STAR Highlights
– 2024 RHIC/AGS annual users’ meeting

Yicheng Feng
(for the STAR Collaboration)

Purdue University

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STAR detector

*Forward upgrades
*BES-II upgrades

STAR Forward 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

recoil-jet yields per trigger \( Y \) ratio \( \text{Au+Au} \) over \( \text{p+p} \),
\[
I_{AA} < 1 \rightarrow \text{medium-induced yield suppression} \rightarrow \text{jet quenching}
\]

greater suppression in smaller “jet radius” \( R \) → jet broadening

\[
I_{AA} = \frac{Y_{\text{Au+Au}}(p_{T,\text{jet}}^{ch}, R)}{Y_{\text{p+p}}(p_{T,\text{jet}}^{ch}, R)}
\]

\[
\mathcal{R}_{\text{small-}R}^{\text{large-}R} = \frac{Y_{\text{A+A}}(p_{T,\text{jet}}^{ch}, \text{small } R)}{Y_{\text{A+A}}(p_{T,\text{jet}}^{ch}, \text{large } R)}
\]
$J/\psi$ production

$J/\psi$ energy dependence

- No significant energy or system dependence

$J/\psi$ system size dependence

$\psi(2s)$ over $J/\psi$ double ratio $< 1 \rightarrow$ sequential suppression
At photon-nucleon center-of-mass energy $W_{\gamma^*N}$ of 25 GeV, the coherent and incoherent $J/\psi$ 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 → possible shadowing effect, color glass condensate

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

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Flow: the collective motion of produced particles

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

- direct flow \((v_1)\)
- elliptic flow \((v_2)\)
$\Delta v_1$ combination dependence on charge and strangeness

- $K^-, \bar{p}, \bar{\Lambda}, \phi, \bar{\Xi}^+, \Omega^-, \bar{\Omega}^+ \rightarrow$ 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
$\nu_1$ splitting and possible EM effect

- particle-antiparticle $\nu_1$ splitting $d\Delta\nu_1/dy$
- pion, kaon, proton $\rightarrow$ 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

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

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

Other possibility: baryon inhomogeneities? [arXiv:2305.08806]
$\nu_1$ of light and hypernuclei at FXT

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

[STAR, PRL 130(2023)211301]
\( \nu_2 \) at FXT – breaking of NCQ scaling

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partonic collectivity
\( \rightarrow \) NCQ scaling: number of constituent quark scaling
\( \rightarrow \) hadron flows follow the same scaling \( \frac{\nu_2}{n_q} \) vs. \( \frac{m_T - m_0}{n_q} \) or \( \frac{\nu_2}{n_q} \) vs. \( \frac{p_T}{n_q} \)

▶ NCQ scaling breaks at \( \sqrt{s_{NN}} \leq 3.2 \text{ GeV} \) → shadowing effect + hadronic interaction
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 → nonflow estimate/subtraction → compare to hydro (IP-Glasma+MUSIC) → estimate U nuclear shape parameter $\beta_{2U}$
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QCD critical point (CP) is one of the most important physics

- $n$: net-proton multiplicity in an event;
  \[ \delta n = n - \langle n \rangle; \quad C_2 = \langle \delta n^2 \rangle; \quad C_4 = \langle \delta n^4 \rangle - 3\langle \delta n^2 \rangle \]

- 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 $\sim 20\text{GeV}$
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Spin transfer to $\Lambda$ from polarized $p+p$ at 200 GeV

$D_{LL}$ 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

updates of BES-II $\sqrt{s_{NN}} = 7.7 - 17.3$ GeV with high precision

Λ, ¯Λ opposite magnetic moment $\rightarrow \vec{B}$ field enhances $P_\Lambda$ and reduce $P_\bar{\Lambda} \rightarrow$ splitting expected

No splitting is observed within uncertainties between Λ and ¯Λ global polarization
Λ polarization along beam has dependence on azimuth w.r.t. EP → vorticity pattern expected due to elliptic and triangular anisotropic flow

comparison with models → measurements provide stringent constraints on the thermal vorticity and shear-induced contributions to hyperon polarization
Isobar blind analyses for the CME

▶ **Chiral Magnetic Effect (CME):** magnetic field + chirality anomaly from QCD vacuum fluctuation → charge separation phenomenon

▶ **Initial expectation:** \( ^{96}_{44}\text{Ru}, ^{96}_{40}\text{Zr} \): 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

flow-induced backgrounds:
resonance decays → estimated by pair excess \( r = \frac{N_{os} - N_{ss}}{N_{os}} \)

nonflow in \( \nu_2 \) 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)

CME is one of the most important physics of the field. Nonflow removal is critical towards final signal characterization.
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Correlation Function (CF): 
\[ C(\mathbf{k}^*) = \mathcal{N} \frac{N_{\text{same event dist. for } k^*}}{N_{\text{mixed event dist. for } k^*}} \]

Lednicky-Lyuboshitz (L-L) Approach

- modeling
  \[ C(\mathbf{k}^*) = \int d^3r^* S(\mathbf{r}^*) |\Psi(\mathbf{r}^*, \mathbf{k}^*)|^2 \]

- S-wave assumed
  \[ \Psi(\mathbf{r}^*) = e^{-i\mathbf{r}^* \cdot \mathbf{k}^*} + \frac{f(\mathbf{k}^*)}{r^*} e^{i\mathbf{r}^* \cdot \mathbf{k}^*} \]
  \[ f(\mathbf{k}^*) \approx \left( \frac{1}{f_0} + \frac{d_0 k^2}{2} - i k^* \right)^{-1} \]

- Gaussian emission source assumed
  \[ S(\mathbf{r}^*) = \left(2\sqrt{\pi}R_G\right)^{-3} e^{-r^2/(4R_G^2)} \]

assuming Gaussian source \( S \)

\[ \rightarrow \text{source size } R_G \]

\( p/d - \Lambda \) correlations in \( \text{Au+Au at 3 GeV} \)

\[ p - \Lambda \text{ spin-average (fm)} \]
\[ f_0 = 2.32^{+0.12}_{-0.11}, \quad d_0 = 3.5^{+2.7}_{-1.3} \]

\( d - \Lambda \text{ mixed with 2 states (fm)} \)
\[ 2S_{1/2} (D): \quad f_0 = -20^{+3}_{-3}, \quad d_0 = 3^{+2}_{-1} \]
\[ 4S_{3/2} (Q): \quad f_0 = 16^{+2}_{-1}, \quad d_0 = 2^{+1}_{-1} \]

\( k^* \) momentum in pair rest frame

\( f_0 \) scattering length

\( d_0 \) effective range
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 → consistent with thermal model and previous publications.

datasets:
- Au+Au 200GeV
- Ru+Ru, Zr+Zr, 200GeV
- U+U 193GeV
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 1st top energy Au+Au with all upgrades

Unprecedented high statistics Au+Au/p+p/p+Au data in 2023-25
Backup
QGP temperature estimate from dielectron spectra

- low-mass region (LMR): $\rho^0$ dissolved in QGP, closer the phase transition $\rightarrow$ fit by $\rho^0$ decay Breit-Wigner $f^{BW}$ with Boltzmann factor $e^{-M/k_B T} \rightarrow T_{\text{LMR}}$
  - 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 $\rightarrow T_{\text{IMR}}$
  - $T_{\text{IMR}} > T_{\text{LMR}}$

$\leftarrow$ thermal dielectrons (decay bkgd’s removed, except for $\rho^0$)

[STAR, arXiv:2402.01998]
Small system flow

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

[STAR, PRL 130(2023)242301]
[STAR, arXiv:2312.07464]
Net-proton fluctuation in p+p at $\sqrt{s_{NN}} = 200$ GeV

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