RHIC/AGS Annual Users' Meeting

New Physical Phenomena Associated with Chiral Fermions/Chirality in Heavy-Ion Collisions

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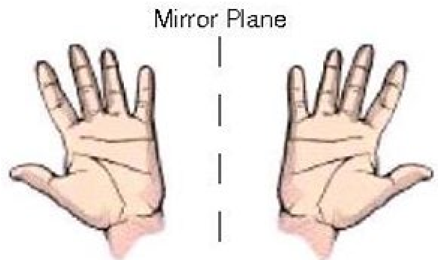
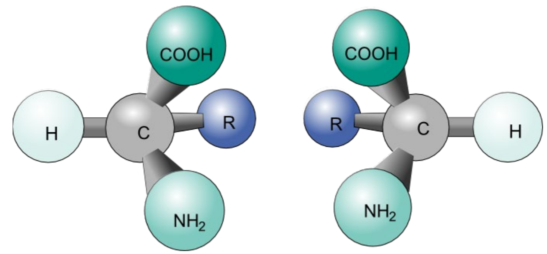
Outline

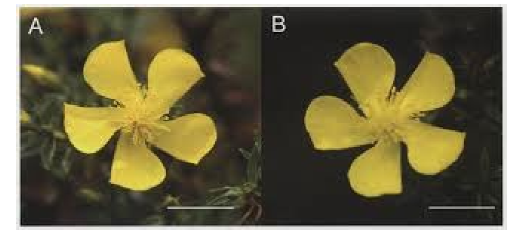
- Chirality, anomalies, and chiral magnetic effect (CME)
- The isobar collisions for CME search
- Realistic evolution of magnetic field
- Deep-learning assisted CME search
- Summary

Chirality

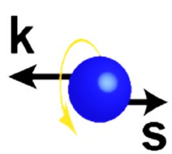
- A common concept



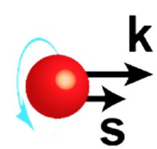




- For massless fermions



$|L\rangle$



$|R\rangle$

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

- Classically

$$\partial_\mu J_V^\mu = 0 = \partial_\mu J_A^\mu$$ with $$J_{V/A}^\mu = J_R^\mu \pm J_L^\mu$$

Chiral anomalies

- Quantumly, in external $U(1)$ gauge field and background geometry

$$\nabla_\mu J^\mu_A = -\frac{e^2}{8\pi^2} F_{\mu\nu}\tilde{F}^{\mu\nu} - \frac{1}{192\pi^2} R^\alpha{}_{\beta\mu\nu}\tilde{R}_\alpha{}^{\beta\mu\nu} + \frac{\Lambda^2}{16\pi^2}\left(2\tilde{R}_{\mu\nu}{}^{\mu\nu} - T_\lambda{}^{\mu\nu}\tilde{T}^\lambda{}_{\mu\nu}\right)$$

ABJ anomaly | Gravitational anomaly | Nieh-Yan anomaly

Chiral anomalies

- Quantumly, in external $U(1)$ gauge field and background geometry

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ABJ anomaly — Gravitational anomaly — Nieh-Yan anomaly

- Macroscopic anomalous chiral transport phenomena
  - Chiral magnetic effect (CME): Axial imbalance + B field = vector current
    (Kharzeev 2004; Kharzeev-Fukushima-McLerran-Warringa 2007; …)
  - Chiral separation effect (CSE): vector imbalance + B field = axial current
    (Son-Zhitnitsky 2004; …)
  - Chiral vortical effect (CVE): Temperature + vorticity = vector/axial current
    (Erdmenger etal 2008; Banerjee etal 2008; Torabian-Yee 2009; …)
  - Chiral torsional effect (CTE): Temperature + torsion = vector/axial current
    (Khaidukov-Zubkov 2018; Imaki-Yamamoto 2019; Nissinen-Volovik 2019; …)
  - … …

Chiral anomalies

- Quantumly, in external $U(1)$ gauge field and background geometry

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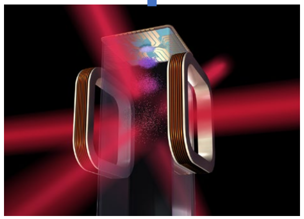
ABJ anomaly   Gravitational anomaly   Nieh-Yan anomaly

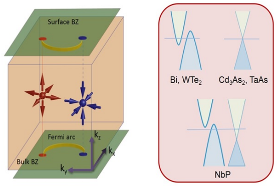
- Macroscopic anomalous chiral transport phenomena

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

Temperature

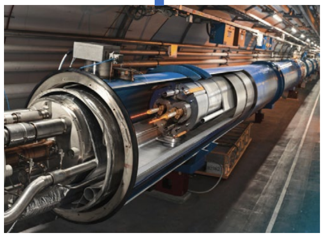


Cold atomic gases



Weyl/Dirac semimetals

Supernovae



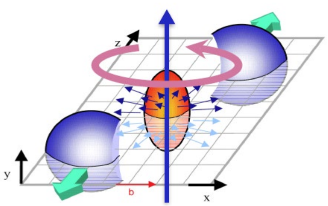
Heavy-ion collisions

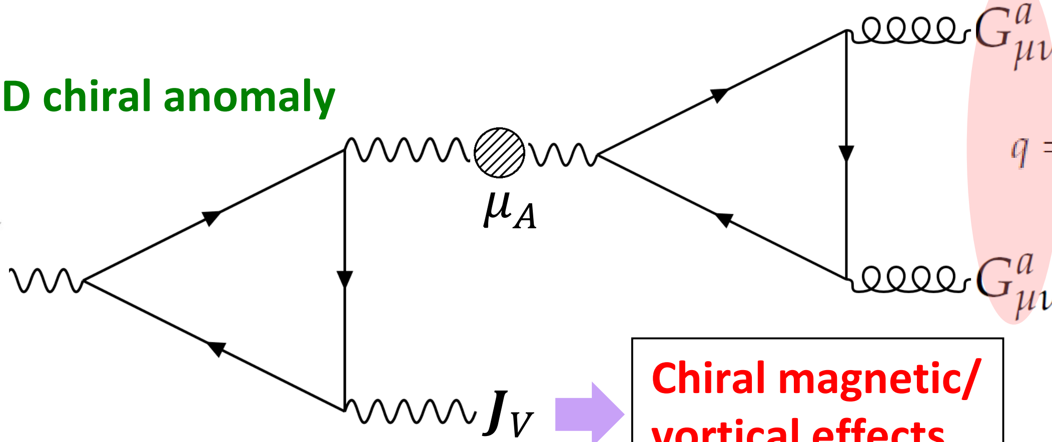
Probe QCD topological sector

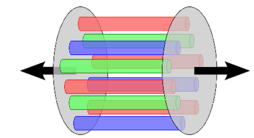
QCD chiral anomaly

QED chiral anomaly

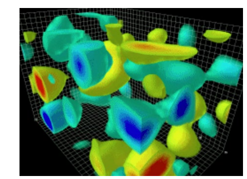
B,ω





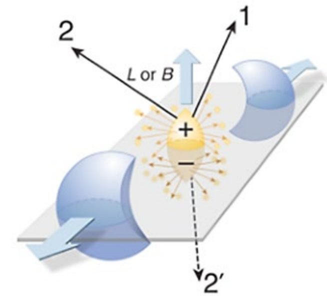


$$q = \frac{g^2}{32\pi^2}\int d^4x G^a_{\mu\nu}\tilde{G}^{\mu\nu}_a$$



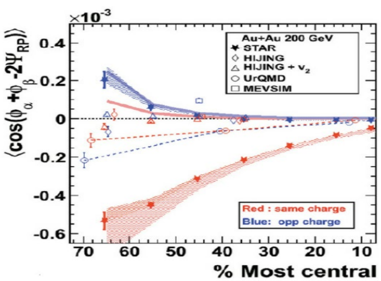
Chiral magnetic/ vortical effects

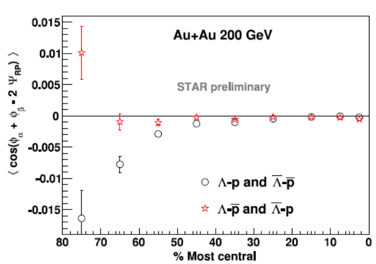
Initial state topological fluctuations



Observable:
e.g. γ-correlator

(Voloshin 2004)

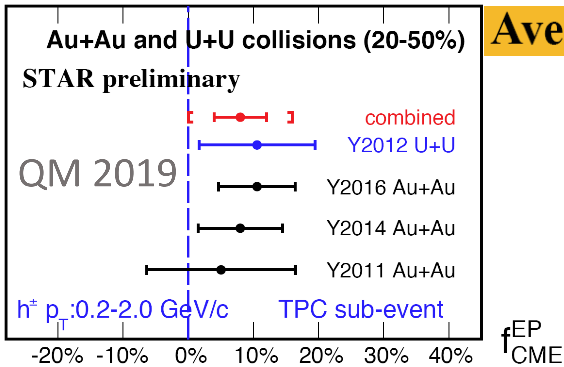




(STAR 2009, 2014)

Difficulties in observing CME

- Small signal versus big elliptic-flow related backgrounds

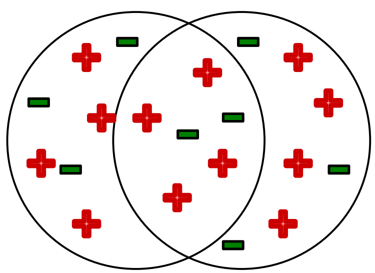


Averaged CME fraction = (8±4±8)%

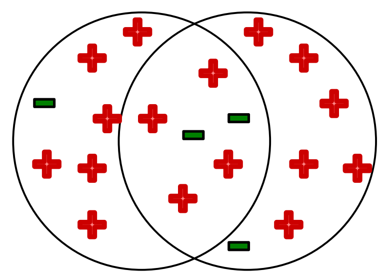
Exp. talk by Abdelrahman 10:30AM

One eccentric geometry gives two outcomes, B field and v_2. Difficult to disentangle them.

- Isobar collisions: fix v_2 but vary B field



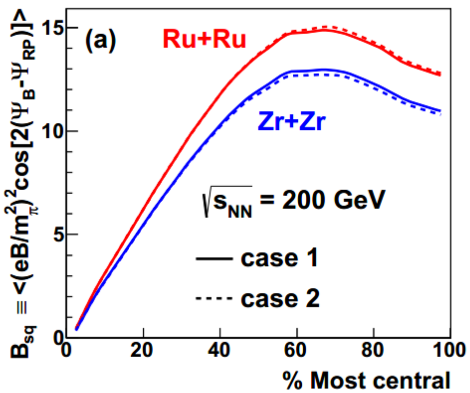
Vs

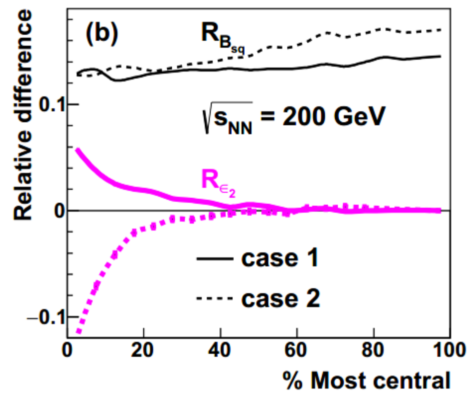


${}_{40}^{96}Zr + {}_{40}^{96}Zr$ ${}_{44}^{96}Ru + {}_{44}^{96}Ru$

Difficulties in observing CME

- Isobar collisions: fix v_2 but vary B field

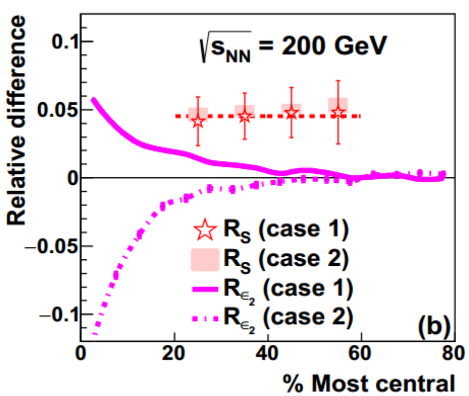


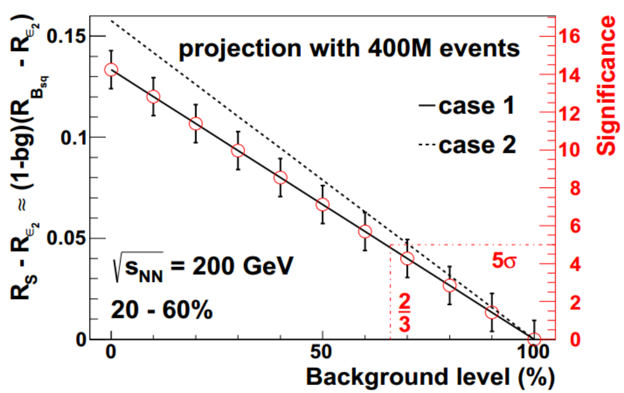


Relative difference R=2(Ru-Zr)/(Ru+Zr)

Centrality 20-60%:
sizable R for B: $\mathbf{R_{B_{sq}} \sim 10 - 20\%}$
small R for eccentricity: $\mathbf{R_{\varepsilon_2} < 2\%}$

- Signal versus background level





RHIC first run 2018 produces 3B events.
If bg level = 88%, signal significance= 5σ
If bg level =93%, signal significance= 3σ

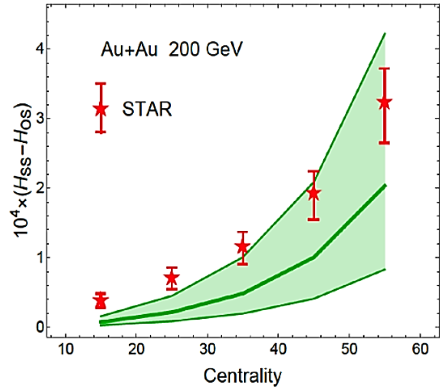
If background level = 67 %, 400M events give 5σ signal

(Deng-XGH-Ma-Wang 2016, 2018)

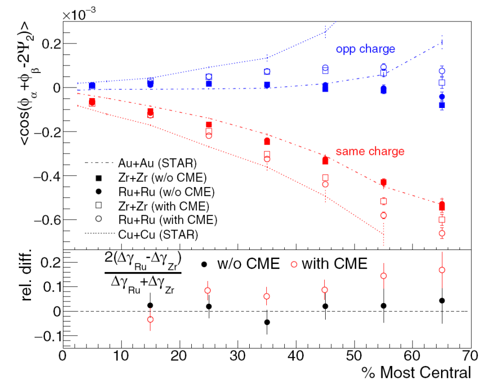
Evolution of B field

Difficulties in quantifying CME

- Quantifying CME in theory: hydrodynamic and transport models



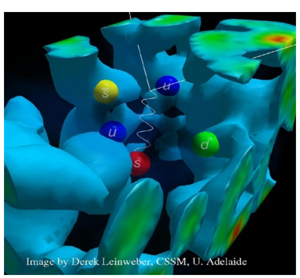
(AVFD: Liao etal 2018, 2019)

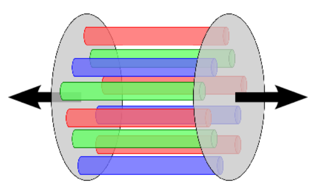


(AMPT: Ma-Zhang 2011; Deng-XGH-Ma-Wang 2018)

- Main theoretical uncertainties:

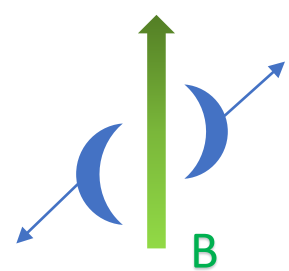
Initial axial charges



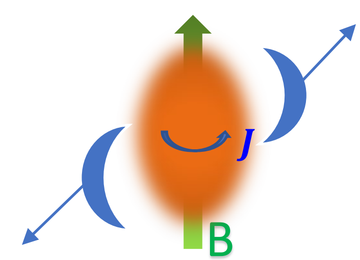


(Early attempt: Muller- Schlichting-Sharma 2016)

Realistic evolution of B field



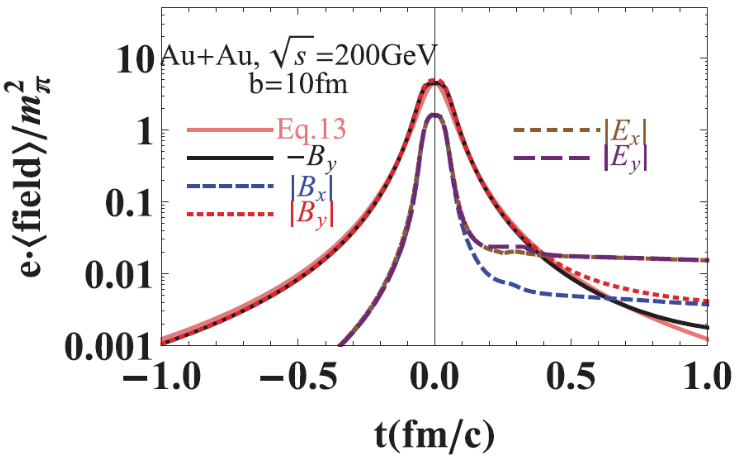
In vacuum: moving charges



In conductor: Faraday effect

Realistic evolution of B field

- If quark-gluon matter is insulating (Deng-XGH 2012; XGH 2015; and many others)



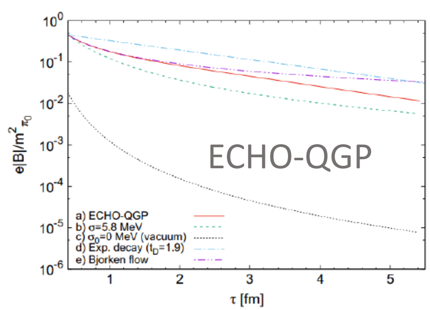
Well fitted by

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

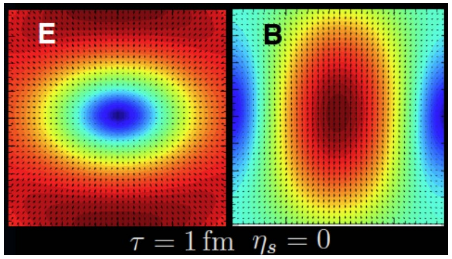
Life time of B field

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

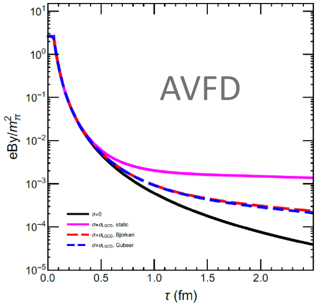
- In hydro stage: couple Maxwell with hydro equations



(Inghirami etal 2016)



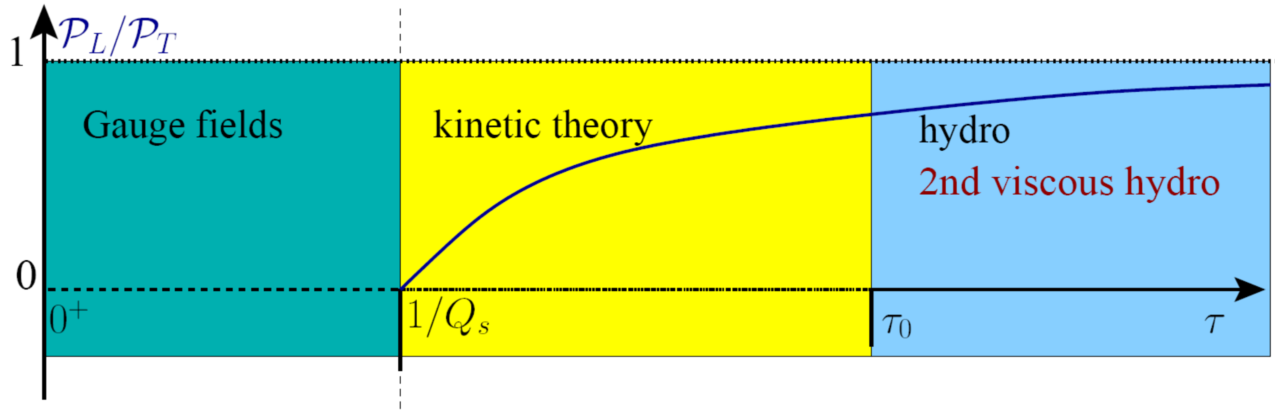
(Gursoy-Kharzeev-Rajagopal-Shen 2018)



(Huang-Kharzeev-Liao-Shi-She 2020)

Realistic evolution of B field

- But what is the pre-hydro evolution and the IC for hydro?



- We study the pre-hydro evolution for $t \sim Q_s^{-1} - \tau_0$ by solving coupled Maxwell and Boltzmann equations

$$\begin{cases} [p^\mu \partial_\mu + eQ_a p_\mu F^{\mu\nu}\partial_{p^\nu}] f_a(t, \mathbf{x}, \mathbf{p}) = \mathcal{C}[f_a] \qquad a = q, \bar{q}, g \\ \partial_\mu F^{\mu\nu} = j^\nu \\ j^\mu = e \sum_F Q_F s_F \int \frac{d^3\mathbf{p}}{(2\pi)^3 E_p} p^\mu \left(f_q^F - f_{\bar{q}}^F\right) \end{cases}$$

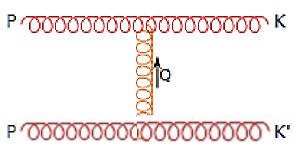
Initial condition for EM field: moving colliding nuclei in vacuum
Initial condition for q and g: CGC inspired distribution (Blaizot-Wu-Yan 2014)

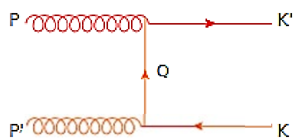
Realistic evolution of B field

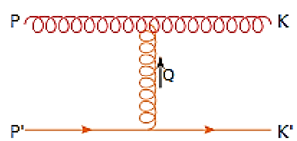
- For the collision kernel: 2-2 processes

$$\mathcal{C}[f^a_{\mathbf{p}}] = \frac{1}{2E_p\nu_a}\sum_{b,c,d}\frac{1}{s_{cd}}\int\frac{d^3\mathbf{p}'}{(2\pi)^3 2E_{\mathbf{p}'}}\frac{d^3\mathbf{k}}{(2\pi)^3 2E_{\mathbf{k}}}\frac{d^3\mathbf{k}'}{(2\pi)^3 2E_{\mathbf{k}'}}$$
$$\times (2\pi)^4\delta^{(4)}(P+P'-K-K')|\mathcal{M}^{ab}_{cd}|^2$$
$$\times \left[f^c_{\mathbf{k}}f^d_{\mathbf{k}'}(1+\epsilon_a f^a_{\mathbf{p}})(1+\epsilon_b f^b_{\mathbf{p}'}) - f^a_{\mathbf{p}}f^b_{\mathbf{p}'}(1+\epsilon_c f^c_{\mathbf{k}})(1+\epsilon_d f^d_{\mathbf{k}'})\right]$$

$$|\mathcal{M}|^2 \ni gg \leftrightarrow q\bar{q},\ gq \leftrightarrow gq,\ g\bar{q} \leftrightarrow g\bar{q},\ gg \leftrightarrow gg$$

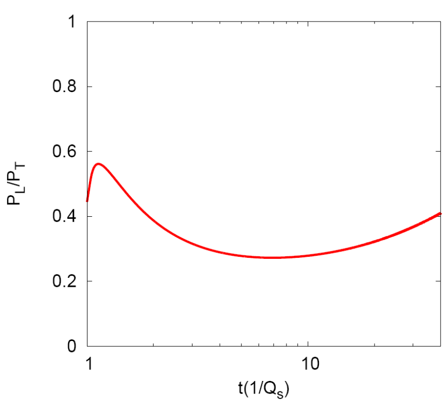






Plus s, u channels

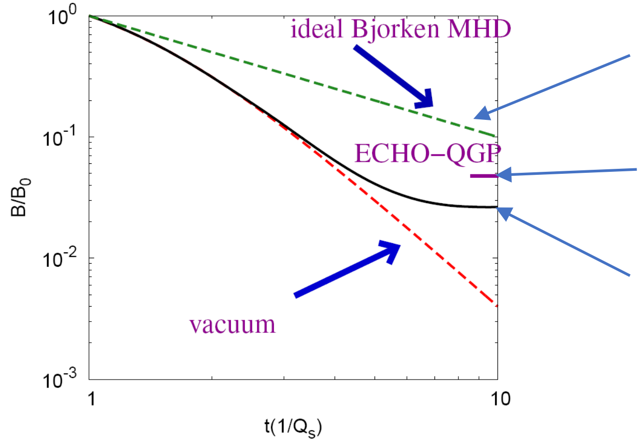
Under 2-2 scattering, the system evolves towards hydrodynamization



(Yan-XGH to appear)

Realistic evolution of B field

- The B field (In case of Bjorken longitudinal expansion)

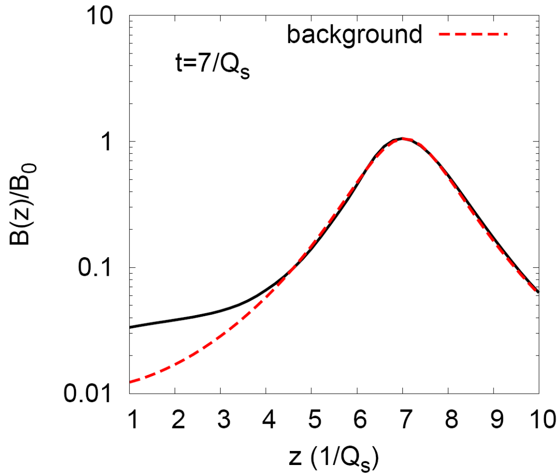


(Roy-Pu-Rezzola-Rischke 2015)

(Inghirami etal 2016)

(Yan-XGH to appear)

- Longitudinal distribution of B field



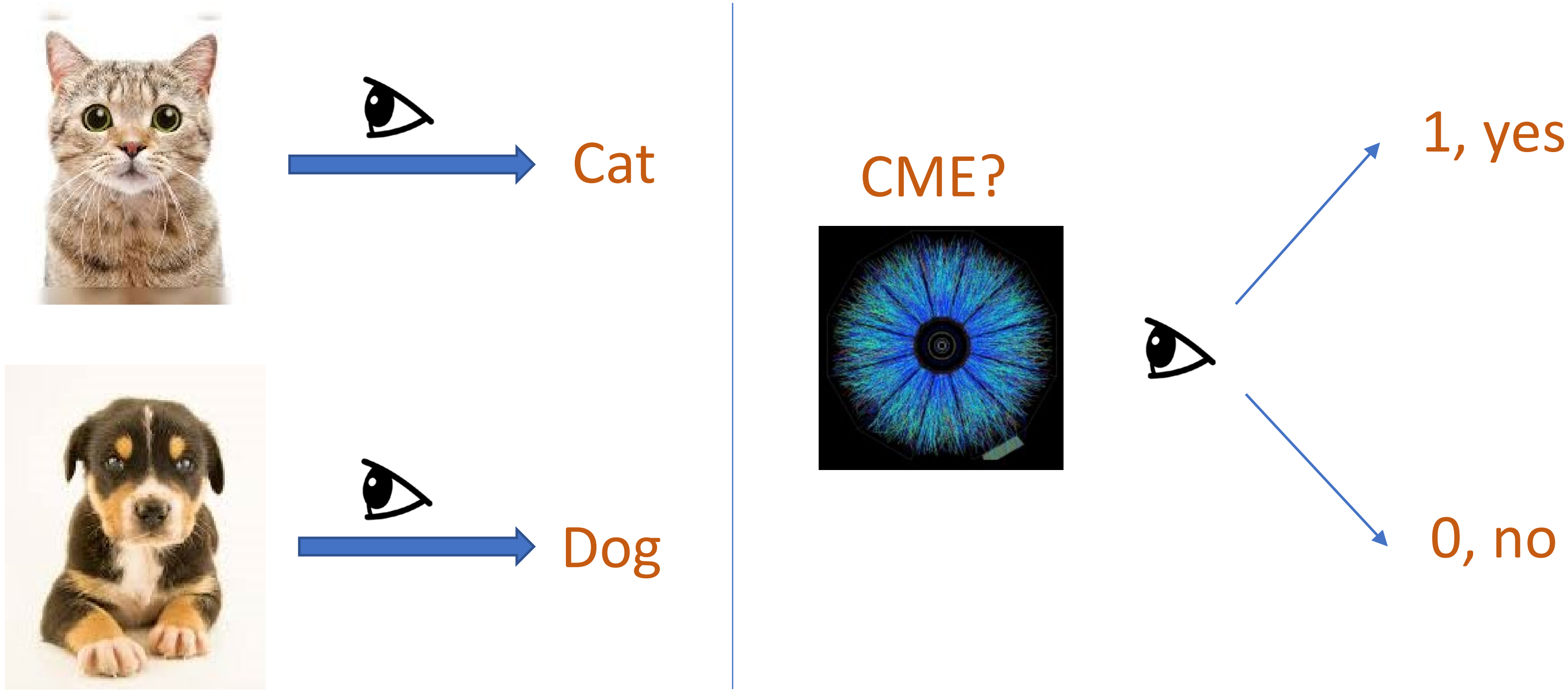
Background = B field by moving nucleus

(Yan-XGH to appear)

Deep-learning and CME search

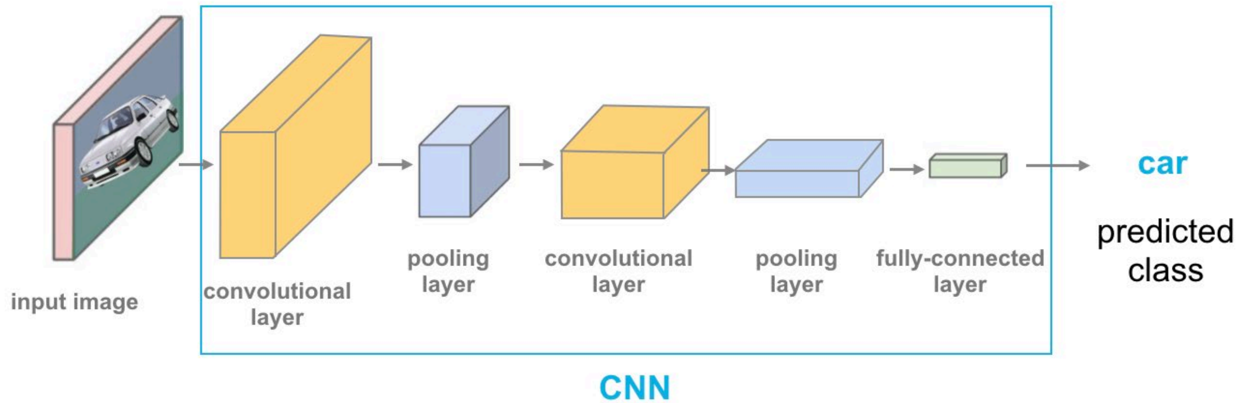
Deep-learning assisted CME search

- Recall the main challenge of CME search:
  Find a way to disentangle signal and elliptic-flow backgrounds
- Any designed observable is based on hadron distribution in momentum space.
  Why don't we just look at the distribution itself?

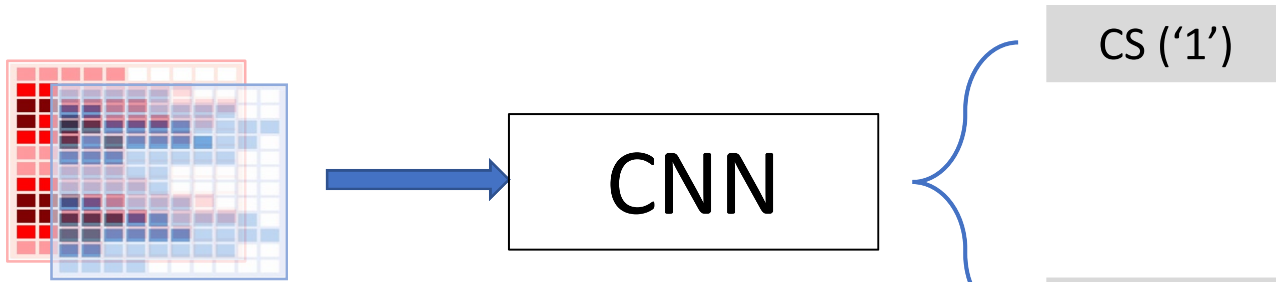


Deep-learning assisted CME search

- We train a machine to recognize initial charge separation (mimicking CME): Supervised learning
- We use Convolutional Neural Network (CNN) : good at pattern recognition of figures.



In our case: input = $\pi^{\pm}$ with $|Y| < 1$ projected on (p_x, p_y)-plane generated by AMPT



AMPT simulation (with or without initial charge separation)

Deep-learning assisted CME search

- We use 50000 events for training for blue each box

f		$\sqrt{s_{NN}}$ (GeV)						
Centrality		11.5	14.5	19.6	27	39	62.4	200
	0-10							
	10-20							
	20-30							
	30-40							
	40-50							
	50-60							

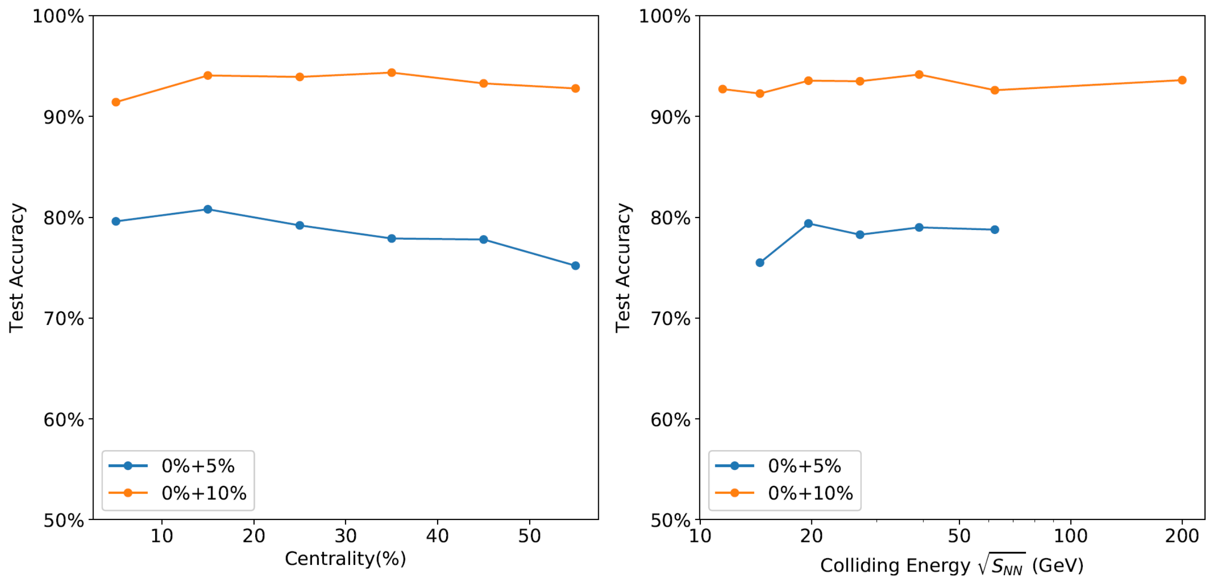
$f = 0$: No CME, Label '0'

$f = 5\%$ and 10%: With CME, Label '1'

Deep-learning assisted CME search

- Test: very robust. The machine learns key feature of charge separation. Insensitive to centrality and energy.

CNN	0+5%	0+10%
Accuracy (Under training cond.)	78.47%	93.38%

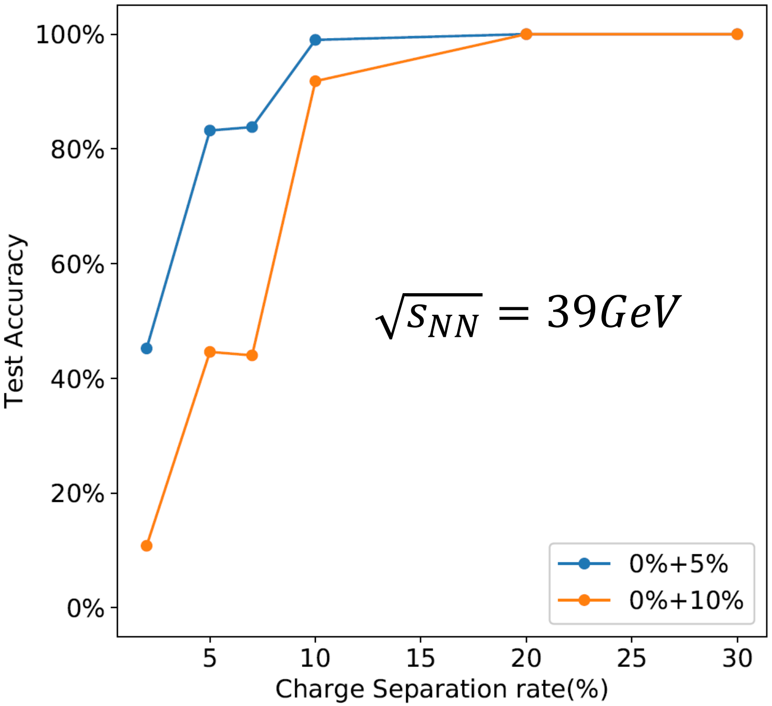


(Zhao-Zhou-XGH to appear)

Deep-learning assisted CME search

- Test: very robust. The machine learns key feature of charge separation. Insensitive to centrality and energy.

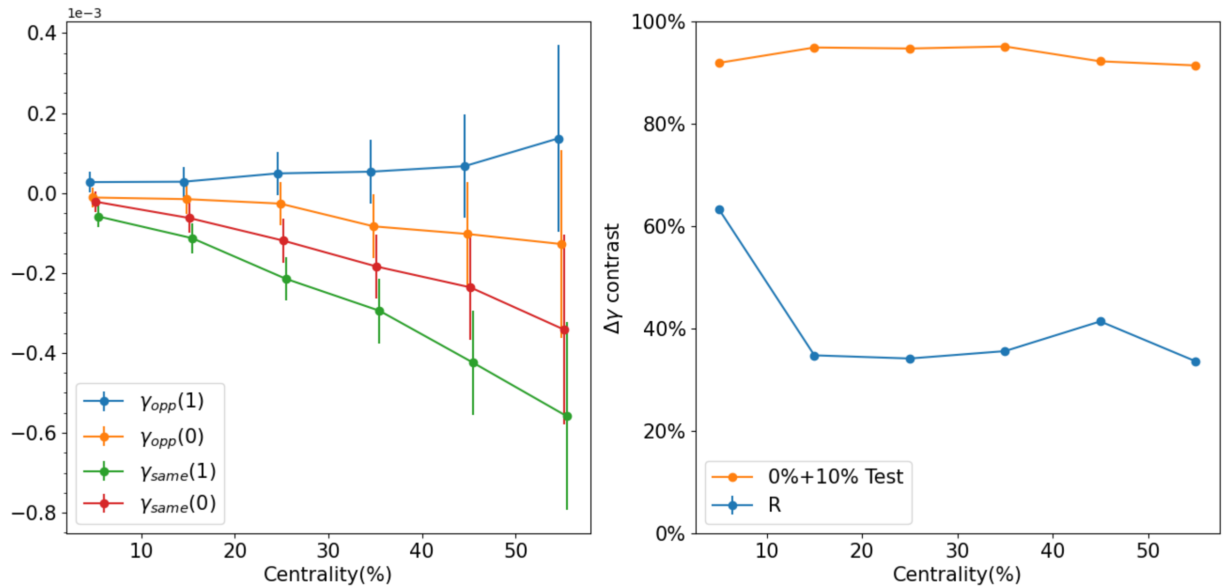
- Output: accuracy P_1
- P_1=the possibility of having CS, indicating robustness



(Zhao-Zhou-XGH to appear)

Deep-learning assisted CME search

- Test: Comparing to γ-correlator with 10% CS



$$\gamma_{same} = \left\langle \cos\left(\phi_\alpha^{(\pm)} + \phi_\beta^{(\pm)} - 2\Phi_R\right)\right\rangle$$

$$\gamma_{opp} = \left\langle \cos\left(\phi_\alpha^{(\pm)} + \phi_\beta^{(\mp)} - 2\Phi_R\right)\right\rangle$$

$$\Delta\gamma = \gamma_{opp} - \gamma_{same}$$

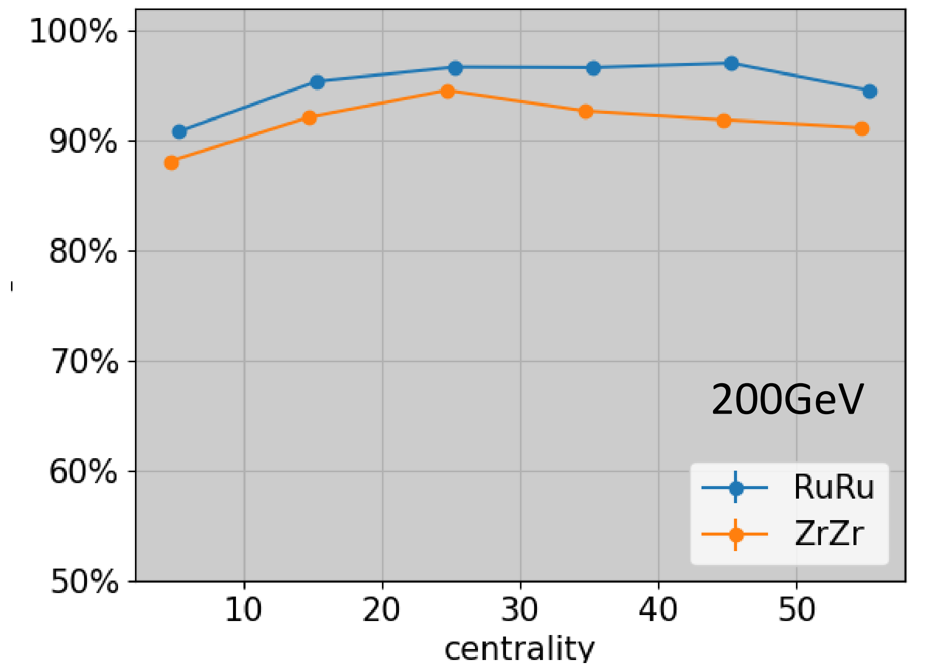
$$R_\gamma = \frac{|\Delta\gamma(1) - \Delta\gamma(0)|}{|\Delta\gamma(1)| + |\Delta\gamma(0)|}$$

(Zhao-Zhou-XGH to appear)

Deep-learning assisted CME search

- Using the machine trained by AuAu data to test isobar collisions

${}^{96}_{44}Ru + {}^{96}_{44}Ru$ with CS $f = 11\%$ and
${}^{96}_{40}Zr + {}^{96}_{40}Zr$ with CS $f = 10\%$



(Zhao-Zhou-XGH to appear)

Summary

Summary

- We study the pre-hydro evolution of B field, see the Faraday retaining effect for B field. This result may used as initial condition of hydro computation of B field.
- We train a CNN that can recognize the initial charge separation pattern (mimicking CME). The machine behaves robust against centrality, energy, and colliding systems.

Thank you!

Deep-learning assisted CME search

- Recall the main challenge of CME search:
  Find a way to disentangle signal and elliptic-flow backgrounds
- Any designed observable is based on hadron distribution in momentum space.
  Why don't we just look at the distribution itself?