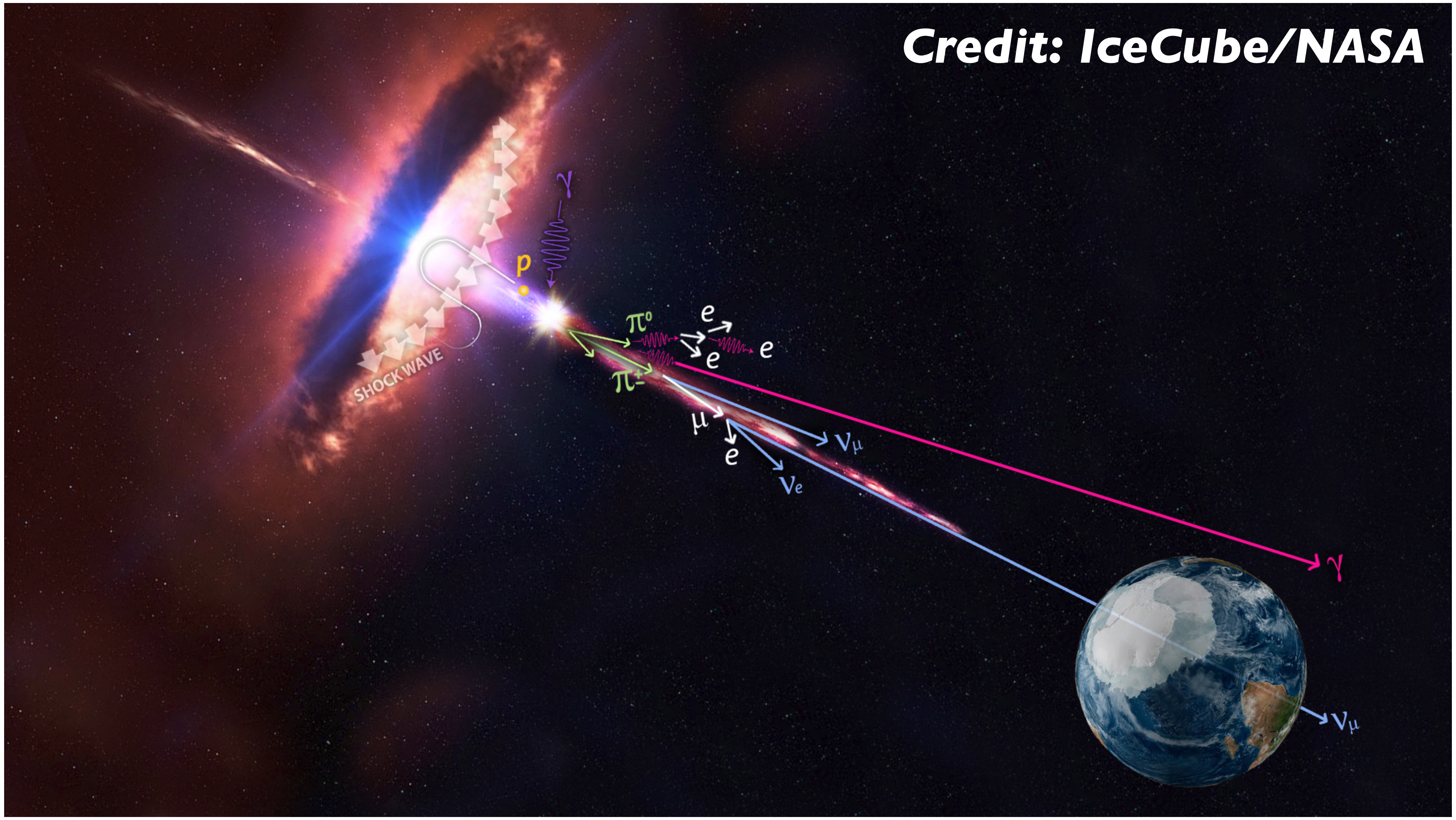


Neutrino telescopes as QCD microscopes

Rhorry Gauld

Nikhef Jamboree, 18th December 2018

NWO Netherlands Organisation for Scientific Research

Nikhef

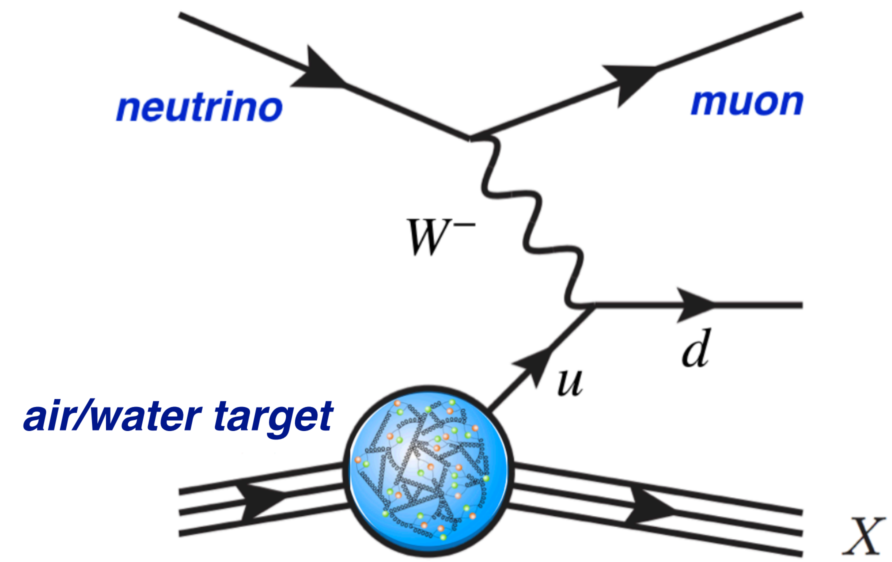
Young generation - My trajectory to Nikhef

- **DPhil, Oxford**
  - Heavy quarks physics
- **Postdoc IPPP, Durham**
  - Collider phenomenology
- **Postdoc ETH, Zurich**
  - Higher-order corrections
- **VENI Grant at Nikhef**

Eidgenössische Technische Hochschule Zürich
Swiss Federal Institute of Technology Zurich

"… from colliders to the cosmos"

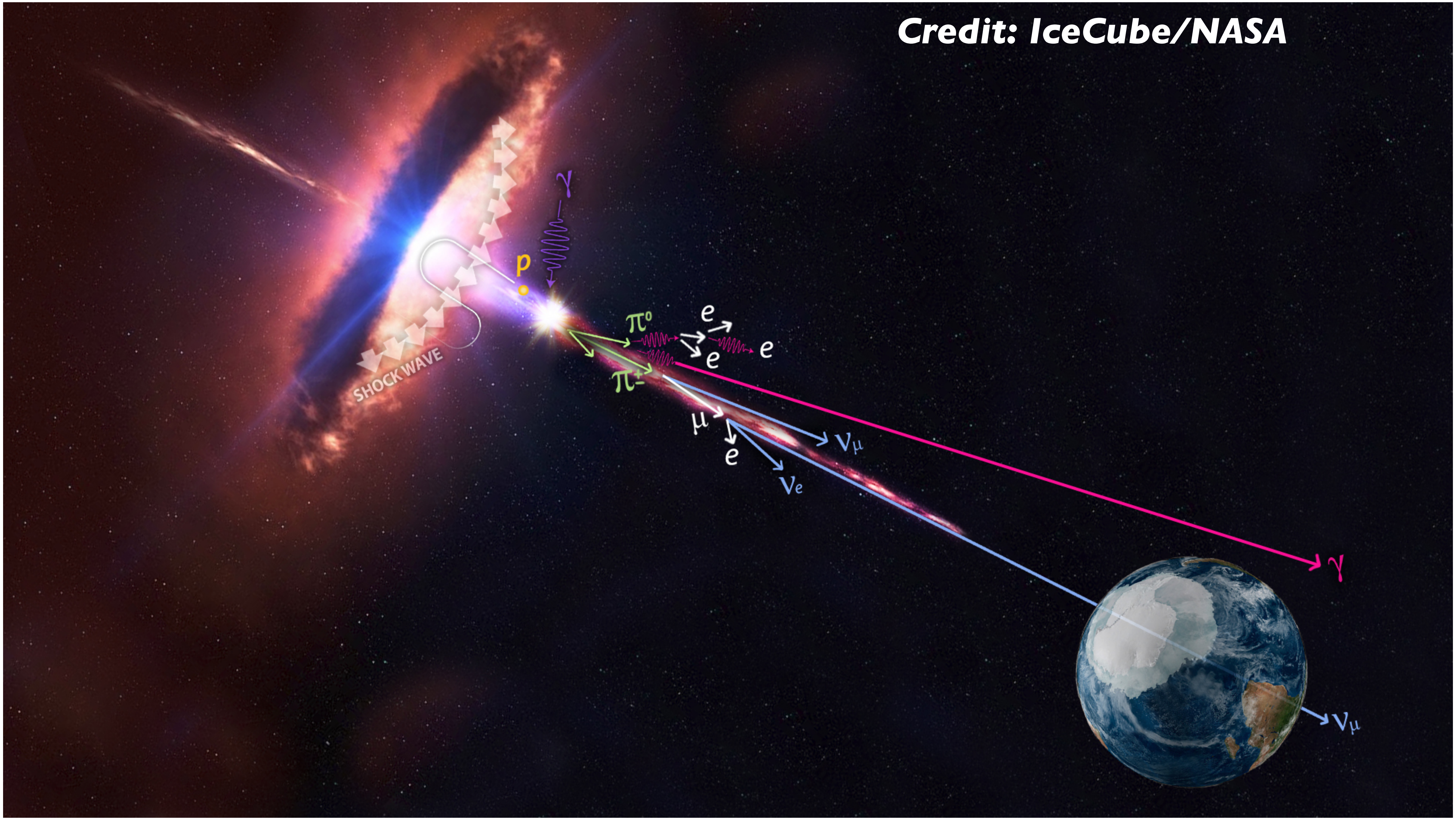
Overview



- **Neutrino telescopes**
  - why is QCD relevant?
- **Challenges:**
  - data-driven
  - theoretical (skipped for time)
- **BGR18 predictions**
- **Concluding remarks**

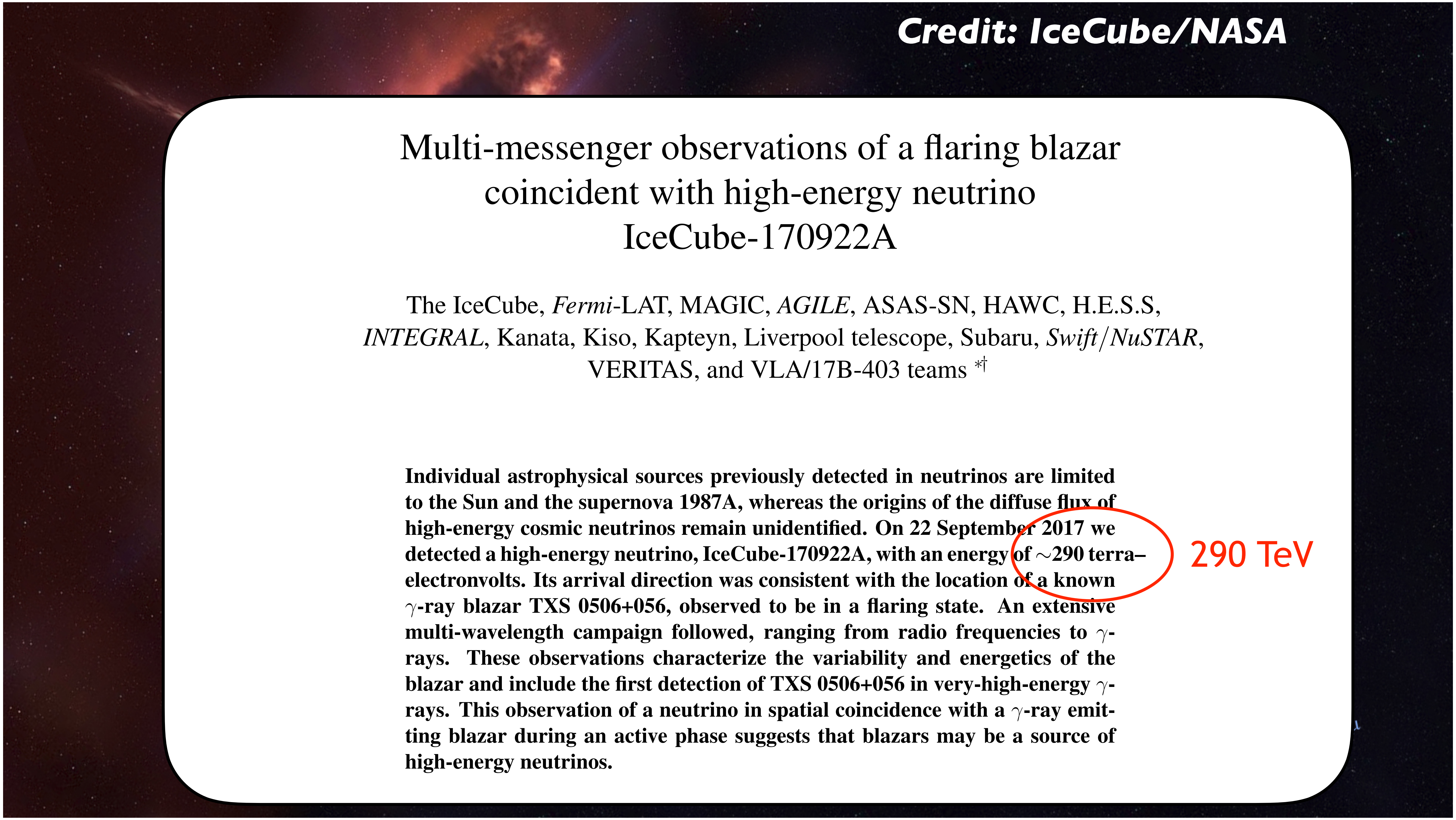
Valerio Rhorry Juan

Neutrino messengers



- Weakly interacting, point to production source (unhindered after production)
- Indicative of cosmic ray accelerators (come from charged pion/kaon decays)

Neutrino messengers



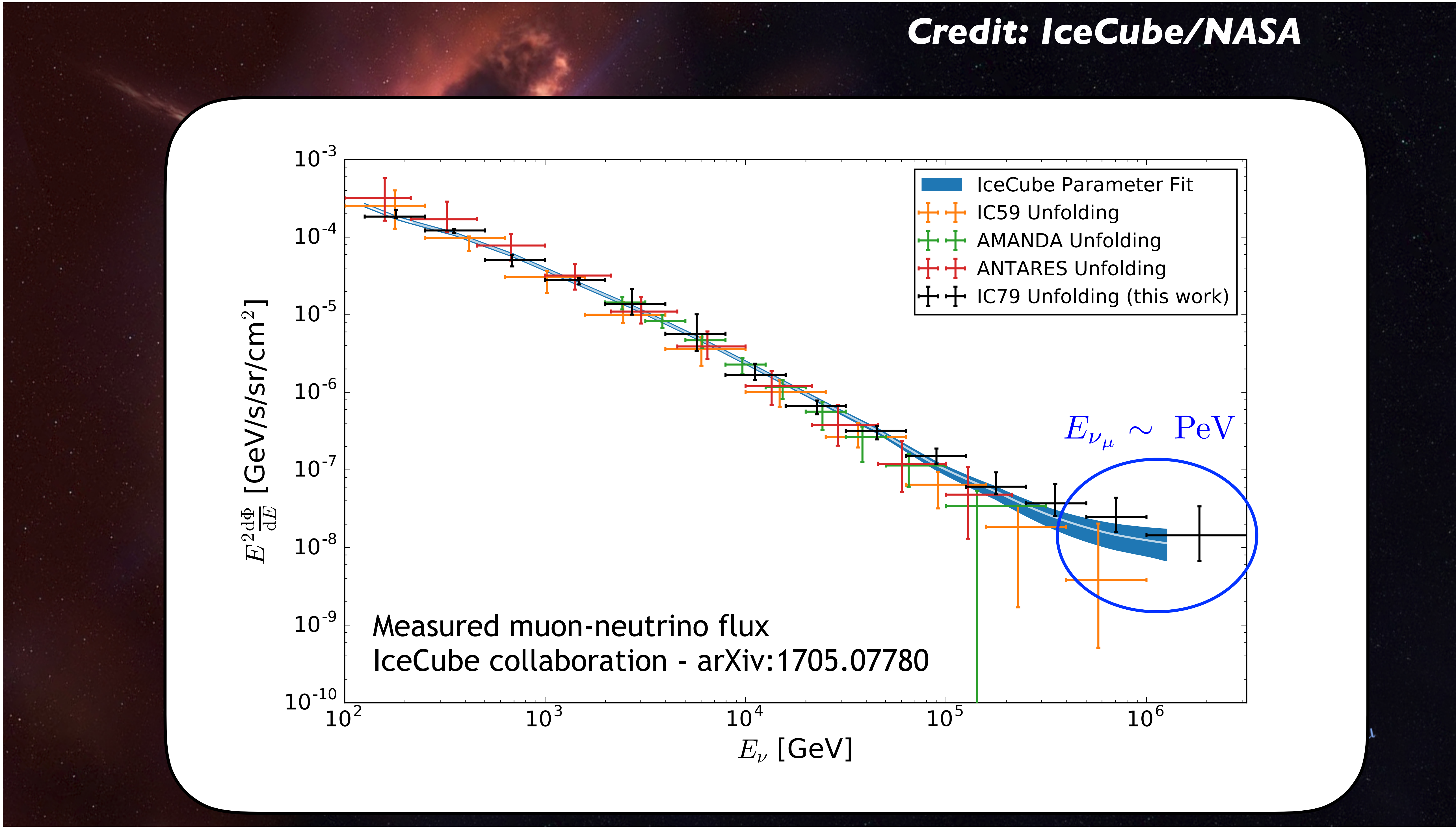
Multi-messenger observations of a flaring blazar coincident with high-energy neutrino IceCube-170922A

The IceCube, *Fermi*-LAT, MAGIC, *AGILE*, ASAS-SN, HAWC, H.E.S.S, *INTEGRAL*, Kanata, Kiso, Kapteyn, Liverpool telescope, Subaru, *Swift*/*NuSTAR*, VERITAS, and VLA/17B-403 teams *†

Individual astrophysical sources previously detected in neutrinos are limited to the Sun and the supernova 1987A, whereas the origins of the diffuse flux of high-energy cosmic neutrinos remain unidentified. On 22 September 2017 we detected a high-energy neutrino, IceCube-170922A, with an energy of ∼290 terra–electronvolts. Its arrival direction was consistent with the location of a known γ-ray blazar TXS 0506+056, observed to be in a flaring state. An extensive multi-wavelength campaign followed, ranging from radio frequencies to γ-rays. These observations characterize the variability and energetics of the blazar and include the first detection of TXS 0506+056 in very-high-energy γ-rays. This observation of a neutrino in spatial coincidence with a γ-ray emitting blazar during an active phase suggests that blazars may be a source of high-energy neutrinos.

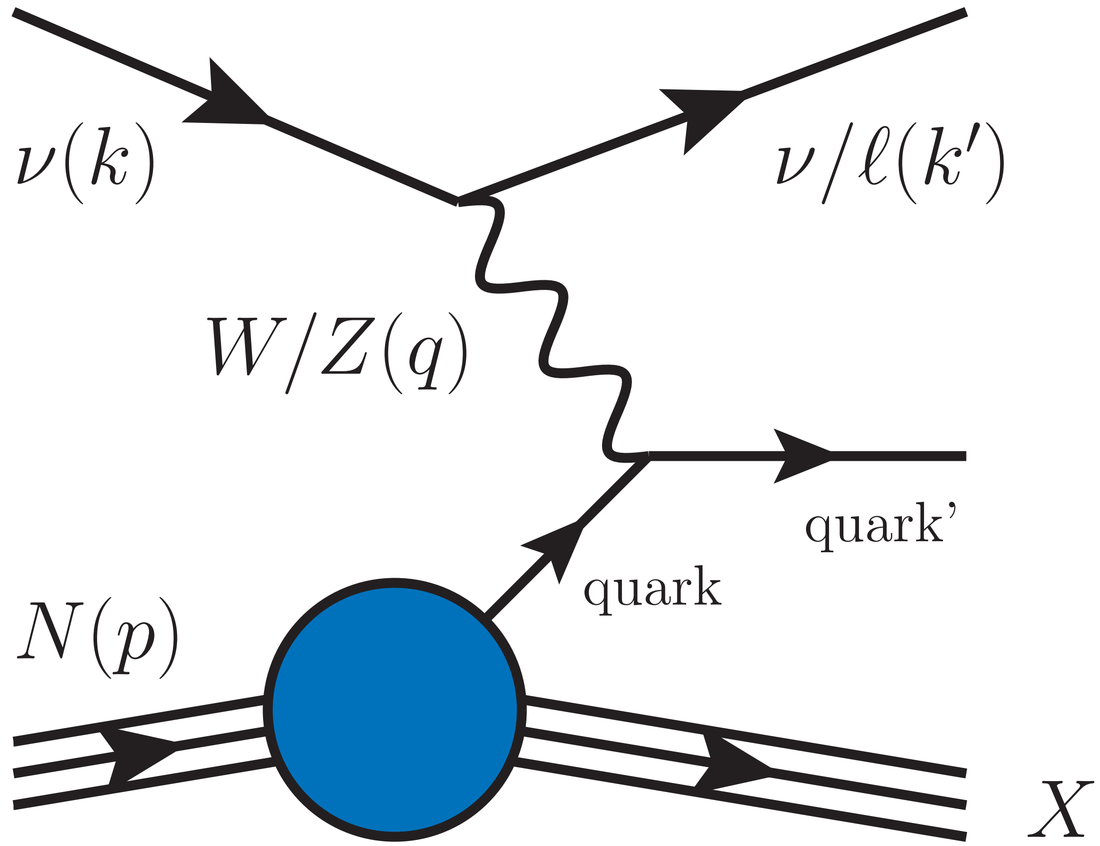
- Weakly interacting, point to production source (unhindered after production)
- Indicative of cosmic ray accelerators (come from charged pion/kaon decays)

Neutrino messengers

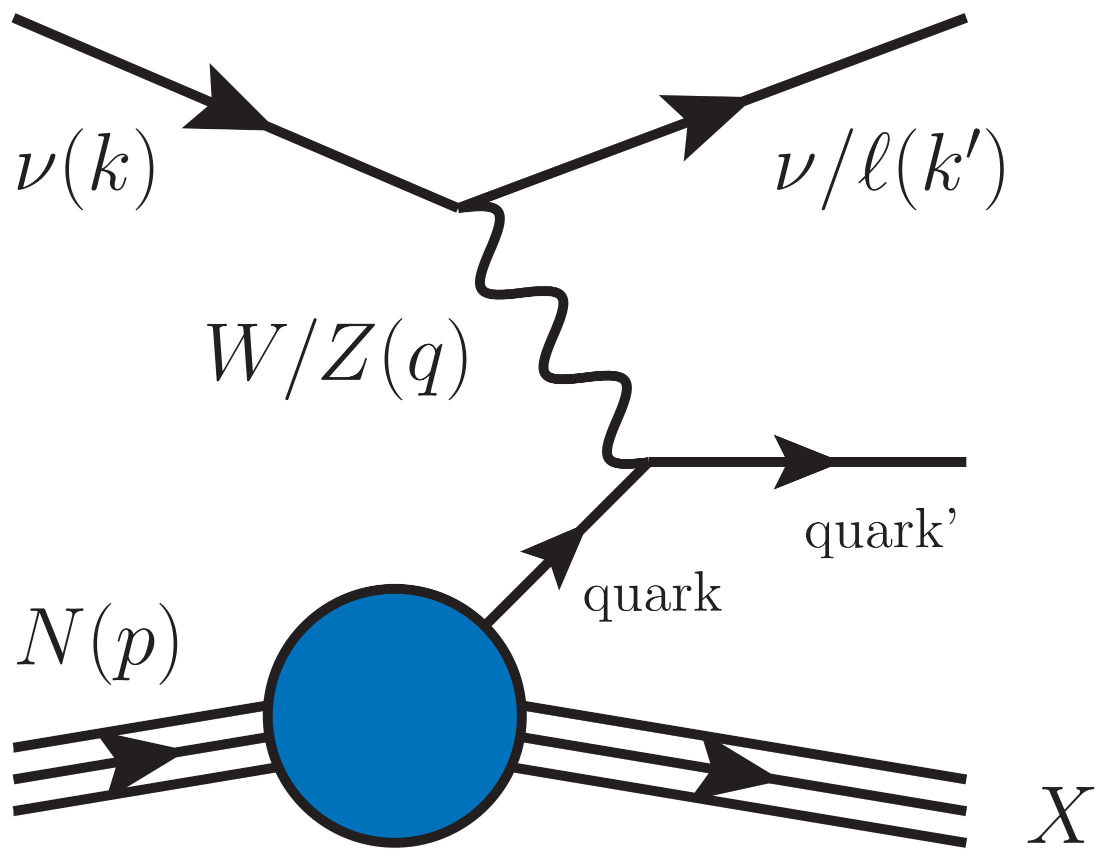


- Weakly interacting, point to production source (unhindered after production)
- Indicative of cosmic ray accelerators (come from charged pion/kaon decays)

Neutrino-nucleon Deep Inelastic Scattering



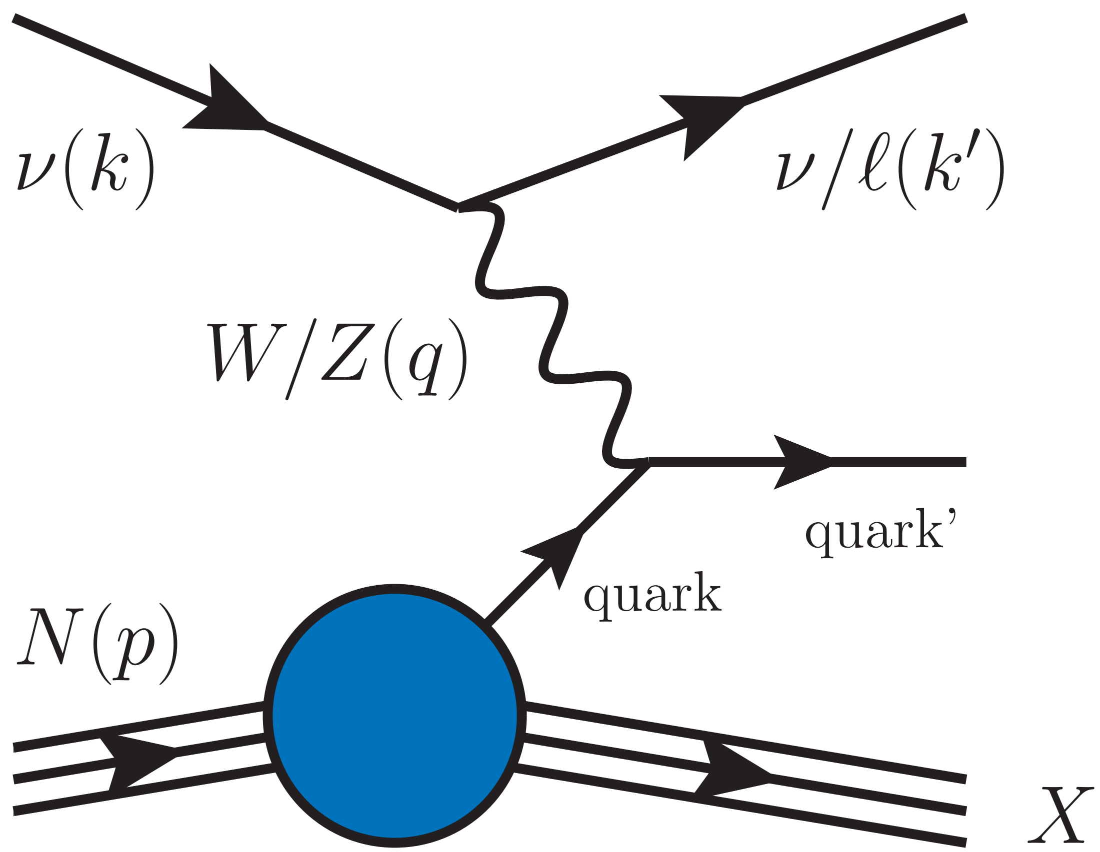
Neutrino-nucleon Deep Inelastic Scattering



$$s = (k+p)^2 = m_N^2 + 2m_N E_\nu$$

Total CoM Energy

Neutrino-nucleon Deep Inelastic Scattering



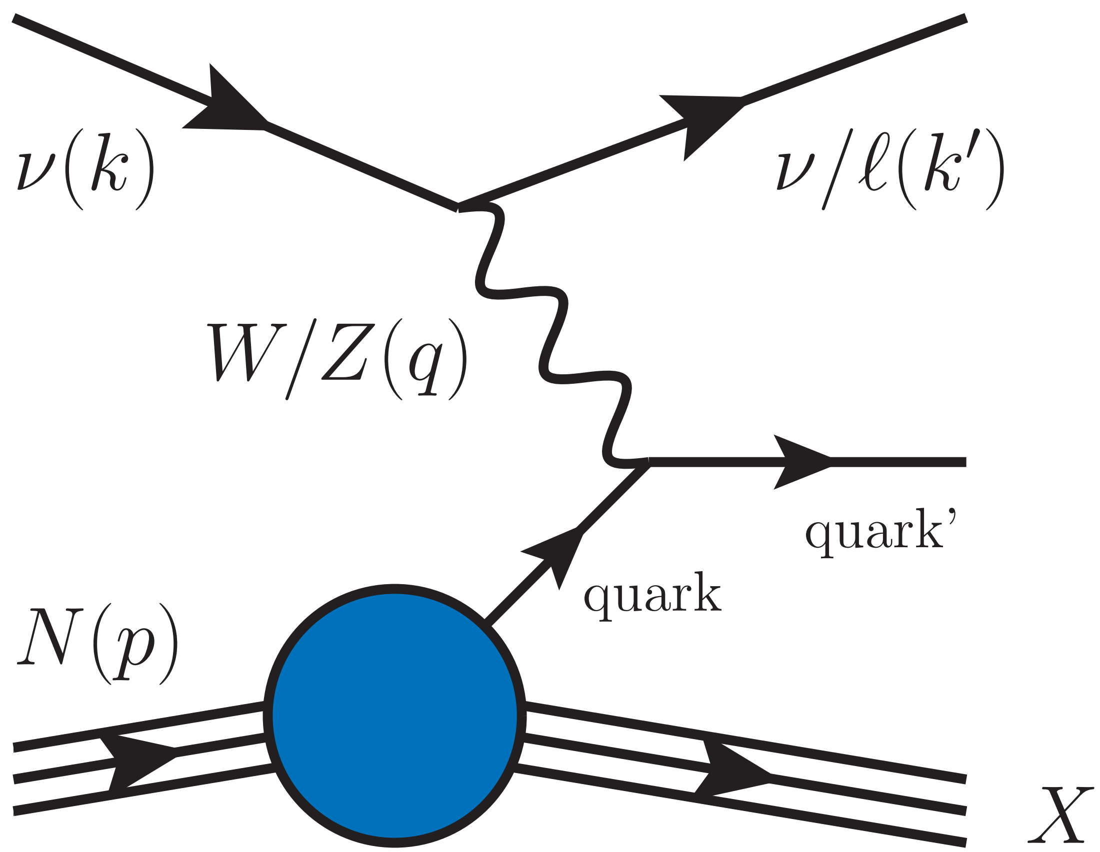
$$s = (k+p)^2 = m_N^2 + 2 m_N E_\nu$$

Total CoM Energy

$$Q^2 = -q^2 = -(k-k')^2$$

$$Q^2 \in [Q^2_{\mathrm{min}}, 2 m_N E_\nu]$$

Neutrino-nucleon Deep Inelastic Scattering



$$s = (k+p)^2 = m_N^2 + 2m_N E_\nu$$

Total CoM Energy

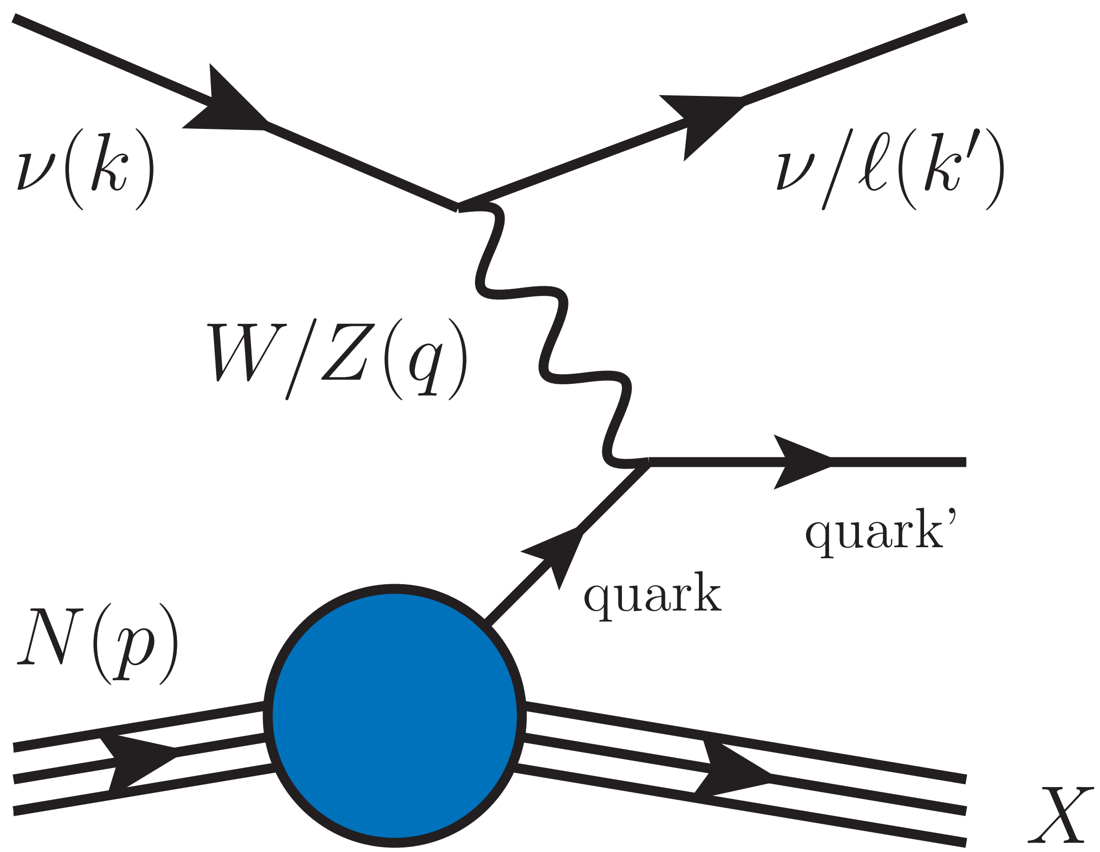
$$Q^2 = -q^2 = -(k-k')^2$$

$Q^2 \in [Q^2_{\min}, 2m_N E_\nu]$

$$y = \frac{q \cdot p}{k \cdot p} = 1 - \frac{E'}{E_\nu}$$

Elasticity, $y \in [0,1]$

Neutrino-nucleon Deep Inelastic Scattering



$$s = (k+p)^2 = m_N^2 + 2m_N E_\nu$$

Total CoM Energy

$$Q^2 = -q^2 = -(k-k')^2$$

$Q^2 \in [Q^2_{\text{min}}, 2m_N E_\nu]$

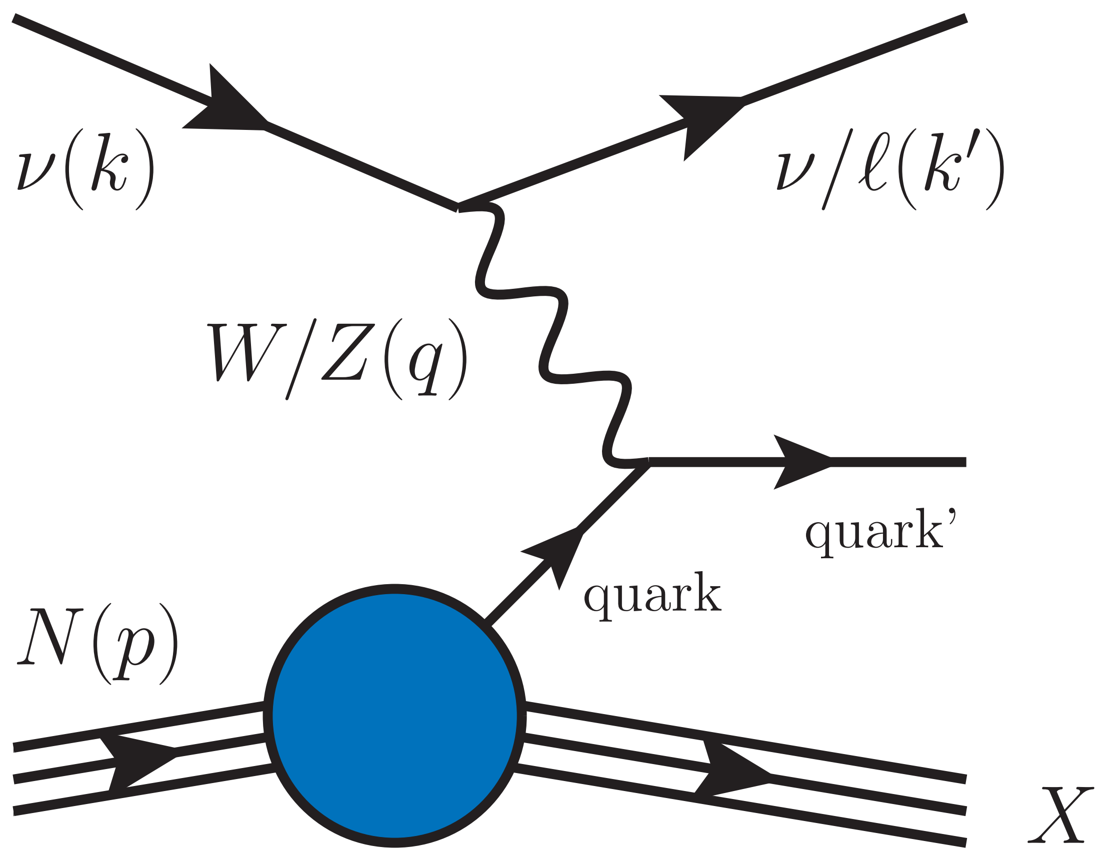
$$y = \frac{q \cdot p}{k \cdot p} = 1 - \frac{E'}{E_\nu}$$

Elasticity, $y \in [0,1]$

$$x = \frac{Q^2}{2q \cdot p} = \frac{Q^2}{2m_N y E_\nu}$$

$x \in [x_{\text{min}}(Q^2_{\text{min}}), 1]$

Neutrino-nucleon Deep Inelastic Scattering



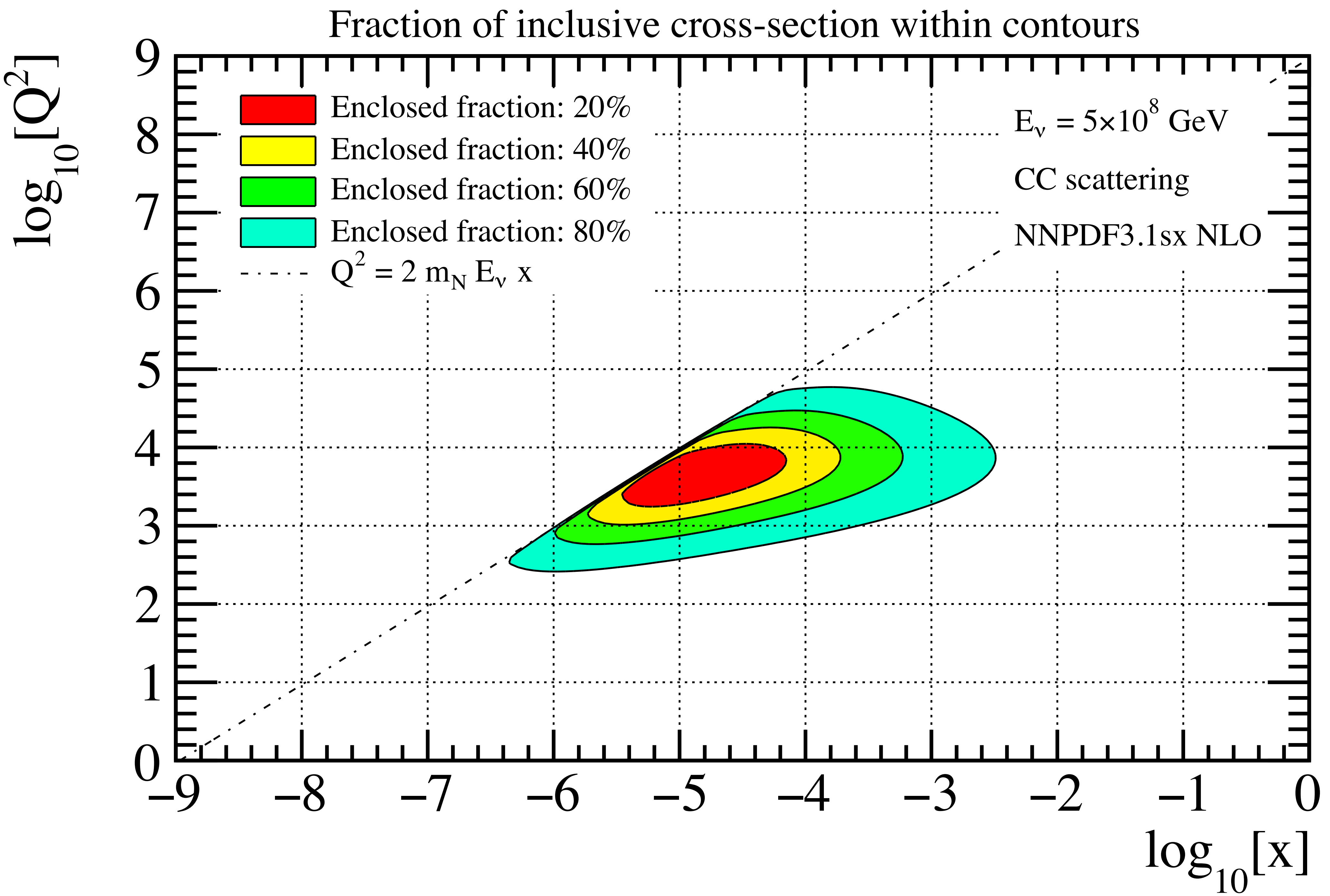
$$\frac{\mathrm{d}^2\sigma^{\mathrm{CC}}_{\nu(\bar{\nu})N}(x,Q^2,E_\nu)}{\mathrm{d}x\,\mathrm{d}Q^2} = \frac{G_F^2 M_W^4}{4\pi x(Q^2+M_W^2)^2}\left(Y_+ F_{2,\mathrm{CC}}^{\nu(\bar{\nu})N}(x,Q^2) \mp Y_- x F_{3,\mathrm{CC}}^{\nu(\bar{\nu})N}(x,Q^2) - y^2 F_{L,\mathrm{CC}}^{\nu(\bar{\nu})N}(x,Q^2)\right)$$

Kinematic pre-factor

$F_i(x,Q^2)$ — DIS Structure functions (QCD)

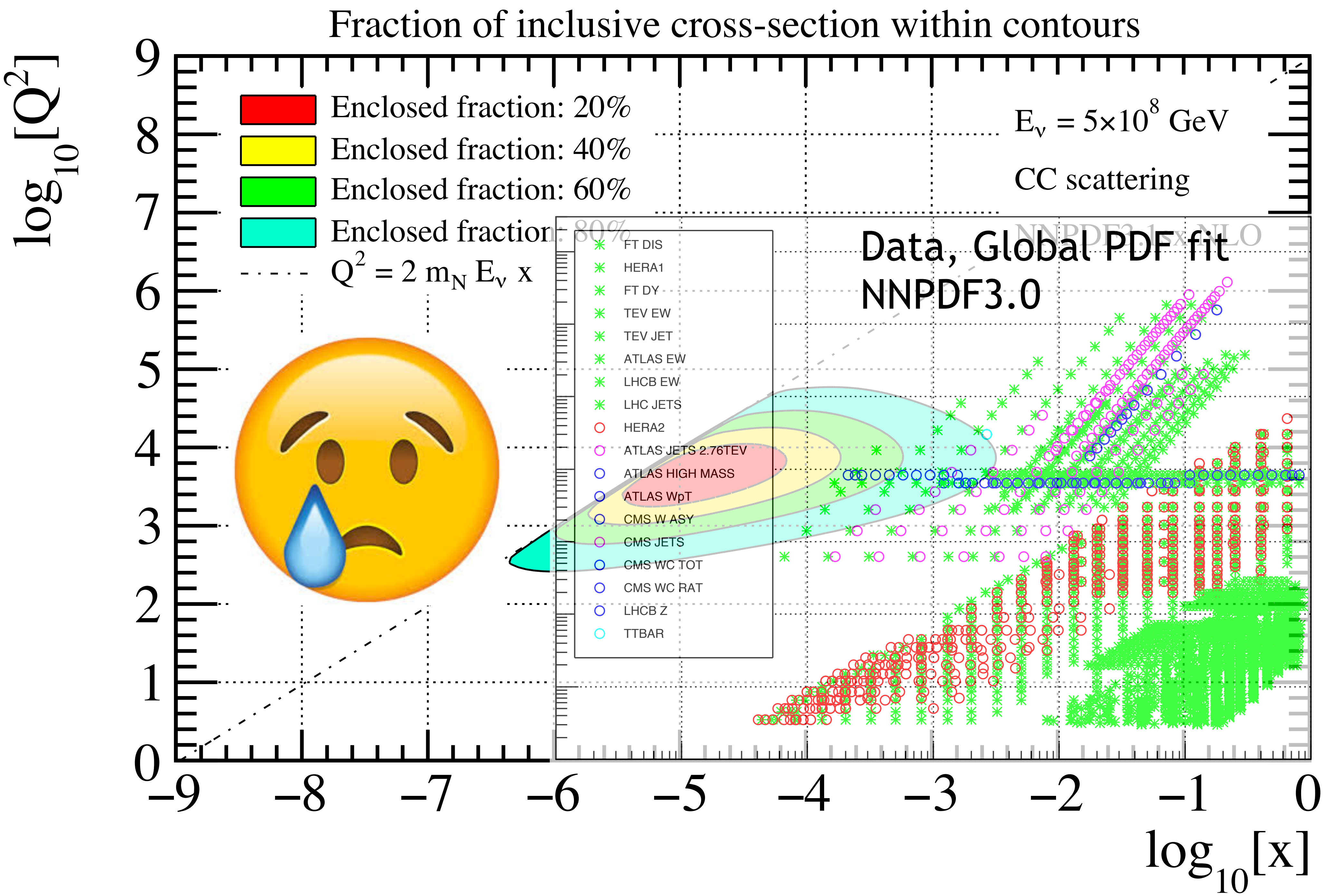
Note: $Y_\pm = 1 \pm (1-y)^2$

Example, 500 PeV neutrino $(5 \times 10^8 \text{ GeV})$



$$\frac{\mathrm{d}^2\sigma_{\nu I}^{CC}}{\mathrm{d}x\,\mathrm{d}Q^2}\,(x, Q^2, E_\nu)$$

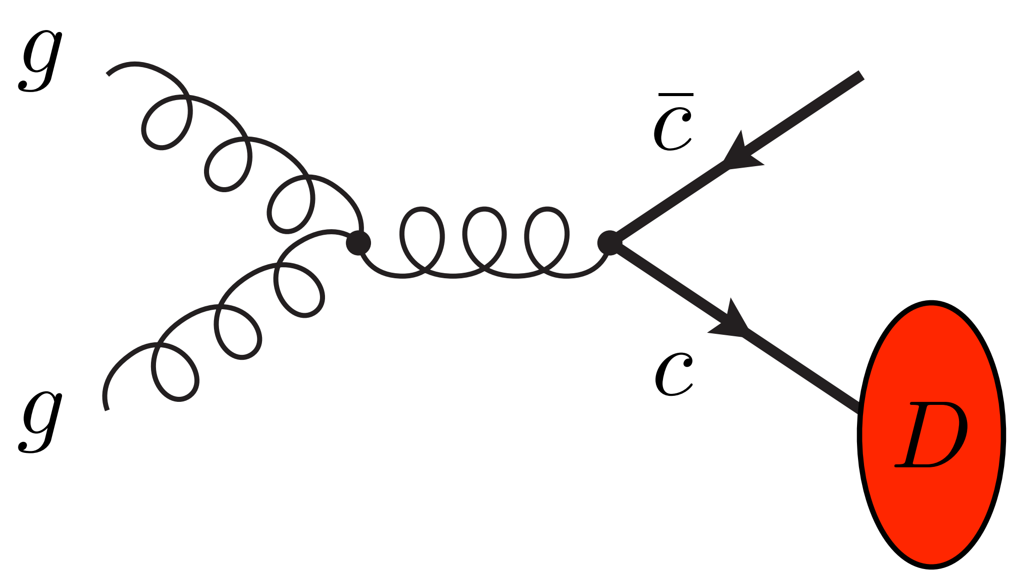
Example, 500 PeV neutrino $(5 \times 10^8 \text{ GeV})$

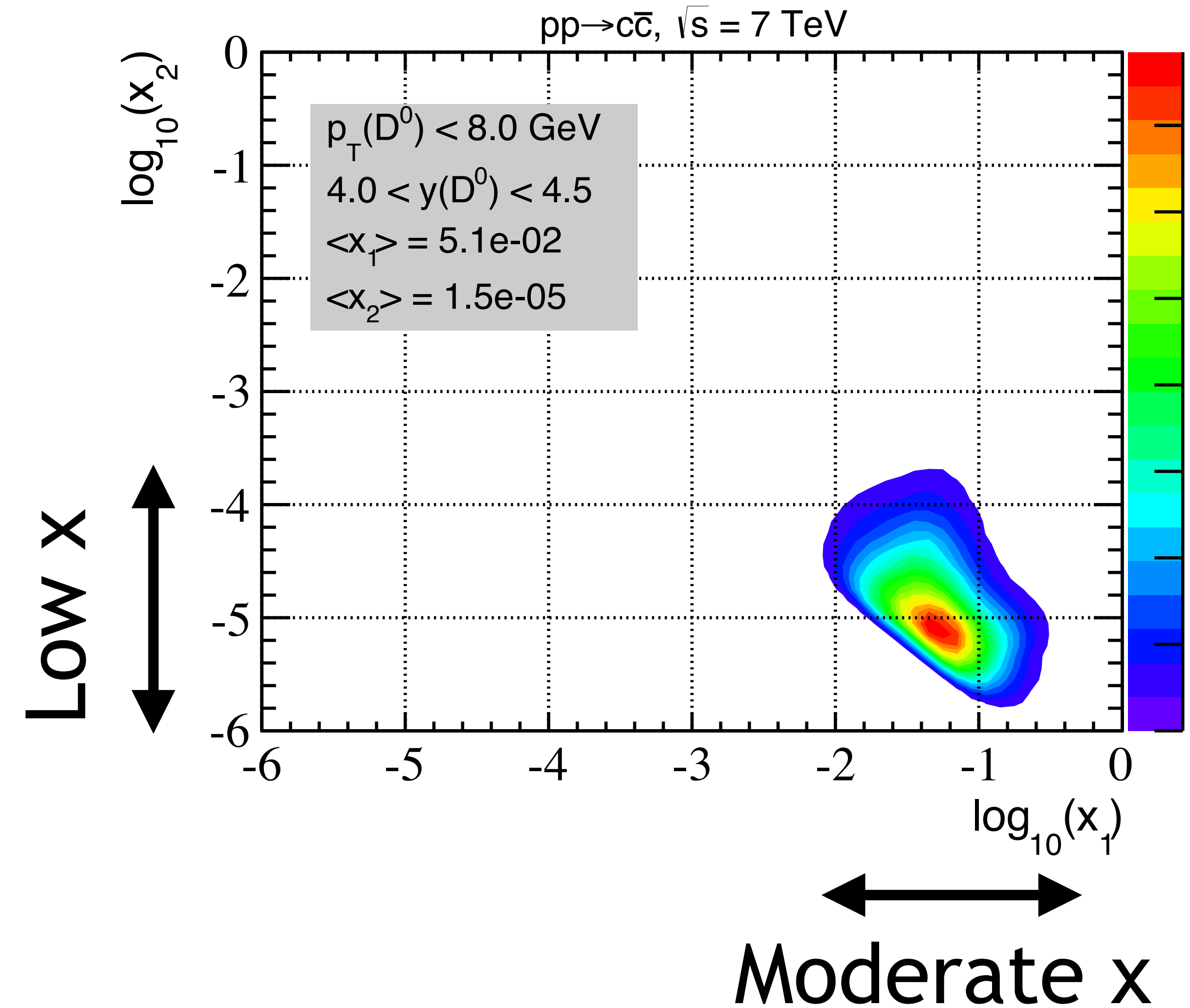


$$\frac{\mathrm{d}^2\sigma_{\nu I}^{CC}}{\mathrm{d}x\,\mathrm{d}Q^2}\,(x, Q^2, E_\nu)$$

D-hadrons at LHCb

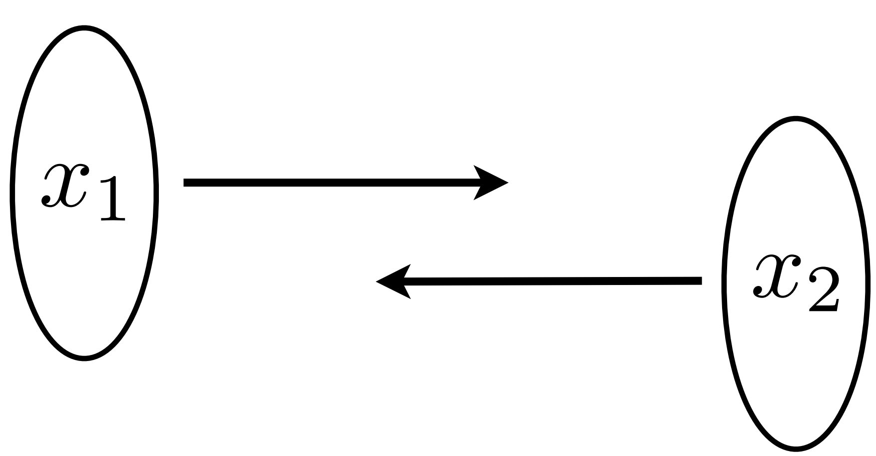
$$pp \to D + X$$

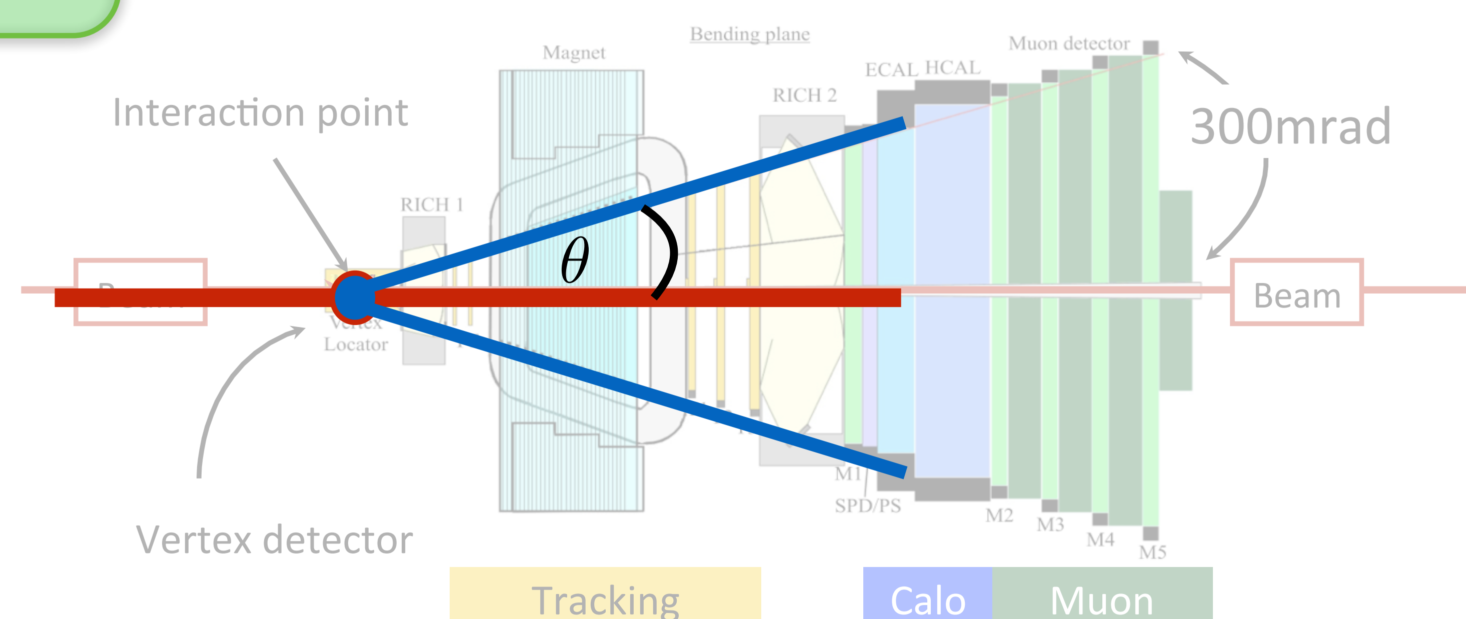




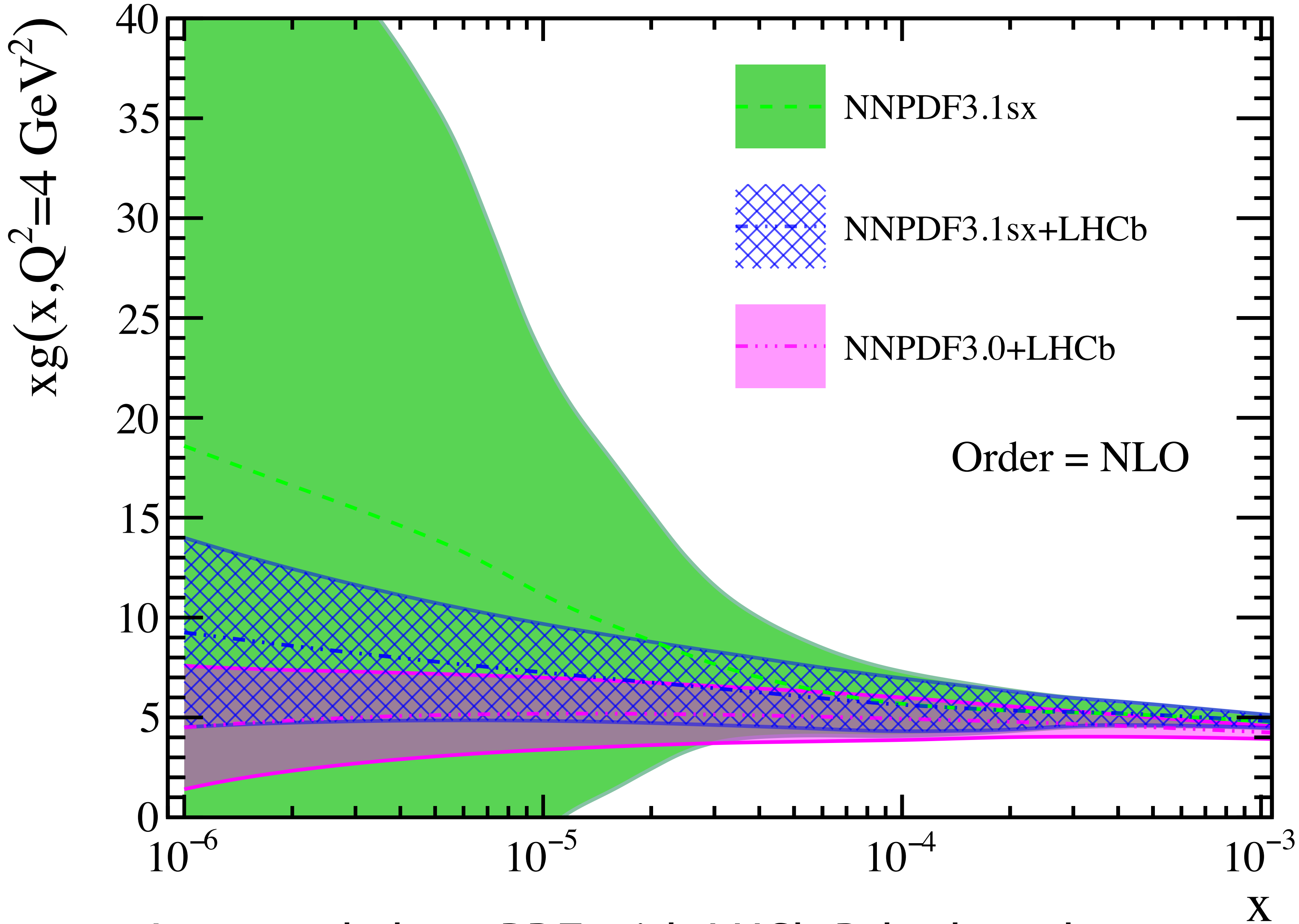
LO PDF sampling occurs at

$$x_{1,(2)} = \frac{m_T}{\sqrt{S}}\left(e^{(-)y_3} + e^{(-)y_4}\right)$$





D-hadrons at LHCb



Improved gluon PDF with LHCb D-hadron data

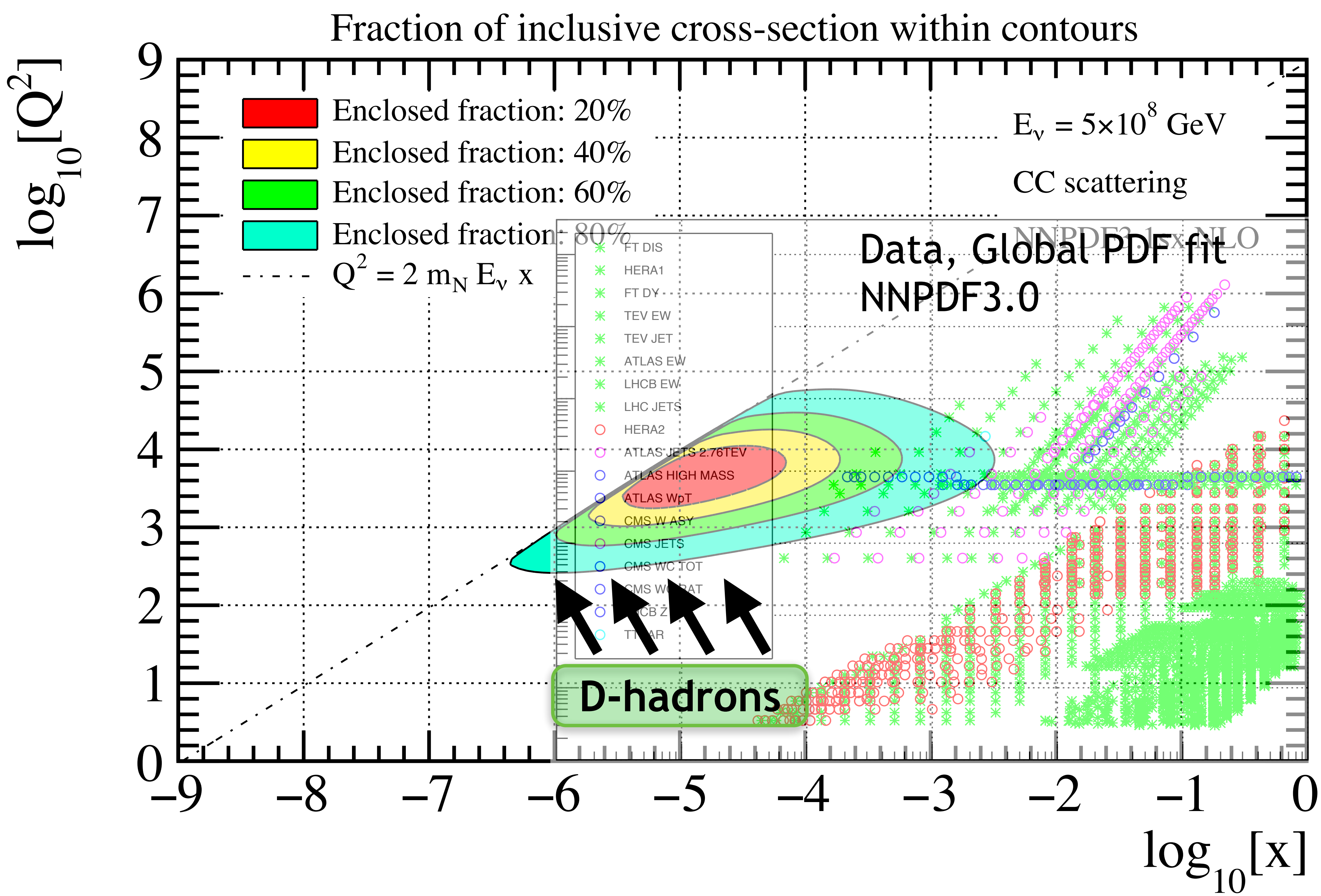
Precise gluon PDF:
low-x and low-Q2

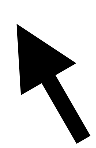
PDF evolution

$Q^2 \uparrow \quad x \downarrow$

Precise neutrino cross-section
lower-x and larger-Q2

Example, 500 PeV neutrino

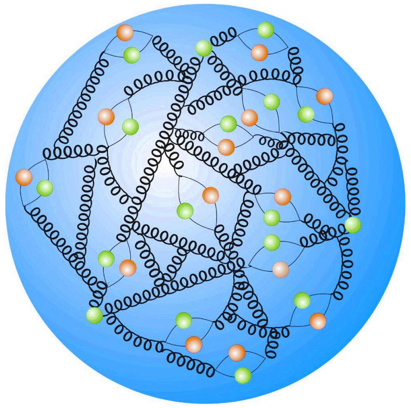


 = PDF Evolution

$$\frac{d^2\sigma^{CC}_{\nu I}}{dx\,dQ^2}\,(x, Q^2, E_\nu)$$

Bringing it all together

- **Perturbative accuracy**
  - NNLO+NLLx accurate predictions for Structure Functions
  - APFEL *Bertone, Carrazza, Rojo*, arXiv:1310.1394
  - HELL: *Bonvini et al.*, arXiv:1607.02153, 1708.07510, 1805.06460, 1805.08785



- **Parton distribution functions**
  - NNPDF3.1sx free protons, arXiv:1710.05935
  - LHCb D-hadron data, arXiv:1302.2864, 1510.01707, 1610.02230

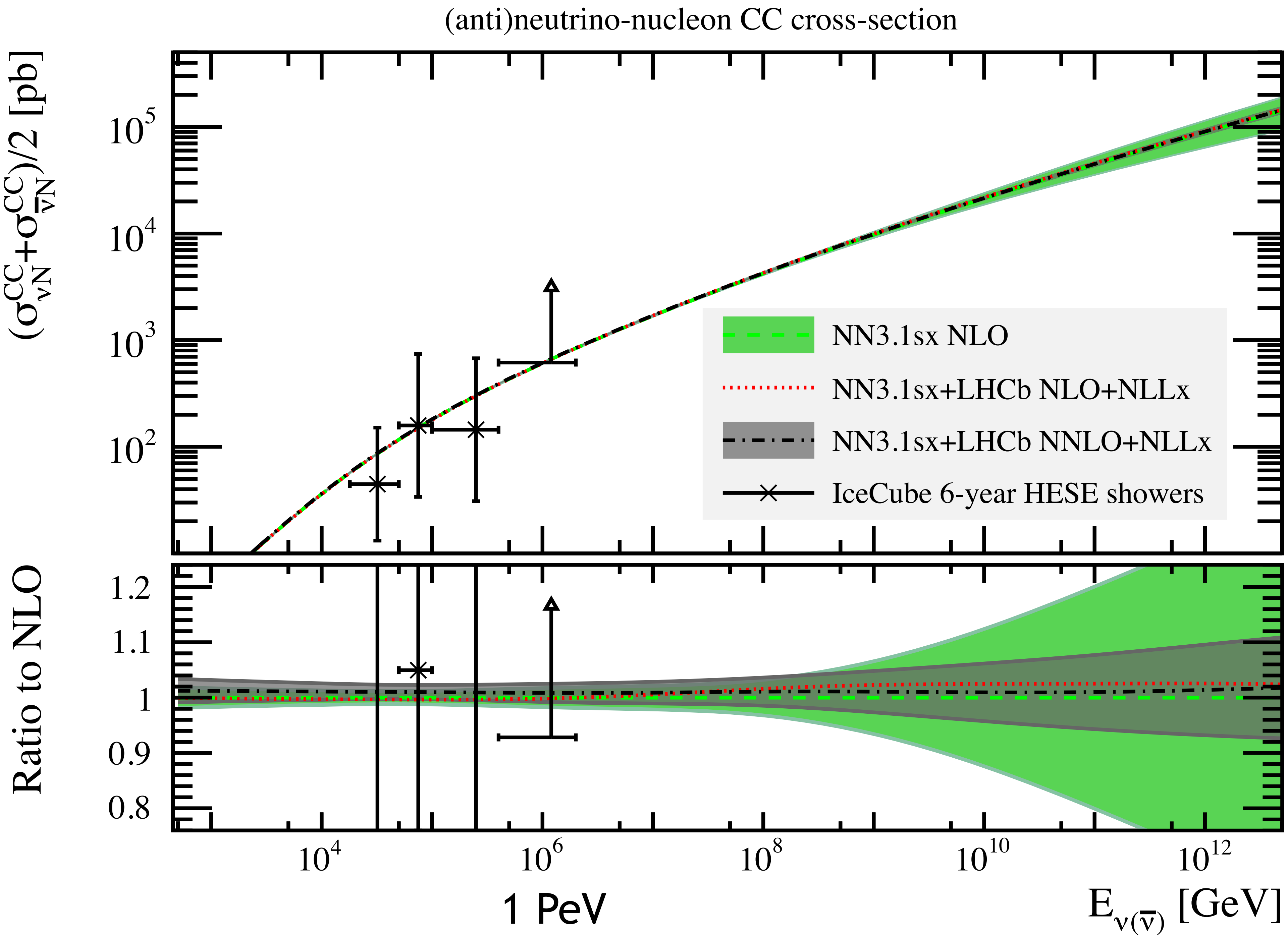
- **Heavy quark mass effects**
  - FONLL matching scheme, *Forte et al.*, arXiv:1001.2312
  - Top quark mass effects included at NLO, e.g. $\nu + q_d \to \ell^- + t$

- **Nuclear corrections (Target is $\mathrm{H_2O}$)**
  - Obtained with EPPS16 nPDFs, *Eskola et al.*, arXiv:1612.05741

$$F^{\mathrm{H_2O}} = \frac{1}{2+A}\left(2F^p + ZF^{p,A} + NF^{n,A}\right) \qquad Z=8,\; N=8,\; A=Z+N$$

Results - BGR18

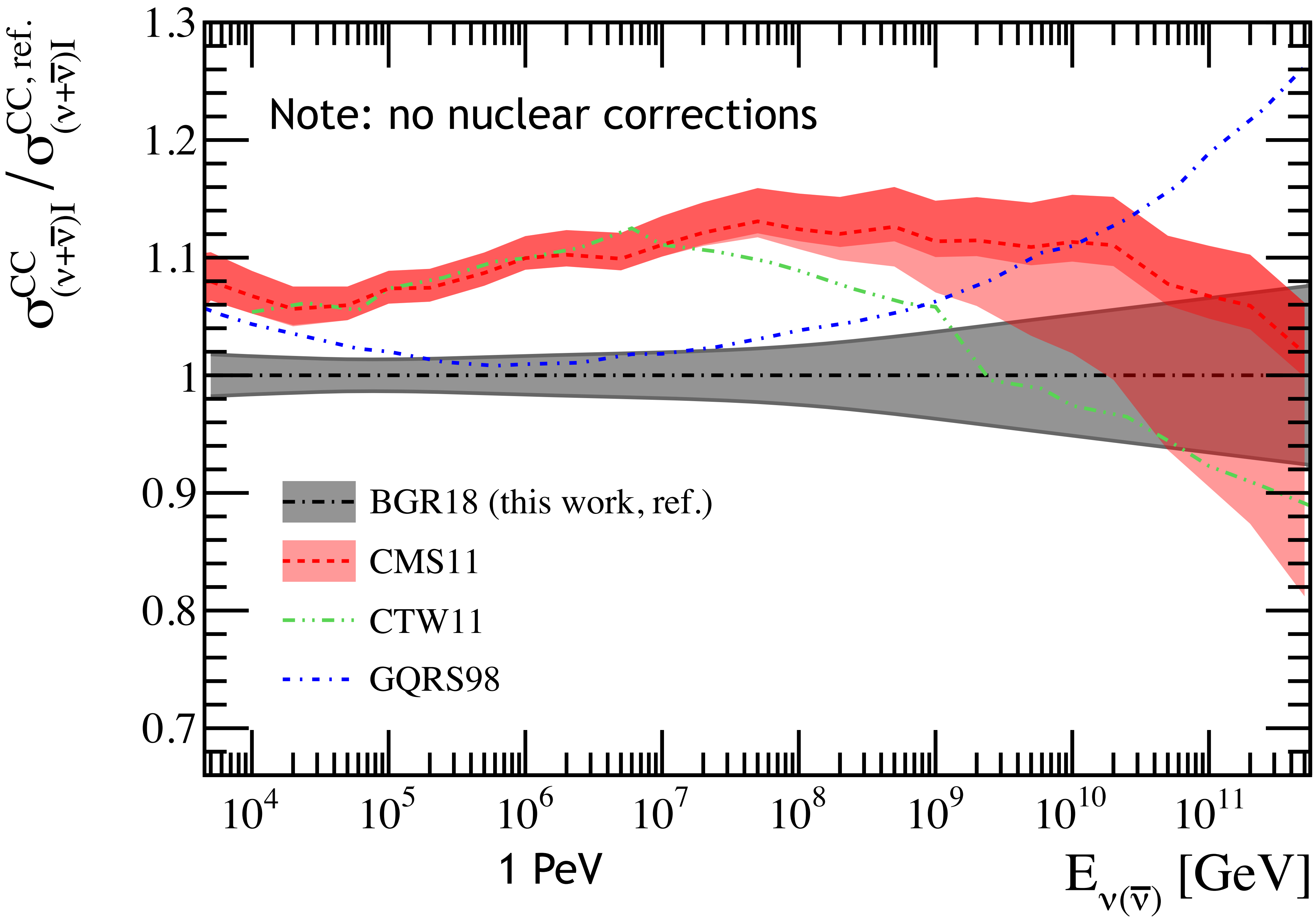
For details: ***Bertone***, ***Gauld***, ***Rojo***, arXiv:**1808.02034**



- Nuclear corrections relevant in PeV range
- Theoretical predictions stable (<10% unc.) into multi PeV range

Results - BGR18

For details: ***Bertone***, ***Gauld***, ***Rojo***, arXiv:**1808.02034**



- Significant differences (10%) w.r.t. to older benchmark calculations
- Origin understood, more accurate **BGR18** predictions should be used

BGR18

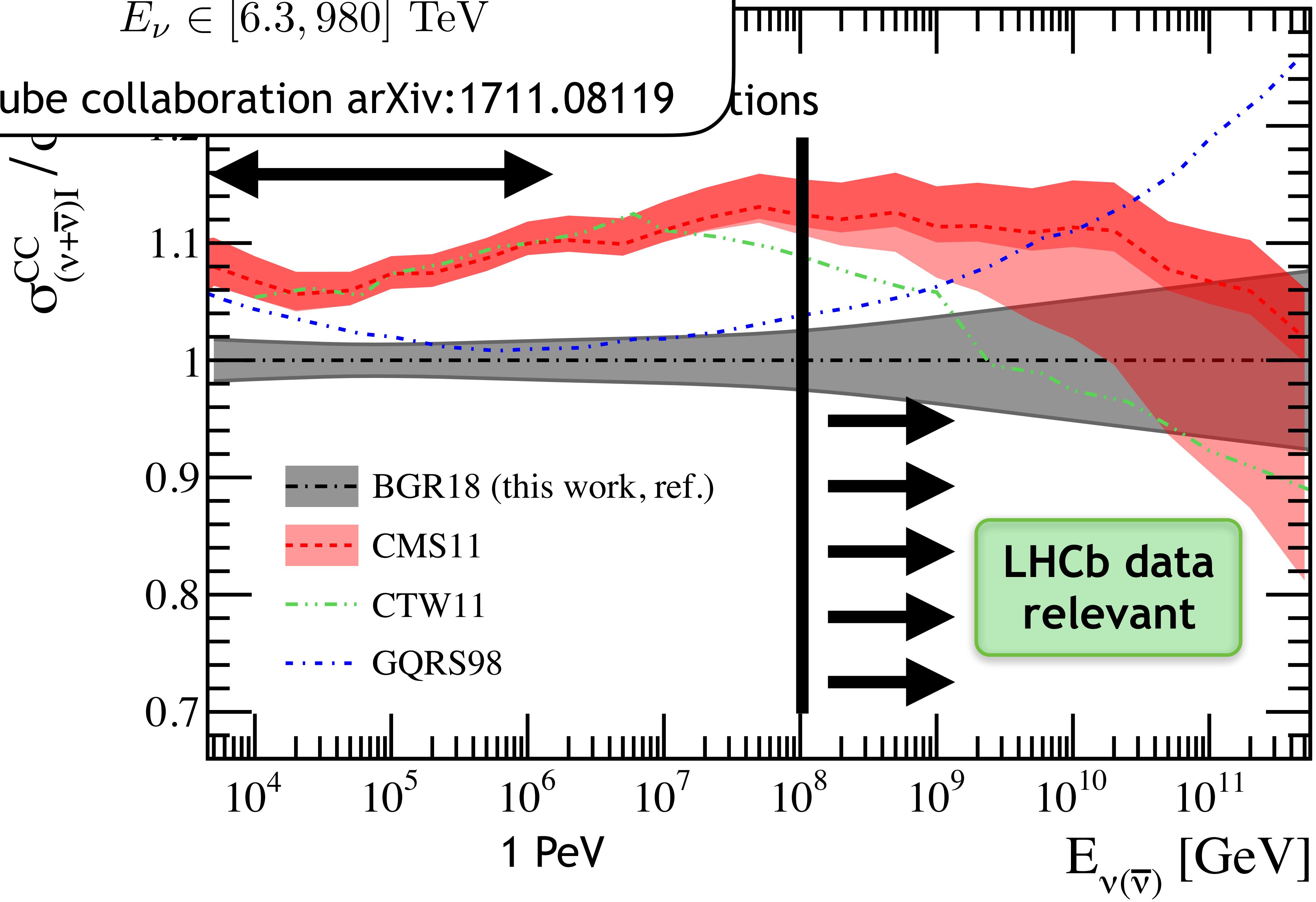
Rojo, arXiv:**1808.02034**

Measurement of the multi-TeV neutrino cross section with IceCube using Earth absorption

$$\frac{\sigma^{\text{obs.}}}{\sigma^{\text{CMS11}}} = 1.30^{+0.21}_{-0.19}(\text{stat.})^{+0.39}_{-0.43}(\text{sys.})$$

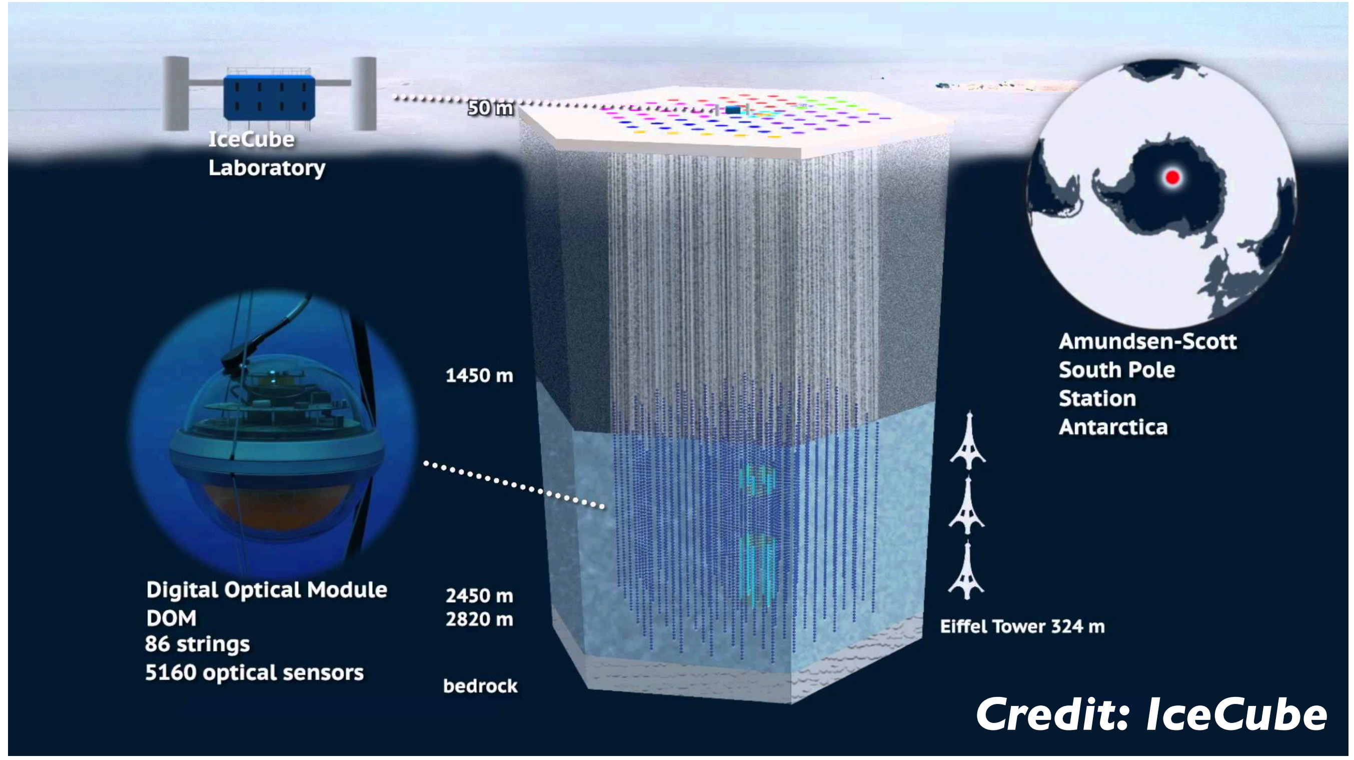
$$E_\nu \in [6.3, 980]\ \text{TeV}$$

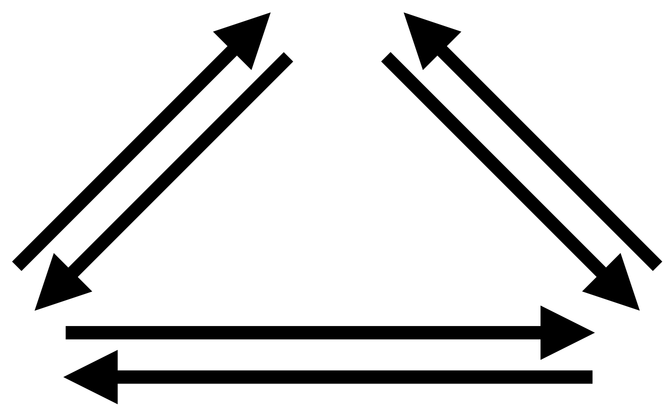
IceCube collaboration arXiv:1711.08119

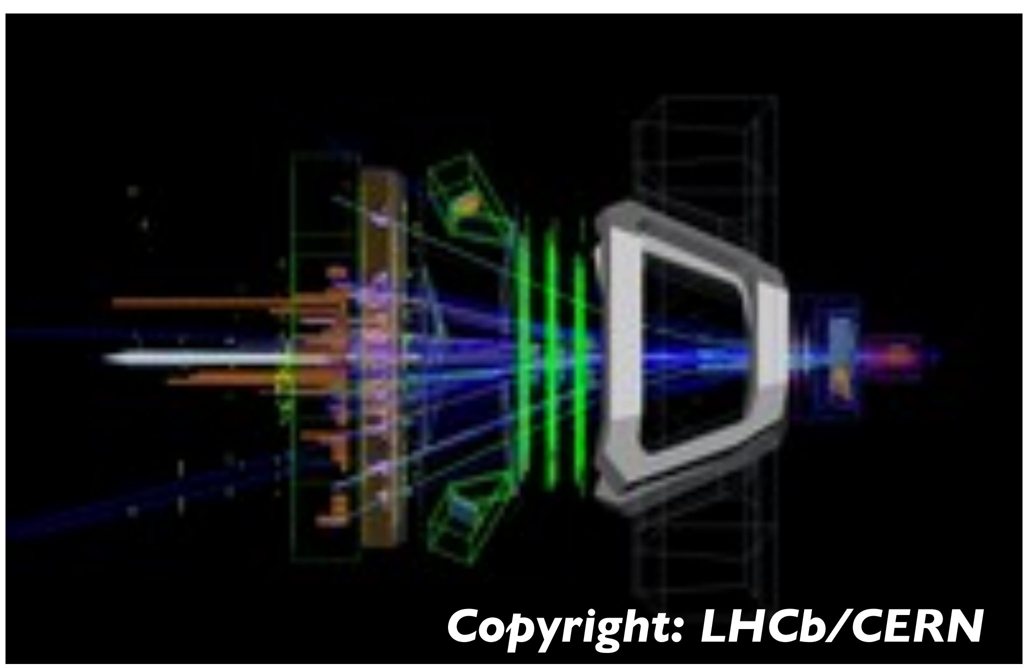


- Significant differences (10%) w.r.t. to older benchmark calculations
- Origin understood, more accurate **BGR18** predictions should be used

Neutrino telescopes







Collider experiments

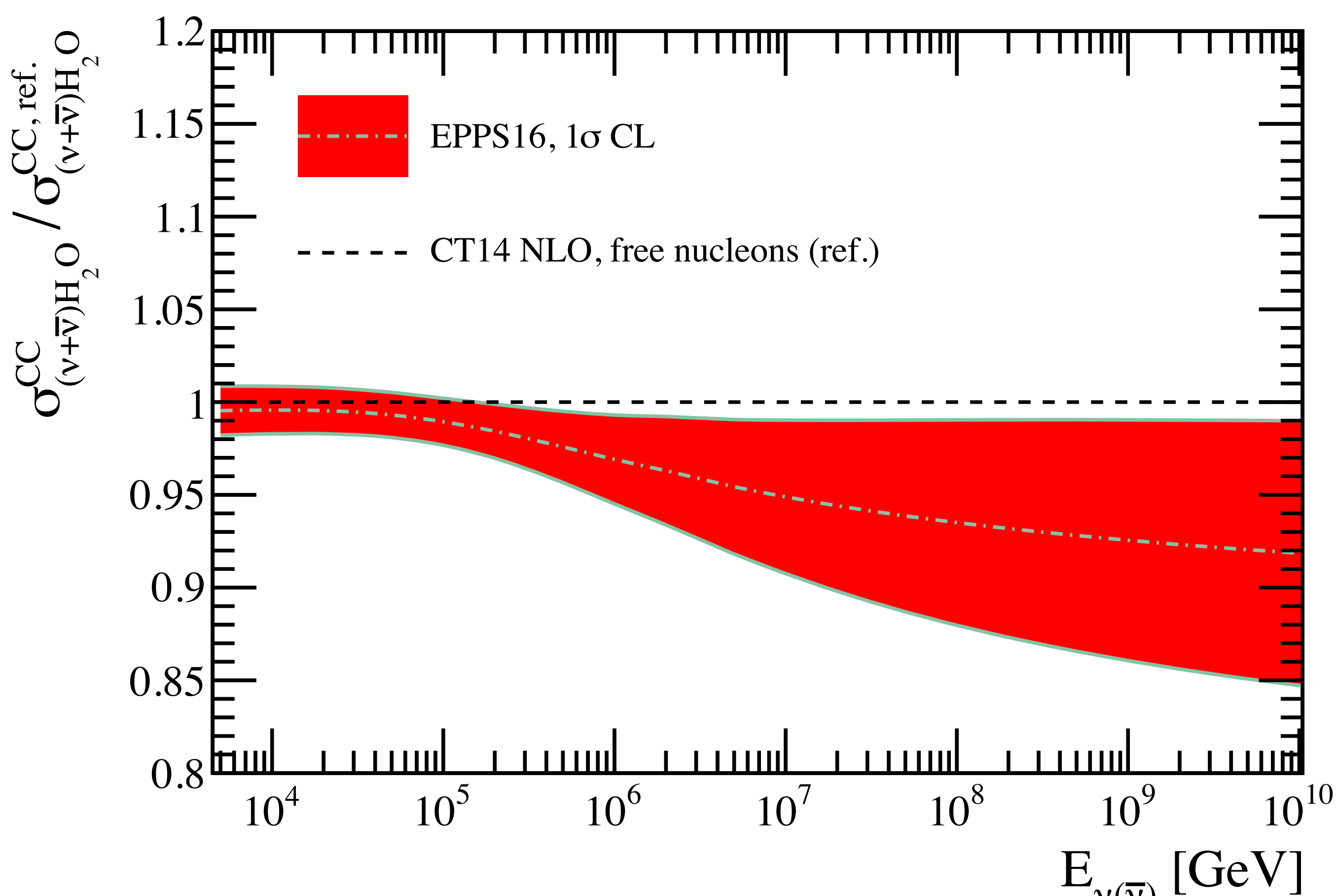
Theory

Nuclear corrections

Mass averaged Structure Function: $$F^{\mathrm{H_2O}} = \frac{1}{2+A}\left(2F^p + ZF^{p,A} + NF^{n,A}\right)$$

UHE neutrino-Water cross-section: $$\sigma_{\nu\mathrm{H_2O}}(E_\nu) = \frac{1}{18}\left(2\sigma_{\nu p}(E_\nu) + \sigma_{\nu O}(E_\nu)\right).$$

$$\sigma_{\nu\mathrm{H_2O}}(E_\nu) \simeq \frac{\sigma_{\nu I}(E_\nu)}{18}\left(2 + R_{\nu O}(E_\nu)\right).$$



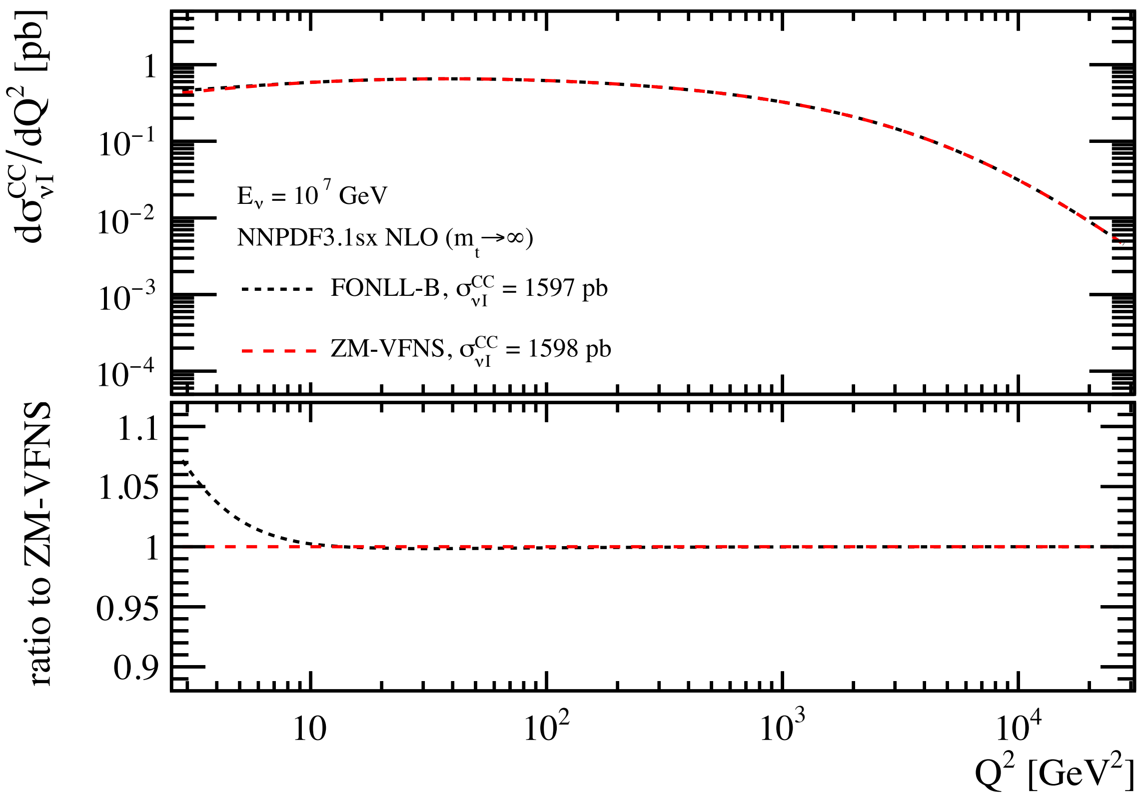
$$R_{\nu O}(E_\nu) \equiv \left(\frac{\sigma^{\mathrm{bound}}_{\nu O}(E_\nu)}{\sigma^{\mathrm{free}}_{\nu O}(E_\nu)}\right)$$

Computed with EPPS16

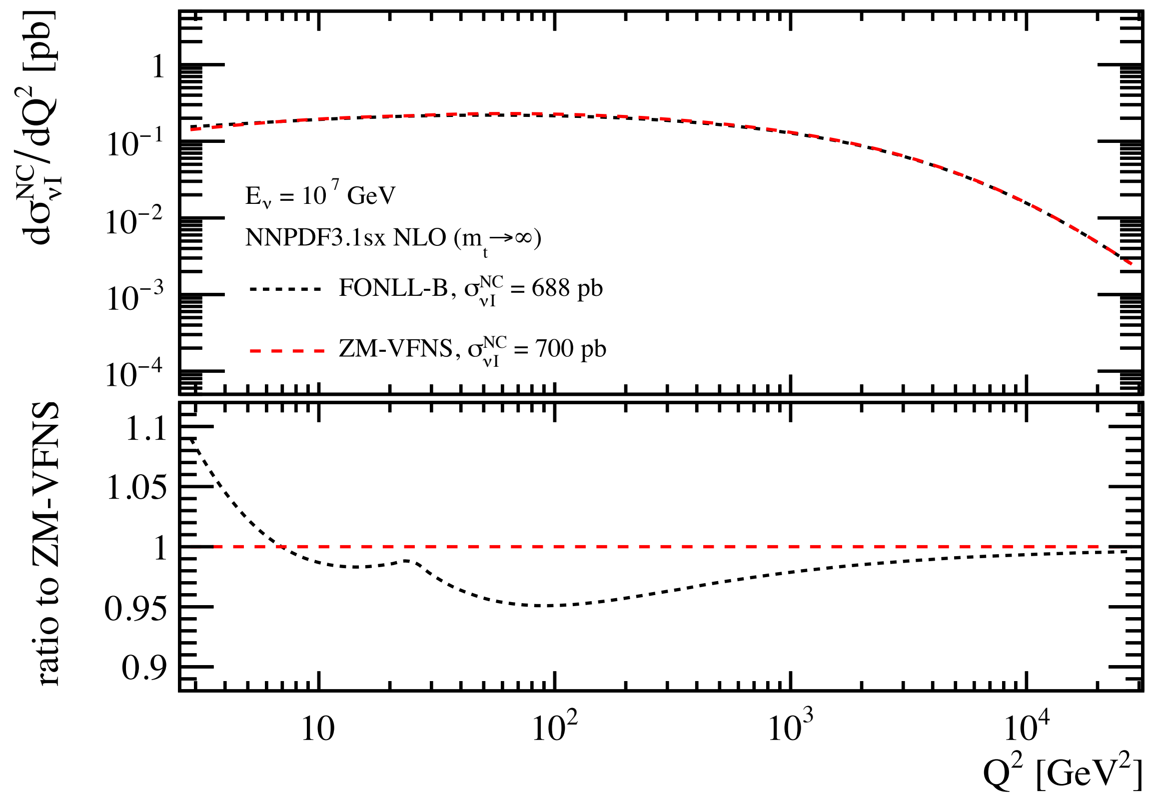
Can also use D-hadron data in p-Pb:

Gauld - arXiv: 1508.07629
LHCb - arXiv: 1707.02750
Kusina et al. - arXiv: 1712.07024

Heavy quark mass effects in DIS



CC: c-/b-quark effects unimportant



NC: c-/b-quark effects small-ish

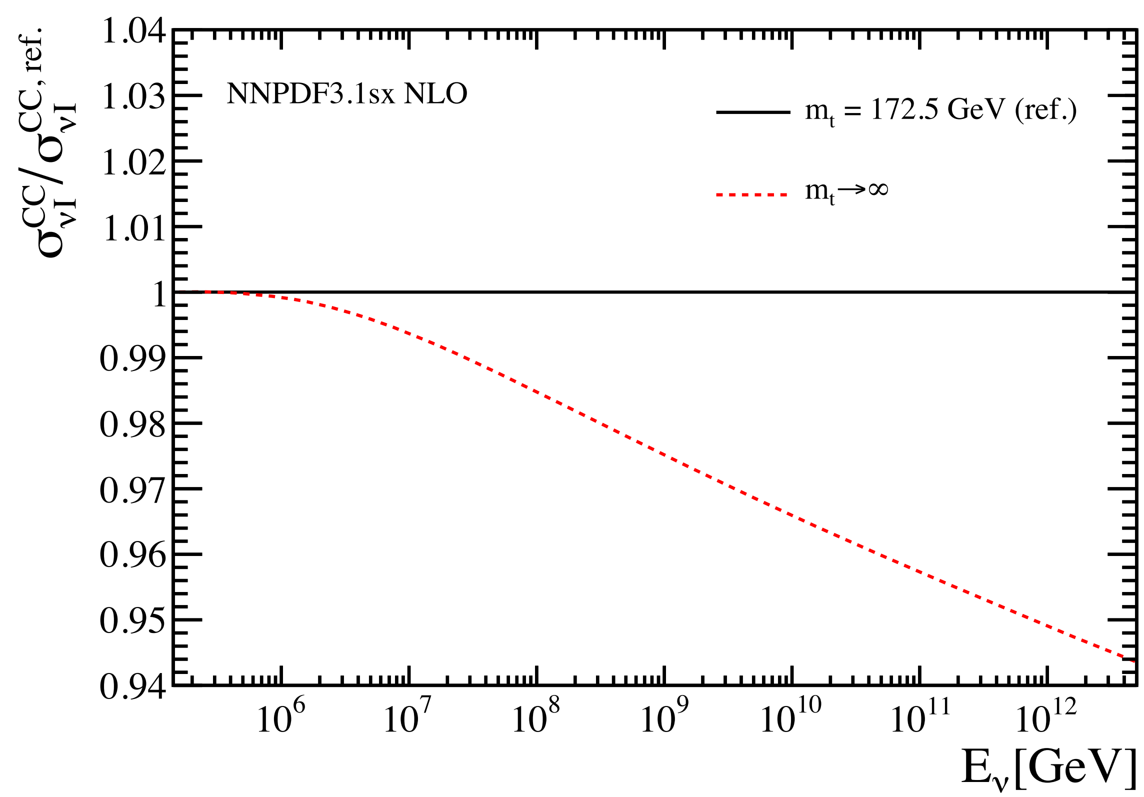
Top quark production also possible:

$$\text{CC}: \quad \nu + q_d \to \ell^- + t$$

Kinematically possible if:

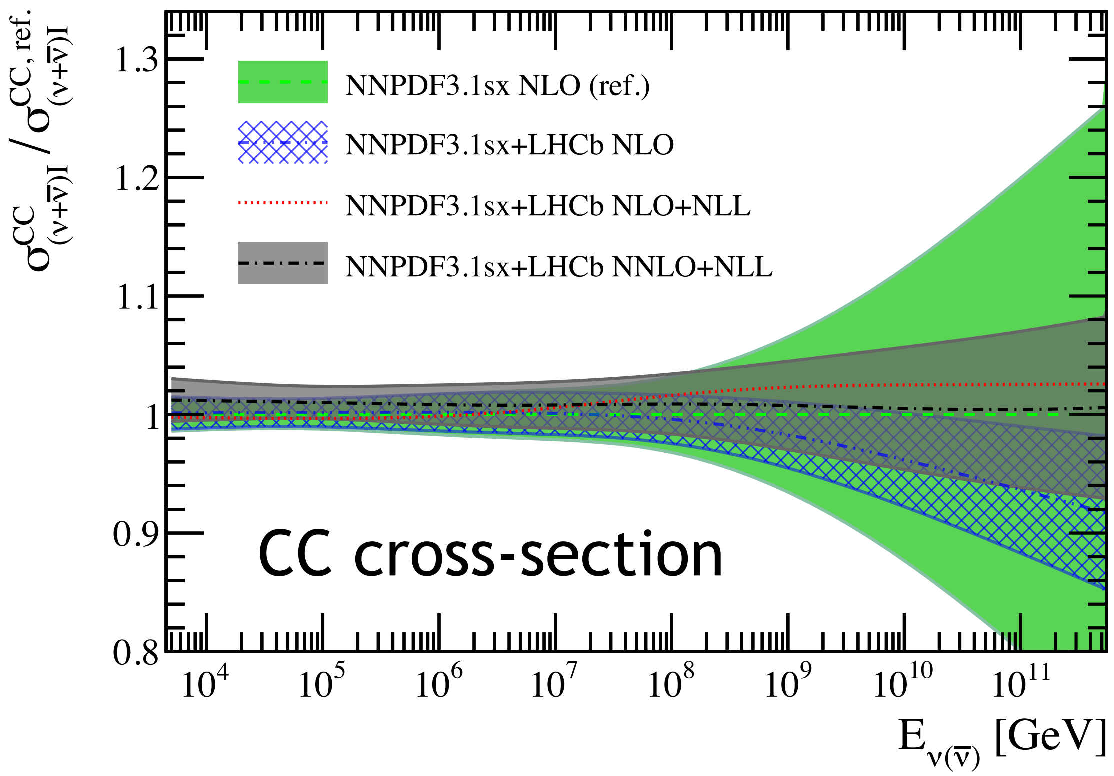
$$W^2 = \frac{Q^2(1-x)}{x} > m_t^2$$

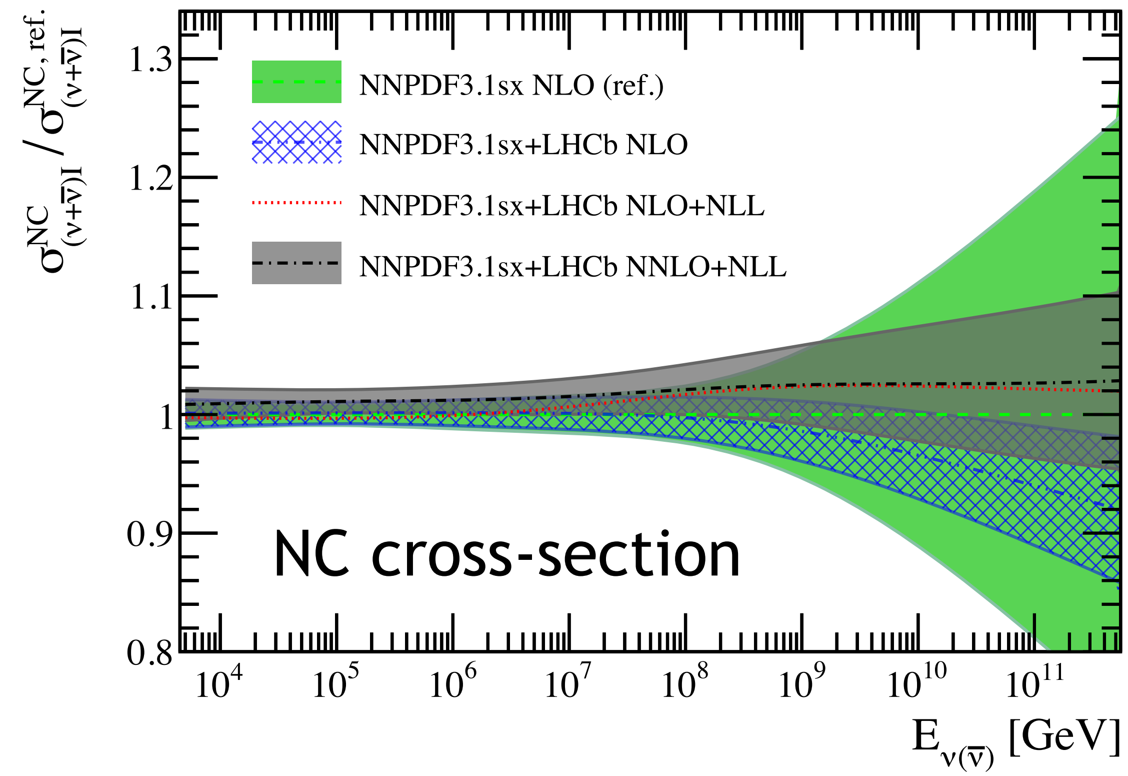
b-quark PDF generation enhanced at small x



CC: top-quark effects important

Perturbative stability



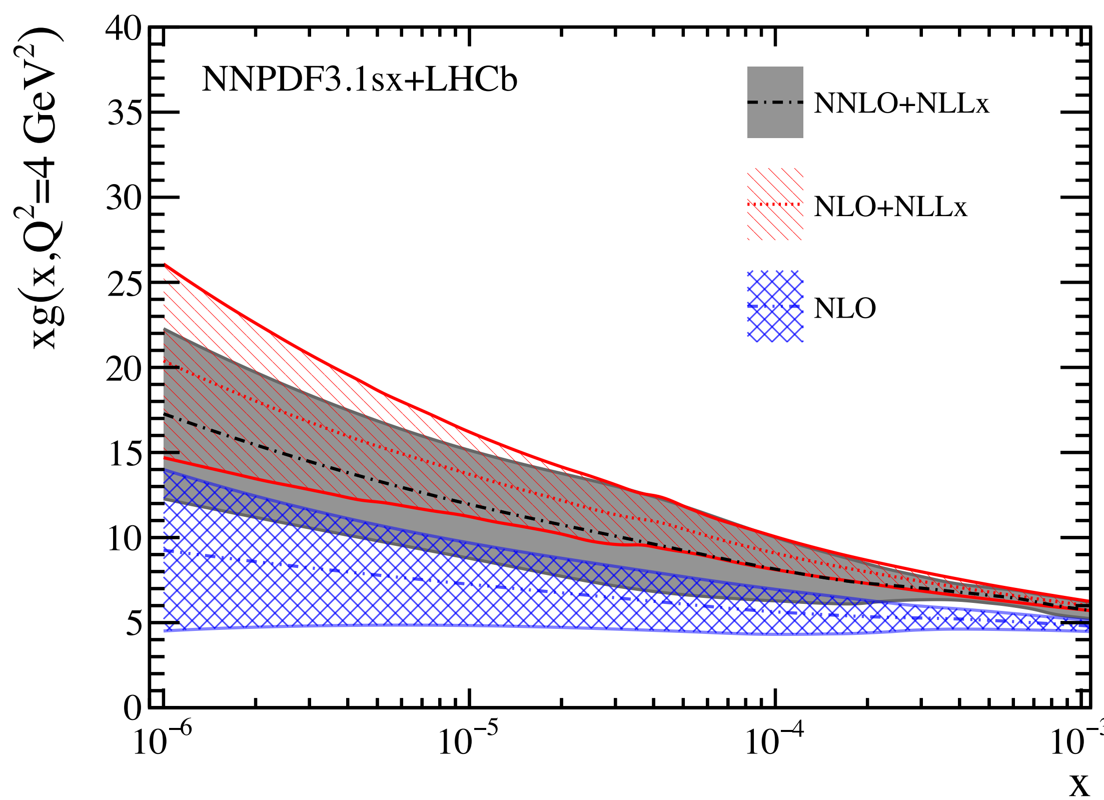


Differences in input PDFs ~(20-30)%

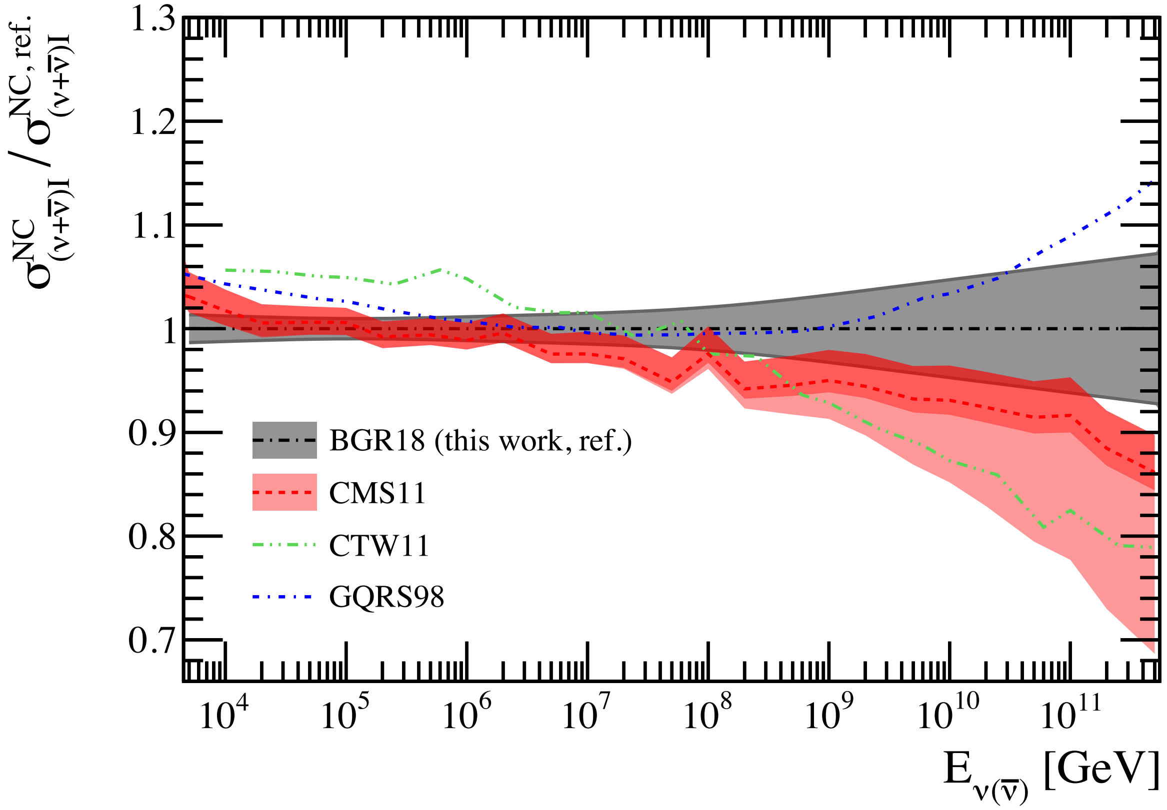
Cancellations between coefficient functions and PDFS:

$$F_i(x,Q^2) = \sum_{a=g,q} \int_x^1 \frac{dz}{z} C_{i,a}\left(\frac{x}{z},Q^2\right) f_a\left(z,Q^2\right)$$

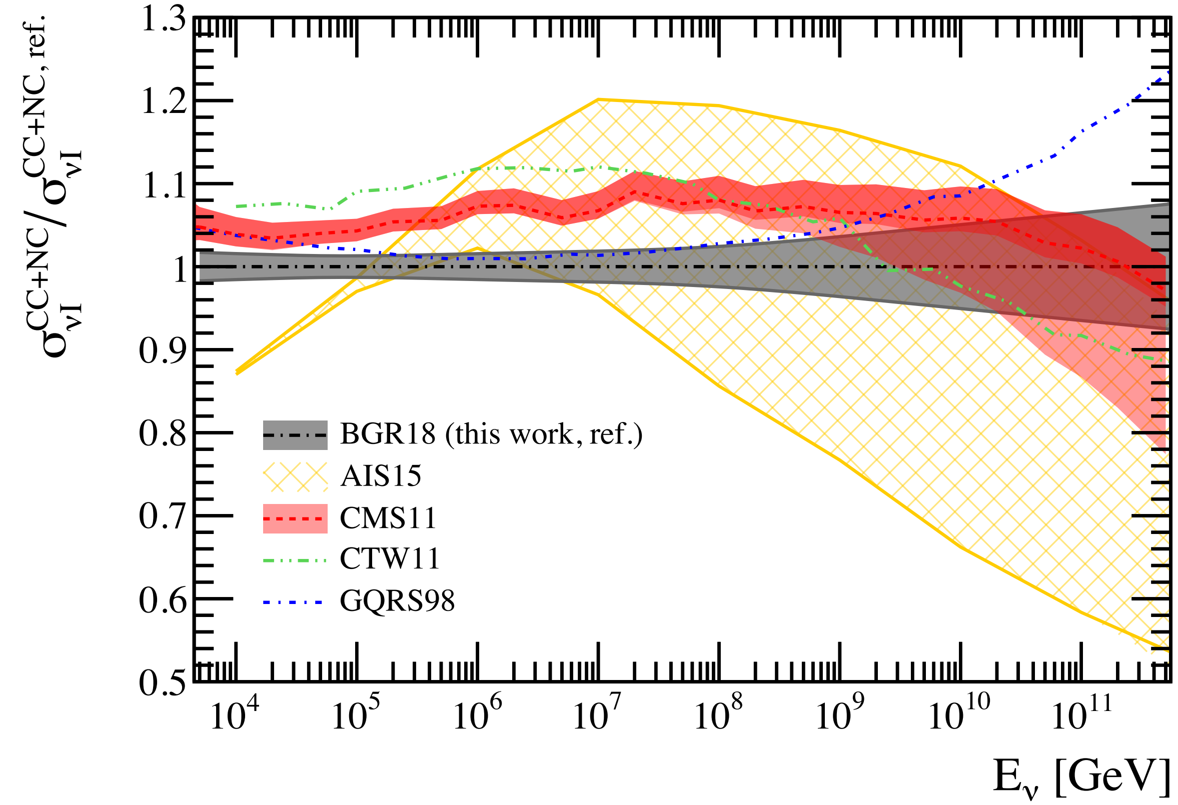
=> Cross-section level ~(2-3)%



Other results



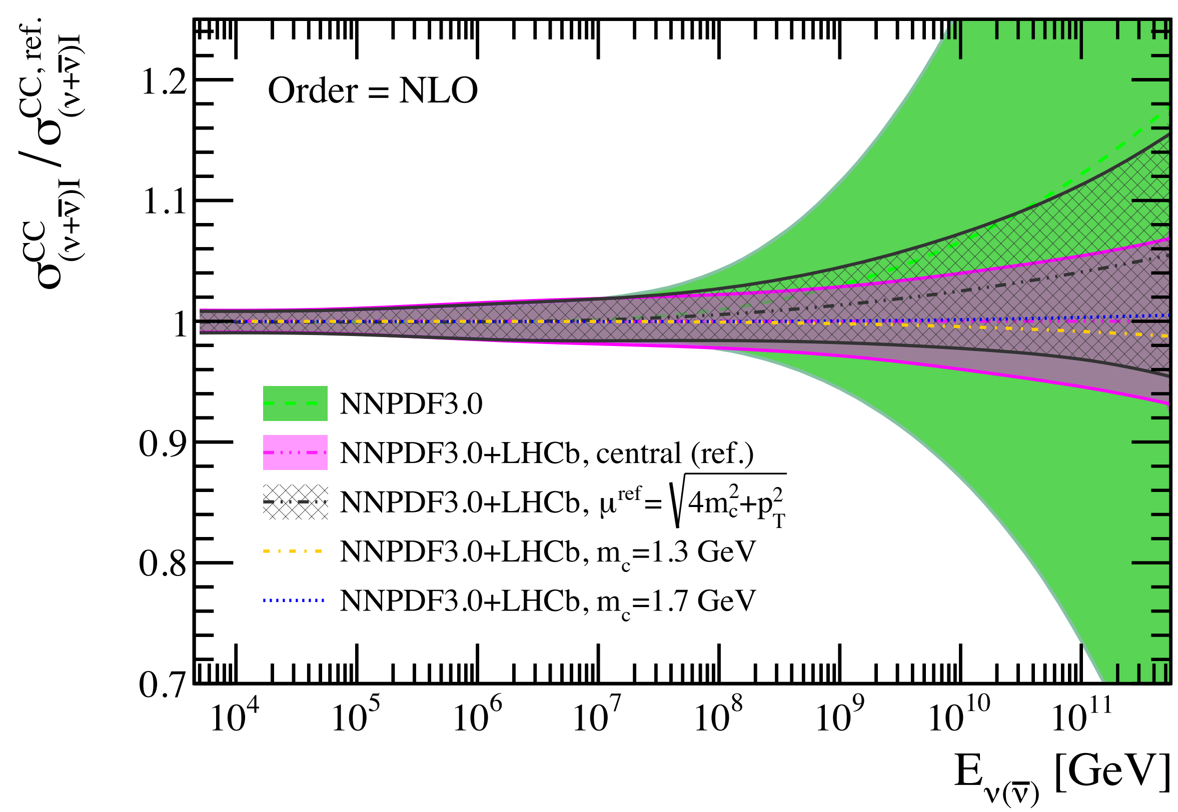
Comparison of NC cross-section



Comparison of CC+NC cross-section

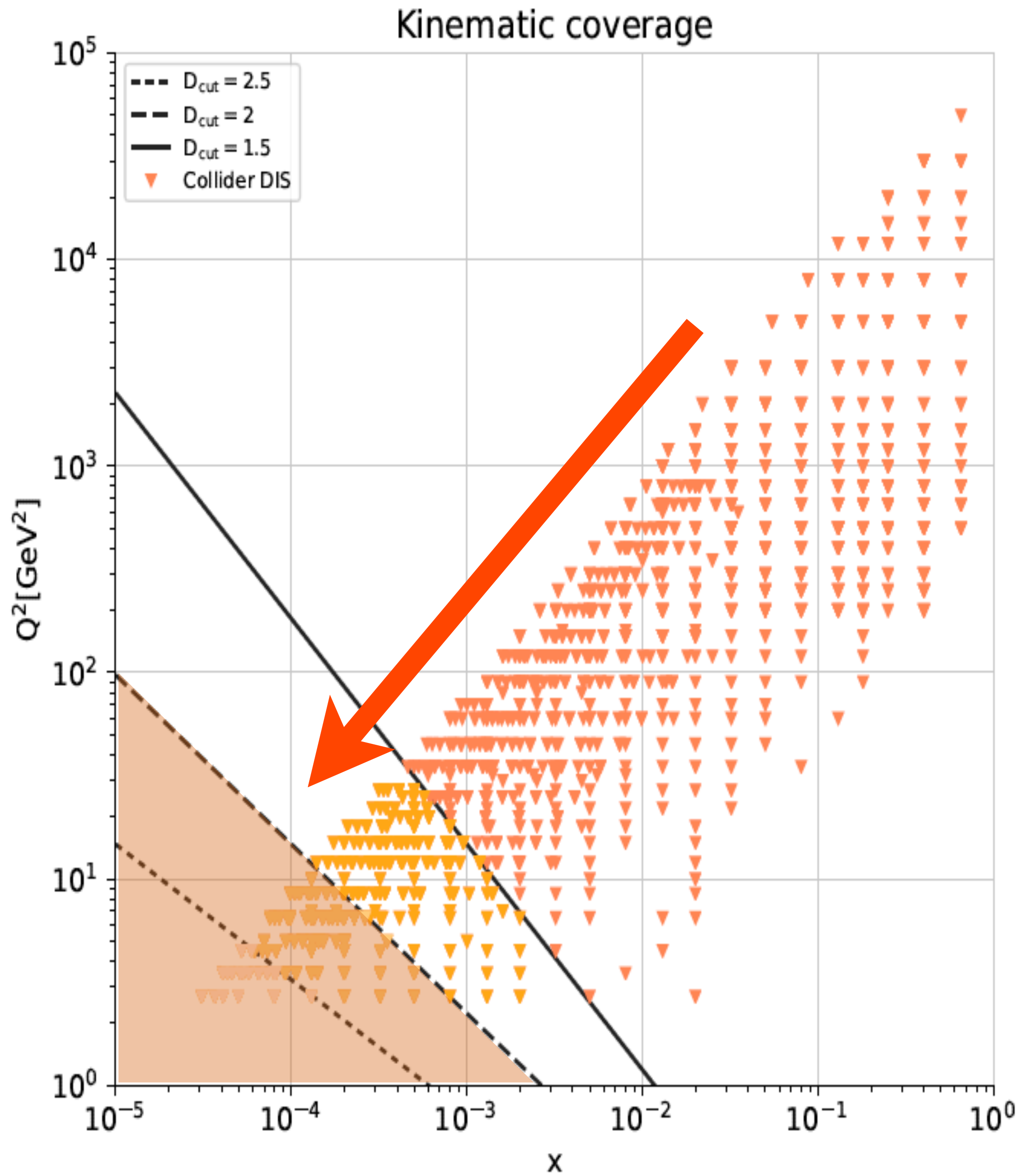
Dependence of UHE cross-section on treatment of LHCb D-hadron data

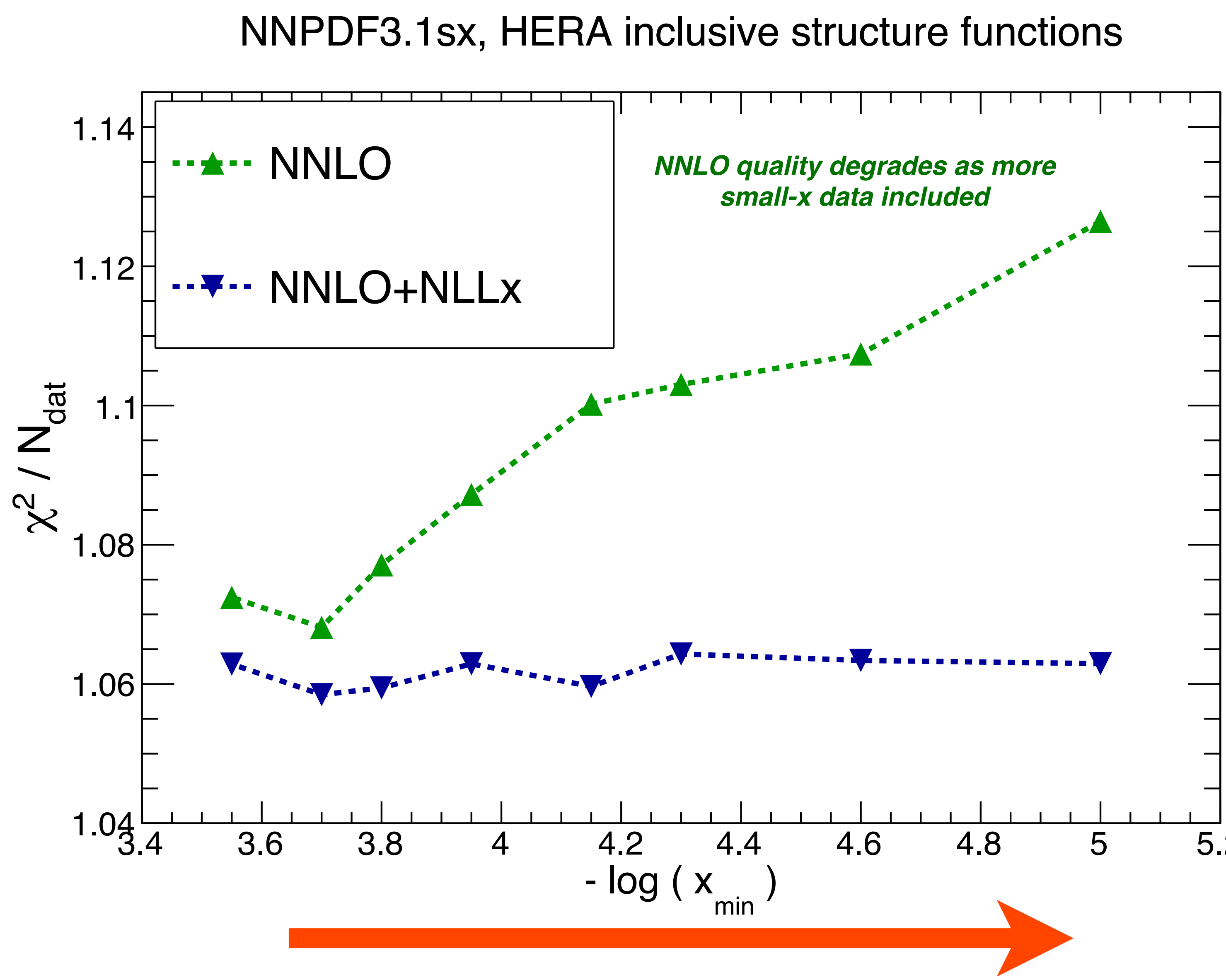
- Scale variations
- c-quark mass variation



BFKL dynamics at small-x

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





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!**

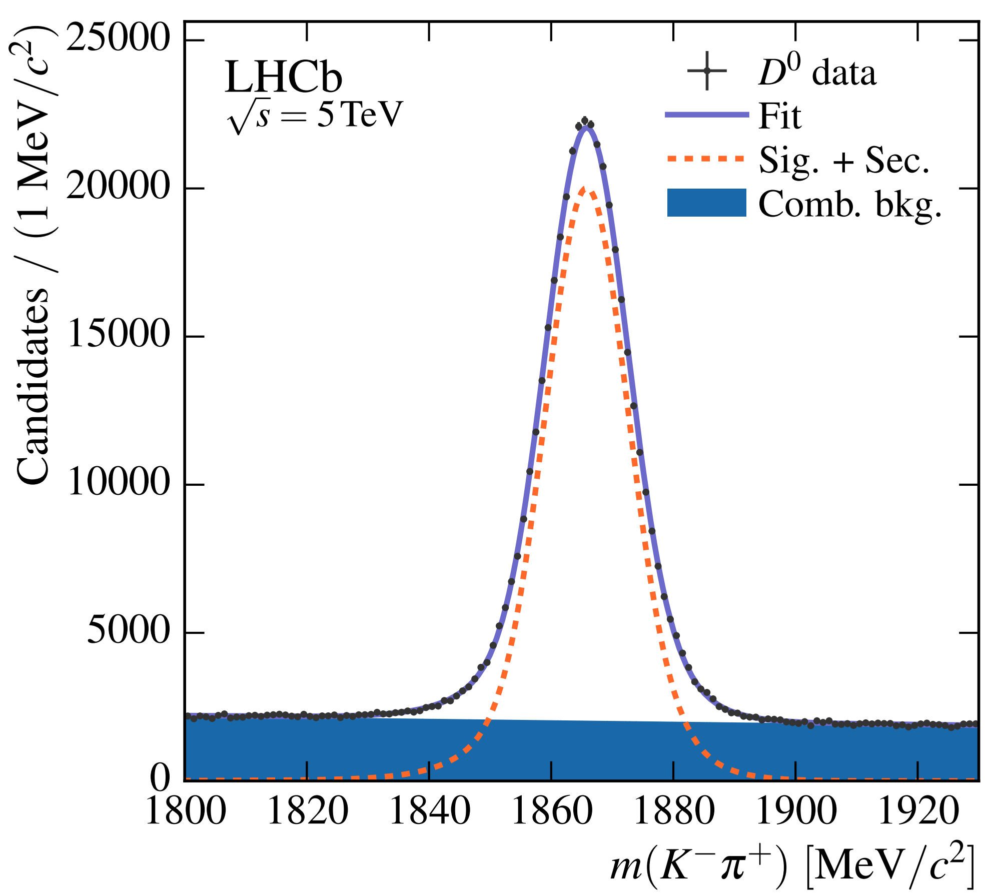
charm-quark (pair) production - LHCb

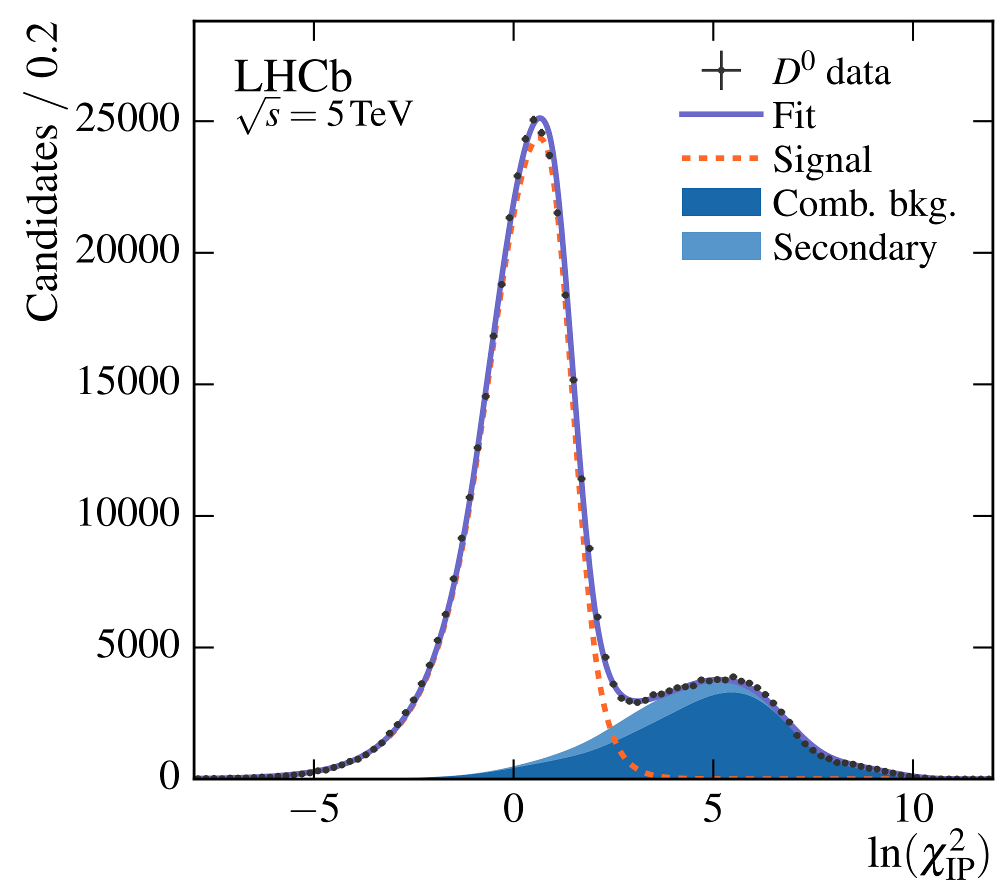
$$pp \to D^0 + X$$
$$D^0 \to K^-\pi^+$$

Exclusively reconstruct D-hadrons within experimental acceptance

For example, LHCb fiducial region:

$$p_T^D < 8\ \text{GeV}$$
$$2.0 < y^D < 4.5$$





Measurements performed double differentially in p_T^D and y_D

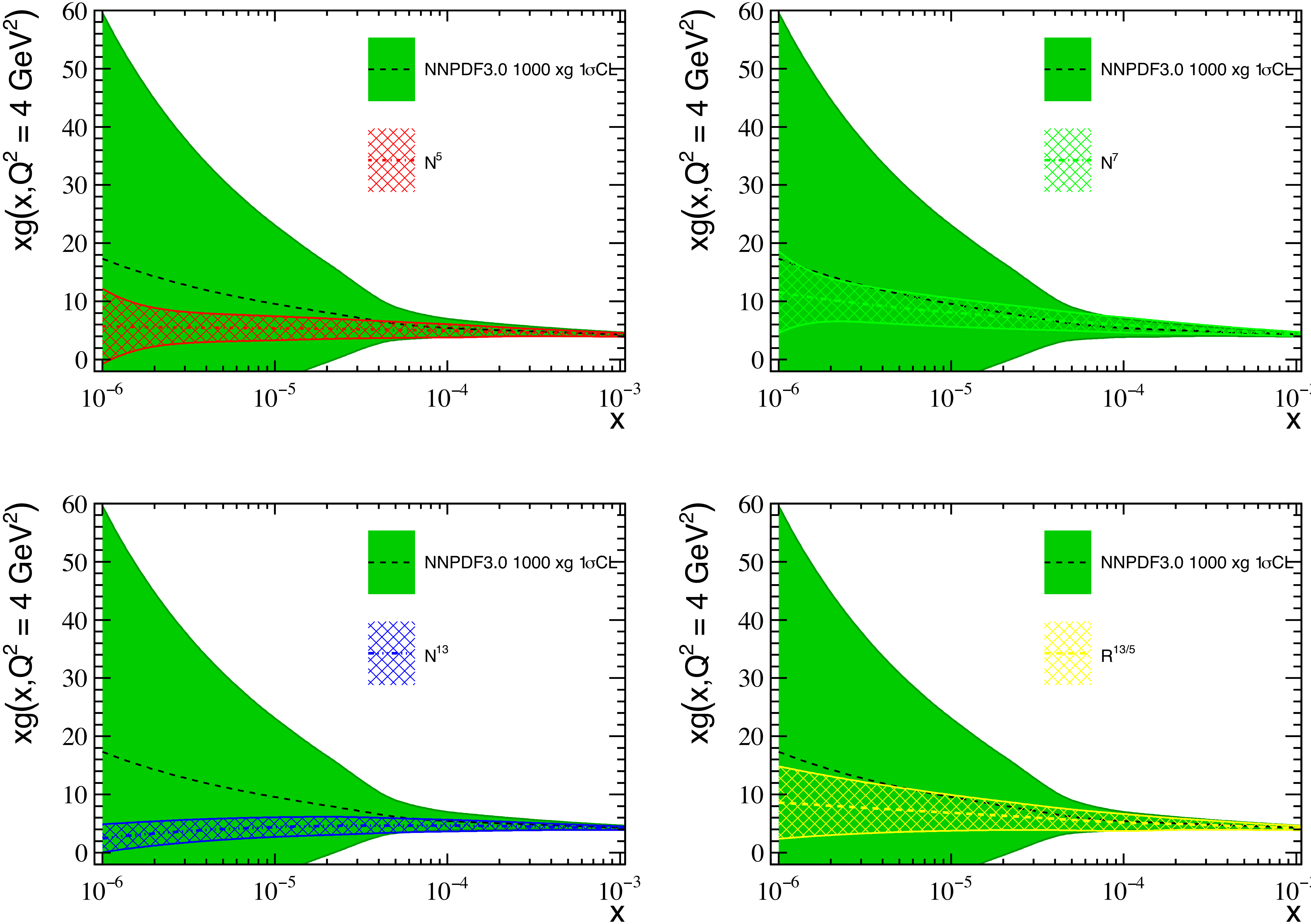
$$N_X^{ij} = \frac{d^2\sigma(\mathrm{X\ TeV})}{dy_i^D d(p_T^D)_j} \Bigg/ \frac{d^2\sigma(\mathrm{X\ TeV})}{dy_{\mathrm{ref}}^D d(p_T^D)_j}$$

Measurements performed at multiple hadronic CoM values

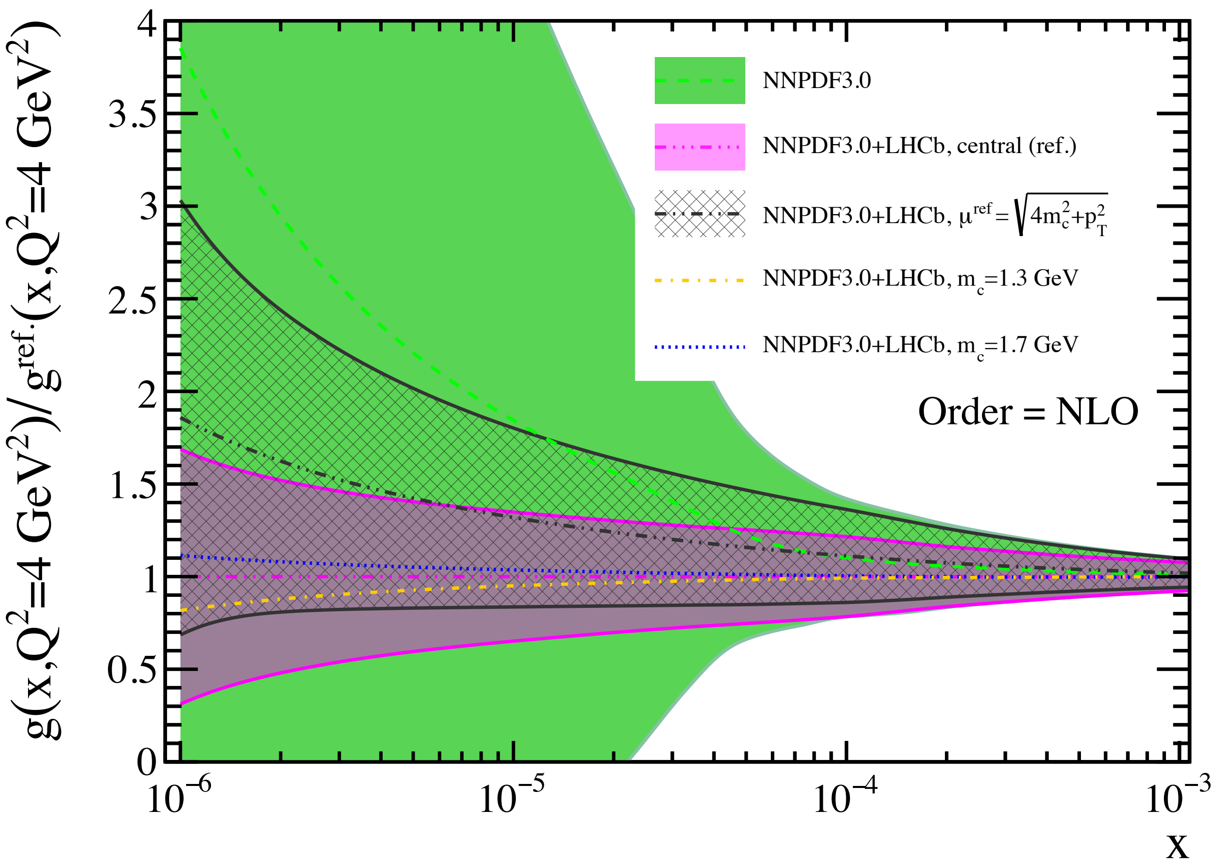
$$R_{13/X}^{ij} = \frac{d^2\sigma(13\ \mathrm{TeV})}{dy_i^D d(p_T^D)_j} \Bigg/ \frac{d^2\sigma(\mathrm{X\ TeV})}{dy_{\mathrm{i}}^D d(p_T^D)_j}$$

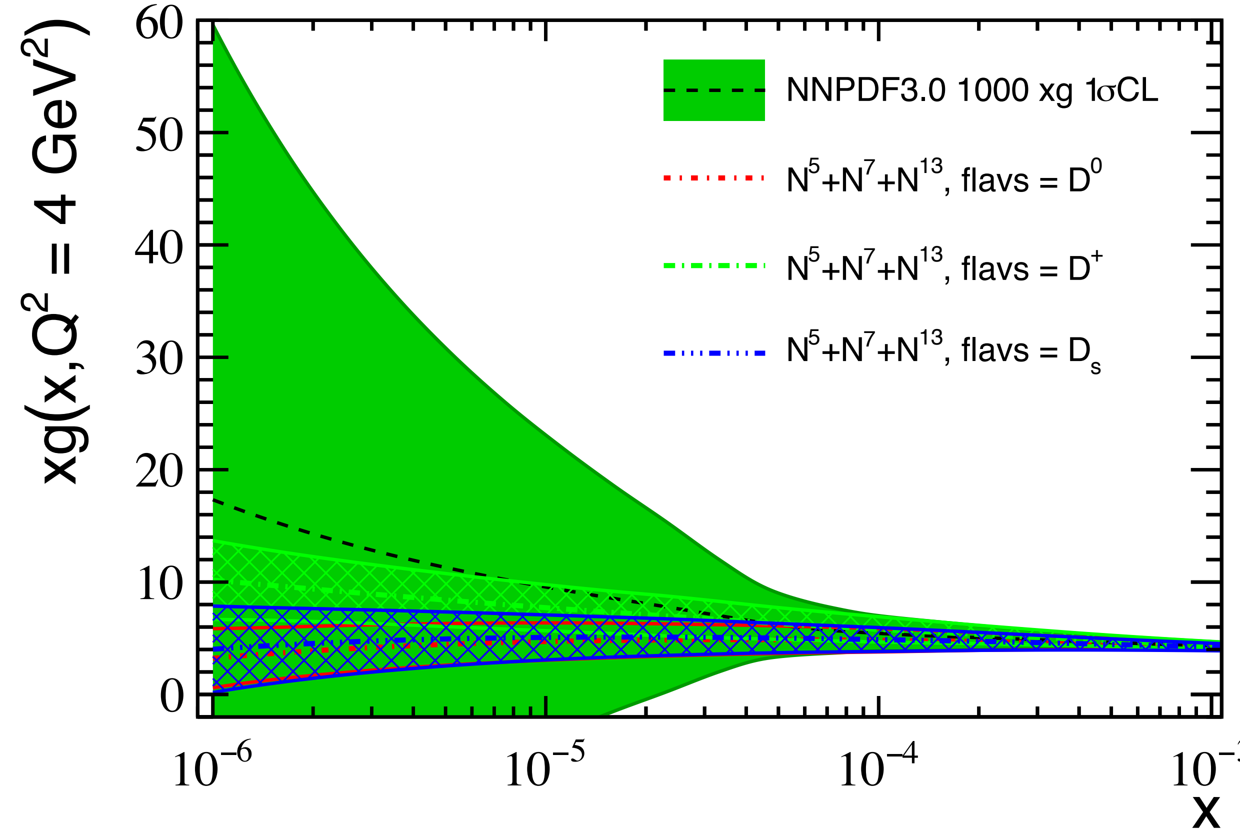
$$x_{1,(2)} = \frac{m_T}{\sqrt{S}} \left(e^{(-)y_3} + e^{(-)y_4} \right)$$

Hadronic CoM Energy



For details, R. Gauld, J. Rojo: arXiv 1610.09373

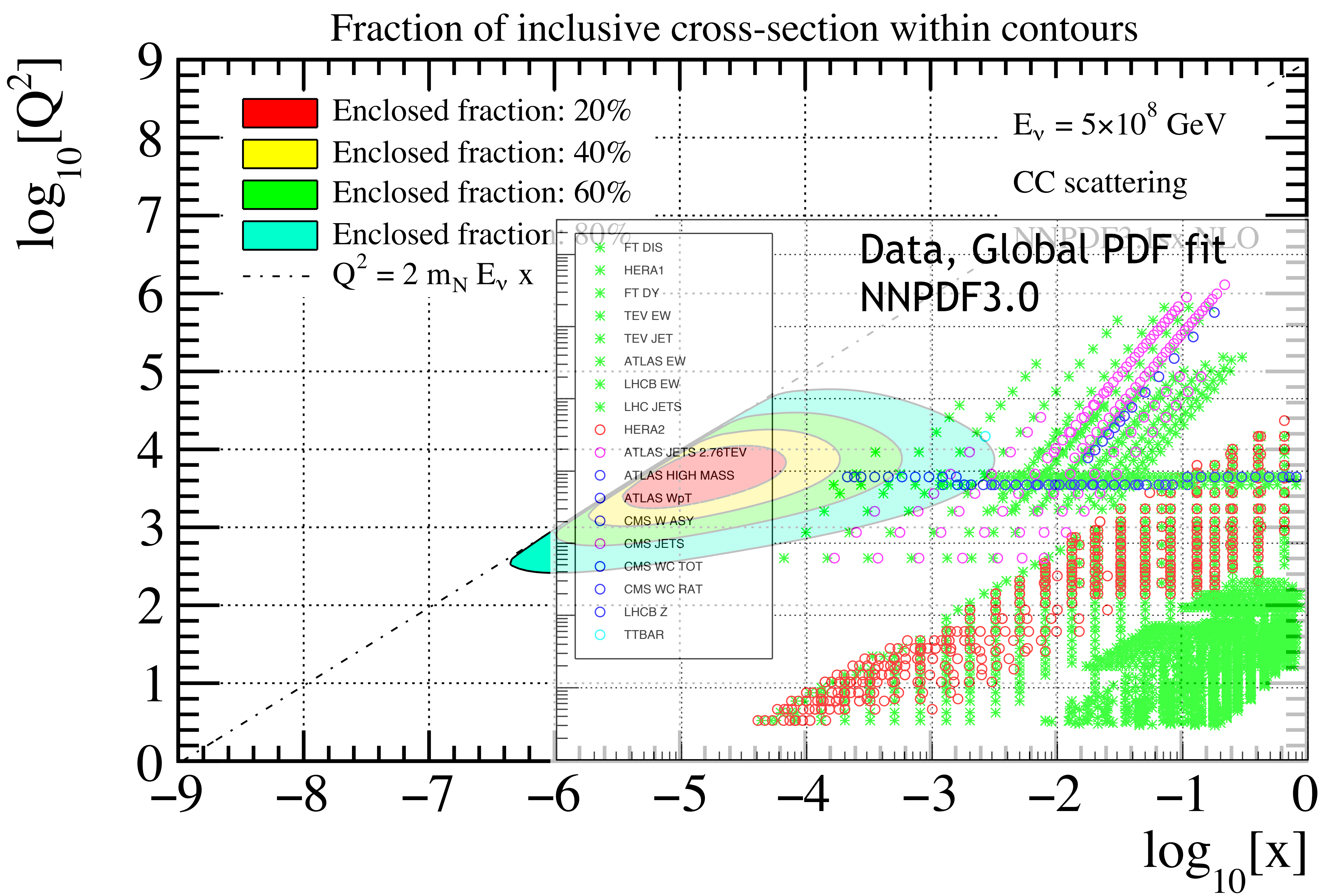




	NLO		NLO+NLLx		NNLO+NLLx	
Dataset ($N_{\rm dat}$)	$\chi^2_{\rm orig}/N_{\rm dat}$	$\chi^2_{\rm new}/N_{\rm dat}$	$\chi^2_{\rm orig}/N_{\rm dat}$	$\chi^2_{\rm new}/N_{\rm dat}$	$\chi^2_{\rm orig}/N_{\rm dat}$	$\chi^2_{\rm new}/N_{\rm dat}$
N_5 (78)	1.0	0.71	1.11	0.78	1.61	0.84
N_7 (72)	0.8	0.69	0.84	0.72	0.96	0.75
N_{13} (119)	1.51	1.13	1.6	1.16	2.0	1.22
N_{5+7+13} (269)	1.17	0.89	1.25	0.93	1.61	0.98
$R_{13/5}$ (99)	1.64	1.66	1.87	1.79	1.83	1.74

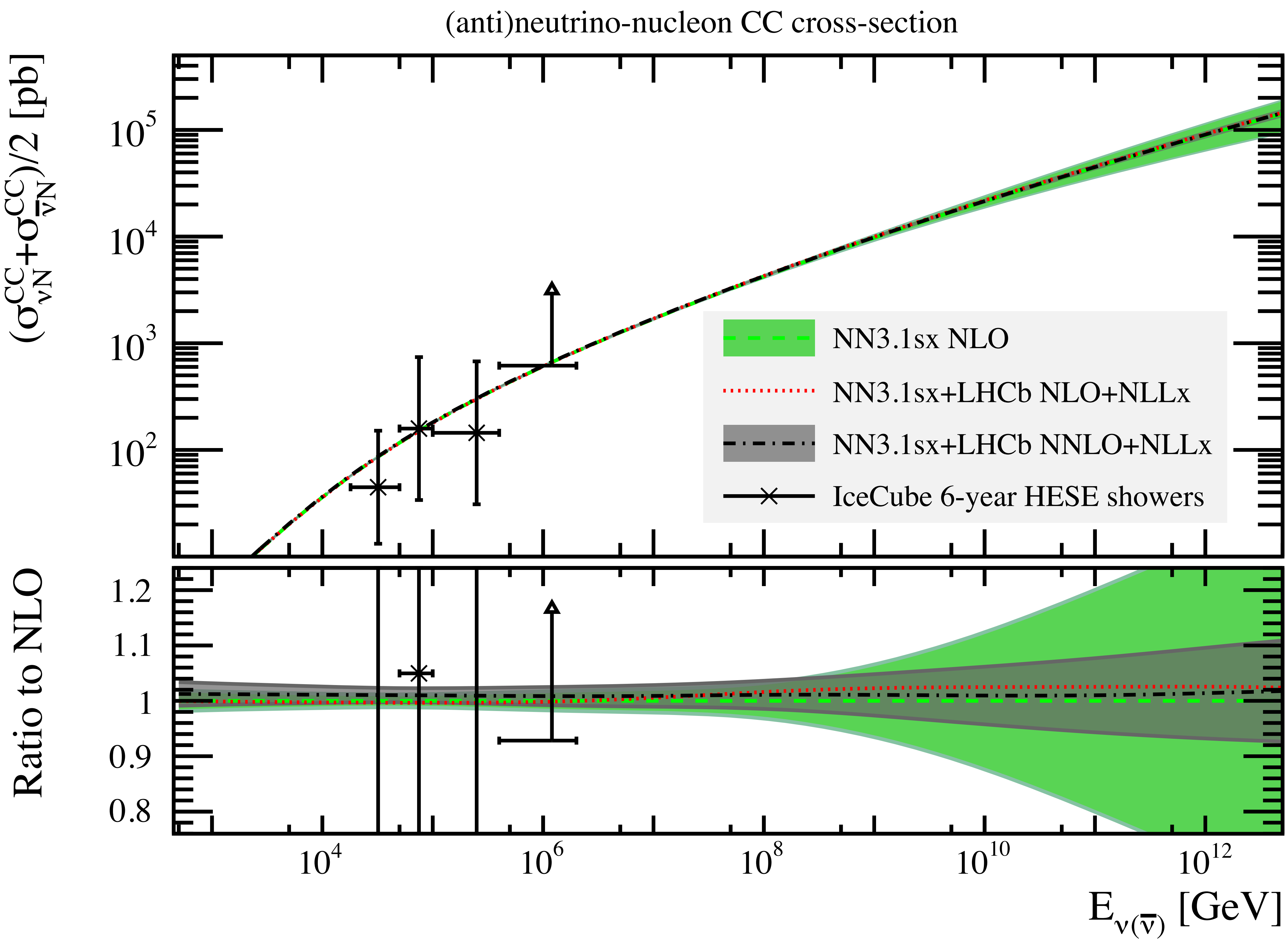
Chi-squared values for NNPDF3.1sx fits - Bertone, Gauld, Rojo: arXiv 1808.02034

Example, 500 PeV neutrino



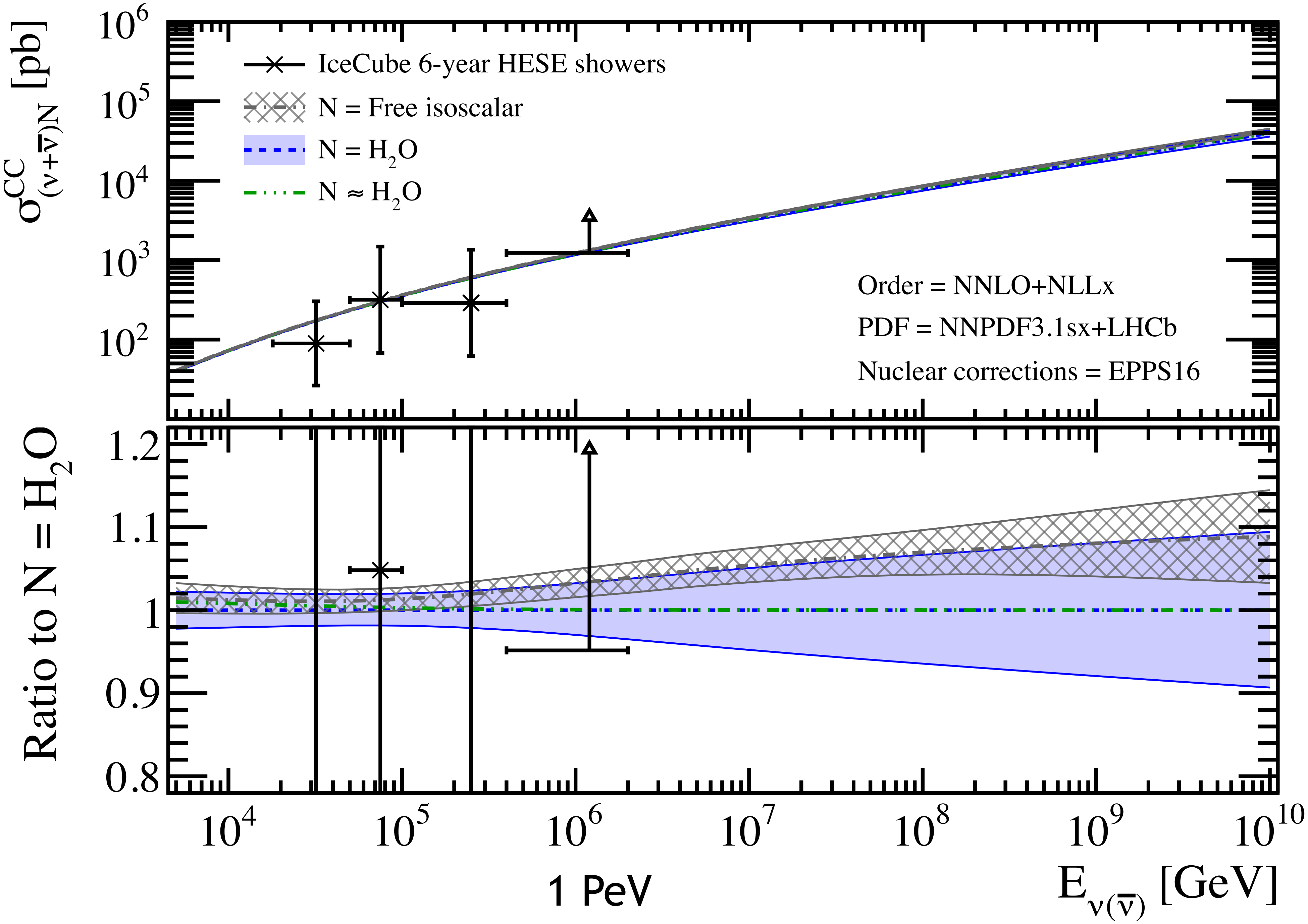
$$\sigma_{\nu I}^{CC}(E_\nu) = \int_{Q^2_{\rm min}}^{Q^2_{\rm max}} \mathrm{d}Q^2 \left[\int_{x_0(Q^2)}^{1} \mathrm{d}x \frac{\mathrm{d}^2\sigma_{\nu I}^{CC}}{\mathrm{d}x\,\mathrm{d}Q^2}(x, Q^2, E_\nu) \right]$$

Impact of LHCb data on UHE cross-section



Results - BGR18

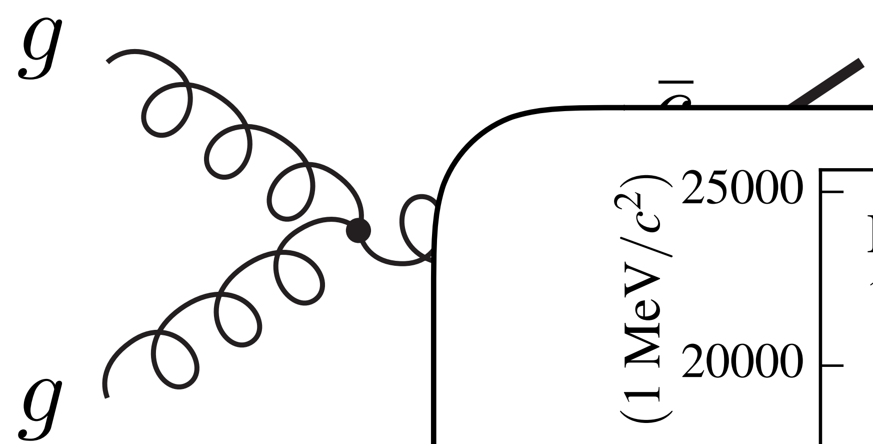
For details: ***Bertone*, *Gauld*, *Rojo***, arXiv:**1808.02034**

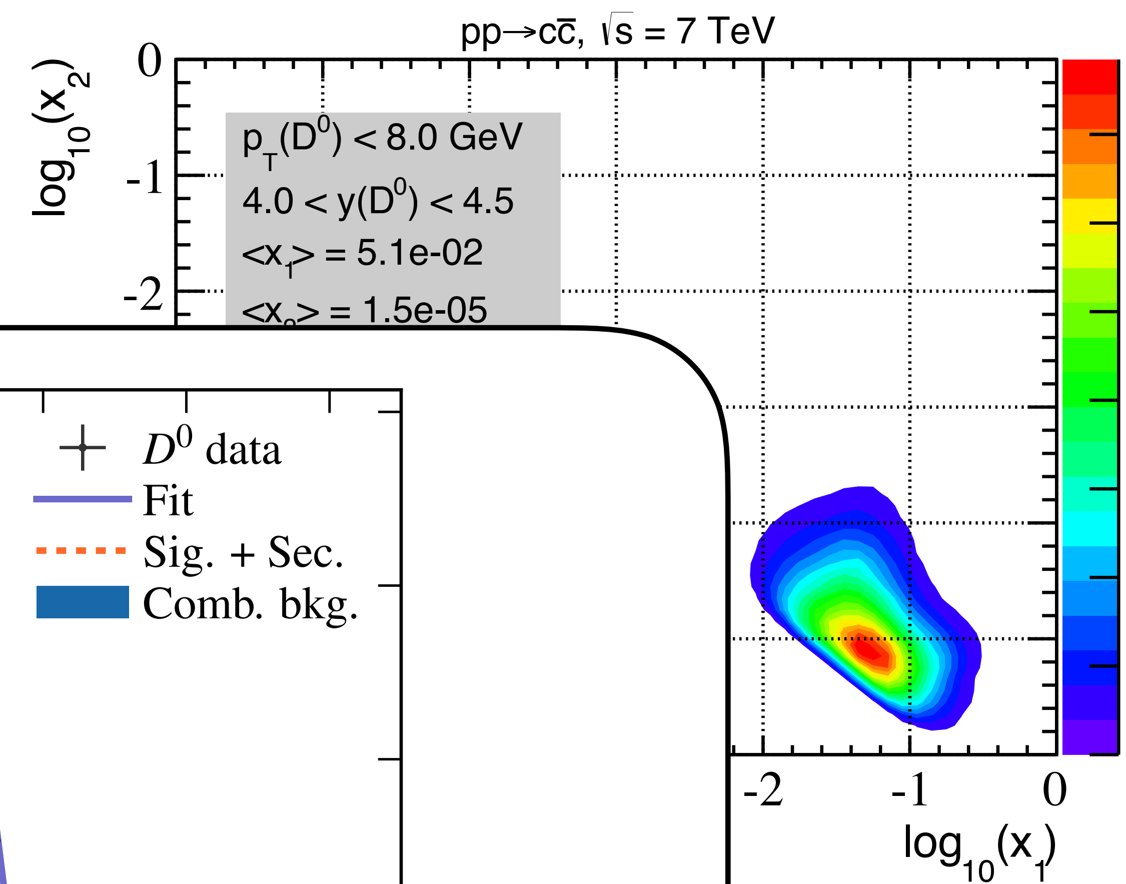


- Nuclear corrections relevant in PeV range
- Theoretical predictions stable (<10% unc.) into multi PeV range

D-hadrons at LHCb

$$pp \to D + X$$

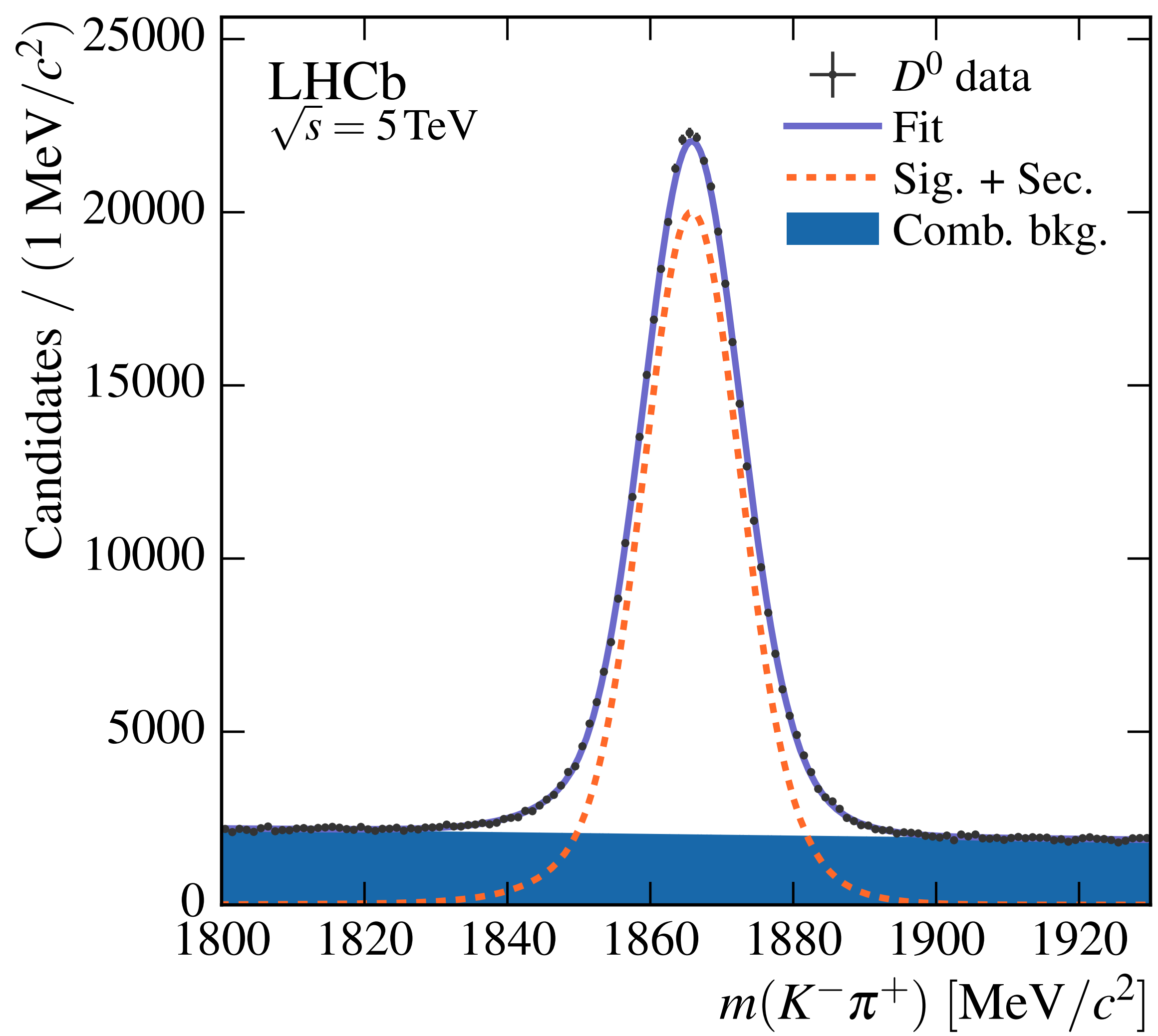




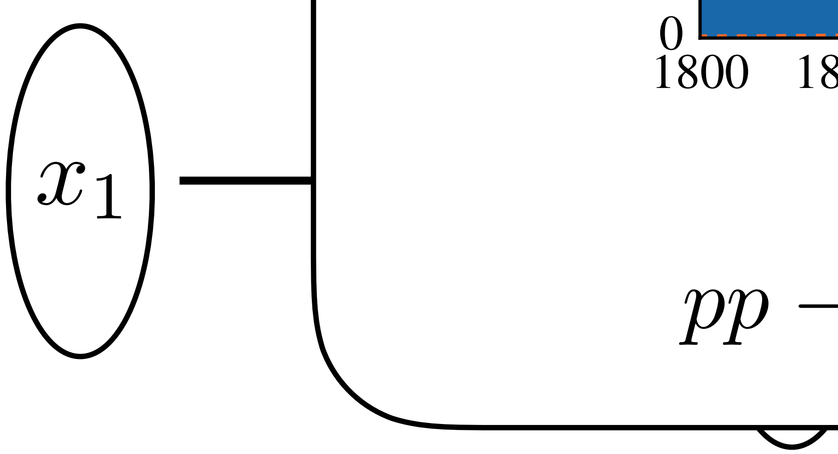
oderate x

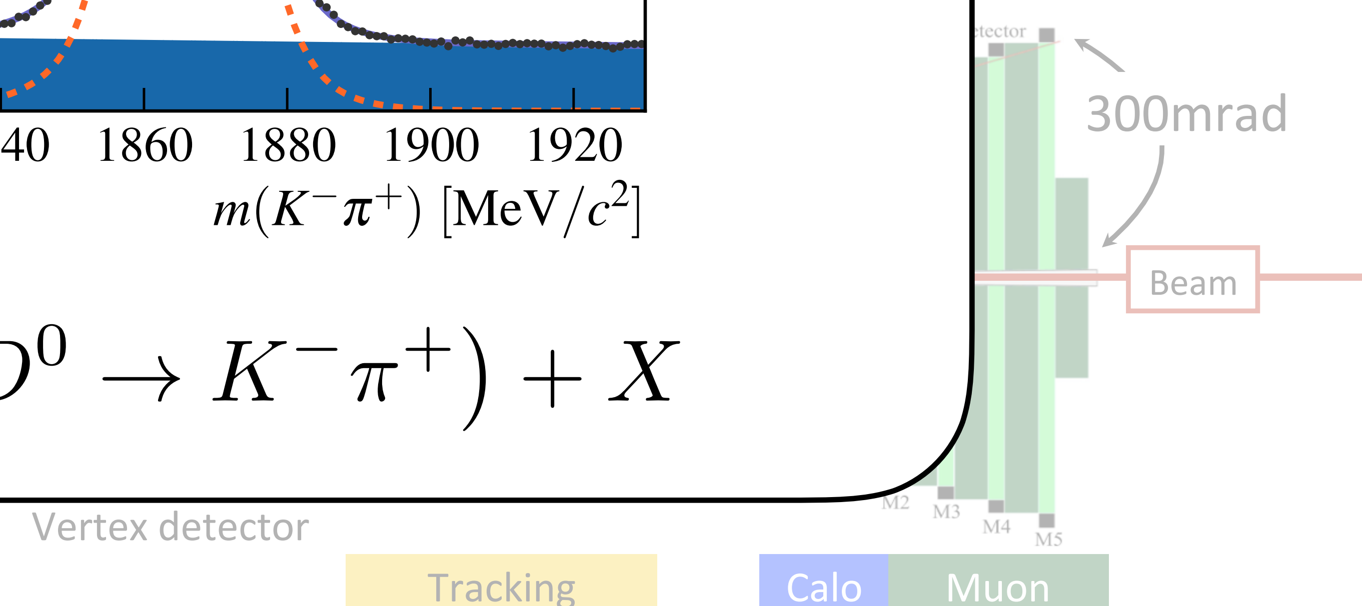
LO PDF sam

$$x_{1,(2)} = \frac{m_T}{\sqrt{S}}$$



$$pp \to (D^0 \to K^- \pi^+) + X$$





Next on the agenda…

In progress: *RG*, arXiv:1901.XX