# *Bridging collider physics and neutrino telescopes with charm production*

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VU Amsterdam & Theory group, Nikhef


**Focus Session: the Neutrino Universe**
**Physics@Veldhoven 2018**
**Veldhoven, 23/01/2018**

# the neutrino universe

Observation of ultra-high energy (UHE) neutrino events at **IceCube** heralds start of **neutrino astronomy**


*Neutrinos are not **deflected or attenuated**: unique probes of extreme astrophysical events*

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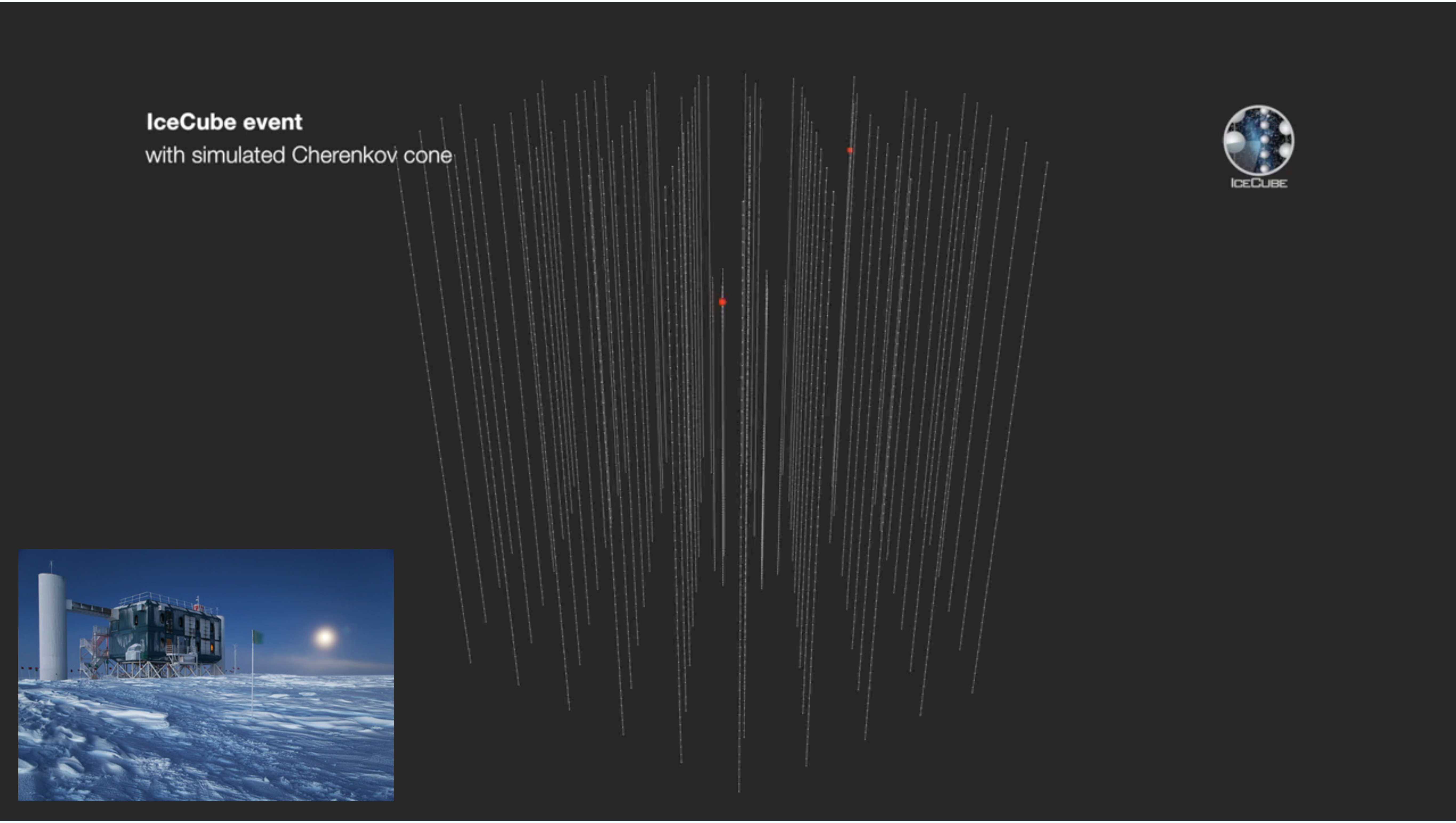

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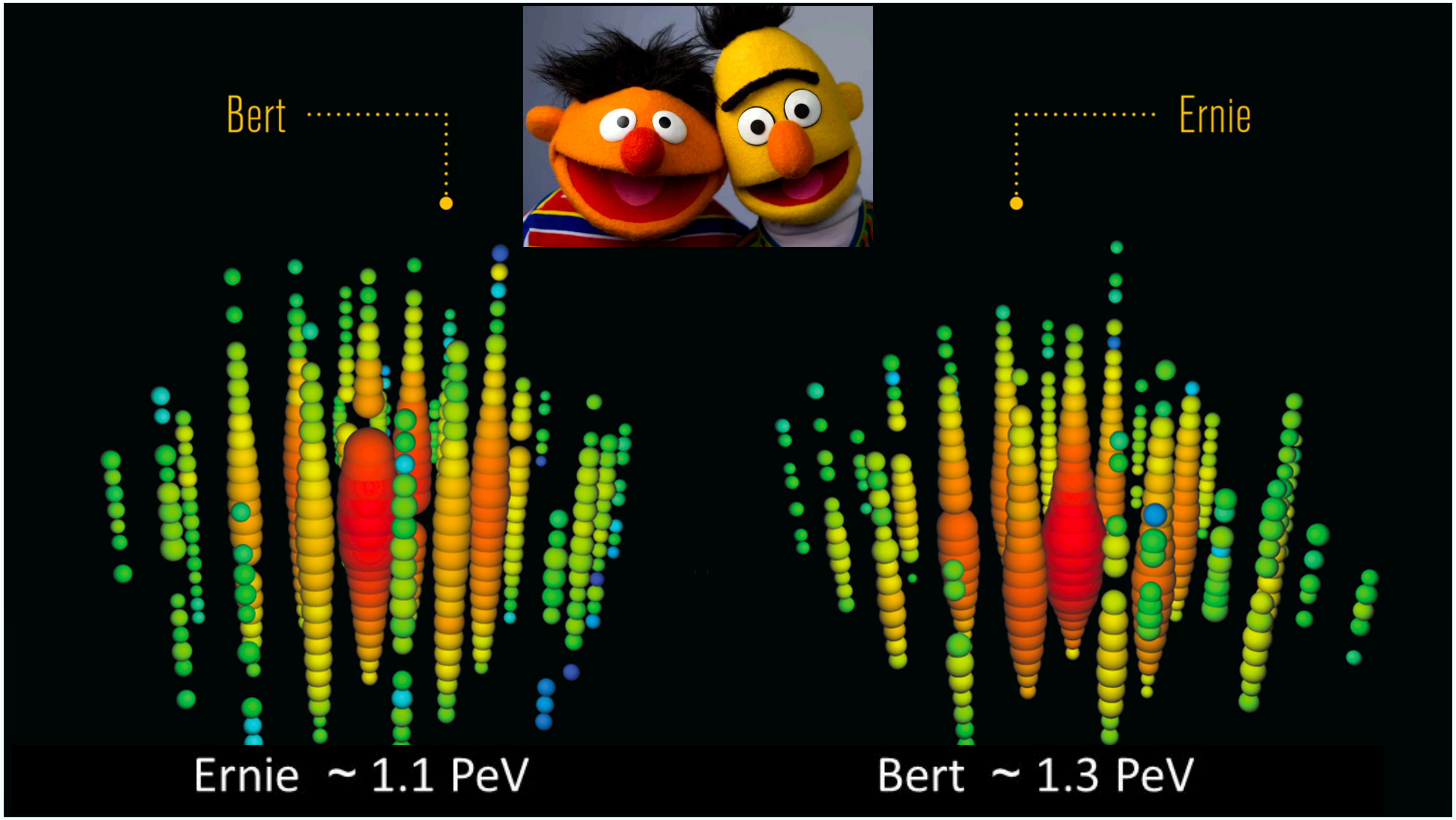
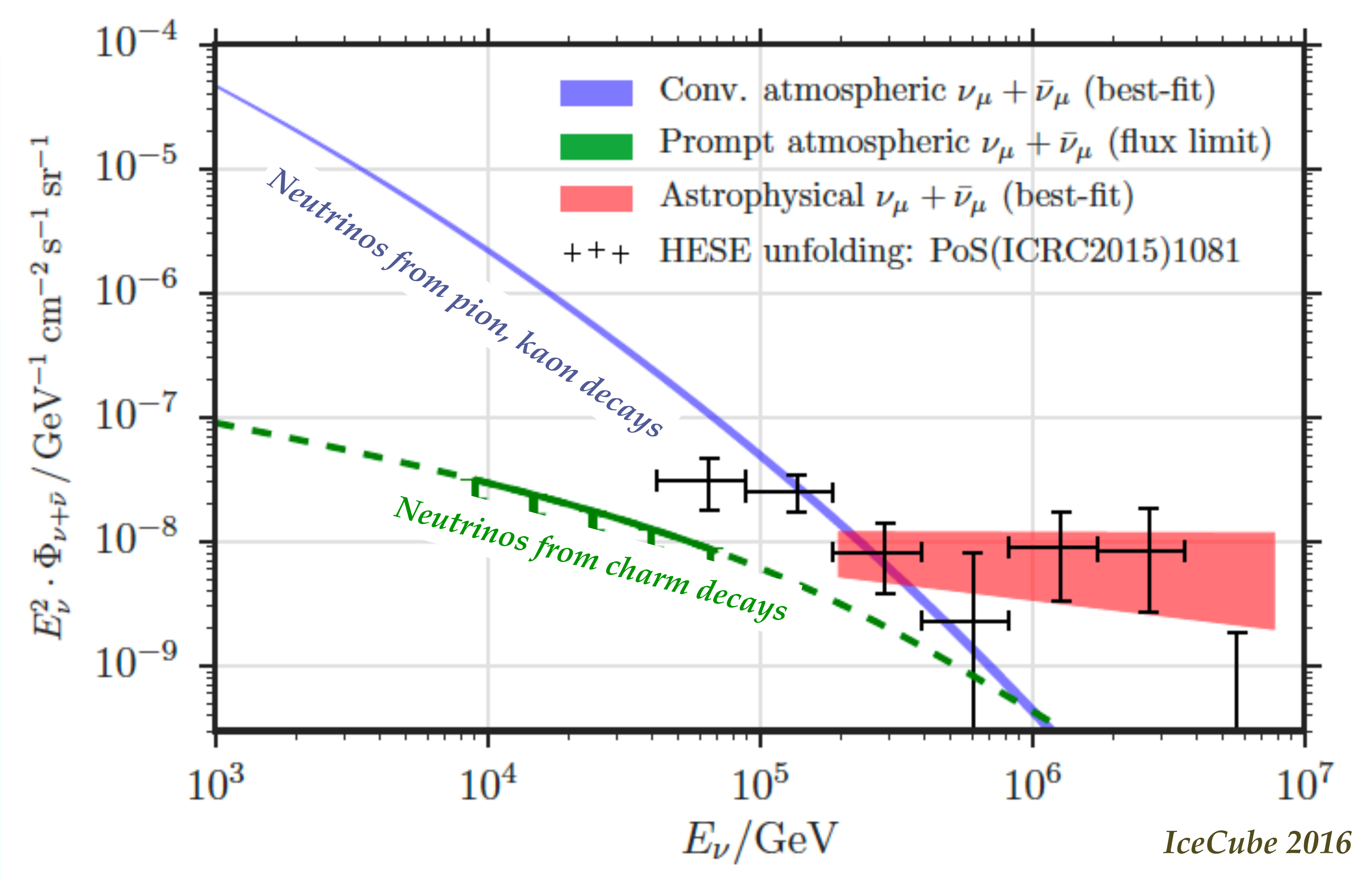



*Same centre-of-mass energy than in proton-proton collisions at the TeV!*

# from neutrino telescopes to particle physics

What do these **high-energy neutrinos** have to do with **particle physics?** Well, a lot, including:

- Probing **Quantum Chromodynamics** (the strong interaction) in **new extreme regimes**
- Understand the **internal structure of the proton** in an unexplored region
- Provide stringent tests of **Beyond the Standard Model** at energies above the reach of colliders



# backgrounds to neutrino astronomy

At UHEs dominant **background for astrophysical neutrinos** are ***D* meson decays** from cosmic ray collisions

***Conventional backgrounds: p + Air (N,O)***
***=> pions, kaons (light hadrons) + X***
***=> neutrinos + X***

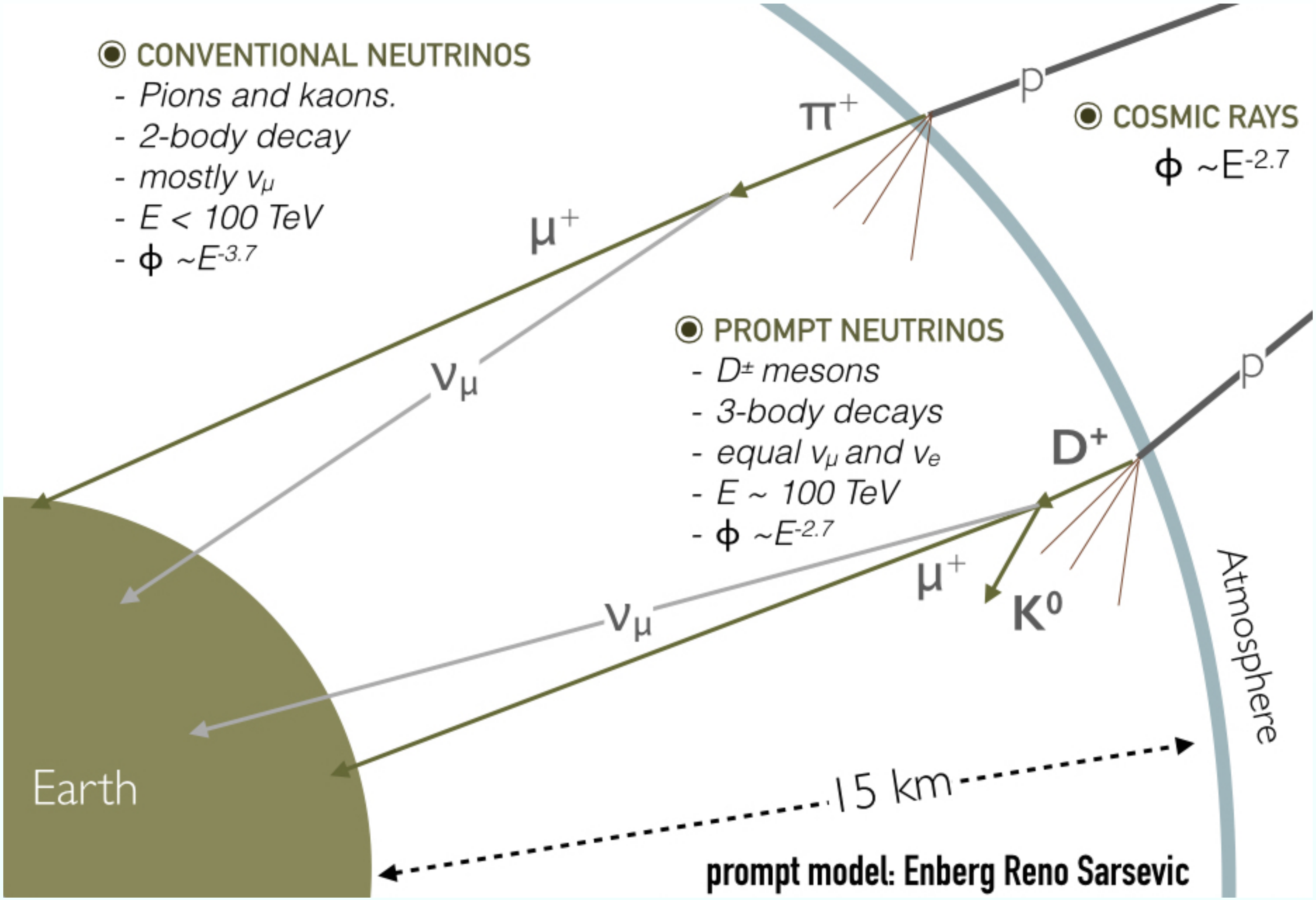
- ☑ Bigger production cross-sections
- ☑ **Longer lifetimes** (more time to interact before decaying)

***Prompt backgrounds: p + Air (N,O)***
***=> D mesons + X (ie, $D^+ = [c\bar{d}]$ )***
***=> neutrinos + X***

- ☑ Smaller production cross-sections
- ☑ Shorter **lifetimes** (less time to interact before decaying)

# backgrounds to neutrino astronomy

*D* **meson** production at these extreme energies **poorly understood** with **large theory uncertainties**



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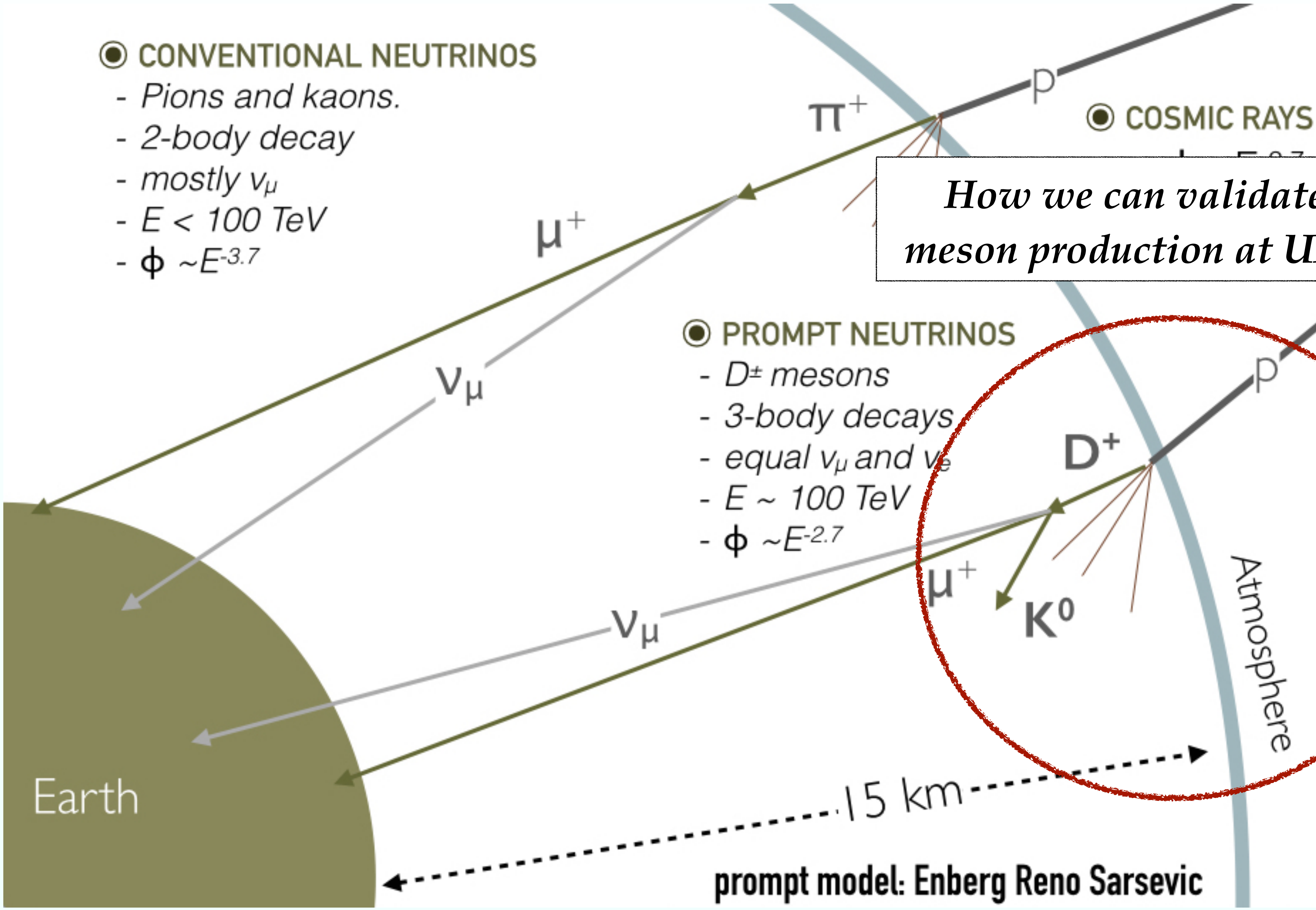
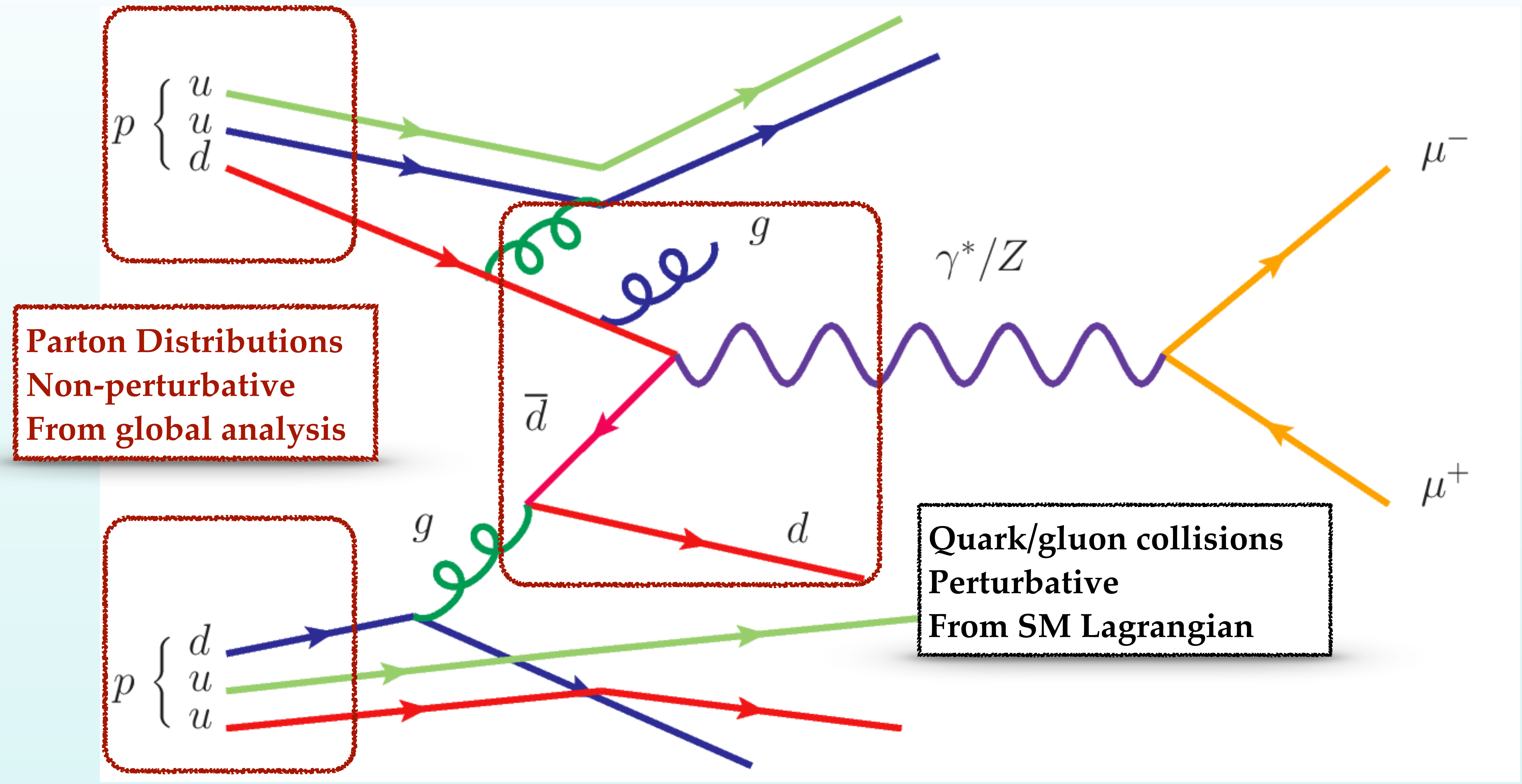



***How we can validate D meson production at UHEs?***

# anatomy of hadronic collisions

In high-energy **hadron colliders** the collisions involve **composite particles** (protons) with internal substructure (quarks and gluons): the LHC is actually a **quark/gluon collider!**




Calculations of **cross-sections** in hadron collisions require the combination of **perturbative cross-sections** with **non-perturbative parton distribution functions (PDFs)**

# the inner life of protons

Distribution of energy that **quarks and gluons carry inside proton** quantified by **Parton Distributions**

$$g(x, Q)$$

$g(x,Q)$: **Probability** of **finding a gluon inside a proton**, carrying a fraction $x$ of the proton momentum, when probed with energy $Q$

$Q$: **Energy of the quark/gluon collision**
Inverse of the resolution length

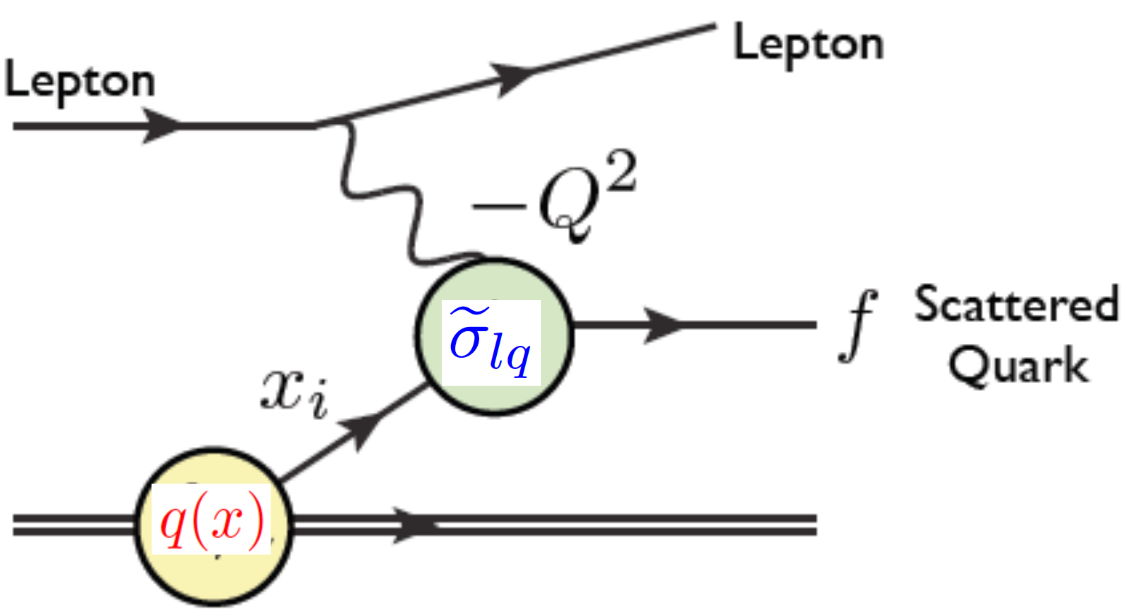
$x$: **Fraction of the proton's momentum**

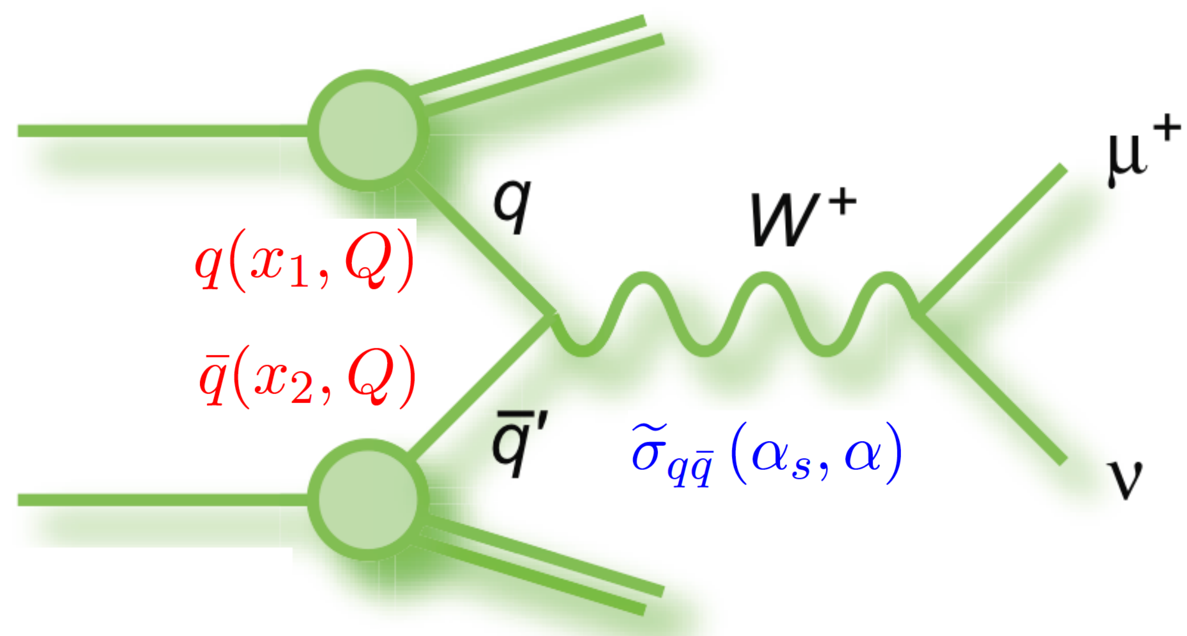
***PDFs** determined by **non-perturbative QCD dynamics***

*Extract from experimental data within a **global analysis***

$$\sigma_{lp} \simeq \widetilde{\sigma}_{lq}(\alpha_s, \alpha) \otimes q(x, Q)$$

$$\sigma_{pp} \simeq \widetilde{\sigma}_{q\bar{q}}(\alpha_s, \alpha) \otimes q(x_1, Q) \otimes \bar{q}(x_2, Q)$$



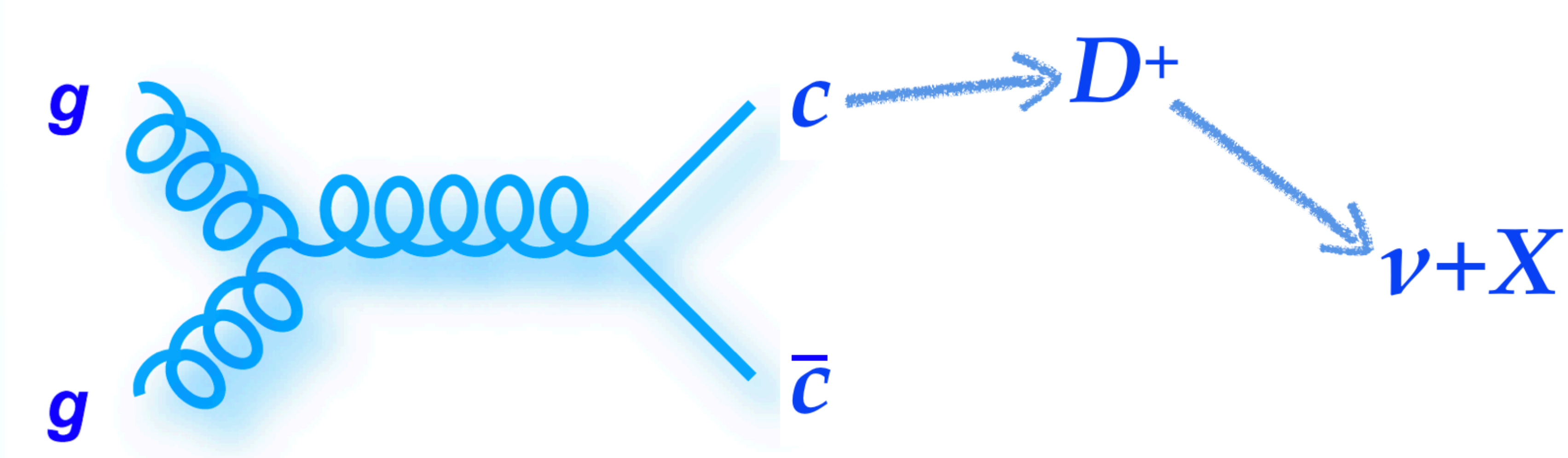




***Extract PDFs from lepton-proton collisions***

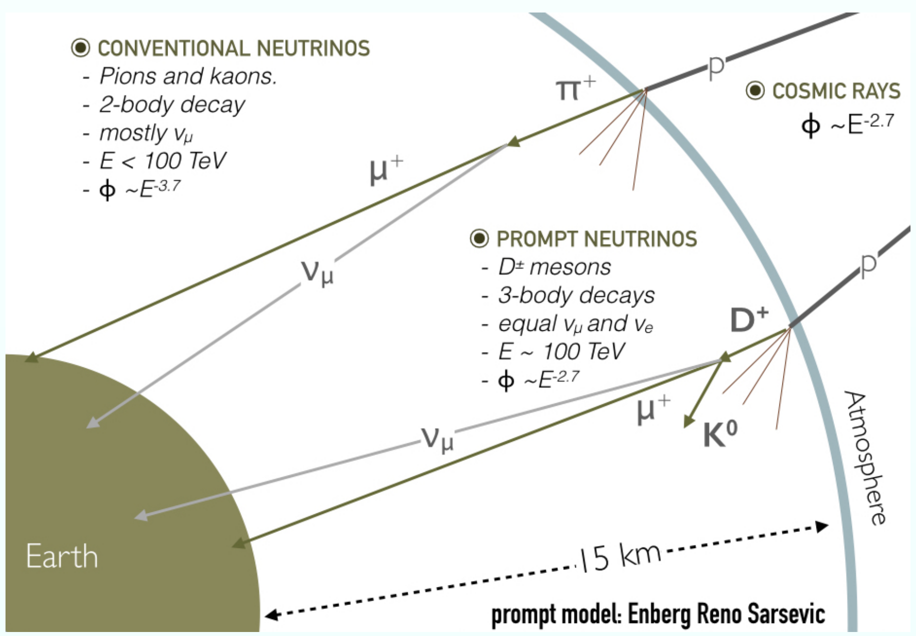
***Use PDFs to predict proton-proton cross-sections***

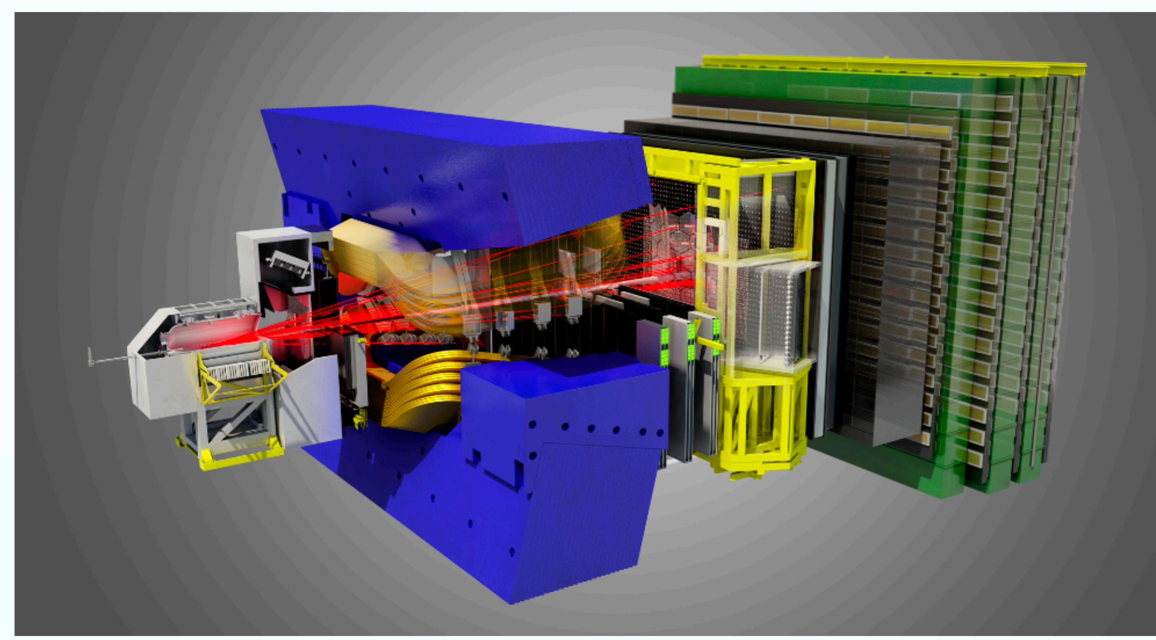
# LHC to the rescue!

To obtain robust theory predictions, include ***D* meson production data from LHCb** into PDF fit to constrain **small-*x* gluon** and validate the **theoretical calculations**




*IceCube* $E_{CR} = 100$ *PeV* $\xrightarrow{\text{Lorentz boost}}$ *LHCb* $E_{lab} \approx 14$ *TeV*



*Direct overlap kinematics between charm production in UHE cosmic rays and at the LHC*

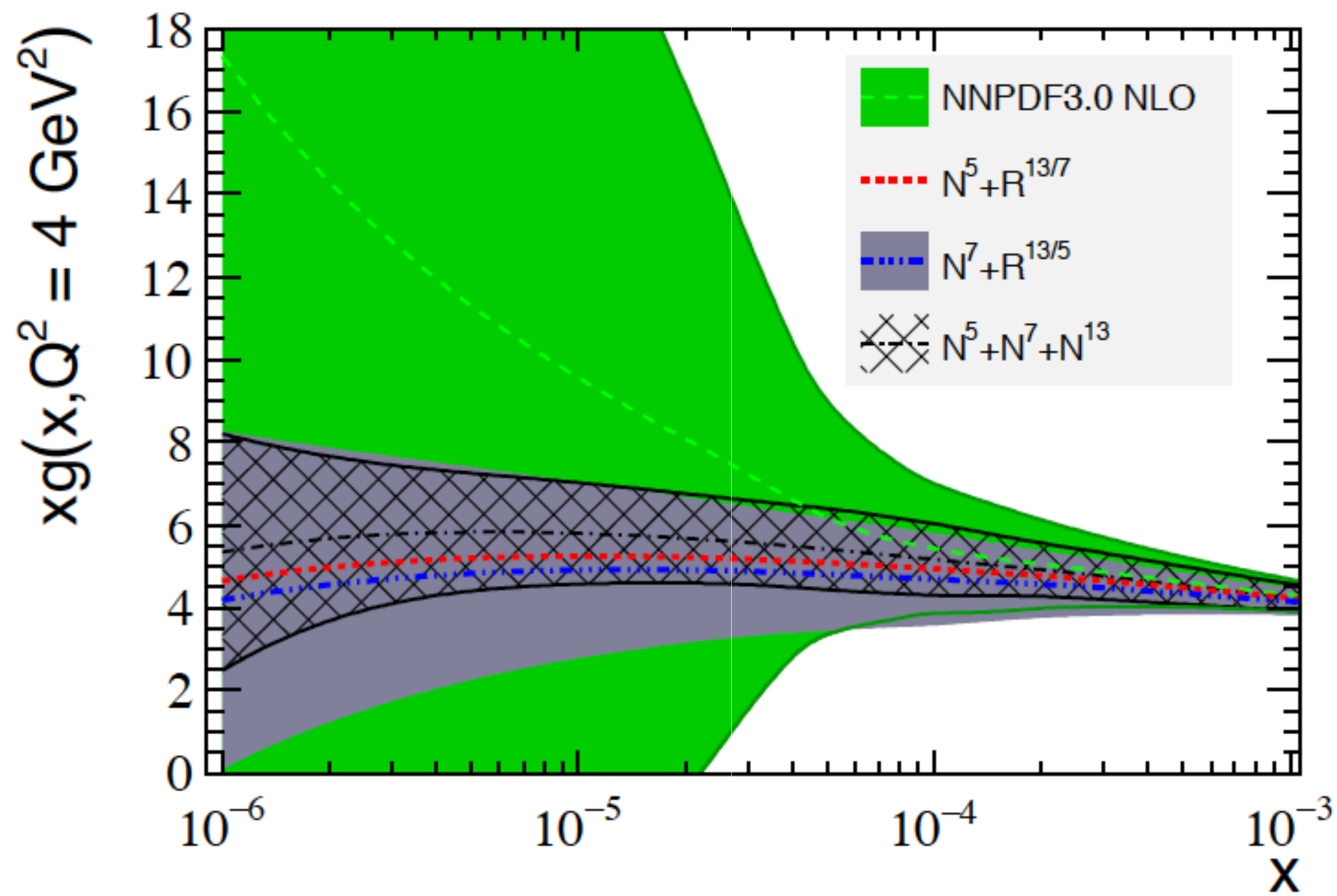
# precision determination of the small-x gluon

- LHCb **D cross-sections** available at **5, 7, and 13 TeV**
- Fit data, either **normalised distributions** or **cross-section ratios** (13 TeV/7 TeV and 13 TeV/5 TeV)
- Up to a **factor 10 reduction on the small-x gluon** uncertainties down to **x ≲ $10^{-6}$**

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

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

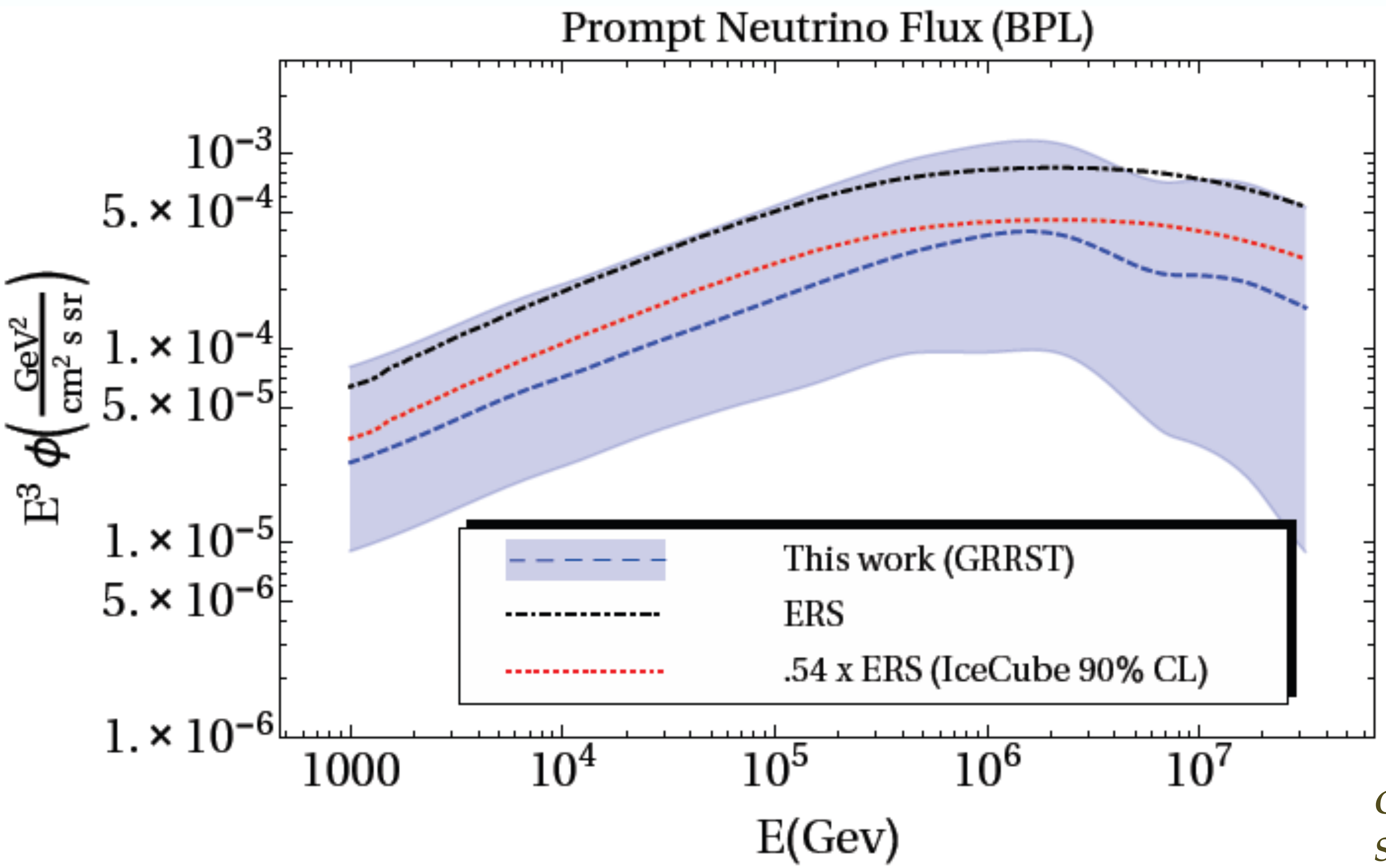
*Impact of LHCb 5+7+13 TeV D meson xsec data*




*Gauld, JR 16*

# backgrounds to neutrino astronomy

Using our **updated QCD theory for D meson production**, validated with the LHCb measurements, we can provide updated predictions for the **prompt neutrino flux** at neutrino telescopes

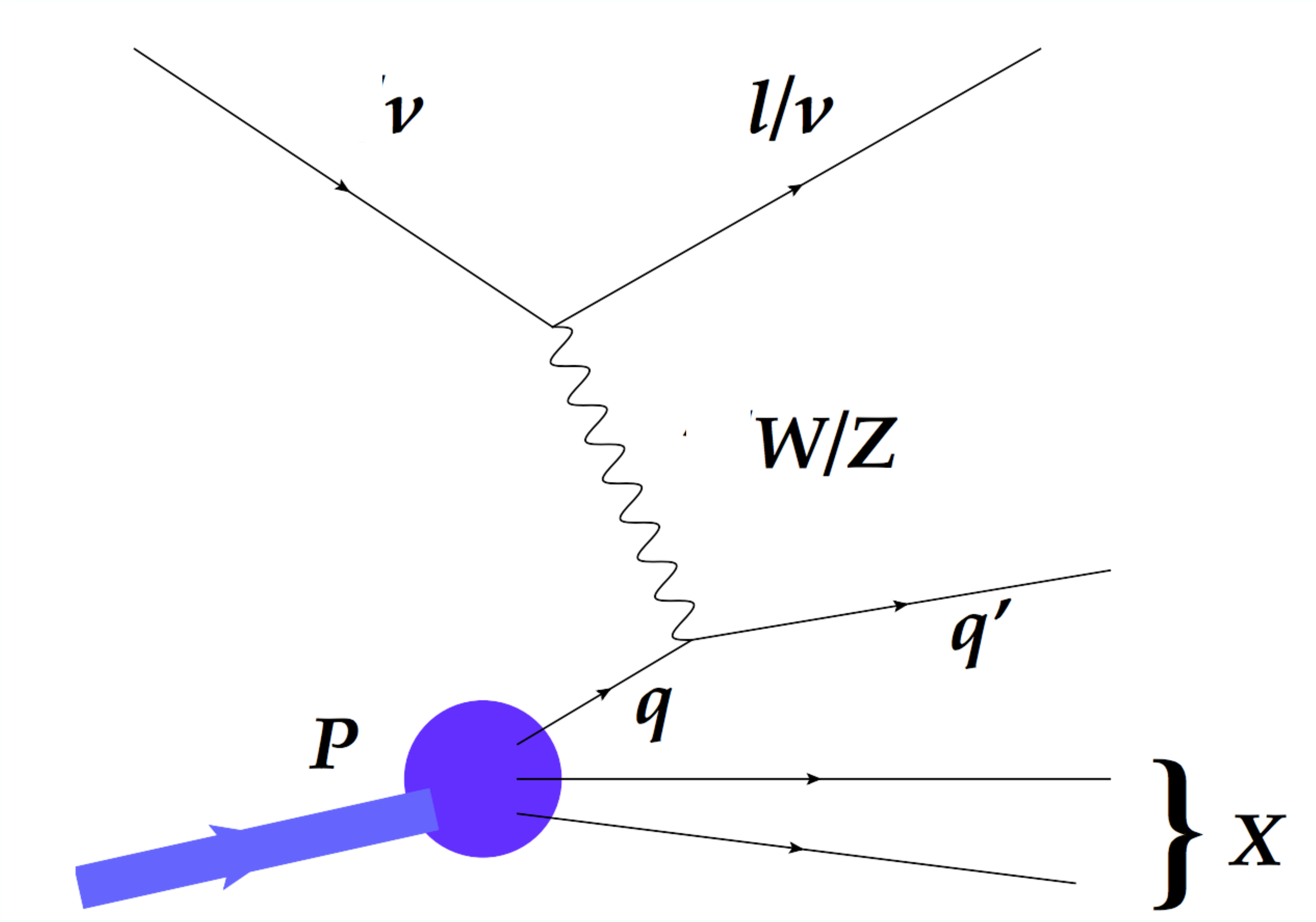



*Gauld, JR, Rottoli, Sarkar, Talbert 15*

*We predict that detection of the prompt neutrino flux should be within reach!*

# neutrino telescopes: the ultimate QCD microscope

Turning now to the **signal production cross-sections,** the UHE neutrinos interact with the ice/sea nucleons by means of the **deep-inelastic scattering** process




Outstanding probe of the **internal proton structure** below the range covered by colliders

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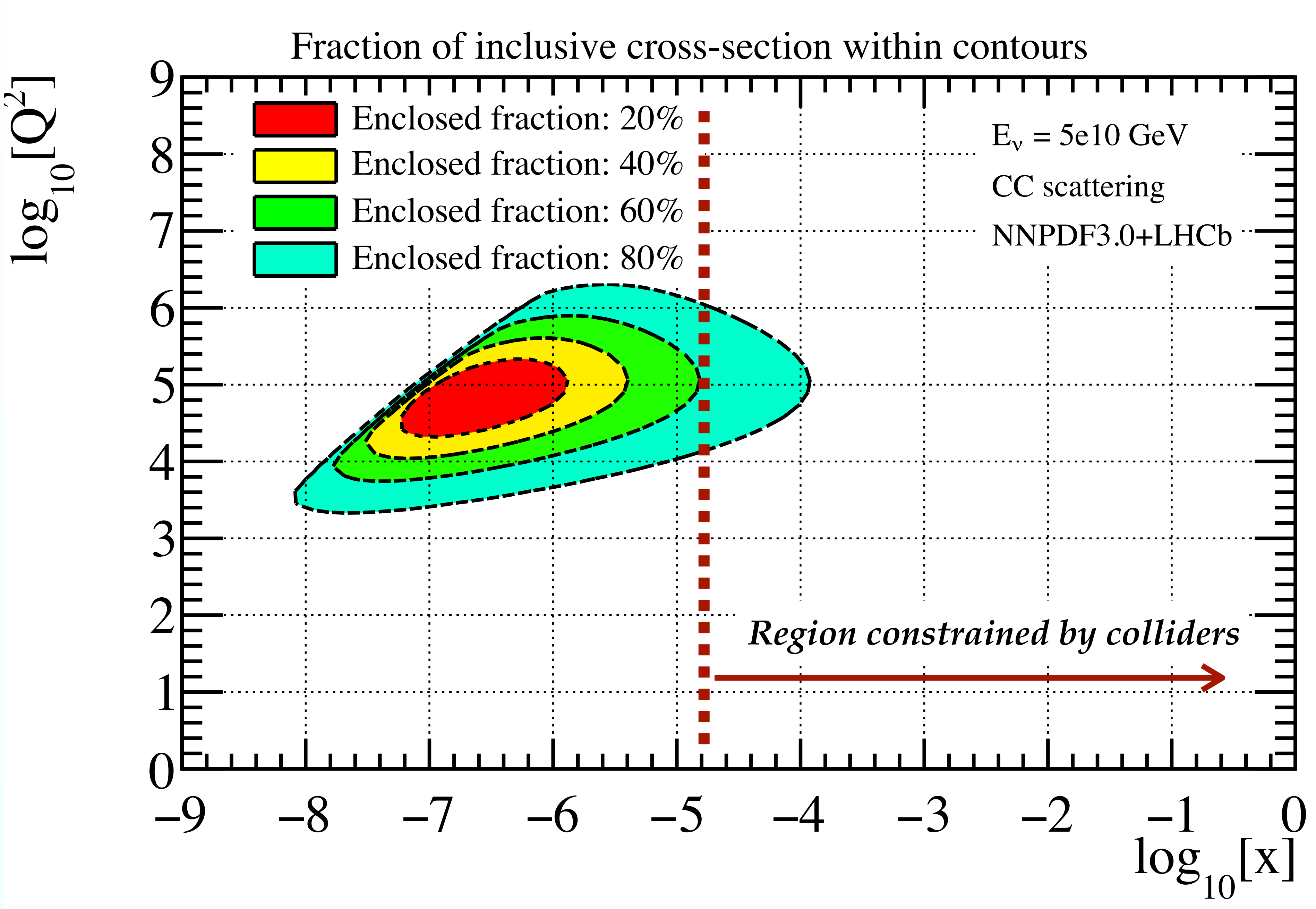


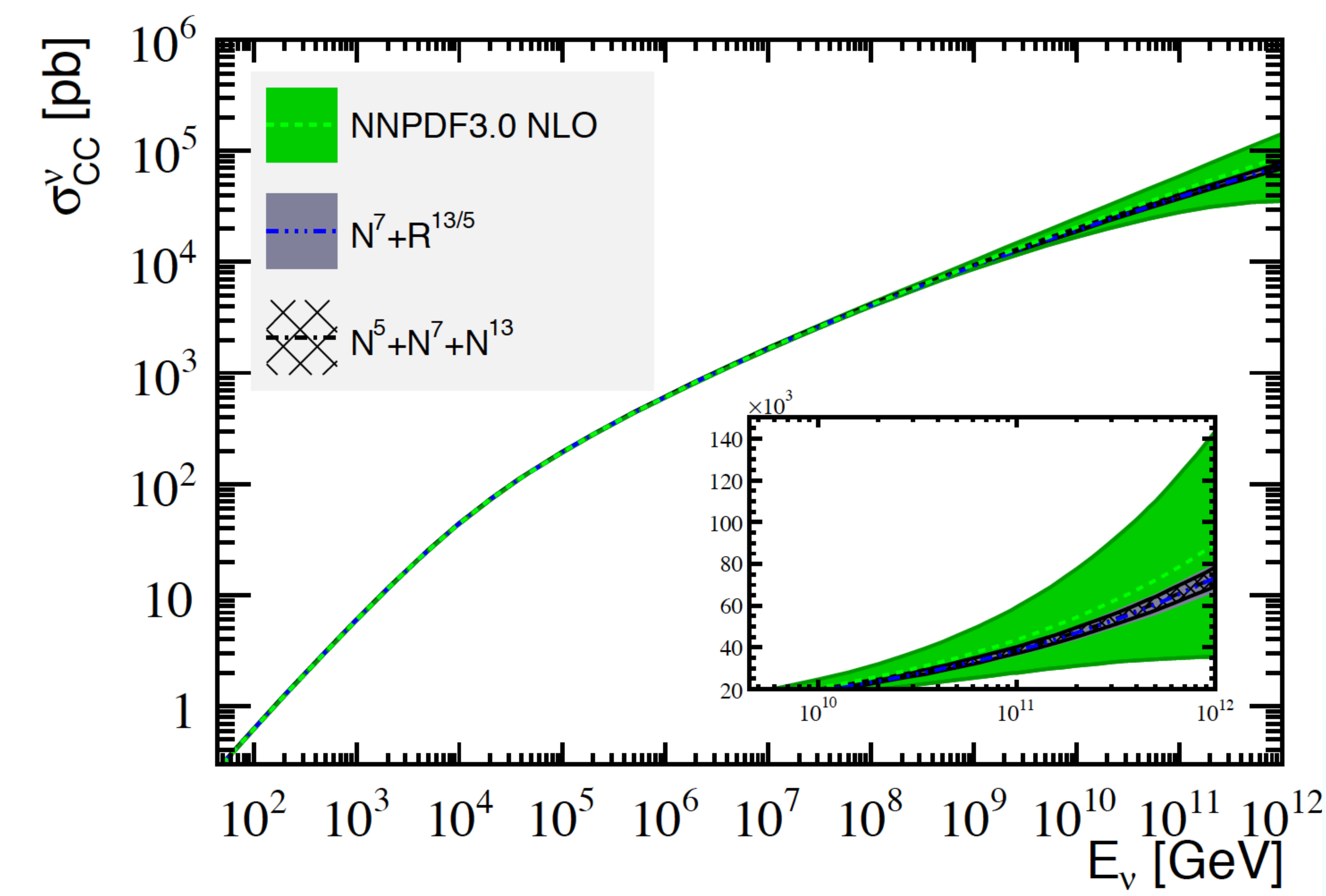

*x: Fraction of the proton's momentum carried by quarks/gluons*

Outstanding probe of the **internal proton structure** below the range covered by colliders!

# neutrino telescopes: the ultimate QCD microscope

Measurements of the UHE cross-section at neutrino telescopes allows probe the strong interaction in a novel extreme regime, where qualitatively new dynamics are expected to arise

***QCD at small-x: BFKL dynamics, gluon saturation, connection with heavy ion collisions ….***




*Gauld, JR 16*

**Constraints from LHCb charm production** instrumental for **signal cross-sections at neutrino telescopes**

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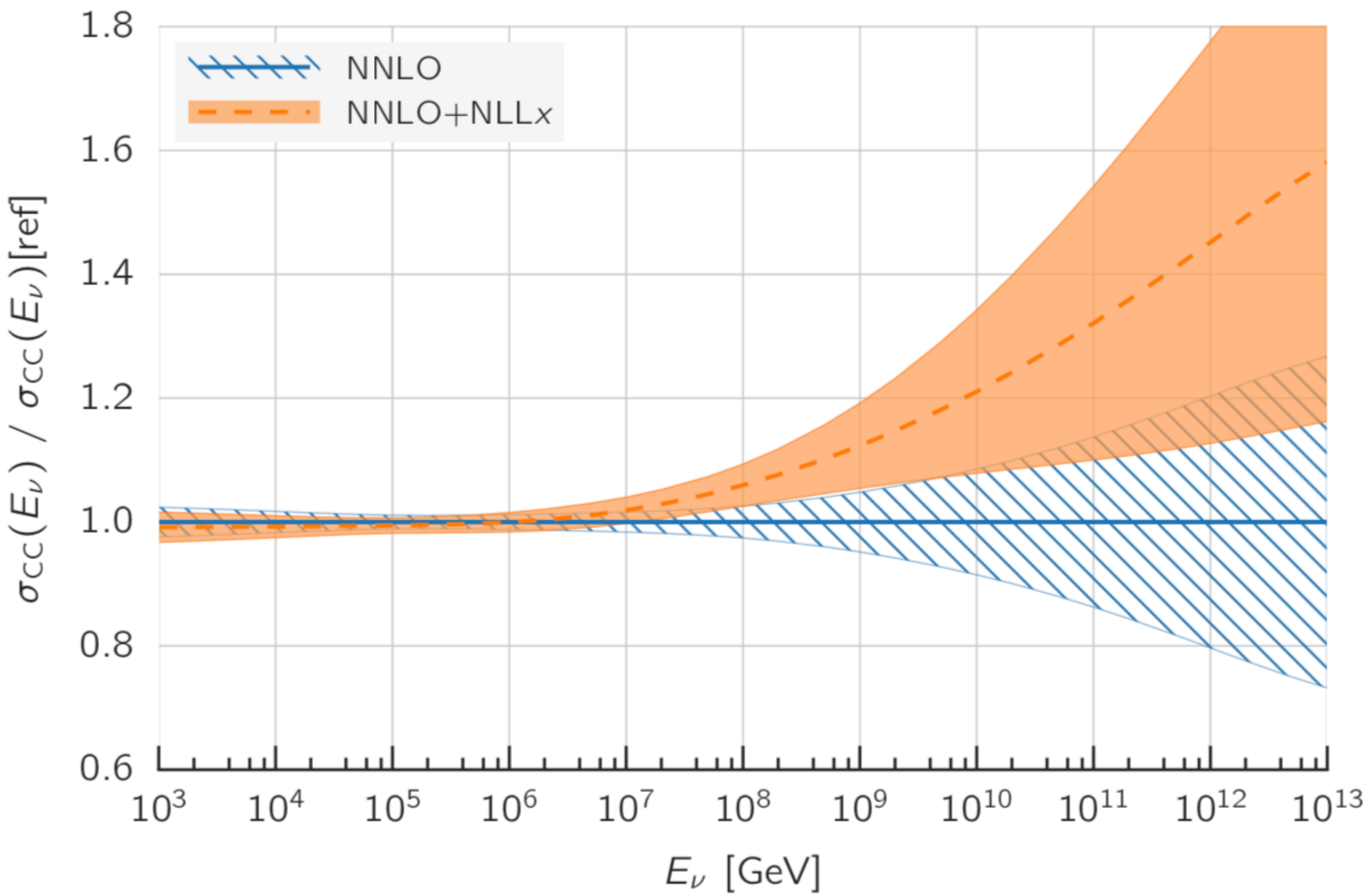



**High-energy QCD (matched to BFKL)**

**Standard QCD (collinear factorisation)**

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

**Explore a new world of QCD dynamics!**

# Beyond collinear QCD: BFKL resummation

- **Perturbative fixed-order QCD calculations** have been extremely successful in describing a **wealth of data** from proton-proton and electron-proton collisions

- At small-*x*, **logarithmically enhanced terms in *1/x* become dominant** and need to be resummed to all orders: eventually a **new framework beyond collinear QCD** is required

- ***BFKL/high-energy/small-x resummation*** can be matched to the ***DGLAP collinear framework***, and thus be included into a standard PDF analysis

*Used for every single LHC calculation!*

**DGLAP Evolution in $Q^2$**

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

**BFKL Evolution in x**

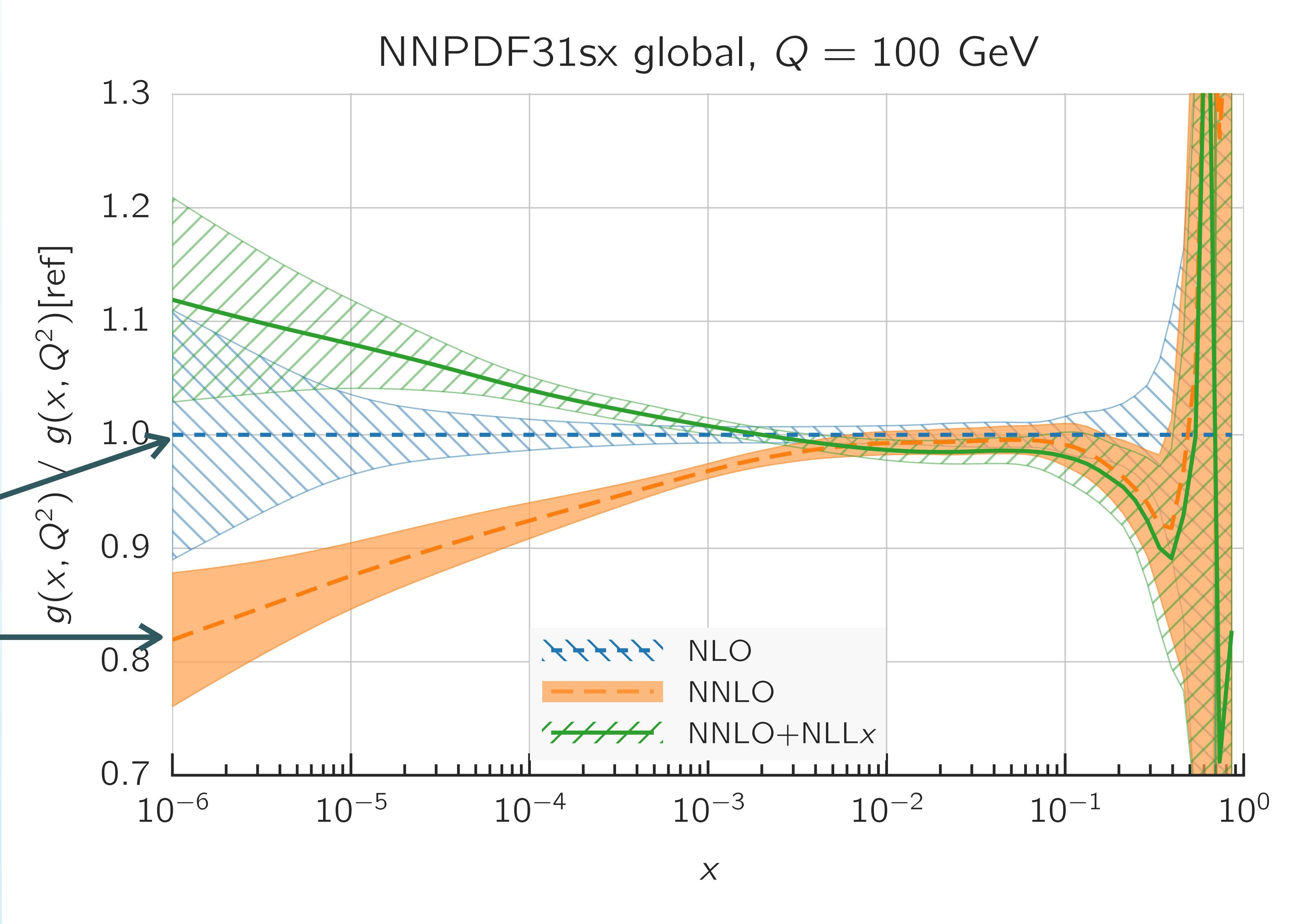
$$-x\frac{d}{dx} f_+(x,\mu^2) = \int_0^\infty \frac{d\nu^2}{\nu^2} K\left(\frac{\mu^2}{\nu^2}, \alpha_s\right) f_+(x,\nu^2)$$

***BFKL dynamics proposed 40 years ago, but no inconclusive evidence found …***

# A new world at small-x

***NNPDF3.1 (N)NLO+NLL fits stabilize the perturbative PDF expansion at small-x and improve the fit quality to the small-x HERA lepton-proton collider data***

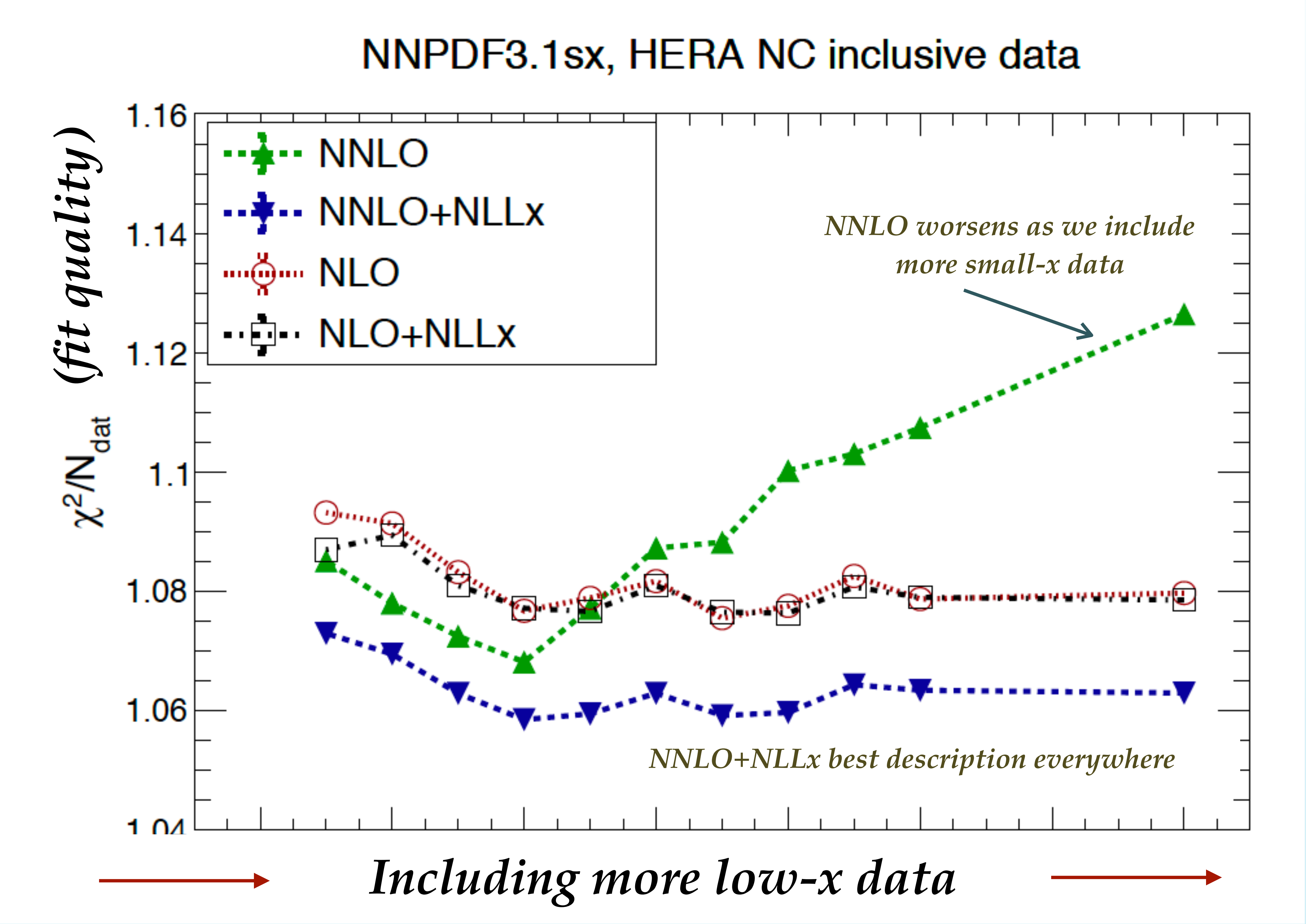
***Fixed-order QCD perturbation theory unstable here ….***




*Ball, Bertone, Bonvini, Marzani, JR,Rottoli 16*

# evidence for BFKL dynamics in HERA data

Excellent fit quality to **inclusive and charm HERA** data achieved in the **entire ($x,Q^2$) region**



**Science**
Life and Physics

# 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

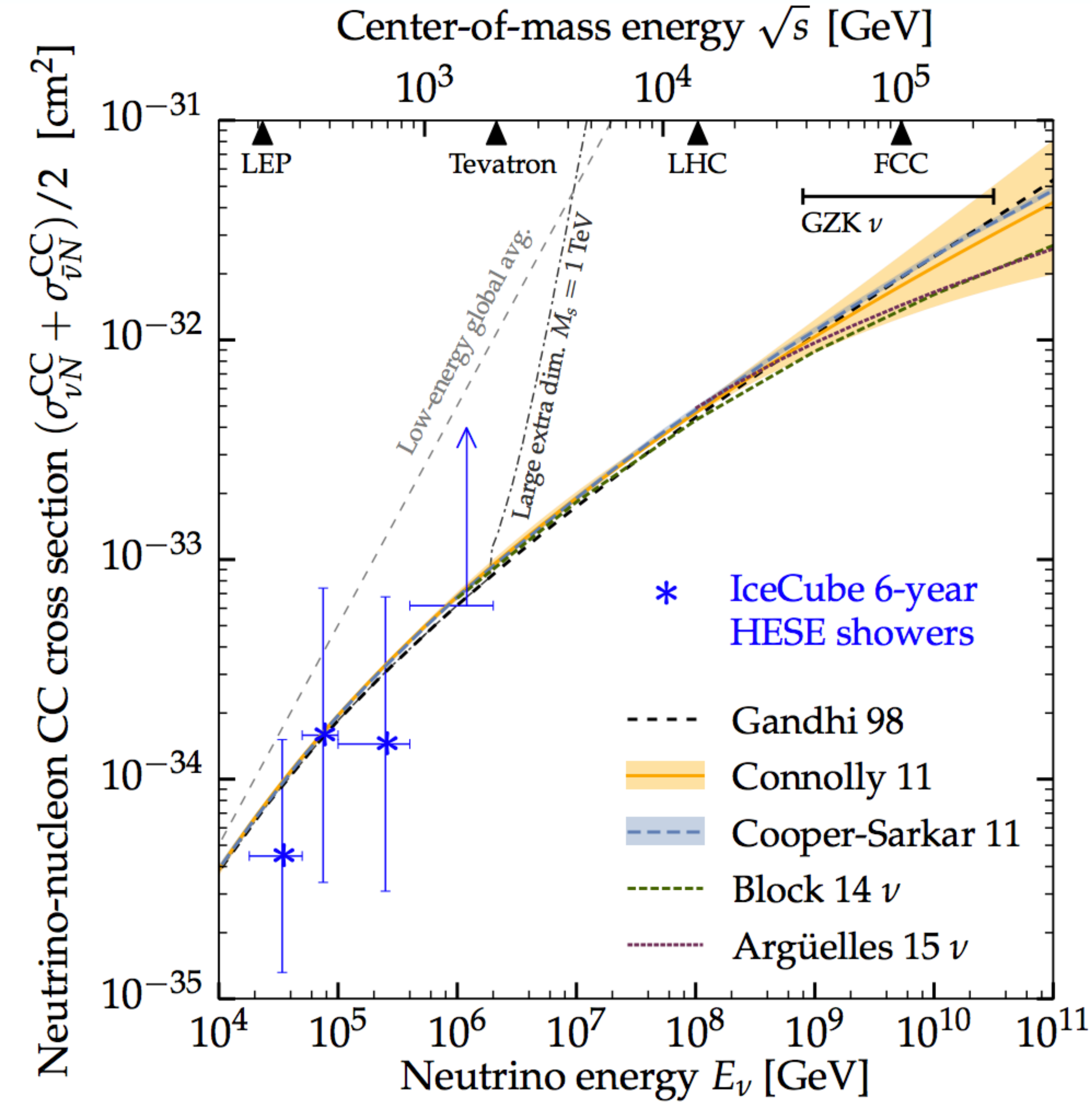
529 59

*Jon Butterworth, the Guardian, 28/12/2018*


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-

# We are getting there ....

**First measurements** of the UHE cross-section based on **IceCube 6 yr data**




*IceCube 16*
*Bustamante, Connoly 16*

# Summary and outlook

- Charm production in the forward region from LHCb provides stringent constraints on the **small-x PDFs**

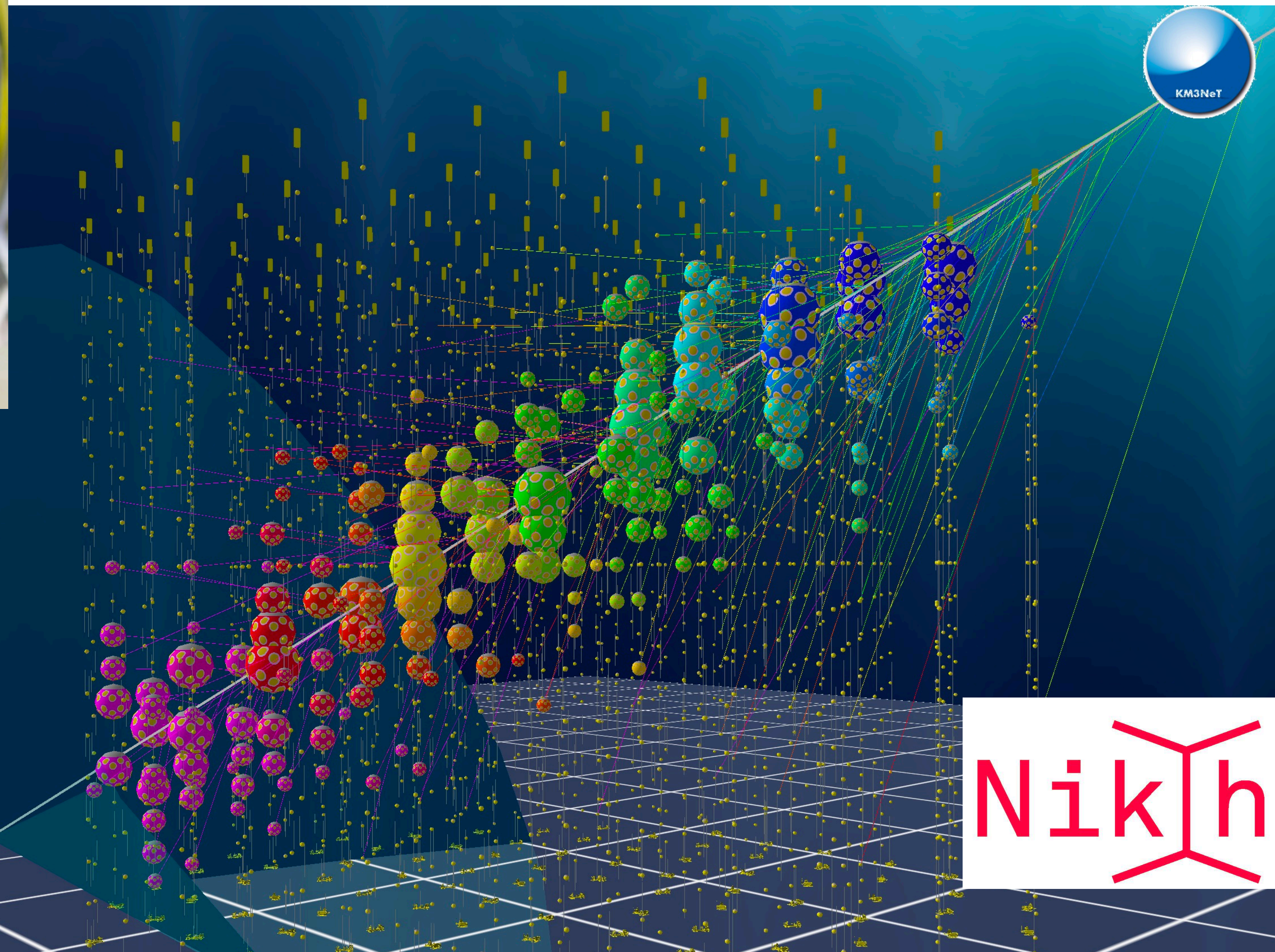
- The combination of **5 TeV, 7 TeV and 13 TeV *D* meson production from LHCb** allows a **precision determination of the small-x gluon PDF** way beyond the HERA coverage

- This improved small-x gluon allows accurate predictions for **signal and background events at neutrino telescopes**, making possible the start of a **precision physics program with UHE neutrino events**

- We can **test the strong interaction** in a brand new regime beyond the collider reach

**KM3NeT**

*Opens a new window on our universe*



*Neutrino telescopes such as **KM3NET** and **IceCube** illustrate the beautiful, non-trivial, **interplay between particle and astroparticle physics**, highlighting their **multiple synergies***

KM3NeT

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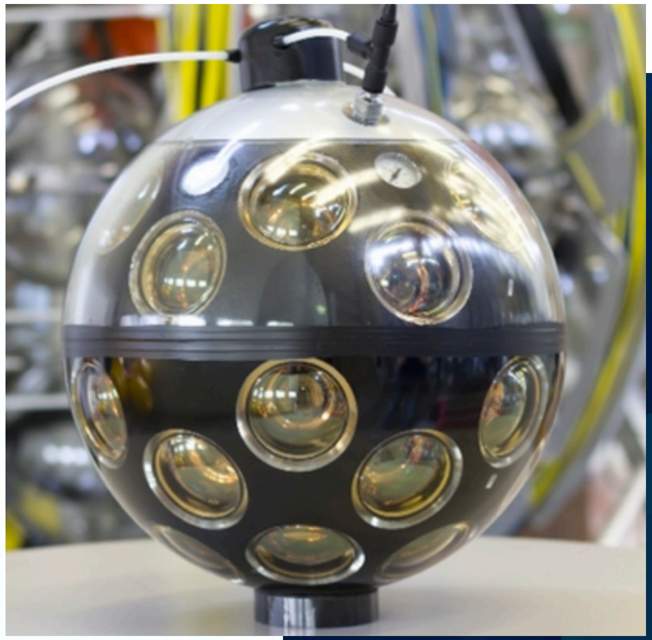

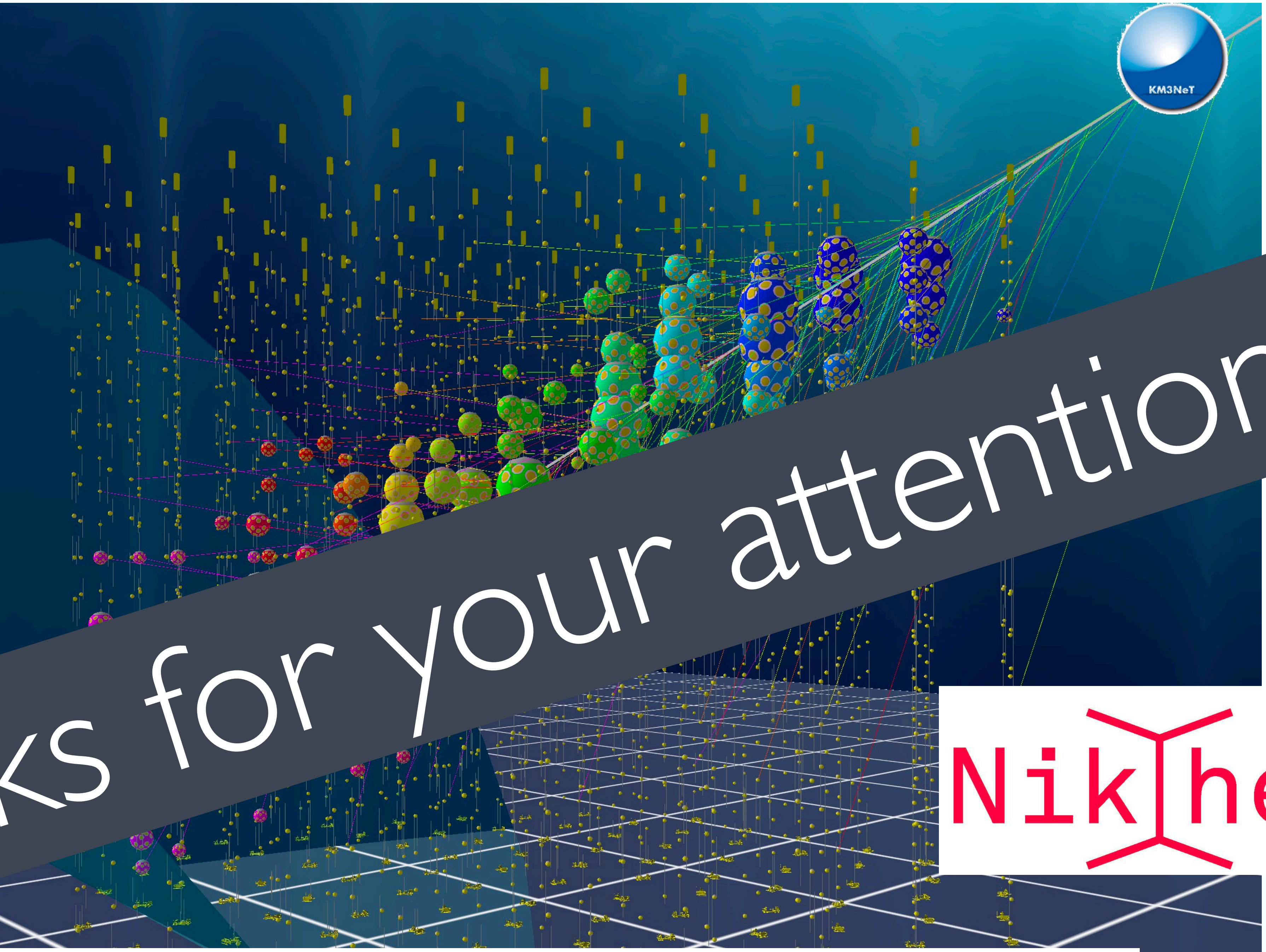


Thanks for your attention!

Nikhef

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