(n)PDF issues and opportunities at the Forward Physics Facility

Maria Vittoria Garzelli

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Nuclear PDFs: present status

* QCD field under active investigation these days

* Not too many experimental data available for the fits

* A few fits available, mostly at NLO.
  Only three fits at NNLO (KA15, TUJU19 and nNNPDF).

* Fits rely mainly on legacy fixed-target data (DIS and Drell-Yan).
  $\rightarrow$ limited x coverage ($x \gtrsim 0.01$)

* $d + Au \rightarrow \pi + X$ at RHIC added to better constrain gluons.

* Recent incorporation, in some fits, of pPb collision data at the LHC.
  $\rightarrow$ extends x coverage ($x \gtrsim 0.002$ with Run-I data)

- Important assumption 1): a factorization theorem applies to pA and AA collisions, in a similar way as in pp collision. Not yet proven!

- Important assumption 2): all nuclear effects in pA collisions are ascribed to PDFs, whereas other possible cold nuclear matter effects are not modelled, at least in present analyses. Too much of a simplification ?

Nuclear PDF fits: some definitions and assumptions

* Nucleon PDFs built from proton and neutron ones:

$$f_i^{N/A}(x, Q^2) = \frac{Z \cdot f_i^{p/A} + (A - Z) \cdot f_i^{n/A}}{A}$$

* Assumption: $f_i^{n/A}$ obtained from $f_i^{p/A}$ by imposing

$$d_i^n = u_i^p \text{ and } u_i^n = d_i^p$$

  BUT Charge symmetry violation effects ? Small-x studies.

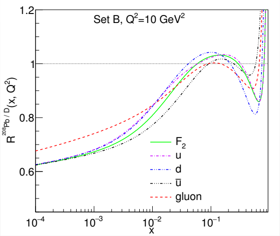
* Assumption: baryon number and momentum sum rules are applied to individual nucleons during the nuclear PDF fit.
  BUT No warranty that the sum rules should be obeyed exactly by a nucleon embedded in a nucleus!

* Nuclear modification factors: $R_i^{p/A} = f_i^{p/A}(x, Q^2)/f_i^p(x, Q^2)$
  BUT Baseline proton PDFs not always fitted together with the nPDF!
  $\Rightarrow$ Issues in case of different assumptions in the two fits.

Nuclear modification factors R_p^{Pb}

$*$ Shadowing: $R < 1$ for $x \lesssim 0.1$ (a possible explanation: parton recombination/fusion process enhanced in nuclear target: partons with large spatial uncertainties (small x), can leak to a neighbor nucleon)

$*$ Antishadowing: $R > 1$ for $0.1 \lesssim x \lesssim 0.3$, related to shadowing.



[arXiv:1611.03670]

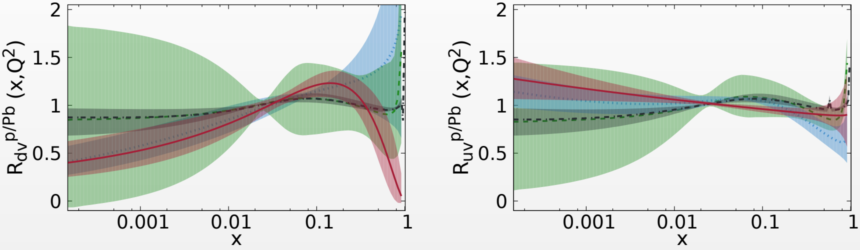
$*$ EMC effect: $R < 1$ for $0.3 \lesssim x \lesssim 0.7$ (attributed to in-medium nucleon swelling, nucleon-nucleon short range correlations, binding, ...).

$*$ Fermi smearing: $R > 1$ for $0.7 \lesssim x < A$ short range nucleon correlations deform the nuclear structure functions mainly at large x.

No explicit modelization of nuclear effects occurs in most global fits of nPDFs. The modifications of the structure functions by nuclear effects are absorbed into the nPDF themselves.

$\Rightarrow$ Evergreen questions: how to write a parameterization for nPDFs ?

u_v and d_v nPDFs: a comparison of recent nPDF NLO fits TUJU19/EPPS16/nCTEQ15/KA15

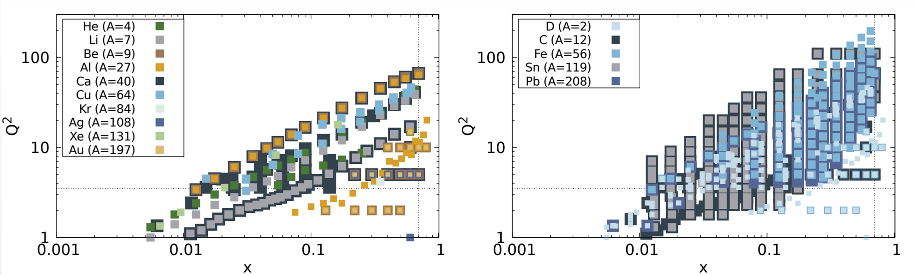


from arXiv:[1908.03355]

∗ For TUJU19 and nCTEQ15 PDFs, the nuclear modification factor for d_v quarks displays the typical shadowing/antishadowing/EMC behaviour, whereas this does not appear to be true in case of the u_v quark

⇒ The data are not sensitive enough to the flavour dependence of the valence quarks, good agreement among the fits only when considering (u_v + d_v)

Kinematic reach of present fixed-target DIS data used in nPDF fits

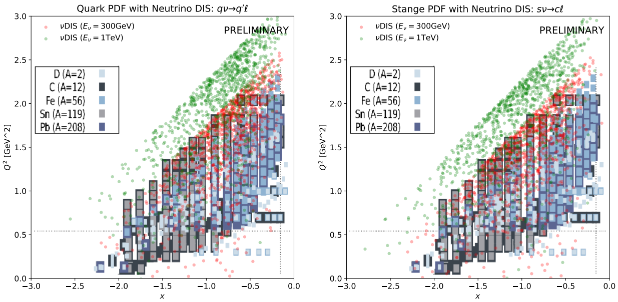


from M. Walt et al. [arXiv:1908.03355]

∗ These data mainly refer to experiments with charged lepton beams.

∗ Data on ν interactions on Fe and Pb targets (CDHSW, CHORUS) also included.

Adding future data at the FPF would extend (Q^2, x) coverage



preliminary modifications of previous plot by F. Kling

∗ Inclusive CC DIS and charm production in CC DIS.

∗ Extended coverage to larger Q^2 possible thanks more energetic ν beams with respect to the past.

Constraining nPDFs at the Forward Physics Facility

- Assuming that the beams reaching the FPF are mainly constituted by ν and μ,
- Assuming the the fluxes of these particles at the detector position are well under control, one can measure:

  $\nu + A$ CC (and NC) DIS events (inclusive and charm production),

  $\mu + A$ NC (and CC) DIS events
  (if one can isolate vertices associated to μ interactions in the detector),

  for a variety of nuclear targets A
  (if one can substitute the detector from time to time).

- Being able to disentangle ν and $\bar{\nu}$ induced events allows for quark flavor separation.
- Charm production in CC DIS is particularly sensitive to strange sea (V_{dc} is Cabibbo-suppressed with respect to V_{sc}).

νA CC DIS: some formulas

$$\frac{\mathrm{d}^2\sigma}{\mathrm{d}x\,\mathrm{d}y} = N^{l}\left[y^2 x F_1^{l} + (1-y)\,F_2^{l} \mp \left(y - \frac{y^2}{2}\right) x F_3^{l}\right],$$

with $x \equiv Q^2/(2q\cdot p)$, $y \equiv 1 - E'/E$ in target rest-frame ($Q^2 \approx y\,x\,s$),
with structure functions

$$F_i\left(x,\ Q^2\right) = \sum_j C_i^j\left(x,\,\alpha_s(\mu^2),\,\mu^2/Q^2\right) \otimes f_j\left(x,\,\mu^2\right),$$

and with normalization factor for $l = \nu$

$$N^{\nu,\,\mathrm{CC}} = \frac{G_{\mathrm{F}}^2\,M_W^4\,Q^2}{4\pi\,x\,y\,\left(Q^2 + M_W^2\right)^2},$$

For ν and $\bar{\nu}$ at LO:

$$\begin{aligned} F_1^{\nu} &= d + s + b + \bar{u} + \bar{c} + \bar{t}\,, \\ F_2^{\nu} &= 2x\,(d + s + b + \bar{u} + \bar{c} + \bar{t})\,, \\ F_3^{\nu} &= 2\,(d + s + b - \bar{u} - \bar{c} - \bar{t})\,, \end{aligned} \tag{1}$$

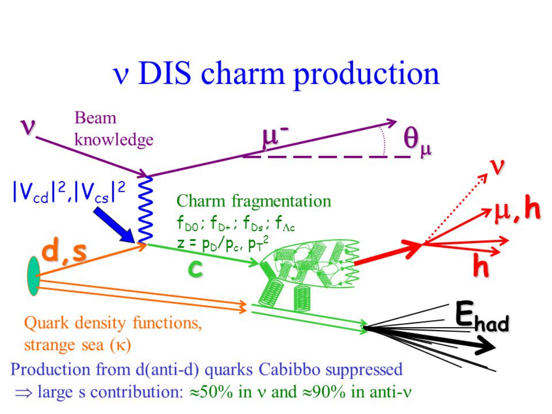
and

$$\begin{aligned} F_1^{\bar{\nu}} &= u + c + t + \bar{d} + \bar{s} + \bar{b}\,, \\ F_2^{\bar{\nu}} &= 2x\,(u + c + t + \bar{d} + \bar{s} + \bar{b})\,, \\ F_3^{\bar{\nu}} &= 2\,(u + c + t - \bar{d} - \bar{s} - \bar{b})\,. \end{aligned} \tag{2}$$

$\Rightarrow$ (u, d) flavour decomposition is allowed by distinguishing ν and $\bar{\nu}$ events.

Charm production in ν-induced CC DIS and strange sea

* Charm/Anticharm production in CC DIS has direct sensitivity to $s(x)$, $\bar{s}(x)$ at LO
* One can separate $s(x)$ and $\bar{s}(x)$ by disentangling ν and $\bar{\nu}$ events.



picture by G. De Lellis

Strange sea in (n)PDFs

$*$ At present, one of the most uncertain partons in both nuclear and proton PDF fits. In some cases, results are consequences of strict assumptions: e.g. $u(x) = d(x) = s(x) = \bar{s}(x)$ or fixed values of $f_s = \bar{s}/(\bar{s} + \bar{d})$ or $R_s = (s(x) + \bar{s}(x))/(\bar{u}(x) + \bar{d}(x))$

$*$ Big uncertainties and attitude partly motivated by the fact that data from different experiments seem to be partially incompatible among each other.

$*$ Legacy data used in PDF fits to determine strange sea:

- massive high-density detectors providing dimuon data (CDHS, CDHSW, CCFR, CharmII, NuTeV, NOMAD)
- bubble chamber data (BEBC)
- nuclear emulsions (E531, CHORUS)

$*$ The incapability of simultaneously obtaining a good fit of all previous ones has led the PDFs and nPDF collaborations to discharge some data (e.g. NuTeV).

$*$ Additionally, recent precise LHC data (in particular Drell-Yan) turn out to also be sensitive to strange quark distributions. They point to a larger strange component with respect to the dimuon data, generating some tension with the latter.

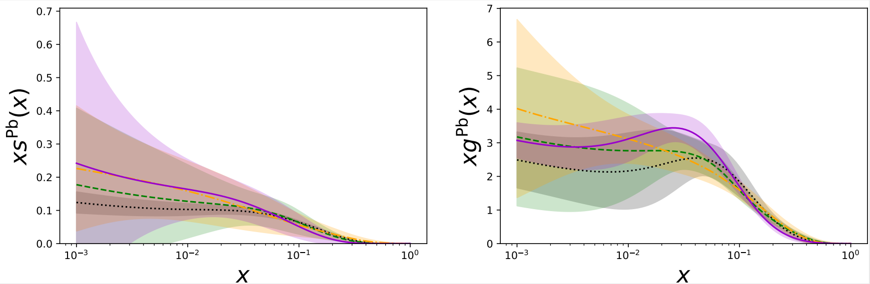
$*$ Important to quantify strange sea in nPDF even to understand if the observed enhanced abundance of produced strange anti-barions in AA collisions can be ascribed to the onset of a QGP.

Modification of a nPDF fit induced by *pPb* Drell-Yan data: the nCTEQ15WZ fit w.r.t. nCTEQ15

∗ ATLAS and CMS experimental data systematically above the theory predictions with nCTEQ15 ($\sim 5\%$).

∗ A normalization uncertainty is included into the fit.

∗ Considering this, and including LHC Drell-Yan data into the fit, lead to enhanced strange sea and even enhanced gluon (sensitivity to g with relatively small-x through the NLO qg channel):



nCTEQ15/EPPS16/NNPDF2.0/nCTEQ15WZ *from [arXiv:2007.09100]*

Issues and uncertainties affecting the inclusion of legacy $\nu + A$ data in PDF fits

$*$ Dimuon data issues:

– uncertainty on which one of the two muons matches to the EW vertex / hadronic decay.

– (in-heavy-medium) fragmentation uncertainties

– missing the identification of the parent D-hadron

– Uncertainties on Branching Fractions for the decays of the D-hadrons originating the μ

$*$ Emulsion data issues:

– low statistics

– off-line reconstruction of the event topology/kinematics + pileup

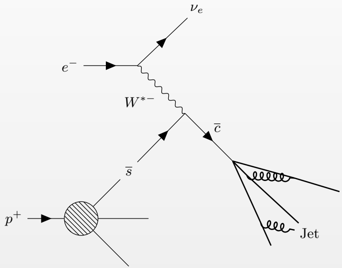
Will the detector technologies at the FPF facility overcome these issues ?

Opportunities offered by emulsion experiments

* Consider all decay modes (not only the dimuons)
* Measure the relevant Branching Fractions
* Use different targets, covering a wide range of A values, substituting them during the run-pauses
  $\Rightarrow$ Interesting and useful to constraining the A-dependence of nPDFs. At present there are abundant data useful for nPDF fits only for a very limited number of targets.
* Reconstruct the relevant quantities of each event, by topological + kinematics methods:
  $E_\nu = E_\ell + E_{had}$ can be reconstructed.
  Knowledge of (E_ν, E_ℓ, $\theta_{\ell,\nu}$) allows to derive (Q^2, x_{Bj}).

  In emulsions, E_ν present energy resolution of 30%.
  Is it enough for getting precise QCD constraints ?

Recent proposals to constrain strange quarks at the EIC: use c-jets



$*$ c-jets are less prone to fragmentation uncertainties than D-hadron, especially when using large R radius ($R \sim 1$)

from arXiv:[2006.12520]

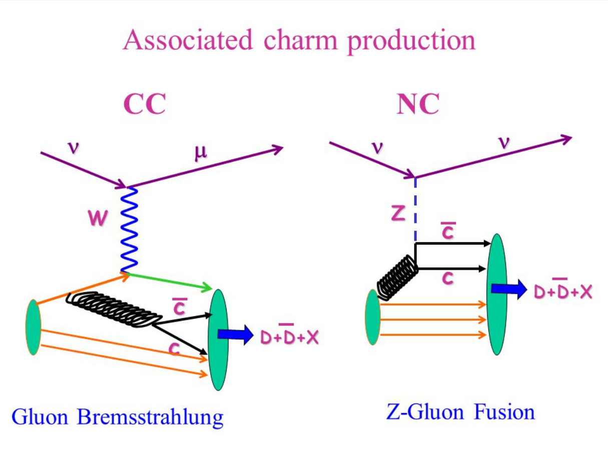
$*$ EIC ep collisions at $\sqrt{s} = 10,\ 275$ GeV will allow to probe large x.

$*$ Can FPF made a similar measurements using neutrinos with $E_{lab} \sim 1$ TeV (corresponding to $\sqrt{s} \sim 45$ GeV for a νp collision) ?

$*$ Is it possible to build detectors for c-jets at the FPF ?

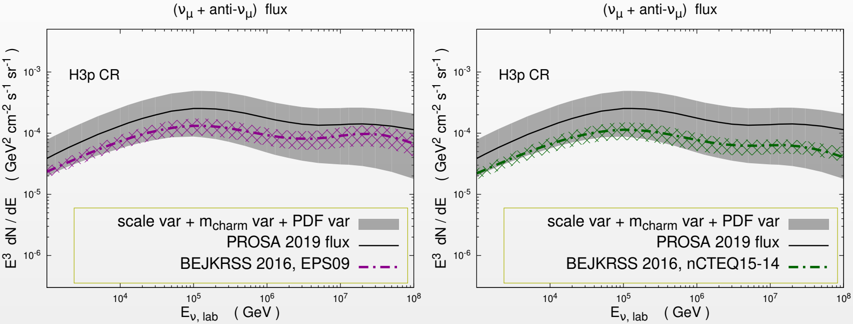
charm-anticharm associated production in CC and NC DIS

Some sensitivity to the gluons: can we recognize these events at the FPF ?



picture by G. De Lellis

Example of application of nPDF fits: predictions for prompt atmospheric neutrino fluxes



from [arXiv:1911.13164]

∗ How will these predictions change when more reliable nPDF fits (in particular for the gluon case) will be available ?

∗ A reliable estimate of the gluon nPDF uncertainty is also still an open problem for many nPDF fits.

Conclusions

$*$ nPDF: indispensable input for AA studies (in the hypothesis factorization is still valid).

$*$ nPDF fits: room for large improvements.

$*$ Useful data:

- Legacy data (fixed-target DIS and DY),
- RHIC and LHC present (and future) data,
- EIC (large x) and LHeC (small x) future data: supposed to be precise, but still far to come.
- Detectors at the FPF as a more immediate way of obtaining, already during the HL-LHC phase, a bunch of interesting complementary results, mainly exploiting ν and $\bar{\nu}$ beams at $\mathcal{O}$(TeV) lab. energies, impinging on a variety of nuclear targets.