Spin and Forward Physics with STAR

Carl Gagliardi
Texas A&M University
for the STAR Collaboration

Outline

- Introduction
- Longitudinal spin structure: gluon and anti-quark polarization
- Transverse spin structure: TMDs and visualizing color interactions
- Spin and p+A physics at forward rapidities
- Physics with tagged forward protons
Fundamental questions regarding proton spin

- How do quarks and gluons conspire to provide the proton’s spin \( \frac{1}{2} \)?
  - What is the role of gluons?
    - Reminder – gluons contribute \( \sim 50\% \) of the proton’s momentum
  - What is the role of sea quarks?
  - How much orbital angular momentum is needed?

- What is the dynamic structure of the proton?
  - How do we go beyond longitudinal parton distribution functions to a 2D+1 picture in coordinate and momentum space?
  - Can we visualize color interactions in QCD?
RHIC: the Relativistic Heavy Ion Collider

- Search for and study the Quark-Gluon Plasma
- Explore the partonic structure of the proton
- Determine the partonic structure of nuclei
RHIC: the world’s first (and only!) polarized hadron collider

- Spin varies from rf bucket to rf bucket (9.4 MHz)
- Spin pattern changes from fill to fill
- Spin rotators provide choice of spin orientation
- Billions of spin reversals during a fill with little depolarization

Spin and Forward Physics with STAR -- Carl Gagliardi – HESZ 2017
Mid Rapidity Detectors
-1 < η < 1
Full azimuthal coverage
Uniform acceptance
Excellent particle identification

The **Solenoidal Tracker At RHIC**
Longitudinal spin structure: Gluon and anti-quark polarization
Gluon polarization without RHIC data

Unpolarized input data

Unpolarized PDFs
Gluon polarization without RHIC data

\[ S_z = \frac{1}{2} = \frac{1}{2} \Delta \Sigma + \Delta G + \langle L_z \rangle \]

Polarized DIS: \(~0.3\)

Poorly constrained by DIS

Kinematic region of polarized measurements

Leader et al, PRD 82, 114018 (2010)

Fit to DIS and SIDIS data

\[ \Delta G = 0.32 \pm 0.19 \]

\[ \Delta G = -0.34 \pm 0.46 \]
Exploring gluon polarization at RHIC

\[ A_{LL} = \frac{\sigma^{++} - \sigma^{+-}}{\sigma^{++} + \sigma^{+-}} \propto \frac{\Delta f_a \Delta f_b}{f_a f_b} \hat{a}_{LL} \]

\( \Delta f \): polarized parton distribution functions

\[ \frac{\Delta G}{G}, \quad \frac{\Delta G}{G}, \quad \frac{\Delta q \ G}{q \ G}, \quad \frac{\Delta q \ q}{q \ q} \]

Partonic fractions in jet production at RHIC

For most RHIC kinematics, \( gg \) and \( qg \) dominate, making \( A_{LL} \) for jets sensitive to gluon polarization.
Inclusive jet $A_{LL}$ from the 2009 RHIC run

- STAR measured $A_{LL}$ for inclusive jets at 200 GeV during the 2009 RHIC run
- Results draw a narrow road through the previous predictions
- Far more precise than previous measurements
- Systematically larger than expected by DSSV’08
- Positive gluon polarization in the sampled region $x > 0.05$
Gluon polarization with RHIC data

- Both DSSV and NNPDF have released new polarized PDF fits
- Both find the 2009 RHIC results provide significantly tighter constraints on gluon polarization than previous measurements
- Both find evidence for positive gluon polarization in the region $x > 0.05$
  - DSSV: $0.19^{+0.06}_{-0.05}$ at 90% c.l. for $0.05 < x$
  - NNPDF: $0.23 \pm 0.07$ for $0.05 < x < 0.5$

Spin and Forward Physics with STAR -- Carl Gagliardi – HESZ 2017
What’s next?

- Need to **increase precision in the currently sampled region** to consolidate the observation of non-zero gluon polarization
What’s next?

- Need to **increase precision in the currently sampled region** to consolidate the observation of non-zero gluon polarization
- Need to **extend sensitivity to lower** $x_g$ where current extrapolations have very large uncertainties

Spin and Forward Physics with **STAR** -- Carl Gagliardi – HESZ 2017
Next steps

- RHIC had very successful runs with 510 GeV pp collisions during 2012 and 2013
  - Higher center-of-mass energy probes lower $x$ partons
- $A_{LL}$ at 510 GeV is well described by global fits that previously gave a good description of the 2009 measurements at 200 GeV
Next steps

- RHIC had very successful runs with 510 GeV pp collisions during 2012 and 2013
  - Higher center-of-mass energy probes lower x partons
- $A_{LL}$ at 510 GeV is well described by global fits that previously gave a good description of the 2009 measurements at 200 GeV
- STAR took additional 200 GeV pp data during 2015
  - Will reduce uncertainties for $A_{LL}$ at 200 GeV by a factor of $\sim 1.6$
Further constraining the $x$ dependence

- **Di-jet measurements** sample a much narrower range of $x$ values than inclusive jets
- Use to constrain the shape of $\Delta g(x)$
  - Minimize extrapolation errors outside the sampled region
Di-jets at forward rapidity and higher $\sqrt{s}$

- Di-jet measurements at forward rapidity and higher $\sqrt{s}$ provide more precise mapping of $\Delta g(x)$ at lower $x$
  - Reaching $x$ of $\sim 0.02$ now
  - Will push well below $x \sim 0.01$ with additional data that has already been recorded
  - Will reach $x \sim 10^{-3}$ in several years with a forward upgrade
Why is $\Delta \Sigma$ so small?

\[ \Delta \Sigma = \int_{0}^{1} (\Delta u + \Delta \bar{u} + \Delta d + \Delta \bar{d} + \Delta s + \Delta \bar{s}) \, dx \]

- Polarized inclusive DIS data measure $\Delta u + \Delta \bar{u}$ and $\Delta d + \Delta \bar{d}$
- Polarized semi-inclusive DIS data provide flavor separation, but uncertainties remain large
  - FNAL E866 found surprising structure in the unpolarized anti-quark distributions
  - Might the polarized anti-quark distributions also contain surprises?
  - Can separate polarized quark and anti-quark flavors with W production
    - Only left-handed quarks and right-handed anti-quarks participate
    - Complementary to semi-inclusive DIS
    - No fragmentation function uncertainties
    - Extremely clean theoretically
W $A_L$ and anti-quark polarization

- $W^{+/−}$ asymmetries from 2012 data hint at $Δ\bar{u} > Δ\bar{d}$
  - This is opposite from the unpolarized distributions
**W A_L and anti-quark polarization**

### Data:
- STAR
  - Fits: NNPDF
  - arXiv:1702.05077

### STAR
- W^+/W^- asymmetries from 2012 data hint at $\Delta \bar{u} > \Delta \bar{d}$
  - This is opposite from the unpolarized distributions
- Preliminary results from 2013 with much smaller uncertainties strengthen the hint

---

Spin and Forward Physics with **STAR** -- Carl Gagliardi – HESZ 2017
Transverse spin structure: TMDs and visualizing color interactions
Why TMDs?

• Image the transverse and longitudinal (2+1d) structure of the nucleon and nuclei
  – Tomography of the nucleon!
• Access to transverse momenta at non-perturbative scales
  – Probe at the confinement scale
• Exhibit correlations arising from spin-orbit effects
Initial state: TMDs and Twist-3

Requires 2 scales:
- Hard scale $Q^2$
- Soft scale $p_T$

SIDIS, Drell-Yan, W/Z, ...

Access the full transverse momentum dynamics $k_T$

Single hard scale: $p_T$
Appropriate for inclusive $A_N(\pi^0, \gamma, \text{jet})$
Access the average transverse momentum $<k_T>$

\[-\int d^2 k_{\perp} \frac{k_{\perp}^2}{M} f_{1T}^{\perp q} (x, k_{\perp}^2) \bigg|_{\text{SIDIS}} = T_{q,F}(x, x)\]
Separating initial- from final-state effects

**Sivers or twist-3 mechanisms:**

Sensitive to proton spin – parton transverse motion correlations

- Signatures:
  - $A_N$ for jets or direct photons
  - $A_N$ for $W^+/-$, $Z^0$, Drell-Yan
  - $A_N$ for heavy flavor (gluon)

- Sivers NOT universal
  - Sign change from SIDIS to $W$, $Z$, and Drell-Yan

**Collins or novel FF mechanisms:**

Sensitive to transversity

- Signatures:
  - Collins effect
  - Interference fragmentation functions (IFF)
  - $A_N$ for pions → novel FF

- Collins predicted to be universal
Color interactions in QCD

Controlled non-universality of the Sivers function

QCD:

\[ \text{DIS} \]
Final-state interaction
Opposite colors attract

\[ \text{Drell-Yan, W or Z} \]
Initial-state interaction
Like colors repel

\[ \gamma^* \]

\[ \text{Sivers}_{\text{DIS}} = - \text{Sivers}_{\text{Drell-Yan}} \text{ or Sivers}_W \text{ or Sivers}_Z \]

\[ A_N \text{ for direct photon has related sign change in Twist-3} \]

Critical test of factorization

Opportunity to visualize the repulsive interaction
between like color charges

Can explore all of these observables
in 510 GeV pp collisions at RHIC
STAR performed an exploratory measurement of $A_N$ for W production with a small data set recorded in 2011

- W kinematics fully reconstructed

- Favors sign change if evolution effects are modest
  - TMD evolution is non-perturbative at low $k_{\perp}$ - no absolute theory predictions
Definitive measurement

- See the sign change if evolution effects are less than factor of 5
- Probe anti-quark Sivers function for the first time
- Directly measure the evolution effects
  - Need new data to constrain non-perturbative contribution
  - Access similar observables at comparable $x$ but very different $Q^2$
    - $W$ and $Z \ A_N$ at 510 GeV
    - Drell-Yan at 510 GeV

Recently completed 2017 RHIC run
$A_N$ for direct photon

- Sensitive to the sign change in the Twist-3 formalism
- Collinear objects, but more complicated evolution than DGLAP
  - Not sensitive to TMD evolution
- Provides an indirect constraint on the Sivers function via their integral relationship

Not a replacement for $A_N(W, Z, DY)$, but an important complementary piece of the puzzle
Transversity

- Quark polarization along spin of a transversely polarized proton
  - Third collinear, leading twist distribution
  - Chiral odd
- Before \textit{STAR}, only observed in SIDIS combined with e^+e^-
- Much less data than for helicity
- Several recent global analyses including:
  - Collins effect input:
    - PRD 93, 014009
    - PRD 92, 114023
  - IFF input:
    - PRD 94, 034012
  - All show large uncertainties
First transversity signals in hadronic collisions

Significant measurements of transversity convoluted with:
- Di-hadron interference fragmentation function (IFF)
  - STAR data now in preliminary global analysis (Radici, DIS 2017)
- Collins fragmentation function

Both have similar magnitudes in 200 and 500 GeV pp collisions

Observations of transversity at very high scales
- $Q^2$ up to 900 GeV$^2$ for Collins at 500 GeV

Complementary results that obey different evolution equations

Spin and Forward Physics with STAR -- Carl Gagliardi – HESZ 2017
π⁺⁻ azimuthal distribution in jets

**First Collins effect measurements in pp collisions** are reasonably described by two recent calculations that convolute the transversity distribution from SIDIS with the Collins FF from $e^+e^-$ collisions

- Tests the predicted **universality of the Collins FF**
- TMD evolution effects appear to be small
Additional azimuthal modulations

- Inclusive jet $A_N$
  - Sensitive to the gluon Sivers function via the Twist-3 relationship

- “Collins-like” effect
  - World’s first ever limit on linearly polarized gluons in a polarized proton
Projected uncertainties for upcoming results

- Final Collins results from 200 GeV collisions will be coming soon
- Recorded > 10 times as much data at 510 GeV in 2017 as in 2011
  - Precision data at fixed $x$, different $\sqrt{s}$ ideal to constrain TMD evolution
- Also have data for a first look at the Collins effect in p+Au collisions
Spin and p+A physics at forward rapidities
Transverse spin asymmetries in high energy p+p

- Large transverse single-spin asymmetries over a very wide range of $\sqrt{s}$
- Naïve collinear pQCD predicted $A_N \sim 0.001$
- May arise from
  - Initial-state effects: Sivers effect / twist-3
  - Final-state effects: Transversity + Collins fragmentation function
  - Or a combination of the two
STAR Forward Meson Spectrometer: FMS

- Pb-glass EM calorimeter covering $2.6 < \eta < 4$ and full azimuth
  - Neutral pions / eta / EM jet-like events
  - Direct photons with addition of Pre-shower before 2015 run
  - Drell-Yan and $J/\psi$ with addition of Post-shower before 2017 run
Transverse spin asymmetries in high energy p+p

- Large transverse single-spin asymmetries over a very wide range of $\sqrt{s}$
- Naïve collinear pQCD predicts $A_N \sim 0.001$
- May arise from
  - Initial-state effects: Sivers effect / twist-3
  - Final-state effects: Transversity + Collins fragmentation function
  - Or a combination of the two
- Signal doesn’t seem to fall-off at high $p_T$
  - Maybe something else?
Forward $\pi^0 A_N$ in 200 GeV pp

$A_N$ vs. Energy, averaged over pseudo-rapidity.

Compare 3 selection criteria based on photon energy outside the cone (all with 35mR cone and no soft $E$ cut).

For $\pi^0$ with $X_F<0.45$:
- Events with "opposite-side" photons or "no" photons have similar $A_N$.
- Same side photons lead to much reduced $A_N$.

For $\pi^0$ with $X_F>0.45$:
- Observation of additional photons reduces $A_N$.

- $\pi^0$ with **opposite-side photons** or **no additional photons** have similar asymmetries
- $\pi^0$ with **additional same-side photons** lead to much reduced $A_N$
$A_N$ for EM jet-like events at 500 GeV

Cluster the observed FMS photon candidates using anti-$k_T$ with $R=0.7$

**$\pi^0$-Jets** —
Exactly 2 photon candidates with
$m_{\gamma\gamma} < 0.3$ GeV
$Z_{\gamma\gamma} < 0.8$

**2$\gamma$-EM-Jets ($\eta$ + continuum)** —
$m_{\gamma\gamma} > 0.3$ GeV

**EM-Jets** — with >2 photon candidates

- Isolated $\pi^0$ also have large asymmetries in 500 GeV pp
- Asymmetries for jettier events are much smaller
Collins asymmetry for $\pi^0$ in EM jet

- Collins asymmetry of $\pi^0$ in EM jet-like events too small to explain the inclusive $\pi^0 A_N$
EM jet-like $A_N$ vs number of photons

- $A_N$ decreases as EM jets become jettier. Also is much smaller when there is a coincident jet at mid-rapidity.
  - Raises serious questions how much of the large forward $\pi^0$ $A_N$ arises from $2 \rightarrow 2$ parton scattering

Only 1 photon candidate in anti-$k_T$ R=0.7

5 photon candidates in anti-$k_T$ R=0.7

Jettier events
First $\pi^0 A_N$ results from polarized $p+Au$

\[ A_N \] vs. $p_T$ for $X_F=0.2, 0.3, 0.4, 0.5, 0.6, 0.7$

Shaded bands show systematic uncertainty, dominated by dependence of $A_N$ on observed BBC multiplicity $\rightarrow$ central vs. peripheral collisions

- CGC calculations in some of the possible channels predicted that $A_N$ would be suppressed when scattering off a saturated gluon field
  - Preliminary results from 2015 find little suppression
Back-to-back angular correlations

• CGC predicts suppression of back-to-back correlations
• PHENIX found evidence in 200 GeV d+Au collisions
• STAR 2015 data are being analyzed for $\pi^0\pi^0$ and EM jet – EM jet azimuthal correlations in pp, p+Al, p+Au (and d+Au in 2016)
  – Still working on FMS gain uniformity and stability
  • Both cancel out in $A_N$
Scanning the FMS $\pi^0\pi^0$ correlation in $p_T$ and $x$

- With 2015 statistics, STAR can study the evolution of $Q_s^2(x)$ with $A$.

Spin and Forward Physics with STAR -- Carl Gagliardi – HESZ 2017
Direct photon $R_{pAu}$

Data from p+Au run in 2015 (and 2023)

- Direct photon will provide:
  - Substantial improvement in our understanding of nuclear PDFs in the near term
  - Alternative observable and kinematics to EIC in the long term
- 2015 data analysis well underway

Projected impact on gluon nPDFs from world data: incl. LHC pA

<table>
<thead>
<tr>
<th>$R_{pAu}^g(x,Q^2 = 1.69,\text{GeV}^2)$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Data from p+Au run in 2015 (and 2023)</td>
</tr>
</tbody>
</table>

Spin and Forward Physics with STAR -- Carl Gagliardi – HESZ 2017
Physics with forward tagged protons
Roman pots in STAR

- Roman pots from pp2pp were installed 55 m each side of the STAR interaction region prior to the 2009 RHIC run
  - Had dedicated 4-day running time with special beam optics
- Roman pots were moved much closer to interaction point prior to the 2015 RHIC run (Phase II*)
  - Now can operate with normal RHIC beam optics
  - Integrated a large fraction of the total delivered luminosity during the 2015 ($\sqrt{s} = 200$ GeV) and 2017 ($\sqrt{s} = 510$ GeV) RHIC runs
Roman pots in STAR

- Roman pots from pp2pp were installed 55 m each side of the STAR interaction region prior to the 2009 RHIC run
  - Had dedicated 4-day running time with special beam optics
- Roman pots were moved much closer to interaction point prior to the 2015 RHIC run (Phase II*)
  - Now can operate with normal RHIC beam optics
  - Integrated a large fraction of the total delivered luminosity during the 2015 ($\sqrt{s} = 200$ GeV) and 2017 ($\sqrt{s} = 510$ GeV) RHIC runs

For acceptance at 200 GeV, scale $-t$ by $(200/500)^2$
Ongoing analyses

- **Elastic scattering**

- **Central Exclusive Production (CEP)**
  - $p + p \rightarrow p + X + p$
  - Diffractive $X = $ particles, glueballs

- **Single Diffraction Dissociation**

- Took high-quality data on all three processes during the 2015 (200 GeV) run, and even more during the 2017 (510 GeV) run
  - Here only show preliminary 2015 results on CEP at 200 GeV

- Also looking at correlation of forward $\pi^0 A_N$ with Roman pot activity
  - Could a large fraction of the $\pi^0 A_N$ be diffractive?
Identifying CEP: the $\pi^+\pi^-$ case

- Identification and momentum reconstruction of all final state particles provides the ability to ensure exclusivity of the system via momentum balance check
- Very small background!
\( \pi^+\pi^- \) invariant mass distribution at 200 GeV

- Broad structure extending from \( \pi^+\pi^- \) threshold to \( \sim 1 \text{ GeV} \)
- Sharp drop at about 1 GeV
- Resonance-like structure between 1-1.5 GeV
  - Expect \( \sim 70K \) events with \( M(\pi^+\pi^-) > 1 \text{ GeV} \) from full 2015 data set

Spin and Forward Physics with STAR -- Carl Gagliardi -- HESZ 2017
$\pi^+\pi^-$ invariant mass distribution at 200 GeV

- Broad structure extending from $\pi^+\pi^-$ threshold to ~1 GeV
- Sharp drop at about 1 GeV
- Resonance-like structure between 1-1.5 GeV
  - Expect ~70K events with $M(\pi^+\pi^-) > 1$ GeV from full 2015 data set
- Essential features are similar to measurements in $pp$ at 63 GeV (AFS at ISR) and $p\bar{p}$ 1.96 TeV (CDF)
Prominent peak around 1.5-1.6 GeV

Some enhancement in the f2(1270)/f0(1370) region

In spectrum measured by WA102 (fixed target), there is a significant contribution from f0(980) not seen by STAR
  – K acceptance is very small at such low p_T

Expect ~10^4 exclusive K^+K^- events in the full 2015 data set
  – Will permit cross section and partial wave analyses
What about orbital angular momentum?

- Generalized parton distributions (GPDs), measured via exclusive reactions, provide access to $L_q$ and $L_g$
- Exclusive $J/\psi$ production in ultra-peripheral collisions with transversely polarized $p+p$ and $p+Au$ provides access to the GPD $E_g$
  - The GPD $E$ is responsible for orbital angular momentum
  - Only access world-wide to $E_g$ before EIC
- First measurements started in 2015 enabled by the Roman Pot phase II* upgrade to STAR

\[
\frac{1}{2} = J_{q}^{z} + J_{g}^{z} = \frac{1}{2} \Delta \Sigma + \sum_{q} J_{q}^{z} + J_{g}^{z}
\]
\[
J_{q,g}^{z} = \frac{1}{2} \left( \int_{-1}^{1} x \, dx \left( H^{q,g} + E^{q,q} \right) \right)_{t \to 0}
\]
Planned forward upgrade for the 2020’s

- Forward di-jets will extend gluon polarization to $x < \sim 10^{-3}$
- Transverse spin phenomena:
  - Precision TMDs through jets at forward rapidity
  - Precision $A_N$(Drell-Yan) to complete the Sivers measurements
- Also an extensive suite of measurements in p+A collisions
Sivers and Collins coverage at RHIC

- Kinematics of RHIC
  - Dramatic extension in \((x, Q^2)\) reach before EIC
  - \(W\) production probes the highest \(Q^2\) over a wide \(x\) range
  - **Precision tests of universality** when EIC data become available
Drell-Yan $R_{pA}$ at 200 GeV

- Similar statistics in 200 GeV pp, p+Au, p+Al
- Significant improvement in our knowledge of sea quark densities in heavy nuclei
- Significant extension of the $Q^2$ lever arm at low $x$ relative to future EIC data

Projected impact on sea quark nPDFs
Conclusions

• The STAR Spin and Forward Physics programs have made a number of striking observations

• STAR has a huge body of additional spin and forward physics data under analysis

• The STAR Forward Upgrade will provide a bright future for STAR in the coming decade

• STAR is a key component of the RHIC Cold QCD program: an essential bridge between the physics of RHIC and the physics of the future Electron Ion Collider
**STAR** as a jet and di-jet detector

- Large and uniform acceptance makes **STAR** an excellent jet detector
- Good agreement with NLO predictions for both inclusive jet and di-jet cross sections

**Inclusive jets @ 200 GeV**

\[
\int L \, dt = 19 \text{ pb}^{-1} \pm 8\%
\]

**Di-jets @ 200 GeV**

- STAR preliminary

**Di-jets @ 500 GeV**

- STAR preliminary

---

**Spin and Forward Physics with **STAR** -- Carl Gagliardi -- HESZ 2017**