Theory Predictions

for PDF fitting

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EKO [arXiv: 2202.02338]

EKO

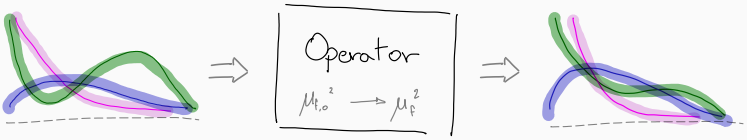
Evolution Kernel Operators

The main purpose is to solve DGLAP equations:

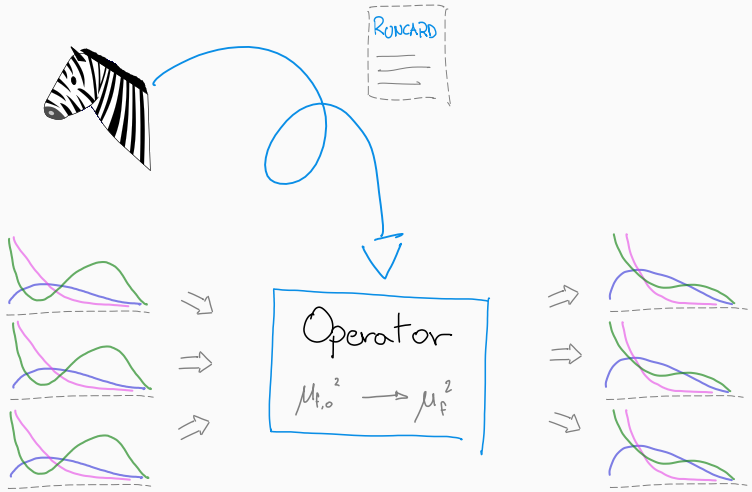
$$\mu_F^2 \frac{\mathrm{d}\mathsf{f}}{\mathrm{d}\mu_F^2}(\mu_F^2) = \mathsf{P}(a_s(\mu_R^2), \mu_F^2) \otimes \mathsf{f}(\mu_F^2)$$

These equations define a set of linear operators $\mathsf{E}(\mu_F^2 \leftarrow \mu_{F,0}^2)$ on PDF sets

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



Independent of boundary condition → PDF fitting

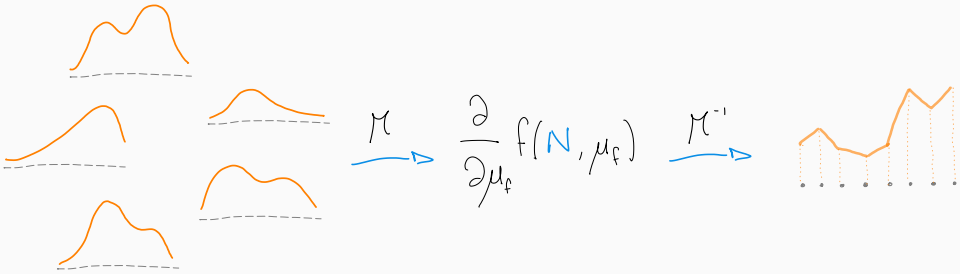


Solved in Mellin (N-) space, but the operator is recasted in ***x*-space**.

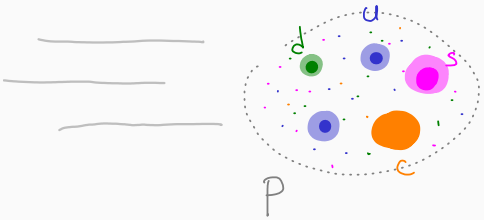
Via piecewise Lagrange-interpolation:

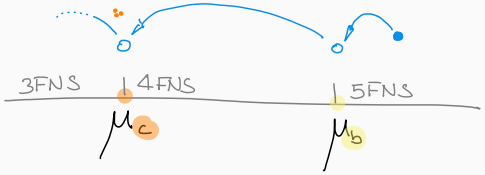
INPUT PDF is interpolated with polynomials, and ***analytically*** Mellin transformed

OUTPUT PDF is given on grid points, and Mellin inverted ***numerically***



Consistent evolution of **intrinsic** heavy quark distributions.



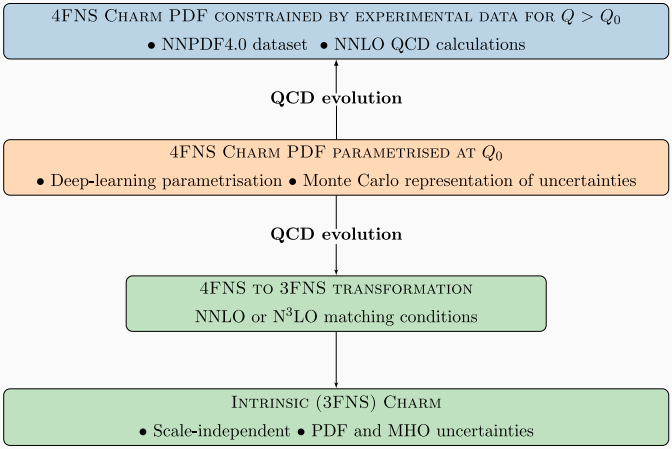


Full **backward VFNS** evolution (i.e. across thresholds and with intrinsic).

And more to come (MHOU, QED, N^{3}LO, ...).

Intrinsic Charm in the Proton [in press]

Based on NNPDF4.0 [arxiv:2109.02653].

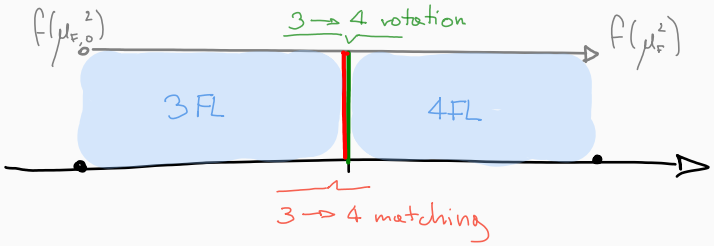


Intrinsic it is the charm PDF in the **3FNS**, where the charm is actually considered massive (and consequently *factorization scale independent* – collinear divergencies are protected by the mass)

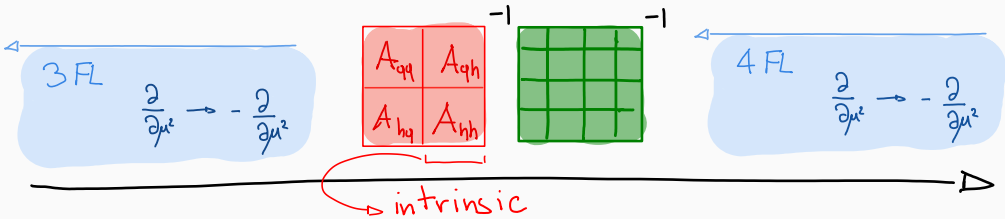
For (forward) evolution across a matching scale μ_h^2:

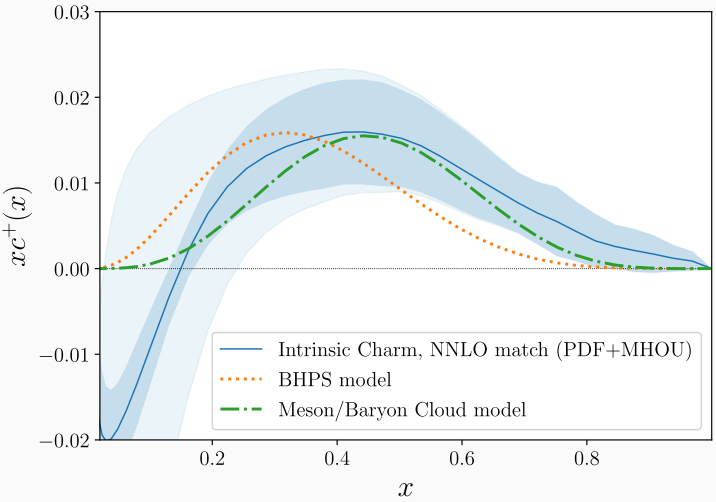
$$\mathsf{f}^{(n_f+1)}(\mu_{F,1}^2) = \left[\mathsf{E}^{(n_f+1)}(\mu_{F,1}^2 \leftarrow \mu_h^2)\mathsf{R}^{(n_f)}\mathsf{A}^{(n_f)}(\mu_h^2)\mathsf{E}^{(n_f)}(\mu_h^2 \leftarrow \mu_{F,0}^2)\right] \times \mathsf{f}^{(n_f)}(\mu_{F,0}^2)$$

The **Operator Matrix Element** (OME) $\mathsf{A}^{(n_f)}(\mu_h^2)$ is partially known up to N^{3}LO.



Inverse operator (the OME can be inverted either *perturbatively* or *numerically*)

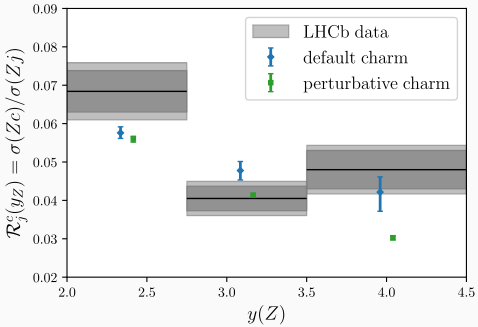


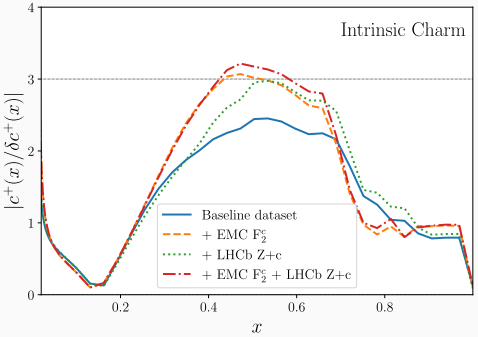


[BHPS] or [Meson/Baryon Cloud Model]

Message 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%**

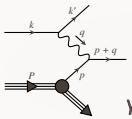




We found a 3σ evidence of intrinsic charm

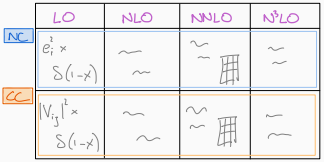
- match better recent **LHCb** Z+c measurement [PRL128-082001]
- result is **stable** with mass variation, dataset variation

yadism [IN PREPARATION]



Yadism

Yet Another DIS Module



DIS coefficient function database

Independent of **boundary** condition → PDF fitting.

Several other features: **TMC**, multiple **FNS**, generic matching scales, interpolation, ...

Constant benchmark against `APFEL`. ✓
Multiple benchmarks against `QCDNUM`. ✓
Benchmark with original FONLL. ✓

NLO	light	heavy	intrinsic
NC	✓	✓	✓
CC	✓	✓	✓
NNLO			
NC	✓	partially tabulated	✗
CC	✓	tabulated	✗
N^3LO			
NC	✓		
CC	✓		

+ FONLL (cf. *matching conditions*)

There is even another couple of levels of nesting:

PROJECTIONS F_2, F_L, and F_3

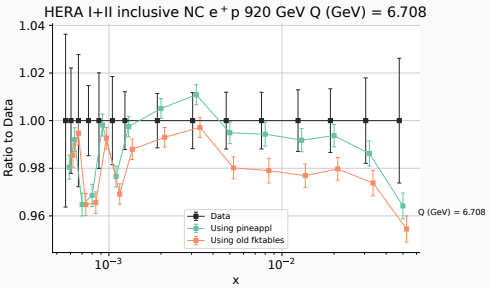
CHANNELS non-singlet, singlet, gluon

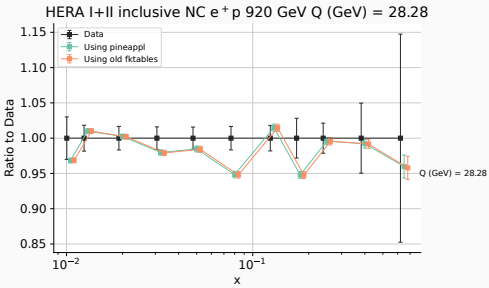
But up to NNLO everything is equally available (while at N^3LO it is not always true).

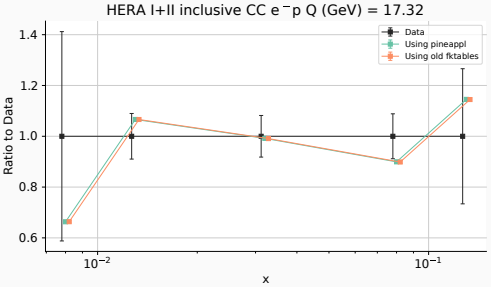
So NC is currently implemented up to NNLO [VVM05 MVV05 MV00] light and NLO heavy [Hek19] (i.e. both $O(a_s^2)$). Same for CC light [MRV08 MVV09] and heavy (for which implementation is currently in progress).

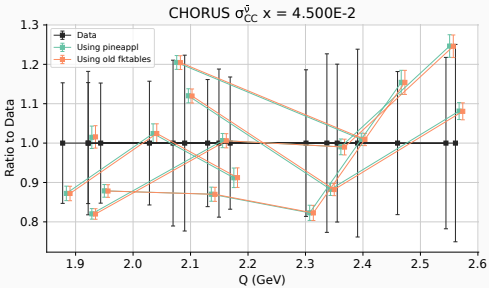
For both processes *intrinsic* contributions are accounted at NLO.

available | updated | not yet implemented | missing | not planned

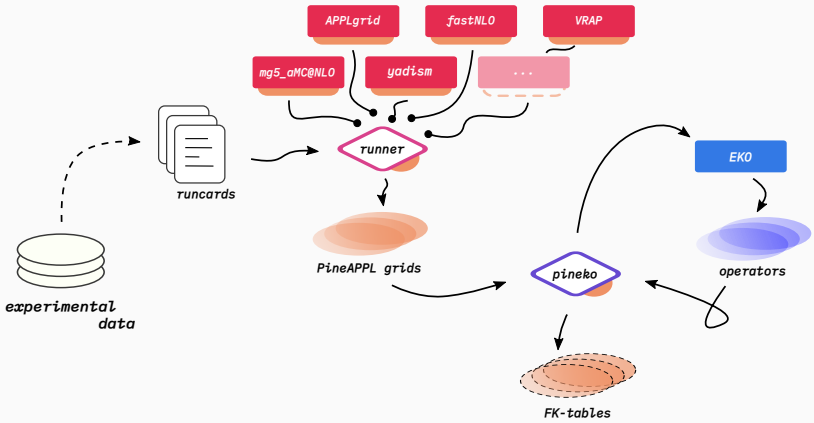

HERA I+II inclusive NC e⁺p 920 GeV Q (GeV) = 6.708
Ratio to Data
x
Q (GeV) = 6.708
Data
Using pineappl
Using old fktables


HERA I+II inclusive NC e⁺p 920 GeV Q (GeV) = 28.28
Ratio to Data
x
Q (GeV) = 28.28
Data
Using pineappl
Using old fktables


HERA I+II inclusive CC e⁻p Q (GeV) = 17.32
Ratio to Data
x
Data
Using pineappl
Using old fktables


CHORUS σ$^{\bar{\nu}}_{CC}$ x = 4.500E-2
Ratio to Data
Q (GeV)
Data
Using pineappl
Using old fktables

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`

Goal produce `FastKernel` tables used in PDF fitting

Summary

Why should one use:

EKO? because:

- it produces "out of the box" **operators**
- the operators can be immediately used **together with grids**
- it joins advantages of x **and** N **space**
- it is getting more and **more physics features** (intrinsic, backward VFNS, QED, N^{3}LO)

yadism? because:

- direct production **DIS grids**
- extensive (and extended) database of **coefficient functions**
- thorough implementation of **FNS** (and more...)

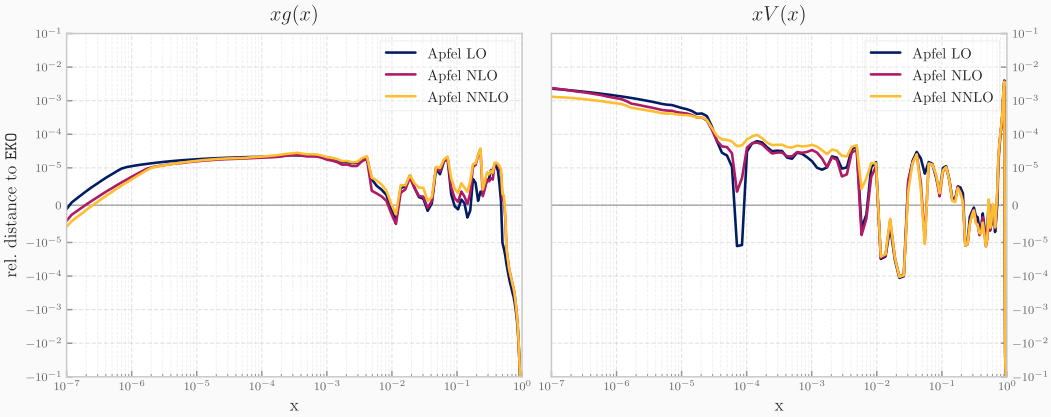
Pipeline? because:

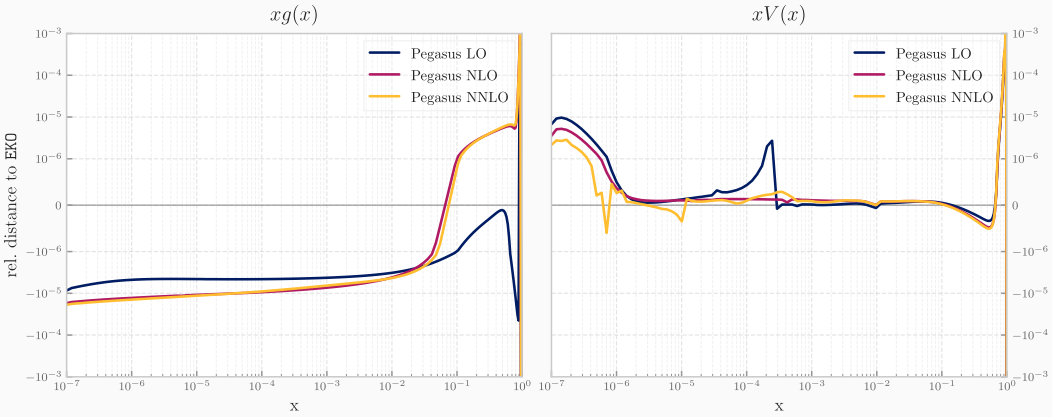
- it makes **easy, flexible, and reproducible**
- to produce **performant theory** predictions for PDF fitting

Intrinsic charm itself is a *joint* product of EKO and **NNPDF4.0** efforts.

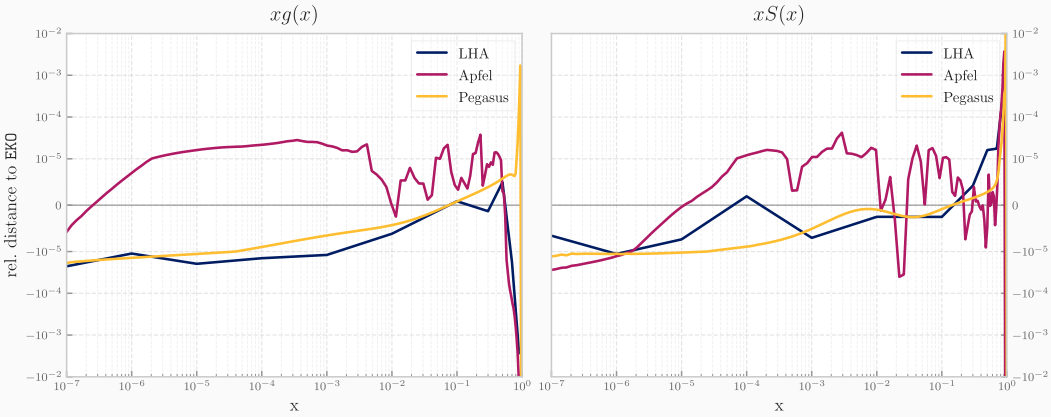
Thank you for listening!

EKO

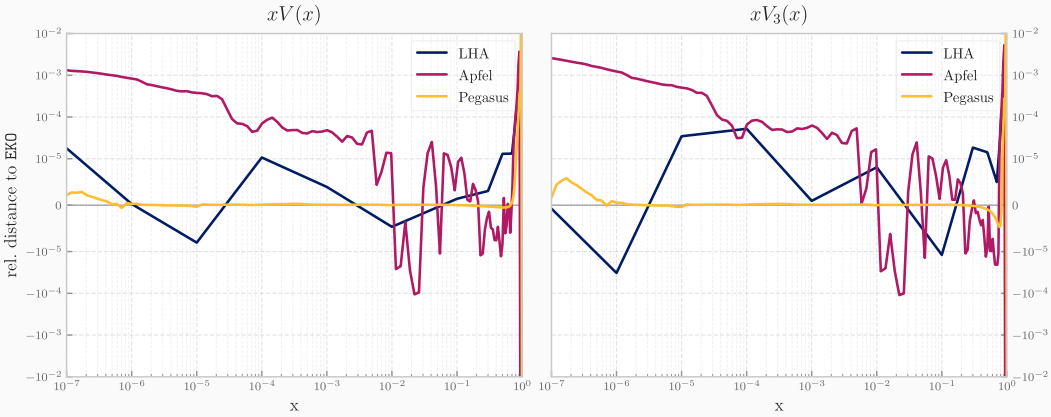

$xg(x)$
$xV(x)$
Apfel LO
Apfel NLO
Apfel NNLO
rel. distance to EKO
x
x


$xg(x)$
$xV(x)$
Pegasus LO
Pegasus NLO
Pegasus NNLO
rel. distance to EKO
x
x

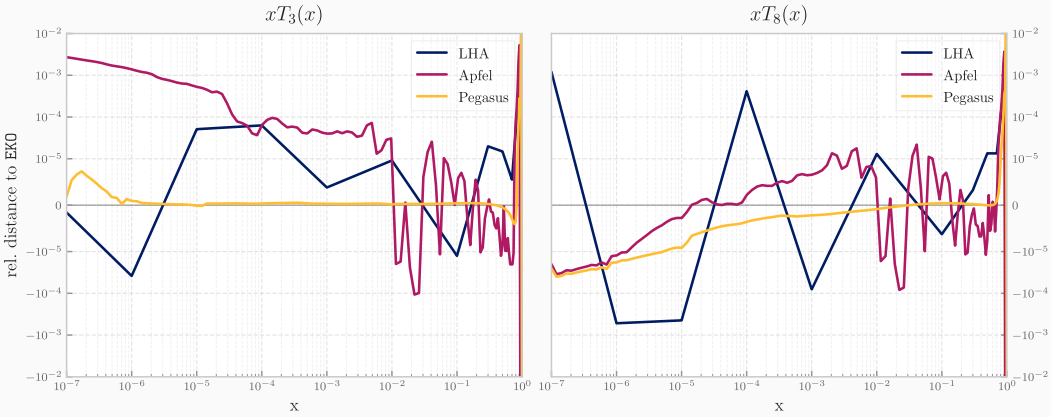
EKO LHA BENCHMARK: g AND Σ



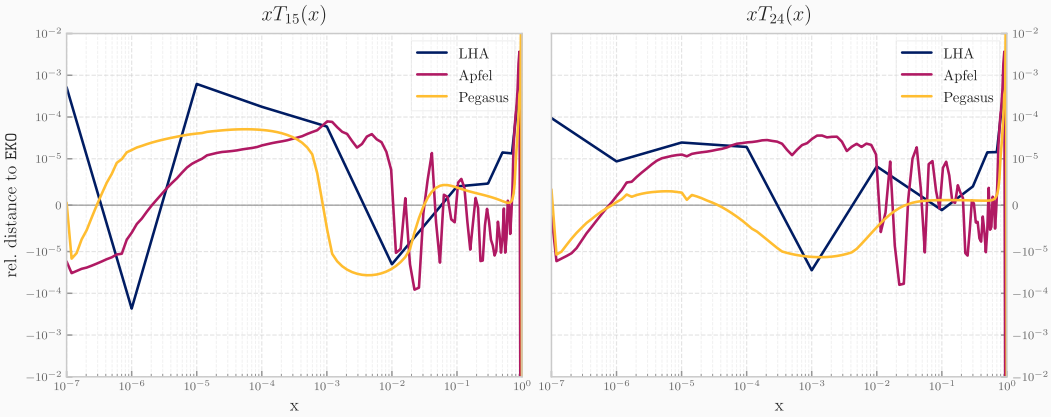
EKO LHA benchmark: V and V_3

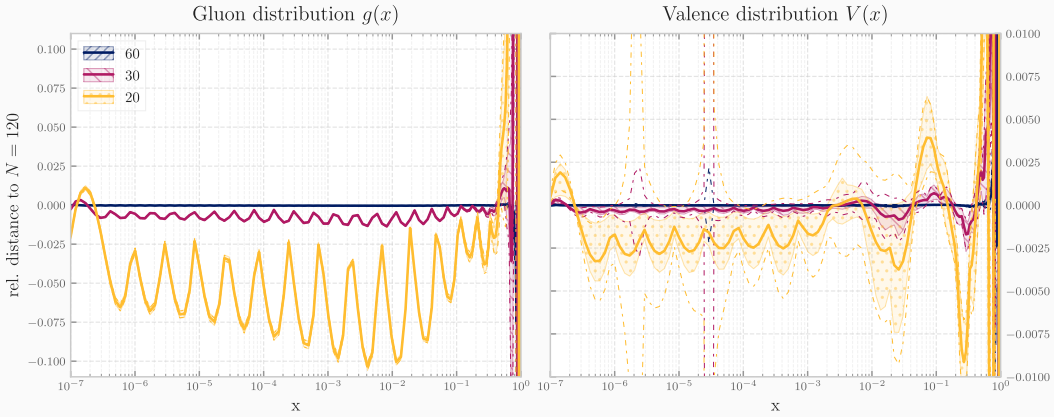


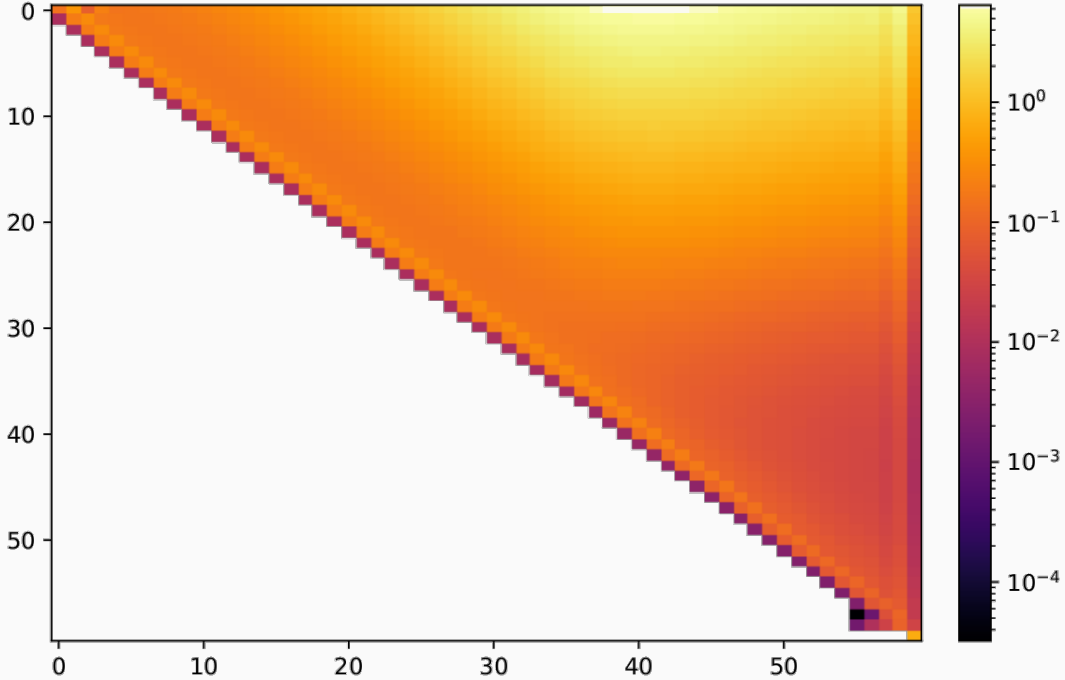
EKO LHA BENCHMARK: T_3 AND T_8

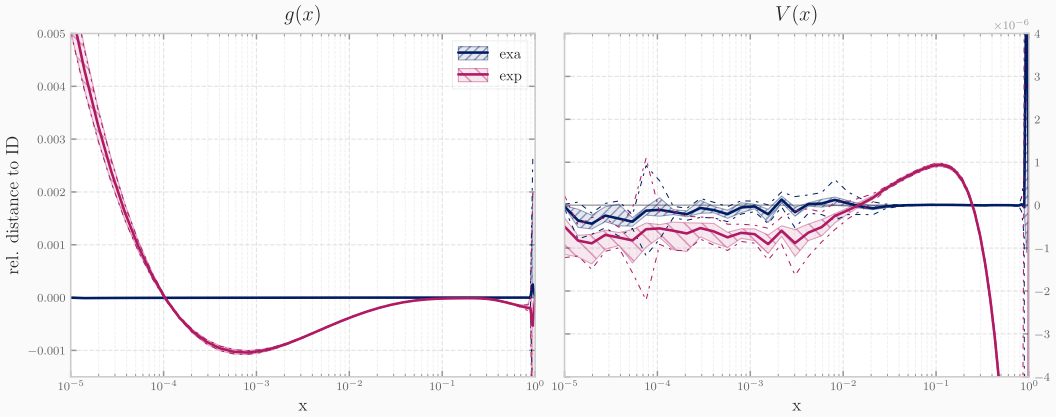


EKO LHA BENCHMARK: T_{15} AND T_{24}

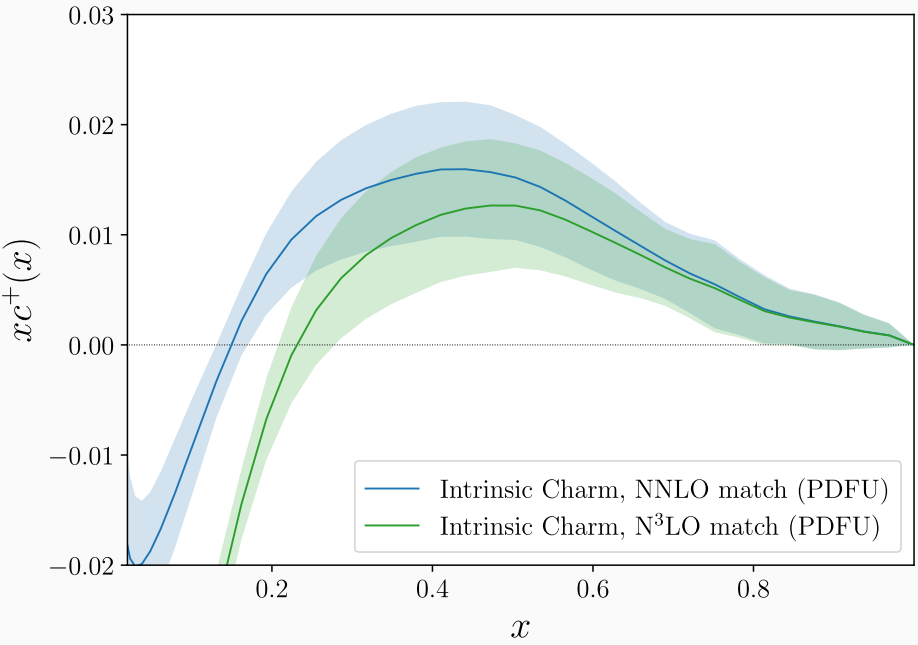



Gluon distribution $g(x)$
Valence distribution $V(x)$
60
30
20
rel. distance to $N = 120$
x
x

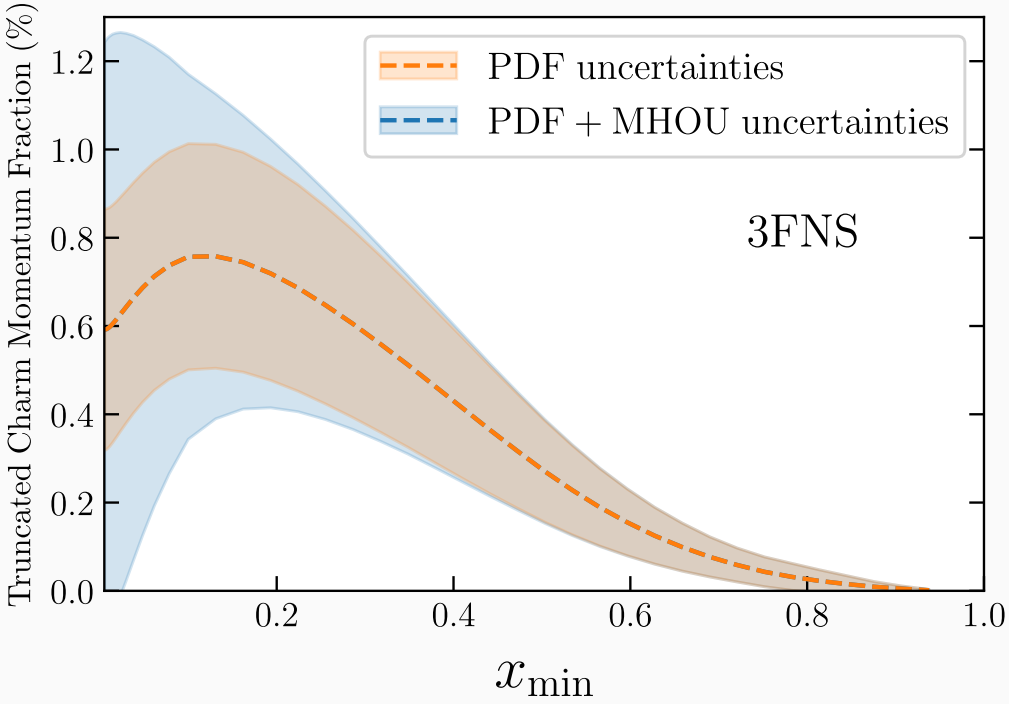

0
10
20
30
40
50
0
10
20
30
40
50
10^{0}
10^{-1}
10^{-2}
10^{-3}
10^{-4}

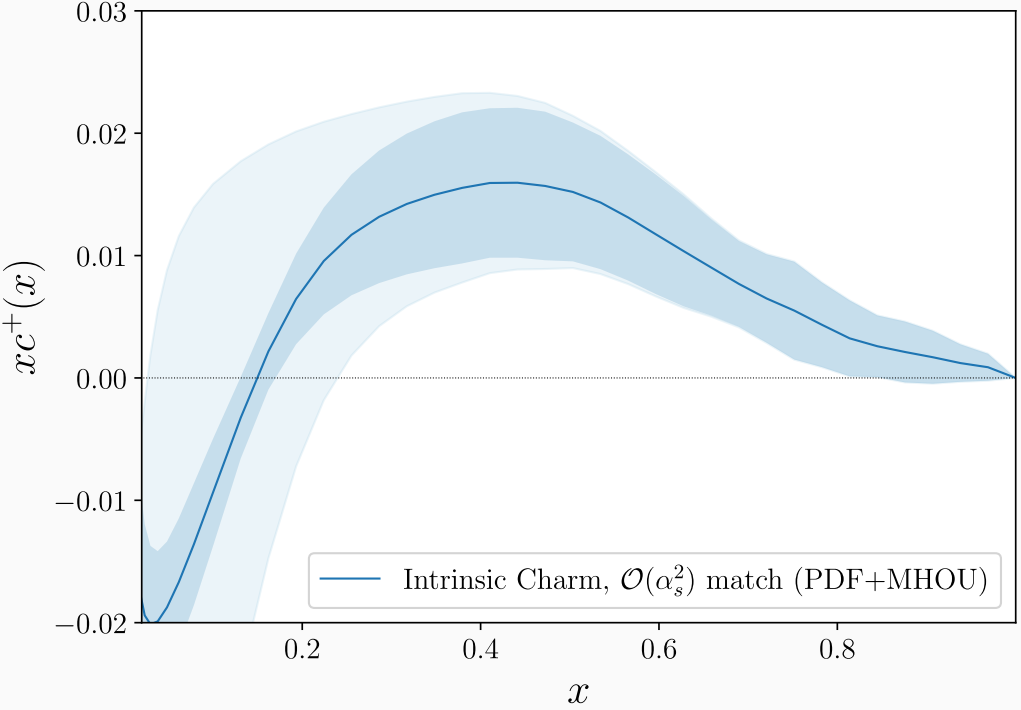

$g(x)$
$V(x)$
exa
exp
rel. distance to ID
x
x
0.005
0.004
0.003
0.002
0.001
0.000
−0.001
$\times 10^{-6}$
4
3
2
1
0
−1
−2
−3
−4
10^{-5}
10^{-4}
10^{-3}
10^{-2}
10^{-1}
10^{0}

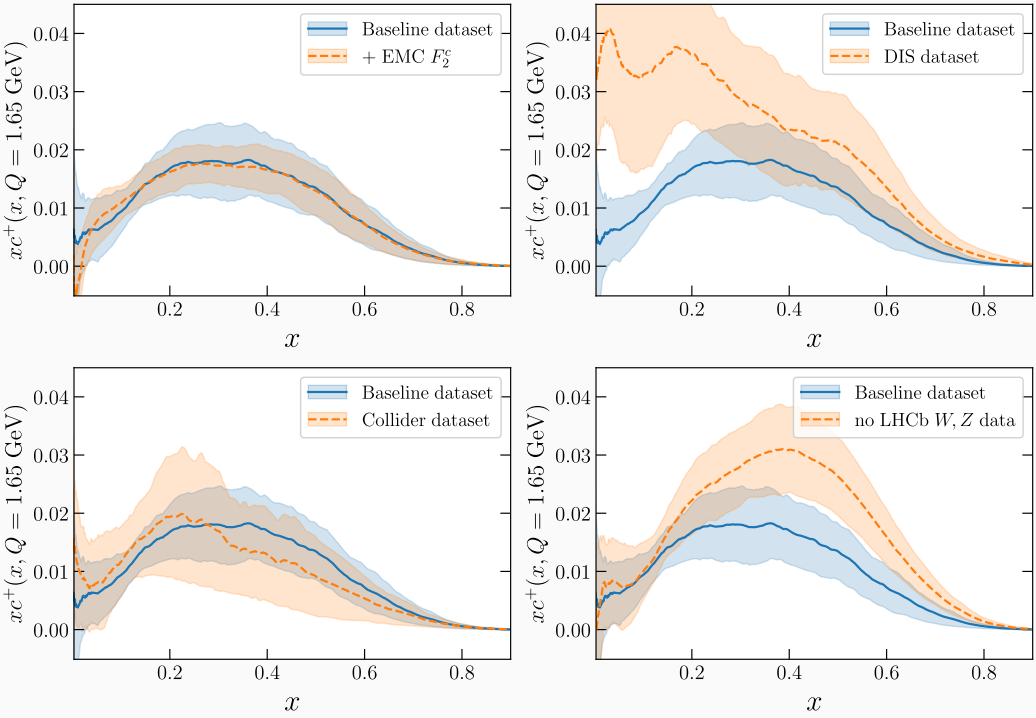
Intrinsic Charm

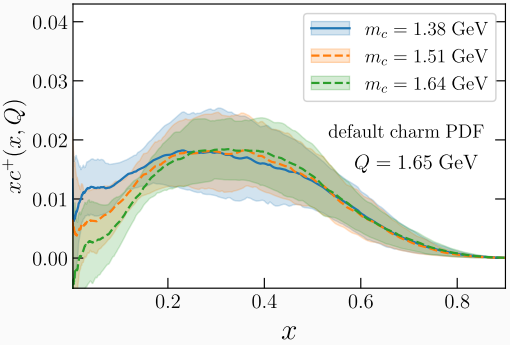


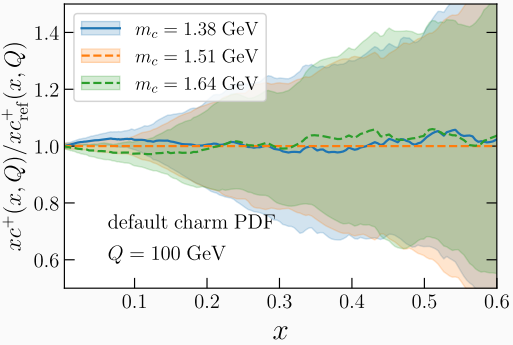
3FNS comparison – NNLO matching vs N^{3}LO

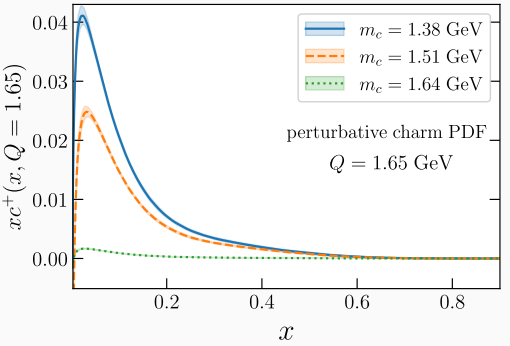

PDF uncertainties
PDF + MHOU uncertainties
3FNS
Truncated Charm Momentum Fraction (%)
0.0
0.2
0.4
0.6
0.8
1.0
1.2
0.2
0.4
0.6
0.8
1.0
$x_{\min}$

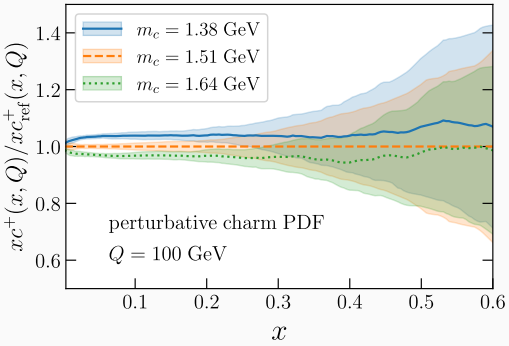

0.03
0.02
0.01
0.00
−0.01
−0.02
$xc^+(x)$
0.2
0.4
0.6
0.8
x
Intrinsic Charm, $\mathcal{O}(\alpha_s^2)$ match (PDF+MHOU)


Baseline dataset
+ EMC F_2^c
Baseline dataset
DIS dataset
Baseline dataset
Collider dataset
Baseline dataset
no LHCb W, Z data
$xc^+(x, Q = 1.65\ \text{GeV})$
x
0.00
0.01
0.02
0.03
0.04
0.2
0.4
0.6
0.8

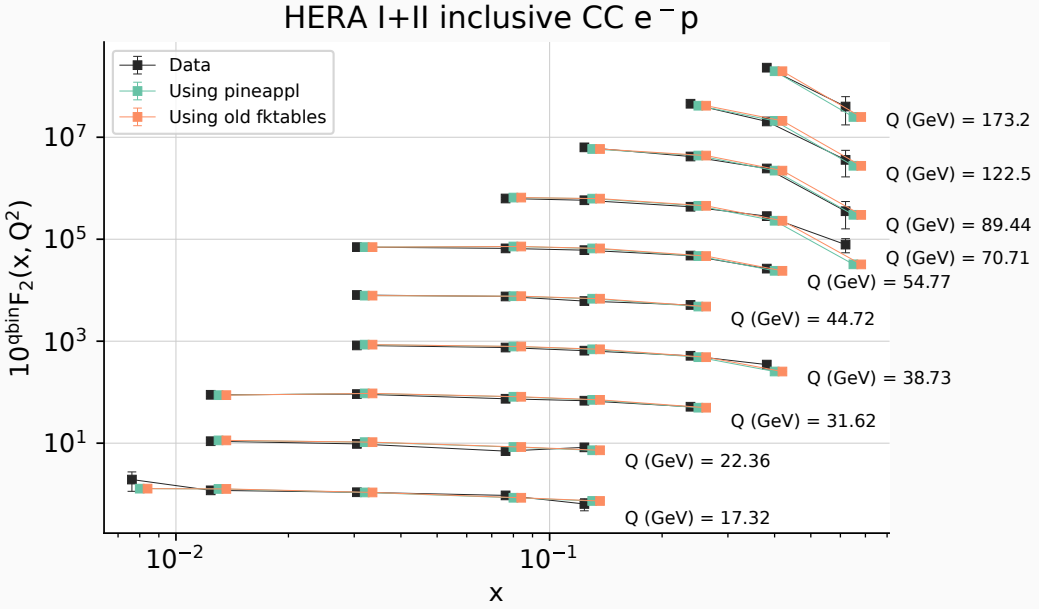

$m_c = 1.38$ GeV
$m_c = 1.51$ GeV
$m_c = 1.64$ GeV
default charm PDF
$Q = 1.65$ GeV
$xc^+(x, Q)$
x

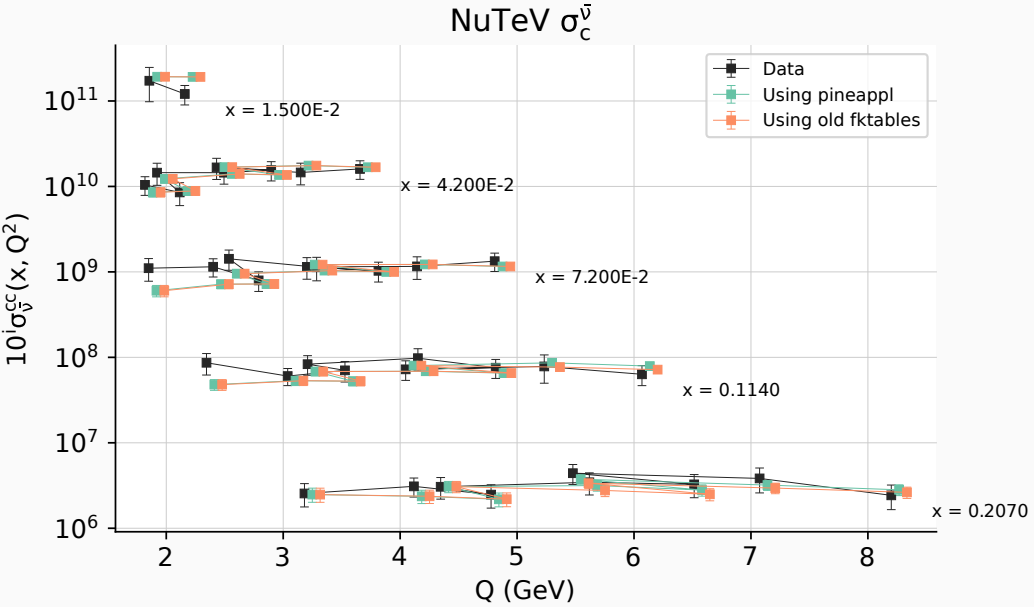

$m_c = 1.38$ GeV
$m_c = 1.51$ GeV
$m_c = 1.64$ GeV
default charm PDF
$Q = 100$ GeV
$xc^+(x, Q)/xc^+_{\rm ref}(x, Q)$
x


$m_c = 1.38$ GeV
$m_c = 1.51$ GeV
$m_c = 1.64$ GeV
perturbative charm PDF
$Q = 1.65$ GeV
$xc^+(x, Q = 1.65)$
x


$m_c = 1.38$ GeV
$m_c = 1.51$ GeV
$m_c = 1.64$ GeV
perturbative charm PDF
$Q = 100$ GeV
$xc^+(x, Q)/xc^+_{\rm ref}(x, Q)$
x

yadism


HERA I+II inclusive CC e⁻p
Data
Using pineappl
Using old fktables
10^{7}
10^{5}
10^{3}
10^{1}
$10^{\text{qbin}}F_2(x, Q^2)$
10^{-2}
10^{-1}
x
Q (GeV) = 173.2
Q (GeV) = 122.5
Q (GeV) = 89.44
Q (GeV) = 70.71
Q (GeV) = 54.77
Q (GeV) = 44.72
Q (GeV) = 38.73
Q (GeV) = 31.62
Q (GeV) = 22.36
Q (GeV) = 17.32


NuTeV $\sigma_c^{\bar{\nu}}$
Data
Using pineappl
Using old fktables
x = 1.500E-2
x = 4.200E-2
x = 7.200E-2
x = 0.1140
x = 0.2070
$10^i\sigma_{\bar{\nu}}^{cc}(x, Q^2)$
Q (GeV)