The STAR
Forward Rapidity Upgrade

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for the STAR Collaboration
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Context

1. **Emerging Nucleons**
   How are gluons, sea quarks, and their intrinsic spins distributed in space and momentum in the nucleon?

2. **Nuclear Medium**
   How do colored quarks and gluons and colorless jets interact with the nuclear medium?
   How does the nuclear environment affect quark and gluon distributions?
   Are abundant low-momentum gluons confined within nucleons?

3. **Gluon Saturation**
   What happens to the gluon density at high energy?
   Are the properties of a saturated gluonic state universal among all nuclei?
Transverse Spin Effects

- Origin of large transverse asymmetries at high $x_F$
  \[ A_{UT} = \frac{d\sigma^\uparrow - d\sigma^\downarrow}{d\sigma^\uparrow + d\sigma^\downarrow} \]

- Disentangle initial and final state effects
  - Transversity distribution
  - Spin-orbit correlations, fragmentation functions
  - Transverse momentum dependent vs. higher twist

Tagged jets

Charged pions

Pions in jets

Current data for Collins and Sivers asymmetry:
- COMPASS: $h_T^\pm < 1.6$ GeV
- HERMES: $h_T < 1$ GeV
- JLab Hall-A: $h_T < 0.45$ GeV
- JLab 12 (upcoming)
- RHIC 500 GeV: $1 < h < 4$ Collins
- STAR W bosons
- STAR pp DY: $\sqrt{s} = 500$ GeV
Helicity Asymmetries

\[ A_{LL} = \frac{\sigma^{++} - \sigma^{+-}}{\sigma^{++} + \sigma^{+-}} \]

\[ \int_{0.05}^{1} \Delta g(x, Q^2) dx = 0.2^{+0.06}_{-0.07} \]


Projections:

\[ \sqrt{s} = 510 \text{ GeV} \]
\[ \text{anti-}k_T, R = 0.6 \]
\[ E_{T3} > 5 \text{ GeV} \]
\[ E_{T4} > 8 \text{ GeV} \]

\[ \sqrt{x_1} \cdot \sqrt{x_2} = m_{jj}/\sqrt{s} \]
Nuclear Distribution Functions

- Poorly constrained, esp. towards low $x$
- LHC data at very high $Q^2$
  \[ R_{pA} = \frac{1}{\langle N_{coll} \rangle} \frac{dN_{pA}}{dN_{pp}} \]
- Direct photons $\rightarrow$ gluon PDF
- Drell-Yan production $\rightarrow$ sea quarks $2.5 < \eta < 4.5$

Projections:
Gluon Saturation

- Saturation scale
  \[ Q_A^2(x) \approx A^{1/3} Q_S^2(x) \]
- Scan kinematic range: \( x \) & \( Q^2 \)
  - Trigger \( p_T \)
  - Associated \( p_T \)
- Test \( A \)-dependence
  - \( p + Al, p + Au \)
- Other probes (forward)
  - \( \gamma \)-hadron correlation
  - \( \gamma \) –jet correlation

\[ \text{Azimuthal Correlations} \]
\[ W = 200 \text{ GeV} \]
\[ \eta_1 = 3.8, \eta_2 = 0, \text{ central} \]
\[ p_1 = 1.5 \text{ GeV}, p_2 = 0.2 - 1.5 \text{ GeV} \]
The STAR Forward Calorimeter System and Forward Tracking System


Highlights of the STAR midrapidity Physics Program after 2020


New detector upgrades for potential polarized $p + p$ collisions at $\sqrt{s} = 510$ GeV
Forward Calorimeter System

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<tr>
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<th>p+p / p+A</th>
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<tbody>
<tr>
<td>ECAL</td>
<td>$\approx 10%/\sqrt{E}$</td>
<td>$\approx 20%/\sqrt{E}$</td>
</tr>
<tr>
<td>HCAL</td>
<td>$\approx 60%/\sqrt{E}$</td>
<td>n/a</td>
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Preshower detector
EM calorimeter
- PHENIX PbSc
- New readout SiPM/APD
- Not compensating

Hadronic calorimeter
- $L = 4 \cdot \lambda_I$
- Sampling iron-scintillator
- Same readout

Calorimeter R&D as part of EIC studies, beam test, and in situ setup at STAR
Balance of cost and performance
Cost $\approx$ $2.0$ M
FCS – Research & Development

- Efforts for ECAL and HCAL as part of EIC R&D
- ECAL test in 2017
  - Hamamatsu SiPM $6 \times 6 \text{ mm}^2$
  - FEE boards and digitizers
  - Integrated into STAR (DAQ, trigger)
- FCS test in 2018
  - Large scale ECAL prototype with HCAL towers
Forward Tracking System

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<td>Tracking</td>
<td>charge separation</td>
<td>$\frac{\delta p}{p} \approx 20 - 30%$ at $0.2 &lt; p_T &lt; 2.0 \text{ GeV/c}$</td>
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- 3 layers of silicon mini-strip disk
  - $z = 90, 140, 187 \text{ cm}$
  - Builds on experience of STAR IST (Intermediate Silicon Tracker)

- 4 layers of small-strip Thin Gap Chambers
  - $z = 270, 300, 330, 360 \text{ cm}$
  - Use of STAR TPC electronics for readout
  - Significant reduction of the project cost

Cost $\approx 3.3$ M, mostly from Chinese consortium (with UIC and BNL)
FTS – Research & Development

3 Silicon disks:
- 12 wedges, each with 128 azimuthal & 8 radial strips
- Single-sided double-metal Silicon Mini-strip sensors
  - under development @UIC
- Several different frontend chips, APV25-S1 chip (IST)
  - DAQ system for FTS same as IST
  - Replicating the IST cooling system

4 sTGC disks:
- Based on ATLAS R&D from SDU
  - $\approx 0.5\% X_0$ per layer
  - Position resolution $\sim 100 \mu m$ in x & y direction
- Read out with existing TPC electronics
- Prototype in preparation at SDU
  - $\frac{1}{4}$ length of ATLAS module
  - 30 cm x 30 cm module with 2 layers
The STAR collaboration has proposed a forward detector upgrade that combines tracking and calorimetry at $2.5 < \eta < 4$.

Hadron structure measurements are highly relevant for the physics of a future electron-ion collider.

Further tests are planned during 2019 RHIC operations for a full installation and readiness after the beam energy scan (phase II).
RHIC as a Polarized Proton Collider

- AGS
- LINAC
- Booster
- Hydrogen Jet Polarimeter
- Carbon Polarimeters
- Siberian Snakes
- PHENIX
- STAR
- Spin Rotators
- Tune Jump Quads
- Helical Partial Snake
- AGS pC Polarimeter
- Strong Snake
- 200 MeV Polarimeter
- Carbon Polarimeters
- Spin Flipper
- Siberian Snakes
- Polarized Source

Graph:
- Integrated polarized proton luminosity L[pb⁻¹]
- Time [weeks in physics]

- 2012 P = 52%
- 2013 P = 53%
- 2015 P = 55%
- 2017 P = 53%
- (L_peak limited)

- 2009 P = 34%
- 2006 P = 55%
- 2005 P = 47%
- 2003 P = 34%
Physics Performance

Matching jet reconstruction and partonic kinematics ($3<\eta<4$)

Drell-Yan identification (boosted decision trees)
Efficiencies & Resolution

Pions
- $p_T = 0.2$ GeV/$c$
- $p_T = 1.0$ GeV/$c$
- $p_T = 2.0$ GeV/$c$
dashed: wrong sign

Full detector simulation

$\delta p_T / p_T \approx 25 - 50\%$
$3^\circ < \theta < 8^\circ$

Muons
- $p_T = 0.2$ GeV/$c$
- $p_T = 1.0$ GeV/$c$
- $p_T = 2.0$ GeV/$c$