Intrinsic Charm in the Proton

The 4th EIC-Asia Workshop

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Intrinsic charm in models

Assumption: the static proton wave function does not contain charm quarks

No intrinsic charm

It does not need to be so, charm can be defined as an operator matrix element

$$\langle p|\bar{c}\gamma^{\mu_1}D^{\mu_2}\ldots D^{\mu_n}c|p\rangle = A_c^n p^{\mu_1}\ldots p^{\mu_n} - \text{traces} \qquad A_c^n = \int_0^1 dx x^{n-1}c(x)$$

THE INTRINSIC CHARM OF THE PROTON

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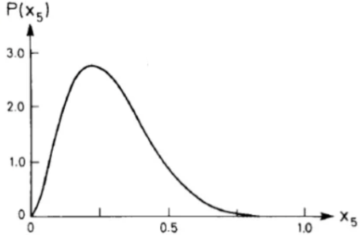
Received 22 April 1980

$$p\rangle = \mathscr{P}_{3q}\; uud\rangle + \mathscr{P}_{5q}\; uudc\bar{c}\rangle + \ldots$$



Recent data give unexpectedly large cross-sections for charmed particle production at high x_F in hadron collisions. This may imply that the proton has a non-negligible uudc$\bar{c}$ Fock component. The interesting consequences of such a hypothesis are explored.

[PLB 93 (1980) 451; PRD 89 (2014) 074008]

Intrinsic charm in QCD

What is intrinsic charm?

Do not factor charm mass singularities into operator matrix element

Choose $n_f = 3$ scheme

Charm PDF purely intrinsic, scale-independent

Intrinsic charm is charm in the $n_f = 3$ (decoupling) scheme

$$\underbrace{f_c^{(n_f)} = 0}_{\text{3FNS charm}} \quad \rightarrow \quad \underbrace{f_c^{(n_f+1)}}_{\text{4FNS charm}} \propto \alpha_s \ln \frac{Q^2}{m_c^2} \left(P_{qg} \otimes \underbrace{f_g^{(n_f+1)}}_{\text{4FNS gluon}} \right) + \mathcal{O}\left(\alpha_s^2\right) \qquad \textbf{NLO matching}$$

How to measure intrinsic charm?

Determine PDFs from data, go to $n_f = 3$ result, look at the result

1) Parametrise PDFs in $n_f = 3$ (3FNS) and match up for fitting

2) Parametrise PDFs in $n_f = 4$ (4FNS) and match down for determining intrinsic charm

$$c^{(n_f=4)}(x,Q) \simeq c^{(n_f=4)}_{\text{(pert)}}(x,Q) + c^{(n_f=4)}_{\text{(intr)}}(x,Q)$$

- $c^{(n_f=4)}(x,Q)$: Extracted phenomenologically from data
- $c^{(n_f=4)}_{\text{(pert)}}(x,Q)$: from pQCD evolution and matching
- $c^{(n_f=4)}_{\text{(intr)}}(x,Q)$: from intrinsic component $c^{(n_f=3)}_{\text{(intr)}}(x) \neq 0$

Large matching uncertainties [I. Bierenbaum *et al.*; J. Ablinger *et al.*]

1. Evidence for intrinsic charm quarks in the proton
[Nature **608** (2022) 7923 483]

How intrinsic charm is determined in NNPDF

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

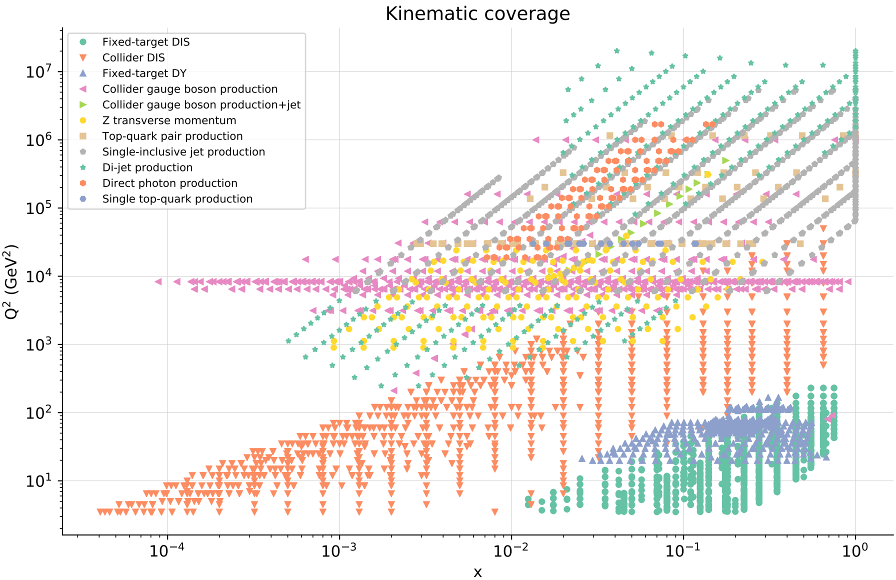
NNLO or N^3LO matching conditions

↓

Intrinsic (3FNS) Charm

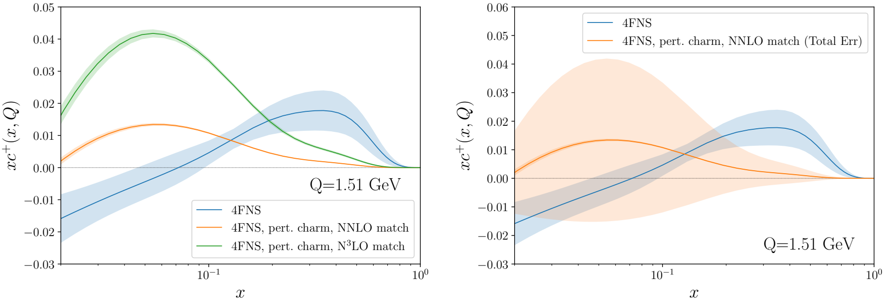
• Scale-independent • PDF and MHO uncertainties

The NNPDF4.0 data set



$$Q_0 = 1.65 \text{ GeV} > m_c = 1.51 \text{ GeV}$$

Perturbative charm vs intrinsic charm in 4FNS



We performed two fits: one assuming vanishing intrinsic charm (perturbative) and one assuming non-vanishing intrinsic charm

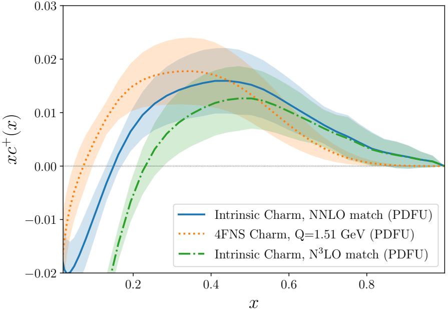
Fit quality ($N_{\rm dat} = 4618$):
$\chi^2/N_{\rm dat} = 1.20$ (vanishing intrinsic charm) $\chi^2/N_{\rm dat} = 1.16$ (vanishing intrinsic charm)

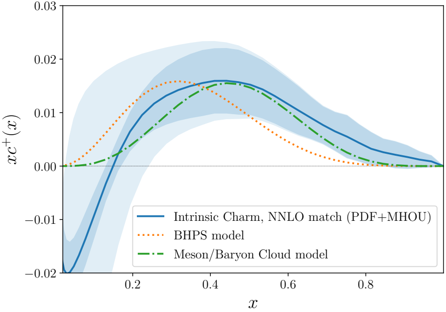
The charm PDF in 4FNS turns out to be significantly different in the two cases

Even if one accounts for different perturbative accuracy in matching conditions (NNLO or N^{3}LO) in perturbative charm, they are not compatible in the large-x region

What happens in the 3FNS?

From 4FNS charm to 3FNS charm





The intrinsic charm (3FNS) PDF looks valence-like at large x, with a peak at $x \sim 0.4$

The Intrinsic charm PDF is small in absolute terms, but it is clearly different from zero

The matching between the 4FNS and the 3FNS has little effect on the peak region (no charm is radiatively generated)

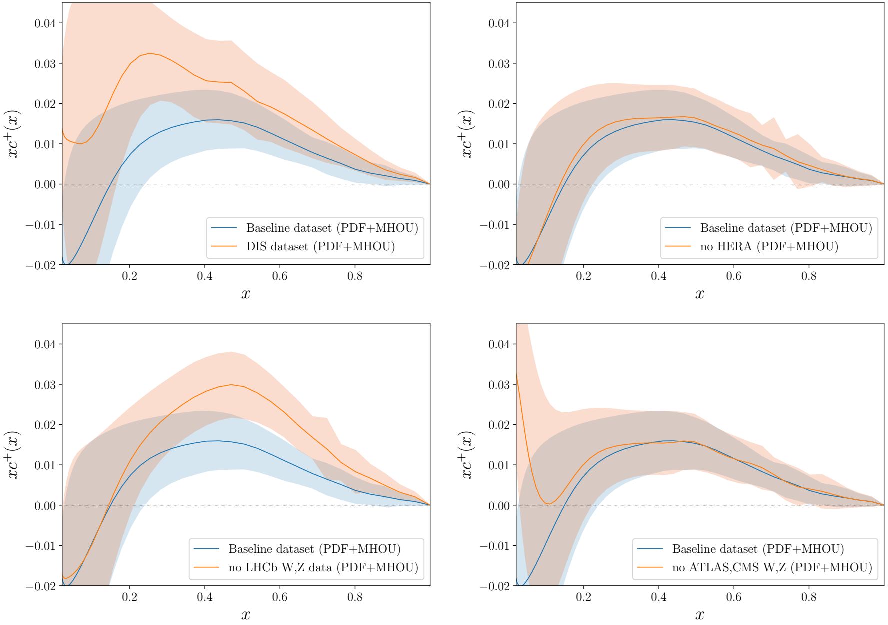
The valence-like peak is stable upon inclusion of MHOUs (estimated as the difference between results obtained with NLO or N^{3}LO matching)

MHOUs dominate at small x where intrinsic charm becomes compatible with zero

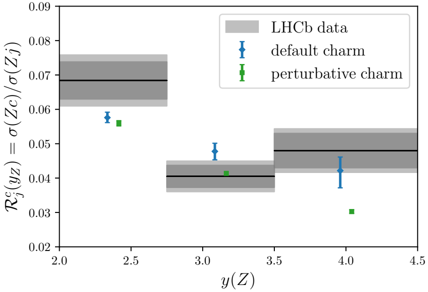
Charm momentum fraction: $\langle c \rangle = 0.62 \pm 0.28_{\rm PDF} \pm 0.54_{\rm MHOU}\%$

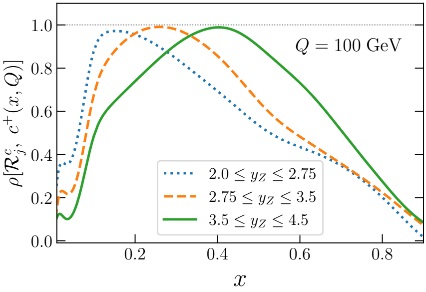
The valence-like peak is qualitatively consistent with predictions from models

Which data drives intrinsic charm?



The LHCb $Z + c$ data





<u>The ratio between c-tagged and untagged Z+jet events</u>

$$\mathcal{R}_j^c \equiv \frac{\sigma(pp \to Z + \text{charm jet})}{\sigma(pp \to Z + \text{jet})} = \frac{N(c\text{−tag})}{N(\text{jets})}$$

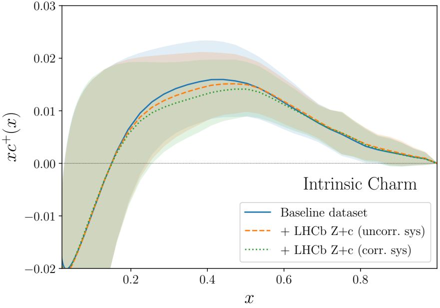
Theoretical predictions obtained at NLO QCD
with `POWHEG-BOX` interfaced to `Pythia8` with the Monash 2013 tune
for showering, hadronisation, and underlying event

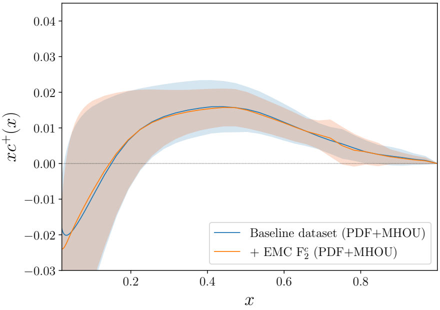
At forward rapidities, perturbative charm does not describe the data well

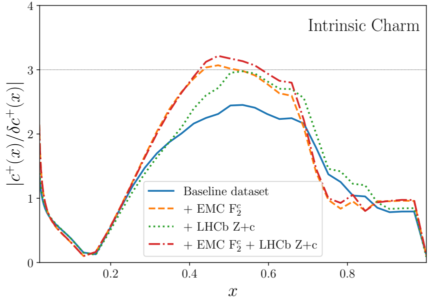
The data uncertainty is rather smaller than the prediction uncertainty

Sensitivity to charm at large x

Significance of intrinsic charm







Additional determinations including LHC $Z + c$ and/or EMC F_2^c measurements

Intrinsic charm PDF is stable

Local significance or pull:
size of intrinsic charm PDF
in units of its uncertainty

2.5σ for baseline
3.0σ with LHCb $Z + c$ and/or EMC F_2^c

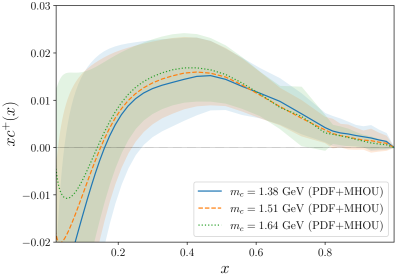
Robustness of intrinsic charm

Does intrinsic charm depend
on the value of m_c?
No: results stable upon varying m_c

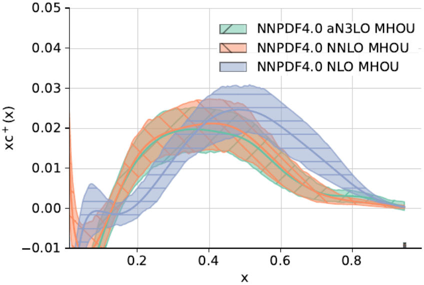
Is intrinsic charm affected
by underestimated MHOUs?
No: results stable at N^{3}LO

Does intrinsic charm
depend on parametrisation?
No: results stable if the basis changes

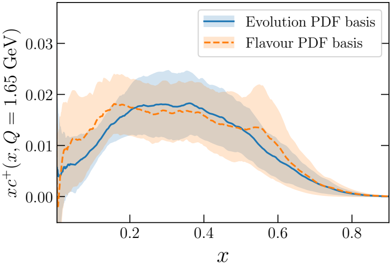
Dependence on the value of m_c



Dependence on the perturbative accuracy



Dependence on the parametrisation basis



2. The intrinsic charm quark valence distribution of the proton
[Phys.Rev. **D109** (2024) L091501]

Is intrinsic charm really valence?

What happens if one attempts to determine c and $\bar{c}$ separately?

Is total charm c^+ stable?

Is there an asymmety between c and $\bar{c}$ (as there is between s and $\bar{s}$)?

Methodology

Parametrise $V_{15}(x,Q_0) = [u^- + d^- + s^- - 3c^-](x,Q_0)$, $Q_0 = 1.65$ GeV, $q^- = q - \bar{q}$

Impose the sum rule $Q_{15} = \int_0^1 dx V_{15}(x,Q_0) = 3$ (optional)

Ensure cross section positivity by replacing the neutral current F_2^c positivity observable with its charged current-counterparts F_2^{c,W^-} and $F_2^{\bar{c},W^*}$

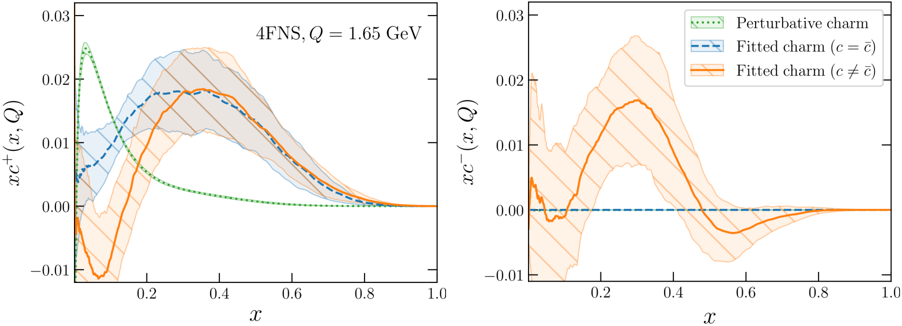
Otherwise the methodology is as in NNPDF4.0

The accuracy of the determination is NNLO in QCD

Determine c and $\bar{c}$ in the 4FNS ($Q_0 > m_c = 1.51$ GeV) from the NNPDF4.0 data set

Invert the matching conditions to determine the intrinsic $c - \bar{c}$ in the 3FNS

The valence charm PDF



xc^+ and xc^- in the 4FNS at $Q_0 = 1.65$ GeV (above $m_c = 1.51$ GeV)

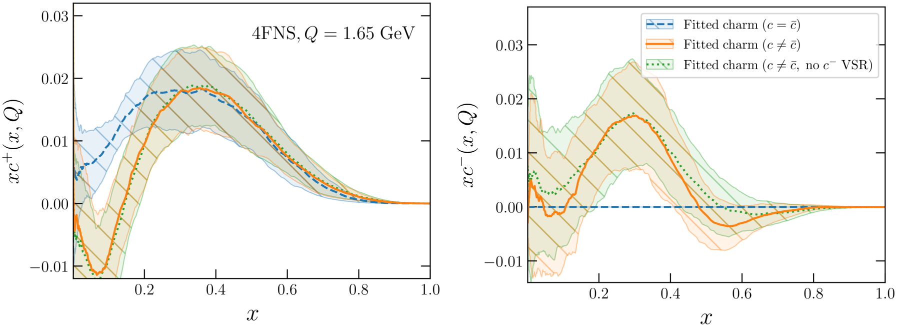
The purely perturbative valence PDF vanishes at $Q = m_c$ at NNLO
(and is tiny beyond NNLO or at higher Q)

The total charm xc^+ is quite stable, especially around the peak at $x \sim 0.4$

The χ^2 per data point for the global dataset decreases from
1.162 ($c = \bar{c}$) to 1.151 ($c \neq \bar{c}$)

The valence charm xc^- is nonzero and positive in the $x \in [0.2, 0.4]$ region
and consistent with zero elsewhere within uncertainites

The valence charm PDF



xc^+ and xc^- in the 4FNS at $Q_0 = 1.65$ GeV (above $m_c = 1.51$ GeV)

Repeat the determination by not imposing the charm valence sum rule

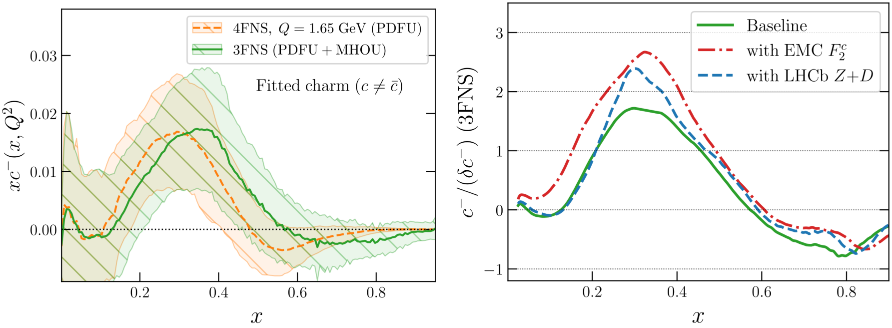
Total c^+ and valence xc^- charm distributions remain unchanged

We determine $Q_c = \int_0^1 dx(c - \bar{c})(x, Q_0) = 0.07 \pm 0.14$

The valence sum rule is enforced by the data

Results are also stable upon variations of PDF parametrisation basis, the value of m_c, and the kinematic cuts in W^2 and Q^2

Intrinsic valence charm



xc^+ and xc^- in the 3FNS (below $m_c = 1.51$ GeV)

MHOU estimated as the change in the 3FNS PDFs when matching at N^{3}LO

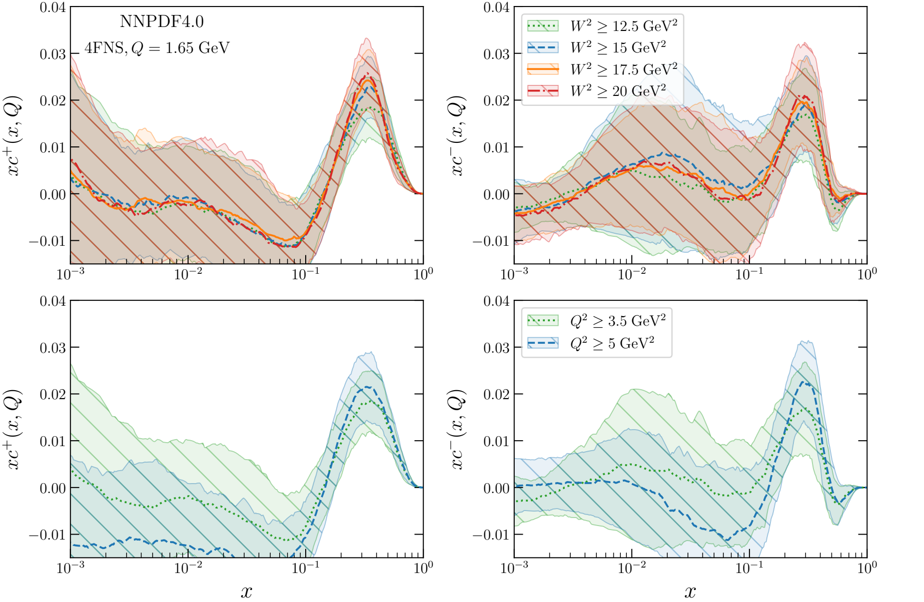
The 3FNS and 4FNS c^- PDFs are quite close, implying that the theory uncertainty is smaller than the PDF uncertainty (unlike for c^+)

The intrinsic c^- is nonzero and positive roughly in the same x region as fitted c^-

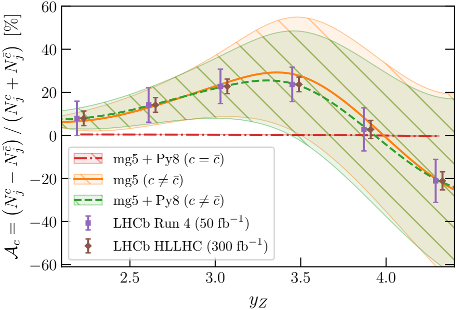
The significance of intrinsic c^- is less than 2σ at its maximum around $x \sim 0.5$, though this is enhanced by EMC F_2^c and LHCb $Z * D$ data

The significance of c^+ (not shown) remain unaltered (3σ around $x \sim 0.5$)

Robustness on variations of kinematic cuts



Charm asymmetries in $Z + c$ at LHCb



The charm asymmetry for $Z + c$ production

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

N_j^c ($N_j^{\bar{c}}$) are D-mesons events containing c ($\bar{c}$)

reconstruct c and $\bar{c}$ jet events in bins of y_Z
by tagging D-mesons from displaced vertices

the measurement is similar to $\mathcal{R}_j^c(y_Z)$ at LHCb

Theoretical computations obtained with `mg5 aMC@NLO` at LO matched to `Pythia8`

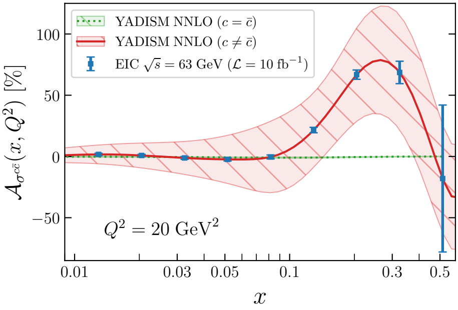
The forward-backward asymmetry of the Z decay
generates a small asymmetry $\mathcal{A}_c \neq 0$ even when $c = \bar{c}$

The LO effect due to an asymmetry between c and $\bar{c}$ is much larger

The effect is stable upon showering and hadronisation corrections

LHCb projection show that a vaence charm component as large as currently determined could be detected at 2σ-4σ level

Charm-tagged DIS at the EIC

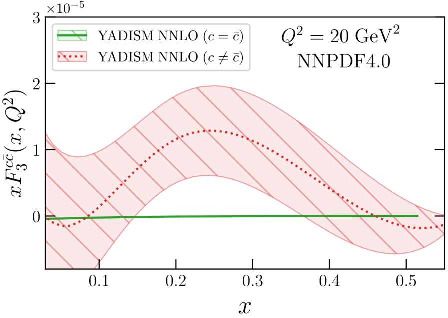


The reduced cross section asymmetry

$$\mathcal{A}_{\sigma^{c\bar{c}}}(x, Q^2) \equiv \frac{\sigma^{c}_{\rm red}(x,Q^2) - \sigma^{\bar{c}}_{\rm red}(x,Q^2)}{\sigma^{c\bar{c}}_{\rm red}(x,Q^2)}$$

Need to reconstruct final-state D-mesons by identifying their decay products

A nonvanishing charm valence component can be measured at the EIC to very high significance even for a moderate amount of integrated luminosity



The charm-tagged structure functions

$$F_2^{c\bar{c}} \qquad xF_3^{c\bar{c}}$$

$xF_3^{c\bar{c}}$ is proportional to c^- at LO hence it is a direct handle on valence charm

Even without projected EIC measurements, measuring a non-vanishing $xF_3^{c\bar{c}}$ would significantly constrain the charm valence PDF

3. What about longitudinally polarised charm?
[Eur.Phys.J. C84 (2024) 189]

Charm in polarised DIS

The current treatment of charm in polarised DIS: ZM-VFN scheme (charm is massless)

Extend the FONLL GM-VFN scheme [NPB 834 (2010) 116] to polarised DIS

$$g_1^{\mathrm{FONLL}} = g_1^{\mathrm{FFNS,3}} + g_1^{\mathrm{FFNS,4}} - g_1^{\mathrm{double-counting}}$$

$g_1^{\mathrm{FFNS,3}}$ retains all mass effects at a finite order
$g_1^{\mathrm{FFNS,4}}$ resums all collinear logs, but has no power-like terms
$g_1^{\mathrm{double-counting}}$ is the overlap between FFNS,3 and FFNS,4

NNLO splitting functions [NPB 889 (2014) 351; PLB 748 (2015) 432; JHEP 01 (2022) 193]

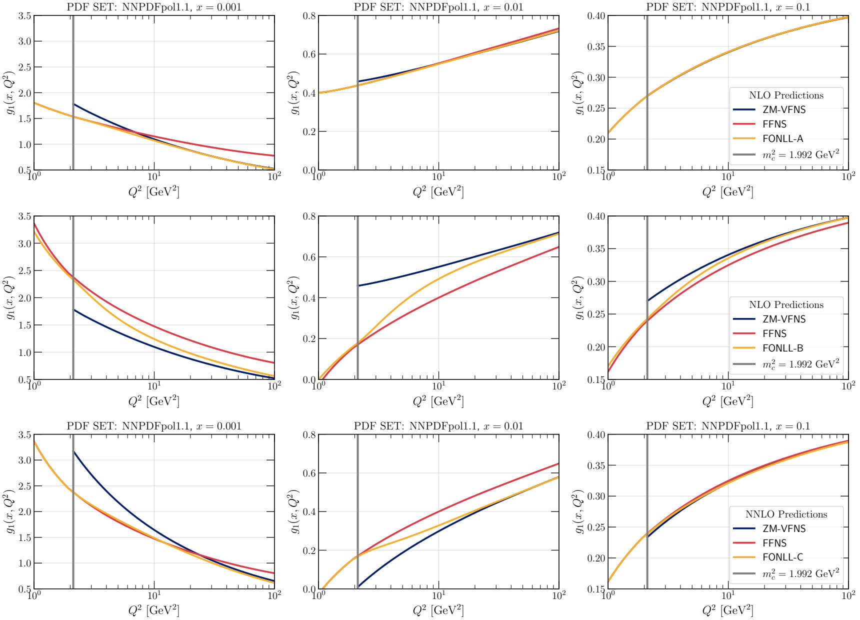
NNLO matching conditions [NPB 988 (2023) 116114]

NNLO massless coefficient functions [NPB 417 (1994) 61]

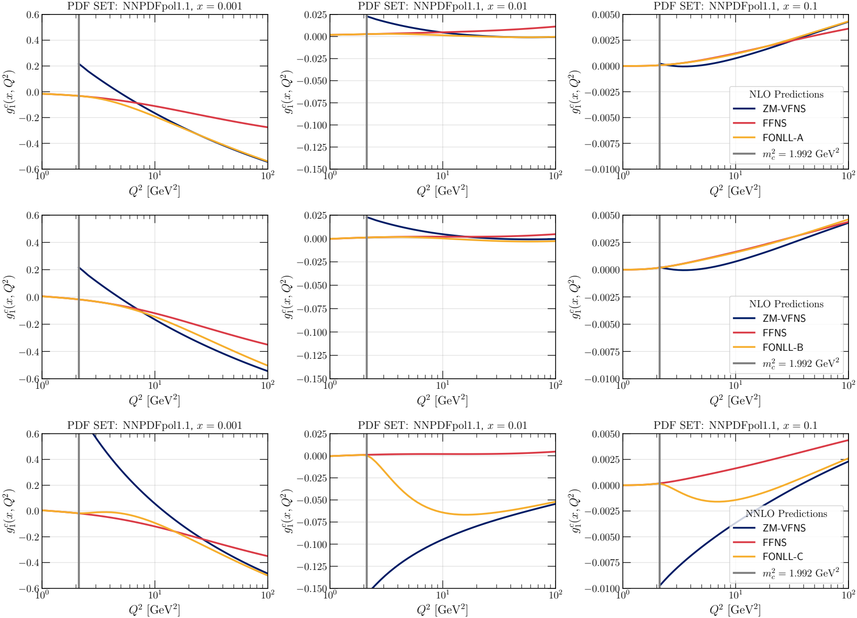
NNLO massive coefficient functions [PRD 98 (2018) 014018; NPB 897 (2015) 612; ibid. 953 (2020) 114945; ibid. 964 (2021) 115331; PRD 104 (2021) 034030; NPB 988 (2023) 116114; ibid. 999 (2024) 116427]

implemented in EKO [EPJ C82 (2022) 976] and YADISM [arXiv:2401.15187]

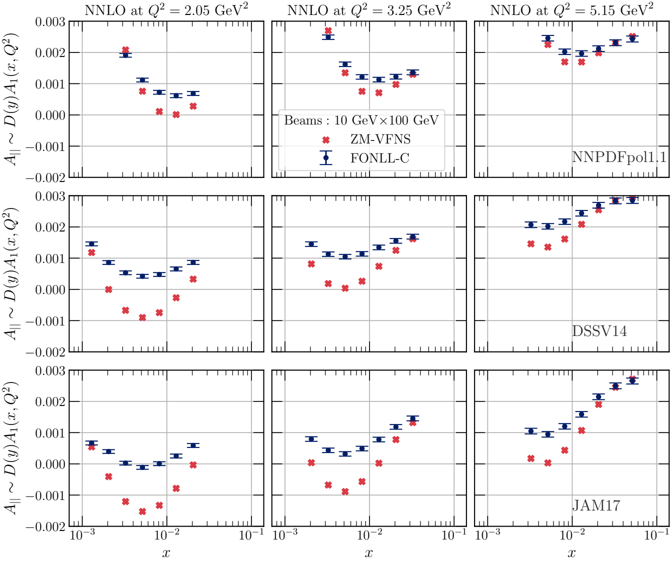
FONLL structure functions: g_1



FONLL structure functions: g_1^c



Impact of FONLL on asymmetries at the EIC: $A_\parallel$



The difference between predictions obtained with either the ZM-VFN or the FONLL schemes is larger than the projected experimental uncertainties (irrespective of the input PDF set)

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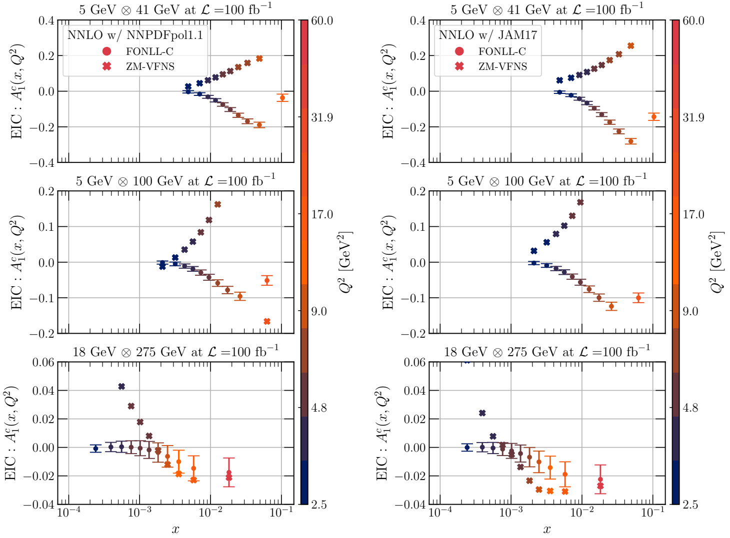

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4. Summary

To conclude

The valence structure of charm in the proton

Valence peak for total charm at 3σ

Valence charm PDF in valence region at $1-2\sigma$

Intrinsic charm compatible with zero (large uncertainties) for $x \lesssim 0.1$

Sea compatible with zero (large uncertainties for $x \lesssim 0.1$ and $x \gtrsim 0.5$

Reliable PDFs

Fitted charm for independence of m_c and matching

MHOUs and N^{3}LO for accurate central values and reliable uncertainties

Results stable upon variations of cuts

The FONLL GM-VFN scheme has been extended to polarised DIS

Charm mass effects are sizeable on the scale of the precision of EIC experimental data

ToDo

Better charmed jet definition — More data — Polarised intrinsic charm?

The EIC will play a crucial role in all these goals

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Thank you