The Chiral Magnetic Effect and its Search in Heavy Ion Collisions

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PLAN

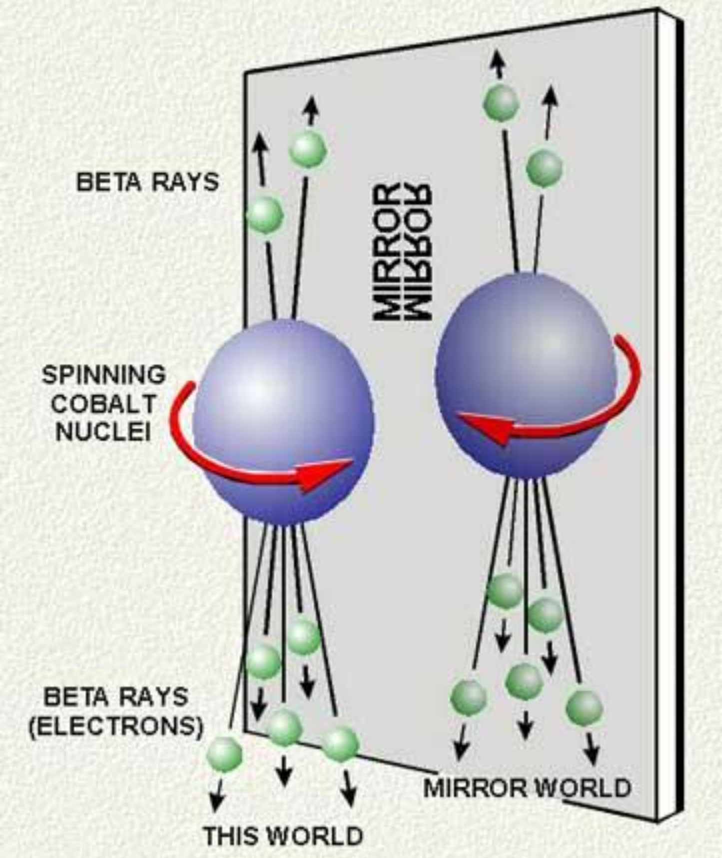
- Physics motivation of the Chiral Magnetic Effect (CME)

- How do we search for the CME in heavy-ion collisions?
- What have we found?

- What are we going to do next?

White House reveals first image of deep space from Webb Space Telescope

ALL ARE MATTER; ALMOST NO VISIBLE ANTIMATTER



CP VIOLATION

CP is violated in weak interaction, ~10^{-3}, e.g. $K_L \rightarrow 2\pi$, BR≈2×10^{-3}

CKM CP violation is too small to explain the matter-antimatter asymmetry $B/\gamma \sim 10^{-10}$
by some ~10 order orders of magnitude

Need CP violation in the strong interaction

In the standard model
one expects the same level of CP violation in electroweak and strong interaction

THE θ–*VACCUM* TERM

' t Hooft PRD 1976

$$\mathcal{L}_{QCD} = \sum_q \left(\bar{\psi}_{qi} i\gamma^\mu \left[\delta_{ij}\partial_\mu + ig\left(G^\alpha_\mu t_\alpha\right)_{ij} \right] \psi_{qj} - m_q \bar{\psi}_{qi}\psi_{qi} \right) - \frac{1}{4} G^\alpha_{\mu\nu} G^{\mu\nu}_\alpha + \theta \frac{\alpha_s}{8\pi} G^\alpha_{\mu\nu} \tilde{G}^{\mu\nu}_\alpha$$

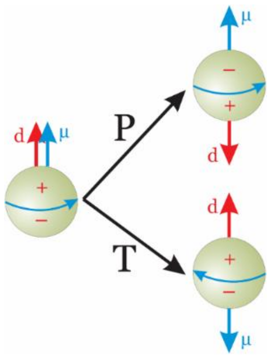
quarks — quark-gluon interactions — quarks — gluons: $= \frac{1}{2}\left(E^2 - B^2\right)$

'tHooft vacuum: $+\theta \frac{\alpha_s}{8\pi} G^\alpha_{\mu\nu} \tilde{G}^{\mu\nu}_\alpha = -\theta \frac{\alpha_s}{2\pi} \vec{E}_\alpha \cdot \vec{B}_\alpha$

Gluon pseudoscalar density

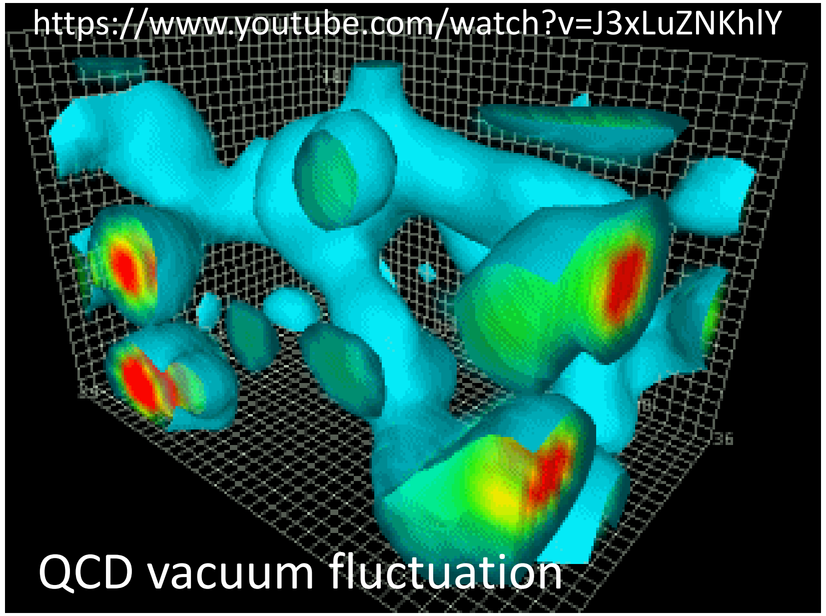
Explicitly breaks CP

Low energy: $\theta \sim 0$



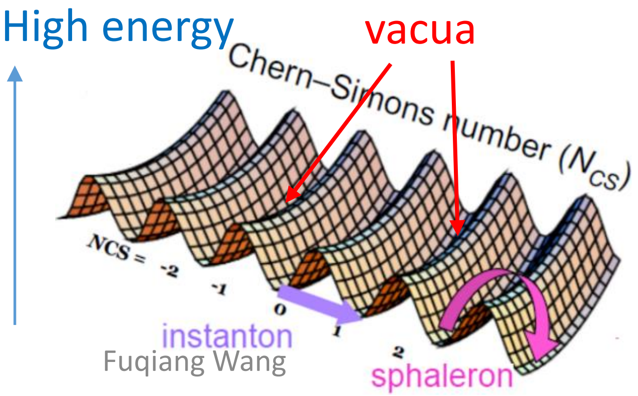
The neutron EDM should be finite, but not observed.

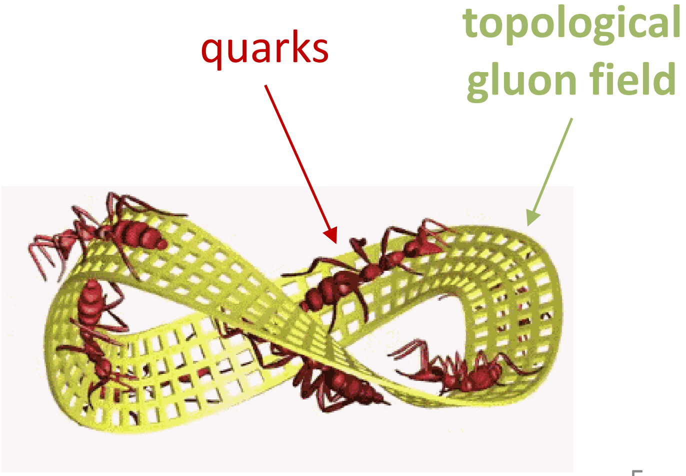
Peccei&Quinn,1977: Axion field



Topological charge: $Q_W = \frac{\alpha_s}{8\pi} \int G^\alpha_{\mu\nu} \tilde{G}^{\mu\nu}_\alpha \, d\mathbf{r}dt$

CS winding number: $N_{CS} = \nu = N_R - N_L = 2Q_W$



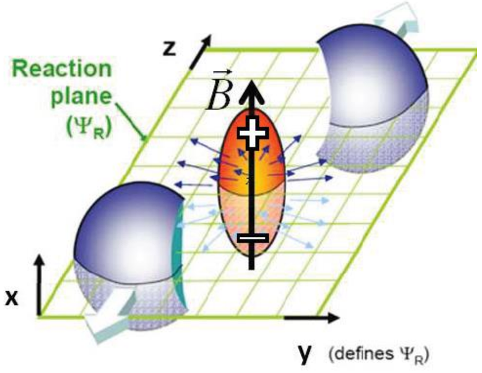


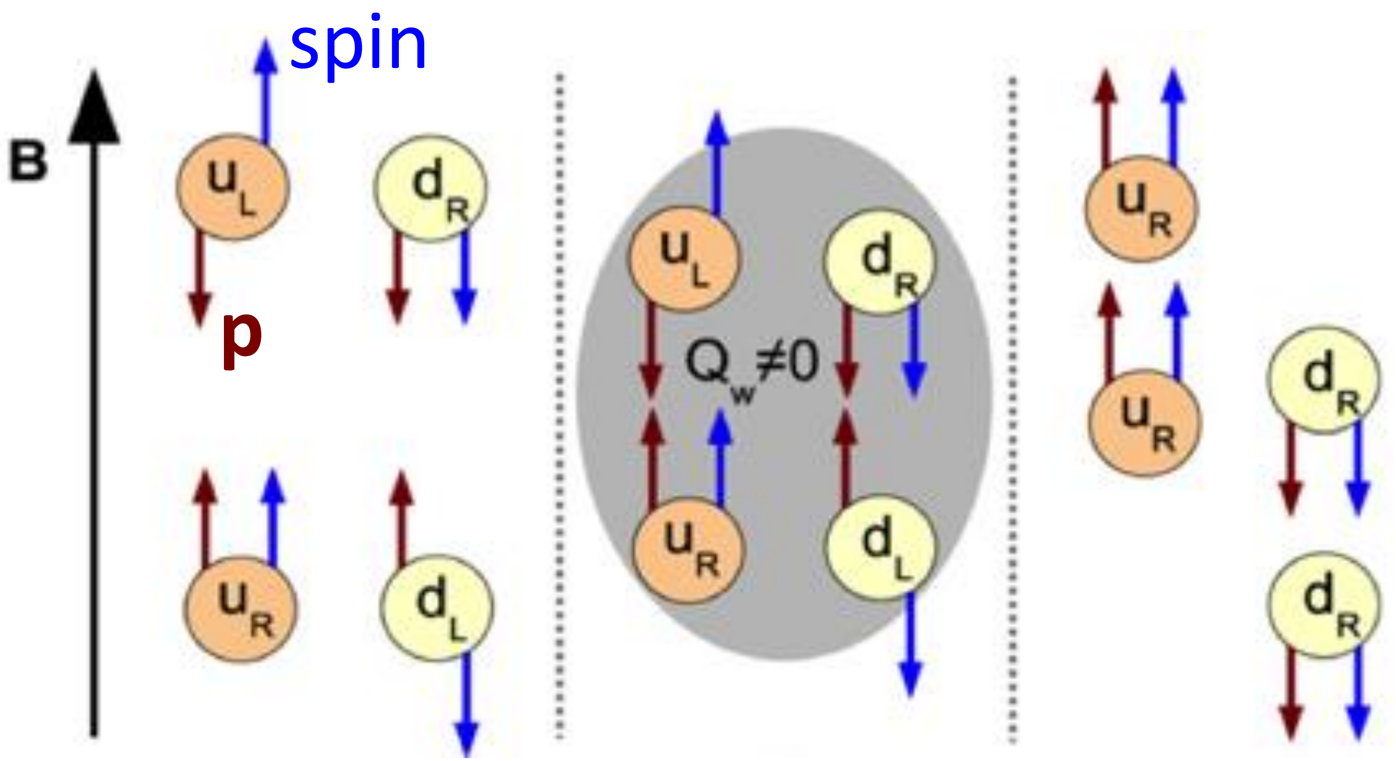
CAN WE OBSERVE THE TOPOLOGICAL QCD VACUUM?

(and quark handedness, P and CP violations)

QCD anomaly → chirality is not conserved

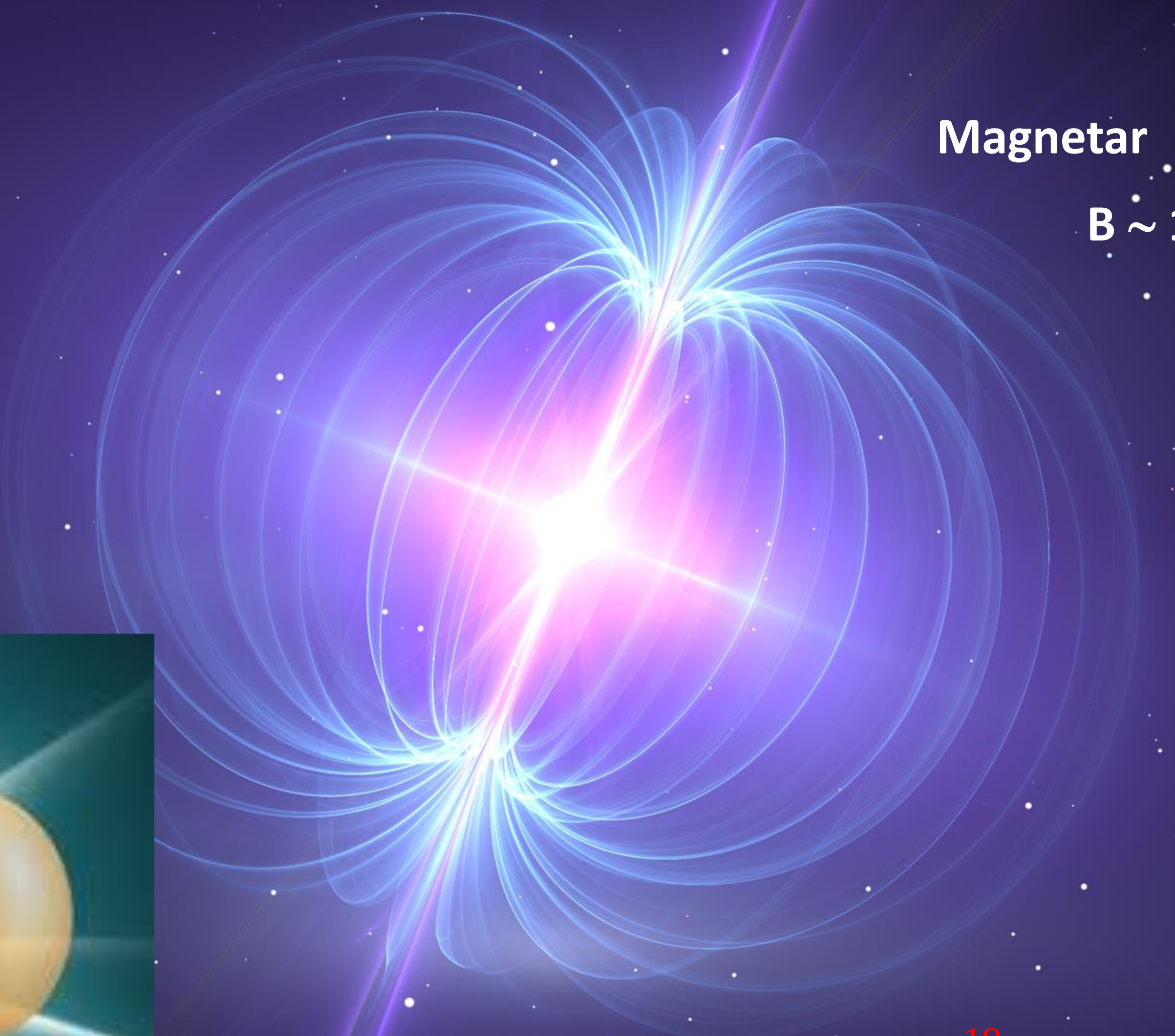
Need a strong magnetic field!





Kharzeev, et al. Nucl. Phys. A 803 (2008) 227

How strong is the magnetic field?

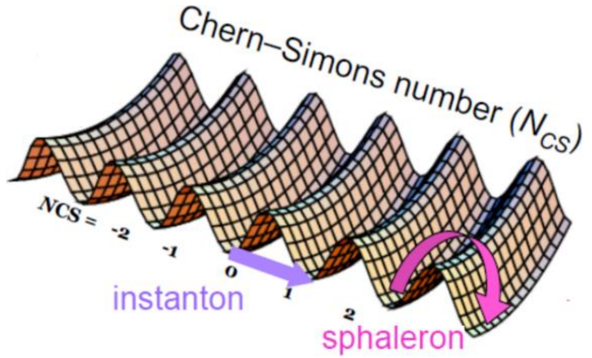


Magnetar

B ~ 10^{11} T

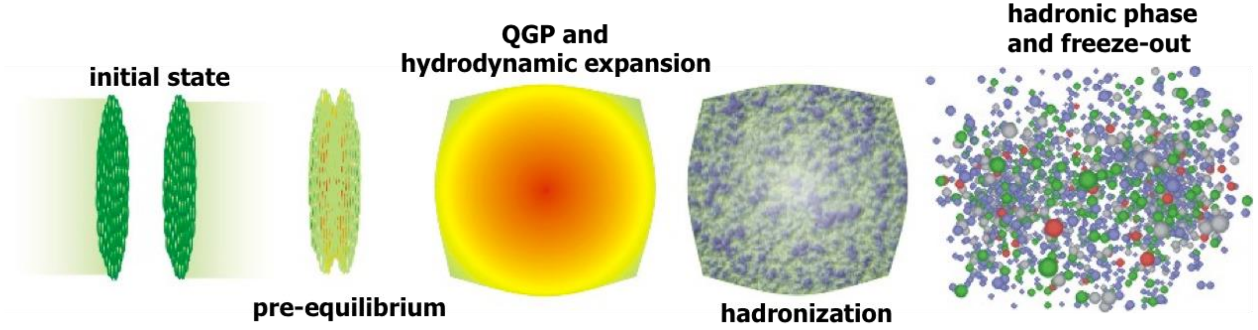
$$B = \frac{\mu_0}{4\pi} \cdot \frac{qv}{r^2} \cdot \gamma \cdot 2 = 10^{-7} \frac{50 \cdot 1.6\times10^{-19} \cdot 3\times10^{8}}{(7\times10^{-15})^2} \cdot 100 \cdot 2 = 10^{15}\ \mathrm{T}$$

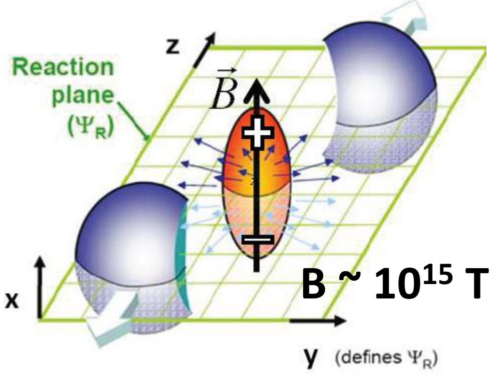
TO SEARCH FOR THE CME IN QCD

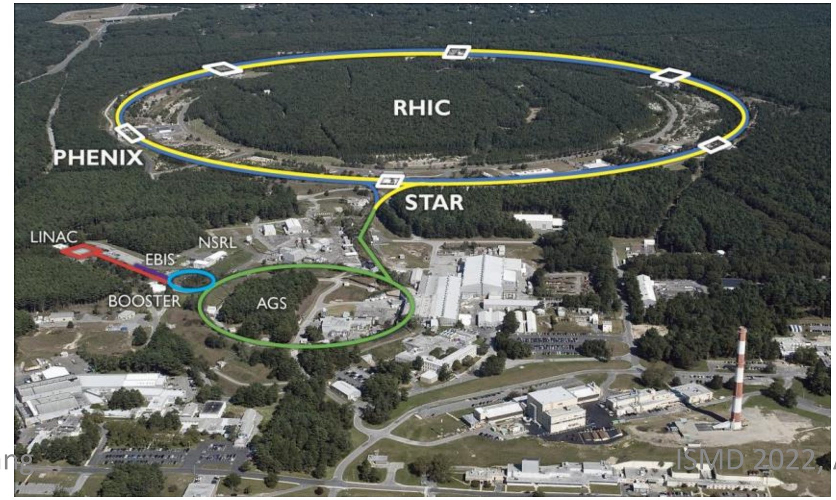


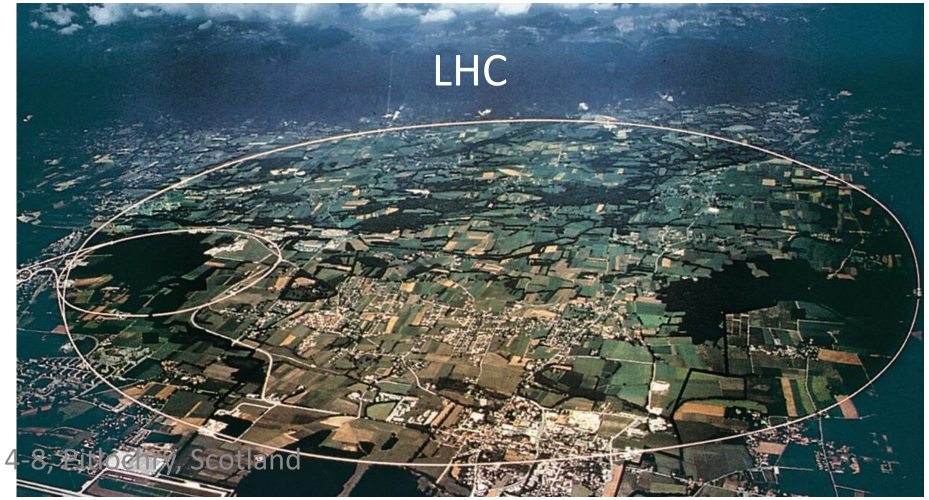
- Need a QCD machine to recreate the early universe
- Need strong magnetic field

Use heavy-ion collisions

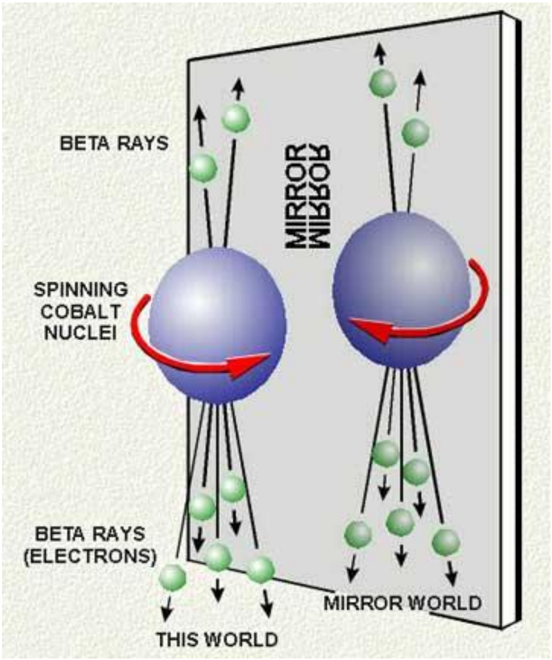


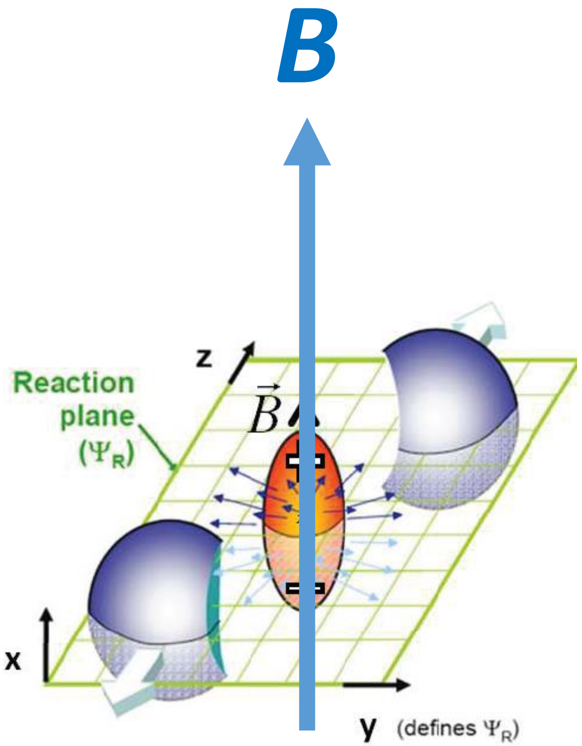


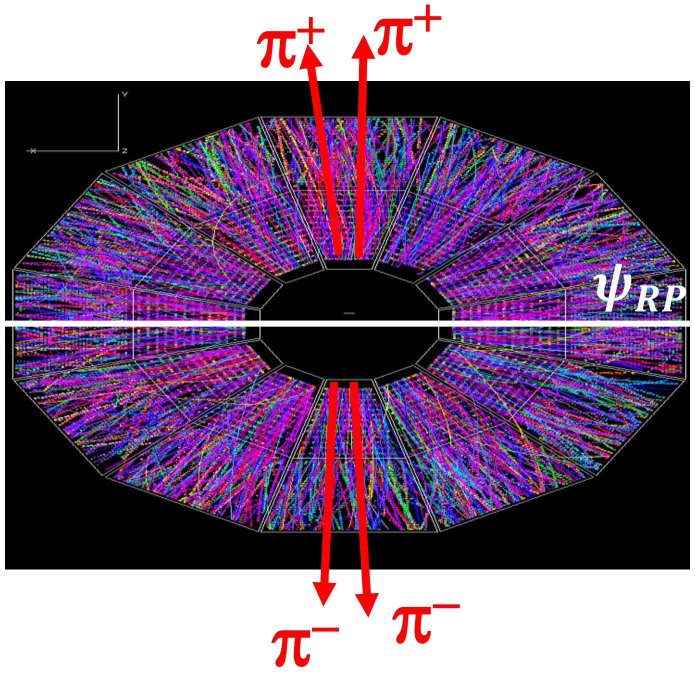




HOW TO MEASURE CHARGE SEPARATION







Voloshin, PRC 70 (2004) 057901

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

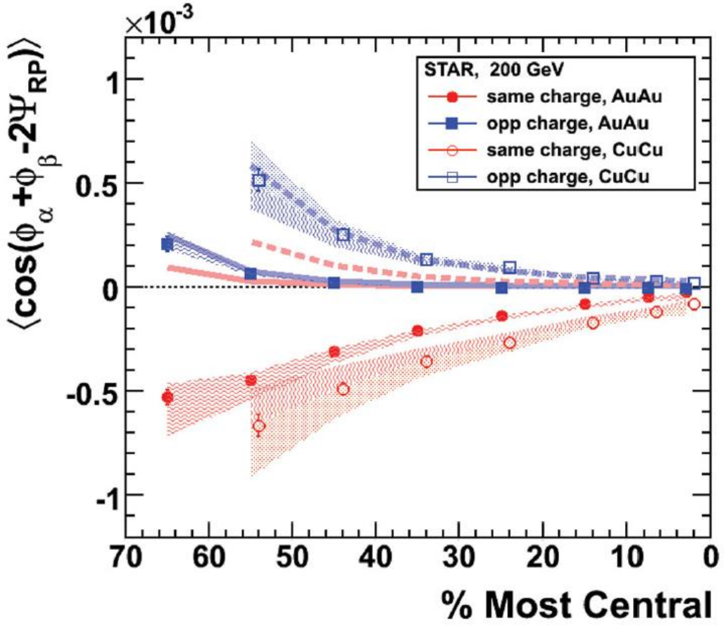
$$\gamma_{+-,-+} > 0, \quad \gamma_{++,--} < 0$$

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

$$\Delta\gamma > 0$$

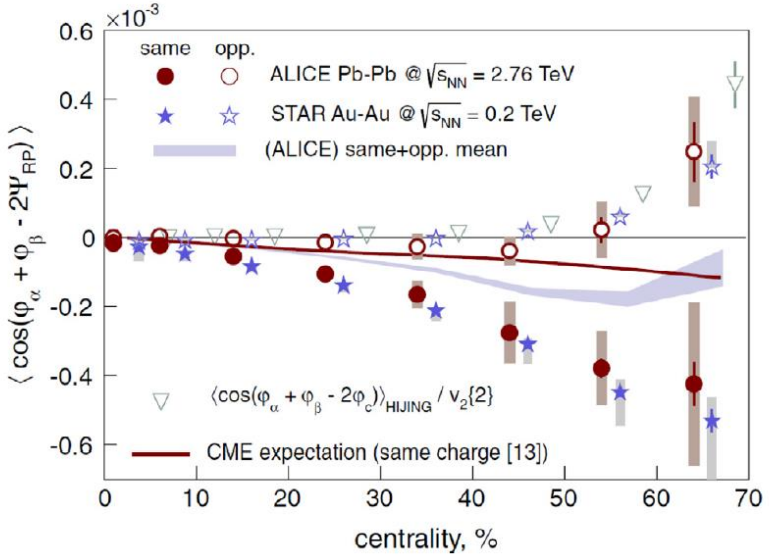
- parity-odd observables will average to zero
- have to measure charge correlations, or variance/covariance
- will be proportional to Parity^2, so subject to P-even backgrounds
- How big is the signal? hard to predict from first principle
  Guesstimate 1%, or 10^{-4} in correlation measurement

INDEED STRONG SIGNALS WERE OBSERVED



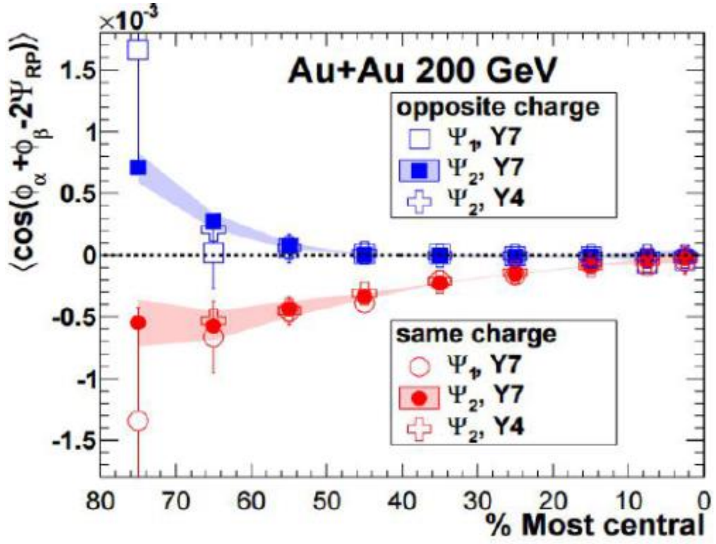
STAR, PRL 103 (2009) 251601
PRC 81 (2010) 054908.

STAR, 2009



ALICE, PRL 110 (2013) 012301

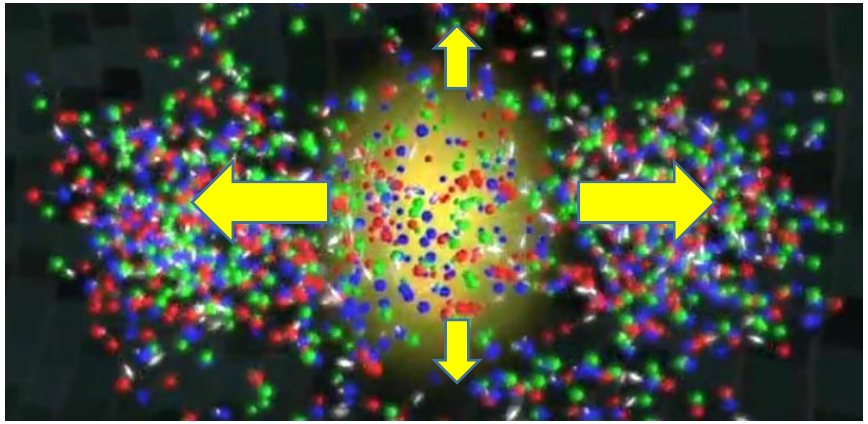
ALICE, 2013



STAR, PRC 88 (2013) 064911

STAR, 2013

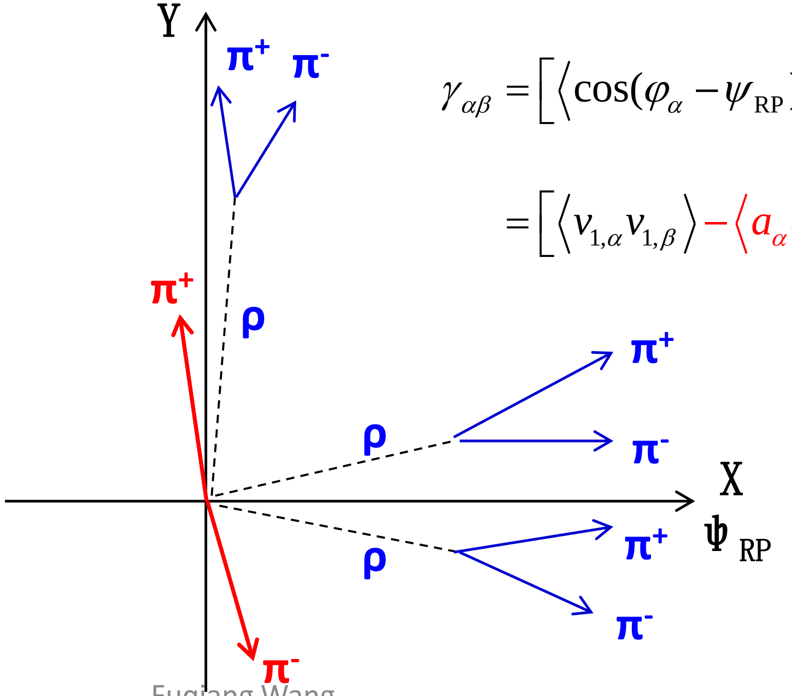
CORRELATION BACKGROUND



FW 2009; Bzdak, Koch, Liao 2010; Pratt, Schlichting 2010; …

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

$$\frac{dN_\pm}{d\varphi} \propto 1 + 2v_1 \cos\varphi^\pm + 2a_\pm \cdot \sin\varphi^\pm + 2v_2 \cos 2\varphi^\pm + \ldots$$



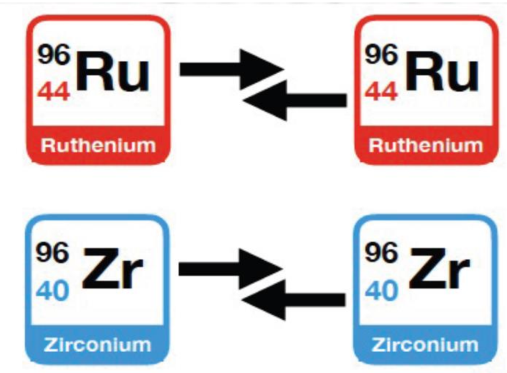
$$\gamma_{\alpha\beta} = \left[\langle \cos(\varphi_\alpha - \psi_{\mathrm{RP}})\cos(\varphi_\beta - \psi_{\mathrm{RP}})\rangle - \langle \sin(\varphi_\alpha - \psi_{\mathrm{RP}})\sin(\varphi_\beta - \psi_{\mathrm{RP}})\rangle\right] + \left[\frac{N_{\mathrm{cluster}}}{N_\alpha N_\beta}\langle \cos(\varphi_\alpha + \varphi_\beta - 2\varphi_{\mathrm{cluster}})\cos(2\varphi_{\mathrm{cluster}} - 2\psi_{\mathrm{RP}})\rangle\right]$$

$$= \left[\langle v_{1,\alpha} v_{1,\beta}\rangle - \langle a_\alpha a_\beta \rangle\right] + [\text{charge-independent Bkg (e.g. mom. conservation)}] + \frac{N_{\mathrm{cluster}}}{N_\alpha N_\beta}\langle \cos(\varphi_\alpha + \varphi_\beta - 2\varphi_{\mathrm{cluster}})\rangle v_{2,\mathrm{cluster}}$$

$$\Delta\gamma_{\mathrm{bkg}} = 2\langle a_1^2 \rangle + \frac{N_{\mathrm{cluster}}}{N_\alpha N_\beta}\langle \cos(\varphi_\alpha + \varphi_\beta - 2\varphi_{\mathrm{cluster}})\rangle v_{2,\mathrm{cluster}} \propto v_{2,\rho} / N$$

NONFLOW x FLOW

STRATEGY



Ruthenium

Zirconium

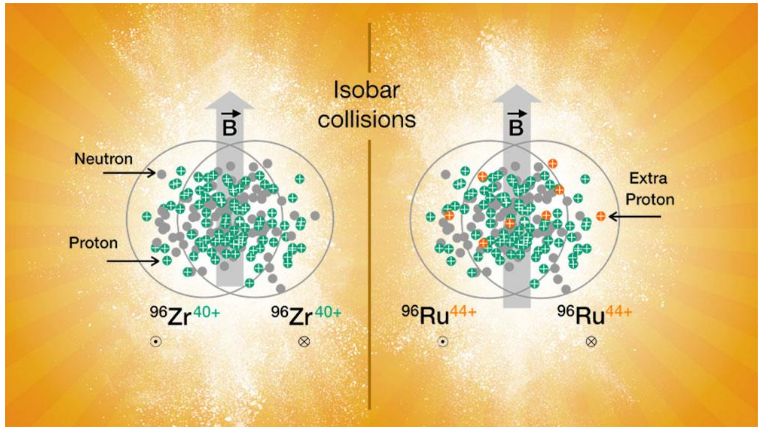
- Isobar collisions
  - ➢ Same mass number (A=Z+N)

    Strong interaction physics is blind to proton vs. neutron

    → **same QCD background**
  - ➢ Different atomic number (Z)

    Magnetic field is produced by the passing protons

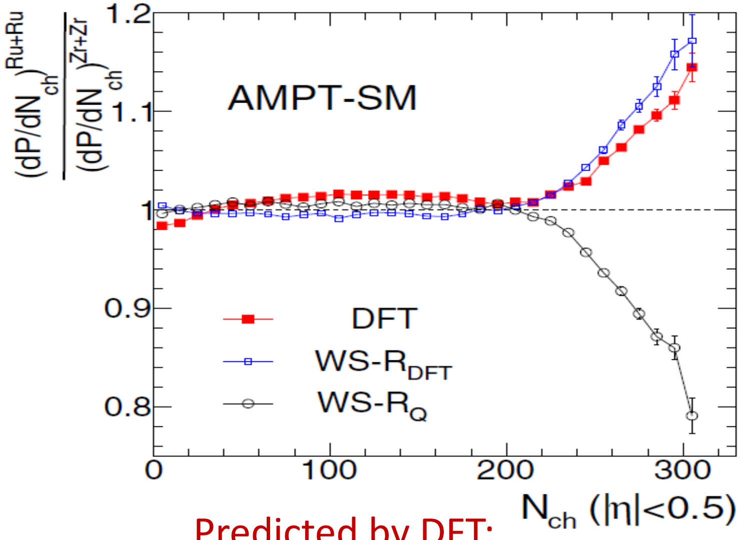
    → different magnetic field → **different CME signal**



- 2B events are taken for each system
- 3σ significance if signal is 10% of the measured $\Delta\gamma$

- Isobar blind analysis
  - ✓ Recommended by BNL Physics Advisory Committee
  - ✓ First time in heavy ion collisions
  - ✓ Design even before data taking: *Methods for a blind analysis of isobar data collected by the STAR Collaboration*, Nucl. Sci. Tech. 32 (2021) 48

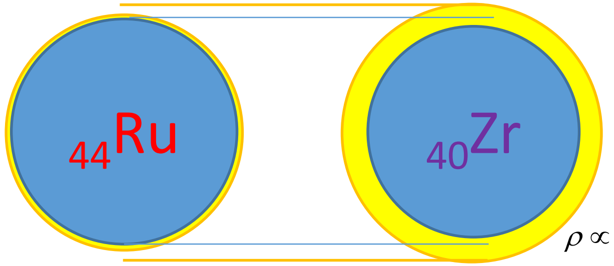
ISOBAR SYSTEMS ARE NOT IDENTICAL



Predicted by DFT:

*Hanlin Li et al. PRC **98** (2018) 054907*
*Haojie Xu et al. PRL **121** (2018) 022301*

Halo-neutron

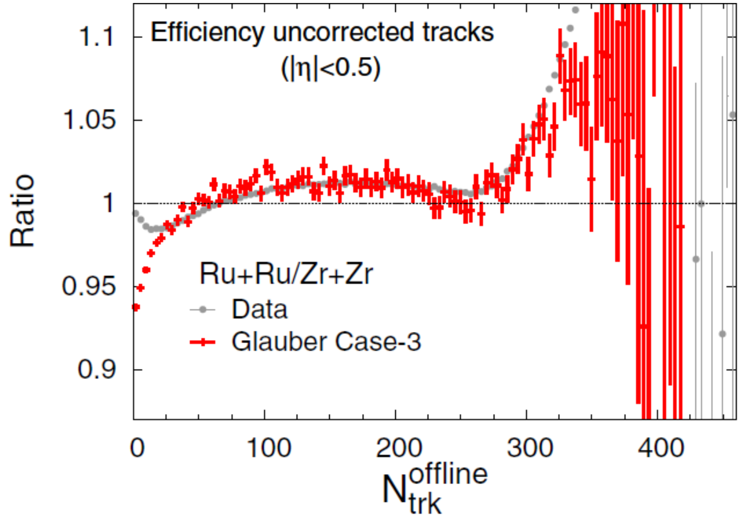


$$\rho \propto \left[1+\exp\left(\frac{r-R}{a}\right)\right]^{-1}$$

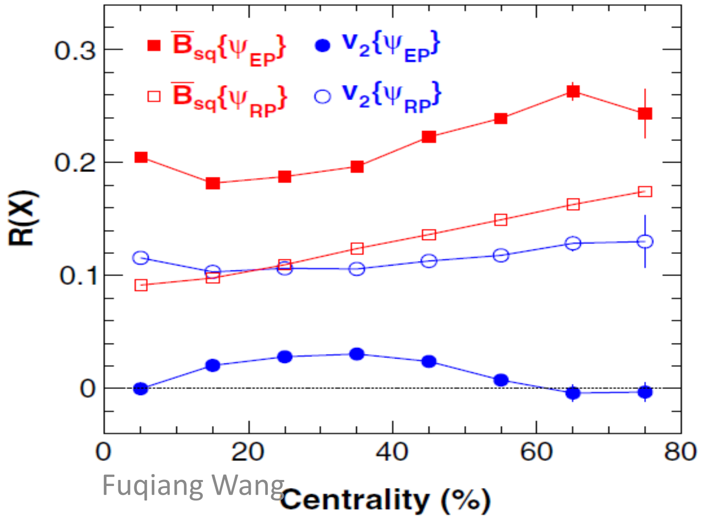
Larger charge radius
Little neutron skin

Smaller charge radius
Thicker neutron skin

Overall size: Ru < Zr
→ Larger energy density in Ru > Zr
→ Larger multiplicity in Ru > Zr

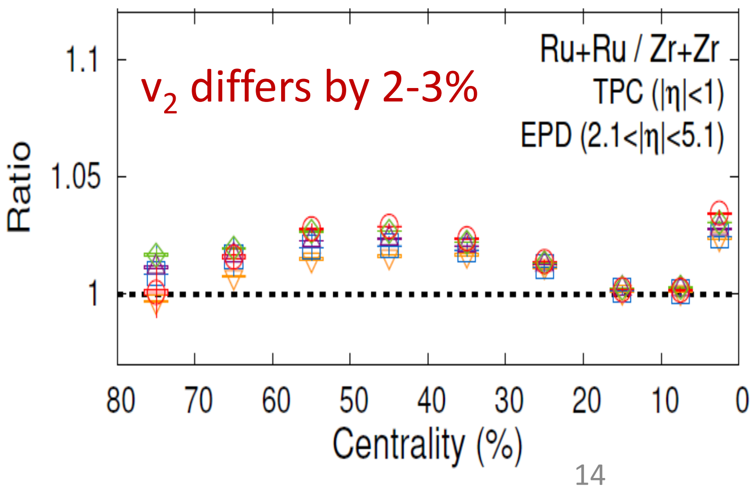


Verified by isobar data:
STAR, PRC 105 (2022), 2109.00131



$$\Delta\gamma_{\rm bkg} = \frac{4N_{\rm 2p}}{N^2}\left\langle \cos(\phi_\alpha + \phi_\beta - 2\phi_{\rm 2p})\right\rangle v_{2,\rm 2p}$$

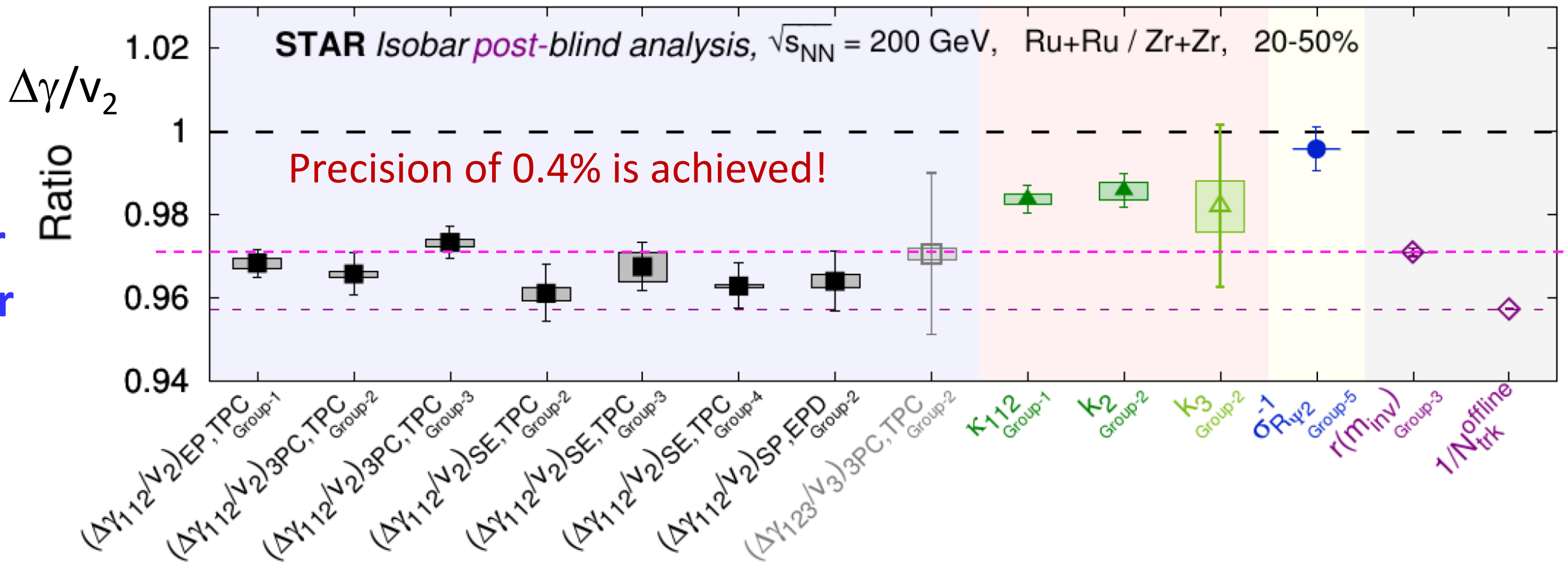
Normalize by v_2 and N → $N\Delta\gamma/v_2$



ISOBAR COLLISION RESULTS

STAR, PRC 105 (2022), 2109.00131

$\Delta\gamma/v_2$ isobar ratio smaller than unity



Primary reason: Mult. difference

$\Delta\gamma_{\mathrm{bkg}} \propto N_{\mathrm{cluster}} / N^2$

REMAINING NONFLOW EFFECTS

Feng, FW, et al., PRC 105 (2022) 024913, arXiv:2106.15595

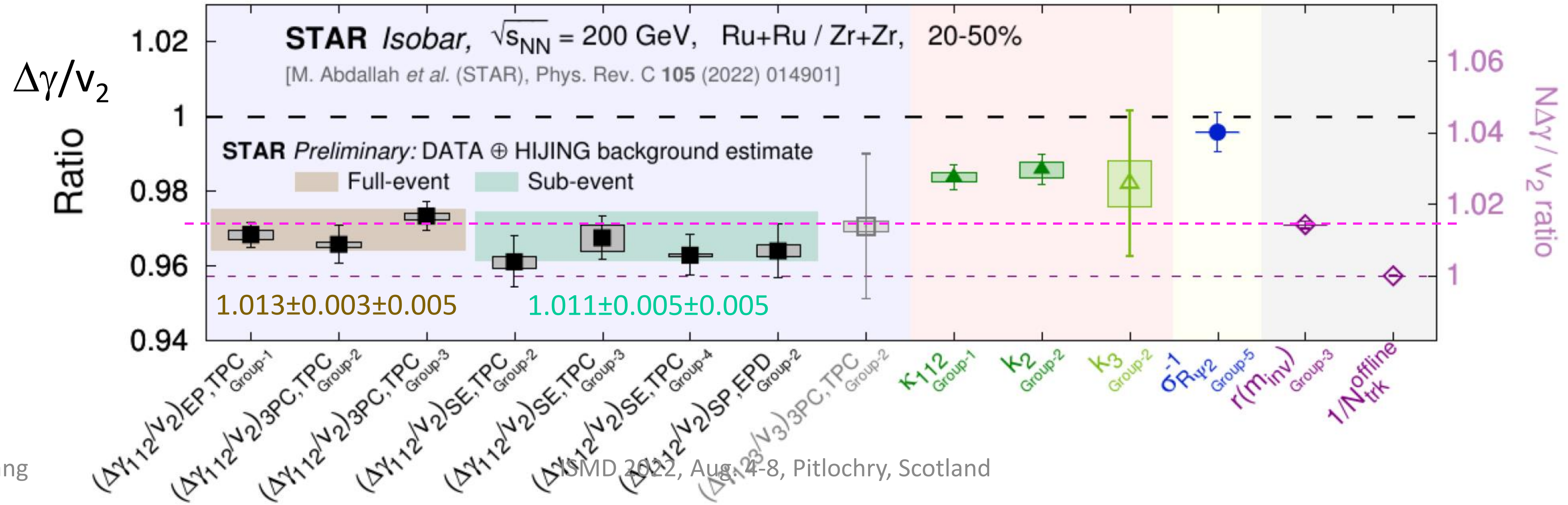
$$C_3 = \frac{C_{2p}N_{2p}}{N^2} v_{2,2p} v_2 + \frac{C_{3p}N_{3p}}{2N^3}; \quad C_{2p} \equiv \langle \cos(\alpha+\beta-2\phi_{2p}) \rangle, \quad C_{3p} \equiv \langle \cos(\alpha+\beta-2c) \rangle_{3p}$$

$$\varepsilon_2 \equiv \frac{C_{2p}N_{2p}}{N} \cdot \frac{v_{2,2p}}{v_2}, \quad \varepsilon_3 \equiv \frac{C_{3p}N_{3p}}{2N}$$

$$v_2^{*2} = v_2^2 + v_{2,\mathrm{nf}}^2, \quad \varepsilon_{\mathrm{nf}} \equiv v_{2,\mathrm{nf}}^2 / v_2^2$$

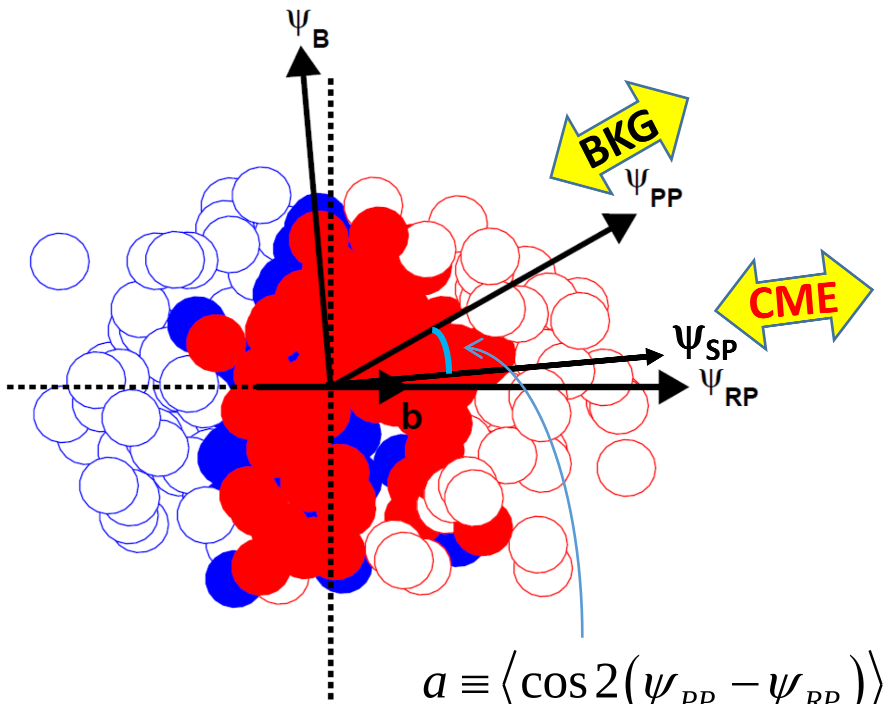
$$N \approx N_+ \approx N_-, \quad \Delta X \equiv X^{\mathrm{Ru}} - X^{\mathrm{Zr}}$$

$$\frac{(N\Delta\gamma/v_2^*)^{\mathrm{Ru}}}{(N\Delta\gamma/v_2^*)^{\mathrm{Zr}}} \equiv \frac{(NC_3/v_2^{*2})^{\mathrm{Ru}}}{(NC_3/v_2^{*2})^{\mathrm{Zr}}} \approx \frac{\varepsilon_2^{\mathrm{Ru}}}{\varepsilon_2^{\mathrm{Zr}}} \cdot \frac{(1+\varepsilon_{\mathrm{nf}})^{\mathrm{Zr}}}{(1+\varepsilon_{\mathrm{nf}})^{\mathrm{Ru}}} \cdot \frac{\left(1+\frac{\varepsilon_3/\varepsilon_2}{Nv_2^2}\right)^{\mathrm{Ru}}}{\left(1+\frac{\varepsilon_3/\varepsilon_2}{Nv_2^2}\right)^{\mathrm{Zr}}} \approx \frac{\varepsilon_2^{\mathrm{Ru}}}{\varepsilon_2^{\mathrm{Zr}}} - \frac{\Delta\varepsilon_{\mathrm{nf}}}{1+\varepsilon_{\mathrm{nf}}} + \frac{\frac{\varepsilon_3/\varepsilon_2}{Nv_2^2}}{1+\frac{\varepsilon_3/\varepsilon_2}{Nv_2^2}} \left(\frac{\Delta\varepsilon_3}{\varepsilon_3} - \frac{\Delta\varepsilon_2}{\varepsilon_2} - \frac{\Delta N}{N} - \frac{\Delta v_2^2}{v_2^2} \right)$$



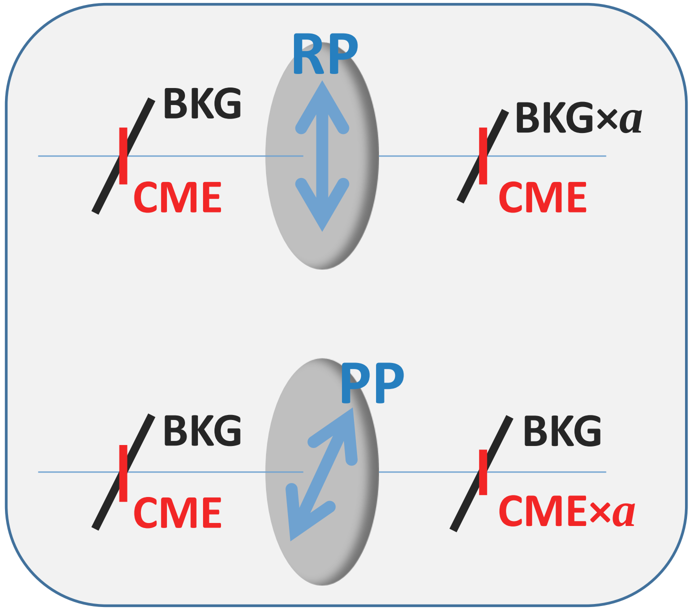
SPECTATOR & PARTICIPANT PLANES

H.-j. Xu, FW, et al., CPC 42 (2018) 084103, arXiv:1710.07265
S.A. Voloshin, PRC 98 (2018) 054911, arXiv:1805.05300



$$a \equiv \langle \cos 2(\psi_{PP} - \psi_{RP}) \rangle$$

INTRA-EVENT "CME-v_2 FILTER"



IN THE SAME EVENT

$$\Delta\gamma\{\mathrm{SP}\} = a\Delta\gamma_{Bkg}\{\mathrm{PP}\} + \Delta\gamma_{CME}\{\mathrm{PP}\}/a$$

$$\Delta\gamma\{\mathrm{PP}\} = \Delta\gamma_{Bkg}\{\mathrm{PP}\} + \Delta\gamma_{CME}\{\mathrm{PP}\}$$

$$A = \Delta\gamma\{\mathrm{SP}\}/\Delta\gamma\{\mathrm{PP}\}$$

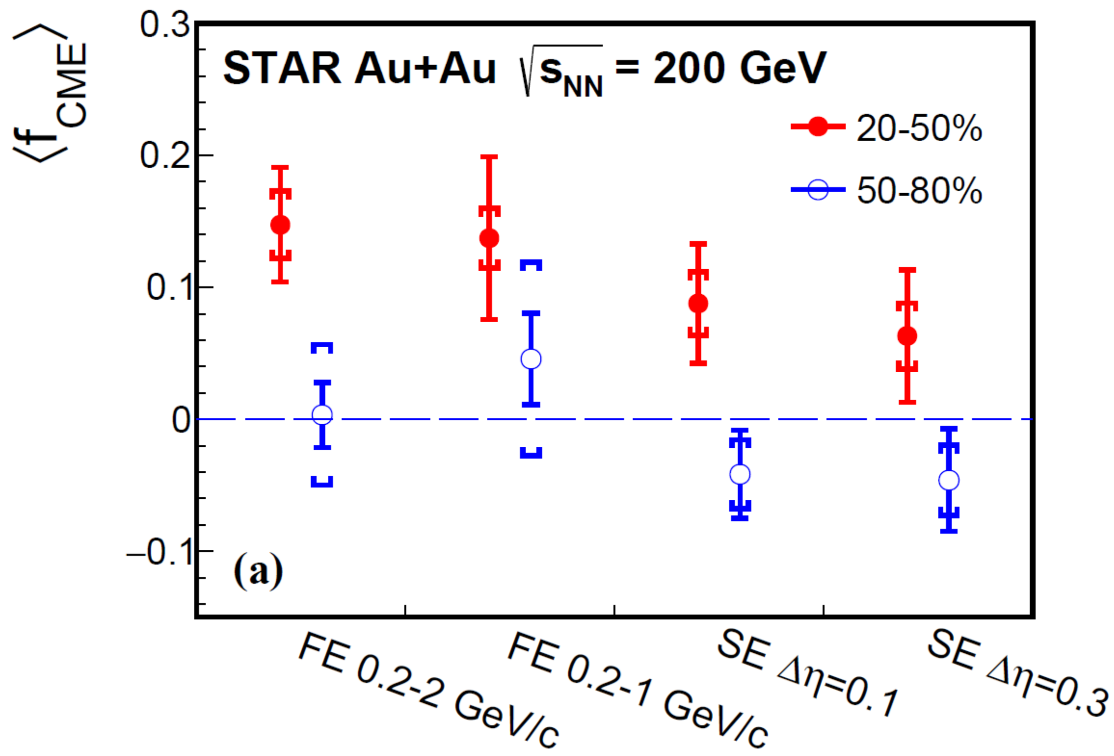
$$a = v_2\{\mathrm{SP}\}/v_2\{\mathrm{PP}\}$$

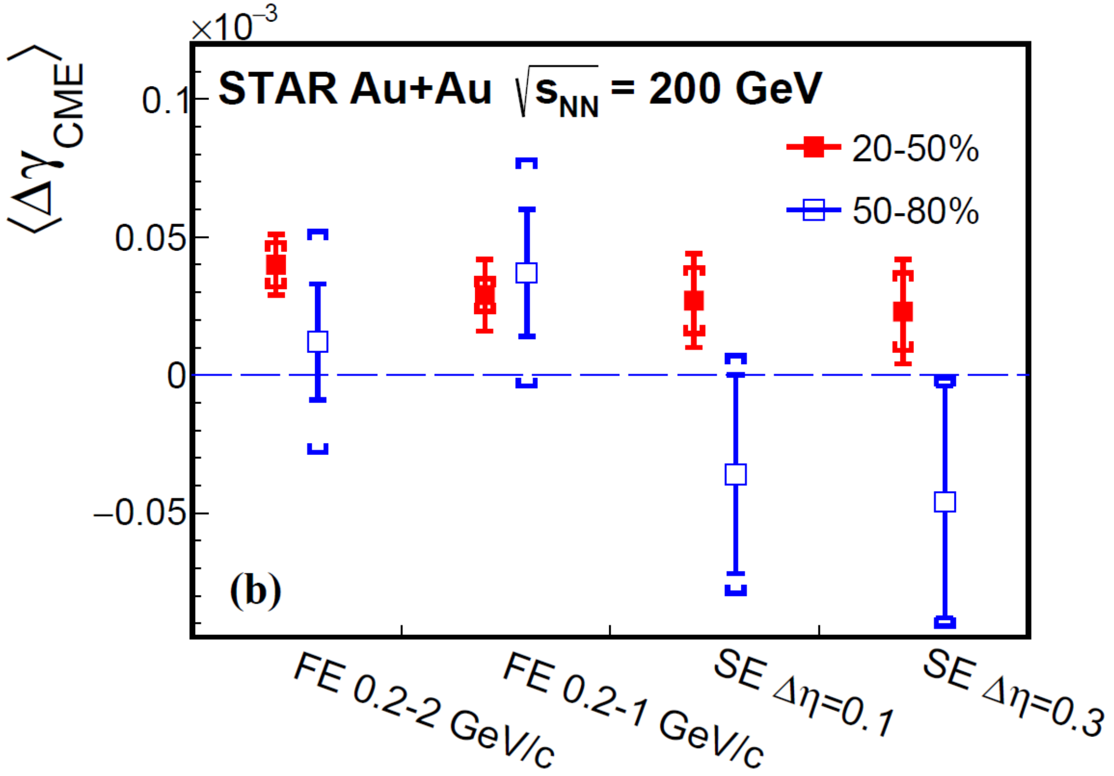
$$\Delta\gamma\{\mathrm{SP}\}/a - \Delta\gamma\{\mathrm{PP}\} = (1/a^2 - 1)\Delta\gamma_{CME}\{\mathrm{PP}\}$$

$$f_{CME} = \frac{\Delta\gamma_{CME}\{\mathrm{PP}\}}{\Delta\gamma\{\mathrm{PP}\}} = \frac{A/a - 1}{1/a^2 - 1}$$

Au+Au Collisions at 200 GeV (2.4B MB)

STAR, PRL 128 (2022) 092301, arXiv:2106.09243





- Consistent-with-zero signal in peripheral 50-80% collisions with relatively large errors
- Indications of finite signal in mid-central 20-50% collisions, with 1-3σ significance
- Possible remaining nonflow effects

REMAINING NONFLOW EFFECTS

STAR, PRL 128 (2022) 092301, arXiv:2106.09243

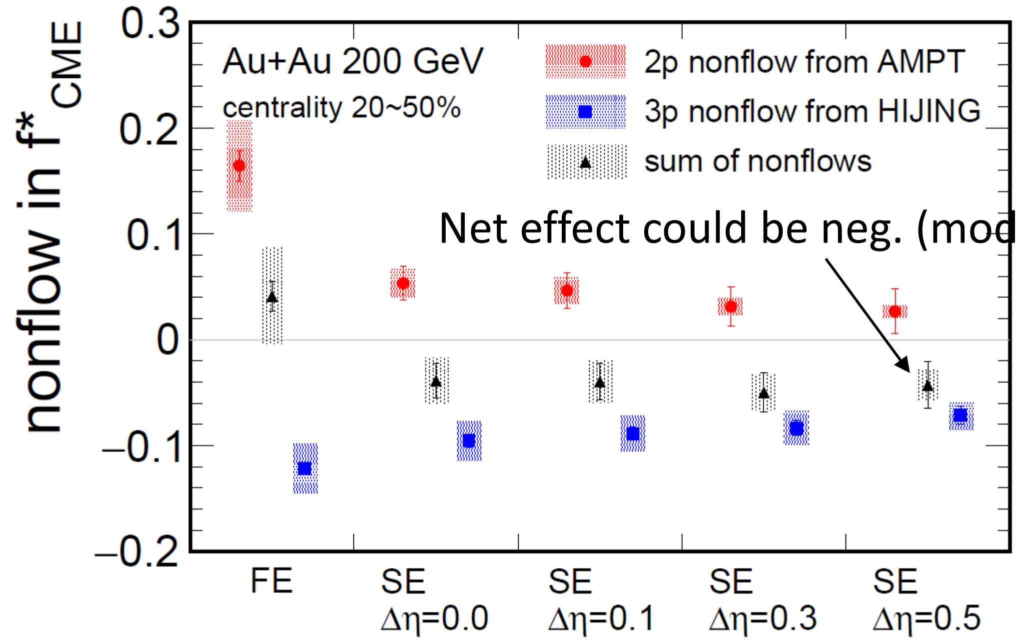
Feng, FW, et al., PRC 105 (2022) 024913, arXiv:2106.15595

$$f_{\rm CME} = \frac{\Delta\gamma_{\rm CME}\{\rm PP\}}{\Delta\gamma\{\rm PP\}} = \frac{A/a - 1}{1/a^2 - 1}$$

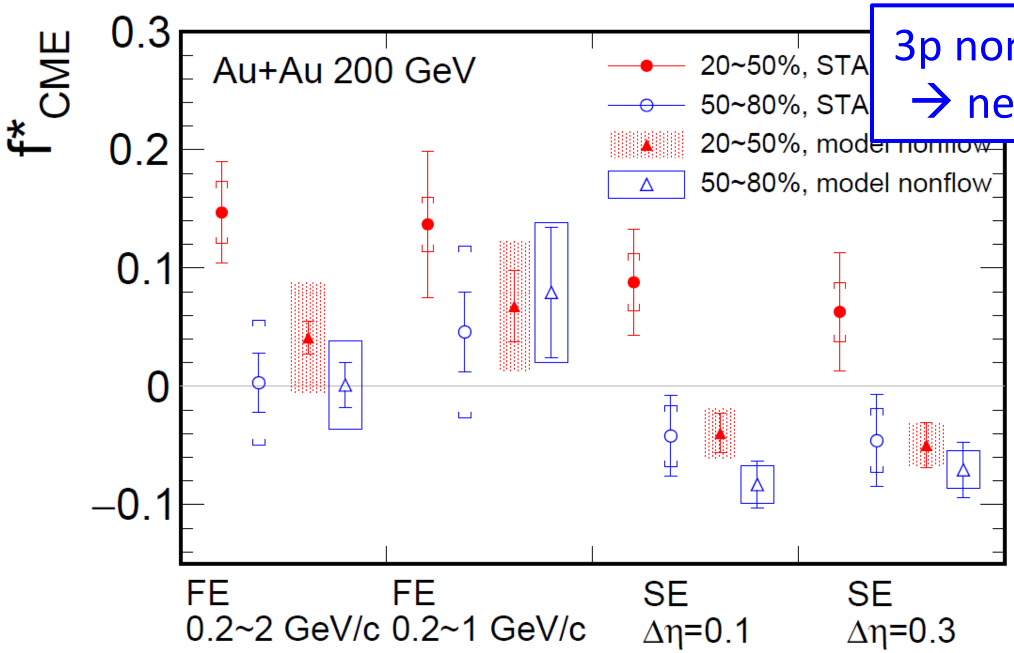
Nonflow in v_2 → positive $f_{\rm CME}$

$$\frac{\left(N\Delta\gamma / v_2^*\right)^{\rm Ru}}{\left(N\Delta\gamma / v_2^*\right)^{\rm Zr}} \approx \frac{\varepsilon_2^{\rm Ru}}{\varepsilon_2^{\rm Zr}} \cdot \frac{\left(1+\varepsilon_{\rm nf}\right)^{\rm Zr}}{\left(1+\varepsilon_{\rm nf}\right)^{\rm Ru}} \cdot \frac{\left(1+\frac{\varepsilon_3/\varepsilon_2}{Nv_2^2}\right)^{\rm Ru}}{\left(1+\frac{\varepsilon_3/\varepsilon_2}{Nv_2^2}\right)^{\rm Zr}}$$

$$\frac{A}{a} = \frac{\Delta\gamma\{\rm SP\}/v_2\{\rm SP\}}{\Delta\gamma\{\rm PP\}^*/v_2\{\rm PP\}^*} = \frac{C_3\{\rm SP\}/v_2^2\{\rm SP\}}{C_3\{\rm PP\}^*/v_2^2\{\rm PP\}^*} = \frac{1+\varepsilon_{\rm nf}}{1+\frac{\varepsilon_3/\varepsilon_2}{Nv_2^2\{\rm PP\}}}$$



Net effect could be neg. (model dep.)



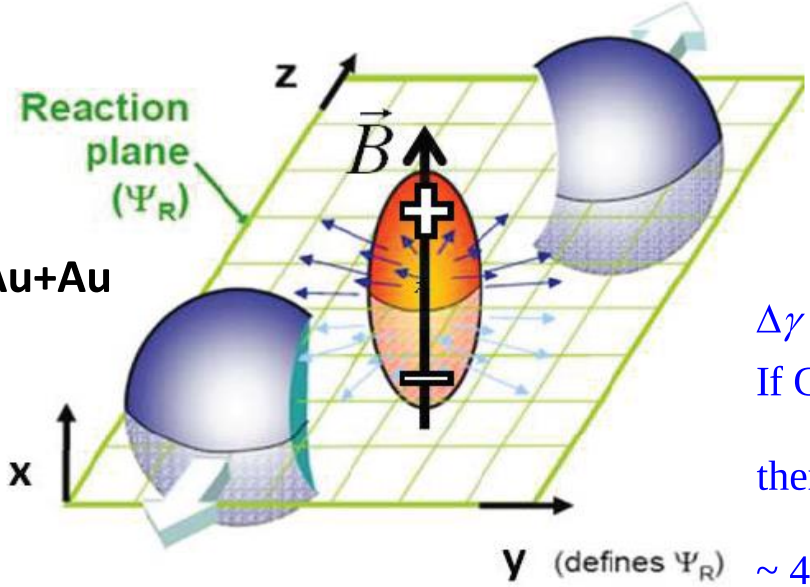
3p nonflow in Δγ → negative $f_{\rm CME}$

There may indeed be hint of CME in the data

Au+Au vs. ISOBAR

Feng, FW, et al., PLB 820 (2021) 136549, arXiv:2103.10378

Au+Au

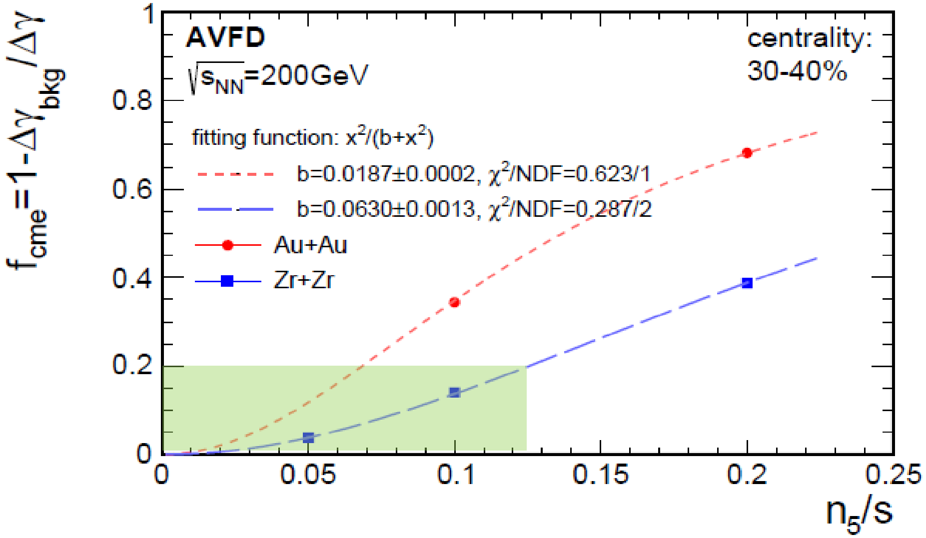


$\Delta\gamma \propto B^2$

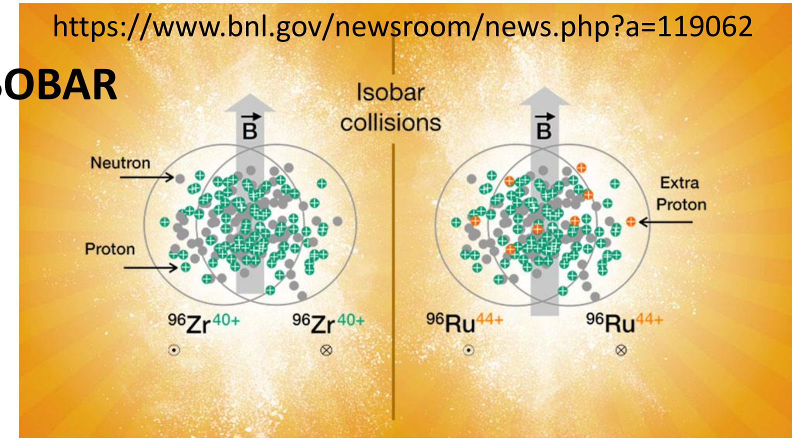
If CME signal is 10%,

then $\frac{\Delta\gamma^{Ru}}{\Delta\gamma^{Zr}} - 1 \approx 1.5\%$

$\sim 4\sigma$ effect



ISOBAR



Bkg $\propto$ 1/N → isobar/AuAu ~ 2

B ~ $A^{1/3}$ → CME: AuAu/isobar ~ 1.5

Can be x3 smaller f_{CME} @same n_5/s

SUMMARY & OUTLOOK

- CME is a very important physics. We have to quantify it.
- Background being of the order of 90% is a game changer.

- Isobar collisions: anticipated **precision down to 0.4%.**
  New background estimate, signal consistent with zero, not contradictory to Au+Au.
  Refine nonflow and extract upper limit.

- STAR Au+Au data (2.4 B MB events) **hint a finite CME signal** with small significance;
  Need more rigorous nonflow studies.
  Expect 20B Au+Au from 2023+25 runs.