Central Questions in Nucleon Structure

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Exploring the nucleon:
Of fundamental importance in science

Know what we are made of!

Test our ability to use QCD:
Asymptotic Freedom, Factorization

Explore and Understand QCD:
Lattice, Models

Nucleon as tool for discovery:
RHIC Heavy Ions, LHC Tevatron High-\(E_T\) jets NuTeV anomaly, ...
- We can probe the quark-gluon structure of the Nucleon in short-distance processes:

- Diverse probes: DIS, DVCS, Drell-Yan, pp→jetX, ...

\[ \frac{1}{Q} \]
Questions to ask:

- What are the momentum distributions of quarks, anti-quarks, and gluons? \( p = xP \)
- What flavor symmetries hold—or how are they broken? \( \bar{u} \) vs. \( \bar{d} \), \( s \) vs. \( \bar{s} \)? Isospin-symmetry between \( p \) and \( n \)?
- How are quarks and gluons distributed spatially?
- How do partons carry the proton spin-1/2? (Spins & orbital angular momenta)
- What difference does $\leftarrow$ vs. $\rightarrow$ make? What novel features arise?
- How are quarks and gluons correlated?
These are central questions of the field.

The challenge is: Map out the Nucleon

Its complete spin, flavor, gluon landscape

- We have a pretty good picture of some aspects
- We are learning about others
- We are still in the dark in many cases

We’ll have a good chance to get all the answers with present and next-generation facilities!
Momentum distributions of quarks and gluons
• **An important part of our picture of the nucleon:**
  
  Gluons rule at small-\(x\)!

• **We know a lot, but ...**
• but ... some aspects little understood, for example:

  sea quarks and gluon at high-\(x\), valence at very-high-\(x\)

Testing ground for models of Proton wave function
Measure at Jlab-12 GeV
  sea: DY

Not an academic problem: LHC
Measure at HERA, EIC
$F_L \propto \frac{\alpha_s}{2\pi} x \int_x^1 \frac{d\xi}{\xi} \xi (1 - \xi) g \left( \frac{x}{\xi}, Q^2 \right) + \ldots$

One observable among many: $dF_2/d\log(Q^2)$, $ep \rightarrow \text{jet+jet+X}$, charm, ...
Helicity structure of the Nucleon

\[ \Delta q(x) = \begin{array}{c} \text{Diagram} \\ - \end{array} \]

\[ \Delta g(x) = \begin{array}{c} \text{Diagram} \\ - \end{array} \]
A major motivation: Explore the proton spin!

\[ \frac{1}{2} = \frac{1}{2} \Delta \Sigma + \Delta G + L_q + L_g \]

- q+\bar{q} spin contribution
- Gluon spin contribution
- Orbital ang. momenta

\[ \frac{1}{2} \int_0^1 dx \left[ \Delta u + \Delta \bar{u} + \Delta d + \Delta \bar{d} + \Delta s + \Delta \bar{s} \right] \]

\[ \int_0^1 dx \Delta g(x) \]

“Quotable” properties of the proton
How sure are we?
And, what are the details?

$g_1(x, Q^2)$

$\Delta u + \Delta \bar{u} + \Delta d + \Delta \bar{d} + \Delta s + \Delta \bar{s}$

$q$ and $\bar{q}$ spins carry
$\sim 25\%$ of proton spin

How sure are we?
And, what are the details?
• **Rests on a number of things:**

  • small-x extrapolation of structure function
  
  • at small-x, typically $Q^2$ small as well. Higher twists?

  To really nail it down, need measurements at lower $x$. And: at current $x$, but higher $Q^2$ → **EIC**

• use of SU(3) symmetry:

$$
\int_0^1 dx \, g_1 = \frac{1}{9} \Delta \Sigma + \frac{1}{12} [\Delta u + \Delta \bar{u} - \Delta d - \Delta \bar{d}] + \frac{1}{36} [\Delta u + \Delta \bar{u} + \Delta d + \Delta \bar{d} - 2(\Delta s + \Delta \bar{s})]
$$

\[ g_A = 1.257 \pm \ldots \]

\[ 3F - D = 0.575 \pm 0.05 \]

Bjorken
• if all true, current picture is:

\[
\frac{1}{2} \Delta \tilde{h} \\
\frac{1}{2} (\Delta u + \Delta \tilde{u}) \\
\frac{1}{2} (\Delta s + \Delta \bar{s}) \\
\frac{1}{2} (\Delta d + \Delta \bar{d})
\]

• is it correct?

• would like to know more: \( \Delta \tilde{u} \) vs. \( \Delta \bar{d} \) vs. \( \Delta \bar{s} \) etc.
• **Important applications for models:**

\[
|p\rangle = \begin{array}{c}
\frac{1}{\sqrt{2}} \left( \begin{array}{c}
|u\rangle \\
|d\rangle
\end{array} \right) + \begin{array}{c}
\frac{1}{\sqrt{2}} \left( \begin{array}{c}
|u\rangle \\
|d\rangle
\end{array} \right) + \begin{array}{c}
\frac{1}{\sqrt{2}} \left( \begin{array}{c}
|u\rangle \\
|d\rangle
\end{array} \right) + \ldots
\end{array}
\end{array}
\]

**Many models predict** \(\Delta \bar{u} > 0\), \(\Delta \bar{d} < 0\)

Thomas, Signal, Cao; Holtmann, Speth, Fässler; Diakonov, Polyakov, Weiss; Glück, Reya; Schäfer, Fries; Kumano; Wakamatsu; ...

**Various avenues for addressing these questions**
At RHIC:

\[ A_{L}^{PV} = \frac{\sigma_{+} - \sigma_{-}}{\sigma_{+} + \sigma_{-}} \]

- W+charm at RHIC-II

unpol.
In lepton scattering: “SIDIS”

- Major topic at Jlab-12 GeV
EIC:

J. Seele

also, at EIC:

$g_5 \propto \Delta u - \Delta d - \Delta s$

$\sin^2(\Theta_W)$?
• **Bjorken’s sum rule**

\[
\int_0^1 dx \, g_1^{ep-en}(x, Q^2) = \frac{1}{6} \frac{g_A}{g_V} \left\{ 1 - \frac{\alpha_s(Q^2)}{\pi} - \frac{43}{12} \frac{\alpha_s^2(Q^2)}{\pi^2} - 20.215 \frac{\alpha_s^3(Q^2)}{\pi^3} \right\}
\]

high-order perturbation theory

\[
+ \frac{M^2}{Q^2} \int_0^1 x^2 \, dx \left\{ \frac{2}{9} g_1^{ep-en}(x, Q^2) + \frac{1}{6} g_2^{ep-en}(x, Q^2) \right\}
\]

target-mass corrections

\[- \frac{1}{Q^2} \frac{4}{27} F_u - d(Q^2) \quad \text{Twist-4 matrix elements} \sim \langle \bar{q} \tilde{F} q \rangle\]

• Precision QCD. Currently tested at \(\sim 10\%\).
   Can it be tested at \(\sim 1\) or \(2\%\)?
The gluon spin distribution $\Delta g$

Not much information until recently:

$$\frac{d g_1}{d \log(Q^2)} \propto \frac{\alpha_s}{2\pi} P_{ag} \otimes \Delta g(x, Q^2) + \text{quark contrib.}$$

Bag model Chen, Ji $\Delta G \approx 0.3$

$\Delta G \approx 1.8 \text{ (@ 1GeV}^2\text{)}$

"axial anomaly" Altarelli et al.

$\Delta G \approx 0.4$

$\Delta G \approx -1.7$
• NOW:

PHENIX Preliminary

- Run5 Photon Trigger
- Run6 Photon Trigger, high $p_T$

GRSV-max

$\Delta g = -g$

GRSV-std

$\Delta g = 0$

Scaling error of 40% is not included.

$A_{LL}(\Delta g/g)$

jet(s), $c\bar{c}$, ...

HERMES, COMPASS
Challenge will be to really extract $\Delta g$ and its integral:

$$\Delta \sigma = \sum_q \int dx_g \int dx_q \Delta g(x_g, p_T) \Delta q(x_q, p_T) \Delta \hat{\sigma}^{gg}(x_g, x_q, p_T, \alpha_s(p_T)) + \ldots$$

$\rightarrow$ Need “Global analysis”

Eventually, for integral will likely need additional information, in particular from smaller $x$

$\sim$ RHIC 200 GeV midrap. data
- RHIC at 500 GeV, and with jet+jet, gamma+jet at forward kinematics
- An Electron-Ion Collider!
\[ \frac{dg_1}{d\log(Q^2)} \propto -\Delta g(x, Q^2) \quad \text{at small } x \]

\[ E_e = 7, E_p = 150 \text{ at } L = 10^{33} \]
What’s the structure of a Transversely polarized Nucleon?
Transversity:

\[ \delta q(x) = + - \]

\[ \sim \]

in helicity basis:

Helicity-flip!

Ralston, Soper; Jaffe, Ji; ...
the physics involved:

* “odd chirality”  $\rightarrow$ helicity-flip, $\chi_{SB}$

* no mixing with gluons

* tensor charge

\[
\langle P | \bar{q} i \sigma^{\mu \nu} \gamma^5 q | P \rangle = \int_0^1 dx \left[ \delta q(x) - \delta \bar{q}(x) \right]
\]

* difference to helicity probes relativistic / dynamical effects
• Opportunities for measurement?

* not in inclusive DIS, but:

```
π
```

“Collins effect”
→ azimuthal asym.

* this effect actually appears to be there: HERMES
information on Collins fragm. fct. has become available from BELLE in $e^+e^- \rightarrow \pi\pi X$
The future:

- **SIDIS at COMPASS, Jlab-12 GeV**
- **Collins-type asymmetries at RHIC**
- **Drell-Yan:**

![Diagram of Drell-Yan process]

- **azimuthal asymmetries in SIDIS at EIC**
Transverse spin offers further new insights into Nucleon structure.

\[ \text{correlation } \sim \vec{S}_T \cdot \left( \vec{P} \times \vec{k}_T \right) \]

Sivers
Where would this show up?

\[ e p \uparrow \rightarrow e \pi X \]

\[ \sin(\phi - \phi_S) \sum_q e_q^2 f_{1T}^{q}(x) D_q(z) \]

SMC, HERMES, COMPASS, CLAS

Seen!
In pp scattering: involved (in disguised form) in large "left-right" asymmetries

\[ A_N = \frac{L - R}{L + R} \]
What’s the physics of the Sivers functions?

• involves orbital angular momentum

• T-invariance of QCD: they involve a “rescattering” in the color field of the remnant

Probes overlap of proton wave fcts. with $J_z = \pm 1/2$

Attractive!
• intuitive (model-based) picture:

![Diagram showing a proton interacting with a photon and quarks](image)
profound physics implication:
→ process-dependence of Sivers functions

DIS: “attractive”
DY: “repulsive”

\[ \text{Sivers}|_{\text{DIS}} = -\text{Sivers}|_{\text{DY}} \]

hugely important in QCD -- tests much of what we know about description of hard processes
Many avenues for important measurements:

- **Drell-Yan**
  - RHIC / RHIC-II
  - GSI, J-PARC

- correlations in $pp \rightarrow \text{jet+jet X}$ at RHIC (now data!)

- detailed studies of azimuthal asymmetries in SIDIS at EIC at high $Q^2$
What’s the spatial structure of the Nucleon?
Over the last decade, theory has understood that parton distributions and form factors are special cases of a much more powerful representation of nucleon structure: “Generalized Parton Distributions”

Müller, Robaschik; Ji; Radyushkin

- **$x$:** average quark momentum fraction
- **$\xi$:** “skewing parameter” = $x_1 - x_2$
- **$t$:** 4-momentum transfer $^2$
What we dream of:

Tomographic images of the nucleon:

\[ \int d^2 \Delta_\perp e^{-i\Delta_\perp \cdot b_\perp} H_q(x, \xi = 0, -\Delta^2_\perp) = q(x, b_\perp) \]

At EIC: spatial distribution of sea and glue
Quantify orbital motion of partons in nucleon

\[ J_q = \frac{1}{2} \lim_{t \to 0} \int dx \, x \left[ H_q(x, \xi, t) + E_q(x, \xi, t) \right] \]

\[ = \frac{1}{2} \Delta q + L_q \]

GPDs have potential to take our picture of the nucleon to a new level.
HE setup: $e^{+/-} (10 \text{ GeV}) + p (250 \text{ GeV})$ \hspace{1cm} L = $4.4 \cdot 10^{32} \text{ cm}^{-2}\text{s}^{-1}$ \hspace{1cm} 38 pb$^{-1}$/day

LE setup: $e^{+/-} (5 \text{ GeV}) + p (50 \text{ GeV})$ \hspace{1cm} L = $1.5 \cdot 10^{32} \text{ cm}^{-2}\text{s}^{-1}$ \hspace{1cm} 13 pb$^{-1}$/day

Sandacz

Precision of DVCS unpolarized cross sections

for one out of 6 $Q^2$ intervals 
($8 < Q^2 < 15 \text{ GeV}^2$)

$\langle Q^2 \rangle = 10.4 \text{ GeV}^2$

Projected results

- also: gluon imaging with exclusive $J/\Psi$

Frankfurt, Strikman, Weiss
The challenge is: Map out the Nucleon
Its complete spin, flavor, gluon landscape

We'll have a good chance to get all the answers with present and next-generation facilities!
• a little further into the future: prompt photons

\[ \vec{p} + \vec{p} \rightarrow \gamma + \text{jet} + X \text{ with STAR + EEMC at} \]
\[ \sqrt{s} = 200 \text{ GeV (320 pb}^{-1}) + \sqrt{s} = 500 \text{ GeV (800 pb}^{-1}) \]
RHIC offers great possibilities to probe $\Delta g$:

<table>
<thead>
<tr>
<th>Reaction</th>
<th>Dom. partonic process</th>
<th>probes</th>
<th>LO Feynman diagram</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\bar{p}p \rightarrow \pi + X$ [61, 62]</td>
<td>$\bar{g}g \rightarrow gg$</td>
<td>$\Delta g$</td>
<td>![Diagram 1]</td>
</tr>
<tr>
<td>$\bar{p}p \rightarrow \text{jet(s)} + X$ [71, 72]</td>
<td>$\bar{g}g \rightarrow gg$</td>
<td>$\Delta g$</td>
<td>(as above)</td>
</tr>
<tr>
<td>$\bar{p}p \rightarrow \gamma + X$</td>
<td>$\bar{g}g \rightarrow \gamma q$</td>
<td>$\Delta g$</td>
<td>![Diagram 2]</td>
</tr>
<tr>
<td>$\bar{p}p \rightarrow \gamma + \text{jet} + X$</td>
<td>$\bar{g}g \rightarrow \gamma q$</td>
<td>$\Delta g$</td>
<td>![Diagram 3]</td>
</tr>
<tr>
<td>$\bar{p}p \rightarrow \gamma\gamma + X$ [67, 73, 74, 75, 76]</td>
<td>$\bar{g}g \rightarrow \gamma\gamma$</td>
<td>$\Delta q, \Delta \bar{q}$</td>
<td>![Diagram 4]</td>
</tr>
<tr>
<td>$\bar{p}p \rightarrow DX, BX$ [77]</td>
<td>$\bar{g}g \rightarrow c\bar{c}, b\bar{b}$</td>
<td>$\Delta g$</td>
<td>![Diagram 5]</td>
</tr>
<tr>
<td>$\bar{p}p \rightarrow \mu^+\mu^-X$ (Drell-Yan) [78, 79, 80]</td>
<td>$\bar{q}q \rightarrow \gamma^* \rightarrow \mu^+\mu^-$</td>
<td>$\Delta q, \Delta \bar{q}$</td>
<td>![Diagram 6]</td>
</tr>
<tr>
<td>$\bar{p}p \rightarrow (Z^0, W^\pm)X$ [78]</td>
<td>$\bar{q}q \rightarrow Z^0, q'\bar{q} \rightarrow W^\pm$</td>
<td>$\Delta q, \Delta \bar{q}$</td>
<td>![Diagram 7]</td>
</tr>
</tbody>
</table>

NLO corrections known in all cases.

Authors:
- Jäger, Schäfer, Stratmann, WV
- Jäger, Stratmann, WV; Signer et al.
- Gordon, WV; Contogouris et al.; Gordon, Coriano
- Stratmann, Bojak
- Weber; Gehrmann; Kamal