STAR Highlights
– 2024 RHIC/AGS annual users' meeting

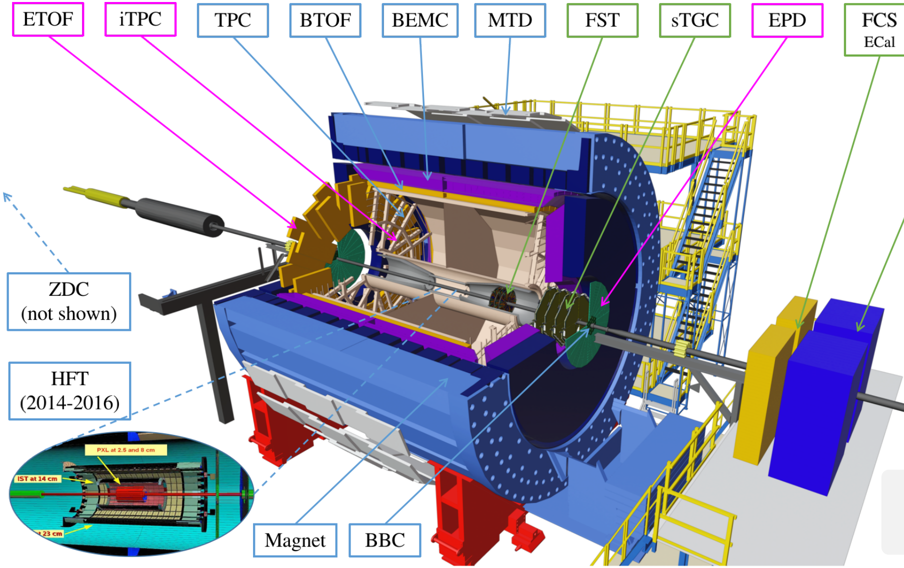
Yicheng Feng
(for the STAR Collaboration)

Purdue University

June 13, 2024

Supported in part by the U.S. Department of Energy Office of Science

STAR detector



*Forward upgrades
*BES-II upgrades

STAR Foward Systems and Related Topics
X. Liang, Tue. 1:00pm

Endcap Time-of-Flight Detector in BES
Y. Soehngen, Wed. 9:45am

Outline

1. Jet & Heavy Flavor

2. Flow

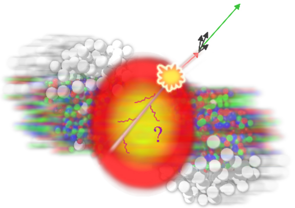
3. QCD critical point search

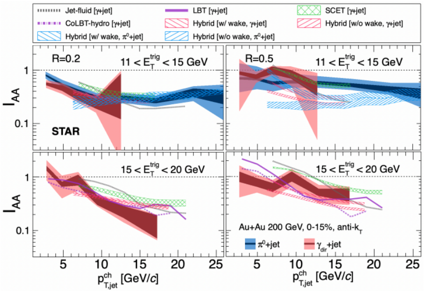
4. Chirality/Vorticity

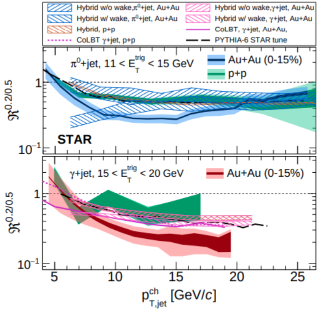
5. Hyperon-nucleon interaction

Jet modification

[STAR, arXiv:2309.00145,2309.00156]







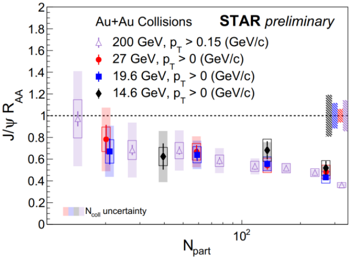
- recoil-jet yields per trigger (Y) ratio Au+Au over p+p, $I_{AA} < 1 \rightarrow$ medium-induced yield suppression $\rightarrow$ jet quenching
- greater suppression in smaller "jet radius" $R \rightarrow$ jet broadening

$$I_{AA} = \frac{Y^{\text{Au+Au}}(p^{\text{ch}}_{T,\text{jet}}, R)}{Y^{p+p}(p^{\text{ch}}_{T,\text{jet}}, R)}$$

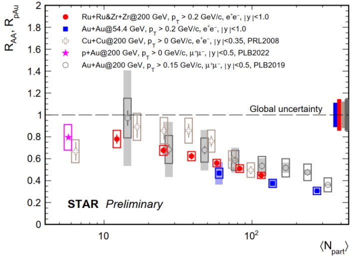
$$\mathfrak{R}^{\frac{\text{small-}R}{\text{large-}R}} = \frac{Y^{\text{A+A}}(p^{\text{ch}}_{T,\text{jet}}, \text{small } R)}{Y^{\text{A+A}}(p^{\text{ch}}_{T,\text{jet}}, \text{large } R)}$$

J/ψ production

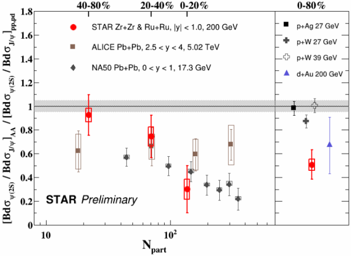
J/ψ energy dependence

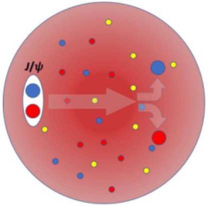


J/ψ system size dependence



$\psi(2s)$ over J/ψ ratio

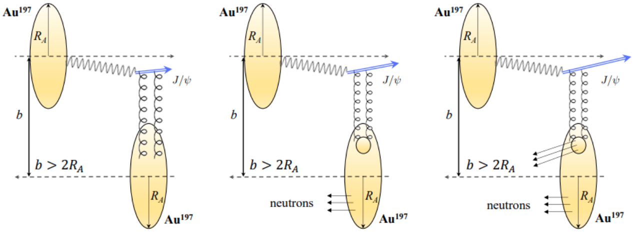




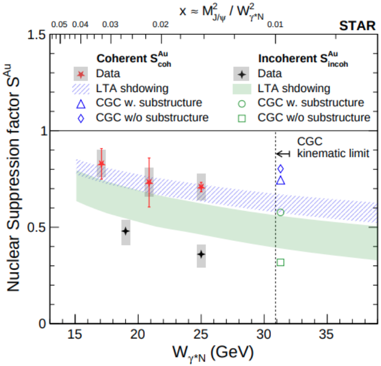
- No significant energy or system dependence
- $\psi(2s)$ over J/ψ double ratio $< 1 \rightarrow$ sequential suppression

J/ψ photoproduction in UPC

A. Ikbal, Tue. 4:00pm



(a) Coherent, nucleus stays intact (b) Incoherent with elastic nucleon (c) Incoherent with nucleon dissociation



[STAR, arXiv:2311.13637, arXiv:2311.13632]

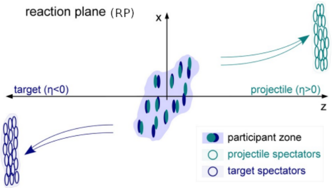
- At photon-nucleon center-of-mass energy $W_{\gamma*N}$ of 25 GeV, the coherent and incoherent J/ψ cross sections of Au nuclei are found to be $(71 \pm 10)\%$ and $(36 \pm 7)\%$, respectively, of that of free protons.
- comparison with models $\rightarrow$ possible shadowing effect, color glass condensate

S^{Au}: ratio between J/ψ cross section and the impulse approximation (IA). IA neglects all nuclear effects except for coherence.

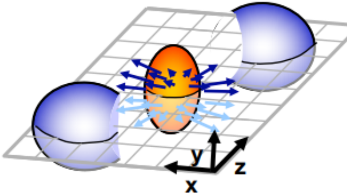
Outline

Flow: the collective motion of produced particles

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



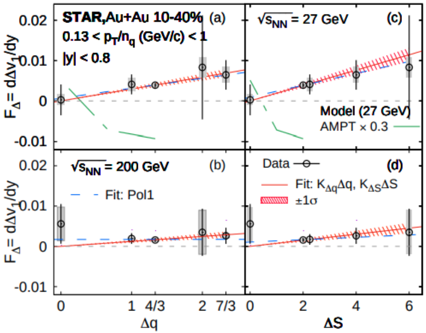
direct flow (v_1)



elliptic flow (v_2)

Δv_1 combination dependence on charge and strangeness

A. Ikbal, Tue. 4:00pm
A. Dash, Wed. 4:30pm



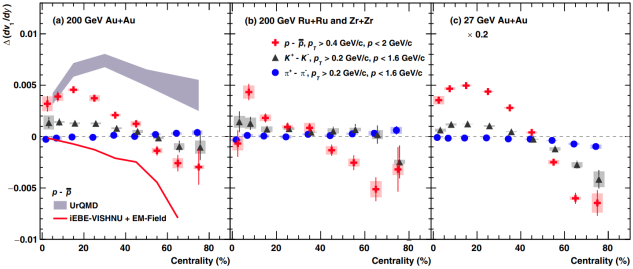
Δq	ΔS	Δv_1 combination
0	0	$[\bar{p}(\bar{u}\bar{u}\bar{d}) + \phi(s\bar{s})] - [K^-(\bar{u}s) + \bar{\Lambda}(\bar{u}\bar{d}\bar{s})]$
1	2	$[\bar{\Lambda}(\bar{u}\bar{d}\bar{s})] - [\frac{1}{3}\Omega^-(sss) + \frac{2}{3}\bar{p}(\bar{u}\bar{u}\bar{d})]$
$\frac{4}{3}$	2	$[\bar{\Lambda}(\bar{u}\bar{d}\bar{s})]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

[STAR, arXiv:2304.02831]

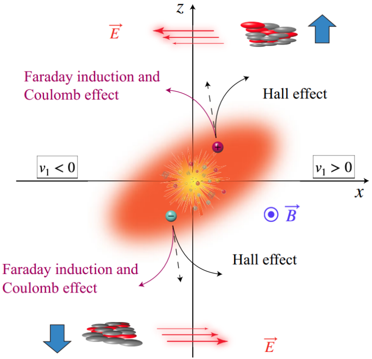
- K^-, $\bar{p}$, $\bar{\Lambda}$, ϕ, $\bar{\Xi}^+$, Ω^-, $\bar{\Omega}^+$ $\rightarrow$ no u, d quarks $\rightarrow$ no transported quarks
- assuming coalescence $\rightarrow$ $d\Delta v_1/dy \propto \Delta q, \Delta S$
- qualitatively consistent with Hall effect (Hall$>$Faraday+Coulomb) in 10-40% centrality

v_1 splitting and possible EM effect

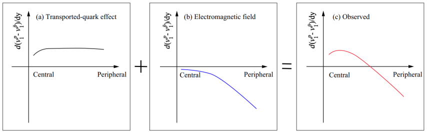
D. Shen, Tue. 9:25am
A. Dash, Wed. 4:30pm



[STAR, PRX 14(2024)011028]



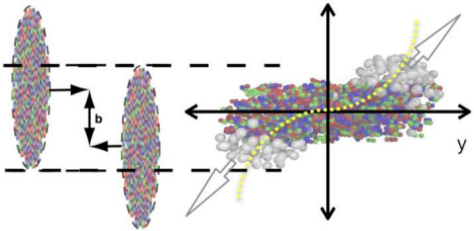
- particle-antiparticle v_1 splitting $d\Delta v_1/dy$
- pion, kaon, proton $\to$ qualitatively interpreted by transported quark + electromagnetic field (Hall$<$Faraday+Coulomb) in peripheral collisions.

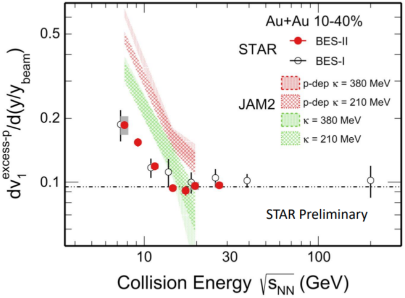


Other possibility: baryon inhomogeneities? [arXiv:2305.08806]

Excess proton flow v_1 in BES-II

E. Duckworth, Tue. 3:00pm





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

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

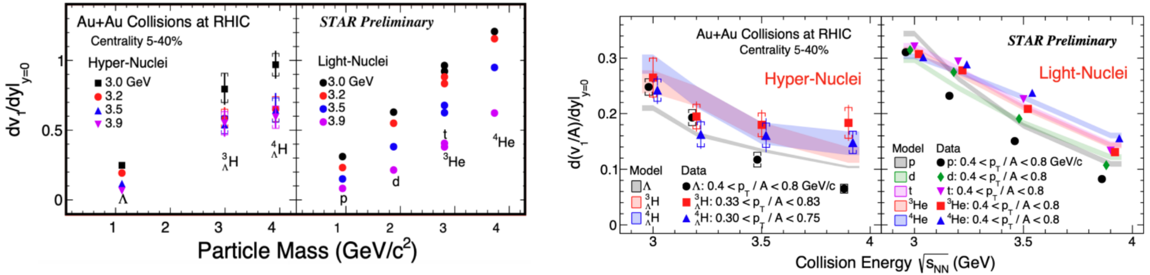
$$v_{1,\text{excess}} = \frac{v_{1,p} - v_{1,\bar{p}}}{1 - N_{\bar{p}}/N_p}$$

- BES-II: higher precision than BES-I
- $\sqrt{s_{\text{NN}}} > 11.5$ GeV flat scale; $\sqrt{s_{\text{NN}}} \leq 11.5$ GeV deviate → change in medium/collision dynamics
- Mean field model predicts the trend at low $\sqrt{s_{\text{NN}}}$, but higher → data to constraint model EOS

Other possibility: baryon inhomogeneities? [arXiv:2305.08806]

v_1 of light and hypernuclei at FXT

P. Sinha, Tue. 10:45am

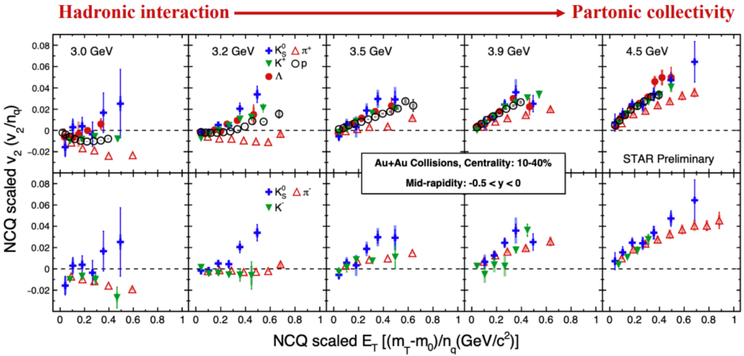


[STAR, PRL 130(2023)211301]

- dv_1/dy scales with mass number
- $\sqrt{s_{\mathrm{NN}}} \downarrow \rightarrow \mu_B \uparrow \rightarrow$ light and hyper nuclei abundance $\uparrow$
- $\sqrt{s_{\mathrm{NN}}} \downarrow \rightarrow d(v_1/A)/dy \uparrow$
- JAM2 mean field + coalescence calculations explains the energy dependence

v_2 at FXT – breaking of NCQ scaling

P. Sinha, Tue. 10:45am
E. Duckworth, Tue. 3:00pm



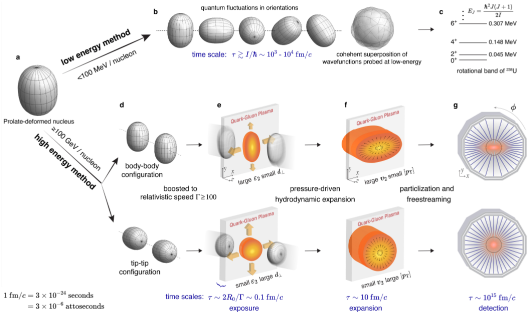
partonic collectivity
$\rightarrow$ NCQ scaling: number of constituent quark scaling
$\rightarrow$ hadron flows follow the same scaling $\frac{v_2}{n_q}$ vs. $\frac{m_T - m_0}{n_q}$ or $\frac{v_2}{n_q}$ vs. $\frac{p_T}{n_q}$

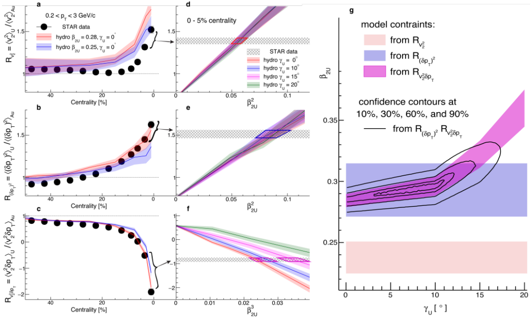
- NCQ scaling breaks at $\sqrt{s_{\mathrm{NN}}} \leq 3.2$ GeV $\rightarrow$ shadowing effect + hadronic interaction

Imaging nuclear shape from heavy-ion collisions

P. Sinha, Tue. 10:45am

[STAR, arXiv:2401.06625]

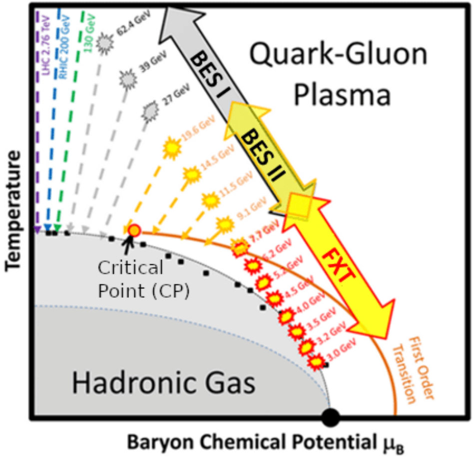




- Nuclear surface shape $R(\theta,\phi) = R_0(1+\beta_2[\cos\gamma Y_{2,0} + \sin\gamma Y_{2,2}])$
- Central U+U/Au+Au ratio of $\langle v_2^2\rangle$, $\langle(\delta p_T)^2\rangle$, $\langle v_2^2 \delta p_T\rangle$ data $\rightarrow$ nonflow estimate/subtraction $\rightarrow$ compare to hydro (IP-Glasma+MUSIC) $\rightarrow$ estimate U nuclear shape parameter β_{2U}

Outline

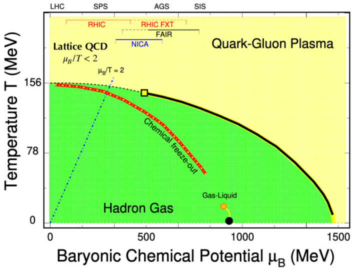
1. Jet & Heavy Flavor
2. Flow
3. QCD critical point search
4. Chirality/Vorticity
5. Hyperon-nucleon interaction



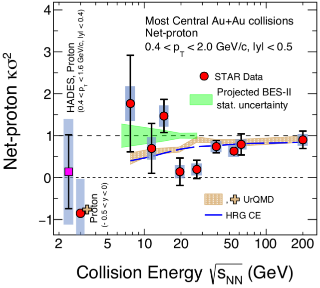
Net-proton fluctuation in BES-II

Y. Huang, Wed. 2:30pm
B. Mondal, Poster

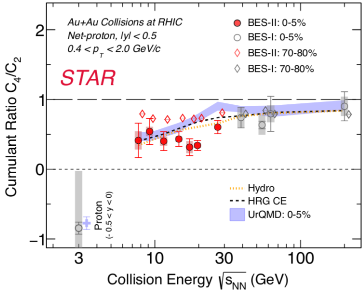
[B. Mohanty, N. Xu, arXiv:2101.09210]

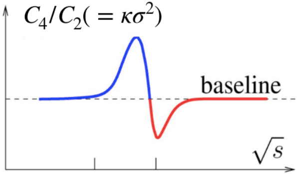


BES-I [STAR, PRL 126(2021)092301]



BES-II



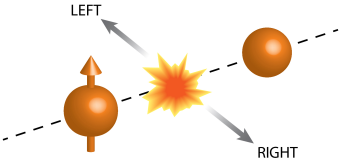


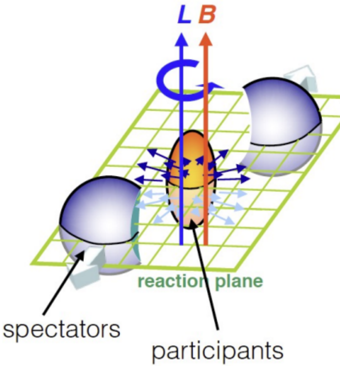
[M. Stephanov, PRL 107(2011)052301]

- QCD critical point (CP) is one of the most important physics
- n: net-proton multiplicity in an event;
  $\delta n = n - \langle n \rangle$; $C_2 = \langle \delta n^2 \rangle$; $C_4 = \langle \delta n^4 \rangle - 3\langle \delta n^2 \rangle$
- non-monotonic behavior expected around critical point
- BES-II $\rightarrow$ measurements with higher precision compared to BES-I
- C_4/C_2 in 0-5% $\rightarrow$ deviation from 70-80% and non-CP models ~ 20GeV

Outline

1. Jet & Heavy Flavor
2. Flow
3. QCD critical point search
4. Chirality/Vorticity
5. Hyperon-nucleon interaction

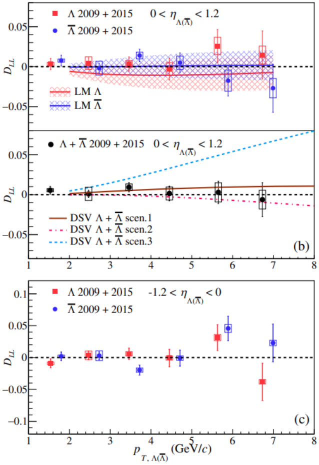


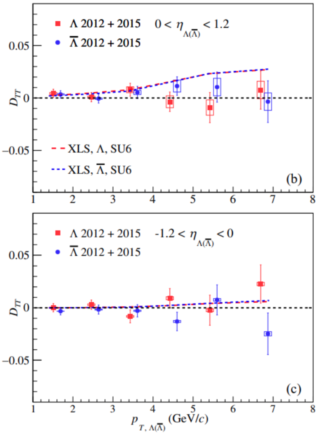


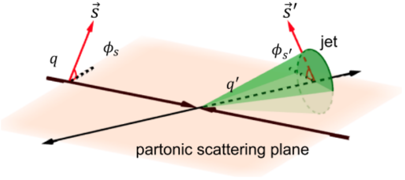
Spin transfer to Λ from polarized p+p at 200 GeV

J. Vanek, Tue. 4:30pm

[STAR, PRD 109(2024)012004]





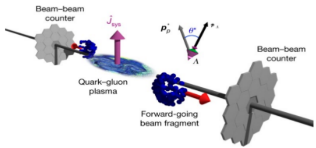


- D_{LL} longitudinal spin transfer rate from polarized p to $\Lambda(\bar{\Lambda})$
- D_{TT} transverse spin transfer rate from polarized p to $\Lambda(\bar{\Lambda})$
- consistent with models $\rightarrow$ helpful to understand the spin structure of nucleons and hyperons

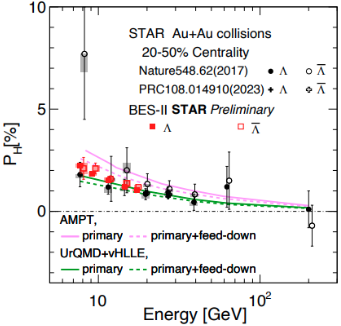
Λ global polarization

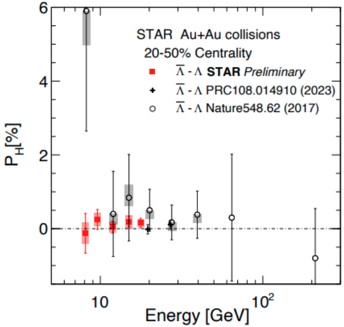
X. Gou, Tue. 9:00am

STAR, Nature 548 (2017) 62



Courtesy of P. Tribedy



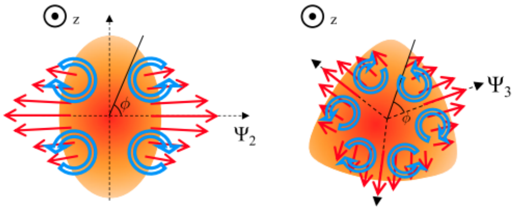


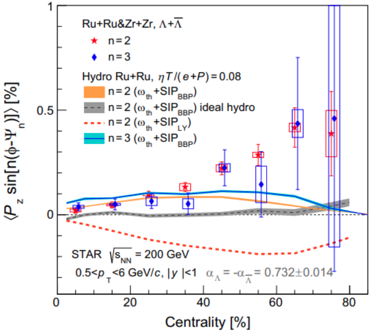
- updates of BES-II $\sqrt{s_{\rm NN}} = 7.7 - 17.3$ GeV with high precision
- Λ, $\bar{\Lambda}$ opposite magnetic moment $\rightarrow$ $\vec{B}$ field enhances $P_{\bar{\Lambda}}$ and reduce P_{Λ} $\rightarrow$ splitting expected
- No splitting is observed within uncertainties between Λ and $\bar{\Lambda}$ global polarization

Λ local polarization

X. Gou, Tue. 9:00am

[STAR, PRL 131(2023)202301]

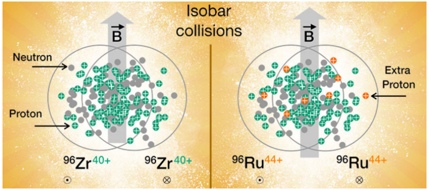


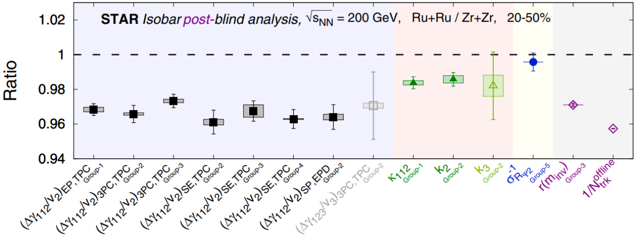


- Λ polarization along beam has dependence on azimuth w.r.t. EP $\rightarrow$ vorticity pattern expected due to elliptic and triangular anisotropic flow
- comparison with models $\rightarrow$ measurements provide stringent constraints on the thermal vorticity and shear-induced contributions to hyperon polarization

Isobar blind analyses for the CME

Y. Feng, Wed. 5:00pm



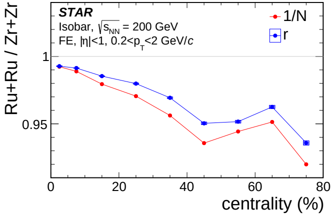


- **Chiral Magnetic Effect (CME):** magnetic field + chirality anomaly from QCD vacuum fluctuation → charge separation phenomenon
- **Initial expectation:** ${}^{96}_{44}$Ru, ${}^{96}_{40}$Zr: same A, different Z → same background, different signal Ru+Ru: proton number ↑ → magnetic field ↑ → CME signal ↑ → $\Delta\gamma/v_2$ ↑ → 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] .

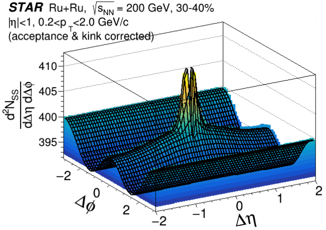
Isobar post-blind analyses for the CME

Y. Feng, Wed. 5:00pm

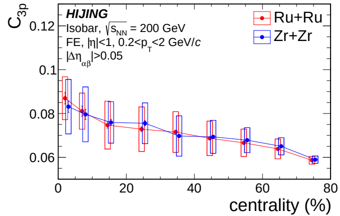
flow-induced backgrounds:
resonance decays → estimated by pair excess $r = \frac{N_{\rm OS} - N_{\rm SS}}{N_{\rm OS}}$

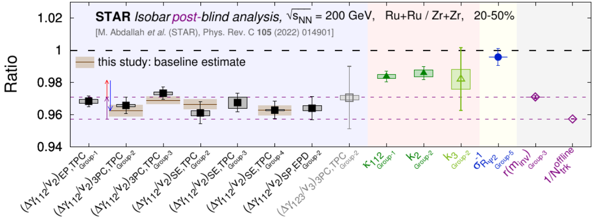


nonflow in v_2 measurement:
fit two-particle $(\Delta\eta, \Delta\phi)$ 2D distribution to decompose



3-particle nonflow:
HIJING model → no flow → solely 3p nonflow bkg





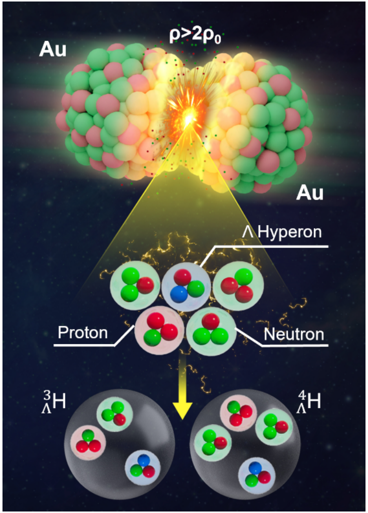
- **Post-blind:** nonflow background baseline estimate → CME upper limit 10% $(95\%$ CL)

  [STAR, arXiv:2308.16846, 2310.13096] .

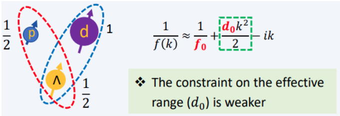
- CME is one of the most important physics of the field. Nonflow removal is critical towards final signal characterization.

Outline

1. Jet & Heavy Flavor
2. Flow
3. QCD critical point search
4. Chirality/Vorticity
5. Hyperon-nucleon interaction



$p/d - \Lambda$ correlations in Au+Au at 3 GeV

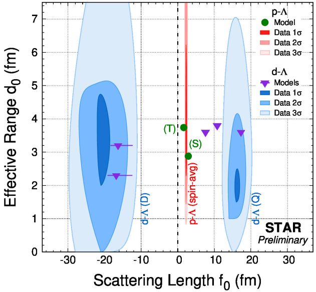


Correlation Function (CF):

$$C(\boldsymbol{k}^*) = \mathcal{N}\frac{\text{same event dist. for } \boldsymbol{k}^*}{\text{mixed event dist. for } \boldsymbol{k}^*}$$

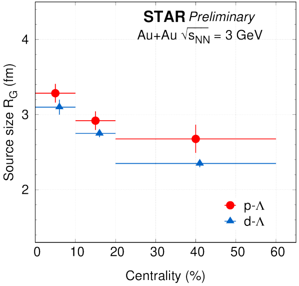
Lednicky-Lyuboshitz (L-L) Approach

- modeling
  $C(\boldsymbol{k}^*) = \int d^3\boldsymbol{r}^* S(\boldsymbol{r}^*)|\Psi(\boldsymbol{r}^*, \boldsymbol{k}^*)|^2$
- S-wave assumed
  $\Psi(\boldsymbol{r}^*) = e^{-i\boldsymbol{r}^*\cdot\boldsymbol{k}^*} + \frac{f(\boldsymbol{k}^*)}{r^*}e^{i\boldsymbol{r}^*\cdot\boldsymbol{k}^*}$
  $f(\boldsymbol{k}^*) \approx \left(\frac{1}{f_0} + \frac{d_0\boldsymbol{k}^*}{2} - i\boldsymbol{k}^*\right)^{-1}$
- Gaussian emission source assumed
  $S(\boldsymbol{r}^*) = (2\sqrt{\pi}R_G)^{-3}e^{-\boldsymbol{r}^{*2}/(4R_G^2)}$



$p - \Lambda$ spin-average (fm)
$f_0 = 2.32^{+0.12}_{-0.11}$, $d_0 = 3.5^{+2.7}_{-1.3}$
$d - \Lambda$ mixed with 2 states (fm)
$^2S_{1/2}$ (D): $f_0 = -20^{+3}_{-3}$, $d_0 = 3^{+2}_{-1}$
$^4S_{3/2}$ (Q): $f_0 = 16^{+2}_{-1}$, $d_0 = 2^{+1}_{-1}$

assuming Gaussian source S
$\rightarrow$ source size R_G

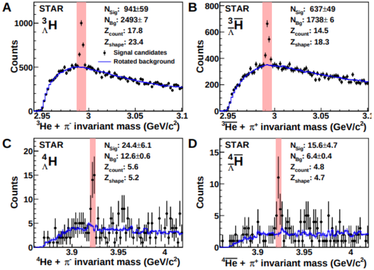


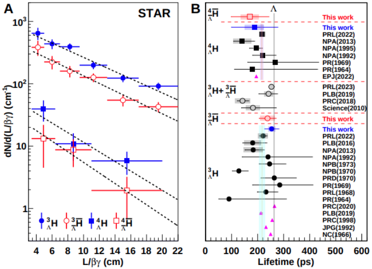
$\boldsymbol{k}^*$ momentum in pair rest frame
f_0 scattering length
d_0 effective range

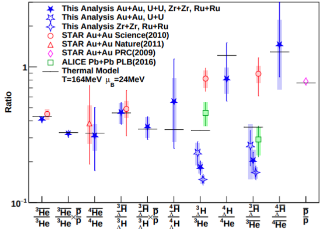
Hypernuclei production – first observation of ${}^{4}_{\Lambda}\bar{H}$

I. Vassiliev, Wed. 10:30am

[STAR, arXiv:2310.12674]





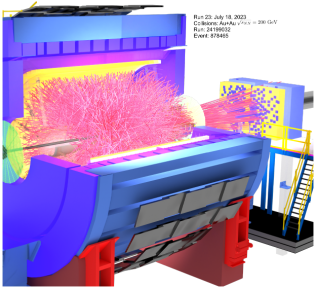


- First observation of antimatter hypernucleus ${}^{4}_{\Lambda}\bar{H}$
- Measurements of ${}^{3}_{\Lambda}H$, ${}^{3}_{\Lambda}\bar{H}$, ${}^{4}_{\Lambda}H$, ${}^{4}_{\Lambda}\bar{H}$ yields and lifetimes.
- Yield ratios $\rightarrow$ consistent with thermal model and previous publications.

datasets:
Au+Au 200GeV
Ru+Ru, Zr+Zr, 200GeV
U+U 193GeV

Summary and Outlook

- STAR continues producing results of great impact for important physics on QCD
- Many new analyses ongoing
- Fully upgraded STAR detector
  - BES and forward upgrades in operation since 2022
  - Run 23 was the 1^{st} top energy Au+Au with all upgrades
- Unprecedented high statistics Au+Au/p+p/p+Au data in 2023-25

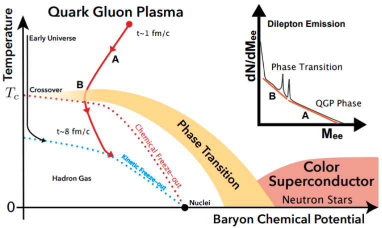


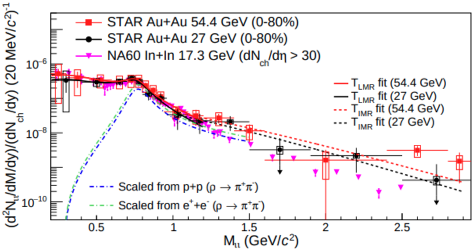
[STAR, BUR Runs 24-25]

Backup

Previous STAR highlights
AUM2023
AUM2022

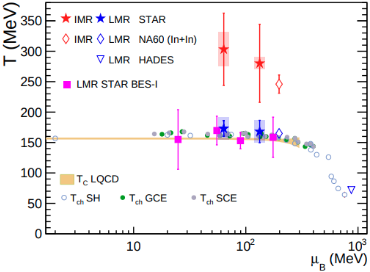
QGP temperature estimate from dielectron spectra





← thermal dielectrons (decay bkgd's removed, except for ρ^0)

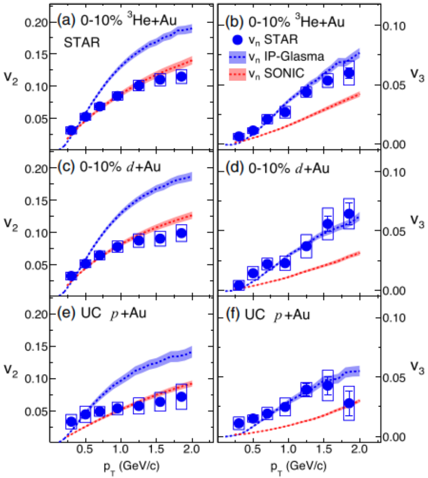
[STAR, arXiv:2402.01998]



- low-mass region (LMR): ρ^0 dissolved in QGP, closer the phase transition $\rightarrow$ fit by ρ^0 decay Breit-Wigner f^{BW} with Boltzmann factor $e^{-M/k_B T}$ $\rightarrow$ T_{LMR}
  - measurements (STAR: BES-I, BES-II; NA60; HADES) consistent with LQCD calculation and thermal models
- intermediate-mass region (IMR): earlier in QGP $\rightarrow$ fit by Boltzmann function $\rightarrow$ T_{IMR}
  - $T_{\mathrm{IMR}} > T_{\mathrm{LMR}}$

Small system flow

Z. Yan, Tue. 2:00pm
P. Sinha, Tue. 10:45am



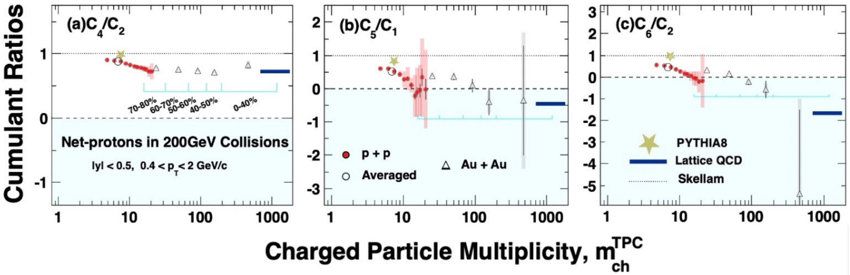
[STAR, PRL 130(2023)242301]

[STAR, arXiv:2312.07464]

- $v_2(p_T)$ dependent on the colliding systems, $v_3(p_T)$ system-independent
- v_2(p+Au) $<$ v_2(d+Au, ^{3}He+Au) $\rightarrow$ sub-nucleonic eccentricity fluctuations

Net-proton fluctuation in p+p at $\sqrt{s_{\rm NN}} = 200$ GeV

[STAR, arXiv:2311.00934]



- ratios below the expectations of Skellam distribution
- PYTHIA8 calculations fail to reproduce those ratios
- connecting to Au+Au results at 200 GeV