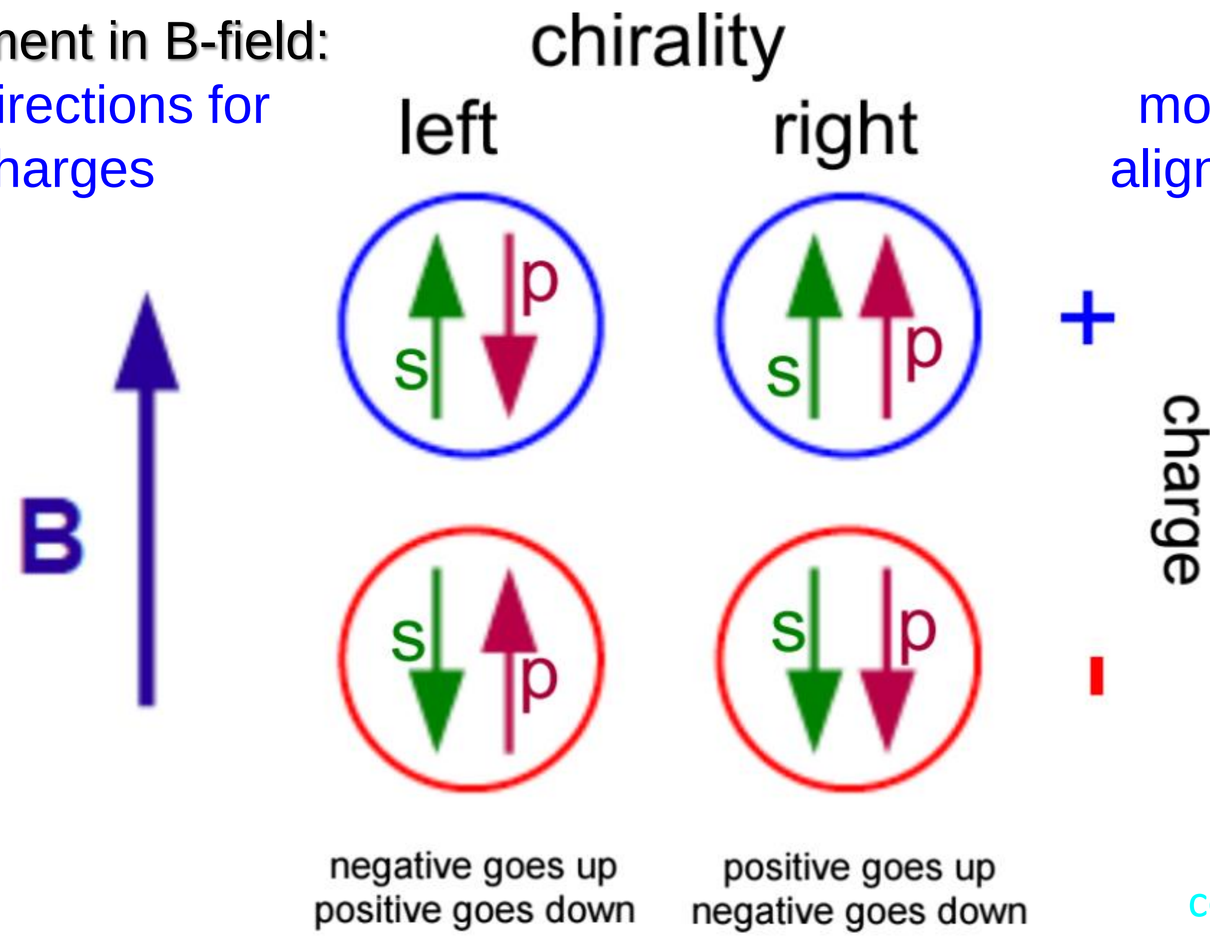
CME/CVE in high-energy heavy-ion collisions

Gang Wang (UCLA)

Chiral Magnetic effect: magnetic field + chirality = current

spin alignment in B-field: opposite directions for opposite charges

handedness: momentum and spin, aligned or anti-aligned



courtesy of P.Sorensen

An excess of right or left handed quarks lead to a current flow along the magnetic field.

$$\vec{J} = \frac{e^2}{2\pi^2}\,\mu_5\,\vec{B}$$

Chiral magnetic effect in $ZrTe_5$

nature physics

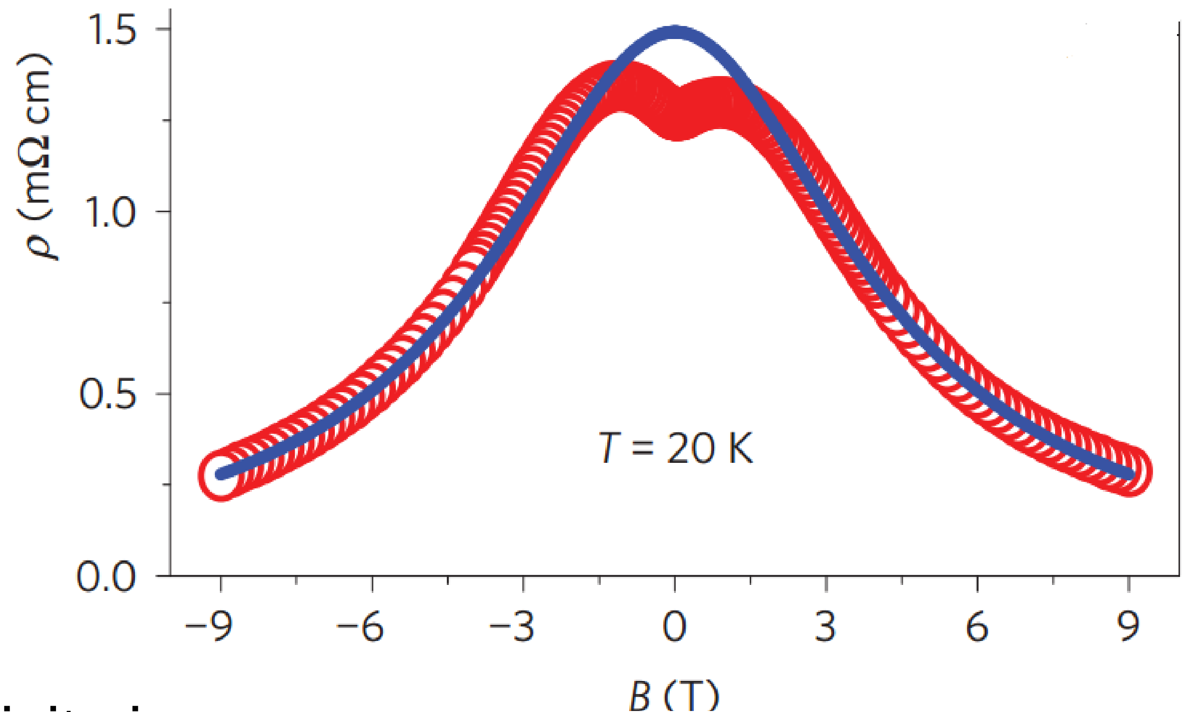
Qiang Li, Dmitri E. Kharzeev, Cheng Zhang, Yuan Huang, I. Pletikosić, A. V. Fedorov, R. D. Zhong, J. A. Schneeloch, G. D. Gu & T. Valla

Nature Physics 12, 550 (2016)

$$\vec{J} = \frac{e^2}{2\pi^2}\,\mu_5\,\vec{B}$$

Man-made chirality:

$$\mu_5 = \frac{3}{4}\frac{v^3}{\pi^2}\frac{e^2}{\hbar^2 c}\frac{\mathbf{E}\cdot\mathbf{B}}{T^2+\frac{\mu^2}{\pi^2}}\tau_V$$



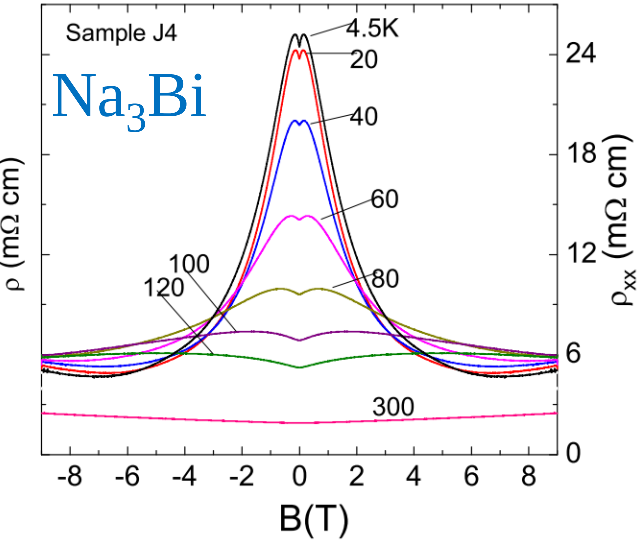
When E||B, CME conductivity is

$$\sigma_{CME}^{zz} = \frac{e^2}{\pi\hbar}\frac{3}{8}\frac{e^2}{\hbar c}\frac{v^3}{\pi^3}\frac{\tau_V}{T^2+\frac{\mu^2}{\pi^2}}B^2$$

B dependence of the negative magnetoresistance is nicely fitted with CME contribution to the electrical conductivity.

A whole industry of CME is semimetals

Dirac semimetal

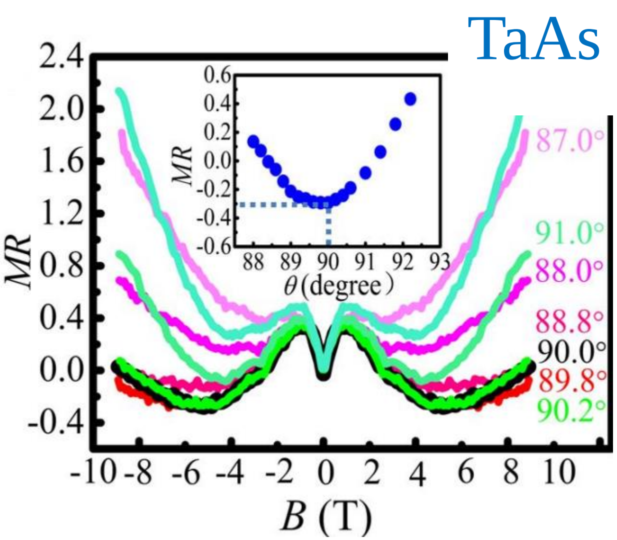


$ZrTe_5$ - Q. Li, D. Kharzeev, et al (BNL and Stony Brook Univ.)
arXiv:1412.6543; Nature Physics 12, 550 (2016)

Na_3Bi - J. Xiong, N. P. Ong et al (Princeton Univ.)
arxiv:1503.08179; Science 350:413,2015

Cd_3As_2 - C. Li et al (Peking Univ. China)
arxiv:1504.07398; Nature Commun. 6, 10137 (2015).

Weyl semimetal



TaAs - X. Huang et al (IOP, China)
arxiv:1503.01304; Phys. Rev. X 5, 031023

NbAs - X. Yang et al (Zhejiang Univ. China)
arxiv:1506.02283

NbP - Z. Wang et al (Zhejiang Univ. China)
arxiv:1504.07398

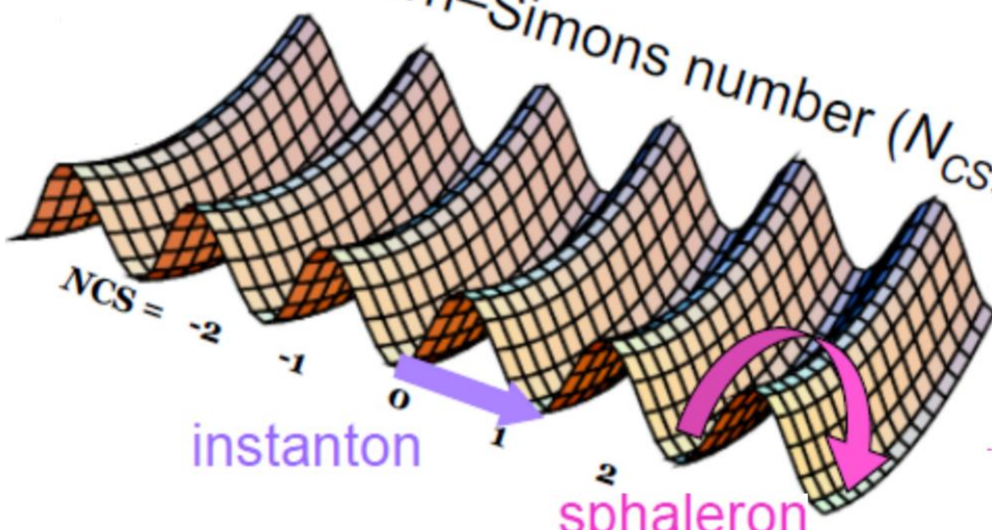
TaP - Shekhar, C. Felser, B. Yang et al (MPI-Dresden)
arxiv:1506.06577

Why study CME in heavy-ion collisions?

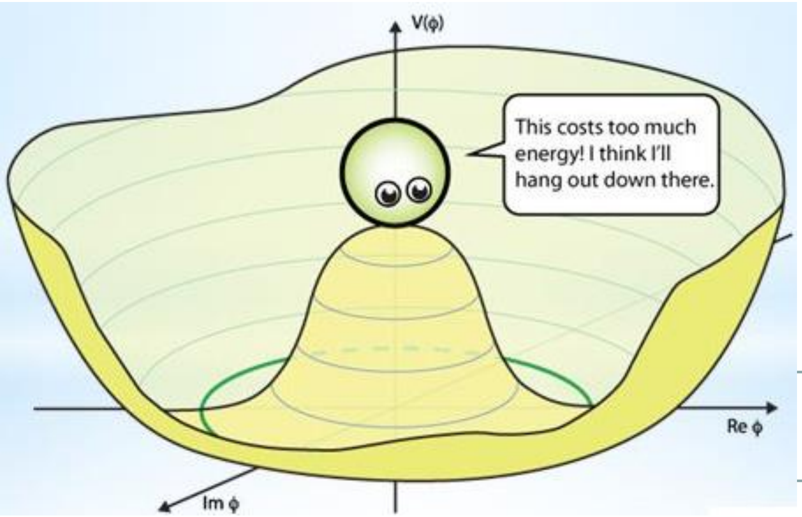
Understand 1) the strong B field and many fancy effects

Y. Hirono, D. E. Kharzeev and Y. Yin PRD 92,125031 (2015)

2) vacuum transition



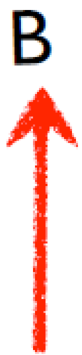
D. Diakonov, Prog. Part. Nucl. Phys. 51, 173 (2003)

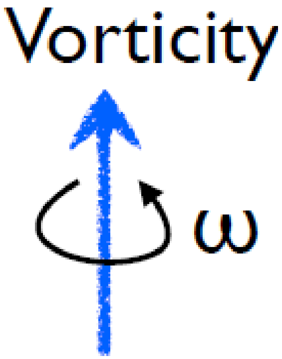


3) chiral symmetry restoration

Chiral Vortical Effect

Chiral Magnetic Effect vs **Chiral Vortical Effect**





Chiral Magnetic Effect		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)

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

Electric charge separation

Baryonic charge separation

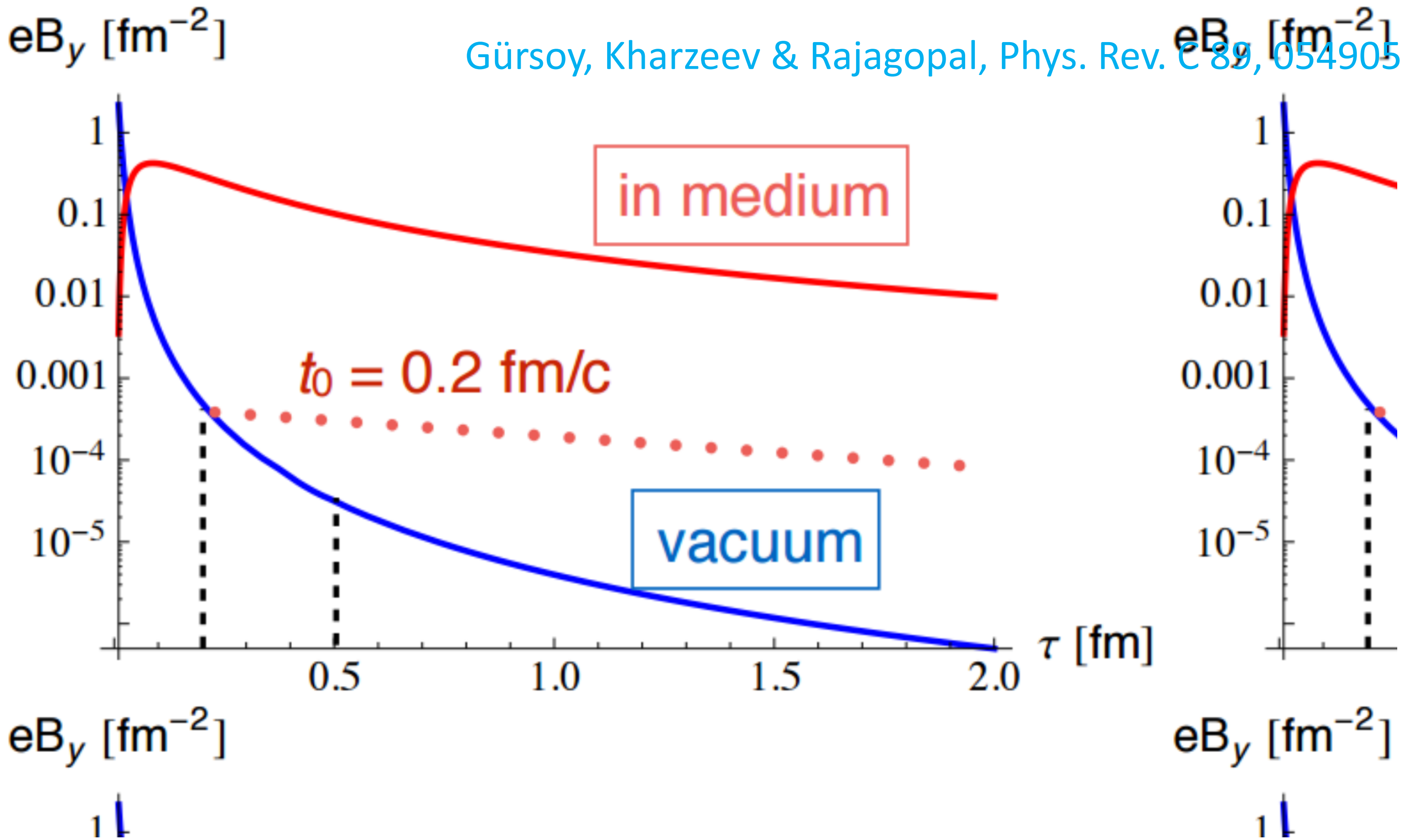
Do we have experimental evidence of B or ω?

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

Frozen B fields

- In vacuum, the B field falls like a rock.
- A conducting medium is need to save the day.
- How much has B fallen off when the medium comes in play?

Gürsoy, Kharzeev & Rajagopal, Phys. Rev. C 89, 054905 (2014)



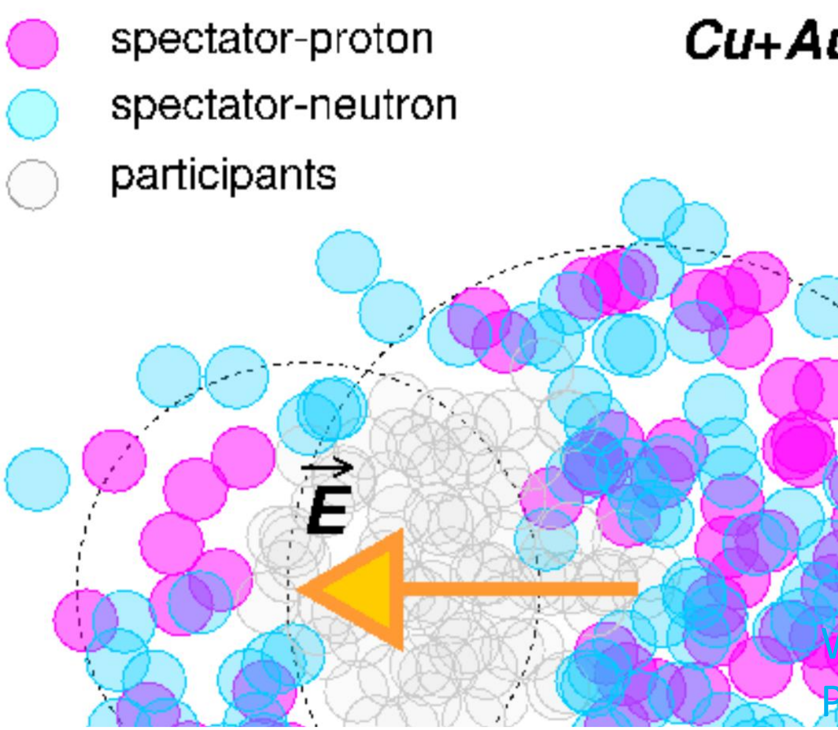
An indirect evidence: E

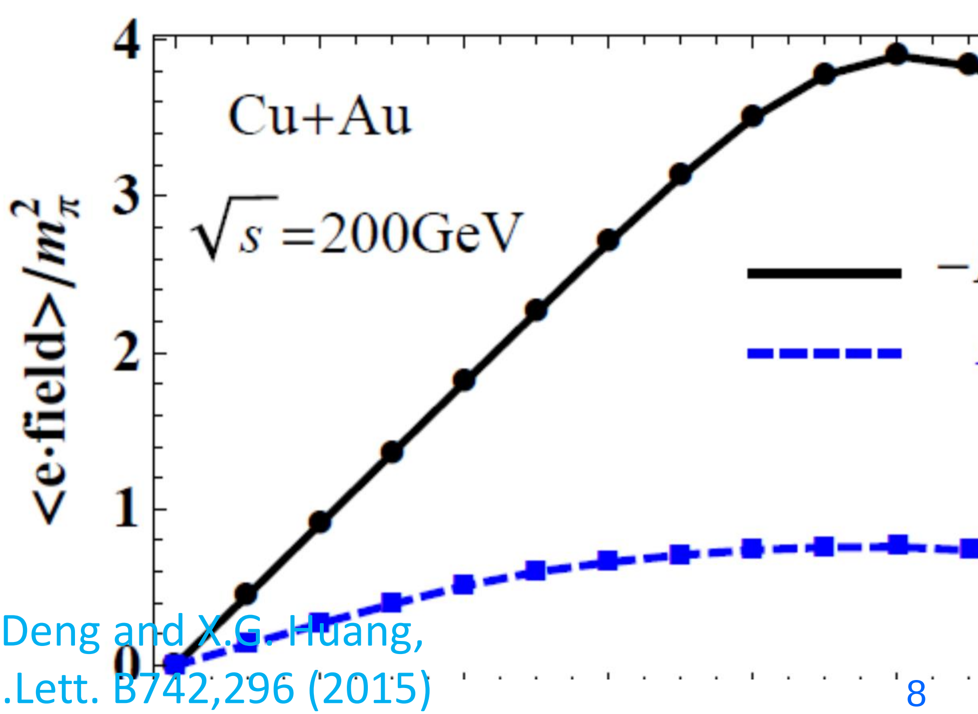
- Asymmetric collisions (Cu+Au) create in-plane electric fields.
- Similar to the B field, and easier to observe:
  - h^+ goes along E and h^- to the opposite
  - charge-dependent of v_1 Y. Hirono et al., Phys.Rev. C 90 (2014) no.2, 021903

$$\frac{dN^{\pm}}{d\phi} \propto 1 + 2v_1 \cos(\phi - \Psi_1) \pm 2d_E \cos(\phi - \psi_E) \cdots$$

$$v_1^{\pm} = v_1 \pm d_E \langle \cos(\Psi_1 - \psi_E) \rangle$$

ψ_E: electric field direction
d_E: electric dipole





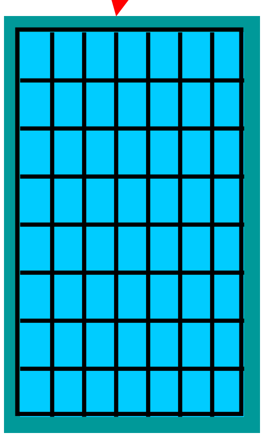
W.T. Deng and X.G. Huang, Phys.Lett. B742,296 (2015)

How to measure v_1

- **First-order event plane determined from spectator neutrons**
- **Minimal, if any, non-flow effects**

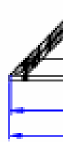
$$v_1 = \langle \cos(\varphi - \Psi_1) \rangle / \langle \cos(\Psi_1 - \Psi_{RP}) \rangle$$

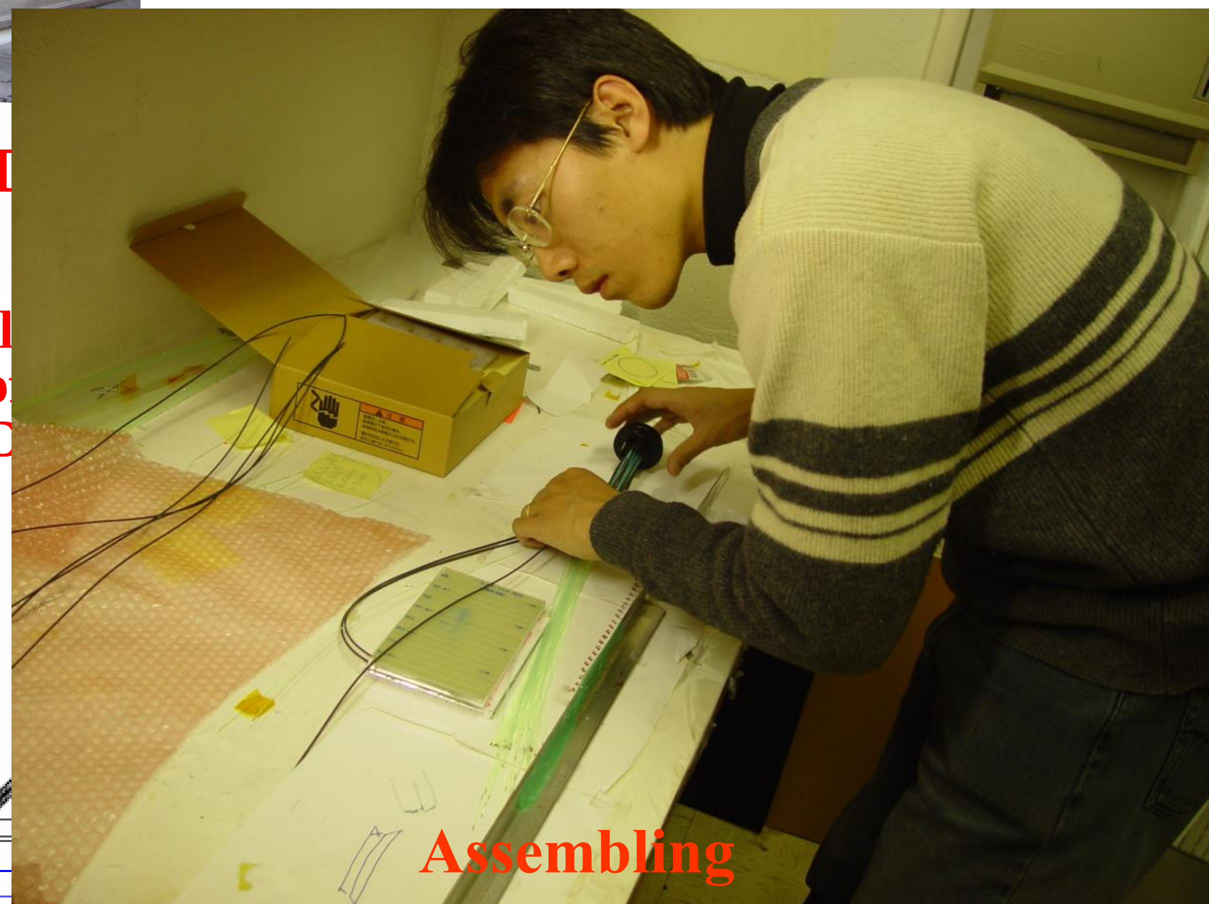
SMD is 8 horizontal slats & 7 vertical slats located at 1/3 of the depth of the ZDC



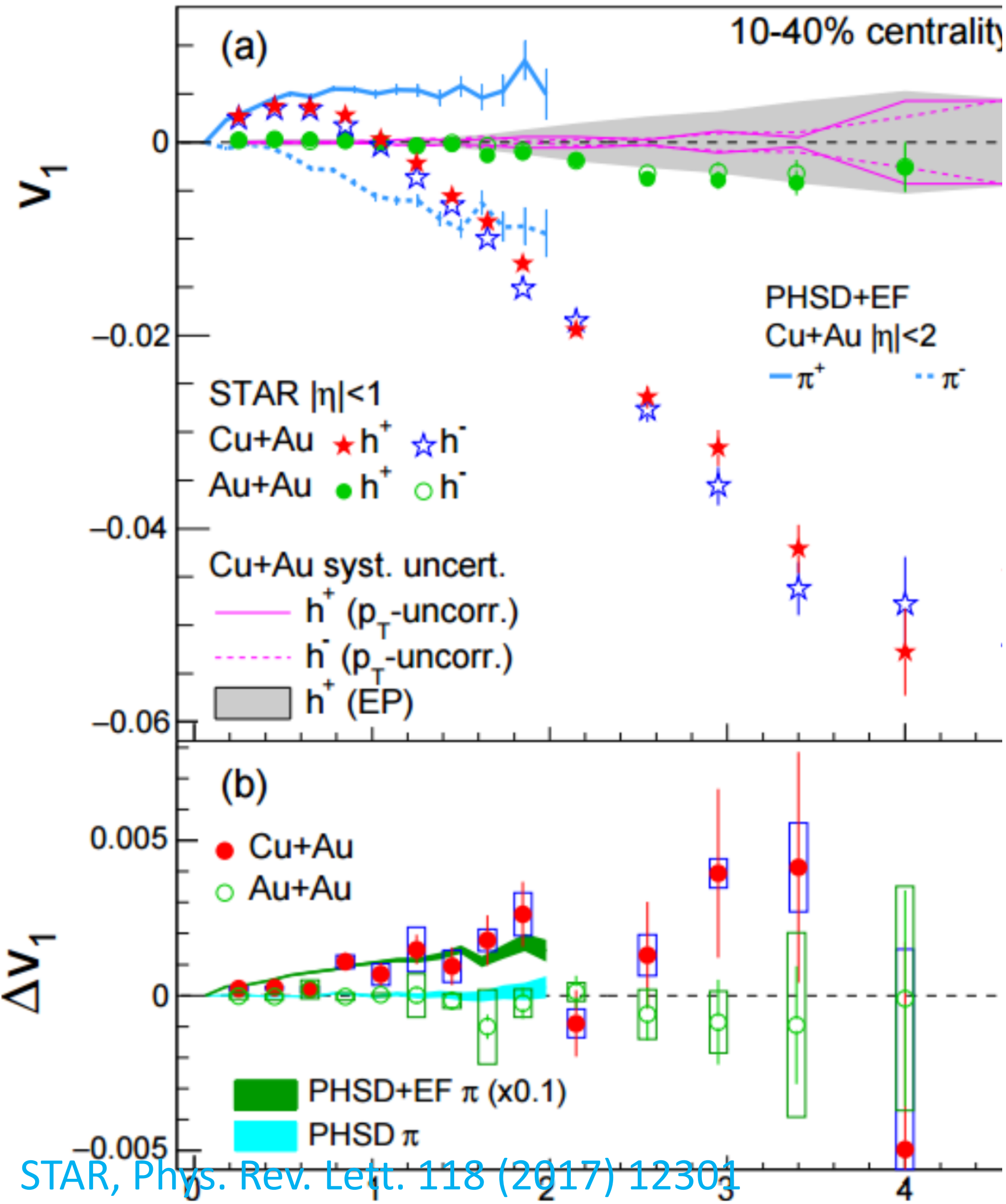
ZD

Scintil
slats o
Max D





v_1 in Cu+Au@200 GeV



STAR, Phys. Rev. Lett. 118 (2017) 12301

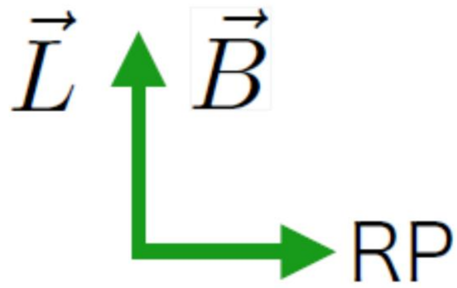
$$v_1^{\pm} = v_1 \pm d_E \langle \cos(\Psi_1 - \psi_E) \rangle v_1^{\pm} =$$

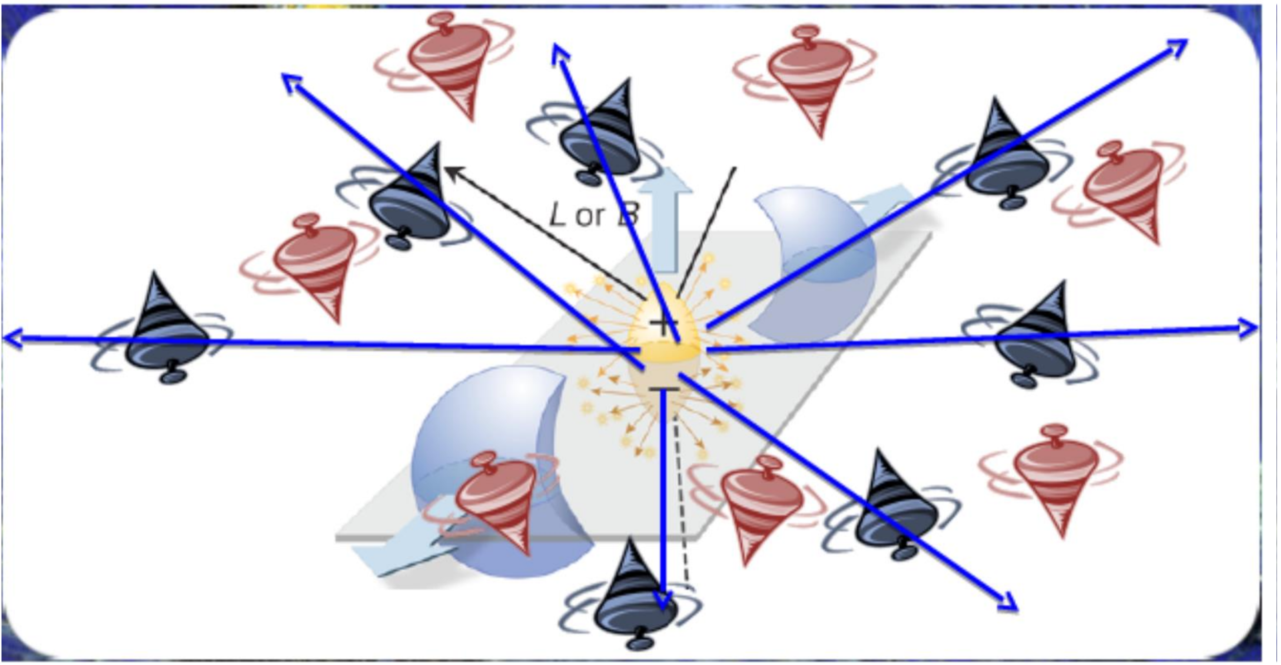
ψ_E: electric field direction
d_E: electric dipole

- On average, ψ_E is along the ψ_{RP} direction.
- $v_1(p_T)$ shows a difference between h^+ and h^-.
- The sign is right.
- The magnitude is 10% of what was expected.
- The initial electric field does leave an imprint on final-stage particles!
- Not all quarks are created in early times.

More direct probe in B and ω

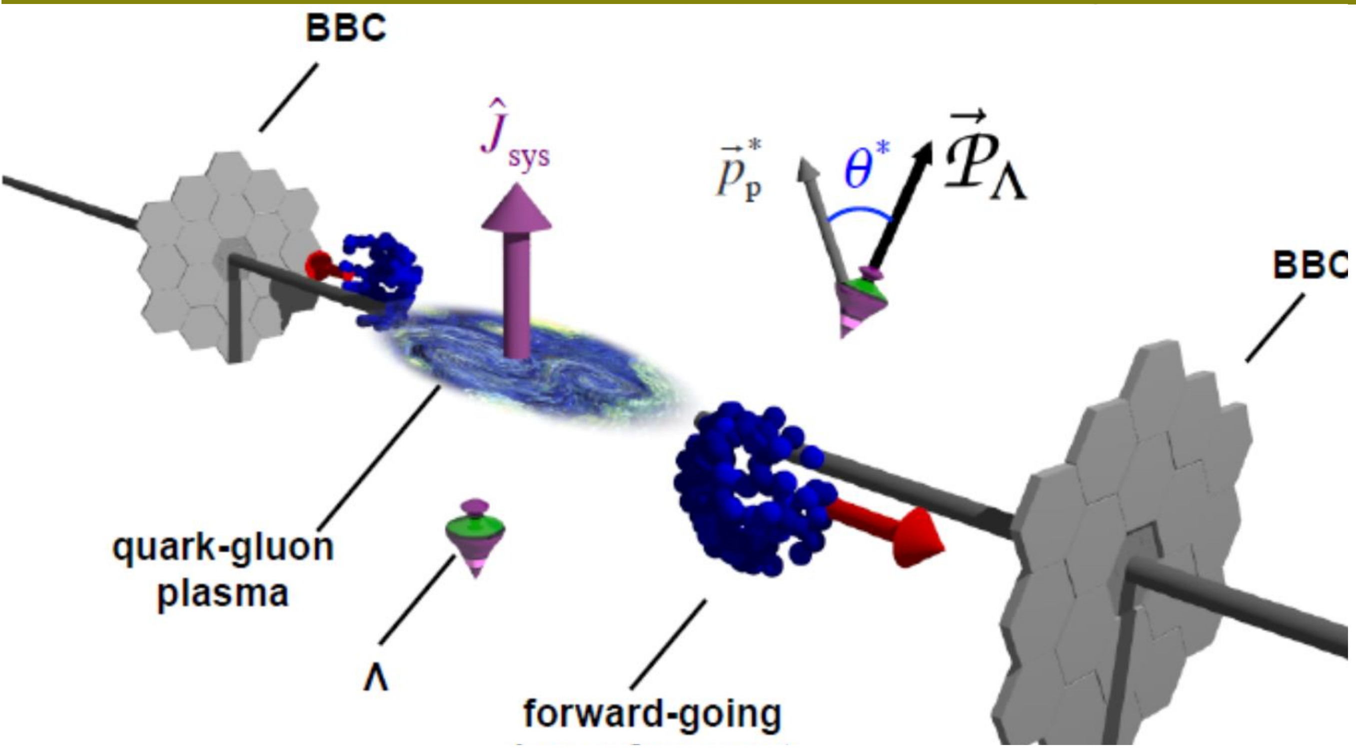
Non-zero angular momentum (~$10^3\hbar$) transfers to Λ polarization

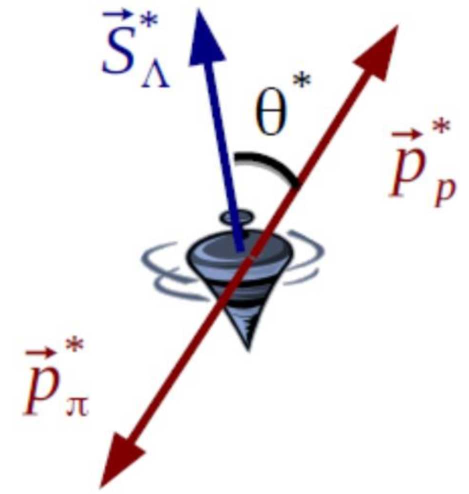




- spin-orbit coupling
  - spins of Λ and anti-Λ are both aligned with the angular momentum L
- spin alignment by the B field
  - Λ spin anti-aligned with B
  - anti-Λ spin aligned with B

How to measure polarization





daughter protons prefer to go along Λ spin (opposite for anti-Λ)

ψ_1 from either ZDC-SMD or BBC

$$P_H = \frac{8}{\pi\alpha}\frac{\langle\sin(\Psi_1 - \phi_p^*)\rangle}{\mathrm{Res}(\Psi_1)}\mathrm{sg}$$

ϕ_p^*: ϕ of daughter proton in Λ rest frame

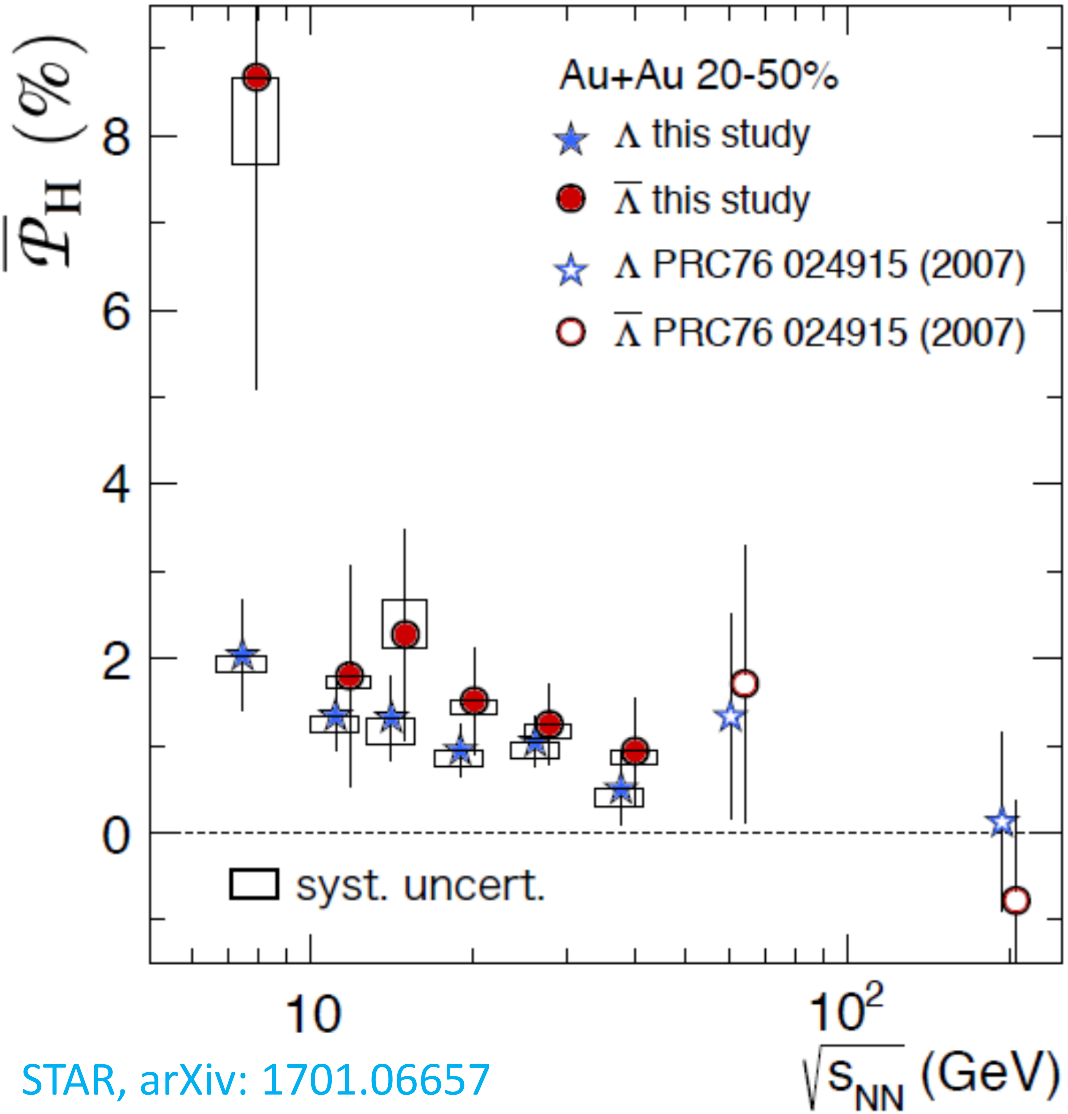
Ψ_1: 1st-order event plane

sgn_Λ: 1 for Λ, -1 for anti-Λ

α: Λ decay parameter (=0.642±0.013)

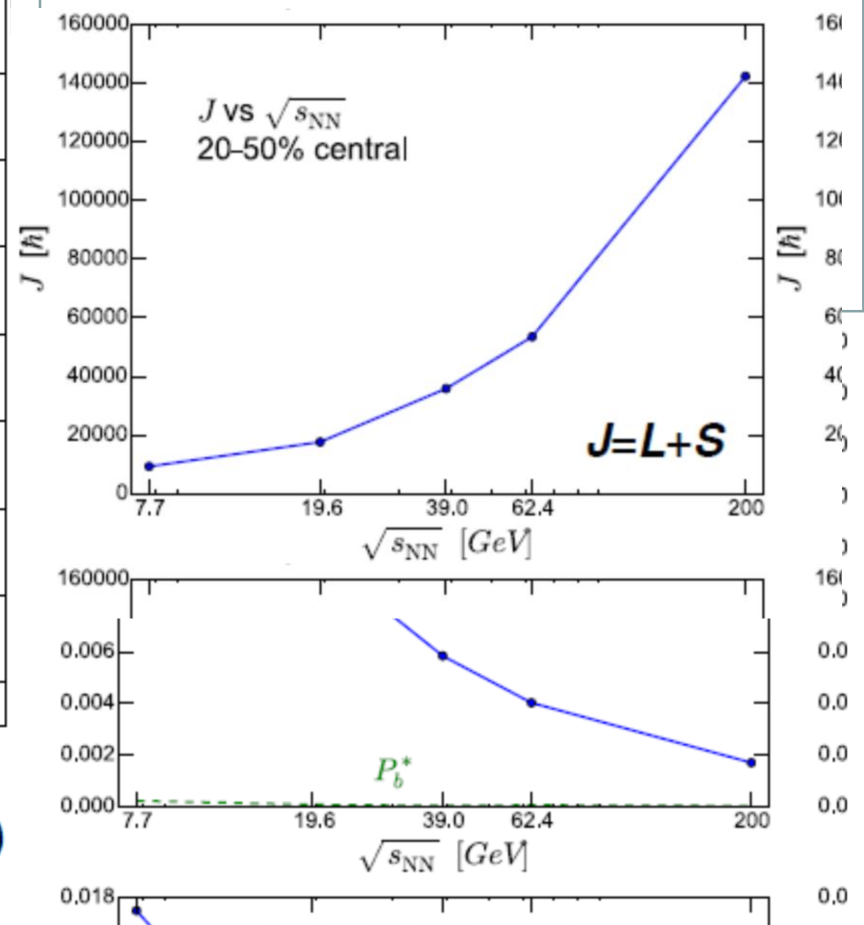
STAR, PRC 76 024915 (2007)

Λ global polarization



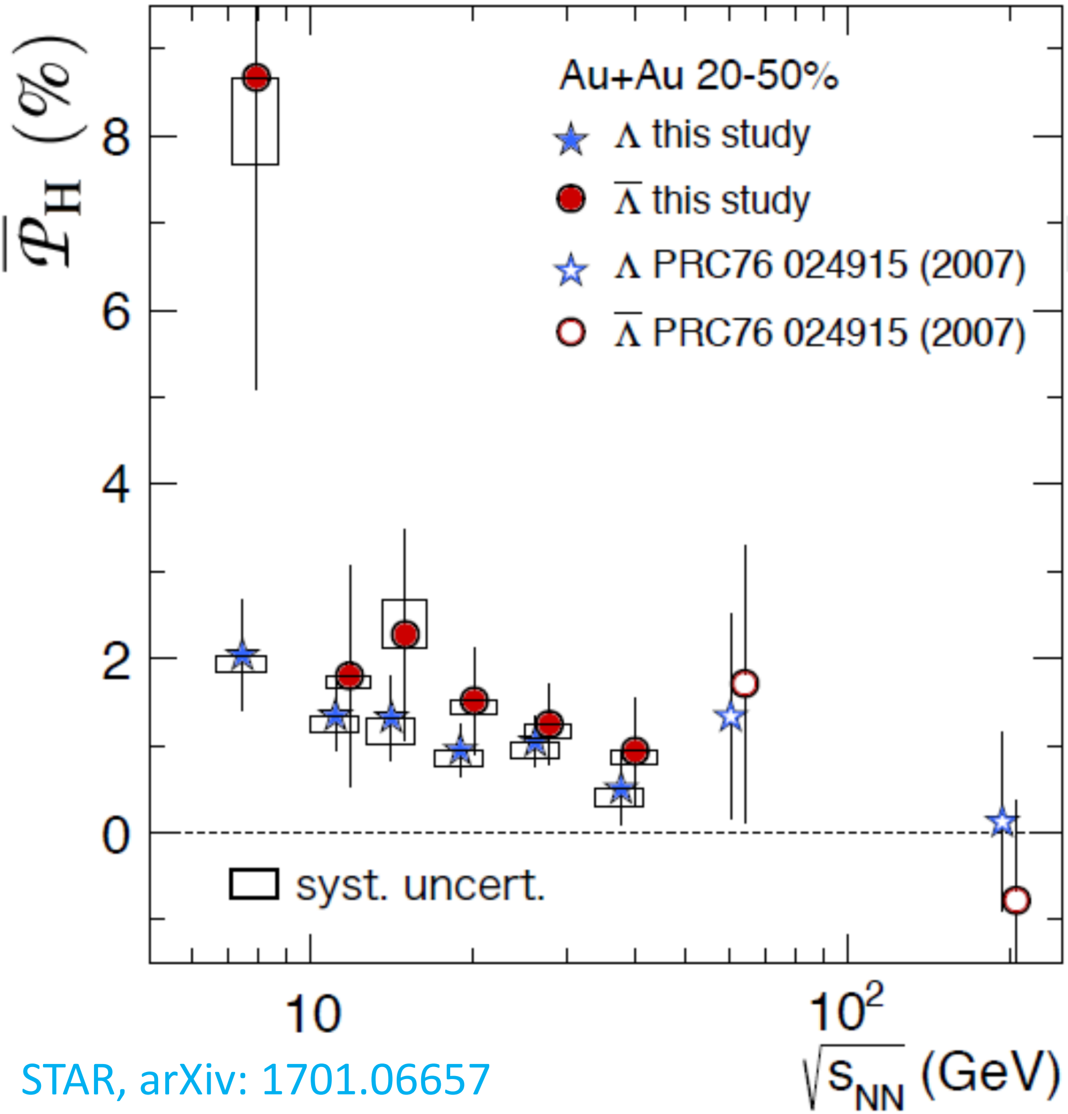
STAR, arXiv: 1701.06657

- positive signals: vorticity!
- initial L is larger at higher energies,



I. Karpenko and F. Becattini, Eur. Phys. J. C (2017) 77: 213

Λ global polarization



STAR, arXiv: 1701.06657

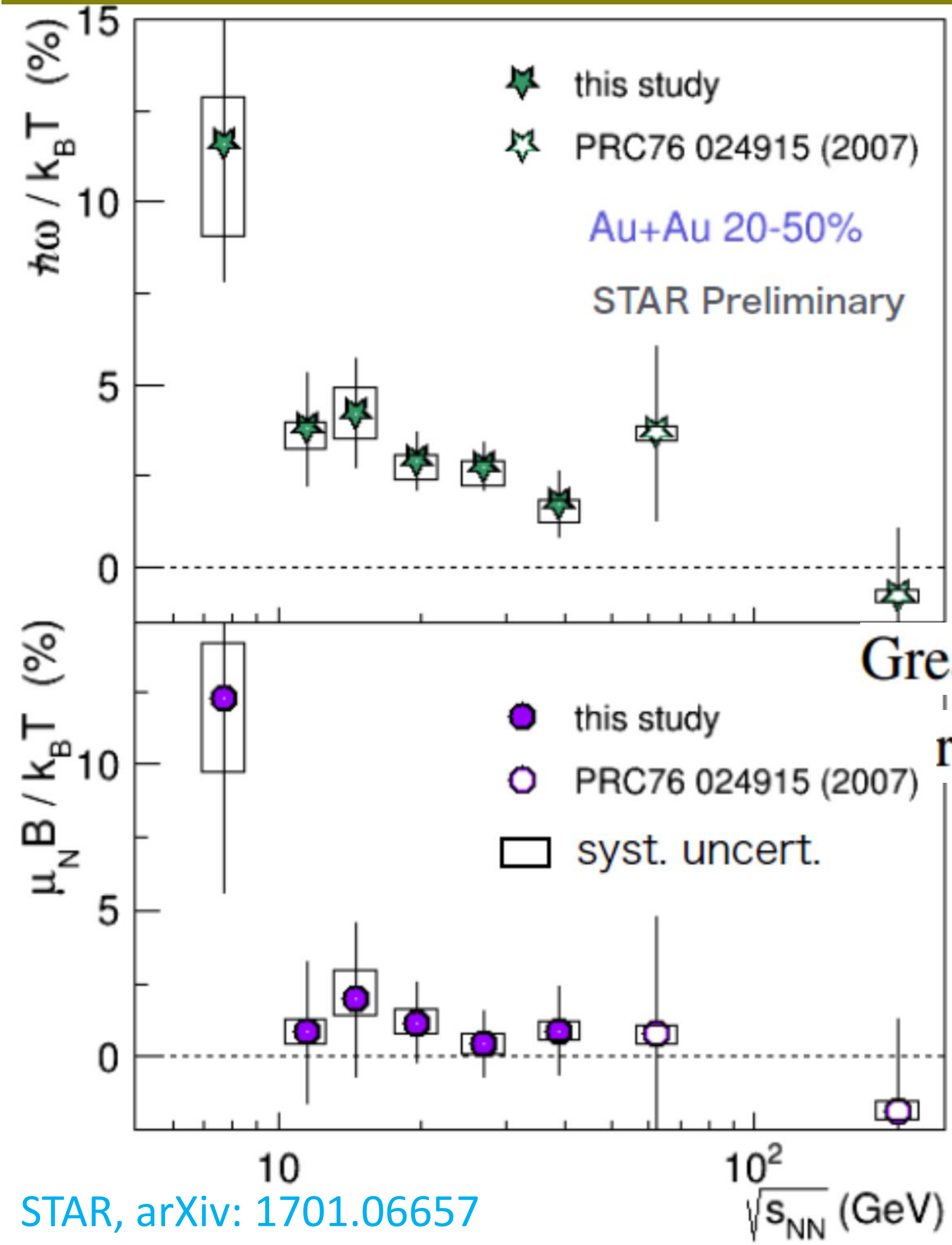
- positive signals: vorticity!
- systematically, $P_H(\Lambda) < P_H(\text{anti-}\Lambda)$ implying a B-field effect
- for small polarization

$$P_\Lambda \approx \frac{1}{2}\frac{\omega}{T} + \frac{\mu_\Lambda B}{T}$$

$$P_{\bar{\Lambda}} \approx \frac{1}{2}\frac{\omega}{T} - \frac{\mu_\Lambda B}{T}$$

F. Becattini et al, arXiv: 1610.02506

ω and B



STAR, arXiv: 1701.06657

- vorticity
  - $\omega/T \sim$ 2-10% ($\hbar$=1,k_B=1)
  - $\omega \approx (9 \pm 1) \times 10^{21}\ s^{-1}$ far surpasses other known fluids:

solar subsurface flow ($10^{-7}\ s^{-1}$)

supercell tornado cores ($10^{-1}\ s^{-1}$)

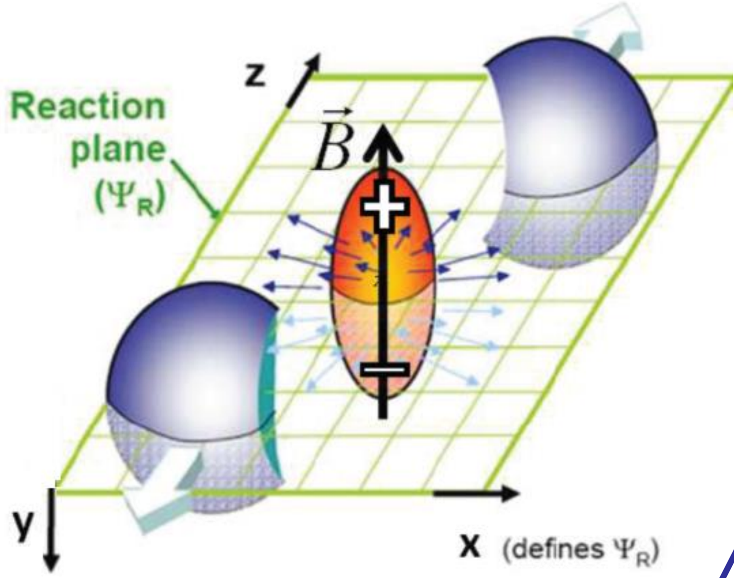
Great Red Spot of Jupiter (up to $10^{-4}\ s^{-1}$)

rotating, heated soap bubbles ($100\ s^{-1}$)

superfluid nanodroplets ($10^{7}\ s^{-1}$)

- B field
  - possible direct measure of B field, but consistent with zero
  - need more statistics

CME observable: direct measurement?

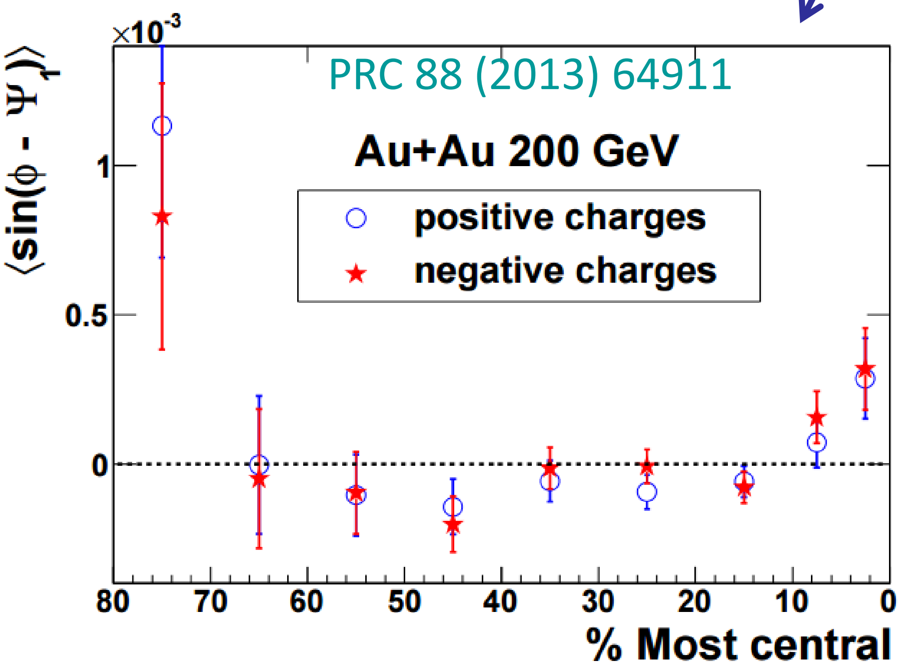


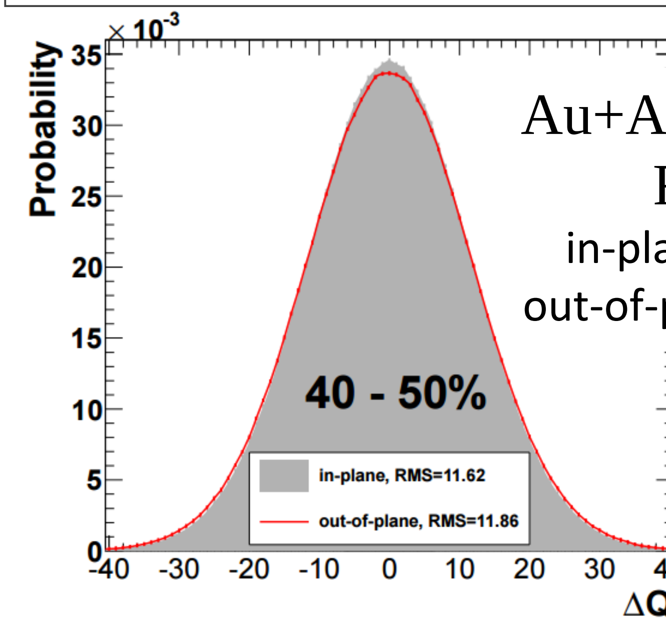
$$\frac{dN_\pm}{d\phi} \propto 1 + 2a_\pm \cdot \sin\left(\phi^\pm - \Psi_{RP}\right)$$

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

There should be more out-of-plane charge fluctuation than in-plane.

Indeed, we see this effect, which is on percent level!

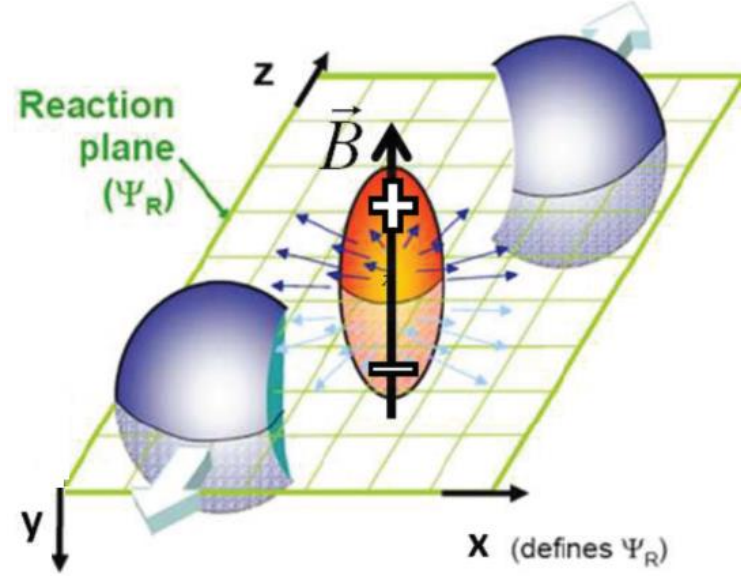




Au+Au 200 GeV
RMS:
in-plane = 11.62
out-of-plane = 11.86

CME observable: γ correlator

S. Voloshin, PRC 70 (2004) 057901



A better way to quantify the extra charge fluctuation.

A few similar observables yield similar results

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

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

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

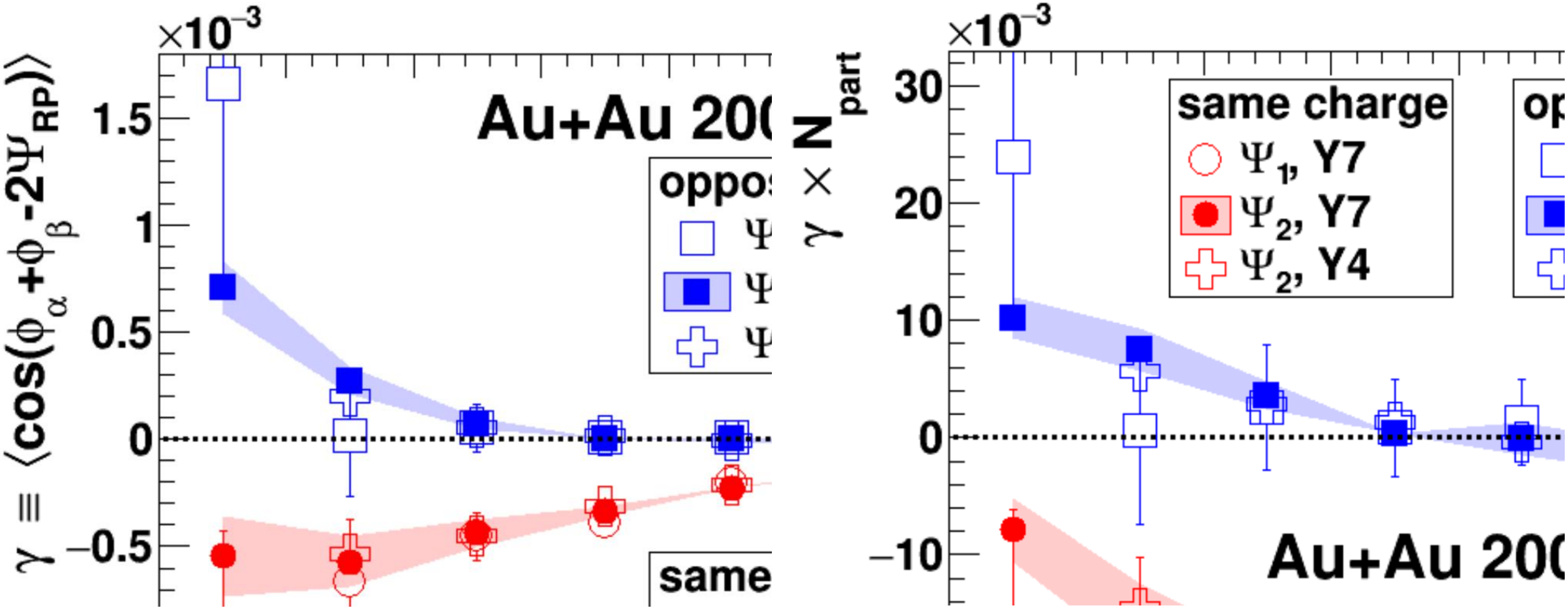
background effects: largely cancel out

P-even quantity: still sensitive to charge separation

$$\frac{B_{in} - B_{out}}{B_{in} + B_{out}} = v_{2,cl} \frac{\left\langle \cos(\phi_\alpha + \phi_\beta - 2\phi_{cl}) \right\rangle}{\left\langle \cos(\phi_\alpha - \phi_\beta) \right\rangle}$$

Charge separation signal

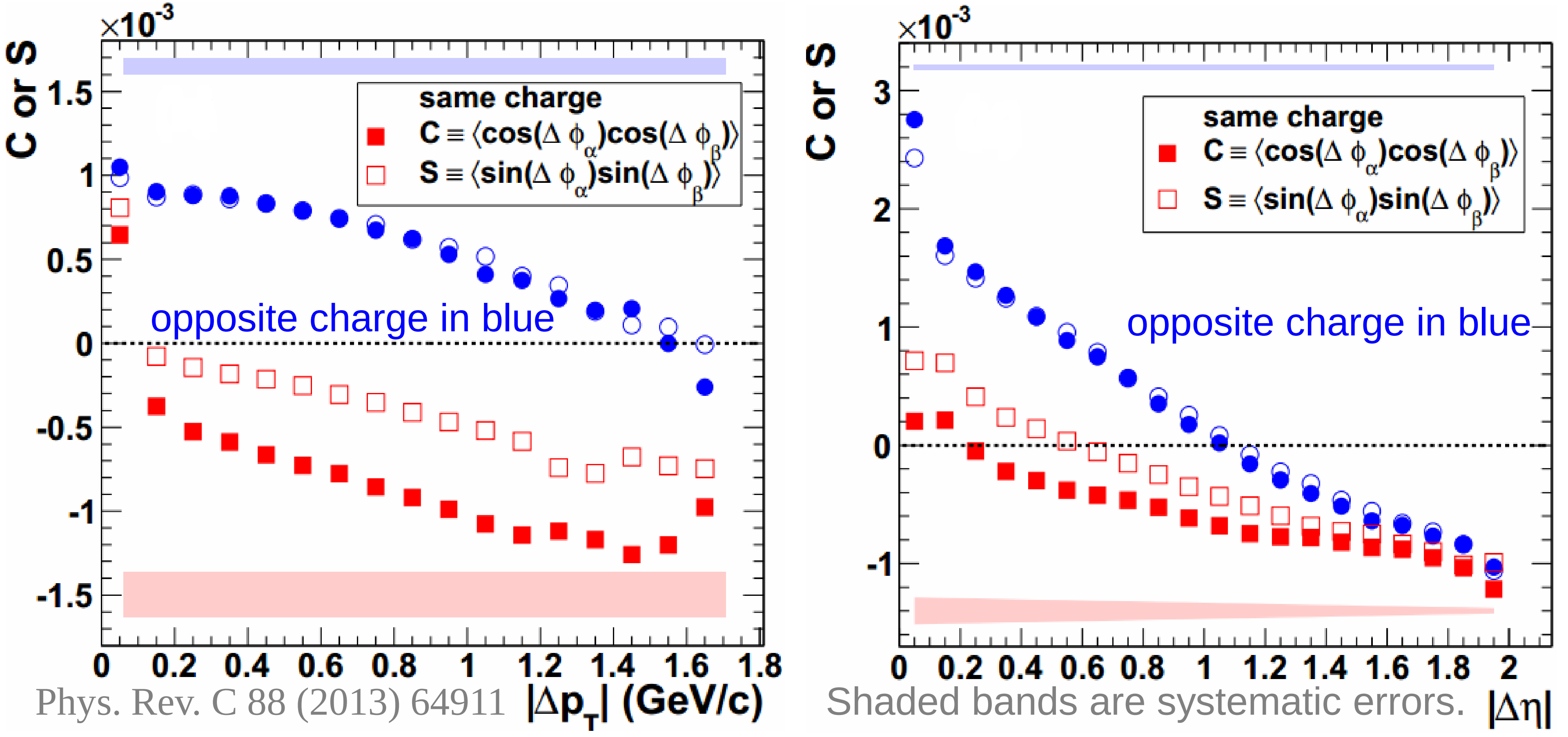
PRL 103(2009)251601;PRC 81(2010)54908;PRC 88 (2013) 64911



- γ_{os} > γ_{ss}, consistent with CME expectation
- Consistent between different years (2004 and 2007)
- Confirmed with 1st-order EP (from spectator neutron v_1)

Short range correlations

200 GeV Au+Au: 40 - 60%

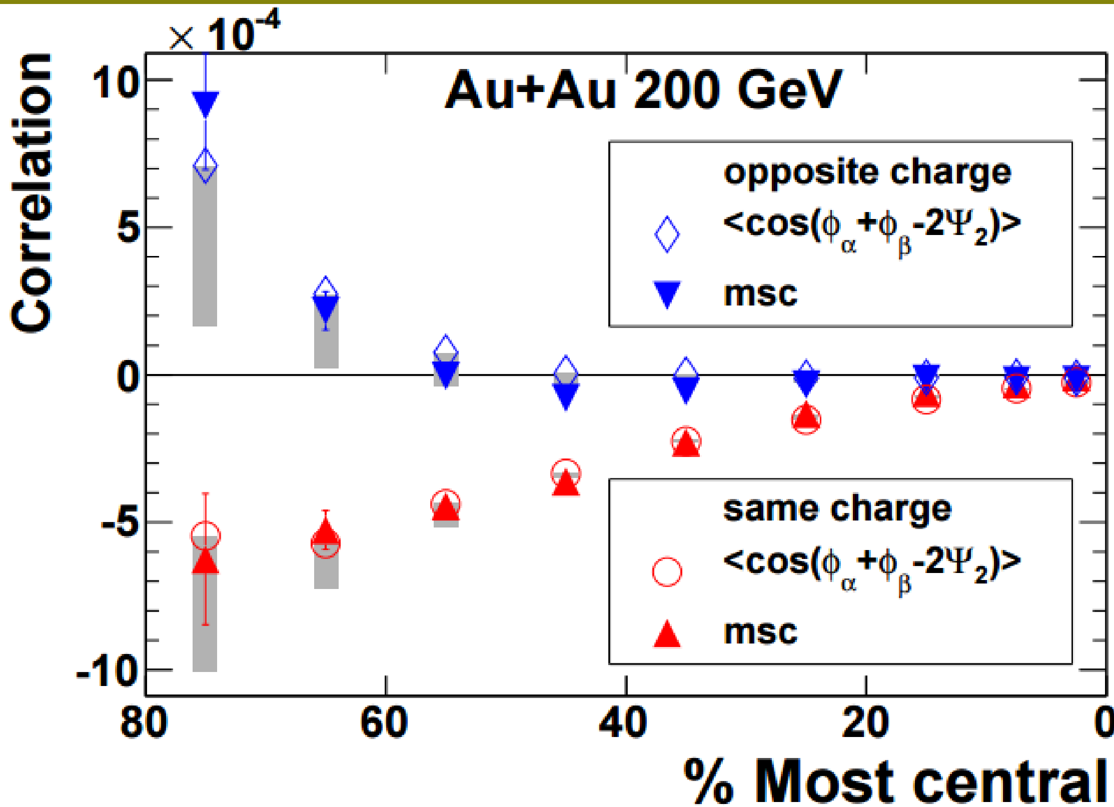


Phys. Rev. C 88 (2013) 64911

Shaded bands are systematic errors.

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

Modulated sign correlator (msc)



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

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

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

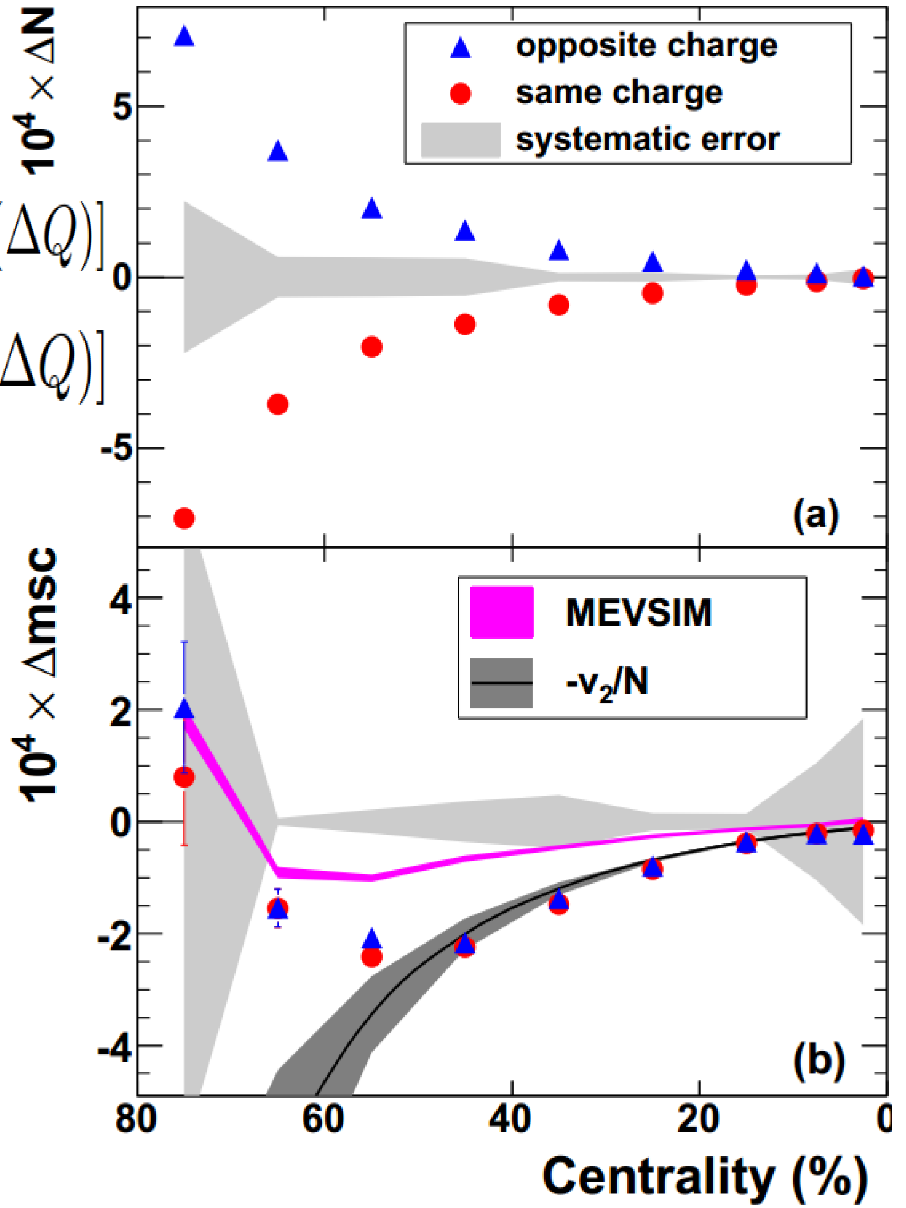
Phys. Rev. C 88 (2013) 64911

Charge-independent background

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

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

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

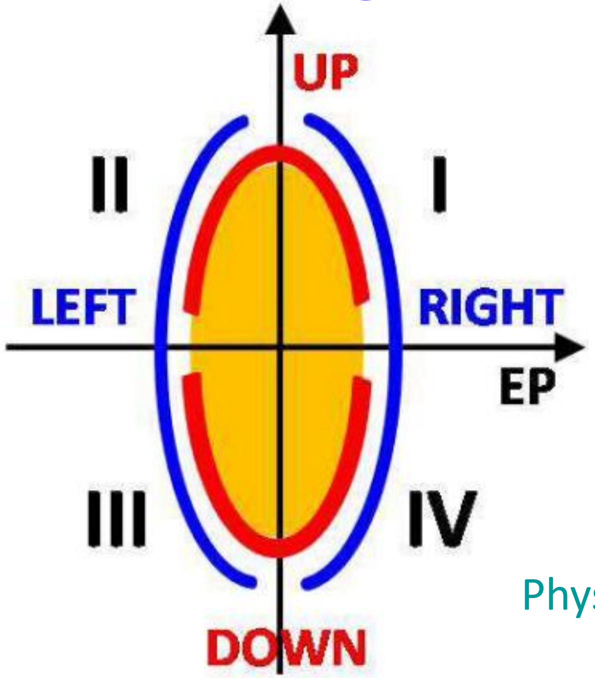


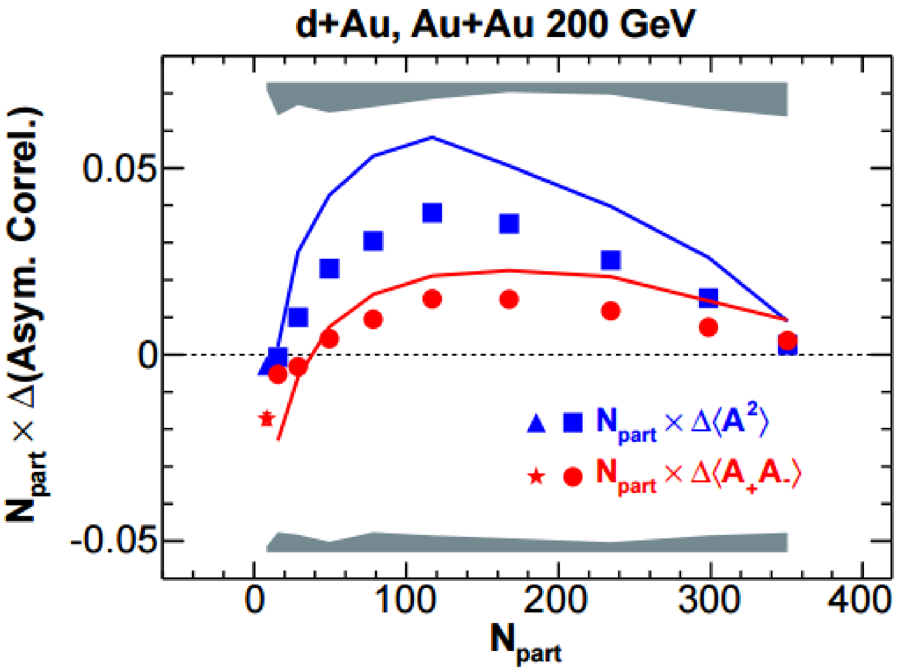
- msc was splitted to study bg
- $N_{IN}(\Delta Q)$ stands for the number of events with ΔQ units of in-plane charge separation, and $\mathrm{msc}_{IN}(\Delta Q)$ stands for the <msc> in those events.
- MEVSIM and -v_2/N tell us that the CI bg is likely due to momentum conservation + v_2

Phys. Rev. C 88 (2013) 64911

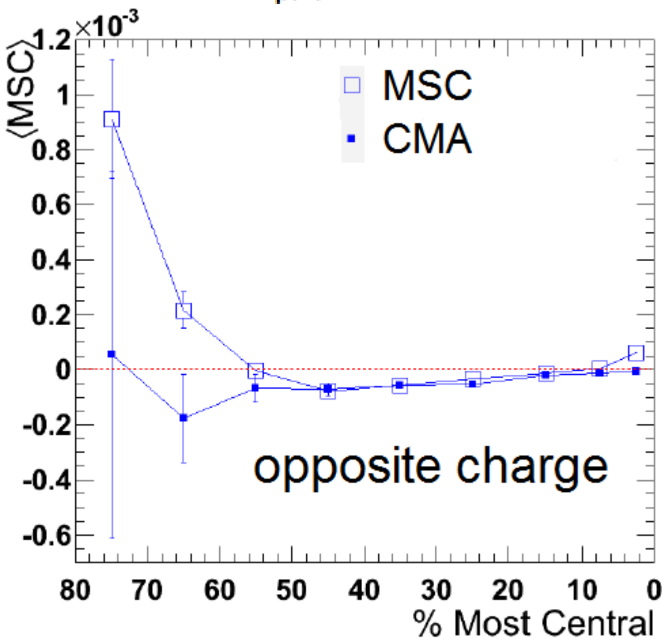
Charge multiplicity asymmetry correlator

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

Multi-particle charge-sensitive correlator

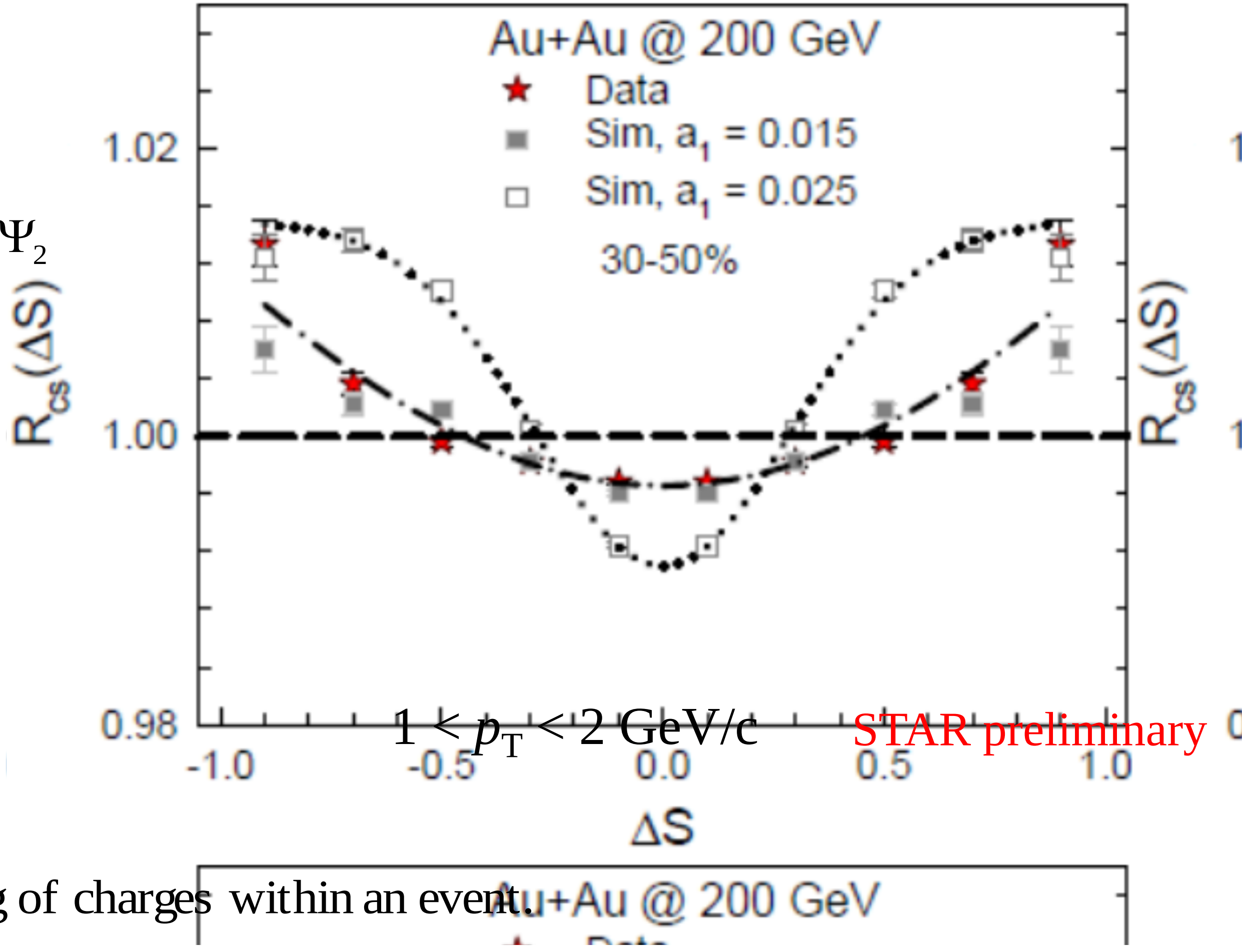
$$R_{cs}(\Delta S) = C_p(\Delta S) / C_p^{\perp}(\Delta S)$$

$$\left\langle S_p^{h^+} \right\rangle = \frac{\sum_1^p \sin(\Delta\varphi^+)}{p} \qquad \Delta\varphi = \varphi - \Psi_2$$

$$\left\langle S_n^{h^-} \right\rangle = \frac{\sum_1^n \sin(\Delta\varphi^-)}{n}$$

$$\Delta S = \left\langle S_p^{h^+} \right\rangle - \left\langle S_n^{h^-} \right\rangle$$

$$C_p(\Delta S) = \frac{N_{\text{real}}(\Delta S)}{N_{\text{shuffled}}(\Delta S)}$$



$N_{\text{shuffled}}(\Delta S)$ from random shuffling of charges within an event.

- Multi-particle charge-sensitive correlator is used to measure charge separation (ΔS) relative to Ψ_2 plane
- Concave for CME-driven charge separation; flat or convex for all non-CME related backgrounds
- Concave distribution observed in Au+Au

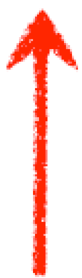
4 correlators

- γ correlator
  - easy to use and to correct for EP resolution
- Modulated sign correlator (msc)
  - reduced from γ
  - not good for mixed PID
- Charge multiplicity asymmetry correlator
  - roughly equivalent to msc
  - not good for mixed PID
  - hard to correct for EP resolution
- Multi-particle charge-sensitive correlator
  - roughly equivalent to γ
  - not good for mixed PID
  - hard to correct for EP resolution
  - have to compare with simulation to extract signal

In the following lectures, we stick to γ correlator.

Chiral Vortical Effect

Chiral Magnetic Effect vs **Chiral Vortical Effect**



Chiral Magnetic Effect		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)
Electric charge separation		Baryonic charge separation

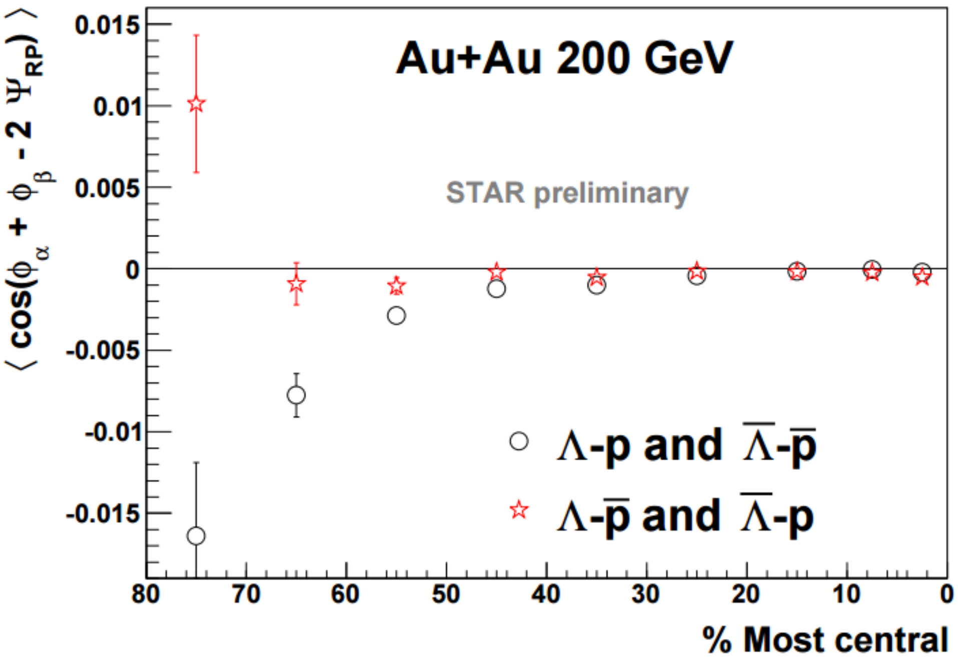
Peak magnetic field ~ 10^{15} Tesla ! (Kharzeev et al. NPA 803 (2008) 227)

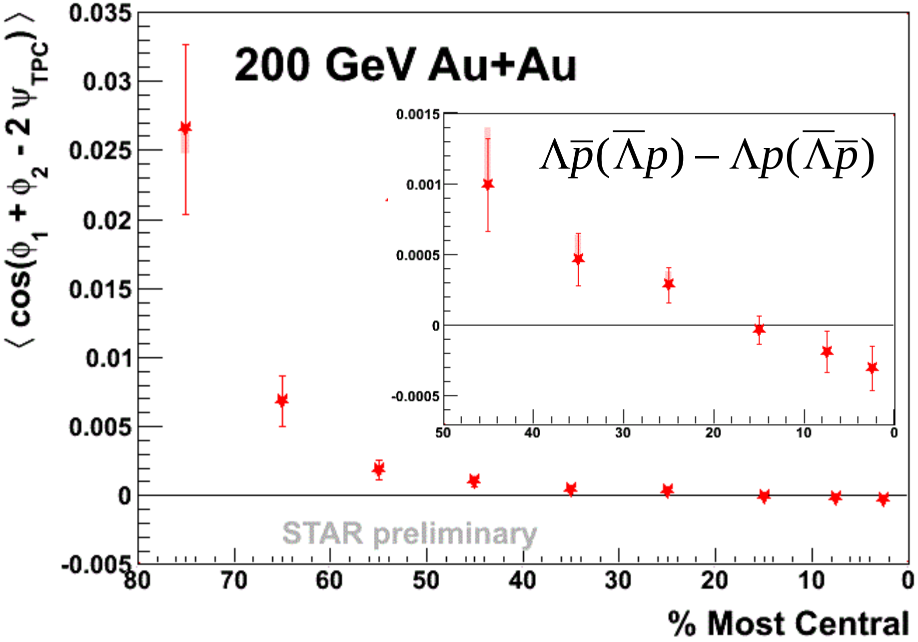
$$\langle \cos(\phi_{\Lambda} + \phi_{p} - 2\Psi_{RP}) \rangle$$

correlate Λ–p to search for the CVE.

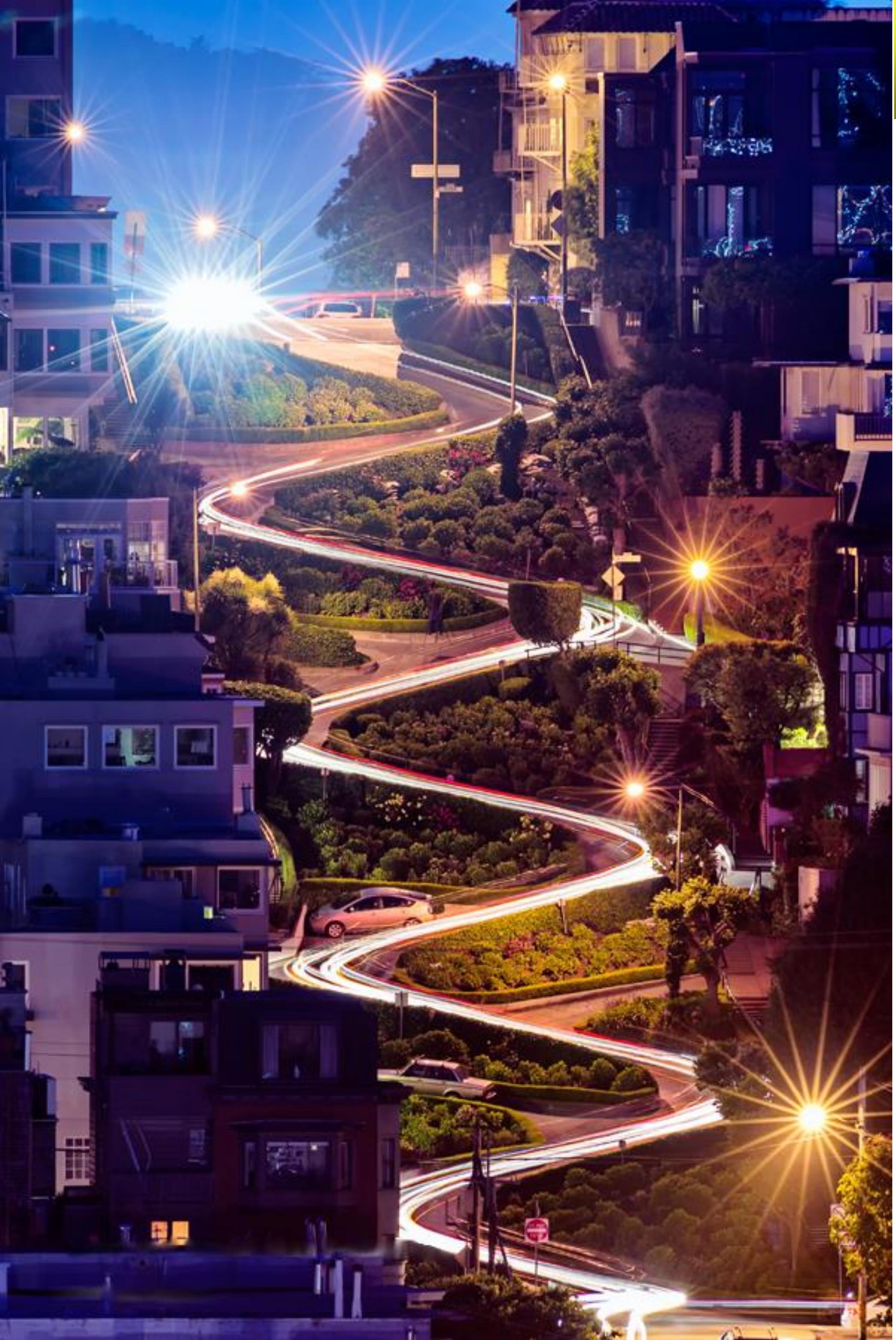
D. Kharzeev, D. T. Son, PRL 106 (2011) 062301

CVE observable





- same baryon number: Λp and $\bar{\Lambda}\bar{p}$
- opposite baryon number: $\Lambda\bar{p}$ and $\bar{\Lambda}p$
- "same B" < "oppo B" in mid-central and peripheral collisions: consistent with the CVE expectation.

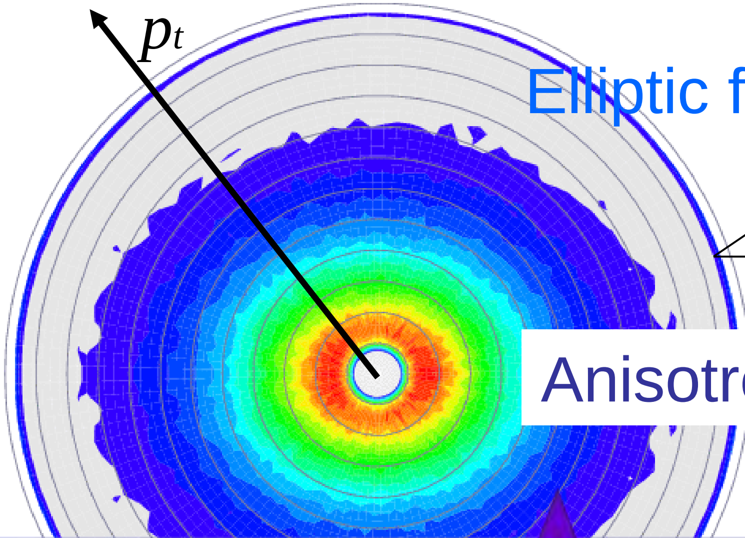


Summary

a long and winding road,
and still miles to go ...

but highlights here
and there ...

Back-up slides

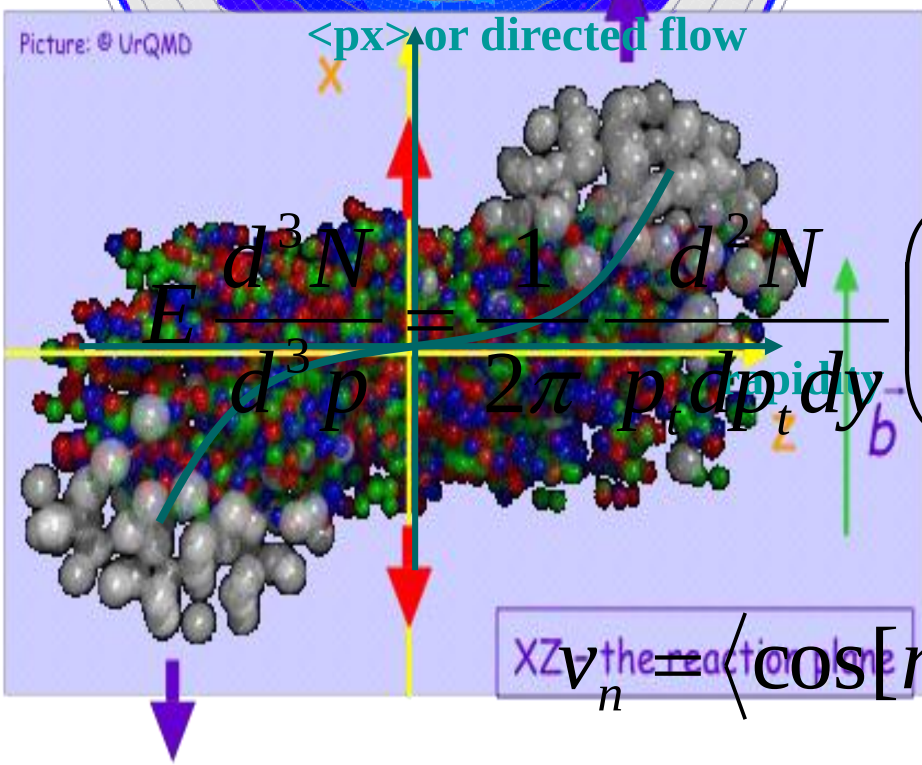


Elliptic flow

Anisotropic flow

Directed flow

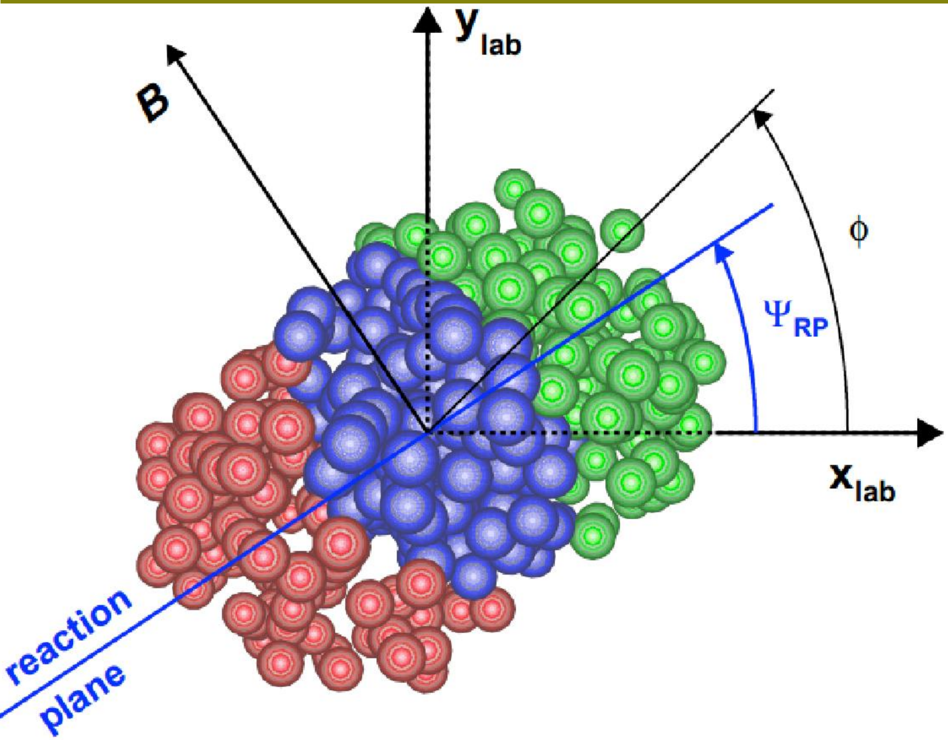
Higher harmonics

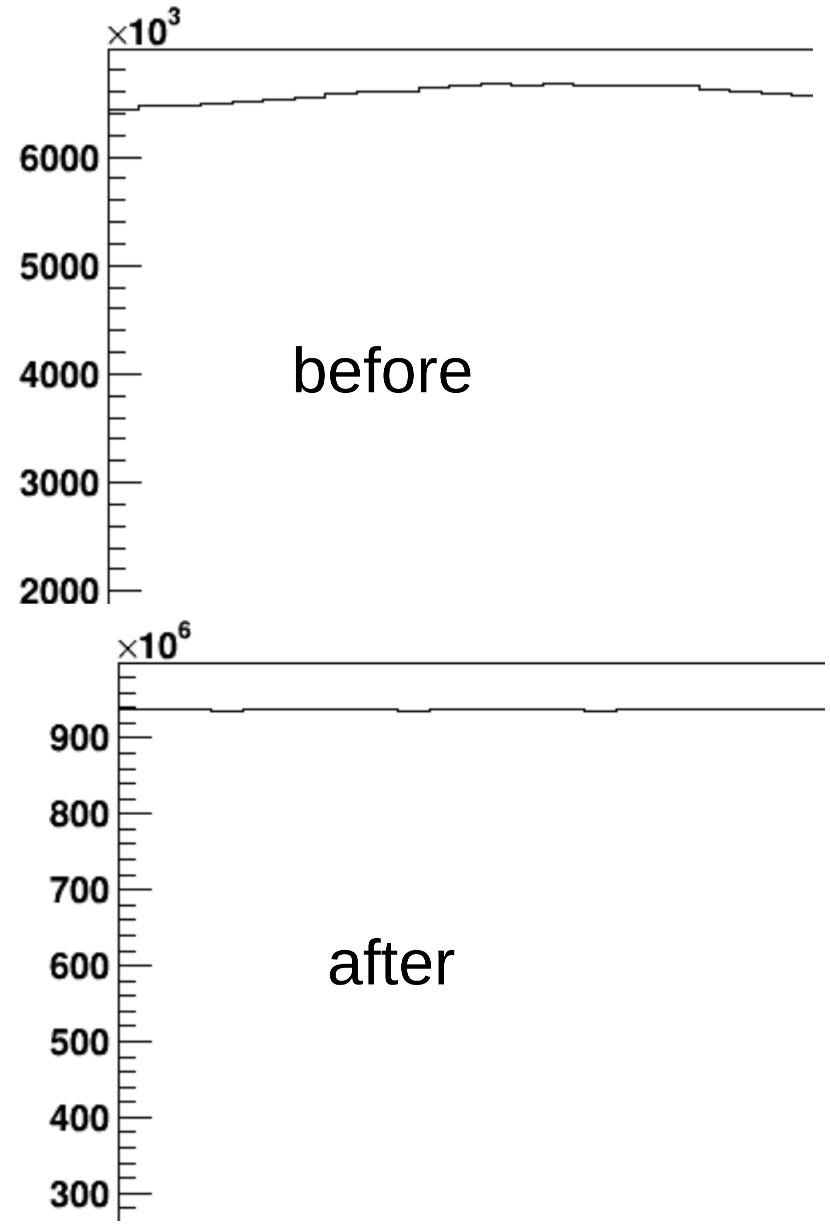


$$E\frac{d^3N}{d^3p} = \frac{1}{2\pi}\frac{d^2N}{p_t\,dp_t\,dy}\left(1 + \sum_{n=1}^{\infty} 2v_n \cos[n(\varphi - \psi_r)]\right)$$

$$v_n = \langle \cos[n(\varphi - \psi_r)] \rangle$$

Event plane





The estimated reaction plane is called the event plane.

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

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

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

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