Constraining pion PDFs with J/psi production

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In collaboration with
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Why are Pions Important?

• Pions are the force carrier within the nucleus (Yukawa, 1935).

• Nambu-Goldstone bosons of spontaneous symmetry breaking of chiral symmetry $SU(3)_L \ast SU(3)_R$. The lightest QCD bound state.

• Pion cloud picture of nucleons is important in understanding the flavor asymmetry of sea quarks of nucleons.

• ...
Experimental Approach for Proton PDFs
Experimental Approach for Pion PDFs

No rest targets of pions!
Pion-induced Reactions

• Drell-Yan: $\pi^\pm p \rightarrow \mu^+ \mu^- X$ (sensitive to valence quarks)
  [Marcia Quaresma’s talk]
  • LO: $q\bar{q} \rightarrow \mu^+ \mu^-$
  • NLO: $q\bar{q} \rightarrow \mu^+ \mu^- G, qG \rightarrow \mu^+ \mu^- q$
  • NNLO: $q\bar{q}G \rightarrow \mu^+ \mu^- G, qG \rightarrow \mu^+ \mu^- qG, GG \rightarrow \mu^+ \mu^- q\bar{q}$

• Direct photon: $\pi^\pm p \rightarrow \gamma X$ (sensitive to gluons)
  [Alexey Guskov’s talk]
  • LO: $q\bar{q} \rightarrow \gamma G, qG \rightarrow \gamma q$

• Jpsi: $\pi^\pm p \rightarrow J/\psi X$ (sensitive to gluons)
  [Stephane Platchkov’s talk]
  • LO: $q\bar{q} \rightarrow c\bar{c} \rightarrow J/\psi X, GG \rightarrow c\bar{c} \rightarrow J/\psi X$
  • NLO: $q\bar{q} \rightarrow c\bar{c}G \rightarrow J/\psi X, GG \rightarrow c\bar{c}G \rightarrow J/\psi X, qG \rightarrow c\bar{c}q \rightarrow J/\psi X$
OW pion PDF
[J.F. Owens, PRD 30, 943 (1984)]

\[ \pi^\pm p \rightarrow J/\psi X \]

Fits to data of J/psi and DY production.
SMRS
[Sutton et al., PRD 45, 2349 (1992)]

\[ \pi^\pm p \rightarrow \gamma X \]

\[ \pi^\pm p \rightarrow \mu^+\mu^- X \]

Fits to data of direct-$\gamma$ and DY production.
## Pion PDFs (before 2018)

<table>
<thead>
<tr>
<th>PDF</th>
<th>DY</th>
<th>Direct $\gamma$</th>
<th>$J/\psi$</th>
<th>LN</th>
<th>Refs.</th>
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</thead>
<tbody>
<tr>
<td>OW</td>
<td>*</td>
<td>*</td>
<td>*</td>
<td></td>
<td>PRD 1984</td>
</tr>
<tr>
<td>ABFKW</td>
<td>*</td>
<td>*</td>
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<td>PLB 1989</td>
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<tr>
<td>SMRS</td>
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<td>PRD 1992</td>
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<tr>
<td>GRV</td>
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<td>GRS</td>
<td>*</td>
<td></td>
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<td></td>
<td>EPJC 1999</td>
</tr>
</tbody>
</table>

- Valence quarks are well constrained by Drell-Yan data.
- Sea and gluons are constrained by the number of valence quarks and the momentum sum rule.
- Direct photon and $J/\psi$ data help to better constrain the gluons and thus sea quarks.
- GRS: relating sea quarks and gluons by a constituent quark model.
Pion PDFs (before 2018)

- PDFs were mainly determined by Drell-Yan, single $\gamma$, J/psi data.
- 20% difference of valence quarks at $x = 0.5$!
JAM18: Include leading neutron (LN) electroproduction from HERA [Barry et al., PRL 121, 152001 (2018)]

- Uncertainties are much reduced using DY+LN, as compared to DY alone.
Leading neutron (LN) electroproduction from HERA

Sullivan processes from a nucleon’s pion cloud

Off-shell persistence of composite pions and kaons
S.X. Qin et al., PRC 97, 015203 (2018)
Statistical approach
[Bourrely and Soffer, NPA 981, 118 (2019)]

\[ x Q^\pm(x) = \frac{A_Q X_Q^\pm x^b Q}{\exp[(x - X_Q^\pm)/\bar{x}] + 1} \]

\[ x \tilde{Q}^\pm(x) = \frac{A(X_Q^\mp)^{-1} x^\tilde{b}}{\exp[(x + X_Q^\mp)/\bar{x}] + 1} \]

\[ x G_\pi(x) = A_G x^{b_G} / (\exp(x/\bar{x}) - 1) \]

\[ \bar{x} = 0.09: \text{a universal temperature} \]
xFitter: [Novikov et al., arXiv:2002.02902]

<table>
<thead>
<tr>
<th>Experiment</th>
<th>Normalization uncertainty</th>
<th>Normalization factor</th>
<th>$\chi^2/N_{\text{points}}$</th>
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<tr>
<td>E615</td>
<td>15%</td>
<td>1.160 ± 0.020</td>
<td>206/140</td>
</tr>
<tr>
<td>NA10 (194 GeV)</td>
<td>6.4%</td>
<td>0.997 ± 0.014</td>
<td>107/67</td>
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<tr>
<td>NA10 (286 GeV)</td>
<td>6.4%</td>
<td>0.927 ± 0.013</td>
<td>95/73</td>
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<tr>
<td>WA70</td>
<td>32%</td>
<td>0.737 ± 0.012</td>
<td>64/99</td>
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</table>

Figure 3 shows the obtained pion PDFs in comparison to a recent analysis by JAM [26], and to GRVPI1 [22] — the only set available in the LHAPDF6 [39] library. The new valence distribution presented here is in good agreement with JAM, and both disagree with the early GRV analysis. The relatively difficult to determine sea and gluon distributions are different in all three PDF sets, however, this new PDF and the JAM determination agree within the larger uncertainties of our fit.

FIG. 3. Comparison between the pion PDFs obtained in this work, a recent determination by the JAM collaboration [26], and the GRVPI1 pion PDF set [22].

xFitter is consistent with JAM but disagrees with GRV.
# Pion PDFs (2020)

<table>
<thead>
<tr>
<th>PDF</th>
<th>DY</th>
<th>Direct $\gamma$</th>
<th>$J/\psi$</th>
<th>LN</th>
<th>Refs.</th>
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</thead>
<tbody>
<tr>
<td>OW</td>
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<td></td>
<td>*</td>
<td></td>
<td>PRD 1984</td>
</tr>
<tr>
<td>ABFKW</td>
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<td>*</td>
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<td>PLB 1989</td>
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<td>SMRS</td>
<td>*</td>
<td>*</td>
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<td>JAM</td>
<td>*</td>
<td></td>
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</tr>
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<td>BS</td>
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<td>*</td>
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</table>
At $x > 0.1$, $q_v(x)$ of OW, ABFKW and GRV are significantly lower than others'.

$Q^2 = 9.6 \text{ GeV}^2$
Pion PDFs: Sea Quarks

\[ Q^2 = 9.6 \text{ GeV}^2 \]
At $x > 0.1$, $G(x)$ of JAM and xFitter are significantly lower than others'.
Dimuon Invariant-mass Spectrum (COMPASS Pion-Induced 2015 Run)

Large $J/\psi$ cross sections!
# Pion-induced J/psi Data from Fixed-target Experiments

<table>
<thead>
<tr>
<th>Paper</th>
<th>Reference</th>
<th>Year</th>
<th>Collab</th>
<th>$E_{\text{sqrt(s)}}$ (GeV)</th>
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<th>Targets</th>
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<tr>
<td><strong>Fermilab</strong></td>
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<tr>
<td>Branson</td>
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<td>Anderson</td>
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<td>Beatrice</td>
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Goals of This Work

• Color evaporation model calculations of $J/\psi$ production: LO/NLO

• Three pion PDFs: GRV, xFitter and JAM with different gluon strength at large-$x$.

• To see how well the pion-induced $\sigma_{J/\psi}(x_F)$ over a wide range of beam energy – [40, 515] GeV, can be described.
Model Dependence of $c\bar{c}$ pairs Fragmentation

• **Color singlet model (CSM)**: only pairs with matched quantum number of the charmonium.

• **Color evaporation model (CEM)**: all pairs with mass less than $D\bar{D}$ threshold. One fragmentation parameter for each charmonium.

• **Non-relativistic QCD model (NRQCD)**: all pairs of different color and spin states fragmenting with different probabilities – long-distance matrix elements (LDMEs).
Calculations of $A + B \rightarrow J/\psi + X$ in Color Evaporation Model

\[
\frac{d\sigma_{J/\psi}}{d^3P_{J/\psi}} = F \int_{2m_c}^{2m_D} \frac{d\sigma_{c\bar{c}}(M_{c\bar{c}}, P_{c\bar{c}})}{dM_{c\bar{c}} d^3P_{c\bar{c}}} dM_{c\bar{c}}; P_{J/\psi} = P_{c\bar{c}}
\]

\[
d\sigma_{c\bar{c}}(M_{c\bar{c}}, P_{c\bar{c}})[AB \rightarrow c\bar{c}X]
= \sum_{i,j} \int f_{i/A}(x_1, \mu_F) f_{j/B}(x_2, \mu_F) d\hat{\sigma}_{c\bar{c}}(x_1P_A, x_2P_B, \mu_F, \mu_R)[ij \rightarrow c\bar{c}X] dx_1 dx_2
\]

LO/NLO calculations of $d\hat{\sigma}_{c\bar{c}}[ij \rightarrow c\bar{c}X]$:

Data vs. CEM NLO

[Gavai et al., IJMPA 10, 3043 (1995)]
Data vs. CEM LO/NLO

[π⁻ + Be → Jψ + X at 515 GeV, PRD 53, 4723 (1996)]

\[ m_c = 1.5 \text{ GeV}, \mu_F = 2m_c, \mu_R = m_c, \text{ F determined by the fit.} \]

- The GG contribution dominates except at very forward or backward directions.
- The weighting of GG contribution is enhanced in the NLO calculations.
Sensitivity of $\sigma_{J/\psi}(x_F)$ to the $q_v(x_1)$ and $G(x_1)$ of Pions

\[ x_1 = 0.5 \times \left( \sqrt{\frac{x_F^2 + \frac{4Q^2}{s}}{s}} + x_F \right) \]
Data vs. CEM NLO

[Pi+ + p → Jpsi + X at 39.5 GeV, PLB 98, 220 (1981)]

NLO

Calculations of all three PDFs describe the data well.
Data vs. CEM NLO

[\( \pi^- + \text{Pt} \rightarrow \text{Jpsi} + \text{X} \) at 200 GeV, Z. Phys. C20,101(1983)]

- To well describe the data for \( x_F > 0.2 \), an appropriate weighting of GG and q\bar{q} contributions is necessary.
- The agreement of CEM calculations and data is in the sequence of GRV, xFitter and JAM.
Data vs. CEM NLO

[π⁻ + Be → Jpsi + X at 515 GeV, PRD 53, 4723 (1996)]

• To well describe the data for xF>0.5, an appropriate weighting of GG and q̅q contributions is necessary.
• The agreement of CEM calculations and data is in the sequence of GRV, xFitter and JAM.
Data vs. CEM Calculations

- The fragmenting F factor is more or less stable across energy.
- GRV with the strongest large-x strength gives the best description.
Summary

• Pion PDFs have been determined by the Drell-Yan, direct photon, J/psi and recently leading-neutron data. Nevertheless discrepancy of valence quark and gluon densities at $x>0.1$ is seen.

• Within the color evaporation model, the high-energy large-$x_F$ J/psi data are shown to be sensitive to the pion gluon distribution at $x>0.1$.

• With the coming new data of meson-induced J/psi from COMPASS/AMBER, all high-statistic fixed-target J/psi data sets could be used to improve the less-known gluon distributions in pion/kaon PDFs.