VALENCE CHARM IN THE PROTON

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Heavy Flavors at High p_T

Edinburgh, November 30, 2023

VALENCE CHARM IN THE PROTON

THE NNPDF COLLABORATION

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Amsterdam-CERN-Edinburgh-INFN-Milan-NIKHEF-Turin-Yväskylä

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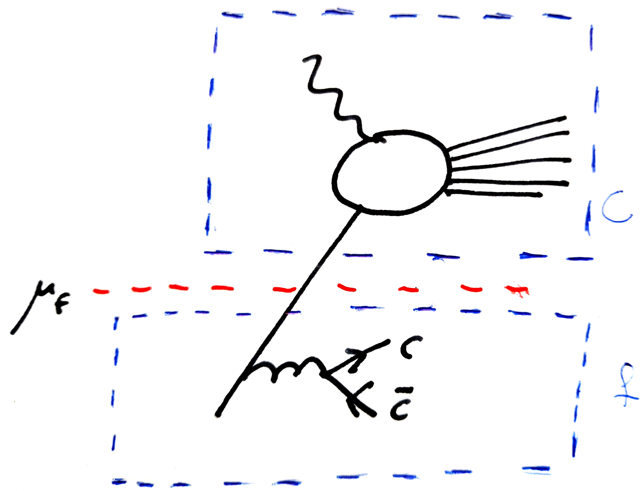
INTRINSIC CHARM?

WHAT IS NOT INTRINSIC CHARM?

perturbative charm generation



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

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

WHAT IS NOT INTRINSIC CHARM?

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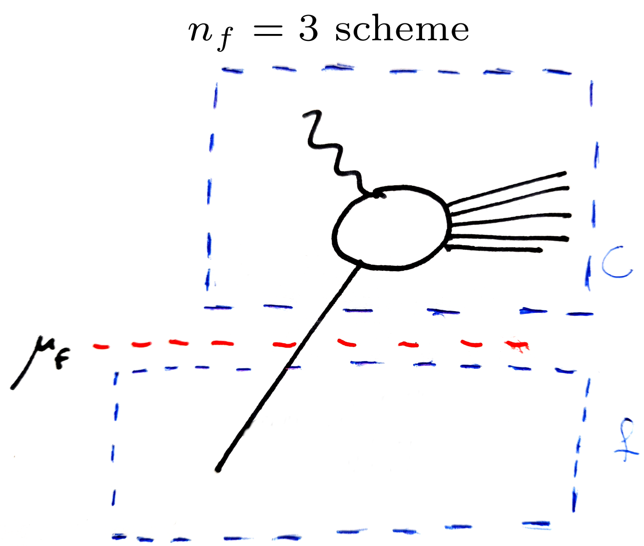
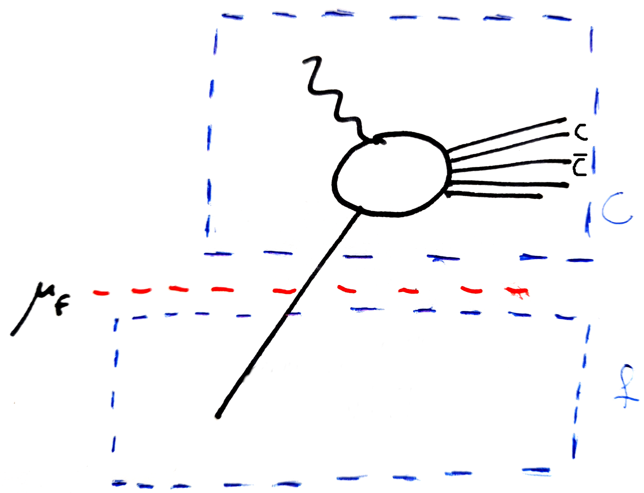


- MASSIVE QUARKS $\Rightarrow$ NO COLLINEAR SINGULARITY
- MAY WORK IN $n_f = 3$ SCHEME $\Rightarrow$ CHARM DECOUPLES FROM PDF EVOLUTION
- .

WHAT IS NOT INTRINSIC CHARM?

$n_f = 3$ scheme



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- MAY WORK IN $n_f = 3$ SCHEME $\Rightarrow$ CHARM DECOUPLES FROM PDF EVOLUTION
- PERTURBATIVE CHARM PRODUCTION IN COEFFICIENT FUNCTION

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 $\overline{\mathrm{MS}}$ $\Leftrightarrow$ 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-ongoing)

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

M. Buza et al.: Charm

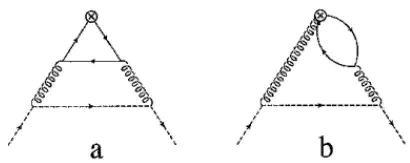


Fig. 2. $O(\alpha_s^2)$ contributions to the purely-singlet OME $A^{PS}_{q'q}$. Here q and q' are represented by the *dashed* and *solid lines* respectively. In the case of $q' = H$ these graphs contribute to the heavy-quark OME A^{PS}_{Hq}

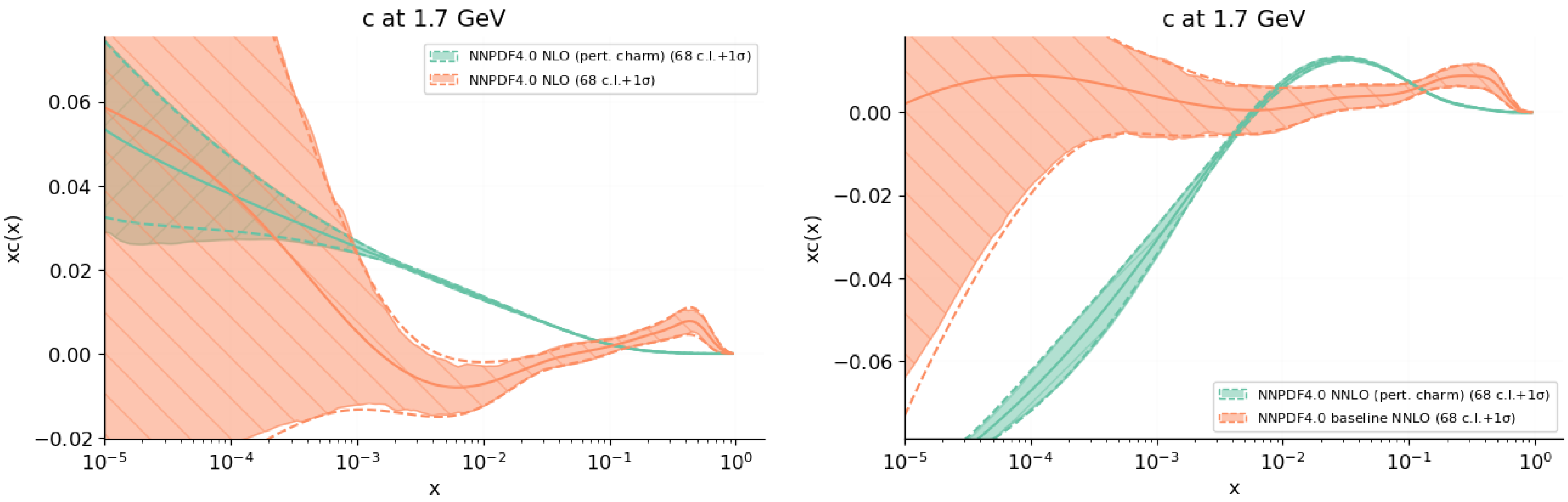
WHAT IS NOT INTRINSIC CHARM?

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 NNLO



WHAT IS INTRINSIC CHARM?

- DEFINE CHARM PDF AS OME:

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

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

- 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

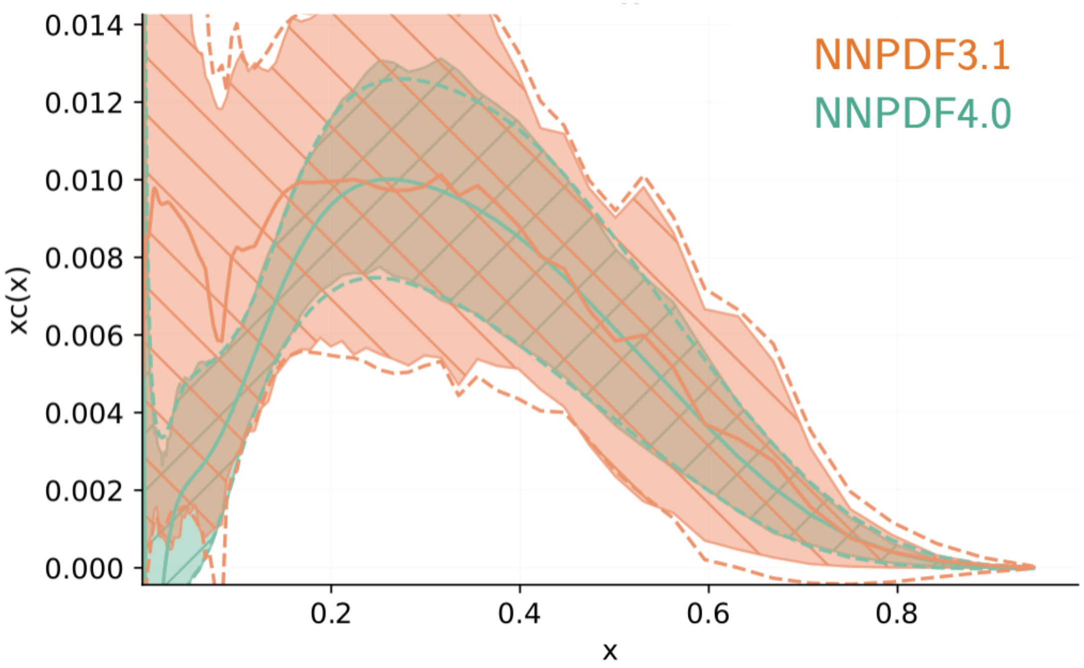
TWO POSSIBILITIES

- 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
- LARGE N^{3}LO CORRECTIONS TO MATCHING (Blümlein, Ablinger et al.)
  $\Rightarrow$ LARGE MHOU AT NNLO

DISCOVERY OF INTRINSIC CHARM

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

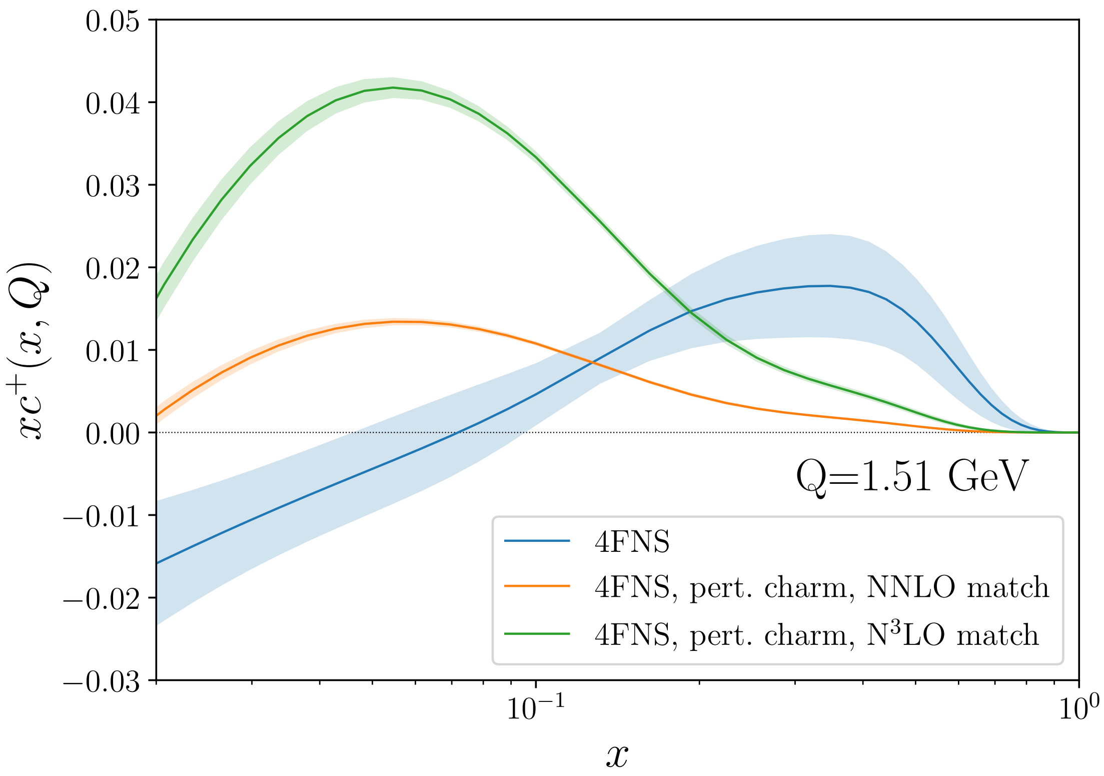
- NNPDF CHARM PDF ⇒ DETERMINED FROM THE DATA ALONG WITH ALL OTHER PDFS:
  - MORE REALISTIC UNCERTAINTIES
  - INDEPENDENT OF MATCHING CONDITIONS:
    - ∗ STABLE UPON VARIATION OF m_c
    - ∗ INSENSITIVE TO MHO CORRECTIONS
- NNPDF4.0 AND NNPDF3.1 FULL AGREEMENT
- NNPDF4.0 SIGNIFICANTLY SMALLER UNCERTAINTIES THANKS TO ML METHDOLOGY



THE CHARM PDF: FITTED VS PERTURBATIVE

- NNPDF CHARM PDF ⇒ 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
- RESULT DIFFERS SIGNIFICANTLY FROM PERTURBATIVE CHARM EVEN ACCOUNTING FOR MHOU
- INTRINSIC-LIKE, VALENCE-LIKE BUMP AT LARGE x

4FNS

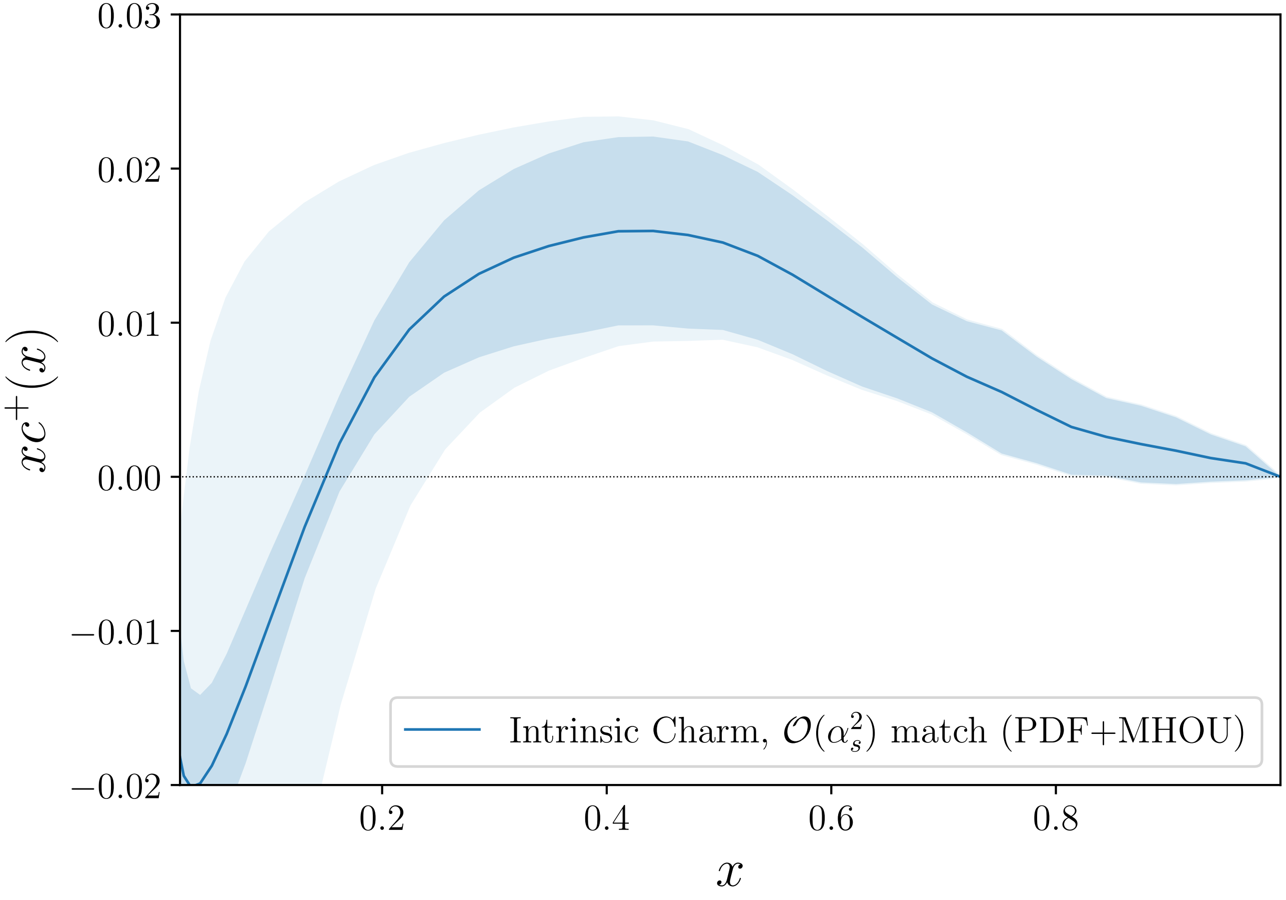


IS IT INTRINSIC CHARM?

INTRINSIC CHARM

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

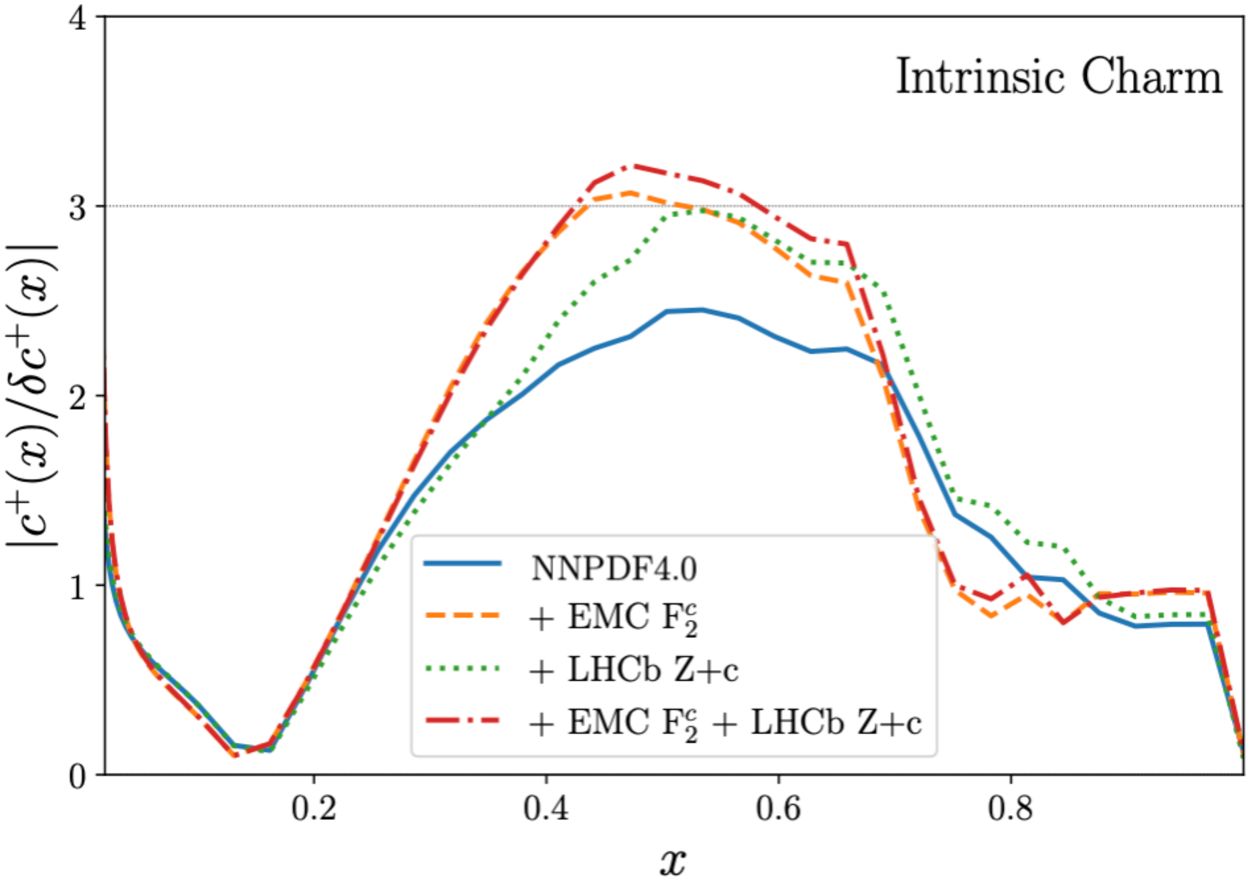
3FNS



INTRINSIC CHARM
PUBLISHED EVIDENCE

- EVIDENCE INCREASED UPON INCLUSION OF EMC (1983) F_2^c & LHCb (2021) $Z + c$
- NOT INCLUDED IN DEFAULT BECAUSE OF POSSIBLE EXPT/TH ISSUES
- PERFECT MUTUAL CONSISTENCY

3FNS



MORE THAN 3 σ EVIDENCE

VALENCE CHARM

QUESTIONS AND ANSWERS

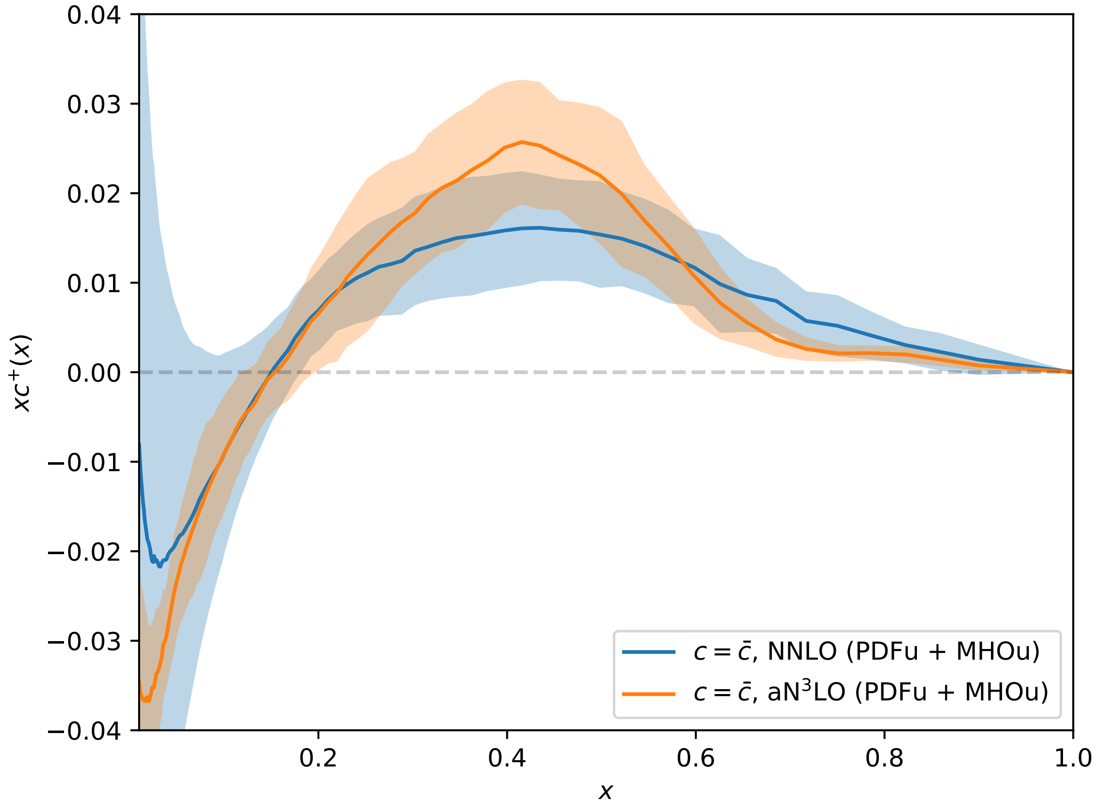
- IS THE MHOU ESTIMATE RELIABLE? APPROXIMATE $\mathrm{N^3LO}$ MATCHING?
- IS IT REALLY "VALENCE"
- IS IT A HIGHER TWIST EFFECT?

- NNPDF4.0 WITH MHOUS; NNPDF4.0 $\mathrm{N^3LO}$ IMPROVED $\mathrm{N^3LO}$ MATCHING (Blümlein, Ablinger et al., 2023)
- INDEPENDENTLY PARAMETRIZED c, $\bar{c}$
- PDFS WITH VARIED KINEMATIC CUTS

CHARM AT aN^{3}LO

- IMPROVED N^{3}LO MATCHING (Blümlein, Ablinger et al., 2023) $\Rightarrow$ SOMEWHAT REDUCED INSTABILITY
- (APPROXIMATE) N^{3}LO PDFs $\Rightarrow$ " TRUE" MHOU
- MHOU (THEORY COVMAT FROM SCALE VARIATION) INCLUDED IN N^{3}LO RESULTS

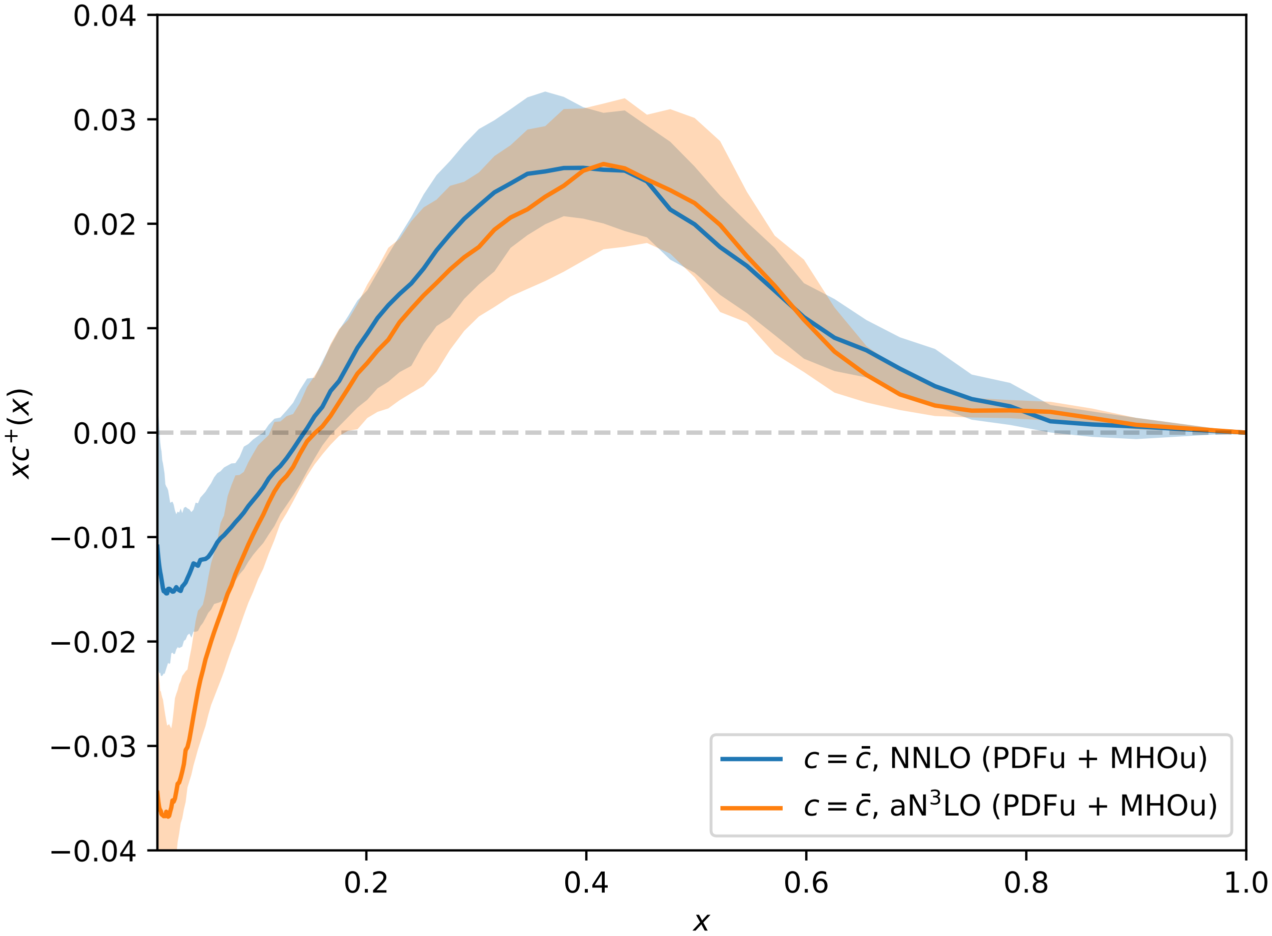
3FNS



MHOUs FROM SCALE VARIATION

- MHOU INCLUDED $\Rightarrow$ NNLO CENTRAL VALUE VERY CLOSE TO aN3LO!
- MHOU ALMOST UNCHANGED FROM NNLO TO aN3LO $\Rightarrow$ RELIABLE IN VALENCE REGION
- SIGNIFICANT UNCERTAINTY FROM INVERSE MATCHING FOR $x \lesssim 0.1$

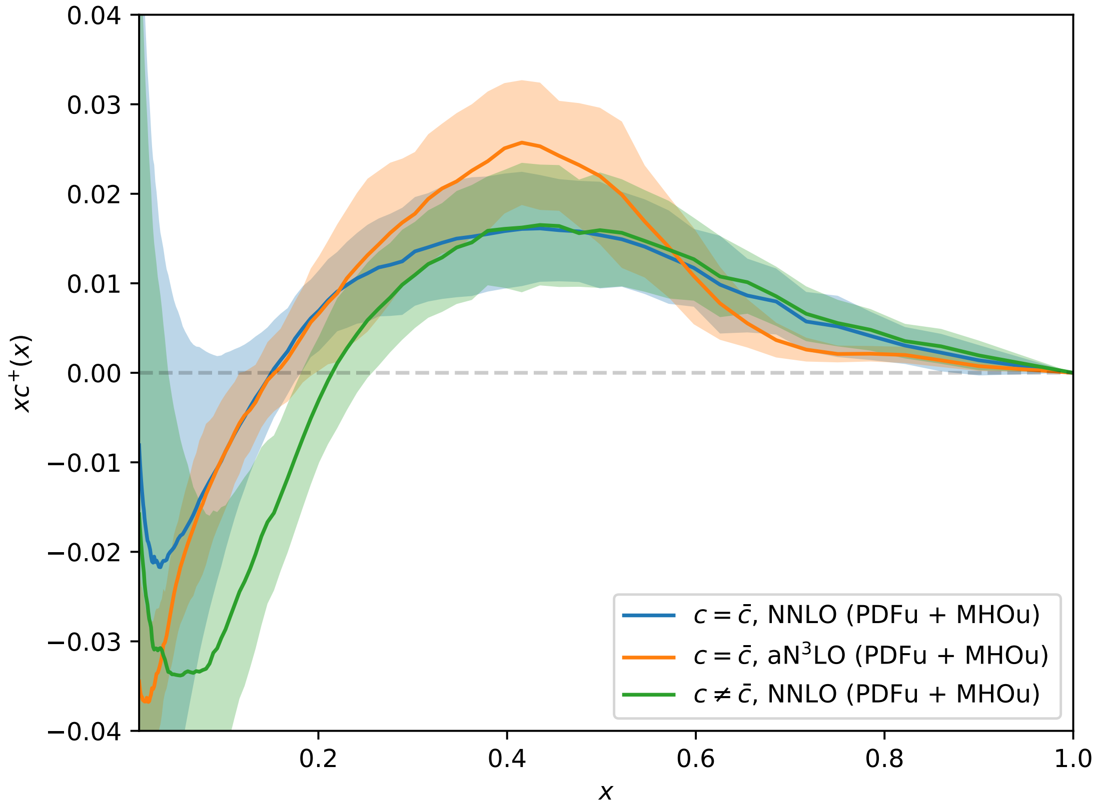
3FNS



A VALENCE CHARM PDF?

- INDEPENDENT PARAMETRIZATION FOR "SEA" $c^+ = c + \bar{c}$ AND "VALENCE" $c^- = c - \bar{c}$ PDFs
- TOTAL CHARM UNCHANGED

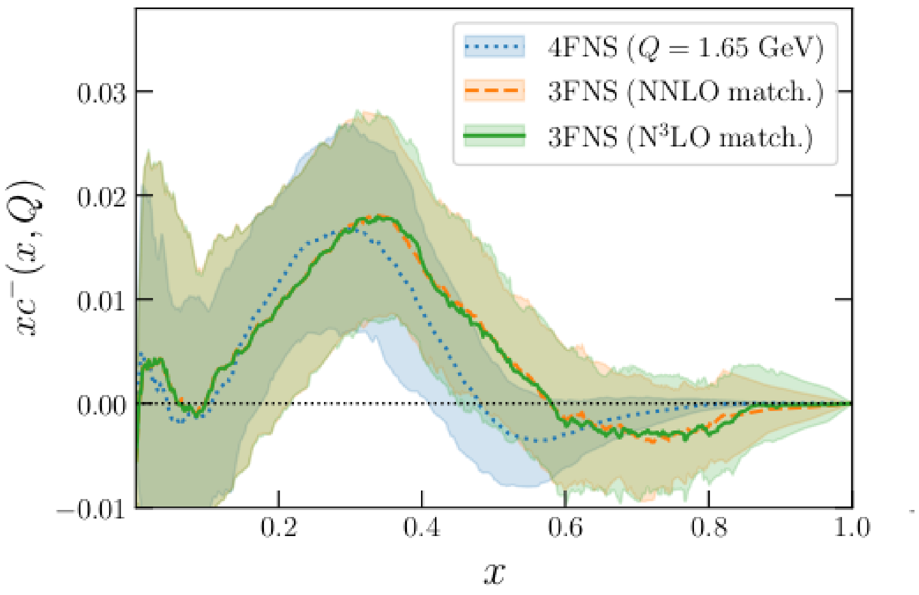
3FNS



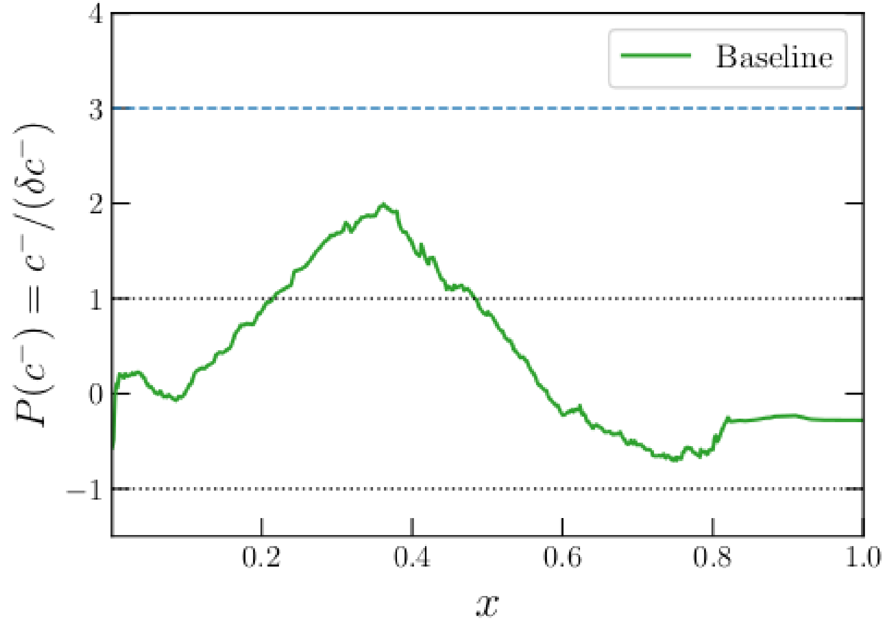
VALENCE CHARM

- $n_f = 4$ VALENCE PDF FROM PERTURBATIVE MATCHING VANISHES UP TO NNLO
- NONVANISHING VALENCE GENERATED BY PERTURBATIVE EVOLUTION AT NNLO, BY MATCHING AT N^{3}LO

$c^-(x) = c(x) - \bar{c}(x)$



PULL (3FNS)

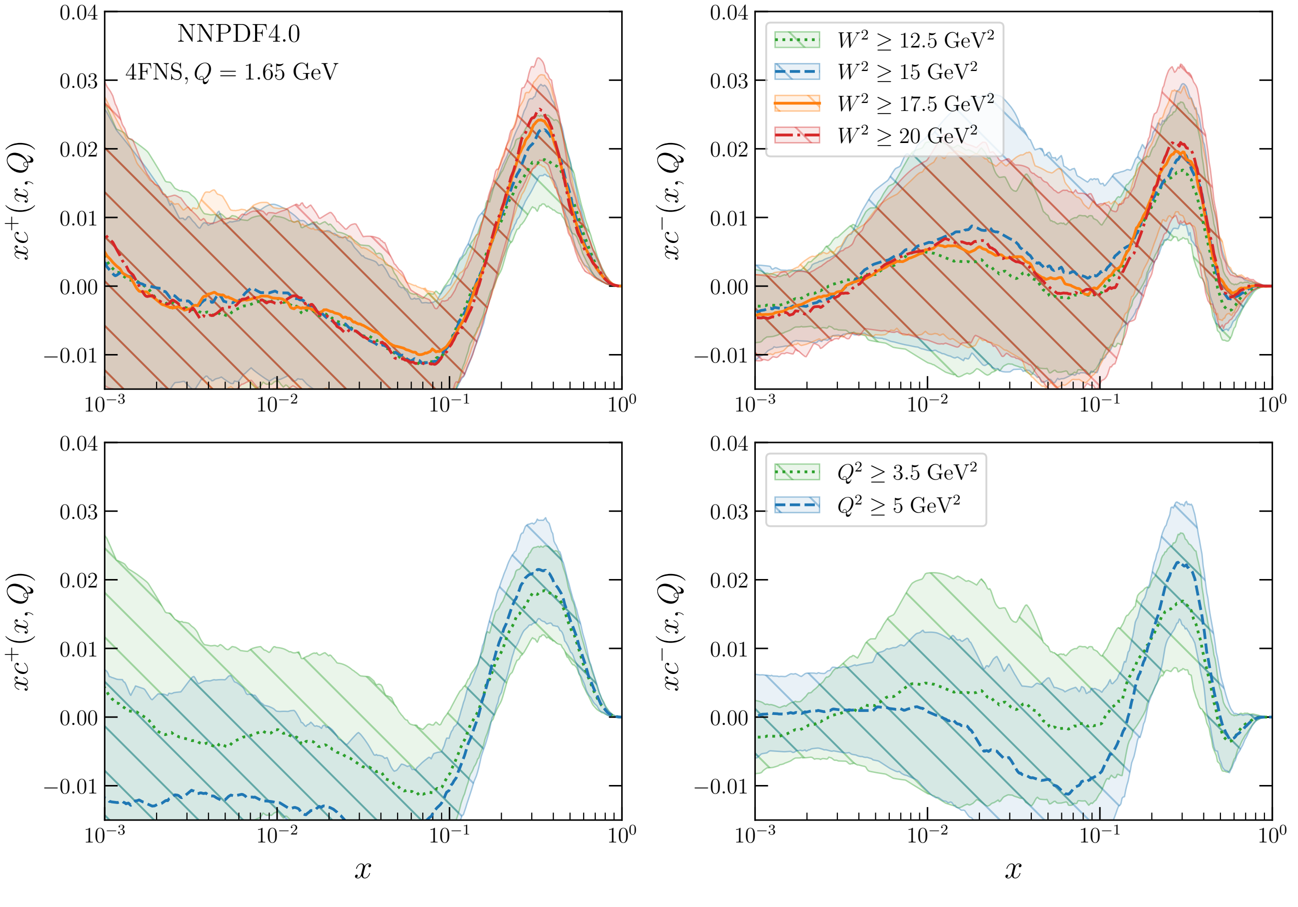


- NONVANISHING VALENCE CHARM PDF IN VALENCE REGION
- MATCHING TO $n_f = 3$ PERTURBATIVELY STABLE FOR VALENCE

HIGHER TWIST?

- BOTH SEA AND VALENCE CHARM INSENSITIVE TO RAISED CUTS IN Q^2 & W^2
- N^{3}LO & MHOU PDFs SHOWN PREVIOUSLY $\Rightarrow$ DOUBLED Q^2 CUT

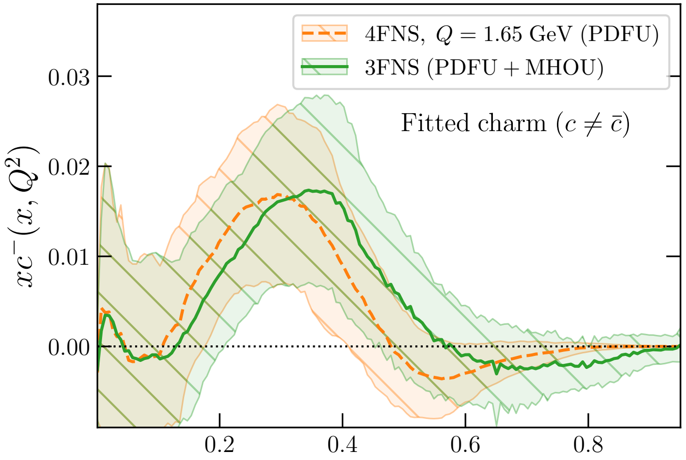
4FNS

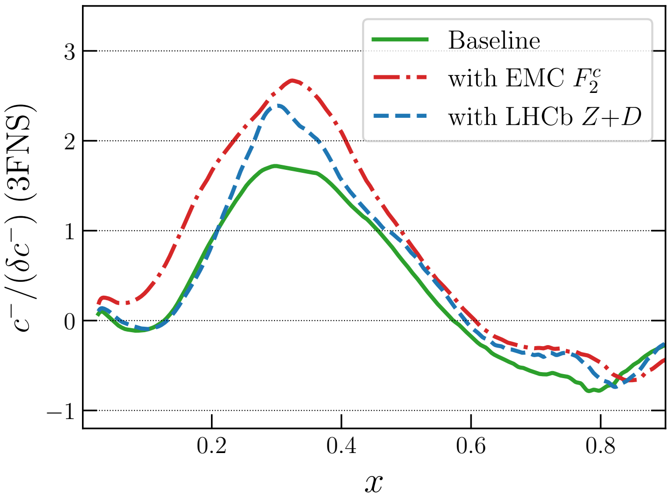


VALENCE PROTON STRUCTURE

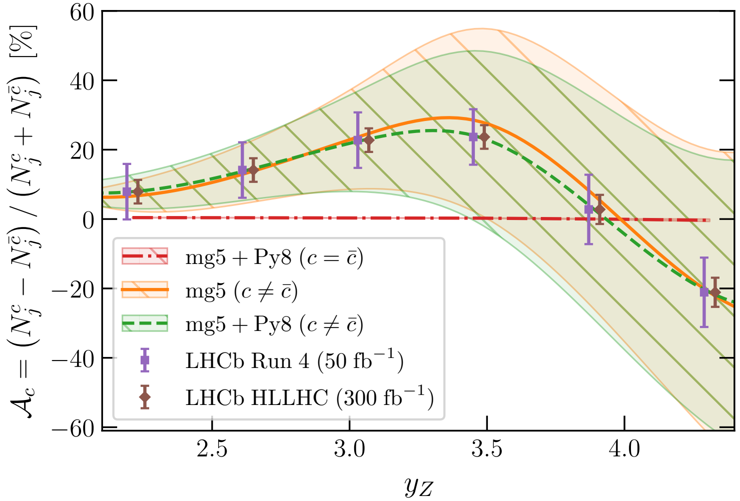
MORE DATA FOR VALENCE CHARM

THE EMC AND LHCb DATA

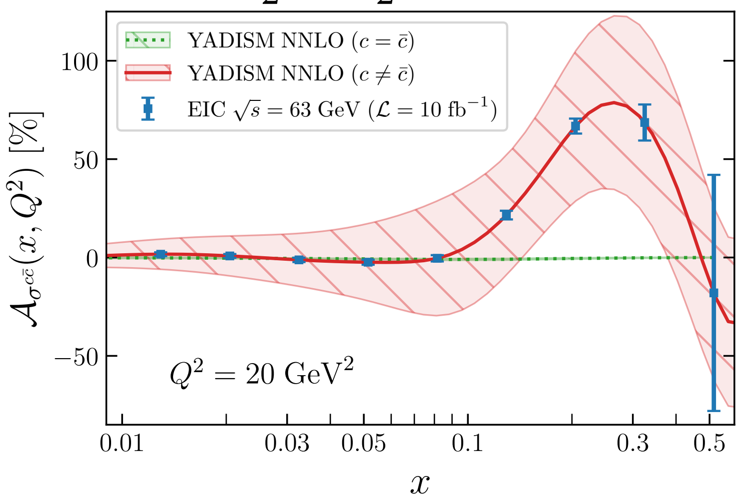




$Zc/Z\bar{c}$: LHCb HL-LHC



$F_2^c - F_2^{\bar{c}}$ EIC

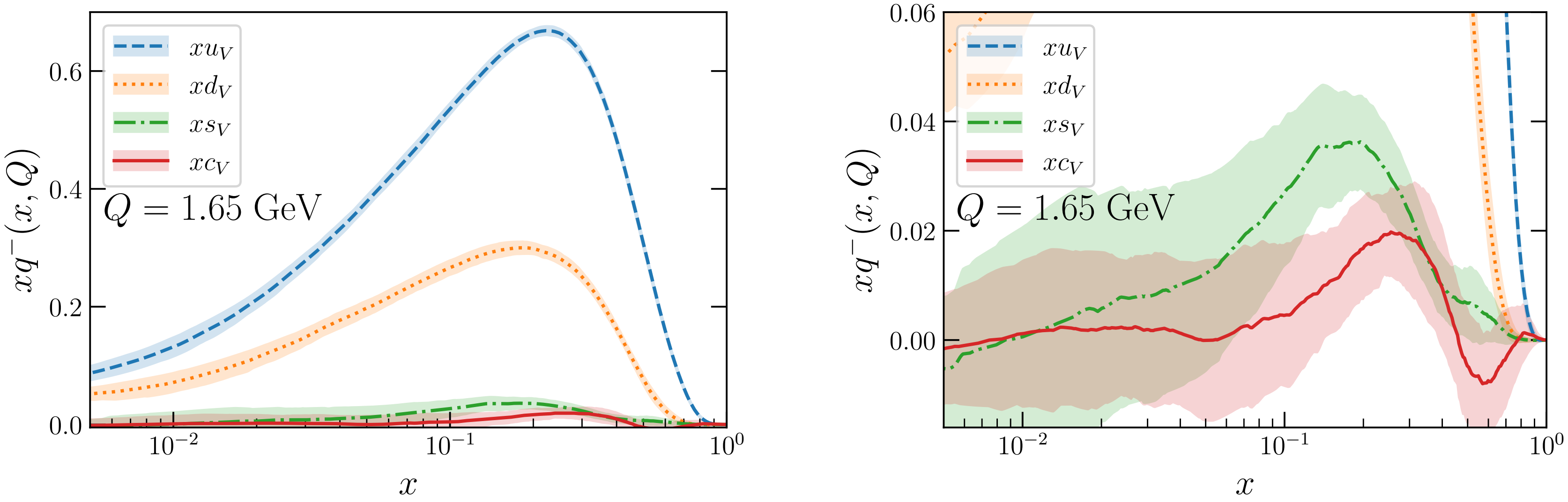


- LHCb (2021) & EMC (1983) DATA SLIGHTLY INCREASE VALENCE SIGNIFICANCE
- Zc ASYMMETRY LHCb HL-LHC & F_2^c EIC $\Rightarrow$ DISCOVERY

THE VALENCE PDFs

- SCALING OF SHAPE WITH MASS?
- WHAT ABOUT THE B QUARK?

4FNS



SUMMARY

MOTIVATION: RELIABLE PDFs

- FITTED CHARM FOR INDEPEDENCE OF m_c & MATCHING
- MHOUs FROM COVMAT FOR ACCURATE CENTRAL VALUES
- aN^{3}LO FOR RELIABLE UNCERTAINTIES
- RAISED CUTS FOR PERTURBATIVITY

RESULTS: THE VALENCE STRUCTURE

- VALENCELIKE PEAK FOR TOTAL CHARM AT 3σ
- 1-2 σ VALENCE CHARM PDF IN VALENCE REGION
- INTRINSIC CHARM SEA COMPATIBLE WITH ZERO WITHIN LARGE UNCERTAINTIES FOR LARGE $x \lesssim 0.1$

TO DO

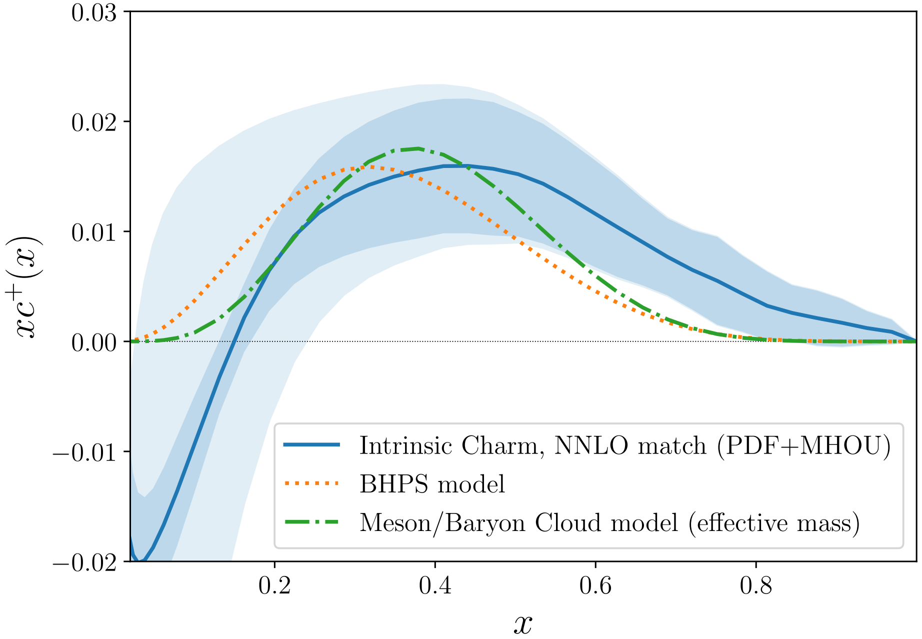
- BETTER CHARMED JET DEFINITIONS $\Rightarrow$ NNLO
- MORE DATA $\Rightarrow$ FIVE σ EVIDENCE
- $c - \bar{c}$ ASYMMETRY PHENOMENOLOGY

EXTRAS

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

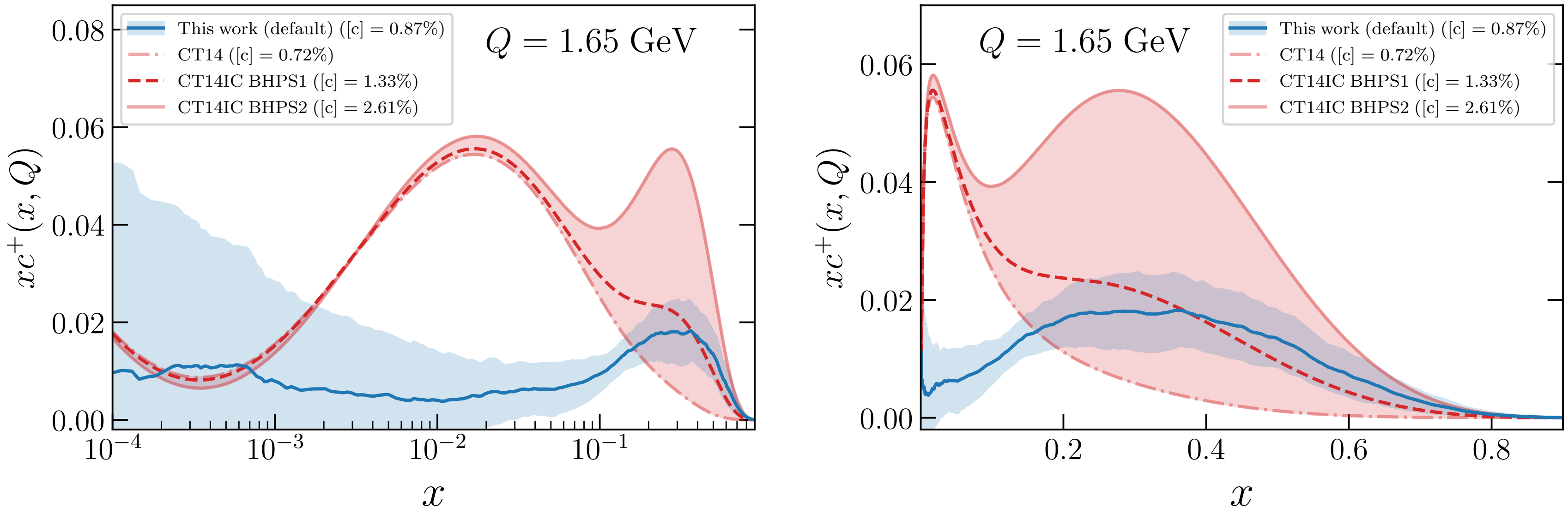


QUALITATIVE AGREEMENT

MODEL FITS

- CT FITTED BPHS NORMALIZATION USING S-ACOT (PROBLEMATIC)
- LOW $Q_0 = 1.3$ GEV
- BEST FIT $\langle c \rangle \sim 1\%$ (CT14) OR $\langle c \rangle \sim 0.5\%$ (CT18)

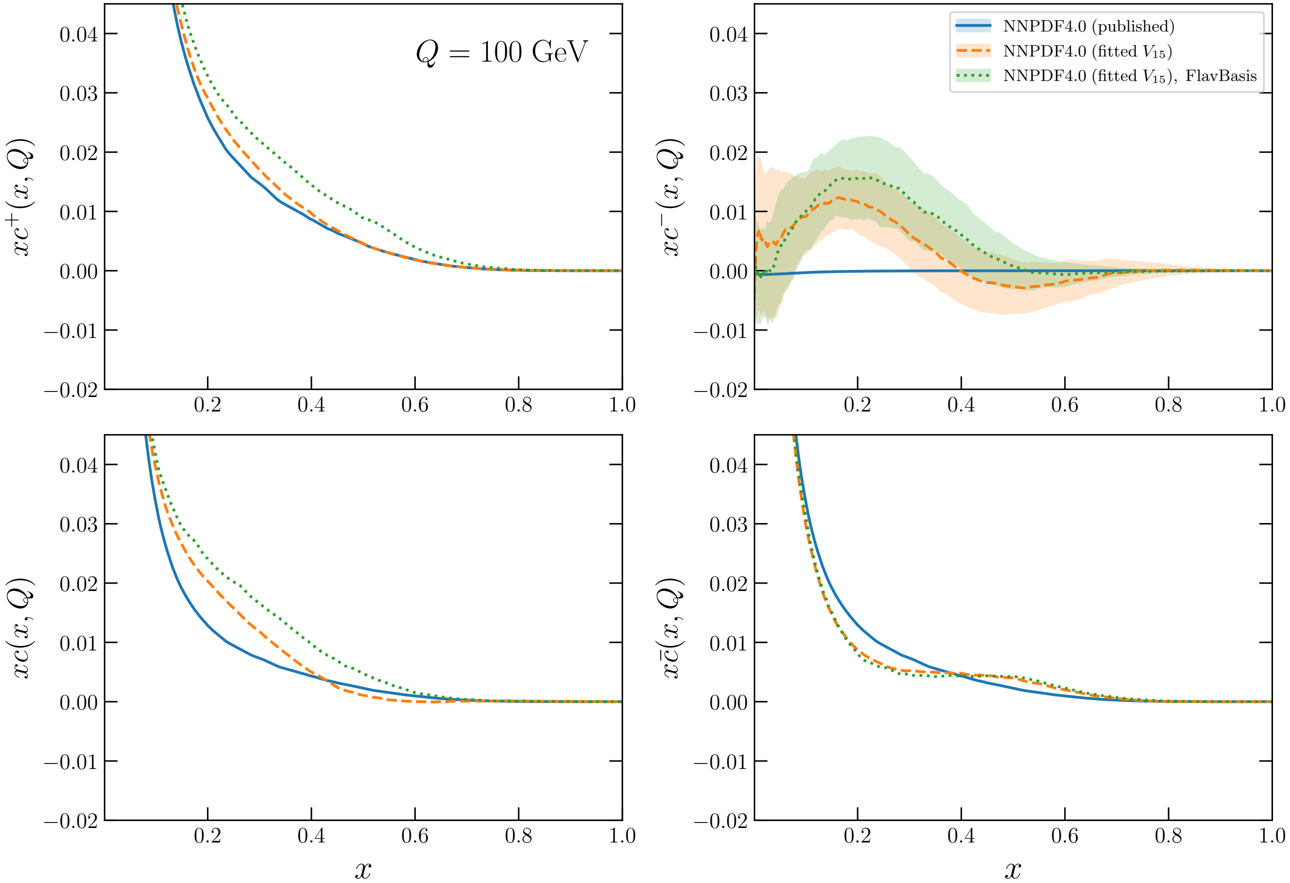
NNPDF4.0 INTRINSIC CHARM VS. CT14 FIT



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

STABILITY:

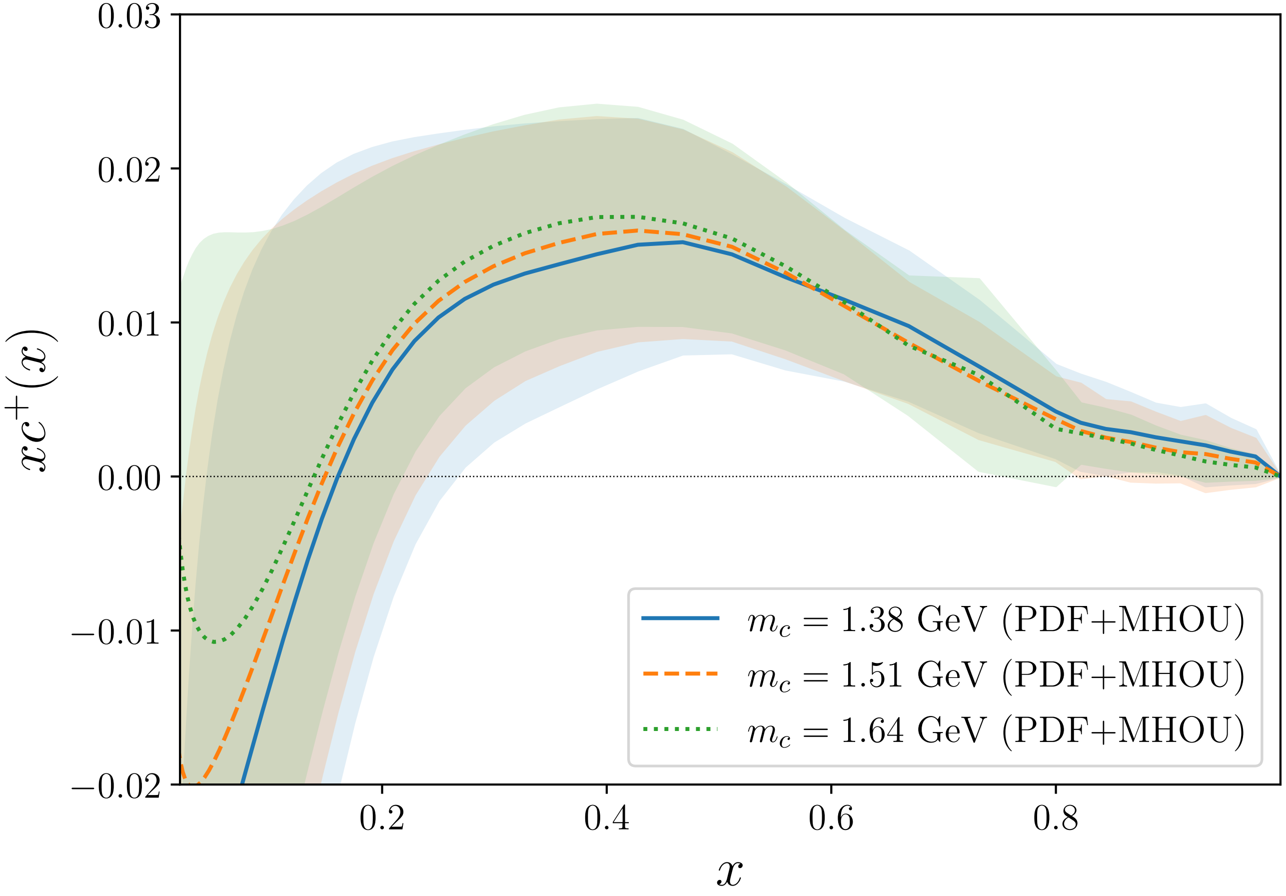
PDF BASIS



- NEGLIGIBLE DEPENDENCE ON THE CHOICE OF BASIS

STABILITY:

CHARM MASS

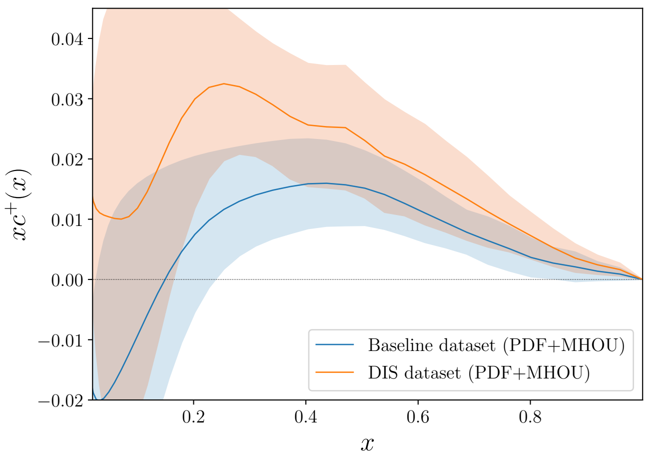


- NEGLIGIBLE DEPENDENCE ON m_c (UNLIKE PERTURBATIVE CHARM)

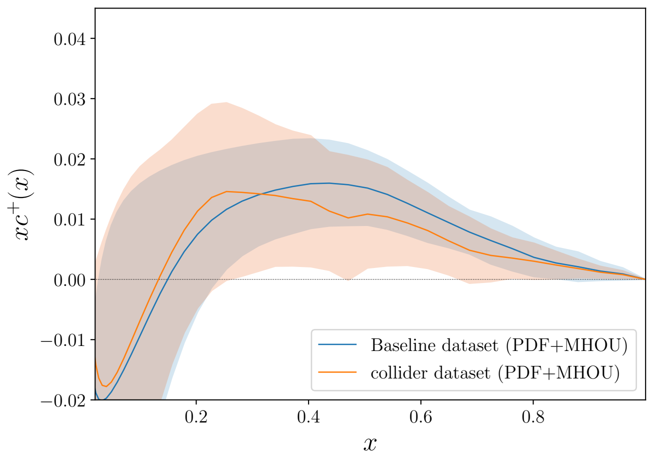
WHICH DATA DRIVE THE ANSWER?:

DATA SUBSETS $n_F = 3$

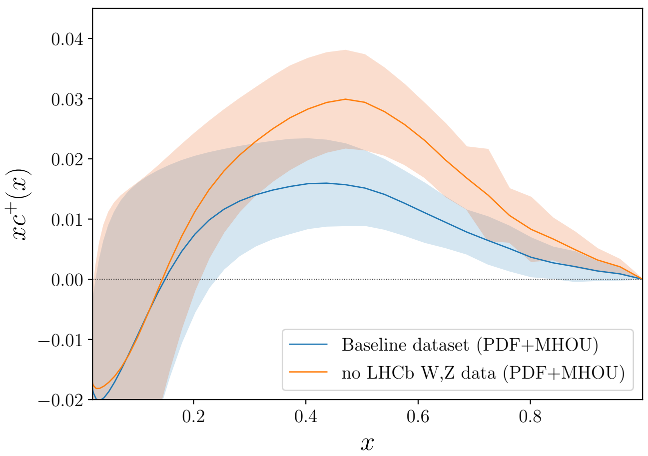
DIS ONLY



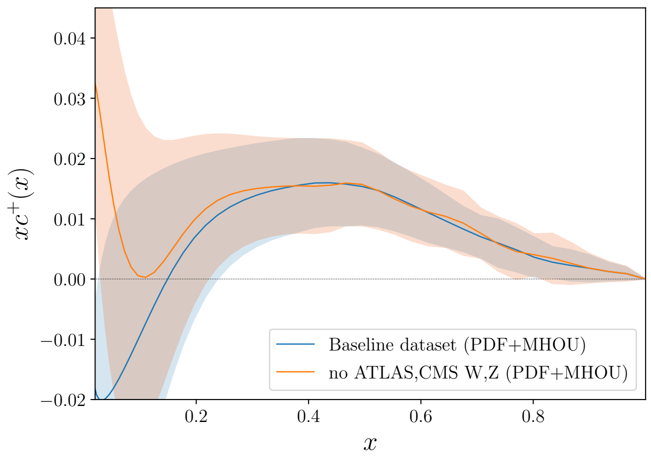
COLLIDER ONLY



NO LHCB



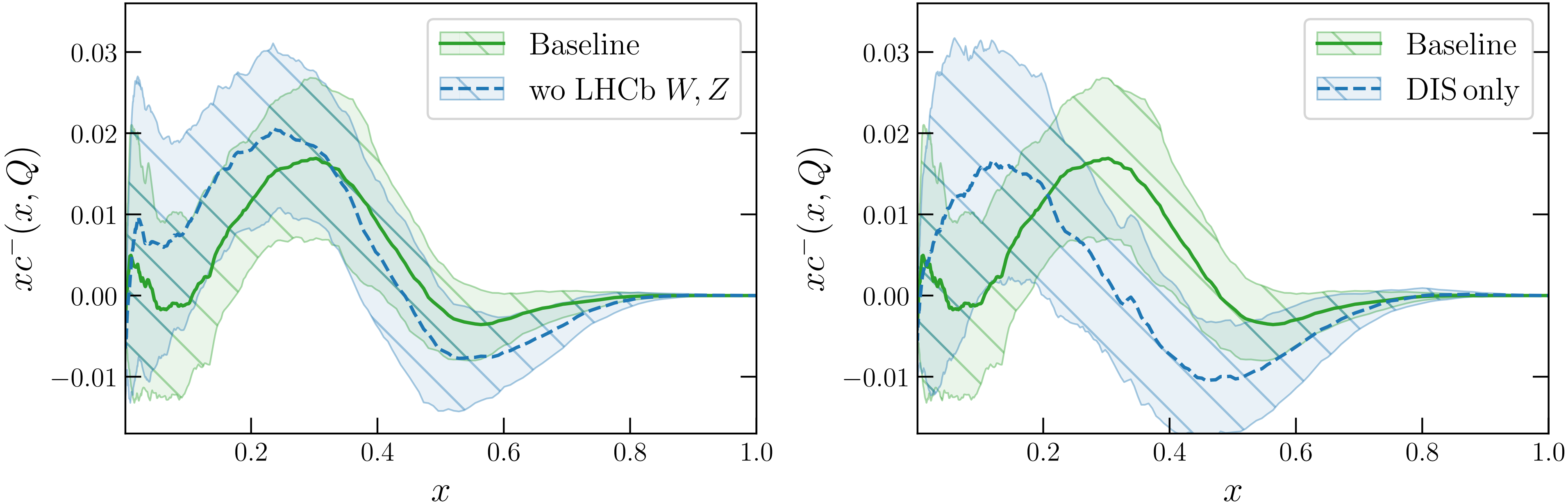
NO ATLAS/CMS DY



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

WHICH DATA DRIVE THE ANSWER?:

VALENCE PDF

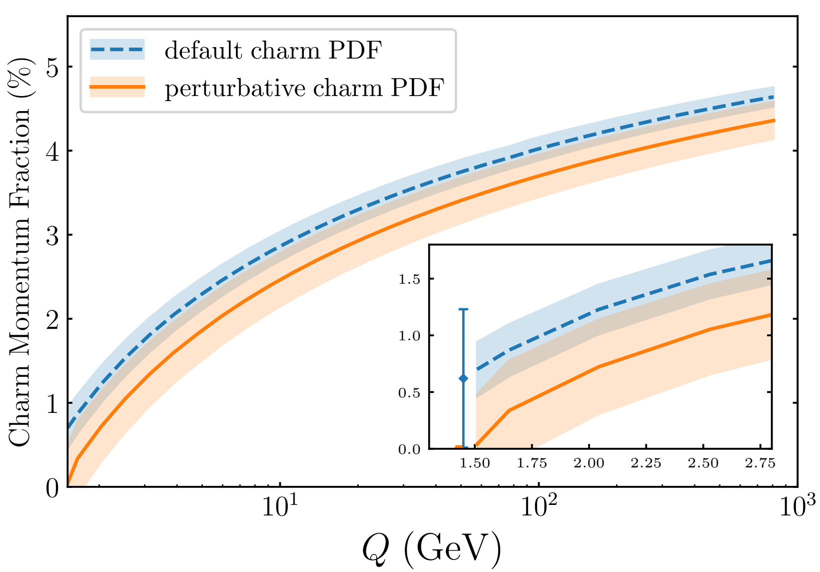


- LHCb W, Z NO IMPACT
- DIS AND COLLIDER EQUALLY IMPORTANT FOR PRECISION

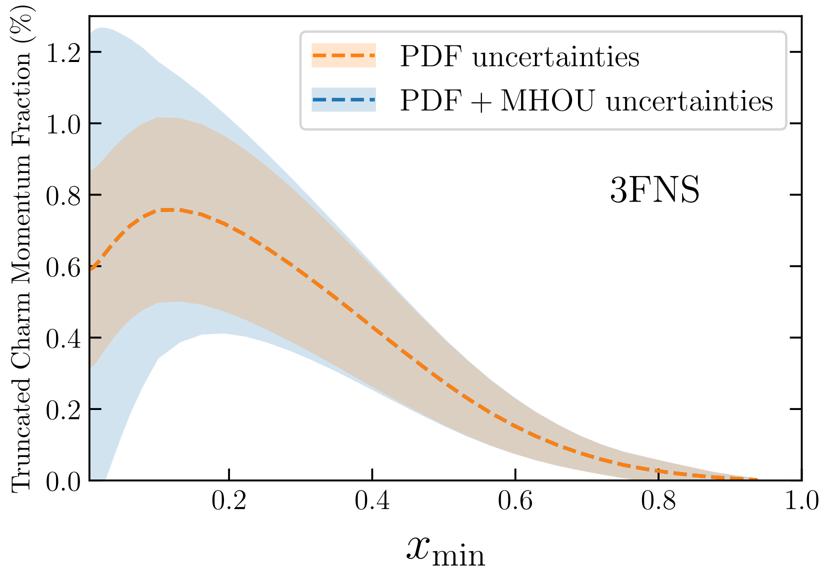
THE CHARM MOMENTUM FRACTION

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

$n_f = 4$: FITTED VS. PERTURBATIVE



$n_f = 3$: MOMENTUM INTEGRAL

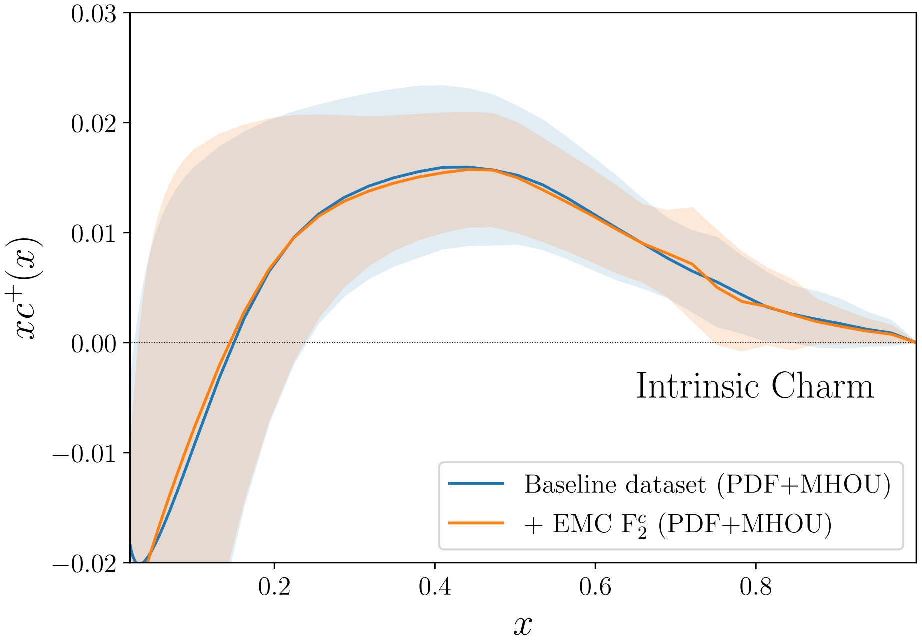


- $n_f = 4$ MOMENTUM FRACTION DETERMINED TO GOOD ACCURACY
- LARGE MHOU AT SMALL $x \Rightarrow$ TOTAL INTRINSIC MOMENTUM FRACTION COMPATIBLE WITH ZERO

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

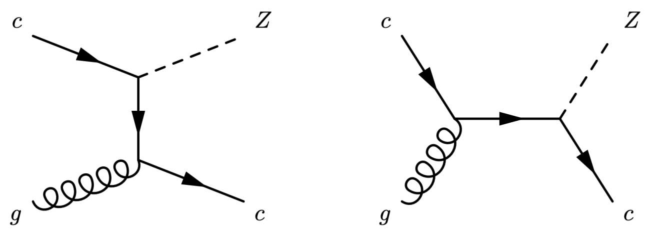
INTRINSIC CHARM WITH EMC DATA INCLUDED



COMPLETE CONSISTENCY!

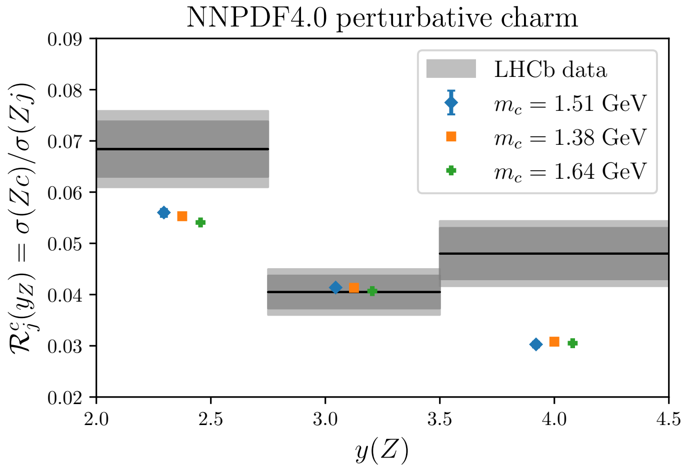
MORE DATA
LHCb 2021

MEASUREMENT OF Z+CHARM PRODUCTION

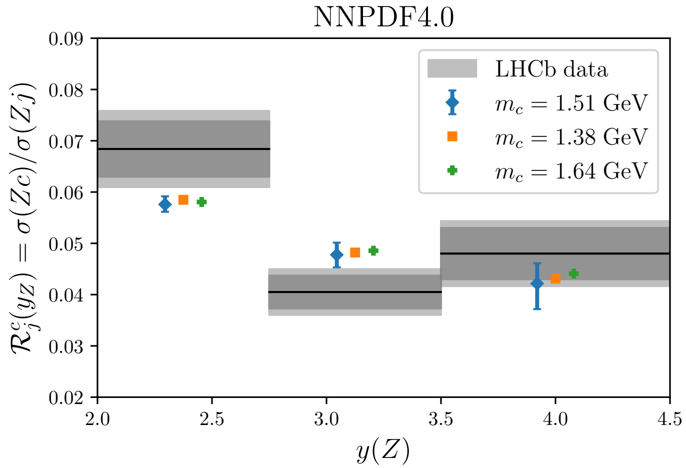


DATA VS THEORY PREDICTION

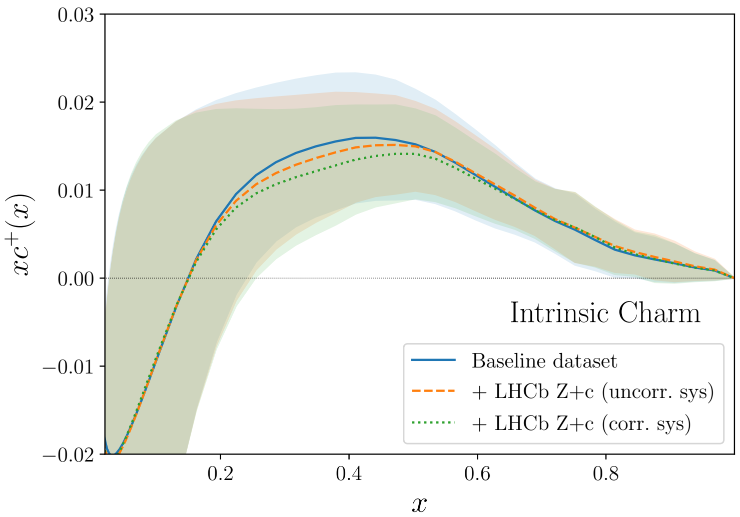
NO INTRINSIC CHARM



NNPDF4.0 INTRINSIC CHARM



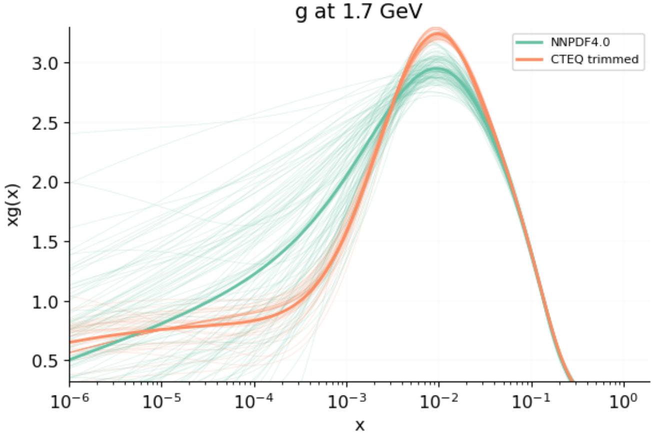
INTRINSIC CHARM WITH LHCb DATA INCLUDED: COMPLETE CONSISTENCY



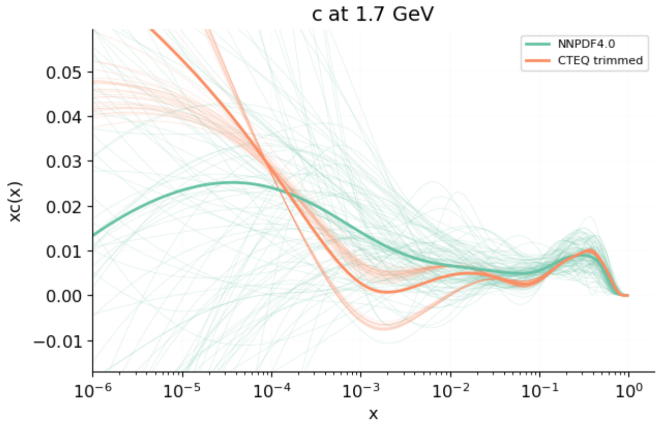
“HOPSCOTCH” OVERLEARNT PDFs

PDFs

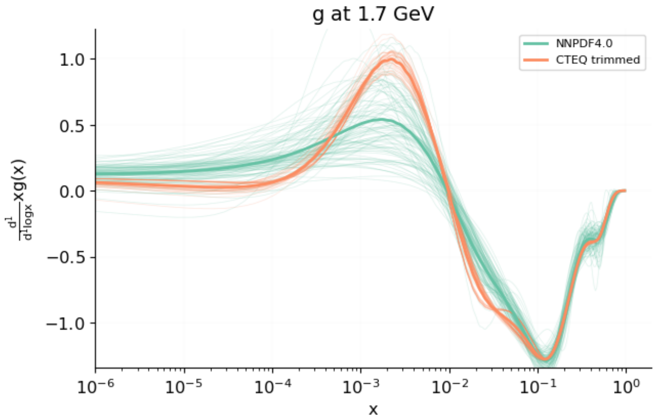
gluon

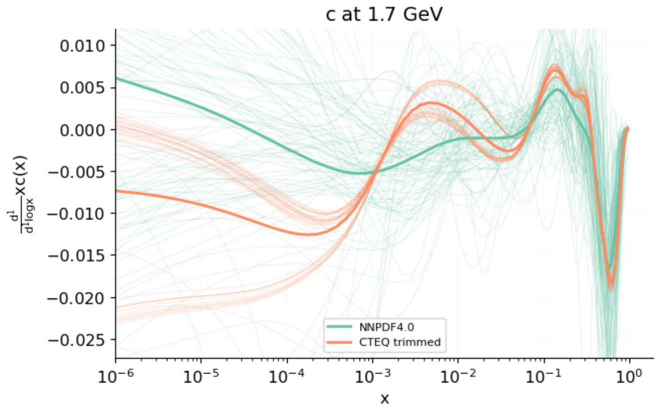


charm



KINETIC ENERGY (DIFFERENTIAL ARCLENGTH)

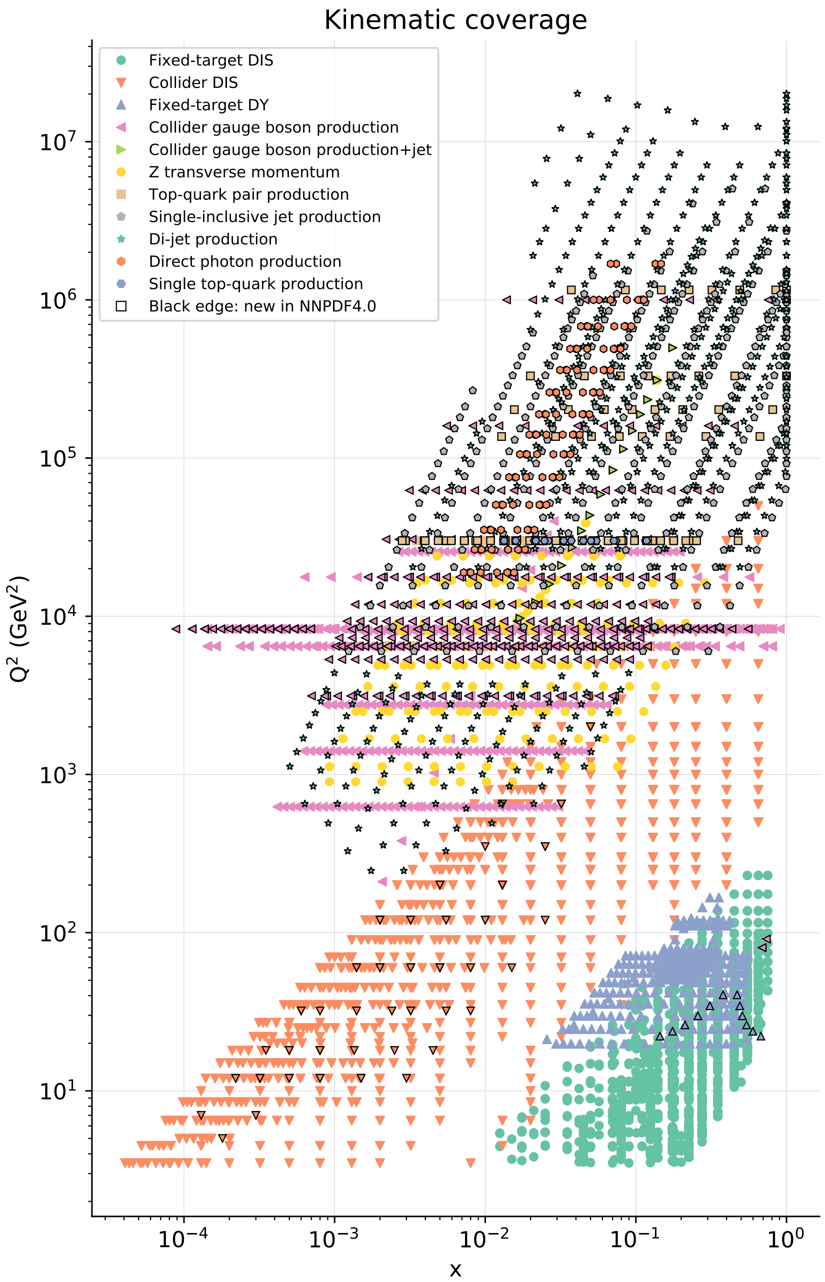




- HS OVERLEARNT BY CONSTRUCTION
- CAN BE REPRODUCED IN NNPDF4.0 BY FORCING OVERLEARNING

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 $Z \to ee$ 2 fb	✓	✓	✓	✓	✓
LHCb $W, Z \to \mu$ 7 TeV	✓	✓	✓	✓	✓
LHCb $W, Z \to \mu$ 8 TeV	✓	✓	✓	✓	✓
LHCb $Z \to \mu\mu, ee$ 13 TeV	✓	✗	✗	✗	✗

ATLAS

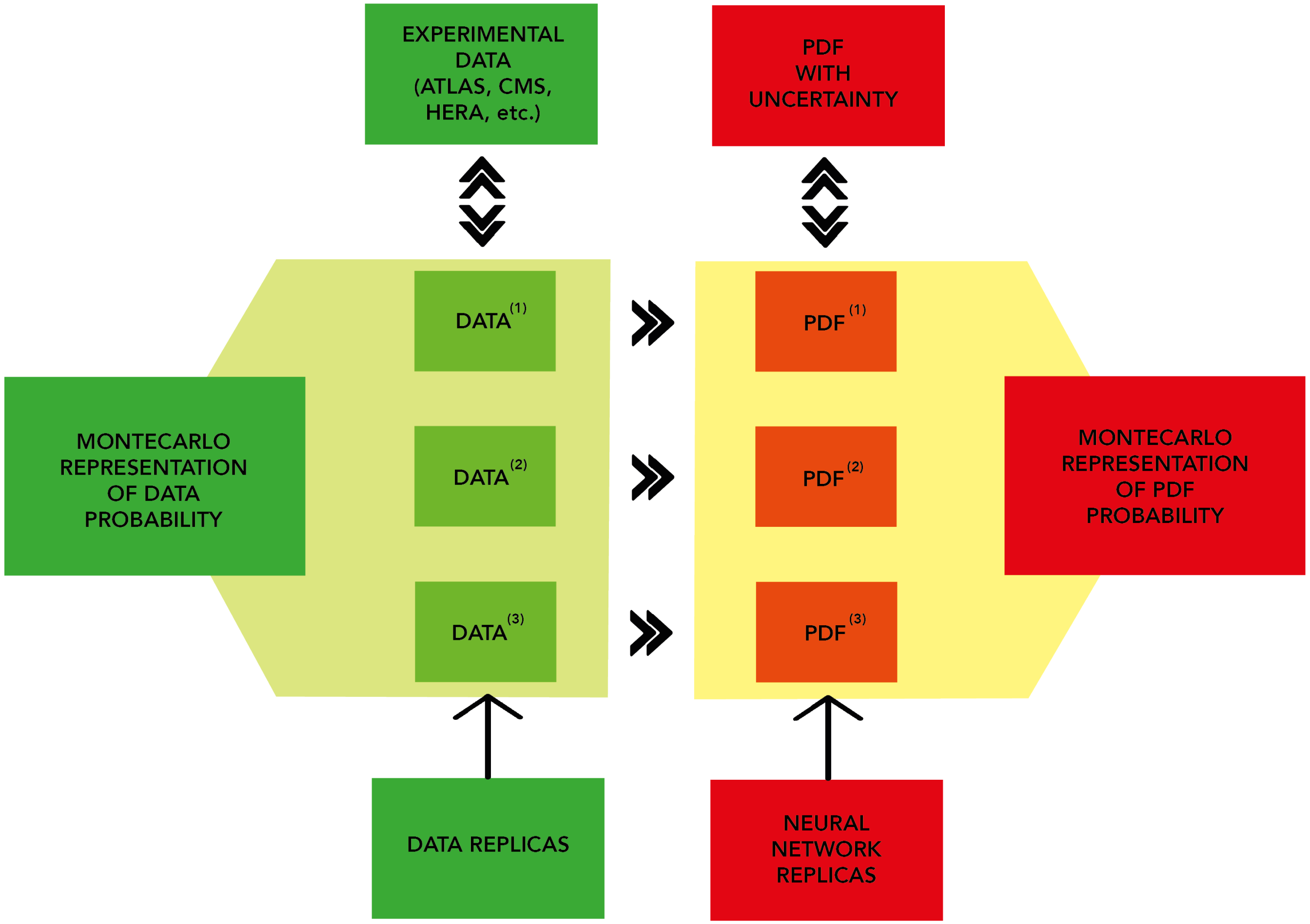
Data set	NNPDF4.0	NNPDF3.1	ABMP16	CT18	MSHT20
ATLAS W, Z 7 TeV (2010)	✓	✓	✓	✓	✓
ATLAS W, Z 7 TeV (2011)	✓	✓	✗	✓	✓
ATLAS low-mass DY 7 TeV	✓	✓	✗	✗	✗
ATLAS high-mass DY 7 TeV	✓	✓	✗	✗	✓
ATLAS W 8 TeV	✓	✗	✗	✗	✓
ATLAS DY 2D 8 TeV	✓	✗	✗	✗	✓
ATLAS high-mass DY 2D 8 TeV	✓	✗	✗	✗	✓
ATLAS $\sigma_{W,Z}$ 13 TeV	✓	✗	✓	✗	✗
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+jet 13 TeV	✓	✗	✗	✗	✗
CMS $t\bar{t}$ dilepton 13 TeV	✓	✗	✗	✗	✗
CMS single top $\sigma_t + \sigma_{\bar{t}}$ 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 LIKELIHHOD SHAPE (FUNCTIONAL FORM) NOT NECESSARY



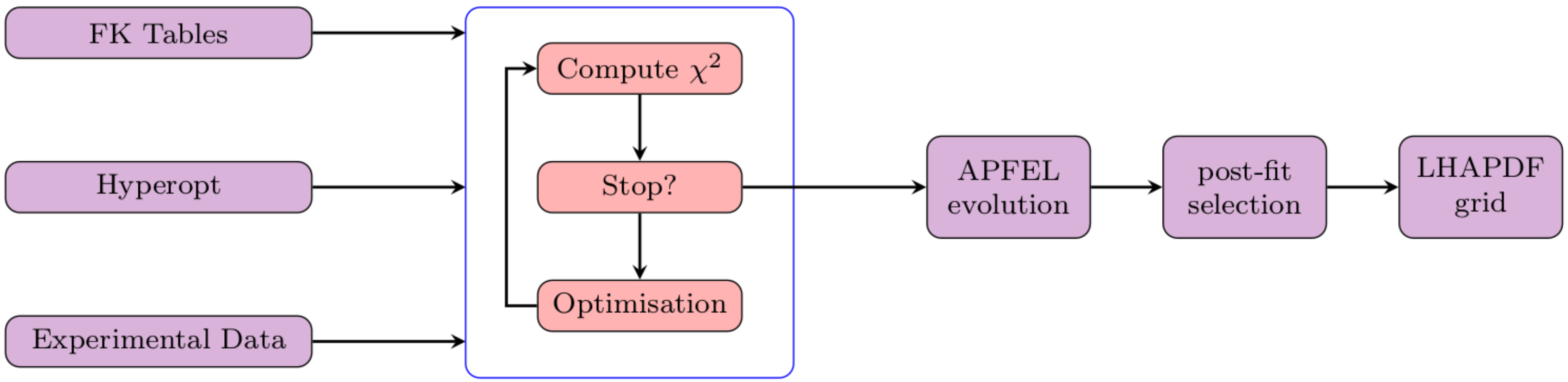
FINAL PDF SET: $f_i^{(a)}(x,\mu)$;
i =up, antiup, down, antidown, strange, antistrange, charm, gluon; $j = 1, 2, \ldots N_{\rm rep}$

THE NNPDF CODE STRUCTURE

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

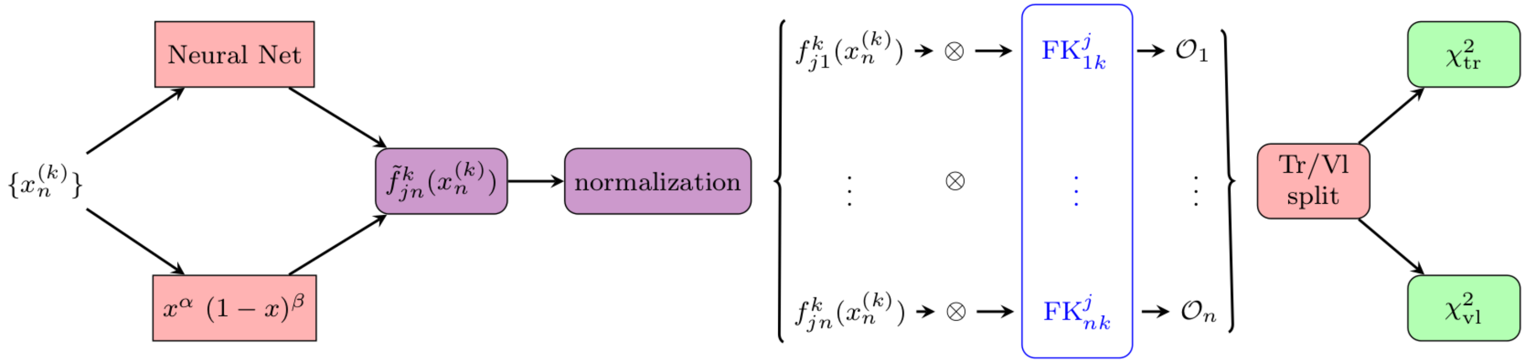
AVERAGE FITTING TIME PER REPLICA AND USE OF RESOURCES
SAME DATASET FOR OLD AND NEW METHODOLOGIES IN CPU AND GPU
CPU: INTEL(R) CORE(TM) I7-4770 AT 3.40GHZ; GPU: NVIDIA TITAN V

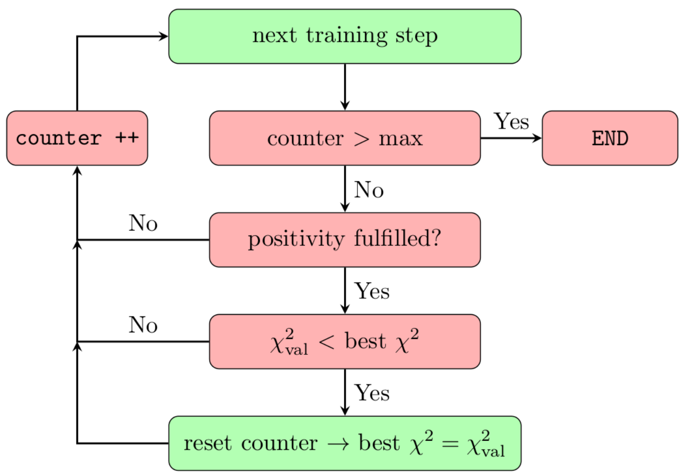
	NNPDF31 CODEBASE	NNPDF40 CODEBASE IN CPU	NNPDF40 CODEBASE IN GPU
TIME	15.2 H.	38 ± 5 MIN.	6.6 MIN.
RAM USE	1.5 GB	6.1 GB	NA



MINIMIZATION AND CROSS-VALIDATION

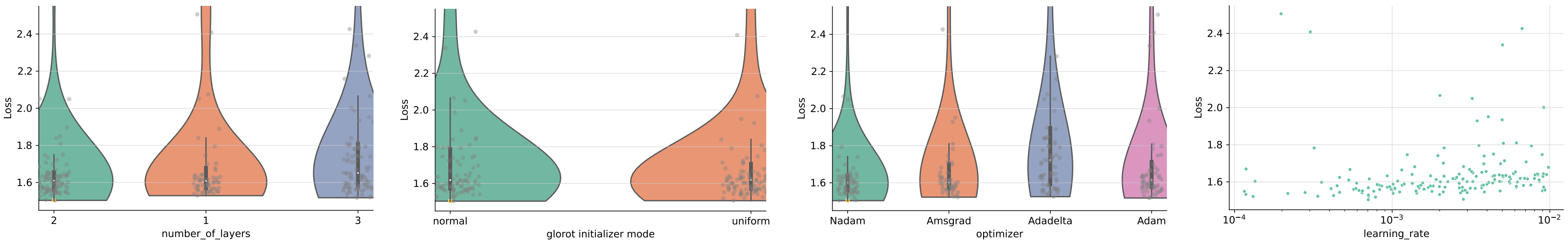
- DATA REPLICAS ⇒ PDF REPLICAS
- EACH PDF REPLICA: PREPROCESSED NEURAL NET
- NEURAL NET ⇒ OBSERVABLES
- RANDOM TRAINING-VALIDATION SPLIT, χ^2 TO TRAINING DATA REPLICAS MINIMIZED
- TRAINING STOPS IF VALIDATION χ^2 GROWS FOR A WHILE (PATIENCE)
- LOWEST VALIDATION χ^2 ⇒ OPTIMAL FIT



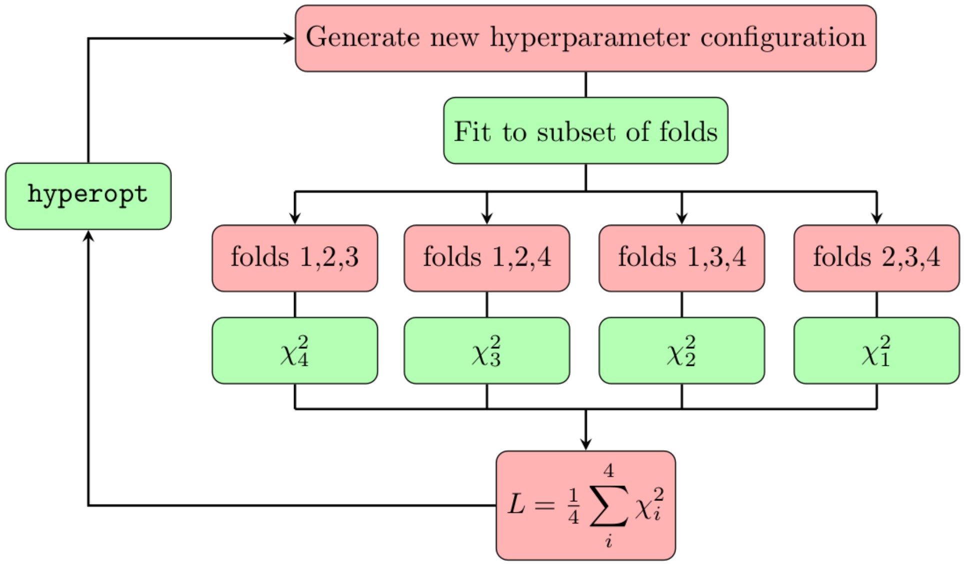


HYPEROPTIMIZATION

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



K-FOLDING



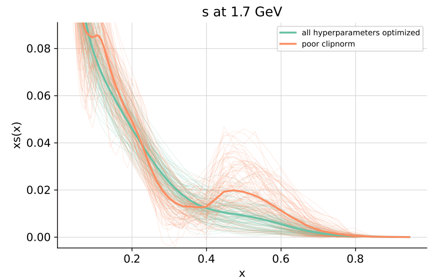
Fold 1		
CHORUS σ^{ν}_{CC}	HERA I+II inc NC e^+p 920 GeV	BCDMS p
LHCb Z 940 pb	ATLAS W, Z 7 TeV 2010	CMS Z p_T 8 TeV (p_T^{ll}, y_{ll})
DY E605 $\sigma^p_{\rm DY}$	CMS Drell-Yan 2D 7 TeV 2011	CMS 3D dijets 8 TeV
ATLAS single-$\bar{t}$ y (normalised)	ATLAS single top R_t 7 TeV	CMS $t\bar{t}$ rapidity $y_{t\bar{t}}$
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. $\sigma^{\rm red}_{b\bar{b}}$
NMC p	NuTeV $\sigma^{\bar{\nu}}_c$	LHCb $Z \to ee$ 2 fb
CMS W asymmetry 840 pb	ATLAS Z p_T 8 TeV (p_T^{ll}, M_{ll})	D0 $W \to \mu\nu$ asymmetry
DY E886 $\sigma^p_{\rm DY}$	ATLAS direct photon 13 TeV	ATLAS dijets 7 TeV, R=0.6
ATLAS single antitop y (normalised)	CMS $\sigma^{\rm tot}_{tt}$	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^{ν}_c	LHCb $W, Z \to \mu$ 7 TeV	LHCb $Z \to ee$
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 $\sigma^d_{\rm DY}/\sigma^p_{\rm DY}$	CDF Z rapidity (new)
ATLAS $\sigma^{\rm tot}_{tt}$	ATLAS single top y_t (normalised)	CMS $\sigma^{\rm tot}_{tt}$ 5 TeV
CMS $t\bar{t}$ double diff. ($m_{t\bar{t}}, y_t$)		

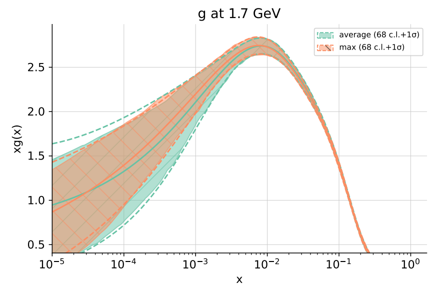
Fold 4		
CHORUS $\sigma^{\bar{\nu}}_{CC}$	HERA I+II inc NC e^+p 820 GeV	LHCb $W, Z \to \mu$ 8 TeV
LHCb $Z \to \mu\mu$	ATLAS W, Z 7 TeV 2011 Fwd	ATLAS W^-+jet 8 TeV
ATLAS low-mass DY 2011	ATLAS Z p_T 8 TeV (p_T^{ll}, y_{ll})	CMS W rapidity 8 TeV
D0 Z rapidity	CMS dijets 7 TeV	ATLAS single top y_t (normalised)
ATLAS single top R_t 13 TeV	CMS single top R_t 13 TeV	

NO K-FOLDING



- 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

K-FOLDING VARIATION

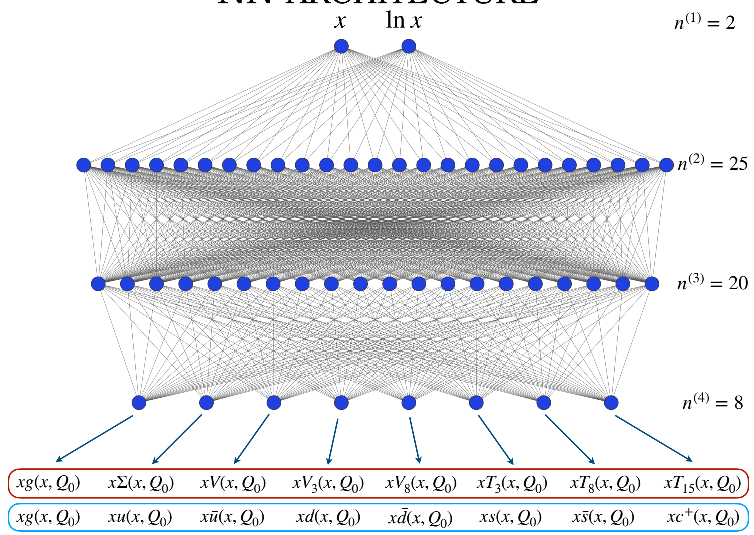


THE ML METHODOLOGY

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 $\Lambda^{(\mathrm{pos})}$	185	106	2
Initial integrability $\Lambda^{(\mathrm{int})}$	10	10	10

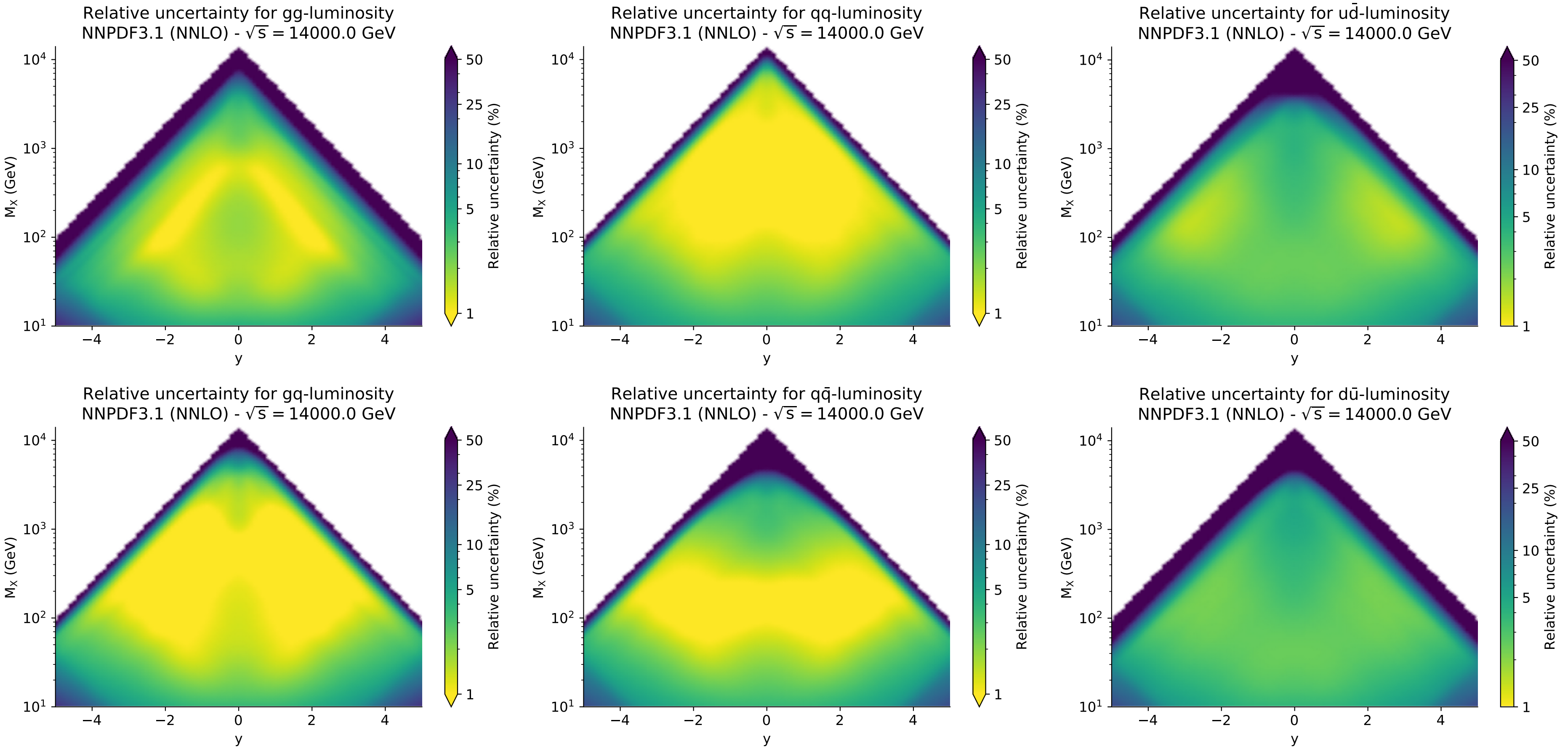
NN ARCHITECTURE



- 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...

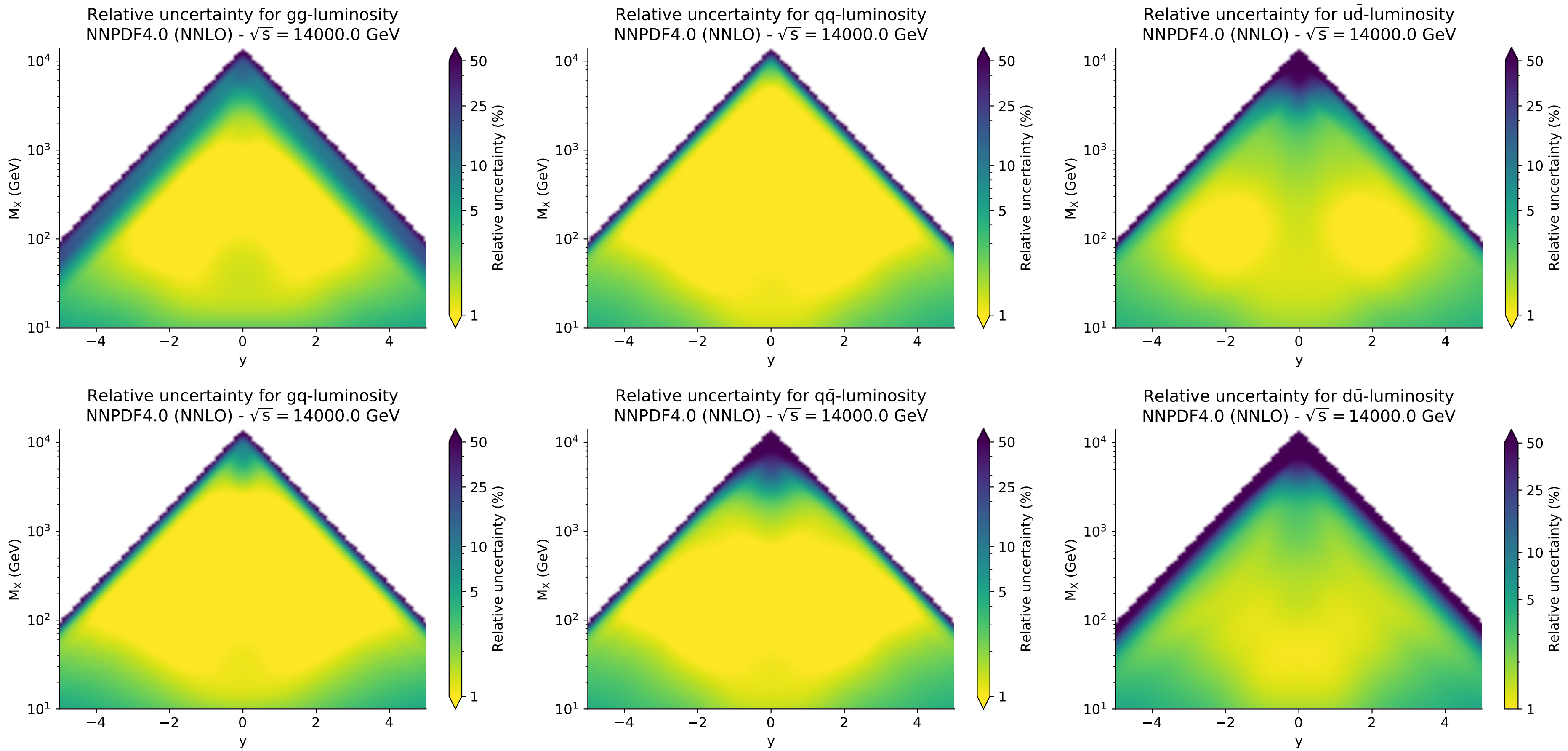
GLUON SINGLET FLAVORS



- 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, $-4 \lesssim y \lesssim 4$