STAR Highlights

Rongrong Ma (For the STAR Collaboration)
Brookhaven National Laboratory
• Study QCD and QCD phase diagram with $p+p$ and heavy-ion collisions
Outline

1. Cold QCD physics

2. Beam Energy Scan

3. RHIC top energy

Credit: P. Sorensen, T. Ullrich
STAR Detector

ETOF  iTPC  BTOF  BEMC  MTD  FST  sTGC  EPD  ECal  HCal

HFT (2014-2016)

BES-II Upgrade
Forward Upgrade

X. Liang, Wed. 9:30 AM
Z. Wang, Wed. 3:50 PM
Cold QCD Physics
RHIC’s Final Word on Gluon Helicity

- DSSV global fit including up-to-date jet, dijet, pion, $W$ data
- $\int_{0.05}^{1} dx \Delta g = 0.218 \pm 0.027$

R. L. Jaffe, A. Manohar, NPB 337 (1990) 509
Transversity $h_1(x)$

$\pi^+\pi^-$ azimuthal asymmetry; interference FF

$$h_1(x) \approx \vec{S}_+ - \vec{S}_-$$

$$A_{UT}^{\sin(\phi_{RS})} = \frac{d\sigma^\uparrow - d\sigma^\downarrow}{d\sigma^\uparrow + d\sigma^\downarrow} \propto \frac{\sum_{i,j,k} j_1^{ilp_a(x_a)} j_1^{ilp_b(x_b)} H_1^{h_1h_2h_3} (z, M_h)}{\sum_{i,j,k} j_1^{ilp_a(x_a)} j_1^{ilp_b(x_b)} D_1^{h_1h_2h_3} (z, M_h)}$$
**Transversity $h_1(x)$**

$\pi^+\pi^-$ azimuthal asymmetry; interference FF

$A_{\sin(\phi_{RS})}^{\sigma} \propto \frac{d\sigma^\uparrow - d\sigma^\downarrow}{d\sigma^\uparrow + d\sigma^\downarrow} \propto \sum_{i,j,k} h_{1i}^{\ell p_a(x_a)} h_{1j}^{\ell p_b(x_b)} H_{1}^{xh_{2l}^{h_j^{h_k}(z, M_h)}}$

- Latest measurement in 510 GeV $p+p$ collisions

- Large asymmetry at high $\eta \rightarrow$ significant quark transversity at large $x$
  - Small asymmetry at negative $\eta$ due to small transversity at low $x$
**Transversity $h_1(x)$**

$\pi^+\pi^-$ azimuthal asymmetry; interference FF

$$A_{UT}^{\sin(\phi_{RS})} = \frac{d\sigma^\uparrow - d\sigma^\downarrow}{d\sigma^\uparrow + d\sigma^\downarrow} \propto \sum_{i,j,k} h_1^{ip_a(x_a)} f_1^{ip_b(x_b)} H_1^{qh_2(k)}(z, M_h)$$

- First measurement of unpolarized $\pi^+\pi^-$ cross section in 200 GeV $p+p$ collisions
  - Good agreement with PYTHIA
  - Can constrain gluon fragmentation

- Towards a model-independent extraction of transversity
Beam Energy Scan
Search for CP: Net-Proton Fluctuation

- BES-I: non-monotonic trend with collision energy with 3.1σ
  - BES-II COL: significantly improve BES-I results
  - BES-II FXT: fill the gap between 3 – 7.7 GeV
Search for CP: Light Nuclei Yield Ratio

STAR, PRL 130 (2023) 202301

\[ \frac{N_t \times N_p}{N_d^2} \]

Sensitive to neutron density fluctuation ➔ non-smooth behavior at CP or first-order phase transition

- BES-I: in 0-10% central collisions, data deviate from coalescence baseline at 19.6 and 27 GeV with a combined significance of 4.1σ
  - BES-II data will allow more differential measurements
Search for QGP Signature: NCQ Scaling

- Number-of-constituent-quark scaling holds within 10% for \((m_T - m_0)/n_q > 0.5 \text{ GeV}/c^2\)
  - Also observed at 14.6 GeV
  → Dominance of partonic interactions

**19.6 GeV**

![Graph showing v2 vs. (mT - m0)/n_q for both particles and anti-particles]
**QGP Temperature at RHIC**

- Thermal dileptons with mass between 1-3 GeV/c^2
  - Emitted from the QGP phase
- QGP temperature from mass spectrum slope \( T \approx 320 \) MeV
  - No blue-shift effect

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Z. Ye, Wed. 12:00 PM
Rapidity dependence of $v_1$ at 27 GeV

- $v_1(\eta)$: first dedicated EPD analysis
- Collapse to a common curve with other energies
- Can be used to constrain $T$-dependence of medium viscosity
• No significant splitting between $\Lambda$ and anti-$\Lambda$
  – Upper limit of difference: < 0.24% for 19.6 GeV and < 0.35% for 27 GeV with 95% confidence level
• No strong dependence on rapidity → challenge many theoretical predictions


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Top RHIC Energy
Flow in Small Systems

- Data at midrapidity
  - $v_2^{He+Au} \approx v_2^{d+Au} > v_2^{p+Au}$
  - $v_3^{He+Au} \approx v_3^{d+Au} \approx v_3^{p+Au}$

- Suggests significant influence of sub-nucleonic fluctuations
  - Need to study pre-flow

<table>
<thead>
<tr>
<th></th>
<th>Nucleon Glauber $\varepsilon_2(\varepsilon_3)$</th>
<th>Sub-Nucleon Glauber $\varepsilon_2(\varepsilon_3)$</th>
</tr>
</thead>
<tbody>
<tr>
<td>0-5% $p+Au$</td>
<td>0.23(0.16)</td>
<td>0.38(0.30)</td>
</tr>
<tr>
<td>0-5% $d+Au$</td>
<td>0.54(0.18)</td>
<td>0.51(0.31)</td>
</tr>
<tr>
<td>0-5% $^3He+Au$</td>
<td>0.50(0.28)</td>
<td>0.52(0.35)</td>
</tr>
</tbody>
</table>

Nucleon Glauber: J. L. Nagle, et. al., PRL 113 (2014) 112301
Sub-nucleon: K. Welsh, et. al., PRC 94 (2016) 024919

Courtesy of S. Huang

STAR, PRL 130 (2023) 242301
**p+p: Jet Energy-Energy Correlator**

![Diagram showing transition region between partons and hadrons](image)

**Normalized EEC**

\[
\text{EEC} = \frac{\sum_{jets} \sum_{i} \frac{E_i E_j}{p_{T,jet}^2}}{\sum_{j} E_{i,jet}^2} \cdot \frac{1}{d(\Delta R)}
\]

- **Transition region (onset of hadronization)** scales with \(1/p_{T,jet} \rightarrow \Delta R \cdot p_{T,jet} \sim 2-3 \text{ GeV/c}^{\text{a}}

  - Also observed at LHC

- **pQCD calculation describes partonic phase quite well**

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**15 < Jet \( p_T < 20 \text{ GeV/c} **

- STAR Preliminary

**30 < Jet \( p_T < 50 \text{ GeV/c} **

- STAR Preliminary

K. Lee, et. al., arXiv:2205.03414

P. Komiske, et. al., PRL 130 (2023) 051901

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**Au+Au: Hadron Chemistry in Jets**

### p+p vs. Au+Au

#### STAR Preliminary

- **Au+Au, √s_{NN} = 200 GeV, 0-20%**
- **p+p, √s = 200 GeV**

#### Graph

- **Anti-k_T**
  - Jet p_T^{raw} > 10 GeV/c
  - p_T^{const} > 3.0 GeV/c

- **Inclusive**
  - Au+Au, Jet R = 0.3
  - p+p, Jet R = 0.3

- **[PRL97(2006)152301]**
- **[PRL63(2006)161]**

- **p/π ratio significantly smaller in jets compared to bulk**

- **Similar p/π ratio in jets with p_T^{const} > 3 GeV/c in p+p and Au+Au collisions**

- **Measurements with lower p_T^{const} cuts are underway**

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Au+Au: Sequential $\Upsilon$ Suppression

First measurement of suppression of three $\Upsilon$ states separately at RHIC

- Upper limit for $\Upsilon(3S)$ in 0-60%
- $>3\sigma$ difference for $\Upsilon(1S)$ and $\Upsilon(3S)$
- $\Upsilon(2S)$ lies in between
Source information through pion momentum correlation (femtoscopy)

\[ C_2(Q) = 1 - \lambda + \lambda \ast K(Q; \alpha, R) \ast (1 + e^{- (RQ)^\alpha}) \]

- Non-Gaussian source observed in Au+Au collisions
  - Deviates further from Gaussian in central collisions

\[ Q: \text{relative momentum} \]
\[ R: \text{source size} \]
\[ \alpha: \text{Lévy exponent} \]
Test the different scenarios with charge ($Q$) and baryon ($B$) number.

Quark carrier: \( \frac{Q}{B} \approx \frac{Z}{A} \)

Junction carrier: \( \frac{Q}{B} < \frac{Z}{A} \)
• Measure charge difference ($\Delta Q$) between two isobar collisions, and compare $B/\Delta Q$ vs. $A/\Delta Z$

• Significantly more baryon stopping than model calculation in which quarks carry baryon number

• Favors the scenario that baryon junction carries baryon number
Summary & Outlook

✓ STAR continues to produce highly impactful results for studying the QCD phase diagram and fundamental features of QCD

➢ Stay tuned for more results from $p+p$, BES-II, top energy HI

✓ Run23-25: entering the precision era
  – Unprecedented statistics for $p+p$, $p+Au$, $Au+Au$ collisions
  – Low material budget
  – STAR detector with enhanced capabilities
    • Particle identification; tracking; extended coverage
  – Measurements connecting to future EIC
Backup
Unpolarized Anti-quark PDF

$W$ cross-section ratio at RHIC can provide constraints around similar $x$ region at high $Q^2$

$$R_W = \frac{\sigma_W^+}{\sigma_W^-} \sim \frac{u(x_1)d(x_2) + u(x_2)d(x_1)}{\bar{u}(x_1)d(x_2) + \bar{u}(x_2)d(x_2)}$$

- Cross-section ratio vs. lepton rapidity
- Overall agreement with current PDF fits. Can be used to further constrain anti-quark distributions
\[ \Delta M = M - M_g \]

\[ R_g = \Delta R(\text{jet}_1, \text{jet}_2) \]

- \( \Delta M / M \) anti-correlated with \( R_g \) \( \Rightarrow \) Early soft wide-angle radiation constrains angular phase space of late splittings
- Well described by event generators

\[ \Delta R(\text{jet}_1, \text{jet}_2) = \Delta R(\text{jet}_1, \text{jet}_2) \]

\[ R_g = \Delta R(\text{jet}_1, \text{jet}_2) \]

\[ \Delta M = M - M_g \]

\[ \Delta M / M \]

\[ 0 < R_g < 0.15 \]

\[ 0.15 < R_g < 0.3 \]

\[ 0.3 < R_g < 0.4 \]

\[ p + p, \sqrt{s} = 200 \text{ GeV} \]

\[ \text{anti-}k_T \text{ full jets, } R=0.4, |\eta|<0.6 \]

\[ (z_{\text{cut}1}, \beta_1) = (0,0), (z_{\text{cut}2}, \beta_2) = (0.1,0) \]

MultiFolded with \( p_T, Q, M, M_g, R_g, z_g \)

\[ 20 < p_{T,jet} < 30 \text{ GeV/c} \]
**Search for CP: Net-Proton Fluctuation**

### Central Au + Au Collisions

- **STAR (0 - 5%)**
  - net-proton
  - proton

<table>
<thead>
<tr>
<th>Collision Energy $\sqrt{s_{NN}}$ (GeV)</th>
<th>Central Au + Au Collisions</th>
</tr>
</thead>
<tbody>
<tr>
<td>2</td>
<td>HRG</td>
</tr>
<tr>
<td>5</td>
<td>GCE</td>
</tr>
<tr>
<td>10</td>
<td>CE</td>
</tr>
<tr>
<td>20</td>
<td>net-proton</td>
</tr>
<tr>
<td>50</td>
<td>proton</td>
</tr>
</tbody>
</table>

#### Results
- **BES-I**: non-monotonic trend with collision energy with 3.1$\sigma$
  - BES-II COL: significantly improve BES-I results
  - BES-II FXT: fill the gap between 3 – 7 GeV

### Graphical Data
- Graph showing the ratio $C_4/C_2$ vs collision energy $\sqrt{s_{NN}}$ (GeV) with data points and model predictions.


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Search for CP: Net-Proton Fluctuation

- **BES-I**: non-monotonic trend with collision energy with $3.1\sigma$
  - BES-II COL: significantly improve BES-I results
  - BES-II FXT: fill the gap between $3 - 7$ GeV

- **BES-II**: negative $C_4/C_2$ at 3 GeV
  - Consistent with UrQMD
  - Hadronic interaction dominates

- *Stay tuned for more BES-II results*
HF Electron $v_2$ at 54.4 and 27 GeV

- 27 GeV: consistent with zero
- 54.4 GeV:
  - Significant $v_2$ comparable to that at 200 GeV
  - Charm quarks gain $v_2$ at $T$ close to $T_c$
  - Transport models seem to underpredict $v_2$ (1-2σ for $p_T > 0.5$ GeV/c)
  - Consistent with NCQ scaling $\Rightarrow$ may reach local thermal equilibrium with the QGP
Search for CME at 27 GeV

\[ \Delta \gamma = \gamma_{os} - \gamma_{ss} \]
\[ \Delta P = P_{\Lambda} - P_{\bar{\Lambda}} \]

Expect negative event-by-event correlation in case of B and CME

- Background does not contribute to the covariance
- No correlations observed beyond statistical fluctuations
  - CME signal still elusive; Run23+25 Au+Au data might provide an answer
**Isobar Collisions: Jet $v_2$**

- Sizable $v_2$ for high $p_T$ tracks and jets $\rightarrow$ path-length dependence of jet-medium interaction
- No obvious jet $R$ dependence. Could be due to hard-core selection.

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Search for CME at 27 GeV

D. Kharzeev, L. McLerran, H. Warringa, NPA 803 (2008) 227

STAR, PRC 108 (2023) 014909

Y. Feng, Poster

\[ \Delta a_1 = \langle \sin(\phi^+ - \psi_{RP}) \rangle - \langle \sin(\phi^- - \psi_{RP}) \rangle \]

\[ \Delta n_{\Lambda+\bar{\Lambda}}^{obs} = \frac{N_L^{obs} - N_R^{obs}}{\langle N_L^{obs} + N_R^{obs} \rangle} \]

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**Study Phase Structure: Net-Proton Fluctuation**

- LQCD calculation with crossover transition: $C_3/C_1 > C_4/C_2 > C_5/C_1 > C_6/C_2$
- BES-I: data above 7.7 GeV consistent with expected ordering
- BES-II: opposite trend at 3 GeV → hadronic interaction dominates → CP exits above 3 GeV
Charm quarks are significantly more suppressed than bottom quarks

- Deviate from null hypothesis of same energy loss

✓ Parton mass dependence of energy loss in the QGP