The RHIC Cold QCD Plan for 2017 to 2023
A Portal to the EIC

Renee Fatemi

September 27th, 2016
First Collisions!

Last scheduled pp Run

BES-II

sPHENIX

To the EIC!

2000

2017

2019-2020

2022-2025

>2025
Extremely productive time for RHIC!

First Collisions!

This is where we are coming from...
“We recommend a high-energy high-luminosity polarized EIC as the highest priority for new facility construction following the completion of FRIB.”

- LRP recommendation III

This is where we want to go!
First Collisions!

Last scheduled pp Run

BES-II

sPHENIX

To the EIC!

How can we best utilize RHIC in the period leading up to the EIC?

How do we get there?
First indication of a non-zero gluon spin in the Proton!

\[ \int_{x_{\text{min}}}^{1} dx \Delta g \]

\[ Q^2 = 10 \text{ GeV}^2 \]

\[ x_{\text{min}} \]

\[ 10^{-5} \quad 10^{-4} \quad 10^{-3} \quad 10^{-2} \quad 10^{-1} \quad 1 \]

\[ 10^{-1} \quad 10^{-2} \quad 10^{-3} \quad 10^{-4} \quad 10^{-5} \]

\[ 0 \]

\[ 0.5 \]

\[ 1 \]

\[ 1.5 \]

\[ \text{DIS + SIDIS} \]

\[ 90\% \text{ C.L. constraint} \]

\[ \text{DSSV 2014} \]

\[ \text{with 90\% C.L. band} \]

\[ \text{RHIC projection data \leq 2015} \]

\[ \text{EIC projection} \]

\[ \sqrt{s} = 78 \text{ GeV} \]

\[ \text{DSSV Collaboration} \quad \text{arXiv:1602.03922} \]
First significant indication of **flavor symmetry breaking** in the light polarized sea.

Large transverse single spin asymmetries persist at high center of mass energies.
Large transverse single spin asymmetries persist at high center of mass energies

...and do not appear to originate from 2-2 scattering.
First significant asymmetries sensitive to transversity measured in hadronic collisions!
First measurements of the predicted Sivers’ sign change.
What are the opportunities for additional running before an EIC?

- **2017** - 12 weeks at 500 GeV approved by PAC
- **2021?** - PAC encouraged collaborations and BNL to consider additional pp/pA running during the time between BES-II and the turn on of sPHENIX
- **2023** - 8 weeks of transversely polarized pp at 200 GeV
- **2023** - 8 weeks each of transversely polarized p+Al and p+Au at 200 GeV

What are the most pressing questions to answer during this time?
<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>2017</td>
<td>p̅p @ 510</td>
<td>400 pb⁻¹ 12 weeks</td>
<td>Sensitive to Sivers effect non-universality through TMDs and Twist-3 $T_{q,p}(x,t)$</td>
<td>$A_N$ for $\gamma$, $W^\pm$, $Z^0$, DY</td>
<td>$A_N^{DY}$: Postshower to FMS@STAR</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>Sensitive to sea quark Sivers or ETQS function</td>
<td>$A_{UT}^{\sin(\phi_t-2\phi_h)}$, $A_{UT}^{\sin(\phi_t-\phi_h)}$ modulations of $h^\pm$ in jets, $A_{UT}^{\sin(\phi_t)}$ for jets</td>
<td>None</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>Evolution in TMD and Twist-3 formalism</td>
<td>$A_{UT}$ for $J/\Psi$ in UPC</td>
<td>None</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>Transversity, Collins FF, linearly polar. Gluons, Gluon Sivers in Twist-3</td>
<td></td>
<td>None</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>First look at GPD $E_g$</td>
<td></td>
<td>None</td>
</tr>
<tr>
<td>2023</td>
<td>p̅p @ 200</td>
<td>300 pb⁻¹ 8 weeks</td>
<td>subprocess driving the large $A_N$ at high $x_F$ and $\eta$</td>
<td>$A_N$ for charged hadrons and flavor enhanced jets</td>
<td>Yes Forward instrum.</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>evolution of ETQS fact. properties and nature of the diffractive exchange in $p^+p$ collisions.</td>
<td>$A_N$ for $\gamma$, $A_N$ for diffractive events</td>
<td>None</td>
</tr>
<tr>
<td>2023</td>
<td>p̅Au @ 200</td>
<td>1.8 pb⁻¹ 8 weeks</td>
<td>What is the nature of the initial state and hadronization in nuclear collisions</td>
<td>$R_{pAu}$ direct photons and DY</td>
<td>$R_{pAu}(DY)$: Yes Forward instrum.</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>Nuclear dependence of TMDs and nFF</td>
<td>$A_{UT}^{\sin(\phi_t-\phi_h)}$ modulations of $h^\pm$ in jets, nuclear FF</td>
<td>None</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>Clear signatures for Saturation</td>
<td>Dihadrons, $\gamma$-jet, $h$-jet, diffraction</td>
<td>Yes Forward instrum.</td>
</tr>
<tr>
<td>2023</td>
<td>p̅Al @ 200</td>
<td>12.6 pb⁻¹ 8 weeks</td>
<td>$A$-dependence of nPDF, $A$-dependence of TMDs and nFF</td>
<td>$R_{pAl}$ direct photons and DY</td>
<td>$R_{pAl}(DY)$: Yes Forward instrum.</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>$A$-dependence for Saturation</td>
<td>$A_{UT}^{\sin(\phi_t-\phi_h)}$ modulations of $h^\pm$ in jets, nuclear FF</td>
<td>None</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>Dihadrons, $\gamma$-jet, $h$-jet, diffraction</td>
<td>Yes Forward instrum.</td>
</tr>
<tr>
<td>202X</td>
<td>p̅p @ 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. hadron in jet modulations at $\eta &gt; 1$ and mid-rapidity observables as in 2017 run</td>
<td>Yes Forward instrum.</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>quantitative comparisons of the validity and the limits of factorization and universality in lepton-proton and proton-proton collisions</td>
<td></td>
<td>None</td>
</tr>
<tr>
<td>202X</td>
<td>p̅p @ 510</td>
<td>1.1 fb⁻¹ 10 weeks</td>
<td>$\Delta g(x)$ at small $x$</td>
<td>$A_{LL}$ for jets, di-jets, $h\gamma$-jets at $\eta &gt; 1$</td>
<td>Yes Forward instrum.</td>
</tr>
</tbody>
</table>

Table 1-2: Summary of the Cold QCD physics program proposed in the years 2017 and 2023 and if an additional 500 GeV run would become possible.
<table>
<thead>
<tr>
<th>Year</th>
<th>$\sqrt{s}$ (GeV)</th>
<th>Delivered Luminosity</th>
<th>Scientific Goals</th>
<th>Observable</th>
<th>Required Upgrade</th>
</tr>
</thead>
<tbody>
<tr>
<td>2023</td>
<td>$p^+p @ 200$</td>
<td>300 pb$^{-1}$ 8 weeks</td>
<td>$A_{UT}^{\sin(\phi_s-\phi_h)}$ modulations of $h^+$ in jets, $A_{UT}^{\sin(\phi_s-\phi_h)}$ in jets, $A_N$ for $\sqrt{s}$ for $\gamma$, $W^{\pm}$ for $\gamma$, Dihadrons, $\gamma$-jet, h-jet, diffraction</td>
<td>$R_{p\bar{p}}$: DY</td>
<td>Yes Forward instrum.</td>
</tr>
<tr>
<td>2023</td>
<td>$p^+Au @ 200$</td>
<td>1.8 pb$^{-1}$ 8 weeks</td>
<td>$A_{UT}^{\sin(\phi_s-\phi_h)}$ modulations of $h^+$ in jets, nuclear FF</td>
<td>$R_{p\bar{p}}$: direct photons and DY</td>
<td>Yes Forward instrum.</td>
</tr>
<tr>
<td>2023</td>
<td>$p^+Al @ 200$</td>
<td>1.2 pb$^{-1}$ 8 weeks</td>
<td>$A_{UT}^{\sin(\phi_s-\phi_h)}$ modulations of $h^+$ in jets, nuclear FF</td>
<td>$R_{p\bar{p}}$: direct photons and DY</td>
<td>Yes Forward instrum.</td>
</tr>
<tr>
<td>2023</td>
<td>$p^+p @ 510$</td>
<td>1.1 fb$^{-1}$ 10 weeks</td>
<td>$A_{UL}$ for Collins observables, i.e., hadron in jet modulations at $\eta &gt; 1$ and mid-rapidity observables as in 2017 run</td>
<td>$A_{UL}$ for jets, di-jets, h$\gamma$-jets at $\eta &gt; 1$</td>
<td>Yes Forward instrum.</td>
</tr>
<tr>
<td>2023</td>
<td>$\bar{p}p @ 510$</td>
<td>1.1 fb$^{-1}$ 10 weeks</td>
<td>$\Delta g(x)$ at small $x$</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Table 1-2: Summary of the Cold QCD physics program proposed in the years 2017 and 2023 and if an additional 500 GeV run would become possible.
PHYSICS OPPORTUNITIES:

i. Tests of non-universality of Sivers function and transverse momentum dependent (TMD) factorization

ii. Collect critical experimental input on TMD evolution

iii. Measure virtually unconstrained sea quark Sivers functions

iv. Verify relationship between TMD and twist-3 observables

v. Provide access to transversity, Collins fragmentation functions and linear gluon polarization
• Expand traditional 1D momentum PDF’s $\rightarrow$ 3D!

• Correlations between proton spin and parton transverse momentum are sensitive to orbital angular momentum. Effects are encapsulated in a PDF called the Sivers function.

• Theoretical efforts initially driven by QCD spin community but are essential in particle physics as well, for example in describing Higgs production.

• As in collinear case, interpretation of data rests on robustness of the theoretical framework and experimental tests of factorization and evolution.
TMD Factorization and Evolution

- RHIC will test TMD factorization and evolution via measurements of the single spin asymmetry $A_{UT}$ of reconstructed $W^+$, $W^-$ and $Z^0$.

- Asymmetries also provide new constraints on sea-quark Sivers functions.

**Detector:** EMCal + mid-rapidity charge sign discrimination. Requires wide acceptance of soft hadrons for full $W$ reconstruction.
TMD Factorization and Evolution

- RHIC will also measure forward Drell-Yan $e^+e^-$ pairs for $2.5 < \eta < 4.0$
- The orange square is the statistical uncertainty achievable with 400 pb$^{-1}$. The theoretical curves are before and after including possible evolution.

DETECTOR: Forward EMCal + pre/post shower for QCD background suppression.
TMD Universality and Evolution

- TMD’s may also be studied in fragmentation. The Collins FF encapsulates the correlation between the transverse spin of the quark and the transverse momentum of the fragmentation hadrons.

- The Collins function is accessible the single spin asymmetry $A_{UT}$ of the azimuthal distribution of charged pions, kaons and protons inside of a jet.

- Measurements of $A_{UT}$ will test the universality and evolution of the Collins FF.

Data: STAR Preliminary, Theory: Kang et al.

With 400 pb$^{-1}$ errors at 500 GeV $\approx$ 200 GeV

**DETECTOR:** mid-rapidity pion, kaon and proton PID, charged and neutral particle detection for jet reconstruction and tracker for vertexing.
Sign Change and Evolution in Twist-3 Framework

- The Sivers TMD has a twist-3 analogue - an initial state $q$-$g$-$q$ correlator.

- Twist-3 and TMD frameworks encapsulate the same physics and are related via:
  $$T_{q,F}(x,x) = -\int d^2k_\perp \frac{|k_\perp|^2}{M} f_{1T}^{q,q}(x,k_\perp^2)|_{SIDIS}$$

- Measurements of $A_{UT}$ of direct photons for $2.5 < n < 4$ will provide a direct test of this relationship!

- 200 GeV measurement made in run 15 will provide information on twist-3 evolution.

**DETECTOR:** Forward EMCal + pre-shower
Generalized Parton Distributions

GPD’s provide a snapshot of the spatial distributions, as a function of momentum fraction, of the quarks and gluons inside the proton.

- RHIC can access the GPD E function for gluons via measurements of $A_{UT}$ of $J/\psi$ in ultra-peripheral collisions.
- A significant asymmetry would be the FIRST sign of a non-zero GPD $E_g$.
- GPD $E_g$ is sensitive to spin-orbit correlations and provides input on angular momentum component of the spin puzzle.

**DETECTOR:** EMCals to reconstruct mid-rapidity $J/\psi$ and Roman pots to reconstruct elastically scattered proton
PHYSICS OPPORTUNITIES:

i. Reduce uncertainties on $\Delta G$ in low $x$ ($\sim 10^{-3}$) regime

ii. Push Sivers, transversity and Collins measurements into high ($>0.3$) and low ($\sim 10^{-3}$) regimes

iii. Reduce uncertainties on ALL observables in run 17 by factor of 2, allowing for a quantitative test on the limits of universality and factorization in $e+p$ and $p+p$ collisions.

RUN 21?

<table>
<thead>
<tr>
<th>Lumi</th>
<th>1 fb$^{-1}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Species</td>
<td>proton+proton</td>
</tr>
<tr>
<td>Spin</td>
<td>T+T or L+L</td>
</tr>
<tr>
<td>$\sqrt{s}$</td>
<td>500 GeV</td>
</tr>
</tbody>
</table>
Accessing $\Delta G$ at lower $X$

Di jet reconstruction at mid-rapidity and forward regions will provide access to low $x$ regime.

**DETECTOR:** charged and neutral particle detection for jet reconstruction and tracking for vertexing.
$A_{UT}$ of Charged Hadrons in Forward Jets

- Mid-rapidity jet $A_{UT}$ samples an $x$ range of 0.02-0.3.
- RHIC could push sensitivity to high $x$ ($>0.3$) as well as lower $x$ ($\sim10^{-3}$) by reconstructing jets and charged hadrons ($h^+/h^-$) in the forward direction.
- Measurements of $A_{UT}$ will test the universality and evolution of the Collins FF.

DETECTOR: Charged sign separation for $h^+/h^-$ (no PID), charged and neutral particle detection for jet reconstruction and tracking for vertexing.
**A_{UT} of Forward Jets with high z hadrons**

Jet $A_{UT}$ is sensitive to twist-3 "Sivers-like" correlators, which are expected to be opposite sign for u and d quarks.

- Test of the relationship between twist-3 and TMD formalism
- Facilitates interpretation of the small inclusive jet $A_{UT}$ measured by AnDY

**DETECTOR:** Charged sign separation for h+/h- (no PID), charged and neutral particle detection for jet reconstruction and tracking for vertexing.
Current and Projected TMD Data
PHYSICS OPPORTUNITIES:

i. Study A dependence of spin dependent fragmentation in nuclear matter
Fragmentation Properties in Nuclei

- Extend current hadron in jet AUT analysis from p+p to p+Au.
- First dataset collected on p+Au in 2015.
- Run in 2023 will permit the study of A-dependence.

**DETECTOR:** PID, charged and neutral particle detection for jet reconstruction and tracking for vertexing.
PHYSICS OPPORTUNITES:

i. Isolate origin of the large forward single spin asymmetries.

ii. Study spin effects in Diffraction
Origin of Large Single Spin Asymmetries

• New work suggests that twist-3 FF could explain large forward pion $A_N$

• Predictions for charged hadrons at both 200 and 500 GeV in the forward region would help confirm the validity of this approach.

Phys. Rev. D 89 (2014) 111501

Detector: Forward tracking with PID would be ideal. Charged sign separation for $h^+/h^-$ would be sufficient for negative pions.
Origin of Large Single Spin Asymmetries

- If data taken in 2015 and 2017 reveals a large diffractive contribution to the SSA this opens a new area of study.

- Motivates study of spin dependent diffraction via detection of rapidity-gap jet events.

**DETECTOR:** charged and neutral particle detection for jet reconstruction and tracking for vertexing. Roman Pots to detect protons.
What upgrades are necessary?

**RUN 17** - Use standard STAR suite for mid-rapidity. Postshower upgrade for Forward Meson Spectrometer will be complete before spring running.

**RUN 2021+**
- **MID-RAPIDITY** - Both STAR and sPHENIX can do jet reconstruction. STAR also has PID capabilities.
- **FORWARD -RAPIDITY** - Both STAR and sPHENIX need additional Electromagnetic and Hadronic Calorimeters and tracking.
STAR Forward Calorimeter + Tracking Upgrade

Install in forward region
2.3 < η < 4.0

4-interaction length thick Pb-scintillator plate HCAL

Re-purpose PHENIX Pb-scintillator EMcal

Four planes of silicon strip detectors comprised of 12 wedges each.

Designed to provide charge-sign discrimination and vertex determination.
Wrap-up

- The RHIC Spin Program has made significant contributions since first collisions in 2001. And there are more still in the pipeline!

- As recommended by the LRP, we should utilize the existing RHIC infrastructure to continue to explore the spin structure of the proton.
  1. Complete the measurements that can only be done at a p+p, p+A collider
  2. Pursue measurements that will allow us to optimize the EIC program.
  3. Keep the cold QCD community strong and engaged as we move towards an EIC.

- The RHIC Spin and cold QCD community has developed a plan to complete the RHIC mission arXiv: 1602.03922.

- Additional investments in detector upgrades are necessary.