Overview of STAR measurements on flow, chirality, and vorticity

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STAR

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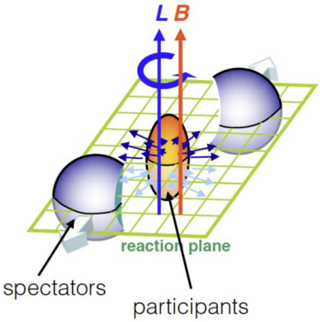
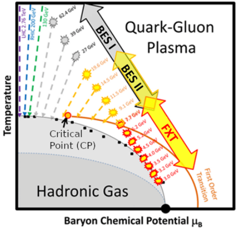
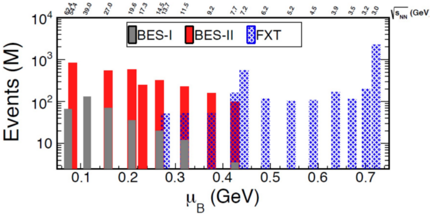
Physics of interest



- Quark Gluon Plasma (QGP) produced in high energy heavy-ion collisions (HIC)
  QGP: deconfined quarks and gluons over extended volume
  HIC: nuclei (e.g., Au) collide at nearly the speed of light
- Collective motion → flow
  QGP phase transition, equation of state of medium produced, nuclei shape, ...
- Global angular momentum (vorticity) → spin polarization
  rotation of QCD matter, spin degree of freedom
- QCD vacuum fluctuation → chirality anomaly + Magnetic field → chiral magnetic effect (CME)
  $\mathcal{P}$ and $\mathcal{CP}$ violation in strong interaction

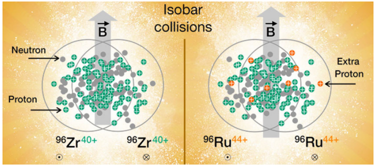
Some of the recent experiments at STAR





Beam Energy Scan (BES):
Au+Au collisions at different energies ($\sqrt{s_{\mathrm{NN}}}$)

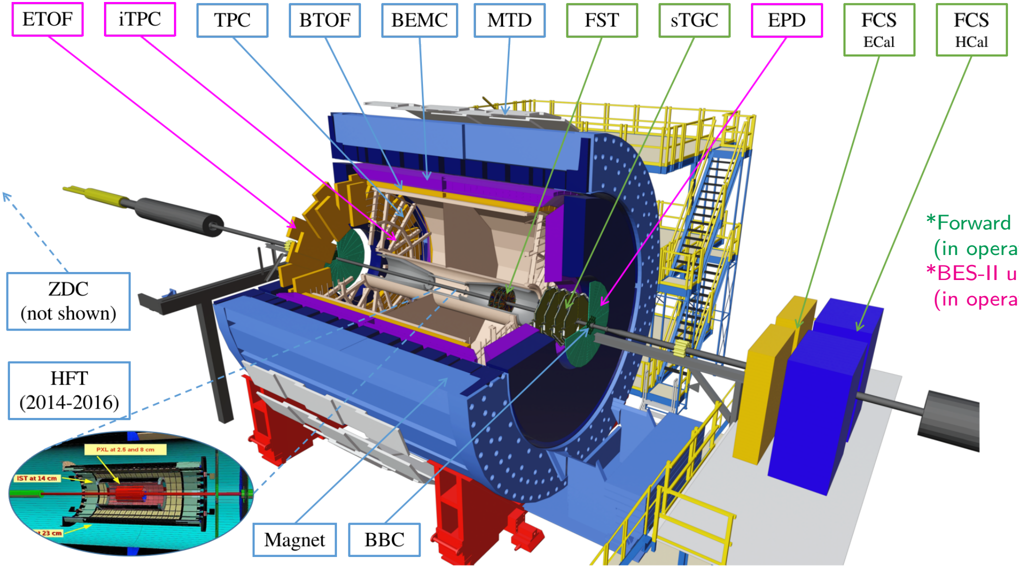
- BES-II (2018-2021): large increase of statistics
- FXT (2018-2021): fixed target experiments, lower collision energy
- Study the phases of QCD matter and search for QCD critical point, varying baryon chemical potential (μ_B)



Isobar collisions (2018):
$^{96}_{44}$Ru + $^{96}_{44}$Ru vs $^{96}_{40}$Zr + $^{96}_{40}$Zr

- Different proton numbers → different magnetic field
  Same nucleon number → similar QCD background
- Complication: nuclear structure difference
- Comparison to search for the chiral magnetic effect (CME)

STAR detector



ETOF

iTPC

TPC

BTOF

BEMC

MTD

FST

sTGC

EPD

FCS ECal

FCS HCal

ZDC (not shown)

HFT (2014-2016)

Magnet

BBC

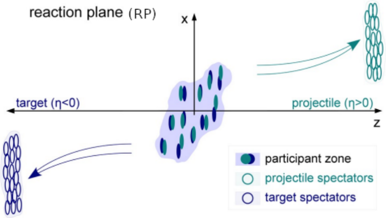
*Forward upgrades
(in operation since 2022)
*BES-II upgrades
(in operation since 2018)

Outline

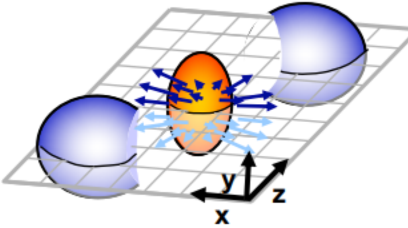
1. Flow
2. Vorticity
3. Chirality

Flow: the collective motion of produced particles

$$\frac{dN}{d\phi} \propto 1 + \sum_{n=1} 2v_n \cos n(\phi - \Psi_{\mathrm{RP}})$$

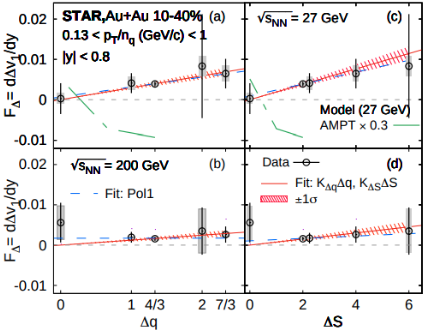


directed flow (v_1)



elliptic flow (v_2)

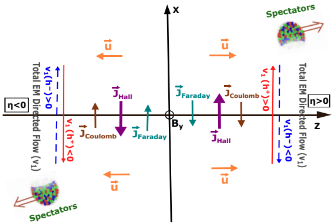
Δv_1 combination dependence on charge and strangeness



Δq	ΔS	Δv_1 combination
0	0	$[\bar{p}(\bar{u}\bar{u}\bar{d}) + \phi(s\bar{s})] - [K^-(\bar{u}s) + \bar{\Lambda}(\bar{u}\bar{d}\bar{s})]$
1	2	$[\bar{\Lambda}(\bar{u}\bar{d}\bar{s})] - [\frac{1}{3}\Omega^-(sss) + \frac{2}{3}\bar{p}(\bar{u}\bar{u}\bar{d})]$
$\frac{4}{3}$	2	$[\bar{\Lambda}(\bar{u}\bar{d}\bar{s})] - [K^-(\bar{u}s) + \frac{1}{3}\bar{p}(\bar{u}\bar{u}\bar{d})]$
2	6	$[\overline{\Omega}^+(\bar{s}\bar{s}\bar{s})] - [\Omega^-(sss)]$
$\frac{7}{3}$	4	$[\overline{\Xi}^+(\bar{d}\bar{s}\bar{s})] - [K^-(\bar{u}s) + \frac{1}{3}\Omega^-(sss)]$

[STAR, arXiv:2304.02831]

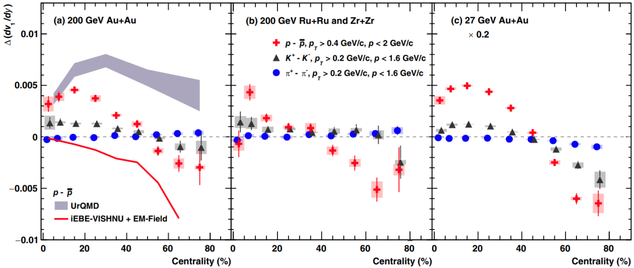
very strong magnetic fields are expected in early stages of heavy-ion collisions



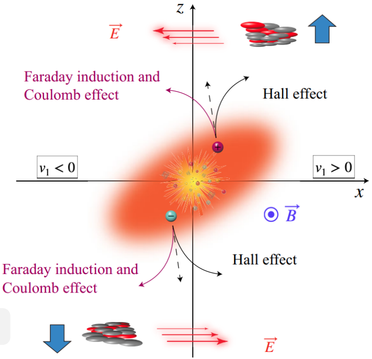
- K^-, $\bar{p}$, $\bar{\Lambda}$, ϕ, $\bar{\Xi}^+$, Ω^-, $\bar{\Omega}^+$ → no u, d quarks → no transported quarks
- Assume coalescence hadronization; EM effect → splitting $\propto \Delta q$.
- qualitatively consistent with Hall effect (Hall>Faraday+Coulomb) in 10-40% centrality

Other possibility: baryon inhomogeneities? [Parida, Chatterjee, arXiv:2305.08806]
simultaneous fit on Δq and ΔS? [Nayak, Shi, Lin, PLB849(2024)138479]

v_1 splitting and possible EM effect

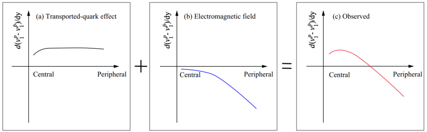


[STAR, PRX 14(2024)011028]



including transported quarks

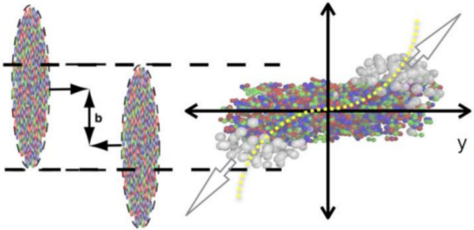
- particle-antiparticle v_1 splitting $d\Delta v_1/dy$
- pion, kaon, proton → consistent with positive transported quark contribution + electromagnetic field (Hall$<$Faraday+Coulomb) in peripheral collisions.



Other possibility: baryon inhomogeneities? [Parida, Chatterjee, arXiv:2305.08806] → Λ, p: similar splitting

Excess proton flow v_1 in BES-II

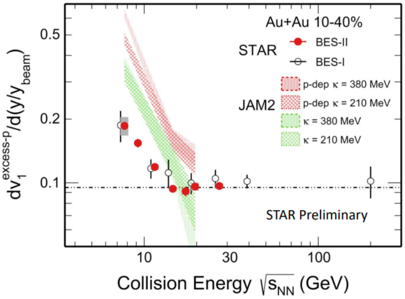
Proton directed flow is predicted to be a sensitive probe of the EoS of the produced medium.



$$N_p v_{1,p} = N_p v_{1,\text{medium}} + (N_p - N_{\bar{p}}) v_{1,\text{excess}}$$

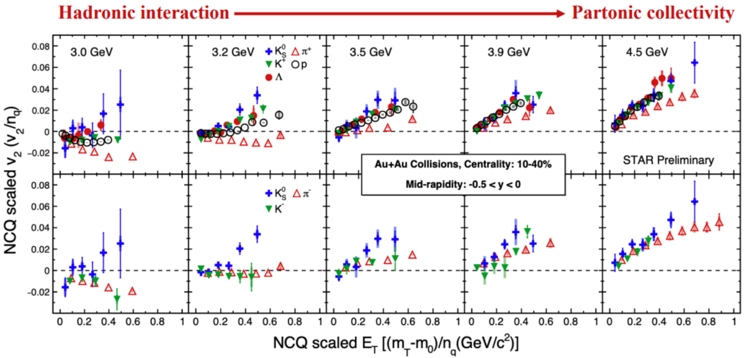
assuming $v_{1,\text{medium}} = v_{1,\bar{p}}$

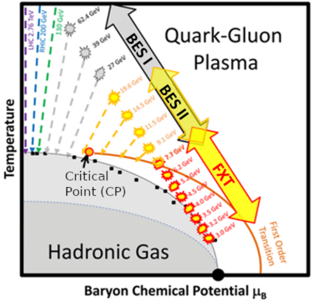
$$v_{1,\text{excess}} = \frac{v_{1,p} - v_{1,\bar{p}}}{1 - N_{\bar{p}}/N_p}$$



- BES-II: higher precision than BES-I
- v_1 slope of excess proton:
  $\sqrt{s_{\text{NN}}} > 11.5$ GeV scales with y/y_{beam};
  $\sqrt{s_{\text{NN}}} \leq 11.5$ GeV deviate from scaling
  → change in medium/collision dynamics
- Mean field models predict the trend, but over-predict the measurements at lower $\sqrt{s_{\text{NN}}}$
  → data can constrain EoS

v_2 at fixed target experiments – breaking of NCQ scaling

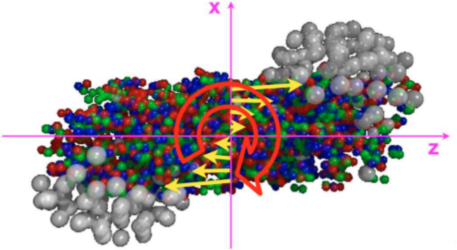


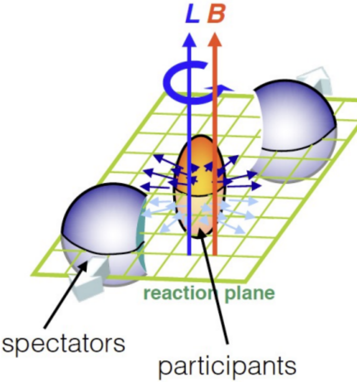


- partonic collectivity → NCQ scaling: number of constituent quark scaling → hadrons follow the same scaling $\frac{v_2}{n_q}$ vs. $\frac{m_T - m_0}{n_q}$ or $\frac{p_T}{n_q}$
- Gradual breaking of NCQ scaling $\sqrt{s_{\rm NN}} \leq 3.2$ GeV → shadowing effect + hadronic interaction

Outline

1. Flow
2. Vorticity
3. Chirality

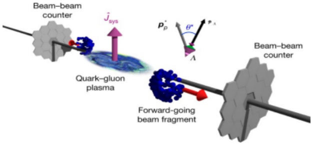




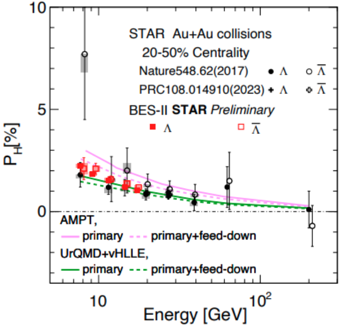
Λ global polarization

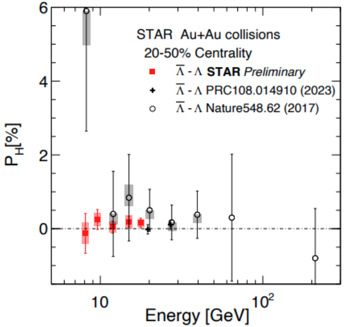
Non-central collision → global angular momentum → spin-orbit coupling → global polarization

STAR, Nature 548 (2017) 62



Courtesy of P. Tribedy





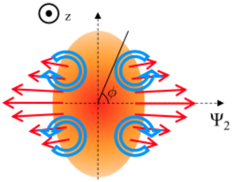
- Updates from BES-II $\sqrt{s_{\rm NN}} = 7.7 - 17.3$ GeV with high precision (improved statistics & event plane resolution)
- Λ, $\bar\Lambda$ opposite magnetic moment
  $\rightarrow \vec{B}$ field enhances $P_{\bar\Lambda}$ and reduce P_Λ → splitting expected
- No splitting is observed within uncertainties between Λ and $\bar\Lambda$ global polarization → late-stage magnetic field $B < 9.4 \times 10^{12}$ T (19.6GeV); $B < 1.4 \times 10^{13}$ T (27GeV) [STAR, PRC108(2023)014910]

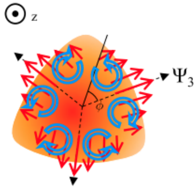
$$P_H = \frac{8}{\pi \alpha_H} \langle \sin(\Psi_{\rm RP} - \phi_p^*) \rangle$$

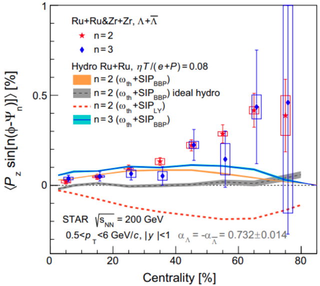
H: hyperons, Λ or $\bar\Lambda$ here
α_H: decay parameter
ϕ_p^*: decay daughter p ($\bar p$) azimuth in Λ ($\bar\Lambda$) rest frame

Λ local polarization

[STAR, PRL 131(2023)202301]







$$P_z = \frac{\langle \cos \theta_p^* \rangle}{a_H \langle \cos^2 \theta_p^* \rangle}$$

θ_p^*: decay daughter p ($\bar{p}$) polar angle in Λ ($\bar{\Lambda}$) rest frame w.r.t. beam direction

- Λ polarization along beam has dependence on azimuth w.r.t. EP
  → vorticity pattern expected due to elliptic and triangular anisotropic flow
  → local polarization w.r.t. both Ψ_2, Ψ_3 observed with similar magnitudes
- comparison with models → measurements provide constraints on the thermal vorticity and shear-induced contributions to hyperon polarization

Outline

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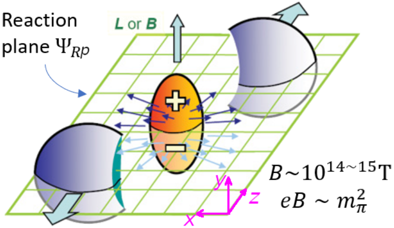
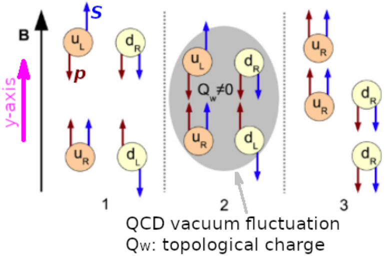
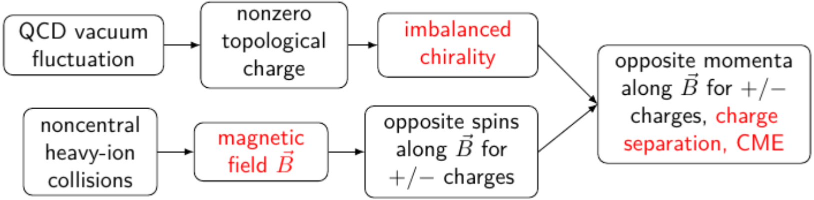




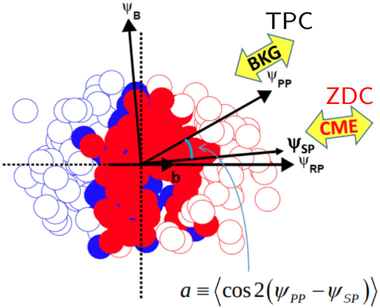


QCD vacuum fluctuation → nonzero topological charge → imbalanced chirality

noncentral heavy-ion collisions → magnetic field $\vec{B}$ → opposite spins along $\vec{B}$ for $+/-$ charges

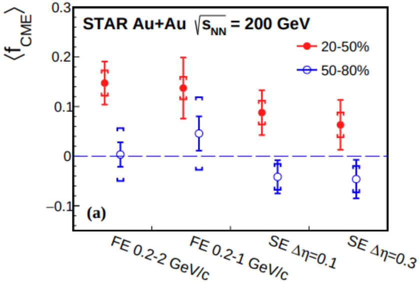
opposite momenta along $\vec{B}$ for $+/-$ charges, charge separation, CME

CME signal extraction: SP/PP comparison method



[H. Xu, *et al.*, CPC **42**(2018)084103]

[Voloshin, PRC 98(2018)054911]



[STAR, PRL 128(2022)092301]

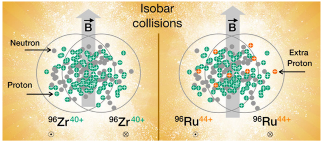
$$a = v_2\{\mathrm{SP}\}/v_2\{\mathrm{PP}\}$$

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

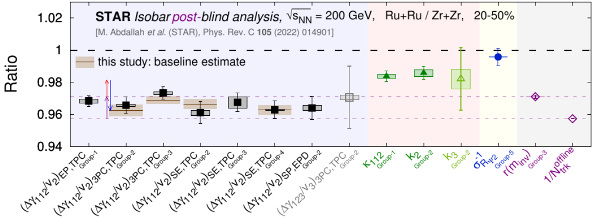
$$f_{\mathrm{CME}} = \frac{\Delta\gamma_{\mathrm{CME}}\{\mathrm{EP}\}}{\Delta\gamma\{\mathrm{EP}\}} = \frac{A/a - 1}{1/a^2 - 1}$$

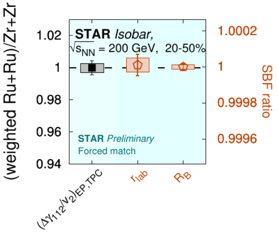
- The azimuthal correlator $\Delta\gamma$ is widely used, with backgrounds like resonance decays coupled with flow $\gamma_{\mathrm{OS}} = \langle \cos(\phi_1^{\pm} + \phi_2^{\mp} - 2\Psi_{\mathrm{RP}}) \rangle$, $\gamma_{\mathrm{OS}} = \langle \cos(\phi_1^{\pm} + \phi_2^{\mp} - 2\Psi_{\mathrm{RP}}) \rangle$, $\Delta\gamma = \gamma_{\mathrm{OS}} - \gamma_{\mathrm{SS}}$
- Both SP (spectator plane) and PP (participant plane) measure signal and flow-coupled background, but with different responses → SP, PP comparison → separate the signal and background
- The measurements shows positive f_{CME} with $2 \sim 3\sigma$ significance.

The isobar collision: CME upper limit



- **initial expectation:** $^{96}_{44}$Ru, $^{96}_{40}$Zr: same A, different Z → same background, different signal
- Ru+Ru: proton number ↑ → magnetic field ↑ → CME signal ↑ → $\Delta\gamma/v_2$ ↑ → Ru/Zr > 1





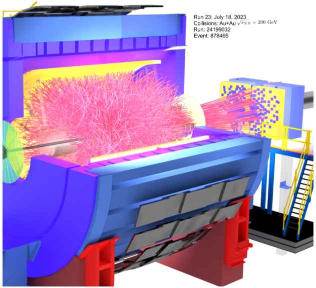
- **STAR blind analysis** [STAR, PRC 105(2022)014901] → isobar ratios Ru/Zr < 1, opposite to the initial expectation ← multiplicity diff. ← nuclear structure [Xu *et al.*, PRL121(2018)022301] .
- Nonflow background baseline estimate → CME upper limit 10% (95% CL). [STAR, PRR6(2024)L032005, PRC110(2024)014905, QM2023] Forced match method (N, v_2, EP res.) [STAR, QM2023] → consistent with unity

Summary and Outlook

Summary

This talk focuses on selected recent studies on flow, vorticity, and chirality, amid numerous other key findings

- Observed v_1 splitting between particles and antiparticles. Physics interpretations: EM effects? Baryon inhomogeneity?
- Proton v_1 measurements and excess proton v_1 offers constraints to EoS of the matter produced
- v_2 NCQ scaling breaks at low energy
- Λ and $\bar{\Lambda}$ polarization consistent within uncertainties. Non-zero local polarization relative to 2nd and 3rd order event planes
- CME searches with SP/PP comparison and isobar comparison → currently no firm conclusion on CME → looking forward to new data



Outlook

- Fully upgraded STAR detector (BES-II and forward upgrades completed) → better resolution, wider acceptance
- Unprecedented high statistics Au+Au/p+p at $\sqrt{s_{\mathrm{NN}}} = 200$ GeV in 2023-2025 → anticipated great improvement of precision

[STAR, Beam Use Request, Runs 24-25]

[Hot QCD White Paper, arXiv:2303.17254]

[The Present and Future of QCD, NPA1047(2024)122874]