18th 全国中高能核物理大会

Magnetic field and vorticity in heavy-ion collisions

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Outline

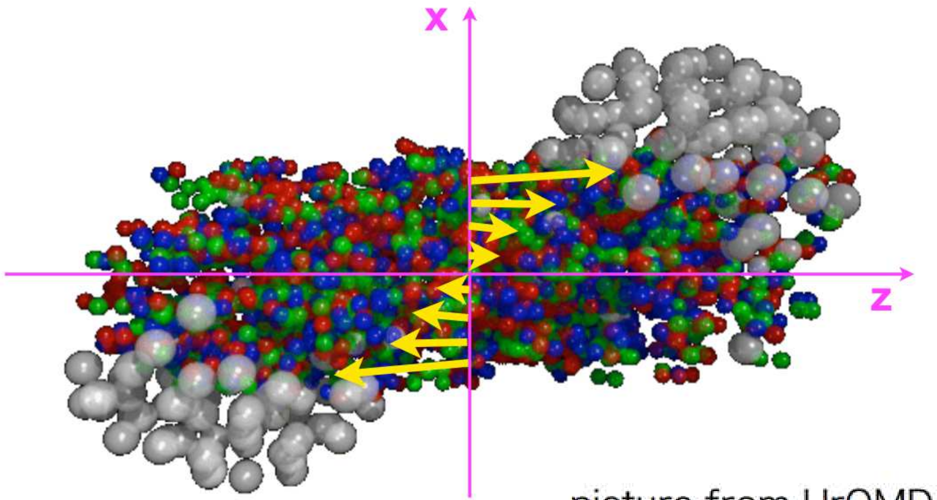
- **Generation of fluid vorticity and magnetic field**

- **Vorticity and spin polarization**
  Λ spin polarization and the "sign puzzle"

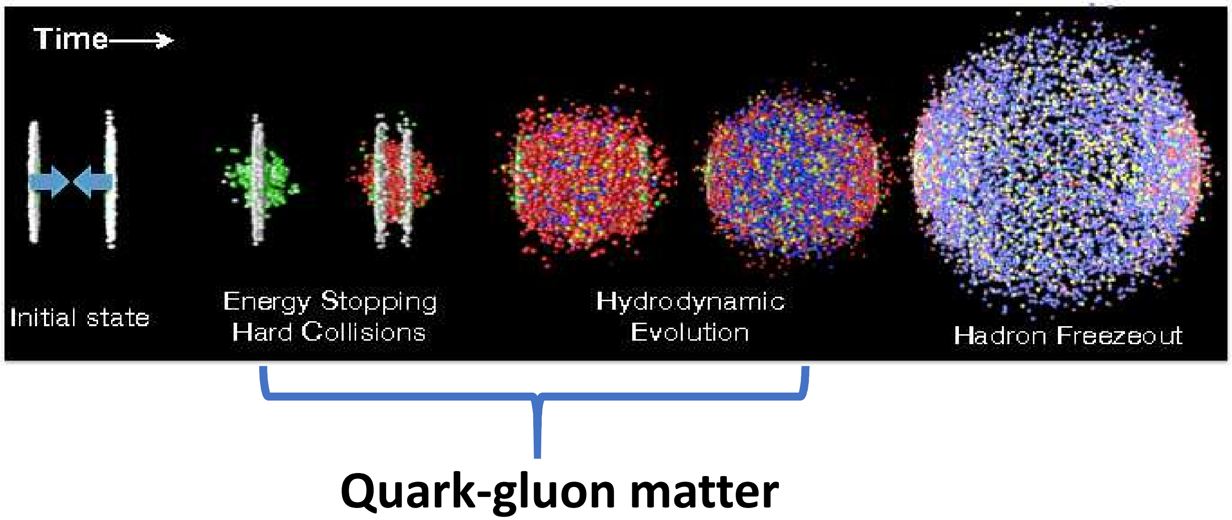
- **Magnetic field and charge separation observable**
  Chiral magnetic effect and isobar collisions

- **Summary**

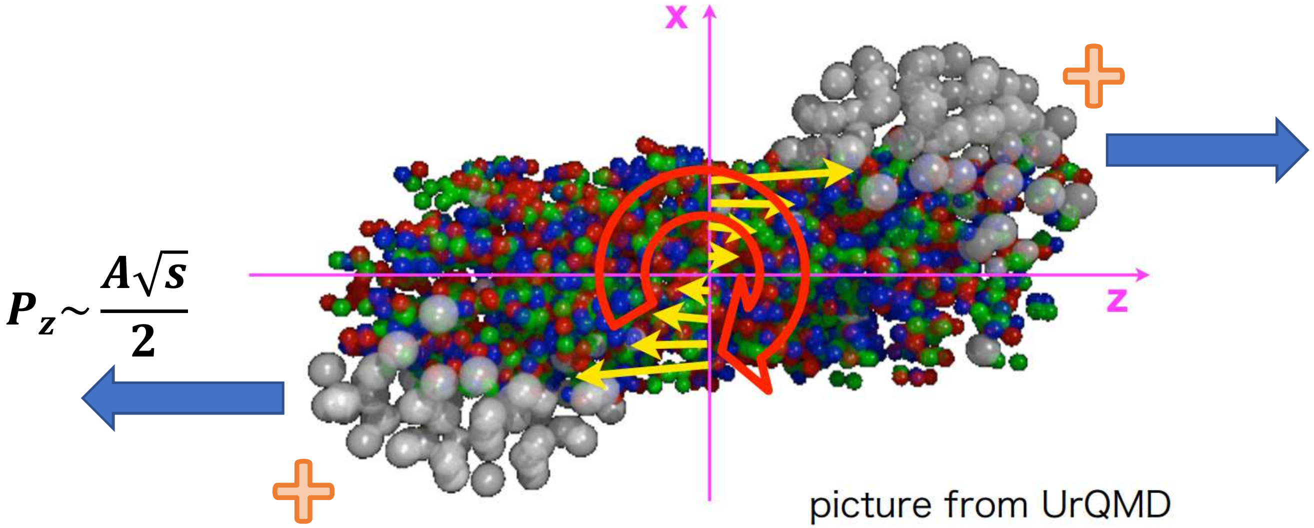
Heavy-ion collisions



picture from UrQMD



Heavy-ion collisions



Global angular momentum

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

Magnetic field

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

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

Vorticity by global AM

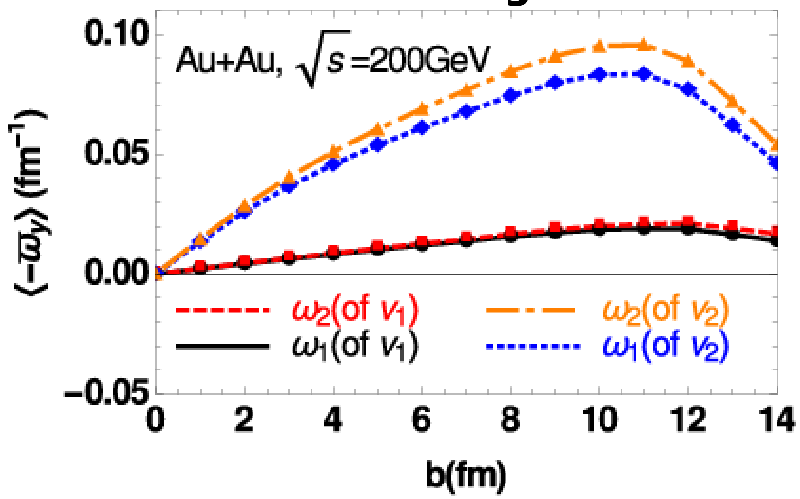
Global angular momentum

Local fluid vorticity

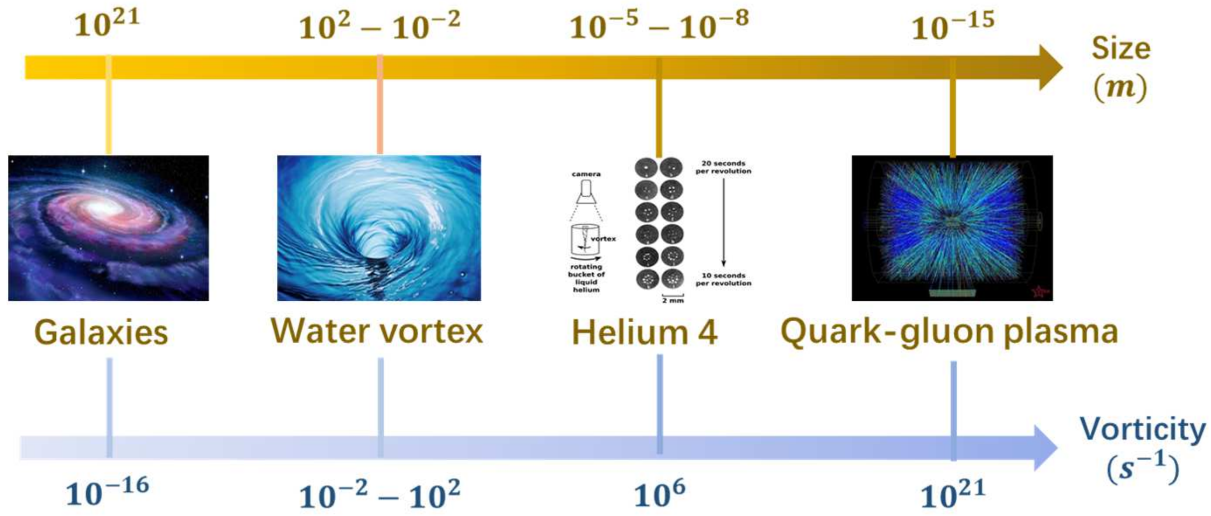
$$\boldsymbol{\omega} = \frac{1}{2}\nabla \times \boldsymbol{v}$$

(Angular velocity of fluid cell)

Deng-XGH 2016

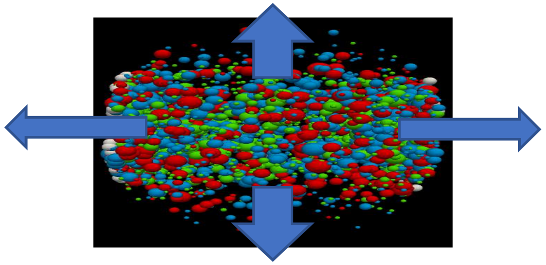


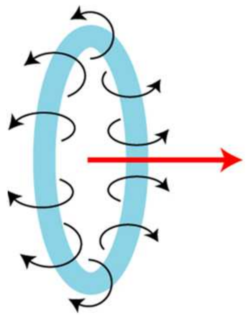
The most vortical fluid: Au+Au@RHIC at b=10 fm is $10^{20} - 10^{21}s^{-1}$

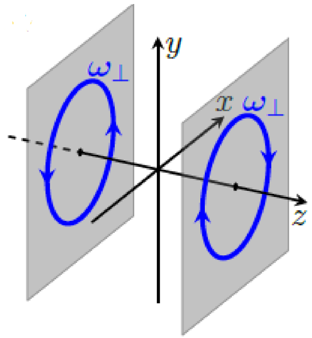


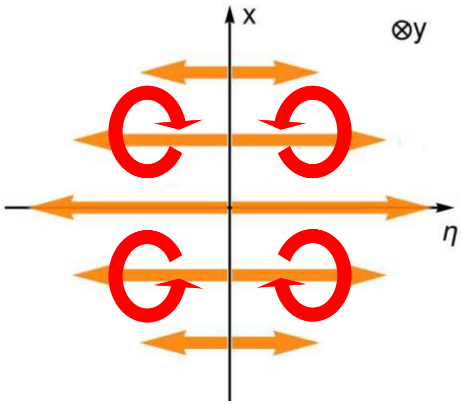
See also: Jiang, Lin, Liao 2016; Becattini etal 2015,2016; Csernai etal 2016; Pang-Petersen-Wang-Wang 2016; Xia-Li-Wang 2017,2018; Sun-Ko 2017; Wei-Deng-XGH 2018; …

Vorticity by inhomogeneous expansion

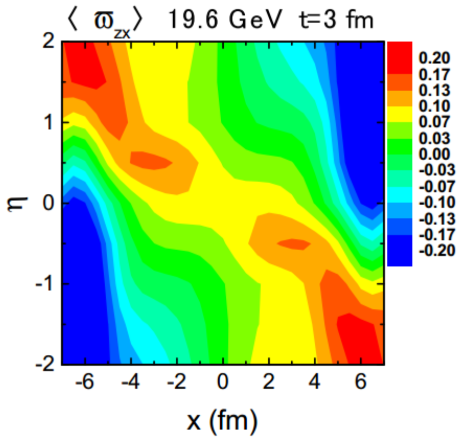


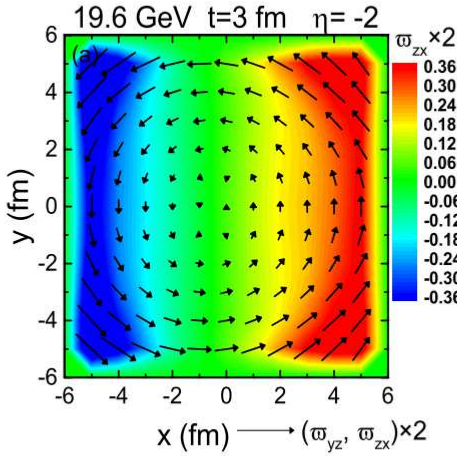






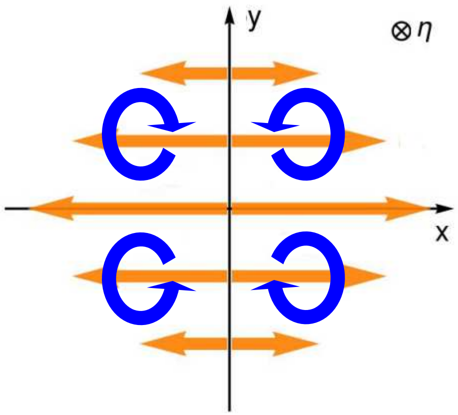
Transverse



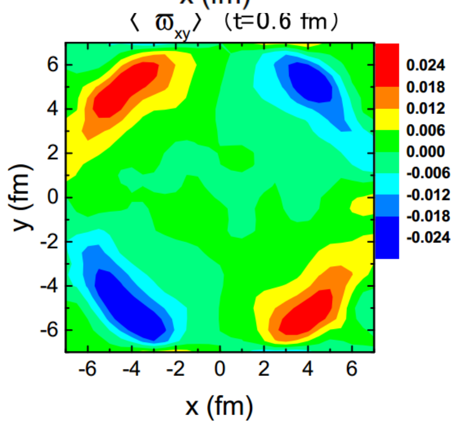


Wei,Deng,XGH 2018

Thermal vorticity

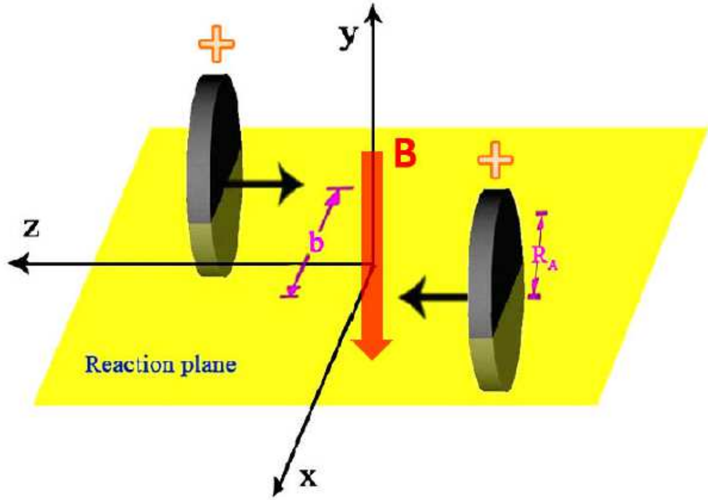


Longitudinal

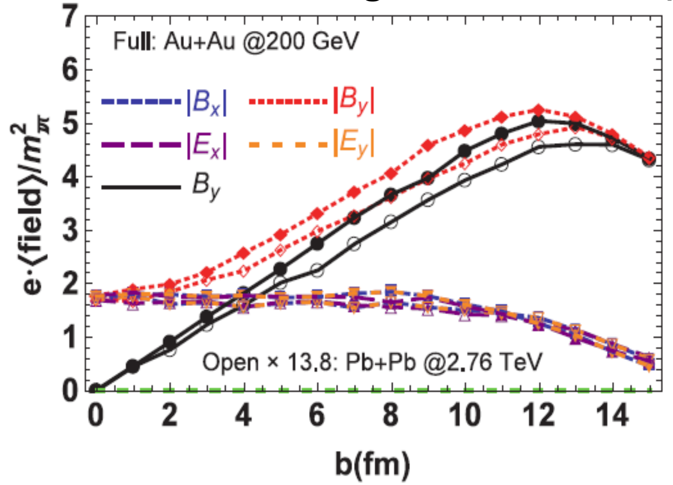


(see also: Becattini etal 2017; Jiang,Lin,Liao 2016; Xia,Li,Wang 2017; Teryaev,Usubov 2015, …)

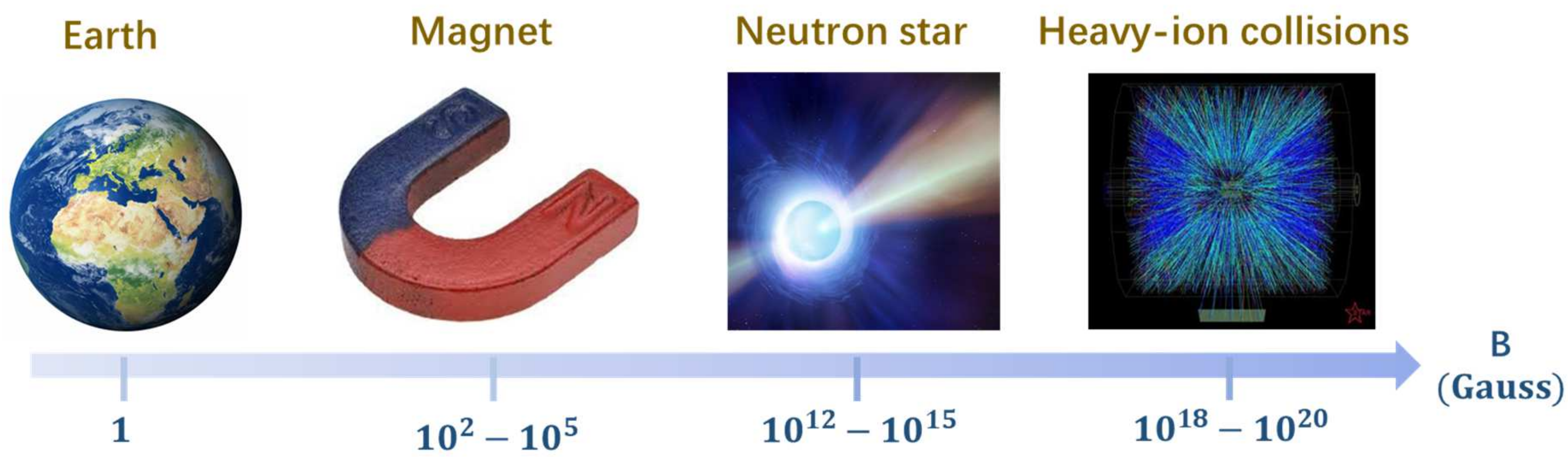
Magnetic fields in HIC



Deng and XGH 2012



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

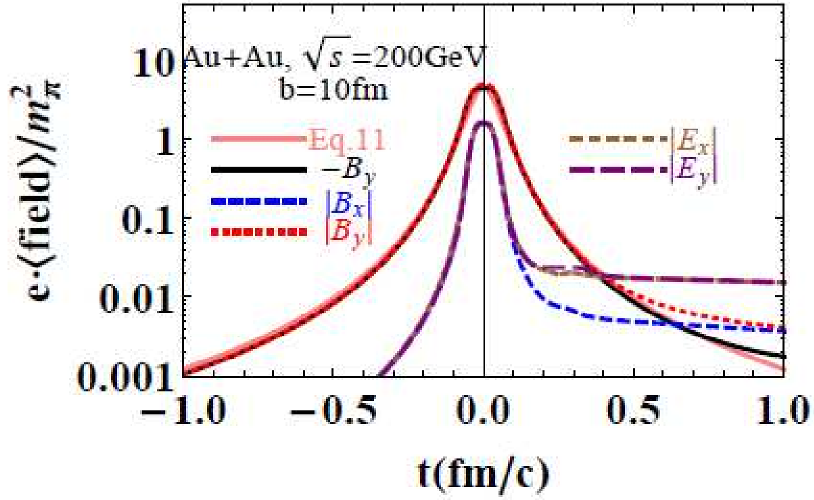


Known and unknown about ω and B

- We know ω = ω(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 don't know ω at very low $\sqrt{s}$; other sources of ω (jet, Einstain-de Haas effect, turbulence, …)
- 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 evolution of B

- If quark-gluon matter is insulating



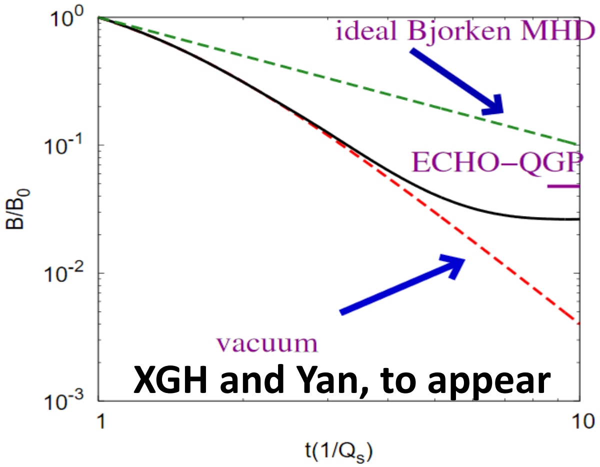
Well fitted by XGH 2015

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

Life time of B field

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

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

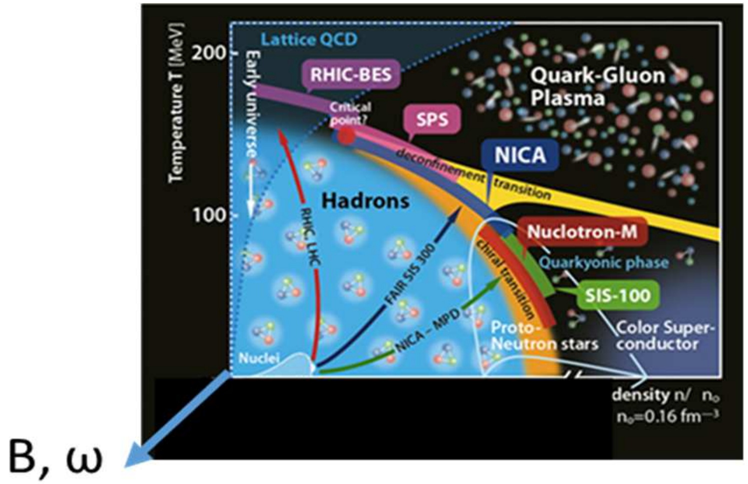


- Maxwell + Boltzman Eqs.
- 2-2 scattering (gg-gg, gq-gq)
- Assume Bjorken symmetry

B field retained much longer

Effects of ω and B

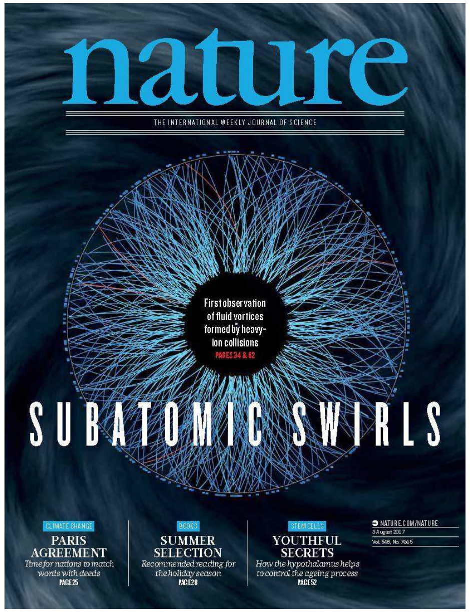
- They can induce many novel effects
- ω :
  - ◆Λ spin polarization
  - ◆Φ and K Spin alignment
  - ◆Chiral vortical effect,
    chiral vortical wave, …
  - ◆Reduction of scalar condensate,
    rotational chiral soliton lattice, …

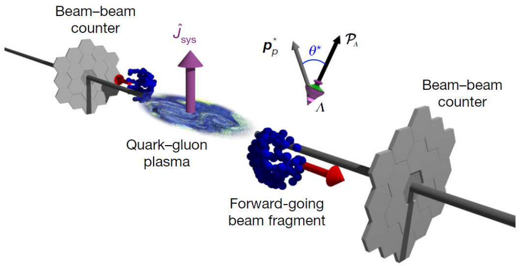


- B :
  - ◆Chiral magnetic effect
  - ◆Chiral separation effect, chiral magnetic wave
  - ◆(Inverse) Magnetic catalysis of ChSB
  - ◆EM-induced directed flow, Hall effect, photon elliptic flow, photoproduction of hadrons, anisotropic pressure and viscosities, broadening of dilepton spectrum, vacuum birefringence, … …

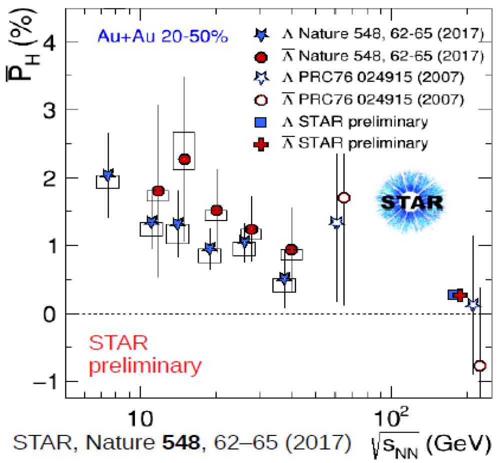
Λ spin polarization

Breakthrough measurement:2017





Averaged vorticity from 7.7 GeV-200 GeV: $\omega \approx (9 \pm 1) \times 10^{21} s^{-1}$ **"Most vortical fluid!"**



STAR, Nature **548**, 62–65 (2017)

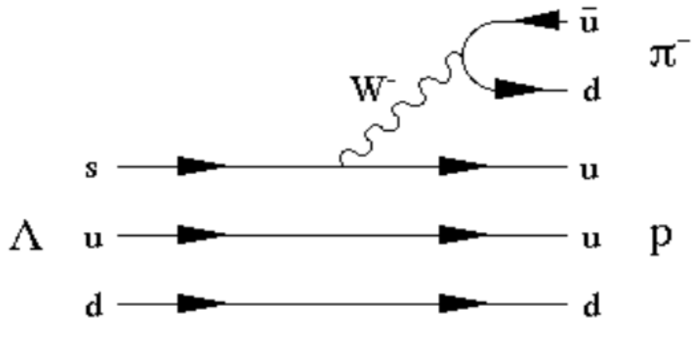
LETTER

doi:10.1038/nature23004

Global Λ hyperon polarization in nuclear collisions

The STAR Collaboration*

Why Λ hyperon?



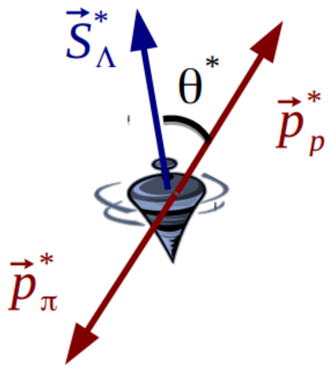
$\Lambda \Rightarrow p\pi^-$

parity-violating decay of hyperons

In case of Λ's decay, daughter proton preferentially decays in the direction of Λ's spin (opposite for anti-Λ)

$$\frac{dN}{d\Omega^*} = \frac{1}{4\pi}(1 + \alpha \mathbf{P_\Lambda} \cdot \mathbf{p_p^*})$$

α: Λ decay parameter (=0.642±0.013)
P_Λ: Λ polarization
p_p^*: proton momentum in Λ rest frame

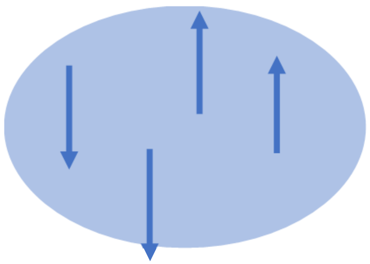


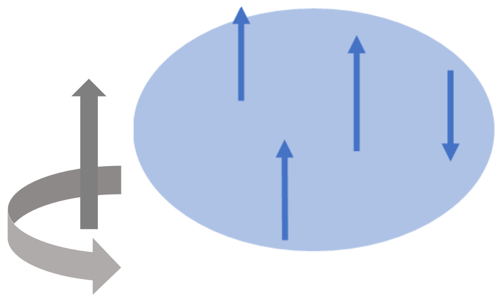
$\Lambda \rightarrow p + \pi^+$
(BR: 63.9%, cτ ~7.9 cm)

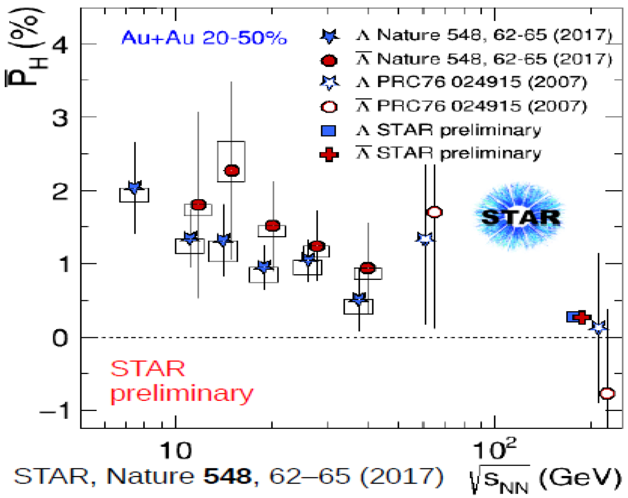
Spin-vorticity coupling

Early idea: Liang-Wang 2004

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







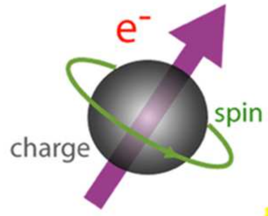
$$\mathrm{P} = \frac{N_\uparrow - N_\downarrow}{N_\uparrow + N_\downarrow} \sim \frac{\langle \omega \rangle}{T}$$

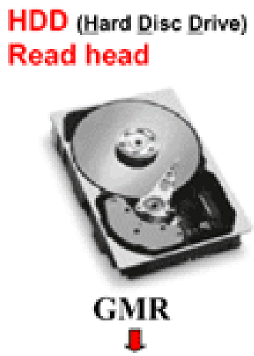
Possible magnetic-field contribution. A way to measure B?

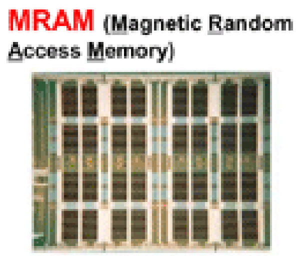
$$H = H_0 - \boldsymbol{\omega} \cdot \boldsymbol{J} - \boldsymbol{m} \cdot \boldsymbol{B}$$

Subatomic spintronics

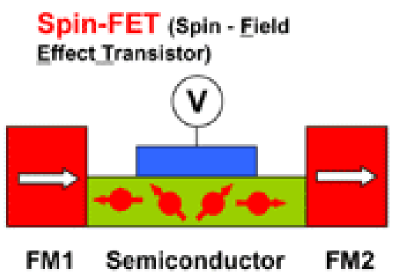
- **Electronics: let charge work for us**
- **Spintronics: let spin work for us**







M. Johnson, *IEEE Spectrum* **37**, 33 (2000).



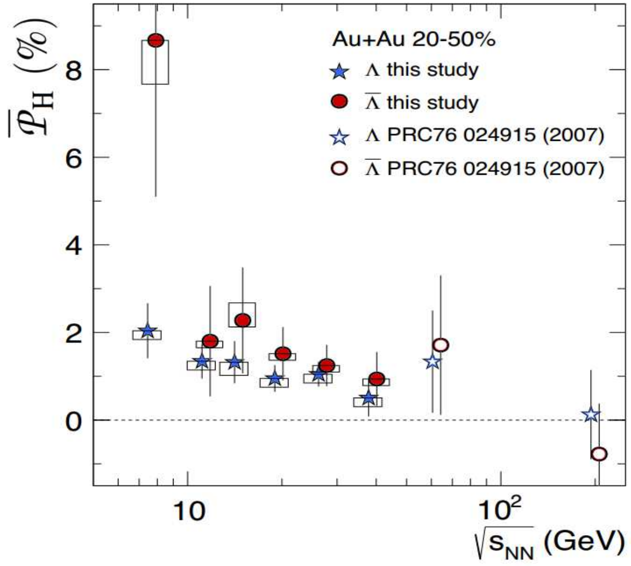
S. Datta and B. Das, *Appl. Phys. Lett.* **56**, 665 (1990).

- **The STAR 2017 paper opened the era of subatomic spintronics (spin-polarization probe of quark-gluon matter)**
- **May also give insight to proton spin puzzle?**

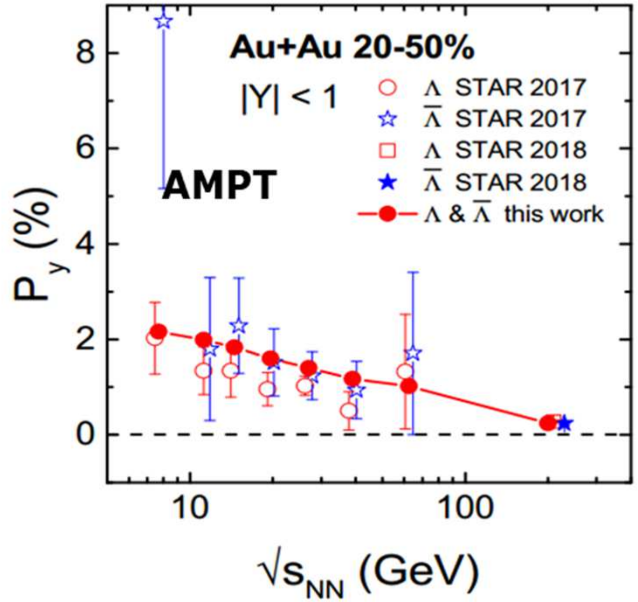
Theory vs experiment

The global spin polarization:

STAR 2017



Wei-Deng-XGH 2018



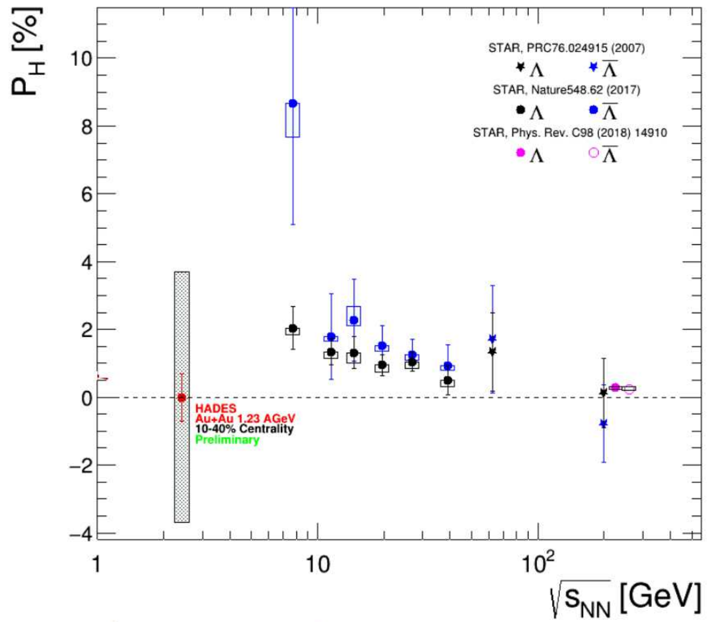
Experiment = Theory

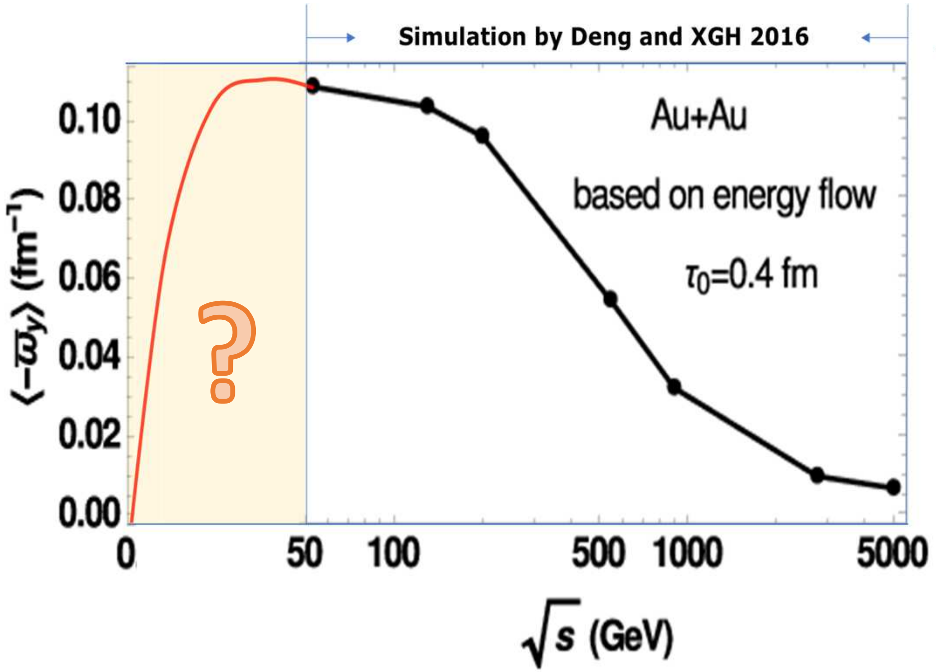
See also: Xia-Li-Wang 2017; Sun-Ko 2017; Karpenko-Becattini 2017

Theory vs experiment

The global spin polarization: going to very low $\sqrt{s}$

STAR 2017 + HADES 2019





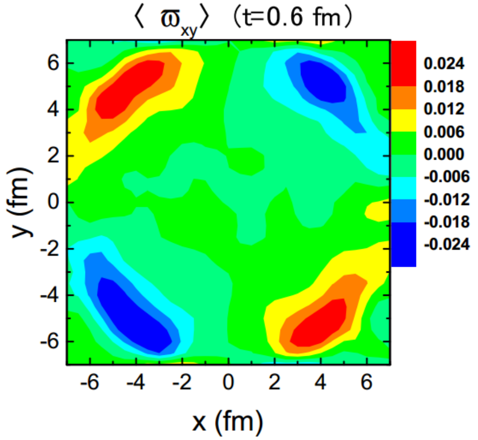
Experiment = ? = Theory

Need to study vorticity at very low $\sqrt{s}$

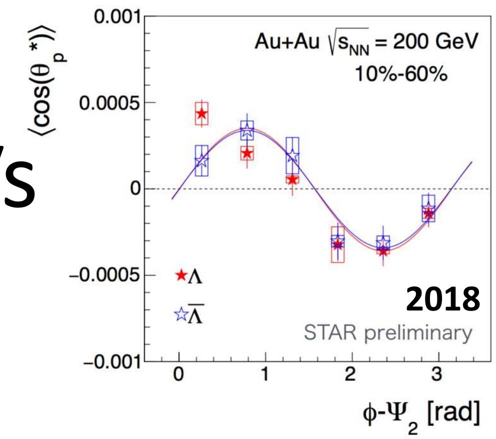
A "sign puzzle"

- **But: discrepancies between theory and experiments**

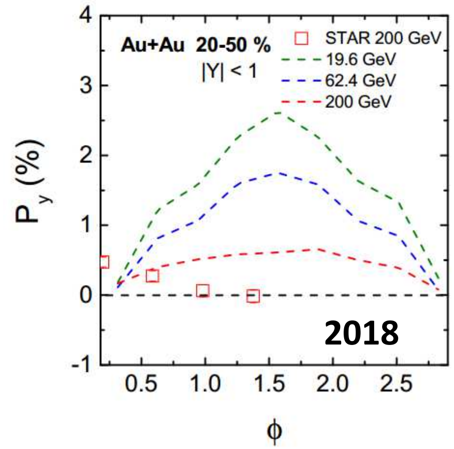
1) longitudinal polarization vs ϕ



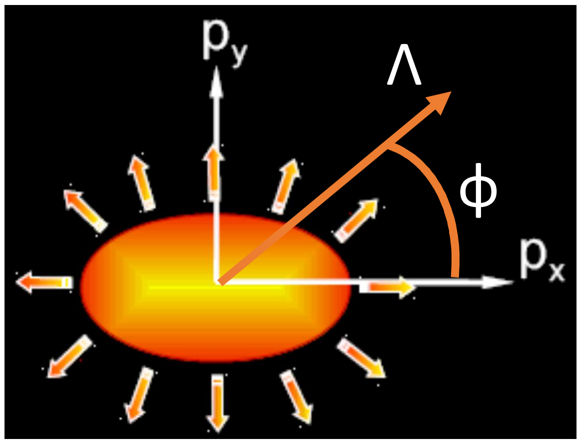
Vs



2) Transverse polarization vs ϕ



Azimuthal angle ϕ



Experiment Refs:

STAR Collaboration, arXiv:1805.04400

arXiv:1905.11917

Niida, Quark matter 2018

C. Zhou, Quark matter 2018

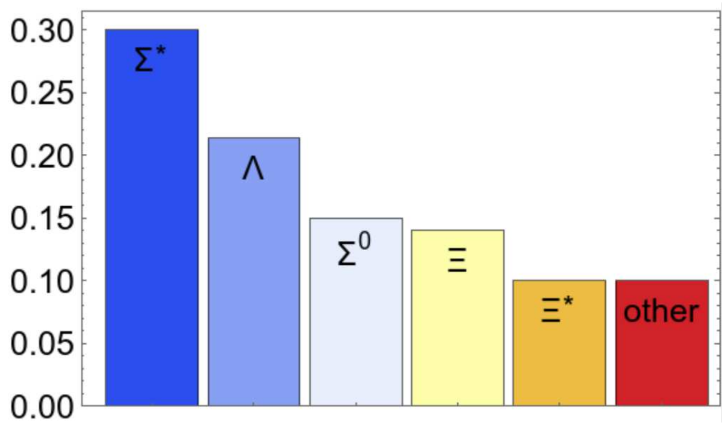
B. Tu, Quark matter 2018

A "sign puzzle"

- **To resolve the discrepancies, from the theory side, we need to:**
  - Understand the properties of fluid vorticity itself (done)
  - Understand the decays contribution from other hyperons
  - Find other observables which are always helpful: spin-alignment at central collisions, the chiral vorticity effects, … …
  - Understand how vorticity polarizes spin and how the spin polarization evolves: spin kinetic theory or spin hydrodynamics
  - … …

Feed-down effects

(1) A large fraction of the Λ hyperon comes from decays of higher-lying hyperons



Cf. Hui Li

(2) The feed-down effect may provide a resolution to the "polarization sign puzzle". For example, EM decay, if Σ is polarization along the vorticity, its daughter Λ must be polarized opposite to the vorticity

$$\Sigma^0 \to \Lambda + \gamma \qquad \left(\frac{1}{2}\right)^+ \to \left(\frac{1}{2}\right)^+ 1^-$$

Decay channels

TABLE II. The primordial yield ratio N_i/N_Λ, spin, parity, and decay channels of strange particles

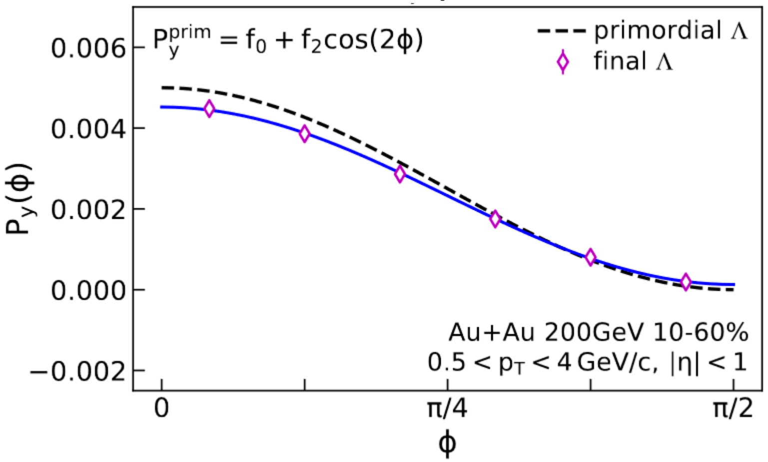
	N_i/N_Λ	spin and parity	decay channel
Λ	1	$1/2^+$	-
$\Lambda(1405)$	0.236	$1/2^-$	$\Sigma^0\pi$
$\Lambda(1520)$	0.265	$3/2^-$	$\Sigma^0\pi$
$\Lambda(1600)$	0.098	$1/2^+$	$\Sigma^0\pi$
$\Lambda(1670)$	0.061	$1/2^-$	$\Sigma^0\pi$, $\Lambda\eta$
$\Lambda(1690)$	0.112	$3/2^-$	$\Sigma^0\pi$
Σ^0	0.686	$1/2^+$	$\Lambda\gamma$
Σ^{*0}	0.533	$3/2^+$	$\Lambda\pi$
Σ^{*+}	0.535	$3/2^+$	$\Lambda\pi$, $\Sigma^0\pi$
Σ^{*-}	0.524	$3/2^+$	$\Lambda\pi$, $\Sigma^0\pi$
$\Sigma(1660)$	0.068	$1/2^+$	$\Lambda\pi$, $\Sigma^0\pi$
$\Sigma(1670)$	0.125	$3/2^-$	$\Lambda\pi$, $\Sigma^0\pi$
Ξ^0	0.343	$1/2^+$	$\Lambda\pi$
Ξ^-	0.332	$1/2^+$	$\Lambda\pi$
Ξ^{*0}	0.228	$3/2^+$	$\Xi\pi$
Ξ^{*-}	0.224	$3/2^+$	$\Xi\pi$

Xia-Li-XGH-Huang 2019

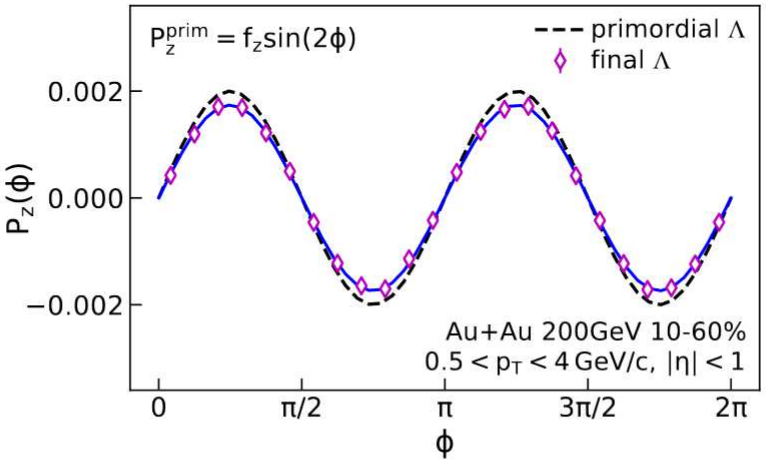
Decay contribution

- Assuming the primordial particles are polarized the same :

Transverse polarization



Longitudinal polarization



Conclusion:

Feed-down decays suppress 10% the primordial polarization, but it does not solve the sign puzzle

Sign puzzle is still there.

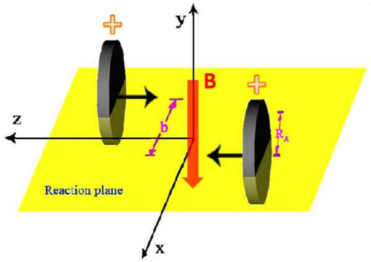
Any suggestions, comments, are welcome.

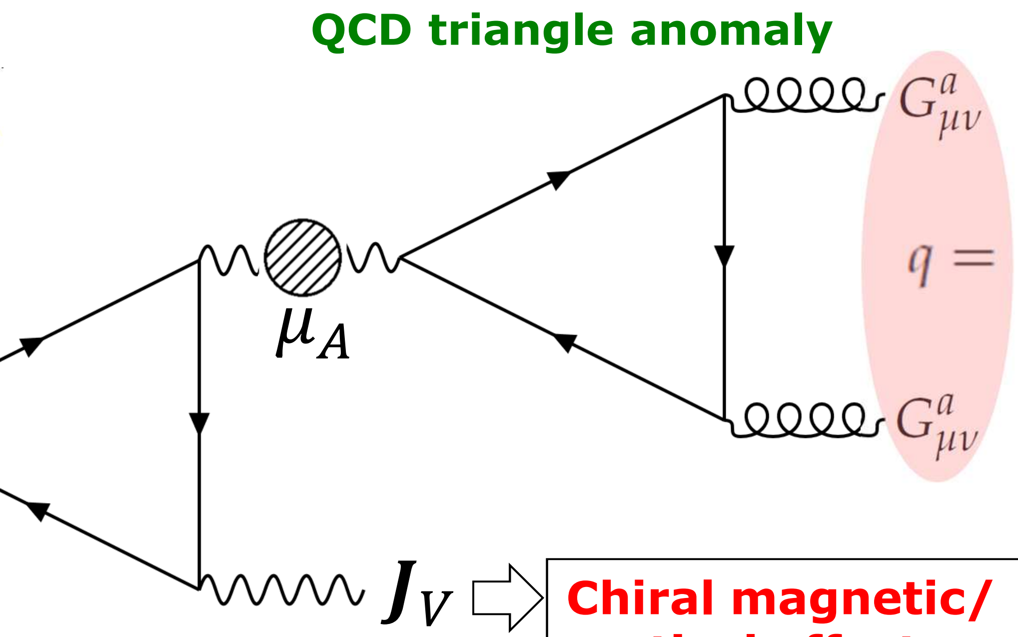
Xia-Li-XGH-Huang 2019

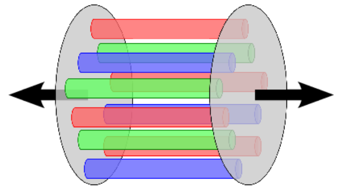
See also: Becattini-Cao-Speranza, 2019

Charge separation observable

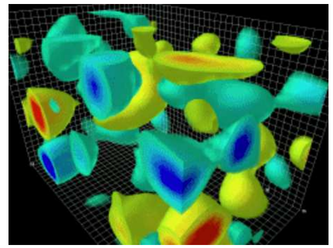
Chirality generation and CME,CVE

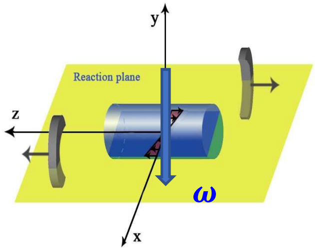






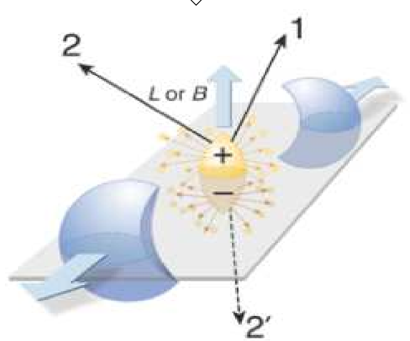
$$q = \frac{g^2}{32\pi^2} \int d^4x G^a_{\mu\nu} \tilde{G}^{\mu\nu}_a$$





QED triangle anomaly

Chiral magnetic/ vortical effects



Initial state topological fluctuations

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

Experimental test of CME

Event-by-event charge separation wrt. reaction plane

We investigate the charge dependent two-particle correlations with respect to the reaction plane:

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

Direct measurement of "*a*" would yield zero value. So we need "three point-correlator"—observable "γ"!

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

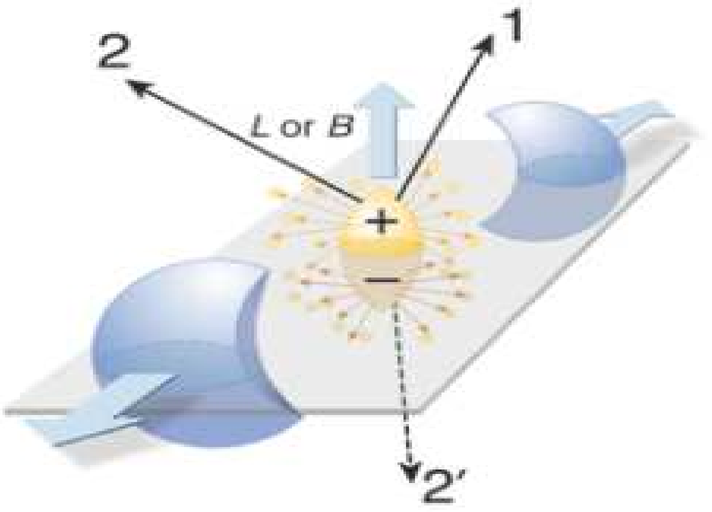
$$= [\langle v_{1,\alpha} v_{1,\beta}\rangle + B_{in}] - [\langle a_\alpha a_\beta\rangle + B_{out}]$$

Directed flow: expected to be same for "same sign" and "opposite sign"

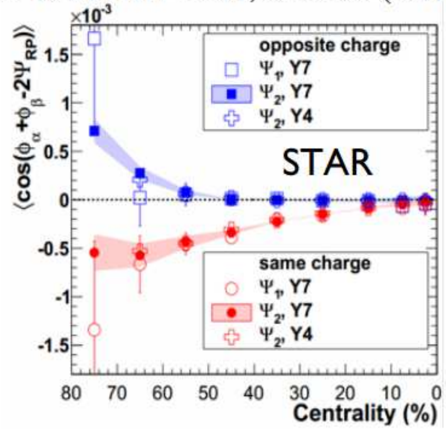
Background effects: could cancel out, but flow-related background may still exist.

P-even quantity: still sensitive to separation effect, i.e., different for "same sign" and "opposite sign"

S. Voloshin, Physical Review C. 70 (2004) 057901

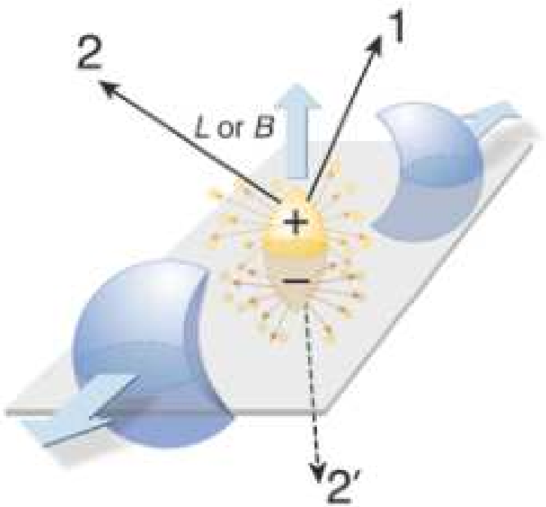


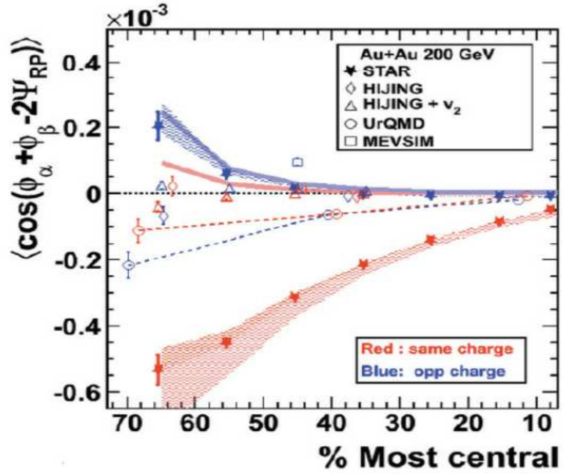
PHYSICAL REVIEW C **81**, 054908 (2010)



Experimental test of CME

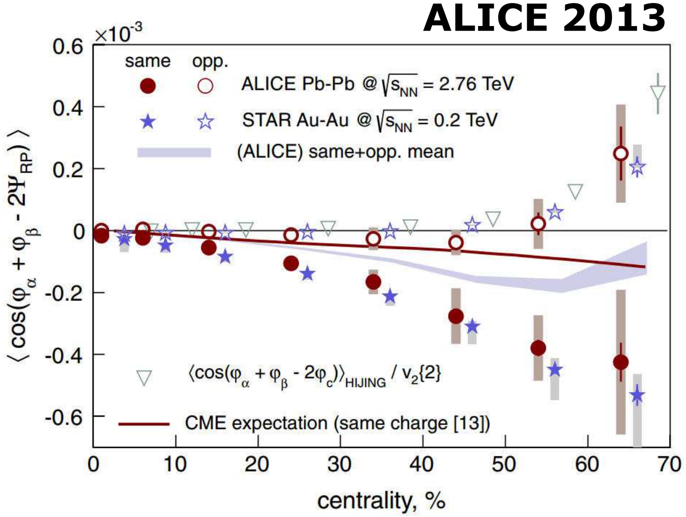
Event-by-event charge separation wrt. reaction plane



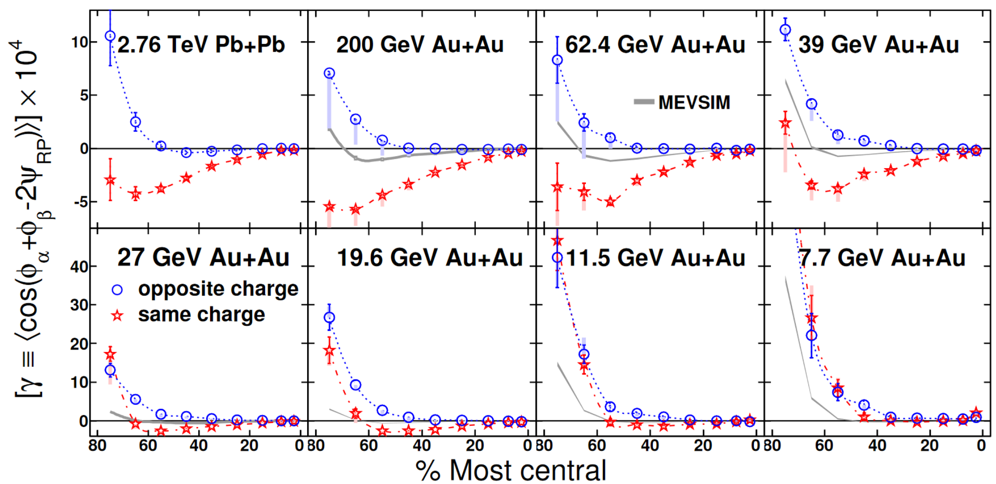


STAR 2010

ALICE 2013



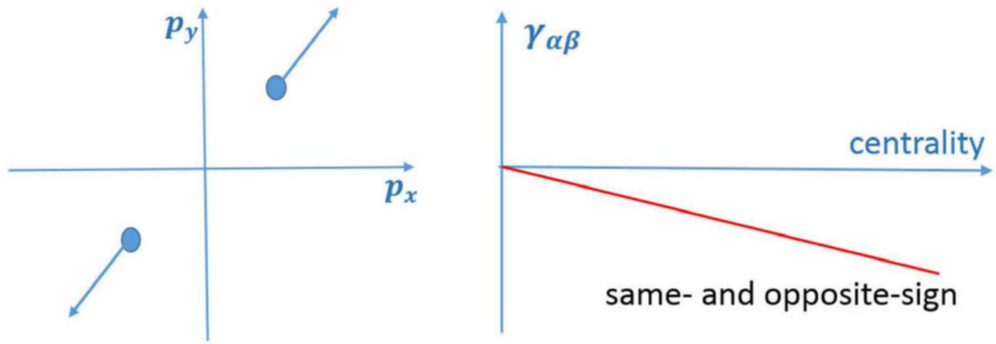
STAR 2014



Back-ground contributions to CME

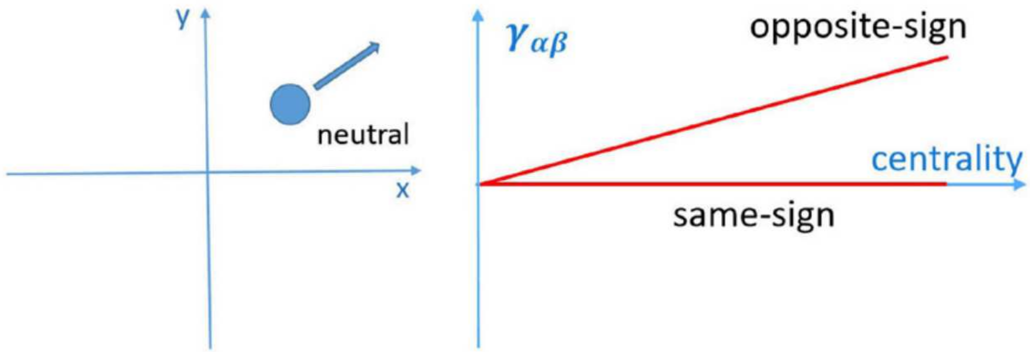
Back-ground contributions to gamma correlator

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 cluster/resonance/hadrons 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)

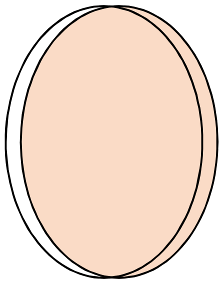
6) Modeling background contributions, **new observables**.
(LCC, Resonance decays, ……)

Challenges but also opportunities for theorists!

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

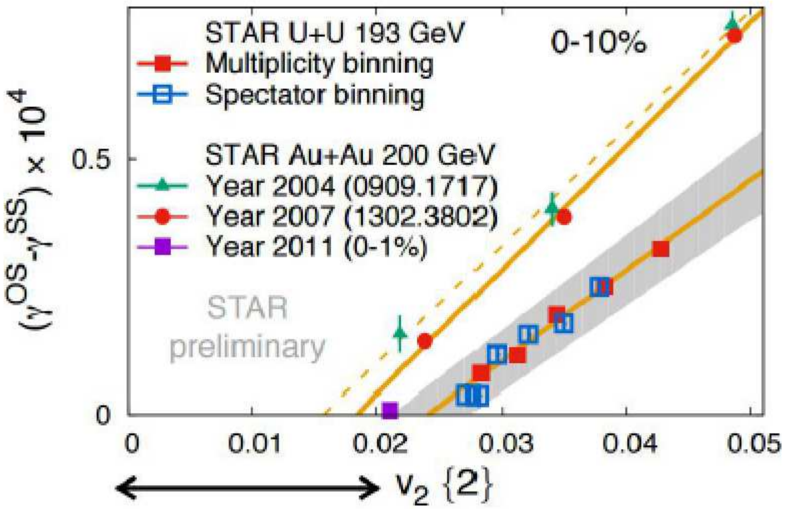


U nucleus is deformed,

Very cental body-body:

B=0 while $v_2 \neq 0$

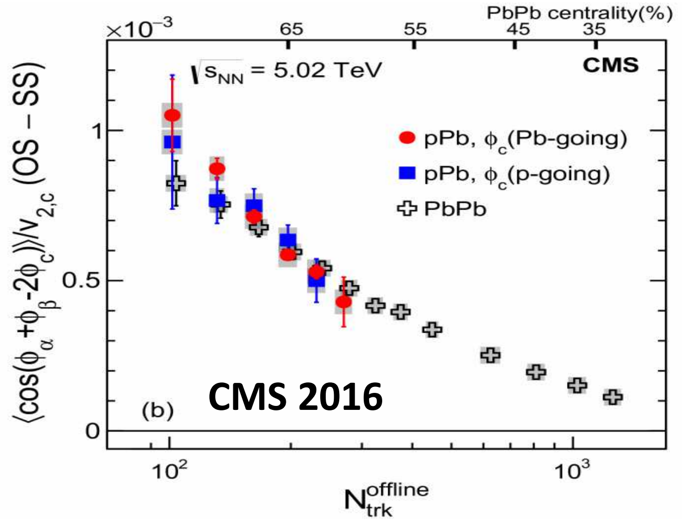
Voloshin 2010



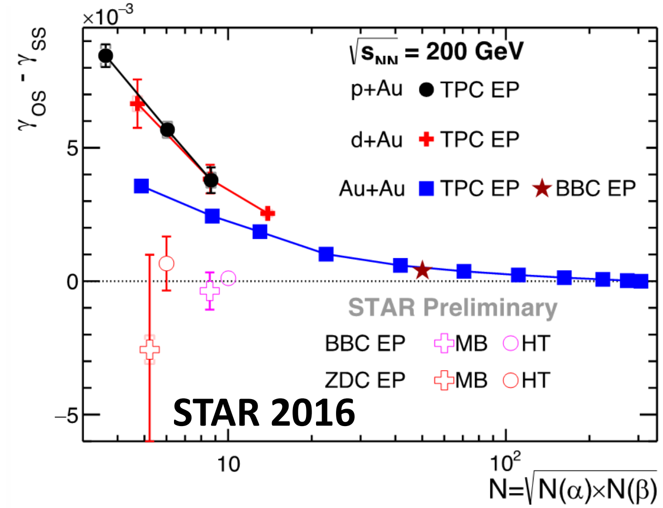
Wang 2012
Tribedy 2017

Experimental methods

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



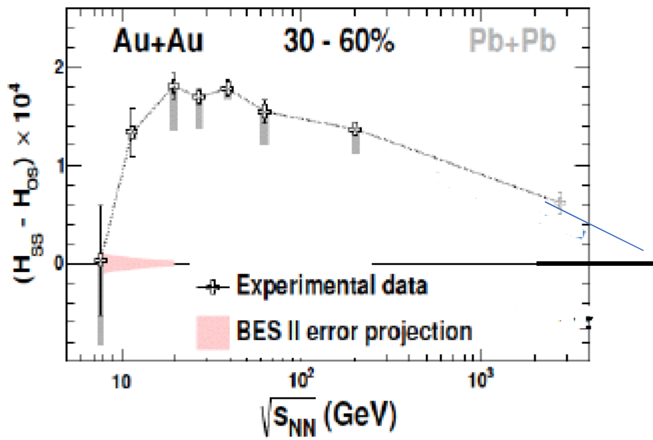
γ in p+Pb ~ in Pb+Pb at LHC



Δγ in p+Au and d+Au zero at RHIC

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

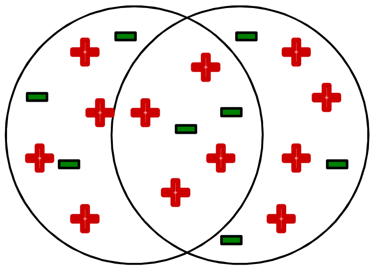
Strong energy dependence of the signal



STAR 2014

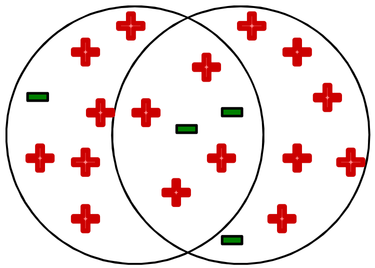
Experimental methods

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



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

Vs

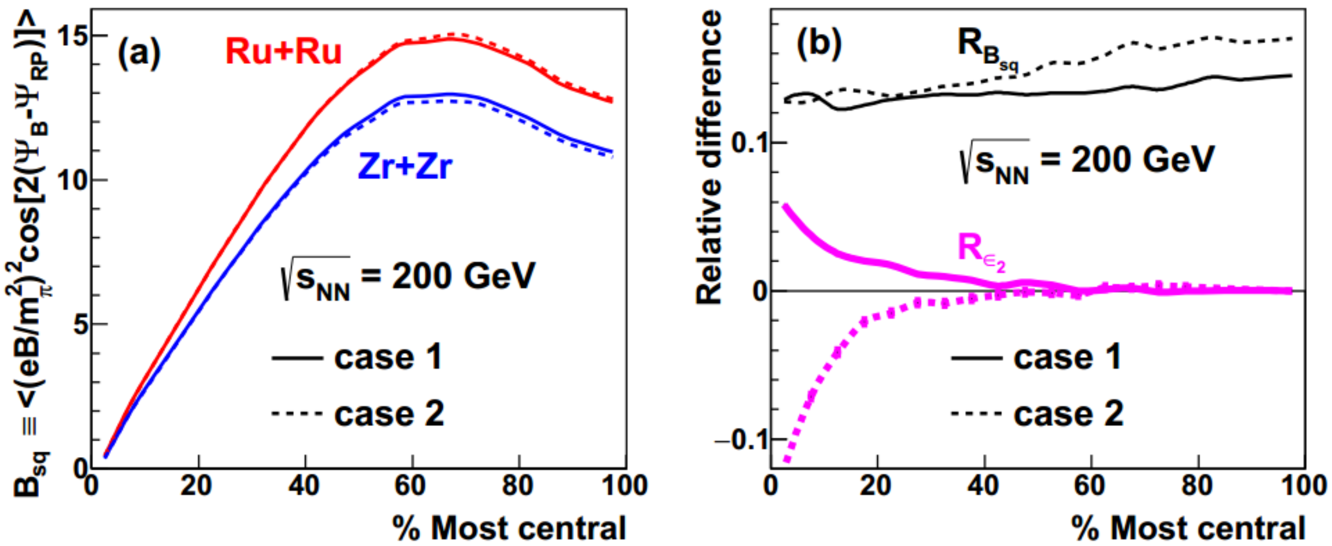


$^{96}_{44}Ru + ^{96}_{44}Ru$

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

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)

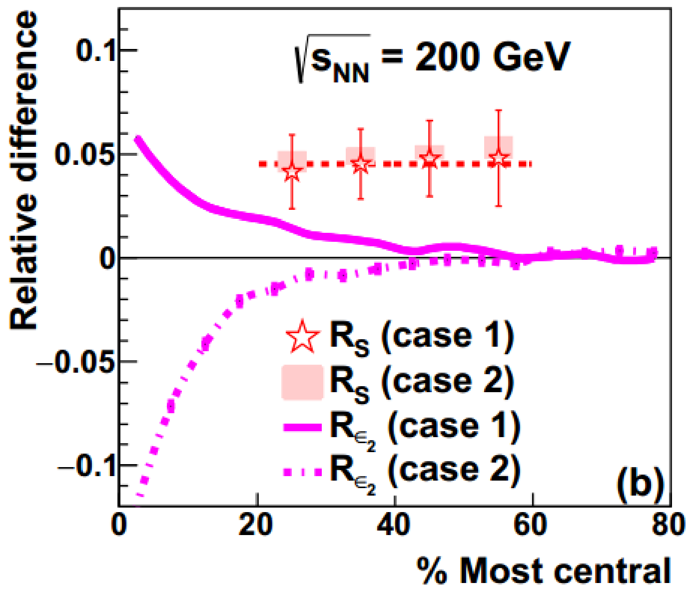
Centrality 20-60%: sizable difference in B ($R_{B_{sq}} \sim 10-20\%$) but small difference in eccentricity ($R_{\varepsilon_2} < 2\%$)

Isobar collisions

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

As $\rm R_{B_{sq}}$ and $\rm R_{\varepsilon_2}$ 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

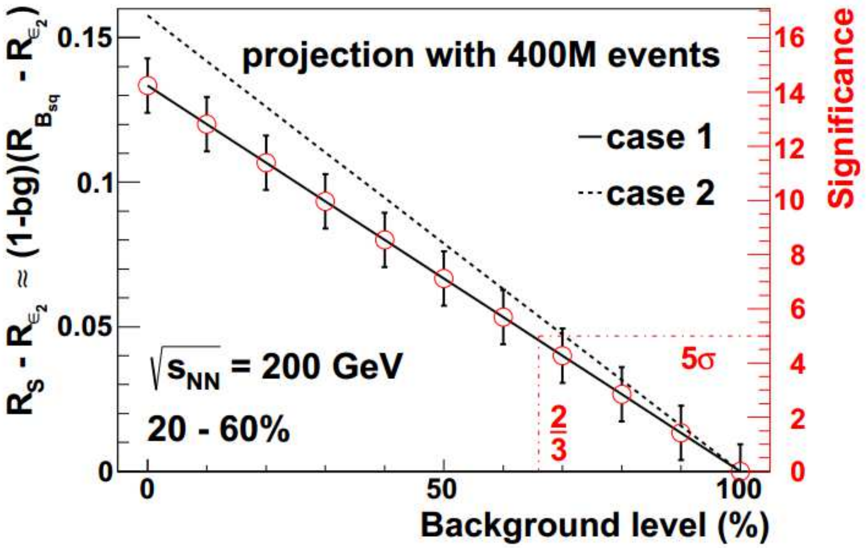
bg=2/3
400M events
5σ signal

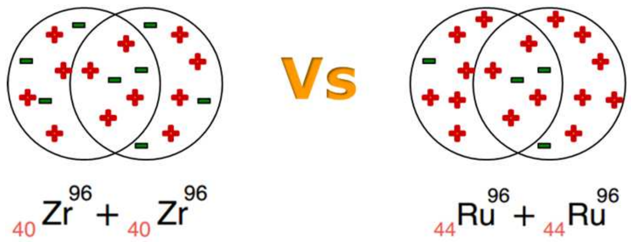
If bg=4/5
1.2B events
5σ signal

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 finished
Data analysis is undergoing

Other anomalous transports:

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

Summary

- Heavy-ion collisions generate the most vortical fluid under strongest magnetic field
- Global Λ spin polarization may due to vorticity by OAM. The local Λ spin polarization shows “sign puzzles”
- Chiral magnetic effect probe unique probe to QCD topological sector. Strong background contributions.
- Isobar collisions done in 2018 is promising

An era of subatomic spintronics and QED⊗QCD

Thank you!

New Development of Hydrodynamics and its applications in Heavy-ion Collisions

30 October 2019 to 2 November 2019
Asia/Shanghai timezone

Quark matter 2019 Satellite meeting:

- Overview
- Timetable
- Registration
- Participant List

We are delighted to announce the Workshop on "New development of hydrodynamics and its applications in Heavy-Ion Collisions", which will be hosted by Fudan University as a satellite meeting of Quark Matter 2019 (Wuhan, November 3-9, 2019), from October 30 to November 2 in Shanghai. The goal of this workshop is to bring together theorists and experimentalists worldwide to discuss the current status and future of the relativistic hydrodynamic modeling in the field of high-energy heavy-ion collisions. The scientific program of this workshop will be devoted to various aspect of hydrodynamics, with respect to the recent experimental progress achieved at RHIC and the LHC. A list of topics includes:

Li Yan
Xu-Guang Huang
Huichao Song
Huan Zhong Huang
Yugang Ma

https://napp.fudan.edu.cn/indico/event/7/overview

Table of anomalous chiral transports

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

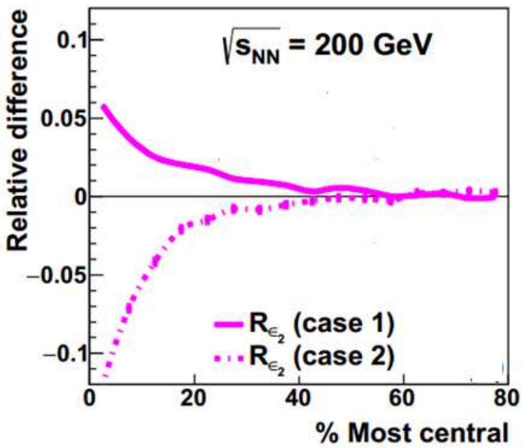
	$\boldsymbol{E}$	$\boldsymbol{B}$	$\boldsymbol{\omega}$
$\boldsymbol{J}_V$	σ Ohm's law	$\frac{e^2}{2\pi^2}\mu_A$ Chiral magnetic effect	$\frac{e}{\pi^2}\mu_V\mu_A$ Vector chiral vortical effect
$\boldsymbol{J}_A$	$\propto \frac{\mu_V\mu_A}{T^2}\sigma$ Chiral electric separation effect	$\frac{e^2}{2\pi^2}\mu_V$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

Isobar collisions: by-product 1

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

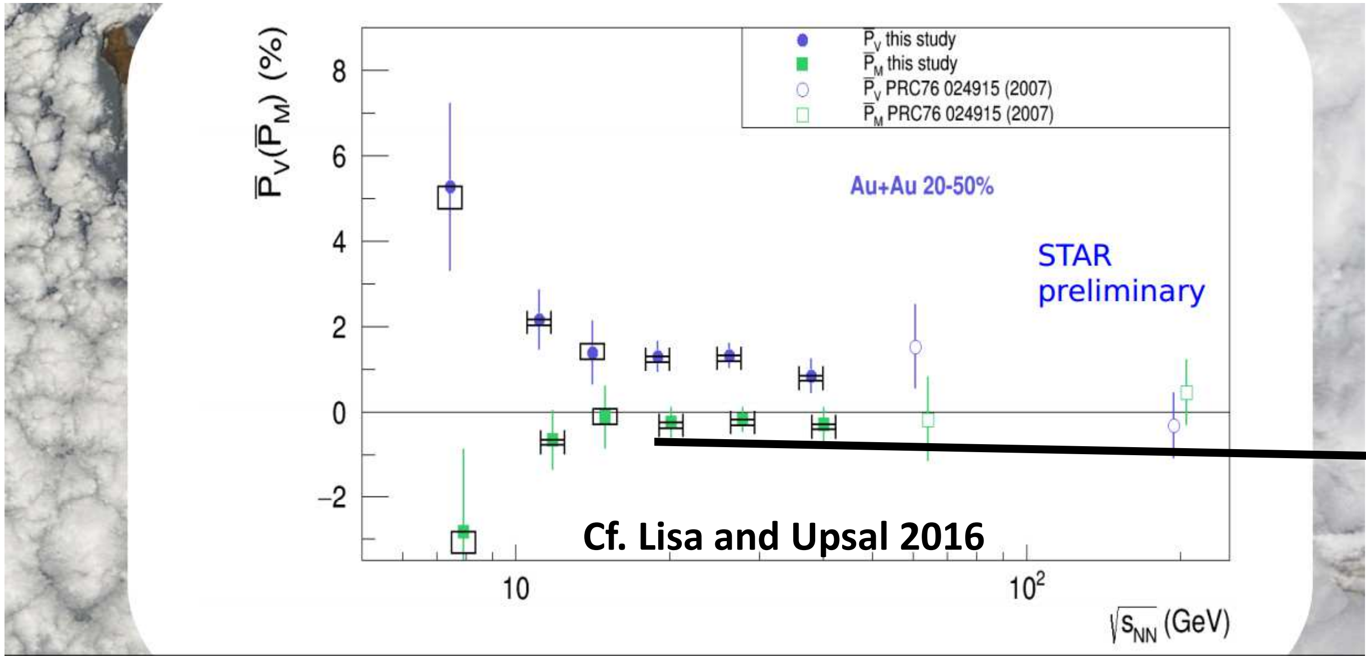
		R_0(fm)	a(fm)	β_2
Case 1	Ru	5.085	0.46	0.158
	Zr	5.02	0.46	0.08
Case 2	Ru	5.085	0.46	0.053
	Zr	5.02	0.46	0.217



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

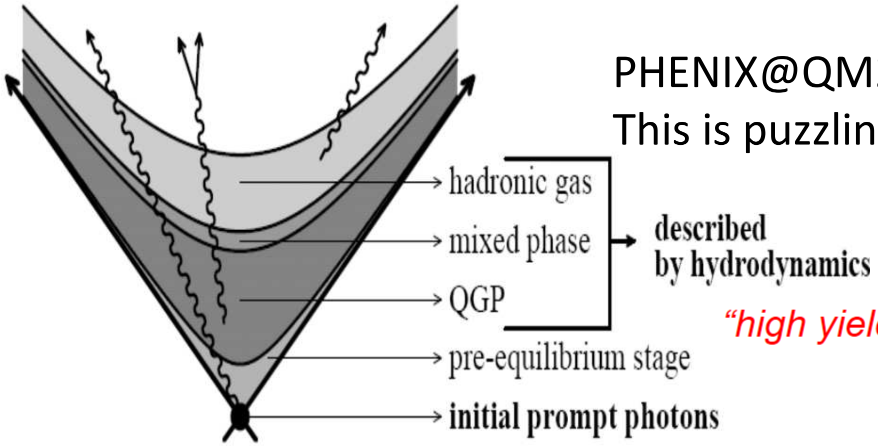
$$P_{\text{Vortical}} = \frac{1}{2}\left(P_{\Lambda} + P_{\bar{\Lambda}}\right) \qquad P_{\text{Magnetic}} = \frac{1}{2}\left(P_{\Lambda} - P_{\bar{\Lambda}}\right)$$

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"

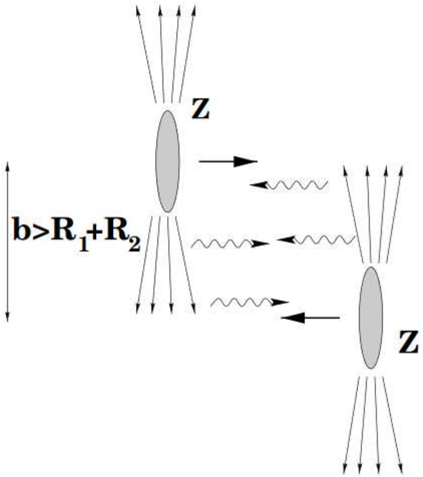
One possible solution: anisotropy in the early stage, like the magnetic field.

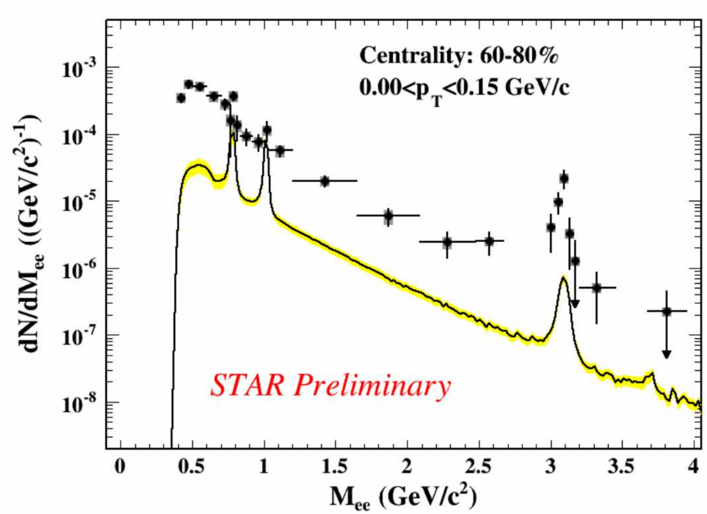
(Basar, Skokov, Kharzeev 2012, Tuchin 2012, Muller, Wang, Yang 2013, Yee 2013, …)

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

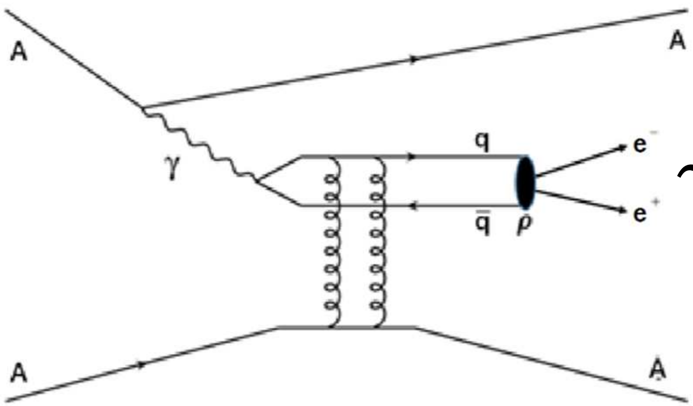
Isobar collisions: by-product 4

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

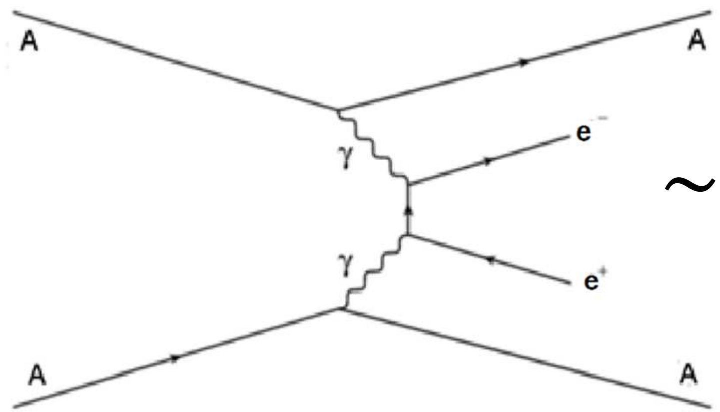




Scenario 1: photonuclear interaction



$\sim Z^2$



$\sim Z^4$