Recent Results on Nucleon and Nuclei Structure from the JAM Collaboration

Chris Cocuzza (Temple U.)

April 26, 2022
1. Introduction
2. Spin-Averaged Sea Asymmetry
3. Helicity Sea Asymmetry
4. Isovector Nuclear Effects
5. Other JAM Results
JAM Collaboration

3-dimensional structure of nucleons:
• Parton distribution functions (PDFs)
• Fragmentation functions (FFs)
• Transverse momentum dependent distributions (TMDs)
• Generalized parton distributions (GPDs)

Collinear factorization in perturbative QCD

Simultaneous determinations of PDFs, FFs, etc.

Monte Carlo methods for Bayesian inference
Current State of JAM Global Analyses

Data space

DIS

SIDIS

Unpolarized only

$^3$H

$^3$He

$^3$He

D

D

$p$

$p$

$p$

$pp$ Jets

$pp$ $W^\pm/Z$

$\pi^\pm$

$h^\pm$

$\pi^\pm$

$K^\pm$

Drell-Yan

$p$ $D$

$p$ $D$

$^3$He

$^3$He

$^3$He

Theory

Collinear Factorization

NLO now
NNLO future

Target Mass Corrections

Small $x$ Evolution

Higher Twists

Methodology

Traditional Parameterization

Neural Nets

MC Approach

Maximum Likelihood
+Hessian/Lagrange

Simultaneous Paradigm

Helicity PDFs

Unpol. PDFs

Frag. Functions

Pol. SIDIS

$\pi^\pm$

$K^\pm$

$h^\pm$

Unpolarized only

3H

3He

3He

D

D
A Global Analysis

Simultaneous extractions of spin-averaged PDFs, helicity PDFs, and FFs

Part 1: Introduction
# Database

<table>
<thead>
<tr>
<th>Spin-Averaged PDFs</th>
<th>BCDMS, NMC, SLAC, HERA, JLab</th>
<th>3863</th>
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<tbody>
<tr>
<td>Drell-Yan</td>
<td>Fermilab E866, E906</td>
<td>205</td>
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<tr>
<td>W/Z Boson</td>
<td>CDF/D0, STAR, LHCb, CMS</td>
<td>153</td>
</tr>
<tr>
<td>Jets</td>
<td>CDF/D0, STAR</td>
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<tr>
<td>Polarized DIS</td>
<td>COMPASS, EMC, HERMES, SLAC, SMC</td>
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<td>Polarized W/Z Boson</td>
<td>STAR, PHENIX</td>
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</tr>
</tbody>
</table>

**Part 1: Introduction**

**Spin-Averaged PDFs**

**Helicity PDFs**

**$\pi, K, h$ FFs + PDFs**
Part 1: Introduction

Parameters to Observables

Parameterize PDFs at input scale $Q_0^2 = m_c^2$

$$f_i(x) = N x^\alpha (1 - x)^\beta (1 + \gamma \sqrt{x + \eta x})$$

Evolve PDFs using DGLAP

$$\frac{d}{d \ln(\mu^2)} f_i(x, \mu) = \sum_j \int_x^1 \frac{dz}{z} P_{ij}(z, \mu) f_j\left(\frac{x}{z}, \mu\right)$$

Calculate Observables

$$d\sigma_{DY} = \sum_{i,j} H_{ij}^{DY} \otimes f_i \otimes f_j$$
The $\chi^2$ function

Now that the observables have been calculated...

$$\chi^2(a) = \sum_{i,e} \left( \frac{d_{i,e} - \sum_k r^k_e \beta^{k}_{i,e} - T_{i,e}(a)/N_e}{\alpha_{i,e}} \right)^2 + \sum_k \left( r^k_e \right)^2 + \left( \frac{1 - N_e}{\delta N_e} \right)^2$$
Bayes’ Theorem

Now that we have calculated $\chi^2(a, \text{data})$...

Likelihood Function

$$\mathcal{L}(a, \text{data}) = \exp \left( -\frac{1}{2} \chi^2(a, \text{data}) \right)$$

Bayes’ Theorem

$$\mathcal{P}(a|\text{data}) \sim \mathcal{L}(a, \text{data}) \pi(a)$$
Data Resampling

\[ \tilde{\sigma} = \sigma + \mathcal{N}(0, 1) \alpha \]

Part 1: Introduction

Pseudo-Data \rightarrow Data \rightarrow Uncorrelated Uncertainties

Original Data

Replica Data

Parameter Space

Data Resampling

\[ \tilde{\sigma} = \sigma + \mathcal{N}(0, 1) \alpha \]

Uncorrelated Uncertainties

Data
1. Introduction

2. Spin-Averaged Sea Asymmetry

3. Helicity Sea Asymmetry

4. Isovector Nuclear Effects

5. Other JAM Results

Bayesian Monte Carlo extraction of sea asymmetry with SeaQuest and STAR data

Christopher Cocuzza, Wally Melnitchouk, Andreas Metz, Nobuo Sato

We perform a global QCD analysis of unpolarized parton distributions within a Bayesian Monte Carlo framework, including the new W-lepton production data from the STAR Collaboration at RHIC and Drell-Yan di-muon data from the SeaQuest experiment at Fermilab. We assess the impact of these two new measurements on the light antiquark sea in the proton, and the $\bar{d}$ – $\bar{u}$ asymmetry in particular. The SeaQuest data are found to significantly reduce the uncertainty on the $\bar{d}/\bar{u}$ ratio at large parton momentum fractions $x$, strongly favoring an enhanced $\bar{d}$ sea up to $x \approx 0.4$, in general agreement with nonperturbative calculations based on chiral symmetry breaking in QCD.

https://arxiv.org/abs/2109.00677

Introduction to Sea Asymmetry

Part 2: Spin-Averaged Sea Asymmetry

Cannot be explained from gluons splitting into quark-antiquark pairs

Meson Cloud Models
Chiral Soliton Models
Statistical Models

Still questions at high $x > 0.2$ and for helicity asymmetry
### Kinematic Coverage (Spin-Averaged)

#### Deep Inelastic Scattering
- BCDMS, NMC, SLAC, HERA, Jefferson Lab
- Points: 3863

#### Drell-Yan
- Fermilab E866, E906
- Points: 205

#### W/Z Boson Production
- CDF/D0, STAR, LHCb, CMS
- Points: 153

#### Jets
- CDF/D0, STAR
- Points: 200

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**Diagram**: 
- **Legend**:
  - SeaQuest
  - STAR W
  - NuSea
  - BCDMS
  - NMC
  - SLAC
  - JLab BONuS
  - JLab Hall C
  - HERA
  - CDF/D0 W/Z

- **Axes**: 
  - $Q^2$ (GeV$^2$)
  - $x$ (range unspecified)

- **Notations**:
  - New STAR data
  - New SeaQuest data
Well-known tension between NuSea and SeaQuest
Impact from STAR and SeaQuest

**STAR:** Moderate reduction of uncertainties

**SeaQuest:** Large reduction of uncertainties, especially at $x > 0.2$.

$\frac{\bar{d}}{\bar{u}} > 1$ up to $x \approx 0.4$, in agreement with models.
Sources of Asymmetry

\[ Q^2 = 10 \text{ GeV}^2 \]

\[ x(\bar{d} - \bar{u}) \]

\[ \int_{0.01}^{1} dx (\bar{d} - \bar{u}) \]
Comparison to other fits and pion cloud model

Good agreement with pion cloud model
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Polarized Antimatter in the Proton from Global QCD Analysis

C. Cocuzza, W. Melnitchouk, A. Metz, N. Sato

We present a global QCD analysis of spin-dependent parton distribution functions (PDFs) that includes the latest polarized W-lepton production data from the STAR collaboration at RHIC. These data allow the first data-driven extraction of a nonzero polarized light quark sea asymmetry $\Delta \bar{u} - \Delta \bar{d}$ within a global QCD framework with minimal theoretical assumptions. Within our simultaneous extraction of polarized PDFs, unpolarized PDFs, and pion and kaon fragmentation functions, we also extract a self-consistent set of antiquark polarization ratios $\Delta \bar{u}u$ and $\Delta \bar{d}d$.

Kinematic Coverage (Helicity)

<table>
<thead>
<tr>
<th>Category</th>
<th>Collaborations</th>
<th>Points</th>
</tr>
</thead>
<tbody>
<tr>
<td>Deep Inelastic Scattering</td>
<td>COMPASS, EMC, HERMES, SLAC, SMC</td>
<td>365</td>
</tr>
<tr>
<td>W/Z Boson Production</td>
<td>STAR, PHENIX</td>
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</tr>
<tr>
<td>Jets</td>
<td>STAR, PHENIX</td>
<td>61</td>
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</table>
STAR Quality of Fit

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

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

<table>
<thead>
<tr>
<th>process</th>
<th>( N_{\text{dat}} )</th>
<th>( \chi^2/N_{\text{dat}} )</th>
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<td></td>
<td></td>
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<td>0.93</td>
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<tr>
<td>inclusive jets</td>
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<td>0.81</td>
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<tr>
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<tr>
<td>PHENIX ( W^\pm /Z )</td>
<td>6</td>
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<tr>
<td>total</td>
<td><strong>587</strong></td>
<td><strong>0.85</strong></td>
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<td>unpolarized</td>
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<td></td>
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<tr>
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<td><strong>1.11</strong></td>
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<tr>
<td>SIA ( (\pi^\pm) )</td>
<td>231</td>
<td>0.85</td>
</tr>
<tr>
<td>SIA ( (K^\pm) )</td>
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<td>0.49</td>
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<tr>
<td>total</td>
<td><strong>5495</strong></td>
<td><strong>1.05</strong></td>
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</table>
Part 3: Helicity Sea Asymmetry

Resulting Asymmetry

Positivity Constraints:

$|\Delta f(x, Q^2)| < f(x, Q^2)$

DSSV08 shows positive asymmetry at low $x < 0.1$

NNPDF shows hint of positive asymmetry at intermediate $x$

Our result is strongly positive in both regions of $x$

$Q^2 = 10 \text{ GeV}^2$
Proton Spin Contributions

Inclusion of RHIC W/Z data shows that $\Delta \bar{u}$ ($\Delta \bar{d}$) contribution is small and positive (negative).

<table>
<thead>
<tr>
<th>Flavor</th>
<th>JAM moment (truncated)</th>
<th>Lattice Moment (full)</th>
<th>Difference</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\Delta u^+$</td>
<td>0.779(34)</td>
<td>0.864(16)</td>
<td>0.085</td>
</tr>
<tr>
<td>$\Delta d^+$</td>
<td>-0.370(40)</td>
<td>-0.426(16)</td>
<td>0.056</td>
</tr>
</tbody>
</table>

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Isosvector EMC effect from global QCD analysis with MARATHON data

C. Cocuzza, C. E. Keppel, H. Liu, W. Melnitchouk, A. Metz, N. Sato, A. W. Thomas

We report the results of a Monte Carlo global QCD analysis of unpolarized parton distribution functions (PDFs), including for the first time constraints from ratios of $^3$He to $^3$H structure functions recently obtained by the MARATHON experiment at Jefferson Lab. Our simultaneous analysis of nucleon PDFs and nuclear effects in $A = 2$ and $A = 3$ nuclei reveals the first indication for an isovector nuclear EMC effect in light nuclei. We find that while the MARATHON data yield relatively weak constraints on the $F_2/F_2^p$ neutron to proton structure function ratio and on the $d/u$ PDF ratio, they suggest an enhanced nuclear effect on the $d$-quark PDF in the bound proton, questioning the assumptions commonly made in nuclear PDF analyses.

https://arxiv.org/abs/2104.06946

# Kinematic Coverage

## Deep Inelastic Scattering
- BCDMS, NMC, SLAC, HERA, Jefferson Lab **3863 points**

## Drell-Yan
- Fermilab E866 **250 points**

## W/Z Boson Production
- Tevatron CDF/D0, LHC ATLAS/CMS **239 points**

## Jets
- Tevatron CDF/D0, RHIC STAR **196 points**

*New MARATHON data*
**Isospin Symmetry**

How to relate quarks between protons and neutrons?

It is usually approximated that:

\[ u_{p/A} \approx d_{n/A} \]

\[ d_{p/A} \approx u_{n/A} \]

- “Free” nucleon
- (Approx.) Symmetric Nuclei \((D, ^{56}Fe)\)
- Asymmetric Nuclei \((^{3}He, ^{3}H, ^{197}Au)\)
Part 4: Isovector Nuclear Effects

**Isovector Effect**

Mean Field Approximation in the valence region:

\[ q(x) = \frac{p^+}{p^+ - V^+} q_0 \left( \frac{p^+}{p^+ - V^+} x - \frac{V_q^+}{p^+ - V^+} \right) \]

- **Nucleon Momentum**
- **PDF in absence of Vector Potential**
- **Net Vector Field on Quark**
- **Net Vector Field on Nucleon**

Isovector Effect

Mediated by $I_3 = \pm 1$ mesons, dependent on third component of isospin

Parameterize phenomenologically:

$$\tilde{q}_{N/A}(p^2) = q_N + \nu(p^2) \delta q_{N/A} + \ldots$$

Virtuality

$$\nu(p^2) = (p^2 - M^2)/M^2 \ll 1$$

Part 4: Isovector Nuclear Effects

**Symmetries**

\[
\begin{align*}
\delta u_{p/D} &= \delta d_{n/D} \\
\delta d_{p/D} &= \delta u_{n/D} \\
\delta u_{p/^3\text{He}} &= \delta d_{n/^3\text{He}} \\
\delta u_{p/^3\text{He}} &= \delta d_{n/^3\text{He}} \\
\delta d_{p/^3\text{He}} &= \delta u_{n/^3\text{He}} \\
\delta d_{p/^3\text{He}} &= \delta u_{n/^3\text{He}}
\end{align*}
\]

\[(u, d) \times (p, n) \times (D, ^3\text{He}, ^3\text{H}) = 12 \text{ Functions}\]

\[
\begin{align*}
\delta u_{p/D} &= \delta u_{p/^3\text{H}} \\
\delta d_{p/D} &= \delta d_{p/^3\text{H}}
\end{align*}
\]

**Isospin Symmetry**

\[
\delta u_{p/^3\text{He}} \approx \delta d_{p/^3\text{He}}
\]

**No Isovector**

\[
(\delta u + 2\delta d)/2
\]

**Just two functions!**
Nuclear PDFs

\[ q_{N/A}^{(on)}(x, Q^2) = \left[ f_{N/A}^{N/A} \otimes q_N \right] \]

\[ q_{N/A}^{(off)}(x, Q^2) = \left[ \tilde{f}_{N/A}^{N/A} \otimes \delta q_{N/A} \right] \]

Contains Virtuality

\[ \nu(p^2) = \frac{(p^2 - M^2)}{M^2} \ll 1 \]

\[ \Delta u_3 \equiv \frac{u_{p/3^H} - d_{n/3^H}}{u_{p/3^H} + d_{n/3^H}} \]

\[ \Delta d_3 \equiv \frac{d_{p/3^H} - u_{n/3^H}}{d_{p/3^H} + u_{n/3^H}} \]

Measures strength of isovector effect
Part 4: Isovector Nuclear Effects

Impact from MARATHON

Measurement of the $F_{2}^{n}/F_{2}^{p}$, $d/u$ Ratios and $A = 3$ EMC Effect in Deep Inelastic Electron Scattering Off the Tritium and Helium Mirror Nuclei

\[ d/u \text{ Ratio} \]

\[ F_{2}^{n}/F_{2}^{p} \text{ Ratio} \]

\[ A = 3 \text{ EMC Effects} \]
Impact on $d/u$

$d/u$ ratio largely constrained by W boson production data (mostly Tevatron)
Impact on $F_2^n/F_2^p$

Slight shift towards MARATHON + KP model result
Impact from MARATHON

MeAsurement of the \( F_n^2/F_p^p \), \( d/u \) RAtios and \( A = 3 \) EMC Effect in Deep Inelastic Electron Scattering Off the Tritium and Helium MirrOr Nuclei

\[
\frac{d}{u} \text{ Ratio}
\]

\[
\frac{F_n^2}{F_p^p} \text{ Ratio}
\]

\[
A = 3 \text{ EMC Effects}
\]
First global QCD analysis of JLab $^3$He/D and MARATHON data
Isovector Extraction

\[ \Delta_{3}^{u} \equiv \frac{u_{p/3H} - d_{n/3H}}{u_{p/3H} + d_{n/3H}} \]

\[ \Delta_{3}^{d} \equiv \frac{d_{p/3H} - u_{n/3H}}{d_{p/3H} + u_{n/3H}} \]

Signal for non-zero effect above \( x \gtrsim 0.4! \)
Impact from MARATHON

MeAssurement of the $F^n_2/F^p_2$, $d/u$ RAtios and $A = 3$ EMC Effect in Deep Inelastic Electron Scattering Off the Tritium and Helium MirrOr Nuclei

$d/u$ Ratio

$F^n_2/F^p_2$ Ratio

$A = 3$ EMC Effects
Isospin Symmetry

How to relate quarks between protons and neutrons?

It is usually approximated that:

\[ u_{p/A} \approx d_{n/A} \]
\[ d_{p/A} \approx u_{n/A} \]

But the correct equations are:

\[ u_{p/A} = d_{n/A}^* \]
\[ d_{p/A} = u_{n/A}^* \]

where \( A^* \) is the mirror nuclei of \( A \)
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Part 5: Other JAM Results

Gluon Polarization (2021)

How well do we know the gluon polarization in the proton?
Y. Zhou, N. Sato, W. Melnitchouk

https://arxiv.org/abs/2201.02075

\[ \int_0^1 dx [\Delta u^+ - \Delta d^+] = g_A \quad \int_0^1 dx [\Delta u^+ + \Delta d^+ - 2\Delta s^+] = a_8 \]

\[ |\Delta f(x, Q^2)| < f(x, Q^2) \]

Can MS parton distributions be negative?
Alessandro Candido, Stefano Forte and Felix Hekhorn

Positivity and renormalization of parton densities
John Collins, Ted C. Rogers, Nobuo Sato
Part 5: Other JAM Results

Small $x$ Global Analysis (2021)

First analysis of world polarized DIS data with small-$x$ helicity evolution

Daniel Adamiak,¹,∗ Yuri V. Kovchegov,¹,† W. Melnitchouk,²
Daniel Pitonyak,¹,† Nobuo Sato,²,† and Matthew D. Sievert¹,†

https://arxiv.org/abs/2102.06159

$x < 0.1$

Prediction, not extrapolation!
Transversity JAM20 (2020)

Origin of single transverse–spin asymmetries in high–energy collisions


Part 5: Other JAM Results

\[ \delta q \equiv \int_0^1 dx [h_1^q(x) - h_1^{\bar{q}}(x)] \]

\[ g_T \equiv \delta u - \delta d \]

Sivers function (moment)

Collins function (moment)

Transversity PDF
Summary and Outlook
Sea Asymmetries

Bayesian Monte Carlo extraction of sea asymmetry with SeaQuest and STAR data

Polarized Antimatter in the Proton from Global QCD Analysis

$\frac{\bar{d}}{\bar{u}}$

$x(\bar{d} - \bar{u})$

$Q^2 = 10 \text{ GeV}^2$

$\frac{\delta}{\delta_{\text{baseline}}} x$

$A_L^W$

$\sqrt{s} = 510 \text{ GeV}$

$p_T > 25 \text{ GeV}$

$\Delta \bar{u} = \Delta \bar{d}$ fit

$\Delta \bar{u} - \Delta \bar{d}$

$Q^2 = 10 \text{ GeV}^2$
Isovector EMC Effect

Isovector EMC effect from global QCD analysis with MARATHON data
Summary and Outlook

More JAM Results

How well do we know the gluon polarization in the proton?

Origin of single transverse–spin asymmetries in high–energy collisions

First analysis of world polarized DIS data with small–$x$ helicity evolution
Jefferson Lab 12 GeV will provide new information on helicity PDFs and nuclear effects at high $x$

EIC will provide new information on helicity PDFs at low $x$
Thank you to Yiyu Zhou and Patrick Barry for helpful discussions.
Backup
Part 1: JAM Methodology

Error Quantification

For a quantity $O(a)$: (for example, a PDF at a given value of $(x, Q^2)$)

$$E[O] = \int d^n a \, \rho(a \mid data) \, O(a)$$

$$V[O] = \int d^n a \, \rho(a \mid data) \, [O(a) - E[O]]^2$$

Exact, but $n = \mathcal{O}(100)$!

Build an MC ensemble

$$E[O] \approx \frac{1}{N} \sum_k O(a_k)$$

$$V[O] \approx \frac{1}{N} \sum_k [O(a_k) - E[O]]^2$$

Average over $k$ sets of the parameters (replicas)
Part 1: JAM Methodology

Multi-Step Strategy
Putting it all together…

\[ E[O] \approx \frac{1}{N} \sum_k O(a_k) \]

\[ V[O] \approx \frac{1}{N} \sum_k [O(a_k) - E[O]]^2 \]
Deep Inelastic Scattering

Virtuality:

\[ Q^2 = -q^2 \]

Bjorken x:

\[ x = \frac{Q^2}{2p \cdot q} \]

Invariant mass of outgoing particles:

\[ W^2 = (p + q)^2 \]
Difficult to describe at extreme rapidity
Part 3: Helicity Sea Asymmetry

Quark and Antiquark Polarizations
Spin Up/Down PDFs

\[ q_{↑↓} = \frac{1}{2}(q \pm \Delta q) \]

Large impact from RHIC
**EMC Ratios**

$$R(D) = \frac{F_2^D}{F_2^p + F_2^n}$$

$$R(^3\text{He}) = \frac{F_2^{^3\text{He}}}{2F_2^p + F_2^n}$$

$$R(^3\text{H}) = \frac{F_2^{^3\text{H}}}{F_2^p + 2F_2^n}$$

$$\mathcal{R} = \frac{R(^3\text{He})}{R(^3\text{H})}$$

**Significant differences between JAM result and KP model result**
Current State of Helicity PDFs

Proton spin puzzle:
\[ \frac{1}{2} = \frac{1}{2} \Delta \Sigma + \Delta G + L_q + L_g \]

\[ \Delta \Sigma = \int_0^1 dx \sum_q \Delta q^+ \]
\[ \Delta G = \int_0^1 dx \Delta g \]

Still a lot to learn about helicity PDFs at low \( x \) and the helicity sea quark PDFs!
Combining experiment and lattice in a global QCD analysis is feasible!
Opportunities at the EIC

EIC Impact on Helicity PDFs (2021)

Revisiting quark and gluon polarization in the proton at the EIC

Y. Zhou,1 C. Cocuzza,2 F. Delcarro,3 W. Melnitchouk,3 A. Metz,2 and N. Sato3

https://arxiv.org/abs/2105.04434

\[
\Delta G_{\text{trunc}}(Q^2) \equiv \int_{x_{\min}}^{1} dx \Delta g(x, Q^2),
\]

\[
\Delta \Sigma_{\text{trunc}}(Q^2) \equiv \int_{x_{\min}}^{1} dx \sum_q \Delta q^+(x, Q^2).
\]

<table>
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<th>SU(3)</th>
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<td>✓</td>
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<tr>
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<td>mid</td>
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<td>✓</td>
</tr>
<tr>
<td>3</td>
<td>high</td>
<td>✓</td>
<td>✓</td>
</tr>
<tr>
<td>4</td>
<td>low</td>
<td>✓</td>
<td>✓</td>
</tr>
<tr>
<td>5</td>
<td>mid</td>
<td>✓</td>
<td>✓</td>
</tr>
<tr>
<td>6</td>
<td>high</td>
<td>✓</td>
<td>✓</td>
</tr>
</tbody>
</table>

\[
x_{\min} = 10^{-4}, Q^2 = 10 \text{ GeV}^2
\]

\[
A_{LL}^p
\]

\[
\delta_{\text{EIC}} / \delta
\]
Impact of Parity Violating DIS (2021)

\[ g_1^{\gamma Z} \approx \frac{1}{9} (\Delta u^+ + \Delta d^+ + \Delta s^+) \]

\[ A_{UL} = \frac{G_F x Q^2}{2\sqrt{2}\pi\alpha} \left( \frac{g_A^e Y + g_1^{\gamma Z} + g_V^e Y + g_5^{\gamma Z}}{x y^2 F_1 + (1 - y) F_2} \right) \]

No impact on \( \Delta G \), but large impact on \( \Delta \Sigma \) thanks to constraints on \( \Delta s^+ \)
Impact of EIC at small $x$ (2021)

First analysis of world polarized DIS data with small-$x$ helicity evolution

Daniel Adamiak, Yuri V. Kovchegov, W. Melnitchouk, Daniel Pitonyak, Nobuo Sato, and Matthew D. Sievert

Uncertainties remain consistent even below EIC kinematics
Latest Fragmentation Functions (2021)

Simultaneous Monte Carlo analysis of parton densities and fragmentation functions

E. Moffat, W. Melnitchouk, T. C. Rogers, N. Sato

https://arxiv.org/abs/2101.04664