Novel probes of small-*x* QCD from HERA, the LHC, and beyond

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Nuclear Theory / RIKEN Seminar

Brookhaven National Laboratory (BNL), 30/11/2018

The inner life of protons

See also ``The structure of the proton in the LHC precision era''

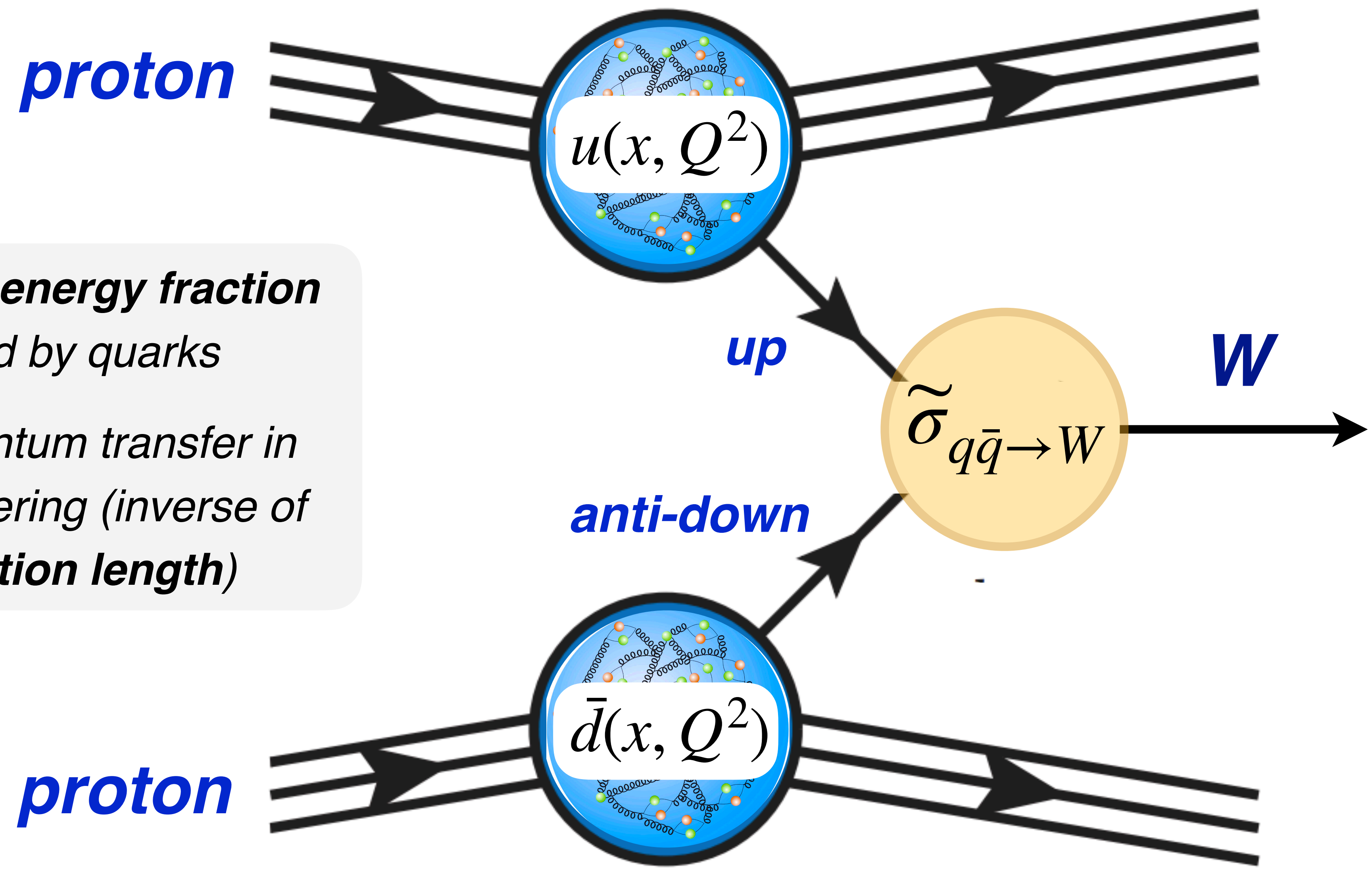
Gao, Harland-Lang, JR (Physics Reports 17)

Parton distributions @ LHC

QCD Factorisation theorem:

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

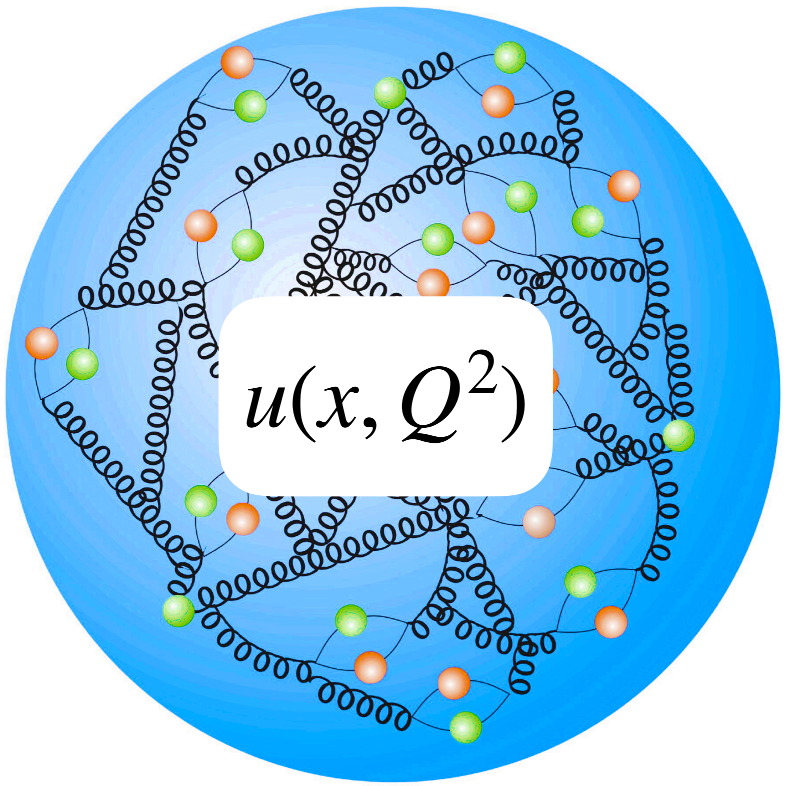
$$N_{\mathrm{LHC}}(W) \sim q \otimes \bar{q} \otimes \widetilde{\sigma}_{q\bar{q}\to W} + \mathcal{O}(\alpha_s)$$



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

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

Parton distributions @ LHC



Challenging to compute **from first principles**

↓

Determine from data:

Global QCD analysis

Mass? Spin? Heavy quarks?

Event rates LHC, RHIC, IceCube?

DGLAP evolution

(*upwards in Q*)

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

Momentum sum rule

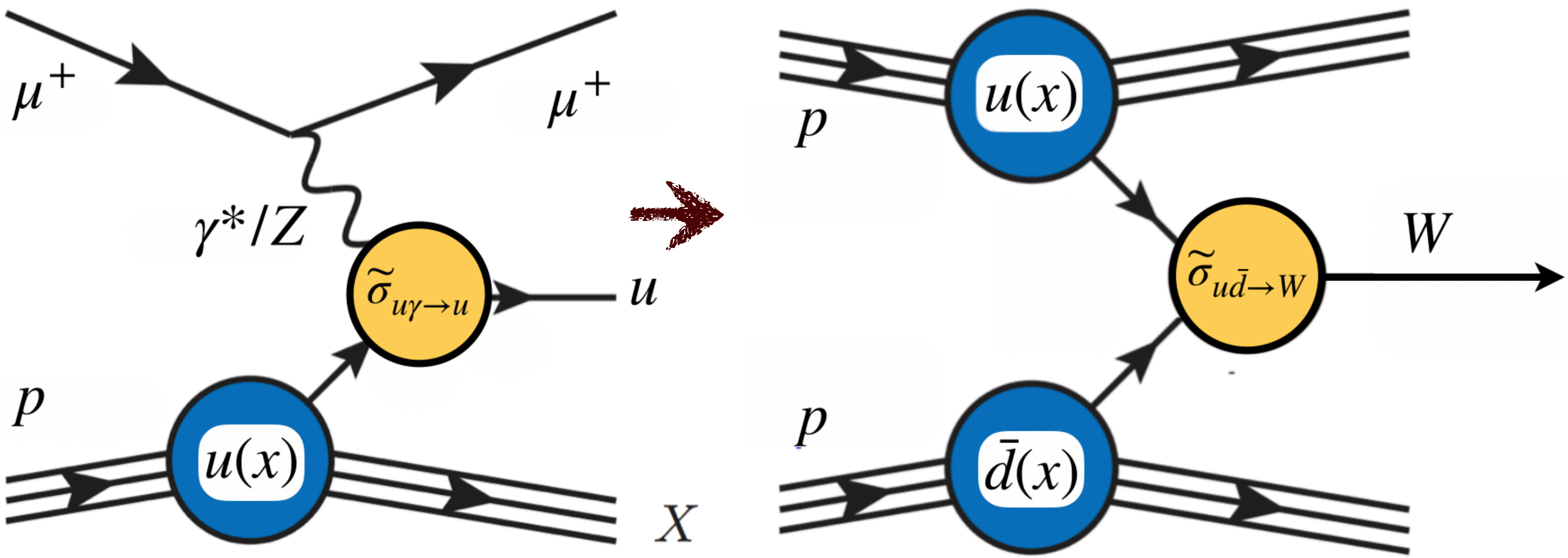
(*energy conservation*)

$$\int_0^1 dx\, x \left(\sum_{i=1}^{n_f} (q_i((x, Q^2) + \bar{q}_i(x, Q^2)) + g(x, Q^2) \right) = 1$$

QCD factorisation

The **QCD factorization theorems** guarantees **PDF universality**

$$\sigma_{l\,p\to\mu\,X} = \widetilde{\sigma}_{u\gamma\to u} \otimes u(x) \quad \rightarrow \quad \sigma_{p\,p\to W} = \widetilde{\sigma}_{u\bar{d}\to W} \otimes u(x) \otimes \bar{d}(x)$$

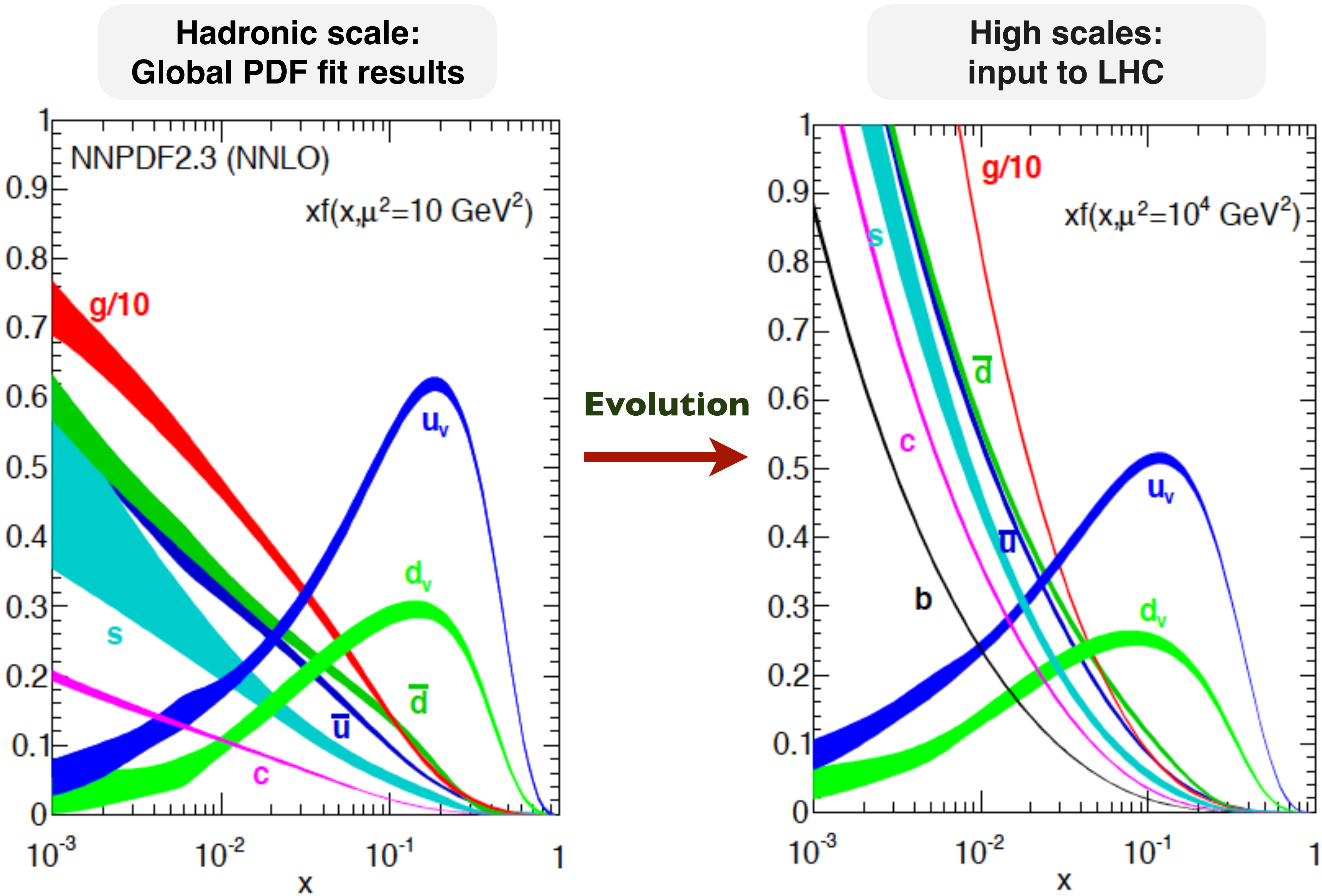


*Determine PDFs in **lepton-proton collisions** (deep-inelastic scattering) …*

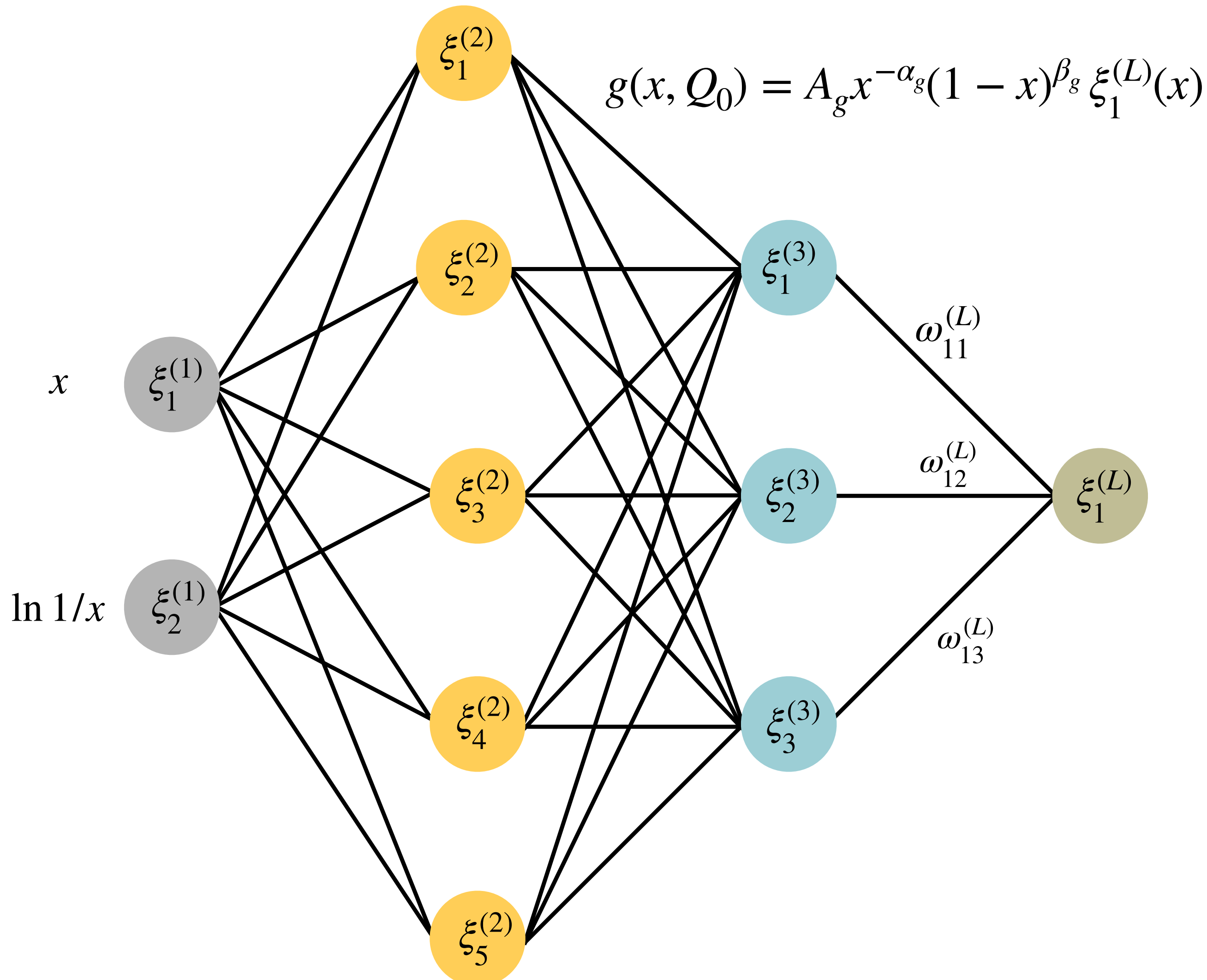
*… and use them to compute predictions for **proton-proton collisions***

From the proton mass to the LHC

- **Extract PDFs** at hadronic scales (few GeV**),** where **non-perturbative QCD** sets in
- Use **perturbative evolution** to compute PDFs at high scales as **input to LHC predictions**



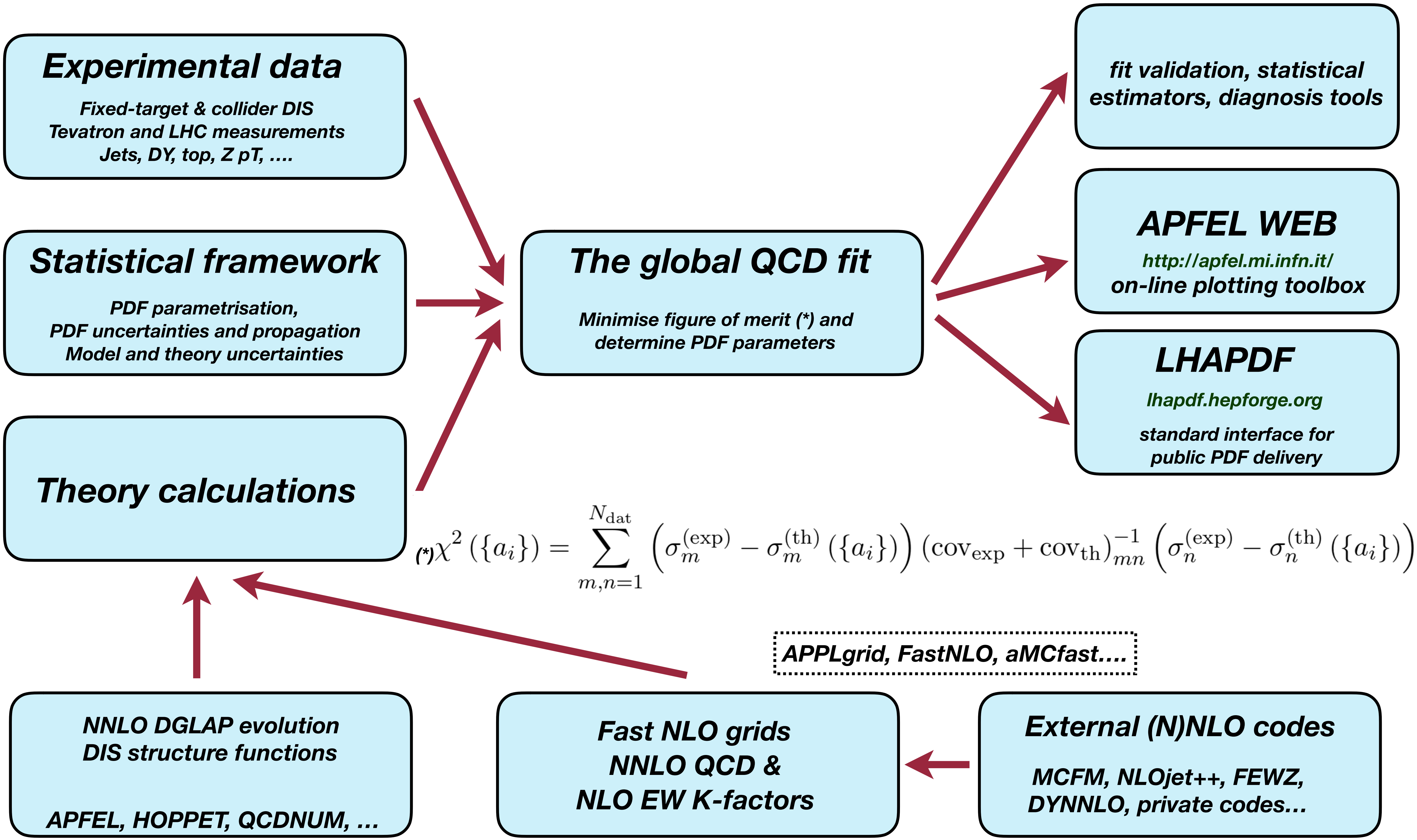
The NNPDF approach to PDF fits



- **Neural Networks** as universal unbiased interpolants to **parametrise PDFs:** eliminate model assumptions
- **Monte Carlo replicas** to propagate uncertainties wo Gaussian assumptions
- **Genetic algorithms** and **Machine Learning** to explore parameter space

	Proton PDFs	***Nuclear PDFs***
Traditional	$g(x) \simeq x^{-b}(1-x)^c$	$R_g(x,A) \simeq (1+bx+cx^2)\times A^d$
Neural Nets	$g(x) \simeq \mathrm{NN}(x)$	$R_g(x,A) \simeq \mathrm{NN}(x,A)$

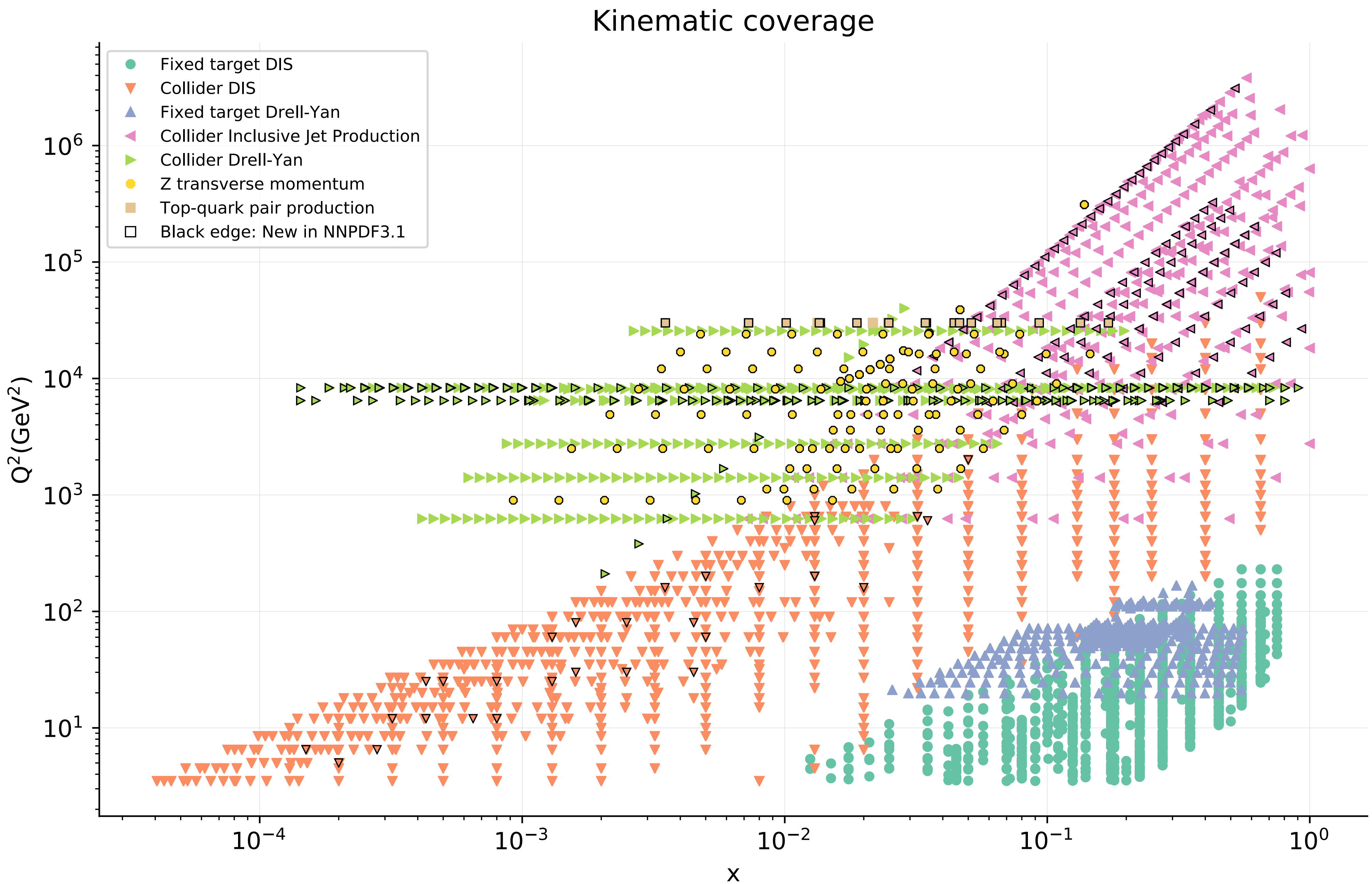
The NNPDF approach to PDF fits



$$(*)\ \chi^2\left(\{a_i\}\right) = \sum_{m,n=1}^{N_{\rm dat}} \left(\sigma_m^{(\rm exp)} - \sigma_m^{(\rm th)}\left(\{a_i\}\right)\right)\left({\rm cov}_{\rm exp} + {\rm cov}_{\rm th}\right)^{-1}_{mn}\left(\sigma_n^{(\rm exp)} - \sigma_n^{(\rm th)}\left(\{a_i\}\right)\right)$$

*Combine **precision measurements** and **state-of-the-art theory** within robust statistical framework*

The NNPDF approach to PDF fits



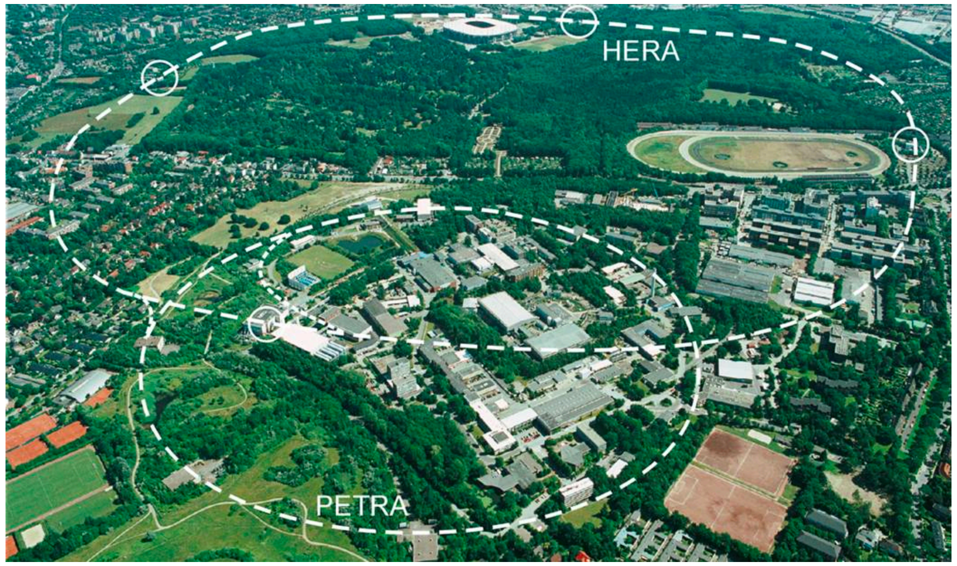
Highly non-trivial validation of the **QCD factorisation framework**:

Including **O(5000) data** points, from **O(40) experiments**, some of them with ≲**1% errors**,

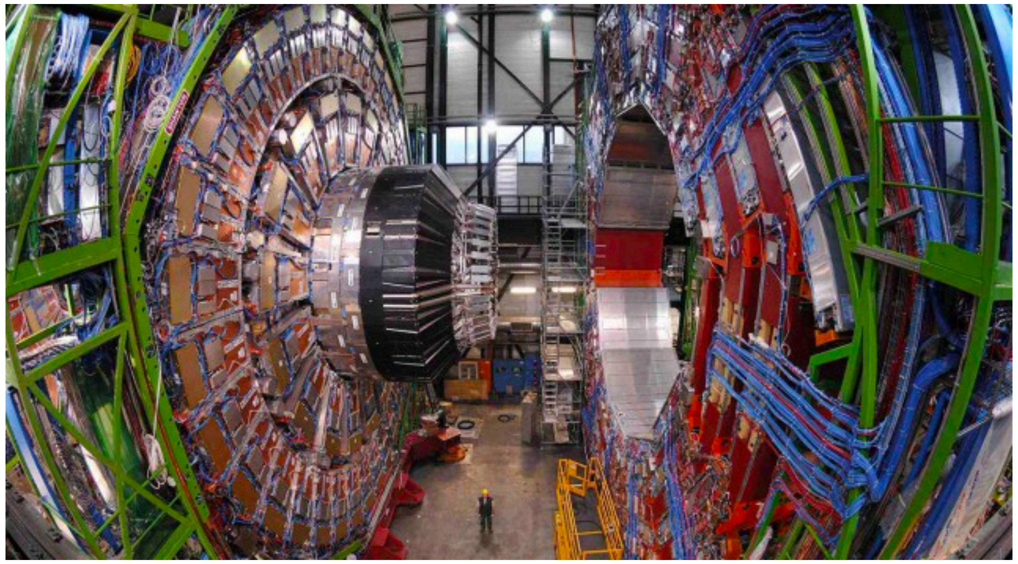
yet the global PDF fit achieves $\chi^2/N_{dat} \approx 1$!

Novel probes of small-x QCD

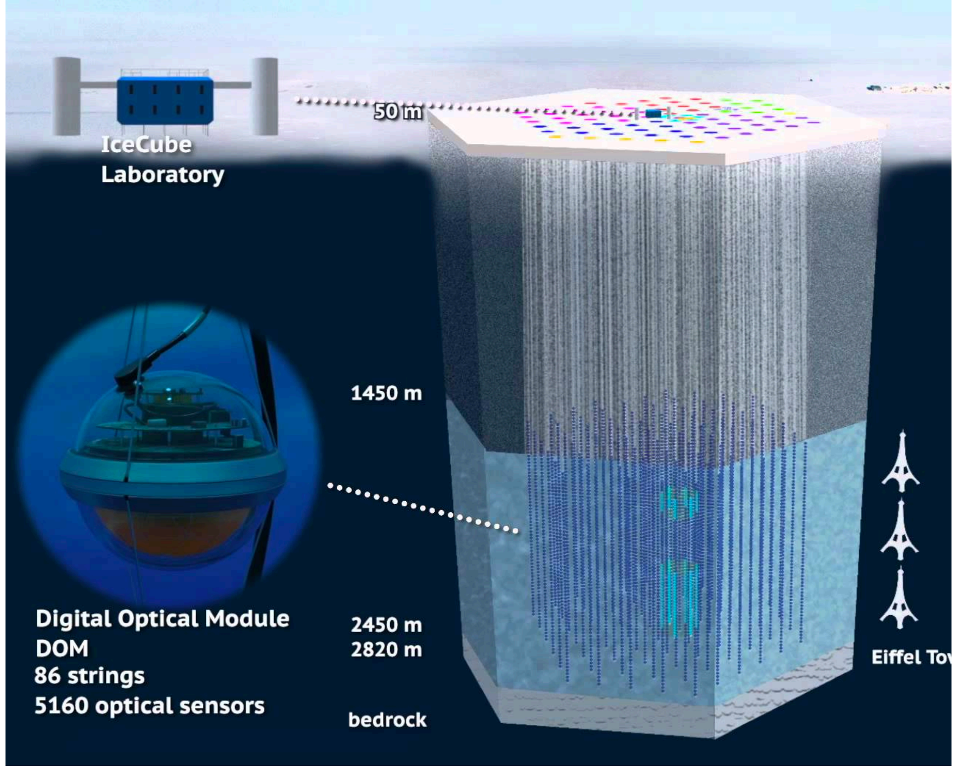
HERA: evidence for BFKL dynamics in inclusive structure functions



LHC: charm production and the small-x gluon PDF



IceCube: ultra high-energy neutrino-nucleus cross-sections



Heavy ions: towards a NNPDF fit of nuclear PDFs

Evidence for BFKL dynamics from HERA

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

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

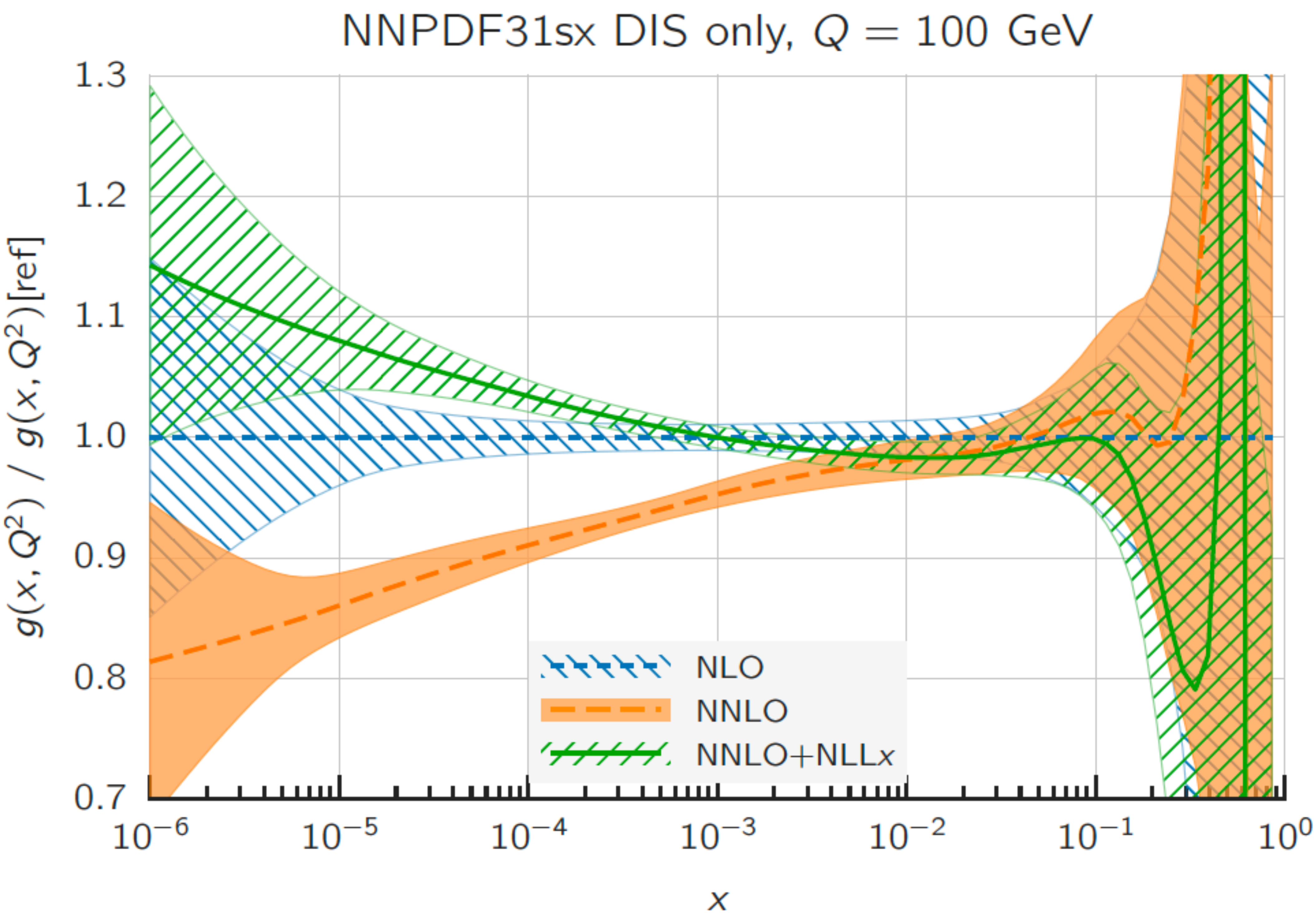
$$\frac{\partial}{\partial \ln 1/x} f_+(x,Q^2) = \int_0^\infty \frac{d\nu^2}{\nu^2} K\left(\frac{Q^2}{\nu^2}, \alpha_s(Q^2)\right) f_+(x,\nu^2)$$

ABF, CCSS, TW + others, 94-08

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

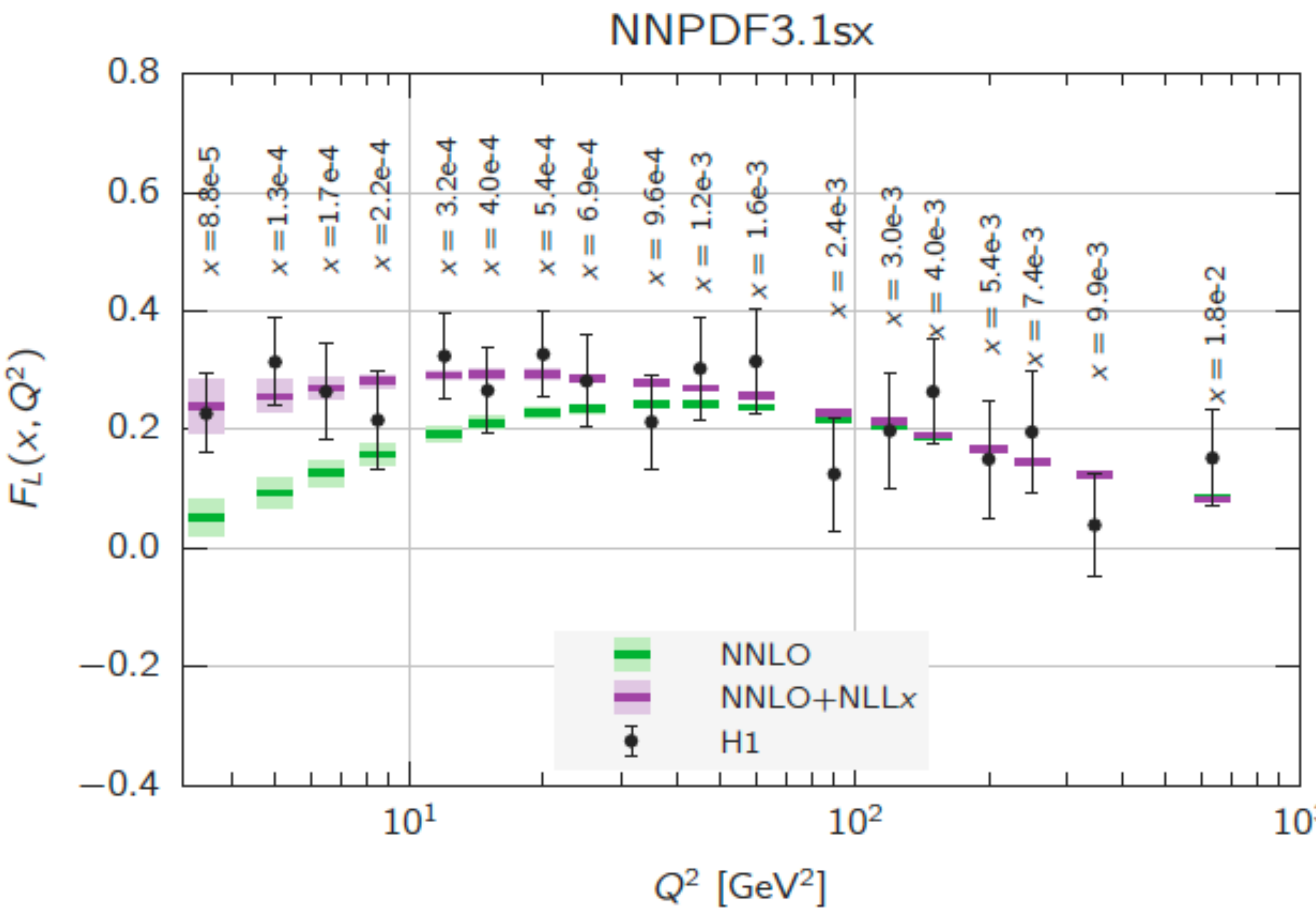
PDF fits with small-x resummation

BFKL resummation **stabilises perturbative behaviour** of small-x **gluon**

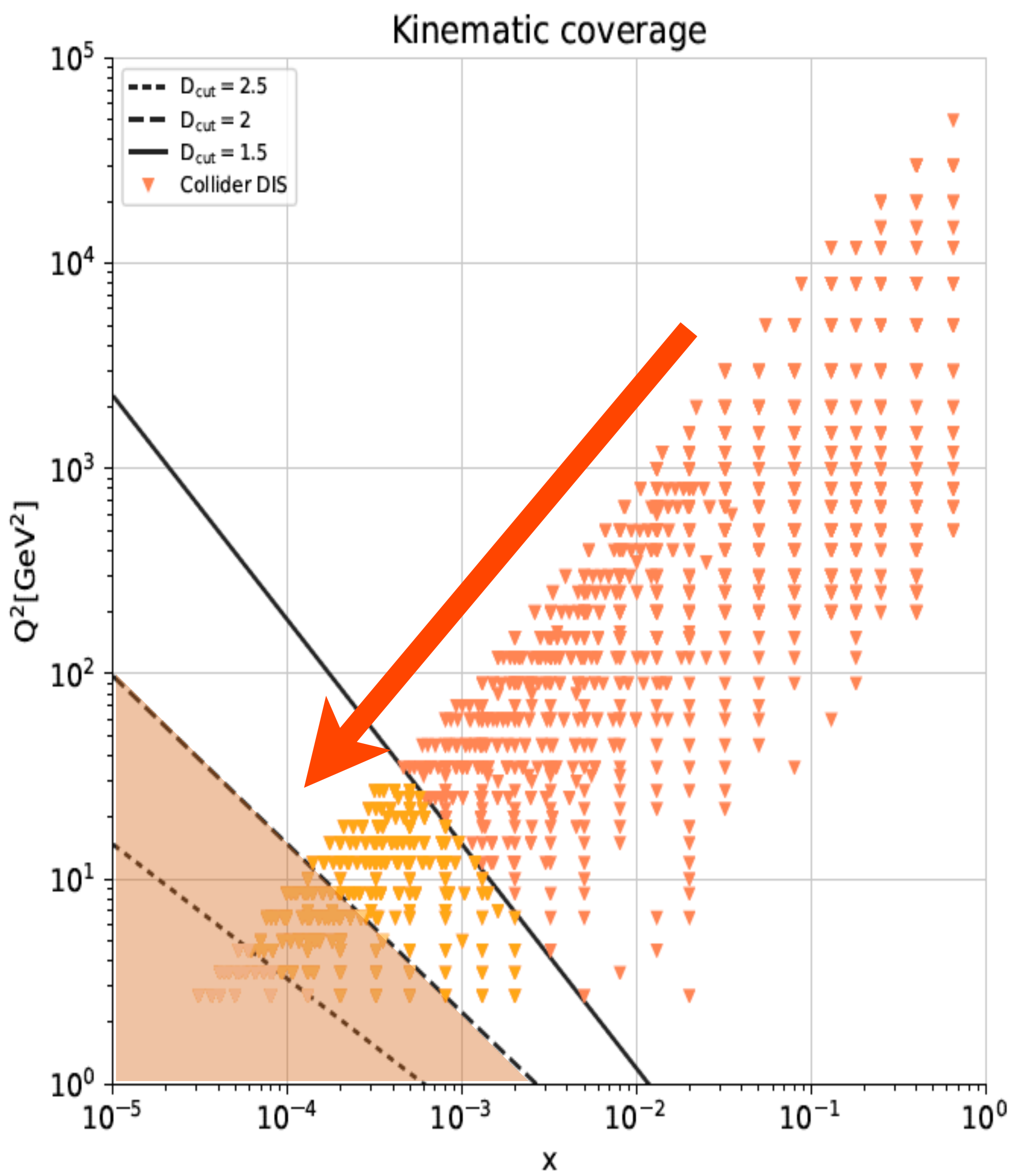


PDF fits with small-x resummation

BFKL resummation **stabilises perturbative behaviour** of small-x $\mathbf{F_L}$

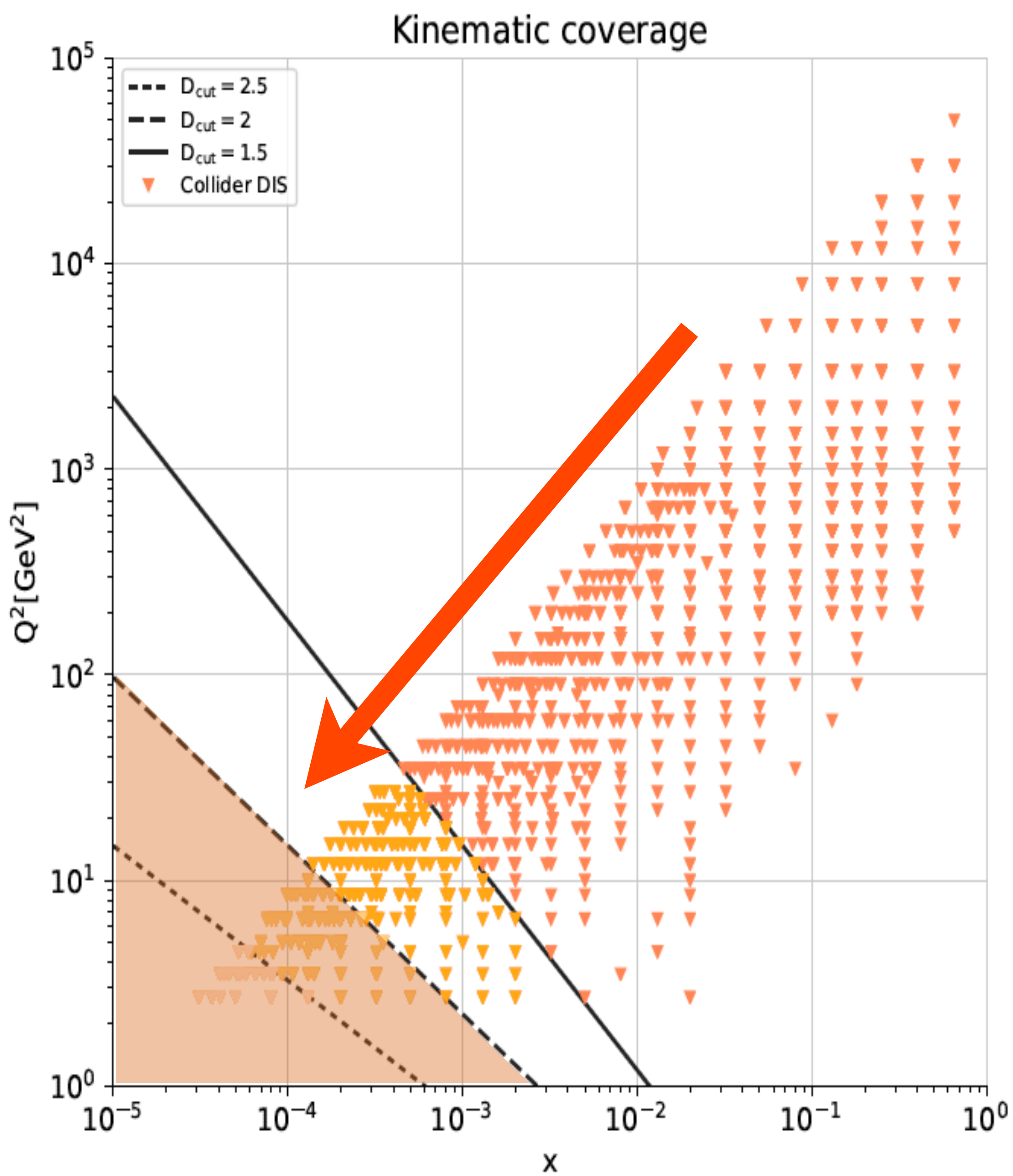


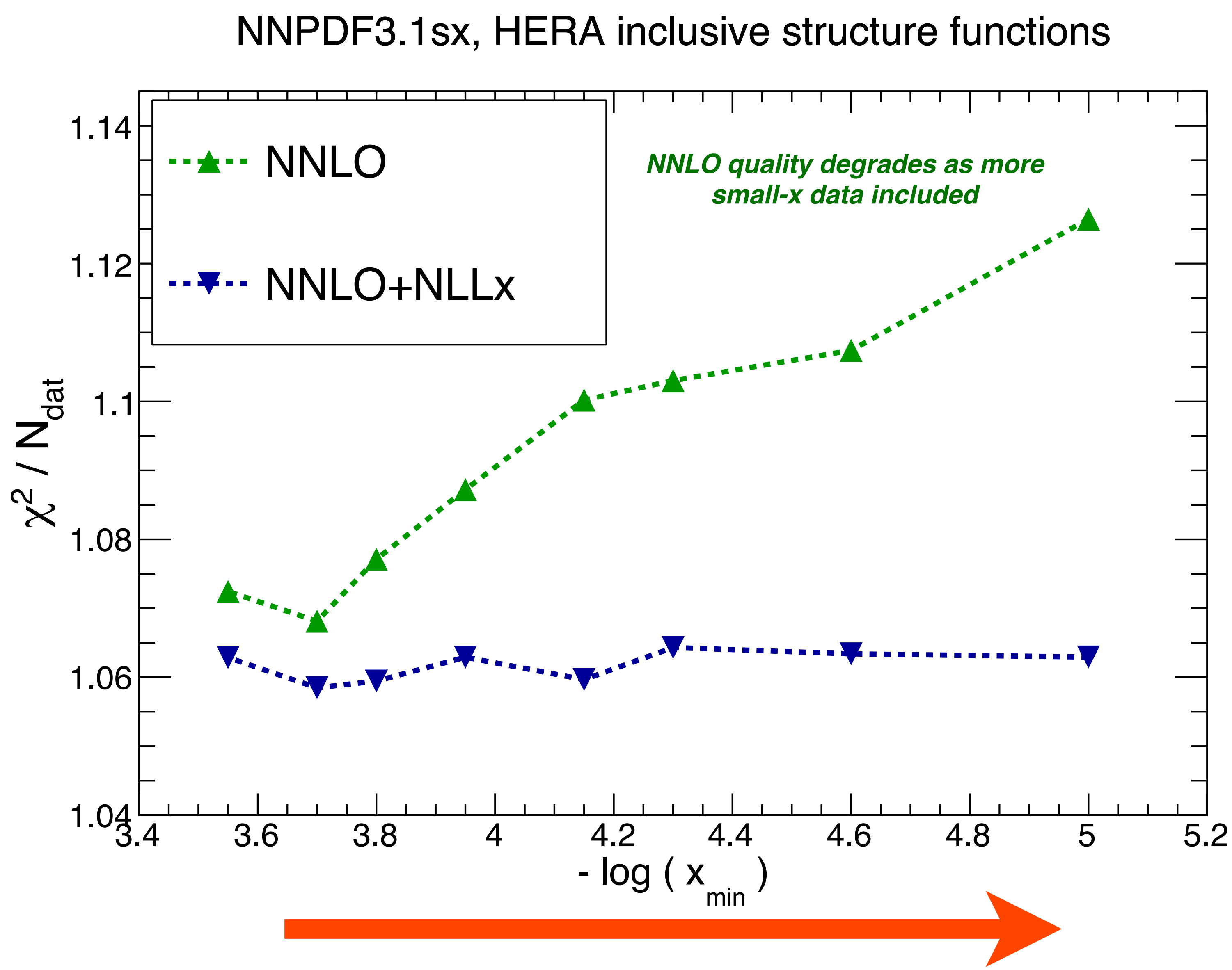
Evidence for BFKL dynamics



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

Evidence for BFKL dynamics

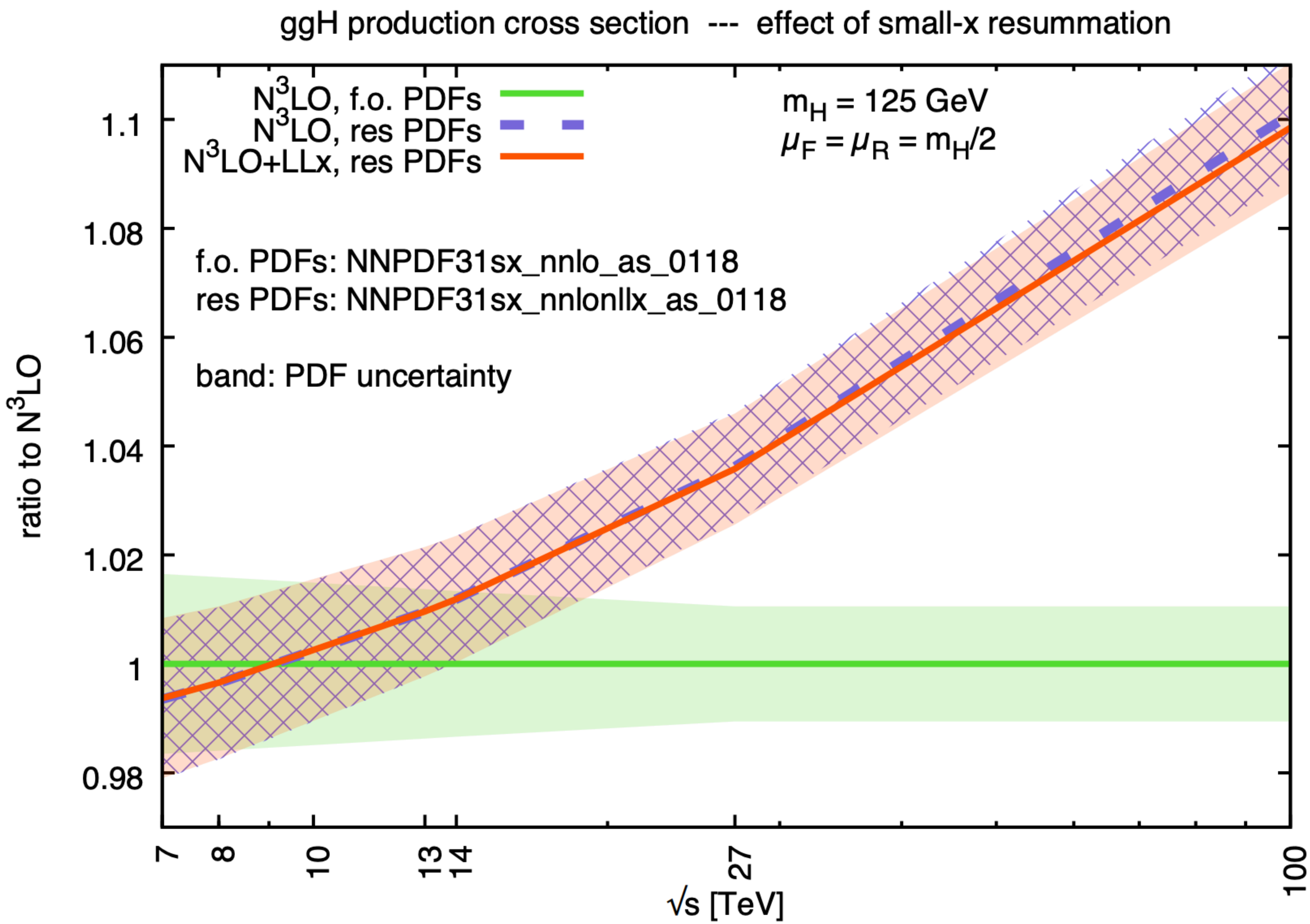




Monitor the **fit quality** as one includes more data from the **small-*x* region**

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

Implications at the LHC



100% effects for Higgs physics at the FCC

Bonvini, Marzani 18

‘New Physics’ within QCD

Science
Life and Physics

The Guardian

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

Jon Butterworth

@jonmbutterworth
Thu 28 Dec 2017 17.30 GMT

529 59

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-

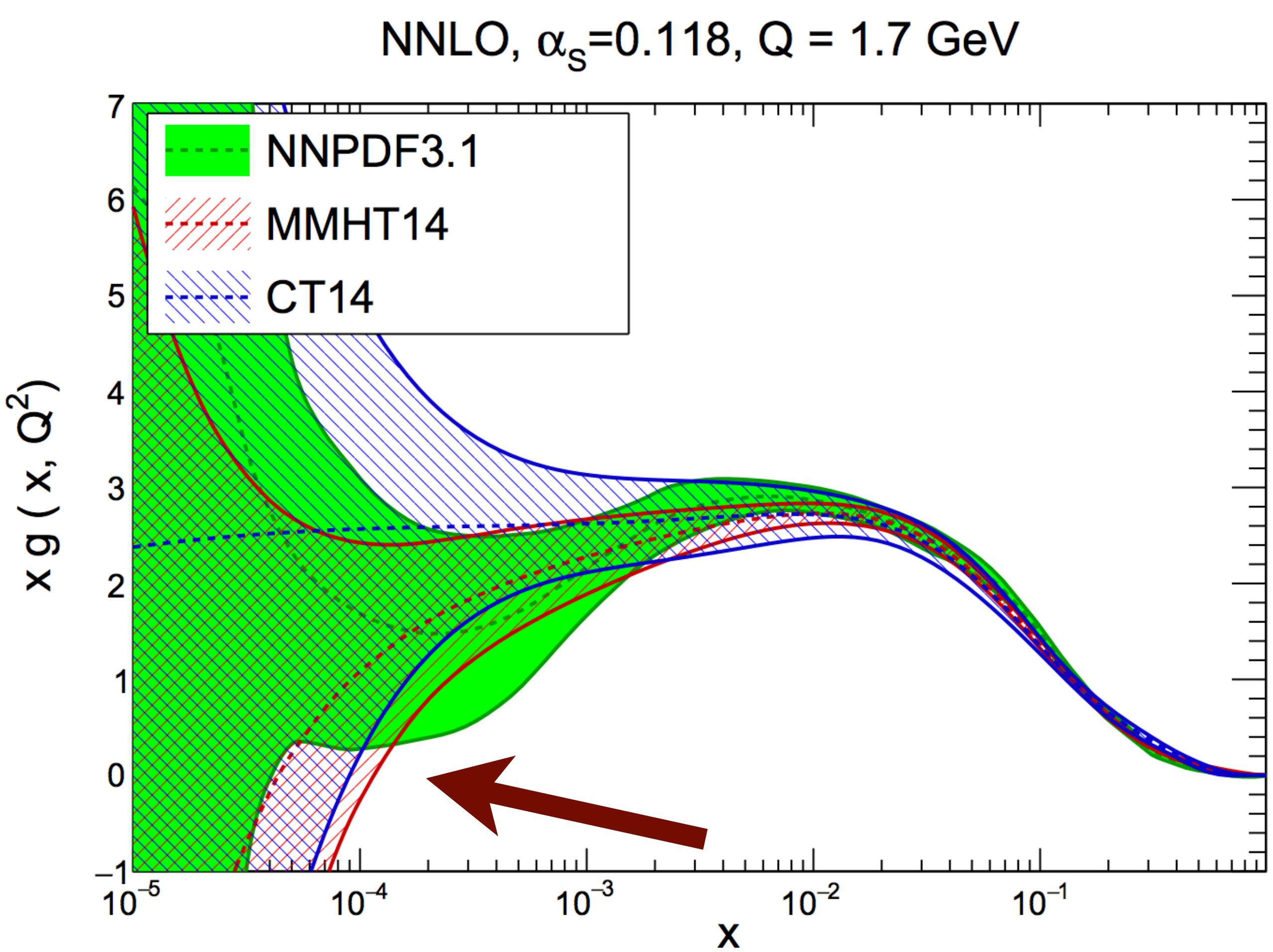
The small-x gluon from charm production

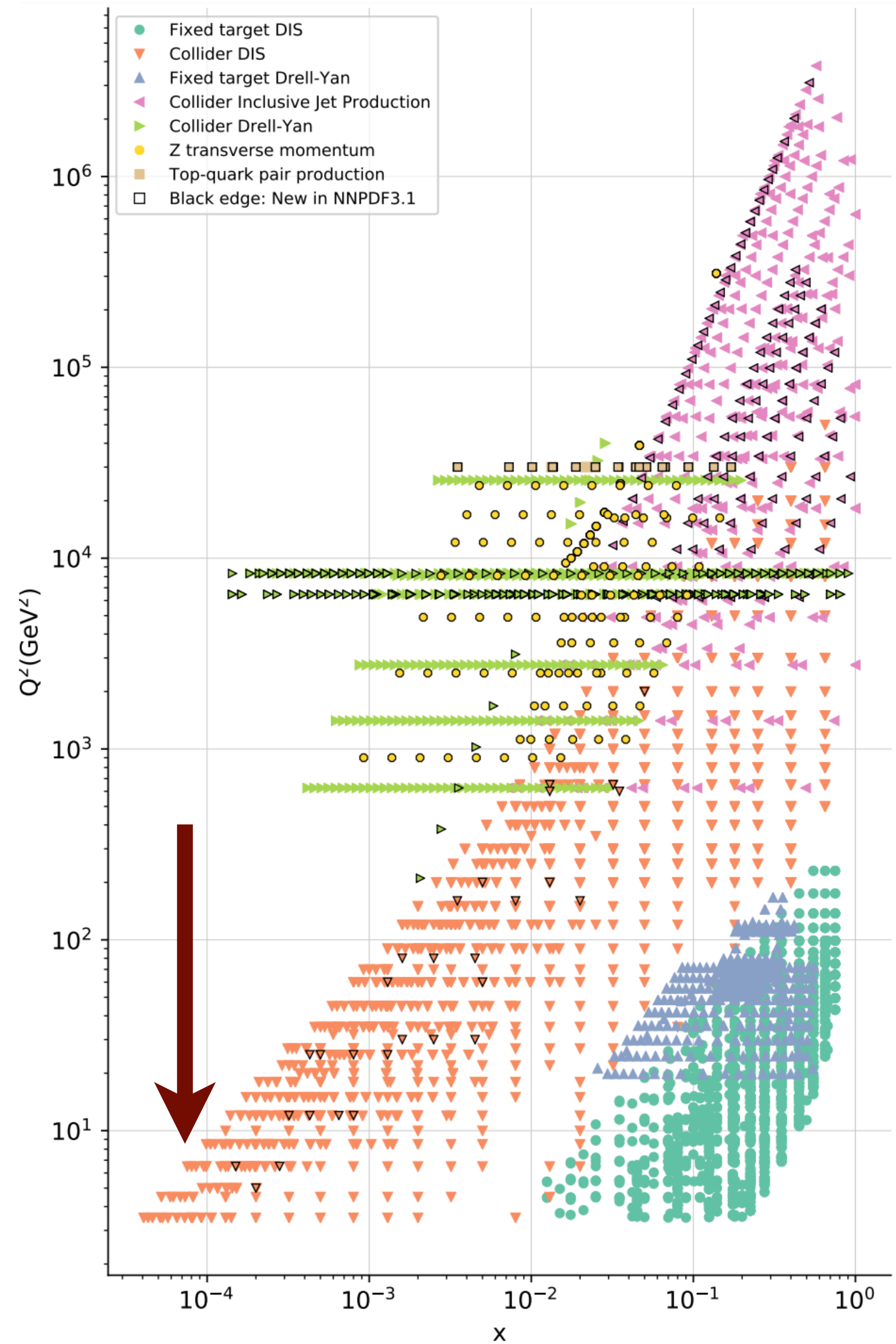
Gauld, JR, Rottoli, Talbert 15

Gauld, JR 16

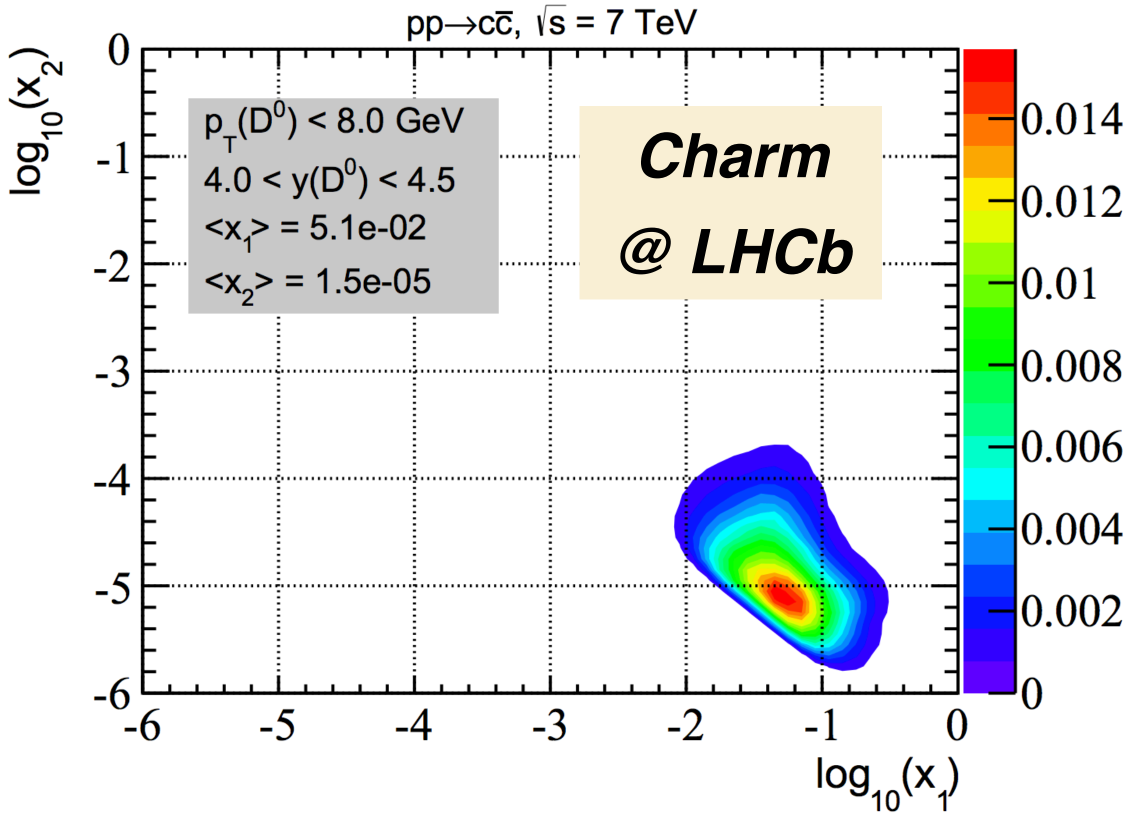
The small-x gluon from HERA data

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



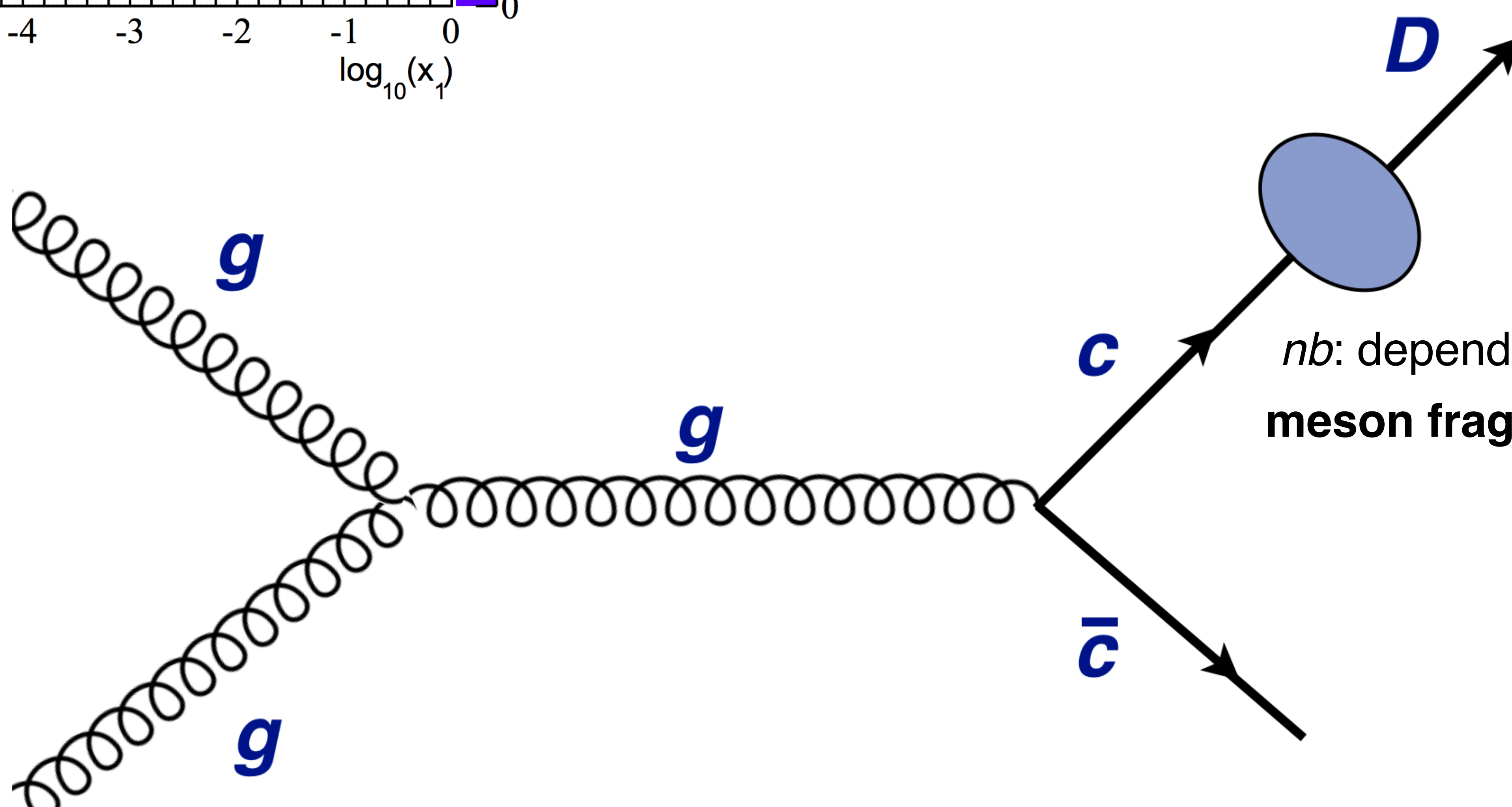


Forward charm production



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

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



nb: dependence on **D meson fragmentation**

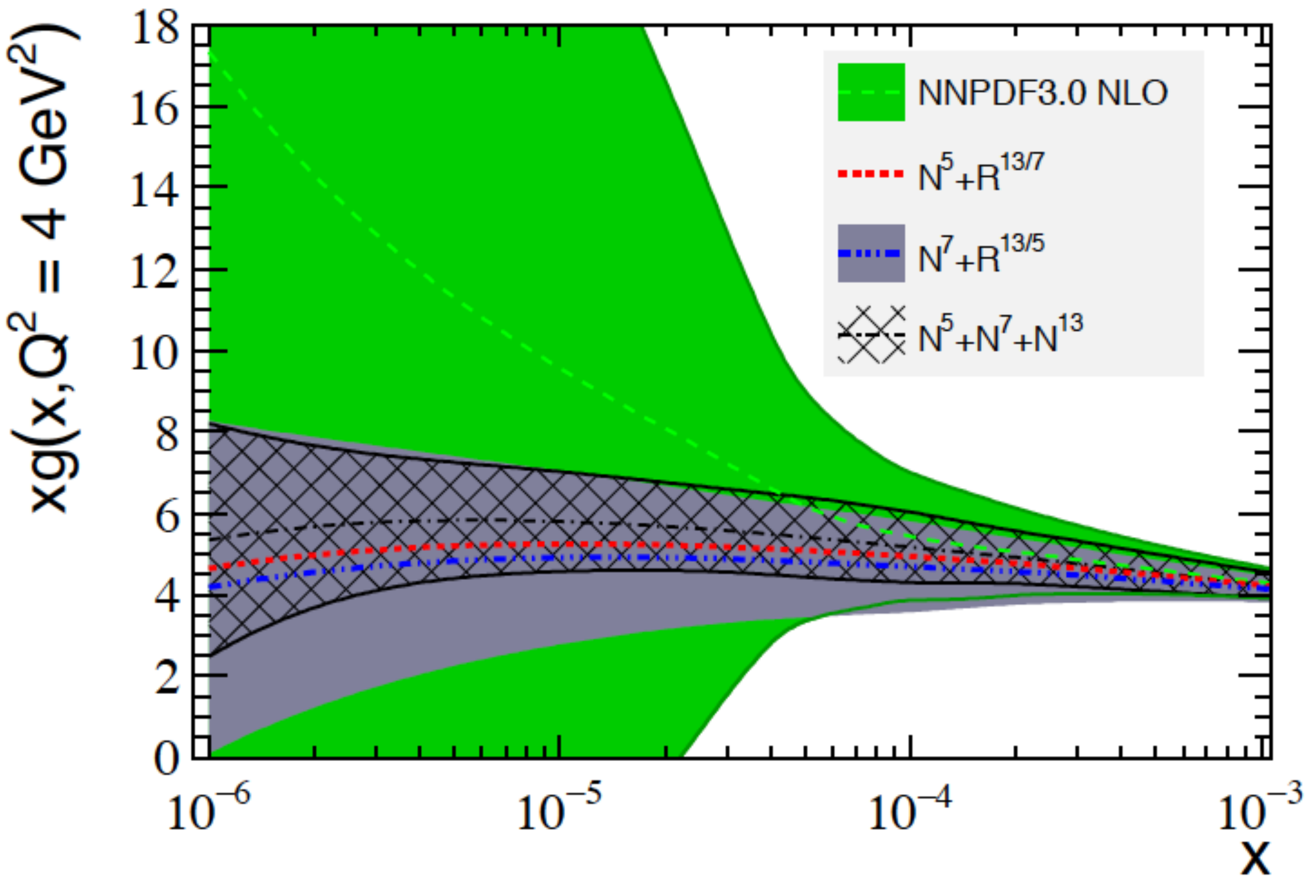
Forward charm production

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

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

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

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

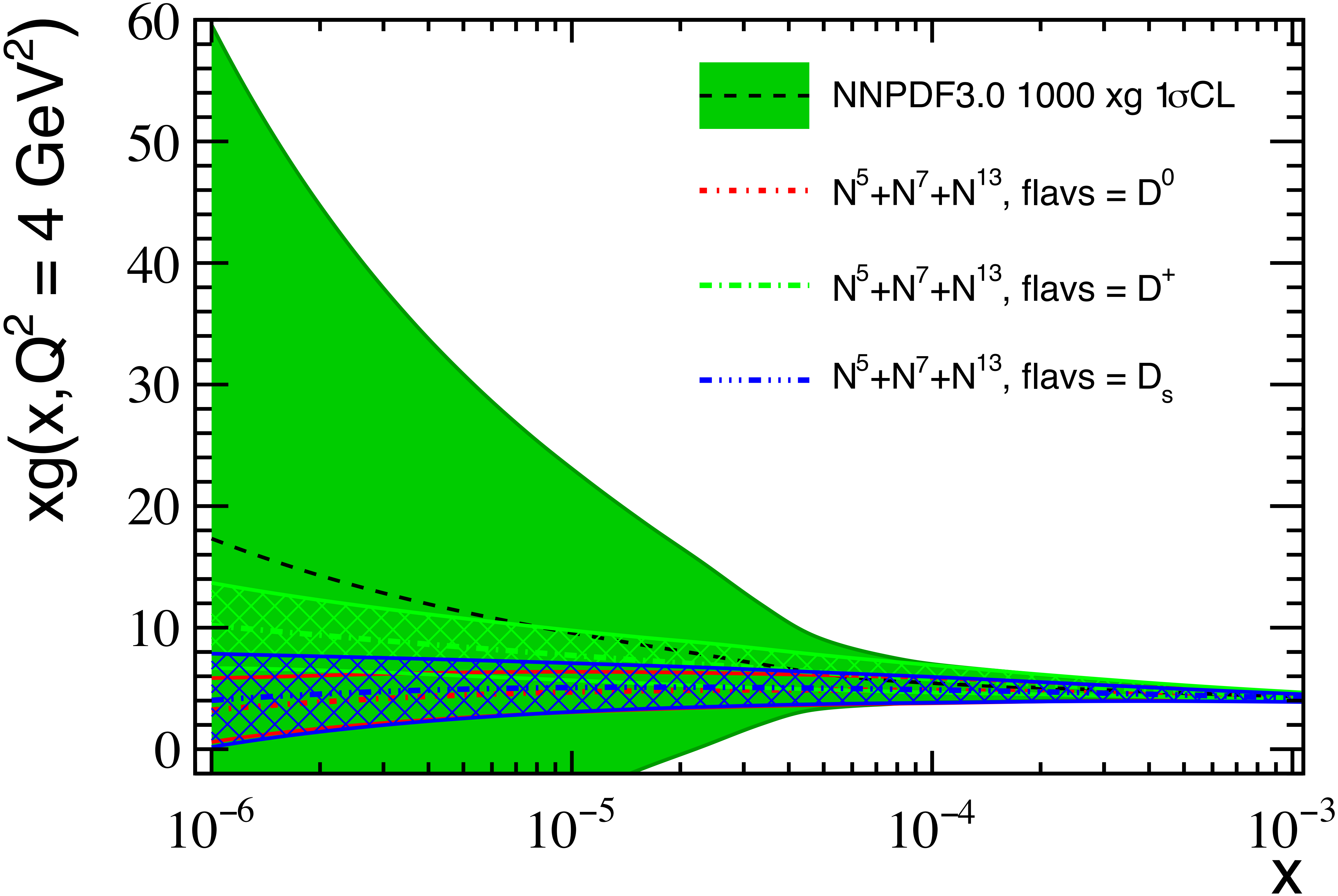


Excellent description of all LHCb datasets and ratios (after **errata** corrected)

$N_5(84)$	$N_7(79)$	$N_{13}(126)$	$R_{13/5}(107)$	$R_{13/7}(102)$
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

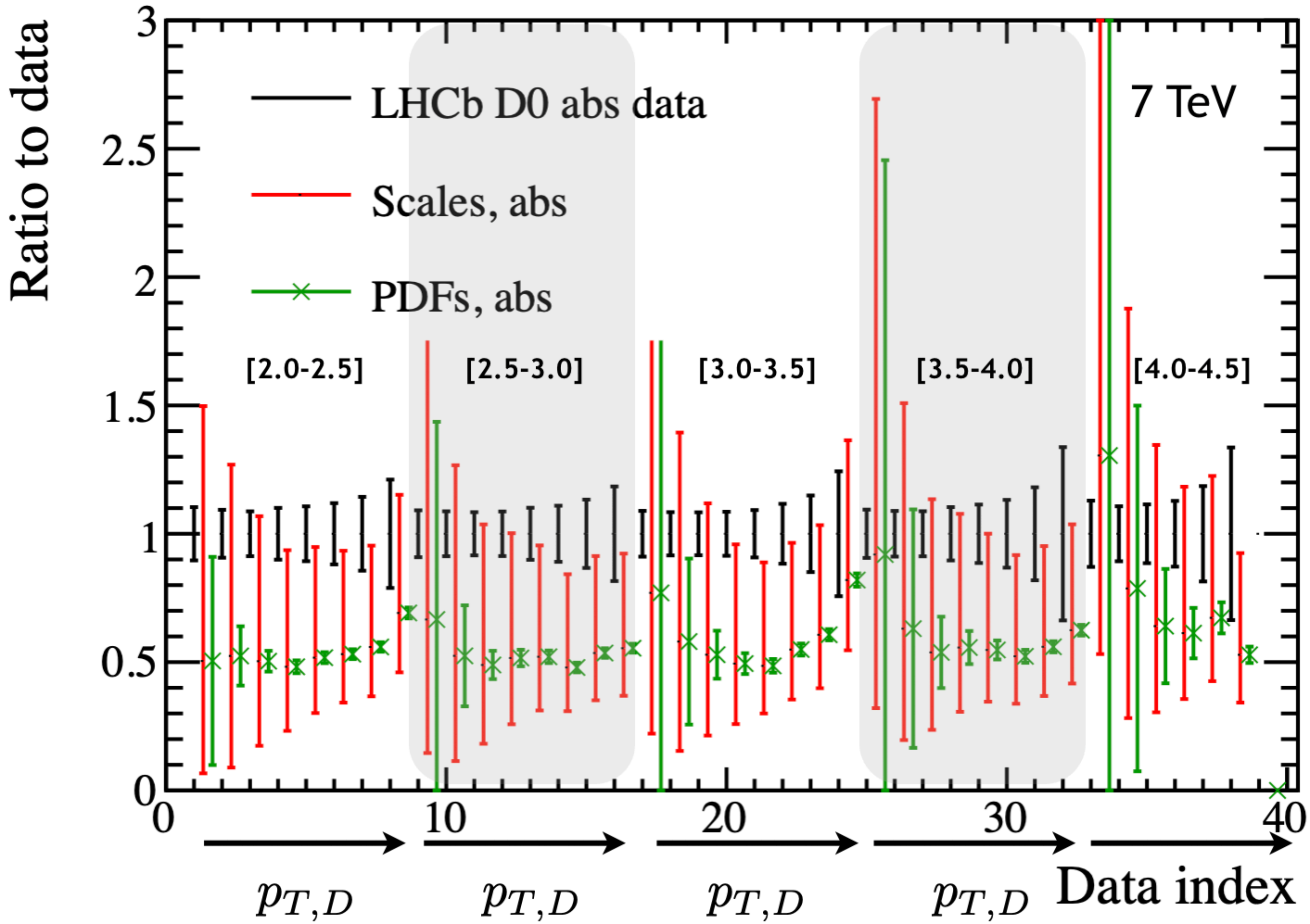
Forward charm production

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



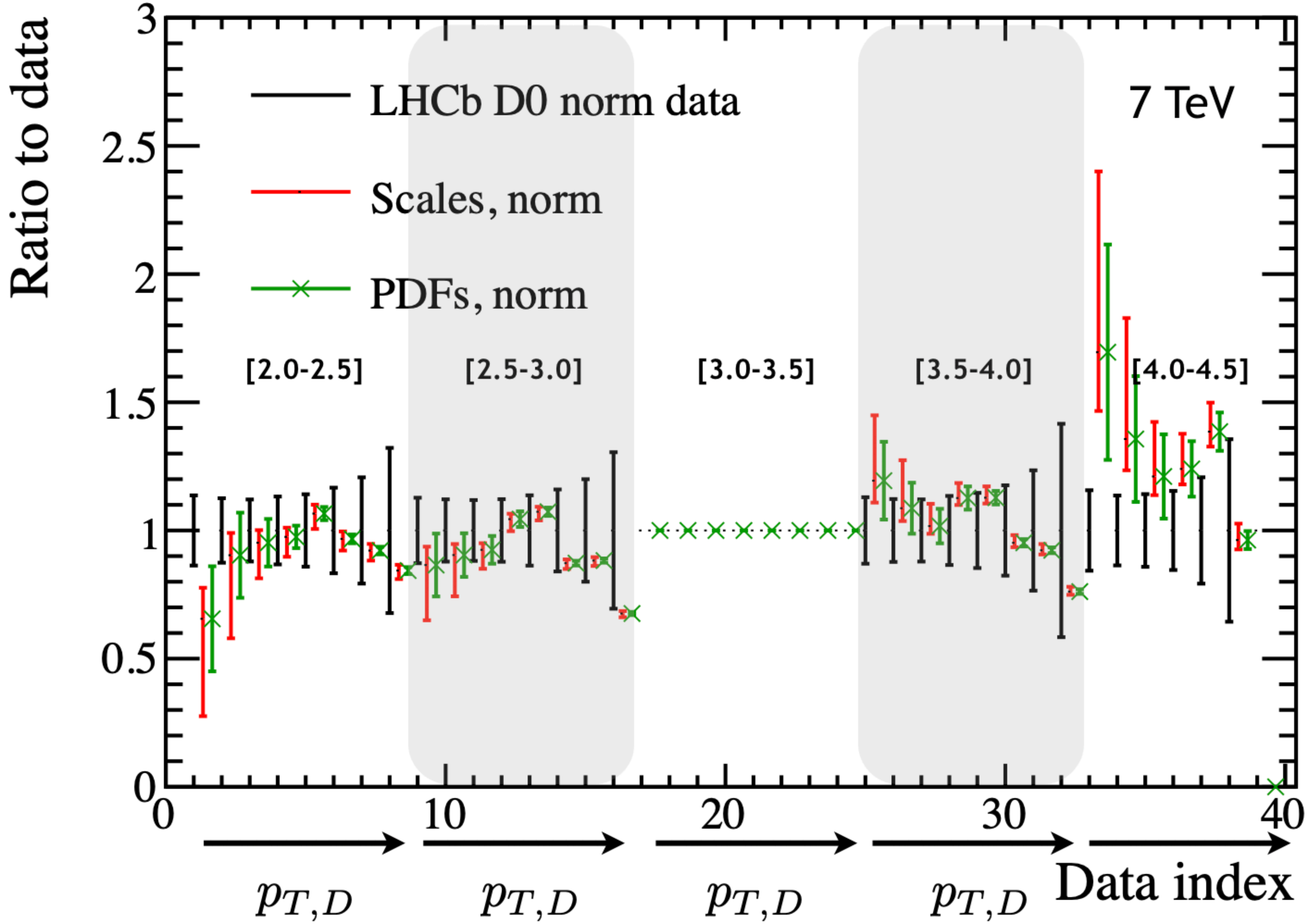
Forward charm production

Cross-section ratios: improved perturbative stability



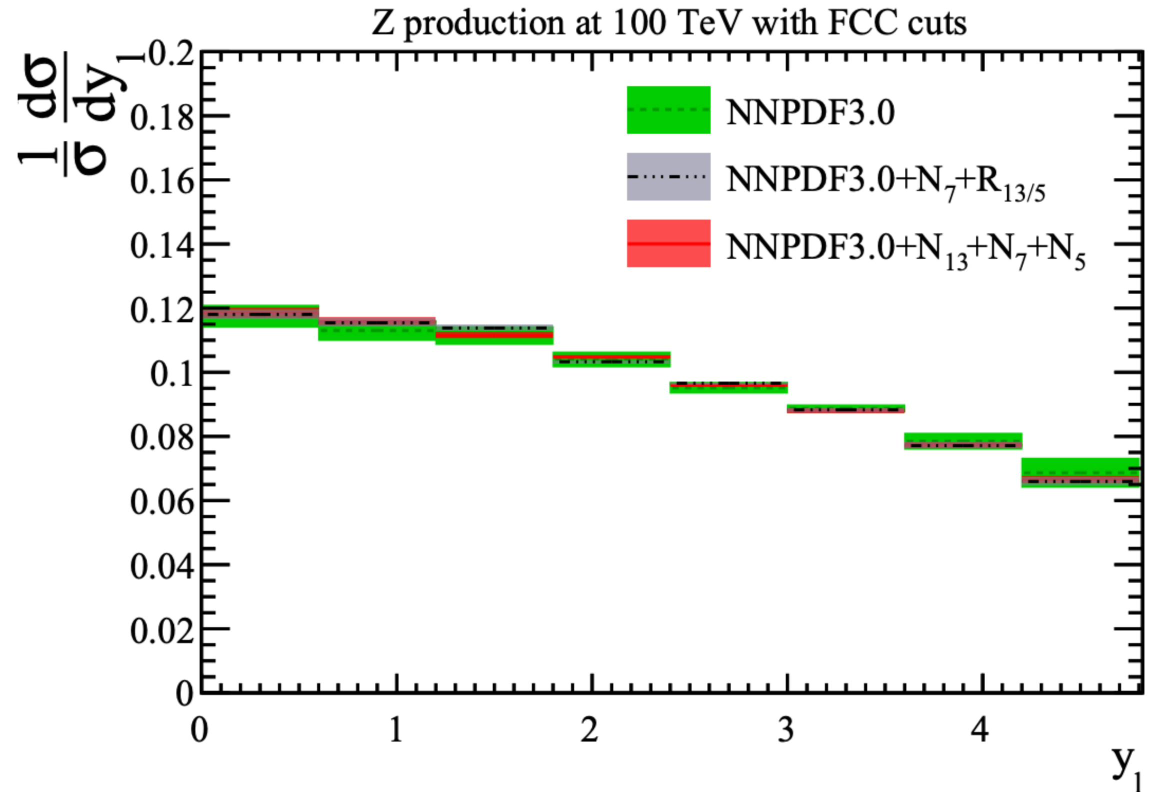
Forward charm production

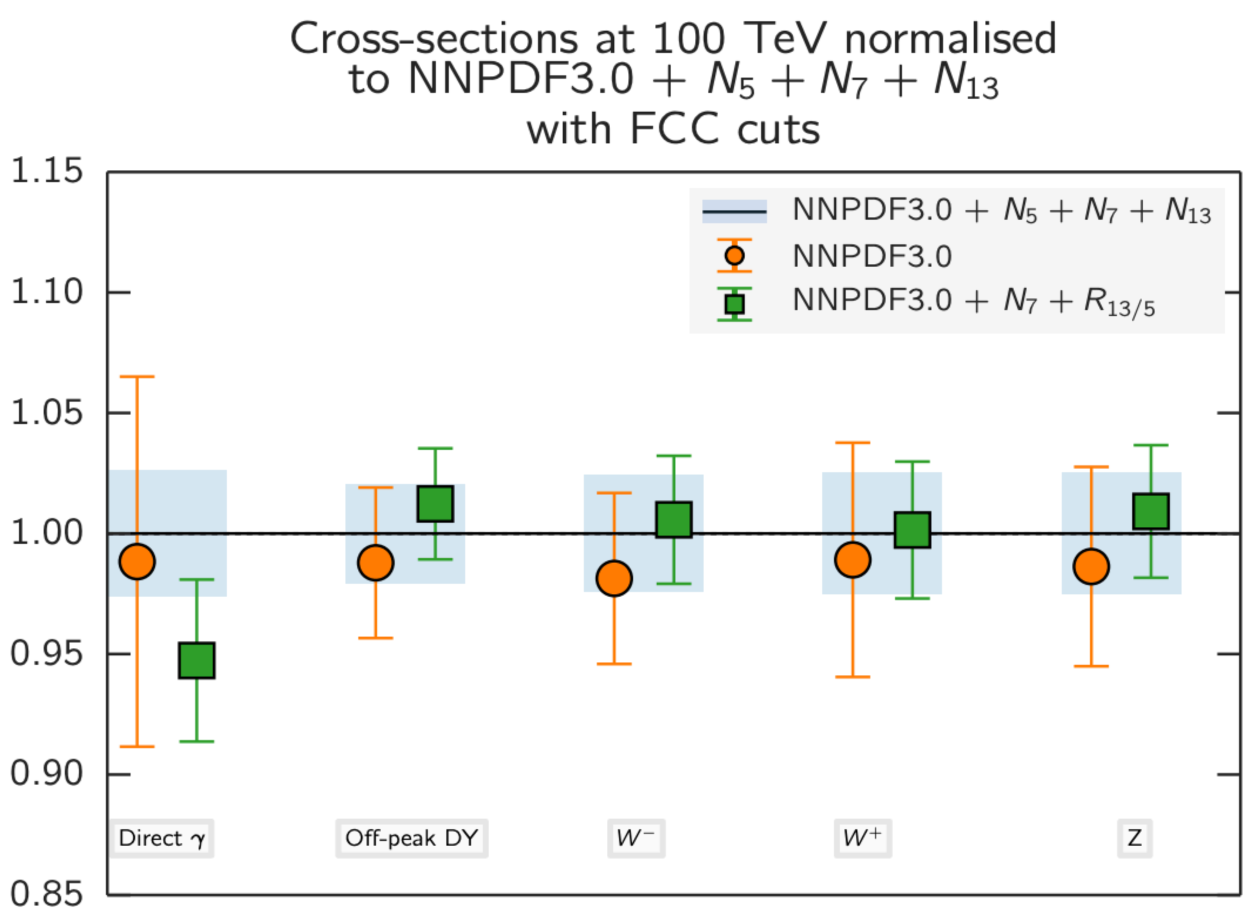
Cross-section ratios: improved perturbative stability

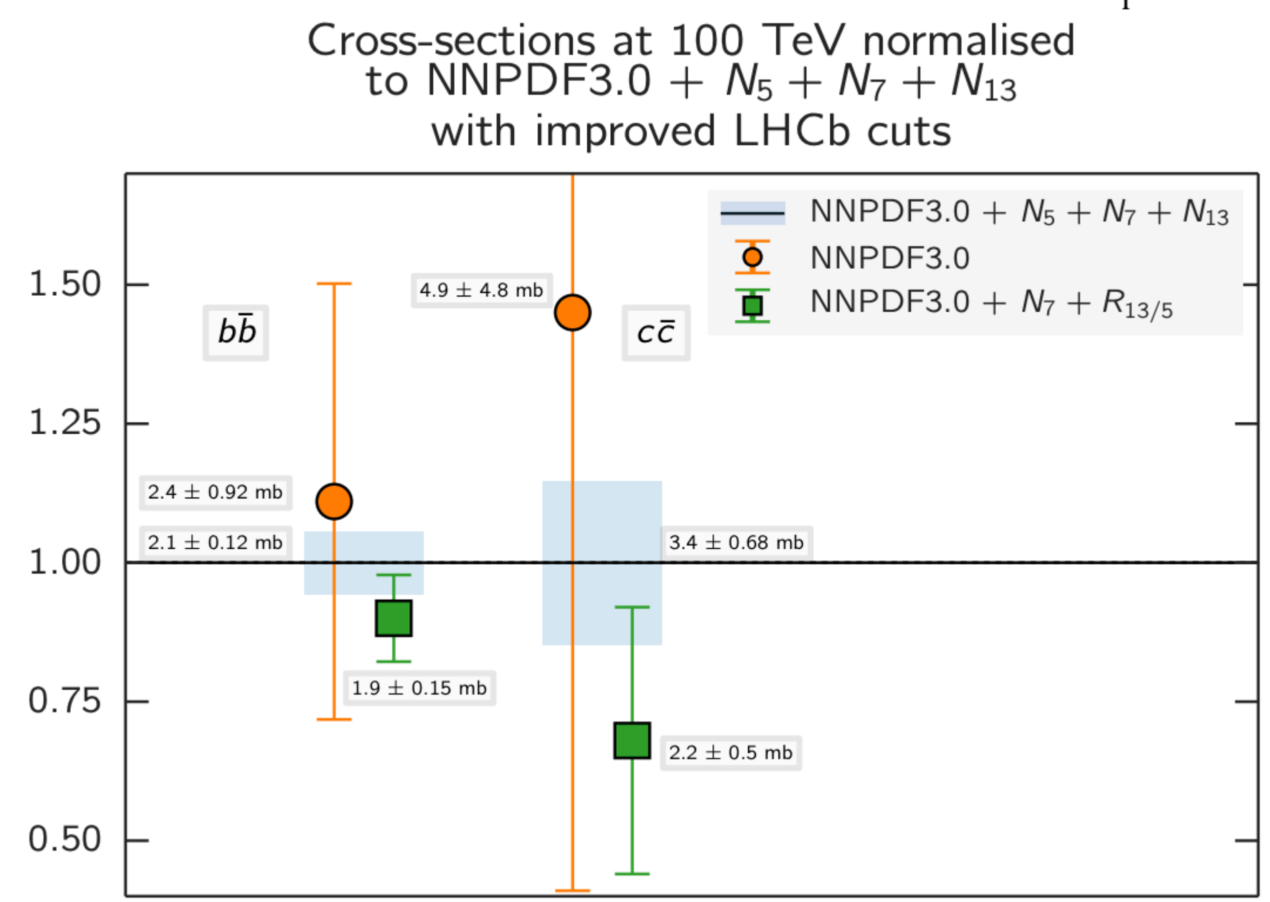


Implications for future colliders

- At a 100 TeV collider even **electroweak processes** are sensitive to small-x region
- Precision phenomenology will require pinning down PDFs down to ***very small-x***







Neutrino telescopes as QCD microscopes

Gauld, JR, Rottoli, Talbert, Sarkar 15

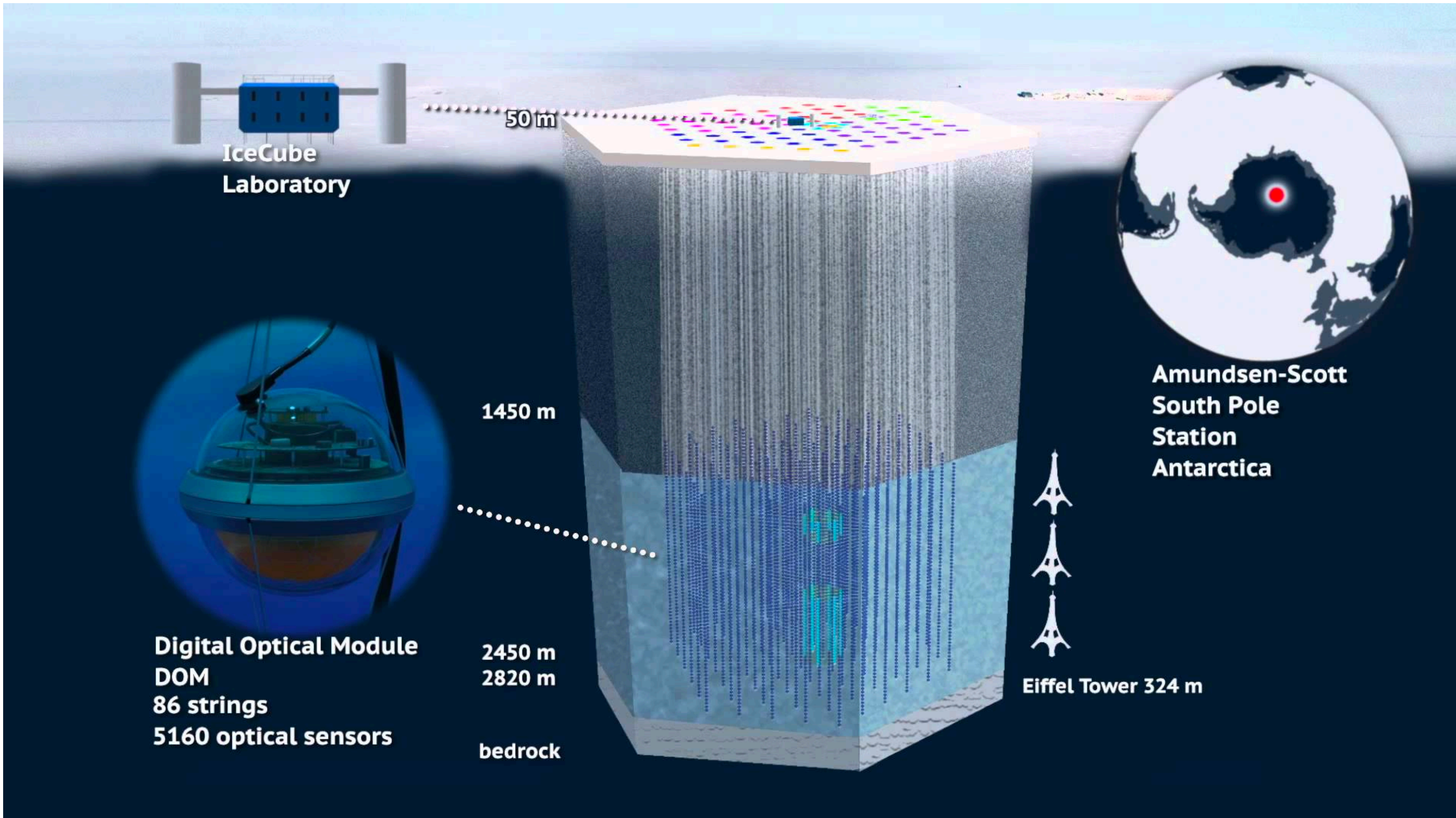
Bertone, Gauld, JR 18

Neutrino telescopes

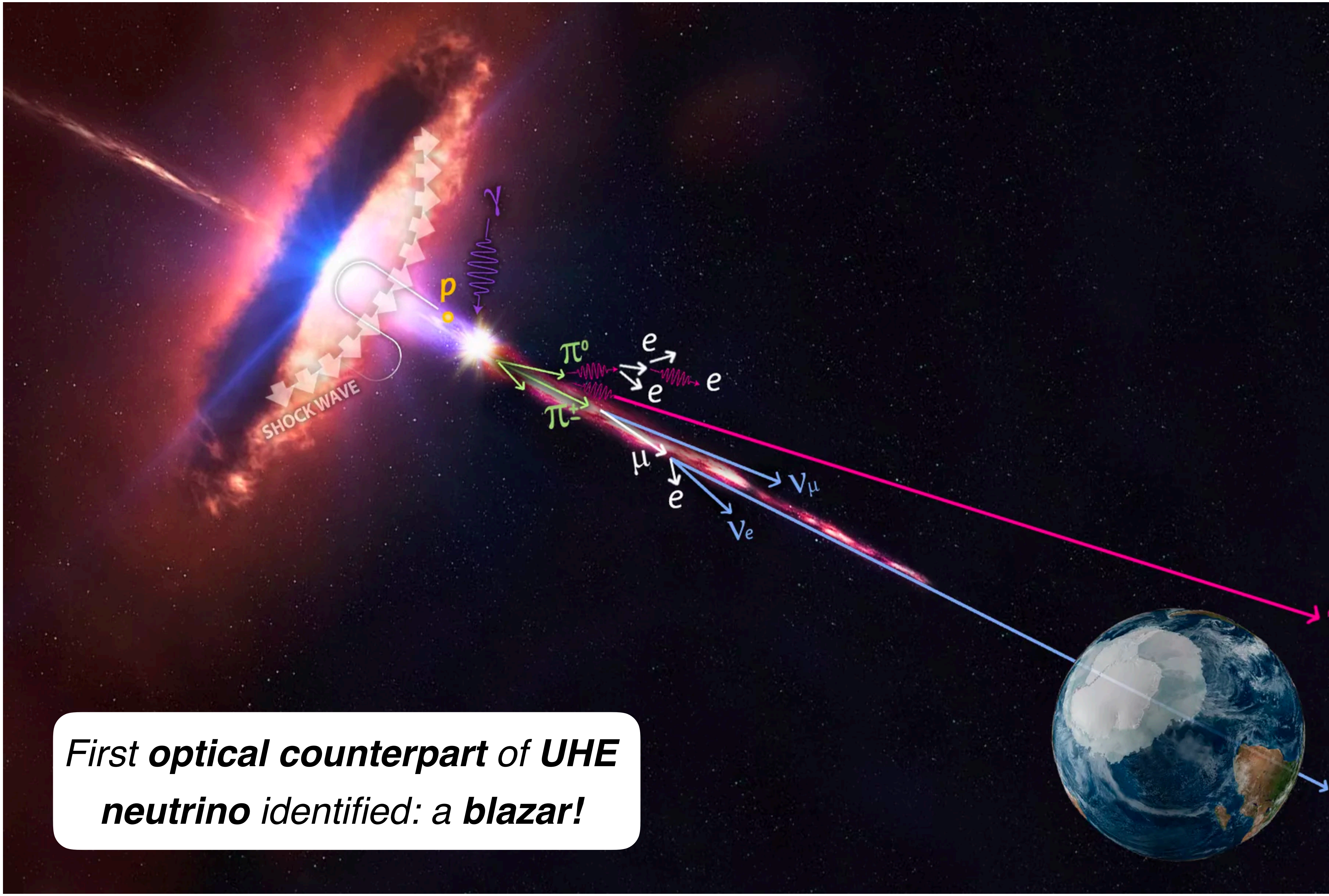
Ultra-high energy (UHE) neutrinos: novel window to the **extreme Universe!**

Neutrino telescopes

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



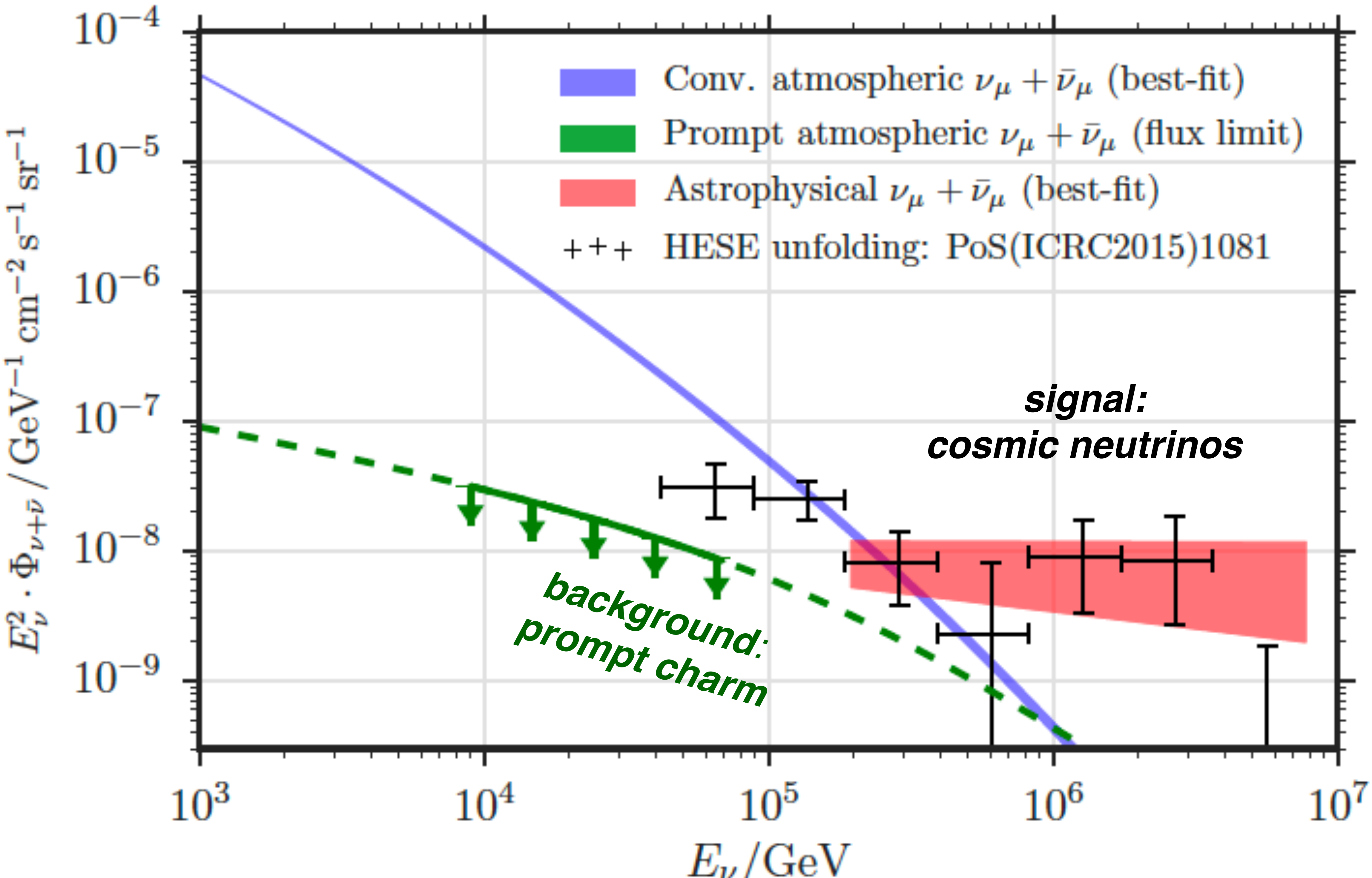
Unveiling cosmic neutrino origin



Neutrino telescopes as QCD microscopes

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

***background**: prompt charm production*



Neutrino telescopes as QCD microscopes

signal*: cosmic neutrino - nucleus scattering*

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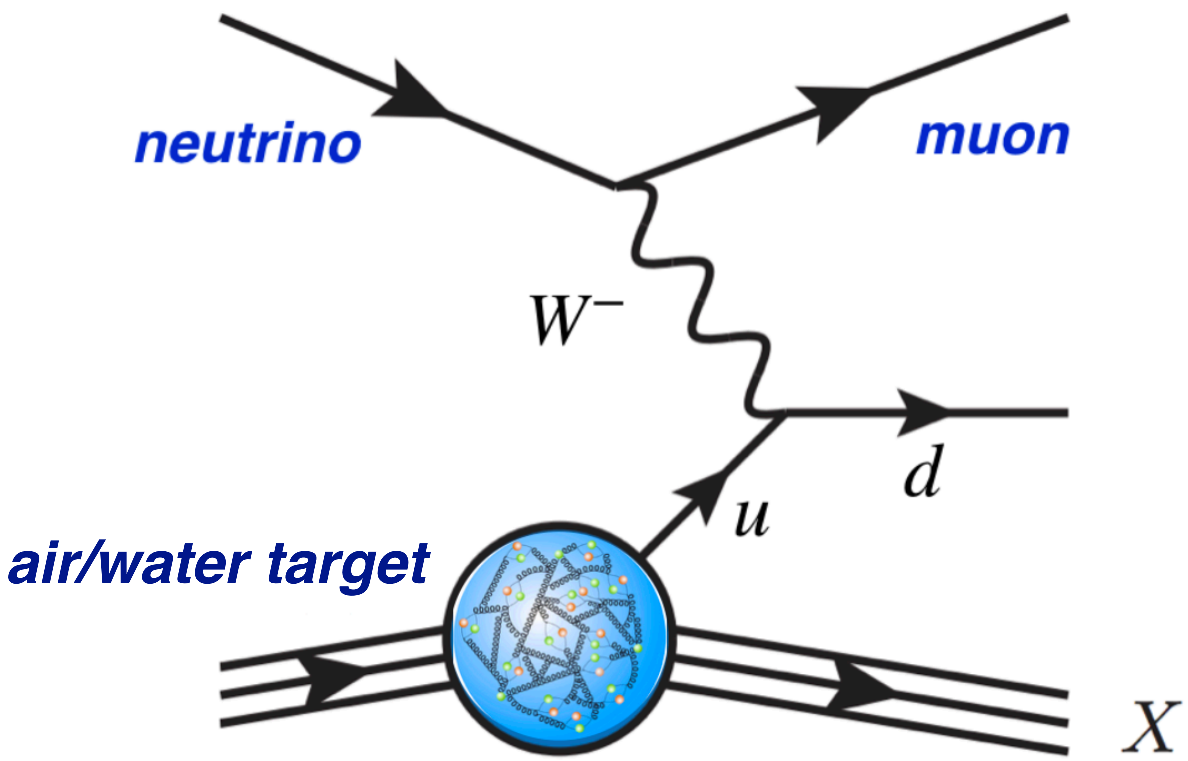

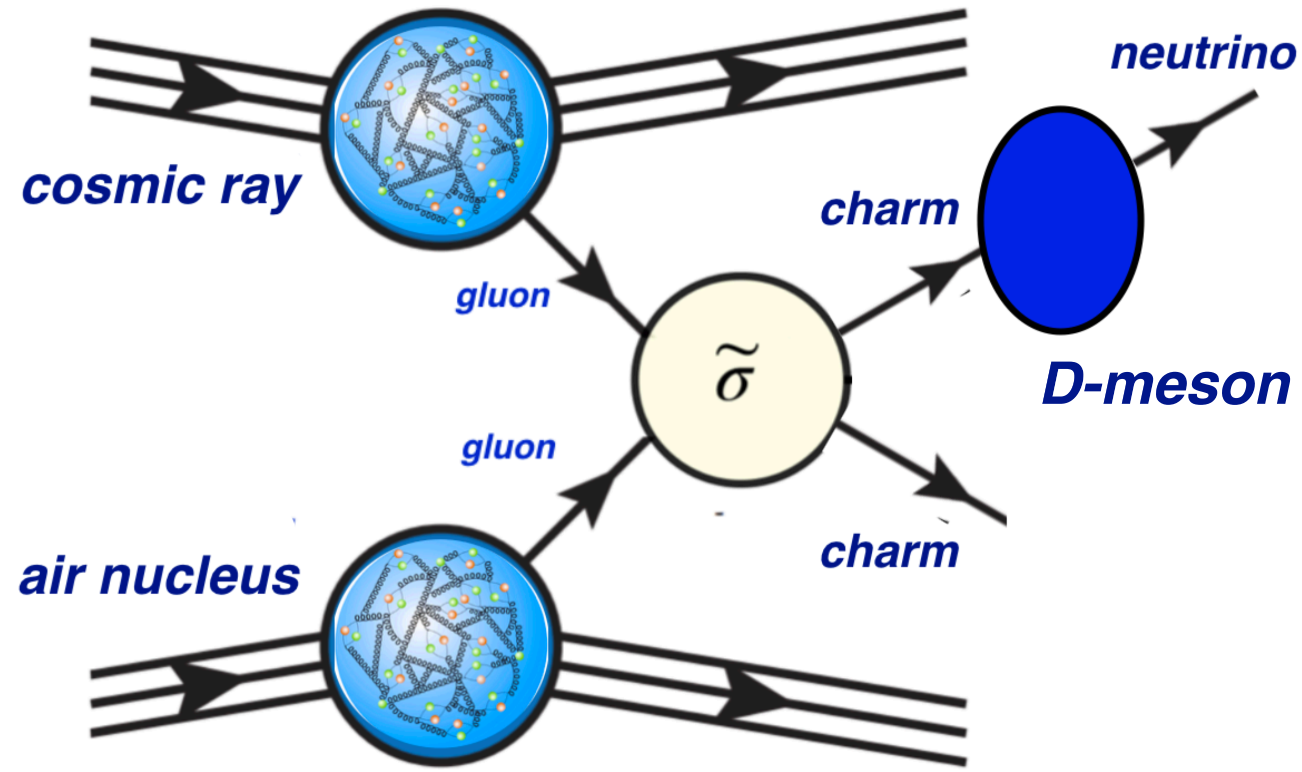

Sensitive to **small-*x* quarks** (and thus gluons via evolution) down to **x** ≃ **10^{-8}** and **Q** ≃ **M$_W$**

Sensitive to **small-*x* gluons** down to **x** ≃ **10^{-6}** and **Q** ≃ **M$_{charm}$** in the **centre-of-mass frame**

Neutrino telescopes as QCD microscopes

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

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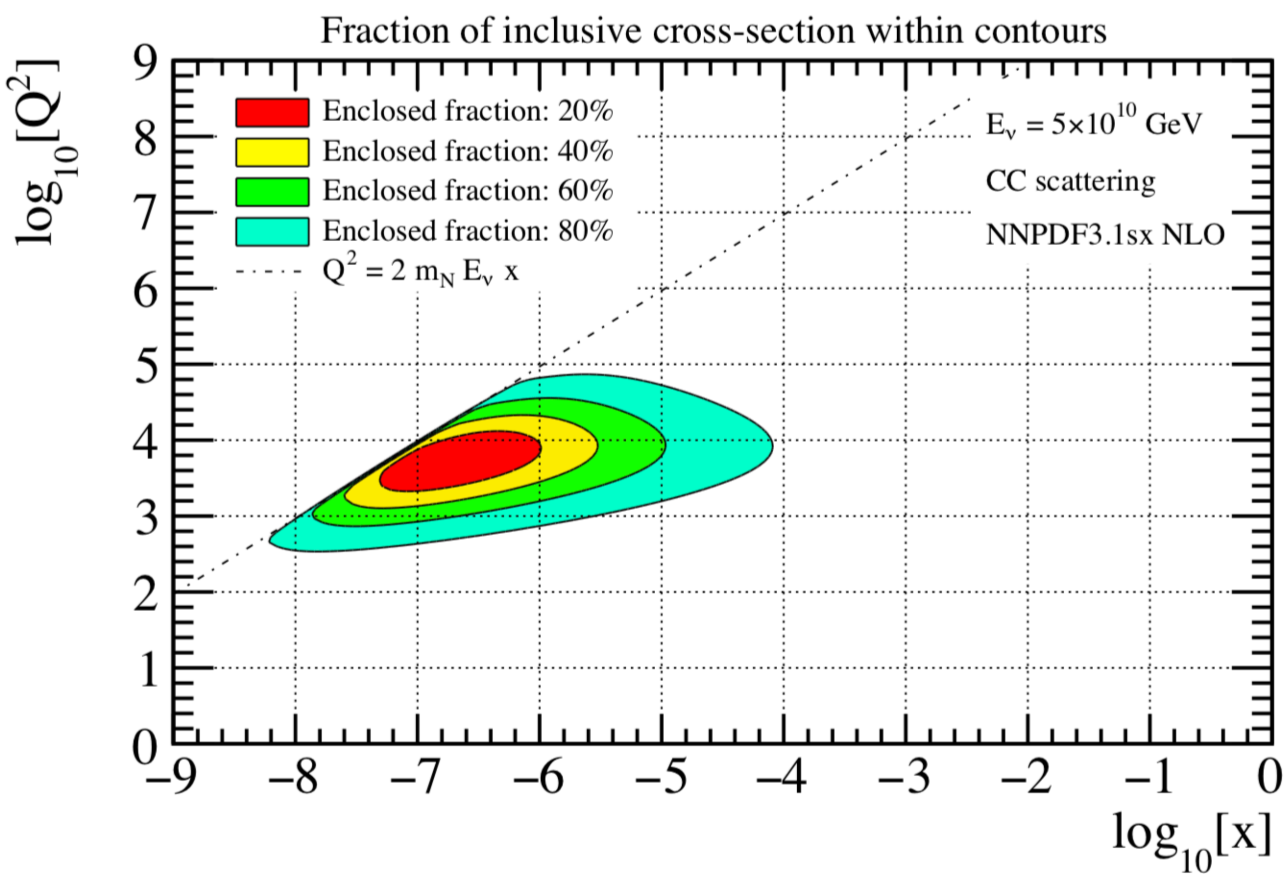
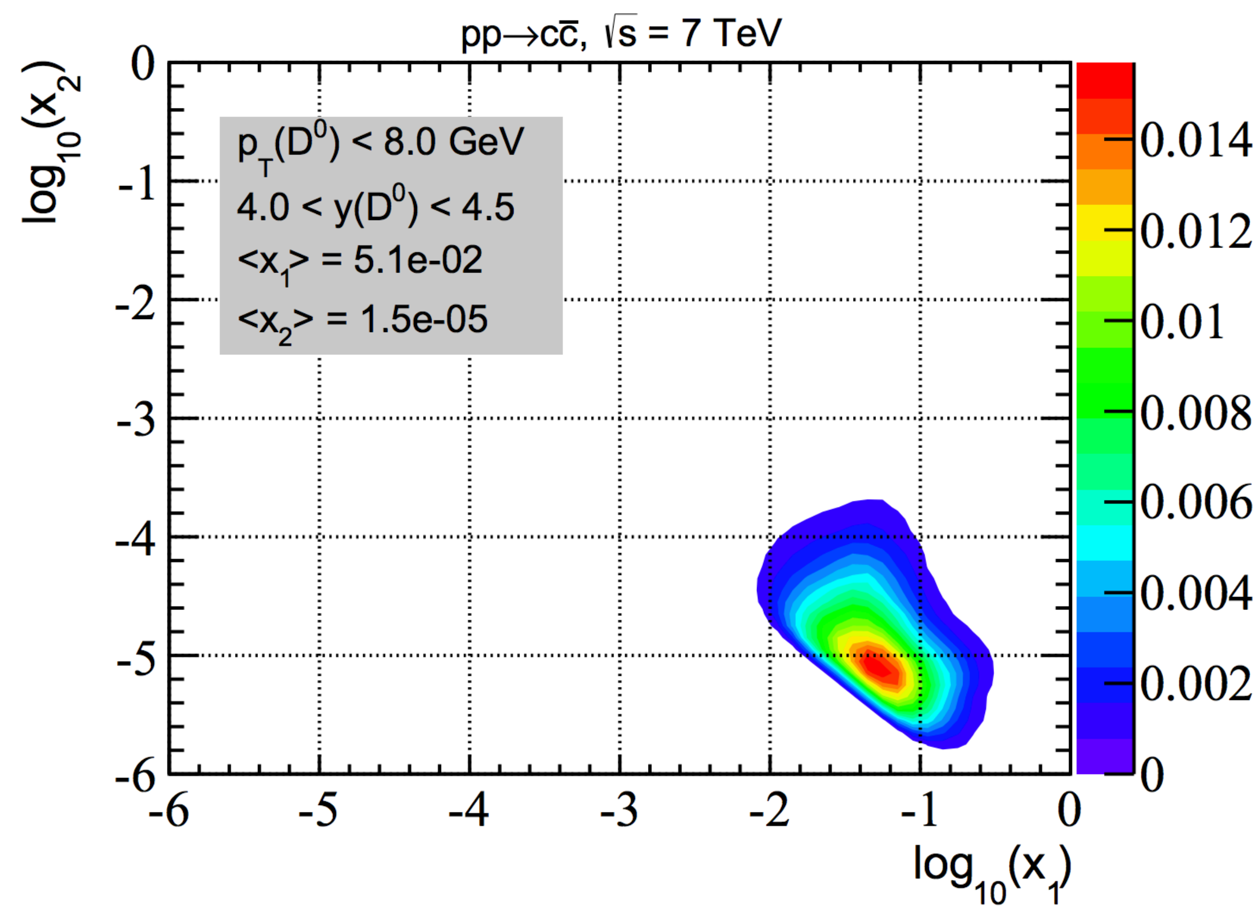




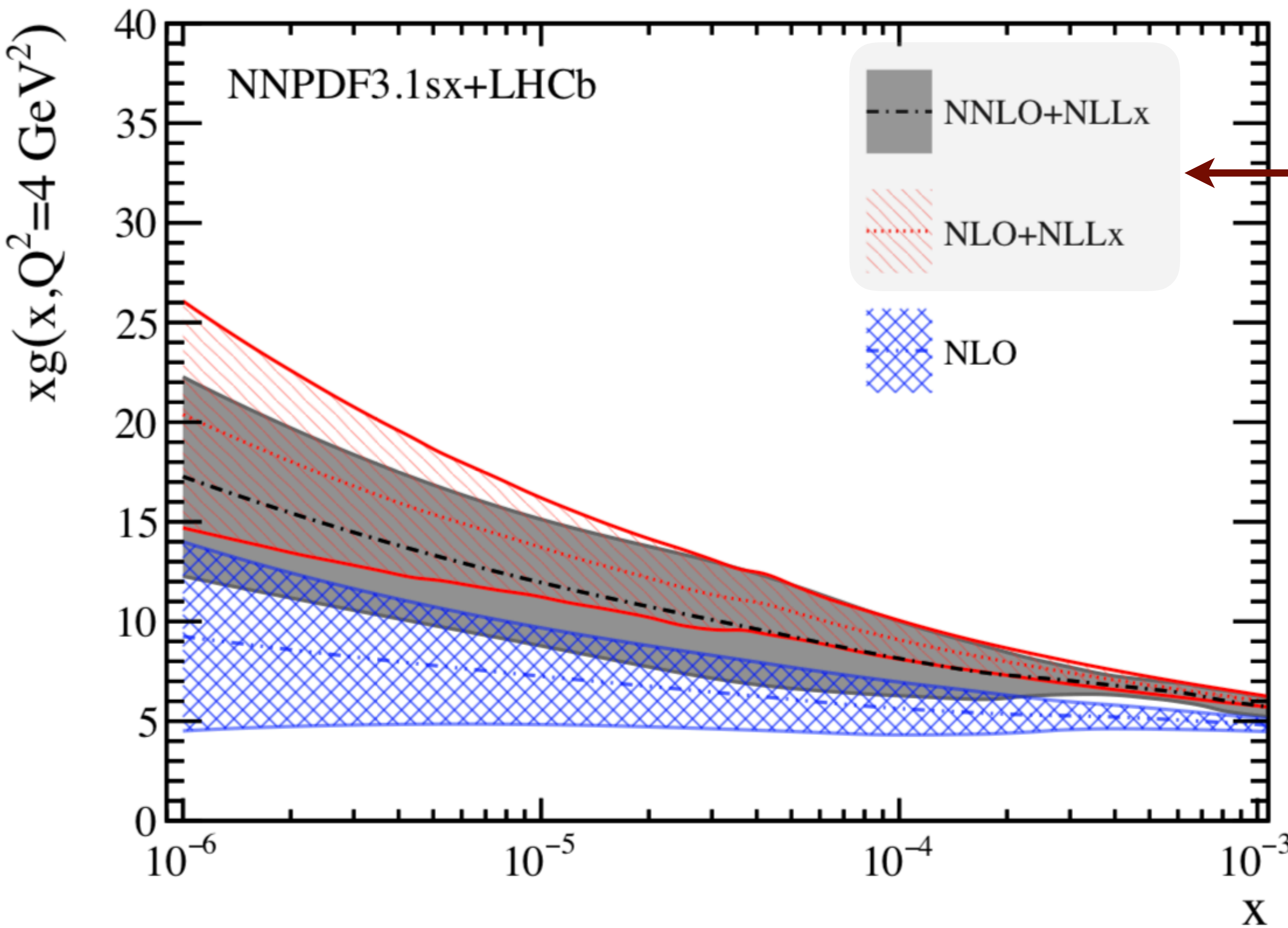
Sensitive to **small-*x* quarks** (and thus gluons via evolution) down to **x** ≃ **10^{-8}** and **Q** ≃ **M_W**

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

Forward charm production revisited

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

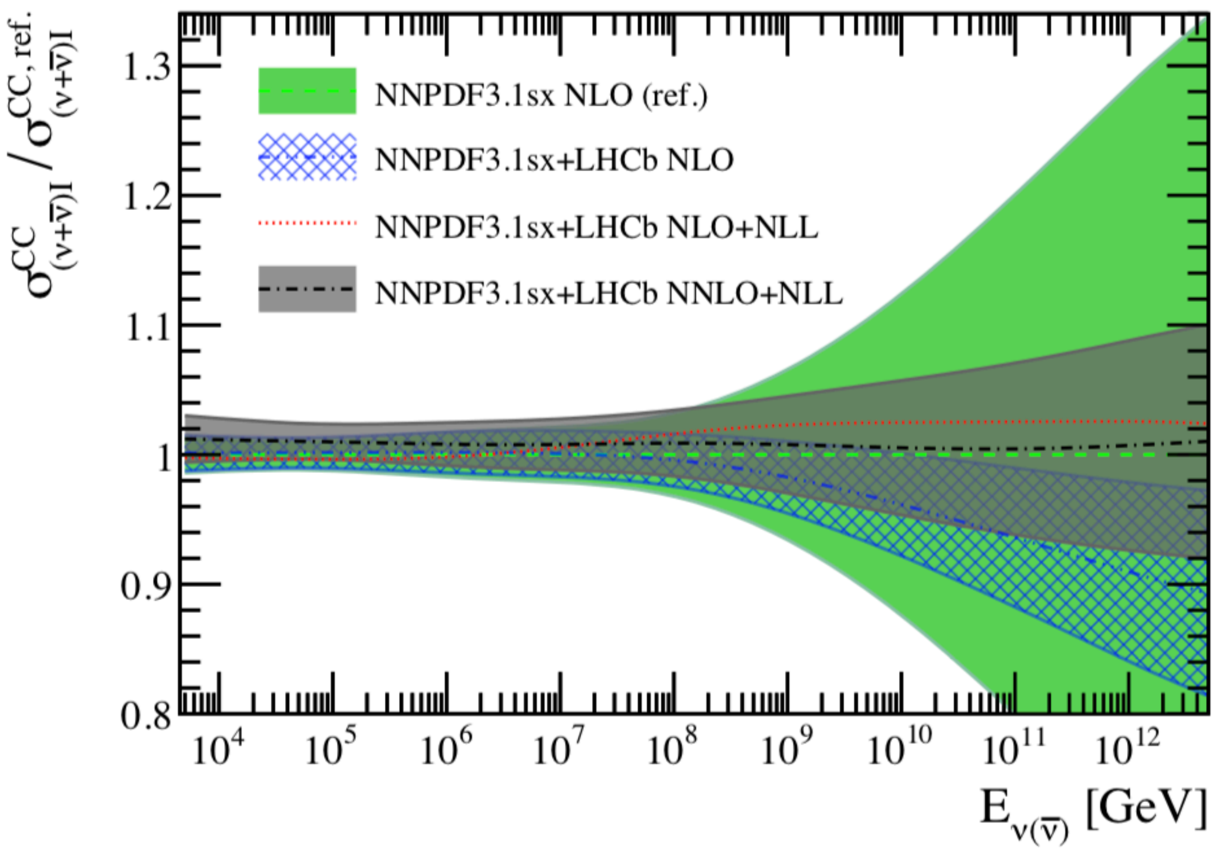
Similar reduction of gluon PDF errors at **small-*x*** + **increase in central value**

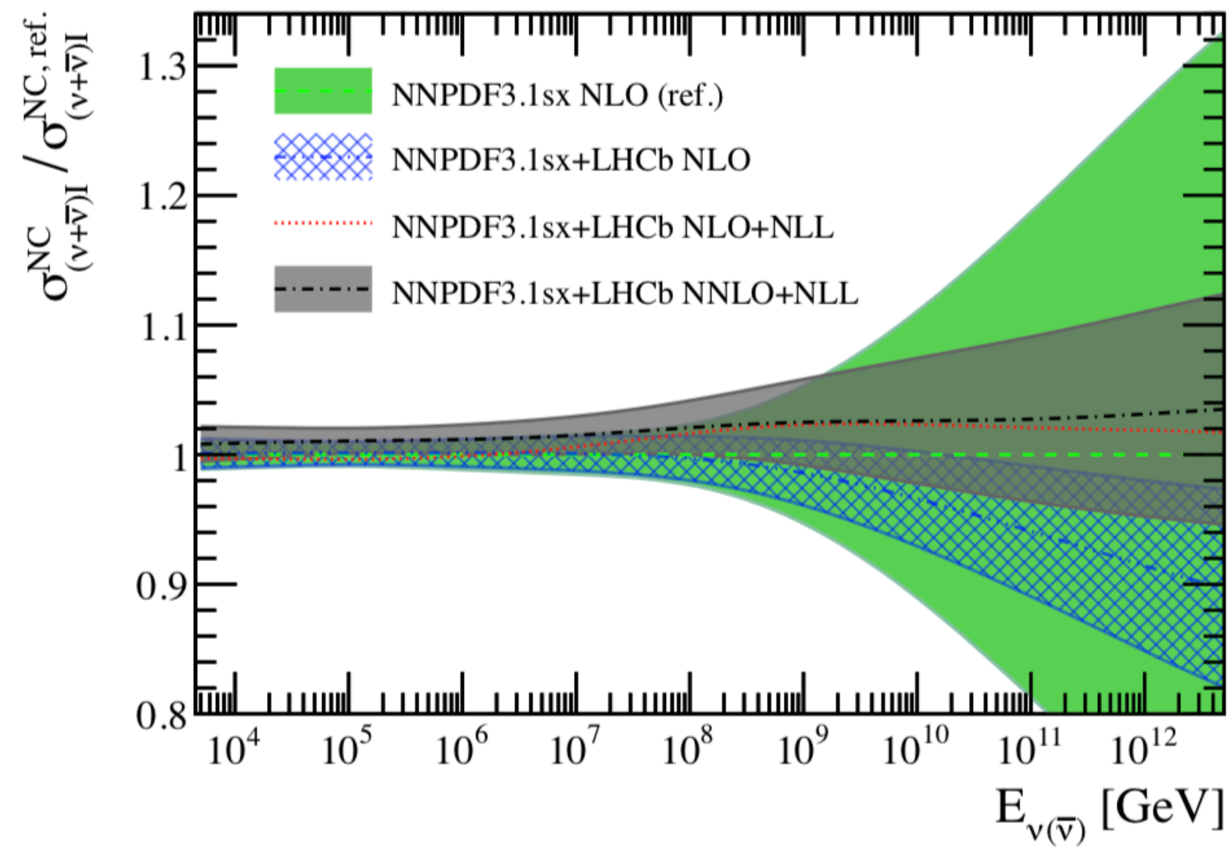


BFKL effects included

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

UHE neutrino-nucleus cross-section



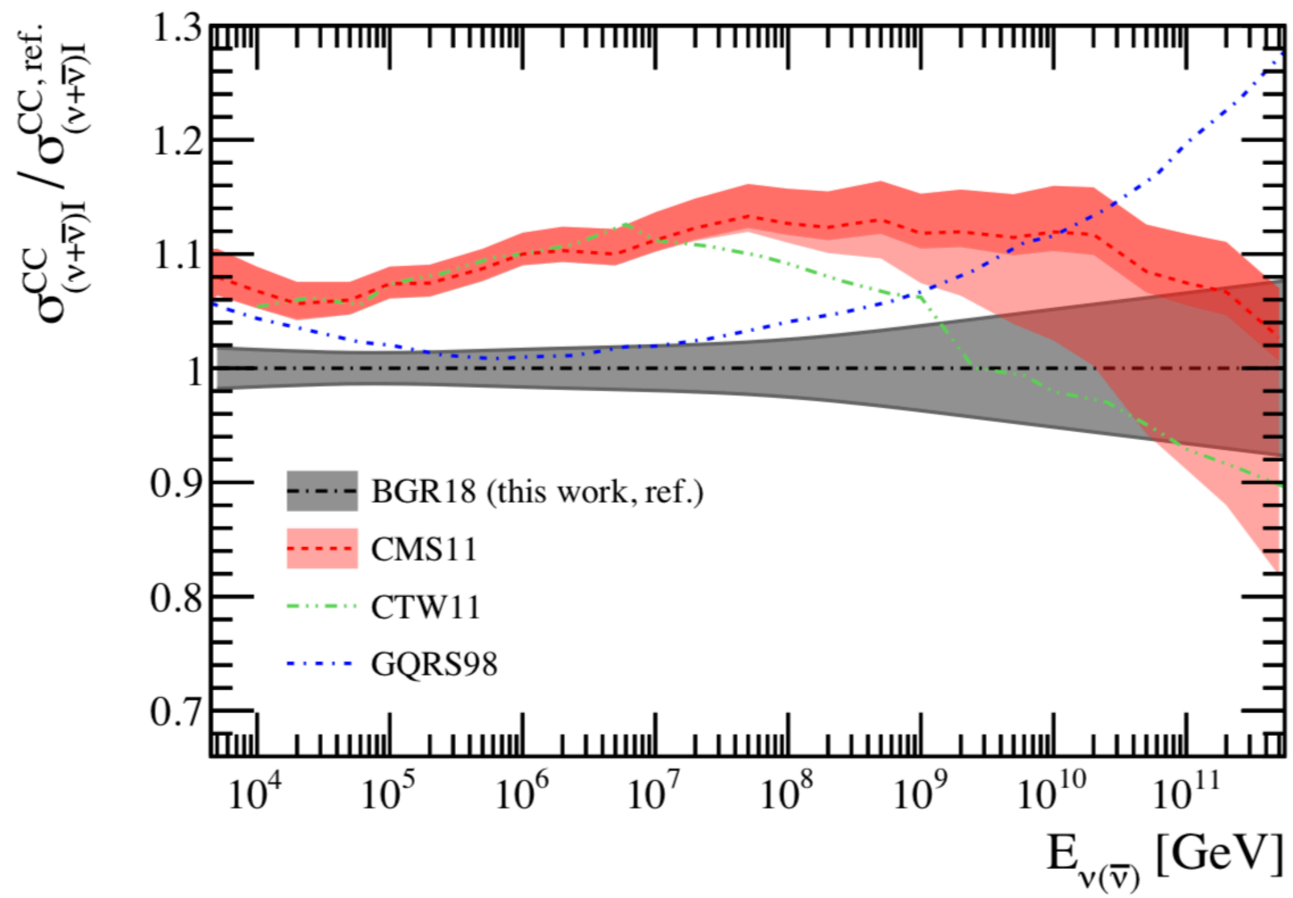


State-of-the-art predictions for **ultra-high energy** neutrino interactions

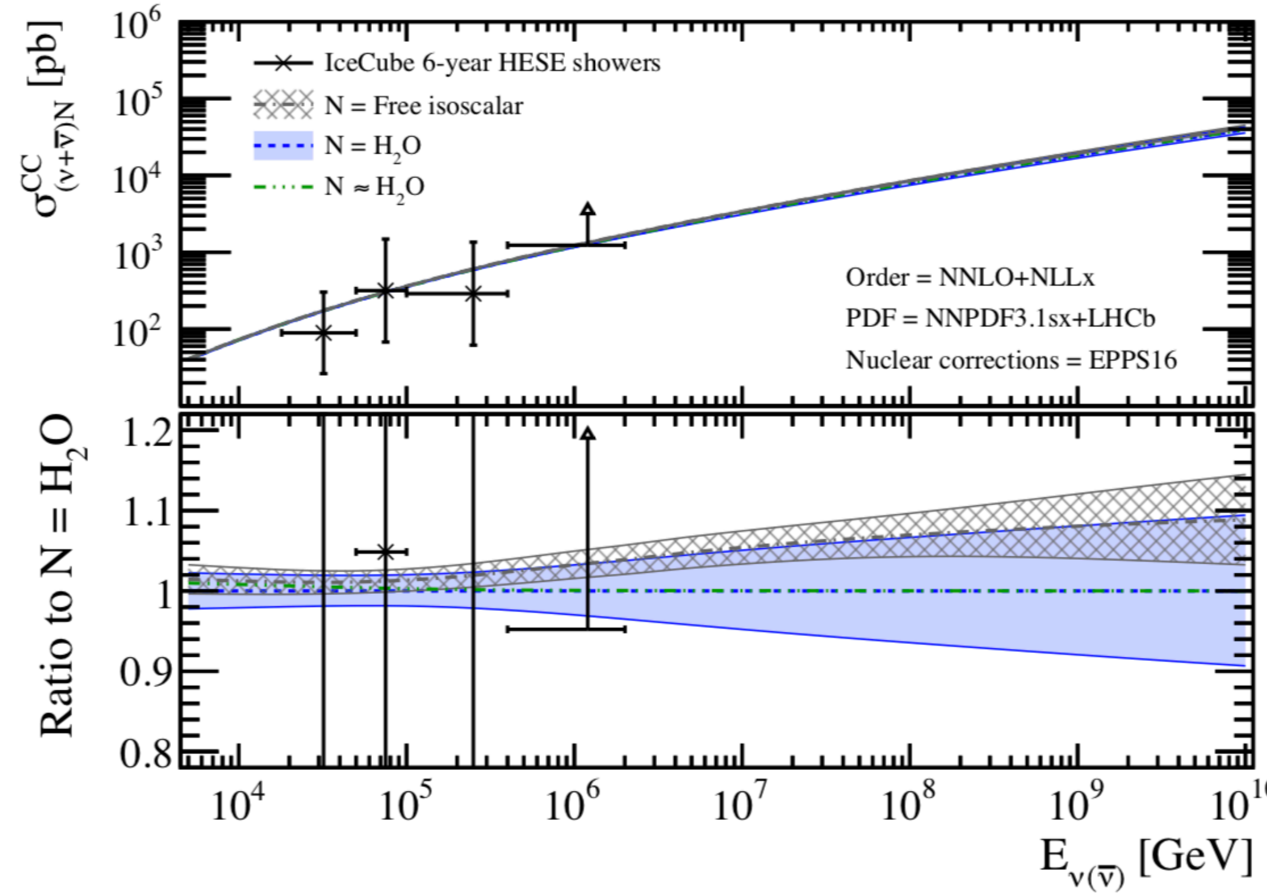
- **BFKL small-x effects** in PDFs and deep-inelastic structure functions
- Constraints on small-x PDFs from **LHCb charm production**
- Accounting for **nuclear corrections** and heavy-quark-initiated contributions

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!**

Nuclear PDF fits

work in progress with R. Abdul Khalek and J. Ethier

Why nuclear PDFs?

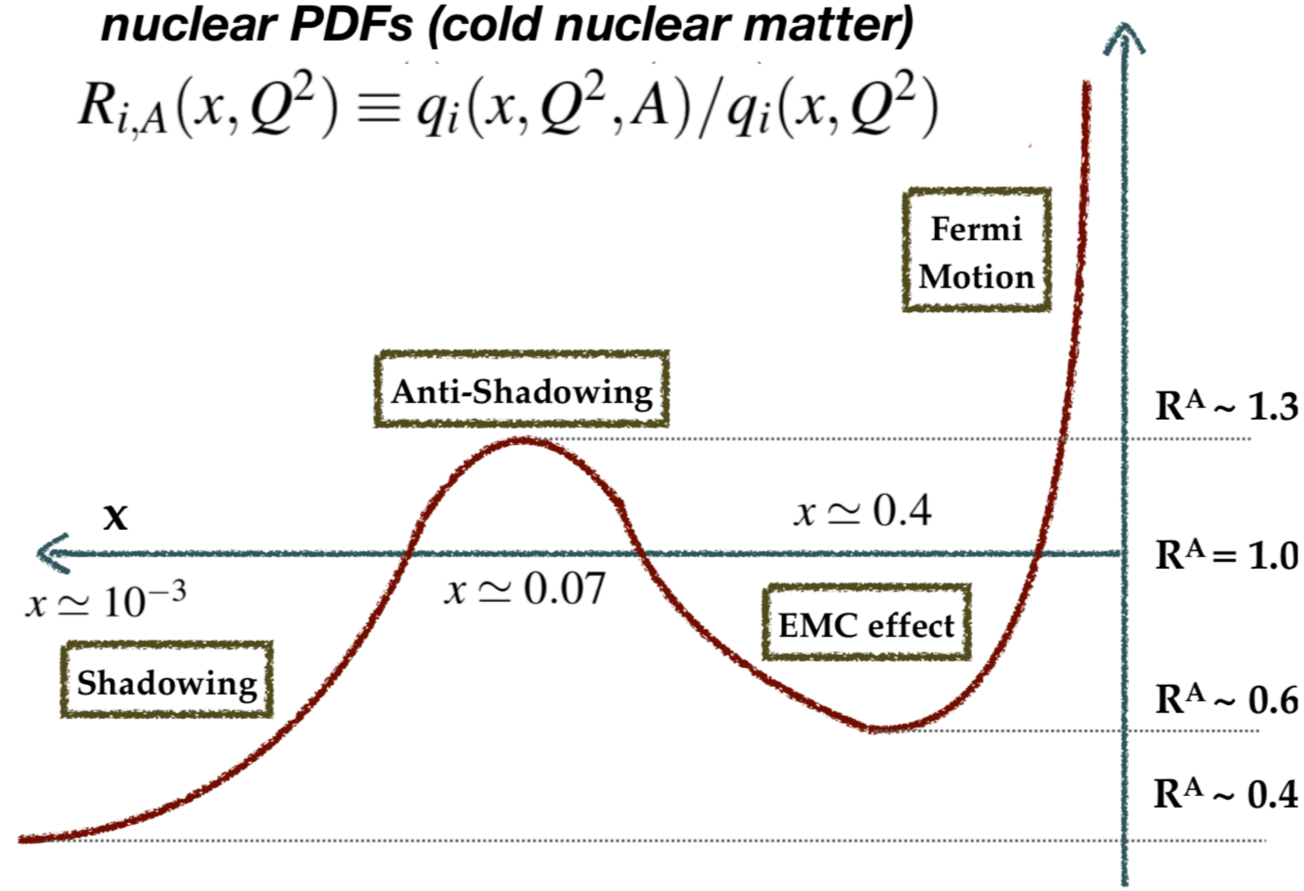
- Cold nuclear matter effects modify the **PDFs of bound nucleons** as compared to the free-proton case

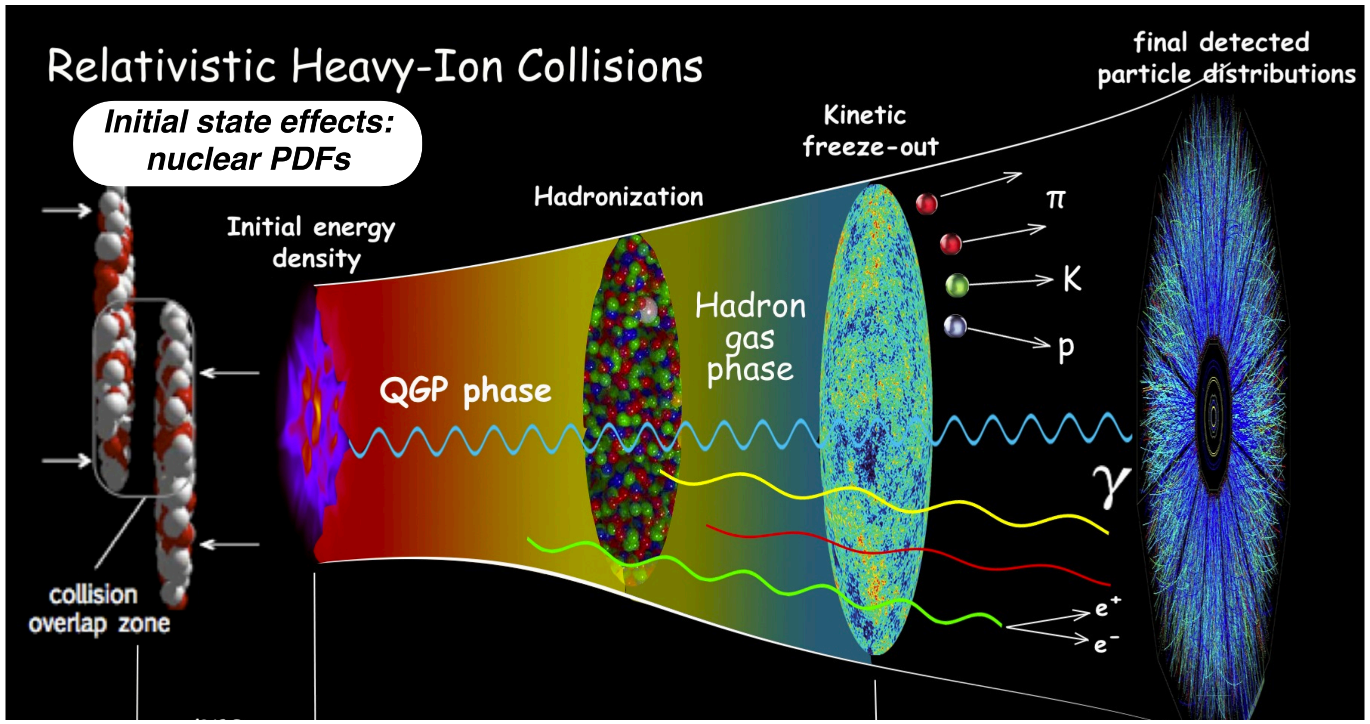
- Rich connection with **nuclear calculations**: EMC effect, shadowing

- Non-linear gluon interactions enhanced in heavy nuclei: **Color Glass Condensate**?

nuclear PDFs (cold nuclear matter)

$$R_{i,A}(x,Q^2) \equiv q_i(x,Q^2,A)/q_i(x,Q^2)$$

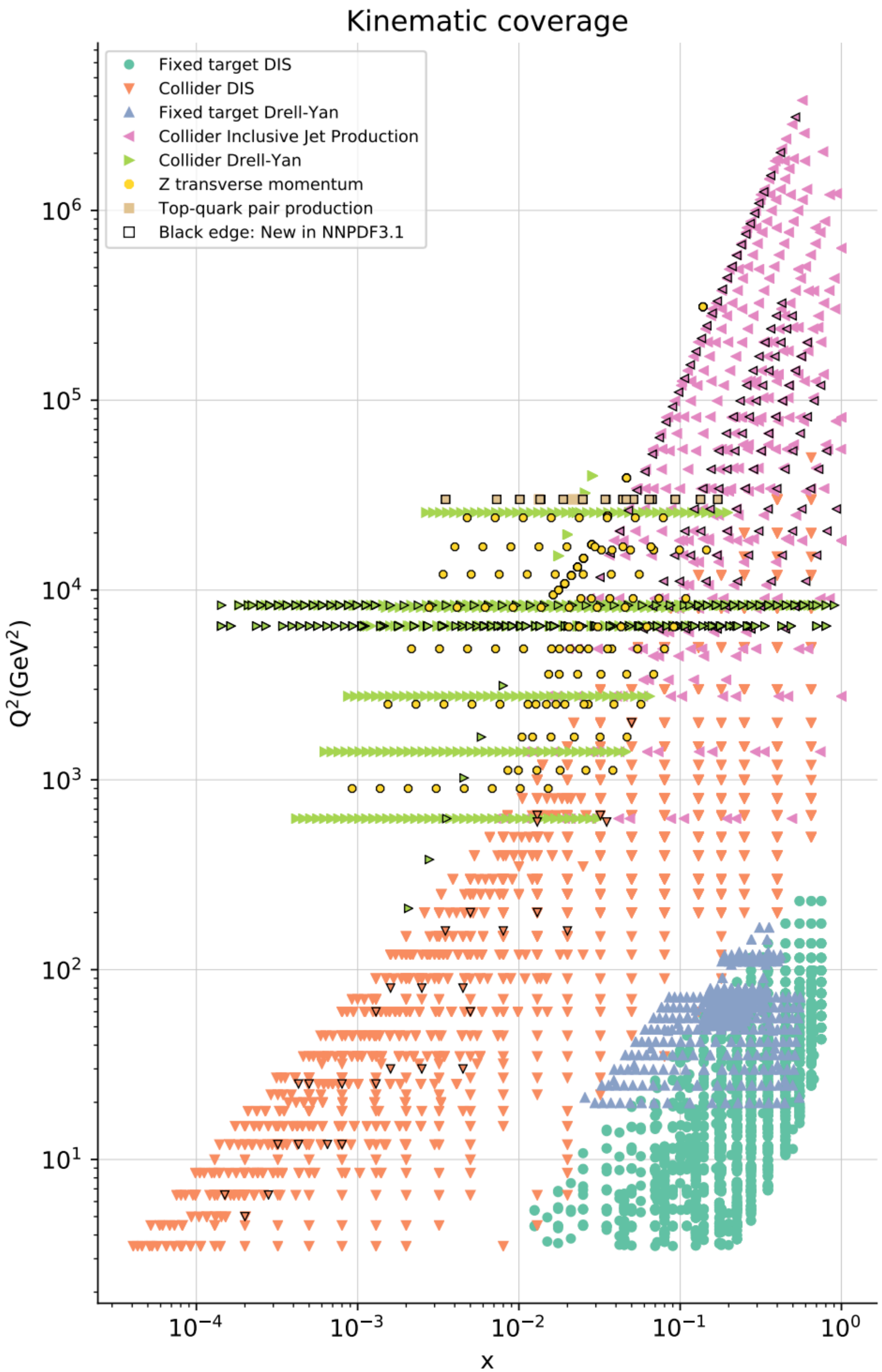




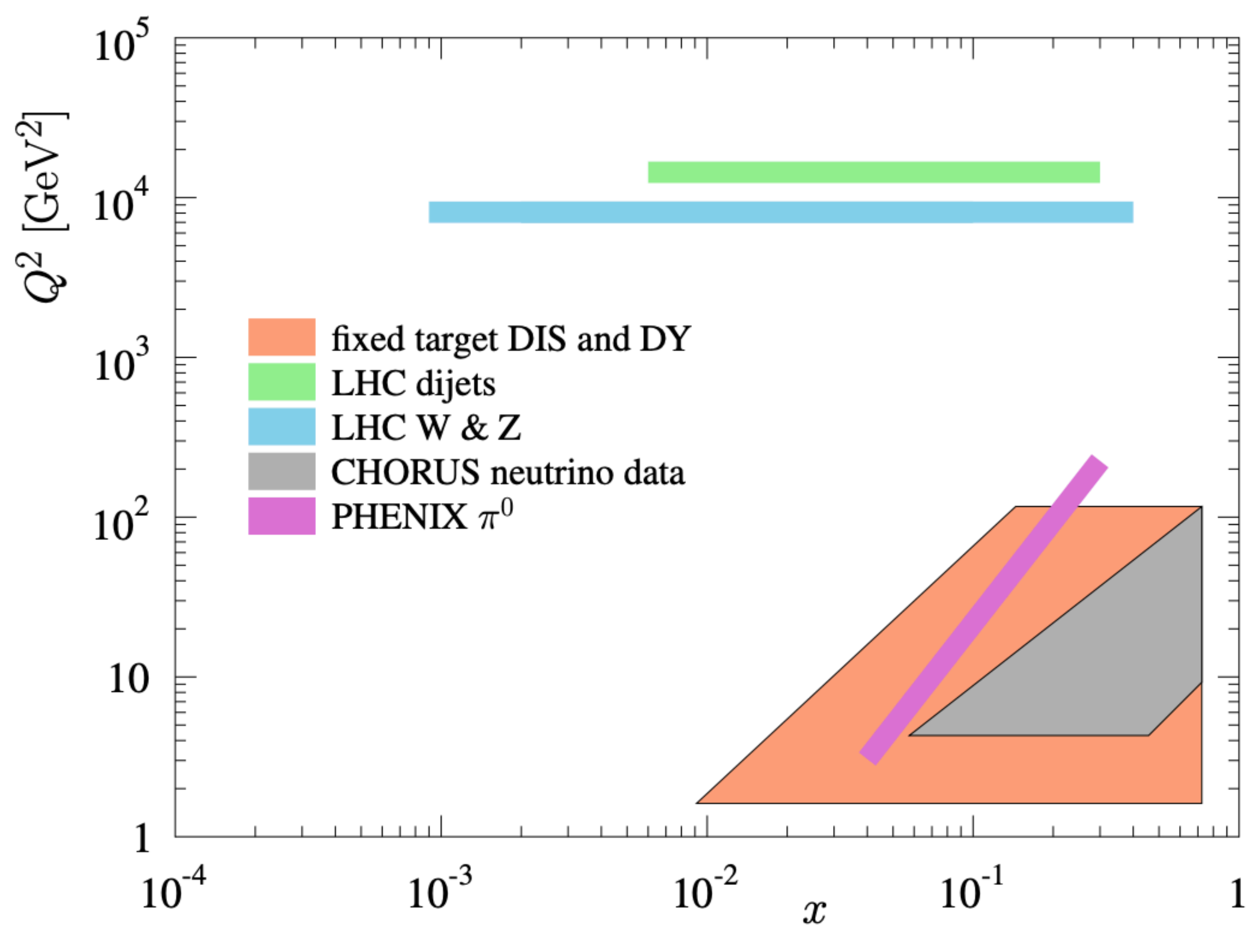
- nPDFs relevant for the **initial state of heavy-ion collisions**: benchmarks for Quark-Gluon Plasma characterisation

- nPDFs also required for **ultra-high-energy astrophysics** e.g. neutrino telescopes such as IceCube

From protons to heavy nuclei



- Nuclear dataset << proton dataset
- Limited info on **nuclear gluon and quark sea**, few constraints for $x < 10^{-2}$
- Recently: info from **p+Pb collisions**
- **EIC essential** for the understanding of nuclear quarks and gluon DoF!



From protons to heavy nuclei

Here I present **preliminary nNNPDF1.0 results** based on NC DIS nuclear data only

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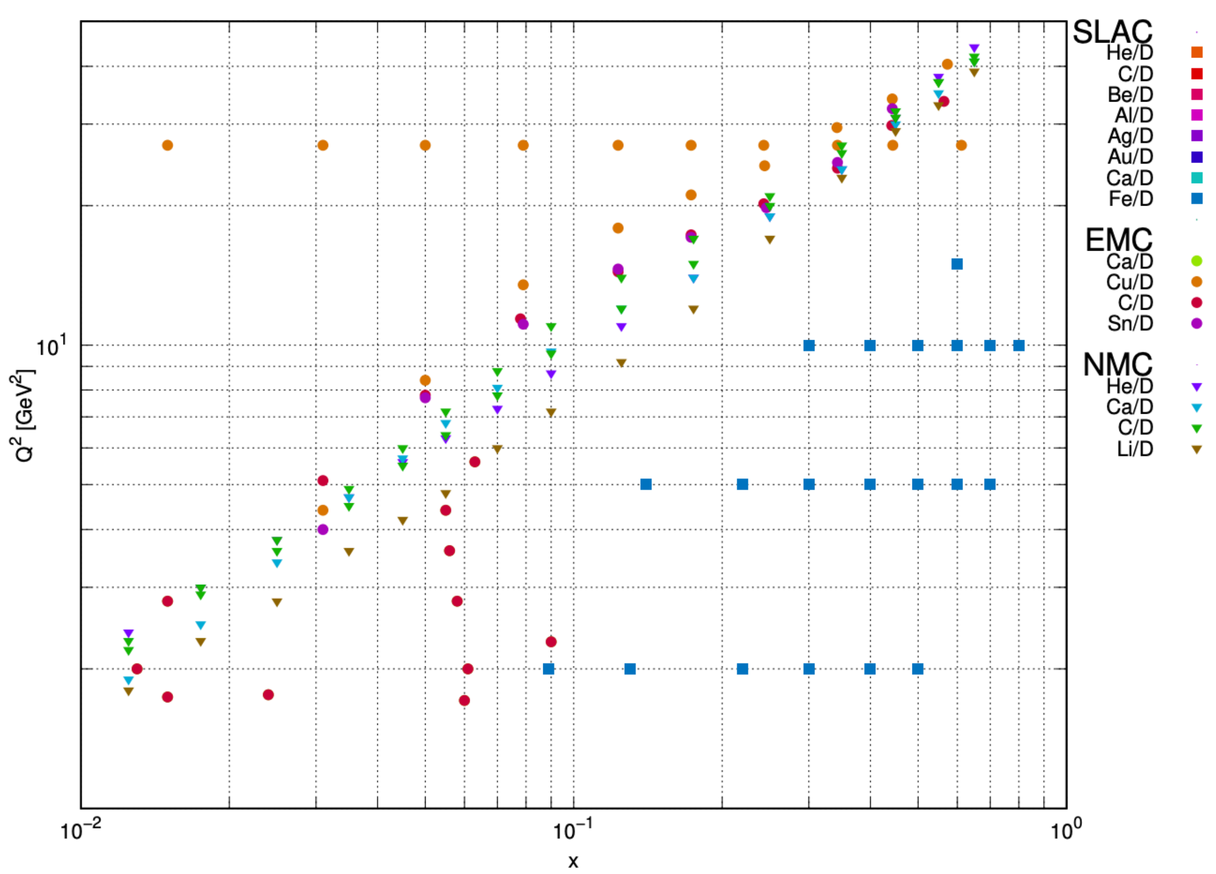
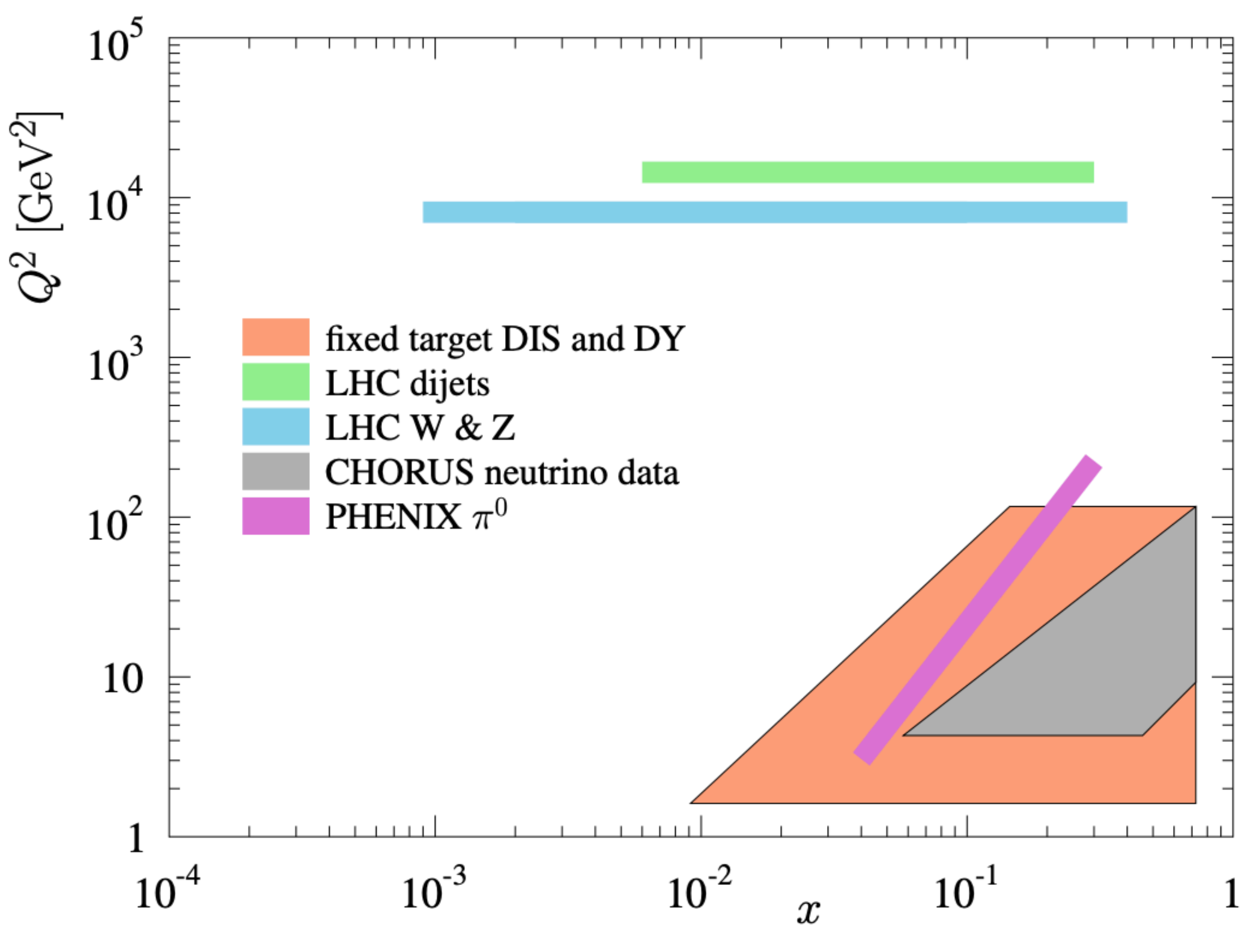
- Recently: info from **p+Pb collisions**
- **EIC essential** for the understanding of nuclear quarks and gluon DoF!





Towards nNNPDF1.0

- Parametrize nPDFs with ANNs with ***x, ln(x), A*** as input: **fully model-independent**

$$q_i(x, Q_0, A) = B_i x^{-\alpha_i}(1-x)^{\beta_i}\mathrm{NN}(x, A)\,, \quad i = g, \Sigma, T_8$$

- Gluon normalisation (*A*-dependent) fixed by the **momentum sum rule**

$$B_g(A) = \left(1 - \int_0^1 dx\, x\Sigma(x, Q_0, A)\right) \Big/ \int_0^1 dx\, xg(x, Q_0, A)$$

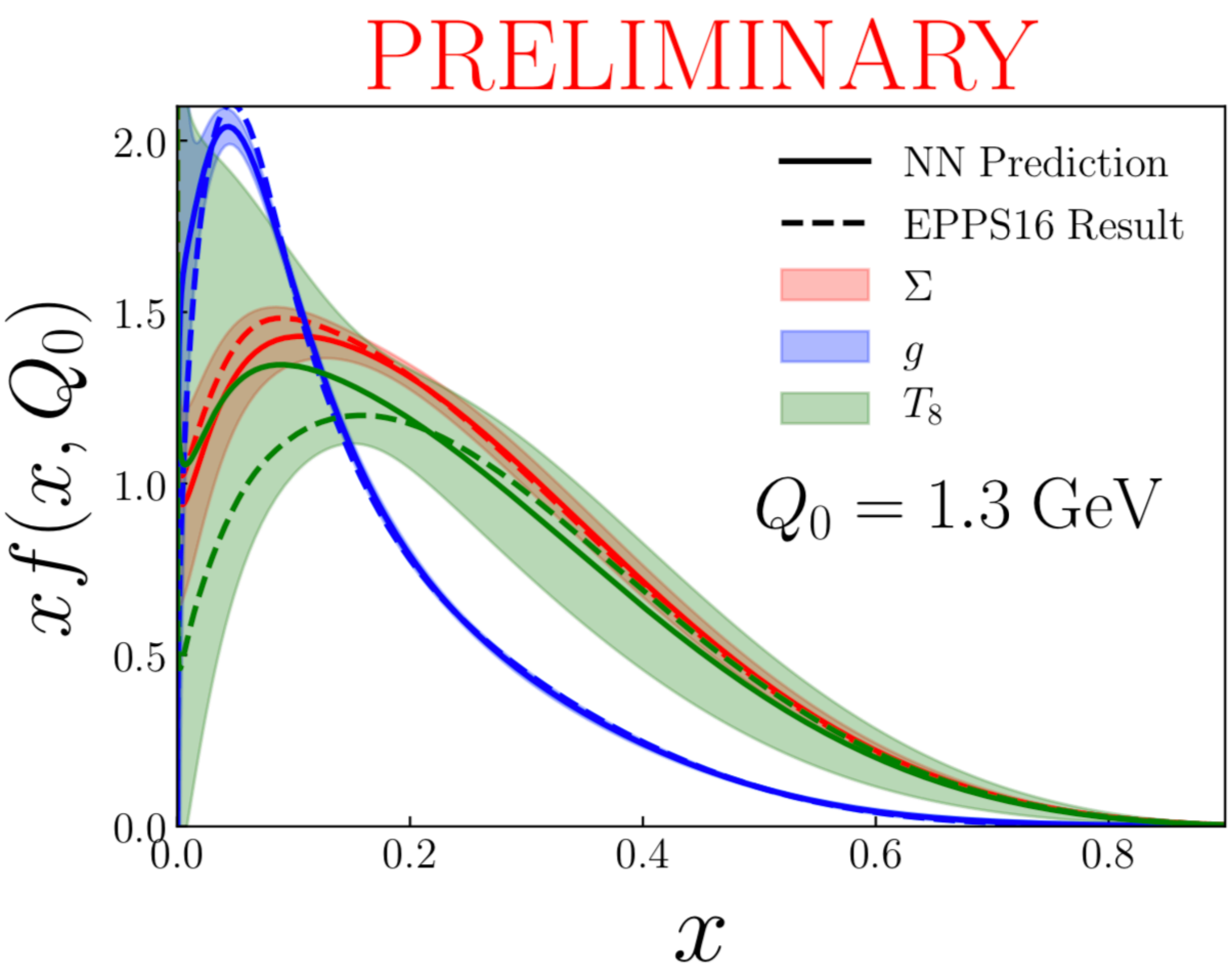
- **Proton boundary condition** implemented as a **penalty** in the figure of merit

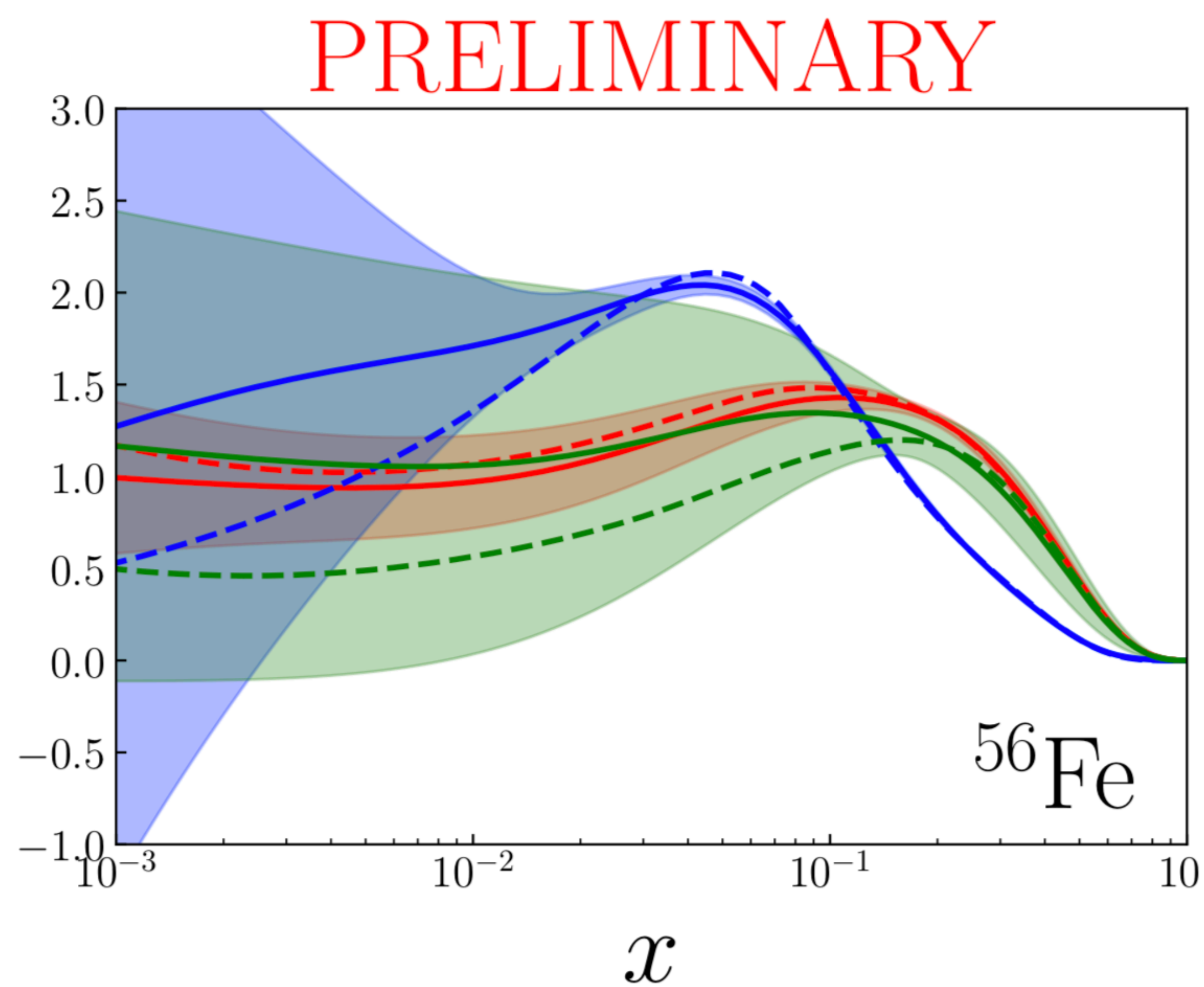
$$\chi^2 = \sum_{j=1}^{n_{\mathrm{dat}}} \frac{\left(F_j^{(\mathrm{exp})} - F_j^{(\mathrm{th})}\right)^2}{\sigma_j^{(\mathrm{exp})2}} + \lambda \sum_{i=g,\Sigma,T_8} \sum_{k=1}^{n_x} \frac{\left(q_i(x_k, Q_0, A) - q_i^{(\mathrm{ref})}(x_k, Q_0, A=1)\right)^2}{\left(\delta q_i^{(\mathrm{ref})}(x_k, Q_0, A=1)\right)^2}$$

$q_i^{(\mathrm{ref})}(x_k, Q_0, A=1)$ Isoscalar **NNPDF3.1** NNLO global fit

Closure testing validation

- Generate **pseudo-data** from a known underlying theory, say EPPS16, and check that this is reproduced at the fit level for various levels of statistical noise
- **Level 0 Closure Test**: experimental data matches input theory, χ^2 vanishingly small
- Large PDF uncertainties at **small-*x*** due to kinematic coverage of nuclear data





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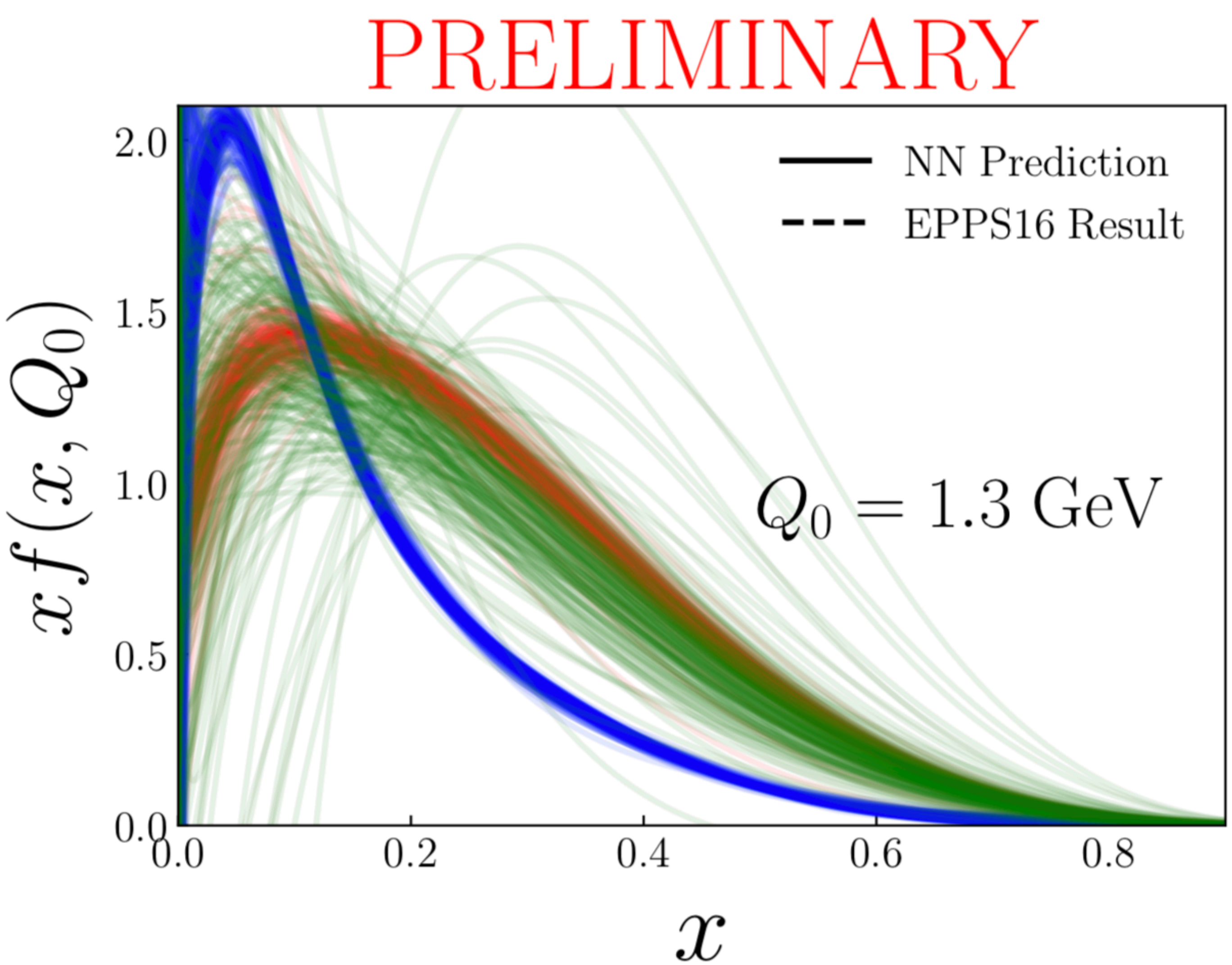

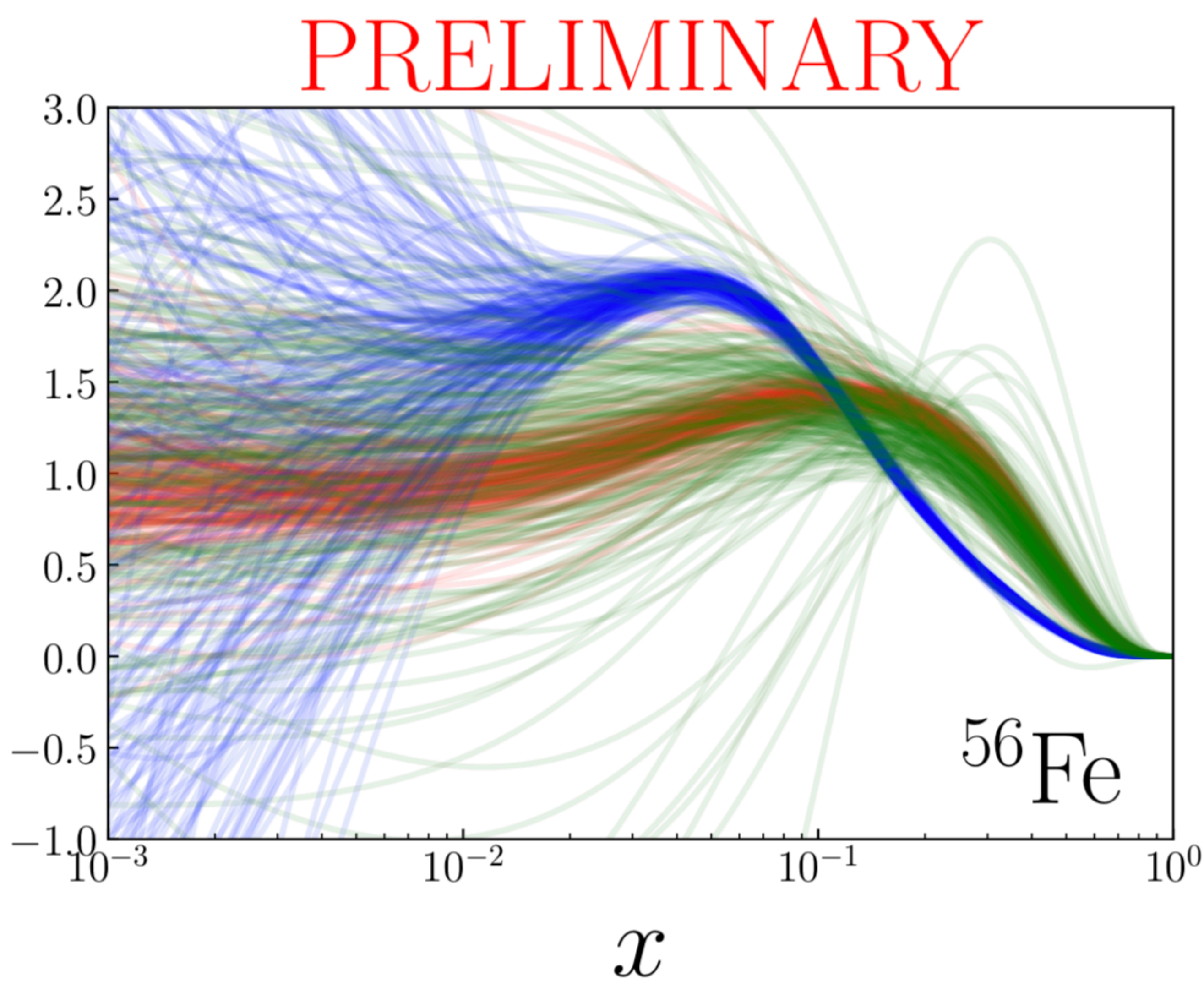

Proton boundary condition

Specially important to constrain the **nPDFs of light nuclei**

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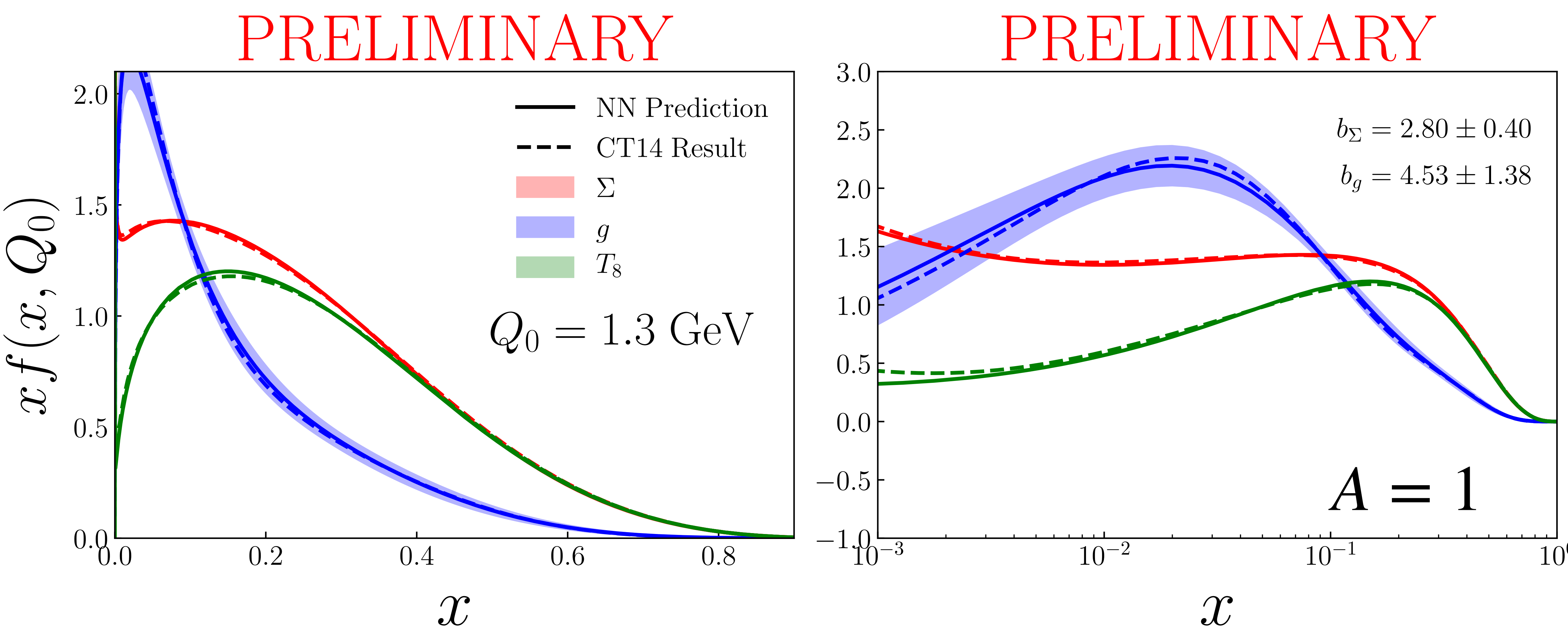

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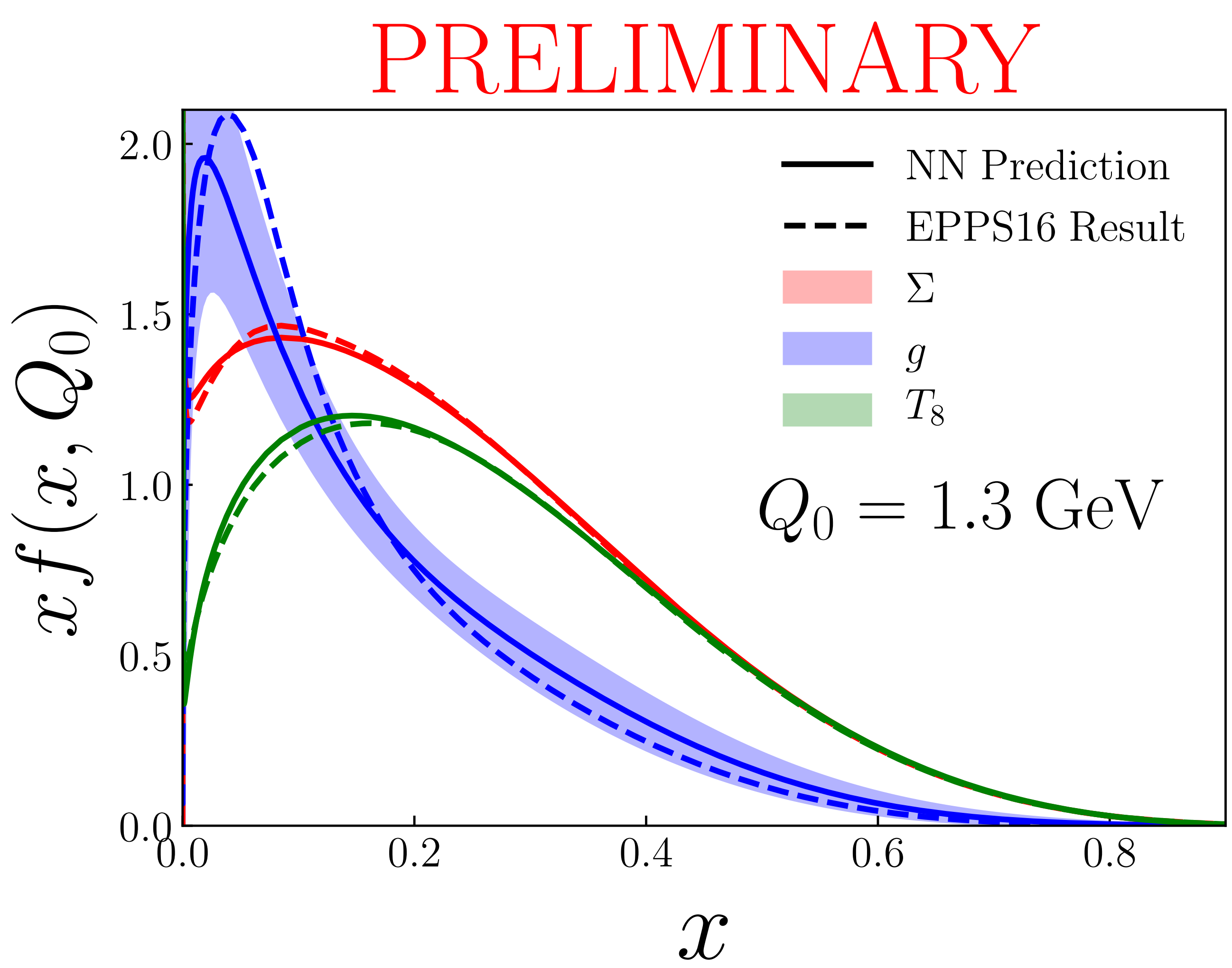

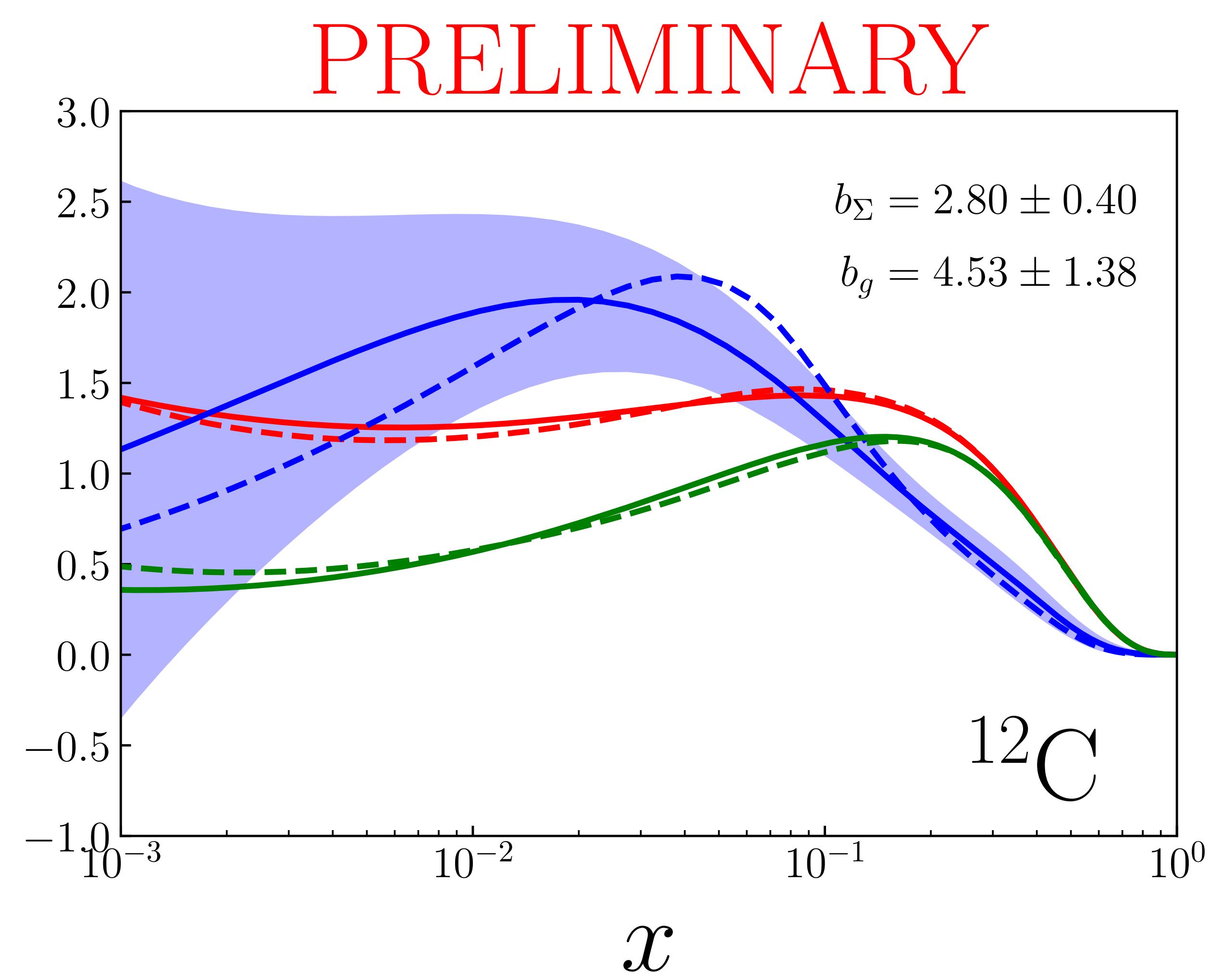

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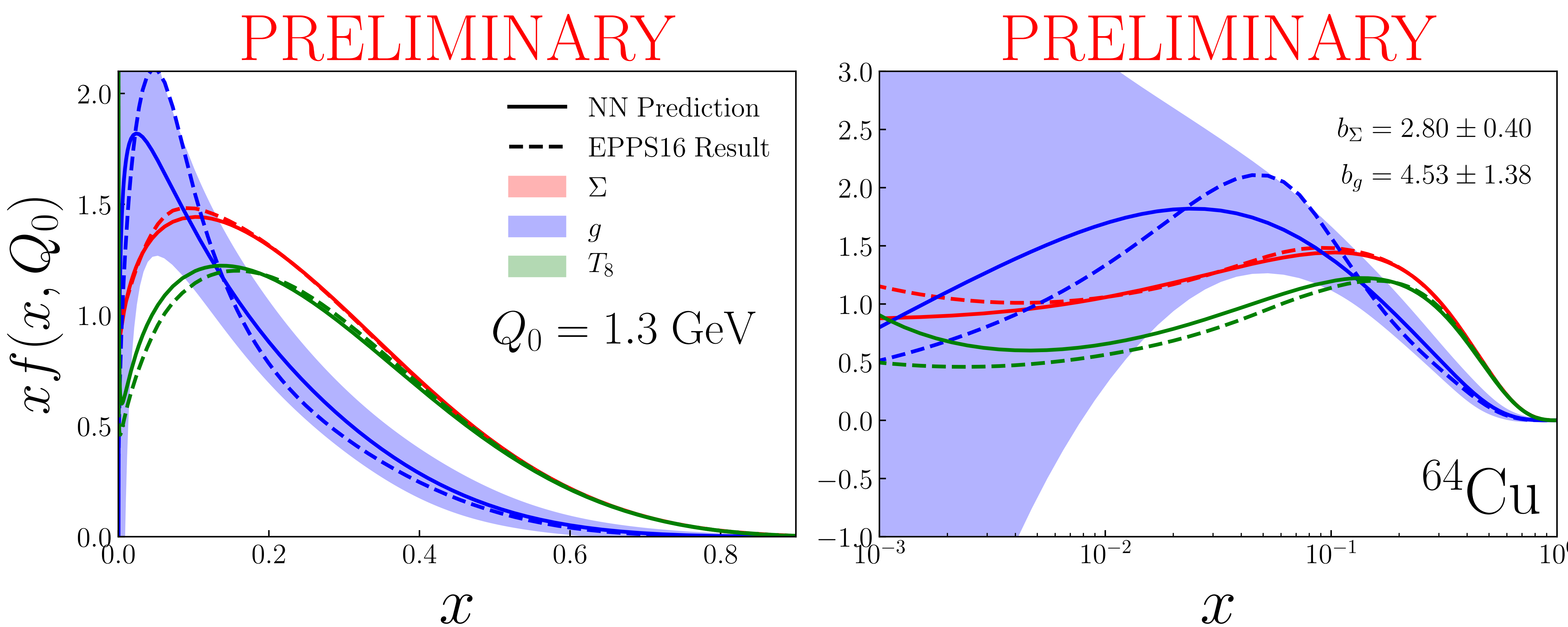

Summary and outlook

- QCD is an **extremely rich theory,** with many exciting phenomena specially in the small partonic momenta / high energies / large densities regions

- Unambiguous evidence for **BFKL dynamics** has been found at last in HERA data, following a long of experimental and theory effort

- **Charm production at the LHC** provides a direct probe of small-x gluon beyond the coverage of the HERA structure functions

- **Neutrino astrophysics** requires direct input from small-*x* QCD, both for the calculation of the signal cross-sections and for the background event rates

- Nuclear PDFs probe the interface of particle, nuclear, and astroparticle physics: ongoing work towards a **global NNPDF analysis of nPDFs**