Topics on \textbf{QCD} and Spin Physics

(sixth lecture)

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Spin (revisited)

naive quark spin \( \approx \) parton spin \( \approx \) QCD parton spin

polarized DIS:

EMC experiment: not the naive picture

strange quarks polarization?
gluon polarization?

from moments to parton densities:

first moments \( \approx \) sum rules parton densities \( \approx \) more insight

flavor symmetry & models more observables!
More spin dependent observables:

**inclusive DIS**

\[
g_1^p(x, Q^2) \quad g_1^n(x, Q^2)
\]

\[
g_1^N(x, Q^2) = \left( \pm \frac{1}{12} \Delta q_3^{NS} + \frac{1}{36} \Delta q_8^{NS} + \frac{1}{9} \Delta \Sigma \right) \otimes \left( 1 + \frac{\alpha_s}{2\pi} \Delta C_q \right) + \sum_q e_q^2 \frac{\alpha_s}{2\pi} \Delta g \otimes \Delta C_g.
\]

**unknowns**

\[
\Delta u, \Delta \bar{u}, \Delta d, \Delta \bar{d}, \Delta s, \Delta \bar{s}, \Delta g
\]

\[
\frac{d}{d \ln Q^2} \Delta q_3^{NS} = \frac{\alpha_s}{2\pi} \Delta P_{qq}^1 \otimes \Delta q_3^{NS}
\]

\[
\frac{d}{d \ln Q^2} \left( \frac{\Delta \Sigma}{\Delta g} \right) = \frac{\alpha_s}{2\pi} \left( \frac{\Delta P_{qq}^1}{\Delta P_{gg}^1} \right) \otimes \left( \frac{2f \Delta P_{qq}^1}{\Delta P_{gg}^1} \right) \otimes \left( \Delta \Sigma \Delta g \right)
\]
More spin dependent observables:

**SIDIS asymmetries**

\[ A_1^N h(x, Q^2) \approx \frac{\int_Z dz g_1^N h(x, z, Q^2)}{\int_Z dz F_1^N h(x, z, Q^2)} \]

\( N = p, D, He \)

\( h = \pi^\pm, K^\pm, h^\pm \)

\[ g_1^N h(x, z, Q^2) = \sum_{q, q'} e_i^2 \left\{ \Delta q_i(x, Q^2) D_{q_i}^h(z, Q^2) \right\} \]

\[ + \frac{\alpha_s(Q^2)}{2\pi} \left[ \Delta q_i \otimes \Delta C_{ij} \otimes D_{q_j}^h + \Delta q_i \otimes \Delta C_{ig} \otimes D_g^h + \Delta g \otimes \Delta C_{gj} \otimes D_{q_j}^h \right] \]

\[ D_1 = D_{\pi^+} = D_{\pi^-} \]

\[ D_2 = D_{\pi^+} = D_{\pi^-} \]

\[ D_3 = D_{\pi^+} = D_{\pi^-} \]

\[ 2g_{1p}^{\pi^+(-)} \approx \frac{4}{9} (\Delta u + \Delta \bar{u}) \otimes D_{1(2)}^\pi + \frac{1}{9} (\Delta d + \Delta \bar{d}) \otimes D_{2(1)}^\pi \]

\[ + \frac{1}{9} (\Delta \bar{d} - 4\Delta \bar{u}) \otimes (D_{1(2)}^\pi - D_{2(1)}^\pi) \]
More spin dependent observables:

polarized pp collisions

\[ A_{LL} \equiv \frac{d\Delta \sigma}{d\sigma} = \frac{d\sigma^{++} - d\sigma^{+-}}{d\sigma^{++} + d\sigma^{+-}} \]

\[
d\Delta \sigma = \sum_{ab} \int dx_a \int dx_b \Delta f_a(x_a, Q^2) \Delta f_b(x_b, Q^2) \times d\hat{\sigma}_{ab}(x_a, x_b, p_T).
\]

\[
d\Delta \sigma = \sum_{ab} \int dx_a \int dx_b \int dz \Delta f_a(x_a, Q^2) \Delta f_b(x_b, Q^2) D_c^h(z, Q^2) \times d\hat{\sigma}_{abc}(x_a, x_b, z, p_T).
\]

numerically involved: Mellin tricks
DSSV helicity distributions:  D.de Florian, R.S., M. Stratmann, W. Vogelsang 2008

<table>
<thead>
<tr>
<th>Experiment</th>
<th>Data Type</th>
<th>Data Points</th>
</tr>
</thead>
<tbody>
<tr>
<td>EMC, SMC, DIS</td>
<td>DIS</td>
<td>34</td>
</tr>
<tr>
<td>COMPASS DIS</td>
<td>DIS</td>
<td>15</td>
</tr>
<tr>
<td>E142, E143, E154, E155</td>
<td>DIS</td>
<td>123</td>
</tr>
<tr>
<td>HERMES DIS</td>
<td>DIS</td>
<td>39</td>
</tr>
<tr>
<td>HALL-A DIS</td>
<td>DIS</td>
<td>3</td>
</tr>
<tr>
<td>CLAS DIS</td>
<td>DIS</td>
<td>20</td>
</tr>
<tr>
<td>SMC SIDIS</td>
<td>SIDIS $h^\pm$</td>
<td>48</td>
</tr>
<tr>
<td>HERMES SIDIS</td>
<td>SIDIS $h^\pm$</td>
<td>54</td>
</tr>
<tr>
<td></td>
<td>SIDIS $\pi^\pm$</td>
<td>36</td>
</tr>
<tr>
<td></td>
<td>SIDIS $K^\pm$</td>
<td>27</td>
</tr>
<tr>
<td>COMPASS SIDIS</td>
<td>SIDIS $h^\pm$</td>
<td>24</td>
</tr>
<tr>
<td>PHENIX 200 GeV pp, $\pi^0$</td>
<td>DIS</td>
<td>20</td>
</tr>
<tr>
<td>PHENIX 62 GeV pp, $\pi^0$</td>
<td>DIS</td>
<td>5</td>
</tr>
<tr>
<td>STAR 200 GeV pp, jet</td>
<td>DIS</td>
<td>19</td>
</tr>
<tr>
<td><strong>Total:</strong></td>
<td></td>
<td><strong>467</strong></td>
</tr>
</tbody>
</table>

DIS $\sim$ 50%
SIDIS $\sim$ 40%
RHIC $\sim$ 10%
DSSV helicity distributions: parameterization

\[
x(\Delta q + \Delta \bar{q})(x, Q_0^2) = N_q x^{\alpha_q} (1 - x)^{\beta_q} (1 + \gamma_q \sqrt{x} + \eta_q x)
\]

\[
x\Delta \bar{q}(x, Q_0^2) = N_{\bar{q}} x^{\alpha_{\bar{q}}} (1 - x)^{\beta_{\bar{q}}} (1 + \eta_{\bar{q}} x)
\]

\[
x\Delta g(x, Q_0^2) = N_g x^{\alpha_g} (1 - x)^{\beta_g} (1 + \eta_g x)
\]

\[
Q_0^2 = 1 \text{GeV}^2
\]

NLO evolution \(\alpha_s\) MRST

\[
\alpha_{u+\bar{u}} = \alpha_{u+\bar{u}} \quad \alpha_{d+\bar{d}} = \alpha_{d+\bar{d}} \quad \Delta s = \Delta \bar{s}
\]

\[
(\Delta u^1 + \Delta \bar{u}^1) - (\Delta d^1 + \Delta \bar{d}^1) = (F + D)[1 + \epsilon_{SU(2)}]
\]

\[
(\Delta u^1 + \Delta \bar{u}^1) + (\Delta d^1 + \Delta \bar{d}^1) - 2(\Delta s^1 + \Delta \bar{s}^1) = (3F - D)[1 + \epsilon_{SU(3)}]
\]
DSSV helicity distributions: scheme

\[ A_{LL}^{NLO-\overline{MS}}(DSSV) \equiv A_{LL}^{EXP} \]

\[ g_1^{NLO-\overline{MS}}(DSSV) \over F_1^{NLO-\overline{MS}}(MRST) \equiv A_1^{EXP} \]

not “unique”: \( F_1(x, Q^2) \) from data

from parameterization from \( F_2(x, Q^2) \) and \( R(x, Q^2) \)

fit just \( g_1(x, Q^2) \)

approximation:

\[ \frac{g_1^{NLO-\overline{MS}}}{F_1^{NLO-\overline{MS}}} + O\left(\frac{1}{Q^2}, \alpha_s^2\right) = A_1 \]
DSSV helicity distributions:

very good!

no significant tension

\[ \chi^2 / d.o.f. \approx 0.88 \]
DSSV helicity distributions: DIS data

new compass data also in good agreement
DSSV helicity distributions: SIDIS data

new compass data also in good agreement
DSSV helicity distributions: RHIC data

important constraint on gluons despite large uncertainties
Not included

no NLO yet...

\[ \Delta g/g \]

- COMPASS 2-had, \( Q^2 < 1 \text{ GeV}^2 \)
- COMPASS charm
- HERMES (prel.)
- SMC

\( Q^2 = 1 \text{ GeV}^2 \)
\( Q^2 = 10 \text{ GeV}^2 \)
DSSV helicity distributions: $u_{tot} d_{tot}$

Very well constrained

Agrees with DIS-only fits

Valence-like behavior
DSSV helicity distributions: $u\bar{u}$

- Small and positive?
- Large uncertainties

sidis driven
DSSV helicity distributions: ubar

small and positive?

large uncertainties

sidis driven
DSSV helicity distributions: dbar

larger and negative?

larger uncertainties

h/π tension?
DSSV helicity distributions: SU(2) breaking

breakning similar to unpolarized case

similar patterns in many models
DSSV helicity distributions: strangeness

always though to be negative...
mainly determined by sidis (kaon)
becomes negative at small $x$?
DSSV helicity distributions: gluons

\[
\Delta g^{1, [0.05 \rightarrow 0.2]} \equiv \int_{0.05}^{0.2} \Delta g \, dx
\]

RHIC region

\[
\Delta \chi^2 = 1
\]

\[
\Delta \chi^2 / \chi^2 = 2\%
\]

<table>
<thead>
<tr>
<th></th>
<th>[0.0 \rightarrow 1.0]</th>
<th>[0.001 \rightarrow 1.0]</th>
</tr>
</thead>
<tbody>
<tr>
<td>( \Delta u + \Delta u )</td>
<td>0.813 ( +0.011 -0.012 )</td>
<td>0.793 ( +0.028 -0.034 )</td>
</tr>
<tr>
<td>( \Delta d + \Delta \bar{d} )</td>
<td>-0.458 ( +0.011 -0.009 )</td>
<td>-0.416 ( +0.035 -0.025 )</td>
</tr>
<tr>
<td>( \Delta \bar{u} )</td>
<td>0.036 ( +0.021 -0.020 )</td>
<td>0.028 ( +0.059 -0.059 )</td>
</tr>
<tr>
<td>( \Delta \bar{d} )</td>
<td>-0.115 ( +0.029 -0.029 )</td>
<td>-0.089 ( +0.090 -0.080 )</td>
</tr>
<tr>
<td>( \Delta \bar{s} )</td>
<td>-0.057 ( +0.010 -0.012 )</td>
<td>-0.006 ( +0.028 -0.031 )</td>
</tr>
<tr>
<td>( \Delta g )</td>
<td>-0.084 ( +0.106 -0.120 )</td>
<td>0.013 ( +0.702 -0.314 )</td>
</tr>
<tr>
<td>( \Delta \Sigma )</td>
<td>0.242 ( +0.015 -0.018 )</td>
<td>0.366 ( +0.042 -0.062 )</td>
</tr>
</tbody>
</table>

measured region

low x extrapolation
QCD and Spin Physics

a collection of topics that highlight the link between theory and experiment

many “surprises”, lively discussions, still learning...

pQCD as a tool to connect phenomena relates experiment to the underlying protagonists

step by step approach: changing picture

just the first steps...