STAR Heavy Ion and Cold QCD program for 2021+ runs

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Outline:

• STAR Upgrades
  • Upgrades for BES-II
  • Forward Upgrades
• Heavy Ion Physics for 2021+
• Cold QCD Physics for 2021+
• Summary
**STAR Detector Upgrades for BES-II**

**Endcap Time of Flight (2019)  
\(-1.5 < \eta < -1\)**
- Extend PID from \(\eta = -1\) to \(-1.5\);
- Improve the fixed target program;

**Event Plane Detector (2018)  
\(2.1 < |\eta| < 5.1\)**
- Replace Beam-Beam Counter (BBC);
- Extend rapidity coverage;
- Improve triggering capabilities;
- Improve event plane resolution;

**inner TPC (2019)  
\(|\eta| < 1.5\)**
- Replace all inner TPC sectors;
- Increase rapidity coverage;
- Improve momentum and dE/dx resolution;
- Decrease minimum \(p_T\) from 125 MeV to 60 MeV;
STAR Forward Upgrade Ongoing:

- At $2.5 < \eta < 4$
  - Si disks + Small Thin Gap Chambers (STGC) for tracking;
  - Electromagnetic and hadronic calorimeters;

<table>
<thead>
<tr>
<th>Detector</th>
<th>p+p and p+A</th>
<th>A+A</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>$\sim 50%/\sqrt{E} + 10%$</td>
<td>---</td>
</tr>
<tr>
<td>Tracking</td>
<td>Charge separation</td>
<td></td>
</tr>
</tbody>
</table>

- Photon suppression $0.2 < p_T < 2$ GeV/c, with 20-30% $1/p_T$
STAR Forward Upgrade: ECal & HCal

**Location:** 7 m from the IP, at $2.5 < \eta < 4$

**Readout:** SiPMs
- Used in Trigger
- Split in 2 movable halves inside and outside of ring
- Slightly projective

**ECal:**
- Reuse PHENIX PbSc calorimeter with new readout;
- On front face $\rightarrow$ 1496 channel;
  - Tower size: $5.52 \times 5.52 \times 33 \text{ cm}^3$
  - 66 sampling cells with 1.5 mm Pb
  - 4 mm Sc & Wavelength shifting fibers

**HCal:**
- Fe/Sc (20mm/3mm) sandwich;
- 520 channels in total;
- Tower size $10 \times 10 \times 84 \text{ cm}^3$
  - In close collaboration with EIC R&D

**Preshower**
- Use EPD as preshower;

Installation of entire system (HCal + ECal + Electronics) finished last week
~ 10 month to commission systems before Run-22 500 GeV pp
STAR Forward Upgrade: ECal & HCal

Construction completed last week
STAR Forward Upgrade: Silicon and sTGC

3 Silicon disks: at 146, 160, and 173 cm from IP
Built on successful experience with STAR IST
➢ Single-sided double-metal mini-strip sensors
   • Granularity: fine in $\phi$ and coarse in $R$
   • Si from Hamamatsu
➢ Frontend chips: APV25-S1 $\rightarrow$ IST all in hand
➢ Material budget: $\sim$1.5% per disk
➢ Reuse
   • IST DAQ system for FTS
   • IST cooling system

4 sTGC disks: at 307, 325, 343 and 361 cm from IP
Inside Magnet pole tip opening:
   • Inhomogeneous magnetic field
➢ 4 quadrants double sided sTGC $\rightarrow$ 1 layer
   • Diagonal strips to break ambiguities in the sTGC
➢ Position resolution: $\sim$200 $\mu$m
➢ Material budget: $\sim$0.5% per layer,
➢ Readout: based on VMM-chips
   • following ATLAS design

Installation of entire Si and sTGC finalized by Mid of September 2021
~2-4 month to commission systems before Run-22 500 GeV pp
The 2021+ Physics program

**Mid-rapidity -1.5 < \eta < 1.5**

- **A+A Beam:**
  - FXT & 7.7 GeV: Au+Au (2021)
  - 200 GeV: Au+Au (2023/25)
  - 200 GeV: O+O (2021)

- **Physics Topics:**
  - Complete BES-II program:
    - Elliptic flow;
    - Chiral magnetic effect;
    - Azimuthal femtoscopy;
    - Net proton kurtosis;
    - Dilepton...
  - Origin of small system collectivity via O+O;
  - Exploring the Nuclear Equation-of-State (EoS);
  - Exploring the Microstructure of the QGP

- **p_up+p_up & p_up+A Beam:**
  - Beam:
    - 500 GeV: p+p (2022)
    - 200 GeV: p+p and p+A (2024)

- **Physics Topics:**
  - Improve statistical precision:
    - Sivers effect in dijet and W/Z production;
    - Collins effect for hadrons in jets;
    - Transversity and IFF;
    - Diffractive studies for spatial imaging of nucleon;
    - Measurement of GPD $E_g$ through UPC J/Ψ;
    - Nuclear PDF and fragmentation function;

**Forward-rapidity 2.5 < \eta < 4**

- **A+A Beam:**
  - 200 GeV: Au+Au (2023/25)

- **Physics Topics:**
  - Temperature dependence of viscosity through flow harmonics up to $\eta^\sim4$;
  - Constrain longitudinal structure of initial state;
  - Global vorticity transfer:
    - Rapidity dependence of $\Lambda$, $\Xi$, $\Omega$ polarization at STAR

- **p_up+p_up & p_up+A Beam:**
  - Beam:
    - 500 GeV: p+p (2022)
    - 200 GeV: p+p and p+A (2024)

- **Physics Topics:**
  - TMD measurements at high x:
    - Transversity, Collins;
    - Sivers through DY and jets
  - UPC J/Ψ GPD at forward rapidity;
  - Nuclear PDFs and FF:
    - $R_{pA}$ for direct photons & DY, and hadrons
    - Gluon Saturation through di-hadrons, $\gamma$-Jets, di-jets

All of these measurements are critical to the scientific success of EIC to test universality and factorization.
BES-II Progress:

- Collecting 7.7 GeV data in 2021 to finish the BES-II program;
- 7.7 GeV is the essential bridge between Collider and FXT data;
- Hints of features at 7.7 GeV in several studies from BES-I;
- The planned Run-21 FXT measurements at $\sqrt{s_{NN}} = 3$ GeV with the iTPC and eTOF give access to protons higher moment, precision $\phi$, hyper-nuclei, and dilepton measurements;
- FXT data combined with collider data probes nuclear stopping.

<table>
<thead>
<tr>
<th>Beam Energy (GeV/nucleon)</th>
<th>$\sqrt{s_{NN}}$ (GeV)</th>
<th>$\mu_B$ (MeV)</th>
<th>Run Time</th>
<th>Number Events Requested (Recorded)</th>
<th>Date Collected</th>
</tr>
</thead>
<tbody>
<tr>
<td>13.5</td>
<td>27</td>
<td>156</td>
<td>24 days</td>
<td>(560 M)</td>
<td>Run-18</td>
</tr>
<tr>
<td>9.8</td>
<td>19.6</td>
<td>206</td>
<td>36 days</td>
<td>400 M (582 M)</td>
<td>Run-19</td>
</tr>
<tr>
<td>7.3</td>
<td>14.6</td>
<td>262</td>
<td>60 days</td>
<td>300 M (324 M)</td>
<td>Run-19</td>
</tr>
<tr>
<td>5.75</td>
<td>11.5</td>
<td>316</td>
<td>54 days</td>
<td>230 M (235 M)</td>
<td>Run-20</td>
</tr>
<tr>
<td>4.59</td>
<td>9.2</td>
<td>373</td>
<td>102 days</td>
<td>160 M (162 M)</td>
<td>Run-20+20b</td>
</tr>
<tr>
<td>31.2</td>
<td>7.7 (FXT)</td>
<td>420</td>
<td>0.5-1.1 days</td>
<td>100 M (50 M+112 M)</td>
<td>Run-19+20</td>
</tr>
<tr>
<td>19.5</td>
<td>6.2 (FXT)</td>
<td>487</td>
<td>1.4 days</td>
<td>100 M (118 M)</td>
<td>Run-20</td>
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<tr>
<td>13.5</td>
<td>5.2 (FXT)</td>
<td>541</td>
<td>1.0 day</td>
<td>100 M (103 M)</td>
<td>Run-20</td>
</tr>
<tr>
<td>9.8</td>
<td>4.5 (FXT)</td>
<td>589</td>
<td>0.9 days</td>
<td>100 M (108 M)</td>
<td>Run-20</td>
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<tr>
<td>7.3</td>
<td>3.9 (FXT)</td>
<td>633</td>
<td>1.1 days</td>
<td>100 M (117 M)</td>
<td>Run-20</td>
</tr>
<tr>
<td>5.75</td>
<td>3.5 (FXT)</td>
<td>666</td>
<td>0.9 days</td>
<td>100 M (116 M)</td>
<td>Run-20</td>
</tr>
<tr>
<td>4.59</td>
<td>3.2 (FXT)</td>
<td>699</td>
<td>2.0 days</td>
<td>100 M (200 M)</td>
<td>Run-19</td>
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<tr>
<td>3.85</td>
<td>3.0 (FXT)</td>
<td>721</td>
<td>4.6 days</td>
<td>100 M (259 M)</td>
<td>Run-18</td>
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<tr>
<td>3.85</td>
<td>7.7</td>
<td>420</td>
<td>11-20 weeks</td>
<td>100 M</td>
<td>Run-21²</td>
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</table>
Small System Run: O+O at $\sqrt{s_{NN}} = 200$ GeV

- Prediction of different energy dependence for symmetric and asymmetric systems;
- Small symmetric system with similar $N_{\text{part}}$ to p/d+Au, but different nucleon/sub-nucleon fluctuations;
- Analyzing power for 2k-particle cumulants $\nu_n\{2k\}$ scales with $N_{\text{events}} \times N_{\text{part}}^{2k}$; much less running time needed than for smaller nuclei;

See Shengli Huang’s talk for details.
Constrain Longitudinal Structure of Initial State

\[ r_n(\eta_a, \eta_b) = \frac{V_{n\Delta}(-\eta_a, \eta_b)}{V_{n\Delta}(\eta_a, \eta_b)} \]

- \( V_{n\Delta}(\eta_a, \eta_b) \) is the Fourier coefficient calculated with pairs of particles in different \( \eta \) regions;
- \( r_n(\eta_a, \eta_b) \) sensitive to different initial state inputs:
  - 3D-Glasma model: weaker decorrelation, describes CMS \( r_2 \) but not \( r_3 \)
  - Wounded nucleon model: stronger decorrelation than data
- Precise measurement of \( r_n \) over a wide rapidity window will provide a stringent constraint:
  - Pin down the nature of the 3-dimensional initial state of heavy ion collisions;
  - Constrain different models of QCD from colliding nuclei;

See Maria Stefaniak’s talk for details.
Global Vorticity Transfer

- How exactly is the global vorticity dynamically transferred to the fluid?
- How is the local thermal vorticity of the fluid transferred to the spin angular momentum of the produced particles during the process of hadronization and decay?
  - Rapidity dependence of $\Lambda$, $\Xi$, $\Omega$ $P_H$ at STAR, probe the nature of global vorticity transfer: Initial geometry and local thermal vorticity + hydro predict opposite trends.
- Can we reconcile $P_H$ with vector meson spin alignment $\rho_{00}$? Strong force field effect?
  - Precise measurements of $\rho_{00}$ of $K^*$, $\phi$, $J/\psi$. 

Improved PID, extended $\eta$ coverage by iTPC and Forward detectors
Cold QCD Program:

• Kinematic coverage for 200 and 500 GeV p+p at STAR is 0.005<x<0.5;
• Provides best overlap with the x-Q^2 coverage of EIC;
• Precise factorization and universality tests;
• Overlapping x coverage enables detailed evolution studies;

Also see David Kapukchyan’s poster.

<table>
<thead>
<tr>
<th>√s (GeV)</th>
<th>Species</th>
<th>Luminosity</th>
<th>Year</th>
</tr>
</thead>
<tbody>
<tr>
<td>500</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>
• Forward rapidity at STAR provides an unique opportunity to probe high gluon densities in p+Au collisions;
• STAR Forward upgrades characterize non-linear gluon effects through charged di-hadrons, γ-jet, di-jets;

See Xiaoxuan Chu’s talk for details.
- Exclusive $J/\psi$ TSSA measurement in UPC;
- Access GPD $E_g$ for gluons, sensitive to spin-orbit correlation;
- iTPC and forward detectors will enable a high-impact measurement
  - A factor of 9-10 more data combining iTPC and forward upgrades, expected statistical error 0.02 for $\langle W_{\gamma p} \rangle = 14$ GeV;
Nuclear PDF

- Direct photon measurement: constrain nuclear **gluon distribution** in a broad $x$ range;
- Drell-Yan: constrain nuclear **sea quark distribution** in a broad $x$ range;
- Contribute to a stringent test of the universality of nuclear PDFs when combined with data from EIC;
Summary

• The STAR BES-II upgrades have been running very well since 2019;

• The Forward Upgrade is progressing very well, will be fully ready in 2022;

• These upgrades will substantially extend STAR’s kinematic reach and further enhance its particle identification capabilities;

• The combination of the existing and ongoing detector upgrades enables a rich and compelling scientific program in the next few years.
Back Up
• The rapidity dependence of the flow measurement is sensitive to $\eta/s(T)$;
• Lower beam energy at RHIC provides stronger variations of the temperature with rapidity;
• The BES-II and the forward upgrade of STAR will provide precise estimations of different azimuthal correlation observables;
Collins Effect

JetEIC Workshop 2020

• Collins effect combines the collinear quark transversity in the proton with the TMD dependent Collins fragmentation function;

• Precision measurements at both energies probe TMD evolution and provide important cross-checks and essential $x-Q^2$ overlap with EIC;

• Collins effect in $p+Au$ will provide an alternative universality test and a unique probe of the spin dependence of hadronization in cold nuclear matter;