Neutrino Telescopes as QCD Microscopes

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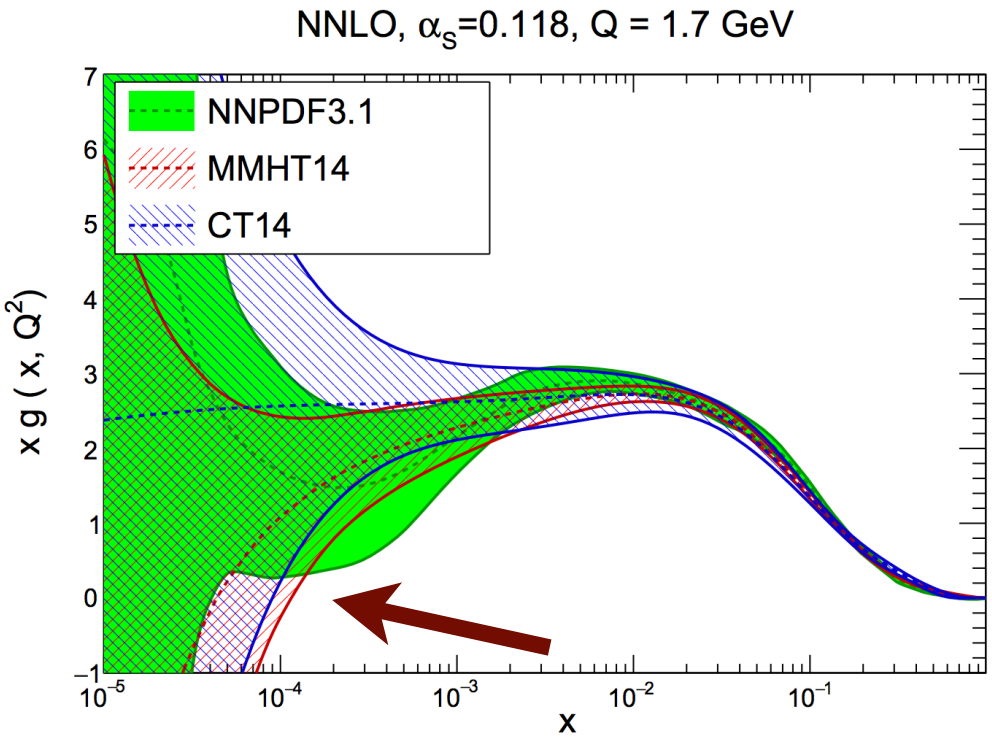
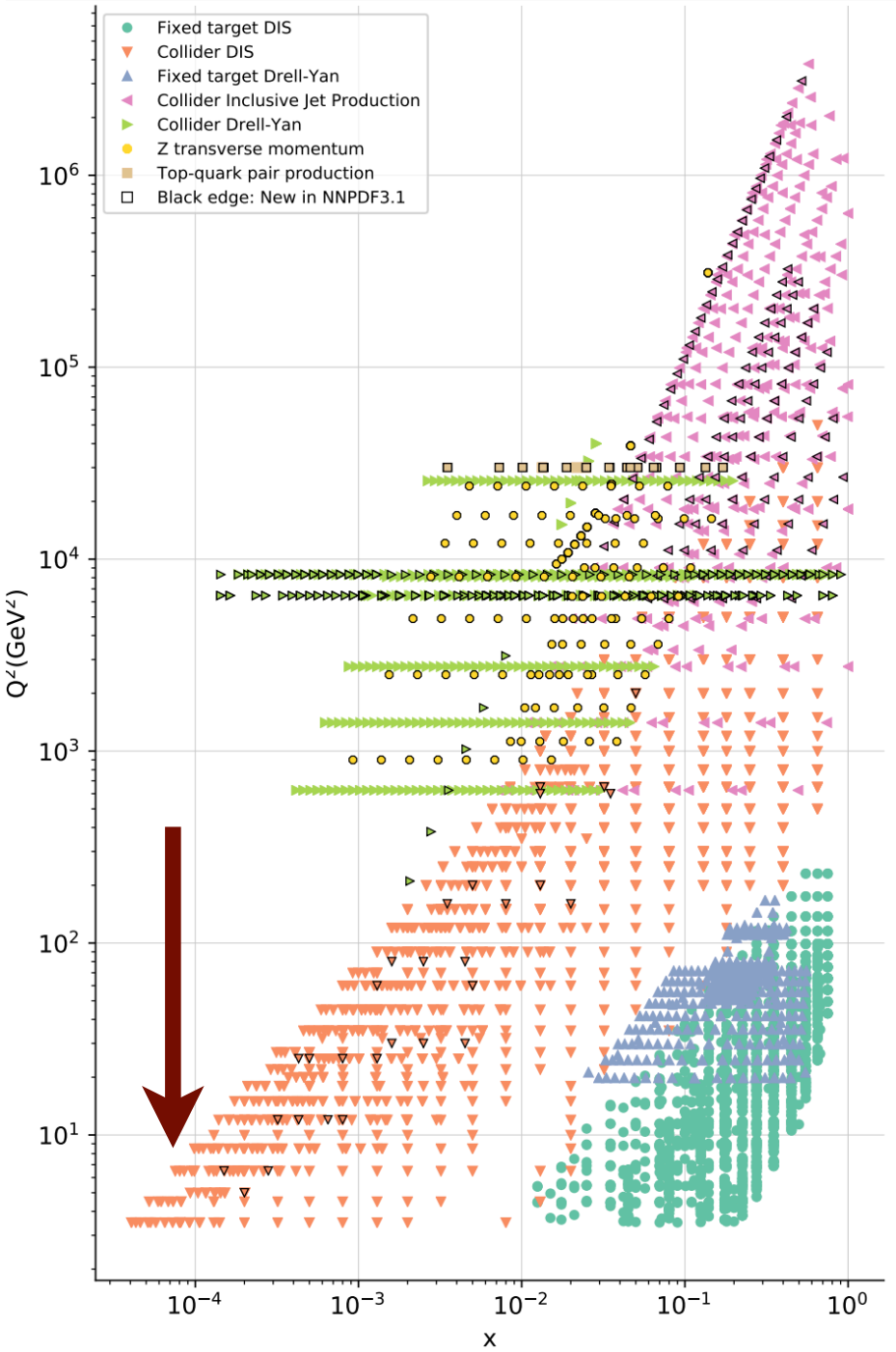
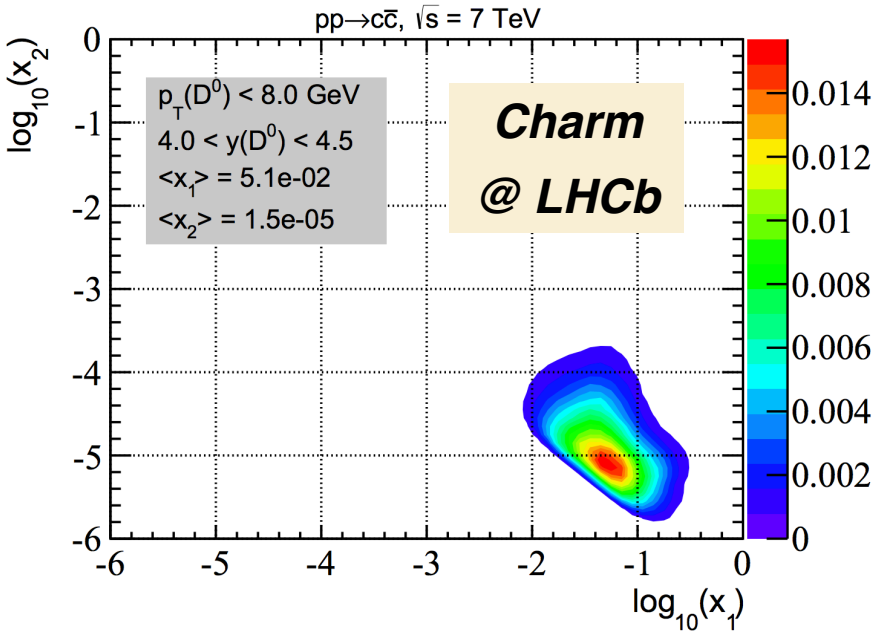
The small-x gluon from HERA data

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



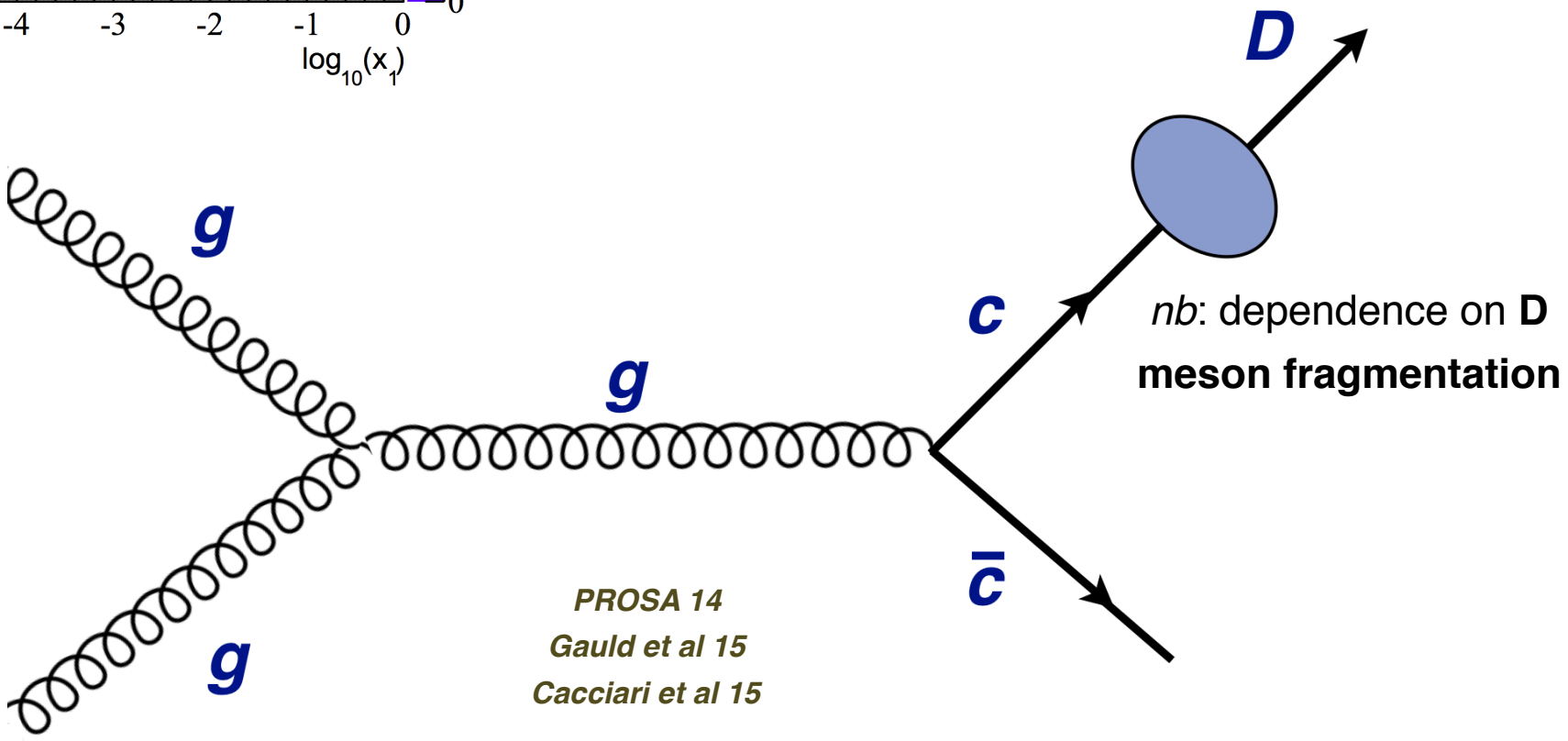


Forward charm production



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

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



nb: dependence on **D meson fragmentation**

PROSA 14
Gauld et al 15
Cacciari et al 15

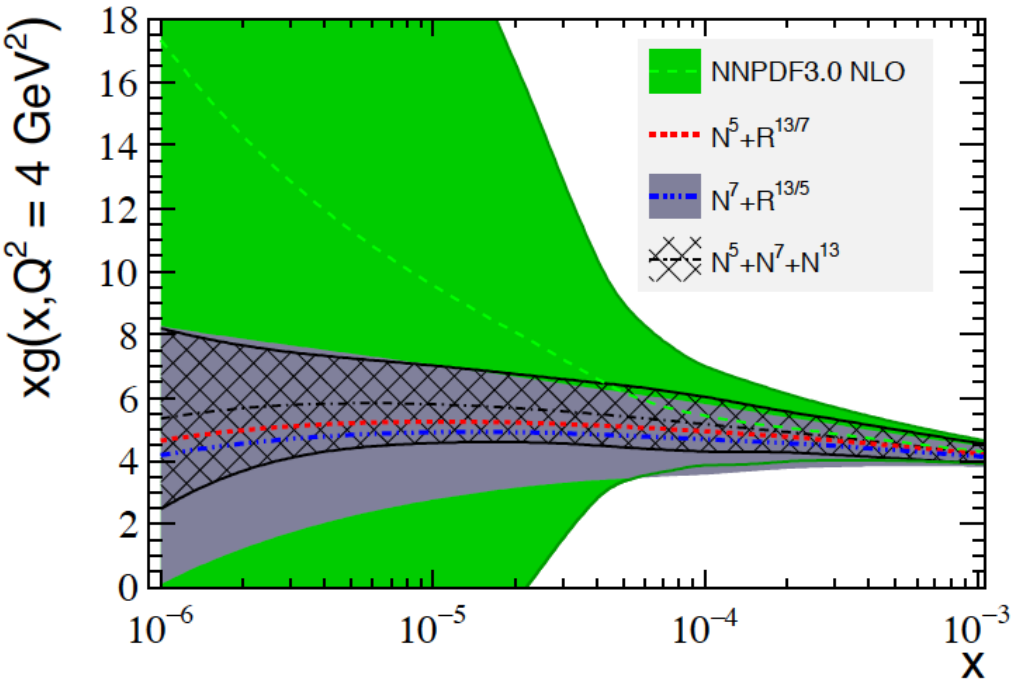
Forward charm production

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

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

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

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



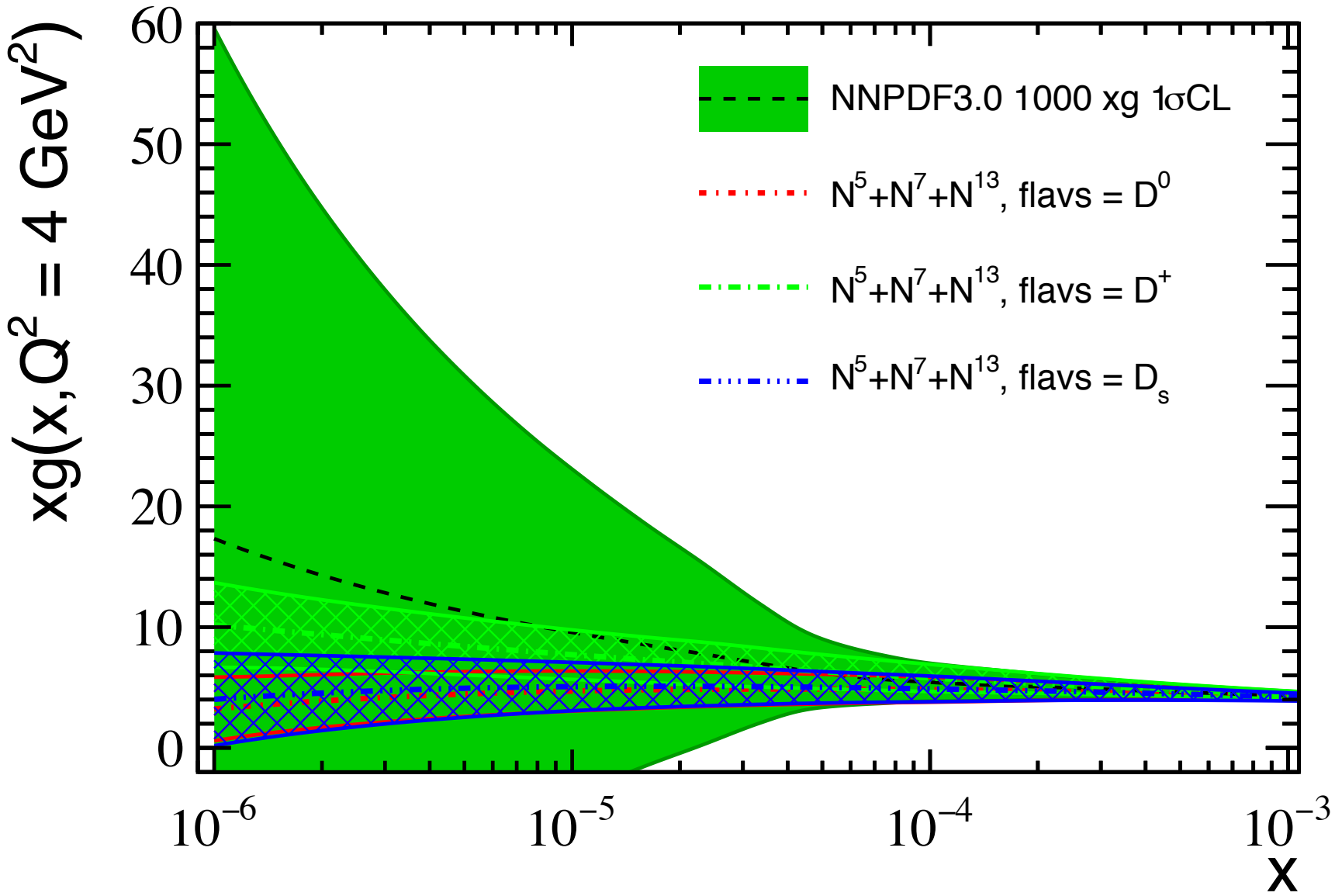
Gauld, JR 16

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**



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 Q^2

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

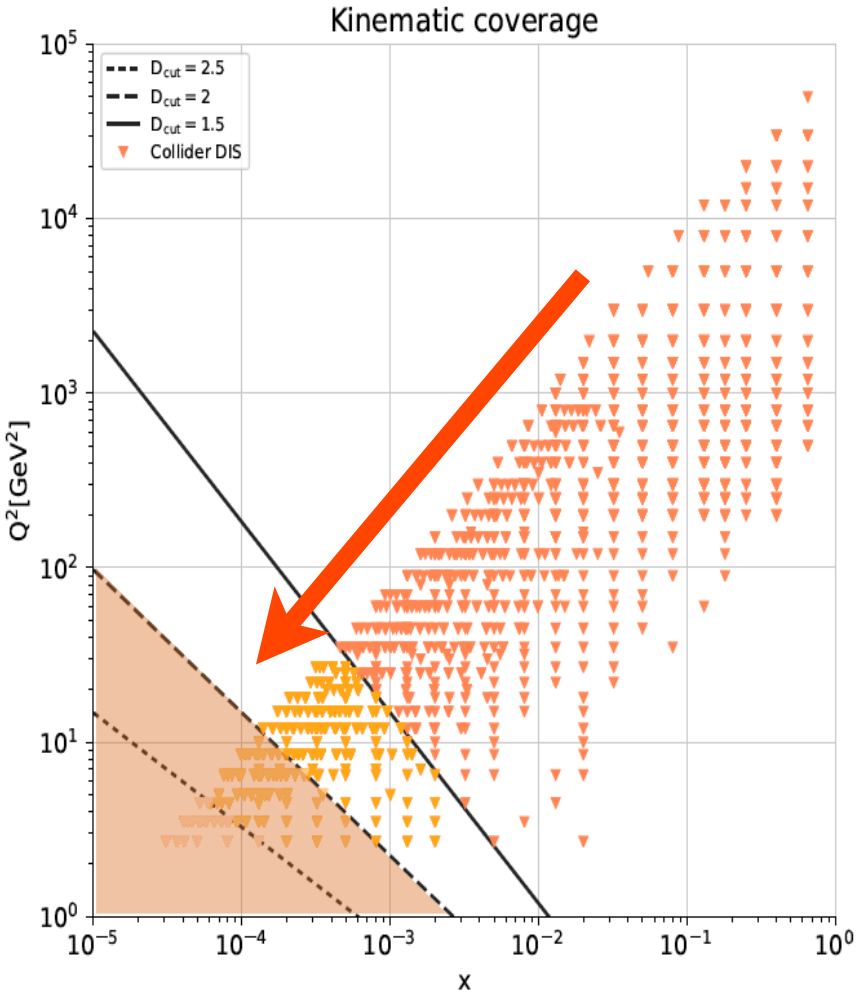
BFKL Evolution in x

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

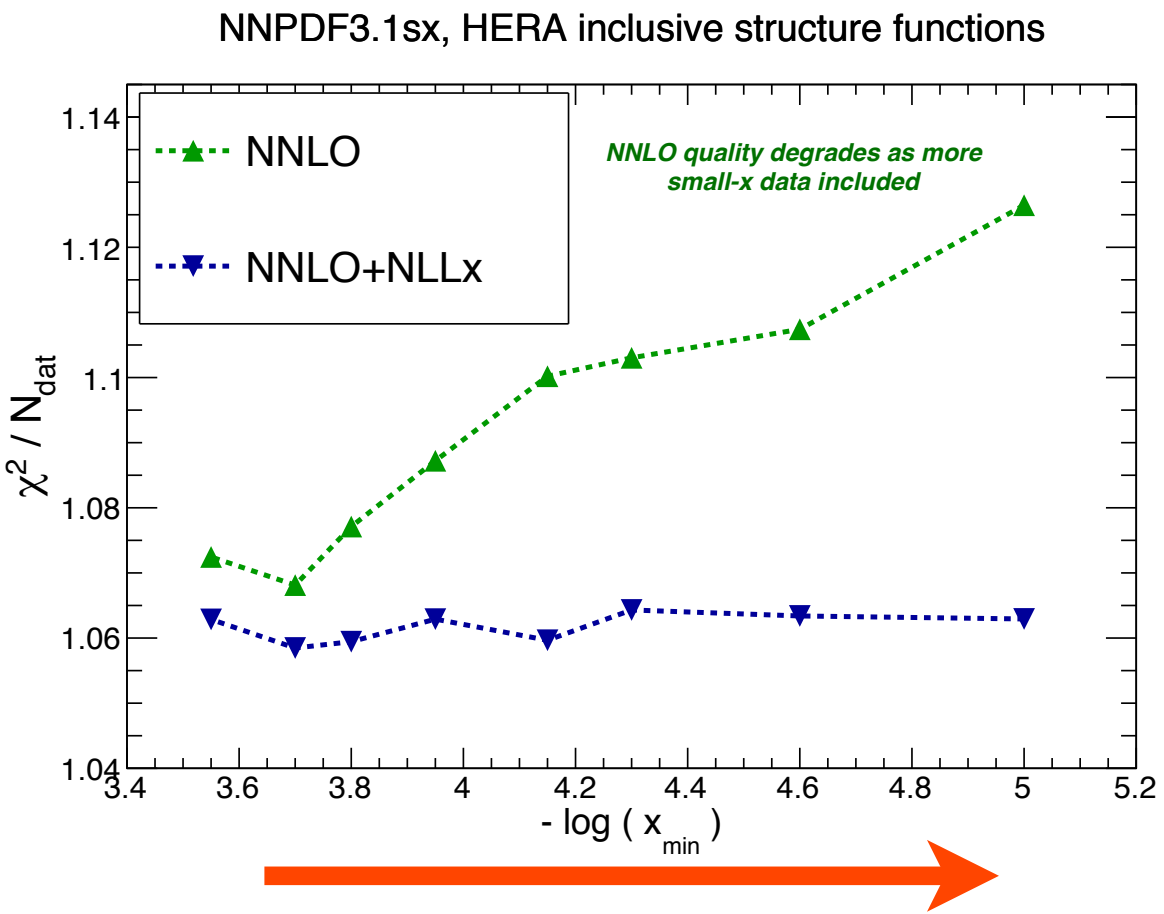
ABF, CCSS, TW + others, 94-08

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

BFKL dynamics at small-x



Ball et al 17, xFitter 18



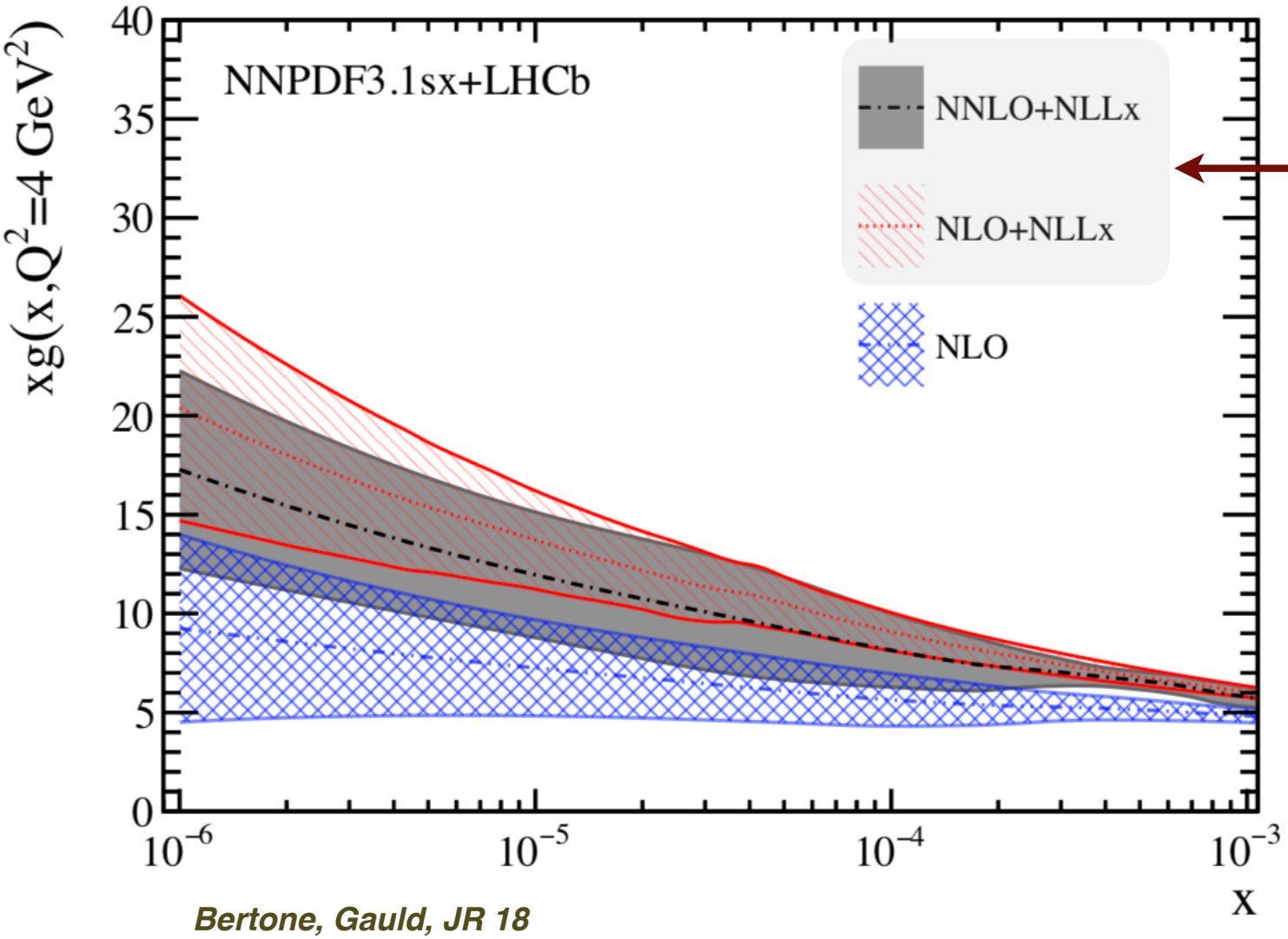
Monitor the **fit quality** as one includes more data from the **small-x region**

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

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 18

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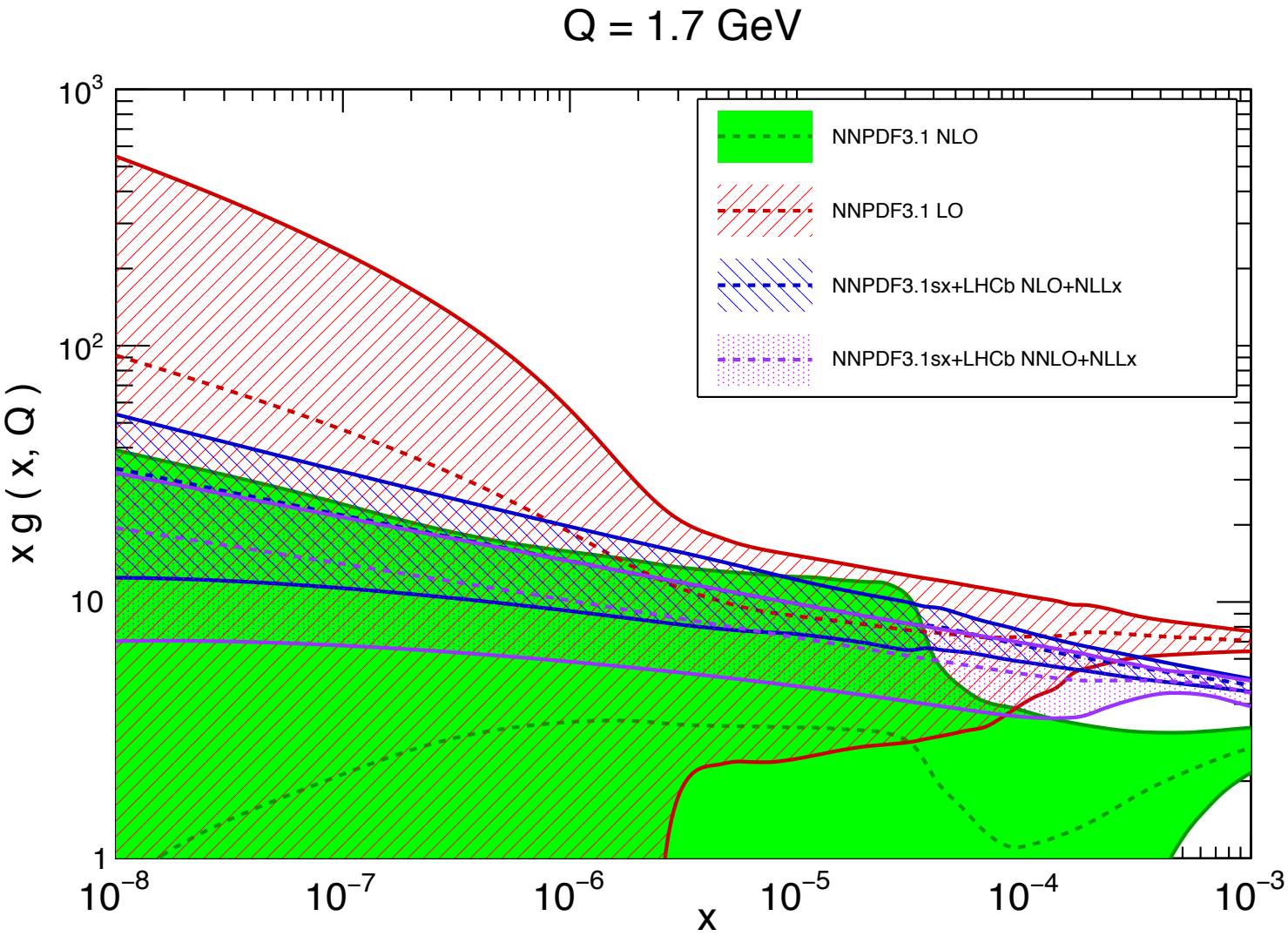

small-x resummation: excellent **perturbative convergence** even for **x** ≃ 10^{-8}

Suitable for MC tuning: available in Pythia8

Neutrino telescopes

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

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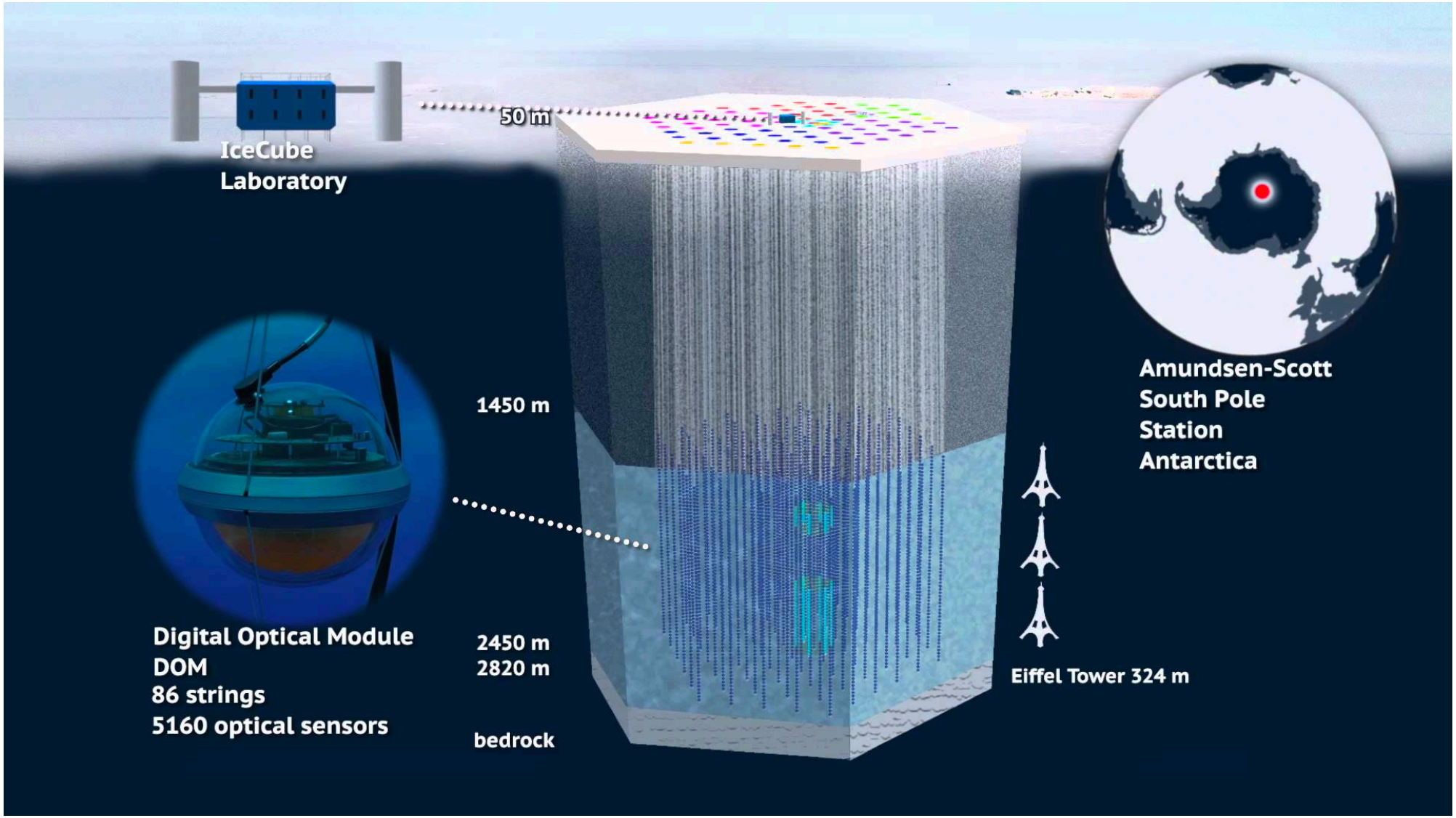
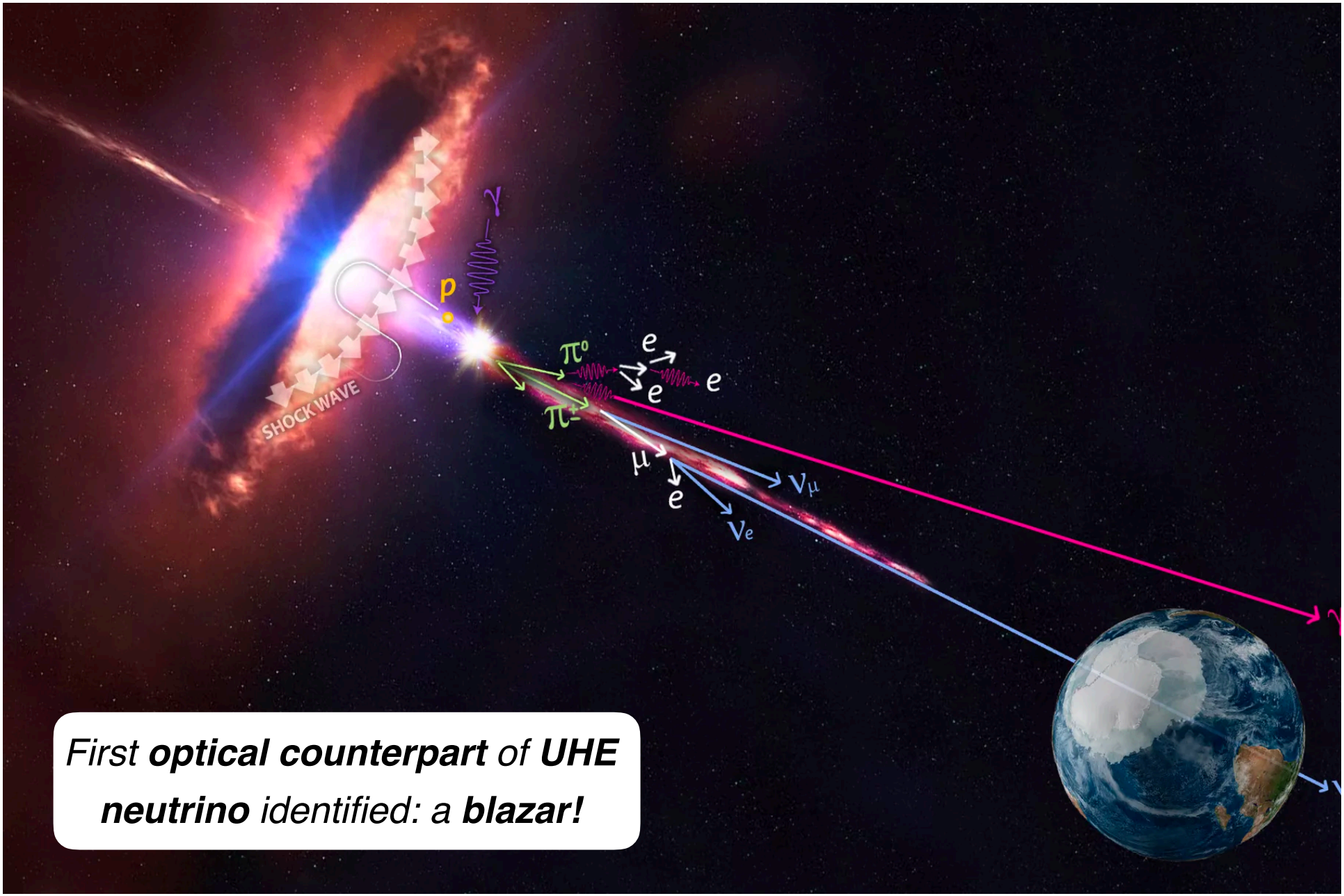


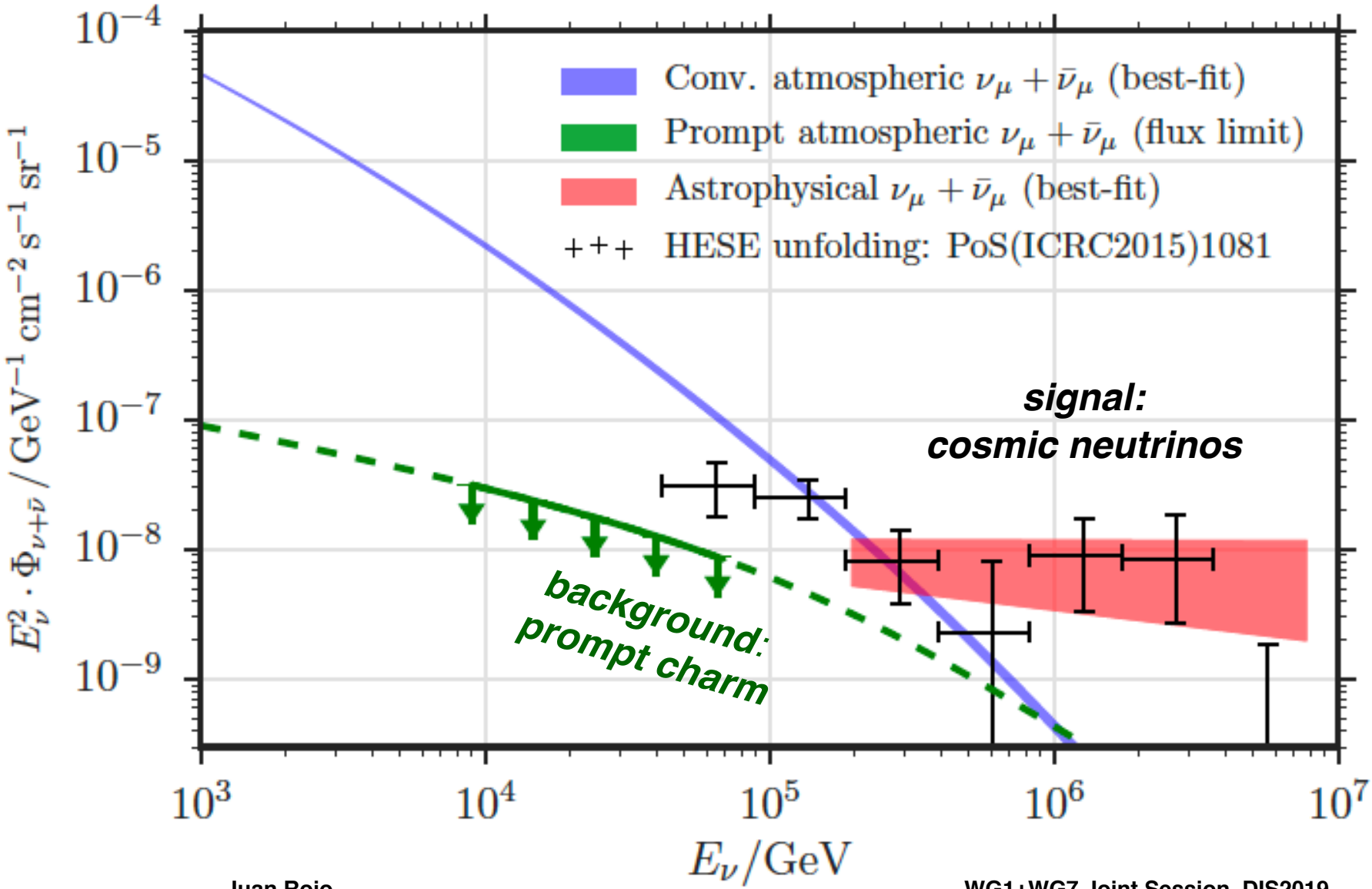
The birth of neutrino astronomy



Neutrino telescopes as QCD microscopes

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

***background**: prompt charm production*



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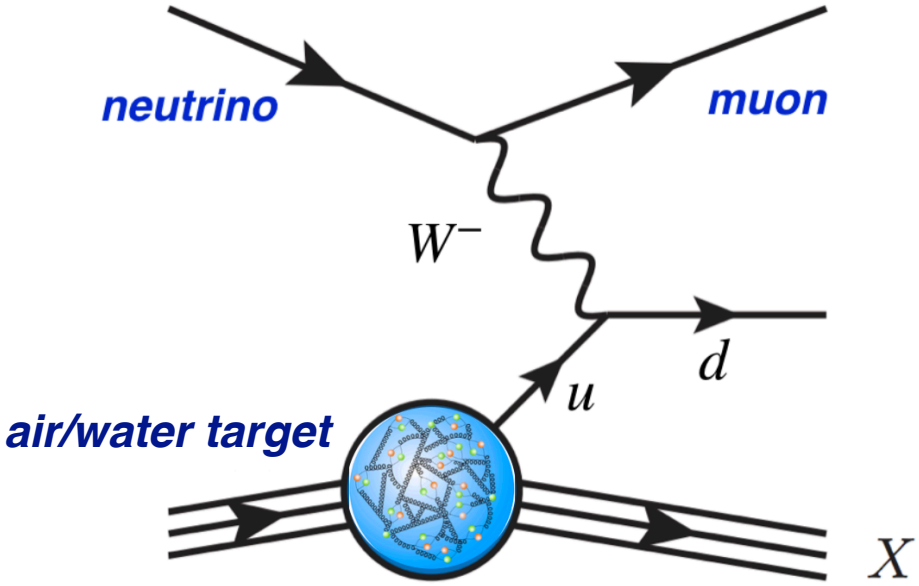

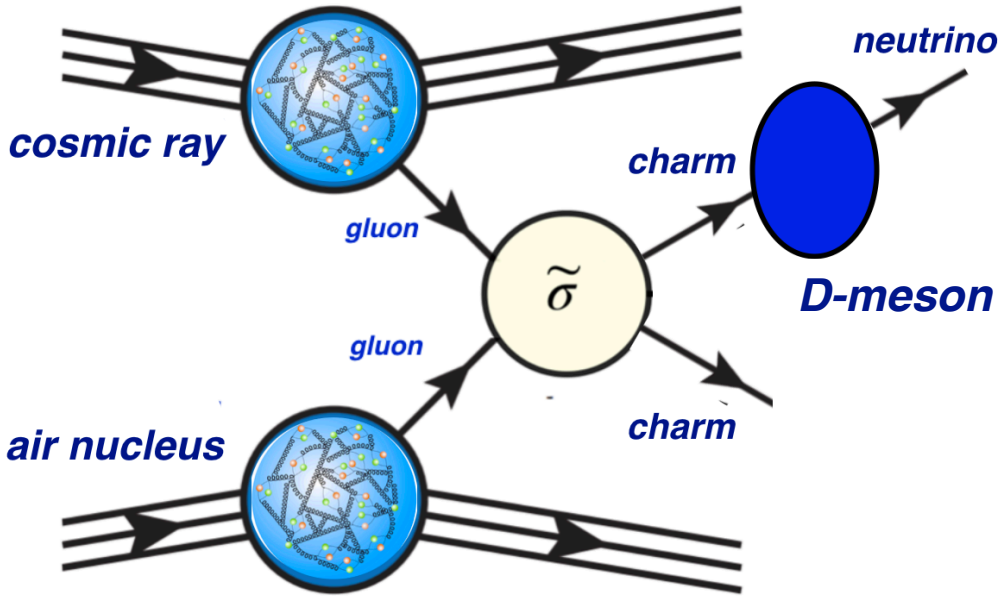

Sensitive to **small-*x* quarks** (and thus gluons via evolution) down to **x** ≃ 10^{-8} and **Q** ≃ M_W

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

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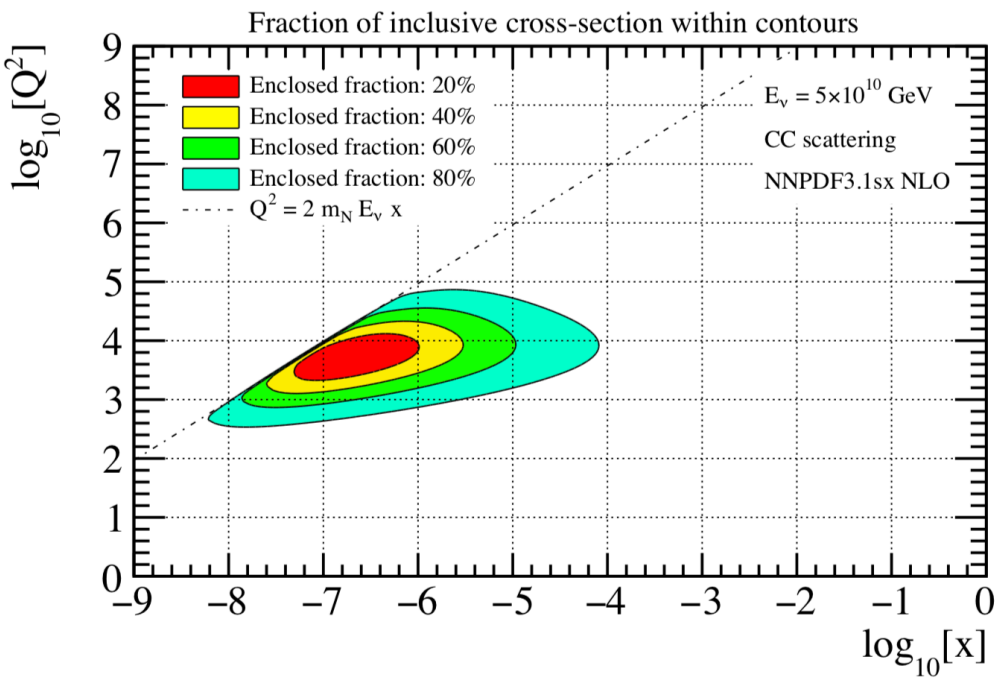

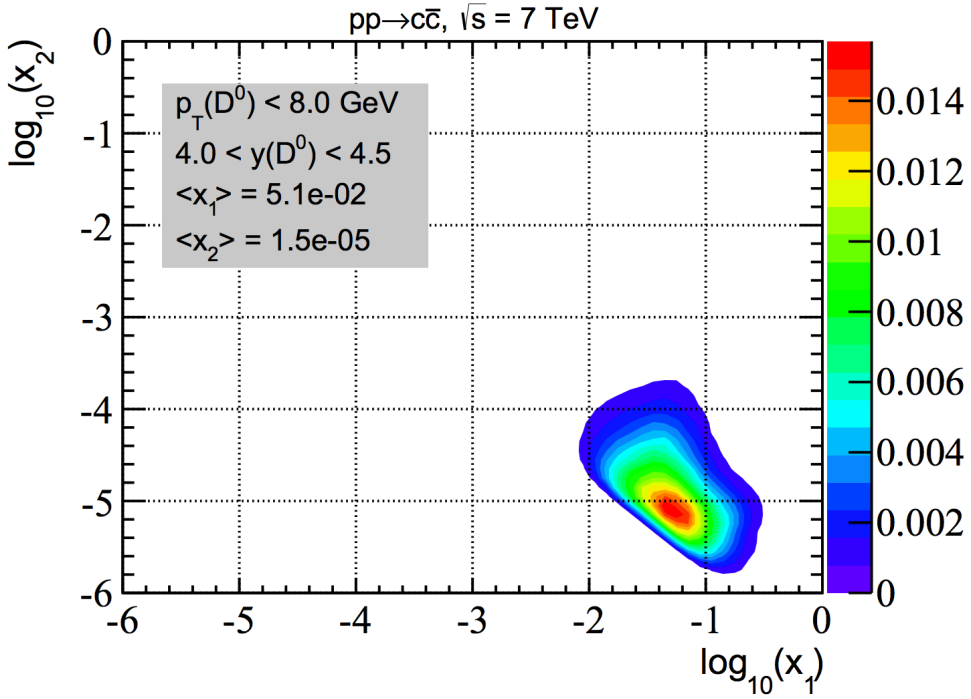

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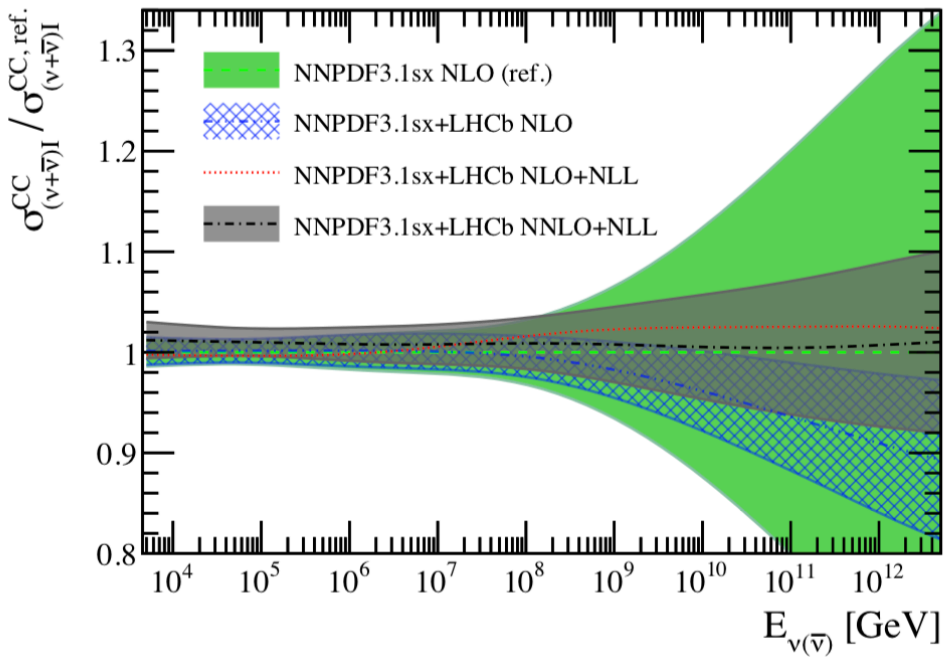
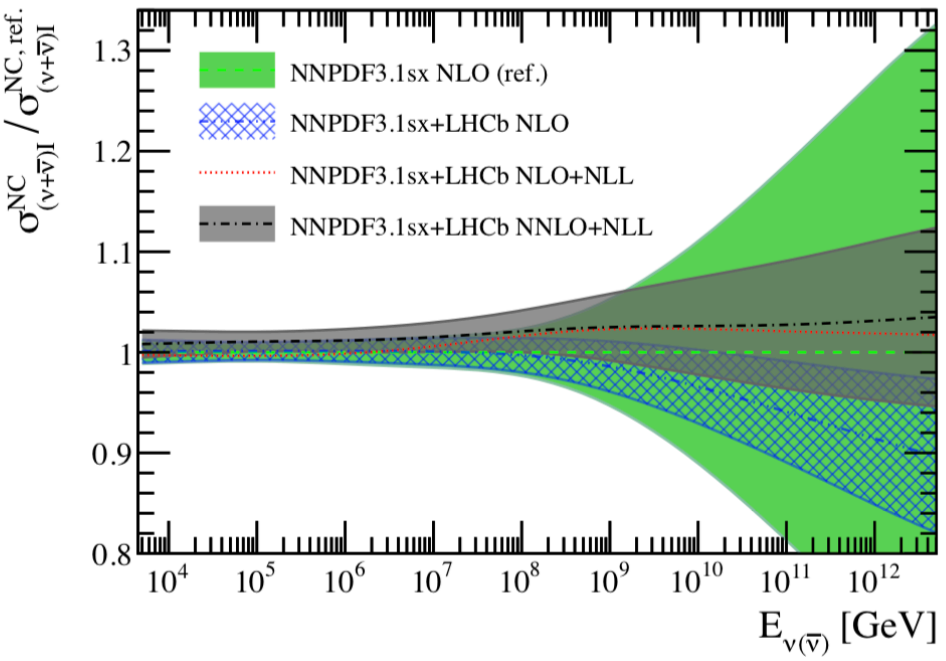
UHE neutrino-nucleus cross-section

Bertone, Gauld, JR 18



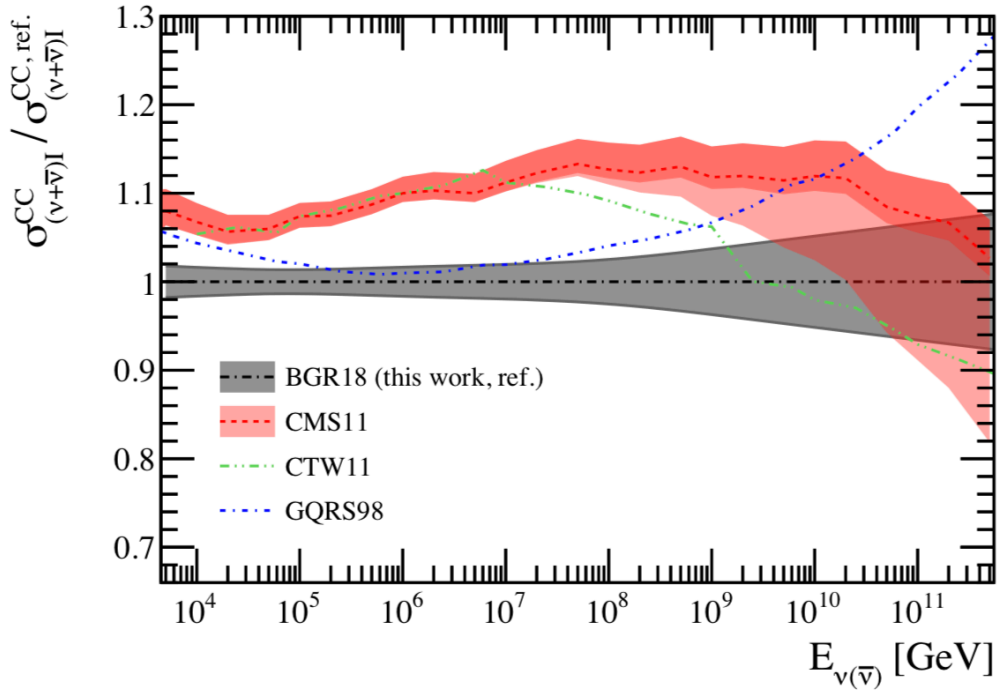


State-of-the-art predictions for **ultra-high energy** neutrino interactions

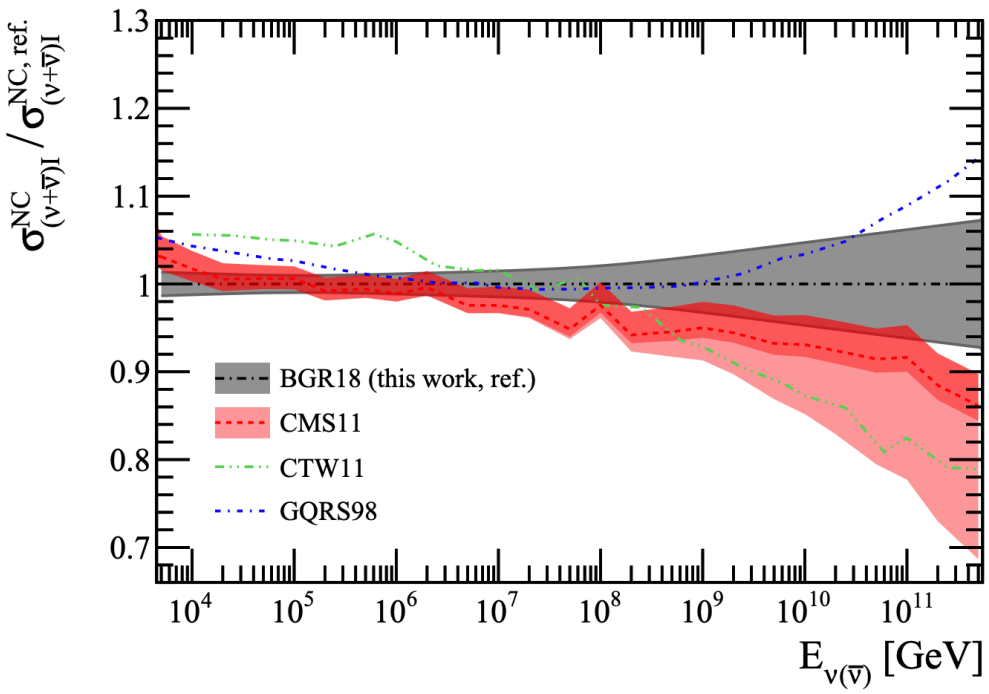
- **BFKL small-x effects** in PDFs and deep-inelastic structure functions
- Constraints on small-x PDFs from **LHCb charm production**
- Accounting for **nuclear corrections** and heavy-quark-initiated contributions

UHE neutrino-nucleus cross-section

Charged Current



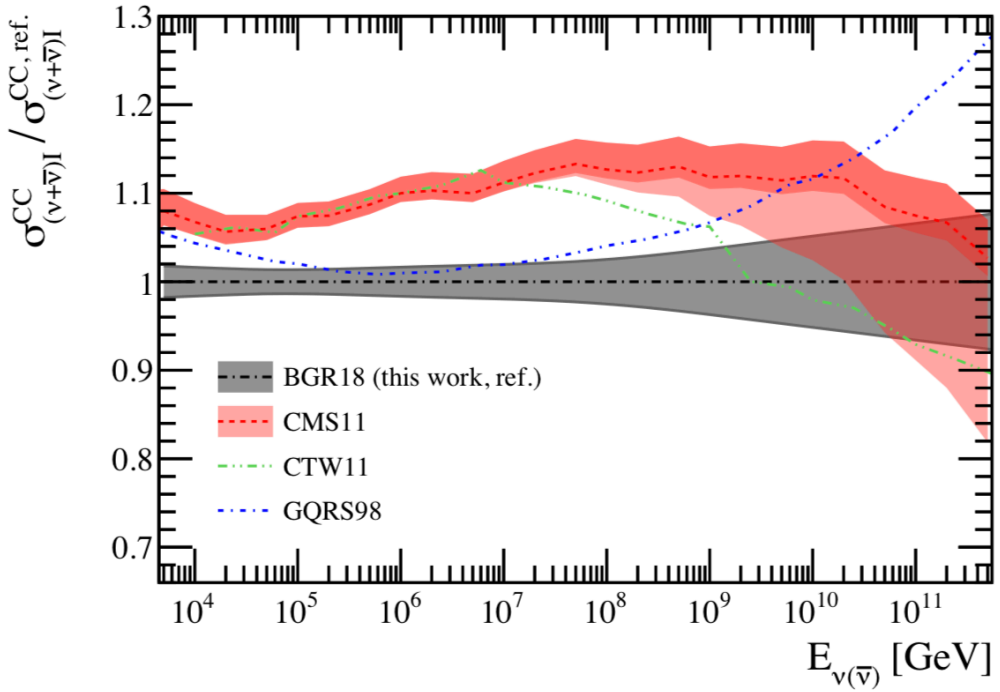
Neutral Current



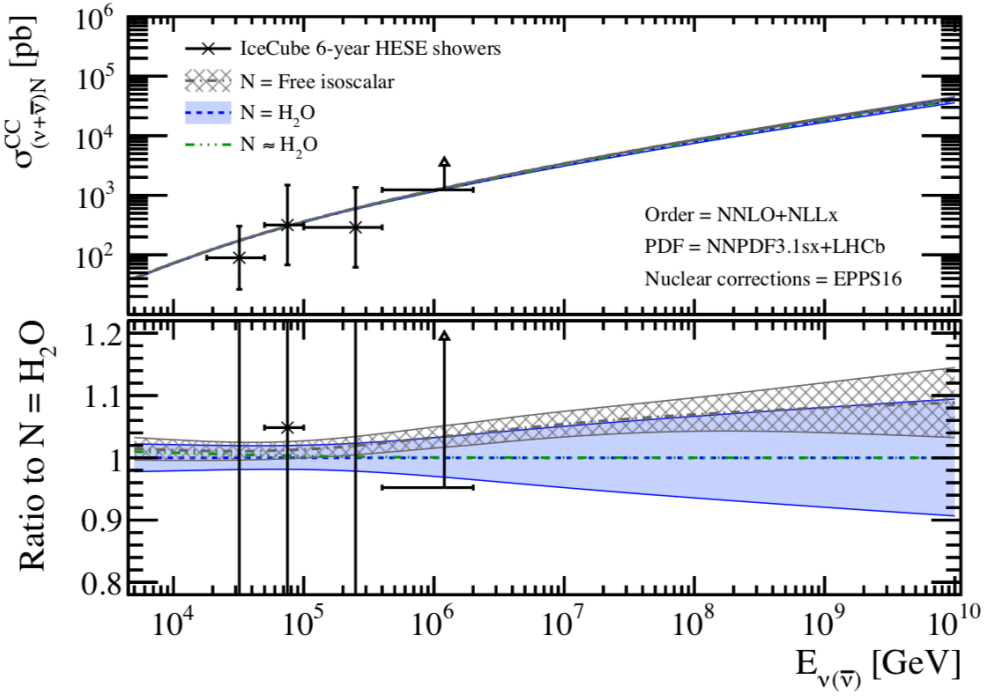
- Differences both at **intermediate** (updated PDFs, improved treatment of heavy quarks) and **high energies** (LHCb constraints, BFKL effects)
- Nuclear effects important: constrain them with LHCb **charm production in p+Pb**
- IceCube and other neutrino telescopes are the **ultimate QCD microscopes!**

UHE neutrino-nucleus cross-section

*Comparison with **previous results***



*Comparison with **IceCube data***



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Summary and outlook

- LHCb provides unique information on the **structure of the proton**
- 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 charm data and BFKL small-*x* resummation
- Ongoing implementation of BGR18 in **GENIE** will allow detailed phenomenological studies in neutrino (astro-)physics