Proton Structure and PDFs

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XXVII International Workshop on Deep Inelastic Scattering and Related Subjects (DIS2019)

DIS 2019

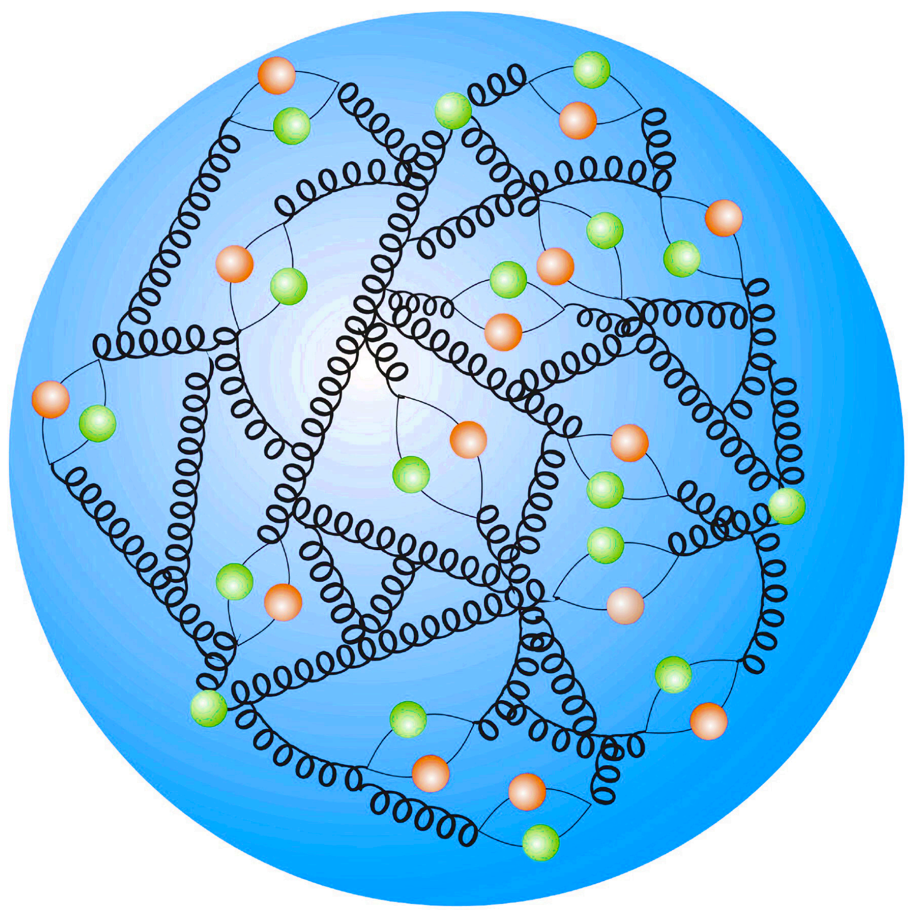
8-12 April

TORINO

The inner life of protons

The many faces of the proton

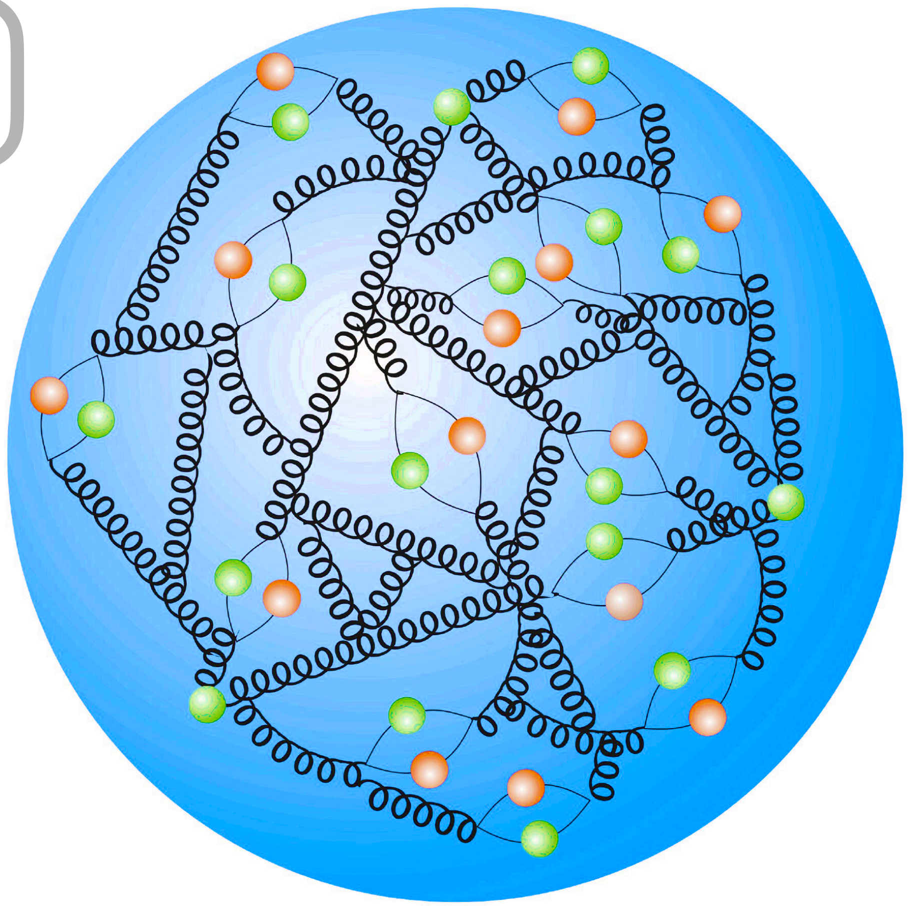
QCD bound state of **quarks** and **gluons**



The many faces of the proton

QCD bound state of **quarks** and **gluons**

Origin of mass?



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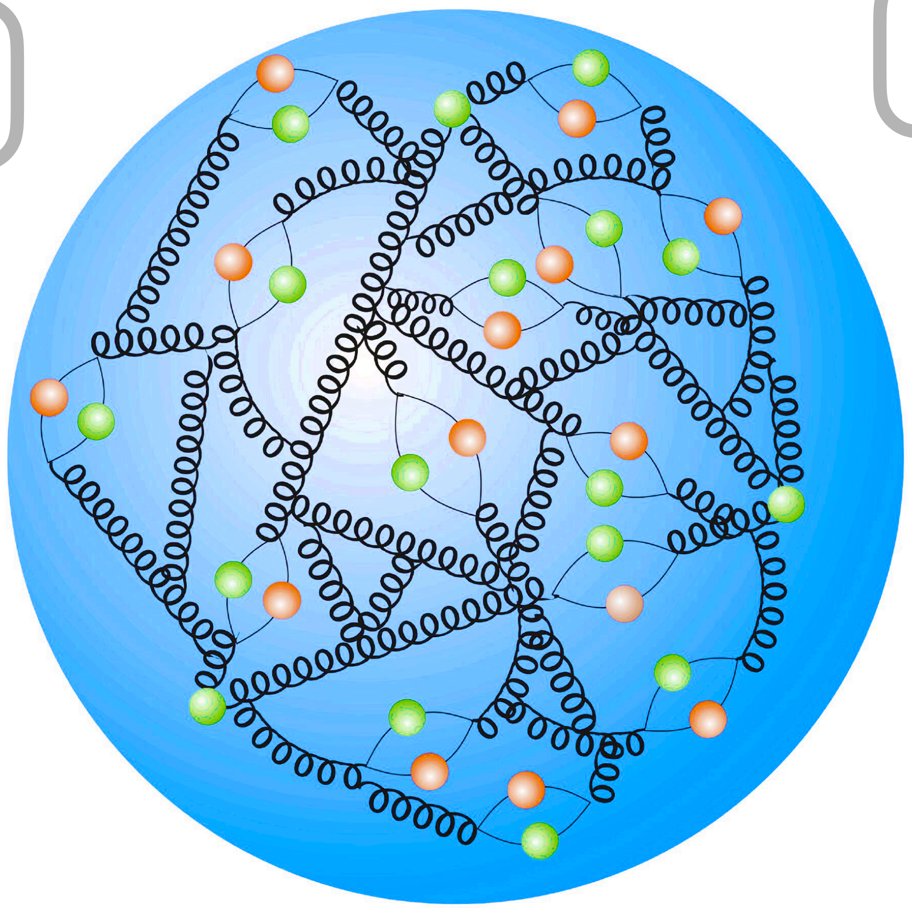

Origin of spin?

The many faces of the proton

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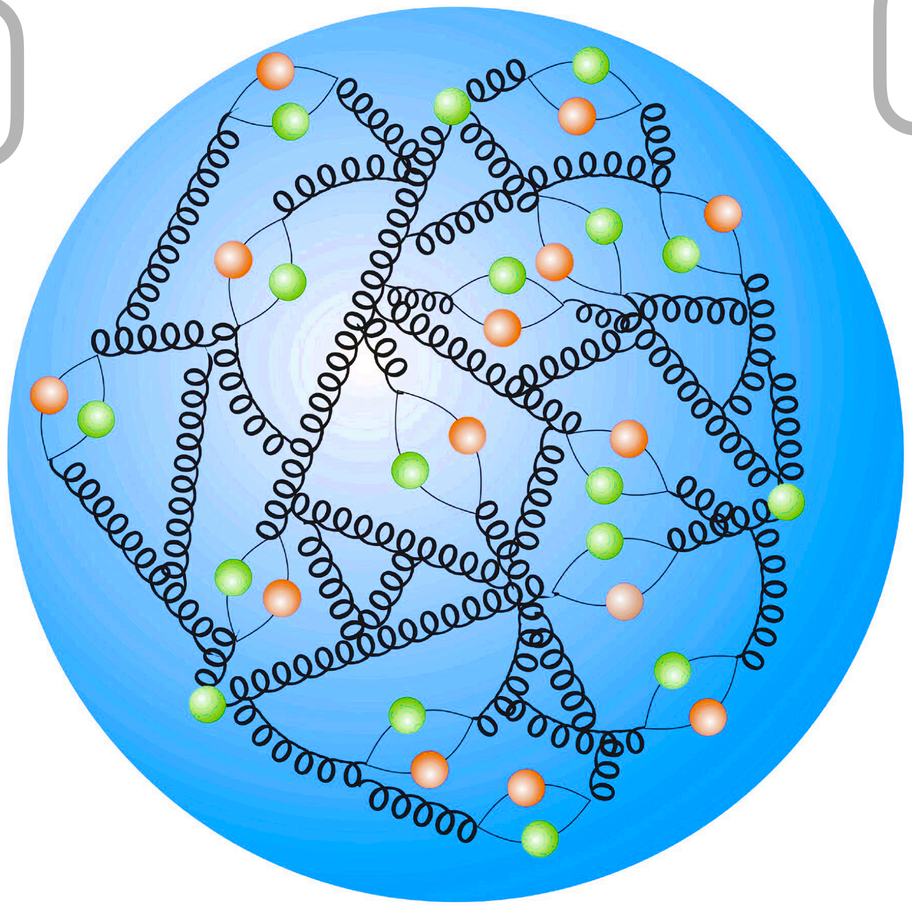
Origin of mass?

Origin of spin?

Gluon-dominated matter?



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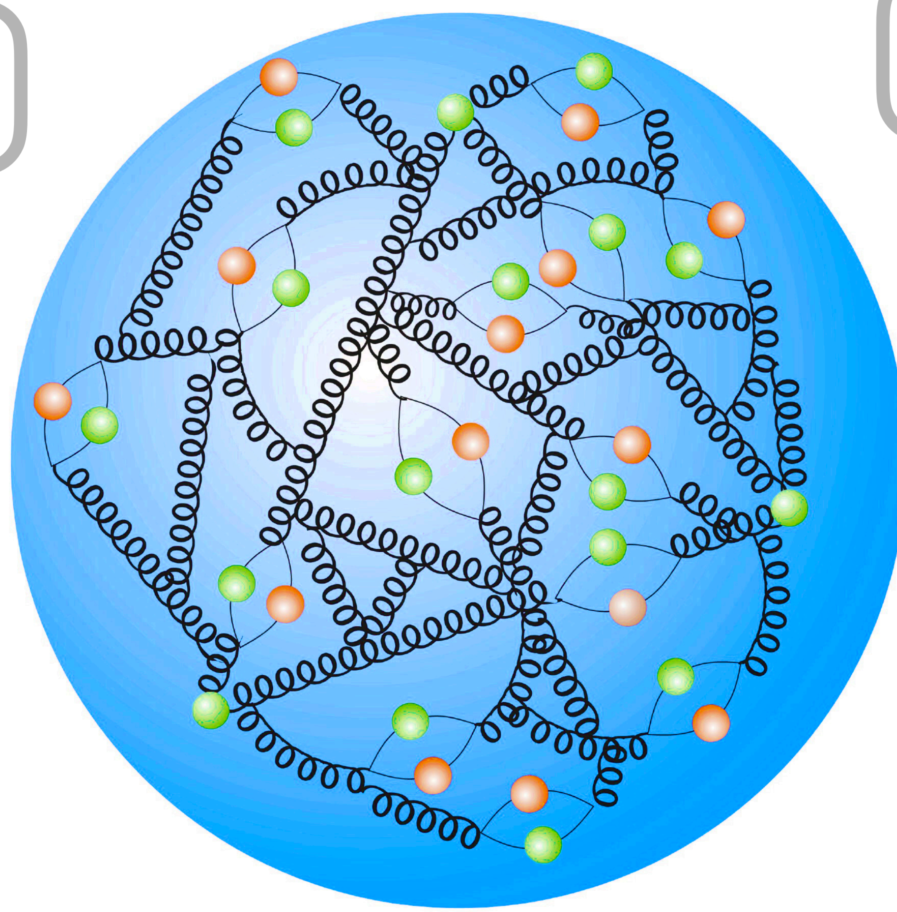

Gluon-dominated matter?

3D imaging?

The many faces of the proton

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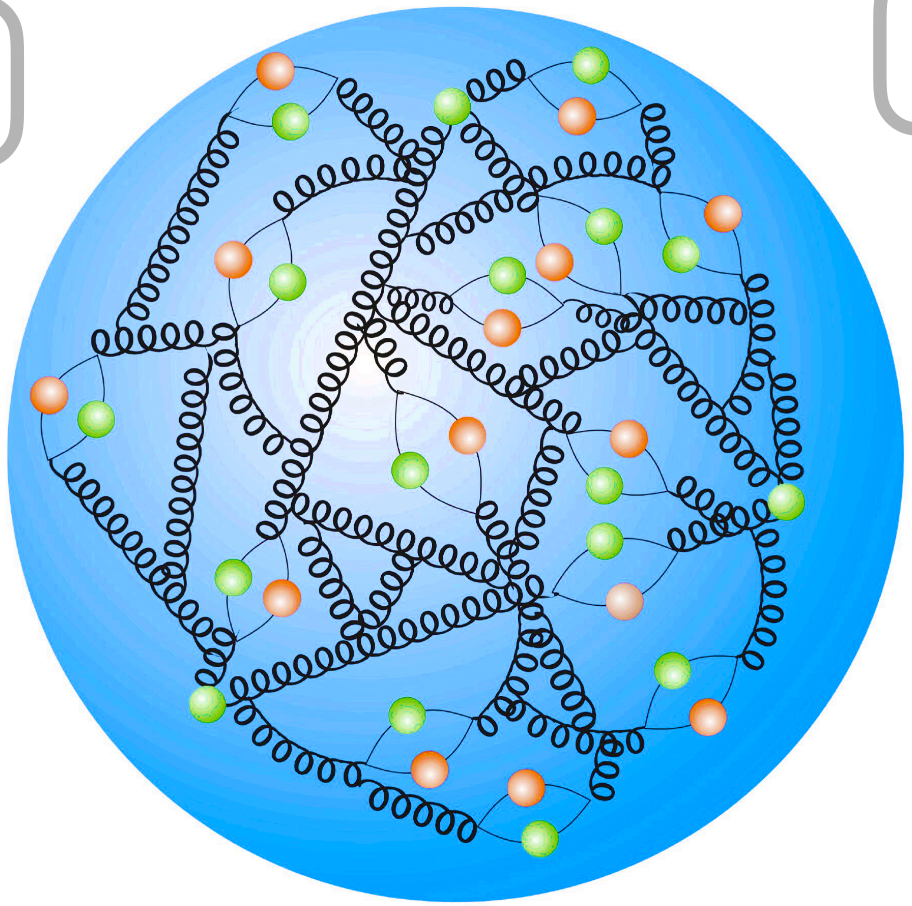

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Heavy quark content?

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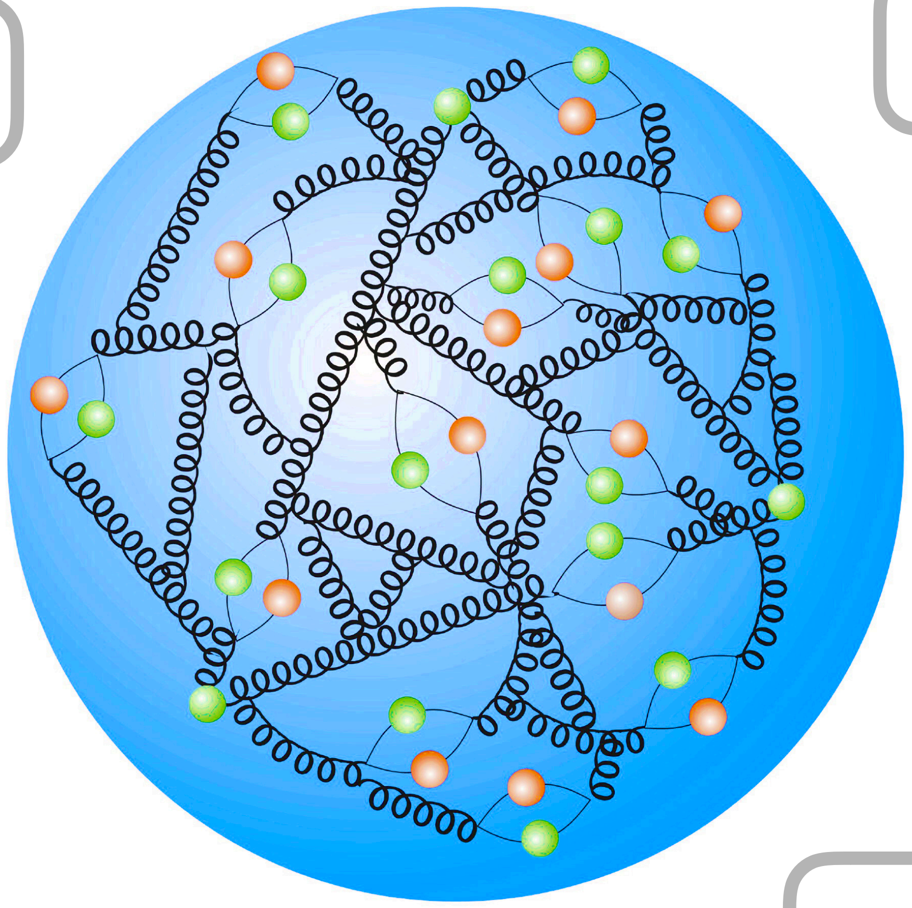


Gluon-dominated matter?

3D imaging?

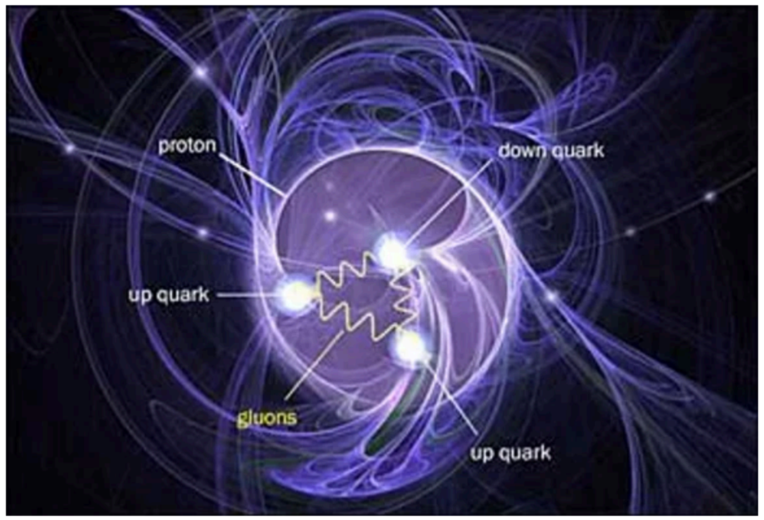
Heavy quark content?

Nuclear modifications?

The proton in the spotlight

THE SCIENCES

Proton Spin Mystery Gains a New Clue



Non-zero gluon polarisation

Scientific American (2014)

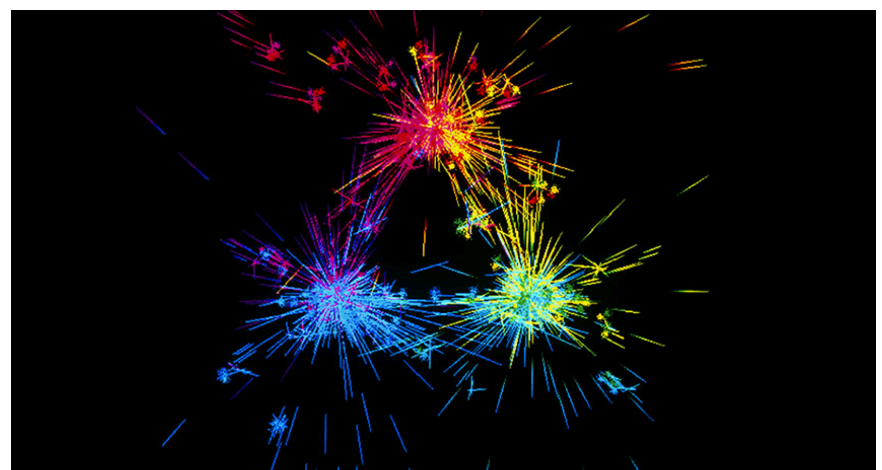
Nucleon pressure

NEWS PARTICLE PHYSICS

The inside of a proton endures more pressure than anything else we've seen

For the first time, scientists used experimental data to estimate the pressure inside a proton

BY EMILY CONOVER 1:18PM, MAY 16, 2018

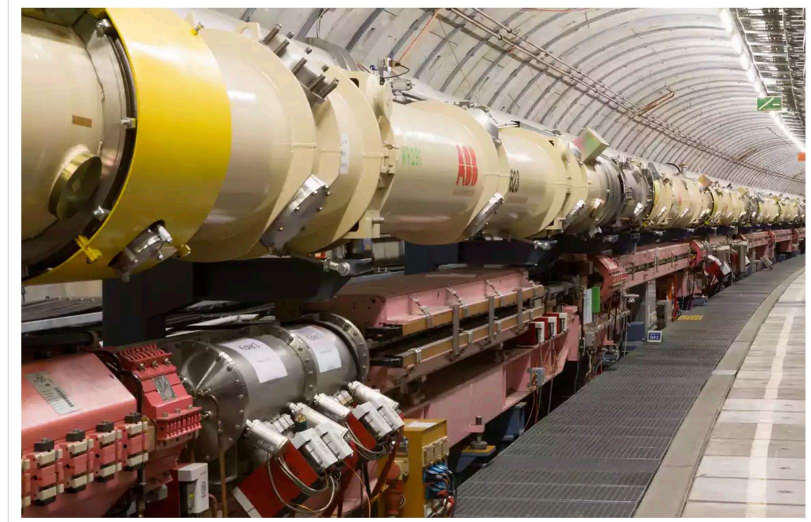


FEELING THE PRESSURE Extreme pressures are found within the proton, scientists report. The proton contains three particles called quarks (illustrated) as well as gluons, which hold the particle together.

Science News (2018)

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

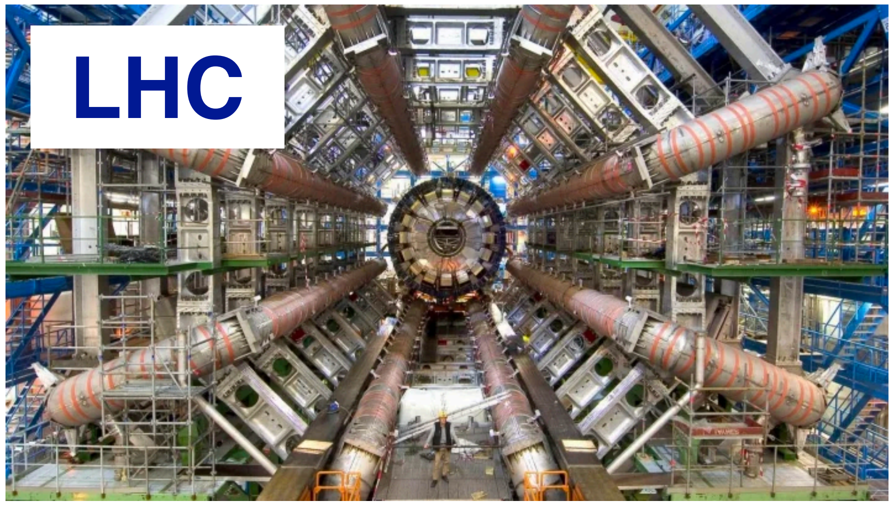


BFKL dynamics

The Guardian (2017)

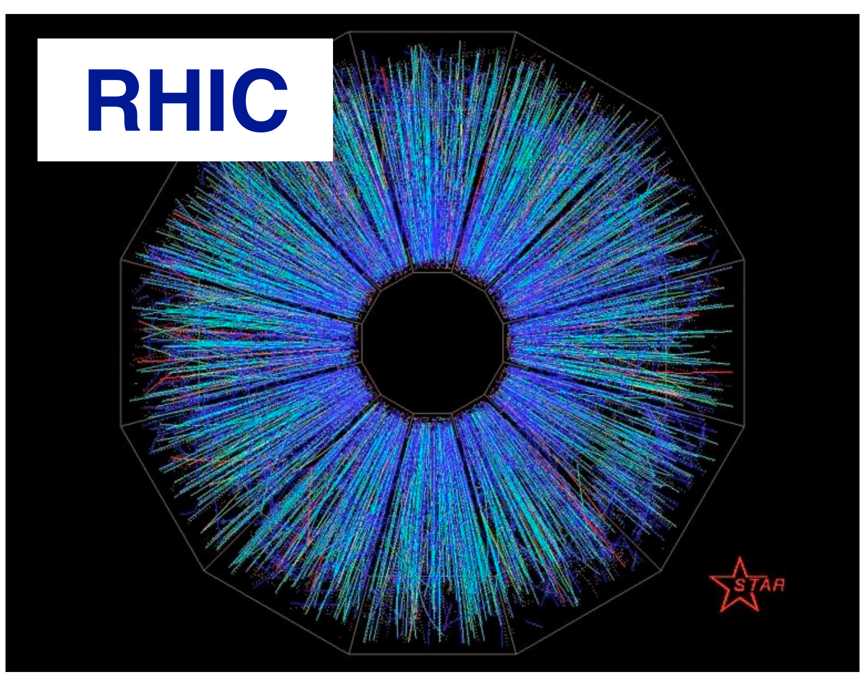
The proton keeps surprising us as an endless source of **fundamental discoveries**

From colliders to the cosmos



New **elementary particles** beyond the **Standard Model?**

Origins and properties of **cosmic neutrinos**?



Nature of **Quark-Gluon Plasma** in **heavy-ion collisions?**

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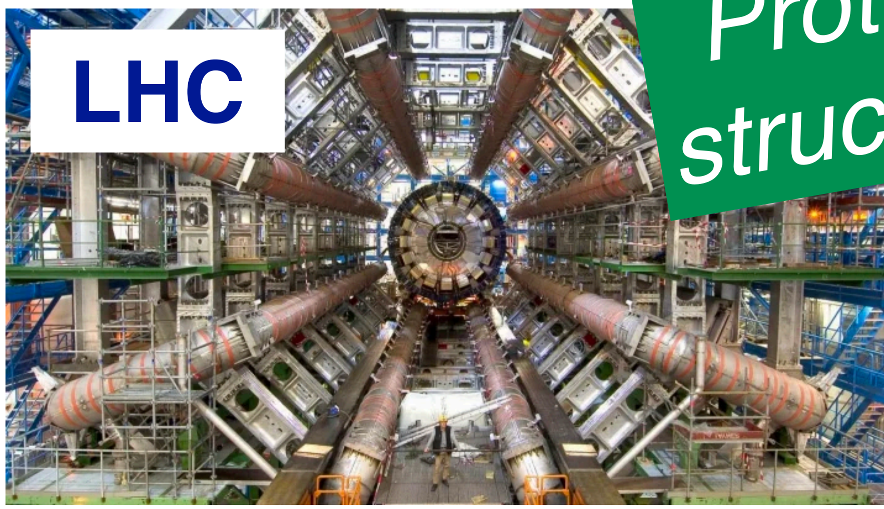

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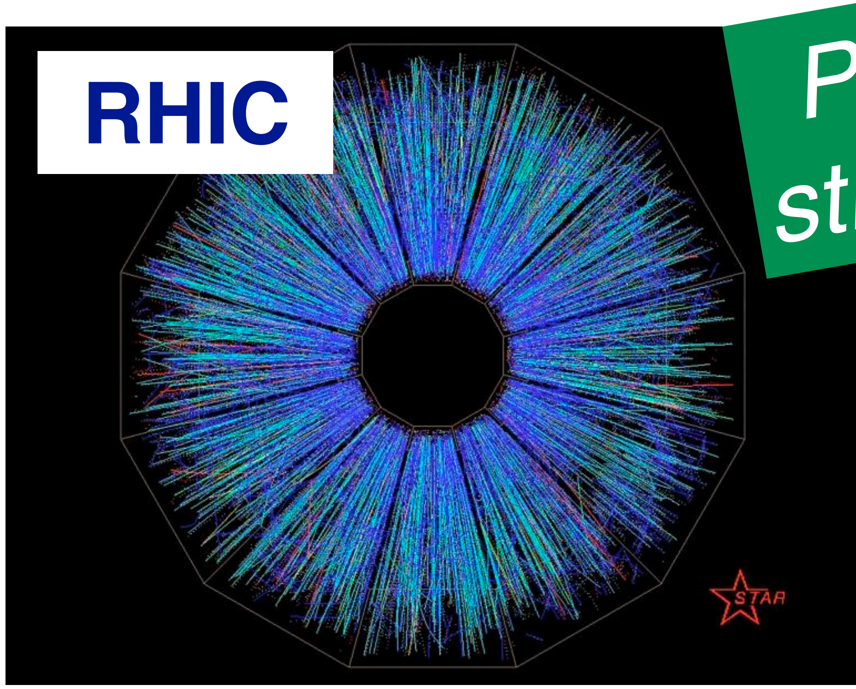
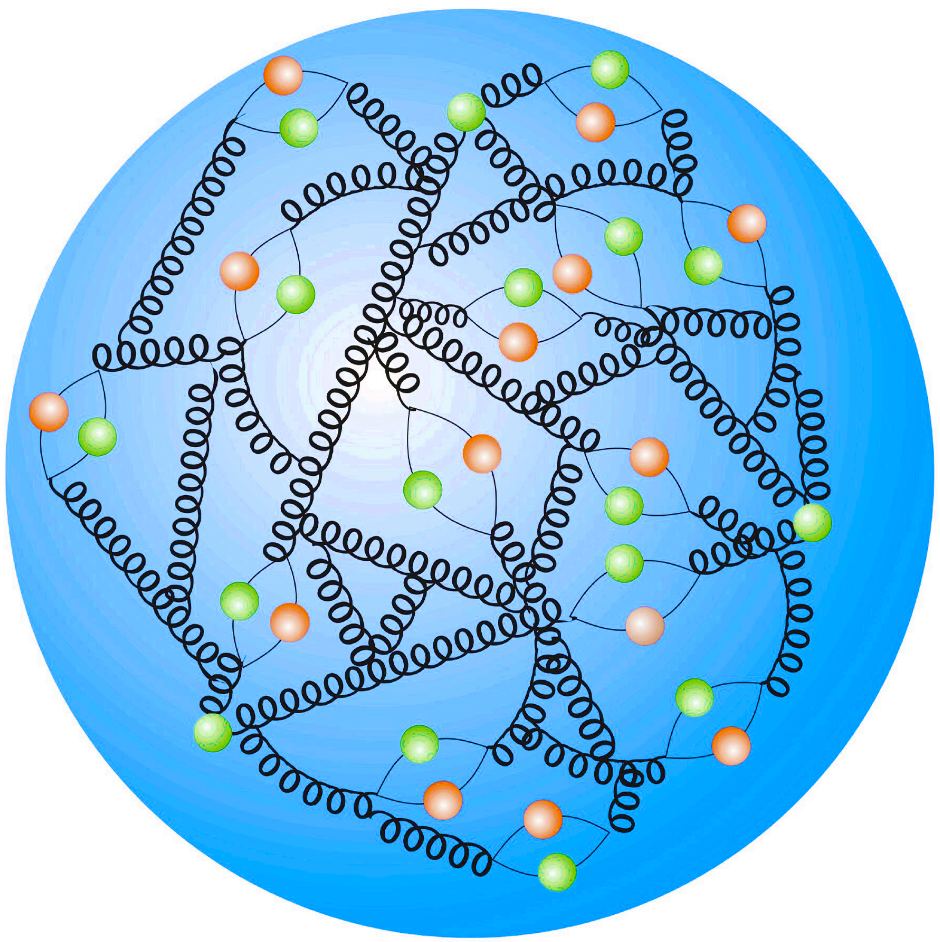


Nature of **Quark-Gluon Plasma** in **heavy-ion collisions?**

Parton Distributions

Proton energy divided among constituents: **quarks** and **gluons**



Parton Distribution Functions (PDFs)

Determine from **data:**

Global QCD analysis

Parton Distributions

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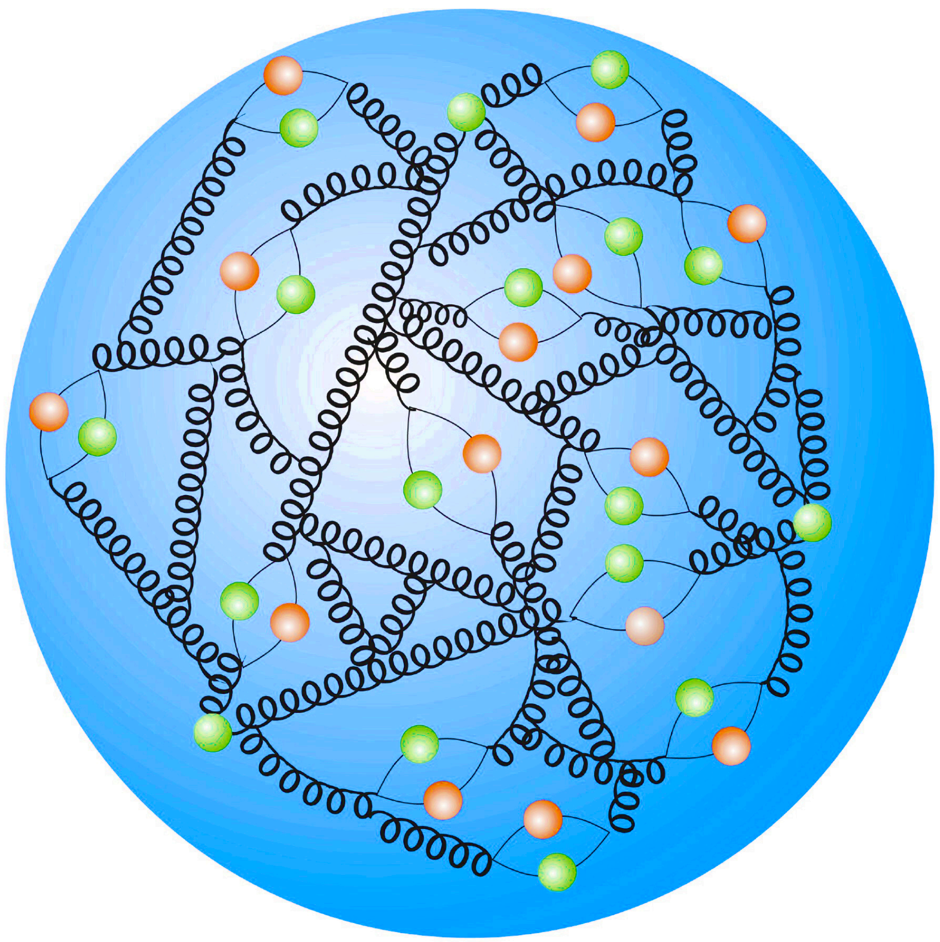

Parton Distribution Functions (PDFs)

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Global QCD analysis

Lattice QCD starting to also make an impact

Parton Distributions

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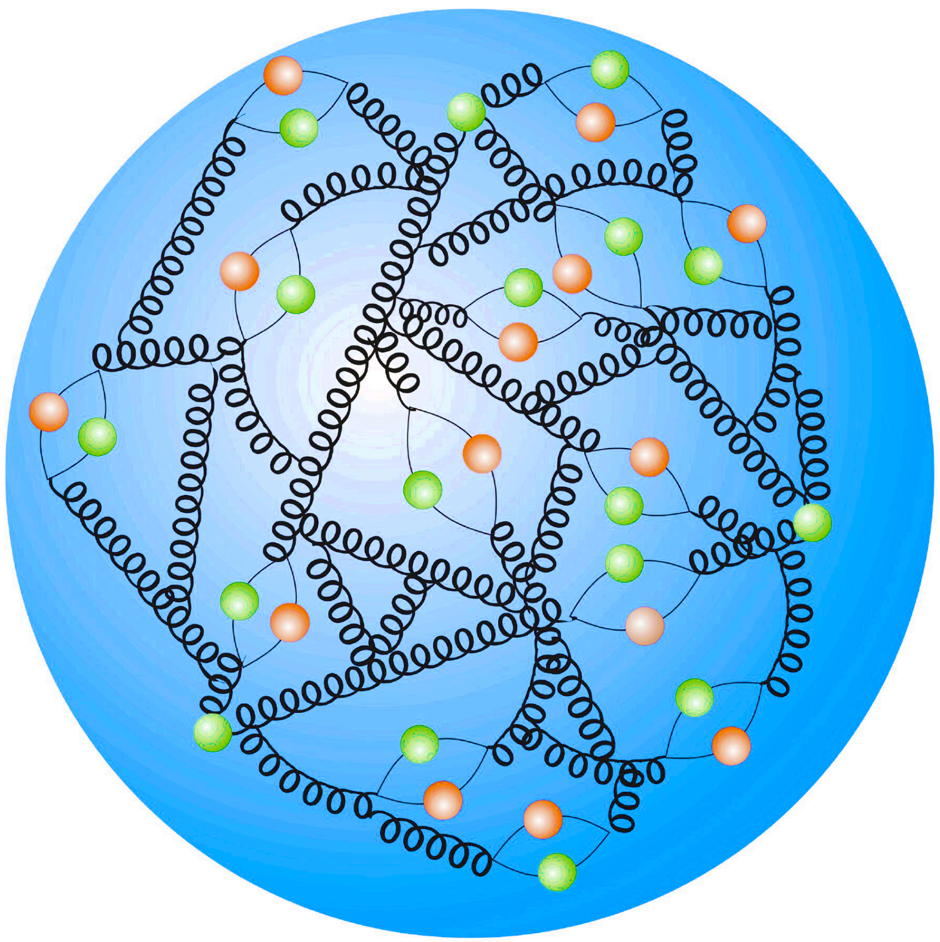

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Mass? Spin?

Heavy quark content?

Novel QCD dynamics?

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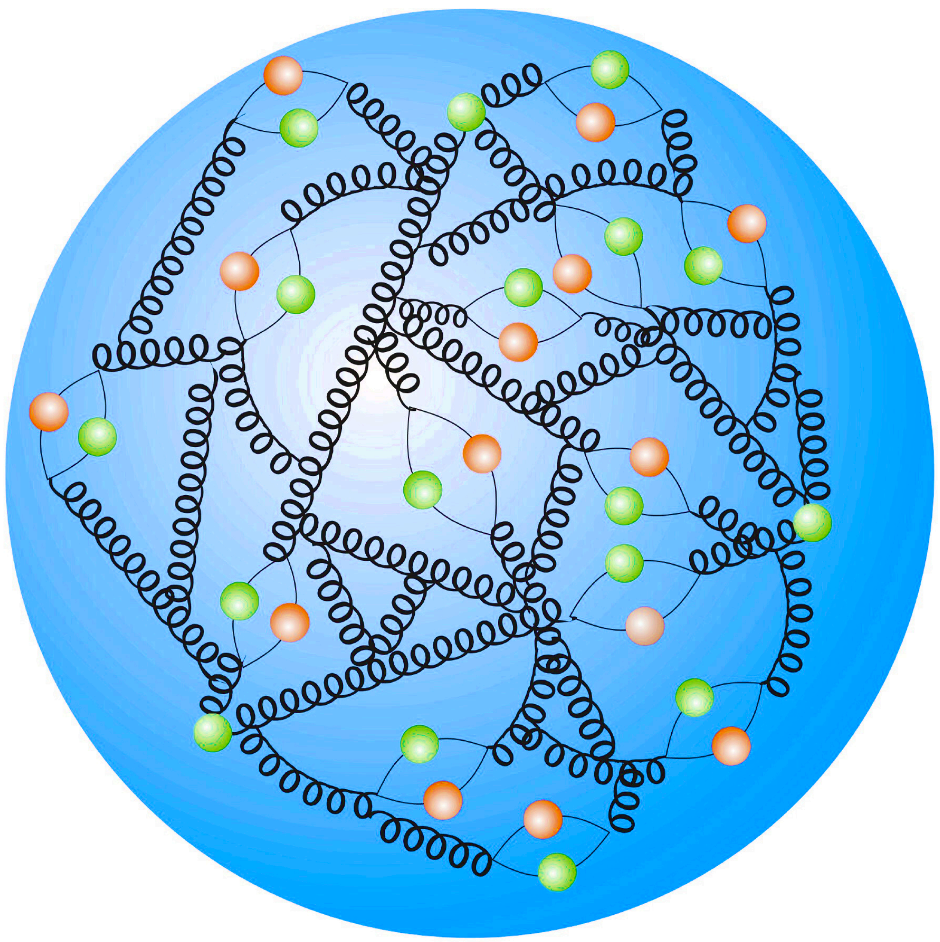

Parton Distribution Functions (PDFs)

Determine from **data:**

Global QCD analysis

Mass? Spin?
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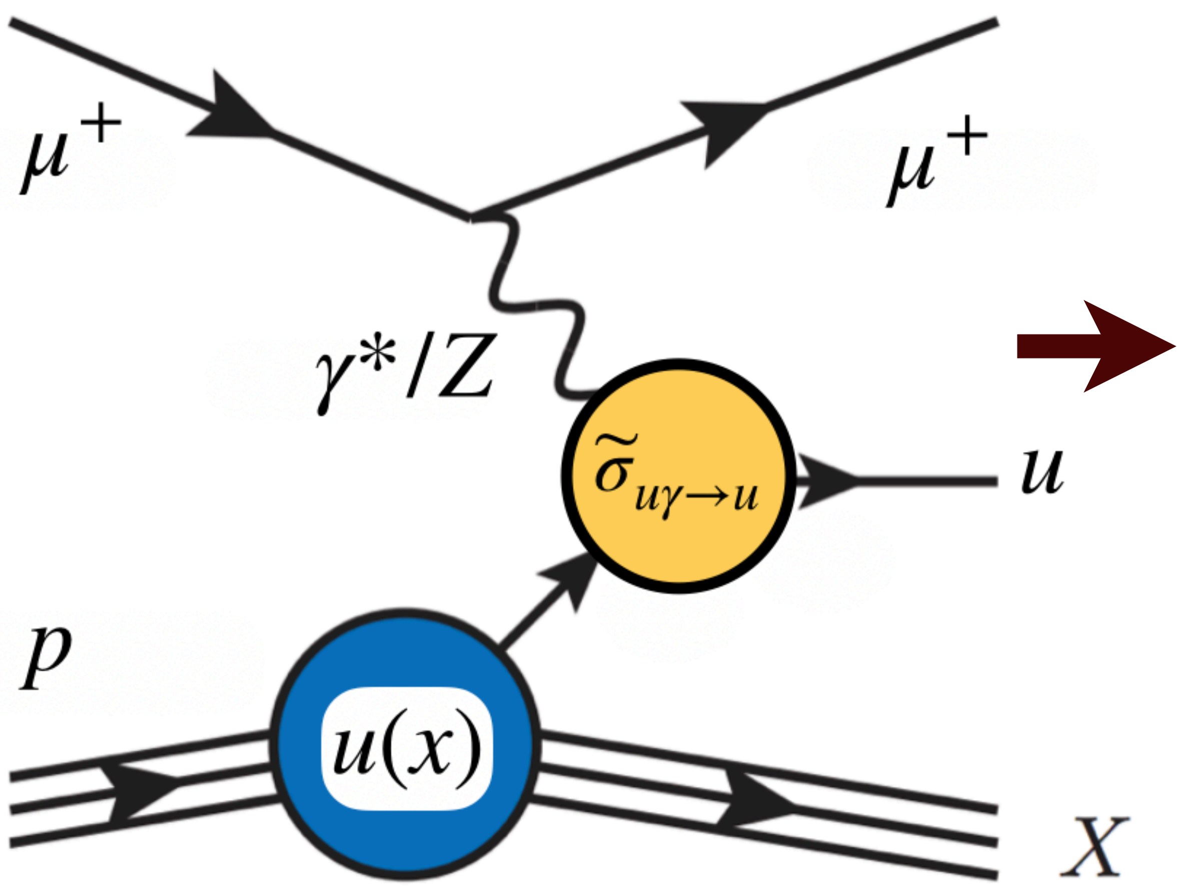
Novel QCD dynamics?

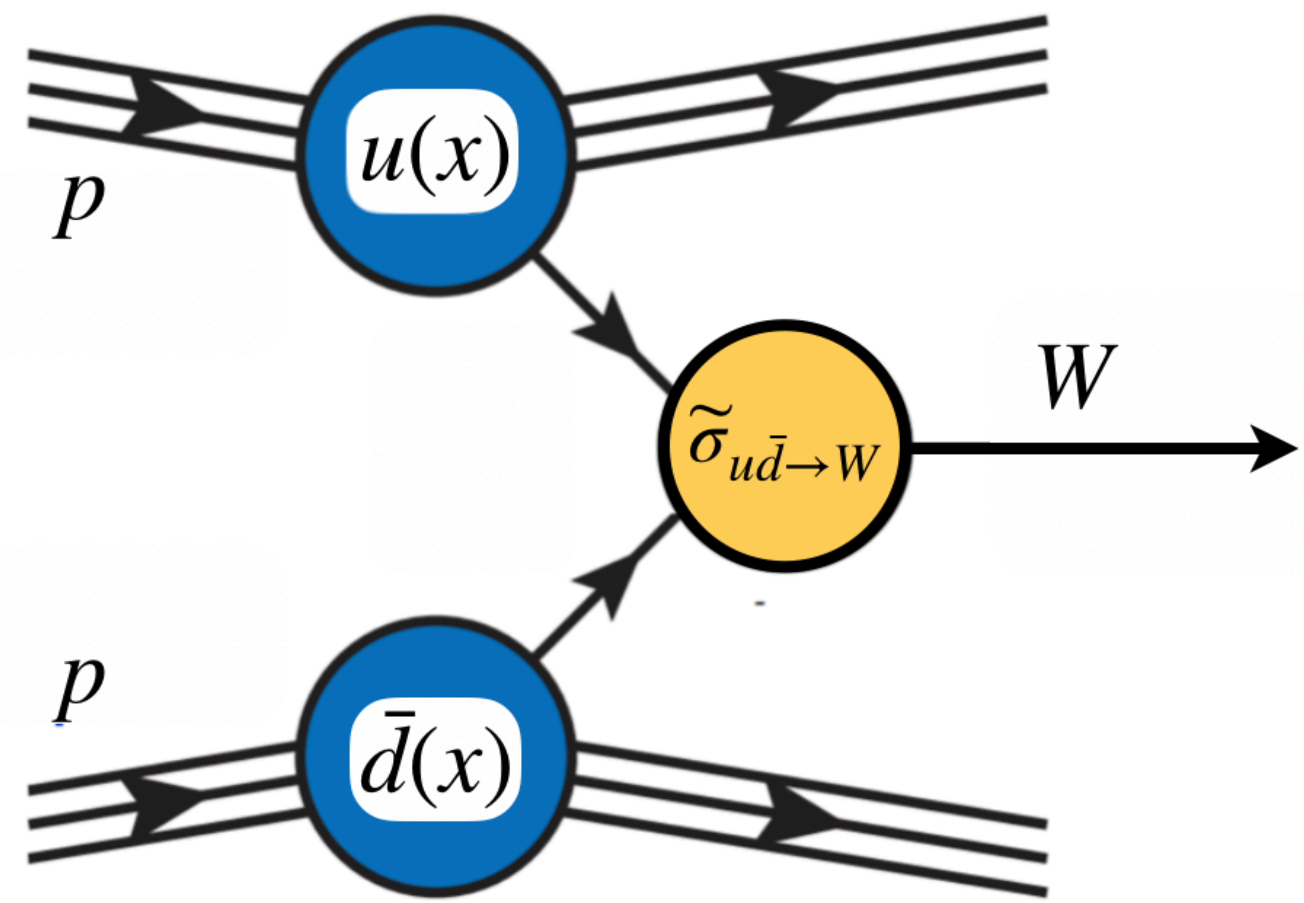
Theoretical predictions for LHC, RHIC, IceCube?

The Global QCD analysis paradigm

QCD factorisation theorems: **PDF universality**

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





*Determine PDFs from **deep-inelastic scattering**…*

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

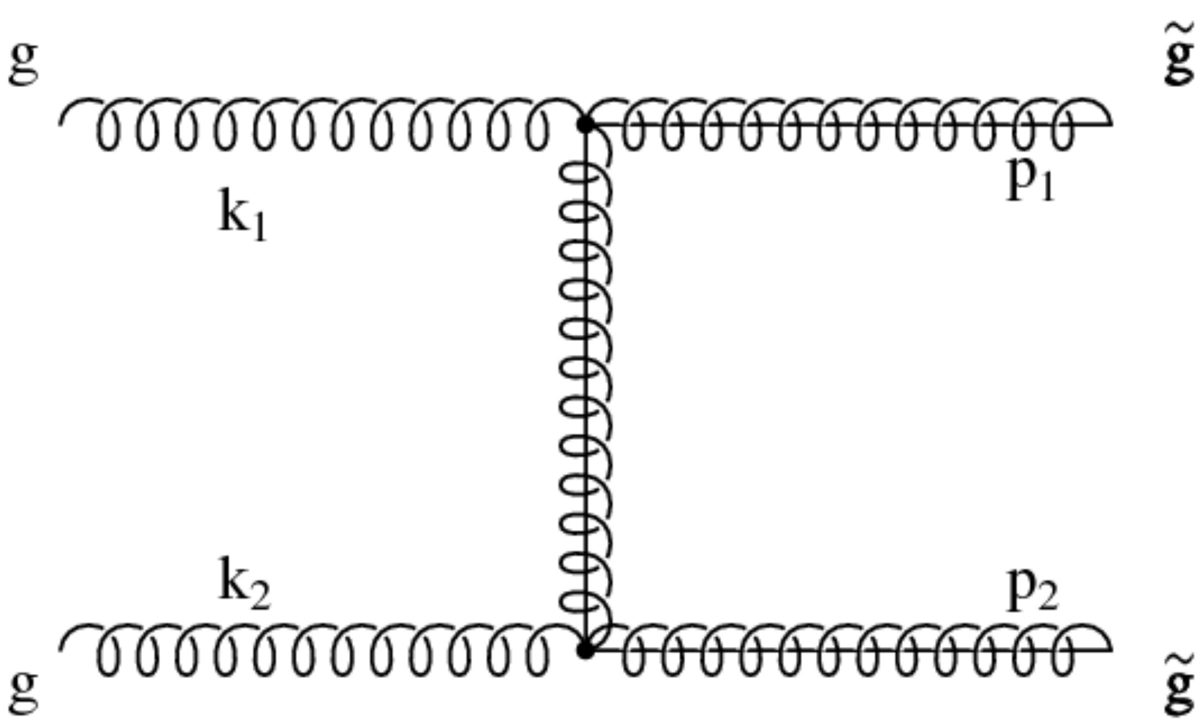
Why do we need better PDFs?

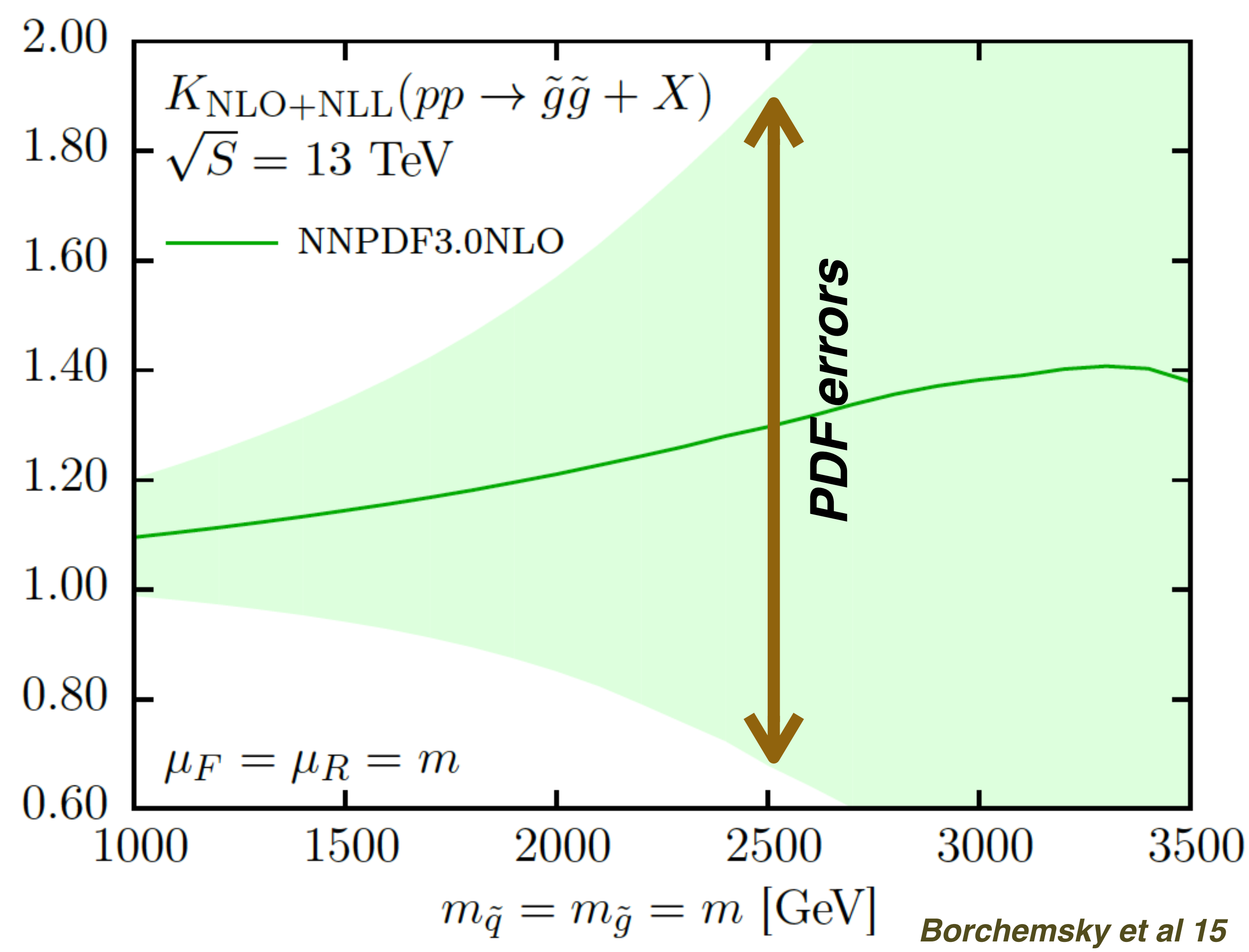
Why do we need better PDFs?

PDF uncertainties in the production of **New Physics heavy resonances** up to **100%**

Due to limited coverage of the **large Bjorken-*x* region**

gluino-pair production in supersymmetry





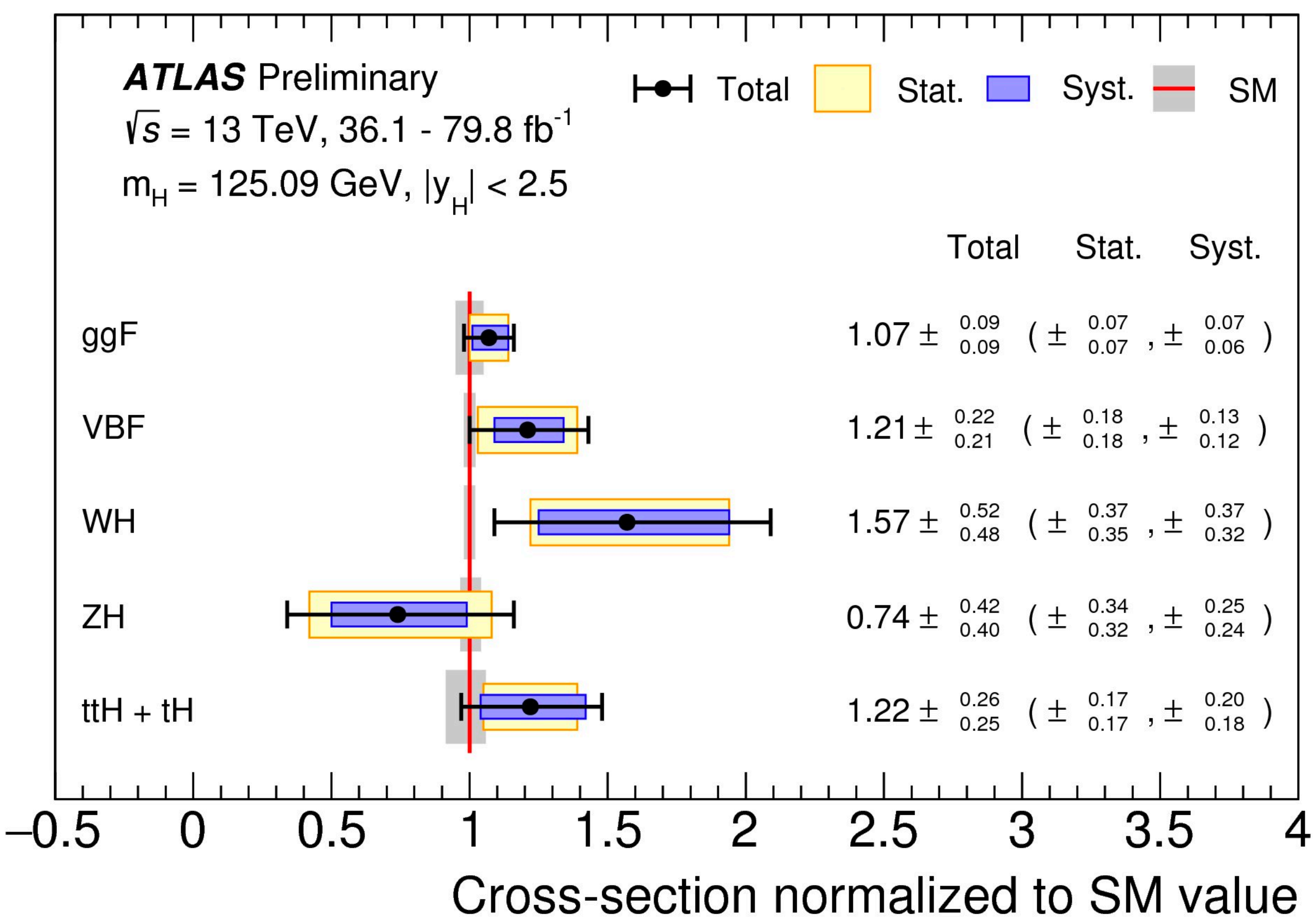
Borchemsky et al 15

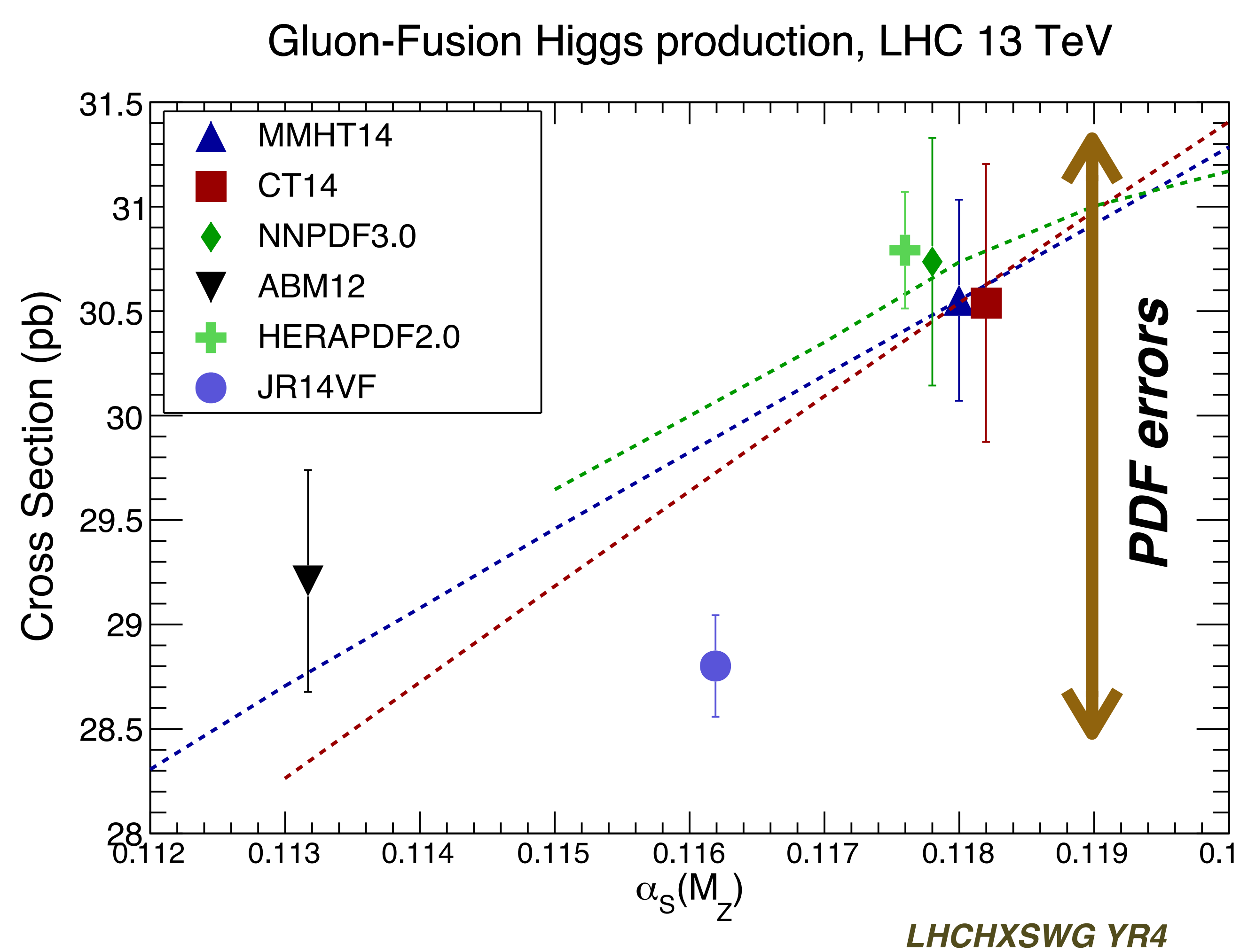
Why do we need better PDFs?

PDF uncertainties one of dominant theory errors in Higgs production cross-sections

any small **deviations of Higgs couplings** from SM predictions: **smoking gun for BSM**

Inclusive Higgs production rates

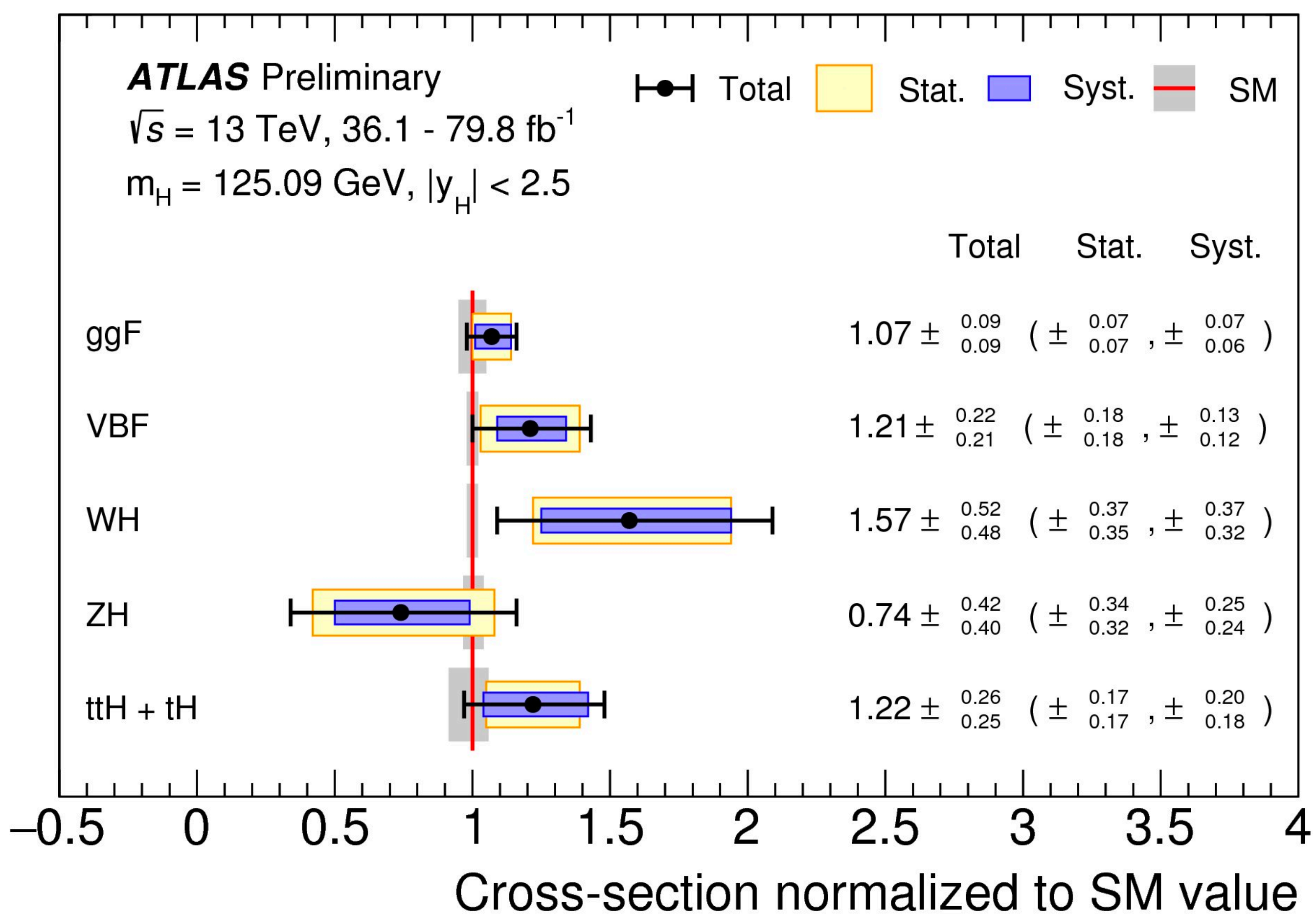


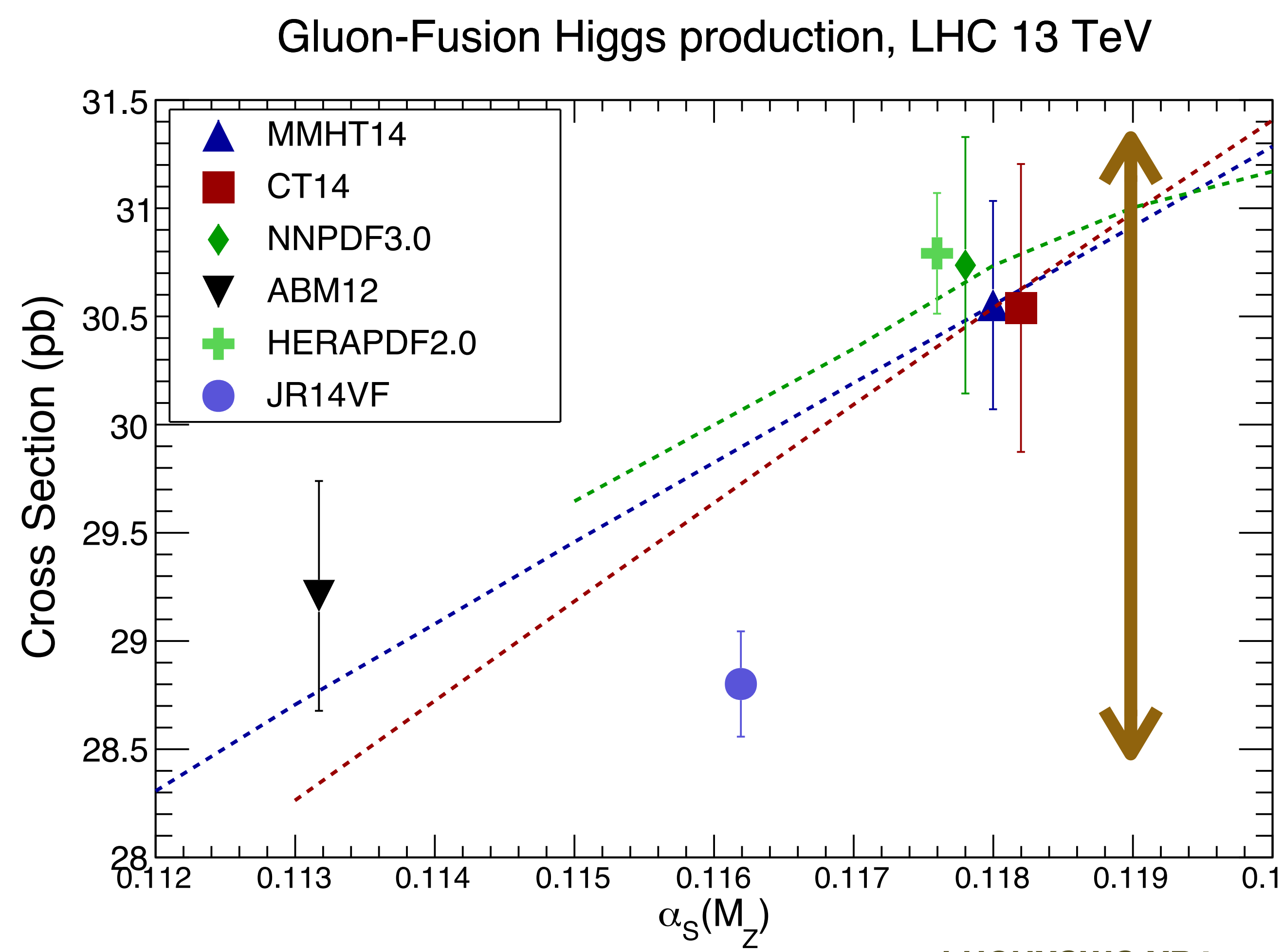


Why do we need better PDFs?

Snowmass 13

BSM model	Deviations in Higgs coupling to W, Z weak bosons	bottom quarks	photons
New heavy Higgs boson	6%	6%	6%
Two-Higgs Doublet model	1%	10%	1%
Composite Higgs	-3%	-9%	-9%
New heavy top-like quark	-2%	-2%	+2%





LHCHXSWG YR4

Why do we need better PDFs?

- Heavy bSM physics beyond the direct reach of the LHC can be **parametrised in a model-independent** in terms of a **complete** basis of higher-dimensional operators: this is the **Standard Model Effective Field Theory**

$$\mathcal{L}_{\rm SMEFT} = \mathcal{L}_{\rm SM} + \sum_i^{N_{d6}} \frac{c_i}{\Lambda^2}\mathcal{O}_i^{(6)} + \sum_j^{N_{d8}} \frac{b_j}{\Lambda^4}\mathcal{O}_j^{(8)} + \ldots \,,$$

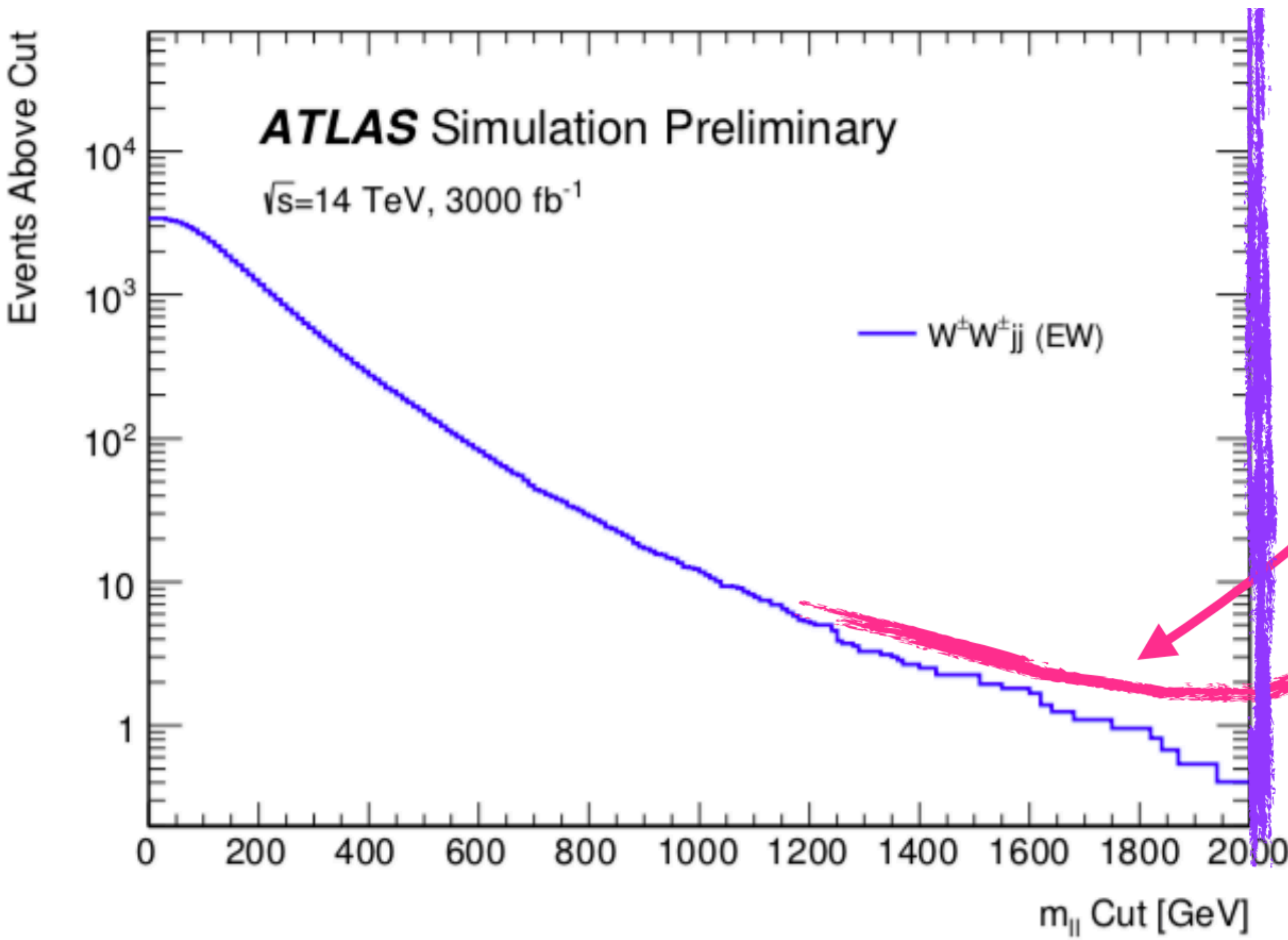
- Some operators induce **growth with the partonic centre-of-mass energy**: increased sensitivity in LHC cross-sections in the TeV region

$$\sigma(E) = \sigma_{\rm SM}(E)\left(1 + \sum_i^{N_{d6}} \omega_i \frac{c_i\, m_{\rm SM}^2}{\Lambda^2} + \sum_i^{N_{d6}} \widetilde{\omega}_i \frac{c_i\, E^2}{\Lambda^2} + \mathcal{O}\left(\Lambda^{-4}\right)\right)$$

*enhanced sensitivity from **TeV-scale processes:***
unique feature of LHC

Why do we need better PDFs?

Deviation from SM prediction in high energy tails?



CA Lee, HL/HE-LHC Jamboree, 1 March 2019

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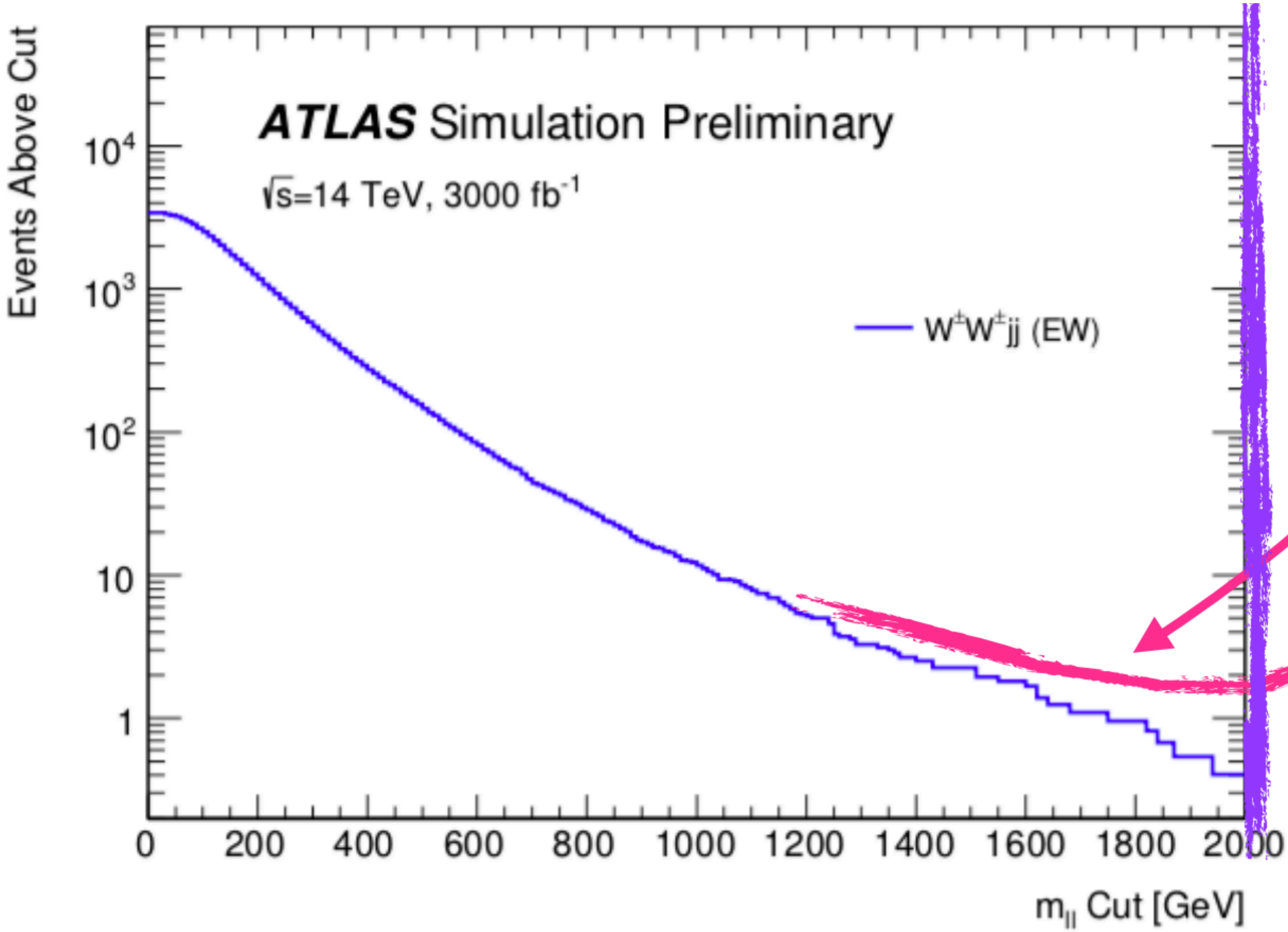

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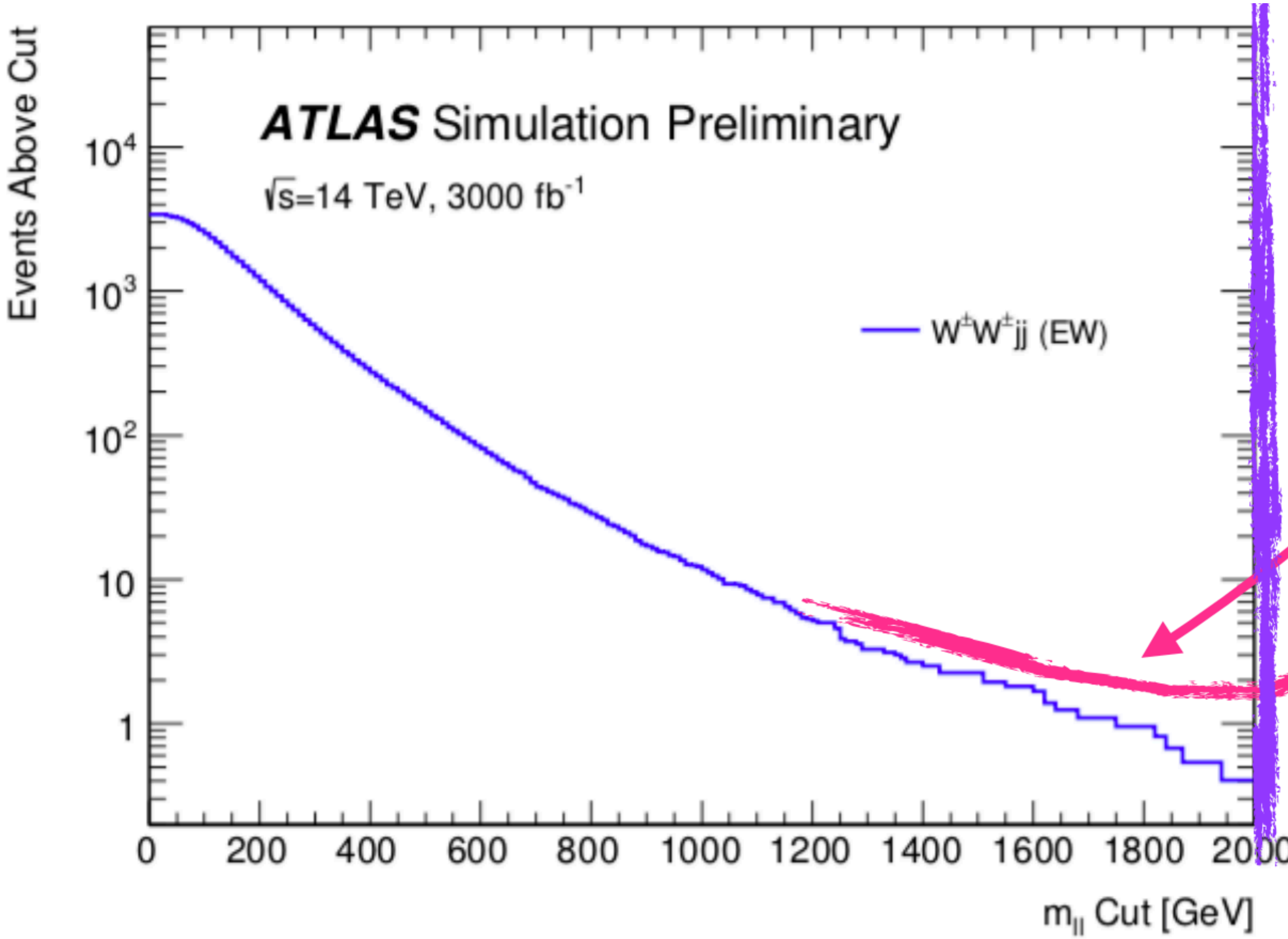
SMEFT interpretation: from a massive particle at high energies …

Why do we need better PDFs?

Deviation from SM prediction in high energy tails?



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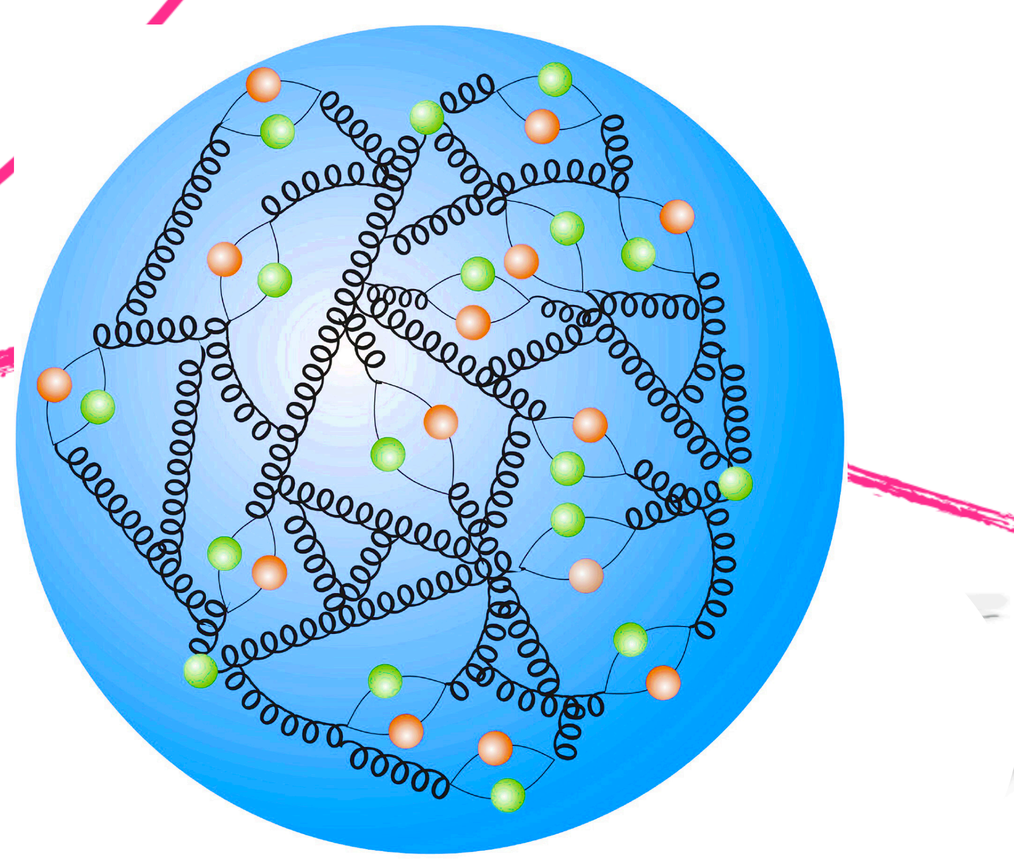


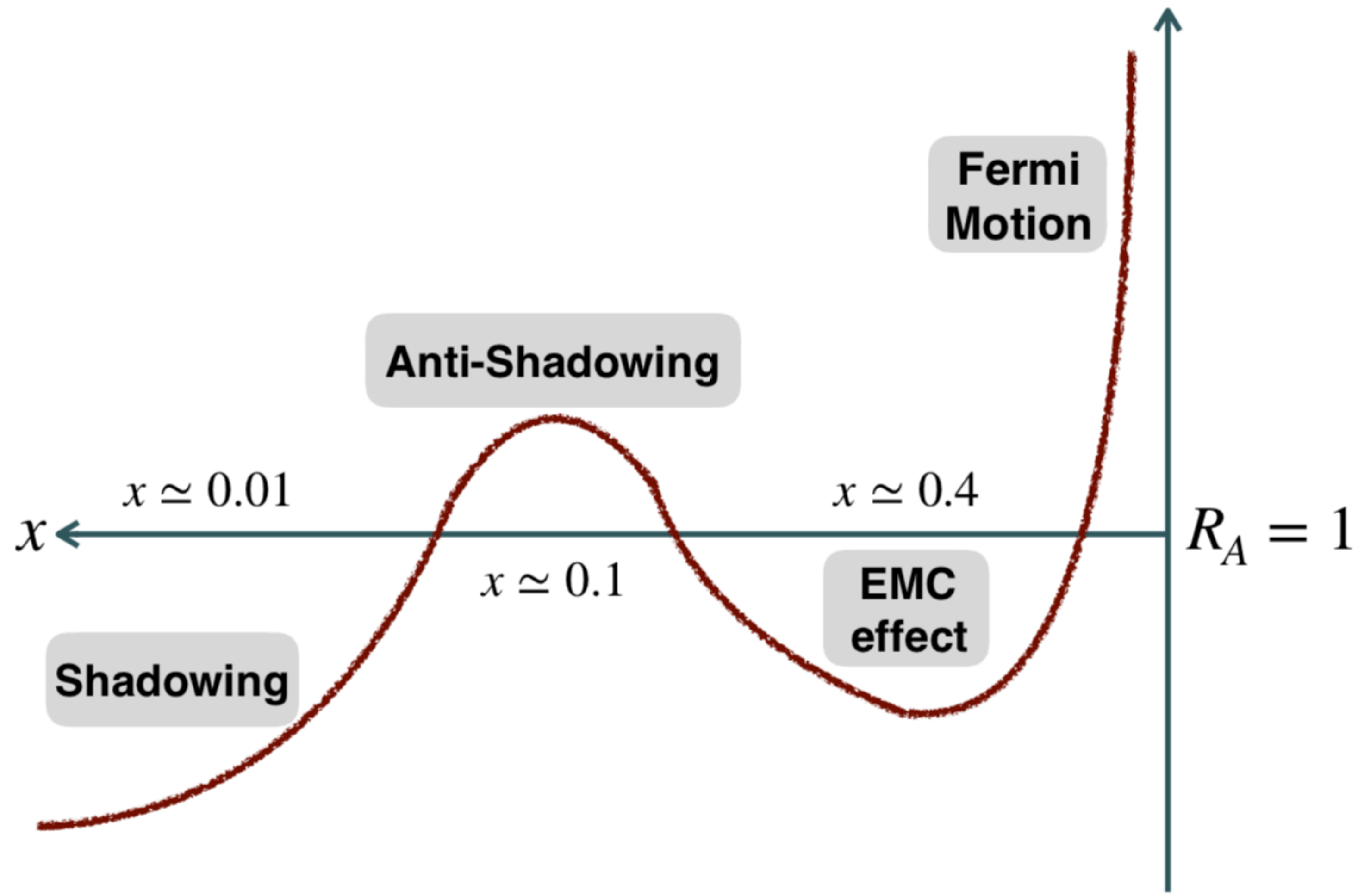
Iranipour WG3

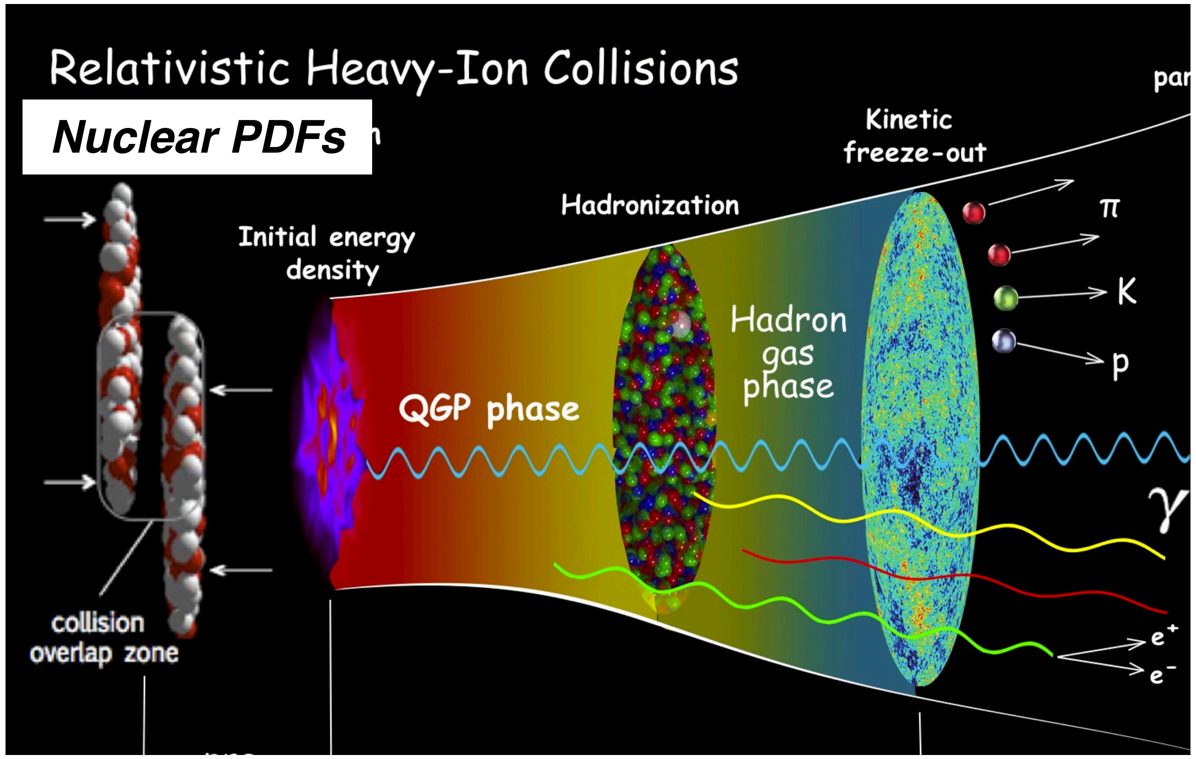
…or reflecting our limited understating of proton structure?

Hot and Cold Nuclear Matter

- Cold nuclear matter effects modify the **PDFs of bound nucleons** as compared to the **free-proton case**
- Rich **QCD phenomenology**: EMC effect, shadowing, non-linear evolution, ….
- Onset of **new gluon-dominated state of matter**: the Color Glass Condensate

$$R_A = \frac{\text{Bound Nucleon PDF in Nucleus } A}{\text{Free nucleon PDF}}$$

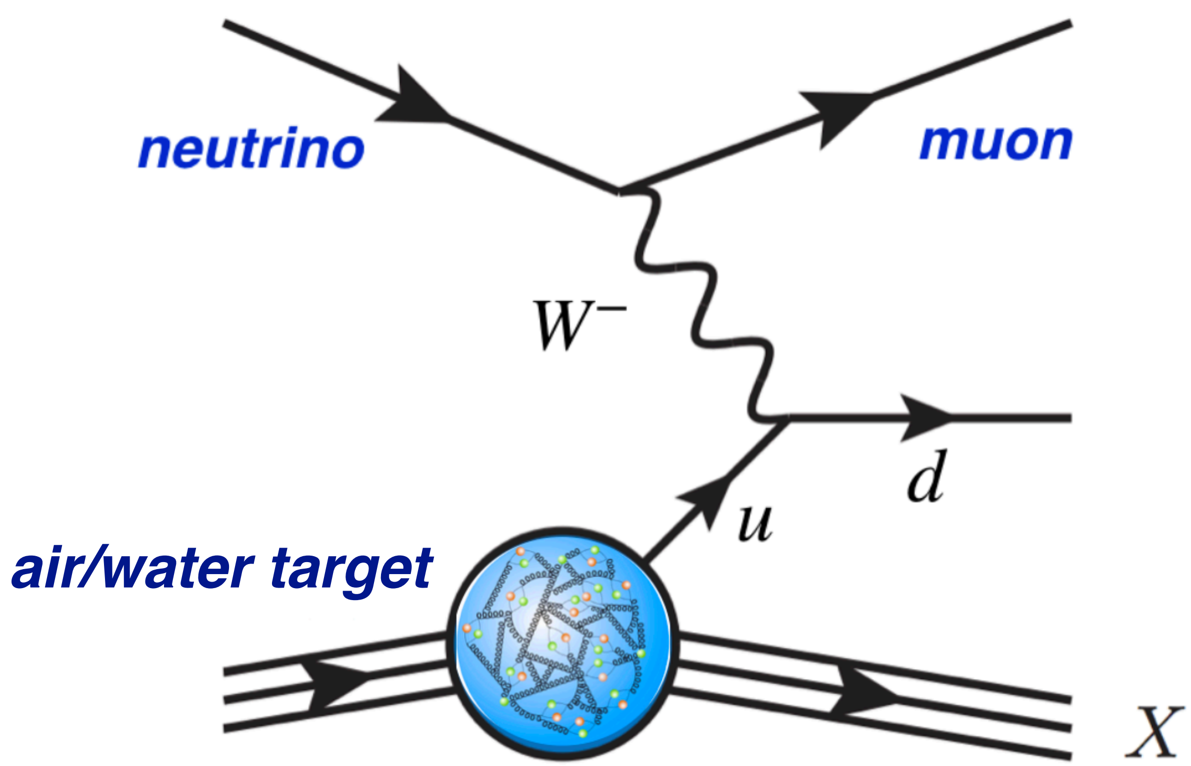


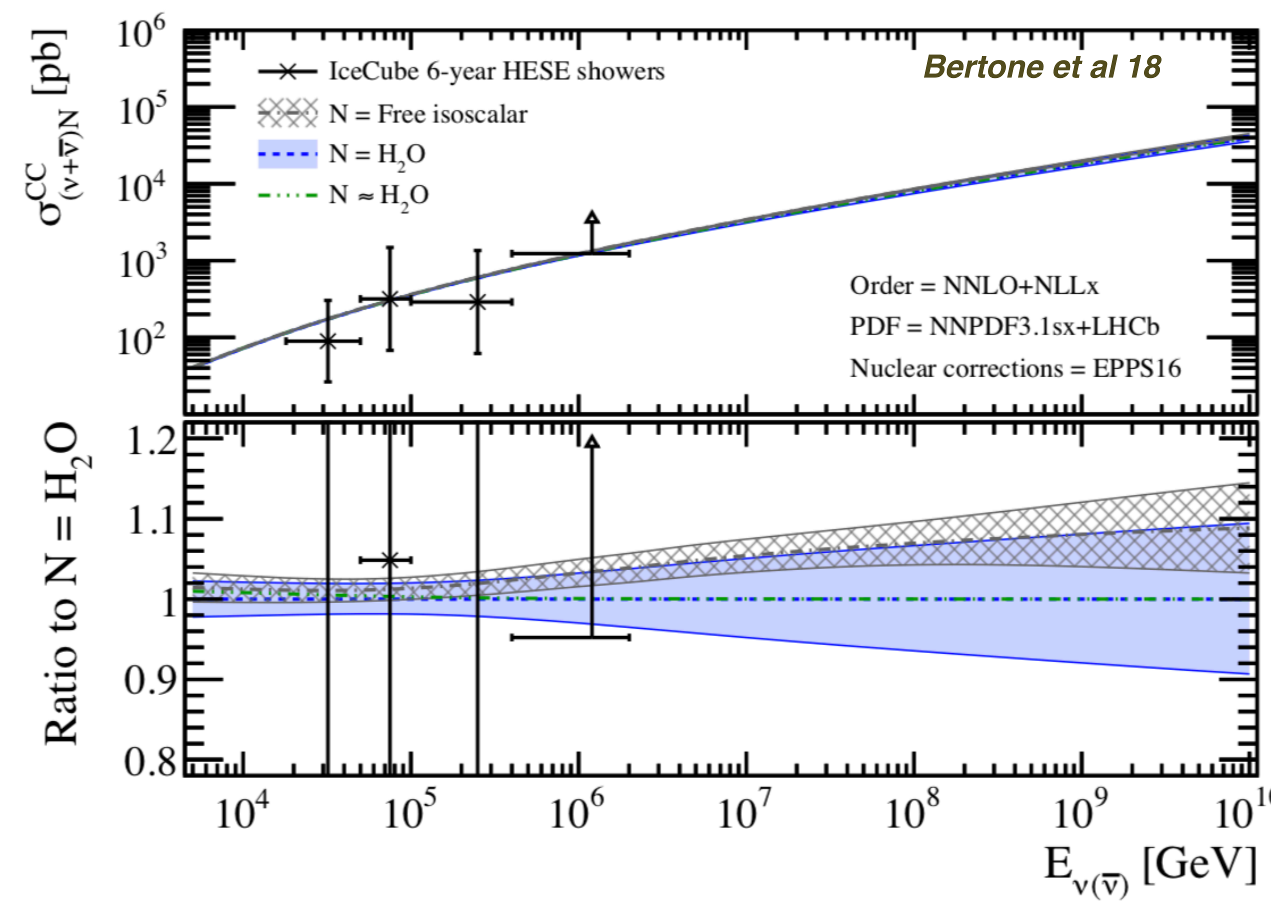


- **Initial state of heavy-ion collisions**: Quark-Gluon Plasma characterisation
- nPDFs also required for **ultra-high-energy astrophysics** e.g. neutrino telescopes

Neutrino telescopes as QCD microscopes

Ultra-high energy (cosmic) neutrino *- nucleus scattering:*
unique probe of ***small-x PDFs and QCD***





JR WG1+WG7

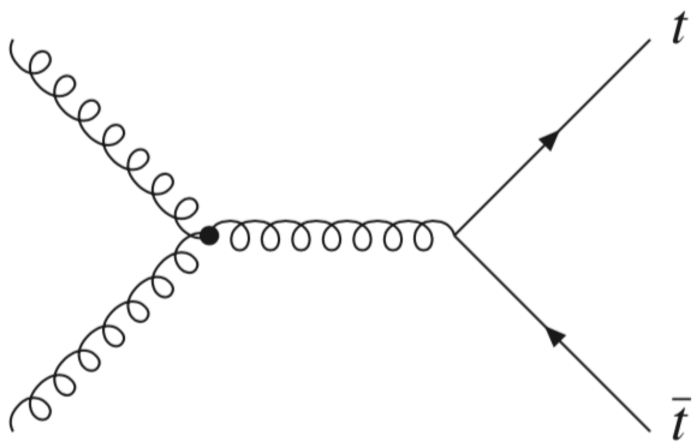
Sensitive to **small-*x* quarks** (and gluons via evolution)
down to **x** ≃ **10^{-8}** at **Q** ≃ **M_W**

Recent progress in the proton structure

PDF information from p+p collisions

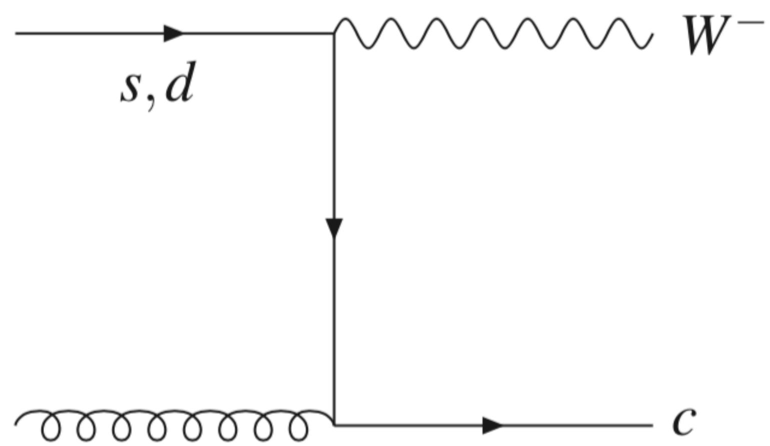
large-x gluon

Top quark pair production



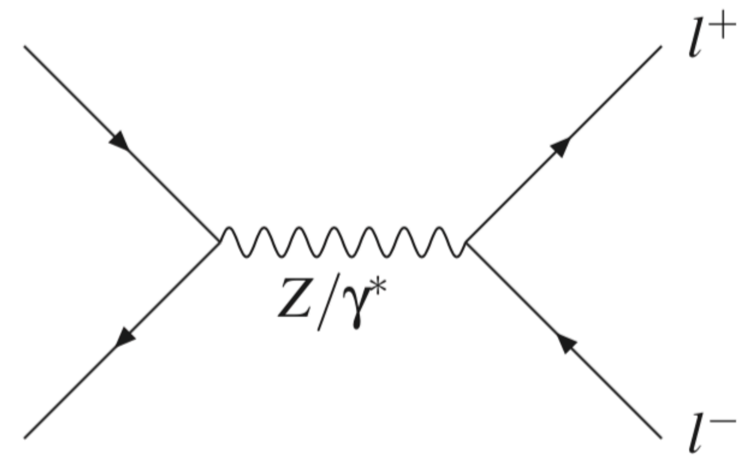
strangeness

$W+c$ production

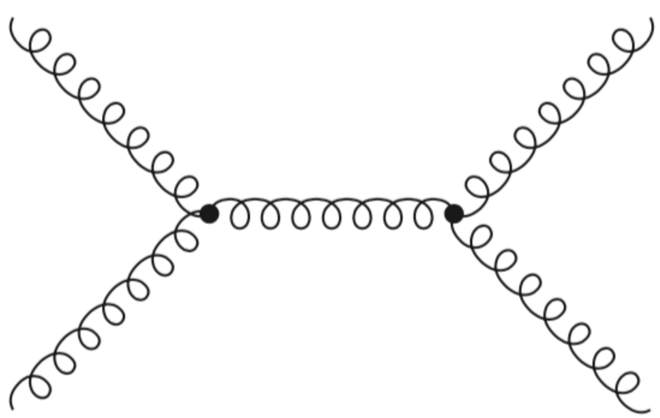


antiquarks

Drell–Yan production

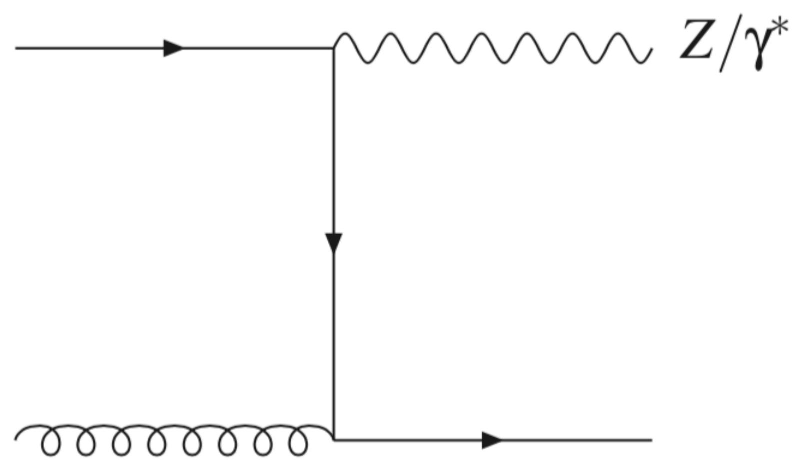


Jet production



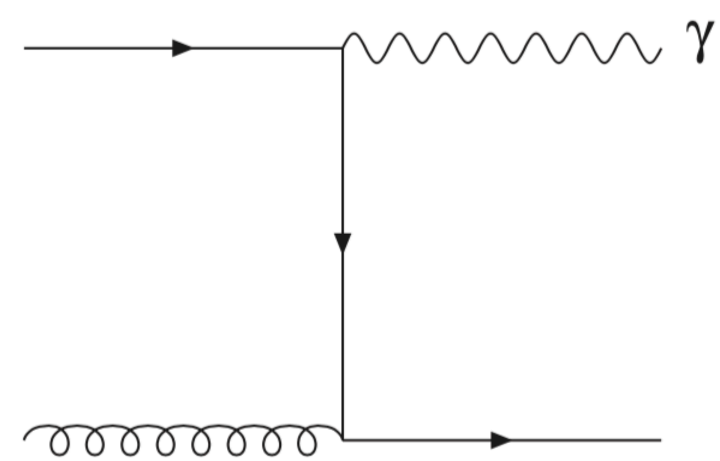
large-x gluon

$Z\ p_T$



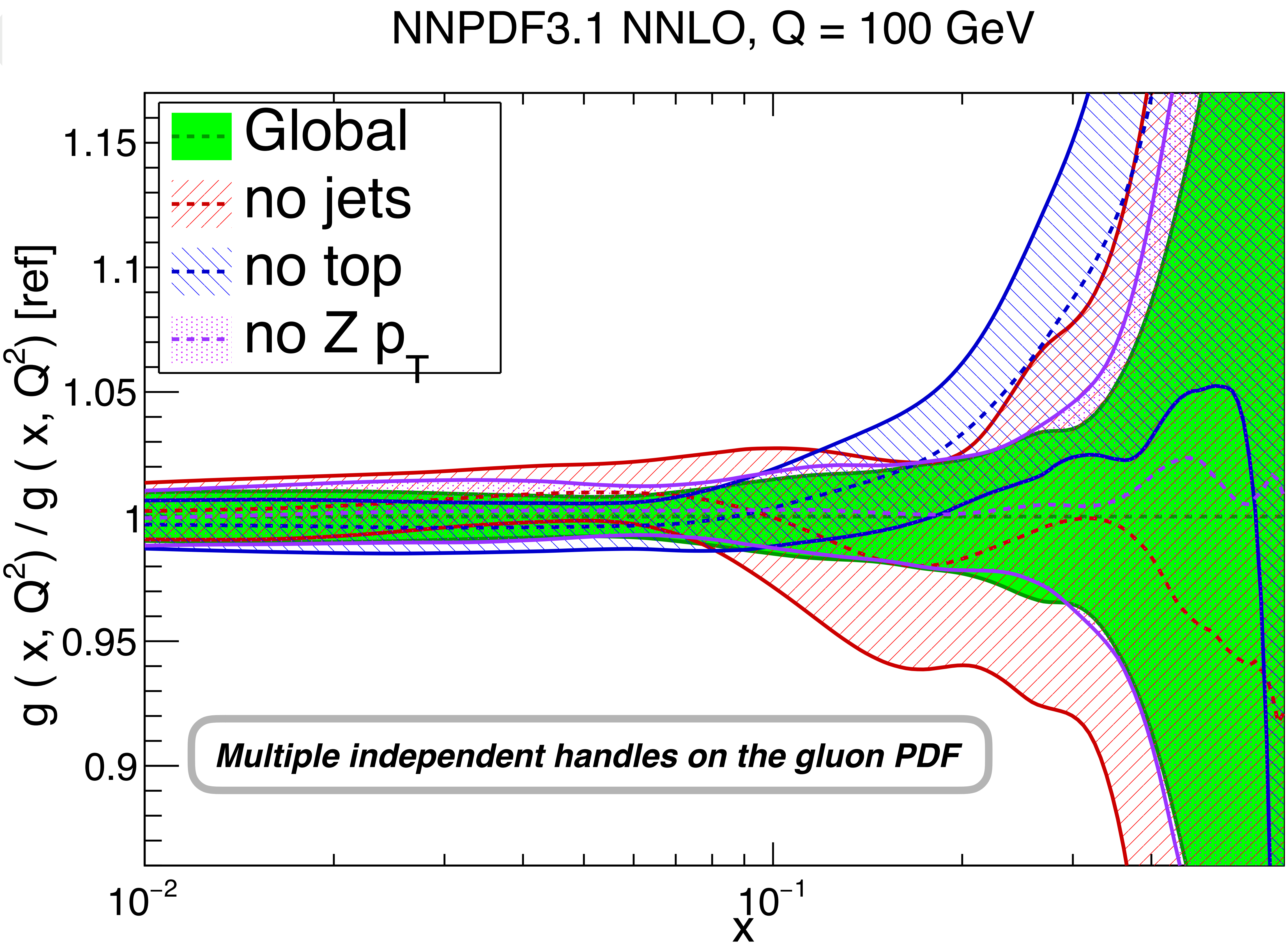
medium-x gluon

Direct photon production



medium-x gluon

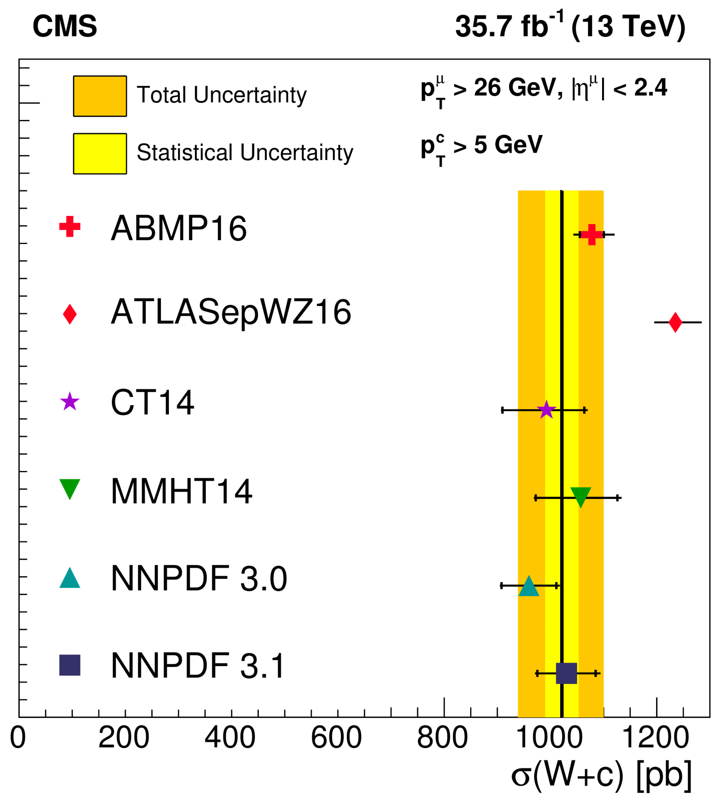
One glue to bind them all

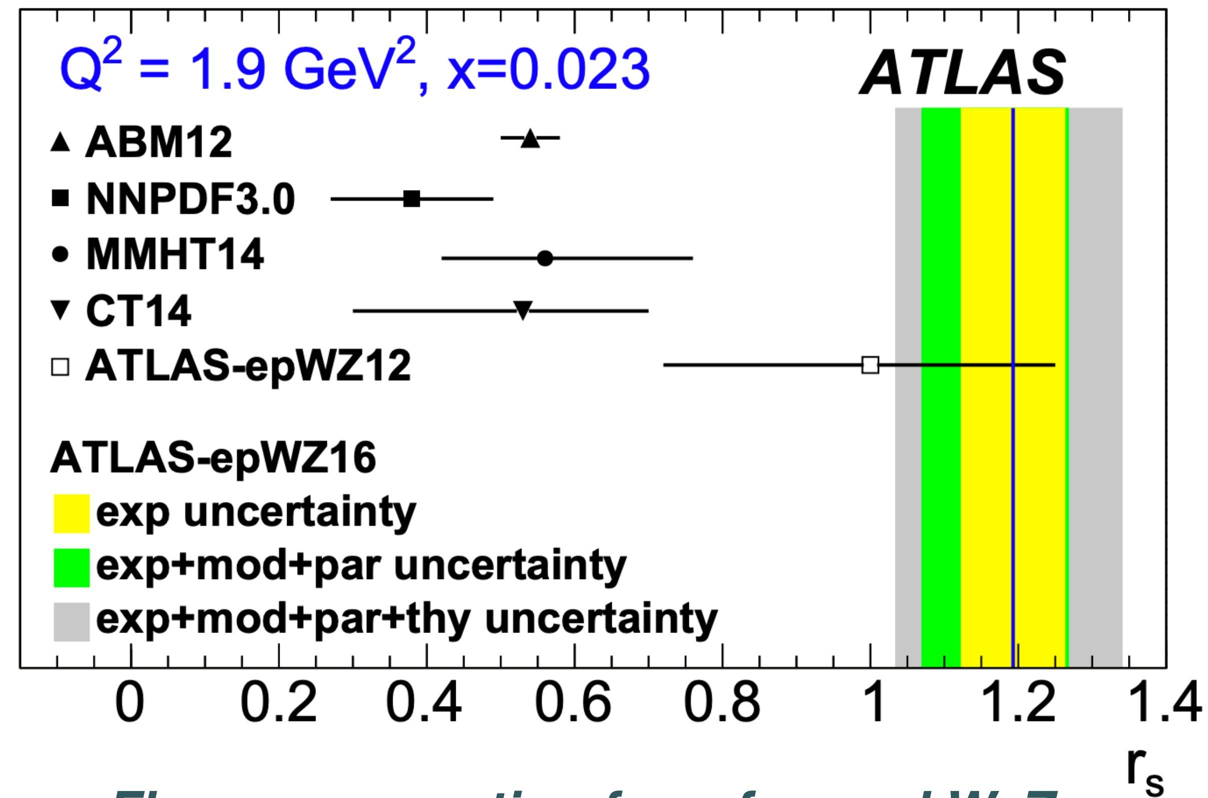


Constraints from LHC data

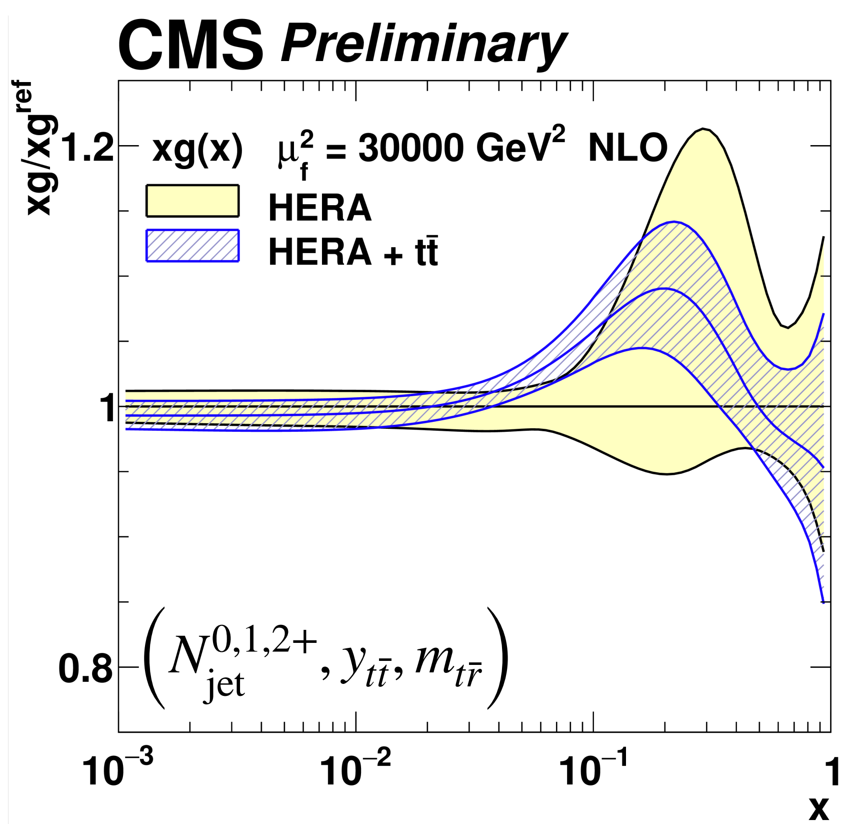
Combined interpretation within global fit?

The strangeness conundrum: inclusive W,Z vs W+c

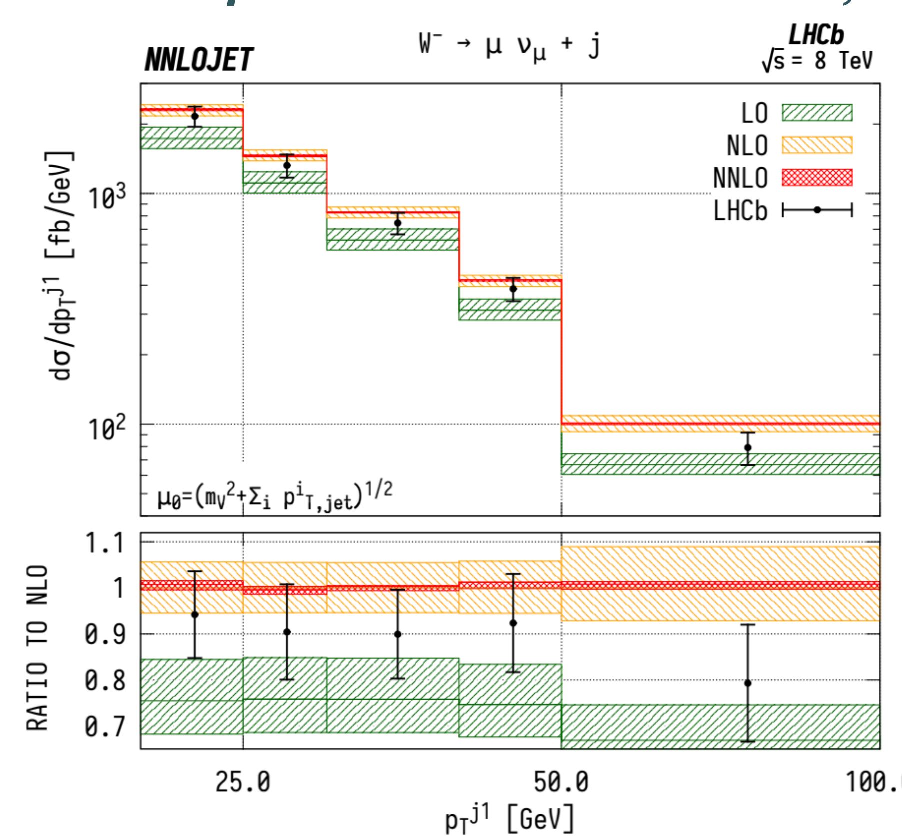




Multi-differential top quark pairs



Flavour separation from forward W, Z



Gehrmann-De Ridder et al 19

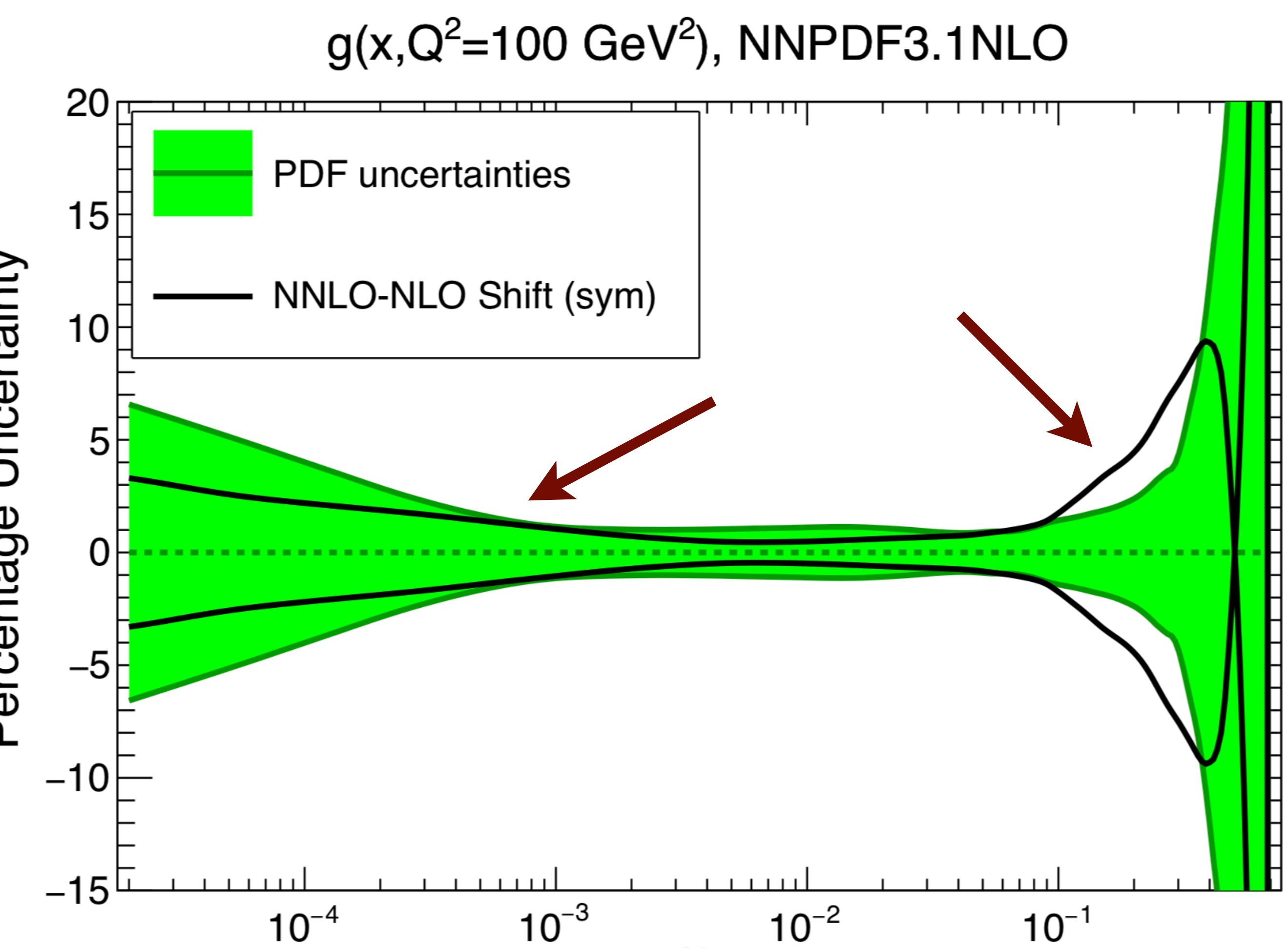
QCD uncertainties in PDF fits

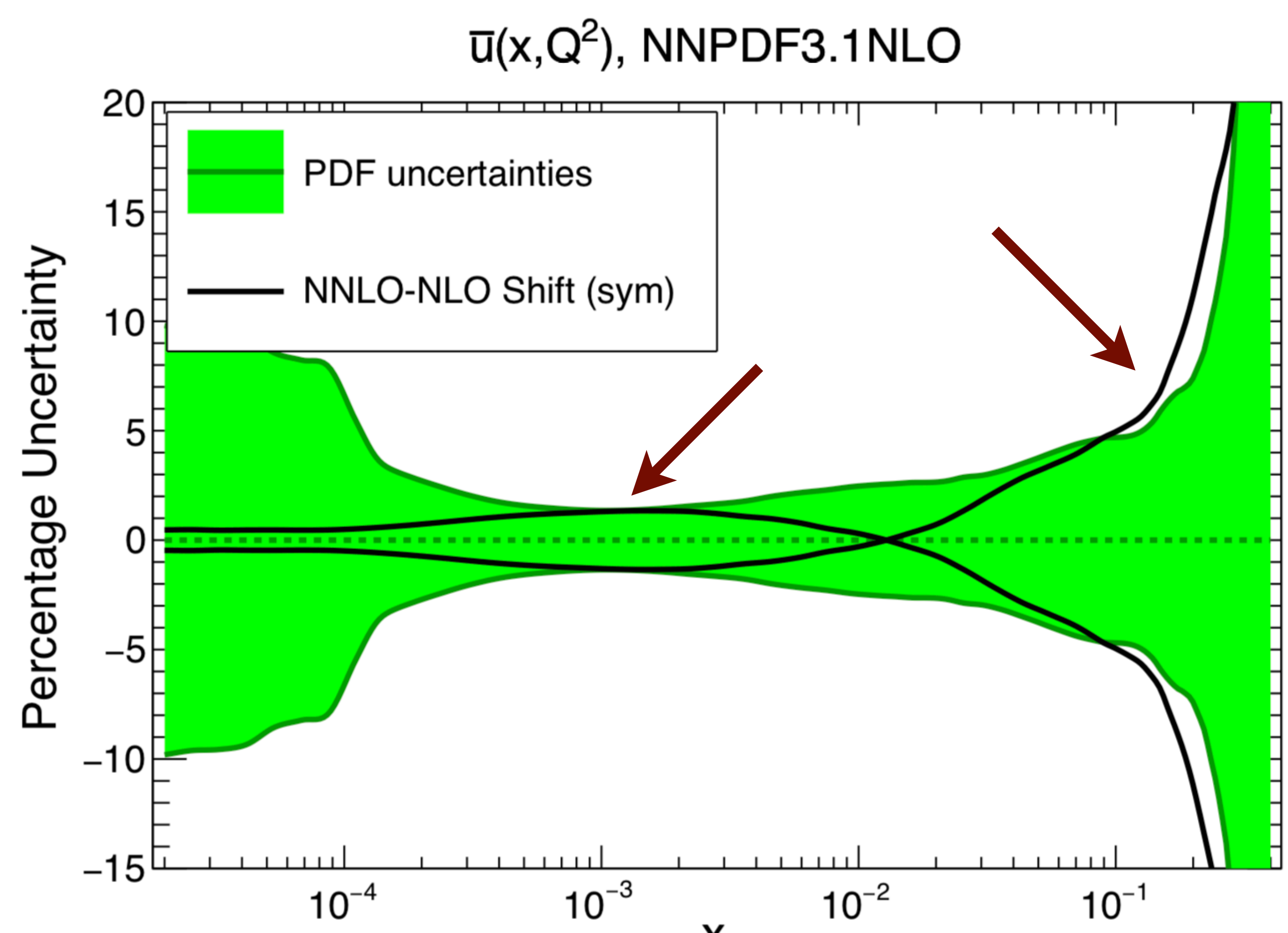
Standard global PDF fits are based on **fixed-order QCD calculations**

$$\sigma = \alpha_s^{p}\sigma_0 + \alpha_s^{p+1}\sigma_1 + \alpha_s^{p+2}\sigma_2 + \mathcal{O}(\alpha_s^{p+3})$$

The truncation of the perturbative series has associated a theoretical uncertainty: **Missing Higher Order (MHO)** uncertainty

How severe is **ignoring MHOUs** in modern global PDFs fits?

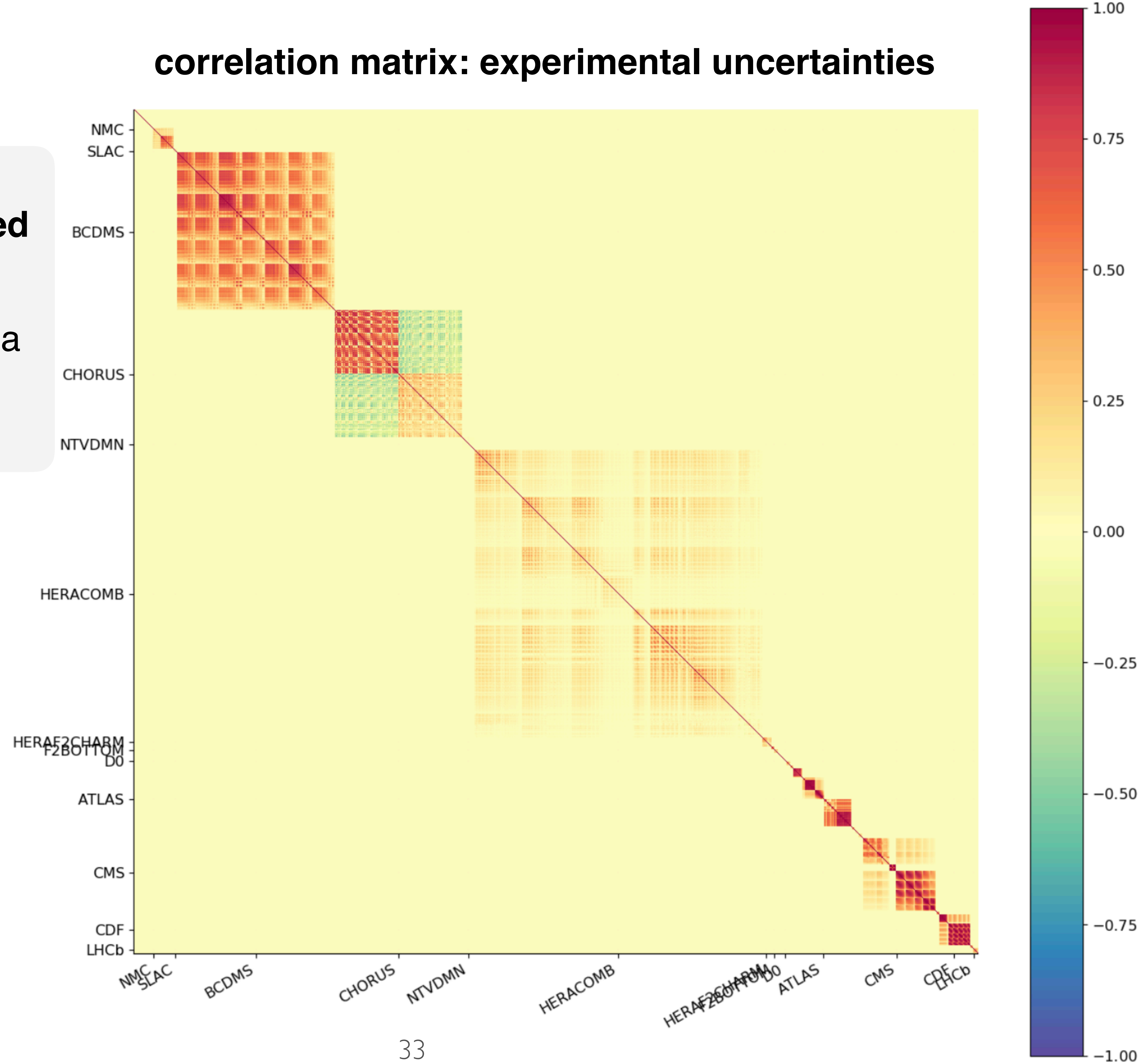




QCD uncertainties in PDF fits

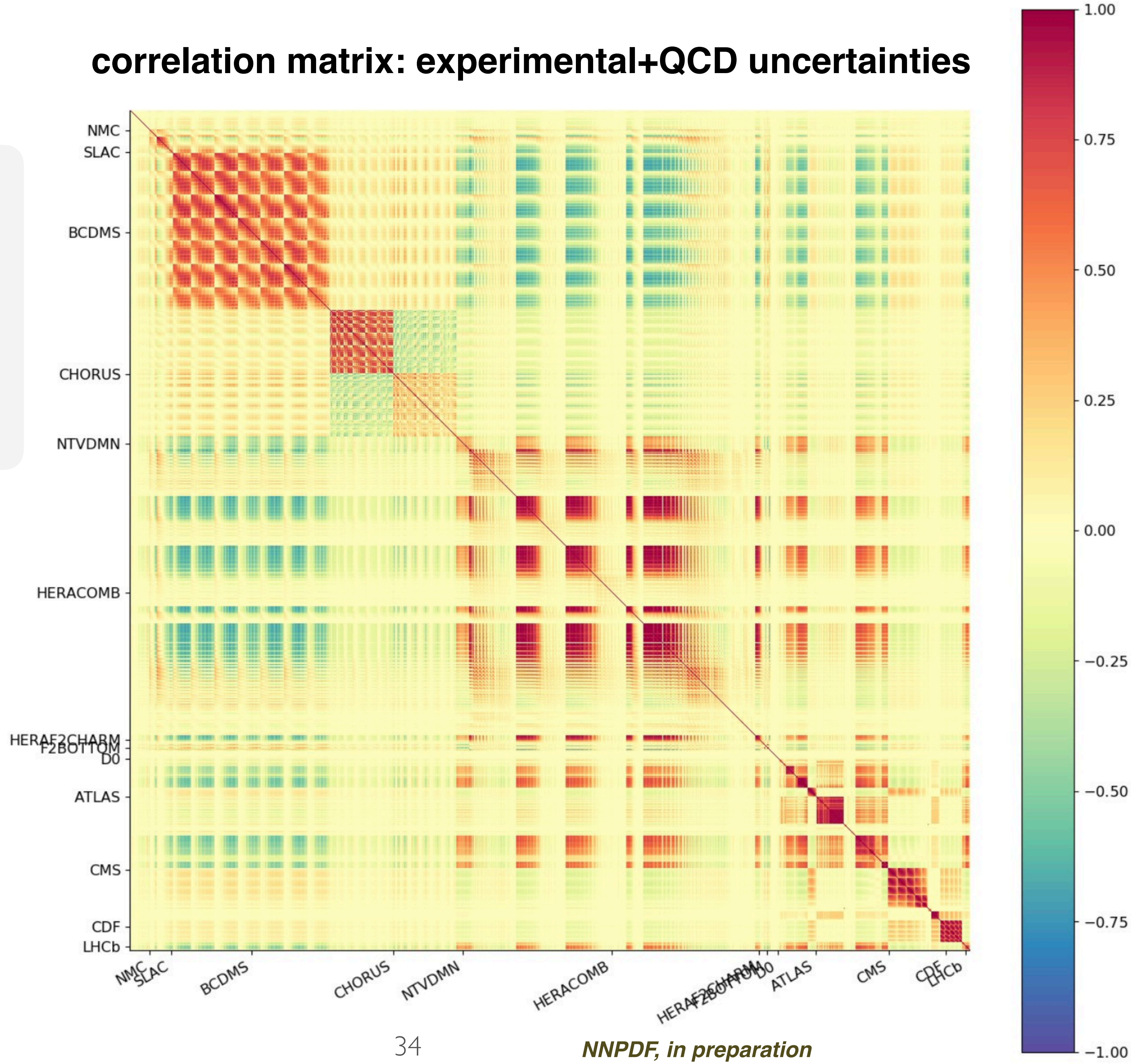
Experiment-induced correlations:

only present within a single dataset



QCD uncertainties in PDF fits

Theory-induced correlations between different experiments *e.g.* DIS and LHC



Harland-Lang, Voisey WG1

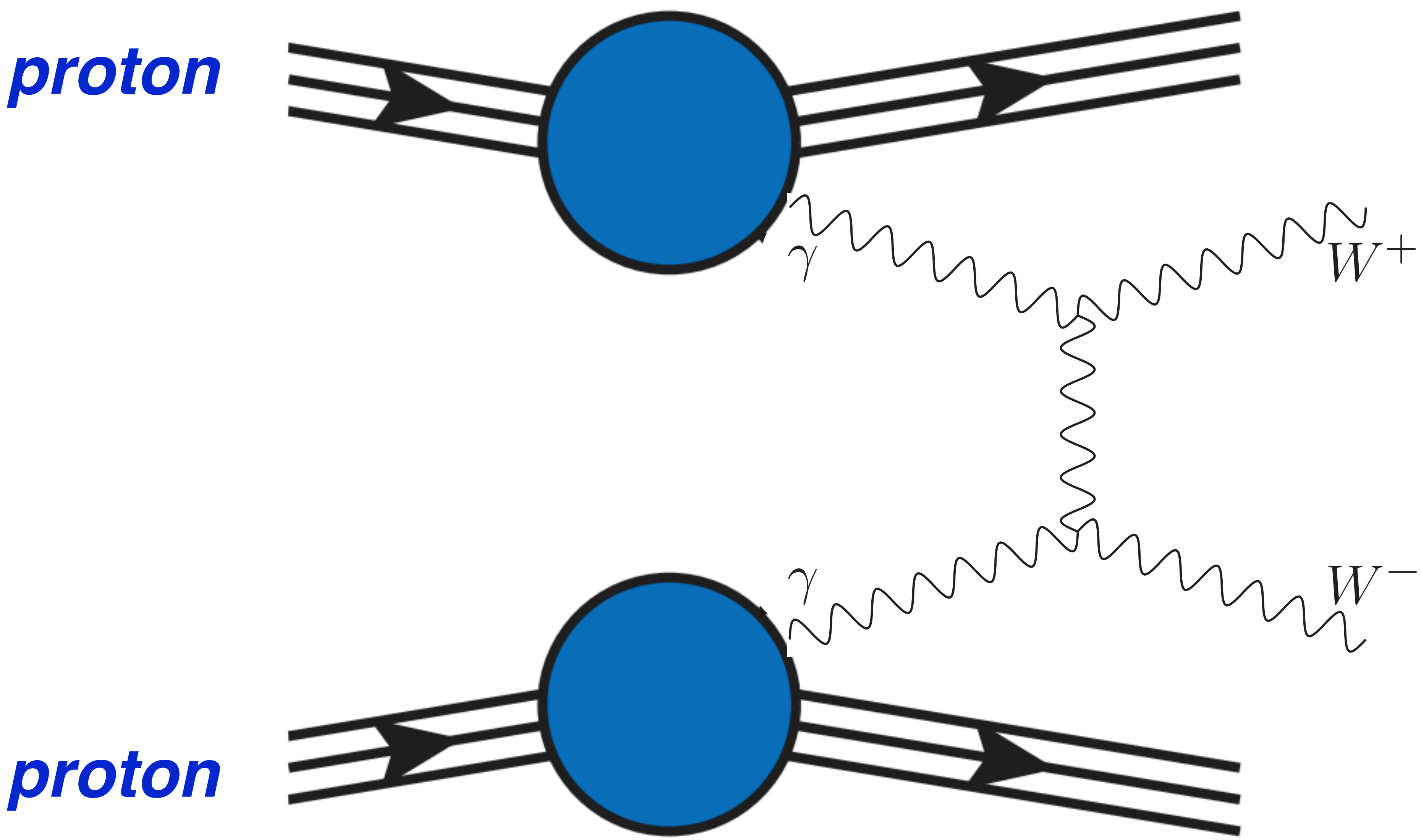
NNPDF, in preparation

Let there be light: the photon PDF

- The proton contains not only quark and gluons as constituents: also **photons!**
- The photon PDF can be evaluated from deep-inelastic **structure functions F_2 and F_L**

LuxQED: Manohar et al 16,17

- Required for consistent implementation of **electroweak corrections** at the LHC



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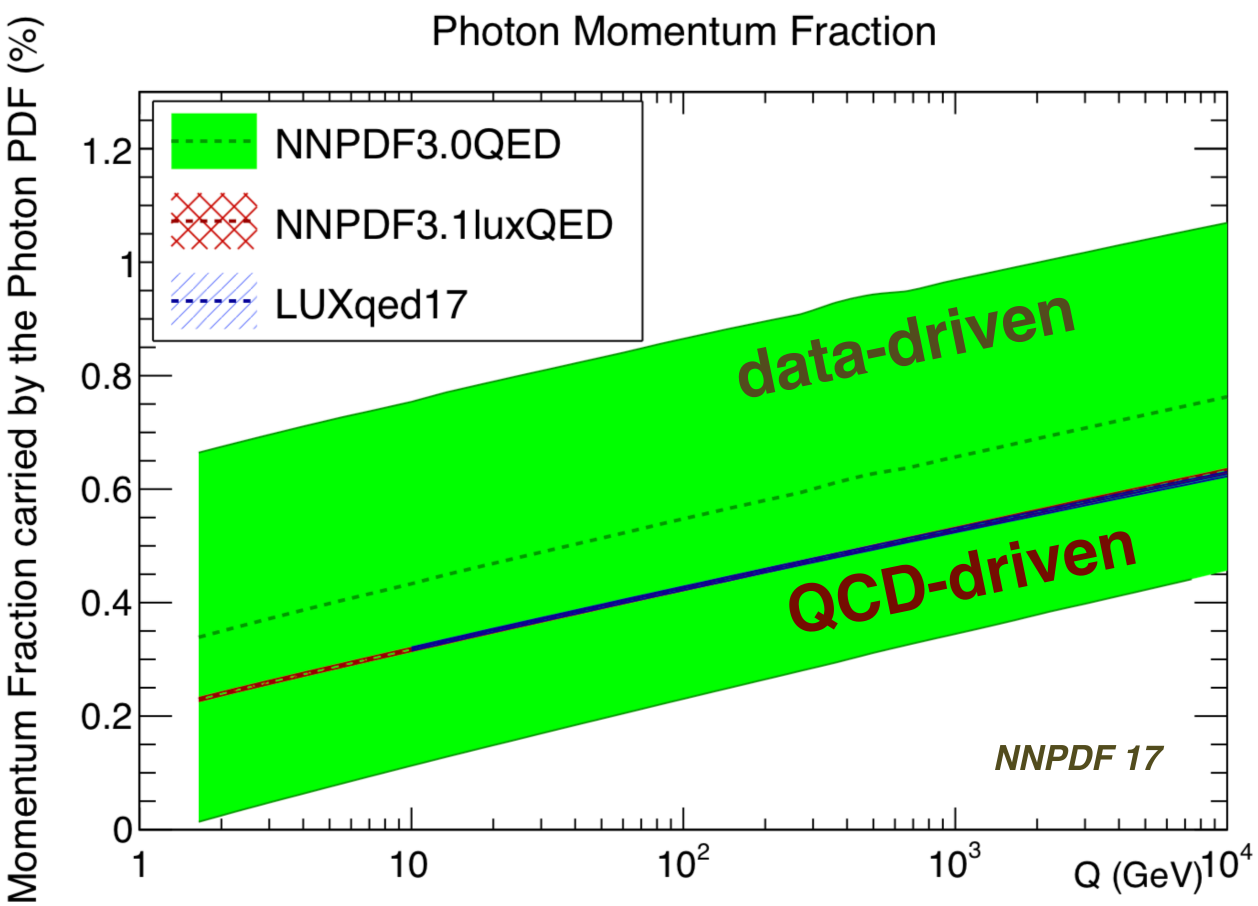

Up to 0.5% of proton's momentum ***carried by photons***

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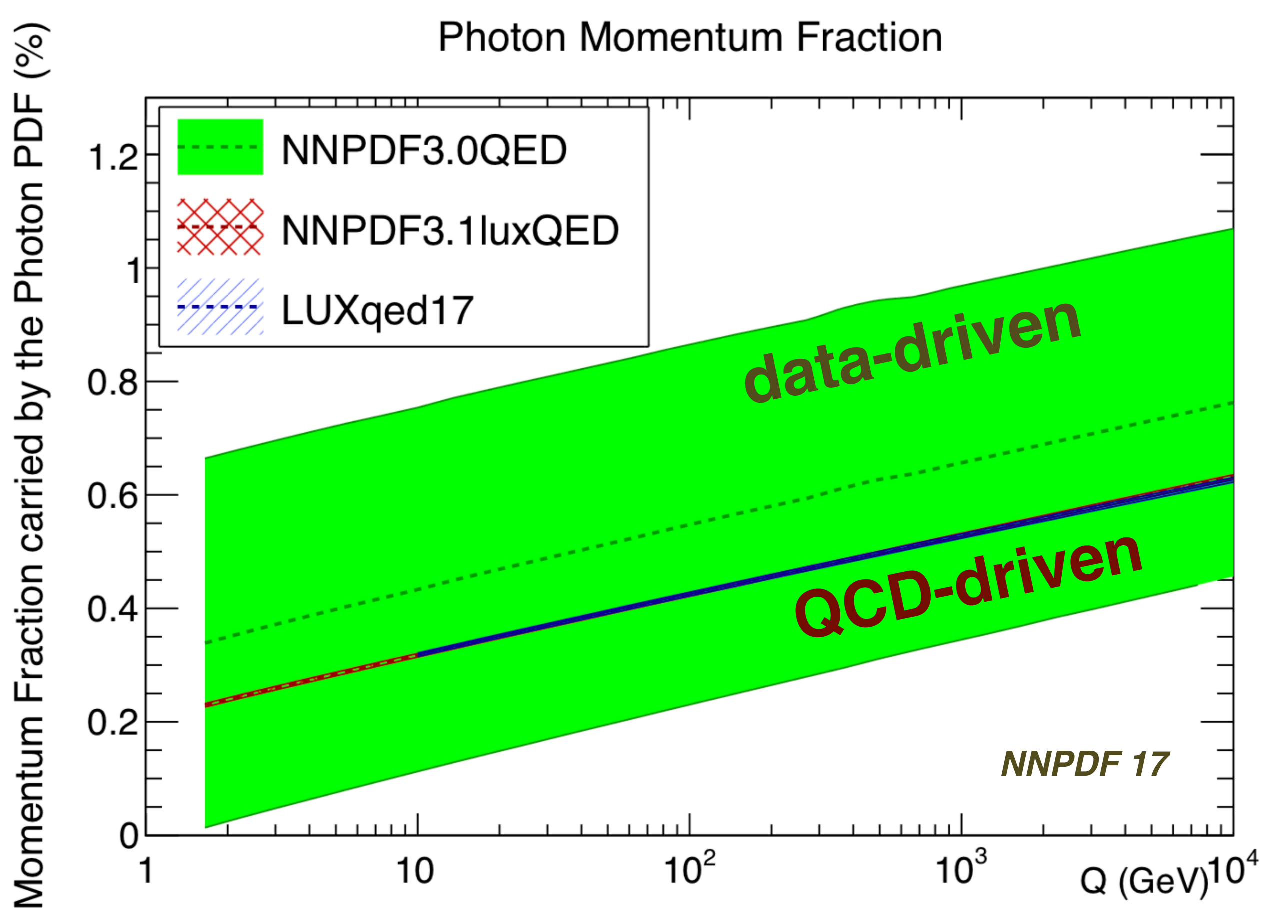
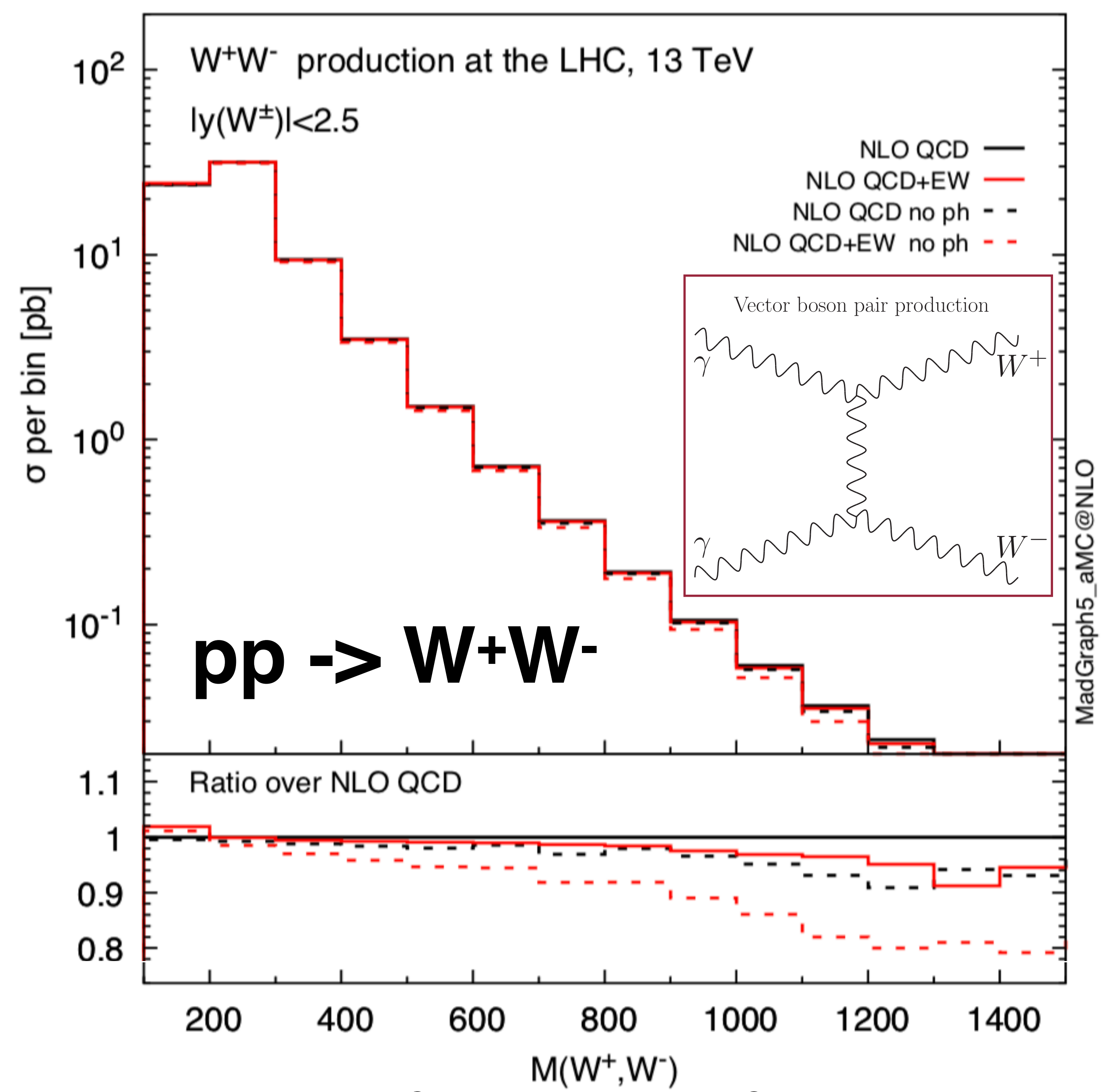
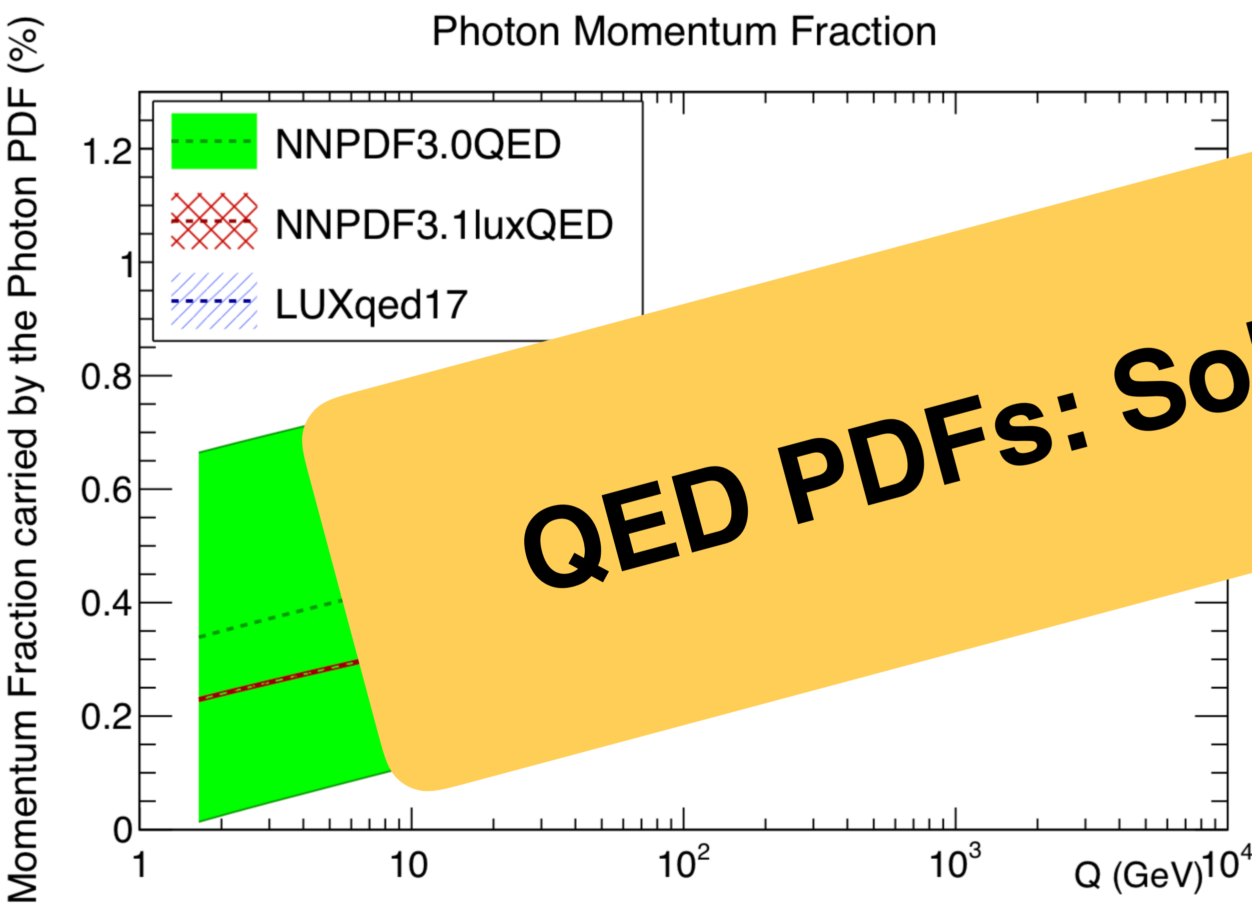


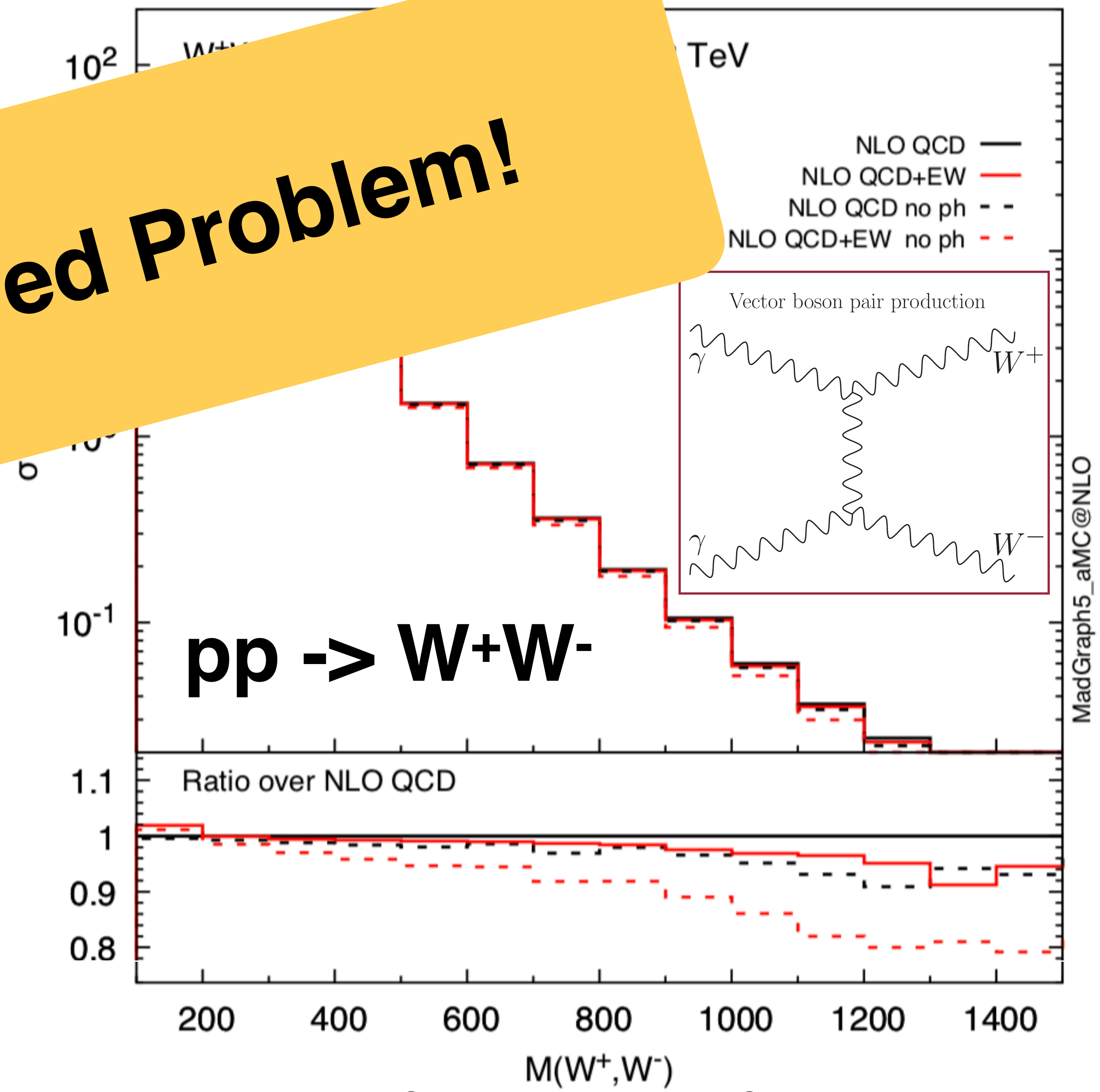


Up to 0.5% of proton's momentum ***carried by photons***

Let there be light: the photon PDF

- The proton contains not only quark and gluons as constituents: also **photons!**
- The photon PDF can be evaluated from deep-inelastic **structure functions F_2 and F_L**
- Required for consistent implementation of **electroweak corrections** at the LHC

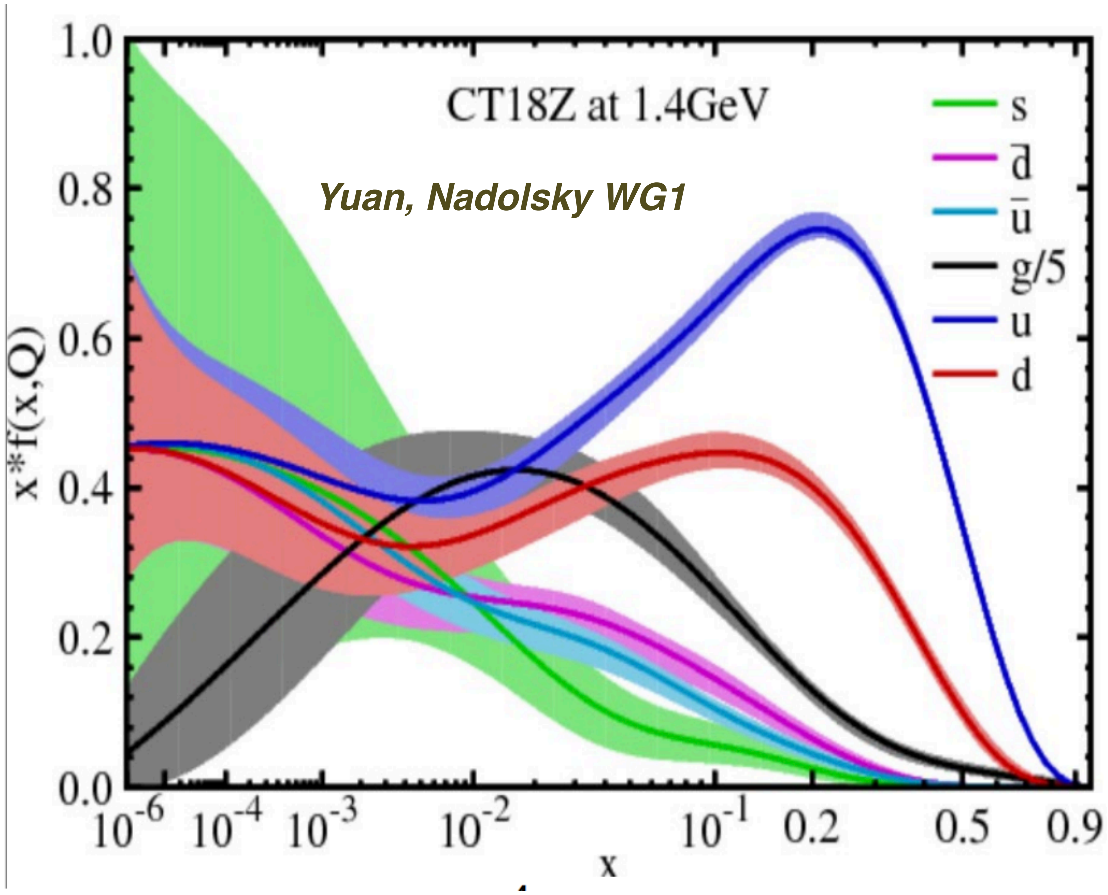




QED PDFs: Solved Problem!

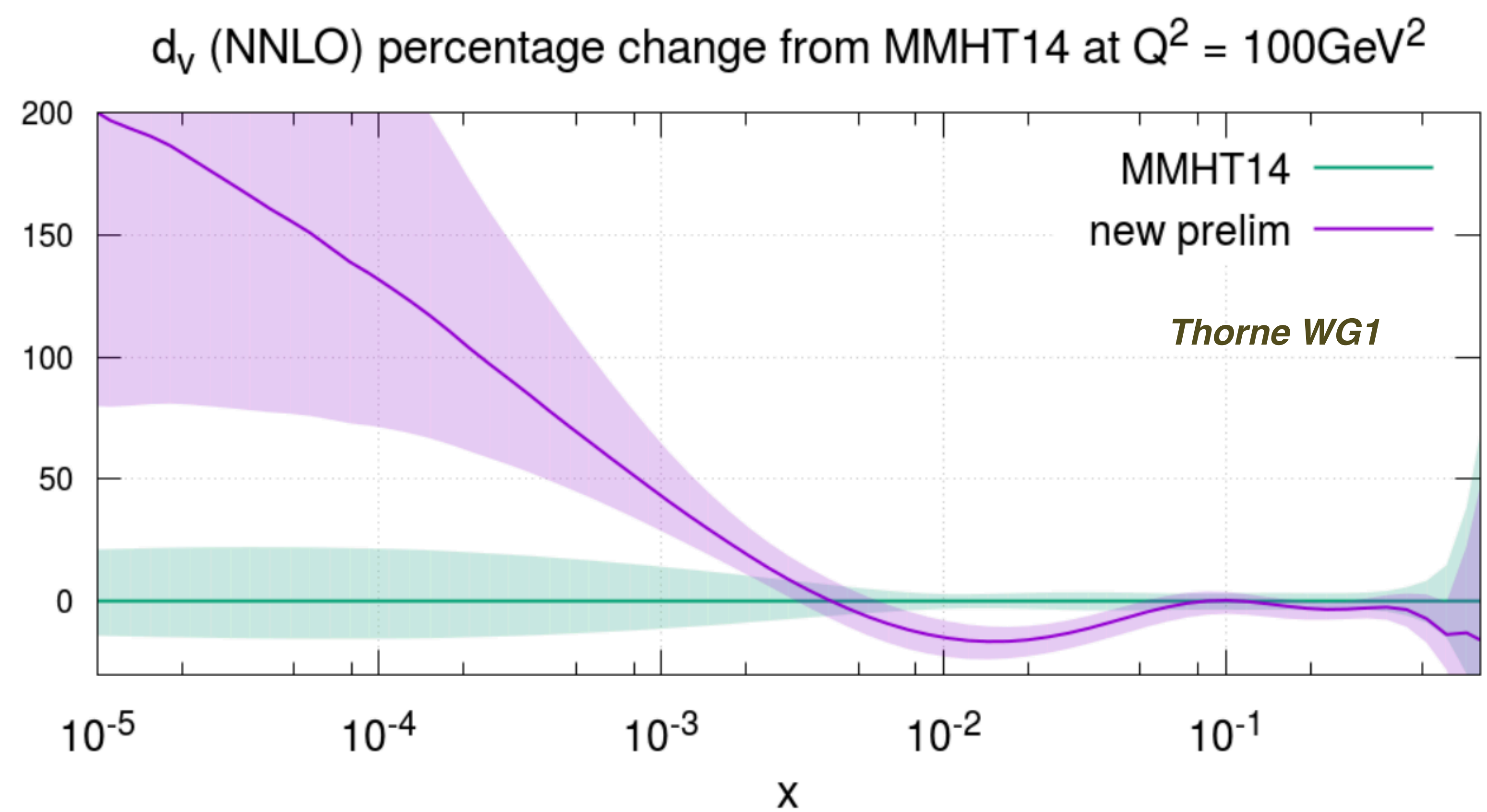
*Up to 0.5% of proton's momentum **carried by photons***

Updating the global PDF analyses

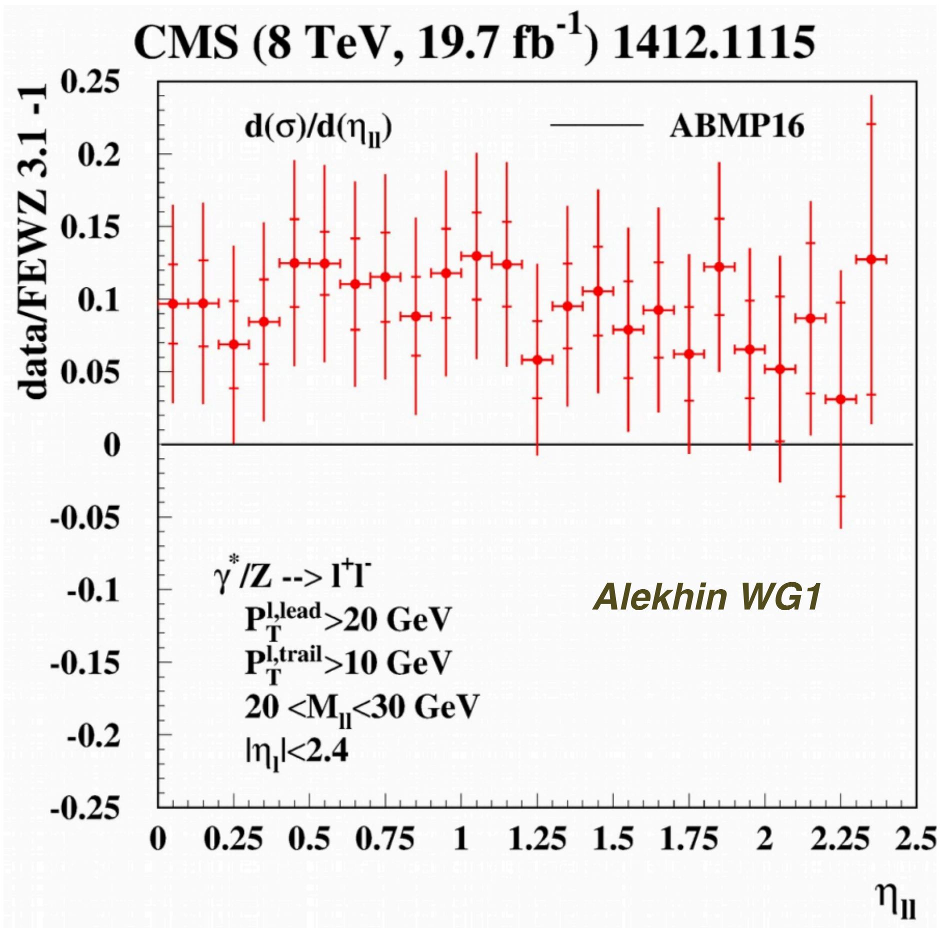


- **CT18/CT18Z** is the follow-up of CT14 (without/with ATLAS W,Z 2011)
- Added new LHC measurements boosted by the **ePump** and **PDFsense** tools
- Systematic studies of dataset compatibility

- **``MMHT" update** in progress
- Many new LHC data, extended parametrisation, NNLO calculations, …
- QED sets ready for release

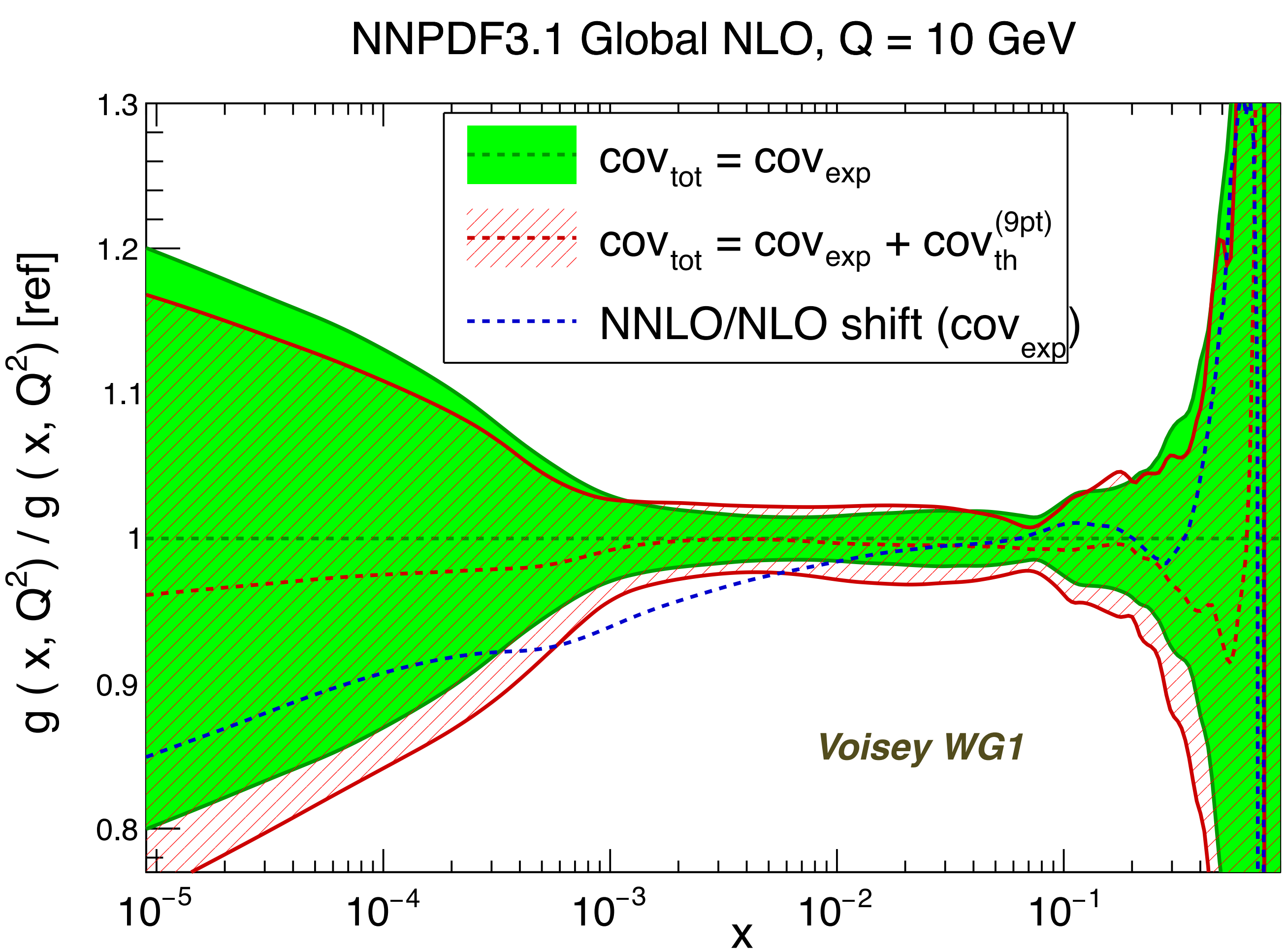


Updating the global PDF analyses



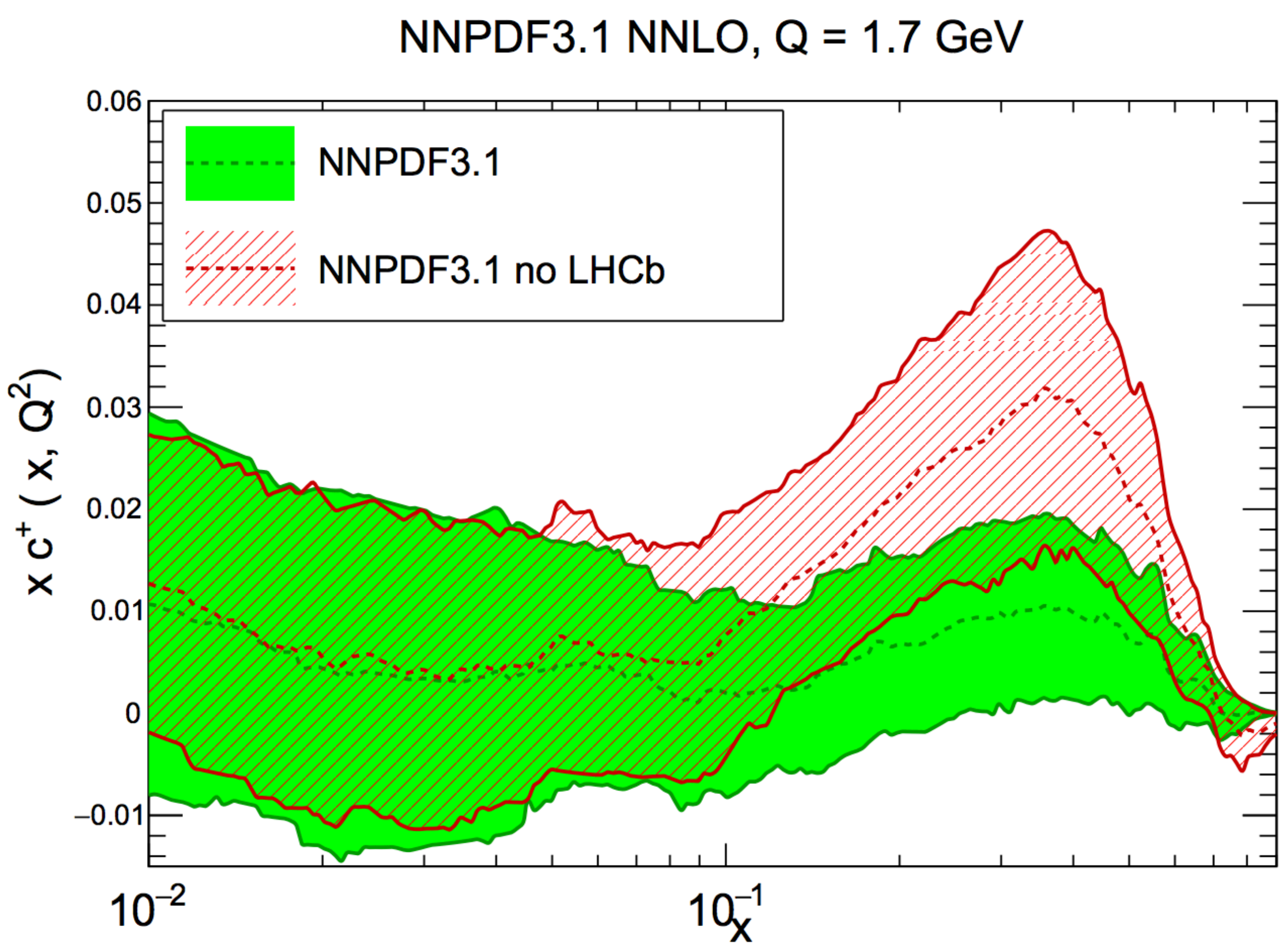
- **ABM** updates focusing on adding LHC Drell-Yan and top quark production data
- Studies of the impact of **higher twists**
- Potential tensions between ATLAS and CMS?

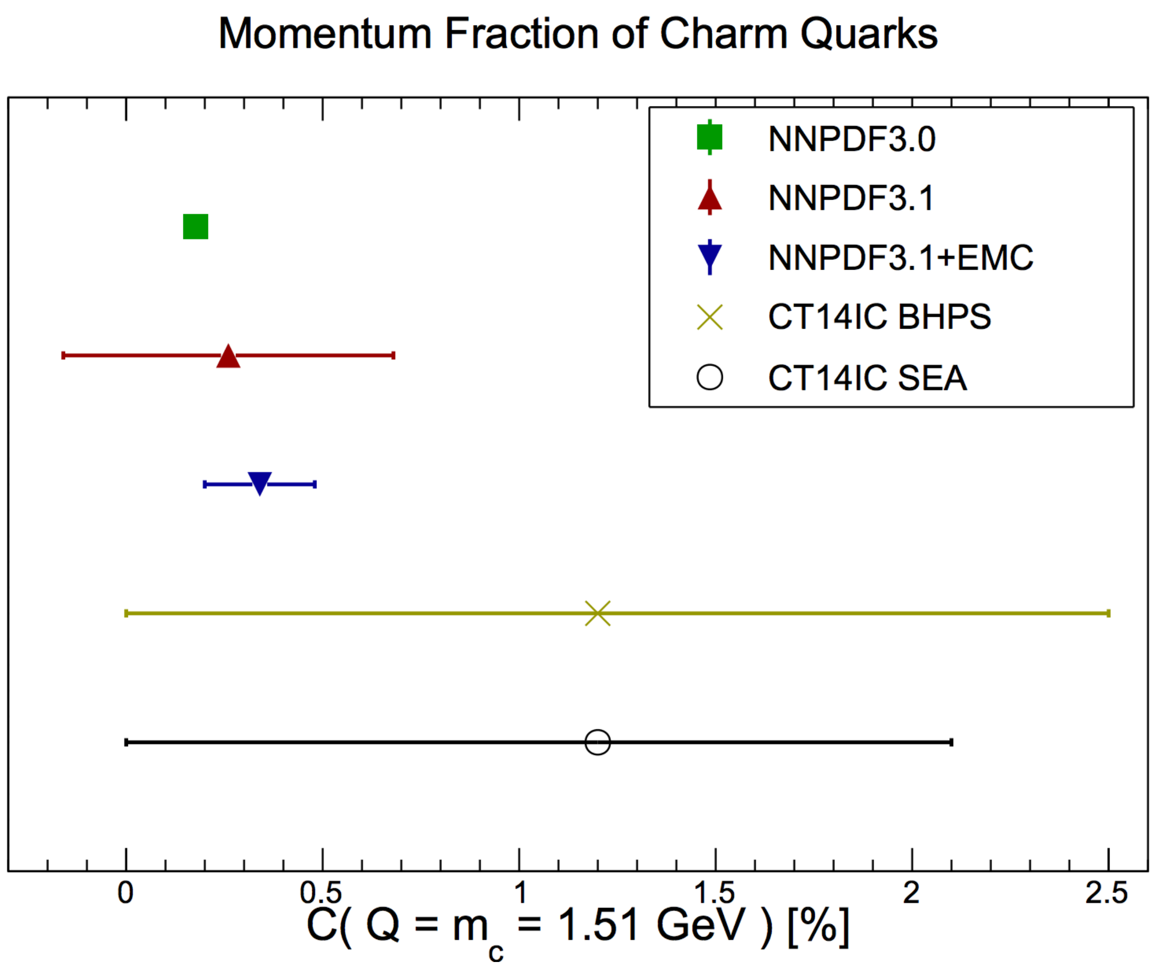
- **NNPDF3.1** released in 2017, with QED, small-x (BFKL), and $\alpha_S(M_Z)$ fits follow-ups
- PDF sets **with MHOUs** near completion
- Towards **NNPDF4.0:** new LHC data, improved methodology (TensorFlow for minimisation), MHOUs at NNLO, …



A charming proton?

Charm quark mass ≃ proton mass: does the proton contain charm?





- LHC electroweak measurements provides information on the charm content of protons
- Can be tested in *Z+D*, high p_T *D*, *photon+D*

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

Indications of a ***small but non-zero charm content of protons***

Evidence for BFKL dynamics

NNPDF3.1 fits based on **fixed order** (NNLO) and **small-*x* resumed** (NNLO+NLLx) theory

Altarelli, Ball, Forte 08, Bonvini et al 15,16

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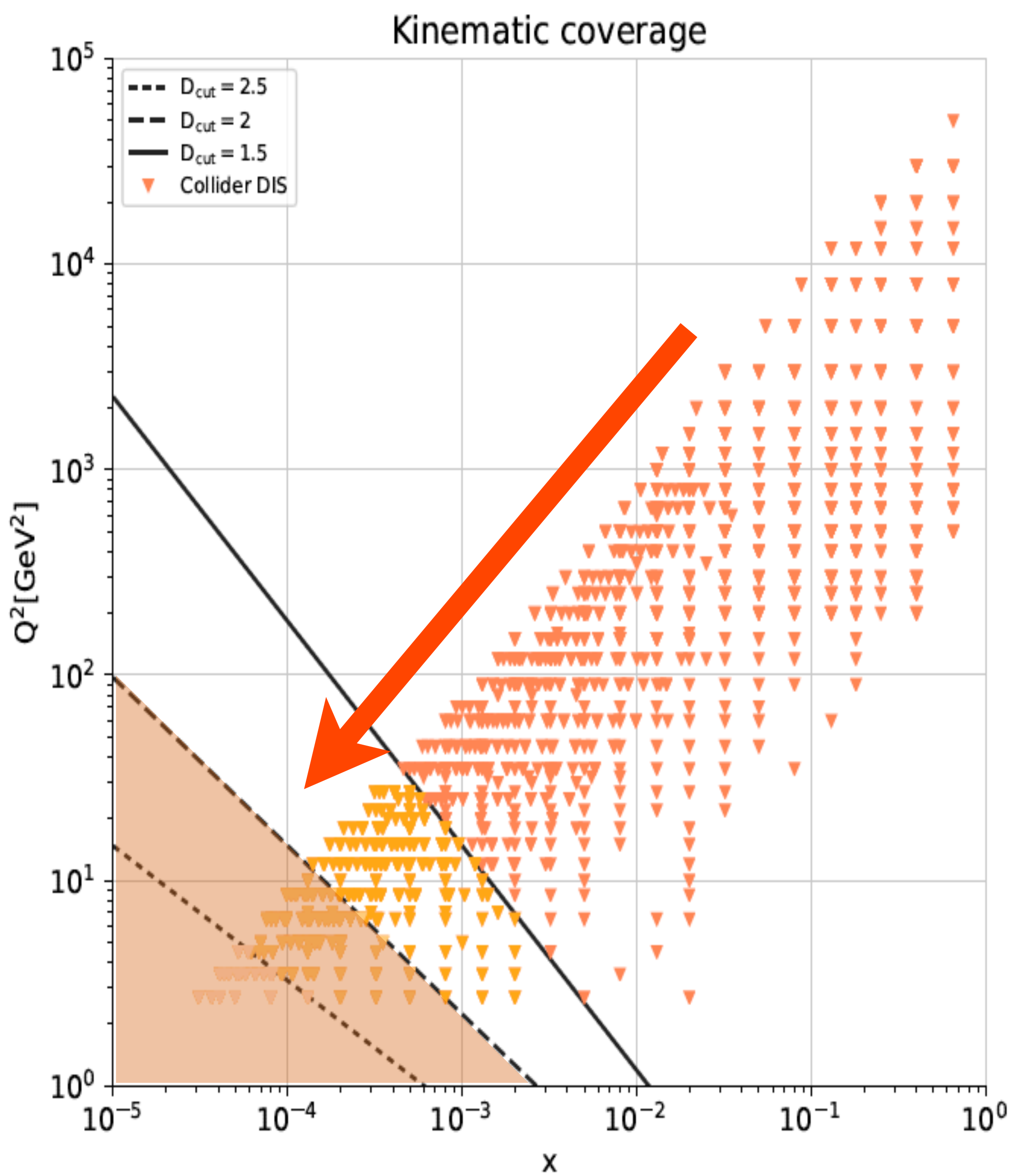

Monitor the **fit quality** as one includes more data from the **small-*x* region**

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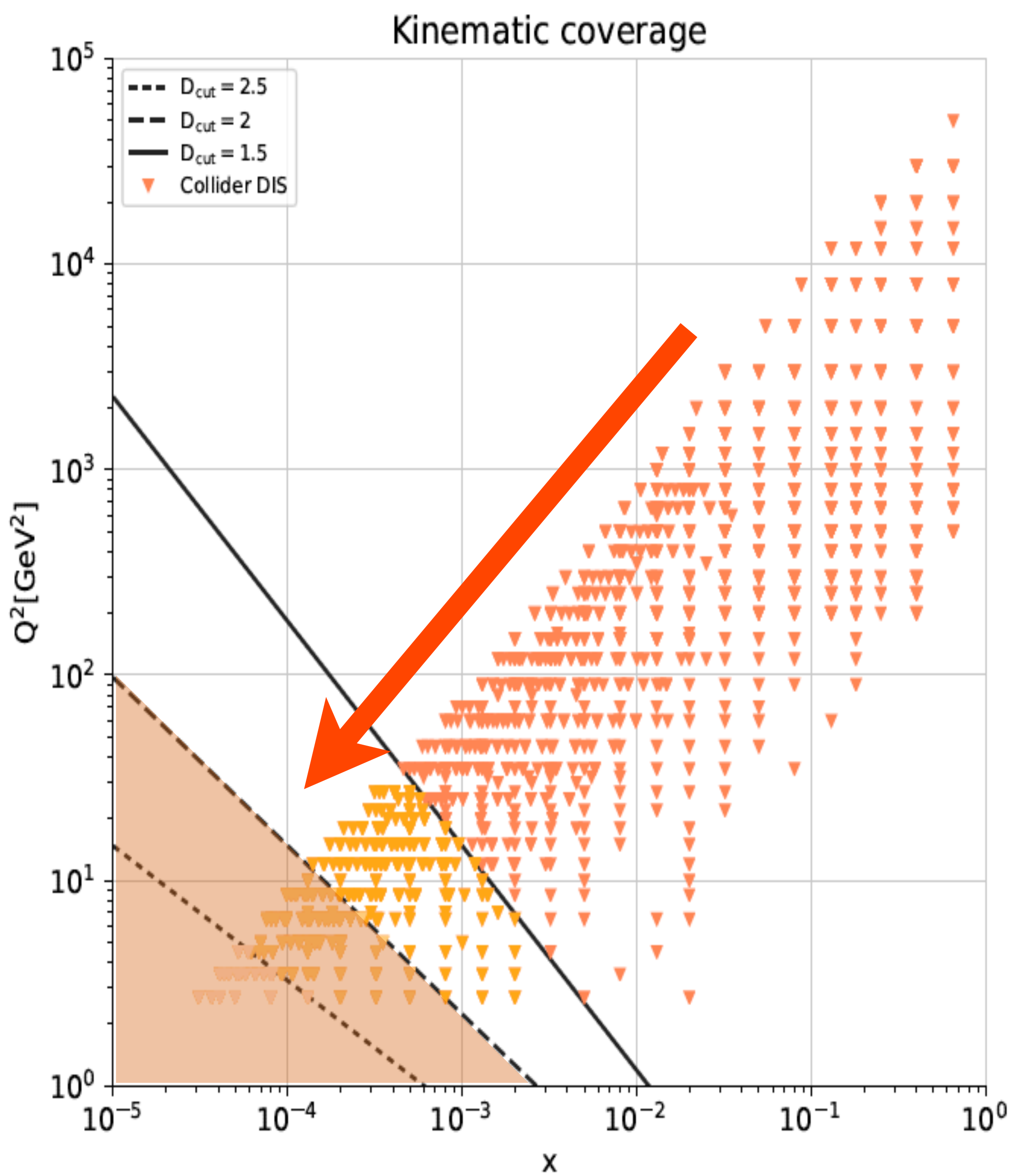
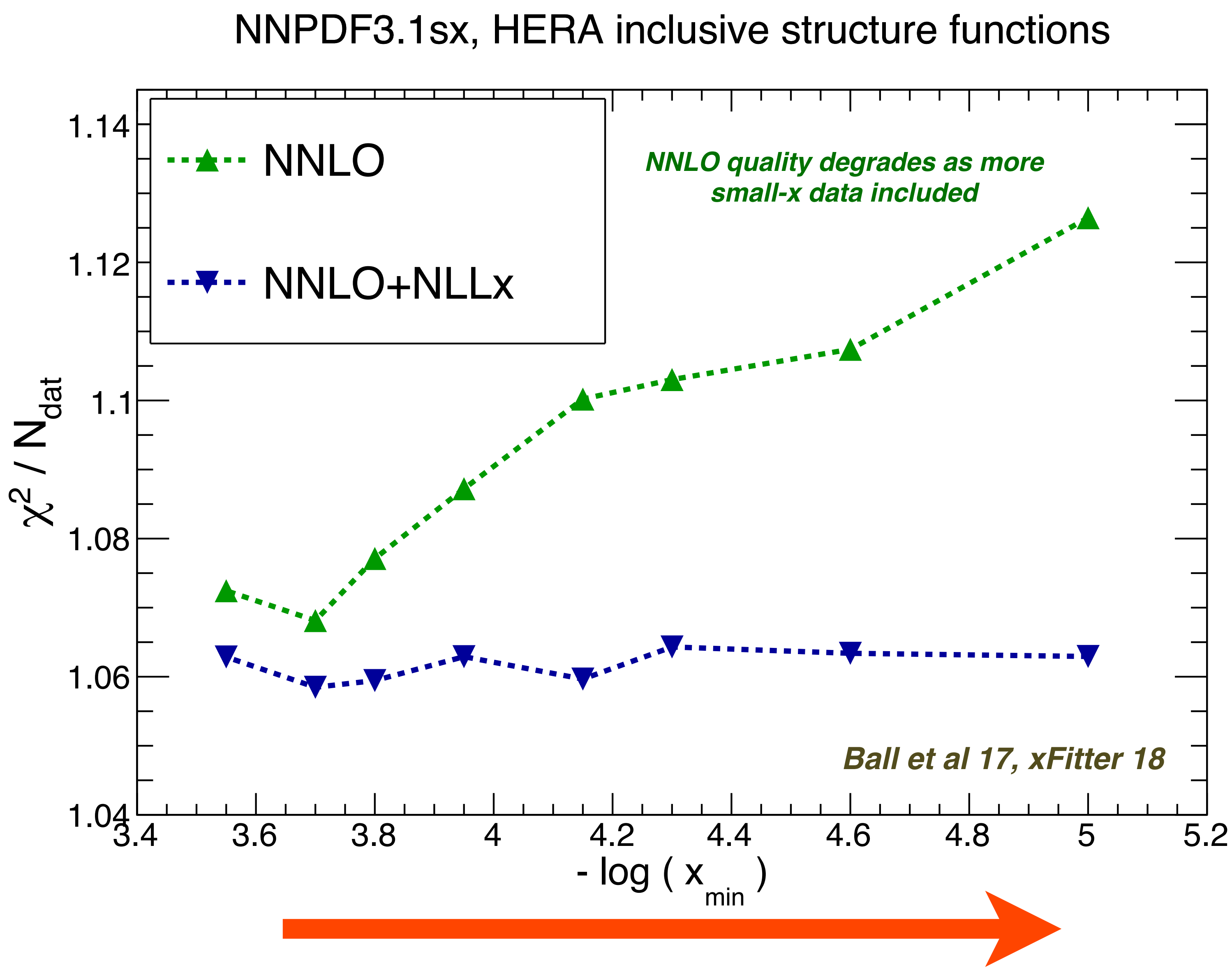




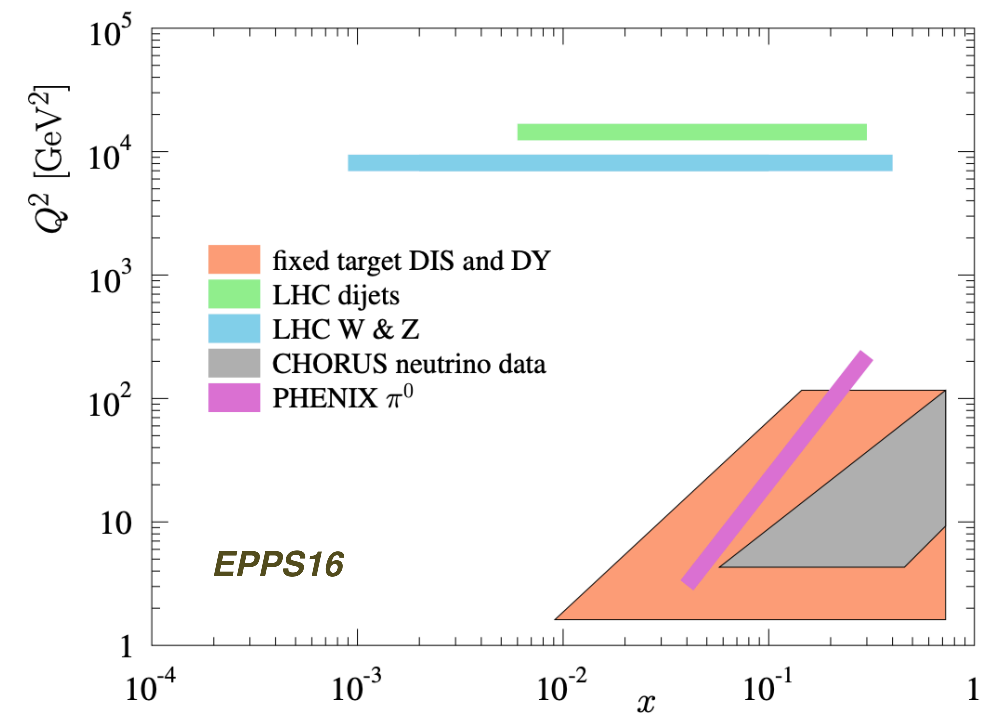
Monitor the **fit quality** as one includes more data from the **small-*x* region**

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

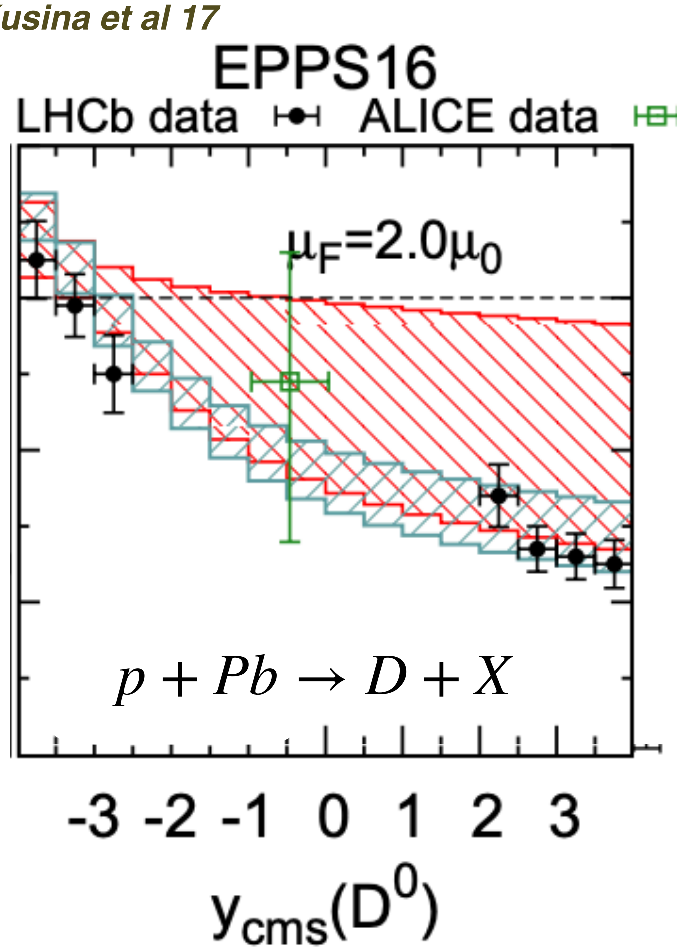
Progress in nuclear PDFs

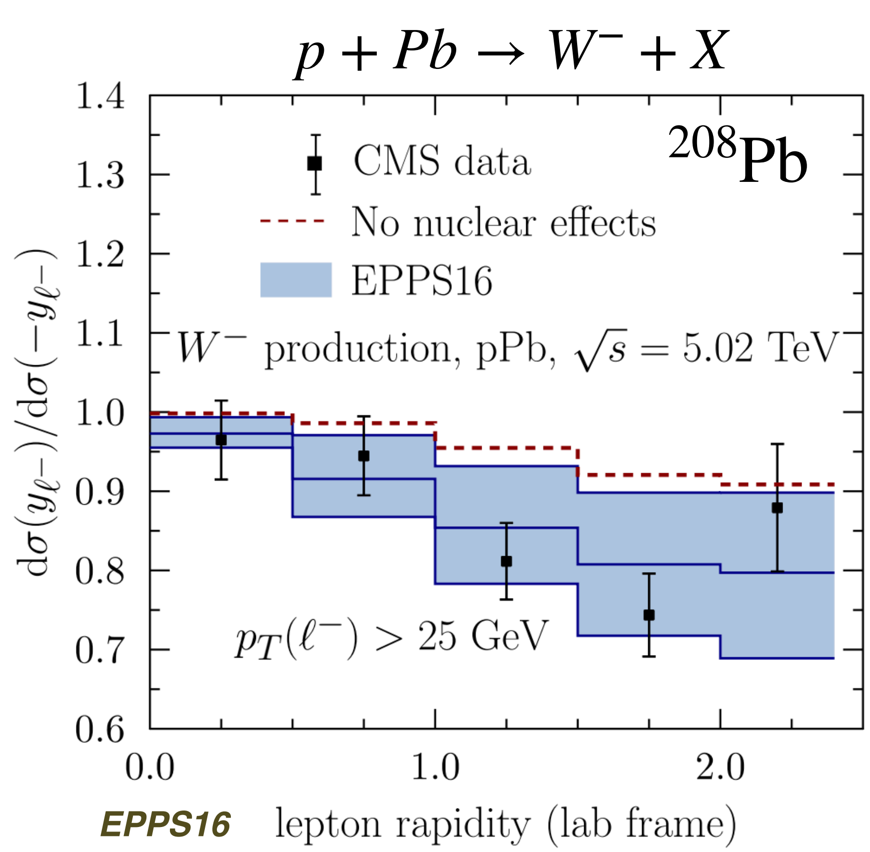
- Constraints from **LHC proton+lead collisions**: *W, Z,* jets, charm, quarkonia, Drell-Yan, direct photons, …

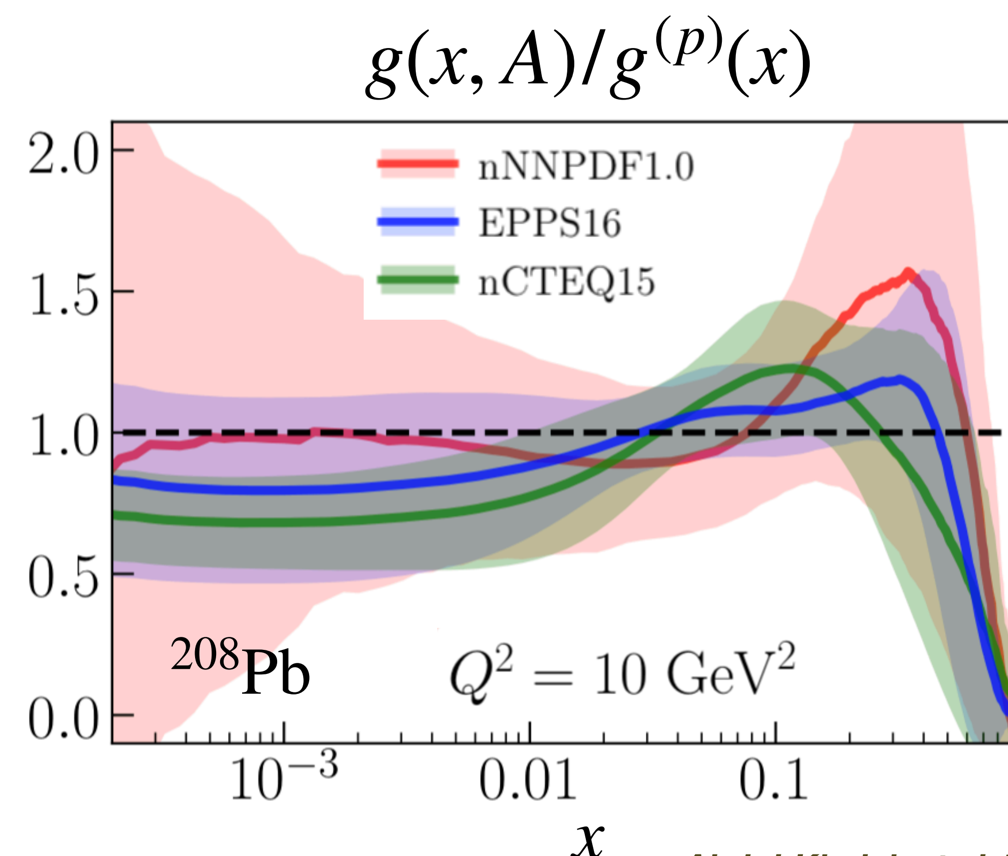
- **Theoretical** and **methodological** improvements: nPDF uncertainty estimate, NNLO QCD effects, …



Kusina et al 17







Abdul-Khalek et al 19

Nuclear PDF analyses catching up with global proton PDF fits!

The lattice QCD frontier

PDFs are defined as nucleon matrix elements of quark fields separated in the **light-cone**

$$q(x) = \int_{-\infty}^{+\infty} d\xi^- \, e^{-ixP^+\xi^-} \, \langle N | \, \overline{\psi}(\xi^-) \, \Gamma W(\xi^-, 0) \, \psi(0) \, | N \rangle$$

Quasi-PDFs instead involve **euclidean separations** and can be computed on the lattice

$$\tilde{q}(x, P_3) = \int_{-z_{\rm max}}^{+z_{\rm max}} \frac{dz}{4\pi} \, e^{-ixP_3 z} \, \langle N | \, \overline{\psi}(0, z) \, \Gamma W(z, 0) \, \psi(0, 0) \, | N \rangle$$

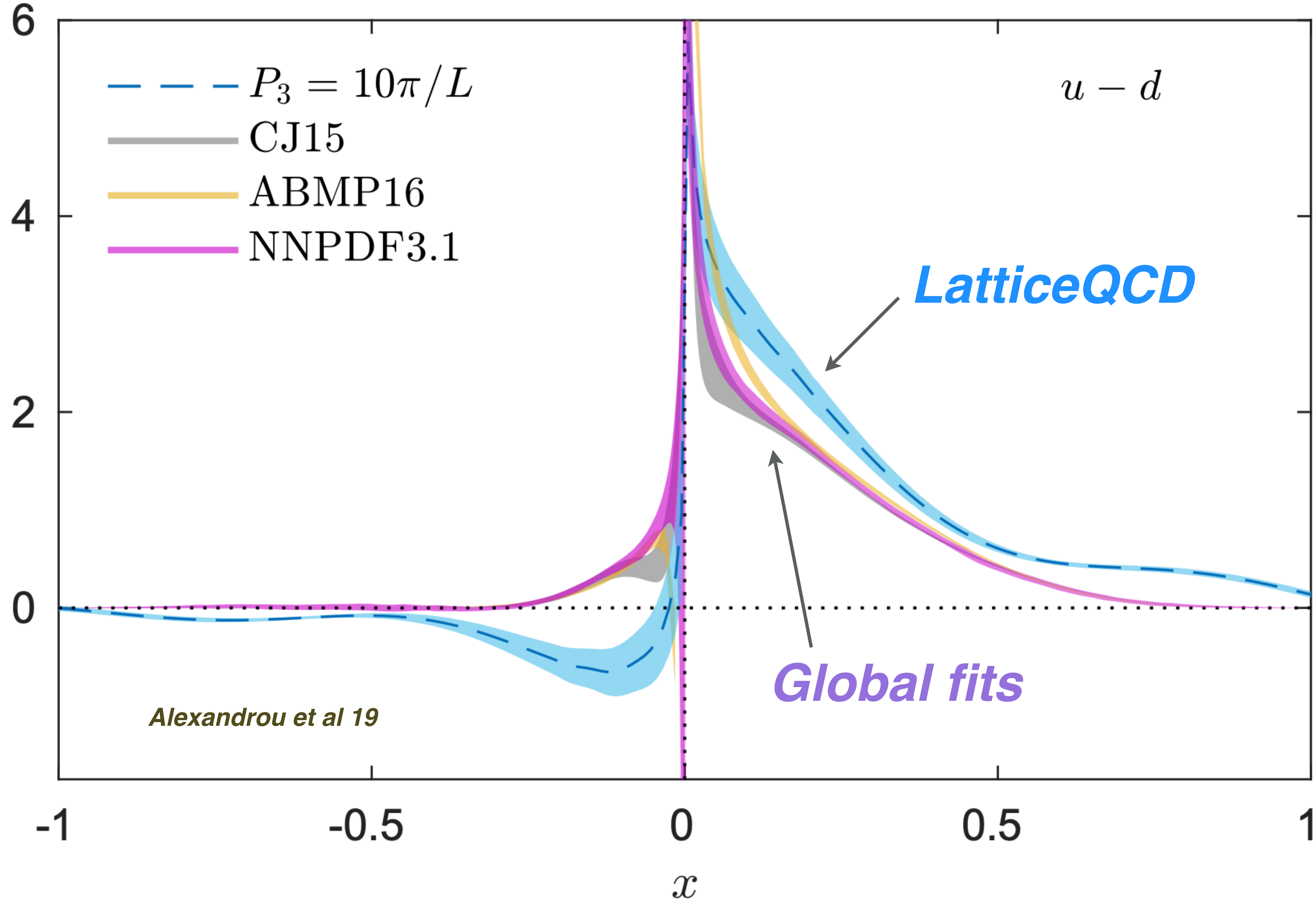
The two objects can be matched using the **Large Momentum EFT:**

$$q(x, \mu) = \int_{-\infty}^{\infty} \frac{d\xi}{|\xi|} C\left(\xi, \frac{\mu}{P_3}\right) \tilde{q}\left(\frac{x}{\xi}, \mu, P_3\right) + O\left(\frac{m_N^2}{P_3^2}, \frac{\Lambda_{QCD}^2}{P_3^2}\right)$$

Direct computation of ***x*-space PDFs** now feasible

PDFLattice White Paper
Lin et al 17

The lattice QCD frontier



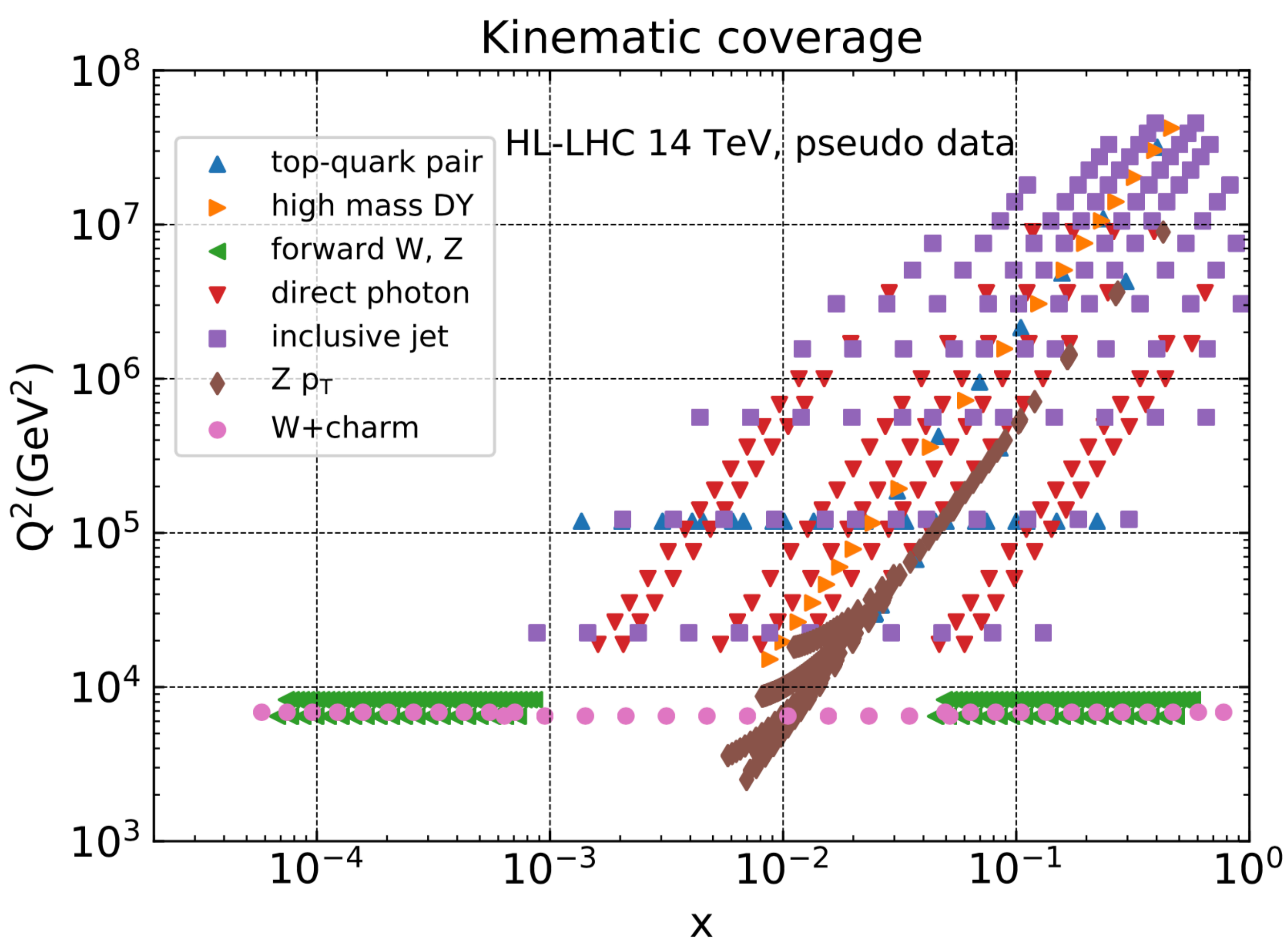
Direct computation of ***x*-space PDFs** now feasible

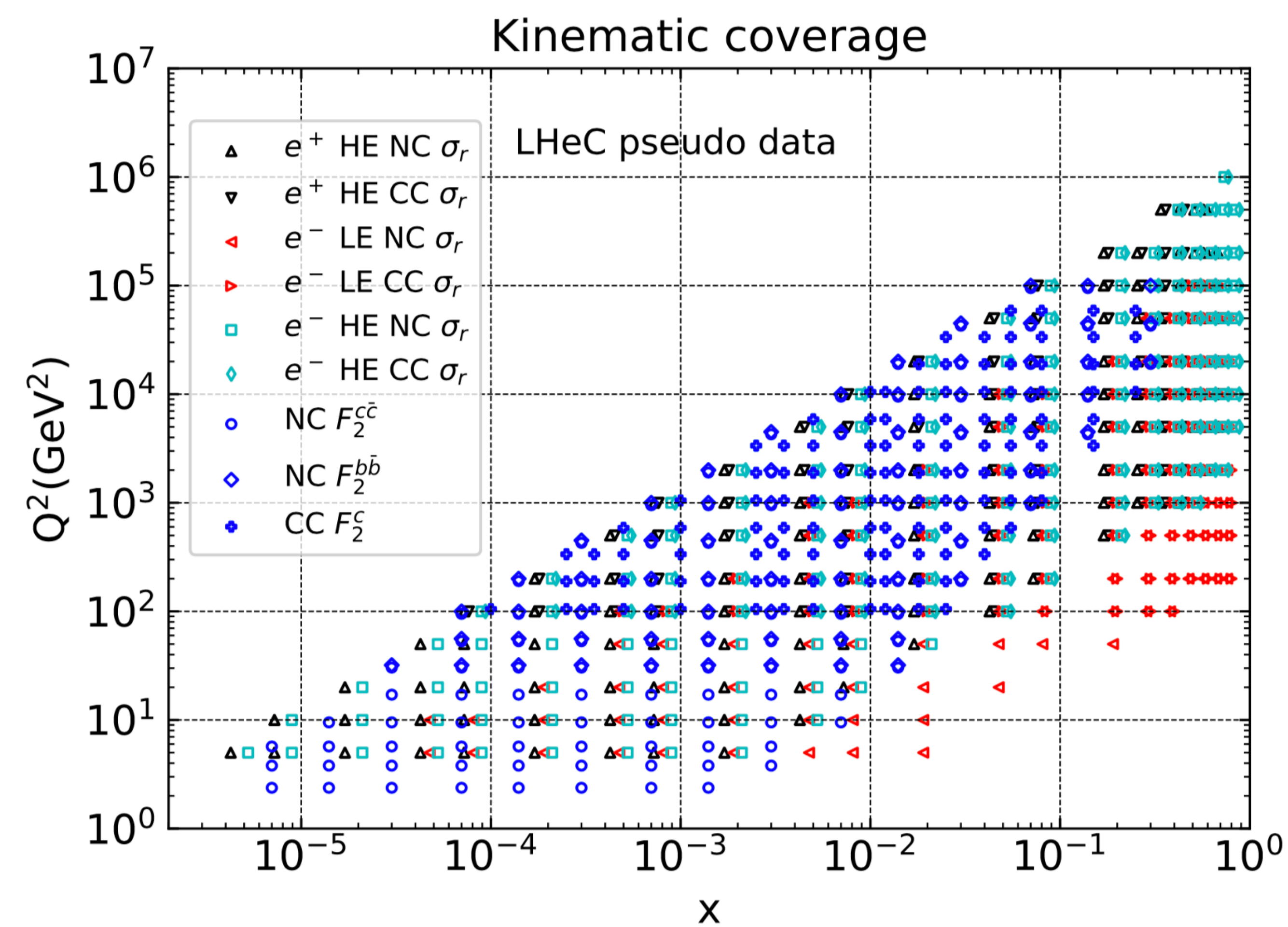
What next?

See also Rik's talk

Towards ultimate PDFs at the HL-LHC and LHeC

Exploit **novel facilities** for precision studies of the proton structure

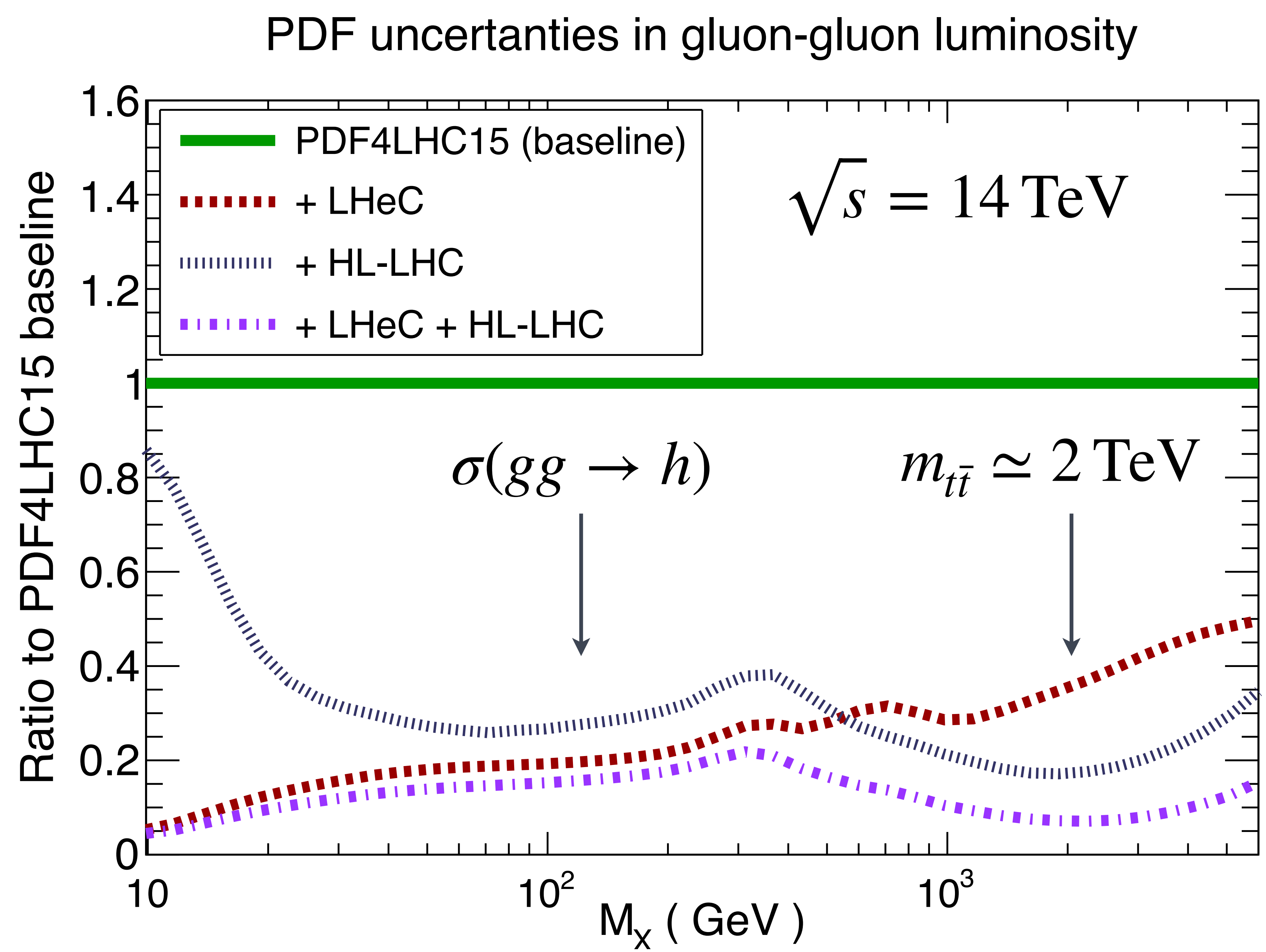




Fully **complementary** in terms of PDF constraints, possible synchronous operation

Towards ultimate PDFs at the HL-LHC and LHeC

Exploit **novel facilities** for precision studies of the proton structure



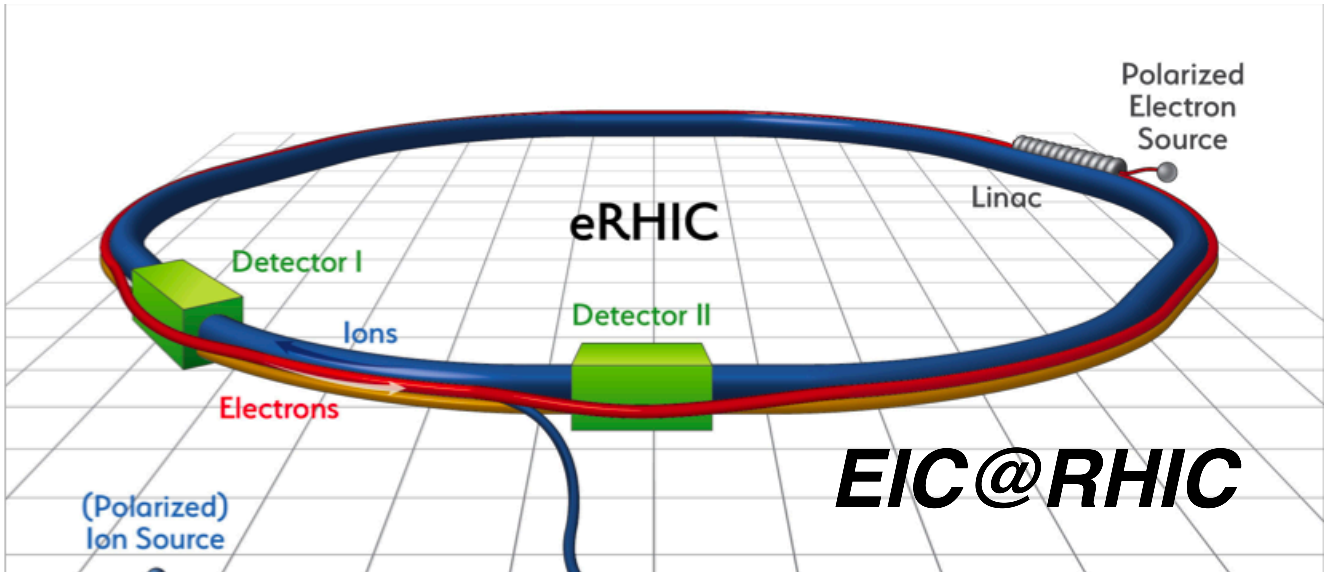
Abdul-Khalek et al. 18

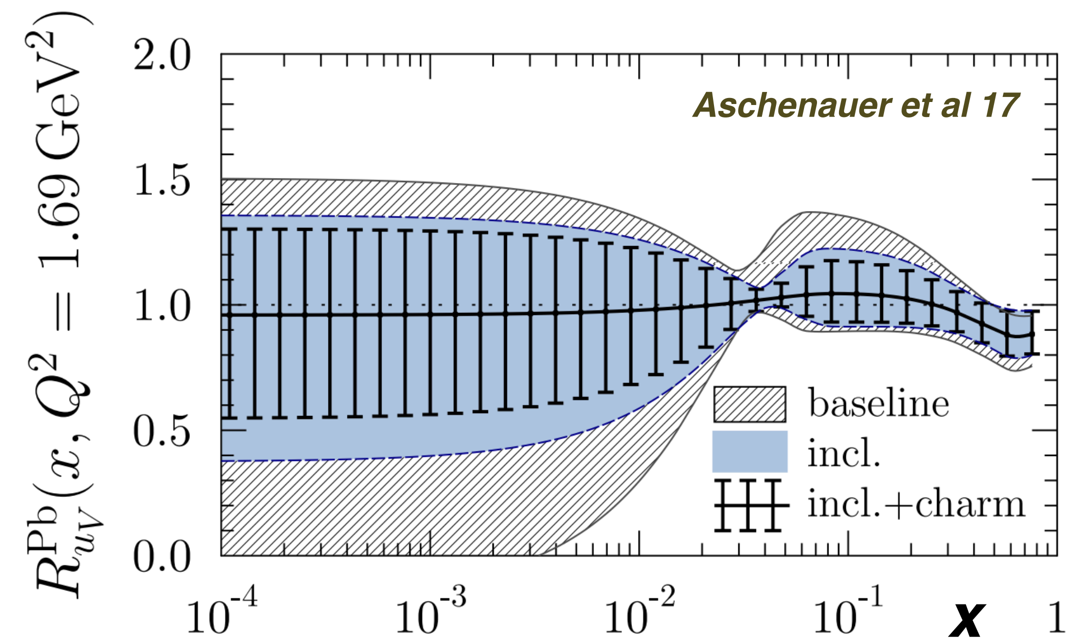
Harland-Lang, Gwenlan
WG1+WG7

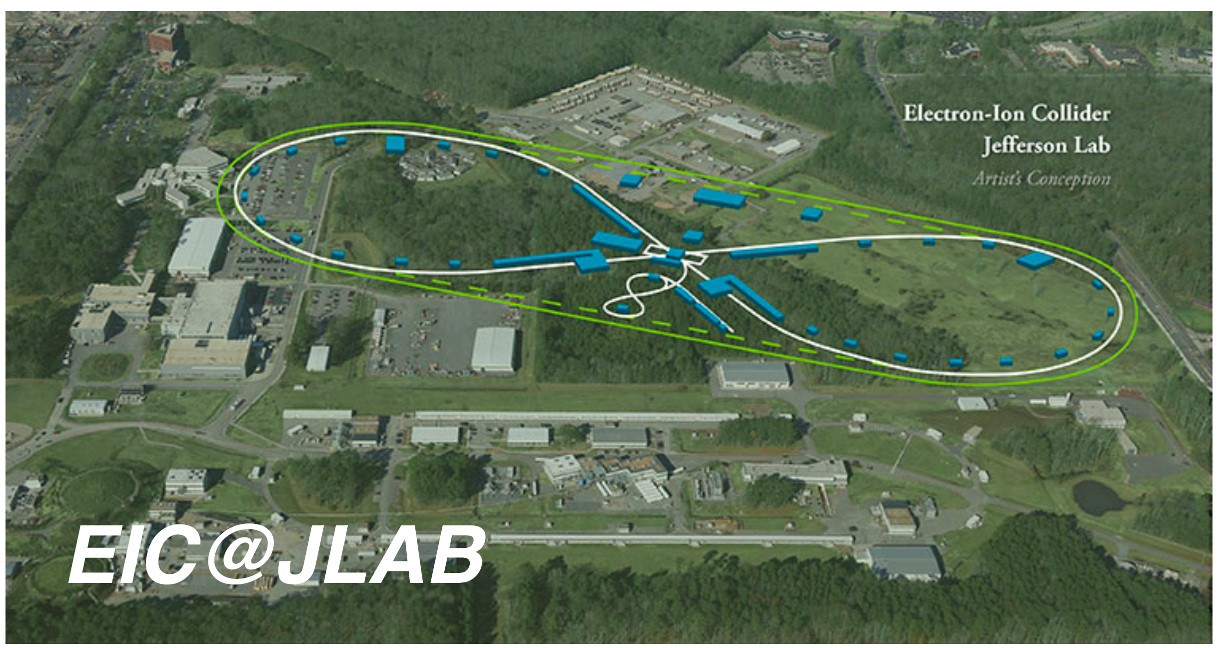
A reduction of PDF uncertainties by **up to a factor 10** could be within reach

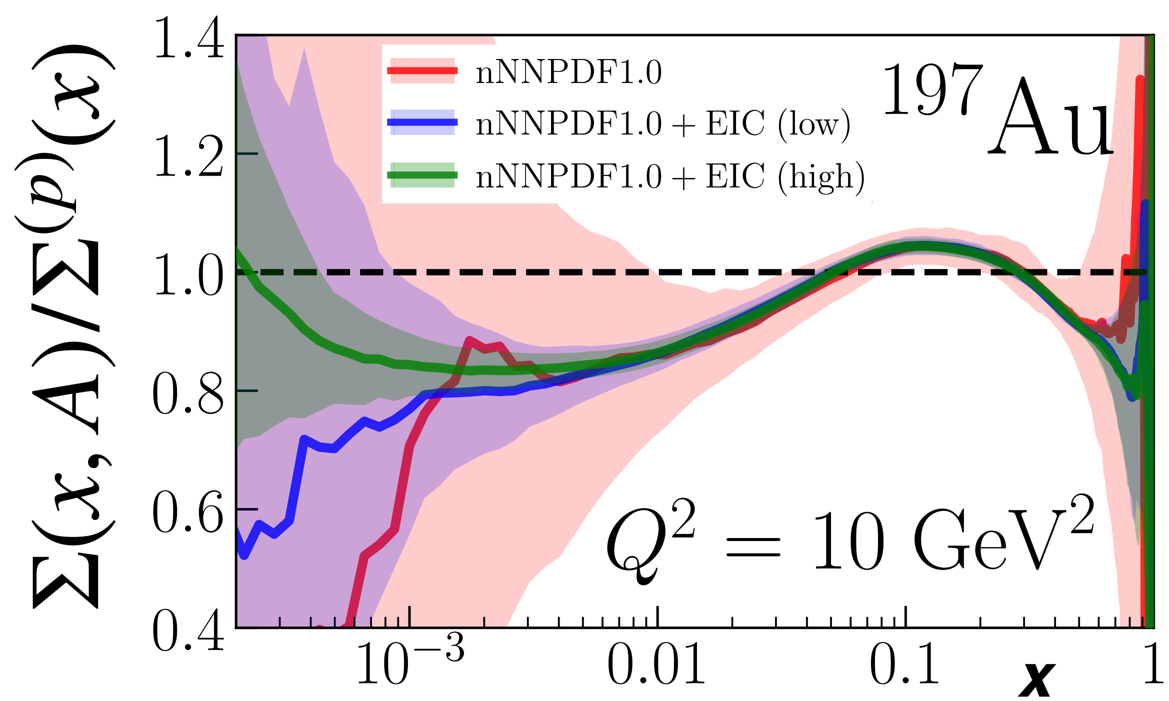
Nuclear structure at the Electron-Ion Collider

Unique facility to study **QCD matter** and **nucleon/nuclear structure**







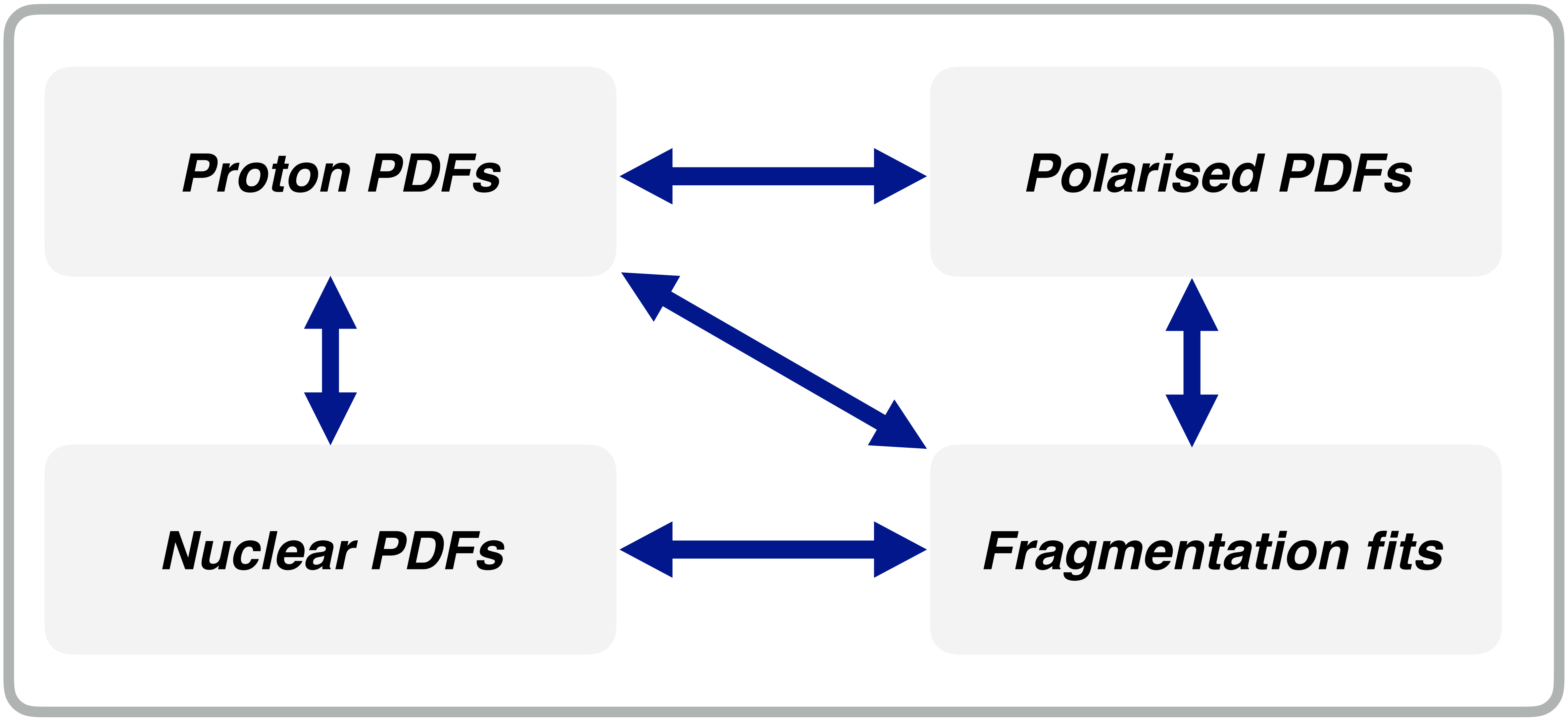


Abdul-Khalek et al 19

Pinning down nuclear PDFs at small-*x*: onset of gluon-dominated matter?

Universal QCD fits

Pushing the **precision frontier** of **QCD fits** requires accounting for **cross-talk** between different **non-perturbative QCD** quantities

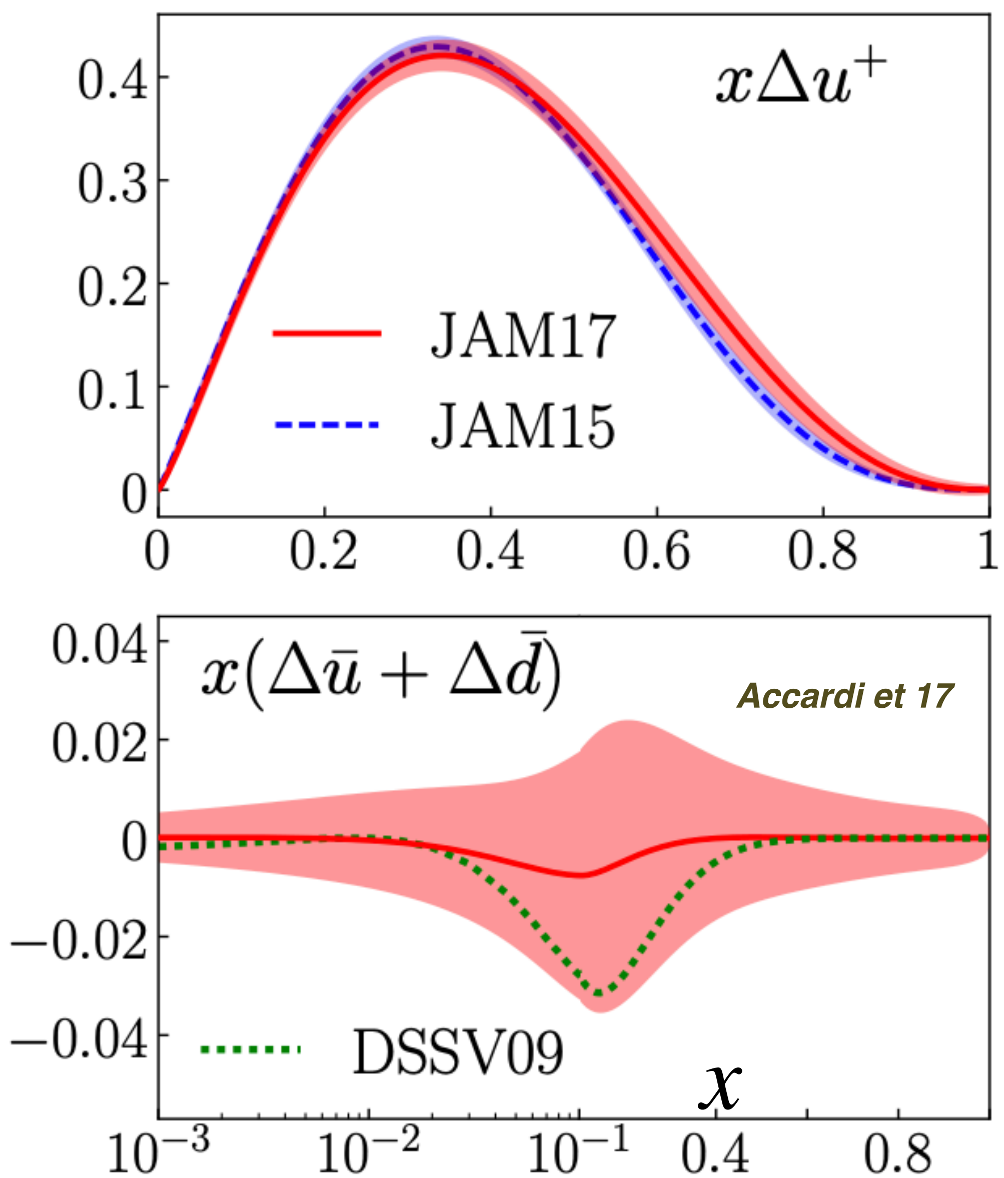


*Towards **universal/integrated global analyses** of non-perturbative QCD*

Universal QCD fits

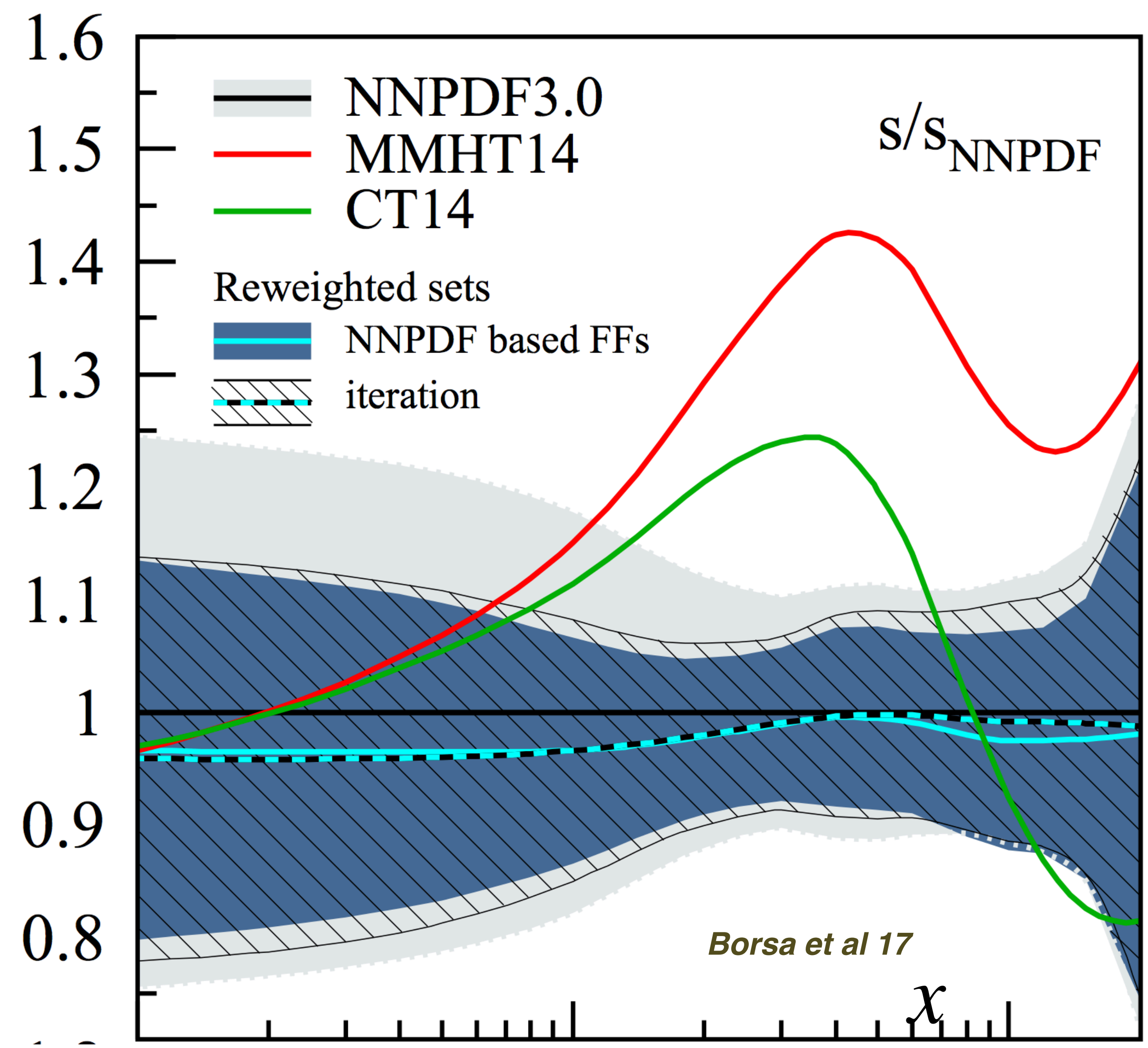
Pushing the **precision frontier** of **QCD fits** requires accounting for **cross-talk** between different **non-perturbative QCD** quantities

Polarised PDFs + FFs



Sato WG1

Unpolarised PDFs + FFs



Summary and outlook

The accurate determination of the **quark and gluon structure of the proton** is an essential ingredient for **LHC phenomenology** and **beyond**

- **LHC measurements** start to dominate the global PDF fit results

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- … but also **wrapping up**: QED effects on PDFs, BFKL dynamics in HERA data, ….

Summary and outlook

The accurate determination of the **quark and gluon structure of the proton** is an essential ingredient for **LHC phenomenology** and **beyond**

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- Long-term of QCD global analyses: both exploiting future facilities (HL-LHC, LHeC, EIC) and integrating consistently its multiple dimensions: (p)PDFs + FFs + nPDFs + TMDs ….

The fascinating study of the proton structure never stops surprising us, stay tuned!

Summary and outlook

The accurate determination of the **quark and gluon structure of the proton** is an essential ingredient for **LHC phenomenology** and **beyond**

- **LHC measurements** start to dominate the global PDF fit results
- Recent progress in **longstanding** ... ttice QCD constraints, strange ...
- … but ... DFs, BFKL dynamics in HERA data, ….
- Long-term ... QCD global analyses: both exploiting future facilities (HL-LHC, LHeC, EIC) and integrating consistently its multiple dimensions: (p)PDFs + FFs + nPDFs + TMDs ….

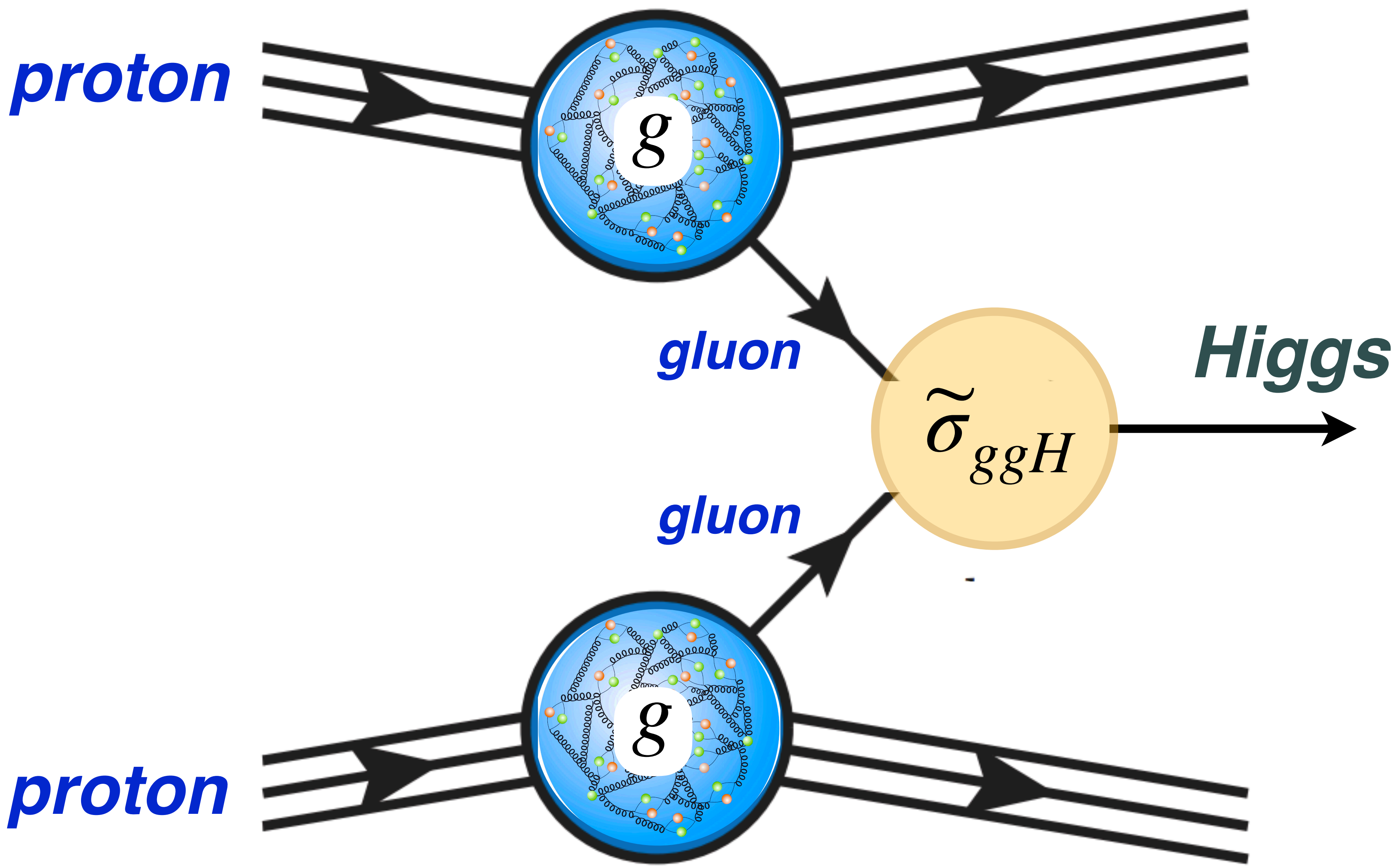
Thanks for your attention!

The fascinating study of the proton structure never stops surprising us, stay tuned!

Extra Material

Parton Distributions

$$N_{\mathrm{LHC}}(H) \sim \underbrace{g \otimes g}_{\text{Parton Distributions}} \otimes \widetilde{\sigma}_{ggH}$$



All-order structure: **QCD factorisation theorems**

Parton Distributions

$$g(x, Q)$$

Energy of hard-scattering reaction**:** inverse of resolution length

Probability of **finding a gluon inside a proton**, carrying a fraction ***x*** of the proton momentum, when probed with energy ***Q***

x: fraction of proton momentum carried by gluon

Dependence on *x* fixed by **non-perturbative QCD dynamics**: extract from experimental data

- **Energy conservation**: momentum sum rule

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

- **Quark number conservation**: valence sum rules

$$\int_0^1 dx\, \left(u(x, Q^2) + \bar{u}(x, Q^2) \right) = 2$$

Parton Distributions

$$g(x, Q)$$

Probability of **finding a gluon inside a proton**, carrying a fraction ***x*** of the proton momentum, when probed with energy ***Q***

x: fraction of proton momentum carried by gluon

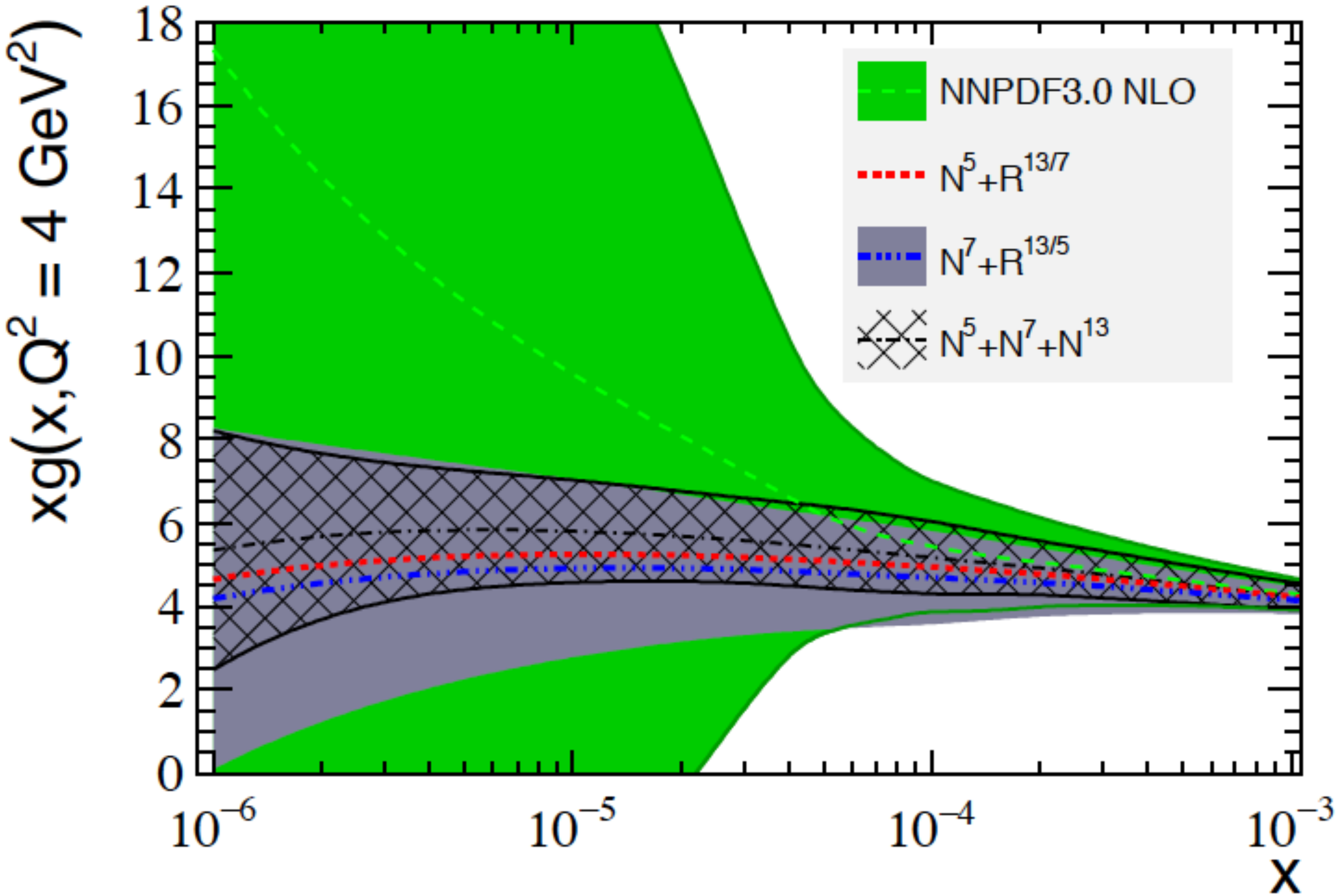
Energy of hard-scattering reaction**:** inverse of resolution length

Dependence on ***Q*** fixed by **perturbative QCD dynamics**: computed up to $\mathcal{O}\left(\alpha_s^4\right)$

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

***DGLAP** parton evolution equations*

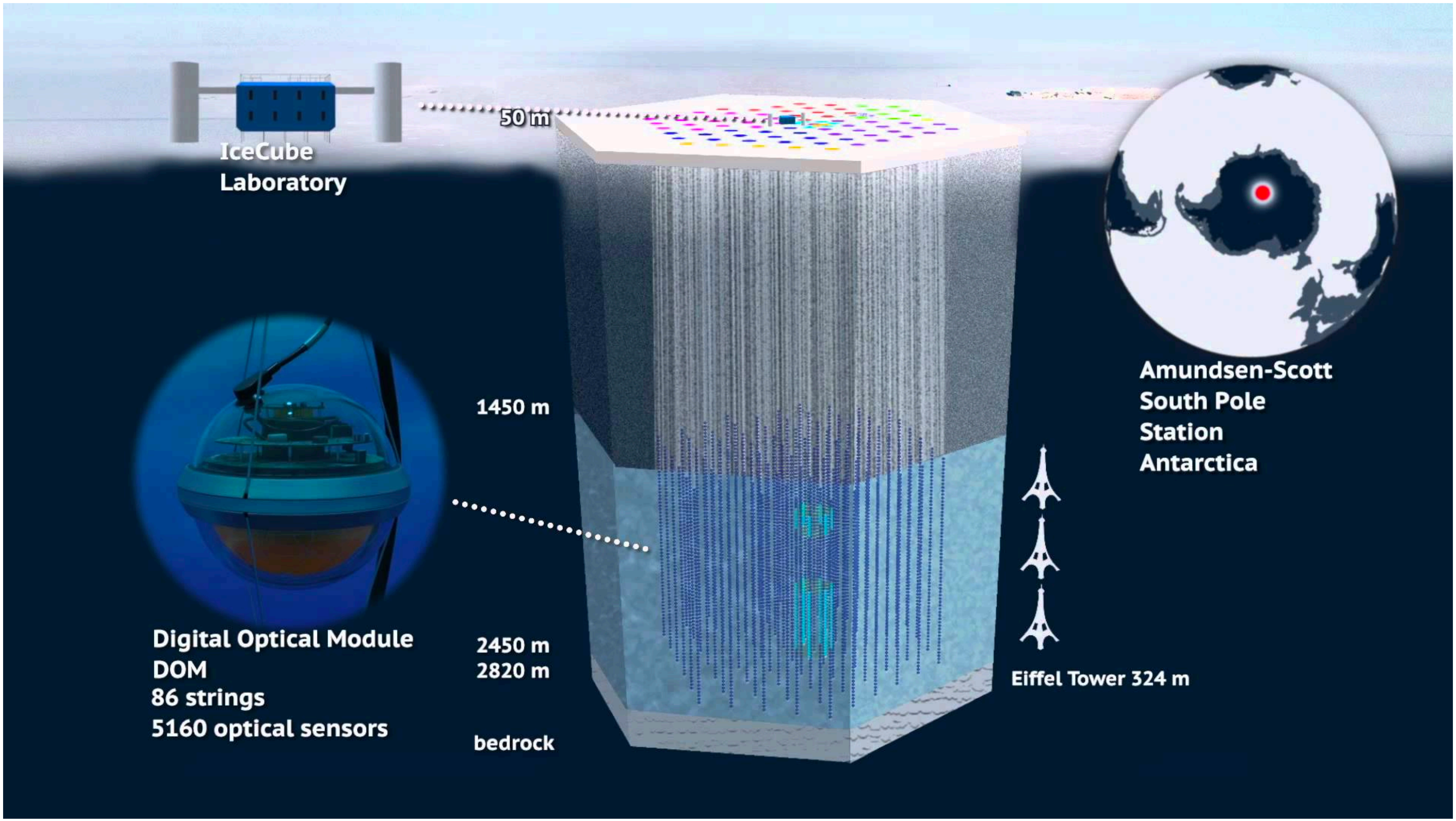
Forward charm production



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

Neutrino telescopes

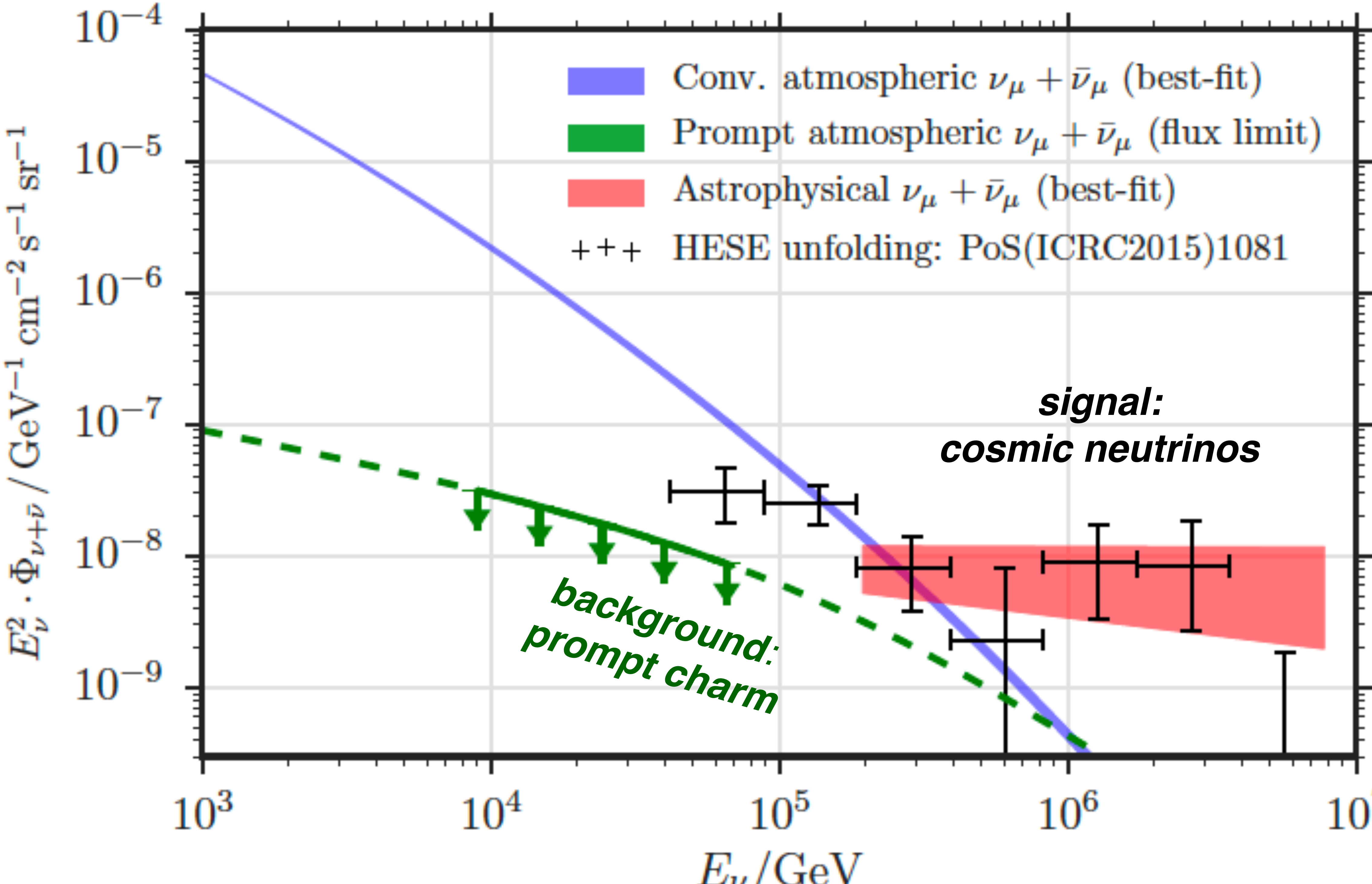
Ultra-high energy (UHE) neutrinos: novel window to the **extreme Universe!**



Neutrino telescopes as QCD microscopes

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

***background**: prompt charm production*



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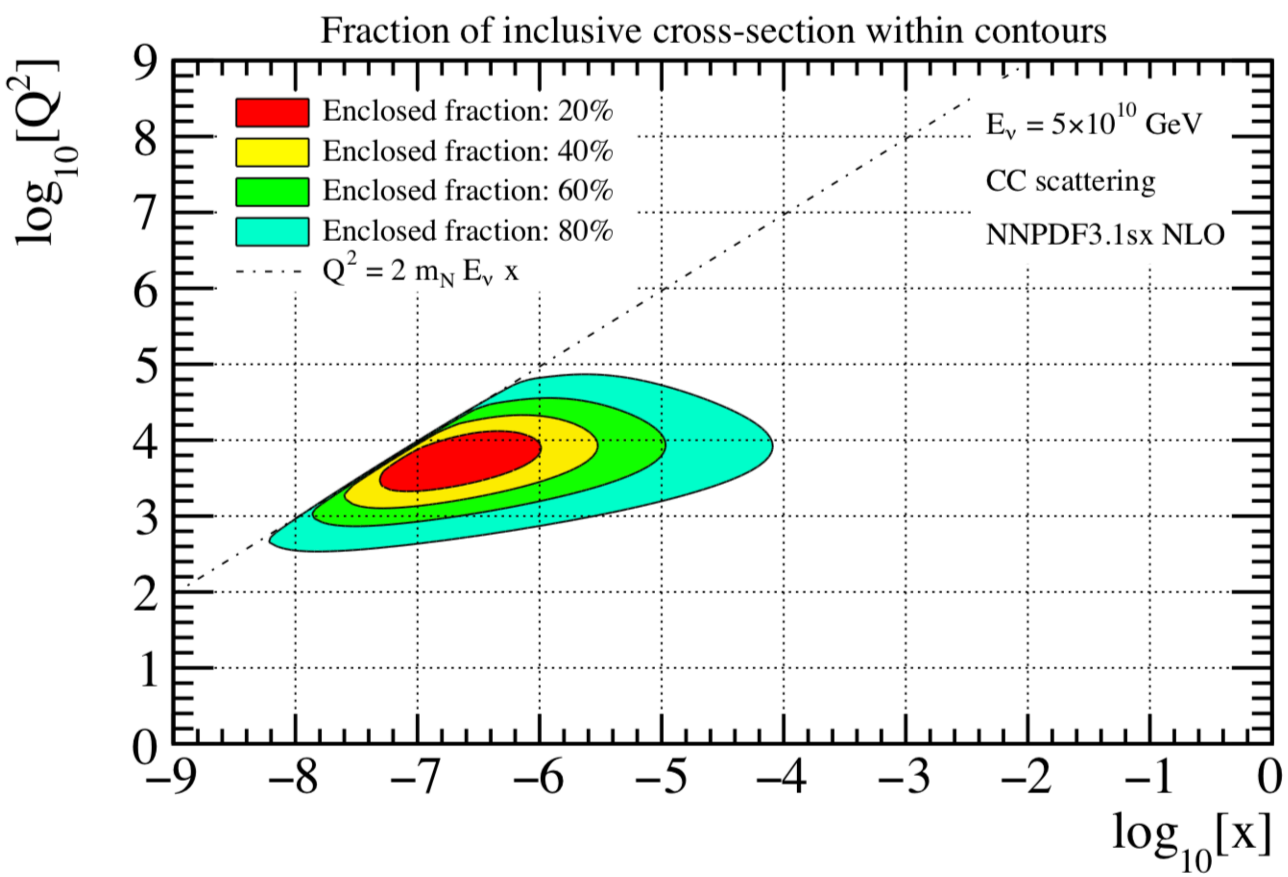
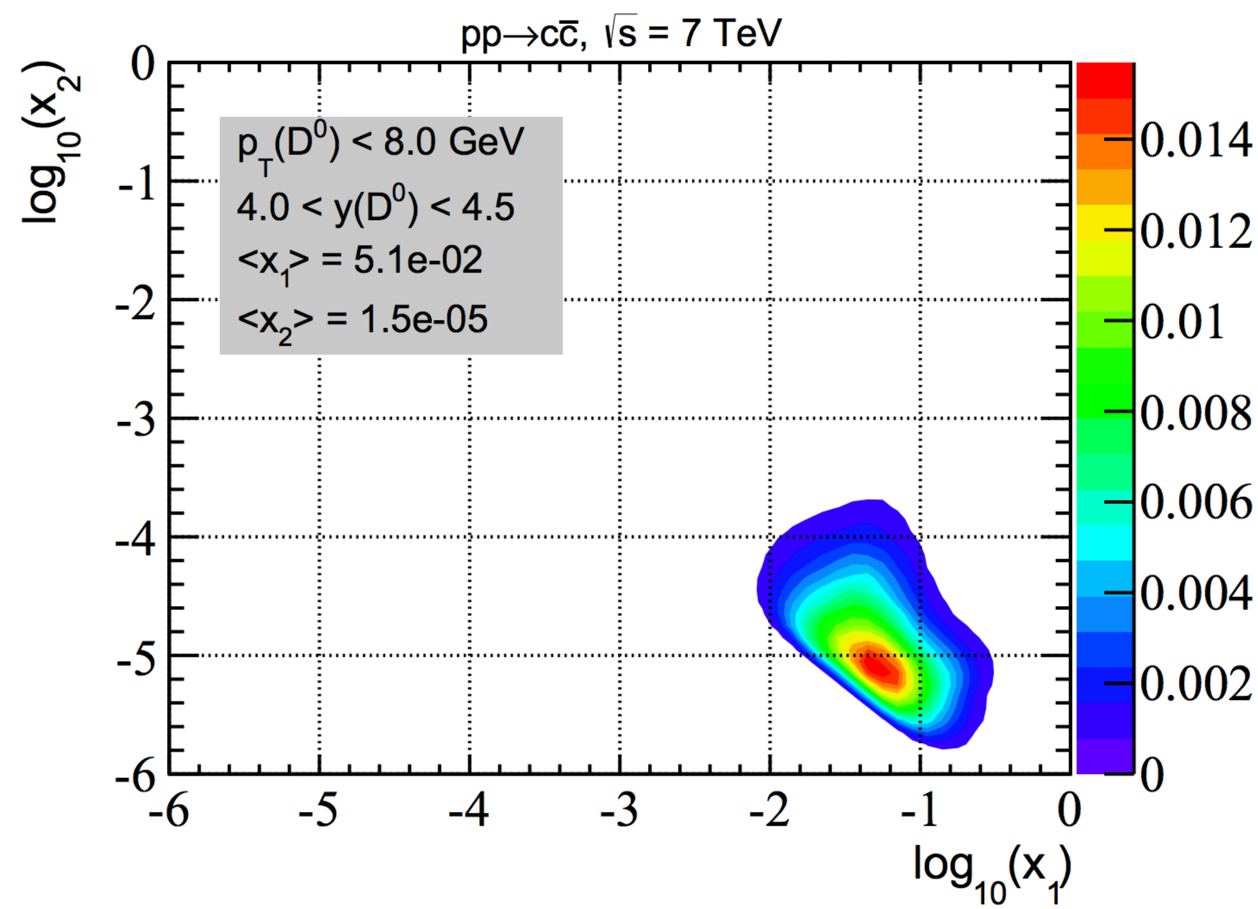


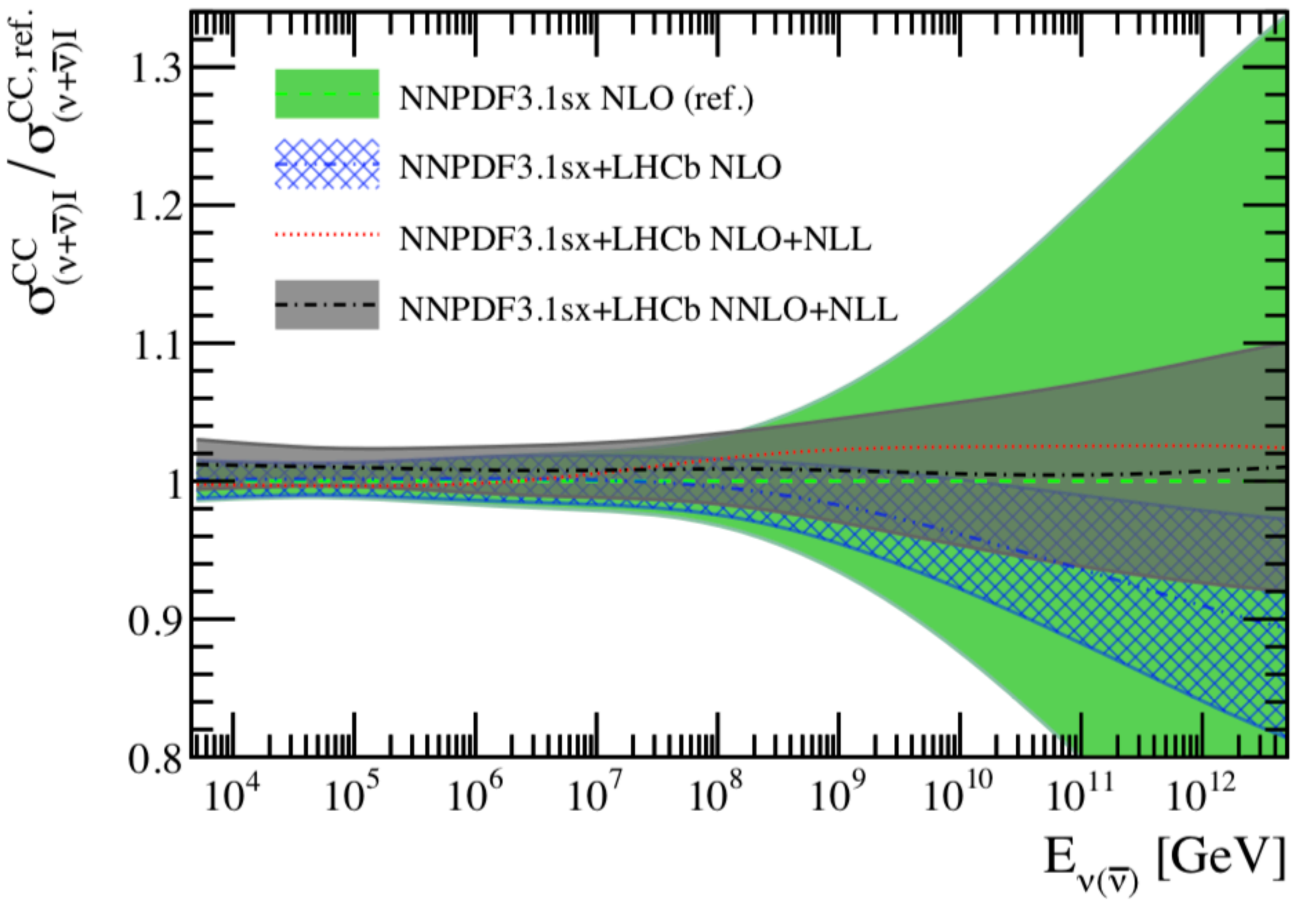
***background**: prompt charm production*

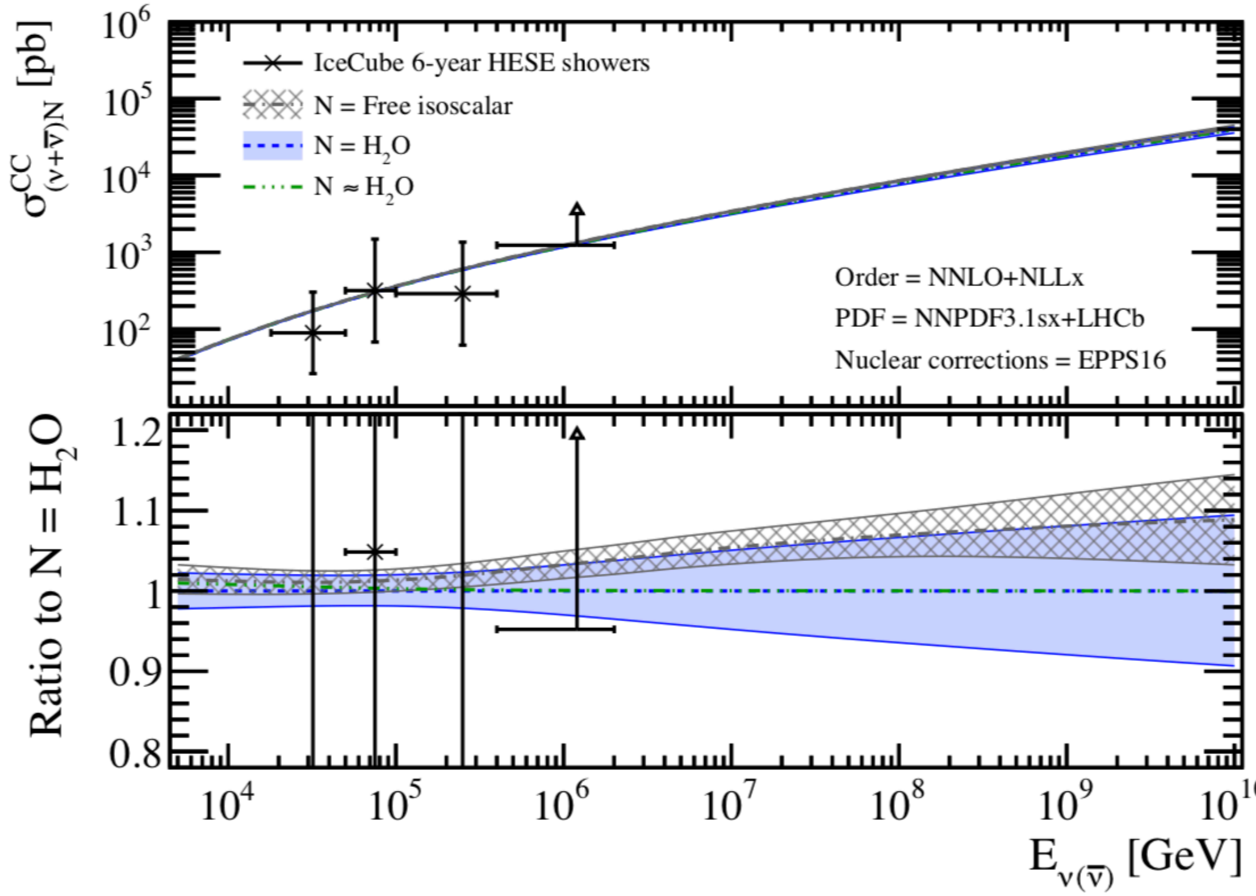


Sensitive to **small-*x* quarks** (and thus gluons via evolution) down to **x** ≃ **10^{-8}** and **Q** ≃ **M_W**

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

UHE neutrino-nucleus cross-section

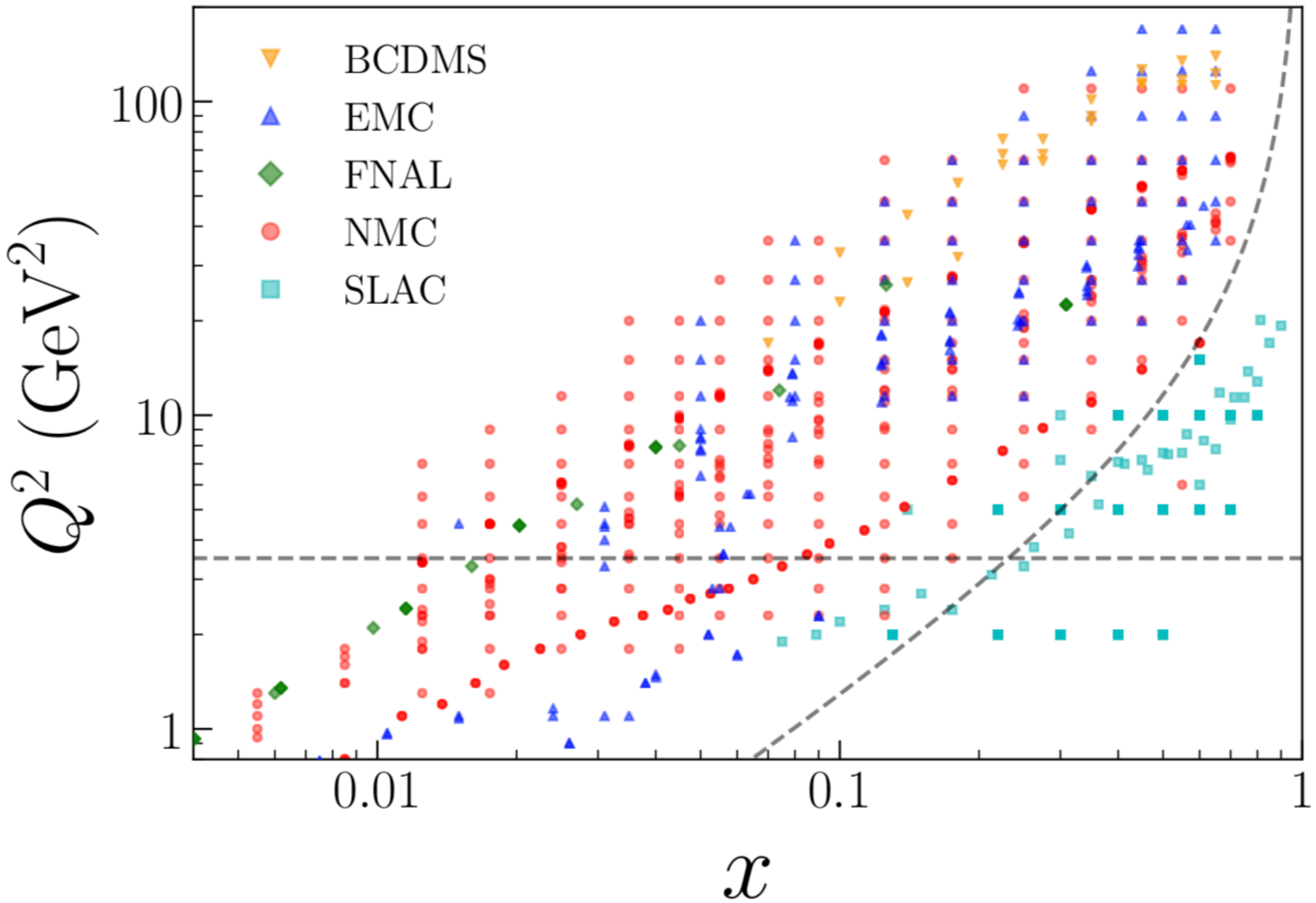




State-of-the-art predictions for **ultra-high energy** neutrino interactions

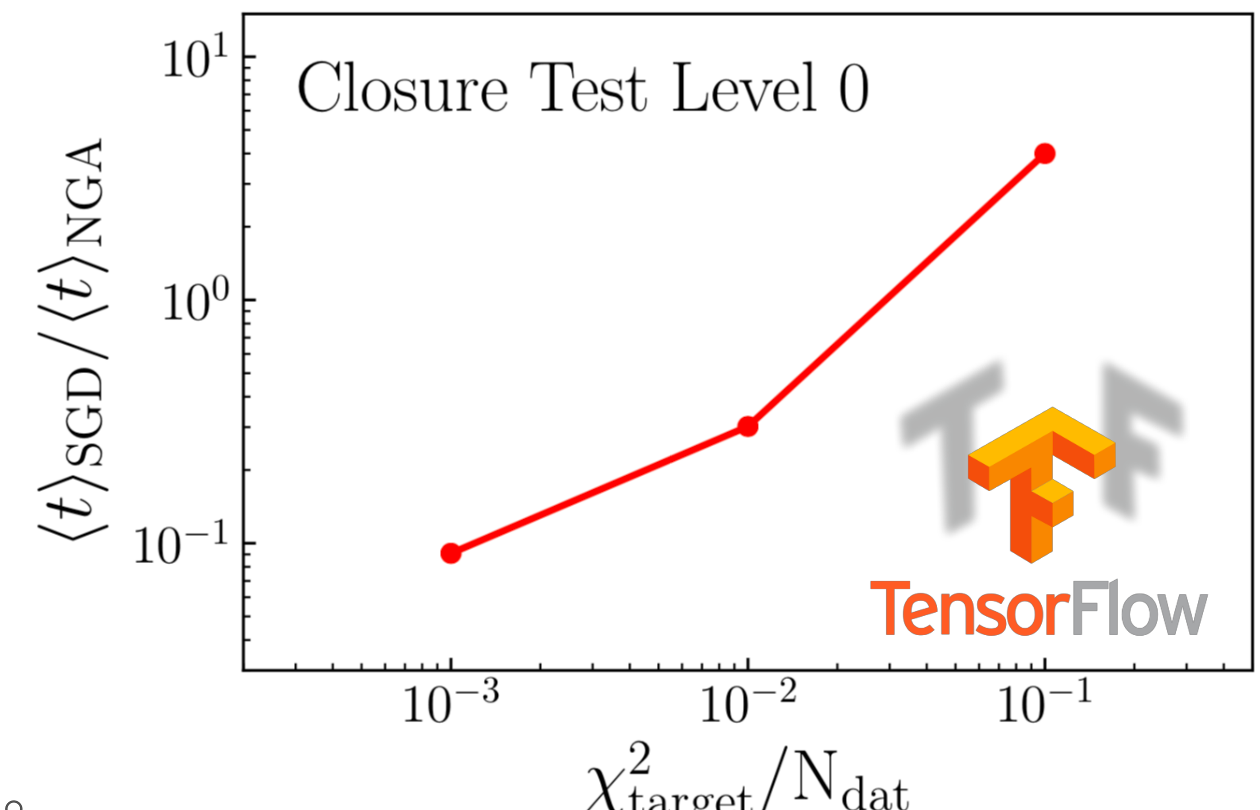
- **BFKL small-*x* resummation effects** in PDFs and structure functions
- Constraints on small-*x* PDFs from **LHCb charm production**
- IceCube and other neutrino telescopes are the **ultimate QCD microscopes!**

nNNPDF1.0



- First determination of **nuclear PDFs** based on the NNPDF framework
- Neutral-current DIS data for a range of *A* values
- Impose well-known free-nucleon PDFs as **boundary condition for *A=1***

- NN training with Google's *TensorFlow*: **Stochastic Gradient Descent**
- Factor 10 (or more) speed up as compared to evolutionary optimisers used in NNPDF



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