Status of nuclear PDFs after the first LHC p-Pb run

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Summary
Introduction
Theoretical Foundations: Collinear factorization

- Factorization

\[ d\sigma = \sum_{i,j} f_i(Q_f^2) \otimes d\sigma_{ij}(Q_f^2, Q_r^2) \otimes f_j(Q_f^2) + \mathcal{O}(Q_f^{-2n}) \]
Theoretical Foundations: Collinear factorization

- Factorization

\[ d\sigma = \sum_{i,j} f_i(Q_f^2) \otimes d\sigma_{ij}(Q_f^2, Q_r^2) \otimes f_j(Q_f^2) + O(Q_f^{-2n}) \]

Parton distribution functions (PDFs)

Coefficient functions (calculable by perturbative methods)
Theoretical Foundations: Collinear factorization

- Factorization

\[ d\sigma = \sum_{i,j} f_i(Q_f^2) \otimes d\sigma_{ij}(Q_f^2, Q_r^2) \otimes f_j(Q_f^2) + \mathcal{O}(Q_f^{-2n}) \]

Parton distribution functions (PDFs)

Coefficient functions (calculable by perturbative methods)

- PDFs obey the DGLAP equations

\[ Q^2 \frac{\partial f_i(x, Q^2)}{\partial Q^2} = \sum_j P_{ij}(Q^2) \otimes f_j(x, Q^2) \]

Splitting functions (calculable by perturbative methods)
Theoretical Foundations: Collinear factorization

- Factorization

\[ d\sigma = \sum_{i,j} f_i(Q_f) \otimes d\sigma_{ij}(Q_f^2, Q_r^2) \otimes f_j(Q_f) + O(Q_f^{-2n}) \]

- Non-linear power corrections predicted to be important even at perturbative scales, particularly for large \( A \).

- Often supplemented with external models for hadronization (e.g. PYTHIA).

- Also used in computing the initial conditions for fluid dynamical description of heavy-ion collisions [PRC93 (2016) NO.2, 024907].
## Current global analyses: Situation 2 months ago

| Feature                                    | EPS09         | DSSZ12        | KA15         | NCTEQ15      |
|--------------------------------------------|---------------|---------------|--------------|--------------|
| Order in $\alpha_s$                        | LO & NLO     | NLO           | NNLO         | NLO          |
| Neutral current DIS $\ell+A/\ell+d$        | ✓             | ✓             | ✓            | ✓            |
| Drell-Yan dilepton $p+A/p+d$                | ✓             | ✓             | ✓            | ✓            |
| RHIC pions $d+Au/p+p$                       | ✓             | ✓             | ✓            | ✓            |
| Neutrino-nucleus DIS                       |               |               |              |              |
| $Q$ cut in DIS                              | 1.3 GeV      | 1 GeV         | 1 GeV        | 2 GeV        |
| datapoints                                 | 929           | 1579          | 1479         | 708          |
| free parameters                            | 15            | 25            | 16           | 17           |
| error analysis Hessian                      | Hessian       | Hessian       | Hessian N.N  | Hessian 35   |
| error tolerance $\Delta \chi^2$             | 50            | 30            | N.N          | CTEQ6M-like  |
| Free proton baseline PDFs                   | CTEQ6.1       | MSTW2008      | JR09         |              |
| Heavy-quark effects                         | none          | ✓             | none         | ✓            |
| Flavour separation                         |               |               |              | some         |
| Reference                                  | [JHEP 0904 065] | [PR D85 074028] | [PRD 93, 014026] | [PR D93 085037] |
## Current global analyses: Situation now

|                           | EPPS16 | DSSZ12 | KA15 | NCTEQ15 |
|---------------------------|--------|--------|------|---------|
| Order in $\alpha_s$      | NLO    | NLO    | NNLO | NLO     |
| Neutral current DIS $\ell+A/\ell+d$ | ✓      | ✓      | ✓    | ✓       |
| Drell-Yan dilepton $p+A/p+d$ | ✓      | ✓      | ✓    | ✓       |
| RHIC pions $d+Au/p+p$     | ✓      | ✓      | ✓    | ✓       |
| Neutrino-nucleus DIS     | ✓      | ✓      | ✓    | ✓       |
| Drell-Yan dilepton $\pi+A^1$ | ✓      | ✓      | ✓    | ✓       |
| LHC $p+Pb$ jet data      | ✓      | ✓      | ✓    | ✓       |
| LHC $p+Pb$ $W, Z$ data   | ✓      | ✓      | ✓    | ✓       |
| $Q$ cut in DIS datapoints | 1.3 GeV | 1 GeV  | 1 GeV | 2 GeV  |
|                          | 1811   | 1579   | 1479 | 708     |
|                          | 20     | 25     | 16   | 17      |
| Free proton baseline PDFs| CT14NLO | MSTW2008 | JR09 | CTEQ6M-like |
| Heavy-quark effects      | ✓      | ✓      | ✓    | ✓       |
| Flavour separation       | full   | none   | none | some    |
| Reference                | [arXiv:1612.05741] | [PR D85 074028] | [PRD 93, 014026] | [PR D93 085037] |

$^1$ Poster by P. Paakkinen
Analysis procedures
What is actually parametrized?

- The standard definition of nuclear PDFs

\[
\frac{f_i^{p/A}(x, Q^2)}{f_i^{p}(x, Q^2)} \equiv R_i^A(x, Q^2)
\]

Nuclear modifications

- Why the two components?
- Much of the data are ratios of the form

\[
\frac{F_2^A(x, Q^2)}{F_2^p(x, Q^2)}
\]

⇒ In a global analysis \( f_i^p \) must always be supplied.
⇒ Nuclear PDFs are always relative to the free-proton PDFs.
What is actually parametrized?

- The standard definition of nuclear PDFs

\[ f_i^p/A(x,Q^2) \equiv R_i^A(x,Q^2) \]

Free proton baseline

Nuclear modifications

- Most (EPS09, DSSZ,...) impose the flavour independence (FI) at \( Q^2 = Q_{0}^2 \):

\[ R_{uv}^{}(x,Q_{0}^2) = R_{dv}^{}(x,Q_{0}^2) \]

\[ R_{\bar{u}}^{}(x,Q_{0}^2) = R_{\bar{d}}(x,Q_{0}^2) = R_{s}^{}(x,Q_{0}^2) \]

- The FI immediately destroyed by the DGLAP at \( Q^2 > Q_{0}^2 \)

\[ \rightarrow \text{No reason to assume FI in the first place.} \]

- nCTEQ15: flavour variation for the valence quarks.

- EPPS16: flavour dependent valence & sea quarks.
The standard analysis procedure

- Based on considering $\chi^2$ figure-of-merit function

$$\chi^2_{\text{global}} \equiv \sum_{i,j} [T_i(\vec{a}) - D_i] C_{ij}^{-1} [T_j(\vec{a}) - D_j]$$

- Solve the DGLAP
- Compute the cross sections
- Update $f\{a\}$
- Evaluate $\chi^2$
- Uncertainty analysis

Parametrize $f\{a\}$ at the initial scale $Q_0^2$

If $\chi^2_{\text{new}} < \chi^2_{\text{previous}}$ and no more improvement, then $\Rightarrow$ Best fit.
Uncertainty analysis: the Hessian method

- Expand the global $\chi^2$ around the minimum

$$\chi^2_{\text{global}} \approx \chi^2_0 + \sum_{i,j} (a_i - a_i^0) H_{ij} (a_j - a_j^0) = \chi^2_0 + \sum_i z_i^2$$

Hessian matrix

Parameter variations
Uncertainty analysis: the Hessian method

- Expand the global $\chi^2$ around the minimum

$$\chi^2_{\text{global}} \approx \chi^2_0 + \sum_{i,j} (a_i - a^0_i) H_{ij} (a_j - a^0_j) = \chi^2_0 + \sum_i z_i^2$$

- The $z_i$ coordinates (linear combinations of $a_i$) are $\sim$ uncorrelated and one can use the standard law of error propagation

$$\left(\delta X\right)^2 = \sum_i \left(\frac{\partial X}{\partial z_i} \times \delta z_i\right)^2, \quad \delta z_i = \frac{\delta z_i^+ + \delta z_i^-}{2}$$
Uncertainty analysis: the Hessian method

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$$\langle (\delta X)^2 \rangle = \sum_i \left( \frac{\partial X}{\partial z_i} \times \delta z_i \right)^2, \quad \delta z_i = \frac{\delta z_i^+ + \delta z_i^-}{2}$$

- Define the PDF uncertainty sets $S_i^{\pm}$

$$S_1^{\pm} \equiv \pm \delta z_1^{\pm} (1, 0, \ldots, 0)$$

$$\vdots$$

$$S_N^{\pm} \equiv \pm \delta z_N^{\pm} (0, 0, \ldots, 1)$$

$$\implies (\delta X)^2 = \frac{1}{4} \sum_i \left[ X(S_i^+) - X(S_i^-) \right]^2$$
Uncertainty analysis: the Hessian method

- The current fits define $\delta z_i^{\pm}$ such that they correspond to fixed $\Delta \chi^2_{\text{global}}$.
- Ideally, $\Delta \chi^2_{\text{global}} = 1$.
- For the parametrization bias, the global fits take $\Delta \chi^2_{\text{global}} \gg 1$.

|       | EPPS16 | DSSZ12 | nCTEQ15 |
|-------|--------|--------|---------|
| $\Delta \chi^2$ | 52     | 30     | 35      |

- The $\Delta \chi^2$ determination in EPS09, EPPS16, nCTEQ15:
  - Based on dynamical tolerance determination [EPJ C63 189] (90% confidence limits)
- The $\Delta \chi^2$ determination in DSSZ
  - Not exactly specified.
The use of experimental data is not unambiguous
The kinematic reach of the experimental input

- The data in global fits in a \((x, Q^2)\) plane.
- The LHC data opens a previously unexplored kinematic region.
Experimental input: The LHC data — how should it be used?

- How to use the LHC data (p-Pb & Pb-Pb) to extract information on $R_A^i(x, Q^2)$?

Answer #1: Measured absolute distributions

\[ \text{Data} \]

| CMS (pPb 5.02 TeV) |
|---------------------|
| -134.6 nb |

Data
MCFM + CT10
MCFM + CT10 + EPS09
MCFM + CT10 + DSSZ

ll → Z → pPb

| l lab η > 20 GeV/c, | l T p |
|---------------------|---------|
| Luminosity uncertainty: 3.5% |

\[ d\sigma = \sum_{i,j} f_{p_i}(Q^2 f_i) \otimes d\sigma_{ij}(Q^2 f_i, Q^2 r) \otimes f_{Pb_j}(Q^2 f_i) \]

\[ f_{p_i}(x, Q^2) \equiv R_A^i(x, Q^2) \]

⇒ Cannot disentangle the effects of proton PDF $f_{p_i}(\sim 90\%)$ and nuclear modifications $R_{Pb}^i(\sim 10\%)$.

⇒ Interpretation ambiguous.

This approach was nevertheless used in a recent PDF-reweighting study by nCTEQ [ARX:1610.02925].
Experimental input: The LHC data — how should it be used?

- How to use the LHC data (p-Pb & Pb-Pb) to extract information on $R_i^A (x, Q^2)$?
- Answer #1: Measured absolute distributions

\[ d\sigma = \sum_{i,j} f^p_i (Q^2_f) \otimes d\sigma_{ij} (Q^2_f, Q^2_r) \otimes f^{Pb}_j (Q^2_f) \]

\[ f^{P/A}_i (x, Q^2) \equiv R_i^A (x, Q^2) \otimes f^p_i (x, Q^2) \]

\[ \rightarrow \text{Cannot disentangle the effects of proton PDF } f^p_i (\sim 90\%) \text{ and nuclear modifications } R_i^{Pb} (\sim 10\%). \]

\[ \rightarrow \text{Interpretation ambiguous.} \]

- This approach was nevertheless used in a recent PDF-reweighting study by nCTEQ [ARXIV:1610.02925].
Experimental input: The LHC data — how should it be used?

- How to use the LHC data (p-Pb & Pb-Pb) to extract information on $R_i^A(x, Q^2)$?
- Answer #2: Distributions normalized to the integrated one

- Part of the dependence of the proton PDF $f_i^p$ cancels. How much?
- CMS dijets:

| PDF + nPDF          | dijets_{CMS} (15) |
|---------------------|-------------------|
| CT10 + DSSZ         | 94.441            |
| CT10 + EPS09        | 10.526            |
| CT10 only           | 116.187           |
| MSTW2008 + DSSZ     | 56.365            |
| MSTW2008 + EPS09    | 5.522             |
| MSTW2008 only       | 67.763            |

⇒ Still significant dependence on the baseline $f_i^p(x, Q^2)$.
How to use the LHC data (p-Pb & Pb-Pb) to extract information on $R_i^A(x, Q^2)$?

- Answer #3: Forward-to-backward ratios $R_{FB}$

$$R_{FB} = \frac{d\sigma(\eta > 0)}{d\sigma(\eta < 0)}$$

- As much as possible of the dependence on the proton PDF $f_i^P$ cancels.
- Cancel also experimental uncertainties (especially if the correlations are known) but lose some information also.
- Cannot use the Pb-Pb data in this way.
- $R_{FB} \neq 1$ for: nuclear mods in PDFs + isospin + phase-space effects.
Experimental input: The story of neutrino-nucleus DIS

- Several measurements (NuTeV, CCFR, CHORUS, CDHSW, Minerva) on high-energy neutrino-nucleus DIS ($\nu$-$A$ and $\bar{\nu}$-$A$).

- Data available only as absolute cross sections $d\sigma_{\nu,\bar{\nu}}^{i,\text{exp}}(xdy)$. 

  $\implies$ Sensitive to both the free proton baseline & nuclear corrections.

- The works of nCTEQ & DSSZ use directly the extracted structure functions.

  $\implies$ nCTEQ found tension with the $\ell^-$-$A$ DIS data:

  [Phys. Rev. Lett. 106 (2011) 122301]

  > A fit with no $\nu$-$A$ data

  > Selected $\nu$-$A$ (NuTeV) data points with a computed baseline
Experimental input: The story of neutrino-nucleus DIS

- To reduce the theoretical bias & experimental uncertainties a following observable was suggested [PRL 110 (2013) 212301]

\[
\frac{d\sigma_{i,\text{exp}}^{\nu,\bar{\nu}}}{dxdy} \equiv \frac{d\sigma_{i,\text{exp}}^{\nu,\bar{\nu}}}{dxdy} / \sigma_{\text{exp}}^{\nu,\bar{\nu}}(E_i),
\]

\[
\sigma_{\text{exp}}^{\nu,\bar{\nu}}(E_i) = \sum_i d\sigma_{i,\text{exp}}^{\nu,\bar{\nu}} \Delta x_y \delta E_i, E_i 
\approx \text{integrated xsec at fixed } E
\]

- A typical pattern of antishadowing + EMC effect clearly visible.

- The CHORUS $\nu$-Pb and $\bar{\nu}$-Pb data included in the EPPS16 analysis in this way — accounting for the correlated systematics.
Experimental input: Rethink the old $\ell^- A$ DIS data

- Ambiguities in the use of old NMC, EMC, SLAC $\ell^- A$ DIS data:

  “Isoscalarized” structure functions reported by the experiments (used e.g. in EPS09, DSSZ, nCTEQ15 analyses):

  \[
  \hat{F}_2^A = \frac{1}{2} F_2^{p,A} + \frac{1}{2} F_2^{n,A}
  \]
Experimental input: Rethink the old $\ell^- A$ DIS data

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  The true structure functions (used now in EPPS16):

  \[
  F_2^A = \frac{Z}{A} F_2^{p,A} + \frac{N}{A} F_2^{n,A}
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Experimental input: Rethink the old $\ell^- A$ DIS data

- Ambiguities in the use of old NMC, EMC, SLAC $\ell^- A$ DIS data:

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$$\hat{F}_2^A = \frac{1}{2} F_{p,A}^p + \frac{1}{2} F_{n,A}^n$$

The true structure functions (used now in EPPS16):

$$F_2^A = \frac{Z}{A} F_{p,A}^p + \frac{N}{A} F_{n,A}^n$$

- Both ways have been used — the latter one less sensitive to experimental assumptions.
Comparison of the current global fits
The EPPS16 nuclear modification for $^{208}\text{Pb}$ at $Q^2 = m_{\text{charm}}^2$.

- Total uncertainties shown as blue bands, individual error sets in green.
The EPPS16 nuclear modification for $^{208}$Pb at $Q^2 = m_{\text{charm}}^2$

- Total uncertainties shown as blue bands, individual error sets in green
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- Total uncertainties shown as blue bands, individual error sets in green
The EPPS16 nuclear modification for $^{208}\text{Pb}$ at $Q^2 = 10 \text{ GeV}^2$

- Total uncertainties shown as blue bands, individual error sets in green
The EPPS16 nuclear modification for $^{208}$Pb at $Q^2 = 10000$ GeV$^2$

- Total uncertainties shown as blue bands, individual error sets in green
Comparison between nCTEQ15 and EPPS16, $Q^2 = 10 \text{ GeV}^2$

- Typically smaller uncertainties in nCTEQ15 ⇐ more restrictive parametrization
- Larger high-$x$ gluon uncertainties in nCTEQ15 ⇐ looser cuts and no LHC data
- Behaviour of the nCTEQ15 valence sector ⇐ isospin-symmetric DIS data + no $\nu-A$ DIS

[ARXIV:1612.05741]
Comparison between EPS09, DSSZ and EPPS16

- No flavour freedom in EPS09 nor DSSZ.
  \[ R_{\text{valence}} \equiv \frac{u_{V}^{p/Pb} + d_{V}^{p/Pb}}{u_{V}^{p} + d_{V}^{p}} \]

- All three consistent (modulo the large-\(x\) valence quarks of DSSZ).

- Typically larger uncertainties in EPPS16 (more degrees of freedom).

\[ R_{\text{light sea}} \equiv \frac{\bar{u}^{p/Pb} + \bar{d}^{p/Pb} + \bar{s}^{p/Pb}}{\bar{u}^{p} + \bar{d}^{p} + \bar{s}^{p}} \]
Effects of nuclear PDFs in LHC p-Pb observables
More net shadowing for $y_Z > 0$ than for $y_Z < 0$

$\Rightarrow$ suppression in $R_{FB}$

The CMS data deviates significantly from unity for non-symmetric acceptance in the c.m. frame.
Effects of nuclear PDFs in the p-Pb data: W production

- More net shadowing for $y_{\ell^\pm} > 0$ than for $y_{\ell^\pm} < 0$
  $\Rightarrow$ suppression in $R_{FB}$

- A large isospin effect present in W production [JHEP 1103 (2011) 071]
  $\Rightarrow$ The data deviates significantly from unity
An EMC effect for $\eta_{\text{dijet}} < 0$, antishadowing for $\eta_{\text{dijet}} > 0$

$\implies$ an enhancement in $R_{\text{FB}}$

The data deviates significantly from unity for non-symmetric acceptance [JHEP 1310 (2013) 213].
Effects of nuclear PDFs in the p-Pb data: dijet production

nCTEQ15: larger high-\(x\) gluon uncertainty ⇒ a wider uncertainty band for dijets.

The mild nuclear effects of DSSZ gluons lead to a result similar with no effects.

Dijets constitute currently the most stringent probe of large-\(x\) gluons.
The way forward
The way forward... just a part of it
Near-future prospects

- For the new p-p baseline at $\sqrt{s} = 5$ TeV direct measurements of nuclear modification $R_{pPb}$ are now possible (more or less also at $\sqrt{s} = 8$ TeV).

[CMS-HIN-16-003]

- Provide theoretically a cleaner sensitivity to $R_A(x, Q^2)$ but....
Near-future prospects

- For the new p-p baseline at $\sqrt{s} = 5$ TeV direct measurements of nuclear modification $R_{pPb}$ are now possible (more or less also at $\sqrt{s} = 8$ TeV).

![Graph showing CMS Preliminary results for $R_{pPb}$ with different $p_T$ ranges](image)

- Provide theoretically a cleaner sensitivity to $R^A_i(x, Q^2)$ but....
- It is important that in such measurements the correlated systematics between p-p and p-Pb are accounted for.
- Preferably in a common fiducial phase space.
Near-future prospects: The importance of symmetric phase space

- An example of the importance of common fiducial phase space: $R_{BF}$ with a symmetric acceptance in lab frame vs. symmetric acceptance in c.m. frame

$\sqrt{s} = 5.02 \text{ TeV}$

- $-3 < \eta_{\text{leading}}$, $\eta_{\text{subleading}} < 3$
- $p_T^{\text{leading}} > 120 \text{ GeV}$
- $p_T^{\text{subleading}} > 30 \text{ GeV}$

$\Rightarrow$ Theoretical uncertainties can be made smaller by experimental cuts.
Near-future prospects: The Drell-Yan process

- Intermediate-mass Drell-Yan process at forward direction would provide a nice probe of small-\( x \) sea quarks [Arleo et al., Phys. Rev. D95 (2017) 011502].

![Graph showing Drell-Yan cross-section](image)

- Within the possibilities of e.g. LHCb with the Run-II luminosity [LHCb-PUB-2016-011].
- New low-mass Drell-Yan measurements expected from Fermilab SeaQuest experiment [FERMILAB-THESIS-2016-13].
Prospects for other probes — $J/\psi$ (+ other quarkonia)

- The theoretical description of $J/\psi$ in $p-A$ collisions not yet fully understood — could involve nuclear absorption etc...

- Fresh idea [LANSBERG ET.AL, EUR.PHYS.J. C77 (2017) NO.1, 1]:

$$d\sigma^{J/\psi} = f_g(Q_f^2) \otimes d\sigma_{gg}^{J/\psi}(Q_f^2, Q_r^2) \otimes f_g(Q_f^2)$$

Fit the coefficient functions to $p-p$ data

- Neglects all but the gluon-gluon channel

- A consistent description of the data with only effects from nuclear PDFs.
Prospects for other probes — open heavy flavour

- The potential of D (and B) meson production has been demonstrated in p-p
  \[\text{[ARXIV:1610.09373 & EUR.PHYS.J. C75 (2015) NO.8, 396]}\]

- Different theoretical treatments e.g.
  - NLL parton-level calculation + PYTHIA
  - NLO GM-VFNS + fragmentation functions

- Can be done also in p-Pb collisions (e.g. ALICE, LHCb)

\[xg(x,Q^2) = 4 \text{GeV}^2\]
Prospects for other probes — ultra peripheral collisions (UPC)

- It has been argued that UPC vector meson (e.g. J/$\psi$) production in Pb-Pb collisions is particularly sensitive to nuclear gluon

\[ \sigma^{\gamma^A \to V} \propto \left[ g^A(x, Q^2) \right]^2 \]

[ARXIV:1603.01919]

- Exact relation to inclusive NLO (and beyond) PDFs?

H. Paukkunen (Jyväskylä Univ.)
Status of nuclear PDFs after the first LHC p-Pb run
Quark Matter 2017, February 10th
Overviewed the recent progress on the global analysis of nuclear PDFs

The most important developments new ingredients in the latest global analysis:

- LHC Run I data \(\Rightarrow\) completely novel constraints
- Neutrino DIS data \(\Rightarrow R_{uV} \sim R_{dV}\)
- Full flavour dependence \(\Rightarrow\) significantly less bias but larger uncertainties

The universality of nuclear PDFs now verified up to the electroweak scale.

More (much!) data expected in the near future — e.g. the p-Pb run at \(\sqrt{s} = 8\) TeV

- The availability of correlated systematics would be advantageous.
- Symmetric acceptance in the c.m. frame would reduce theoretical uncertainties.