LHCb constraints on the proton structure and neutrino astronomy

Juan Rojo
VU Amsterdam & Theory group, Nikhef

LHCb Implications Workshop 2018

CERN, 17/10/2018

Outline

- LHCb constraints on quark flavour separation

- LHCb constraints on small-x gluon

- Implications for neutrino astronomy

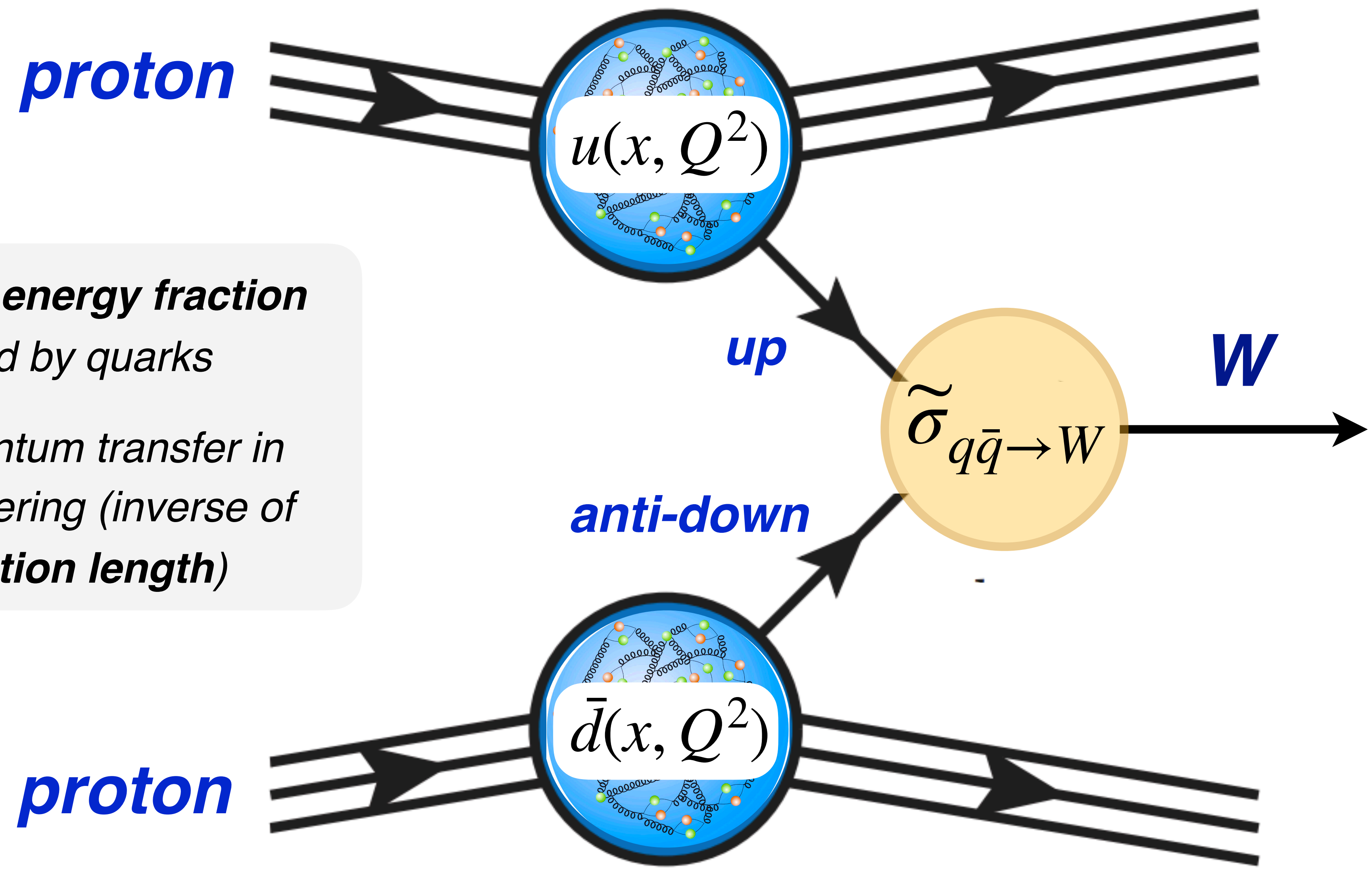
Impact on light quark flavour separation

Parton distributions @ LHC

QCD Factorisation theorem:

Event rates = **parton distributions** + hard-scattering partonic cross-sections

$$N_{\mathrm{LHC}}(W) \sim q \otimes \bar{q} \otimes \widetilde{\sigma}_{q\bar{q}\to W} + \mathcal{O}(\alpha_s)$$



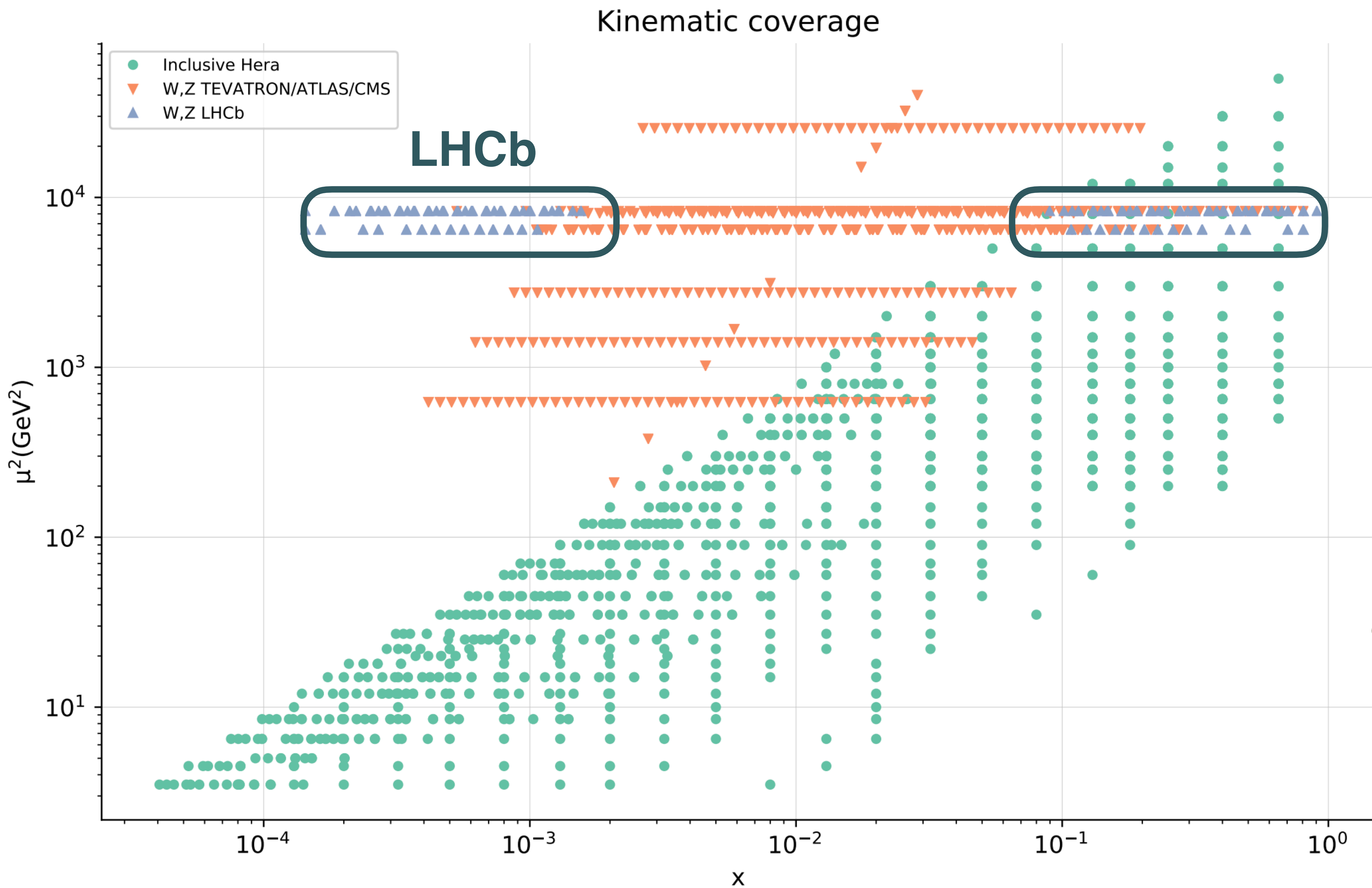
x: *proton's* ***energy fraction*** *carried by quarks*

Q: *momentum transfer in hard scattering (inverse of* ***resolution length****)*

W and Z production at LHCb

Forward coverage of LHCb: unique sensitivity to

small-*x* and large-*x* regions beyond that of ATLAS and CMS

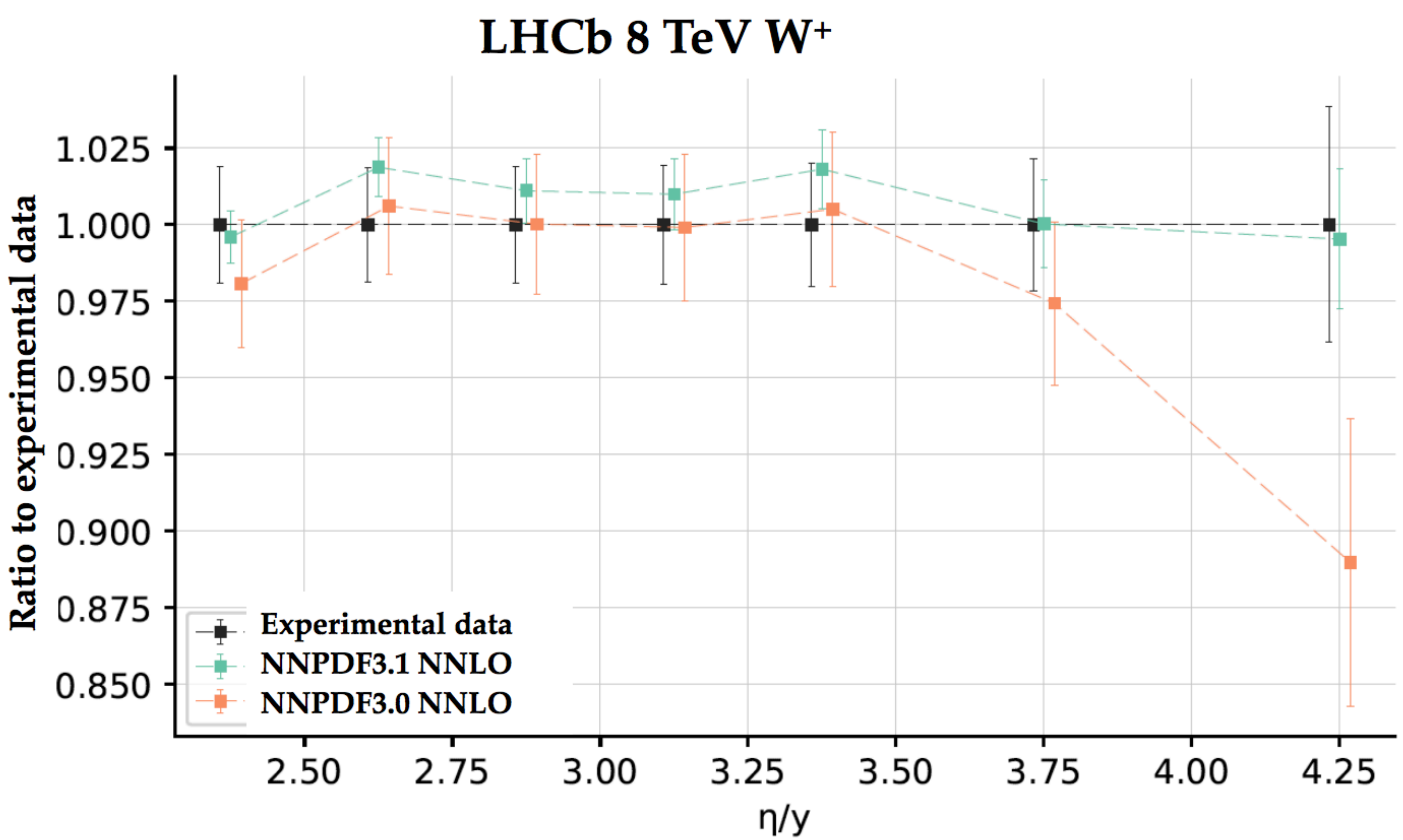


JR 17

LHCb data in NNPDF3.1

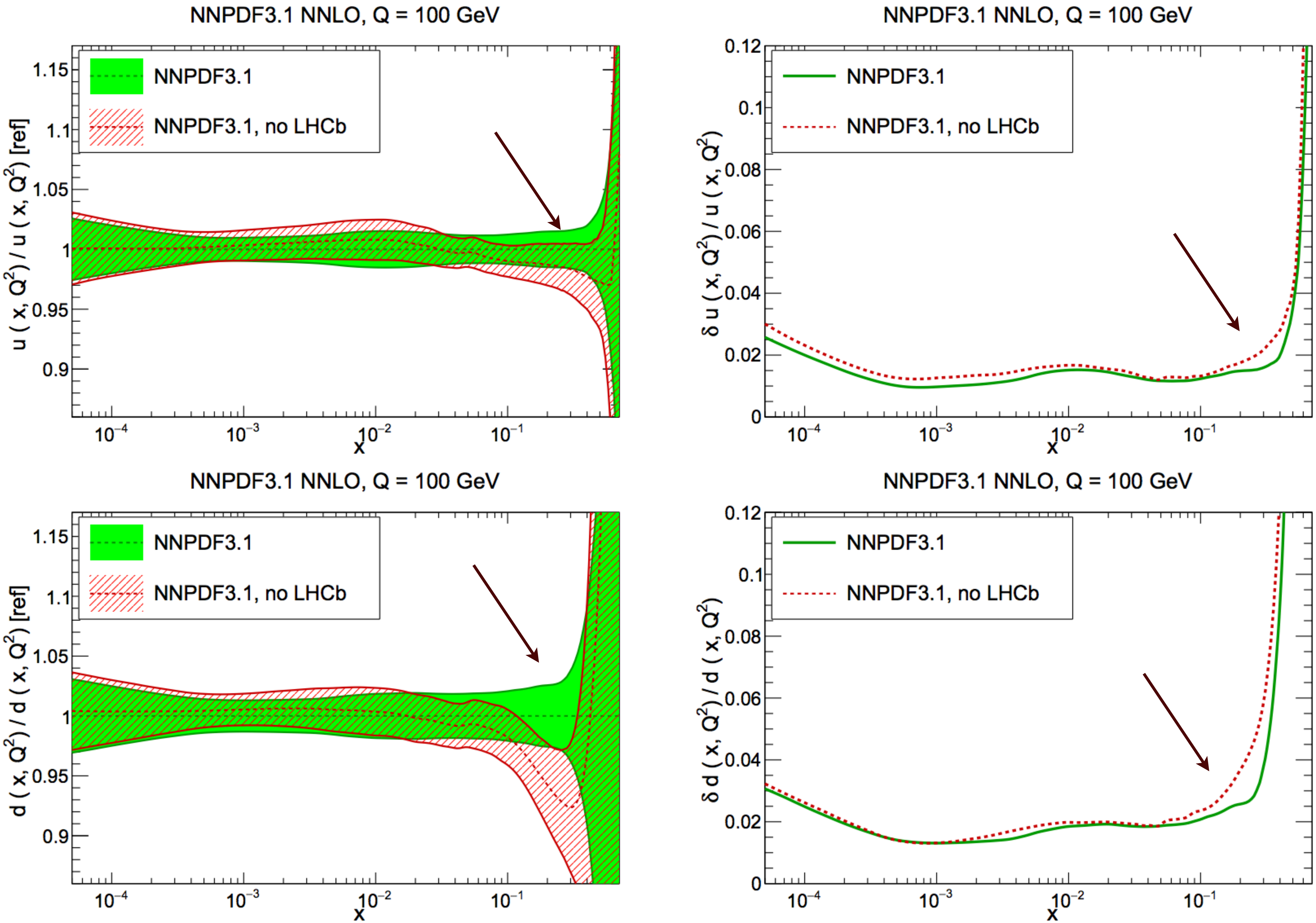
LHCb	Z rapidity 940 pb	[55]	9 (9/9)	$2.0 \leq \eta_l \leq 4.5$	$Q = M_Z$	MCFM+FEWZ
	$Z \to ee$ rapidity 2 fb	[56]	17 (17/17)	$2.0 \leq \eta_l \leq 4.5$	$Q = M_Z$	MCFM+FEWZ
	$W, Z \to \mu$ 7 TeV (*)	[85]	33 (33/29)	$2.0 \leq \eta_l \leq 4.5$	$Q = M_W, M_Z$	MCFM+FEWZ
	$W, Z \to \mu$ 8 TeV (*)	[86]	34 (34/30)	$2.0 \leq \eta_l \leq 4.5$	$Q = M_W, M_Z$	MCFM+FEWZ

*Specially important to **disentangle quark flavour** at **large-x***



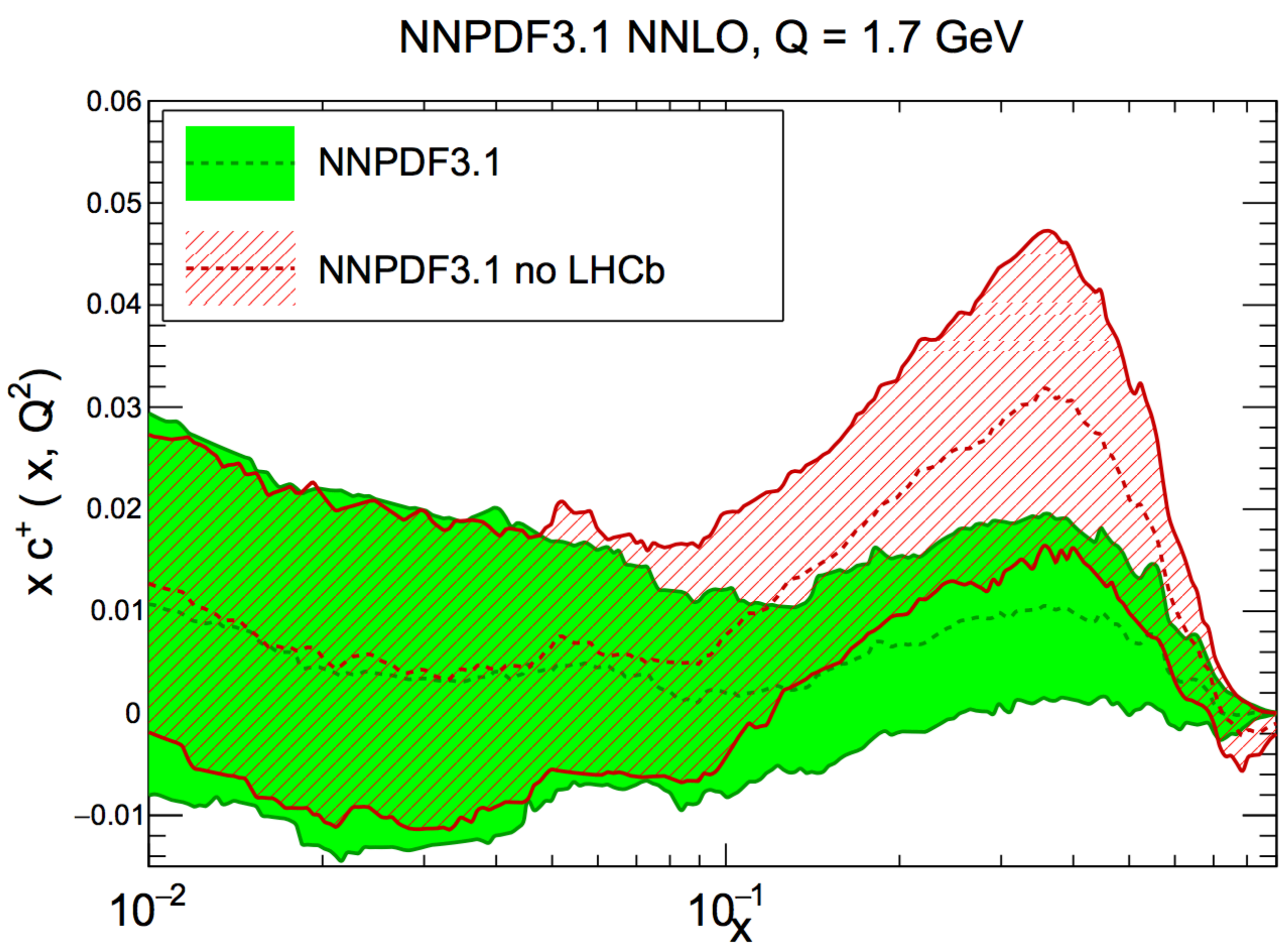
NNPDF 17

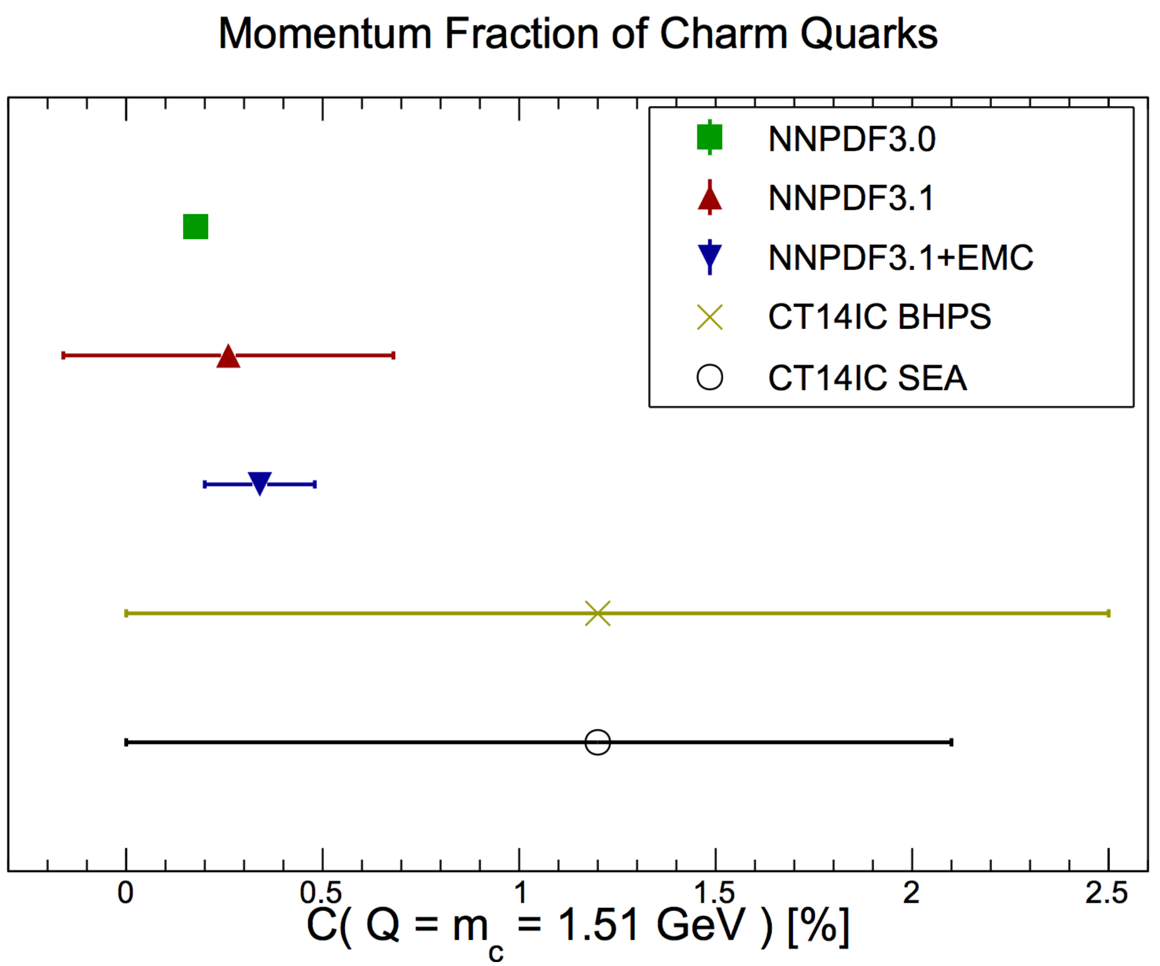
Impact on light quark sea



Impact on the charm PDF

***NNPDF3.1**: independent parametrisation for **charm PDF**, constrained from data*





- LHCb electroweak data provide important info on **charm content of protons**
- **'Intrinsic' charm** bounded to < 0.7% of proton momentum from LHC data
- Still ample **room for improvement!**

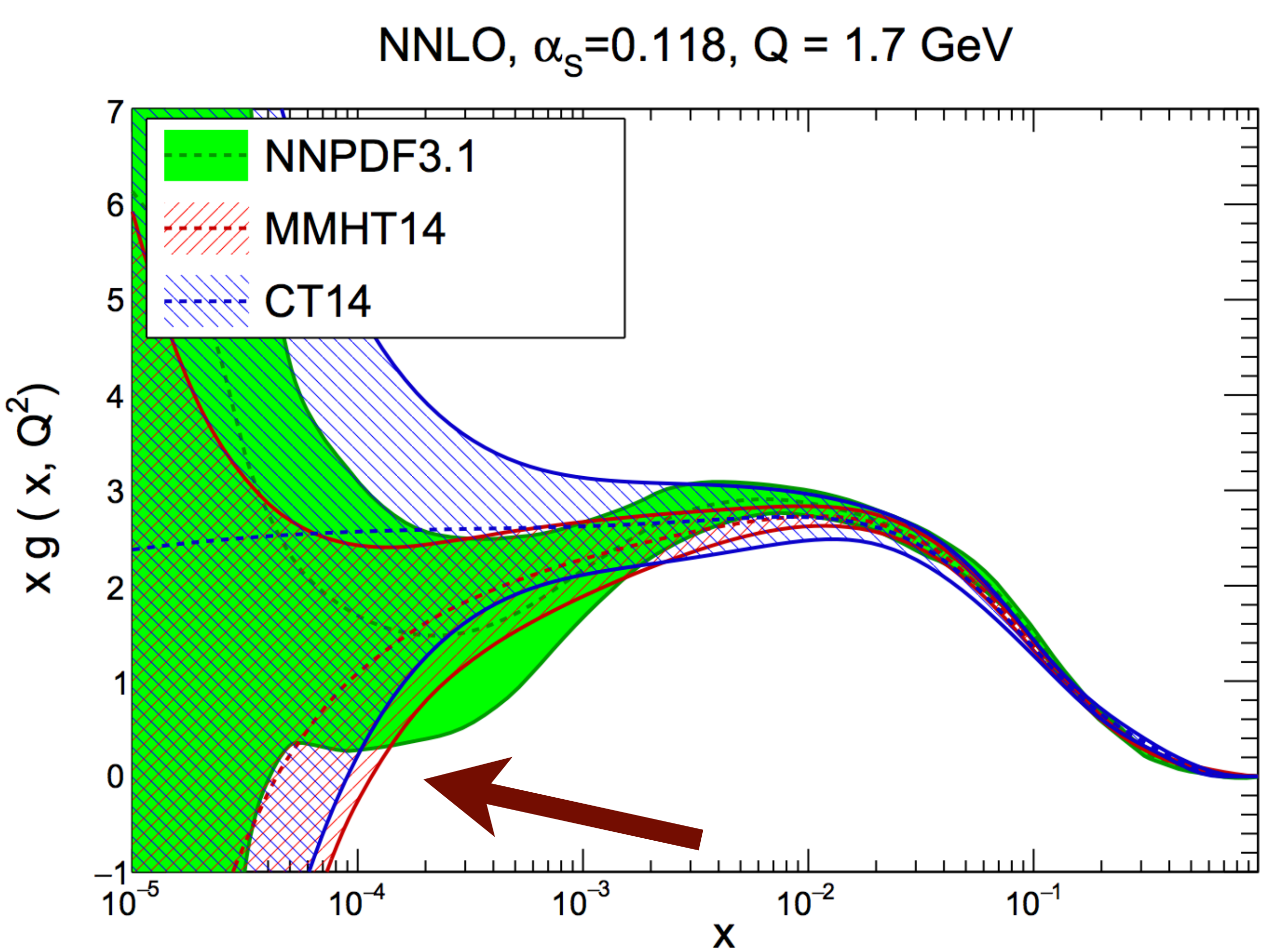
$$C(Q^2) \equiv \int_0^1 dx\, x \left(c(c, Q^2) + \bar{c}(x, Q^2) \right)$$

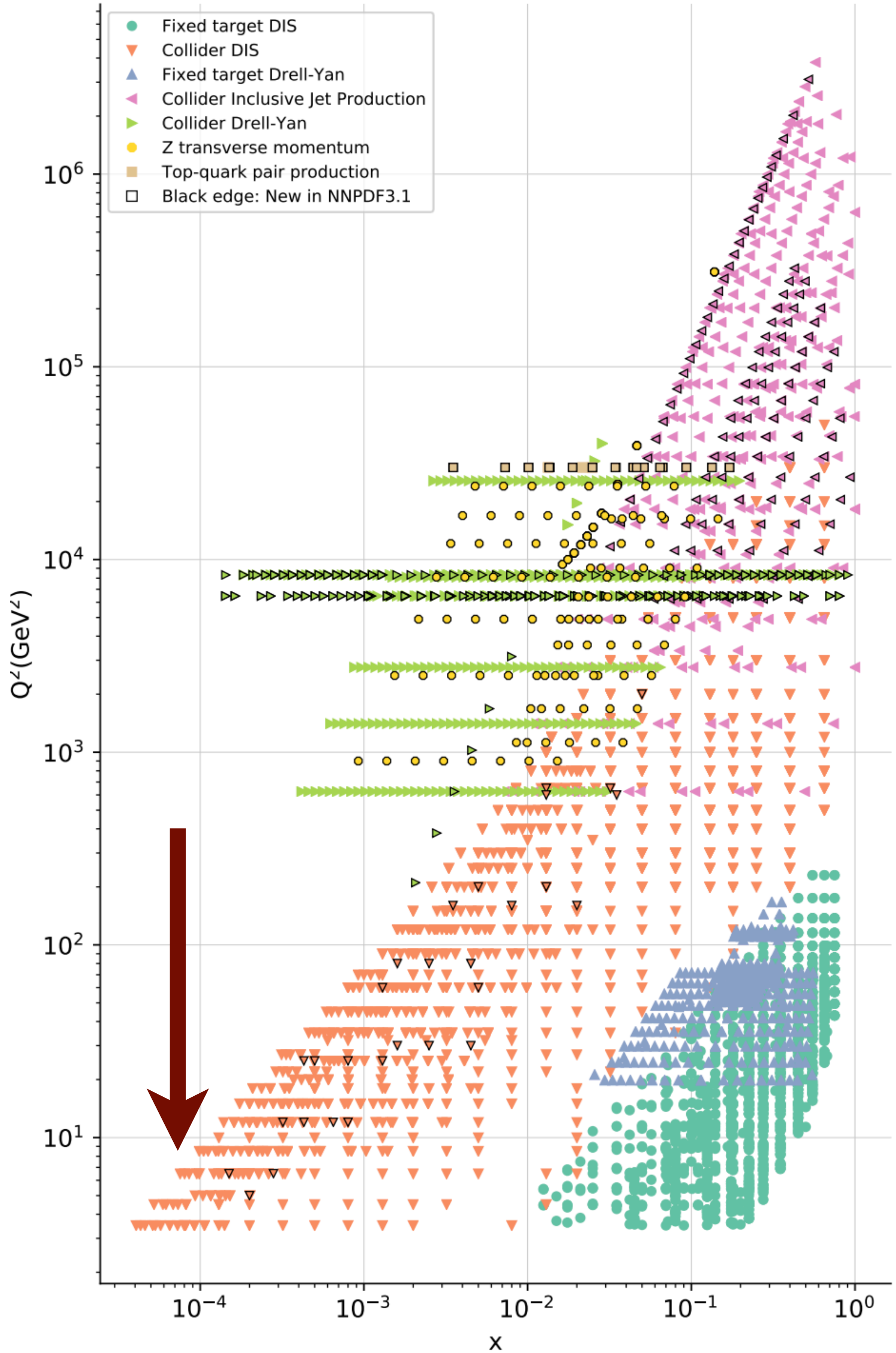
Large intrinsic charm allowed in CT14IC **disfavoured** by LHC(b) data

Impact on small-x gluon

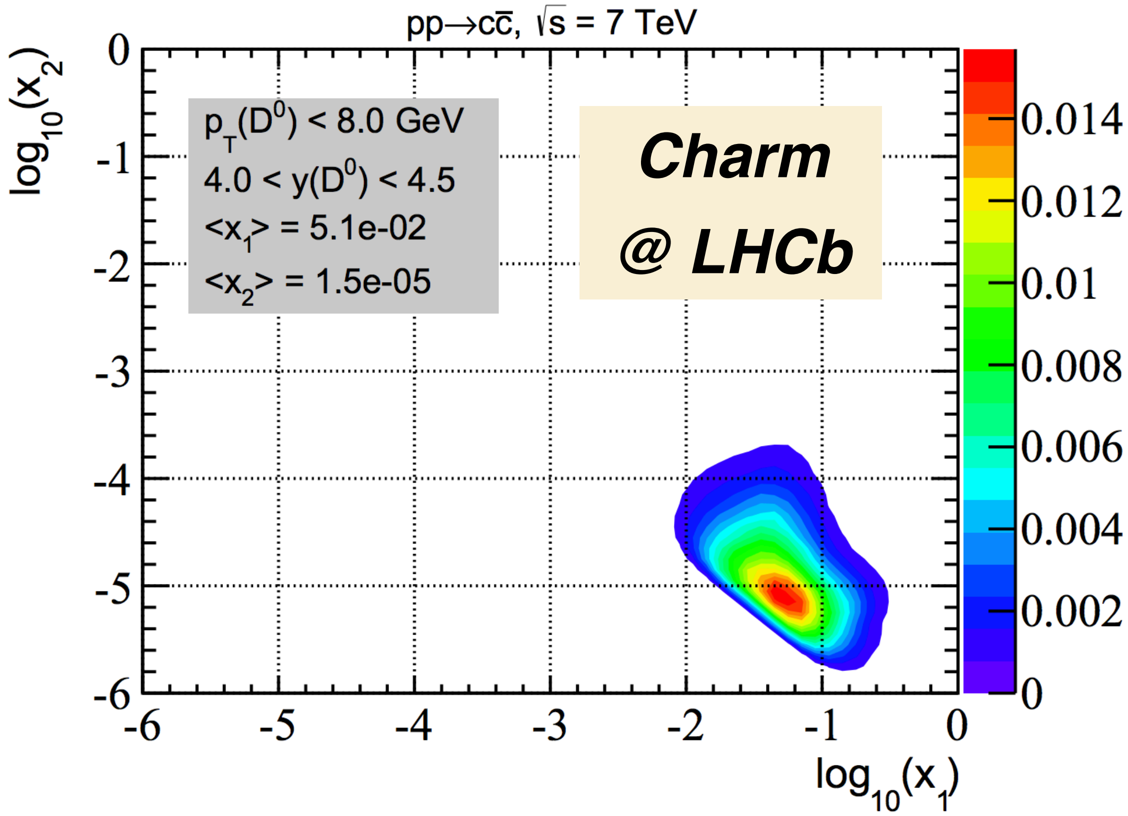
The small-x gluon from HERA data

- Small-x gluon unconstrained: information from HERA **ends for $x<10^{-4}$**
- Very large uncertainties in global fits
- Need processes covering **$x<10^{-4}$ region**



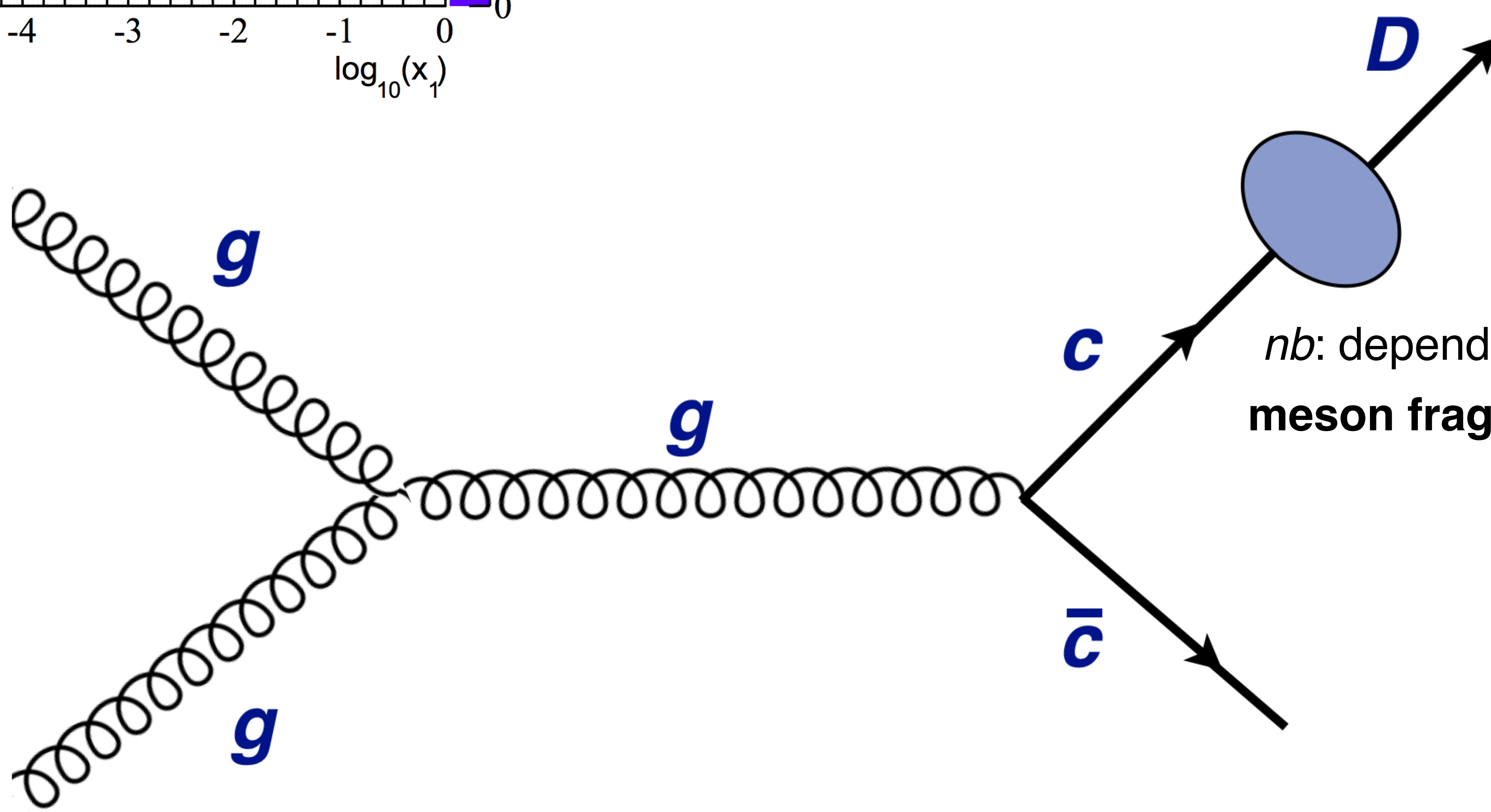


Forward charm production



LHC: charm production from **gluon-gluon scattering**

LHCb: forward coverage, Charm probes down to **x** ≃ **10^{-6}** !



nb: dependence on **D meson fragmentation**

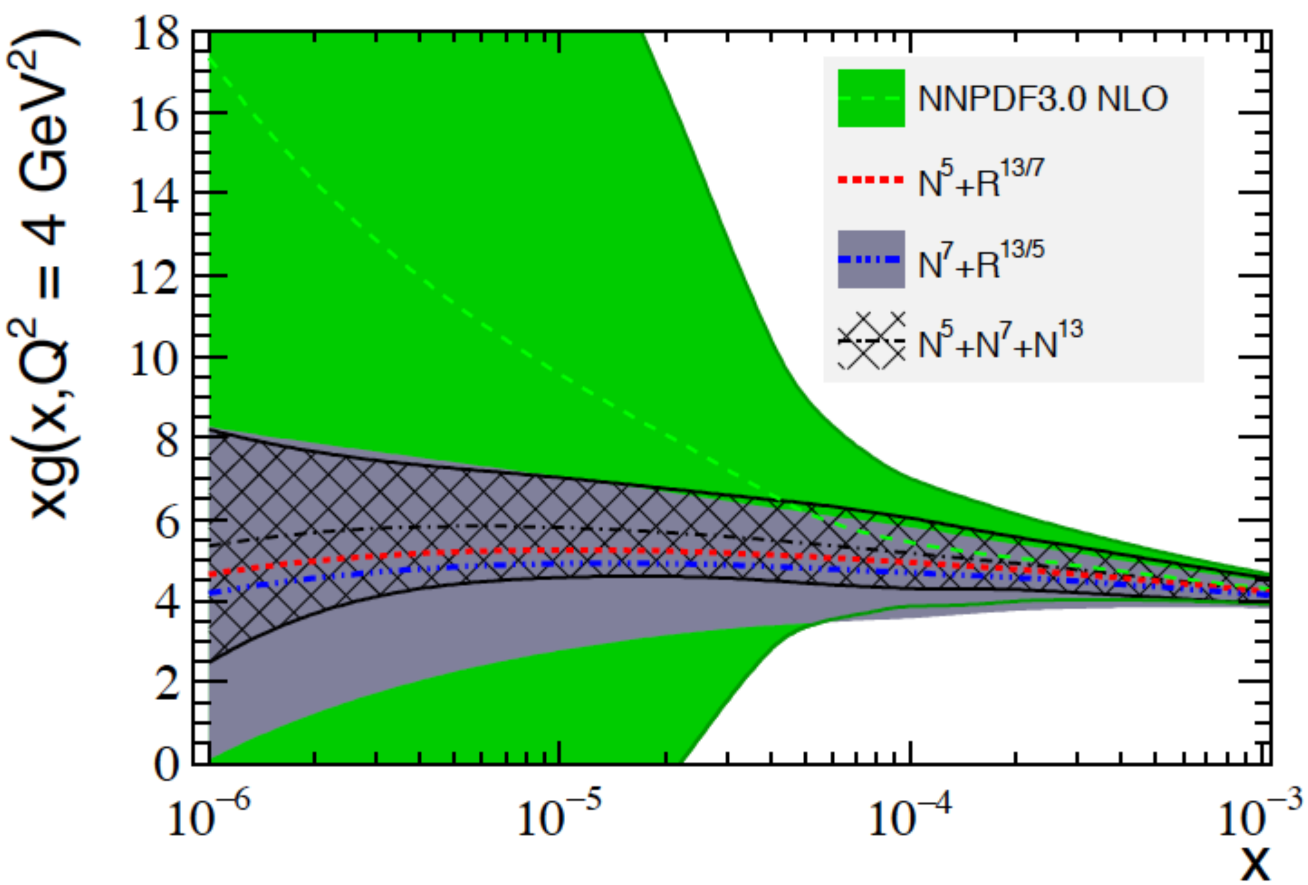
Forward charm production

- Include LHCb D meson production at **5, 7, 13 TeV**
- Fit **normalised distributions** & **ratios between CoM energies** to reduce MHOUs

$$N_X^{ij} = \frac{d^2\sigma(\text{X TeV})}{dy_i^D d(p_T^D)_j} \Big/ \frac{d^2\sigma(\text{X TeV})}{dy_{\text{ref}}^D d(p_T^D)_j} ,$$

$$R_{13/X}^{ij} = \frac{d^2\sigma(\text{13 TeV})}{dy_i^D d(p_T^D)_j} \Big/ \frac{d^2\sigma(\text{X TeV})}{dy_i^D d(p_T^D)_j}$$

gluon PDF uncertainties reduced by **factor 10** at **x** ≃ **10^{-6}**



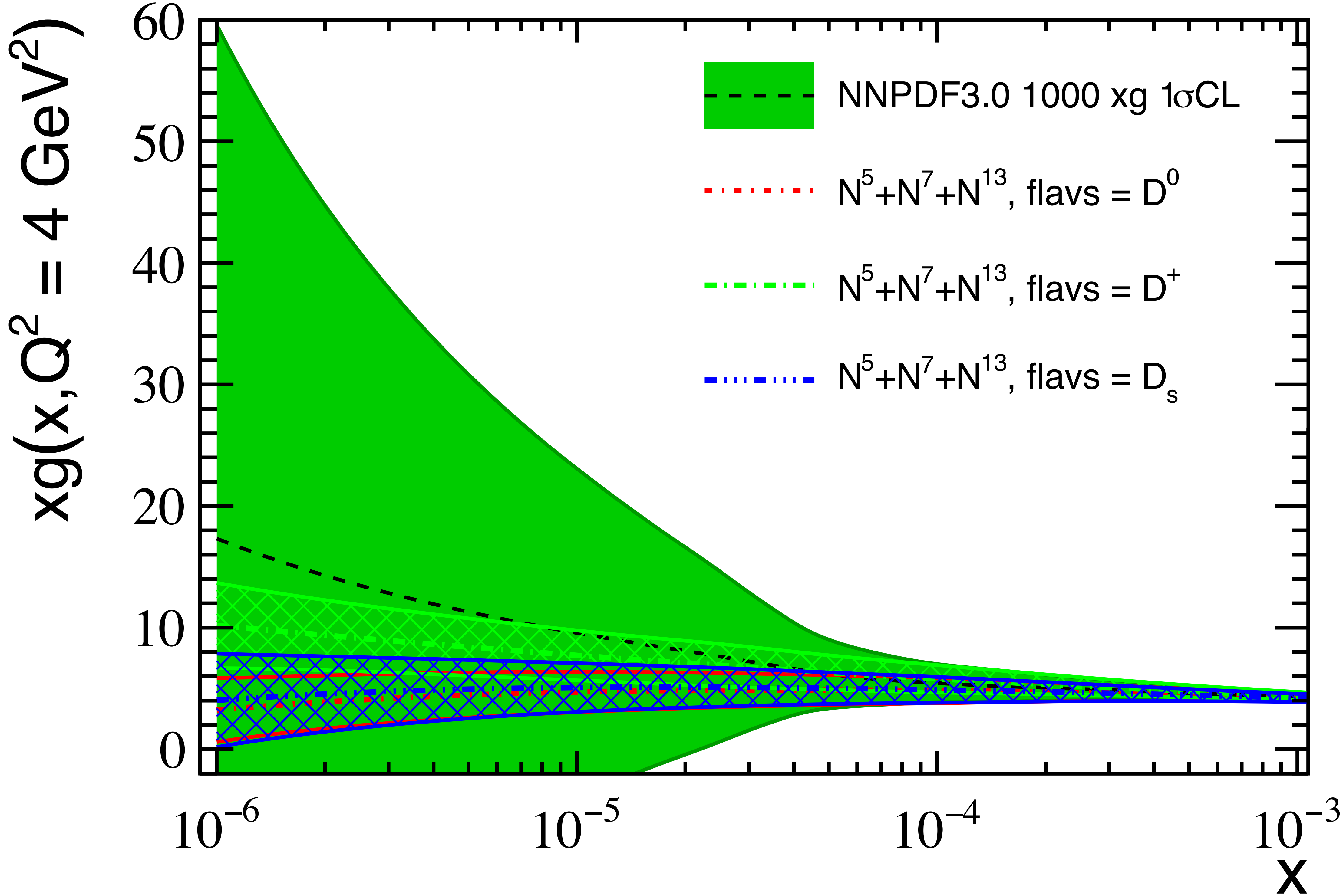
Gauld, JR 16

Excellent description of all LHCb datasets and ratios (after **errata** corrected)

$N_5(84)$	$N_7(79)$	$N_{13}(126)$	$R_{13/5}(107)$	$R_{13/7}(102)$
1.97	1.21	2.36	1.36	0.80
0.86	0.72	1.14	1.35	0.81
1.31	**0.91**	1.58	1.36	0.82
0.74	0.66	**1.01**	1.38	0.80
1.08	0.81	1.27	**1.29**	0.80
1.53	0.99	1.73	1.30	**0.81**
1.07	0.81	1.34	1.35	**0.81**
0.82	**0.70**	1.07	**1.35**	0.81
0.84	**0.71**	**1.10**	1.36	0.81

Forward charm production

Results stable wrt choice of **fitted D meson species**



‘New Physics’ within QCD

Science
Life and Physics

The Guardian

Jon Butterworth
@jonmbutterworth
Thu 28 Dec 2017 17.30 GMT

529 | 59

After 40 years of studying the strong nuclear force, a revelation

This was the year that analysis of data finally backed up a prediction, made in the mid 1970s, of a surprising emergent behaviour in the strong nuclear force

In the mid 1970s, four Soviet physicists, Batlisky, Fadin, Kuraev and Lipatov, made some predictions involving the strong nuclear force which would lead to their initials entering the lore. “BFKL” became a shorthand for a difficult-to-

BFKL dynamics at small-x

- **QCD calculations in the DGLAP factorisation framework** successful in describing data from proton-proton and electron-proton collisions
- Need to go **beyond DGLAP**: at small-x, logarithmically enhanced terms in *1/x* become dominant and need to be **resummed to all orders**
- **BFKL (high-energy, small-*x*) resummation** can be matched to DGLAP collinear framework and included into PDF fits

DGLAP Evolution in Q²

$$\frac{\partial}{\partial \ln Q^2} f_i(x,Q^2) = \int_x^1 \frac{dz}{z} P_{ij}\left(\frac{x}{z}, \alpha_s(Q^2)\right) f_j(z,Q^2)$$

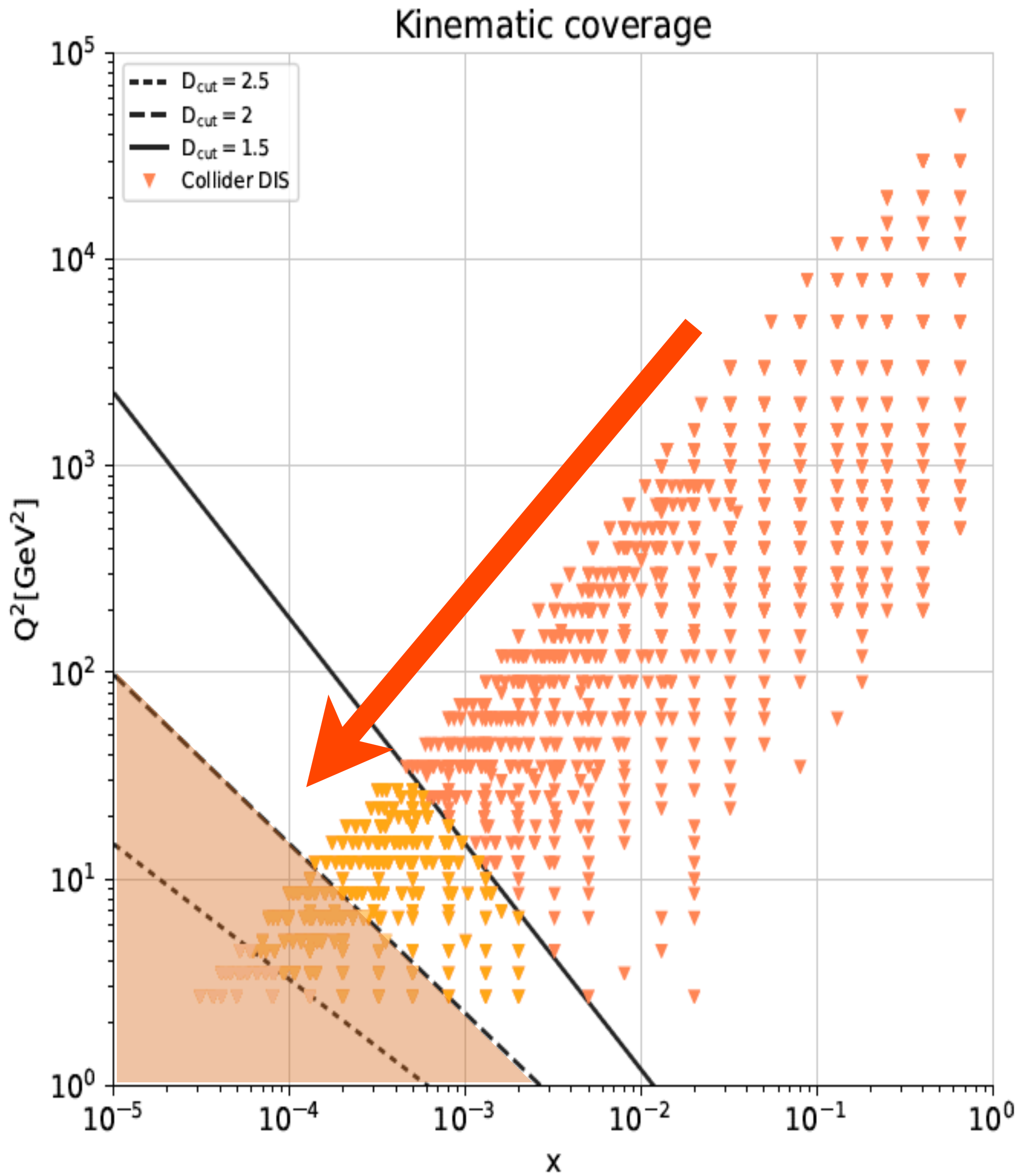
BFKL Evolution in x

$$\frac{\partial}{\partial \ln 1/x} f_+(x,Q^2) = \int_0^\infty \frac{d\nu^2}{\nu^2} K\left(\frac{Q^2}{\nu^2}, \alpha_s(Q^2)\right) f_+(x,\nu^2)$$

ABF, CCSS, TW + others, 94-08

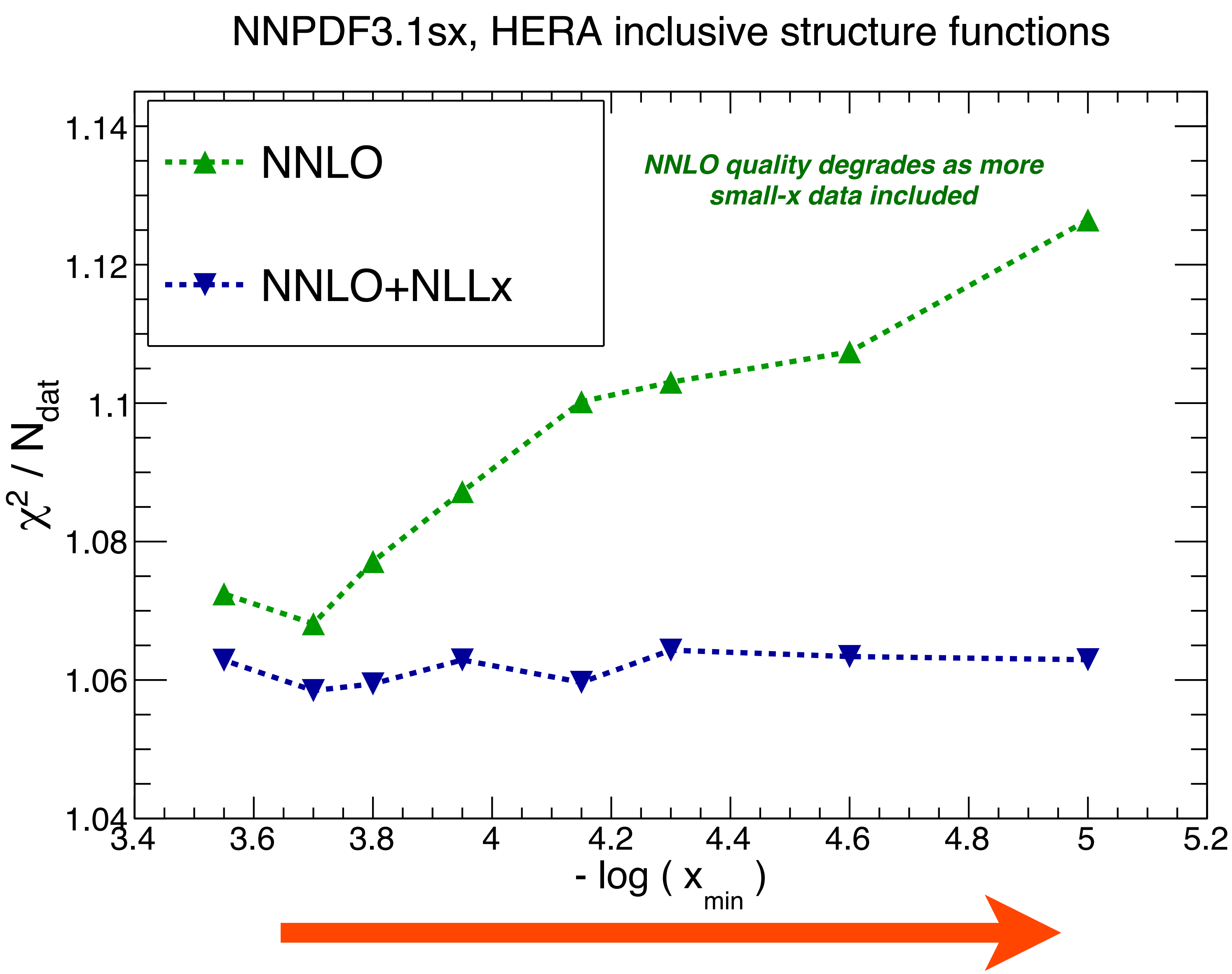
$$P_{ij}^{\mathrm{N}^k\mathrm{LO}+\mathrm{N}^h\mathrm{LL}x}(x) = P_{ij}^{\mathrm{N}^k\mathrm{LO}}(x) + \Delta_k P_{ij}^{\mathrm{N}^h\mathrm{LL}x}(x)$$

BFKL dynamics at small-x



Monitor the **fit quality** as one includes more data from the **small-x region**

Ball, Bertone, Bonvini, Marzani, JR, Rottoli 17

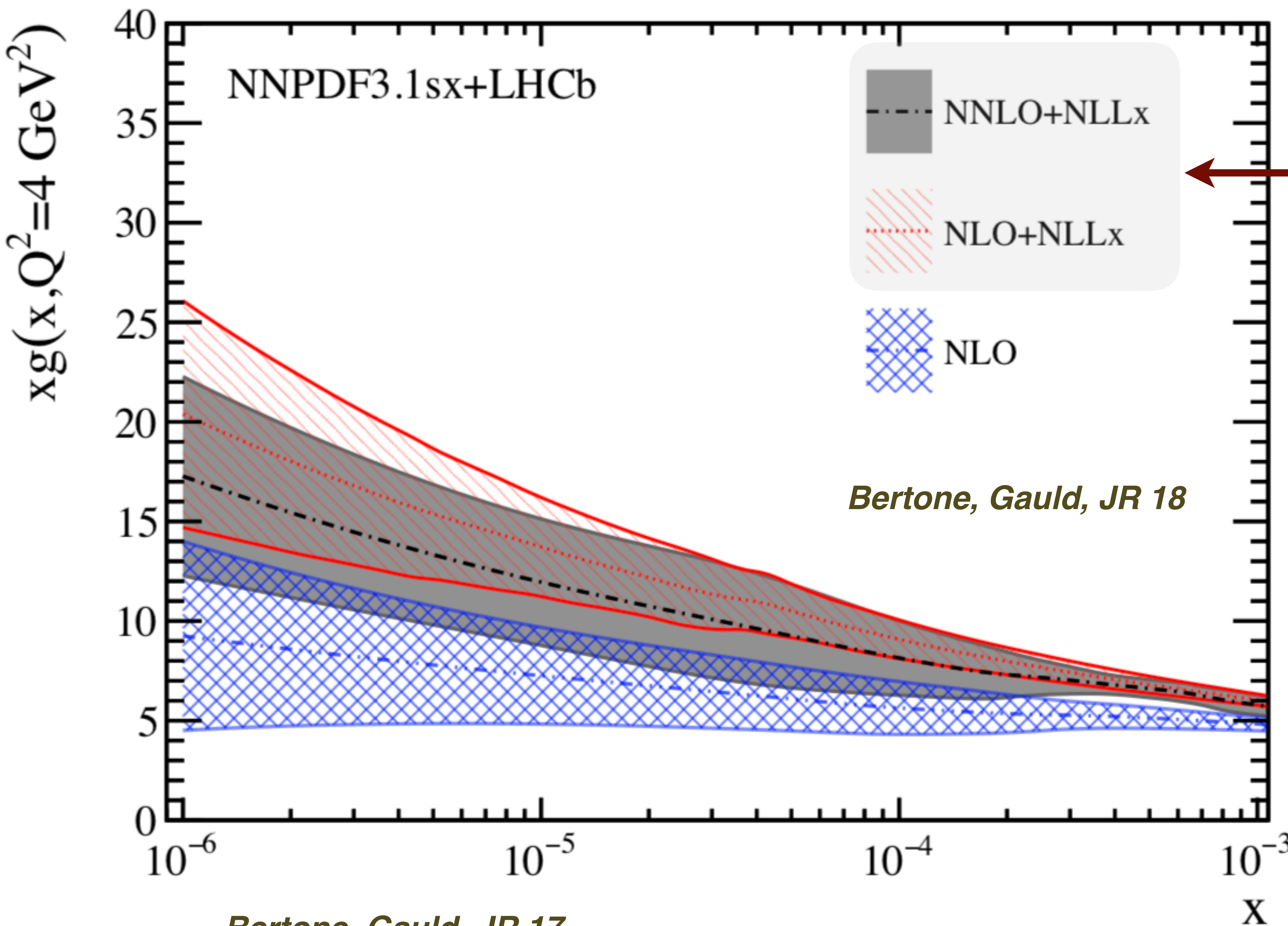


Best description of **small-x HERA data** only possible with **BFKL effects!**

Forward charm production revisited

LHCb D meson production included in **NNPDF3.1sx (N)NLO+NLL*x*** fits

Similar reduction of gluon PDF errors at **small-*x*** + **increase in central value**



BFKL effects included

small-x resummation: excellent **perturbative convergence** even for **x ≃ 10^{-6}**

Bertone, Gauld, JR 17

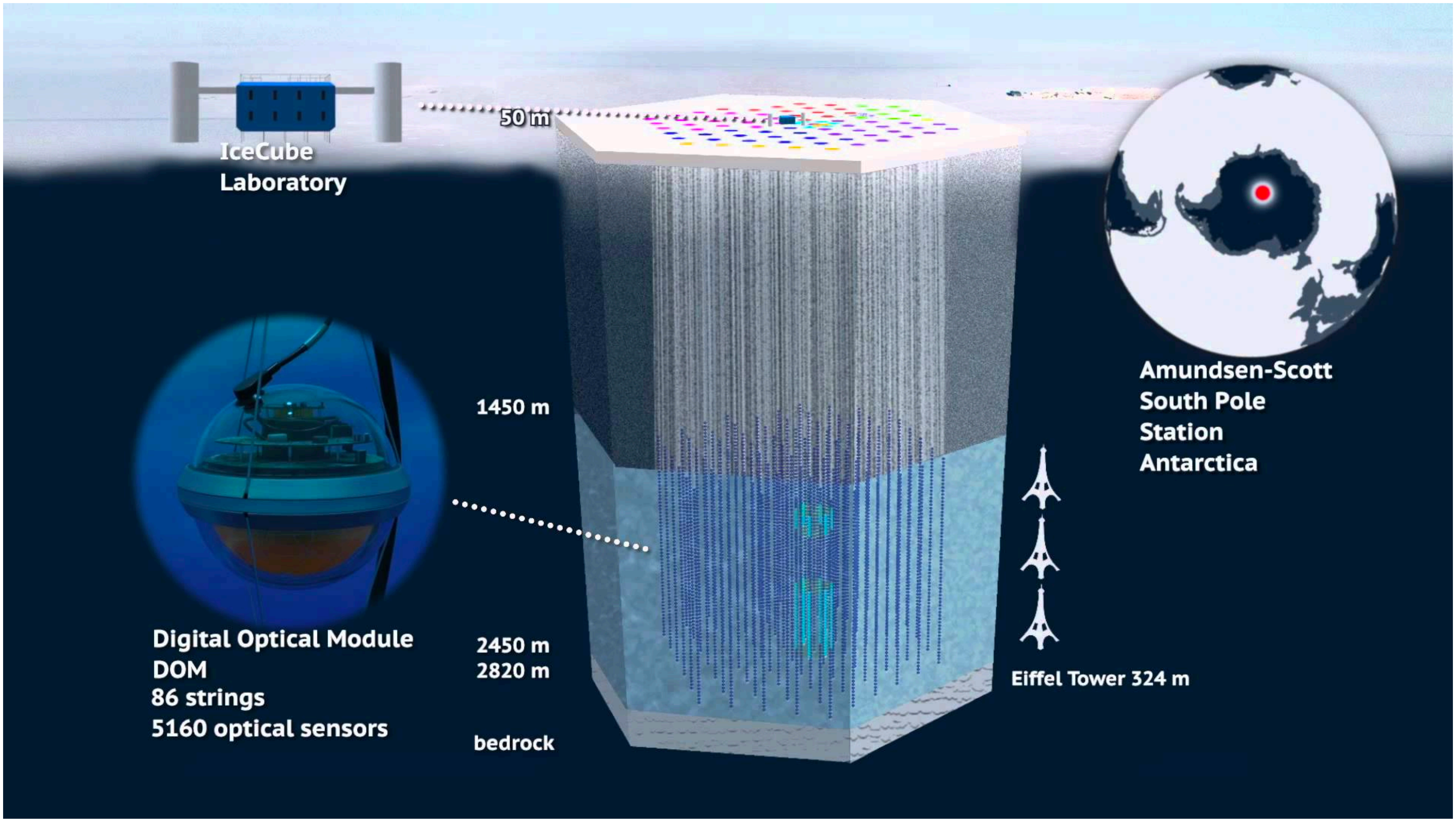
Impact on neutrino astronomy

Neutrino telescopes

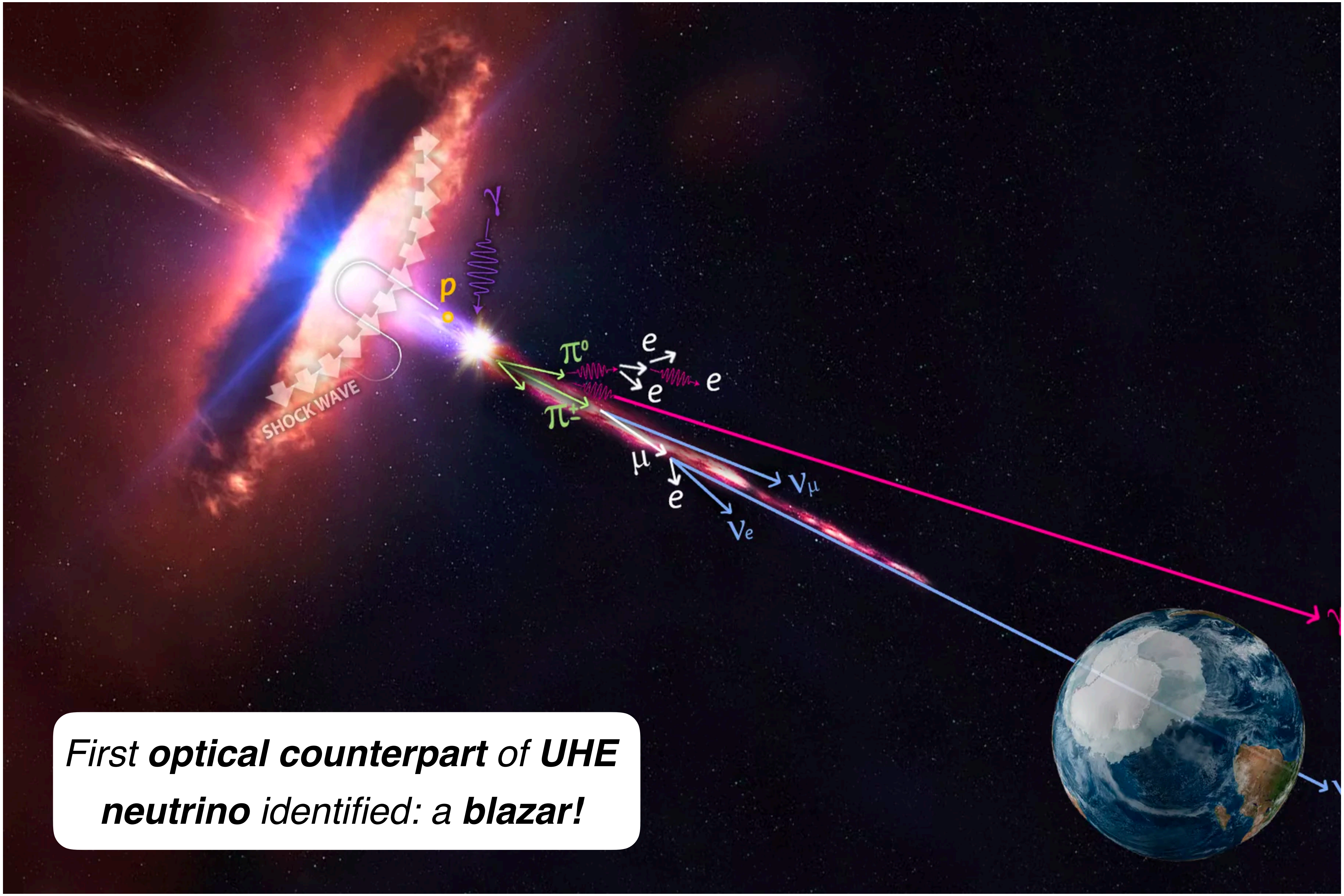
Ultra-high energy (UHE) neutrinos: novel window to the **extreme Universe!**

Neutrino telescopes

Ultra-high energy (UHE) neutrinos: novel window to the **extreme Universe!**



Unveiling cosmic neutrino origin

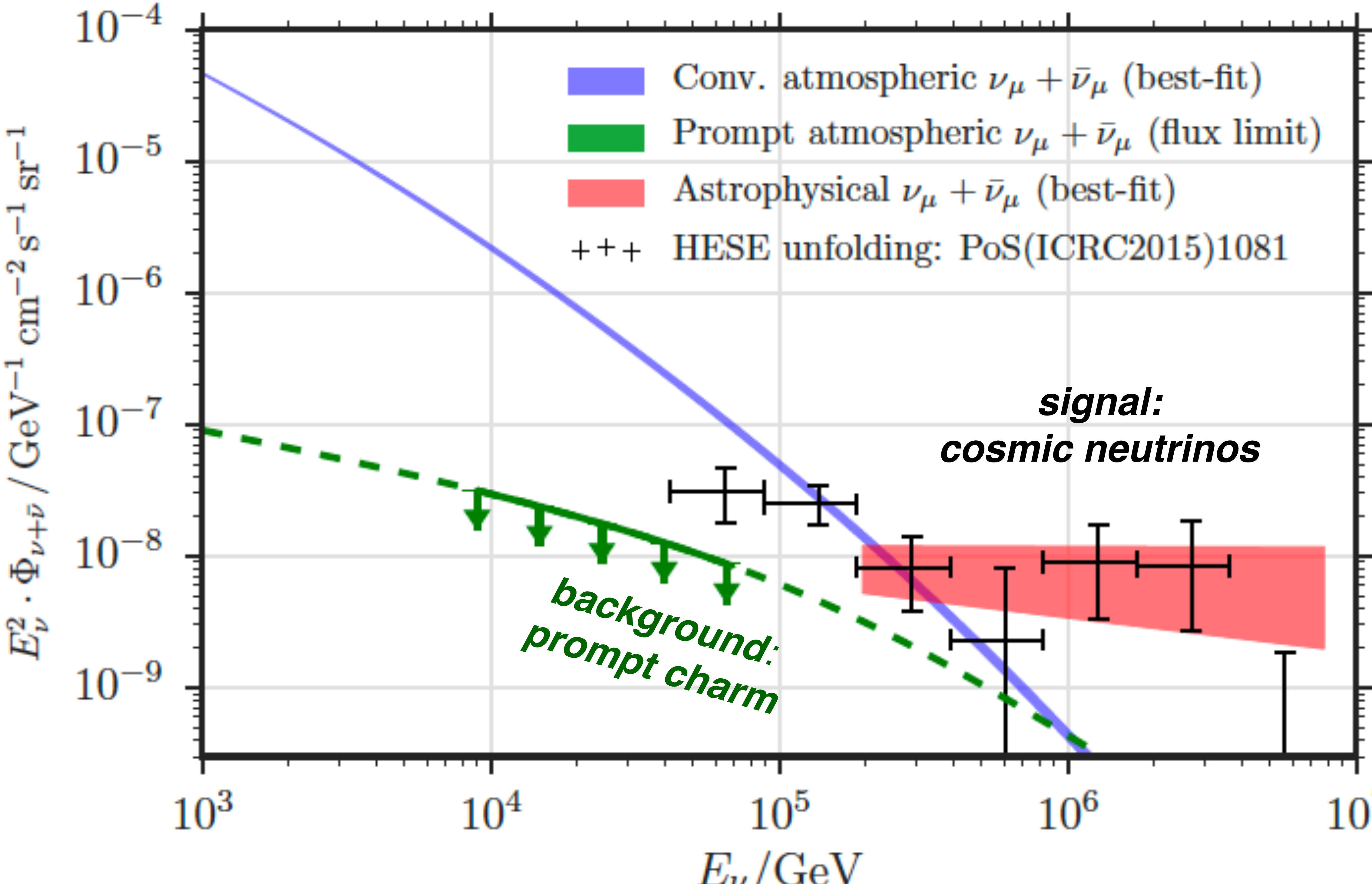


First ***optical counterpart*** *of* ***UHE neutrino*** *identified: a* ***blazar!***

Neutrino telescopes as QCD microscopes

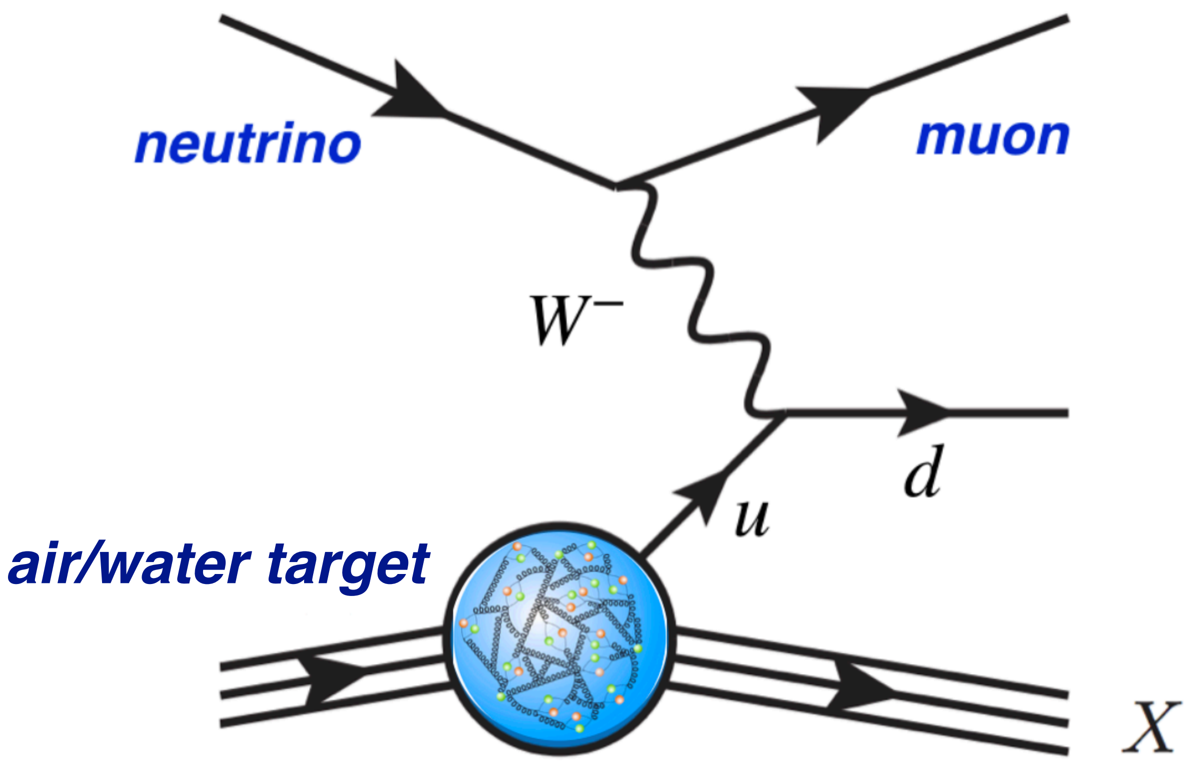
***signal**: cosmic neutrino - nucleus scattering*

***background**: prompt charm production*

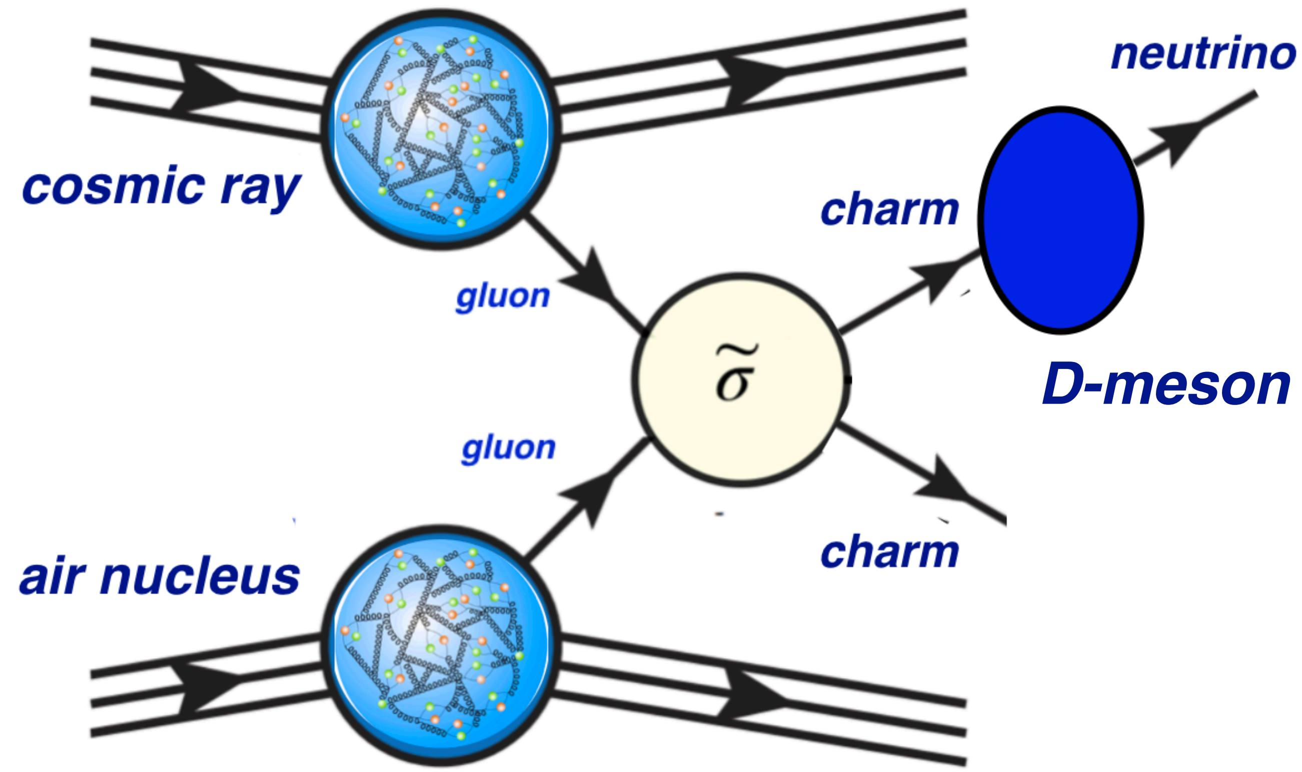


Neutrino telescopes as QCD microscopes

***signal**: cosmic neutrino - nucleus scattering*



***background**: prompt charm production*

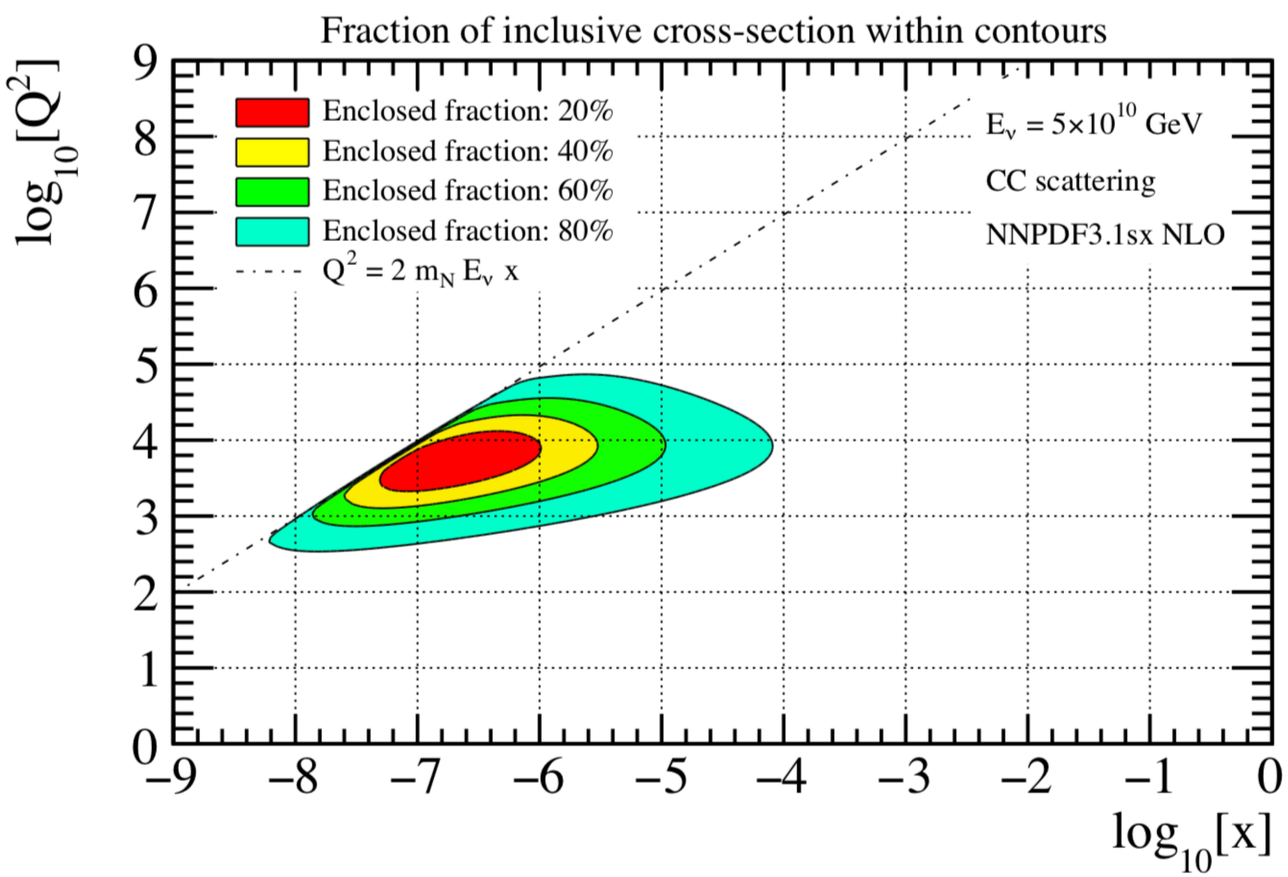


Sensitive to **small-*x* quarks** (and thus gluons via evolution) down to **$x \simeq 10^{-8}$** and **$Q \simeq M_W$**

Sensitive to **small-*x* gluons** down to **$x \simeq 10^{-6}$** and **$Q \simeq M_{charm}$** in the **centre-of-mass frame**

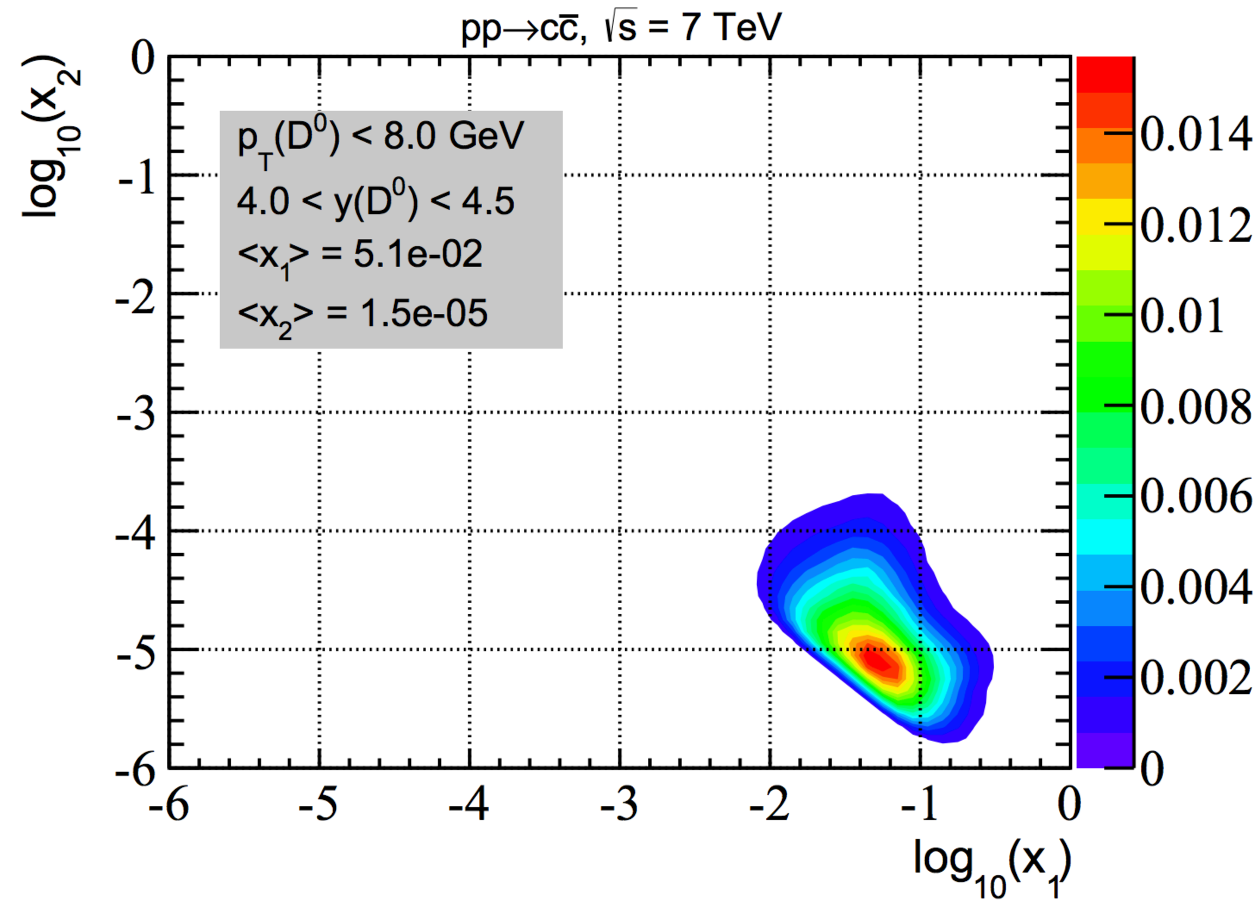
Neutrino telescopes as QCD microscopes

signal: *cosmic neutrino - nucleus scattering*



Sensitive to **small-*x* quarks** (and thus gluons via evolution) down to **$x \simeq 10^{-8}$** and **$Q \simeq M_W$**

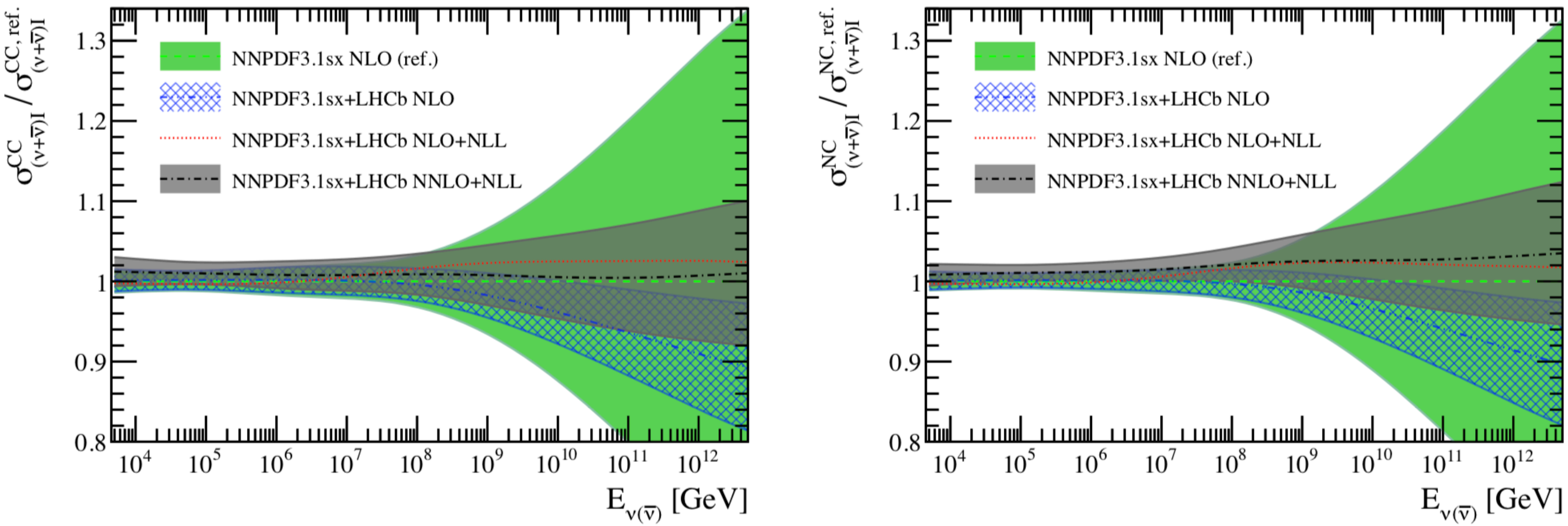
background: *prompt charm production*



Sensitive to **small-*x* gluons** down to **$x \simeq 10^{-6}$** and **$Q \simeq M_{charm}$** in the **centre-of-mass frame**

UHE neutrino-nucleus cross-section

Bertone, Gauld, JR 17

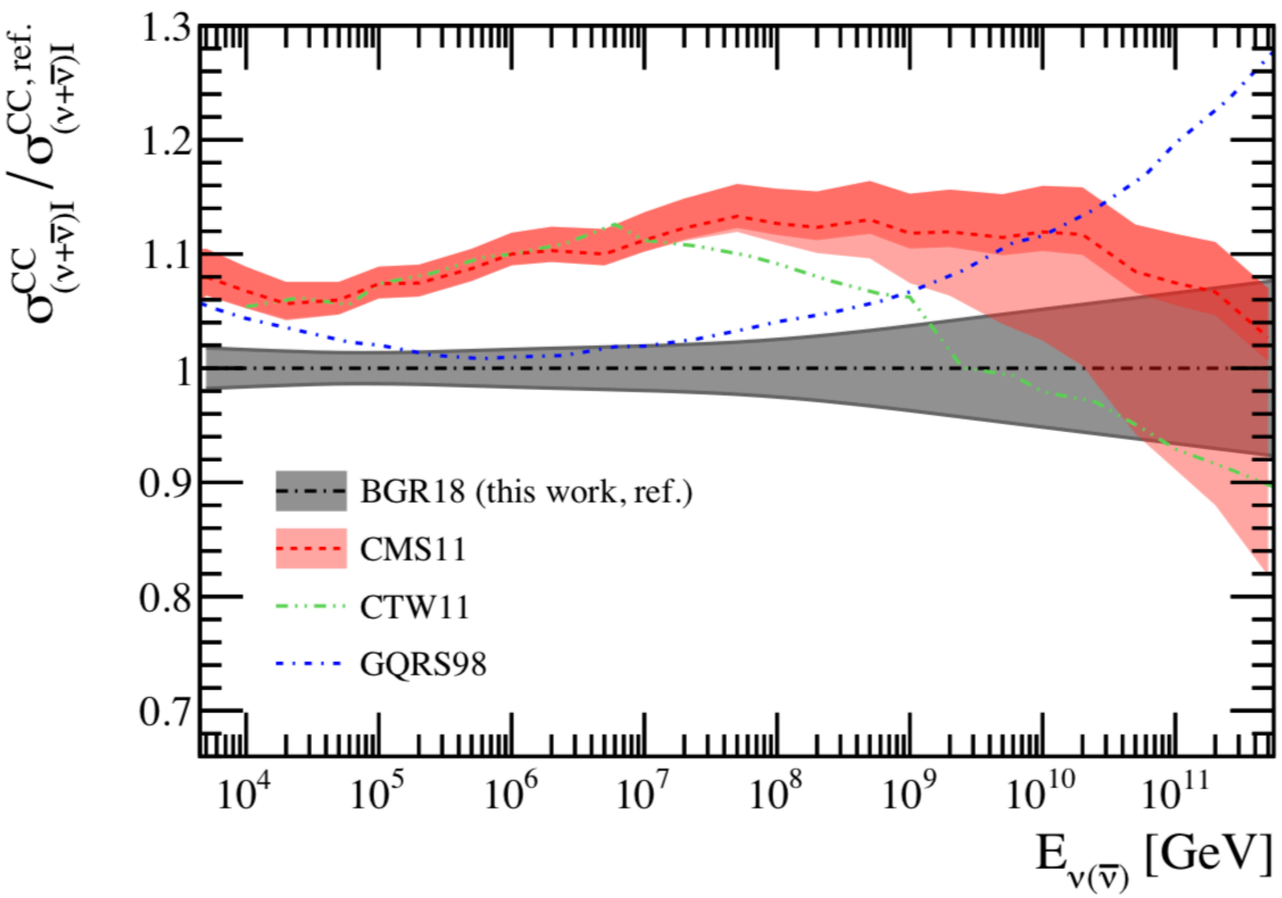


State-of-the-art predictions for **ultra-high energy** neutrino interactions

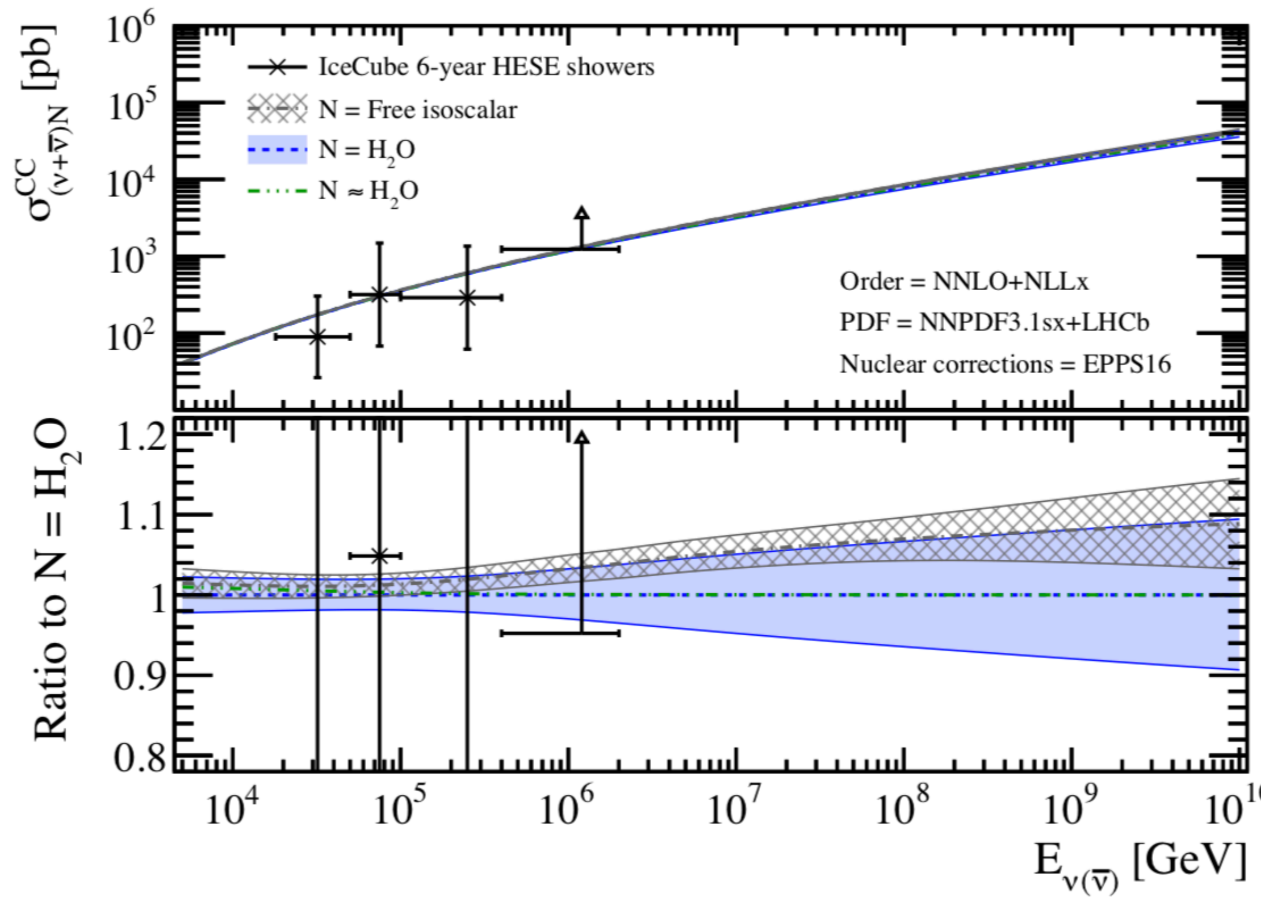
- **BFKL small-x effects** in PDFs and deep-inelastic structure functions
- Constraints on small-x PDFs from **LHCb charm production**
- Accounting for **nuclear corrections** and heavy-quark-initiated contributions

UHE neutrino-nucleus cross-section

*Comparison with **previous results***



*Comparison with **IceCube data***



- Differences both at **intermediate** (better PDFs, improved treatment of heavy quarks) and **high energies** (LHCb constraints, BFKL effects)
- Nuclear effects important: constrain them with LHCb **charm production in p+Pb**
- IceCube and other neutrino telescopes are the **ultimate QCD microscopes!**

Projections for HL-LHC

A luminous future

- In the framework of the update of the **European Strategy for Particle Physics**, a CERN Yellow Report will evaluate the physics potential of the **HL-LHC** (to appear in Dec 2018)

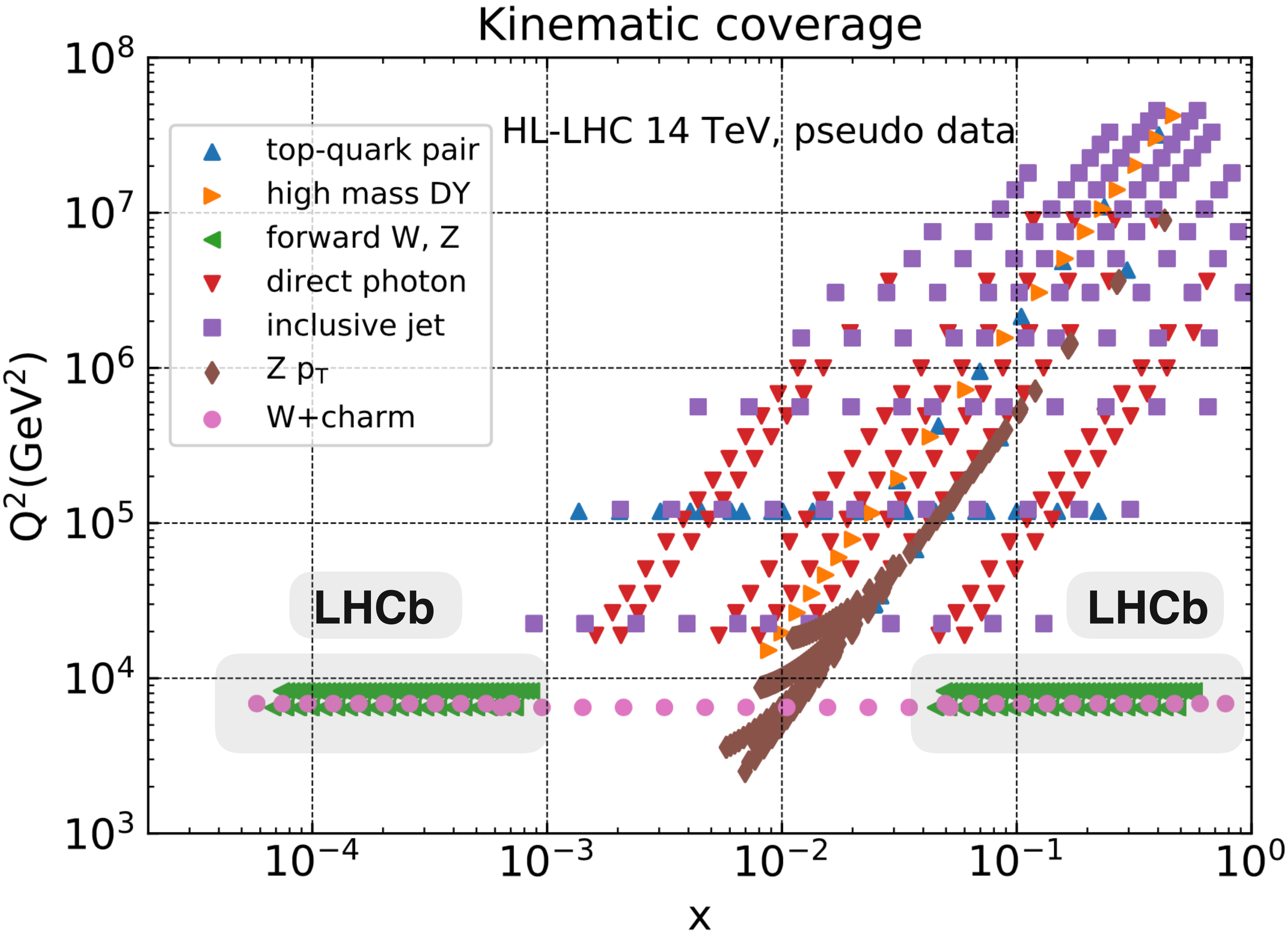
- We have studied the **impact of HL-LHC data on PDFs**, including projections with (future) LHCb measurements.

- LHCb pseudo-data on **forward inclusive W,Z** and **W+charm production**

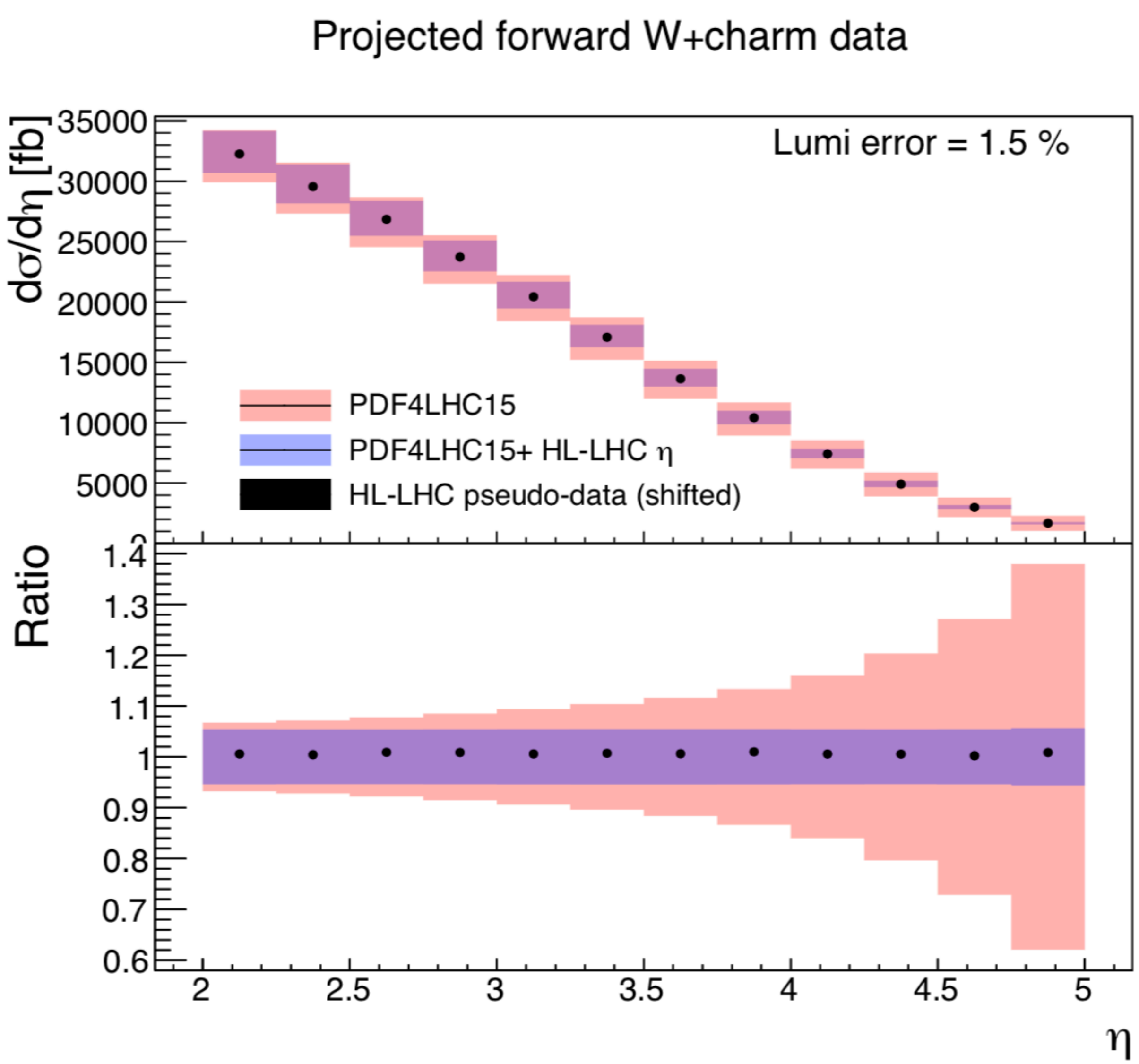
Abdul-Khalek, Bailey, Gao, Harland-Lang, JR (2018)

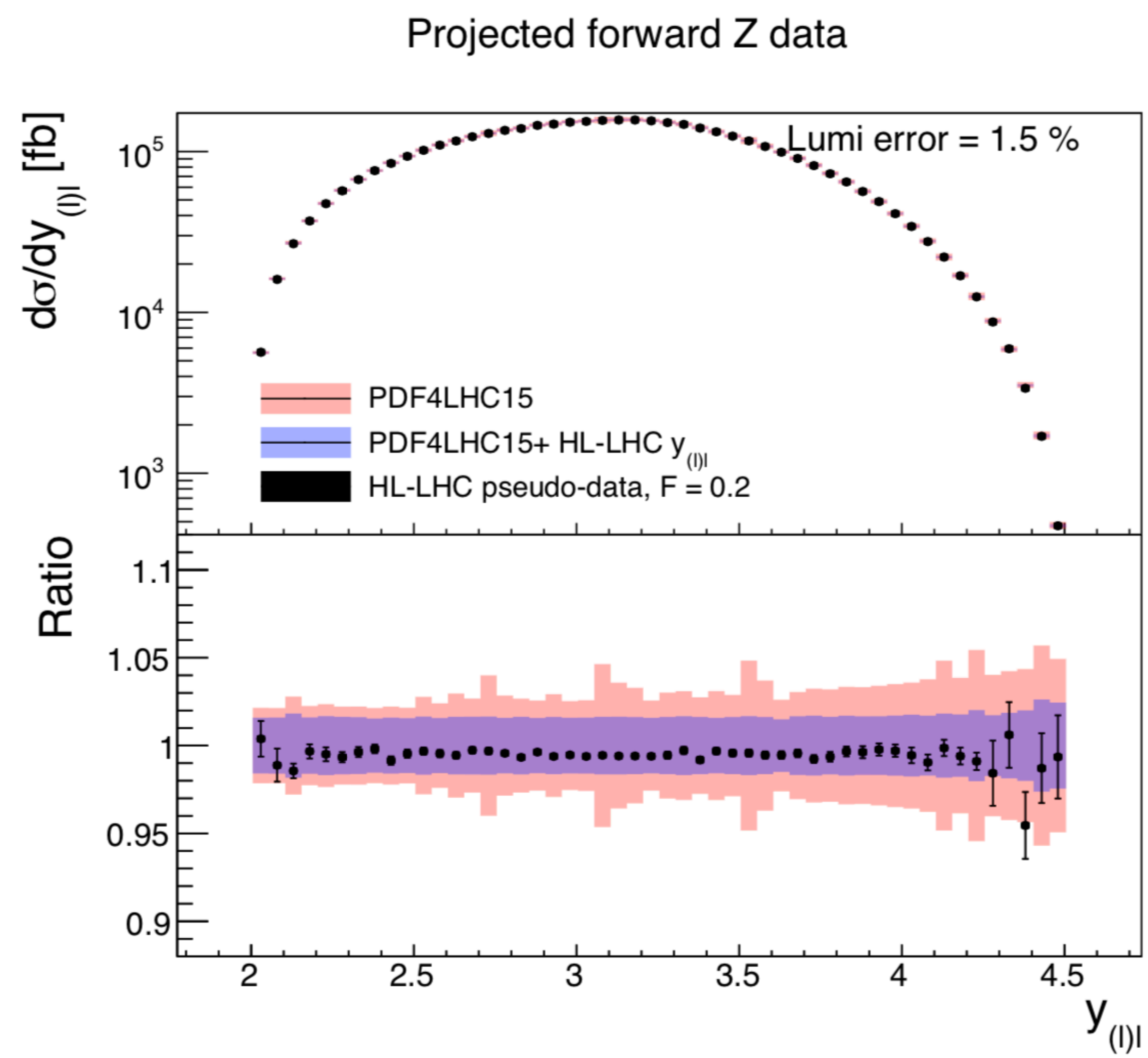
Process	Kinematics	$N_{\rm dat}$
$Z\ p_T$	$20\,\text{GeV} \le p_T^{ll} \le 3.5$ TeV $12\,\text{GeV} \le m_{ll} \le 150$ GeV $\lvert y_{ll}\rvert \le 2.4$	162
high-mass Drell-Yan	$p_T^{l1(2)} \ge 40(30)$ GeV $\lvert\eta^l\rvert \le 2.5,\ m_{ll} \ge 116$ GeV	21
top quark pair	$m_{t\bar{t}} \simeq 5$ TeV, $\lvert y_t\rvert \le 2.5$	26
W+charm (central)	$p_T^\mu \ge 26$ GeV, $p_T^c \ge 5$ GeV $\lvert\eta^\mu\rvert \le 2.4$	6
W+charm (forward)	$p_T^\mu \ge 20$ GeV, $p_T^c \ge 20$ GeV $p_T^{\mu+c} \ge 20$ GeV $2 \le \eta^\mu \le 5,\ 2.2 \le \eta^c \le 4.2$	12
Direct photon	$E_T^\gamma \lesssim 3$ TeV, $\lvert\eta_\gamma\rvert \le 2.5$	53
Forward W, Z	$p_T^l \ge 20$ GeV, $2.0 \le \eta^l \le 4.5$ $2.0 \le y_{ll} \le 4.5$ $60 \le m_{ll} \le 120$ GeV	90
Inclusive jets	$\lvert y\rvert \le 3,\ R = 0.4$	54
Total		424

A luminous future



HL-LHC constraints from LHCb





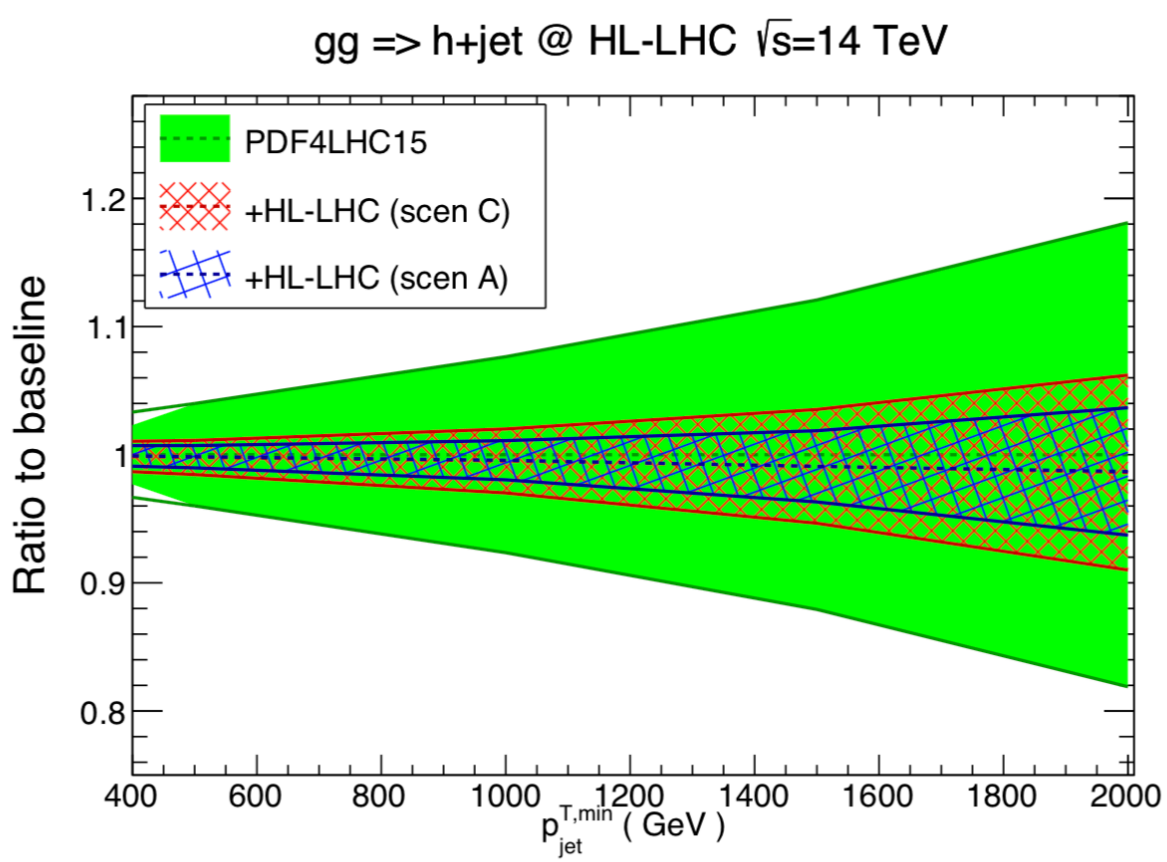
Forward W+charm

Forward inclusive W and Z

Future LHCb measurements will be specially useful to constrain the **quark flavour separation in the large-*x* region**, including strangeness

HL-LHC constraints on PDFs

PDF uncertainties HLLHC / Current	10 GeV < M_X < 40 GeV	40 GeV < M_X < 1 TeV	1 TeV < M_X < 6 TeV
g-g luminosity	0.58 (0.49)	0.41 (0.29)	0.38 (0.24)
q-g luminosity	0.71 (0.65)	0.49 (0.42)	0.39 (0.29)
quark-quark luminosity	0.78 (0.73)	0.46 (0.37)	0.60 (0.45)
quark-antiquark luminosity	0.73 (0.70)	0.40 (0.30)	0.61 (0.50)



HL-LHC data will lead to **stringent constraints on PDFs**, reducing uncertainties by up to a **factor 4**, and making possible precise predictions of central processes such as **Higgs p_T**

LHCb instrumental for PDFs also in HL-LHC era!

Summary and outlook

- LHCb provides unique information on the **structure of the proton**
- W,Z boson production constraints **quark flavour separation** including charm
- Charm production constraints **small-x gluon** beyond the HERA coverage

- **Neutrino astrophysics** requires direct input from **small-x QCD**
- Precision calculation of UHE neutrino-nucleon cross-section with LHCb data
- Also important for **prompt neutrinos** (dominant background)