HENPIC online forum

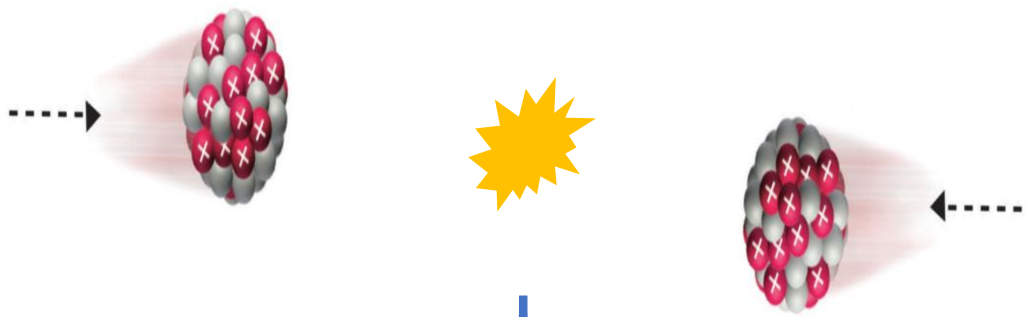
Magnetic Field, Chirality, and Spin Polarization

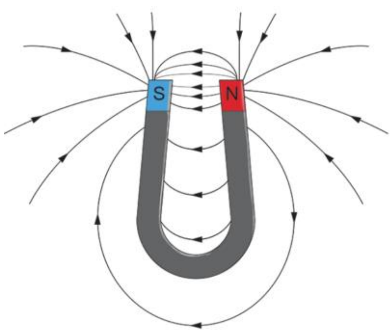
Xu-Guang Huang

Fudan University, Shanghai

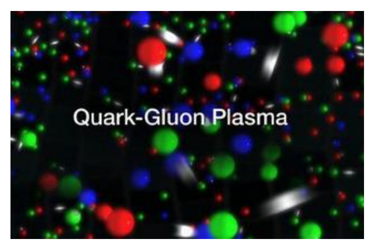
April 16 , 2020

Outline





+

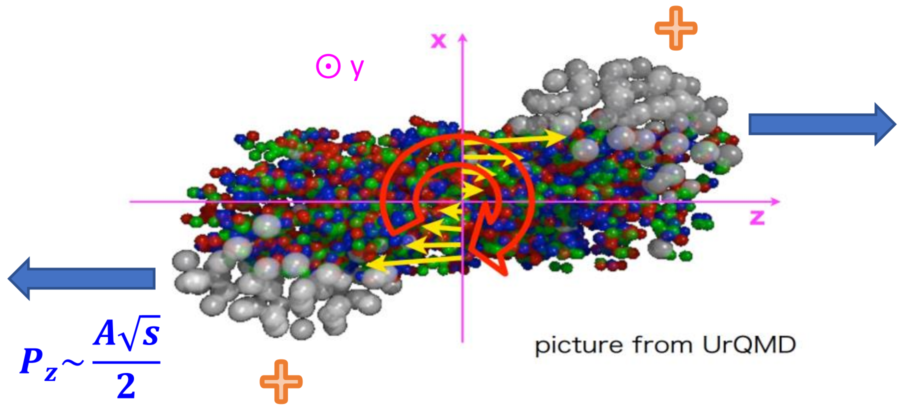


+

- Chiral magnetic/vortical effects
- Hyperon spin polarization
- Vector meson spin alignment
- … …

Magnetic field and vorticity

Angular momentum and magnetic field



$$J_0 \sim \frac{Ab\sqrt{s}}{2} \sim 10^6 \hbar$$

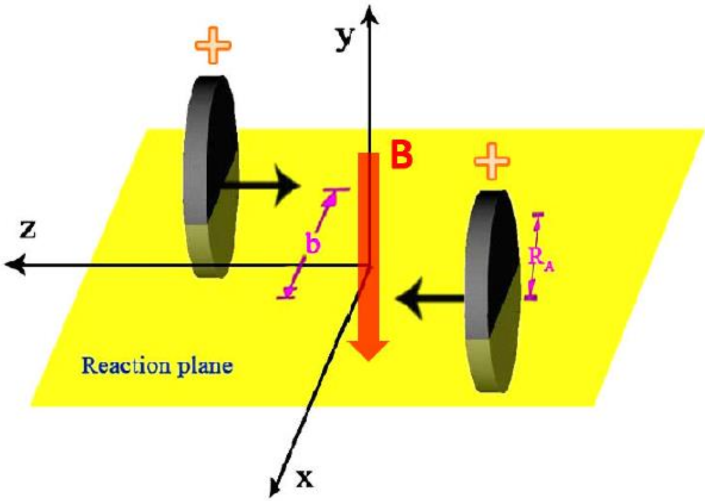
Global angular momentum

$$eB \sim \gamma \alpha_{\mathrm{EM}} \frac{Z}{b^2} \sim 10^{18}\ \mathrm{G}$$

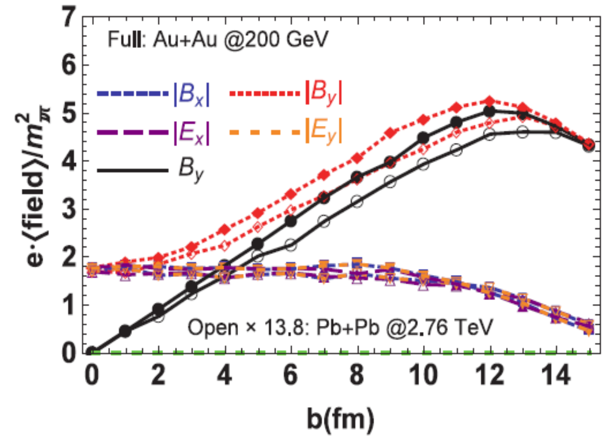
Strong Magnetic field

(RHIC Au+Au 200 GeV, b=10 fm)

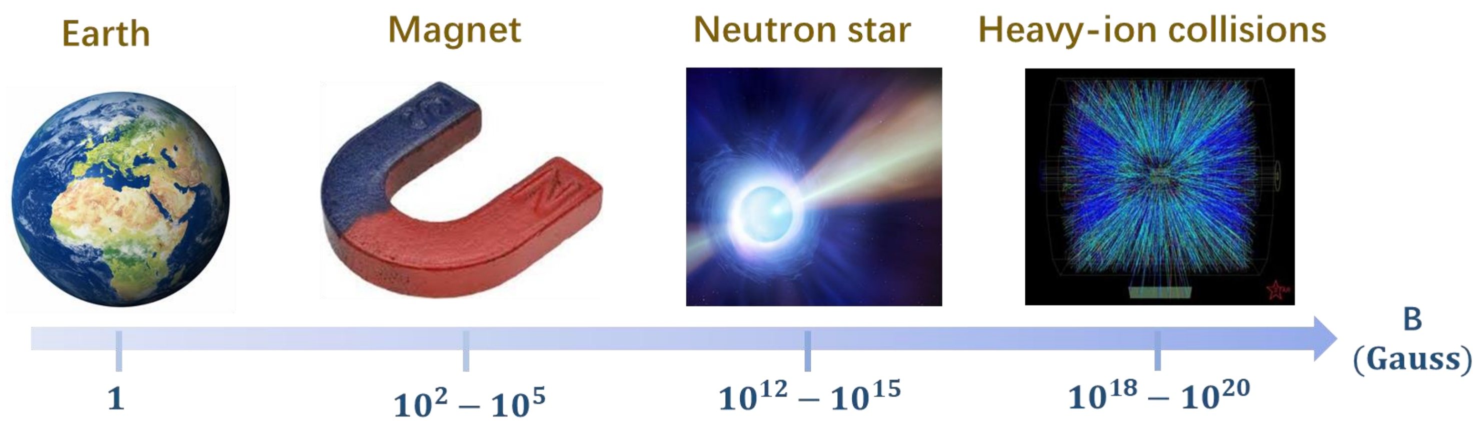
Magnetic field



(Deng-XGH 2012, and many others)



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



Vorticity by global angular momentum

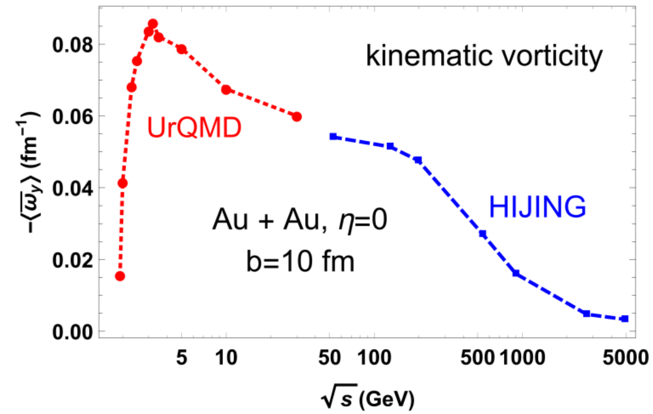
Global angular momentum

Local fluid vorticity

$$\omega = \frac{1}{2}\nabla \times v$$

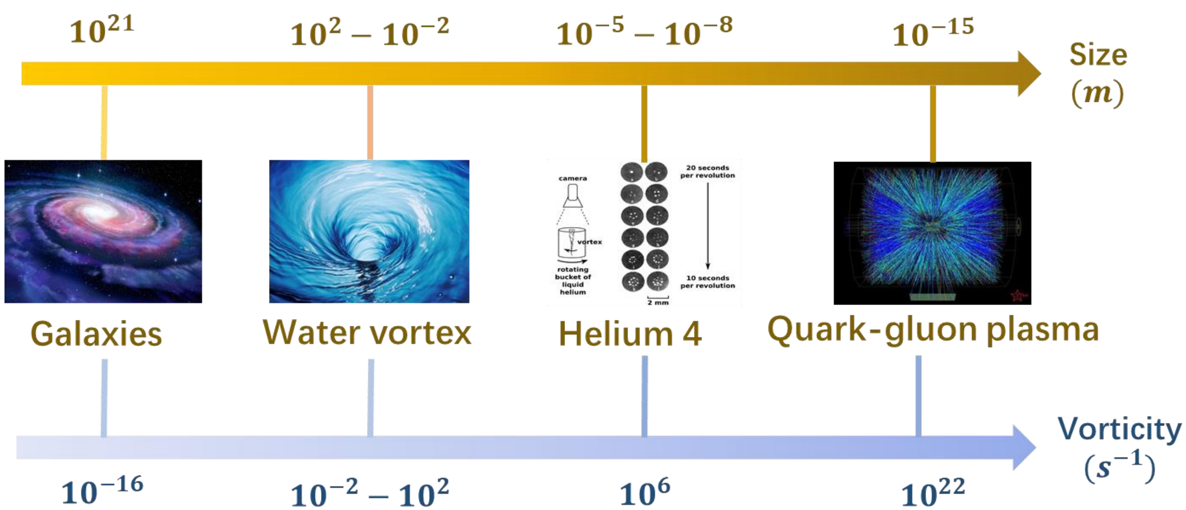
(Angular velocity of fluid cell)

Energy dependence of initial vorticity



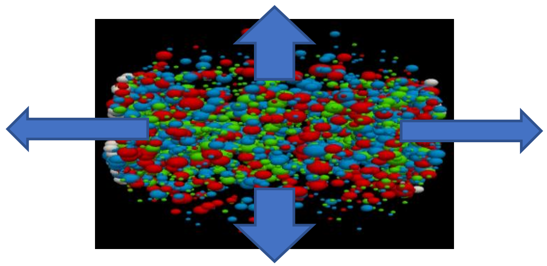
(Deng-XGH 2016; Deng-XGH-Ma-Zhang 2020; XGH 2020)

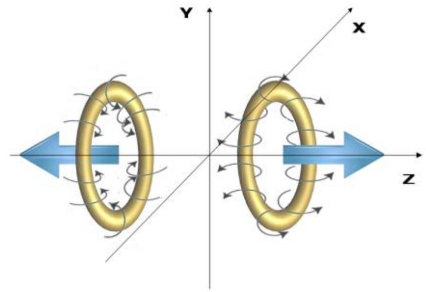
The most vortical fluid: Au+Au@RHIC at b=10 fm is $10^{20} - 10^{21} s^{-1}$

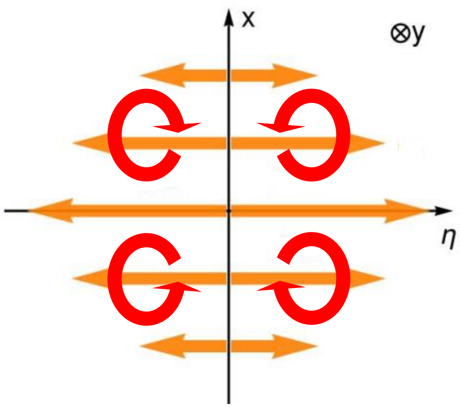


(See also: Jiang-Lin-Liao 2016; Becattini-Karpenko etal 2015,2016; Xie-Csernai etal 2014,2016,2019; Pang-Petersen-Wang-Wang 2016; Xia-Li-Wang 2017,2018; Sun-Ko 2017; Wei-Deng-XGH 2018; … …)

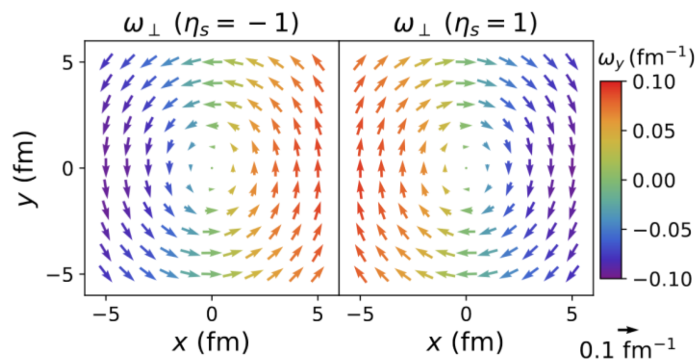
Vorticity by inhomogeneous expansion



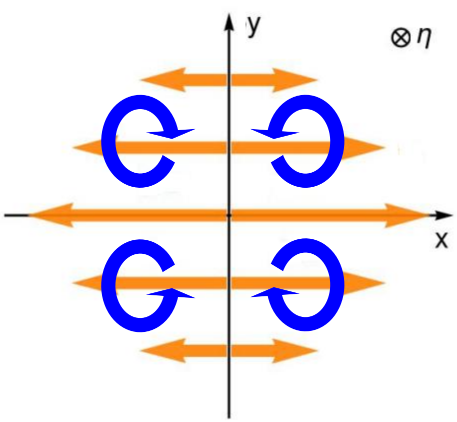




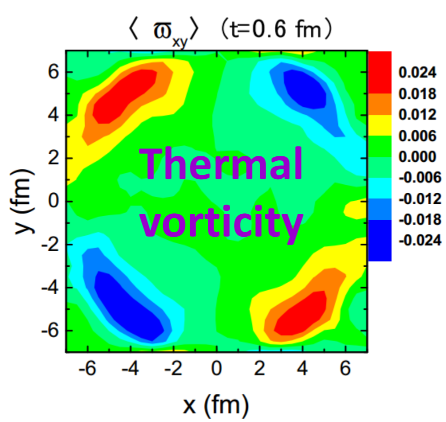
Transverse



(Xia-Li-Wang 2017)



Longitudinal

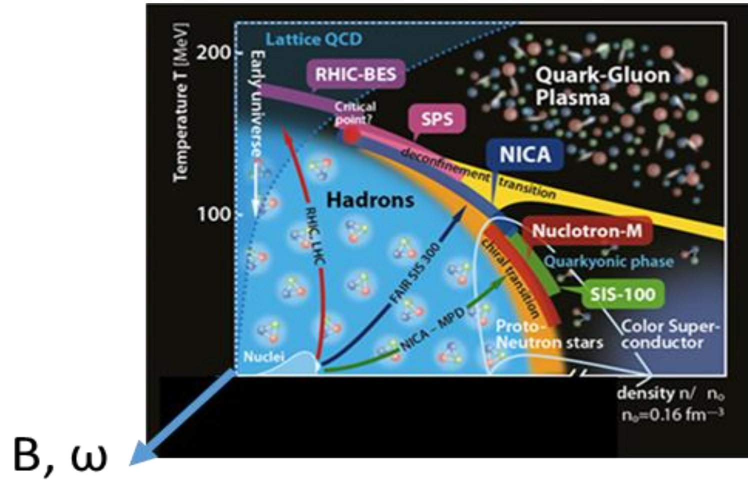


(Wei-Deng-XGH 2018)

(See also: Karpenko-Becattini 2017; Csernai etal 2014; Teryaev-Usubov 2015; Ivanov-Soldatov 2018; … …)

Effects of ω and B

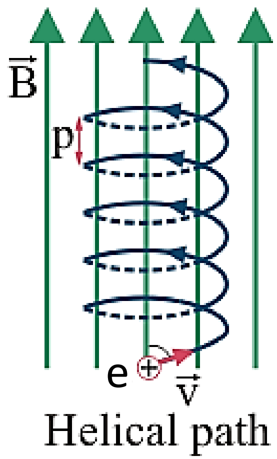
- They can induce many novel effects
- ω :
  - ◆ Λ spin polarization
  - ◆ Φ and K Spin alignment
  - ◆ Chiral vortical effect, chiral vortical wave, …
  - ◆ Reduction of scalar condensate, rotational chiral soliton lattice, …
- B :
  - ◆ Chiral magnetic effect
  - ◆ Chiral separation effect, chiral magnetic wave
  - ◆ (Inverse) Magnetic catalysis of ChSB
  - ◆ EM-induced directed flow, Hall effect, photon elliptic flow, photoproduction of hadrons, anisotropic pressure and viscosities, vacuum birefringence, … …



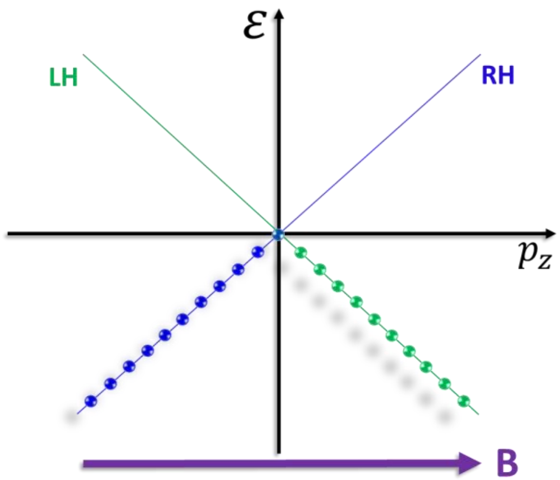
Chiral magnetic and vortical effects

Chiral anomaly as spin-polarization phenomenon

- Lowest Landau level of massless fermion: spin polarized



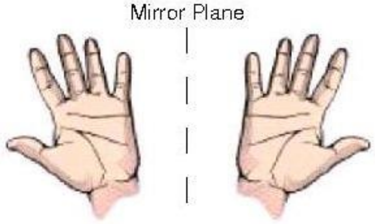
$n = 0$



$$E_n^2 = p_z^2 + 2neB$$

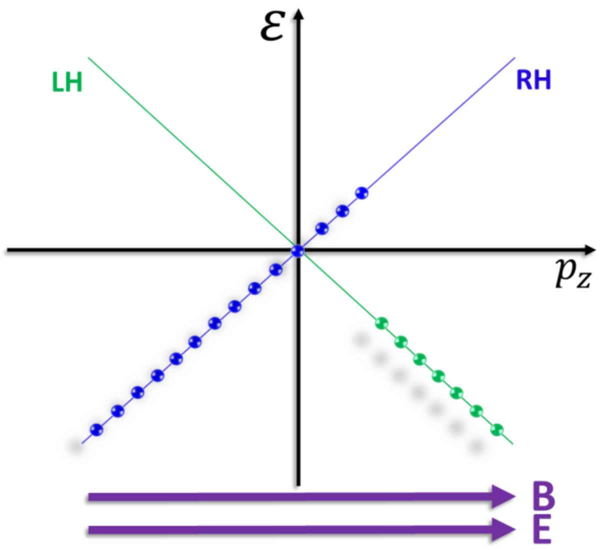
- Two conserved currents with left- and right-chirality

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



Chiral anomaly as spin-polarization phenomenon

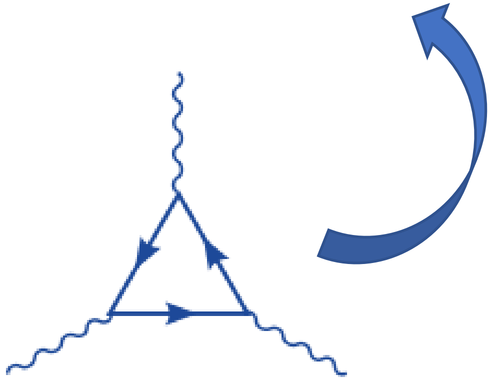
- Lowest Landau level of massless fermion: spin polarized



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

is no longer conserved:

- $N_{R/L} = V \frac{p_F^{R/L}}{2\pi} \frac{eB}{2\pi}$
- $\frac{d}{dt} N_A = \frac{d}{dt}(N_R - N_L)$
  $= V \frac{\dot{p}_F^R - \dot{p}_F^L}{2\pi} \frac{eB}{2\pi} = V \frac{eE}{\pi} \frac{eB}{2\pi}$
- $\partial_\mu J_A^\mu = \frac{e^2}{2\pi^2} \boldsymbol{E} \cdot \boldsymbol{B}$



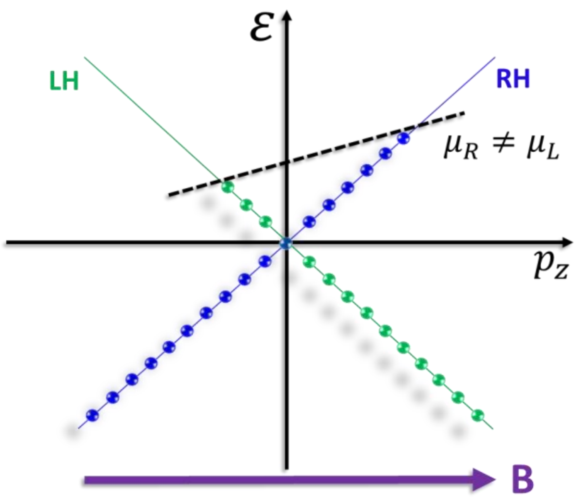
(Adler 1969;
Bell-Jackiw 1969)

- One conserved current

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

Chiral magnetic/separation effects (CME,CSE)

- Remove the E field but put Fermi surfaces



$$J_R = n_R$$
$$J_L = -n_L$$

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

$$J_V = J_R + J_L = \frac{eB}{4\pi^2}(p_F^R - p_F^L)$$
$$= \frac{eB}{2\pi^2}\mu_A$$ CME current

$$J_A = J_R - J_L = \frac{eB}{4\pi^2}(p_F^R + p_F^L)$$
$$= \frac{eB}{2\pi^2}\mu_V$$ CSE current

(Kharzeev et al 2004-2008;

Vilenkin 1980; Son-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:

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

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

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

$$J_R = n_R$$
$$J_L = -n_L$$
$$n_{R/L} = \frac{p_F^{R/L}\omega}{2\pi}\frac{p_F^{R/L}}{2\pi}$$

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

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

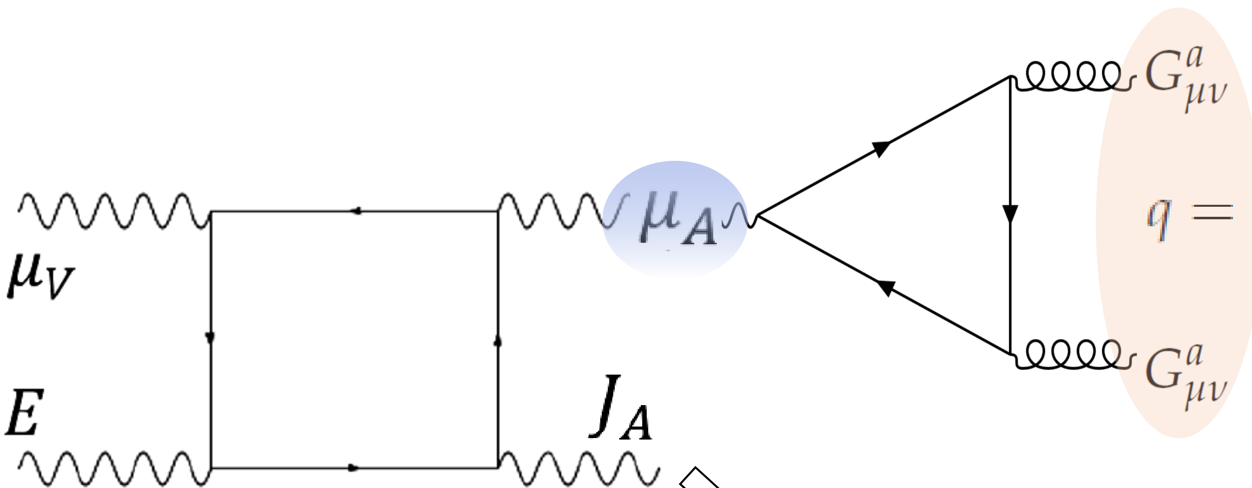
CVE currents

(Erdmenger etal 2008; Banerjee etal 2008; Son-Surowka 2009; ……)

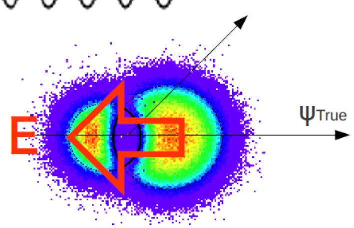
More rigorous calculation shows a $(T^2/6)\boldsymbol{\omega}$ term in $\boldsymbol{J}_A$ (Landsteiner etal 2011; Glorioso etal 2017)

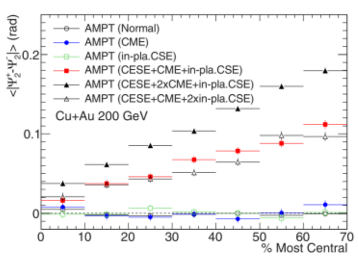
Chiral electric separation effect

- Electric field induced anomalous transport



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

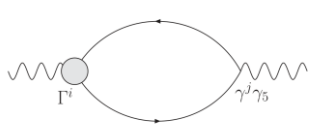




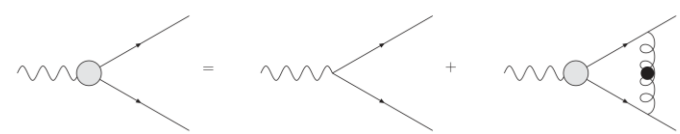
(Ma-XGH 2015)

Chiral electric separation effect (CESE)

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



with



(XGH-Liao 2013; Jiang-XGH-Liao 2015)

Table of anomalous chiral transports

- Transport phenomena closely related to chirality and quantum anomalies

	$\boldsymbol{eE}$	$\boldsymbol{eB}$	$\boldsymbol{\omega}$
$\boldsymbol{J}_V$	σ Ohm's law	$\frac{1}{2\pi^2}\mu_A$ Chiral magnetic effect	$\frac{1}{\pi^2}\mu_V\mu_A$ Vector chiral vortical effect
$\boldsymbol{J}_A$	$\propto \frac{\mu_V\mu_A}{T^2}\sigma$ Chiral electric separation effect	$\frac{1}{2\pi^2}\mu_V$ Chiral separation effect	$\frac{T^2}{6}+\frac{\mu_V^2+\mu_A^2}{2\pi^2}$ Axial chiral vortical effect
Wave mode	$\varepsilon=\alpha_A n_A\sqrt{2\sigma_2\chi_e\alpha_V\alpha_A}\mathbf{k}\cdot\boldsymbol{E}$ Chiral electric wave	$\varepsilon=\sigma_A\sqrt{\alpha_V\alpha_A}\mathbf{k}\cdot\boldsymbol{B}$ Chiral magnetic wave	$\varepsilon=\frac{\mu_V}{2\pi^2\chi_\mu}\mathbf{k}\cdot\boldsymbol{\omega}$ Chiral vortical wave

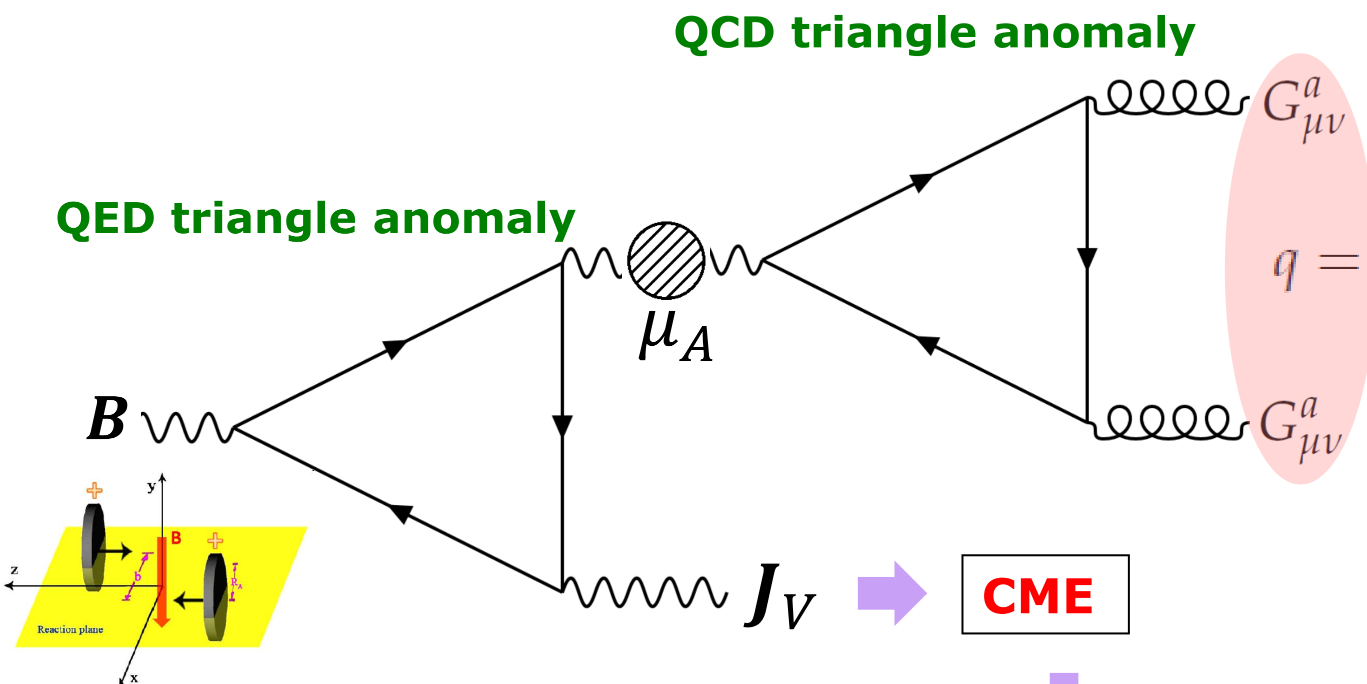
Well established in theory. But where to observe them:

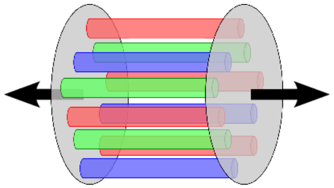
strong $\boldsymbol{B}$ or $\boldsymbol{\omega}$; massless fermions; violation of parity (CME, VCVE,CESE).

(Reviews: XGH ROPP2016; Kharzeev-Liao-Voloshin-Wang PPNP2016; Hattori-XGH NST2017; Zhao-Wang PPNP2019; Li-Wang 2020; Liu-XGH 2020)

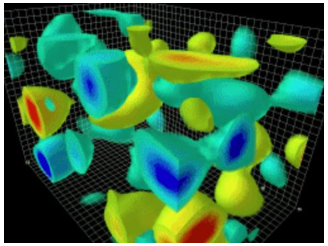
CME in heavy ion collisions

CME in heavy-ion collisions

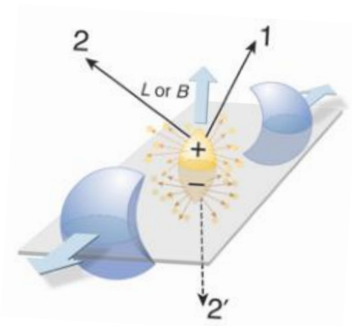




$$q = \frac{g^2}{32\pi^2}\int d^4x G^a_{\mu\nu}\tilde{G}^{\mu\nu}_a$$



CME



Initial state topological fluctuations

A probe of nontrivial topology of QCD using B field!

The observable of CME

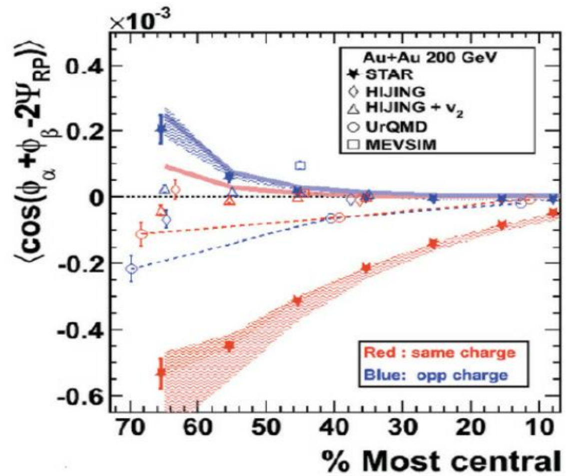
Event-by-event charge separation wrt. reaction plane

The gamma correlator **(Voloshin 2004)**

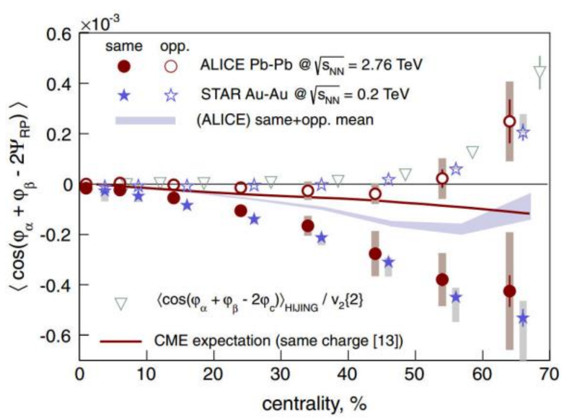
$$\gamma = \left\langle \cos(\varphi_\alpha + \varphi_\beta - 2\psi_{RP}) \right\rangle$$

- $\gamma_{++} \sim \gamma_{--} < 0$
- $\gamma_{+-} \sim \gamma_{-+} > 0$
- Increase with centrality

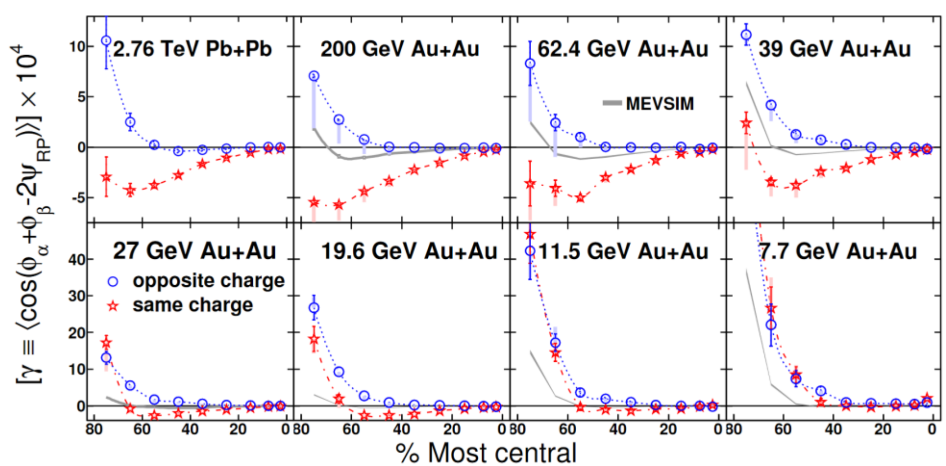
STAR 2009



ALICE 2013



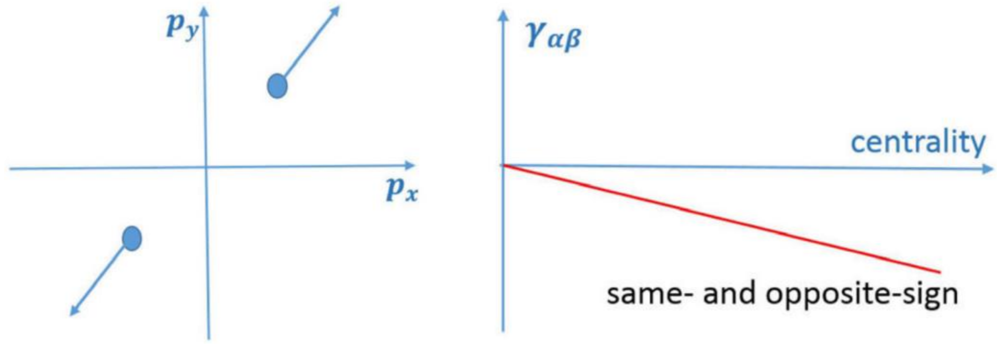
STAR 2014



Background contributions

Back-ground contributions to gamma correlator

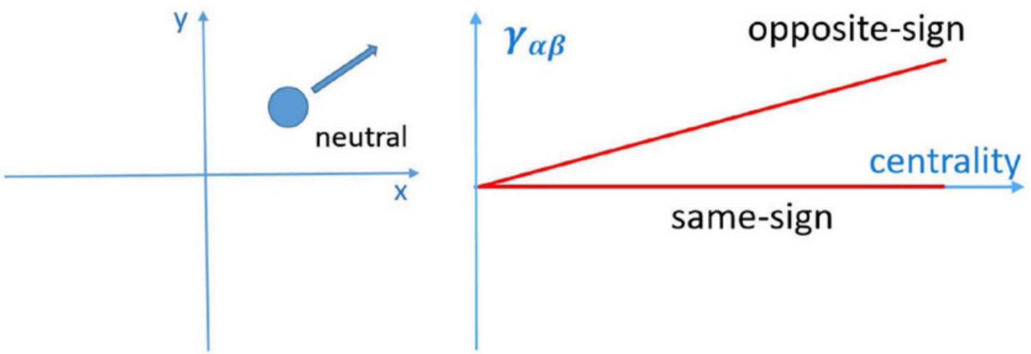
Transverse momentum conservation (Pratt 2010; Liao, Bzdak, Koch 2011):



- Charge blind
- $\gamma \propto -v_2/N$
- Can be subtracted in

$$\Delta\gamma = \gamma_{OS} - \gamma_{SS}$$

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



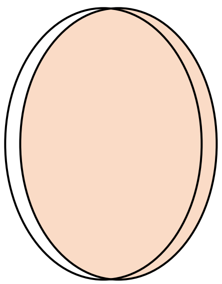
$$\gamma_{OS} \propto v_2/N, \gamma_{SS} \sim 0$$

Main challenge: how to separate the background effects?

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

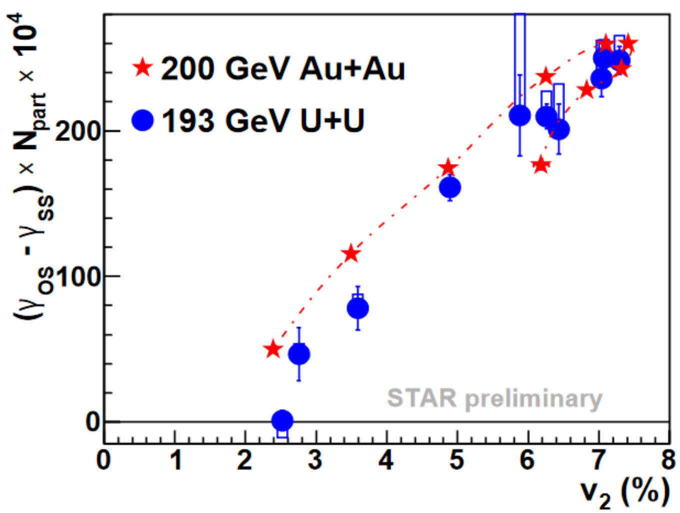


U nucleus is deformed,

Very central body-body:

B=0 while $v_2 \neq 0$

Voloshin 2010

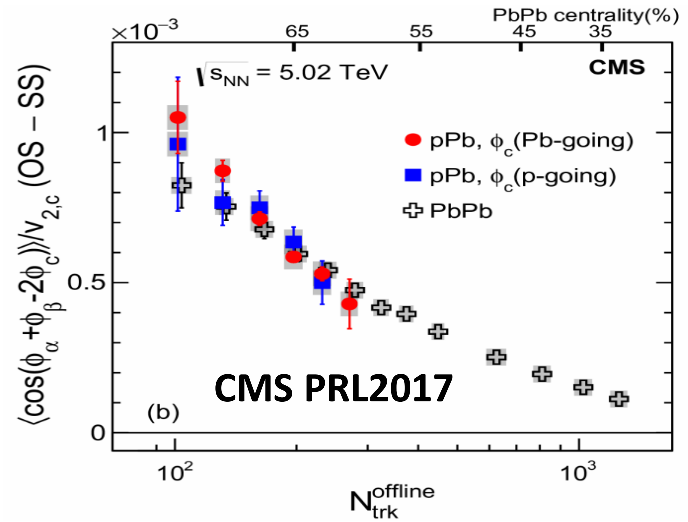


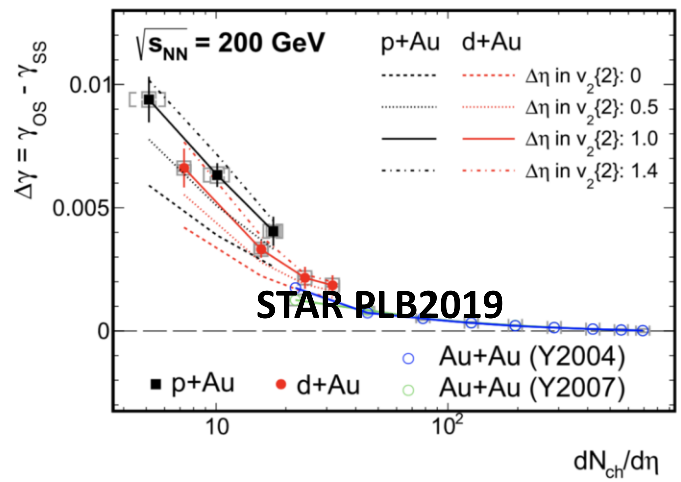
Wang 2012

Updated:
J.Zhao for STAR@QM2019

Experimental methods

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





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

Purely background? (B lifetime different; no correlation to reaction plane), why p(d)+A ≥ A+A?

Xe-Xe at 5.44 TeV show similar trend (QM2019)

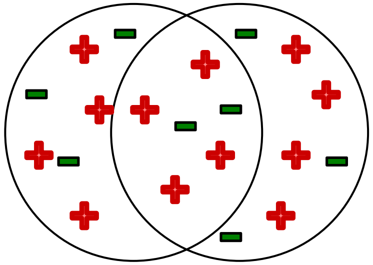
Experimental methods

Some other proposed methods:

- **Pair invariant mass dependence** — **Zhao-Wang 2019**
- **Check different event planes** — **Xu etal 2017**
- **Signed balance functions** — **Tang 2019**
- **R-correlator** — **Magdy etal 2017**
- **… …**

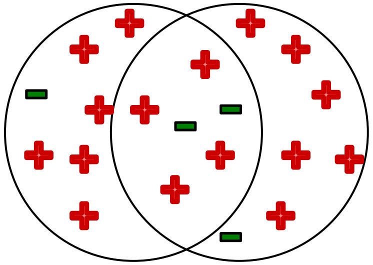
Experimental methods

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



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

Vs

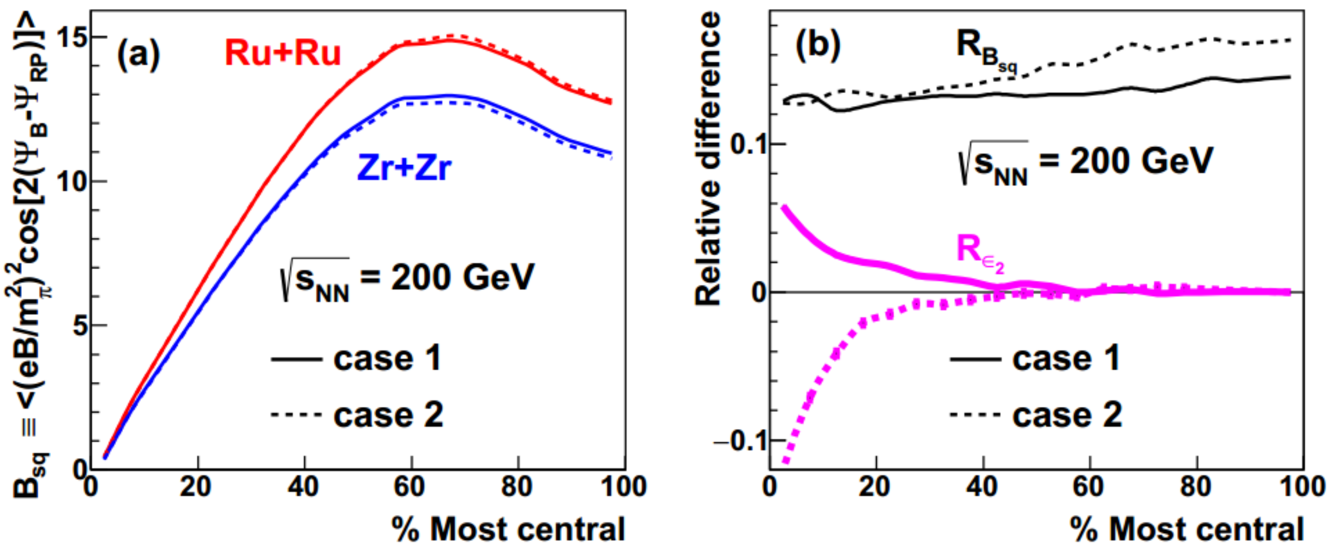


$^{96}_{44}Ru + ^{96}_{44}Ru$

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

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

See also: Xu etal 2017, 2018; Magdy etal 2018; Sun-Ko 2018; Shi etal 2019

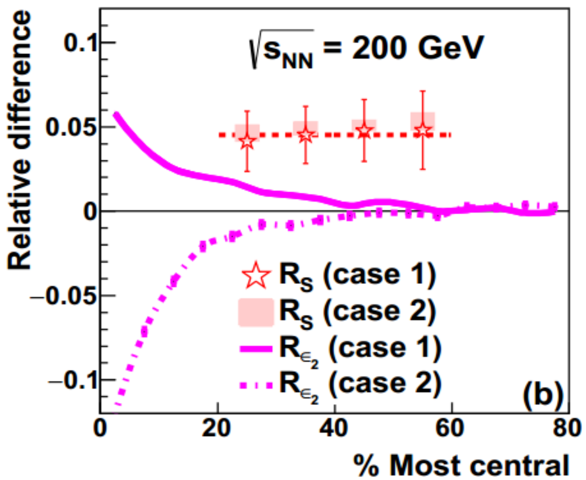
Isobar collisions

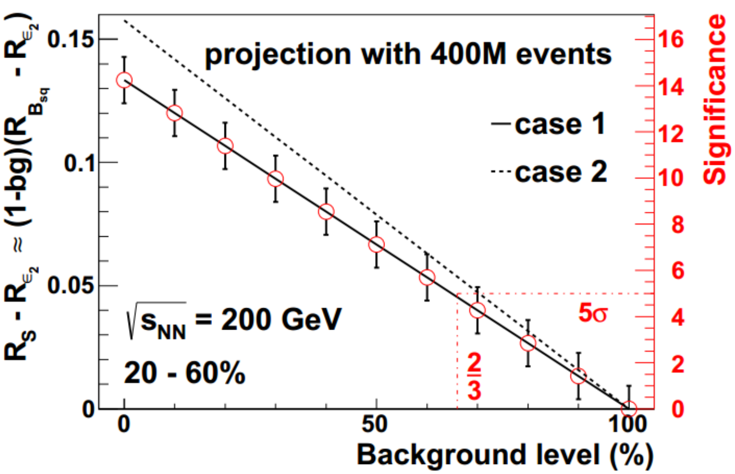
Gamma correlator $S \equiv N_{\text{part}}\Delta\gamma$, here N_{part} compensates dilution effect, as both CME and v2 background $\propto 1/N_{\text{part}}$

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, 2018





First run: 2018 @ RHIC
3.1B events for each type of collision

If bg=93%
3.1B events
3σ signal

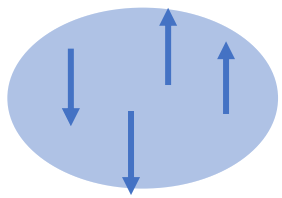
Spin polarization

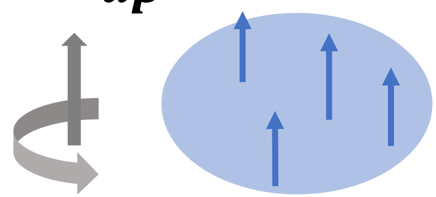
How vorticity polarizes spin?

Early idea: Liang-Wang PRL2005; Voloshin 2004

Vorticity interpretation (at thermal equilibrium)

$$H = H_0 - \boldsymbol{\omega} \cdot \boldsymbol{S} \quad \longrightarrow \quad \frac{dN}{d\boldsymbol{p}} \sim e^{-(H_0 - \boldsymbol{\omega}\cdot\boldsymbol{S})/T}$$





$$\longrightarrow \quad \mathrm{P} = \frac{N_\uparrow - N_\downarrow}{N_\uparrow + N_\downarrow} \sim \frac{\omega}{2T}$$

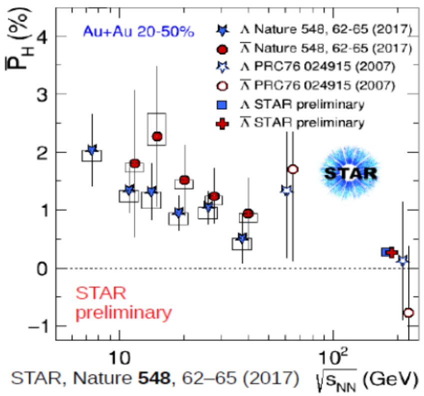
More rigorous derivation (Becattini etal 2013; Fang etal 2016; Liu etal 2020)

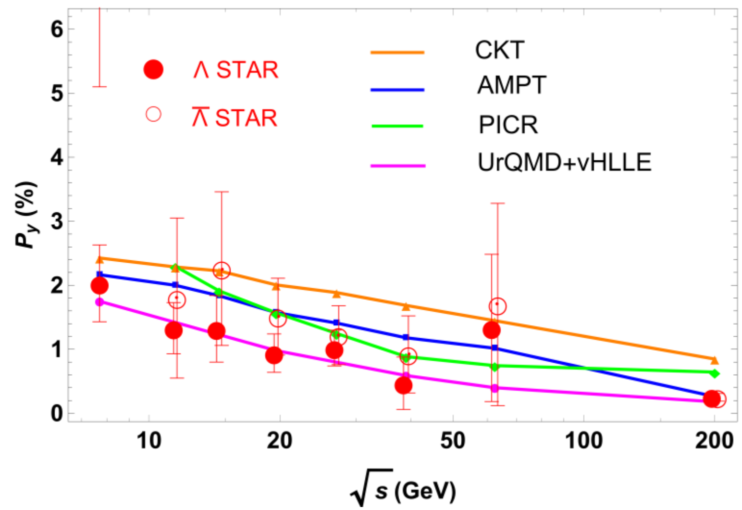
$$P^\mu(p) = \frac{1}{4m}\epsilon^{\mu\nu\rho\sigma}p_\nu \frac{\int d\Sigma_\lambda p^\lambda f'(x,p)\varpi_{\rho\sigma}(x)}{\int d\Sigma_\lambda p^\lambda f(x,p)} + O(\varpi^2)$$

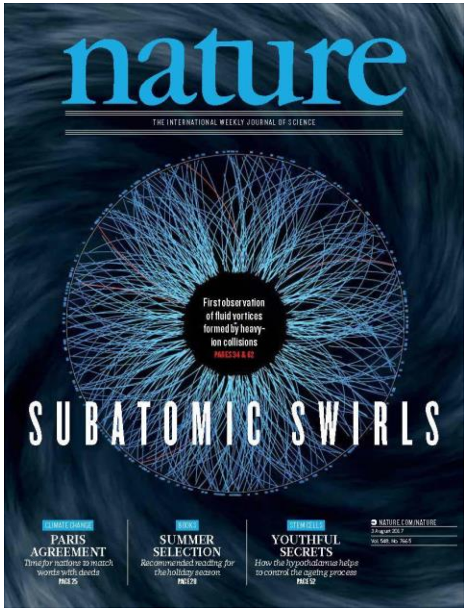
- Valid at global equilibrium. $f(x,p)$ is the distribution function (Fermi-Dirac)
- Thermal vorticity $\varpi_{\rho\sigma} = \left(\frac{1}{2}\right)\left(\partial_\sigma \beta_\rho - \partial_\rho \beta_\sigma\right)$
- Spin polarization is enslaved to thermal vorticity, not dynamical
- Friendly for numerical simulation (a spin Cooper-Frye type formula)

Global Λ spin polarization

The global polarization: **Experiment = Theory**



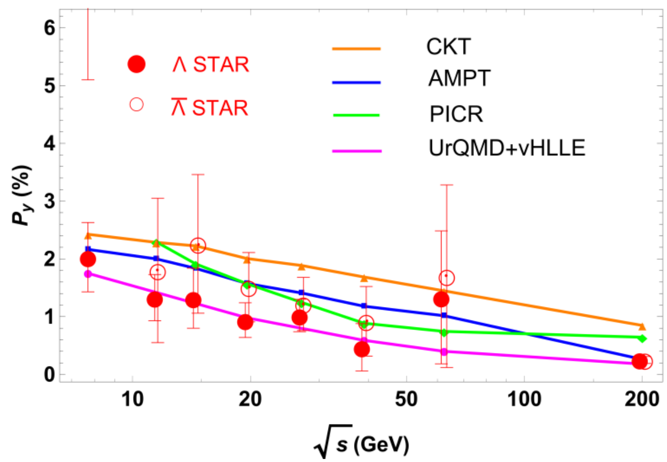




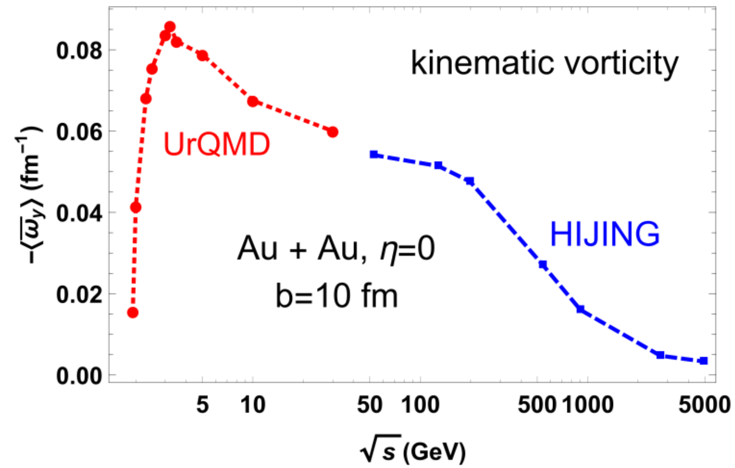
(Sun-Ko PRC2017; Wei-Deng-XGH PRC2019; Xie-Wang-Csernai PRC2017; Karpenko-Becattini EPJC2016; Li-Pang-Wang-Xia PRC2017; Shi-Li-Liao PLB2018; …)

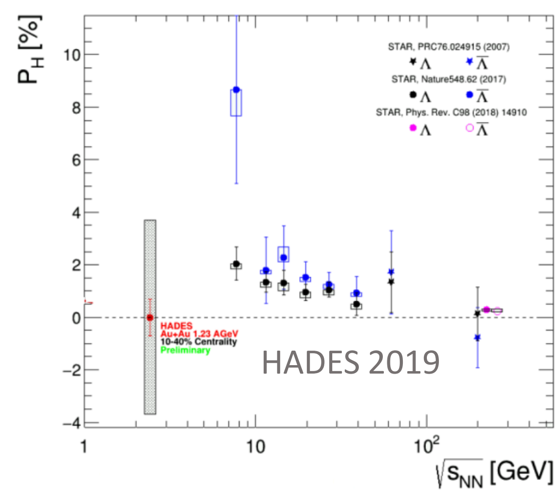
Global Λ spin polarization

The global polarization: **Experiment = Theory**



VS





Need to study polarization at very low $\sqrt{s}$: NICA, FAIR, HIAF, BES II@RHIC?

Differential Λ spin polarization

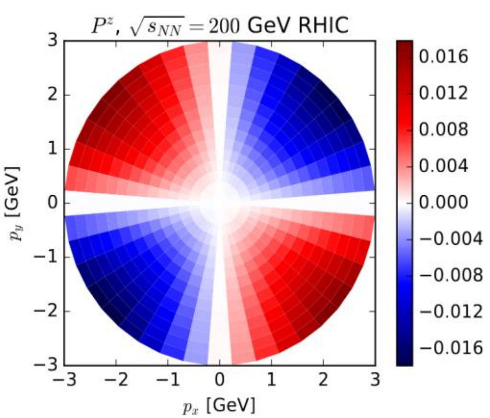
The global Λ polarization reflects the total amount of angular momentum retained in the mid-rapidity region. How is it distributed in different ϕ ?

- Spin harmonic flow: $$\frac{dP_{y,z}}{d\phi} = P_{y,z} + 2f_{2y,z}\sin(2\phi) + 2g_{2y,z}\cos(2\phi) + \cdots$$

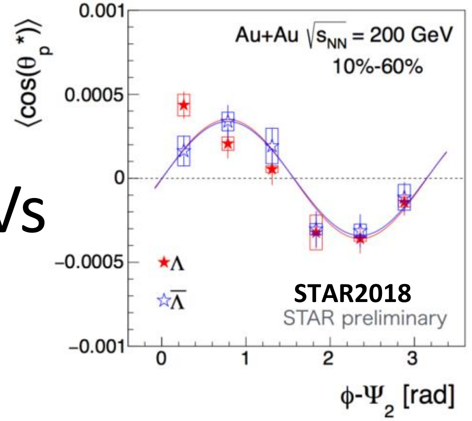
1) longitudinal polarization vs ϕ

2) Transverse polarization vs ϕ

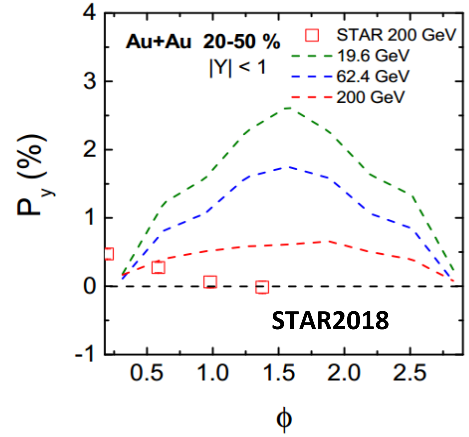
(Becattini-Karpenko PRL2018)



Vs



(Wei-Deng-XGH PRC2019)



$f_{2z}^{\text{ther}} < 0$ $\quad$ $f_{2z}^{\text{exp}} > 0$ $\quad$ $g_{2y}^{\text{ther}} < 0, g_{2y}^{\text{exp}} > 0$

We have a spin "sign problem"!

Vector meson spin alignment

Vorticity can also polarize spin of vector mesons, e.g. ϕ meson

Consider recombination $q + \bar{q} \to \phi$, the density matrix of q:

$$\rho^q = \frac{1}{2}\begin{pmatrix} 1+P_q & 0 \\ 0 & 1-P_q \end{pmatrix}$$

The density matrix of ϕ is obtained from $\rho^q \otimes \rho^{\bar{q}}$ in basis of |↑↑), |↑↓)- |↓↑), and (↓↓ |

$$\rho^V = \begin{pmatrix} \frac{(1+P_q)(1+P_{\bar{q}})}{3+P_q P_{\bar{q}}} & 0 & 0 \\ 0 & \frac{1-P_q P_{\bar{q}}}{3+P_q P_{\bar{q}}} & 0 \\ 0 & 0 & \frac{(1-P_q)(1-P_{\bar{q}})}{3+P_q P_{\bar{q}}} \end{pmatrix}$$

Suppose $P_q = P_{\bar{q}}$,

$$\rho_{00}^{\rho(\mathrm{rec})} = \frac{1-P_q^2}{3+P_q^2} < \frac{1}{3}$$

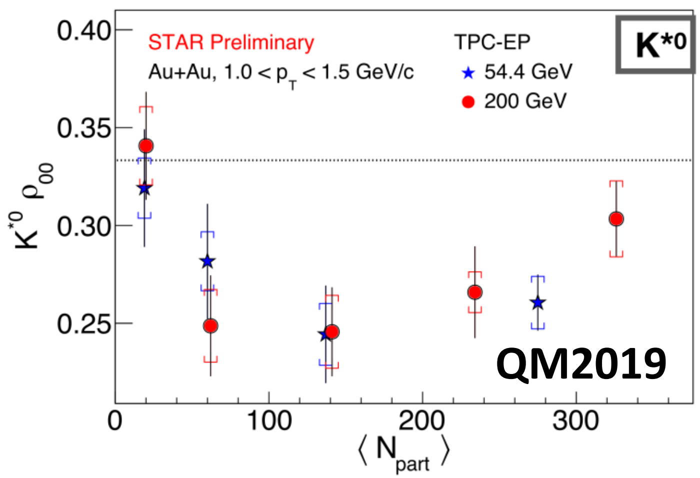
If fragmentation

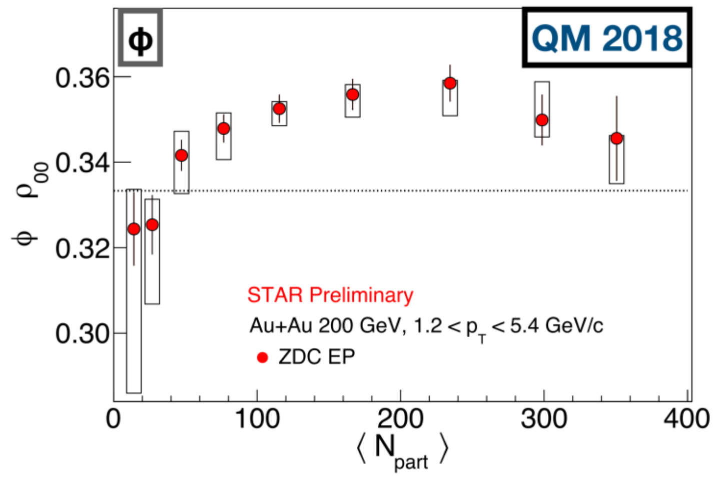
$$\rho_{00}^{V(frag)} = \frac{1+\beta P_q^2}{3-\beta P_q^2} > \frac{1}{3}$$

Liang-Wang 2005

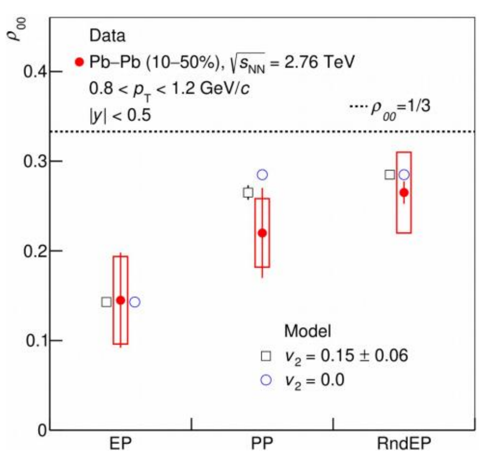
Given that P is few percent, ρ_{00} is expected close to 1/3

Vector meson spin alignment





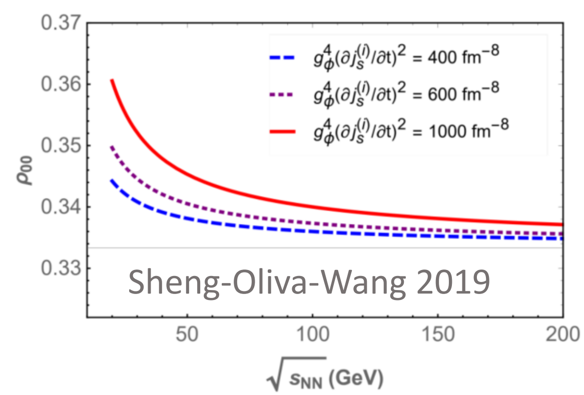
ALICE@QM2019



Puzzle:

- Too big and Sign is not as expected!

A recent theory based on strangeness magnetic field:



Spin sign problem and alignment puzzle

Attack the puzzles from theory side:

- Understand the vorticity (☺)
- Effect of feed-down decays (Xia-Li-XGH-Huang PRC2019, Becattini-Cao-Speranza EPJC2019)
  (Measured Λ may from decays of heavier particles)
- Go beyond equilibrium treatment (spin as a dynamic d.o.f)
  spin hydrodynamics
  spin kinetic theory
- Initial condition
  (Initial polarization, initial flow, … …)
- Other possibilities
  (chiral vortical effect (Liu-Sun-Ko 2019), mesonic mean-field(Csernai-Kapusta-Welle PRC2019), other spin chemical potential (Wu-Pang-XGH-Wang PRR2019, Florkowski etal2019), contribution from gluons, … …)
- New observables (ExHIC-P Collaboration 2002.10082)

Spin hydrodynamics

Relativistic idea spin hydrodynamics (Florkowski etal PRC2018)

Relativistic dissipative spin hydrodynamics (Hattori-Hongo-XGH-Matsuo-Taya PLB2019)

- Identify (quasi-)hydrodynamic variables: T and u^μ (4 for translation), $\omega^{\mu\nu} = -\omega^{\nu\mu}$(spin chemical potential, 3 for rotation, 3 for boost).
- Derivative expansion. Apply 2nd law of thermodynamics.
- Constitutive relations up to $O(\partial)$

$$T^{\mu\nu}_{(0)} = e u^\mu u^\nu + p(g^{\mu\nu} + u^\mu u^\nu)$$

heat current — shear viscosity — bulk viscosity

$$T^{\mu\nu}_{(1)} = -2\kappa\left(Du^{(\mu} + \beta\partial_\perp^{(\mu}\beta^{-1}\right)u^{\nu)} - 2\eta\partial_\perp^{<\mu}u^{\nu>} - \zeta(\partial_\mu u^\mu)\Delta^{\mu\nu}$$
$$-2\lambda\left(-Du^{[\mu} + \beta\partial_\perp^{[\mu}\beta^{-1} + 4u_\rho\omega^{\rho[\mu}\right)u^{\nu]} - 2\gamma\left(\partial_\perp^{[\mu}u^{\nu]} - 2\Delta^\mu_\rho\Delta^\nu_\lambda\omega^{\rho\lambda}\right)$$

boost heat current — rotational viscosity

- Hydrodynamic equations

$$\partial_\mu\left(T^{\mu\nu}_{(0)} + T^{\mu\nu}_{(1)} + O(\partial^2)\right) = 0$$

Energy-momentum conservation

$$\partial_\mu(u^\mu s^{\alpha\beta}) = T^{\beta\alpha}_{(1)} - T^{\alpha\beta}_{(1)} + O(\partial^2)$$

Angular momentum conservation

$$p = p(e, s^{\alpha\beta})$$

Equation of state

- Israel-Stewart type theory

$$\tau_\eta(D\sigma_\eta^{\mu\nu})_\perp + \sigma_\eta^{\mu\nu} = 2\eta\partial_\perp^{\langle\mu}u^{\nu\rangle}, \qquad \tau_\lambda(Dq^\mu)_\perp + q^\mu = \lambda(Du^\mu + \beta\partial_\perp^\mu T - 4\Omega^{\mu\nu}u_\nu),$$
$$\tau_\zeta(D\sigma_\zeta^{\mu\nu})_\perp + \sigma_\zeta^{\mu\nu} = \zeta\theta\Delta^{\mu\nu}, \qquad \tau_\gamma(D\phi^{\mu\nu})_\perp + \phi^{\mu\nu} = 2\gamma(\partial_\perp^{[\mu}u^{\nu]} + 2\Omega_\perp^{\mu\nu}),$$

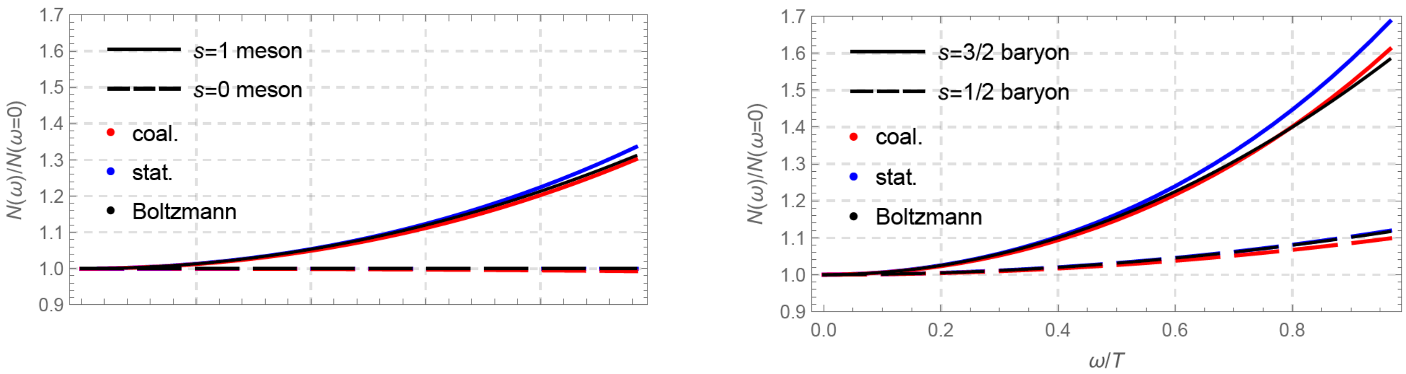
Spin dependent hadron yields

Vorticity is the "spin chemical potential" (ExHIC-P Collaboration 2002.10082)

$$E_{\rm h} = \sqrt{m_{\rm h}^2 + \boldsymbol{p}^2} - \boldsymbol{\mu}^{\rm ch}\cdot\boldsymbol{Q}_{\rm h} - \omega^{\rm ch} s_z$$

$$\Rightarrow \quad \frac{N^{\rm stat/coal}(\omega)}{N^{\rm stat/coal}(\omega=0)} \sim 1 + \frac{s(1+s)}{6}\left(\frac{\omega}{T}\right)^2$$

Naively, it is the same order as ρ_{00}, could be cross-check of vector spin alignment



Observable: ratio of e.g. $\frac{N_\phi}{N_K}$ or $\frac{N_\Omega}{N_\Xi}$ as function of centrality and energy

Summary

- Strong magnetic field and vorticity in heavy-ion collisions
- They provide novel probes to QCD matter through chiral anomalous transports and spin polarization
- Isobar collisions are very promising to disentangle the CME signal and the flow backgrounds
- Differential spin polarization and vector meson spin alignment remain as puzzles

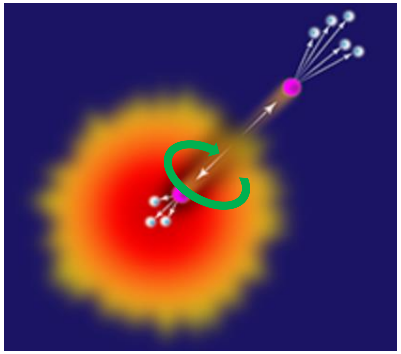
Need more works in both theory and experiments

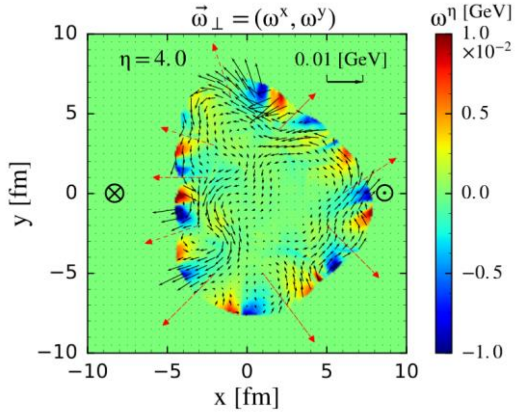
Thank you!

Back up

Other sources of vorticity

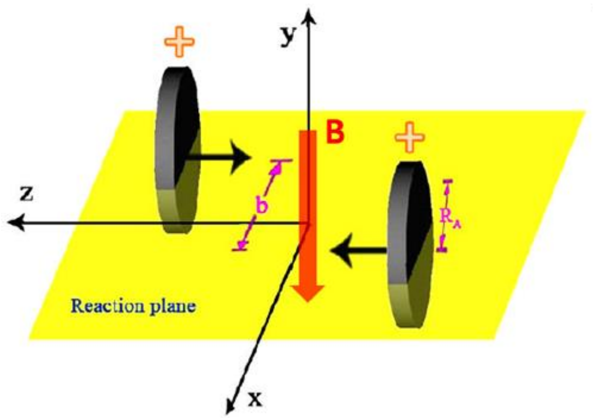
1) Jet

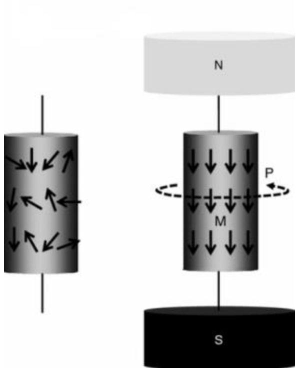




(Pang-Peterson-Wang-Wang 2016)

2) Magnetic field





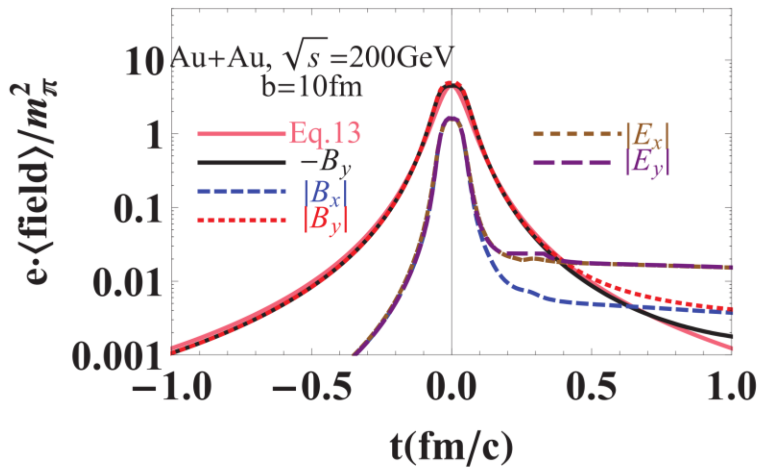
Einstein-de-Haas effect

More about ω and B

- We know $\omega = \omega(b, \sqrt{s}, r, t)$ in different collisions systems (Au + Au, Cu + Au, …) for various ω (kinematic, thermal, temperature, nonrelativistic, …)
- We know e-by-e fluctuation of ω and its correlation with collision geometry
- We know other sources of ω (jet, Einstein-de Haas effect, initial vortical fluctuation, …), but they are not carefully examined
- We know $B=B(b, \sqrt{s}, r)$ at $t=0$ in different collisions systems (Au + Au, Cu + Au, …)
- We know e-by-e fluctuation of B and its correlation with collision geometry
- We don’t know time evolution of B

Time dependence of B

- If quark-gluon matter is insulating

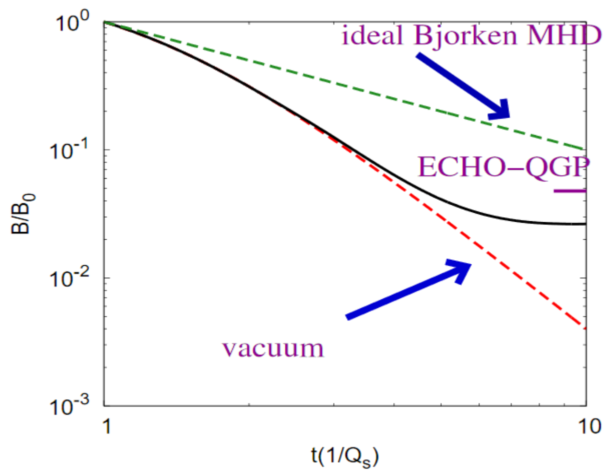


(Deng-XGH 2012; XGH 2015)

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

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

- If quark-gluon matter is conducting (the realistic case)



- Maxwell + Boltzman Eqs.
- 2-2 scattering (gg-gg, gq-gq)
- Assume Bjorken symmetry

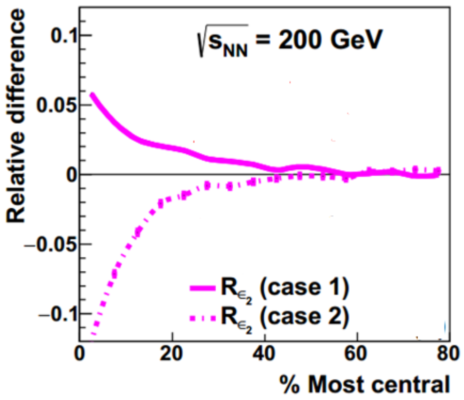
B field retained much longer

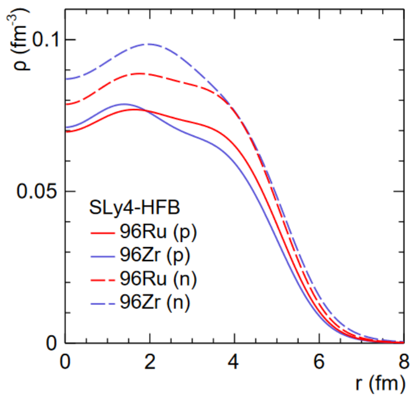
(XGH-Yan to appear)

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



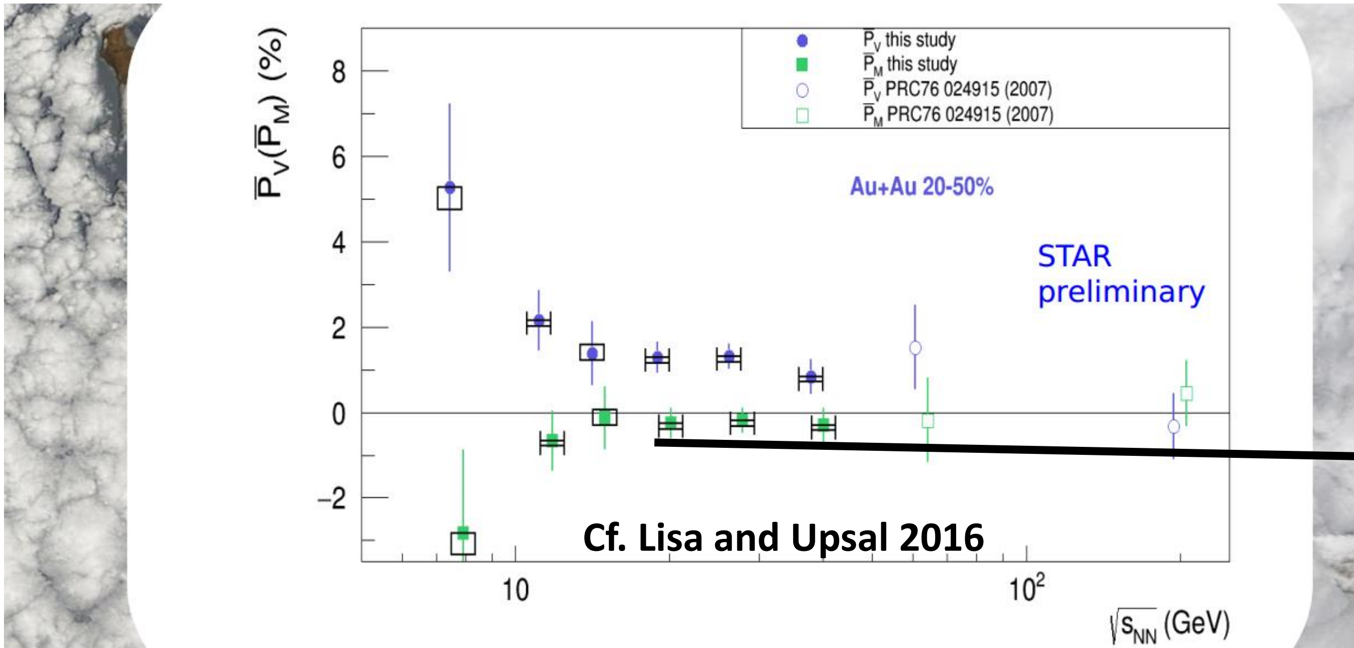


Measurement of the v_2 at central collision can tell us about the deformation of the nuclei

Xu, Wang, etal 2017

Isobar collisions: by-product 2

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



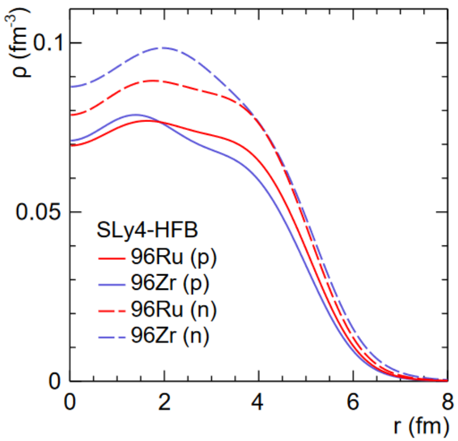
Decomposition into vortical and magnetic

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

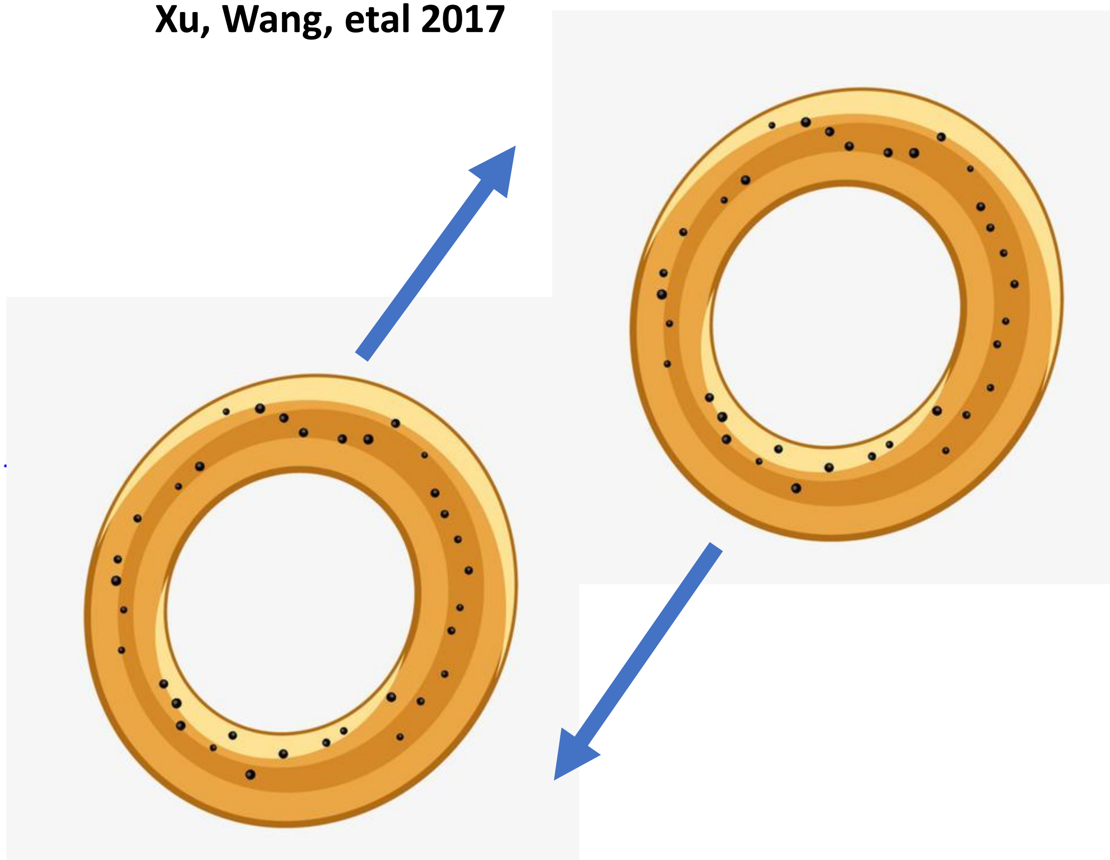
Expect 10% difference between Zr+Zr and Ru+Ru, if it is due to magnetic field. Need beam energy scan

Isobar collisions: by-product 2.1

By product 2.1: local polarization and nuclear structure?



Xu, Wang, etal 2017

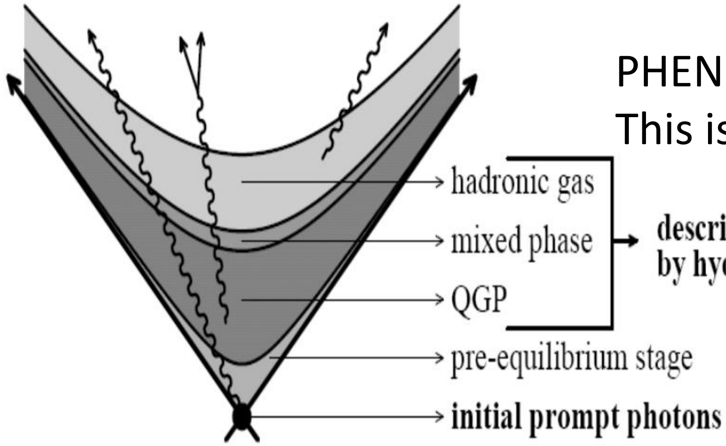


Spin polarization vs centrality in donut-donut collision would be different from bread-bread collision?

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"

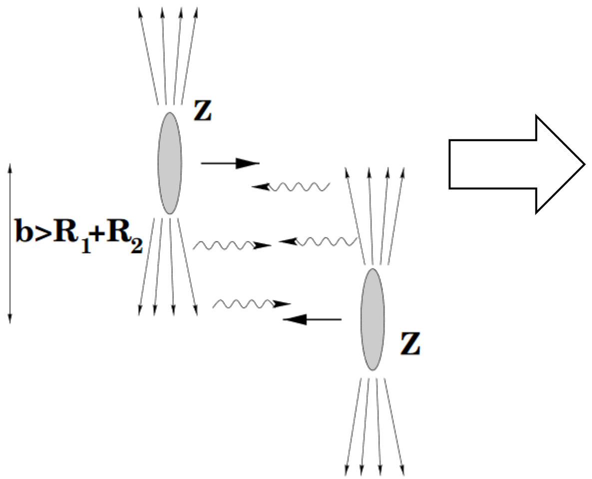
One possible solution: anisotropy in the early stage, like the magnetic field.

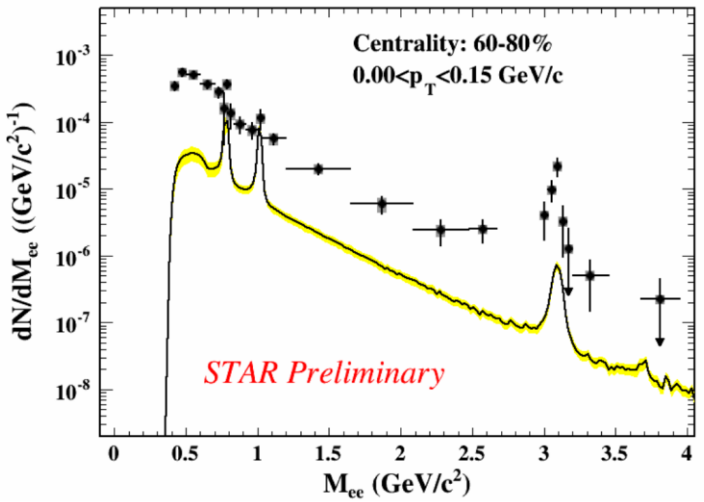
(Basar, Skokov, Kharzeev 2012, Tuchin 2012, Muller, Wang, Yang 2013, Yee 2013, …)

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

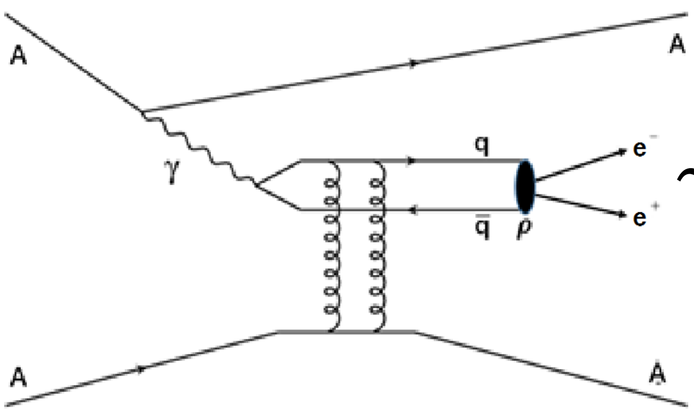
Isobar collisions: by-product 4

By product 4: enhanced dilepton production in very peripheral collisions? Useful for UPC.

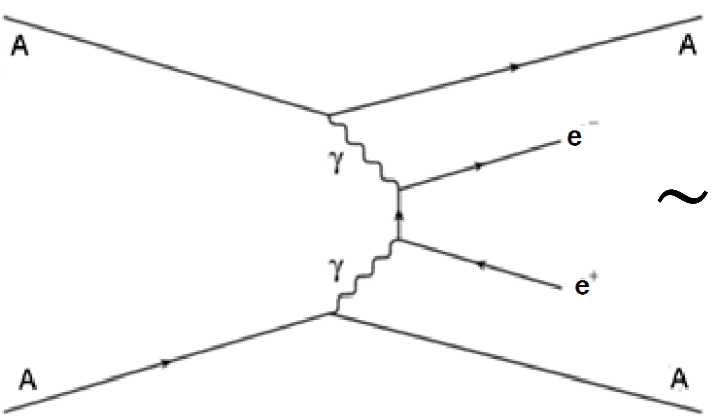




Scenario 1: photonuclear interaction



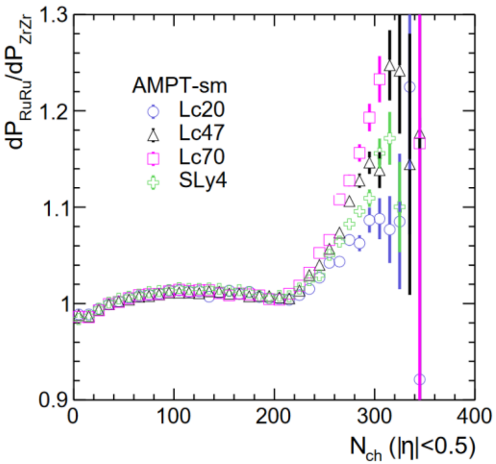
$\sim Z^2$

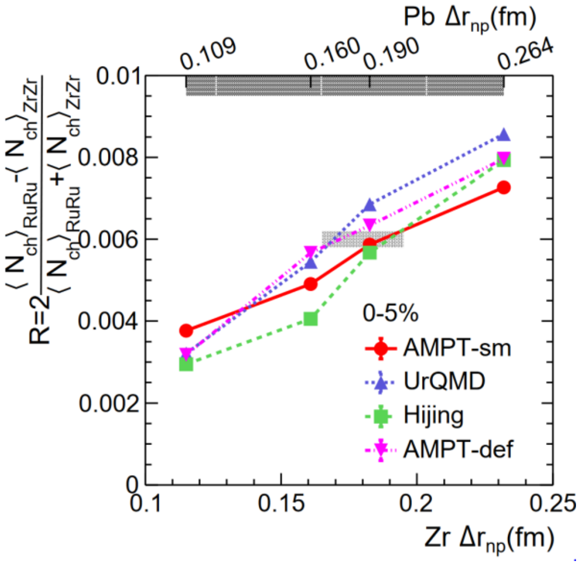


$\sim Z^4$

Isobar collisions: by-product 5

By product 5: probe the neutron skin





Provides useful information about symmetry energy.