First combined analysis of (un)polarized PDFs and FFs and beyond

Nobuo Sato
University of Connecticut
DNP, Hadron Structure
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Motivations
Mapping the parton structure of the nucleon

**Challenges:**

- **Quantitative** limits of $x, Q^2, z, ...$ where factorization theorems are applicable

- Universality of non perturbative objects → **predictive power**

- QCD analysis framework that extracts **simultaneously** all non-perturbative objects (including TMDs)

- Framework with the same theory assumptions
Mapping the parton structure of the nucleon

- Need for a **reliable** Bayesian likelihood analysis:
  
  - Retire maximum likelihood methods that can lead to biased results (CT, MMHT, DSSV, ...)
  
  - Embrace likelihood analysis via MC methods (JAM, NNPDF)
  
  - Faithful representation of uncertainties consistent with Bayes’ theorem
Bayesian likelihood analysis

- Inclusion of modern data analysis techniques
  - Bayesian theorem
    \[ P(f|\text{data}) = \mathcal{L}(\text{data}, f)\pi(f) \]
  - Estimation of expectation values and variances:
    - data resampling
    - partition and cross validation
    - iterative Monte Carlo (IMC)
    - nested sampling
History
Inclusion of all JLab 6 GeV data $\rightarrow 0.1 < x < 0.7$

Non vanishing twist 3 quark distributions

Residual twist 4 contributions consistent with zero
Existing measurements of $d_2$ are in the resonance region
→ quark-hadron duality

$$d_2(Q^2) \equiv \int_0^1 dx x^2 \left[ 2g_1^{\tau 3}(x, Q^2) + 3g_2^{\tau 3}(x, Q^2) \right]$$
SU2, SU3 constraints imposed

What determines the sign of $\Delta s^+$?
JAM16: FFs
NS, Ethier, Melnitchouk, Hirai, Kumano, Accardi (PRD)

- $\pi$ and $K$ Belle, BaBar up to LEP energies
- JAM and DSS $D^K_{s+}$ consistent
JAM17: $\Delta$PDF + FF
Ethier, NS, Melnitchouk (PRL)

- No SU(3) constraints
- Sea polarization consistent with zero
- Precision of $\Delta$SIDIS is not sufficient to determine sea polarization
Flat priors that gives flat $a_8$ in order to have an unbiased extraction of $a_8$.

Data prefers smaller values for $a_8 \rightarrow 25\%$ larger total spin carried by quarks.

$a_3$ which is in a good agreement with values from $\beta$ decays within 2\%.

<table>
<thead>
<tr>
<th>obs.</th>
<th>JAM15</th>
<th>JAM17</th>
</tr>
</thead>
<tbody>
<tr>
<td>$g_A$</td>
<td>1.269(3)</td>
<td>1.24(4)</td>
</tr>
<tr>
<td>$g_8$</td>
<td>0.586(31)</td>
<td>0.46(21)</td>
</tr>
<tr>
<td>$\Delta \Sigma$</td>
<td>0.28(4)</td>
<td>0.36(9)</td>
</tr>
<tr>
<td>$\Delta \bar{u} - \Delta \bar{d}$</td>
<td>0</td>
<td>0.05(8)</td>
</tr>
</tbody>
</table>
Present
Goals

+ Extract PDFs, $\Delta$PDFs and FFs \textit{simultaneously}
  - DIS, SIDIS($\pi, K$), DY
  - $\Delta$DIS, $\Delta$SIDIS($\pi, K$)
  - $e^+e^-(\pi, K)$
+ Consistent extraction of $s$ and $\Delta s$

Likelihood analysis (first steps)

+ Use maximum likelihood to find a candidate solution
+ Use resampling to \textbf{check for stability} and estimate uncertainties
+ 80 shape parameters and 91 data normalization parameters: \textbf{171 dimensional space}
\( Q^2 = 10 \text{ GeV}^2 \)

- \( \bar{d} - \bar{u} \) constrained mainly by DY
- SIDIS is in agreement with DY’s \( \bar{d} - \bar{u} \)
- \( s - \bar{s} \neq 0 \)
Comparison with other groups

- dashed: MMHT14
- dashed-dotted: CT14
- dotted: CJ15
- dot-dot-dash: ABMP16

Big differences for $s, \bar{s}$ distributions
For CJ and CT, $s = \bar{s}$

- MMHT uses neutrino DIS
- SIDIS favors a strange suppression
- and a larger $s, \bar{s}$ asymmetry
Recall no SU2, SU3 imposed

$\Delta s$, $\Delta \bar{u}$, $\Delta \bar{d}$ are much better known than $\Delta \bar{s}$

It means, most of the uncertainty on $\Delta s^+$ is from $\Delta \bar{s}$
JAM18: IMC runs (preliminary)

← flat priors

← DIS no HERA

← DIS with HERA

← DIS with HERA + DY
... and beyond
SIDIS+Lattice analysis of nucleon tensor charge
Lin, Melnitchouk, Prokudin, NS, Shows (PRL)

- Extraction of transversity and Collins FFs from SIDIS $A_{UT}$+Lattice $g_T$

- In the absence of Lattice, SIDIS has no significant constraints on $g_T$  
  (See talk by W. Melnitchouk)
First global Monte Carlo analysis of pion PDFs
Barry, NS, Melnitchouk, Ji (PRL)
How to probe pion structure

+ $\pi + A \rightarrow l\bar{l} + X$ (Drell-Yan)

+ $\pi + A \rightarrow \gamma + X$ (prompt photons)

+ $e + p \rightarrow e' + n + X$ (SIDIS) $\rightarrow$ small $x_\pi$ gluon PDF
Factorization setup

\[ \frac{d\sigma}{dxdQ^2dy} \sim f_{p \to \pi+n}(y) \times \sum_q \int_{x/y}^1 \frac{d\xi}{\xi} C(\xi) q \left( \frac{x/y}{\xi}, Q^2 \right) \]
\section*{\textbf{EFT setup}}

- The splitting function \( (y = k^+/p^+ = x/x_\pi) \)

\[
f_{p\to\pi+n}(y) = \frac{g_A^2 M^2}{(4\pi f_\pi)^2} \int dk_\perp^2 \frac{y(k_\perp^2 + y^2 M^2)}{(1 - y)^2 D_{\pi N}^2} |F|^2
\]

- UV regulators used in the literature

\[
F = \begin{cases} 
[1 - \frac{(t - m_\pi^2)^2}{(t - \Lambda^2)^2}]^{1/2} & \text{Pauli-Villars} \\
(\Lambda^2 - m_\pi^2) / (\Lambda^2 - t) & t\text{-dependent monopole} \\
\exp[(t - m_\pi^2) / \Lambda^2] & t\text{-dependent exponential} \\
\exp[(M^2 - s) / \Lambda^2] & s\text{-dependent exponential} \\
y^{-\alpha_\pi(t)} \exp[(t - m_\pi^2) / \Lambda^2] & \text{Regge exponential},
\end{cases}
\]
pQCD setup

- $\pi^- + W \rightarrow l\bar{l} + X$ (Drell-Yan)

$$\frac{d\sigma}{dx_F dQ^2} = \sum_{a,b} \int d\xi d\zeta \ C_{a,b}(\xi, \zeta) f_{a/\pi^-}(\xi) f_{b/W}(\zeta)$$

- $e + p \rightarrow e' + n + X$ (LN)

$$\frac{d\sigma}{dx dQ^2 dy} \sim f_{p\rightarrow\pi+n}(y) \times \sum_q \int_{x/y}^{1} \frac{d\xi}{\xi} C(\xi) f_{q/\pi^+} \left( \frac{x/y}{\xi} \right)$$

- We parametrize PDFs in $\pi^-$

  + Valence: $\bar{u}_v = d_v$
  + Sea: $u = d = s = \bar{s}$
  + Gluon: $g$
Our new analysis extends previous pion PDF analysis down to $x \sim 0.001$.

The OPE+pQCD can describe the HERA data simultaneously with the DY data.

$$F_2^{LN(3)}(x, Q^2, y) = 2 f_{p \rightarrow \pi + n}(y) F_2^\pi(x_\pi, Q^2)$$

$$r(x, Q^2, y) = \frac{d^3 \sigma^{LN}/dx dQ^2 dy}{d^2 \sigma^{inc}/dx dQ^2} \Delta y$$
Results

- Significant reduction of the uncertainties
- Non-overlapping uncertainties → tensions among the data
- Accuracy will be improved with future TDIS (JLab12/EIC)
Results

- Model dependence in LN is comparable to statistical uncertainties
- DY+LN cannot discriminate among the OPE models
Results

Constraints from HERA significantly increase $\langle x^g_\pi \rangle$. The role of the glue is more important than suggested by DY alone.

In contrast, the strength of the sea is reduced.

Due to momentum sum rule $\langle x^{\text{valence}}_\pi \rangle$ decreases.
Results

- We performed an additional analysis of LN+DY+E866
- good description of E866 data except for large $x$
Summary and outlook