Spin Physics Highlights from STAR

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For the STAR Collaboration

ICNFP 2014
August 2, 2014
Contributions to the Proton’s Spin

Consider proton moving right

Proton spin $\Rightarrow$

$\Delta q(x)$  $\Rightarrow$  $
\Delta g(x)$  $\Leftarrow$

Longitudinal
Polarization

Polarized DIS: $\sim 0.3$
Puzzling for $\sim 25$ years

Proton spin sum rule:

$$\frac{1}{2} \hat{h} = \frac{1}{2} \sum_q S_q^z + S_g^z + \sum_q L_q^z + L_g^z$$

Proton spin $\uparrow$

$\delta q(x)$  $\uparrow$  $\downarrow$

Transverse
Polarization

Transversity

Relatively poorly constrained
But $S_g$ coming into focus!
Understanding Spin in Proton Collisions at STAR

• Probing Gluon Polarization with Jets and $\pi^0$’s
• Probing Sea Quark Polarization with W’s
• Probing Transverse Structure with Jets and $\pi^0$’s
  – And with W’s, Z’s, and other probes
• Looking to the Future
Solenoidal Tracker at RHIC

RHIC as Spin Collider
- “Siberian Snakes” → mitigate depolarization resonances
- Spin rotators provide choice of spin orientation independent of experiment
- Spin direction varies bucket-to-bucket (9.4 MHz)
- Spin pattern varies fill-to-fill

Inclusive hadron measurements:
- Barrel E/M Calorimeter (BEMC),
- Endcap E/M Calorimeter (EEMC),
- Forward Meson Spectrometer (FMS)
  FPD (east) not shown

Jet and W/Z measurements:
- TPC + Barrel + Endcap EMC

NIM A499, 245 (2003)

A. Gibson, Valparaiso; STAR Spin Highlights; ICNFP

August 2, 2014
Solenoidal Tracker at RHIC

**Inclusive hadron measurements:**
Barrel ElectroMagnetic Calorimeter (BEMC),
Endcap ElectroMagnetic Calorimeter (EEMC),
and
Forward Meson Spectrometer (FMS)

*FPD (east) not shown*

**Jet and W/Z measurements:**
TPC +
Barrel + Endcap EMC
Datasets from RHIC at STAR

- Many published results from 2006, 2009 datasets
  - And W’s more recently
- Preliminary results and work in progress from, especially
  - 2011 500 GeV trans.
  - 2012 200 GeV trans.
  - Large 510 GeV long. datasets in 2012 and 2013
• Probing Gluon Polarizations with Jets and $\pi^0$’s
• Probing Sea Quark Polarization with W’s
• Probing Transverse Structure with Jets and $\pi^0$’s
  – And with W’s, Z’s, and other probes
• Looking to the Future
Probing (Gluon) Polarized PDF’s With Jets

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

\[A_{LL}\] for, e.g. jets, sensitive to polarized PDF’s (\(\Delta f\)) and partonic asymmetry, \(\hat{a}_{LL}\)

Asymmetries at different values of \(p_T\) or \(\sqrt{s}\)

\(\rightarrow\) sample different mix of partonic subprocesses
STAR Detector has:
- Full azimuthal coverage
- Charged particle tracking from TPC for $|\eta| < 1.3$
- E/BEMC provide electromagnetic energy reconstruction for $-1 < \eta < 2.0$

STAR well suited for jet measurements

Anti-$K_T$ Jet Algorithm:
- Radius = 0.6
- Used in both data and simulation
2009 Inclusive Jet $A_{LL}$

- 2009 results have factor of 3 to 4 better statistical precision than 2006 results

- Result divided into two pseudorapidity ranges which emphasize different partonic kinematics

- Result lies consistently above the 2008 DSSV fit
Integral of $\Delta g(x)$ in range $0.05 < x < 1.0$ increases substantially, now significantly above zero.

Uncertainty shrinks substantially from DSSV* to new DSSV fit.

First firm evidence of non-zero gluon polarization!
Integral of $\Delta g(x)$ in range $0.05 < x < 1.0$ increases substantially, now significantly above zero.

Uncertainty shrinks substantially from DSSV* to new DSSV fit

Uncertainty on integral over low $x$ region is still sizable

[See also new NNPDF fit arXiv:1406.5539]
Probing Low $x$ Gluons With $\pi^0 A_{LL}$

- STAR has measured $\pi^0 A_{LL}$ in three different pseudorapidity ranges
  - Different kinematics, different fragmentation, different systematics
  - Here with data from 2006
- $qg$ scattering dominates at high $\eta$ with high $x$ quarks and low $x$ gluons
- No large asymmetries seen

- $|\eta| < 0.95$
- $1.0 < \eta < 2.0$
- $\eta = 3.2, 3.7$

PRD 80, 111108(R) (2009)
PRD 89, 012001 (2014)
Wissink SPIN2008

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Updated Prediction for $\pi^0 A_{LL}$

- NNPDFpol1.1 includes jet results from STAR and PHENIX, including the recently submitted 2009 STAR inclusive jets
- Greater precision needed to constrain the fit

STAR data with NNPDF predictions

Figure 16: (Left panel) Predictions for the neutral-pion spin asymmetry compared to data measured by STAR [26]. (Right panel) Prediction for the neutral- and charged-pion spin asymmetries in the kinematic range accessed by upcoming PHENIX measurements.
**π^0 A_{LL} Prospects in 2012 Dataset**

- Work underway at STAR with 2012 dataset (x10 luminosity) at intermediate pseudorapidity
  - Large improvement in stat. uncertainty projected, as shown
- And with 2012 and 2013 datasets at forward pseudorapidity

![Diagram showing p_T vs. A_{LL} for π^0 production]

- Higher CoM energy
  - 200 → 510 GeV
  - Pushes to lower x gluon

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• Looking to the Future
Probing Sea Quark Polarizations With W’s

\[ u + \bar{d} \to W^+ \to e^+ + \nu \]

\[ d + \bar{u} \to W^- \to e^- + \bar{\nu} \]

- W's couple directly to the quarks and antiquarks of interest
- Detect W's through e^+/e^- decay channels
- Longitudinally, excellent probes of sea quark polarizations
- Also an important probe of transverse physics

Measure parity-violating single-spin asymmetry:

(Helicity flip in one beam while averaging over the other)

\[ A_L = \frac{\sigma_+ - \sigma_-}{\sigma_+ + \sigma_-} \]
Results from 2012 W’s

\[ \int A_L(x, Q^2) \, dx \]

\[ \Delta \chi^2 \]

\[ \Delta \bar{d} \]

\[ \Delta \bar{u} \]

STAR data move the world sea quark fits!

DSSV+: DSSV+COMPASS
DSSV++: DSSV+ & STAR-W 2012
DSSV++: DSSV+ & RHIC-W proj. (2009-2013)

arXiv:1404.6880 [Accepted by PRL]
[See also new NNPDF fit arXiv:1406.5539]

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W Projections

2011-2012 Results

\[ \int L_{2011+2012} = 140 \text{ pb}^{-1} \]

\[ \vec{p} + p \rightarrow W^+ \rightarrow e^+ + \nu \]
\[ \sqrt{s} = 510 \text{ GeV} \quad 25 < E_T^e < 50 \text{ GeV} \]

\[ \int L_{2011+2012} = 140 \text{ pb}^{-1} \]

\[ \vec{p} + p \rightarrow W^- \rightarrow e^- + \bar{\nu} \]
\[ \sqrt{s} = 510 \text{ GeV} \quad 25 < E_T^e < 50 \text{ GeV} \]

\[ L_{\text{delivered}} = 320 \text{ pb}^{-1} \]

\[ <P> = 53\% \]

\[ W^+ \]

\[ W^- \]

\[ W^+ W^- \]

\[ W^+ W^+ \]

[Accepted by PRL]

NEW: arXiv:1404.6880

Includes Forward GEM Tracker at STAR, fully installed in 2013

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Understanding Spin in Proton Collisions at STAR

• Probing Gluon Polarizations with Jets and $\pi^0$’s
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• Looking to the Future
• Anomally large $A_N$ observed for nearly 40 years
  – In naïve, co-linear, leading-order/leading-twist QCD expect very small $A_N$, especially at high sqrt(s)

\[ A_N = \frac{d\sigma^{\uparrow\downarrow} - d\sigma^{\downarrow\uparrow}}{d\sigma^{\uparrow\uparrow} + d\sigma^{\downarrow\downarrow}} \]

$d\sigma^{\uparrow\downarrow}$ – cross section for leftward scattering when beam polarization is spin-up(down)

Positive $A_N$ – more $\pi^0$ to left of (up) polarized beam

For a 2$\pi$ detector, $A_N$ manifests as an azimuthal ($\phi$) asymmetry

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Puzzle of Large Transverse Spin Asymmetries, $A_N$

- Persists at STAR/RHIC
  - At forward pseudorapidity
  - At high $x_F$

- Interesting features in $A_N$
  - Persists to surprisingly large $p_T$
  - Larger in $\eta$’s than $\pi^0$’s?
  - In relatively isolated $\pi^0$’s, not in jets
  - Smaller when there’s central activity
Mechanisms for Transverse Single-spin Asymmetries

**Sivers mechanism:** asymmetry in the forward jet or $\gamma$ production

D. Sivers, PRD 41, 83 (1990); 43, 261 (1991)

\[
\langle S_p \cdot (p \times k_{T,\text{parton}}) \rangle \neq 0
\]

Sensitive to proton spin–parton transverse motion correlations (needs $L_z$)

**Collins mechanism:** asymmetry in the forward jet fragmentation

J. Collins, NP B396, 161 (1993)

\[
\langle S_q \cdot (p \times k_{T,\pi}) \rangle \neq 0
\]

Sensitive to transversity ($h_1$)

\[
\pi^\pm \text{ Kinematic Variables}
\]

\[
z = p_\pi / p_{\text{jet}}
\]

\[
j_T(k_{T,\pi}) = \pi p_T \text{ relative to jet axis}
\]

**Twist-3 mechanism:** Asymmetry from multi-parton correlation functions

e.g. Qiu and Sterman, PRL 67, 2264 (1991); PRD 59, 014004 (1998)

**Correlators closely related to $k_T$ moments of TMD’s**

Boer, Mulders, Pijlman, NPB 667, 201 (2003)
Mechanisms for Transverse Single-spin Asymmetries

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\[ \langle S_q \cdot (p \times k_{T,\pi}) \rangle \neq 0 \]

Sensitive to transversity ($h_1$)

$\pi^\pm$ Kinematic Variables:
\[ z = p_\pi / p_{jet} \]
\[ j_T (k_{T,\pi}) = \pi p_T \text{ relative to jet axis} \]

Inclusive hadron asymmetries:

Unable to isolate contributions

**Sivers, Collins, twist-3** $\sim \sin(\phi_S)$

$\phi_S$—angle between spin and event plane
Mechanisms for Transverse Single-spin Asymmetries

**Sivers mechanism:** asymmetry in the forward jet or $\gamma$ production

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$\langle S_p \cdot (p \times k_{T,\text{parton}}) \rangle \neq 0$

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$\langle S_q \cdot (p \times k_{T,\pi}) \rangle \neq 0$

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$\pi^+$ Kinematic Variables

$z = p_\pi / p_{\text{jet}}$

$j_T (k_{T,\pi}) = \pi p_T$ relative to jet axis

---

Separate Sivers and Collins:

Go beyond inclusive production - *e.g. Jets, correlations, direct photons*

**Sivers** $\sim \sin(\phi_S)$

$\phi_S$—angle between spin and event plane

**Collins** $\sim \sin(\phi_S - \phi_h)$

$\phi_h$—angle of hadron around jet axis

---
Sivers and Collins Analyses for Jets at 200 GeV

\[ p^+ + p \rightarrow \text{jet} + X \]

\[ p_T (\text{GeV/c}) \]

\[ \pi^+ \text{ Asymmetry} \]
\[ \pi^- \text{ Asymmetry} \]

STAR measured transverse single-spin asymmetries for inclusive jet production at central pseudorapidity and \( \sqrt{s} = 200 \text{ GeV} \) (2006)

\[ A_{UT}^{\sin(\phi_S)} : \text{consistent with zero} \]

\[ A_{UT}^{\sin(\phi_S-\phi_h)} : \text{hints of non-zero asymmetry with charge-sign dependence} \]
2012 STAR data provide opportunity for higher precision and greatly reduced systematic uncertainties at $\sqrt{s} = 200$ GeV analysis well underway.

2011 STAR data provide opportunity for first measurements of central pseudorapidity inclusive jet asymmetries at $\sqrt{s} = 500$ GeV → Increased sensitivity to gluonic subprocesses

No sign of large asymmetry in preliminary results – consistent with 200 GeV and also with theoretical expectations.
• Probing Gluon Polarizations with Jets and $\pi^0$'s
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• Looking to the Future
Sivers Function and Sign Change
Prospects at STAR with W, Z, Drell-Yan

- $A_N$ in Drell-Yan, W/Z production at RHIC provide excellent complement to SIDIS
  - Attractive from a theoretical perspective (no frag. func. needed as for $\pi^0$'s, etc.)
  - Sivers function “famously” changes sign when comparing with transverse asymmetries from SIDIS
    - Collins, J. C., 2002, Phys. Lett. B 536, 43
  - Direct photon sign change as well
  - Probe wide range of $Q^2$
  - Test the universality and factorization of TMD’s, constrain their evolution – important tests of QCD

- Major targets for 2015-2016

- FMS (forward EM calorimetry) Preshower Upgrade in 2015
  - Allows separation among photons, $\pi^0$’s, charged hadrons, and electrons
  - Supports direct photon and DY measurements
A_N(W^+/-, Z^0) Results from 2011

- Preliminary results with 25 pb^{-1} of data
- Projections for 2016 show A_N(W^+/-, Z^0) will constrain sea quark Sivers distribution and make a statement on the Sivers sign change
- An excellent complement to SIDIS
  - No fragmentation (and so no fragmentation function uncertainty)
  - High Q^2

S. Fazio and D. Smirnov PoS(DIS2014)237

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Understanding Spin in Proton Collisions at STAR

- Probing Gluon Polarizations with Jets and $\pi^0$'s
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- Looking to the Future
Probing very low $x$ gluons with Forward Calorimeter Upgrade: 2020

**ECal:**
Tungsten-Powder-Scintillating-fiber
2.3 cm Moliere Radius, Tower-size: 2.5x2.5x17 cm$^3$
23 $X_0$

**HCal:**
Lead and Scintillator tiles, Tower size of 10x10x81 cm$^3$
4 interaction length
https://drupal.star.bnl.gov/STAR/starnotes/public/sn0605

\[
x_1 = \frac{1}{\sqrt{s}} \left( p_{T3} e^{\eta_3} + p_{T4} e^{\eta_4} \right)
\]
\[
x_2 = \frac{1}{\sqrt{s}} \left( p_{T3} e^{-\eta_3} + p_{T4} e^{-\eta_4} \right)
\]

Dijet measurements provide direct access, at leading order, to parton $x$’s (contrast inclusive jets)
Dijet Projections with the Forward Calorimeter Upgrade

$\sqrt{s} = 500 \text{ GeV}$

$-1 < \eta < 2$

$2.8 < \eta < 3.7$

$R_{\text{cone}} = 0.7$

$E_{T1} > 8 \text{ GeV}$

$E_{T2} > 5 \text{ GeV}$

$L = 1 \text{ fb}^{-1}$

$P = 60\%$

https://drupal.star.bnl.gov/STAR/starnotes/public/sn0605

B. Surrow PoS(DIS2014) 241

Probe gluons to $x \sim 10^{-3}$

An attractive probe at rather low $x$ before the EIC era
eRHIC and eSTAR (>2025) will offer unprecedented reach in $Q^2$ and $x$
Intrigued?

• By Spin Physics?
  – Studies on nucleon spin at PHENIX, K. Tanida in this session
  – The New Spin Physics Program of the COMPASS Experiment, L. Silva, Saturday 16:30

• By detector upgrades?
  – The Heavy Flavor Tracker and its performance in STAR at RHIC, S. Margetis, Tuesday 17:50
  – PHENIX Upgrade, E. Mannel, Tuesday 17:30

• By STAR?
  – STAR highlight talk on Heavy Ion Physics, S. Shi in this session
  – Quarkonia at STAR, B. Trzeciak, Saturday 15:50
  – Pion-kaon femtoscopy in Au+Au collisions at STAR, K. Poniatowska, Sat. 17:15
  – Open Heavy Flavor Measurements at STAR, D. Tlusty, Wed. 11:20
  – Overview of results from phase I of the Beam Energy Scan Program at RHIC, D. McDonald, last Tues.
Spin Physics at STAR

- Inclusive Jets
  - After 25 years, evidence of non-zero gluon polarization in the proton
- Pushing to lower $x$ gluons
  - With forward detectors, $\sqrt{s} = 510$ GeV, large datasets, detector upgrades
- W’s and Z’s improving our understanding of sea quark polarizations
- Exploration of large transverse asymmetries, $A_N$, continues
  - TMD (e.g. Sivers, Collins) and Twist-3 phenomenology
  - Efforts to disentangle initial-state (e.g. Sivers) and final-state (e.g. Collins) effects; and confirming both in a pp environment
  - Tests of universality, factorization, and evolution of TMD’s
- Large datasets on hand, analyses underway
  - 2011, 2012, 2013
- Detector upgrades continue
  - FGT forward tracking 2013, forward calorimetry: FPS+FMS 2015, FCS 2020
- Continuing data taking planned
  - 2015, 2016, and beyond
- Stay tuned!

A. Gibson, Valparaiso; STAR Spin Highlights; ICNFP

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| Year | #          | NSAC LRP Milestone                                                                 |
|------|------------|-----------------------------------------------------------------------------------|
| 2013 | HP8        | Measure flavor-identified $q$ and $\bar{q}$ contributions to the spin of the proton via the longitudinal-spin asymmetry of $W$ production. |
| 2013 | HP12 (update of HP1, met in 2008) | Utilize polarized proton collisions at center of mass energies of 200 and 500 GeV, in combination with global QCD analyses, to determine if gluons have appreciable polarization over any range of momentum fraction between 1 and 30% of the momentum of a polarized proton. |
| 2015 | HP13 (new) | Test unique QCD predictions for relations between single-transverse spin phenomena in p-p scattering and those observed in deep-inelastic lepton scattering. |
Relativistic Heavy Ion Collider as a Spin Collider

Concert of Facilities
- OPPIS → LINAC → AGS → RHIC

Polarized-proton Collider
- Mitigate effects of depolarization resonances with “Siberian Snakes”
- Polarization measured with CNI polarimeter
- Spin rotators provide choice of spin orientation independent of experiment

RHIC Beam Characteristics
- Clockwise beam: “blue”; counter-clockwise beam: “yellow”
- Spin direction varies bucket-to-bucket (9.4 MHz)
- Spin pattern varies fill-to-fill

Recent Spin Results from STAR - Drachenberg
Solenoidal Tracker at RHIC

Inclusive hadron measurements:
Barrel ElectroMagnetic Calorimeter (BEMC),
Endcap ElectroMagnetic Calorimeter (EEMC),
and
Forward Meson Spectrometer (FMS)

Jet and W/Z measurements:
TPC + Barrel + Endcap EMC
STAR’s Endcap Electromagnetic Calorimeter

- Scintillating strip SMD
  - $\phi$ segmented into 12 sectors
  - Two active planes
  - 288 strips per plane
- Resolution of a few mm

- Nucl. Instrum. Meth. A 499 (2003) 740.
- Lead/scintillator sampling EM calorimeter
  - Covers $1.09 < \eta < 2.00$ over full $2\pi$ azimuth
  - 720 optically isolated projective towers ($\sim 22 \times X_0$)
  - 2 pre-shower, 1 post-shower layers, and an additional shower maximum detector (SMD)
- Photon trigger places thresholds on maximum tower energy and the 3x3 patch of surrounding towers
Install 6 planes of GEM detectors

FGT = Forward GEM Tracker
GEM = gaseous electron multiplier

Improve charged particle tracking at very forward angles

Obtain better measurement of W decay particles
FPD EM Calorimeter
Small cells only
Two 7x7 arrays

FMS
Pb Glass EM Calorimeter
pseudo-rapidity 2.7<\eta<4.0
Small cells: 3.81x3.81 cm
Outer cells: 5.81 x 5.81 cm

Forward EM Calorimetry In STAR.
STAR Detector in 2014

HFT: Heavy Flavor Tracker, MTD: Muon Telescope Detector
STAR Detector in 2018-2019

**iTPC**: inner TPC, **EPD**: Event Plane and Centrality Detector, **ETOF**: End-cap TOF, **Fixed Target**
STAR Detector in 2021-2022

FCS/FTS: Forward Calrimeter/Tracking System, RP II: Full Roman Pot Phase II
STAR Detector in 2025+

CEMC: Central EM Calorimeter, eTRK: electron Tracker, TRD: Transition Radiation Detector
The very successful STAR detector will evolve into an EIC detector
Proton Helicity Structure

Dedicated detector
Current data for Sivers asymmetry:
- COMPASS $h^\pm$: $P_{hT} < 1.6$ GeV, $z > 0.1$
- HERMES $\pi^{0,\pm}, K^{\pm}$: $P_{hT} < 1$ GeV, $0.2 < z < 0.7$
- JLab Hall-A $\pi^{\pm}$: $P_{hT} < 0.45$ GeV, $0.4 < z < 0.6$

Planned:
- JLab 12

$Q^2 = 6400$ GeV$^2$
\( \pi^0 A_{LL} \) Prospects in 2012 Dataset

- Work underway at STAR with 2012 dataset (x10 luminosity) at intermediate pseudorapidity
  - Large improvement in stat. uncertainty projected, as shown
- And with 2012 and 2013 datasets at forward pseudorapidity

- Higher CoM energy
  - 200 \rightarrow 510 \text{ GeV}
  - Pushes to lower \( x \) \( g \)

2006 data
PRD 89, 012001 (2014)

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• DSSV++
- DSSV 14

FIG. 1 (color online). Gluon helicity distribution at $Q^2 = 10 \text{ GeV}^2$ for the new fit, the original DSSV analysis of [3], and for an updated analysis without using the new 2009 RHIC data sets (DSSV*, see text). The dotted lines present the gluon densities for alternative fits that are within the 90% C.L. limit. The $x$ range primarily probed by the RHIC data is indicated by the two vertical dashed lines.
Inclusive jet projections

- Significant improvement in statistical precision with data collected in 2011-2013 and expected in 2015
- Expect to reduce uncertainties on $\Delta g$ by a factor of $\sim 2$

\[ A_{LL} \]

\[ x_T = \frac{2p_T}{\sqrt{s}} \]
Results from 2012 W’s

![Graph showing results from 2012 W’s with various notations and arrows pointing to different data points and chi-squared values.]

DSSV+: DSSV+COMPASS
DSSV++: DSSV+ & STAR-W 2012
DSSV++: DSSV+ & RHIC-W proj. (2009-2013)

[arXiv:1404.6880] [Accepted by PRL]

[See also new NNPDF fit arXiv:1406.5539]

A. Gibson, Valparaiso; STAR Spin Highlights; ICNFP
Includes Forward GEM Tracker at STAR, fully installed in 2013

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Theory: TMDs vs. Twist-3

Intermediate $Q_T$
$Q \gg Q_T/p_T \gg \Lambda_{QCD}$

Transverse momentum dependent
$Q \gg Q_T = \Lambda_{QCD}$
$Q \gg p_T$

Collinear/twist-3
$Q, Q_T \gg \Lambda_{QCD}$
$p_T \sim Q$

Need 2 scales $Q^2$ and $p_t$
Remember $pp$: most observables one scale
Exception: $DY, W/Z$-production

Need only 1 scale $Q^2$ or $p_t$
But should be of reasonable size
should be applicable to most $pp$ observables $A_N(\pi^0/\gamma/jet)$
$A_N$: How to get to THE underlying Physics

Goal: measure less inclusive

**SIVERS/Twist-3**

- $A_N$ for $\pi^0$ and $\eta$ with increased $p_T$ coverage
- $A_N$ for jets, direct photons
- $A_N$ for heavy flavour $\rightarrow$ gluon
- $A_N$ for $W^{+/-}, Z^0$

**Collins Mechanism**

- Rapidity dependence of
  - $A_N$ for $\pi^0$ and $\eta$ with increased $p_T$ coverage
  - $A_N$ for jets, direct photons
  - $A_N$ for heavy flavour $\rightarrow$ gluon

- Asymmetry in jet fragmentation
  - $\pi^+/\pi^0$ azimuthal distribution in jets
  - Interference fragmentation function

Sensitive to **proton spin** – parton **transverse motion** correlations not universal between SIDIS & pp

Sensitive to **transversity** universal between SIDIS & pp & $e^+e^-$
$p^+ + p \rightarrow \pi^0 + X$

- E704, $\sqrt{s} = 19.4$ GeV
- STAR, $\sqrt{s} = 200$ GeV, $\langle \eta \rangle = 3.3$
- STAR, $\sqrt{s} = 200$ GeV, $\langle \eta \rangle = 3.7$
- STAR, $\sqrt{s} = 200$ GeV, $\langle \eta \rangle = 1.5$
- PHENIX, $\sqrt{s} = 62.4$ GeV, $3.1 < \eta < 3.8$

$A_N$

$\langle p_T \rangle$ [GeV/c] vs $x_F$
The famous sign change of the Sivers fct.

critical test for our understanding of TMD’s and TMD factorization
Twist-3 formalism predicts the same

QCD:

**DIS:**
γq-scattering
attractive FSI

**pp:**
qqbar-anhilation
repulsive ISI

\[ S_{\text{Sivers}}^{\text{DIS}} = -S_{\text{Sivers}}^{\text{DY}} \text{ or } S_{\text{Sivers}}^{\text{W}} \text{ or } S_{\text{Sivers}}^{Z_0} \]

\( A_N(\text{direct photon}) \) measures the sign change through Twist-3

will also be \( A_N(\text{DY}) \) and \( A_N(W^{\pm}/Z^0) \) test of TMD evolution

All three observables can be attacked in
one 500 GeV Run by STAR
STAR Detector

Time Projection Chamber (TPC) Charged Particle Tracking $|\eta|<1.3$

Barrel Electromagnetic Calorimeter (BEMC): $|\eta|<1$

Endcap Electromagnetic Calorimeter: $1<\eta<2$

$\eta = 0$

$\eta = 1$

$\eta = -\ln(\tan(\theta/2))$
