Theory Predictions in PDF Fitting

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

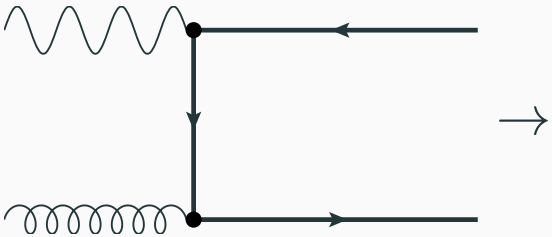
Outline

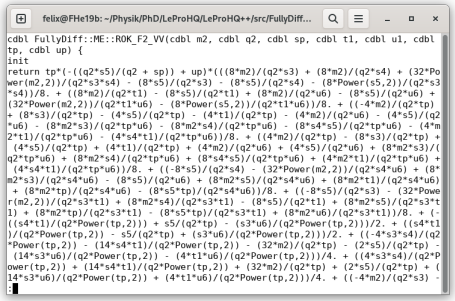
1. Motivation
2. `PineAPPL` [JHEP12.108]
3. `EKO` [2202.02338]
4. Evidence for Intrinsic Charm in the Proton [in print]
5. `yadism` [in preparation]
6. Outlook

1. Motivation

Including New Computation

- Computing new observables is expensive both in runtime (days/weeks) and development time (month/years)
- E.g. NLO heavy quark production in polarized DIS [PRD98.014018] [1910.01536] [PRD104.016033]

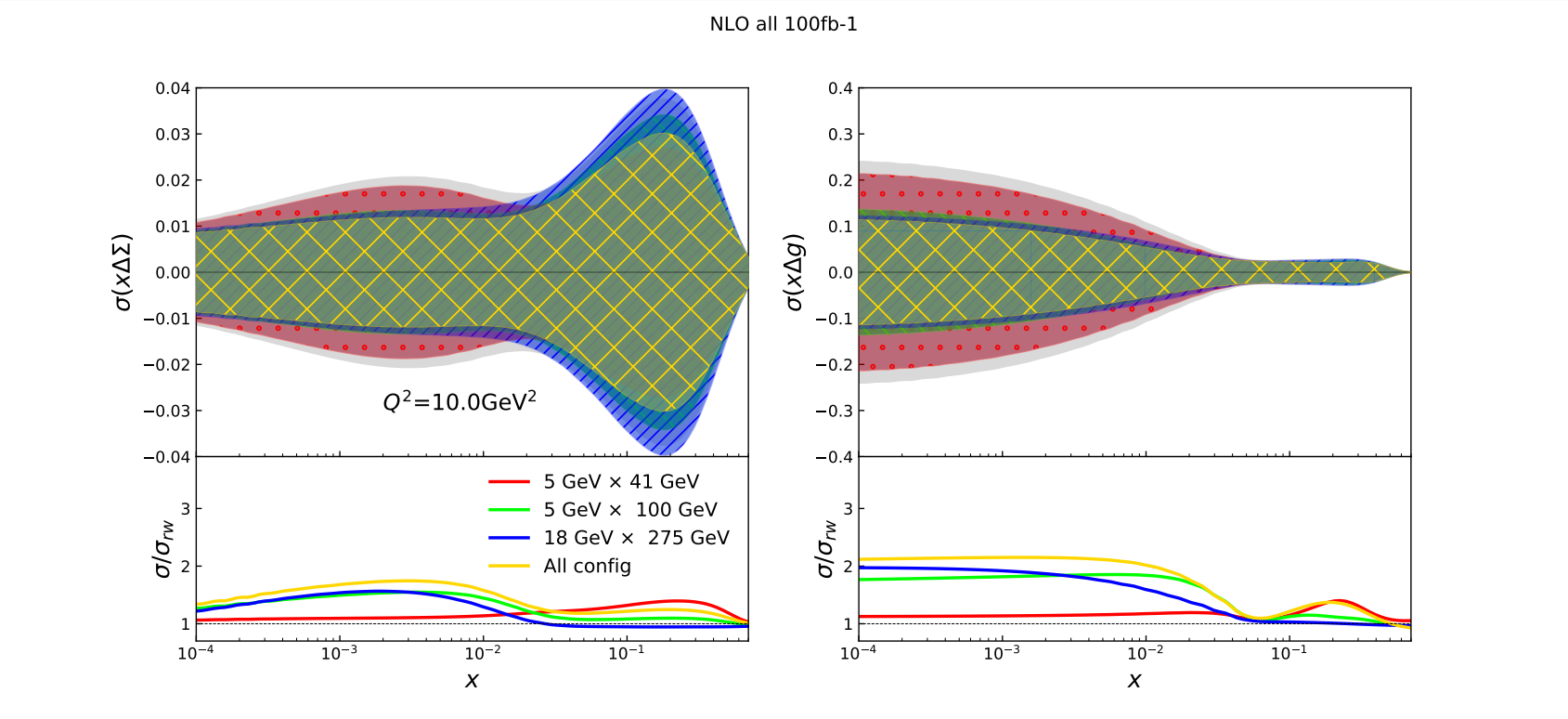




- How to measure the actual impact on PDFs?

Reweighting

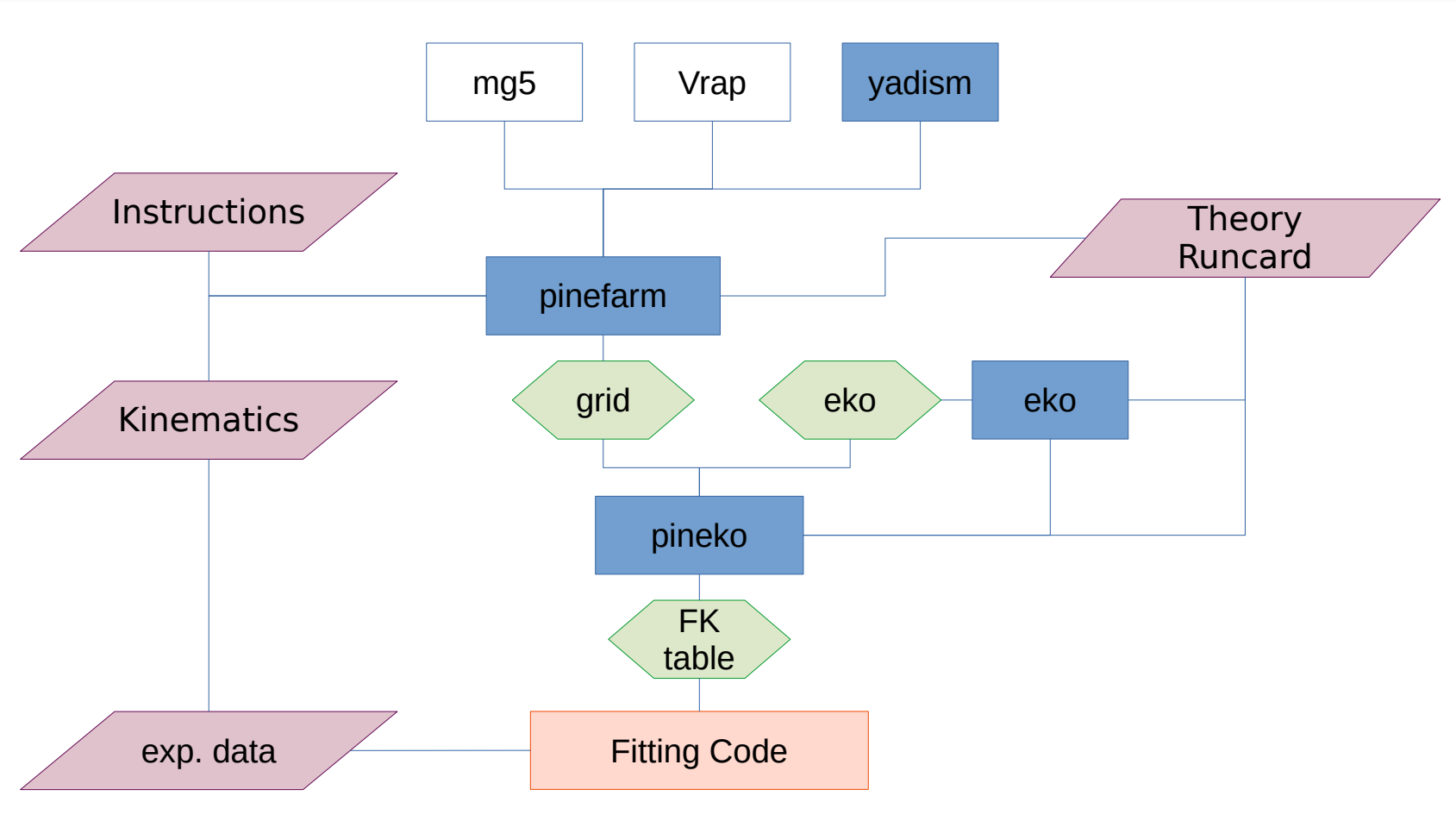
Reweighting is possible [PRD104.114039] - and even needed for the EIC



but a new PDF fit would be better!

New Theory Prediction Pipeline

Produce FastKernel (FK) tables!



The workhorse in the background: PineAPPL

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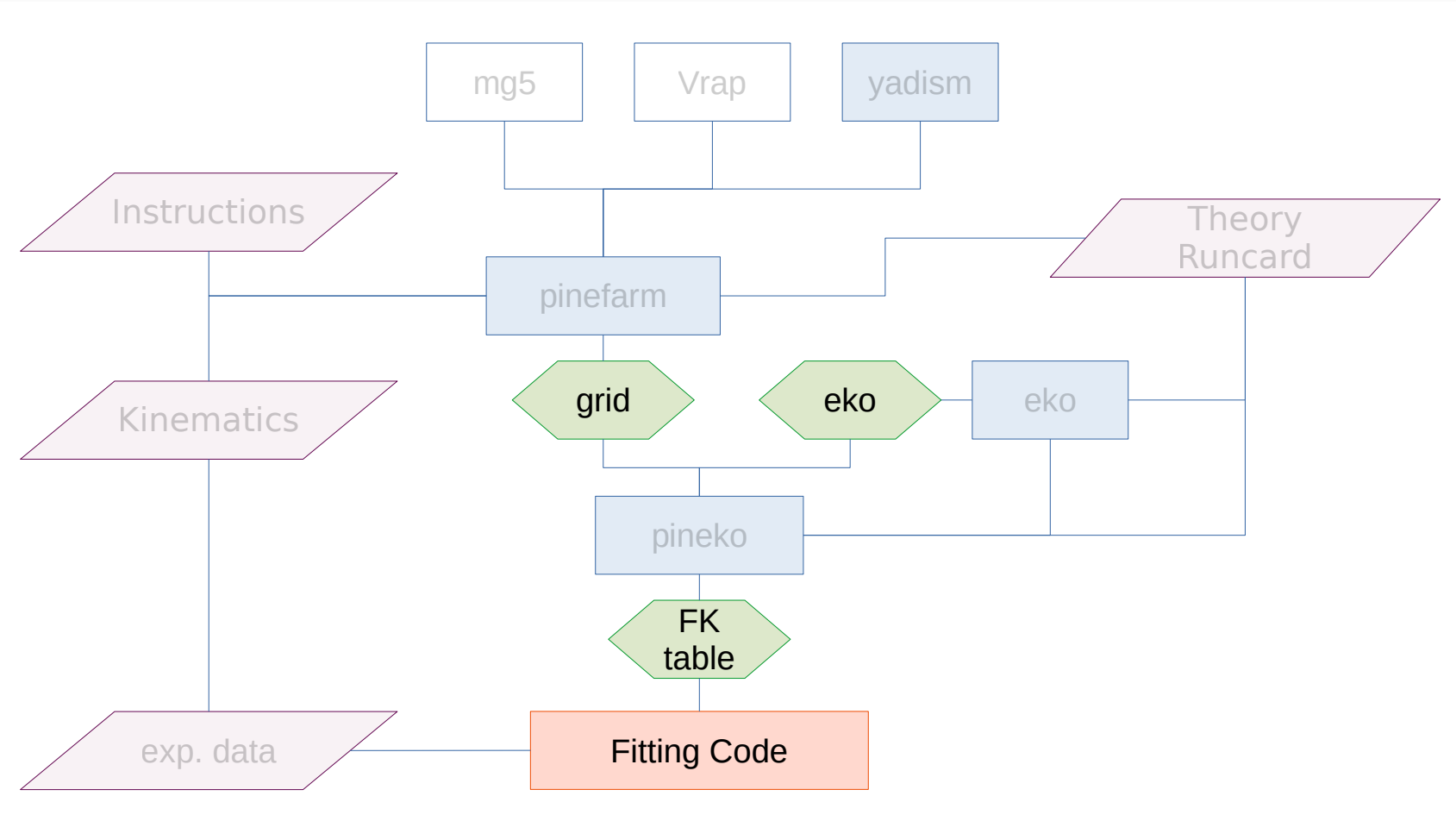

The workhorse in the background: PineAPPL

New Theory Prediction Pipeline

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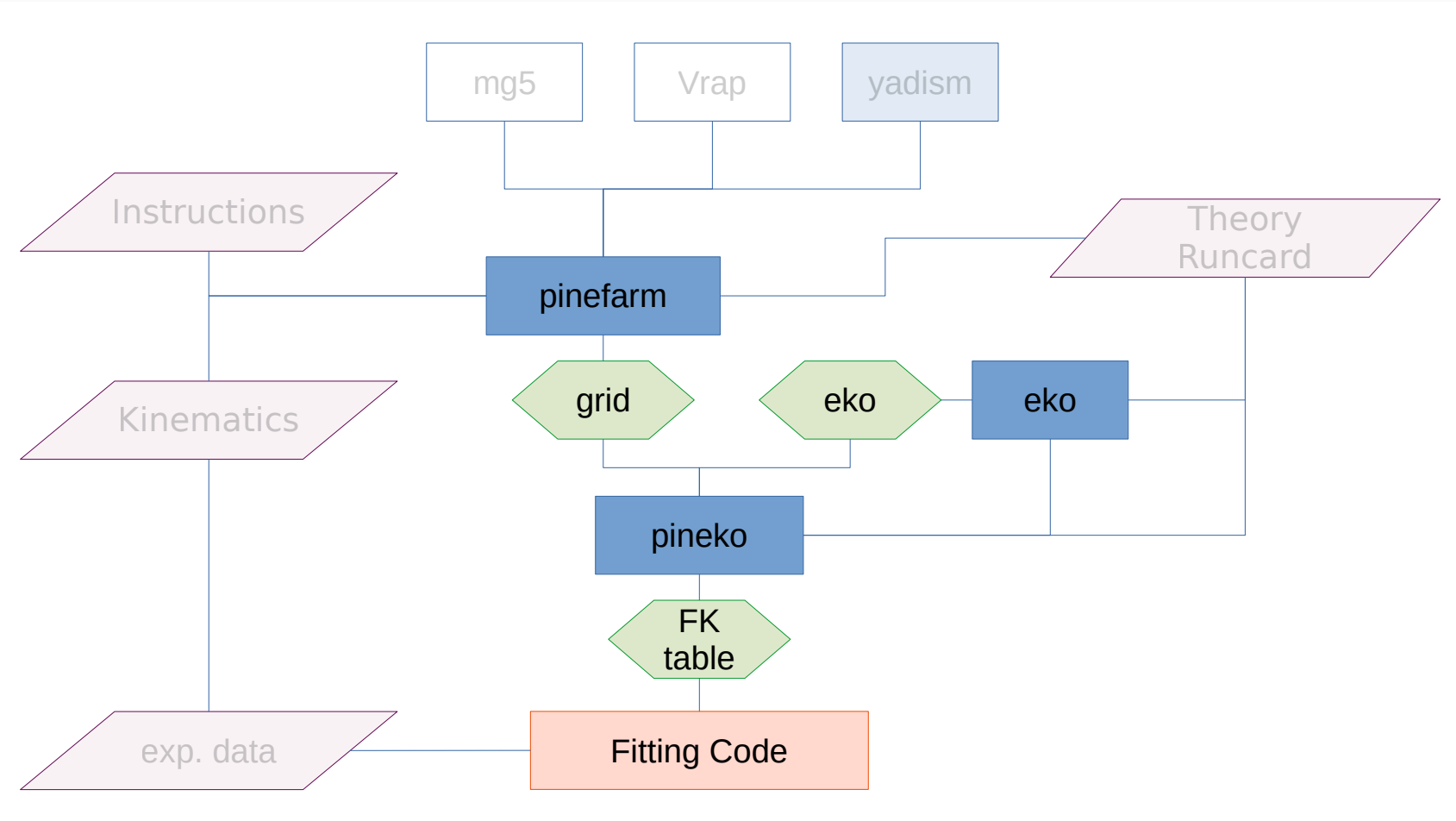

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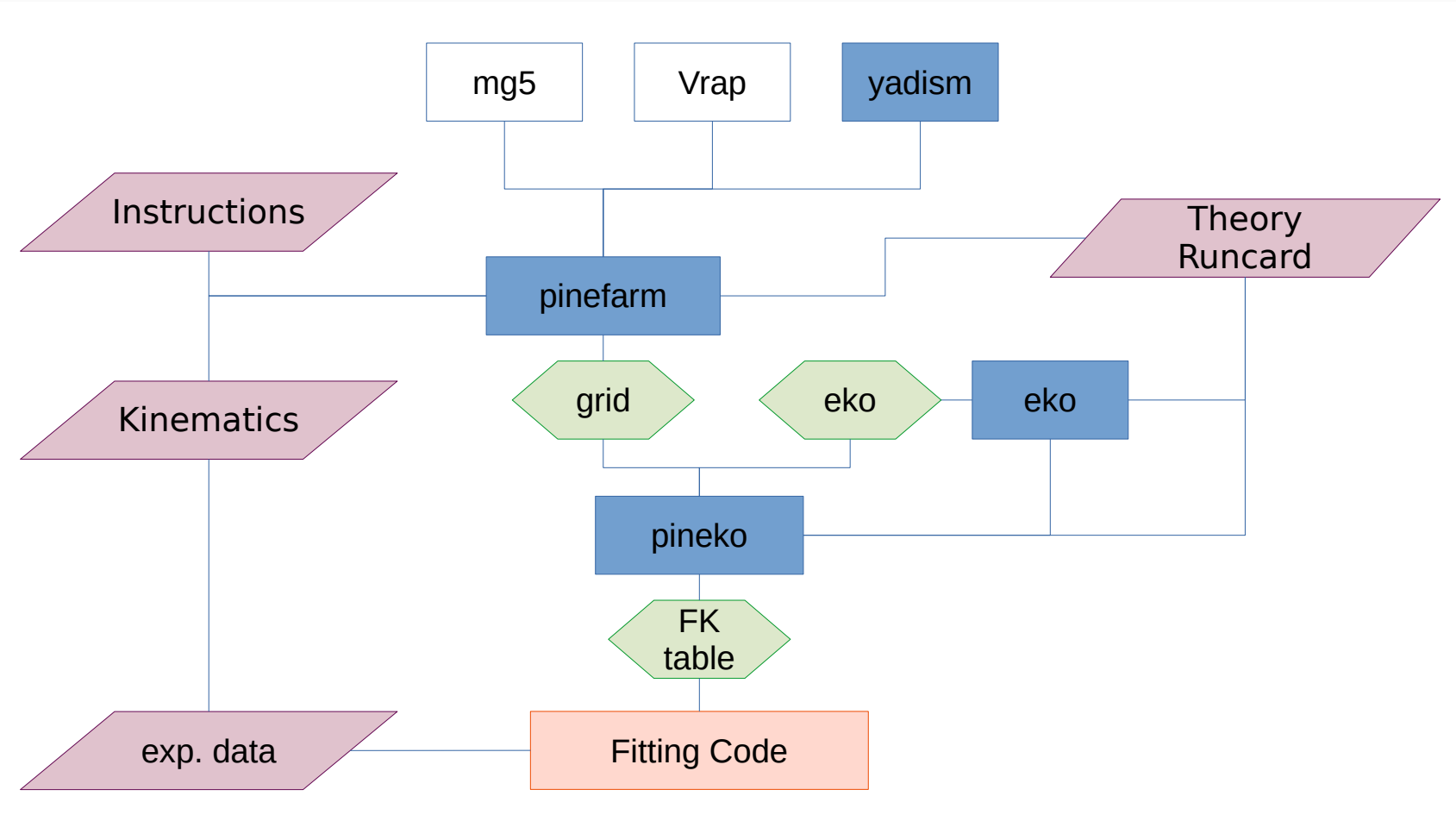


The workhorse in the background: PineAPPL

2. PineAPPL [JHEP12.108]

About PineAPPL

PineAPPL is a fast interpolation grid library that

- extends to arbitrary orders in QCD and EW coupling
- provides a very good CLI
- provides several interfaces: Rust, Python, C/C++, Fortran
- can convert APPLgrid [EPJC66.503] and FastNLO [DIS12.217]

Check the documentation: `https://n3pdf.github.io/pineappl/`

The Command Line Interface

The CLI (`pineappl`) serves for the everyday life questions:

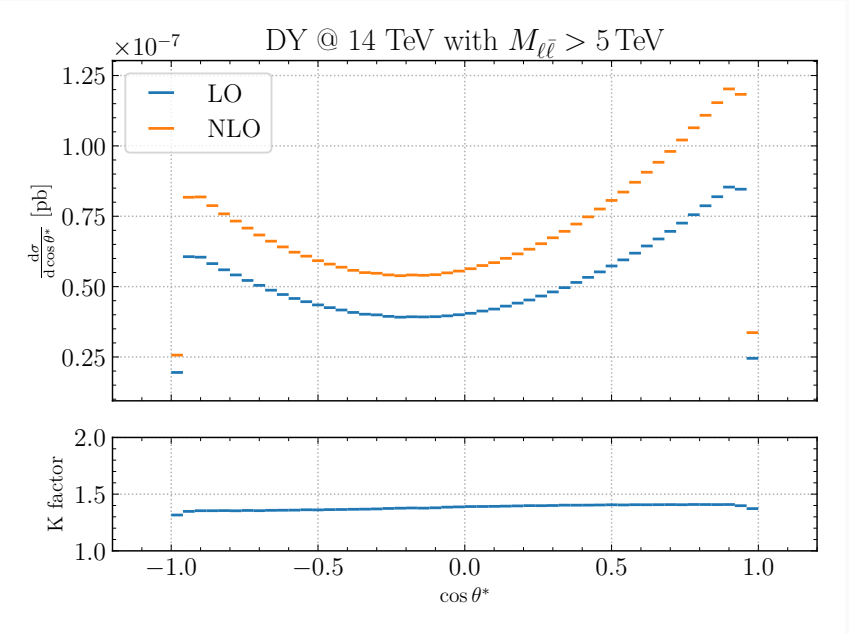
- `convolute` - get the predictions for any PDF set including uncertainties
- `channels` - split the predictions into luminosity channels
- `orders` - split the predictions into perturbative orders
- `info` - access meta data
- `plot` - generate a (customizable) python plot script

The Command Line Interface

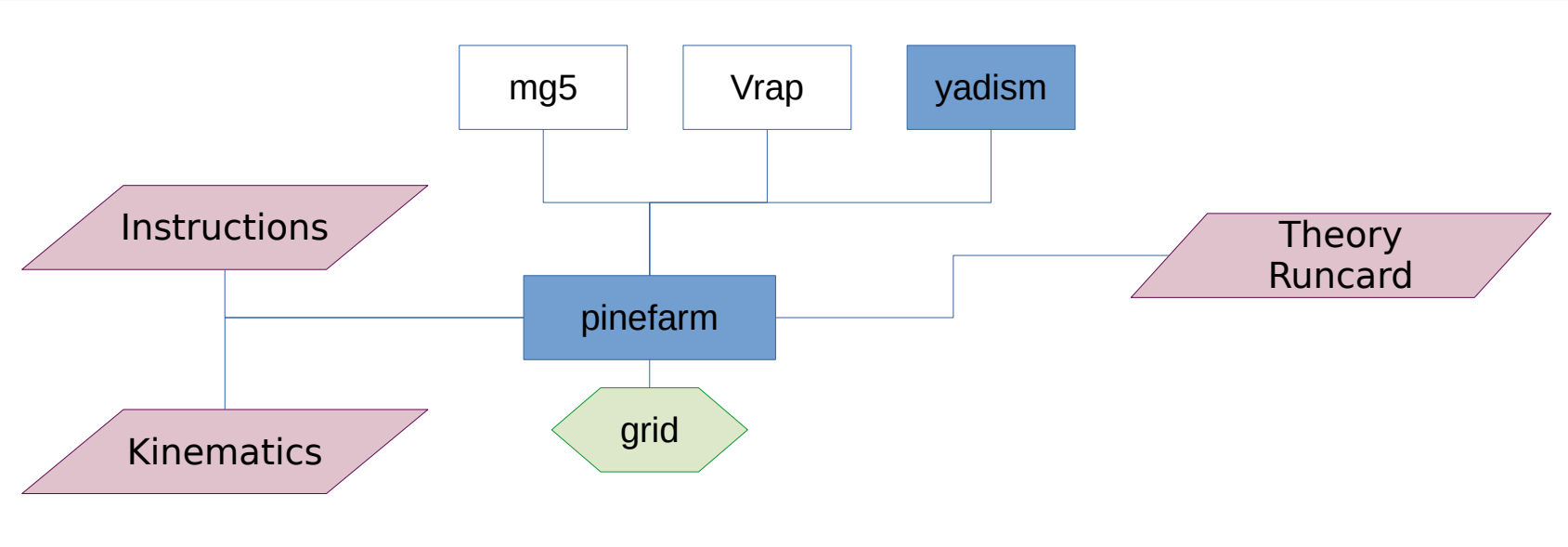
```
$ pineappl convolute CMS_DY_14TEV_MLL_5000_COSTH.pineappl.lz4 \
    NNPDF40_nnlo_as_01180
b       costh     dsig/dcosth  scale uncertainty
         []           [pb]            [%]
--+-------+------+-----------+--------+--------
0       -1    -0.96 5.0382145e-8    -4.73     4.32
1    -0.96    -0.92 1.6366674e-7    -4.98     4.62
2    -0.92    -0.88 1.6611145e-7    -5.06     4.70
3    -0.88    -0.84 1.5983761e-7    -5.08     4.74
4    -0.84     -0.8 1.5374426e-7    -5.09     4.75
5     -0.8    -0.76 1.4800320e-7    -5.10     4.76
6    -0.76    -0.72 1.4238050e-7    -5.10     4.76
7    -0.72    -0.68 1.3708378e-7    -5.10     4.76
8    -0.68    -0.64 1.3191722e-7    -5.12     4.78
9    -0.64     -0.6 1.2720559e-7    -5.13     4.79
[...]
```

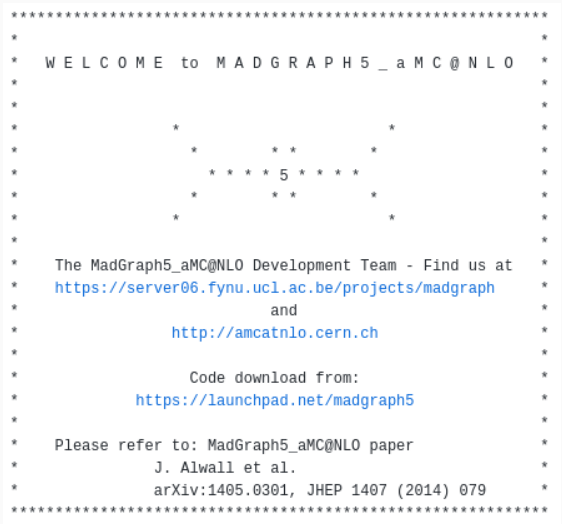
The Python Interface

```python
import lhapdf
import pineappl
# load PDF
pdf = lhapdf.mkPDF("NNPDF40_nnlo_as_01180",0)
# load grid
grid = pineappl.grid.Grid.read("CMS_DY_14TEV_MLL_5000_COSTH.pineappl.lz4")
# convolute
print(grid.convolute_with_one(2212,pdf.xfxQ2,pdf.alphasQ2))
# prints the same list of numbers
```

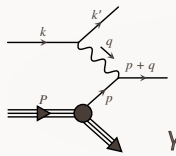


Interface to Other Programs: `pinefarm`





[JHEP07.079]



Yadism

Yet Another DIS Module

[in preparation]

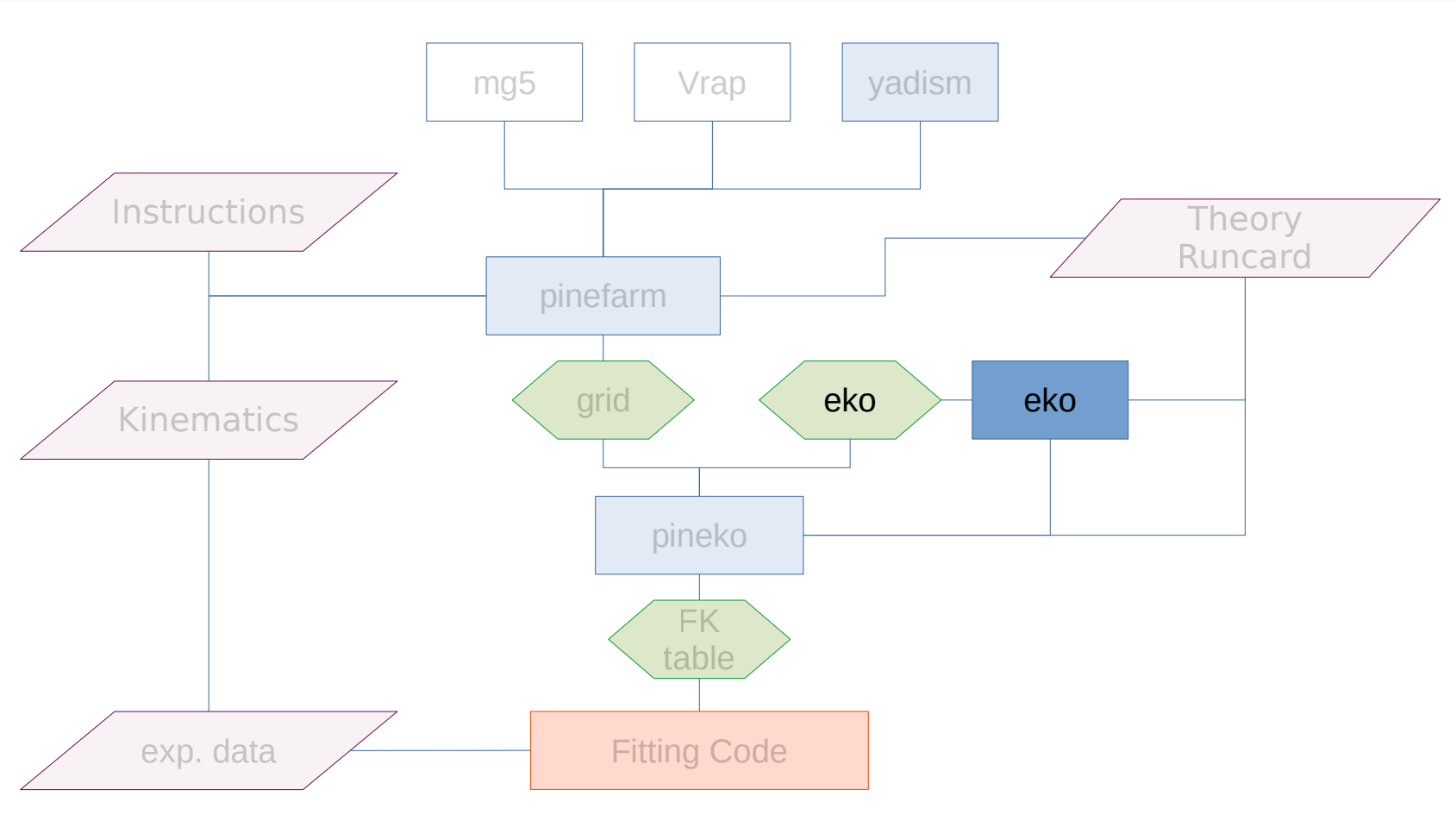
Vrap [PRD69.094008]

more MC interfaces coming soon

3. EKO [2202.02338]

New Theory Prediction Pipeline

Produce FastKernel (FK) tables!



The workhorse in the background: PineAPPL

EKO Definition

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) $\mathbf{E}$:

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

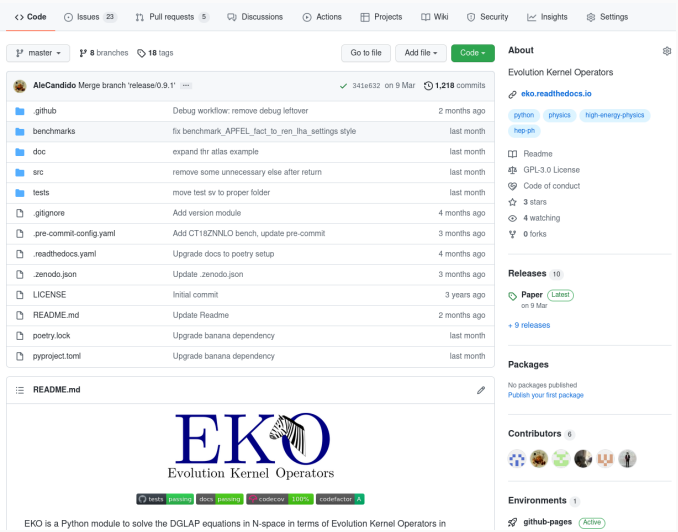
with

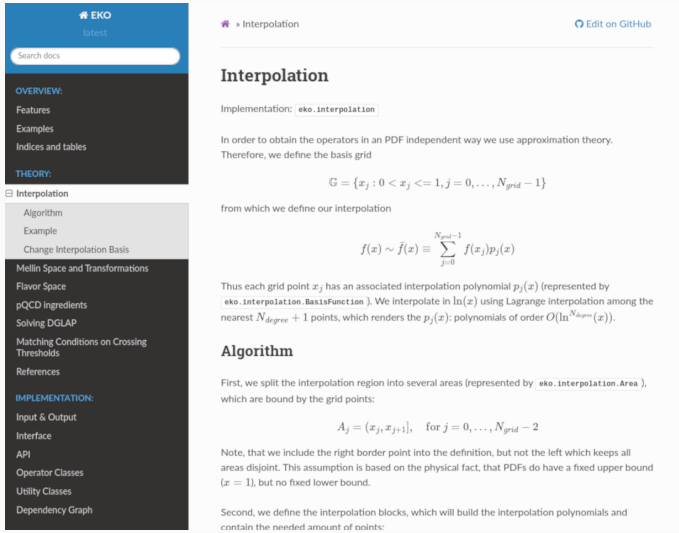
$$\mathbf{f}(\mu_F^2) = \mathbf{E}(\mu_F^2 \leftarrow \mu_{F,0}^2) \otimes \mathbf{f}(\mu_{F,0}^2)$$

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 IC
- Backward VFNS evolution (i.e. across thresholds and with intrinsic) $\rightarrow$ see IC

EKO Project Management

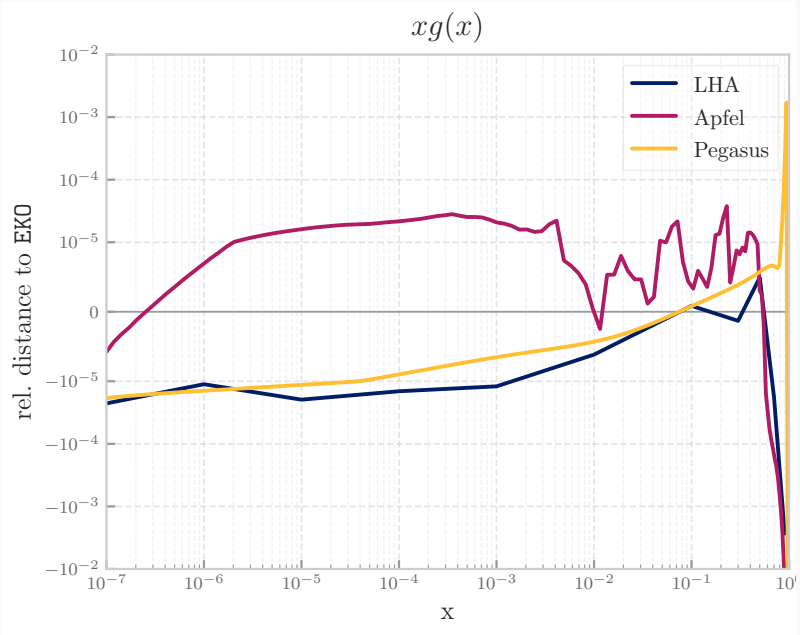


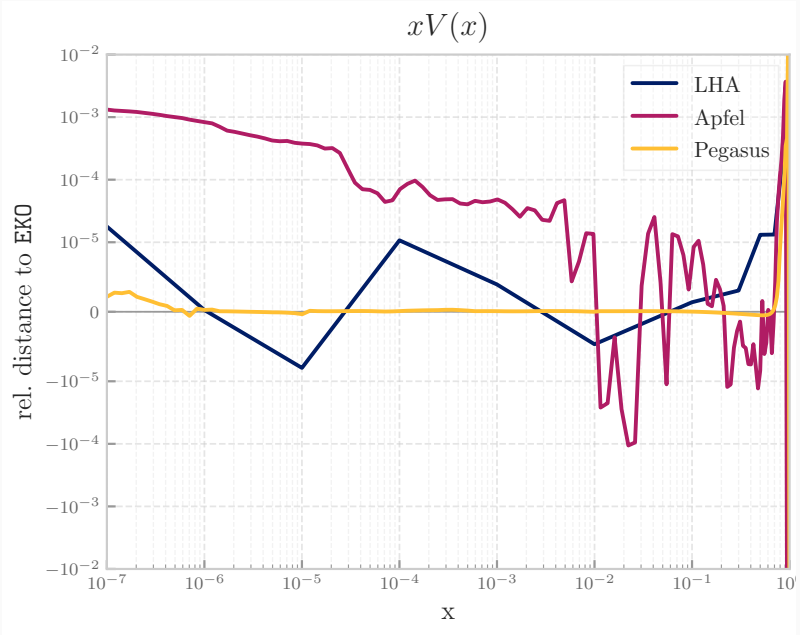


- Fully open source: `https://github.com/N3PDF/eko`
- Written in Python
- Fully documented: `https://eko.readthedocs.io/`

EKO Benchmarks

LHA benchmark [0204316][0511119]:



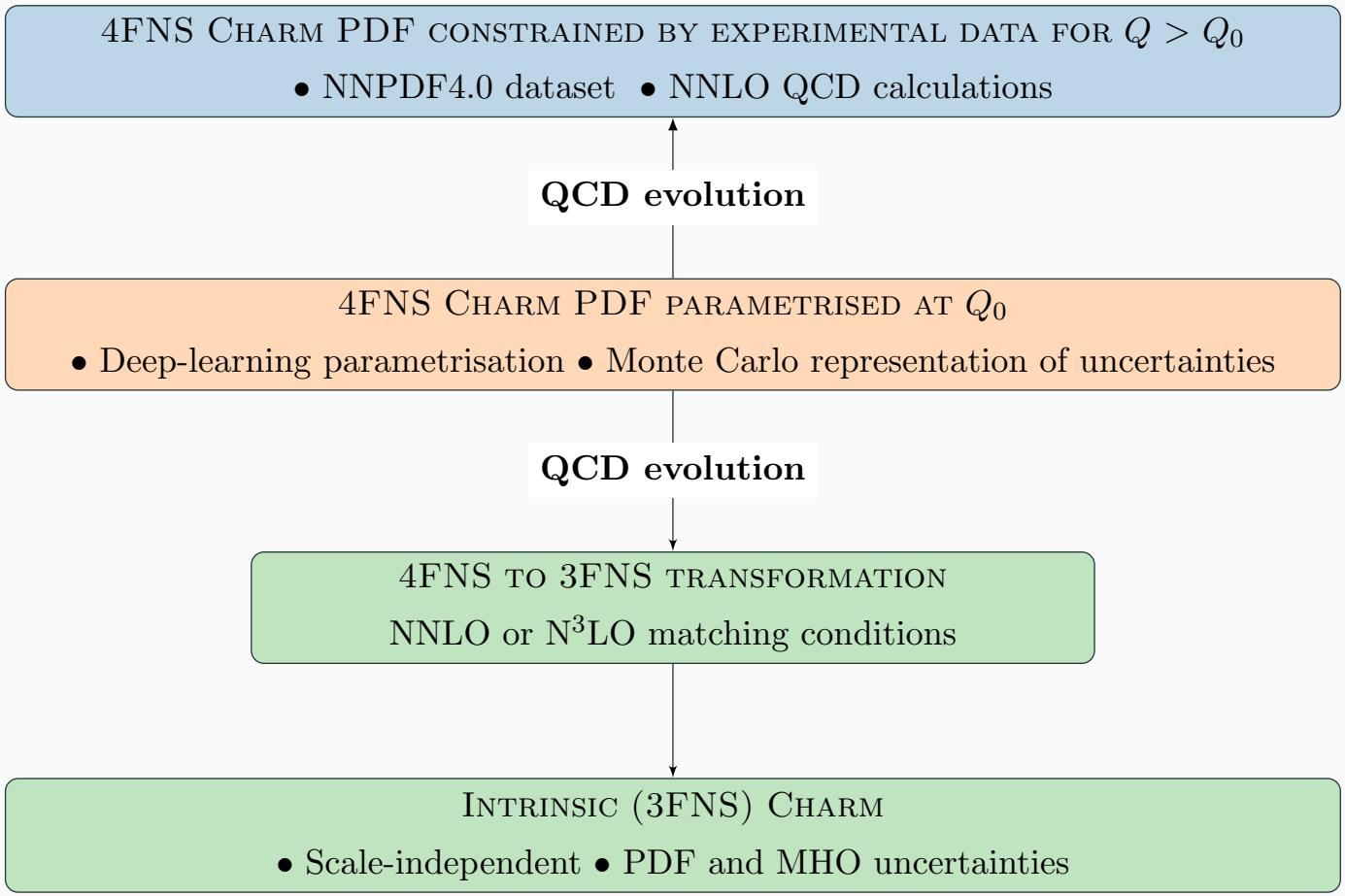


$\Rightarrow$ EKO is working!

4. Evidence for Intrinsic Charm in the Proton [in print]

Intrinsic Charm: Strategy

based on NNPDF4.0 [EPJC82.428]



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 $\mathrm{N^3LO}$)

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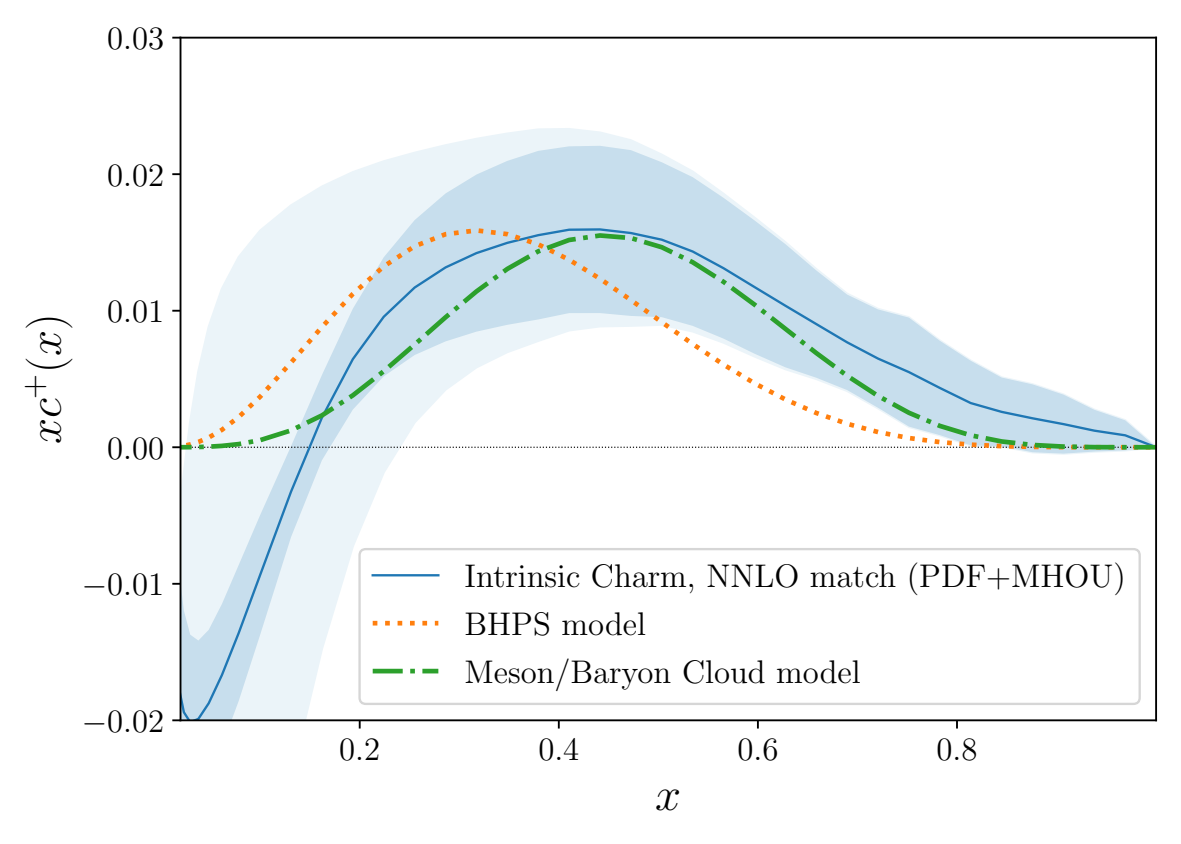
with $\mathbf{R}^{(n_f)}$ a flavor rotation matrix and $\tilde{\mathbf{A}}^{(n_f)}(\mu_h^2)$ the operator matrix elements (partially known up to $\mathrm{N^3LO}$)

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

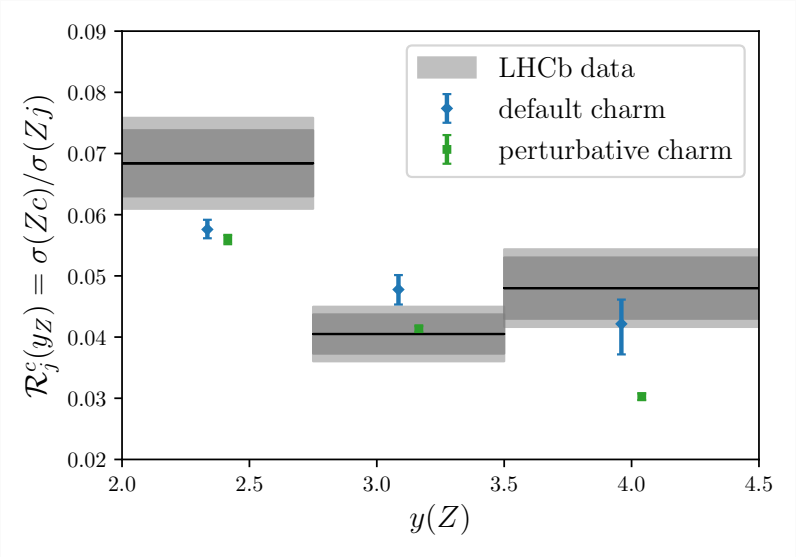
Intrinsic Charm: PDF plot



[BHPS] or [Meson/Baryon Cloud Model]

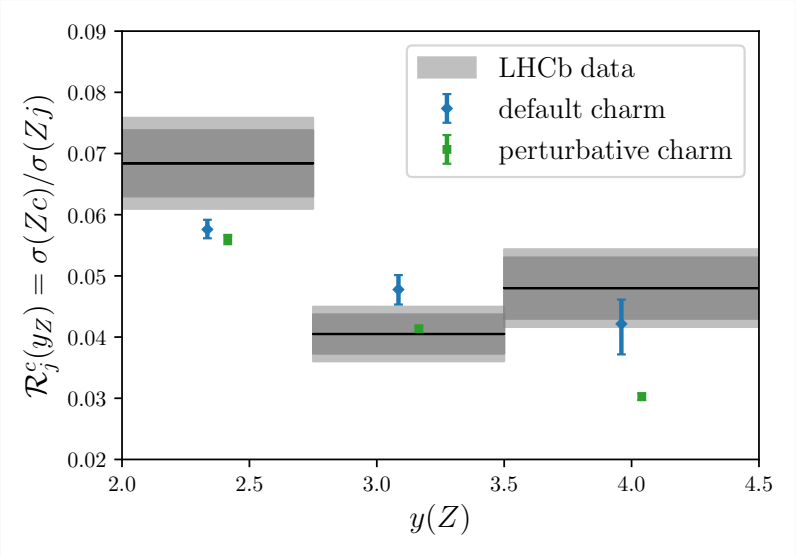
- in **3FNS** a valence-like peak is present
- for $x \leq 0.2$ the perturbative uncertainties are quite large
- the carried momentum fraction is within **1%**

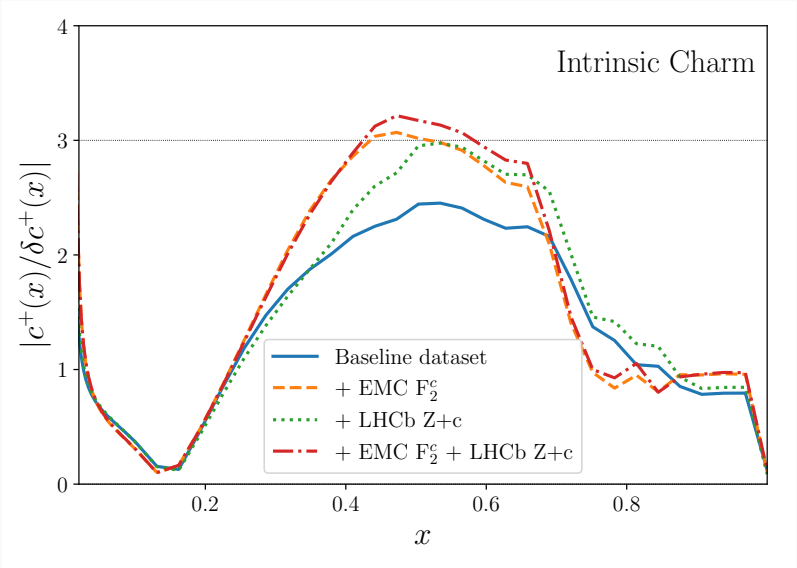
Intrinsic Charm: LHCb and Significance



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

Intrinsic Charm: LHCb and Significance

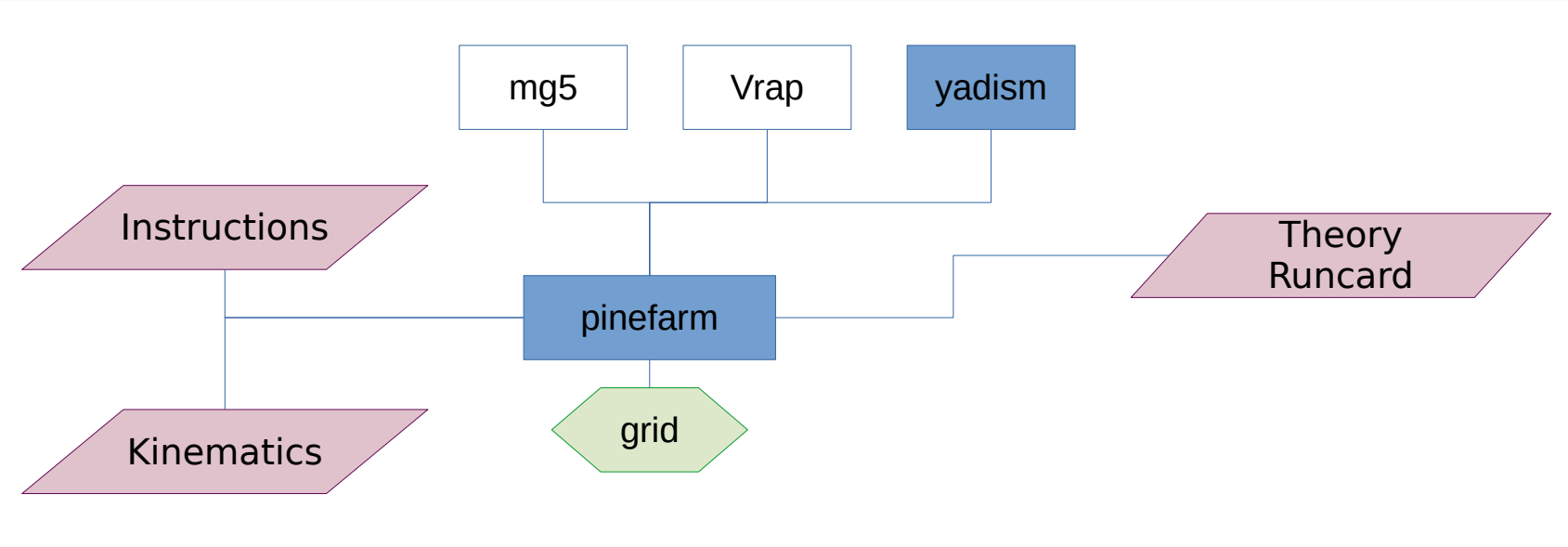


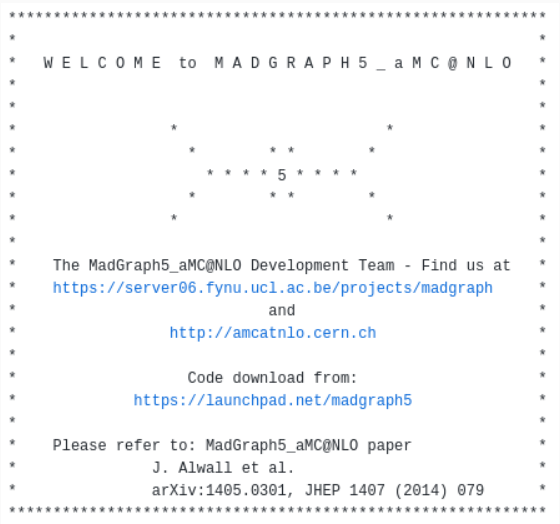


- match better recent **LHCb** Z+c measurement [PRL128.082001]
- we find a **3σ** evidence of intrinsic charm
- result is **stable** with mass variation, dataset variation

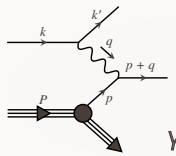
5. yadism [in preparation]

Interface to Other Programs: `pinefarm`





[JHEP07.079]



Yadism

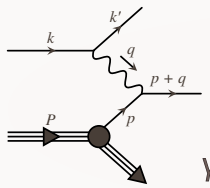
Yet Another DIS Module

[in preparation]

Vrap [PRD69.094008]

more MC interfaces coming soon

`yadism` Physics Features



Yadism

Yet Another DIS Module

- DIS coefficient function database
- independent of boundary condition $\rightarrow$ PDF fitting
- separate features: TMC, FNS
- constant benchmark against `APFEL`

same improvement in terms of project management as `EKO`!

Coefficient Functions

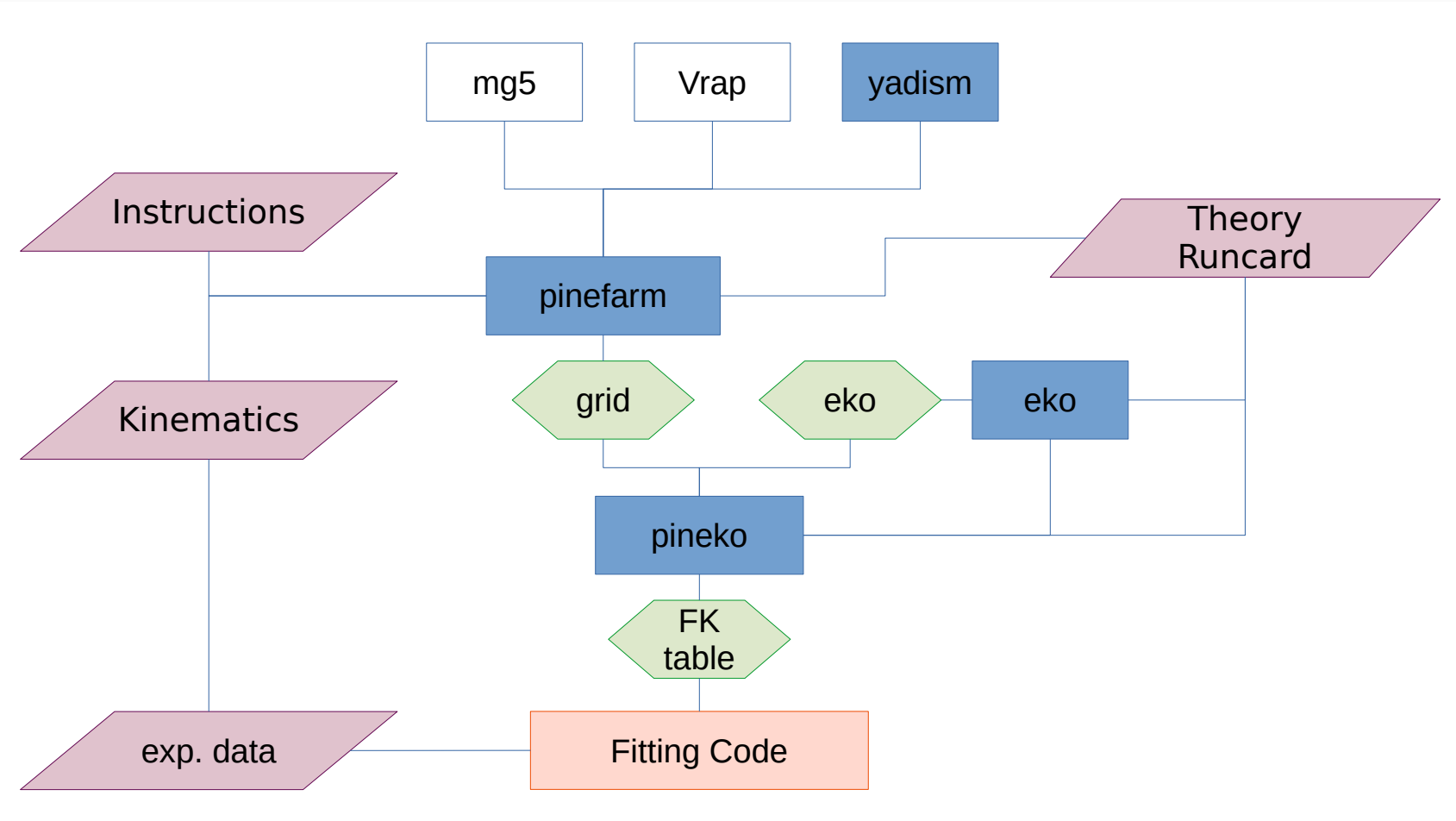
- implemented coefficient functions:

	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.]

- implemented flavor number schemes: FFNS, ZM-VFNS, FONLL

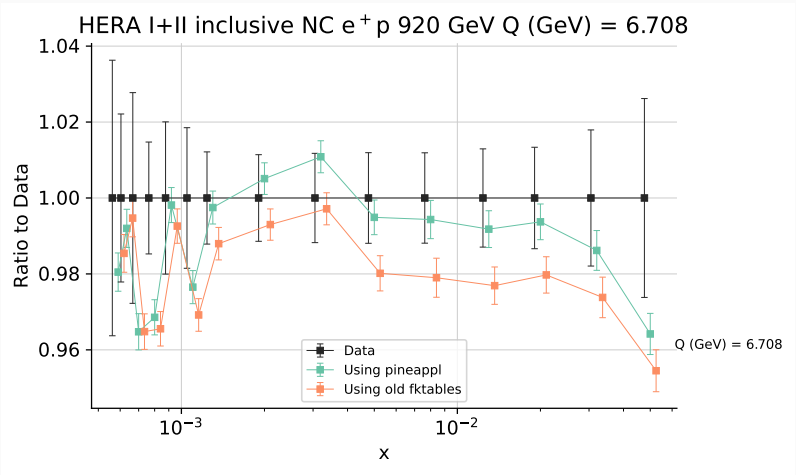
New Theory Prediction Pipeline

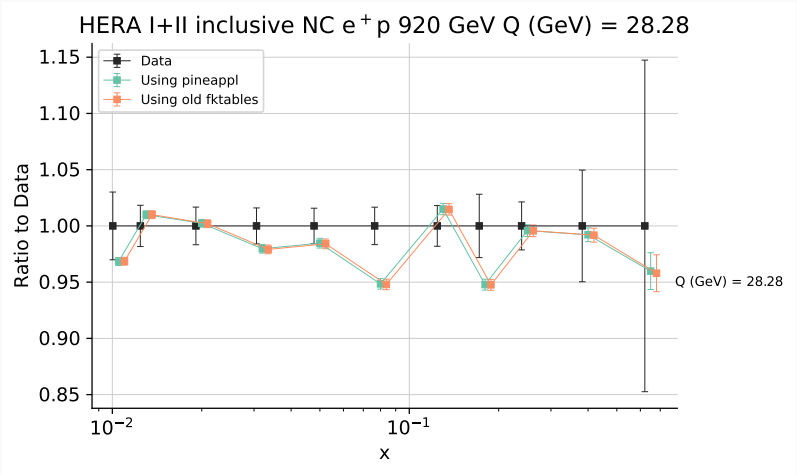
Produce FastKernel (FK) tables!

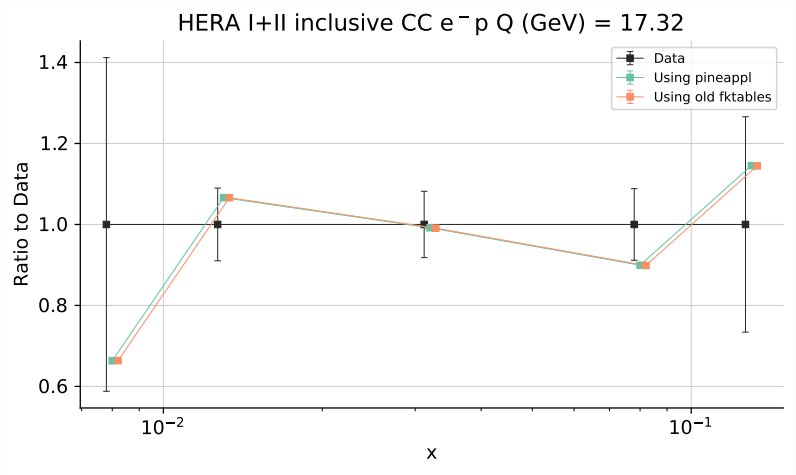


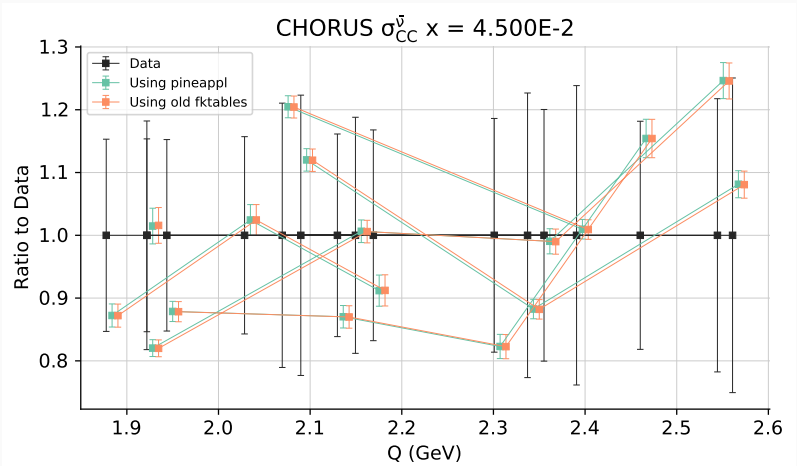
The workhorse in the background: PineAPPL

Comparison `yadism` against `APFEL`









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

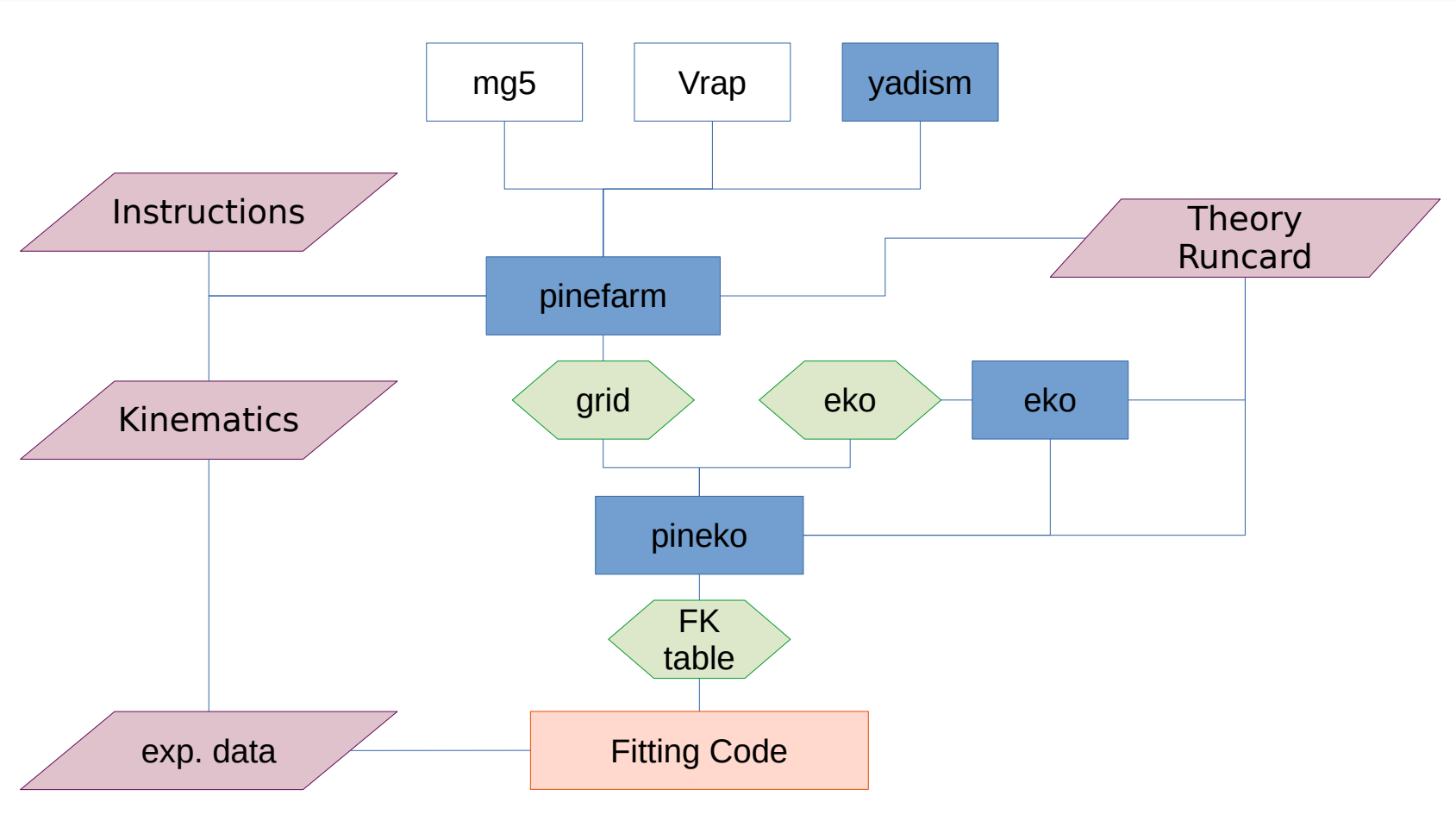
6. Outlook

Outlook

- extend to N3LO
- include MHOU
- include QED corrections
- add polarized setup
- extend to fragmentation function
- ...

New Theory Prediction Pipeline

Produce FastKernel (FK) tables!

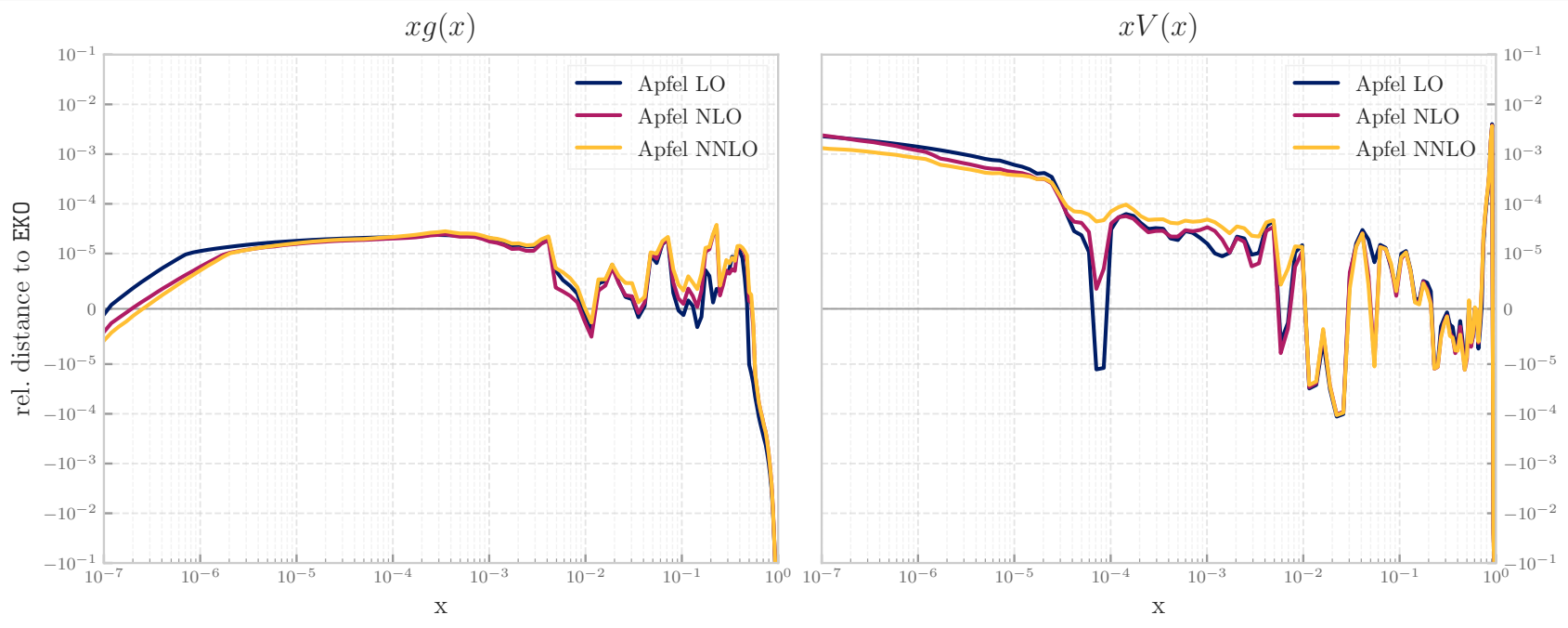


The workhorse in the background: PineAPPL

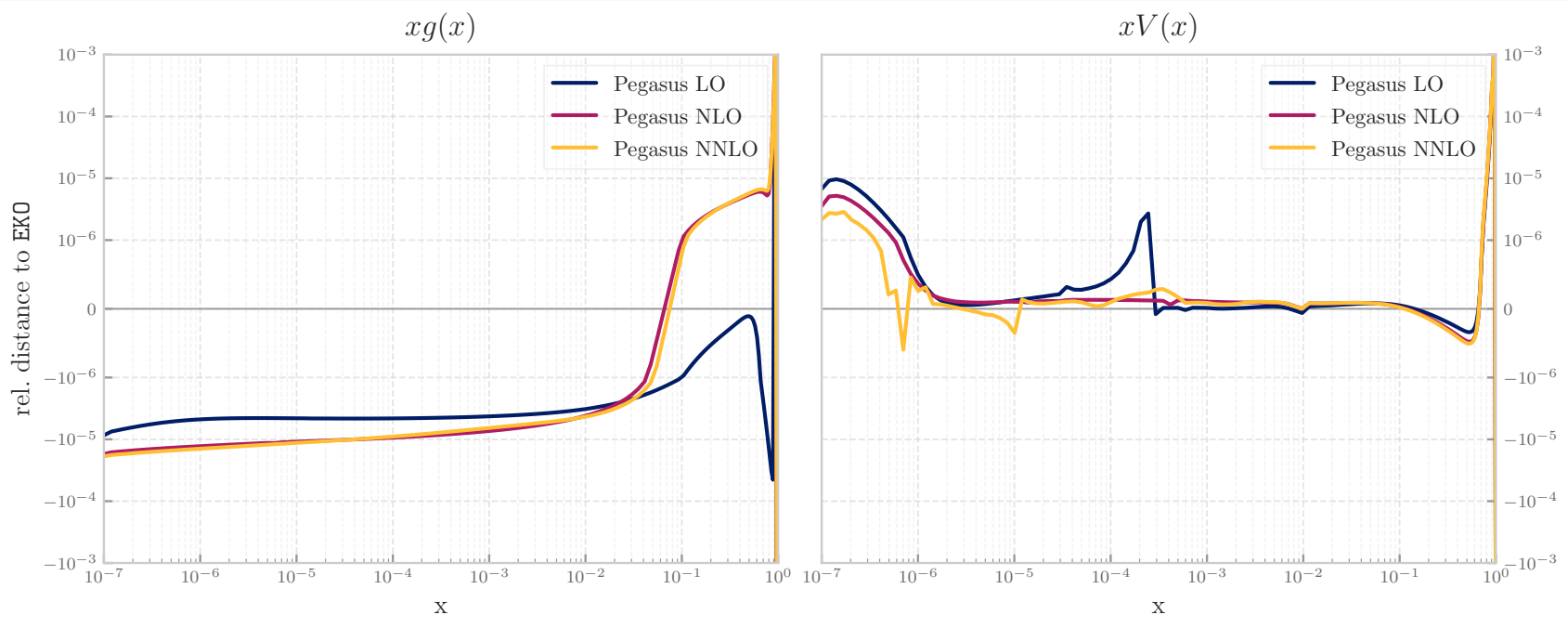
Thank you!

7. Backup slides

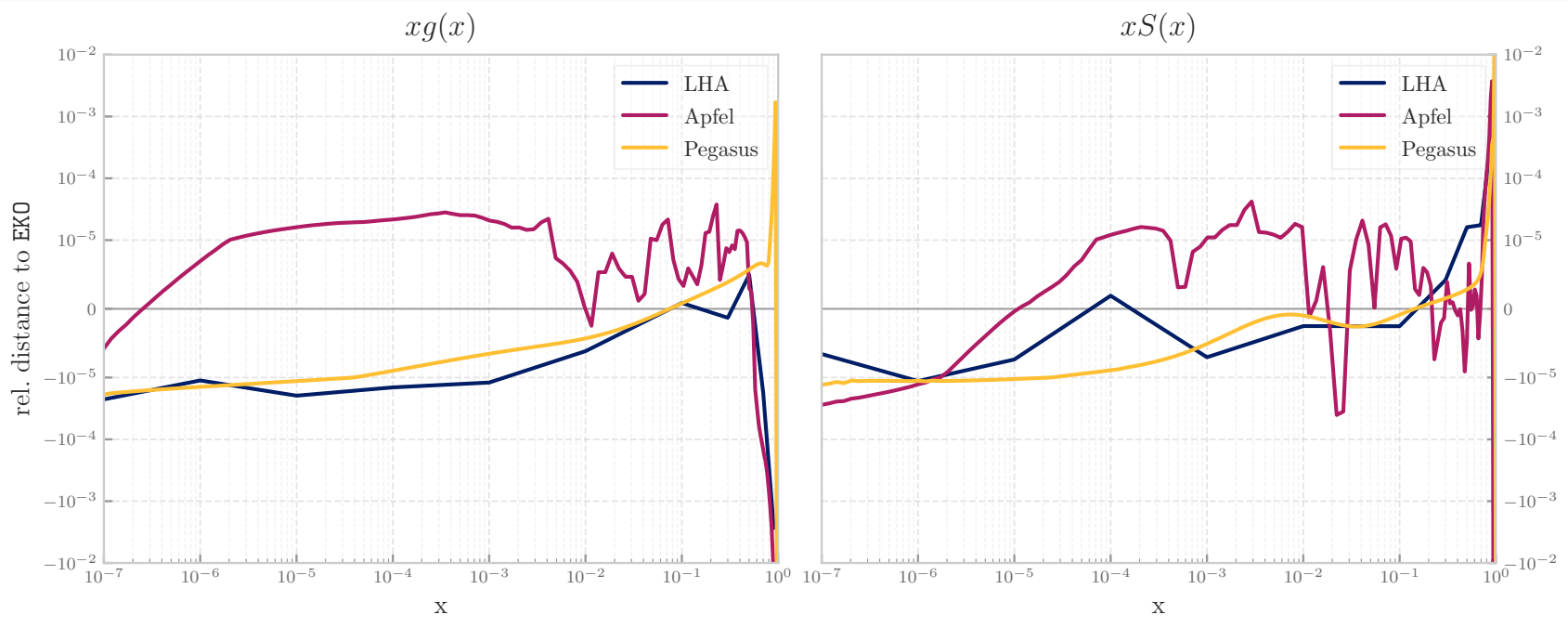
EKO APFEL **benchmark**



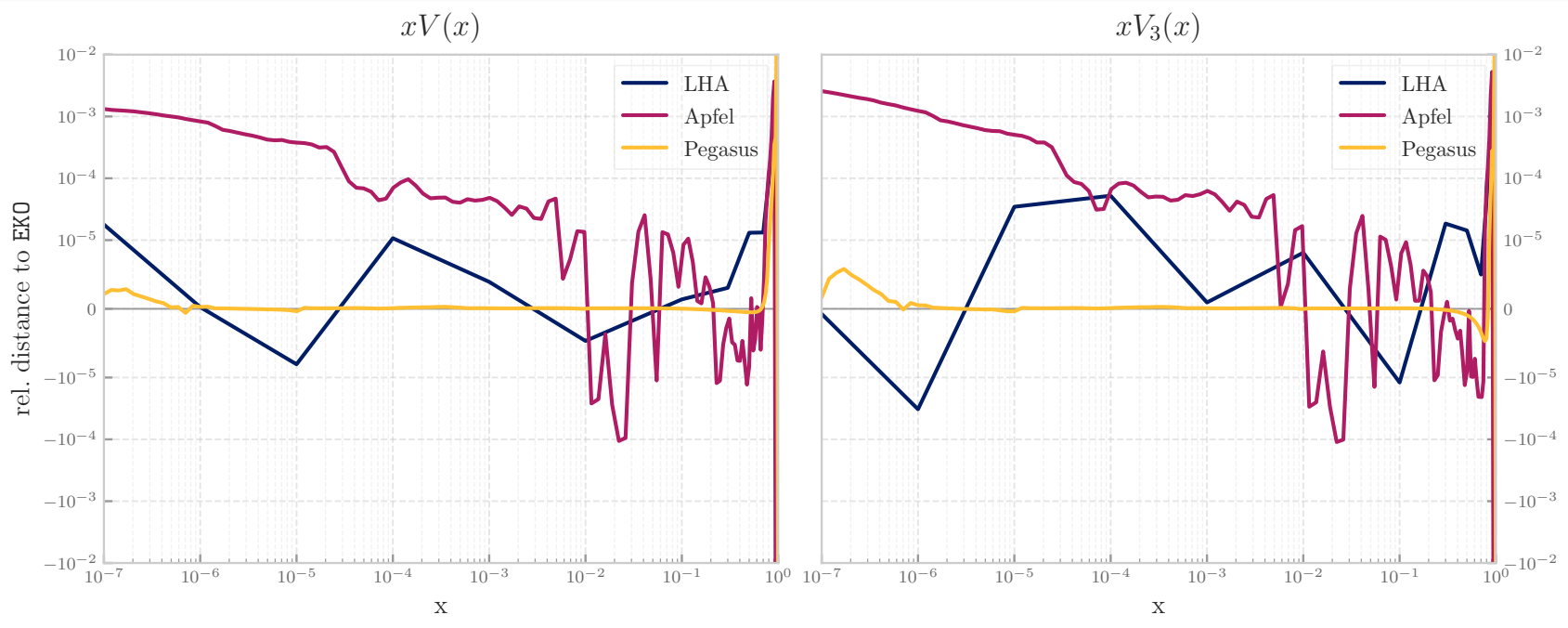
EKO PEGASUS **benchmark**



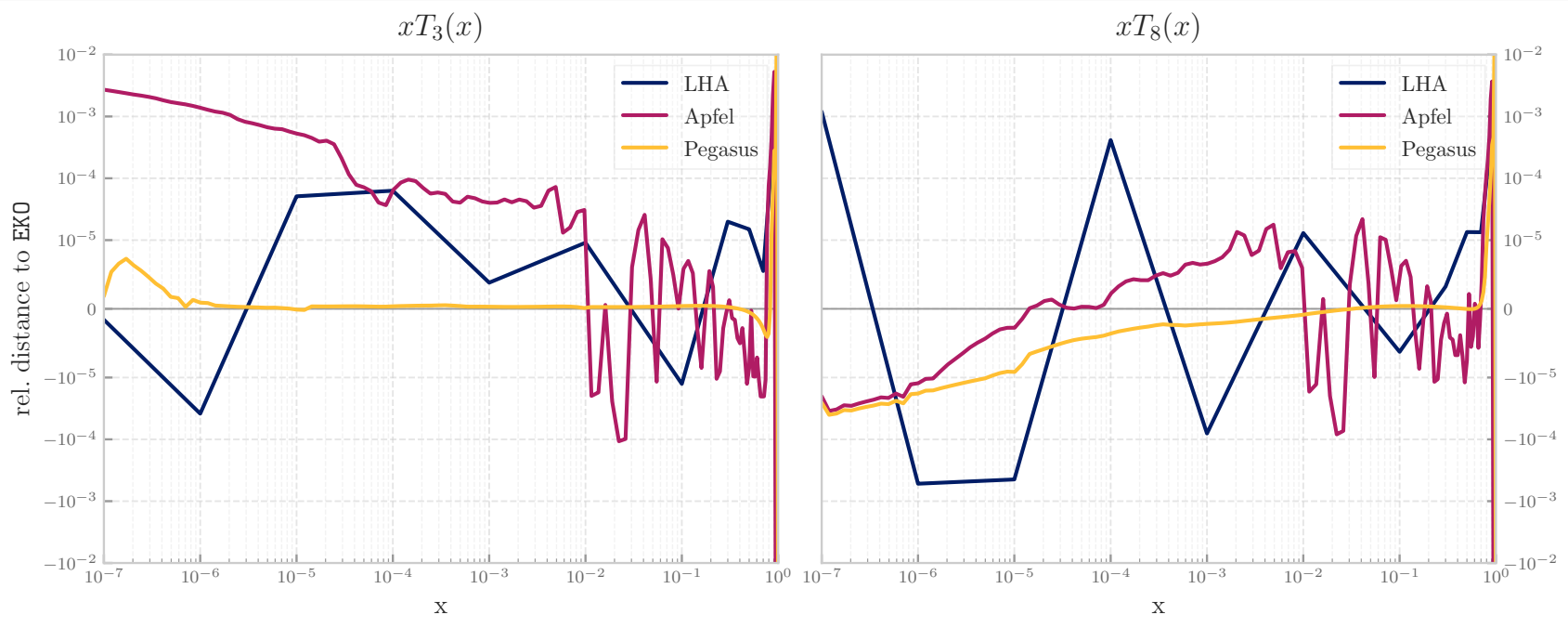
EKO LHA benchmark: g and Σ



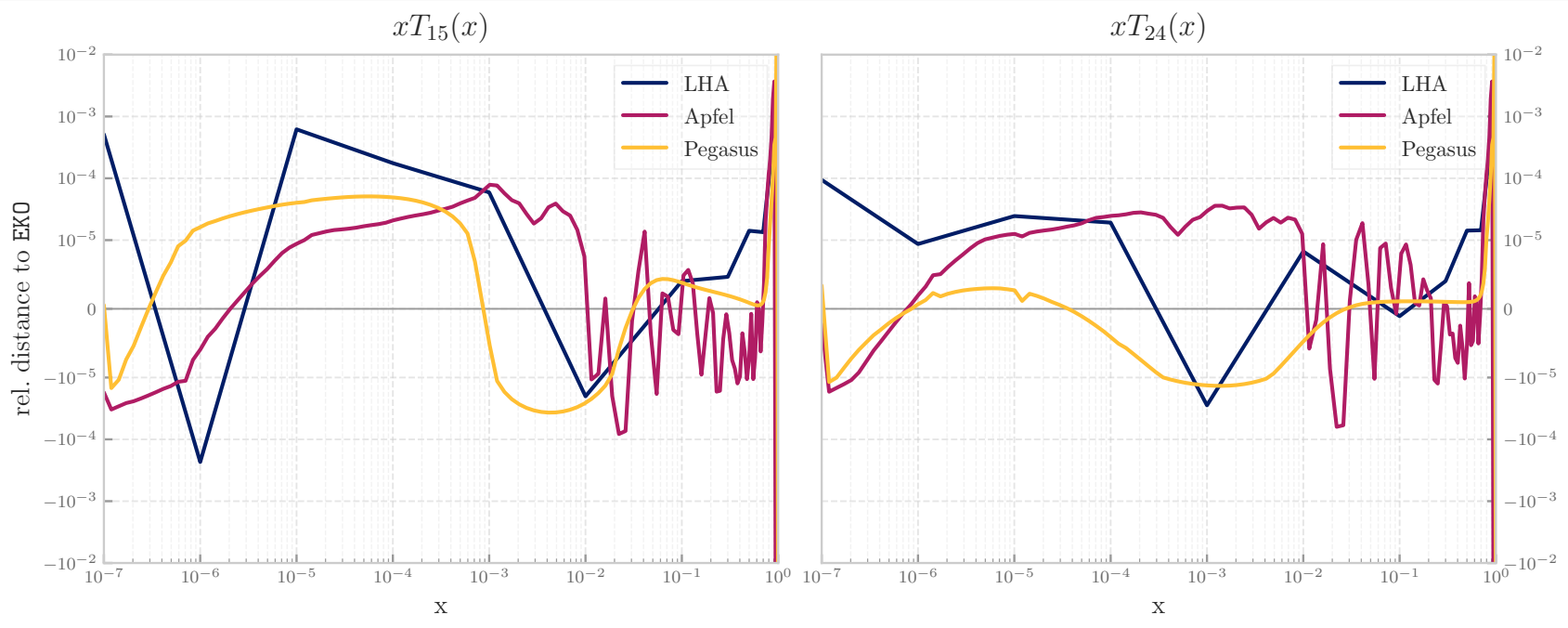
EKO LHA benchmark: V and V_3



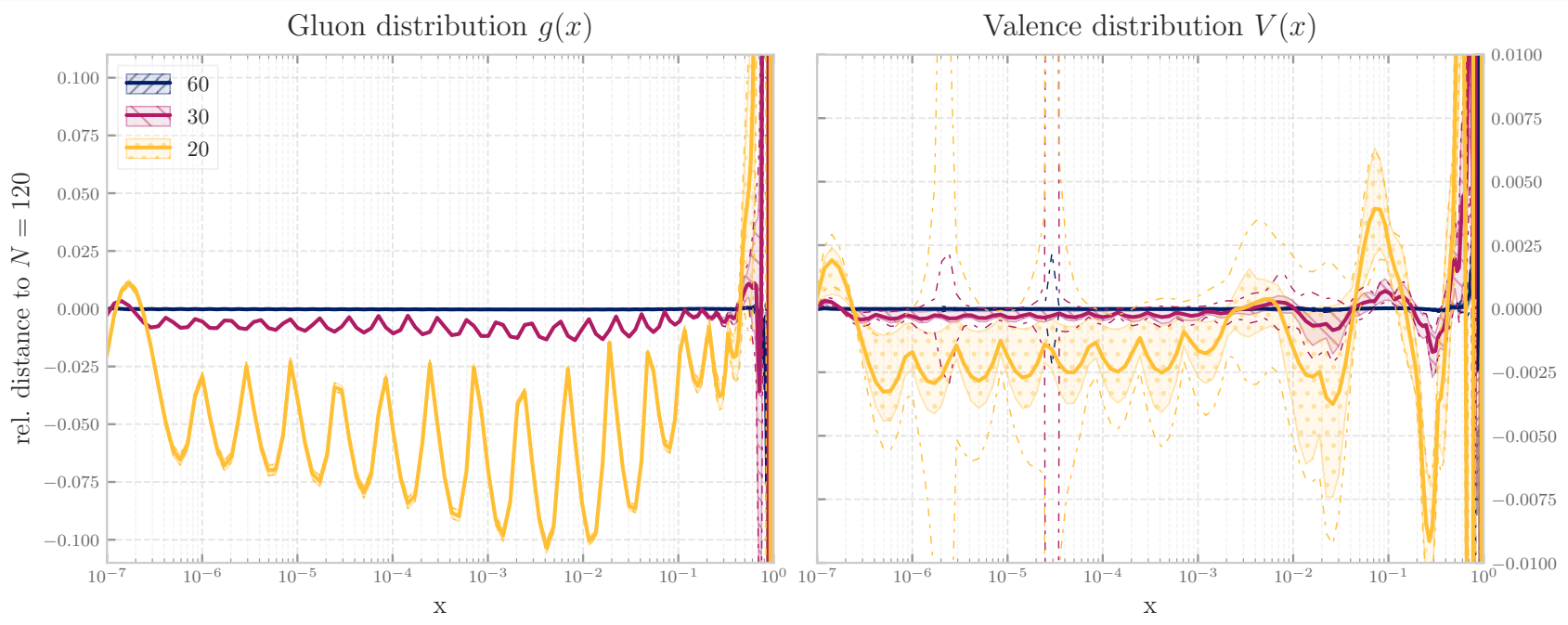
EKO LHA benchmark: T_3 and T_8



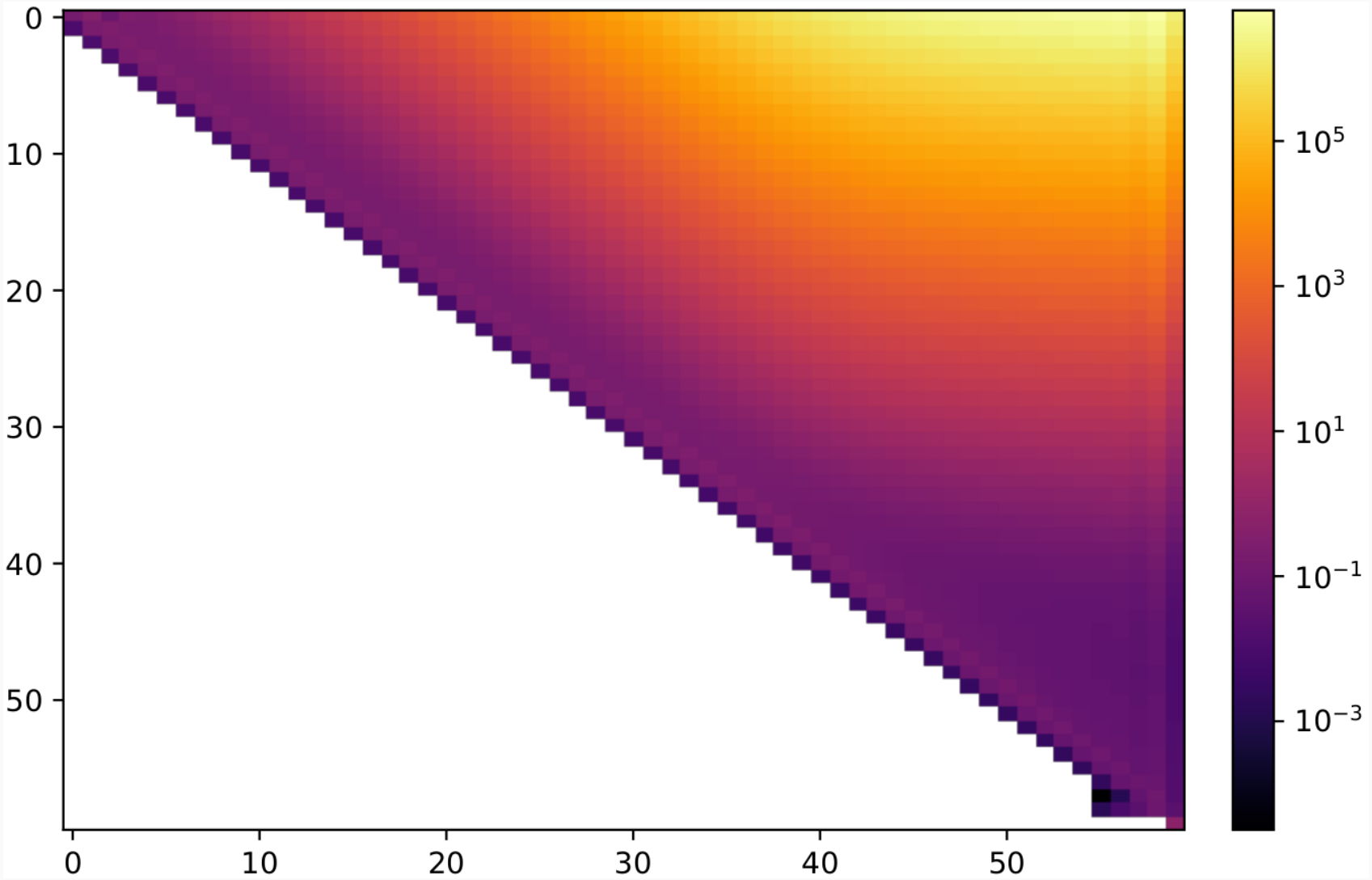
EKO LHA benchmark: T_{15} and T_{24}



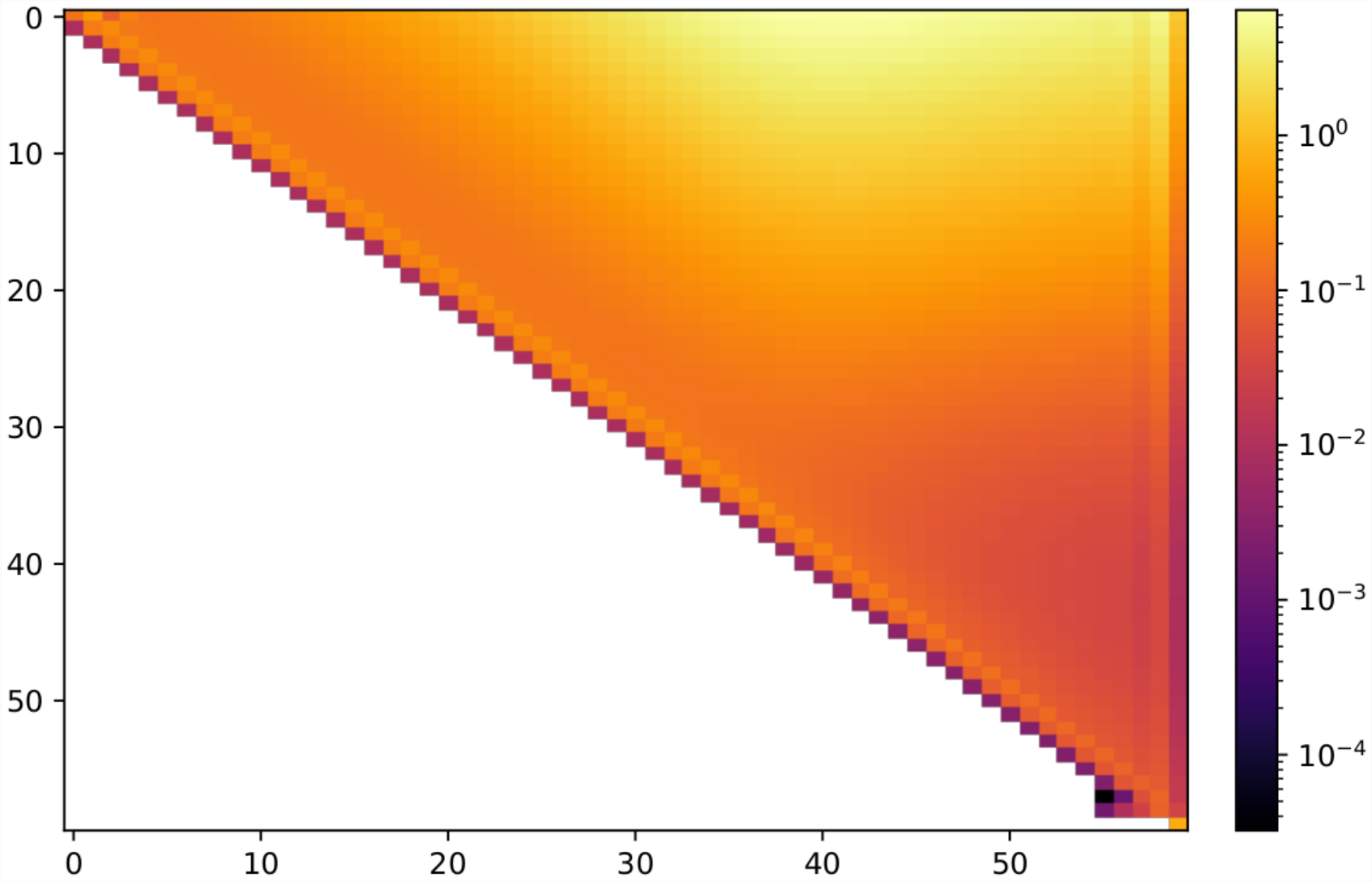
EKO Interpolation Error



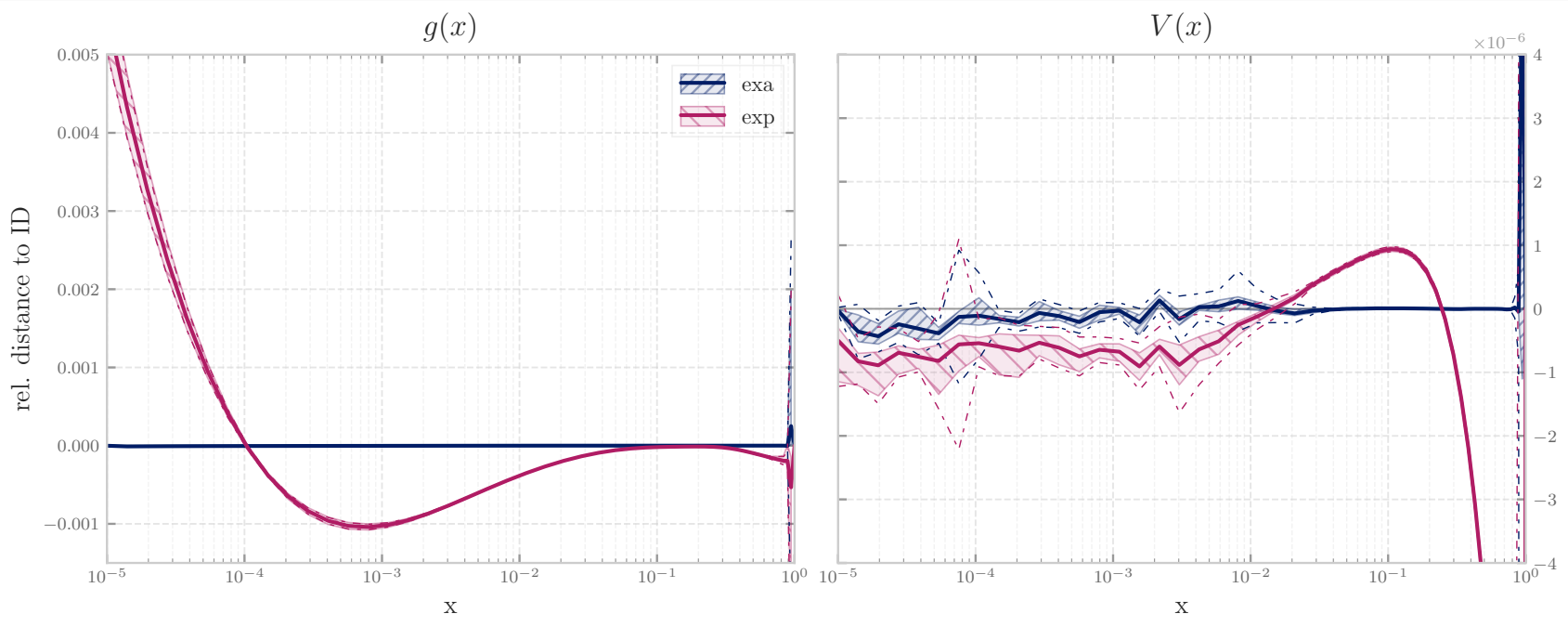
EKO Snapshot $S \leftarrow S$



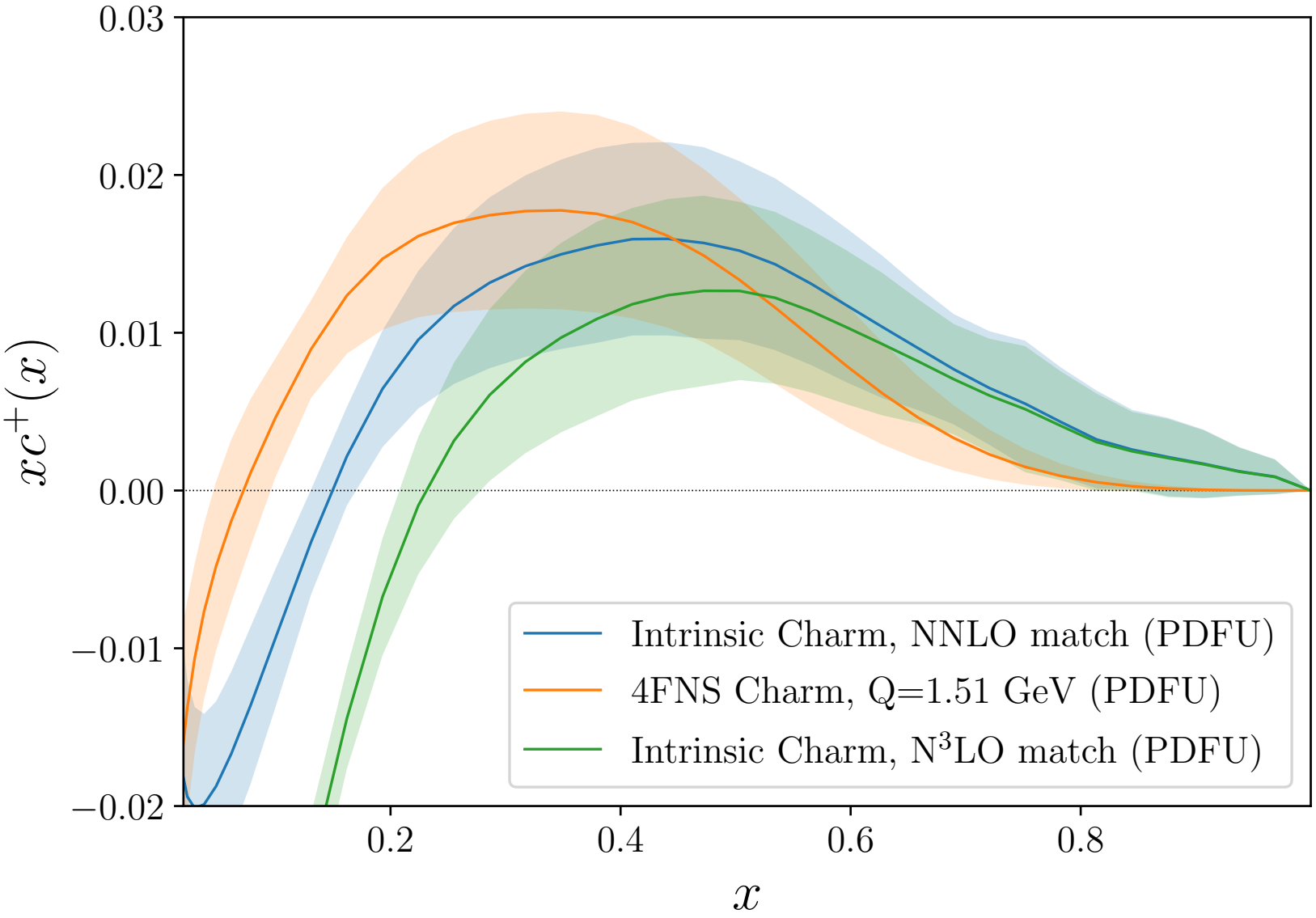
EKO Snapshot $V \leftarrow V$



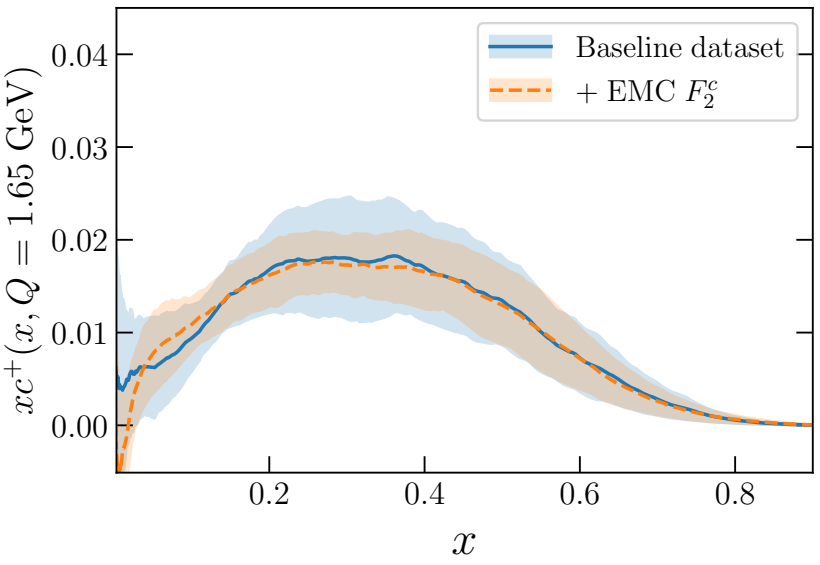
EKO Backward Evolution

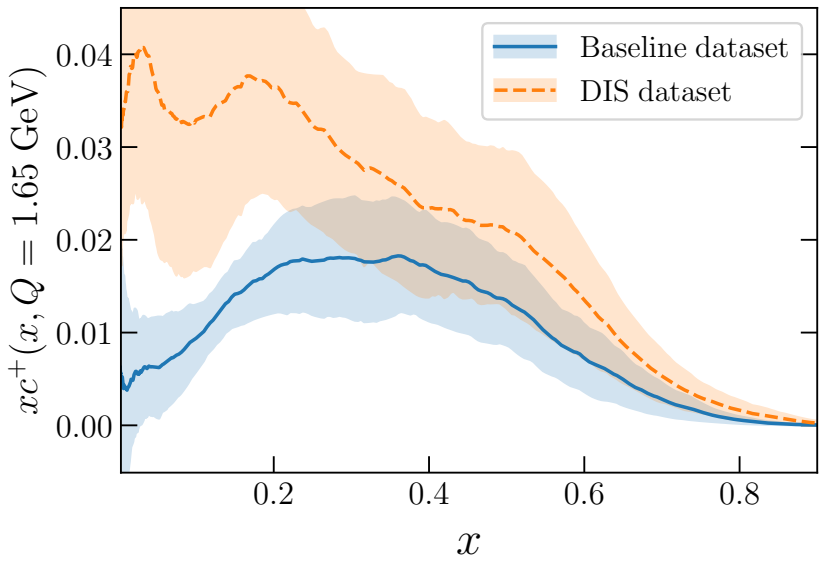


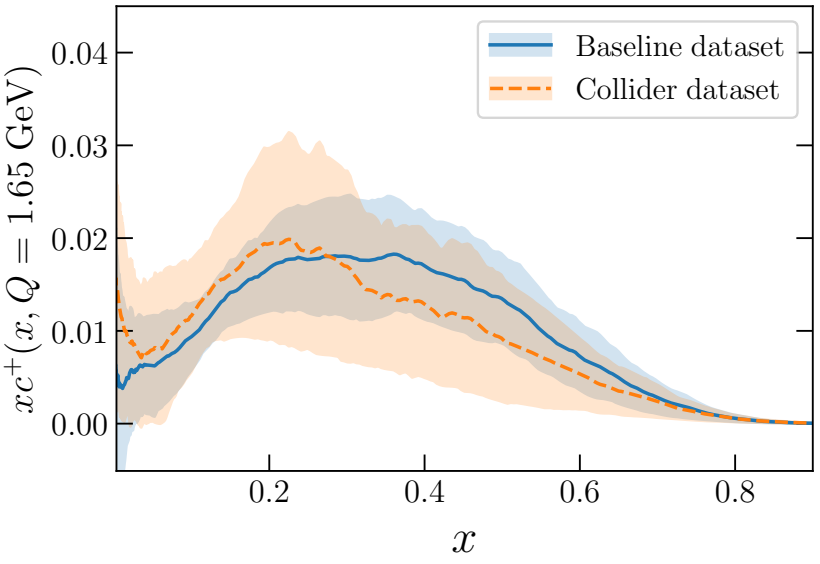
IC - uncertainties splitted

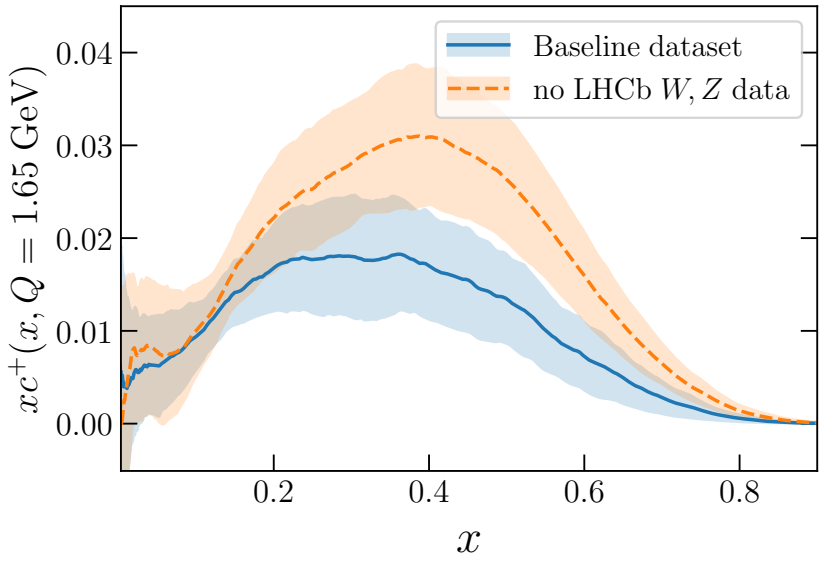


IC - dataset variation

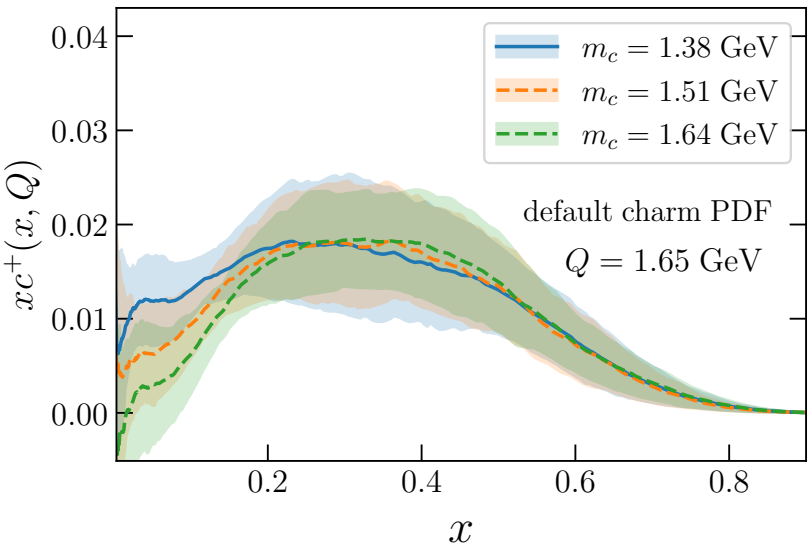


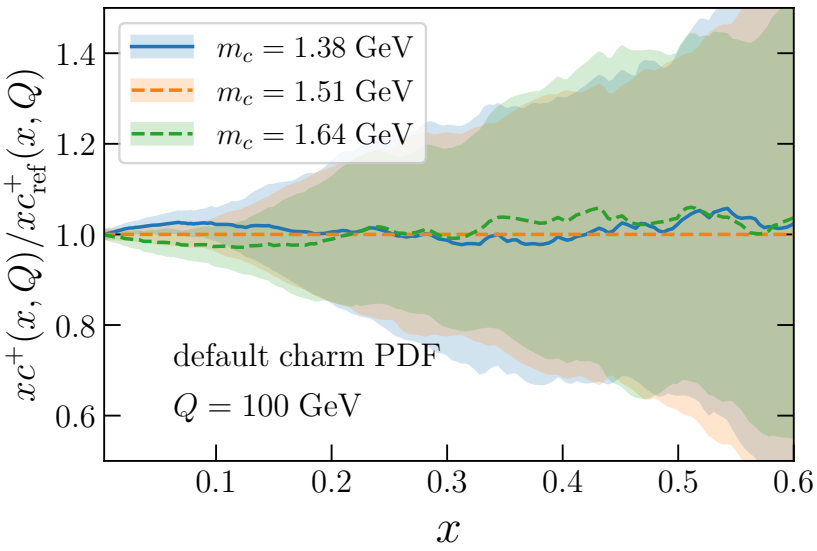


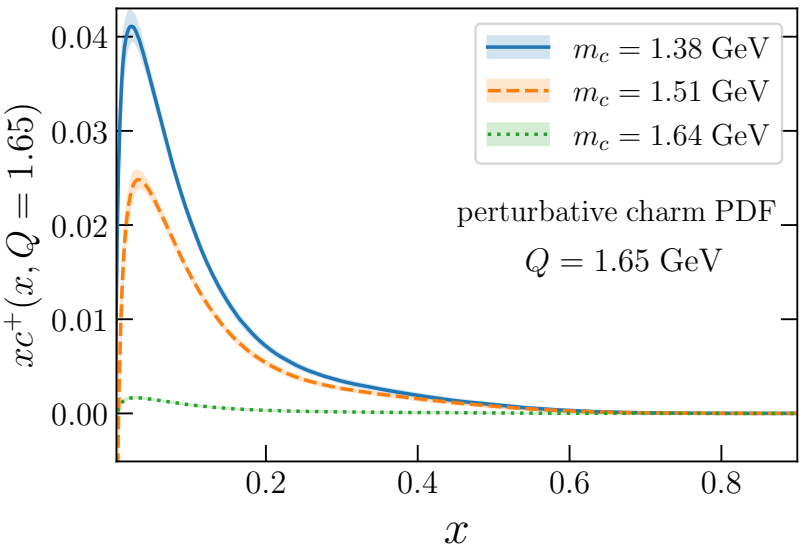


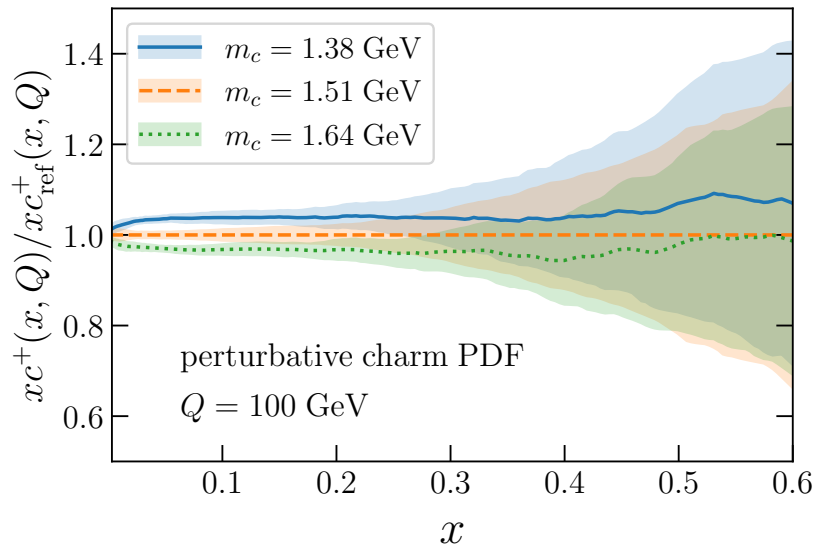


IC - mass variation

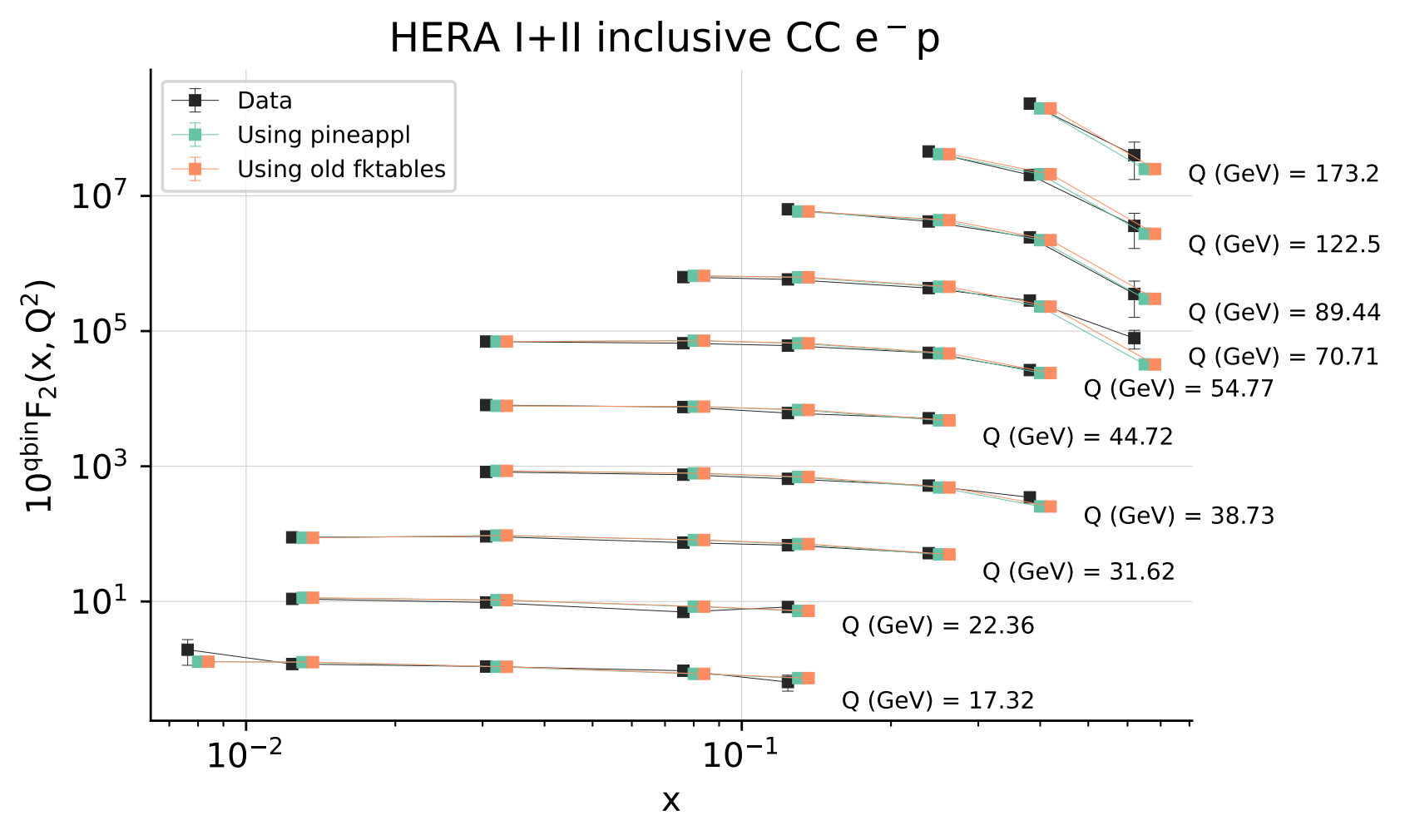








Comparison `yadism` against `APFEL`



Comparison `yadism` against `APFEL`