Overview of RHIC Longitudinal Spin Physics Program

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Many thanks to the PHENIX and STAR collaborations for providing the latest results
Three Decades of the Proton Spin Puzzle

• Early expectation: large gluon polarization

Axial anomaly
Cheng & Li, PRL (1989)

\[ \Delta \Sigma' = \Delta \Sigma - \frac{\alpha_s}{2\pi} \Delta G \]
\[ \frac{\alpha_s}{2\pi} \Delta G = 0.3 \pm 0.1 \]

EMC, 1980s

\[ \frac{1}{2} = \frac{1}{2} \Delta q + L^z_q + \Delta G + L^z_g \]

\[ \Delta q \sim 30\% \ (SIDIS/DIS) \]

\[ \Delta G \sim 40\% \ (RHIC) \]

\[ L \sim? \ (RHIC, FNAL?) \]
Outline

- Longitudinal spin physics program at RHIC
- Gluon polarization
- Flavor identified sea-quark polarization
- Outlook
Polarized Proton Collider at RHIC

- **PHOBOS**
  - Spin Rotators (longitudinal polarization)
  - Siberian Snakes

- **PHENIX**
  - Spin Rotators (longitudinal polarization)

- **STAR**
  - Siberian Snakes

- **BRAHMS**
  - Siberian Snakes

**Absolute Polarimeter (H↑ jet)**

**RHIC pC Polarimeters**

**200 MeV Polarimeter**

**AGS pC Polarimeter**

**Strong AGS Snake**

**Helical Partial Siberian Snake**

**Pol. H⁻ Source**

**Siberian Snakes**

**p+p collisions**

62 ≤ √s ≤ 500 GeV
History of RHIC Spin Runs

RHIC is capable of delivering the polarized p+p/p/A for precision spin physics

- A very challenging task to deliver polarized p+p, excellent performance from 2012+
- Longitudinally and transversely polarized p+p,
- Transversely polarized p+Au and p+Al, in 2015
Physics with Longitudinally Polarized p+p Collisions

\[ A_{LL} = \frac{(N^{++}-N^{-})}{(N^{++}+N^{+})} \]

\[ A_{L} = \frac{(N^{+-}-N^{-})}{(N^{++}+N^{-})} \]
PHENIX Detector at RHIC

Central Arms  $|\eta| < 0.35$
- Identified charged hadrons
- Neutral Pions
- Direct Photon
- Heavy Flavor

Muon Arms  $1.2 < |\eta| < 2.4$
- J/Psi
- Heavy Flavor
- Charged hadrons

MPC  $3.1 < |\eta| < 3.9$
- Neutral Pion’s
- Eta’s

BBC  (Relative) luminosity

ZDC
The STAR Experiment

Large acceptance:
Tracking: TPC+TOF, \(-1.3 < \eta < 1.3\)
Central EMCal: \(-1 < \eta < 2\)
Forward EMCal(FMS): \(2.5 < \eta < 4.2\)
BBC, ZDC

- Jets
- Pi0 and (identified)charged hadrons
- Electrons & Muons
Gluon Polarization
Gluon Polarization and $\pi^0$ (or jet) $A_{LL}$

$A_{LL} = \frac{(N^{++} - N^{+-})}{(N^{++} + N^{+-})}$

- Parton distribution functions
- Partonic hard scattering rates
- Fragmentation functions

$$\Delta \sigma(pp \to \pi^0 X) \approx \Delta q(x_1) \otimes \Delta g(x_2) \otimes \Delta \hat{s}^{gg \to gg}(\hat{s}) \otimes D_q^{\pi^0}(z)$$

DIS  ?  pQCD  e^+e^-

Di-photon mass: $\pi^0$ peak

Run13 Diphoton Invariant Mass

$A_{LL}^{\pi^0} = \frac{A_{LL}^{\pi^0 + BG} - w_{BG}A_{LL}^{BG}}{1 - w_{BG}}$

Relative fractions

Solid: $s=200 \text{ GeV}$
Dotted: $s=500 \text{ GeV}$
First Precision Measurements of Longitudinal Double-Spin Asymmetry $A_{LL}$ from 2009 RHIC Run


PHENIX: PRD 90, 012007 (2014)
First Hint of Non-zero Gluon Polarization from RHIC

• PHENIX and STAR $A_{LL}$ data

$$\int_{0.05}^{1} \Delta g(x, Q^2) dx = 0.2^{+0.06}_{-0.07}$$
@ $Q^2 = 10 \text{ GeV}^2$

PRL 113, 012001 (2014), DSSV

Run 2009
$p+p@200\text{GeV}$

Ming X. Liu, CIPANP2018
More Recent Results from RHIC


<table>
<thead>
<tr>
<th>Year</th>
<th>√s (GeV)</th>
<th>Recorded Luminosity for longitudinally / transverse polarized p+p STAR</th>
<th>Recorded Luminosity for longitudinally / transverse polarized p+p PHENIX</th>
<th>&lt;P&gt; in %</th>
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</thead>
<tbody>
<tr>
<td>2006</td>
<td>62.4</td>
<td>-- pb⁻¹ / 0.2 pb⁻¹</td>
<td>0.08 pb⁻¹ / 0.02 pb⁻¹</td>
<td>48</td>
</tr>
<tr>
<td></td>
<td>200</td>
<td>6.8 pb⁻¹ / 8.5 pb⁻¹</td>
<td>7.5 pb⁻¹ / 2.7 pb⁻¹</td>
<td>57</td>
</tr>
<tr>
<td>2008</td>
<td>200</td>
<td>-- pb⁻¹ / 7.8 pb⁻¹</td>
<td>-- pb⁻¹ / 5.2 pb⁻¹</td>
<td>45</td>
</tr>
<tr>
<td>2009</td>
<td>200</td>
<td>25 pb⁻¹ / -- pb⁻¹</td>
<td>16 pb⁻¹ / -- pb⁻¹</td>
<td>55</td>
</tr>
<tr>
<td></td>
<td>500</td>
<td>10 pb⁻¹ / -- pb⁻¹</td>
<td>14 pb⁻¹ / -- pb⁻¹</td>
<td>39</td>
</tr>
<tr>
<td>2011</td>
<td>500</td>
<td>12 pb⁻¹ / 25 pb⁻¹</td>
<td>18 pb⁻¹ / -- pb⁻¹</td>
<td>48</td>
</tr>
<tr>
<td>2012</td>
<td>200</td>
<td>-- pb⁻¹ / 22 pb⁻¹</td>
<td>-- pb⁻¹ / 9.7 pb⁻¹</td>
<td>61/56</td>
</tr>
<tr>
<td></td>
<td>510</td>
<td>82 pb⁻¹ / -- pb⁻¹</td>
<td>32 pb⁻¹ / -- pb⁻¹</td>
<td>50/53</td>
</tr>
<tr>
<td>2013</td>
<td>510</td>
<td>300 pb⁻¹ / -- pb⁻¹</td>
<td>155 pb⁻¹ / -- pb⁻¹</td>
<td>51/52</td>
</tr>
<tr>
<td>2015</td>
<td>200</td>
<td>52 pb⁻¹ / 52 pb⁻¹</td>
<td>-- pb⁻¹ / 60 pb⁻¹</td>
<td>53/57</td>
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</tbody>
</table>
PHENIX: $\pi^0 A_{LL}$ at central rapidity ($|\eta|<0.35$)

- Access gluon at moderate $x \sim 0.01 \text{ - } 0.2$

**Figure:**
- **Left Panel:**
  - Plot of $p_T$ vs $A_{LL}$ for $pp \rightarrow \pi^0 + X$ at $|\eta|<0.35$, $\sqrt{s}=510$ GeV.
  - Data from PHENIX, showing $6.5\%$ polarization scale uncertainty not shown.
  - Theory curves: LSS10p (dashed), DSSV14 (solid), and NNPDF1.1 (dotted).

- **Right Panel:**
  - All vs $x_T$ for $pp$ at 200 GeV and 510 GeV.
  - Data from PHENIX, showing differences in $A_{LL}$ between the two energies.
  - Theory curves: LSS10p (dashed), DSSV14 (solid), and NNPDF1.1 (dotted).
PHENIX $h^{+/-}$ and HF $e^{+/-}$ $A_{LL}$

- Sensitive to polarized $u$ and $d$ quark as well as gluon distributions through charge sign
  - Statistically limited due to lack of effective triggers
    
    $u + g \rightarrow h^+ + X$
    
    $d + g \rightarrow h^- + X$

- Use HF decay electrons to probe gluon polarization
  - Statistically limited
    
    $$A_{LL} = \frac{\Delta \sigma}{\sigma} = \hat{a}_{gg \rightarrow D \rightarrow e} \frac{\Delta g(x1)}{g(x1)} \frac{\Delta g(x2)}{g(x2)}$$
PHENIX: $J/\psi A_{LL}$ at Forward Rapidity

- Access gluons in small-$x$ region, $x_2 < 0.01$
- At RHIC energies $J/\psi$ production is dominated by gluon-gluon fusion.
  - Statistically limited

$A_{LL}$ for $J/\psi$ at LO:

$$A_{LL} = \frac{\Delta \sigma}{\sigma} = \hat{\alpha}_{gg \rightarrow J/\psi} \frac{\Delta g(x_1)}{g(x_1)} \frac{\Delta g(x_2)}{g(x_2)}$$

$$gg \rightarrow J/\psi + X \rightarrow \mu^+ \mu^- + X$$

PRD 94, 112008 (2016)
STAR: Di-Jet $A_{LL}$, pp 200GeV

arXiv:1805.09742

Probed parton $x_1$ and $x_2$ distributions

di-jet mass
STAR: 510 GeV pp Jet $A_{LL}$

- Preliminary 2012/2013 pp510 $A_{LL}$ results
  - Access smaller $x_g$ than pp200
  - Agree with recent pol PDF predictions
  - Consistent with published pp200 data
Run12 pp510 di-jet $A_{LL}$ measured $|\eta|<0.9$ - consistent with STAR pp200GeV results

Run13 pp510 di-jet $A_{LL}$
STAR: Forward \( \pi^0 \) ALL in pp 510GeV
access small-x gluons

\[ \text{arXiv:1805.09745} \]
In Progress: 200 GeV Inclusive Jet $A_{LL}$

Projected combined Jet $A_{LL}$ from STAR: run2009 + 2015
- Expect 2x improvement over 2009 results
Projected Impact of RHIC data on Gluon Polarization

• Favors positive gluon polarization
  – PHENIX/STAR data:
    • 62GeV $\pi^0 \, A_{LL}$
    • 200GeV $\pi^0 \, A_{LL}$
    • 510GeV $\pi^0 \, A_{LL}$
    • 200/510GeV (di)jets $A_{LL}$
  Statistically limited but could be improved in the future high luminosity program:
    • 200/510GeV charged hadron $A_{LL}$
    • 200/510GeV HF $A_{LL}$
    • 200/510GeV $J/\psi \, A_{LL}$

• EIC future, 2025+
Electroweak Probe for Sea Quarks at High Energy at RHIC

\[ q(x_1) + \bar{q}'(x_2) \rightarrow W^{\pm} \rightarrow e^{\pm} + \nu(\bar{\nu}) \]

\[
A_{L}^{W^+} \approx \frac{-\Delta u(x_1) \bar{d}(x_2)(1 - \cos \theta)^2 + \Delta \bar{d}(x_1) u(x_2)(1 + \cos \theta)^2}{u(x_1) \bar{d}(x_2)(1 - \cos \theta)^2 + \bar{d}(x_1) u(x_2)(1 + \cos \theta)^2}
\]

\[
A_{L}^{W^-} \approx \frac{-\Delta d(x_1) \bar{u}(x_2)(1 + \cos \theta)^2 + \Delta \bar{u}(x_1) d(x_2)(1 - \cos \theta)^2}{d(x_1) \bar{u}(x_2)(1 + \cos \theta)^2 + \bar{u}(x_1) d(x_2)(1 - \cos \theta)^2}
\]
First Direct Measurements of Flavor Identified Sea Quark Polarization

RHIC has unique access to flavor identified sea-quarks via real $W^{+/−}$

STAR: PRL 113, 072301 (2014)

$$A_L^{W^−} \sim \frac{\Delta \bar{u}}{\bar{u}}$$

$$A_L^{W^+} \sim \frac{\Delta d}{d}$$

$$x\Delta \Pi(x, Q^2=10 \text{ GeV}^2)$$

$$x\Delta d(x, Q^2=10 \text{ GeV}^2)$$

First significant constraint on sea-quark polarization
Overall contribution to the proton spin is small [x=0.05-1]
Latest $W^+/-$ $A_L$ from STAR and PHENIX

Most precise $A_L$ from STAR 2013, will further constraint sea-quark polarization
Projected RHIC $W^\pm \rightarrow l^\pm$ data Impact on Sea Quark Polarization Determination

- Expect significant improvement of flavor identified sea quark distributions

The RHIC Spin Program, arXiv: 1501.01220
Unpolarized Sea Quark Distributions

\[ R(x_F) \equiv \frac{\sigma_{W^+}}{\sigma_{W^-}} = \frac{u(x_1)d(x_2) + d(x_1)u(x_2)}{\bar{u}(x_1)d(x_2) + d(x_1)\bar{u}(x_2)} \]

Sea quark flavor asymmetry and pion cloud model

SeaQuest/E906 @Fermilab
Future: PHENIX -> sPHENIX -> EIC@RHIC

Current PHENIX
- PHENIX completed 2016
- 16y+ work
- 100+M$ investment
- 130+ published papers to date

f/sPHENIX
- Comprehensive central upgrade based on BaBar magnet
- fsPHENIX: forward tracking, HCal and muon ID
- Key study of transverse spin
- New collaboration/new ideas

An EIC detector
- Path of sPHENIX upgrade leads to a capable EIC detector
- Large coverage of tracking, calorimetry and PID
- New collaboration/new ideas

~2000
2017→2020
~2025

RHIC: A+A, polarized p+p, polarized p+A
eRHIC: e+p, e+A
sPHENIX at RHIC

- **Large acceptance, high rate next generation experiment at RHIC**
  - QGP and Cold QCD physics with,
    - Jets
    - Heavy quarkonia
    - Open heavy flavor
  - Study p+p, p+A and Au+Au collisions at top energy 200GeV
    - Central barrel: |eta|<1, 2pi coverage
      - EMCal & HCal
      - MVTX/INTT/TPC
    - Forward upgrade being developed
    - DAQ rate: 15kHz

- **Project Status**
  - Granted DOE CD-0, 10/2016
  - CD-1 reviewed, 5/2018
  - Construction: 2018-2022
  - Day-1 physics, ~1/2023
RHIC Multi-Year Plan: sPHENIX 2023-2027+
(Cold QCD plan under development now)

- Jets, hadrons and heavy flavor and more

**Table: RHIC Experimental Plans**

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<tr>
<td>Year-1</td>
<td>Au+Au</td>
<td>200</td>
<td>16.0</td>
<td>7 nb⁻¹</td>
<td>8.7 nb⁻¹</td>
<td>34 nb⁻¹</td>
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<tr>
<td>Year-2</td>
<td>p+p</td>
<td>200</td>
<td>11.5</td>
<td>—</td>
<td>48 pb⁻¹</td>
<td>267 pb⁻¹</td>
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<tr>
<td>Year-2</td>
<td>p+Au</td>
<td>200</td>
<td>11.5</td>
<td>—</td>
<td>0.33 pb⁻¹</td>
<td>1.46 pb⁻¹</td>
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<td>Year-3</td>
<td>Au+Au</td>
<td>200</td>
<td>23.5</td>
<td>14 nb⁻¹</td>
<td>26 nb⁻¹</td>
<td>88 nb⁻¹</td>
<td></td>
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<tr>
<td>Year-4</td>
<td>p+p</td>
<td>200</td>
<td>23.5</td>
<td>—</td>
<td>149 pb⁻¹</td>
<td>783 pb⁻¹</td>
<td></td>
</tr>
<tr>
<td>Year-5</td>
<td>Au+Au</td>
<td>200</td>
<td>23.5</td>
<td>14 nb⁻¹</td>
<td>48 nb⁻¹</td>
<td>92 nb⁻¹</td>
<td></td>
</tr>
</tbody>
</table>

RHIC 2015 pp200
Recorded lumi ~50pb⁻¹
Proposed STAR Forward Upgrade
Access small-x Gluons

To install a Forward Calorimeter System (FCS) in early 2020s:
- EMCal
- Hcal
- Tracking, charge separation

<table>
<thead>
<tr>
<th></th>
<th>p+p / p+A</th>
</tr>
</thead>
<tbody>
<tr>
<td>ECAL</td>
<td>$\approx 10%/\sqrt{E}$</td>
</tr>
<tr>
<td>HCAL</td>
<td>$\approx 60%/\sqrt{E}$</td>
</tr>
</tbody>
</table>

Di-jet in the forward region (2.8<eta<3.7)
Access gluon polarization at low x:
- $X \sim 5\times10^{-3}$ (central + forward)
- $X^\sim <1\times10^{-3}$ (forward - forward)
Summary and Outlook

- **First evidence of non-zero gluon polarization**
  - PHENIX: $\pi^0 A_{\text{LL}}$
  - STAR: 200/510GeV inclusive jets and di-jet $A_{\text{LL}}$

- **First direct measurements of sea-quark polarization with $W^{+/−}$**
  - PHENIX: $W\rightarrow e, \mu$
  - START: $W\rightarrow e$

- **Cold QCD plan being developed**
  - Exciting long-term polarized pp/pA 2020+
    - sPHENIX
    - STAR/Forward upgrade proposal

- **EIC future 2025+**
Backup slides
Latest Pol NNPDFPol Global Fit

[Graphs showing the results of the fit]

- arXiv:1702.05077
- SI/DIS data
- RHIC data
Relative contributions

RHIC Spin Program, arXiv:1501.01220
Access sea-quark with $W^+/-$

Bourrely & Soffer, NP B423 (1994) 329-348

\[ A_L^{W^+} \approx \frac{-\Delta u(x_1)d(x_2)(1 - \cos \theta)^2 + \Delta \bar{d}(x_1)u(x_2)(1 + \cos \theta)^2}{u(x_1)d(x_2)(1 - \cos \theta)^2 + \bar{d}(x_1)u(x_2)(1 + \cos \theta)^2} \]

\[ A_L^{W^-} \approx \frac{-\Delta d(x_1)\bar{u}(x_2)(1 + \cos \theta)^2 + \Delta \bar{u}(x_1)d(x_2)(1 - \cos \theta)^2}{d(x_1)\bar{u}(x_2)(1 + \cos \theta)^2 + \bar{u}(x_1)d(x_2)(1 - \cos \theta)^2} \]
PHENIX: pp510GeV $W^\pm \rightarrow e^\pm A_L$

High $p_T$ electrons from $W^{+/−}$ decays

PRD 93, 051103(R)(2016)
Unpolarized Sea Quark Distributions

\[
R(x_F) \equiv \frac{\sigma_{W^+}}{\sigma_{W^-}} = \frac{u(x_1)d(x_2) + \bar{d}(x_1)u(x_2)}{\bar{u}(x_1)d(x_2) + d(x_1)\bar{u}(x_2)}
\]

C. Bourrely and J. Soffer (2013)

0.1 < x < 0.3