State-of-the-art extractions of pion parton distributions

Patrick Barry (Jefferson Lab)

Light Cone 2021: Physics of Hadrons on the Light Front
What do we want?

To study the makeup of **nuclear matter**

Building blocks of nature are **quarks and gluons**

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What’s the problem?

Quarks and gluons are not directly measurable!
Motivation

• QCD allows us to study the structure of hadrons in terms of partons (quarks, antiquarks, and gluons)

• Use factorization theorems to separate hard partonic physics out of soft, non-perturbative objects to quantify structure
Game plan

What to do:

• **Define** a structure of hadrons in terms of quantum field theories

• **Identify** theoretical observables that factorize into non-perturbative objects and perturbatively calculable physics

• **Perform** **global QCD analysis** as structures are universal and are the same in all processes

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Complicated Inverse Problem

- Factorization theorems involve convolutions of hard perturbatively calculable physics and non-perturbative objects

\[
\frac{d\sigma}{d\Omega} \propto \mathcal{H} \otimes f = \int_x^1 \frac{d\xi}{\xi} \mathcal{H}(\xi) f \left( \frac{x}{\xi} \right)
\]

- Parametrize the non-perturbative objects and perform global fit
Pions

• Pion is the **Goldstone boson** associated with spontaneous symmetry breaking of chiral $SU(2)_L \times SU(2)_R$ symmetry
• Lightest hadron
• Made up of $q$ and $\bar{q}$ constituents

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Experiments to probe pion structure

Drell-Yan (DY)

Leading Neutron (LN)

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Large-\(x_\pi\) behavior

- Generally, the parametrization lends a behavior as \(x_\pi \rightarrow 1\) of the valence quark PDF of \(q_v(x) \propto (1 - x)^\beta\).
- For a fixed order analysis, we find \(\beta \approx 1\).
- Debate whether \(\beta = 1\) or \(\beta = 2\).
- Aicher, Schaefer Vogelsang (ASV) found \(\beta = 2\) with threshold resummation.

ASV valence PDF

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Threshold Resummation in Pion Drell-Yan

Global QCD Analysis of Pion Parton Distributions with Threshold Resummation

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Soft gluon resummation in DY

- Fixed-target Drell-Yan notoriously has large-$x_F$ contamination of higher orders
- Large logarithms may spoil perturbation
- Focus on corrections to the most important $q \bar{q}$ channel
- Resum contributions to all orders of $\alpha_s$

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Methods of resummation

• Resummation is performed in conjugate space
• Drell-Yan data needs two transformations
• We can perform a Mellin-Fourier transform to account for the rapidity
  • A cosine appears while doing Fourier transform; options:
    1) Take first order expansion, cosine $\approx 1$
    2) Keep cosine intact
• Can additionally perform a Double Mellin transform
• Explore the different methods and analyze effects
• Double Mellin transform is theoretically cleaner and sums up terms appropriately

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Data and theory comparison

• **Cosine** method tends to overpredict the data at very large $x_F$

• **Double Mellin** method is qualitatively very similar to NLO

• Resummation is largely a high-$x_F$ effect

<table>
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<th>Method</th>
<th>$\chi^2$/npts</th>
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<tr>
<td>NLO+NLL cosine</td>
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<tr>
<td>NLO+NLL expansion</td>
<td>0.95</td>
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<tr>
<td>NLO+NLL double Mellin</td>
<td>0.80</td>
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</tbody>
</table>

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Resulting PDFs

- Large $x$ behavior of $q_v$ **highly sensitive** to method of resummation

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Effective $\beta_v$ parameter

- $q_v(x) \sim (1 - x)^{\beta_v^{\text{eff}}}$ as $x \to 1$
- Threshold resummation does not give universal behavior of $\beta_v^{\text{eff}}$
- NLO and double Mellin give $\beta_v^{\text{eff}} \approx 1$
- Cosine and Expansion give $\beta_v^{\text{eff}} > 2$

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Introducing lattice QCD data in global analysis

PCB, C. Egerer (Jefferson Lab), J. Karpie (Columbia), W. Melnitchouk (Jefferson Lab), C. Monahan (William & Mary, Jefferson Lab), K. Orginos (William & Mary, Jefferson Lab), Jian-Wei Qiu (Jefferson Lab), D. Richards (Jefferson Lab), N. Sato (Jefferson Lab), R. S. Sufian (William & Mary, Jefferson Lab), S. Zafeiropoulos (Aix Marseille Univ.)
Observable

• Lattice calculation is the reduced pseudo Ioffe time distribution (reduced pseudo-ITD)

\[ \mathcal{M}(\nu, z^2) = \frac{\mathcal{M}(\nu, z^2)}{\mathcal{M}(0, z^2)} \]

“loffe time”

\[ \nu = p \cdot z \]

• The UV divergences arising from choosing the spacelike \( z \) cancel from taking the ratio at the rest frame \( p_z = 0 \) (light-like \( z \) does not have these divergences)

• Make use of the “good lattice cross section,” which has convolution structure like experimental observables
Fitting the Data and Systematic Effects

\[
Re[M(\nu, z^2)] = \int_0^1 dx \, q_v(x, \mu_{\text{lat}}) C^{\text{RPTD}}(x\nu, z^2, \mu_{\text{lat}}) + z^2 B_1(\nu) + \frac{a}{|z|} P_1(\nu) + e^{-m_\pi (L-z)} F_1(\nu) + \ldots,
\]

Valence quark distribution in pion

Wilson coefficients for matching

Systematic Effects to parametrize:
- \( z^2 B_1(\nu) \): power corrections
- \( \frac{a}{|z|} P_1(\nu) \): lattice spacing errors
- \( e^{-m_\pi (L-z)} F_1(\nu) \): finite volume corrections

Other potential systematic corrections the data is not sensitive to

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Resulting $\chi^2_{\text{red}}$

- Scenario A: only experimental data
- Scenario B: include lattice data without fitting systematic effects
- Scenario C: Include systematics

<table>
<thead>
<tr>
<th>Process</th>
<th>Experiment</th>
<th>Scenario A</th>
<th>Scenario B</th>
<th>Scenario C</th>
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<td>$\chi^2_{\text{red}}$</td>
<td>$N_{\text{dat}}$</td>
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<td>DY</td>
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<td>61</td>
<td>0.82</td>
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<td></td>
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<td>–</td>
<td>8</td>
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<tr>
<td>Total</td>
<td></td>
<td>225</td>
<td>0.80</td>
<td>251</td>
</tr>
</tbody>
</table>

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Fits to the data

- Systematic effects shown in blue, are very small at low momentum and Ioffe time, $\nu$

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Effect on $q_{\nu}^{\pi}$

- Sizeable effect even when including systematics
Transverse Momentum Dependent Drell-Yan

PCB, N. Y. Cao (Harvard), W. Melnitchouk (Jefferson Lab), N. Sato (Jefferson Lab), L. Gamberg (Penn State Berks), E. Moffat (Penn State Berks), A. Prokudin (Penn State Berks, Jefferson Lab)
$p_T$-dependent spectrum for pion data

- Small-\(p_T\) data – TMD factorization – partonic transverse momentum
- Large-\(p_T\) data – collinear factorization – recoil transverse momentum

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E615 $\pi W$ Drell-Yan

JAM20 Pion PDFs

Fixed Order Analysis

- For the first time, we included large $p_T$-dependent Drell-Yan data, which follows collinear factorization
- Large $p_T$ does not dramatically affect the PDF
- Successfully describe data with a scale $\mu = p_T/2$

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Towards the three-dimensional parton structure of the pion: Integrating transverse momentum data into global QCD analysis.

N. Y. Cao, P. C. Barry, N. Sato, and W. Melnitchouk.

PHYSICAL REVIEW D 103, 114014 (2021)

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TMD factorization in Drell-Yan

• In small-$p_T$ region, Use the CSS formalism for TMD evolution

\[
\frac{d\sigma}{dQ^2\,dy\,dq_T^2} = \frac{4\pi^2\alpha^2}{9Q^2s} \sum_{j,j_A,j_B} H_{jj}^{DY}(Q,\mu_Q, a_s(\mu_Q)) \int \frac{d^2b_T}{(2\pi)^2} e^{i\mathbf{q}_T\cdot\mathbf{b}_T} \\
\times e^{-g_{j/A}(x_A,b_T;b_{max})} \int_{x_A}^1 \frac{d\xi_A}{\xi_A} f_{j_A/A}(\xi_A;\mu_{b_*}) \tilde{C}_{j/A}^{PDF}\left(\frac{x_A}{\xi_A}, b_*; \mu^2_{b_*}, \mu_{b_*}, a_s(\mu_{b_*})\right) \\
\times e^{-g_{j/B}(x_B,b_T;b_{max})} \int_{x_B}^1 \frac{d\xi_B}{\xi_B} f_{j_B/B}(\xi_B;\mu_{b_*}) \tilde{C}_{j/B}^{PDF}\left(\frac{x_B}{\xi_B}, b_*; \mu^2_{b_*}, \mu_{b_*}, a_s(\mu_{b_*})\right) \\
\times \exp\left\{ -g_K(b_T;b_{max}) \ln \frac{Q^2}{Q_0^2} + \tilde{K}(b_*;\mu_{b_*}) \ln \frac{Q^2}{\mu^2_{b_*}} + \int_{\mu_{b_*}}^{\mu_Q} \frac{d\mu'}{\mu'} \left[ 2\gamma_j(a_s(\mu')) - \ln \frac{Q^2}{(\mu')^2} \gamma_K(a_s(\mu')) \right] \right\}
\]

• Fit non-perturbative TMDs to pion-induced E615 data

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Collinear pion PDF

Non-perturbative TMDs to extract
Single Fits in low energy Drell-Yan

- Perform single fits of non-perturbative TMD functions to $pA$ and $\pi A$ data

E615 $\pi A$

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Future Experiments
Datasets -- Kinematics

• Large $x_\pi$ -- Drell-Yan (DY)
• Small $x_\pi$ -- Leading Neutron (LN)
• Not much data overlap
• In DY:
  \[ x_\pi = \frac{1}{2} \left( x_F + \sqrt{x_F^2 + 4\tau} \right) \]
• In LN:
  \[ x_\pi = x_B / \bar{x}_L \]

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EIC kinematics and uncertainties

- Uncertainties are dominated by systematics
- Large range in $x_\pi$, $Q^2$ to overlap Drell-Yan and leading neutron regions

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EIC Impact on Pion PDFs

- Statistical uncertainties are small compared with HERA because of larger luminosity – systematics dominate
- \( s = 5400 \text{ GeV}^2 \), 1.2\% systematic uncertainty, integrated \( \mathcal{L} = 100 \text{fb}^{-1} \)

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Future Experiments

• TDIS experiment at 12 GeV upgrade from JLab, which will tag a proton in coincidence with a spectator proton

• Gives leading proton observable, complementary to LN, but with a fixed target experiment instead of collider (HERA)

• Proposed COMPASS++/AMBER also give $\pi$-induced DY data

• Both $\pi^+$ and $\pi^-$ beams on carbon and tungsten targets

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Conclusions

• Behavior of large-$x$ valence distribution with double Mellin threshold resummation $q_v(x \to 1) \propto (1 - x)^1$

• The marriage between lattice and experimental data sheds light on the pion PDF itself as well as systematics associated with the lattice

• Successful description of large-$p_T$ Drell-Yan data from the pion

• Successfully have performed single fits to low-$p_T$ of both pion TMD and collinear PDFs and Monte Carlo is underway