Pion–nucleus Drell–Yan data as a novel constraint for nuclear PDFs

Petja Paakkinen
in collaboration with K. J. Eskola and H. Paukkunen

University of Jyväskylä

DIS 2017
Motivation: Status of nPDFs in the beginning of 2016

- Many global analyses (EPS09, DSSZ, nCTEQ15...) available.

- Limited amount of data (mostly DIS and DY, but also inclusive pion production) with restricted kinematical reach.
  - Many assumptions needed in the parametrization.

- One of the poorly constrained features is the possible asymmetry in nuclear modifications of valence $u$ and $d$ quarks.

- In EPS09 analysis these are fixed to be the same at $Q = 1.3$ GeV, while nCTEQ15 fit allows them to vary independently.
  - Significantly different results.

? How could we better constrain this?
  - Dutta et al. [PRC 83 (2011) 042201] suggested that pion–nucleus Drell–Yan dilepton data could be used.
Cancellation of pion PDFs in nuclear ratios

Consider following ratios:

\[ R_A^{+/−}(x_2) \equiv \frac{dσ_{DY}^{π^+ + A}/dx_2}{dσ_{DY}^{π− + A}/dx_2} \]

\[ R_{A1/A2}^{−}(x_2) \equiv \frac{1}{A_1} \frac{dσ_{DY}^{π− + A_1}/dx_2}{dσ_{DY}^{π− + A_2}/dx_2} \]

Assuming isospin (IS) and charge conjugation (CC) symmetry

\[
\begin{align*}
  u_{π^+} & \overset{\text{IS}}{=} d_{π−} & \overset{\text{CC}}{=} \bar{d}_{π^+} & \overset{\text{IS}}{=} \bar{u}_{π−} \\
  d_{π^+} & \overset{\text{IS}}{=} u_{π−} & \overset{\text{CC}}{=} \bar{u}_{π^+} & \overset{\text{IS}}{=} \bar{d}_{π−}
\end{align*}
\]

when pion sea quarks can be neglected, the LO approximation for a narrow enough invariant mass bin gives

\[ R_A^{+/−}(x_2) \approx \frac{4\bar{u}_A(x_2) + d_A(x_2)}{4u_A(x_2) + \bar{d}_A(x_2)} \]

\[ R_{A1/A2}^{−}(x_2) \approx \frac{4u_{A_1}(x_2) + \bar{d}_{A_1}(x_2)}{4u_{A_2}(x_2) + \bar{d}_{A_2}(x_2)} \]
Consider following ratios:

\[ R^+_A(x_2) \equiv \frac{d\sigma^\pi^+ + A / dx_2}{d\sigma^\pi^- + A / dx_2} \]

\[ R^-_{A_1/A_2}(x_2) \equiv \frac{\frac{1}{A_1} d\sigma^\pi^- + A_1 / dx_2}{\frac{1}{A_2} d\sigma^\pi^- + A_2 / dx_2} \]

Assuming isospin (IS) and charge conjugation (CC) symmetry

\[ u_{\pi^+} \overset{\text{IS}}{=} d_{\pi^-} \quad \overset{\text{CC}}{=} \bar{d}_{\pi^+} \overset{\text{IS}}{=} \bar{u}_{\pi^-} \]

\[ d_{\pi^+} \overset{\text{IS}}{=} u_{\pi^-} \quad \overset{\text{CC}}{=} \bar{u}_{\pi^+} \overset{\text{IS}}{=} \bar{d}_{\pi^-} \]

when pion sea quarks can be neglected, the LO approximation for a narrow enough invariant mass bin gives

\[ R^+_A(x_2) \approx \frac{4\bar{u}_A(x_2) + d_A(x_2)}{4u_A(x_2) + \bar{d}_A(x_2)} \]

\[ R^-_{A_1/A_2}(x_2) \approx \frac{4u_{A_1}(x_2) + \bar{d}_{A_1}(x_2)}{4u_{A_2}(x_2) + \bar{d}_{A_2}(x_2)} \]

The dependence on pion PDFs essentially cancels...
Consider following ratios:

\[ R_A^{+/-}(x_2) \equiv \frac{d\sigma_{DY}^{\pi^+ + A}}{dx_2}{d\sigma_{DY}^{\pi^+ + A}}{/dx_2} \]

\[ R_{A1/A2}^{-}(x_2) \equiv \frac{1}{A_1}d\sigma_{DY}^{\pi^- + A_1} / dx_2 \frac{1}{A_2}d\sigma_{DY}^{\pi^- + A_2} / dx_2 \]

Assuming isospin (IS) and charge conjugation (CC) symmetry

\[ u_\pi^+ \overset{\text{IS}}{=} d_\pi^- \overset{\text{CC}}{=} \bar{d}_\pi^+ \overset{\text{IS}}{=} \bar{u}_\pi^- \]

\[ d_\pi^+ \overset{\text{IS}}{=} u_\pi^- \overset{\text{CC}}{=} \bar{u}_\pi^+ \overset{\text{IS}}{=} \bar{d}_\pi^- \]

when pion sea quarks can be neglected, the LO approximation for a narrow enough invariant mass bin gives

\[ R_A^{+/-}(x_2) \approx \frac{4\bar{u}_A(x_2) + d_A(x_2)}{4u_A(x_2) + \bar{d}_A(x_2)} \]

\[ R_{A1/A2}^{-}(x_2) \approx \frac{4u_{A_1}(x_2) + \bar{d}_{A_1}(x_2)}{4u_{A_2}(x_2) + \bar{d}_{A_2}(x_2)} \]

→ The dependence on pion PDFs essentially cancels... also in NLO [PLB 768 (2017) 7-11]:

![Graph showing the cancellation of pion PDFs in nuclear ratios](image)
The NA10 collaboration has corrected their data for isospin effects: D is perfectly isoscalar \((Z = A/2)\), but W is not \((A = 184 \text{ and } Z = 74)\).

We correct our results similarly with

\[
\left( \frac{R_\text{W/D}}{R_\text{isocalar-W/W}} \right)_{\text{isospin corrected}}^{\text{NLO}} = \left( \frac{R_\text{W/D}}{R_\text{isocalar-W/W}} \right)_{\text{LO no nPDFs}} \times \left( \frac{R_\text{W/D}}{R_\text{isocalar-W/W}} \right)_{\text{NLO}}
\]

We also need to account for the 6\% systematic overall normalization uncertainty in the NA10 data.

We find the higher beam energy predictions to be within the given uncertainty interval, but for the lower energy we need \(\sim 12\%\) correction.
Both the EPS09 [JHEP 0904 (2009) 065] and nCTEQ15 [PRD 93 (2016) no.8, 085037] are in a good agreement with the data.

Large differences in the uncertainty estimates.

![Graphs showing comparison of nPDF results.](attachment:image.png)
Both the EPS09 [JHEP 0904 (2009) 065] and nCTEQ15 [PRD 93 (2016) no.8, 085037] are in a good agreement with the data.

Large differences in the uncertainty estimates.

Study the $R_{W/D}^-$ ratio measured by NA10 at large $x_2$, where only the valence quarks in nuclei contribute.

A clear mutual separation in the predictions with nCTEQ error sets 25 ($R_{uV}^A \ll R_{dV}^A$) and 26 ($R_{uV}^A \sim R_{dV}^A$).

The studied observables are thus sensitive to mutual differences in valence quark nuclear modifications.
Comparison of nPDF results

- Both the EPS09 [JHEP 0904 (2009) 065] and nCTEQ15 [PRD 93 (2016) no.8, 085037] are in a good agreement with the data.

  - Large differences in the uncertainty estimates.

- Study the $R_{W/D}^-$ ratio measured by NA10 at large $x_2$, where only the valence quarks in nuclei contribute.

- A clear mutual separation in the predictions with nCTEQ error sets 25 ($R_{uV}^A \ll R_{dV}^A$) and 26 ($R_{uV}^A \sim R_{dV}^A$).

  - The studied observables are thus sensitive to mutual differences in valence quark nuclear modifications.

- The nCTEQ15 error bands are large since the flavor dependence was allowed, but not well constrained.

- The EPS09 error sets underestimate the true uncertainty because flavor dependence of valence quark nuclear modifications was not allowed.
Motivated by the above results, these data were used in the new EPPS16 [EPJC 77 (2017) no.3, 163] analysis.

See the following talk by H. Paukkunen.

Similar results as with EPS09, but with larger errors (as expected).
Motivated by the above results, these data were used in the new EPPS16 [EPJC 77 (2017) no.3, 163] analysis.

See the following talk by H. Paukkunen.

Similar results as with EPS09, but with larger errors (as expected).

Compared to nCTEQ15 there is a reduction in error estimates.

Not due to these data: At the moment more stringent constraints come from neutrino DIS.

These observables could in principle constrain the valence asymmetry, but the available data is not precise enough.
New observable!

- Dependence on sea quarks can be reduced by studying ratio of the *difference* of the negative and positive charged pion cross-sections

\[
R_{A_1/A_2}^{\text{diff.}}(x_2) = \frac{\frac{1}{A_1}(d\sigma_{\pi^+}^{-} + A_1/dx_2 - d\sigma_{\text{DY}}^+ / dx_2)}{\frac{1}{A_2}(d\sigma_{\pi^+}^{-} + A_2/dx_2 - d\sigma_{\text{DY}}^+ / dx_2)}
\]

- In LO this ratio depends only on nuclear valence distributions

\[
R_{A_1/A_2}^{\text{diff.}}(x_2) \approx \frac{4u_{A_1}^V(x_2) - d_{A_1}^V(x_2)}{4u_{A_2}^V(x_2) - d_{A_2}^V(x_2)}
\]

- Good sensitivity to the *u/d*-asymmetry

\[
R_{A/D}^{\text{diff.}} \approx \frac{u_p^V/A + d_p^V/A}{u_p^V + d_p^V} - \frac{5}{3} \left(1 - \frac{2Z}{A}\right) \frac{u_p^V/A - d_p^V/A}{u_p^V + d_p^V}
\]

- Predictions of \(R_{A_1/A_2}^{\text{diff.}}\) with beam energy and acceptance available at the COMPASS experiment are shown.
Conclusions

- The considered $\pi + A$ DY data are compatible with modern nPDFs.
  - Can be used in a global analysis without causing significant tension (as seen in EPPS16).

- The cross-section ratios are largely independent of pion PDFs.
  - The inclusion of these data in global fits of nuclear PDFs does not impose significant new theoretical uncertainties.

- The considered observables are sensitive to the possible $u/d$-asymmetry of nuclear modification factors.
  - The data are not precise enough to pin this down completely.
  - We find a good agreement between the data and $u/d$-symmetric (EPS09) nuclear modifications.
  - Our analysis suggests that the most extreme differences in $u$ and $d$ quark nuclear modifications as given by particular nCTEQ15 error sets are disfavored by the NA3 and NA10 datasets.
  - We propose a new observable which has a good sensitivity to the valence modification asymmetry.
Data not precise and disagrees with predictions.

Choice of pion PDFs become significant at low masses.

→ Not reasonable to include into a global analysis.