Highlights from the STAR Experiment

Zhangbu Xu (BNL) for the STAR Collaboration

- Discoveries of Breit-Wheeler process and Vacuum Birefringence
- Initial State (PDF and small systems)
- Viscosity [$\eta/s(T)$]: Multiple Harmonics and Rapidity Correlations
- Hard Probes (Jets and Heavy-Flavor)
- Origin of global polarization and vorticity
- Chiral and thermal properties
- BES and Critical Point search
- Upgrades and Summary

19 Oral presentations and 38 posters
STAR Overview

- Discoveries of Breit-Wheeler process and Vacuum Birefringence (Daniel Brandenburg, Tue 9:00 HK)

- Initial State

- Viscosity $[\eta/s(T)]$: Multiple Harmonics and Rapidity Correlations

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- Summary
Observations of Breit-Wheeler process and Vacuum Birefringence

- 1934, Breit and Wheeler, **Collision of two light Quanta to create matter and antimatter** ($e^+e^-$) rather than exact relations. It is also hopeless to try to observe the pair formation in laboratory experiments with two beams of x-rays or γ-rays meeting each other on account of the smallness of $\sigma$ and the insufficiently large available densities of quanta. In the considerations of Williams, however, the large nuclear electric fields lead to large densities of quanta in moving frames of reference. This, together with the large number

Feynman Diagram for Vacuum Birefringence

1. Observation of exclusive Breit-Wheeler process with all possible kinematic distributions (yields, $M_{ee}$, $P_T$, angle)
2. Observation of Vacuum Birefringence at 6.7σ in UPC
STAR Overview

- **Discoveries** of Breit-Wheeeler process and Vacuum Birefringence

- **Initial State**
  (Daniel Brandenburg, Tue 9:00 HK
  Roy Lacey, Tue 9:40 BR3
  Yanfang Liu, Tue 15:00 BR3)

- **Viscosity** $[\eta/\text{s}(T)]$: Multiple Harmonics and Rapidity Correlations

- **Hard Probes**

- **Origin of global** polarization and vorticity

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- **Upgrades and Summary**
New observable in $\rho$ photoproduction

Observation of $8\sigma$ statistical significance of $\cos(4\phi)$ modulation QCD birefringence?

- Predicted to be sensitive to Generalized Transverse Momentum Distribution (GTMD):
  “offer direct access to the second derivative of the saturation scale w.r.t gluon spatial distribution”
- Expected magnitude scales with $(P_\perp/M_\rho)^2$
- Tensor Pomeron …

Comparison with other experiments and expectations from fluctuation-driven $\varepsilon_n$ from quark Glauber model

- $^3$He+Au and all $v_3$ data NEW
- Three non-flow subtraction methods give similar $v_n(p_T)$ in each system.
- $v_3(p_T)$ similar for central p/d/$^3$He+Au
- Glauber model shape $\varepsilon_n$ are different between w/o and with sub-nucleon fluctuations.

Comparison with other experiments and expectations from fluctuation-driven $\varepsilon_n$ from quark Glauber model

STAR measurements consistent with dominant roles of multiplicity and fluctuation-driven shape ($\varepsilon_n$)
Quarkonium production in p+p

- Data show strong non-linear dependence (correlation between soft and hard processes)
- Models (MPI, CGC, Percolation) qualitatively describe data trends
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• **Discoveries** of Breit-Wheeler process and Vacuum Birefringence

• **Initial State**

• **Viscosity** $[\eta/s(T)]$: Multiple Harmonics and Rapidity Correlations
  (Maowu Nie, Tue 9:00 BR1
  Niseem Magdy, Wed 9:40 BR3)

• **Hard Probes**
  • Origin of global **polarization and vorticity**
  • **Chiral and thermal** properties
  • BES and **Critical Point** search
  • Upgrades and Summary

Event-Plane Detector (EPD)
At 27 GeV

www.star.bnl.gov

Quark Matter 2019, Wuhan
Longitudinal flow decorrelation at 27 GeV

\[ r_n(\eta) = \left( \frac{V_n(-\eta)V_n^*(\eta_{\text{ref}})}{V_n(\eta)V_n^*(\eta_{\text{ref}})} \right) \]

- No energy dependence of \( r_2 \) at RHIC energies
- Clear energy dependence of \( r_3 \) at RHIC energies
Nonlinear mode-coupling coefficient:

\[
\chi_{n+2,2n} = \frac{\langle v_{n+2} \cos((n+2)\Psi_{n+2} - 2\Psi_2 - n\Psi_n) \rangle}{\sqrt{\langle v_2^2 v_n^2 \rangle}}
\]

Event-Plane Angular Correlation:

\[
\rho_{n+2,2n} \sim \langle \cos((n+2)\Psi_{n+2} - 2\Psi_2 - n\Psi_n) \rangle
\]

Both coefficients can be used to distinguish hydrodynamic models.
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- **Initial State**
- **Viscosity \([\eta/s(T)]\):** Multiple Harmonics and Rapidity Correlations
- **Hard Probes**
  (Matthew Kelsey, Tue 15:40 BR3, David Stewart, Tue 12:20 BR2, Saehanseul Oh, Tue 9:00 BR2, Raghav Kunnawalkam Elayalli, Wed 9:20 BR2)
- **Origin of global polarization and vorticity**
- **Chiral and thermal** properties
- **BES and Critical Point** search
- **Upgrades and Summary**
Open charm and bottom

- First observation of significant non-zero bottom hadron flow (>3σ) at RHIC
- Observation of bottom suppression less than charm at RHIC (>3σ)

• Using HFT displaced vertex for heavy-flavor decay topology
• Observation of Λ_c/D enhancement: arXiv:1910.14628
• New charmed electron ν_{1,2} are consistent with D⁰ measurements

STAR Preliminary

- Au+Au $\sqrt{s_{NN}}$=200 GeV
- 0-80%
- $p_T$ (GeV/c)
- $V_2(b \rightarrow e)$
- Non-flow
- Ne_{coll} uncert.
- $R_{AA}$
- $R_{b\rightarrow e}$
- $R_{c\rightarrow e}$
- $R_{D}$
- Null hyp.
Recoil and transverse jets in p+Au

- At "jet-like" $p_T (>\sim 8 \text{ GeV/c})$ transverse $\Delta \phi$ (background) negligible compared to recoil spectra
- Study with centrality defined by backward Beam-Beam Counter

Clear jet spectra per trigger suppression for high EA (event activity) relative to low EA
Jet fragmentation functions and shapes

- First Au+Au jet fragmentation functions from STAR
  - Jet fragmentation functions for charged jets in 40-60% events
  - Unfolded results compared to PYTHIA 8

- Jet shapes
  - Distribution of jet energy as a function of distance from the jet axis

Event-plane dependent measurements

low-$p_T$ particles: larger yields and pushed toward larger $r$ in out-of-plane direction
→ In-medium path length effects of jet quenching
Jet substructure and differential energy loss

Matched dijet $A_J$ for narrow and wide recoil jets!

For a given dijet definition wide and narrow jets appear to undergo similar levels of energy loss and recovery

These jets lose energy as single color jet and split outside medium

Vary energy loss and recovery by dijet finding parameters

→ vary path length of recoil jet in medium

Also report new p+p results
- Jet substructure baseline - Well calibrated

Raghav Kunnawalkam Elayavalli, Wed 9:20 BR2
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• Hard Probes
  • Origin of global polarization and vorticity
    (Joey Adams, Wed 14:00 BR1 Subhash Singh, Wed 11:20 BR3)

• Chiral and thermal properties

• BES and Critical Point search

• Upgrades and Summary
dependence of global polarization

• Previous study across broad range of $\sqrt{s_{NN}}$ suggests strong beam energy dependence

• New data at 27 & 54.4 GeV with high statistics for $\Lambda/\bar{\Lambda}$, centrality, rapidity and $p_T$ dependence

New datasets with high statistics follow previous measured trend

2 The STAR Collaboration, Global Lambda hyperon polarization in nuclear collisions: evidence for the most vortical fluid. Nature 548 (2017) 62
Vector meson (K*) spin alignment

\[
dN/d(cos\theta^*) = N_0 \times [(1 - \rho_{00}) + (1/3 \rho_{00} - 1) \cos(\theta^*)]
\]

For both 54.4 and 200 GeV

- \(\rho_{00} < 1/3\) at low \(p_T\) and for mid-centrality
- qualitatively consistent with coalescence of polarized quarks but lack quantitative agreement
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  (Florian Seck, Wed 16:20 BR3
   Yufu Lin, Tue 14:40 BR2
   Jie Zhao, Tue 14:20 BR2)
- **BES and Critical Point search**
- **Upgrades and Summary**
New dielectron spectra at 27 and 54.4 GeV

Use HFT capability to disentangle thermal and charm contributions at IMR

STAR Preliminary
CME developments

Measure participant and reaction planes in EPD
New STAR capability for CME search at 27 GeV

Au+Au and U+U collisions (20-50%)

STAR preliminary

Ψ_{PP} and Ψ_{RP} to disentangle signal/background.
Fractions are extracted in U+U and Au+Au,
Averaged CME fraction = (8 ± 4 ± 8)%
CME developments

1) Count pair’s momentum ordering in $p_y$

$$B_{P,y}(S_y) = \frac{N_{+ -}(S_y) - N_{+ +}(S_y)}{N_+}$$

$$B_{N,y}(S_y) = \frac{N_{- +}(S_y) - N_{- -}(S_y)}{N_-}$$

2) Count net-ordering (e.g. excess of pos. leading neg.) for each event:

$$\delta B_y(\pm 1) = B_{P,y}(\pm 1) - B_{N,y}(\pm 1)$$

$$\Delta B_y = \delta B_y(+1) - \delta B_y(-1)$$

3) Look for enhanced event-by-event fluctuation of net-ordering in $y$ direction.

$$r = \frac{\sigma \Delta B_y}{\sigma \Delta B_x} (>1 \text{ with CME})$$

New Search with Signed Balance Function:

Both $r_{\text{rest(lab)}}$ and $R_B$ are larger than realistic model with no CME.
Data difficult to explain by backgrounds only.
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- **BES and Critical Point** search
  (Muhammad Usman, Wed 11:40 HK Dingwei Zhang, Wed 9:00 BR1 Kishora Nayak, Tue 14:20 BR1 Ashish Pandav, Tue 11:20 BR3)
- **Upgrades and Summary**
Identified particle spectra at new energy and FXT

**New Energies with high statistics presented:**
- **Au+Au:** 54.4 GeV (FXT)  
  **Al+Au:** 4.9 GeV

**Extend AGS results in fixed-target data**

- Chemical and kinetic freeze-out
- Quark coalescence and jet quenching in large $p_T$ range
Excitation functions of $v_1$ slope and $v_2$

New data at FXT, 27 and 54.4 GeV

Mesons and produced baryons: negative $v_1$ slope
NCQ scaling for produced particles
Yield ratio shows non-monotonic behavior on collision energy in 0-10% Au+Au collisions.

Flat energy dependence of yield ratio observed in JAM model does not describe data.

Nucleus yield ratio -- Neutron density fluctuations

\[ N_t \cdot \frac{N_p}{N_d^2} = g(1 + \Delta n), \]

with \( g = 0.29 \)

Yield ratio is related to neutron density fluctuations.
Sixth-order cumulants of baryon and charge

O(4) chiral theory: $C_6$ of baryon number and electric charge fluctuations remain negative at chiral transition temperature.

For most central collisions:

$C_6/C_2 < 0$ for 200 GeV

$C_6/C_2 > 0$ for 54.4 GeV
Beam Energy Scan Phase II upgrades and events

Collider mode

<table>
<thead>
<tr>
<th>Collision Energy (GeV)</th>
<th>7.7</th>
<th>9.1</th>
<th>11.5</th>
<th>14.5</th>
<th>19.6</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\mu_B$ (MeV) in 0-5% central collisions</td>
<td>420</td>
<td>370</td>
<td>315</td>
<td>260</td>
<td>205</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Observables</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>$R_{CP}$ up to $p_T = 5$ GeV/c</td>
<td>-</td>
</tr>
<tr>
<td>Elliptic Flow ($\phi$ mesons)</td>
<td>80</td>
</tr>
<tr>
<td>Chiral Magnetic Effect</td>
<td>50</td>
</tr>
<tr>
<td>Directed Flow (protons)</td>
<td>20</td>
</tr>
<tr>
<td>Azimuthal Femtoscopy (protons)</td>
<td>35</td>
</tr>
<tr>
<td>Net-Proton Kurtosis</td>
<td>70</td>
</tr>
<tr>
<td>Dileptons</td>
<td>100</td>
</tr>
<tr>
<td>$&gt;5\sigma$ Magnetic Field Significance</td>
<td>50</td>
</tr>
</tbody>
</table>

| Required Number of Events | 100 | 160 | 230 | 300 | 400 |

Achieved in BES-I (Millions) 4.3 N/A 11.7 12.6 36
Achieved in BES-II so far 3* 324 581

Typically factor 20 more than for BES-I with iTPC+EPD+eTOF upgrades
Two more runs in 2020+2021

<table>
<thead>
<tr>
<th>Energy (GeV)</th>
<th>7.7</th>
<th>3.9</th>
<th>3.2</th>
<th>3.0</th>
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</thead>
<tbody>
<tr>
<td>$\mu_B$(MeV)</td>
<td>420</td>
<td>633</td>
<td>699</td>
<td>721</td>
</tr>
<tr>
<td>FXT (GeV)</td>
<td>31.2</td>
<td>7.3</td>
<td>4.55</td>
<td>3.85</td>
</tr>
</tbody>
</table>

Achieved in BES-II so far 324 581

BES-II started this year

Fixed-Target Mode
The forward upgrade in STAR includes **Calorimeters (ECAL & HCAL) and Trackers (silicon microstrip tracker & sTGC)** dedicated for studying the nuclear structure, QGP (rapidity correlation/hyperon polarization).

### Forward Tracker
- 3 silicon disks
- 4 sTGC layers

### Forward Calorimeters
- Pre/post-shower: scintillator
- ECAL: PbSc towers (18 $X_0$)
- HCAL: FeSc plates (4.5 $\lambda$)

<table>
<thead>
<tr>
<th>Detector</th>
<th>pp and pA</th>
<th>AA</th>
</tr>
</thead>
<tbody>
<tr>
<td>ECAL</td>
<td>$\sim 10% / \sqrt{E}$</td>
<td>$\sim 20% / \sqrt{E}$</td>
</tr>
<tr>
<td>HCAL</td>
<td>$\sim 60% / \sqrt{E}$</td>
<td>---</td>
</tr>
<tr>
<td>Tracking</td>
<td>Charge separation, Photon suppression</td>
<td>$0.2 &lt; p_T &lt; 2 \text{ GeV/c}$ with $20 - 30% 1/p_T$</td>
</tr>
<tr>
<td>ID</td>
<td>Name</td>
<td>Institution/University</td>
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<tr>
<td>736</td>
<td>Kishora Nayak</td>
<td>CCNU</td>
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<tr>
<td>743</td>
<td>Niseem Magdy</td>
<td>UIC</td>
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<tr>
<td>680</td>
<td>Roy Lacey</td>
<td>SBU</td>
</tr>
<tr>
<td>671</td>
<td>Maowu Nie</td>
<td>SDU/SBU</td>
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<tr>
<td>750</td>
<td>Joey Adams</td>
<td>OSU</td>
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<tr>
<td>438</td>
<td>Subhash Singh</td>
<td>KSU</td>
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<td>667</td>
<td>Jie Zhao</td>
<td>Purdue</td>
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<td>669</td>
<td>Yufu Lin</td>
<td>CCNU/BNL</td>
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<tr>
<td>739</td>
<td>Ashish Pandav</td>
<td>NISER</td>
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<tr>
<td>378</td>
<td>Matthew Kelsey</td>
<td>LBNL</td>
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<td>Yanfang Liu</td>
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<td>439</td>
<td>David Stewart</td>
<td>Yale</td>
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<td>Raghav</td>
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<td>381</td>
<td>Kunnawalkam Elayavalli</td>
<td>WSU</td>
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<td>355</td>
<td>Saehanseul Oh</td>
<td>Yale/BNL</td>
</tr>
<tr>
<td>646</td>
<td>Daniel Brandenburg</td>
<td>SDU/BNL</td>
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<td>287</td>
<td>Florian Seck</td>
<td>Darmstadt</td>
</tr>
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<td>462</td>
<td>Dingwei Zhang</td>
<td>CCNU</td>
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<td>384</td>
<td>Muhammad Usman</td>
<td>CCNU/THU</td>
</tr>
<tr>
<td>388</td>
<td>Yi Yang</td>
<td>NCKU</td>
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Talks and posters available at  [https://drupal.star.bnl.gov/STAR/presentations](https://drupal.star.bnl.gov/STAR/presentations)
Backup slides
STAR is composed of 67 institutions from 13 countries and region, with a total of 679 collaborators.

STAR Collaboration Acknowledgements:

We thank the RHIC Operations Group and RCF at BNL, the NERSC Center at LBNL, and the Open Science Grid consortium for providing resources and support. This work was supported in part by the Office of Nuclear Physics within the U.S. DOE Office of Science, the U.S. National Science Foundation, the Ministry of Education and Science of the Russian Federation, National Natural Science Foundation of China, Chinese Academy of Science, the Ministry of Science and Technology of China and the Chinese Ministry of Education, the National Research Foundation of Korea, Czech Science Foundation and Ministry of Education, Youth and Sports of the Czech Republic, Hungarian National Research, Development and Innovation Office, New National Excellency Programme of the Hungarian Ministry of Human Capacities, Department of Atomic Energy and Department of Science and Technology of the Government of India, the National Science Centre of Poland, the Ministry of Science, Education and Sports of the Republic of Croatia, RosAtom of Russia and German Bundesministerium fur Bildung, Wissenschaft, Forschung and Technologie (BMBF) and the Helmholtz Association.
$\gamma \gamma \rightarrow e^+ e^-$ in UPC vs. Peripheral Au+Au

![Graph showing the comparison between UPC and 60-80% Au+Au collisions.]

Characterize difference in spectra vis $\sqrt{\langle P_\perp^2 \rangle}$

<table>
<thead>
<tr>
<th></th>
<th>UPC Au+Au</th>
<th>60-80% Au+Au</th>
</tr>
</thead>
<tbody>
<tr>
<td>Measured</td>
<td>$38.1 \pm 0.9$</td>
<td>$50.9 \pm 2.5$</td>
</tr>
<tr>
<td>QED</td>
<td>37.6</td>
<td>48.5</td>
</tr>
<tr>
<td>$\langle b \rangle$ range</td>
<td>$\approx 20$ fm</td>
<td>$\approx 11.5 - 13.5$ fm</td>
</tr>
</tbody>
</table>

- Lowest order QED calculation of $\gamma \gamma \rightarrow e^+ e^-$ describes both spectra ($\pm 1 \sigma$)
- Best fit for spectra in 60-80% collisions found for Breit-Wheeler shape plus $14 \pm 4$ (stat.)$\pm 4$ (syst.) MeV/c broadening
- Proposed as probe of trapped magnetic field or Coulomb scattering in QGP [1-3]

STAR Observes $4.8\sigma$ difference in $\sqrt{\langle P_\perp^2 \rangle}$ for the $\gamma \gamma \rightarrow e^+ e^-$ process in UPC vs. 60-80% Au+Au collisions
p/d/\(^3\)He+Au results between STAR and PHENIX

\(v_2\) results are similar between STAR and PHENIX

\(v_3\) measured by STAR is similar to \(v_3\) from PHENIX for \(^3\)He+Au, and more than a factor of 3 larger for p/d+Au collisions
Energy Dependence of Cumulants Ratios

\[ \kappa \sigma^2 \] measurement at 54.4 GeV agrees with existing BES-I measurement's trend. Form precise baseline for critical fluctuation at lower beam energies.
Slope ordering The slope increases with the expected strength of magnetic field in three systems (CuAu, AuAu, UU).

Removing the trivial contribution, normalized $v_3$ slope is consistent with $v_2$ slope within $0.2\sigma$, dominated by large $v_3$ slope uncertainty, while normalized $v_3$ slope is $1.5\sigma$ above zero. Results suggest background contributions.
Test of CME with Isobar collisions

3.1B events for both Ru+Ru, Zr+Zr collected over 8 weeks
Plans for blind analyses of the data was laid down from the beginning

Blinding method document in arXiv

Mock data challenge
- Test data structure (27 GeV files)

Isobar-Mixed Analysis
- QA, physics & code freezing (One run is Ru+Zr)

Isobar-Blind Analysis
- Run-by-run QA, full analysis (One run is Ru/Zr)

Isobar-Unblind Analysis
- Full analysis (Ru and Zr separated)

Blind analysis (by 5 separate STAR groups)
Status: Analysis codes developed from ”mixed” data now frozen & documented
Next: short period of run-by-run QA checks (still blinded) before running each analysis