QCD Chirality Workshop 2015

Search for the Chiral Magnetic Effect at STAR

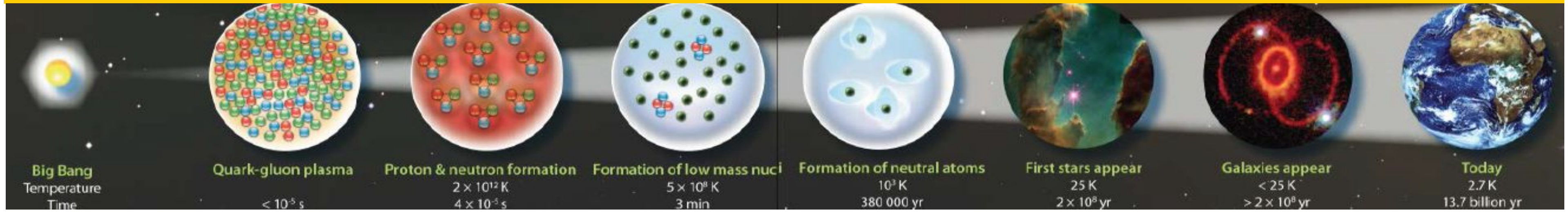
Gang Wang (UCLA)

for the STAR Collaboration

Outline

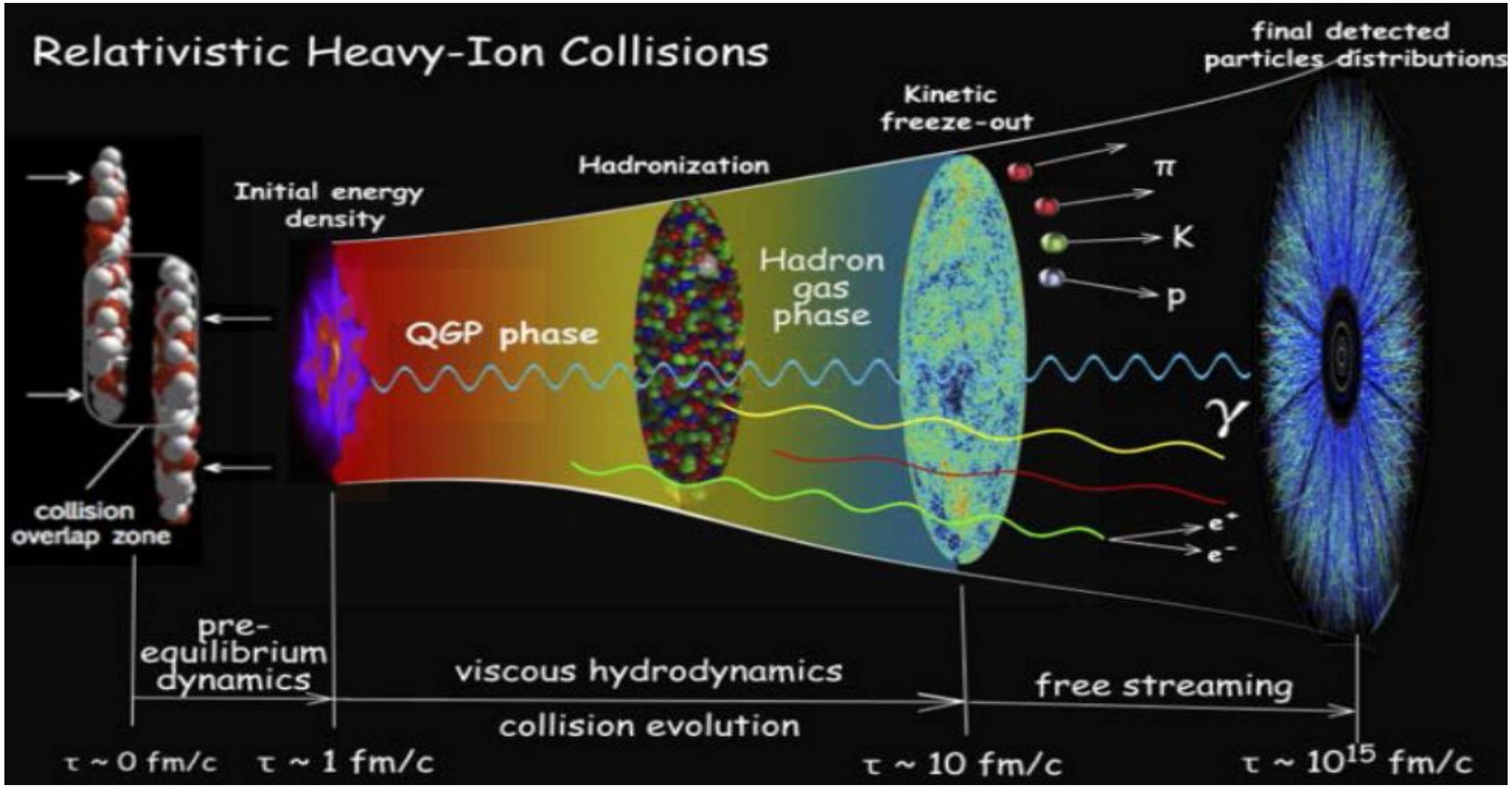
- Motivation
- STAR Experiment
- Chiral Magnetic Effect (CME)
- Summary
- Outlook

Big Bang & Micro-Bangs

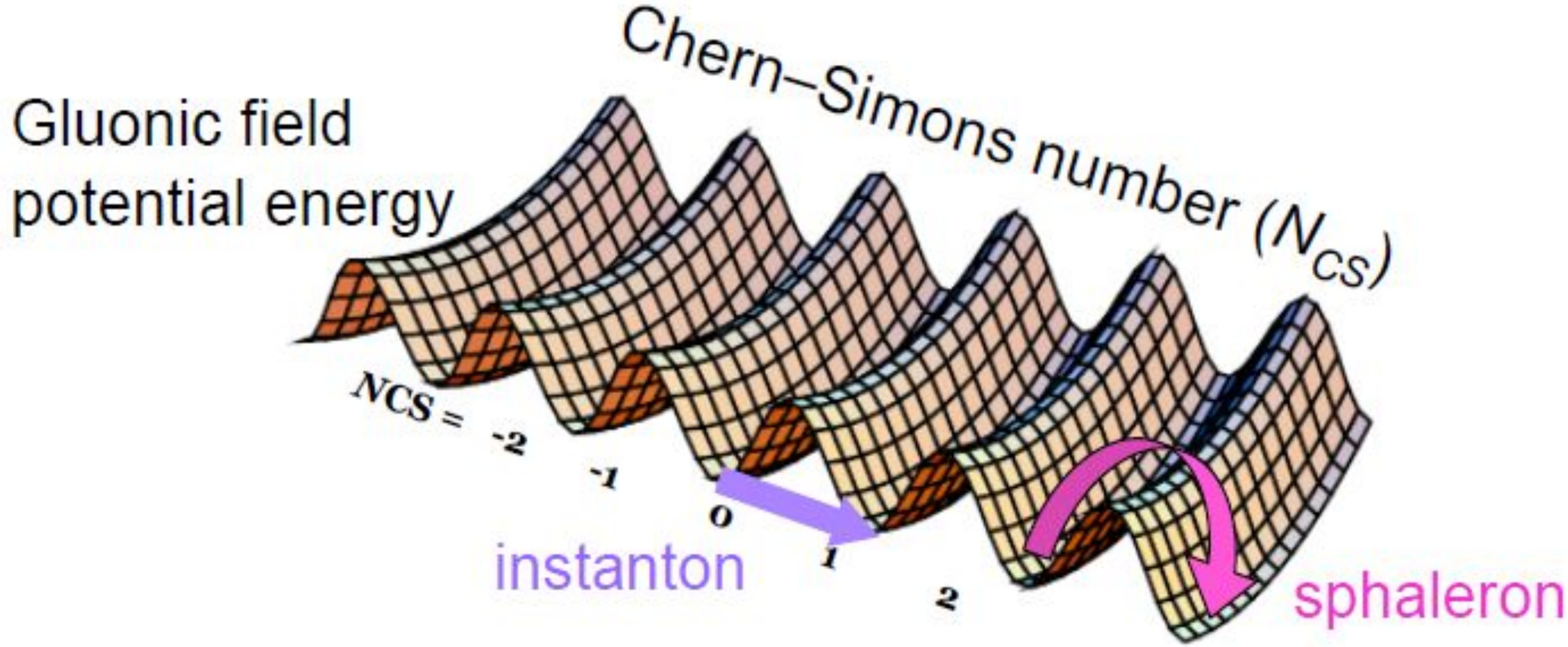


What if the vacuum/domain we live in is not a true ground state?

- "false" vacua will topple into lower states
- we may learn from the Micro-Bangs



QCD vacuum transition

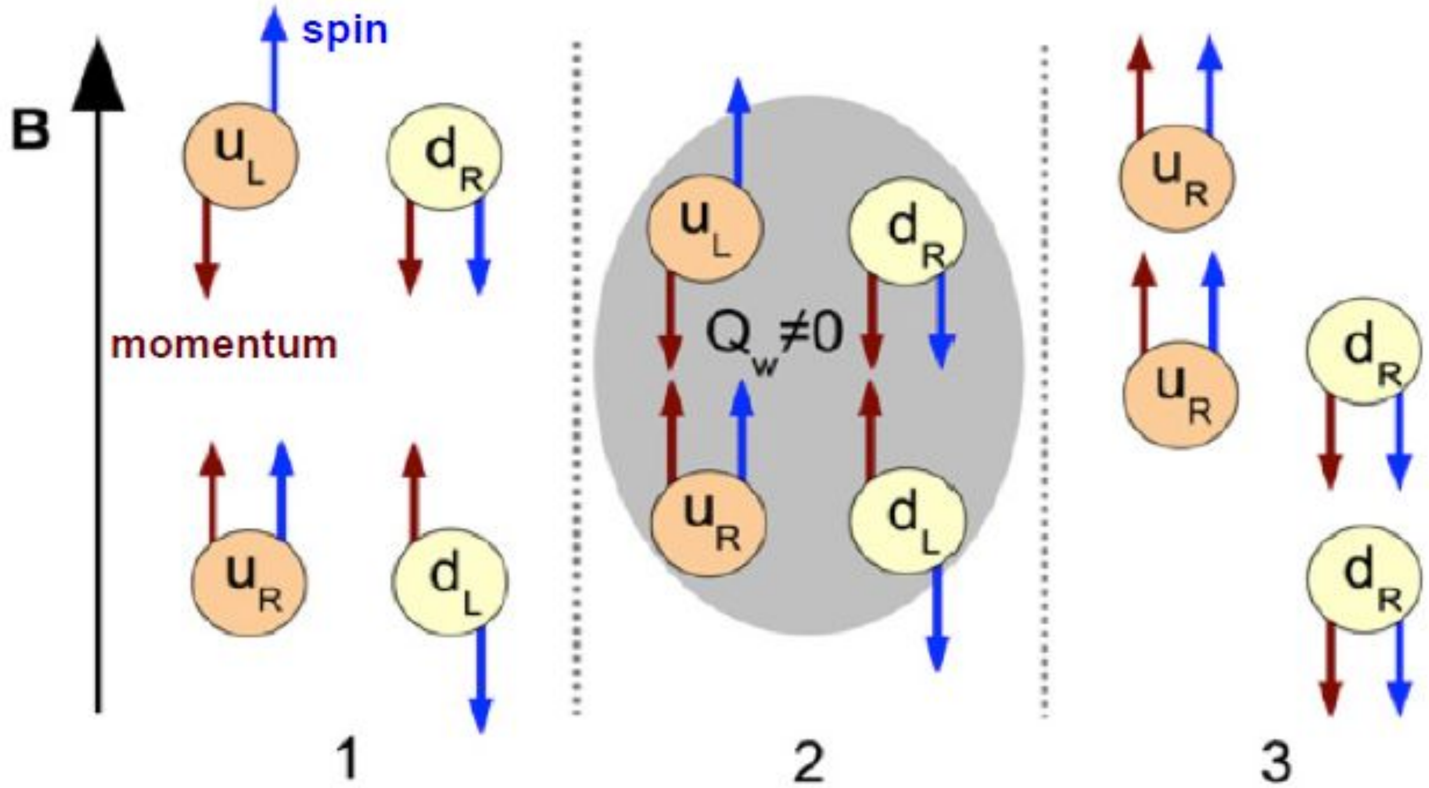


D. Diakonov, Prog. Part. Nucl. Phys. 51, 173 (2003)

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

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

Chiral Magnetic Effect

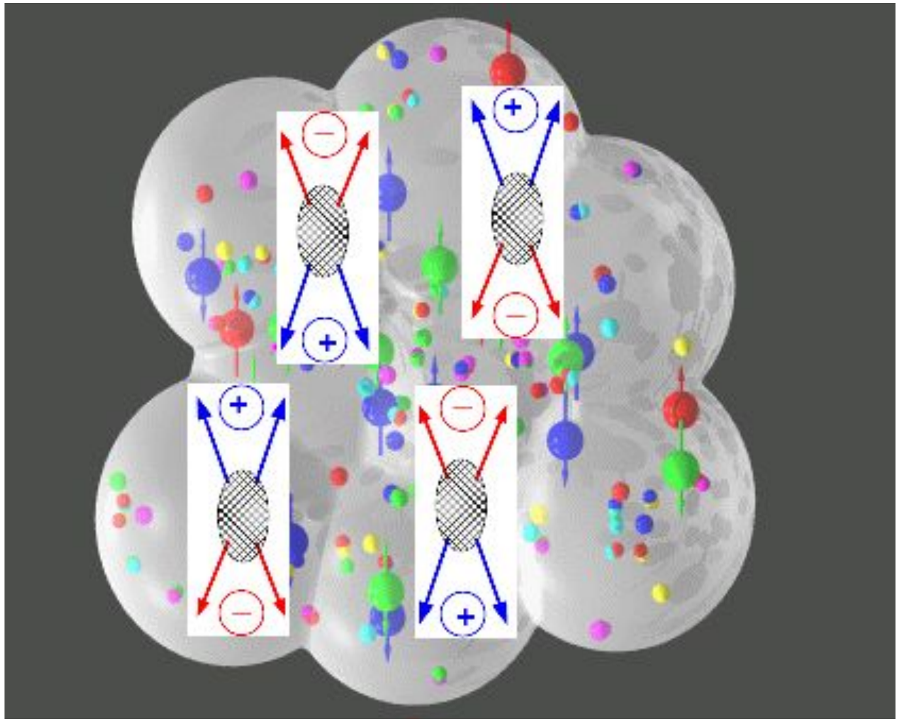


Chiral Magnetic Effect **(CME):** finite chiral charge density induces an electric current along external magnetic field.

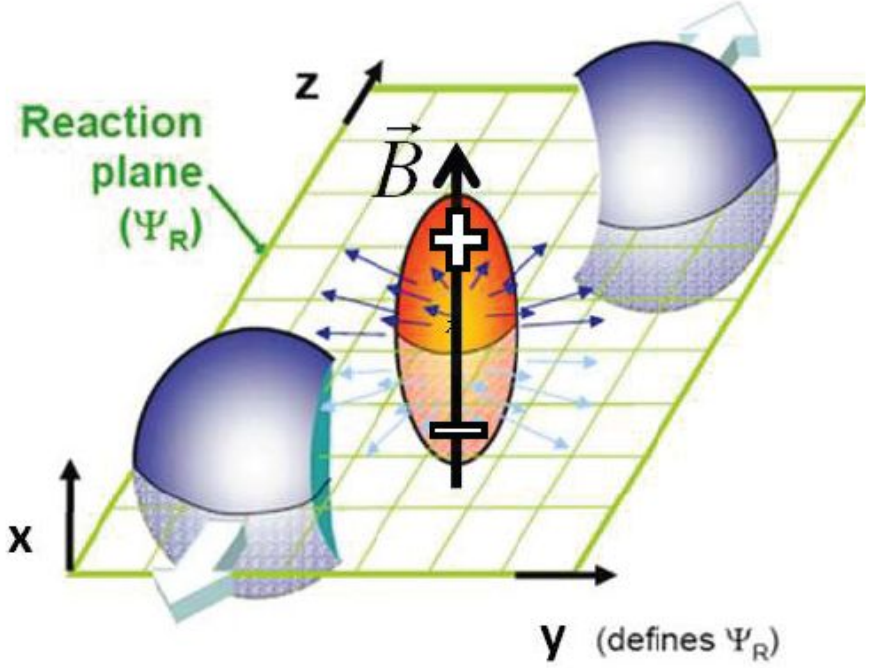
$$j_V = \frac{N_c e}{2\pi^2}\mu_A B$$ → electric charge separation along *B* field

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

Observable



CME => charge separation across RP



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

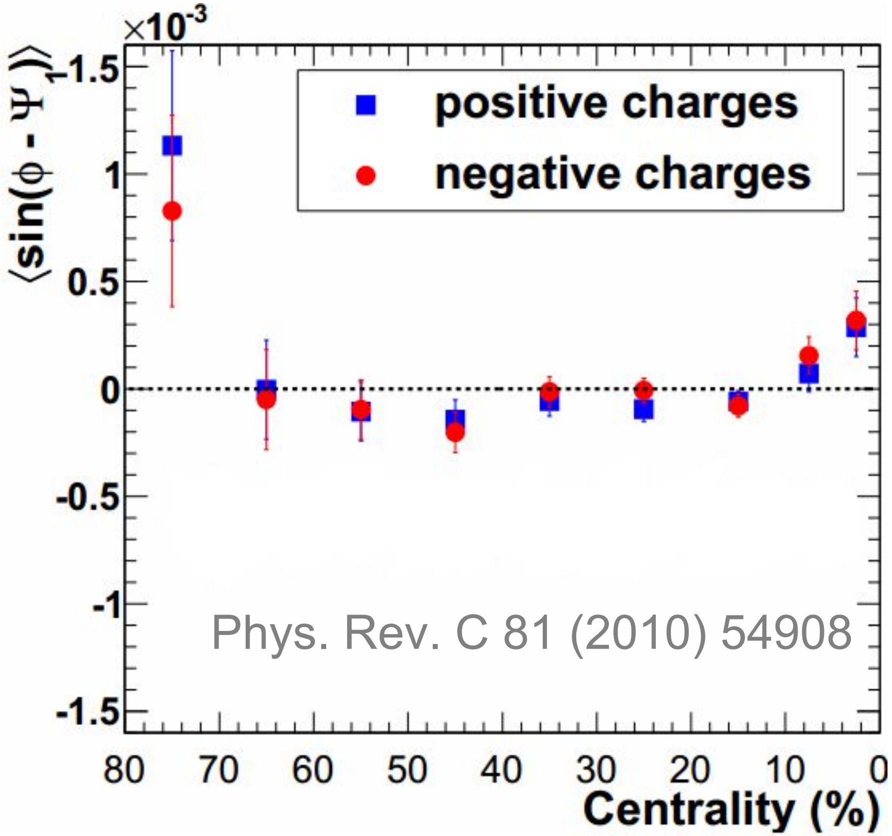
charge separation effect beyond conventional physics background

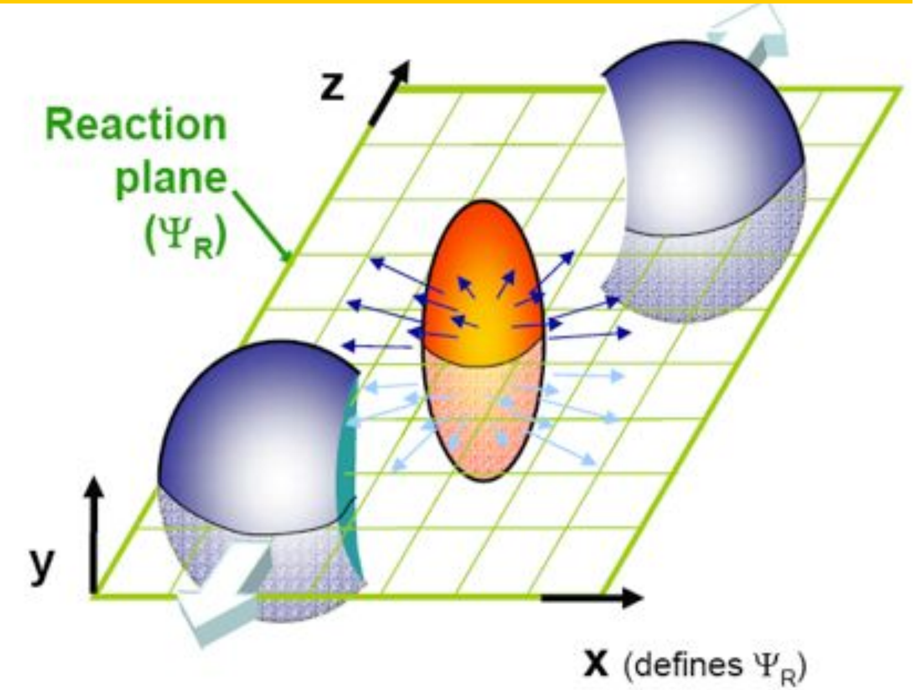
S. Voloshin, PRC 70 (2004) 057901,
Kharzeev, PLB633:260 (2006)
Kharzeev, McLerran, Warringa, NPA803:227 (2008)

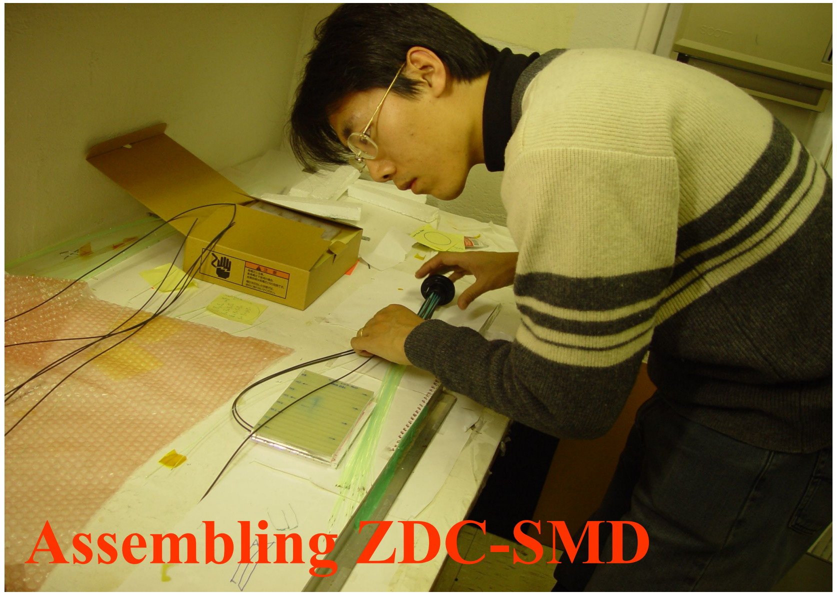
CME + Local Parity Violation

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

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



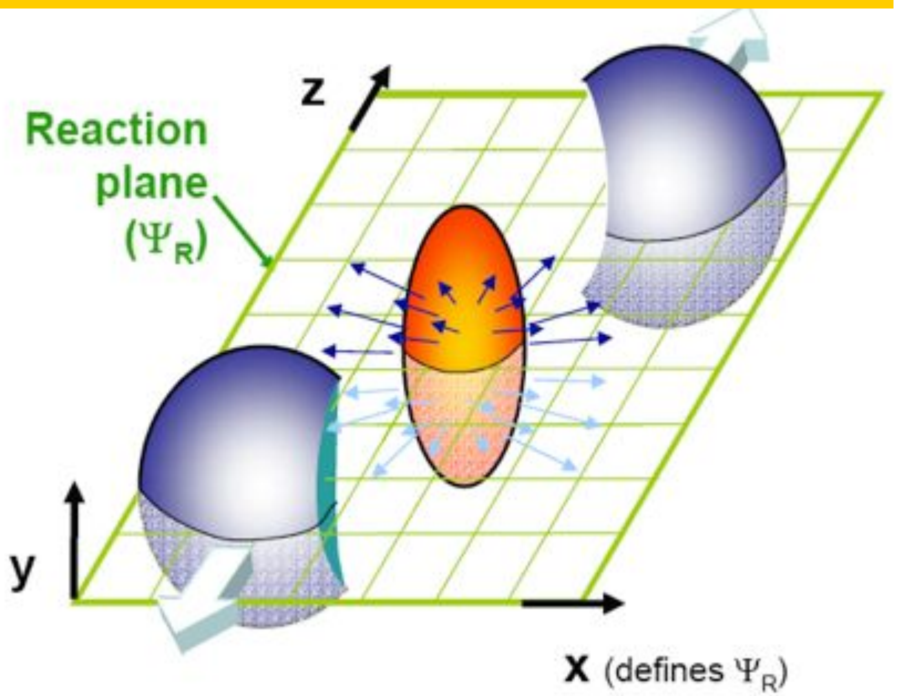




γ correlator

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

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



S. Voloshin, PRC 70 (2004) 057901

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

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

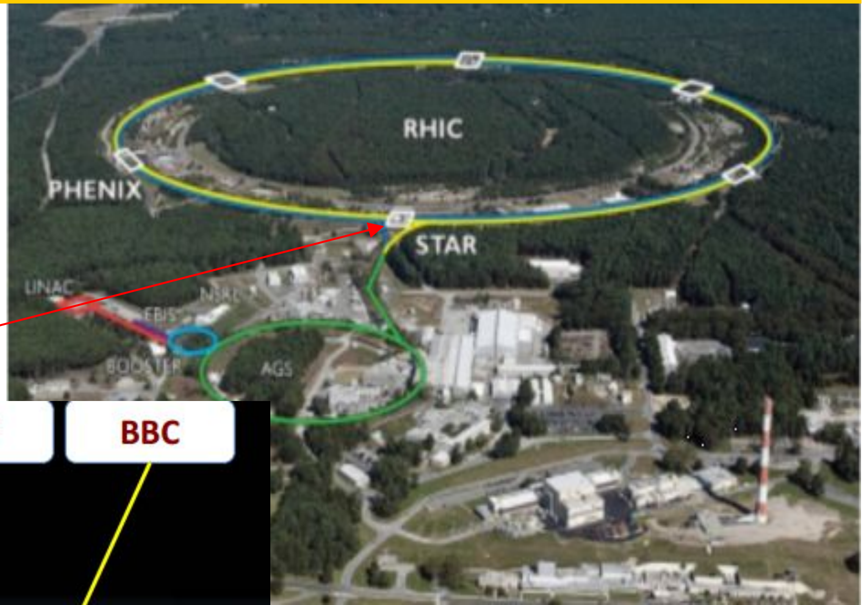
background effects: largely cancel out

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

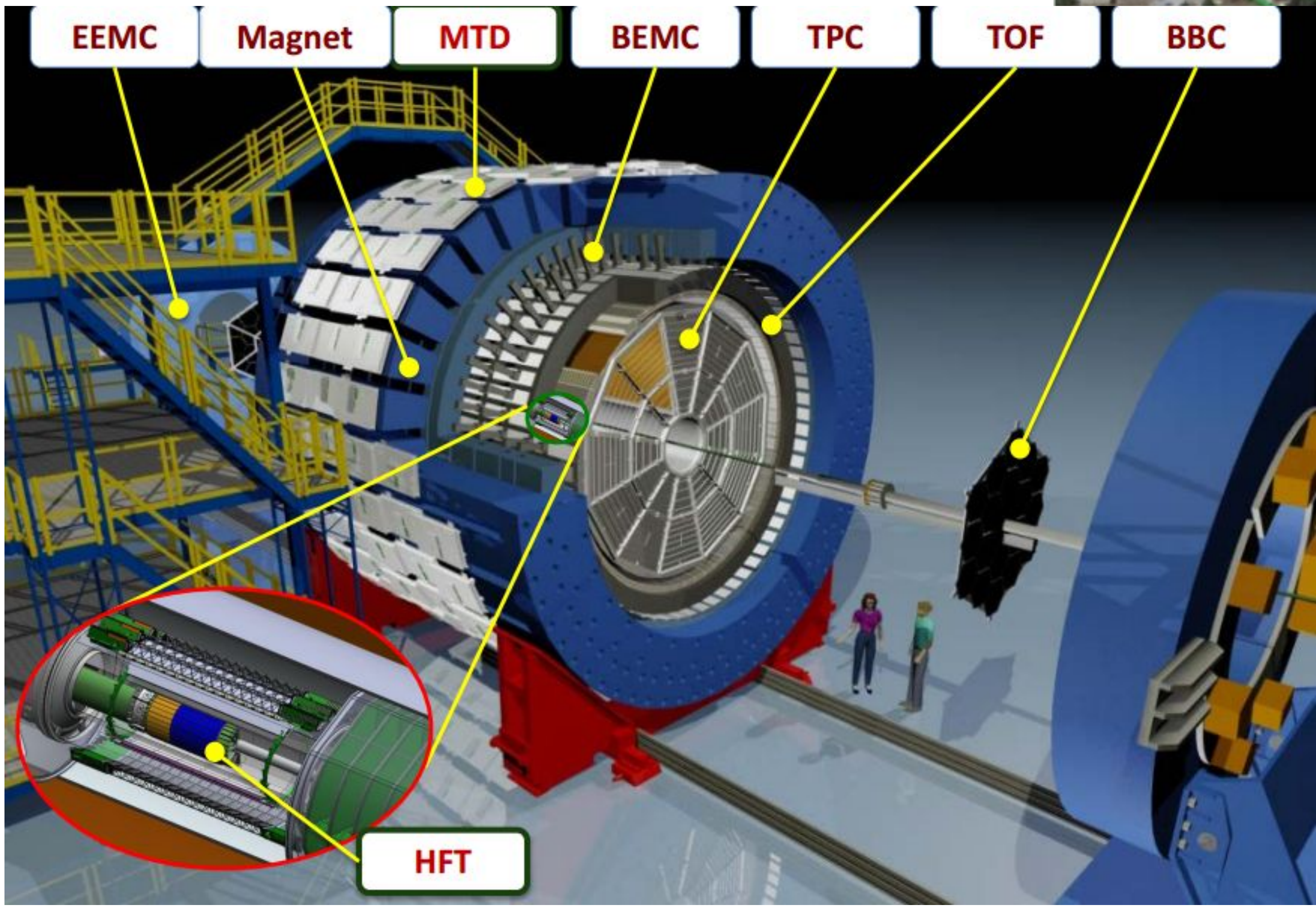
P-even quantity: still sensitive to charge separation

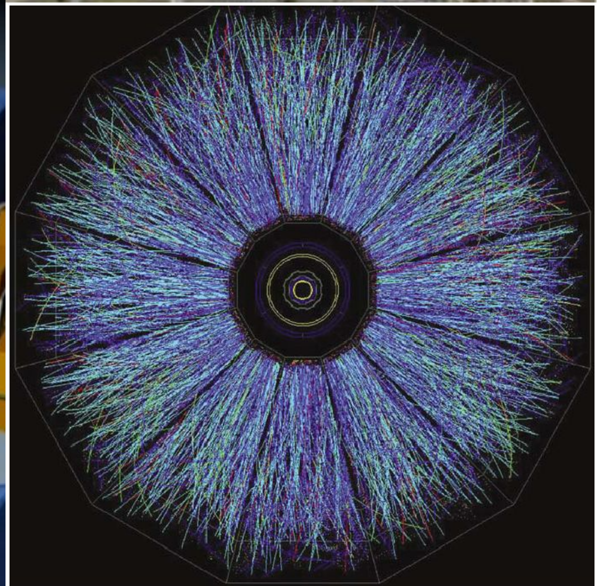
STAR experiment

Relativistic Heavy Ion Collider (RHIC)

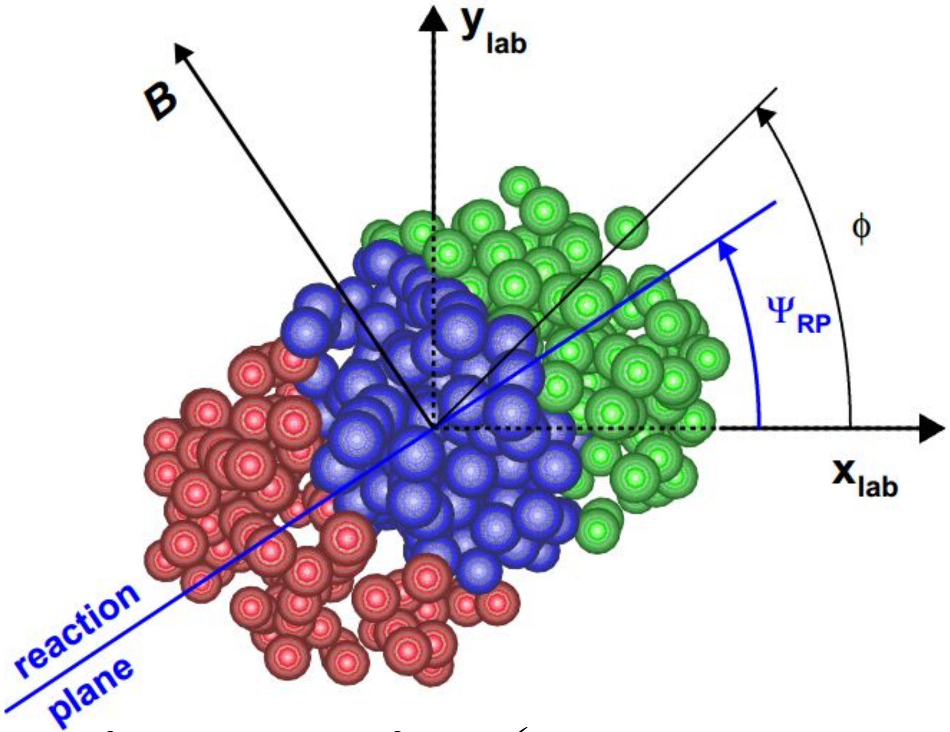


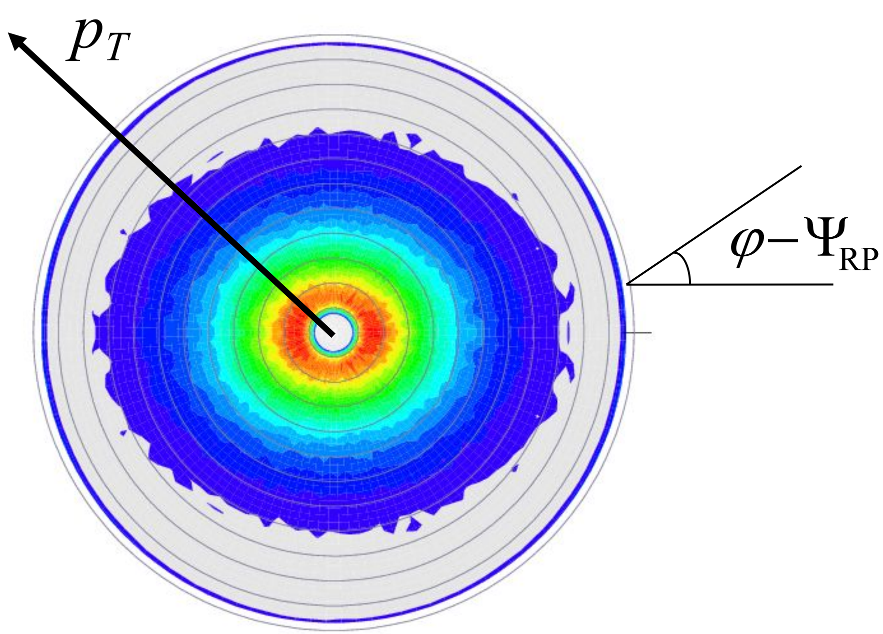
Solenoidal Tracker at RHIC (STAR)





Azimuthal anisotropy





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

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

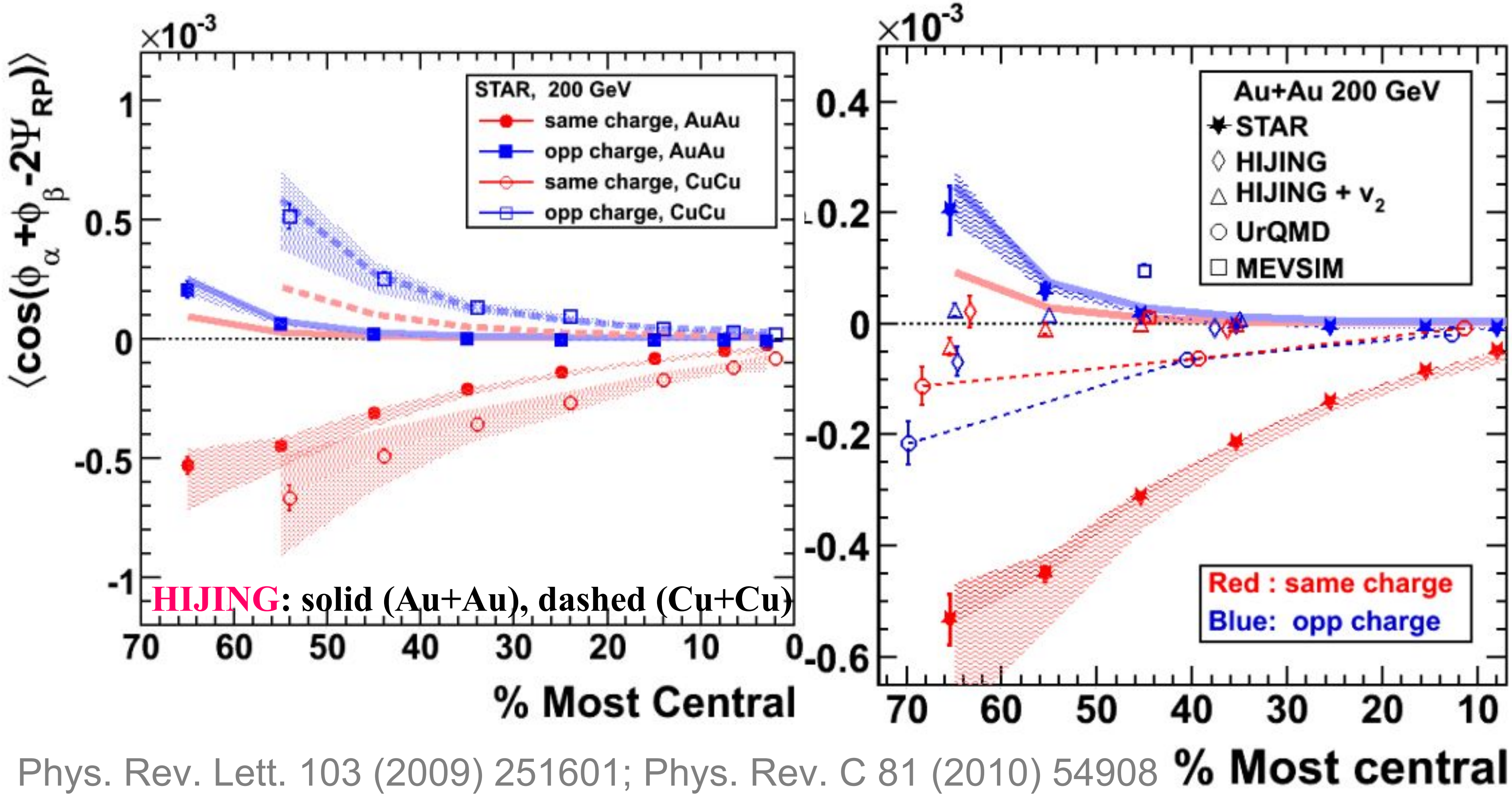
The estimated reaction plane is called the event plane.

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

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

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

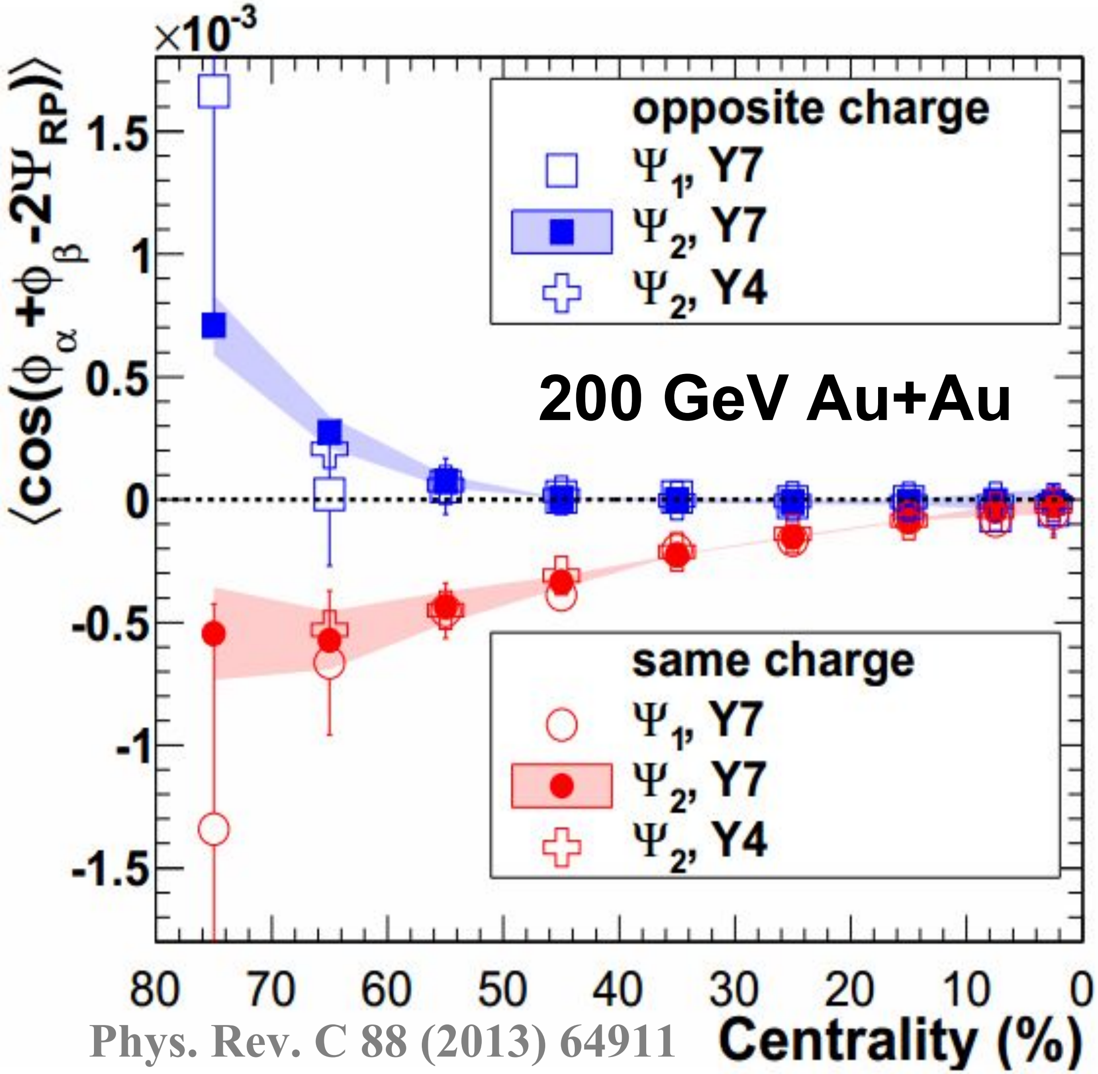
γ at 200 GeV



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

- $\gamma_{os} > \gamma_{ss}$, consistent with CME expectation: both AuAu and CuCu
- Not explained by known event generators

1st-order EP

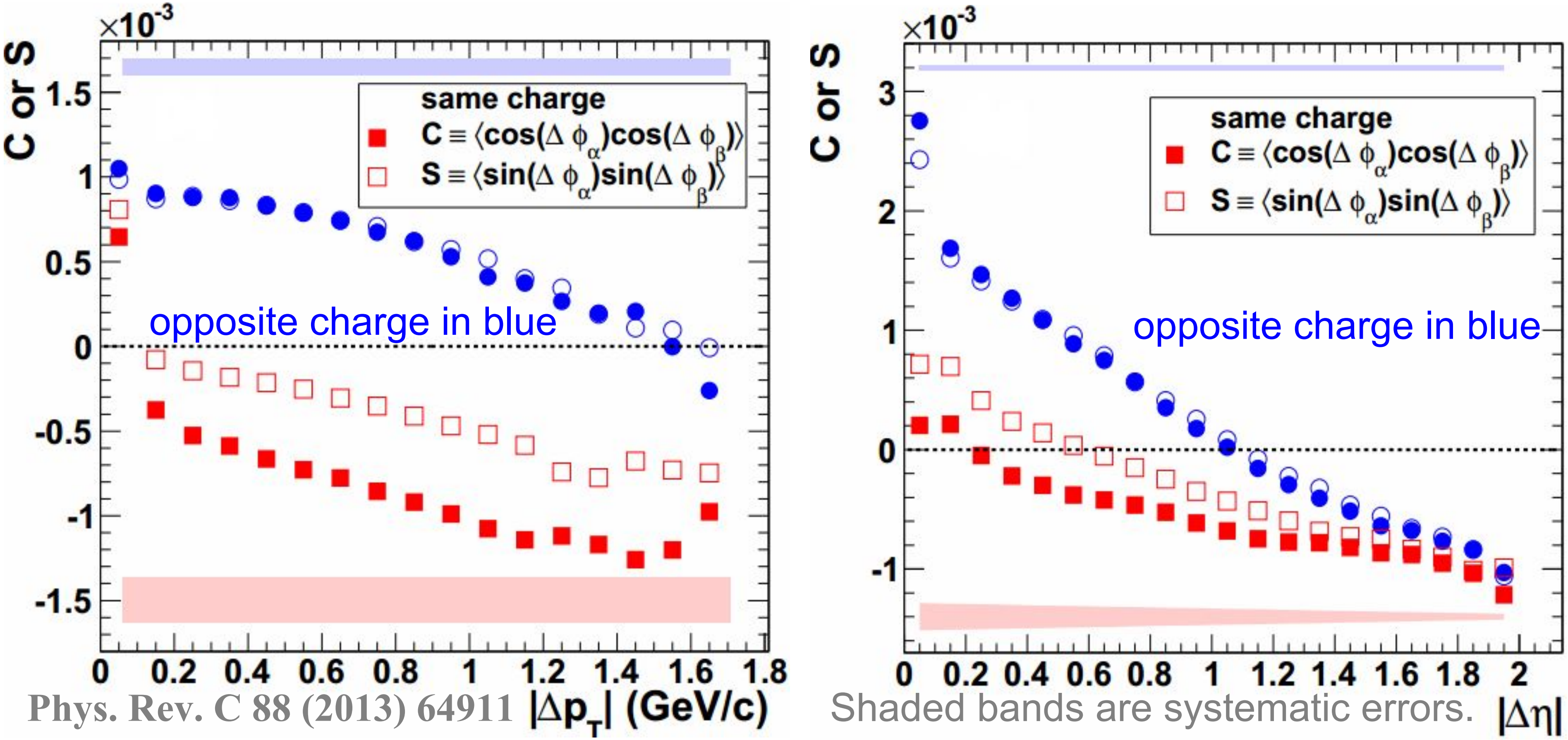


Phys. Rev. C 88 (2013) 64911

- Consistent between different years (2004 and 2007)
- Confirmed with 1st-order EP (from spectator neutron v_1)

HBT+Coulomb

200 GeV Au+Au: 40 - 60%

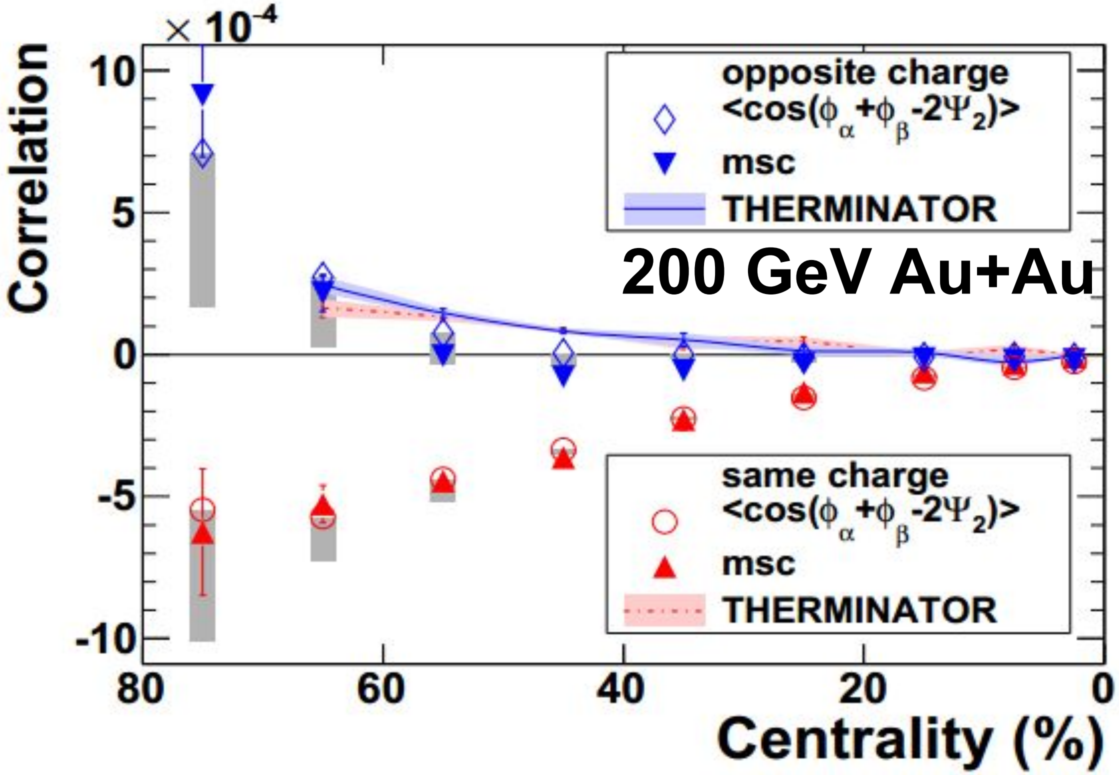


Phys. Rev. C 88 (2013) 64911

Shaded bands are systematic errors.

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

Modulated sign correlator (msc)



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

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

- 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

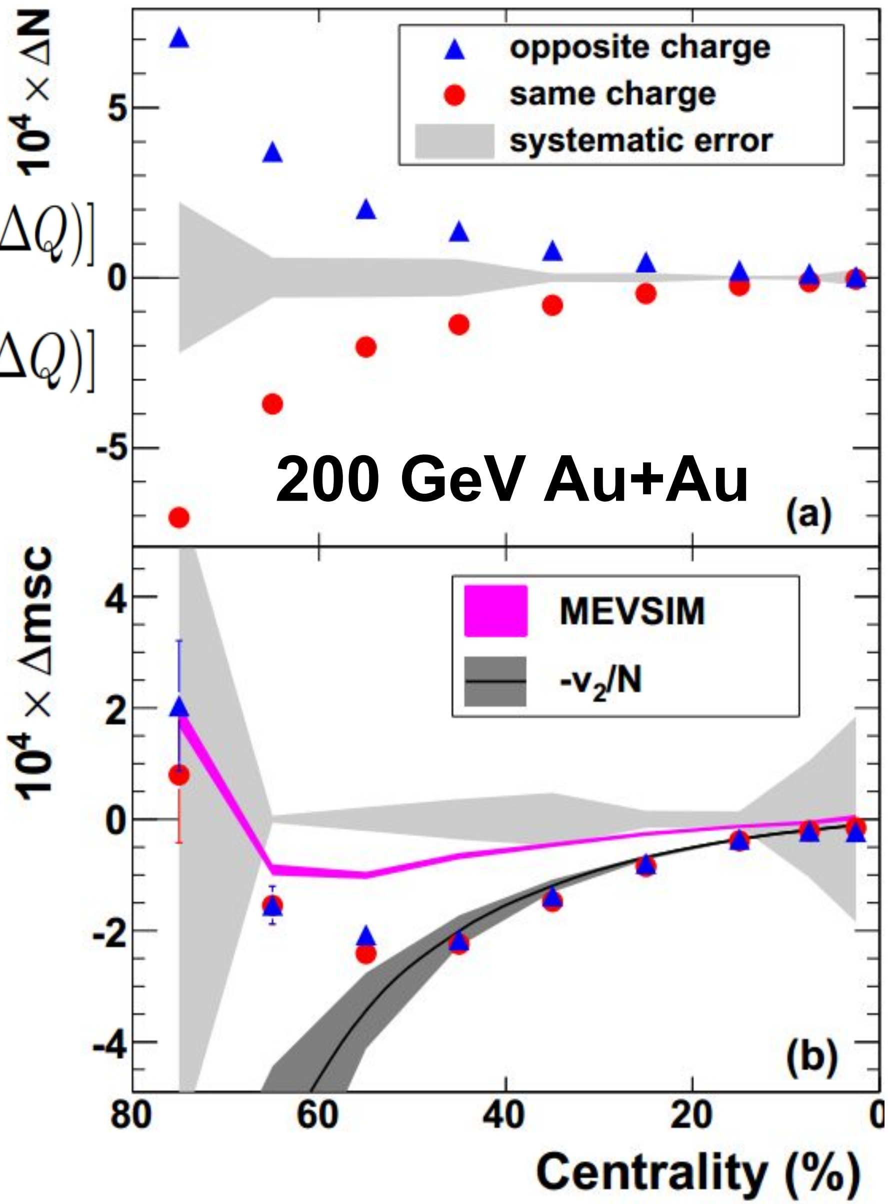
Phys. Rev. C 88 (2013) 64911

Charge-independent background (Δmsc)

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

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

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



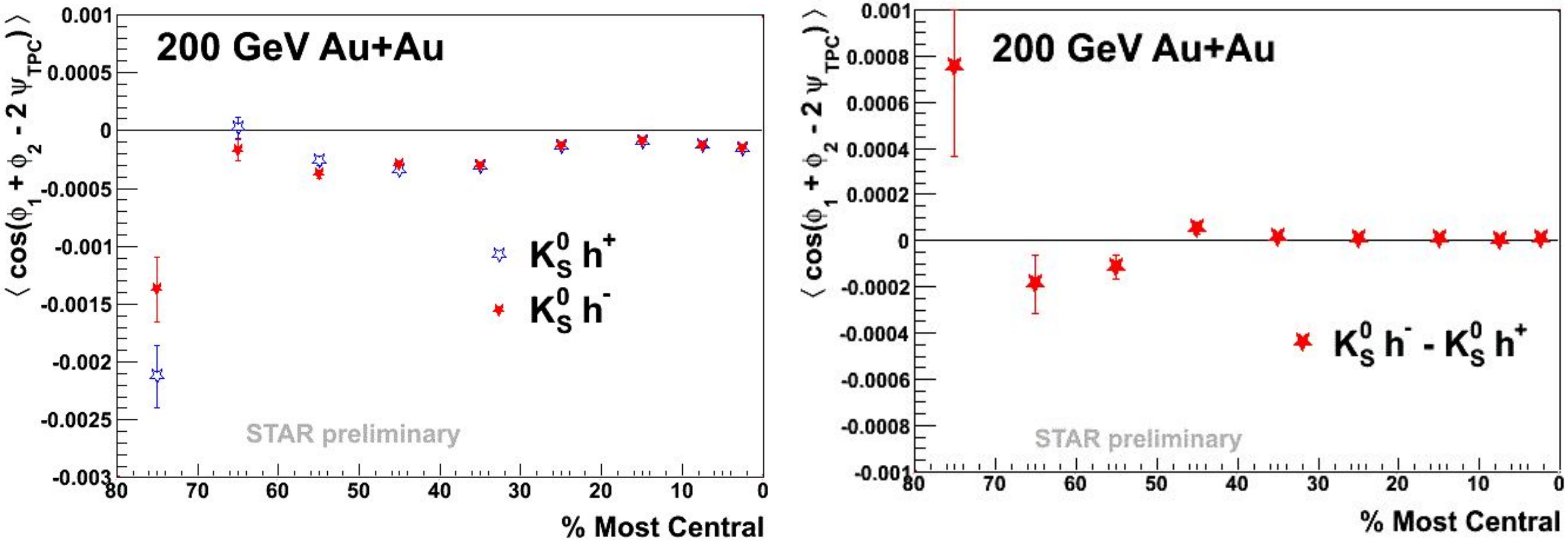
- msc was split to study background

- $N_{IN}(\Delta Q)$ stands for the number of events with ΔQ units of in-plane charge separation, and $\mathrm{msc}_{IN}(\Delta Q)$ 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

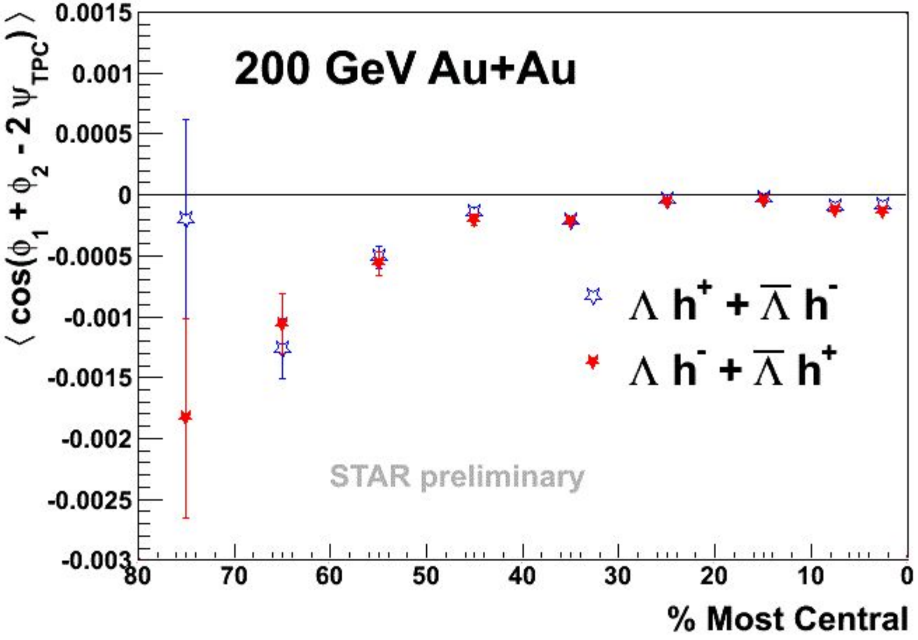
Phys. Rev. C 88 (2013) 64911

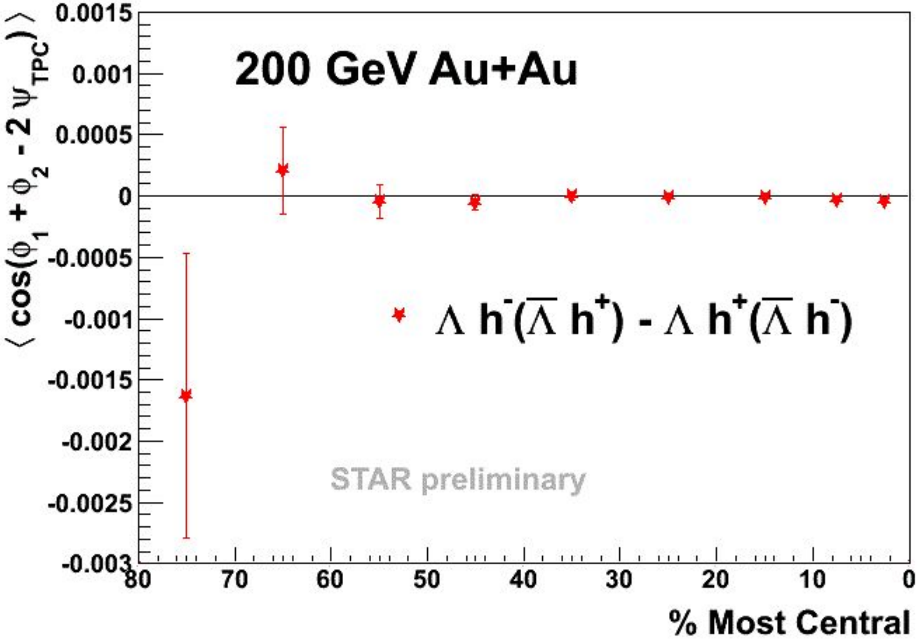
K^0_S-hadron correlation



- Correlations of K^0_S-h^- and K^0_S-h^- consistent with each other: no charge-dependent separation

Λ-hadron correlation

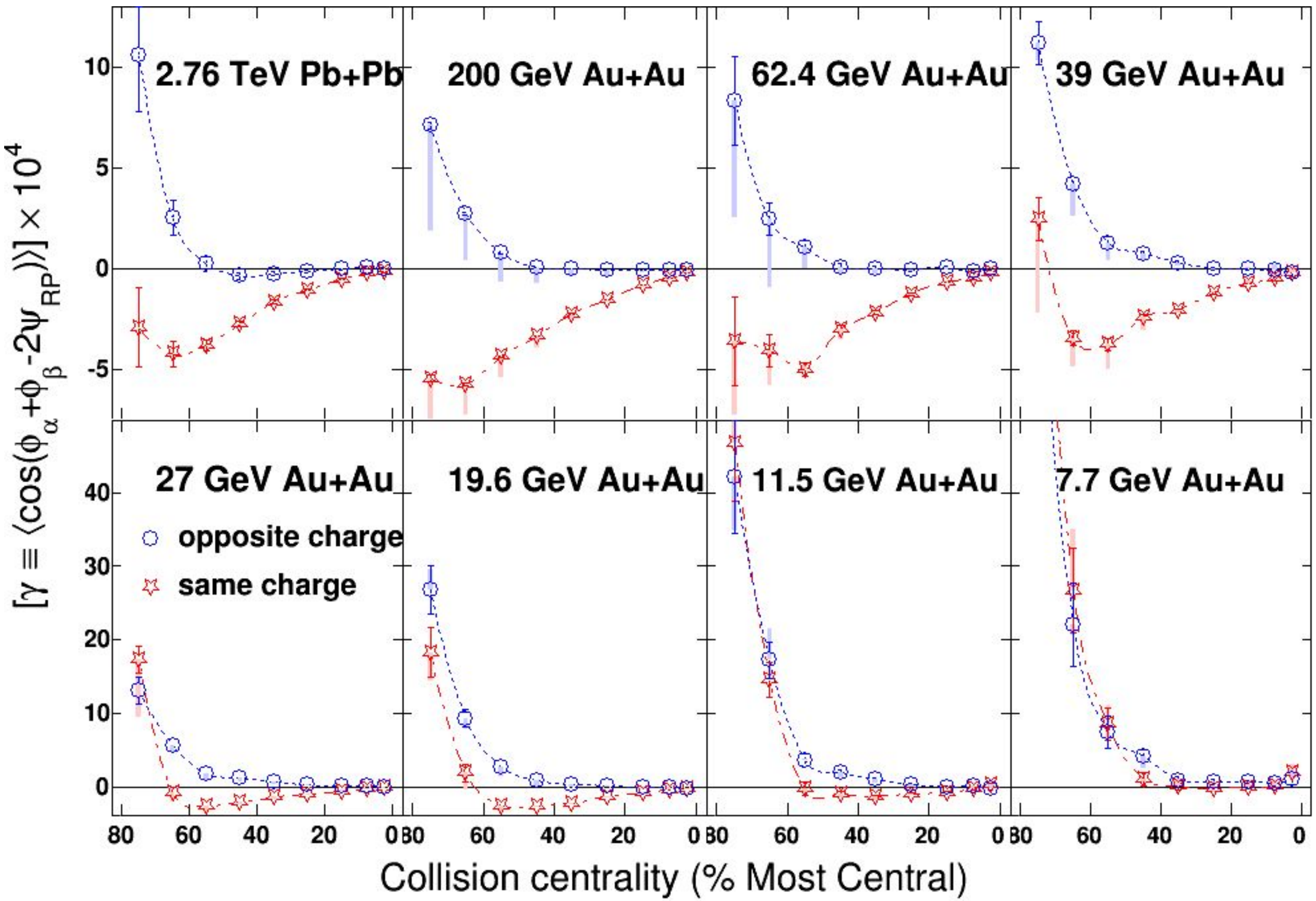




- Correlations between Λ and $h^{\pm}$ also show no charge-dependent separation
- Separation observed for $h^{\pm}$-$h^{\pm}$ is sensitive to electric charge
- Strange quarks participate in the chiral dynamics in a similar way as u/d

Beam Energy Scan

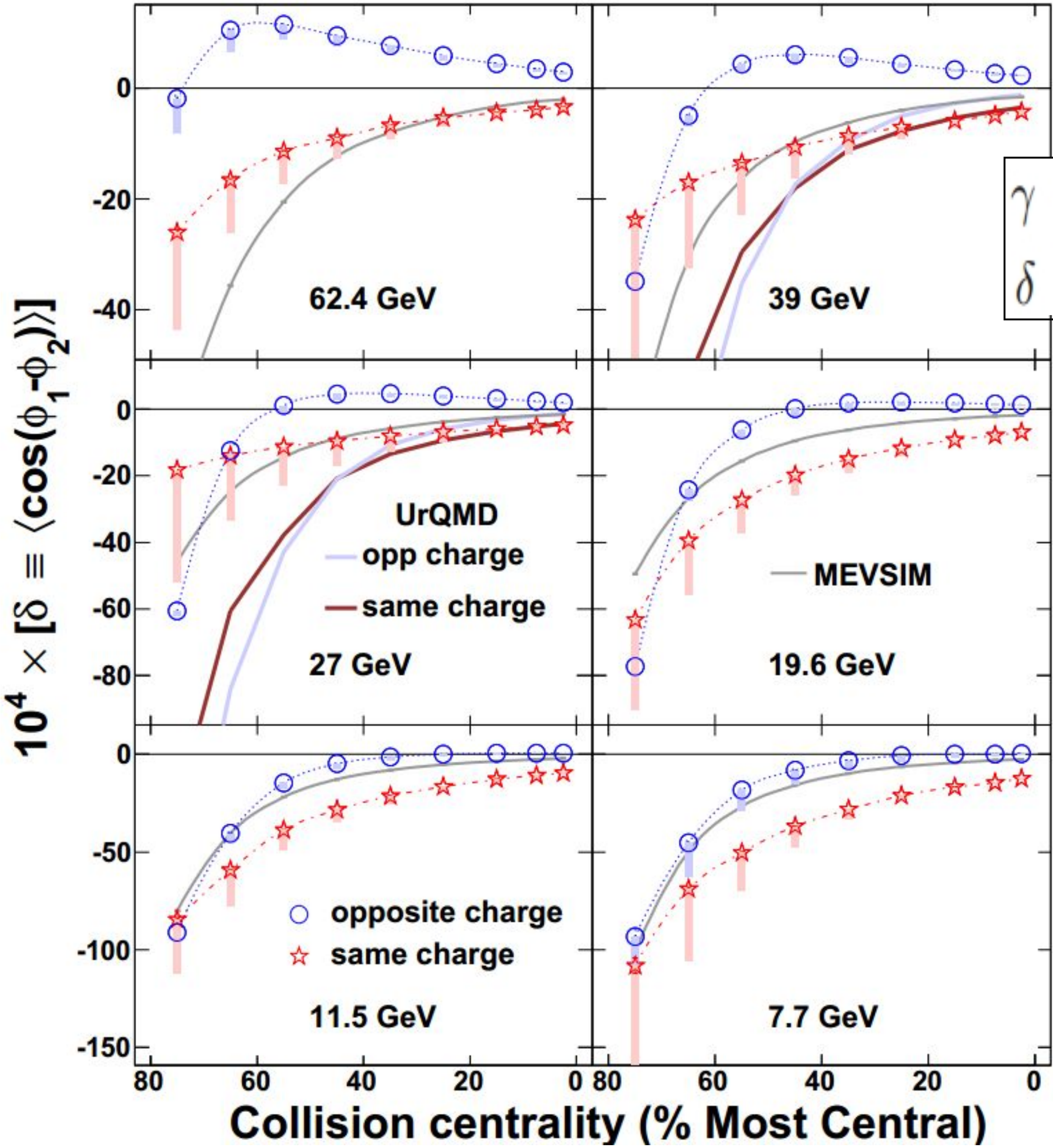
ALICE, Phys. Rev. Lett. 110, 012301 (2013); STAR, Phys. Rev. Lett 113 (2014) 052302



At lower beam energies, charge separation starts to diminish.

Flow-related background

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



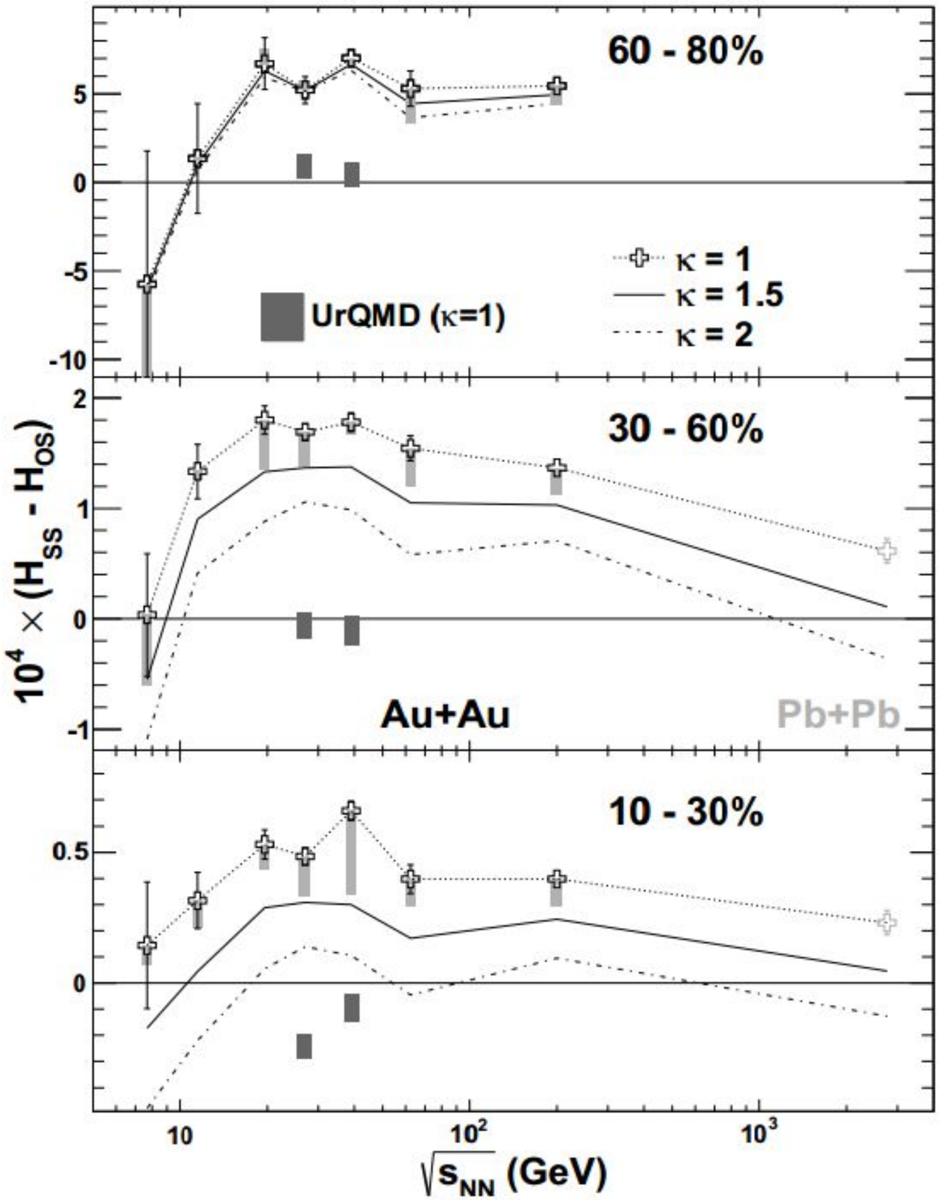
A. Bzdak, V. Koch and J. Liao, Lect. Notes Phys. 871, 503 (2013).

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

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

CME contribution

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

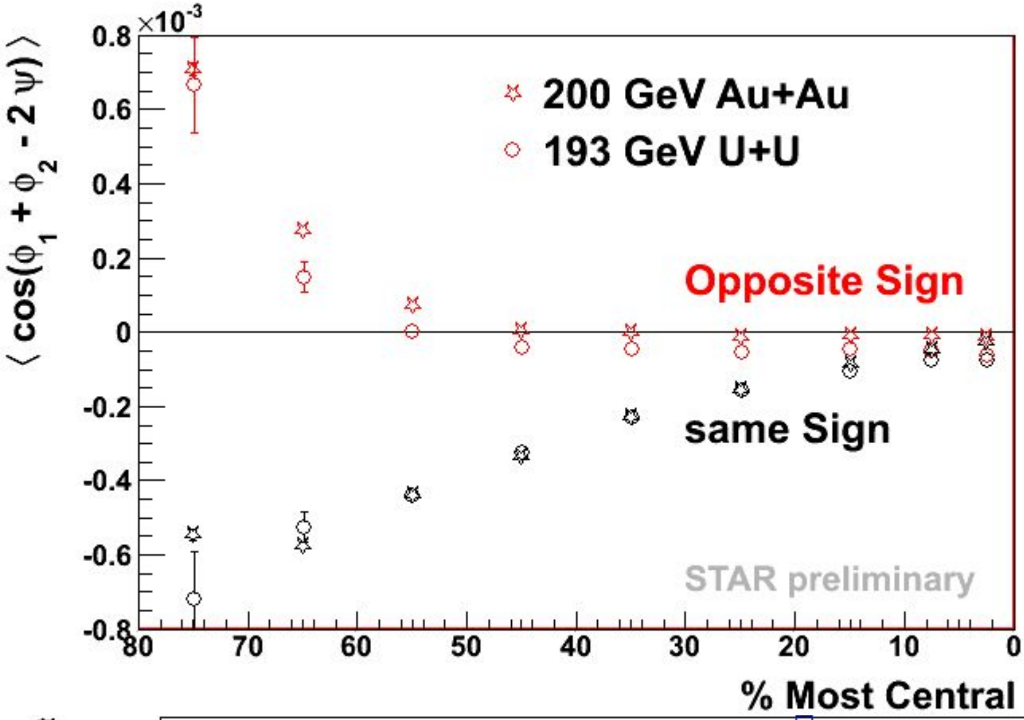


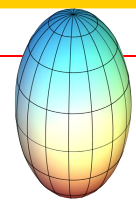
$$H^{\kappa} = (\kappa v_2 \delta - \gamma)/(1 + \kappa v_2)$$

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

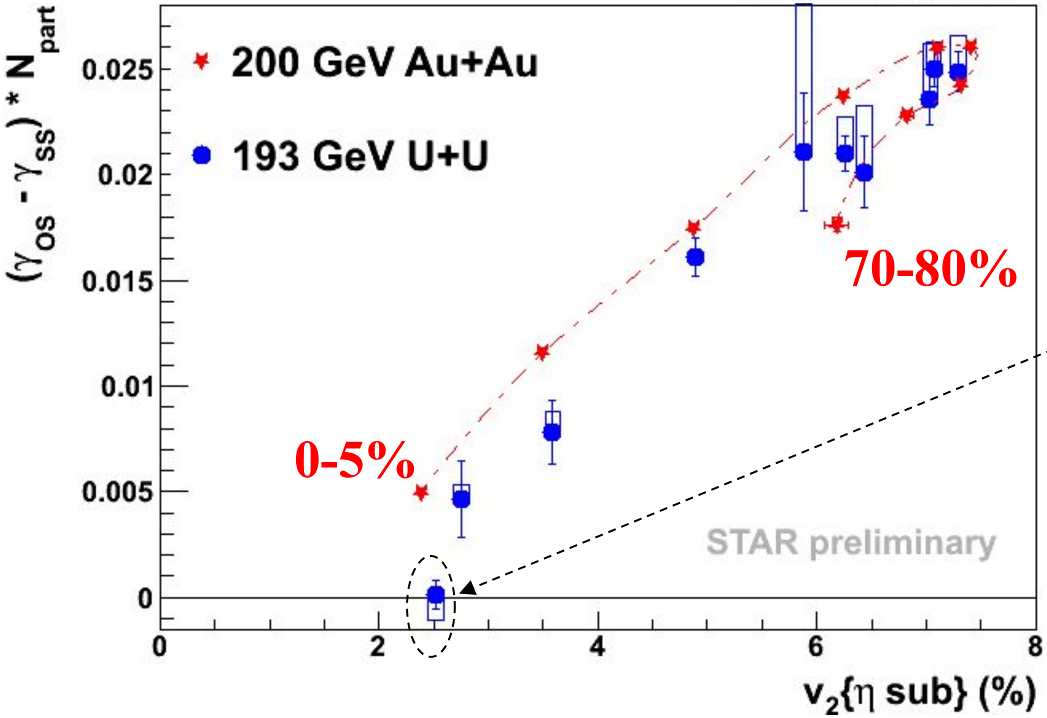
- $\kappa \approx 2 - v_{2,F}/v_{2,\Omega}$: F and Ω denote the full phase space and the finite detector acceptance, respectively
- CME signal via *H* decreases to zero from 19.6 GeV to 7.7 GeV
- Probable domination of hadronic interactions over partonic ones
- Need better estimate of κ and better statistics

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%

Summary

- three-point correlator γ shows charge separation w.r.t RP
  - signal robust with different EPs (1st- and 2nd-order)
  - robust when suppressing HBT+Coulomb
  - robust with a reduced correlator, msc
  - robust in Au+Au, Cu+Cu, Pb+Pb and U+U
  - 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 mostly comes from momentum conservation+v_2
  - flow-related bg could be subtracted via *H* correlator

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:

10% difference in B field → 20% difference in γ

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

Outlook: Cu+Au

Ohm's Law

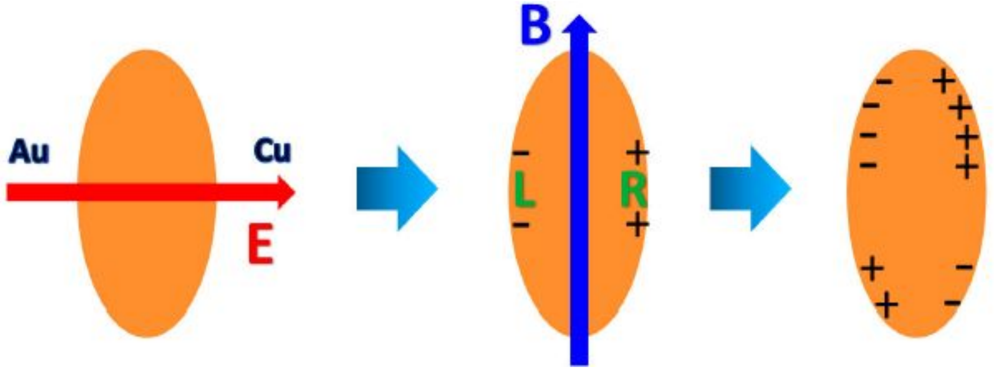
Chiral Magnetic Effect

	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

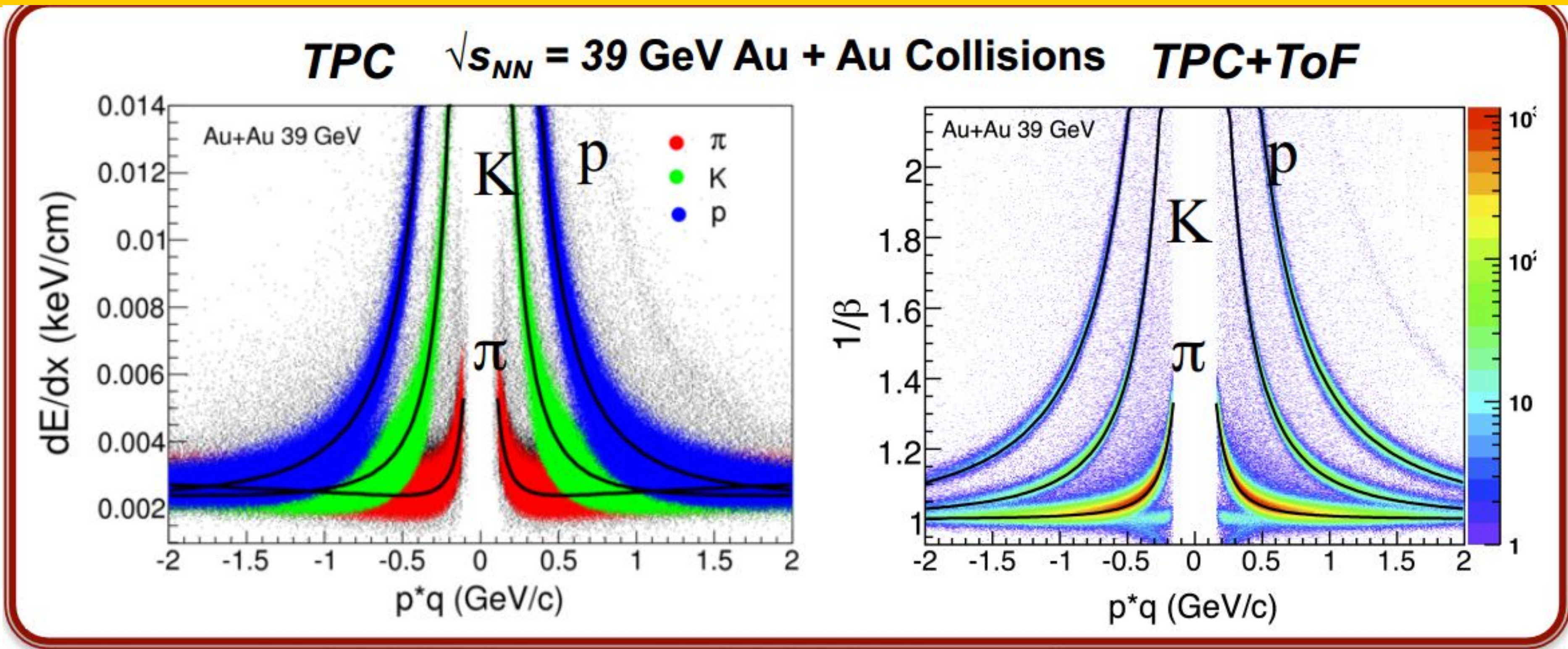


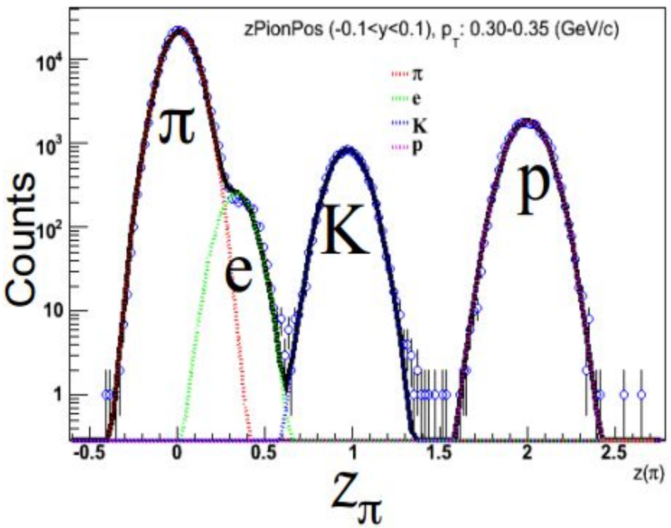
in-plane charge separation

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

Backup slides

Particle identification



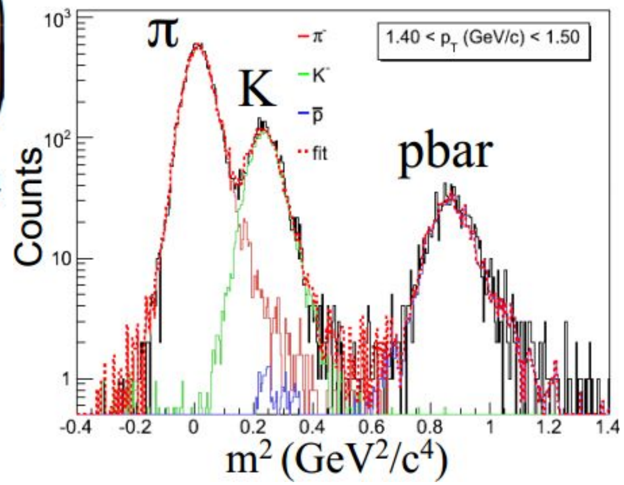


$$z = \log\left(\frac{(dE/dx)_{meas.}}{(dE/dx)_{theory}}\right)$$

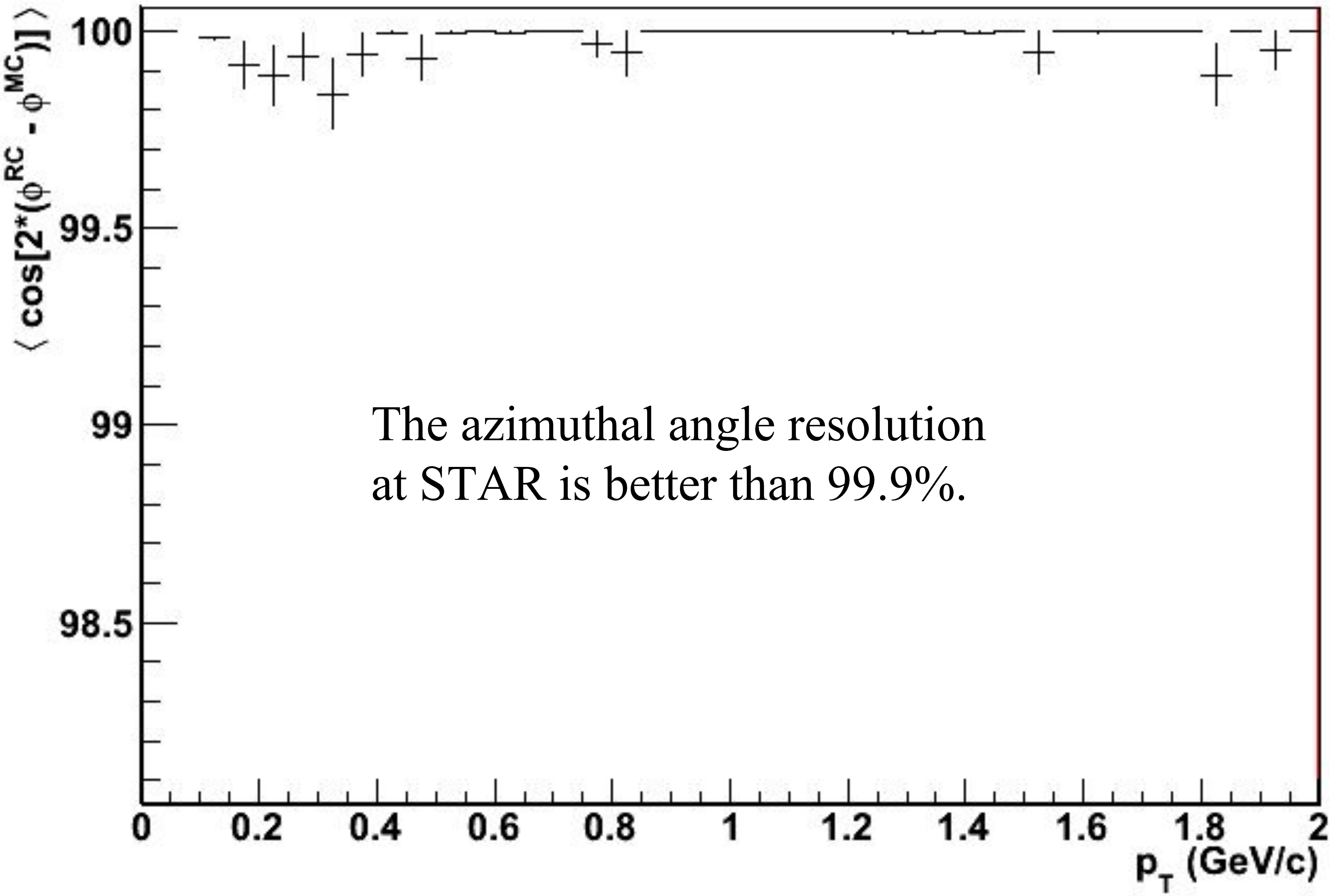
H. Bichsel, NIM A. 562 (2006) 154

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

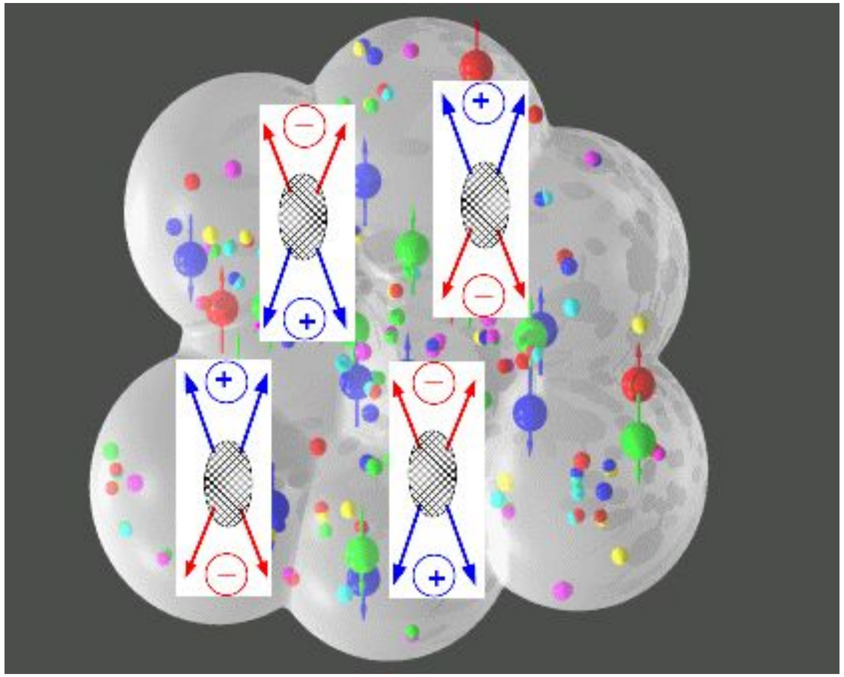
c=velocity of light,
L=path length



Excellent tracking

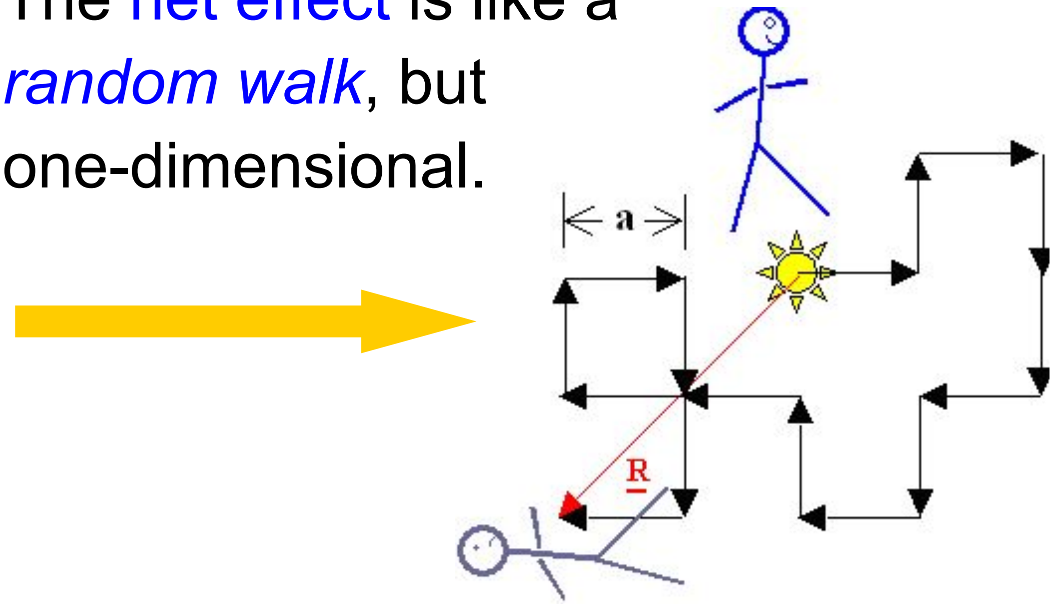


Dilution effect



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* = $\sqrt{n}$

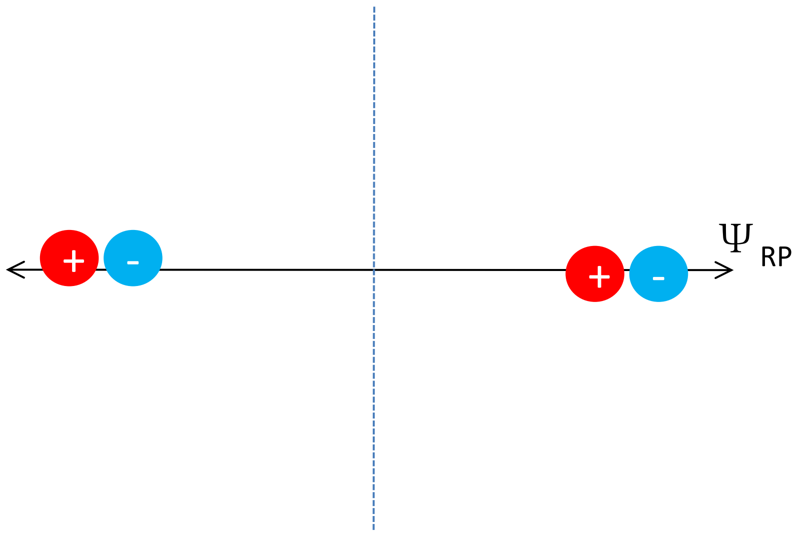
Our measurement of PV is like R_n^2, expected to be n.

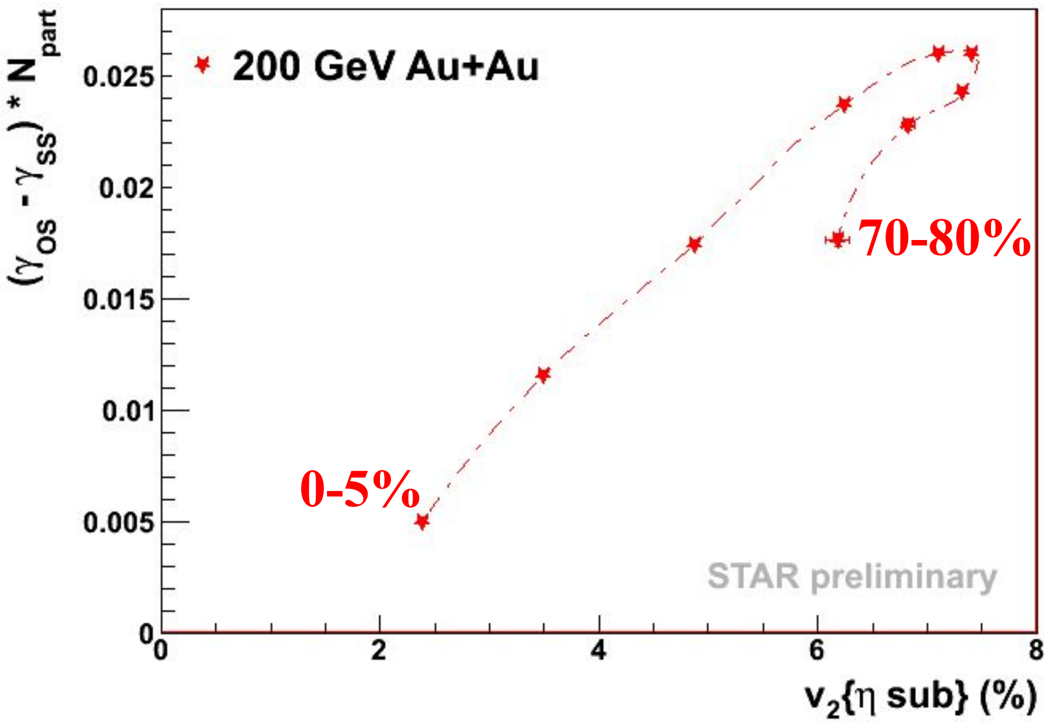
Compared with going in one fixed direction, where $R_n^2 = n^2$,

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



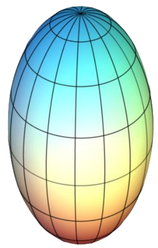


$$\langle \cos(\phi_\alpha + \phi_\beta - 2\Psi_{RP}) \rangle$$
$$= \langle \cos((\phi_\alpha + \phi_\beta - 2\phi_{res}) + 2(\phi_{res} - \Psi_{RP})) \rangle$$
$$\approx \frac{f_{res} \langle \cos(\phi_\alpha + \phi_\beta - 2\phi_{res}) \rangle v_{2,res}}{N_{ch}}$$

STAR, Phys. Rev. C72 (2005) 014904

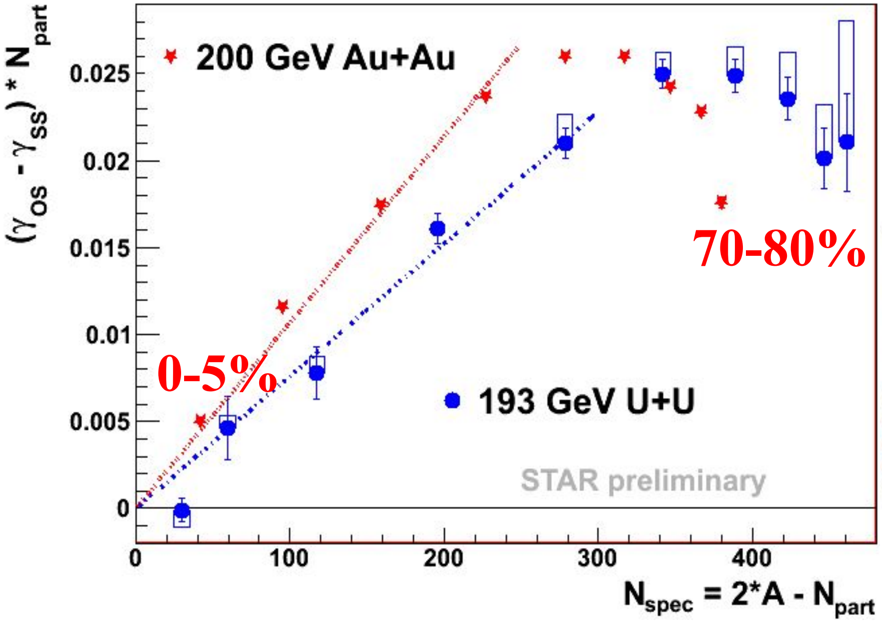
Seemingly correlated!

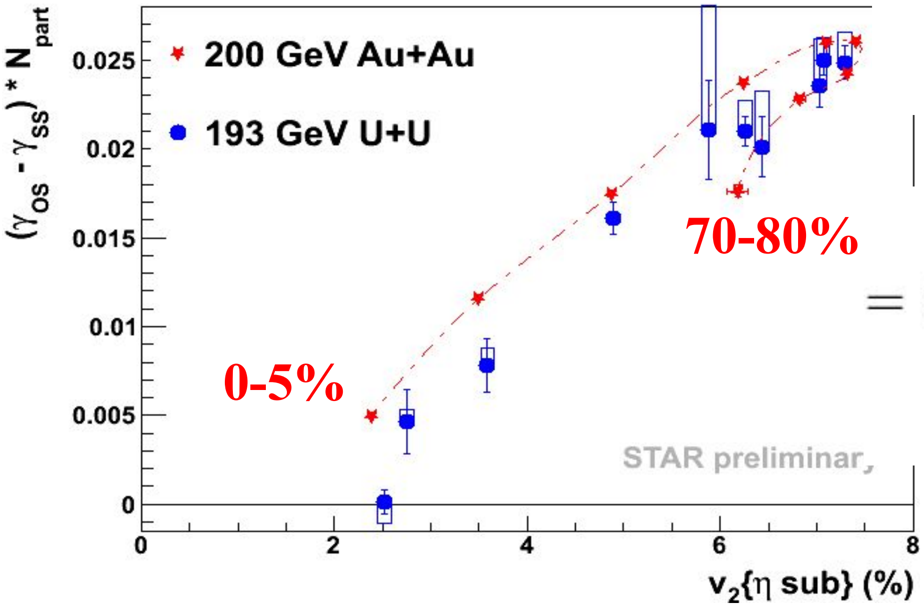
Can we disentangle the relationship with U+U?



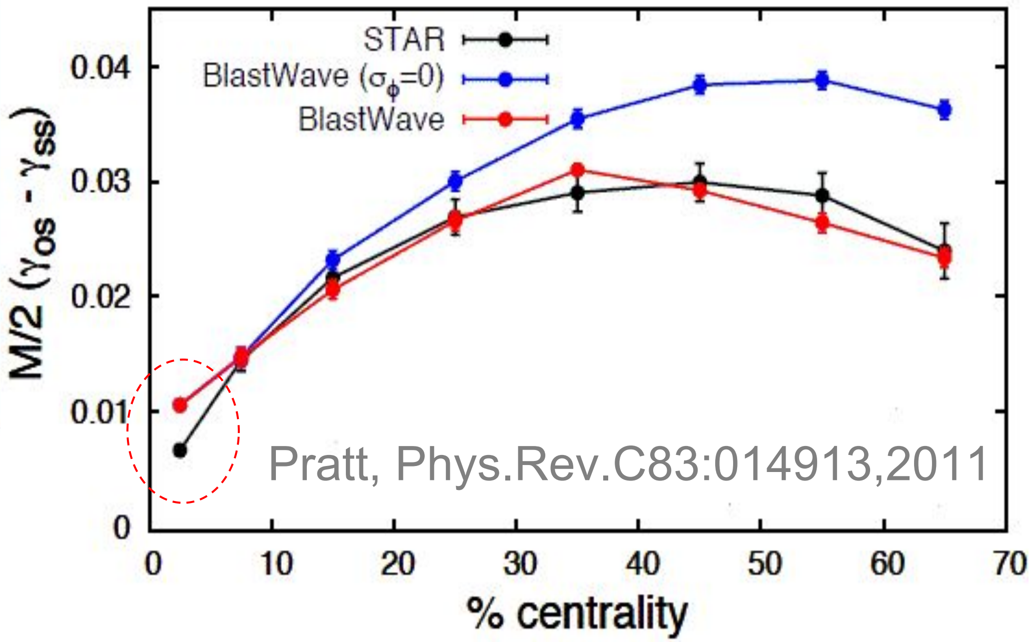
In RHIC run2012, STAR took 350M minbias events and 14M central trigger events.

Possible physics background

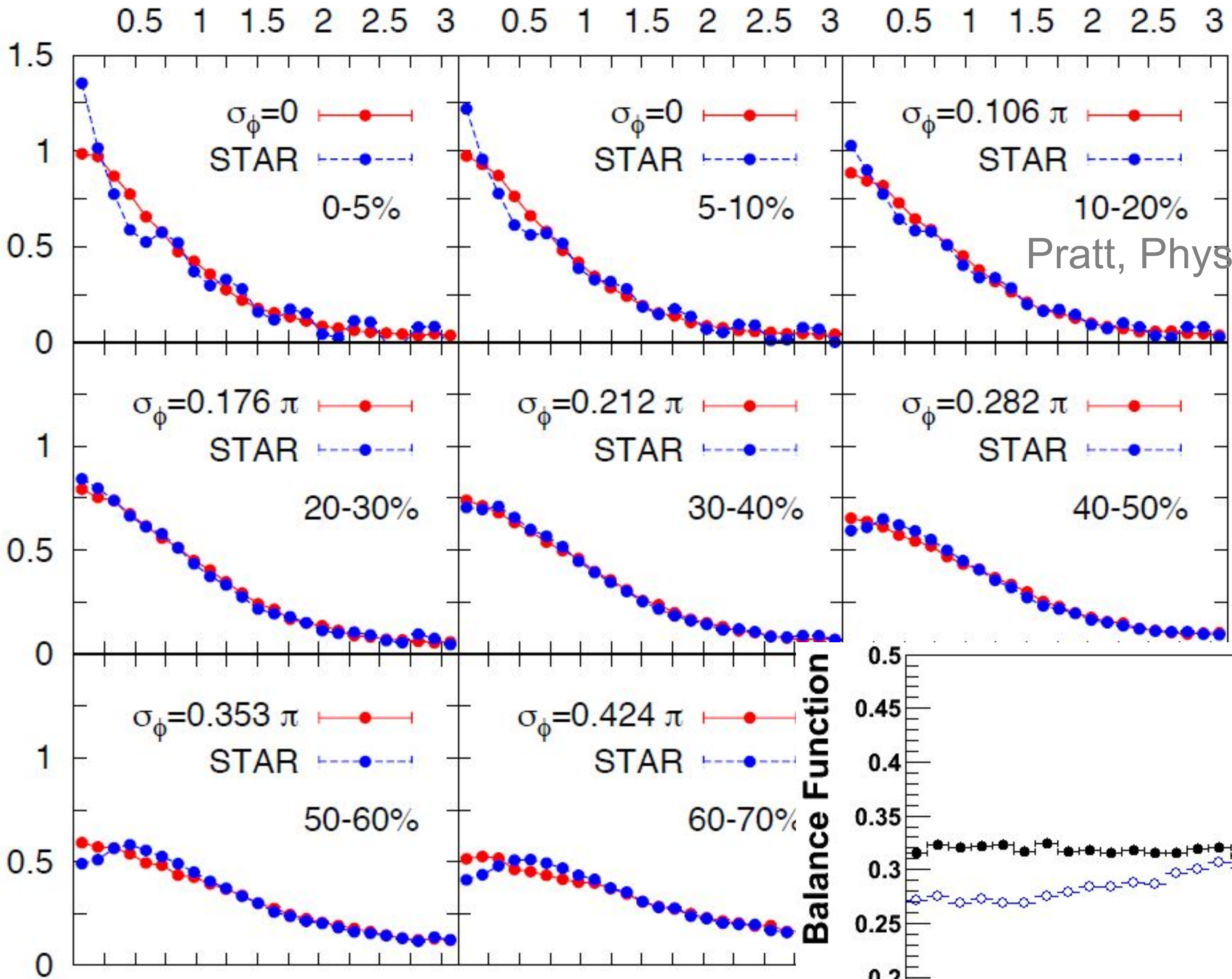




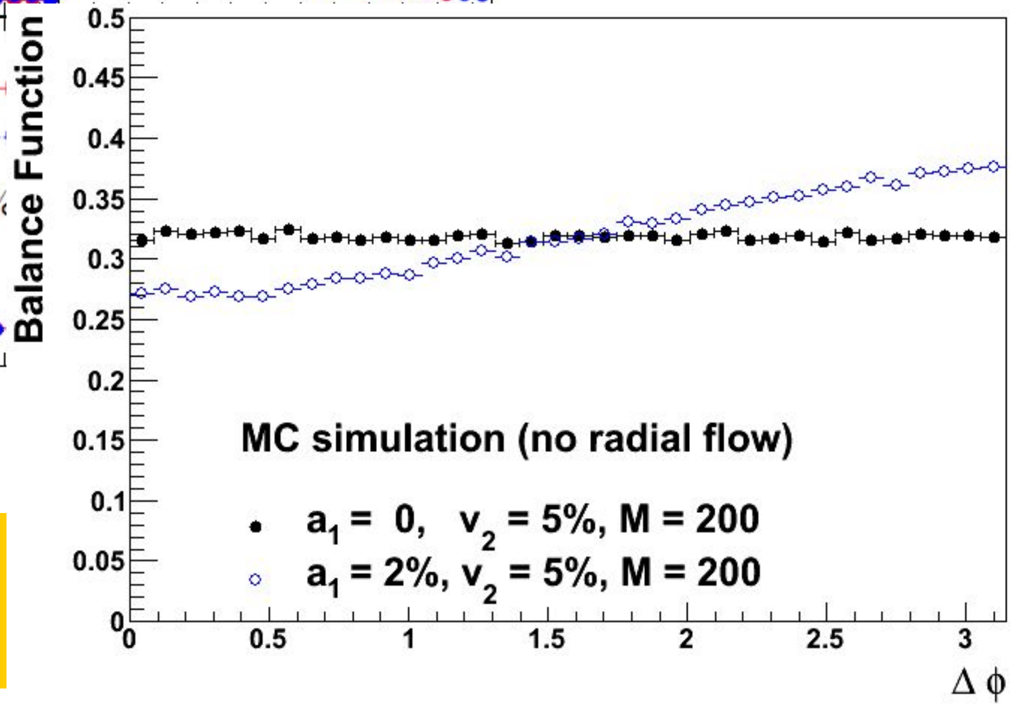
charge conservation/cluster + v_2



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



Pratt, Phys.Rev.C83:014913,2011



Balance function