Parton Distributions:
Towards SnowMass 2021

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Snowmass 2021 Energy Frontier working group

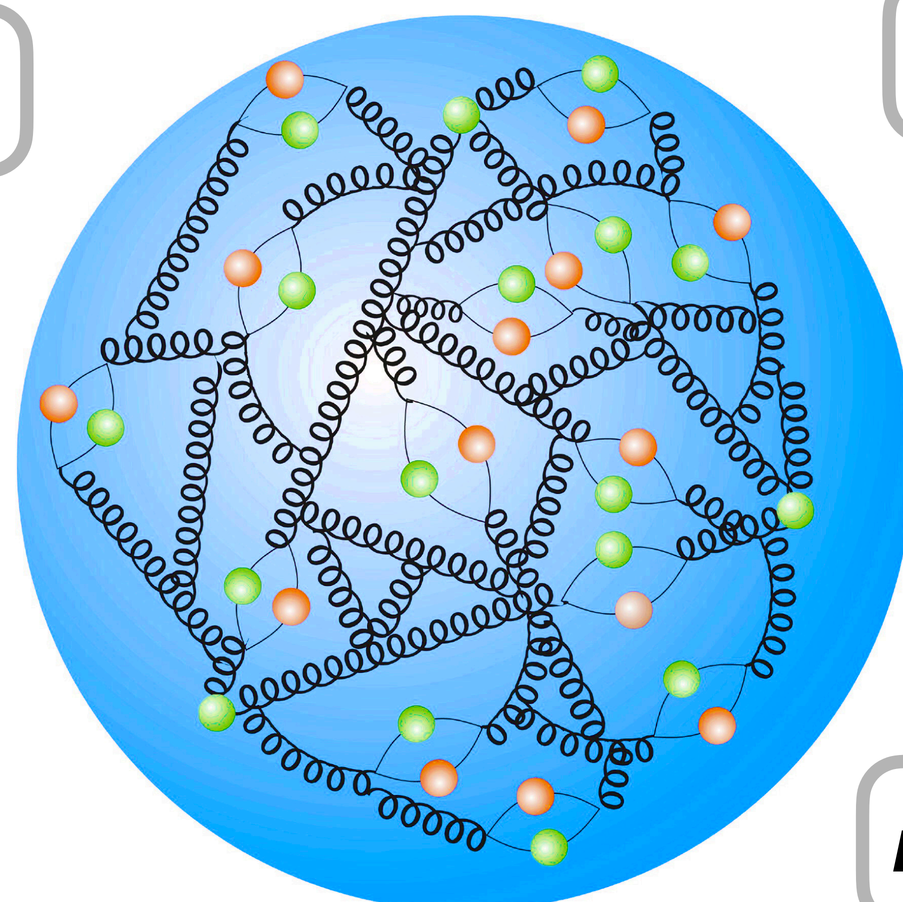
EF06: QCD and Strong Interactions, Hadronic Structure and forward QCD

Why Parton Distributions?

address open puzzles in our understanding of QCD

origin of mass?

spin budget?



3D imaging?

gluon-dominated matter?

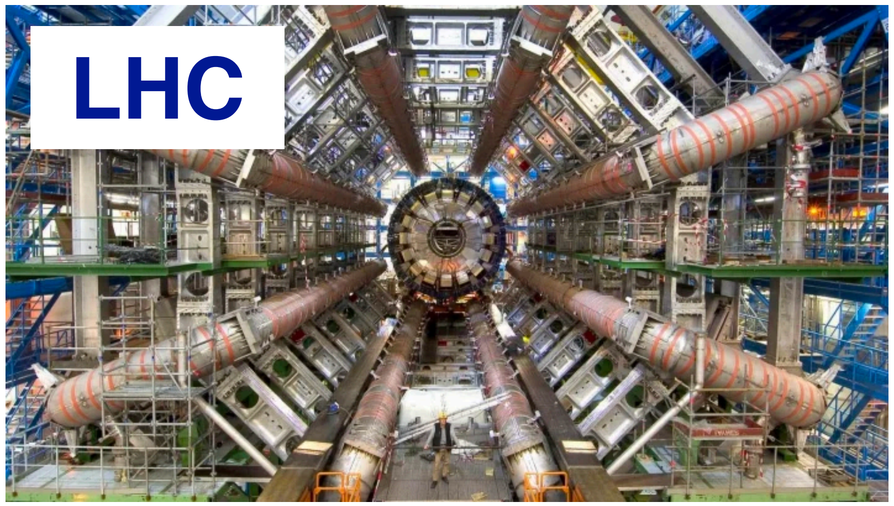
nuclear modifications?

heavy quark content?

photon & lepton content?

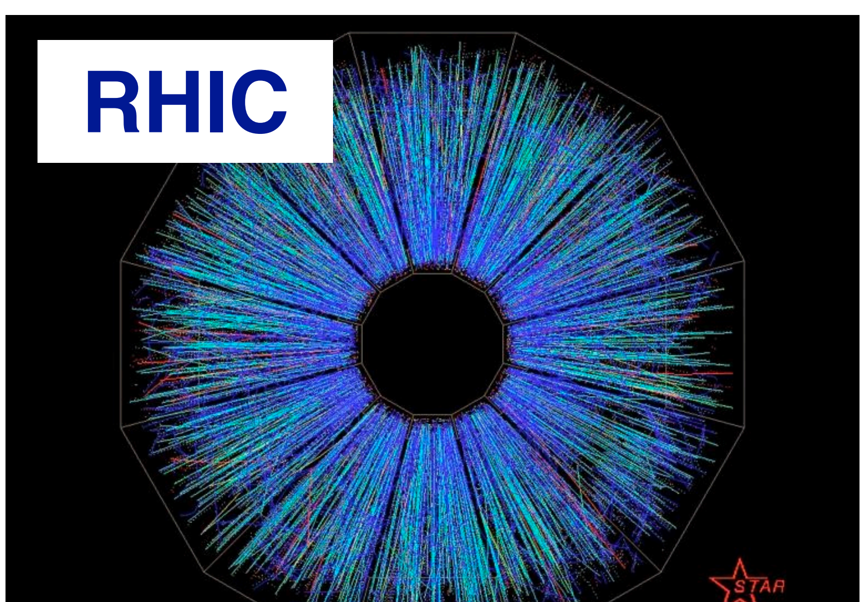
Why Parton Distributions?

crucial for precise theoretical predictions



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

Origins and properties of **cosmic neutrinos**?



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

Progress since Snowmass 2013

PDFs circa Snowmass 2013

1

ANL-HEP-CP-13-48
FERMILAB-FN-0967-CMS-T

Working group report: QCD

Conveners: J. M. Campbell, K. Hatakeyama, J. Huston, F. Petriello

J. Andersen, L. Barzè, H. Beauchemin, T. Becher, M. Begel, A. Blondel, G. Bodwin, R. Boughezal, S. Carrazza, M. Chiesa, G. Dissertori, S. Dittmaier, G. Ferrera, S. Forte, N. Glover, T. Hapola, A. Huss, X.Garcia i Tormo, M. Grazzini, S. Höche, P. Janot, T. Kasprzik, M. Klein, U. Klein, D. Kosower, Y. Li, X. Liu, P. Mackenzie, D. Maitre, E. Meoni, K. Mishra, G. Montagna, M. Moretti, P. Nadolsky, O. Nicrosini, F. Piccinini, L. Reina, V. Radescu, J. Rojo, J. Russ, S. Sapeta, A. Schwartzman, P. Skands, J. Smillie, I. W. Stewart, F. J. Tackmann, F. Tramontano, R. Van de Water, J. R. Walsh, S. Zuberi

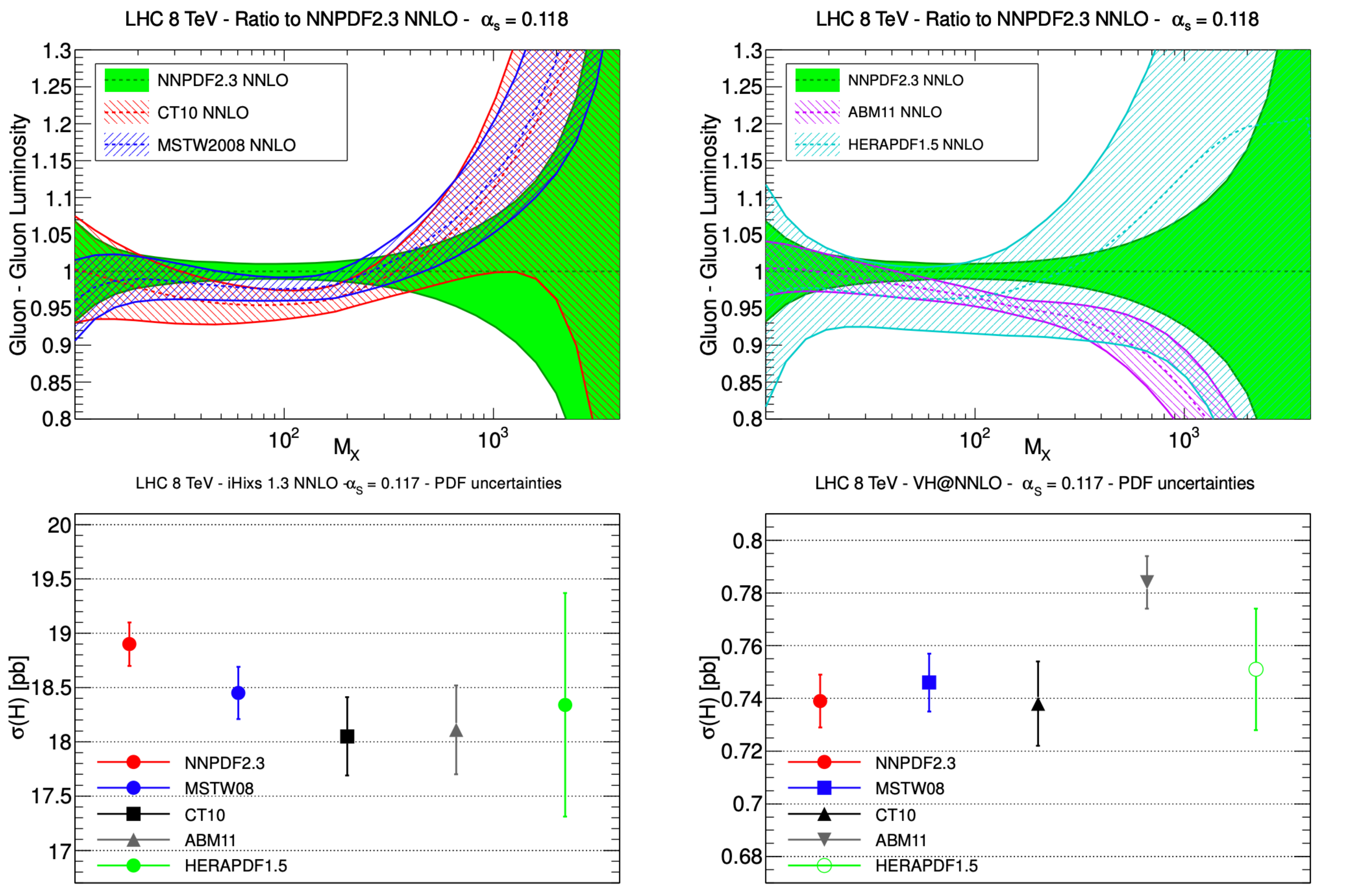
October 22, 2013

1.1 Executive summary

arxiv:1310:5189

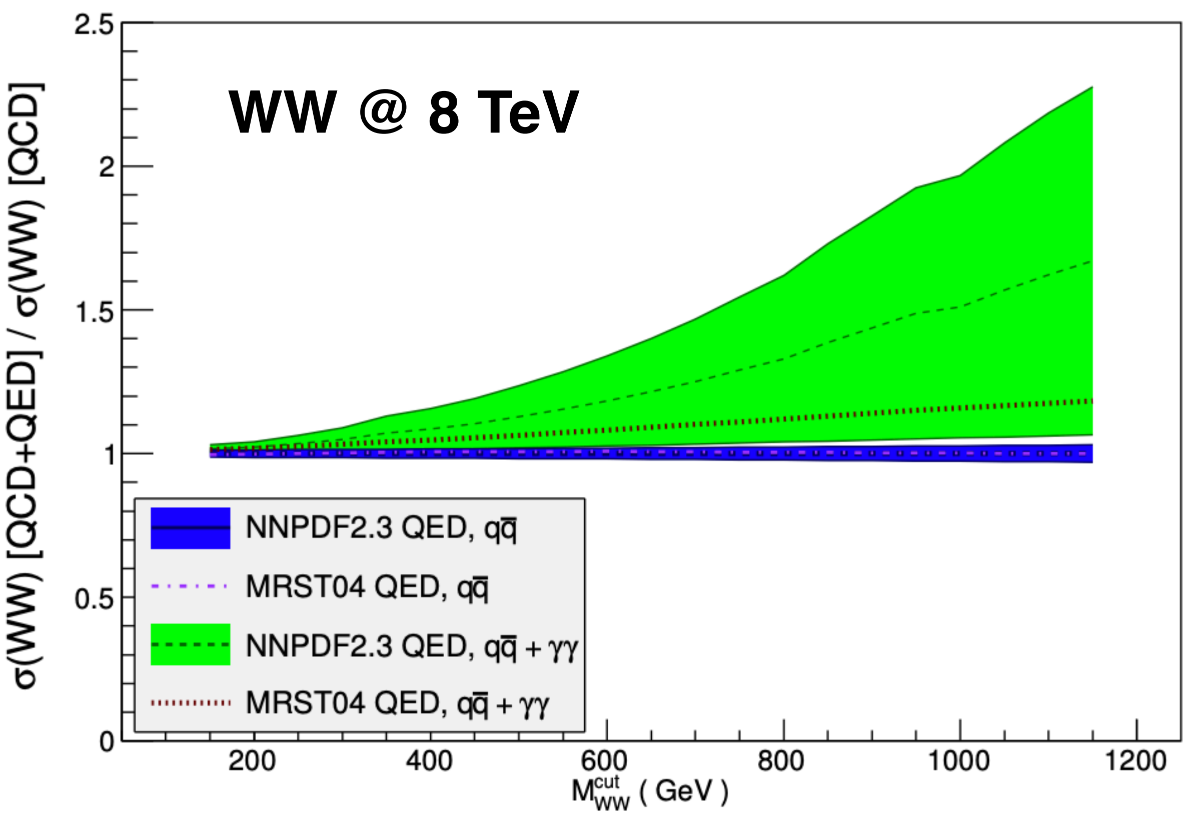
A quantitative description of Nature requires a detailed understanding of quantum chromodynamics (QCD) phenomenology. The success of Run 1 of the LHC relied upon advanced QCD simulation tools to support and guide experimental analyses, and the discovery of the Higgs boson illustrated the indispensable role of the QCD community in enabling discovery science. From parton distribution functions with robust errors, through calculations to the next-to-next-to-leading order and beyond in perturbative QCD, to the development of sophisticated Monte Carlo tools more faithful to the underlying hard dynamics, every advance from over a decade of research was needed to make this historic discovery possible. Run 2 of the LHC marks the beginning of the precision phase in our study of the mechanism of electroweak symmetry breaking. Quantitative QCD analyses will become ever more indispensable in unraveling the origin of what we have found.

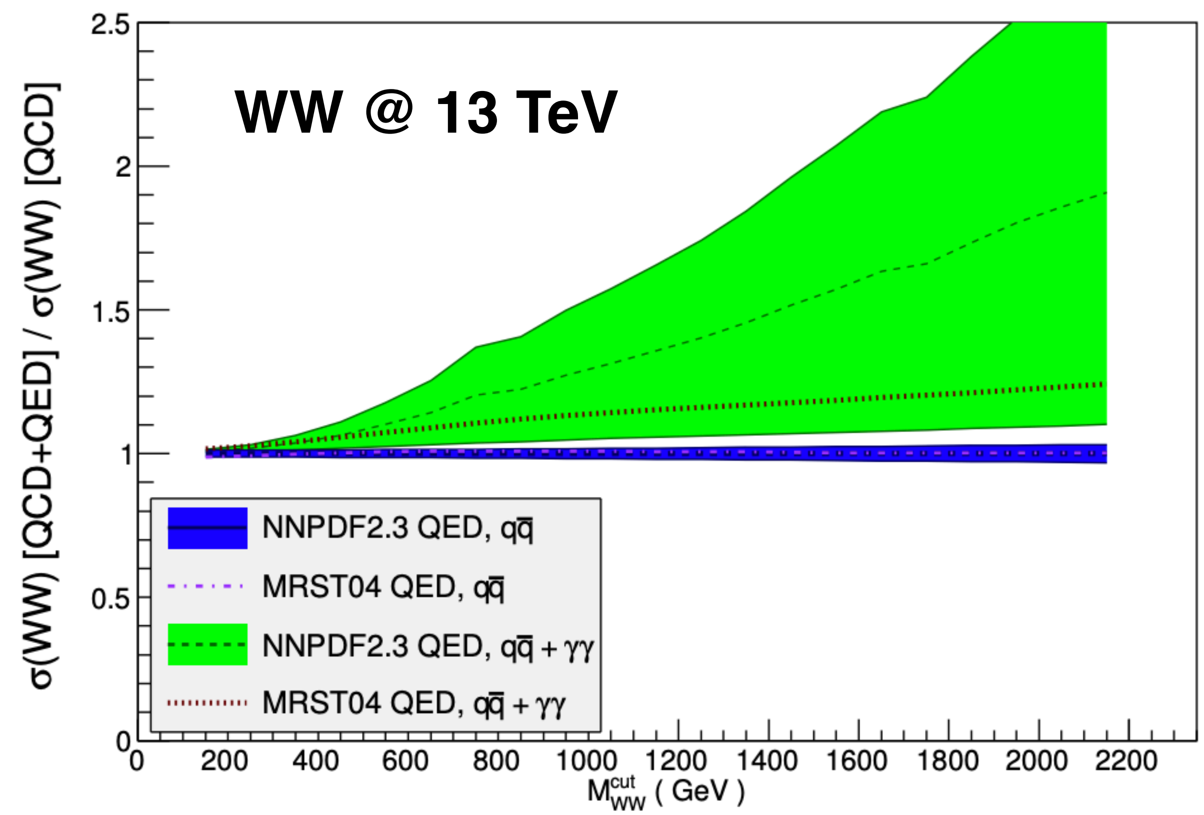
PDFs circa Snowmass 2013



global PDF sets included little or none LHC data, first comparisons with LHC xsecs

PDFs circa Snowmass 2013





initial studies of **QED PDFs:**

large errors in model-independent determinations of the photon PDF

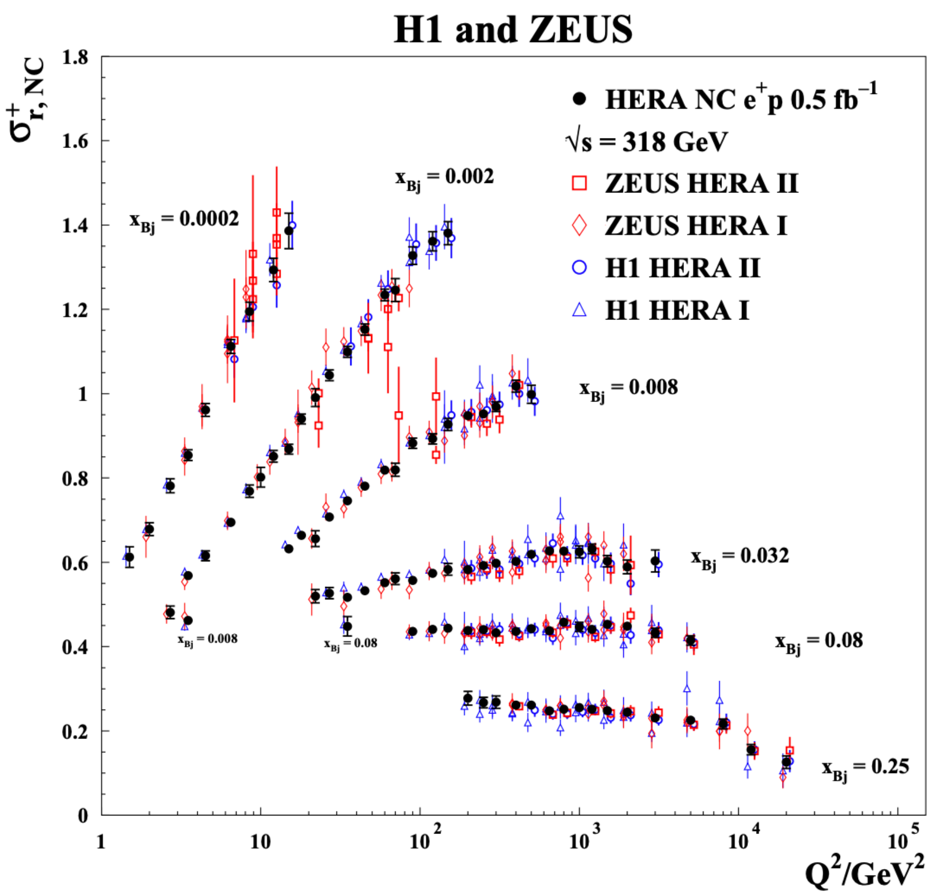
in addition to Snowmass-specific studies, other **PDF benchmarking exercises** carried out:

- Heavy quark schemes (Les Houches 2010)
- PDF4LHC Run I report (2011)
- PDF benchmarking with LHC data (2013)
- ……

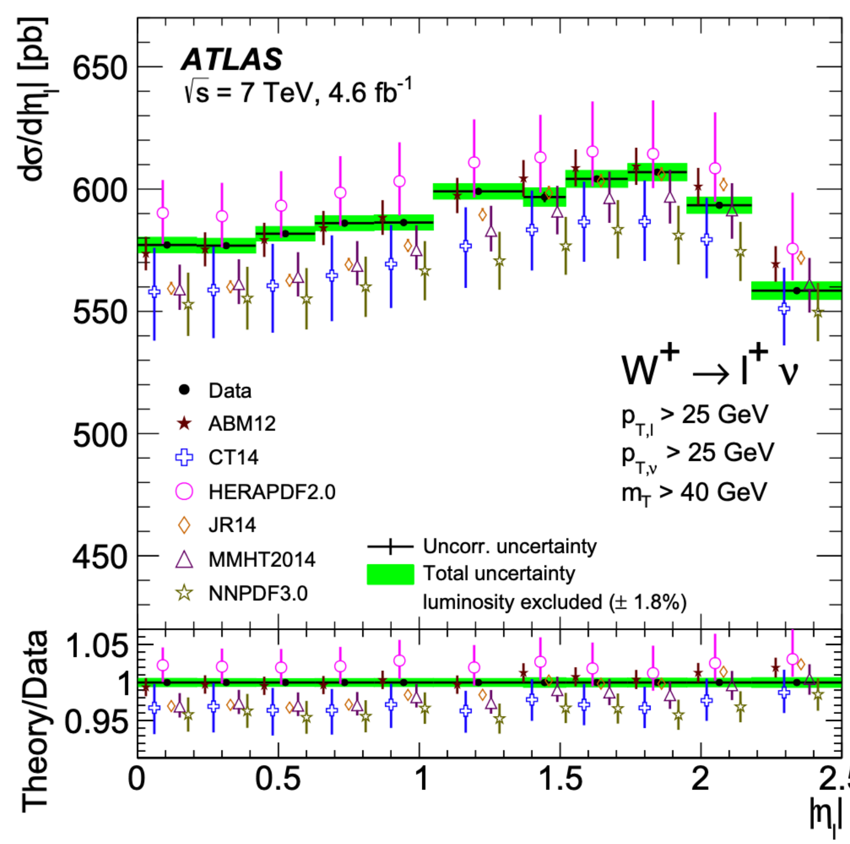
intense work toward a better understanding of global PDF fits

Progress: new data

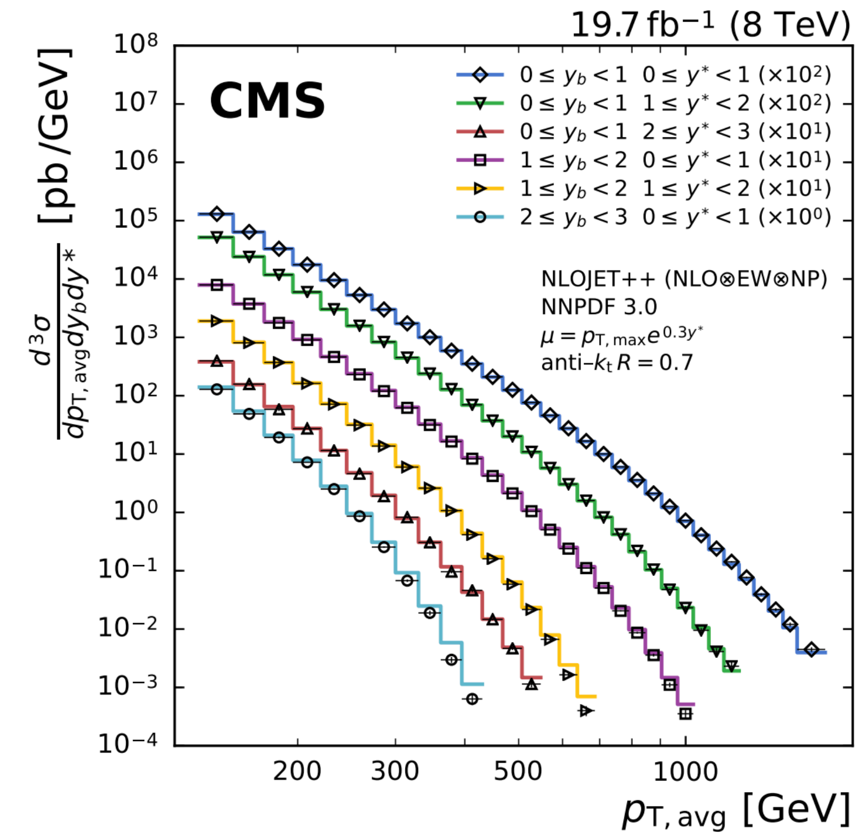
a plethora of **new PDF-sensitive datasets** have become available, in particular from the LHC experiments



HERA legacy combinations: backbone of PDF fits (inclusive, charm & bottom)



precision W, Z & Drell-Yan: constraints on quark flavour separation & strangeness

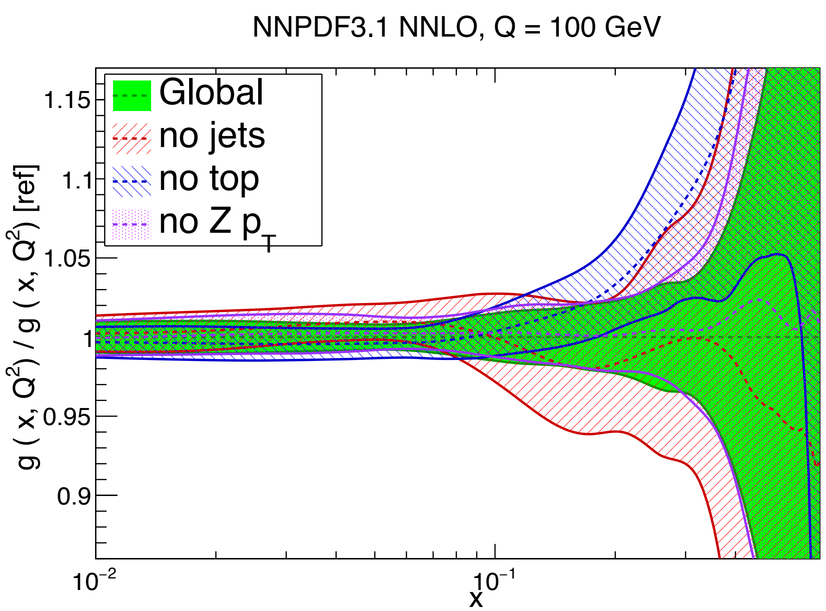


incl. jet and dijet production: probes of the large-x gluon

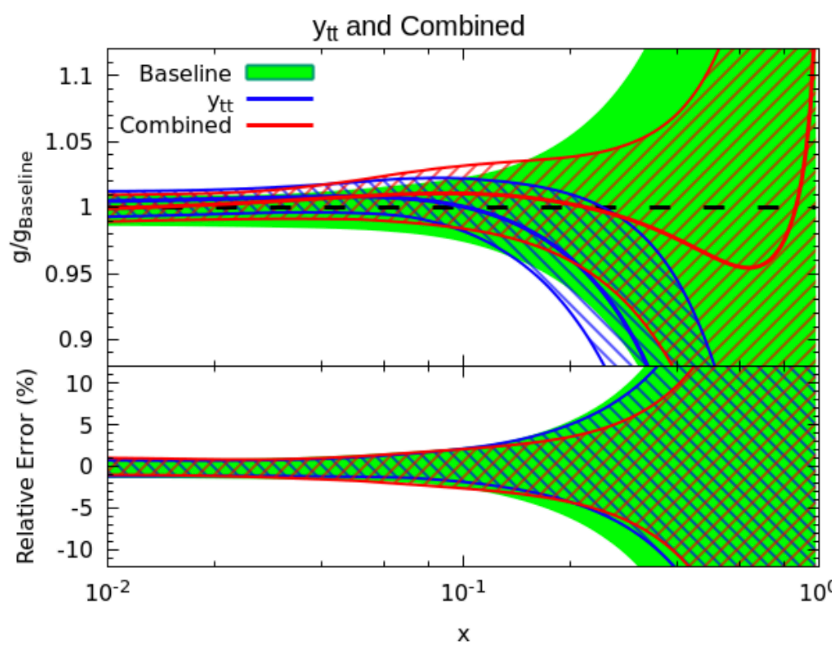
also: differential single and double top quark measurements, Z transverse momentum, isolated photons, charm production in the forward region, ….

Progress: new data

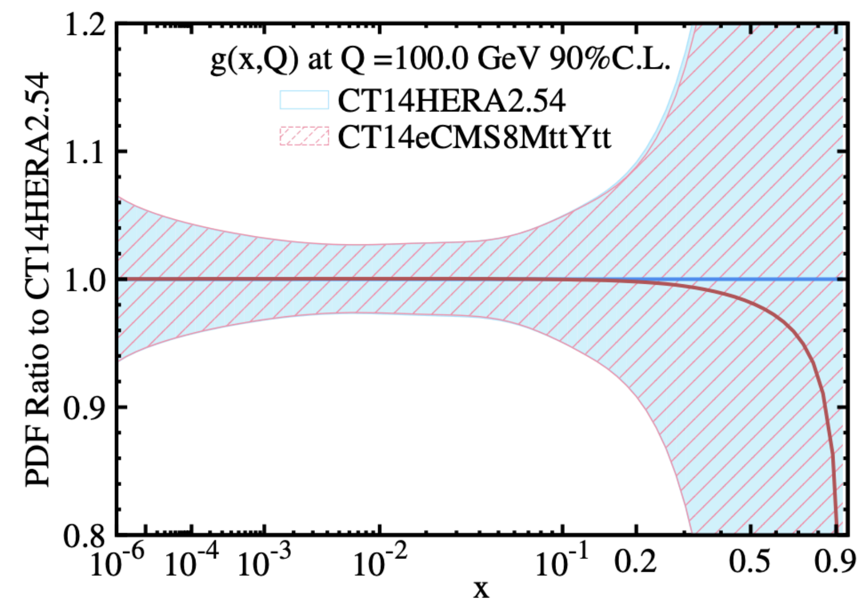
studies of **PDF impact** of new processes carried out by many groups



NNPDF



Bailey, Harland-Lang



CT + Czakon, Mitov

interpretation of LHC data often differs between groups, e.g. concerning top quark data

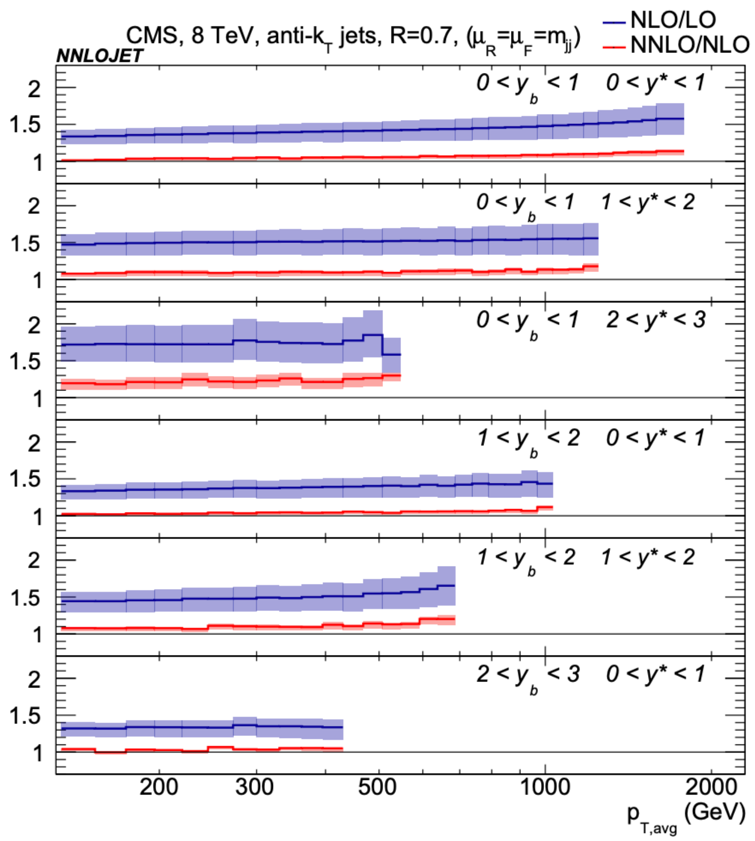
why **assessment of impact** of new data can differ so much between groups?

- Methodological differences, *e.g.* Hessian with tolerance vs MC replicas, refit vs profiling/rw, …
- Differences choices of fitted distributions, *e.g.* rapidity vs p_T, normalised vs absolute
- Ill-defined experimental correlation matrices, strong sensitivity to correlation model

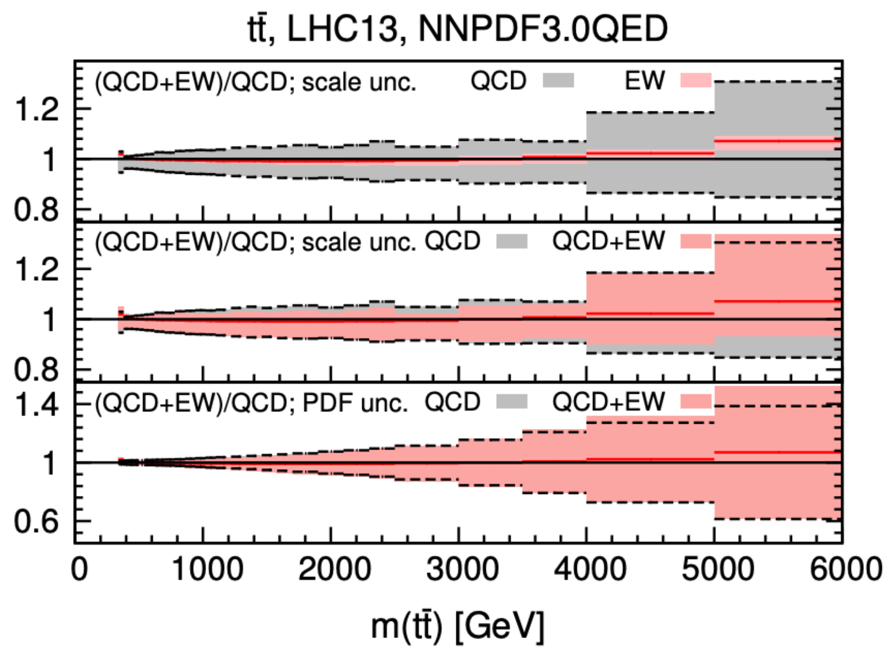
the better the data, the more challenging the PDF interpretations!

Progress: better theory

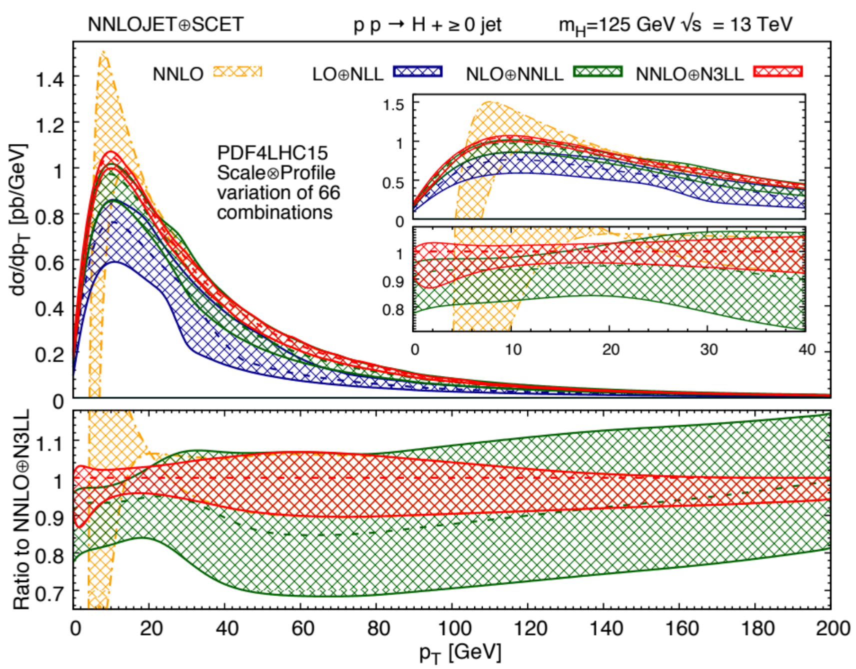
higher order QCD (NNLO) and electroweak (NLO) corrections now available for (essentially) all **relevant processes for PDF fits**



incl. jet, 2D & 3D dijets



differential top-quark pair



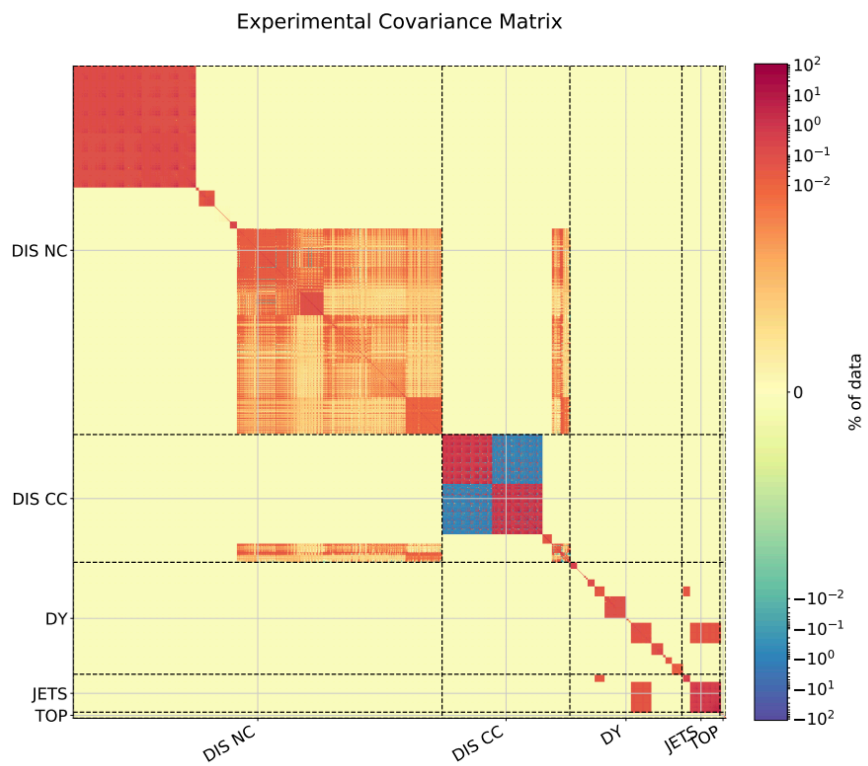
W, Z transverse momentum

*strong evidence that **NNLO PDF fits are markedly superior** to NLO ones*
(do we even need still NLO PDFs?)

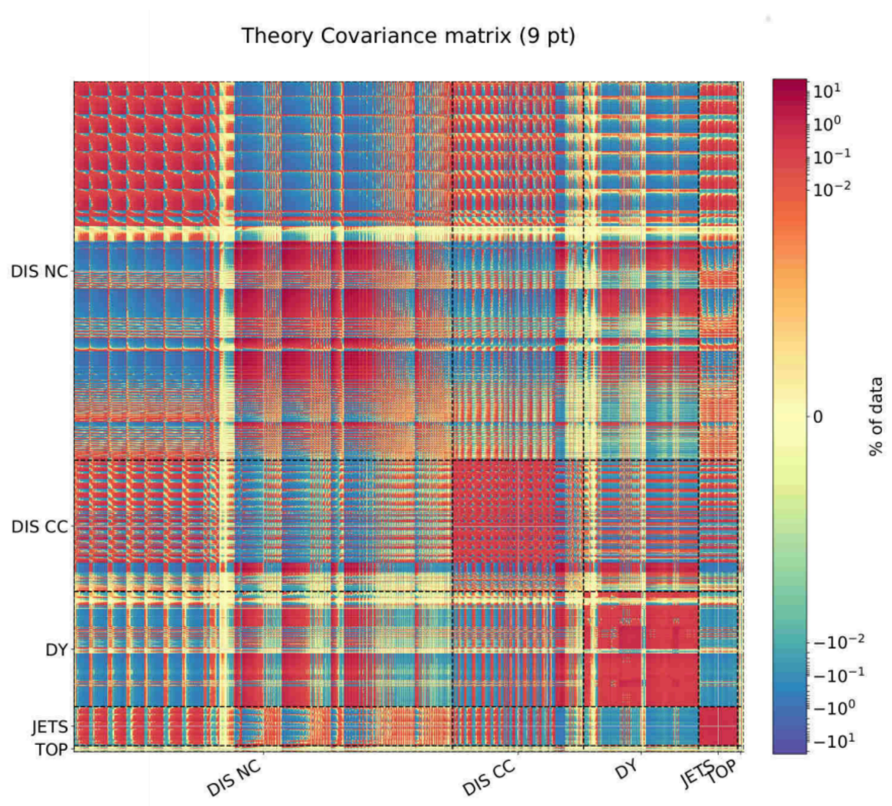
*for many processes the state-of-the-art theory prediction includes **all-order resummation:** need to combine with resummation-improved PDFs for consistency?*

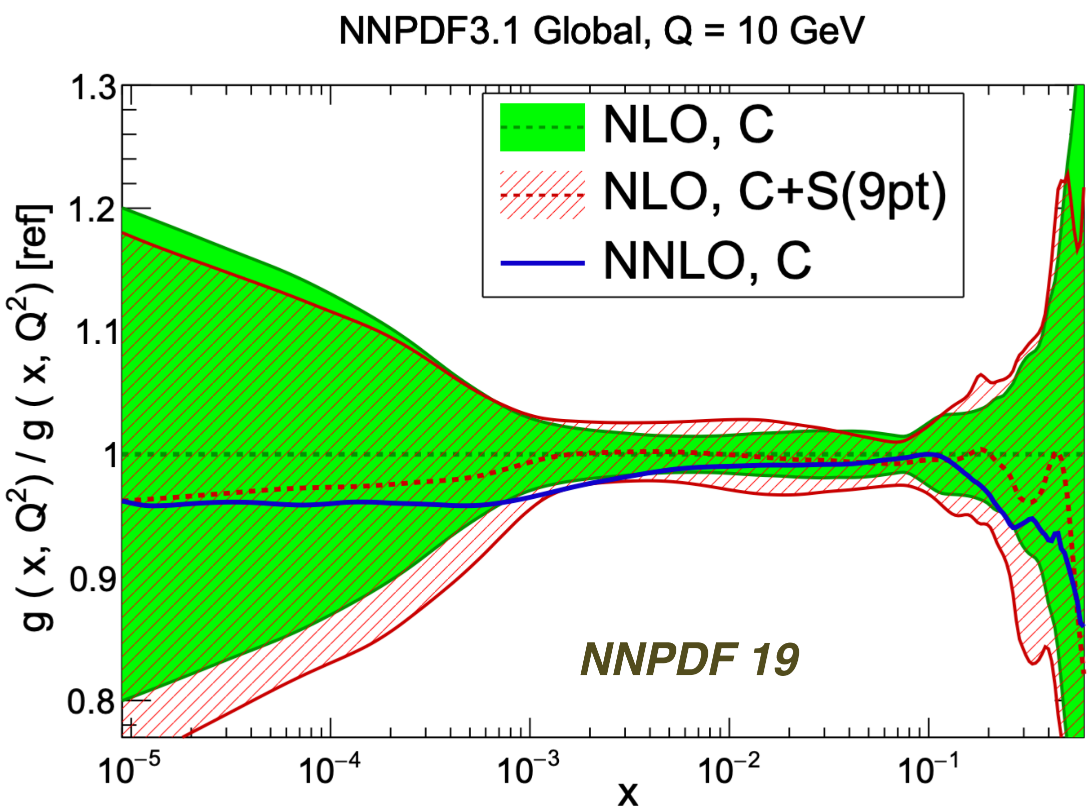
Progress: better theory

impact of Missing Higher Order uncertainties (MHOUs) on PDF fits quantified



- Consistent inclusion of MHOUs crucial for any global interpretation of high-energy data: so far missing in PDF fits
- MHOUs not only increase uncertainties, they induce an altogether **new pattern of theory-driven correlations**
- At NLO effect of MHOUs comparable with “normal” PDF errors

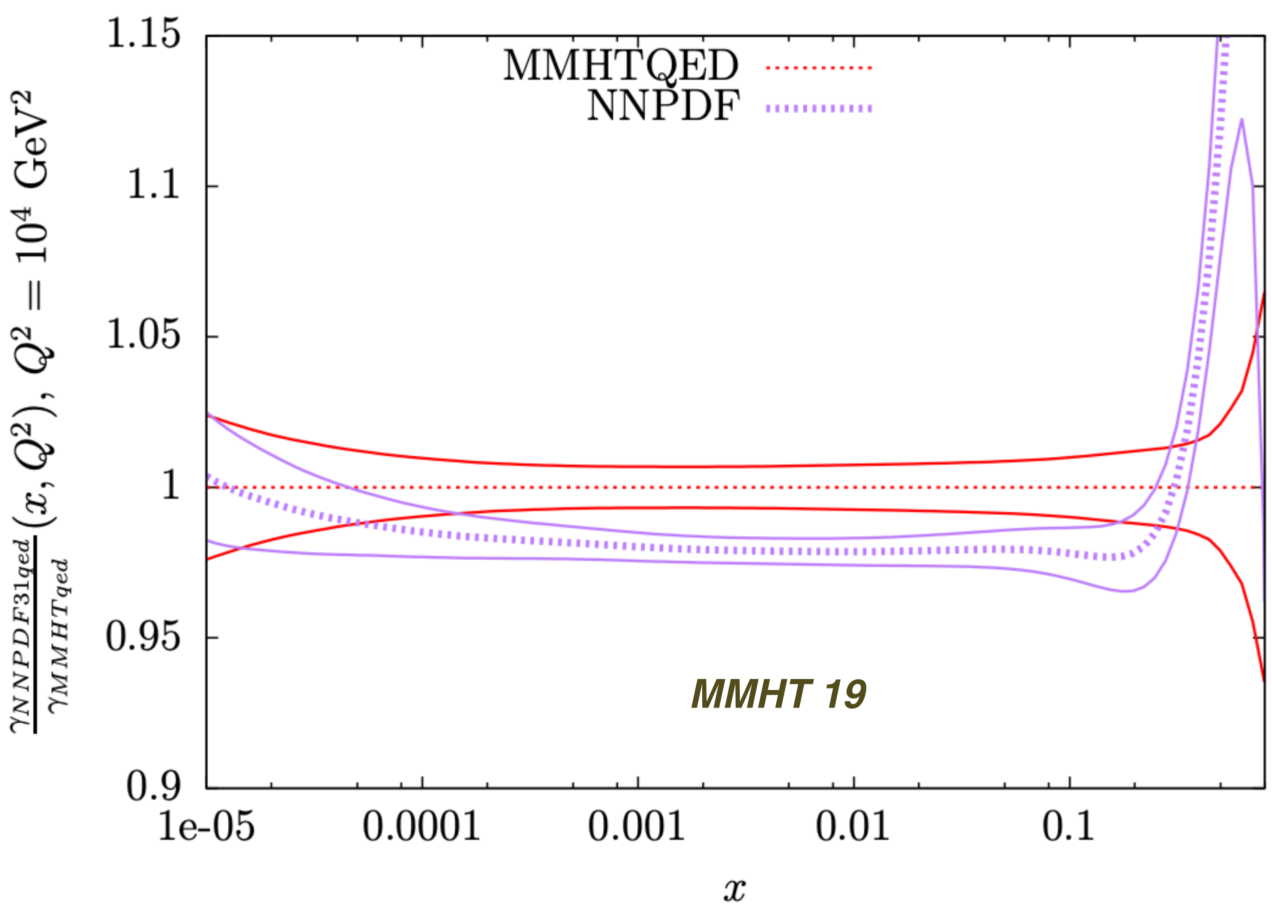


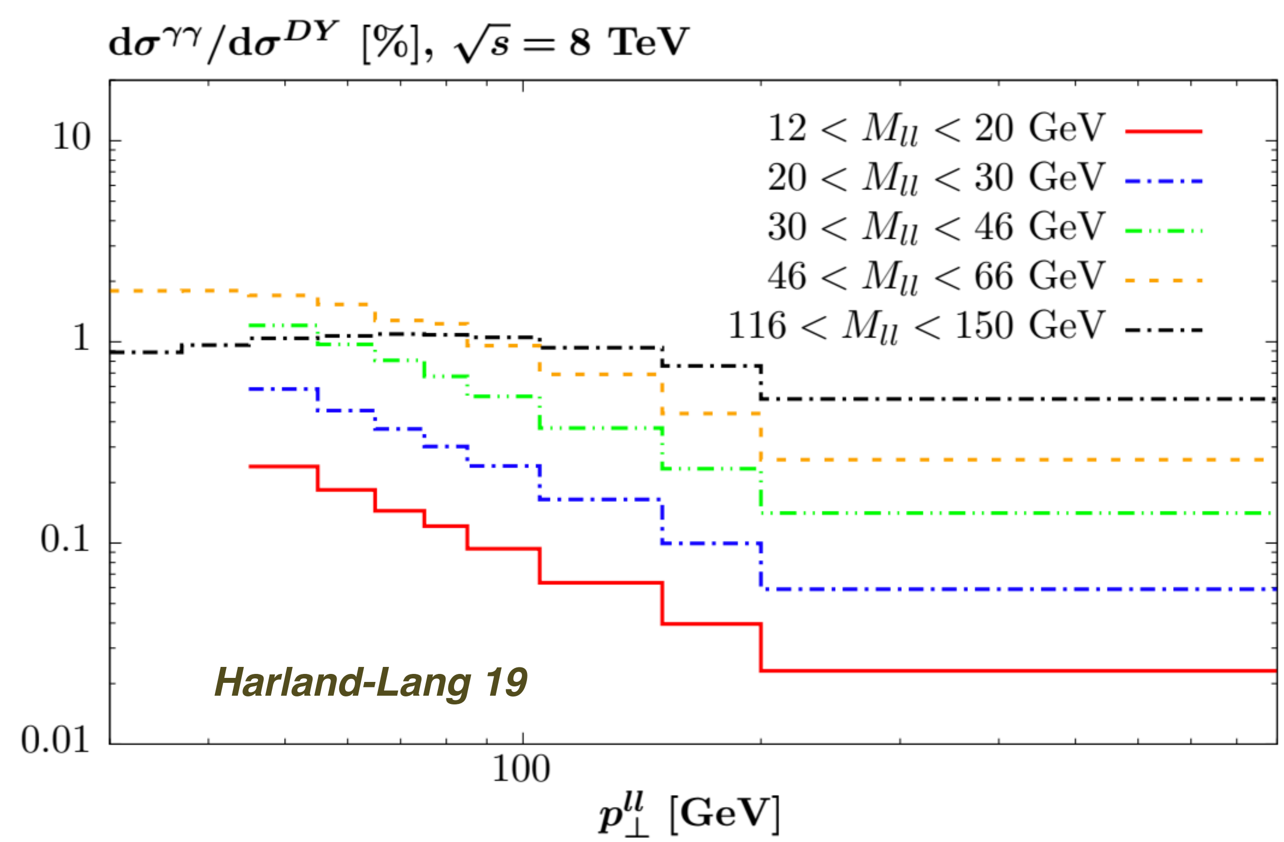


Progress: better theory

precision determination of photon and lepton PDFs for **photon-initiated processes**

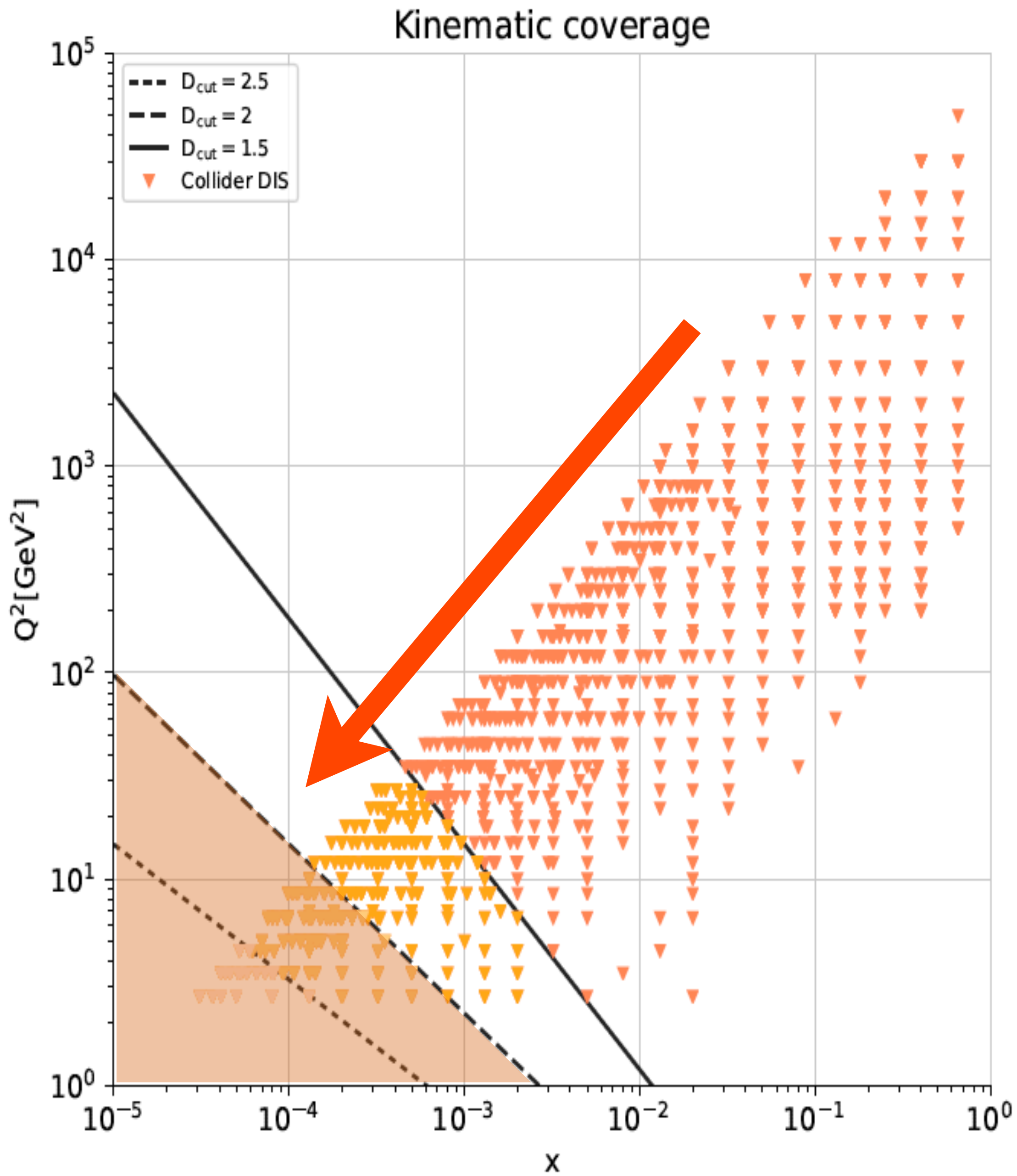
- Inclusion of **QED and EW effects** in matrix elements: also in PDFs for consistency
- Photon PDFs (and from them lepton PDFs) can be expressed in terms of DIS structure functions
- Most global PDF fits provide now QED sets based on variants of the **LUXqed formalism**. Also we now have a much better understanding of photon-initiated processes

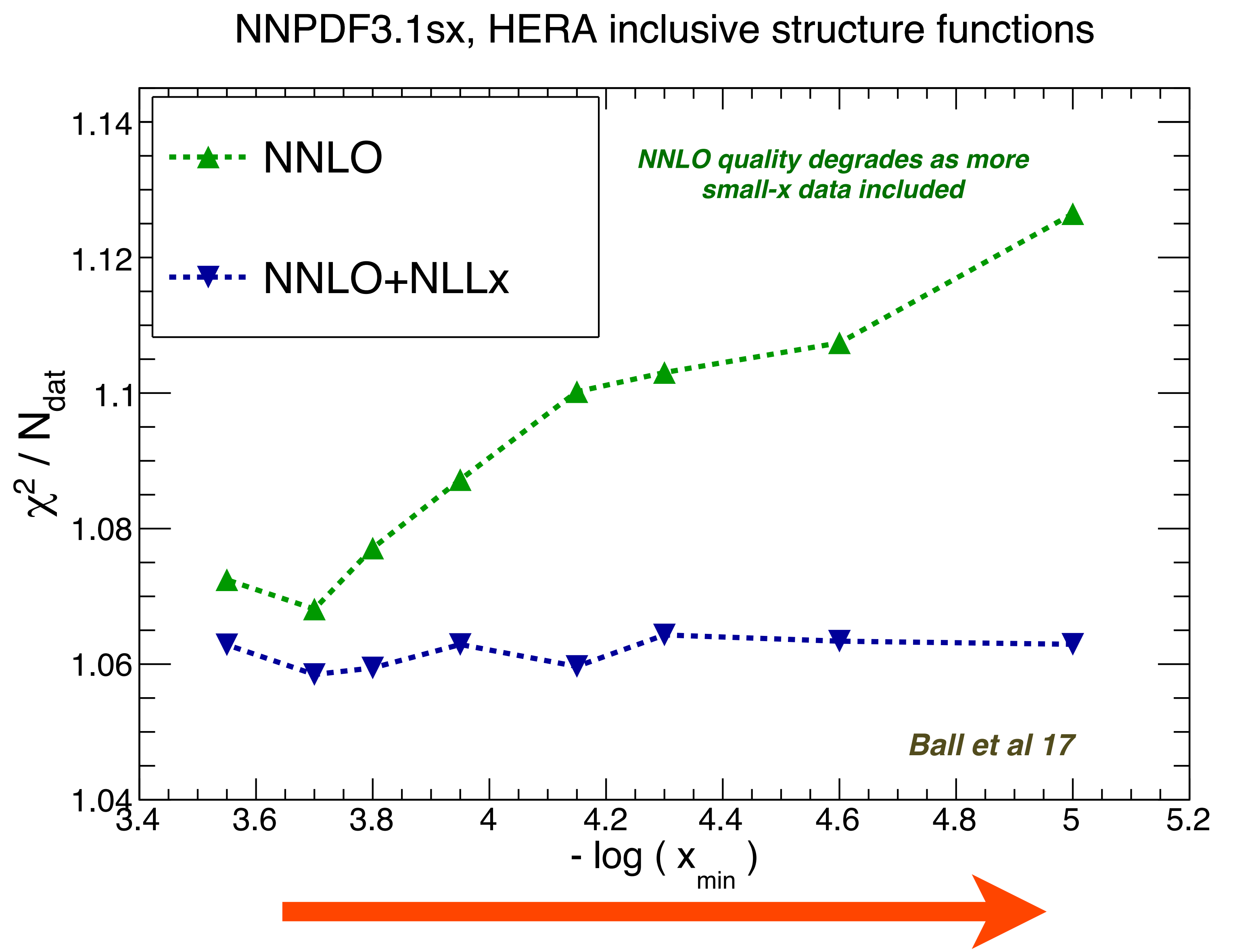




Progress: better theory

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





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!**

Methodological improvements

In **Machine Learning** applications, the model has several parameters which are typically **adjusted by hand** (trial and error) rather than algorithmically:

- Network architecture: number of layers of neurons per layer, activation functions, …
- Choice of minimiser (which of the Gradient Descent variants?)
- Learning rate, momentum, memory, size of mini-batches, ….
- Regularisation parameters, stopping, dropout rate, patience, …

one can avoid the need of subjective choice by means of **an hyperoptimisation procedure**, where all model and training/stopping parameters are determined algorithmically

Such hyperoptimisation requires introducing a **reward function** to grade the model. Note that this is different from the **cost function:** the latter is optimised separately model by model (e.g. for each NN architecture) while the former compares between all optimised models

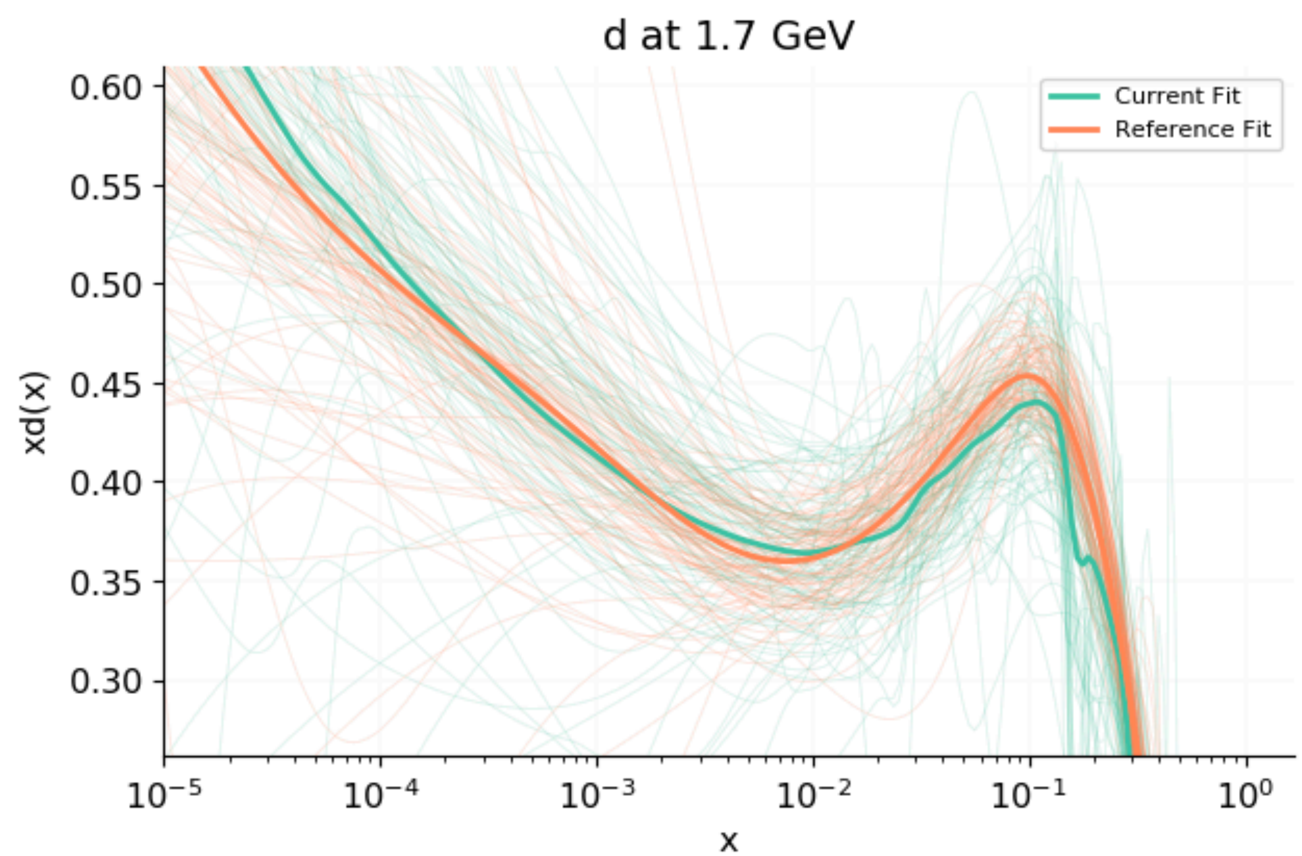
e.g. cost function $C = E_{\rm tr}$

reward function $R = \frac{1}{2}\left(E_{\rm val} + E_{\rm test}\right)$

Methodological improvements

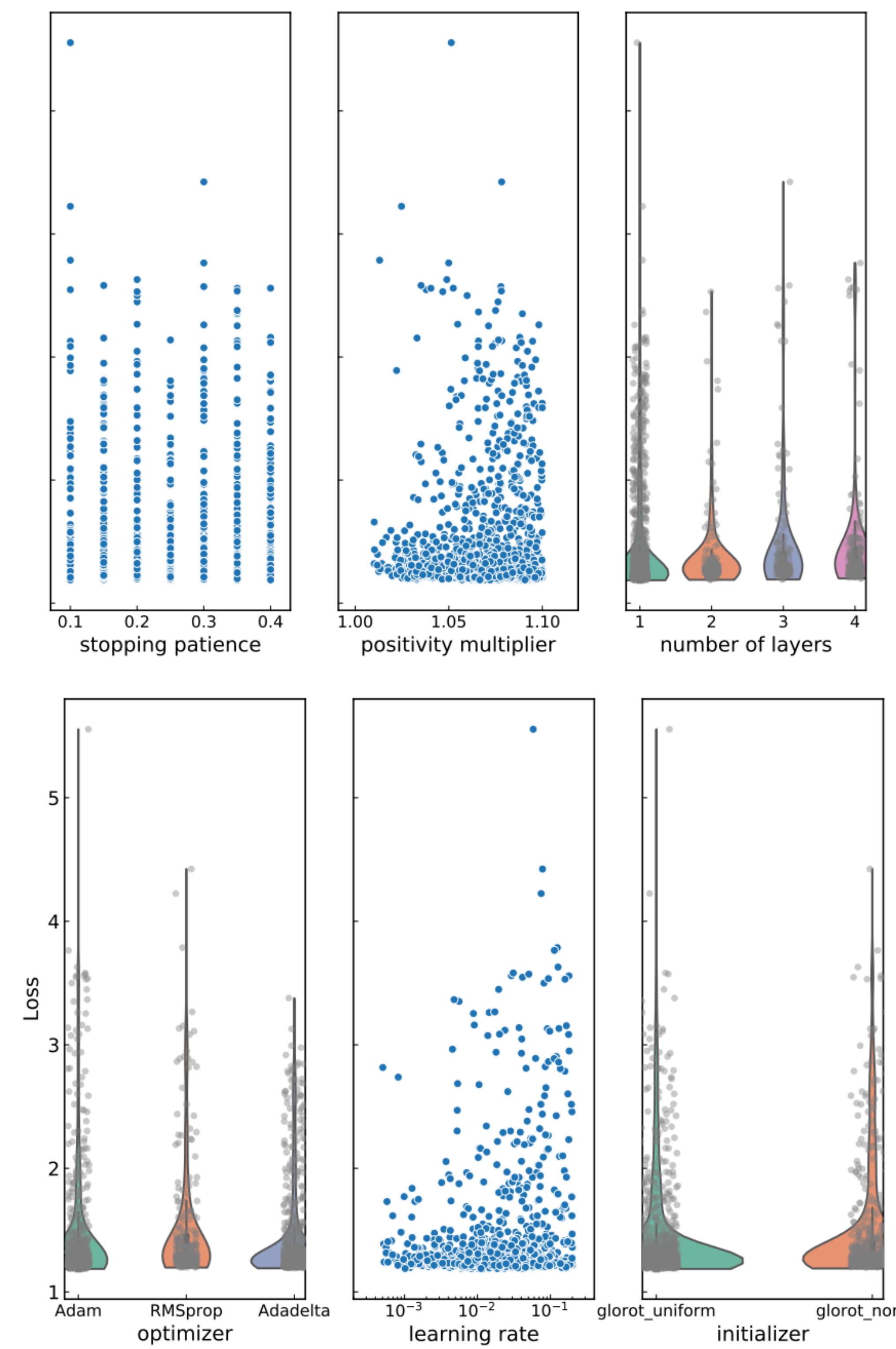
hyper-optimised neural network PDF fits

- per-replica training time reduced by **factor O(30)** thanks to **SGD minimisers in TensorFlow**
- **smoother** individual replicas, higher fraction of replicas satisfying quality requirements



	n3fit	NNPDF 3.1
χ^2	1.149	1.158
Avg time	70 minutes	35 hours
Memory	16 Gb	5 Gb
Good replicas	95%	70%

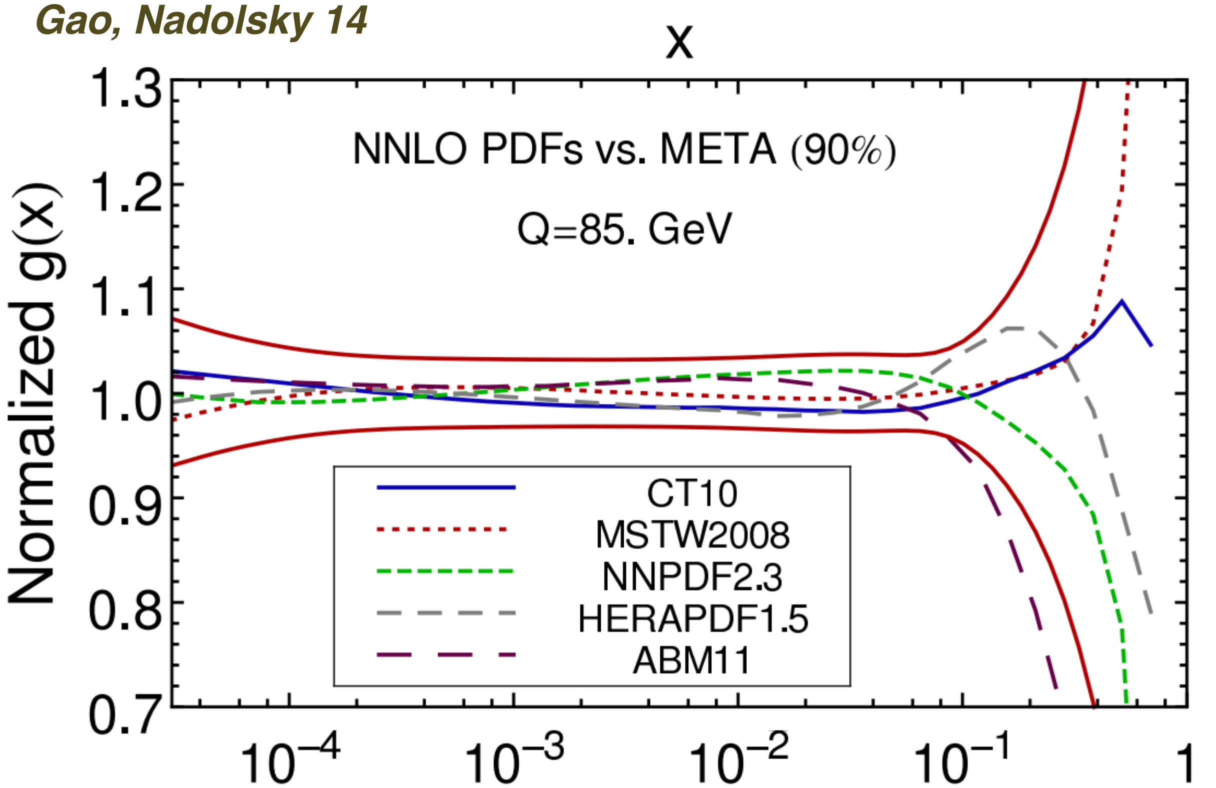
Carrazza, Cruz-Martinez 19



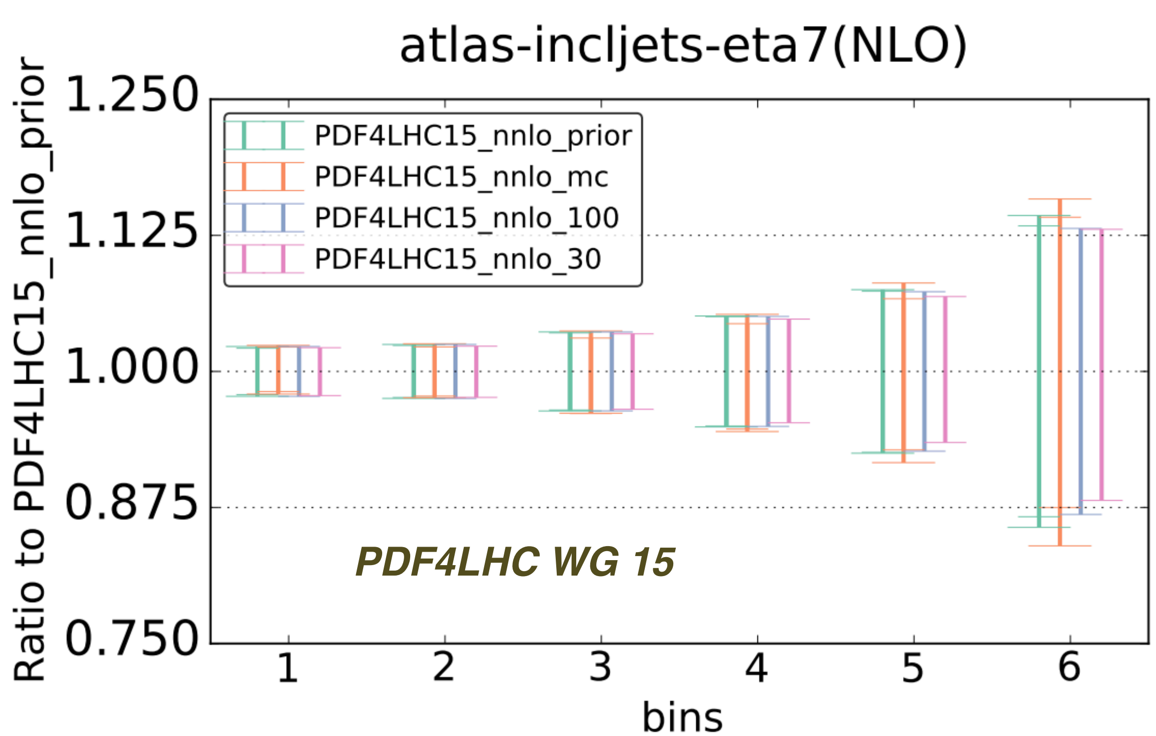
Methodological improvements

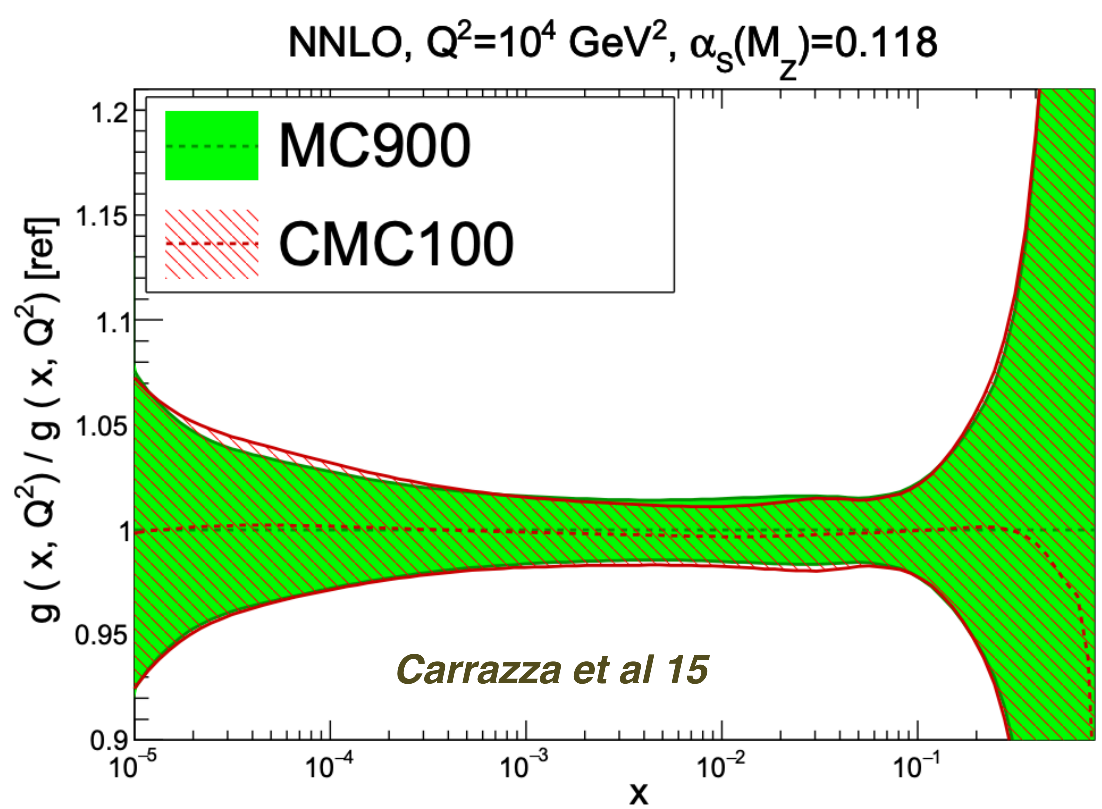
reduction, compression, and **combination tools** for PDF fits

Gao, Nadolsky 14



- Statistical combination of global fits and subsequent reduction to optimised sets for pheno
- Lead to **PDF4LHC15 combination**, widely used for LHC applications
- New ideas inspired in ML, for example using generative adversarial networks

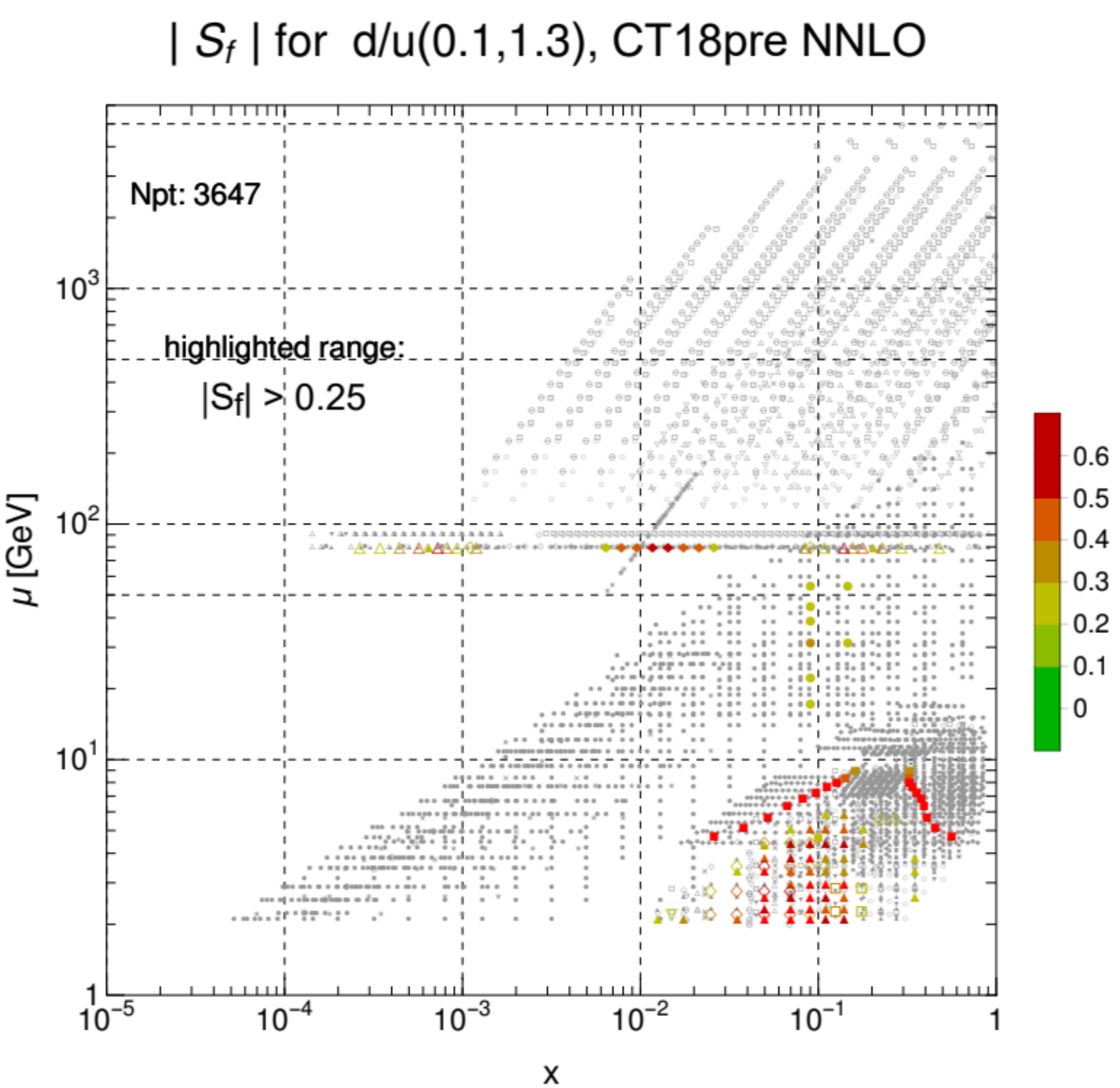


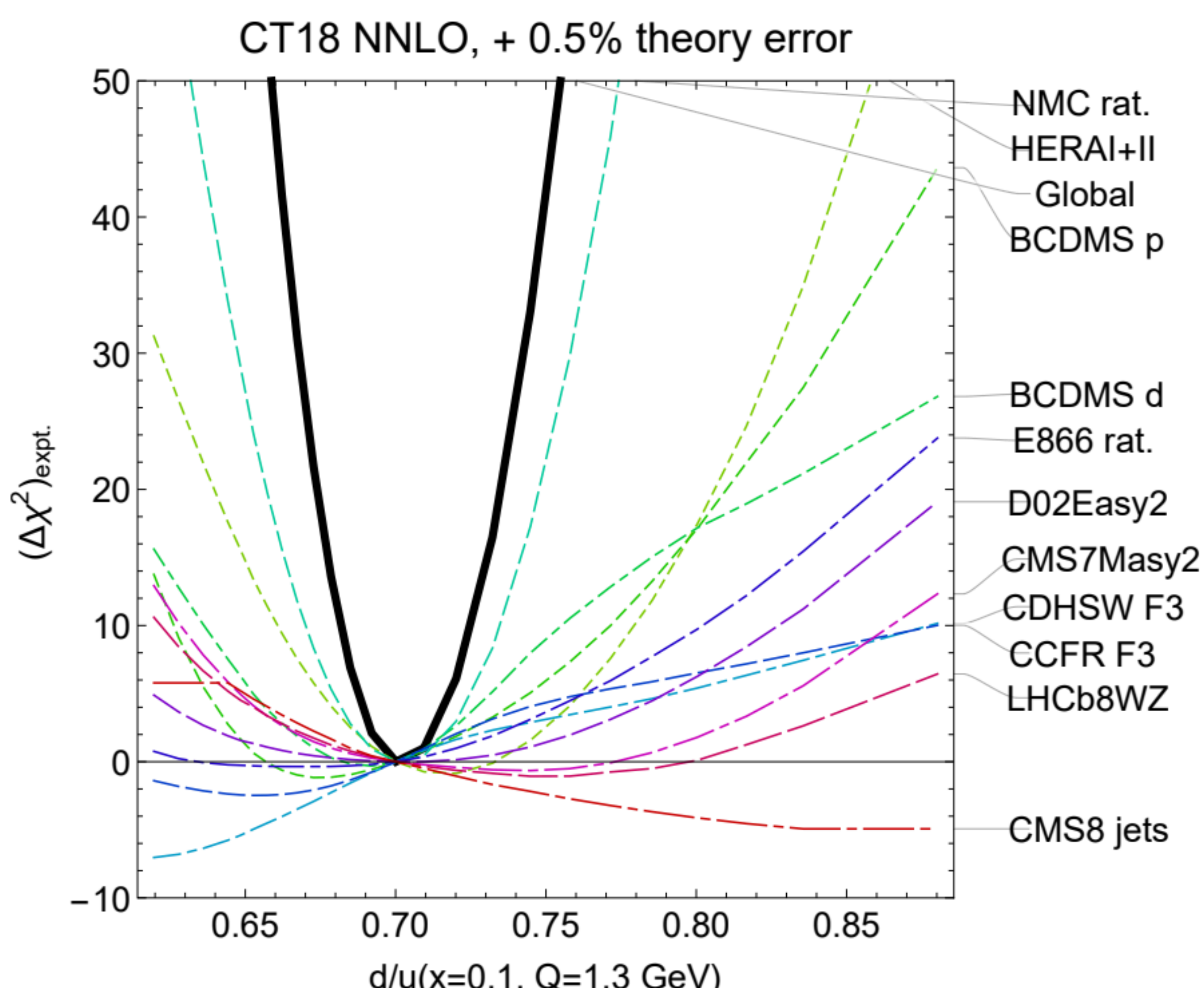


Methodological improvements

new tools to **quantify impact of new data** in approximate ways

producing a full-fledged PDF fit is often very CPU-time consuming, and thus approximate methods to estimate impact in PDF fits have been developed: **profiling**, **reweighting**, *L2* sensitivity…. also progress in visualisation and **dimensionally reduction** strategies





PDFsense, Wang et al 18

Global PDF fits@ 2020

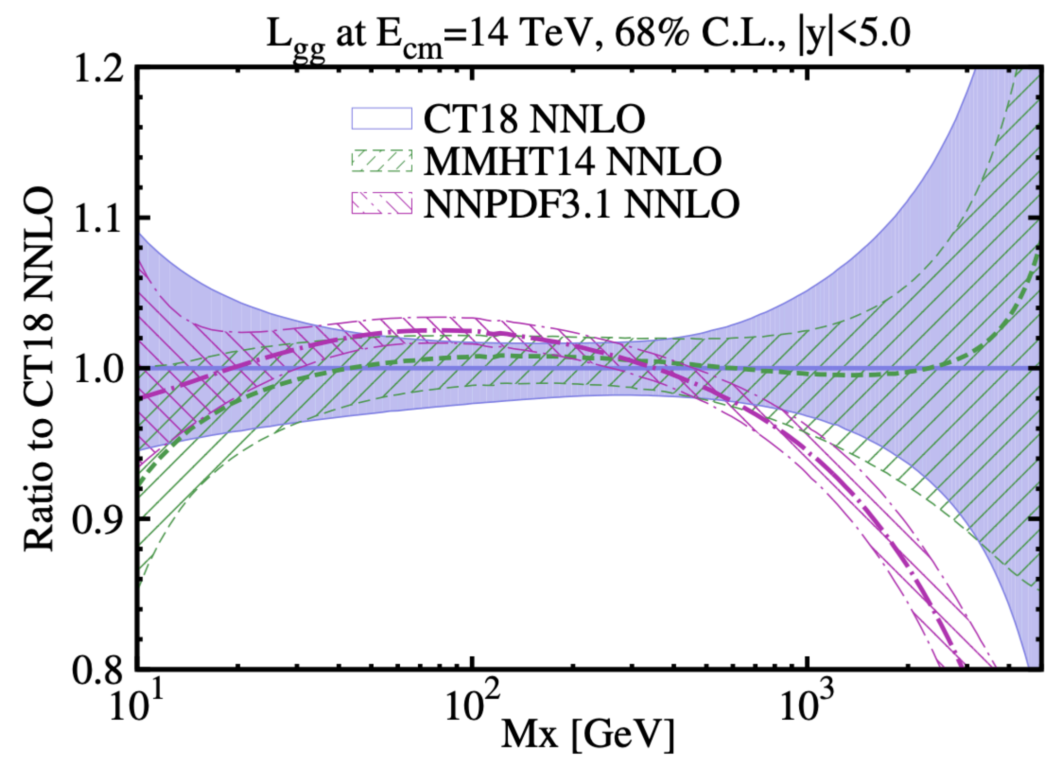
current global PDF fits rely heavily on **LHC constraints**

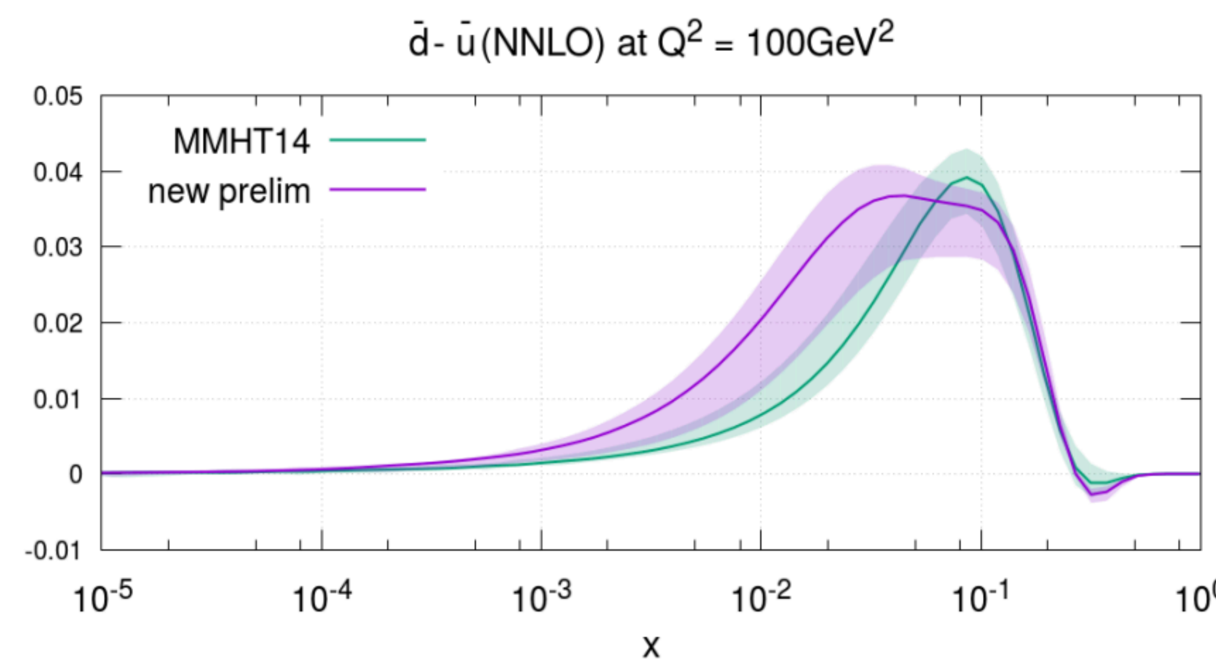
- **CT18** (Dec 2019): many new LHC data, improved parametrisation and error estimates, variants released for different datasets and theory inputs

- Update of MMHT14, **"MMHT"20** should be released soon. Also many new LHC measurements included + methodological improvements

- **NNPDF3.1** (June 2017) already included several LHC data (top diff, Z pT, ATLAS W,Z11). Work in progress towards **NNPDF4.0,** based on novel ML techniques + Runs I & II data

CT18, "MMHT"20, NNPDF3.1 based on **comparable datasets**: towards **new PDF4LHC combination?**





Challenges for SnowMass 2021 and beyond

PDF studies in Snowmass 2021

PDF-related topics in Snowmass'13 [arXiv:1310.5189] and 21' studies

Topic	Status, 2013	Status and plans, 2020
Benchmarking of PDFs for the LHC	Before PDF4LHC'2015 recommendation	In progress toward PDF4LHC'2X recommendation
PDFs with NLO EW contributions	MSTW'04 QED, NNPDF2.3 QED	Needs an update using LuXQED and other photon PDFs; PDFs with leptons and massive bosons
PDFs with resummations	Small x (in progress)	Needs an update for PDFs with small-x and threshold resummations
Parton luminosities at 14, 33, 100 TeV	CT10, MSTW2008, NNPDF2.3 Update at 100 in CERN YR (1607.01831)	Need an update based on the latest PDFs
LHC processes to measure PDFs	W/Z, single-incl. jet, high-p_T Z, $t\bar{t}$, $W+c$ production	updates on these processes + $Q\bar{Q}$, dijet, $\gamma/W/Z$ +jet, low-Q DY, …
Future experiments to probe PDFs	LHC Run-2 DIS: LHeC	LHC Run-3 DIS: EIC, LHeC, …

NEW TASKS in THE HL-LHC ERA:

Obtain complete NNLO and N3LO predictions for PDF-sensitive processes	Improve models for correlated systematic errors	Find ways to constrain large-x PDFs without relying on nuclear targets
Develop and benchmark fast NNLO interfaces	Estimate NNLO theory uncertainties	Develop an agreement on comparing and combining PDF fits

2020-05-20 Pavel Nadolsky, EF06 TG kick-off meeting 2

Toward N3LO PDFs

For many crucial LHC processes **N3LO** represents the precision frontier

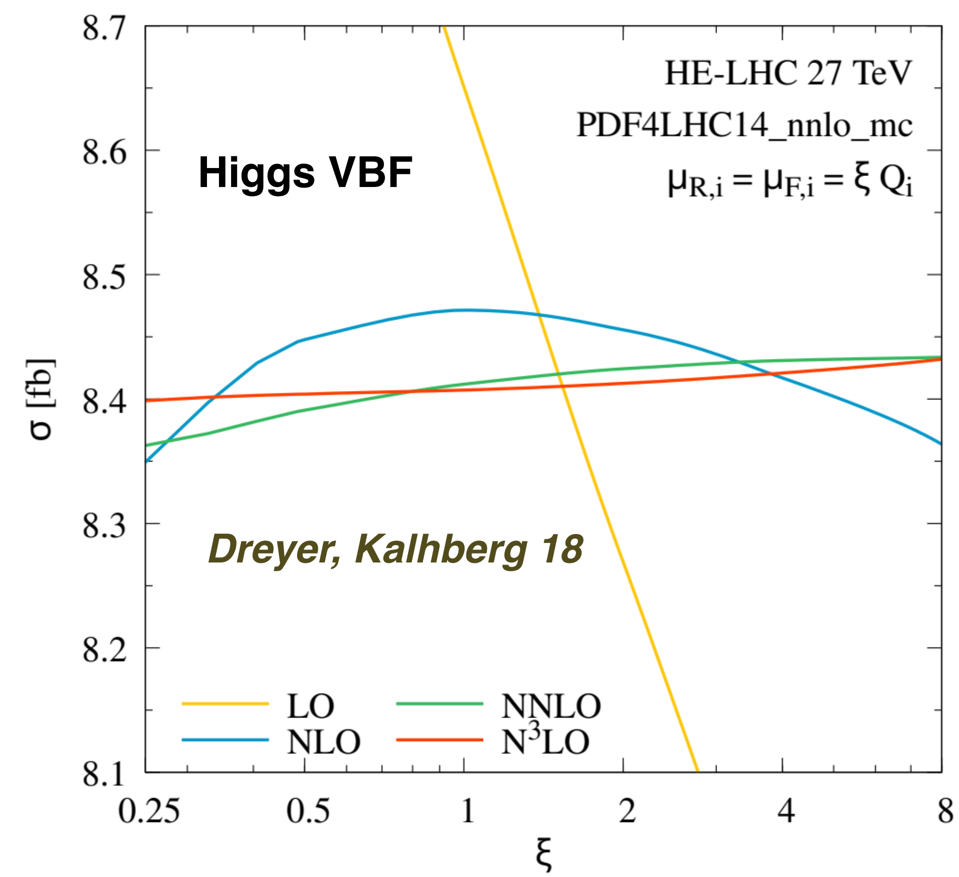
- **N3LO splitting functions** available, not yet implemented in evolution codes.

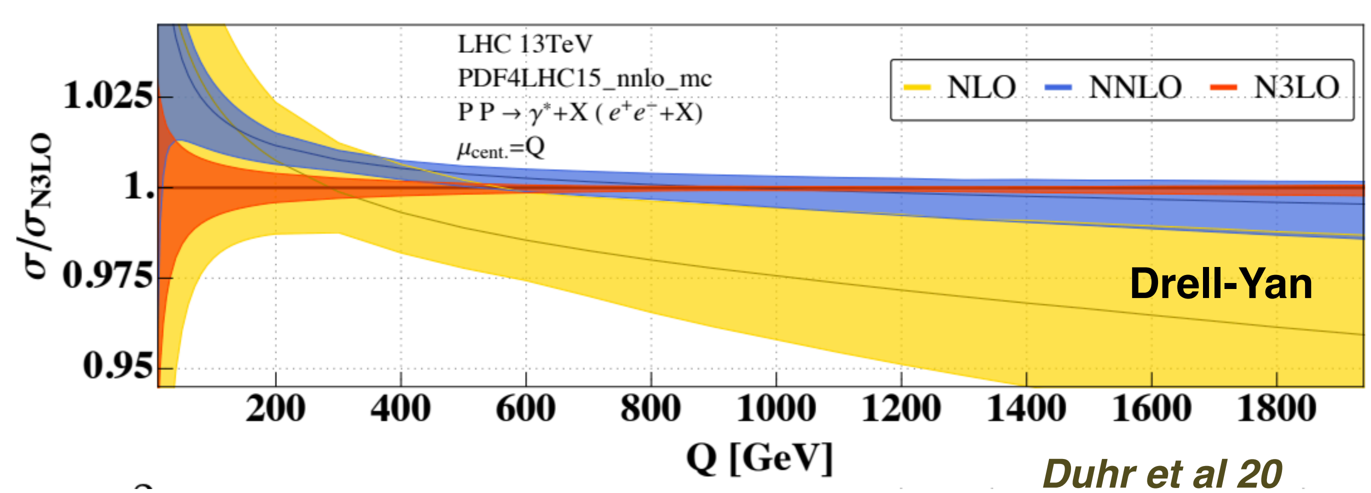
- Same for **N3LO** coefficient functions

- **N3LO** hard-scattering cross-sections not available for most PDF-sensitive processes, but one could use approximations (*e.g.* from resummation)

- A global **NNLO fit with MHOUs** would reveal the potential impact of N3LO corrections on PDFs

possibly one of the **most urgent milestones** for PDF fitters!

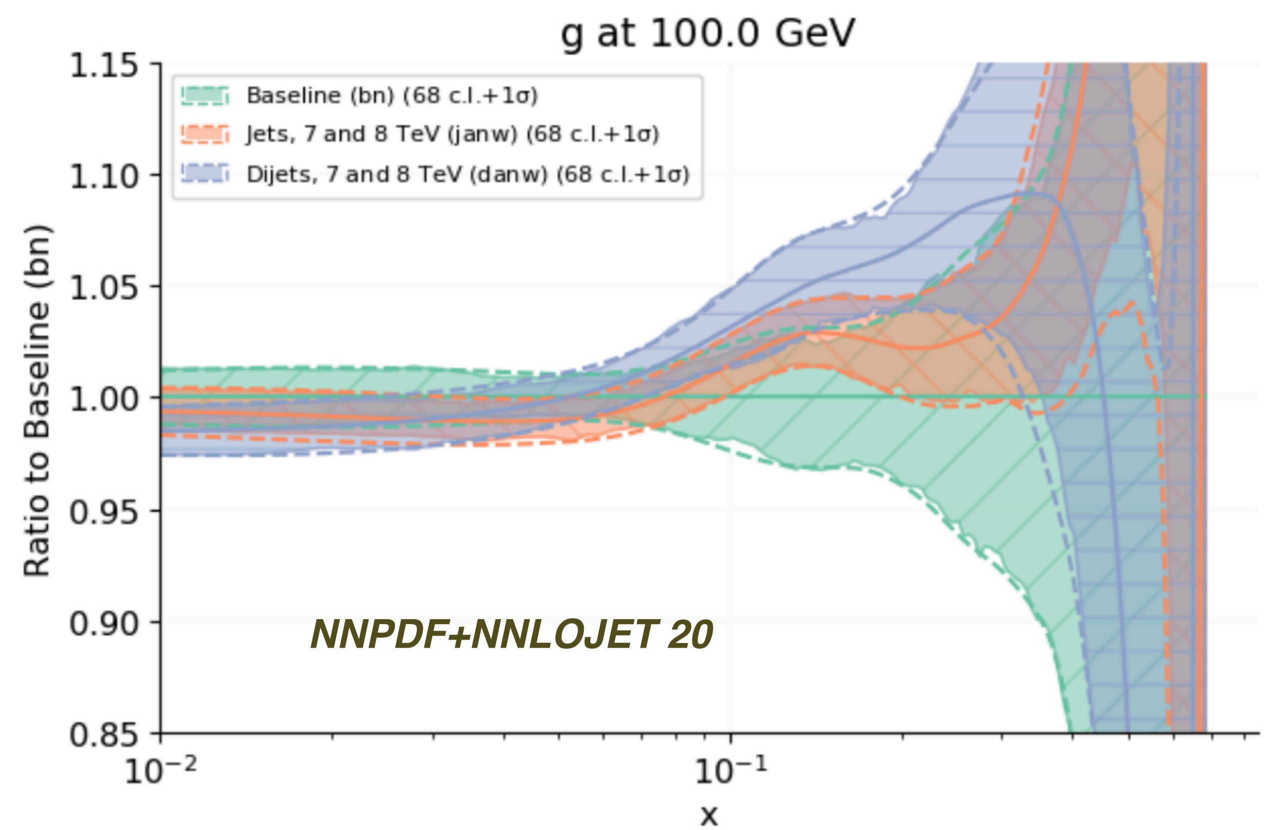


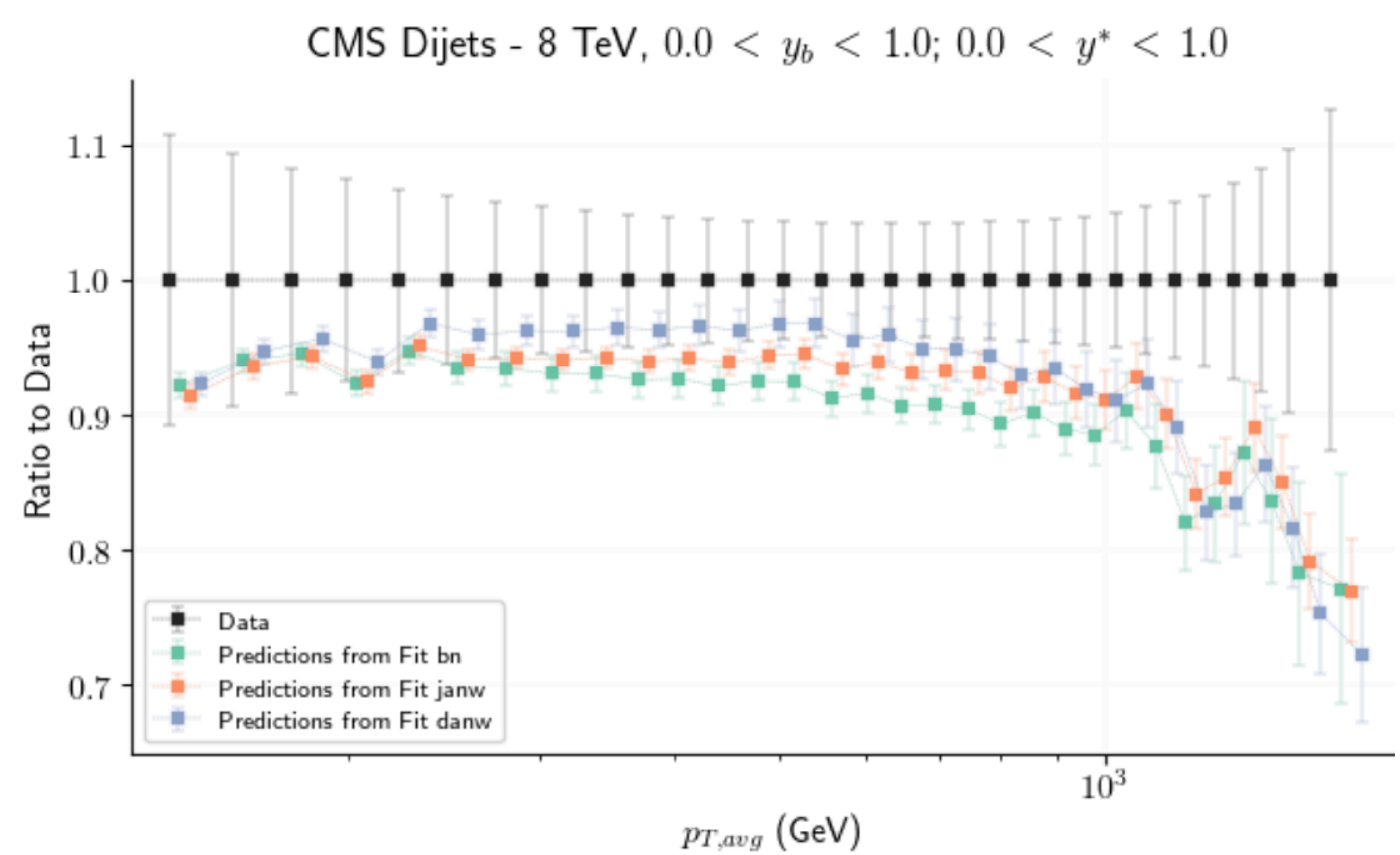


Pinning down the large-x gluon

- Several gluon-sensitive processes available, do they all pull in the same direction?
- Interpretation of single-inclusive jet production is hampered by sensitivity to correlation model
- **Dijet cross-sections** can be successfully included in the NNLO PDF analysis: good fit quality, superior pull on the gluon, no issues with the experiomental covmat
- **Over-constraining** the global PDF fit with multiple gluon-sensitive measurements is now possible

In the global fit, by construction, ***each dataset pulls in a different direction.*** *The question is whether these pulls are statistically distributed as expected ….*





The strangest proton?

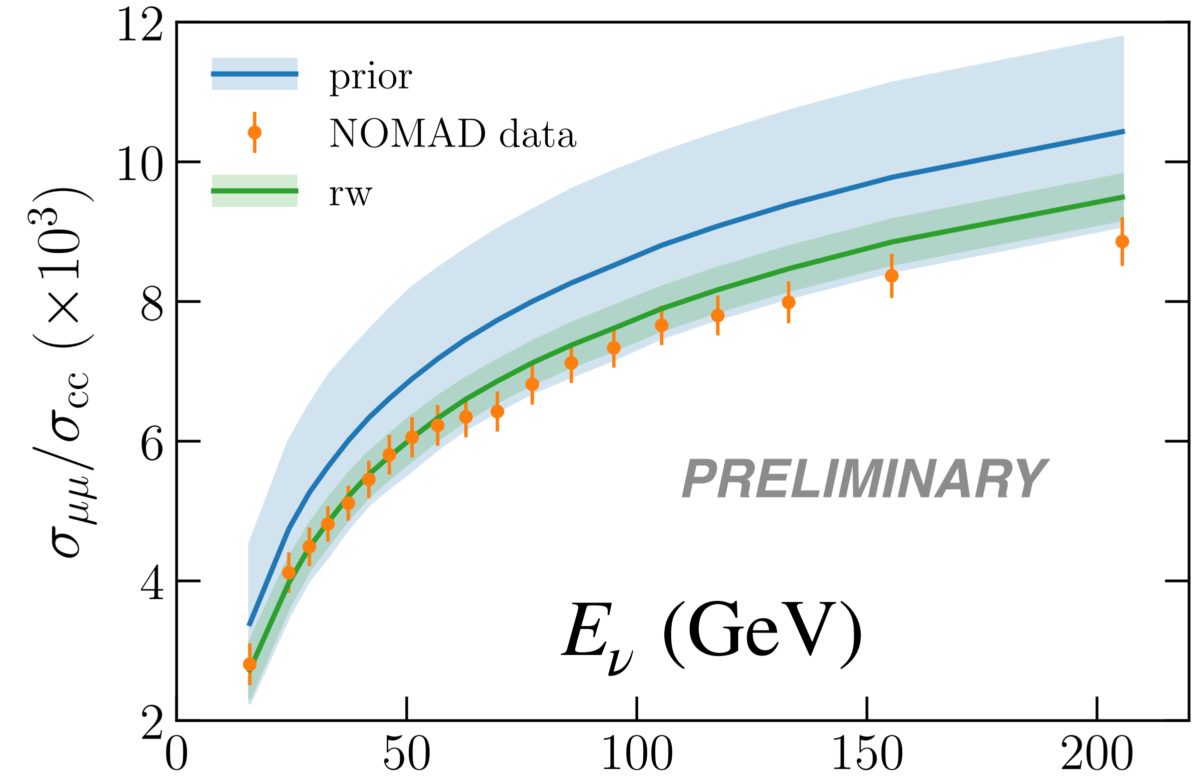
- several probes on the **strangeness content of the proton** available, but different trends on R_S : neutrino DIS prefers suppression, ATLAS W,Z symmetric sea

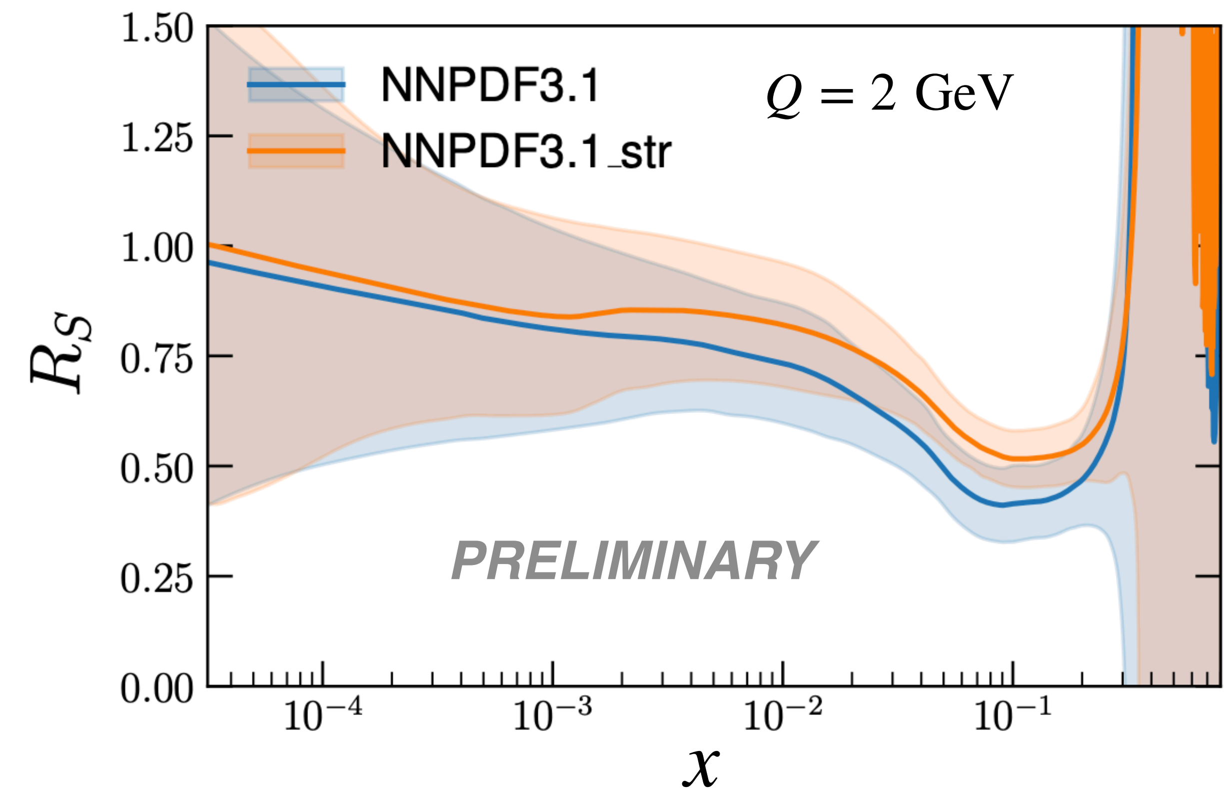
$$R_S(x, Q) \equiv \frac{s^+(x, Q)}{\bar{u}(x, Q) + \bar{d}(x, Q)}$$

a ``proton strangeness" crisis?

- Work in progress towards including **all strange-sensitive measurements** in global fit: NuTeV and NOMAD DIS (with NNLO theory), LHC W,Z, ATLAS and CMS W+c production at 7 and 13 TeV

- Good description for all datasets achieved, **no evidence for tensions** or inconsistencies

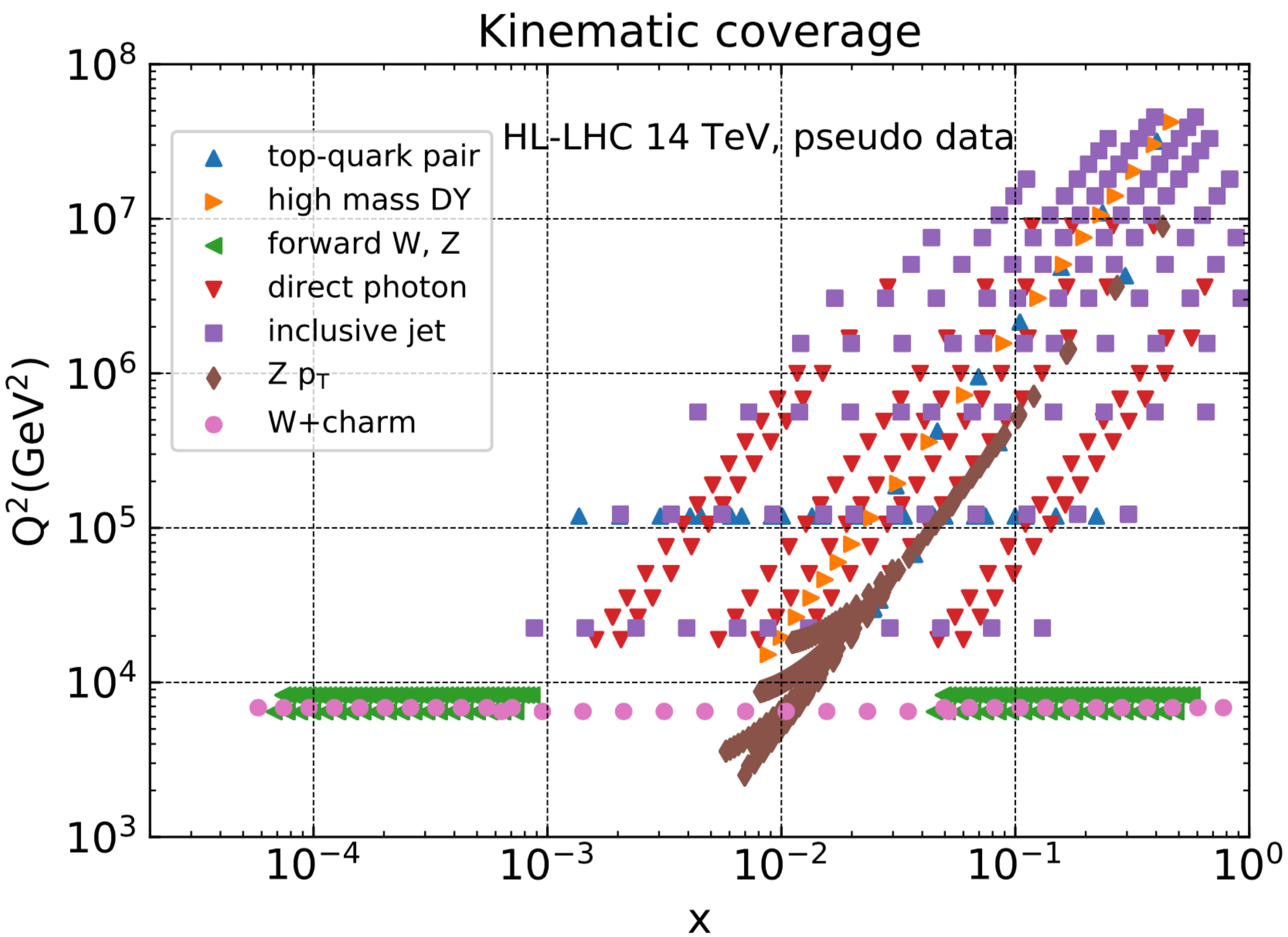


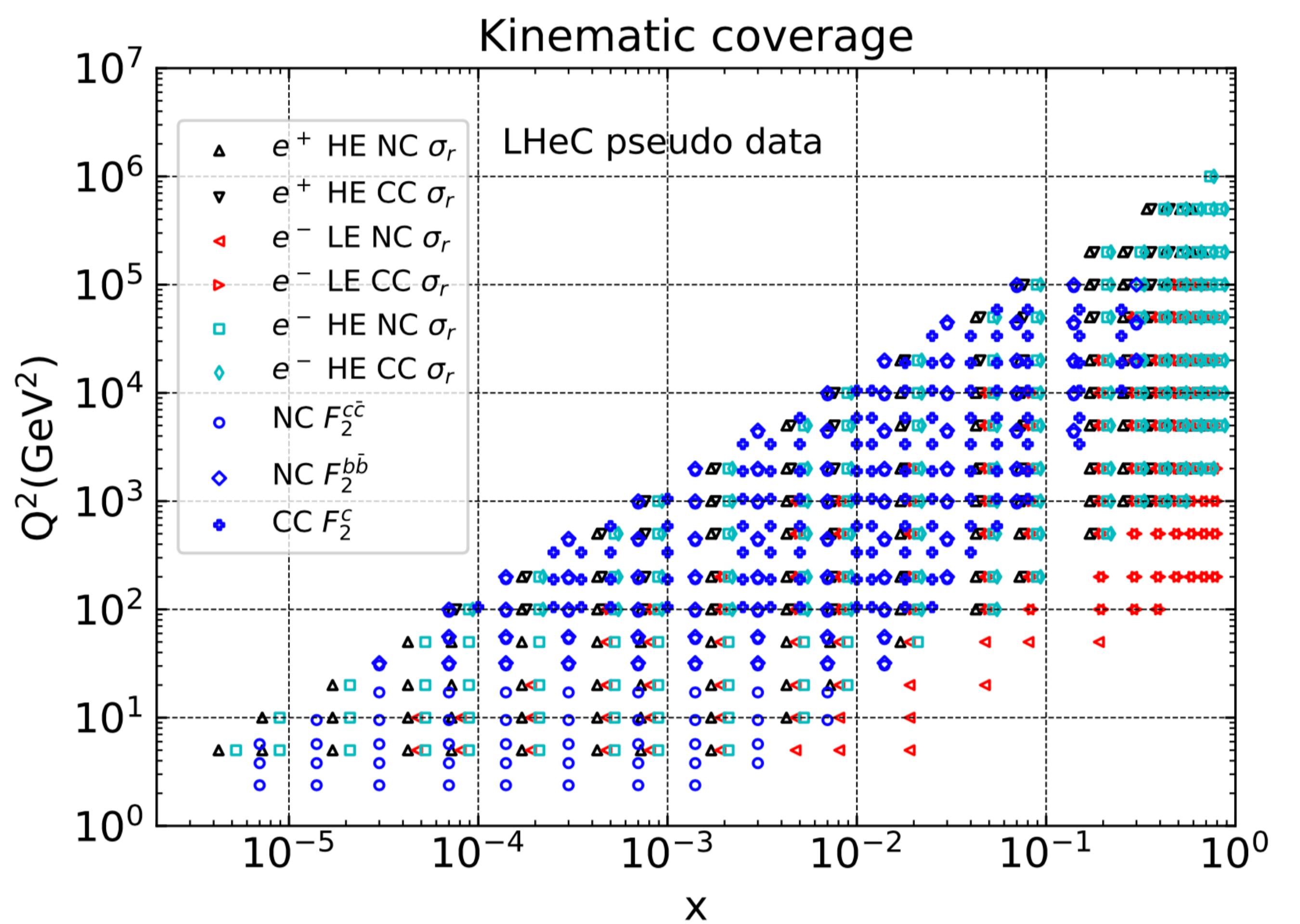


Faura, Iranipour, Nocera, Rojo, Ubiali, prelim

Towards ultimate PDFs at the HL-LHC and LHeC

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



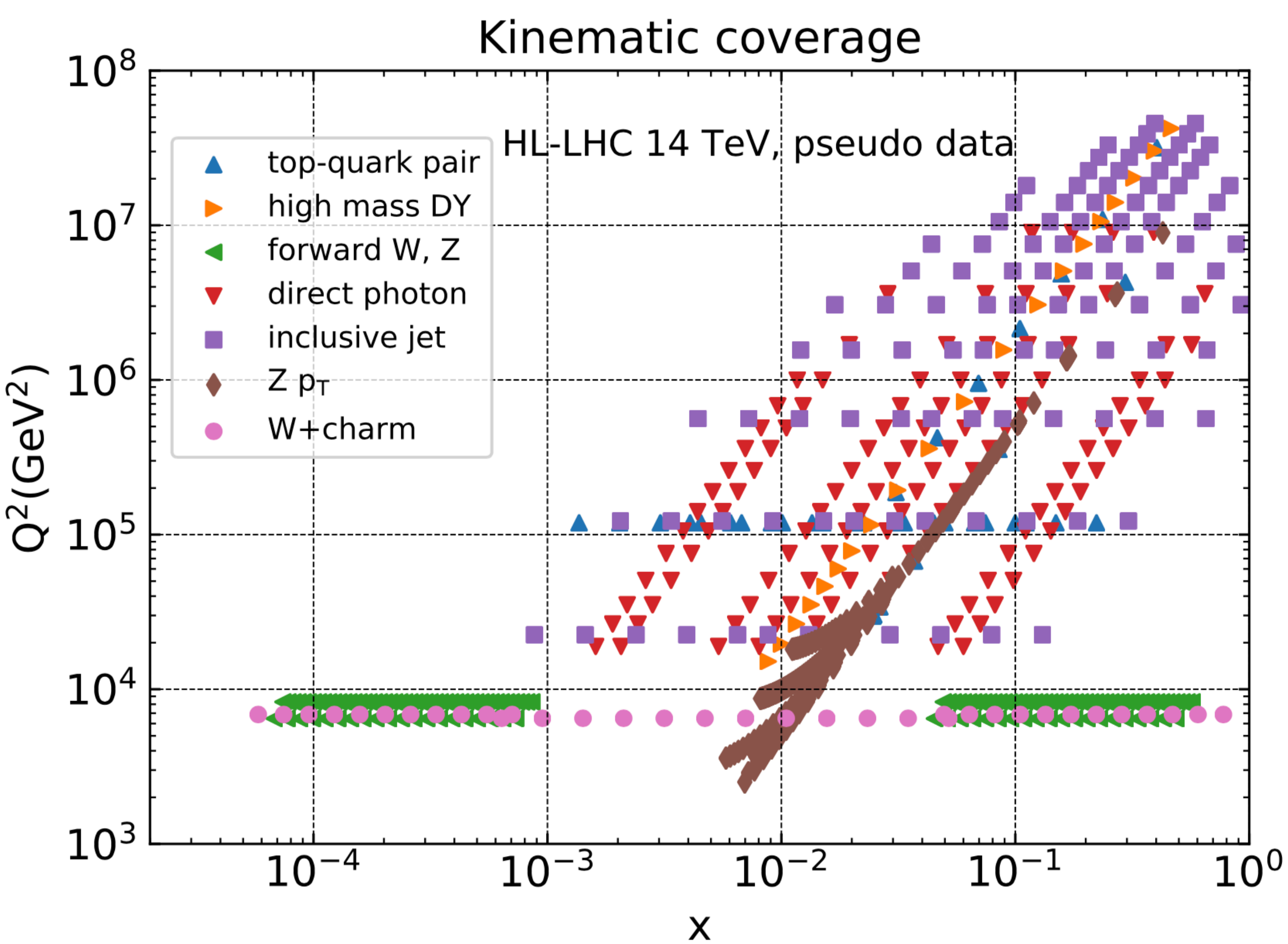


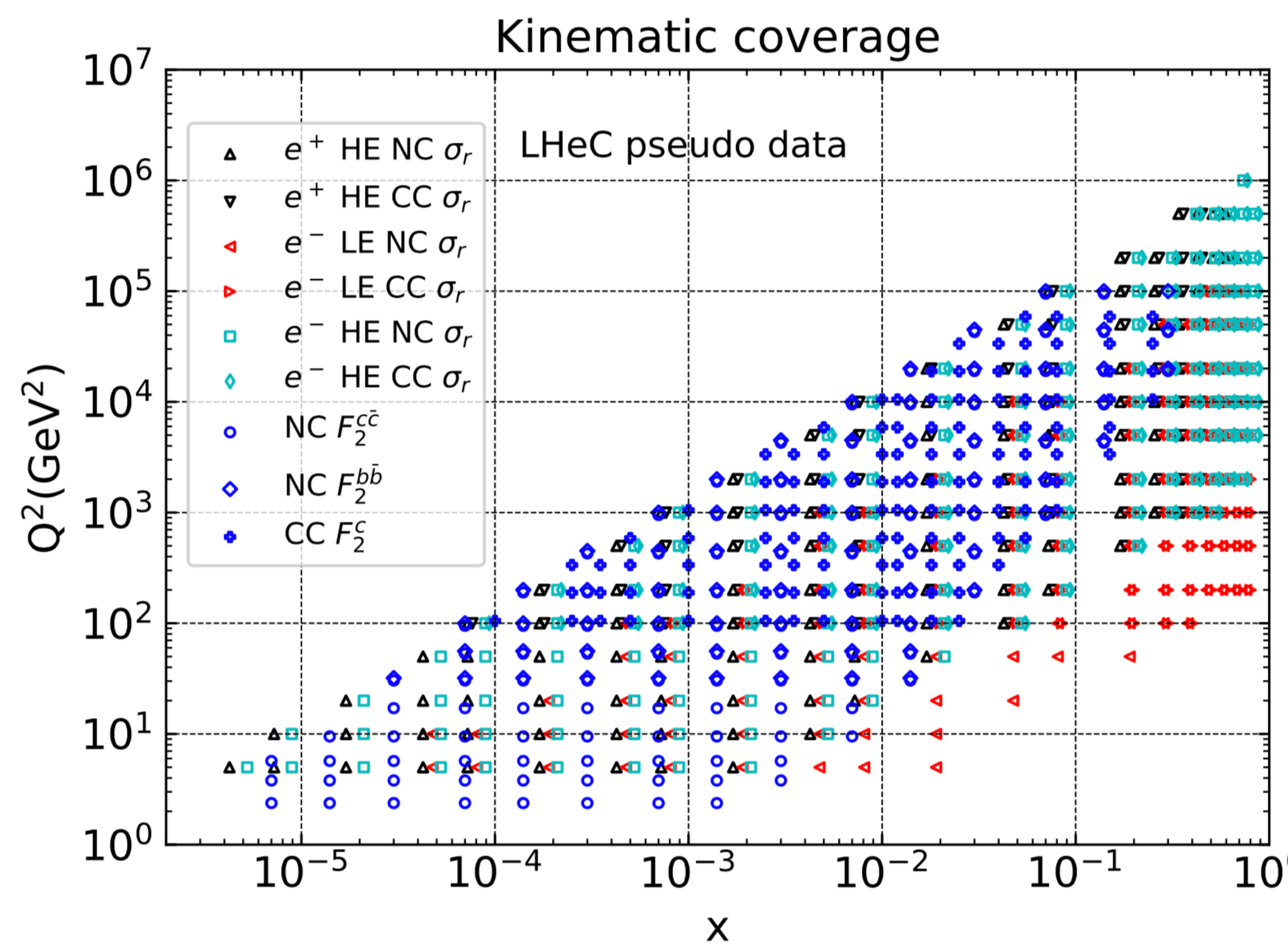
Fully **complementary** in terms of PDF constraints, possible synchronous operation

Towards ultimate PDFs at the HL-LHC and LHeC

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

unfortunately the LHeC was not included in the EPPSU …



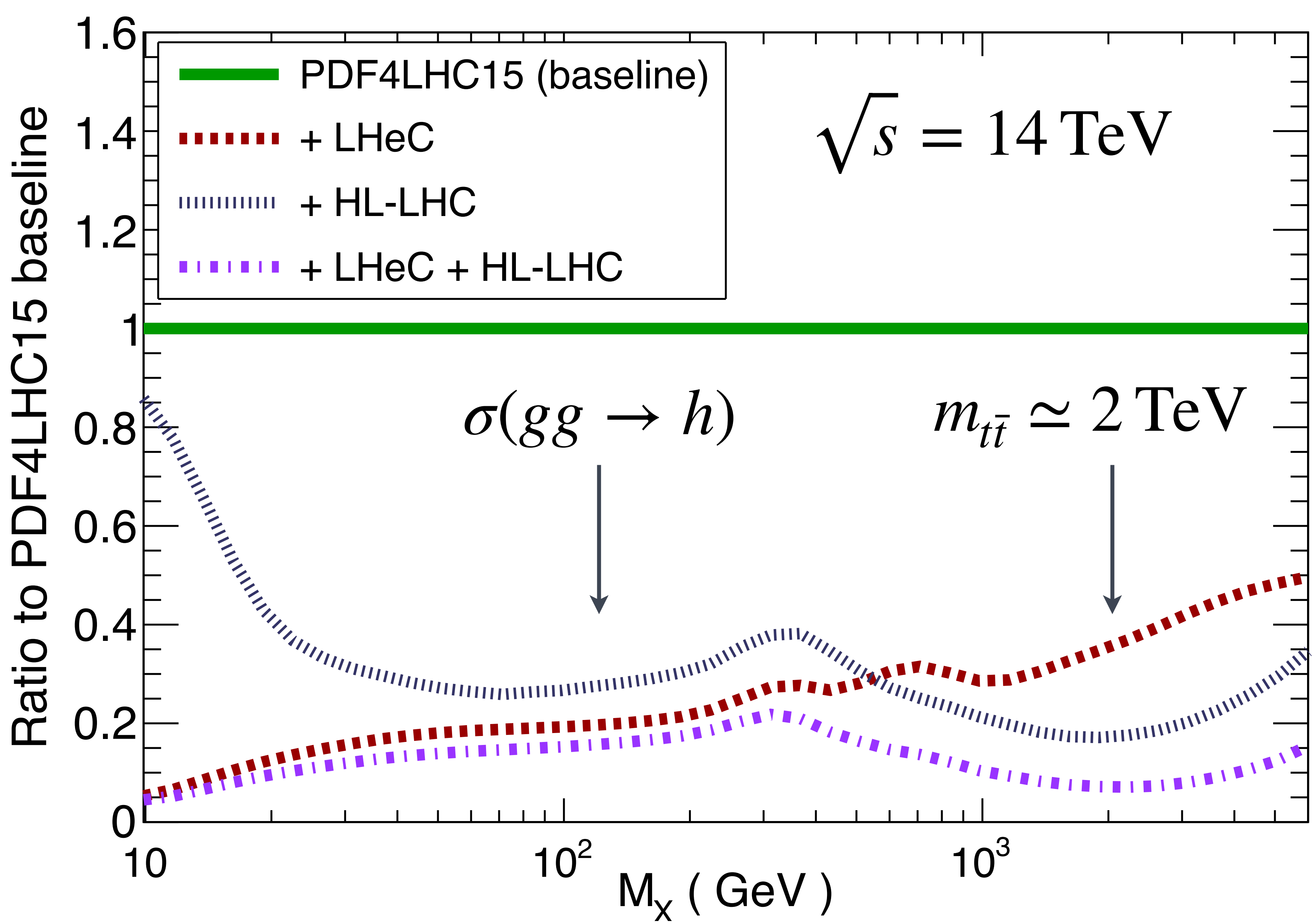


Fully **complementary** in terms of PDF constraints, possible synchronous operation

Towards ultimate PDFs at the HL-LHC and LHeC

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

PDF uncertanties in gluon-gluon luminosity

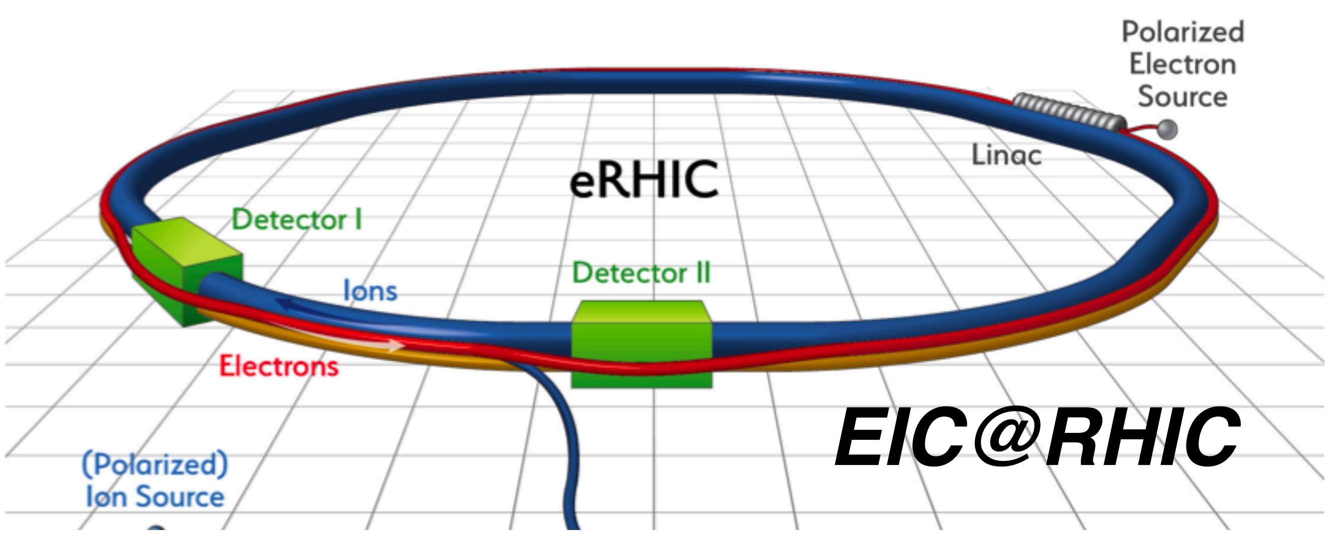


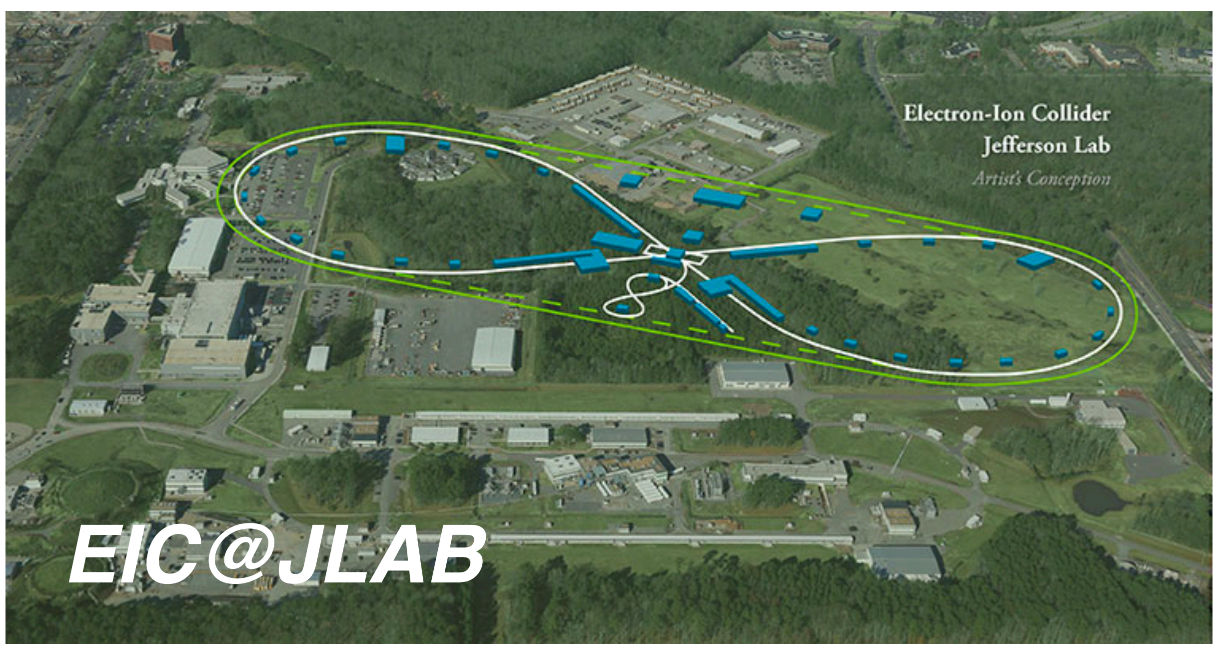
Abdul-Khalek et al. 18,19

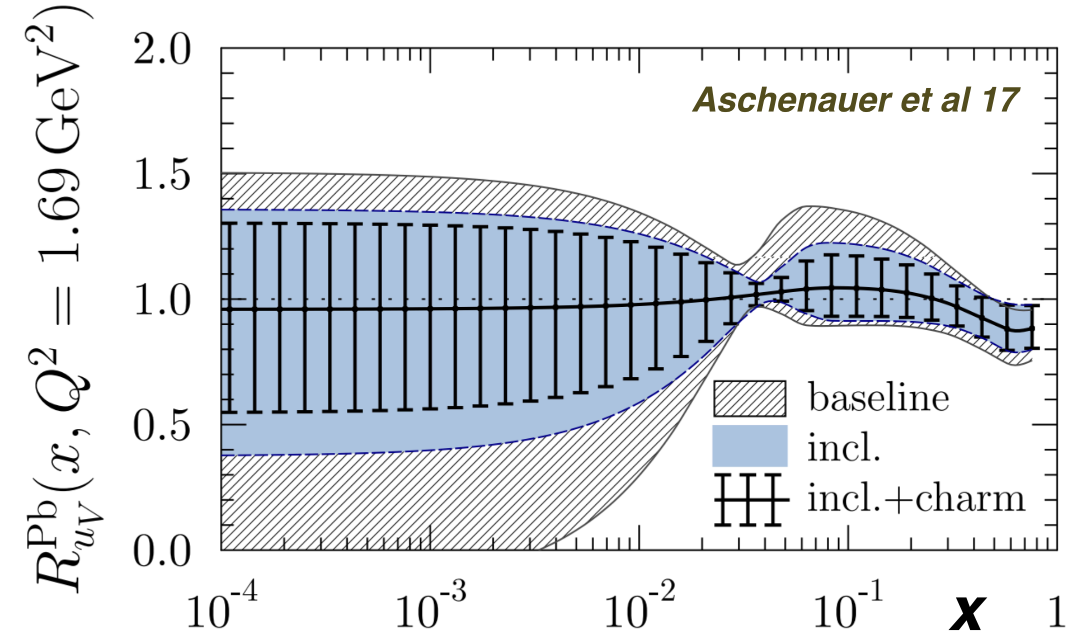
A reduction of PDF uncertainties by **up to a factor 10** could be within reach

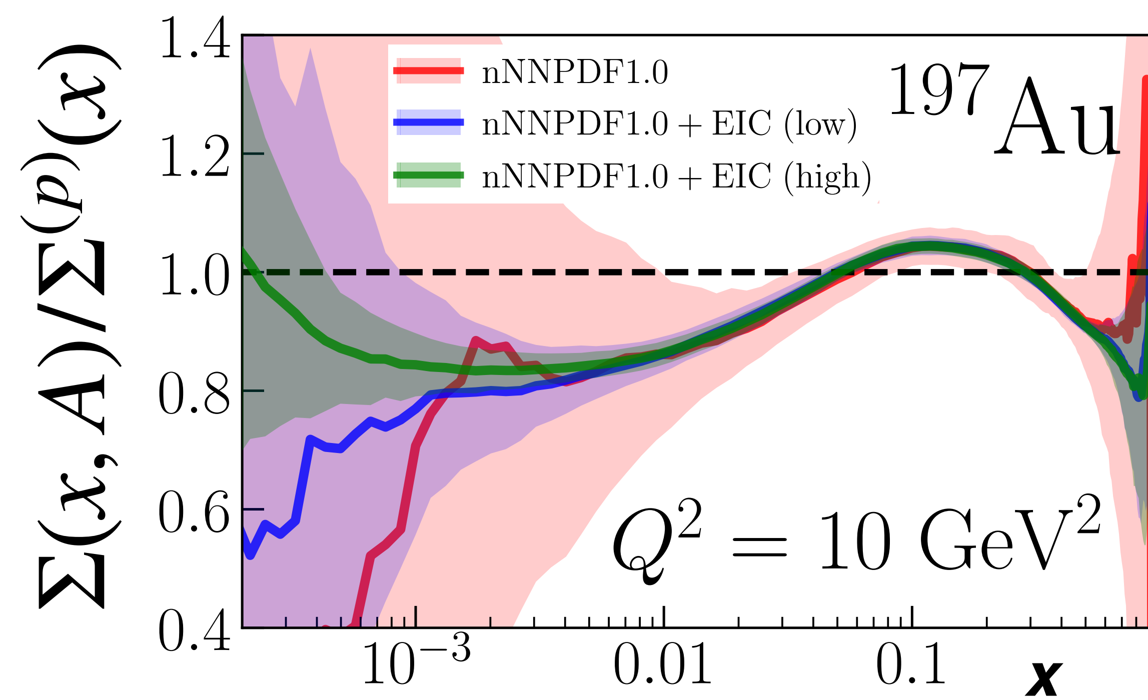
Nuclear structure at the Electron-Ion Collider

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







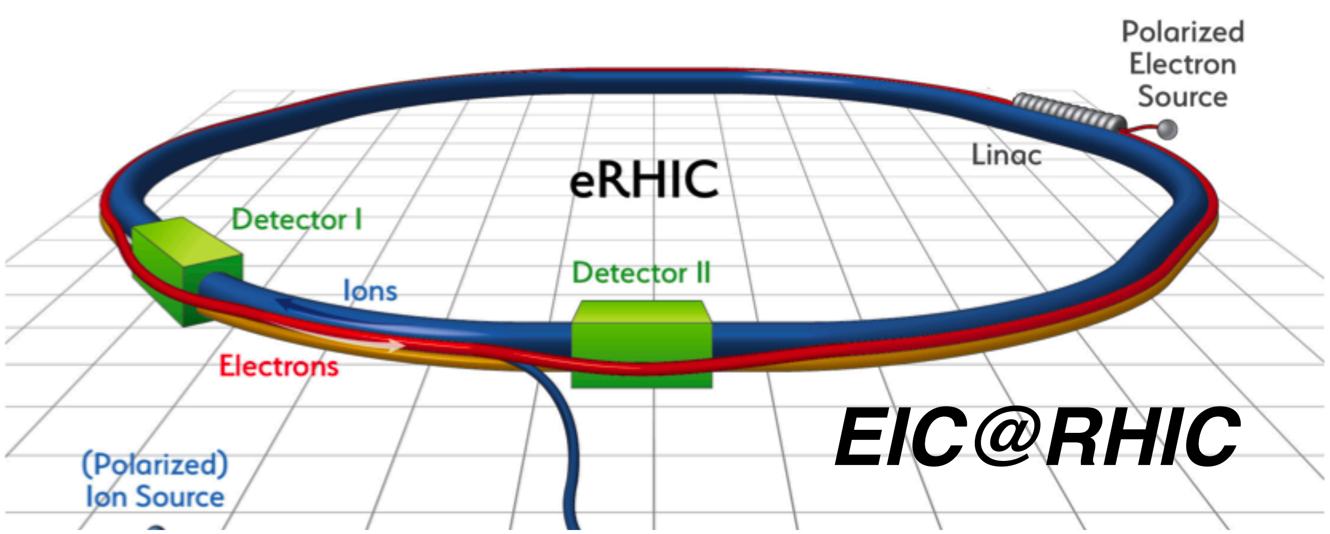


Abdul-Khalek et al 19

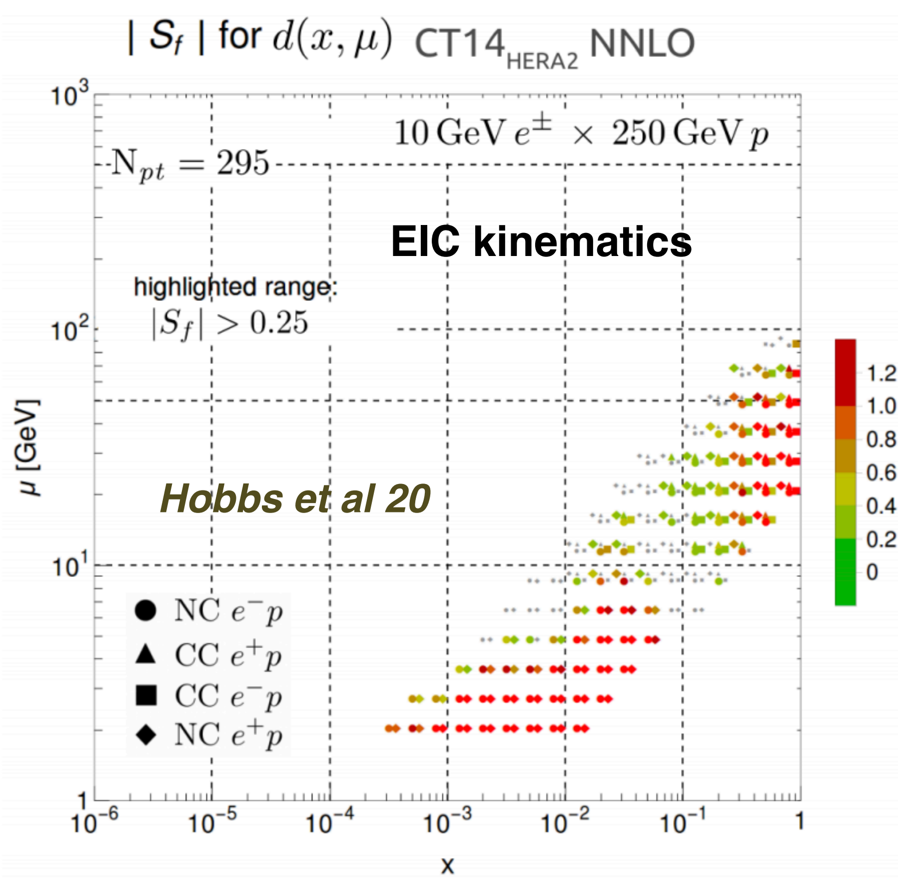
Pinning down nuclear PDFs at small-*x*: onset of gluon-dominated matter?

Nucleon structure at the Electron-Ion Collider

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



- Synergies between **EIC, proton PDF fits, and LHC pheno** deserve a lot more attention
- After all, the EIC is likely to be the **only lepton-nucleon collider** operating in our lifetimes!
- Assess impact on proton PDFs of simulated EIC pseudo-data: ongoing Yellow Report studies



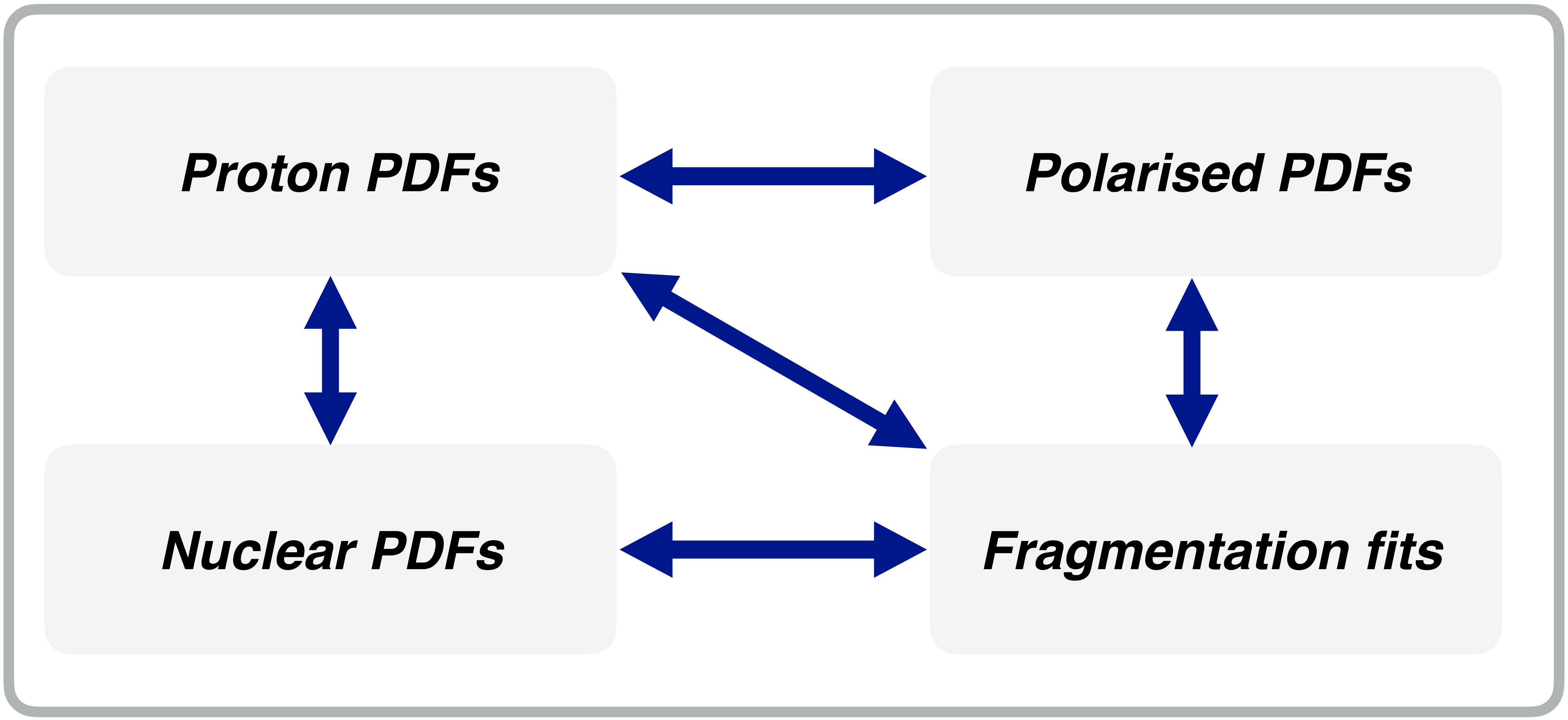
What can the EIC do for proton PDFs?

- Replace the old fixed target DIS data
- Improved, cleaner coverage of large-x region
- Robust large-x sea quarks from deuteron projectiles
- New probes of the gluon from jets ….

lots of unexplored potential!

Universal QCD fits

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

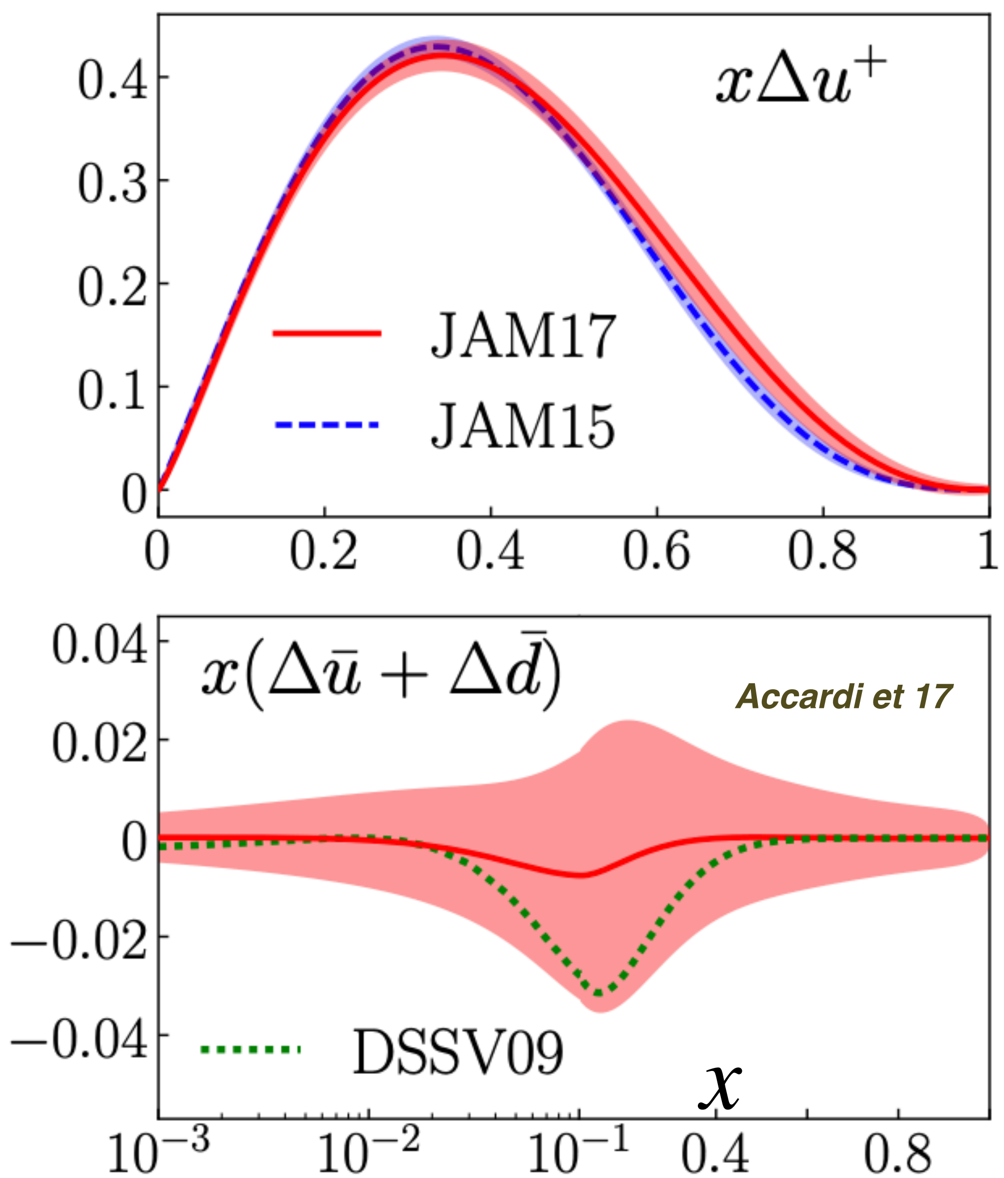


*Towards **universal/integrated global analyses** of non-perturbative QCD*

Universal QCD fits

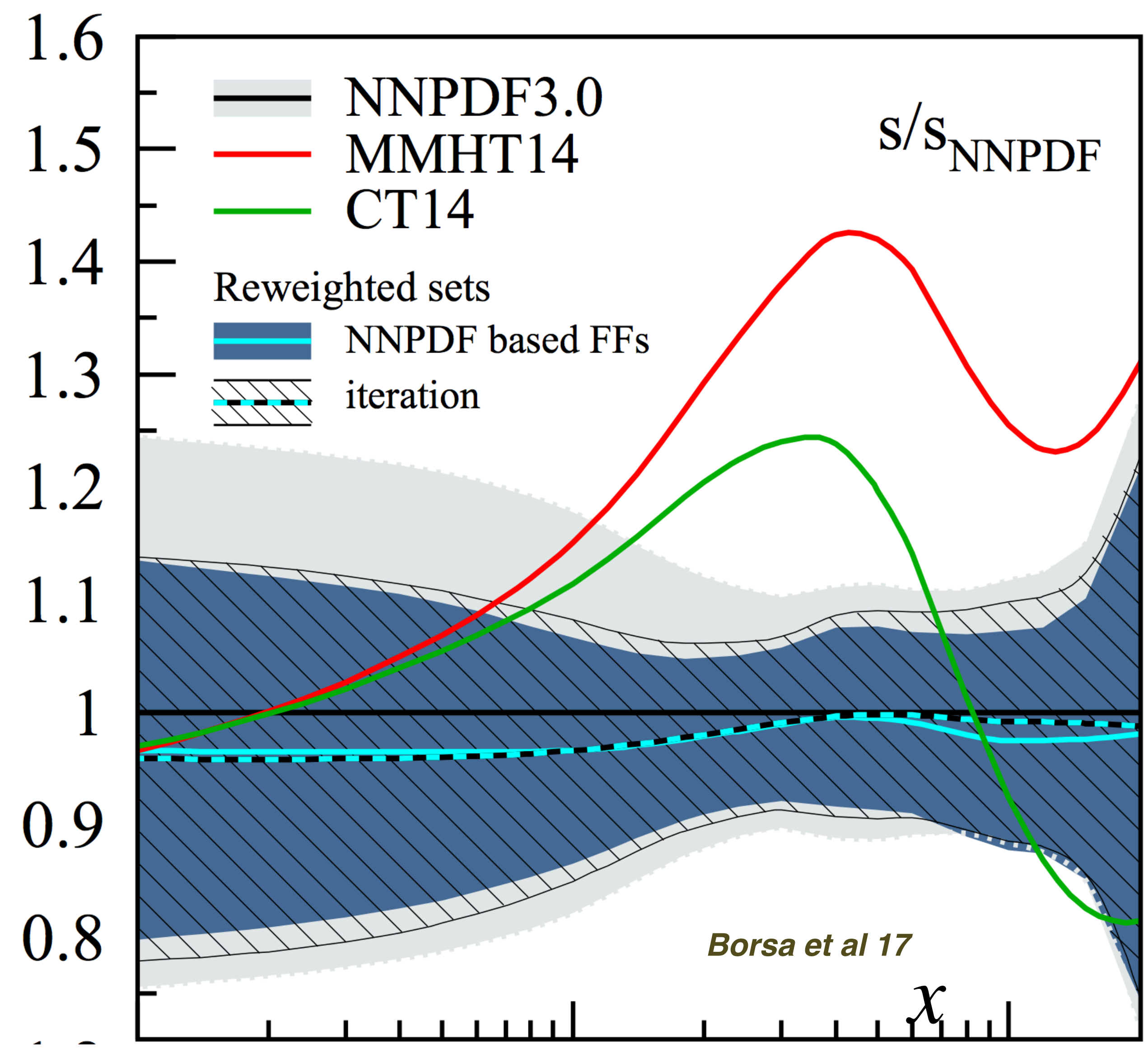
Pushing the **precision frontier** of **QCD fits** requires accounting for **cross-talk** between different **non-perturbative QCD quantities**

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** play a heavy role in the global PDF fit results

- Recent progress in **longstanding issues**: QCD uncertainties on PDFs, Lattice QCD constraints, strange and charm content of the proton, fits with **dijet cross-sections**…

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

- **Several challenges** for PDF fitters in the short and medium term: N3LO PDFs, resummation, improved benchmarking, better understanding the new precise LHC datasets, methodological developments, advanced computational and ML tools ….

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

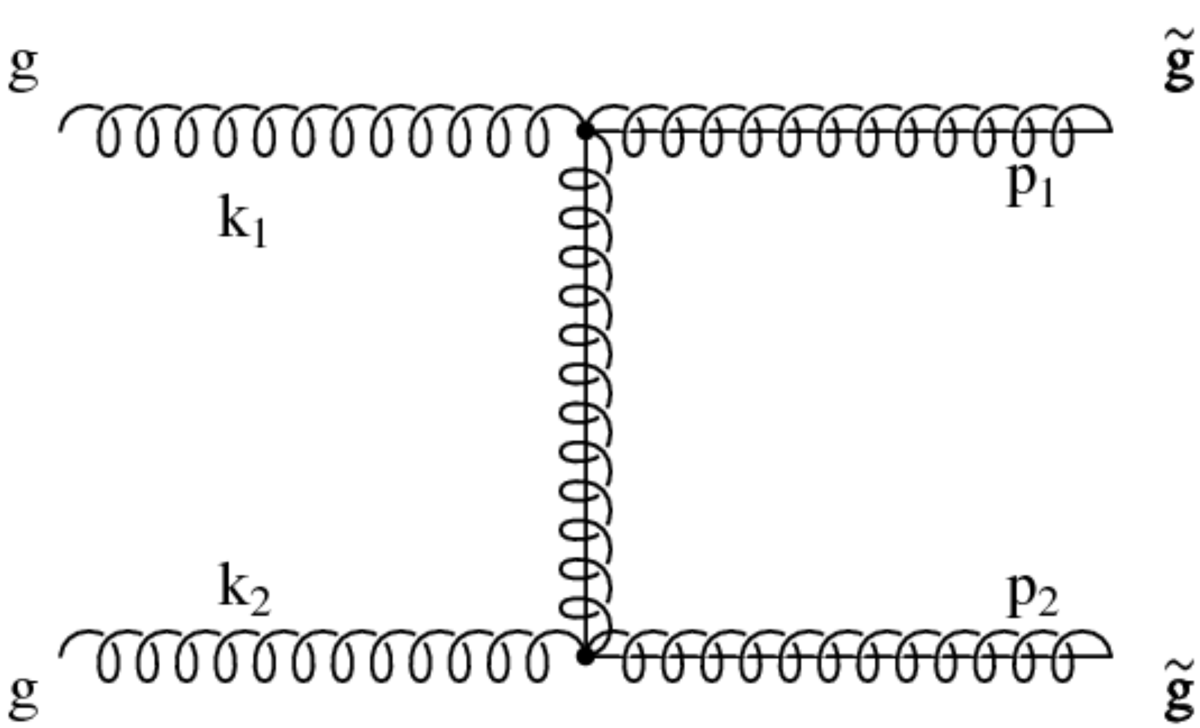
Extra Material

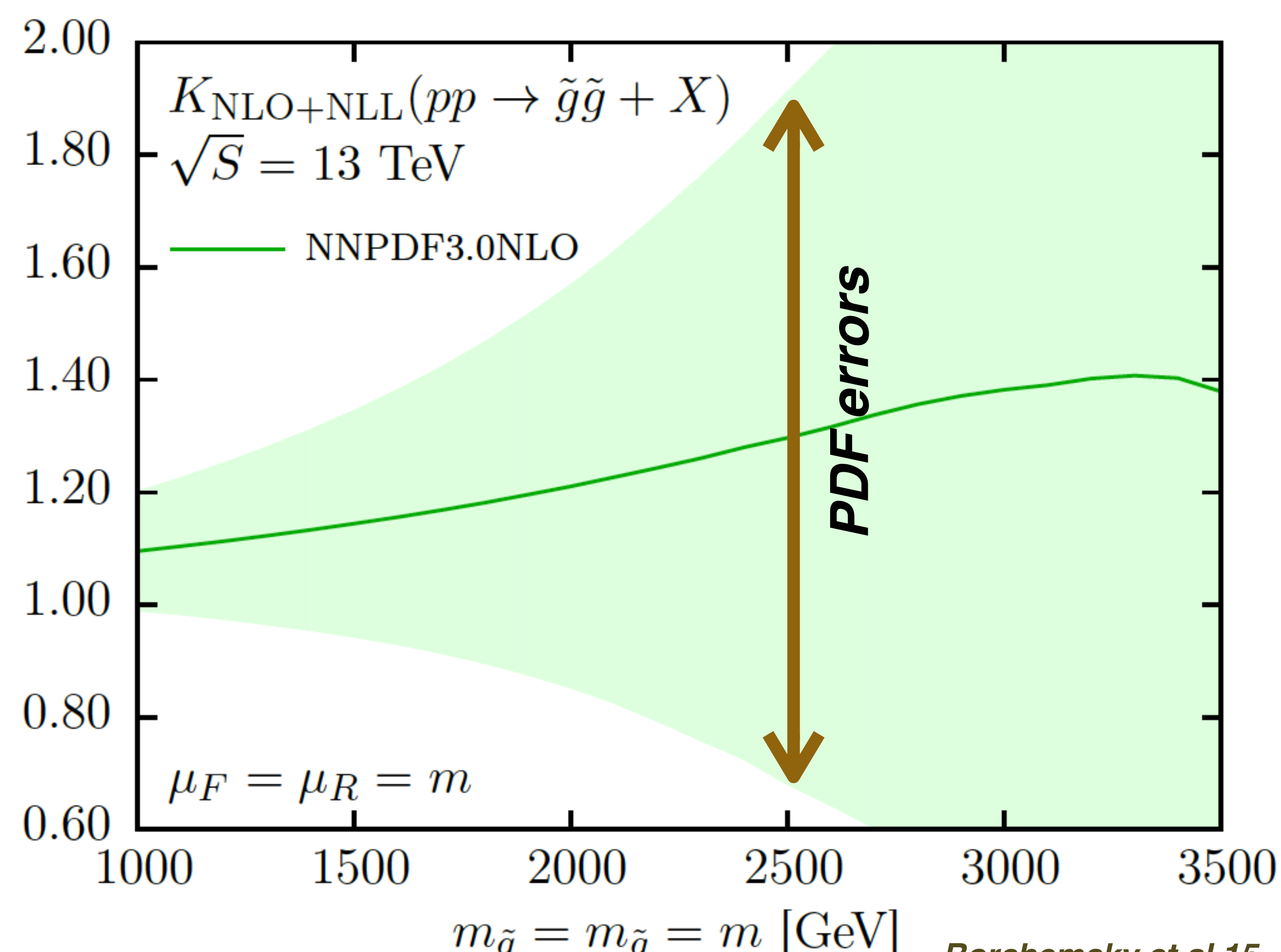
Why do we need better PDFs?

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





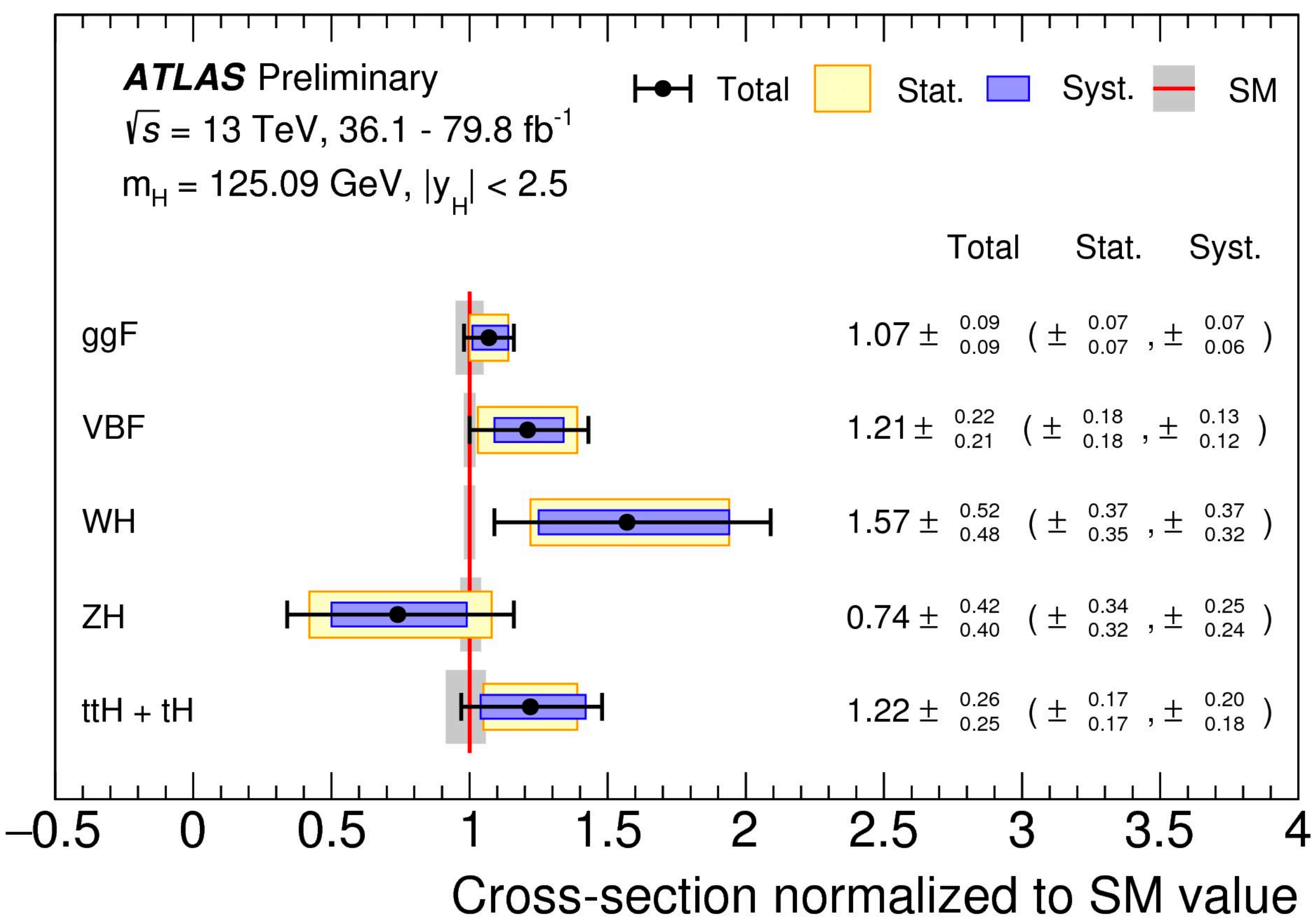
Borchemsky et al 15

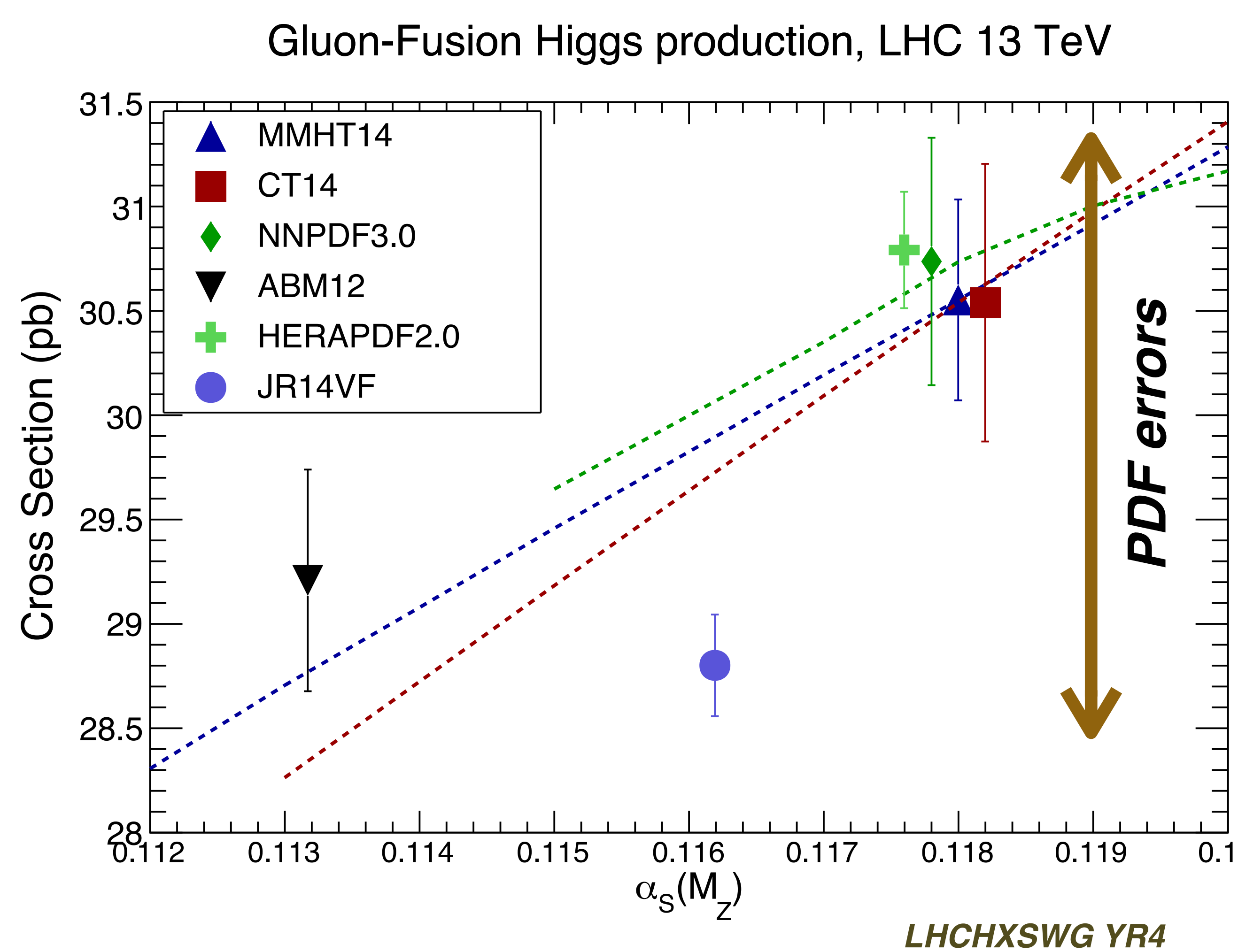
Why do we need better PDFs?

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

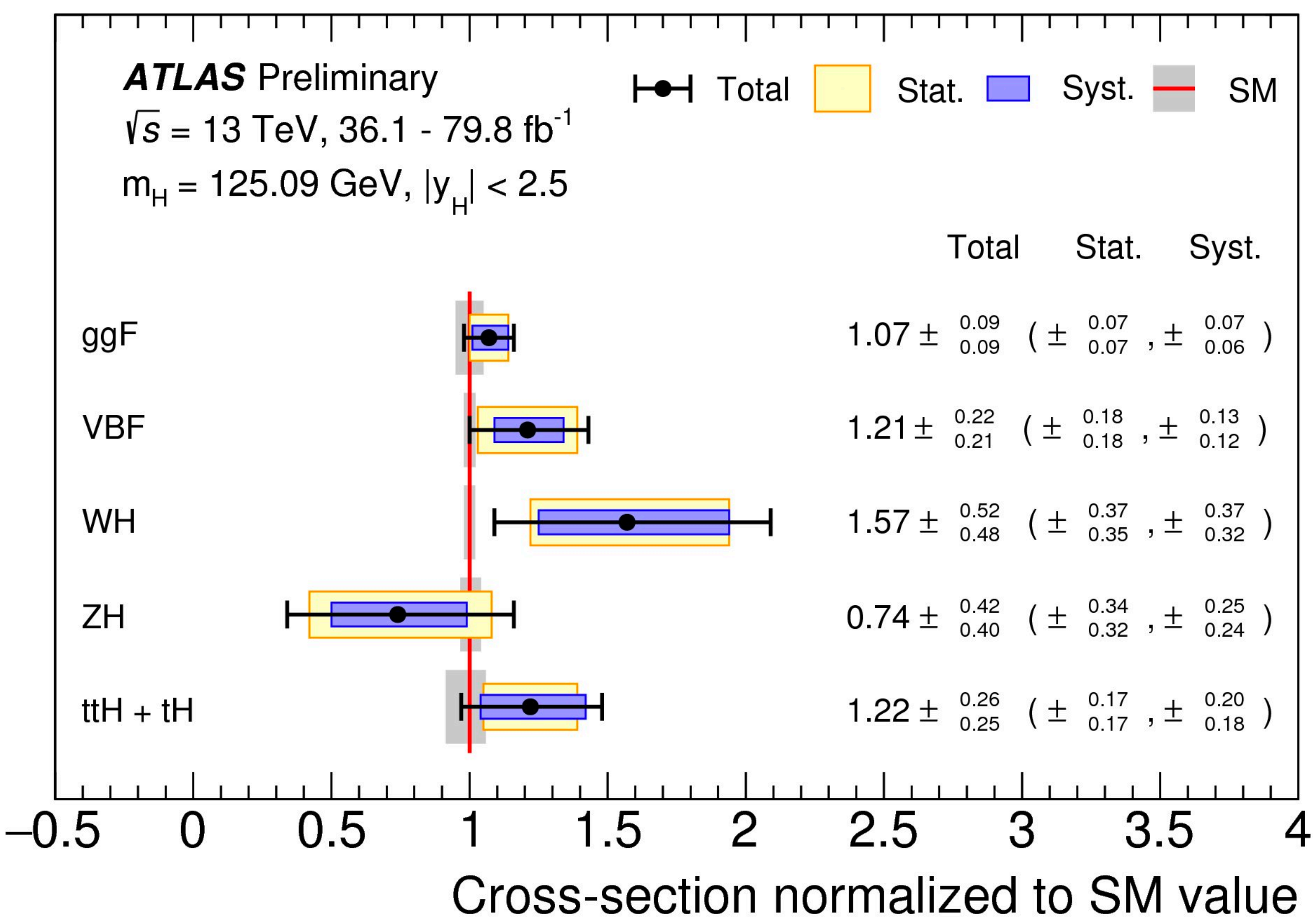


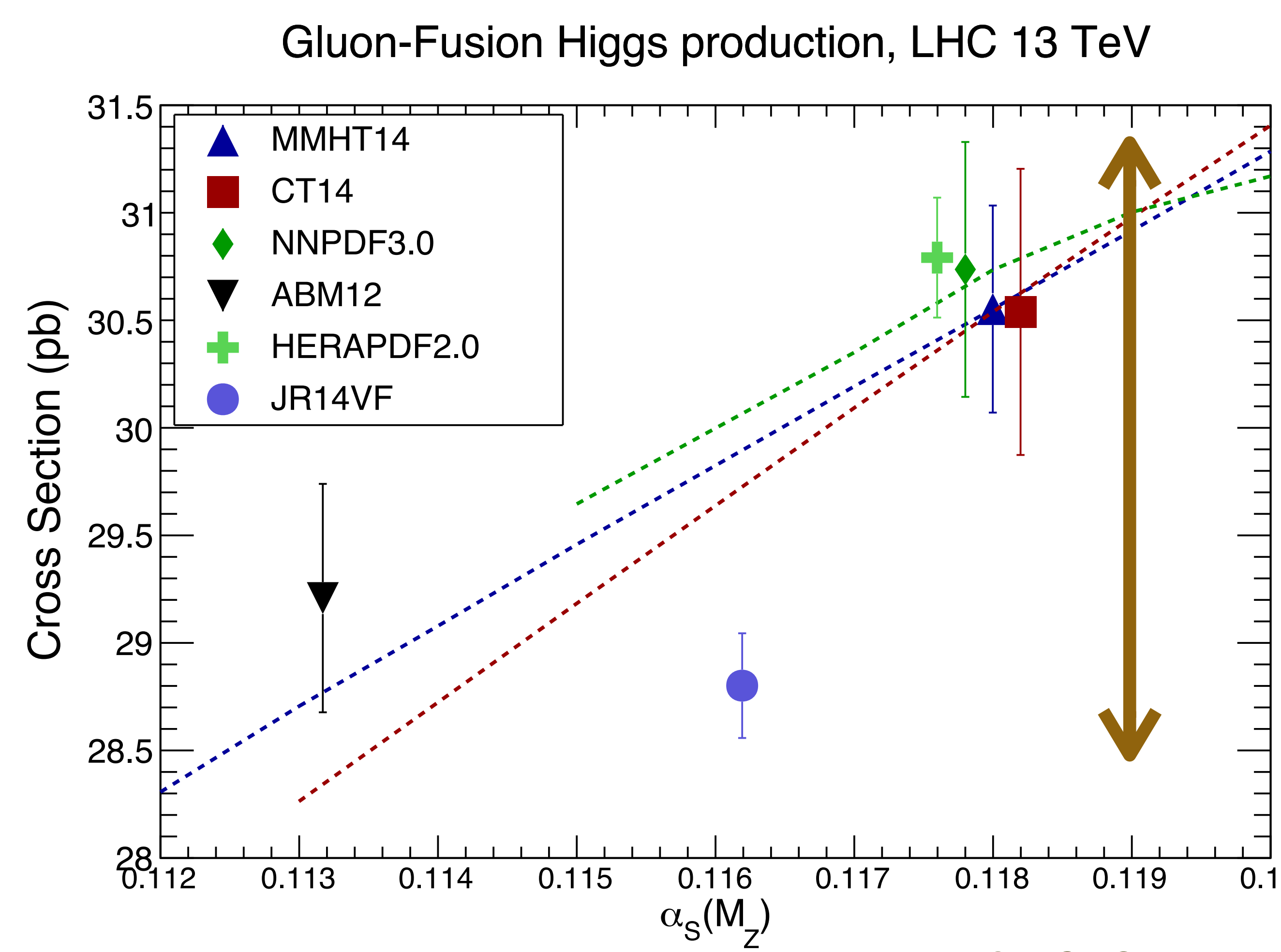


Why do we need better PDFs?

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**

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

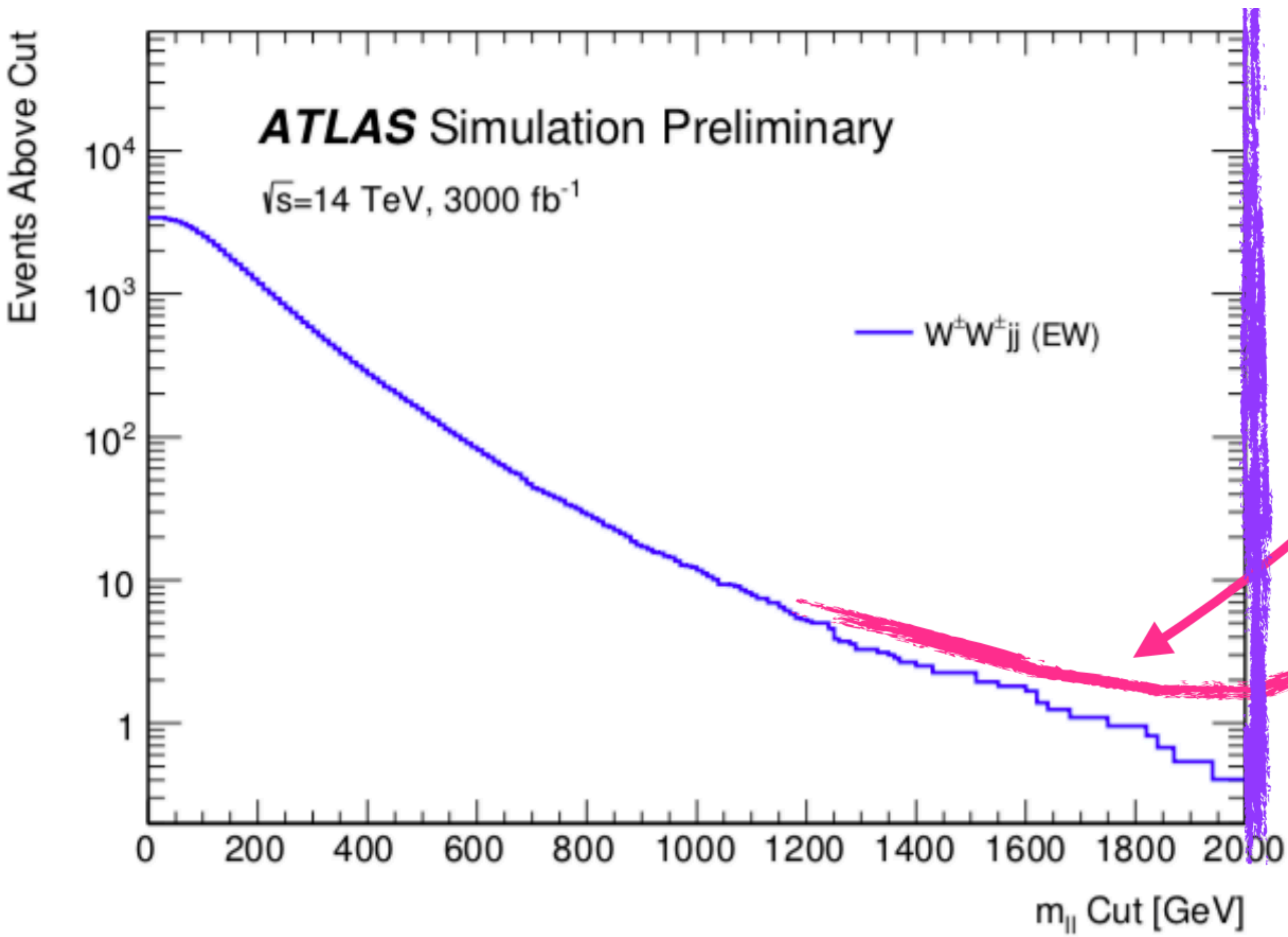
- Some operators induce **growth with the partonic centre-of-mass energy**: increased sensitivity in LHC cross-sections in the TeV region

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

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

Why do we need better PDFs?

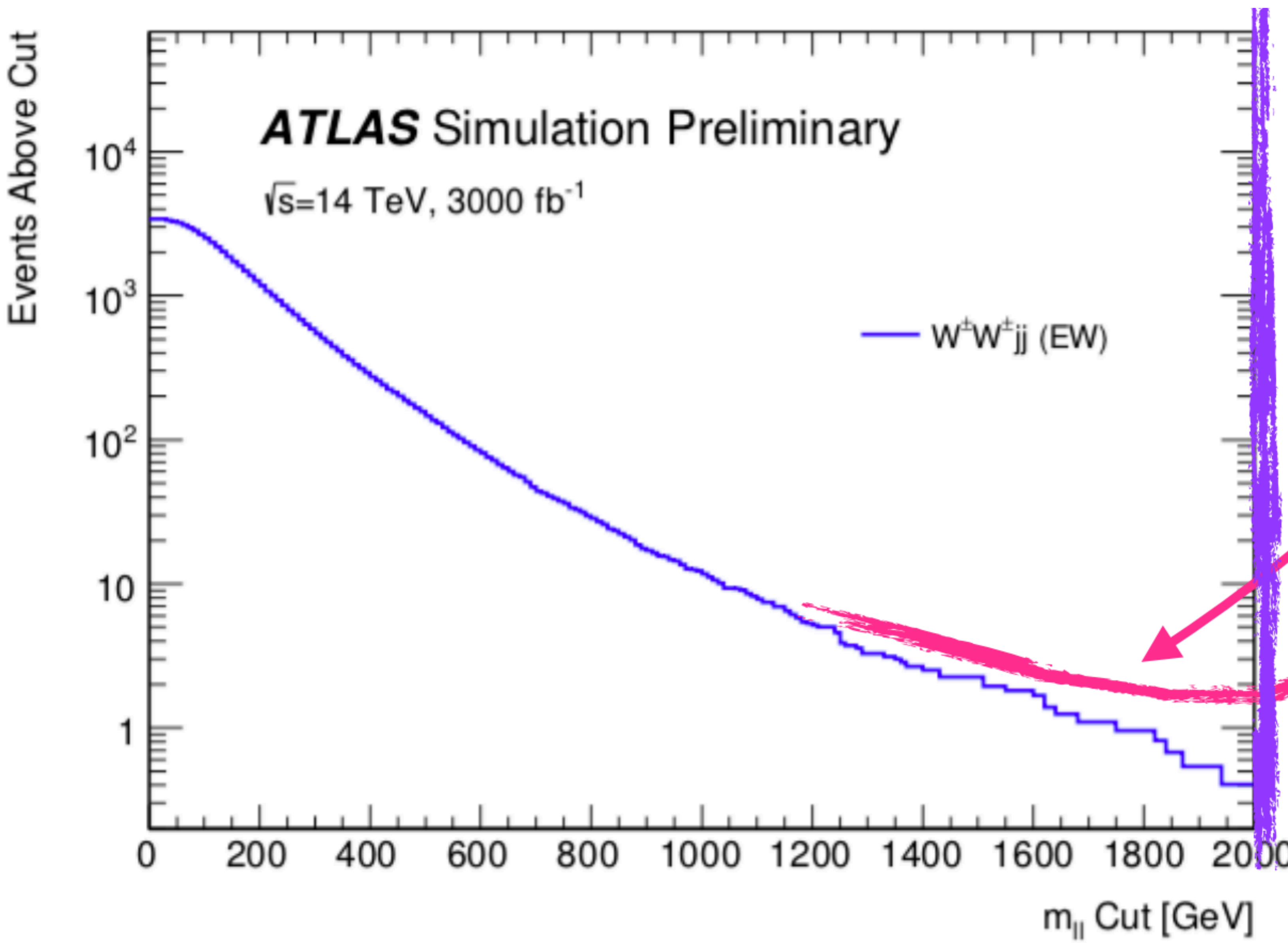
Deviation from SM prediction in high energy tails?



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

Why do we need better PDFs?

Deviation from SM prediction in high energy tails?

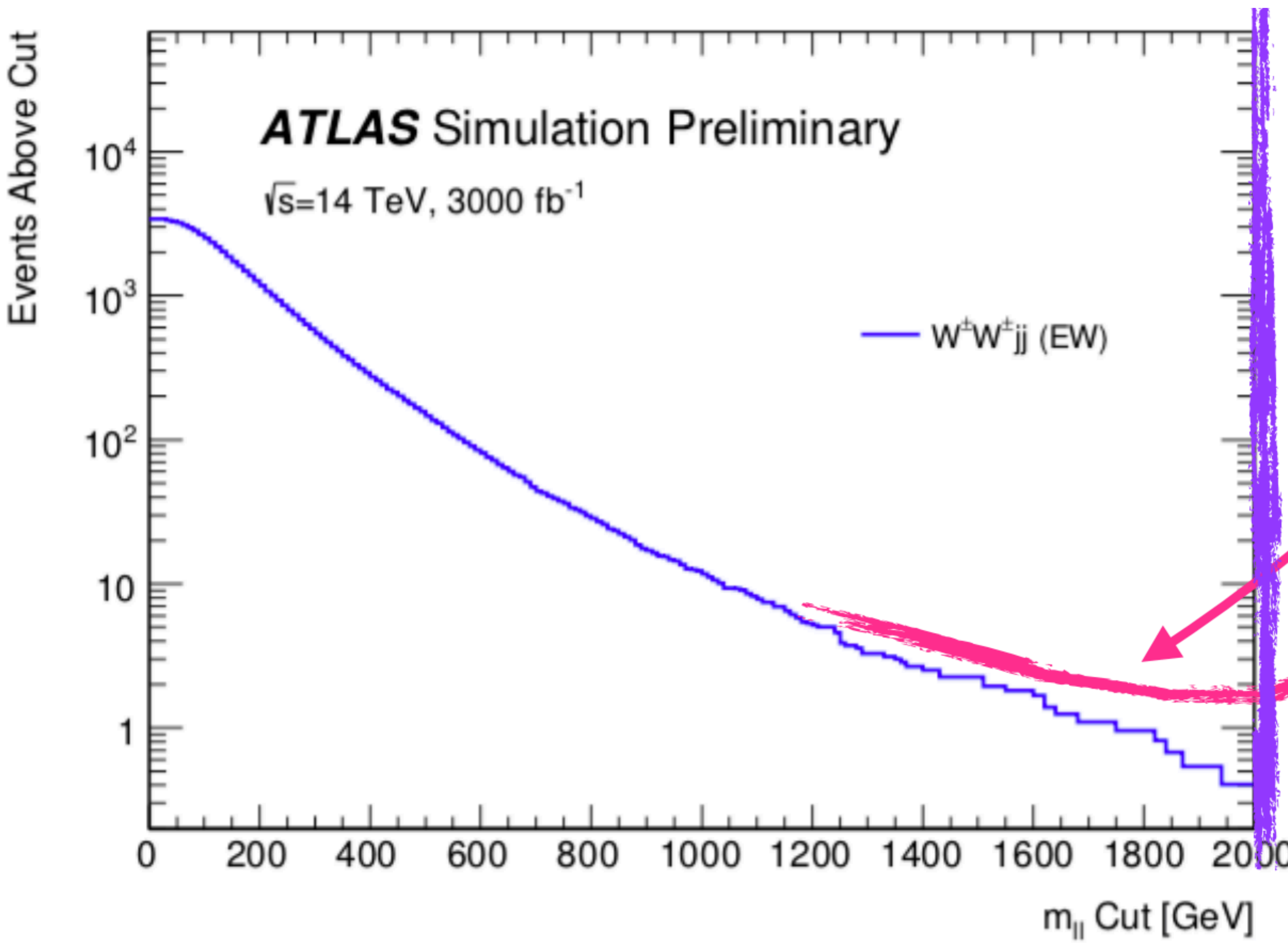


CA Lee, HL/HE-LHC Jamboree, 1 March 2019

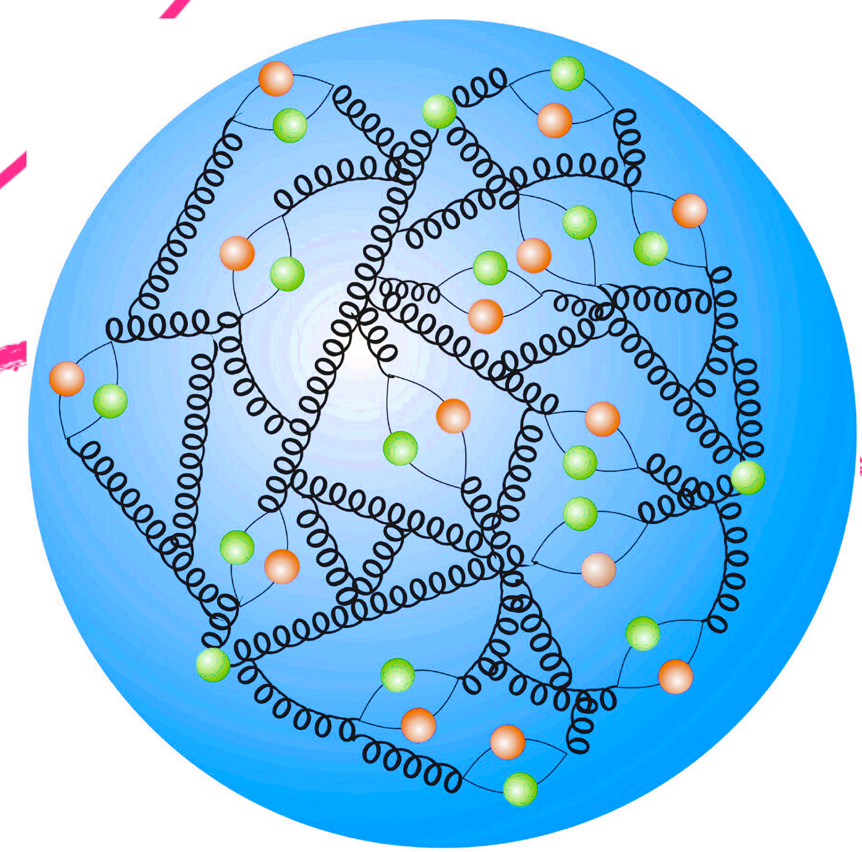
SMEFT interpretation: from a massive particle at high energies …

Why do we need better PDFs?

Deviation from SM prediction in high energy tails?



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



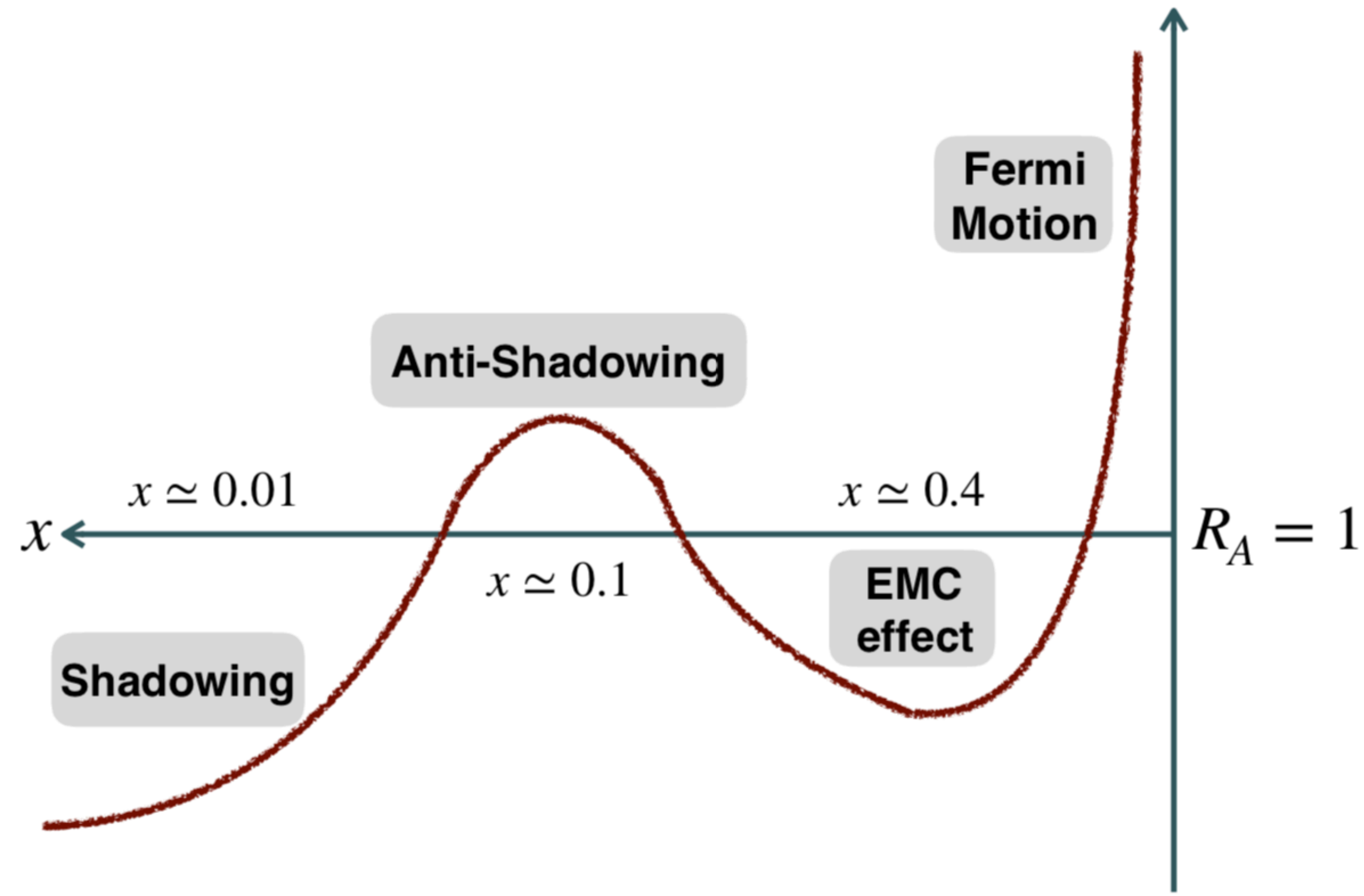
Iranipour WG3

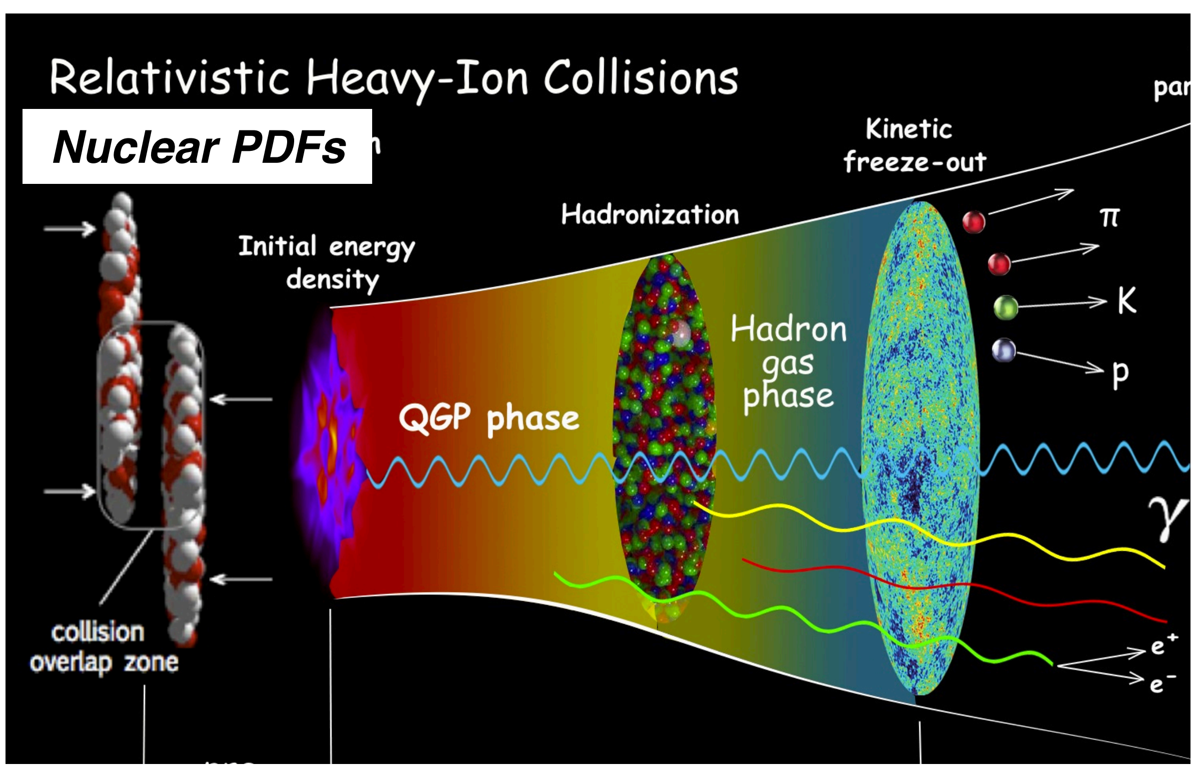
…or reflecting our limited understating of proton structure?

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

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

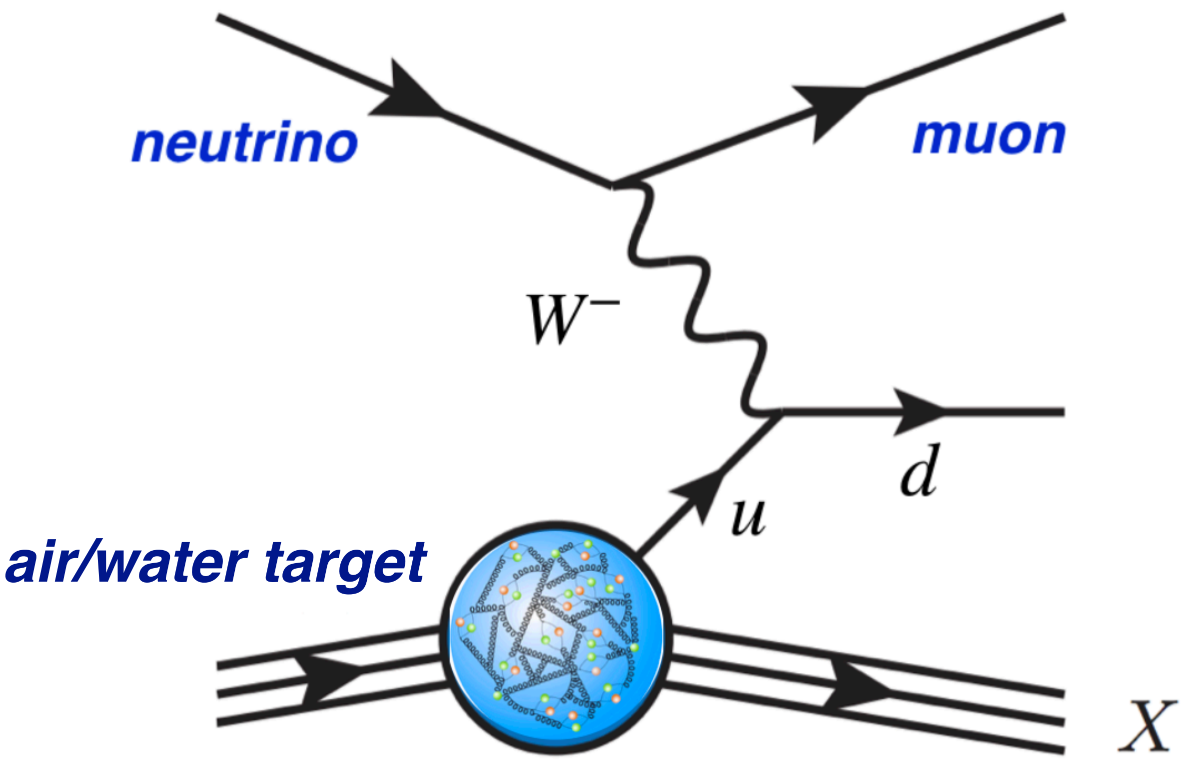


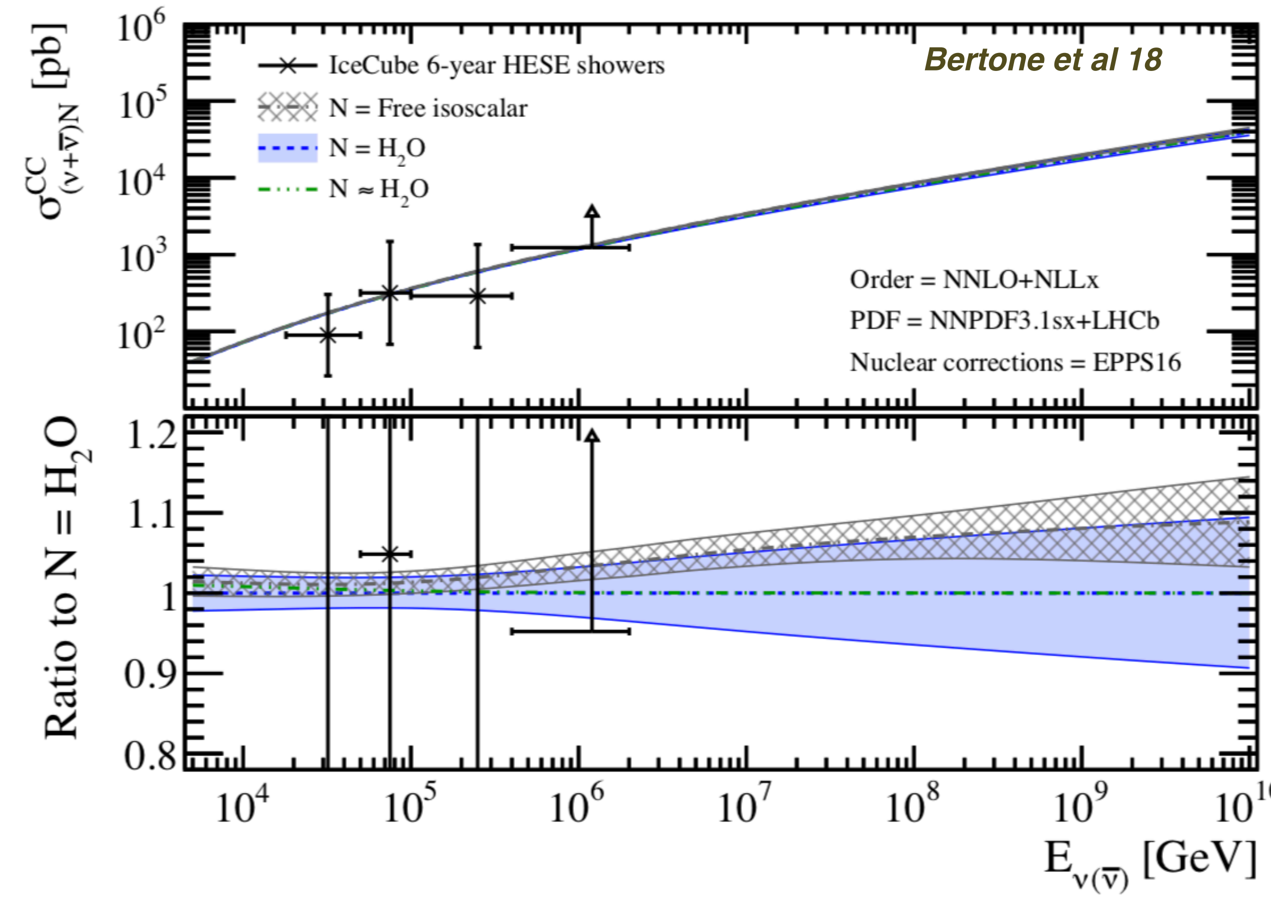


- **Initial state of heavy-ion collisions**: Quark-Gluon Plasma characterisation
- nPDFs also required for **ultra-high-energy astrophysics** e.g. neutrino telescopes

Neutrino telescopes as QCD microscopes

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





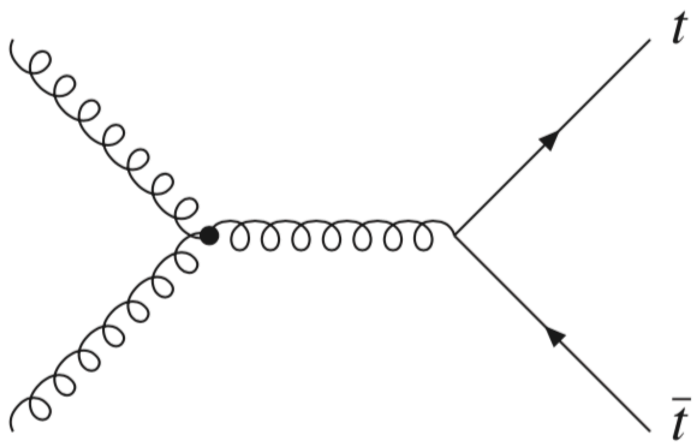
JR WG1+WG7

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

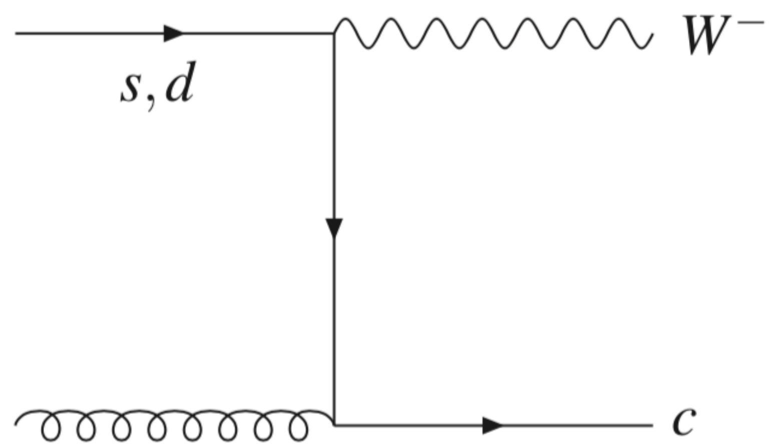
PDF information from p+p collisions

large-x gluon | *strangeness* | *antiquarks*

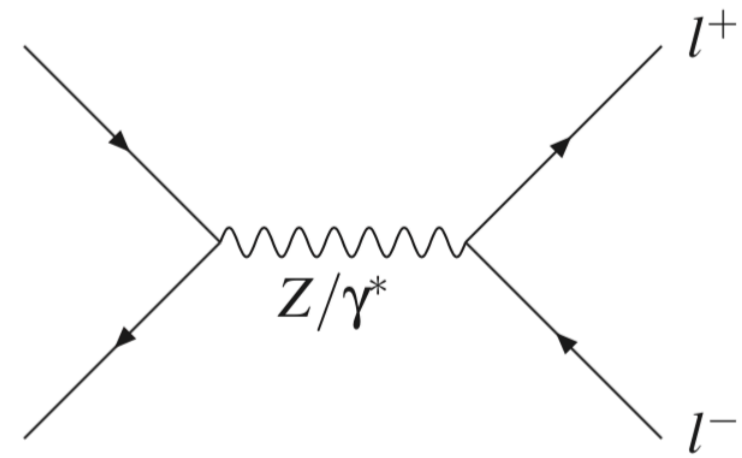
Top quark pair production



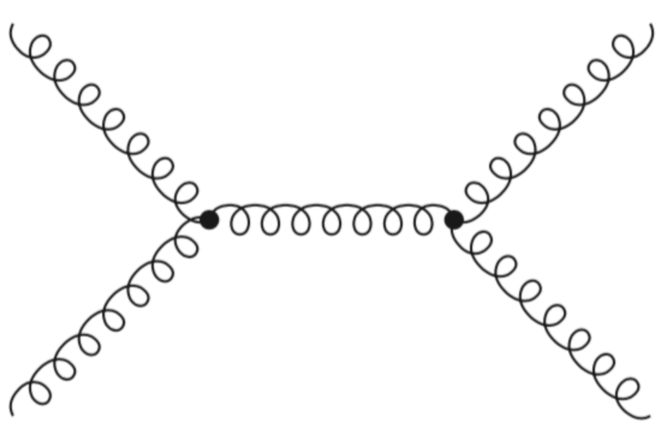
$W + c$ production



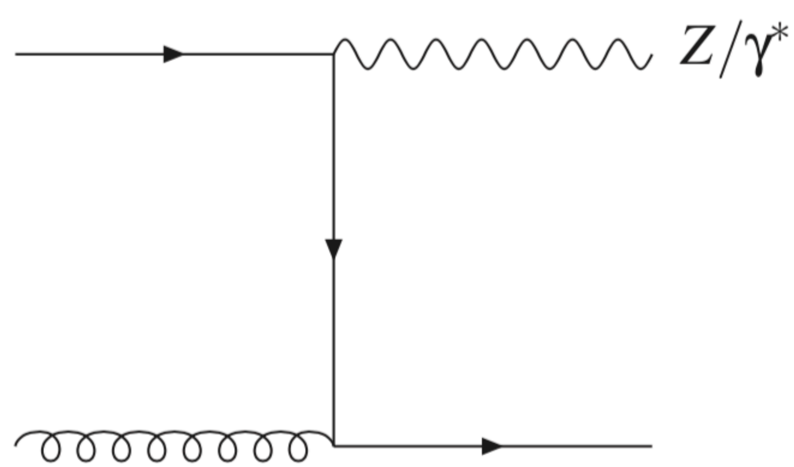
Drell–Yan production



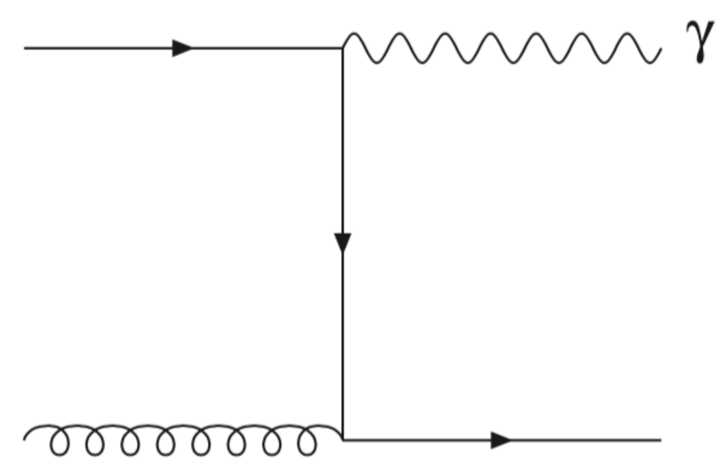
Jet production



$Z\ p_T$

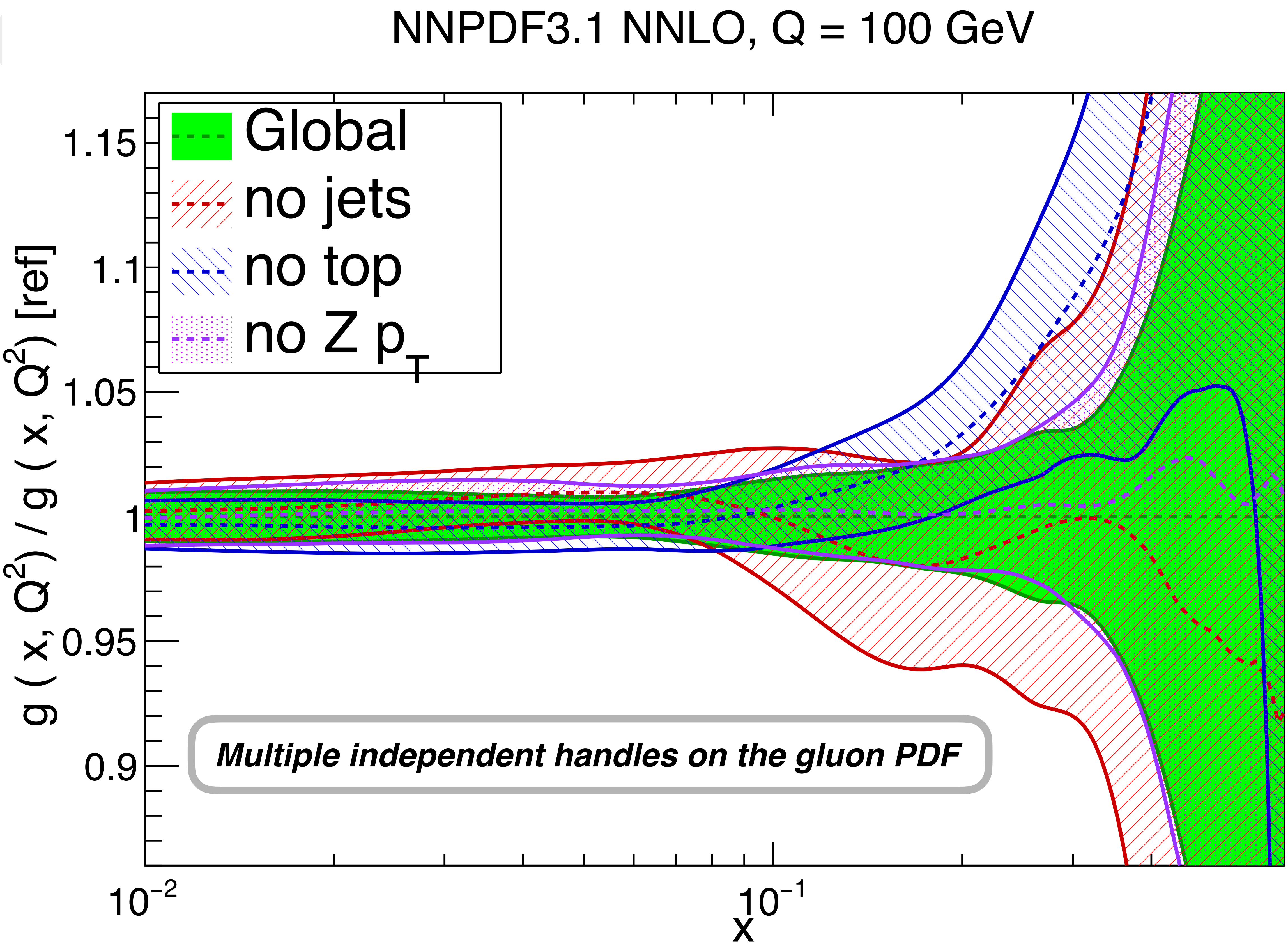


Direct photon production



large-x gluon | *medium-x gluon* | *medium-x gluon*

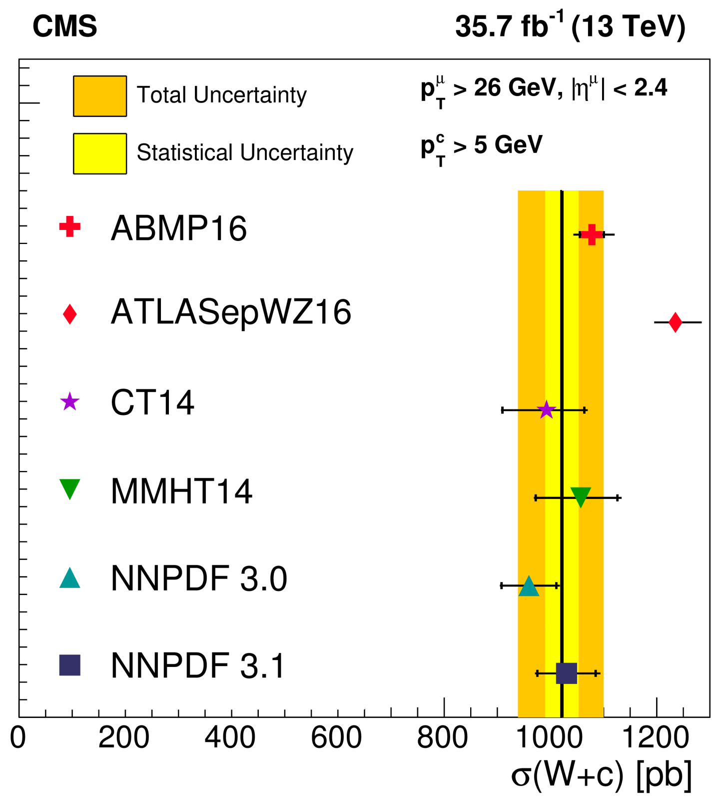
One glue to bind them all

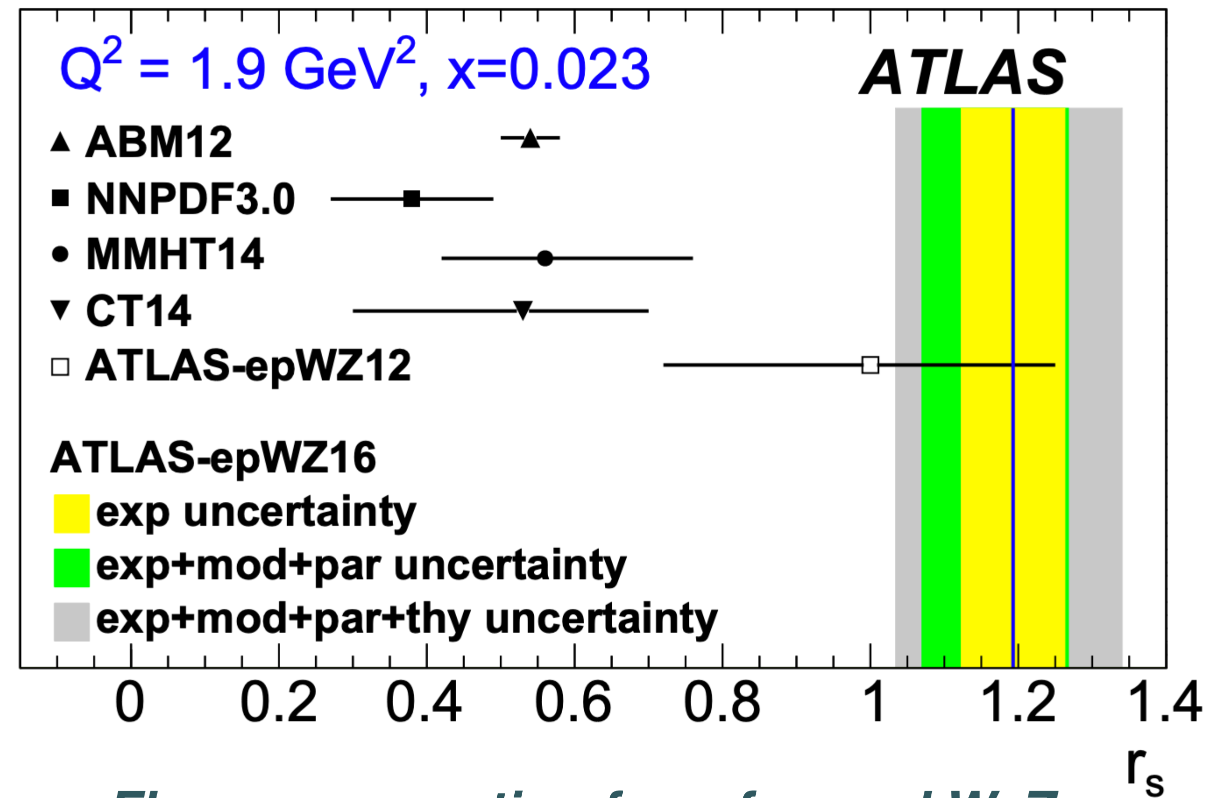


Constraints from LHC data

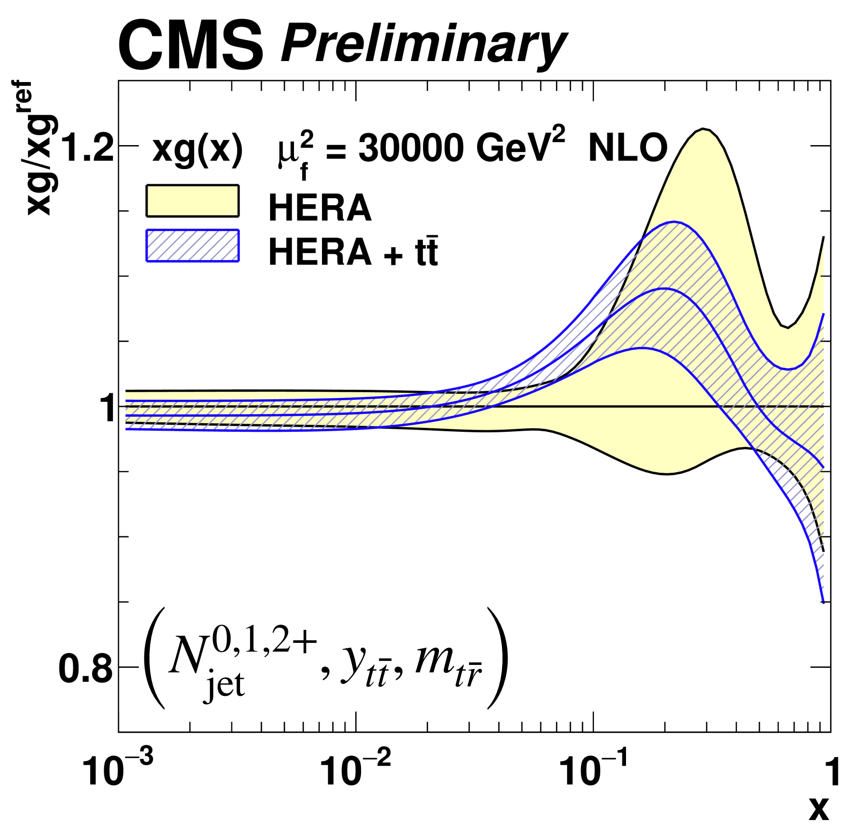
Combined interpretation within global fit?

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

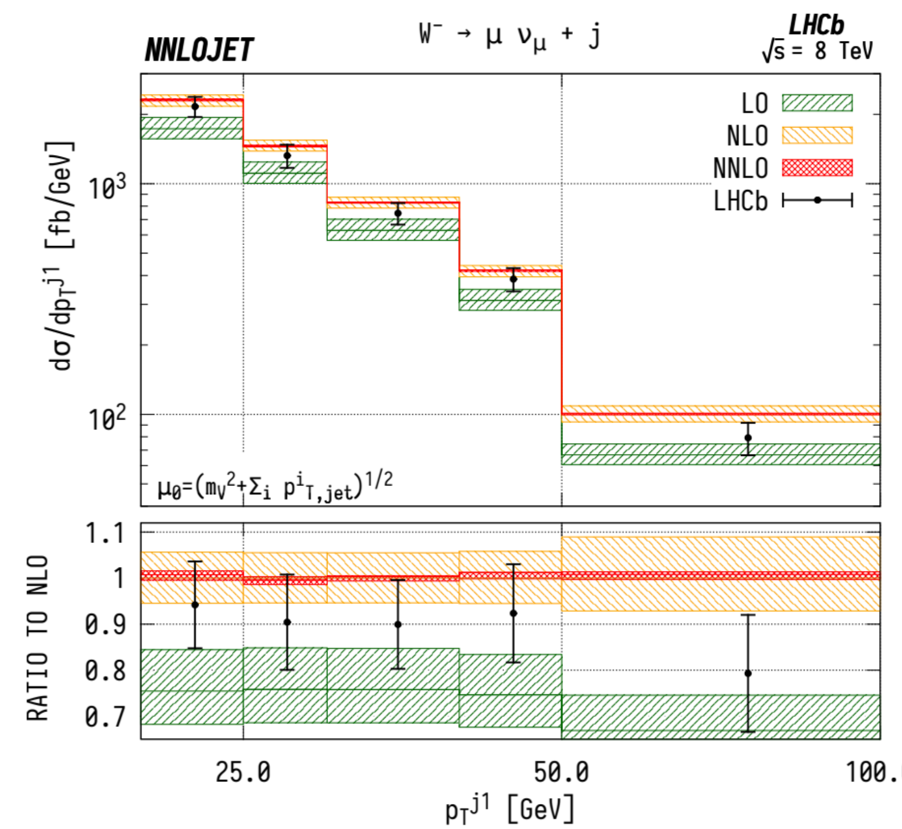




Multi-differential top quark pairs



Flavour separation from forward W, Z



Gehrmann-De Ridder et al 19

QCD uncertainties in PDF fits

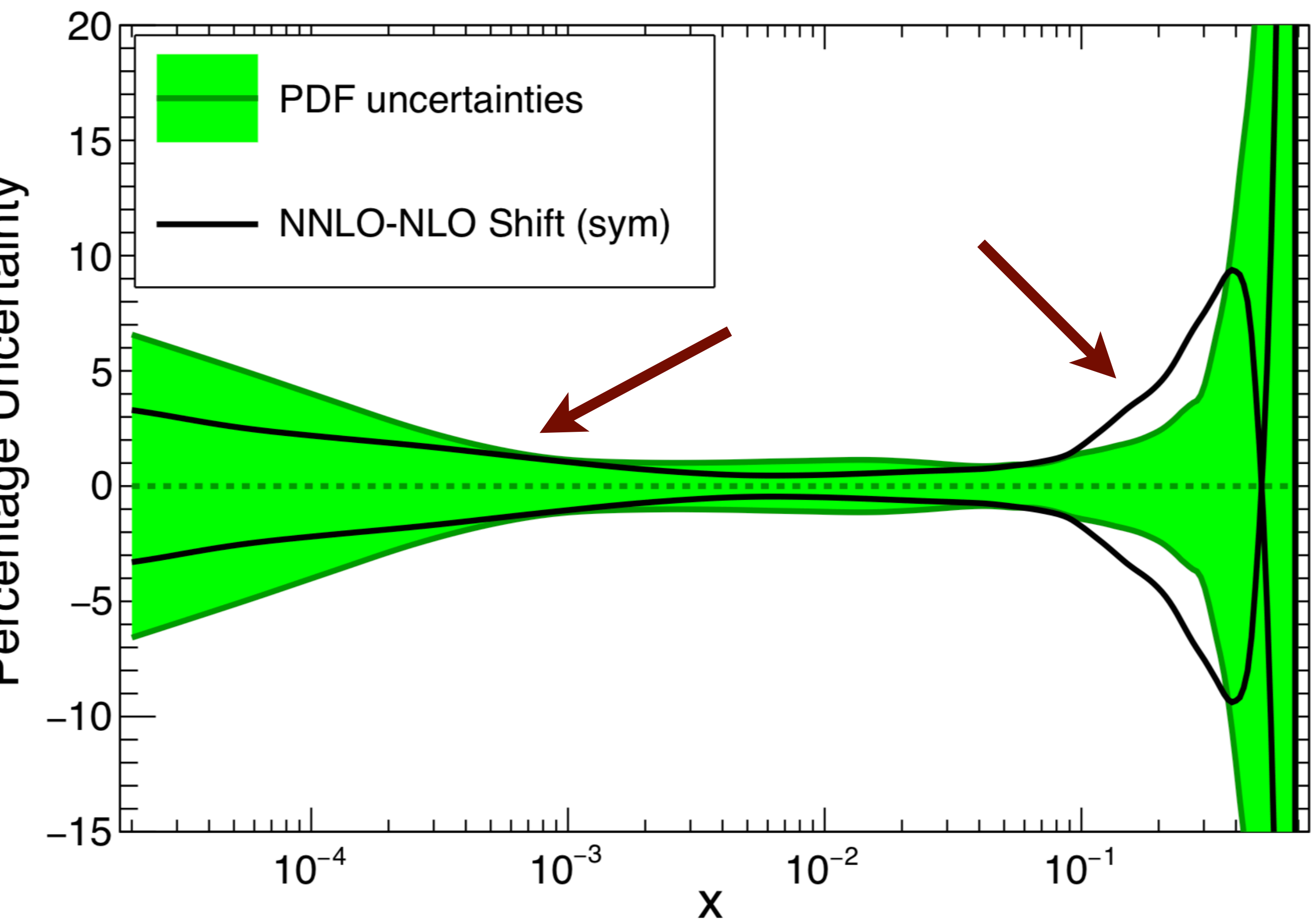
Standard global PDF fits are based on **fixed-order QCD calculations**

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

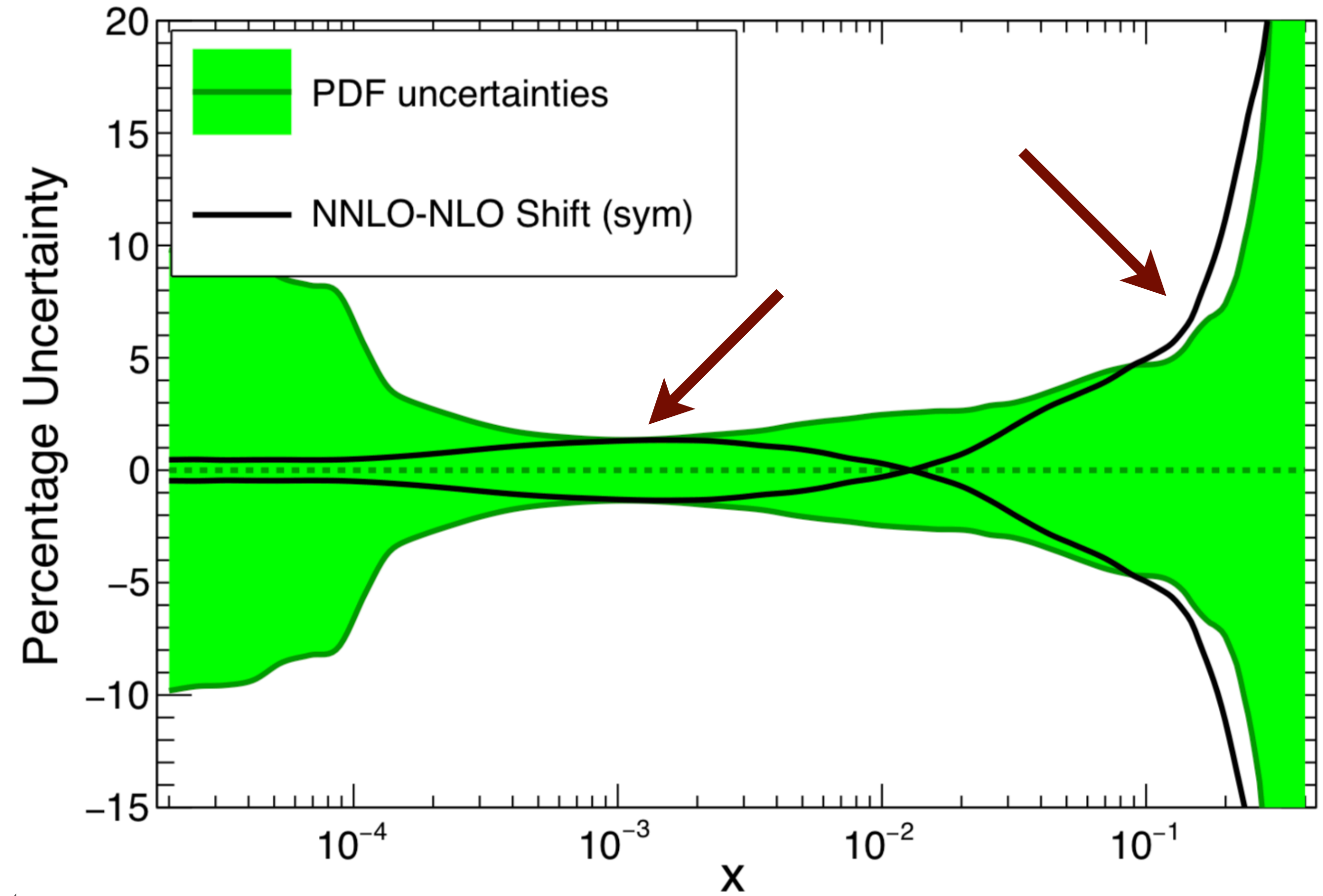
The truncation of the perturbative series has associated a theoretical uncertainty: **Missing Higher Order (MHO)** uncertainty

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

$g(x,Q^2=100\ \text{GeV}^2)$, NNPDF3.1NLO



$\bar{u}(x,Q^2)$, NNPDF3.1NLO

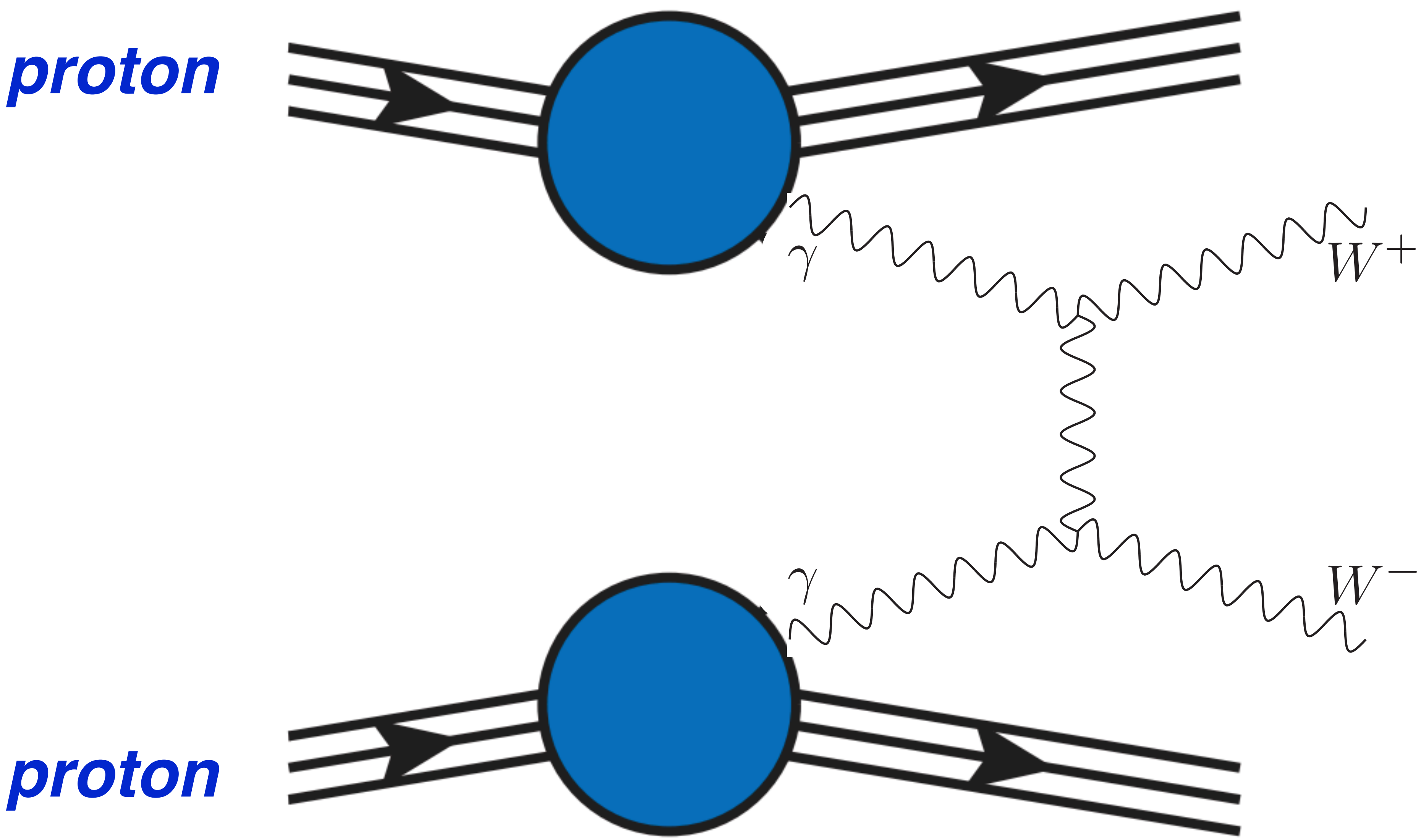


Let there be light: the photon PDF

- 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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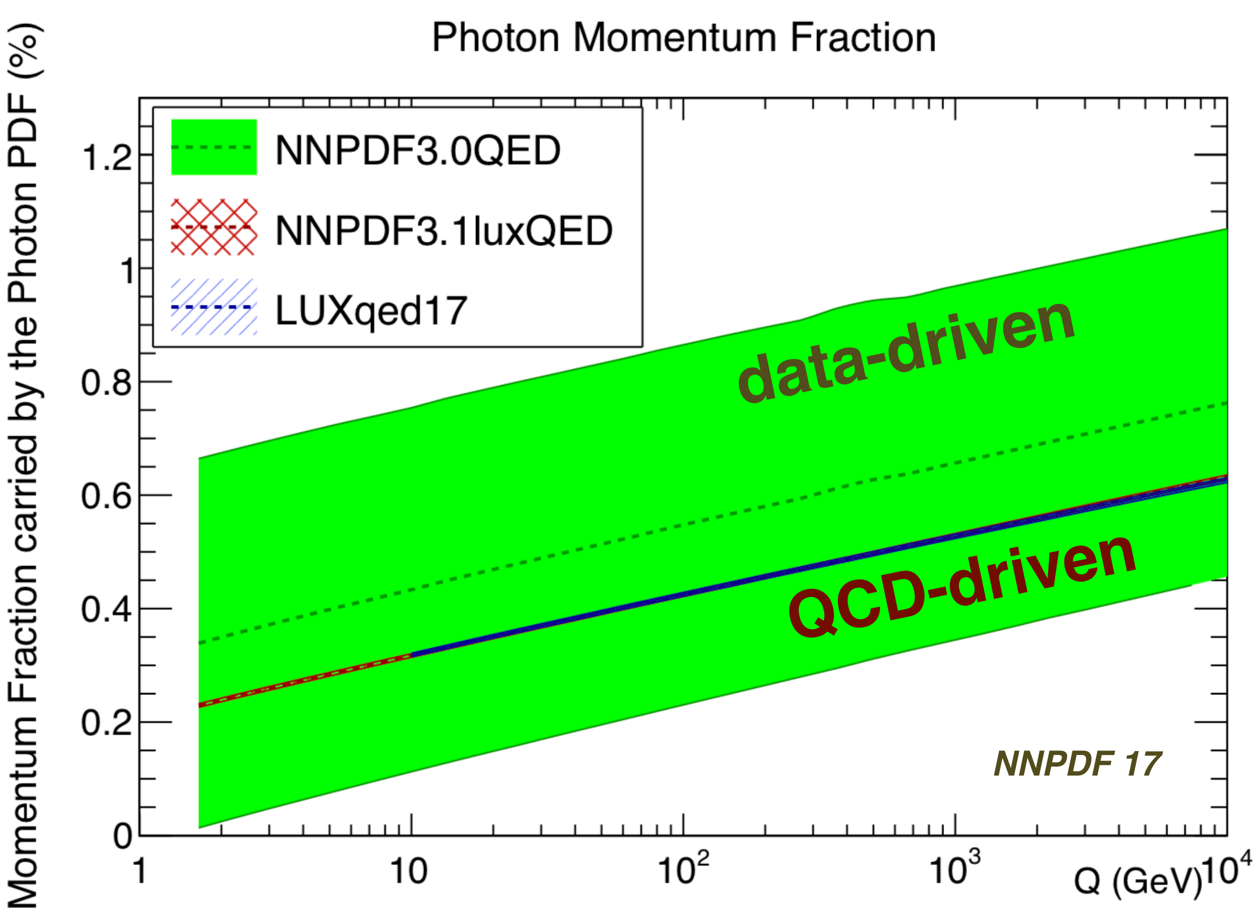
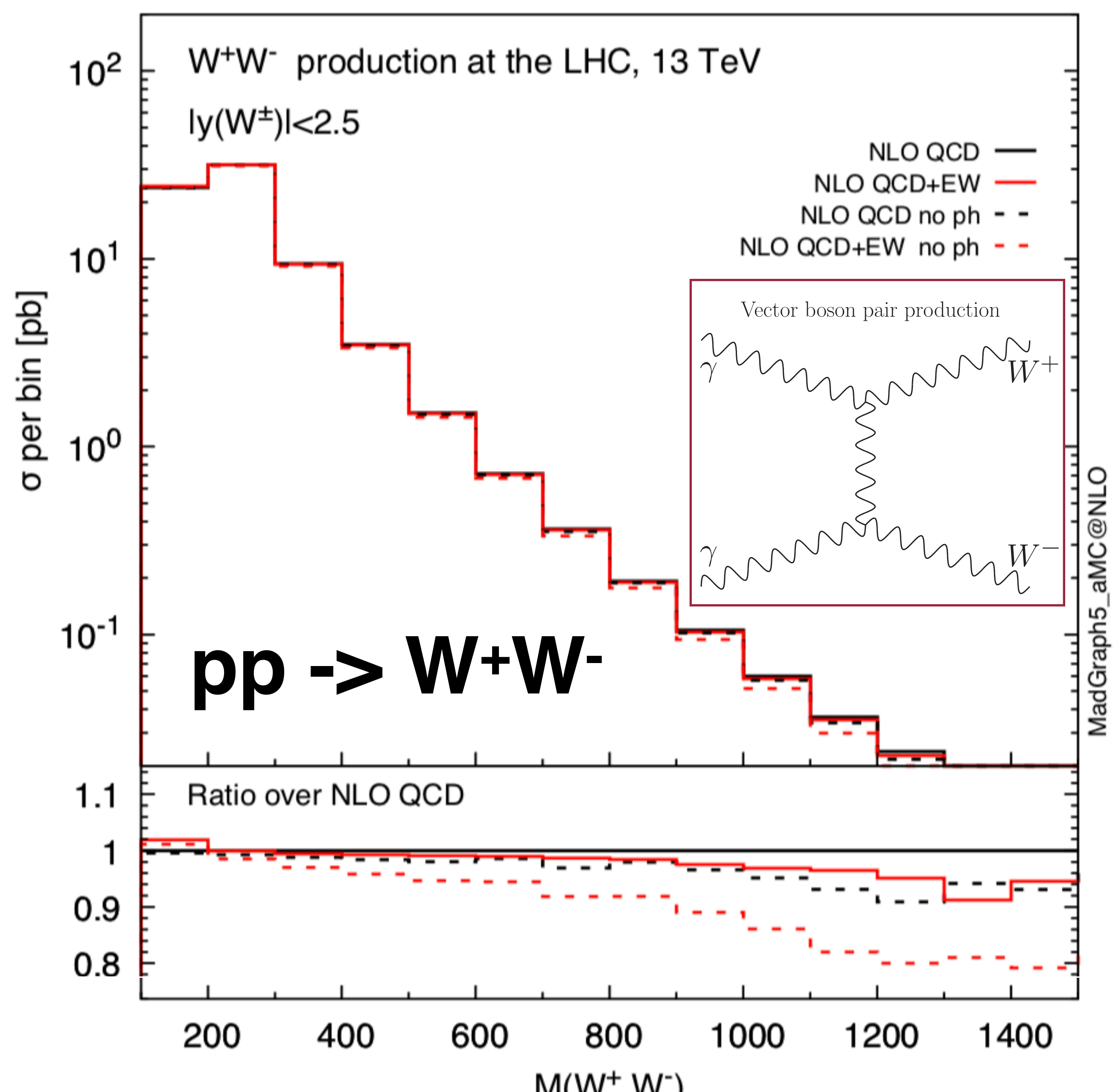
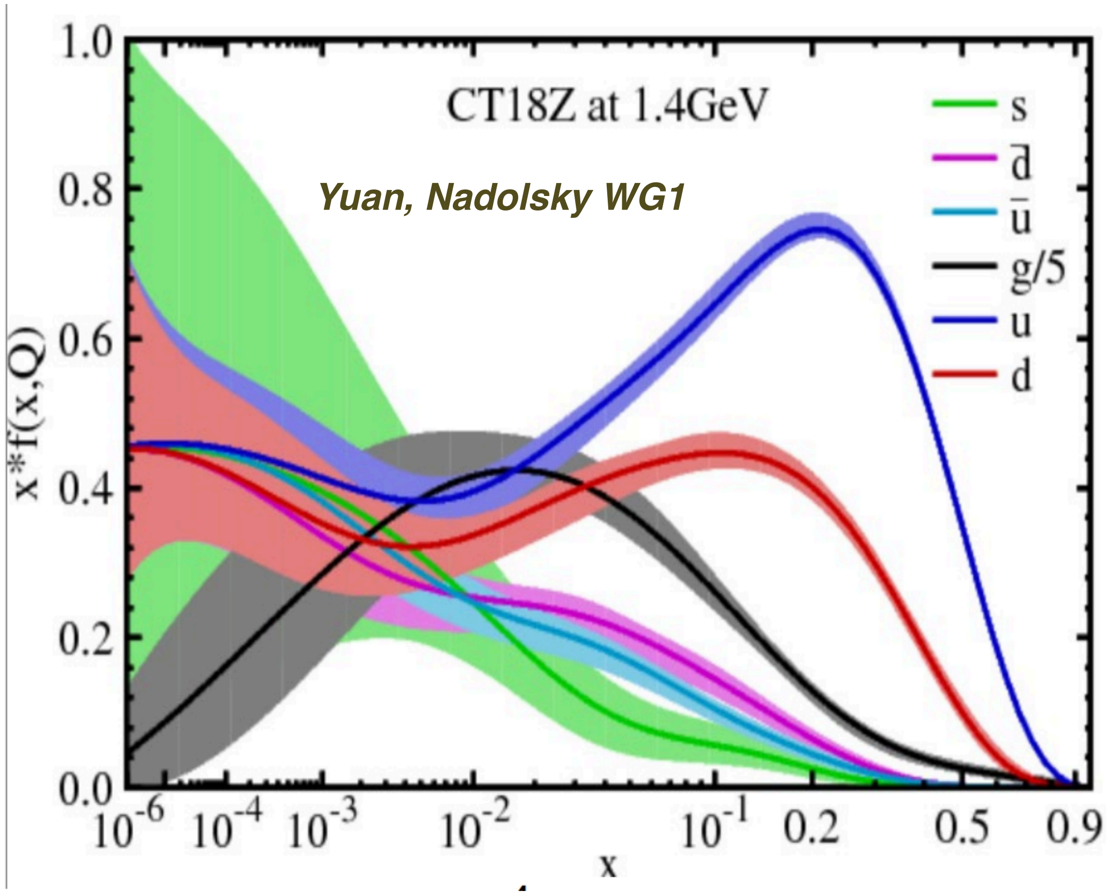


Up to 0.5% of proton's momentum ***carried by photons***

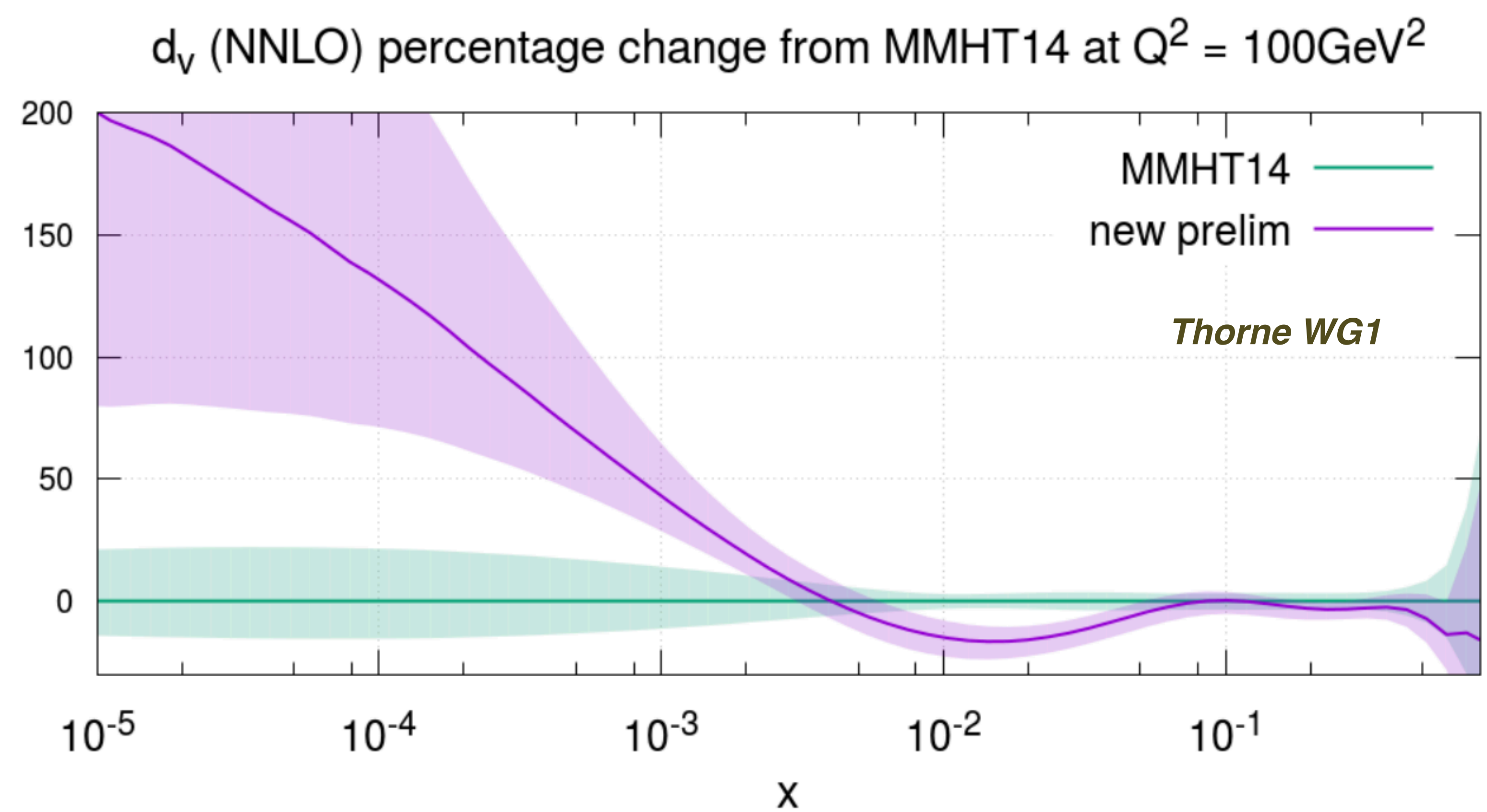


Updating the global PDF analyses

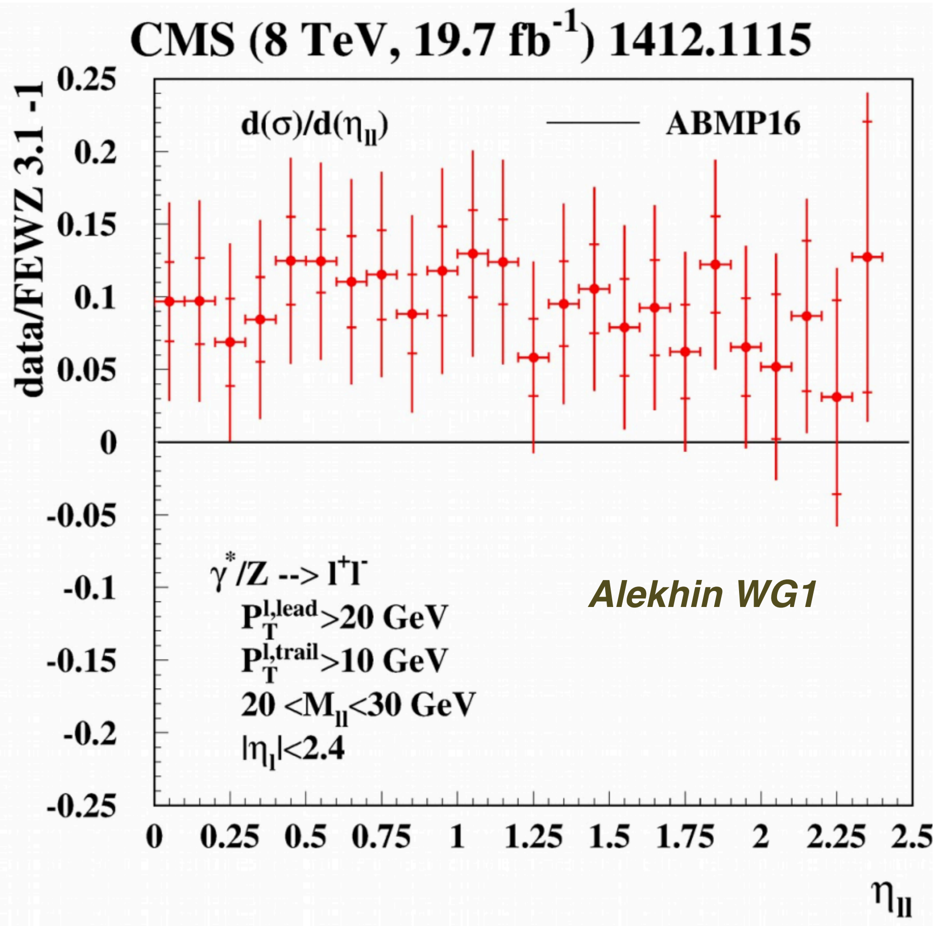


- **CT18/CT18Z** is the follow-up of CT14 (without/with ATLAS W,Z 2011)
- Added new LHC measurements boosted by the **ePump** and **PDFsense** tools
- Systematic studies of dataset compatibility

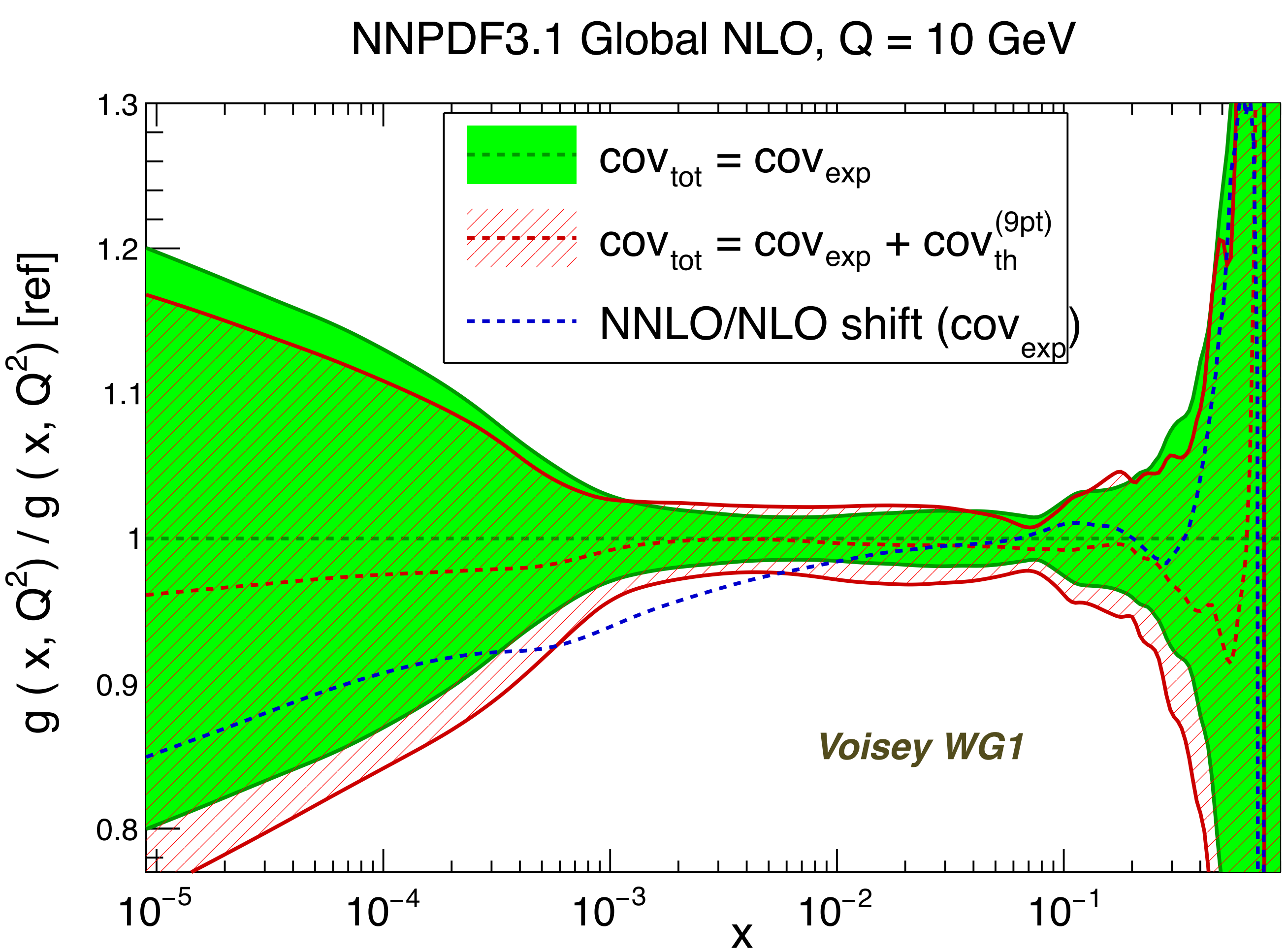
- **``MMHT" update** in progress
- Many new LHC data, extended parametrisation, NNLO calculations, …
- QED sets ready for release



Updating the global PDF analyses



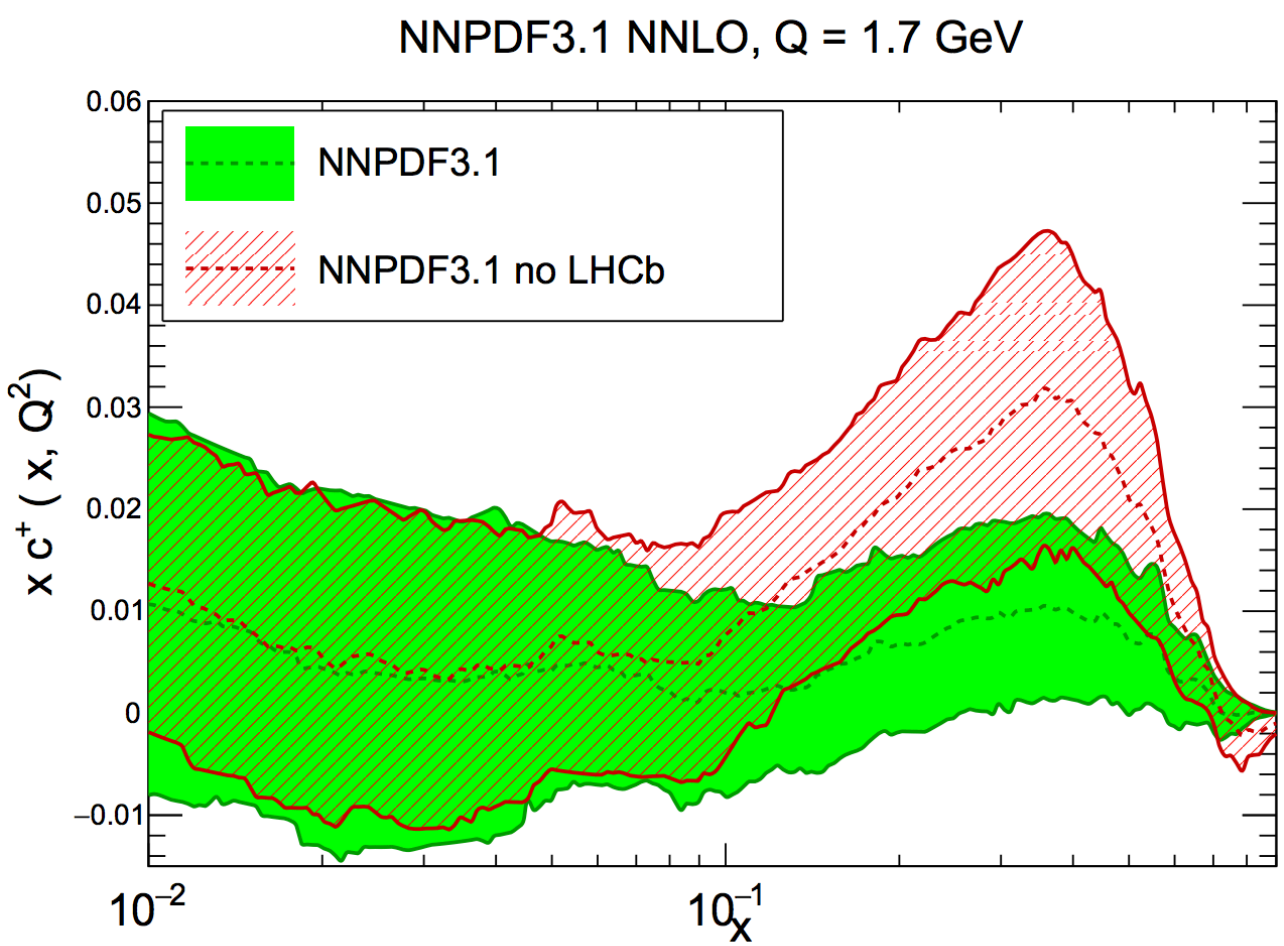
- **ABM** updates focusing on adding LHC Drell-Yan and top quark production data
- Studies of the impact of **higher twists**
- Potential tensions between ATLAS and CMS?

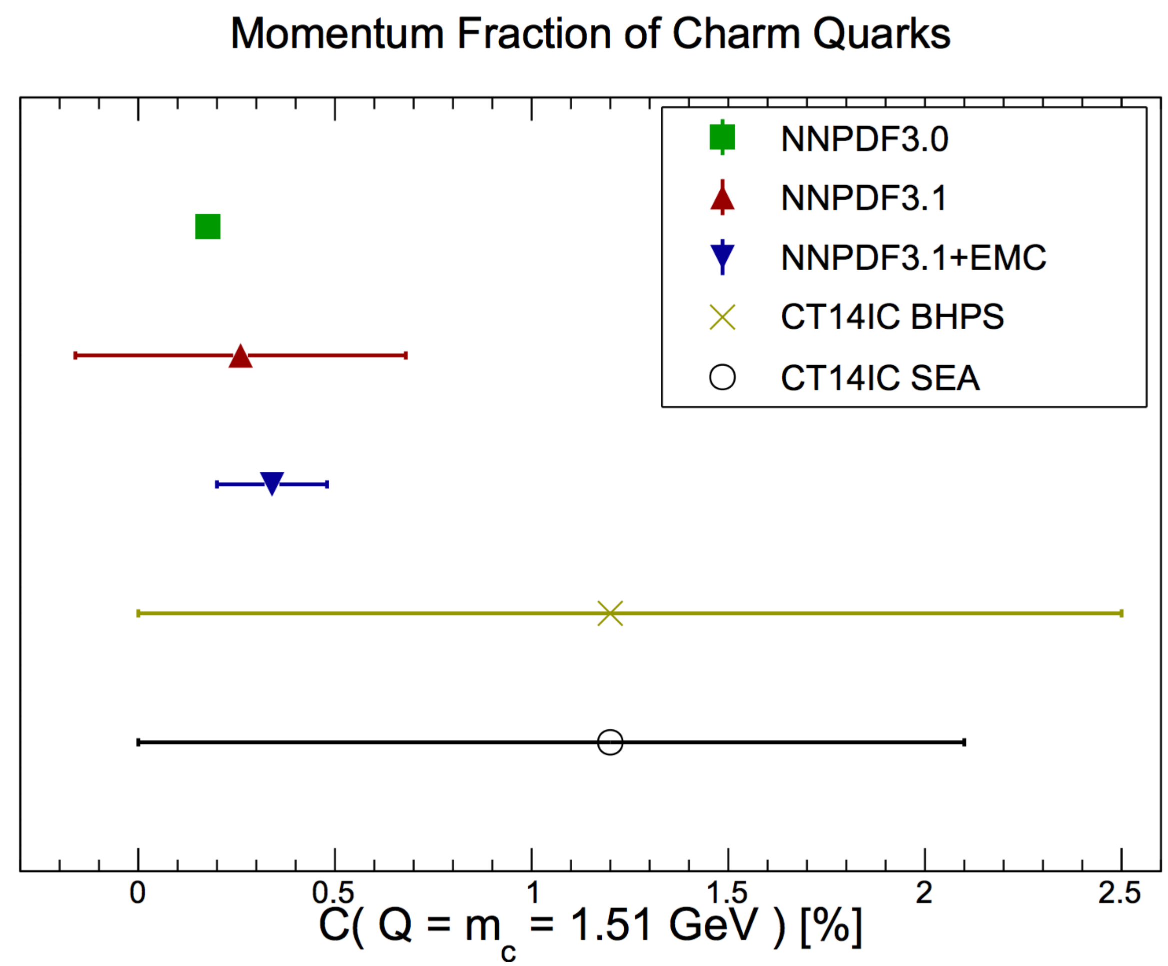


- **NNPDF3.1** released in 2017, with QED, small-x (BFKL), and $\alpha_S(M_Z)$ fits follow-ups
- PDF sets **with MHOUs** near completion
- Towards **NNPDF4.0:** new LHC data, improved methodology (TensorFlow for minimisation), MHOUs at NNLO, …

A charming proton?

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





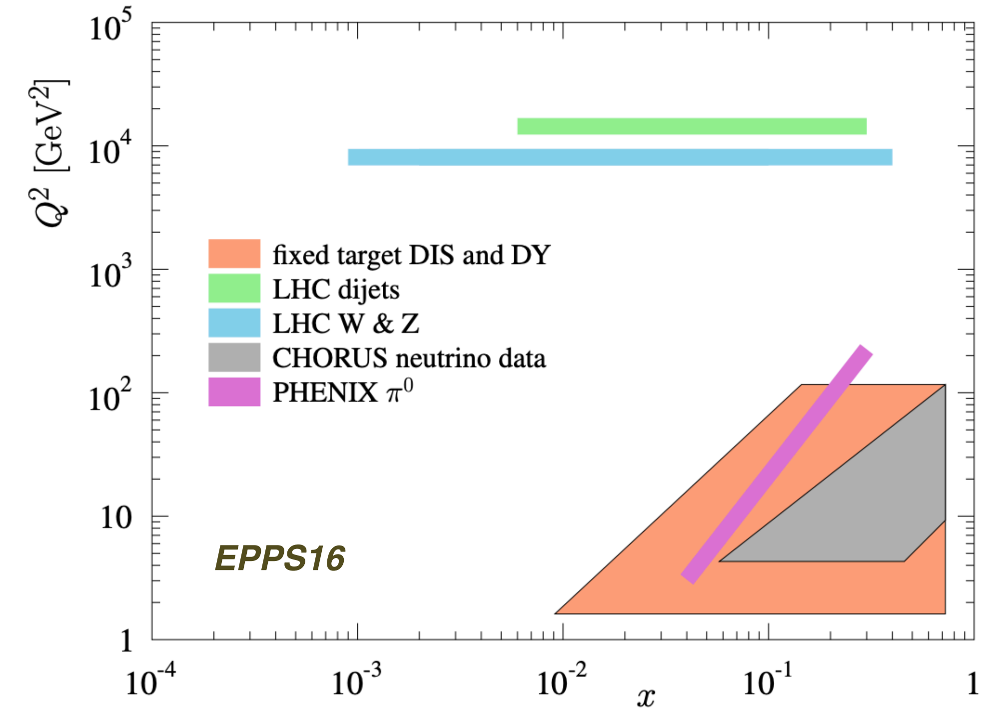
- LHC electroweak measurements provides information on the charm content of protons
- Can be tested in *Z+D*, high p_T *D*, *photon+D*

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

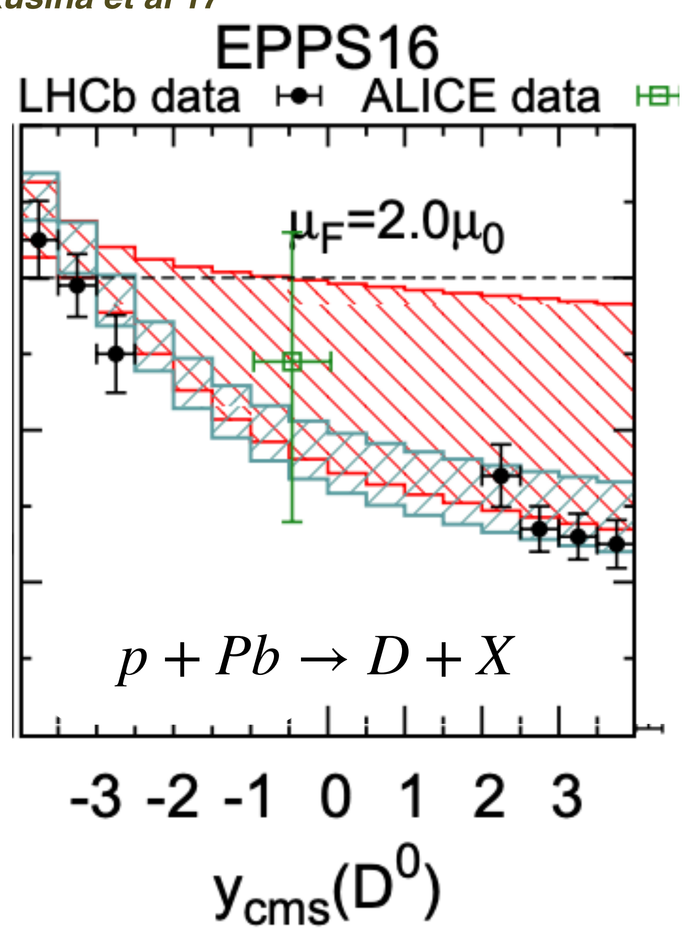
Indications of a ***small but non-zero charm content of protons***

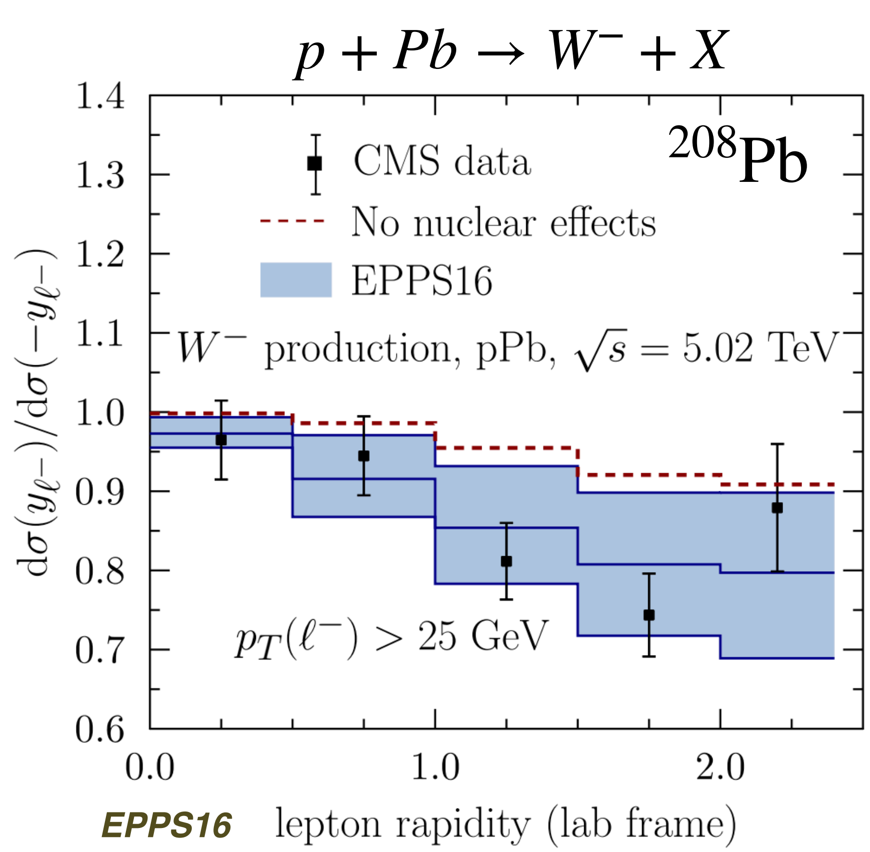
Progress in nuclear PDFs

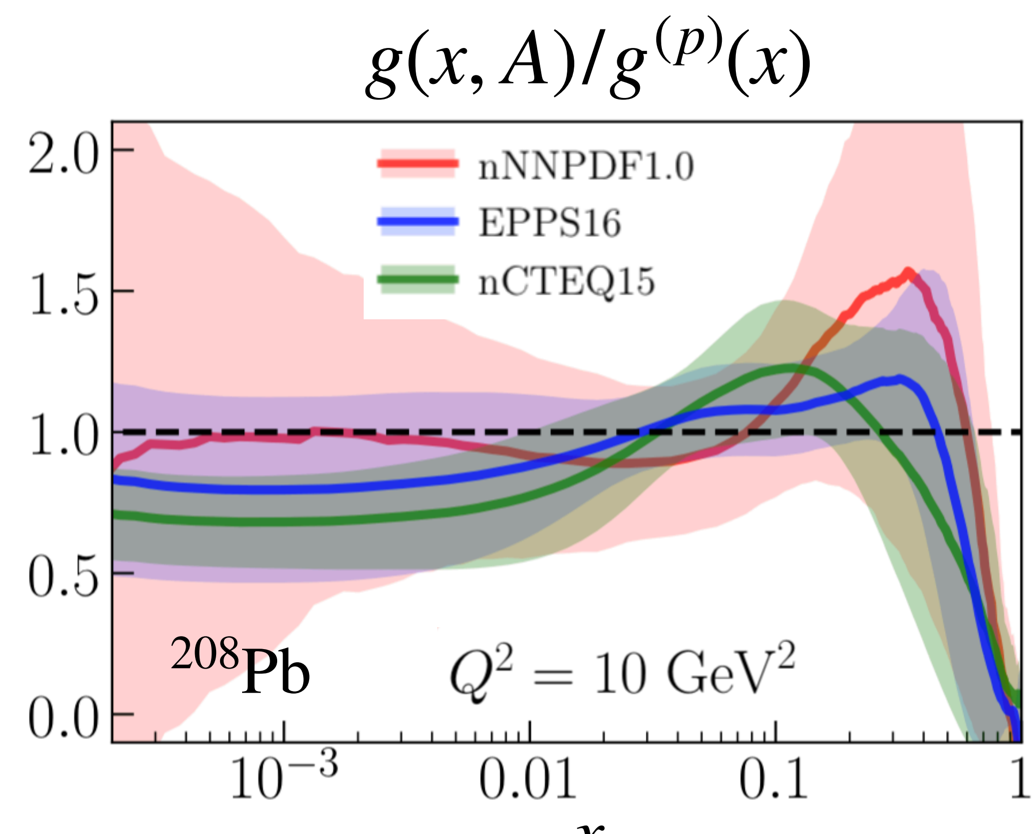
- Constraints from **LHC proton+lead collisions**: *W, Z,* jets, charm, quarkonia, Drell-Yan, direct photons, …
- **Theoretical** and **methodological** improvements: nPDF uncertainty estimate, NNLO QCD effects, …



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

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

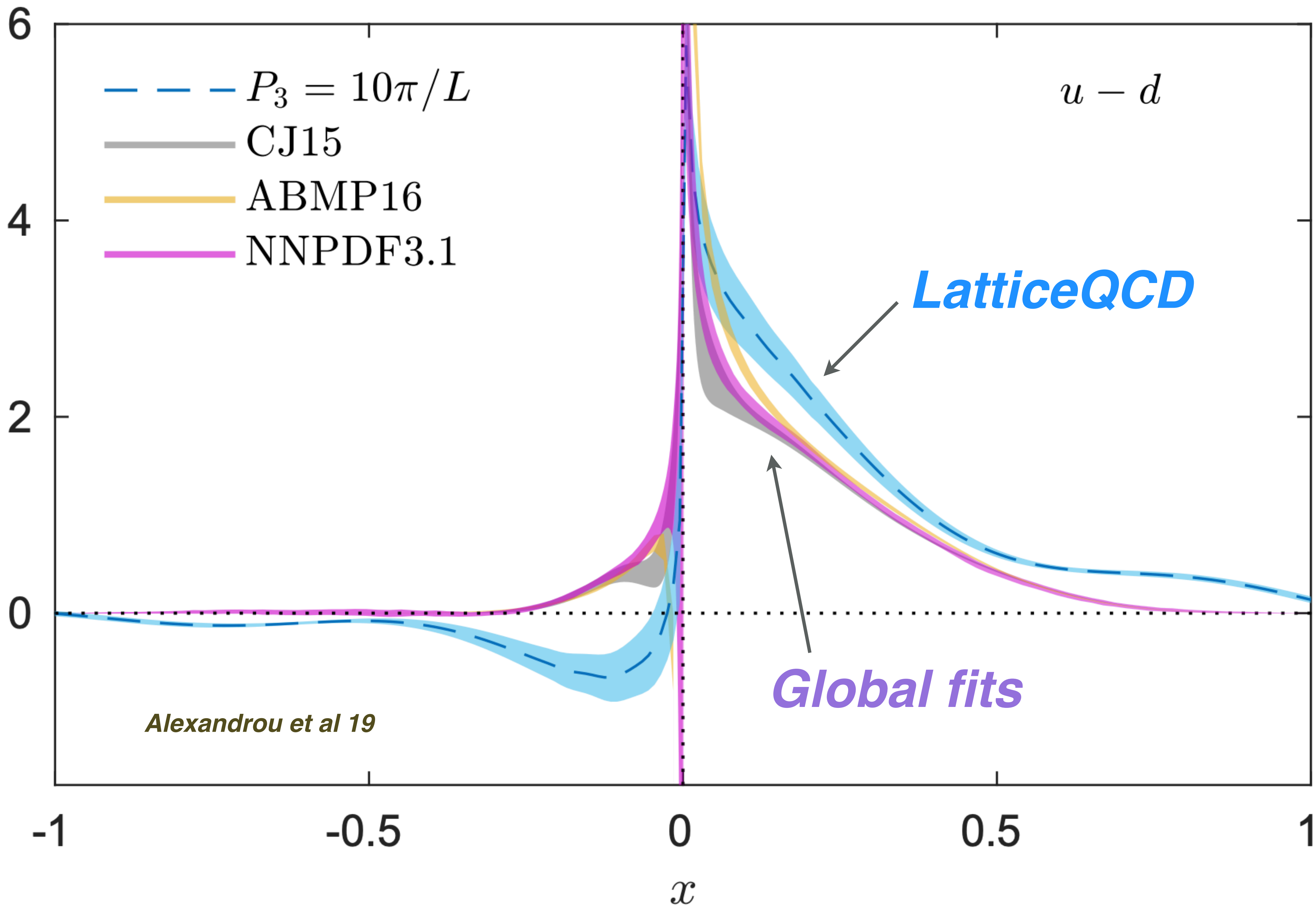
The two objects can be matched using the **Large Momentum EFT:**

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

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

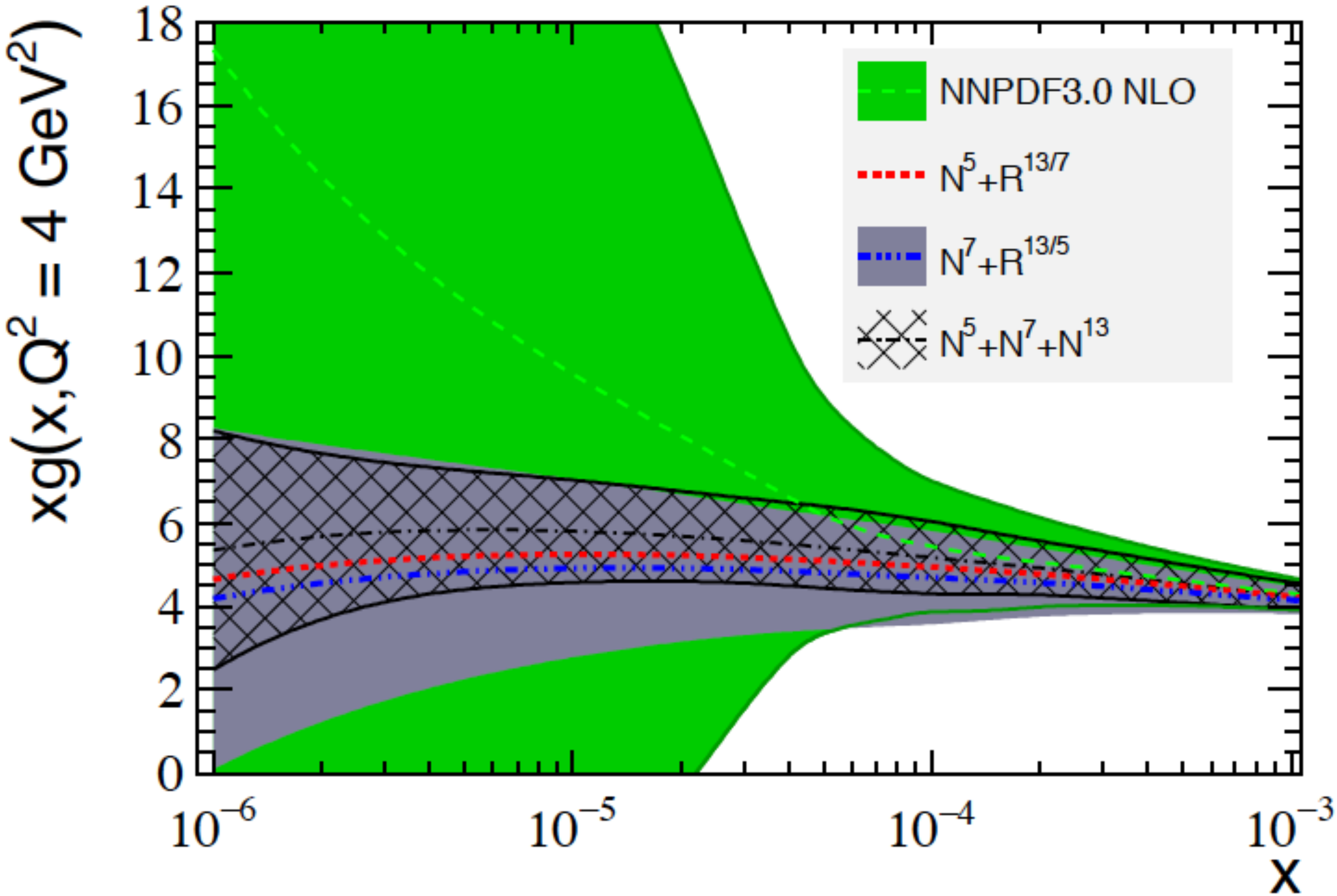
PDFLattice White Paper
Lin et al 17

The lattice QCD frontier



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

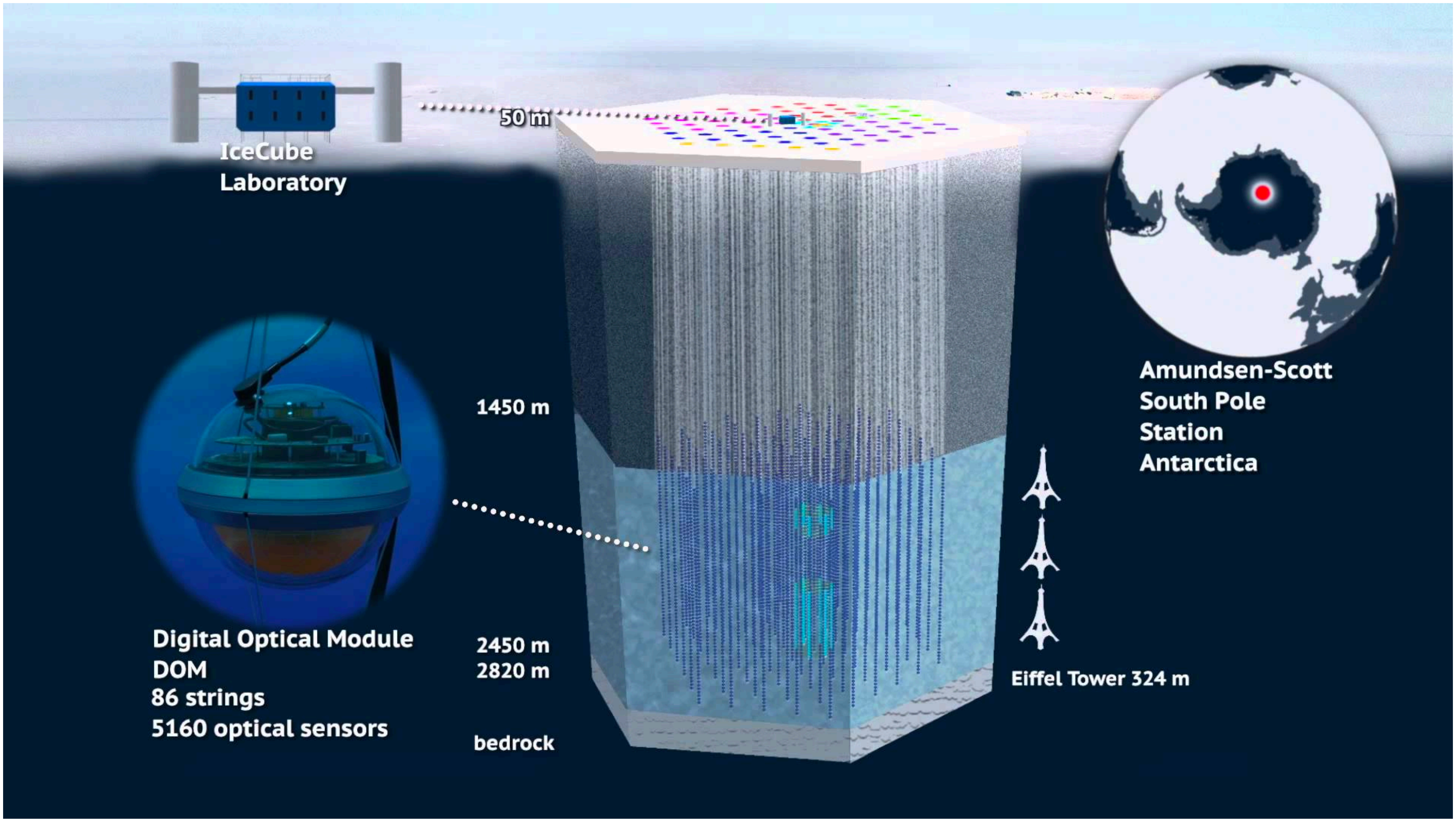
Forward charm production



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

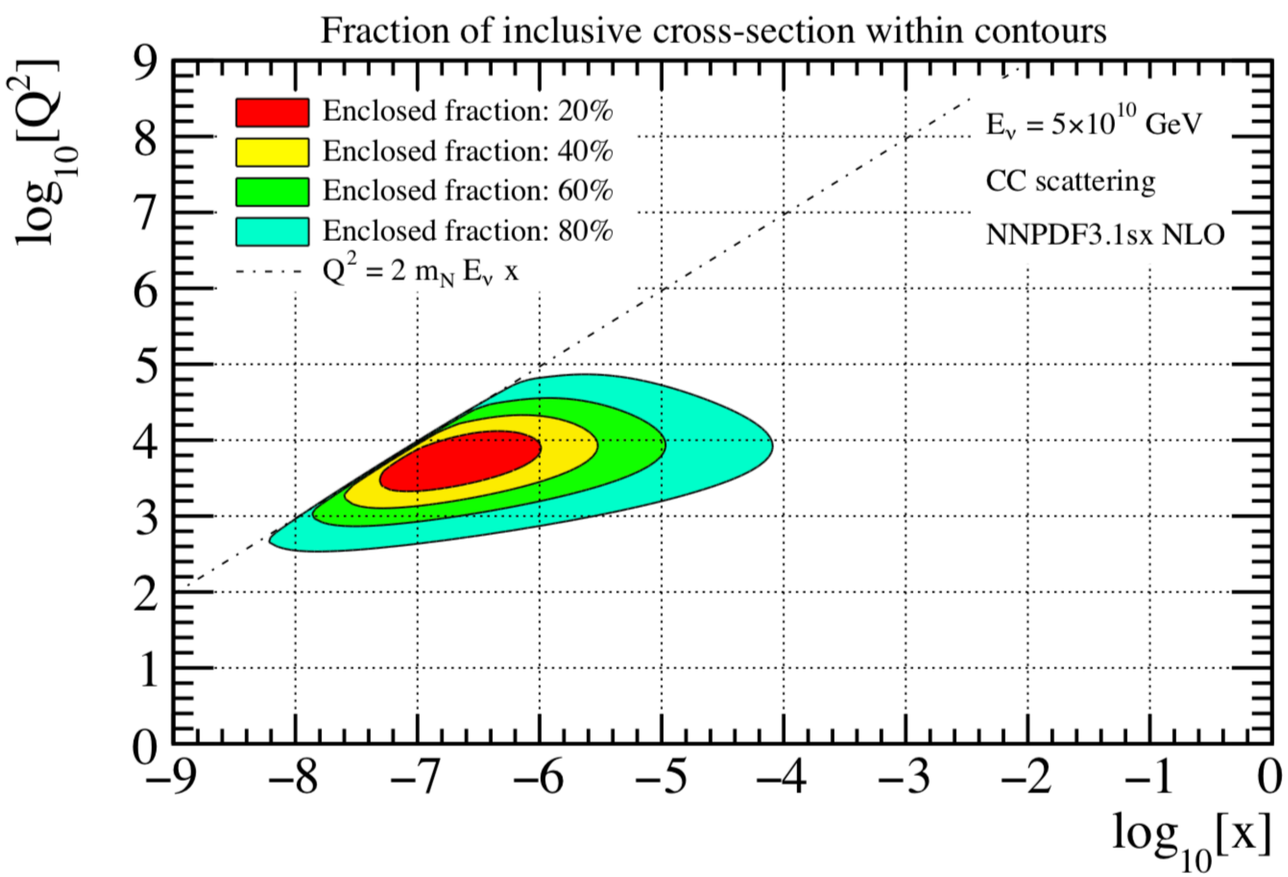
Neutrino telescopes

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



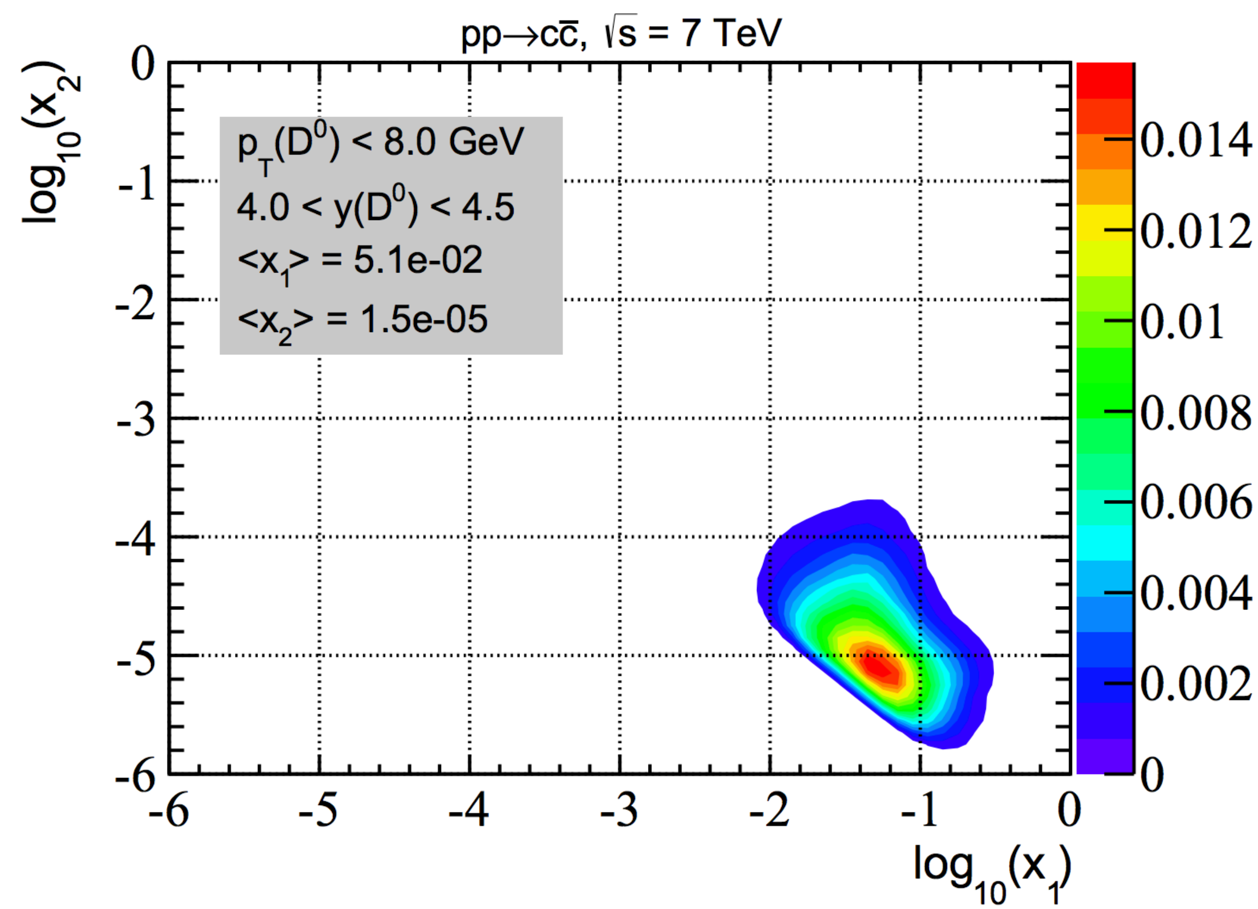
Neutrino telescopes as QCD microscopes

signal: *cosmic neutrino - nucleus scattering*



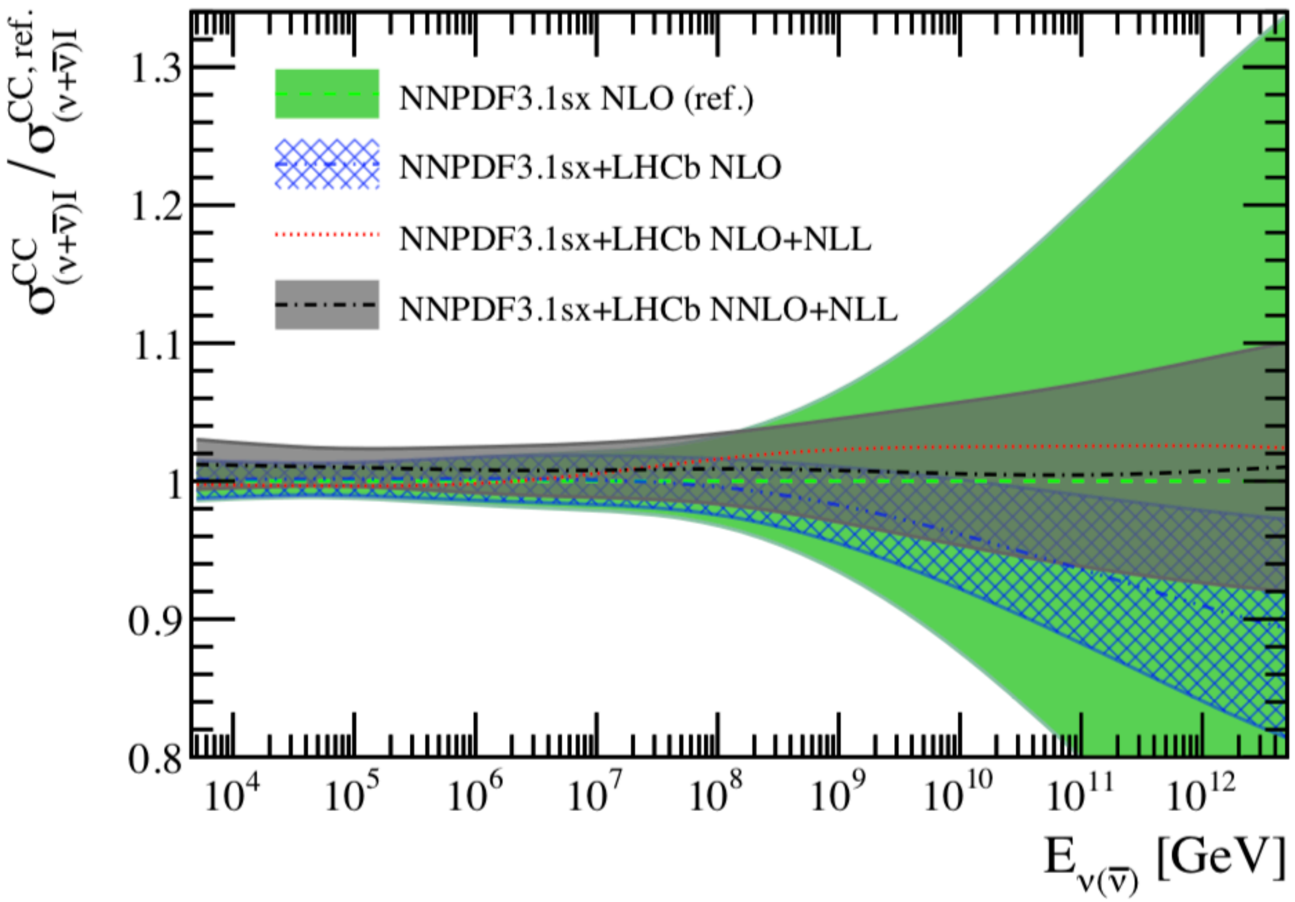
Sensitive to **small-*x* quarks** (and thus gluons via evolution) down to **x** ≃ **10^{-8}** and **Q** ≃ **M_W**

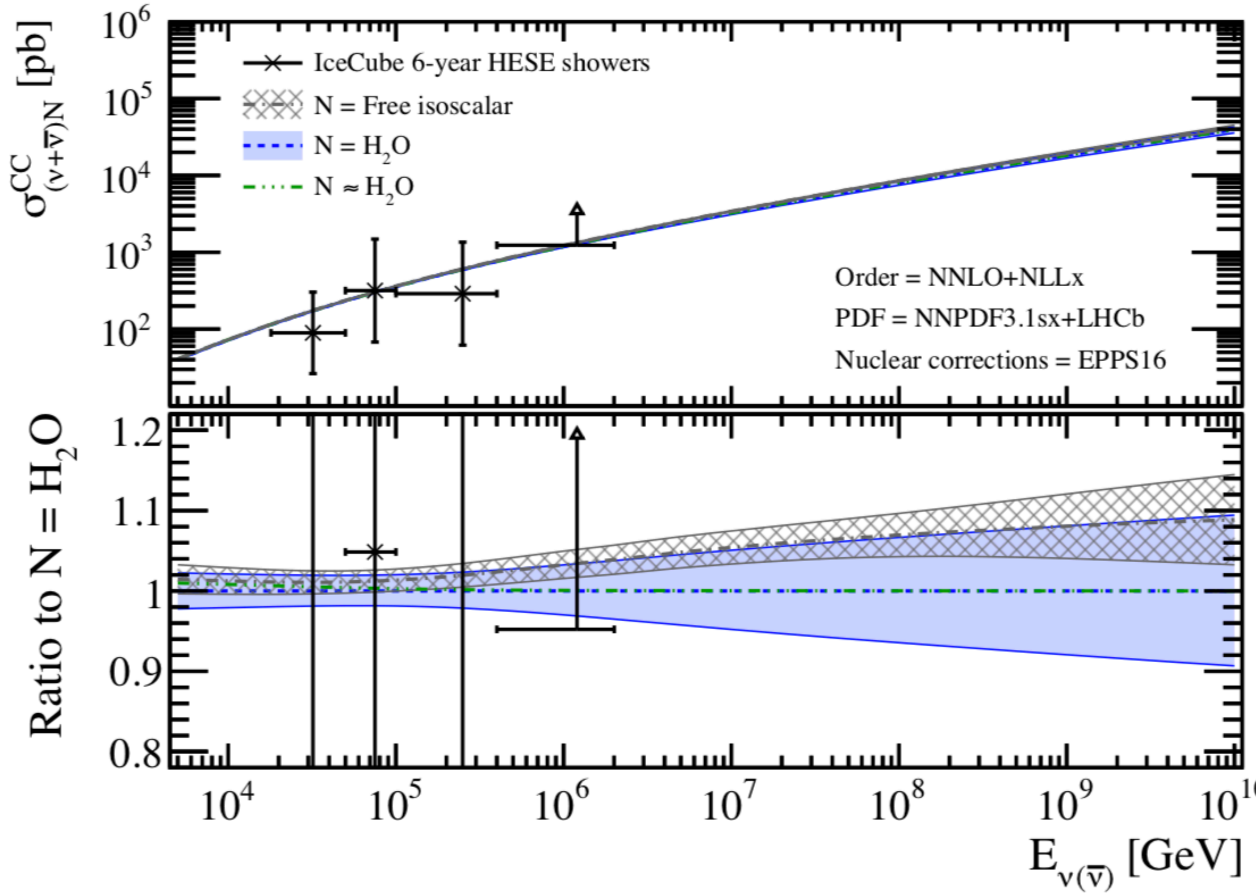
background: *prompt charm production*



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!**