Intrinsic Charm in the Proton

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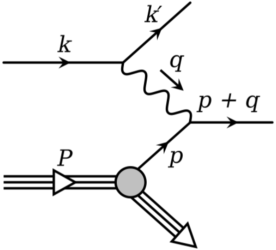
Physics opportunities with proton beams at SIS100, February 2024

Overview

1. Fitting PDFs as e.g. in NNPDF4.0 [EPJC82.428]
2. Evidence for intrinsic charm quarks in the proton [Nature608.483]
3. The intrinsic charm quark valence distribution of the proton [2311.00743]
4. Summary

Fitting PDFs as e.g. in NNPDF4.0 [EPJC82.428]

Parton Distribution Functions

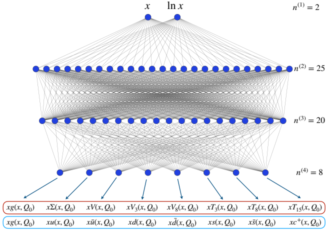


Parton Distribution Functions (PDF) $\mathbf{f}(x, \mu_F^2)$

- universal functions to describe high-energy QCD scattering
- describe the fundamental constituents of the proton: quarks, gluons
- μ_F-dependence: DGLAP equations!
- x-dependence: fit!

How to fit a PDF? Use Machine Learning!

Methodology:



taken from [EPJC82.428]

Theory:

$$
\begin{aligned}
s'^2 \frac{d^2\sigma^{(1),H,fin}_{\vec{\kappa},bb',g}}{dt_1\,du_1} = \alpha\alpha_s g^{\kappa_1}_{b,Q} g^{\kappa_2}_{b',Q} K_{g\gamma} N_C C_F \Bigg[-\frac{2}{u_1} P^H_{\kappa_3,gg}(x_1) \\
\left\{ B^{(0)}_{\vec{\kappa},\mathrm{QED}}(x_1 k_1) \left(\ln\left(\frac{s_4^2}{m^2(s_4+m^2)} \right) - \ln(\mu_F^2/m^2) \right) - 2B^{(1)}_{\vec{\kappa},\mathrm{QED}}(x_1 k_1) \right\} \\
+ C_A \frac{s_4}{2\pi(s_4+m^2)} \left(\int d\Omega_n\, R_{\vec{\kappa},\mathrm{OK}} \right)^{finite} \\
+ 2C_F \frac{s_4}{2\pi(s_4+m^2)} \int d\Omega_4\, R_{\vec{\kappa},\mathrm{QED}} \Bigg] . \qquad (5.36)
\end{aligned}
$$

taken from [1910.01536]

Experiment:

p_T [GeV]	Dimuon cross section (pb)	Dielectron cross section (pb)	Dilepton cross section (pb)
0 - 1.0	8.8945 ±0.23955	9.0042 ±0.29596	9.2821 ±0.29778
1.0 - 2.0	23.05 ±0.61831	23.482 ±0.75597	22.786 ±0.70765
2.0 - 3.0	31.799 ±0.84297	32.848 ±1.0437	32.062 ±0.96367
3.0 - 4.0	35.663 ±0.93277	37.025 ±1.1681	36.225 ±1.0621
4.0 - 5.0	36.455 ±0.94616	37.578 ±1.1785	36.882 ±1.0681
5.0 - 6.0	35.099 ±0.90895	36.201 ±1.1302	35.579 ±1.0246
6.0 - 7.0	33.122 ±0.85768	34.275 ±1.0673	33.547 ±0.96264
7.0 - 8.0	30.967 ±0.8023	32.2 ±1.0003	31.324 ±0.89554
8.0 - 9.0	28.702 ±0.74434	29.834 ±0.92491	29.089 ±0.82773
9.0 - 10.0	26.669 ±0.69291	27.369 ±0.84751	26.933 ±0.76278

taken from [JHEP12.061]

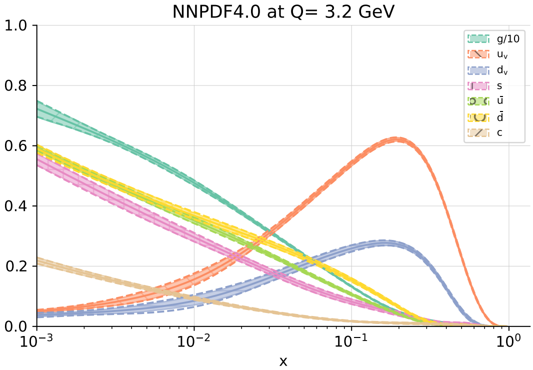
Strategy:

repeat until converged:

guess candidate PDF $f(Q_0^2) \to$ compute theory predictions T $\to$ compare to data D

NNPDF4.0 [EPJC82.428]

- $\sim$ 4500 data points from $\sim$ 90 datasets
- use NNLO pQCD predictions
- fit 8 independent functions in NN: $g, u, \bar{u}, d, \bar{d}, s, \bar{s}, c^+ = c + \bar{c}$
- fitting scale $Q_0 = 1.65\,\mathrm{GeV} > m_c = 1.51\,\mathrm{GeV}$
- uncertainties via MC replicas
- typical uncertainties in data region: singlet $\sim 1\%$, non-singlet $\sim 2-3\%$
- checks: closure tests [EPJC82.330] + future tests [APhysPolB.52.243]



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

What is intrinsic charm?

- NNPDF4.0 determines the total charm distribution $c^+ = c + \bar{c}$
- **fitted charm** is an arbitrary mixture of

perturbative charm

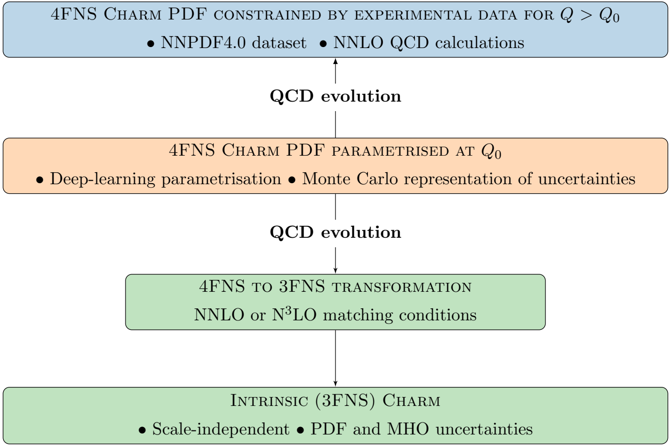
- fully perturbative, i.e., predictable at all scales
- generated by perturbative radiation
- always present above heavy quark threshold

non-perturbative charm

- **intrinsic charm**
- part of the static proton wave functions
- present at all scales

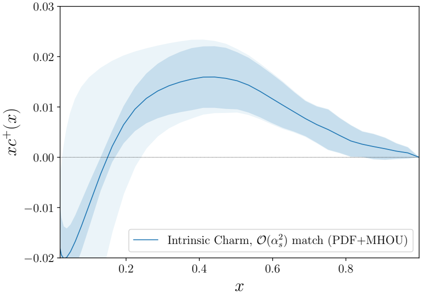
some use a model for intrinsic charm (e.g. [BHPS]), but we don't!

Strategy



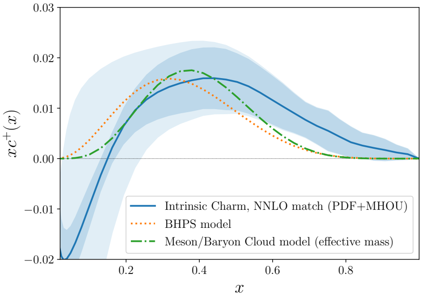
4FNS Charm PDF constrained by experimental data for $Q > Q_0$
• NNPDF4.0 dataset • NNLO QCD calculations
QCD evolution
4FNS Charm PDF parametrised at Q_0
• Deep-learning parametrisation • Monte Carlo representation of uncertainties
QCD evolution
4FNS to 3FNS transformation
NNLO or N^3LO matching conditions
Intrinsic (3FNS) Charm
• Scale-independent • PDF and MHO uncertainties

Discovery of intrinsic charm



- we find a peak for intrinsic charm
- for $x \leq 0.2$ the perturbative uncertainties are quite large
- the carried momentum fraction is within 1%

Data driven intrinsic charm vs. models



[BHPS] or [Meson/Baryon Cloud Model]

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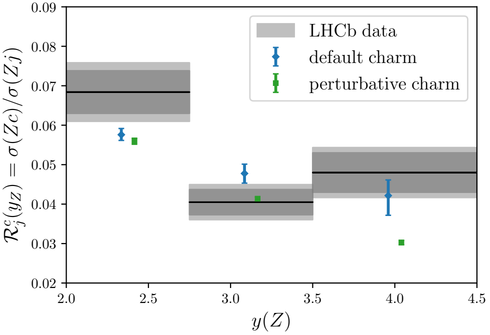
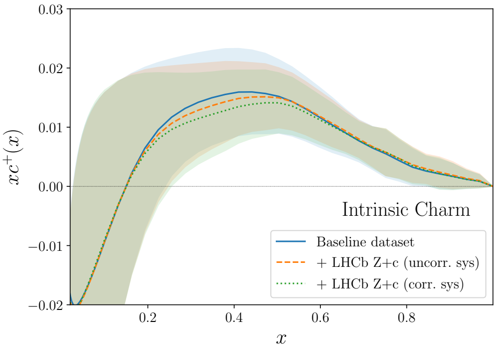
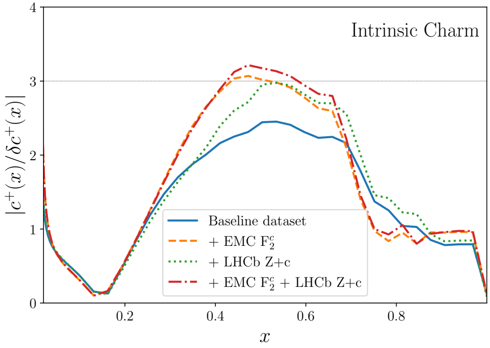
Z+charm @ LHCb [PRL128.082001]





- assuming intrinsic charm predicts better recent measurement
- reweighting is consistent

Significance

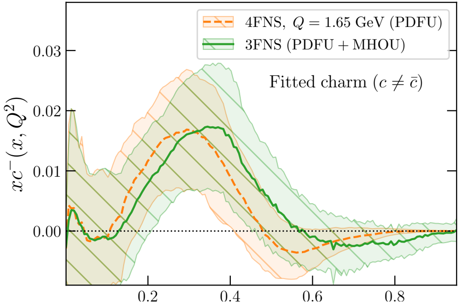


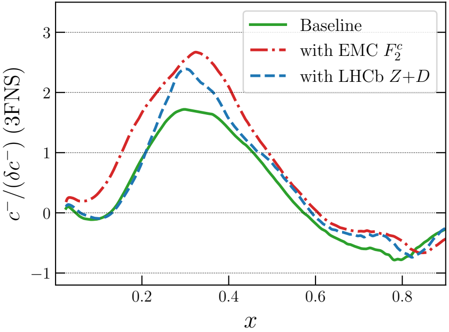
- we find a 3σ evidence of intrinsic charm
- result is stable with mass variation, dataset variation

The intrinsic charm quark valence distribution of the proton [2311.00743]

Fitting the valence charm distribution

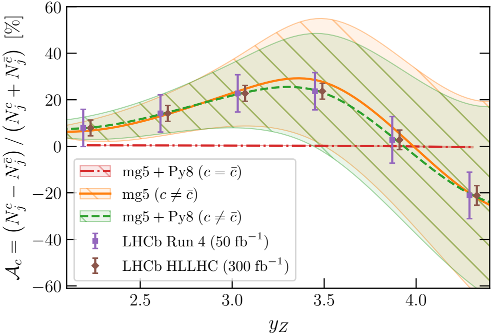
- fit in addition valence charm distribution $c^{-} = c - \bar{c}$
- perturbative charm comes from pair production
- $\Rightarrow$ asymmetric charm must be intrinsic





Measuring the valence charm distribution

Charm asymmetries in Z+c @ LHCb



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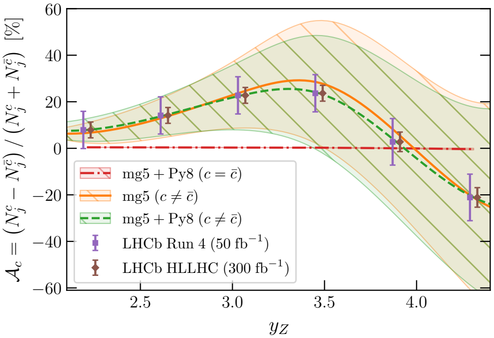
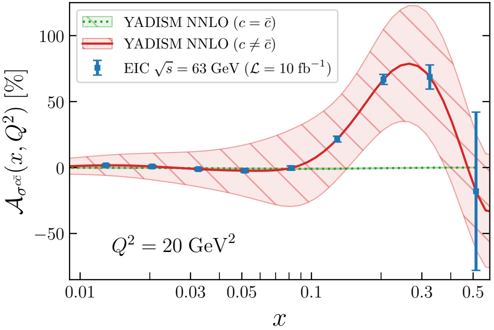


Charm-tagged DIS at the EIC



Summary

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- we fit charm to experimental data
- we remove perturbative charm component
- intrinsic charm is non-zero with 3σ significance
- more data $\rightarrow c^+$ with 5σ significance

- finding a valence charm distribution signals intrinsic charm
- with current data we can not give a clear answer
- we need experimental measurements sensitive to valence charm

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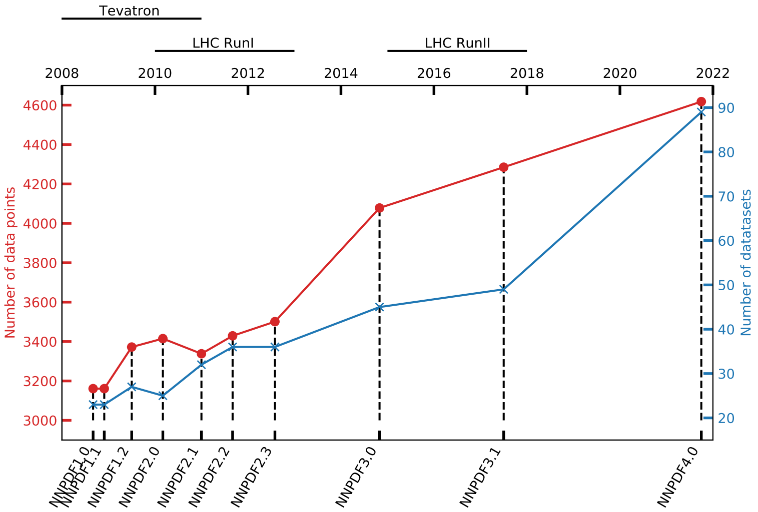
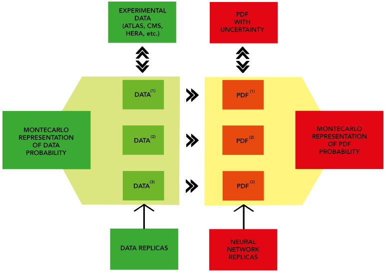
Danke! Thanks! Kiitos!

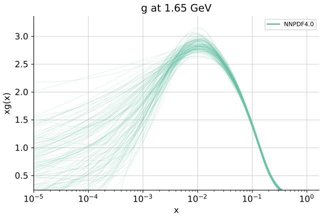
Backup slides

Data: History

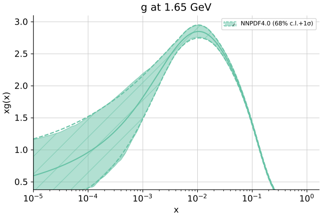


Methodology: Replicas



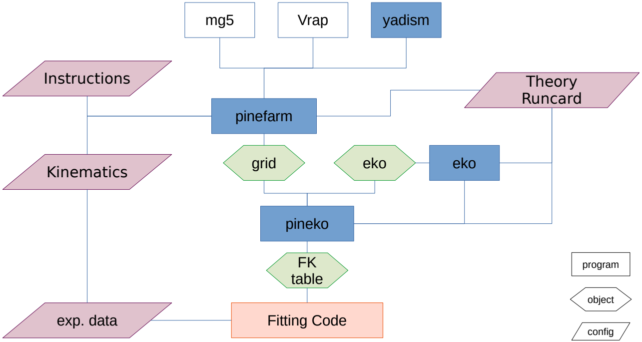


- Data is given by central values and covariance matrix
- generate Monte Carlo data replicas which as an ensemble represent the experiment
- fit one PDF replica to each data replica
- $\Rightarrow$ ensemble of PDF replica



New Theory Prediction ~~Pipeline~~ Pineline [2302.12124]

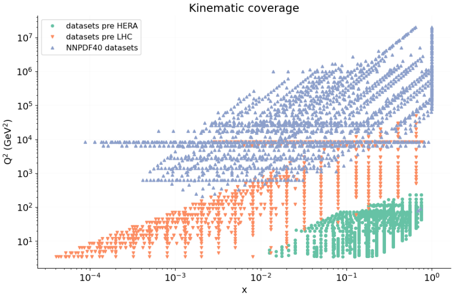
Produce FastKernel (FK) tables!



The workhorse in the background: PineAPPL

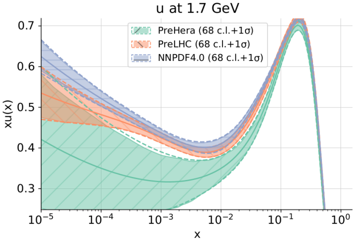
Checks: Future Tests [Acta Phys.Polon.B52.243]

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



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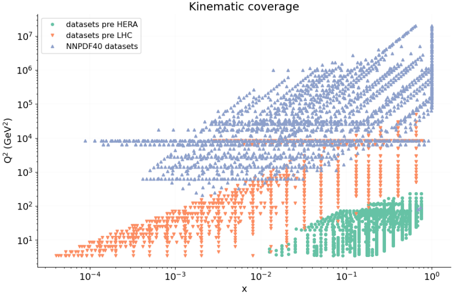
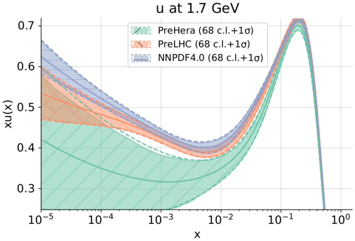


χ^2/N (exp. and PDF covmat)

(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

QCD Evolution

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

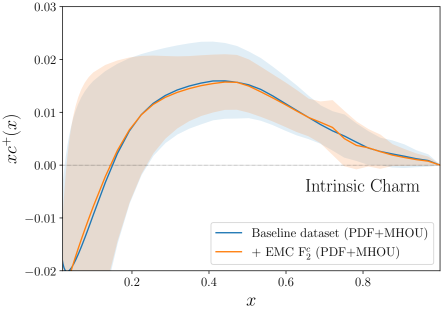
$$\tilde{\mathbf{f}}^{(n_f+1)}(\mu_{F,1}^2) = \tilde{\mathbf{E}}^{(n_f+1)}(\mu_{F,1}^2 \leftarrow \mu_h^2)\mathbf{R}^{(n_f)}\tilde{\mathbf{A}}^{(n_f)}(\mu_h^2)\tilde{\mathbf{E}}^{(n_f)}(\mu_h^2 \leftarrow \mu_{F,0}^2)\tilde{\mathbf{f}}^{(n_f)}(\mu_{F,0}^2) \tag{1}$$

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:

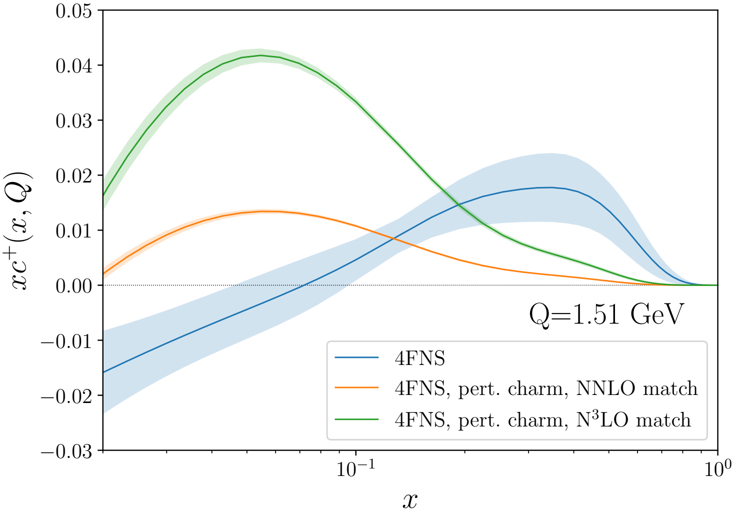
- invert $\tilde{\mathbf{E}}^{(n_f)}$: simple (invert RGE flow) ✓
- invert $\mathbf{R}^{(n_f)}$: simple (static matrix) ✓
- invert $\tilde{\mathbf{A}}^{(n_f)}$: expanded or exact

EMC [NPB461.181]



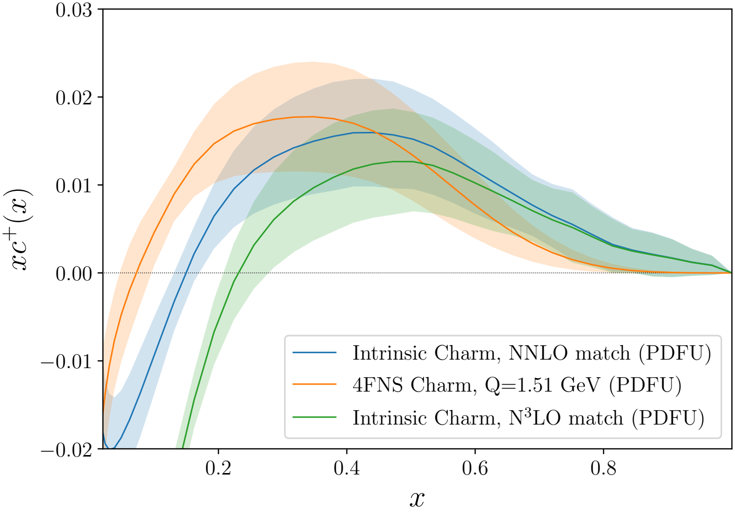
- direct measurement of F_2^c
- evidence for intrinsic charm claimed, but experiment disputed
- adding EMC data is consistent

IC vs. PC

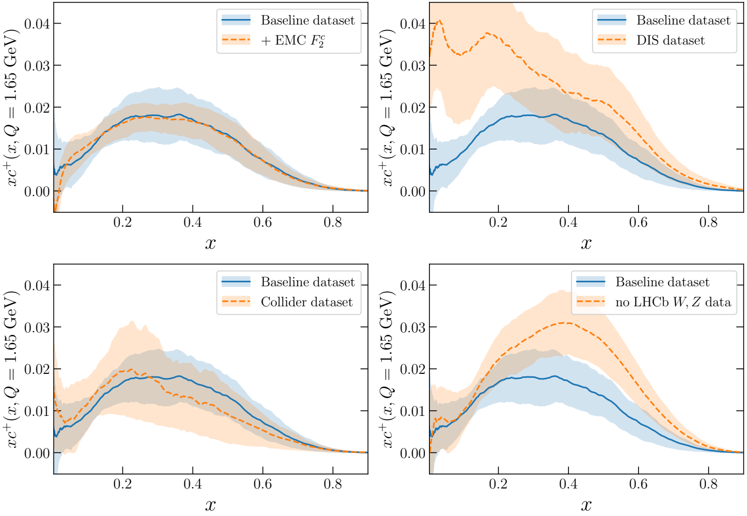


0.05
0.04
0.03
0.02
0.01
0.00
−0.01
−0.02
−0.03
$xc^+(x, Q)$
10^{-1}
10^0
x
Q=1.51 GeV
4FNS
4FNS, pert. charm, NNLO match
4FNS, pert. charm, N^{3}LO match

IC - uncertainties splitted



IC - dataset variation



IC - mass dependency