Theory Predictions in PDF Fitting

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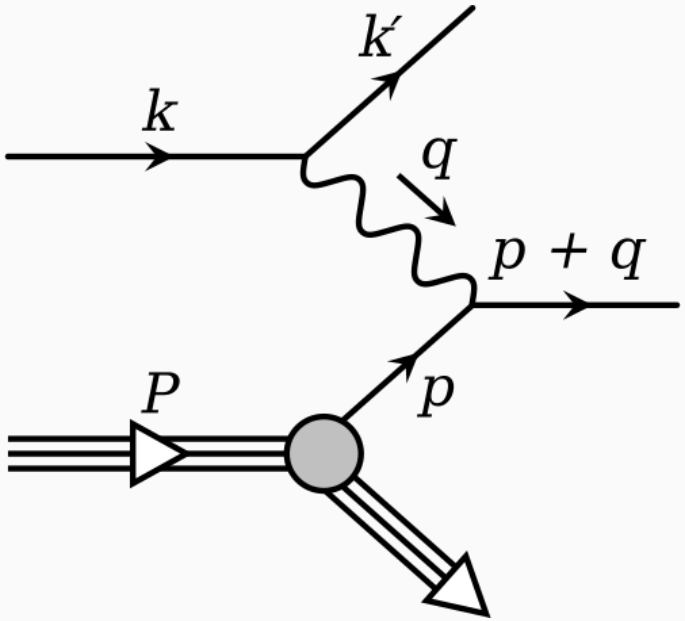
Outline

1. Motivation
2. `PineAPPL` [JHEP12.108]
3. `EKO` [2202.02338]
4. `yadism` [in preparation]
5. `banana`
6. Outlook

1. Motivation

Parton Distribution Functions

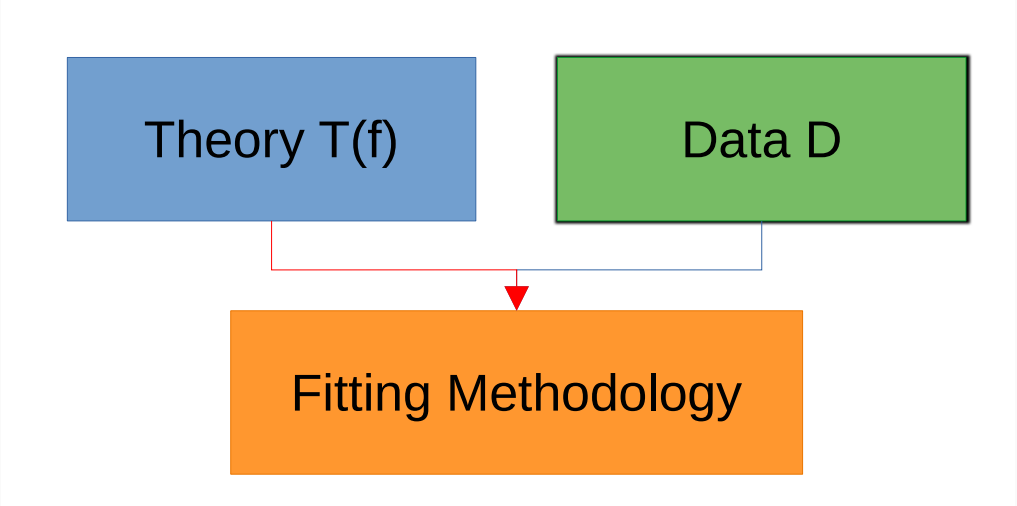


Parton Distribution Functions (PDF) $\mathbf{f}(x, \mu_F^2)$

- describe the fundamental constituents of the proton: quarks, gluons
- μ_F-dependence: DGLAP equations!
- x-dependence: fit!

PDFs for Theories / Theories for PDFs

Guess a candidate PDF $\mathbf{f}(x, \mu_F^2)$

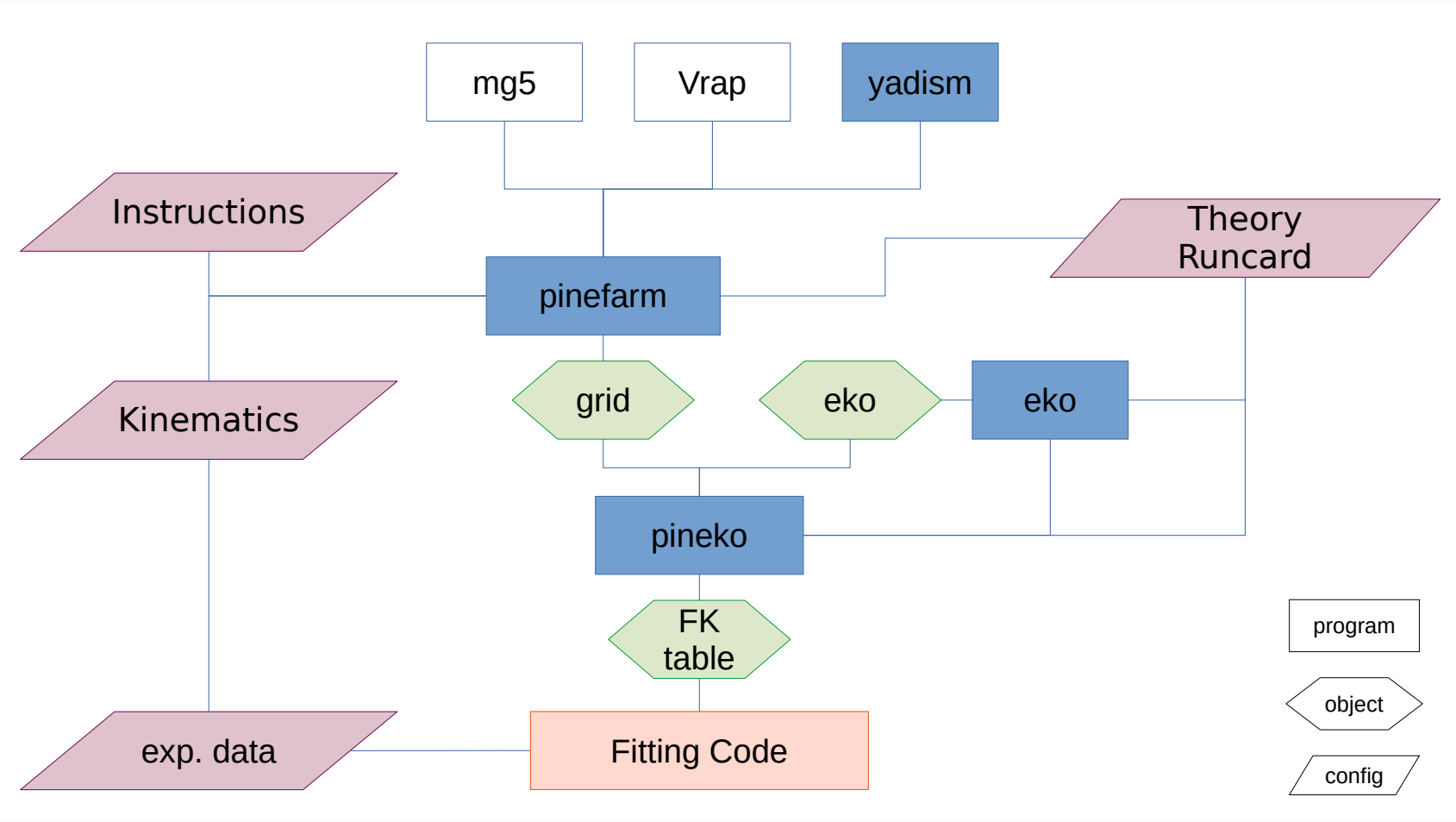


But,

- Theory calculation are *very* expensive in development time (month/years) and even expensive on run time (days/weeks)
- How to measure the impact of a new theory calculation on the PDF?

New Theory Prediction Pipeline

Produce FastKernel (FK) tables!



The workhorse in the background: `PineAPPL`

New Theory Prediction Pipeline

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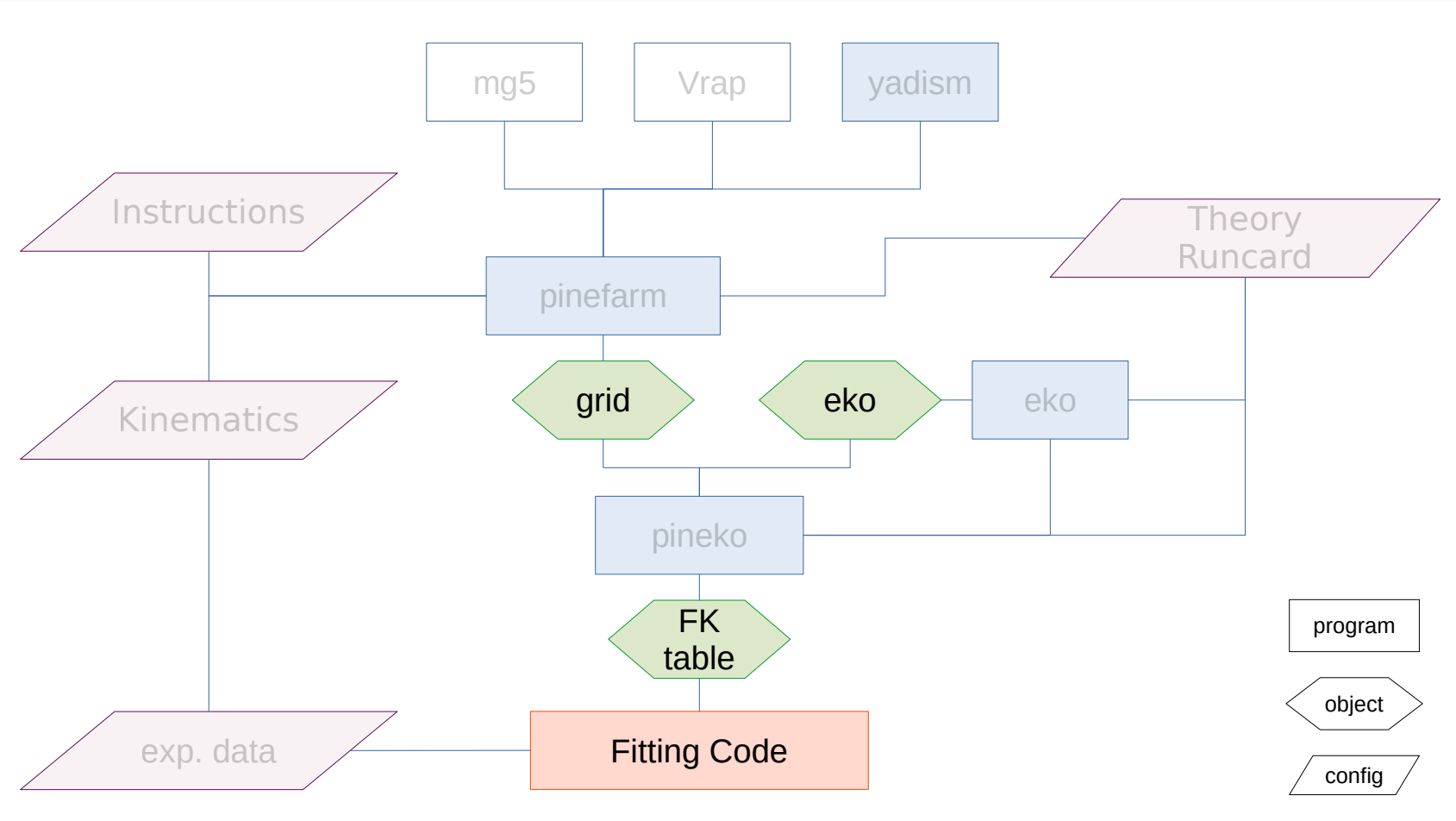

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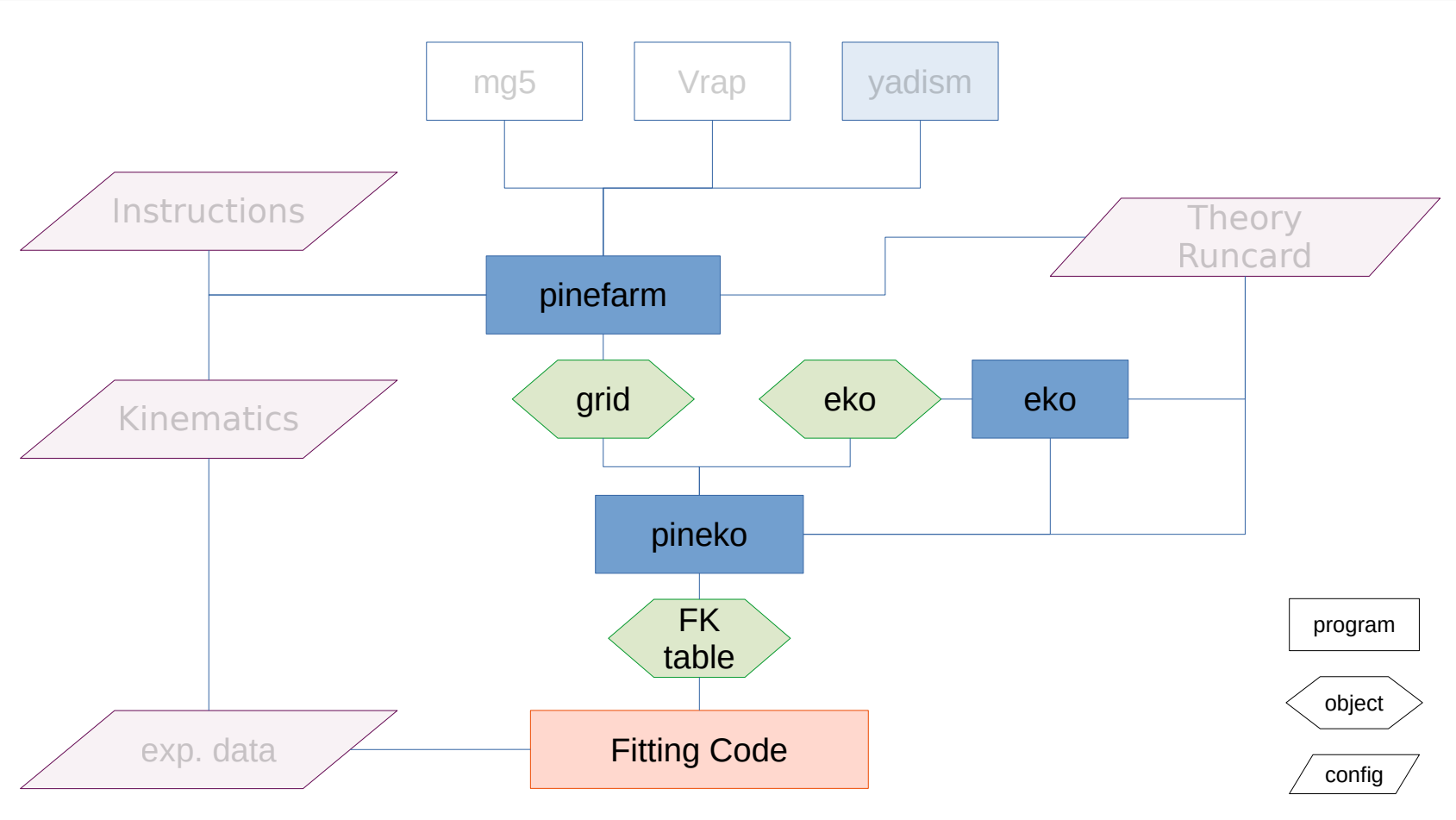

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New Theory Prediction Pipeline

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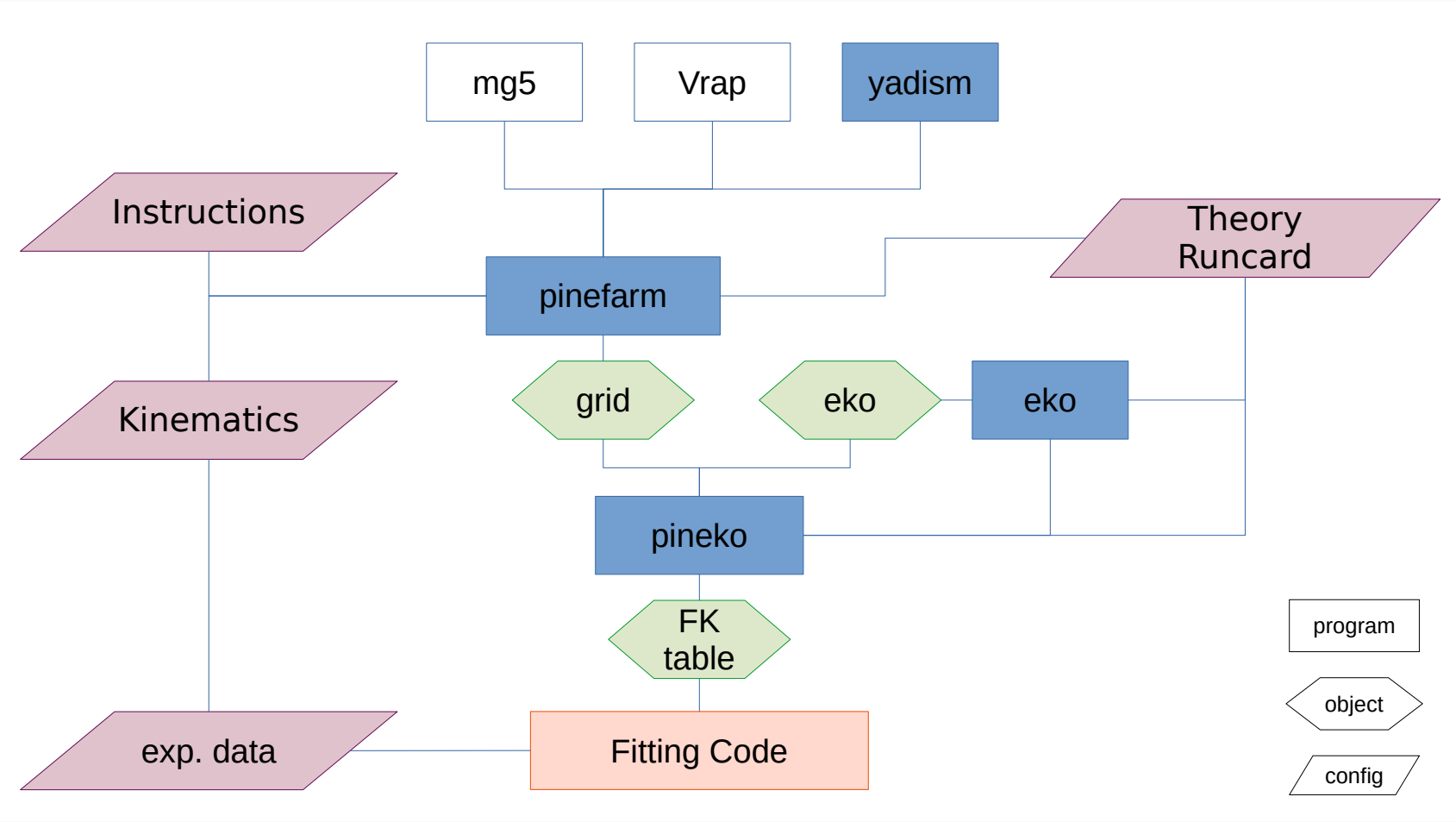


The workhorse in the background: `PineAPPL`

2. PineAPPL [JHEP12.108]

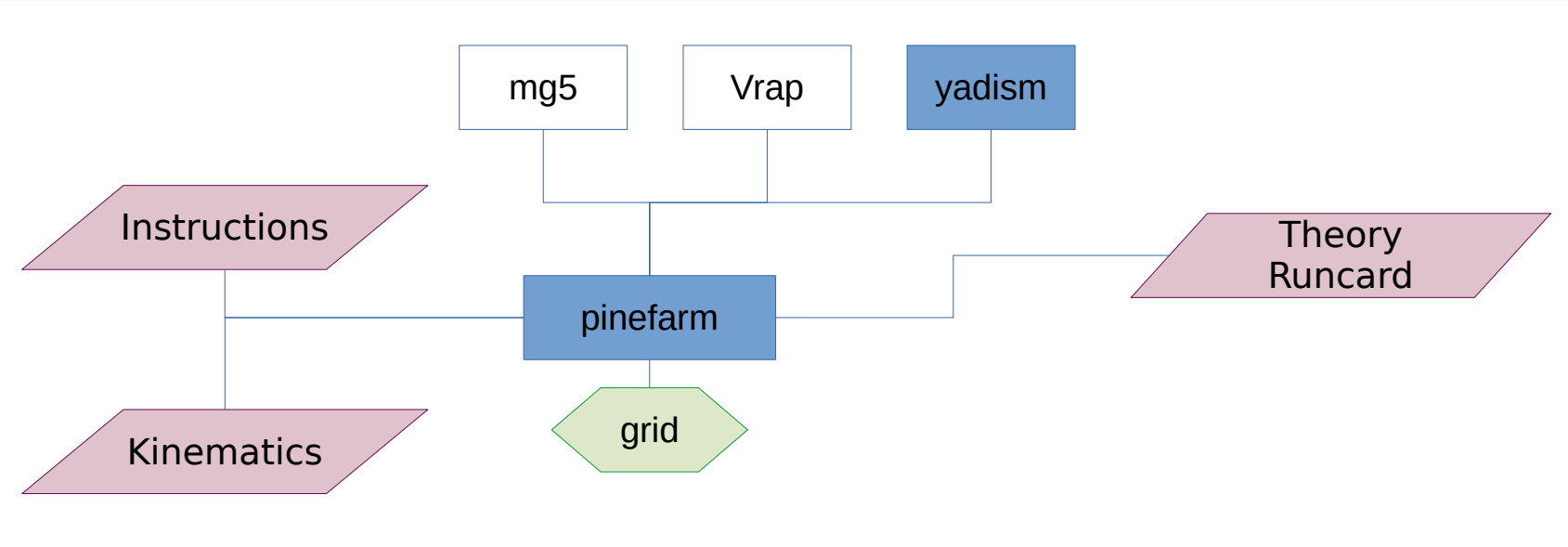
About PineAPPL

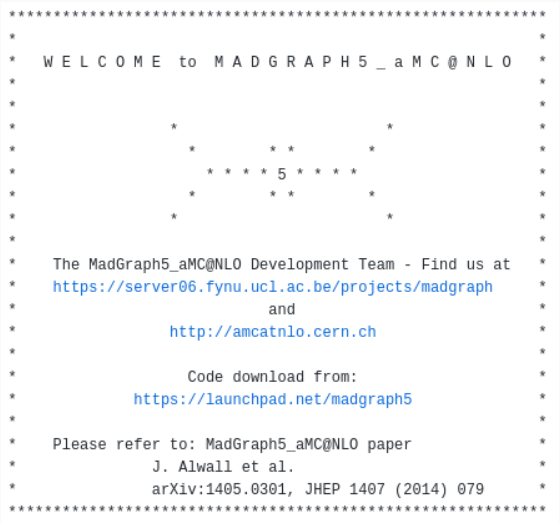
PineAPPL is a fast interpolation grid library that

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

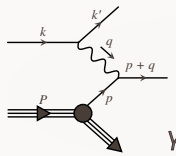
https://github.com/NNPDF/pineappl
https://nnpdf.github.io/pineappl/

Interface to Other Programs: `pinefarm`





[JHEP07.079]



Yadism

Yet Another DIS Module

[in preparation]

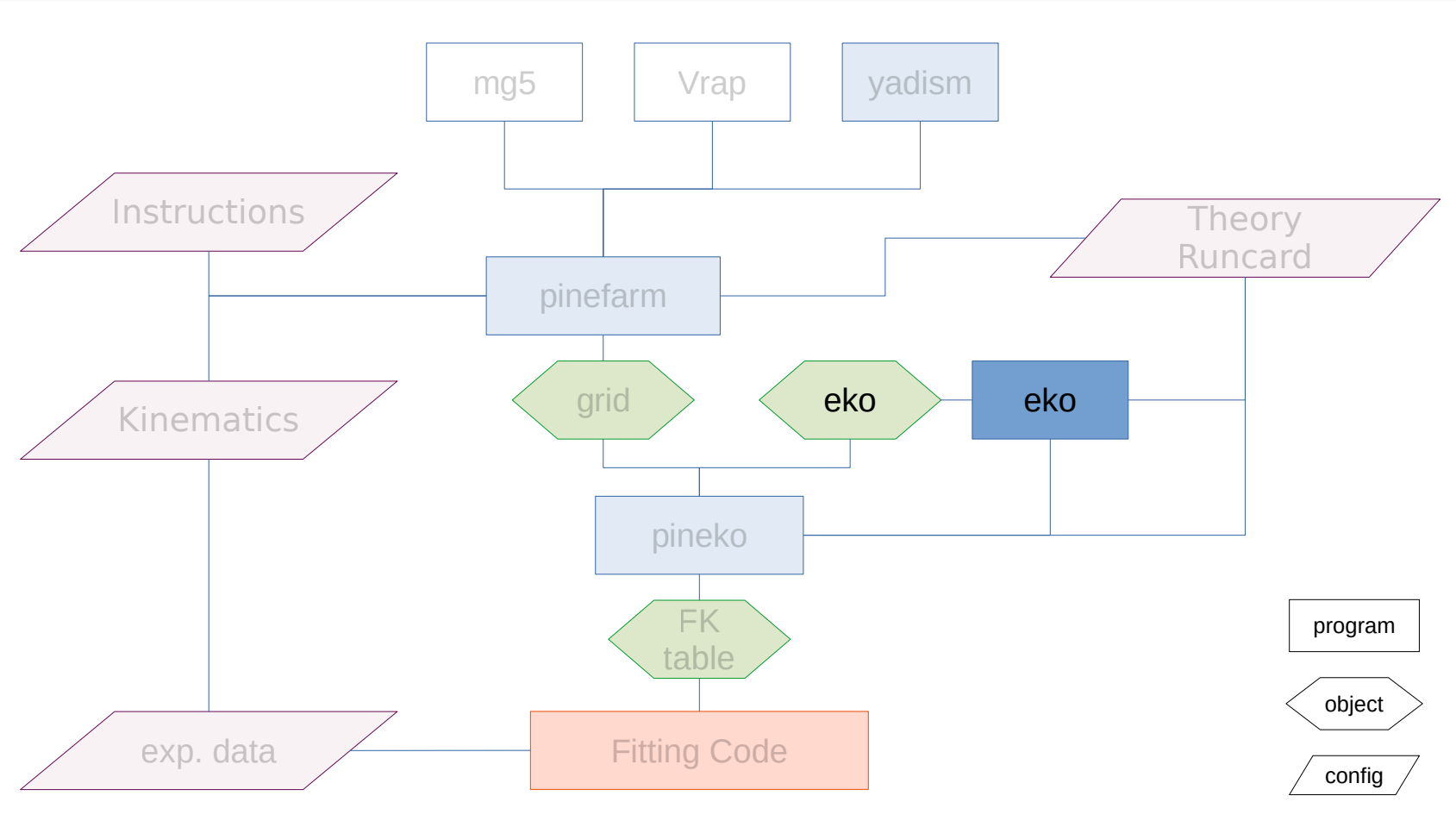
Vrap [PRD69.094008]

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) $\mathbf{E}$:

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

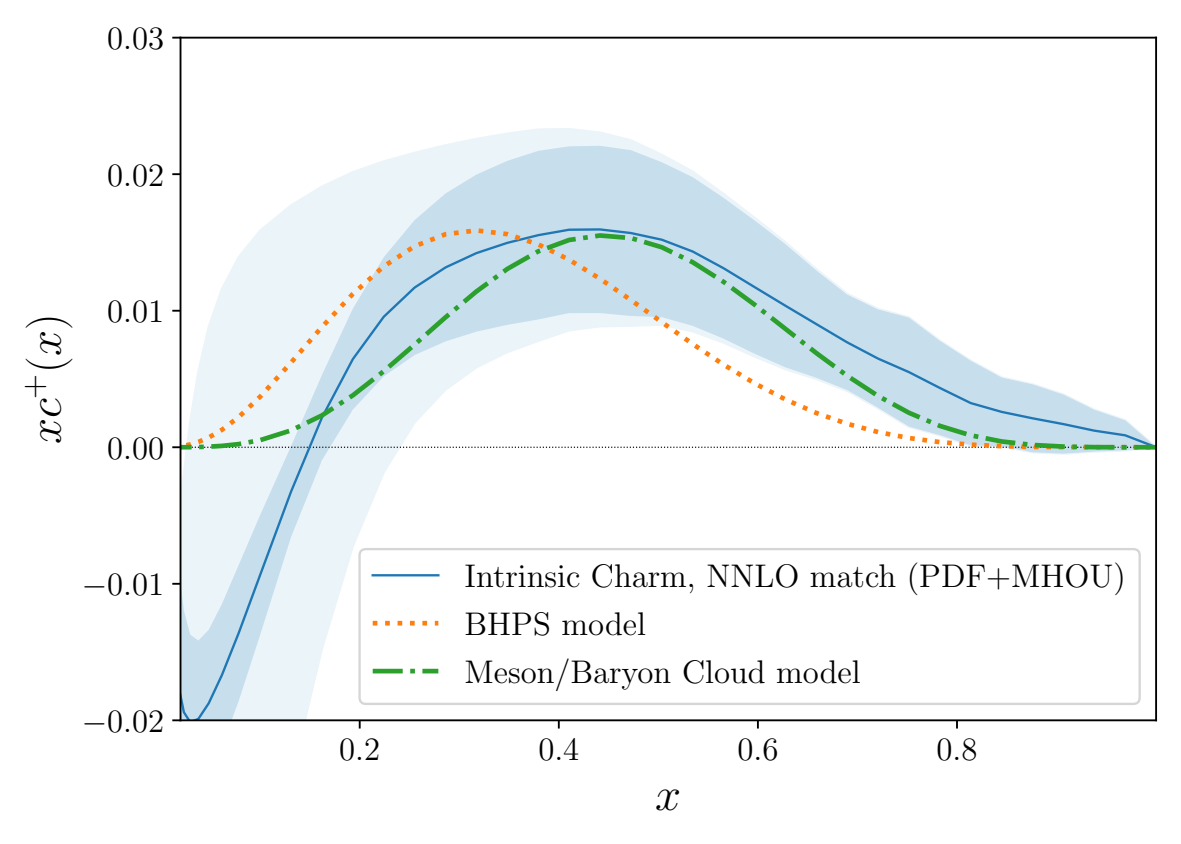
with

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

`https://github.com/NNPDF/eko`

`https://eko.readthedocs.io`

Evidence for Intrinsic Charm [Nature608.483]

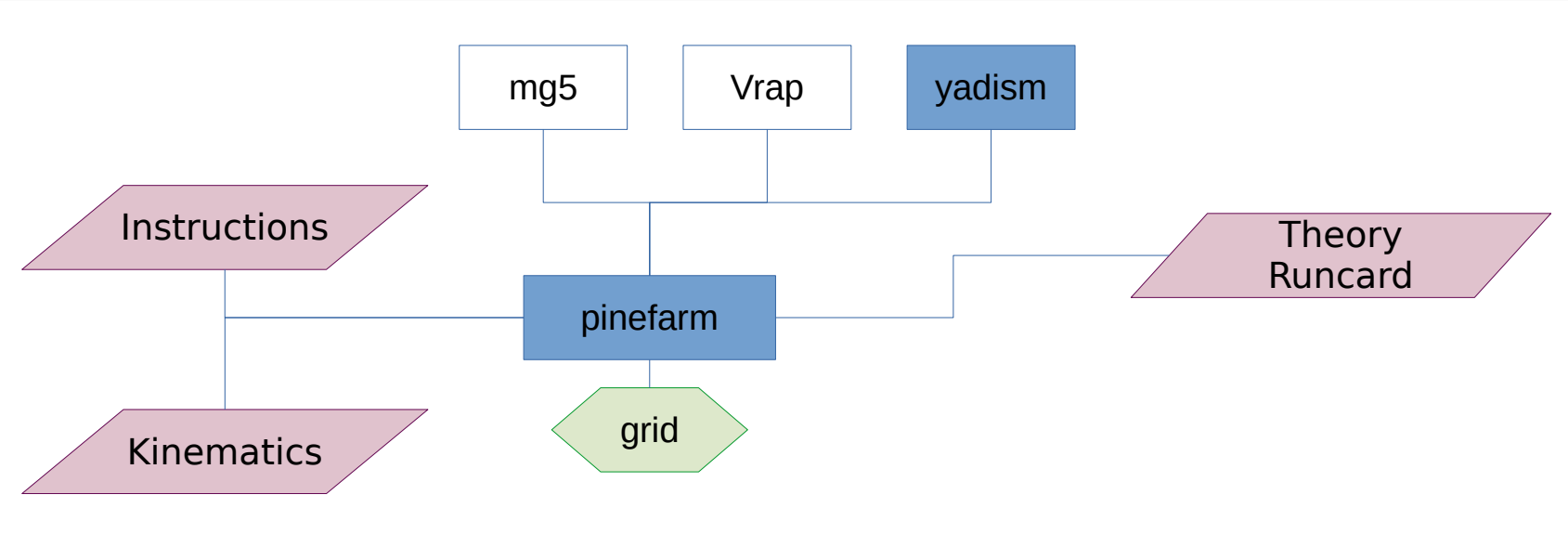


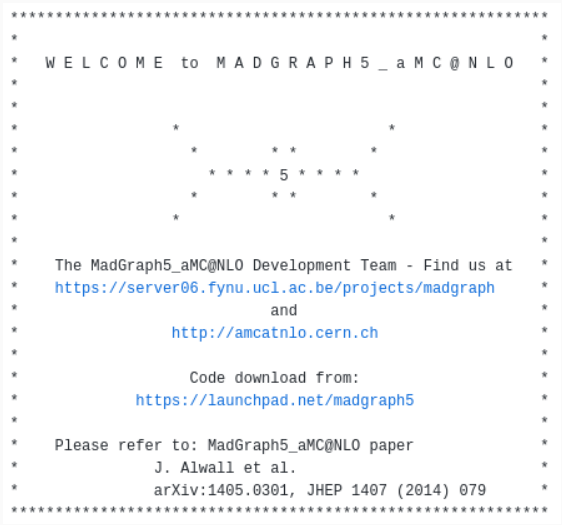
[BHPS] or [Meson/Baryon Cloud Model]

- 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%**

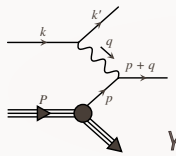
4. yadism [in preparation]

Interface to Other Programs: `pinefarm`





[JHEP07.079]



Yadism

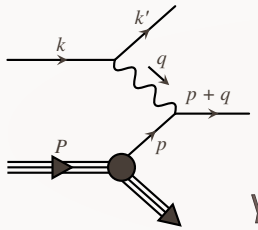
Yet Another DIS Module

[in preparation]

Vrap [PRD69.094008]

more MC interfaces coming soon

yadism Physics Features



Yadism

Yet Another DIS Module

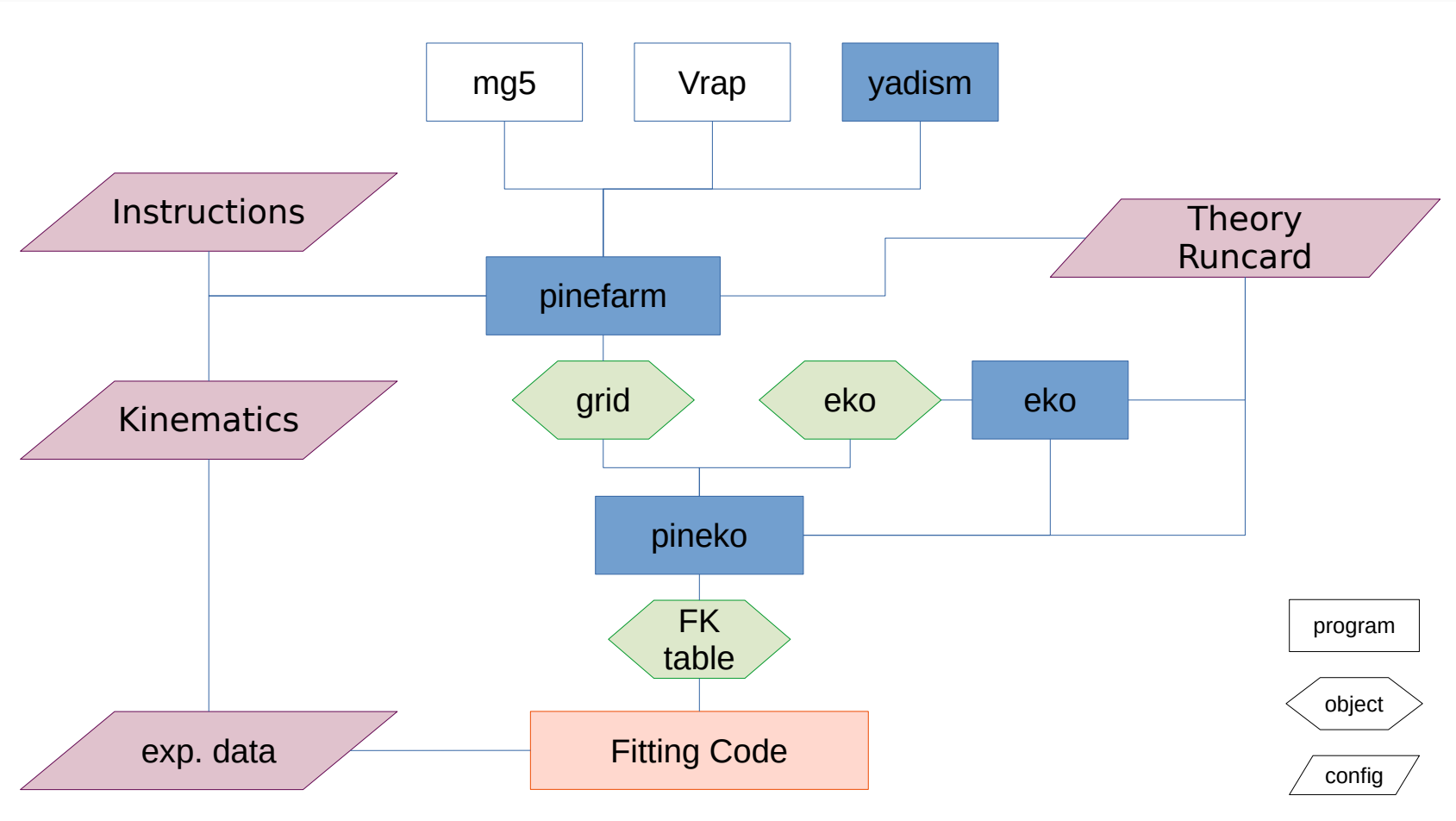
- DIS coefficient function database
- independent of boundary condition $\rightarrow$ PDF fitting
- separate features: target mass corrections, different Flavor Number Schemes
- PineAPPL interface

https://github.com/NNPDF/yadism

https://yadism.readthedocs.io

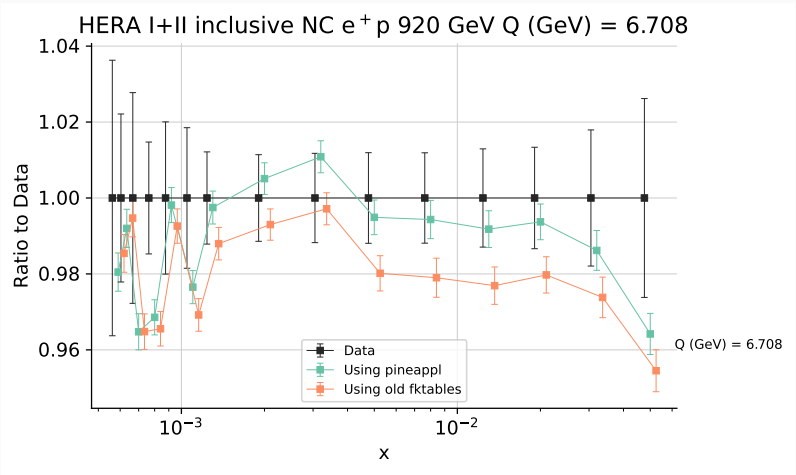
New Theory Prediction Pipeline

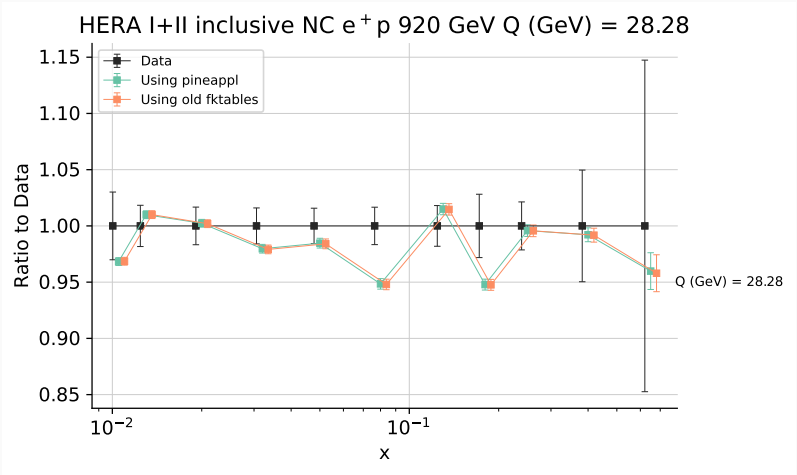
Produce FastKernel (FK) tables!

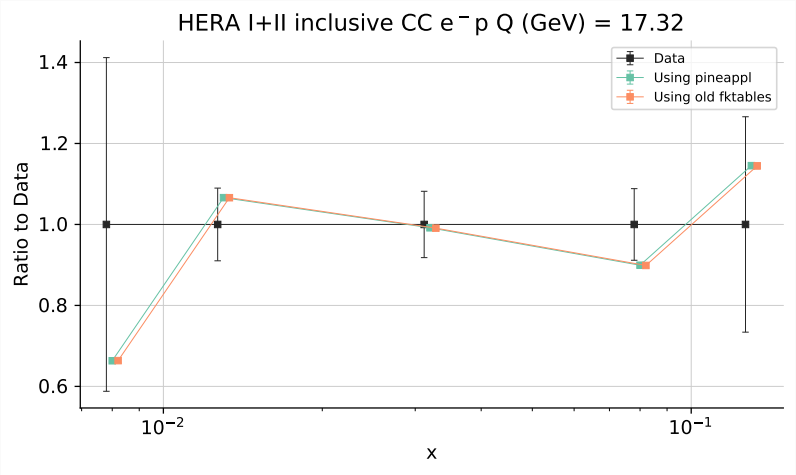


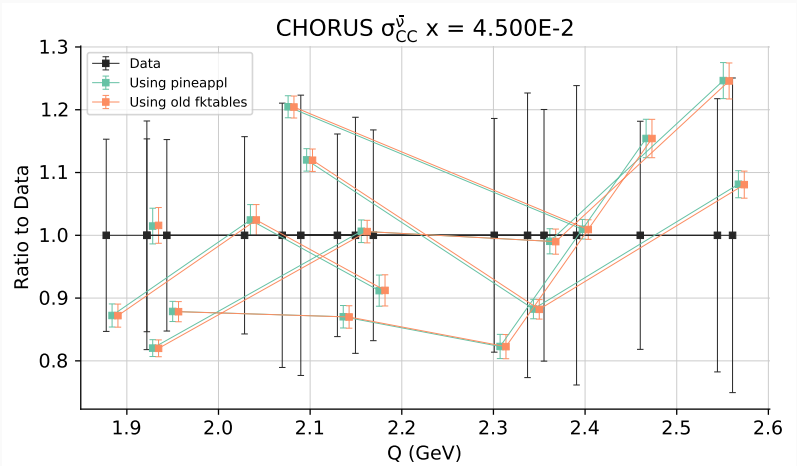
The workhorse in the background: `PineAPPL`

Comparison `yadism` against `APFEL`









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

5. banana

banana

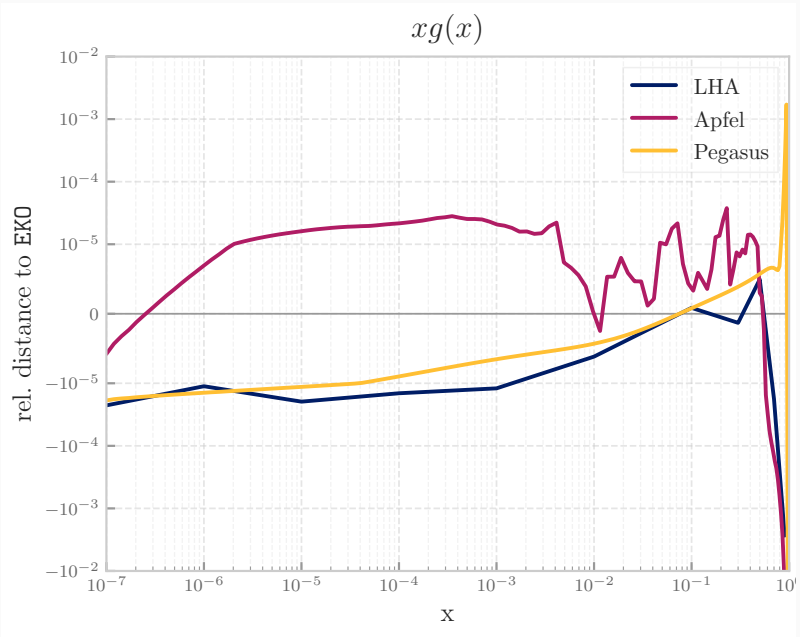
- do a constant benchmark against external programs: `APFEL`, `PEGASUS`, ...
- provide a benchmarking system and benchmark tools (e.g. fake PDFs)
- provide a navigator to browse comparisons - based on top of IPython

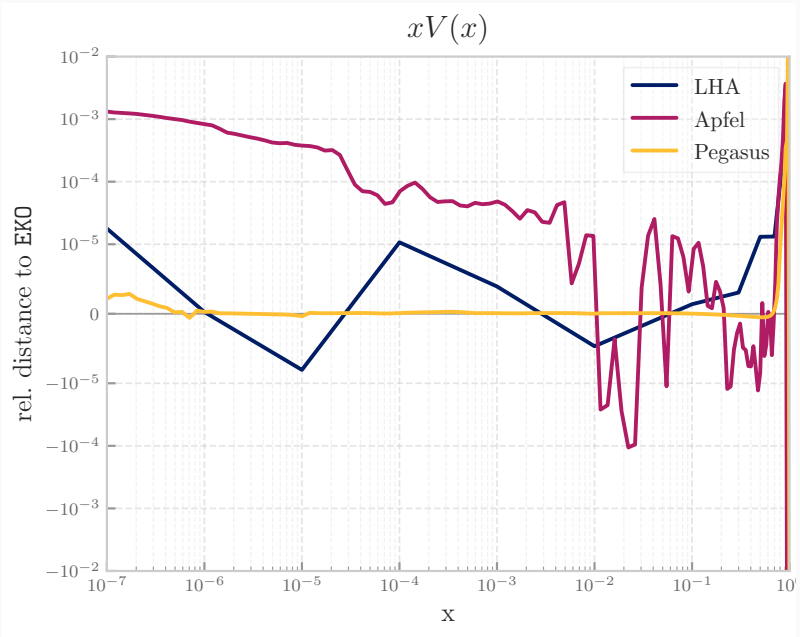
`https://github.com/N3PDF/banana`

`https://banana-hep.readthedocs.io`

EKO Benchmarks

LHA benchmark [0204316][0511119]:





$\Rightarrow$ EKO is working!

6. Outlook

Outlook

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

New Theory Prediction Pipeline

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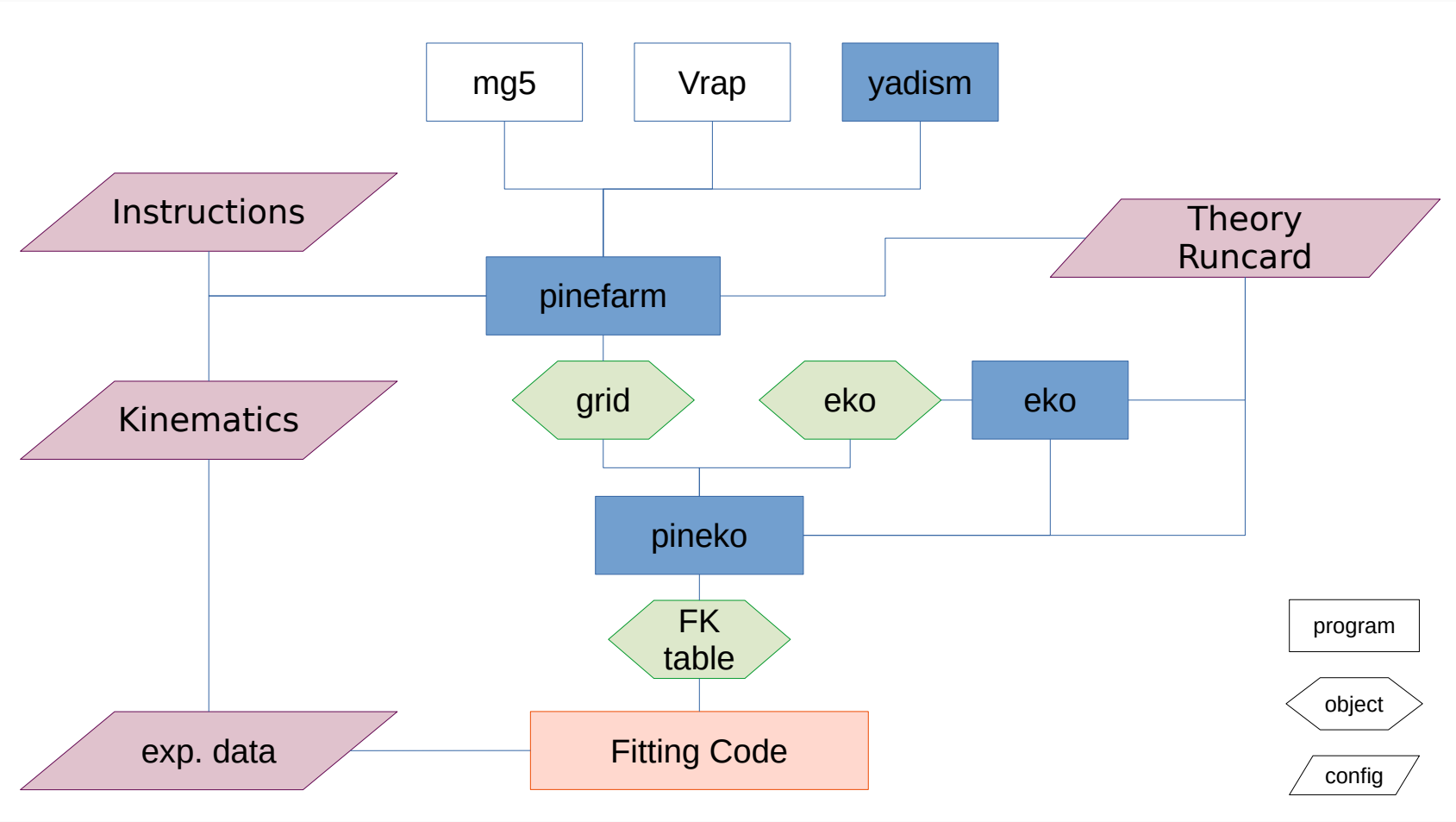


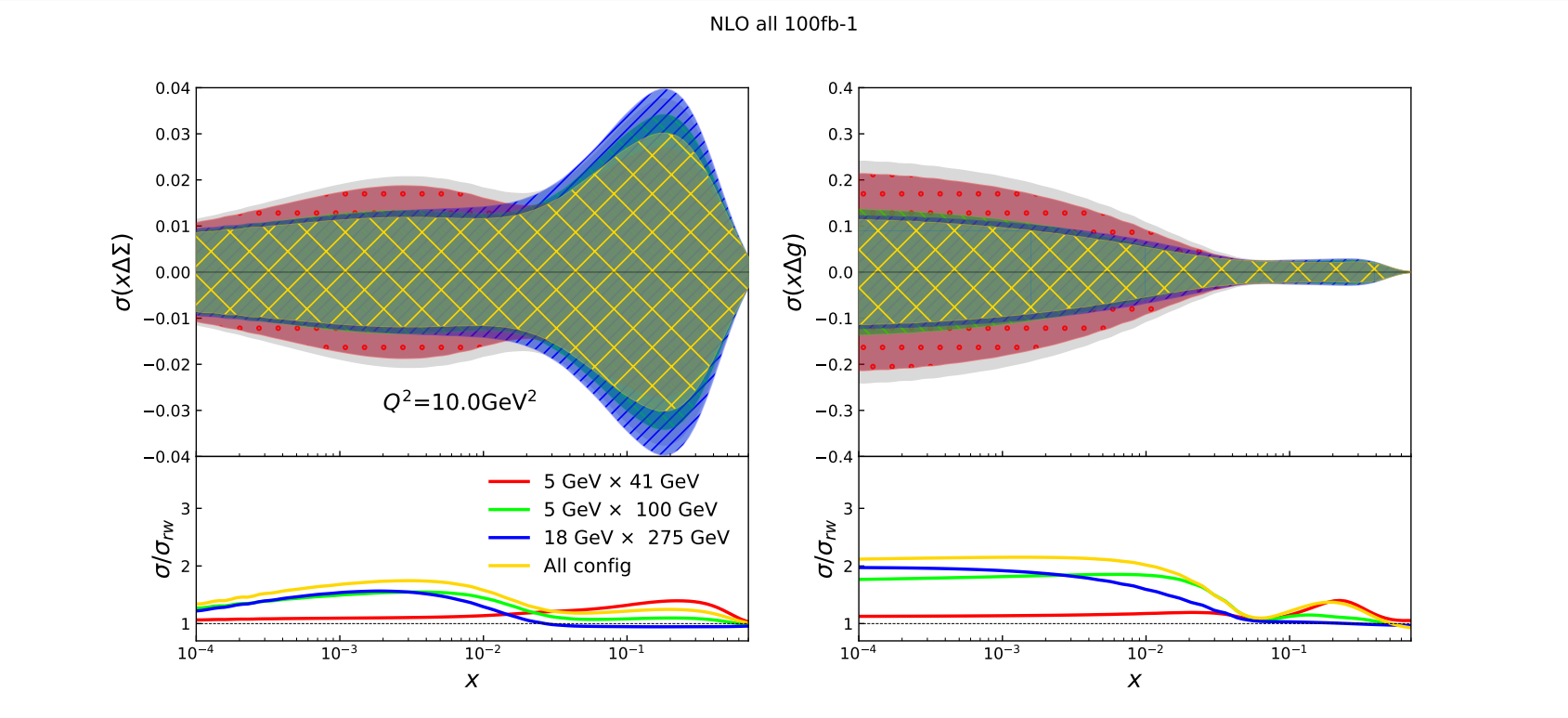
The workhorse in the background: `PineAPPL`

Thank you!

7. Backup slides

Reweighting

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



but a new PDF fit would be better!

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
- Backward VFNS evolution (i.e. across thresholds and with intrinsic)

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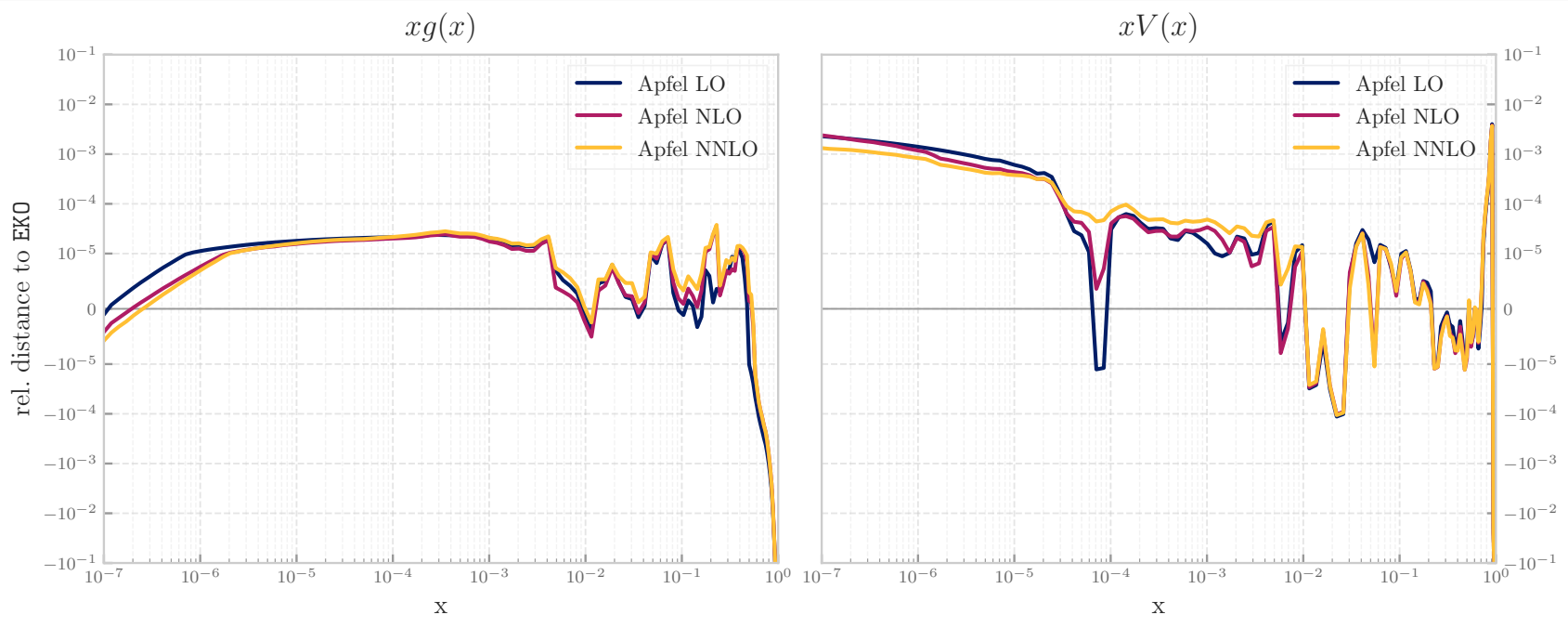
with $\mathbf{R}^{(n_f)}$ a flavor rotation matrix and $\tilde{\mathbf{A}}^{(n_f)}(\mu_h^2)$ the operator matrix elements (partially known up to $\mathrm{N^3LO}$)

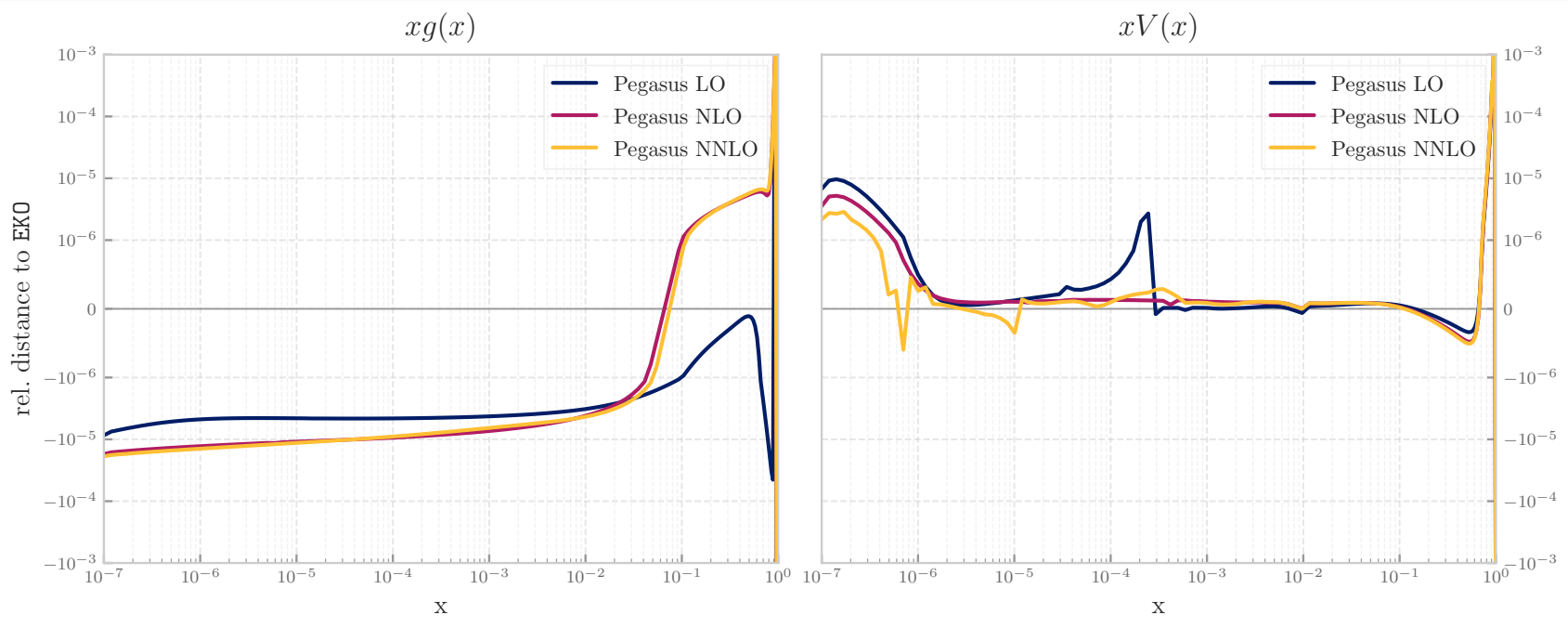
for backward evolution:

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

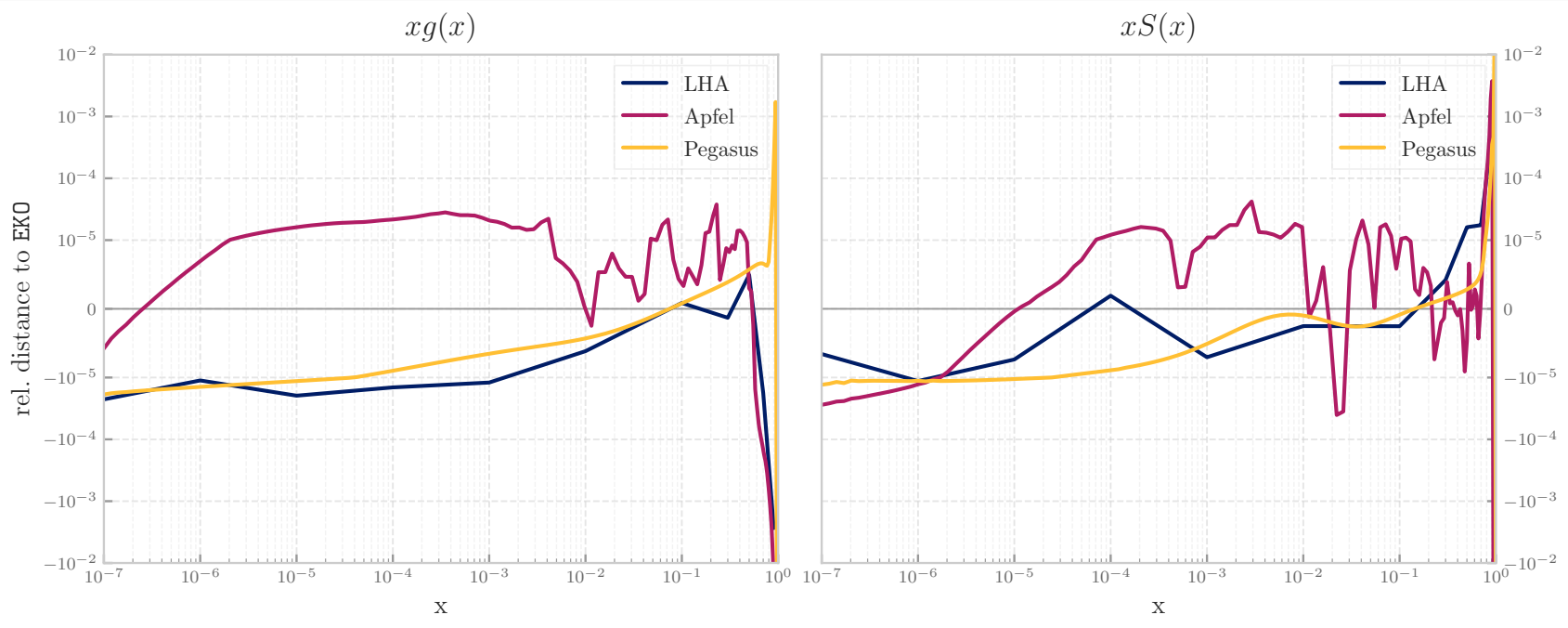
EKO APFEL **benchmark**



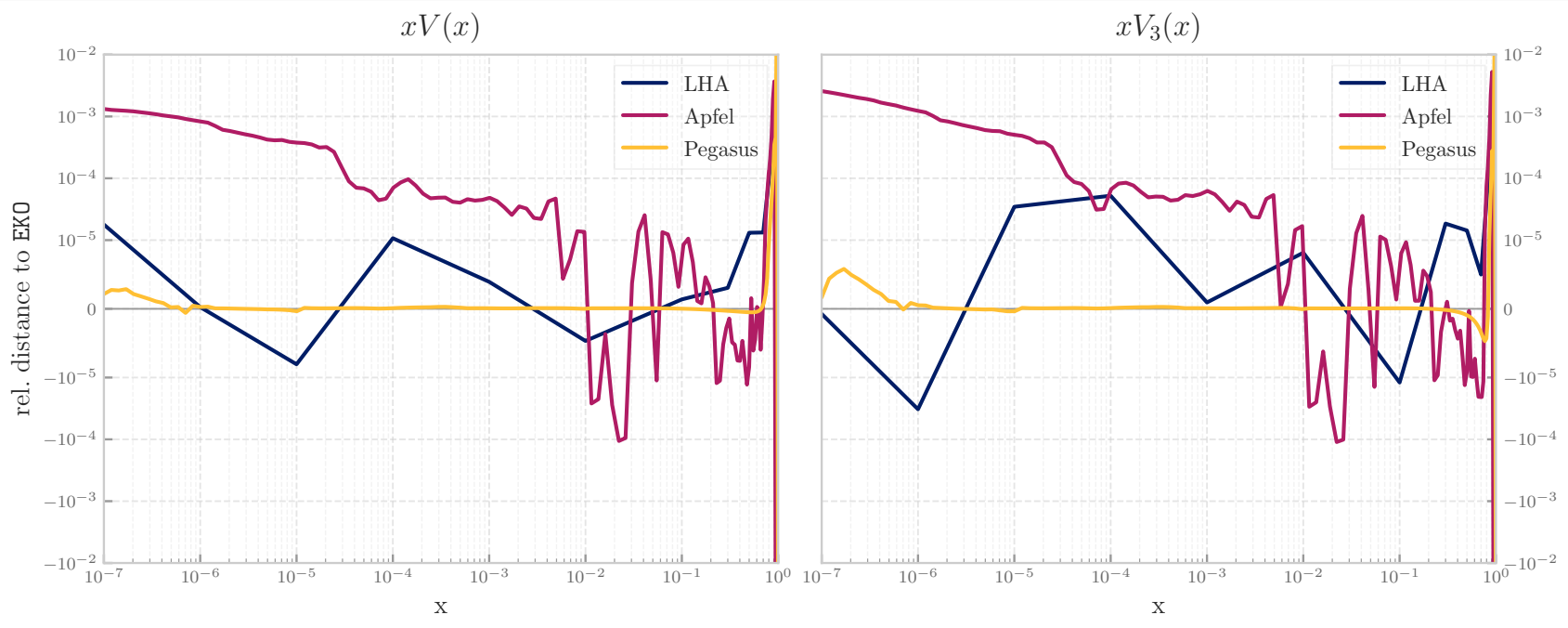
EKO PEGASUS **benchmark**



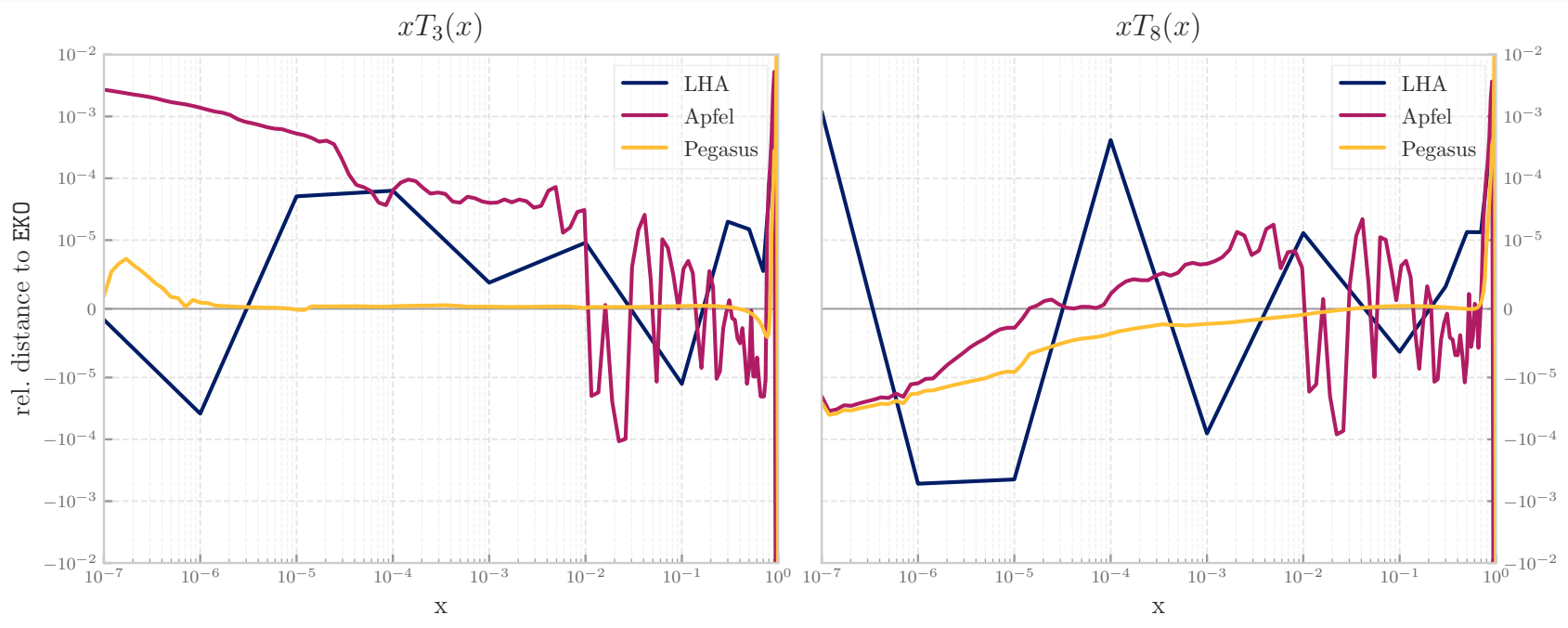
EKO LHA benchmark: g and Σ



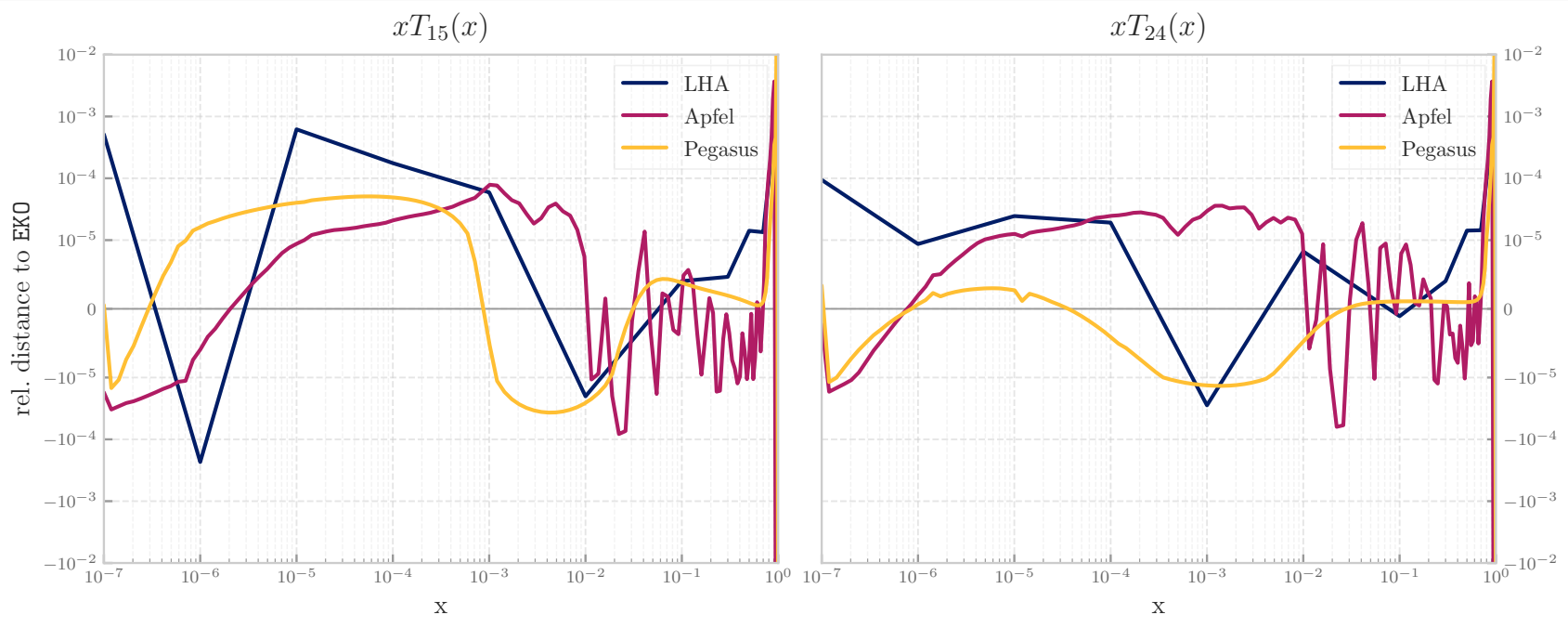
EKO LHA benchmark: V and V_3



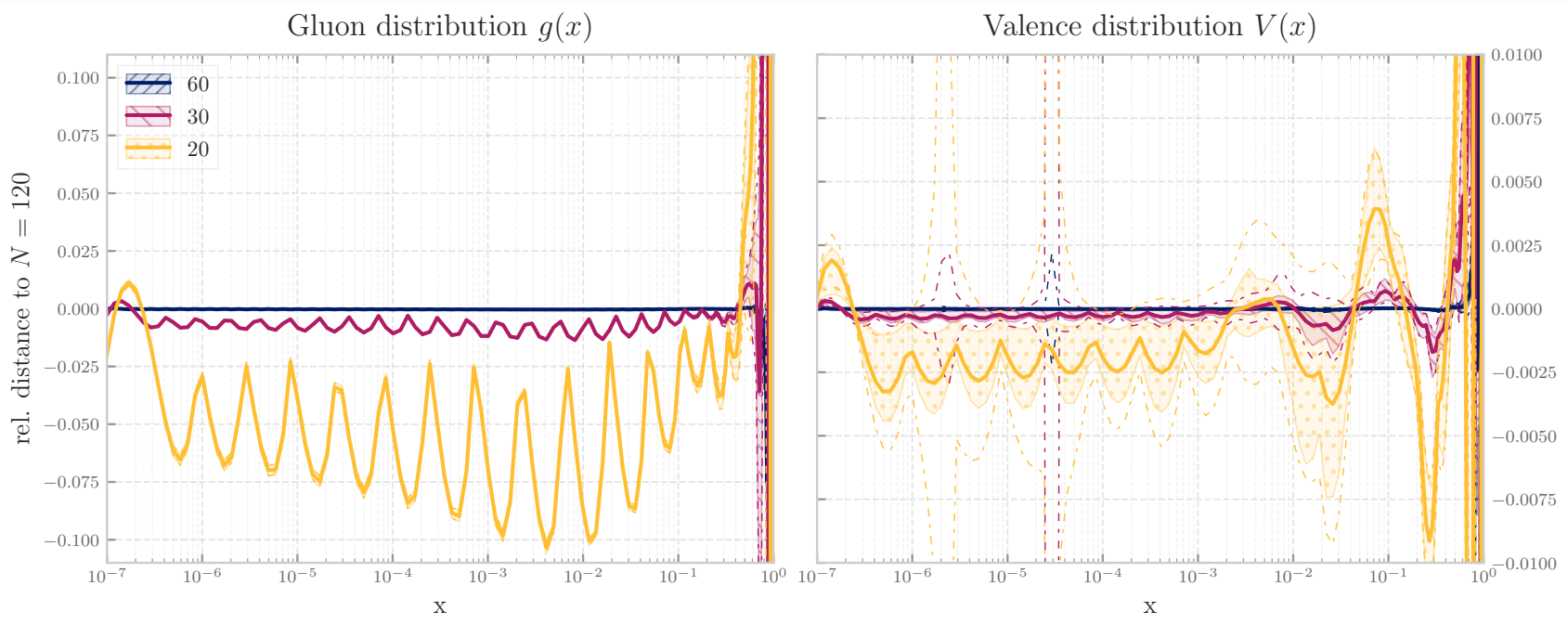
EKO LHA benchmark: T_3 and T_8



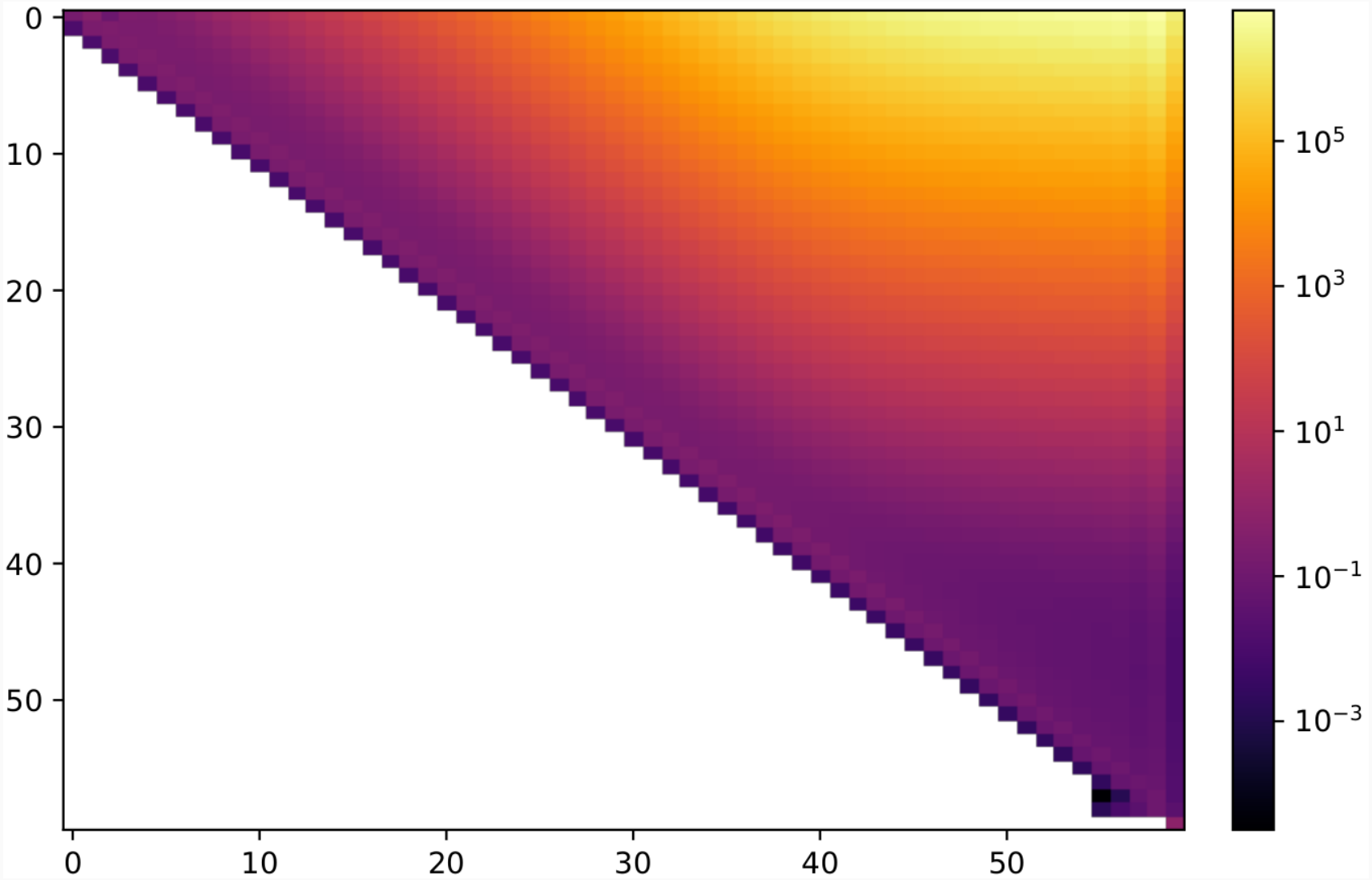
EKO LHA benchmark: T_{15} and T_{24}



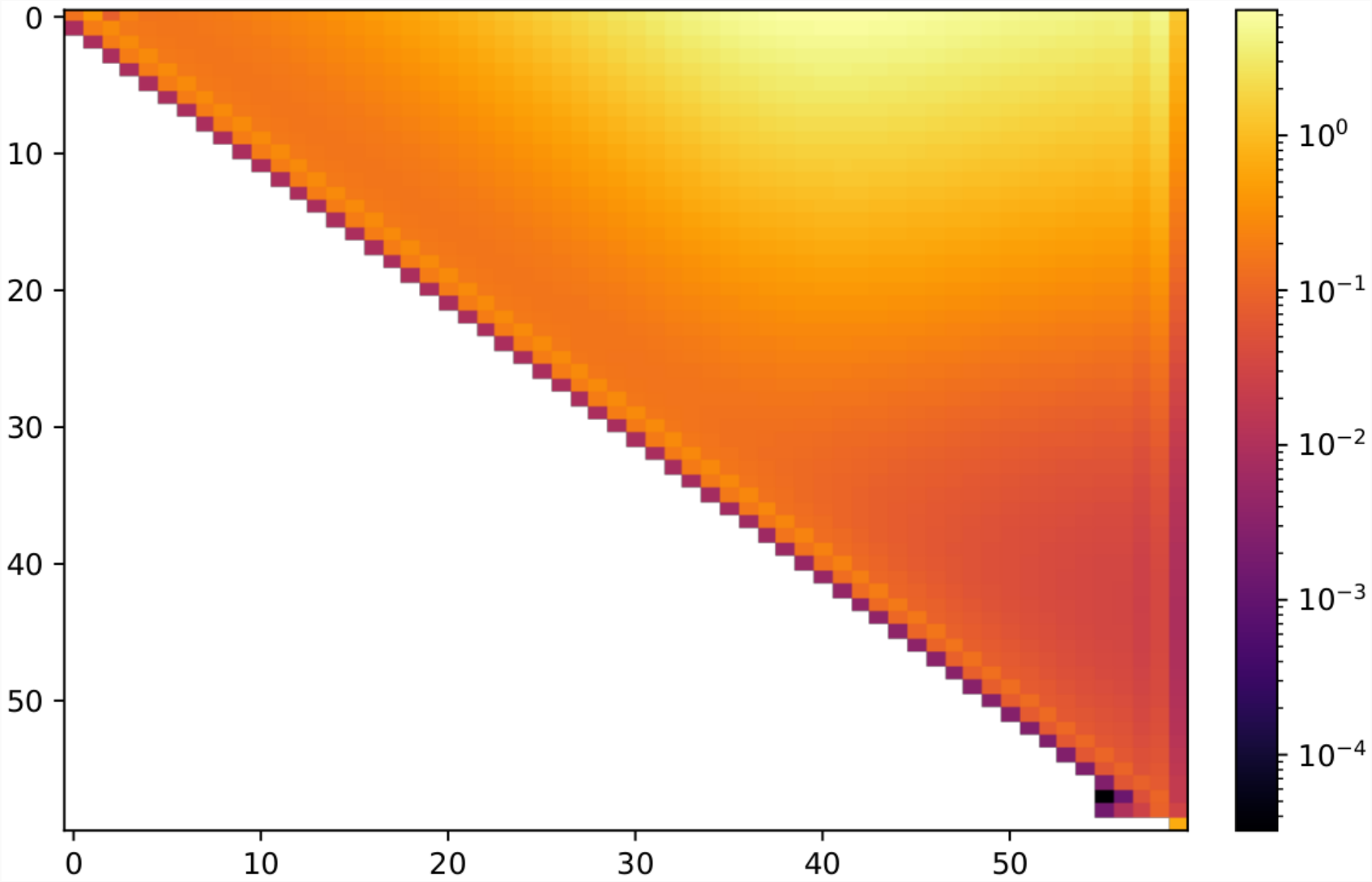
EKO Interpolation Error



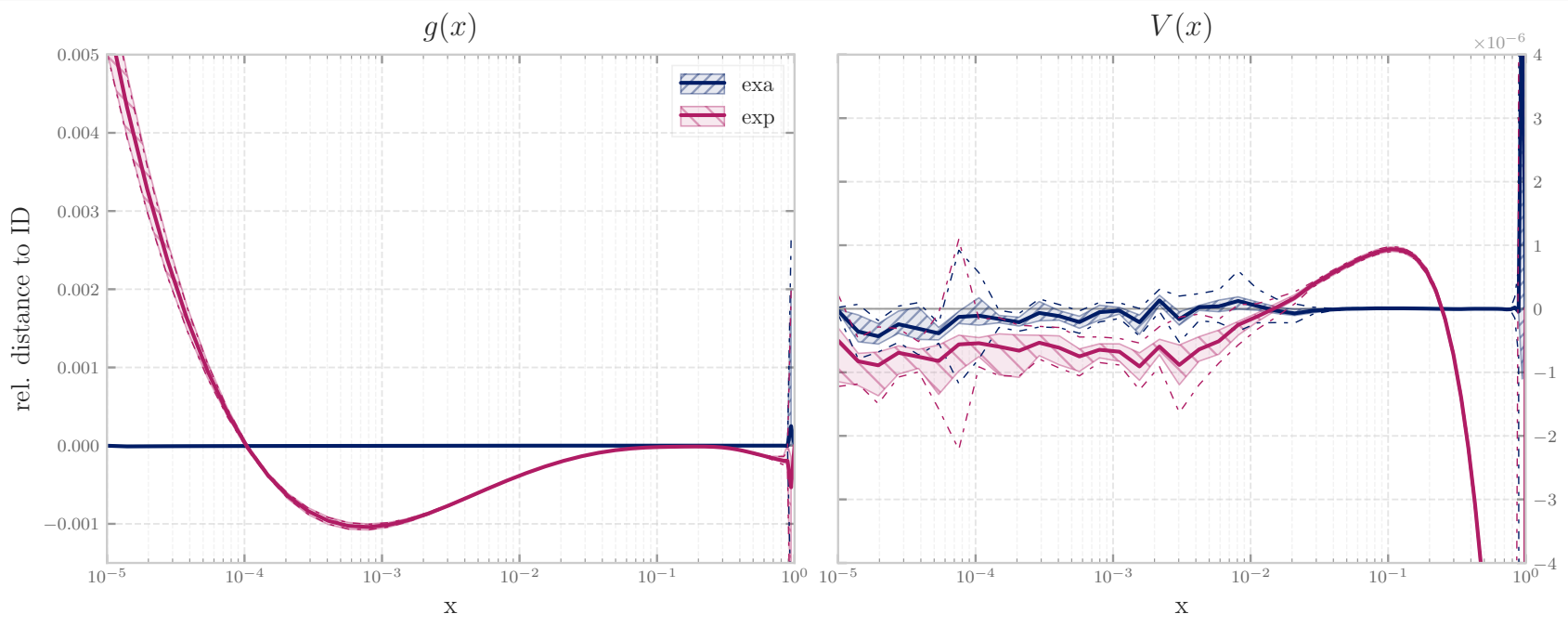
EKO Snapshot $S \leftarrow S$



EKO Snapshot $V \leftarrow V$

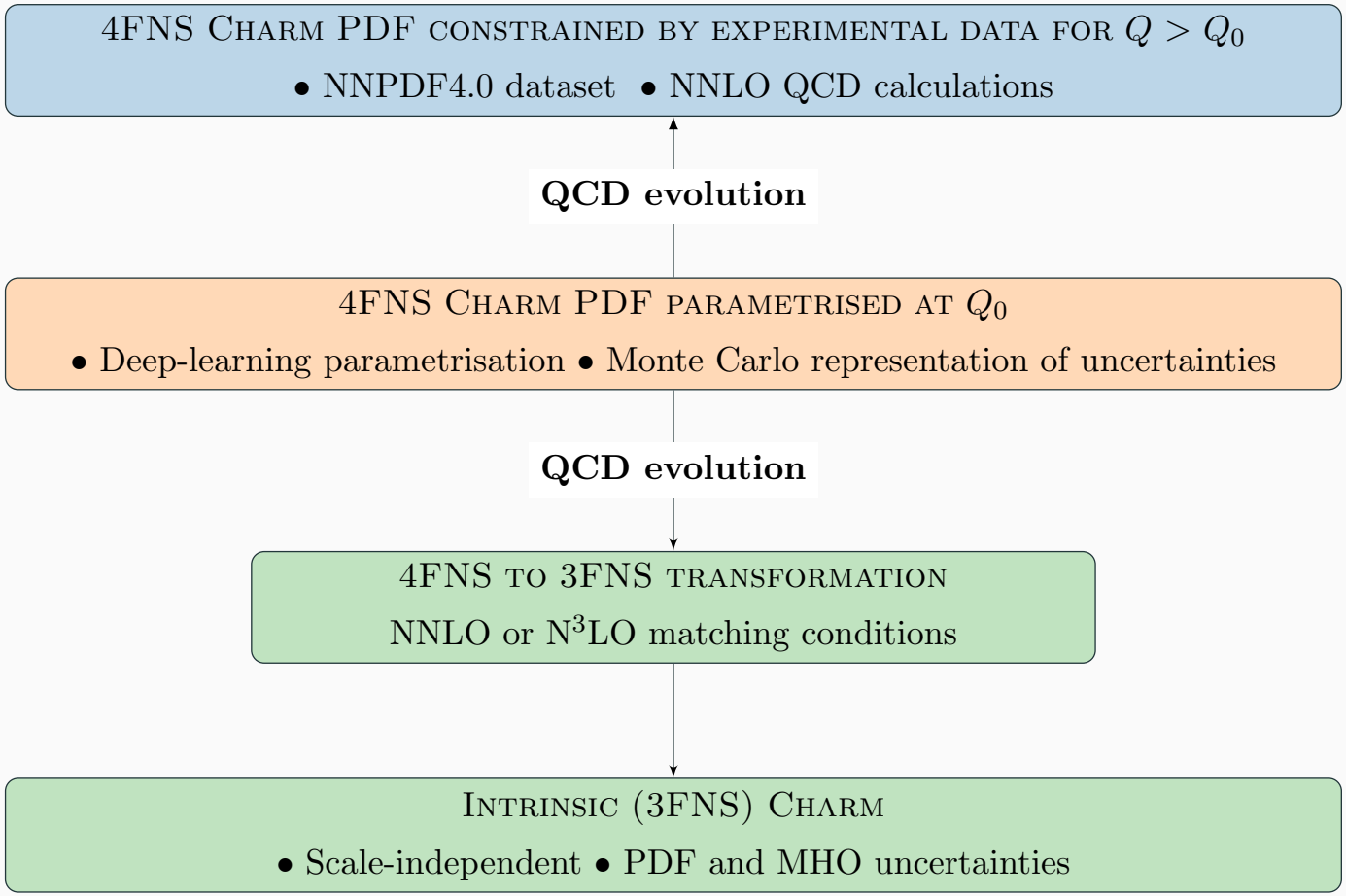


EKO Backward Evolution

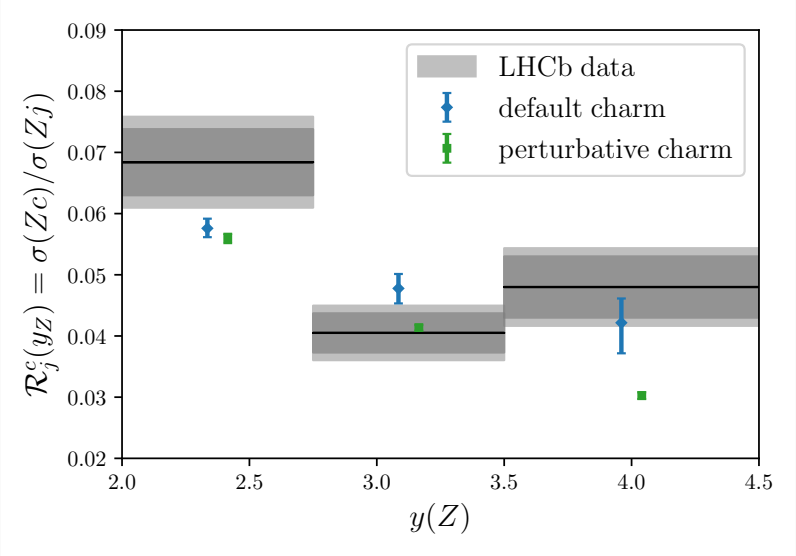


Intrinsic Charm: Strategy

based on NNPDF4.0 [EPJC82.428]

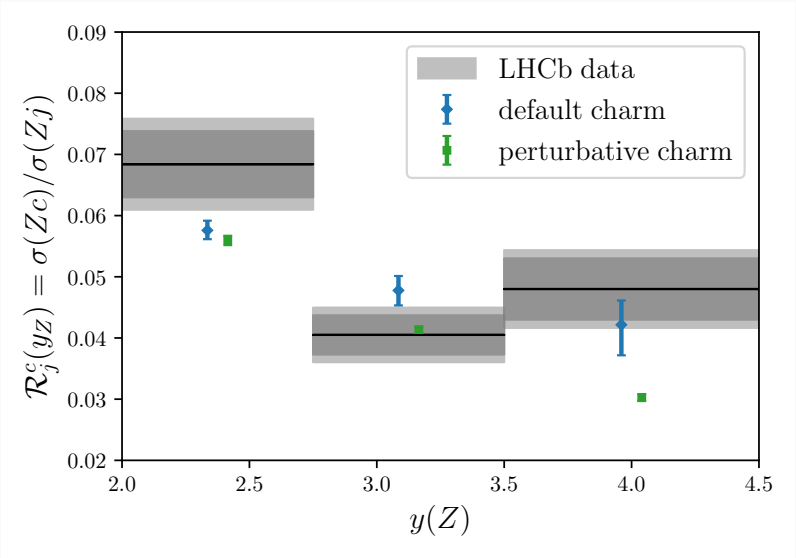


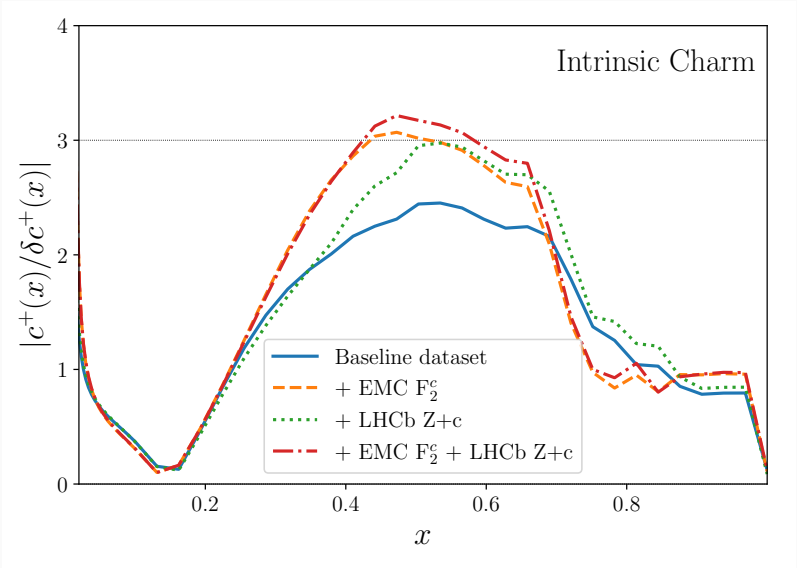
Intrinsic Charm: LHCb and Significance



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

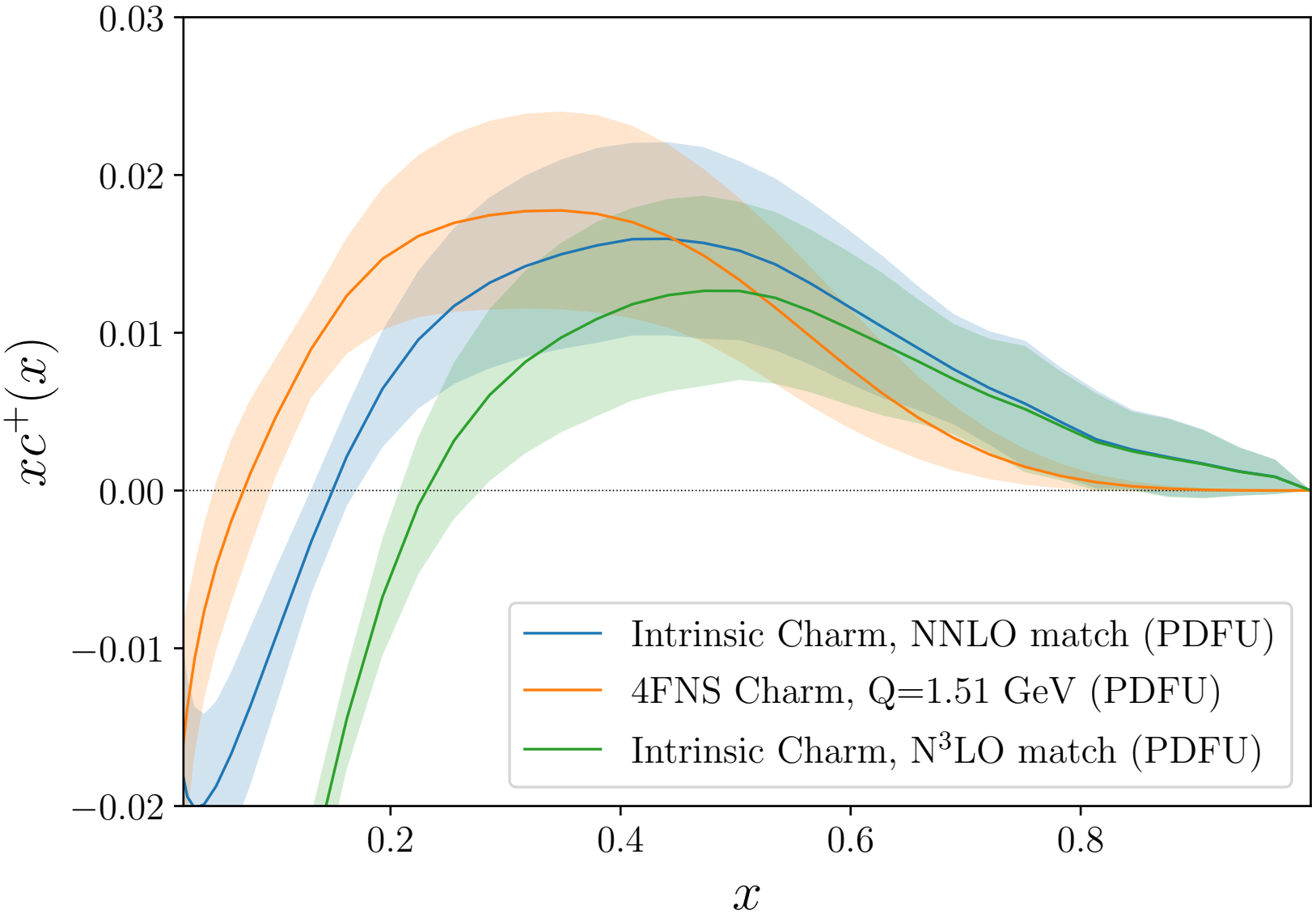
Intrinsic Charm: LHCb and Significance



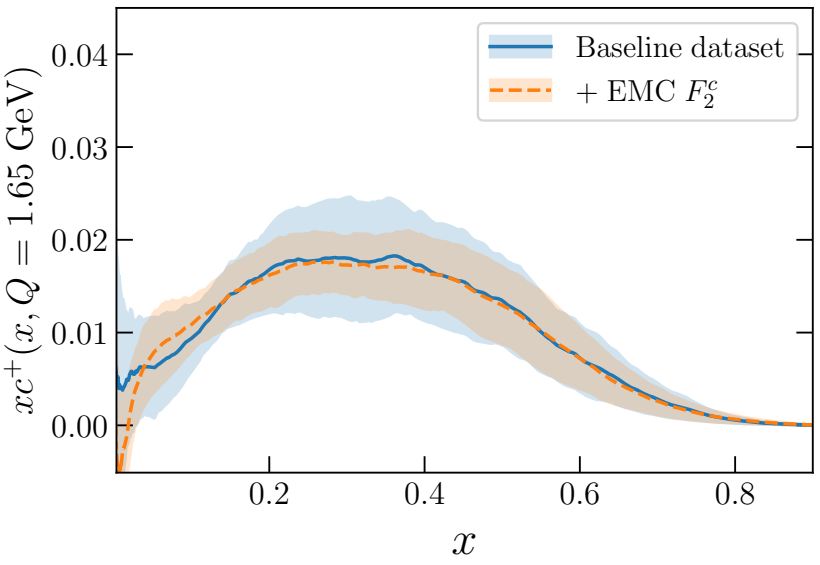


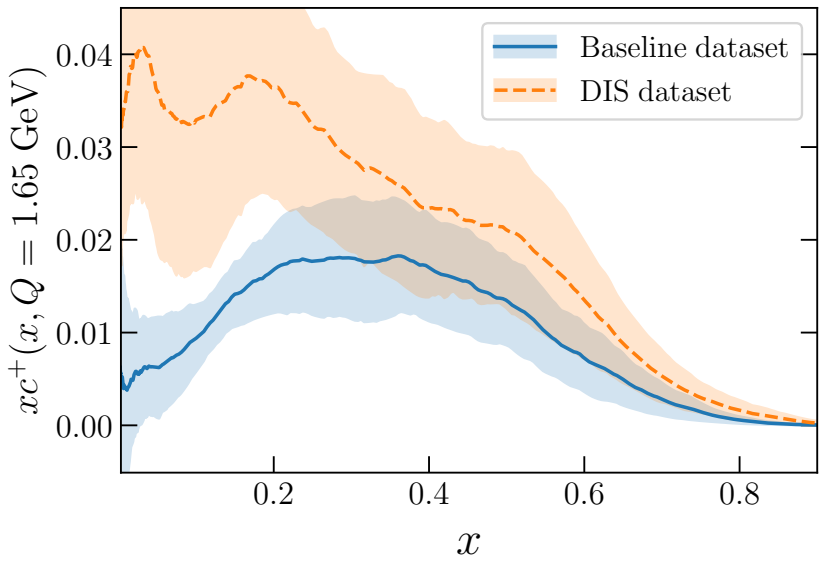
- match better recent **LHCb** Z+c measurement [PRL128.082001]
- we find a **3σ** evidence of intrinsic charm
- result is **stable** with mass variation, dataset variation

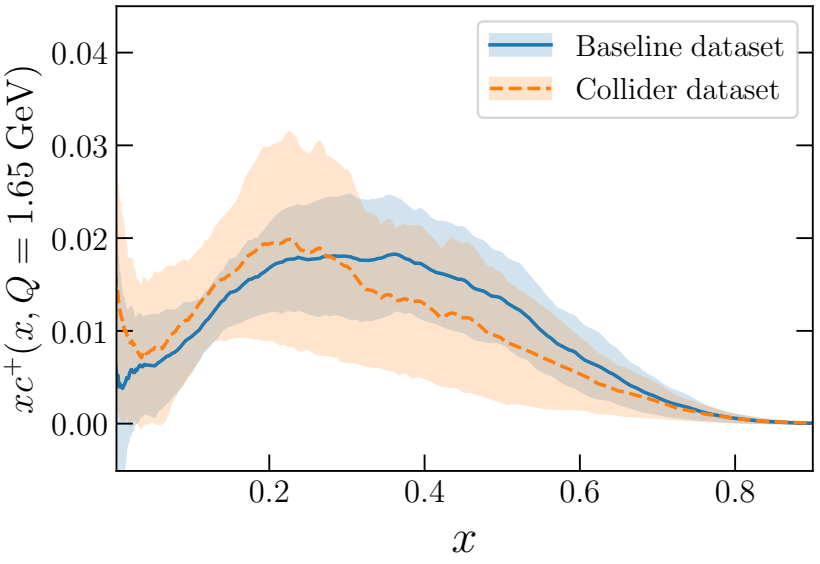
IC - uncertainties splitted

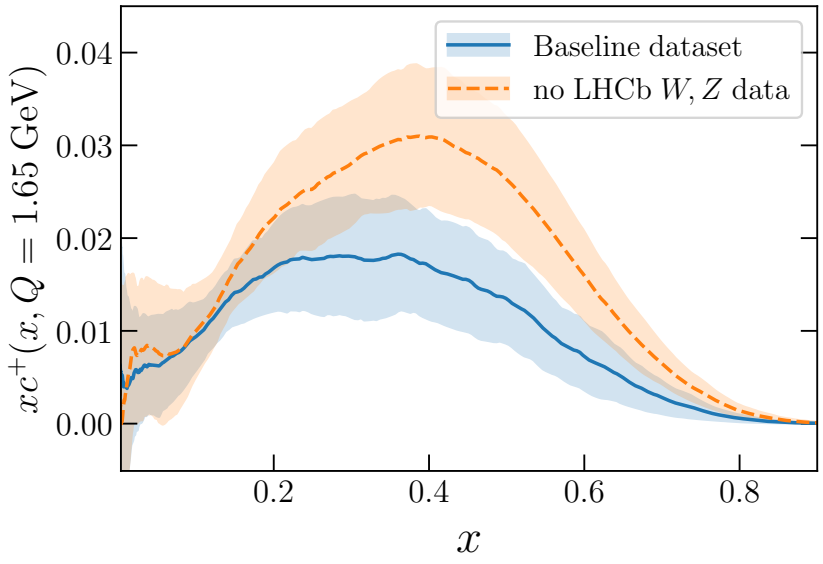


IC - dataset variation

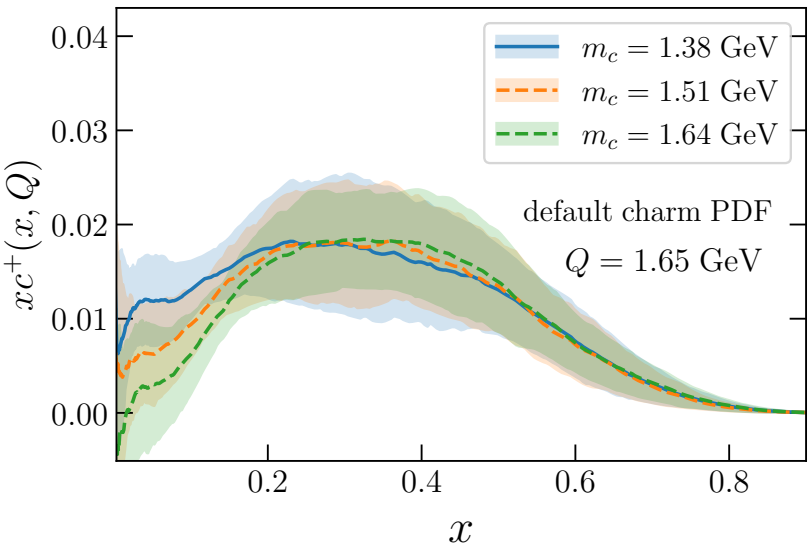


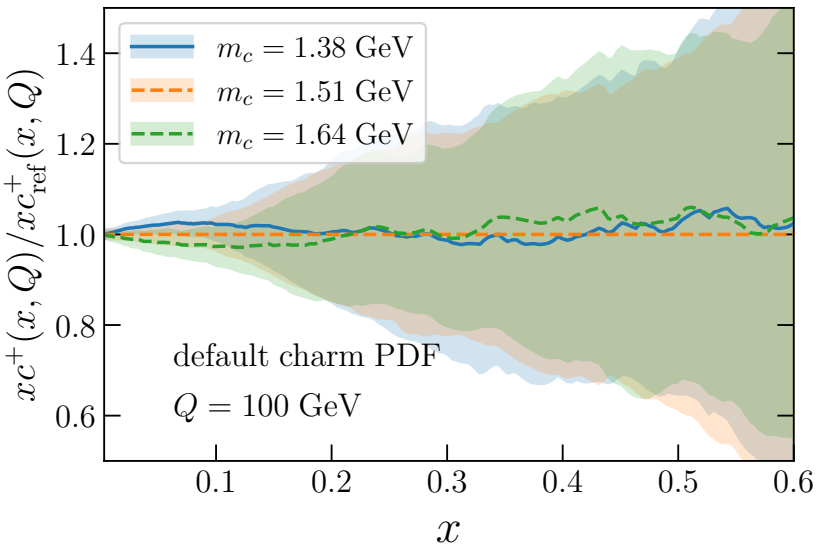


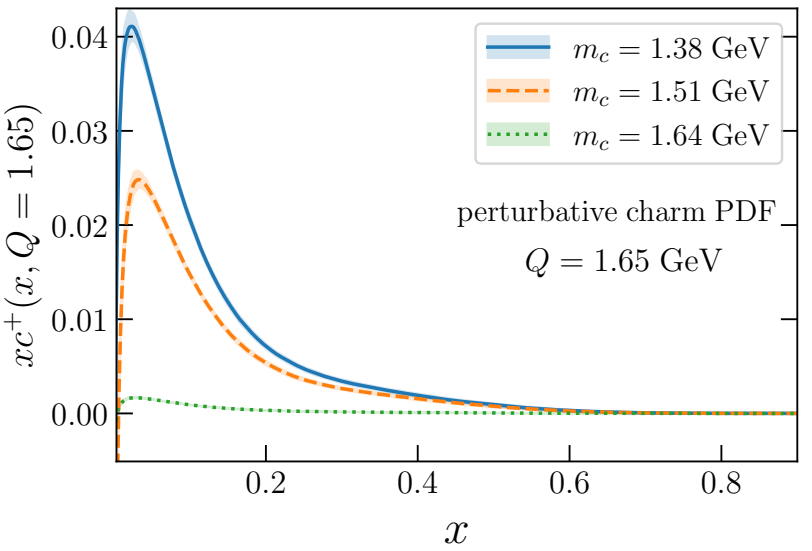


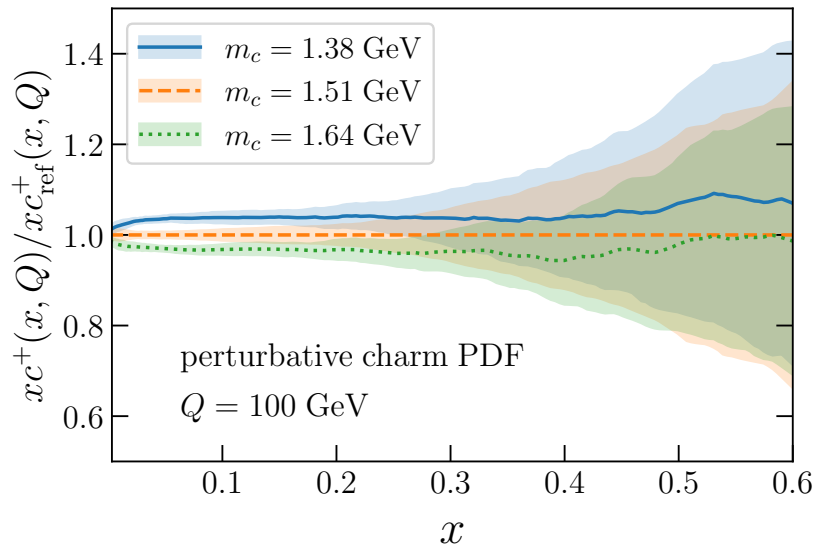


IC - mass variation









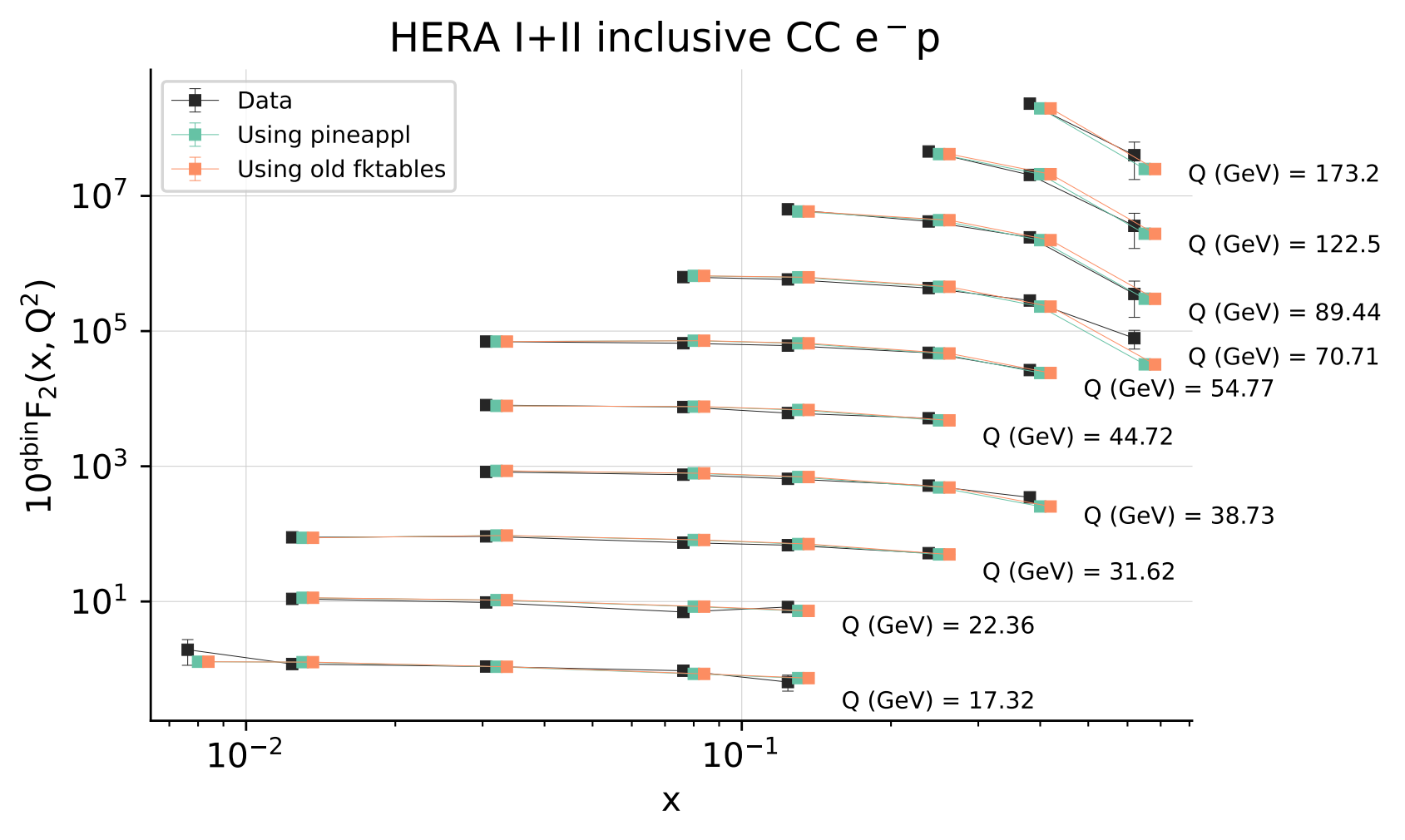
`yadism` Coefficient Functions

- 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

Comparison `yadism` against `APFEL`



Comparison `yadism` against `APFEL`