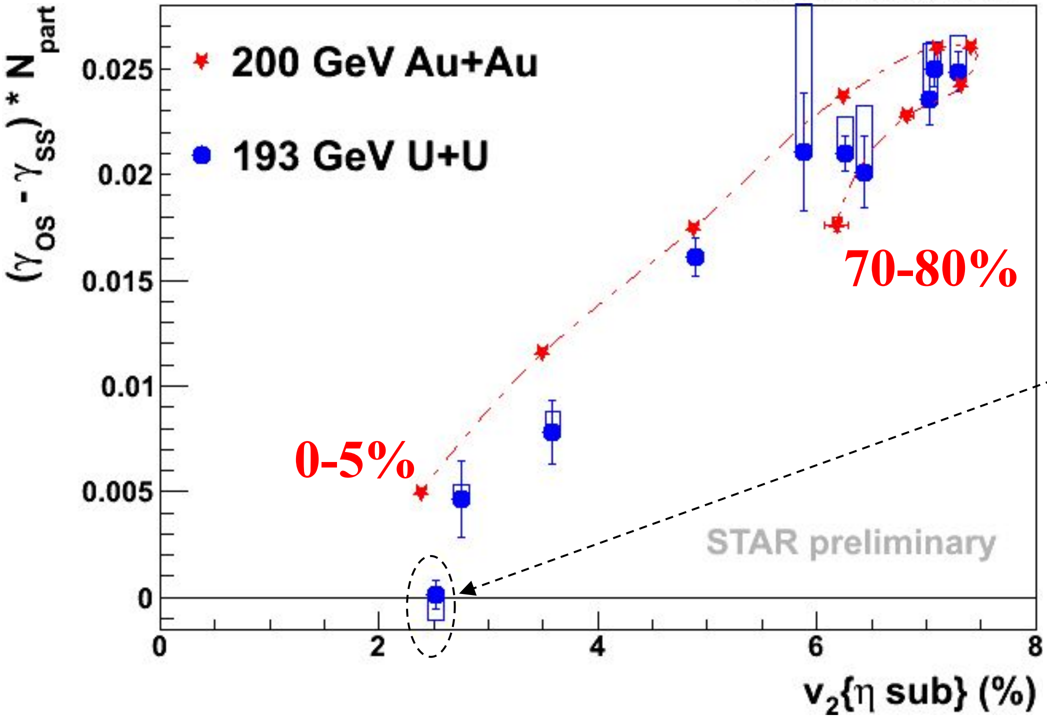
Another test: U+U



- Similar signals in U+U



- Consider γ_{OS}-γ_{SS} to be the signal
- N_{part} accounts for dilution effects



- A dedicated trigger for events with 0-1% spectator neutrons.
- With magnetic field suppressed, the charge separation signal disappears (and v_2 is still ~2.5%).

Chiral Vortical Effect

Chiral Magnetic Effect vs Chiral Vortical Effect

Chirality Imbalance (μ_A) -- Chirality Imbalance (μ_A)

Magnetic Field ($\omega\ \mu_e$) -- Fluid Vorticity ($\omega\ \mu_B$)

↓ ↓

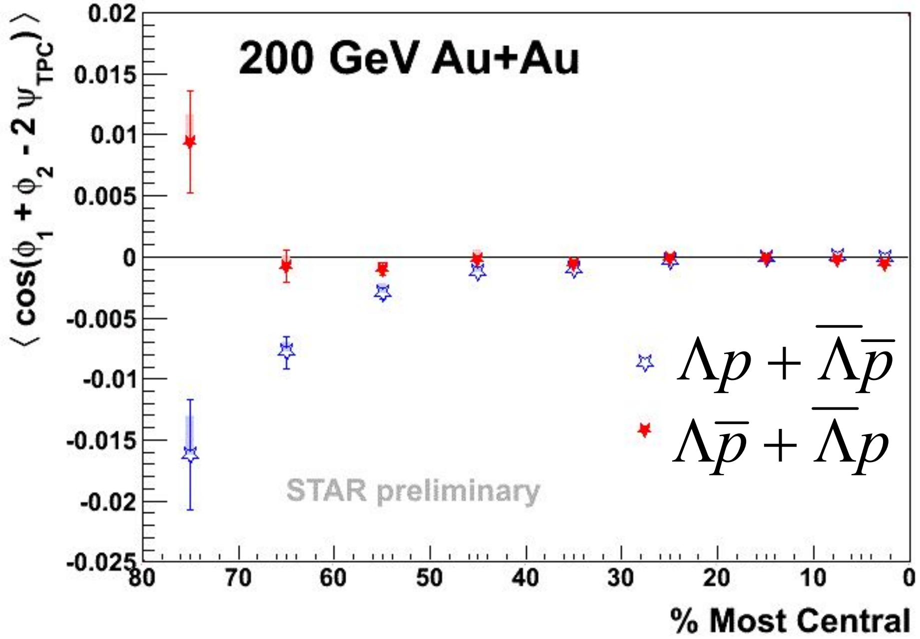
Electric Charge (j_e) -- Baryon Number (j_B)

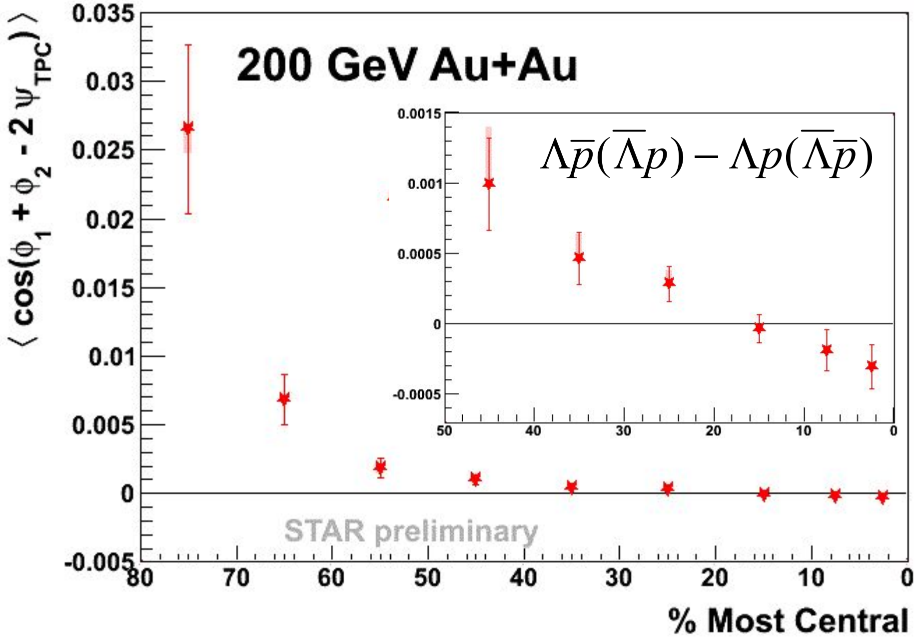
D. Kharzeev, D. T. Son, PRL 106 (2011) 062301

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

correlate Λ–p to search for the Chiral Vortical Effect

Λ-proton correlation





❖ Λp and $\overline{\Lambda}\overline{p}$ (same baryon number) show a similar behavior;

❖ $\Lambda\overline{p}$ and $\overline{\Lambda}p$ (opposite baryon number) show a similar behavior;

❖ "same B" is systematically lower than "oppo B" in the mid-central and peripheral collisions, consistent with the CVE expectation.

Summary II

- three-point correlation shows charge separation w.r.t RP
  - signal robust with different (1st- and 2nd-order) EPs
  - robust when suppressing HBT+Coulomb
  - robust with a reduced correlator, msc
  - robust in Au+Au, Pb+Pb and U+U (also in Cu+Cu, not shown)
  - robust from 19.6 GeV to 2.76 TeV

- signal of charge separation seems to disappear when
  - one charged particle is replaced with a neutral strange particle
  - the collision energy is down to ~7.7 GeV
  - the magnetic field from spectators is supressed (v_2 is still sizable)

- we also learn
  - CI bg comes from momentum conservation+v_2
  - flow-related bg could be subtracted via H

- CVE signal has been observed for the first time
  - more investigations underway

Outlook: another test ground

Isobars are atoms (nuclides) of different chemical elements that have the same number of nucleons.

For example, $^{96}_{44}$Ruthenium and $^{96}_{40}$Zirconium

	$^{96}_{44}Ru+^{96}_{44}Ru$ vs $^{96}_{40}Zr+^{96}_{40}Zr$
Flow	=
CMW	>
CME	>
CVE	=

Chiral Electric Separation Effect

Ohm's Law

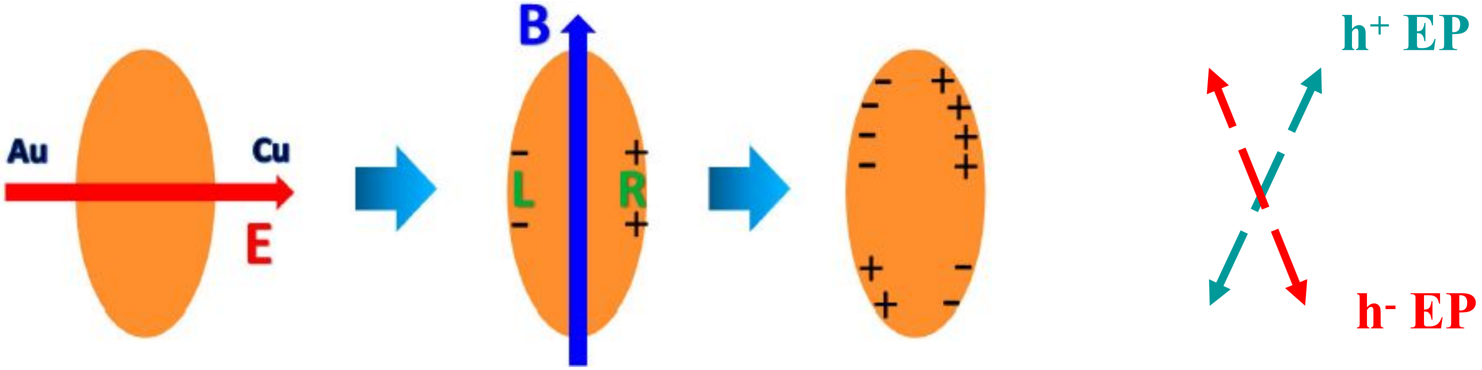
Chiral Magnetic Effect

	E	B
J_V	σ	$(e/2\pi^2)\mu_A$
J_A	$\propto \sigma\mu_V\mu_A/T^2$	$(e/2\pi^2)\mu_V$

Chiral Electric Separation Effect

Chiral Separation Effect

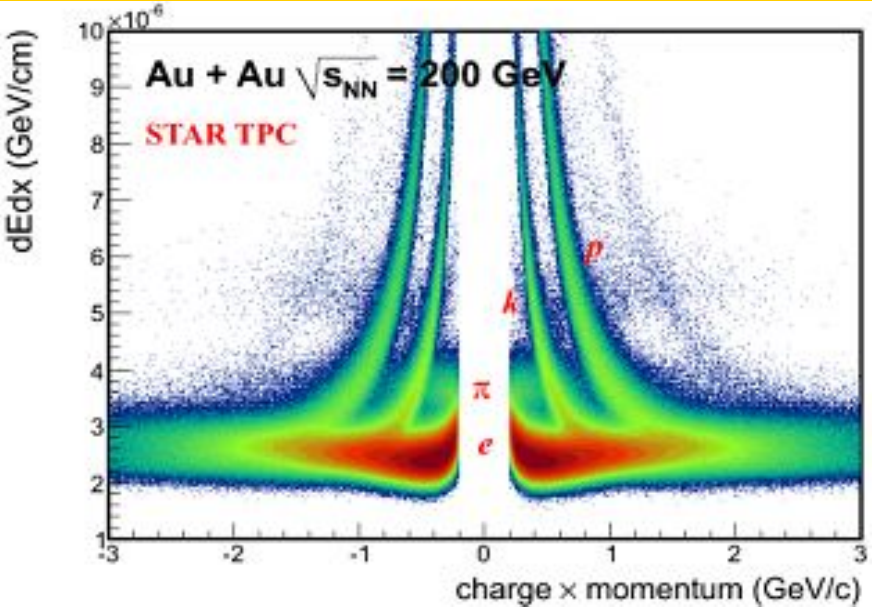
Y. Jiang, X.-G. Huang, J. Liao, arXiv:1409.6395

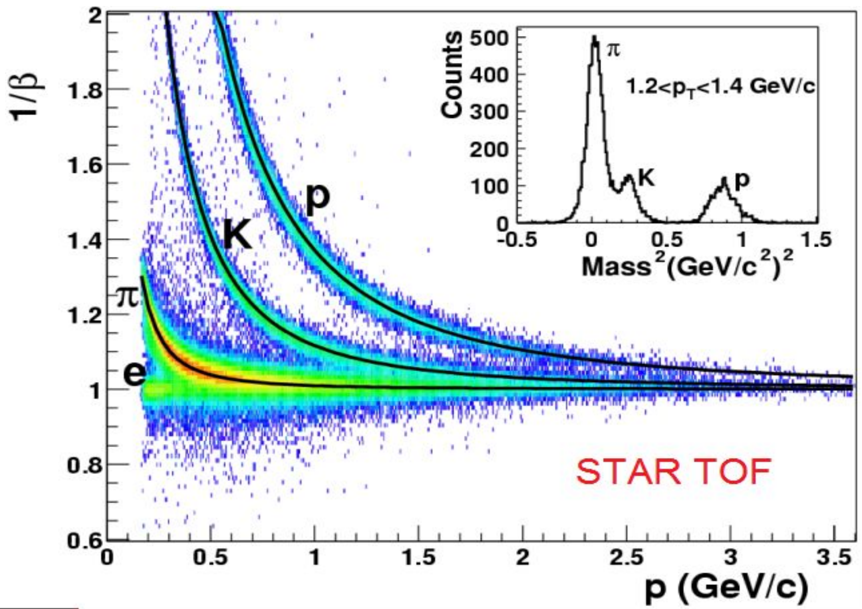


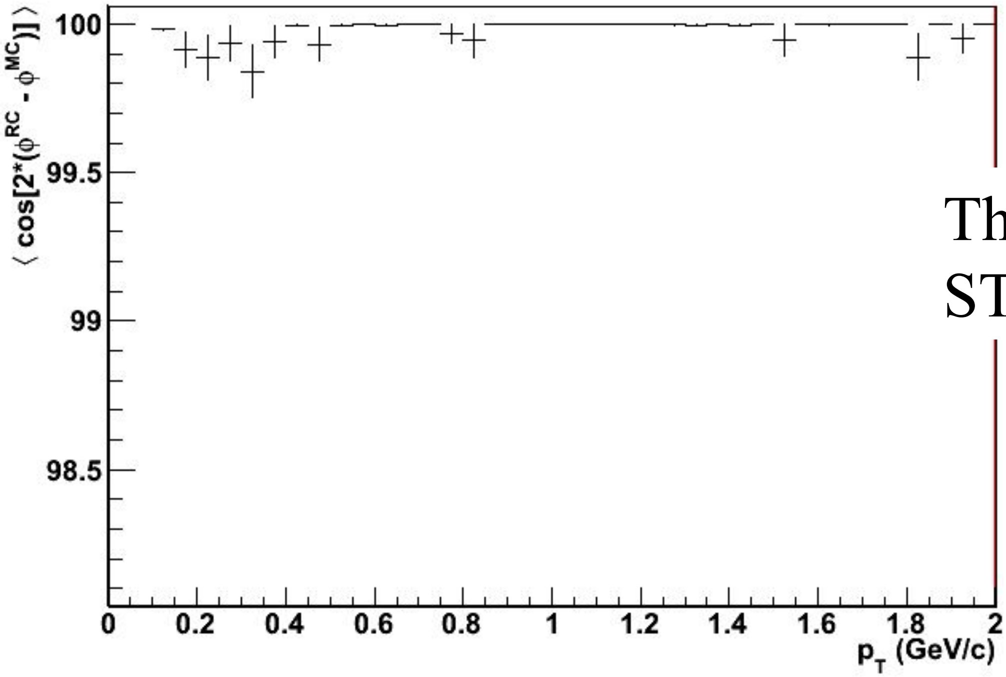
Charged event planes intersect in Cu+Au collisions?

Backup slides

STAR: excellent PID and tracking

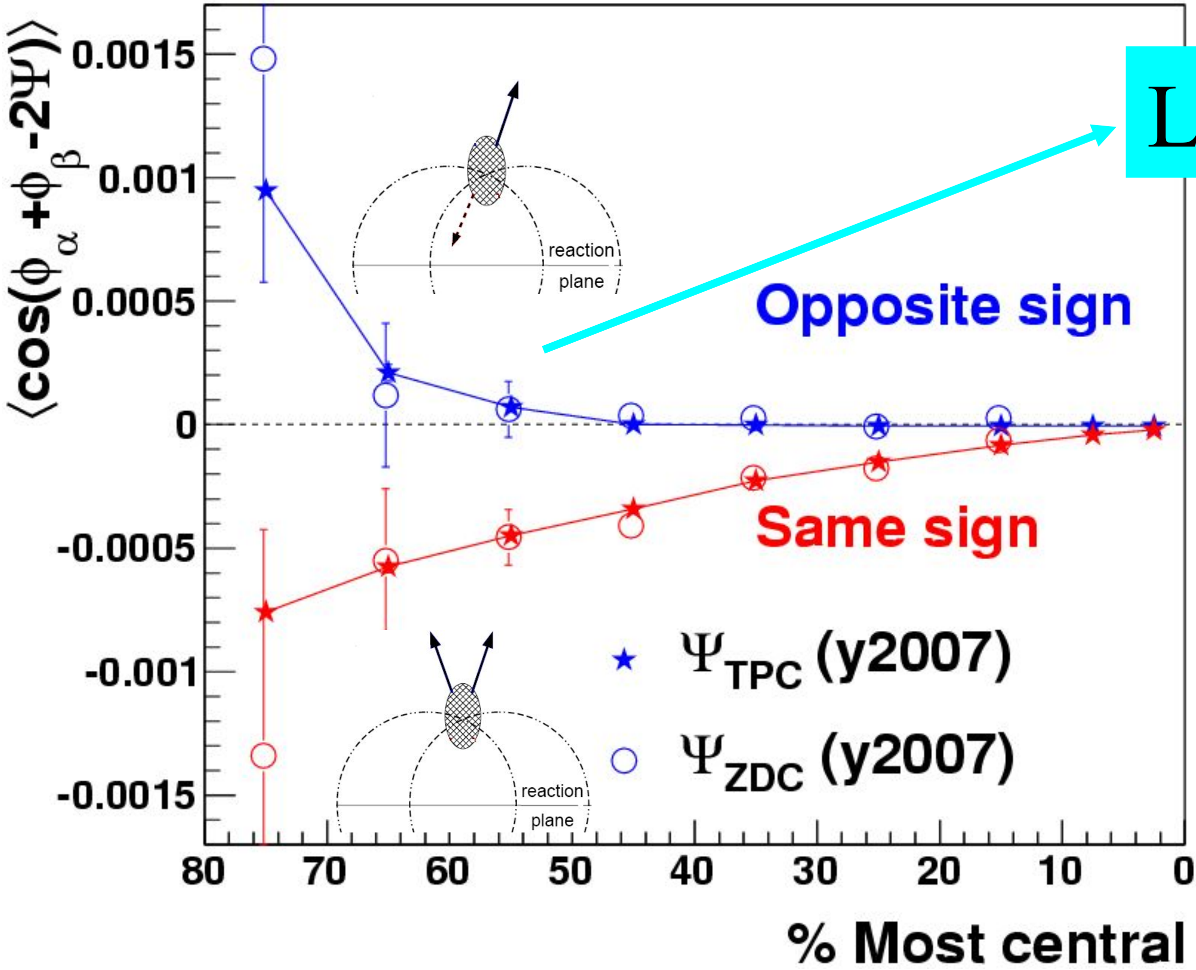




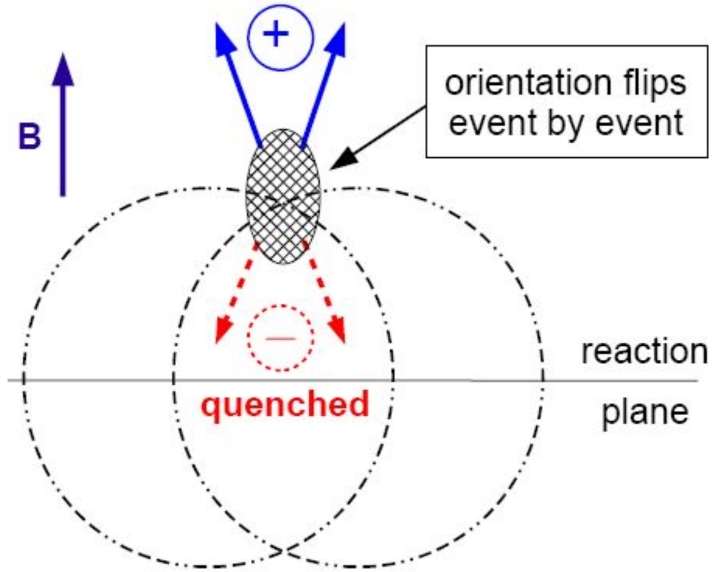


The correlation measurements at STAR are accurate to relative 0.1%.

Results with different EPs

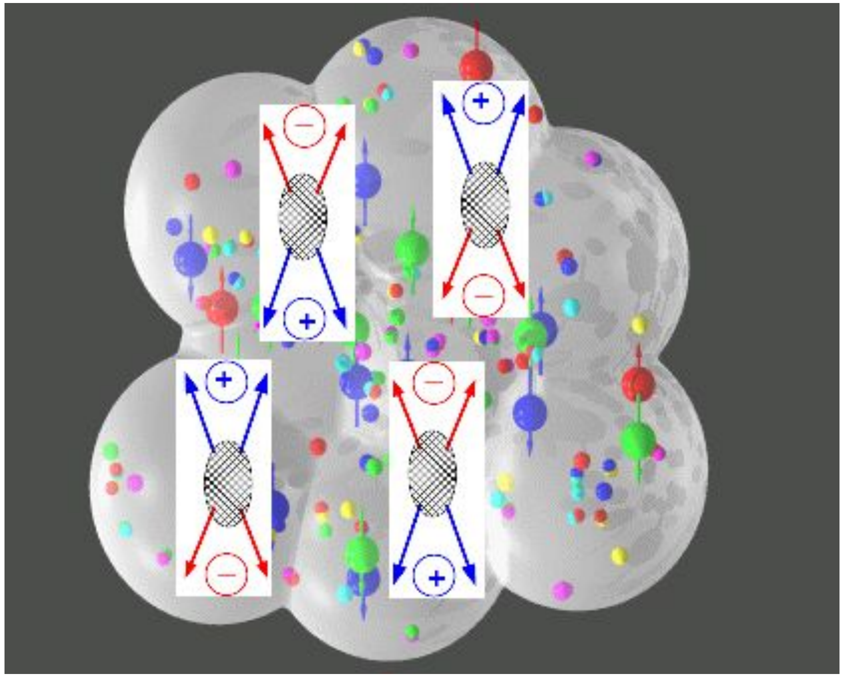


Lost in the medium?



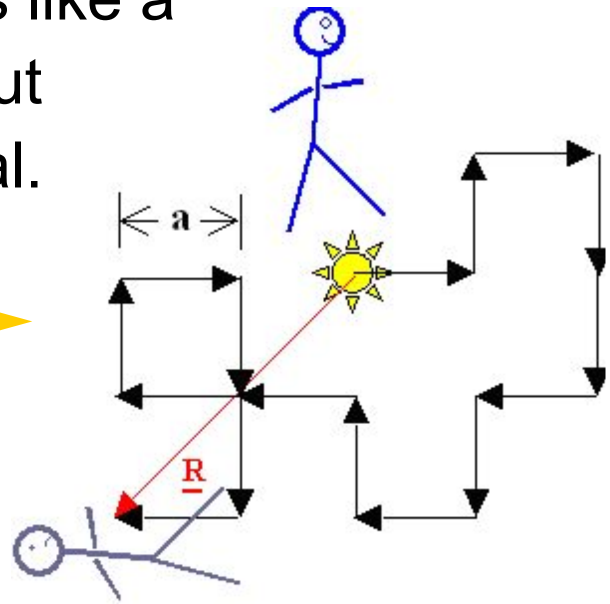
The correlators using TPC/ZDC event planes are consistent with each other.

Dilution effect



In the quark-gluon medium, there could be multiple *P*-odd domains.

The net effect is like a *random walk*, but one-dimensional.

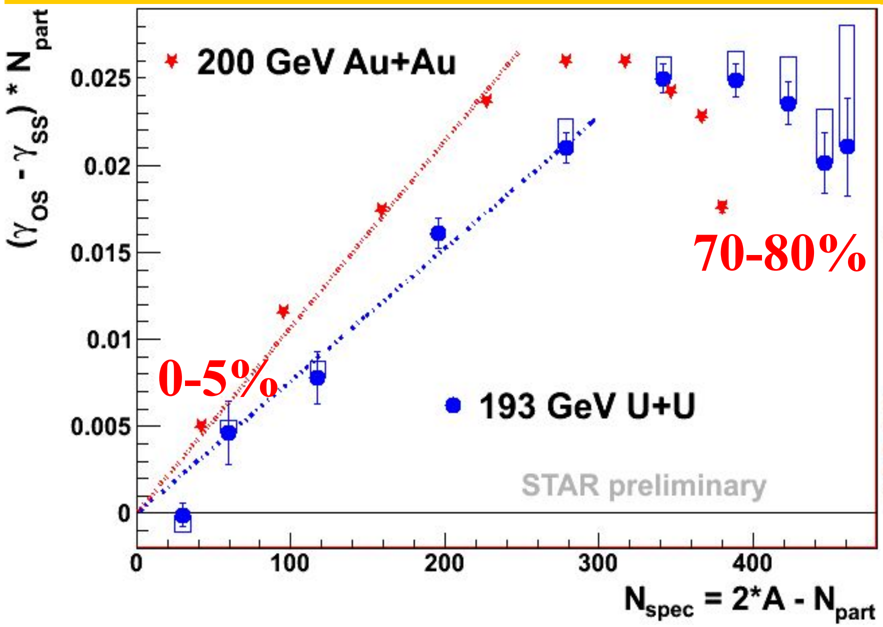


What do we know about the position R_n after n steps?

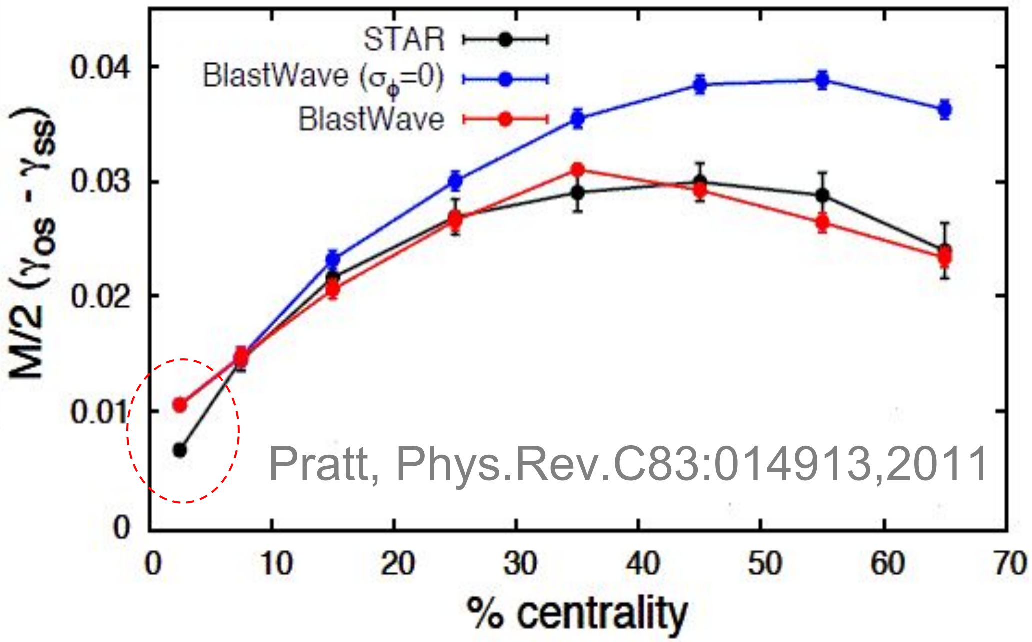
R_n follows a Gaussian distribution: *mean* = 0, and *rms* = $\sqrt{n}$

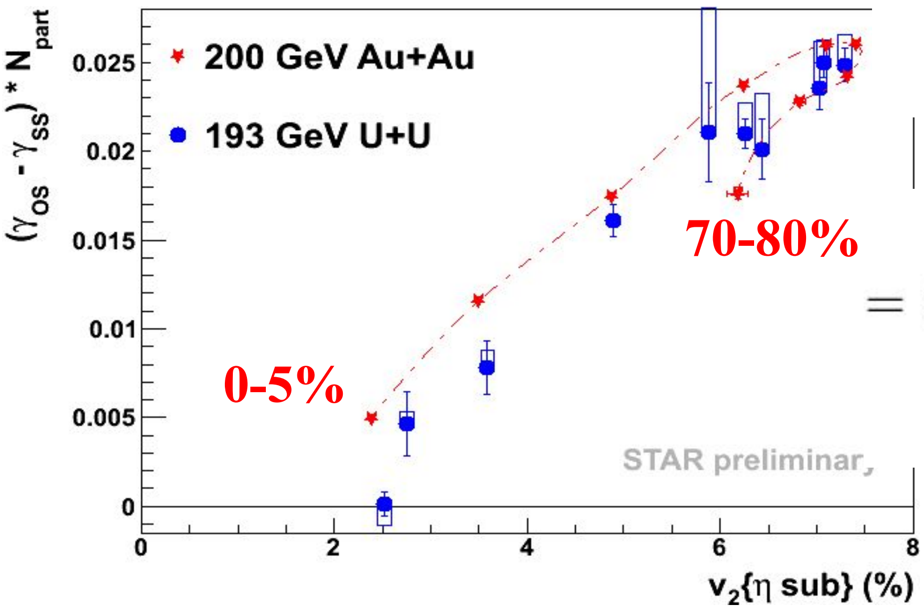
Our measurement of PV is like R_n^2, expected to be n.
Compared with going in one fixed direction, where $R_n^2 = n^2$,
the "random-walk" measurement is diluted by a factor **$\sim n \sim N_{part}$.**

Possible physics background



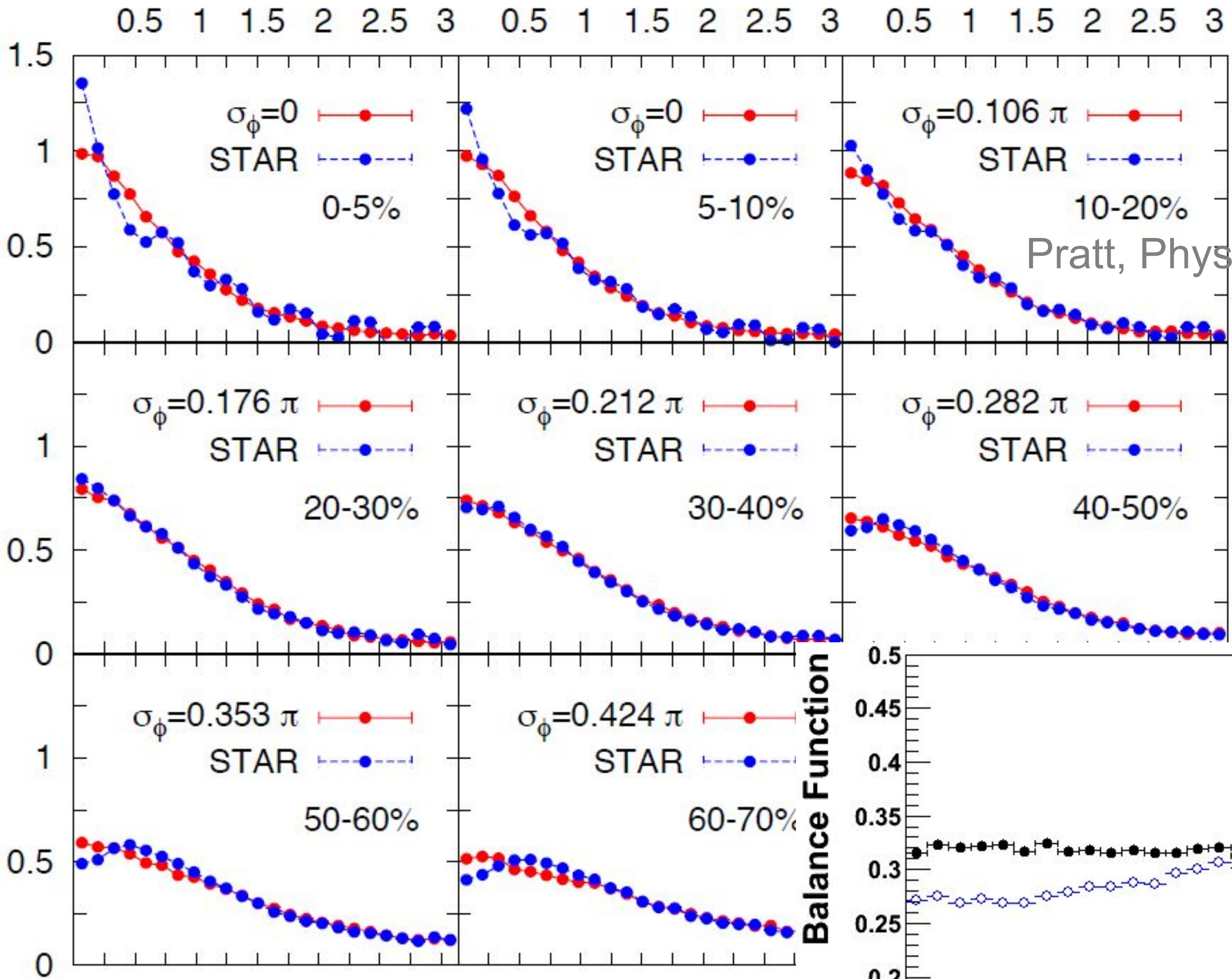
charge conservation/cluster + v_2





$$\begin{aligned}&\langle\cos(\phi_\alpha + \phi_\beta - 2\Psi_{RP})\rangle\\ &= \langle\cos((\phi_\alpha + \phi_\beta - 2\phi_{res}) + 2(\phi_{res} - \Psi_{RP}))\rangle\\ &\approx \frac{f_{res}\,\langle\cos(\phi_\alpha + \phi_\beta - 2\phi_{res})\rangle\, v_{2,res}}{N_{ch}}\end{aligned}$$

Balance function



Pratt, Phys.Rev.C83:014913,2011