NUCLEON SPIN STRUCTURE – FUTURE EXPERIMENTS

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…+ JPARC, …
Where are we now?

What do we hope to learn in the (not-too distant) future?

What experiments are “on the books”?
- Ongoing Program at RHIC and COMPASS
- Jefferson Lab at 12 GeV (2014…)
- [Apologies to JPARC, FAIR, FNAL,…]
- The more distant future: EIC

Conclusion and Outlook
INTRODUCTION

The Nucleon – pre 1960s
Static properties

The Nucleon at moderate resolution…
Valence quark distributions

…a closer look…
Gluons and sea quarks

… and at very high resolution
“wee partons” at small momentum fraction x
INTRODUCTION

The Nucleon – pre 1960s
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…a closer look…
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… and at very high resolution
“wee partons” at small momentum fraction $x$
LONGITUDINAL SPIN STRUCTURE

What would we LIKE to observe?

Traditional “1-D” Parton Distributions (PDFs)
(inclusive, integrated over many variables)

\[ q(x, h \cdot H; Q^2) \]

\[ q_1(x) = \frac{1}{2} \sum_i e_i^2 \Delta q_i(x) \]

\[ \Delta q = q \downarrow \uparrow - q \uparrow \uparrow \sim \left< P, s \left| \bar{q} \gamma^\mu \gamma^5 q \right| P, s \right> \]

Integrated over all momentum fractions \( x \): Total fraction of nucleon spin carried by quark helicities
Remaining contributions must come from quark orbital angular momentum and gluons:

\[ \frac{1}{2} = S_p = \frac{1}{2} \sum_i \int_0^1 \Delta \Sigma \Delta q(x) dx + L_q + J_G \]
PRESENT SITUATION

Asymmetries in pp at RHIC

DSSV:
PRL 101, 072001 (2008)
WHAT’S MISSING?

- $\Delta u/u$ and $\Delta d/d$ at high $x$ still poorly constrained
- What is happening with the strange sea polarization? $>0? =0? <0?$ Zero crossing? (Tension DIS – SIDIS)
- Is the sea polarization isospin-symmetric? (note: we already know $\bar{u} \neq \bar{d}$)
- Gluon helicity distribution at large $x$ and a small $x$? What is the integral $\Delta G$?
- What happens at really small $x << 0.01$?
- … and where is the rest of the nucleon spin? (only 30-40% explained by quark helicities)
  Orbital angular momentum of quarks, total angular momentum carried by gluons...
BEYOND THE 1-D PICTURE

What would we LIKE to observe?

Traditional “1-D” Parton Distributions (PDFs)
(inclusive, integrated over many variables)

$q(x, h \cdot H; Q^2)$

3-D Picture of parton flavor, spin and momentum (TMDs)

$q(H, \vec{S}_\perp, x, \vec{k}_\perp, h, \vec{s}_\perp; Q^2)$

3-D parton orbits (GPDs)

$q(\vec{S}, x, \vec{r}_\perp, \vec{s}; Q^2)$
BEYOND INCLUSIVE:

What CAN we observe?

Example: TMDs

- Have 2 pseudoscalars \((h, H)\), 2 vectors \((\hat{z}, \vec{k} \perp)\) and 2 axial vectors \((\vec{S} \perp, \vec{s} \perp)\)
- Observables depend on \(x\) (and \(Q^2\)) and must be scalars!
- 3 possibilities without \(\vec{k} \perp\):
  - 1 (ordinary PDFs \(\Rightarrow\) unpolarized structure function \(F_1\))
  - \(H \cdot h\) (helicity PDFs \(\Rightarrow\) spin structure function \(g_1\))
  - \(\vec{S} \perp \cdot \vec{s} \perp\) (transversity PDFs/structure function \(h_1\))
- 4 possibilities linear in \(\vec{k} \perp\):
  - \(H(\vec{k} \perp \cdot \vec{s} \perp), h(\vec{k} \perp \cdot \vec{S} \perp)\) (“Worm gear” PDFs \(g_{1T}, h_{1L}\))
  - \(\vec{S} \perp \cdot (\vec{k} \perp \times \hat{z}), \vec{s} \perp \cdot (\vec{k} \perp \times \hat{z})\) (Sivers, Boer-Mulders PDFs \(f_{1T}, h_{1T}\))
- Further possibilities quadratic in \(\vec{k} \perp\):
  - “Pretzelosity” \(h_{1T} \perp (\vec{k} \perp \cdot \vec{S} \perp) \cdot (\vec{k} \perp \cdot \vec{s} \perp) - \frac{1}{2} (\vec{S} \perp \cdot \vec{s} \perp)^2 \vec{k}^2 \)
  - \((\vec{k} \perp)^2\) moments of the first three!

Preferably all sorted by quark flavor and for gluons, as well!
TOWARDS A COMPLETE PICTURE:

HOW can we access it?

Electroweak Probe to “see” partons…

DIS ⇒ $F_1$, $g_1$

(1D only, no flavor tagging)

DVCS ⇒ GPDs

...+ extra hadrons to access all observables:

Drell-Yan

SIDIS

W production

Hadron Production
THE PRESENT SITUATION - TMDs

A full program to measure 8 TMDs has just begun...

Fit by Anselmino et al.

Transversity

Sivers Functions
WHAT’S MISSING?

- Tensor charge of the nucleon (analog to vector and axial charges)
- Full mapping of all 11 TMD PDFs as a function of quark flavor in the valence region
- Test of universality
- Test of prediction that time-odd TMDs (e.g., Sivers asymmetry) change sign in Drell-Yan processes
- TMDs of sea quarks and gluons
- Towards a “wave function” of the nucleon including angular orbital momentum (Wigner distribution? Lattice comparison?)
THE FUTURE PROGRAM
WITH COMPASS

- More statistics on TMDs (Data 2010 on transverse p)
- More statistics on $A_{1p}$ (inclusive and tagged) (Data 2011)
- COMPASS-II: Focus on transverse structure of the nucleon
- GPDs: towards orbital angular momentum
- Drell-Yan: Measure TMDs like Sivers, Boer-Mulders, “worm-gear”, “pretzel velocity”

- First two are T-odd: Should reverse sign in Drell-Yan => test!

\[
\left. f_{1T} \right|_{DY} = -\left. f_{1T} \right|_{DIS} \quad \text{and} \quad \left. h_1 \right|_{DY} = -\left. h_1 \right|_{DIS}
\]

Sivers \hspace{1cm} Boer-Mulders
THE COMPASS SPECTROMETER

60 m long

Polarization ≈ 75% from weak pion decay

…will be upgraded for COMPASS II
DRELL-YAN (2014?)

\[ 2.0 \leq M_{\mu\mu} \leq 2.5 \text{ GeV}/c^2 \]

\[ 4.0 \leq M_{\mu\mu} \leq 9.0 \text{ GeV}/c^2 \]
PP PROGRAM AT RHIC  

RHIC: expected to increase Pol. (50% -> 65%), lumi (x3 ?)

STAR + PHENIX upgrades complete for 2012

- Extend x-range for measurements of $\Delta G$:
  - Asymmetric final state ($\pi, \eta, \gamma, \text{jets, etc.}$)
  - Higher CM energy
- (Anti)quark polarization through W production
- pp collisions with single transverse spin -> TMDs, FFs (jet, dijet, dihadron production); universality?
- Polarized Drell-Yan

AnDY: test bed for Drell-Yan experiment to measure SSAs
Since $W$ production is maximally parity violating $\rightarrow W$'s couple only to one parton helicity large $\Delta u$ and $\Delta d$ result in large asymmetries.
EXPECTED RESULTS

Present Situation:

Goal

PHENIX

J. Haggerty (ICHEP 2010)

PHENIX

p^+ + p \rightarrow W^+ + X \rightarrow e^+ + X

STAR

\( \sqrt{s} = 500 \text{ GeV} \)

\( 25 < E_T < 50 \text{ GeV} \)

\( A_L = \frac{\sigma_+ - \sigma_-}{\sigma_+ + \sigma_-} \)

Syst. uncertainty due to background\n
wtd evt. asym. uncertainty of 3.2%

\( \eta \)

DRELL YAN AT RHIC

$A_N^{DY} @ IP-2$

- Idea: have DY feasibility test at IP-2
  - staged measurements over 3 years
  - re-use as much detector equipment as possible to finish till summer 2014

- Measurement:
  - why IP-2
    - transverse polarization
    - measure parallel to $\sqrt{s} = 500$ GeV W-program
  - $\eta > 3, M > 4$ GeV $0.1 < x_f < 0.3$
  - optimizes Signal / Background & DY rate
  - measure $\delta A_N^{DY} \sim 0.015$ for $\int L \sim 100$ pb$^{-1}$

- Proposal approved June 2011 BNL PAC
CLOSE-OUT 6 GeV

- Finish analysis on CLAS eg1-DVCS (SSAs + DSAs in $\pi^{+/0/-}$ production with longitudinally polarized H and D targets) and EG4 (SSFs at low $Q^2$)
- $g_{2p}$ at low $Q^2$ (Hall A)
- Test electron run on HD-ICE

12 GEV PROGRAM (6.6, 8.8 and 11 GeV in Halls A/B/C)

- Inclusive SSFs on p, d, n ($^3$He) in all 3 Halls
- Tagged SSFs and TMDs on p, d, n ($^3$He) in all 3 Halls (including Kaons)

GOAL: Complete map of all PDFs in the valence region $x > 0.1$
NEW CAPABILITIES – HALL A

Super Big Byte

- (Moderately) large acceptance
- Full PID (K and π)
- Well-matched to high-luminosity $^3$He target

SoLID

- Large acceptance (2π)
- Kinematic coverage out to moderately large $P_T$
- Capable of quite high luminosity ($10^{36}$ cm$^{-2}$s$^{-1}$)
- Requires major new funds
POLARIZED 3He TARGETS (APPROX. POL. NEUTRON)
NEW CAPABILITIES – HALL B

CLAS12
(see next slide)

- VERY large acceptance
- Full PID (K and $\pi$)
  (K ID requires major new funds for RICH)
- Moderately high luminosity ($10^{35}$ cm$^{-2}$s$^{-1}$)
  (matched to NH$_3$, ND$_3$)

Polarized Targets

- Standard DNP longitudinal NH$_3$, ND$_3$ targets
  (funded by NSF MRI, under construction)
- HD-Ice target
  (suitability for e$^-$ beam remains to be demonstrated)

Future longitudinally polarized target for CLAS12 (11 GeV program at Jefferson Lab)
- Horizontal $^4$He evaporation cryostat
- 5 T B-field provided by central detector
Base equipment

- Forward Detector
  - TORUS magnet
  - Forward vertex tracker
  - HT Cherenkov Counter
  - Drift chamber system
  - LT Cherenkov Counter
  - Forward ToF System
  - Preshower calorimeter
  - E.M. calorimeter
- Central Detector
  - SOLENOID magnet
  - Barrel Silicon Tracker
  - Central Time-of-Flight

Proposed equipment

- Micromegas (CD & FD)
- RICH counter (FD)
- Neutron detector (CD)
- Small angle tagger (FD)

Under construction; expected to begin data taking in 2015 with upgraded 11 GeV beam
NEW CAPABILITIES – HALL C

Super HMS

- High momentum capability and resolution
- Full PID
- High luminosity polarized $^3$He target (as in Hall A)
INCLUSIVE SSF – HALLS A/C

$^3$He $\rightarrow A_{1n}, g_{1n}$
Important constraint on $\Delta d$ at large $x$

Hall A – BigByte

Hall C – SHMS+HMS

E12-06-122

E12-06-110
INCLUSIVE + TAGGED SSF – HALL B

Improved PDFs from NLO analyses

Better determination of Higher Twist vs. $x$

Improved coverage to evaluate moments

Inclusive $A_1$

SIDIS $A_1$
TMDS – HALL A

First generation: Use transverse $^3$He target with Bigbite and Super Bigbite to measure Sivers, Collins (transversity), “worm-gear” and “pretzelosity” SSAs for $\pi$ and K
Later on: Use longitudinal and transverse $^3$He target (and perhaps transverse p) with SoLID to measure all SSAs (TMDs) for $\pi$. 

**Proton**

- P12-11-108

**Transverse**

- E12-10-006

**Longitudinal**

- P12-11-007
### Comprehensive Program with **Longitudinal** and **Transverse** H, D target

<table>
<thead>
<tr>
<th>Experiment</th>
<th>Quantity</th>
<th>Physics</th>
<th>Target</th>
<th>particle species</th>
<th>Kinematics</th>
<th>beam request</th>
<th>run group</th>
</tr>
</thead>
<tbody>
<tr>
<td>E12-07-107</td>
<td>$A_{UL}^*$, $A_{UL}^{*2\phi}$</td>
<td></td>
<td>NH$_3$ ND$_3$</td>
<td>$\pi^+, \pi^-$, $\pi^0$</td>
<td>$x=0.1-0.7$</td>
<td>30 days</td>
<td>50 days</td>
</tr>
<tr>
<td>E12-09-007b</td>
<td>$\Delta u$, $\Delta d$, $\Delta s$</td>
<td>$x(\Delta u-\Delta d)$</td>
<td>NH$_3$ ND$_3$</td>
<td>$\pi^+, \pi^-$, $\pi^0$</td>
<td>$K^+$, $K^-$, $K^0_s$</td>
<td>x=0.1-0.7</td>
<td>30 days</td>
</tr>
<tr>
<td>E12-09-009</td>
<td>$A_t^*$, $A_{UL}^{*2\phi}$</td>
<td></td>
<td>NH$_3$ ND$_3$</td>
<td>$\pi^+, \pi^-$, $\pi^0$</td>
<td>$K^+$, $K^-$, $K^0_s$</td>
<td>$Q^2=1-9$</td>
<td>30 days</td>
</tr>
<tr>
<td>PR12-11-109b</td>
<td>$A_{UL}$</td>
<td>$h_L$</td>
<td>NH$_3$ ND$_3$</td>
<td>$\pi\pi$, $KK$</td>
<td>$x=0.05-0.6$</td>
<td>30 days</td>
<td>50 days</td>
</tr>
<tr>
<td>PR12-11-111</td>
<td>SIDIS $A_{UT}$</td>
<td>Sivers, Transversity, Pretzelosity</td>
<td>HD</td>
<td>$\pi^+, \pi^-$, $\pi^0$</td>
<td>$K^+$, $K^-$, $K^0_s$</td>
<td>$Q^2=1-10$ GeV$^2$</td>
<td>100 days</td>
</tr>
</tbody>
</table>

**Worm gear, HT**

- Flavor tagging ($\Delta q$); $p_T$ dep.
- Kaons Worm gear
- Two-Hadron (Deferred)

**Transversity, Sivers, Worm Gear, Pretzelosity**
TMDS – CLAS12 (LONG. POL. P,D)

\[ A_1 \rho_T \text{ distr.} \]

\[ \pi^+, \pi^-, \pi^0 \]

\[ \sin \phi \] (Higher Twist)

\[ u \text { quark} (\pi^+) \]

Worm Gear
TMDS – CLAS12
TRANSVERSE HD-ICE (?)

Sivers

Collins

worm gear,
pretzelosity
THE FUTURE: EIC OPTIONS

(2025?)

Both: About $10^{34}$ cm$^{-2}$ s$^{-1}$ (e-nucleon) per interaction point (IP) $\sim$ to $E_p$

EIC at Jefferson Lab

$\sqrt{s} =$14 GeV

MEIC $=$ 1$^{st}$ stage

$\sqrt{s} =$50 GeV

ELIC $=$ 2$^{nd}$ stage

$\sqrt{s} =$105 GeV

$\sqrt{s} =$140 GeV

ERHIC

$\sqrt{s} =$325 GeV p or 130 GeV/u Au

Both: About $10^{34}$ cm$^{-2}$ s$^{-1}$ (e-nucleon) per interaction point (IP) $\sim$ to $E_p$
EIC: SSF EXAMPLE

Pin down $\Delta q$ and especially $\Delta G$ to the lowest $x$ possible

From INT 2010
arx1108p1713v1
SUMMARY: COMPLETING THE PICTURE

- $\Delta u/u$ and $\Delta d/d$ at high $x$ still poorly constrained
- What is happening with the strange sea polarization?
  $>0$? $=0$? $<0$? Zero crossing? (Tension DIS – SIDIS)
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