Research Activity Report

Alessandro Candido - *September 19, 2022*

Summary: Following, the activity report about the research performed in the period October 2019 - September 2022, as a member of the `N3PDF` team, and lately also of the `NNPDF` collaboration, under the supervision of the prof. Stefano Forte. Most of the research has been focused on the development of a new framework, to provide fast, flexible, and reproducible theory predictions for PDF fitting. Despite this being the main effort, a number of other results has been achieved in the meanwhile, from framework's applications, to dedicated studies. Attendance to schools and conferences is reported at the end, together with references to delivered talks.

1 Research

Parton Distribution Functions (PDFs) are a description of the collinear structure of the proton, and possibly other hadrons appearing as input states of the high energy processes. Since PDFs are generated by the non-perturbative QCD dynamics, it is not possible, at the state of the art, to compute them from first principles. Thus we are fitting them.

There are three main ingredients that are essential for PDF fit: data, theory predictions, and the fitting machinery.

Theory Framework

Theory predictions have always been performed in `NNPDF` - PDF fits more in general - by a rather composite ecosystem of different programs. Because of this, it has been developed an interest for improving part of it, and integrating the separate pieces into a single pipeline.

DGLAP evolution determines the PDFs values at any scale from a given border condition at an initial scale. It is thus crucial for fitting, since it is needed to compare the candidates and final determination from the fit at the chosen scale, to the experimental data that are at many different scales.

Several different options can affect the actual DGLAP solution, and for this reason you want a reliable and extendable tool, able to deliver a solution, reusable over and over with a limited cost in computing time.

For this reason we developed **`EKO`** [1][CHM22a], in order to improve some of the features of the former program used (i.e. `APFEL`), and to include a few requirements at design level: compute the solution as a linear operator (as opposed to evolve an initial condition over and over), solve the equation in Mellin space, and have a maintainable and extendable code, to help future contributors.

In the same spirit, and at the same time, we did something similar in the development of **`yadism`** [CHM22b], a provider for DIS predictions (structure functions and reduced cross sections).

Formerly, DIS had a very special role, being the process that was mainly constraint the PDFs themselves, especially driven by HERA data. This was reflected in programs like `APFEL` and `QCDNUM` dispatching both evolution and DIS predictions. This is not any longer true with the advent of LHC data, and many different processes are now included in the fit. Each one playing a different and important role as a part of the global dataset.

With all this in mind, a collaborator (C. Schwan), started writing **`PineAPPL`** [SCHC22], a common interface for many PDFs agnostic calculations. I personally contributed the Python bindings and `EKO` interface, that is part of the main library (being evolution in common to all processes), while I also implemented a `yadism` interface to `PineAPPL`. But being DIS only one of the processes this is on the side of `yadism` itself.

In order to smoothen the process of combining `EKO` outputs with `PineAPPL` grids, we wrote **`pineko`**[BHC⁺22], a further code taking care of the whole process, including the computation of the missing `EKO` operators.

Finally, `yadism` is not the only code interfaced to `PineAPPL`, and working as the provider. Because of the different programs it is more and more difficult to repeat the calculation of all the predictions required for the fit. Thus, we store all the **runcards** in a dedicated repository [SCm⁺22]. We also provide one more program, **`pinefarm`**, able to install all the dependencies for said calculations, and reproduce the results given just the runcard.

A description of the main components, together with a first design of the overall layout of the theory framework, has also been contributed to the Snowmass process [2].

Applications

One of the first applications of `EKO`, has been the determination of a heavy non-perturbative charm component of the proton, the so called **intrinsic charm** [3]. This is result is based on the last release of `NNPDF` family, i.e. `NNPDF4.0`, and the `EKO` bacward evolution, together with its treatment of intrinsic flavors, and the availability of N^3LOmatching conditions.

Another relevant study (yet unpublished), consisted in a parametrization for **neutrinos structure functions**, based on the low energy neutrino DIS data, and the pQCD predictions of `yadism`, still using `NNPDF4.0` as PDF set.

Further studies

It has of main interest for fitting to implement as many theoretical constraints as possible, to sharpen our knowledge of the unknown object, and reduce the amount of degrees of freedom only constrained by experimental data. This is why we attempted to prove **PDFs positivity** [4, 5] through pQCD arguments. It was already assumed as part of the main PDF fits (notably not `NNPDF3.1`), and it has been one of the novelties introduced in `NNPDF4.0`. Though later disputed, the main controversy is about a regime in which the data are also potentially affected by non-perturbative effects, and thus already mostly excluded from the fit itself.

A further study, still ongoing, is about the possible sampling from the determined PDFs distribution, without the support of a neural network, nor a fixed parametrization over a polynomial (or similar) basis. The idea is to directly use the values of the PDFs at given points of interest, and to obtain their distribution by Bayesian inference, by means of an approximate solution (based on a Gaussian approximation) or posterior sampling methods.

2 Schools

During the first year, 2019/2020, I took part in two schools:

- GGI Lectures on the Theory of Fundamental Interactions 2020, *at Galileo Galieli institute in Florence*, Jan 07, 2020 - Jan 24, 2020 https://www.ggi.infn.it/showevent.pl?id=337
- 2020 Fermilab-CERN Hadron Collider Physics Summer School (HCPSS), *remotely, hosted by Fermilab*, Aug 10, 2020 - Aug 21, 2020 https://indico.fnal.gov/event/43762/

3 Conferences

Other than the periodic `NNPDF` meetings (each six months), I could only attend to conferences during my last year, i.e. 2022, due to the global pandemic.

- DIS2022, *Santiago de Compostela*, May 2, 2022 - May 6, 2022 https://indico.cern.ch/event/1072533/

- ICHEP2022, *Bologna*, 6 Jul 2022 - 13 Jul 2022, https://www.ichep2022.it/
  - at which I gave a talk " EKO and yadism: theory predictions for PDF fitting"
- ISMD2022, *Pitlochry, Scottish Highlands*, Jul 31, 2022 - Aug 5, 2022, https://indico.cern.ch/event/1015549/
  - at which I gave a talk " Recent advances in PDF determination: methodology and framework "
- Machine Learning at GGI, *Firenze*, Sep 5, 2022 - Sep 23, 2022, https://www.ggi.infn.it/showevent.pl?id=411
  - and the related conference https://www.ggi.infn.it/showevent.pl?id=414
  - at which I gave a talk " PDF determination: from NN fitting to posterior sampling"

Papers

[1] A. Candido, F. Hekhorn and G. Magni, *EKO: Evolution Kernel Operators*, 2202.02338.

[2] S. Amoroso et al., *Snowmass 2021 whitepaper: Proton structure at the precision frontier*, 2203.13923.

[3] NNPDF collaboration, *Evidence for intrinsic charm quarks in the proton*, *Nature* **608** (2022) 483 [2208.08372].

[4] A. Candido, S. Forte and F. Hekhorn, *Can* $\overline{\mathrm{MS}}$ *parton distributions be negative?*, *JHEP* **11** (2020) 129 [2006.07377].

[5] A. Candido, S. Forte and F. Hekhorn, *Can* $\overline{MS}$ *parton distributions be negative?*, *SciPost Phys. Proc.* **8** (2022) 077 [2108.10774].

Codes

[BHC+22] Andrea Barontini, Felix Hekhorn, Alessandro Candido, Christopher Schwan, Stefano Carrazza, and Juan M. Cruz-Martinez. N3pdf/pineko: Zenodo, September 2022.

[CHM22a] Alessandro Candido, Felix Hekhorn, and Giacomo Magni. N3pdf/eko: Paper, March 2022.

[CHM22b] Alessandro Candido, Felix Hekhorn, and Giacomo Magni. N3pdf/yadism: Fonll-b, February 2022.

[SCHC22] Christopher Schwan, Alessandro Candido, Felix Hekhorn, and Stefano Carrazza. N3pdf/pineappl: v0.5.5, August 2022.

[SCm+22] Christopher Schwan, Alessandro Candido, marcozaro, Juan M. Cruz-Martinez, Felix Hekhorn, Stefano Carrazza, and Emanuele R. Nocera. Nnpdf/runcards: Zenodo, September 2022.