Intrinsic charm in the proton

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Flavoured Jets at the LHC

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Perturbative charm

A common assumption in PDF fits is that the proton wave function does not contain charm quarks but only light quarks

This assumption leads to a purely perturbative charm, namely:

- Charm quark pairs are perturbatively generated in DGLAP evolution
  $f_c^{(3)} = 0$
  $f_c^{(4)} \propto \alpha_s \log\left(\frac{Q^2}{m_c^2}\right) P_{qg} \otimes f_g^{(4)} + \mathcal{O}(\alpha_s^2)$
- Present only above the heavy quark threshold (in 4FNS)
- Fixed by the light flavour and gluon PDFs

However instead of assuming charm completely perturbatively, one may determine it on the same footing as the light quarks

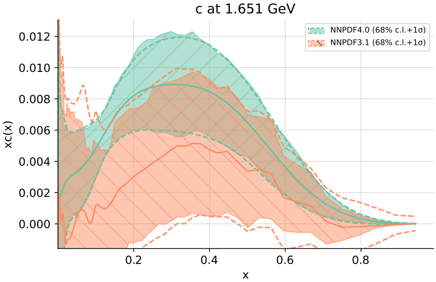
Fitted charm

NNPDF4.0 independently parametrizes the total charm distribution $c^+ = c + \bar{c}$

Fitted charm is a combination of perturbative and intrinsic charm:
$c^{(4)} = c^{(4)}_{pert} + c^{(4)}_{intr}$

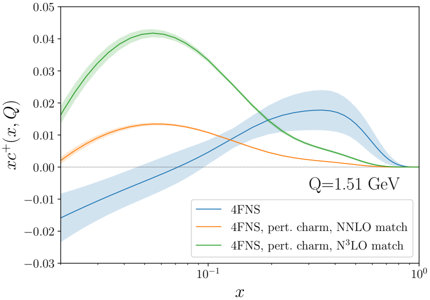
- $c^{(4)}$ extracted from data instead of fixed by light flavour PDFs
- Intrinsic component is present at all scales, $c^{(3)}_{intr} \neq 0$

Intrinsic charm is charm in the 3FNS!



4FNS

Fitted vs perturbative charm PDF



Fitted charm:

- Independent of matching conditions
- More realistic uncertainties

Evidence for intrinsic charm quarks in the proton

NNPDF, 2208.08372

How to determine intrinsic charm?

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^{3}LO matching conditions

Intrinsic (3FNS) Charm

• Scale-independent • PDF and MHO uncertainties

DGLAP evolution with EKO

[Candido, Hekhorn, Magni, 2202.02338]

EKO

Evolution Kernel Operators

Python unit tests passing | Rust unit tests passing | docs passing

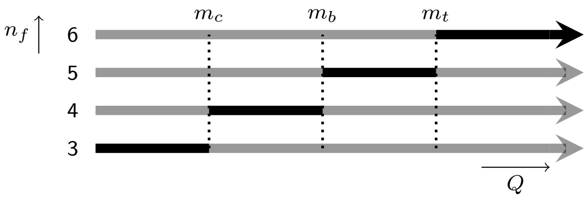
codecov 47% | codefactor A

EKO is a Python module to solve the DGLAP equations in N-space in terms of Evolution Kernel Operators in x-space.

- Implements DGLAP solutions up to aN3LO QCD and NLO QED
- Supports output in pineappl grids (xFitter and NNPDF have pineappl interfaces)
- Supports coexising PDFs in different FNS at all scales

FONLL heavy quarks scheme with EKO

[Candido, Hekhorn, Magni, 2202.02338]

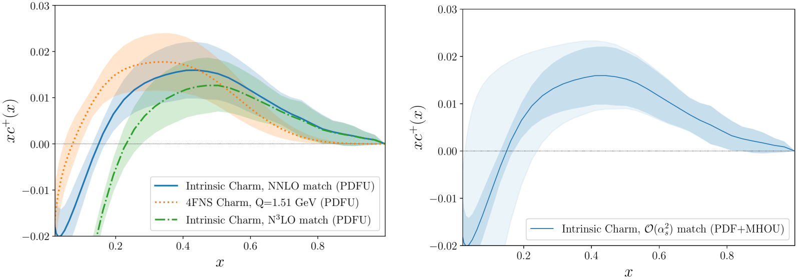


- Implements DGLAP solutions up to aN3LO QCD and NLO QED
- Supports coexising PDFs in different FNS at all scales

$\Rightarrow$ Construct FONLL with coexisting FNS PDFs

$$F_{FONLL} = F^{(4)}(m_c = 0) + F^{(3)}(m_c) - \lim_{m_c \to 0} F^{(3)}(m_c)$$

Evidence for intrinsic charm (in 3FNS)

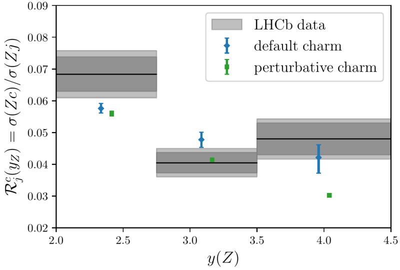


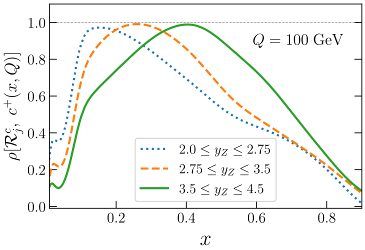
- MHOU estimated from N3LO-NNLO matching difference
- Large perturbative uncertainty for small-x
- PDF dominated uncertainty at large-x
- Non-zero intrinsic charm peak around $x \simeq 0.5$

Z+charm at LHCb

[LHCb, 2109.08084]

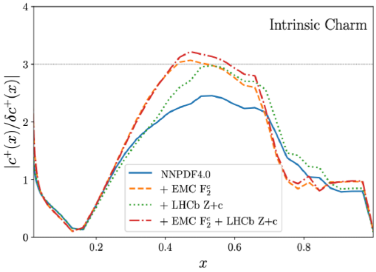
$$\mathcal{R}_j^c \equiv \frac{N_{c\text{ tagged jets}}}{N_{\text{jets}}} = \frac{\sigma\left(pp \to Z + \text{ charm jet }\right)}{\sigma\left(pp \to Z + \text{ jet }\right)}$$





- Assuming intrinsic charm improves prediction of recent measurement
- In particular in the y bin with the strongest correlation to the charm peak

Evidence for intrinsic charm

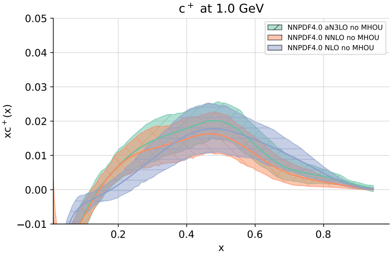


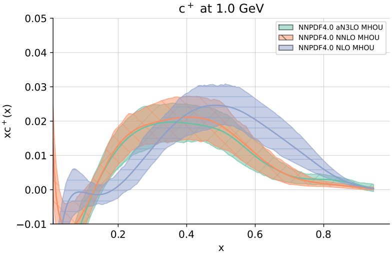
- Local significance of 2.5σ for IC at $x \simeq 0.5$ with default NNPDF4.0
- Evidence increases up to 3σ inclusion of EMC F_2^c and LHCb $Z + c$

Intrinsic charm at N3LO

[NNPDF, 2402.18635]

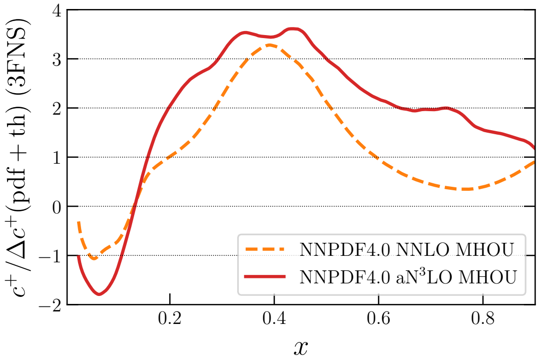
- Consistent N3LO PDF with N3LO matching agrees with NNLO result!
- Convergence further improved by inclusion of MHOUs





3FNS

Intrinsic charm at N3LO



- Evidence for IC stable upon change from NNLO to N3LO
- Local significance of 3σ for IC at $x \simeq 0.4$

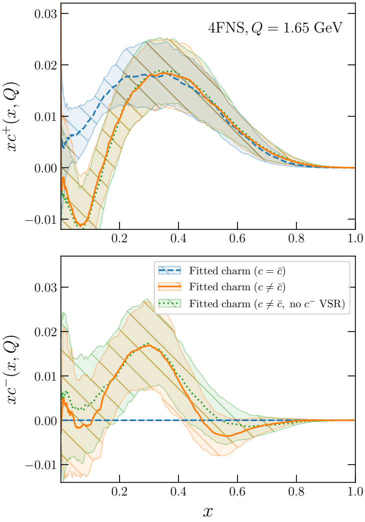
Intrinsic charm quark valence distribution of the proton

NNPDF, 2311.00743

Fitting the valence charm distribution

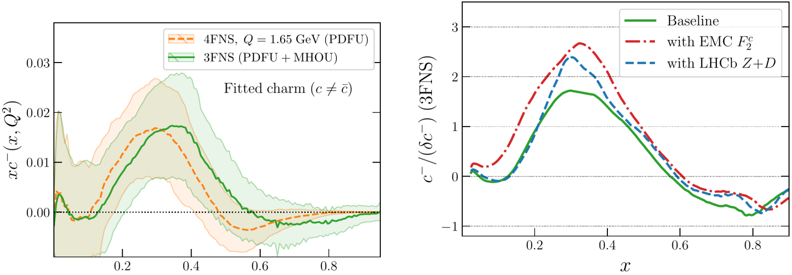
- Extend fitting basis with a valence charm distribution $c^- = c - \bar{c}$
- Perturbative charm is generated in pair production, i.e. $c^- = 0$

$\Rightarrow$ Valence charm must be intrinsic



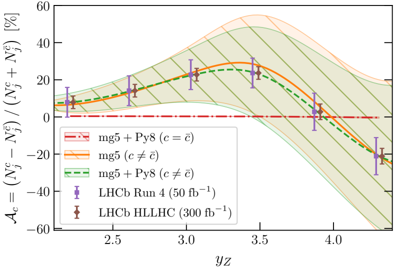
c^+ stable around valance peak

Intrinsic valence charm

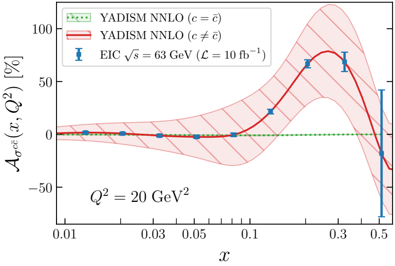


- $c^{-,(3)} \simeq c^{-,(4)}$: smaller MHOU than c^+
- Nonvanishing valance charm PDF at large-x
- LHCb and EMC data increases local valance significance
- Hints at possible nonzero intrinsic valence charm, but more data needed

Measuring the valence charm distribution at LHCb



Charm asymmetries in Z+c at LHCb



Charm-tagged DIS at the EIC

$$\mathcal{A}_c \equiv \frac{N_j^c - N_j^{\bar{c}}}{N_j^c + N_j^{\bar{c}}}$$

$$\mathcal{A}_{\sigma^{cc}} \equiv \frac{\sigma^c_{\text{red}} - \sigma^{\bar{c}}_{\text{red}}}{\sigma^{c\bar{c}}_{\text{red}}}$$

PDF generalization to unseen data

Ongoing

What is the impact of PDF uncertainties when comparing to data not included in the fit?

Systematically study the impact of PDF choice in the agreement between theory and data for datasets not included in the NNPDF4.0 analysis

Sector	Exp.	$\sqrt{s}$ (TeV)	Channel	Observable	$\mathcal{L}$ (fb^{-1})	N$_{\text{dat}}$
W, Z	ATLAS	13	Z p_T spectrum	$\frac{d\sigma}{dp_T^Z}$	36.1	10
	ATLAS	8	Z incl. prod.	$\frac{d\sigma}{d\|y_{ll}\|}$	20.2	7
	CMS	8	W incl. prod.	$\frac{d\sigma_{W^\pm}}{d\eta_l}$	35.9	36
	LHCb	13	Z incl. forward prod.	$\frac{d\sigma_Z}{dy_Z}$	5.1	17
top	ATLAS	13	hadronic	$\left(\frac{1}{\sigma}\right)\frac{d\sigma}{dm_{t\bar{t}}}, \frac{d\sigma}{d\|y_{t\bar{t}}\|}, \frac{d^2\sigma}{d\|y_{t\bar{t}}\|dm_{t\bar{t}}}$	36.1	9, 12, 11
	ATLAS	13	ℓ+jets	$\left(\frac{1}{\sigma}\right)\frac{d\sigma}{dm_{t\bar{t}}}, \frac{d\sigma}{dp_{T,t}}, \frac{d\sigma}{d\|y_t\|}, \frac{d^2\sigma}{d\|y_{t\bar{t}}\|}$	36.1	9, 8, 5, 7
	CMS	13	ℓ+jets	$\left(\frac{1}{\sigma}\right)\frac{d\sigma}{dm_{t\bar{t}}}, \frac{d\sigma}{dp_{T,t}}, \frac{d\sigma}{d\|y_{t\bar{t}}\|}, \frac{d\sigma}{d\|y_t\|}, \frac{d^2\sigma}{d\|y_{t\bar{t}}\|dm_{t\bar{t}}}$	137	15, 16, 10, 11, 35
jets	ATLAS	13	incl. jet R=0.4, 0.7	$\frac{d^2\sigma}{dp_{T,j}d\|y_j\|}$	3.2	177
	ATLAS	13	di-jets R=0.4	$\frac{d^2\sigma}{dm_{jj}d\Delta y}$	3.2	136
	CMS	13	incl. jets R=0.4, 0.7	$\frac{d^2\sigma}{dp_{T,j}d\|y_j\|}$	3.2	78
DIS jets	H1	0.319	incl. jet (low q^2)	$\frac{d^2\sigma}{dq^2dpT}$	0.29	48
	H1	0.319	di-jets (low q^2)	$\frac{d^2\sigma}{dq^2d\langle pT\rangle}$	0.29	48
	H1	0.319	incl. jet (high q^2)	$\frac{d^2\sigma}{dq^2dpT}$	0.351	24
	H1	0.319	di-jets (high q^2)	$\frac{d^2\sigma}{dq^2d\langle pT\rangle}$	0.351	24
	ZEUS	0.3	incl. jet	$\frac{d^2\sigma}{dE_Tdq^2}$	0.038	30
	ZEUS	0.319	incl. jet	$\frac{d^2\sigma}{dE_Tdq^2}$	0.082	30
	ZEUS	0.319	d-jets	$\frac{d^2\sigma}{dE_Tdq^2}$	0.374	22

What is the impact of NNPDF4.0 uncertainties when comparing to data not included in the fit?

- Results are full NNLO, no k-factor approximations
- NNPDF4.0 is baseline PDF without MHOUs
- Shown are χ^2 values with (without) PDF uncertainties

	top l+jets $\frac{d\sigma}{dp{T}_t}$ [CMS, 2108.02803]	top l+jets $\frac{d^2\sigma}{dm_{t\bar{t}}d\vert y_{t\bar{t}}\vert}$ [ATLAS, 1908.07305]
NNPDF4.0	0.768 (0.773)	1.297 (1.338)
CT18	0.712 (0.729)	1.489 (2.347)
MSHT20	0.699 (0.705)	1.585 (2.046)

di-jet 2D [ATLAS, 1711.02692]	inclusive jets R=0.7 [CMS, 2111.10431]	$\frac{d\sigma}{dy_Z}$ 13 TeV [LHCb, 2112.07458]
1.82 (1.91)	2.35 (2.78)	2.21 (2.27)
1.79 (1.91)	2.16 (3.81)	2.19 (2.56)
1.65 (1.92)	2.47 (3.96)	2.24 (2.38)

[Maria Ubiali, LHCP 2024]

While PDFs have different uncertainties, data-theory description of unseen data is similar

Summary

Summary

- Intrinsic charm is a non-perturbative component of the proton wave function
- 3σ local significance of intrinsic total charm
- 1.5σ for significance intrinsic valence charm
- More data for increased significance

- Description of unseen data is similar for various recent global PDF sets

Summary

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- 3σ local significance of intrinsic total charm
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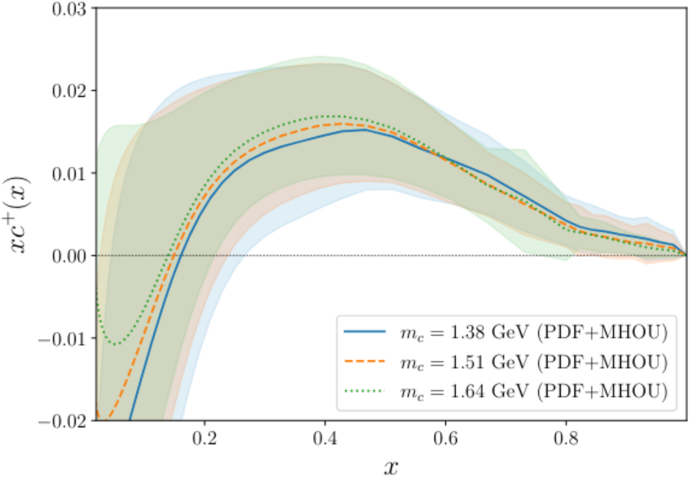
Thank you for your attention!

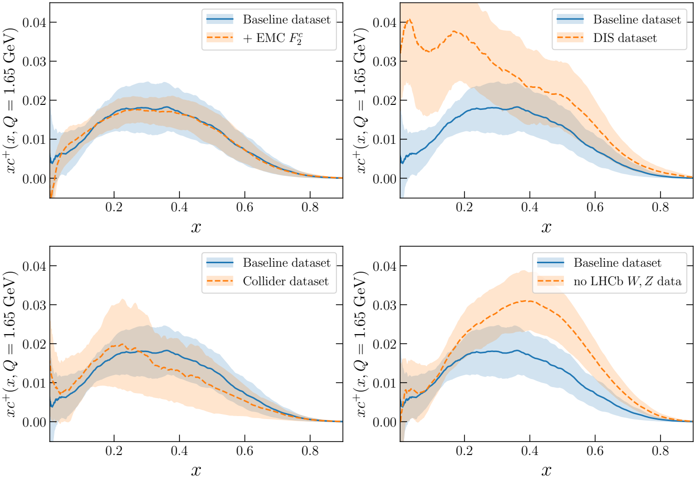
Backup

m_c dependence



3FNS

Dataset variations



4FNS

Higher twist?