Theory Predictions

for PDF fitting

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DI MILANO

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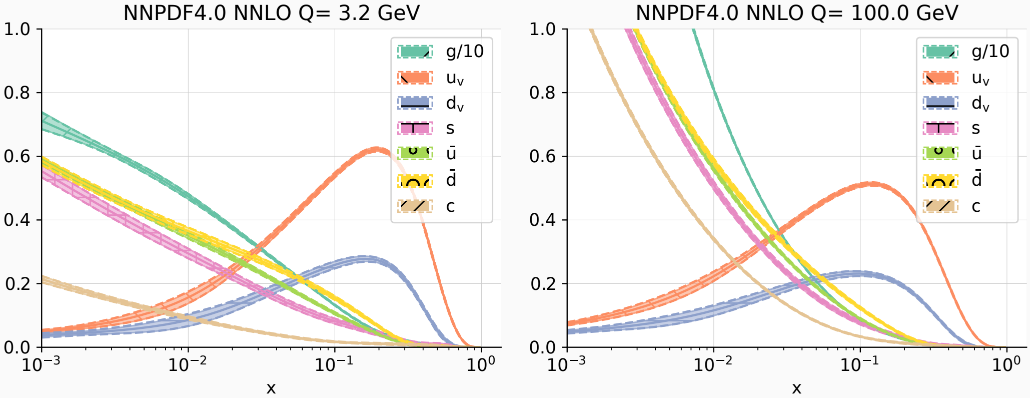
NNPDF4.0 [arXiv: 2109.02653]

NNPDF4.0


NNPDF4.0 NNLO Q= 3.2 GeV
NNPDF4.0 NNLO Q= 100.0 GeV
1.0
0.8
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10^{-3}
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x
g/10
u_v
d_v
s
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$\bar{d}$
c

NNPDF4.0: Highlights

METHODOLOGY new Neural Network, based on widely supported, industry-level library, with further tests and machine-learning inspired improvements

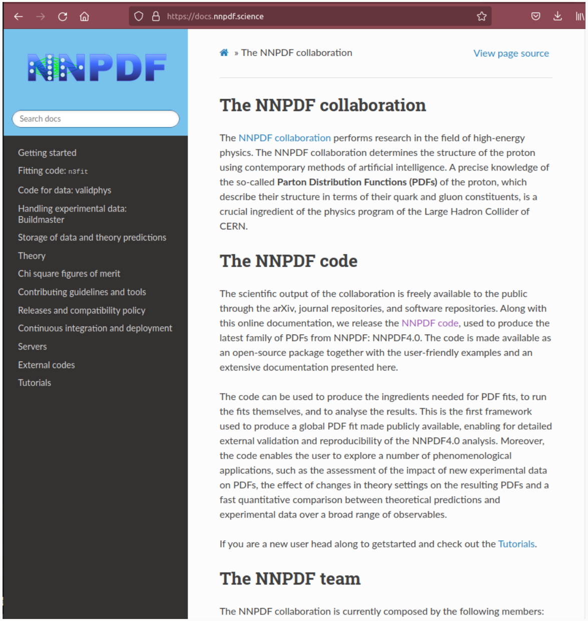
DATA more data from LHC, and a massive increment in the number of processes (jets, dijets, single top, top pair, ...)

ERRORS a consequential great reduction in uncertainty

BACKWARD COMPATIBLE preserving compatibility with `NNPDF3.1`

PUBLIC CODE code public [arXiv: 2109.02671] and documented

- “make your own `NNPDF`!”


https://docs.nnpdf.science
NNPDF
Search docs
Getting started
Fitting code: n3fit
Code for data: validphys
Handling experimental data: Buildmaster
Storage of data and theory predictions
Theory
Chi square figures of merit
Contributing guidelines and tools
Releases and compatibility policy
Continuous integration and deployment
Servers
External codes
Tutorials
» The NNPDF collaboration
View page source

The NNPDF collaboration

The NNPDF collaboration performs research in the field of high-energy physics. The NNPDF collaboration determines the structure of the proton using contemporary methods of artificial intelligence. A precise knowledge of the so-called **Parton Distribution Functions (PDFs)** of the proton, which describe their structure in terms of their quark and gluon constituents, is a crucial ingredient of the physics program of the Large Hadron Collider of CERN.

The NNPDF code

The scientific output of the collaboration is freely available to the public through the arXiv, journal repositories, and software repositories. Along with this online documentation, we release the NNPDF code, used to produce the latest family of PDFs from NNPDF: NNPDF4.0. The code is made available as an open-source package together with the user-friendly examples and an extensive documentation presented here.

The code can be used to produce the ingredients needed for PDF fits, to run the fits themselves, and to analyse the results. This is the first framework used to produce a global PDF fit made publicly available, enabling for detailed external validation and reproducibility of the NNPDF4.0 analysis. Moreover, the code enables the user to explore a number of phenomenological applications, such as the assessment of the impact of new experimental data on PDFs, the effect of changes in theory settings on the resulting PDFs and a fast quantitative comparison between theoretical predictions and experimental data over a broad range of observables.

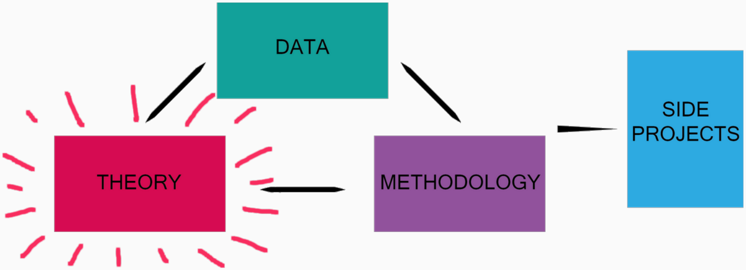
If you are a new user head along to getstarted and check out the Tutorials.

The NNPDF team

The NNPDF collaboration is currently composed by the following members:

NNPDF4.0: Theory?

Mostly the same (not really: K-factors recomputed, a lot of new processes).



But main providers[1] (DIS, evolution, FTDY) are the exact same of **`NNPDF3.1`**.

[1] In particular it is one: **`APFEL`**, and the associated **`APFELcomb`**.

EKO [arXiv: 2202.02338]

EKO Definition

EKO

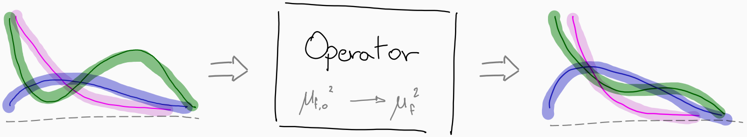
Evolution Kernel Operators

The main purpose is to solve **DGLAP** equations:

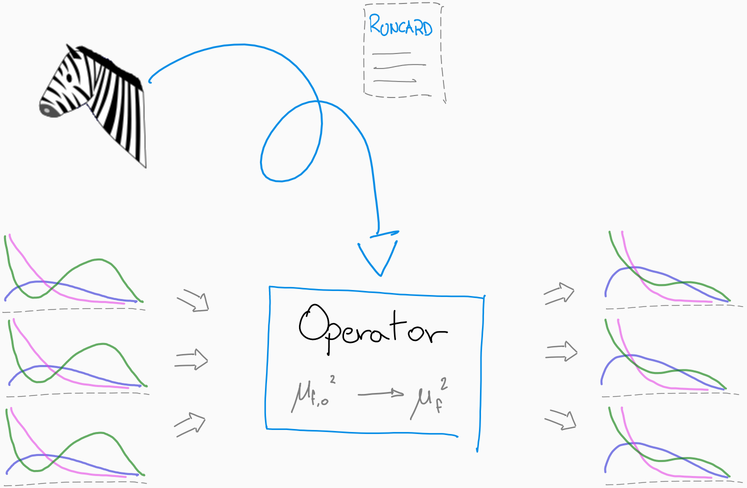
$$\mu_F^2 \frac{\mathrm{d}f}{\mathrm{d}\mu_F^2}(\mu_F^2) = P(a_s(\mu_R^2), \mu_F^2) \otimes f(\mu_F^2)$$

These equations define a set of linear operators $E(\mu_F^2 \leftarrow \mu_{F,0}^2)$ on **PDF** sets

$$f(\mu_F^2) = E(\mu_F^2 \leftarrow \mu_{F,0}^2) \otimes f(\mu_{F,0}^2)$$



Independent of boundary condition → PDF fitting

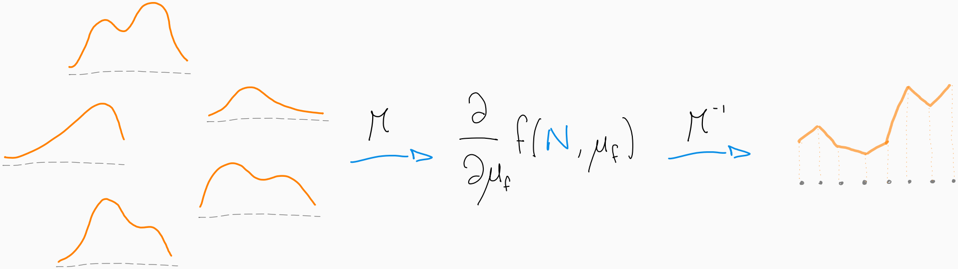


User-friendly Mellin Space

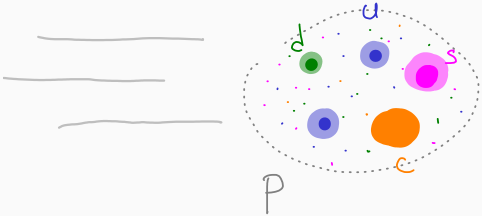
Solved in Mellin (N-) space, but the operator is recasted in ***x*-space**.

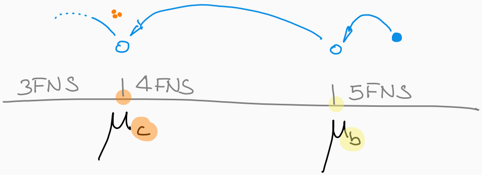
Via piecewise Lagrange-interpolation:

- **INPUT** PDF is interpolated with polynomials, and ***analytically*** Mellin transformed
- **OUTPUT** PDF is given on grid points, and Mellin inverted ***numerically***



Consistent evolution of **intrinsic** heavy quark distributions.





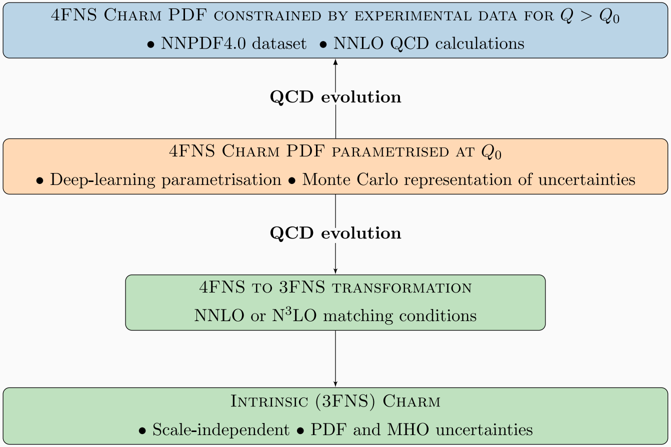
Full **backward** VFNS evolution (i.e. across thresholds and with intrinsic).

And more to come (MHOU, QED, N^{3}LO, ...).

Intrinsic Charm in the Proton [in press]

Intrinsic Charm: Strategy

Based on NNPDF4.0 [arxiv:2109.02653].



4FNS Charm PDF constrained by experimental data for $Q > Q_0$

- NNPDF4.0 dataset
- NNLO QCD calculations

QCD evolution

4FNS Charm PDF parametrised at Q_0

- Deep-learning parametrisation
- Monte Carlo representation of uncertainties

QCD evolution

4FNS to 3FNS transformation

NNLO or N^3LO matching conditions

Intrinsic (3FNS) Charm

- Scale-independent
- PDF and MHO uncertainties

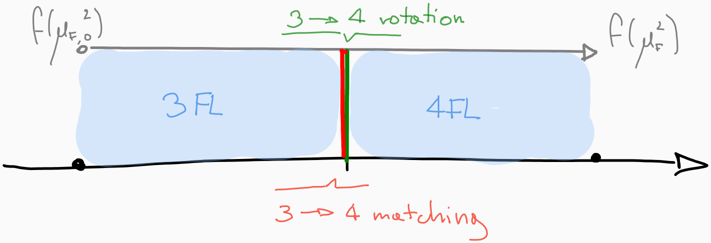
Intrinsic it is the charm PDF in the **3FNS**, where the charm is actually considered massive (and consequently *factorization scale independent* – collinear divergencies are protected by the mass)

Matching Conditions and Backward Evolution

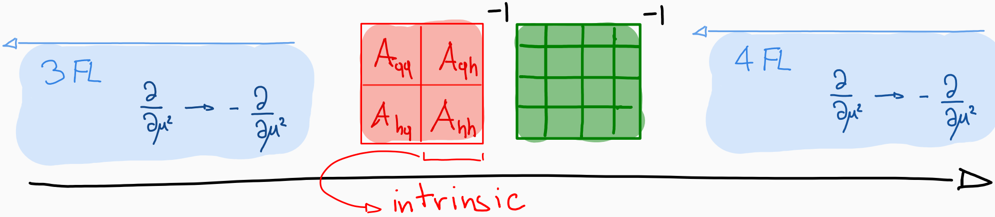
For (forward) evolution across a matching scale μ_h^2:

$$\mathbf{f}^{(n_f+1)}(\mu_{F,1}^2) = \left[\mathbf{E}^{(n_f+1)}(\mu_{F,1}^2 \leftarrow \mu_h^2)\mathbf{R}^{(n_f)}\mathbf{A}^{(n_f)}(\mu_h^2)\mathbf{E}^{(n_f)}(\mu_h^2 \leftarrow \mu_{F,0}^2)\right] \times \mathbf{f}^{(n_f)}(\mu_{F,0}^2)$$

The **Operator Matrix Element** (OME) $\mathbf{A}^{(n_f)}(\mu_h^2)$ is partially known up to N^{3}LO.

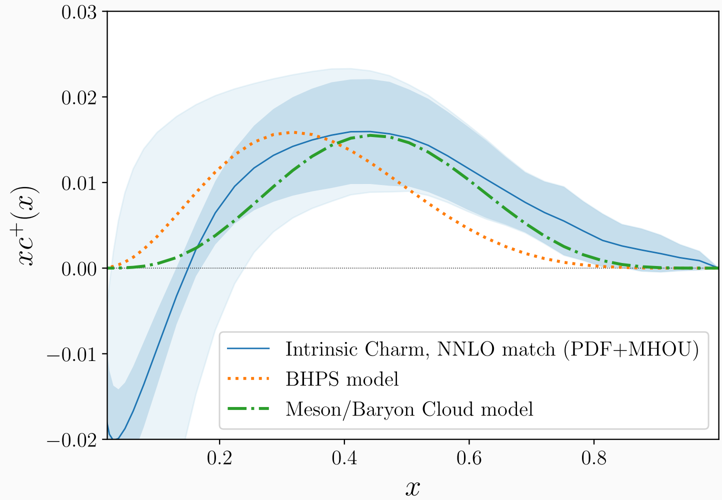


Inverse operator (the OME can be inverted either *perturbatively* or *numerically*)



3 FL
$\frac{\partial}{\partial\mu^2} \to -\frac{\partial}{\partial\mu^2}$
A_{qq}
A_{qh}
A_{hq}
A_{hh}
-1
-1
4 FL
$\frac{\partial}{\partial\mu^2} \to -\frac{\partial}{\partial\mu^2}$
intrinsic

Intrinsic Charm: pdf plot

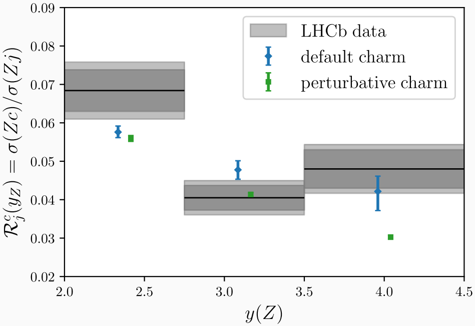


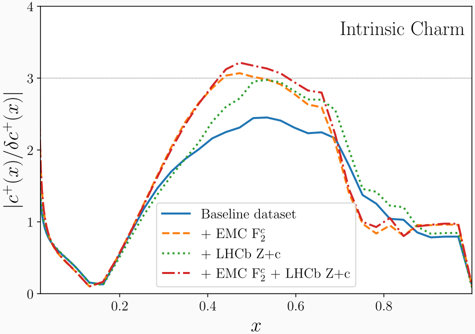
[BHPS] or [Meson/Baryon Cloud Model]

Message In 3FNS a **valence-like peak** is present.

- for $x \leq$ **0.2** the perturbative ***uncertainties*** are quite ***large***
- the carried ***momentum fraction*** is within **1%**

Intrinsic Charm: LHCb and Significance





We found a **3σ** evidence of intrinsic charm

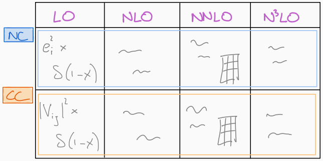
- match better recent **LHCb** Z+c measurement [PRL128-082001]
- result is **stable** with mass variation, dataset variation

yadism [IN PREPARATION]

yadism Physics Features

Yadism

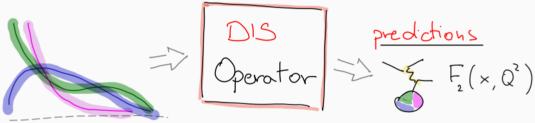
Yet Another DIS Module



	LO	NLO	NNLO	N³LO
NC	$e_i^2 \times \delta(1-x)$			
CC	$\lvert V_{ij} \rvert^2 \times \delta(1-x)$			

DIS coefficient function database

Independent of **boundary** condition → PDF fitting.



Several other features: **TMC**, multiple **FNS**, generic matching scales, interpolation, ...

Constant benchmark against **APFEL**. ✓

Multiple benchmarks against **QCDNUM**. ✓

Benchmark with original FONLL. ✓

DIS coefficients

NLO	light	heavy	intrinsic
NC	✓	✓	✓
CC	✓	✓	✓
NNLO			
NC	✓	partially tabulated	✗
CC	✓	tabulated	✗
N^3LO			
NC	✓		
CC	✓		

+ FONLL (cf. *matching conditions*)

There is even another couple of levels of nesting:

Projections F_2, F_L, and F_3

Channels non-singlet, singlet, gluon

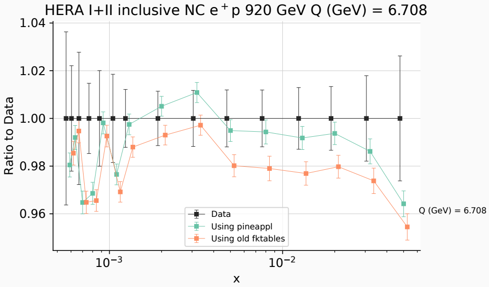
But up to NNLO everything is equally available (while at N^3LO it is not always true).

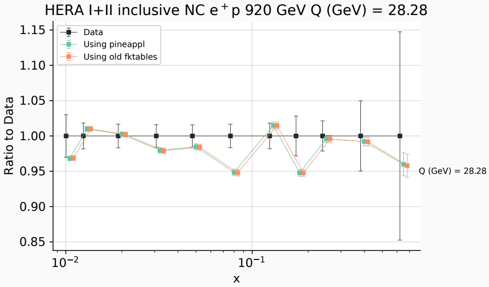
So NC is currently implemented up to NNLO [VVM05 MVV05 MV00] light and NLO heavy [Hek19] (i.e. both $O(a_s^2)$). Same for CC light [MRV08 MVV09] and heavy (for which implementation is currently in progress).

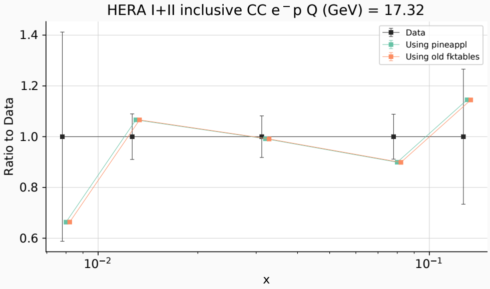
For both processes *intrinsic* contributions are accounted at NLO.

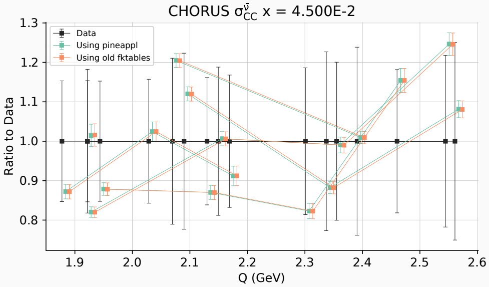
available	updated	not yet implemented	missing	not planned

Comparison yadism against APFEL



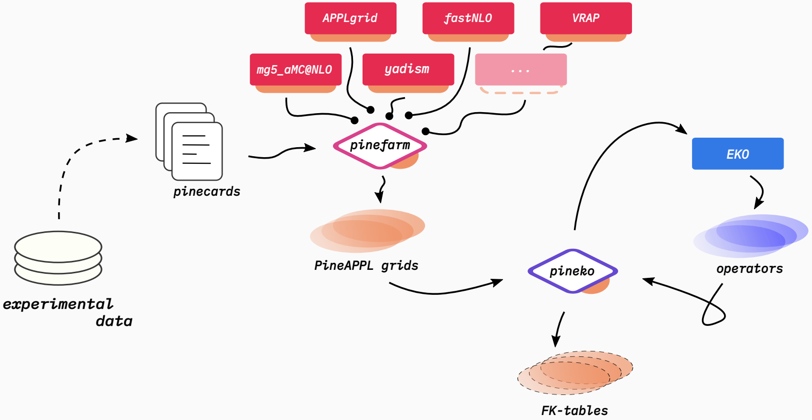






Theory Prediction Pipeline

New Theory Prediction Pipeline



- We're about to develop a new pipeline for theory predictions around `PineAPPL` [arXiv:2008.12789]
- both, `EKO` and `yadism`, are interfaced with `PineAPPL`
- `PineAPPL` also has interfaces to `mg5amc@nlo`, `APPLgrid`, `FastNLO`

Goal produce `FastKernel` tables used in PDF fitting

Summary

Summary: theory

I hope you enjoyed the effort of converting words in pictures. But now is the time of a few words...

- **computing expressions** *is not the end of the story*
- Monte Carlo generators and other providers (e.g. `yadism`) are *essential*
  - but **not enough** for a PDF-like fit (including α_s)
- predictions have to be agnostic to the fitted object, to avoid recomputation → we need interpolation grids note that **interpolation here is not a compromise**, since unknown functions like PDFs are **defined through** interpolation
- `PineAPPL` is such a format, providing extensive tooling and bindings
- interfacing is **crucial**: developing all this software is *expensive*, so the community can not pay the price of doing it over and over → tools have to become **modular** and **interoperable**
- file-**base exchange**, with clear specification of data format helps a lot
  - preferably based on *wide-spread and supported* ***data serialization formats***, e.g. `JSON` or `hdf5`, in order to make them usable by as many programs (and programming languages) as possible in the cheapest way
  - `LHAPDF` is a good example

Summary: our tools

Why should one use:

`EKO`? because:

- it produces “out of the box” **operators**
- the operators can be immediately used **together with grids**
- it joins advantages of ***x* and *N* space**
- it is getting more and **more physics features** (intrinsic, backward VFNS, QED, N^{3}LO)

`yadism`? because:

- direct production **DIS grids**
- extensive (and extended) database of **coefficient functions**
- thorough implementation of **FNS** (and more...)

Pipeline? because:

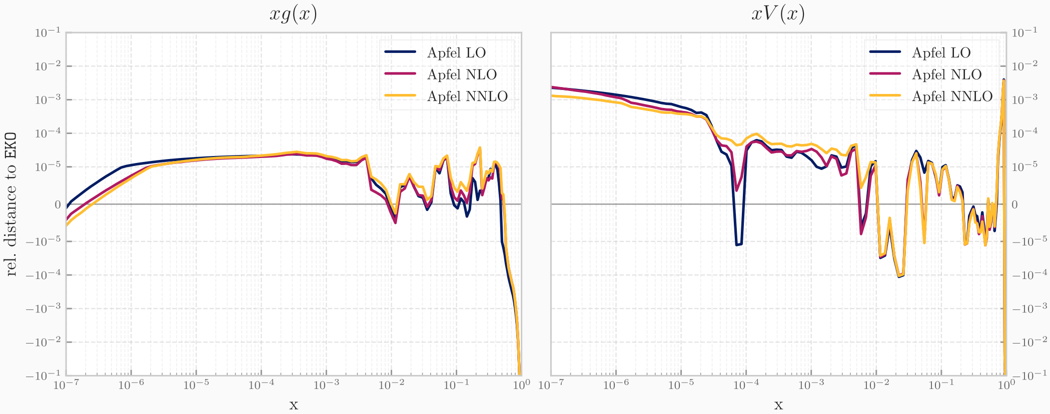
- it makes **easy, flexible, and reproducible**
- to produce **performant theory** predictions for PDF fitting

Intrinsic charm itself is a *joint* product of `EKO` and `NNPDF4.0` efforts.

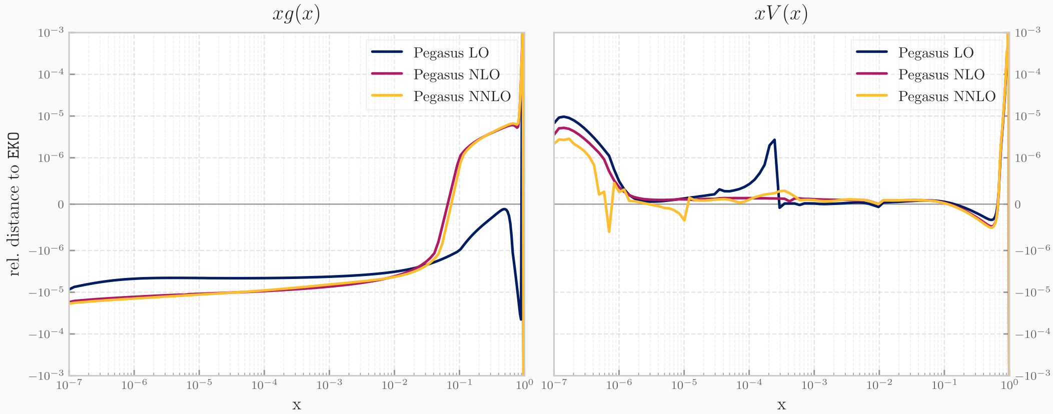
Thank you for listening!

EKO

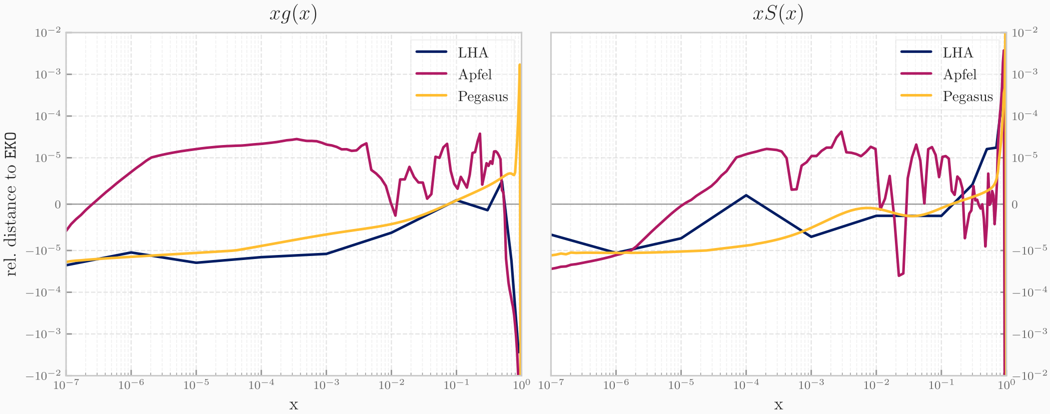
EKO APFEL BENCHMARK



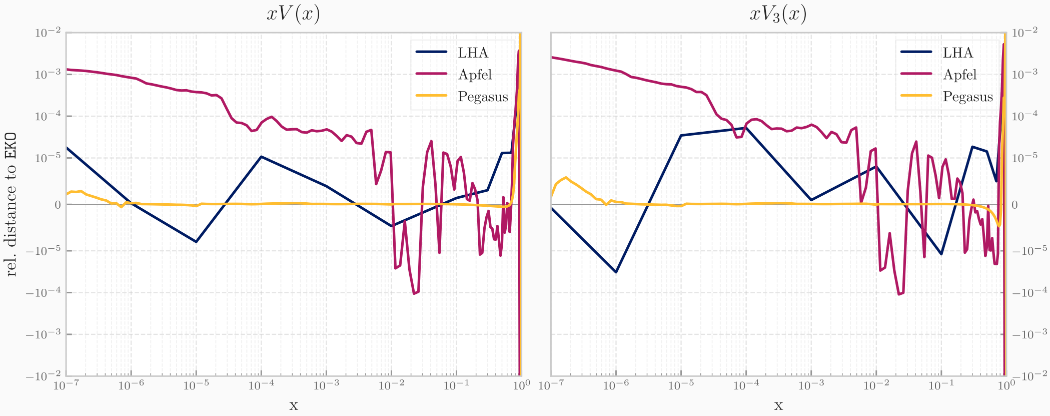
EKO PEGASUS BENCHMARK



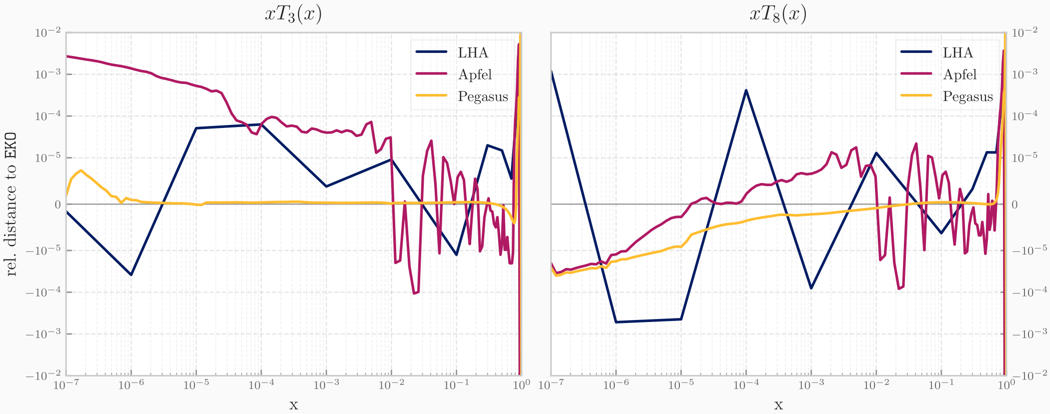
EKO LHA BENCHMARK: g AND Σ



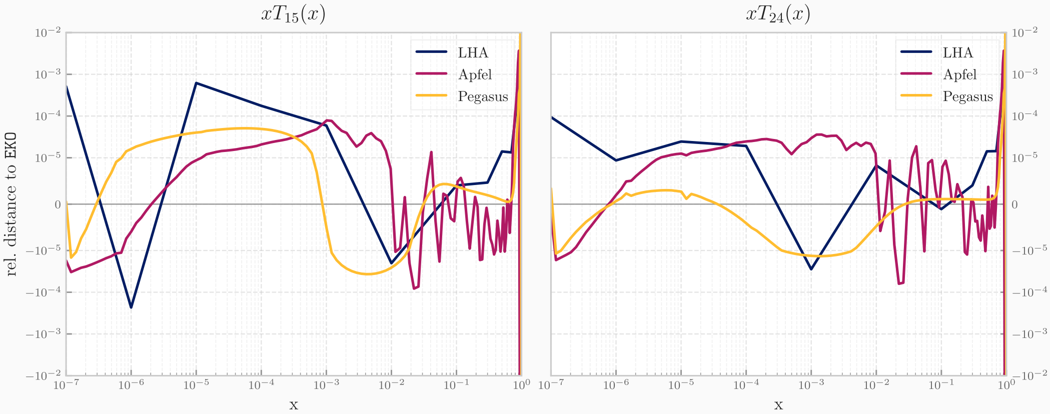
EKO LHA BENCHMARK: V AND V_3



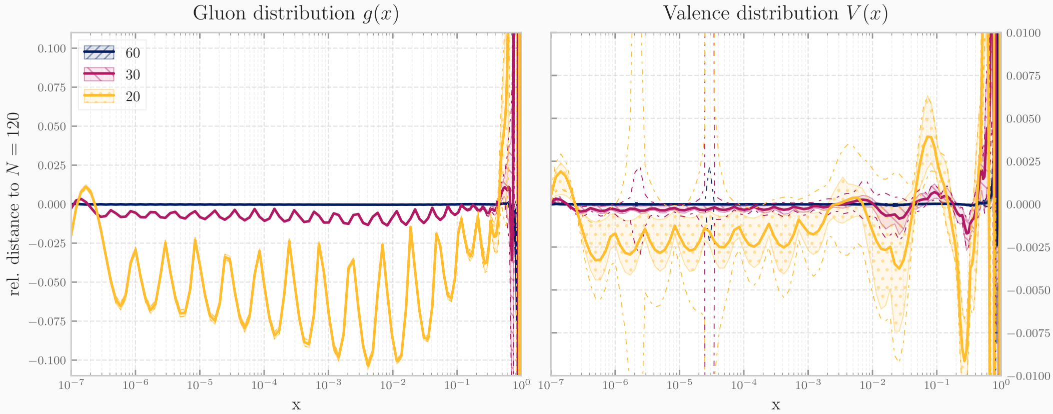
EKO LHA BENCHMARK: T_3 AND T_8



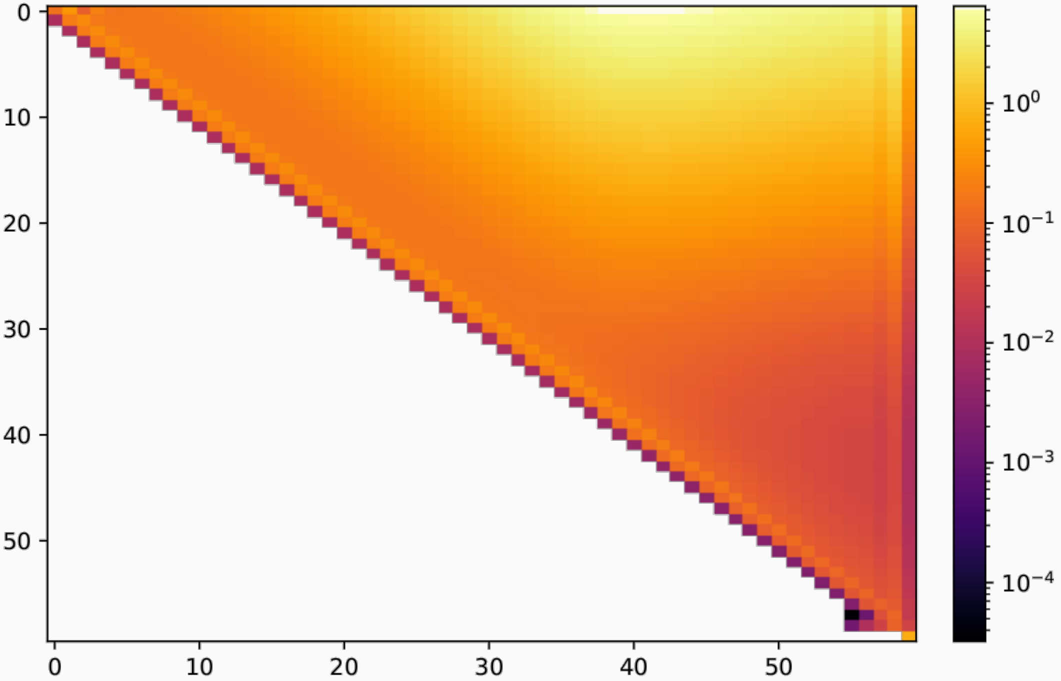
EKO LHA BENCHMARK: T_{15} AND T_{24}



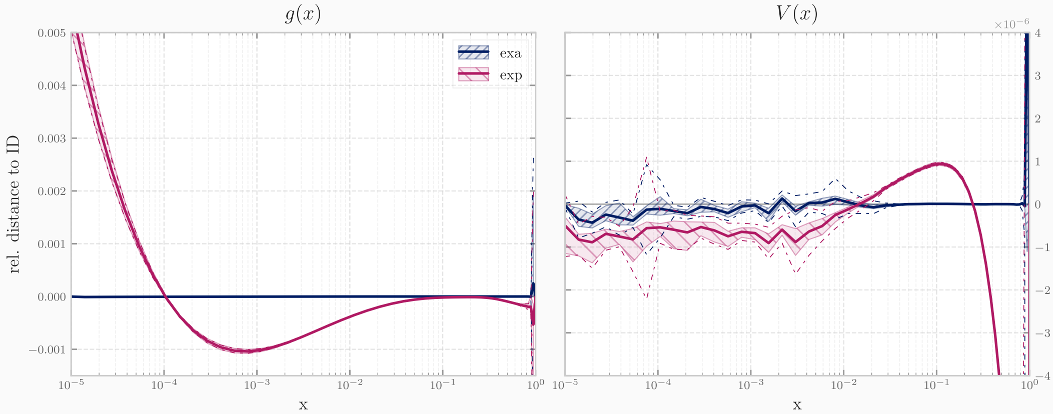
EKO Interpolation Error



EKO Snapshot $V \leftarrow V$

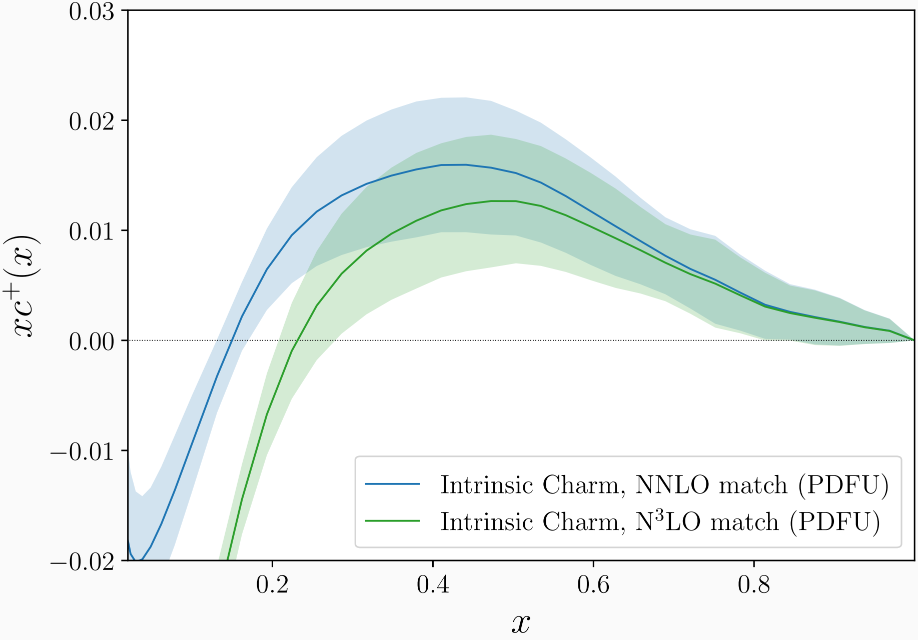


EKO Backward Evolution



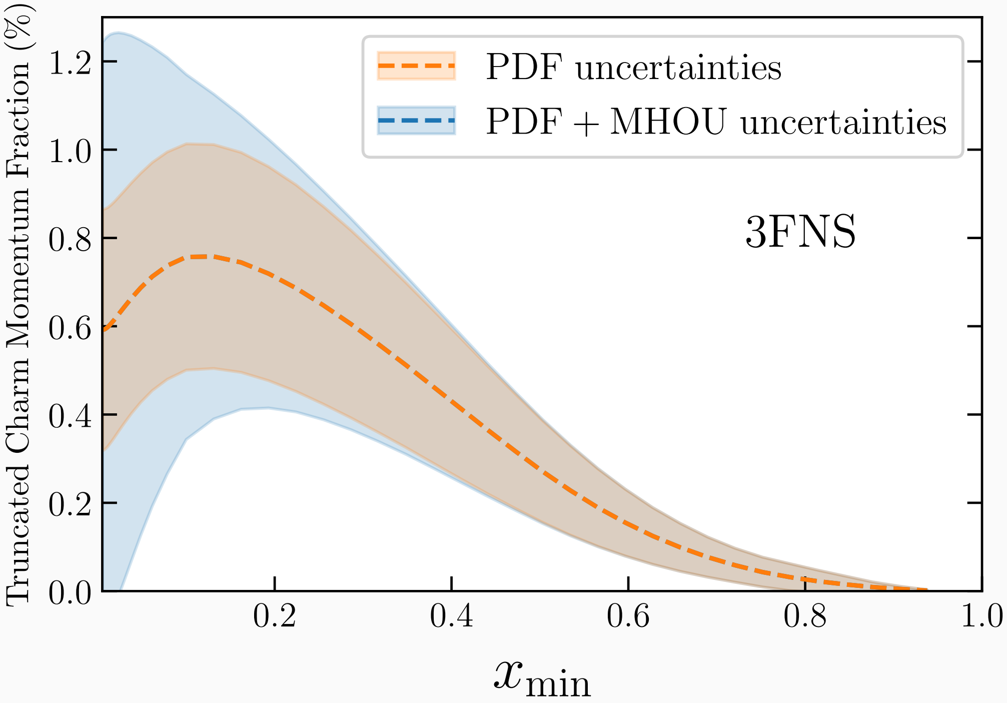
Intrinsic Charm

IC - MATCHING PERTURBATIVE ORDER

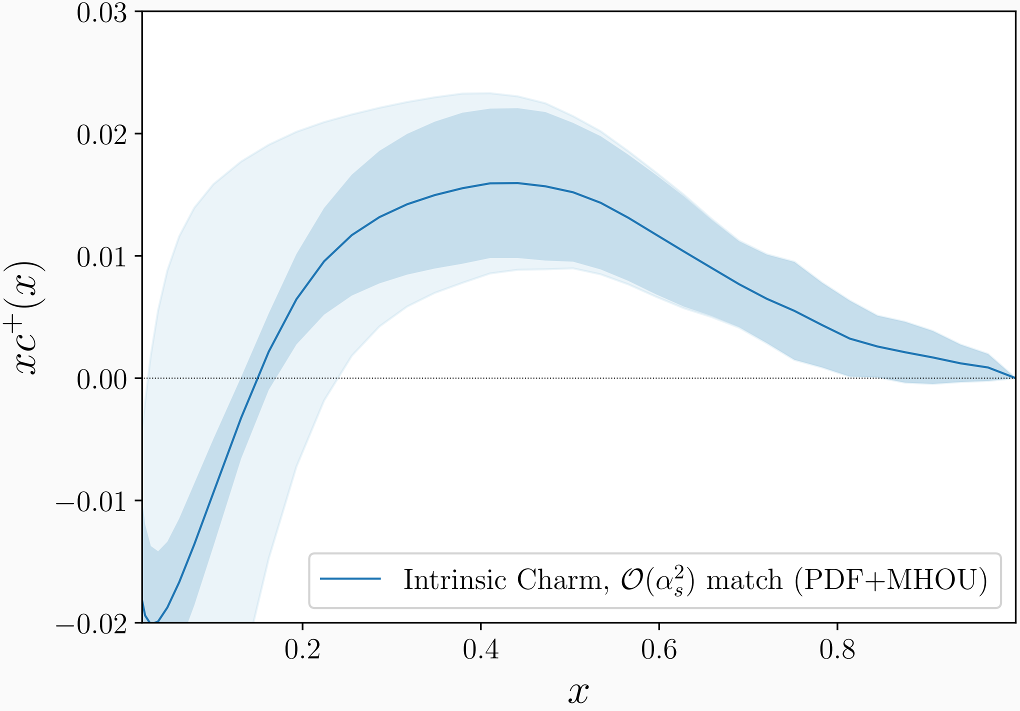


3FNS comparison – NNLO matching vs N^{3}LO

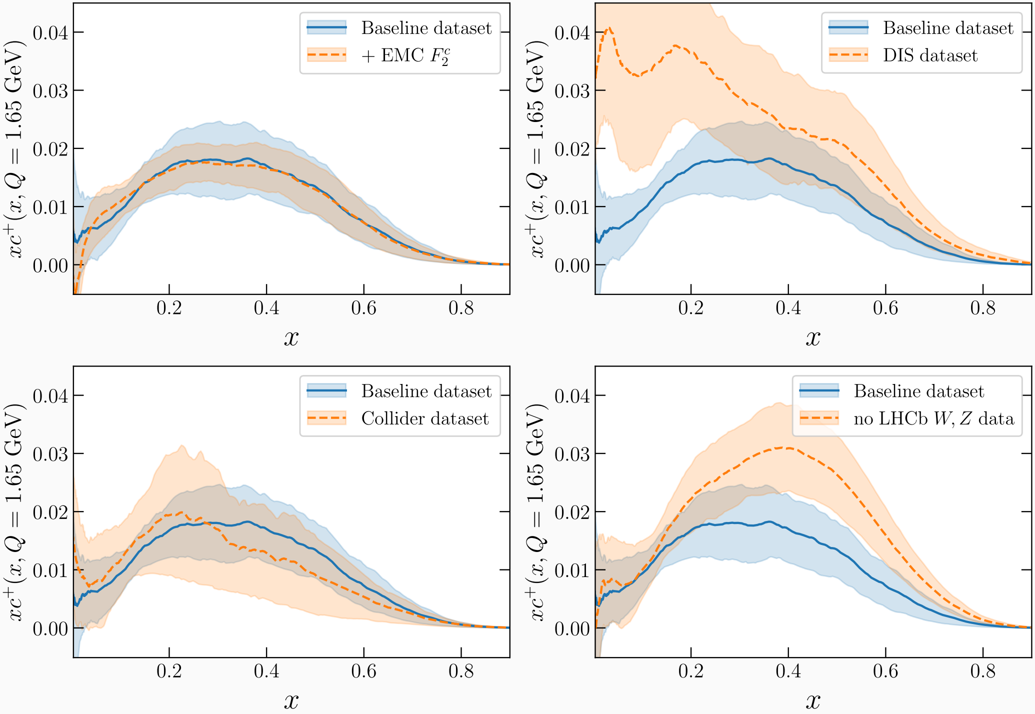
IC - truncated momentum fraction



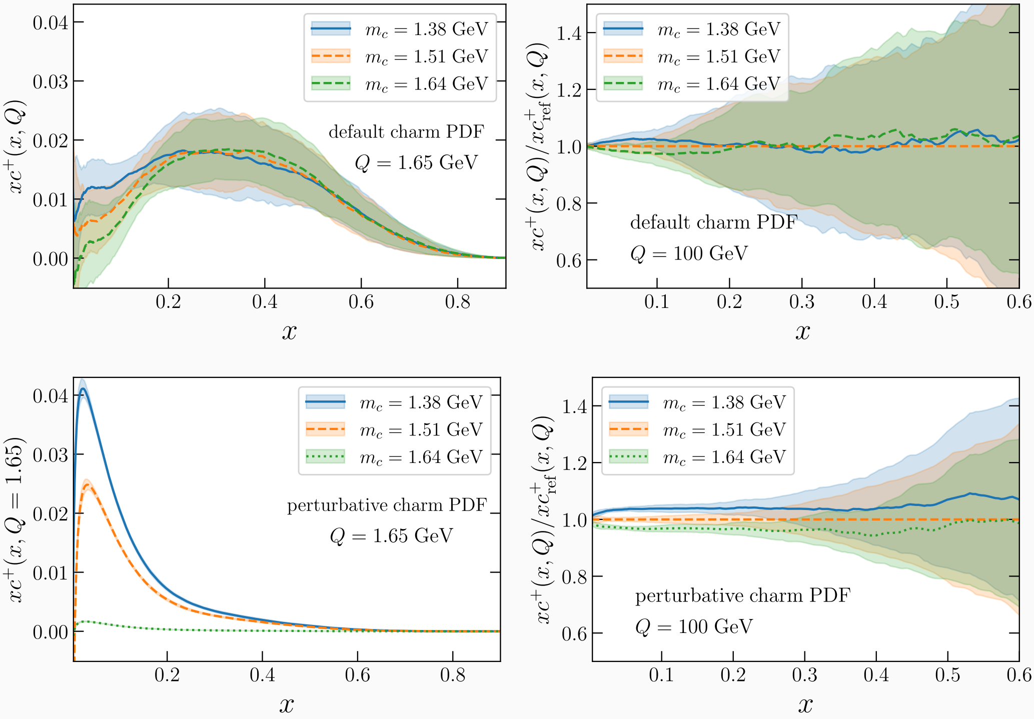
IC - all uncertainties combined



IC - DATASET VARIATION

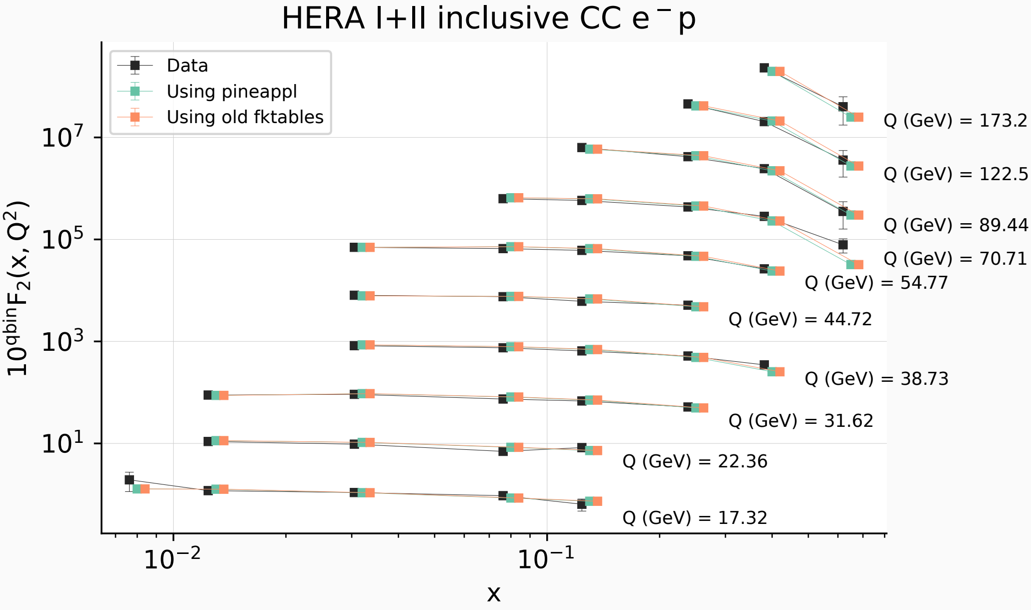


IC - MASS VARIATION

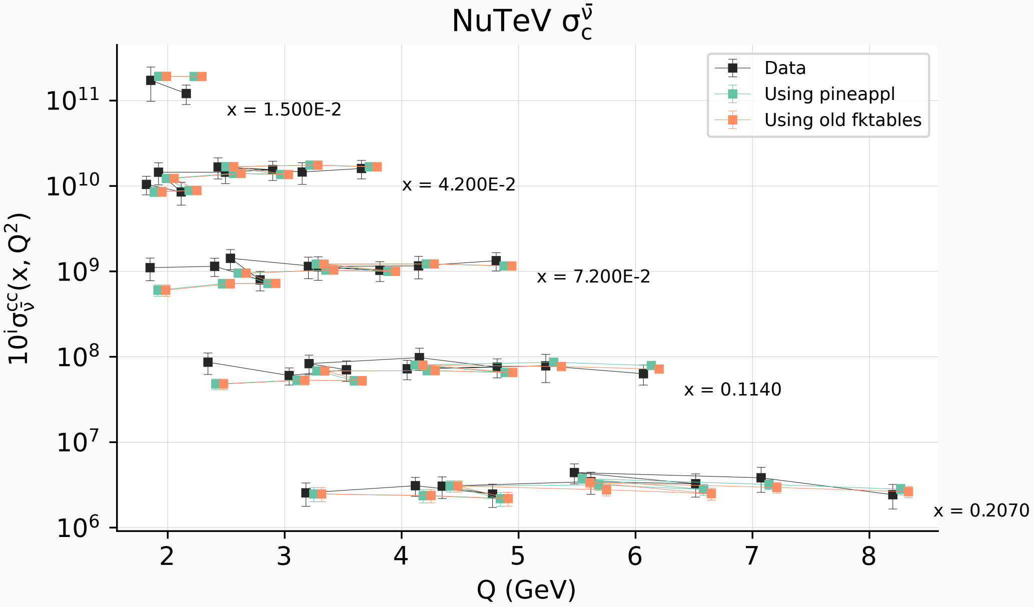


yadism

Comparison `yadism` against APFEL



COMPARISON yadism AGAINST APFEL


NuTeV $\sigma_c^{\bar{\nu}}$
$10^i \sigma_{\bar{\nu}}^{cc}(x, Q^2)$
10^{11}
10^{10}
10^{9}
10^{8}
10^{7}
10^{6}
Q (GeV)
x = 1.500E-2
x = 4.200E-2
x = 7.200E-2
x = 0.1140
x = 0.2070
Data
Using pineappl
Using old fktables