INTRINSIC CHARM IN THE PROTON

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HIGH PRECISION AT THE LHC

MIAPP, AUGUST 19, 2022

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INTRINSIC CHARM IN THE PROTON

THE NNPDF COLLABORATION

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Evidence for intrinsic charm quarks in the proton

The NNPDF Collaboration

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Metrics

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

"INTRINSIC" CONSTITUENTS IN THE PROTON AT THE SSC (1984)

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INTRINSIC CHEVROLETS 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 $x > 0.3$.

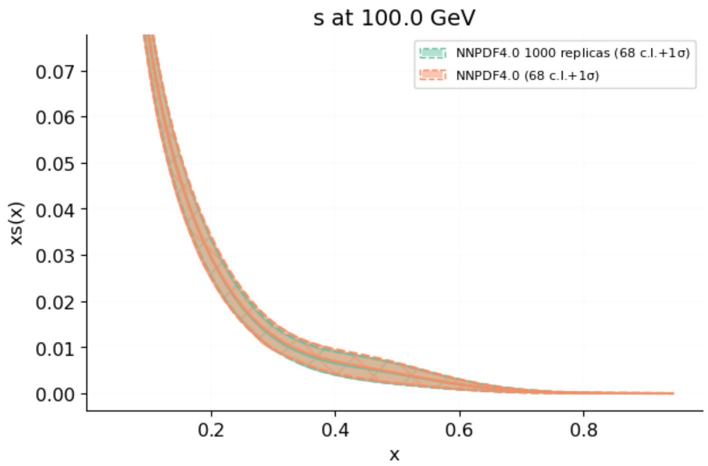
The possible existence of such a new production mechanism is of great importance for design considerations at the SSC[5,6]. An example of the importance of this issue is that, if intrinsic large x production is dominant, experiments and, perhaps, even the machine should be designed to focus on the forward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

IS IT TRIVIAL?

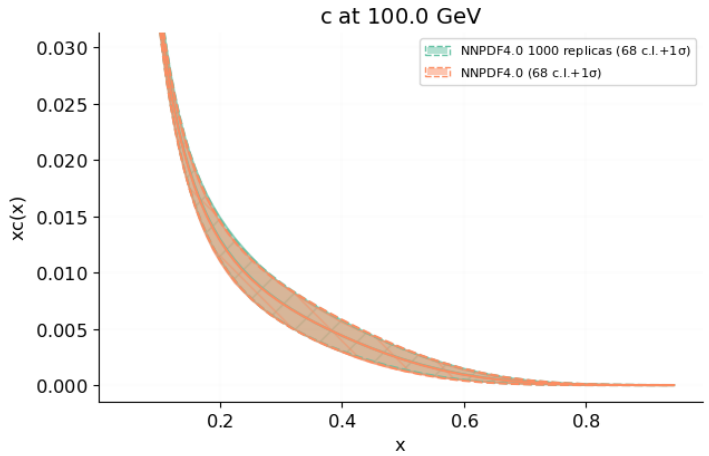
PDFs AT HIGH SCALE

$$Q = 100 \text{ GeV}$$

STRANGE



CHARM

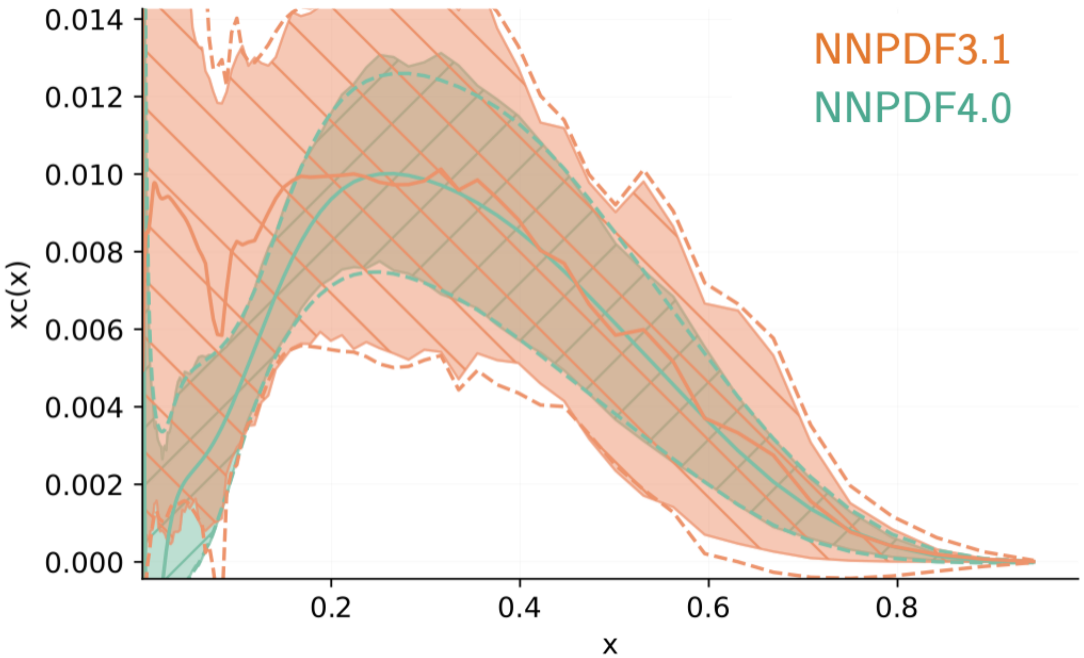


- SEA PDFs AT HIGH SCALE ALL LOOK ALIKE
- IF $Q \gg m_c$, CHARM MASS NEGLIGIBLE: $\ln \frac{Q^2+m_c^2}{m_c^2} \approx \ln \frac{Q^2}{m_c^2}$
- GLUON RADIATION IS FLAVOR BLIND

DECOUPLING

EVOLVE CHARM PDF ($N_f = 4$ SCHEME) DOWN TO $Q \sim m_c$

CHARM PDF (FITTED FROM DATA) AT Q=1.65 GeV



- IF $Q \sim m_c$ ($m_c = 1.51$ GeV), CHARM QUARK DECOUPLES (Collins, Wilczek, Zee, 1978): $\ln \frac{Q^2+m_c^2}{m_c^2} \approx \frac{m_c^2}{Q^2}$
- $N_f = 3$ ACTIVE FLAVORS IN β FUNCTION & EVOLUTION EQUATIONS
- DECOUPLING VS $\overline{\mathrm{MS}}$ $\Leftrightarrow$ DIFFERENT RENORMALIZATION & FACTORIZATION SCHEMES

MATCHING

- PDFs, α_s IN $N_f = 3$ & $N_f = 4$
  RELATED BY MATCHING CONDITIONS

- DETERMINED BY COMPUTING
  OPERATOR MATRIX ELEMENTS
  IN EITHER SCHEME AND EQUATING:
  NNLO (Buza, et al., 1998),
  N^{3}LO (Ablinger, Blümlein et al, 2009-2017)

OME CONTRIBUTING
TO THE CHARM PDF
SOLID $\Rightarrow$ HEAVY; DASHED $\Rightarrow$ LIGHT

M. Buza et al.: Charm

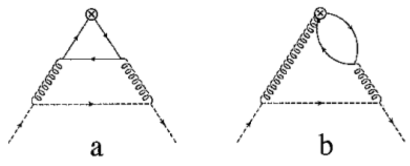


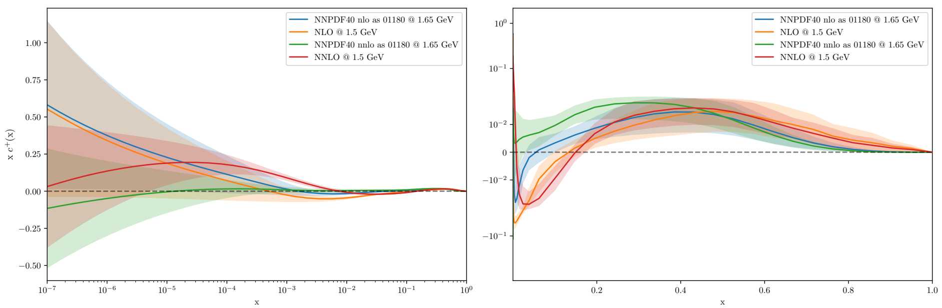
Fig. 2. $O(\alpha_s^2)$ contributions to the purely-singlet OME $A^{\rm PS}_{q'q}$. Here q and q' are represented by the *dashed* and *solid lines* respectively. In the case of $q' = H$ these graphs contribute to the heavy-quark OME $A^{\rm PS}_{Hq}$

PERTURBATIVE CHARM

- NO CHARM PDF IN $N_f = 3$ SCHEME

- IN $N_f = 4$ SCHEME, CHARM DETERMINED BY PERTURBATIVE MATCHING
  STARTING AT NNLO (TWO LOOPS) DOES NOT VANISH AT ANY SCALE (HEAVY QUARK LOOPS)

NLO & NNLO CHARM PDF; $n_f = 3$ VS. $n_f = 4$



INTRINSIC CHARM

- $n_f = 3$ SCHEME $\Rightarrow$ CHARM PDF SCALE-INDEPENDENT (NO COLLINEAR LOGS)

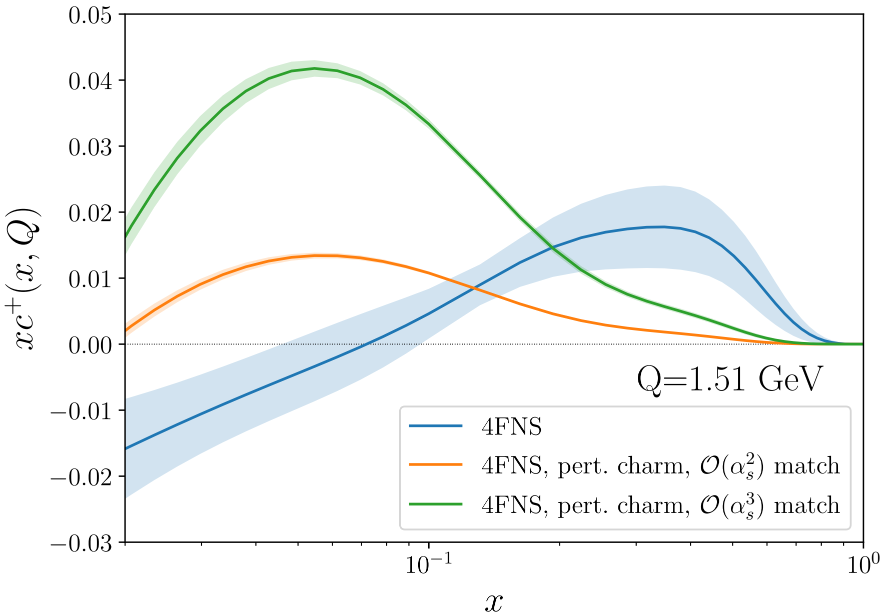
- PERTURBATIVE CHARM $\Leftrightarrow$ VANISHING $n_f = 3$ CHARM

- CHARM PDF AT ALL SCALES FULLY DETERMINED BY MATCHING CONDITIONS

INTRINSIC CHARM $\Leftrightarrow$ NONVANISHING STATIC $n_f = 3$-SCHEME CHARM PDF

THE NNPDF4.0 CHARM PDF ($n_f = 4$ SCHEME)

- NNPDF4.0 CHARM PDF ⇒ DETERMINED FROM THE DATA ALONG WITH ALL OTHER PDFS:
  - MORE REALISTIC UNCERTAINTIES
  - STABLE UPON VARIATION OF m_c
  - INDEPENDENT OF MATCHING CONDITIONS
- DIFFERS SIGNIFICANTLY FROM PERTURBATIVE CHARM
- MATCHING CONDITIONS PERTURBATIVELY UNSTABLE!



INTRINSIC CHARM?

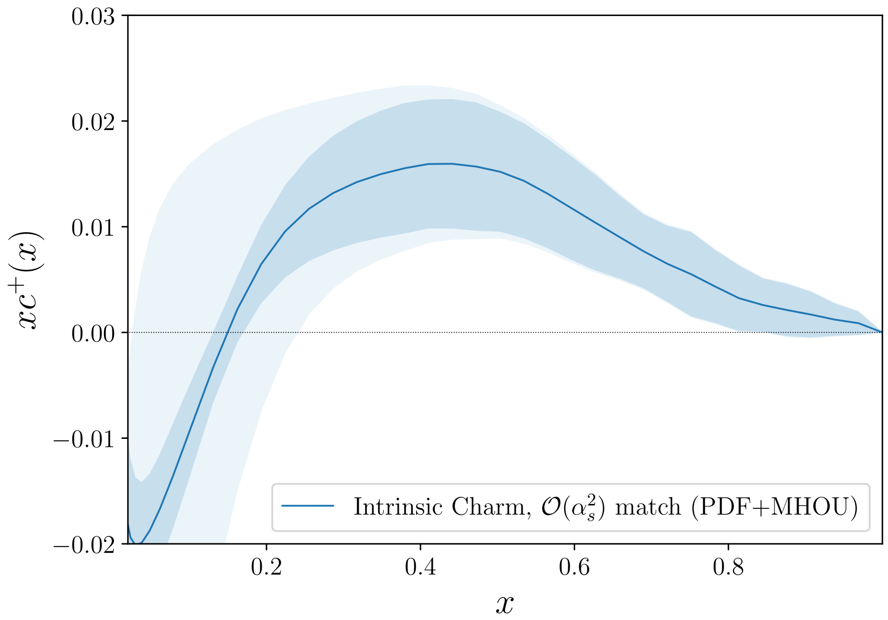
- INVERT MATCHING CONDITIONS ⇒ $N_f = 3$ CHARM PDF
- COMPARE NNLO & N^{3}LO INVERSION TO CONTROL MHOU

INTRINSIC CHARM!

THE EKO CODE (Candido, Hekhorn, Magni, 2022)

- IMPLEMENTS DIRECT & INVERSE EVOLUTION & MATCHING
- N^3LO MATCHING ALSO IMPLEMENTED

THE INTRINSIC ($N_f = 3$) CHARM PDF (NNLO)

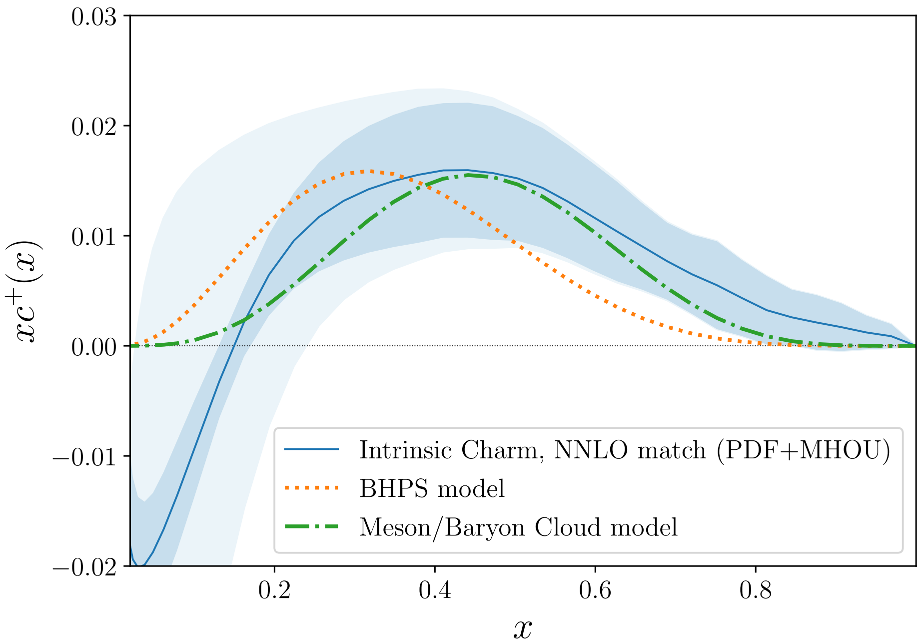


- MHOU ESTIMATED FROM N^3LO-NNLO DIFFERENCE
  - LARGE UNCERTAINTY AT SMALL x
  - NEGLIGIBLE UNCERTAINTY IN VALENCE REGION
- COMPATIBLE WITH ZERO AT SMALL x
- CLEAR EVIDENCE FOR "INTRINSIC" VALENCE PEAK

MODELS

- SHAPE OF INTRINSIC CHARM PREDICTED BY MODELS
- FOCK-SPACE WAVE FUNCTION (Brosky, Hoyer, Peterson, Sakai, 1980)
- MESON CLOUD (Hobbs, Londergan, Melnitchouk, 2014)

NNPDF4.0 INTRINSIC CHARM VS. MODELS

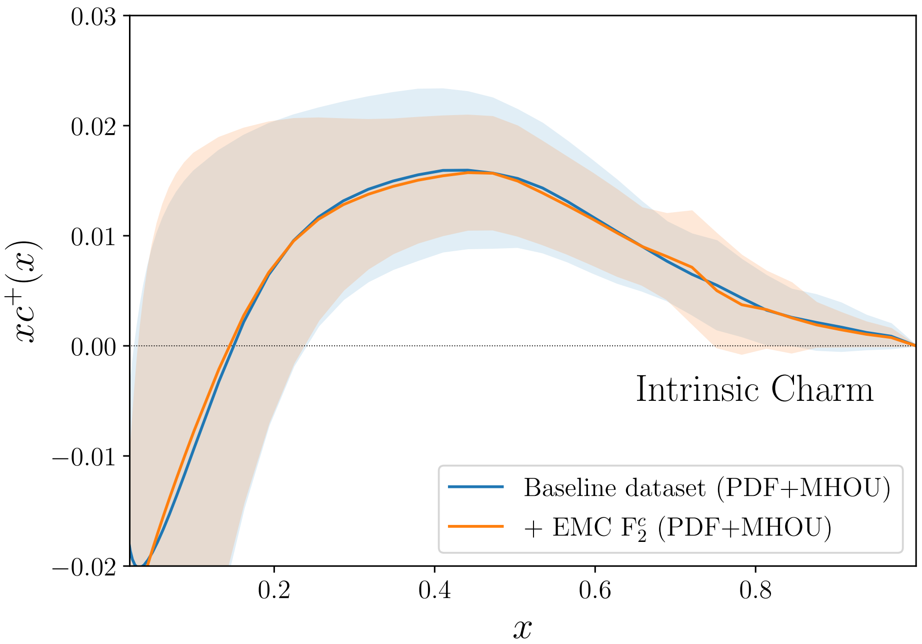


SURPRIZING AGREEMENT!

MORE DATA
EMC 1983

- DIRECT MEASUREMENT OF THE CHARM STRUCTURE FUNCTION F_2^c
- EVIDENCE FOR INTRINSIC CHARM CLAIMED, BUT EXPERIMENT DISPUTED
- NOT INCLUDED IN DEFAULT NNPDF4.0

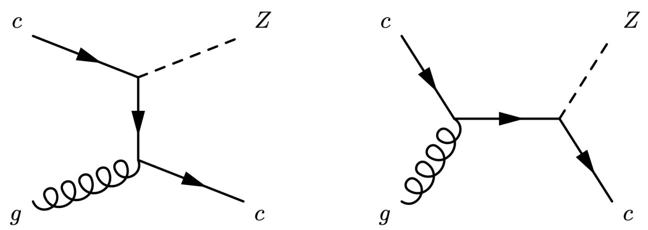
INTRINSIC CHARM WITH EMC DATA INCLUDED



COMPLETE CONSISTENCY!

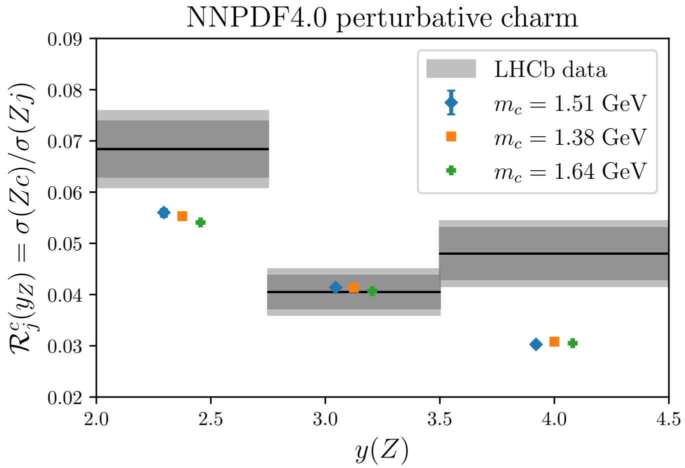
MORE DATA
LHCb 2021

MEASUREMENT OF Z+CHARM PRODUCTION

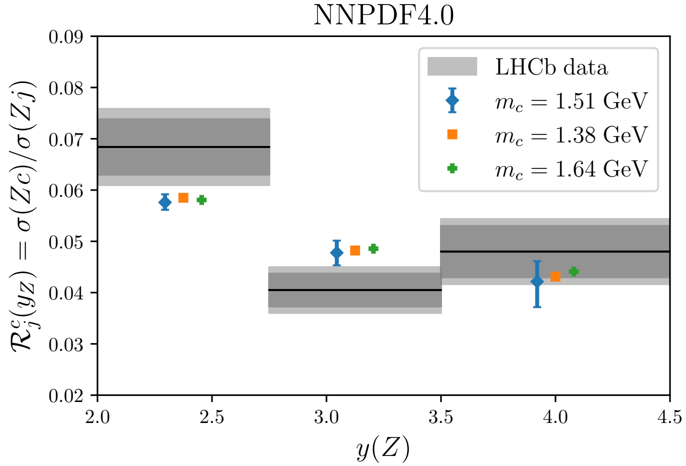


DATA VS THEORY PREDICTION

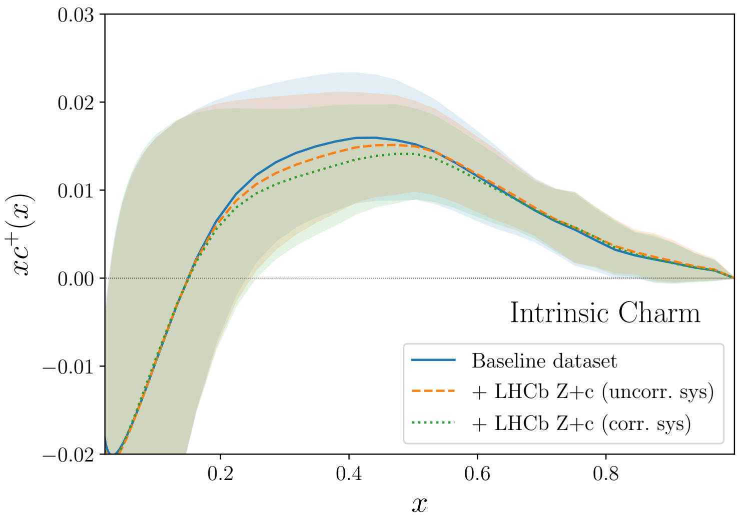
NO INTRINSIC CHARM



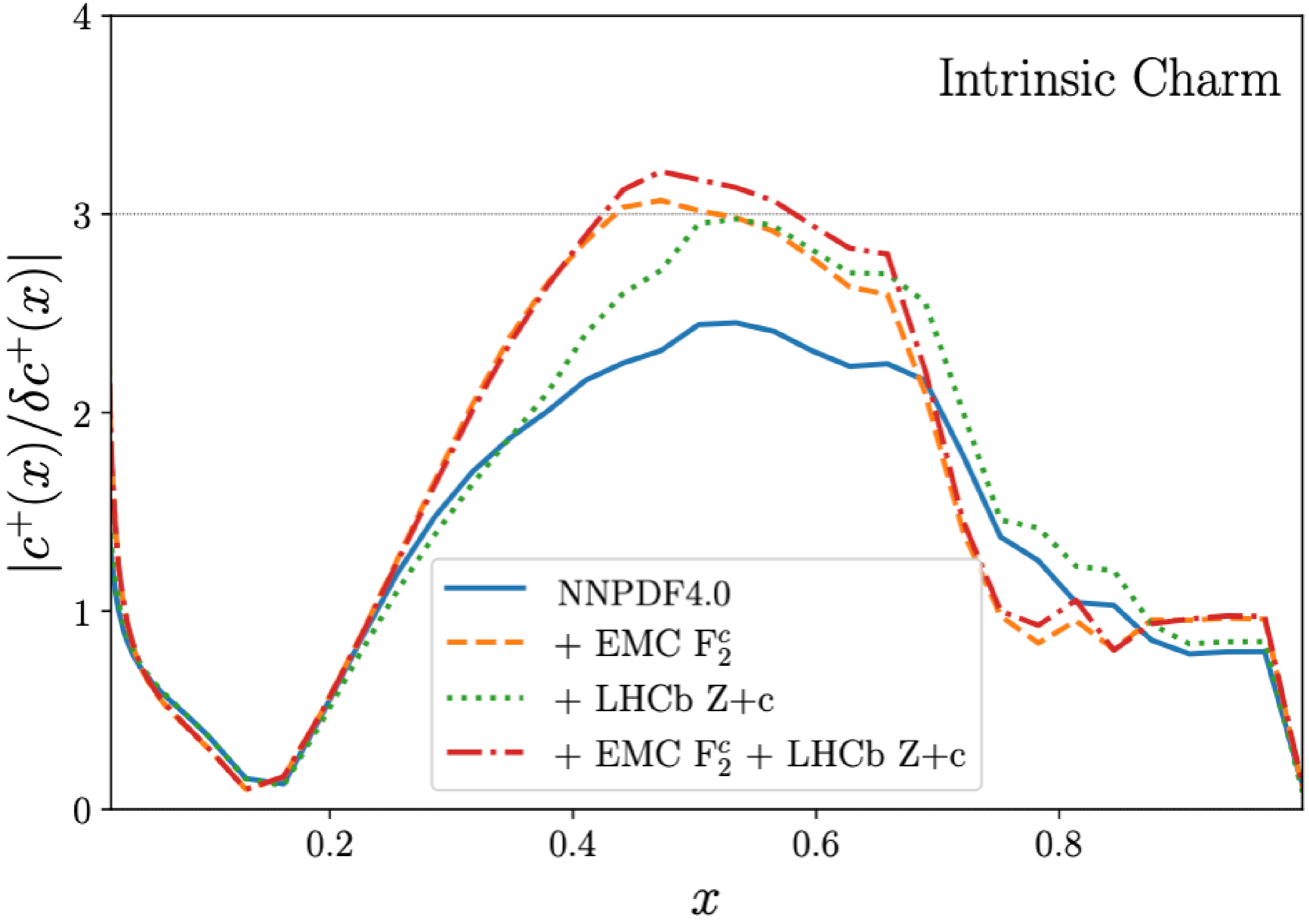
NNPDF4.0 INTRINSIC CHARM



INTRINSIC CHARM WITH LHCb DATA INCLUDED: COMPLETE CONSISTENCY



DISCOVERY OF INTRINSIC CHARM



MORE THAN $3\ \sigma$ EVIDENCE

SUMMARY

WE FITTED THE CHARM PDF IN ORDER TO GET

- REALISTIC ERROR ESTIMATE
- NO STRONG DEPENDENCE ON CHARM MASS
- NO SENSITIVITY TO MHOU IN MATCHING CONDITION

WE FOUND

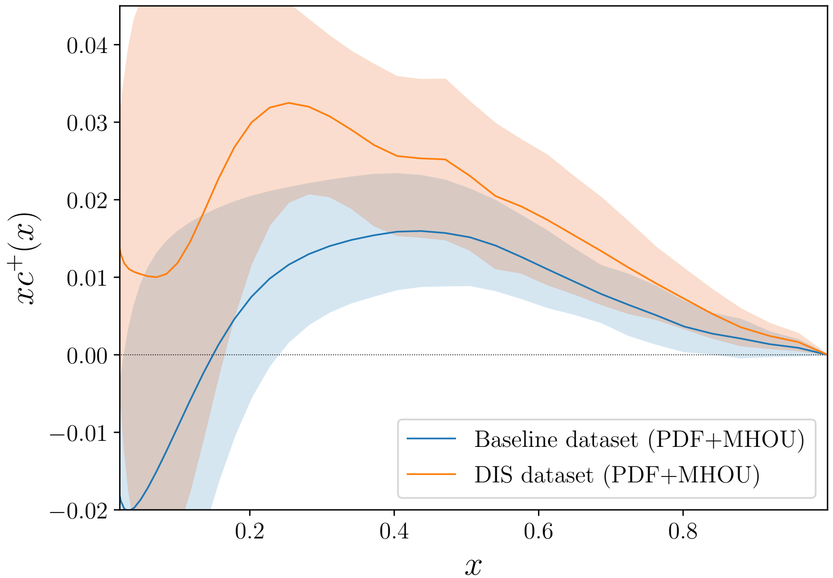
- LARGE UNCERTAINTIES AND CHARM COMPATIBLE WITH ZERO AT SMALL x
- THREE-σ EVIDENCE FOR AN INTRINSIC CHARM VALENCE PEAK

EXTRAS

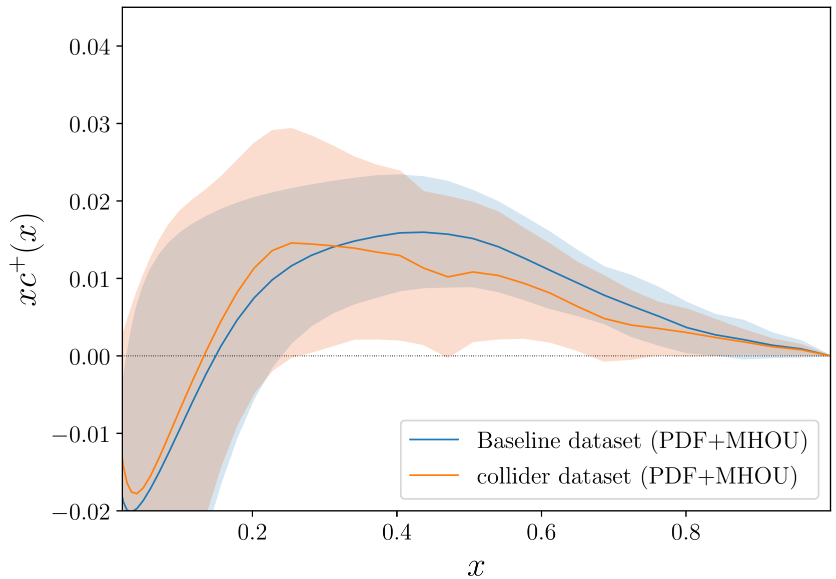
WHICH DATA DRIVE THE ANSWER?:

DATA SUBSETS THREE FLAVOR SCHEME

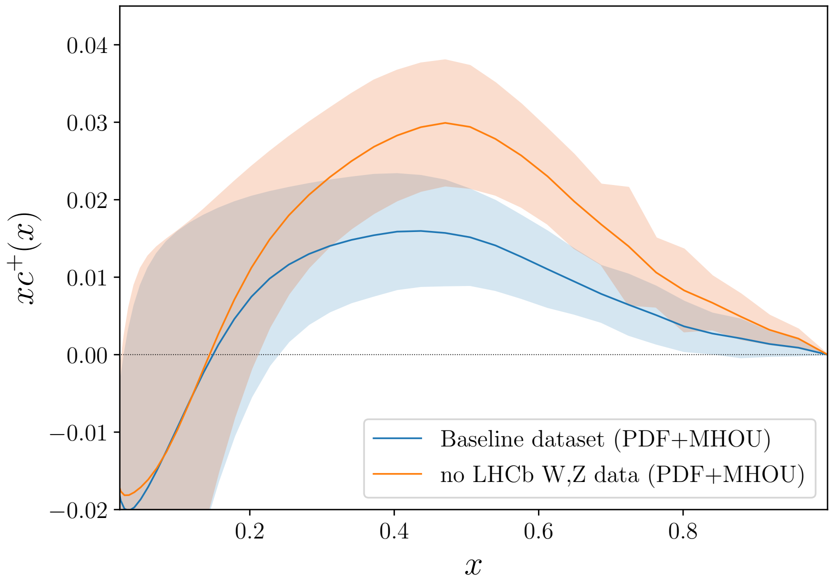
DIS ONLY



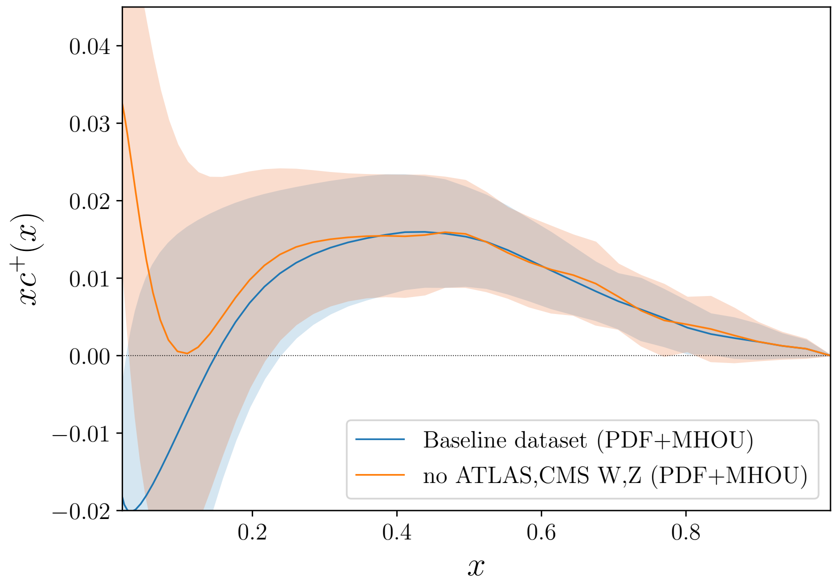
COLLIDER ONLY



NO LHCB

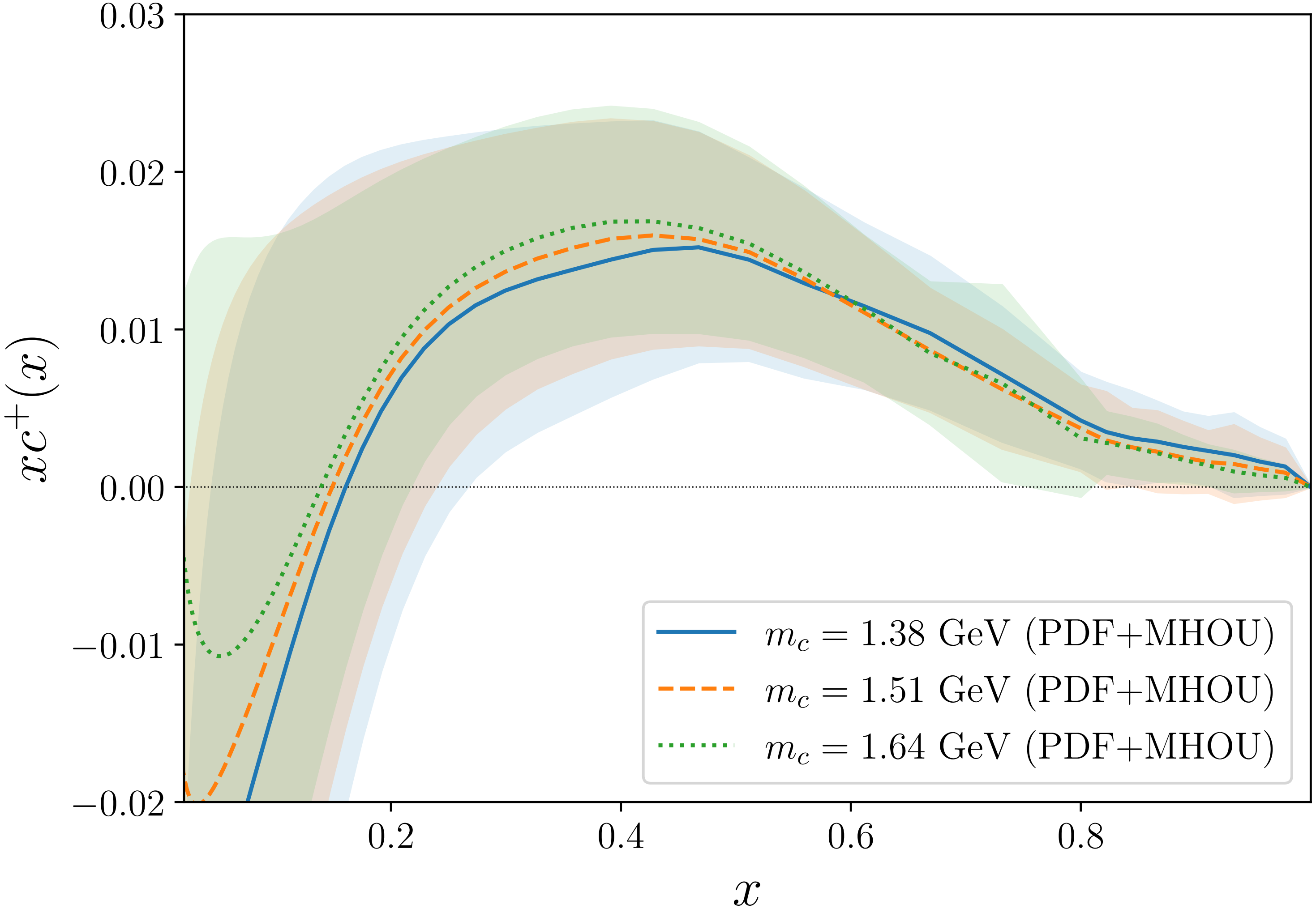


NO ATLAS/CMS DY



STABILITY:

CHARM MASS



STABILITY:

DATA SUBSETS FOUR FLAVOR SCHEME