First simultaneous extraction of spin PDFs and FFs from a global QCD analysis

Jacob Ethier

w/ Jefferson Lab Angular Momentum (JAM) members: Wally Melnitchouk, Nobuo Sato
The Flavor Structure of Nucleon Sea
October 3rd, 2017
Proton spin structure from DIS

• Measured via longitudinal and transverse spin asymmetries

\[
A_\parallel = \frac{\sigma^{\uparrow \downarrow} - \sigma^{\uparrow \uparrow}}{\sigma^{\uparrow \downarrow} + \sigma^{\uparrow \uparrow}} = D \left( A_1 + \eta A_2 \right) \quad A_\perp = \frac{\sigma^{\uparrow \leftrightarrow} - \sigma^{\uparrow \downarrow}}{\sigma^{\uparrow \leftrightarrow} + \sigma^{\uparrow \downarrow}} = d \left( A_2 + \zeta A_1 \right)
\]

→ Virtual photoproduction asymmetries: 

\[
A_1 = \frac{(g_1 - \gamma^2 g_2)}{F_1} \quad A_2 = \gamma \frac{(g_1 + g_2)}{F_1} \quad \gamma^2 = \frac{4M^2 x^2}{Q^2}
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- First moment of polarized structure function \(g_1\):

\[
\int_0^1 dx g_1^p(x, Q^2) = \frac{1}{36} \left[ 8\Delta \Sigma + 3g_A + a_8 \right] \left( 1 - \frac{\alpha_s}{\pi} + O(\alpha_s^2) \right) + O\left( \frac{1}{Q^2} \right)
\]

**Quark contribution:** \(\Delta \Sigma(Q^2) = \int_0^1 dx \left( \Delta u^+(x, Q^2) + \Delta d^+(x, Q^2) + \Delta s^+(x, Q^2) \right)\)

→ DIS requires assumptions about triplet and octet axial charges

“Plus” helicity distributions: \(\Delta q^+ = \Delta q + \Delta \bar{q}\)
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"Plus" helicity distributions: \[ \Delta q^+ = \Delta q + \Delta \bar{q} \]

- DIS requires assumptions about triplet and octet axial charges

- Assuming exact \( SU(2)_f \) and \( SU(3)_f \) values from weak baryon decays

\[ \int dx (\Delta u^+ - \Delta d^+) = g_A \sim 1.269 \quad \int dx (\Delta u^+ + \Delta d^+ - 2\Delta s^+) = a_8 \sim 0.586 \]

\[ \Delta \Sigma_{[10^{-3}, 0.8]} \sim 0.3 \]
JAM15 Analysis – Impact of JLab Data


\[ \Delta \Sigma_{[0.001,0.8]} = 0.31 \pm 0.03 \]

• Low-\(Q^2\) / Low-\(W^2\) cuts

• Systematic treatment of higher twist corrections – based on formalism from J. Blümlein

J. Blümlein and A. Tkabladze
*Nucl. Phys. B553, 427 (1999)*
Strange polarization

- How much does the strange quark contribute to the proton spin?

→ Global QCD analyses indicate non-zero strange polarization – violation of Ellis-Jaffe sum rule

\[ \Delta s^+(Q^2) = \int_0^1 dx \Delta s^+(x, Q^2) \]

**JAM15:** \( \Delta s^+ = -0.1 \pm 0.01 \)

**DSSV09:** \( \Delta s^+ = -0.11 \quad Q^2 = 1 \text{ GeV}^2 \)

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• Assuming \( \sim 20\% \) SU(3)_f symmetry breaking in value of \( a_8 \)
  \( \Delta s^+ \sim -0.03 \pm 0.03 \)

• How does semi-inclusive DIS affect the shape of \( \Delta s^+ \)?
  → More general: what can SIDIS tell us about sea quark contributions?
Semi-inclusive DIS

- SIDIS observables require information on FFs → contains information about quark to hadron fragmentation.

\[ d\sigma^{SIDIS} = \sum_f \int d\xi d\zeta \Delta f(\xi) D_f(\zeta) d\sigma \]

- Which SIDIS observable is most sensitive to strange PDF?

→ Kaon valence structure contains strange flavor \( K^+(u\bar{s}) \) \( K^-(u\bar{s}) \)

- From proton target:

\[ d\sigma^{K^+} \sim 4\Delta u D_{u}^{K^+} + \Delta s D_{\bar{s}}^{K^+} \]
\[ d\sigma^{K^-} \sim 4\Delta \bar{u} D_{\bar{u}}^{K^-} + \Delta s D_{s}^{K^-} + 4\Delta u D_{u}^{K^-} \]

- From deuteron target:

\[ d\sigma^{K^+} \sim 4(\Delta u + \Delta d) D_{u}^{K^+} + 2\Delta \bar{s} D_{\bar{s}}^{K^+} \]
\[ d\sigma^{K^-} \sim 4(\Delta \bar{u} + \Delta \bar{d}) D_{\bar{u}}^{K^-} + 2\Delta s D_{s}^{K^-} + 4(\Delta u + \Delta d) D_{u}^{K^-} \]
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  \[
  d\sigma^{K^+} \sim 4\Delta u D_u^{K^+} + \Delta \bar{s} D_{\bar{s}}^{K^+} \\
  d\sigma^{K^-} \sim 4\Delta \bar{u} D_{\bar{u}}^{K^-} + \Delta s D_s^{K^-} + 4\Delta u D_u^{K^-}
  \]

  Dominate terms in intermediate to large-\( x \) region

  Low-x sensitivity

- From deuteron target:

  \[
  d\sigma^{K^+} \sim 4(\Delta u + \Delta d) D_u^{K^+} + 2\Delta \bar{s} D_{\bar{s}}^{K^+} \\
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**Semi-inclusive DIS**

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\end{array}
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\]
Fragmentation Functions

• SIDIS observables require information on FFs → contains information about quark to hadron fragmentation.

\[ d\sigma^{SIDIS} = \sum_f \int d\xi d\zeta \Delta f(\xi) D_f(\zeta) d\hat{\sigma} \]

→ Choice of kaon FF parameterization influences shape of strange polarization density in SIDIS analysis (Leader et. al.)

→ Recent JAM analysis extracted FFs from single-inclusive e+e− annihilation using the iterative Monte Carlo technique (arXiv:1609:00899)
JAM16 Analysis – SIA analysis

- Closer agreement with DSS analysis for $s^+ \rightarrow K^+$ distribution
JAM17 Combined Analysis

- We perform the first ever combined Monte Carlo analysis of polarized DIS, polarized SIDIS, and SIA data (at NLO)

\[ d\sigma^{DIS} = \sum_f \int d\xi \Delta f(\xi) d\hat{\sigma} \quad d\sigma^{SIA} = \sum_f \int d\zeta D_f(\zeta) d\hat{\sigma} \]

\[ d\sigma^{SIDIS} = \sum_f \int d\xi d\zeta \Delta f(\xi) D_f(\zeta) d\hat{\sigma} \]

- Spin PDFs and FFs are fitted simultaneously
- SU(2) and SU(3) constraints used in DIS only analyses are released

\[ \int_0^1 dx \left( \Delta u^+ - \Delta d^+ \right) \overset{?}{=} g_A \quad \rightarrow \text{Direct test of QCD} \]

\[ \int_0^1 dx \left( \Delta u^+ + \Delta d^+ - 2\Delta s^+ \right) \overset{?}{=} a_8 \quad \rightarrow \text{Combined DIS+SIDIS can determine values for } g_A \text{ and } a_8 \]
Fitting Methods

- Start with functional form for PDFs and FFs, e.g.
  \[ x f(x) = N x^a (1 - x)^b (1 + c \sqrt{x} + dx) \]
- Single \( \chi^2 \) fit of parameters
  - Typically fix parameters that are difficult to constrain
  - Uncertainties determined by Hessian or Lagrange multiplier methods
  - Introduces tolerance criteria

However, \( \chi^2 \) is a highly non-linear function of the fit parameters…there can be many local minima!

- Monte Carlo methods (neural network, Markov chain, nested sampling, etc.)
  - Allows exploration of the parameter/chi-squared landscape
  - Uncertainties determined directly from Monte Carlo sample

- JAM17 uses iterative Monte Carlo procedure for combined PDF/FF analysis
Iterative Monte Carlo (IMC) Fitting Methodology
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Initial iteration: flat sample priors

→ Set of parameters used as initial guess for least-squares fits
Iterative Monte Carlo (IMC) Fitting Methodology

Perform thousands of fits
Iterative Monte Carlo (IMC) Fitting Methodology

Perform thousands of fits

→ Pseudo-data constructed by bootstrap method
Iterative Monte Carlo (IMC) Fitting Methodology

Perform thousands of fits

- Pseudo-data constructed by bootstrap method
- Data is partitioned for cross-validation – training set is fitted via chi-square minimization
Iterative Monte Carlo (IMC) Fitting Methodology

Obtain a set of posteriors

→ Set of parameters that minimize validation chi-square are chosen as posteriors
Iterative Monte Carlo (IMC) Fitting Methodology

Posteriors are sent through a sampler

- **Kernel density estimation (KDE):** estimates the multi-dimensional probability density function of the parameters

- A sample of parameters is chosen from the KDE and used as starting priors for the next iteration

- Iterated until distributions are converged
Iterative Monte Carlo (IMC) Fitting Methodology

Obtain final set of parameters

→ Compute mean and standard deviation of observables

\[ E[\mathcal{O}] = \frac{1}{n} \sum_{k=1}^{n} \mathcal{O}(a_k) \]

\[ V[\mathcal{O}] = \frac{1}{n} \sum_{k=1}^{n} (\mathcal{O}(a_k) - E[\mathcal{O}])^2 \]
Toy Model

- Flat sampling of initial priors

\{ \alpha, \beta \}
**IMC Methodology**

**Toy Model**
- Flat sampling of initial priors
  \[
  \{ \alpha, \beta \} 
  \]
- Initial set of fits $\rightarrow$ posteriors
  \[
  \{ \alpha, \beta \} \rightarrow \{ \alpha, \beta \} 
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**IMC Methodology**

**Toy Model**

- Flat sampling of initial priors
  \[ \{\alpha, \beta\} \]
- Initial set of fits $\rightarrow$ posteriors
  \[ \{\alpha, \beta\} \rightarrow \{\alpha, \beta\} \]
- Posteriors $\rightarrow$ priors for first iteration $\rightarrow$ new posteriors
  \[ \{\alpha, \beta\} \rightarrow \{\alpha, \beta\} \]
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- Posteriors $\rightarrow$ priors for first iteration $\rightarrow$ new posteriors
  \[ \{\alpha, \beta\} \rightarrow \{\alpha, \beta\} \]
- Repeat until convergence...
Parameterizations and Chi-square

**Template function:** \( T(x; \alpha) = \frac{M x^a (1 - x)^b (1 + c\sqrt{x})}{B(n + a, 1 + b) + cB(n + \frac{1}{2} + a, 1 + b)} \)

- **PDFs: n = 1** \( \Delta q^+, \Delta \bar{q}, \Delta g = T(x; \alpha) \)
- **FFs: n = 2, c = 0**
  - **Favored:** \( D_{q+}^h = T(z; \alpha) + T(z; \alpha') \)
  - **Unfavored:** \( D_{q+}^h, g = T(z; \alpha) \)

**Pions:**
- \( D_{\pi^+}^{u} = D_{d}^{\pi^+} = T(z; \alpha) \)
- \( D_{s}^{\pi^+} = \frac{1}{2} D_{s}^{\pi^+} \)

**Kaons:**
- \( D^{K^+}_{u} = D^{K^+}_{d} = \frac{1}{2} D^{K^+}_{d} \)
- \( D_{s}^{K^+} = T(z; \alpha) \)

- **Chi-squared definition:**

\[
\chi^2(\alpha) = \sum_e \left[ \sum_i \left( \frac{D_i^{(e)} N_i^{(e)} - T_i^{(e)}(\alpha)}{\alpha_i^{(e)} N_i^{(e)}} \right)^2 + \sum_k (r_k^{(e)})^2 \right] + \sum_\ell \left( \frac{a(\ell) - \mu(\ell)}{\sigma(\ell)} \right)^2
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Parameterizations and Chi-square

Template function: \[ T(x; a) = \frac{M x^a (1 - x)^b (1 + c \sqrt{x})}{B(n + a, 1 + b) + c B(n + \frac{1}{2} + a, 1 + b)} \]

- PDFs: \( n = 1 \) \( \Delta q^+, \Delta \bar{q}, \Delta g = T(x; a) \)
- FFs: \( n = 2, c = 0 \) Favored: \( D^h_{q^+} = T(z; a) + T(z; a') \)
  Unfavored: \( D^h_{q^+, g} = T(z; a) \)

\[
\begin{align*}
\text{Pions:} & \\
D^\pi^+_{\bar{u}} &= D^\pi^+_d = T(z; a) \\
D^\pi^+_s &= \frac{1}{2} D^\pi^+_s
\end{align*}
\]

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\begin{align*}
\text{Kaons:} & \\
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Penalty for fitting normalizations
Parameterizations and Chi-square

Template function: \[ T(x; \alpha) = \frac{M x^a (1 - x)^b (1 + c \sqrt{x})}{B(n + a, 1 + b) + c B(n + \frac{1}{2} + a, 1 + b)} \]

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\[ D_{\bar{u}}^{\pi^+} = D_{d}^{\pi^+} = T(z; \alpha) \]
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Modified likelihood to include prior information
Data vs Theory – SIDIS

\[ A_1^h = \frac{g_1^h}{F_1^h} \]

<table>
<thead>
<tr>
<th>process</th>
<th>target</th>
<th>( N_{\text{dat}} )</th>
<th>( \chi^2 )</th>
</tr>
</thead>
<tbody>
<tr>
<td>DIS ( p, d, ^3\text{He} )</td>
<td>854</td>
<td>854.8</td>
<td></td>
</tr>
<tr>
<td>SIA ( (\pi^\pm, K^\pm) )</td>
<td>850</td>
<td>997.1</td>
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</tr>
<tr>
<td>SIDIS ( (\pi^\pm) )</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>HERMES</td>
<td>( d )</td>
<td>18</td>
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<tr>
<td>HERMES</td>
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<td>COMPASS</td>
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<td>8.0</td>
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<tr>
<td>COMPASS</td>
<td>( p )</td>
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<tr>
<td>SIDIS ( (K^\pm) )</td>
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<tr>
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<td>COMPASS</td>
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<tr>
<td>COMPASS</td>
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<td>24</td>
<td>12.3</td>
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<tr>
<td><strong>Total:</strong></td>
<td></td>
<td><strong>1855</strong></td>
<td><strong>1969.7</strong></td>
</tr>
</tbody>
</table>

Good agreement overall with all data!
Polarized PDF Distributions

- $\Delta u^+$ consistent with previous analysis
- $\Delta d^+$ slightly larger in magnitude
  - Anti-correlation with $\Delta s^+$, which is less negative than JAM15 at $x \sim 0.2$

- Isoscalar sea distribution consistent with zero
- Isovector sea slightly prefers positive shape at low $x$
  - Non-zero asymmetry given by small contributions from SIDIS asymmetries
Strange polarization

- $\Delta s^+$ distribution consistent with zero, slightly positive in intermediate $x$ range
- Primarily influenced by HERMES K-data from deuterium target
Strange polarization

Why does DIS+SU(3) give large negative $\Delta s^+$?

- Low $x$ DIS deuterium data from COMPASS prefers small negative $\Delta s^+$
- Needs to be more negative in intermediate region to satisfy SU(3) constraint
- $b$ parameter for $\Delta s^+$ typically fixed to values $\sim 6$-$10$, producing a peak at $x \sim 0.1$

- $\Delta s^+$ distribution consistent with zero, slightly positive in intermediate $x$ range
- Primarily influenced by HERMES $K^-$ data from deuterium target
Moments

$g_A = 1.24 \pm 0.04$  
Confirmation of SU(2) symmetry to $\sim 2\%$

$a_8 = 0.46 \pm 0.21$  
$\sim 20\%$ SU(3) breaking $\pm \sim 20\%$; large uncertainty

- Need better determination of $\Delta s^+$ moment to reduce $a_8$ uncertainty!

$\Delta s^+ = -0.03 \pm 0.09$
Moments

\[ \Delta \Sigma = 0.36 \pm 0.09 \]

Slightly larger central value than previous analyses, but consistent within uncertainty.

Preference for slightly positive sea asymmetry; not very well constrained by SIDIS.

\[ \Delta \bar{u} - \Delta \bar{d} = 0.05 \pm 0.08 \]
Fragmentation Functions

- Little change in ‘plus’ distributions from JAM16
  \( \rightarrow s^+ \) to \( K^+ \) FF marginally smaller at low-\( z \) compared to JAM16

- Better agreement with DSS’s strange FF (dashed red line) in intermediate \( z \) region
  than HKNS (dotted red line)

- Uncertainty for unfavored \( \bar{u} \) to \( \pi \) distribution smaller than \( s \) to \( K \)
  \( \rightarrow \) Due to lower precision kaon production data
Summary and Outlook

• Analysis suggests the resolution of the “strange polarization puzzle”
  → Shape of $\Delta s^+$ in DIS+SU(3) analyses is artificial (caused by SU(3) constraint + large-x shape parameter)

• Data sensitive to $\Delta s^+$ distribution give result consistent with zero with large uncertainties
  → Need higher precision polarized SIDIS kaon data

• Difficult to determine $a_8$ with DIS+SIDIS, but results confirm SU(2) symmetry to $\sim 2\%$

• QCD observables yet to be implemented:
  • $W$ asymmetries for constraints on up and down sea polarization
  • Unpolarized SIDIS and single-inclusive $pp$ collision for FFs

• JAM is working towards a universal fit of quark helicity distributions $q^+, q^-$
  • Global analyses of combined unpolarized and polarized data