Evidence for intrinsic charm quarks in the proton [Nature608.483]

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Jefferson Lab Remote Theory Seminar June 2023

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Snowmass 1984

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INTRINSIC CEEVROLETS AT THE SSC

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Summary

The possibility of the production at high energy of heavy quarks, supersymmetric particles and other large mass colored systems via the intrinsic twist-six components in the proton wave function is discussed. While the existing data do not rule out the possible relevance of intrinsic charm production at present energies, the extrapolation of such intrinsic contributions to very high masses and energies suggests that they will not play an important role at the SSC.

sufficiently large. The data from the EMC collaboration[4] on deep-inelastic muon scattering could also be intepreted as suggesting an unexpectedly large charm structure function in the region $x > 0.3$.

The possible existence of such a new production mechanism is of great importance for design considerations at the SSC[5,6]. An example of the importance of this issue is that, if intrinsic large x production is dominant, experiments and, perhaps, even the machine should be designed to focus on the forward "diffractive" regime[5]. The ques-

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Evidence for intrinsic charm quarks in the proton

The NNPDF Collaboration

Nature **608**, 483–487 (2022) | Cite this article

Abstract

The theory of the strong force, quantum chromodynamics, describes the proton in terms of quarks and gluons. The proton is a state of two up quarks and one down quark bound by gluons, but quantum theory predicts that in addition there is an infinite number of quark–antiquark pairs. Both light and heavy quarks, whose mass is respectively smaller or bigger than the mass of the proton, are revealed inside the proton in high-energy collisions. However, it is unclear whether heavy quarks also exist as a part of the proton wavefunction, which is determined by non-perturbative dynamics and accordingly unknown: so-called intrinsic heavy quarks[1]. It has been argued for a long time that the proton could have a sizable intrinsic component of the lightest heavy quark, the charm quark. Innumerable efforts to

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NIEUWS

Proton bevat een wonderlijk extra deeltje: de 'charm quark'

Protonen, fundamentele bouwstenen van alle materie, blijken een nieuw ingrediënt te bevatten: de 'charm quark'. Natuurkundigen reageren opgetogen: 'Verbazingwekkend dat er nog iets nieuws valt te leren over een oude bekende als het proton.'

Frank Rensen 17 augustus 2022, 21:55

WIRED

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Une étude confirme que le proton possède un quark charm intrinsèque

Un nuovo studio fa luce su una sorprendente caratteristica della struttura dei protoni

Pubblicato sulla rivista *Nature* spiega come anche i quark charm, insieme ai più noti e leggeri quark up e quark down, siano da annoverarsi tra i componenti intrinseci dei costituenti atomici, confermando un'ipotesi elaborata oltre 40 anni fa

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Physicists surprised to discover the proton contains a charm quark

The textbook description of a proton says it contains three smaller particles - two up quarks and a down quark - but a new analysis has found strong evidence that it also holds a charm quark

Outline

0. Introduction

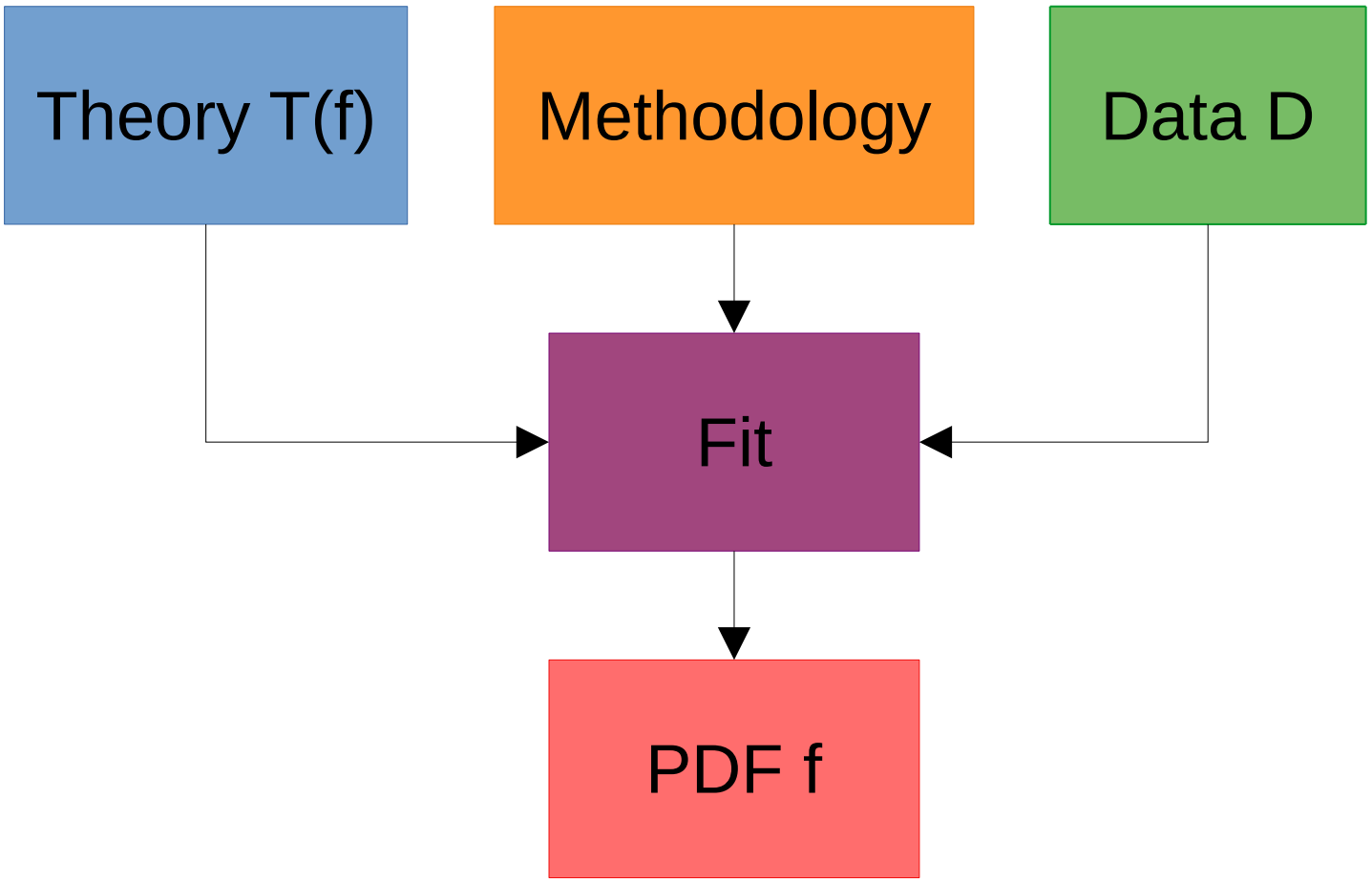
1. NNPDF4.0 [EPJC82.428]

2. Intrinsic Charm [Nature608.483]

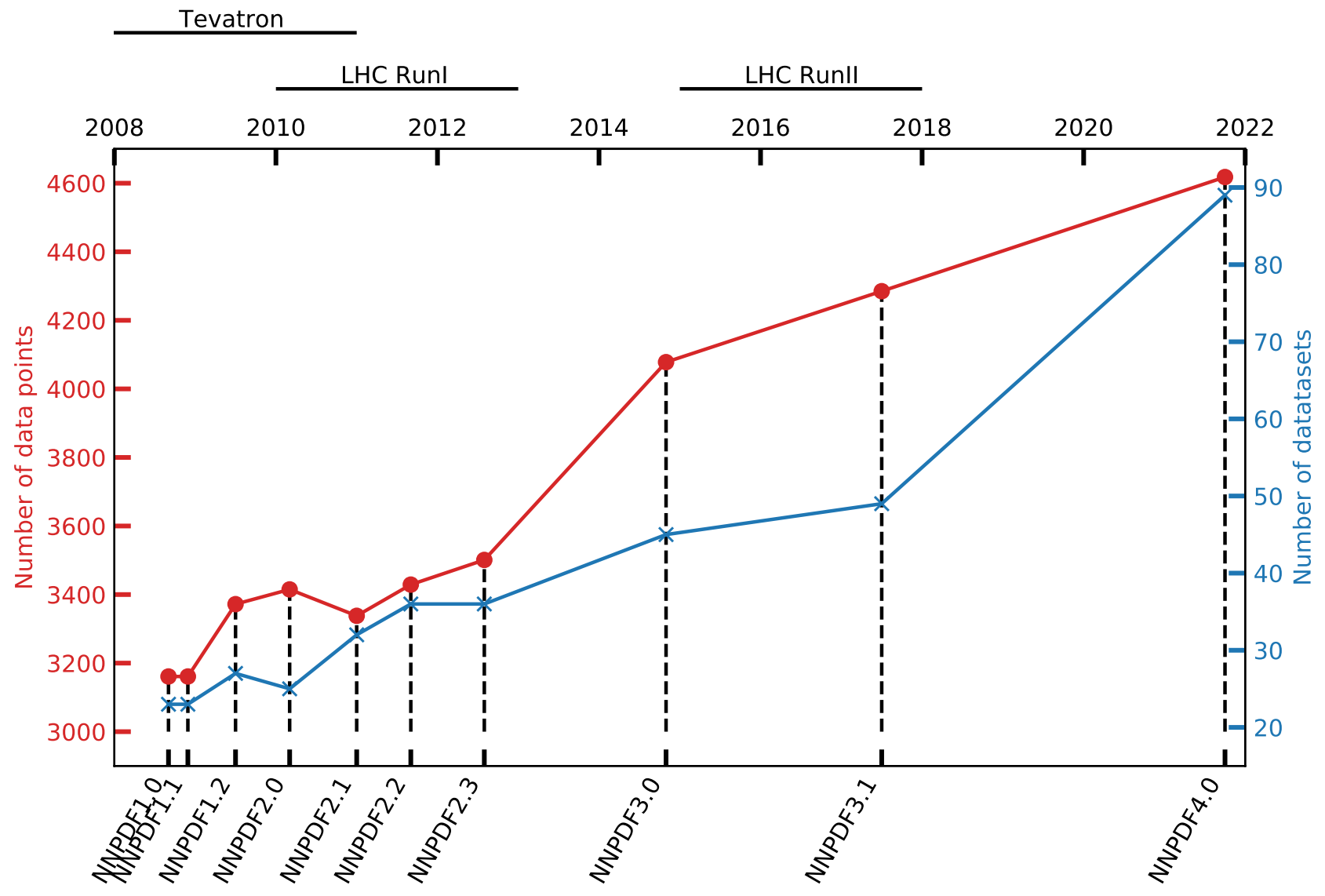
3. Summary

1. NNPDF4.0 [EPJC82.428]

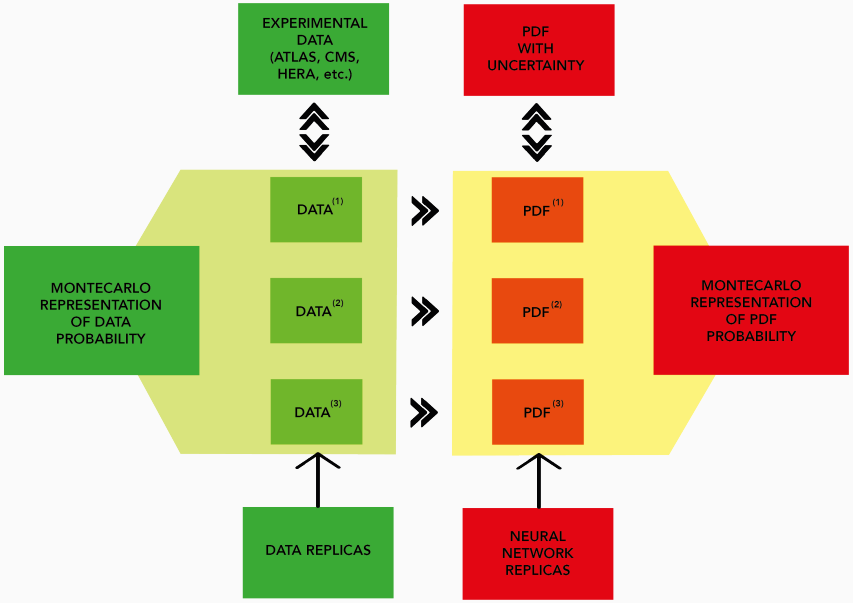
Fitting PDFs



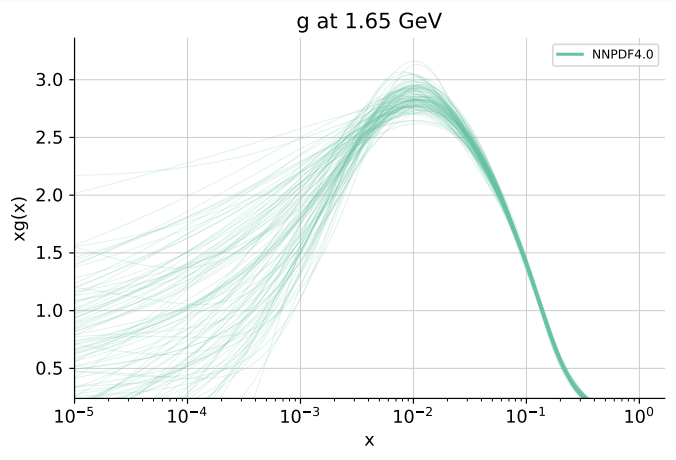
Data: History

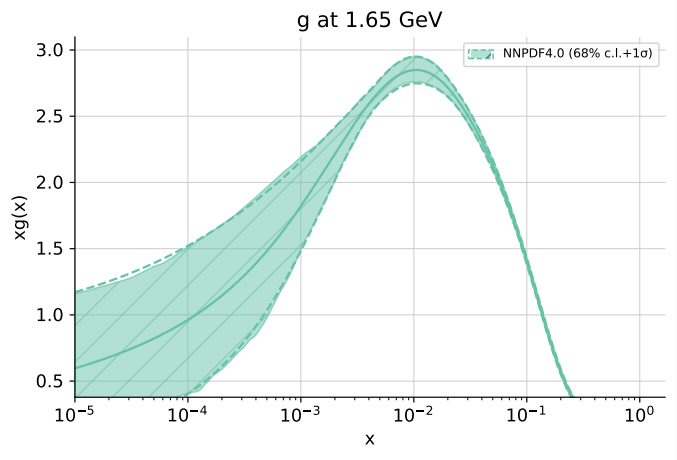


Methodology: Replicas



- Data is given by central values and covariance matrix
- generate Monte Carlo data replicas which as an ensemble represent the experiment
- fit one PDF replica to each data replica
- $\Rightarrow$ ensemble of PDF replica





Theory: `pineline` [2302.12124]

`https://nnpdf.github.io/pineline`

- "Industrialization of High-Energy Theory Predictions":
  - collect diverse generators in an "assembly line"
  - NNPDF4.0: $>$ 4.5k datapoints $+$ $>$ 10 generators
- be reproducible (i.e. track data and metadata) and open source!
- not yet in NNPDF4.0 but any future release

$\Rightarrow$ please provide new calculations in an "interfaceable" way

Theory: PineAPPL

PineAPPL is a fast interpolation grid library that

- extends to arbitrary orders in QCD and EW coupling
- provides a very good Command Line Interface
- provides several interfaces: C, C++, Fortran, Rust, Python
- can convert APPLgrid [EPJC66.503] and FastNLO [DIS12.217]
- interfaces to Mg5 [JHEP07.079], yadism, Vrap [PRD69.094008] - soon MATRIX [EPJC78.537]

https://github.com/NNPDF/pineappl

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

Theory: EKO [EPJC82.976]

EKO
Evolution Kernel Operators

DGLAP:

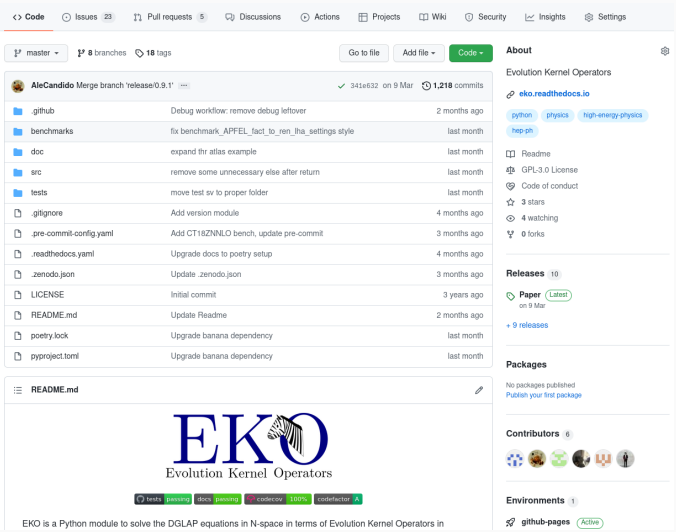
$$\mu_F^2 \frac{\mathrm{d}}{\mathrm{d}\mu_F^2} \mathbf{E}(\mu_F^2 \leftarrow \mu_{F,0}^2) = \mathbf{P}(a_s(\mu_R^2), \mu_F^2) \otimes \mathbf{E}(\mu_F^2 \leftarrow \mu_{F,0}^2)$$

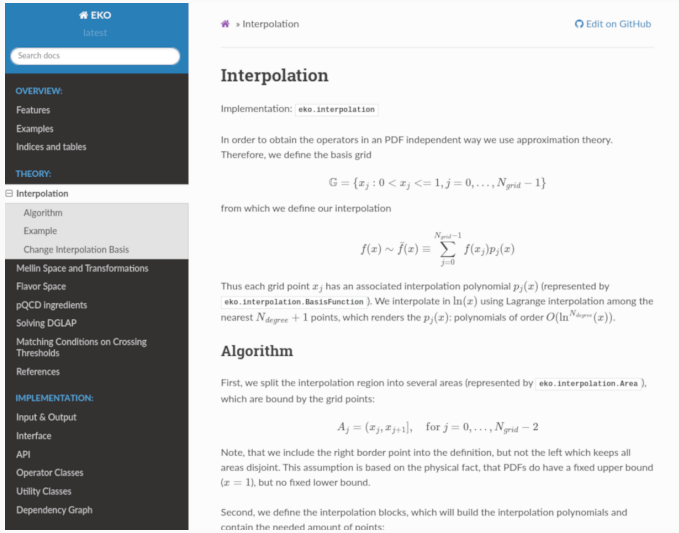
with

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

- compute in Mellin space, but deliver in x space
- correct treatment of intrinsic PDFs

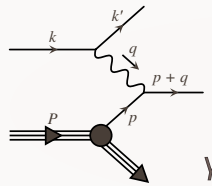
Theory: EKO Project Management





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

Theory: yadism



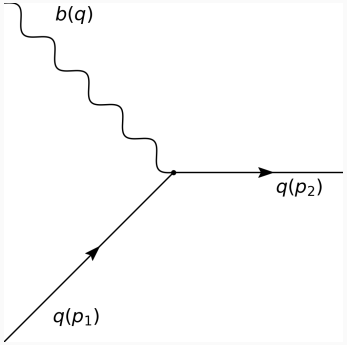
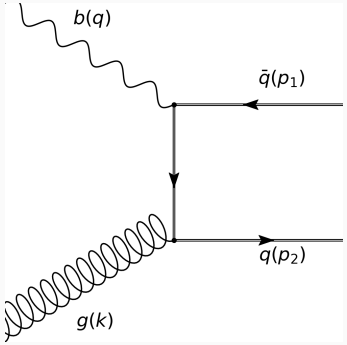
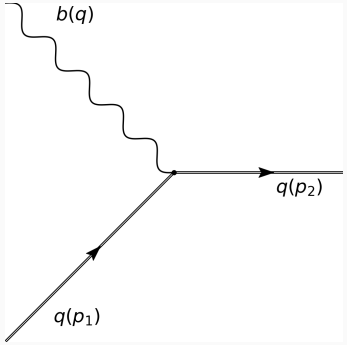
Yadism

Yet Another DIS Module

https://github.com/NNPDF/yadism

https://yadism.readthedocs.io

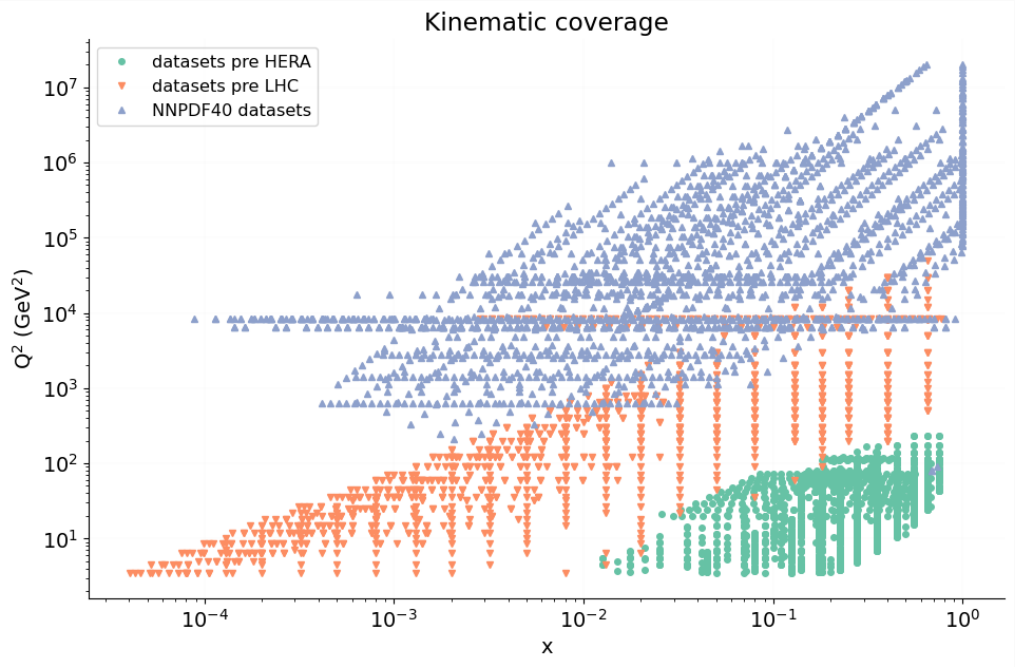
- DIS coefficient function database:

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

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

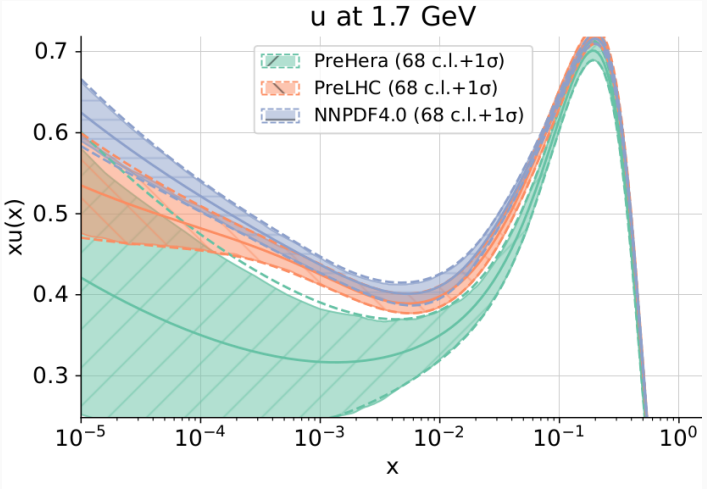
Checks: Future Tests [Acta Phys.Polon.B52.243]

Go to the past and look into the (back then) future!



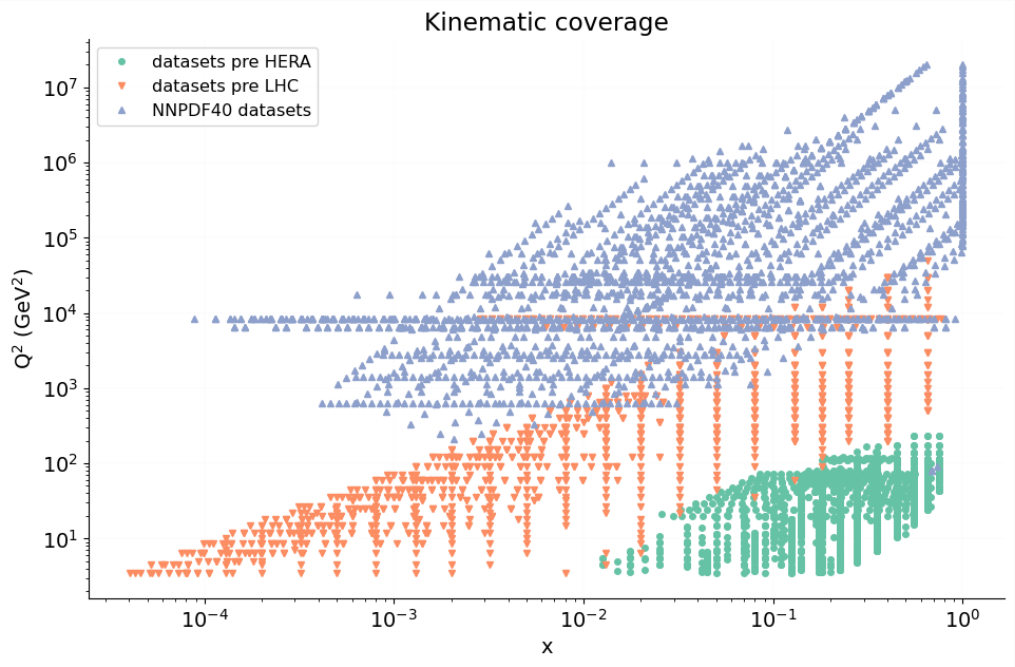
χ^2/N (only exp. covmat)

(dataset)	NNPDF4.0	pre-LHC	pre-Hera
pre-HERA	1.09	1.01	0.90
pre-LHC	1.21	1.20	23.1
NNPDF4.0	1.29	3.30	23.1



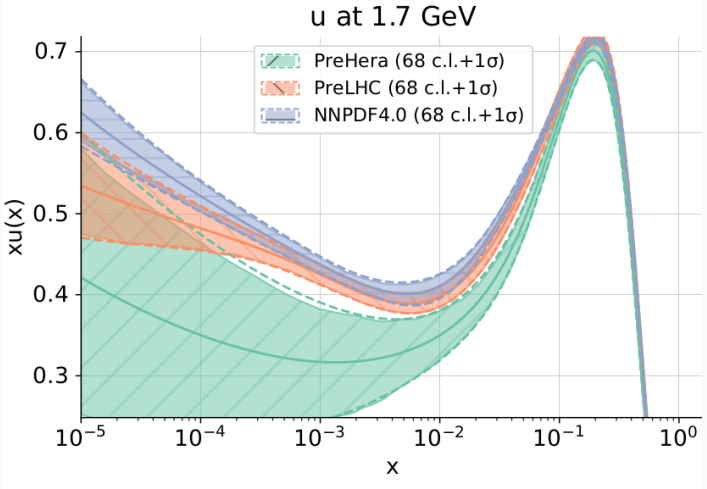
Checks: Future Tests [Acta Phys.Polon.B52.243]

Go to the past and look into the (back then) future!



χ^2/N (exp. and PDF covmat)

(dataset)	NNPDF4.0	pre-LHC	pre-Hera
pre-HERA			0.86
pre-LHC		1.17	1.22
NNPDF4.0	1.12	1.30	1.38



- without data PDF errors have to be big
- with PDF errors the total uncertainty increases, and accommodates for difference between predictions and new data

Checks: Closure Tests [EPJC82.330]

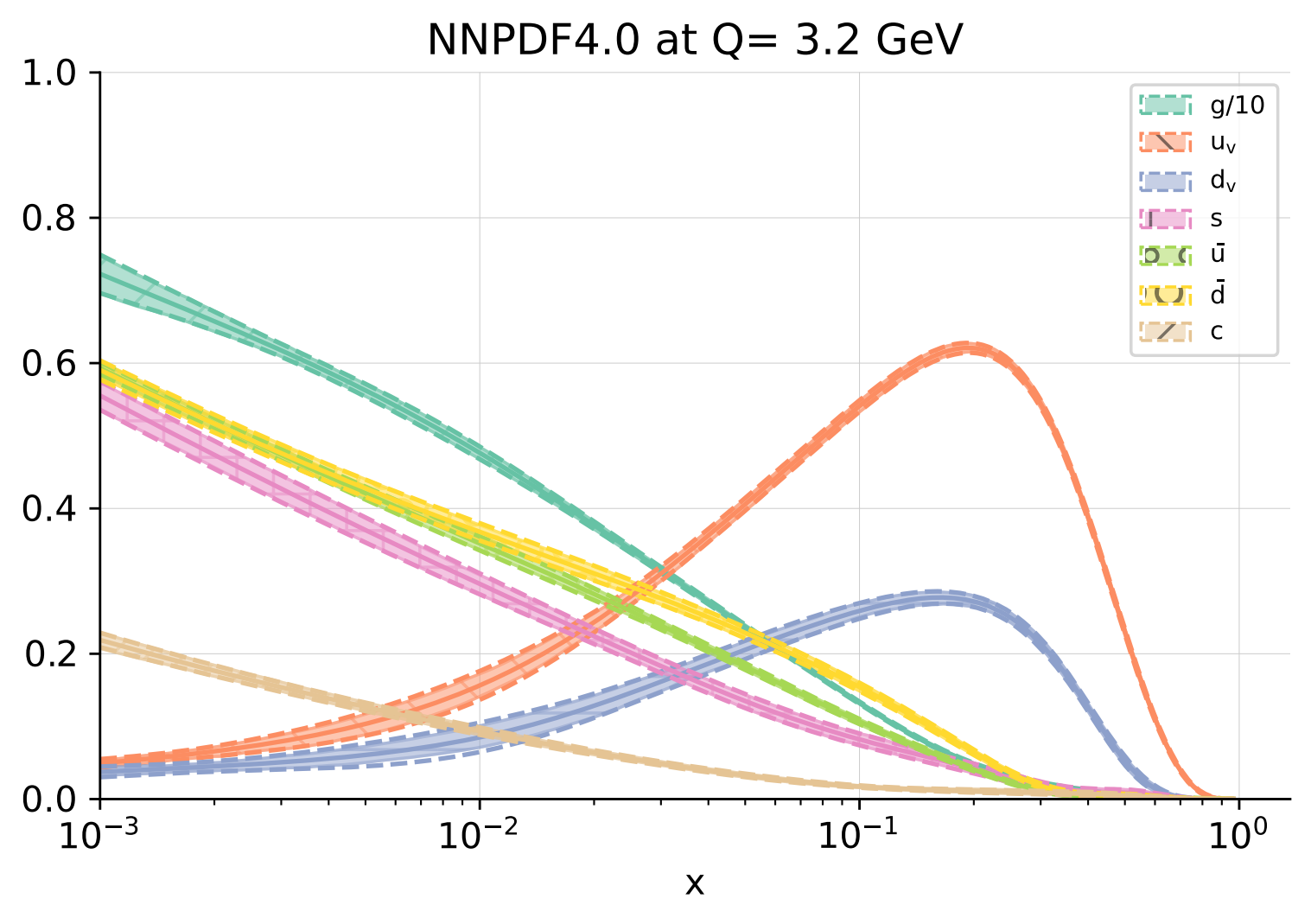
Fake a universe with known input assumptions

1. Assume a "true" underlying PDF (e.g. a single PDF replica)
2. Produce fake data distributed accordingly
3. Perform a fit to this fake data

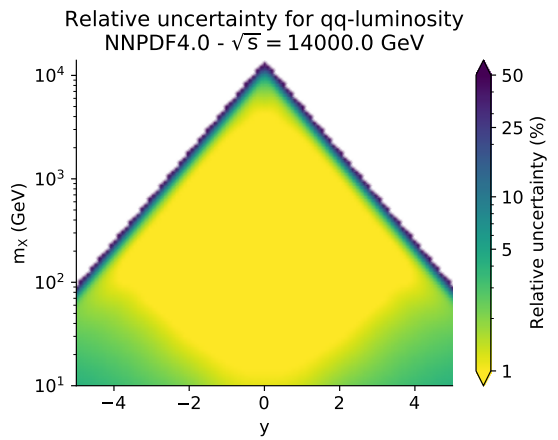
Observe statistical estimators (e.g. bias and variance)
$\rightarrow$ Is the truth within one sigma in 68% of cases?

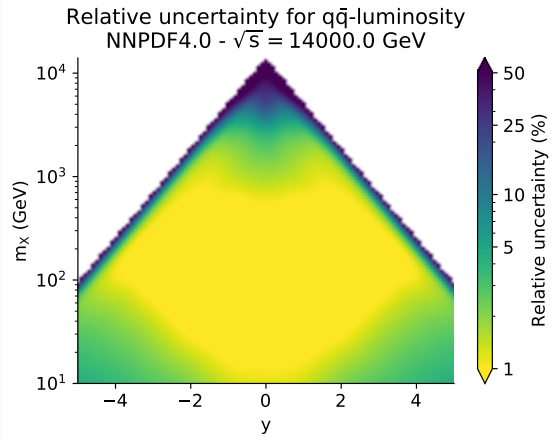
$\sqrt{\text{bias}/\text{variance}}$	$\xi_{1\sigma}^{(\text{data})}$
1.03 ± 0.05	0.68 ± 0.02

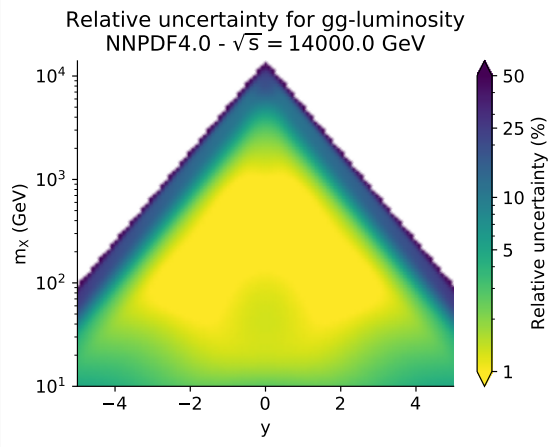
NNPDF4.0: PDF plot

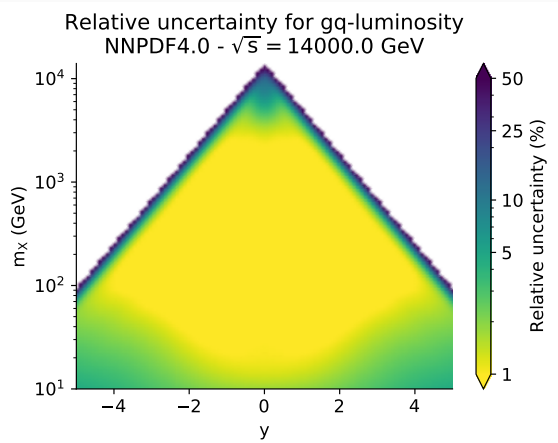


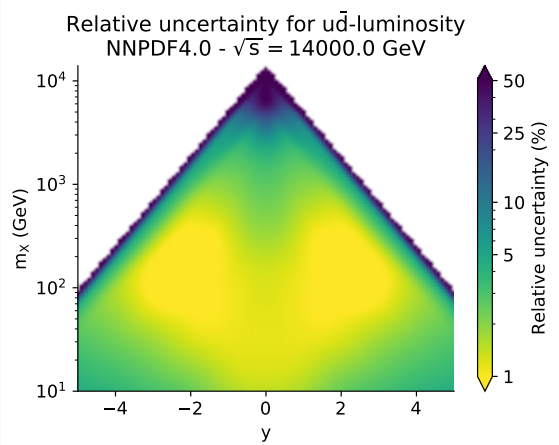
NNPDF4.0: Uncertainties











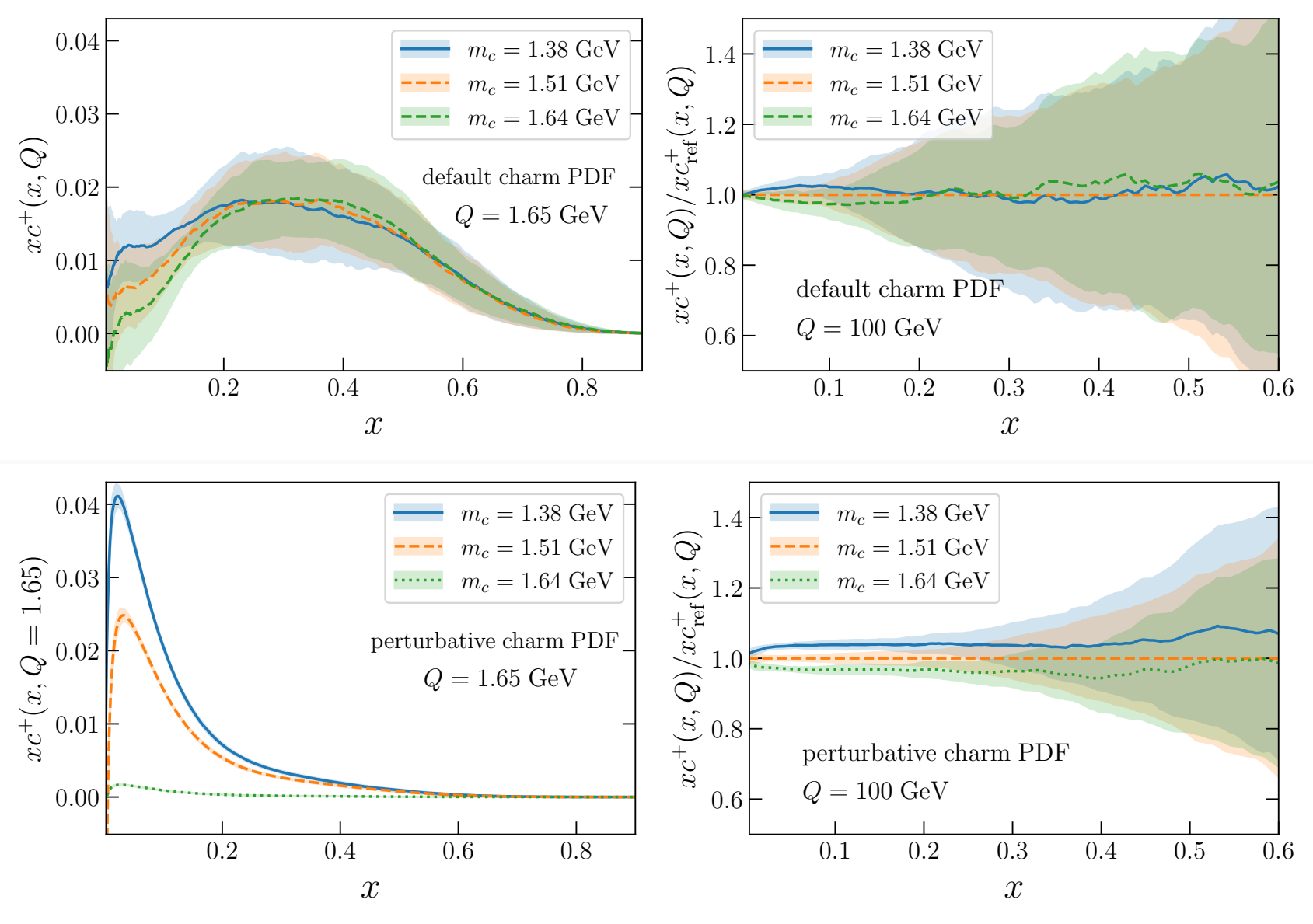
- typical uncertainties in data region: singlet $\sim 1\%$, nonsinglet $\sim 2-3\%$
- data region: $10 \lesssim M_X \lesssim 3 \times 10^3$ GeV, $-4 \lesssim y \lesssim 4$

2. Intrinsic Charm [Nature608.483]

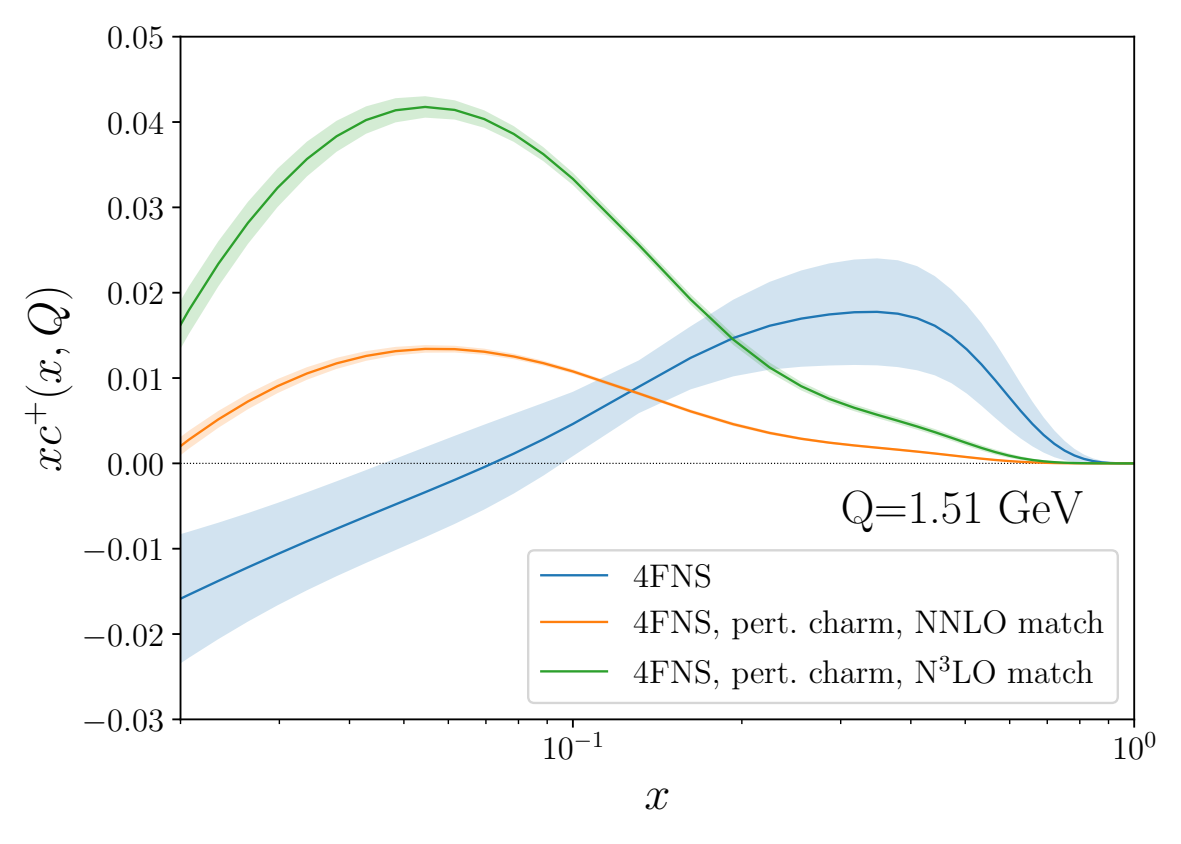
Nomenclature

- **perturbative charm**
  - is fully perturbative, i.e., predictable at all scales
  - generated by matching conditions and evolution
  - always present for $\mu_F > \mu_h = m_h$
  - it is $g \to c\bar{c}$, so (mostly) no asymmetry possible ($c \neq \bar{c}$)
  - default for CTEQ and MSHT
- **intrinsic charm**
  - is non-perturbative
  - charm in 3 light flavor scheme
  - CTEQ: use a model (e.g. [BHPS])
- **fitted charm**
  - default for NNPDF
  - don't assume anything - just fit charm in 4 flavor scheme!
  - is an arbitrary mixture of intrinsic and perturbative charm

Mass Dependency on PDFs



Mass Dependency by OMEs



- slow perturbative convergence of OME: NNLO and N3LO differ significantly

Matching Conditions and Backward Evolution

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

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

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

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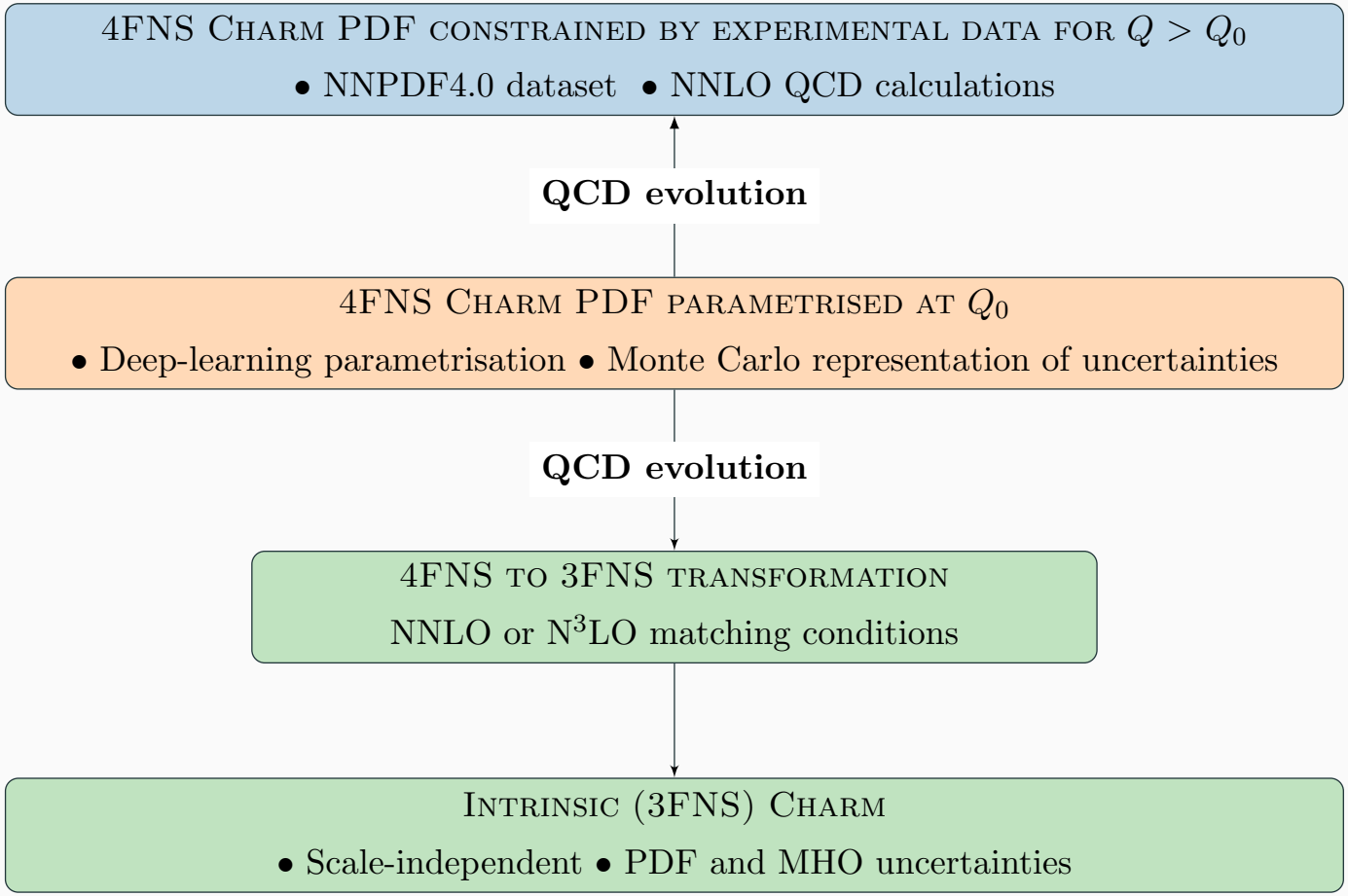
with $\mathbf{R}^{(n_f)}$ a flavor rotation matrix and $\tilde{\mathbf{A}}^{(n_f)}(\mu_h^2)$ the operator matrix elements (partially known up to N^{3}LO)

for backward evolution:

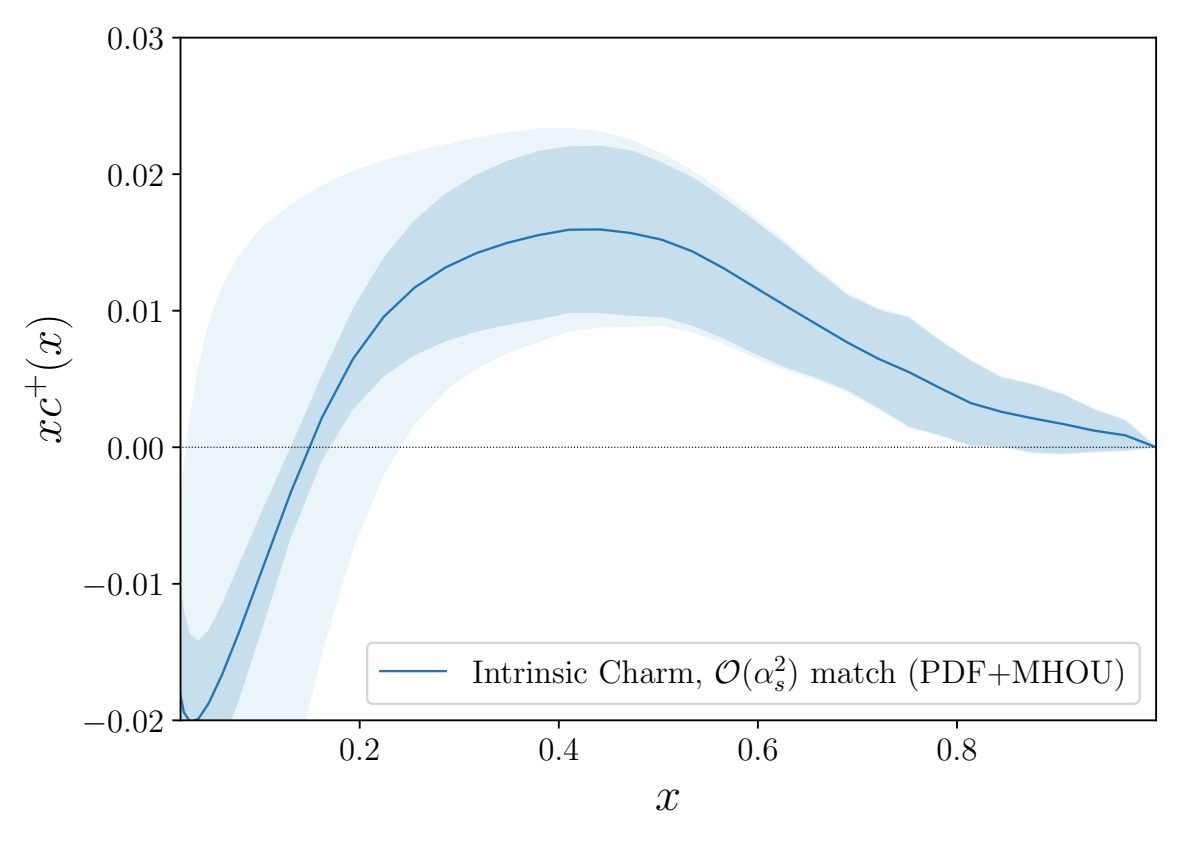
- invert $\tilde{\mathbf{E}}^{(n_f)}$: simple (invert RGE flow) ✓
- invert $\mathbf{R}^{(n_f)}$: simple (static matrix) ✓
- invert $\tilde{\mathbf{A}}^{(n_f)}$: expanded or exact

Strategy

based on NNPDF4.0 [EPJC82.428]

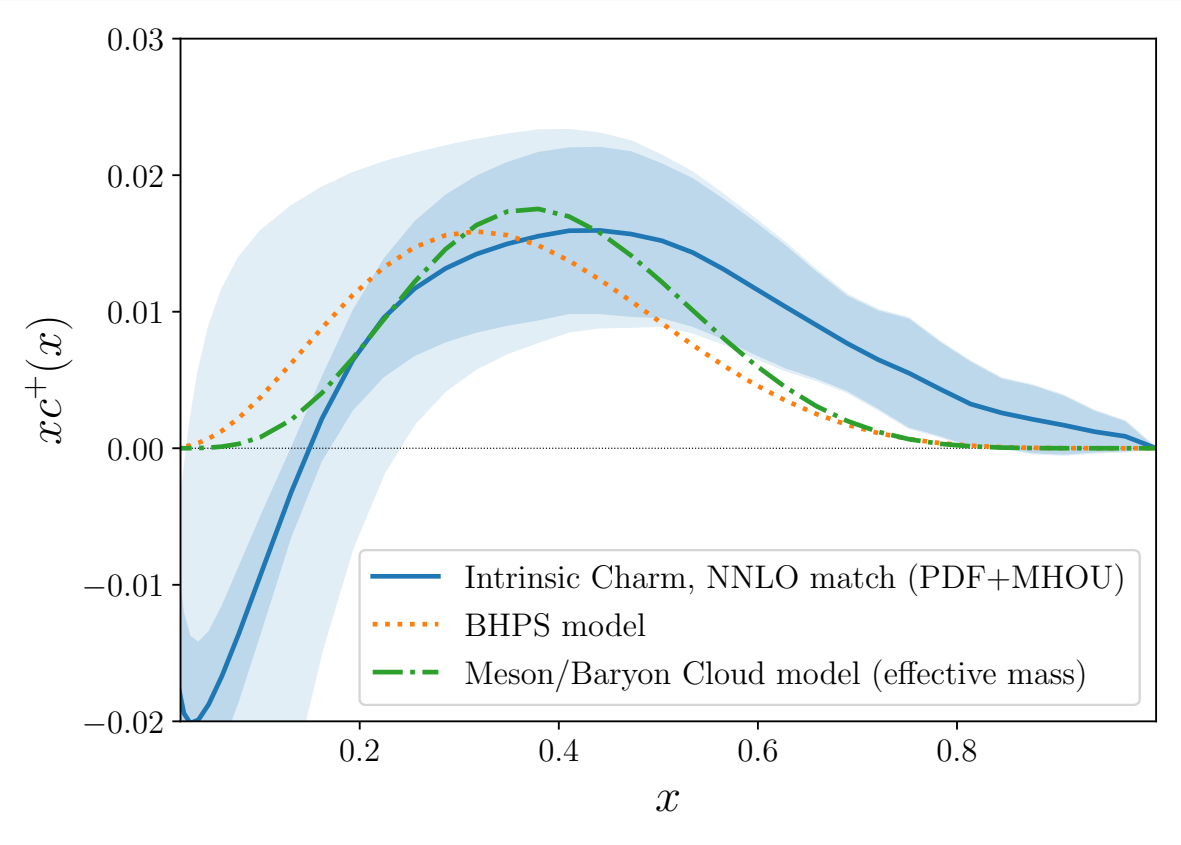


The PDF Plot



- 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%**

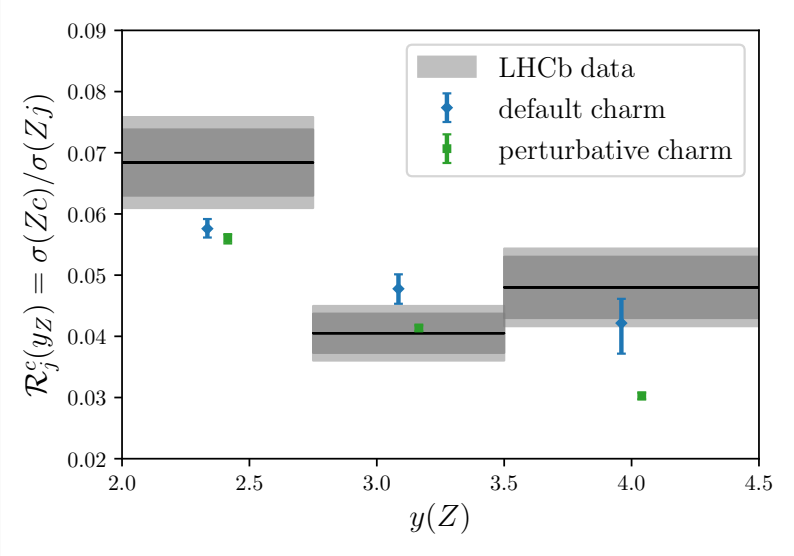
The PDF Plot with Model Comparison

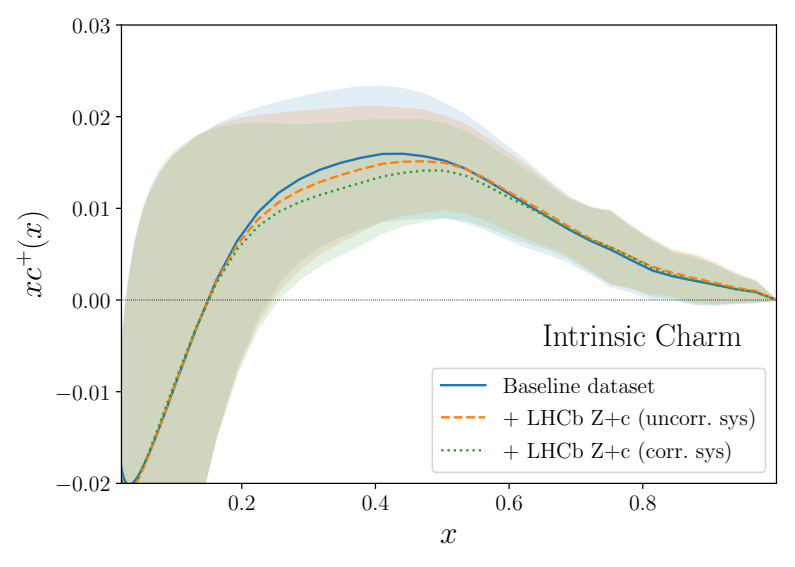


[BHPS] or [Meson/Baryon Cloud Model]

- 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%**

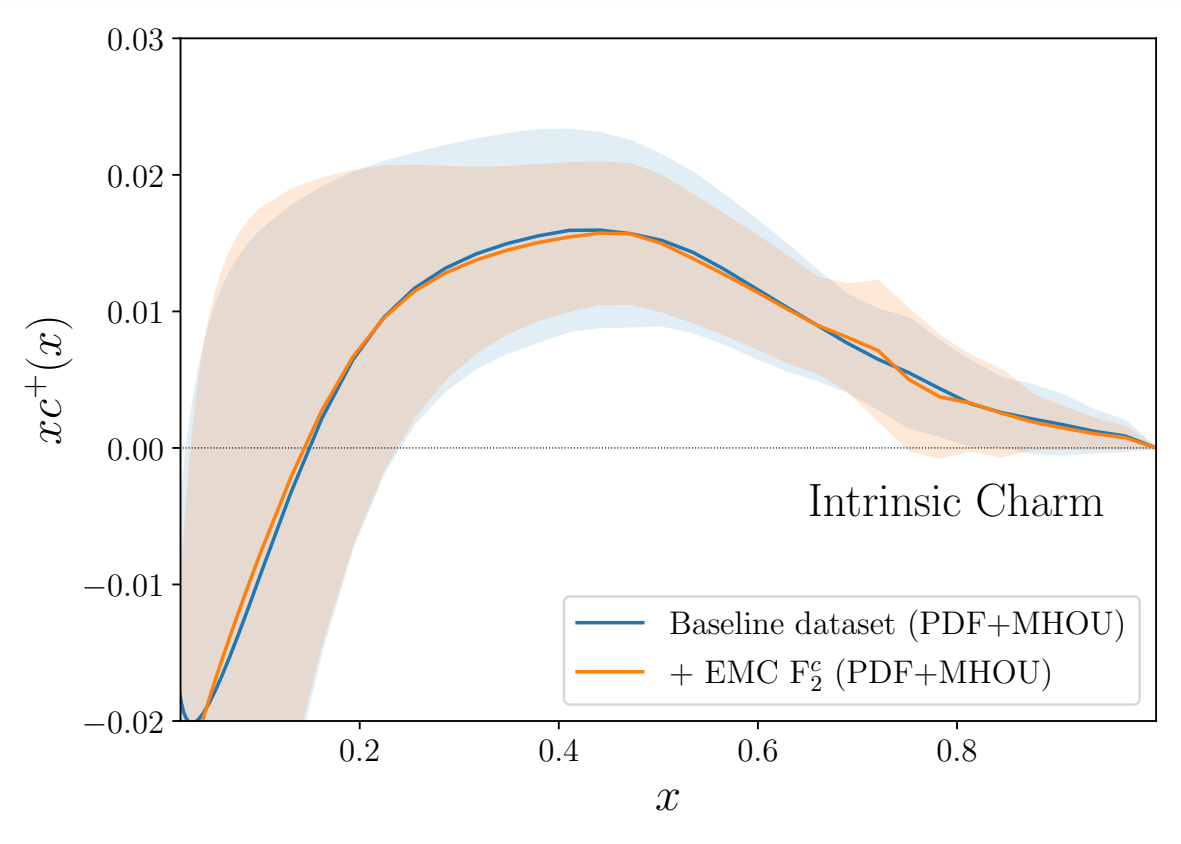
Z+charm @ LHCb [PRL128.082001]





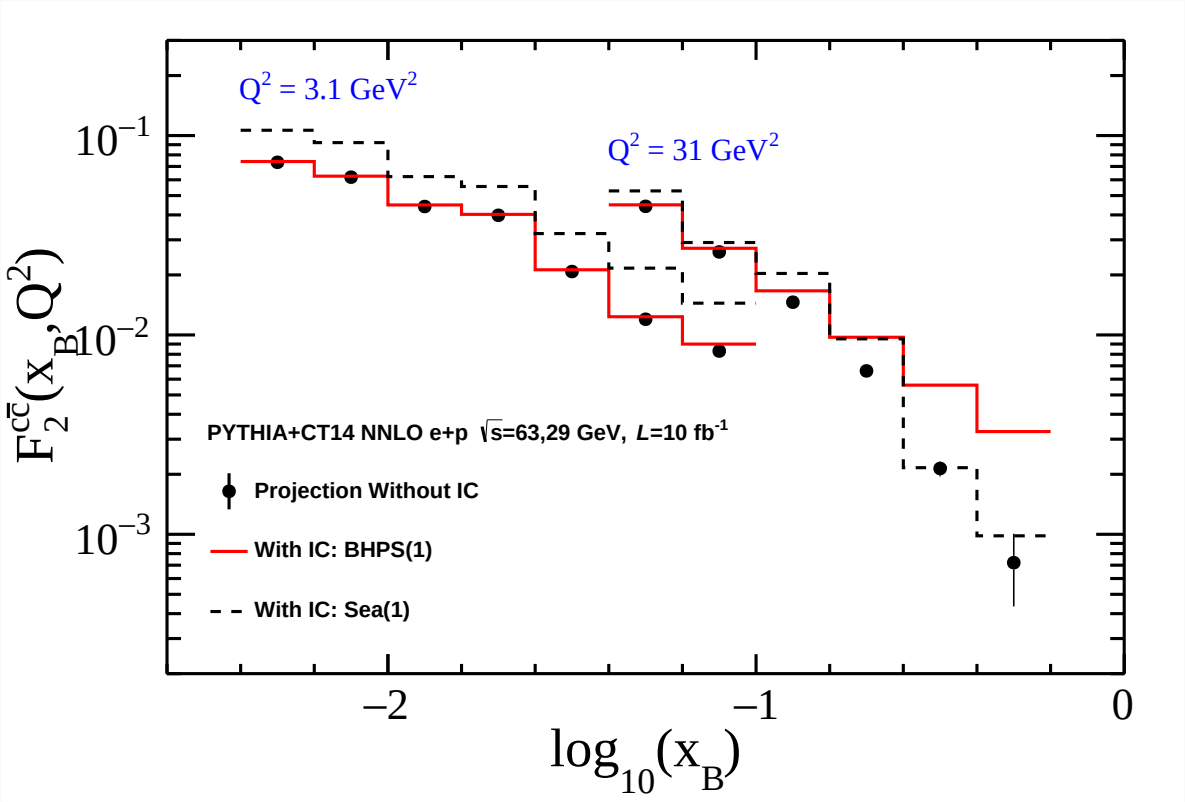
- predict better recent measurement
- reweighting is consistent

EMC [NPB461.181]



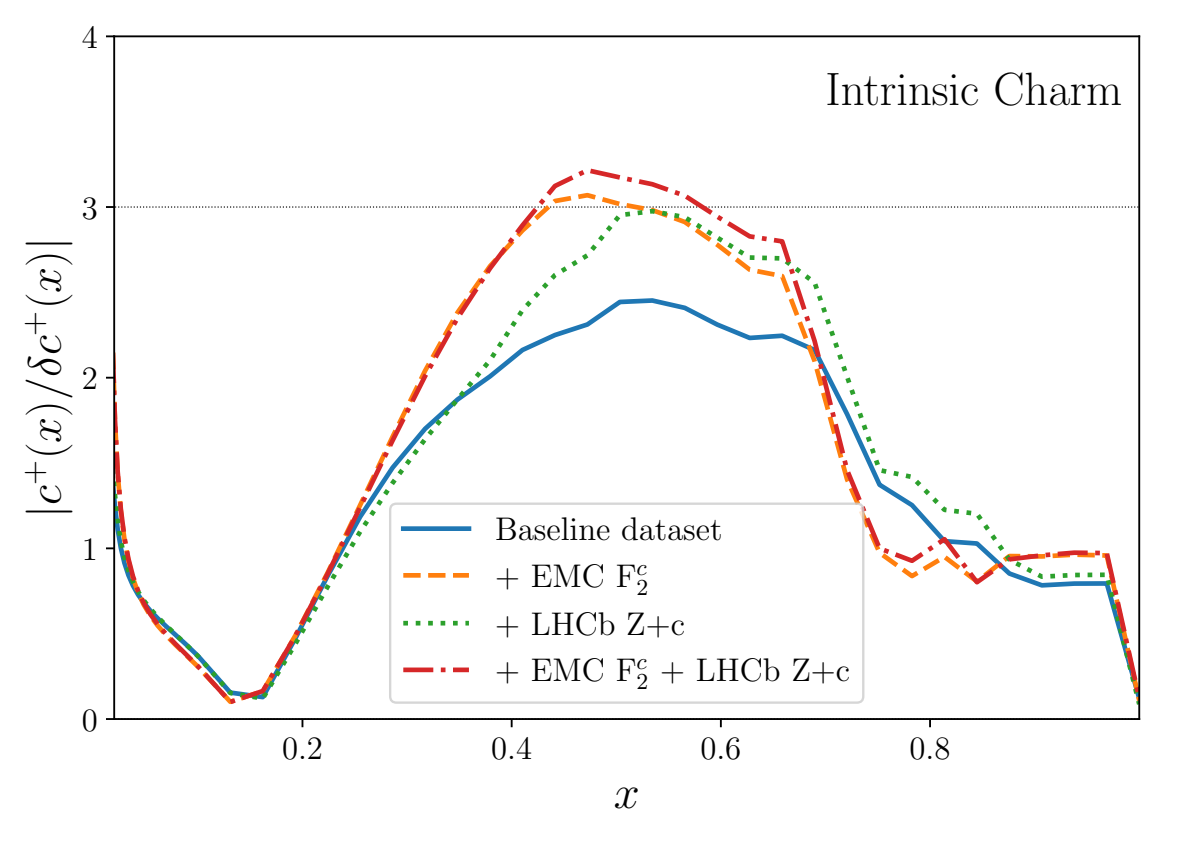
- direct measurement of F_2^c
- evidence for intrinsic charm claimed, but experiment disputed
- adding EMC data is consistent

EIC [PRD104.054002]



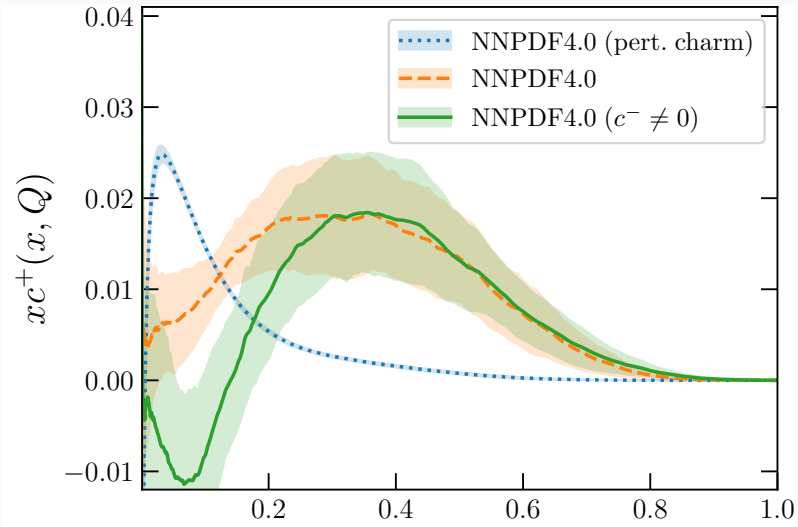
- direct measurement of F_2^c
- can distinguish intrinsic charm scenarios

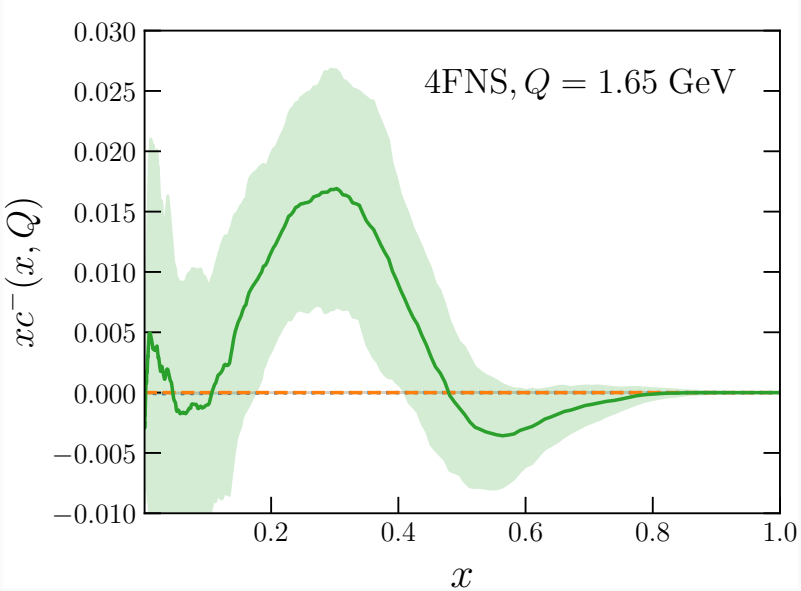
Significance



- we find a **3σ** evidence of intrinsic charm
- result is **stable** with mass variation, dataset variation

Charm Asymmetry (PRELIMINARY!)





- also parametrize $c^- = c - \bar{c} \Rightarrow$ intrinsic!
- significance for baseline now $> 3\sigma$
- $\sim 1.5\sigma$ evidence for $c^- \neq 0$

3. Summary

Summary

We fit the charm PDF in order to get

- realistic error estimate
- no strong dependence on charm mass
- no sensitivity to MHOU in matching condition

We find

- large uncertainties and charm compatible with zero at small x
- 3σ evidence for an intrinsic charm valence-like peak

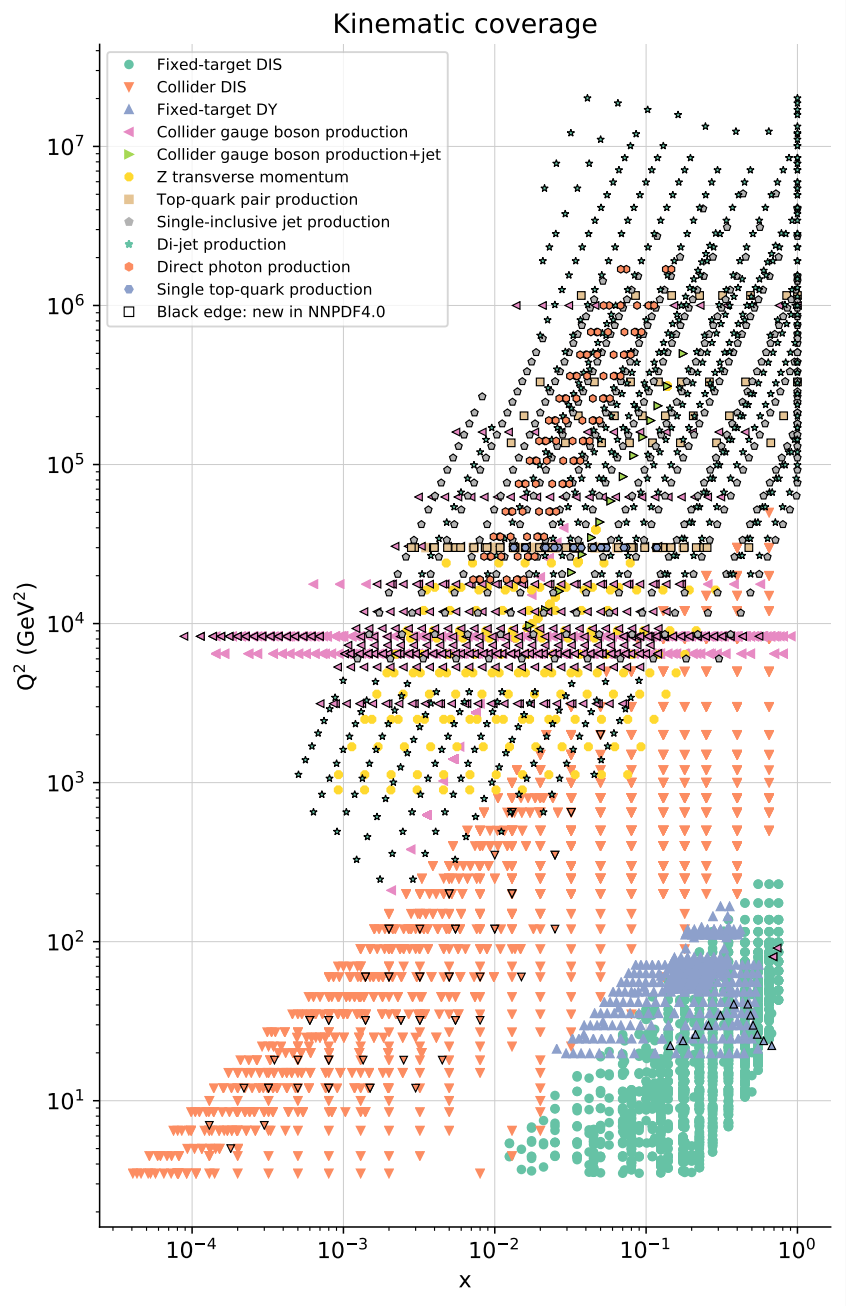
The road ahead:

- more data $\rightarrow 5\sigma$ evidence
- $c - \bar{c}$ asymmetry phenomenology

Thank you!

4. Backup slides

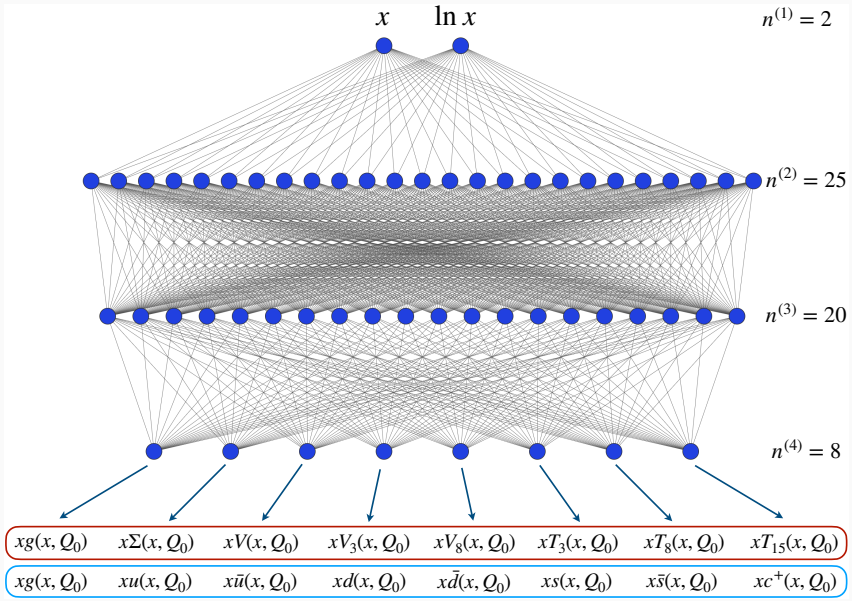
Data: Kinematic Plot



- about 50 new datasets & 400 extra datapoints
- DIS/FTDY: dataset as in NNPDF3.1 + nomad neutrino + SeaQuest DY
- LHC: full 7 TeV and 8 TeV dataset & extensive use of 13 TeV data
- several new processes: prompt photon; single top; dijets; Hera jets

Methodology: Neural Network and Hyperoptimization

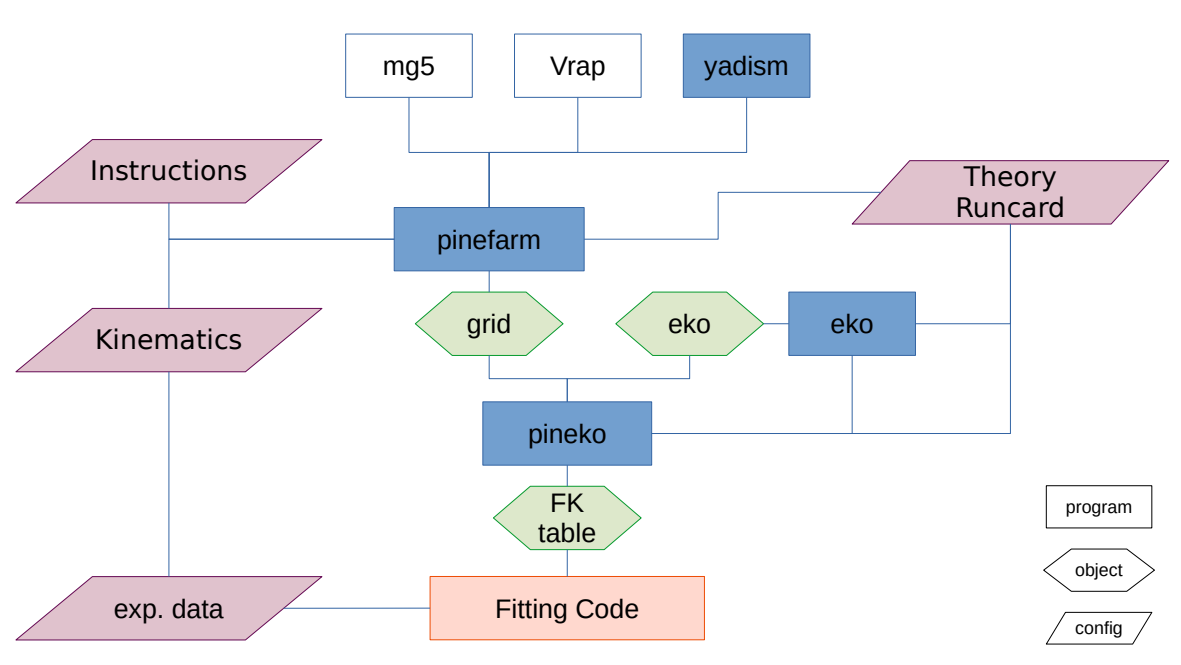
$$f_j(x, Q_0) = x^{-\alpha_j}(1-x)^{\beta_j}\mathrm{NN}_j(x)$$



- functional form: neural network (corresponds to many "effective parametrizations")
- choose model parameters? hyperoptimization! (i.e. scan parameter space)
- prevent overfitting!

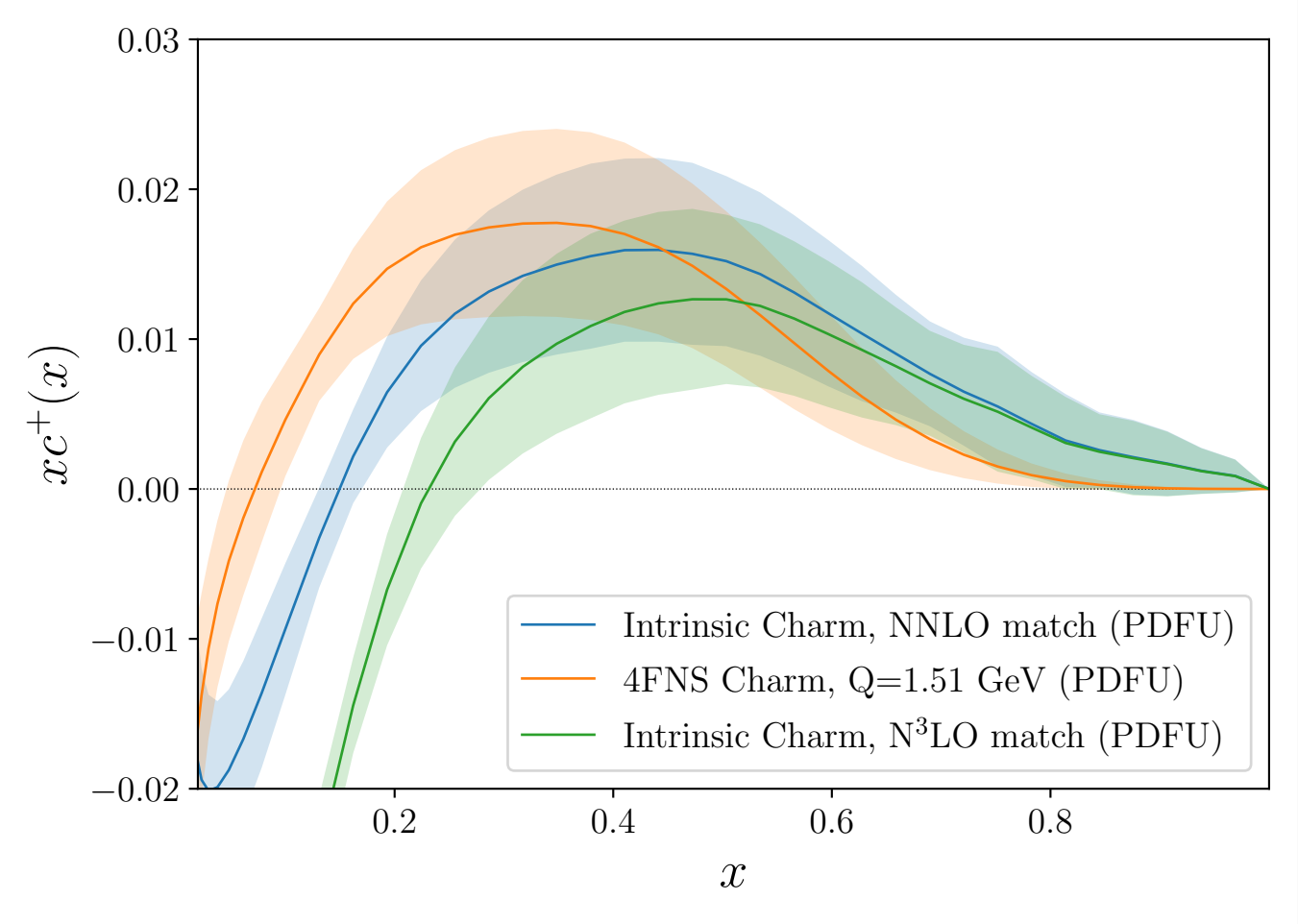
Theory: New Theory Prediction Pipeline

Produce FastKernel (FK) tables!

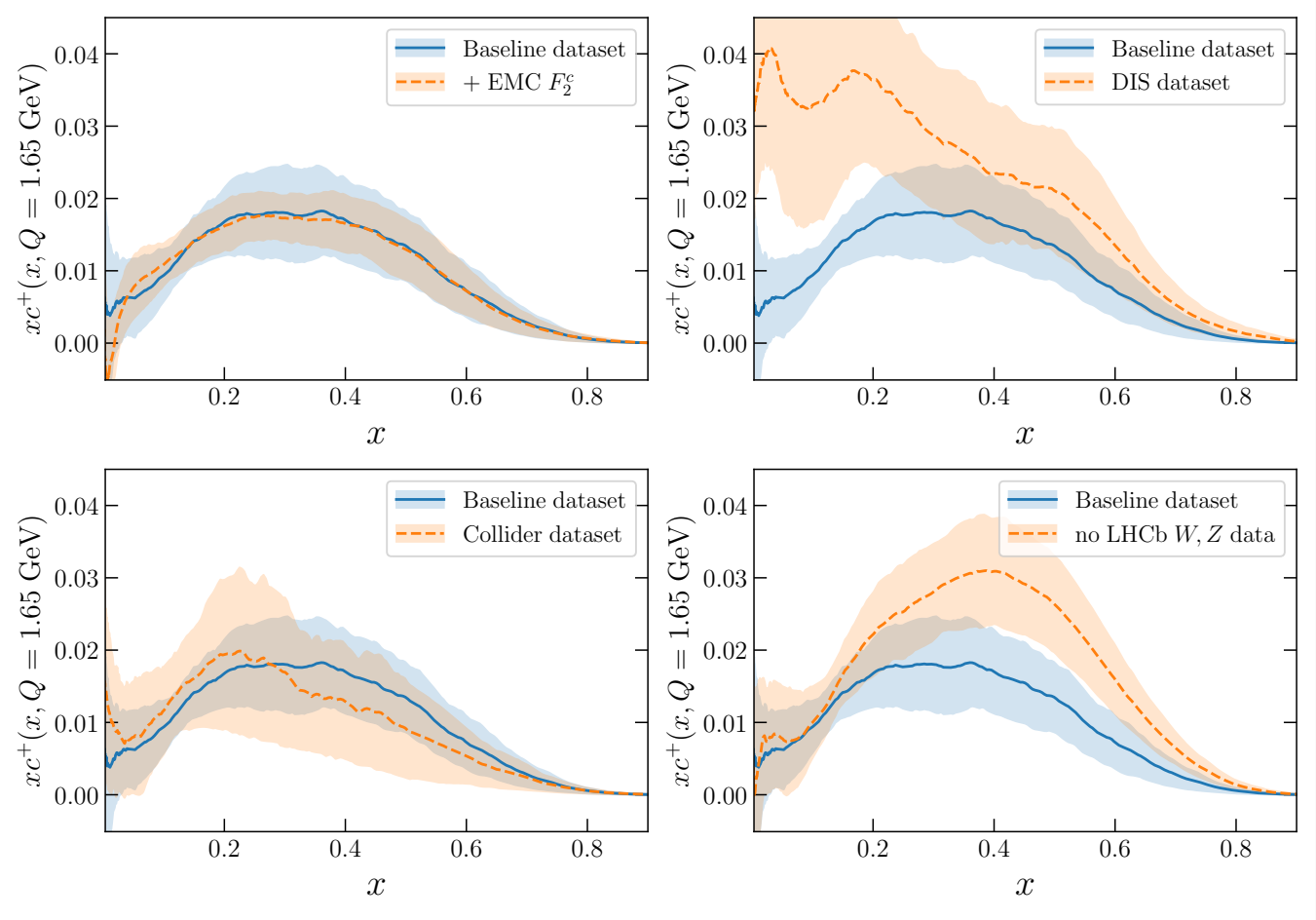


The workhorse in the background: PineAPPL

IC - uncertainties splitted



IC - dataset variation



IC - mass dependency