Spin Physics Program; Goals and Upgrades beyond 2015, and Migration toward eRHIC Capabilities

Carl Gagliardi, TAMU
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for the STAR Collaboration
STAR - Solenoid Tracker at RHIC

0.5 T Solenoidal Magnetic Field

Time Projection Chamber
charged track momentum msmt,
charge determination,
particle identification dE/dx,
collision vertex reconstruction
coverage 30°-150°

Beam-Beam Counters
proton beam collision trigger,
relative luminosity measurement,
local polarimetry (transverse components)

Barrel E.M. Calorimeter
towers and Shower Maximum Det.
neutral e.m. energy measurement,
trigger (towers, patches of towers)
coverage 40°-140°

Forward Meson Spectr.

Endcap E.M. Calorimeter
towers and SMD.
neutral e.m. energy measurement,
trigger (towers, patches of towers)
coverage 15°-40°

Several detectors not shown, e.g. ZDC, FPD, Time-of-Flight, Roman Pots, ... 

A very versatile general purpose instrument, with an evolutionary and physics-driven upgrades.
Key Questions to be Addressed Next:

What are the properties of the strongly-coupled system produced at RHIC, and how does it thermalize?
Are the interactions of energetic partons with QCD matter characterized by weak or strong coupling?
What is the detailed mechanism for partonic energy loss?
Where is the QCD critical point and the associated first-order phase transition line?
Can we strengthen current evidence for novel symmetries in QCD matter and open new avenues?
What other exotic particles are created at RHIC?
What is the partonic spin structure of the proton?
How do we go beyond leading twist and collinear factorization in perturbative QCD?
What is the nature of the initial state in nuclear collisions?

### Envisioned Measurements, Instrumentation, and Timeline

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Xu’s talk yesterday
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What is the partonic spin structure of the proton?

Some of the knowns and unknowns:
- Quark spins carry only a small fraction of the proton spin,
- RHIC is providing sensitive insights in the contribution from gluon spin,
- Insight in the proton’s spin-sea remains limited and relies on fragmentation,
- Transverse spins in the nucleon remain poorly known to date,
- Orbital quark and gluon are likely to contribute, but by how much?
- ...

Measurements at RHIC with transverse beam polarizations offer a unique window on perturbative QCD beyond leading twist and collinear factorization.
Theory: perturbative QCD evaluations, typically at next-to-leading order,

Experiment: observe cross sections (asymmetries) of (hadronized) final states, test applicability of theoretical framework, extend measurements to correlated and selective final states.

Combination: insight in $q, \bar{q}, g, \Delta q, \Delta \bar{q}, \Delta g$

Complementary insights from measurements of $A_{LL}, A_L, A_N, D_{LL}$, inclusive probes, correlations ...
STAR is uniquely suited, at RHIC, for central-rapidity jet measurements, Measured cross section is well-described by perturbative QCD evaluation at NLO,
Gluon Polarization - Inclusive Jets

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Pibero Djawotho, for the STAR collaboration, DIS2011

Gluon Polarization - Inclusive Jets

STAR is uniquely suited, at RHIC, for central-rapidity jet measurements, Measured cross section is well-described by perturbative QCD evaluation at NLO, Precision insights in gluon polarization for \(0.03 < x < 0.3\) from \(A_{LL}\), Near-to-mid-term: precision, resolve \(x\) (correlations), and extend \(x\) range (\(\sqrt{s}\), pseudorapidity).
Gluon Polarization - Inclusive Jets

Complementarity of $\sqrt{s} = 200$ GeV (data) and $\sqrt{s} = 500$ GeV (projected precision):

STAR is uniquely suited, at RHIC, for central-rapidity jet measurements,
Measured cross section is well-described by perturbative QCD evaluation at NLO,
Precision insights in gluon polarization for $\sim 0.03 < x < 0.3$ from $A_{LL}$,
Near-to-mid-term: precision, resolve $x$ (correlations), and extend $x$ range ($\sqrt{s}$, pseudorapidity).
Gluon Polarization - Di-Jets

Sensitivity to Di-jets

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Gluon Polarization - Di-Jets

Projected di-jet precision for extended $\sqrt{s} = 500$ GeV running:

Near-to-mid-term: precision, resolve $x$ (correlations), and extend $x$ range ($\sqrt{s}$, pseudorapidity). Results (surprises) will drive a longer-term program, as may new forward detector capability.
Yields agree with expectations, 139 $W^-$ and 462 $W^+$ candidate events in 12 pb$^{-1}$ are expected to increase significantly with further increases in beam energy,

Yields agree with expectations, 139 $W^-$ and 462 $W^+$ candidate events in 12 pb$^{-1}$
First asymmetries consistent with expectations based on quark polarizations,
Near-to-mid-term: FGT upgrade, coverage and precision with 2-3 runs,
Quark Polarization - leptonic W decay

Six light-weight triple-GEM disks, provide full charge-sign discrimination at high-pT in EEMC region, currently being constructed, c.f. Dunlop’s talk (Tuesday).

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Measurement relies heavily on future luminosity and polarization at $\sqrt{s} = 500$ GeV

Near-to-mid-term: FGT upgrade, coverage and precision with 2-3 runs, Surprises may of course extend this.

Note: W+charm, is exceedingly hard; strange quarks are thus likely to remain elusive.
Note: W physics with transverse spins is more demanding; STAR collected a small “benchmark” sample in Run11.
Quark Polarization - Hyperon Spin Transfer


√s = 200 GeV, run-5 data, mid rapidity

√s = 500 GeV, forward rapidity

Near-term: improved mid-rapidity precision,
Forward hadronic calorimetry (mid-to-long term) would facilitate triggering,
enable a number of hyperon measurements

Hyperon anti-Hyperon discrimination will further improve sensitivity.
Unexpectedly large forward $A_N$, observed at $\sqrt{s} = 200$ GeV, in a regime where pQCD describes the production cross section, rapidly evolving field, motivating significant forward instrumentation upgrades.
Transverse Spin Phenomena

What causes this?
An experimental handle beyond collinear twist-2 perturbative QCD?
Model calculations can qualitatively explain $x_F$ dependence of large $A_N$,

Models *generally* fall short for the $p_T$ dependence,

Kanazawa and Koike, PRD 82, 034009 (2010), recently succeeded in their Twist-3 approach,
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Mid-rapidity Collins Projections

Run-6 analysis accuracy ($\sqrt{s} = 200$ GeV) projected precision $20\text{pb}^{-1}$, 60% polarization

Asymmetries anticipated to be several percent
Near-term: continued characterization to much higher $p_T$, $\sqrt{s} = 500$ GeV, photon $A_N$ - projections for $20\text{pb}^{-1}$, 60% (c.f. Dunlop’s talk)

Mid-to-longer term: large acceptance forward instrumentation upgrade to enable *full* jet reconstruction, correlations, ..., Drell Yan in p+p and p(d)+A
Near-term: continued characterization to much higher $p_T$, $\sqrt{s} = 500$ GeV, photon $A_N$

Mid-to-longer term: large acceptance forward instrumentation upgrade to enable full jet reconstruction, correlations, ..., Drell Yan in $p+p$ and $p(d)+A$

Capabilities:
- pions, eta,
- $e/h$, photon/pion jets,
- tracking in jets,
- Hyperons

Opportunities include:
- correlations,
- photon+jet, $\sqrt{s}=500$ GeV
- Sivers, Collins,
- including flavor
- Spin transfer
- Drell-Yan
... driven by spin physics and p(d)+A physics

Recall Z. Xu’s talk yesterday,

Polarized-proton nucleus scattering would appear to be in the realm of RHIC;
An interesting curiosity, or more? Theorists’ guidance is sought and welcome.
Migration to eRHIC Capabilities

Polarized $^3$He beams are envisioned for eRHIC,

STAR Roman Pots Phase-II upgrade is estimated to have significant acceptance for the spectator protons in collisions involving the neutron,

May offer attractive opportunities already at RHIC, in particular for transverse spin,
4) Any plans or interest your Collaboration has in adapting your detector or detector subsystems (or detector R&D) to study electron-nucleon and electron-ion collisions with an eventual eRHIC upgrade. This is relevant only near the end of the decade addressed here, but will be important for planning purposes. (We may well be forced by financial or environmental considerations, even for a first MeRHIC stage, to consider options in which acceleration of the electron beam is carried out around the RHIC tunnel, requiring some scheme for getting an electron beamline through or around PHENIX and STAR. So it’s worth considering if there is some way you could make use of the e-p and e-A collisions if we provided them.)

Steve Vigdor to Barbara Jacak and Nu Xu, Decadal Plan Charge December 2009.
Migration to eRHIC Capabilities

\[ Q^2 = -(e - e')^2 \]
\[ x = \frac{Q^2}{ys} \]
\[ y = \frac{(q.p)}{(e.p)} \]

eRHIC physics case is the focus of several talks later today; Deep-Inelastic Scattering, inclusive and semi-inclusive, is an integral part of it, that will allow us to study e.g. the gluon distribution in nuclei, energy loss in cold nuclear matter, strange quarks in the nucleon, Focus here on DIS with STAR in the initial (low energy-) stage of eRHIC.
STAR Evolution to eRHIC

a) Scattered Electron Angle  5+100 GeV

b) Scattered Electron Energy  5+100 GeV

y=1

15°
40°
140°
165°

y=1

2 GeV 4 GeV

x = E_e/E_p

20 GeV 10 GeV 6 GeV

20 GeV

4 GeV

10 GeV

50 GeV

y=1

15°
40°
140°
165°

c) Struck Quark Angle  5+100 GeV

d) Struck Quark Energy  5+100 GeV

x = E_q/E_p

10 GeV

50 GeV

2 GeV 4 GeV
STAR Evolution to eRHIC

a) Scattered Electron Angle  5+100 GeV

b) Scattered Electron Energy  5+100 GeV

c) Struck Quark Angle  5+100 GeV

d) Struck Quark Energy  5+100 GeV

Resolution!

Electron beam in Yellow, Hadron beam in Blue.
Towards an eSTAR Concept

Scattered Electron Energy  5+100 GeV

Struck Quark Energy  5+100 GeV

Scattered Electron Energy at Fixed Angle

Bjorken-x

Towards an eSTAR Concept

Scattered Electron Energy  5+100 GeV

Struck Quark Energy  5+100 GeV

Scattered Electron Energy at Fixed Angle

Bjorken-x
Towards an eSTAR Concept

Scattered Electron Energy 5+100 GeV

Struck Quark Energy 5+100 GeV

Towards an eSTAR Concept

Scattered Electron Energy at Fixed Angle

Bending radii \( \sim m \),

Sagitta \( \sim \text{mm} \) (over 40 cm),

At 140°, \( dx/x \sim 2 \) implies:
- \( dE/E \sim 0.5 \) at \( x \sim 10^{-3} \)
- \( dE/E \sim 0.3 \) at \( x \sim 10^{-2} \)
- \( dE/E \sim 0.04 \) at \( x \sim 10^{-1} \)

At 165°, \( dx/x \sim 2 \) implies \( dE/E \sim 0.09 \) at \( 5 \times 10^{-3} \)
Towards an eSTAR Concept - Electron Side

ToF: $\pi$, $K$ identification, $t_0$, electron

ECal: 5 GeV, 10 GeV, ... electron beams

GCT: a compact low-mass tracker with enhanced electron capability;
seek to combine high-threshold (gas) Cherenkov with TPC(-like) tracking.

Simulations and R&D beginning;
- eSTAR task force formed,
- EIC generic R&D:
  - Hadron Calorimeter R&D proposal
  - Multi-institute LOI towards tracking R&D

Note: Hadron Side not shown here.
Closing Remarks

Near-term:

Gluon polarization inclusive measurements are delivering the most precise insight to date, covering $0.02 < x < 0.3$ ($\sqrt{s} = 500$ GeV will widen this), correlation measurements are key to $x$-dependence and, related, extrapolations over unmeasured $x$.

Quark polarization measurements have started, and will benefit greatly from a) the ongoing FGT tracking upgrade and b) a multi-run measurement period.

Transverse spin phenomena continue to surprise; photon $A_N$ and other measurements should allow much better characterization.

Mid-term:

Full study of transverse spin phenomena and $p(d)+A$ measurements form the drivers for a major instrument upgrade (concept) to provide large acceptance in the forward region.

Long-term:

STAR acceptance and PID capabilities appear a reasonable match to inclusive and semi-inclusive DIS at eRHIC for low electron and all hadron beam energies - not for high electron energies.

eSTAR could thus be a path to a timely staged EIC. Task force formed to investigate further, and quantify measurement capabilities.