Anomalous chiral transports in heavy-ion collisions

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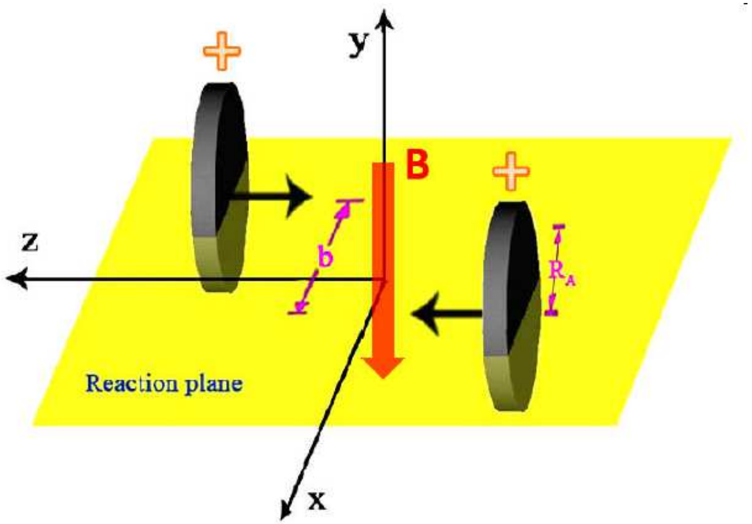
Outline

- Magnetic field and vorticity in heavy-ion collisions
- Chiral anomaly and anomalous chiral transports (ACTs)
- Search of ACTs in heavy-ion collisions
- Isobar collisions
- Summary

Magnetic field and vorticity

Electromagnetic fields in HIC

- **Non-central collision generates magnetic field**



- **How strong is the B field?**

- RHIC Au+Au collision, $Z = 79$, $\sqrt{s} = 200$ GeV ($\Rightarrow v_z \simeq 0.99995c$), impact parameter $b = 5$ fm
- The B field at the colliding time, $t = 0$. Biot-Savart law

$$eB_y \sim 2 \times \gamma \frac{e^2}{4\pi} Z v_z (2/b)^2 \approx 40 m_\pi^2 \sim 10^{19} \text{Gauss}$$

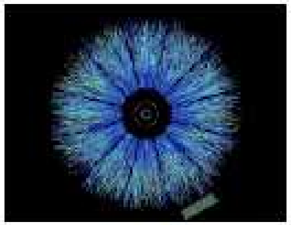
Skokov etal 2009, Voronyuk eatal 2011, Deng and XGH 2012, 2015, … …

Electromagnetic fields in HIC

Comparison of magnetic fields

The Earths magnetic field	0.6 Gauss
A common, hand-held magnet	100 Gauss
The strongest steady magnetic fields achieved so far in the laboratory	4.5×10^5 Gauss
The strongest man-made fields ever achieved, if only briefly	10^7 Gauss
Typical surface, polar magnetic fields of radio pulsars	10^{13} Gauss
Surface field of Magnetars	10^{15} Gauss

http://solomon.as.utexas.edu/~duncan/magnetar.html



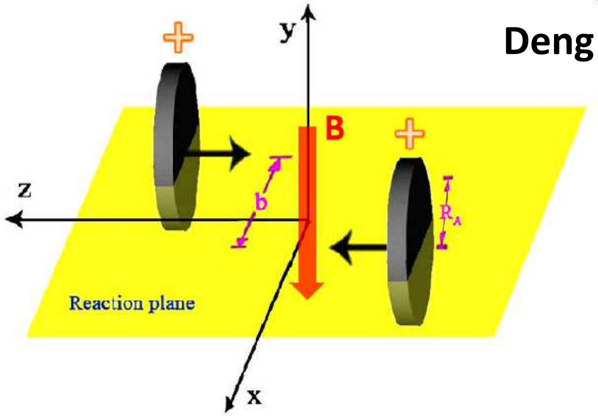
Heavy ion collisions: the strongest magnetic field ever achieved in the laboratory

Off central Gold-Gold Collisions at 100 GeV per nucleon

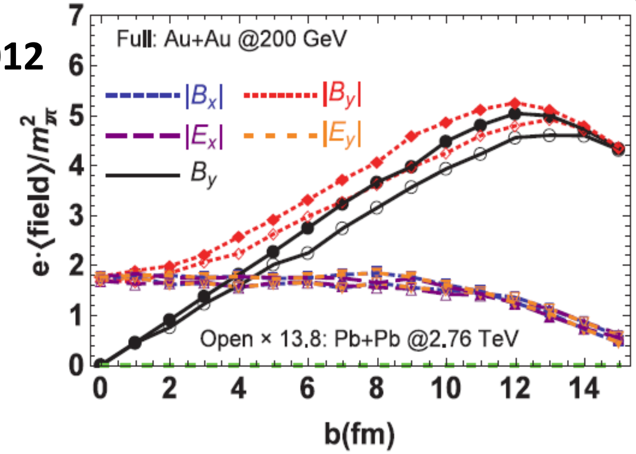
$eB(\tau=0) \sim 10^{19}$ Gauss

Electromagnetic fields in HIC

- More realistic computations of the B fields

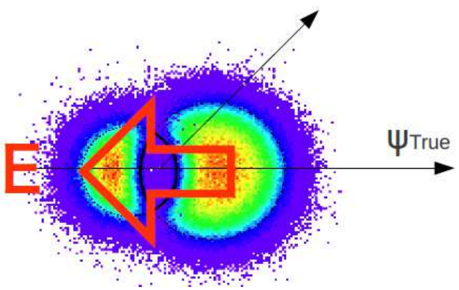


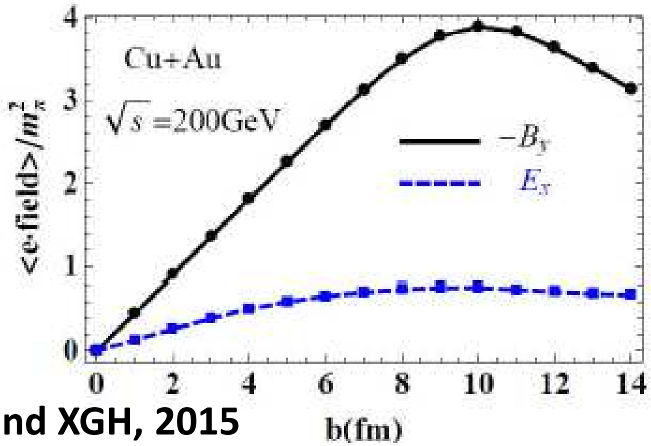
Deng and XGH 2012



- Strongest B fields we have known in current universe: $eB \sim 10^{18}$ G (RHIC)- 10^{20} G (LHC)

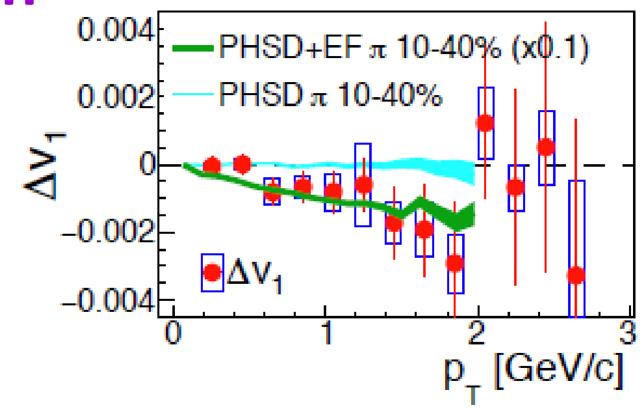
- Strong Electric field in Cu+Au collision





Deng and XGH, 2015

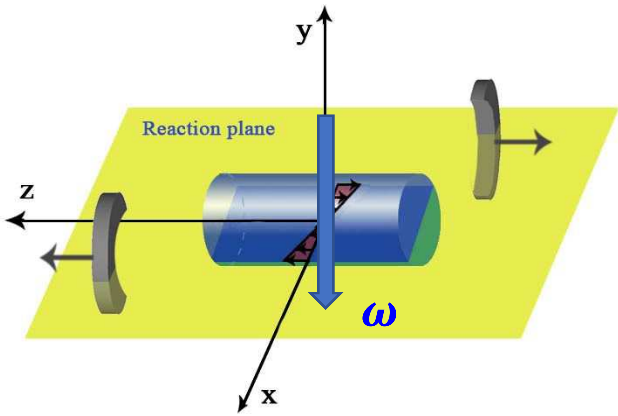
Hirono and Hirano, 2012, STAR 2015



Charge dependence of v1

Flow vorticity in HIC

- **Non-central collision generates flow vorticity**



Finite angular momentum (AM)

⇓

Manifested as flow shear

⇓

Finite vorticity(local rotation)

- **How strong is the vorticity?**

$$\vec{\omega} = \vec{\nabla} \times \vec{v}$$

Total angular momentum: $\boldsymbol{J_0 \sim Ab\sqrt{s}/2}$

The angular momentum: $\boldsymbol{J \sim \int d^3x\, I(x)\, \omega(x)}$

The moment of inertial: $\boldsymbol{I(x) \sim [x^2 - (x \cdot \hat{\omega})^2]\varepsilon(x)}$

Total moment of inertial $\boldsymbol{\int d^3x\, I(x) \sim \sqrt{s} b^2}$, Thus **($b$=10 fm)**

$$\boldsymbol{\omega \sim A/b \sim 10^{24} s^{-1}}$$

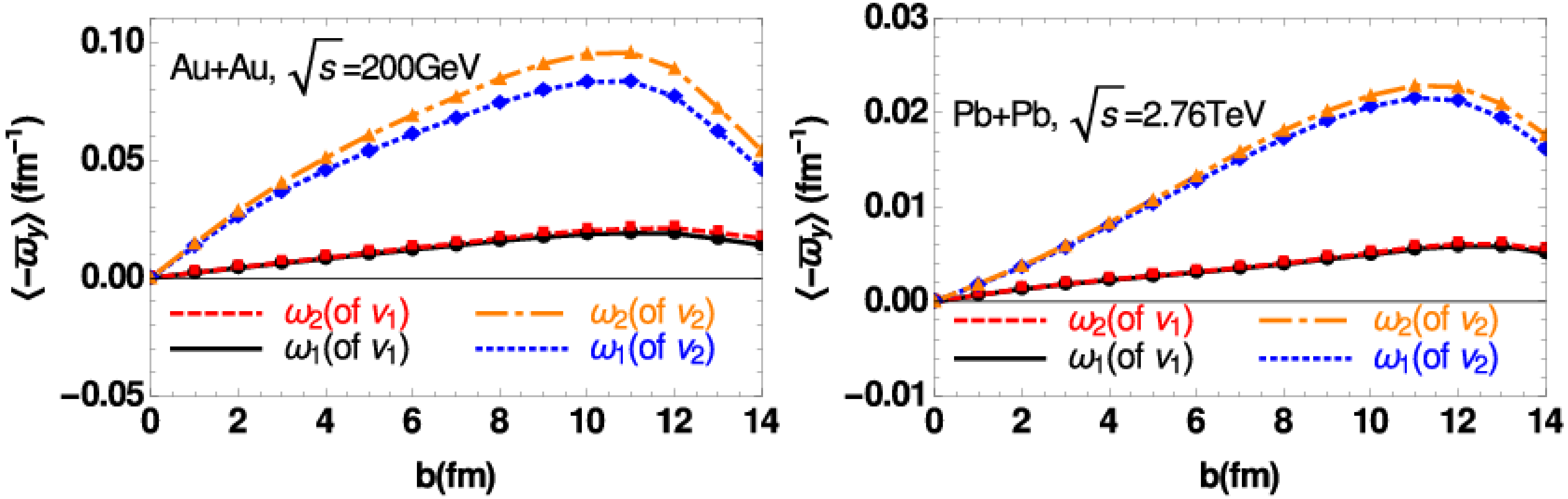
- **A very fast local rotation.**

Fastest man-made rotation via laser light ~ $10^7 s^{-1}$ (Arita etal Nat.Comm. 2013)

Flow vorticity in HIC

- More realistic numerical simulations

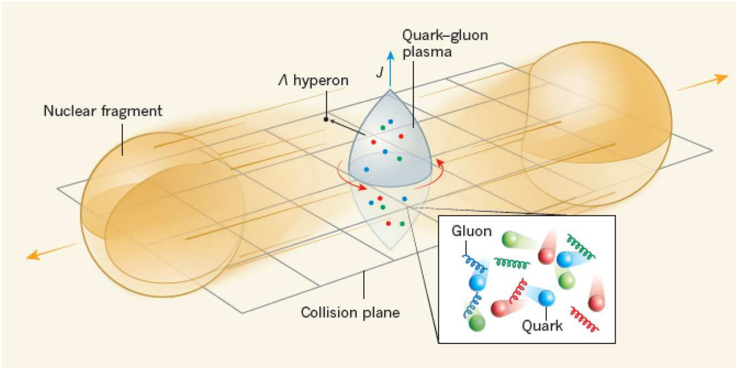
Deng and XGH 2016, Jiang, Lin, Liao 2016



- Vorticity in Au+Au@RHIC at $b = 10$ fm is $10^{21}s^{-1}$
- At RHIC, T~300 MeV, $T\omega \sim 10^4 \text{MeV}^2$ which is comparable to $eB \sim 10^4 \text{MeV}^2$. But at LHC, $T\omega$ is much smaller than eB

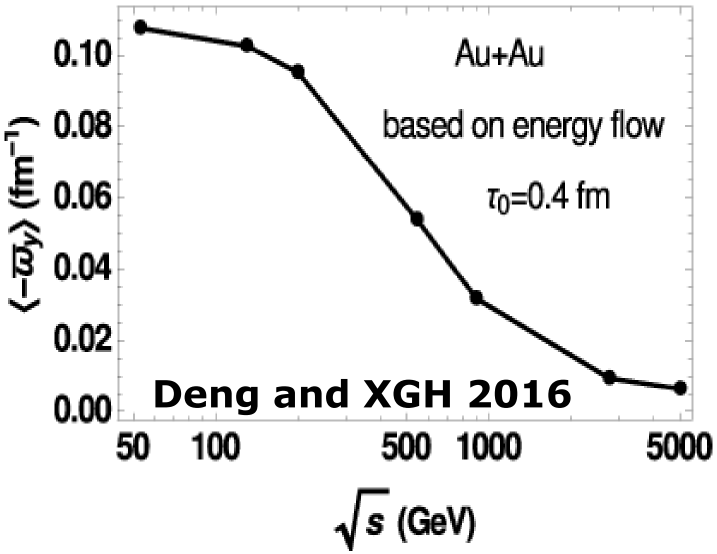
Flow vorticity in HIC

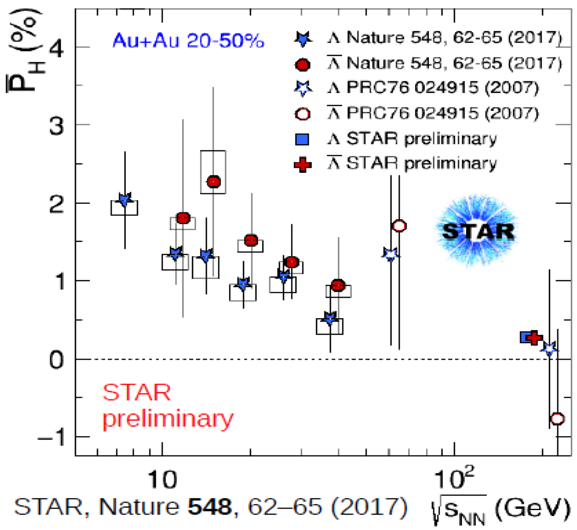
- **Experimental measurement of vorticity: Λ polarization**



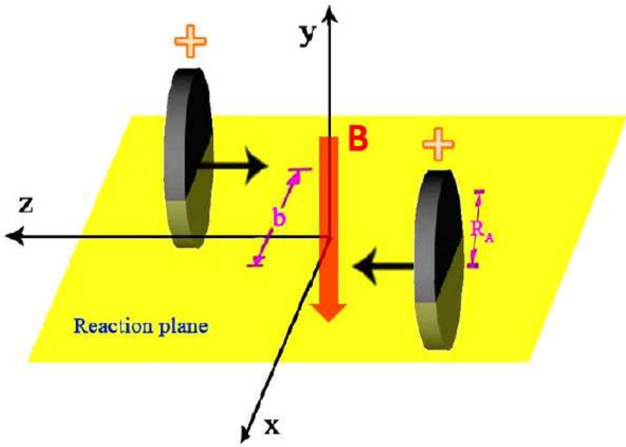
Global spin polarization of Λ hyperon due to spin-vorticity coupling
(Liang, Wang 2005)

- **Averaged $\omega \approx (9 \pm 1) \times 10^{21} s^{-1}$ "Most vortical fluid!"**

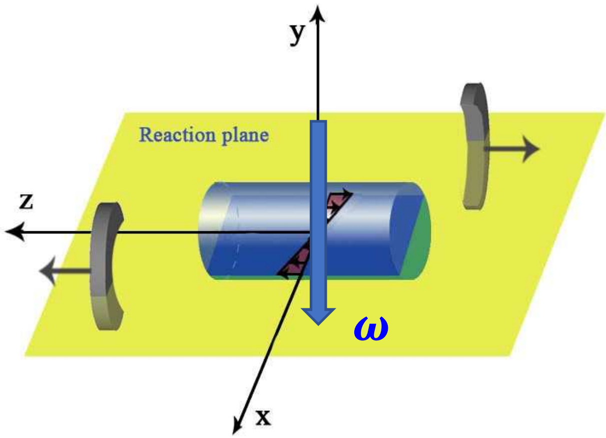




- **Heavy-ion collisions can generate**



Strongest EM fields



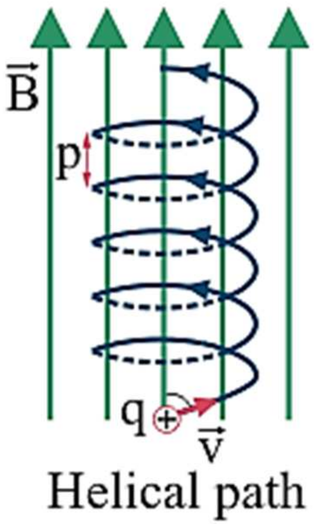
Largest local vorticity

What are the novel effects to the QGP?
Anomalous chiral transports

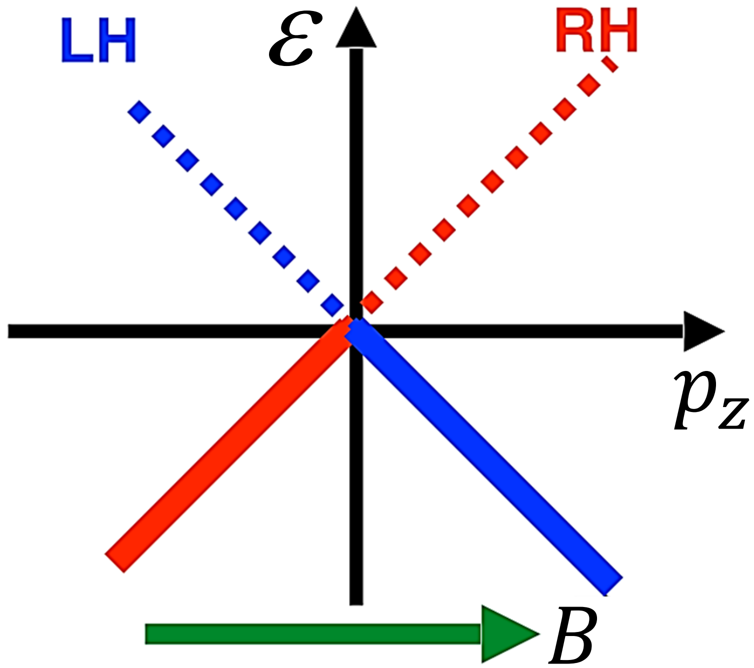
Anomalous chiral transports (ACTs)

Chiral anomaly

- **Lowest Landau level of massless fermion in B**



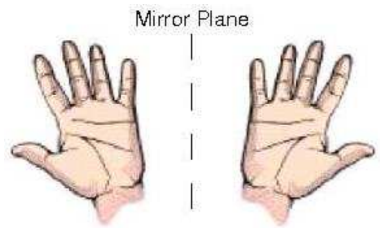
$n = 0$



$$E_n^2 = p_z^2 + 2n\boldsymbol{e}B$$

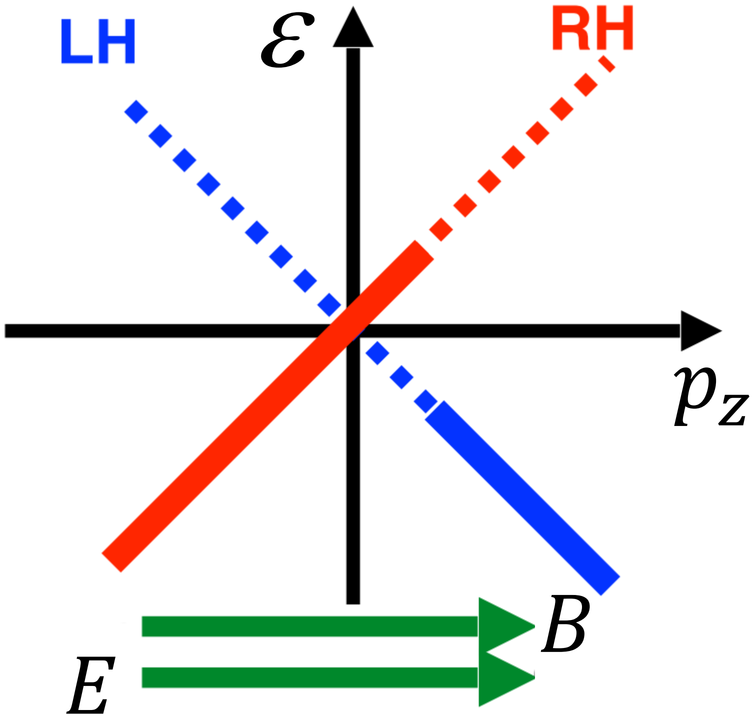
- **Two conserved currents with left- and right-chirality**

$J_R^\mu = \bar{\psi}_R \gamma^\mu \psi_R$ **and** $J_L^\mu = \bar{\psi}_L \gamma^\mu \psi_L$



Chiral anomaly

- Lowest Landau level of massless fermion



- One conserved current

$$J_V^\mu = J_R^\mu + J_L^\mu = \bar{\psi}\gamma^\mu\psi$$

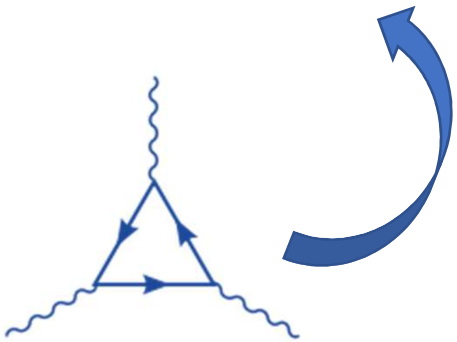
$$J_A^\mu = J_R^\mu - J_L^\mu = \bar{\psi}\gamma^\mu\gamma_5\psi$$

is no longer conserved:

- $N_{R/L} = V \frac{p_F^{R/L}}{2\pi}\frac{eB}{2\pi}$
- $\frac{d}{dt}N_A = \frac{d}{dt}(N_R - N_L)$

$$= V\frac{\dot{p}_F^R - \dot{p}_F^L}{2\pi}\frac{eB}{2\pi} = V\frac{eE}{\pi}\frac{eB}{2\pi}$$

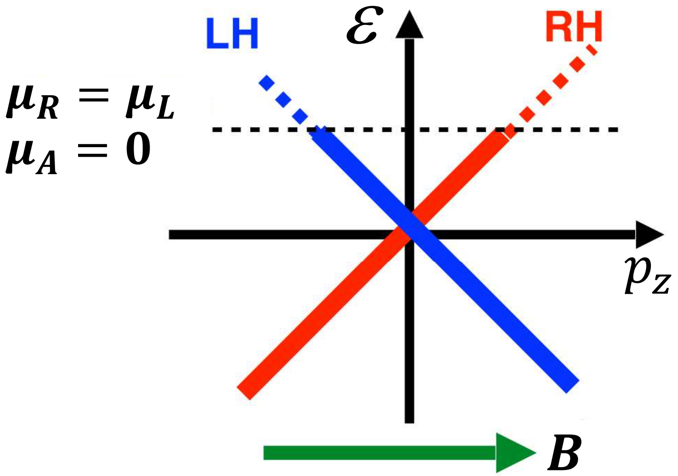
$$\Rightarrow \partial_\mu J_A^\mu = \frac{e^2}{2\pi^2}\boldsymbol{E}\cdot\boldsymbol{B}$$

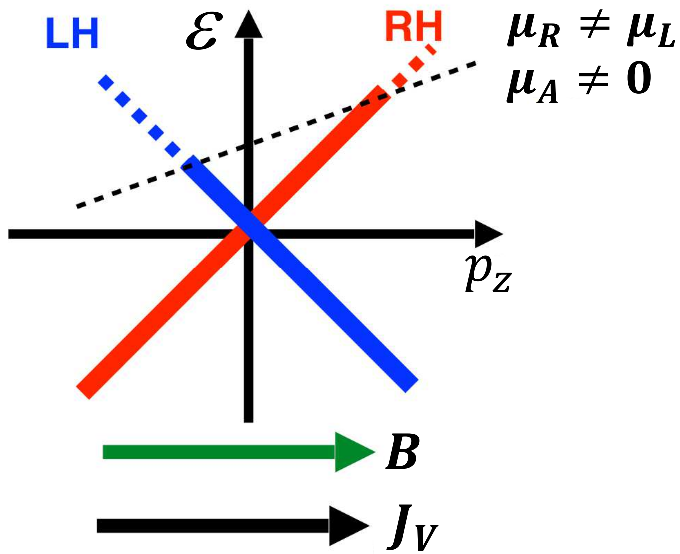


Adler 1969, Bell and Jackiw 1969

Chiral magnetic effect (CME)

- Remove the E field





$$J_R = en_R$$

$$J_L = -en_L$$

$$n_{R/L} \equiv \frac{d^3N_{R/L}}{dxdydz} = \frac{eB}{2\pi}\frac{p_F^{R/L}}{2\pi}$$

$$J_V = J_R + J_L = \frac{e^2B}{4\pi^2}\left(p_F^R - p_F^L\right)$$

$$= \frac{e^2B}{2\pi^2}\mu_A$$

CME current

Kharzeev et al 2004-2008,

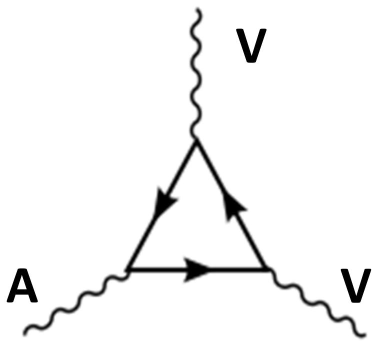
Vilenkin 1980, ……

Chiral magnetic effect (CME)

- CME: vector current induced by B in matter with μ_A

$$J_V = \frac{e^2 \mu_A}{2\pi^2} B$$

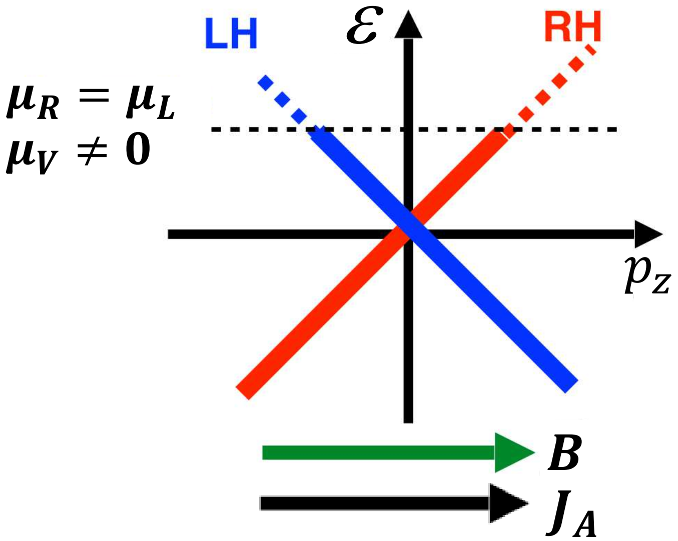
- Macroscopic quantum phenomenon
- P- and CP-odd transport
- Time-reversal even, no dissipation
- Fixed by anomaly coefficient, universal

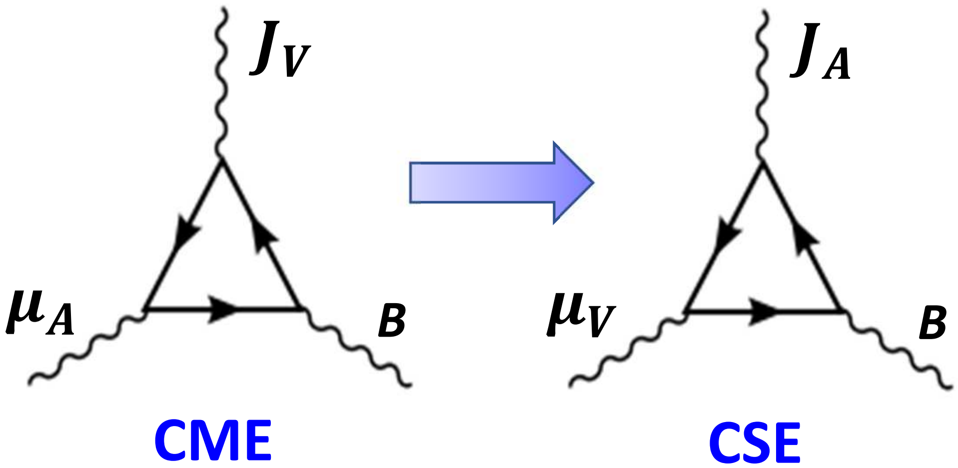


To realize CME, we need:
environmental parity violation (μ_A) and external magnetic field (B)

Chiral separation effect (CSE)

- A dual effect to the CME: axial current induced by B in matter with μ_V





$$J_R = en_R$$

$$J_L = -en_L$$

$$n_{R/L} \equiv \frac{d^3 N_{R/L}}{dxdydz} = \frac{eB}{2\pi}\frac{p_F^{R/L}}{2\pi}$$

$$J_A = J_R - J_L = \frac{e^2 B}{4\pi^2}(p_F^R + p_F^L)$$

$$= \frac{e^2 B}{2\pi^2}\mu_V$$

CSE current

Son and Zhitnitsky 2004 ……

Chiral vortical effect (CVE)

- **Charged particle in magnetic field and in rotation**

In magnetic field, Lorentz force:

$$\boldsymbol{F} = e(\dot{\boldsymbol{x}} \times \boldsymbol{B})$$

In rotating frame, Coriolis force:

$$\boldsymbol{F} = 2\varepsilon(\dot{\boldsymbol{x}} \times \boldsymbol{\omega}) + O(\omega^2)$$

Larmor theorem: $e\boldsymbol{B} \sim 2\varepsilon\boldsymbol{\omega}$

- **"Lowest Landau level" (omit centrifugal force $O(\omega^2)$)**

$$J_R = en_R$$

$$J_L = -en_L$$

$$n_{R/L} = \frac{p_F^{R/L}\omega}{2\pi}\frac{p_F^{R/L}}{2\pi}$$

$$J_V = \frac{e\omega}{4\pi^2}\left((p_F^R)^2 - (p_F^L)^2\right) = \frac{e\omega}{\pi^2}\mu_V\mu_A$$

$$J_A = \frac{e\omega}{4\pi^2}\left((p_F^R)^2 + (p_F^L)^2\right) = \frac{e\omega}{2\pi^2}(\mu_V^2 + \mu_A^2)$$

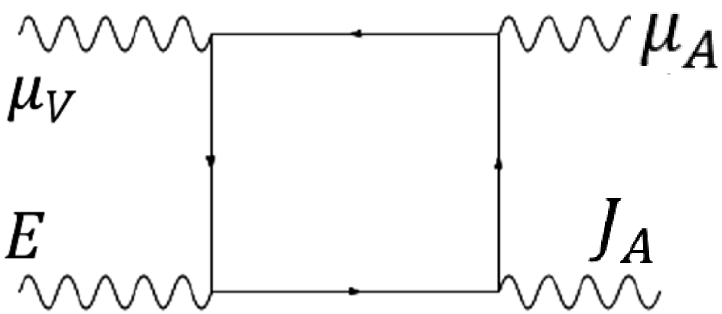
CVE currents

More rigorous calculation shows a $(T^2/6)e\boldsymbol{\omega}$ term in $\boldsymbol{J}_A$ related to gravitational anomaly.
(Landsteiner etal 2011)

Erdmenger etal 2008, Banerjee etal 2008, Son and Surowka 2009 ……

Chiral electric separation effect (CESE)

- **Electric field induced anomalous transport**



$$\mathbf{J}_A \approx 14.5163\,\mathrm{Tr}_f(Q_e Q_A)\frac{\mu_V \mu_A}{T^2}\frac{e^2 T}{g^4 \ln(1/g)}\mathbf{E}$$

- **P-odd, C-odd, T-odd transport (may be dissipative)**
- **Non-universal (receive perturbative correction)**

XGH and Liao 2013, Jiang, XGH, Liao 2015 … …

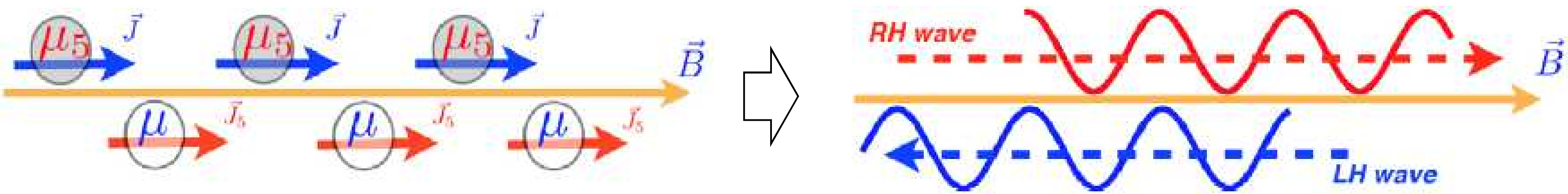
Chiral magnetic wave

Look at the CME and CSE

$$J_V = \frac{e^2 \mu_A}{2\pi^2} B \qquad\qquad J_A = \frac{e^2 \mu_V}{2\pi^2} B$$

CME + CSE give gapless wave modes: chiral magnetic wave
(Kharzeev and Yee 2010)

$$v_R = \frac{N_c e}{4\pi^2} \frac{\partial \mu_R}{\partial n_R}$$

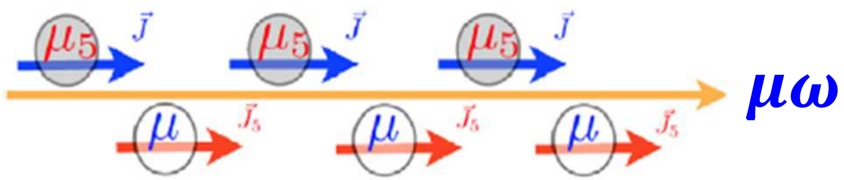


$$v_L = -\frac{N_c e}{4\pi^2} \frac{\partial \mu_L}{\partial n_L}$$

Chiral vortical wave

The vortical analogue of chiral magnetic wave

$$\boldsymbol{J}_A = \frac{T^2}{6} + \frac{\mu_V^2 + \mu_A^2}{2\pi^2}\boldsymbol{\omega}, \qquad \boldsymbol{J}_V = \frac{1}{\pi^2}\mu_V\mu_A\boldsymbol{\omega},$$



- To reveal its dispersion we use continuity eq.

$$\partial_t n_{L,R} + \nabla \cdot \vec{J}_{L,R} = 0$$

- Substitute CVE currents. Obtain Burgers wave equation which is linearized to normal wave equation

$$\partial_t n_{L,R} = \pm\frac{\omega\alpha^2}{\pi^2}\partial_x(n_{L,R}^2) \Longrightarrow \pm\boxed{\frac{2\omega\alpha^2}{\pi^2}}n_0\partial_x(n_{L,R})$$

$$\alpha = \frac{\partial\mu}{\partial n}$$ ~ inverse baryon susceptiblity

CVW velocity

Jiang, XGH, Liao 2015

Table of anomalous chiral transports

- **Transport phenomena closely related to chirality and quantum anomalies.**

	$\boldsymbol{E}$	$\boldsymbol{B}$	$\boldsymbol{\omega}$
$\boldsymbol{J}_V$	σ Ohm's law	$\frac{e^2}{2\pi^2}\mu_A$ Chiral magnetic effect	$\frac{e}{\pi^2}\mu_V\mu_A$ Vector chiral vortical effect
$\boldsymbol{J}_A$	$\propto \frac{\mu_V\mu_A}{T^2}\sigma$ Chiral electric separation effect	$\frac{e^2}{2\pi^2}\mu_V$ Chiral separation effect	$e(\frac{T^2}{6}+\frac{\mu_V^2+\mu_A^2}{2\pi^2})$ Axial chiral vortical effect

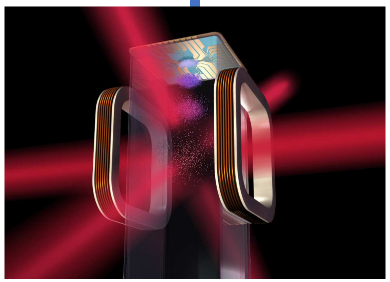
And the collective waves (chiral magnetic wave, chiral vortical wave, chiral electric wave, etc)

Where are anomalous chiral transports?

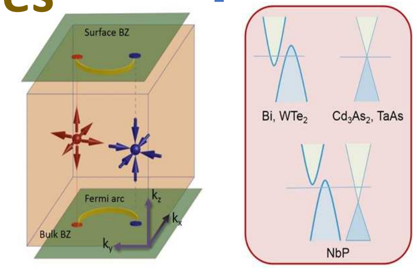
- Universal phenomena that **may** happen across a very broad hierarchy of scales.

$10^{-10}K$ | $1-10^{2}K$ | $10^{10}K$ | $10^{12}K$

Temperature



Cold atomic gases



Weyl/Dirac semimetals

Supernovae

Heavy-ion collisions

Electromagnetic force

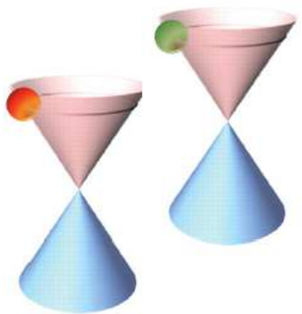
Electroweak force

Strong force

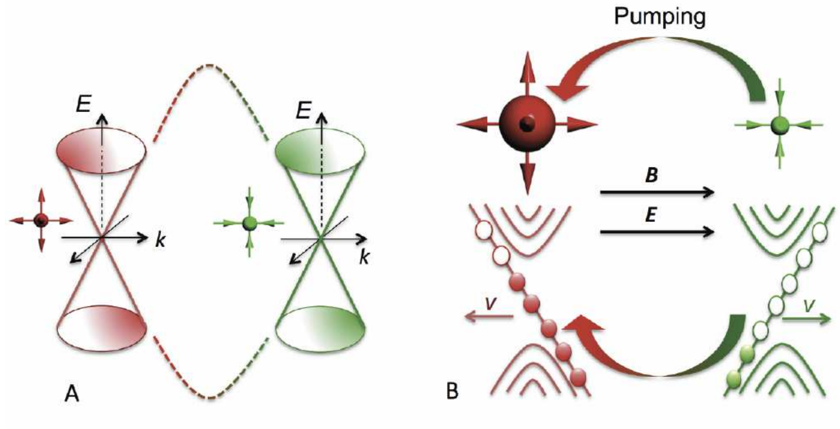
CME on desktop

- **Chiral fermions in 3D semimetals**

Weyl semimetal
(non-degenerated bands)

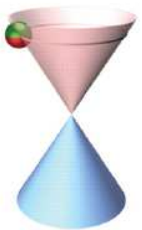


TaAs
NbAs
NbP
TaP

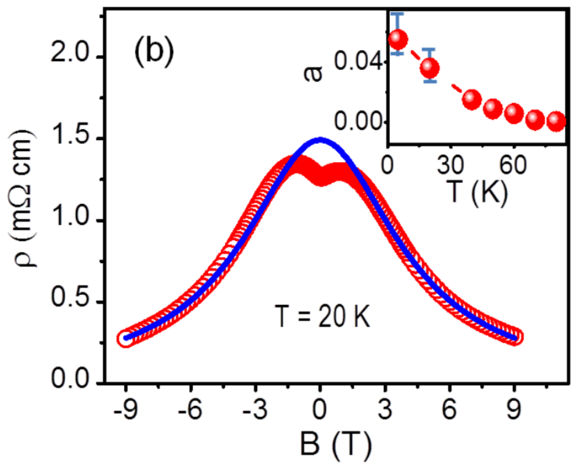


$$\partial_\mu J_5^\mu = C_A \vec{E} \cdot \vec{B}$$

Dirac semimetal
(doubly degenerated bands)



$ZrTe_5$
Na_3Bi,
Cd_3As_2



$$J^i_{\rm CME} = \sigma^{ik}_{\rm CME}\; E^k$$

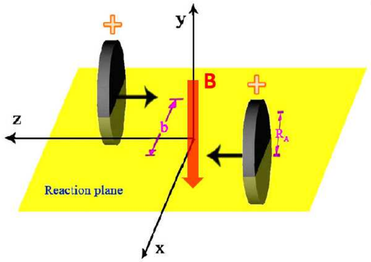
$$\sigma^{zz}_{\rm CME} = \frac{e^2}{\pi\hbar}\,\frac{3}{8}\frac{e^2}{\hbar c}\,\frac{v^3}{\pi^3}\,\frac{\tau_V}{T^2+\frac{\mu^2}{\pi^2}}\,B^2$$

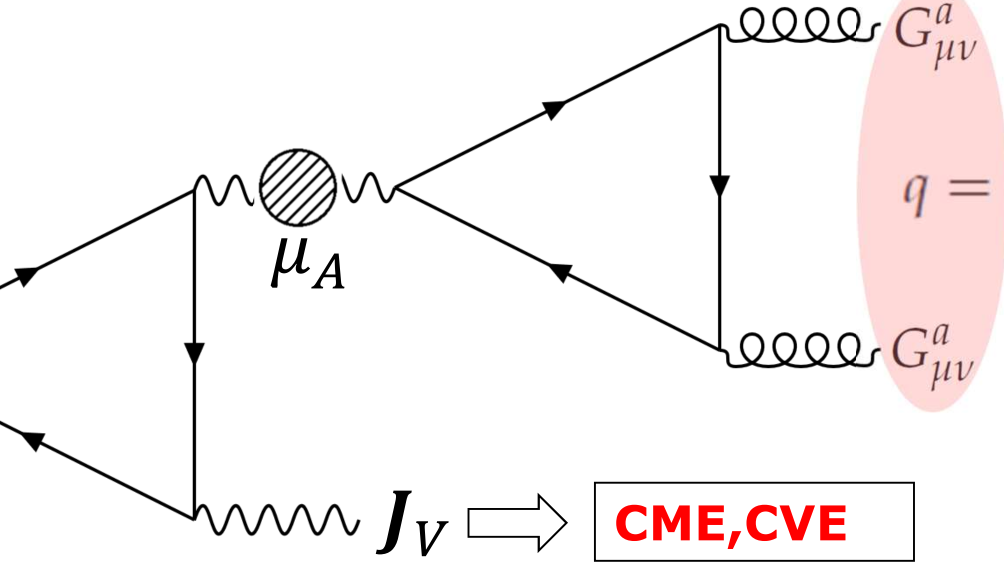
Li et al 2015, … …

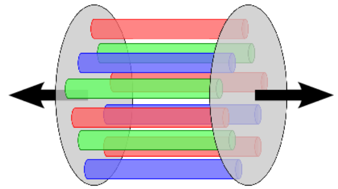
ACTs in heavy ion collisions

Chirality generation and CME,CVE

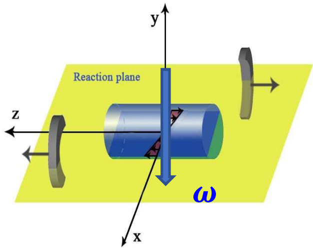
QCD triangle anomaly





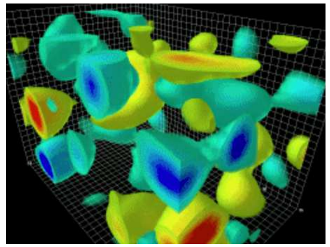


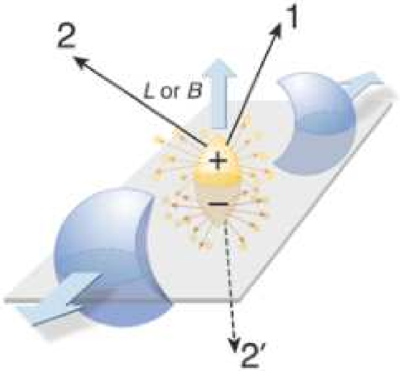
$$q = \frac{g^2}{32\pi^2}\int d^4x\, G^a_{\mu\nu}\tilde{G}^{\mu\nu}_a$$



CME,CVE

QED triangle anomaly



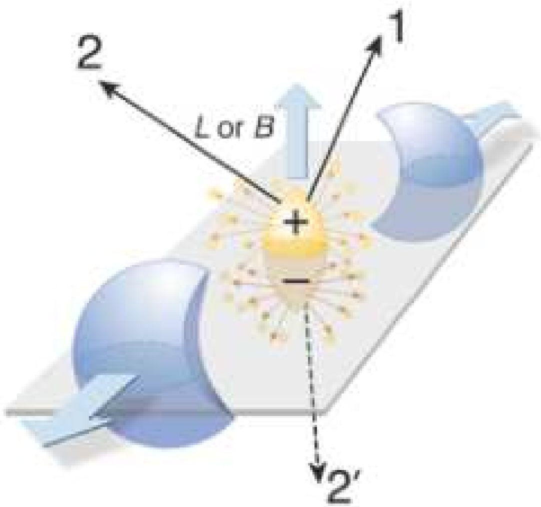


A probe of nontrivial topology of QCD using B field and vorticity!

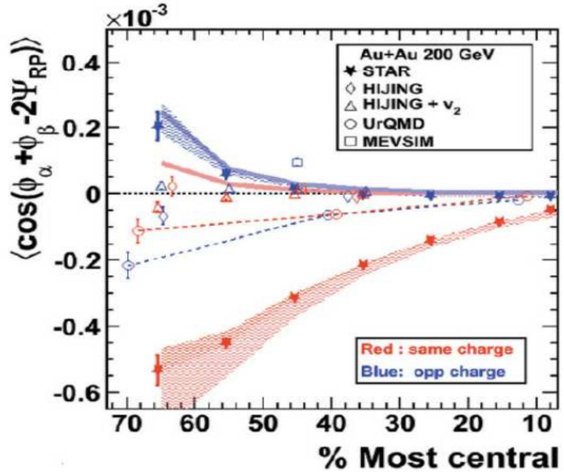
Initial state topological fluctuations

Experimental test of CME

Event-by-event charge separation wrt. reaction plane

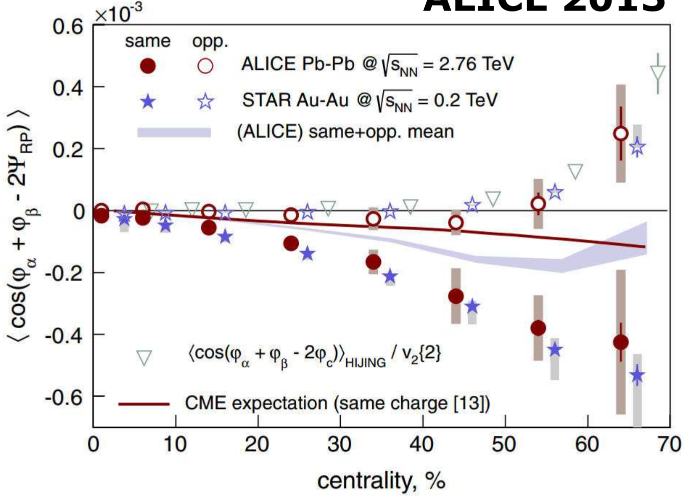


The observable:
The gamma correlator (Voloshin 2004)

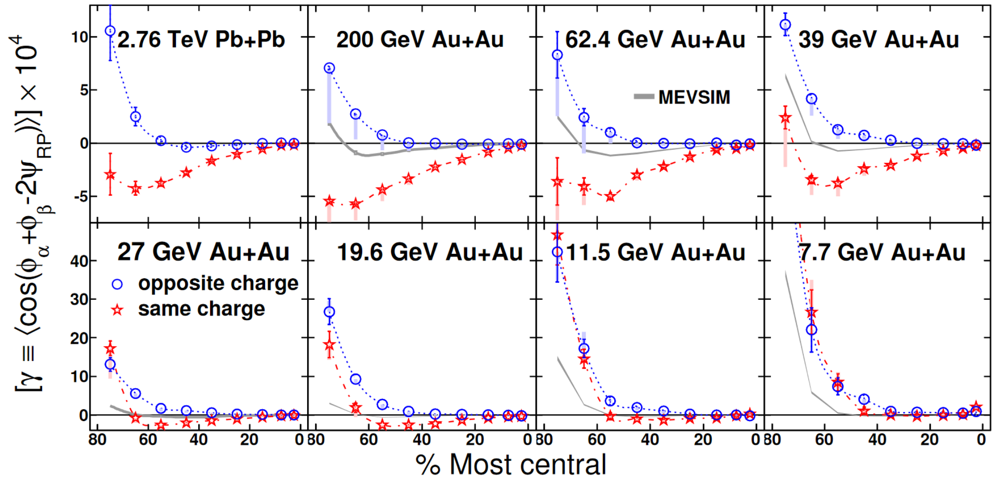


STAR 2009

ALICE 2013

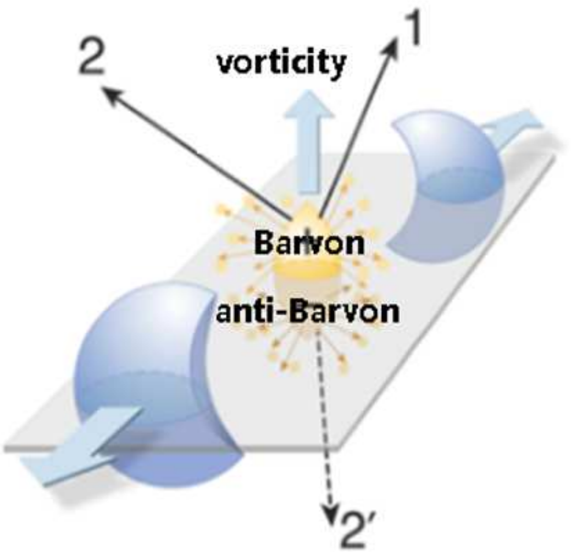


STAR 2014

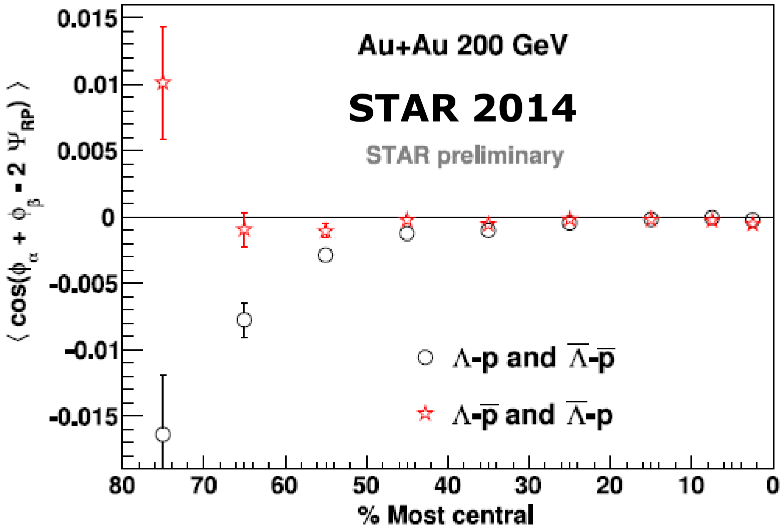


Experimental test of CVE

Event-by-event baryon separation wrt. reaction plane



The vortical gamma correlator

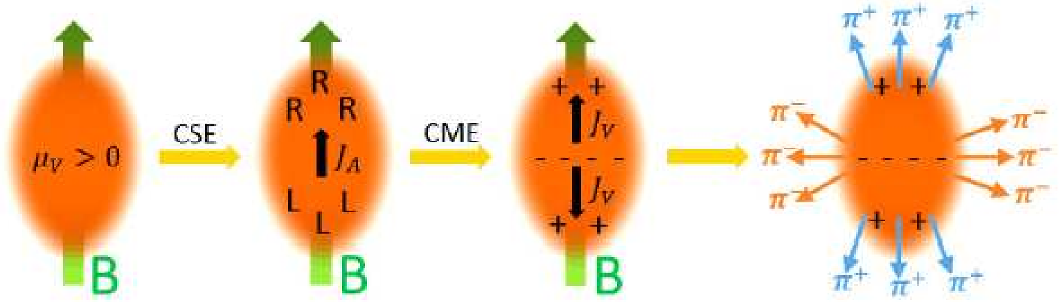


- **Positive opposite-sign correlation, negative same-sign correlation**
- **Increase with centrality = vorticity increases with centrality**

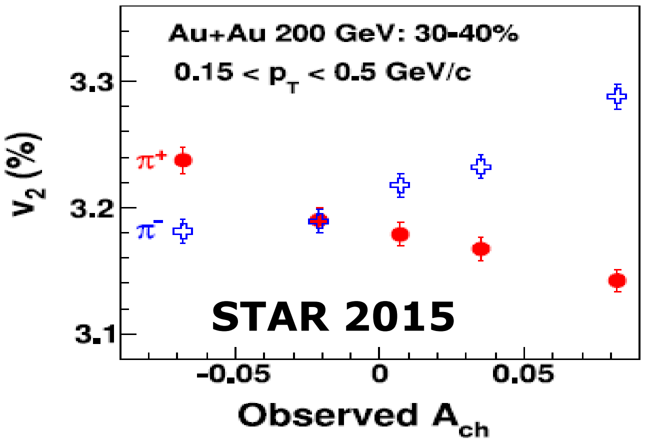
Experimental test of CMW

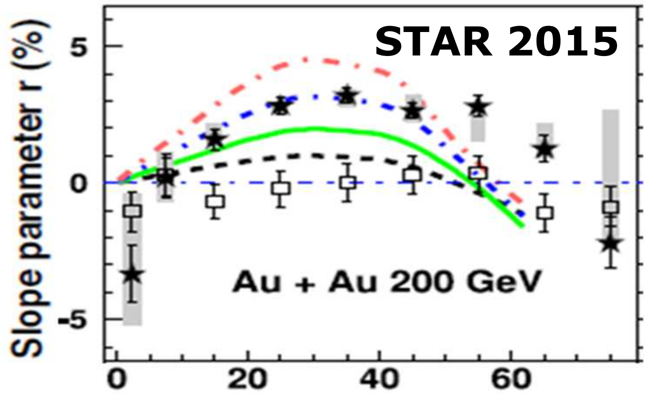
Phenomenology of CMW in heavy-ion collisions:
Elliptic flow splitting of charged pions **(Burnier, Kharzeev, Liao, Yee 2011)**

Intuitive picture



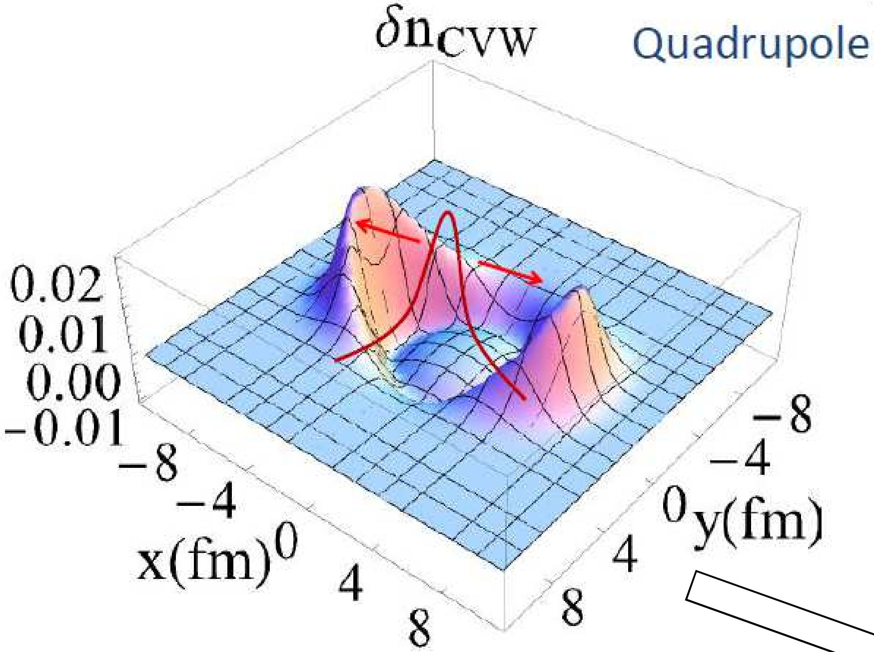
- CMW $\Rightarrow$ $v_2(\pi^-) \neq v_2(\pi^+)$: $v_2(\pi^-) - v_2(\pi^+) \approx rA_\pm$: linear approx. in net charge asymmetry $A_\pm = (N_+ - N_-)/(N_+ + N_-)$



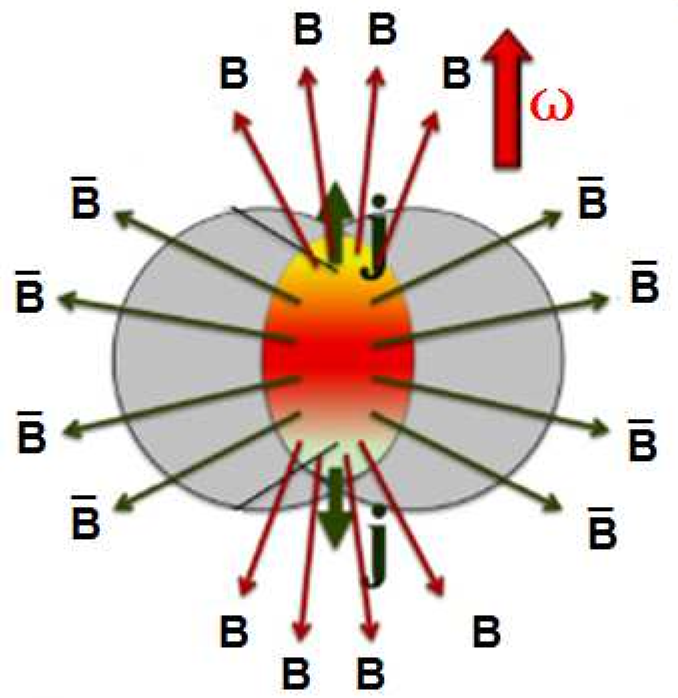


Potential experimental test of CVW

Experimental implication: baryon charge quadrupole



•More baryon charges at the tips of the fireball, more antibaryon charges at the center

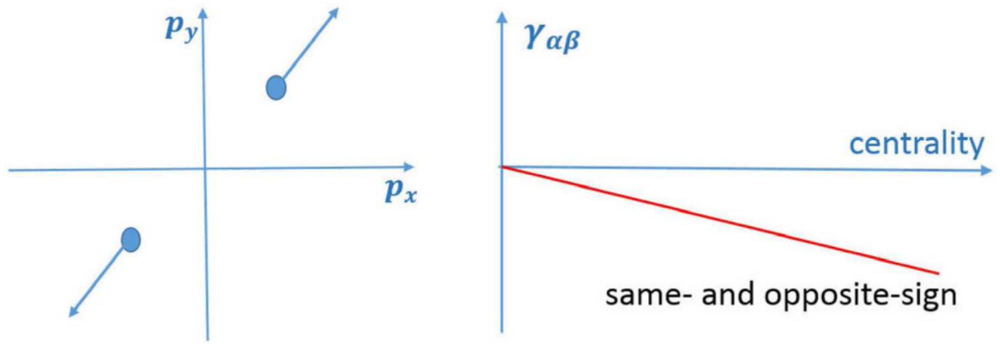


•Stronger in-plane radial expansion lets antibaryons get larger elliptic flow than baryons

Back-ground contributions to CME

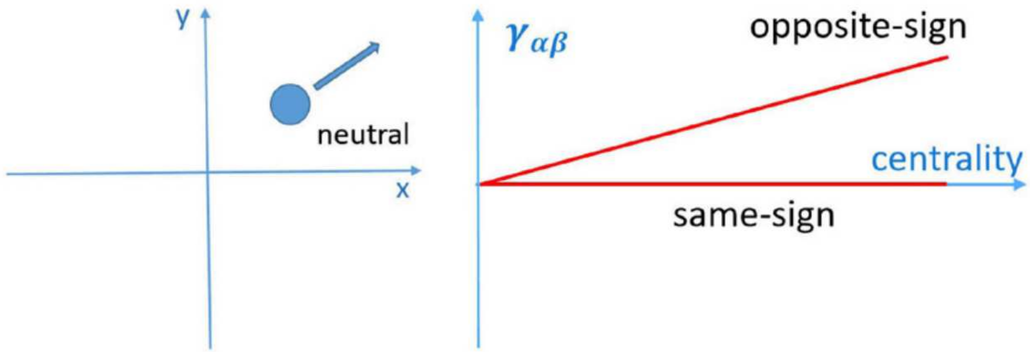
Back-ground contributions to gamma correlator

Transverse momentum conservation **(Pratt 2010; Liao, Bzdak,Koch 2011):**



- **Charge blind**
- $\gamma \propto -v_2/N$
- **Can be subtracted in**
  $\Delta\gamma = \gamma_{\rm OS} - \gamma_{\rm SS}$

Local charge conservation **(Pratt, Schlichting 2011) or neutral resonance decay (Wang 2010) :**



$\gamma_{\rm OS} \propto v_2/N, \gamma_{\rm SS} \sim 0$

Main challenge: how to separate the background effects?

Theoretical uncertainties

Quantify the CME signal from theoretical calculations. But now there are still many uncertainties.

1) The time evolution of the magnetic field.
(coupled Maxwell + hydro or kinetic equations)

2) Modeling the production of initial axial charge.
(Real time simulation of sphaleron transition)

3) Pre-hydro evolution of CME, very early stage.
(CME current far from equilibrium)

4) Frequency and momentum dependent CME coff.
(The B field is neither static nor homogeneous)

5) Finite mass effect, finite response time, high-order corrections.
(New theoretical calculations)

6) Modeling background contributions, new observables.
(LCC, Resonance decays, ……)

Challenges but also opportunities for theorists!

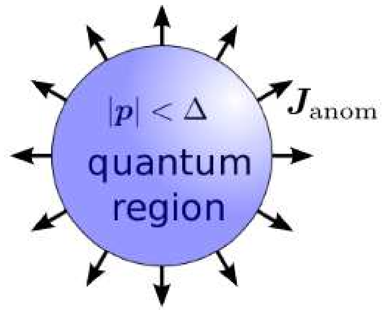
Chiral kinetic theory

- **Kinetic theory with chiral anomaly encoded**

$$\frac{\partial f}{\partial t} + \frac{\partial f}{\partial \boldsymbol{x}}\dot{\boldsymbol{x}} + \frac{\partial f}{\partial \boldsymbol{p}}\dot{\boldsymbol{p}} = C[f]$$

with

$$\dot{\boldsymbol{x}} - \hat{\boldsymbol{p}} + \boldsymbol{b} \times \dot{\boldsymbol{p}} = 0$$
$$\dot{\boldsymbol{p}} + \boldsymbol{B} \times \dot{\boldsymbol{x}} = 0$$



and the Berry monopole

$$\boldsymbol{b} = \frac{\boldsymbol{p}}{2|\boldsymbol{p}|^3}.$$

phase space is $\sqrt{G}$ where $G = (1 + \boldsymbol{b} \cdot \boldsymbol{B})^2$

- **Provide a basis for quantitative description of ACTs in the early and parton stages of HICs**
- **Accurate at $\hbar$ order and valid for weak fields**
- **Fast developing (higher order, strong fields, rotation, …)**

Son-Yamamoto 2012, Stephanov-Yin 2012, Gao-Liang-Pu-Wang-Wang 2012 … …

Anomalous hydrodynamics

- Hydrodynamics with anomalous currents

$$\partial_\mu T^{\mu\nu} = eF^{\nu}{}_{\lambda} j_e^\lambda, \quad \partial_\mu j_e^\mu = 0, \quad \partial_\mu j_5^\mu = -CE^\mu B_\mu$$

with

$$j_e^\mu = nu^\mu + \kappa_B B^\mu + \kappa_\omega \omega^\mu$$
$$j_5^\mu = n_5 u^\mu + \xi_B B^\mu + \xi_\omega \omega^\mu$$

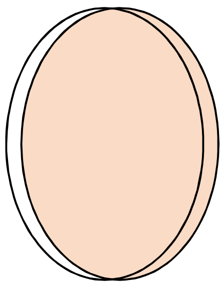
- Anomalous coefficients are self-determined via second law of thermodynamics (Son Surowka 2009)
- Provide a basis for quantitative description of ACTs in the hydro stage of HICs
- Fast developing
- related developments: hydrodynamics with strong magnetic field, with spin d.o.f, … …

Hirono-Hirano-Kharzeev 2014, Shi-Jiang-Liao 2017, Guo-XGH-Deng-Hirono-Kharzeev 2017, … …

Experimental methods

Recall the challenge: How to separate the CME signal from the elliptic flow induced backgrounds?

Way 1: Fix the magnetic field, but vary the flow: central U + U collisions or event shape engineering

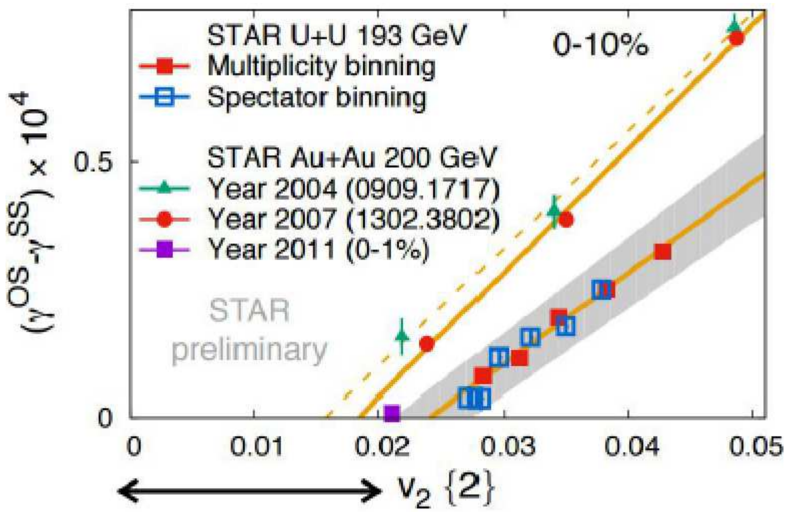


U nucleus is deformed,

Very cental body-body:

B=0 while $v_2 \neq 0$

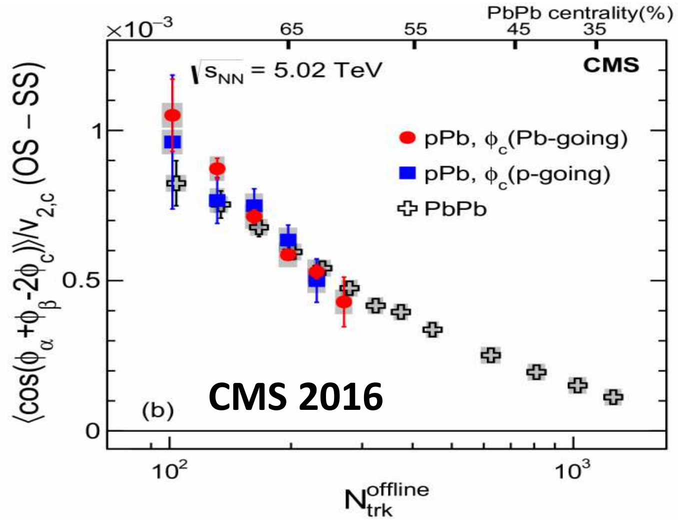
Voloshin 2010

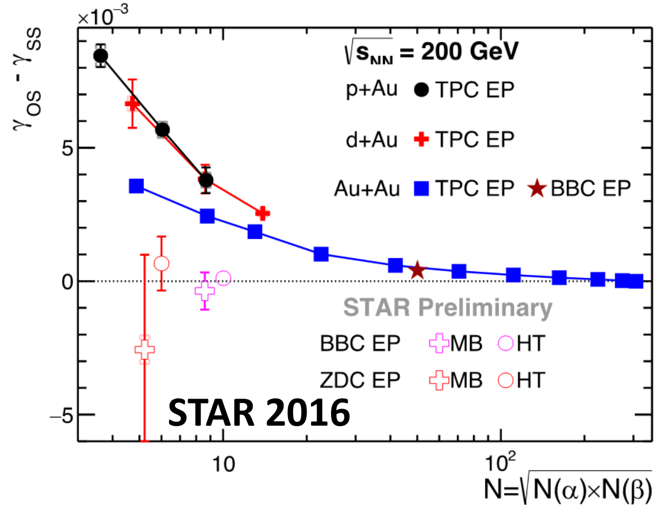


Wang 2012
Tribedy 2017

Experimental methods

Way 1.1: Turn off (?) the magnetic field: high multiplicity p+A, d+A



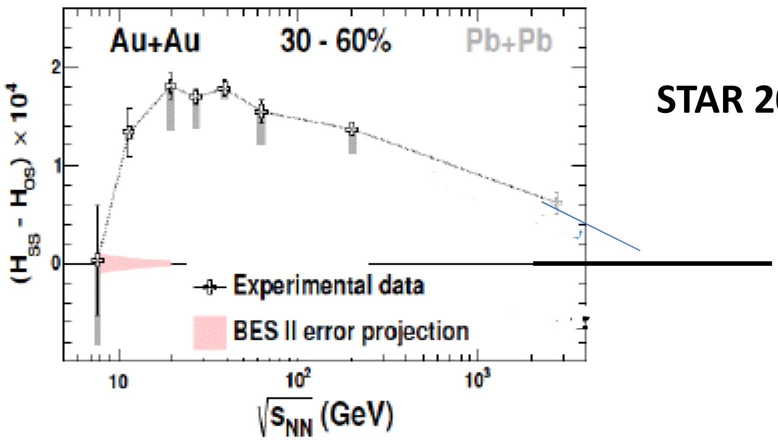


γ in p+Pb ~ in Pb+Pb at LHC

Δγ in p+Au and d+Au zero at RHIC

High energy: Purely background? (B lifetime too short; no correlation to reaction plane)

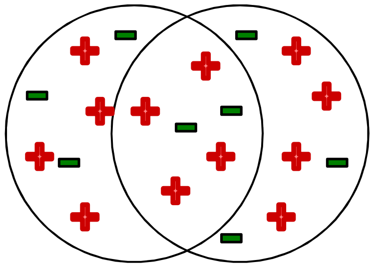
Strong energy dependence of the signal



STAR 2014

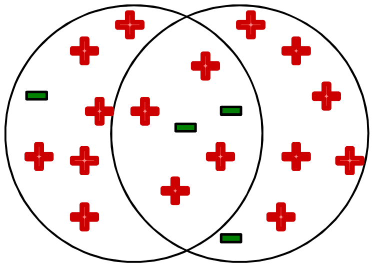
Experimental methods

Way 2: **Fix the flow, but vary the magnetic field: isobar collisions**



$^{96}_{40}Zr + ^{96}_{40}Zr$

Vs



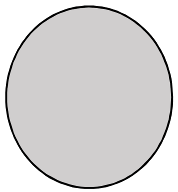
$^{96}_{44}Ru + ^{96}_{44}Ru$

At same energy, same centrality, they would have equal elliptic flow but 10% difference in magnetic field.

The isobar collision

Isobar collisions

Nucleus shape, Wood-Saxon distribution



$$\rho(r,\theta) = \frac{\rho_0}{1+\exp\left[(r - R_0 - \beta_2 R_0 Y_2^0(\theta))/a\right]}$$

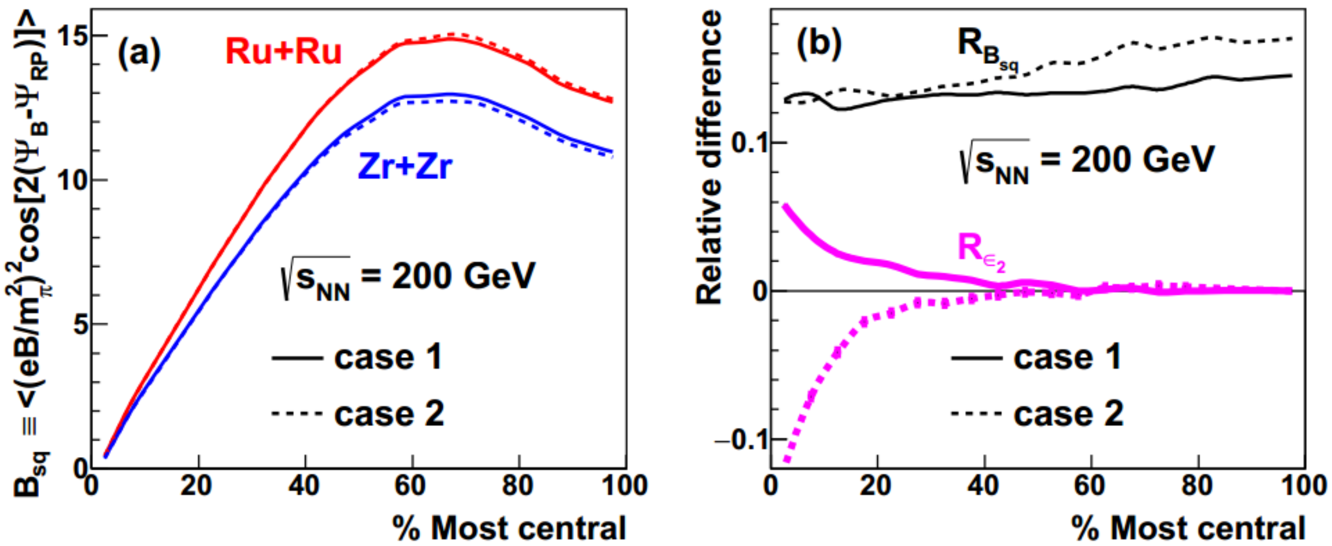
Current experimental data for the parameters:

Case 1: e-A scattering experiments **(nucl. Data tab. 2001)**
Case 2: comprehensive model deductions **(nucl. Data tab. 2001)**

		R_0(fm)	a(fm)	β_2
Case 1	Ru	5.085	0.46	0.158
	Zr	5.02	0.46	0.08
Case 2	Ru	5.085	0.46	0.053
	Zr	5.02	0.46	0.217

Isobar collisions

Initial magnetic field and initial eccentricity



Deng, XGH, Ma, and Wang, 2016

B_{sq} **quantifies magnetic-field fluctuation** (Blozynski, XGH, Zhang, and Liao, 2013)

R is the relative difference: 2(RuRu-ZrZr)/(RuRu+ZrZr)

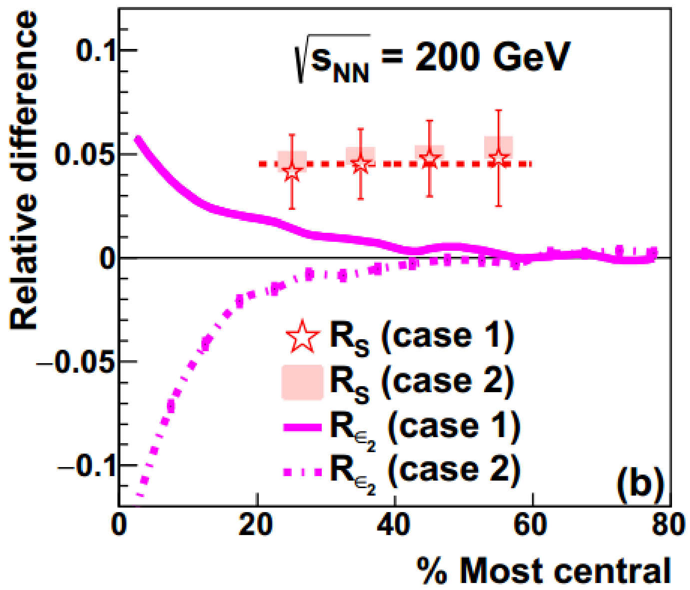
Centrality 20-60%: sizable difference in B ($R_{B_{sq}} \sim 10-20\%$) but small difference in eccentricity ($R_{\varepsilon_2} < 2\%$)

Isobar collisions

Gamma correlator $S \equiv N_{\text{part}} \Delta\gamma$, here N_{part} compensates dilution effect, as both CME and v2 background $\propto 1/N_{\text{part}}$

As $R_{B_{sq}}$ and R_{ε_2} are small, we do perturbative expansion:

$R_S = (1 - bg) R_{B_{sq}} + bg \cdot R_{\epsilon_2}$ **with bg the background level**



Deng, XGH, Ma, and Wang, 2016

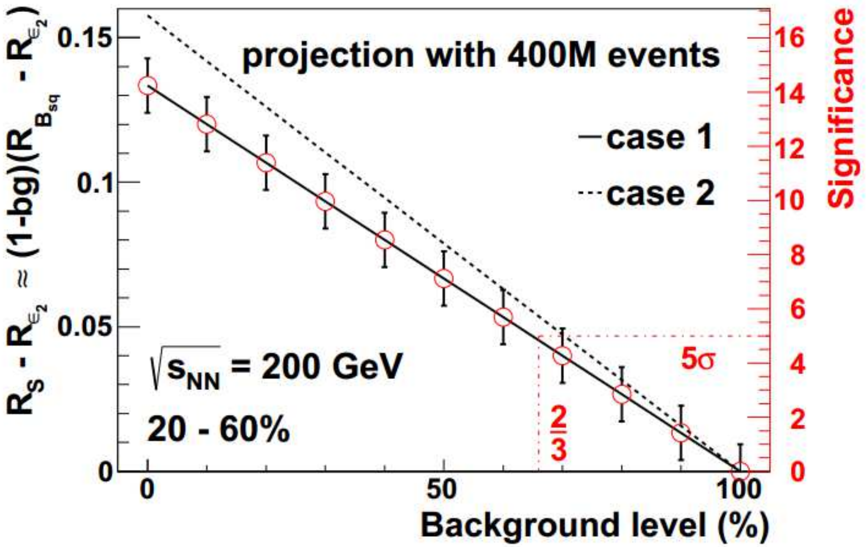
bg=2/3
400M events
5σ signal

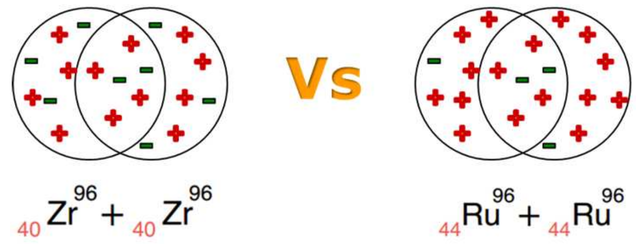
If bg=4/5
1.2B events
5σ signal

Centrality 20-60%: clear difference between CME=1/3 and CME=0 if 400M events.
Very promising to disentangle CME from v2 backgrounds

Isobar collisions

May also determine the background level





First run: 2018 @ RHIC
STAR BUR for 7 weeks

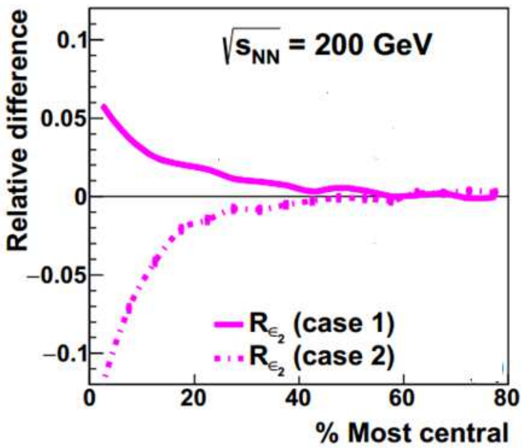
Other anomalous transports:

Observable	$^{96}_{44}Ru + ^{96}_{44}Ru$ vs. $^{96}_{40}Zr + ^{96}_{40}Zr$
flow	$\approx$
CME	$>$
CMW	$>$
CVE	$\approx$

Isobar collisions: by-product 1

By product 1: which nucleus is more deformed, Zr or Ru?

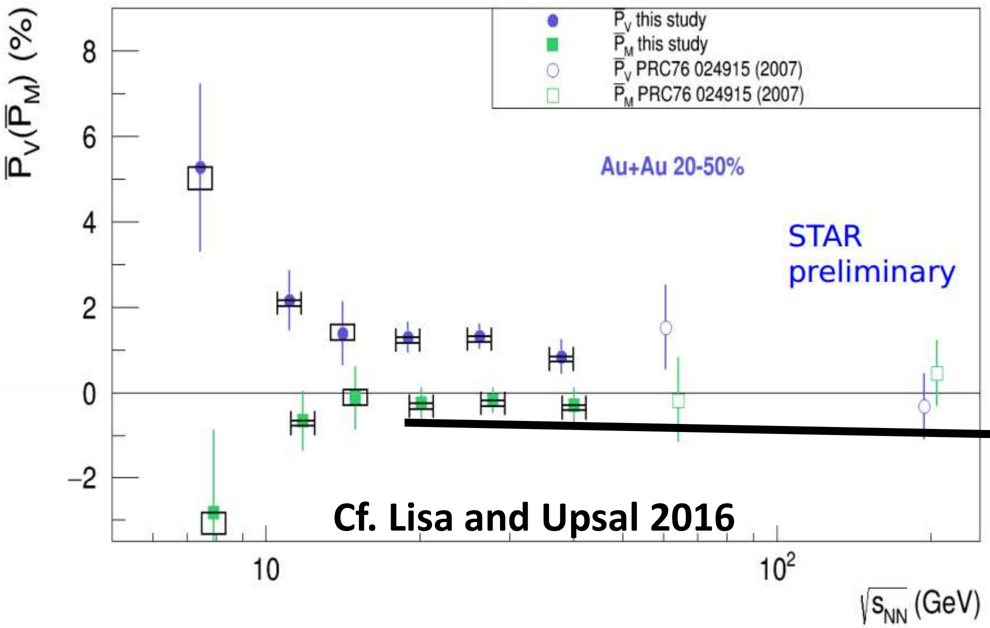
		R_0(fm)	a(fm)	β_2
Case 1	Ru	5.085	0.46	0.158
	Zr	5.02	0.46	0.08
Case 2	Ru	5.085	0.46	0.053
	Zr	5.02	0.46	0.217



Measurement of the v_2 at central collision can tell us about the deformation of the nuclei

Isobar collisions: by-product 2

By product 2: difference between Lambda and anti-Lambda polarizations, Magnetic field or others?



Decomposition into vortical and magnetic

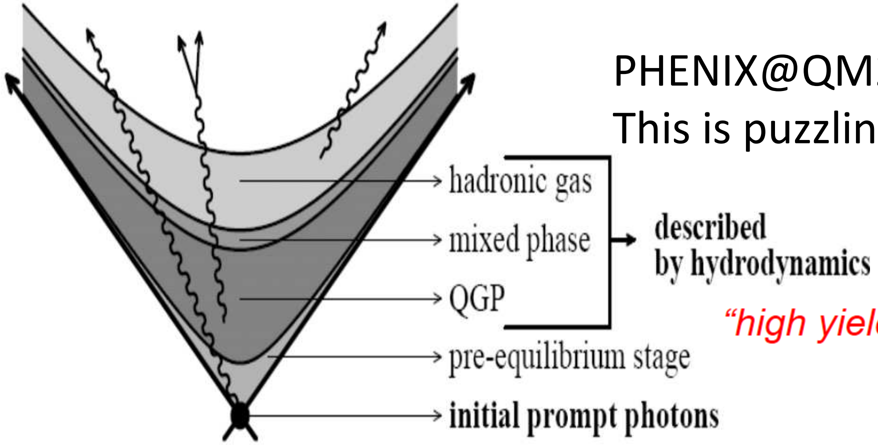
$$P_{\text{Vortical}} = \frac{1}{2}\left(P_{\Lambda} + P_{\bar{\Lambda}}\right) \qquad P_{\text{Magnetic}} = \frac{1}{2}\left(P_{\Lambda} - P_{\bar{\Lambda}}\right)$$

Expect 10% difference between Zr+Zr and Ru+Ru, if it is due to magnetic field. **Need beam energy scan**

Isobar collisions: by-product 3

By product 3: is magnetic field responsible to the PHENIX direct photon puzzle?

When do direct photons emit, early stage or late stage?



PHENIX@QM2012: direct photon has high yield and large v2. This is puzzling.

"high yield -> early emission, high anisotropy -> late emission"

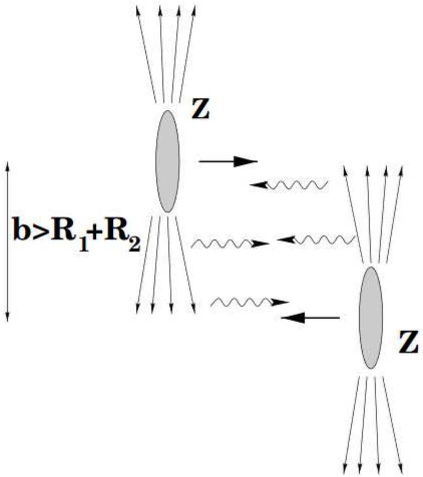
One possible solution: anisotropy in the early stage, like the magnetic field.

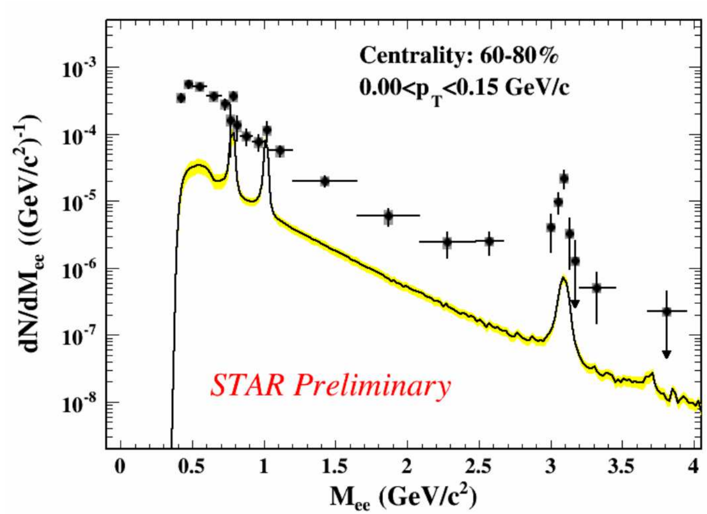
(Basar, Skokov, Kharzeev 2012, Tuchin 2012, Muller, Wang, Yang 2013, Yee 2013, …)

Anisotropy is proportional to B^2, thus can be tested in isobar collisions

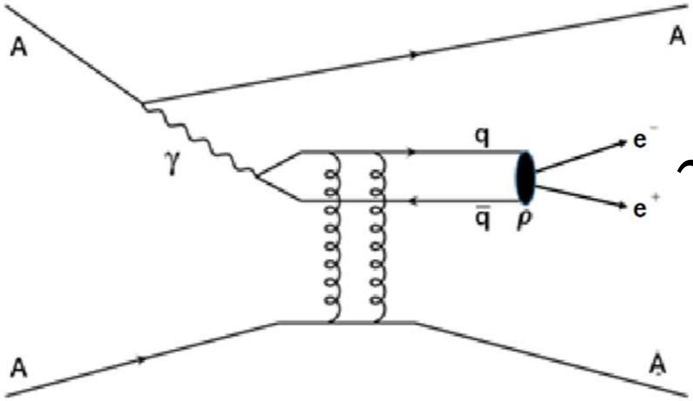
Isobar collisions: by-product 4

By product 4: enhanced dilepton production in very peripheral collisions?

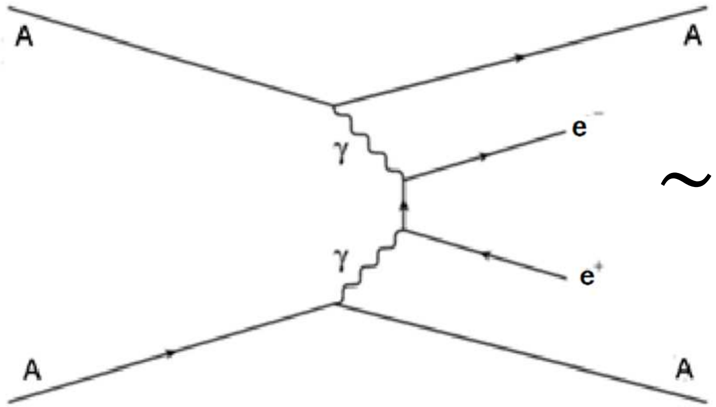




Scenario 1: photonuclear interaction



$\sim Z^2$



$\sim Z^4$

A Way Out

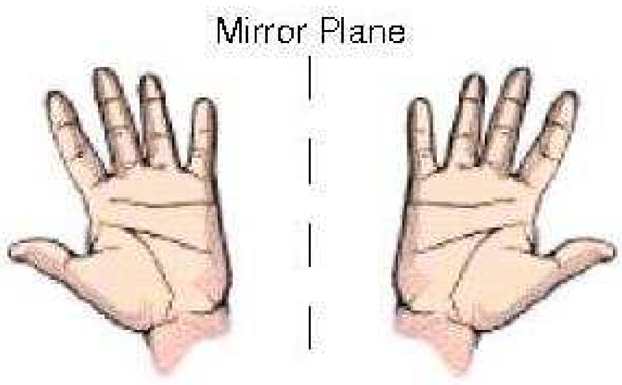
Summary

- **Anomalous chiral transports are universal macroscopic quantum phenomena**
- **They provides a probe to topological sector of QCD in heavy-ion collisions**
- **Experimental signal suffers from strong backgrounds**
- **Isobar collisions run in 2018 are very looked forward**
- **A number of theoretical challenges need to be considered**

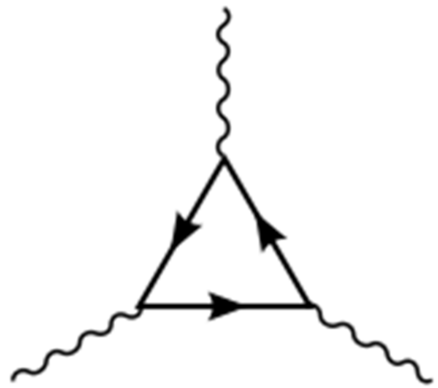
Thank you!

What are anomalous chiral transports?

- Transport phenomena closely related to chiral anomalies: chiral magnetic/vortical effects, etc.
- Usually need environmental violation of parity or charge-parity symmetries



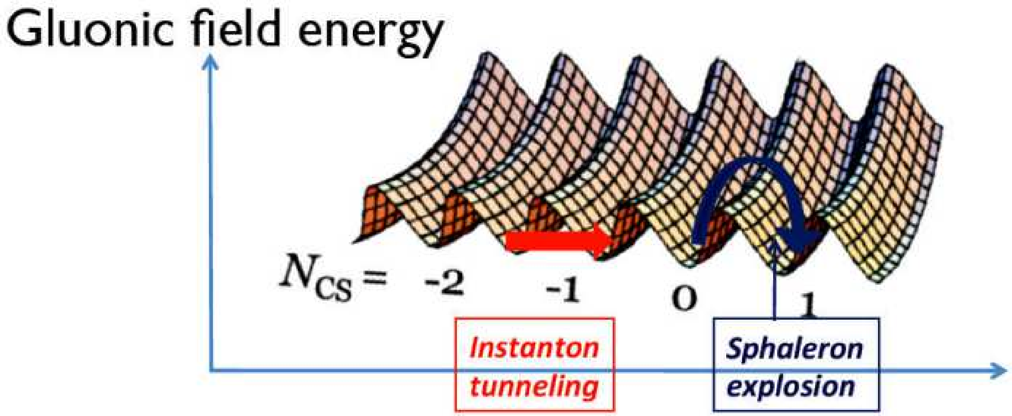
Chirality



Triangle anomaly

Topological sector of QCD

- QCD can have nontrivial vacuum: The theta vacuum



$$N_{CS} = \frac{1}{24\pi^2}\int d^3x\, \varepsilon^{ijk}\mathrm{tr}\left[\left(U^{-1}\partial_i U\right)\left(U^{-1}\partial_j U\right)\left(U^{-1}\partial_k U\right)\right], U \in SU(3)$$

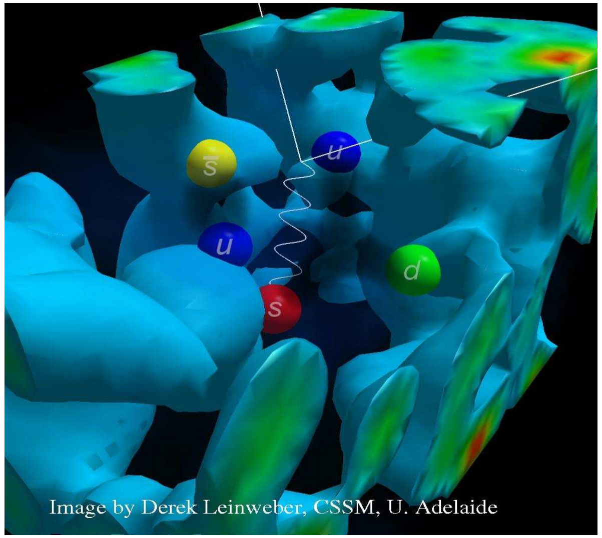
- Transition between 2 vacua is topological (e.g., Instanton, sphaleron)

$$\mathrm{Q} = \frac{1}{32\pi^2}\int d^4x\, G^a_{\mu\nu}\tilde{G}^{\mu\nu}_a = N_{CS}(\mathrm{t}=\infty) - N_{CS}(\mathrm{t}=-\infty)$$

--- P and CP odd transition

Topological sector of QCD

- Topological transition is equally possible for each direction
- Thus we expect to observe only its fluctuation



- If observed, fundamental importance: 1) local Strong P and CP violation; 2) topological sector of QCD vacuum structure
- How to probe it?