INFN Istituto Nazionale di Fisica Nucleare
UNIVERSITÀ DEGLI STUDI DI MILANO

EKO Evolution Kernel Operators & Yadism Yet Another DIS Module

New Software Tools for DGLAP and DIS

Alessandro Candido, Felix Hekhorn, Giacomo Magni

DIS 2022, Santiago di Compostela, May 2022

Acknowledgement: This project has received funding from the European Unions Horizon 2020 research and innovation programme under grant agreement number 740006.

NNPDF N3PDF Machine Learning • PDFs • QCD erc

Outline

1. `EKO` [arXiv: 2202.02338]
2. Intrinsic Charm in the Proton [submitted]
3. `yadism` [in preparation]
4. Theory Prediction Pipeline

1. EKO [arXiv: 2202.02338]

EKO Definition

EKO
Evolution Kernel Operators

DGLAP:

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

as operator equation for the evolution kernel operator (EKO) **E**:

$$\mu_F^2 \frac{\mathrm{d}}{\mathrm{d}\mu_F^2}\mathbf{E}(\mu_F^2 \leftarrow \mu_{F,0}^2) = \mathbf{P}(a_s(\mu_R^2), \mu_F^2) \otimes \mathbf{E}(\mu_F^2 \leftarrow \mu_{F,0}^2)$$

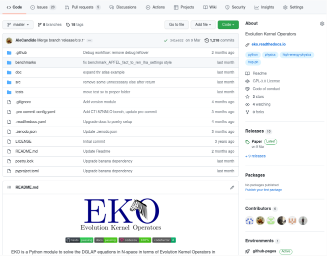
with

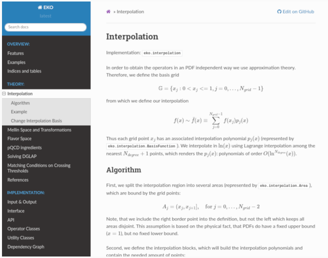
$$\mathbf{f}(\mu_F^2) = \mathbf{E}(\mu_F^2 \leftarrow \mu_{F,0}^2) \otimes \mathbf{f}(\mu_{F,0}^2)$$

EKO Physics Features

- independent of boundary condition $\rightarrow$ PDF fitting
- Mellin (N-) space solution, but momentum (x-) space delivery via piecewise Lagrange-interpolation
- Intrinsic heavy quark distributions $\rightarrow$ see part 2
- Backward VFNS evolution (i.e. across thresholds and with intrinsic) $\rightarrow$ see part 2

EKO Project Management

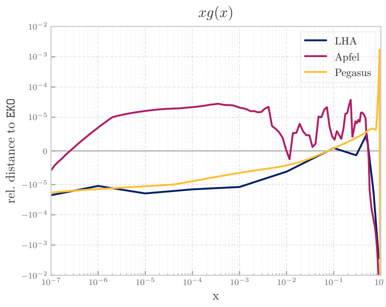


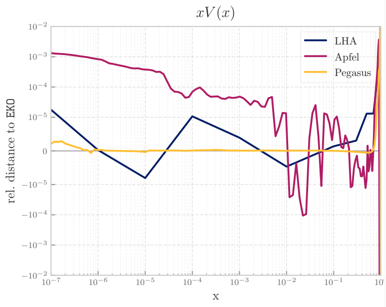


- Fully open source: `https://github.com/N3PDF/eko`
- Written in Python
- Fully documented: `https://eko.readthedocs.io/`
- A cornerstone in a new theory prediction suite $\to$ see part 4

EKO Benchmarks

LHA benchmark [G+02][D+05]:

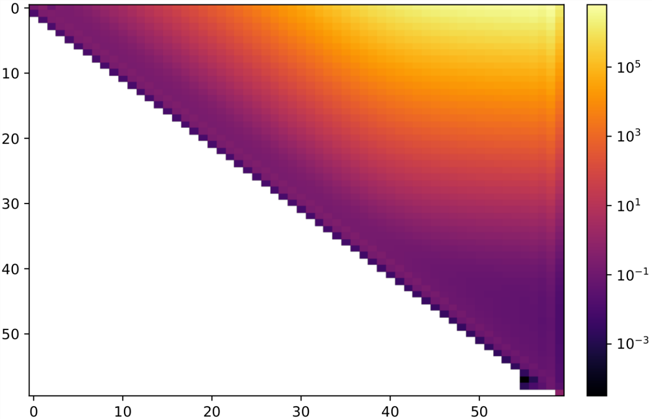




⇒ EKO is working!

EKO Snapshot: $\Sigma \leftarrow \Sigma$

FFNS LO LHA settings: $\Sigma(Q^2 = 10^4\,\mathrm{GeV}^2) \leftarrow \Sigma(Q^2 = 2\,\mathrm{GeV}^2)$



xgrid: $10^{-7}(0) \quad \rightarrow \quad \log \quad \rightarrow \quad \text{lin} \quad \rightarrow \quad 1(59)$,

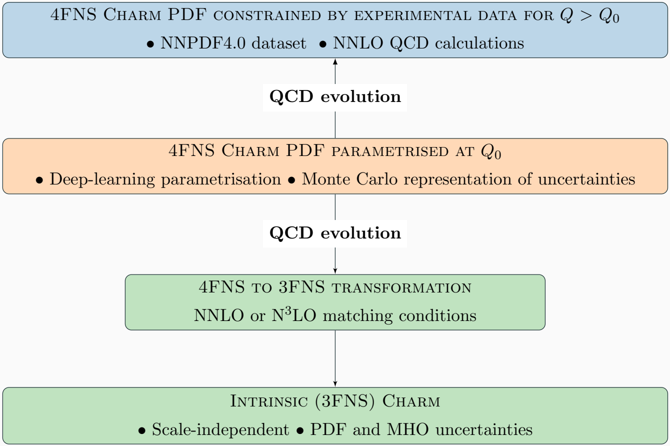
axis: $x \sim$ input $(2\,\mathrm{GeV}^2)$, $y \sim$ output $(10^4\,\mathrm{GeV}^2)$

2. Intrinsic Charm in the Proton

[submitted]

Intrinsic Charm: Strategy

- see poster by G. Magni
- based on NNPDF4.0 [arxiv:2109.02653] - see talk by R. Stegeman



Matching Conditions and Backward Evolution

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

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

with $\mathbf{R}^{(n_f)}$ a flavor rotation matrix and $\tilde{\mathbf{A}}^{(n_f)}(\mu_h^2)$ the operator matrix elements (partially known up to N^{3}LO)

Matching Conditions and Backward Evolution

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

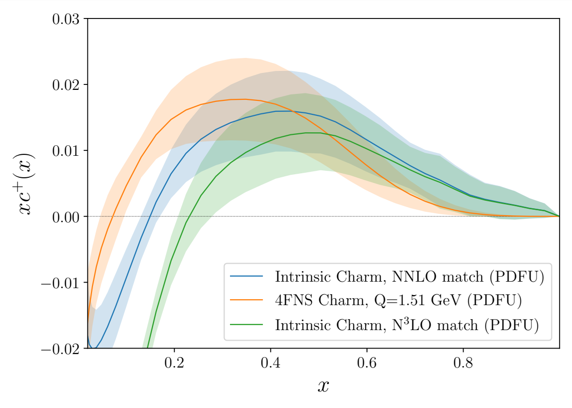
$$\tilde{\mathbf{f}}^{(n_f+1)}(\mu_{F,1}^2) = \tilde{\mathbf{E}}^{(n_f+1)}(\mu_{F,1}^2 \leftarrow \mu_h^2)\mathbf{R}^{(n_f)}\tilde{\mathbf{A}}^{(n_f)}(\mu_h^2)\tilde{\mathbf{E}}^{(n_f)}(\mu_h^2 \leftarrow \mu_{F,0}^2) \times \tilde{\mathbf{f}}^{(n_f)}(\mu_{F,0}^2)$$

with $\mathbf{R}^{(n_f)}$ a flavor rotation matrix and $\tilde{\mathbf{A}}^{(n_f)}(\mu_h^2)$ the operator matrix elements (partially known up to N^{3}LO)

for backward evolution:

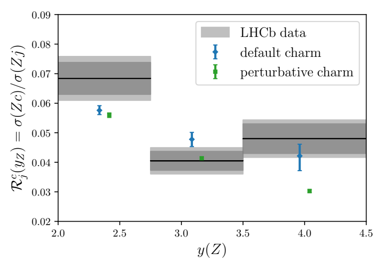
- invert $\tilde{\mathbf{E}}^{(n_f)}$: simple
- invert $\mathbf{R}^{(n_f)}$: simple
- invert $\tilde{\mathbf{A}}^{(n_f)}$: expanded or exact

Intrinsic Charm: PDF plot



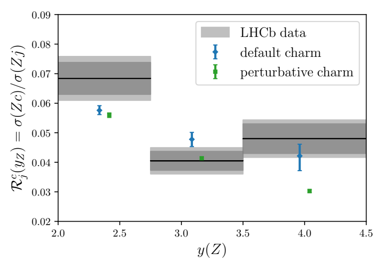
- in **3FNS** valence-like peak is still present
- for $x \leq 0.2$ the perturbative uncertainties are quite large
- the carried momentum fraction is within **1%**

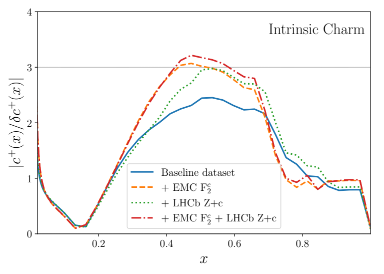
Intrinsic Charm: LHCb and Significance



- match better recent **LHCb** Z+c measurement [PRL128-082001]

Intrinsic Charm: LHCb and Significance





- match better recent **LHCb** Z+c measurement [PRL128-082001]
- we find a **3σ** evidence of intrinsic charm
- result is **stable** with mass variation, dataset variation

3. `yadism` [in preparation]

yadism Physics Features

Yadism

Yet Another DIS Module

- DIS coefficient function database
- independent of boundary condition → PDF fitting
- separate features: TMC, FNS, interpolation
- constant benchmark against APFEL (eventually discovering minor bugs there)

same improvement in terms of project management as EKO!

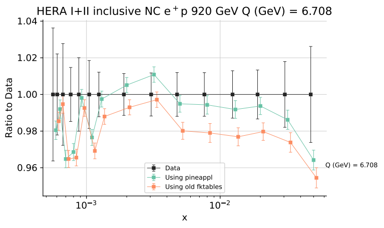
Coefficient Functions

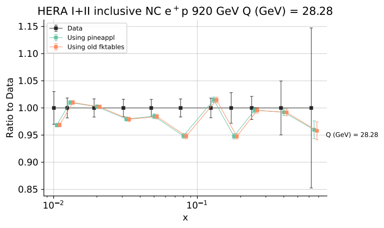
- implemented coefficient functions:

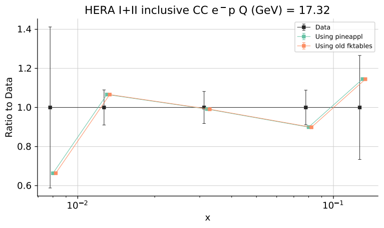
	light	heavy	intrinsic
NC	$O(a_s^2)$ [VVM05,MVV05,MV00]	$O(a_s^2)$ [Hek19]	$O(a_s)$ [KS98]
CC	$O(a_s^2)$ [MRV08,MVV09]	$O(a_s)$ [GKR96]	$O(a_s)$ [in prep.]

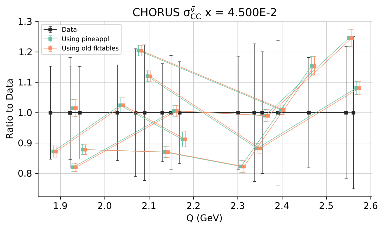
- for CC intrinsic: see talk by K. Kudashkin
- implemented flavor number schemes: FFNS, ZM-VFNS, FONLL

Comparison yadism against APFEL









green, "pineappl" = yadism vs. orange, "old" = APFEL

4. Theory Prediction Pipeline

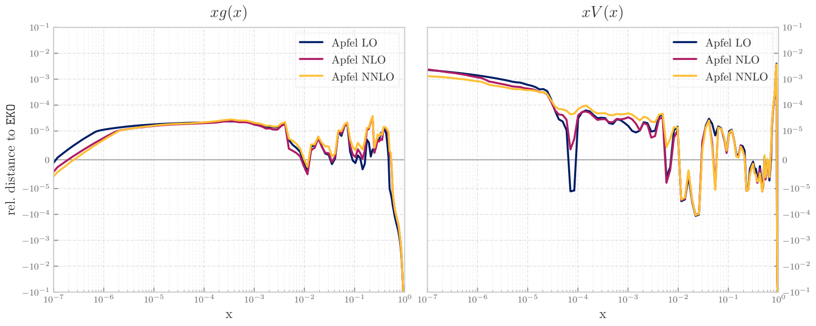
New Theory Prediction Pipeline

- 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
- aim: produce FastKernel tables used in PDF fitting

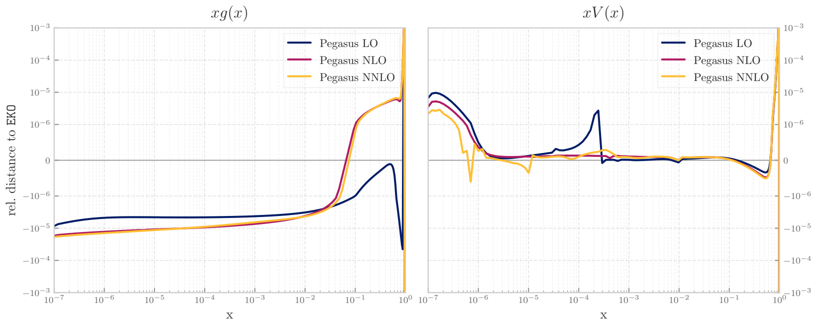
Thank you!

5. Backup slides

EKO APFEL benchmark



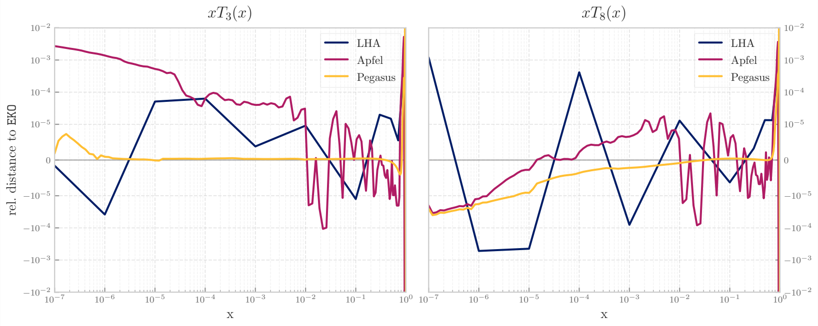
EKO PEGASUS benchmark



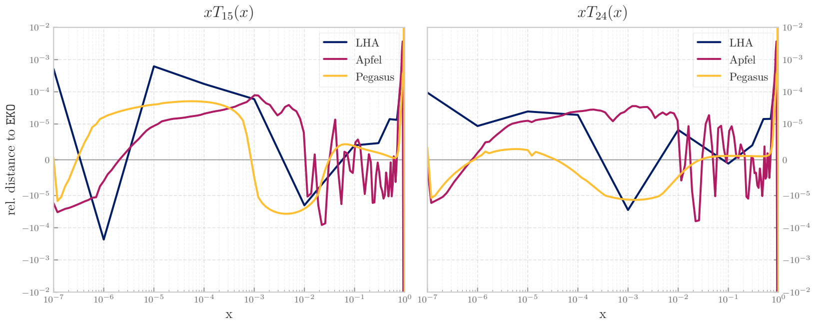
EKO LHA benchmark: g and Σ

EKO LHA **benchmark:** V **and** V_3

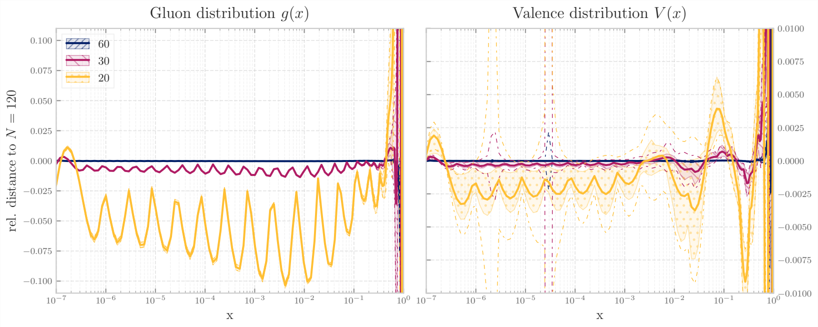
EKO LHA benchmark: T_3 and T_8



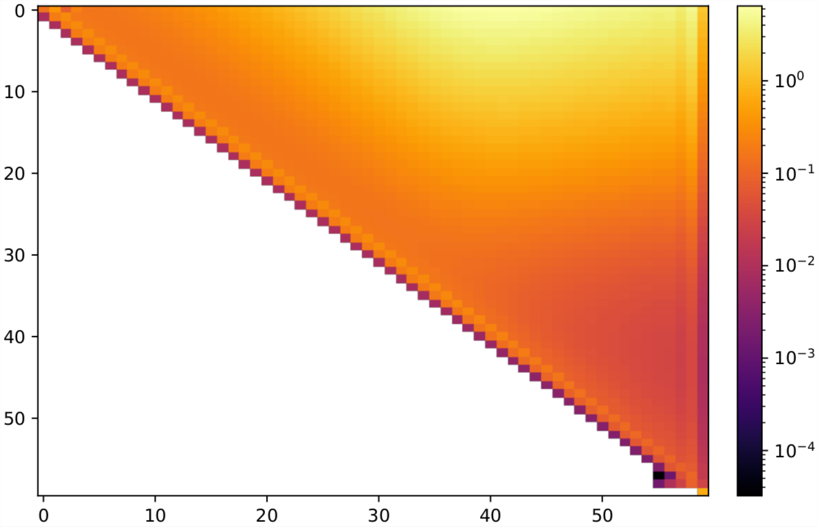
EKO LHA benchmark: T_{15} and T_{24}



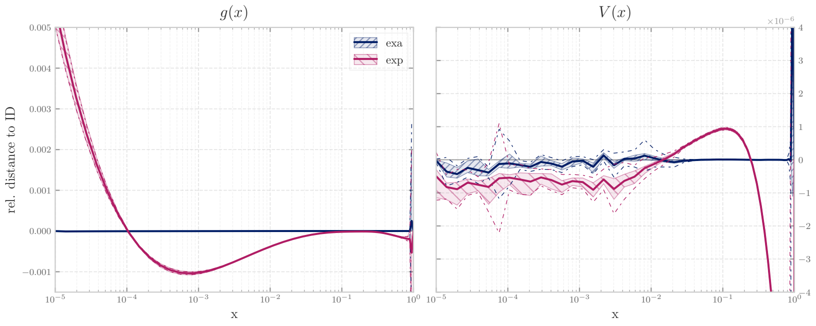
EKO Interpolation Error



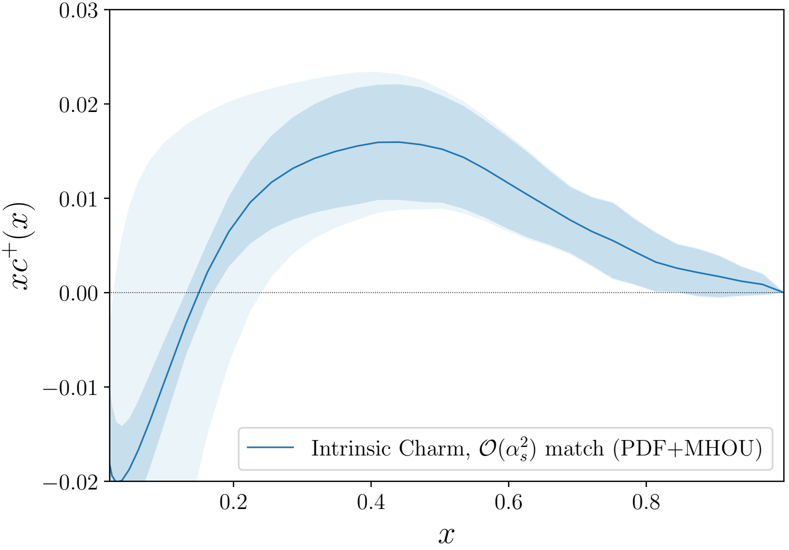
EKO Snapshot $V \leftarrow V$



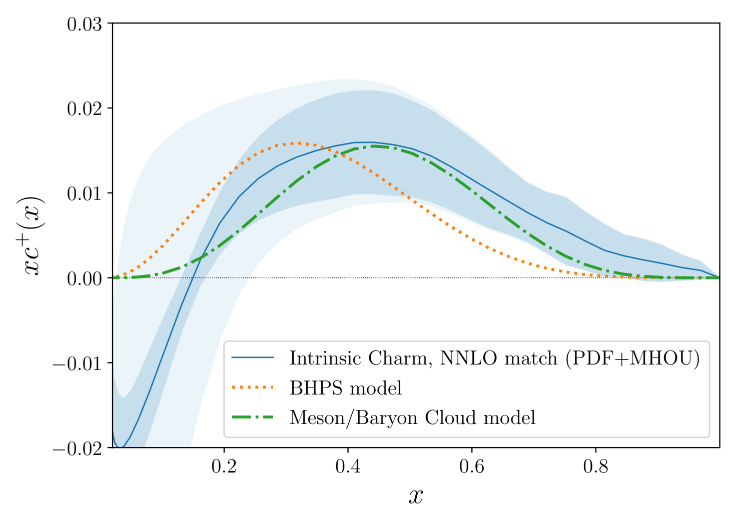
EKO Backward Evolution



IC - all uncertainties combined

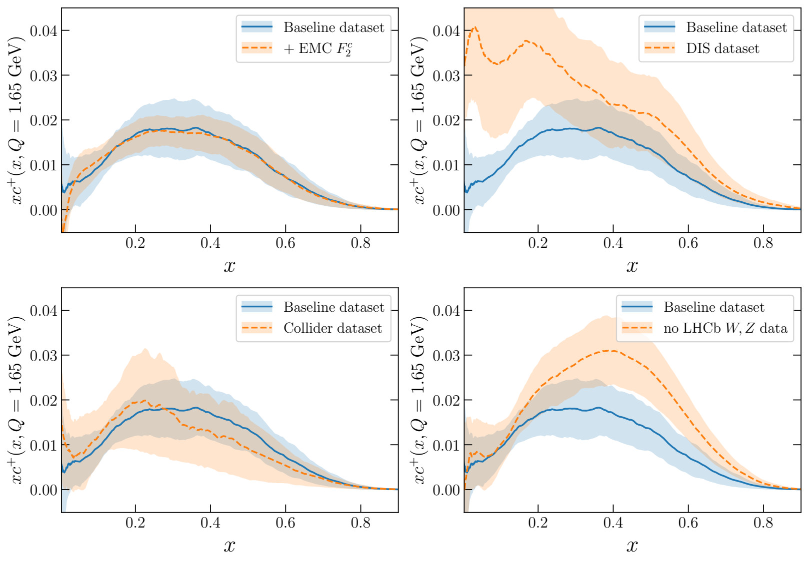


IC - model comparison

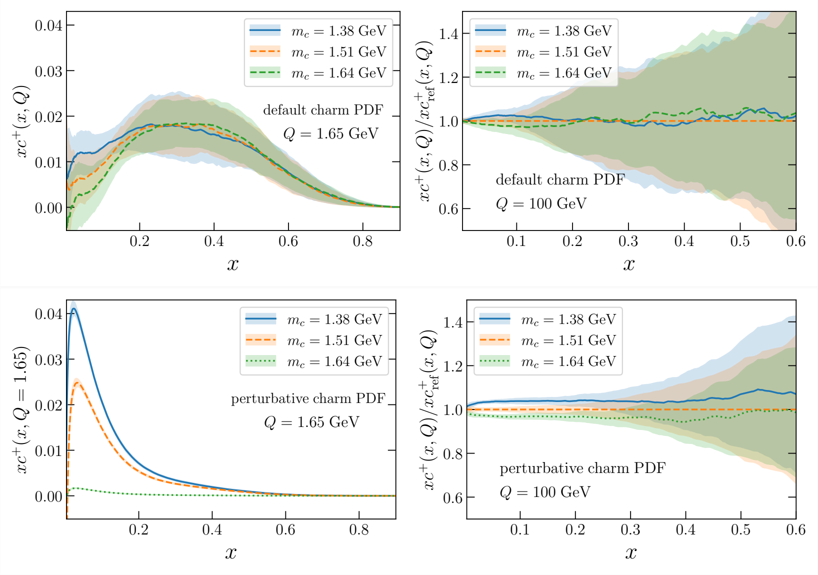


[BHPS] or [Meson/Baryon Cloud Model]

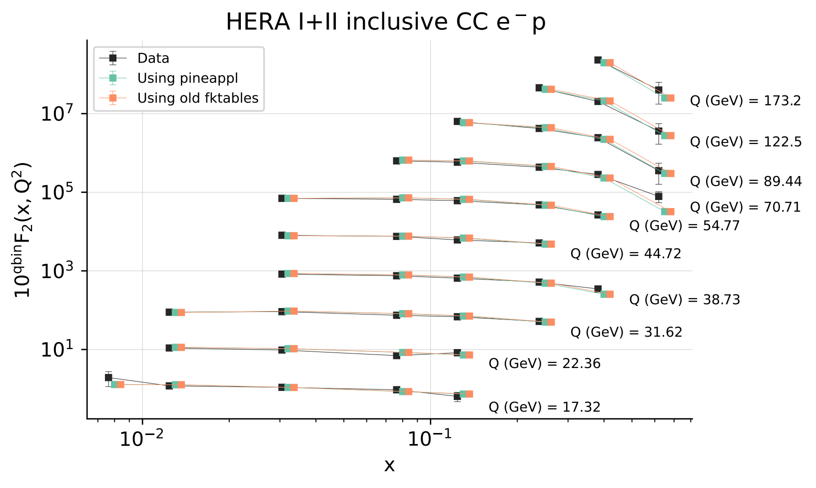
IC - dataset variation



IC - mass variation



Comparison yadism against APFEL



Comparison yadism against APFEL