ISMD2017@Tlaxcala

Phenomenology of anomalous chiral transports in heavy-ion collisions

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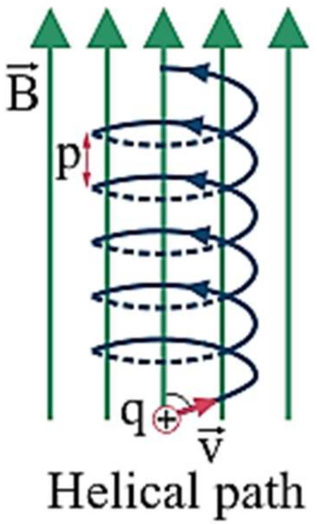
Outline

- Introduction to anomalous chiral transports
- Possible experimental signals and uncertainties
- Isobar collisions
- Summary

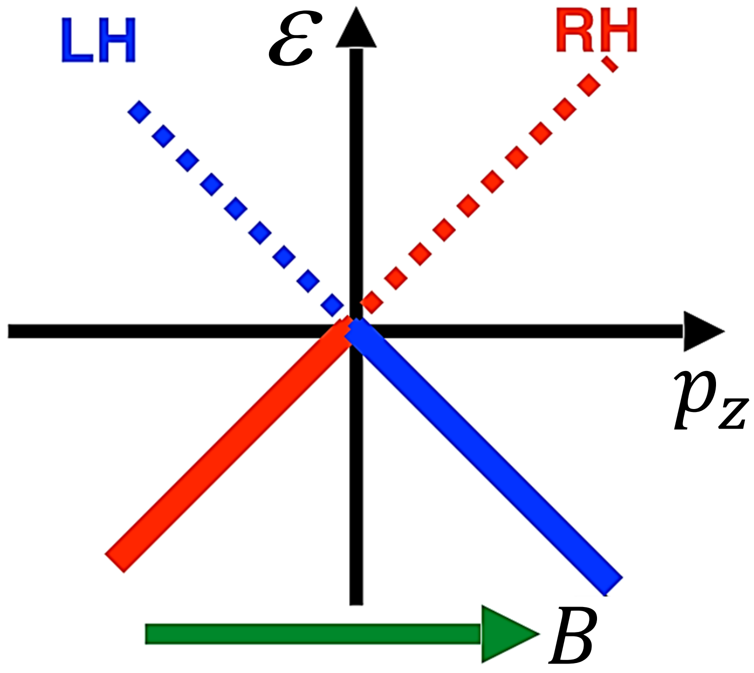
Introduction to anomalous chiral transports

Chiral anomaly

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



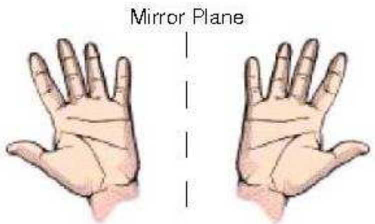
$n = 0$



$$E_n^2 = p_z^2 + 2nqB$$

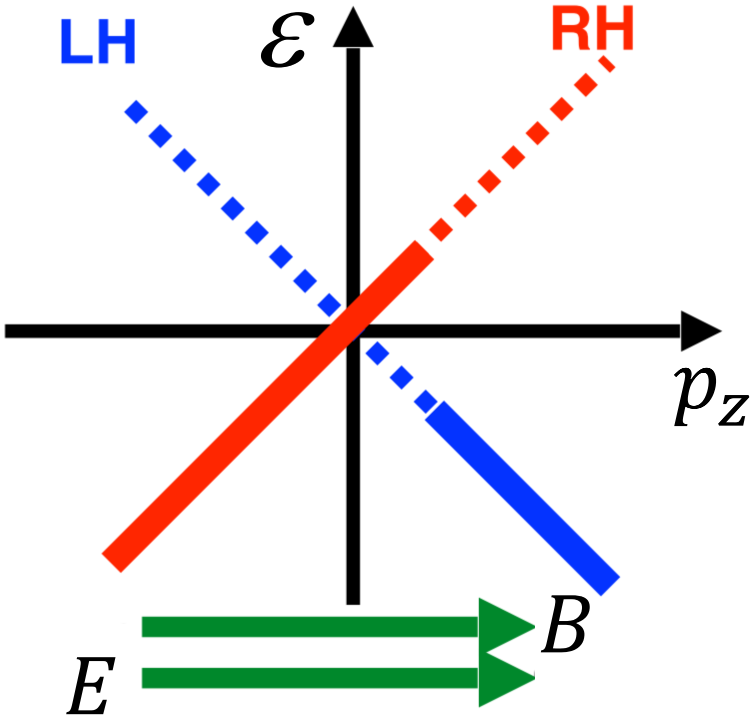
- **Two conserved currents with left- and right-chirality**

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



Chiral anomaly

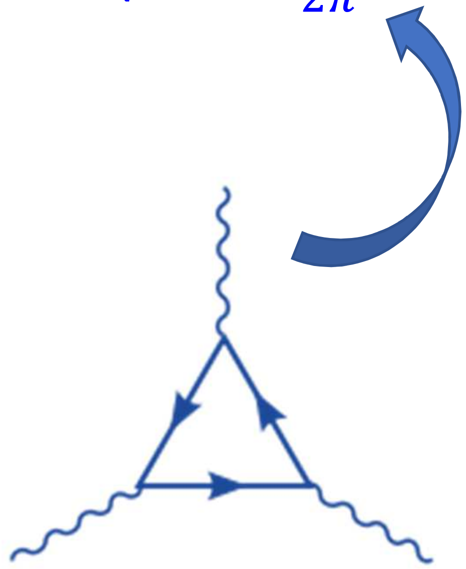
- Lowest Landau level of massless fermion



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

is no longer conserved:

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



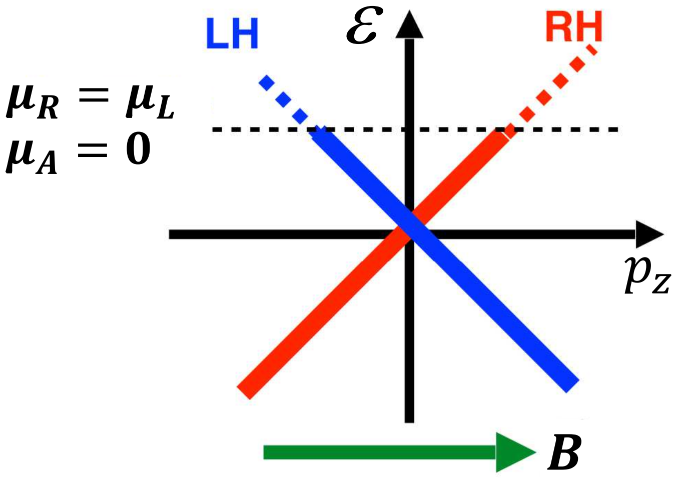
- One conserved current

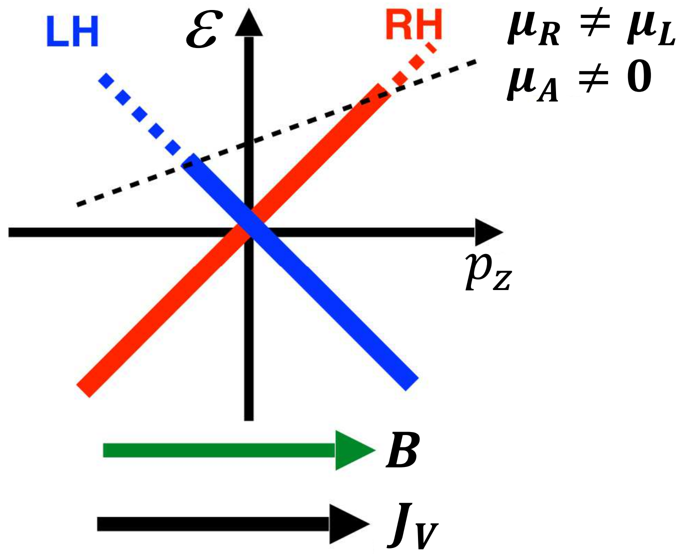
$$J_V^\mu = J_R^\mu + J_L^\mu = \bar{\psi}\gamma^\mu\psi$$

Adler 1969, Bell and Jackiw 1969

Chiral magnetic effect (CME)

- Remove the E field but put Fermi surfaces





$$J_R = en_R$$

$$J_L = -en_L$$

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

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

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

CME current

Kharzeev et al 2004-2008,

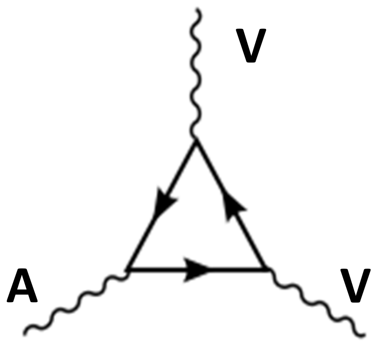
Vilenkin 1980, ……

Chiral magnetic effect (CME)

- **CME: vector current induced by B in matter with μ_{A}**

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

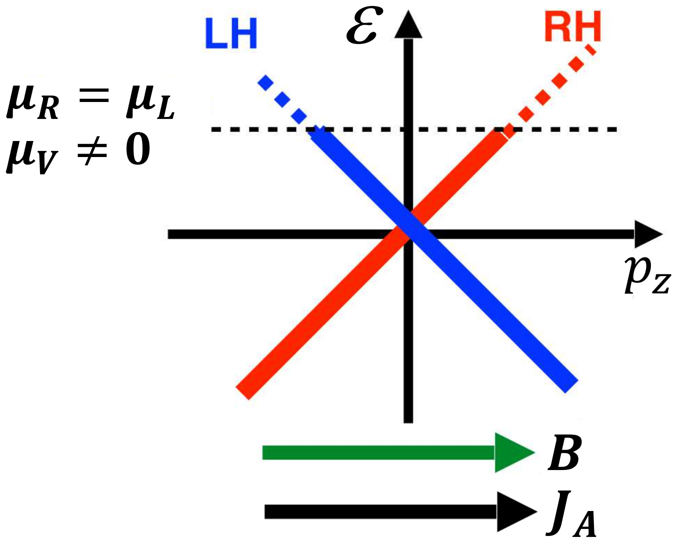
- **Macroscopic quantum phenomenon**
- **P- and CP-odd transport**
- **Time-reversal even, no dissipation**
- **Fixed by anomaly coefficient, universal**

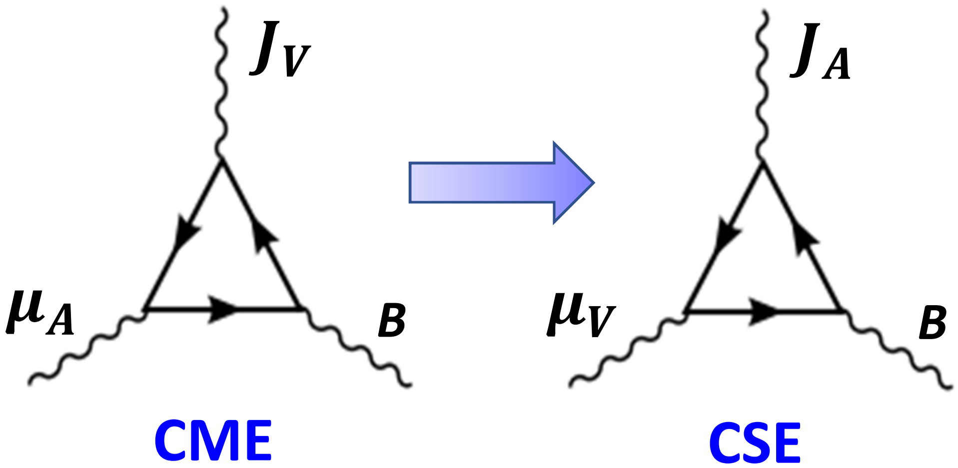


To realize CME, we need:
environmental parity violation (μ_{A}) and external magnetic field (B)

Chiral separation effect (CSE)

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





$$J_R = en_R$$

$$J_L = -en_L$$

$$n_{R/L} \equiv \frac{\mathrm{d}^3 N_{R/L}}{\mathrm{d}x\mathrm{d}y\mathrm{d}z} = \frac{eB}{2\pi}\frac{p_{\mathrm{F}}^{R/L}}{2\pi}$$

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

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

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: $eB \sim 2\varepsilon\omega$

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

$$J_R = e n_R$$

$$J_L = -e n_L$$

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

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

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

CVE currents

More rigorous calculation shows a $(T^2/6)e\omega$ term in J_A related to gravitational anomaly.

(Landsteiner etal 2011)

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

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, etc) induced by them.

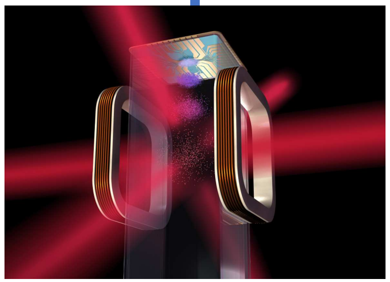
Well established in theory. But where to observe them: You'd better have strong $\boldsymbol{B}$ or $\boldsymbol{\omega}$; massless fermions; violation of parity (CME, VCVE, CESE).

Where are anomalous chiral transports?

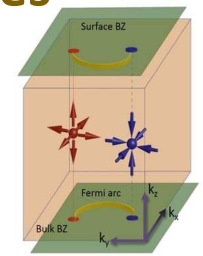
- Universal phenomena that may happen across a very broad hierarchy of scales.

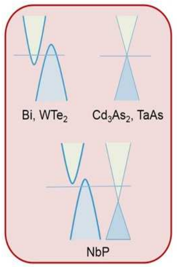
$10^{-10}K$ | $1 - 10^2 K$ | $10^{10}K$ | $10^{12}K$

Temperature



Cold atomic gases





Weyl/Dirac semimetals

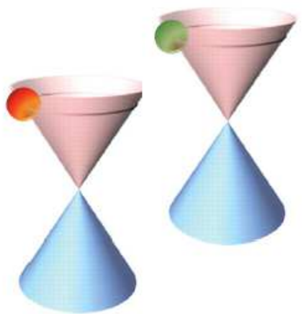
Supernovae

Heavy-ion collisions

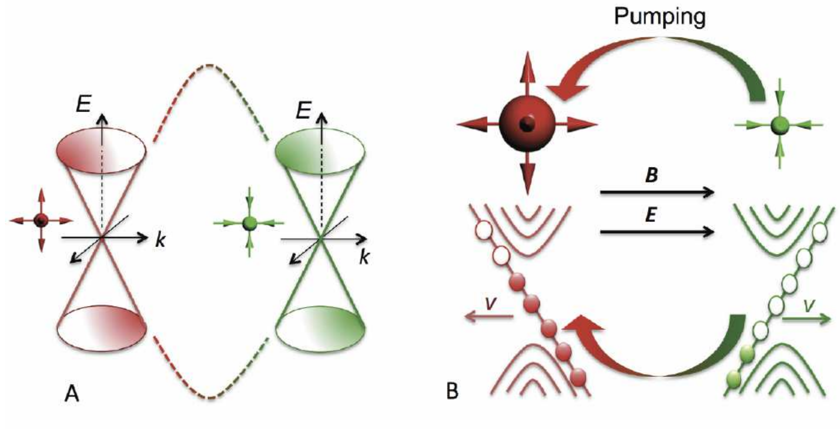
CME on desktop

- **Chiral fermions in 3D semimetals**

Weyl semimetal
(non-degenerated bands)

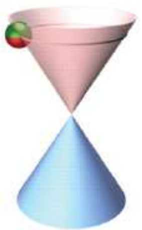


TaAs
NbAs
NbP
TaP

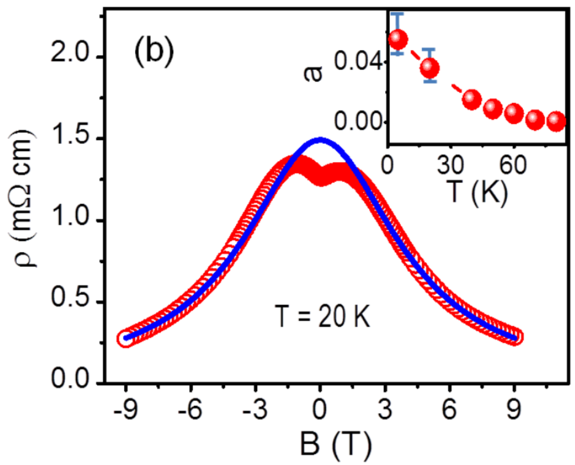


$$\partial_\mu J_5^\mu = C_A \vec{E} \cdot \vec{B}$$

Dirac semimetal
(doubly degenerated bands)



$ZrTe_5$
Na_3Bi,
Cd_3As_2



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

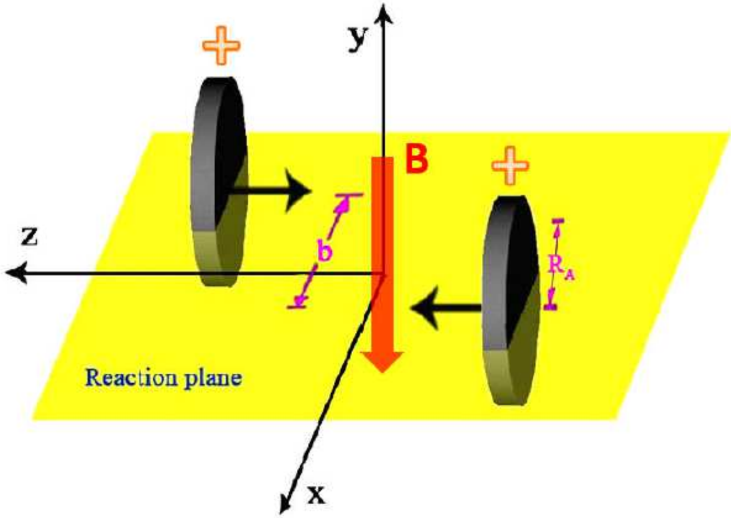
$$\sigma^{zz}_{\rm CME} = \frac{e^2}{\pi\hbar}\ \frac{3}{8}\frac{e^2}{\hbar c}\ \frac{v^3}{\pi^3}\ \frac{\tau_V}{T^2 + \frac{\mu^2}{\pi^2}}\ B^2$$

Li etal 2015

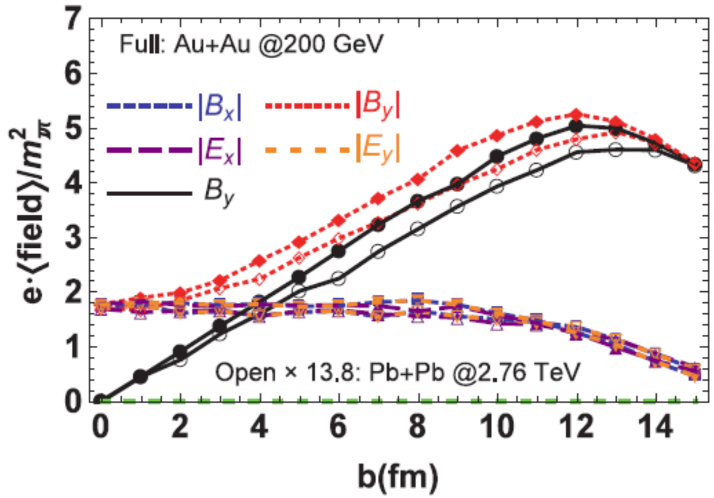
Anomalous chiral transports (ACTs) in heavy ion collisons

Magnetic fields and vorticity

- To realize ACTs, we need B and ω



Deng and XGH 2012



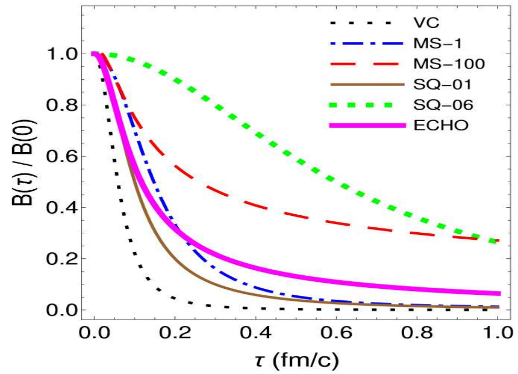
- **Strongest fields** we have known in current universe: $eB \sim 10^{18}$ G (RHIC)- 10^{20} G (LHC)

- Unknow: time evolution of B

$$\langle eB_y(t)\rangle \approx \frac{\langle eB_y(0)\rangle}{(1+t^2/t_B^2)^{3/2}}$$

$$t_B \approx R_A/(\gamma v_z) \approx \frac{2m_N}{\sqrt{s}} R_A$$

In insulating medium

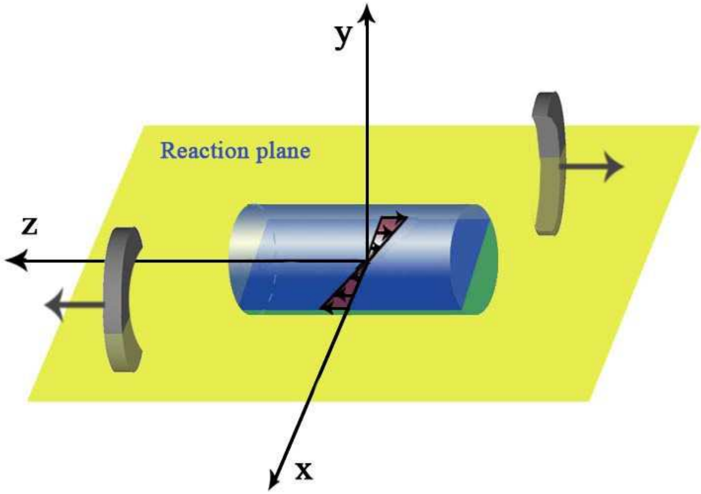


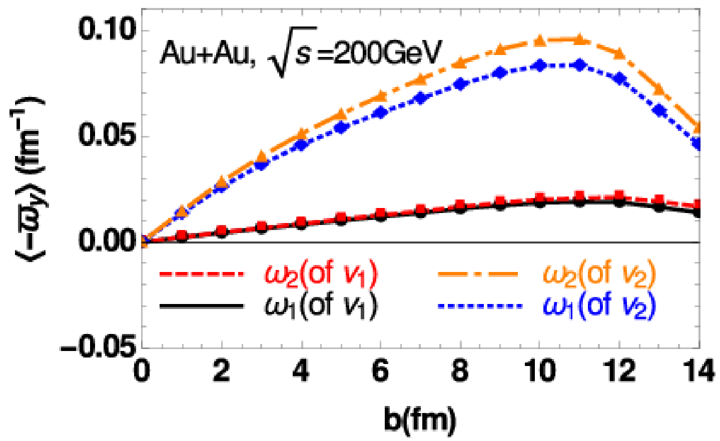
In conducting medium

Magnetic fields and vorticity

- Vorticity ω is the local angular velocity in fluid

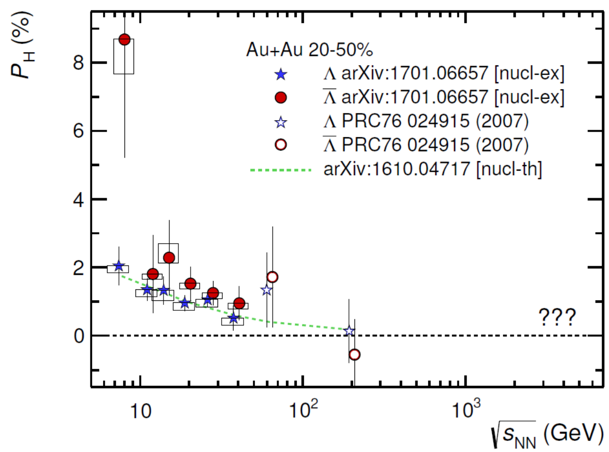
Deng and XGH 2016
Jiang, Liao and Lin 2016



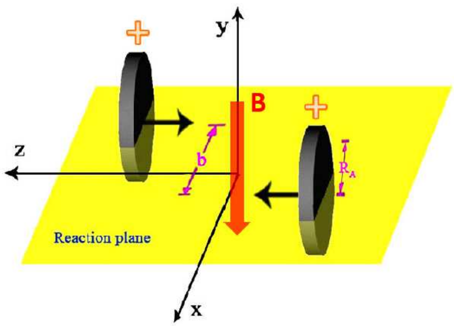


- The most vortical fluid: $\omega \sim 10^{21} s^{-1}$ (RHIC)
- Can be detected by measuring the spin polarization of hadrons, as vorticity can polarize spins

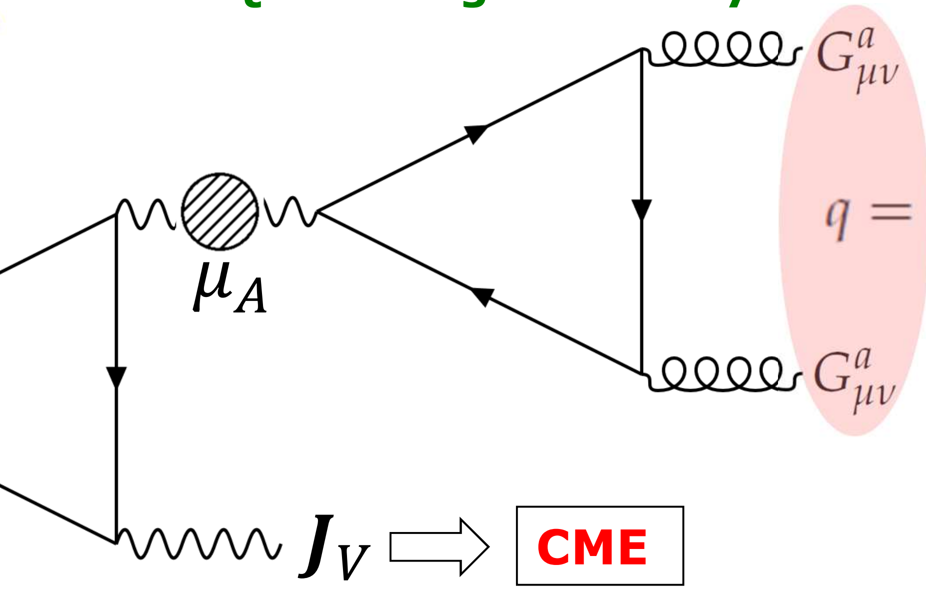
STAR collaboration 2017

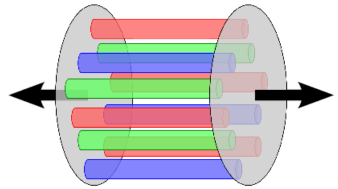


Chirality generation and CME

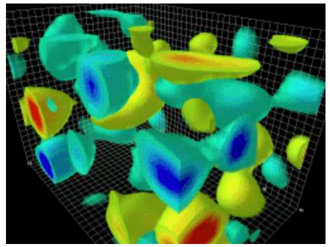


QCD triangle anomaly





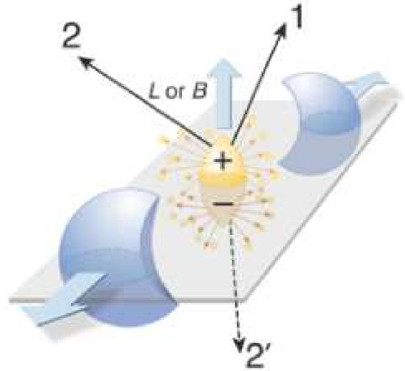
$$q = \frac{g^2}{32\pi^2}\int d^4x G^a_{\mu\nu}\tilde{G}^{\mu\nu}_a$$



CME

QED triangle anomaly

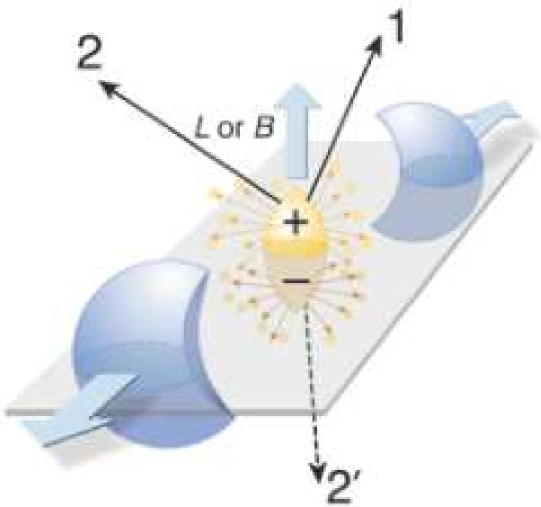
A probe of nontrivial topology of QCD using B field!



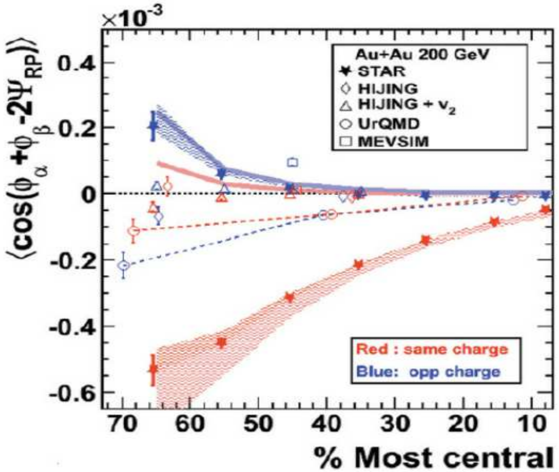
Initial state topological fluctuations

Experimental test of CME

Event-by-event charge separation wrt. reaction plane

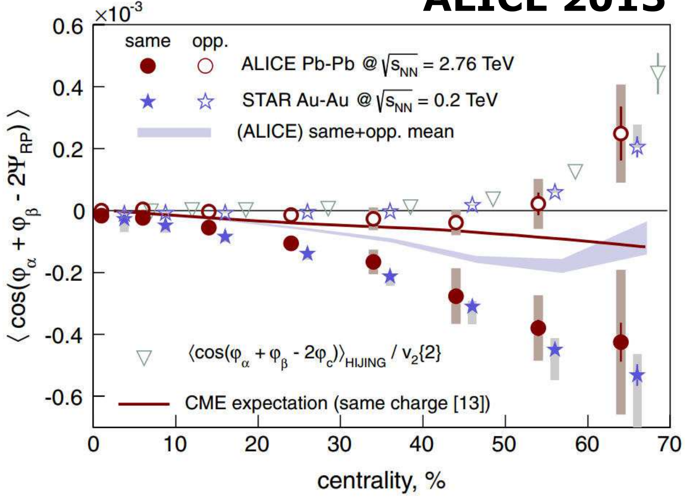


The observable:
The gamma correlator (Voloshin 2004)

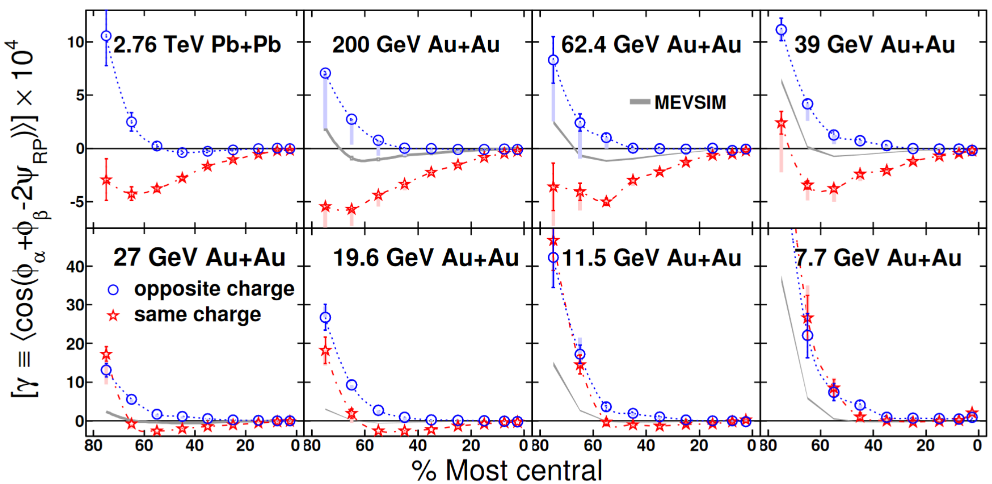


STAR 2009

ALICE 2013



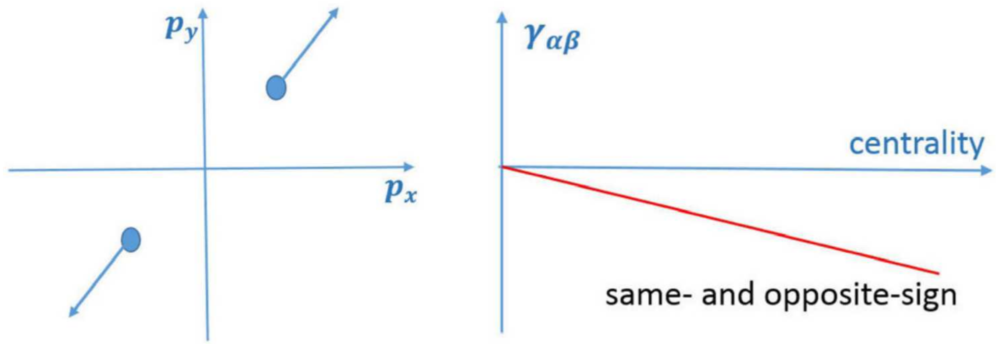
STAR 2014



Back-ground contributions

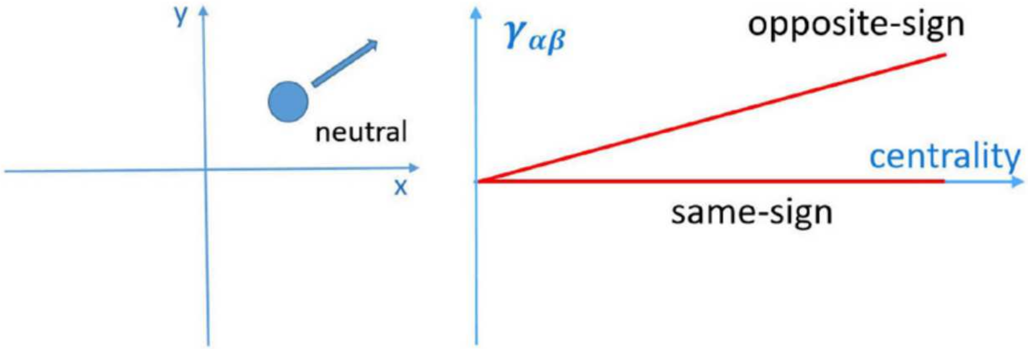
Back-ground contributions to gamma correlator

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

If we can compute CME signal, then OK. 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)

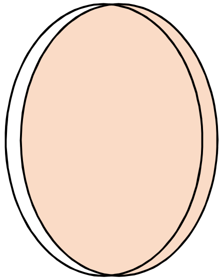
6) Modeling background contributions.
(Vorticity, LCC, Resonance decays, ……)

Challenges but also opportunities to theorists!

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**

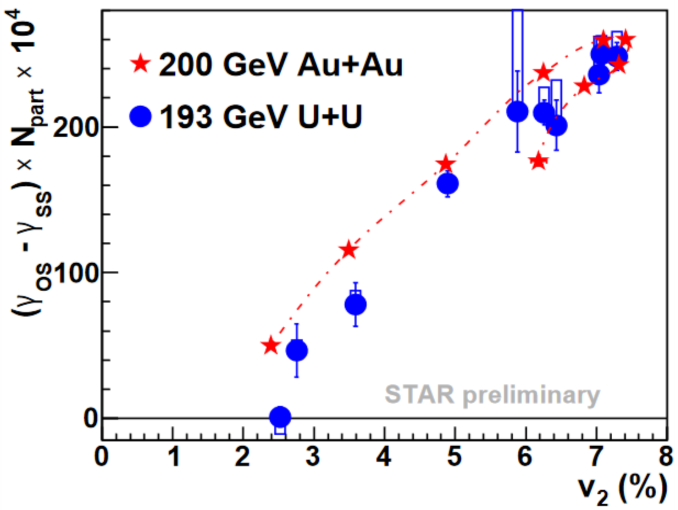


U nucleus is deformed,

Very cental body-body:

B=0 while $v_2 \neq 0$

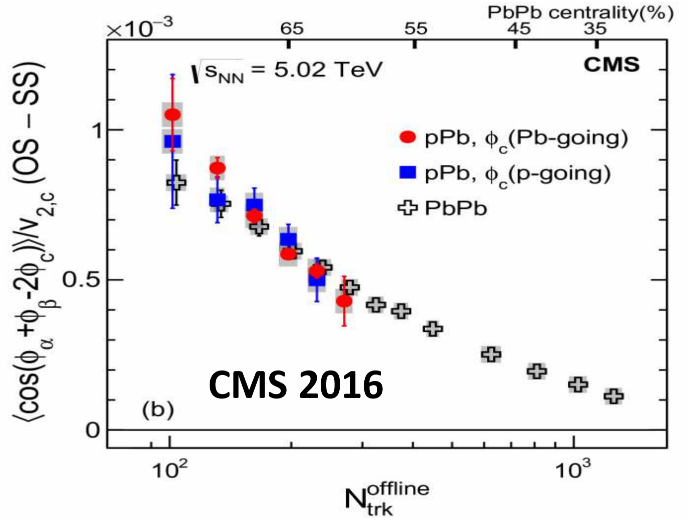
Voloshin 2010

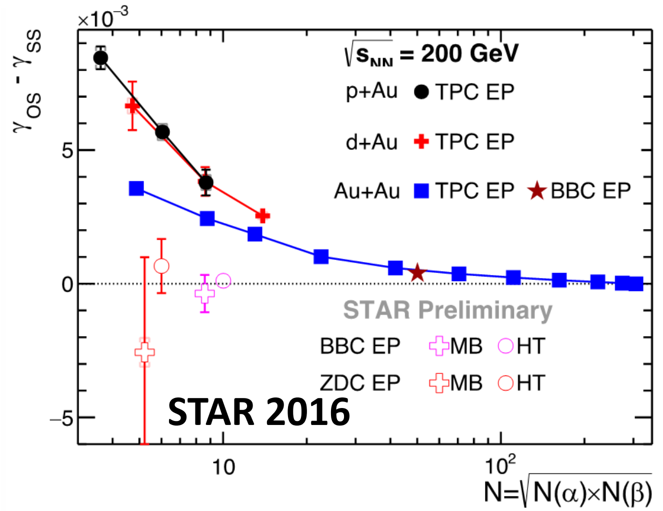


Wang 2012

Experimental methods

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





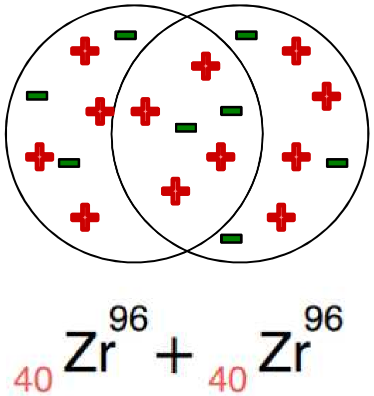
γ in p+Pb ~ in Pb+Pb at LHC   Δγ in p+Au and d+Au zero at RHIC

High energy: Purely background? (B lifetime too short; no correlation to reaction plane), but why the same in p+Pb and Pb+Pb (v_2 are 20-30%different)

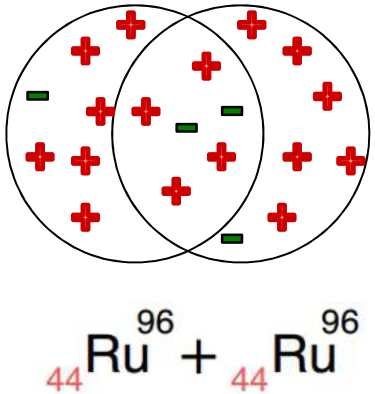
More analysis needed: see talks by J.Zhao and Z.Tu

Experimental methods

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



Vs

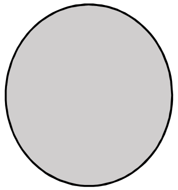


At same energy, same centrality, they would have equal elliptic flow but 10% difference in magnetic field.

The isobar collision

Isobar collisions

Nucleus shape, Wood-Saxon distribution



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

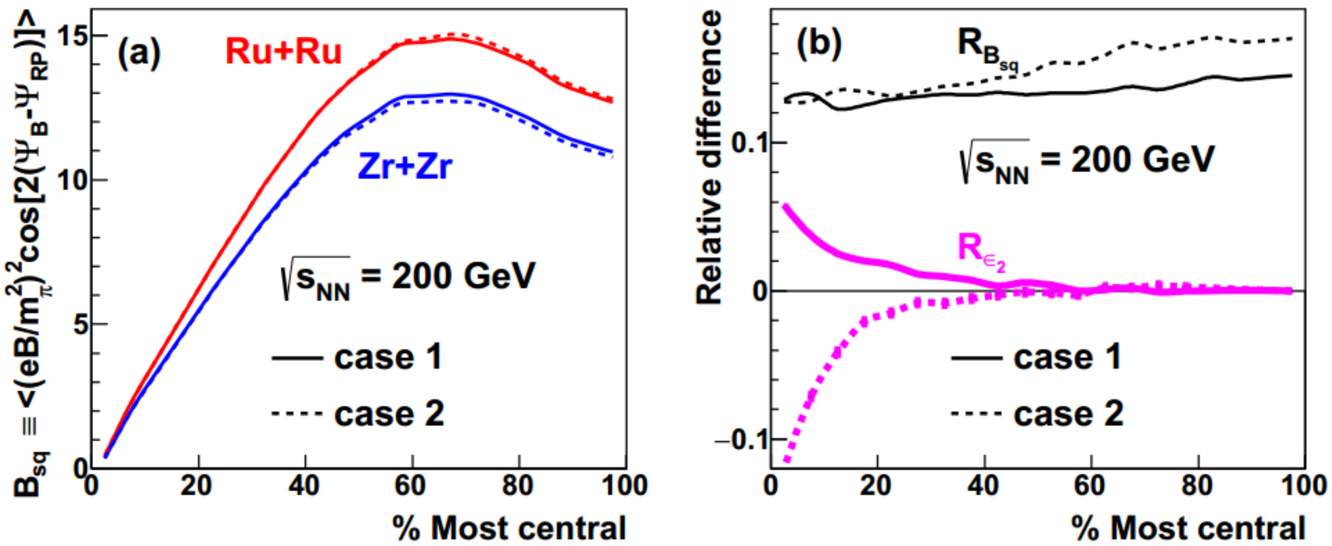
Current experimental data for the parameters:

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 ($R_{\varepsilon_2} < 2\%$)

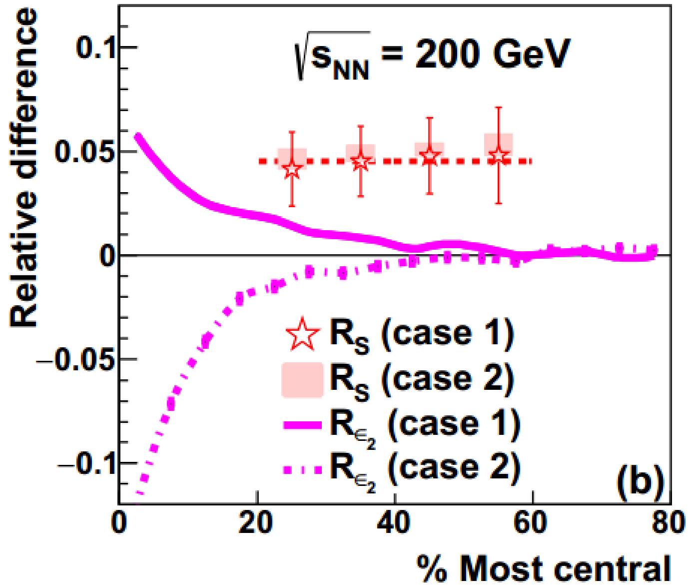
Isobar collisions

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 $\mathrm{R}_{\mathrm{B_{sq}}}$ and $\mathrm{R}_{\varepsilon_2}$ 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



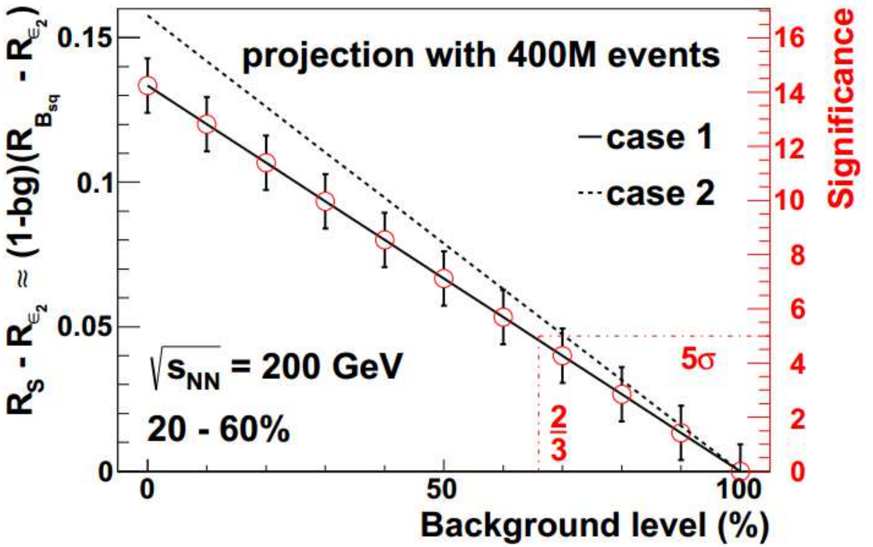
bg=2/3
400M events
5σ signal

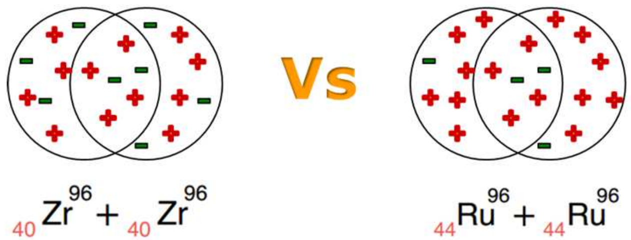
If bg=4/5
1.2B events
5σ signal

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	$\approx$

Summary

- **Anomalous chiral transports are universal macroscopic quantum phenomena**
- **Chiral magnetic effect provides a probe to topological sector of QCD in heavy-ion collisions**
- **Experimental signal suffers from strong backgrounds**
- **Isobar collisions are very promising to disentangle the CME signal and the flow backgrounds**

Need more works in both theory and experiments

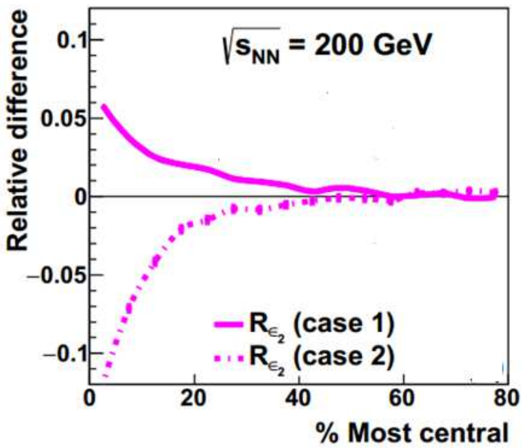
Look forward to RHIC isobar collisions in 2018.

Thank you!

Isobar collisions: by-product 1

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

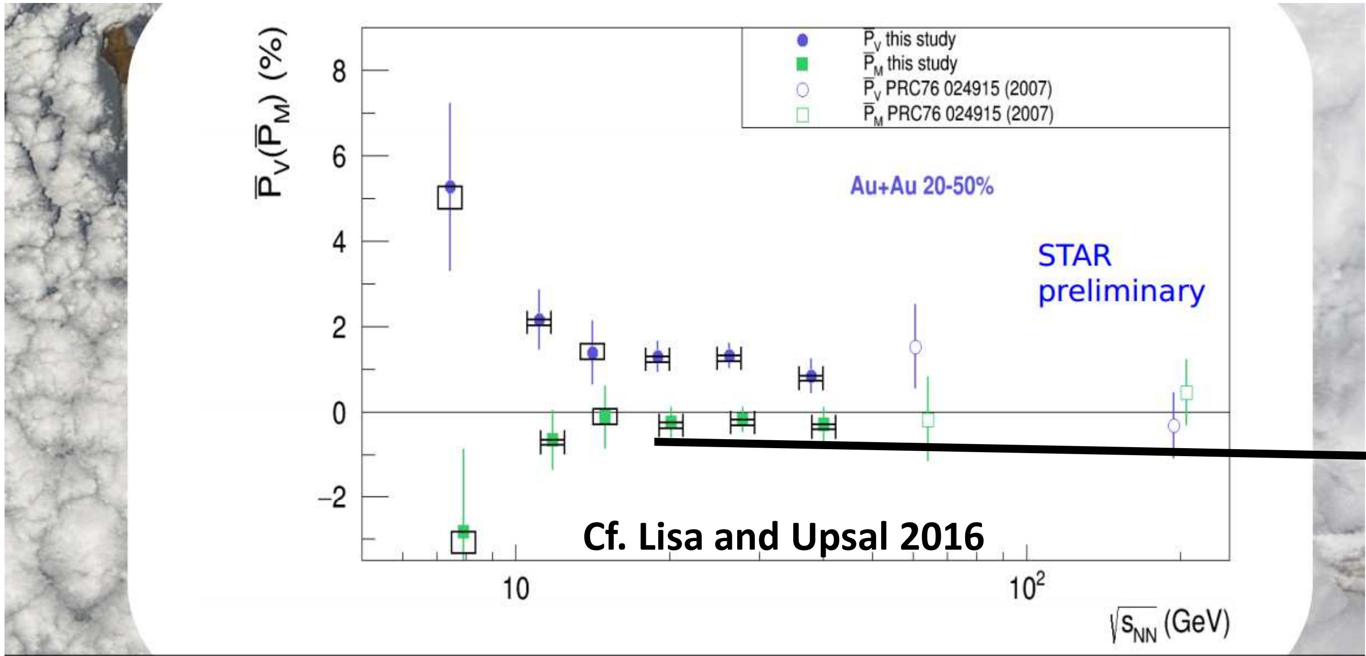
		R_0(fm)	a(fm)	β_2
Case 1	Ru	5.085	0.46	0.158
	Zr	5.02	0.46	0.08
Case 2	Ru	5.085	0.46	0.053
	Zr	5.02	0.46	0.217



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

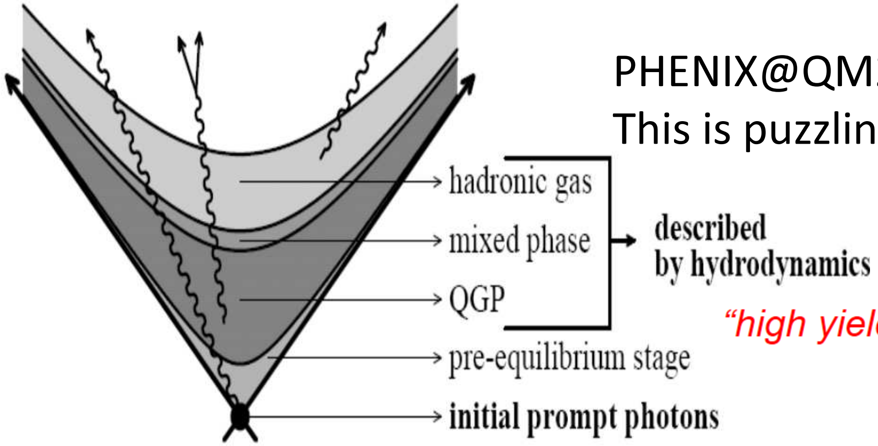
$$P_{\text{Vortical}} = \frac{1}{2}\left(P_{\Lambda} + P_{\bar{\Lambda}}\right) \qquad P_{\text{Magnetic}} = \frac{1}{2}\left(P_{\Lambda} - P_{\bar{\Lambda}}\right)$$

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"

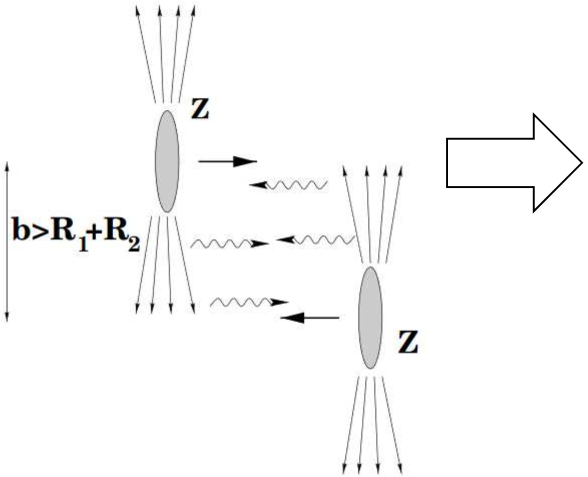
One possible solution: anisotropy in the early stage, like the magnetic field.

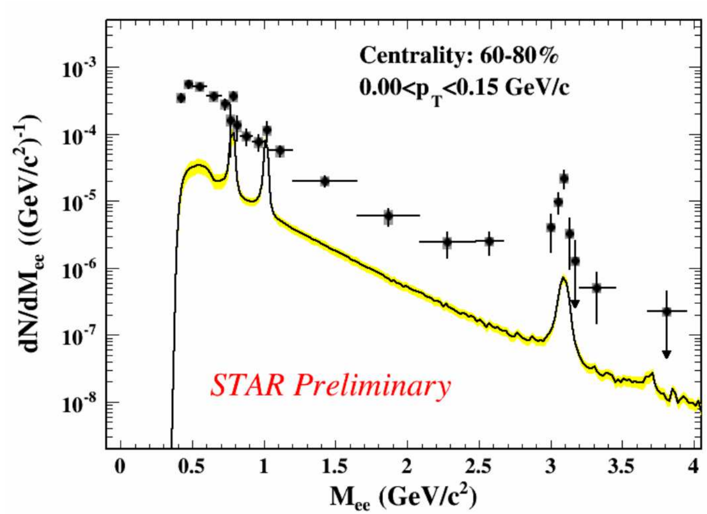
(Basar, Skokov, Kharzeev 2012, Tuchin 2012, Muller, Wang, Yang 2013, Yee 2013, …)

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

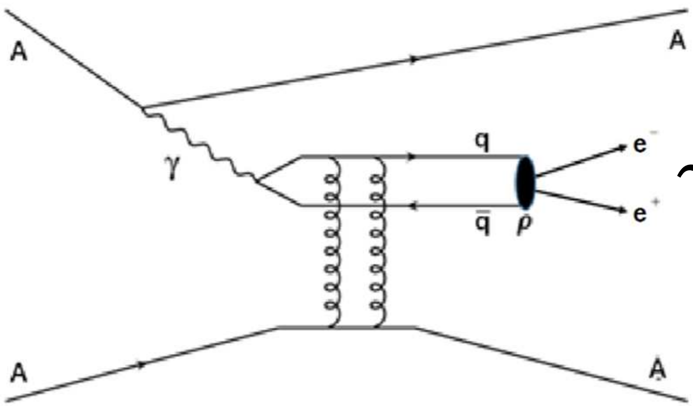
Isobar collisions: by-product 4

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

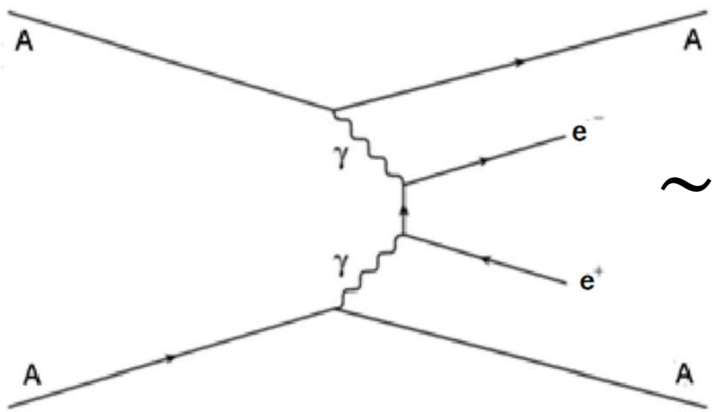




Scenario 1: photonuclear interaction



$\sim Z^2$



$\sim Z^4$