Opportunities with polarized beams at RHIC / EIC

Ernst Sichtermann, LBL

- introduction to RHIC and its detectors,
- recent achievements, open questions,
- near-term opportunities, 2017 run
- completion of RHIC and transition to EIC
Unique opportunities to study nucleon spin properties and spin in QCD, at hard (perturbative) scales with good systematic controls, e.g. from the ~100ns succession of beam bunches with alternating beam spin configurations.
Unique opportunities to study nucleon spin properties and spin in QCD,

**Longitudinal data**

<table>
<thead>
<tr>
<th>Energy (GeV)</th>
<th>Year 1</th>
<th>Year 2</th>
<th>Year 3</th>
<th>Year 4</th>
</tr>
</thead>
<tbody>
<tr>
<td>200</td>
<td>2005</td>
<td>2006</td>
<td>2009</td>
<td>2015</td>
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<tr>
<td>500</td>
<td>2009</td>
<td>2011</td>
<td>2012</td>
<td>2013</td>
</tr>
</tbody>
</table>

**STAR**

<table>
<thead>
<tr>
<th>Energy (GeV)</th>
<th>2005</th>
<th>2006</th>
<th>2009</th>
<th>2015</th>
</tr>
</thead>
<tbody>
<tr>
<td>200</td>
<td>35 pb⁻¹</td>
<td>50 pb⁻¹</td>
<td></td>
<td></td>
</tr>
<tr>
<td>500</td>
<td>400 pb⁻¹</td>
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</tbody>
</table>

**Transverse data**

<table>
<thead>
<tr>
<th>Energy (GeV)</th>
<th>Year 1</th>
<th>Year 2</th>
<th>Year 3</th>
<th>Year 4</th>
</tr>
</thead>
<tbody>
<tr>
<td>200</td>
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<tr>
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<td>2011</td>
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<tbody>
<tr>
<td>200</td>
<td>38 pb⁻¹</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>500</td>
<td>25 pb⁻¹ (400 pb⁻¹)</td>
<td></td>
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</table>

50-60% polarization

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**Polarized proton runs**

- 250/255 GeV
- 100 GeV

- 2003 P = 34%
- 2005 P = 47%
- 2009 P = 56%
- 2011 P = 48%
- 2012 P = 59%
- 2013 P = 53%
- 2015 P = 55%
RHIC - The Current Main Experiments

STAR "DNA":
- large acceptance and low mass,
- full acceptance and PID for $|\eta|<1$, $\Delta \phi \sim 2\pi$,
- complemented with forward E.M. calorimetry
- key strengths for $\pi^0$ and $\eta$
- forward muon arms $1.2<|\eta|<2.4$
- last run now, prepare transition to sPHENIX

ongoing upgrades: near-term FMS-PSD
  iTPC, EPD, ETOF
  FCS+FTS

PHENIX "DNA":
- high resolution and rate capabilities,
- central arms $|\eta|<0.35, \Delta \phi \sim \pi$
  with key strengths for $\pi^0$ and $\eta$
- forward muon arms $1.2<|\eta|<2.4$
- last run now, prepare transition to sPHENIX
The RHIC Spin Physics Program - Key Questions

• What is the polarization of gluons in the polarized proton?

• What is the polarization of the light quarks and anti-quarks?

• Does the Sivers’ function change sign in proton-collisions compared to DIS?

• What are the quark transversity distributions?

• What is the origin of large forward $A_N$?
Gluon Polarization
Gluon Polarization at RHIC - Asymmetry $A_{LL}$

Measurement:  

$$A_{LL} = \frac{\sigma^{\uparrow\uparrow} - \sigma^{\uparrow\downarrow}}{\sigma^{\uparrow\uparrow} + \sigma^{\uparrow\downarrow}} = \sum_{f=q,g} \frac{\Delta f_1}{f_1} \otimes \frac{\Delta f_2}{f_2} \otimes \hat{a}_{LL} \otimes \text{(fragmentation functions)}$$

- Detect and reconstruct particle, jet,  
- Extract beam-spin dependent yields,  
- Measure relative luminosity, beam polarization  
- Evaluate double beam-helicity asymmetry

Advantages:

- High yields of neutral pions, jets at RHIC,  
- Relatively straightforward triggering,  
- Relatively simple reconstruction,  
- Sizable partonic asymmetries

Disadvantages:

- Contributions from several sub-processes,  
- Wide $x_g$ range sampled for each fixed $p_T$  
- $x_g, x_q \sim p_T/\sqrt{s} \cdot \exp(-\eta)$
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$gluon-gluon$ and $quark-gluon$ scattering contributions dominate.
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Gluon Polarization - *Precision* $A_{LL}$ from STAR

Significant advance:
about an order in precision,
two to three times the kinematic range,
compared to initial RHIC data,
initial sensitivity to different $x_g$ from rapidity dependence,

$A_{LL}$ is positive for large $p_T$, indicative of positive gluon polarization.
Gluon Polarization - RHIC Impact

Both the DSSV and the NNPDF groups use RHIC data in their latest PDF fits,

DSSV, Phys.Rev.Lett. 113, 012001


RHIC data, in particular on jets, currently drive the constraints on $\Delta G$ in both fits,

- DSSV: $0.19^{+0.06}_{-0.05}$ at 90% C.L. for $x > 0.05$
- NNPDF: $0.23 \pm 0.07$ for $0.05 < x < 0.5$

i.e. evidence for positive gluon polarization in this kinematic range and at 10 GeV$^2$. 
Gluon Polarization - Status and what is next?

Further precision from jet and neutral pion probes, and from complementary probes

Extend sensitivity to \( \text{smaller } x_g \)
\[ \sqrt{s} = 500 \text{ GeV data, } x_g \sim 1/\sqrt{s}, \]
forward rapidity, \( x_g \sim \exp(-\eta) \),

DSSV, Phys.Rev.Lett. 113, 012001
Gluon Polarization - What to expect next?

- additional constraints from correlated probes, e.g. di-jets, but *not* adtl. kin. coverage,
- longer term opportunity (2020+): EIC, *or* (and?)
  renewed $\sqrt{s} = 500$ GeV operations with forward upgrade
The RHIC-Spin Program - Selected results, open questions

Quark Polarization
Quark Polarization at RHIC

$$\sqrt{s} = 500 \text{ GeV above } W \text{ production threshold},$$

Experiment Signature:
- large $p_T$ lepton, missing $E_T$

Experiment Challenges:
- charge-ID at large $|\text{rapidity}|$
- electron/hadron discrimination
- luminosity hungry!

$$\Delta \sigma^{\text{Born}}(p\bar{p} \to W^+ \to e^+ \nu_e) \propto -\Delta u(x_a)\bar{d}(x_b)(1+\cos \theta)^2 + \Delta \bar{d}(x_a)u(x_b)(1-\cos \theta)^2$$

Spin Measurements:

$$A_L(W^+) = \frac{-\Delta u(x_a)\bar{d}(x_b) + \Delta \bar{d}(x_a)u(x_b)}{u(x_a)d(x_b) + \bar{d}(x_a)u(x_b)} = \begin{cases} -\frac{\Delta u(x_a)}{u(x_a)}, & x_a \to 1 \\ \frac{\Delta \bar{d}(x_a)}{d(x_a)}, & x_b \to 1 \end{cases}$$

$$A_L(W^-) = \begin{cases} -\frac{\Delta d(x_a)}{d(x_a)}, & x_a \to 1 \\ \frac{\Delta \bar{u}(x_a)}{\bar{u}(x_a)}, & x_b \to 1 \end{cases}$$

Initial mid-rapidity data in 2009,
Analysis tour-de-force for both experiments!
Quark Polarization at RHIC - Cross Sections


Data are well-described by NLO pQCD theory (FEWZ + MSTW08),

Support NLO pQCD interpretation of the asymmetry measurements,

Aside, future ratio measurements may provide insights in unpolarized light quark distributions.
Quark Polarization - *More Precise* $A_L$ from RHIC

Anticipated uncertainties:

Quark Polarization - Next Steps
Anticipated uncertainties, and their projected impact:
The RHIC-Spin Program - Selected results, open questions

Transverse Spin Phenomena: Sivers
Calls for continued measurement; PAC approved, LRP supported, planned for 2017, eagerly anticipate forward photon $A_N$ from run-15; $A_N^{DY}$ has published forward jet $A_N$, Drell-Yan: initial measurement at RHIC in 2017 via the electron decay channel, using a post-shower (and UV) upgrade to the STAR forward EM Cal. (FMS), future measurements, in p+A, are drivers in forward upgrade LOI’s.
Lots of work ahead to turn these projections into actual results,

Ample other opportunities, for example
photons, Drell Yan, diffraction, mid-rapidity,
gradual upgrades to existing STAR forward instrumentation, RHICf@STAR,
Measurement relies crucially on the now existing pre-shower to the FMS,

Sensitive to the “sign-change” in the twist-3 formalism,

light valence quarks, at relatively high-$x$,

twist-3 evolution, not TMD evolution.

Constraining this evolution is one of the motivations for running in 2020+
STAR Drell-Yan - Prospects for 2017 Run

No TMD evolution

With TMD evolution

Z.B. Kang et al, ArXiv:1401.5078
The RHIC-Spin Program - Selected results, open questions

Transverse Spin Phenomena: Collins
Quark Transversity at RHIC

At least two methods can provide sensitivity to quark transversity at RHIC

1. spin-dependent modulation of hadron yields within jets,

\[ h_1(x) \otimes H_1^T(z, j_T) \]

2. di-hadron correlation measurements couple transversity with interference-fragmentation.

Both methods have been pursued and have delivered initial results...
STAR $A_{UT}$ - Quark Transversity and Fragmentation

Azimuthal modulation within the jet

$p^\uparrow + p \rightarrow \text{jet} + \pi^+ + X$

STAR Preliminary

$\sin(\phi_S - \phi_H)$

$A_{UT}$

$\Delta R_{\text{min}} \times p_{T,jet} = 1.3 \text{ GeV/c}$

$z$

$0.2$ $0.4$ $0.6$

$0$ $0.05$ $0.1$ $0.15$ $0.2$

Closed points: $\pi^+$; Open points: $\pi^-$

$3.2 \text{ GeV/c}$

Sensitivity to quark transversity and polarized fragmentation,

200 and 500 GeV results are similar; is TMD evolution in FF small?

Non-zero observations open a path to nuclear modification of polarized fragmentation, first analyses in progress,

Particle-identification key to further surprises? Theoretical/phenomenological input sought.
Sensitivity to quark transversity and polarized fragmentation, 200 and 500 GeV results are similar; is TMD evolution in FF small?

Non-zero observations open a path to nuclear modification of polarized fragmentation, first analyses in progress, 

Particle-identification key to further surprises? Theoretical/phenomenological input sought.
The RHIC-Spin Program - Selected results, open questions

Transverse Spin Phenomena: large $A_N$
STAR neutral pion $A_N$ - a continuing puzzle since E704

What causes this?

An experimental handle beyond collinear twist-2 perturbative QCD?

- **Collins effect**: asymmetry comes from the transversity and the spin dependence of jet fragmentation.
  
  - Collins effect: asymmetry comes from the transversity and the spin dependence of jet fragmentation.

- **Sivers effect**: asymmetry comes from spin-correlated $k_T$ in the initial parton distribution.
  
  - Sivers effect: asymmetry comes from spin-correlated $k_T$ in the initial parton distribution.

Photons have asymmetry

Jet vs. Photon sign flip predicted

No asymmetry for the jet axis

Di-jet, photon-jet not exactly back to back

Photons have asymmetry

Jet vs. Photon sign flip predicted
STAR neutral pion $A_N$ - a continuing puzzle since E704

The puzzle continues...

![Graph showing $A_N$ vs. $P_T^{EM,Jet}$ for different energy bins.](image)

- 1-photon events, which include a large $\pi^0$ contribution in this analysis, are similar to 2-photon events.
- Three-photon jet-like events have a clear non-zero asymmetry, but substantially smaller than that for isolated $\pi^0$s.
- $A_N$ decreases as the event complexity increases (i.e., the "jettiness").
- $A_N$ for #photons >5 is similar to that for #photons = 5.

Mriganka Mondal, for the collaboration (DIS 2014)

and points to a need for qualitatively new instrumentation and measurements,

Low-multiplicity observation, consistent with a diffractive production mechanism,

STAR Roman Pots (now) directly measure diffractive $A_N$. Initial analyses in progress.
Completion of RHIC and transition to EIC
Completion of RHIC and transition to EIC

RECOMMENDATION I
The progress achieved under the guidance of the 2007 Long Range Plan has reinforced U.S. world leadership in nuclear science. The highest priority in this 2015 Plan is to capitalize on the investments made.

RECOMMENDATION II
We recommend the timely development and deployment of a U.S.-led ton-scale neutrinoless double beta decay experiment.

RECOMMENDATION III
We recommend a high-energy high-luminosity polarized EIC as the highest priority for new facility construction following the completion of FRIB. [Q3 FY22]

RECOMMENDATION IV
We recommend increasing investment in small-scale and mid-scale projects and initiatives that enable forefront research at universities and laboratories.
**Proposed run schedule for RHIC**

<table>
<thead>
<tr>
<th>Years</th>
<th>Beam Species and Energies</th>
<th>Science Goals</th>
<th>New Systems Commissioned</th>
</tr>
</thead>
<tbody>
<tr>
<td>2016</td>
<td>High statistics Au+Au d+Au energy scan</td>
<td>Complete heavy flavor program First measurement of $\Lambda_c$ Collectivity in small systems</td>
<td>Coherent e-cooling test I</td>
</tr>
<tr>
<td>2017</td>
<td>High statistics Pol. p+p at 510 GeV</td>
<td>Transverse spin physics</td>
<td>Coherent e-cooling test II</td>
</tr>
<tr>
<td>2018</td>
<td>No Run</td>
<td></td>
<td>Low energy e-cooling upgrade</td>
</tr>
<tr>
<td>2019-20</td>
<td>7.7-20 GeV Au+Au (BES-2)</td>
<td>Search for QCD critical point and onset of deconfinement</td>
<td>STAR iTPC upgrade EPD upgrade</td>
</tr>
<tr>
<td>2021</td>
<td>No Run</td>
<td></td>
<td>sPHENIX installation</td>
</tr>
<tr>
<td>2022-23</td>
<td>200 GeV Au+Au with upgraded detectors Pol. p+p, p+Au at 200 GeV</td>
<td>Jet, di-jet, $\gamma$-jet probes of parton transport and energy loss mechanism Color screening for different quarkonia</td>
<td>sPHENIX</td>
</tr>
<tr>
<td>2024---</td>
<td>No Runs</td>
<td></td>
<td>Transition to eRHIC</td>
</tr>
</tbody>
</table>
Completion of RHIC and transition to EIC

Requested by DOE Office of Science Nuclear Physics in Summer 2015,

Approach:
- emphasize measurements that can only be done at a polarized proton collider,
- relate to EIC,
- emphasize flexibility of RHIC for new explorations, e.g. polarized nuclear FF,
- propose only *modest* upgrades,

Universality, factorization focused.
<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>p+p @ 510</td>
<td>400 pb⁻¹ 12 weeks</td>
<td>Sensitive to Sivers effect non-universality through TMDs and Twist-3 $T_{q,F}(x,x)$, Sensitive to sea quark Sivers or ETQS function, Evolution in TMD and Twist-3 formalism, Transversity, Collins FF, linearly pol. Gluons, Gluon Sivers in Twist-3</td>
<td>$A_N$ for $\gamma$, $W^\pm$, $Z^0$, DY</td>
<td>$A_N^{DY}$: Postshower to FMS@STAR</td>
</tr>
<tr>
<td>2023</td>
<td>p+p @ 200</td>
<td>300 pb⁻¹ 8 weeks</td>
<td>First look at GPD $E_g$, 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>2023</td>
<td>p+Au @ 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>$A_N$ for $\gamma$, $A_N$ for diffractive events</td>
<td>None</td>
</tr>
<tr>
<td>2023</td>
<td>p+Al @ 200</td>
<td>12.6 pb⁻¹ 8 weeks</td>
<td>Nuclear dependence of TMDs and nFF, Clear signatures for Saturation</td>
<td>$R_{pAu}$ direct photons and DY, $A_{UT}^{sin(\phi_s-\phi_h)}$ modulations of $h^\ast$ in jets, nuclear FF, Dihadrons, $\gamma$-jet, h-jet, diffraction</td>
<td>$R_{pAu}$(DY): Yes Forward instrum.</td>
</tr>
<tr>
<td>2023</td>
<td>p+p @ 510</td>
<td>1.1 fb⁻¹ 10 weeks</td>
<td>TMDs at low and high $x$, quantitative comparisons of the validity and the limits of factorization and universality in lepton-proton and proton-proton collisions</td>
<td>$A_{UL}$ for Collins observables, i.e. hadron in jet modulations at $\eta &gt; 1$</td>
<td>Yes Forward instrum.</td>
</tr>
<tr>
<td>202X</td>
<td>p+p @ 510</td>
<td>1.1 fb⁻¹ 10 weeks</td>
<td>$Ag(x)$ at small $x$</td>
<td>$A_{UL}$ for jets, di-jets, h/γ-jets at $\eta &gt; 1$</td>
<td>Yes Forward instrum.</td>
</tr>
</tbody>
</table>
Pursue possible Twist-3 origin of forward $A_N$ with improved photon $A_N$ measurements, and charged-pion enhanced jets.
RHIC Cold QCD Plan - p+p highlights, $\sqrt{s} = 500$ GeV

Large-$x$ Collins asymmetries.
Note: the text is taken from a presentation slide and contains some technical terms related to particle physics and detector technology.

**RHIC Cold QCD Plan - STAR Forward Detector Upgrade**

Ensure jet capability ($\sqrt{s} = 500$ GeV), charge-sign discrimination, Drell-Yan, “modest” cost

- 4-6 Si-strip disks, or pixels
  - 8-10 GEM layers have been considered as well

- was: W-powder EM-cal
- now: re-use PHENIX eCAL
- new HCAL, based on STAR-EIC R&D

Forward upgrade to sPHENIX is conceptually similar; only one will be realized (imho).
EIC
Overall Editors:
A. Deshpande (Stony Brook), Z-E. Meziani (Temple), J. Qiu (BNL)

Gluon Saturation in e+A:
T. Ullrich (BNL) and Y. Kovchegov (Ohio State)

Nucleon spin structure (inclusive e+N):
E. Sichtermann (LBNL) and W. Vogelsang (Tübingen)

GPD's and exclusive reactions:
M. Diehl (DESY) and F. Sabatie (Saclay)

TMD's and hadronization and SIDIS:
H. Gao (Duke) and F. Yuan (LBNL)

Parton Propagation in Nuclear Medium:
W. Brooks (TSFM) and J. Qiu (BNL)

Electroweak physics:
K. Kumar (U Mass) and M. Ramsey-Musolf (Wisconsin)

Accelerator design and challenges:
A. Hutton (JLab) and T. Roser (BNL)

Detector design and challenges:
E. Aschenauer (BNL) and T. Horn (CUA)

Senior Advisors:
A. Mueller (Columbia) and R. Holt (ANL)

Successful thanks to many other co-authors and contributions
U.S.-based Electron Ion Collider

ArXiv:1212.1701
U.S.-based Electron Ion Collider

The Next QCD Frontier
Understanding the glue that binds us all

coherent contributions from many nucleons effectively amplify the gluon density being probed.

The EIC was designated in the 2007 Nuclear Physics Long Range Plan as "embodying the vision for reaching the next QCD frontier" (3). It would extend the QCD science frontier in a dramatic and fundamentally important way. The most intellectually pressing questions that an EIC will address relate to our detailed and fundamental understanding of QCD in this frontier environment.

- How are the sea quarks and gluons, and their spins, distributed in space and momentum inside the nucleons? How are these quark and gluon distributions correlated with overall nucleon properties, such as spin direction? What is the role of the orbital motion of sea quarks and gluons in building the nuclear spin?

- Where do the saturation of gluon densities set in? Is there a simple boundary

ArXiv:1212.1701
No competition, really.
No competition, really.
What Aspect Are We Working On Now?

We continue to work on whether the number of future electron ion colliders will be 1 or 0.

(The first possibility is of course highly anticipated based on QCD science and future mission need for the field)

Outlook

Our work continues...

- Independent Vetting of Science Case
- R&D & Design Refinement to Reduce Risk and $$
- Decision on when to go for CDO, Mission Need
- Mechanism for determining “Best Value” to the United States

This was the most upbeat talk on EIC I have seen from this office in the past 10 years or so.
Closing Comments

U.S. EIC is not a done deal, but the prospects are better than ever;
- positive recommendation in the 2015 Long Range Plan for U.S. Nuclear Physics,
- independent science review by the National Academy of Sciences is starting,
- discussion is moving from “science case” to “next steps”:
  - reduce (uncertainty in) cost estimate,
  - establish “mission need”,
  - site selection,

“An EIC is envisioned to start construction after FRIB construction is completed and to be operational by the end of the 2020s.” (2015 Long Range Plan, resource section).

RHIC spin:
- 2017 run is (now) firmly rooted in the BNL facility plan,
- next opportunity will be concurrent with high-luminosity $\sqrt{s} = 200$ GeV p+p and p+A heavy-ion reference data taking in 2023; case articulated for both
  - “modest” instrument upgrades thinkable; most likely forward calorimetry and tracking, limited or no particle-identification,
- strong case for renewed $\sqrt{s} = 500$ GeV, but not currently part of the facility plan.