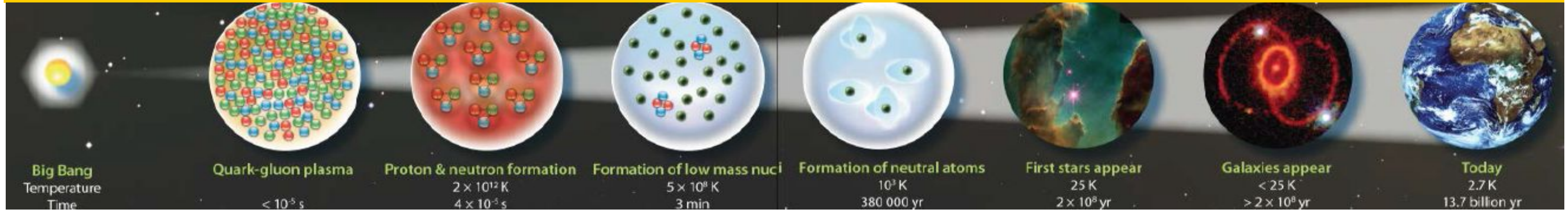
A Review of the Search for Chiral Effects at STAR

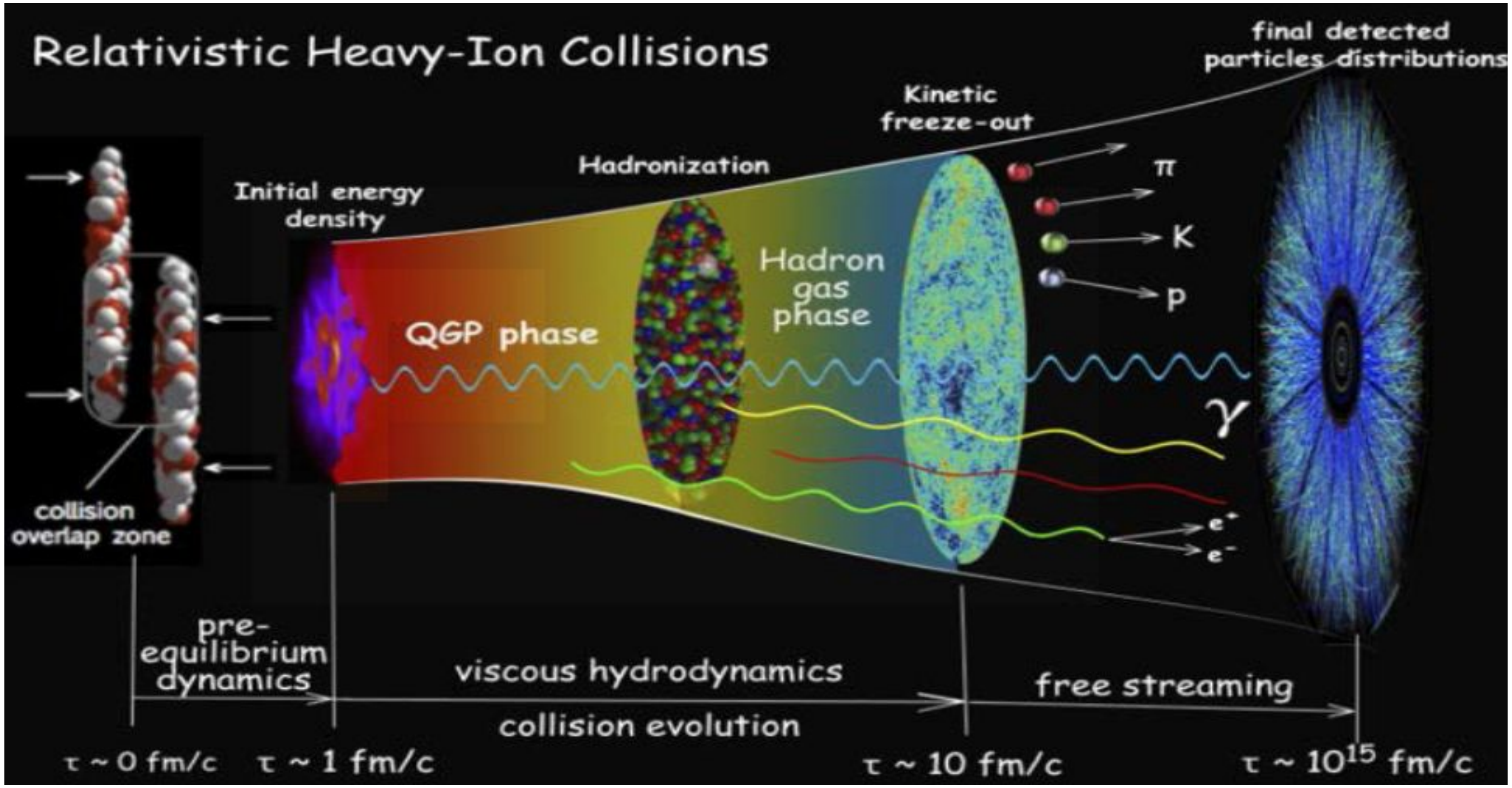
Gang Wang (UCLA)

From Big Bang to Small Bangs

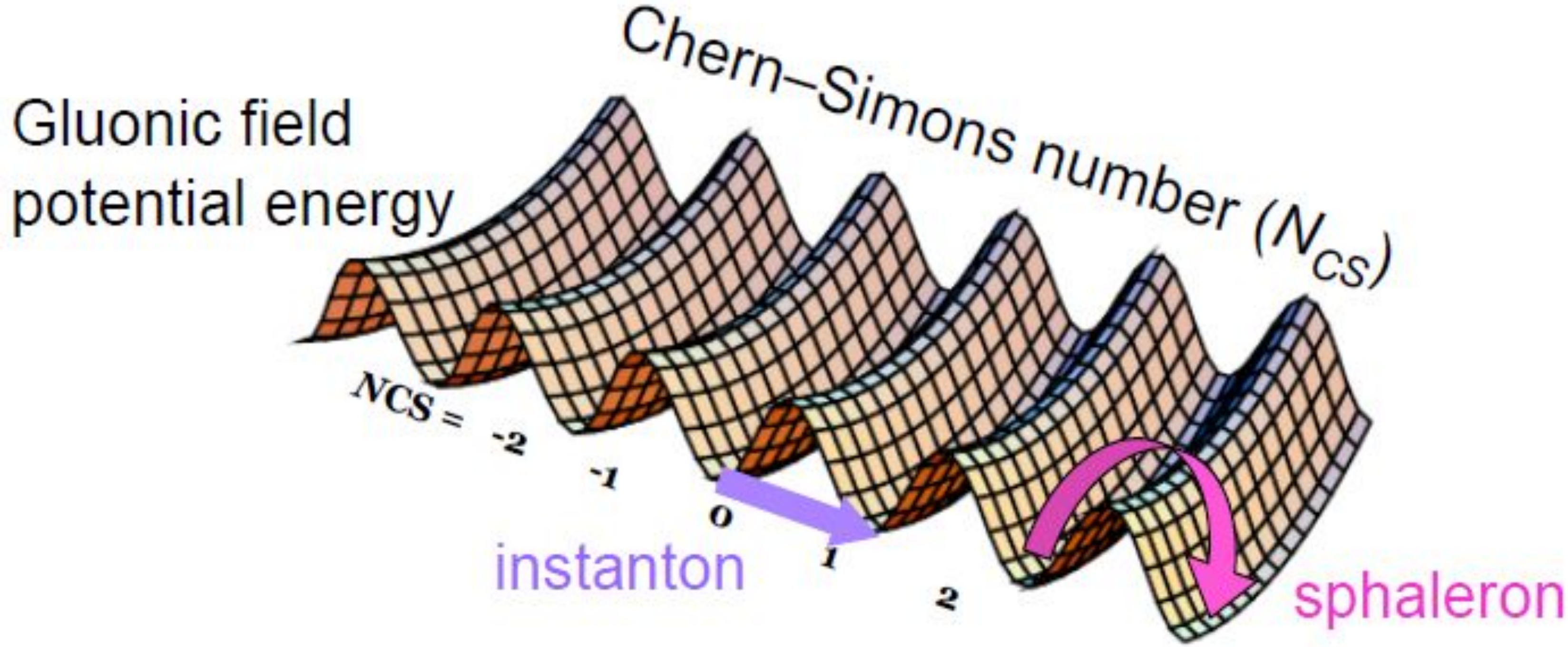


What if the vacuum/domain we live in is not the true ground state?

- the "wrong" vacuum will collapse into a lower state
- one day we may save the world



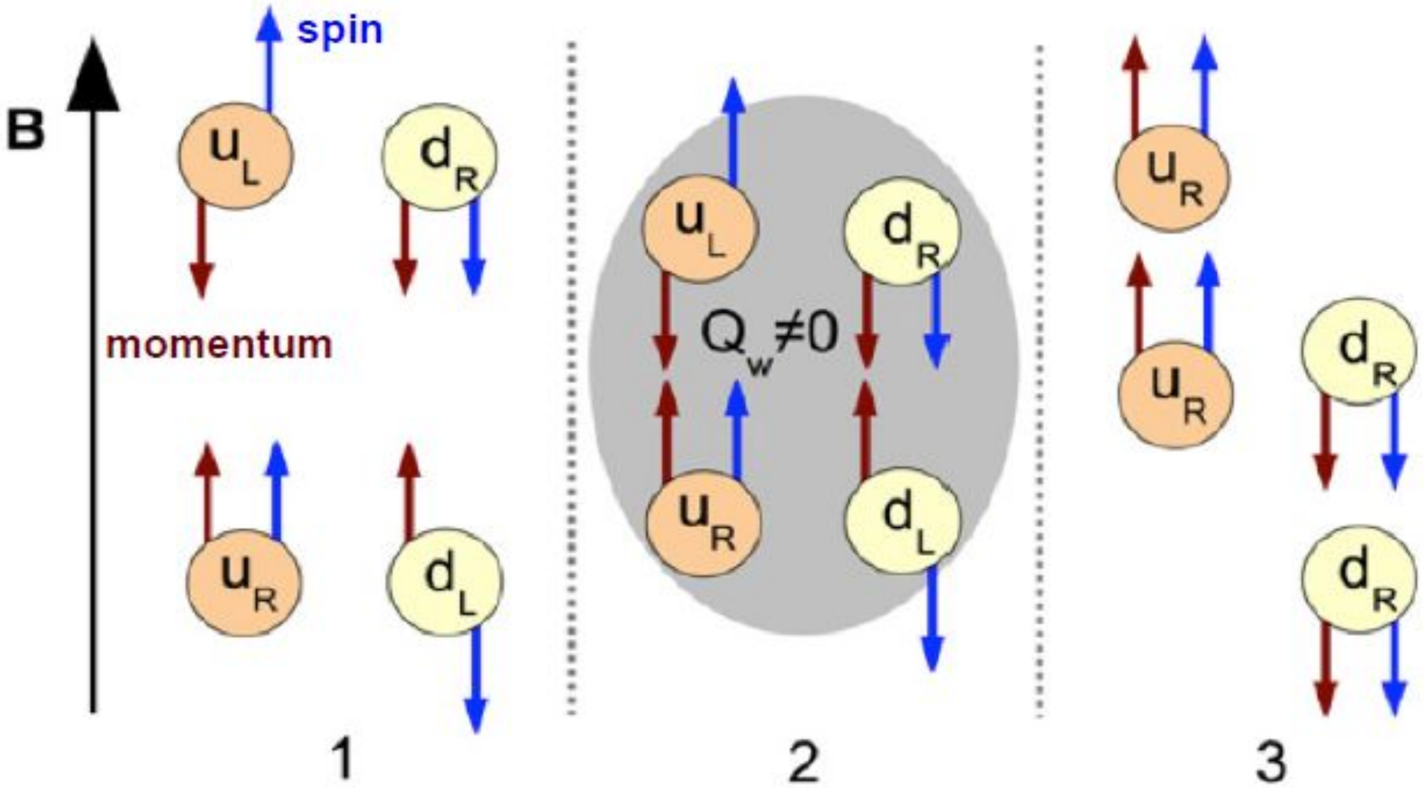
QCD vacuum transition



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

QCD vacuum transition
➔ nonzero topological charge
➔ chirality imbalance

Chiral Magnetic Effect

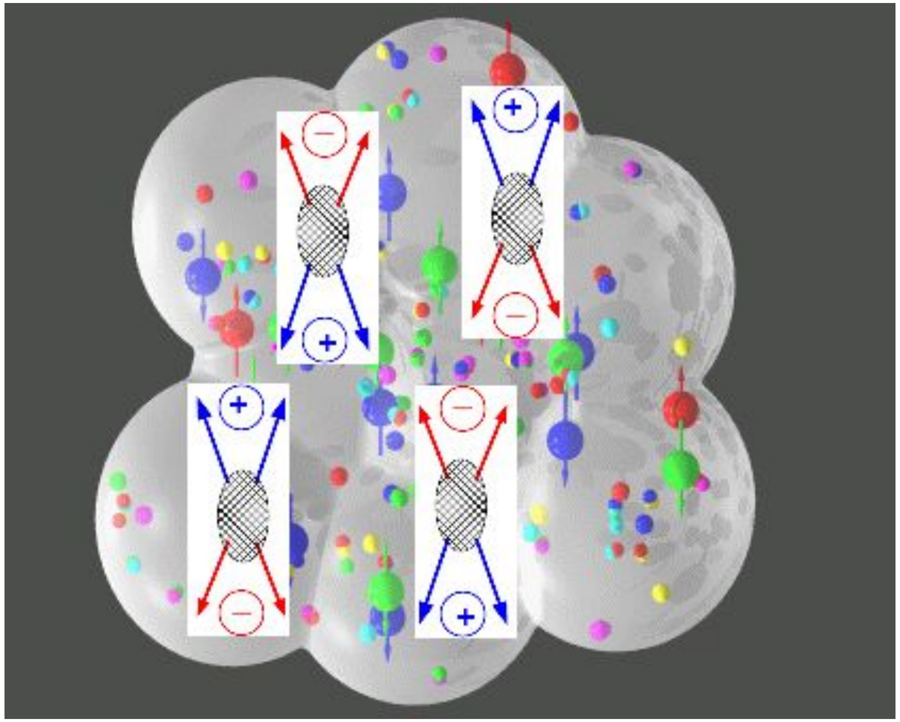


Chiral Magnetic Effect **(CME):** finite chiral charge density induces an electric current along external magnetic field.

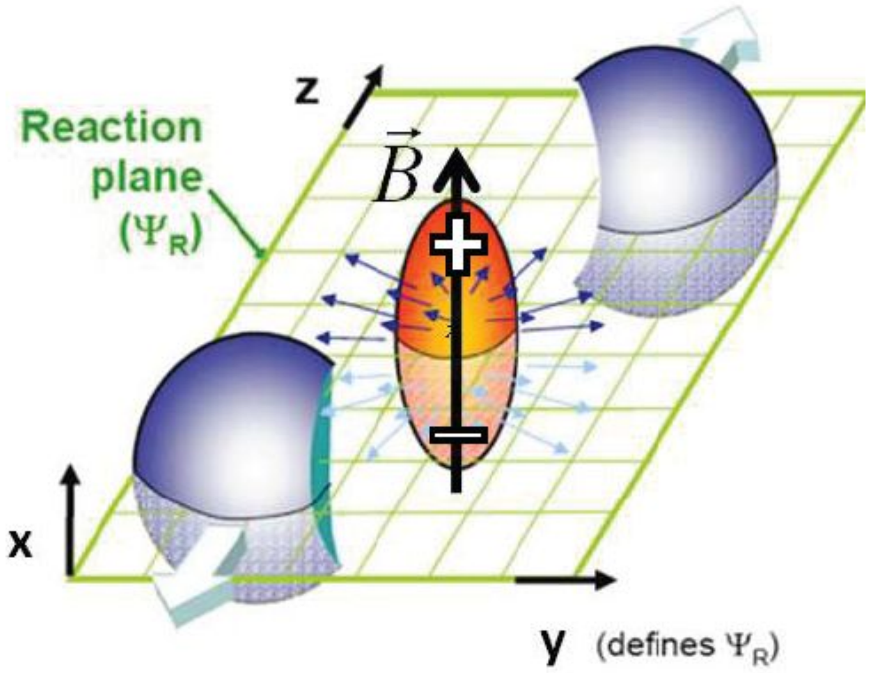
$$j_V = \frac{N_c e}{2\pi^2}\mu_A B$$ ➔ electric charge separation along *B* field

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

Observable



CME => charge separation across RP



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

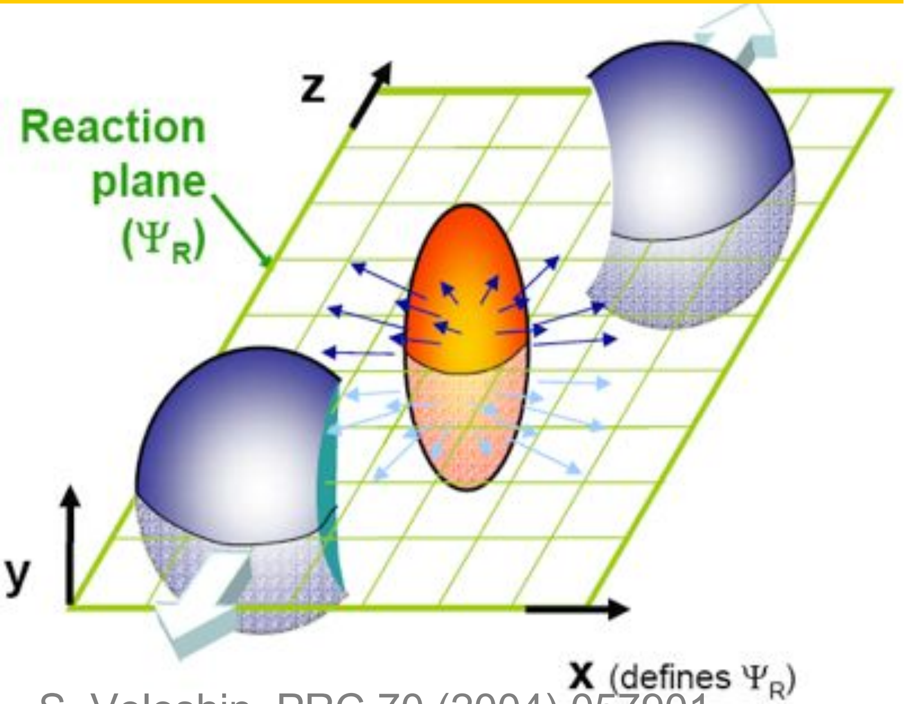
charge separation effect beyond conventional physics background

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

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

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

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

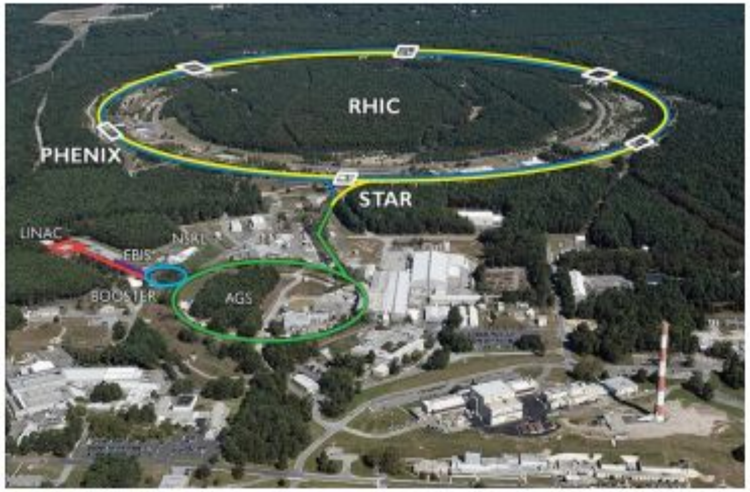
background effects: largely cancel out

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

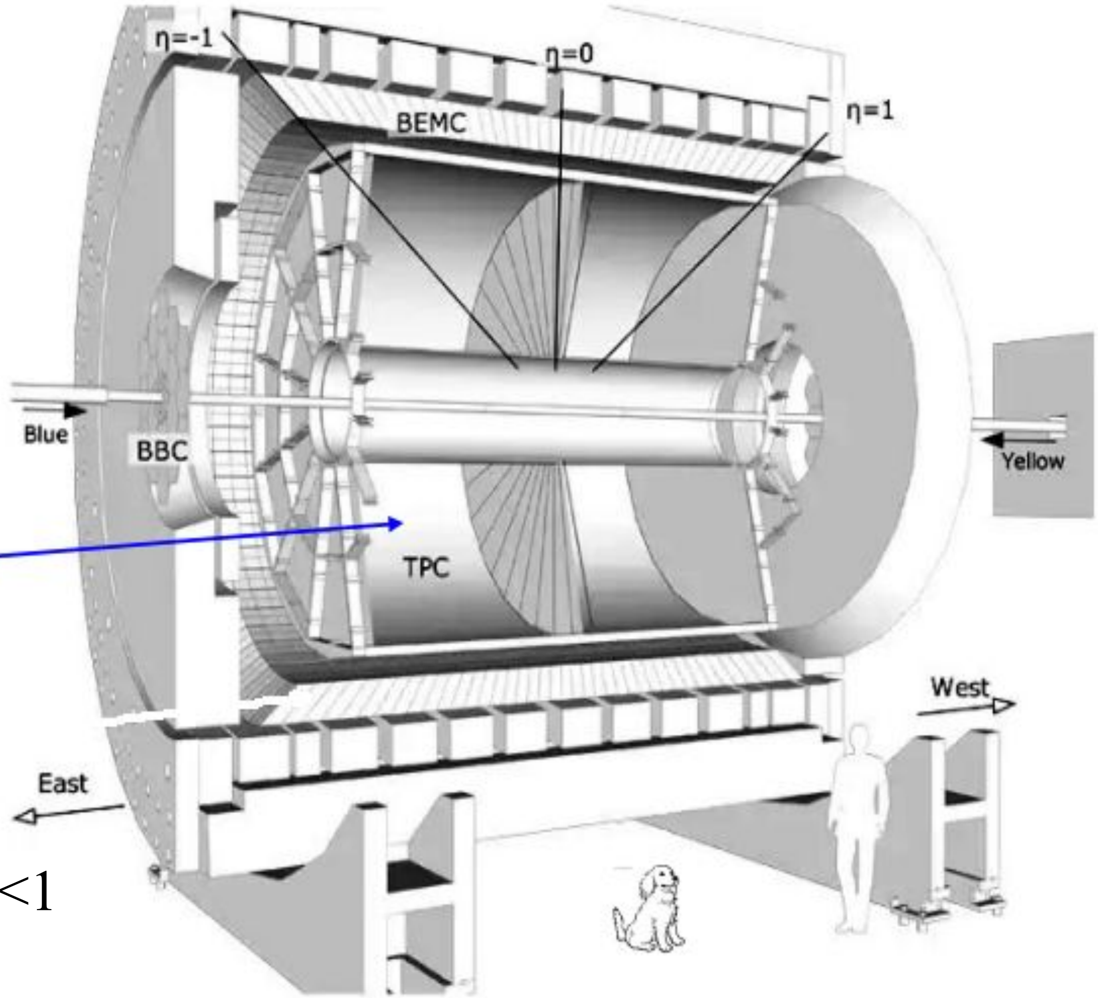
P-even quantity: still sensitive to charge separation

STAR experiment

Relativistic Heavy Ion Collider (RHIC)



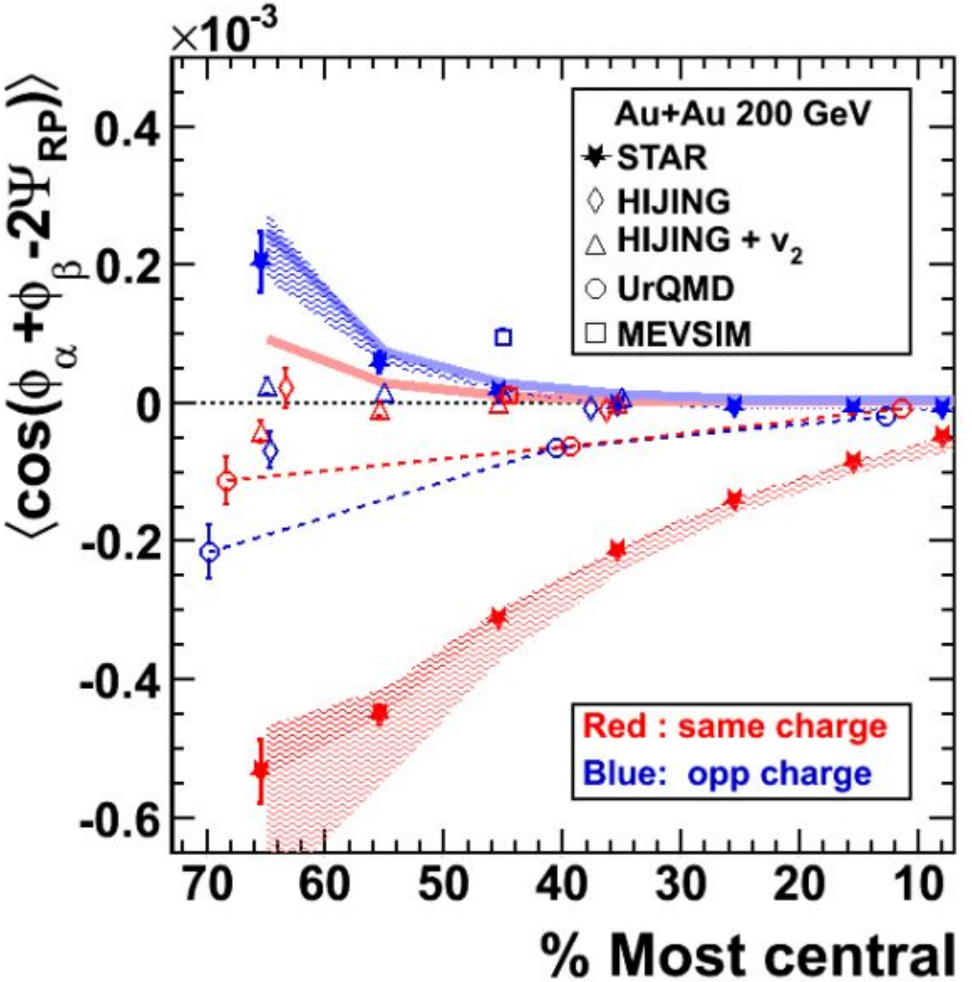
Solenoidal Tracker at RHIC (STAR)

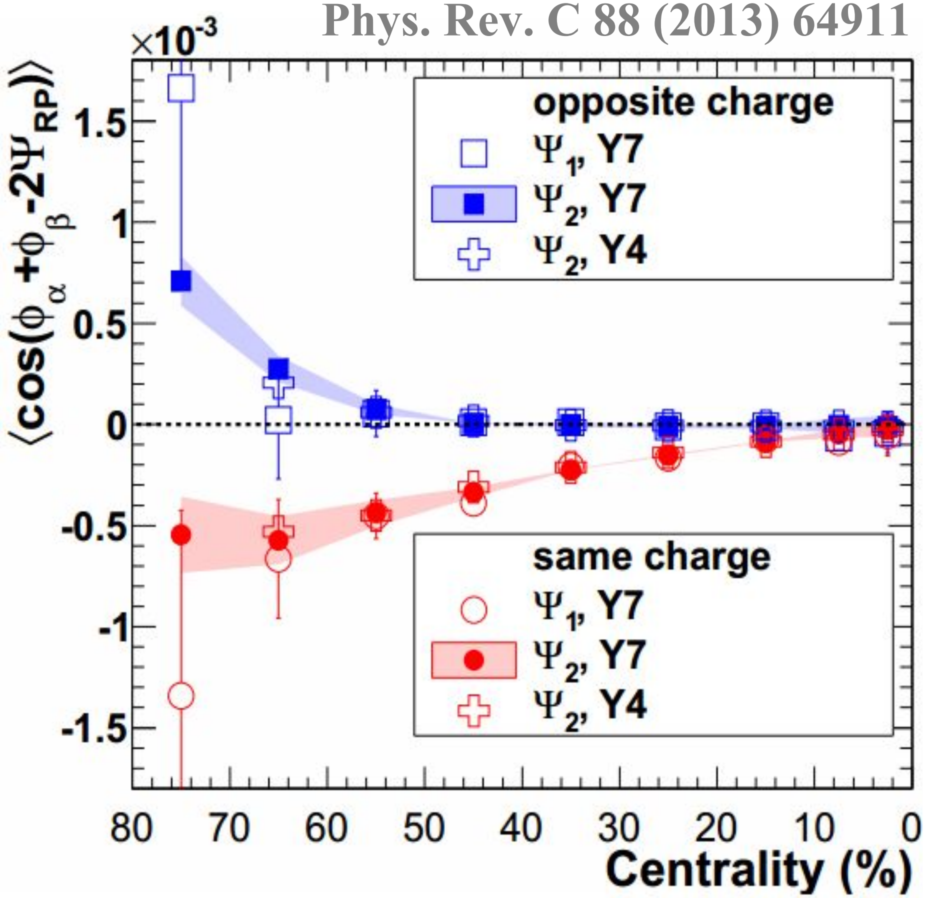


Time Projection Chamber

- full azimuthal coverage
- pseudo-rapidity coverage: $-1<\eta<1$
- TPC tracks -> charged particles

γ at 200 GeV Au+Au



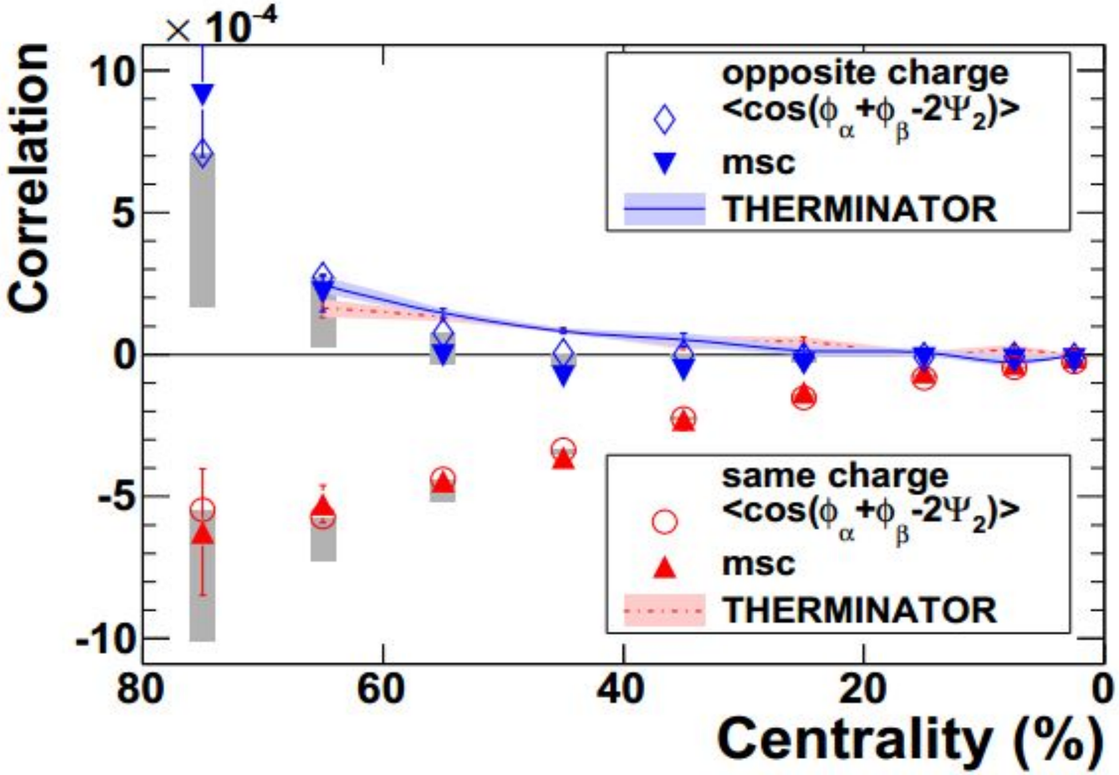


Phys. Rev. C 88 (2013) 64911

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

- Different γ_{os} and γ_{ss}, consistent with the CME expectation
- Not explained by known event generators
- Confirmed with 1st-order EP from spectator neutrons

msc



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

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

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

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

- 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
- also robust after removing HBT+Coulomb effects

Phys. Rev. C 88 (2013) 64911

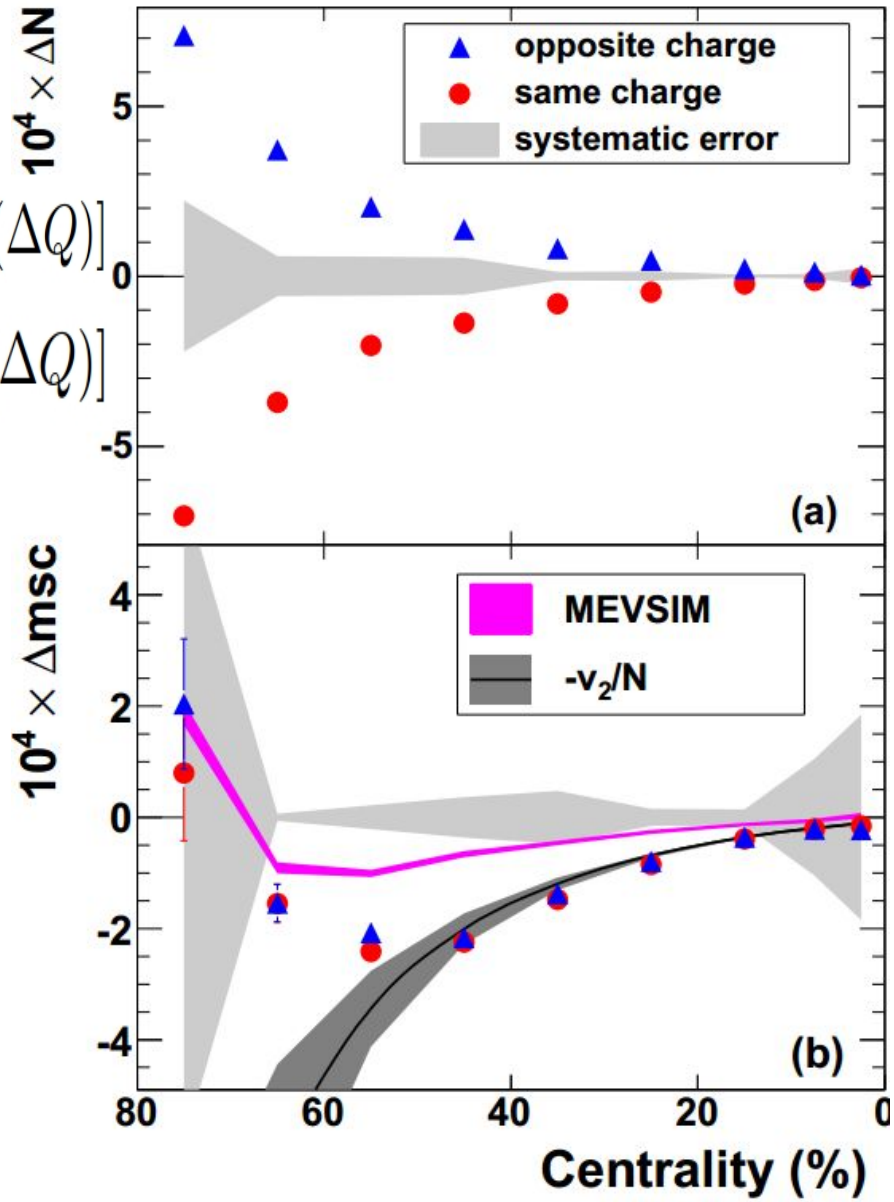
Charge-independent background

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

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

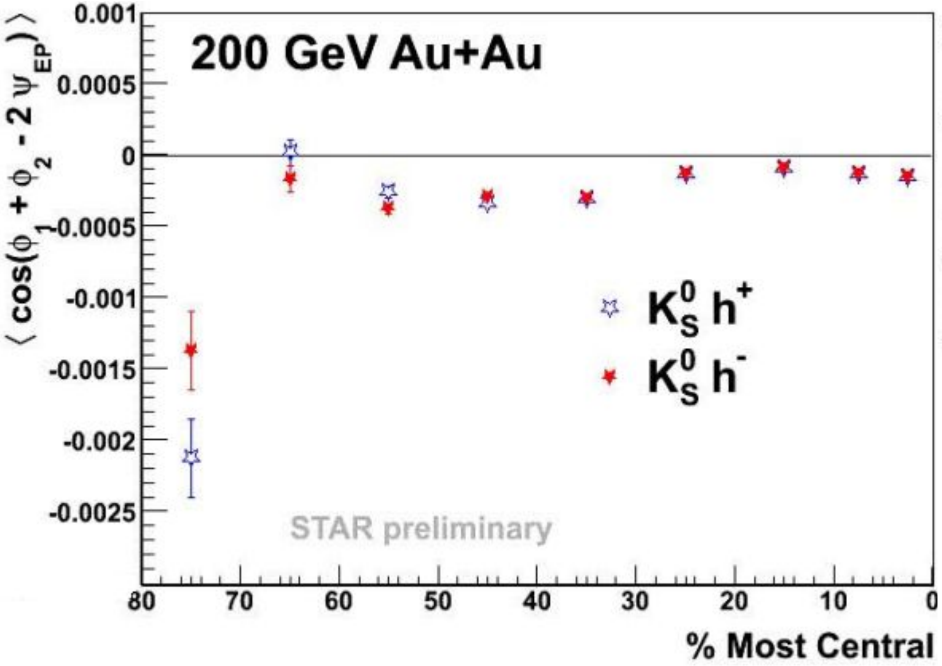
$$\Delta N = \frac{1}{N_E} \sum_{\Delta Q} \langle \text{msc}(\Delta Q) \rangle \left[N_{IN}(\Delta Q) - N_{OUT}(\Delta Q)\right]$$

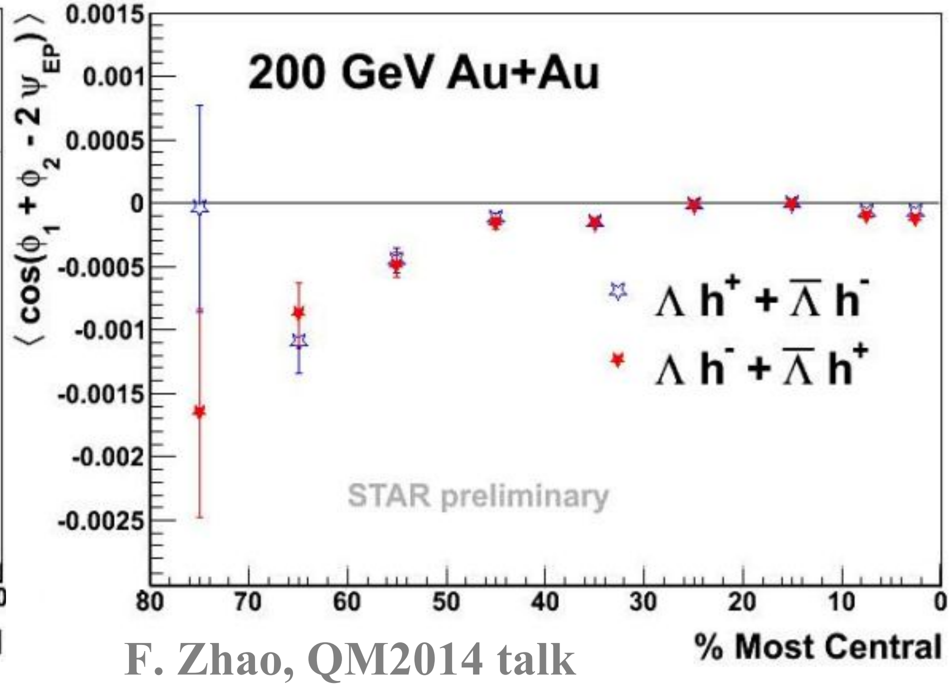
- msc was splitted to study bg
- $N_{IN}(\Delta Q)$ stands for the number of events with ΔQ units of in-plane charge separation, and $\text{msc}_{IN}(\Delta Q)$ stands for the <msc> in those events.
- MEVSIM and $-v_2/N$ tell us that the CI bg is likely due to momentum conservation + v_2



Phys. Rev. C 88 (2013) 64911

Neutral-charged correlation



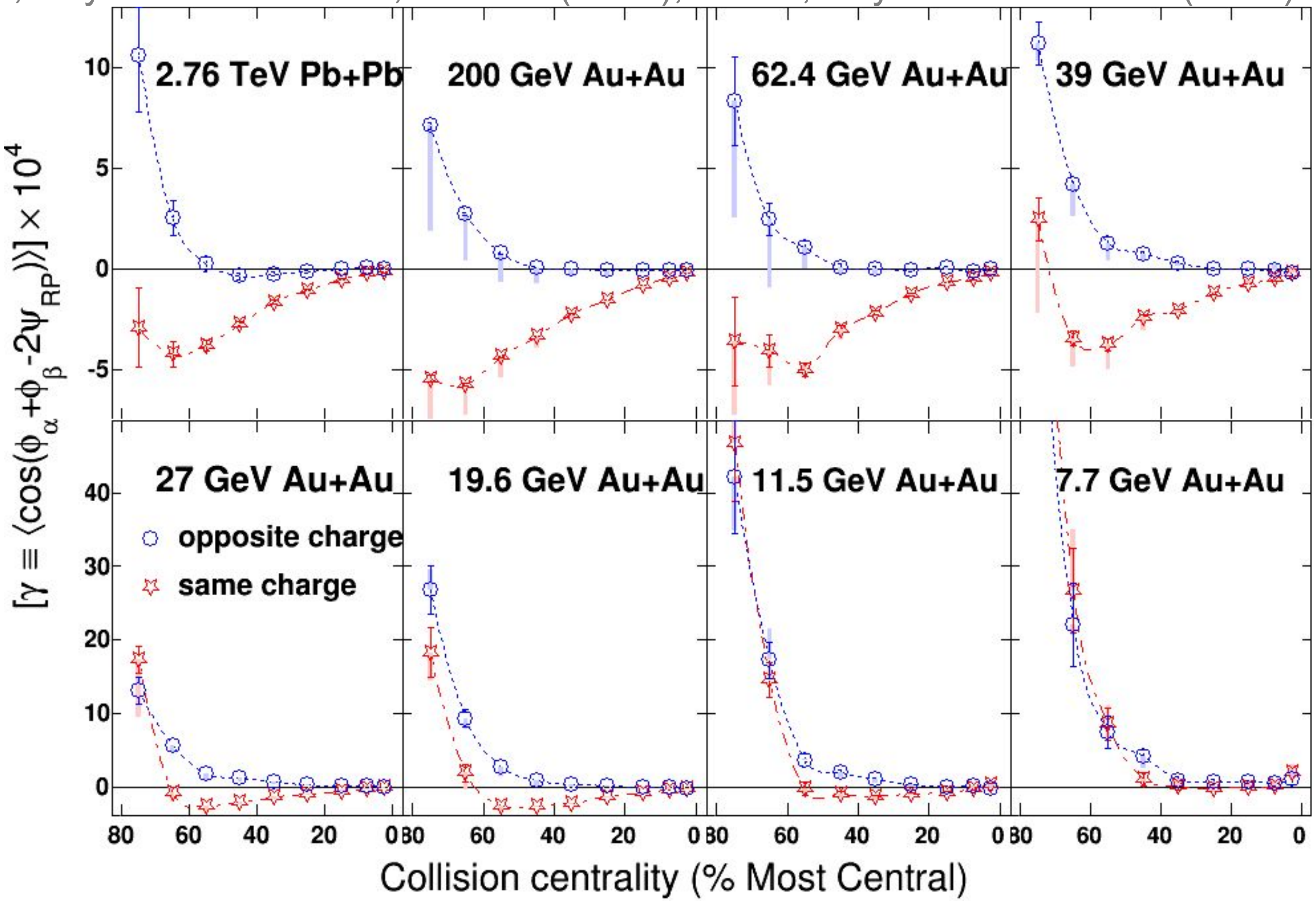


F. Zhao, QM2014 talk

- 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

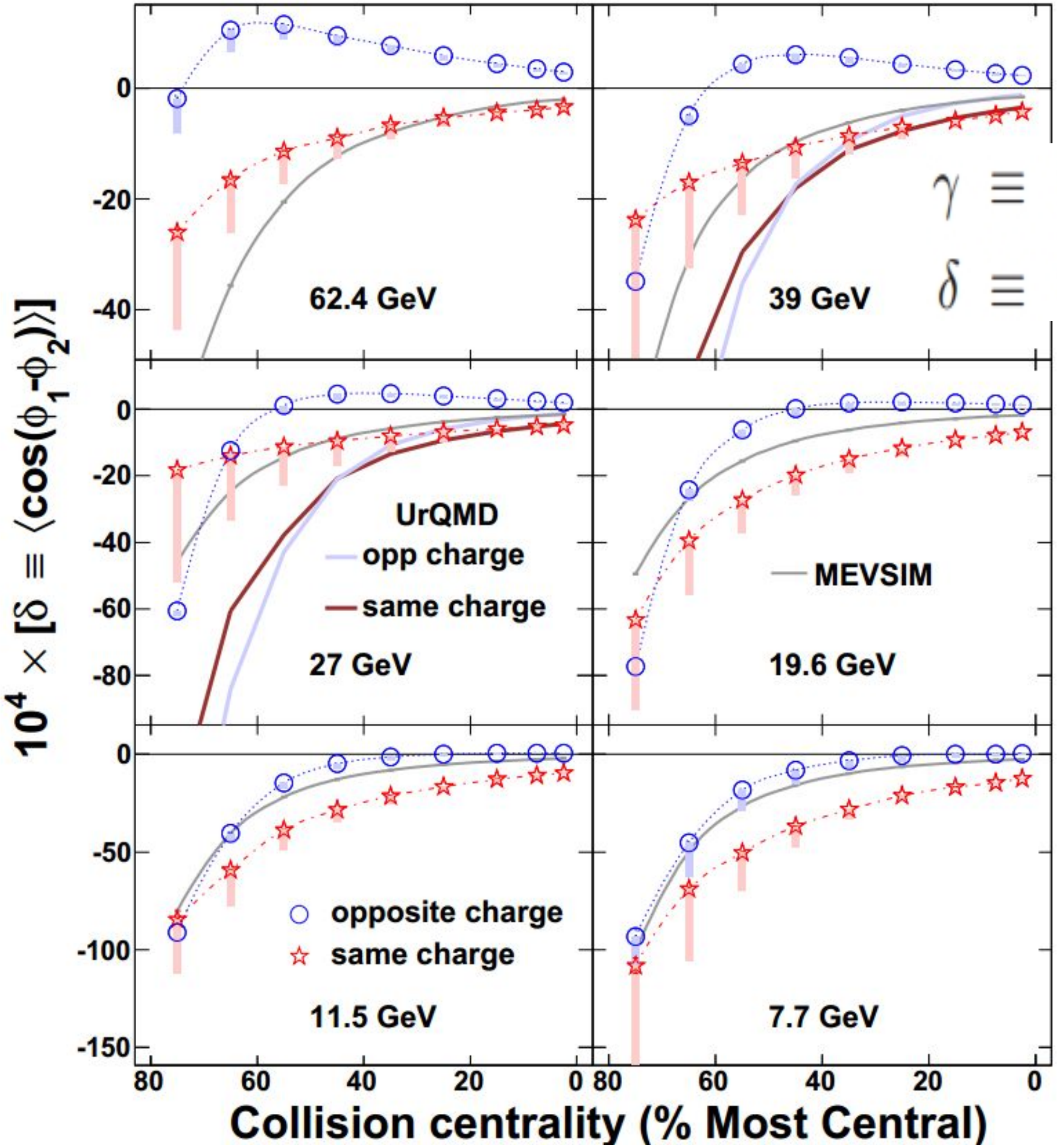
ALICE, Phys. Rev. Lett. 110, 012301 (2013); STAR, Phys. Rev. Lett 113 (2014) 052302



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).

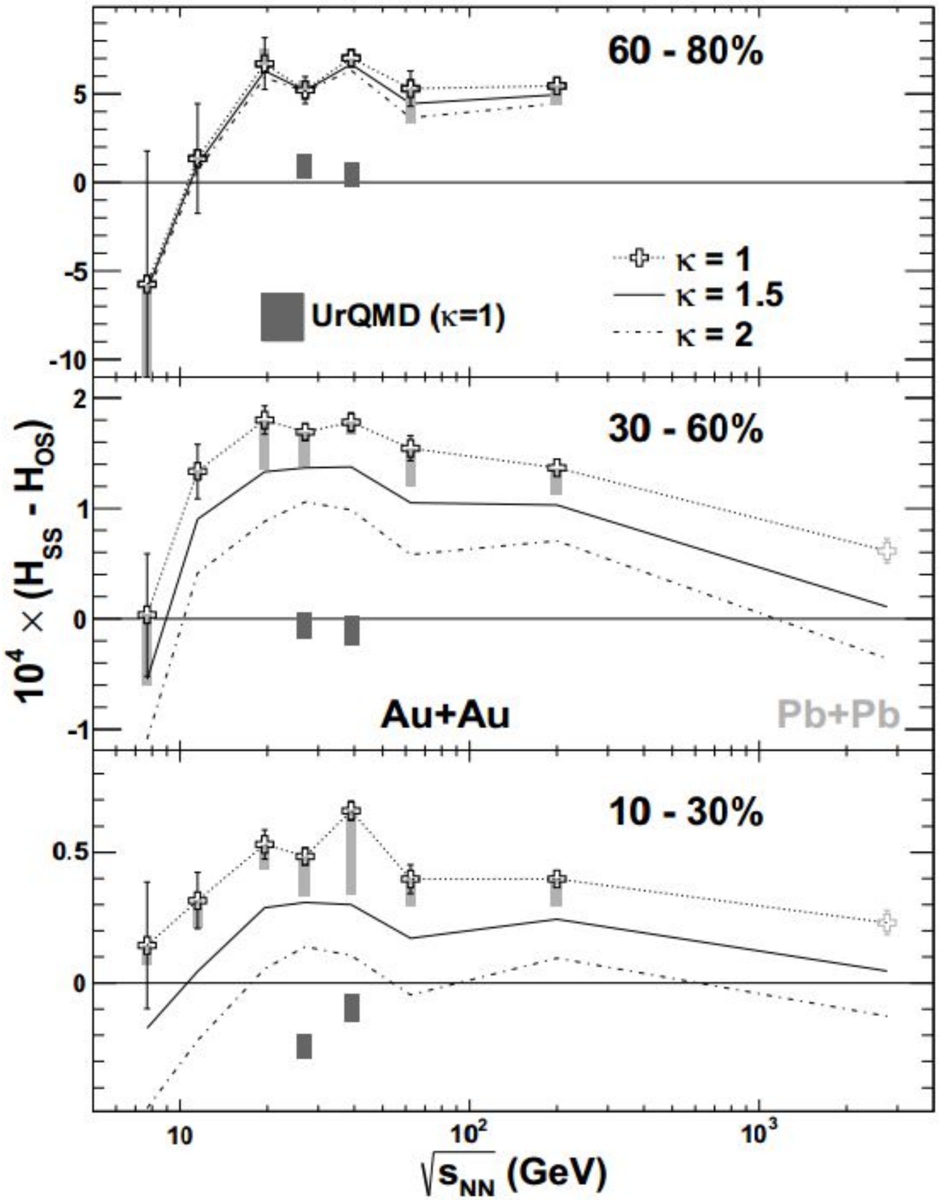
$$\gamma \equiv \langle\cos(\phi_1+\phi_2-2\Psi_{RP})\rangle = \kappa v_2 F - H$$

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

- 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

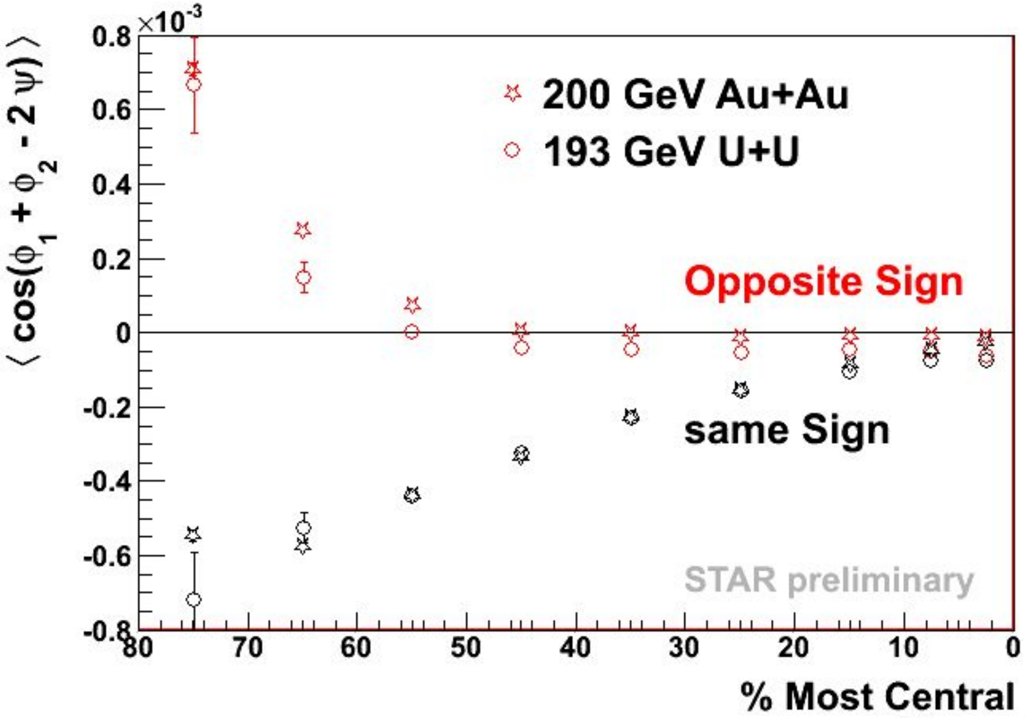
STAR, Phys. Rev. Lett 113 (2014) 052302

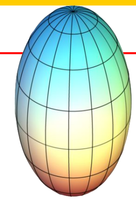


$$H^{\kappa} = (\kappa v_2 \delta - \gamma)/(1 + \kappa v_2)$$

- κ could deviate from 1 owing to a finite detector acceptance and theoretical uncertainties
- the CME signal decreases to 0 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

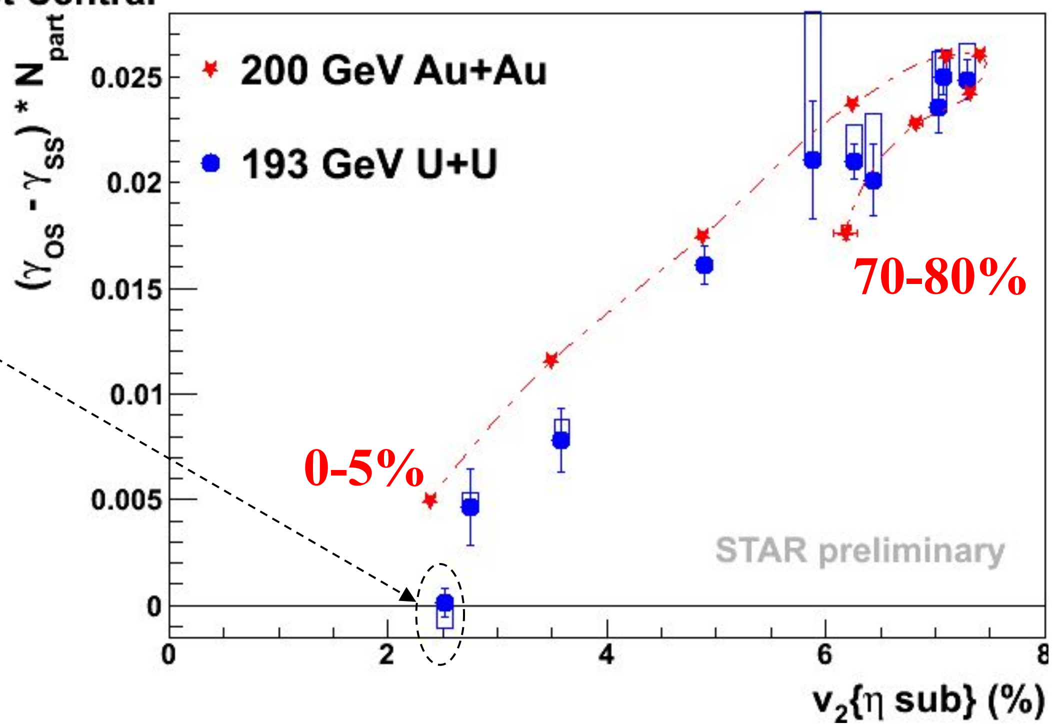
Another test: U+U





- 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

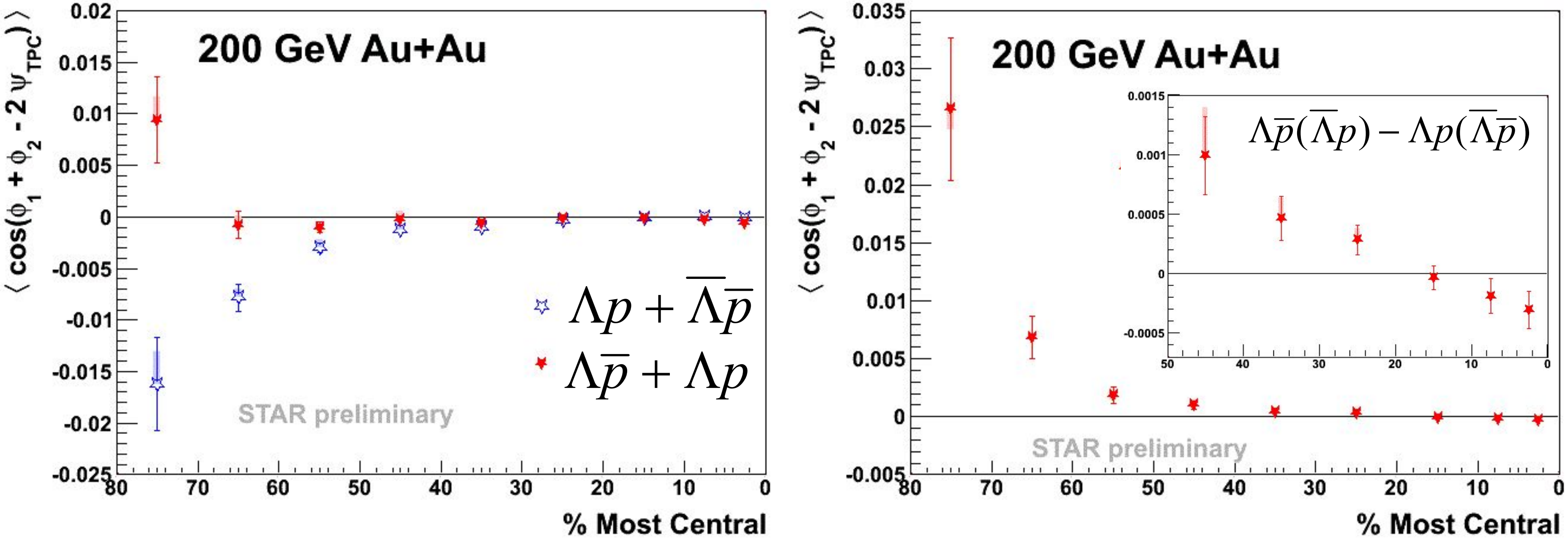
Chirality Imbalance	--	Chirality Imbalance
Magnetic Field	--	Fluid Vorticity
↓		↓
Chiral Magnetic Effect	--	Chiral Vortical Effect
(Electric Charge)	--	(Baryon Number)

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

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

correlate Λ–p to search for the Chiral Vortical Effect.

Λ-proton correlation



F. Zhao, QM2014 talk

- ❖ 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 I

- 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

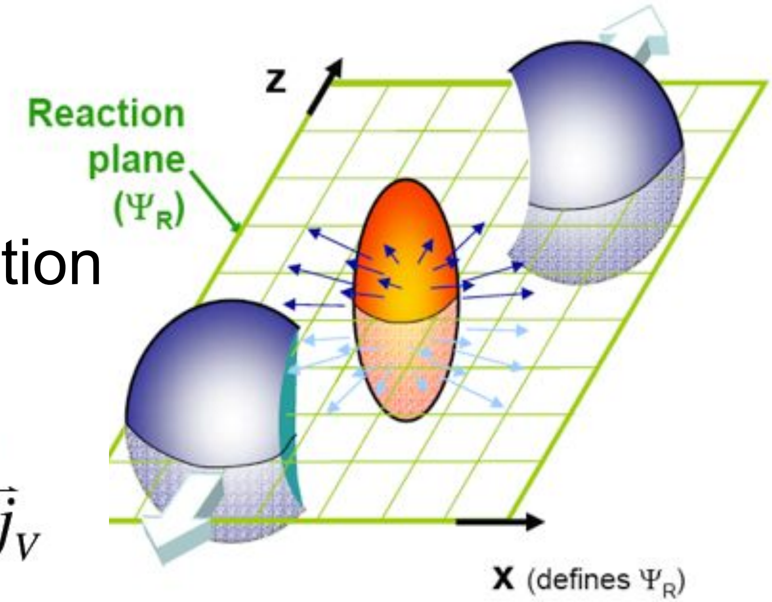
- signal of charge separation seems to disappear when
  - one charged particle is replaced with a neutral strange particle
  - the collision energy is down to ~7.7 GeV
  - the magnetic field from spectators is supressed (v_2 is still sizable)

- 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

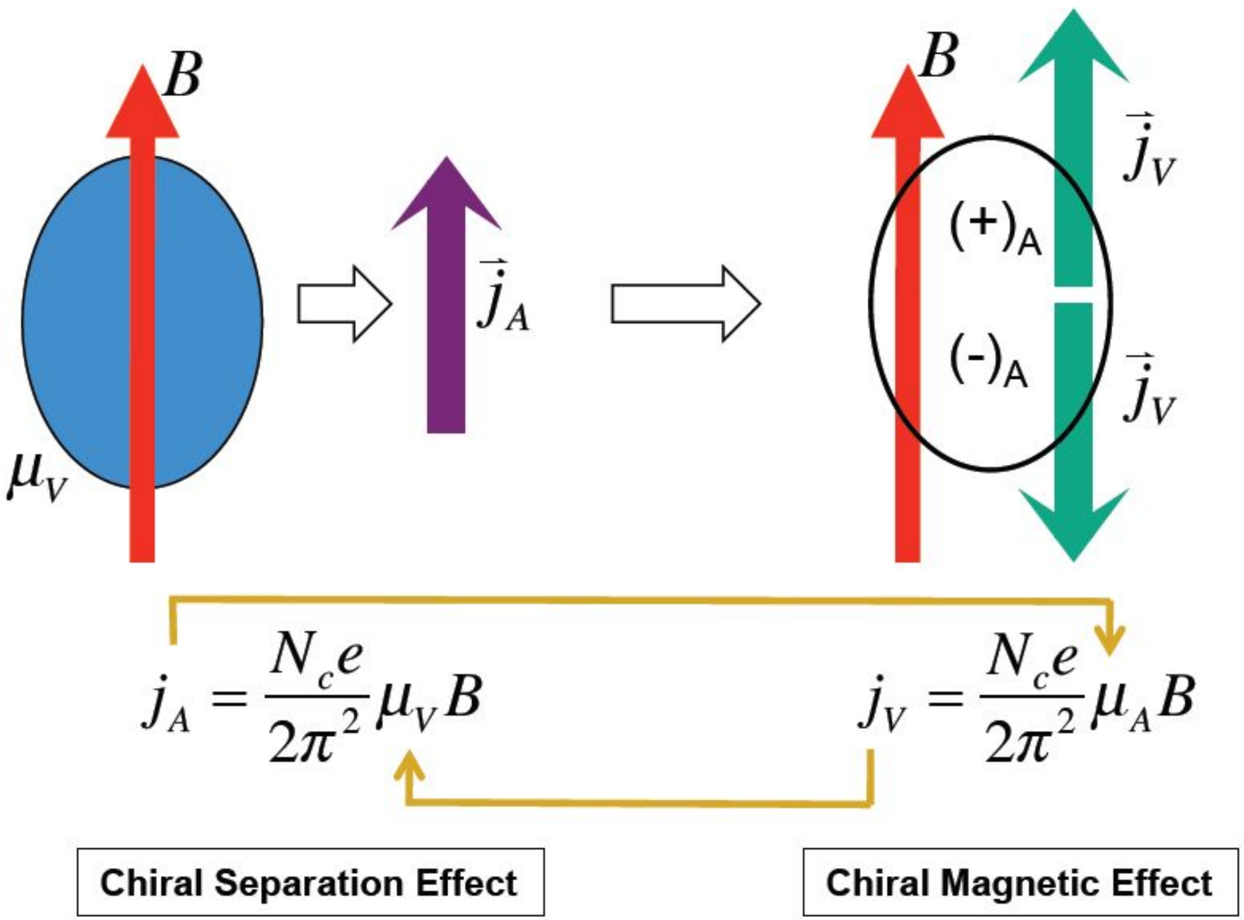
Chiral Magnetic Wave

CSE + CME ➔ Chiral Magnetic Wave:
- collective excitation
- signature of Chiral Symmetry Restoration

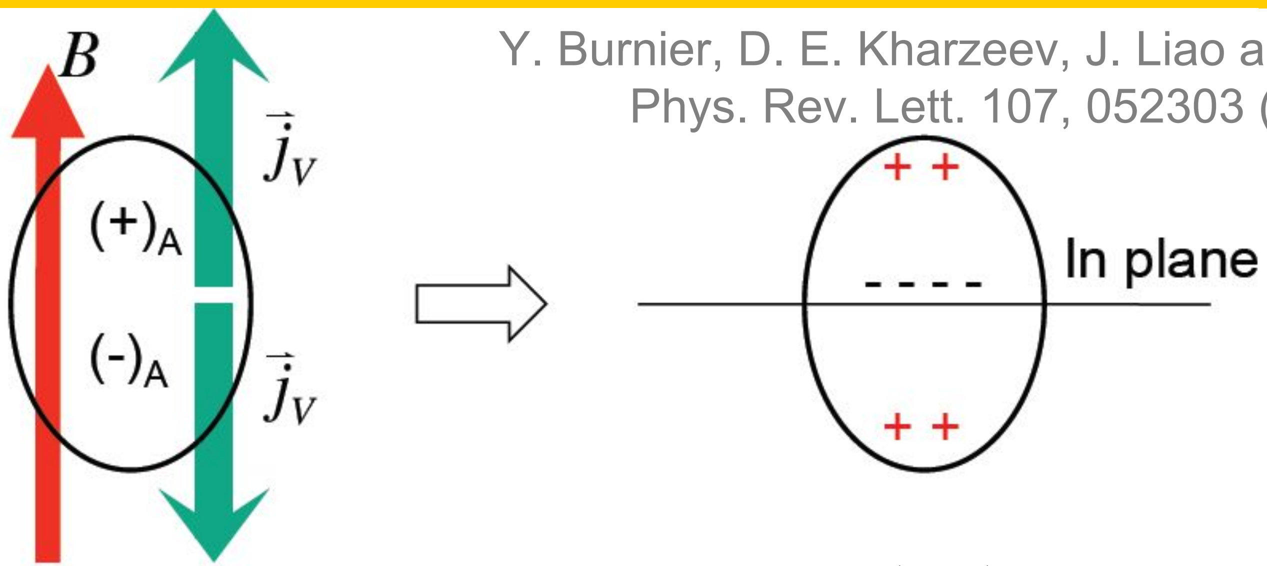


Peak magnetic field ~ **10^{15} Tesla !**

(Kharzeev et al. NPA 803 (2008) 227)



Observable



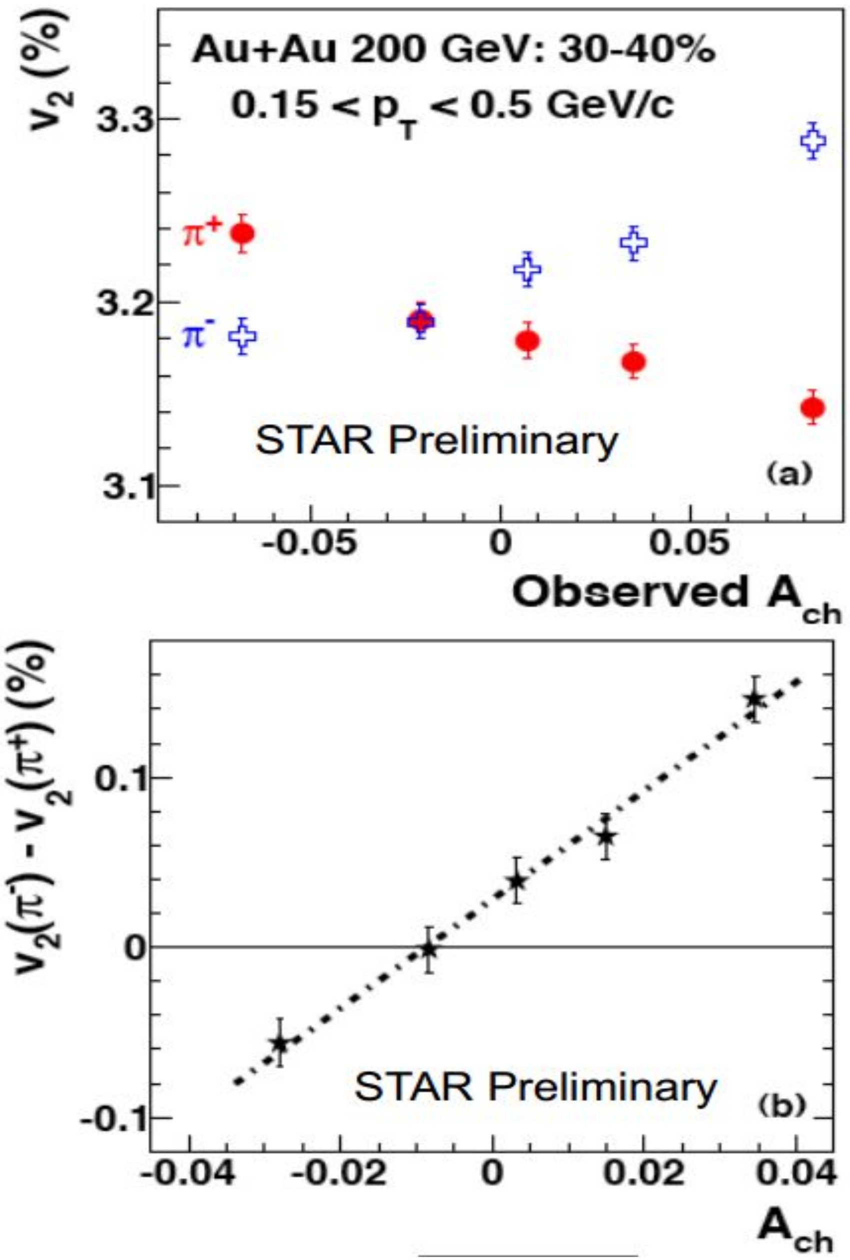
Y. Burnier, D. E. Kharzeev, J. Liao and H-U Yee,
Phys. Rev. Lett. 107, 052303 (2011)

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

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.

Charge asymmetry dependence

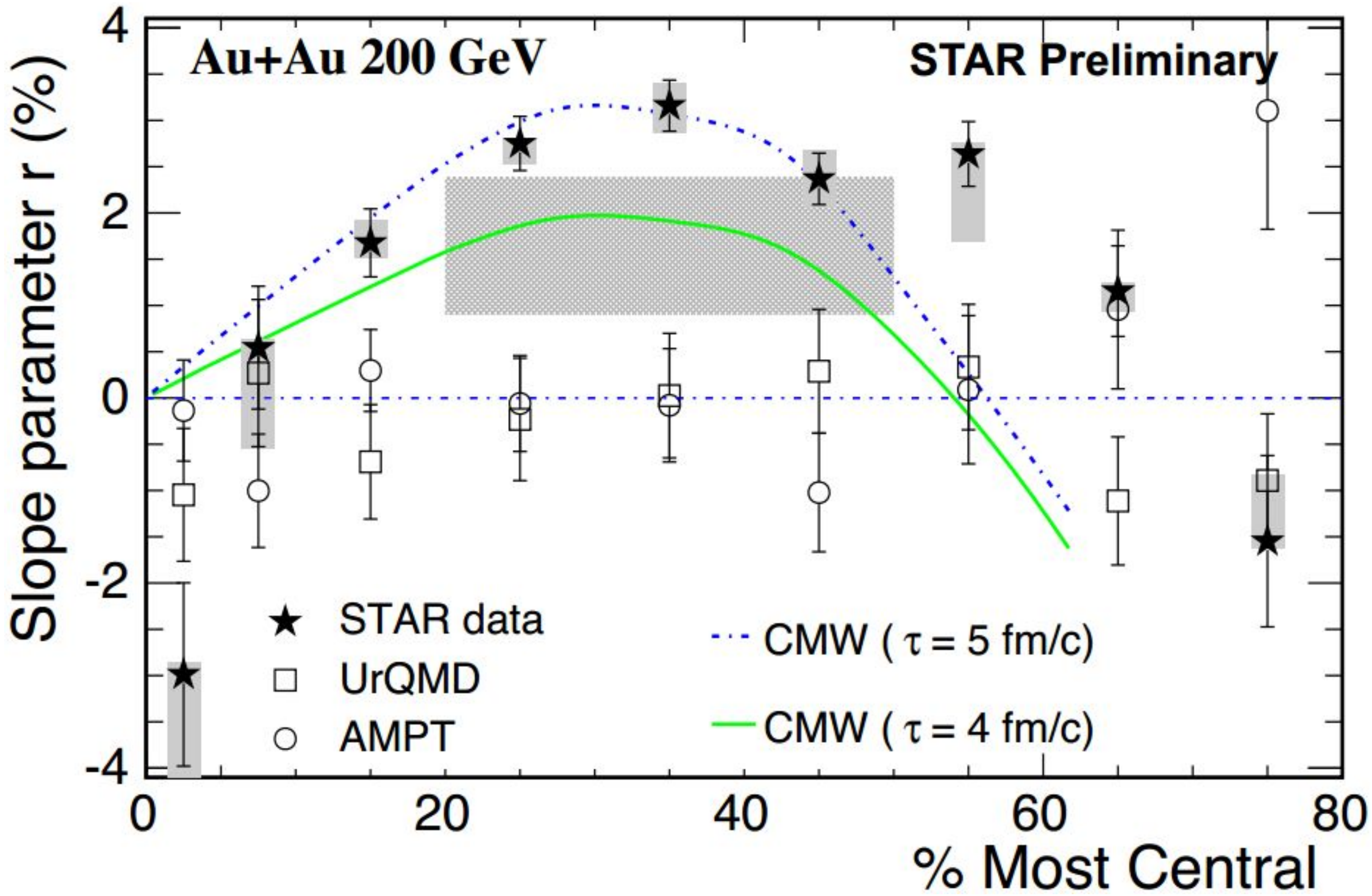


- v_2 was measured with the Q-cumulant method.
- Clear A_{ch} dependency
- $v_2(A_{ch})$ slopes for $\pi^{\pm}$:
  - opposite sign
  - similar magnitude
- v_2 difference vs A_{ch} may have a non-zero intercept: other physics?

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

Slope vs centrality

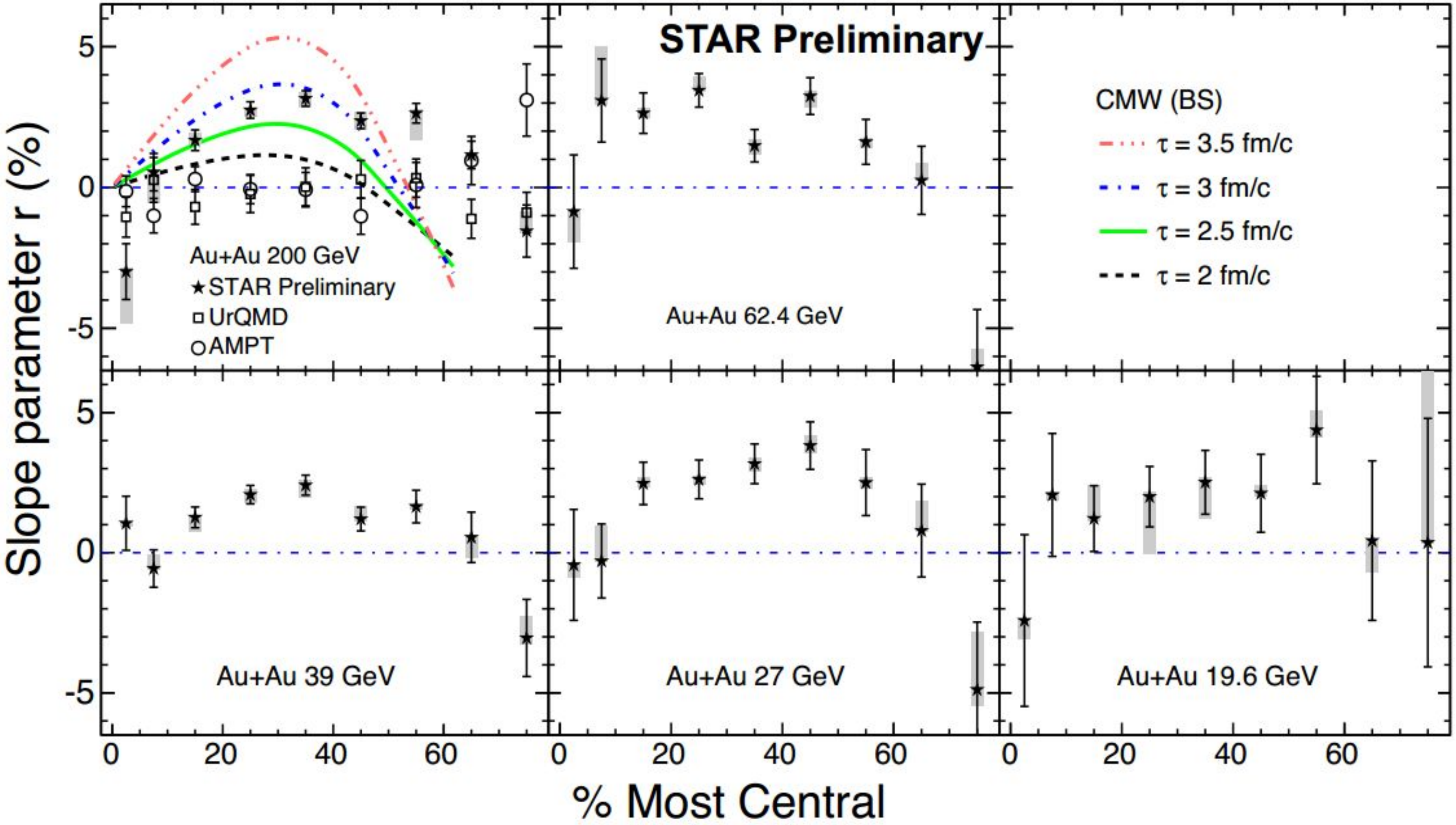
Y. Burnier, D. E. Kharzeev, J. Liao and H-U Yee, arXiv:1208.2537v1 [hep-ph].



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

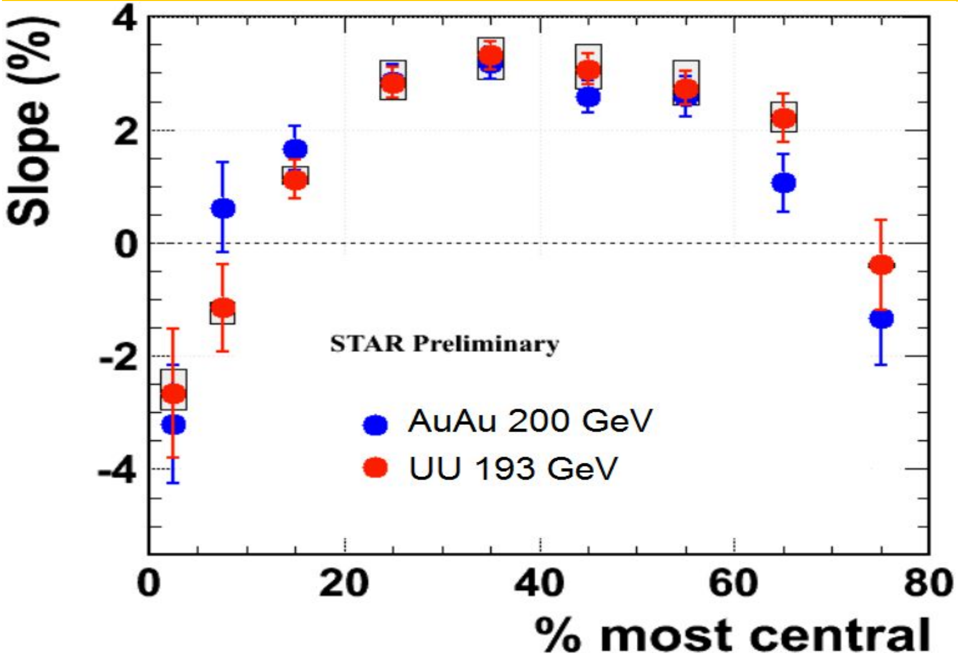
Beam Energy Scan

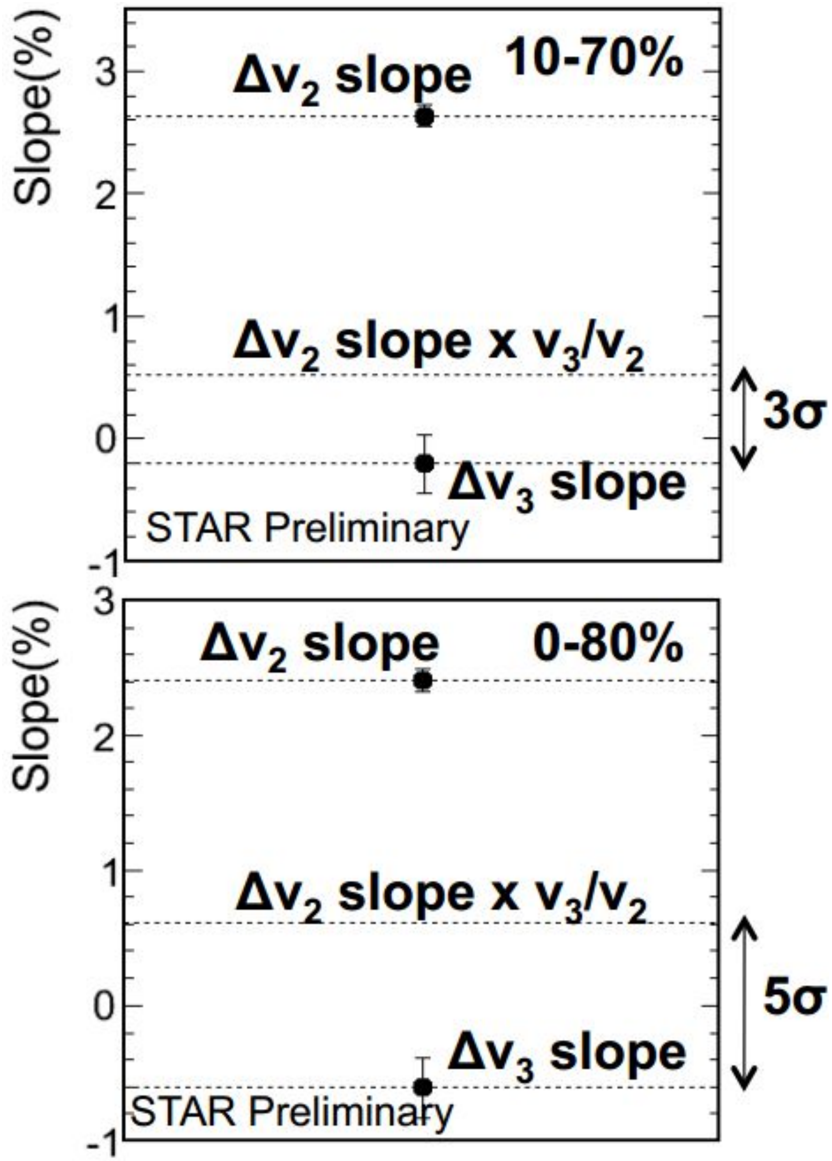
Y. Burnier, D. E. Kharzeev, J. Liao and H-U Yee, arXiv:1208.2537v1 [hep-ph].

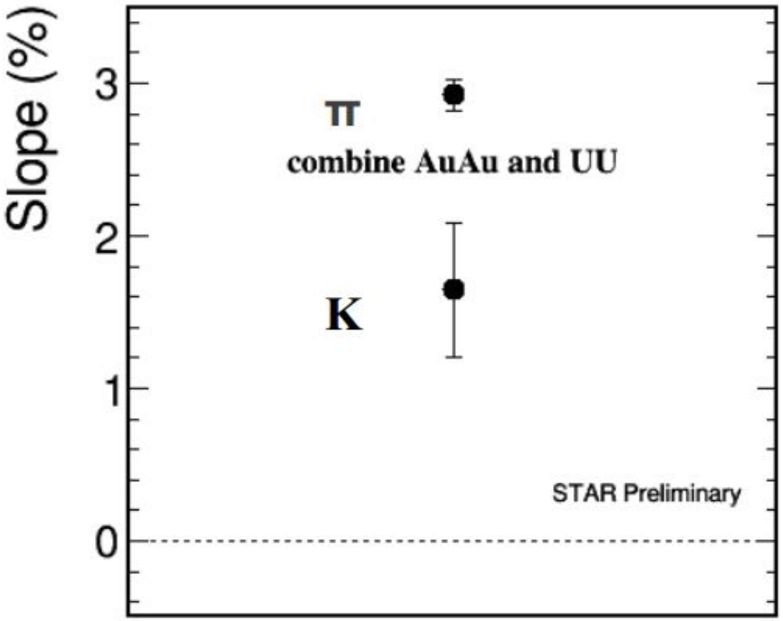


Similar trends are observed for different beam energies, where the errors are small.

More checks: UU, kaon and Δv_3







See Q. Shou's talk

Summary II

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

- On the other hand
  - UrQMD and AMPT (w/o CMW) showed no such effects
  - v_3 results consistent with zero

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

Outlook: another test ground

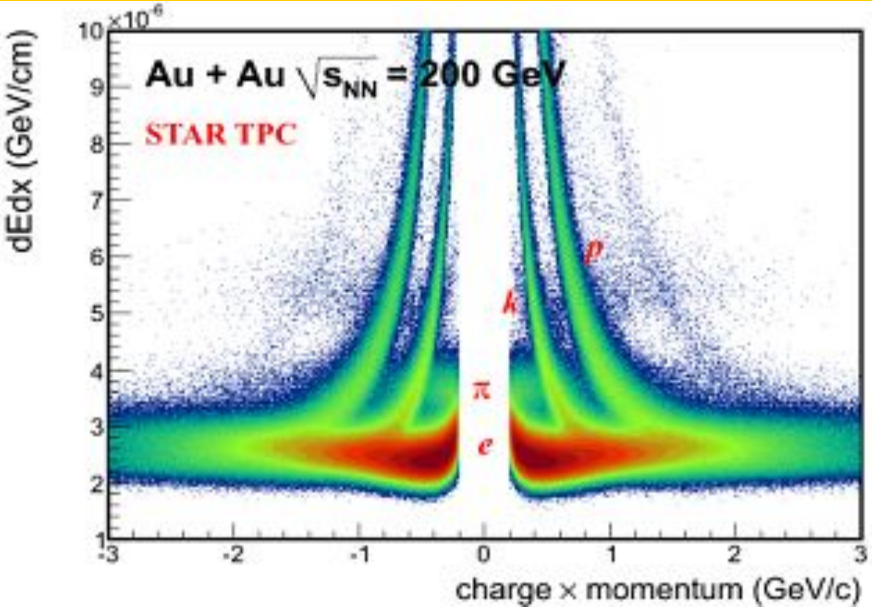
Isobars are atoms (nuclides) of different chemical elements that have the same number of nucleons.

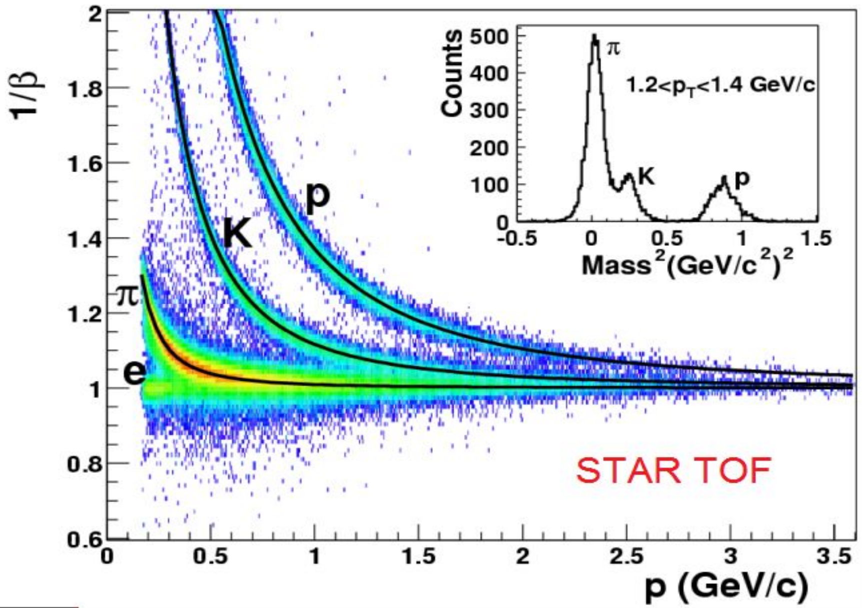
For example, $^{96}_{44}$Ruthenium and $^{96}_{40}$Zirconium

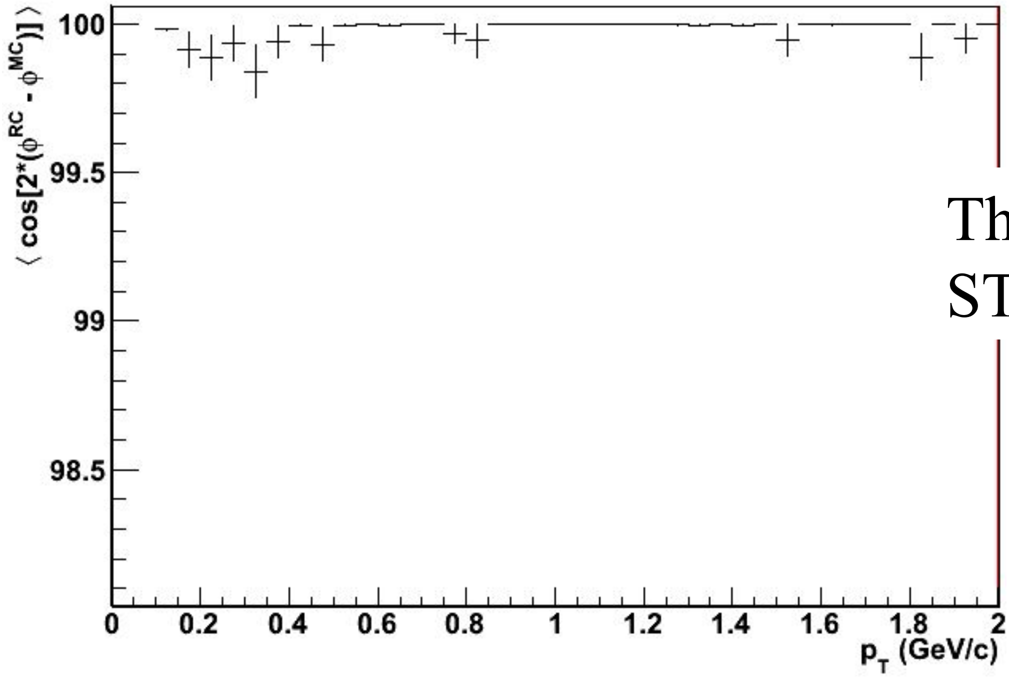
	$^{96}_{44}Ru+^{96}_{44}Ru$ vs $^{96}_{40}Zr+^{96}_{40}Zr$
Flow	=
CME	>
CVE	=
CMW	>

Backup slides

STAR: excellent PID and tracking

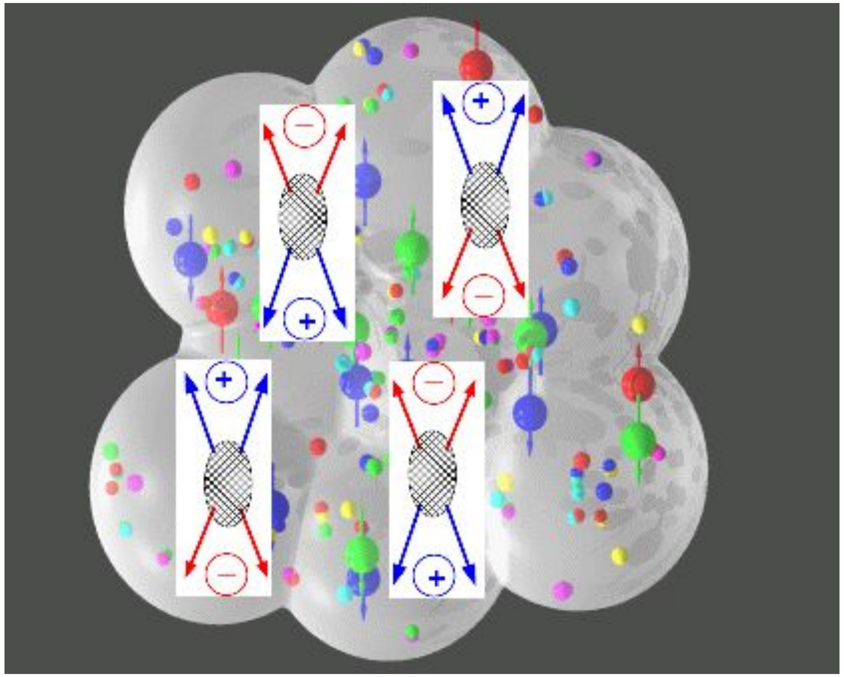






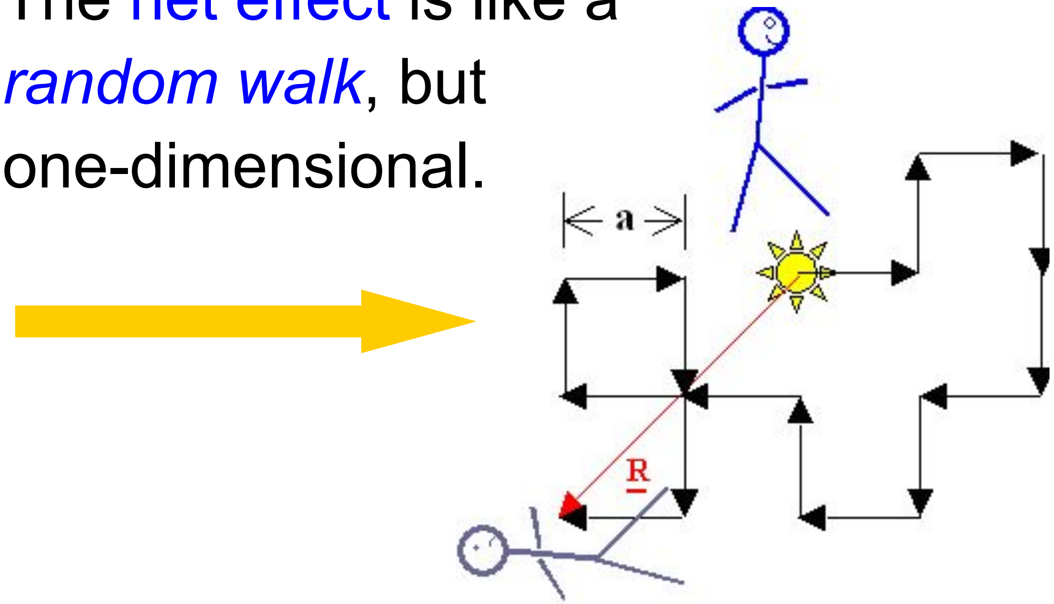
The correlation measurements at STAR are accurate to relative 0.1%.

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.



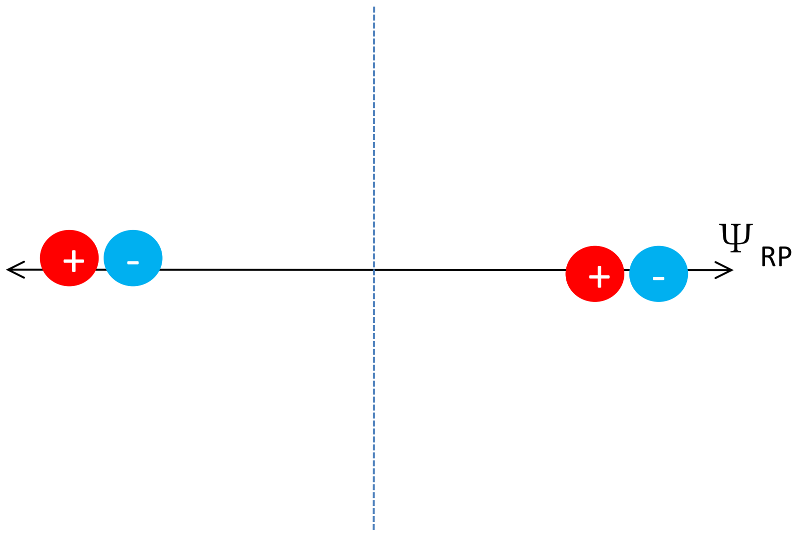
What do we know about the position R_n after n steps?

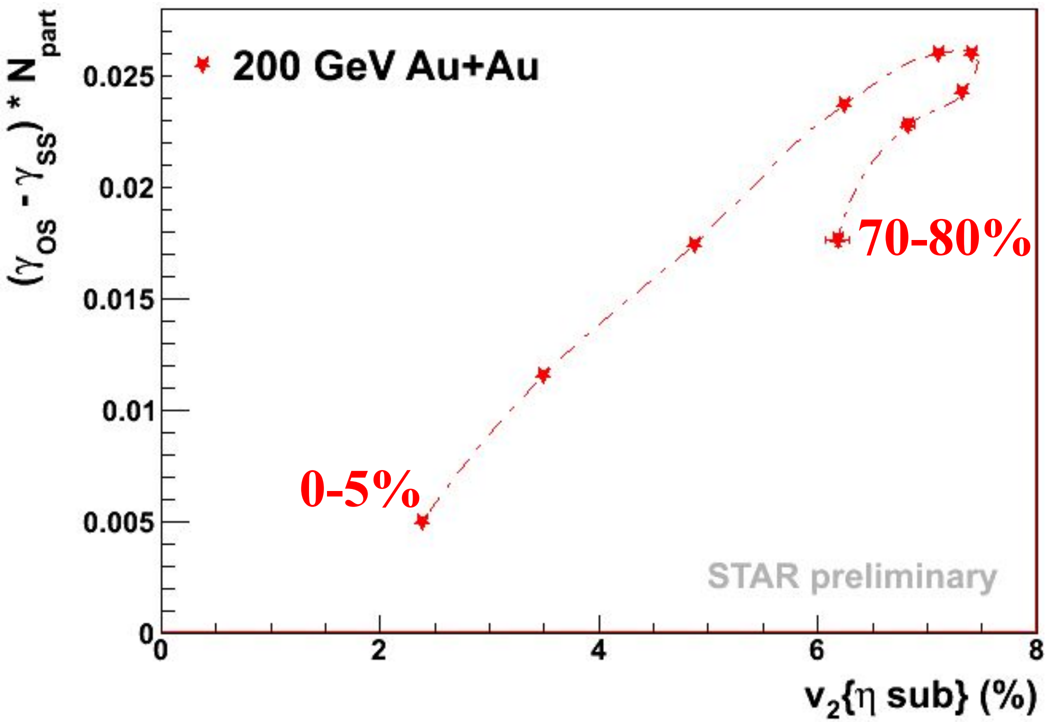
R_n **follows a Gaussian distribution:** *mean* = 0, and *rms* = $\sqrt{n}$

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 $\sim n \sim N_{part}$.

More on flow-related background

charge conservation/cluster + v_2 Pratt, Phys.Rev.C83:014913,2011



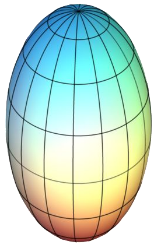


$$
\begin{aligned}
&\langle \cos(\phi_\alpha + \phi_\beta - 2\Psi_{RP}) \rangle \\
&= \langle \cos((\phi_\alpha + \phi_\beta - 2\phi_{res}) + 2(\phi_{res} - \Psi_{RP})) \rangle \\
&\approx \frac{f_{res} \langle \cos(\phi_\alpha + \phi_\beta - 2\phi_{res}) \rangle v_{2,res}}{N_{ch}}
\end{aligned}
$$

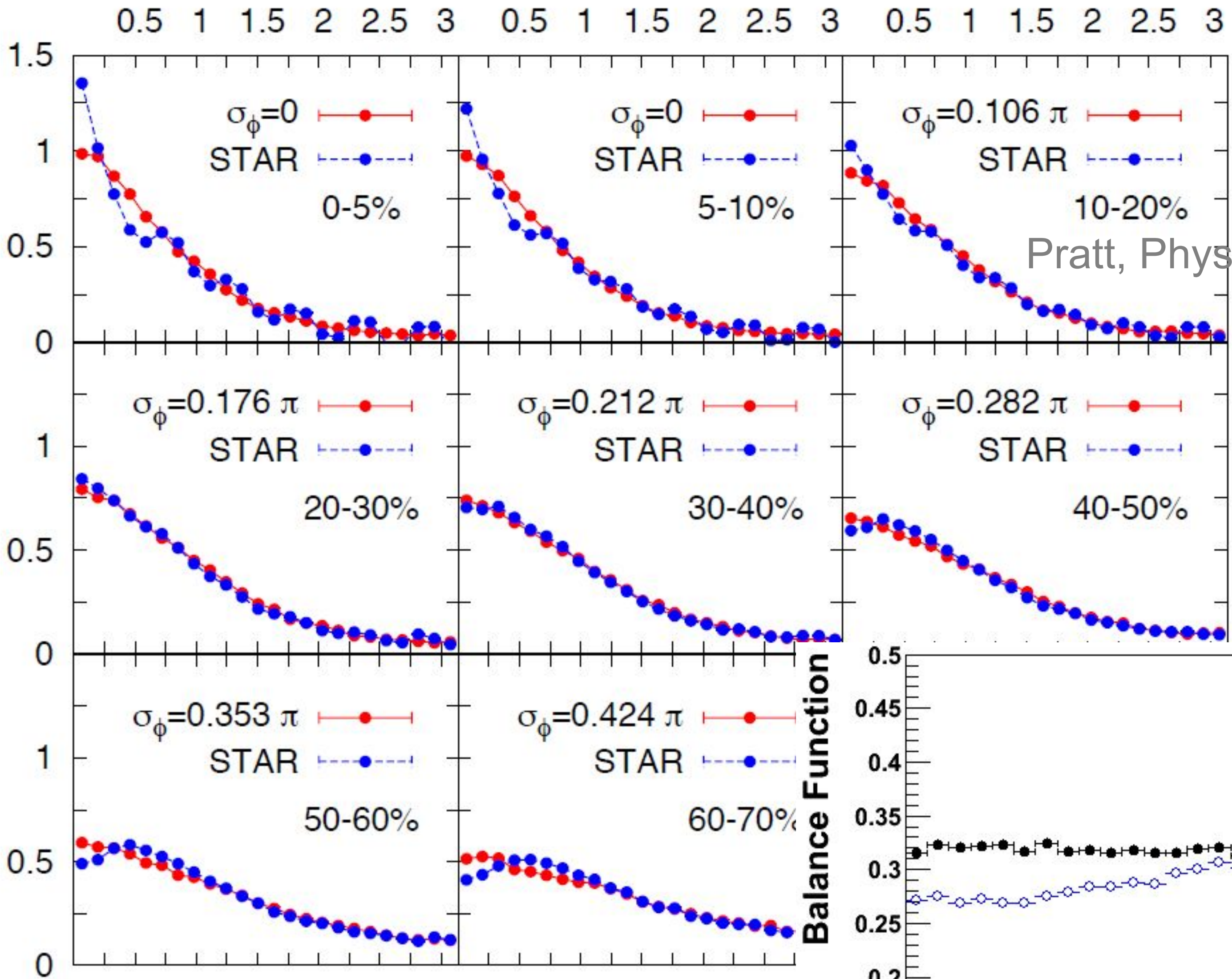
STAR, Phys. Rev. C72 (2005) 014904

Seemingly correlated!

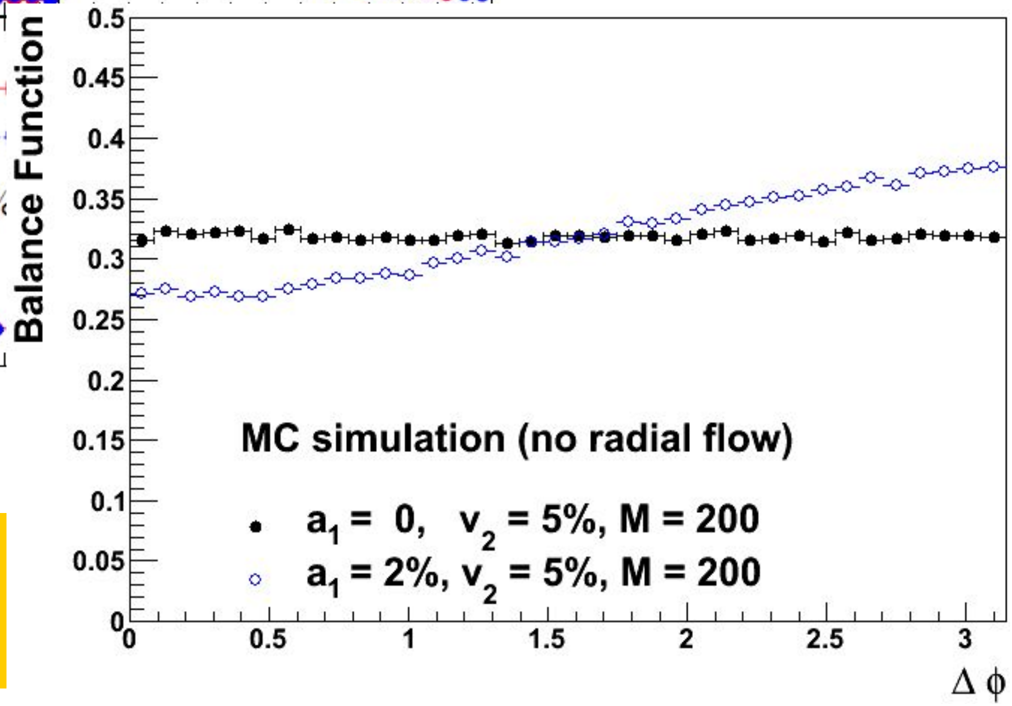
Can we disentangle the relationship with U+U?



In RHIC run2012, STAR took 350M minbias events and 14M central trigger events.

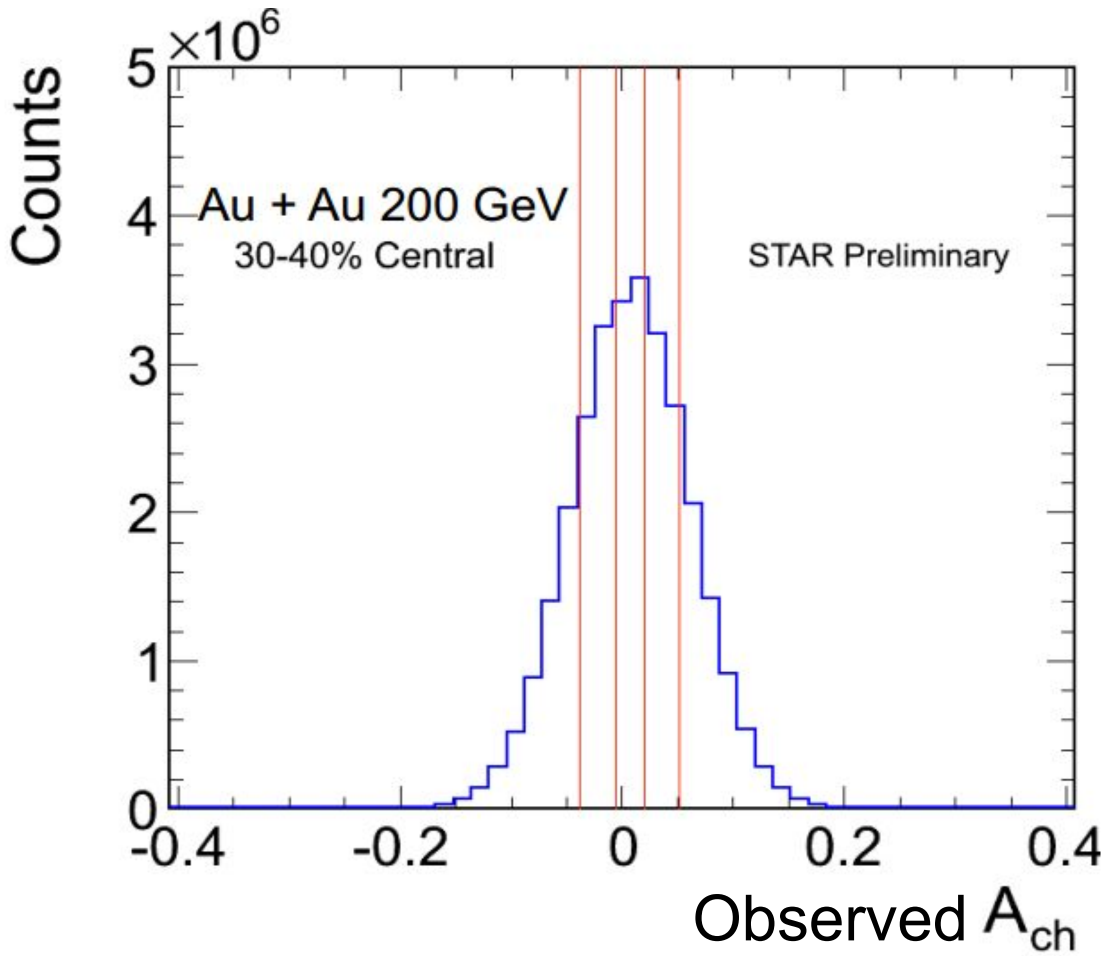


Pratt, Phys.Rev.C83:014913,2011



Balance function

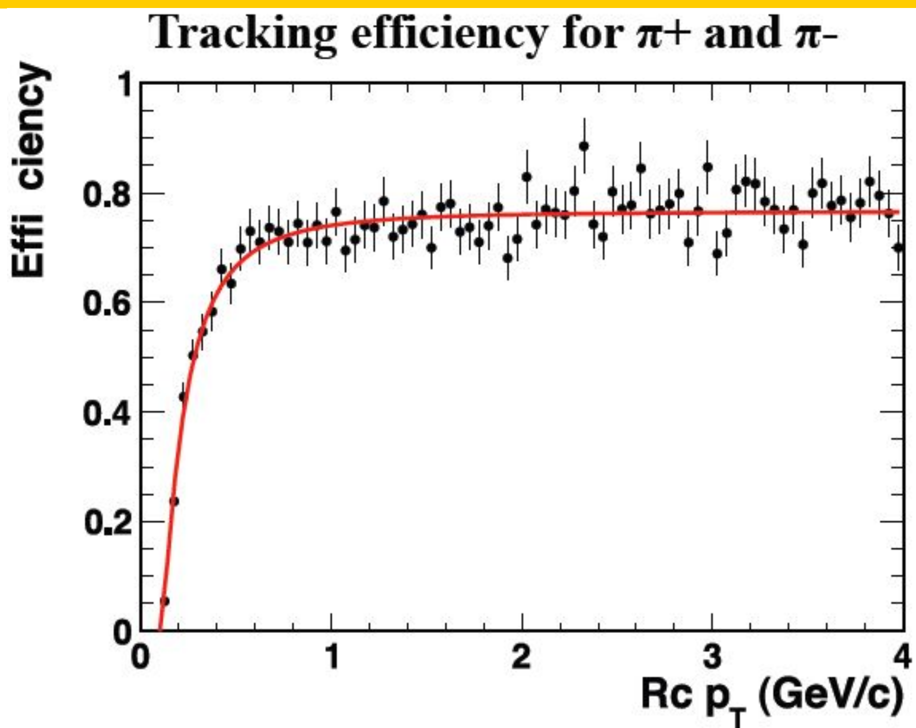
Observed charge asymmetry

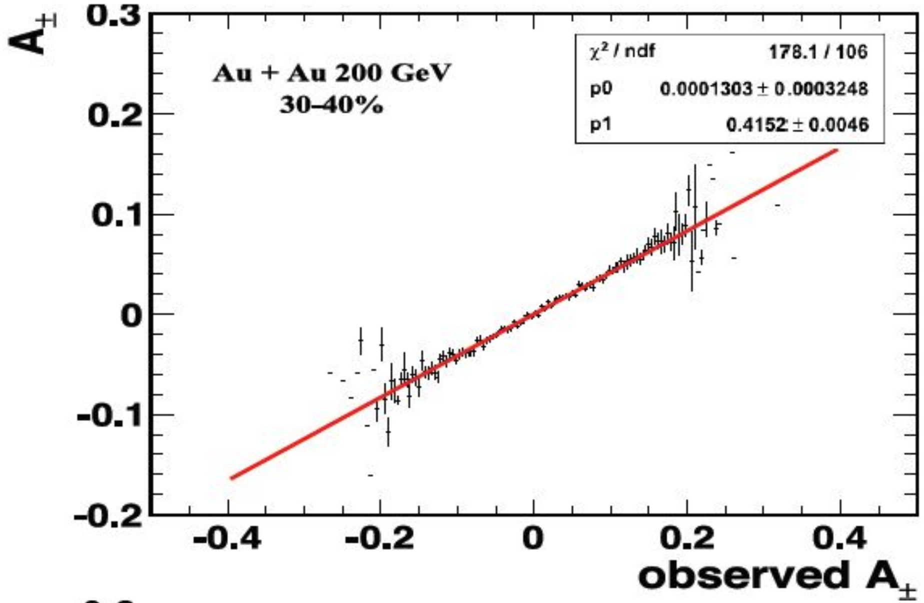


$$A_{ch} = \frac{N^{+} - N^{-}}{N^{+} + N^{-}}$$

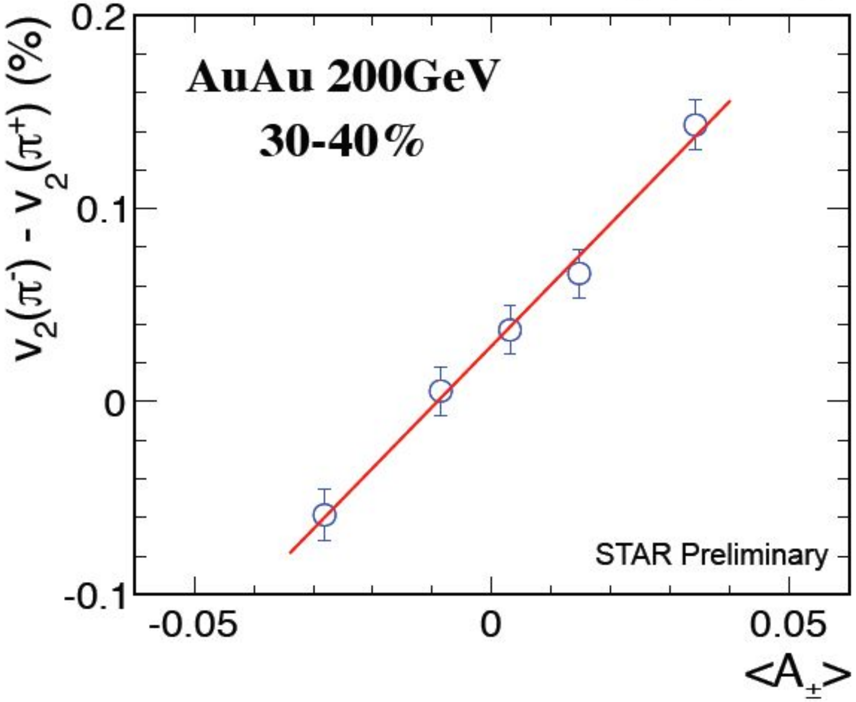
- N^{+} (N^{-}) is the number of positive (negative) particles within $|\eta|<1$.
- The distribution was divided into 5 bins, with roughly equal counts.
- Tracking efficiency was corrected later.

Correction for tracking efficiency





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



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

- Do the same for all centralities