Quark-Gluon Structure of the Nucleon

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Outline

• **Pictures of the proton**
  finding the best degrees of freedom

• **Flavour and spin**
  state-of-the-art global fits to quark and gluon polarization

• **Single-spin asymmetries**
  the quest for quarks in orbit

• **The Sivers function**
  parton orbital angular momentum

• **Is the spin puzzle solved?**
  GPDs + lattice + models $=$ ?
Constituent Quark Model
Pure valence description: proton = $2u + d$

Perturbative Sea
Sea quark pairs from $g \rightarrow q\bar{q}$ should be flavor symmetric:

$$\bar{u} = \bar{d}$$
Flavor Structure of the Proton

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Sea quark pairs from $g \rightarrow q\bar{q}$ should be flavor symmetric: $\bar{u} = \bar{d}$

Non-perturbative models: alternate deg’s of freedom

E866: $\frac{d}{u} > 1$
Flavor Structure of the Proton

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Non-perturbative models: alternate deg's of freedom

Meson Cloud Models
Quark sea from cloud of $0^-$ mesons: $\bar{d} > \bar{u}$

Chiral-Quark Soliton Model
- quark degrees of freedom in a pion mean-field
- nucleon = chiral soliton
- one parameter: dynamically-generated quark mass
- expand in $1/N_c$
- $\sim \bar{u}_R u_L \bar{d}_R d_L$

E866: $\bar{d}/\bar{u} > 1$
The Puzzle of Proton Spin

The proton: spin 1/2
The Puzzle of Proton Spin

The proton: spin 1/2

Where is the other 75%?

The quarks’ spins account for only 25%
Proton Spin Structure

Constituent Quark Model

\[ \Delta u = +\frac{4}{3}, \quad \Delta d = -\frac{1}{3} \]

\[ \Delta q \equiv \mathbf{N}^\uparrow - \mathbf{N}^\downarrow \]
Meson Cloud Models

Li, Cheng, hep-ph/9709293

\[ \Delta q \equiv N^\uparrow - N^\downarrow \]

\[ \Delta u = +\frac{4}{3}, \quad \Delta d = -\frac{1}{3} \]


d"valence"  "sea"

\[ \Delta q_{\text{valence}} > 0 \]

\[ \Delta q_{\text{sea}} < 0 \]

\[ \Delta \bar{q} = 0 \]

“Higher-order” cloud of vector mesons can generate a small polarization.
Proton Spin Structure

Meson Cloud Models

\[ \Delta u = \frac{4}{3}, \quad \Delta d = -\frac{1}{3} \]

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Constituent Quark Model

Chiral-Quark Soliton Model

Light sea quarks polarized:

\[ \Delta \bar{u} \simeq -\Delta \bar{d} > 0 \]

Instanton Mechanism

\[ \sim \bar{u} R u_L \bar{d} R d_L \] transfers helicity from valence \( u \) quarks to \( d \bar{d} \) pairs

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Proton Spin Structure

Meson Cloud Models

Li, Cheng, hep-ph/9709293

0\(^{-}\) meson

"valence"  "sea"

\[ \gamma_5 \]

\[ \Delta q_{\text{valence}} > 0 \]

\[ \Delta q_{\text{sea}} < 0 \]

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Goeke et al, hep-ph/0003324

\begin{align*}
\Delta \bar{u} &\equiv N^\uparrow - N^\downarrow \\
\Delta \bar{d} &\equiv N^\downarrow - N^\uparrow
\end{align*}

Instanton Mechanism

\[ \mathcal{O} \sim \bar{u}_R u_L \bar{d}_R d_L \text{ transfers helicity from valence } u \text{ quarks to } d\bar{d} \text{ pairs} \]

What about gluon spin?
A Wealth of Spin Data

Polarized Deep-Inelastic Scattering

electron / muon beams → Δq

virtual photon

polarized e

polarized nucleon

A sample of the latest data...

COMPASS, PLB 693 (2010)

COMPASS: first SIDIS asym’s with kaon tag and proton target
A Wealth of Spin Data

Polarized Deep-Inelastic Scattering

electron / muon beams → Δq

virtual photon

polarized e
polarized nucleon

Polarized p-p Scattering at RHIC → ΔG

NEW

STAR

Jefferson Lab
Exploring the Nature of Matter

STAR @ DIS2011: A_{LL} for inclusive jets from Run 9; also binned in η
DSSV NLO global fit: $\Delta q$ & $\Delta g$


**FIG. 3** (color online). The flavor asymmetry $x(\Delta u - \Delta d)$ comparison to PHENIX data and previous analyses. Positivity relative to the unpolarized PDFs of the proton at $Q^2 = 10$ GeV$^2$.

**TABLE**

<table>
<thead>
<tr>
<th>$\Delta q$</th>
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DSSV NLO global fit: $\Delta q$ & $\Delta g$


---

### Table III. Truncated first moments

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Sea quark spin: W production @ RHIC

\[ A_{L}^{W^{-}} \sim -\Delta d(x_{1})\bar{u}(x_{2}) + \Delta \bar{u}(x_{1})d(x_{2}) \]
\[ A_{L}^{W^{+}} \sim -\Delta u(x_{1})\bar{d}(x_{2}) + \Delta \bar{d}(x_{1})u(x_{2}) \]

Run 9: First 500 GeV data! only 5 weeks \(\rightarrow\) first glimpse

N.C.R. Makins, PANIC’11, MIT, July 25, 2011
key measurement at RHIC: parity violating single spin asymmetry

\[ A_{L}^{W^{-}} \approx \frac{\Delta d(x_1)\bar{u}(x_2) - \Delta \bar{u}(x_1)d(x_2)}{d(x_1)\bar{u}(x_2) + \bar{u}(x_1)d(x_2)} \]

new versatile NLO MC code
de Florian, Vogelsang, arXiv:1003.4533

simulated impact of RHIC W boson data on global fit

✓ reduction of uncertainties for 0.07 < x < 0.4
✓ can test consistency of low Q² SIDIS data in that x regime
✓ 1st PHENIX & STAR data no impact on fit yet “proof of principle”

Marco Stratmann @ DIS 2011
W program @ RHIC: what can we learn?

key measurement at RHIC: parity violating single spin asymmetry

$A_L^W \approx - \frac{\Delta d(x_1)\bar{u}(x_2) - \Delta \bar{u}(x_1)d(x_2)}{d(x_1)\bar{u}(x_2) + \bar{u}(x_1)d(x_2)}$

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✓ reduction of uncertainties for $0.07 < x < 0.4$
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✓ 1st PHENIX & STAR data no impact on fit yet “proof of principle”

Is there a flavor asym in the polarized sea? → we’ll find out

Marco Stratmann @ DIS 2011
\[ q(x) = q^\uparrow(x) + q^\downarrow(x) \]
\[ \Delta q(x) = q^\uparrow(x) - q^\downarrow(x) \]

**only three sources**

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

1. **Quark polarization**
   \[ \Delta \Sigma \equiv \int dx \left( \Delta u(x) + \Delta d(x) + \Delta s(x) + \Delta \bar{u}(x) + \Delta \bar{d}(x) + \Delta \bar{s}(x) \right) \approx 25\% \text{ only} \]

2. **Gluon polarization**
   \[ \Delta G \equiv \int dx \Delta g(x) \quad \text{small...?} \]

3. **Orbital angular momentum**
   \[ L_z \equiv L_q + L_g \quad ? \]
\[ q(x) = q^\uparrow(x) + q^\downarrow(x) \]
\[ \Delta q(x) = q^\uparrow(x) - q^\downarrow(x) \]

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

1. **Quark polarization**
   \[ \Delta \Sigma \equiv \int dx \ (\Delta u(x) + \Delta d(x) + \Delta s(x) + \Delta \bar{u}(x) + \Delta \bar{d}(x) + \Delta \bar{s}(x)) \approx 25\% \text{ only} \]

2. **Gluon polarization**
   \[ \Delta G \equiv \int dx \ \Delta g(x) \ \text{small...?} \]

3. **Orbital angular momentum**
   \[ L_z \equiv L_q + L_g \]

In friendly, **non-relativistic** bound states like atoms & nuclei (& constituent quark model), particles are in **eigenstates of** \(L\).

Not so for bound, **relativistic Dirac particles** ...

Noble “\( l \)” is **not a good quantum number**

N.C.R. Makins, PANIC’11, MIT, July 25, 2011
In Search of L: Transverse Single-Spin Asymmetries
Single-spin asymmetries in $p^+p \rightarrow \pi X$

$$A_N = \frac{1}{P_{\text{beam}}} \frac{N^\pi_{\text{left}} - N^\pi_{\text{right}}}{N^\pi_{\text{left}} + N^\pi_{\text{right}}}$$

Huge single-spin asymmetry for forward meson production

1991 FNAL E704

200 GeV $p^+$ beam

N.C.R. Makins, PANIC’11, MIT, July 25, 2011
Single-spin asymmetries in $p^\uparrow p \rightarrow \pi X$

$$A_N = \frac{1}{P_{\text{beam}}} \frac{N_\pi^{\text{left}} - N_\pi^{\text{right}}}{N_\pi^{\text{left}} + N_\pi^{\text{right}}}$$

Huge **single-spin asymmetry** for *forward meson production*

**Analyzing Power**

**Observable** $\vec{S}_{\text{beam}} \cdot (\vec{p}_{\text{beam}} \times \vec{p}_\pi)$ **odd under naive Time-Reversal**

N.C.R. Makins, PANIC’11, MIT, July 25, 2011
Large SSAs persist at very high RHIC energies

SSA observables \( \sim \vec{J} \cdot (\vec{p}_1 \times \vec{p}_2) \Rightarrow \text{odd} \) under naive time-reversal

Since QCD amplitudes are T-even, must arise from interference between spin-flip and non-flip amplitudes with different phases

Can’t come from perturbative subprocess:

- \( q \) helicity flip suppressed by \( m_q/\sqrt{s} \)
- need \( \alpha_s \)-suppressed loop-diagram to generate necessary phase

At hard (enough) scales, SSA’s must arise from soft physics: T-odd distribution / fragmentation functions

N.C.R. Makins, PANIC’11, MIT, July 25, 2011
SSA’s at high-energies

Large SSAs persist at very high RHIC energies

T-odd observables

SSA observables $\sim \vec{J} \cdot (\vec{p}_1 \times \vec{p}_2)$

$\Rightarrow$ odd under naive time-reversal

Since QCD amplitudes are T-even, must arise from interference between spin-flip and different phases

The subprocess:

- Must be a spin-orbit structure either in the fragmentation process or within the proton itself

- Need $\alpha_s$-suppressed loop-diagram to generate necessary phase

At hard (enough) scales, SSA’s must arise from soft physics: T-odd distribution / fragmentation functions

N.C.R. Makins, PANIC’11, MIT, July 25, 2011
The “Collins Effect”

\[ h_1(x) \otimes H_1^\perp(z, p_T) \]

Transversity \hspace{1cm} Collins Frag Func

The “Sivers Effect”

\[ f_{1T}(x, k_T) \otimes D_1(z) \]

Sivers Func

\[ \otimes \] denotes convolution over intrinsic quark \( k_T \) & fragmentation \( p_T \)

N.C.R. Makins, PANIC’11, MIT, July 25, 2011
The “Collins Effect”

\[ h_1(x) \otimes H_1^\perp(z, p_T) \]

Transversity  Collins Frag Func\textsuperscript{n}

sensitive to \textit{transversity} and \textit{spin-orbit} effects in fragmentation

\[ \otimes \text{ denotes convolution over intrinsic quark } k_T \text{ & fragmentation } p_T \]

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N.C.R. Makins, PANIC’11, MIT, July 25, 2011
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N.C.R. Makins, PANIC’11, MIT, July 25, 2011
Leptoproduction of Pions with Transverse Target

SIDIS xsec with **transverse target** polarization has **two** similar terms:

\[
\sin(\phi^l_h + \phi^l_S) \Rightarrow h_1 = - \otimes H^\perp_1 = \begin{array}{c}
\uparrow \\
\uparrow
\end{array} - \begin{array}{c}
\downarrow \\
\downarrow
\end{array}
\]

\[
\sin(\phi^l_h - \phi^l_S) \Rightarrow f^\perp_{1T} = - \otimes D_1 = \begin{array}{c}
\uparrow \\
\uparrow
\end{array}
\]

**separate Sivers and Collins mechanisms**

- \( (\phi^l_h - \phi^l_S) \) = angle of hadron relative to **initial** quark spin
- \( (\phi^l_h + \phi^l_S) = \pi + (\phi^l_h - \phi^l_S) \) = hadron relative to **final** quark spin
Leptoproduction of Pions with Transverse Target

SIDIS xsec with \textit{transverse target} polarization has \textit{two} similar terms:

\[
\sin(\phi_h^l + \phi_S^l) \Rightarrow h_1 = \begin{pmatrix} 1 \\ 0 \end{pmatrix} - \begin{pmatrix} 0 \\ 1 \end{pmatrix} \otimes H_1^\perp = \begin{pmatrix} 1 \\ 0 \end{pmatrix} - \begin{pmatrix} 0 \\ 1 \end{pmatrix}
\]

\[
\sin(\phi_h^l - \phi_S^l) \Rightarrow f_{1T}^\perp = \begin{pmatrix} 1 \\ 0 \end{pmatrix} - \begin{pmatrix} 0 \\ 1 \end{pmatrix} \otimes D_1 = \begin{pmatrix} 1 \\ 0 \end{pmatrix}
\]

\[
\angle (\phi_h^l - \phi_S^l) = \text{angle of hadron relative to initial quark spin}
\]

\[
\angle (\phi_h^l + \phi_S^l) = \pi + (\phi_h^l - \phi_S^l) = \text{hadron relative to final quark spin}
\]

both observed!

\begin{itemize}
  \item separate Sivers and Collins mechanisms
  \item both observed!
\end{itemize}
The Sivers Function

\[ f_{1T}^{\perp}(x, k_T) \]

within the proton
Sivers Moments for $\pi$ and $K$ from $H^\uparrow$ & $D^\uparrow$

HERMES final $H^\uparrow$ \textit{PRL} 103 (2009)

$\langle \sin(\phi - \phi_S) \rangle_{UT}$

$\pi^+$

$\pi^0$

$\pi^-$

$K^+$

$K^0$

$2 \langle \sin(\phi - \phi_S) \rangle_{UT}$

$A_{SV}^d$

COMPASS final 2003-04 D

$N.P.B$ 765 (2007) 31

$f_{1T}^\perp(x, k_T) \otimes D_1^\perp(z)$

N.C.R. Makins, PANIC’11, MIT, July 25, 2011
New COMPASS analysis confirms non-zero Sivers effect in SIDIS

COMPASS proton data: confirmation!

- HERMES $H^\uparrow \rightarrow \pi^\pm$
- COMPASS 2007 $H^\uparrow \rightarrow h^\pm$

N.C.R. Makins, PANIC’11, MIT, July 25, 2011
The Leading-Twist Sivers Function: Can it Exist in DIS?

A T-odd function like $f_{1T}^1$ must arise from interference ... but a distribution function is just a forward scattering amplitude, how can it contain an interference?

Brodsky, Hwang, & Schmidt 2002

It looks like higher-twist ... but no, these are soft gluons: “gauge links” required for color gauge invariance
The Leading-Twist Sivers Function: Can it Exist in DIS?

A T-odd function like $f_{1T}^{\perp}$ **must** arise from **interference** ... but a distribution function is just a forward scattering amplitude, how can it contain an interference?

Brodsky, Hwang, & Schmidt 2002

- It looks like higher-twist ... but no, these are **soft gluons**: "gauge links" required for color gauge invariance
- Such soft-gluon reinteractions with the soft wavefunction are **final / initial state interactions** ... and **process-dependent** ...
- e.g. **Drell-Yan**: → Sivers effect should have **opposite sign** cf. SIDIS

\[ q^2 \sim \text{Im} \]

\[ P \]

\[ q \]

\[ P \]

\[ L_z \neq 0 \]
Global Fit to Sivers Asymmetries

As the asymmetry, although compared with data \([12]\), is not a perfect fit, but the result of our computation, using the assumed Sivers asymmetries (solid lines) are compared with the experimental data from Refs. \([10]\) and \([11]\): the SSAs are plotted as a function of one variable at a time, either integration over the other variables has been performed continuously. For the illustrative purposes, we have assumed isospin invariance, writing the fragmentation functions of Eq. (16).

\[
\chi^2 \text{ per data dof} = 102/39 = 2.61
\]

For forthcoming measurements at the energies of 6 and 12 GeV are given predictions for other transverse single spin asymmetries – which are taken inspired by the analysis performed for the deuteron target. The shaded area corresponds to the theoretical computation based on our extracted Sivers functions. Also with HERMES experimental data \([10]\) for pion and kaon production \([11]\) obtained at COMPASS, for which no data is so far available, computed with HERMES experimental data \([10]\) for pion and kaon production \([11]\) obtained at COMPASS, for which no data is so far available, computed at HERMES and COMPASS and show them respectively in Fig. 3 and 4. As the uncertainty of the parameters, as explained in Appendix A.

Global Fit to Sivers Asymmetries

E. Boglione, Transversity2008

Anselmino et al, arXiv:0805.2677

N.C.R. Makins, PANIC‘11, MIT, July 25, 2011
Global Fit to Sivers Asymmetries

\[ xf_{1T}^{(1)}(x) \]

E. Boglione, Transversity2008

Anselmino et al, arXiv:0805.2677

antiquark orbital \( L \neq 0 \) favoured

N.C.R. Makins, PANIC’11, MIT, July 25, 2011
Global Fit to Sivers Asymmetries

Wait a second ... how are we connecting the sign of the Sivers function to the sign of \( L_q \)?

antiquark orbital \( L \neq 0 \) favoured

E. Boglione, Transversity2008
Anselmino et al, arXiv:0805.2677

N.C.R. Makins, PANIC’11, MIT, July 25, 2011
Phenomenology: Sivers Mechanism

M. Burkardt: Chromodynamic lensing

Electromagnetic coupling $\sim (J_0 + J_3)$ stronger for oncoming quarks

Nearly all models predict $L_u > 0$ ...
**Phenomenology: Sivers Mechanism**

**M. Burkardt: Chromodynamic lensing**

*Electromagnetic coupling* \( \sim (J_0 + J_3) \) *stronger for oncoming quarks*

\[ \langle \sin(\phi_h - \phi_S) \rangle^+_{UT} > 0 \] (and opposite for \( \pi^- \))

\[ \therefore \] for \( \phi_S = 0, \phi_h = \pi/2 \) preferred

Model agrees!

**D. Sivers: Jet Shadowing**

Parton energy loss considerations suggest *quenching of jets* from "near" surface of target

\[ \Rightarrow \] quarks from "far" surface should dominate

Opposite sign to data … assuming \( L_u > 0 \) …
Meson Cloud on the back of an Envelope

\[ |p> = p + N\pi + \Delta\pi + ... \]

**Pions** have \( J^P = 0^- = \text{negative parity} \) ... → need \( L = 1 \) to get proton's \( J^P = \frac{1}{2}^+ \)

\( N\pi \) cloud:

\[ \begin{align*}
2/3 & \quad n \ pi^+ \\
1/3 & \quad p \ pi^0
\end{align*} \]

\( \Delta\pi \) cloud:

\[ \begin{align*}
1/2 & \quad \Delta^{++} \ pi^- \\
1/3 & \quad \Delta^+ \ pi^0 \\
1/6 & \quad \Delta^0 \ pi^+
\end{align*} \]
\[ |p\rangle = p + N\pi + \Delta\pi + \ldots \]

**Meson Cloud on the back of an Envelope**

**Pions** have \( J^P = 0^- = \text{negative parity} \) ... 
\[ \rightarrow \text{need } L = 1 \text{ to get proton's } J^P = \frac{1}{2}^+ \]

**\( N\pi \) cloud:**

- 2/3 n \( \pi^+ \)
- 1/3 p \( \pi^0 \)

- 2/3 \( L_z = +1 \)
- 1/3 \( L_z = 0 \)

**\( \Delta\pi \) cloud:**

- 1/2 \( \Delta^{++} \pi^- \)
- 1/3 \( \Delta^+ \pi^0 \)
- 1/6 \( \Delta^0 \pi^+ \)

- 1/2 \( L_z = -1 \)
- 1/3 \( L_z = 0 \)
- 1/6 \( L_z = +1 \)

**Dominant source of:**

orbiting \( u \): n \( \pi^+ \) with \( L_z(\pi) > 0 \)
|p⟩ = p + Nπ + Δπ + ...
Pions have J^P = 0^- = negative parity ...
→ need \( L = 1 \) to get proton’s \( J^P = \frac{1}{2}^+ \)

**Nπ cloud:**
- u
  - 2/3 n \( \pi^+ \)
  - 1/3 p \( \pi^0 \)
- d
  - 1/2 \( \Delta^{++} \pi^- \)
  - 1/3 \( \Delta^+ \pi^0 \)
  - 1/6 \( \Delta^0 \pi^+ \)

\[ \bigotimes \]

\[ \begin{align*}
2/3 & \quad L_z = +1 \\
1/3 & \quad L_z = 0
\end{align*} \]

**Δπ cloud:**
- 1/2 \( \Delta^{++} \pi^- \)
- 1/3 \( \Delta^+ \pi^0 \)
- 1/6 \( \Delta^0 \pi^+ \)

\[ \bigotimes \]

\[ \begin{align*}
1/2 & \quad L_z = -1 \\
1/3 & \quad L_z = 0 \\
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**Dominant source of:**
- orbiting u: n \( \pi^+ \) with \( L_z (\pi) > 0 \)
- orbiting d: \( \Delta^{++} \pi^- \) with \( L_z (\pi) < 0 \)

N.C.R. Makins, PANIC’11, MIT, July 25, 2011
Meson Cloud on the back of an Envelope

\[ |p\rangle = p + N\pi + \Delta\pi + ... \]

**Pions** have \( J^P = 0^- = \text{negative parity} \) ...
\[ \rightarrow \text{need } L = 1 \text{ to get proton's } J^P = \frac{1}{2}^+ \]

\[ N\pi \text{ cloud:} \]

\[
\begin{array}{ccc}
2/3 & n & \pi^+ \\
1/3 & p & \pi^0
\end{array}
\]

\[ \Delta\pi \text{ cloud:} \]

\[
\begin{array}{ccc}
1/2 & \Delta^{++} & \pi^- \\
1/3 & \Delta^+ & \pi^0 \\
1/6 & \Delta^0 & \pi^+
\end{array}
\]

**Dominant source of:**

- orbiting \( u \): \( n \pi^+ \) with \( L_z(\pi) > 0 \)
- orbiting \( d \): \( \Delta^{++} \pi^- \) with \( L_z(\pi) < 0 \)

\( L_u > 0 \)
\( L_d < 0 \)
\( L_{\overline{q}} \neq 0 \)

N.C.R. Makins, PANIC’11, MIT, July 25, 2011
Melis (DIS’11): refit HERMES, COMPASS final Sivers data with \(u\) and \(d\) only

\[ x \Delta N_{i}(x) = \langle \sin(\phi_{s}) \rangle_{\uparrow}^{K_{+}} - 2 \langle \sin(\phi_{s}) \rangle_{\uparrow}^{\pi_{+}} \]

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Melis (DIS’11): refit HERMES, COMPASS final Sivers data with \( u \) and \( d \) only

\[
\Delta N_i^{(1)}(x) = 2 \langle \sin(2\phi) \rangle_{uu} \]

\[
\langle \cos(2\phi_h) \rangle_{uu}
\]

Boer-Mulders moments

\[
\langle \cos(2\phi_h) \rangle_{uu}
\]

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Sivers \( K^+ - \pi^+ \) final

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2 \langle \sin(2\phi^{(i)}) \rangle_{K^+} - 2 \langle \sin(2\phi^{(i)}) \rangle_{\pi^+}
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NEW

\[
B-M \text{ for kaons} \rightarrow \text{dramatic effect!}
\]
**Melis (DIS’11): refit HERMES, COMPASS final Sivers data with *u and d only***

**Boer-Mulders moments**

\[ \langle \cos(2\phi_h) \rangle_{uu} \]

- **h^+**
- **π^+**
- **K^+**
- **h^-**
- **π^-**
- **K^-**

**Sivers K^+ – π^+**

- **Q^2 < \langle Q^2(x_f) \rangle**
- **Q^2 > \langle Q^2(x_f) \rangle**

**NEW**

*B-M for kaons → dramatic effect!*

... and **BRAHMS SSA’s for kaons, never explained ...**
A Coherent Picture Yet?
A Coherent Picture?

- **Transversity**: $h_{1,u} > 0 \quad h_{1,d} < 0$
  → same as $g_{1,u}$ and $g_{1,d}$ in NR limit

- **Sivers**: $f_{1T^\perp,u} < 0 \quad f_{1T^\perp,d} > 0$
  → relation to anomalous magnetic moment*
  $f_{1T^\perp,q} \sim \kappa_q$ where $\kappa_u \approx +1.67 \quad \kappa_d \approx -2.03$
  values achieve $\kappa^{p,n} = \sum_q e_q \kappa_q$ with $u,d$ only

- **Boer-Mulders**: follows that $h_{1^\perp,u}$ and $h_{1^\perp,d} < 0$ ?
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* Burkardt PRD72 (2005) 094020;
  Barone et al PRD78 (2008) 045022;

N.C.R. Makins, PANIC’11, MIT, July 25, 2011
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  \[
  \langle \vec{s}_u \cdot \vec{S}_p \rangle = 0.5 \quad \langle \vec{l}_u \cdot \vec{S}_p \rangle = 0.5 \quad \langle \vec{s}_u \cdot \vec{l}_u \rangle = 0
  \]

**but these TMDs are all independent**


N.C.R. Makins, PANIC’11, MIT, July 25, 2011
\[ q(x) = H^q(x, \xi = 0, t = 0) \]
\[ \Delta q(x) = \tilde{H}^q(x, \xi = 0, t = 0) \]

**PDFs:**
forward limit \((\xi = 0, t = 0)\)

\[ F_1^q(t) = \int_{-1}^{1} dx \, H^q(x, \xi, t) \quad F_2^q(t) = \int_{-1}^{1} dx \, E^q(x, \xi, t) \]

**Elastic form factors:**
first moments in \(x\)

\[ J^q = \frac{1}{2} \Delta \Sigma + L^q \]

**Ji sum rule:**

\[ J^q = \frac{1}{2} \int_{-1}^{1} x \, dx \left[ H^q(x, \xi, t = 0) + E^q(x, \xi, t = 0) \right] \]

**GPDs:** connection to many observables

Note connection of \(H, E\) to Dirac, Pauli form factors ... and their connection to nucleon magnetic moment:

\[ F_1^N(0) + F_2^N(0) = \mu_N \]
Transverse spin on the lattice

Compute quark densities in impact-parameter space via GPD formalism

nucleon coming out of page ... observe spin-dependent shifts in quark densities:

N.C.R. Makins, PANIC’11, MIT, July 25, 2011
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nucleon coming out of page ... observe spin-dependent shifts in quark densities:

Expected picture from quark models + lensing
Among the three combinations responding intrinsics spin contributions, model scale and the magnitude of conservative bound since it is actually given at the low-energy known constant within this bound. (Note that it is a short-dashed, long-dashed, and dash-dotted curves with shown in the left panel of fig. 1, respectively by the solid, works to exclude some range of lattice QCD predictions. Fig. 1. In both panels, the open circle, open triangle, filled circle, and filled triangle, respectively, represent the predictions of the LHPC ∆Σ

The answers for ∆Σ

The information on the quark orbital momenta can evaluate the total angular momentum as well as the orbital influence of the strange-quark components is so small that it never a

The left panel shows the results of the present semi-phenomenological extraction of the total angular momenta as well as for ∆Σ

For completeness, we list below all the initial condi-
Thomas: **cloudy bag model** evolved up to $Q^2$ of expt / lattice

\[\begin{align*}
&2J^u, 2L^u, 2J^d, 2L^d \\
&2J_u, 2L_d, 2L_u
\end{align*}\]

→ **lattice shows** $L_u < 0$ and $L_d > 0$ in longitudinal case at expt’al scales!

*Evolution might explain disagreement with quark models...*
... and Longitudinal spin on the lattice ...

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Evolution might explain disagreement with quark models ...

or not. Wakamatsu evolves down $\rightarrow$ insensitive to uncertain scale of quark models
Density shifts seen on lattice due to GPD $E_q(x, \xi, t)$
Density shifts seen on lattice due to GPD $E_q(x, \zeta, t)$

**The Mysterious E**

E requires L

- $\int E \, dx = \text{Pauli } F_2 \rightarrow (t=0)$ anomalous magnetic moment $\kappa$ ($\therefore$ GPD basics)
- both $F_2$ and $\kappa$ **require** $L \neq 0$ ($\therefore$ N spin flip amplitudes)

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... but **E is not L**

**Ji Sum Rule**

$$2 J_q = \int x \, H_q \big|_{t=0} \, dx + \int x \, E_q \big|_{t=0} \, dx$$

momentum fraction $\int x \, q(x) \, dx = \langle x \rangle_q + E_q^{(2)}$ “anomalous gravito-magnetic moment”

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Brodksy, Drell (1980); Burkardt, Schnell, PRD 74 (2006)
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**Spin Sum Rule**

$$2 \, J_q = \Delta q + 2 \, L_q$$

$$\therefore 2L_q = \left[ \langle x \rangle_q + E_q^{(2)} \right]_{J_q} - \Delta q$$

**Contradiction?**
Density shifts seen on lattice due to GPD $E_q(x, \xi, t)$

**E requires L**
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$$2 J_q = \Delta q + 2 L_q$$

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“$L$” not uniquely defined

Contradiction?

N.C.R. Makins, PANIC’11, MIT, July 25, 2011
\[ J^{J_i} = \frac{i}{2} q^\dagger (\vec{r} \times \vec{D})^z q + \frac{1}{2} q^\dagger \sigma^z q + 2 \text{Tr} E^j (\vec{r} \times \vec{D})^z A^j + \text{Tr}(\vec{E} \times \vec{A})^z \]

\[ L_q \quad \Delta q \quad L_g \quad \Delta g \]

\[ J^{\text{Jaffe}} = \frac{1}{2} q^\dagger (\vec{r} \times i\vec{\nabla})^z q_+ + \frac{1}{2} q^\dagger \gamma_5 q_+ + 2 \text{Tr} F^+ j (\vec{r} \times i\vec{\nabla})^z A^j + \epsilon^{+ij} \text{Tr} F^+ i A^j \]
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\( J_{decomposition} \)

✔ gauge invariance: \( \Delta q, L_q, J_g \)

✔ measure \( L_q \): via GPDs & DVCS

✘ interpret \( L_q \): covariant derivative

\( D^\mu = \partial^\mu + ig^\mu \) brings in gluon interactions

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Proton Spin Decompositions

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N.C.R. Makins, PANIC’11, MIT, July 25, 2011
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New Ideas!

Ongoing work of \textbf{Chen et al} \( \text{PRL 100 (2008), 103 (2009)} \)

& \textbf{Wakamatsu} \( \text{PRD 81 (2010), 83 (2011)} \)

N.C.R. Makins, PANIC’11, MIT, July 25, 2011
Theory: Ji’s $L_{u-d}$ is rock-solid & negative

\[ 2L_q^{Ji} = \left[ \langle x \rangle_q + E_q^{(2)} \right]_{=J_q} - \Delta q \]

- $\langle x \rangle_{u-d}$: well known
- $\Delta u - \Delta d = g_A$: well known
- $E^{(2)}_{u-d}$: all lattice calculations and XQSM agree
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\[ 2(L_u - L_d) \]

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**Compare Jaffe & Ji**
calculate explicitly in $\chi$QSM;
at quark-model scale:

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Negative model value dominated by sea quark $L$!

Need direct measurement of Sivers for sea quarks:
e.g. spin-dependent Drell-Yan
plans @ COMPASS, SeaQuest, RHIC ... stay tuned!

N.C.R. Makins, PANIC’11, MIT, July 25, 2011
With spin around, there’s never a dull moment 😊