Search for the Chiral Magnetic Effect with Charged Hadrons

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5-9 October 2015
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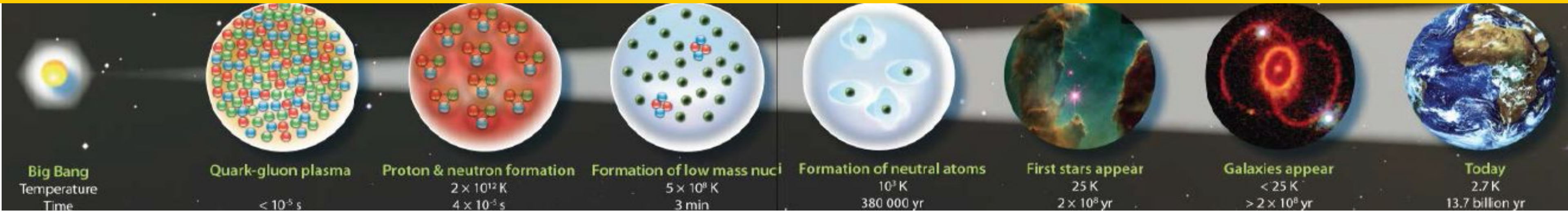
Outline

- Motivation
- Experimental Results
  - Chiral Magnetic Effect (CME)
  - Chiral Magnetic Wave (CMW)
  - Chiral Vortical Effect (CVE)
- Outlook

Phys. Rev. Lett. 103(2009)251601
Phys. Rev. C 81(2010)54908
Phys. Rev. C 88(2013)64911
Phys. Rev. C 89(2014)44908
Phys. Rev. Lett 113(2014)052302
Phys. Rev. Lett 110(2013)012301

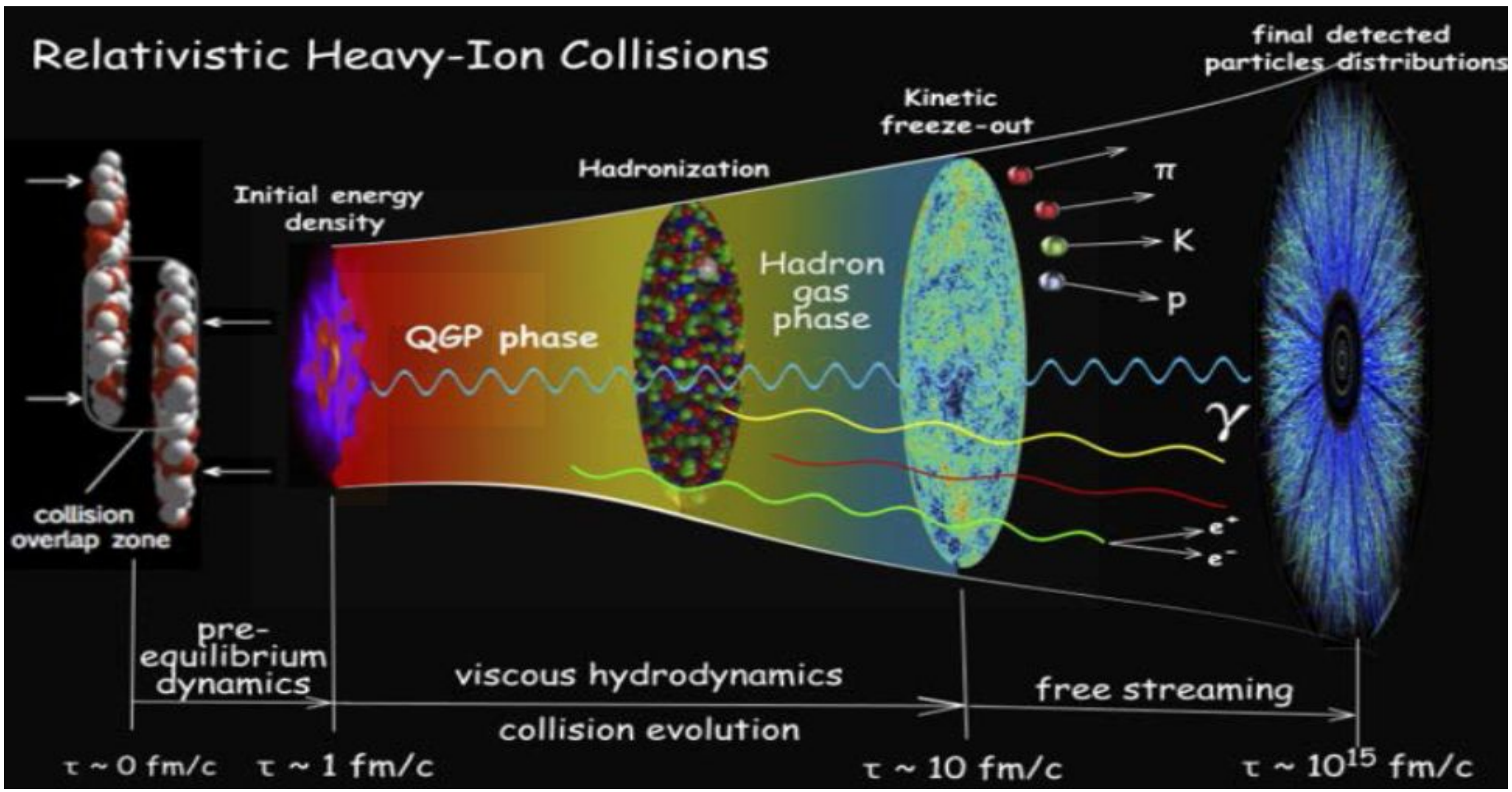
Phys. Rev. Lett 114(2015)252302
PRL Editors' Suggestion

Big Bang & Little Bangs

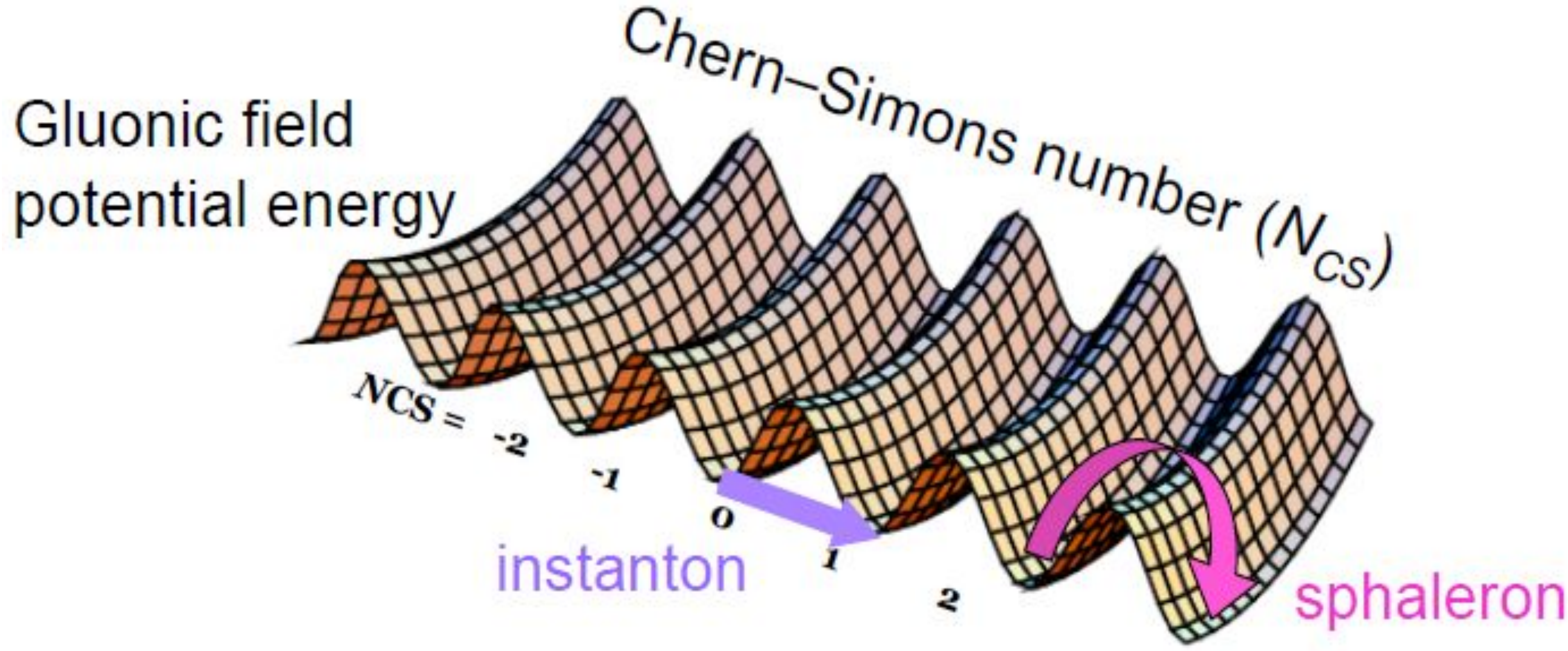


Vacuum transition may occur on a large scale or a small scale.

• we can learn from the Little Bangs



QCD vacuum transition

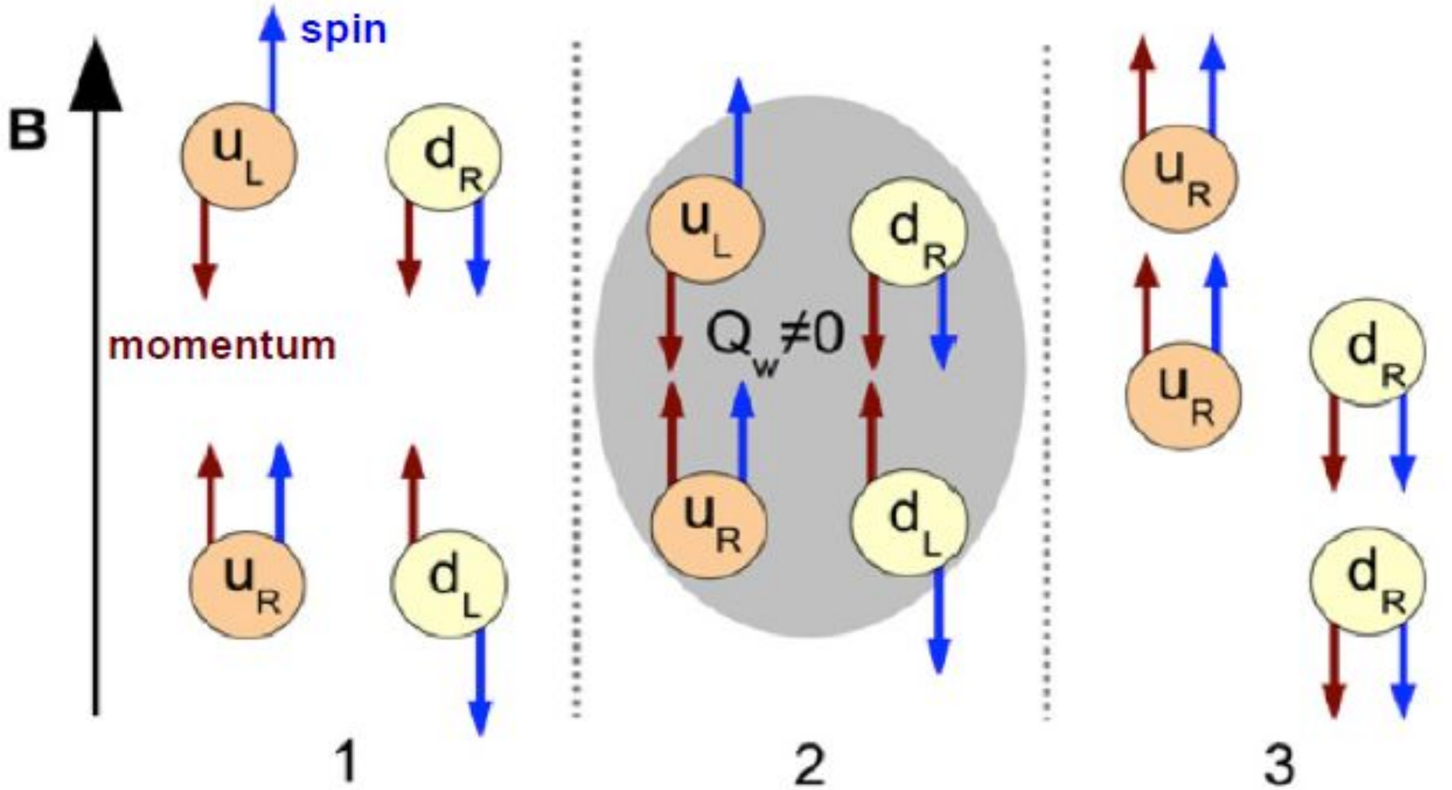


D. Diakonov, Prog. Part. Nucl. Phys. 51, 173 (2003)

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

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.

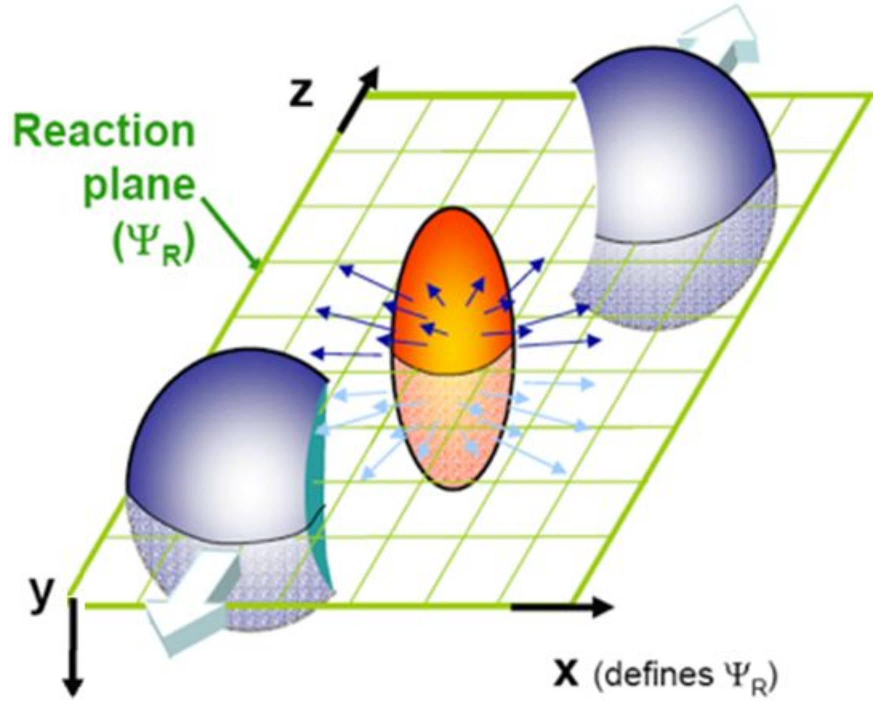
$$\boldsymbol{j}_V = \frac{N_c e}{2\pi^2}\mu_A \boldsymbol{B}$$ ➔ electric charge separation along *B* field

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

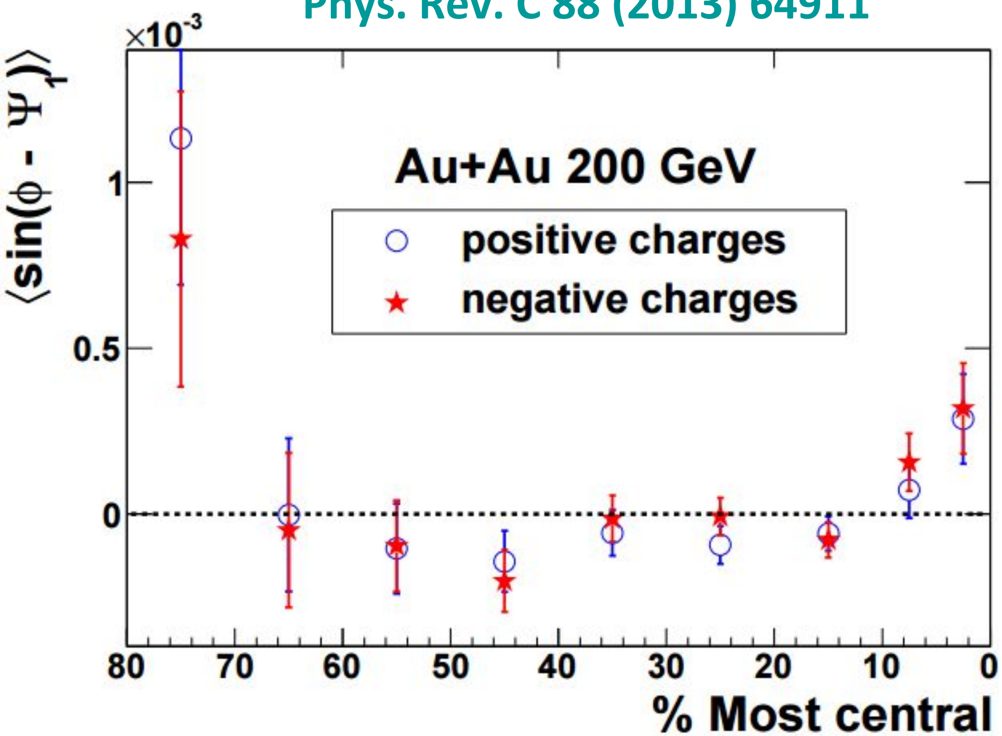
Local Parity Violation + CME

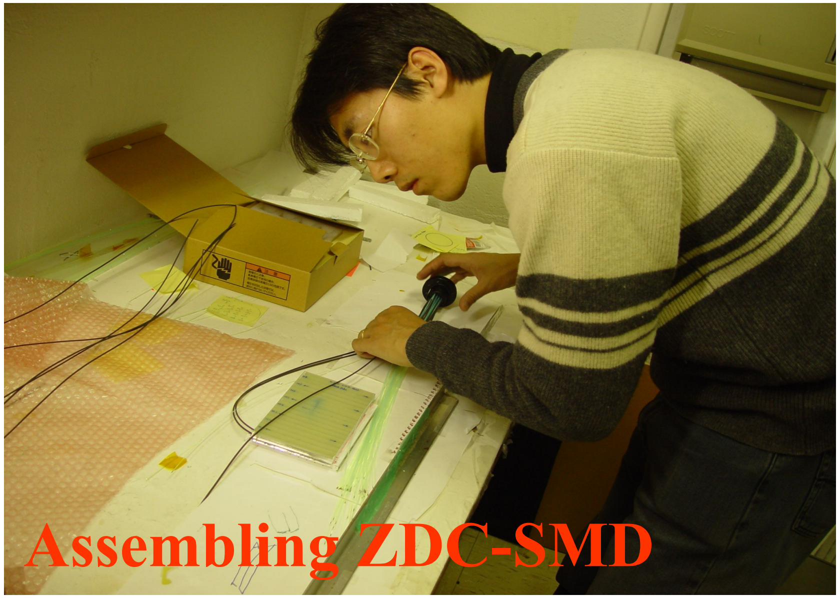
$$\frac{dN_{\pm}}{d\phi} \propto 1 + 2a_{\pm} \cdot \sin\left(\phi^{\pm} - \Psi_{RP}\right)$$

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

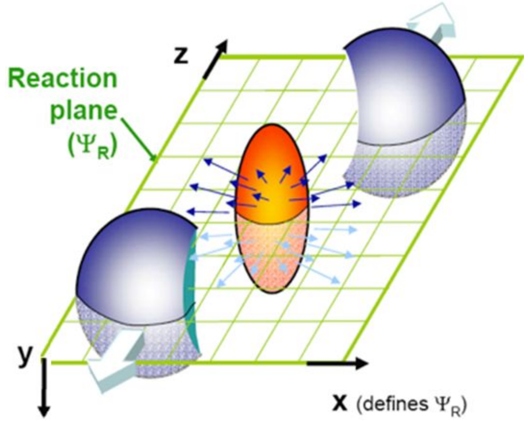


Phys. Rev. C 88 (2013) 64911

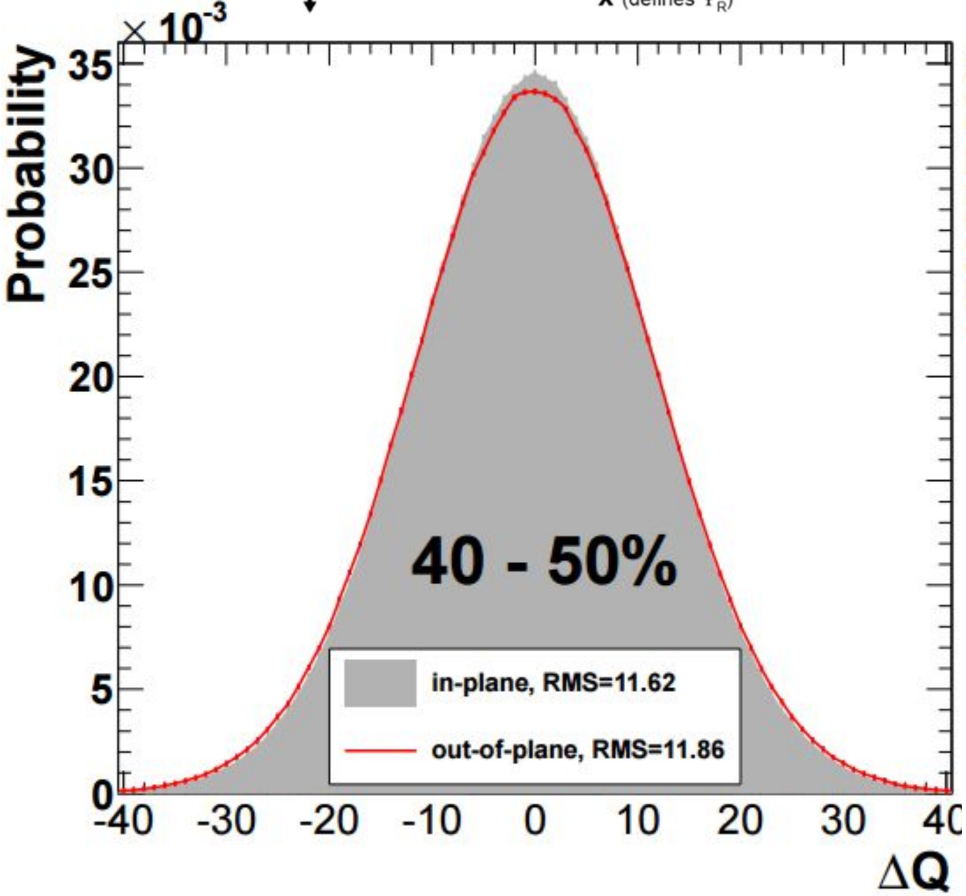


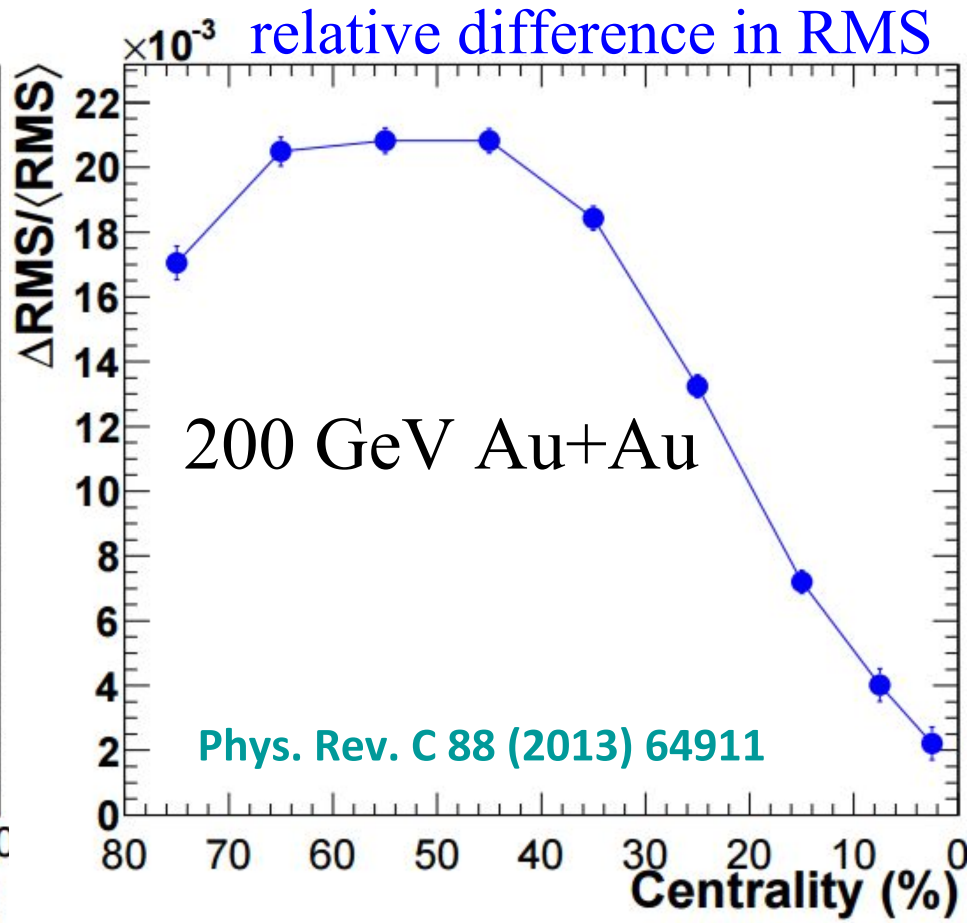


Visual evidence: fluctuation



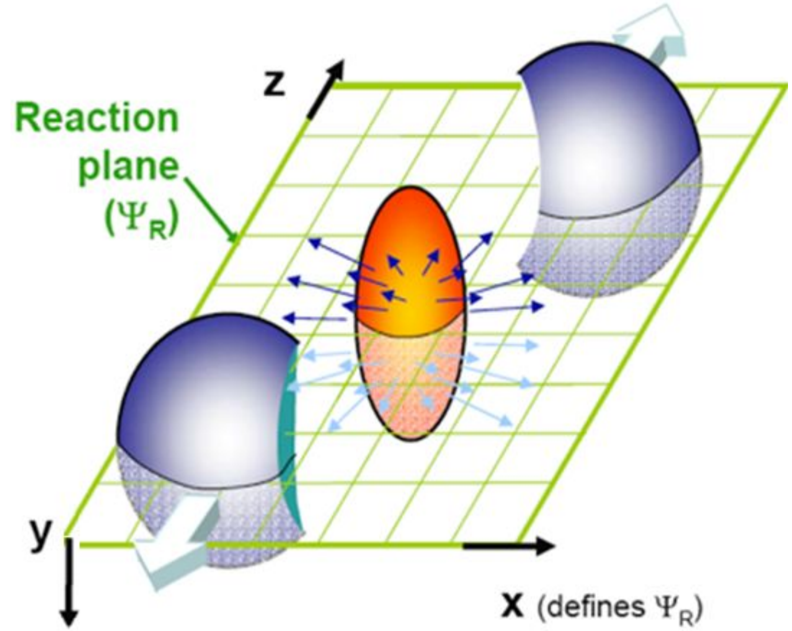
There should be more out-of-plane charge fluctuation than in-plane.
Indeed, we can visualize this effect, which is on percent level!





γ correlator

A better way to quantify the extra charge fluctuation.



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

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

S. Voloshin,
PRC 70 (2004) 057901

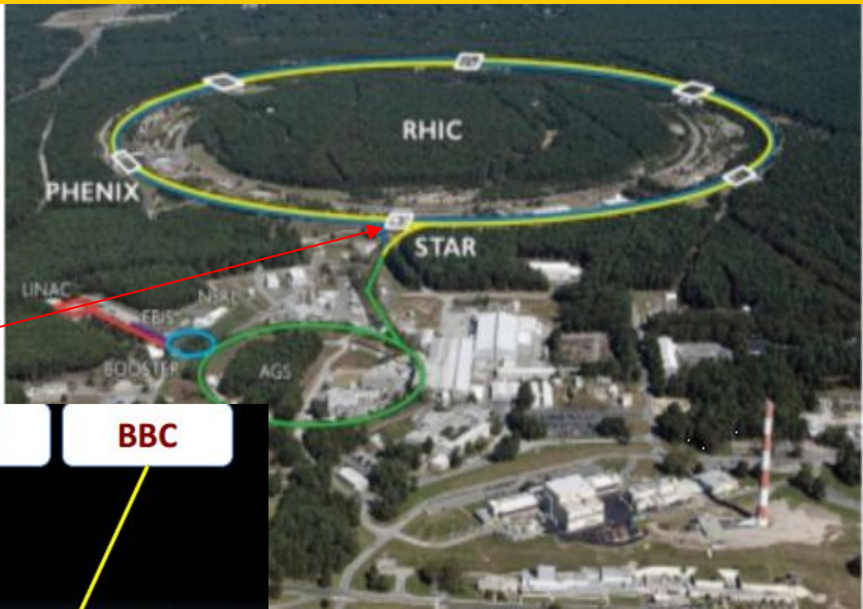
background effects: largely cancel out

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

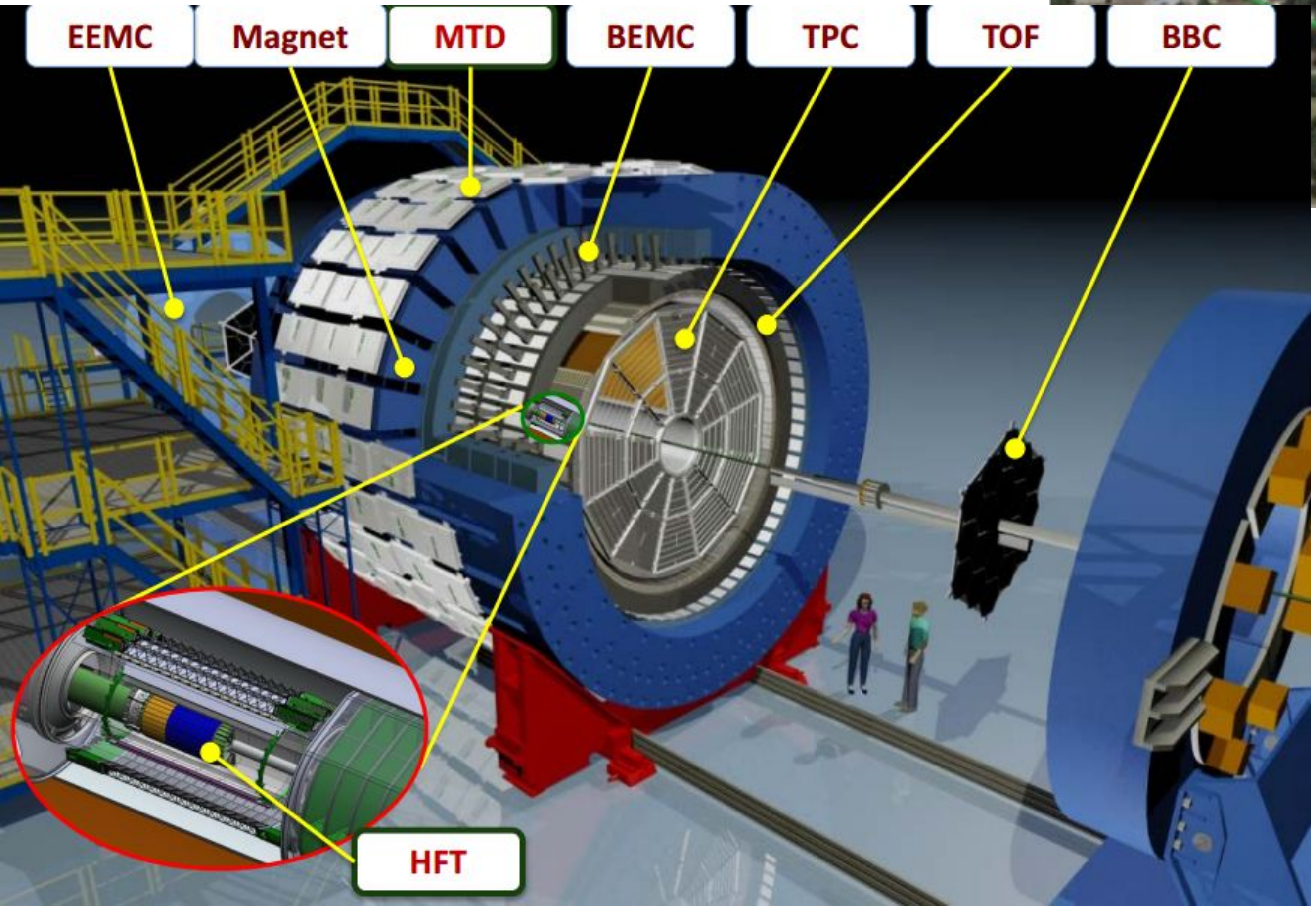
P-even quantity: still sensitive to charge separation

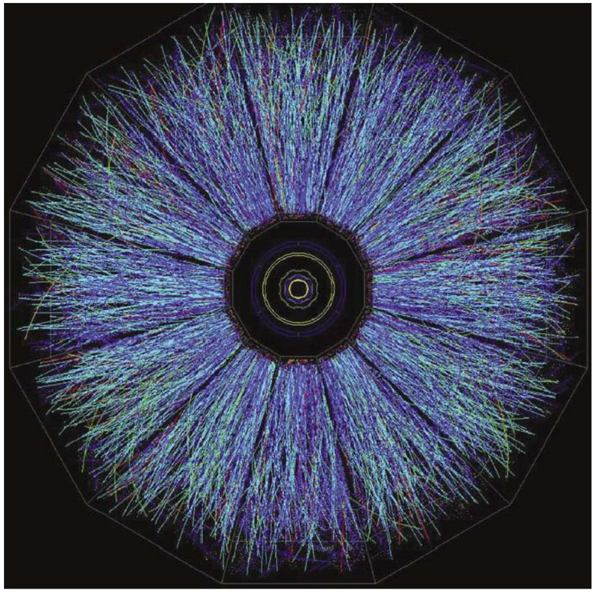
STAR experiment

Relativistic Heavy Ion Collider (RHIC)



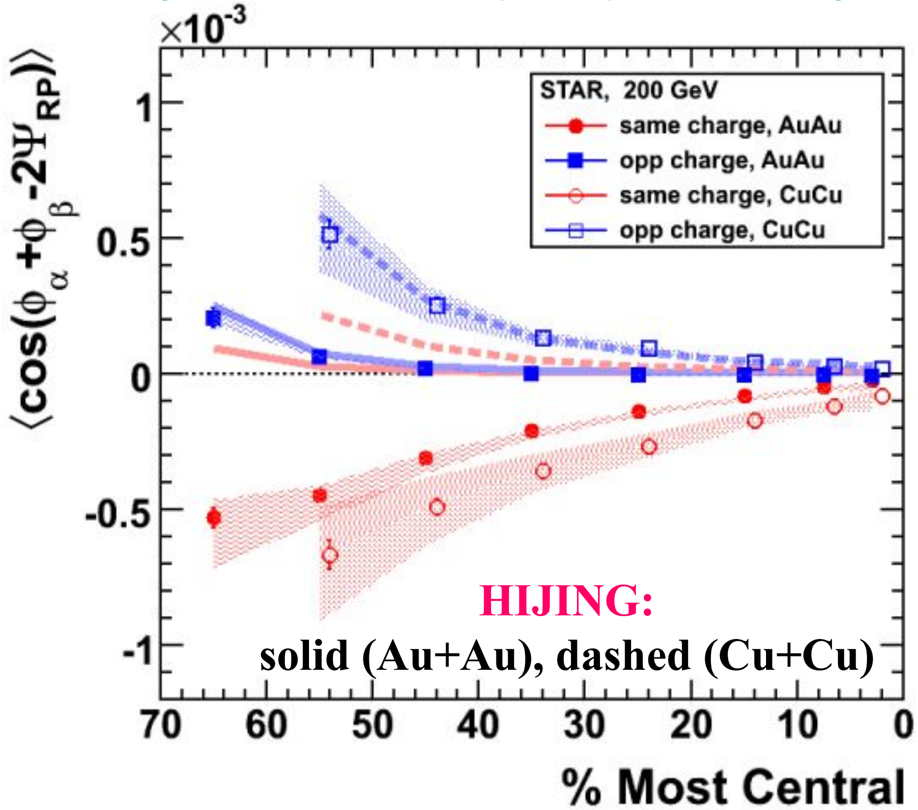
Solenoidal Tracker at RHIC (STAR)

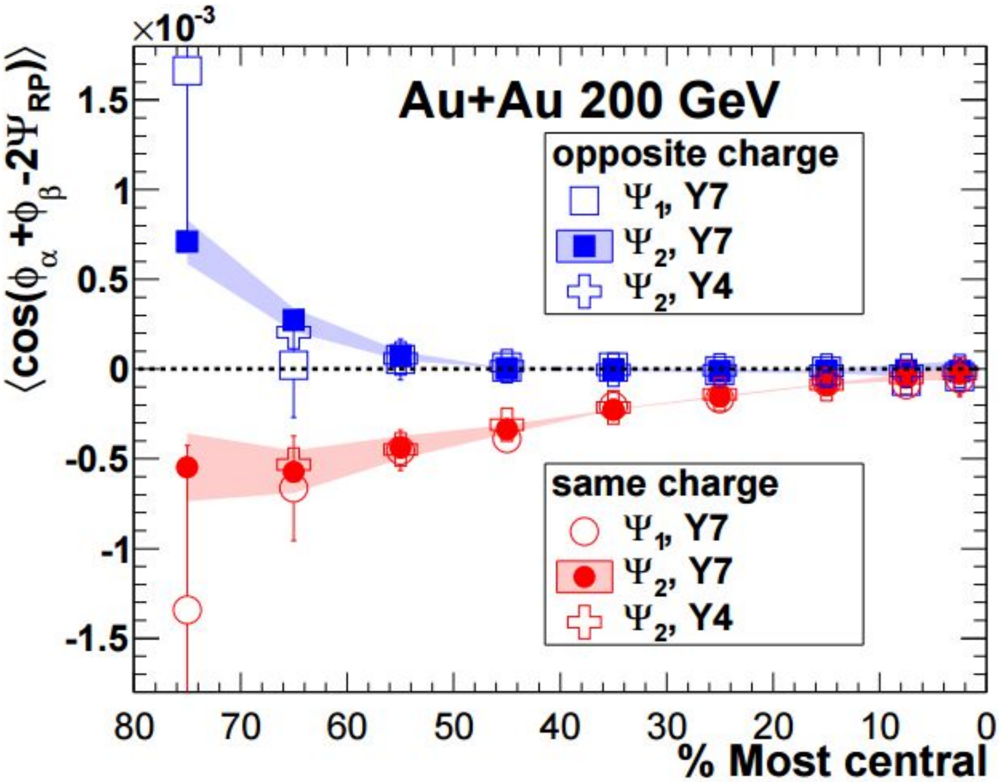




Charge separation signal

Phys. Rev. Lett. 103(2009)251601;Phys. Rev. C 81(2010)54908;Phys. Rev. C 88 (2013) 64911

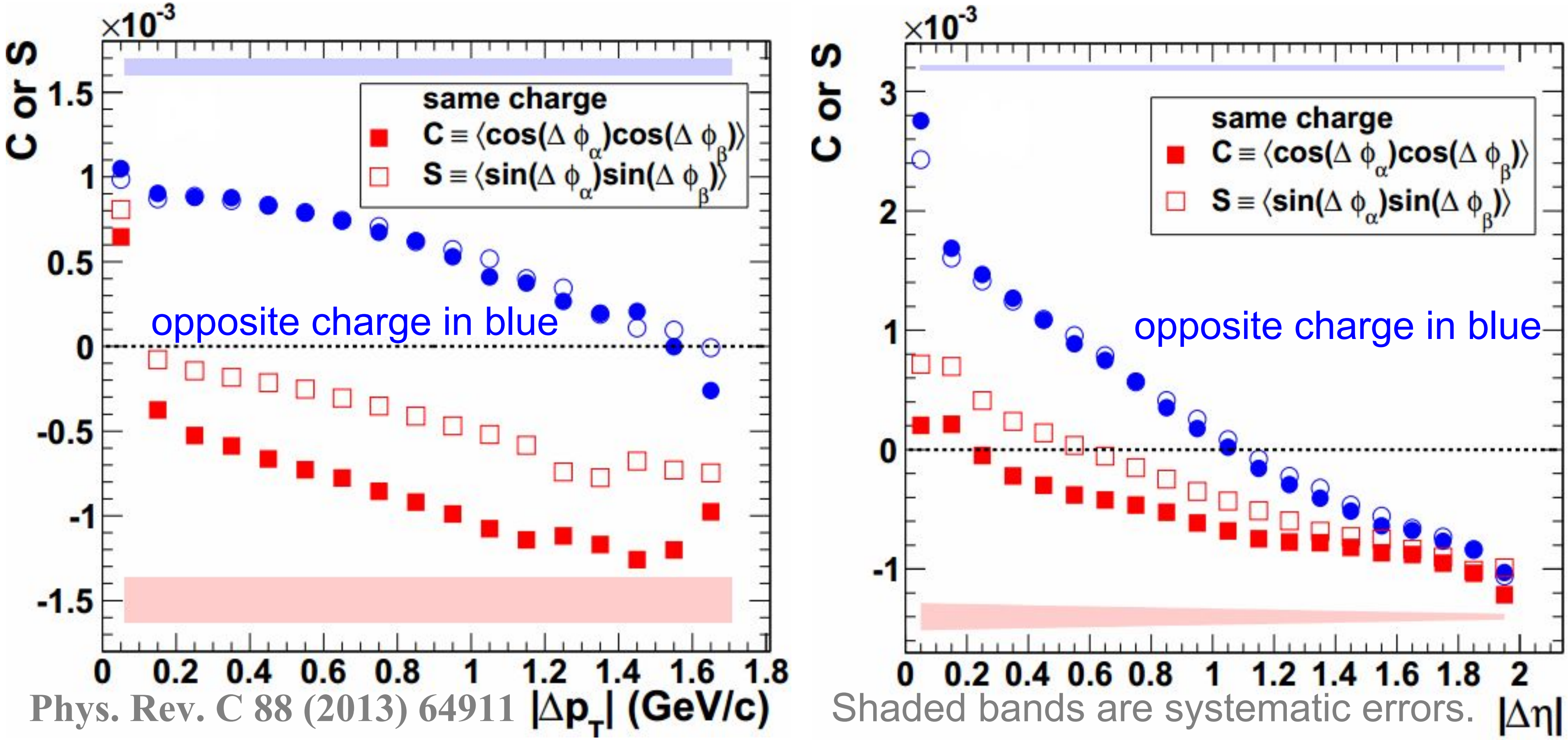




- $\gamma_{os} > \gamma_{ss}$, consistent with CME expectation
- signal in Cu+Cu larger than Au+Au: later-stage effect?
- Consistent between different years (2004 and 2007)
- Confirmed with 1st-order EP (from spectator neutron v_1)
- Not explained by known event generators

Short range correlations

200 GeV Au+Au: 40 - 60%

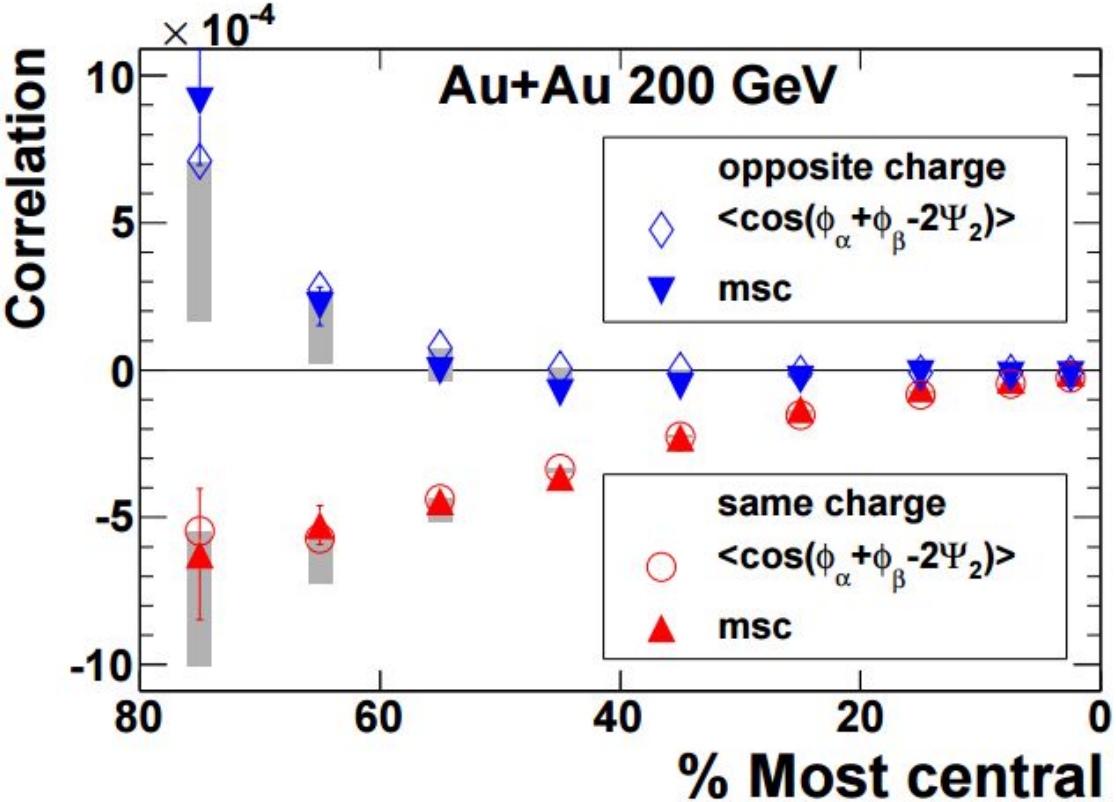


Phys. Rev. C 88 (2013) 64911

Shaded bands are systematic errors.

- Prominent correlations exist at small Δp_T and $\Delta\eta$
- Probably due to HBT+Coulomb

Modulated sign correlator (msc)



$$\langle \cos(\varphi_\alpha + \varphi_\beta - 2\Psi_{RP}) \rangle$$
$$= \langle \cos(\Delta\varphi_\alpha)\cos(\Delta\varphi_\beta) - \sin(\Delta\varphi_\alpha)\sin(\Delta\varphi_\beta) \rangle$$
$$= \langle (M_\alpha M_\beta S_\alpha S_\beta)_{\text{IN}} \rangle - \langle (M_\alpha M_\beta S_\alpha S_\beta)_{\text{OUT}} \rangle$$

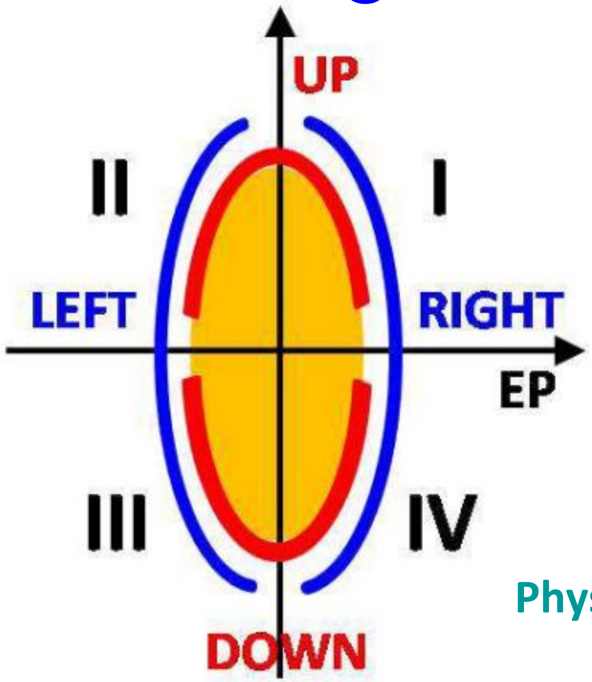
$$\text{msc} \equiv \left(\frac{\pi}{4}\right)^2 \left(\langle S_\alpha S_\beta \rangle_{\text{IN}} - \langle S_\alpha S_\beta \rangle_{\text{OUT}} \right)$$

- robust after removing HBT+Coulomb effects with kinematic cuts ($\Delta\eta$ and Δp_T)
- γ weights different azimuthal regions of charge separation differently
- Modify γ such that all azimuthal regions are weighted equally
- γ is reduced to modulated sign correlator (msc)
- The charge separation signal is confirmed with msc

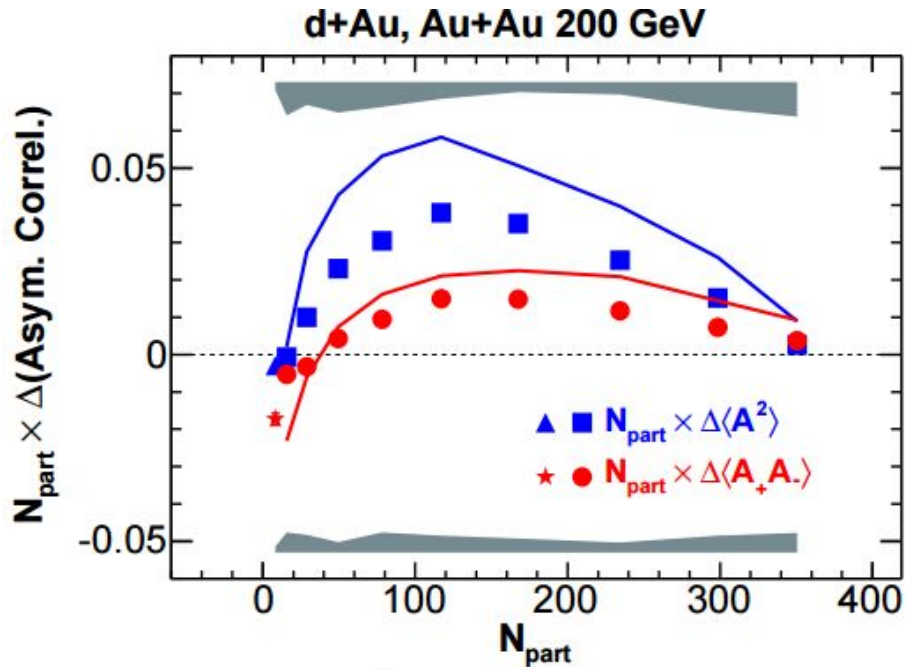
Phys. Rev. C 88 (2013) 64911

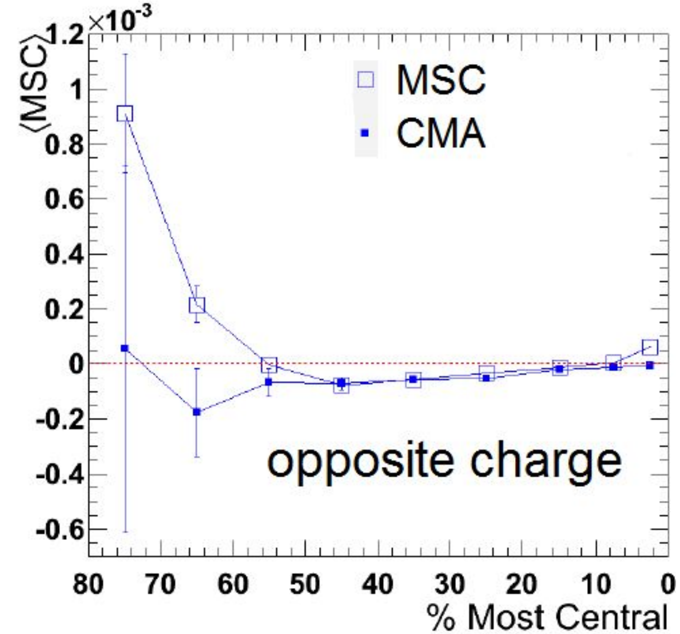
Charge multiplicity asymmetry correlator

count the charges of 4 regions



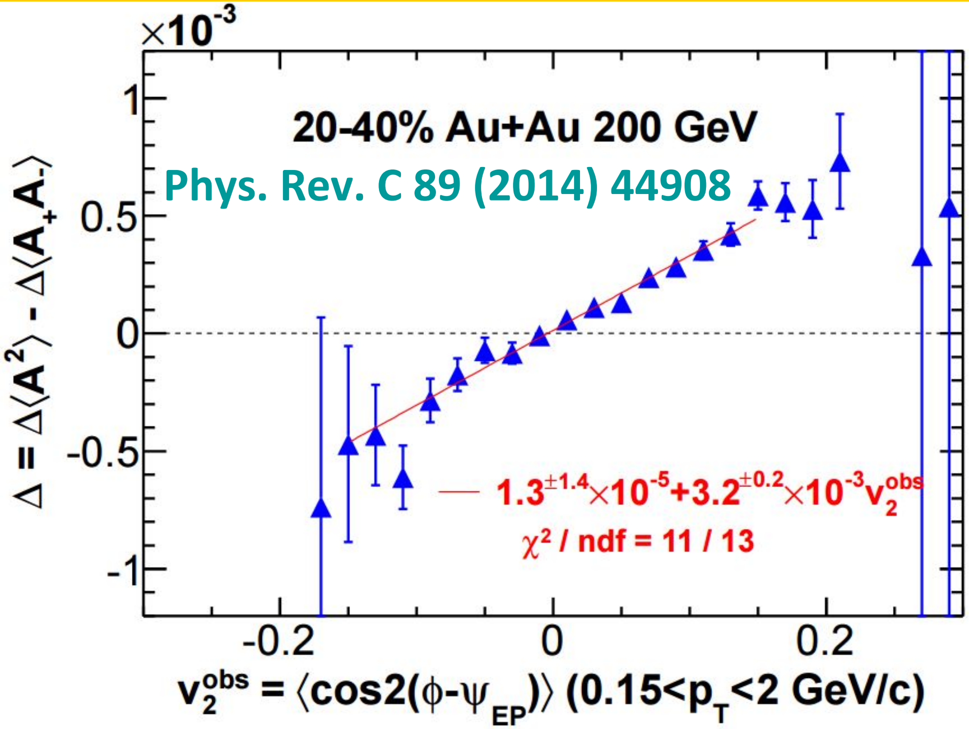
Phys. Rev. C 89 (2014) 44908

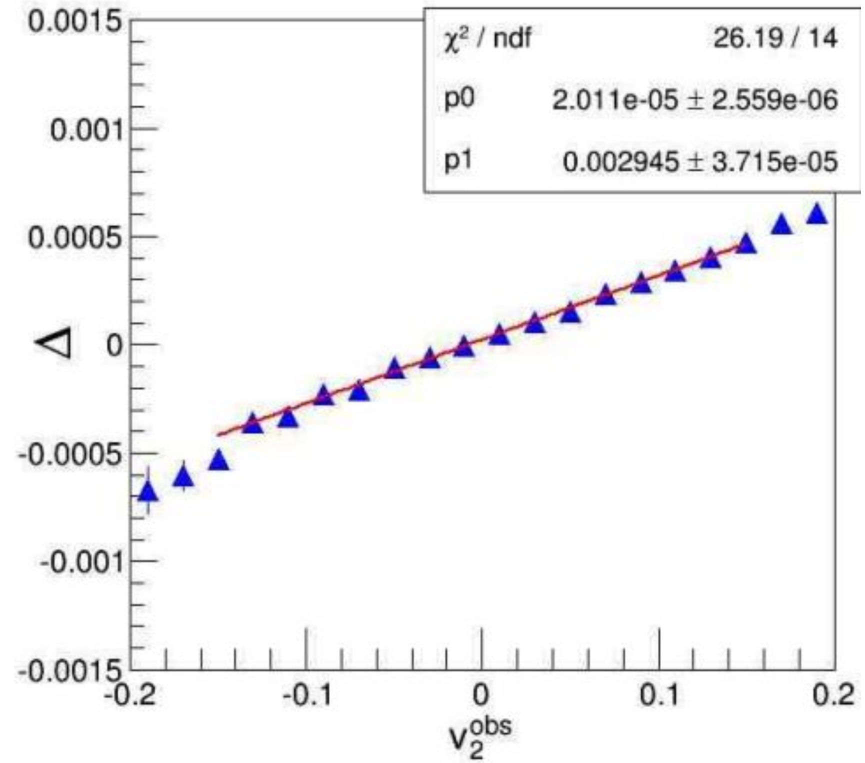




- A similarly reduced correlator, CMA, observes a similar charge separation.
- the CMA correlator (at least the opposite charge) is equivalent to MSC

Charge multiplicity asymmetry correlator





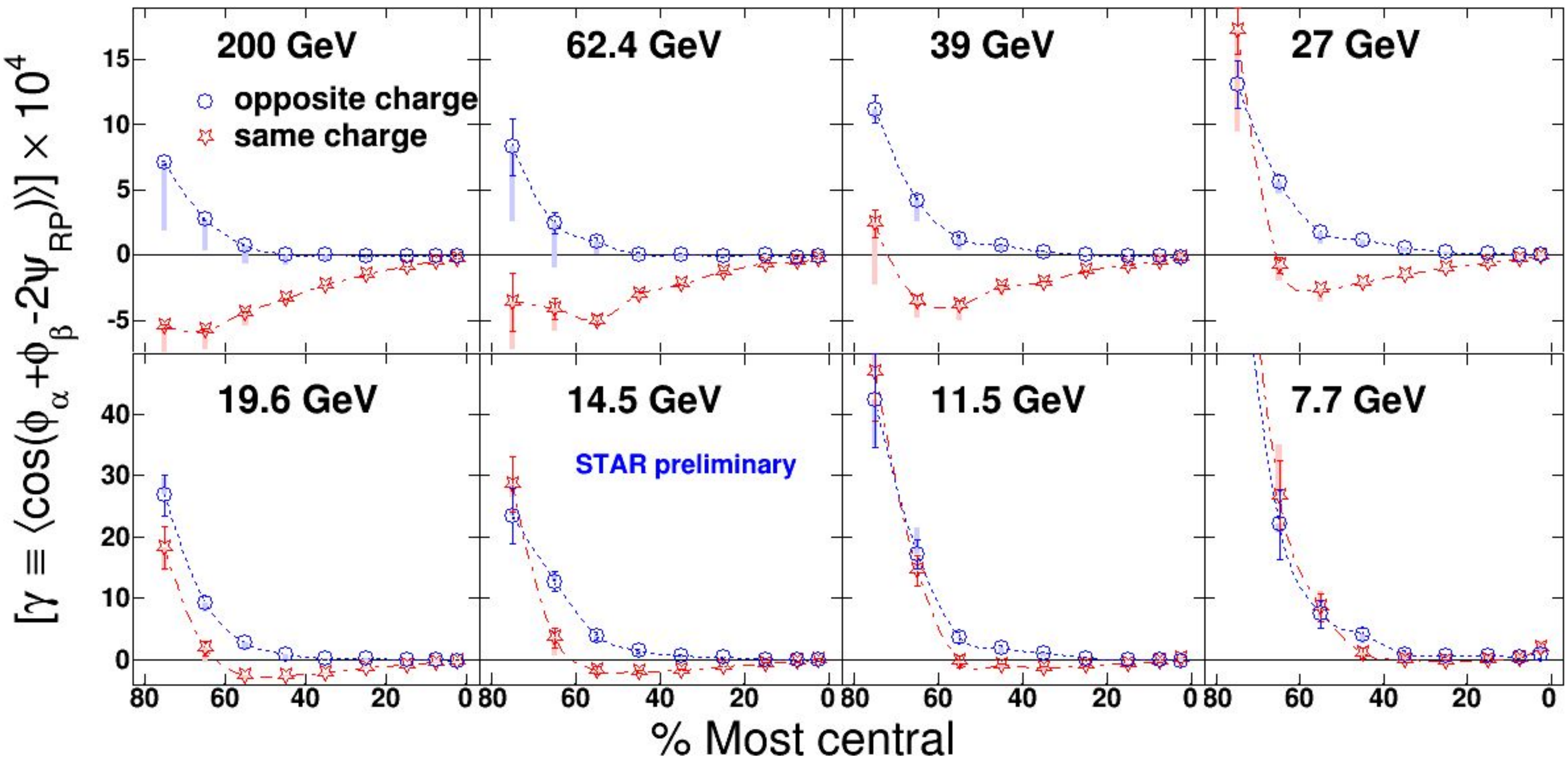
$\Delta = 1.3 \pm 1.4(stat.)^{+4.0}_{-1.0}(syst.) \times 10^{-5}$

$\Delta(v_2^{obs} = 0) = 2.0 \pm 0.3(stat.) \times 10^{-5}$

- A condition on observed v_2 is applied to remove flow-related bg.
- Previously, when $v_2^{obs} = 0$, the signal was consistent with zero!
- Now, new measurements with higher statistics report finite signal: 7σ!
- Beam energy dependence also looks similar to that of γ.

Beam Energy Scan

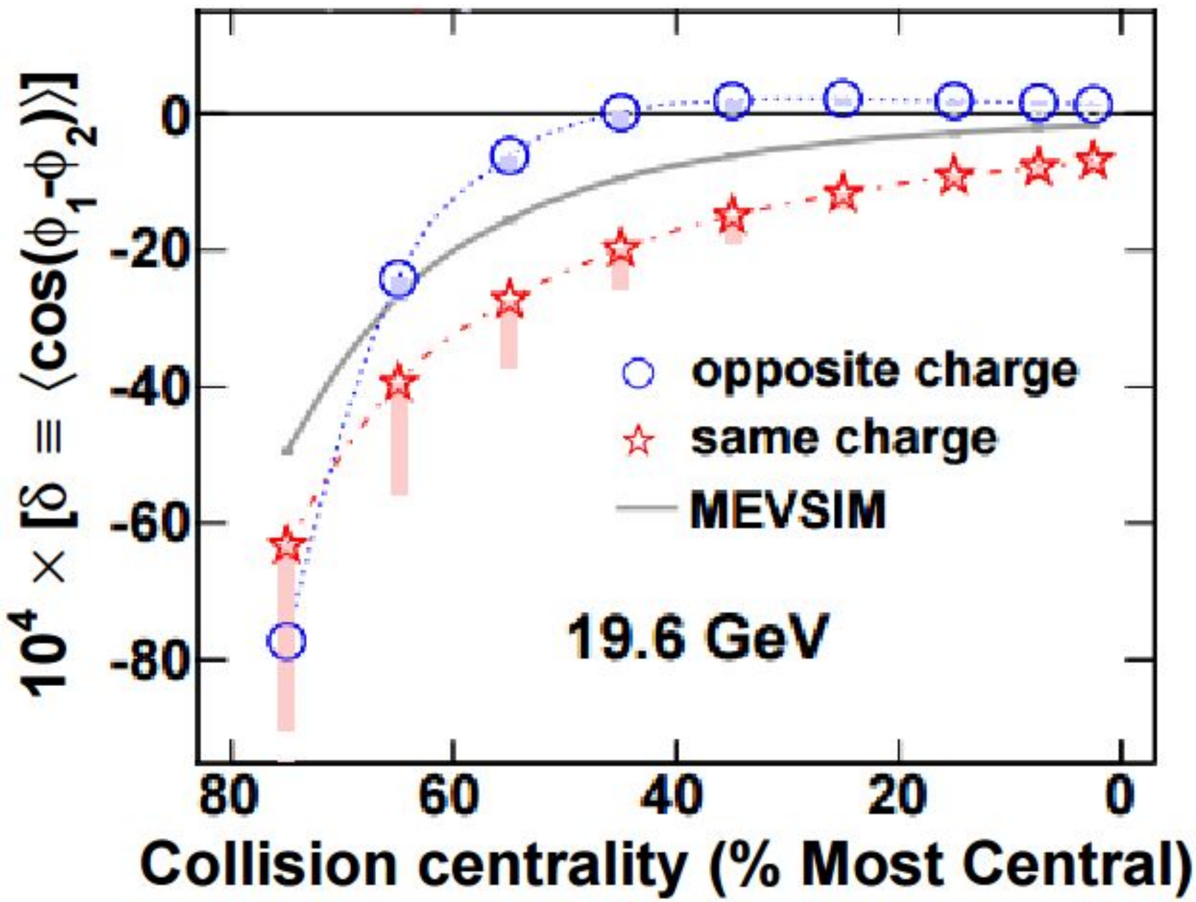
Phys. Rev. Lett 113 (2014) 052302



At lower beam energies, charge separation starts to diminish.

Flow-related background

Phys. Rev. Lett 113 (2014) 052302



- Against CME expectation, $\delta_{OS} > \delta_{SS}$
- Indicate overwhelming background, larger than any possible CME effect.
- Try combining information from γ and δ to retrieve the CME contribution, *H*

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

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

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

Transverse momentum conservation

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

$$\gamma = -\frac{1}{N_{\rm tot}} \frac{\langle p_t \rangle_\Omega^2}{\langle p_t^2 \rangle_F} \frac{2\bar{v}_{2,\Omega} - \bar{\bar{v}}_{2,F} - \bar{\bar{v}}_{2,F}(\bar{v}_{2,\Omega})^2}{1-(\bar{\bar{v}}_{2,F})^2},$$

$$\delta = -\frac{1}{N_{\rm tot}} \frac{\langle p_t \rangle_\Omega^2}{\langle p_t^2 \rangle_F} \frac{1+(\bar{v}_{2,\Omega})^2 - 2\bar{\bar{v}}_{2,F}\,\bar{v}_{2,\Omega}}{1-(\bar{\bar{v}}_{2,F})^2},$$

we have introduced certain weighted moments of v_2:

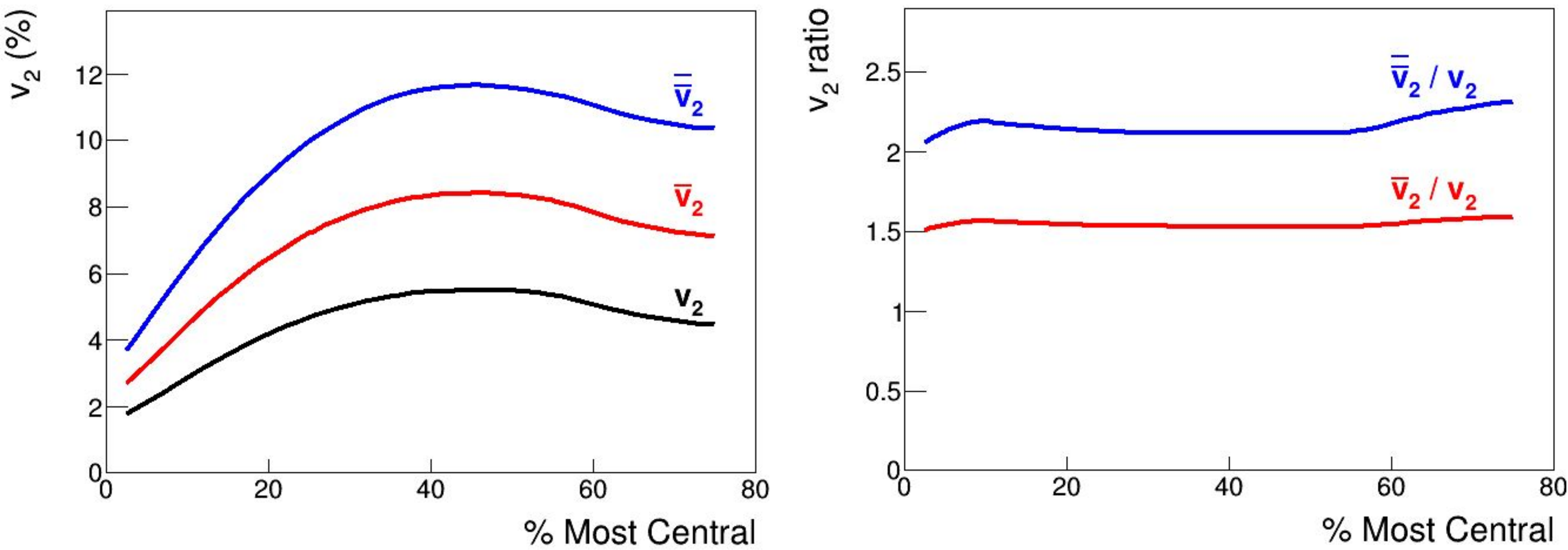
$$\bar{v}_2 = \frac{\langle v_2(p_t,\eta) p_t \rangle}{\langle p_t \rangle}, \qquad \bar{\bar{v}}_2 = \frac{\langle v_2(p_t,\eta) p_t^2 \rangle}{\langle p_t^2 \rangle}.$$

If our measurements are dominated by this type of background,

$$\gamma / \delta \approx 2\bar{v}_{2,\Omega} - \bar{\bar{v}}_{2,F}$$

where F and Ω denote averages that are calculated for all particles in the full phase-space, or for all actually measured particles in the restricted phase-space, respectively.

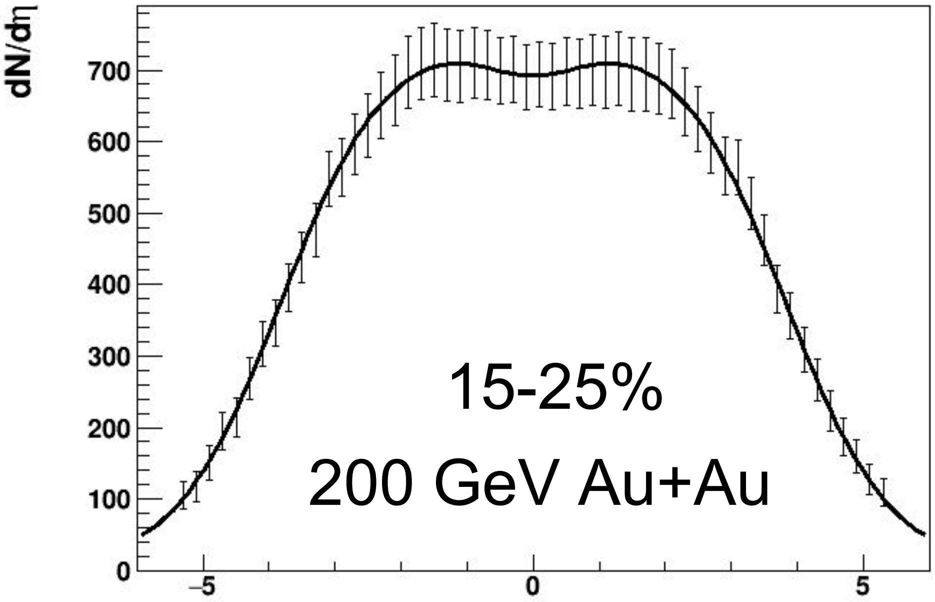
v_2, $\bar{v}_2$ and $\bar{\bar{v}}_2$

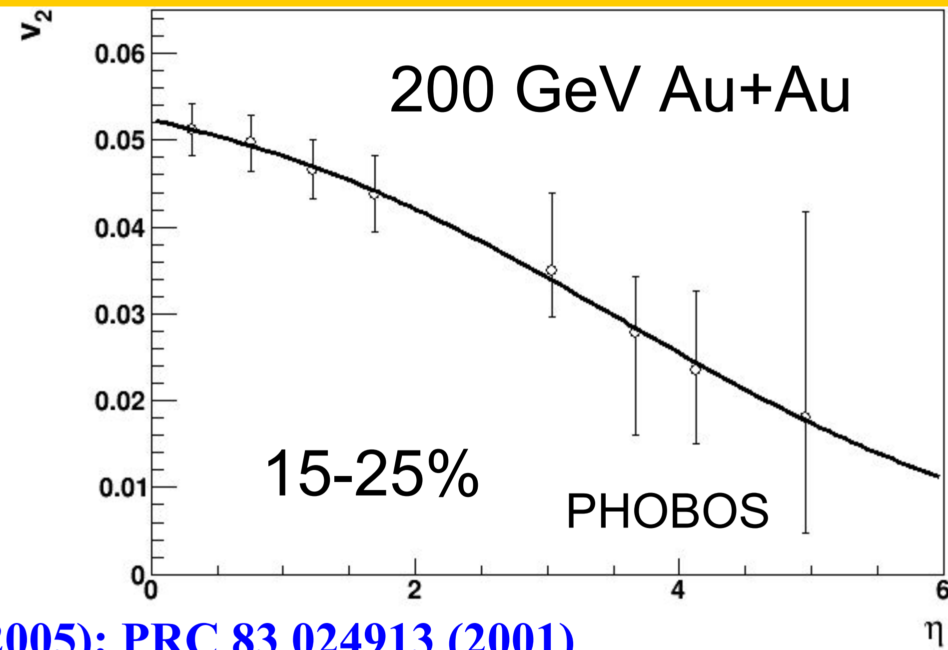


$$\bar{v}_2 = \frac{\langle v_2(p_t,\eta)p_t \rangle}{\langle p_t \rangle}, \qquad \bar{\bar{v}}_2 = \frac{\langle v_2(p_t,\eta)p_t^2 \rangle}{\langle p_t^2 \rangle}$$

The ratios of the p_T-weighted v_2 over conventional v_2 are almost constant over centrality.

$v_{2,\Omega}$ and $v_{2,F}$

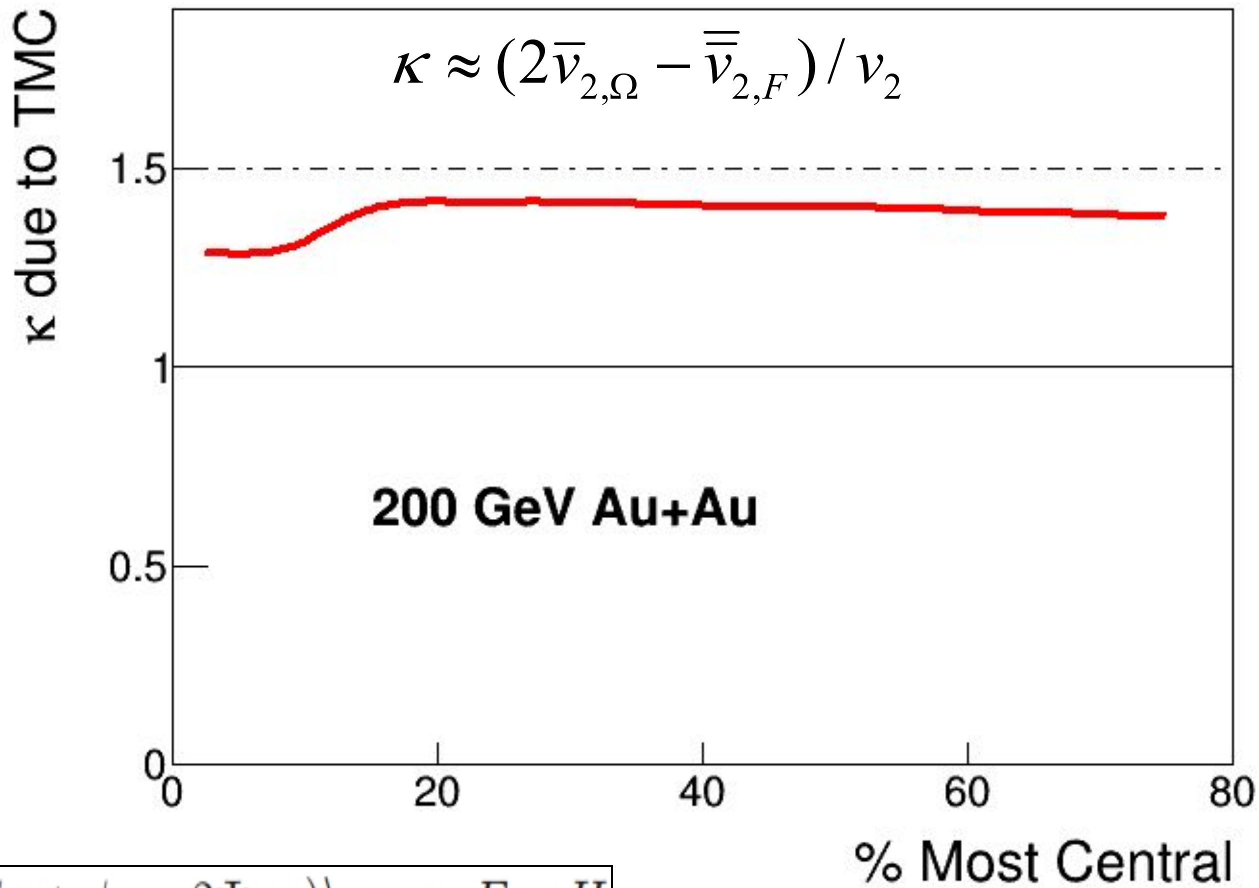




PHOBOS, PRC 72 014904 (2005); PRC 83 024913 (2001)

centrality	$v_{2,\Omega}$ (%)	$v_{2,F}$ (%)	$v_{2,F}/v_{2,\Omega}$
3-15%	3.17	2.66	0.84
15-25%	5.04	3.97	0.79
25-50%	6.21	4.87	0.78

κ due to TMC

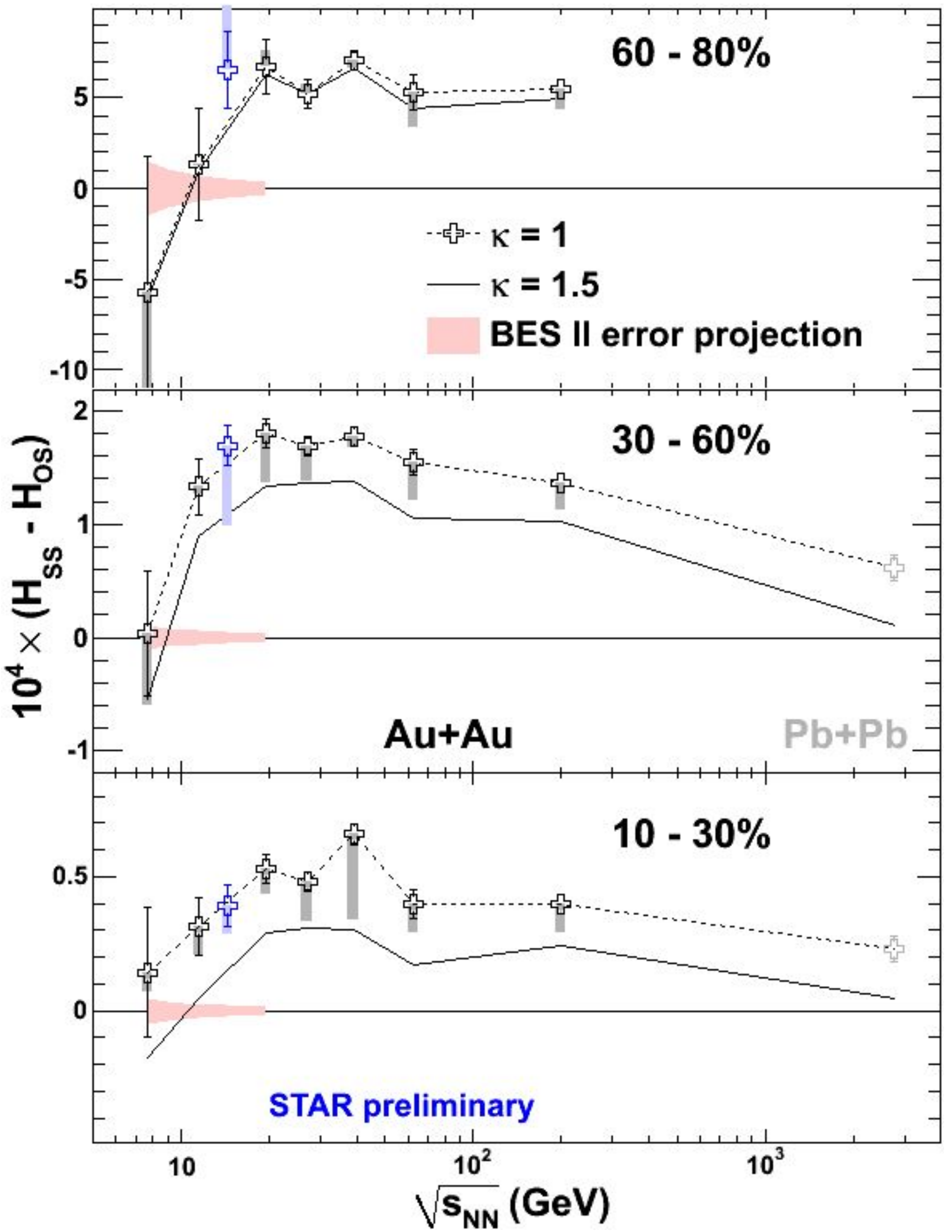


$$\gamma \equiv \langle\cos(\phi_1 + \phi_2 - 2\Psi_{RP})\rangle = \kappa v_2 F - H$$
$$\delta \equiv \langle\cos(\phi_1 - \phi_2)\rangle = F + H,$$

Other effects like Local Charge Conservation (LCC) and resonance decay may lead to smaller κ (closer to unity).

CME contribution

Phys. Rev. Lett 113 (2014) 052302

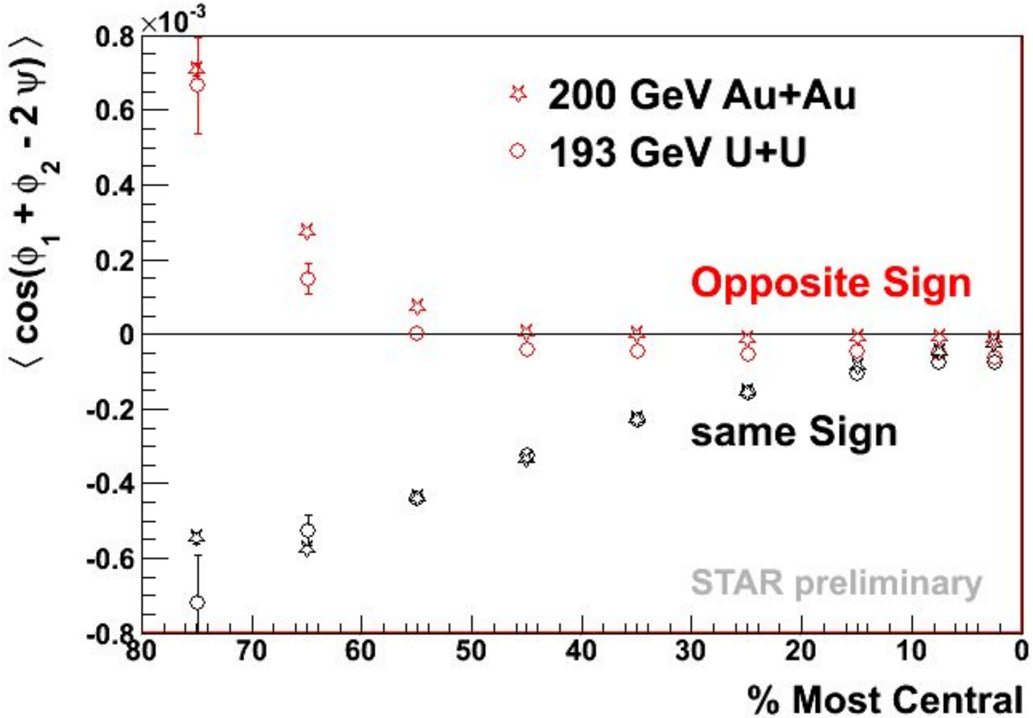


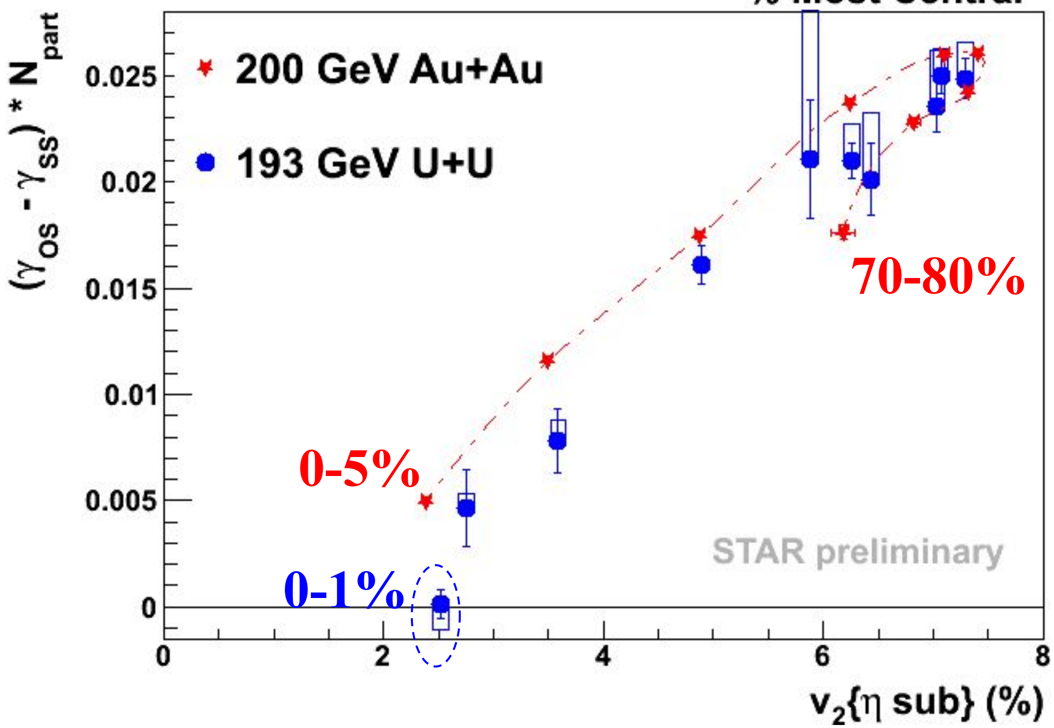
$$H^{\kappa} = (\kappa v_2 \delta - \gamma)/(1 + \kappa v_2)$$

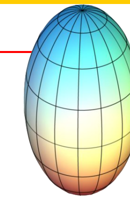
A. Bzdak, V. Koch and J. Liao, Lect. Notes Phys. 871, 503 (2013).

- κ is roughly contained in the range of [1, 1.5].
- CME signal (ΔH) decreases to 0 from 19.6 to 7.7 GeV
- Probable domination of hadronic interactions over partonic ones
- Need more study of κ and more statistics

Deformed nuclei: U+U







- Similar signals in U+U
- Use γ_{OS}-γ_{SS} to quantify 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 (mostly background) disappears, while v_2 is still ~2.5%

Extrapolate to intermediate centrality?

Isobar collisions may work better.

What we learned so far

- signal of charge separation w.r.t RP
  - comfirmed with different EP types (1st- and 2nd-order)
  - remain in Au+Au, Cu+Cu, Pb+Pb and U+U
  - persist from 19.6 GeV to 2.76 TeV
  - repeated with reduced correlators
  - robust when suppressing HBT+Coulomb
  - removal of flow-related bg doesn't kill signal

- signal seems to disappear when
  - the collision energy is down to ~7.7 GeV
  - B field from spectators is supressed (v_2 is still sizable)

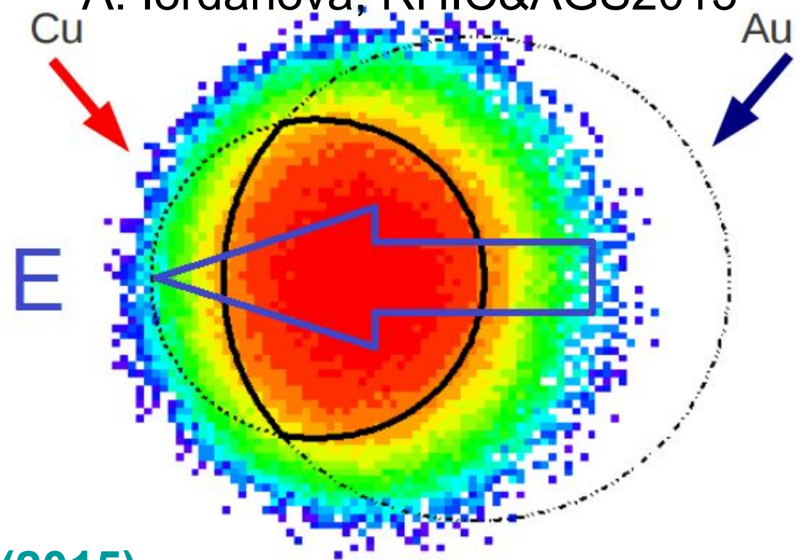
Does the initial B really impact the final-stage particles?

- any evidence?

Study of initial E-field via v_1@CuAu

- Sizable E-field pointing from Au to Cu
- Expect charge-dependent directed flow
  - electric conductivity of QGP
  - relavent to CME/CMW
  - quark/anti-quark creation time

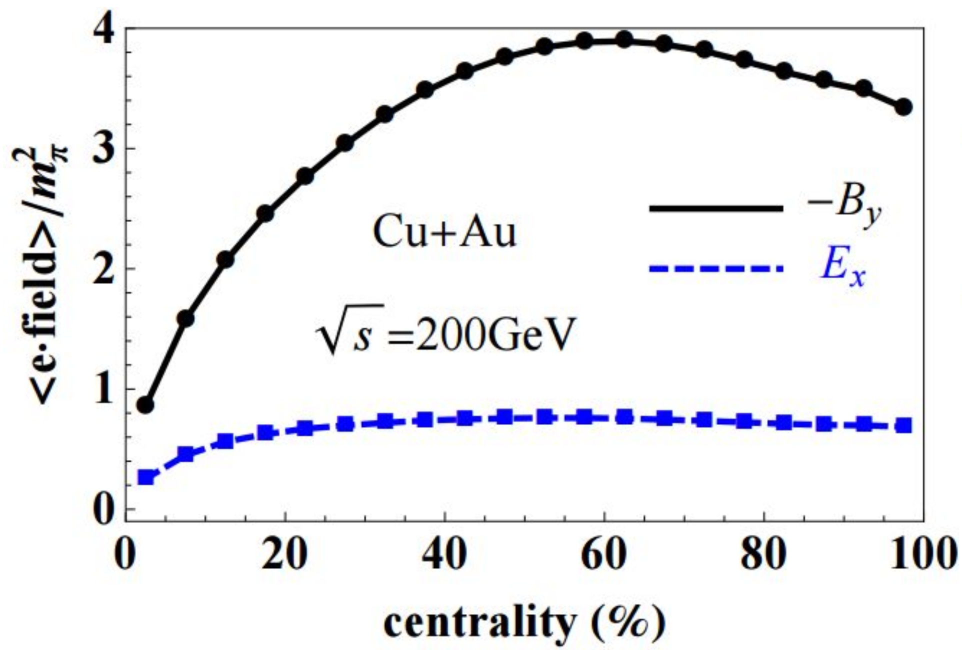
A. Iordanova, RHIC&AGS2013

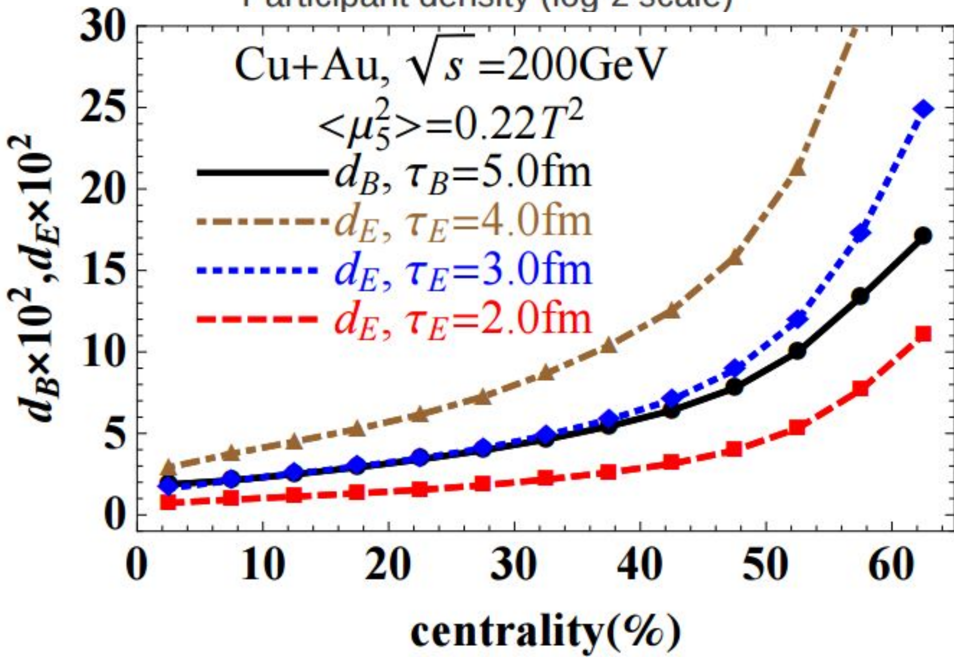


Participant density (log-z scale)

Are the E/B fields strong enough and long enough to leave an imprint?

W.T. Deng and X.G. Huang, Phys.Lett. B742,296 (2015)

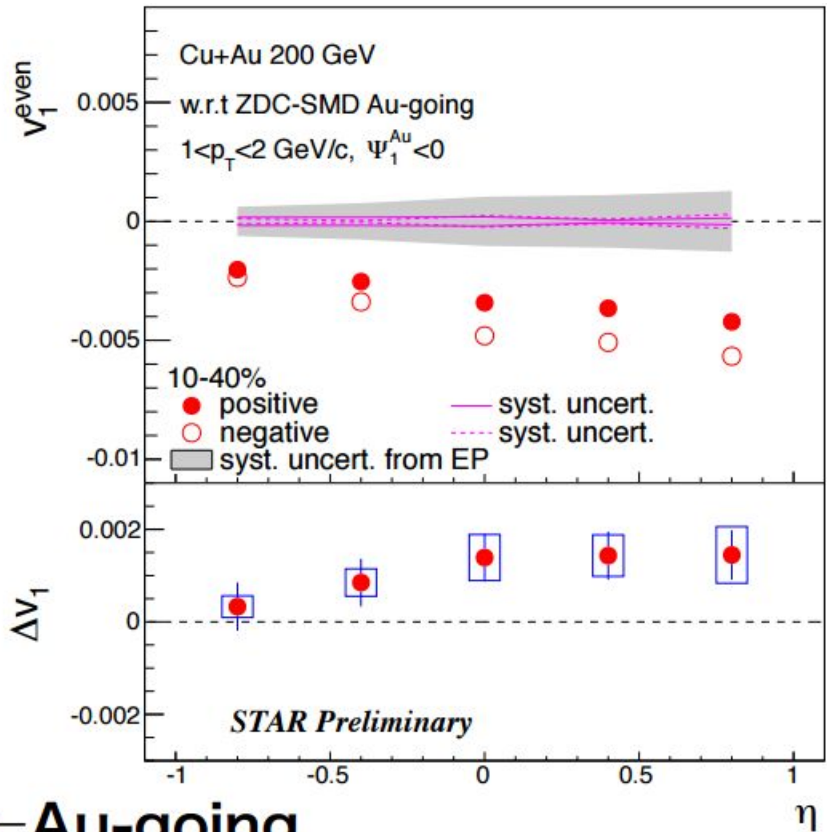




v_1@Cu+Au

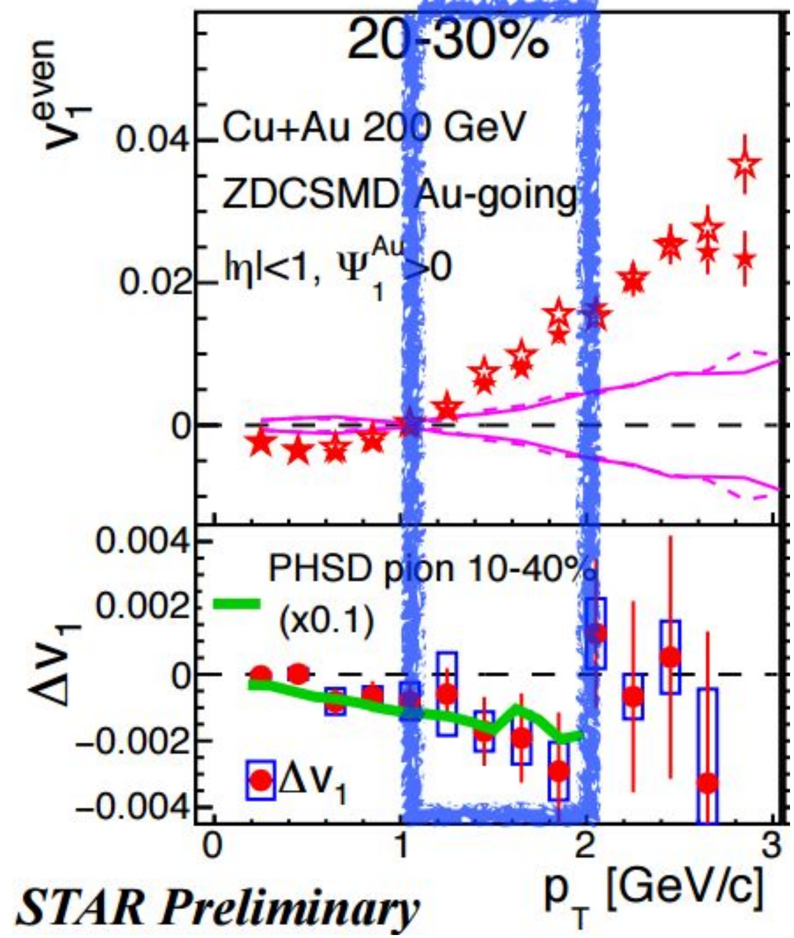
Expect charge-dependence of directed flow due to a dipole deformation

Y. Hirono, M. Hongo and T. Hirano, PRC 90, 021903(R)



←Au-going

signal larger in Cu-going side: later-stage effect?



- $\Delta v_1 = v_1(h^+) - v_1(h^-)$, shows the right sign as expected by the model with initial E-field
- E-field does leave an imprint. So should the B-field?
- help constrain the initial quark / (anti)quark production

Outlook: Isobars

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

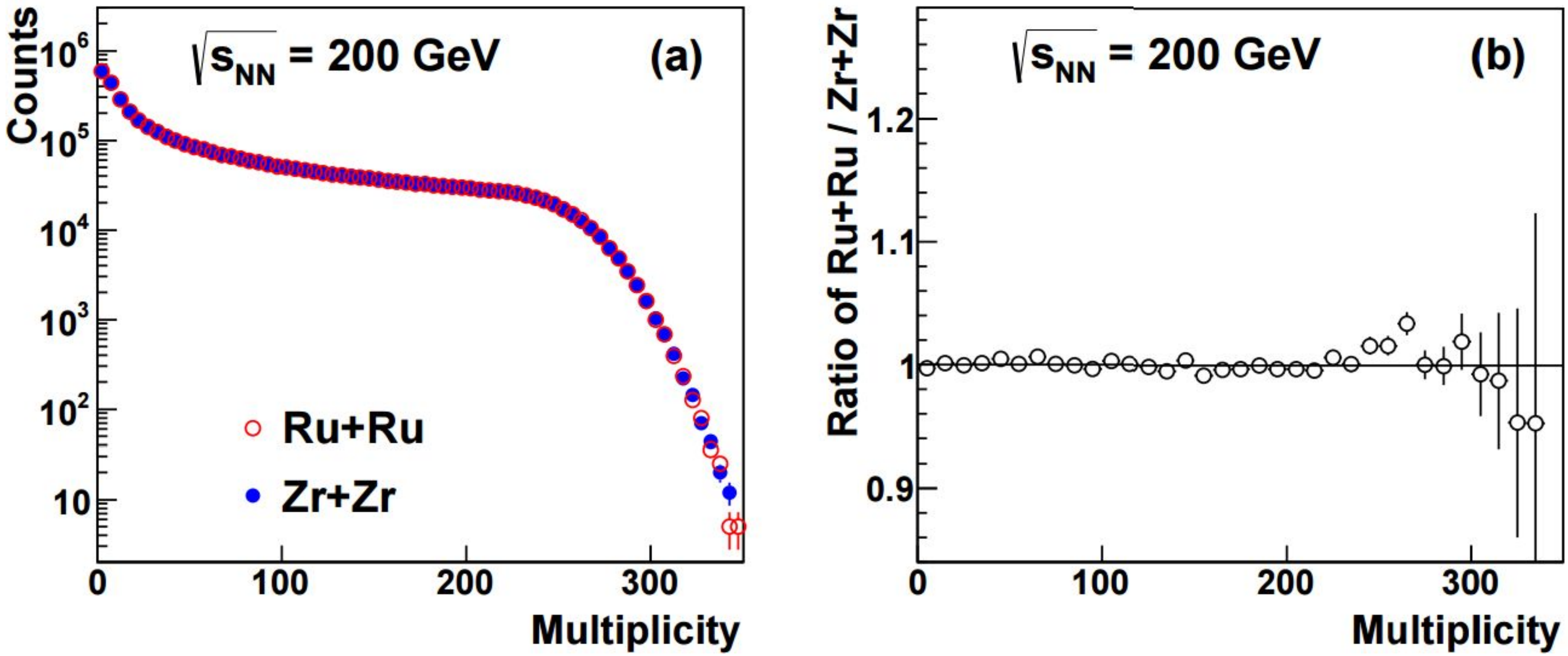
For example, $^{96}_{44}$Ruthenium and $^{96}_{40}$Zirconium:

Up to 10% variation in B field

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

Isobars: multiplicity

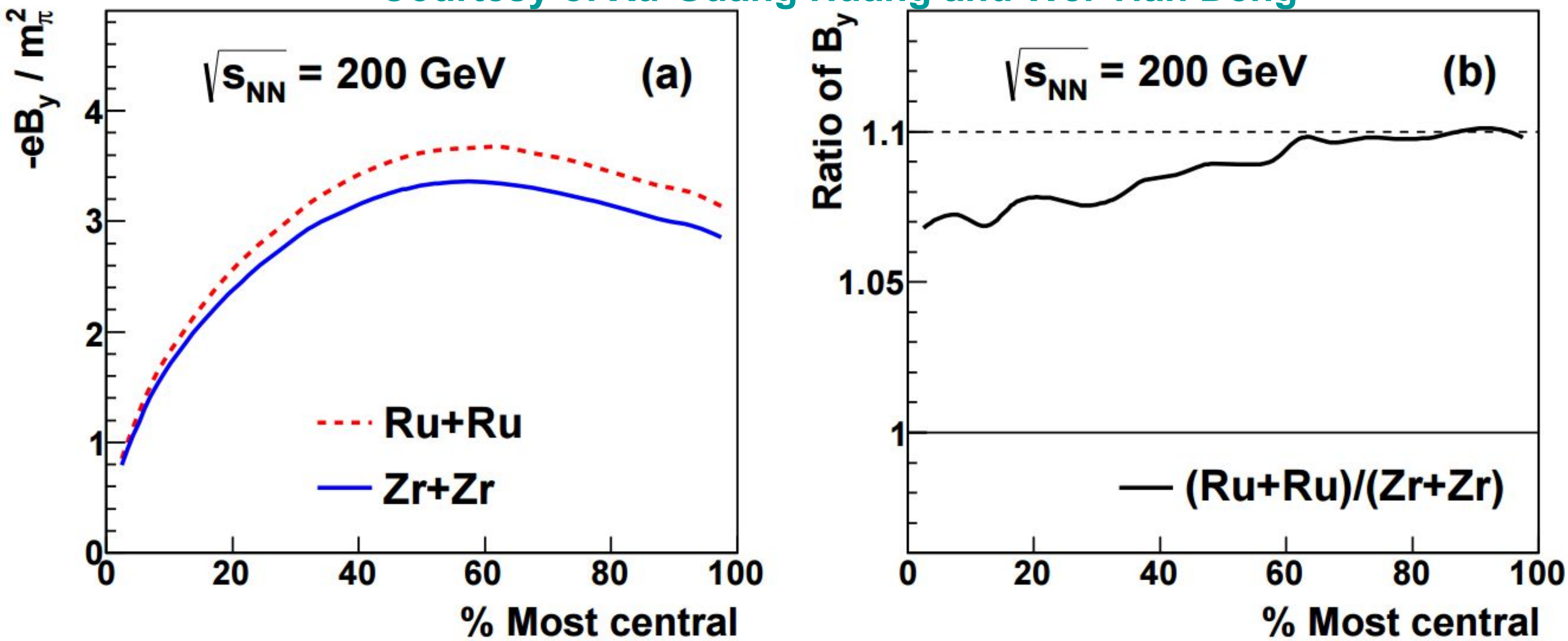
- Almost identical distributions of multiplicity (MC Glauber)
- The ratio is close to 1 except for 0-10% most central events
- Zr is a little deformed (β_2=0.2), and Ru is spherical (β_2=0.05)



Isobars: B field

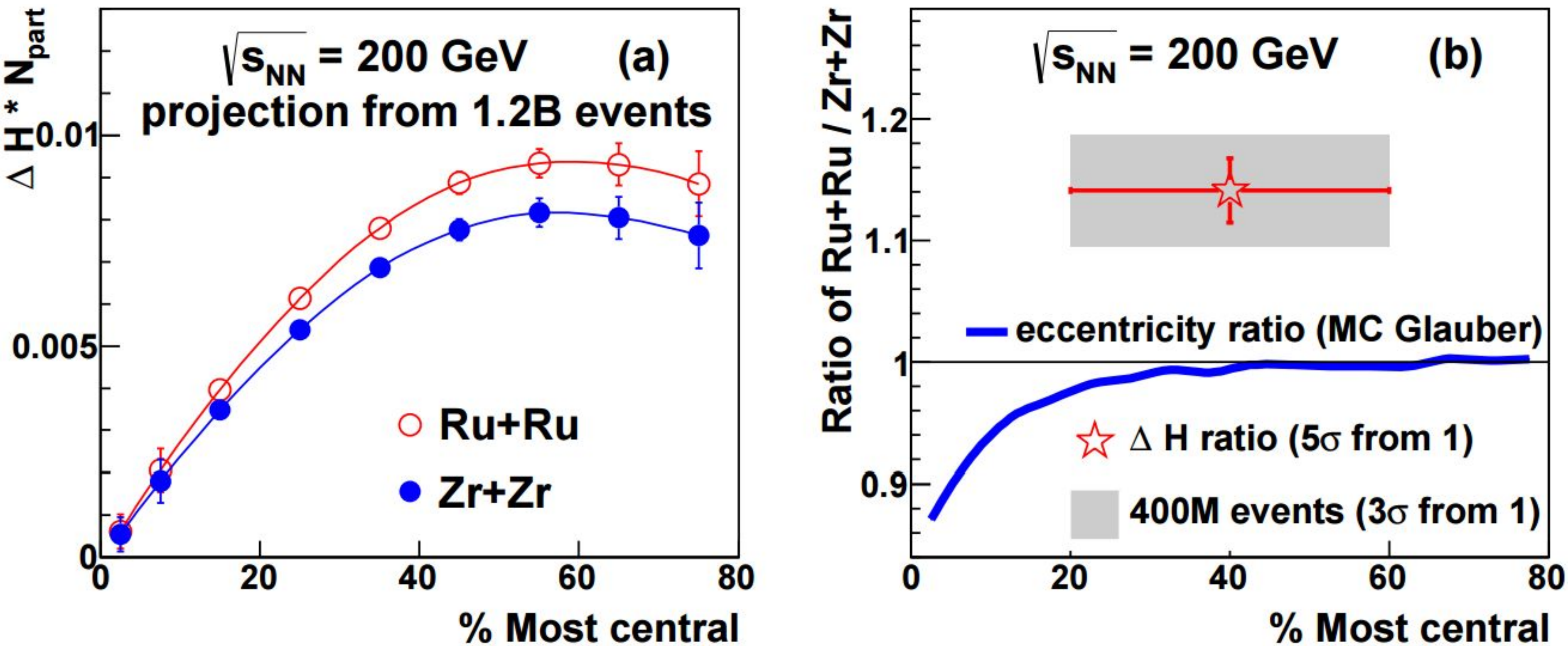
- Clear difference in the B field for the same centrality
- The ratio is close to 1.1 for peripheral events
- Reduces to 1.07 for central events

Courtesy of Xu-Guang Huang and Wei-Tian Deng



Isobars: charge separation

- Projection from 1.2B events shows difference in ΔH
- The ratio is 5σ above 1 (3σ with 400M events)
- If it's v_2-driven, the ratio will follow eccentricity (~ 1)



Outlook: Cu+Au

Ohm's Law

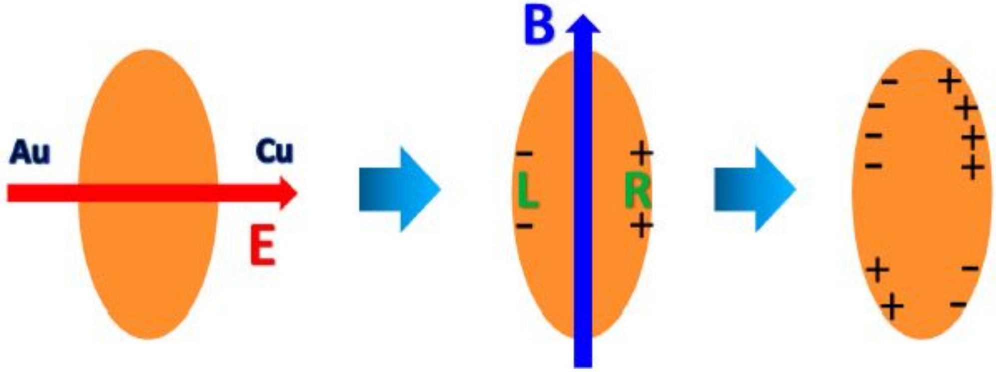
Chiral Magnetic Effect

	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



in-plane charge separation

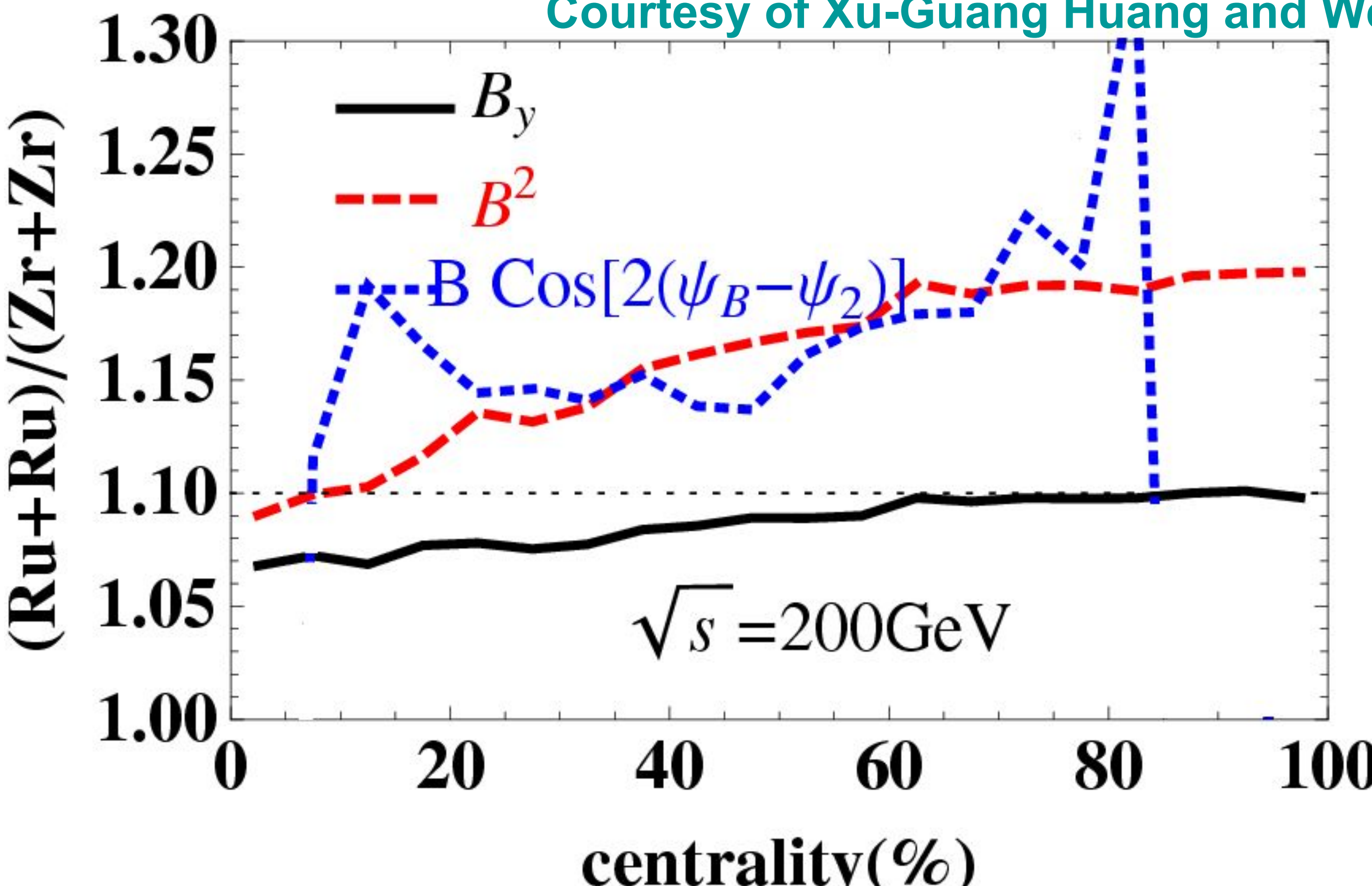
Suppressed γ signal of charge separation in Cu+Au collisions?

Backup slides

Isobars: B field

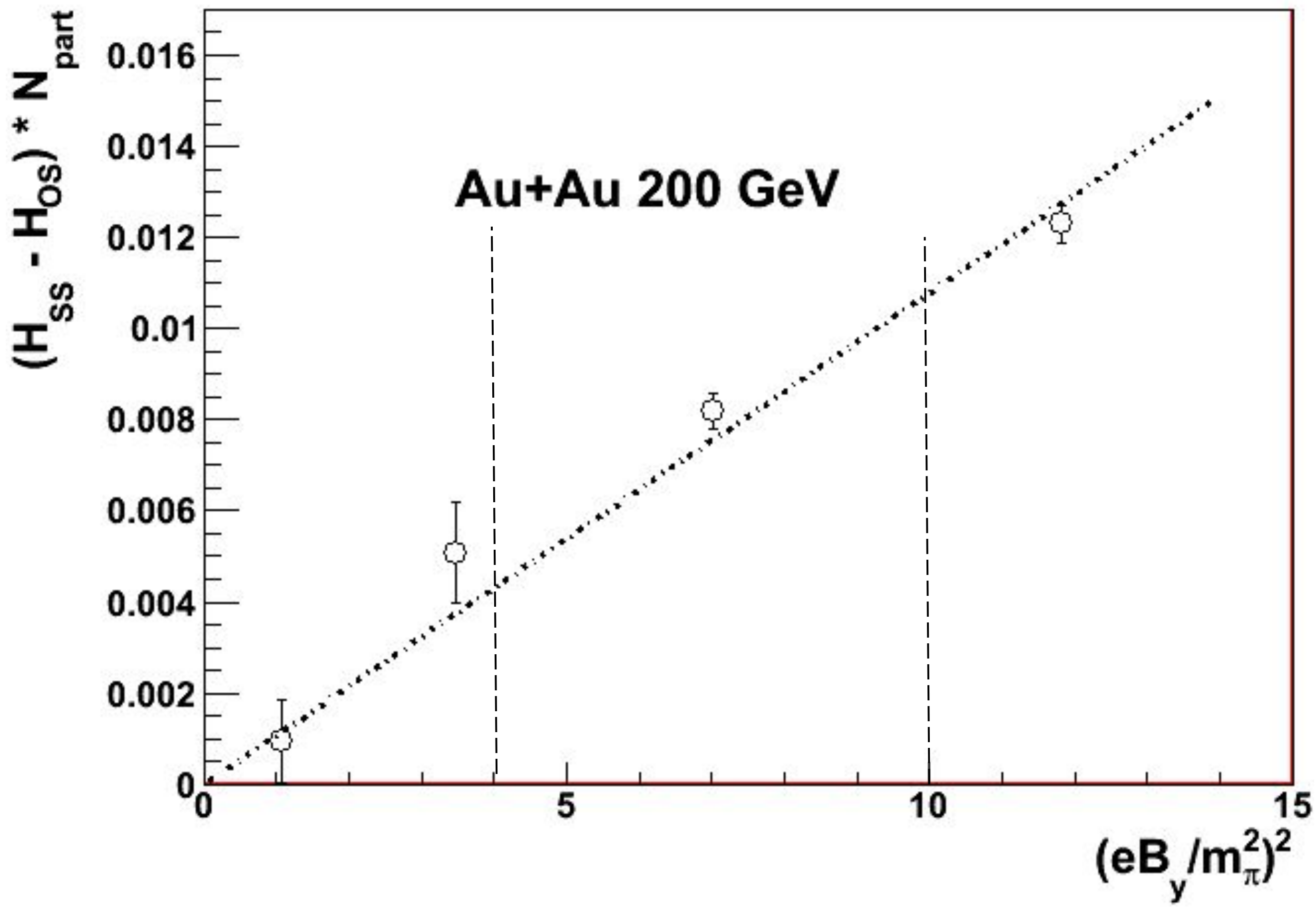
- Which B quantity is sensitive to the charge separation?
- The ratio is similar in term of ~ B^2 for 20-60% collisions
- B•cos(2Δφ) may be more realistic, with a bigger difference
- We use B_y for simplicity

Courtesy of Xu-Guang Huang and Wei-Tian Deng

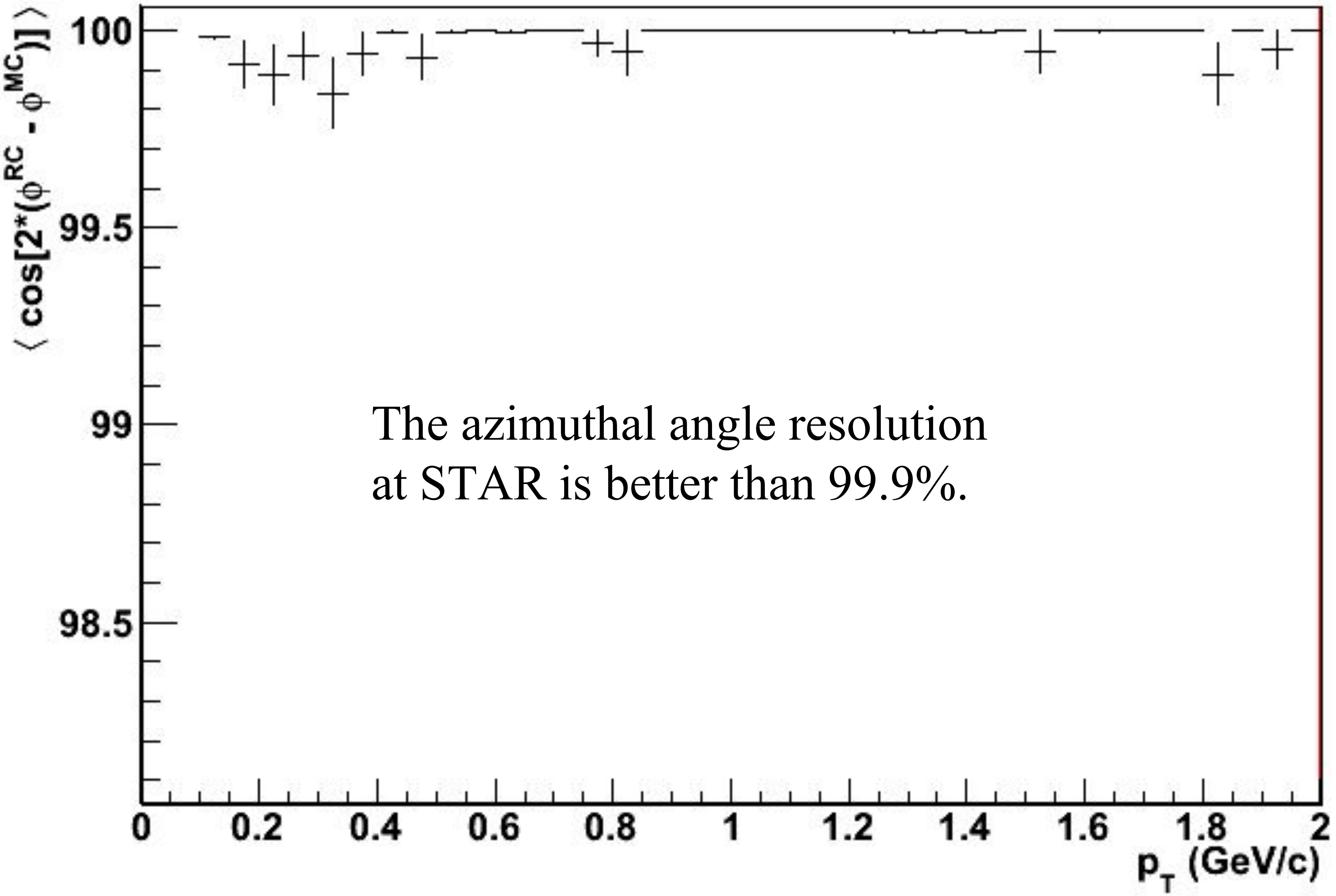


Au+Au 200 GeV

- $\Delta H \cdot N_{part}$ is a roughly linear function of B^2 for Au+Au 200 GeV.
- The 20-60% isobar collisions covers [4, 10] in the x axis.

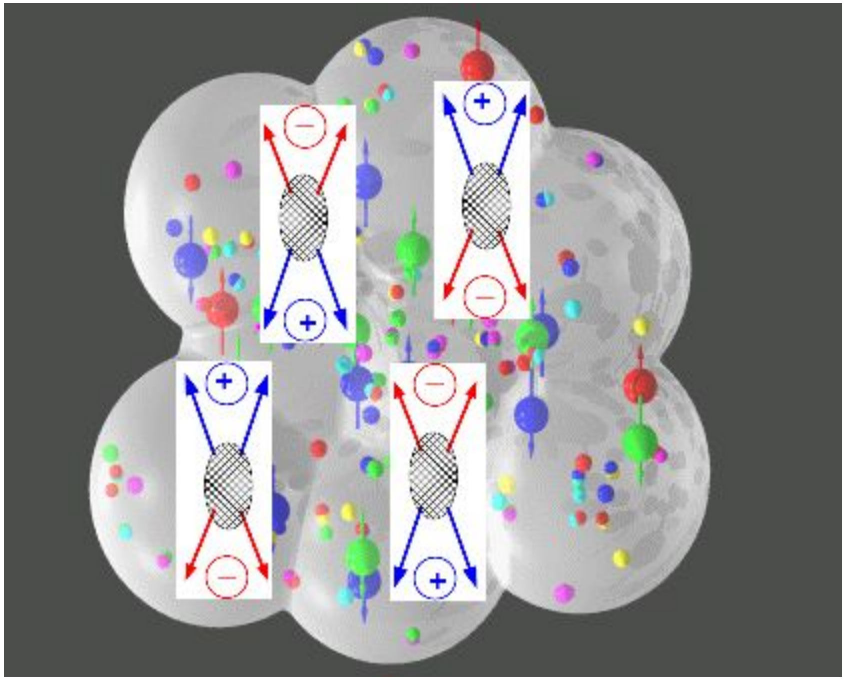


Excellent tracking



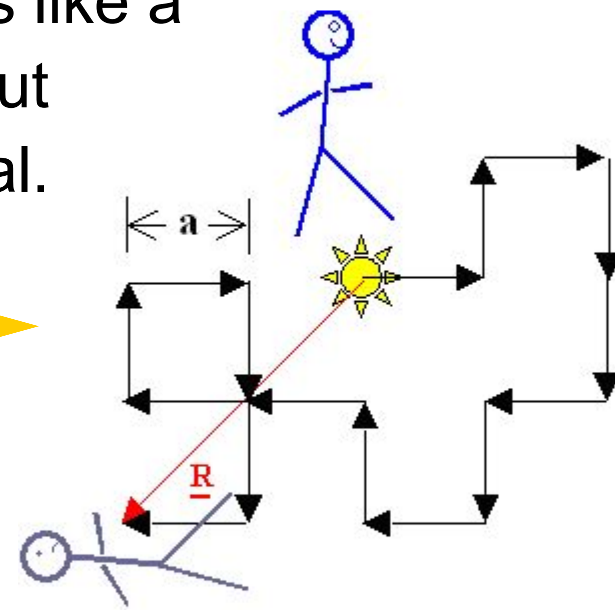
The azimuthal angle resolution at STAR is better than 99.9%.

Dilution effect



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

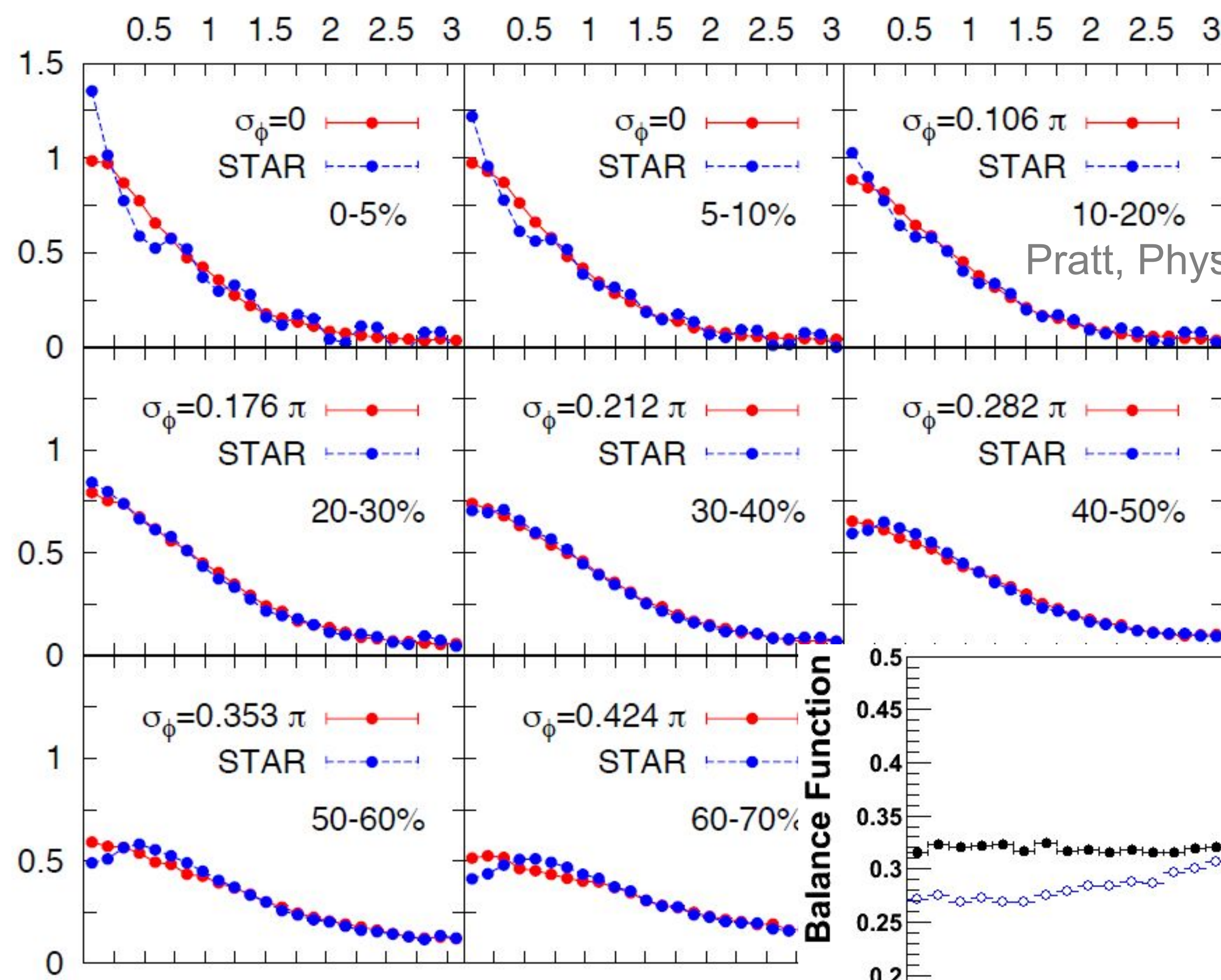
The net effect is like a *random walk*, but one-dimensional.



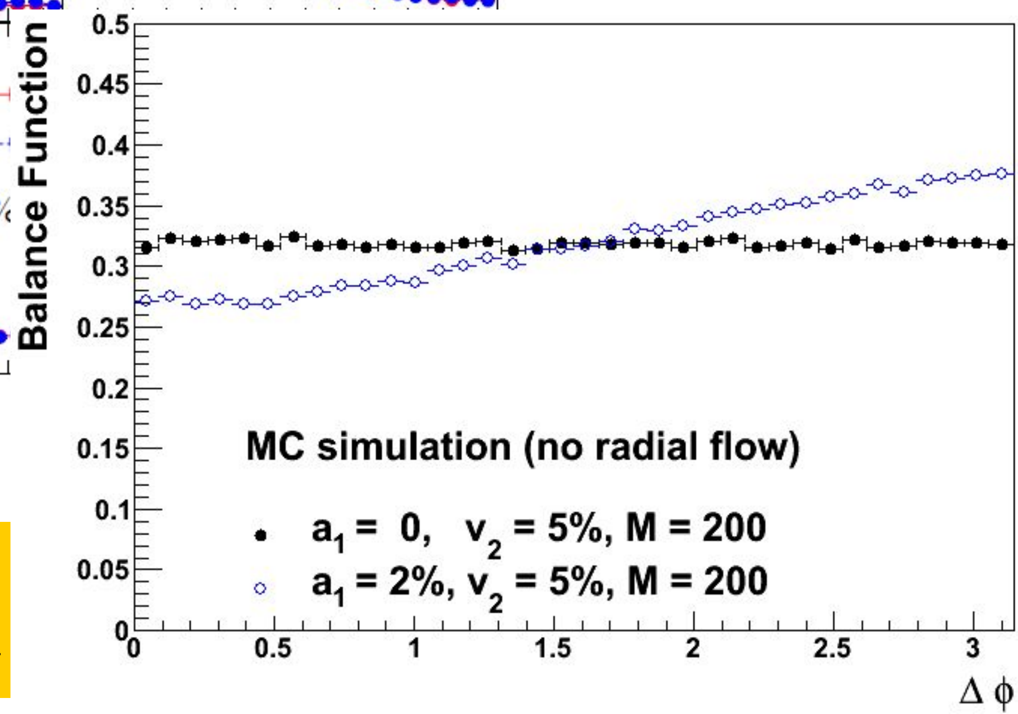
What do we know about the position R_n after n steps?

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



Pratt, Phys.Rev.C83:014913,2011



Balance function