The JAM fits of polarized PDFs

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(for the JAM collaboration)

Jimenez-Delgado, Accardi, Melnitchouk, PRD89 (2014) 034025
The JAM collaboration

The JAM (Jefferson Lab Angular Momentum) Collaboration is an enterprise involving theorists and experimentalists from the Jefferson Lab community to study the quark and gluon spin structure of the nucleon by performing global fits of spin-dependent parton distribution functions (PDFs).

Because of the unique capabilities of Jefferson Lab's CEBAF accelerator in measuring small cross sections at extreme kinematics, the JAM spin PDFs are particularly tailored for studies of the large Bjorken-$x$ region, as well as the resonance-deep inelastic transition region at low and intermediate values of $W$ and $Q^2$.

Parallel effort to our unpolarized PDFs: CJ and JR
Who's who

Theory:

- Pedro Jimenez-Delgado (JLab)
- Alberto Accardi (Hampton U. / JLab)
- Jacob Ethier (William and Mary)
- Wally Melnitchouk (Jlab)
- Nobuo Sato (soon at JLab)

Experiment:

- Harut Avakian (JLab)
- Peter Bosted (JLab / William&Mary)
- Jian-ping Chen (JLab)
- Keith Griffioen (William&Mary)
- Sebastian Kuhn (Old Dominion U.)
- Yelena Prok (Old Dominion U.)
- Oscar Rondon (U. of Virginia)
- Brad Sawatzky (JLab)
The JAM database

Public database with all data on polarized scattering experiments (DIS for now)

www.jlab.org/jam

JAM database - Experiments

<table>
<thead>
<tr>
<th>Experiment</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>COMPASS</td>
<td>proton and deuteron A1, g1</td>
</tr>
<tr>
<td>EMC</td>
<td>proton A1, g1</td>
</tr>
<tr>
<td>HERMES</td>
<td>proton, deuteron, and 3He $A_{par}$, neutron A1</td>
</tr>
<tr>
<td>HERMES2012</td>
<td>proton A2 and g2</td>
</tr>
<tr>
<td>JLab Hall A (E01-012)</td>
<td>3He $A_{par}$, A1, g1</td>
</tr>
<tr>
<td>JLab Hall A (E97-103)</td>
<td>3He (and neutron) asymmetries, g1, g2</td>
</tr>
<tr>
<td>JLab Hall A (E99-117)</td>
<td>3He (and neutron) asymmetries, g1, g2</td>
</tr>
<tr>
<td>JLab Hall B (E01b)</td>
<td>proton and deuteron A1</td>
</tr>
<tr>
<td>JLab Hall C (E01-006 &quot;RSS&quot;)</td>
<td>proton and deuteron $A_{par}$ and $A_{perp}$ (resonance region)</td>
</tr>
<tr>
<td>SLAC E142</td>
<td>3He A1, A2, g1, g2</td>
</tr>
<tr>
<td>SLAC E143</td>
<td>proton and deuteron $A_{par}$, $A_{perp}$</td>
</tr>
<tr>
<td>SLAC E154</td>
<td>3He $A_{par}$, $A_{perp}$</td>
</tr>
<tr>
<td>SLAC E155</td>
<td>proton and deuteron A1, A2, g1, g2</td>
</tr>
<tr>
<td>SLAC E155x</td>
<td>proton and deuteron A2, g2</td>
</tr>
<tr>
<td>SLAC E80/E130</td>
<td>proton $A_{par}$</td>
</tr>
<tr>
<td>SMC</td>
<td>proton and deuteron A1, g1</td>
</tr>
</tbody>
</table>
## Data and theory comparison with other groups

<table>
<thead>
<tr>
<th></th>
<th>DIS</th>
<th>SIDIS</th>
<th>hadron collider</th>
<th>nuclear smearing</th>
<th>TMCs</th>
<th>HT $g_1$</th>
<th>HT $g_2$</th>
</tr>
</thead>
<tbody>
<tr>
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<td></td>
<td></td>
<td></td>
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<td></td>
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</tr>
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<td>✓</td>
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<td>✓</td>
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</tbody>
</table>

(DS0 in 2014)

Presently concentrating on DIS theoretical description

Long-term objective: tick all the boxes (include SIDIS and collider data)
Current status of polarized PDFs

Worse known than the unpolarized

\[\Delta u^+ = \Delta u + \Delta \bar{u} \quad \text{and} \quad \Delta d^+ = \Delta d + \Delta \bar{d}\]

best known

Sea distributions \(\Delta \bar{u}, \Delta \bar{d}, \Delta \bar{s}\)
do not enter in DIS asymmetries

\(\Delta g\) less known, determined mainly
from RHIC data (also COMPASS)

NOTES:
Red: JAM reference (LT, no corrections)
Updated DSSV gluon in arXiv:1404.4293
Data considered at this (first) stage

World data on polarized DIS
(for \( Q^2 \geq 1 \text{ GeV}^2, \ W^2 \geq 3.5 \text{ GeV}^2 \))

Mainly using measured asymmetries:

\[
A_{\parallel} = D(A_1 + \eta A_2)
\]

\[
A_{\perp} = d(A_2 - \xi A_1)
\]

Note: \( D, d \) depend on

\[
R = \frac{F_L}{(1 + \gamma^2)F_2 - F_L}
\]

\[\gamma^2 = 4\frac{M^2}{Q^2}x^2\]

→ We consistently develop our own
Unpolarized analysis in parallel (JR)

Impact of high-statistics data
from JLab is being analyzed

Jlab EG1-dvcs: \( g_1/F_1 \) fresh from the web arXiv:1404.6231
Unpolarized PDF fits with large-\(x\) corrections

- Unpolarized PDF needed to calculate denominators of helicity asymmetries

- Fits developed in parallel to JAM; similar philosophy, focus

\[\rightarrow \textbf{CJ12} \ [\text{CTEQ-JLab}] \ – \text{Owens, Accardi, Melnitchouk} \]
- HT, TMCs
- Nuclear, off-shell corrections
- \textit{Nuclear uncertainties quantified}

\[\rightarrow \textbf{JR14} \ – \text{Jimenez-Delgado, Reya, arXiv:1403.1852} \]
- HT, TMCs
- Nuclear (Paris w.fn. only), off-shell
- \textit{Used in JAM fits}

\[\rightarrow \text{see also ABM 12} \ – \]
- Alekhin, Bluemlein, Moch, PRD86 (2012) 054009
Underlying QCD description

Asymmetries from (un)polarized structure functions:

\[
A_1 = (g_1 - \gamma^2 g_2) \frac{2x}{(1 + \gamma^2) F_2 - F_L} \quad A_2 = \gamma(g_1 + g_2) \frac{2x}{(1 + \gamma^2) F_2 - F_L}
\]

Calculations and RGE evolution using Mellin moments (truncated solutions)

\[
f(n) = \int_0^1 dx \, x^{n-1} f(x)
\]

Leading-twist structure functions in OPE from NLO QCD computations:

\[
g_{1\tau=2}(n, Q^2) = \frac{1}{2} \sum_{q, \bar{q}} e_q^2 \left( \Delta C_{qq}^1 \Delta q + \Delta C_g^1 \Delta g \right)
\]

\[
g_{2\tau=2}(n, Q^2) = g_{2WW} = -\frac{n-1}{n} g_1(n, Q^2) \quad \text{[Wandzura, Wilczek 77]}
\]
Parametrization

Only two independent combinations of quark distributions contribute:

\[ x\Delta u^+ (x, \mu_0^2) = N_u x^{a_u} (1 - x)^{b_u} (1 + A_u \sqrt{x} + B_u x) \]

\[ x\Delta d^+ (x, \mu_0^2) = N_d x^{a_d} (1 - x)^{b_d} (1 + A_d \sqrt{x} + B_d x) \]

\[ \Delta q^+ \equiv \Delta q + \Delta \bar{q} \]

Constrains from hyperon decays relate \( N_u \) and \( N_d \) and fix \( N_s \):

\[ \int_0^1 (\Delta u^+ - \Delta d^+) dx = 1.269 \pm 0.003 \]

\[ \int_0^1 (\Delta u^+ + \Delta d^+ - 2\Delta s^+) dx = 0.586 \pm 0.031 \]

Sea quarks shape fixed by counting rules and imposing:

\[ \lim_{x \to 0} \Delta \bar{q} = 2 \lim_{x \to 0} \Delta q^+ \]

\[ \frac{1}{2} \left( \left| \frac{\Delta \bar{q}^{(2)}}{\Delta s^{(2)}} \right| + \left| \frac{\Delta \bar{s}^{(2)}}{\Delta \bar{q}^{(2)}} \right| \right) = 1 \pm 0.25 \]

For the gluons we leave only \( N_g \) and \( B_g \) as free parameters

→ in practice current DIS data give only mild constraints

Nominally 13 (LT) + 14 (HT) = 27 parameters to be determined
Statistical estimation

Least-squares estimator with *complete treatment* of systematic uncertainties (equivalent to the correlation matrix approach) [CTEQ]:

\[ \chi^2 = \sum_{i=1}^{N} \frac{1}{\Delta_i^2} \left( D_i + \sum_{j=1}^{M} r_j \Delta_{ji} - T_i \right)^2 + \sum_{j=1}^{M} r_j^2 \]

Unfortunately most experiments do not provide enough information

Errors estimated with the *Hessian* approach (linear propagation, works well):

“Vicinity” of the minimum (tolerance) characterized by:

\[ \Delta \chi^2 = \chi^2 - \chi^2_{\text{min}} \leq T^2 = 1 \]
Simple fit without further corrections: REFERENCE

Nuclear targets treated within the “effective polarizations” approximation

\[ g_1^d = (1 - \frac{3}{2} 0.06)(g_1^p + g_1^n) \]
\[ g_1^{He3} = 0.86 \ g_1^n - 0.059 \ g_1^p \]

Baseline for assessing impact of theoretical corrections

→ More similar to DSSV, LSS than to others
Improved description of nuclear targets

Binding, Fermi motion included in “smearing” formalism [Kulagin, Petti 06] → smearing functions \( f_{jN} \) derived from nuclear spectral functions

\[
g_i^A(x) = \sum_{j=1,2} \int dy \; f_{jN}(y, \gamma) \; g_j^N \left( \frac{x}{y} \right) \quad \gamma^2 = 1 + 4 \frac{M^2}{Q^2} x^2
\]

Relevant for medium- to large-\( x \) region

\[\Delta q^+(\text{smear}) / \Delta q^+(\text{ref}) \]

\[x \]

Relevant for \( \Delta d \) in the medium- to large-\( x \) region
Plus target-mass corrections

We use power corrections from finite target mass calculated in the OPE approach:

\[ g_1^{\text{TMC}}(n) = g_1(n) + \frac{M^2}{Q^2} \frac{n^2(n+1)}{(n+2)^2} g_1(n+2) + \mathcal{O}\left(\frac{M^4}{Q^4}\right) \]

[Bluemlein, Tkabladze 99]

Note that the Wandzura-Wilzceck relation holds also after TMCs

\[ \Delta q^+(\text{TMC}) / \Delta q^+(\text{no TMC}) \]

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

Relevant for both \( \Delta u \) and \( \Delta d \) at large-\( x \)

Both nuclear and TMC corrections should be included in global fits
Plus higher twist contributions

We consider also corrections from higher twist contributions:

\[ g_1 = g_1^{\tau=2} + g_1^{\tau=3} + g_1^{\tau=4} \]
\[ g_2 = g_2^{\tau=2} + g_2^{\tau=3} \]

where \( g_1^{\tau=3} \) depends on \( g_2^{\tau=3} \) \[\text{[Bluemlein, Tkapladze 99]}\]

\[ g_1^{\tau=3}(x, Q^2) = 4x^2 \frac{M^2}{Q^2} \left( g_2^{\tau=3}(x, Q^2) - 2 \int_x^1 \frac{dy}{y} g_2^{\tau=3}(y, Q^2) \right) \]

Flexible phenomenological parametrization for \( g_2 \) inspired by \[\text{[Braun et al. 09]}\]

\[ g_2^{\tau=3} = A[\ln x + (1 - x) + \frac{1}{2}(1 - x)^2] + (1 - x)^3[B + C(1 - x) + D(1 - x)^2 + E(1 - x)^3] \]

And a splines approximation for:

\[ g_1^{\tau=4} = \frac{h(x)}{Q^2} \]

Possible scale dependence in \( h \) and \( g_2^{\tau=3} \) neglected compared to exp. errors
Plus higher twist contributions

Considerable improvement of $\chi^2$ for some sets (globally $1.07 \rightarrow 0.98 , 3\sigma$)

Very large changes in $\Delta d$
Plus higher twist contributions

Possible to determine simultaneously higher-twist contributions for $g_1$ and $g_2$

Qualitative agreement with previous (separated) determinations

→ [Leader, Sidorov, Stamenov 2010] on $g_1$

→ [Accardi, Bacchetta, Melnitchouk, Schlegel 2009] [Bluemlein, Bottcher 2012] on $g_2$
Including all corrections: JAM13

Jimenez-Delgado, Accardi, Melnitchouk, PRD89 (2014) 034025

HT contributions are manifestly important for current DIS data

Relevant for both $\Delta u$ and $\Delta d$

$Q^2 = 1 \text{ GeV}^2$

No trace of $\Delta d/d \to 1$ at $x \to 1$ as expected in pQCD
Constraints at large $x$

- Current data cannot discriminate different $\Delta u/u$ and $\Delta d/d$ behaviors
- Try and impose $x \to 1$ pQCD constraints by hand: “JAM+” fit
  - Large systematic (parametrization) uncertainty
  - More data needed at large $x$!
    (e.g., JLab EG1-dvcs, EG1b and JLab12 in near future)

*Jimenez-Delgado, Avakian, Melnitchouk, arXiv:1403.3355*
Impact of Jefferson Lab data

\[ (a) \frac{\Delta u^+}{\Delta u^+} (\text{JAM}) \]

\[ (b) \frac{\text{error}(\Delta u^+)}{\Delta u^+} (\text{JAM}) \]

\[ (c) \frac{\Delta d^+}{\Delta d^+} (\text{JAM}) \]

\[ (d) \frac{\text{error}(\Delta d^+)}{\Delta d^+} (\text{JAM}) \]

40\%-50\% uncertainty reduction
Impact of JLab 12 data

Jimenez-Delgado, Avakian, Melnitchouk, arXiv:1403.3355

60%-70% reduction of experimental uncertainty for $0.6 \leq x \leq 0.8$
Moving forward – including RHIC data

High-$p_T$ pions at RHIC: $pp \rightarrow \pi^0 X$

$$A^\pi_{LL} = \frac{d\Delta \sigma}{d\sigma} = \frac{d\sigma^{++} - d\sigma^{+-}}{d\sigma^{++} + d\sigma^{+-}}$$

We use scaled LO (K-factors):

$$d\Delta \sigma^{NLO} = 1 \times d\Delta \sigma^{LO}$$

$$d\sigma^{NLO} = 1.5 \times d\sigma^{LO}$$

One should use the full calculation, however experimental errors are large
Moving forward – including RHIC data

Already “well described” by central JAM13

PHENIX data constrain $\Delta g$ significantly
   $\rightarrow$ (without affecting quarks or DIS asymmtries)

PHENIX, arXiv:1402.6296

STAR, PRD89(2014)012001

Preliminary!!
Effect on polarized gluons

Quite comparable with DSSV++, except for small-x error band

\[ \int_{0.05}^{0.2} dx \, \Delta g(x, Q^2 = 10\text{ GeV}^2) = 0.15 \pm 0.09 \rightarrow 0.07 \pm 0.03 \]

JAM13 \quad JAM14

Preliminary!!

[DSSV]
Summary and outlook

New polarized PDFs: JAM13

- Nuclear corrections relevant
- Target mass corrections should be used
- Complete inclusion of higher-twists possible, manifestly important

Moving forward – JAM14:

- JLab (+ future JLab12) data will impact large-x $u$- and $d$-quarks
- RHIC pion $A_{LL}$ constrains medium-x gluons
- SIDIS data for flavor separation to be included “soon”

Longer term: RHIC jets & $W$, EIC, …
Backup slides
Theory analysis suggested need for additional nonzero orbital ang. momentum ($L_z = 1$) component in nucleon wave fn.

$\rightarrow$ Leading $(1-x)^3$ behavior from $L_z = 0$ component

$\rightarrow$ $L_z = 1$ gives additional $\log^2(1-x)$ enhancement of $q^\downarrow$

$q^\downarrow \sim (1 - x)^5 \log^2(1 - x)$

Avakian, Brodsky, Deur, Yuan
PRL 99, 082001 (2007)
Theory analysis suggested need for additional nonzero orbital ang. momentum ($L_z = 1$) component in nucleon wave fn.

$L_z = 1$ term needed to delay $\Delta d$ turnover until larger $x$.

Avakian, Brodsky, Deur, Yuan

*PRL* 99, 082001 (2007)
Orbital angular momentum

Global JAM & JAM+ fits can accommodate data without $L_z = 1$ terms.

“OAM” and “OAM+” fits use

$$x \Delta f = N x^\alpha (1 - x)^\beta + N' x^\alpha (1 - x)^5 \log^2 (1 - x)$$

can also accommodate data, with similar overall $\chi^2$

MORE DATA NEEDED!
Several upcoming experiments at JLab will measure

\[ A_1(p, d, ^3\text{He}) \text{ up to } x \sim 0.8 \]