Simultaneous extraction of collinear and transverse momentum dependent parton densities in the pion

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Motivation

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

• Identify physical observables that can be factorized in theory with controllable approximations

• Perform global QCD analysis as structures are universal and are the same in all processes
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
Drell-Yan (DY)

\[ \sigma \propto \sum_{i,j} f^\pi_i (x_\pi, \mu) \otimes f^A_j (x_A, \mu) \otimes C_{i,j} (x_\pi, x_A, Q/\mu) \]
Experiments to Probe Pion Structure

Drell-Yan (DY)

Leading Neutron (LN)

\[ \pi^{-} \rightarrow x \]
\[ q \rightarrow \gamma^{*} \]
\[ \bar{q} \rightarrow l \]

\[ e \rightarrow e' \]
\[ \gamma^{-} \rightarrow \pi^{+} \]
\[ p \rightarrow n \]

\( x f(x_\pi) \) vs. \( x_\pi \)

- Green: valence
- Blue: sea
- Red: glue/10
- Yellow: model dep.

DY
DY + LN

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First Monte Carlo Global QCD Analysis of Pion Parton Distributions

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Large-$x_\pi$ behavior

- Longstanding theoretical debates on $q_v(x) \propto (1 - x)^\beta$ if $\beta = 1$ or $\beta = 2$

Phenomenologically

- Fixed order analyses find $\beta \approx 1$
- Aicher, Schaefer Vogelsang (ASV) found $\beta = 2$ with threshold resummation

ASV valence PDF
JAM analysis with threshold resummation

- Highly dependent on perturbative approach
- NLO and NLO+NLL double Mellin methods better on theoretical grounds

For more details, attend my talk in WG1 on Tuesday at 5:30pm
What about the transverse dimension?

- Available $q_T$-dependent Drell-Yan data from E615
  \[ \text{Phys. Rev. D 39, 92 (1989).} \]
- Fixed Target data (no collider pion data)
Factorization for low-$q_T$ Drell-Yan

• Again, a hard part with two functions that describe structure of beam and target
• So called “$W$”-term

\[
\frac{d^3\sigma}{d\tau dY dq_T^2} = \frac{4\pi^2\alpha^2}{9\tau S^2} \sum q \int d^2b_T e^{ib\cdot q_T} \sum q \frac{H_{q\bar{q}}(Q^2, \mu)}{\bar{f}_{q/\pi}(x, b_T, \mu, Q^2)} \frac{\bar{f}_{q/A}(x, b_T, \mu, Q^2)}{f_{q/\pi}(x, b_T, \mu, Q^2)},
\]
TMD factorization in Drell-Yan

- In small-\(q_T\) region, Use the Collins-Soper-Sterman (CSS) formalism

\[
\frac{d\sigma}{dQ^2 dy dq_T^2} = \frac{4\pi^2\alpha^2}{9Q^2s} \sum_{j,j_A,j_B} H^{DY}_{jj}(Q, \mu_Q, a_s(\mu_Q)) \int \frac{d^2b_T}{(2\pi)^2} e^{i q_T \cdot b_T} 
\]

\[
\times e^{-g_{j/A}(x_A,b_T;\max)} \int_{x_A}^{1} \frac{d\xi_A}{\xi_A} f_{j_A/A}(\xi_A;\mu_{b*}) \tilde{C}_{j/j_A}^{PDF} \left( \frac{x_A}{\xi_A}, b_*, \mu_{b*}^2, \mu_{b*}, a_s(\mu_{b*}) \right) 
\]

\[
\times e^{-g_{j/B}(x_B,b_T;\max)} \int_{x_B}^{1} \frac{d\xi_B}{\xi_B} f_{j_B/B}(\xi_B;\mu_{b*}) \tilde{C}_{j/j_B}^{PDF} \left( \frac{x_B}{\xi_B}, b_*, \mu_{b*}^2, \mu_{b*}, a_s(\mu_{b*}) \right) 
\]

\[
\times \exp \left\{ -g_K(b_T;\max) \ln \frac{Q^2}{Q_0^2} + \tilde{K}(b_*;\mu_{b*}) \ln \frac{Q^2}{\mu_{b*}^2} + \int_{\mu_{b*}}^{\mu'} \frac{d\mu'}{\mu'} \left[ 2\gamma_j(a_s(\mu')) - \ln \frac{Q^2}{(\mu')^2} \gamma_K(a_s(\mu')) \right] \right\}
\]

Can these data constrain the pion collinear PDF?

\[
b_* = \frac{b_T}{\sqrt{1 + b_T^2/b_{\max}^2}} \]

\[
\mu_{b*} = C_1/b_*
\]
Strategy for simultaneous analysis

1. Perform single fit of TMDPDFs to available $pA$ and $\pi A$ data with $Q < 18$ GeV* to obtain the nuclear TMDPDFs

2. Perform the first Monte Carlo (MC) global QCD analysis on $\pi$ PDFs and non-perturbative TMD functions

*Avoid $\Upsilon$ resonance in $9 < Q < 11$ GeV
Description of $pA$ data

- Proton PDFs from the recent JAM analysis including MARATHON data
- Nuclear PDFs from EPPS16
Strategy for simultaneous analysis

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<table>
<thead>
<tr>
<th>Process</th>
<th>Drell-Yan</th>
<th>Leading neutron ep → e' n X</th>
<th>$q_T$-dependent Drell-Yan π W → $\mu^+ \mu^- X$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Observable</td>
<td>$d^2 \sigma/ dx_F d\sqrt{t}$</td>
<td>$F_2^{LN}, r = F_2^{LN}/F_2^{inc}$</td>
<td>$d^2 \sigma/ dx_F dq_T$</td>
</tr>
<tr>
<td>Experiment</td>
<td>E615, NA10</td>
<td>H1, ZEUS</td>
<td>E615, E537</td>
</tr>
</tbody>
</table>

*Avoid $\Upsilon$ resonance in $9 < Q < 11$GeV
Description of $\pi A$ data

• Well describe the E615 data in the $(x_F, q_T)$ spectrum: $\chi^2/npts = 1.45$

• Can also describe rest of the experimental data: $\chi^2_{\text{tot}}/npts = 0.93$
Impact on PDFs

- Similar to the case without inclusion of $q_T$-dependent DY, but with more constrained sea quark
Conclusions

• We have made strides in collinear pion PDF phenomenology by introducing available datasets and theoretical advances

• Inclusion of $q_T$-dependent DY data slightly constrains the sea quark distribution

• Extend framework to LHC data and nucleon PDFs
  • Use different methodologies – CSS, Qiu-Zhang, zeta-prescription
  • Can these precise data constrain nucleon PDFs?

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Backup Slides
Datasets -- Kinematics

\[ Q^2 (\text{GeV}^2) \]

\[ x_\pi \]

- E615
- NA10
- H1
- ZEUS

\[ \text{DY} \]

\[ \text{LN} \]

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Nuclear TMDPDFs – working hypothesis

• Because no $pW$ DY data exist, we must model the tungsten TMDPDF from proton

\[ F_{q/A}(x, b_T, \mu, \zeta) = \frac{Z}{A} F_{q/p/A}(x, b_T, \mu, \zeta) + \frac{A - Z}{A} F_{q/n/A}(x, b_T, \mu, \zeta) \]

• Each object on the right side independently obeys the CSS equation
• Make use of isospin symmetry in that $u/p/A \leftrightarrow d/n/A$, etc.
Parametric form

• We perform a simultaneous extraction of collinear and transverse momentum dependent PDFs using collinear and $p_T$-dependent data

$$g_K(b_T, b_{\text{max}}) = c_0 b_T b_*$$

Generic: $$g_{q/h}(x, b_T) = \frac{(a_1 + (A^{1/3} - 1)a_4)x^{a_2}(1-x)^{a_3} b_T^2}{\sqrt{1 + a_5 b_T^2}}$$

Proton:
- $g_{u/p}(x, b_T) = a_1^u x^{a_2^u} (1-x)^{a_3^u} b_T^2$
- $g_{d/p}(x, b_T) = a_1^d x^{a_2^d} (1-x)^{a_3^d} b_T^2$
- $g_{\text{sea}/p}(x, b_T) = a_1^{\text{sea}} x^{a_2^{\text{sea}}} b_T^2$

Pion:
- $g_{q/\pi}(x, b_T) = \frac{a_1^\pi (1-x)^{a_3^\pi} b_T^2}{\sqrt{1 + a_5^{\pi} b_T^2}}$

The data do not have sensitivity to flavor separation in the pion.
Correlations

- Shown is the correlation of the parameters
- $a_1^\pi$, $a_3^\pi$, $a_5^\pi$ are TMD parameters, rest are collinear
- Notice the lack of correlation between TMD parameters and PDF parameters