

NNPDF



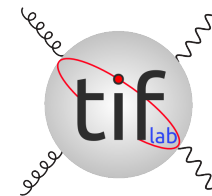
NNPDF
Machine Learning • PDFs • QCD

CHARM IN THE PROTON

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DIPARTIMENTO DI FISICA



INFN
Istituto Nazionale di Fisica Nucleare

ILCAC SEMINAR

NOVEMBER 9, 2022

This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No 740006



CHARM IN THE PROTON

THE NNPDF COLLABORATION

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ILCAC SEMINAR

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

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CONF-8406198

SLAC-PUB-15471

CONF-8406198--45

DE85 013896

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 collaboration⁴ on deep-inelastic muon scattering could also be interpreted 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" regime⁵. The ques-

[nature](#) > [articles](#) > [article](#)Article | [Open Access](#) | [Published: 17 August 2022](#)

Evidence for intrinsic charm quarks in the proton

[The NNPDF Collaboration](#)[Nature](#) 608, 483–487 (2022) | [Cite this article](#)[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 quarks¹. 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

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Associated Content

[Do protons have intrinsic charm? New evidence suggests yes](#)

Benjamin Thompson & Nick Petrić Howe
Nature | [Nature Podcast](#) | 17 Aug 2022

[Evidence at last that the proton has intrinsic charm](#)

Ramona Vogt
Nature | [News & Views](#) | 17 Aug 2022

Sections

Figures

References

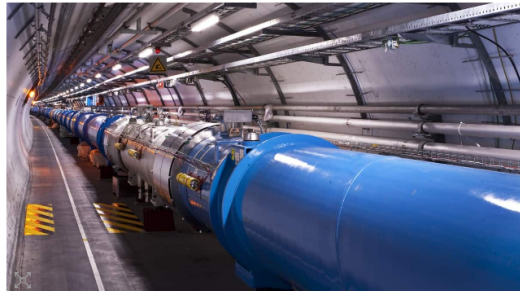
[Abstract](#)[Main](#)[Methods](#)

particles and interactions

PARTICLES AND INTERACTIONS | RESEARCH UPDATE

Protons contain intrinsic charm quarks, machine-learning analysis suggests

23 Aug 2022



The Large Hadron Collider: evidence for intrinsic charm quarks in protons has been found in LHC data.

- [f](#)
- [t](#)
- [in](#)
- [e](#)
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Deutschlandfunk

Dienstag, 08. November 2022

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Startseite / Forschung aktuell / Protonen mit Charm: Auch schwere Quarks finden sich in Kernbausteinen

Protonen mit Charm: Auch schwere Quarks finden sich in Kernbausteinen

Grotelüschen, Frank | 18. August 2022, 16:41 Uhr

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Tutti i prodotti sono selezionati in piena autonomia editoriale. Se acquisti uno di questi prodotti, potremmo ricevere una commissione.

VALENTINA GUDIELMO SCIENZA 29.08.2022

Un nuovo studio fa luce su una sorprendente caratteristica della struttura dei protoni

Pubblicato sulla rivista *Nature* spiega come anche i *quark charm*, insieme ai più noti e leggeri *quark up* e *quark down*, siano da annoverarsi tra i componenti intrinseci dei costituenti atomici, confermando un'ipotesi elaborata oltre 40 anni fa

TRUST MY SCIENCE

Physique · 3 min de lecture

Une étude confirme que le proton possède un quark charm intrinsèque

Fleur Brosseau · 19 août 2022

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Physicists surprised to discover the proton contains a charm quark

The textbook description of a proton says it contains three smaller particles - two up quarks and a down quark - but a new analysis has found strong evidence that it also holds a charm quark



SUMMARY

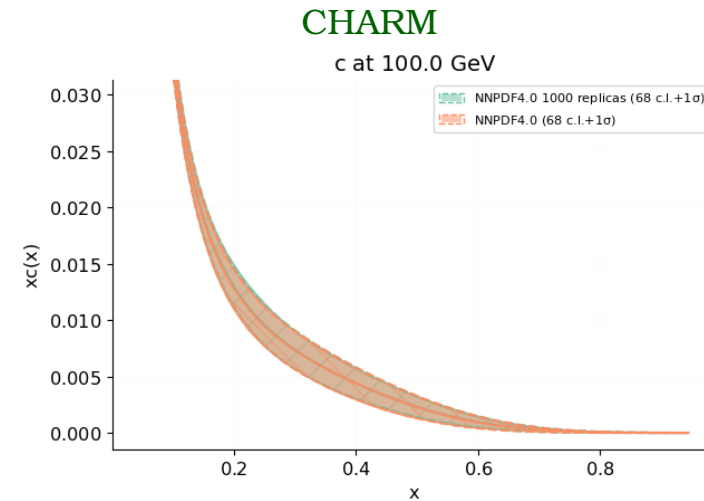
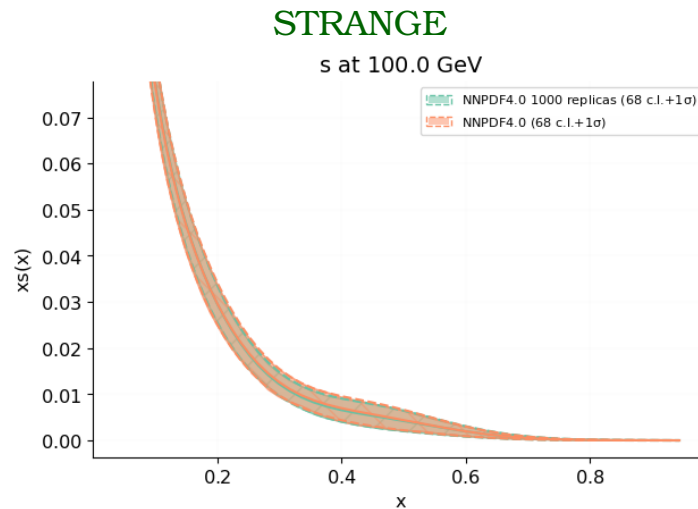
- **WHAT IS INTRINSIC CHARM?**
 - PERTURBATIVE CHARM AND ITS DEFINITION
 - DECOUPLING AND MATCHING
 - THE $n_f = 3$ SCHEME AND OPERATOR MATRIX ELEMENTS
- **THE NNPDF4.0 PDF DETERMINATION**
 - DATA
 - THE NNPDF METHDOLOGY
 - HYPEROPTIMIZATION AND MACHINE LEARNING
- **DISCOVERY OF INTRINSIC CHARM**
 - THE CHARM PDF AND ITS UNCERTAINTIES
 - RESULTS VS. MODELS
 - STABILITY & THE CHARM MASS
- **INTRINSIC CHARM AND DATA**
 - LHC vs. DIS DATA
 - MORE CURRENT DATA
 - FUTURE DATA

WHAT IS
INTRINSIC CHARM?

WHAT IS INTRINSIC CHARM?

PDFs AT HIGH SCALE

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



- **SEA PDFs** AT HIGH SCALE **ALL LOOK ALIKE**

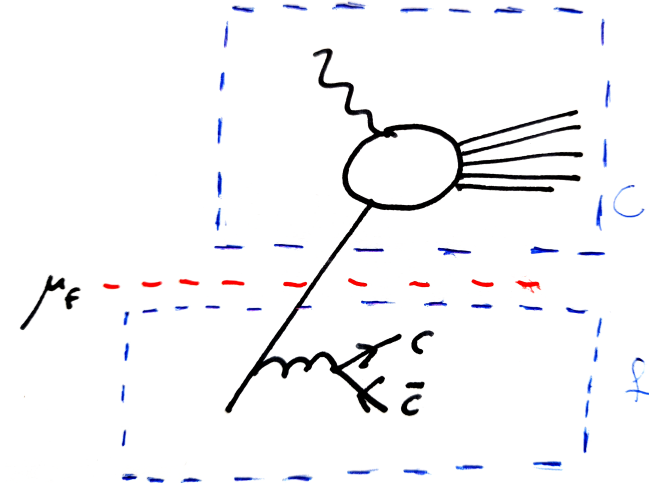
- IF $Q \gg m_c$, CHARM **MASS NEGLIGIBLE**: $\ln \frac{Q^2 + m_c^2}{m_c^2} \approx \ln \frac{Q^2}{m_c^2}$

- **GLUON RADIATION IS FLAVOR BLIND**

WHAT IS **NOT** INTRINSIC CHARM?

- **FACTORIZED** STRUCTURE FUNCTION: $F_2 = \sum_i C_i \otimes f_i$
- COLLINEAR **PARTON RADIATION** UP TO μ_f
INCLUDED IN PDFs f_i
- **CHARM PDF PERTURBATIVELY GENERATED** BY QCD EVOLUTION

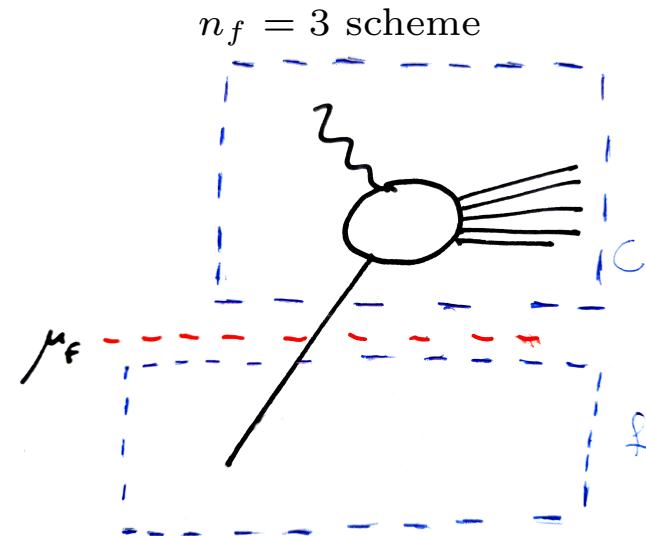
perturbative charm generation



- **MASSIVE** QUARKS \Rightarrow **NO COLLINEAR SINGULARITY**
- .
- .

WHAT IS **NOT** INTRINSIC CHARM?

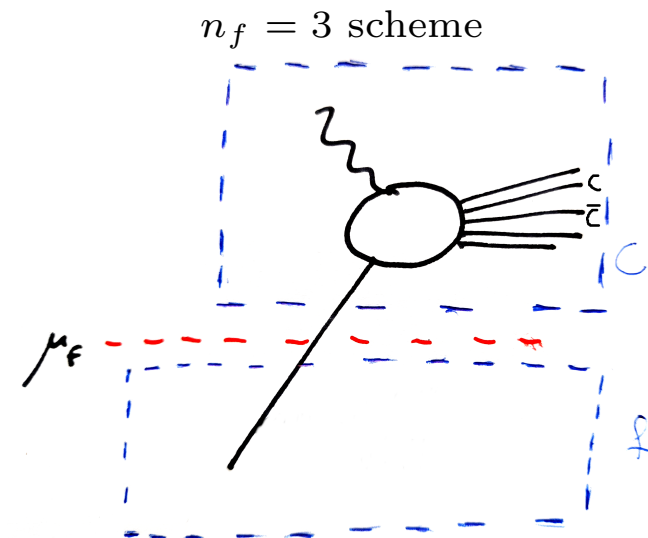
- **FACTORIZED** STRUCTURE FUNCTION: $F_2 = \sum_i C_i \otimes f_i$
- COLLINEAR **PARTON RADIATION** UP TO μ_f
INCLUDED IN PDFs f_i
- **CHARM PDF PERTURBATIVELY GENERATED** BY QCD
EVOLUTION



- **MASSIVE** QUARKS \Rightarrow **NO COLLINEAR SINGULARITY**
- MAY WORK IN $n_f = 3$ **SCHEME** \Rightarrow CHARM **DECOUPLES** FROM PDF EVOLUTION
- .

WHAT IS **NOT** INTRINSIC CHARM?

- **FACTORIZED** STRUCTURE FUNCTION: $F_2 = \sum_i C_i \otimes f_i$
- COLLINEAR **PARTON RADIATION** UP TO μ_f
INCLUDED IN PDFs f_i
- **CHARM PDF PERTURBATIVELY GENERATED** BY QCD
EVOLUTION



- **MASSIVE** QUARKS \Rightarrow **NO COLLINEAR SINGULARITY**
- MAY WORK IN $n_f = 3$ **SCHEME** \Rightarrow CHARM **DECOUPLES** FROM PDF EVOLUTION
- PERTURBATIVE CHARM PRODUCTION IN **COEFFICIENT FUNCTION**

WHAT IS INTRINSIC CHARM?

NAIVE ANSWER

- IN $n_f = 4$ SCHEME, PERTURBATIVELY GENERATED CHARM

$$c(x, Q^2) \sim \alpha_s \ln \frac{Q^2}{M_c^2} P_{qg} \otimes g$$

- PERHAPS LOOK AT $c(x, Q^2 = M_c^2)$?
- BUT ACTUALLY $c(x, Q^2) \sim \alpha_s \ln \frac{Q^2(1-x)/x}{M_c^2} P_{qg} \otimes g \Rightarrow$ SAME UP TO $O(\alpha_s^2)$
- SO LOOK AT $O(\alpha_s^2) \Rightarrow$ SCALE AT WHICH CHARM VANISHES?
- AT $O(\alpha_s^2)$ IT NEVER DOES!

DECOUPLING

- DECOUPLING SCHEME \Rightarrow HEAVY FLAVOR GRAPHS
SUBTRACTED AT ZERO MOMENTUM (Collins, Wilczek, Zee, 1978)
- $N_f = 3$ ACTIVE FLAVORS IN β FUNCTION & EVOLUTION EQUATIONS
- DECOUPLING VS $\overline{\text{MS}}$ \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),

N³LO (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 $A_{q'q}^{\text{PS}}$. 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_{Hq}^{PS}

WHAT IS **NOT** INTRINSIC CHARM?

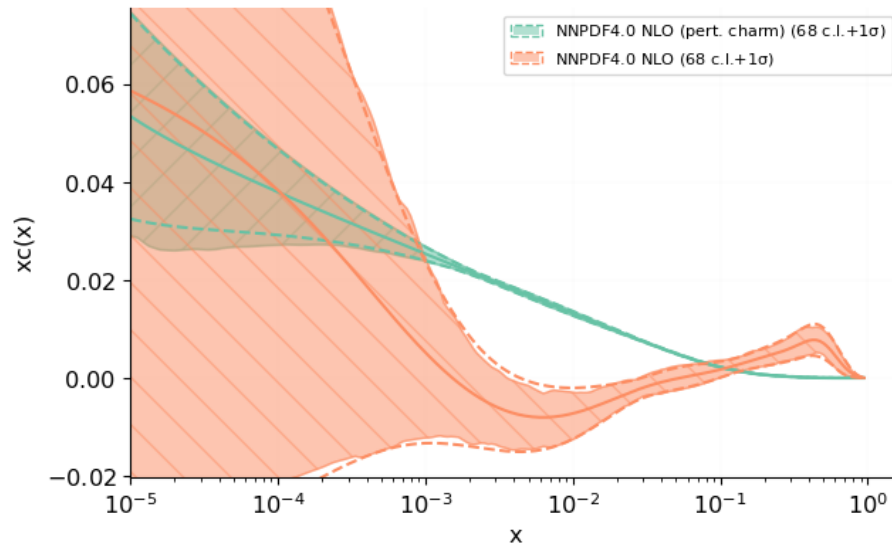
PERTURBATIVE CHARM

- IN $N_f = 3$ SCHEME **CHARM PDF VANISHES**
- IN $N_f = 4$ SCHEME, CHARM **DETERMINED BY PERTURBATIVE MATCHING**
- STARTING AT NNLO (TWO LOOPS) **DOES NOT VANISH AT ANY SCALE**
- .

PERTURBATIVE CHARM PDF, $n_f = 4$ SCHEME, $Q=1.7$ GeV

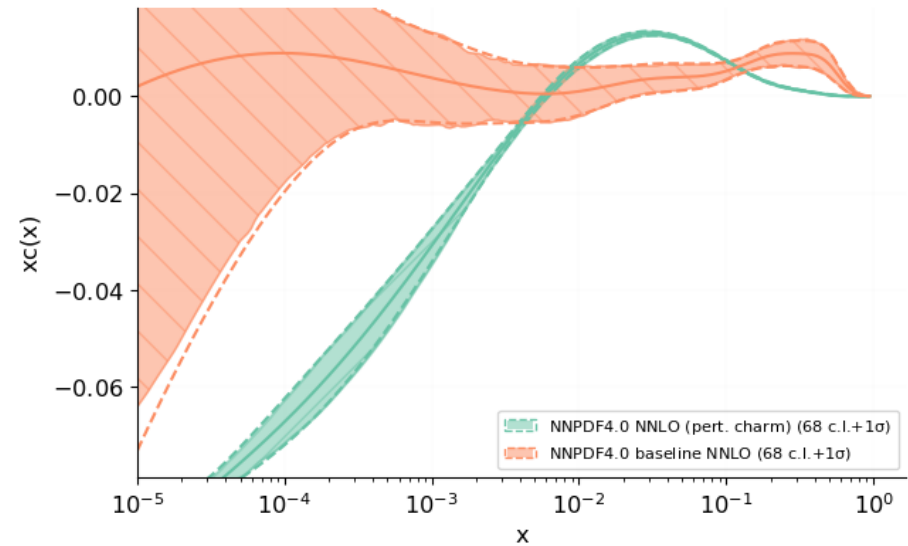
NLO

c at 1.7 GeV



NNLO

c at 1.7 GeV

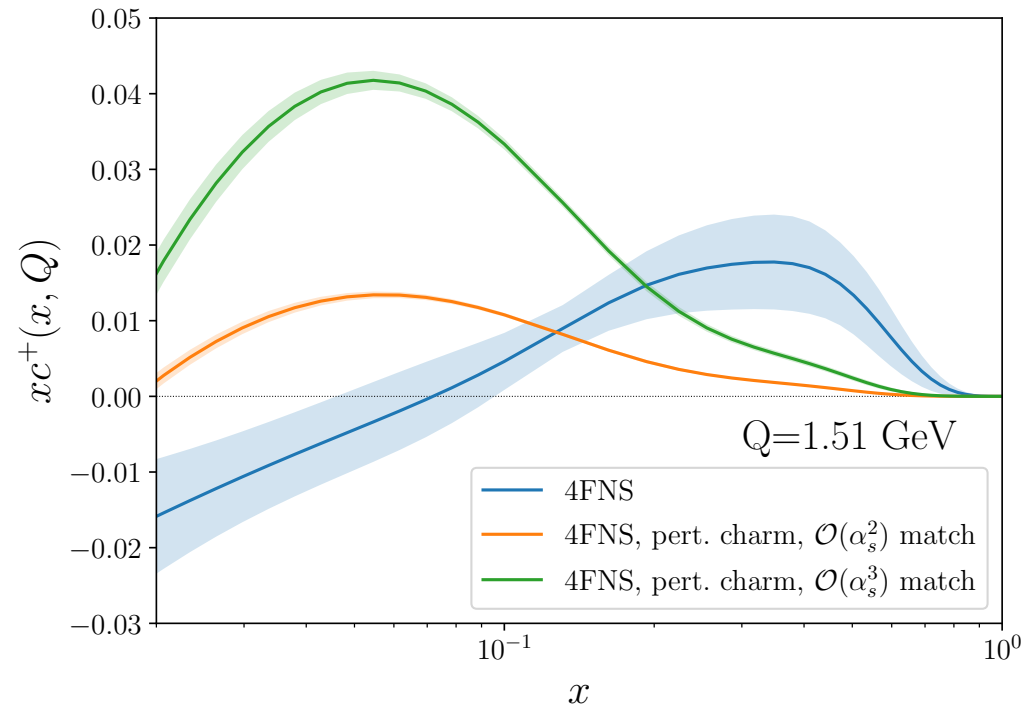


WHAT IS **NOT** INTRINSIC CHARM? PERTURBATIVE CHARM

- IN $n_f = 3$ SCHEME **CHARM PDF VANISHES**
- IN $N_f = 4$ SCHEME, CHARM **DETERMINED BY PERTURBATIVE MATCHING**
- STARTING AT NNLO (TWO LOOPS) **DOES NOT VANISH AT ANY SCALE**
- **SLOW** PERTURBATIVE CONVERGENCE \Rightarrow NNLO AND N³LO **DIFFER** SIGNIFICANTLY

PERTURBATIVE CHARM PDF, $n_f = 4$ SCHEME, $Q=1.7$ GeV

NNLO vs. **N³LO**
(NLO IDENTICALLY ZERO)



WHAT IS INTRINSIC CHARM?

- **DEFINE** CHARM PDF AS OME:

$$\langle p | \bar{c} \gamma^{\mu_1} D^{\mu_2} \dots D^{\mu_n} c | p \rangle = A_c^n p^{\mu_1} \dots p^{\mu_n} - \text{traces}$$

$$A_c^n = \int_0^1 dx x^{n-1} c(x)$$

- **DO NOT FACTOR CHARM MASS SINGULARITIES** INTO OME
- \Rightarrow **CHOOSE** $n_f = 3$ SCHEME
- **CHARM PDF PURELY INTRINSIC**, SCALE-INDEPENDENT

INTRINSIC CHARM IS CHARM IN THE $N_F = 3$ (DECOUPLING) SCHEME

HOW CAN ONE MEASURE INTRINSIC CHARM? (ALMOST) LIKE ANY OTHER PDF

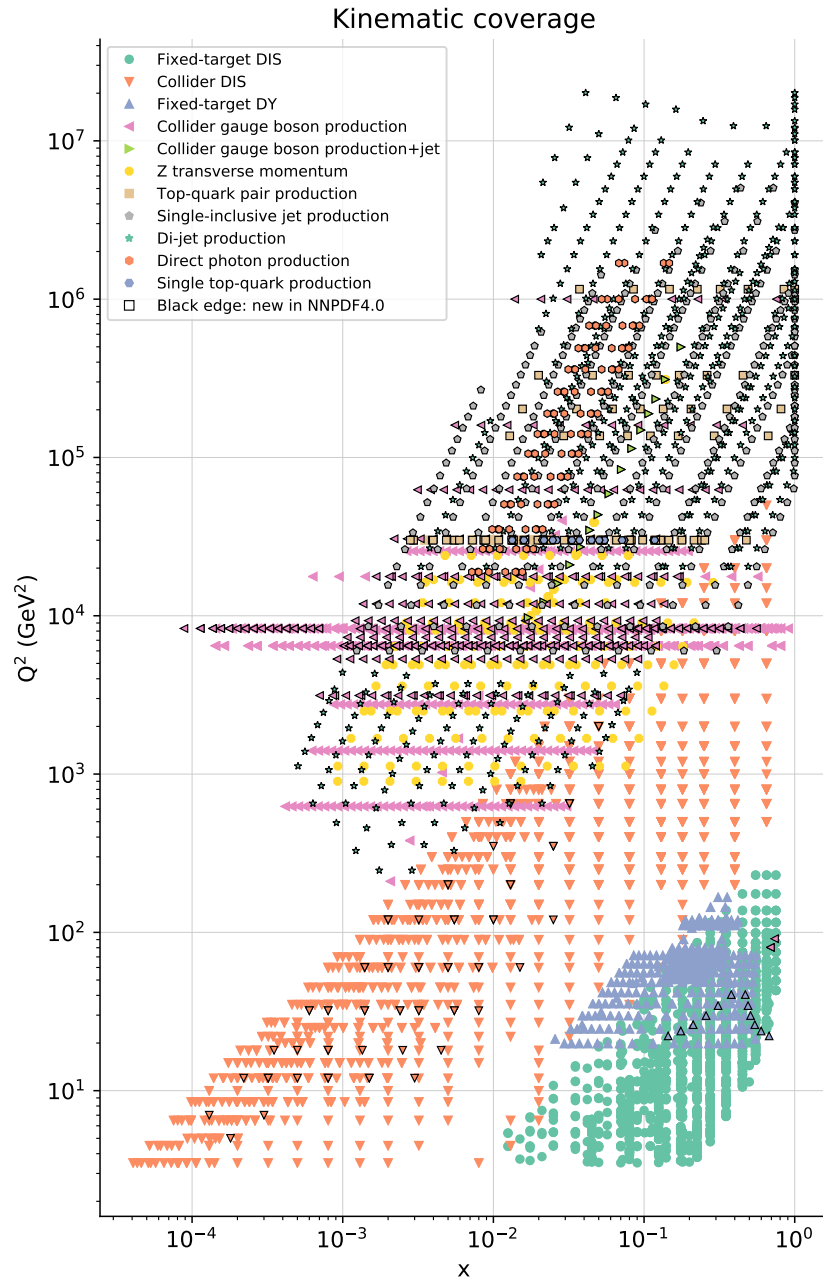
- DETERMINE PDFS FROM DATA
- GO TO $n_f = 3$ SCHEME
- LOOK AT RESULT

TWO POSSIBILITIES

- PARAMETRIZE PDFS IN $n_f = 3$ SCHEME AND MATCH UP FOR FITTING
- PARAMETRIZE PDFS IN $n_f = 4$ SCHEME AND MATCH DOWN FOR DETERMINING IC
- REMEMBER: MATCHING PERTURBATIVELY UNSTABLE \Rightarrow LARGE MHO

PDF DETERMINATION: NNPDF4.0

DATA



- COMPARED TO NNPDF3.1/PDF4LHC21 ABOUT **50 NEW DATASETS** & 400 EXTRA DATAPOINTS
- FULL DIS AND FT DY DATASET
 - AS IN NNPDF3.1: FINAL HERA, NMC, BCDMS, CHORUS, NuTeV
 - NOW ALSO **NOMAD NEUTRINO**
 - **SEAQUEST DY**
- FULL 7 TEV AND 8 TEV DATASET & EXTENSIVE USE OF **13 TEV** DATA:
 - *W*, *Z* PRODUCTION: RAPIDITY DISTRIBUTIONS, ASYMMETRIES, *Z* p_T DISTRIBUTIONS
 - TOP PAIR PRODUCTION: ALL AVAILABLE DISTRIBUTIONS
 - SINGLE-INCLUSIVE JETS
- SEVERAL **NEW PROCESSES**:
 - PROMPT PHOTON
 - SINGLE TOP
 - DIJETS
 - HERA JETS

ABOUT 4000 DATAPOINTS

THE LARGEST DATASET

LHC DATA

LHCb

Data set	NNPDF4.0	NNPDF3.1	ABMP16	CT18	MSHT20
LHCb Z 940 pb	✓	✓	✗	✗	✓
LHCb $Z \rightarrow ee$ 2 fb	✓	✓	✓	✓	✓
LHCb $W, Z \rightarrow \mu$ 7 TeV	✓	✓	✓	✓	✓
LHCb $W, Z \rightarrow \mu$ 8 TeV	✓	✓	✓	✓	✓
LHCb $Z \rightarrow \mu\mu, ee$ 13 TeV	✓	✗	✗	✗	✗

ATLAS

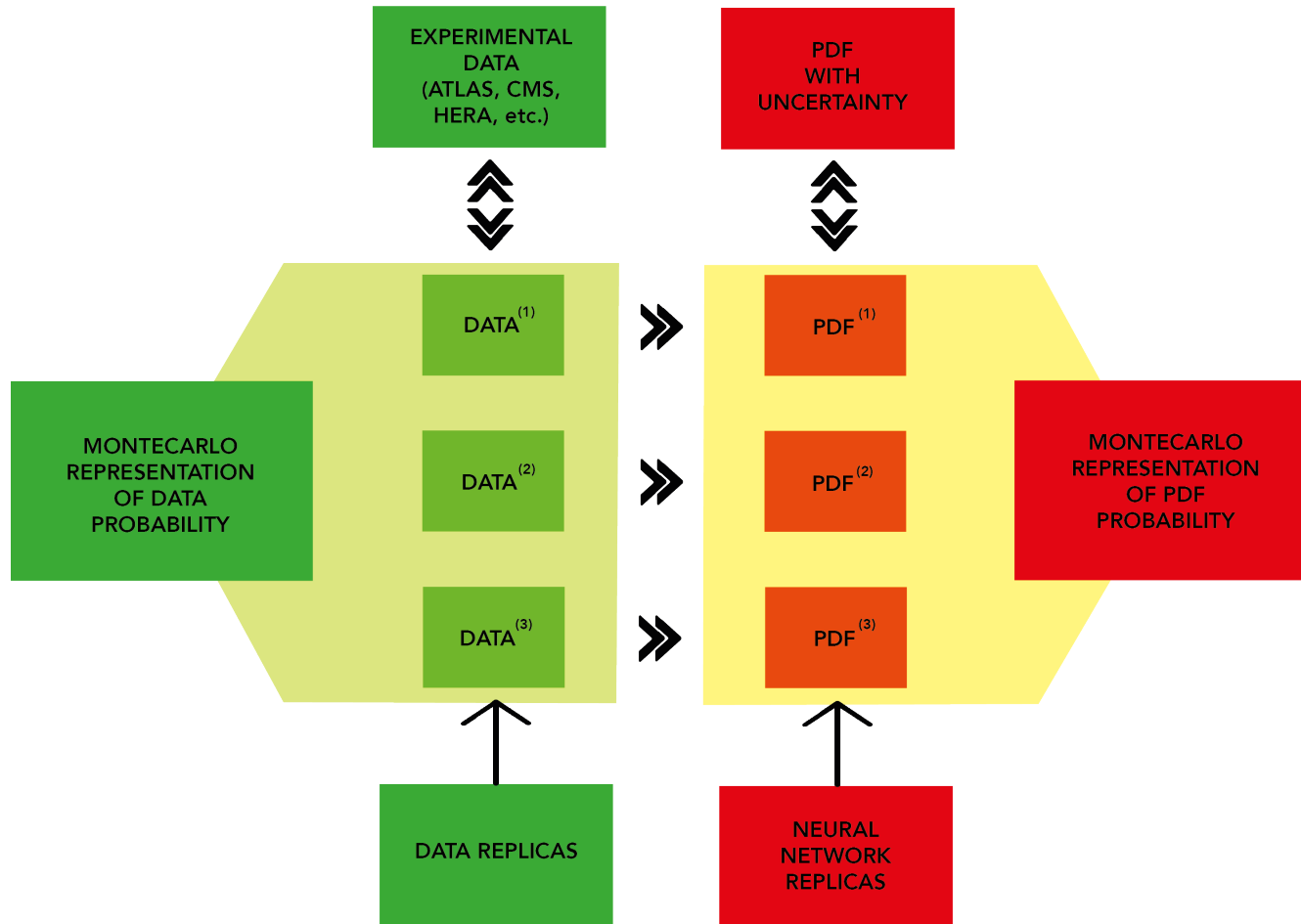
Data set	NNPDF4.0	NNPDF3.1	ABMP16	CT18	MSHT20
ATLAS W, Z 7 TeV (2010)	✓	✓	✓	✓	✓
ATLAS W, Z 7 TeV (2011)	✓	✓	✗	✓	✓
ATLAS low-mass DY 7 TeV	✓	✓	✗	✗	✗
ATLAS high-mass DY 7 TeV	✓	✓	✗	✗	✓
ATLAS W 8 TeV	✓	✗	✗	✗	✓
ATLAS DY 2D 8 TeV	✓	✗	✗	✗	✓
ATLAS high-mass DY 2D 8 TeV	✓	✗	✗	✗	✓
ATLAS $\sigma_{W,Z}$ 13 TeV	✓	✗	✓	✗	✗
ATLAS W^+ +jet 8 TeV	✓	✗	✗	✗	✓
ATLAS $Z p_T$ 8 TeV	✓	✓	✗	✓	✓
ATLAS σ_{tt}^{tot} 7, 8 TeV	✓	✓	✓	✗	✗
ATLAS σ_{tt}^{tot} 13 TeV	✓	✓	✓	✗	✗
ATLAS $t\bar{t}$ lepton+jets 8 TeV	✓	✓	✗	✓	✓
ATLAS $t\bar{t}$ dilepton 8 TeV	✓	✗	✗	✗	✓
ATLAS single-inclusive jets 7 TeV, R=0.6	✗	✓	✗	✓	✓
ATLAS single-inclusive jets 8 TeV, R=0.6	✓	✗	✗	✗	✗
ATLAS dijets 7 TeV, R=0.6	✓	✗	✗	✗	✗
ATLAS direct photon production 13 TeV	✓	✗	✗	✗	✗
ATLAS single top R_t 7, 8, 13 TeV	✓	✗	✓	✗	✗
ATLAS single top diff. 7, 8 TeV	✓	✗	✗	✗	✗
ATLAS single top diff. 8 TeV	✓	✗	✗	✗	✗

CMS

Data set	NNPDF4.0	NNPDF3.1	ABMP16	CT18	MSHT20
CMS W electron asymmetry 7 TeV	✓	✓	✗	✓	✓
CMS W muon asymmetry 7 TeV	✓	✓	✓	✓	✗
CMS Drell-Yan 2D 7 TeV	✓	✓	✗	✗	✓
CMS W rapidity 8 TeV	✓	✓	✓	✓	✓
CMS $Z p_T$ 8 TeV	✓	✓	✗	✓	✗
CMS $W + c$ 7 TeV	✓	✓	✗	✗	✓
CMS $W + c$ 13 TeV	✓	✗	✗	✗	✗
CMS single-inclusive jets 2.76 TeV	✗	✓	✗	✗	✓
CMS single-inclusive jets 7 TeV	✗	✓	✗	✓	✓
CMS dijets 7 TeV	✓	✗	✗	✗	✗
CMS single-inclusive jets 8 TeV	✓	✗	✗	✓	✓
CMS 3D dijets 8 TeV	✗	✗	✗	✗	✗
CMS σ_{tt}^{tot} 5 TeV	✓	✗	✓	✗	✗
CMS σ_{tt}^{tot} 7, 8 TeV	✓	✓	✓	✗	✓
CMS σ_{tt}^{tot} 13 TeV	✓	✓	✓	✗	✗
CMS $t\bar{t}$ lepton+jets 8 TeV	✓	✓	✗	✗	✓
CMS $t\bar{t}$ 2D dilepton 8 TeV	✓	✗	✗	✓	✓
CMS $t\bar{t}$ lepton+jets 13 TeV	✓	✗	✗	✗	✗
CMS $t\bar{t}$ dilepton 13 TeV	✓	✗	✗	✗	✗
CMS single top $\sigma_\ell + \sigma_{\bar{\ell}}$ 7 TeV	✓	✗	✓	✗	✗
CMS single top R_t 8, 13 TeV	✓	✗	✓	✗	✗

THE NNPDF METHODOLOGY

REPLICA SAMPLE OF FUNCTIONS \Leftrightarrow PROBABILITY DENSITY IN FUNCTION SPACE
 KNOWLEDGE OF LIKELIHOOD SHAPE (FUNCTIONAL FORM) NOT NECESSARY



FINAL PDF SET: $f_i^{(a)}(x, \mu)$;

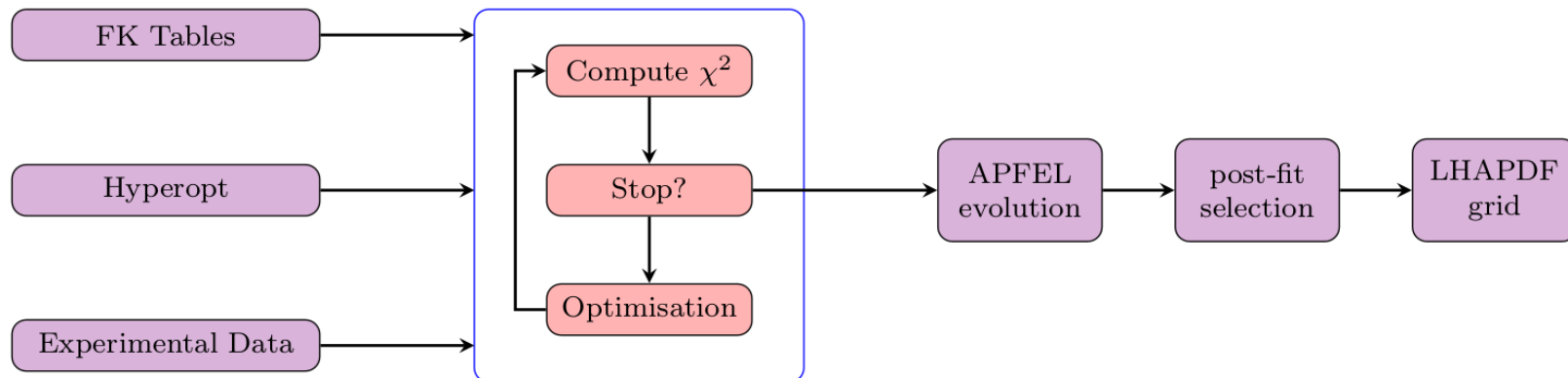
$i = \text{up, antiup, down, antidown, strange, antistrange, charm, gluon}; j = 1, 2, \dots, N_{\text{rep}}$

THE NNPDF CODE STRUCTURE

- MODULAR PYTHON-BASED CODE
- HIGH DEGREE PARALLELIZATION & HARDWARE ACCELERATION

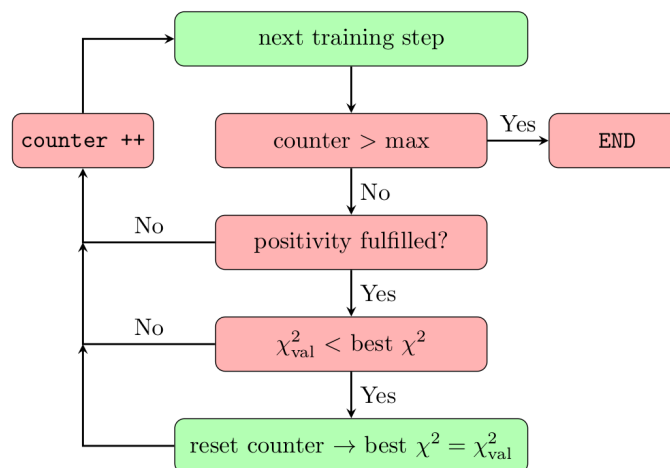
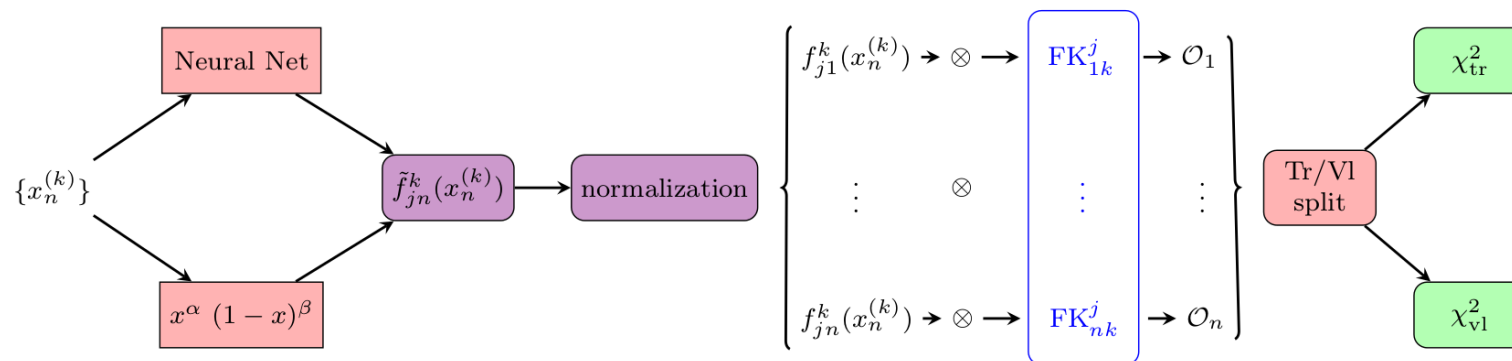
AVERAGE FITTING TIME PER REPLICA AND USE OF RESOURCES
SAME DATASET FOR OLD AND NEW METHODOLOGIES IN CPU AND GPU
CPU: INTEL(R) CORE(TM) I7-4770 AT 3.40GHz; GPU: NVIDIA TITAN V

	NNPDF31 CODEBASE	NNPDF40 CODEBASE IN CPU	NNPDF40 CODEBASE IN GPU
TIME	15.2 H.	38 ± 5 MIN.	6.6 MIN.
RAM USE	1.5 GB	6.1 GB	NA



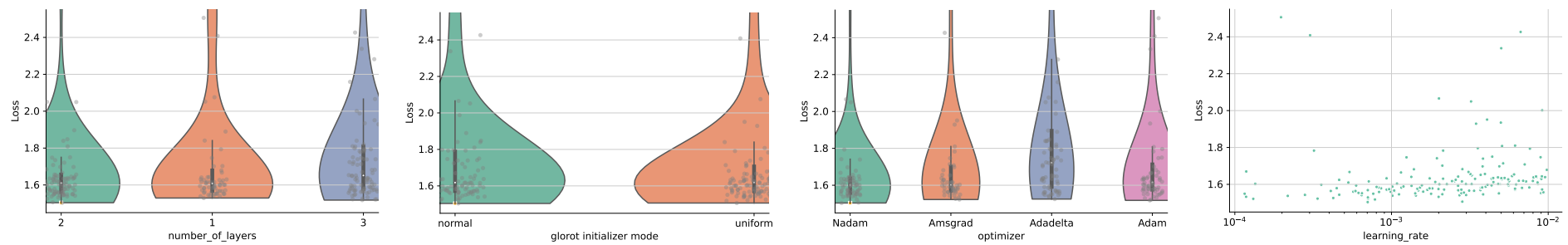
MINIMIZATION AND CROSS-VALIDATION

- DATA REPLICAS \Rightarrow PDF REPLICAS
- EACH PDF REPLICA: PREPROCESSED NEURAL NET
- NEURAL NET \Rightarrow OBSERVABLES
- RANDOM TRAINING-VALIDATION SPLIT, χ^2 TO TRAINING DATA REPLICAS MINIMIZED
- TRAINING STOPS IF VALIDATION χ^2 GROWS FOR A WHILE (PATIENCE)
- LOWEST VALIDATION $\chi^2 \Rightarrow$ OPTIMAL FIT

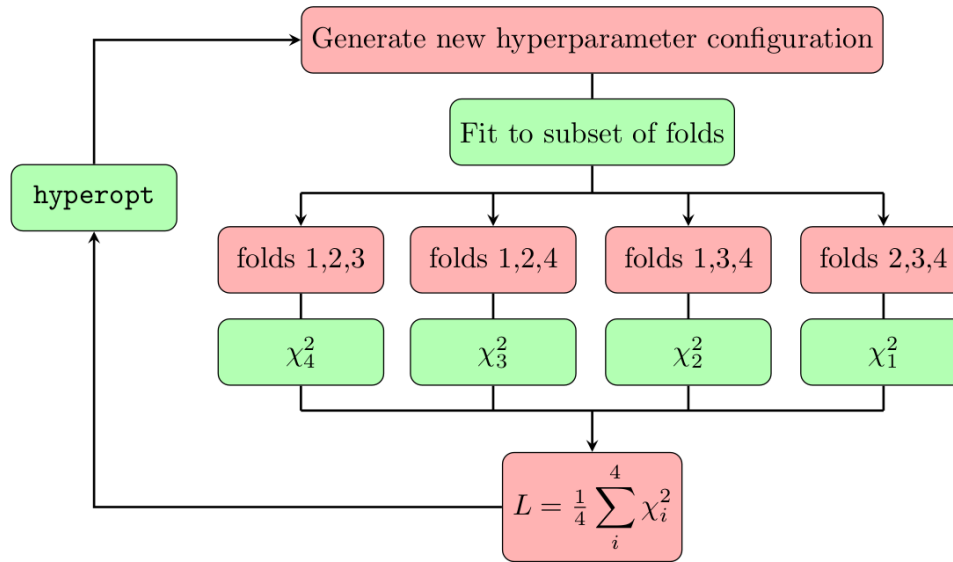


HYPEROPTIMIZATION

- PARAMETRIZATION AND MINIMIZATION **PARAMETERS VARIED**
- **SCAN** OF PARAMETER SPACE
- **BAYESIAN UPDATING** LEADS TO **BEST METHODOLOGY**



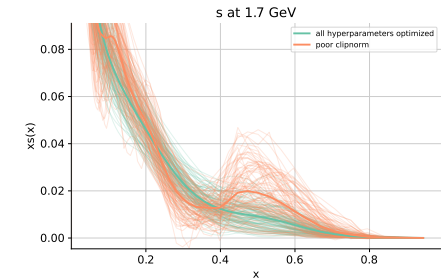
K-FOLDING



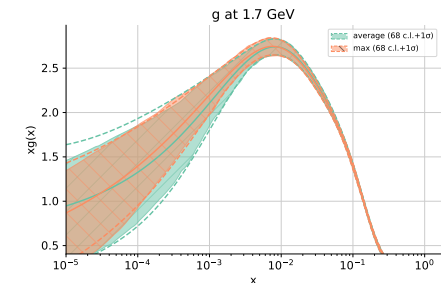
- **HYPEROPTIMIZATION** \Rightarrow **OVERFITTING** (χ^2 TOO GOOD)
- **CHECK GENERALIZATION POWER: K-FOLDING**
 - DIVIDE DATA IN FOLDS
 - **EXCLUDE** ONE FOLD IN TURN FROM FIT
 - **OPTIMIZE** ON THE χ^2 OF THE EXCLUDED FOLDS
 - **BEST AVERAGE** OR **BEST WORST**

Fold 1		
CHORUS σ_{CC}^p	HERA I+II inc NC e^+p 920 GeV	BCDMS p
LHCb Z 940 pb	ATLAS W, Z 7 TeV 2010	CMS Z pr 8 TeV (p_T^j, y_{ll})
DY E605 σ_{DY}^p	CMS Drell-Yan 2D 7 TeV 2011	CMS 3D dijets 8 TeV
ATLAS single- t y (normalised)	ATLAS single top R_t 7 TeV	CMS $t\bar{t}$ rapidity $y_{t\bar{t}}$
CMS single top R_t 8 TeV		
Fold 2		
HERA I+II inc CC e^-p	HERA I+II inc NC e^+p 460 GeV	HERA comb. σ_{bb}^{ind}
NMC p	NuTeV σ_e^p	LHCb $Z \rightarrow ee$ 2 fb
CMS W asymmetry 840 pb	ATLAS Z pr 8 TeV (p_T^j, M_{ll})	D0 $W \rightarrow \mu\nu$ asymmetry
DY E886 σ_{DY}^p	ATLAS direct photon 13 TeV	ATLAS dijets 7 TeV, R=0.6
ATLAS single antitop y (normalised)	CMS σ_{tt}^{int}	CMS single top $\sigma_t + \sigma_{\bar{t}}$ 7 TeV
Fold 3		
HERA I+II inc CC e^+p	HERA I+II inc NC e^+p 575 GeV	NMC d/p
NuTeV σ_e^p	LHCb $W, Z \rightarrow \mu$ 7 TeV	LHCb $Z \rightarrow ee$
ATLAS W, Z 7 TeV 2011 Central selection	ATLAS W^+ +jet 8 TeV	ATLAS HM DY 7 TeV
CMS W asymmetry 4.7 fb	DYE 866 $\sigma_{DY}^d/\sigma_{DY}^p$	CDF Z rapidity (new)
ATLAS σ_{tt}^{int}	ATLAS single top y_t (normalised)	CMS σ_{tt}^{int} 5 TeV
CMS $t\bar{t}$ double diff. ($m_{t\bar{t}}, y_t$)		
Fold 4		
CHORUS σ_{CC}^p	HERA I+II inc NC e^+p 820 GeV	LHCb $W, Z \rightarrow \mu$ 8 TeV
LHCb $Z \rightarrow \mu\mu$	ATLAS W, Z 7 TeV 2011 Fwd	ATLAS W^- +jet 8 TeV
ATLAS low-mass DY 2011	ATLAS Z pr 8 TeV (p_T^j, y_{ll})	CMS W rapidity 8 TeV
D0 Z rapidity	CMS dijets 7 TeV	ATLAS single top y_t (normalised)
ATLAS single top R_t 13 TeV	CMS single top R_t 13 TeV	

NO K-FOLDING



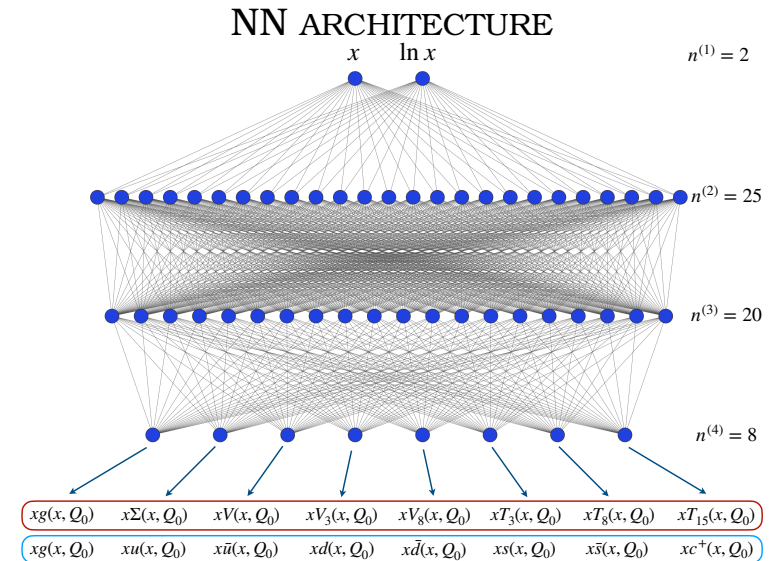
K-FOLDING VARIATION



THE ML METHODOLOGY

HYPEROPTIMIZED PARAMETERS

Parameter	NNPDF4.0	L as in Eq. (3.21)	Flavour basis Eq. (3.2)
Architecture	25-20-8	70-50-8	7-26-27-8
Activation function	hyperbolic tangent	hyperbolic tangent	sigmoid
Initializer	glorot_normal	glorot_uniform	glorot_normal
Optimizer	Nadam	Adadelta	Nadam
Clipnorm	6.0×10^{-6}	5.2×10^{-2}	2.3×10^{-5}
Learning rate	2.6×10^{-3}	2.5×10^{-1}	2.6×10^{-3}
Maximum # epochs	17×10^3	45×10^3	45×10^3
Stopping patience	10% of max epochs	12% of max epochs	16% of max epochs
Initial positivity $\Lambda^{(\text{pos})}$	185	106	2
Initial integrability $\Lambda^{(\text{int})}$	10	10	10



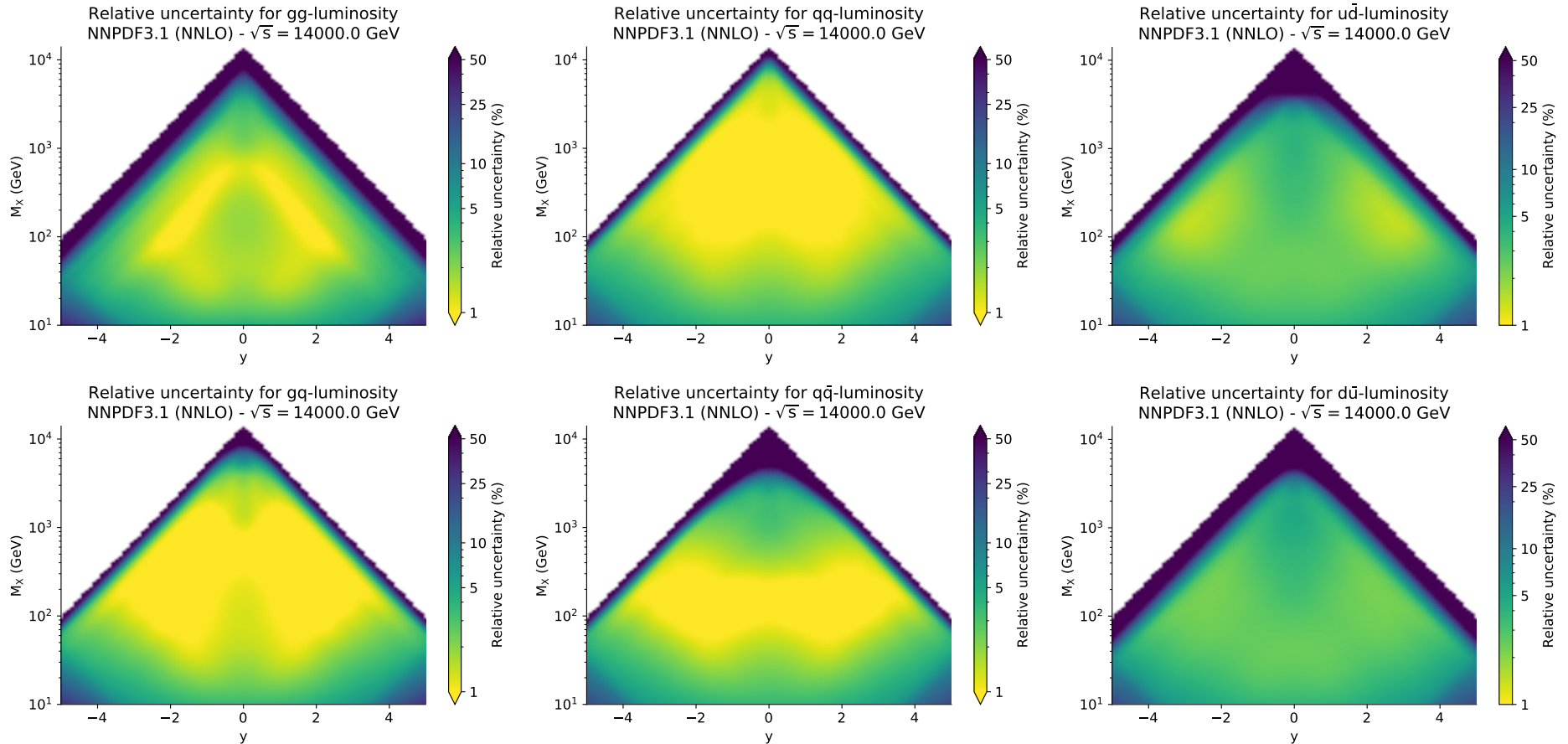
- HYPEROPT ADAPTS TO EXTERNAL CHOICES (E.G. PARAMETRIZATION BASIS)
- SIMILAR RESULTS CAN BE OBTAINED WITH RATHER DIFFERENT SETTINGS
- ~ 800 FREE PARAMETERS

UNCERTAINTIES: FROM NNPDF3.1...

GLUON

SINGLET

FLAVORS



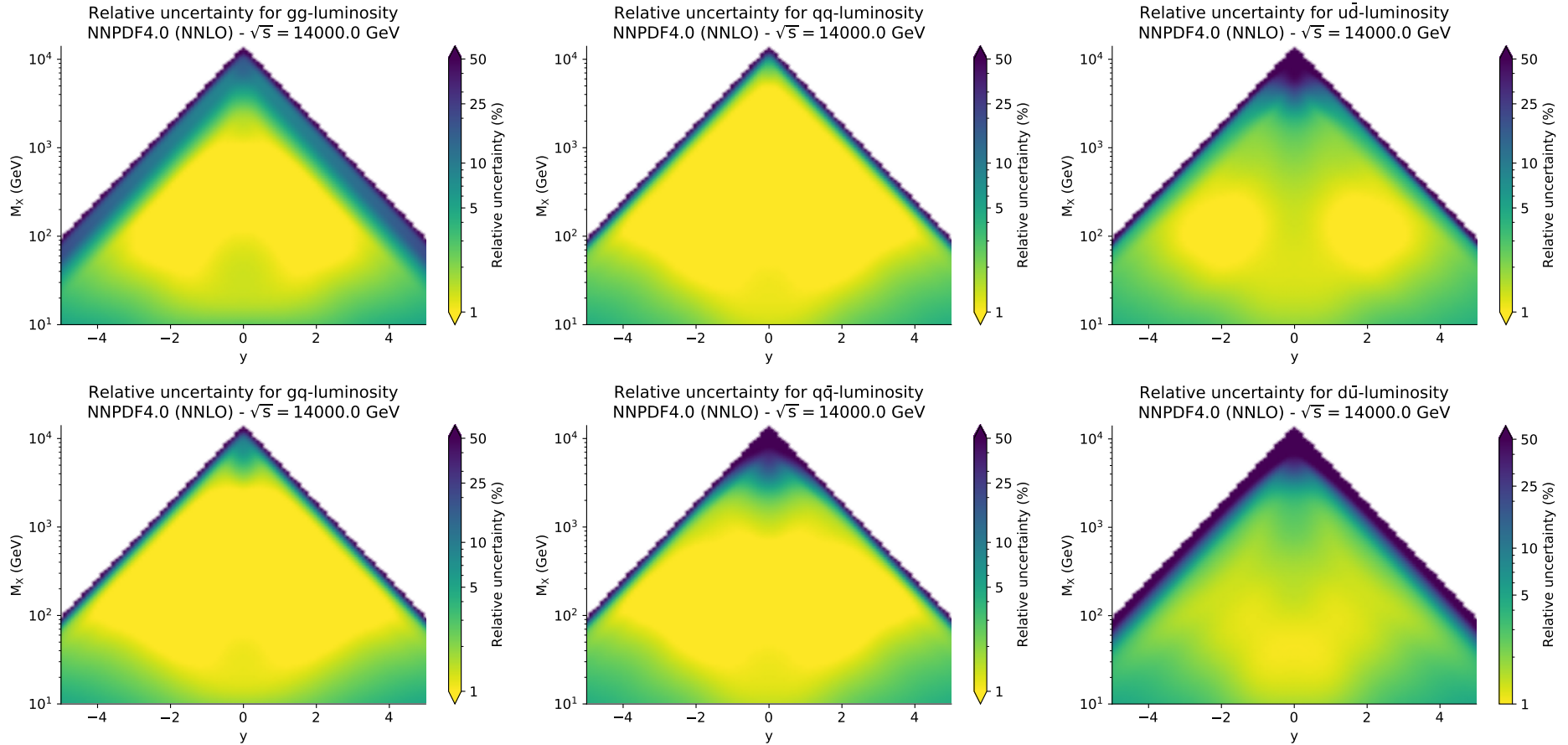
- TYPICAL UNCERTAINTIES IN DATA REGION: SINGLET $\sim 3\%$, NONSINGLET $\sim 5\%$
- DATA REGION: $10^2 \lesssim M_X \lesssim 10^3$ TeV, $-2 \lesssim y \lesssim 2$

UNCERTAINTIES: ...TO NNPDF4.0

GLUON

SINGLET

FLAVORS

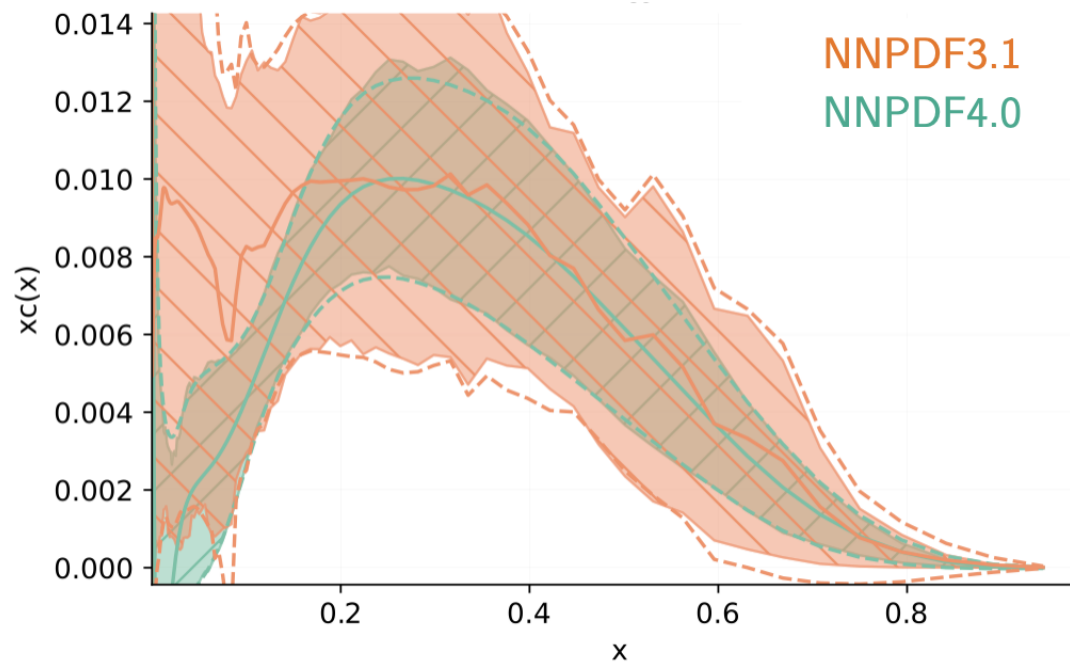


- TYPICAL UNCERTAINTIES IN DATA REGION: SINGLET $\sim 1\%$, NONSINGLET $\sim 2 - 3\%$
- DATA REGION: $10 \lesssim M_X \lesssim 3 \cdot 10^3$ TEV, $-4 \lesssim y \lesssim 4$

DISCOVERY OF INTRINSIC CHARM

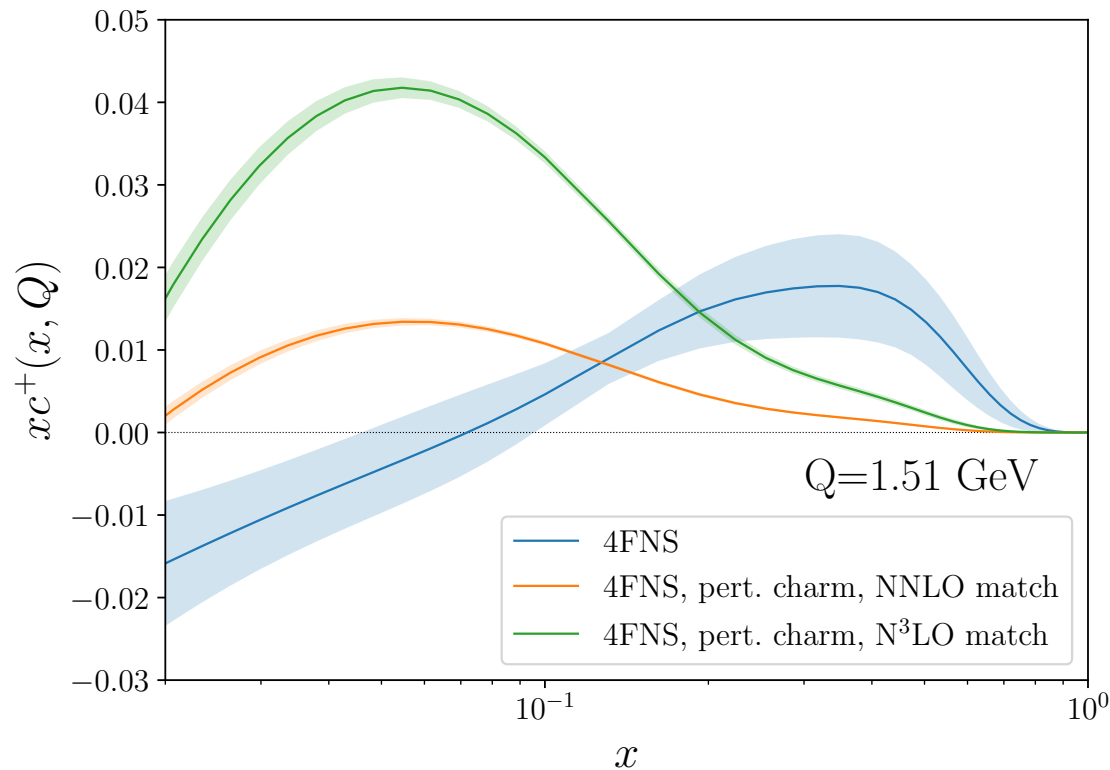
THE CHARM PDF ($n_f = 4$ SCHEME) NNPDF4.0 vs. NNPDF3.1

- NNPDF CHARM PDF \Rightarrow DETERMINED FROM THE DATA ALONG WITH ALL OTHER PDFs:
 - MORE REALISTIC UNCERTAINTIES
 - INDEPENDENT OF MATCHING CONDITIONS:
 - * STABLE UPON VARIATION OF m_c
 - * INSENSITIVE TO MHO CORRECTIONS
- AGREES WITH PREVIOUS DETERMINATION
- SIGNIFICANTLY SMALLER UNCERTAINTIES



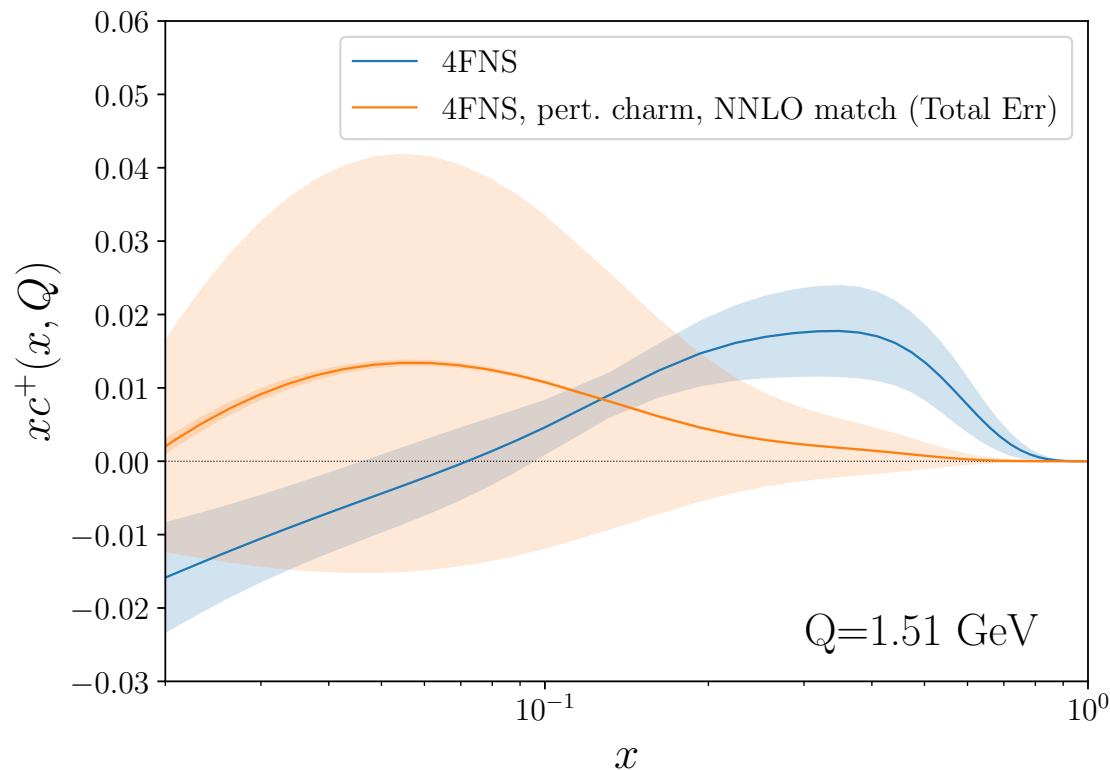
THE CHARM PDF ($n_f = 4$ SCHEME) FITTED VS PERTURBATIVE

- NNPDF CHARM PDF \Rightarrow DETERMINED FROM THE DATA ALONG WITH ALL OTHER PDFs:
 - MORE REALISTIC UNCERTAINTIES
 - INDEPENDENT OF MATCHING CONDITIONS:
 - * STABLE UPON VARIATION OF m_c
 - * INSENSITIVE TO MHO CORRECTIONS
- DIFFERS SIGNIFICANTLY FROM PERTURBATIVE CHARM



THE CHARM PDF ($n_f = 4$ SCHEME) FITTED VS PERTURBATIVE

- NNPDF CHARM PDF \Rightarrow DETERMINED FROM THE DATA ALONG WITH ALL OTHER PDFs:
 - MORE REALISTIC UNCERTAINTIES
 - INDEPENDENT OF MATCHING CONDITIONS:
 - * STABLE UPON VARIATION OF m_c
 - * INSENSITIVE TO MHO CORRECTIONS
- DIFFERS SIGNIFICANTLY FROM PERTURBATIVE CHARM EVEN ACCOUNTING FOR MHO
- INTRINSIC-LIKE, VALENCE-LIKE BUMP AT LARGE x



IS IT INTRINSIC CHARM?

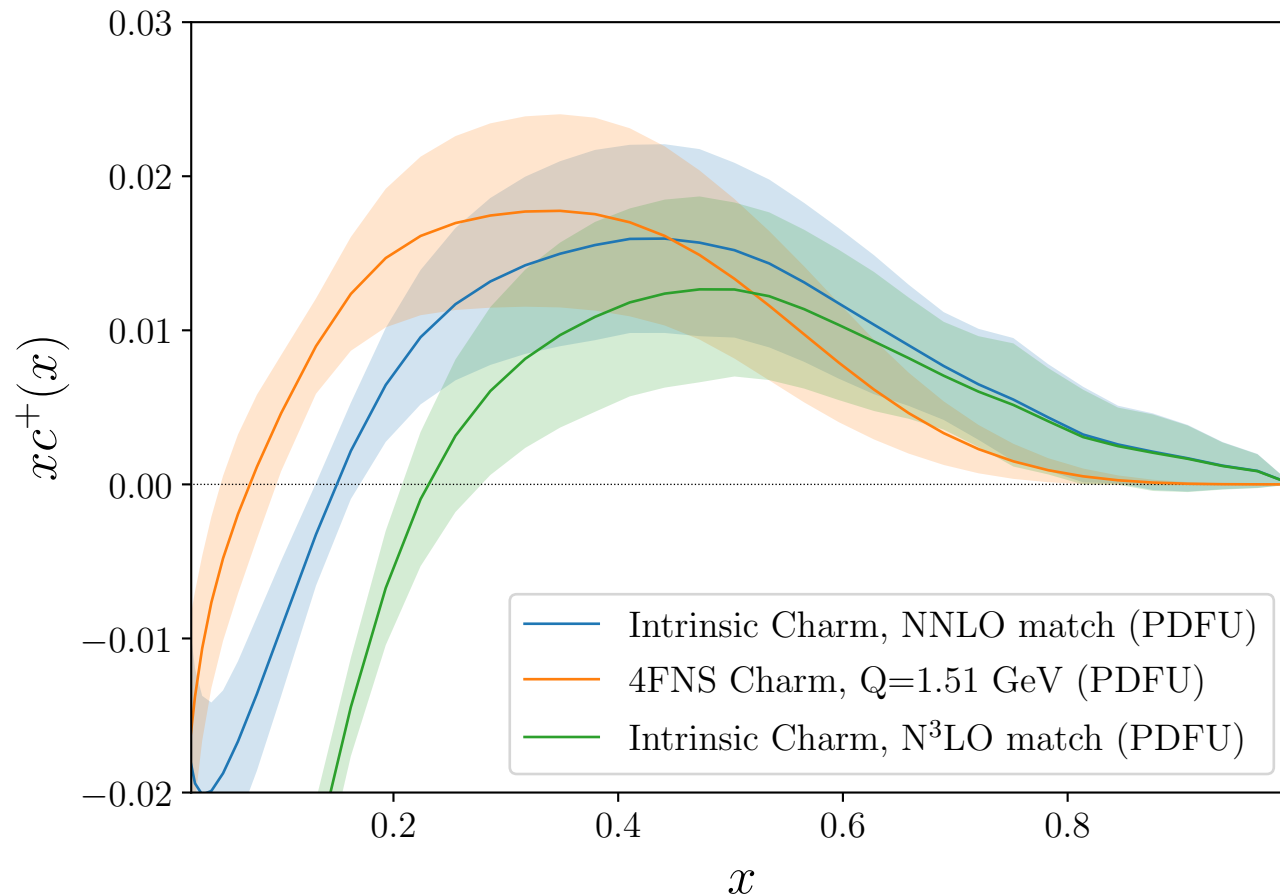
RECALL LARGE & PERTURBATIVELY UNSTABLE CONVERSION TO $N_f = 3$ SCHEME

INTRINSIC CHARM....

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

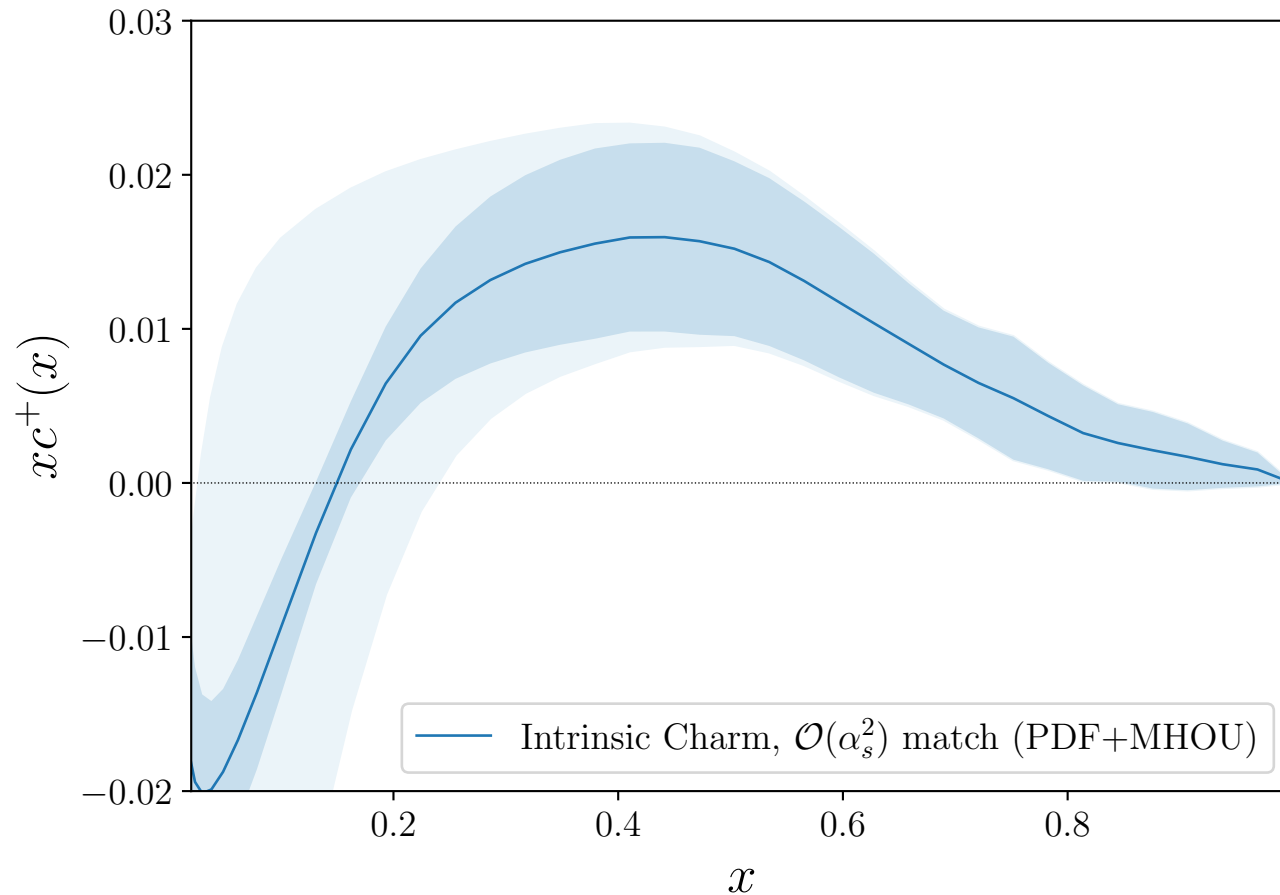
- IMPLEMENTS **DIRECT & INVERSE** EVOLUTION & MATCHING
- **N³LO MATCHING** (Blümlein, Ablinger et al.) ALSO IMPLEMENTED

CHARM PDF: $N_f = 4$ VS $N_f = 3$ (NNLO & N³LO CONVERSION)



INTRINSIC CHARM!

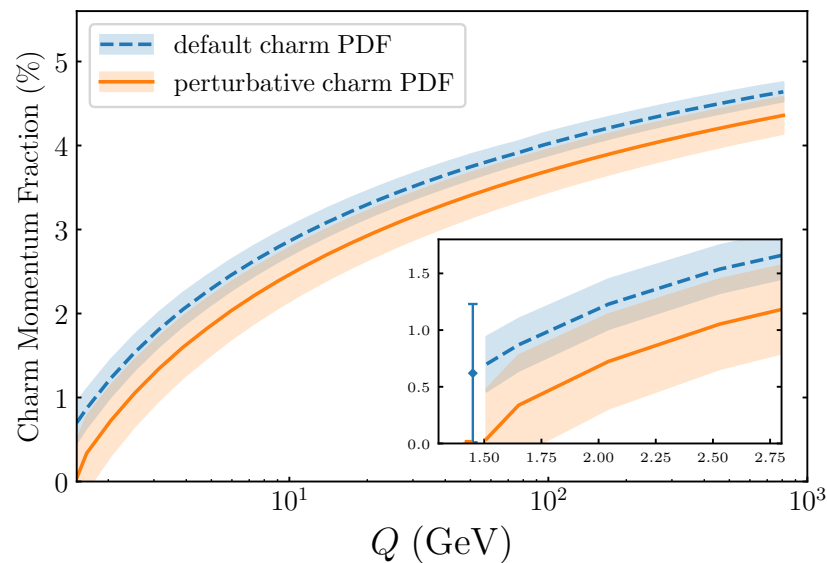
- M³HOU ESTIMATED FROM N³LO-NNLO DIFFERENCE
 - LARGE UNCERTAINTY AT SMALL x
 - NEGLIGIBLE UNCERTAINTY IN VALENCE REGION
- COMPATIBLE WITH ZERO AT SMALL x
- CLEAR EVIDENCE FOR INTRINSIC VALENCE PEAK



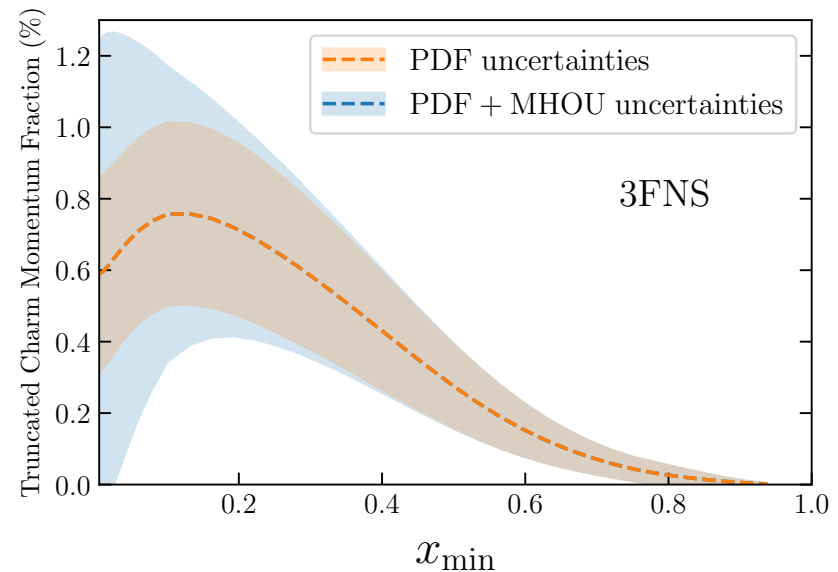
THE CHARM MOMENTUM FRACTION

- $n_f = 4$, $Q = 1.65$ GeV: **FITTED** $\langle c \rangle = 0.87 \pm 0.23_{\text{pdf}}\%$ vs. **PERTURBATIVE** $\langle c \rangle = 0.346 \pm 0.005_{\text{pdf}} \pm 0.44_{\text{mhou}}\%$
- $n_f = 3$, **FITTED** $\langle c \rangle = 0.62 \pm 0.28_{\text{pdf}} \pm 0.54_{\text{mhou}}\%$ vs. **PERTURBATIVE** $\langle c \rangle = 0\%$

$n_f = 4$: FITTED VS. PERTURBATIVE



$n_f = 3$: MOMENTUM INTEGRAL

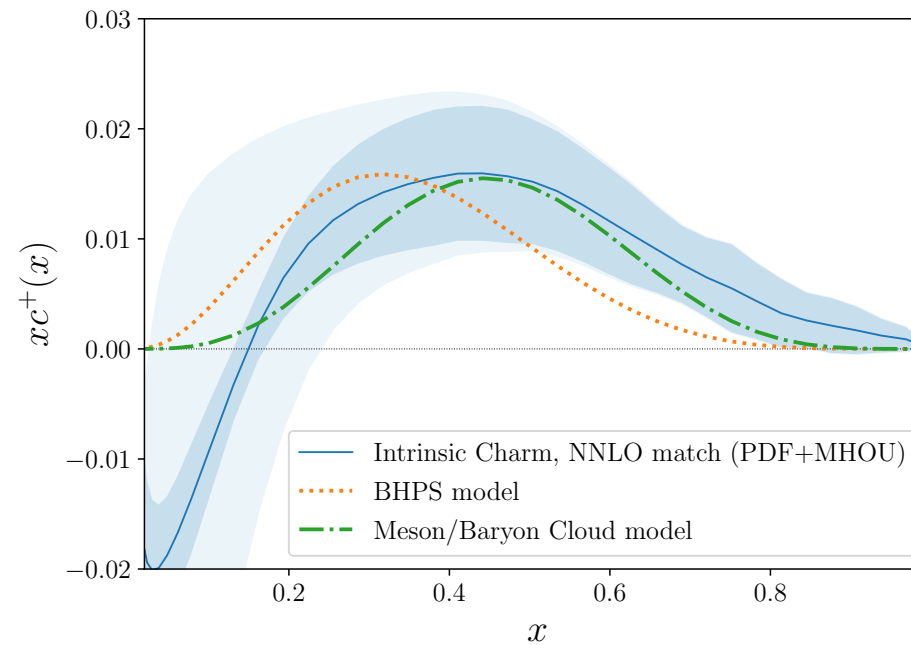


- $n_f = 4$ MOMENTUM FRACTION **DETERMINED TO GOOD ACCURACY**
- **LARGE MHOu** AT SMALL $x \Rightarrow$ **TOTAL INTRINSIC** MOMENTUM FRACTION **COMPATIBLE WITH ZERO**

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

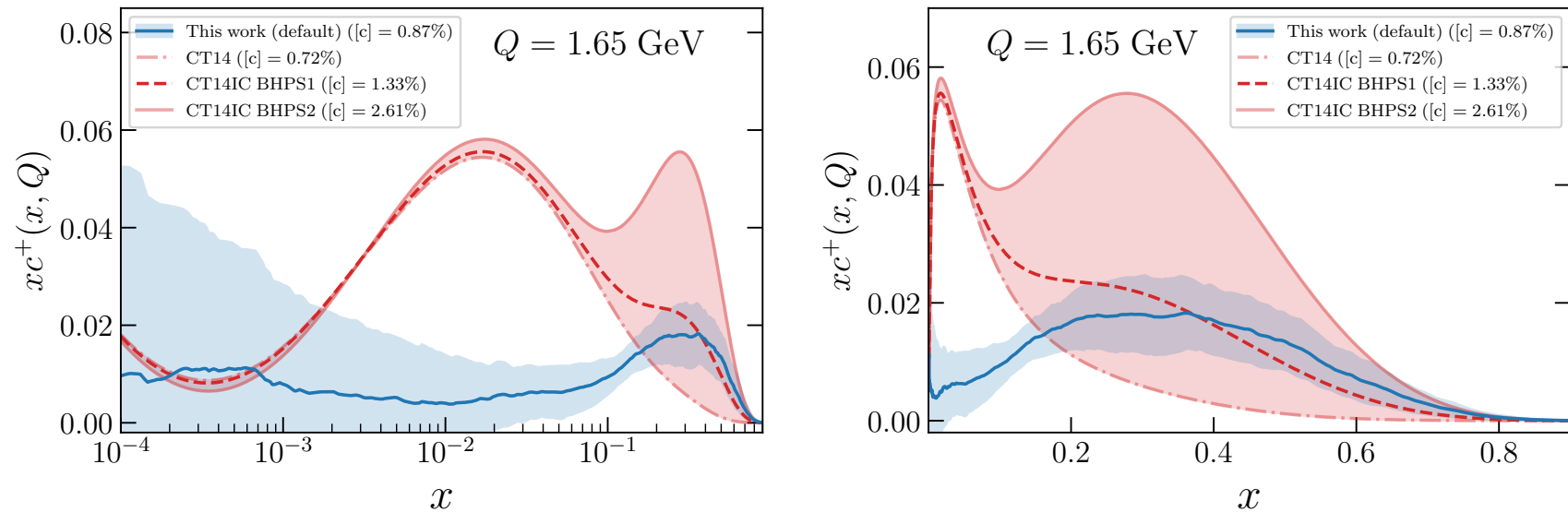


SURPRIZING QUALITATIVE AGREEMENT!

MODEL FITS

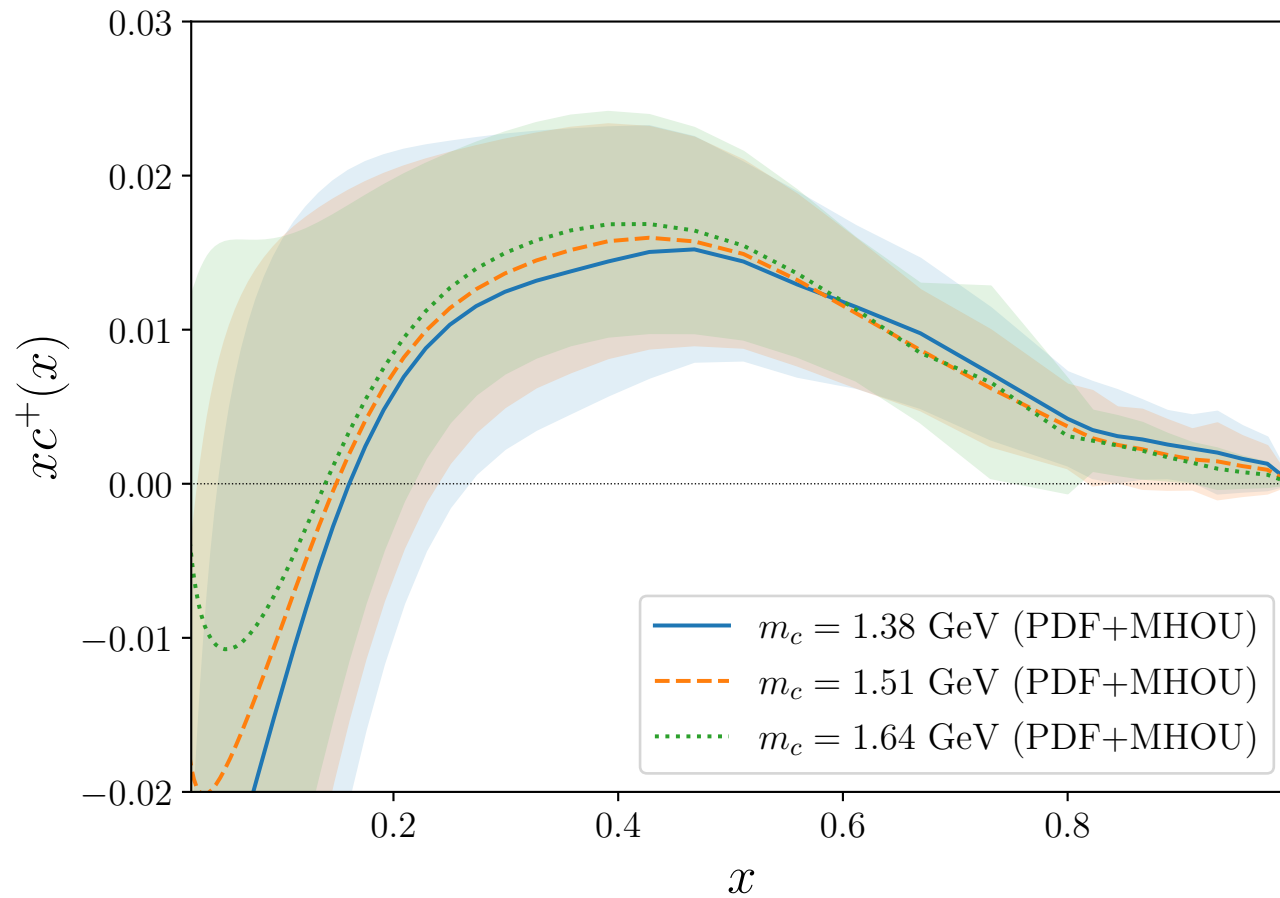
- CT **FITTED** BPHS **NORMALIZATION** IN $N_f = 3$, S-ACOT (PROBLEMATIC: INCOMPATIBLE WITH IC)
- LOW $Q_0 = 1.3$ GEV
- BEST FIT $\langle c \rangle \sim 1\%$ (CT14) OR $\langle c \rangle \sim 0.5\%$ (CT18)

NNPDF4.0 INTRINSIC CHARM VS. CT14 FIT



- **GOOD AGREEMENT** W. NNPDF AT LARGE x FOR SIMILAR NORM.
- **HUGE PERTURBATIVE BUMP** AT SMALL x

**STABILITY:
CHARM MASS**



- **NEGLIGIBLE DEPENDENCE** ON m_c (UNLIKE PERTURBATIVE CHARM)

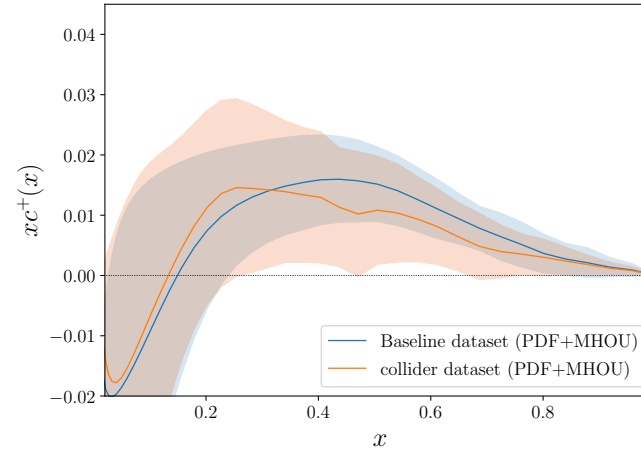
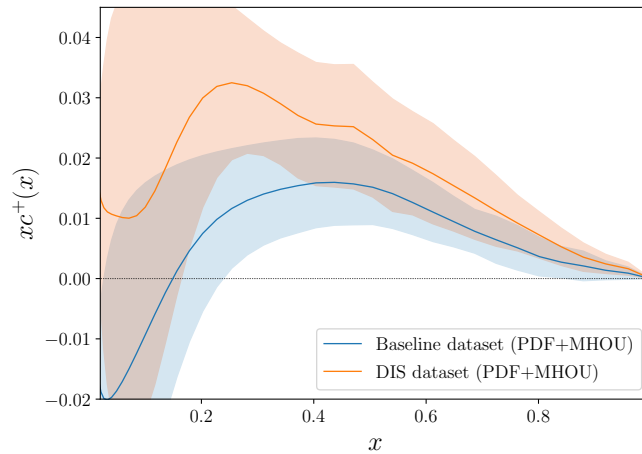
DATA: PAST, PRESENT... AND FUTURE

WHICH DATA DRIVE THE ANSWER?:

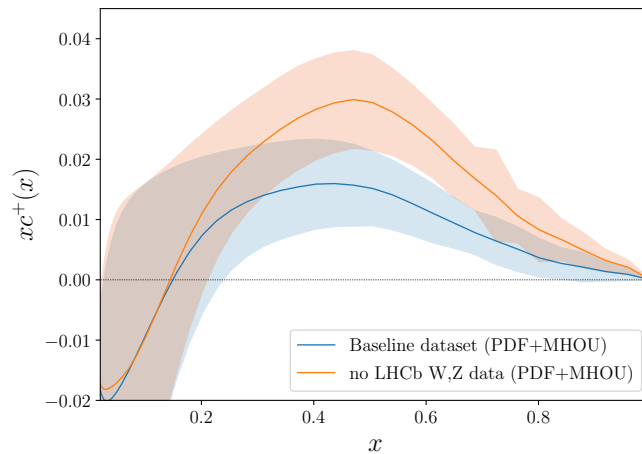
DATA SUBSETS $n_F = 3$

DIS ONLY

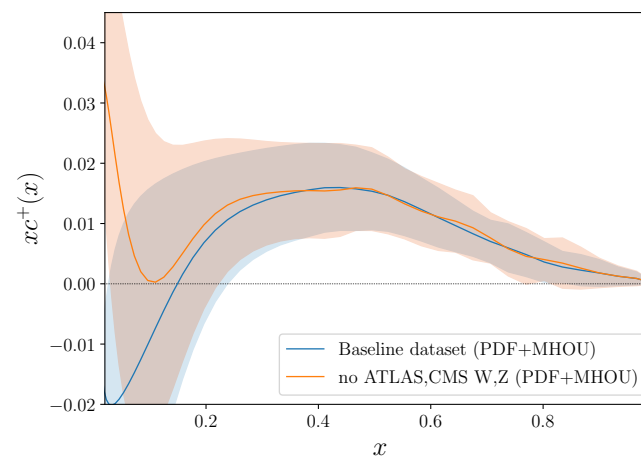
COLLIDER ONLY



NO LHCb



NO ATLAS/CMS DY

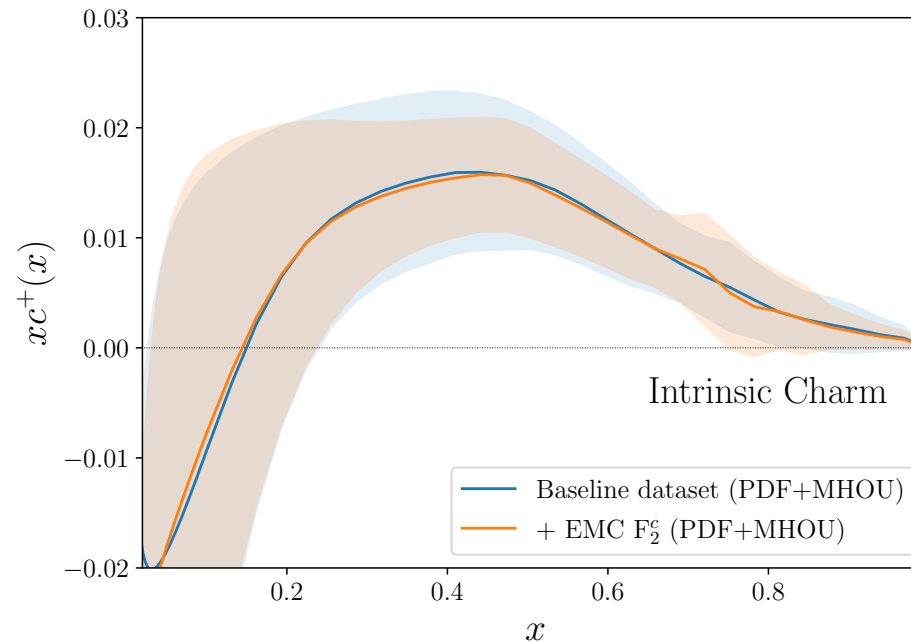


- ALL DATASETS IN AGREEMENT
- COLLIDER DATA MORE IMPORTANT THAN DIS DATA FOR PRECISION
- LHCb W, Z SIGNIFICANT IMPACT

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

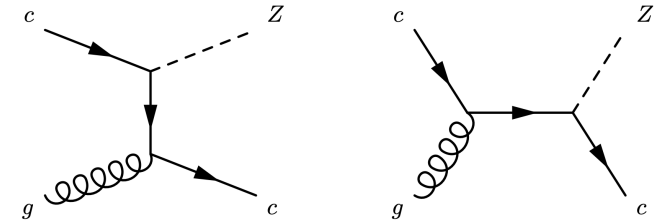
INTRINSIC CHARM WITH EMC DATA INCLUDED



COMPLETE CONSISTENCY!

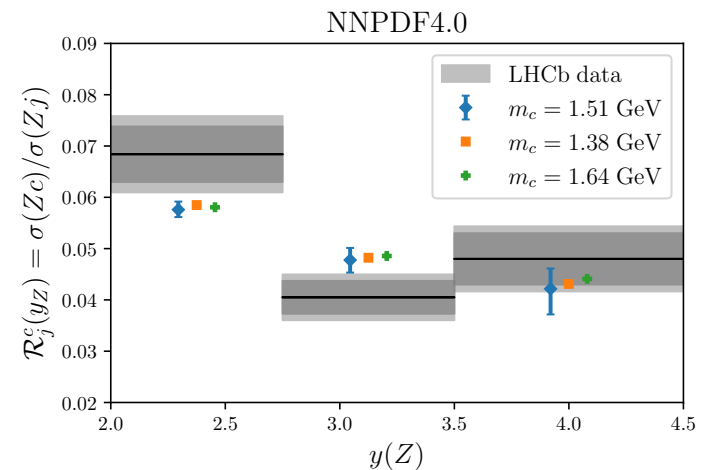
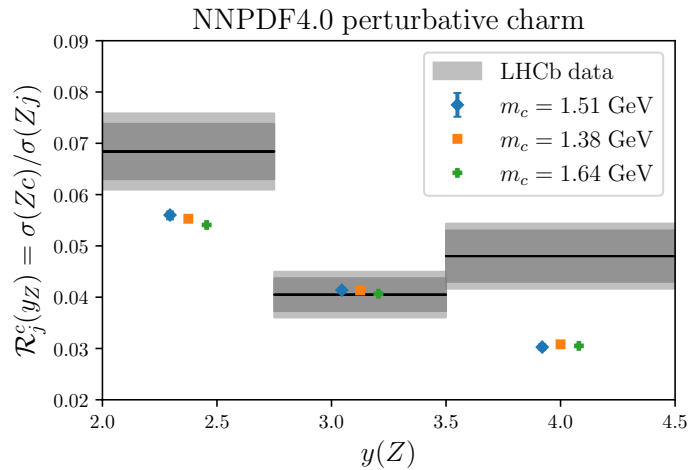
MORE DATA LHCb 2021

MEASUREMENT OF Z +CHARM PRODUCTION

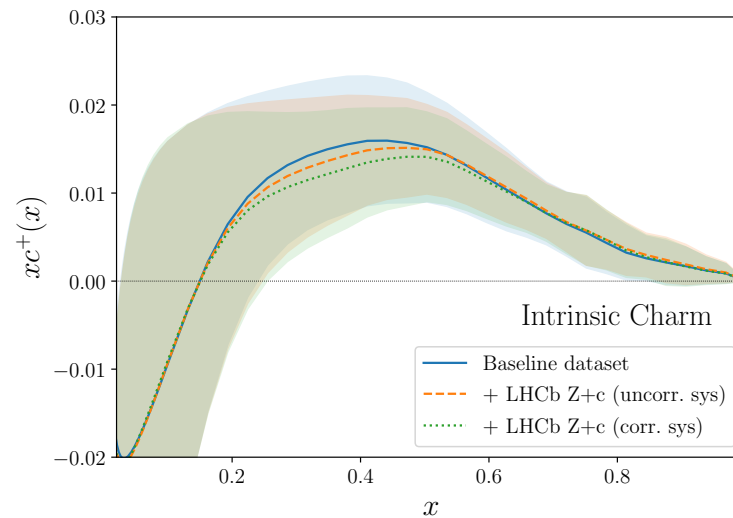


DATA VS THEORY PREDICTION

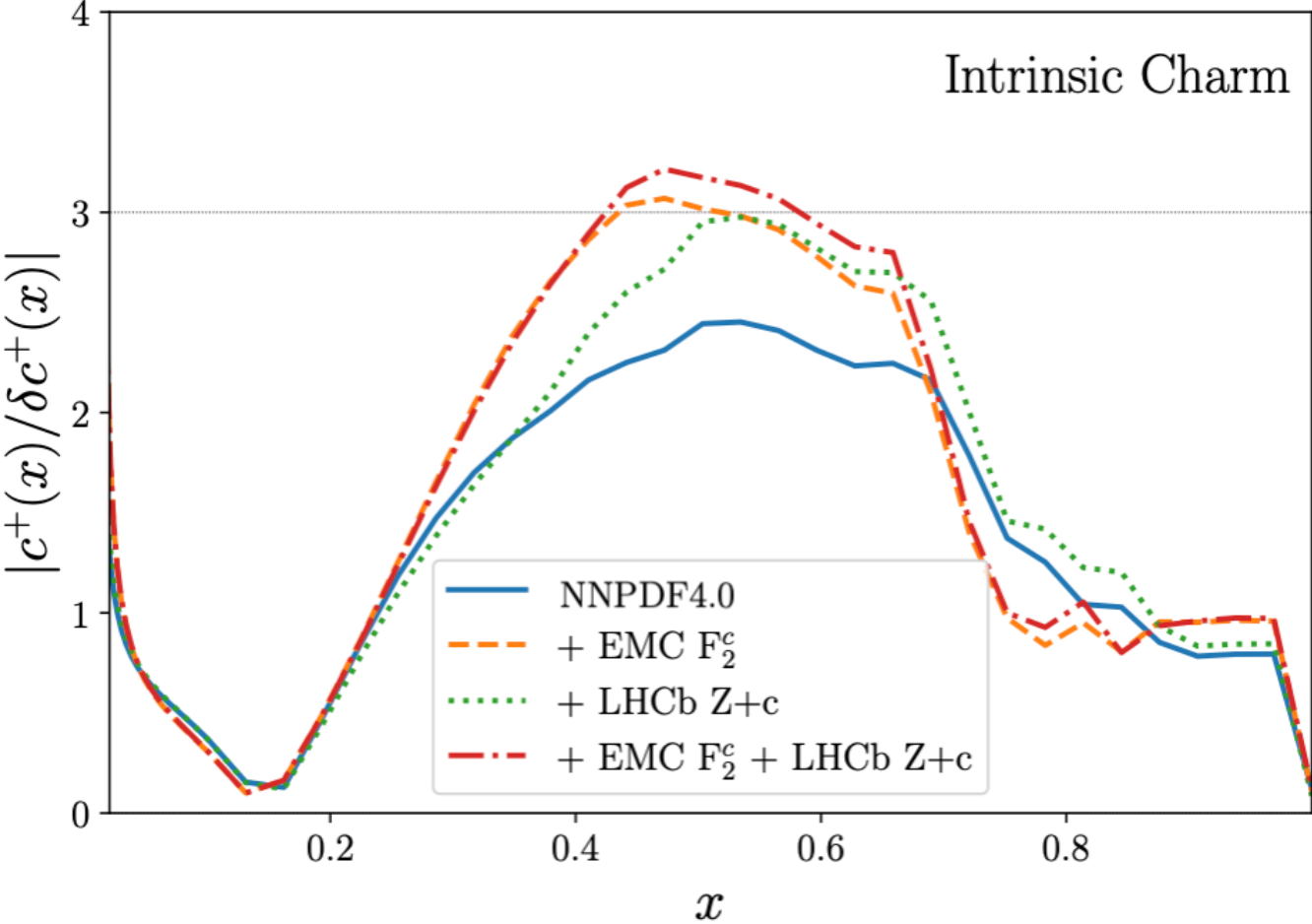
NO INTRINSIC CHARM NNPDF4.0 INTRINSIC CHARM



INTRINSIC CHARM WITH LHCb DATA INCLUDED: COMPLETE CONSISTENCY



INTRINSIC CHARM DISCOVERY
THE CURRENT BEST EVIDENCE

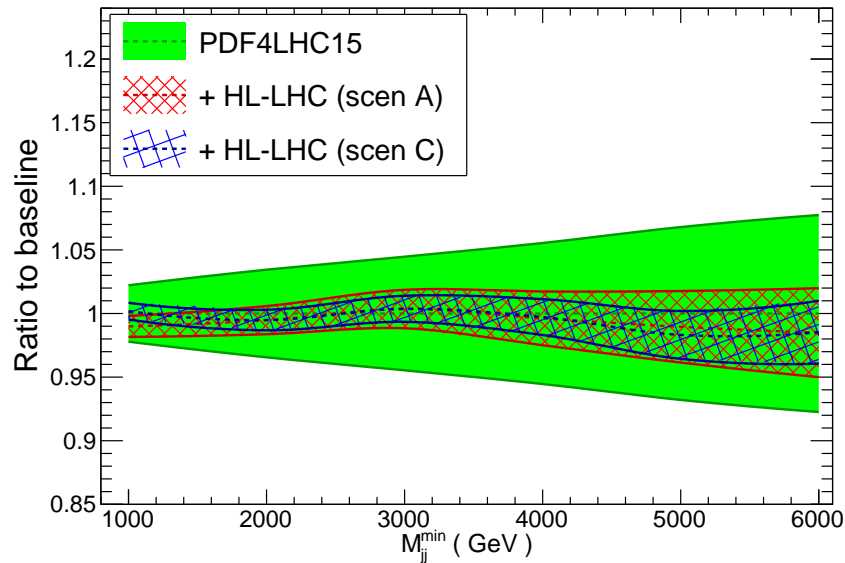


MORE THAN 3σ EVIDENCE

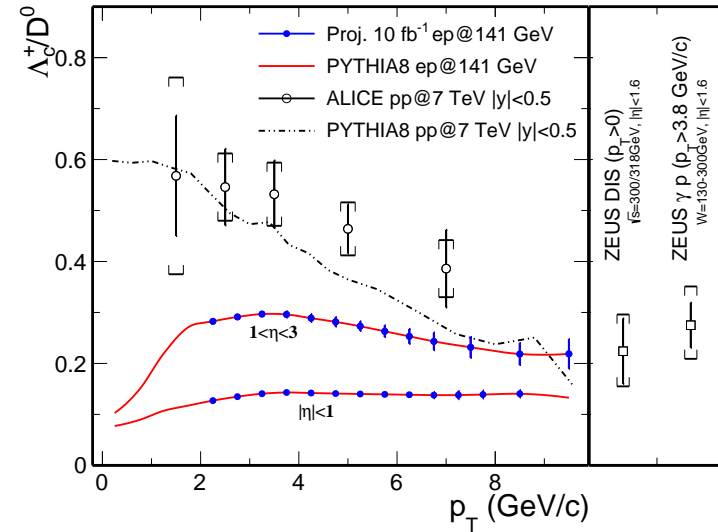
FUTURE DATA

- 2025-2035: HL-LHC W AND Z PRODUCTION
- AFTER 2035: EIC F_2^c

HL-LHC DIJETS: IMPACT ON **GLUON**
Dijet production @ HL-LHC $\sqrt{s}=14$ TeV



CHARM MESON PRODUCTION AT THE EIC



SUMMARY

WE FITTED THE CHARM PDF IN ORDER TO GET

- REALISTIC ERROR ESTIMATE
- NO STRONG DEPENDENCE ON CHARM MASS
- NO SENSITIVITY TO M_{HOU} IN MATCHING CONDITION

WE FOUND

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

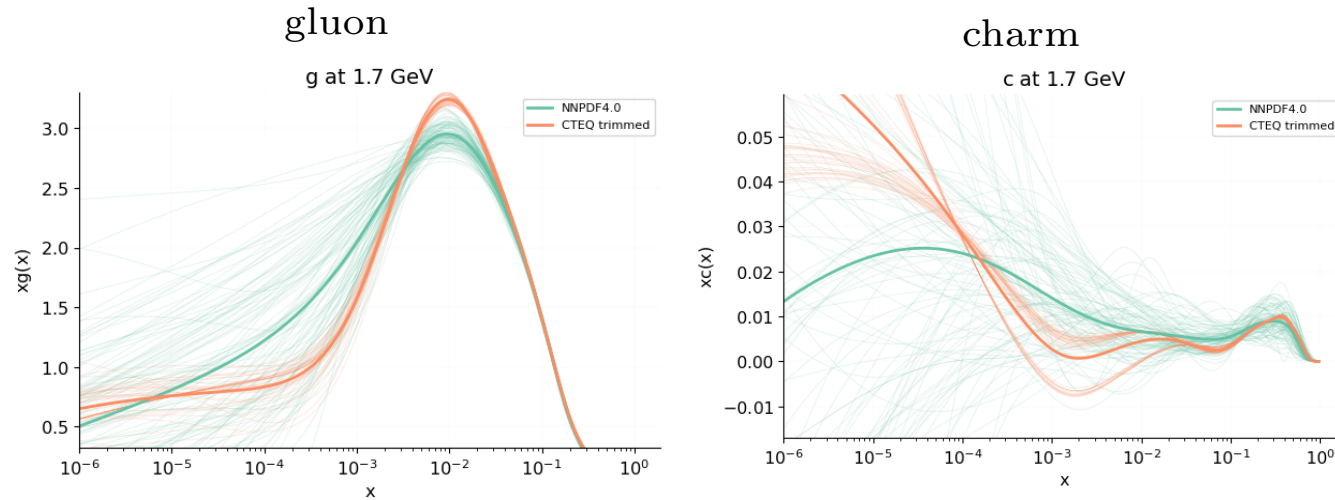
TO DO

- MORE DATA \Rightarrow FIVE σ EVIDENCE
- $c - \bar{c}$ ASYMMETRY DETERMINATION

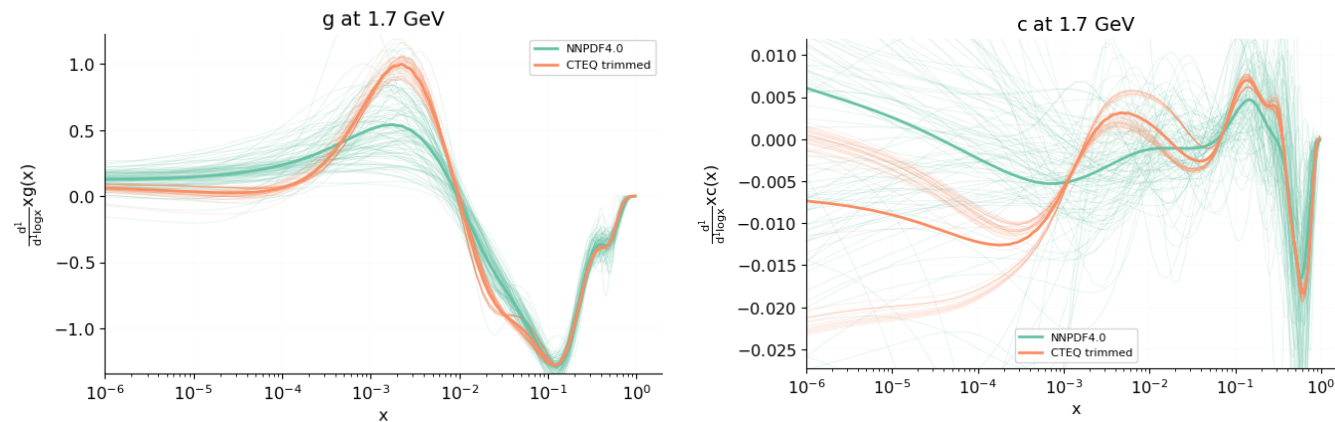
EXTRAS

“HOPSCOTCH” OVERLEARNT PDFs

PDFs



KINETIC ENERGY (DIFFERENTIAL ARCLENGTH)



- **HS OVERLEARNT** BY CONSTRUCTION
- **CAN BE REPRODUCED IN NNPDF4.0** BY FORCING OVERLEARNING