Recent results from the STAR experiment

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Joint Institute for Nuclear Research

Part of this work was supported by Russian Science Foundation under grant № 22-72-10028
STAR detector

- **Tracking and PID (full 2π)**
  - TPC: $|\eta| < 1$
  - iTPC (2019+): $|\eta| < 1.5$
  - TOF: $|\eta| < 1$
  - eTOF (2019+): $-1.6 < \eta < -1$
  - BEMC: $|\eta| < 1$
  - EEMC: $1 < \eta < 2$
  - HFT (2014-2016): $|\eta| < 1$
  - MTD (2014+): $|\eta| < 0.5$ (partial azimuthal coverage)

- **MB trigger and event plane reconstruction**
  - BBC (before 2018): $3.3 < |\eta| < 5$
  - EPD (2018+): $2.1 < |\eta| < 5.1$
  - VPD: $4.2 < |\eta| < 5$
  - ZDC: $6.5 < |\eta| < 7.5$

- **Recent upgrades 2022**
  - FCS: $2.5 < |\eta| < 4$
  - FTS: $2.5 < |\eta| < 4$
  - ECAL & HCAL: $2.5 < |\eta| < 4$
Top RHIC energy
Lattice QCD region

Beam energy scan
High density hot
QCD region

Cold QCD physics
High density region
Beam Energy Scan
Beam Energy Scan to map the QCD phase diagram

Two stages of Beam Energy Scan:
First glance at low energy region, rather low statistics

Stage II: 3 – 54.4 GeV 2017 – 2021
Precise measurements at low energies, large statistics
Light particle production at 27 GeV

High statistics of BES-II allows to make a rapidity dependence study of particle production. With iTPC and eTOF upgrade more high precision data on particle production are on the way at lower energies.
Thermodynamical properties of the medium

Similar rapidity dependence of the $T_{\text{chem}}$ and $\mu_B$, $\mu_S$ over particle multiplicity

Precise study of the QCD phase diagram location of the interaction at different collision energies

Fits by THERMUS Chemical equilibrium model

$\Delta\mu_B \approx 25$ MeV for $\Delta y = 1$ at 27 GeV
Nuclear modification in the medium

$$R_{cp} = \frac{d^2 Ndp/d\eta < N_{coll}> (central)}{d^2 Ndp/d\eta < N_{coll}> (peripheral)}$$

$R_{cp}$ has two regimes in the behavior depending on the collision energy:
- decrease of particle production with high $p_T$ in central collisions at high energies
- smooth growth of particle production in central collisions at low collision energies.

High statistics of BES-II will allow to measure $R_{cp}$ in high $p_T$ region at low collision energies.
Nuclear modification in the medium

\[ R_{cp} = \frac{d^2 N_{dp_t} d\eta / <N_{coll}> (central)}{d^2 N_{dp_t} d\eta / <N_{coll}> (peripheral)} \]

High statistics of BES-II allows to measure nuclear modification factor in high \( p_T \) region for different particles. Allows to compare different particle species which can be sensitive for different QGP effects.
Collective flow of light nuclei demonstrates mass number dependence for BES-II collider energies

Scaling for light nuclei species for $v_2/A$ and for $v_3/A$ taking into account mass number of the nuclei was calculated.

The A-scaling is observed for light nuclei $v_3$ but not for $v_2$. 

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Collective flow of light nuclei

The $v_1$ scaling behavior suggests the light nuclei are formed via nucleon coalescence. The scaling worsens for $p_T/A > 1$ GeV/c in the range $-0.4 < y < -0.3$. Increasing contamination of target-rapidity ($y = -1.045$) fragments may also play a role.

This indicates that no A scaling is observed in these data for light nucleus $v_2$ at 3 GeV. Nucleon coalescence model qualitatively reproduce both the $v_1$ and $v_2$ as functions of rapidity for all investigated light nuclei at the energy, where baryonic interactions dominate the collision dynamic.
Elliptic flow at low energies

Elliptic flow is negative (squeeze-out) at 3 GeV, as expected from the previous AGS data. Grows rapidly with energy.

The quark number scaling has been used at higher energies as a signature of the QGP. At 3 and 3.2 GeV, the scaling is broken down e.g. hadronic gas (not QGP).
Hypernuclei production

Thermal model fails to describe the trend at RHIC energies. Hypernuclei maybe dominantly produced after the hadron chemical freeze-out at RHIC.

The slopes of mid-rapidity $v_1$ for both light- and hyper-nuclei are scaled with $A$ and/or mass across multiple collision energies.

$v_1$ is consistent with hadronic transport (JAM2 mean field + coalescence).

Coalescence calculation consistent with data at $3.5 < \sqrt{s_{NN}} < 10$ GeV, while still significantly higher than data at higher energies.
Two pion femtoscopy results from FXT program

\[ C(q) = N[(1 - \lambda) + \lambda K(q)(1 + G(q))] \], where

\[ G(q) = \exp(-q_{out}^2 R_{out}^2 - q_{side}^2 R_{side}^2 - q_{long}^2 R_{long}^2 - 2q_0 q_l R_{ol}^2) \]

\( R_{side} \) decreases with going out of midrapidity:

- Hints on boost-invariance breaking

Clear rapidity dependence of \( R_{out-long}^2 \):

- Asymmetric rapidity window in analysis, could give rise to non-zero values in rapidity integrated measurement

\( R_{out}, R_{side} \) and \( R_{long} \) increase from peripheral to central collisions reflecting the geometry of the overlapping region.

*STAR* Preliminary

Au+Au \( \sqrt{s_{NN}} = 3 \text{ GeV} \)

\( 0.15 < k_T \text{ (GeV/c)} < 0.6 \)
Two pion femtoscopy results from FXT program

The source shape evolves from oblate to prolate, as energy increases.

New results from the BES-II FXT on emittance volume is in better agreement with HADES results rather than AGS at low collision energies.
Top RHIC energy
Significant $\Omega$ enhancement over $\phi$ is observed in central AuAu collisions.

In central collisions, good agreement between data and recombination model calculations is obtained. $\Omega$ and $\phi$ are predominantly produced through the recombination of thermalized strange quark in QGP.

$\Omega/\phi$ ratio in p+p collisions is close to that in peripheral Au+Au collisions, hinting there may be smooth transition from p+p to Au+Au collisions.

Measured $R_{cp}$ hints the higher energy loss in dense nuclear matter, created at the most central collisions.
Strange hadron production in small systems

Baryon enhancement is observed at intermediate $p_T$ for central d+Au 200 GeV with $\Lambda/K^0_S$

$\sqrt{s_{NN}} = 200$ GeV

**STAR Preliminary**

- $\Lambda$ and $K^0_S$ yields in d+Au at 200 GeV are enhanced

\[\langle dN/dy, \langle N_{part} \rangle \rangle \text{ relative to } pp\]

\[N_{part} \]
Flow in small systems

- Data at midrapidity
  - $v_2^{3\text{He}+\text{Au}} \sim v_2^{d+\text{Au}} > v_2^{p+\text{Au}}$
  - $v_3^{3\text{He}+\text{Au}} \sim v_3^{d+\text{Au}} \sim v_3^{p+\text{Au}}$

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

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

**p+p vs. Au+Au**

- **p/π** ratio significantly smaller in jets compared to bulk
- Similar **p/π** ratio in jets with \( p_T^\text{const} > 3 \text{ GeV/c} \) in \( p+p \) and Au+Au collisions
- Measurements with lower \( p_T^\text{const} \) cuts are underway
Yields and mean $p_T$ as a function of collision multiplicity

Yields and mean $p_T$ of deuterons and anti deuterons in Ru+Ru and Zr+Zr collisions agree well with Au+Au collisions within the uncertainty

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For the $J/\Psi$:

- Low $p_T$: significant CNM effects. Consistent with model predictions.
- High $p_T (> 3 \text{ GeV/c})$: $R_{pAu}$ consistent with unity $\rightarrow$ suppression in AA due to QGP effects.
Heavy flavor production at STAR

- Significant suppression of different Y states in Au+Au collisions at 200 GeV
- Similar $R_{AA}$ for Y states in isobar collisions as in Au+Au at 200 GeV
- No significant collision species dependence of the suppression at similar $<N_{\text{part}}>$ for the J/$\Psi$

STAR, Phys. Rev. Lett. 130 (2023) 112301
Cold QCD effects
Gluon polarization impact on proton spin

\[ S = \frac{1}{2} = \frac{1}{2} \Delta \Sigma + \Delta G + L \]

quarks    gluons    orbital
angular    momentum

DSSV global fit including up-to-date jet, dijet, pion, W data

**DSSV14 + RHIC (≤2022):**
- \( \Delta G = \int_{0.05}^{1} \Delta g(x) dx = 0.22 \pm 0.03 \)
- \( \Delta G = \int_{0.005}^{0.05} \Delta g(x) dx = 0.17 \pm 0.20 \)

**DSSV14:**
- \( \Delta G = \int_{0.05}^{1} \Delta g(x) dx = 0.20 \pm 0.06 \)
- \( \Delta G = \int_{0.001}^{0.05} \Delta g(x) dx = 0.15 \pm 0.50 \)

arXiv:2302.00605
Single spin asymmetry

W bosons production sensitive to flavor, spin, charge simultaneously
Powerful tool to probe sea quark polarization

First experimental observation of a flavor-asymmetry between anti-up and anti-down polarizations, opposite to the unpolarized distributions
Double spin asymmetry

Sub-processes directly sensitive to gluon
Constrain gluon helicity-dependent PDFs

\[ A_{LL} = \frac{\sigma_{\uparrow \uparrow} - \sigma_{\downarrow \downarrow}}{\sigma_{\uparrow \uparrow} + \sigma_{\downarrow \downarrow}} \propto \frac{\Delta f_1}{f_1} \otimes \frac{\Delta f_2}{f_2} \otimes \tilde{a}_{LL} \otimes D_f^h \]

STAR Phys. Rev. D 105, 092011 (2022)

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Measurements with unpolarized beam

Successful STAR run 2022 with forward upgrade
Requested luminosity for the last transverse spin run in 2024 before EIC

<table>
<thead>
<tr>
<th>√s (GeV)</th>
<th>Species</th>
<th>Luminosity</th>
<th>Year</th>
</tr>
</thead>
<tbody>
<tr>
<td>508</td>
<td>p⁺ + p⁻</td>
<td>400 pb⁻¹</td>
<td>2022</td>
</tr>
<tr>
<td>200</td>
<td>p⁺ + p⁻</td>
<td>235 pb⁻¹</td>
<td>2024</td>
</tr>
<tr>
<td>200</td>
<td>p⁺ + Au</td>
<td>1.3 pb⁻¹</td>
<td>2024</td>
</tr>
</tbody>
</table>

And much more to come with STAR detector upgrades and high statistics runs 2023-2025
Summary

✔ STAR experimental program covers a wide range of topics and STAR has collected a unique set of data on a variety of collision systems and collision energies including fixed target data.

✔ STAR detector has gone through several upgrades in a last couple of years to extend its capabilities for high statistics runs.

✔ BES-II has increased statistics by a factor of 10 for most of the energies and provided additional data with FXT mode of STAR detector.

✔ Run 23 was the 1-st top energy Au+Au with all upgrades. STAR recorded 6.5B events before unexpected RHIC shutdown.

✔ Data taking has been very successfully ongoing and new results are on the way with our future high statistics Au+Au/p+p/p/Au runs.
Thank you for the attention!

Part of this work was supported by Russian Science Foundation under grant № 22-72-10028
Backup slides
BES-II statistics and run time

| √sNN (GeV) | Beam Energy (GeV/nucleon) | Collider or Fixed Target | | No. of events (million) | Run Time (days) | No. Events Collected (Request) | Data Collected |
|------------|---------------------------|--------------------------||--------------------------|--------------------------|-----------------|------------------|
| 7.7        | 4                         | 100                      | C  | 0           | 25            | 2.0              | 138 M (140 M)   | Run-19         |
| 7.7        | 8                         | 100                      | C  | 0           | 156           | 24              | 555 M (700 M)   | Run-18         |
| 11.5       | 17.3                      | 100                      | FXT| 2.60        | 276           | 0.5             | 52 M (50 M)     | Run-21         |
| 11.5       | 70                        | 100                      | FXT| 2.51        | 316           | 54              | 235 M (230 M)   | Run-20         |
| 9.2        | 4.59                      | 100                      | FXT| 2.28        | 372           | 102             | 162 M (160 M)   | Run-20+20b     |
| 7.7        | 3.85                      | 100                      | FXT| 2.10        | 420           | 0.5              | 50 M (50 M)     | Run-21         |
| 7.7        | 31.2                      | 100                      | FXT| 2.02        | 443           | 50 M + 112 M + 100 M (100 M) | Run-19+20+21   |
| 7.2        | 26.5                      | 100                      | FXT| 1.87        | 487           | 1.4             | 155 M + 317 M   | Run-18+20      |
| 6.2        | 19.5                      | 100                      | FXT| 1.68        | 541           | 1.0             | 118 M (100 M)   | Run-20         |
| 5.2        | 13.5                      | 100                      | FXT| 1.52        | 589           | 0.9              | 108 M (100 M)   | Run-20         |
| 4.5        | 9.8                       | 100                      | FXT| 1.37        | 633           | 1.1             | 117 M (100 M)   | Run-20         |
| 3.9        | 7.3                       | 100                      | FXT| 1.25        | 666           | 0.9              | 116 M (100 M)   | Run-20         |
| 3.5        | 5.75                      | 100                      | FXT| 1.13        | 699           | 2.0             | 200 M (200 M)   | Run-19         |
| 3.2        | 4.59                      | 100                      | FXT| 1.05        | 721           | 4.6             | 259 M > 2B(100 M > 2B) | Run-18+21     |

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### Polarized Protons

**250/255 GeV**

- 2022 $P = 50\%$
  - $L_{\text{peak limited by STAR}}$
- 2017 $P = 53\%$
  - $L_{\text{peak limited by STAR}}$
- 2013 $P = 53\%$

**100 GeV**

- 2012 $P = 52\%$
- 2015 $P = 55\%$
- 2009 $P = 34\%$
- 2012 $P = 59\%$
- 2011 $P = 48\%$
- 2009 $P = 56\%$
- 2005 $P = 47\%$
- 2003 $P = 34\%$

### Integrated Polarized Proton Luminosity $L [\text{pb}^{-1}]$

<table>
<thead>
<tr>
<th>Year</th>
<th>$\sqrt{s}$ (GeV)</th>
<th>$L$ (pb$^{-1}$)</th>
<th>$&lt;P&gt;$ (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>2006</td>
<td>62.4</td>
<td>--</td>
<td>48</td>
</tr>
<tr>
<td>2009</td>
<td>200</td>
<td>6.8</td>
<td>57</td>
</tr>
<tr>
<td>2009</td>
<td>200</td>
<td>25</td>
<td>38</td>
</tr>
<tr>
<td>2009</td>
<td>500</td>
<td>10</td>
<td>55</td>
</tr>
<tr>
<td>2011</td>
<td>500</td>
<td>12</td>
<td>48</td>
</tr>
<tr>
<td>2012</td>
<td>510</td>
<td>82</td>
<td>56</td>
</tr>
<tr>
<td>2013</td>
<td>510</td>
<td>256</td>
<td>56</td>
</tr>
<tr>
<td>2015</td>
<td>200</td>
<td>50</td>
<td>60</td>
</tr>
</tbody>
</table>

### Long.

- 2013 $P = 56\%$
- 2015 $P = 60\%$

### Trans.

- 2015 $P = 60\%$
- 2017 $P = 55\%$
- 2022 $P = 50\%$

*STAR*
Particle identification at 3 GeV

Detects particles in the $0 < \eta < 2$ range
$\pi$, $K$, $p$, $d$, $t$, $h$, $\alpha$ through dE/dx and ToF
$K^0_s$, $\Lambda$, $\Xi$, $\Omega$, $\varphi$, $^3\Lambda H$, $^4\Lambda H$ through invariant mass

About 260M events analyzed from 2018,
2B more recorded in 2021
Hypernuclei production

300M Au+Au data without iTPC and eTOF
Candidate reconstruction via invariant mass in two body decay

Measured lifetime results at $\sqrt{s_{NN}} = 3.0$ and 7.2 GeV are in a good agreement with each other
The combined results are

$$\tau(\Lambda^3\text{H}) = 221 \pm 15(\text{stat.}) \pm 19(\text{syst.}) \text{ ps.}$$

$$\tau(\Lambda^4\text{H}) = 218 \pm 6(\text{stat.}) \pm 13(\text{syst.}) \text{ ps.}$$

Lifetime measurements are consistent with previous measurements and have higher precision
Global hyperon polarization measurements

Global hyperon polarization over a large range of collision energy is measured and can be described by hydrodynamic and transport models with intense fluid vorticity of the QGP.

The observation of substantial polarization in these collisions may require a reexamination of the viscosity of any fluid created in the collision, of the thermalization timescale of rotational modes, and of hadronic mechanisms to produce global polarization.

\[
\frac{dN}{d\cos \theta^*} = \frac{1}{2} \left( 1 + \alpha_H |\vec{P}_H| \cos \theta^* \right)
\]
Collectivity and temperature of the medium

Parameters: Temperature ($T_{\text{kin}}$) and transverse radial velocity ($\beta$) obtained by fitting the momentum distribution of particles.


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Comparison to thermal model predictions

Grand Canonical Ensemble – B, Q and S are conserved on average
Canonical Ensemble – exact conservation of B, Q and S
Strangeness Canonical Ensemble – exact conservation of S

Blast-wave fits for particle spectra

$$\frac{d^2N}{2\pi p_T dp_T dy} \propto \int_0^R r dr m_T I_0 \left( \frac{p_T \sinh \rho(r)}{T} \right) \times K_1 \left( \frac{m_T \cosh \rho(r)}{T} \right)$$

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Hidden vs. open strangeness production

The thermal model with grand canonical ensemble (GCE) under-predicts the ratios.

The canonical ensemble (CE) calculations reproduce the ratios with a correlation length of 3-4 fm.
Clear enhancement compared to $\rho$ excluded cocktail simulation in LMR and IMR
Thermal dileptons

Excess dielectron spectra in 27 and 54.4 GeV Au+Au collisions and NA60 In+In collisions are similar.

Thermal dielectrons is the major source in IMR

T extracted from low mass region around the pseudo critical temperature $T_{pc}$ (156 MeV)

$T$ in 27 and 54.4 GeV are consistent with each other

$T > T_{pc}$ (156 MeV): emission dominantly from QGP

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HotQCD: PLB 795 (2019) 15-21

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Phase diagram mapping with dielectrons

Tch GCE/SCE: STAR PRC 96, 044904 (2017)

T_{LMR} close to T_{ch} and T_{pc}
ρ meson dominantly emitted around phase transition

T_{IMR} higher than T_{LMR}, T_{ch} and T_{pc}
dielectron dominantly emitted from QGP phase

High statistics data sample between 7.7 GeV and 19.6 GeV in STAR BES-II will help map the kink region

Enhanced tracking and particle identification capabilities with iTPC and eTOF upgrades
Higher-order cumulants at 3 GeV

Cumulants of proton and its ratios at 3 GeV

Higher-order cumulant ratios C4/C2, C5/C1, and C6/C2 in most central events appear least affected by volume fluctuations in the 3 GeV Au+Au collisions

e-Print: 2209.11940 [nucl-ex]

Susceptibility ratios fluctuate near the CP. It can be measured via cumulants of net-protons

\[
C_1 = \langle N \rangle \\
C_2 = \langle (\delta N)^2 \rangle \\
C_3 = \langle (\delta N)^3 \rangle \\
C_4 = \langle (\delta N)^4 \rangle - 3 \langle (\delta N)^2 \rangle^2
\]
Energy dependence of net-proton cumulant ratio

Previous measurements of net-protons by STAR and HADES suggested the sign change at energies of BES-II.

The data and results of both UrQMD and hydrodynamic models of C4/C2 in the most central collisions at 3 GeV are consistent, which signals the effects of baryon number conservation and an energy regime dominated by hadronic interactions.