The STAR Detector Upgrades for the BES-II and Beyond Physics Program

4-9 November 2019 @ Wuhan

Yi Yang
National Cheng Kung University
on behalf of the STAR collaboration
The most versatile particle collider

- The only polarized proton collider in the world
- Type of collisions: p+p, p+Au, Au+Au, d+Au, U+U, Zr+Zr, ...
- Center-of-mass energy for Au+Au collisions: 3.0 - 7.7 - 200 GeV
RHIC provides a unique opportunity to explore the QCD phase diagram with different collision energies

- Search for QCD critical point, 1st order phase transition, turn-off of QGP, etc.


**BES-II** (2019 – 2021):

- **Collider mode**: $\sqrt{s_{NN}} = 7.7, 9.1, 11.5, 14.6, 16.7, 19.6$ GeV
- **Fixed-Target mode**: $\sqrt{s_{NN}} = 3.0, 3.2, 3.5, 3.9, 4.5, 5.2, 6.2, 7.7$ GeV

M.M. Aggarwal et al. (STAR Collaboration), An experimental exploration of the QCD phase diagram: the search for the critical point and the onset of de-confinement. arXiv: 1007.2613

BES-II white paper: https://drupal.star.bnl.gov/STAR/starnotes/public/sn0598
The STAR Detector for BES-I

- Large acceptance: $|\eta| < 1$, $0 < \phi < 2\pi$
- Excellent PID

Diagram shows the STAR detector components:
- BEMC
- Magnet
- TOF
- TPC
- BBC
- VPD
Selected Results from BES-I

Yi Yang @ QM2019
2019 November 4-9
STAR Upgrade for BES-II and Forward Physics

PRL 121, 032301 (2018)

PRL 123, 132301 (2019)

PRC 96 (2017) 44904

PRC 98 (2018) 14910

arXiv:1810.10159
arXiv:1906.03732

RHIC: increase luminosity for low energy beams with e-cooling (LEReC)
Rebuild the inner sectors of the TPC to improve:

- Continuous coverage
- Better $dE/dx$ and $p_T$ resolution
- Extend $\eta$ acceptance from 1.0 to 1.5
- Lower $p_T$ cut from 125 MeV/c to 60 MeV/c

Fully operational since 2019
Expected Impact with iTPC in BES-II

- Provides measurements of the net-proton Kurtosis to assess the sensitivity on the search of the QCD critical point

STAR note 619: A proposal for iTPC upgrade
Event Plane Detector (EPD)

- Designed for event plane determination, centrality definition, and triggering
  - Scintillator based fast detector
  - Large $\eta$ coverage: $2.1 < |\eta| < 5.1$
  - Excellent timing resolution: $\sim 1$ ns
- Fully operational since 2018

Au+Au $\sqrt{s_{NN}} = 27$ GeV

% centrality

$R_{EP}$

Uncorrected $v_2$ (%)
endcap Time-of-Flight (eTOF)

- Installed on one side of STAR (part of FAIR CBM Phase-0)
- Improve PID in $1.1 < \eta < 1.6$
- Multi-gap resistive plate chamber
- Fully installed for 2019
Fixed-Target Au+Au Collisions in STAR

Fixed Target \( z = 2.01 \) m

\[ \sqrt{s_{NN}} = 4.5 \text{ GeV} \]
Cold QCD Program @ RHIC (Run2020+)

- RHIC provides unique opportunities to understand
  - How do sea quarks and gluons contribute to the nucleon spin?
  - How do the confined hadronic states emerge from quarks and gluons?
  - And more...

<table>
<thead>
<tr>
<th>Year</th>
<th>√s (GeV)</th>
<th>Delivered Luminosity</th>
<th>Scientific Goals</th>
<th>Observable</th>
<th>Required Upgrade</th>
</tr>
</thead>
<tbody>
<tr>
<td>STAR</td>
<td>2021/22</td>
<td>p+p @ 510</td>
<td>1.1 fb⁻¹ 10 weeks</td>
<td>TMDs at low and high x</td>
<td>A_{UT} for Collins observables, i.e.</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>hadron in jet modulations at η &gt; 1</td>
<td>A_{LL} for jets, di-jets, h/g-jets at η &gt; 1</td>
</tr>
<tr>
<td></td>
<td>2021/22</td>
<td>p+p @ 510</td>
<td>1.1 fb⁻¹ 10 weeks</td>
<td>Δg(x) at small x</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>STAR</td>
<td>2021/22</td>
<td>p+p @ 200</td>
<td>300 pb⁻¹ 8 weeks</td>
<td>Subprocess driving the large A_{N} at high x; and h</td>
<td>A_{N} for charged hadrons and flavor</td>
</tr>
<tr>
<td>In parallel with PHENIX</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>enhanced jets</td>
</tr>
<tr>
<td>p+Au</td>
<td>2020/21</td>
<td>200</td>
<td>1.8 pb⁻¹ 8 weeks</td>
<td>Initial state and hadronization in nuclear collisions</td>
<td>R_{pAu} direct photons and DY</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>Dihadron, g-jet, h-jet, diffraction</td>
</tr>
<tr>
<td>p+Al</td>
<td>2020/21</td>
<td>200</td>
<td>12.6 pb⁻¹ 8 weeks</td>
<td>A-dependence of nPDF, A-dependence for Saturation</td>
<td>R_{pAl} direct photons and DY</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>Dihadrons, g-jet, h-jet, diffraction</td>
</tr>
</tbody>
</table>
The STAR forward upgrade includes **Calorimetry (ECAL & HCAL)** and **Tracking (silicon microstrip tracker & small-strip Thin Gap Chamber)** dedicated to study nuclear structure, the QGP, etc.

### 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>~10%/\sqrt{E}</td>
<td>~20%/\sqrt{E}</td>
</tr>
<tr>
<td>HCAL</td>
<td>~60%/\sqrt{E}</td>
<td>---</td>
</tr>
<tr>
<td>Tracking</td>
<td>Charge separation</td>
<td>0.2 &lt; $p_T$ &lt; 2 GeV/c with 20 – 30% 1/$p_T$</td>
</tr>
</tbody>
</table>

3 identical disks located at $z = 140, 154, \text{ and } 168 \text{ cm from IP}$

- Acceptance:
  - $0 < \phi < 2\pi$
  - $2.5 < \eta < 4.0$

- Each disk contains 12 modules
A gaseous detector (developed by ATLAS)

- 4 sTGC layers located at 273, 303, 333 and 363 cm from IP
- Each layer is double-sided
  - Provide (diagonal) $x$-$y$ coordinates
- Position resolution: $\sim 100 \, \mu m$
- Acceptance: $2.5 < \eta < 4.0$
- Efficiency greater than 98% achieved
Reuse PHENIX lead-scintillator calorimeter with new SiPM based readout

- Total 12 sectors
- Each sector has $6 \times 6$ EM modules
- EM Module:
  - Each module has 4 independent towers
  - Penetrating WLS fibers for light collection
- First forward upgrade detector installed in STAR (October 2019)
STAR Forward Calorimeters - HCAL

- First hadronic calorimeter in STAR
- Fe/Sc sandwich sampling calorimeter
- R&D and scintillator production are on-going

Prototype in Run 19
Performance of ECAL and HCAL

- Intensive test beam for Forward Calorimeter at FNAL in 2019
- Performances of ECAL and HCAL prototype are close to the requirements

ECAL

Performances of ECAL and HCAL prototype are close to the requirements.
Dedicated personnel with large expertise for each subsystem

and the STAR collaboration, which stands enthusiastically behind the upgrade
Expected Results from STAR Forward Upgrade

**Forward-rapidity 2.5 < η < 4.0**

**A+A**

**Beam:** Full Energy AuAu

**Physics Topics:**
- Temperature dependence of viscosity through flow harmonics up to η\textasciitilde4
- Longitudinal decorrelation up to η\textasciitilde4
- Global Lambda Polarization
  → strong rapidity dependence predicted

**p+p & p+A**

**Beam:**
- 500 GeV: p+p
- 200 GeV: p+p and p+A

**Physics Topics:**
- TMD measurements at high x transversity → tensor charge
- Improve statistical precision for Sivers through DY
- Δg(x,Q^2) at low x through Dijets
- Gluon PDFs for nuclei
  ➢ R_{pA} for direct photons & DY
- Test of Saturation predictions through di-hadrons, γ-Jets

- Constrain the longitudinal structure of initial conditions through correlations vs rapidity

**Measurements at forward region are the key to distinguish the model predictions for global hyperon polarization**

---

**B. Schenke**

**Hydrodynamic calculations:**

**Au+Au 200 GeV**

**HIJING**

F. Beccattini et al. EPJC 75(2015)406
Li, Pang, Wang & Xia, PRC 96 (2017) 054908
Deng & Huang, PRC 93 (2016) 064907

---

Yi Yang @ QM2019
2019 November 4-9
STAR Upgrade for BES-II and Forward Physics
**Expected Results from STAR Forward Upgrade**

**Forward-rapidity** $2.5 < \eta < 4.0$

- **A+A**
  - Beam: Full Energy AuAu
  - Physics Topics:
    - Temperature dependence of viscosity through flow harmonics up to $\eta \sim 4$
    - Longitudinal decorrelation up to $\eta \sim 4$
    - Global Lambda Polarization $\rightarrow$ strong rapidity dependence predicted

- **p+p & p+A**
  - **Beam:**
    - 500 GeV: p+p
    - 200 GeV: p+p and p+A
  - **Physics Topics:**
    - TMD measurements at high $x$
      - transversity $\rightarrow$ tensor charge
    - Improve statistical precision for Sivers through DY
    - $\Delta g(x,Q^2)$ at low $x$ through Di-jets
    - Gluon PDFs for nuclei
      - $R_{pA}$ for direct photons & DY
    - Test of Saturation predictions through di-hadrons, $\gamma$-Jets

**Constrain Nuclear PDFs:** Unique kinematic coverage by STAR forward detectors
- Direct photons $\rightarrow$ gluon PDF
- Drell-Yan production $\rightarrow$ sea quarks

**Constrain Gluon Helicity:** Di-jets $A_{LL}$ at 510 GeV with STAR forward upgrade: constrain $\Delta g(x)$ at $x \sim 10^{-3}$
Summary

- STAR experiment plays a crucial role in understanding the QCD phase diagram and in expanding the frontiers of cold-QCD

- The STAR BES-II upgrades (iTPC, EPD, and eTOF) provide excellent PID with wider $\eta$ coverage and better resolution in $p_T$ and the event plane determination

- The STAR forward upgrade consists of tracking (silicon + sTGCs) + calorimetry (ECAL + HCAL) with a coverage of $2.5 < \eta < 4.0$

- The forward upgrade is on track for data taking in FY-22 and beyond