Higgs Physics and Parton Distributions

Juan Rojo, VU Amsterdam & Nikhef

Celebrating a Decade of the Higgs

TIFR, Mumbay, 9th June 2022

Why Proton Structure?

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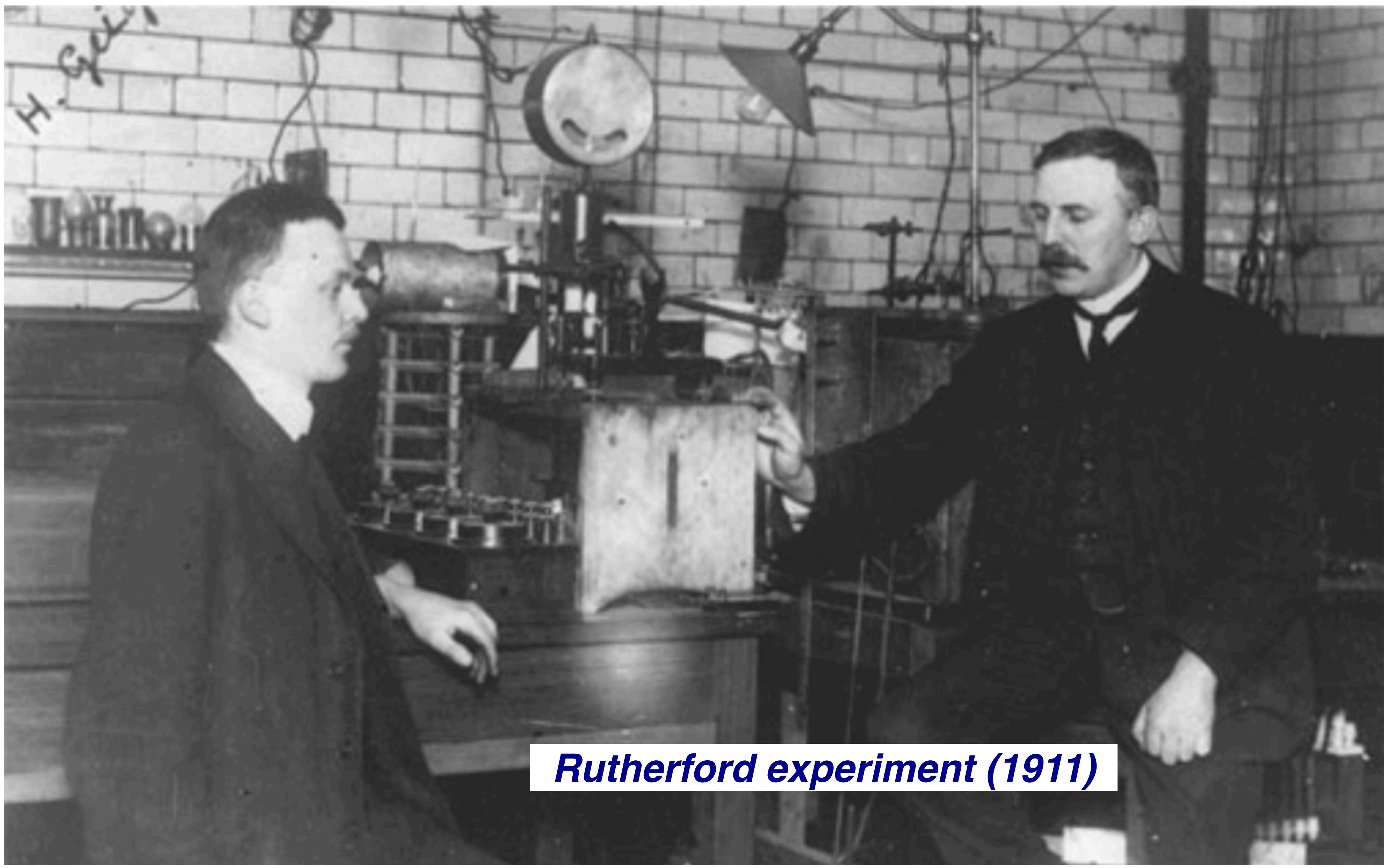
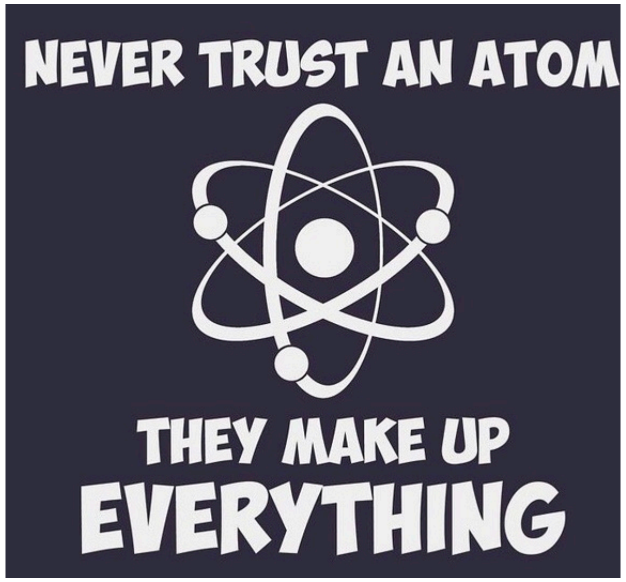
One may claim that the proton **is a rather ``boring" particle**, surely after **one century of studying it**, we know everything about the proton?



Rutherford experiment (1911)

Why Proton Structure?

nothing farther from reality: the proton is a beautiful example of the richness of quantum mechanics: what a **proton is** depends on the **resolution with which we examine it**!



long distances / low energies — *short distances / high energies*

a point particle

$$E \ll 1 \text{ GeV}$$

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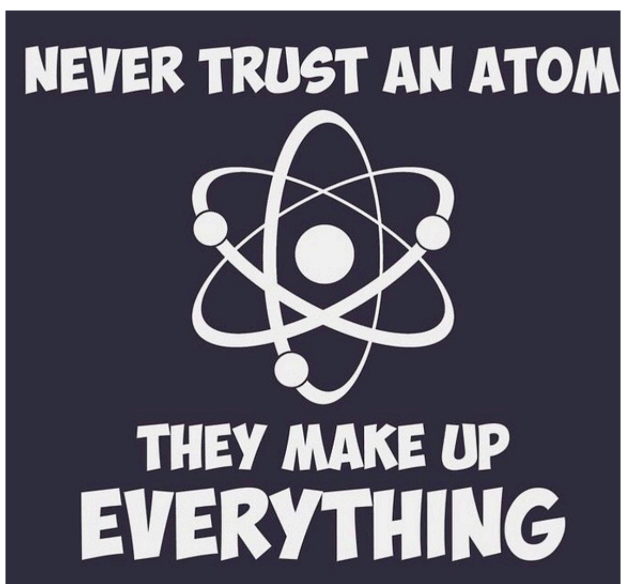

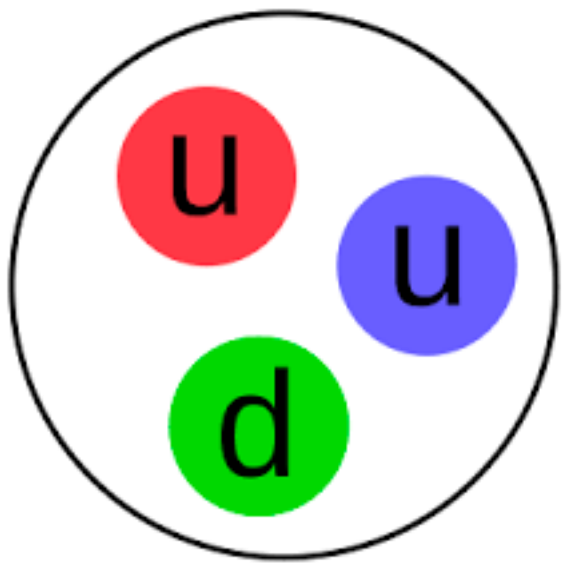

long distances / low energies

short distances / high energies

a point particle

$E \ll 1\ \mathrm{GeV}$

3 valence quarks

$E \sim \mathrm{few}\ \mathrm{GeV}$

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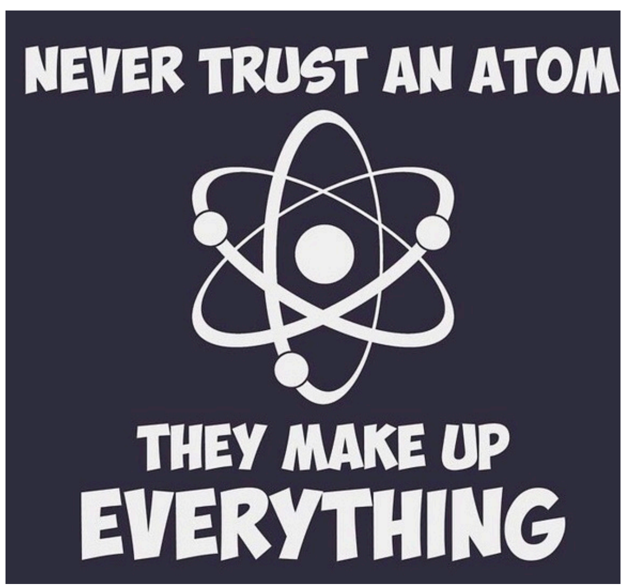

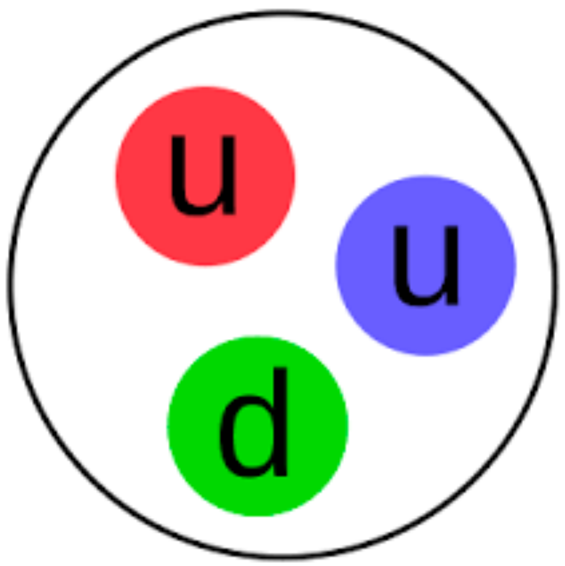

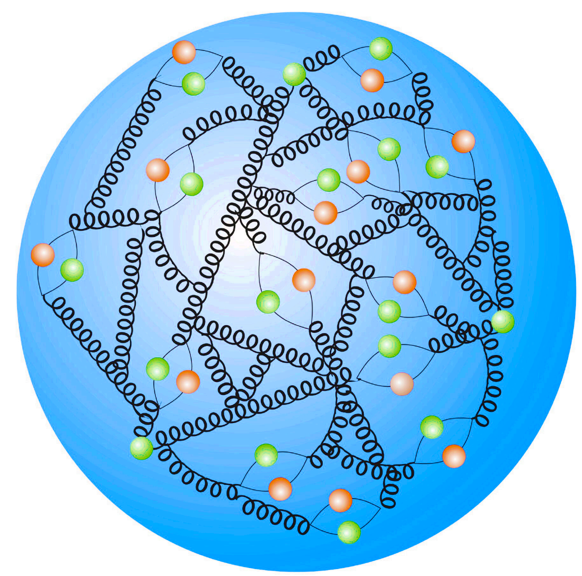

long distances / low energies — *short distances / high energies*

a point particle $E \ll 1\ \mathrm{GeV}$

3 valence quarks $E \sim \text{few GeV}$

sea quarks, gluons $E \sim 50\ \mathrm{GeV}$

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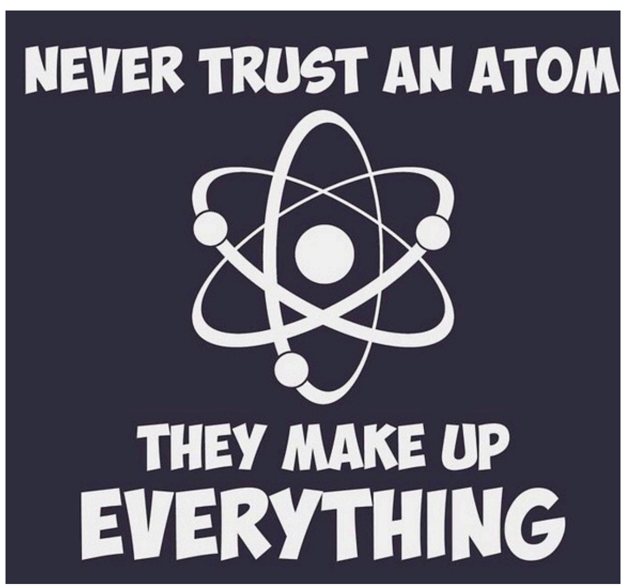
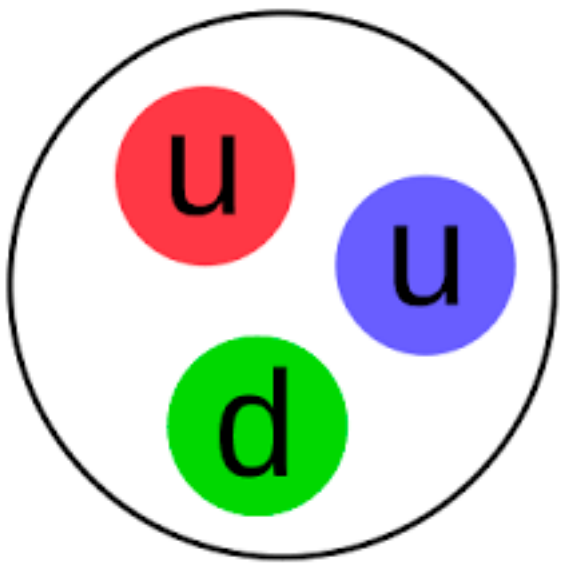
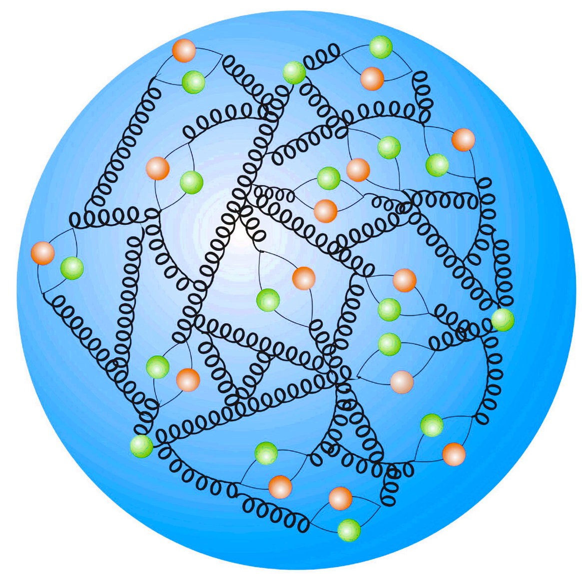
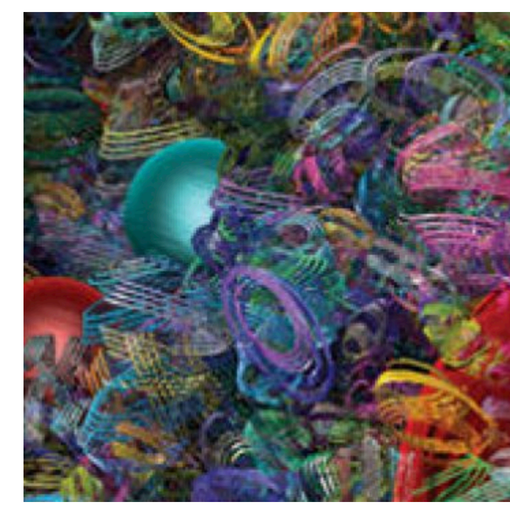








long distances / low energies

short distances / high energies

a point particle

$E \ll 1$ GeV

3 valence quarks

$E \sim$ few GeV

sea quarks, gluons

$E \sim 50$ GeV

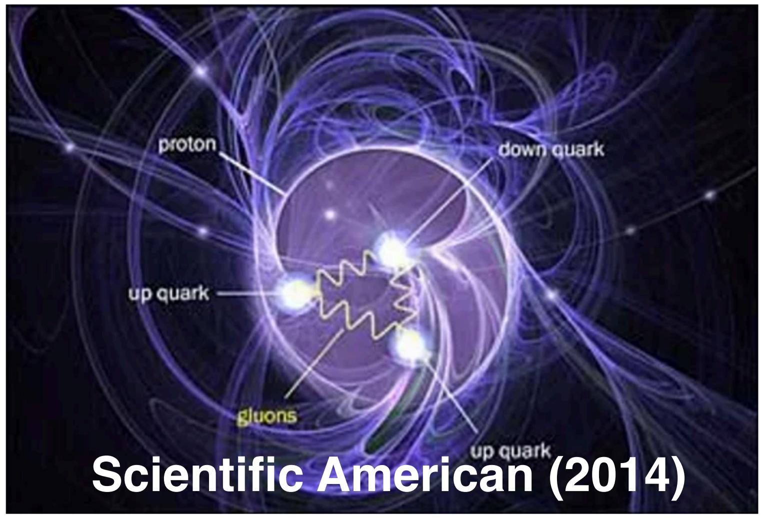
heavy quarks, photons, leptons, Higgs bosons

$E \sim 1$ TeV

A gateway to unravelling QCD

THE SCIENCES

Proton Spin Mystery Gains a New Clue



Gluons contribute to proton spin

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

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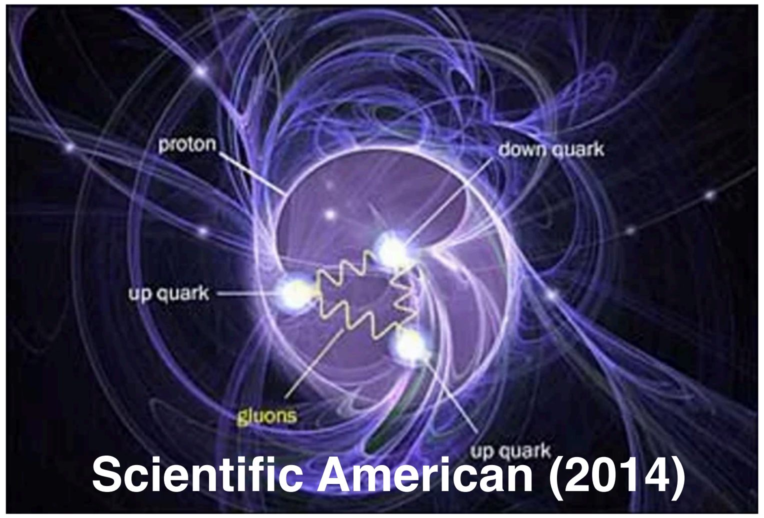

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After 40 years of studying the strong nuclear force, a revelation

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

gluon-dominated state of matter

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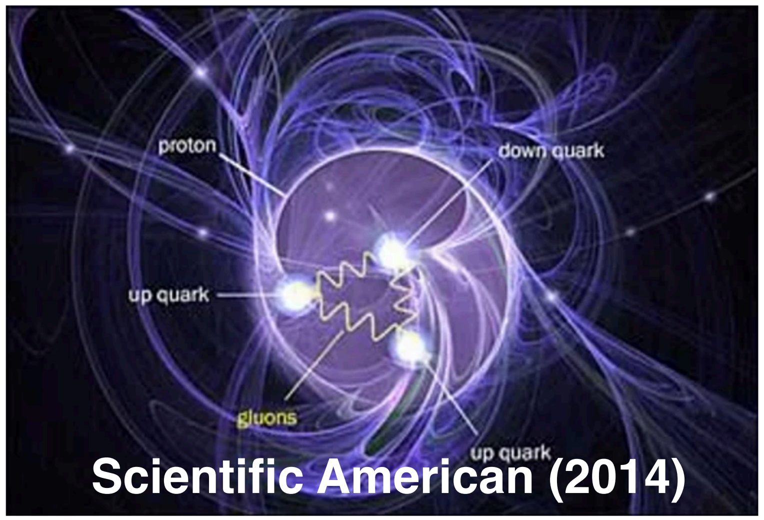

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QUANTUM PHYSICS

Decades-Long Quest Reveals Details of the Proton's Inner Antimatter

27

Twenty years ago, physicists set out to investigate a mysterious asymmetry in the proton's interior. Their results, published today, show how antimatter helps stabilize every atom's core.

Antimatter asymmetry in the proton

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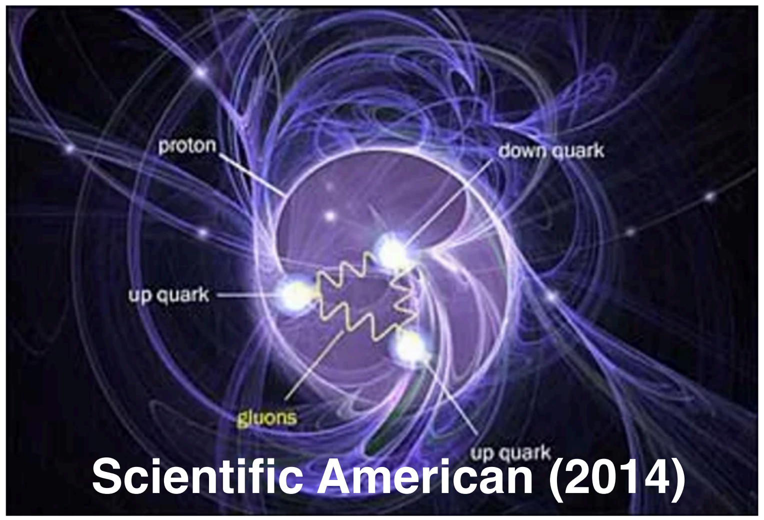

Gluons contribute to proton spin

Intrinsic Charm

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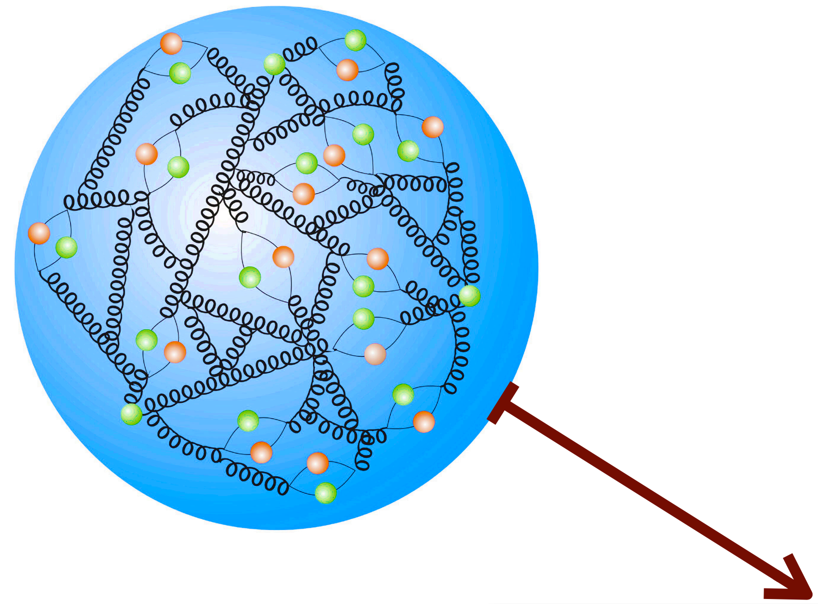
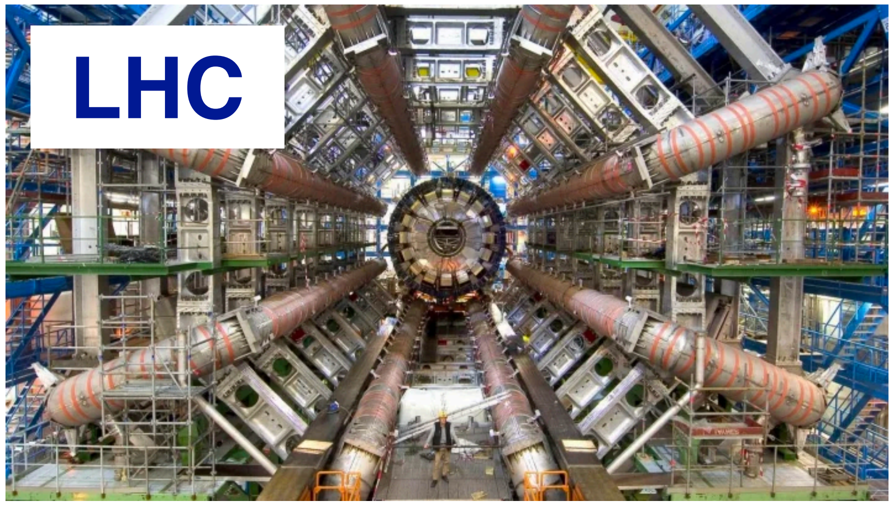


Address fundamental questions about Quantum Chromodynamics

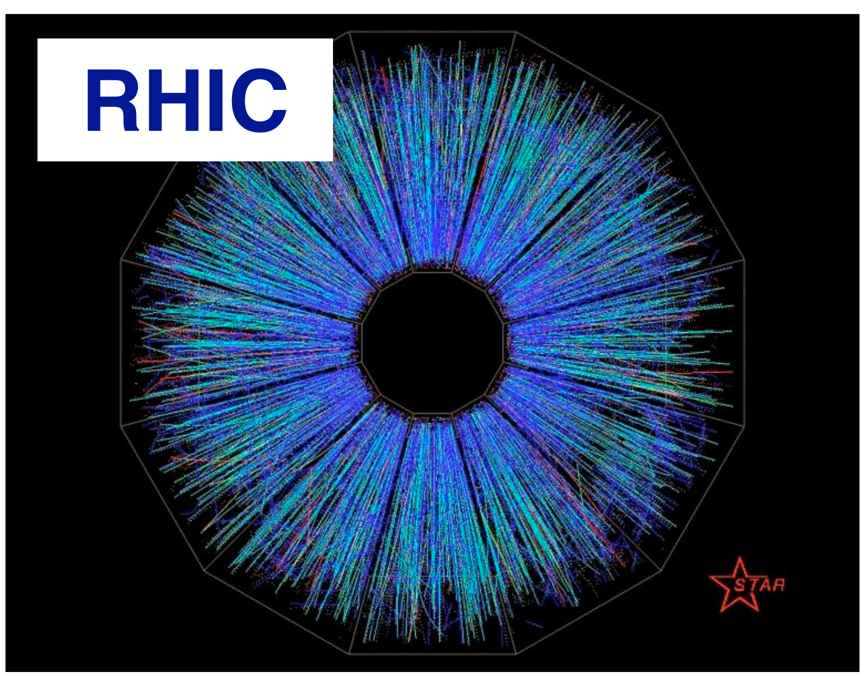
- origin of mass & spin
- **heavy quark** & **antimatter content**
- 3D imaging
- gluon-dominated matter
- **nuclear modifications**
- Interplay with BSM e.g. via **SMEFT PDFs**

From colliders to the cosmos



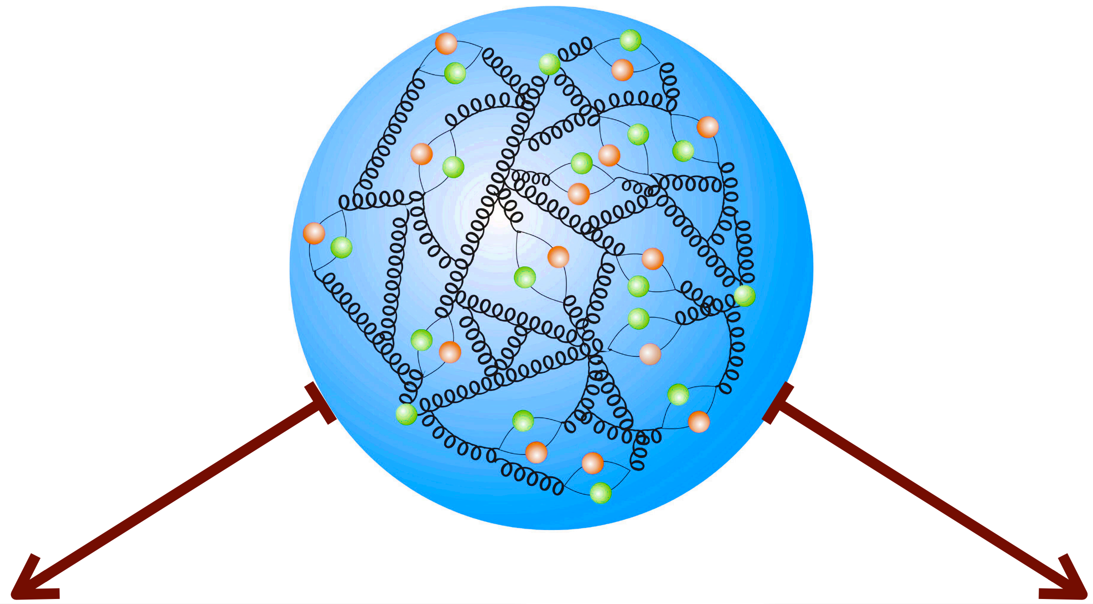
New **elementary particles** beyond the **Standard Model?**

Origins and properties of **cosmic neutrinos**?



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

Why Nucleon Structure?



Key component of predictions for particle, nuclear, and astro-particle experiments

- **pp: ATLAS, CMS, LHCb, ALICE**
- ep: fixed target DIS, HERA
- neutrinos: IceCube, KM3NET, **Forward Physics Facility** @ LHC
- heavy ions: LHC Pb, LHC O, RHIC
- *pp (future): HL-LHC, FCC, SppS*
- ep (future): **Electron-Ion Collider,** LHeC, FCC-eh

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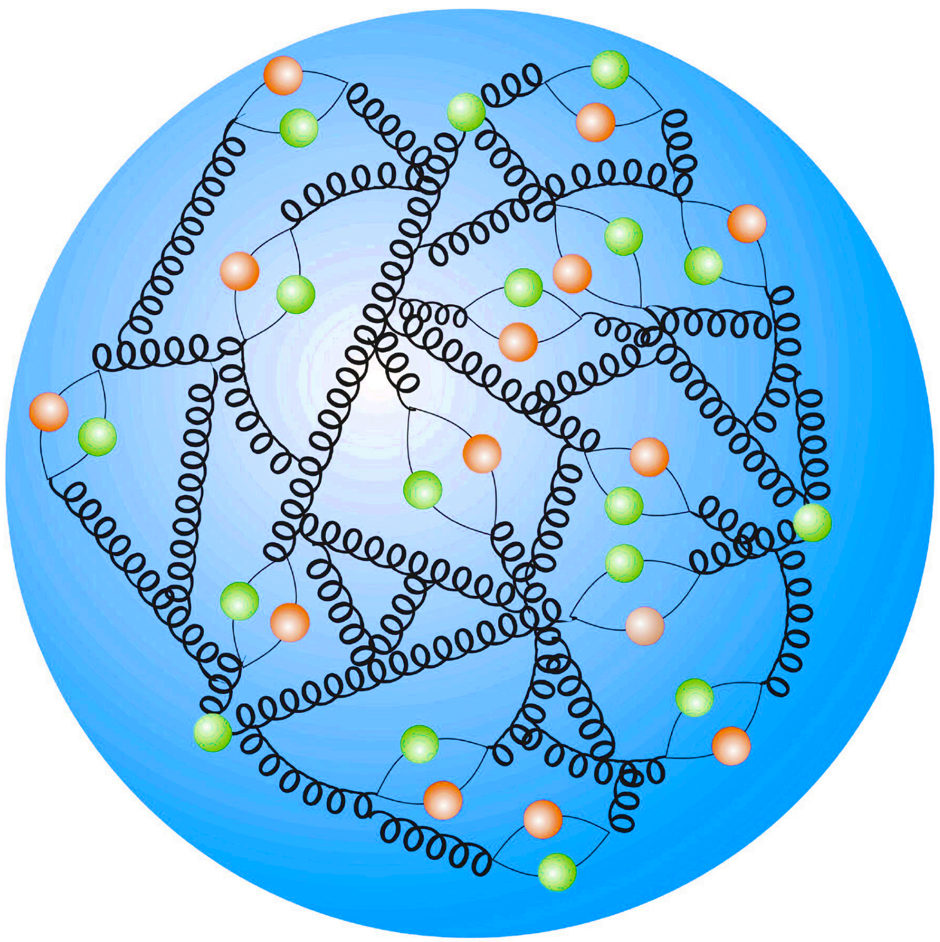
Parton Distributions

Parton Distributions

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



Parton Distribution Functions (PDFs)

↓

Determine from **data:**

Global QCD analysis

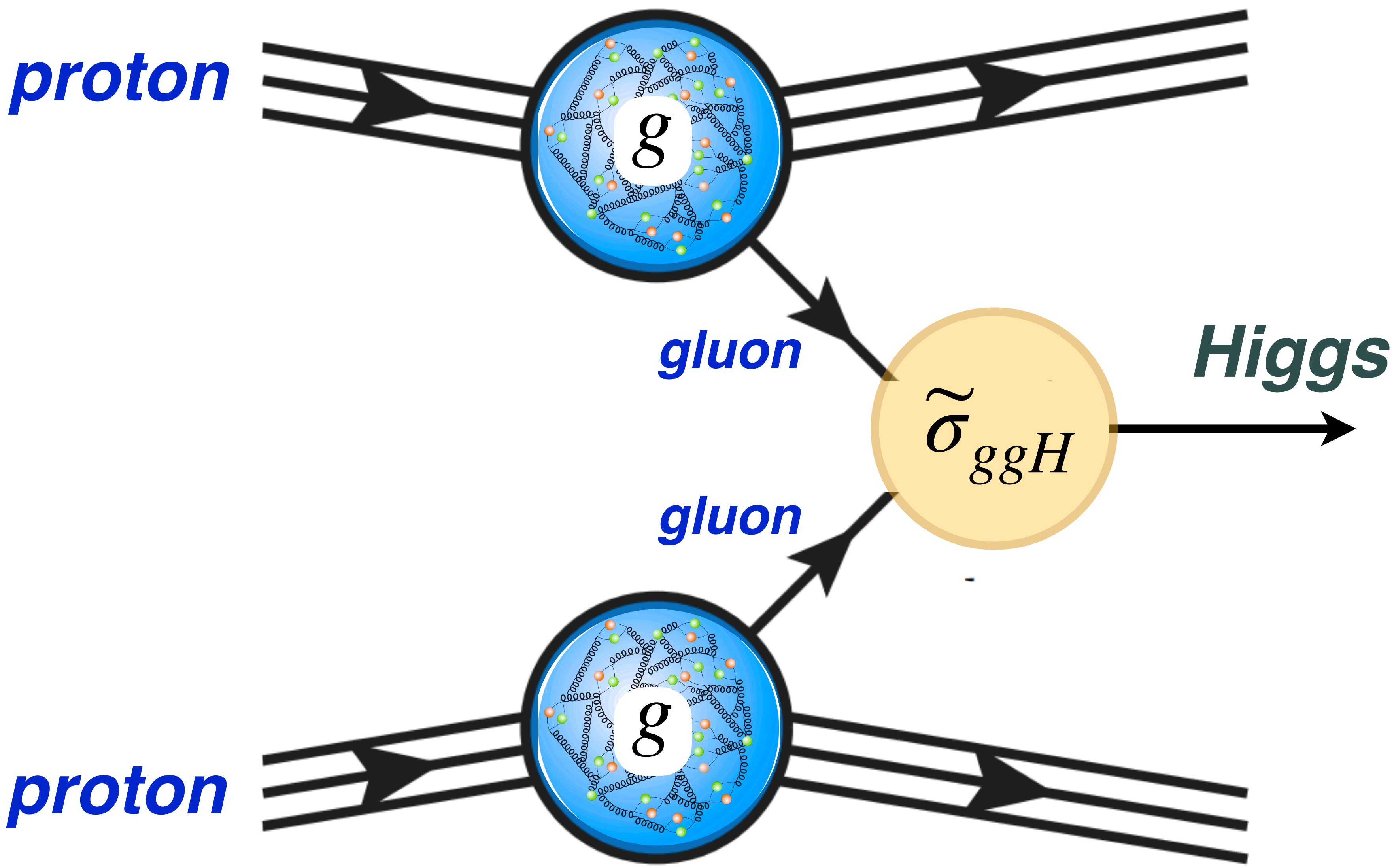
Also important recent results from lattice QCD!

What do we need to extract PDFs from data?

Parton Distributions

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

Parton Distributions



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

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

$$g(x, Q_0, \{a_g\}) = f_g(x, a_g^{(1)}, a_g^{(2)}, \ldots)$$

constrain from data

Quark number conservation

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

Energy conservation: momentum sum rule

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

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

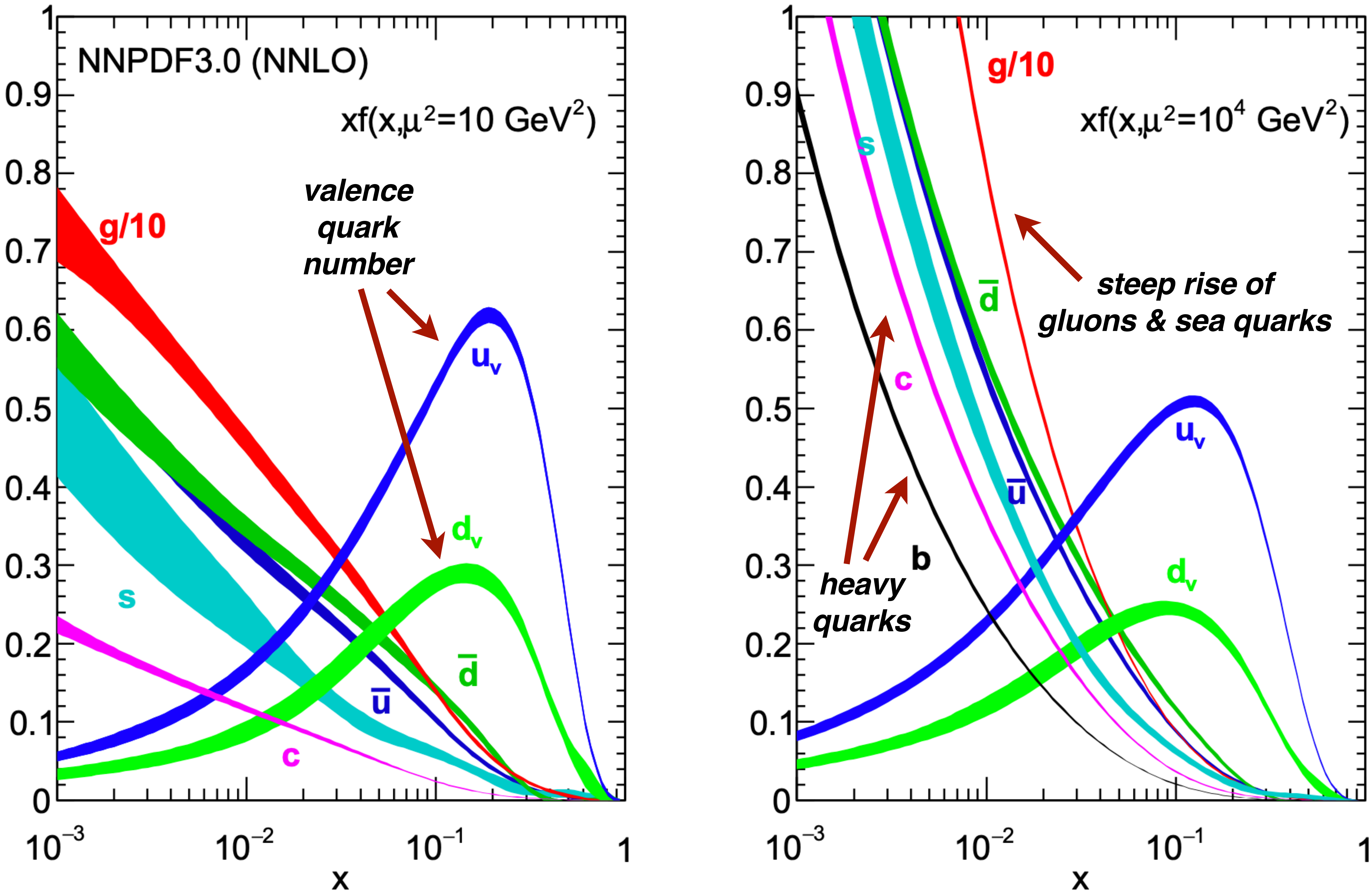
Energy of hard-scattering reaction**:** inverse of resolution length

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*

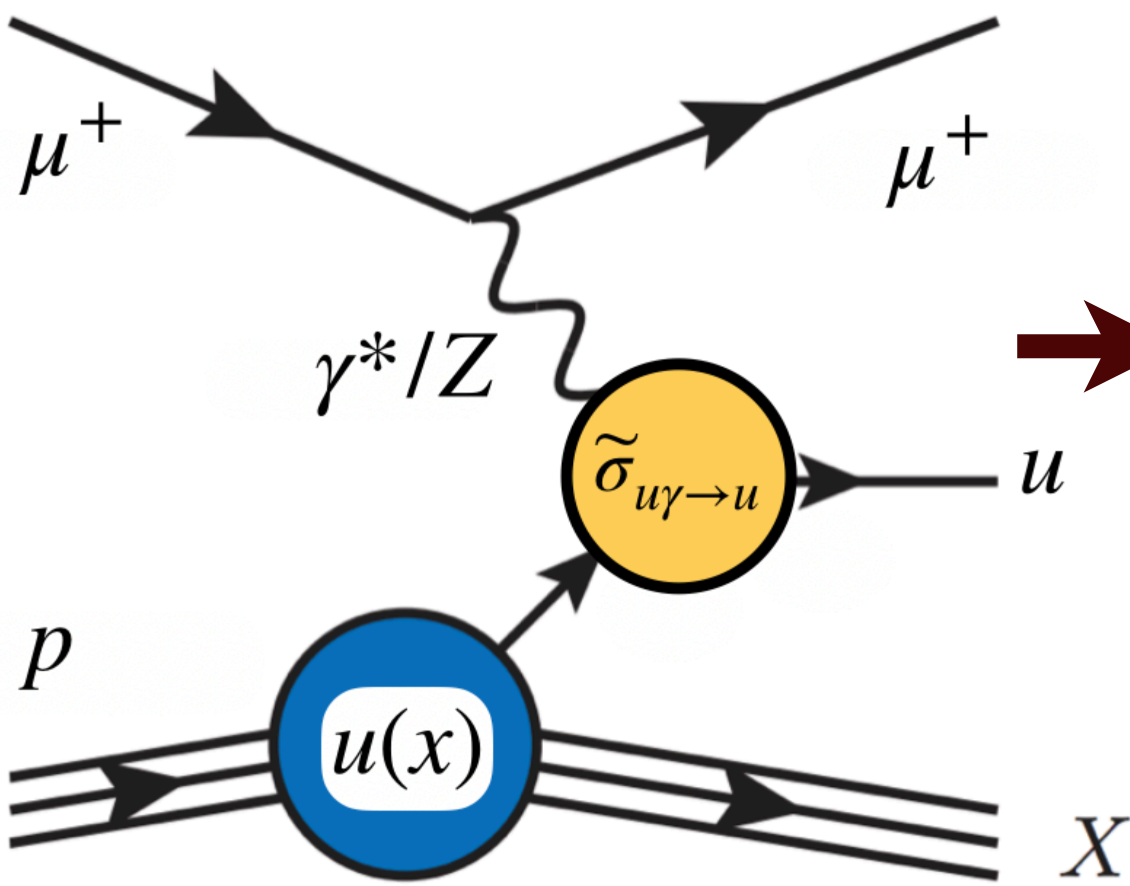
A proton structure snapshop



The global QCD analysis paradigm

QCD factorisation theorems**: PDF universality**

$$\sigma_{l\,p\to\mu\,X} = \widetilde{\sigma}_{u\gamma\to u} \otimes u(x)$$

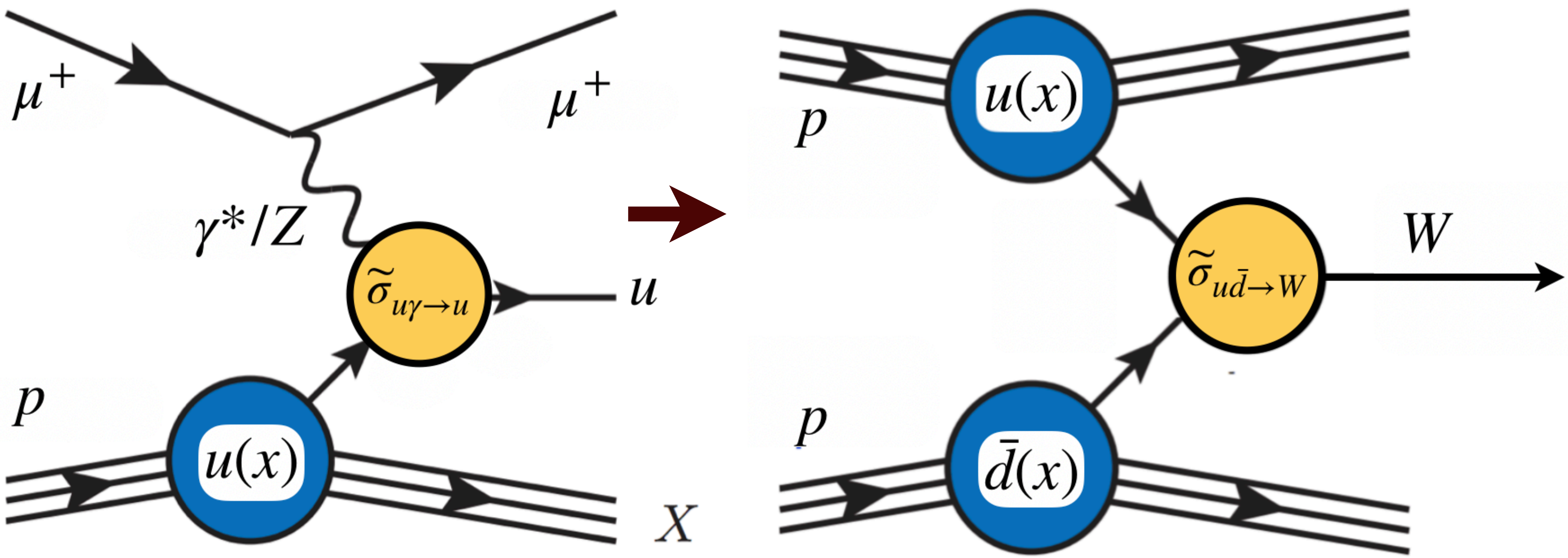


*Determine PDFs from **deep-inelastic scattering**…*

The global QCD analysis paradigm

QCD factorisation theorems: **PDF universality**

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



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

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

The global QCD analysis paradigm

☑ **Parametrise the PDFs** at the boundary (***Q = 1 GeV***) between perturbative and non-perturbative QCD

$$xg(x, Q_0 = 1\ \mathrm{GeV}, \{a\}) = f_g(x, a_g^{(1)}, a_g^{(2)}, \ldots)$$

☑ Evaluate predictions for LHC cross-sections using **QCD factorisation theorem**

$$\sigma_{\mathrm{th}}(M, s, \{a\}) \propto \sum_{ij} \int_{M^2}^{s} d\hat{s}\ \mathscr{L}_{ij}(\hat{s}, s, \{a_i^{(k)}\}, \{a_j^{(k)}\})\, \widetilde{\sigma}_{ij}(\hat{s}, \alpha_s(M))$$

☑ **Extract PDF parameters from data** via log-likelihood maximisation

$$\chi^2\left(\{\boldsymbol{a}^{(k)}\}\right) = \frac{1}{n_{\mathrm{dat}}} \sum_{i,j=1}^{n_{\mathrm{dat}}} \left(\sigma_{\mathrm{i,th}}(\{\boldsymbol{a}^{(k)}\}) - \sigma_{\mathrm{i,exp}}\right) \left(\mathrm{cov}^{-1}\right)_{ij} \left(\sigma_{\mathrm{j,th}}(\{\boldsymbol{a}^{(k)}\}) - \sigma_{\mathrm{j,exp}}\right)$$

☑ Estimate the associated **uncertainties**

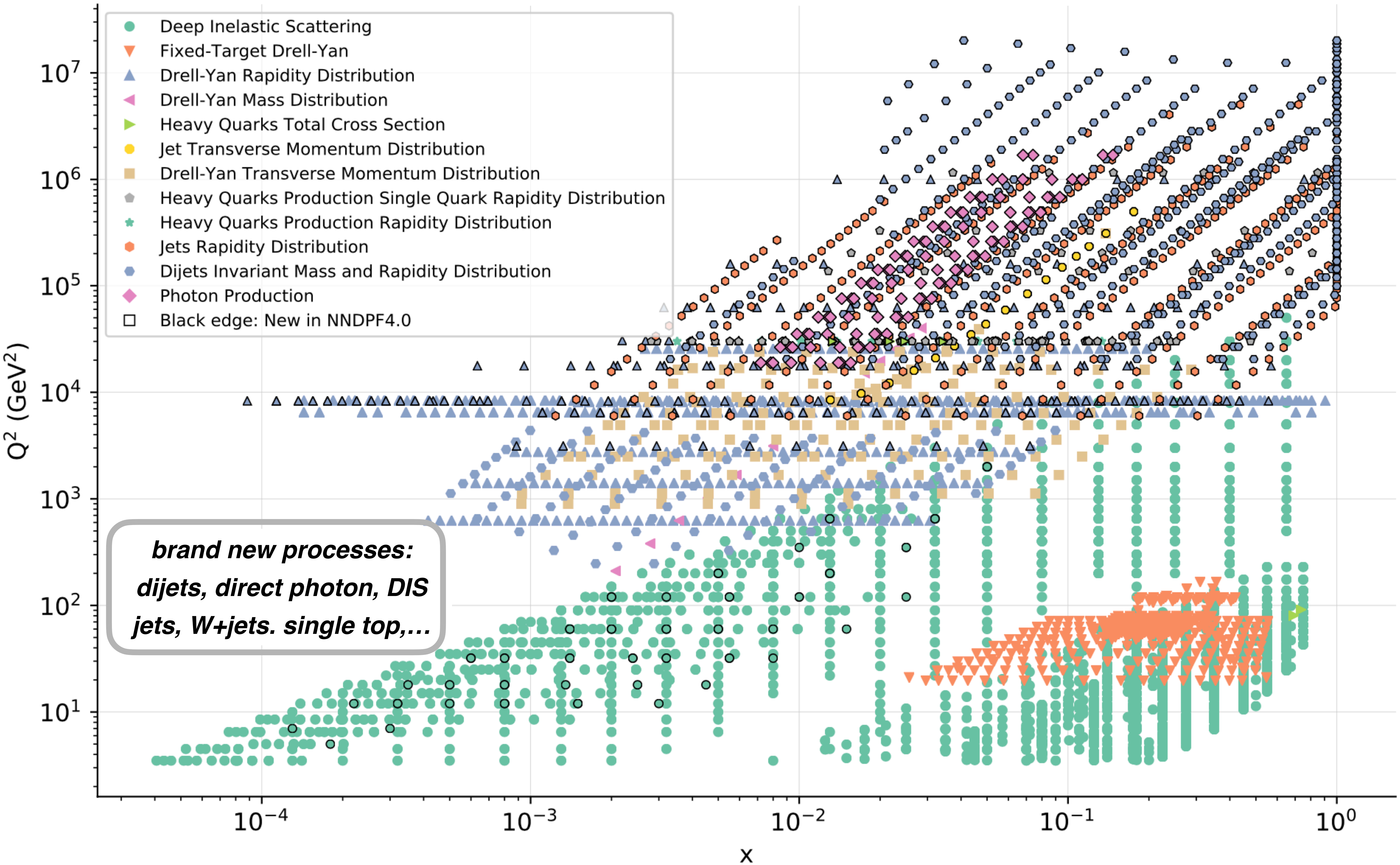
The resulting PDFs are then ready for phenomenological applications
in processed involving **proton/nuclear targets and projectiles**

Parton Distributions at the Dawn of Run III

	NNPDF4.0	MSHT20	CT18	ABMP16
Released	*Sept 2021*: LHAPDF grids + **fitting code**	*Dec 2020*: LHAPDF grids	*Dec 2019*: LHAPDF grids	*Jan 2017*: LHAPDF grids
Parametrisation	Neural networks (**hyperoptimised**)	Functional form + Chebyshev	Functional form + Bernstein	Functional form
Error estimate	Monte Carlo (**closure + future tested**)	Hessian (dynamic tolerance)	Hessian (dynamic tolerance) + Lagrange mult.	Hessian (no tolerance)
Theory settings	NNLO QCD, GM-VFN (+ NLO electroweak)	NNLO QCD GM-VFN	NNLO QCD GM-VFN	NNLO QCD, FFN

+ PDF4LHC21 (Combination of CT18, MSHT20, NNPDF3.1), JAM, HERAPDF, ATLASpdf21, …

The NNPDF4.0 dataset



$\mathcal{O}(50)$ data sets investigated; $\mathcal{O}(400)$ data points more in NNPDF4.0 than in NNPDF3.1

Dataset comparison for global fits

$$N_{\text{data}}(\text{CT18}) \lesssim N_{\text{data}}(\text{MSHT20}) \lesssim N_{\text{data}}(\text{NNPDF4.0})$$

Data set	Ref.	NNPDF3.1	NNPDF4.0	ABMP16	CT18	MSHT20
ATLAS W,Z 7 TeV ($\mathcal{L}=35$ pb^{-1})	[51]	✓	✓	✓	✓	✓
ATLAS W,Z 7 TeV ($\mathcal{L}=4.6$ fb^{-1})	[52]	✓	✓	✗	(✓)	✓
ATLAS low-mass DY 7 TeV	[53]	✓	✓	✗	(✓)	✗
ATLAS high-mass DY 7 TeV	[54]	✓	✓	✗	(✓)	✓
ATLAS W 8 TeV	[79]	✗	(✓)	✗	✗	✓
ATLAS DY 2D 8 TeV	[78]	✗	✓	✗	✗	✓
ATLAS high-mass DY 2D 8 TeV	[77]	✗	✓	✗	(✓)	✓
ATLAS $\sigma_{W,Z}$ 13 TeV	[81]	✗	✓	✓	✗	✗
ATLAS W+jet 8 TeV	[93]	✗	✓	✗	✗	✓
ATLAS Z p_T 7 TeV	[259]	(✓)	✗	✗	(✓)	✗
ATLAS Z p_T 8 TeV	[63]	✓	✓	✗	✓	✓
ATLAS $W+c$ 7 TeV	[83]	✗	✓	✗	(✓)	✗
ATLAS σ_{tt}^{tot} 7, 8 TeV	[65]	✓	✓	✓	✗	✗
ATLAS σ_{tt}^{tot} 7, 8 TeV	[260–265]	✗	✗	✓	✗	✗
ATLAS σ_{tt}^{tot} 13 TeV ($\mathcal{L}=3.2$ fb^{-1})	[66]	✓	✗	✓	✗	✗
ATLAS σ_{tt}^{tot} 13 TeV ($\mathcal{L}=139$ fb^{-1})	[134]	✗	✓	✗	✗	✗
ATLAS σ_{tt}^{tot} and Z ratios	[266]	✗	✗	✗	✗	(✓)
ATLAS $t\bar{t}$ lepton+jets 8 TeV	[67]	✓	✓	✗	✓	✓
ATLAS $t\bar{t}$ dilepton 8 TeV	[89]	✗	✓	✗	✗	✓
ATLAS single-inclusive jets 7 TeV, R=0.6	[73]	✓	(✓)	✗	✓	✓
ATLAS single-inclusive jets 8 TeV, R=0.6	[86]	✗	✓	✗	✗	✗
ATLAS dijets 7 TeV, R=0.6	[148]	✗	✓	✗	✗	✗
ATLAS direct photon production 8 TeV	[100]	✗	(✓)	✗	✗	✗
ATLAS direct photon production 13 TeV	[101]	✗	✓	✗	✗	✗
ATLAS single top R_t 7, 8, 13 TeV	[94, 96, 98]	✗	✓	✓	✗	✗
ATLAS single top diff. 7 TeV	[94]	✗	✓	✗	✗	✗
ATLAS single top diff. 8 TeV	[96]	✗	✓	✗	✗	✗

Data set	Ref.	NNPDF3.1	NNPDF4.0	ABMP16	CT18	MSHT20
CMS W asym. 7 TeV ($\mathcal{L}=36$ pb^{-1})	[267]	✗	✗	✗	✗	✓
CMS Z 7 TeV ($\mathcal{L}=36$ pb^{-1})	[268]	✗	✗	✗	✗	✓
CMS W electron asymmetry 7 TeV	[55]	✓	✓	✗	✓	✓
CMS W muon asymmetry 7 TeV	[56]	✓	✓	✓	✓	✗
CMS Drell-Yan 2D 7 TeV	[57]	✓	✓	✗	(✓)	✓
CMS Drell-Yan 2D 8 TeV	[269]	(✓)	✗	✗	✗	✗
CMS W rapidity 8 TeV	[58]	✓	✓	✓	✓	✓
CMS W,Z p_T 8 TeV ($\mathcal{L}=18.4$ fb^{-1})	[270]	✗	✗	✗	(✓)	✗
CMS Z p_T 8 TeV	[64]	✓	✓	✗	(✓)	✗
CMS $W+c$ 7 TeV	[76]	✓	✓	✗	(✓)	✓
CMS $W+c$ 13 TeV	[84]	✗	✓	✗	✗	(✓)
CMS single-inclusive jets 2.76 TeV	[75]	✓	✗	✗	✗	✓
CMS single-inclusive jets 7 TeV	[147]	✓	(✓)	✗	✓	✓
CMS dijets 7 TeV	[74]	✗	✓	✗	✗	✗
CMS single-inclusive jets 8 TeV	[87]	✗	✓	✗	✓	✓
CMS 3D dijets 8 TeV	[149]	✗	(✓)	✗	✗	✗
CMS σ_{tt}^{tot} 5 TeV	[88]	✗	✓	✗	✗	✗
CMS σ_{tt}^{tot} 7, 8 TeV	[146]	✓	✓	✗	✗	✗
CMS σ_{tt}^{tot} 8 TeV	[271]	✗	✗	✗	✗	✓
CMS σ_{tt}^{tot} 5, 7, 8, 13 TeV	[68, 272–280]	✗	✗	✓	✗	✗
CMS σ_{tt}^{tot} 13 TeV	[69]	✓	✓	✓	✗	✗
CMS $t\bar{t}$ lepton+jets 8 TeV	[70]	✓	✓	✗	✗	✓
CMS $t\bar{t}$ 2D dilepton 8 TeV	[90]	✗	✓	✗	✓	✓
CMS $t\bar{t}$ lepton+jet 13 TeV	[91]	✗	✓	✗	✗	✗
CMS $t\bar{t}$ dilepton 13 TeV	[92]	✗	✓	✗	✗	✗
CMS single top $\sigma_t + \sigma_{\bar{t}}$ 7 TeV	[95]	✗	✓	✓	✗	✗
CMS single top R_t 8, 13 TeV	[97, 99]	✗	✓	✓	✗	✗
CMS single top 13 TeV	[281, 282]	✗	✗	✗	✗	(✓)

Data set	Ref.	NNPDF3.1	NNPDF4.0	ABMP16	CT18	MSHT20
LHCb Z 7 TeV ($\mathcal{L}=940$ pb^{-1})	[59]	✓	✓	✗	✗	✓
LHCb $Z \to ee$ 8 TeV ($\mathcal{L}=2$ fb^{-1})	[61]	✓	✓	✓	✓	✓
LHCb W 7 TeV ($\mathcal{L}=37$ pb^{-1})	[283]	✗	✗	✗	✗	✓
LHCb $W,Z \to \mu$ 7 TeV	[60]	✓	✓	✓	✓	✓
LHCb $W,Z \to \mu$ 8 TeV	[62]	✓	✓	✓	✓	✓
LHCb $W \to e$ 8 TeV	[80]	✗	(✓)	✗	✗	✗
LHCb $Z \to \mu\mu, ee$ 13 TeV	[82]	✗	✓	✗	✗	✗

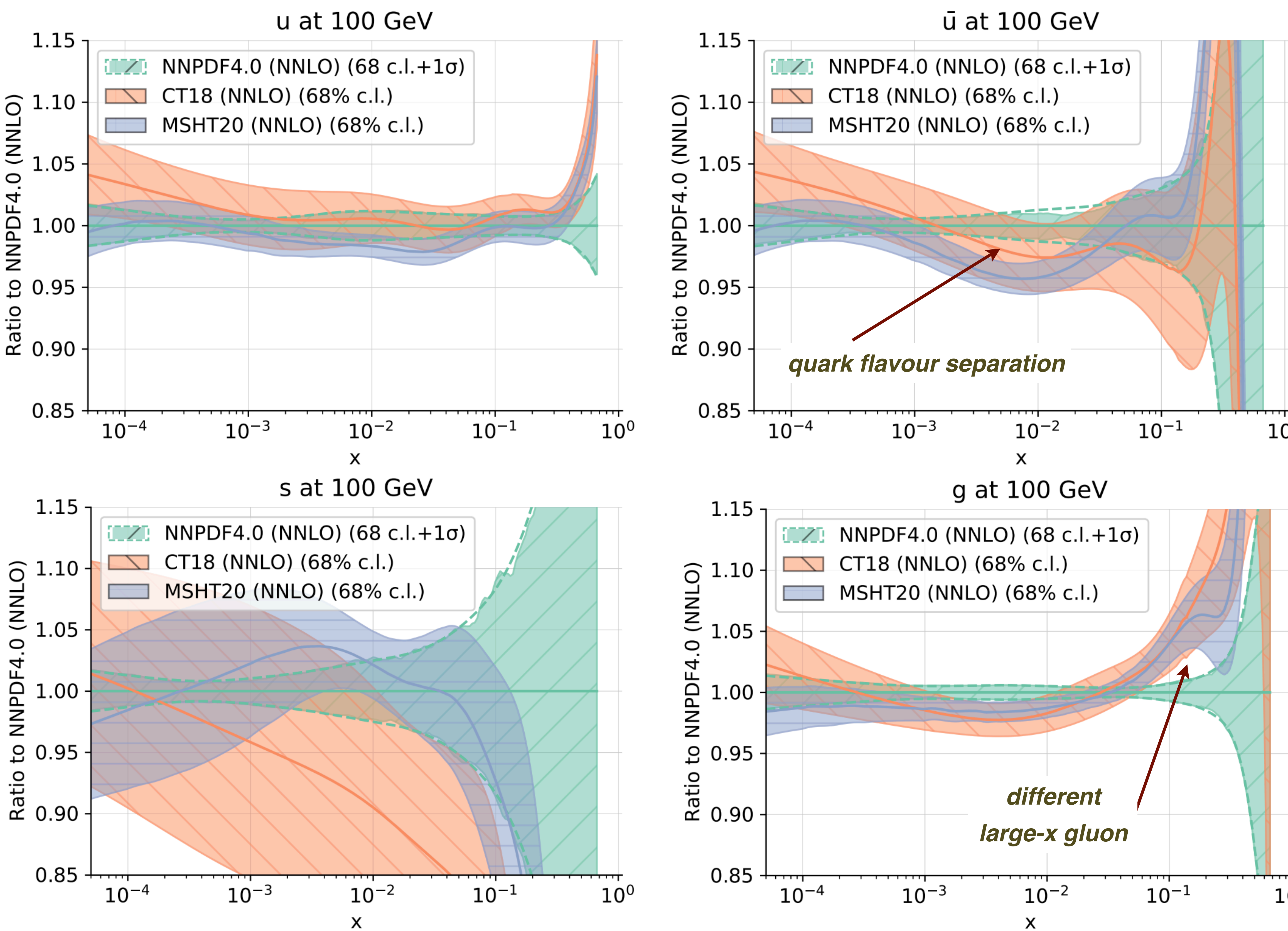
✓ in baseline dataset

✗ not considered

(✓) impact assessed but excluded from baseline

Comparison between global fits

reasonable agreement with CT18 and MSHT20 (with some exceptions)

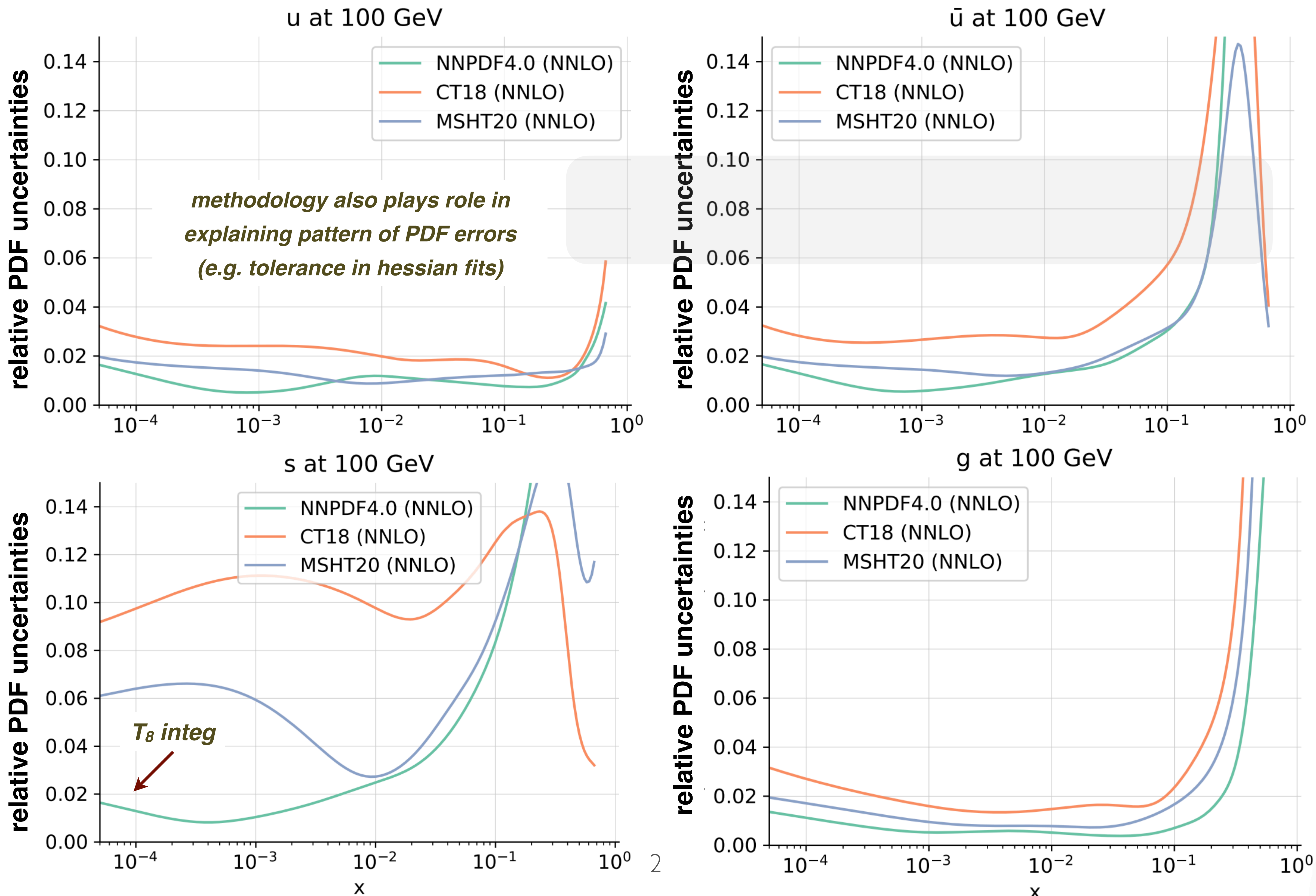


Comparison between global fits

pattern of PDF uncertainties follows (qualitatively) the **dataset size**

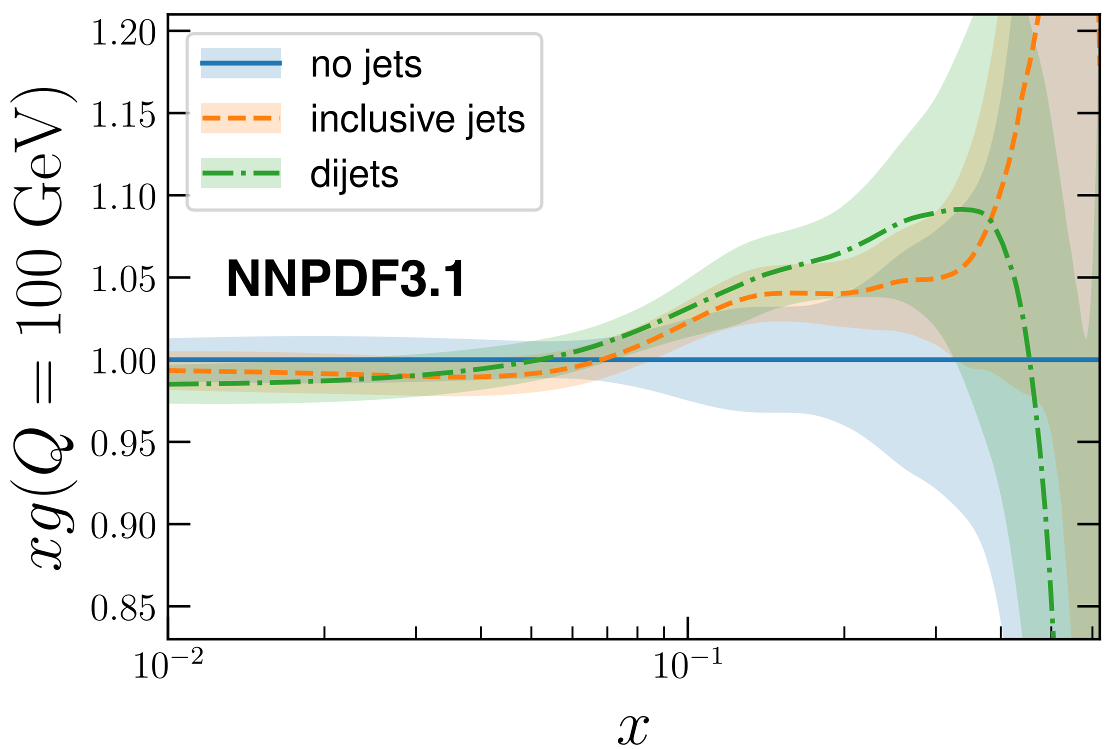
$$\delta_{\rm PDF}({\rm CT18}) \gtrsim \delta_{\rm PDF}({\rm MSHT20}) \gtrsim \delta_{\rm PDF}({\rm NNPDF4.0})$$

$$N_{\rm data}({\rm CT18}) \lesssim N_{\rm data}({\rm MSHT20}) \lesssim N_{\rm data}({\rm NNPDF4.0})$$

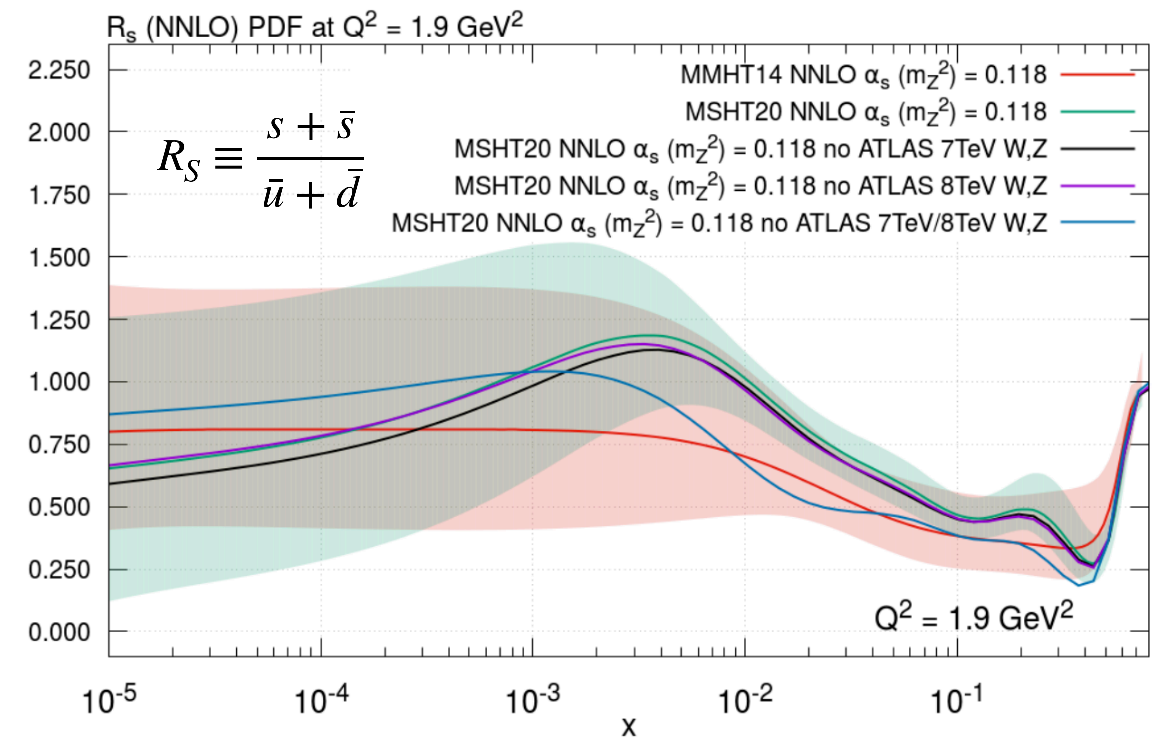


Novel experimental constraints

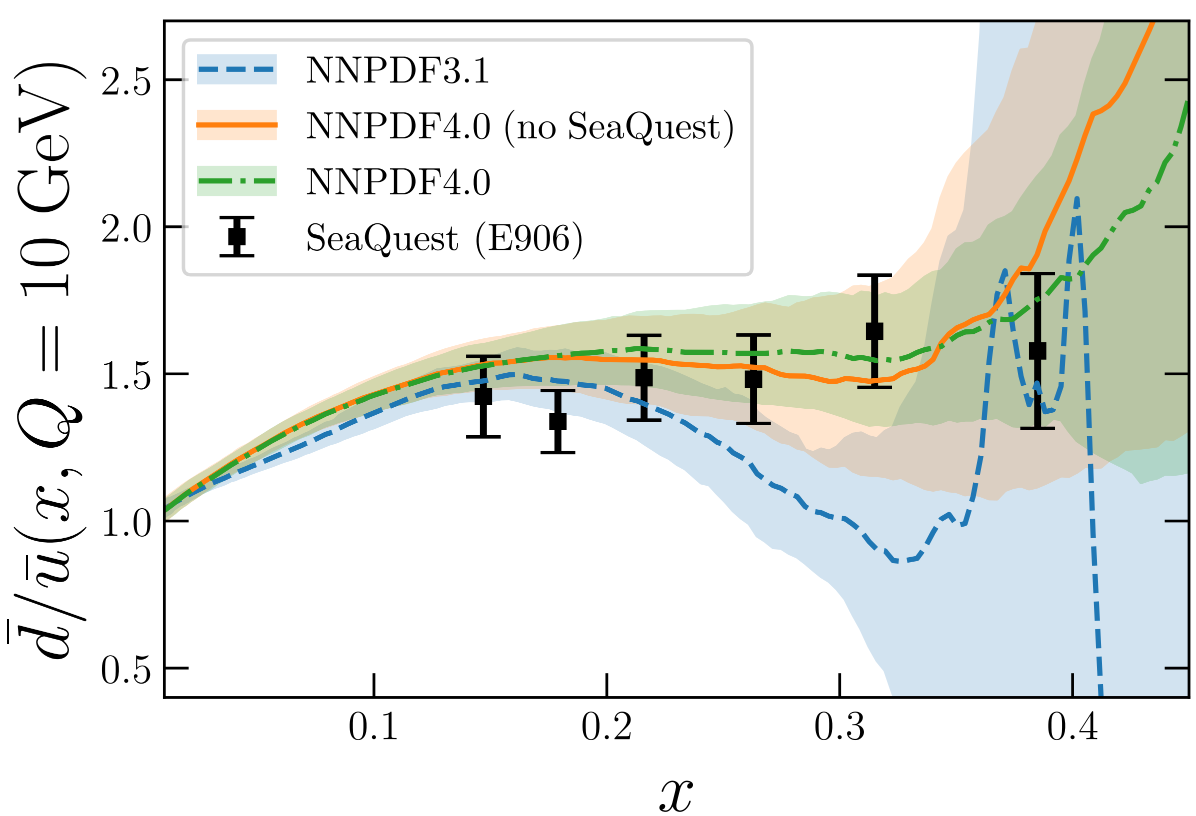
Dijet production



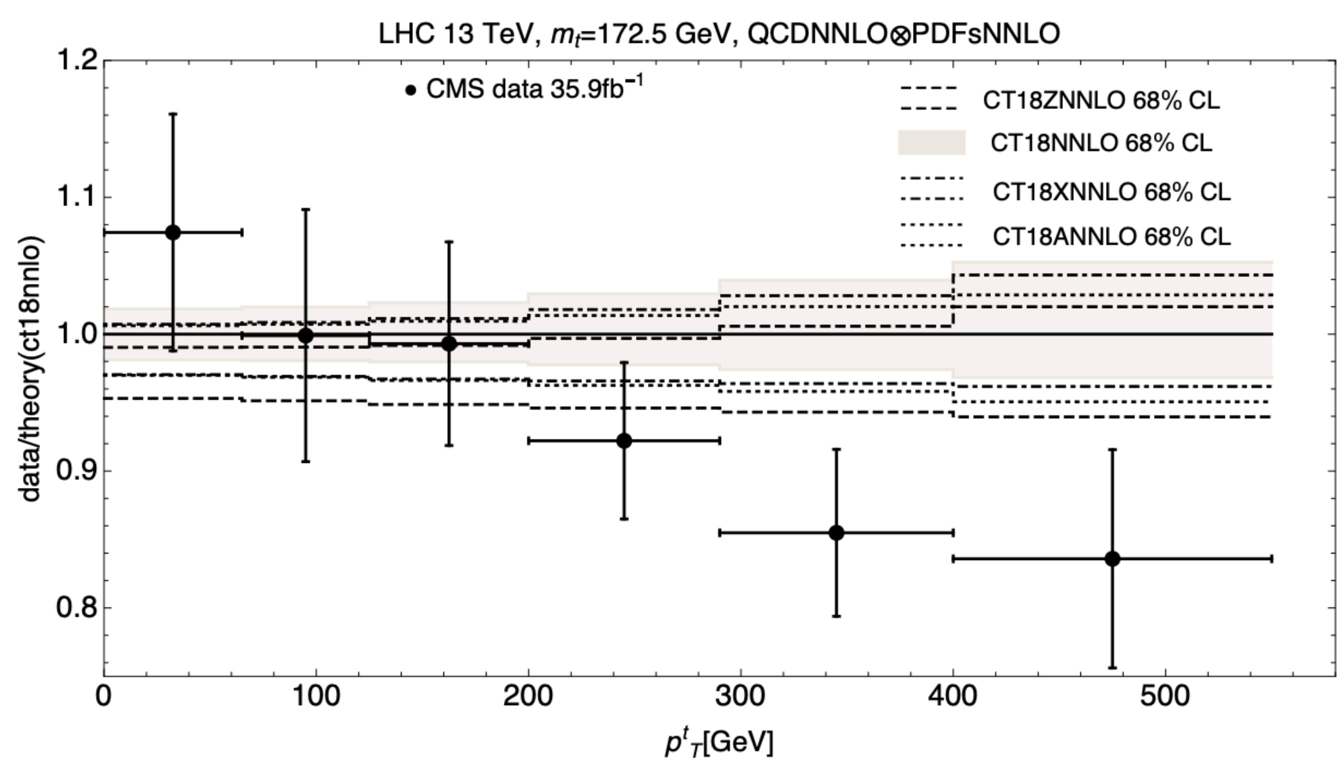
Collider Drell-Yan



SeaQuest Drell-Yan

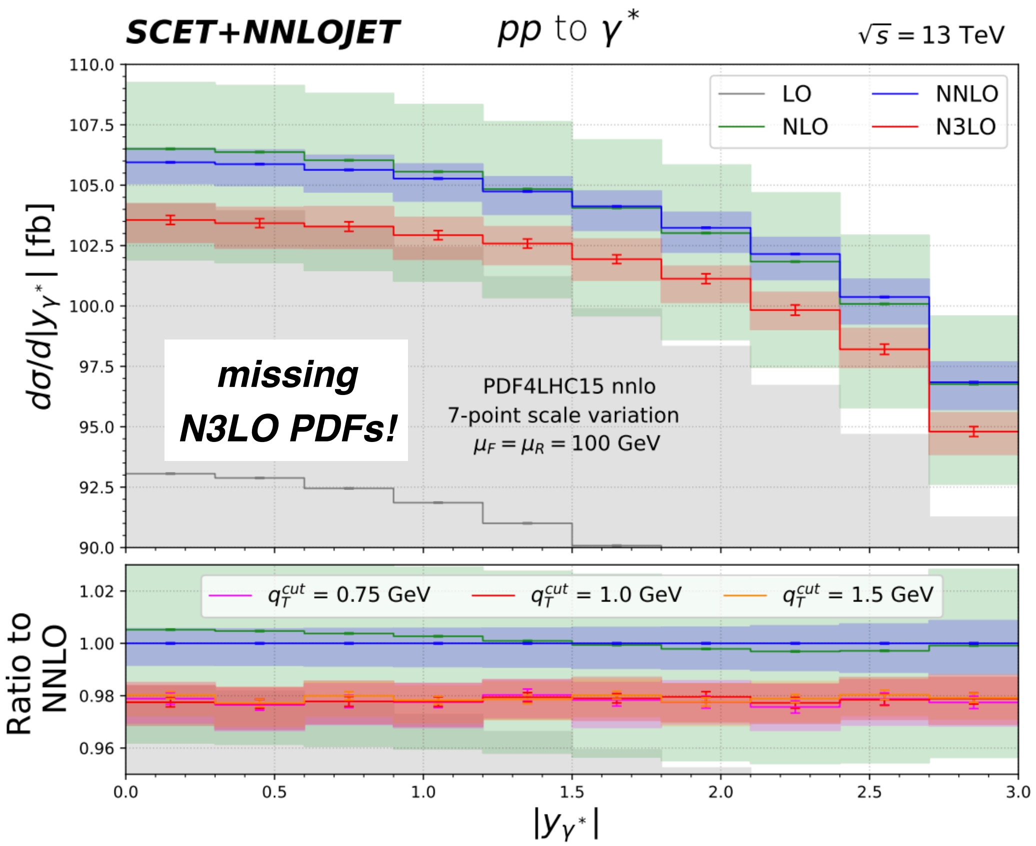


differential top quark pair

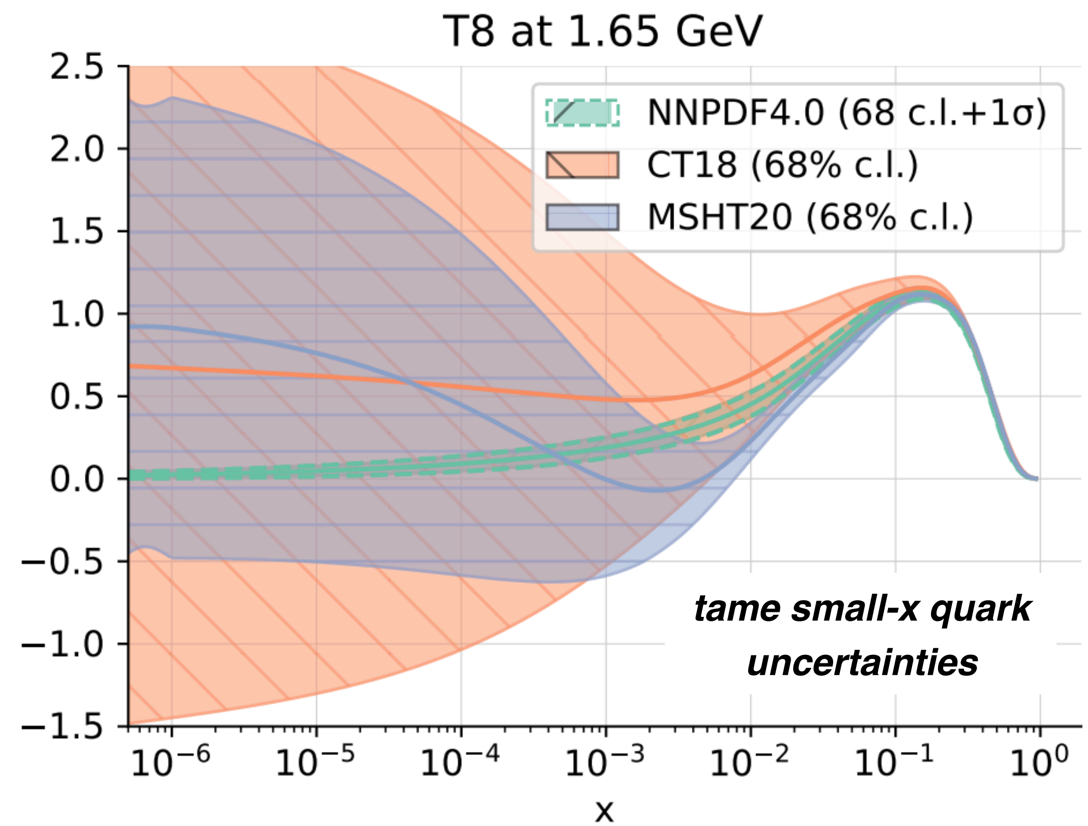


Improved theory calculations

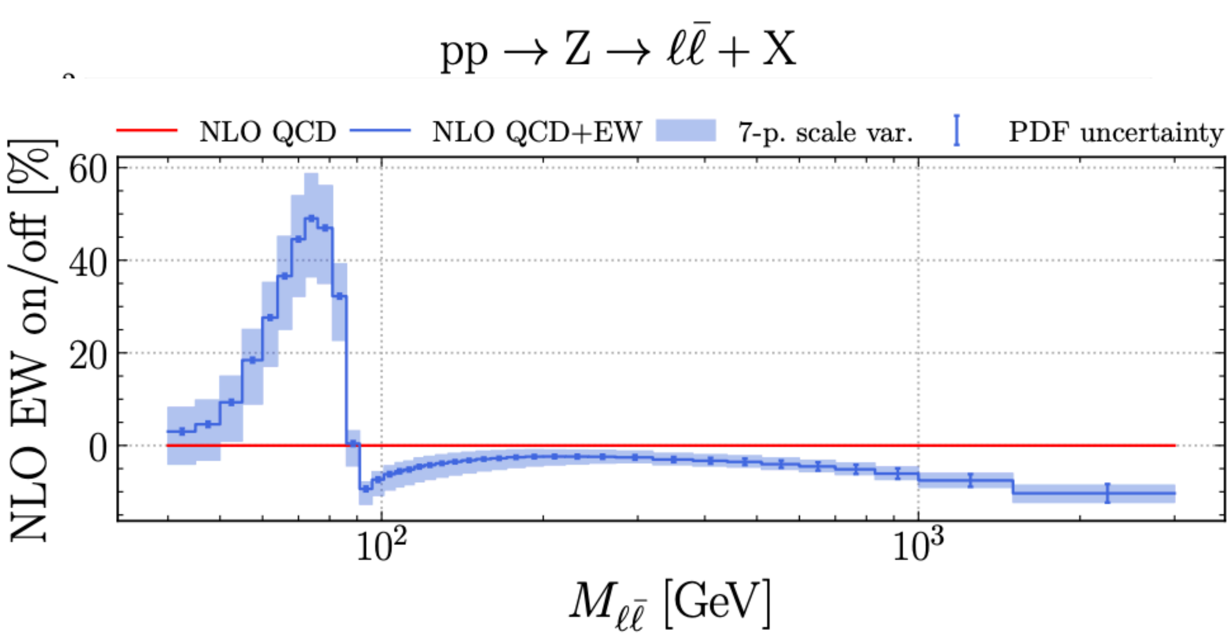
NNLO & N3LO QCD



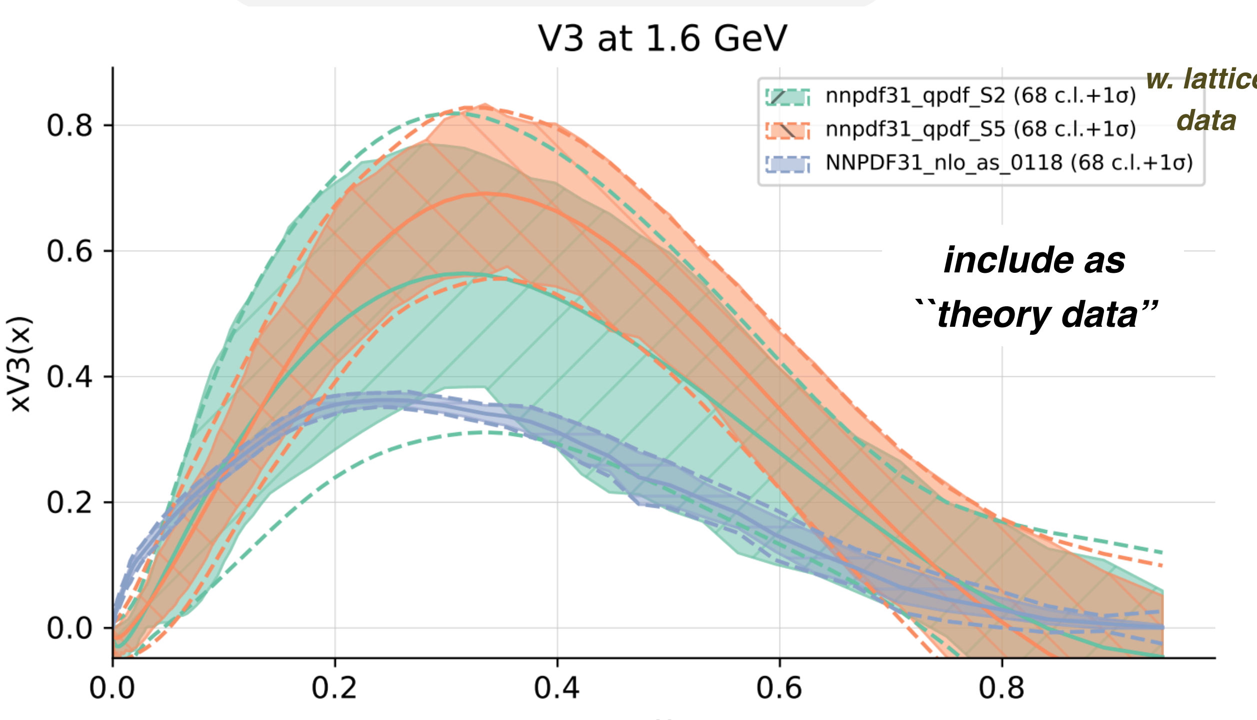
Positivity & integrability of PDFs



NLO EWK corrections



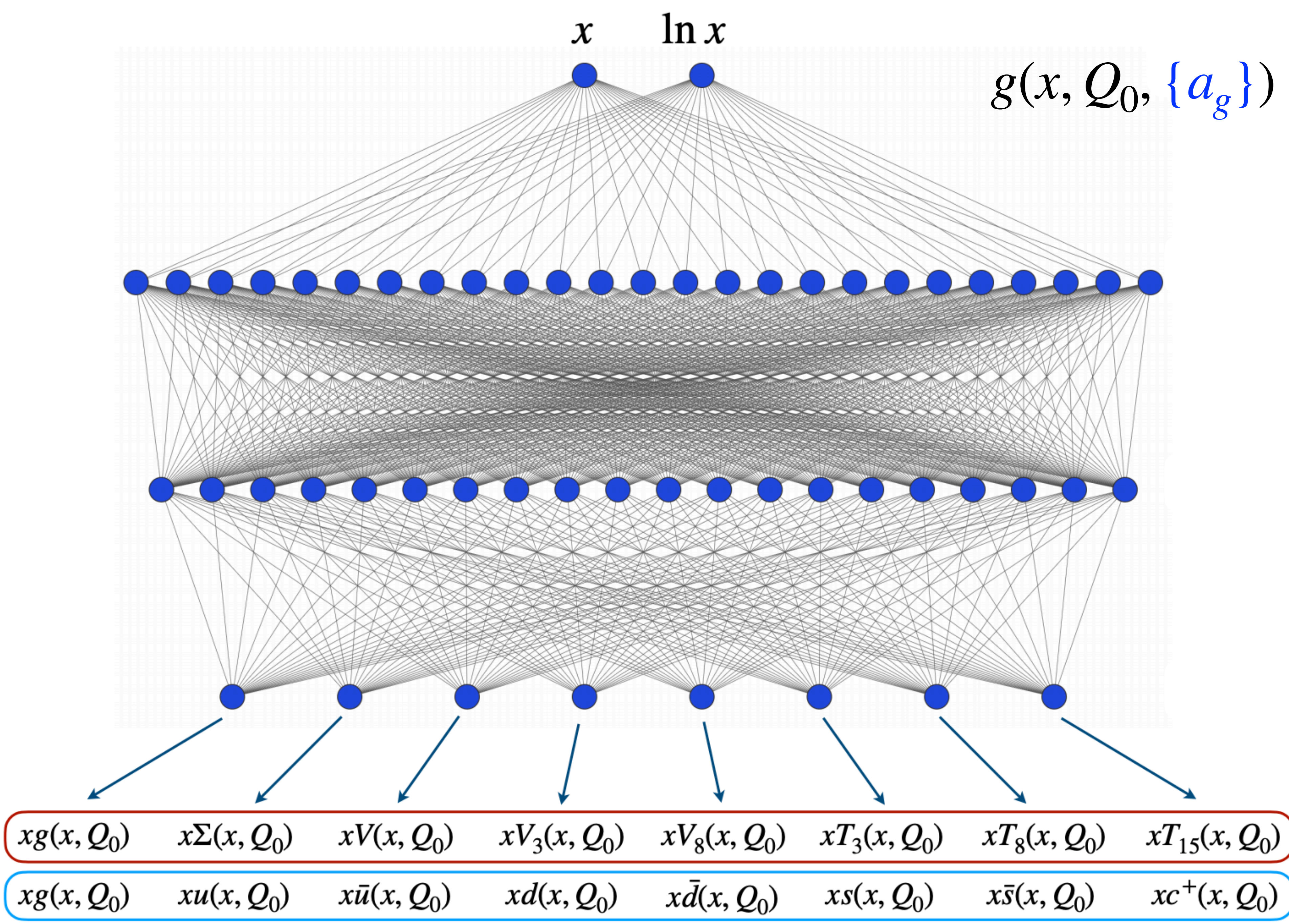
Lattice QCD constraints



NNPDF4.0: fitting methodology

- Model-independent PDF parametrisation with neural networks as **universal unbiased interpolants**
- **Stochastic Gradient Descent** via TensorFlow for neural network training
- Automated model **hyperparameter optimisation:** NN architecture, minimiser, learning rates …
- Validation with **future tests** (forecasting new datasets) and **closure tests** (data based on known PDFs)

$$g(x, Q_0, \{a_g\}) = f_g(x, a_g^{(1)}, a_g^{(2)}, \ldots)$$

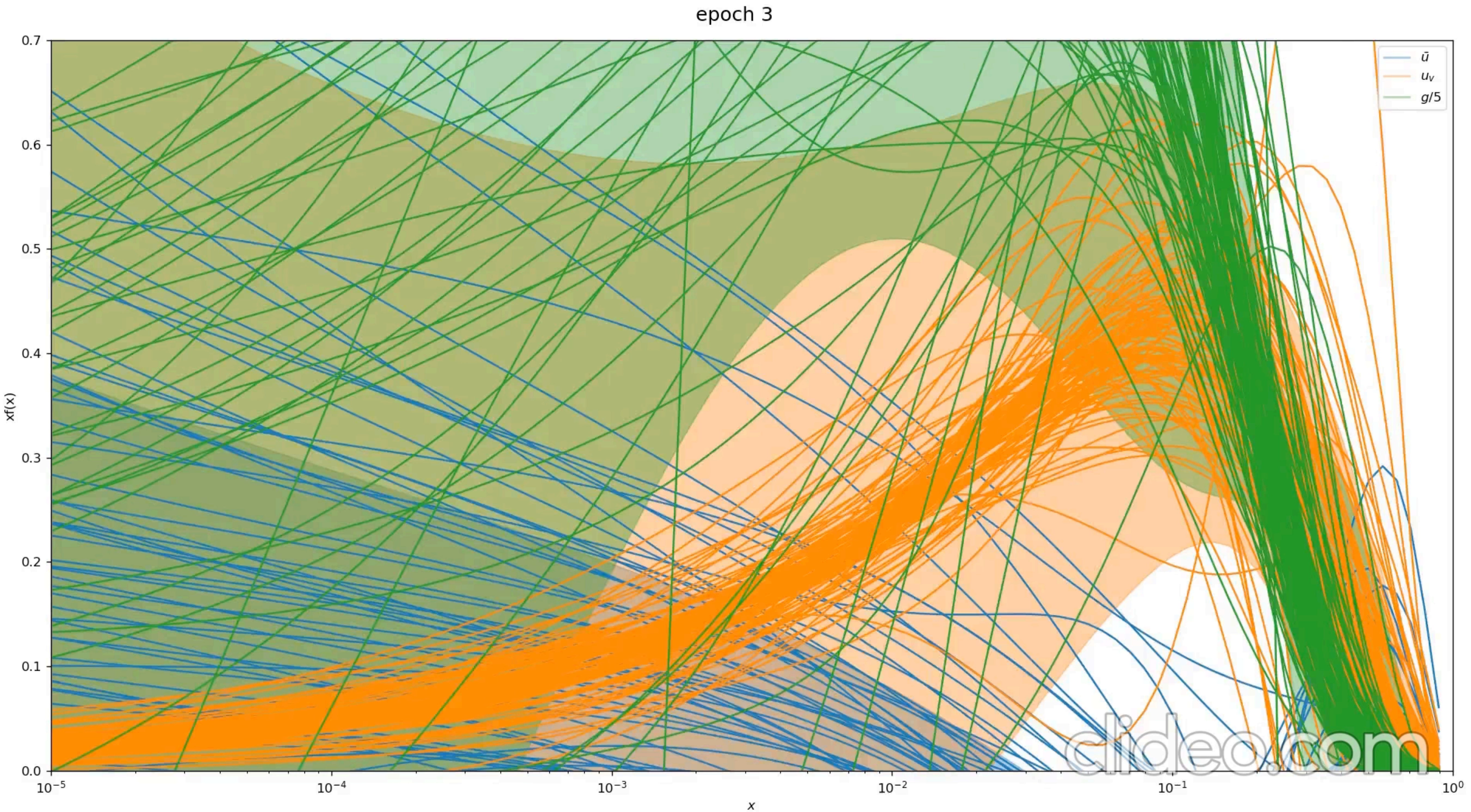


evolution basis

flavor basis

PDFs should be independent of **parametrisation basis!**

NNPDF4.0: fitting methodology



Error estimate based on **Monte Carlo replica method** (band: standard deviation over the MC replicas)

Parton Distributions and Higgs physics

Higgs production and PDFs

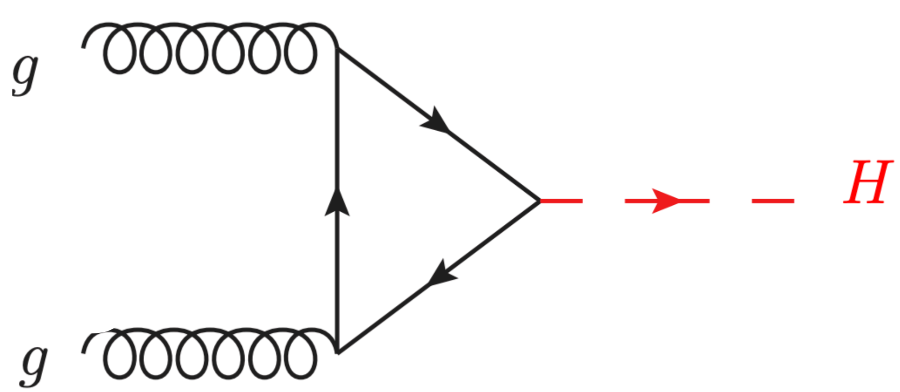
Master Formula for **Higgs production at the LHC**

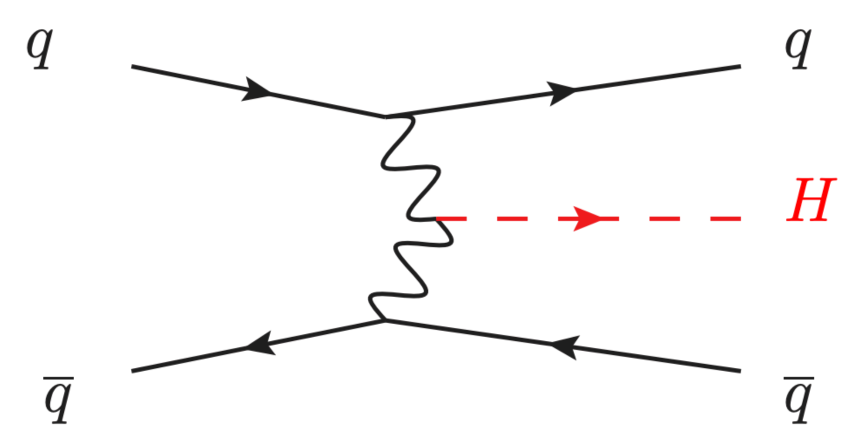
$$\sigma_h(M,s) \propto \sum_{ij} \int_{M^2}^{s} d\hat{s}\; \mathscr{L}_{ij}(\hat{s},s)\; \widetilde{\sigma}_{ij\to h+X}(\hat{s},\alpha_s(M))\,, \quad i,j = u,d,s,g,\ldots$$

partonic luminosity
(non-perturbative QCD,
pheno extraction from data)

hard-scattering matrix element
(perturbative QCD,
evaluate from Feynman diagrams)

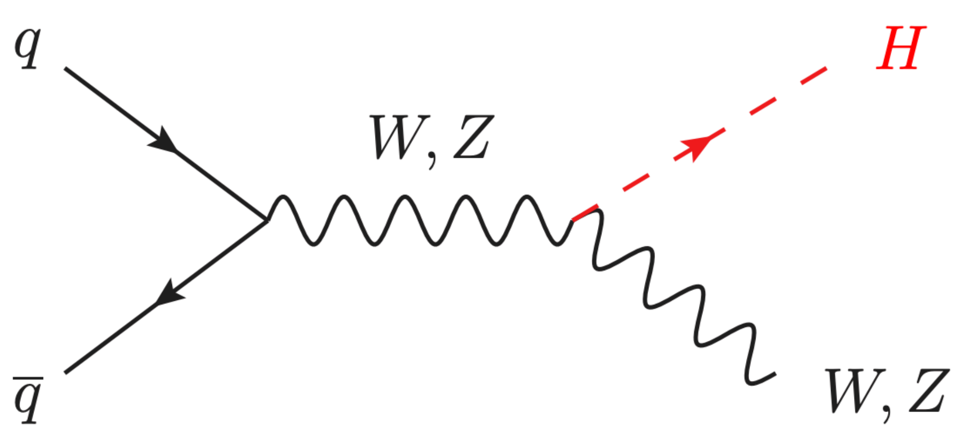
$\mathscr{L}_{gg}$

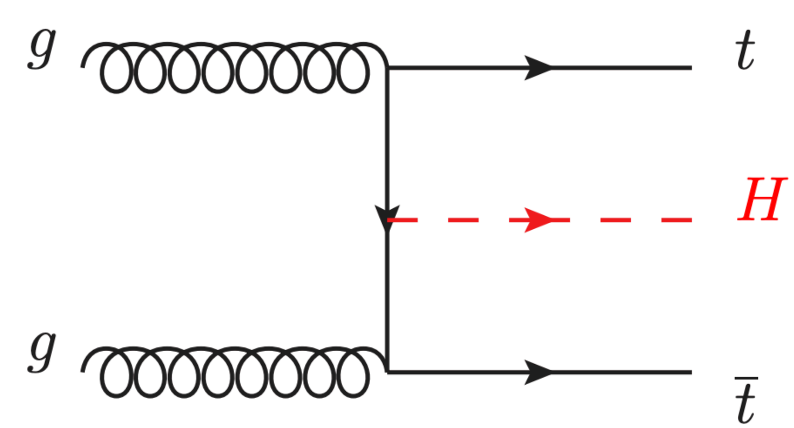




$\mathscr{L}_{qq}$

$\mathscr{L}_{q\bar{q}}$



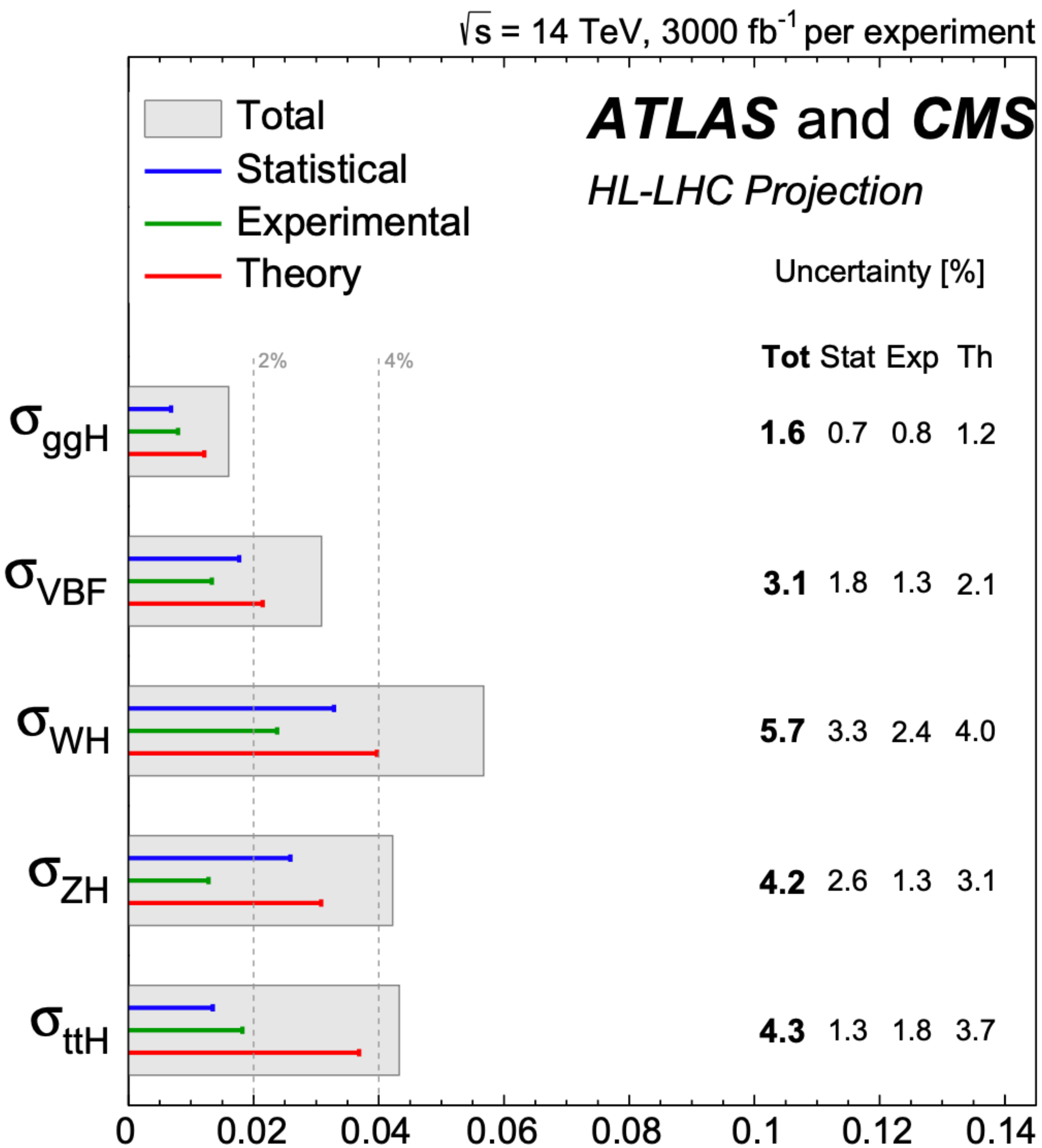


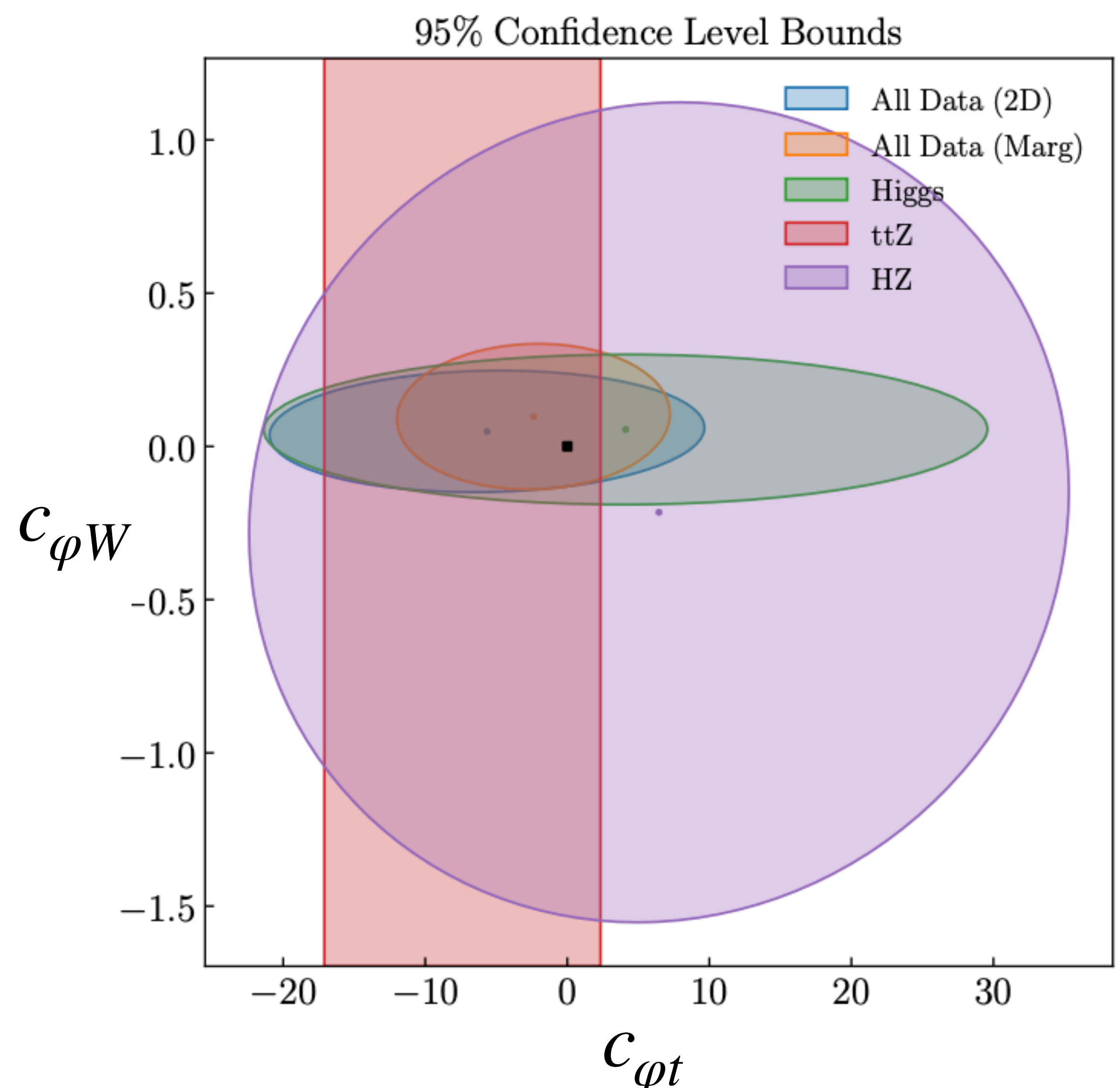
$\mathscr{L}_{gg}$

Higgs production and PDFs

Theory uncertainties, including PDFs, could be limiting factor for **Higgs analyses at HL-LHC**

Improving PDFs makes possible better Higgs measurements and **BSM interpretations** *e.g.* in terms of coupling modifiers or in the **SMEFT framework**





SMEFiT (2021)

Higgs production and PDFs

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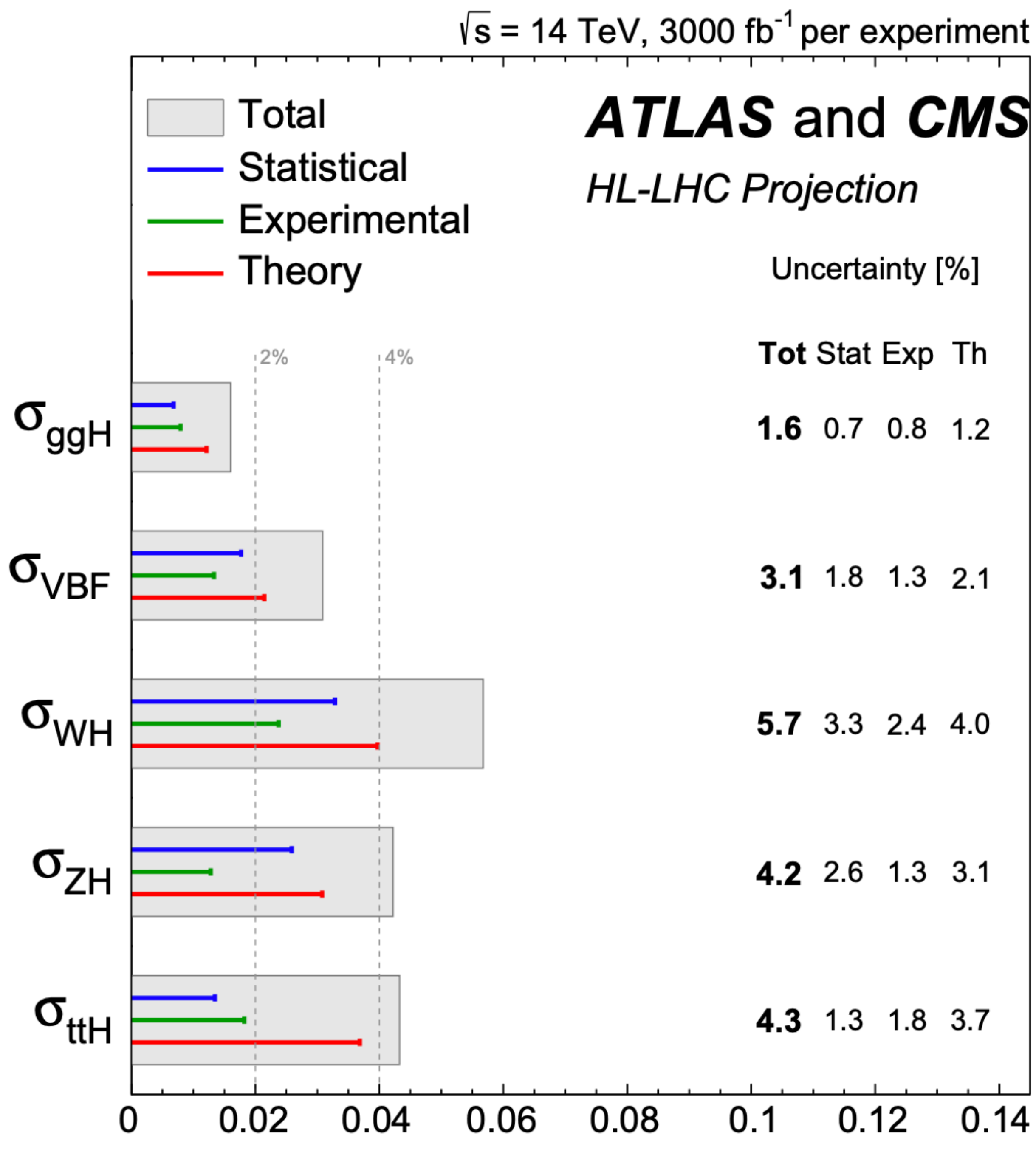
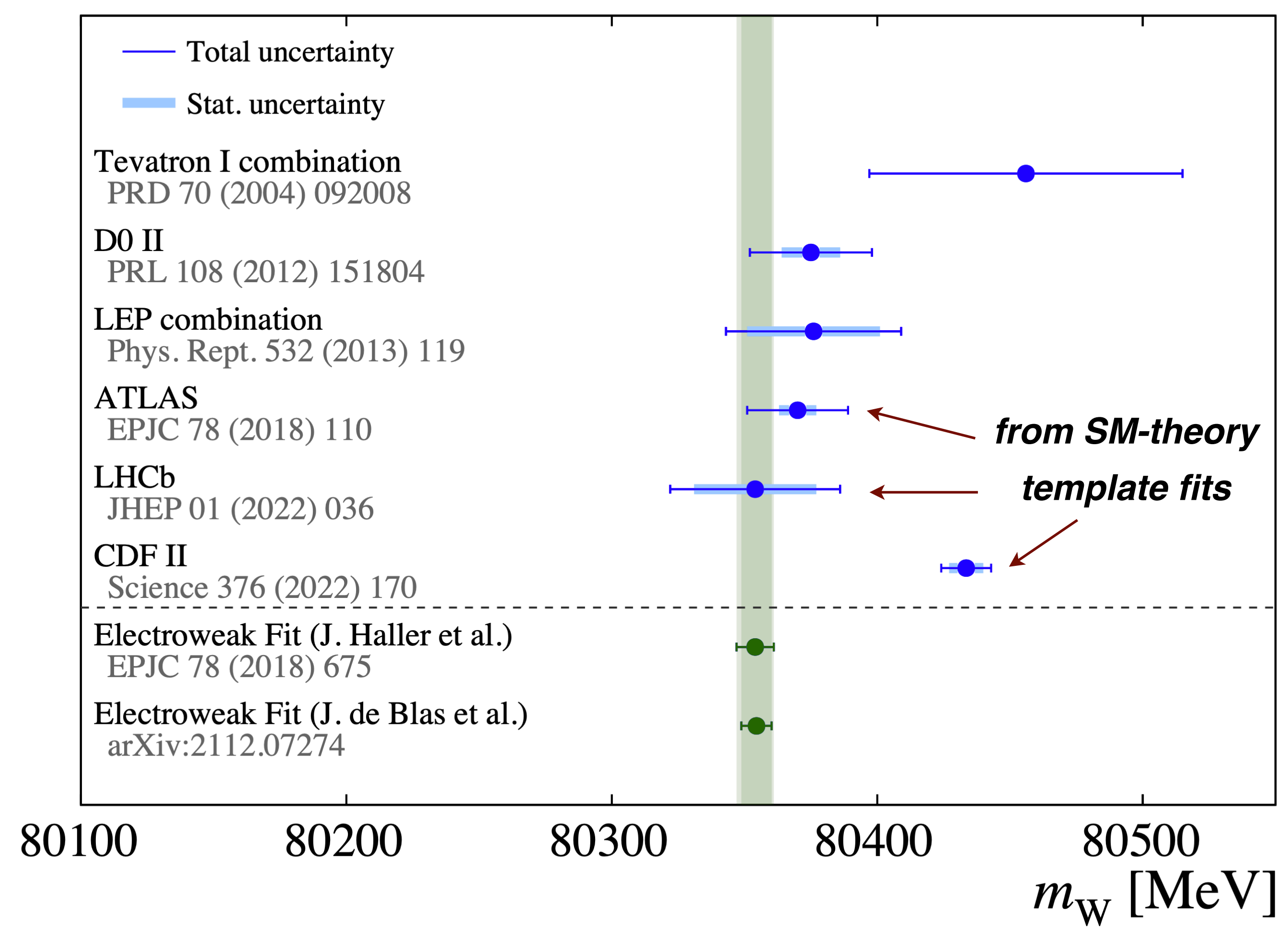
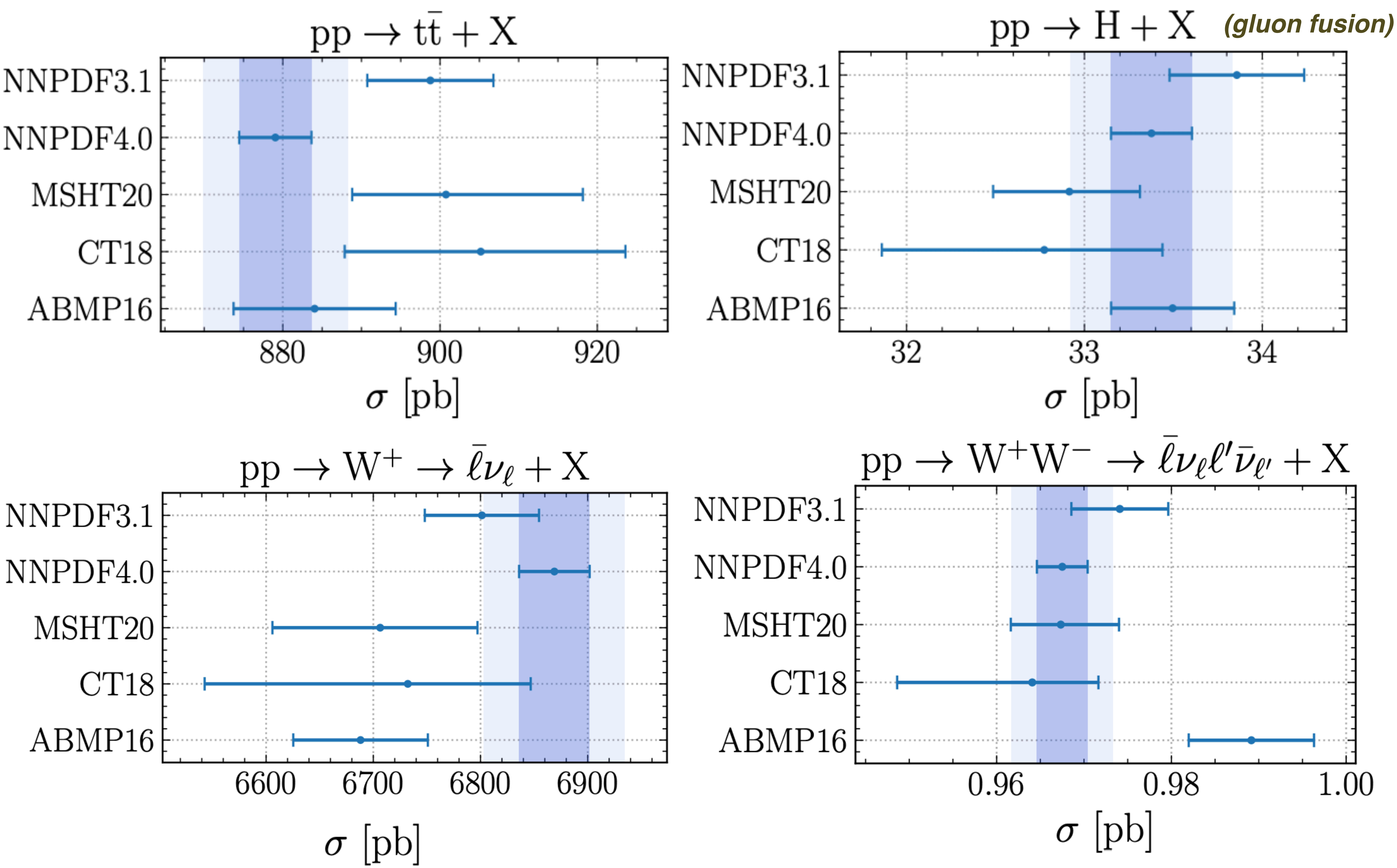


the recent CDF-II M_W anomaly emphasises the key role that precise PDFs and SM calculations have for indirect BSM searches



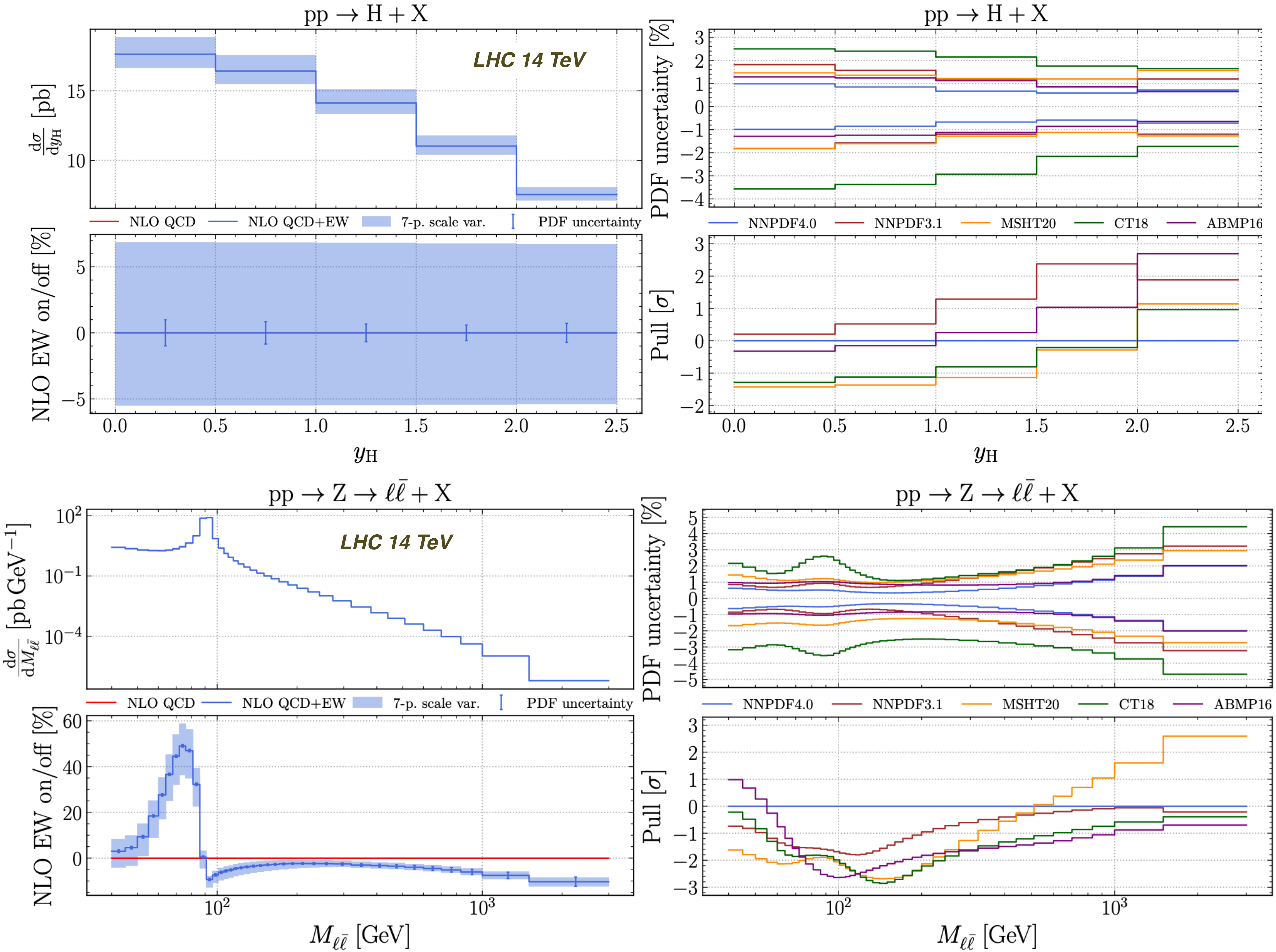
Comparison between modern PDF fits

compare global PDF fits for **inclusive** and **differential LHC cross-sections**



agreement of NNPDF4.0 with CT18 & MSHT20 **at two-sigma level**, differences traced back to large-*x* gluon or quark flavour separation

NLO QCD+EW cross-sections with NNLO PDFs



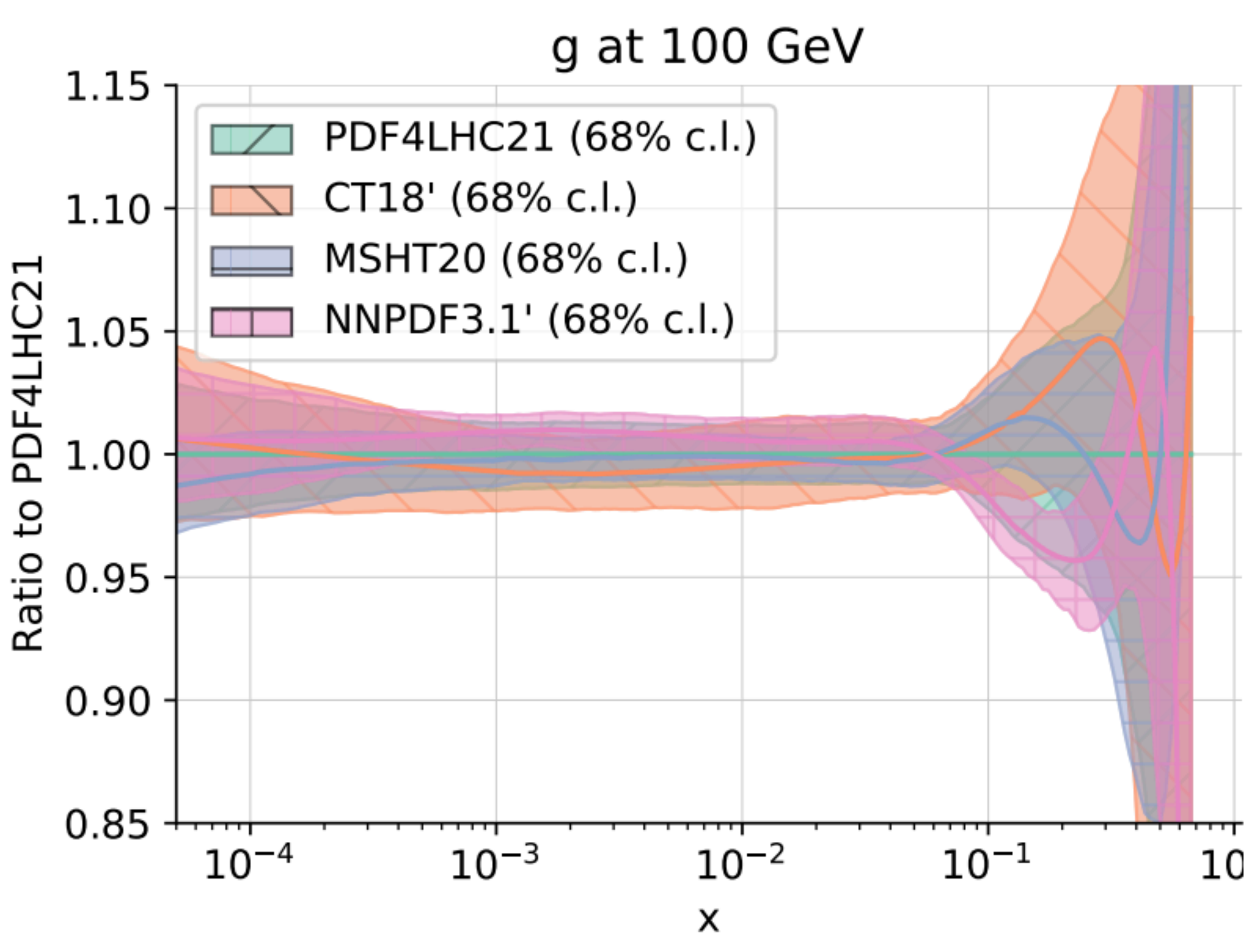
pp → H + X
LHC 14 TeV
dσ/dy_H [pb]
NLO QCD
NLO QCD+EW
7-p. scale var.
PDF uncertainty
NLO EW on/off [%]
y_H
PDF uncertainty [%]
NNPDF4.0
NNPDF3.1
MSHT20
CT18
ABMP16
Pull [σ]
pp → Z → ℓℓ̄ + X
dσ/dM_ℓℓ̄ [pb GeV^−1]
M_ℓℓ̄ [GeV]

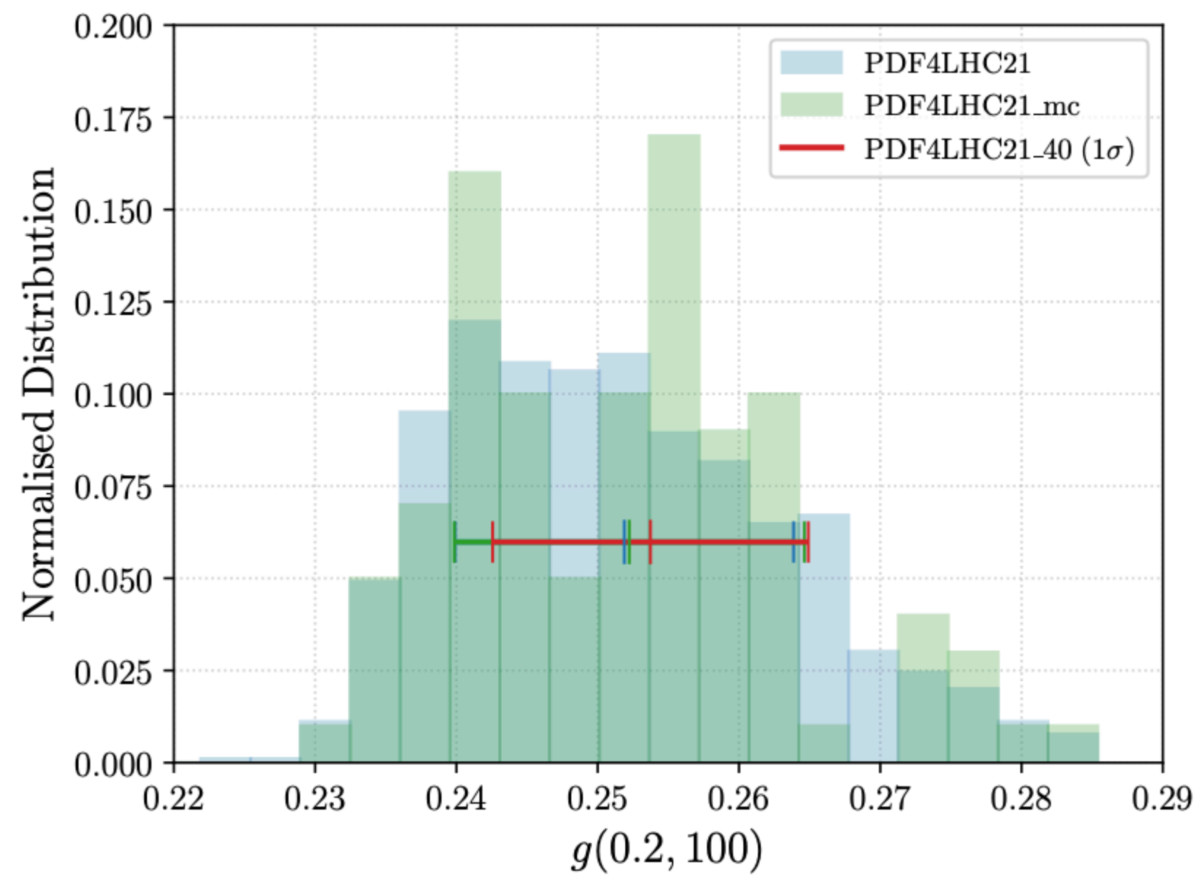
PDF4LHC 21 and Higgs physics

- The **PDF4LHC15 combination** of global PDF fits (CT14, MMHT14, NNPDF3.0) has been extensively used for Higgs predictions and measurements

- The combination has been recently updated to **PDF4LHC21** (now with CT18, MSHT20, NNPDF3.1) leading to consistent predictions with **improved precision**

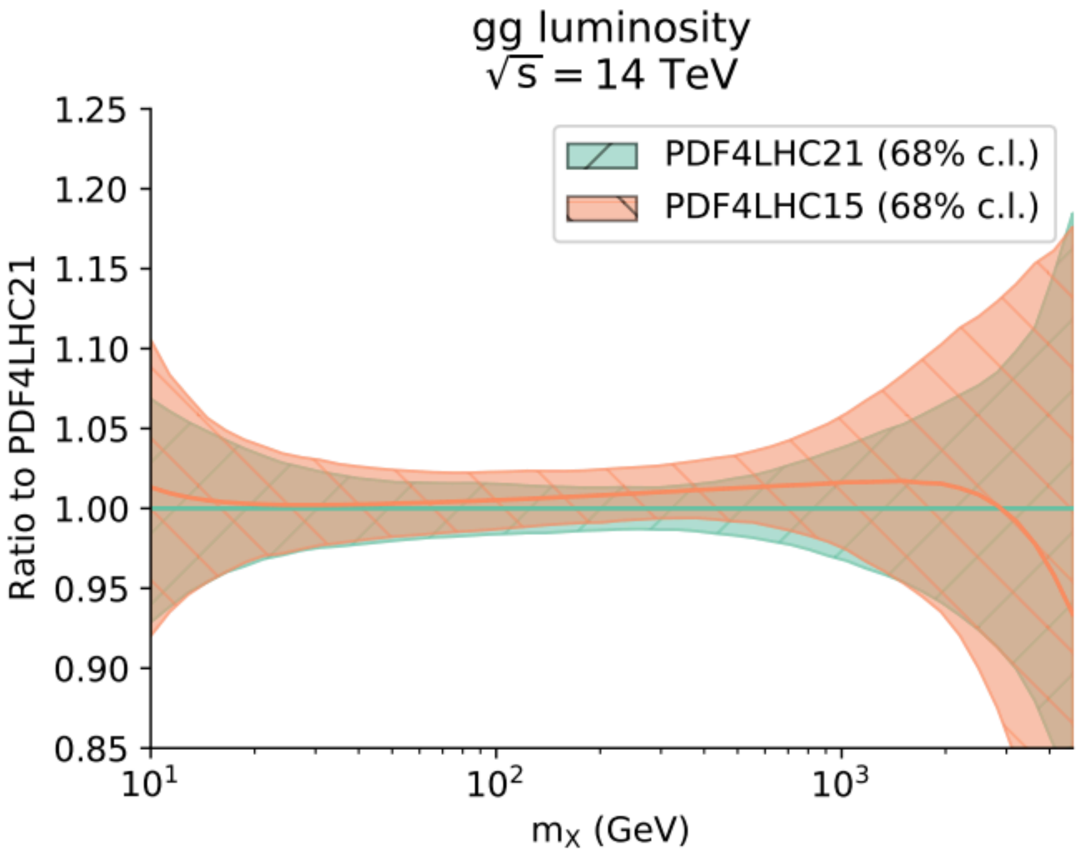
- Several **MC compressed** and **Hessian reduced sets** released, with the former reproducing non-trivial features of the combined probability distribution

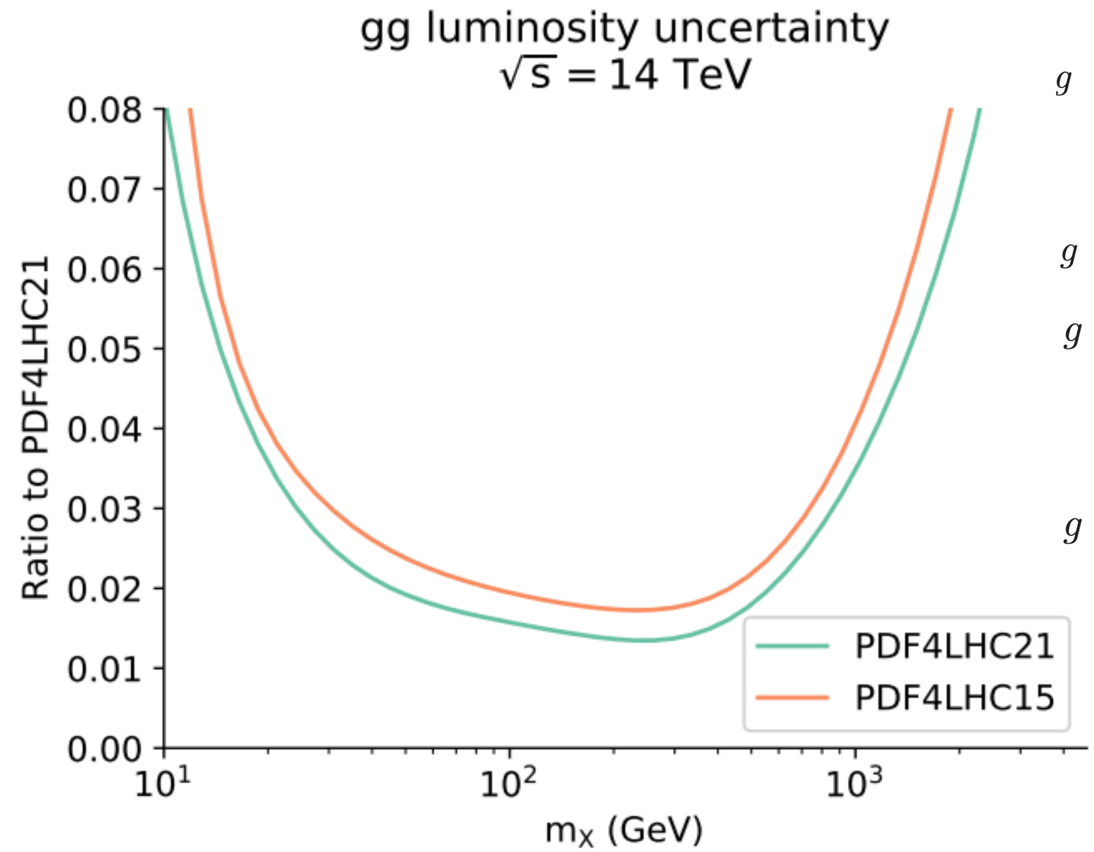


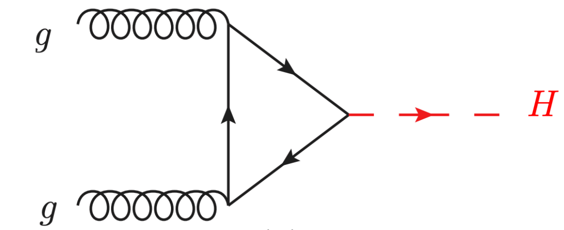


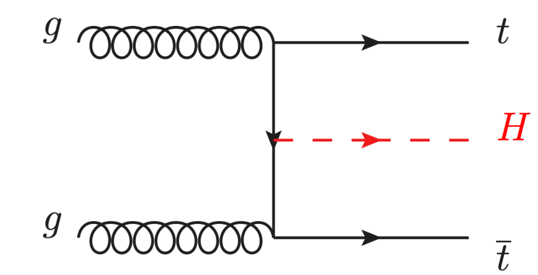
PDF4LHC 21 and Higgs physics

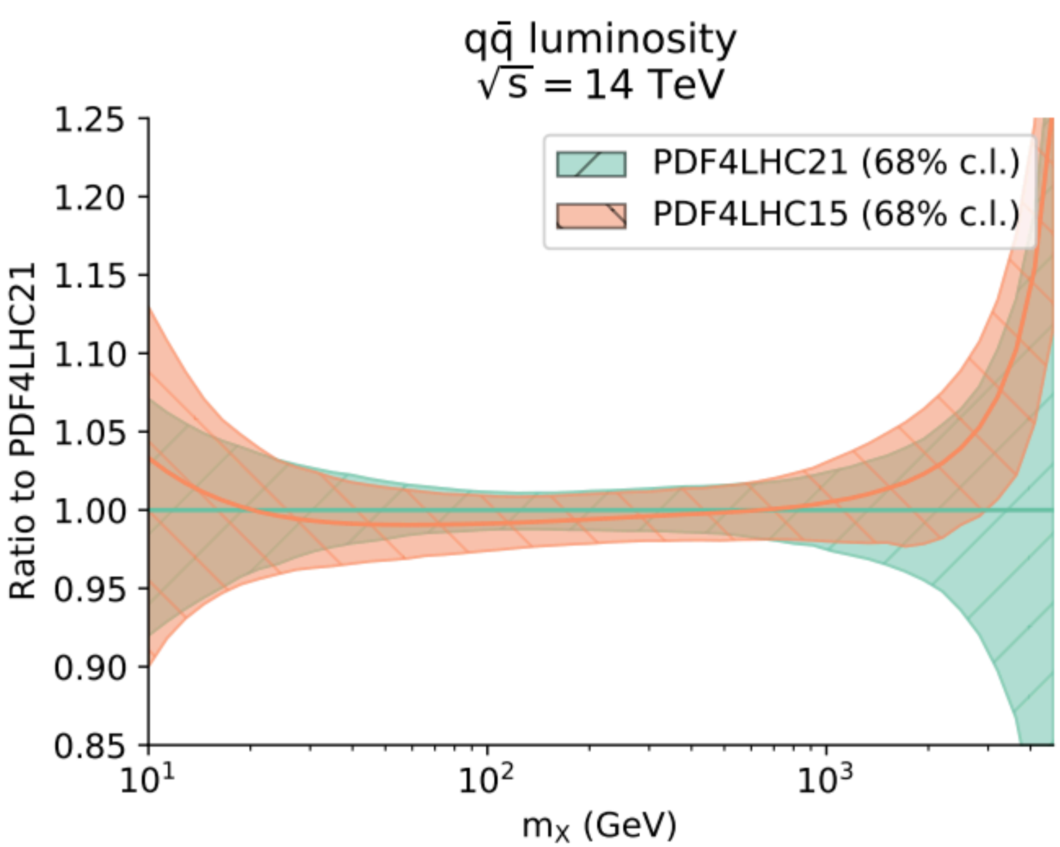
PDF4LHC21 vs PDF4LHC15: consistent predictions with **improved precision**

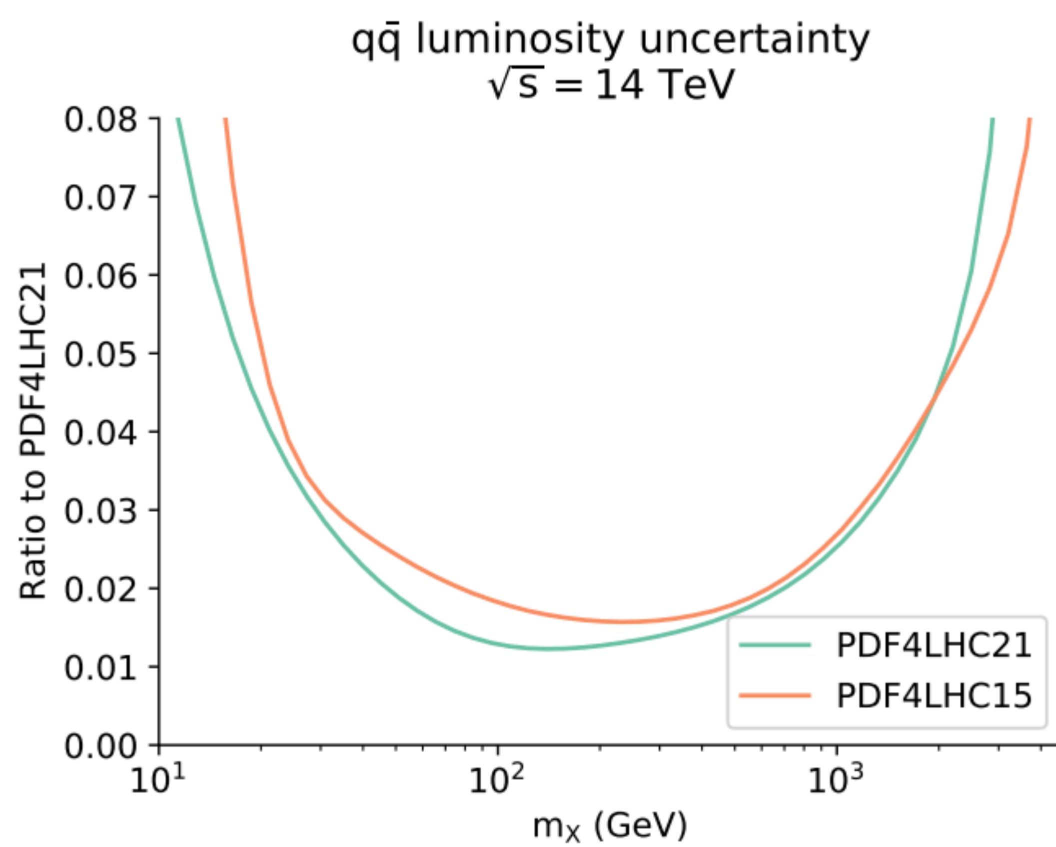


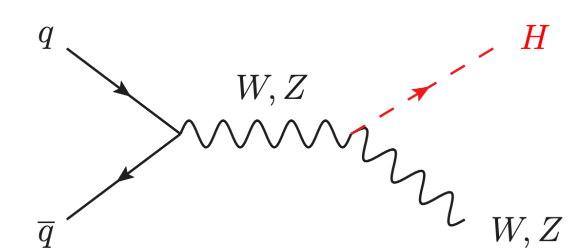






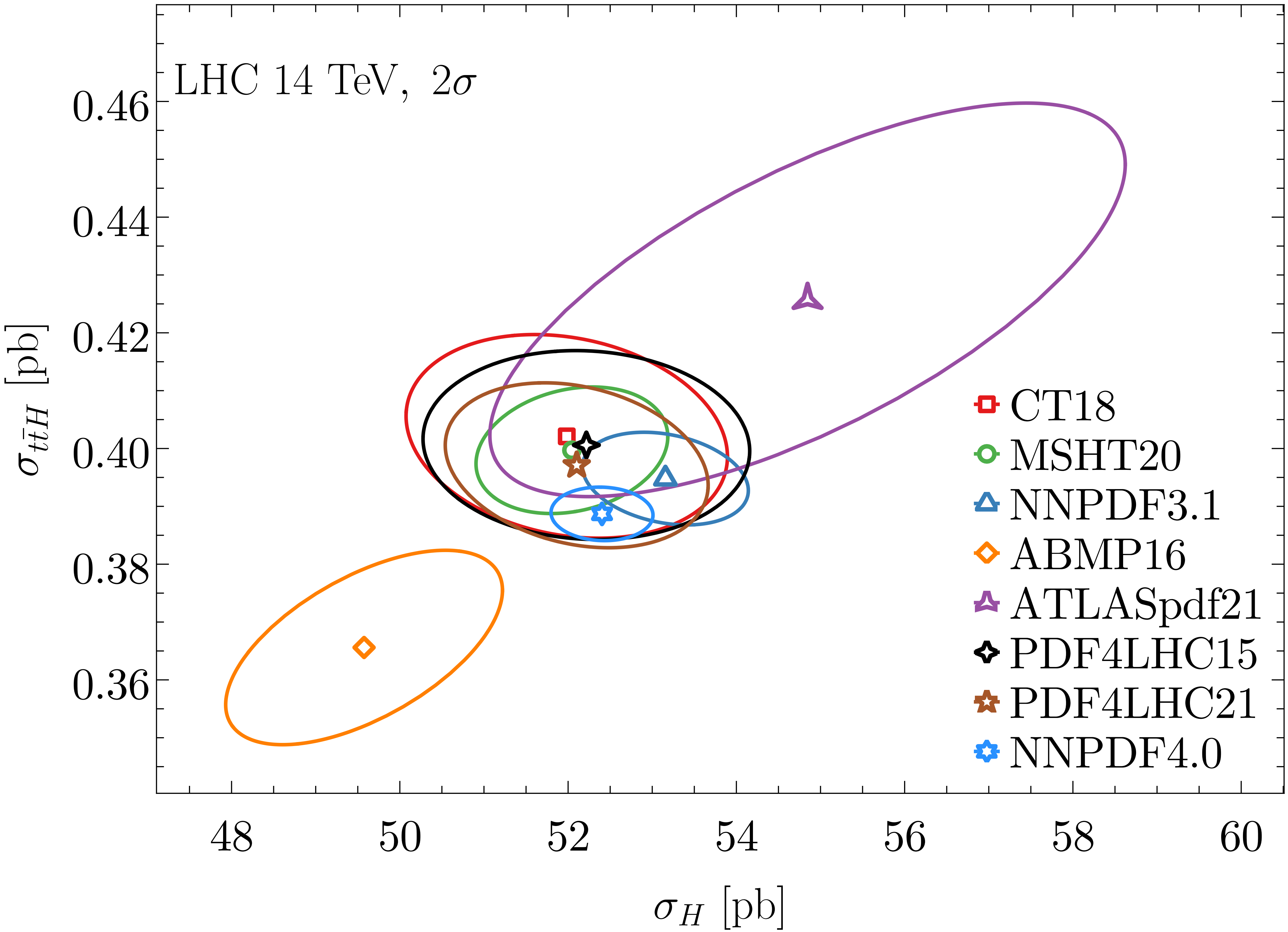






Comparison between modern PDF fits

Global fits **consistent** (but differences in **uncertainties**), ABMP16 and ATLASpdf21 outliers



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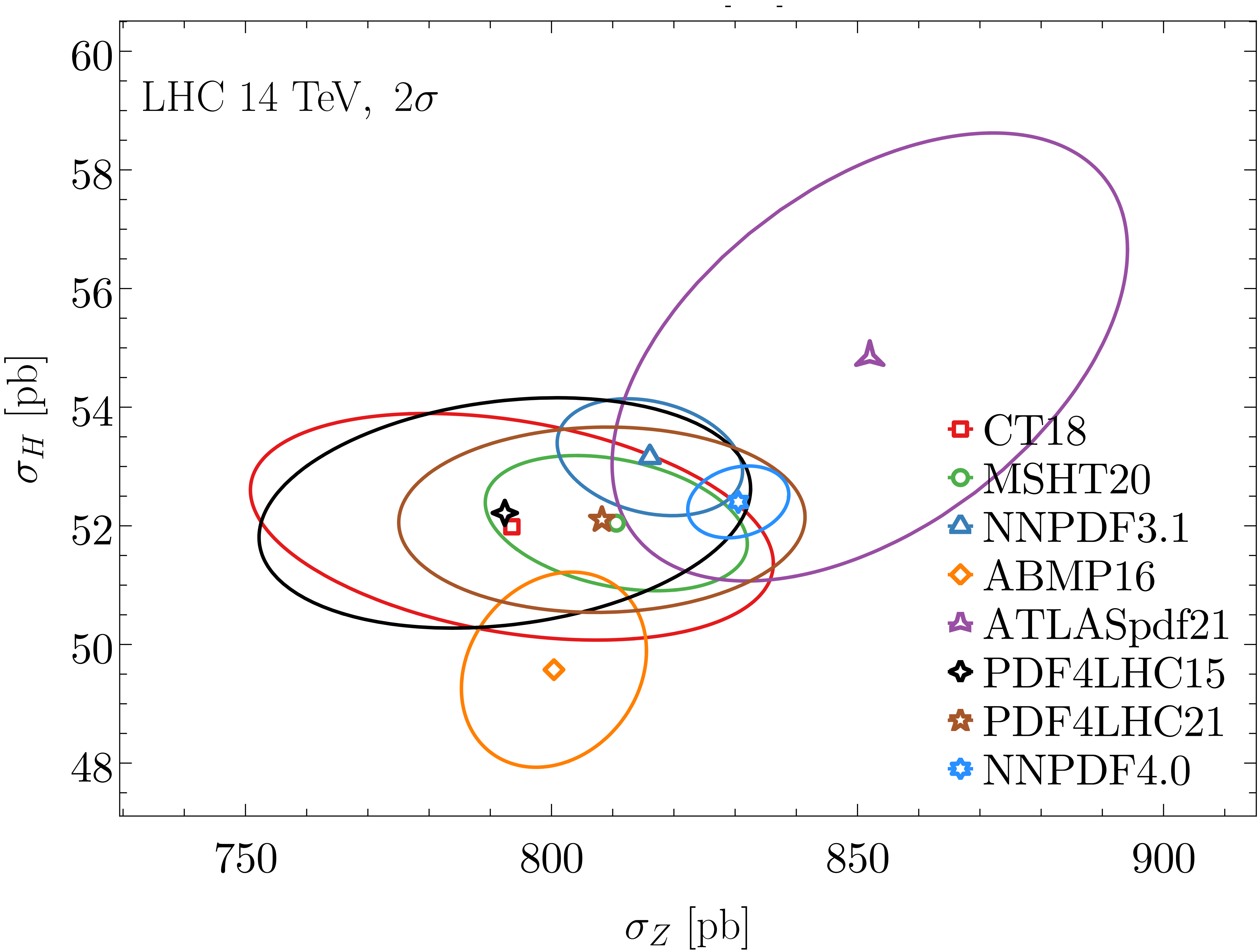
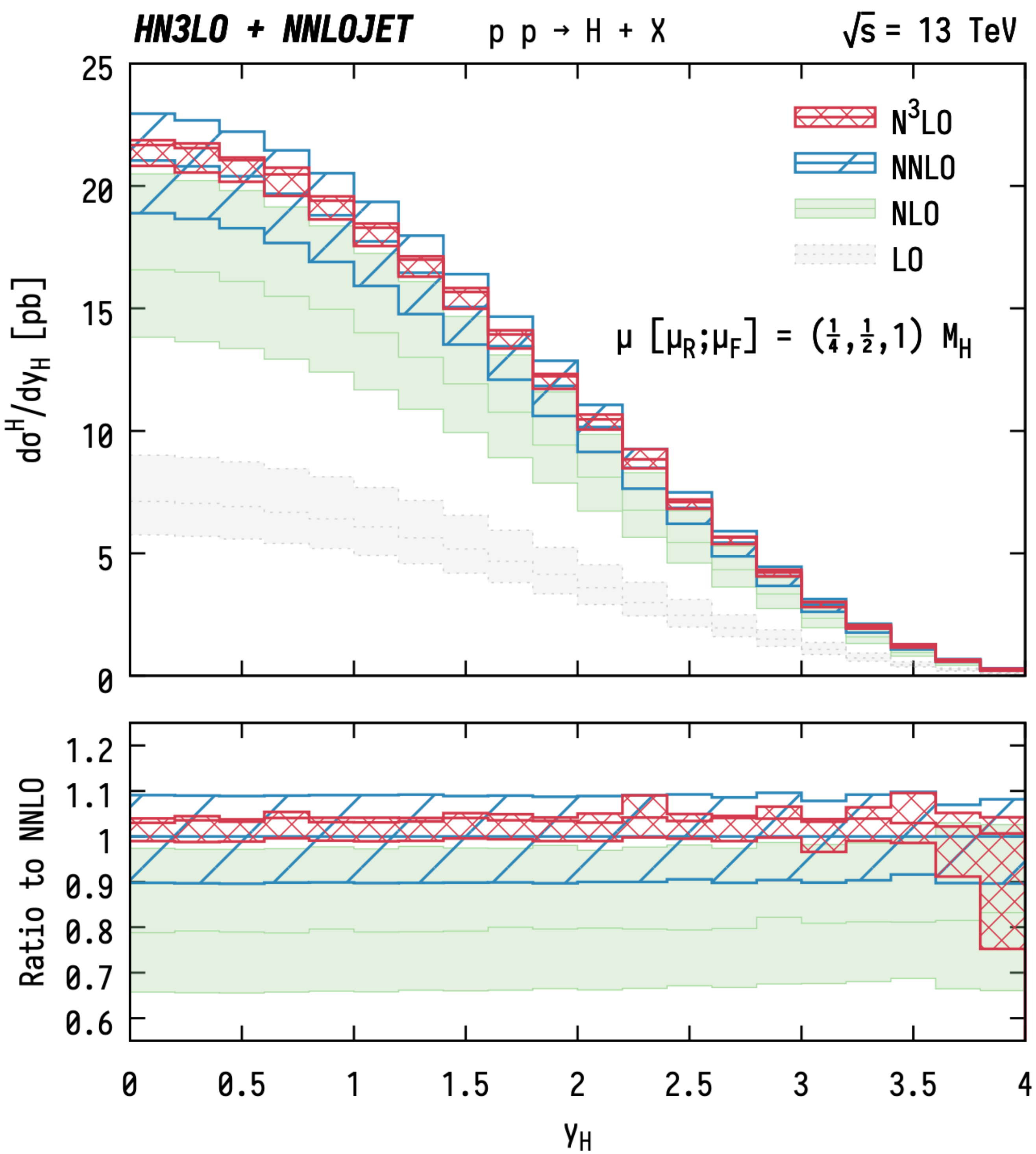


Towards N3LO proton structure

Higher-order QCD calculations are crucial for Higgs phenomenology



Chen et al, 2102.07607

Fully differential N3LO **Higgs in gluon-fusion**

$$\widetilde{\sigma}(\alpha_s, \alpha) = \widetilde{\sigma}^{(0)}\left(1 + c_{1,0}\alpha_s + c_{2,0}\alpha_s^2 + c_{3,0}\alpha_s^3\right)$$

NLO *NNLO* *N3LO*

- Improved **precision & accuracy**: enhance physics reach of the same measurement
- Reliable estimate of **missing higher-order uncertainties** (MHOUs)

For Higgs rapidity distribution in gluon fusion:

- NLO: first sensible estimate of MHOUs
- NNLO: required for O(10%) precision
- N^{3}LO: required for **few-percent** precision
- Good convergence of perturbative expansion

However, full **N3LO accuracy** requires **N3LO PDFs**, which do not exist yet!

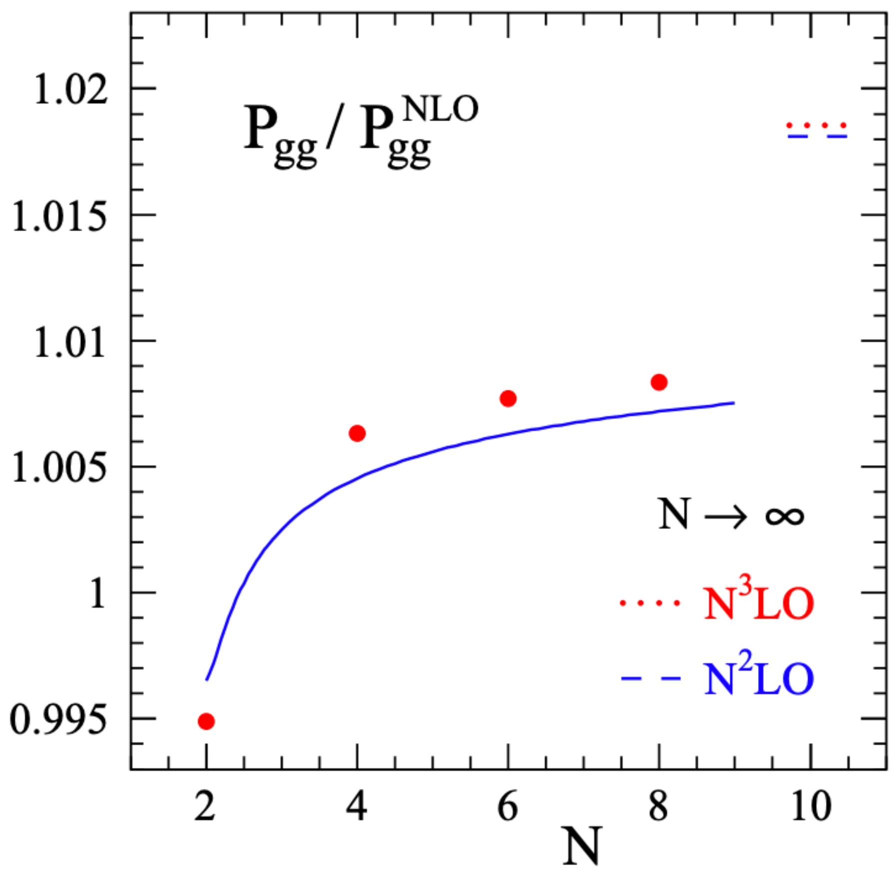
Towards N3LO proton structure

Fully exploiting recent progress in N³LO calculations requires **PDFs extracted at the same order**

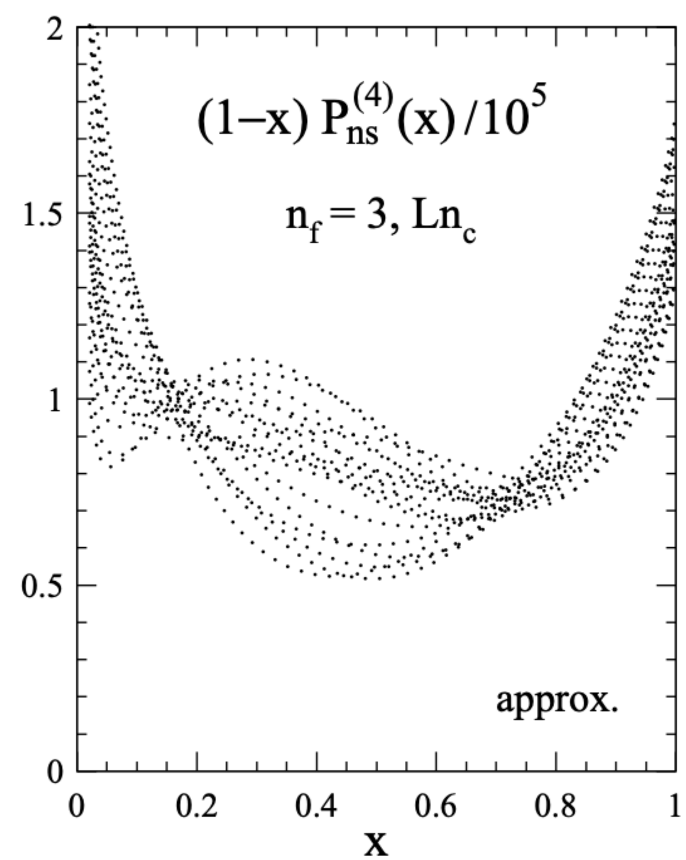
DGLAP splitting functions

$$P_{ij}(x,\alpha_s) = \alpha_s P_{ij}^{(0)}(x) + \alpha_s^2 P_{ij}^{(1)}(x) + \alpha_s^3 P_{ij}^{(2)}(x) + \alpha_s^4 P_{ij}^{(3)}(x) + \alpha_s^5 P_{ij}^{(4)}(x)$$

☑ LO (1973) ☑ NLO (1982) ☑ NNLO (2004) N³LO partial results N⁴LO partial results



Moch et al, 2111.15561



Moch et al, 1812.11818

What do we about about N³LO P_{ij} ?

- low moments of singlet & non-singlet
- large-x limits (cust anomalous dim)
- small-x limits (BFKL resummation)

What else for a **N³LO PDF fit?**

☑ Massless and massive (partially) DIS **coefficient functions**

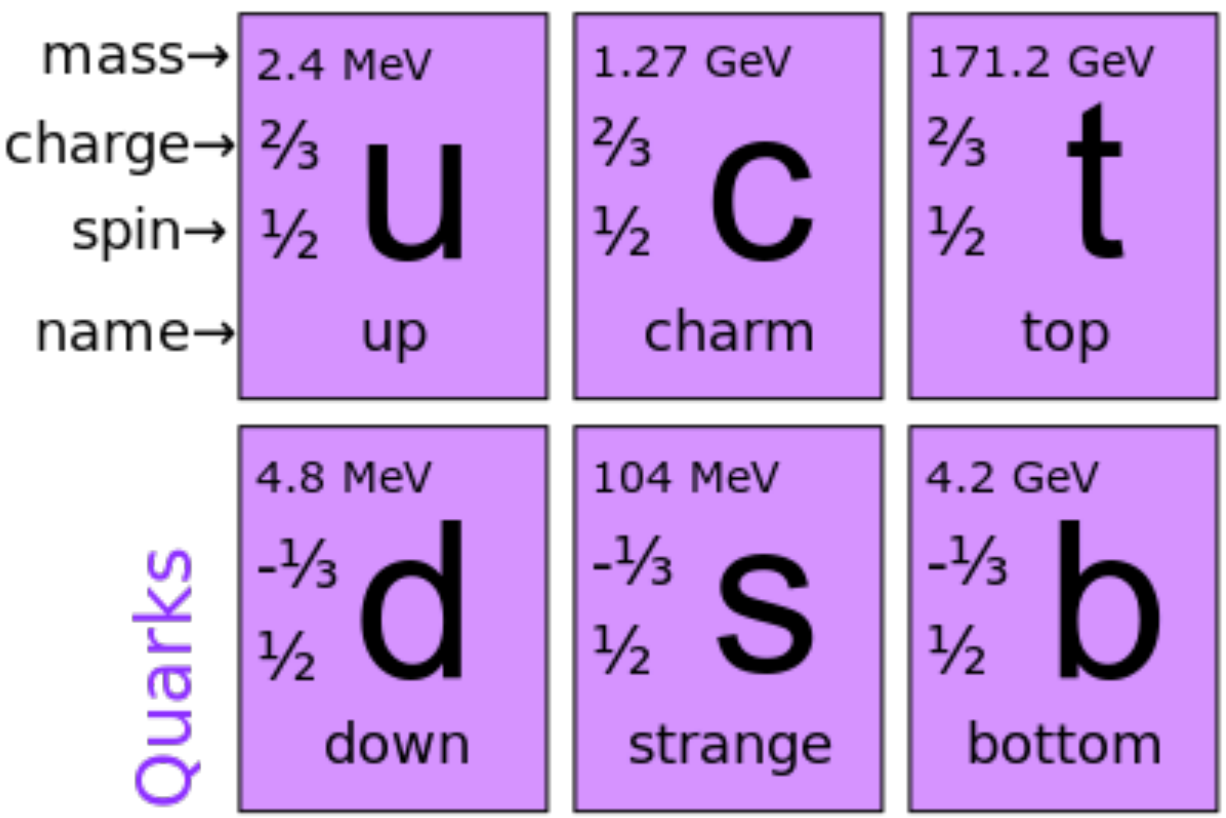
☑ Heavy quark **matching conditions**

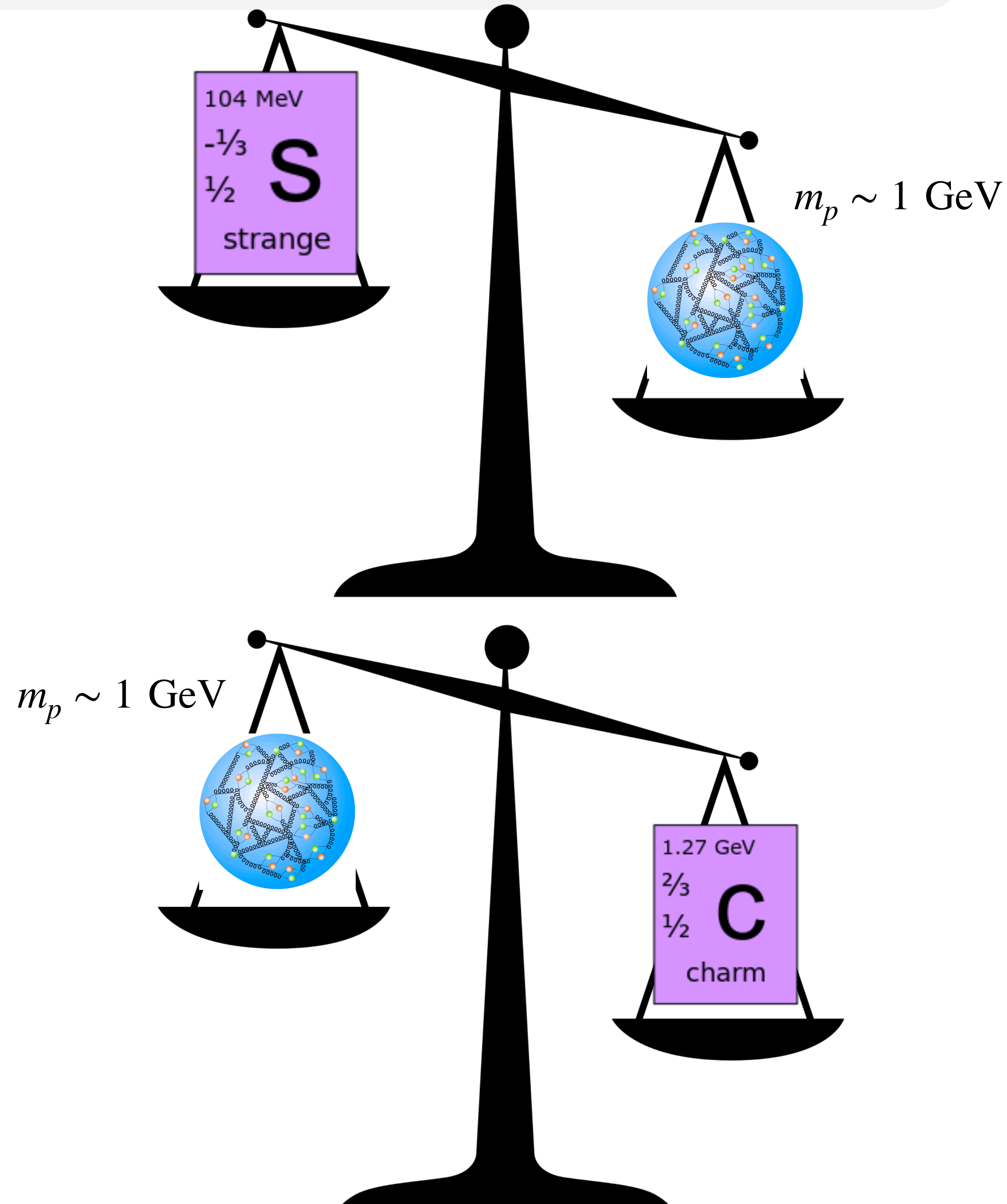
☑ **N³LO K-factors** for LHC observables (subset, e.g. Drell-Yan)

Charm in the proton

The charm content of the proton

common assumption in PDF fits: the static proton wave function does not contain charm quarks:
the proton contains **intrinsic up, down, strange (anti-)quarks** but **no intrinsic charm quarks**





charm quarks heavier than the proton itself!

The charm content of the proton

common assumption in PDF fits: the static proton wave function does not contain charm quarks: the proton contains **intrinsic up, down, strange (anti-)quarks** but **no intrinsic charm quarks**

the charm PDF is **generated perturbatively** (DGLAP evolution) from radiation off gluons and quarks

$$\underbrace{f_c^{(n_f)}}_{\text{3FNS charm}} = 0 \quad \rightarrow \quad \underbrace{f_c^{(n_f+1)}}_{\text{4FNS charm}} \propto \alpha_s \ln \frac{Q^2}{m_c^2} \left(P_{qg} \otimes \underbrace{f_g^{(n_f+1)}}_{\text{4FNS gluon}} \right) + \mathcal{O}\left(\alpha_s^2\right)$$

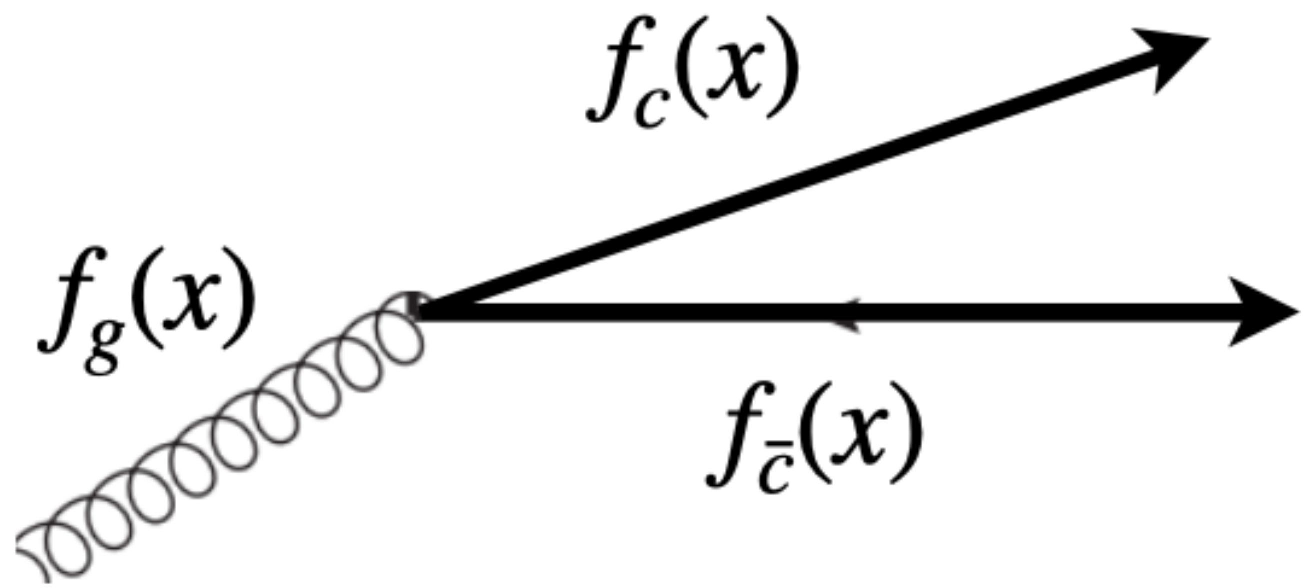
4 flavour scheme, $Q > m_c$

$u^{(4)}, d^{(4)}, s^{(4)}, c^{(4)} g^{(4)}$

$\updownarrow \quad \updownarrow$

3 flavour scheme, $Q < m_c$

$u^{(3)}, d^{(4)}, s^{(3)}, g^{(3)}$



If charm is **perturbatively generated**, the charm PDF is ``**trivial**”

The charm content of the proton

common assumption in PDF fits: the static proton wave function does not contain charm quarks: the proton contains **intrinsic up, down, strange (anti-)quarks** but **no intrinsic charm quarks**

It does not need to be so! An **intrinsic charm component** predicted in many models

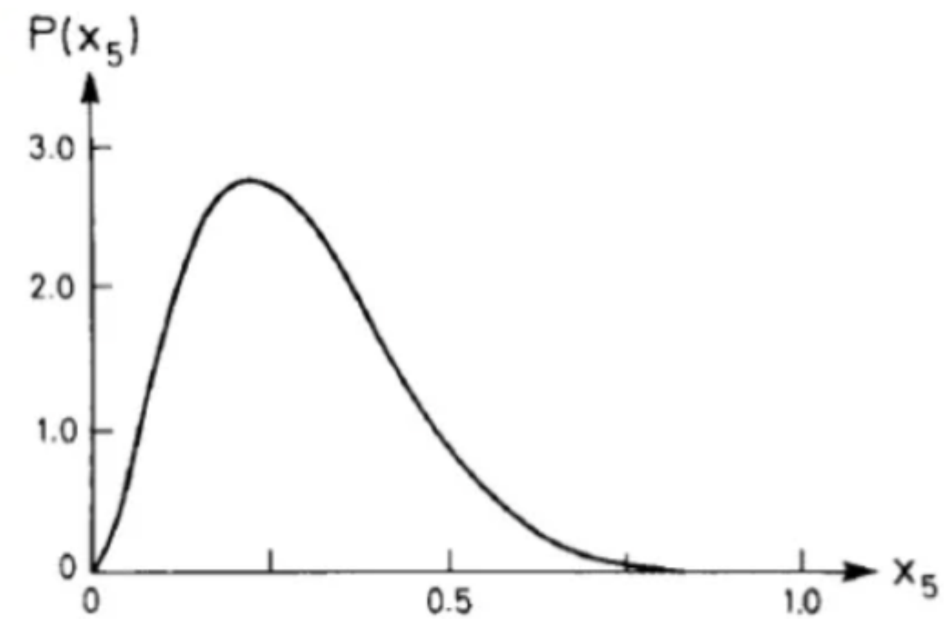
THE INTRINSIC CHARM OF THE PROTON

S.J. BRODSKY [1]
Stanford Linear Accelerator Center, Stanford, California 94305, USA

and

P. HOYER, C. PETERSON and N. SAKAI [2]
NORDITA, Copenhagen, Denmark

Received 22 April 1980



$$|p\rangle = \mathscr{P}_{3q}\,|uud\rangle + \mathscr{P}_{5q}\,|uudc\bar{c}\rangle + \ldots$$

Recent data give unexpectedly large cross-sections for charmed particle production at high x_F in hadron collisions. This may imply that the proton has a non-negligible uudc$\bar{\text{c}}$ Fock component. The interesting consequences of such a hypothesis are explored.

40 years of extensive searches for intrinsic charm: no unambiguous evidence ….

Disentangling intrinsic charm

$$c^{(n_f=4)}(x,Q) \simeq c^{(n_f=4)}_{(\mathrm{pert})}(x,Q) + c^{(n_f=4)}_{(\mathrm{intr})}(x,Q)$$

Extracted phenomenologically from data

from pQCD evolution and matching

from intrinsic component $c^{(n_f=3)}_{(\mathrm{intr})}(x) \neq 0$

4FNS Charm PDF constrained by experimental data for $Q > Q_0$

- NNPDF4.0 dataset
- NNLO QCD calculations

QCD evolution

starting point: NNPDF 4.0 methodology

$Q_0 =$ 1.65 GeV

4FNS Charm PDF parametrised at Q_0

- Deep-learning parametrisation
- Monte Carlo representation of uncertainties

QCD evolution

subtract perturbative component

4FNS to 3FNS transformation

NNLO or N^{3}LO matching conditions

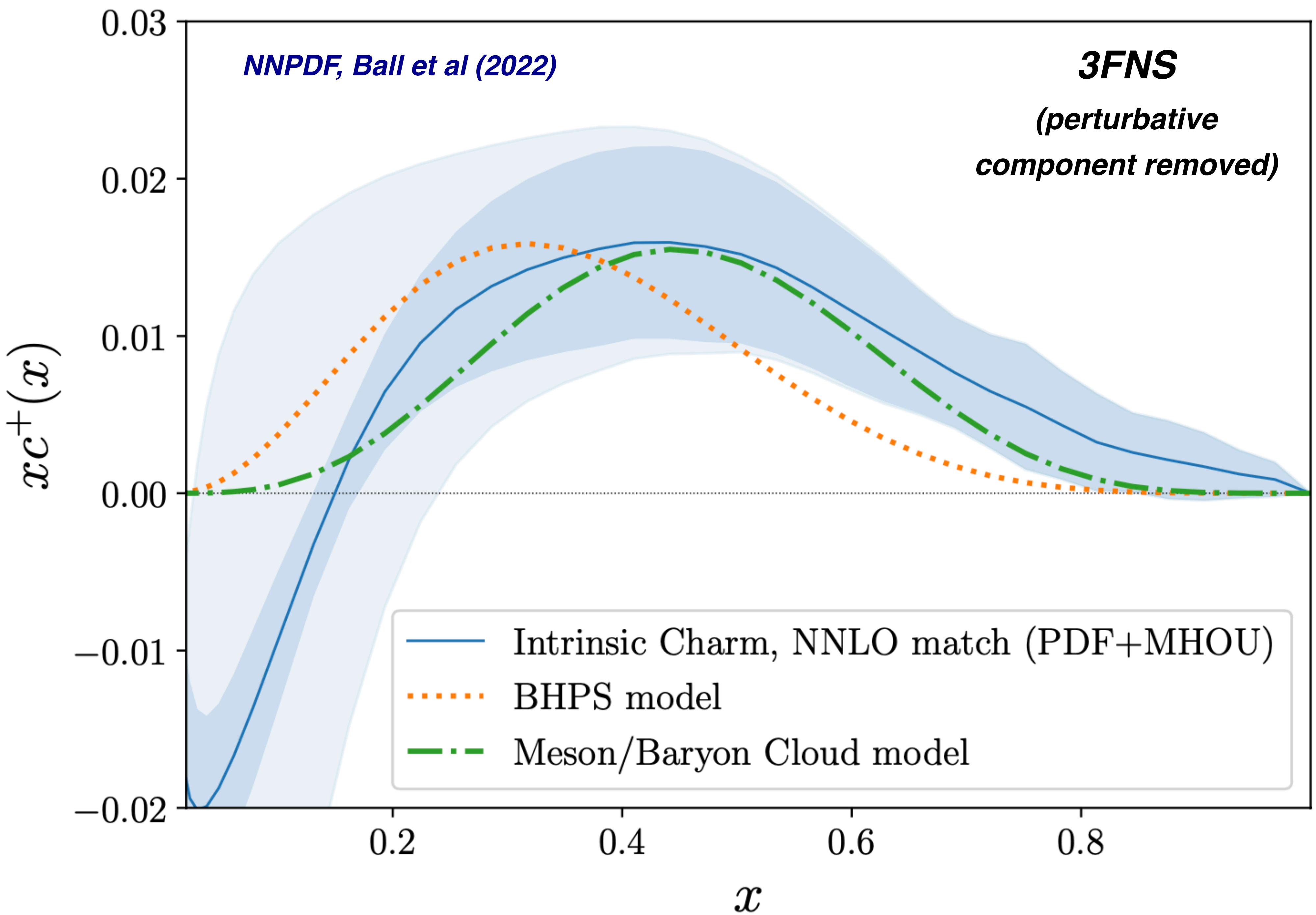
EKO
Evolution Kernel Operators

$$c^{(n_f=3)}(x,Q) = c_{(\mathrm{intr})}(x)$$

Intrinsic (3FNS) Charm

- Scale-independent
- PDF and MHO uncertainties

Intrinsic charm

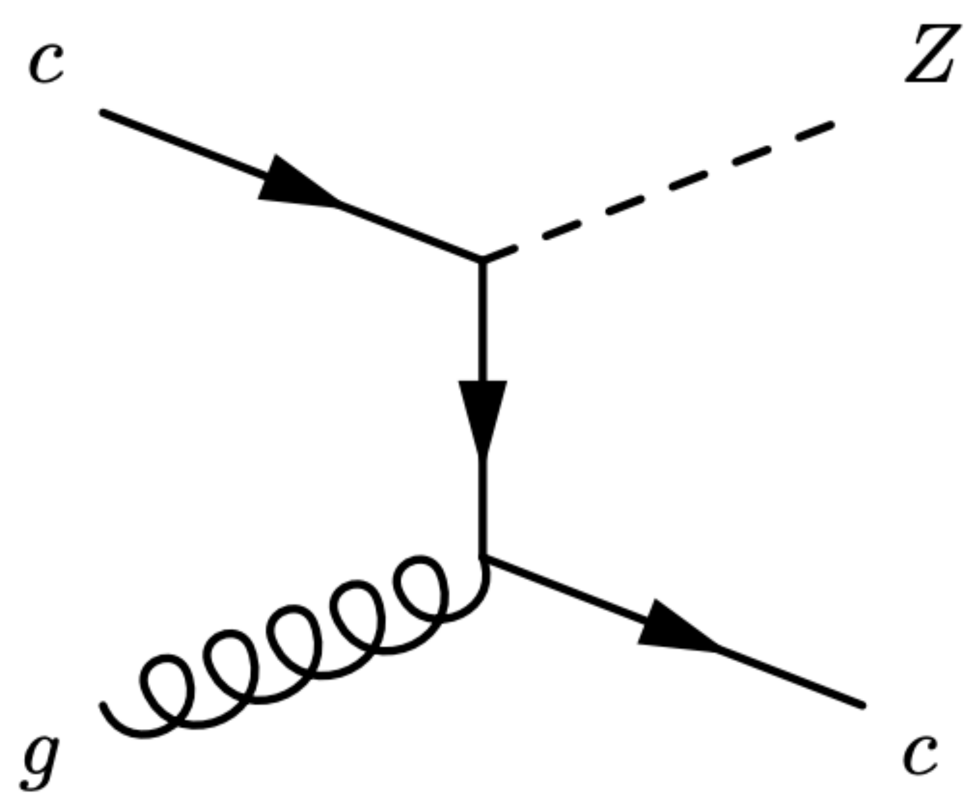


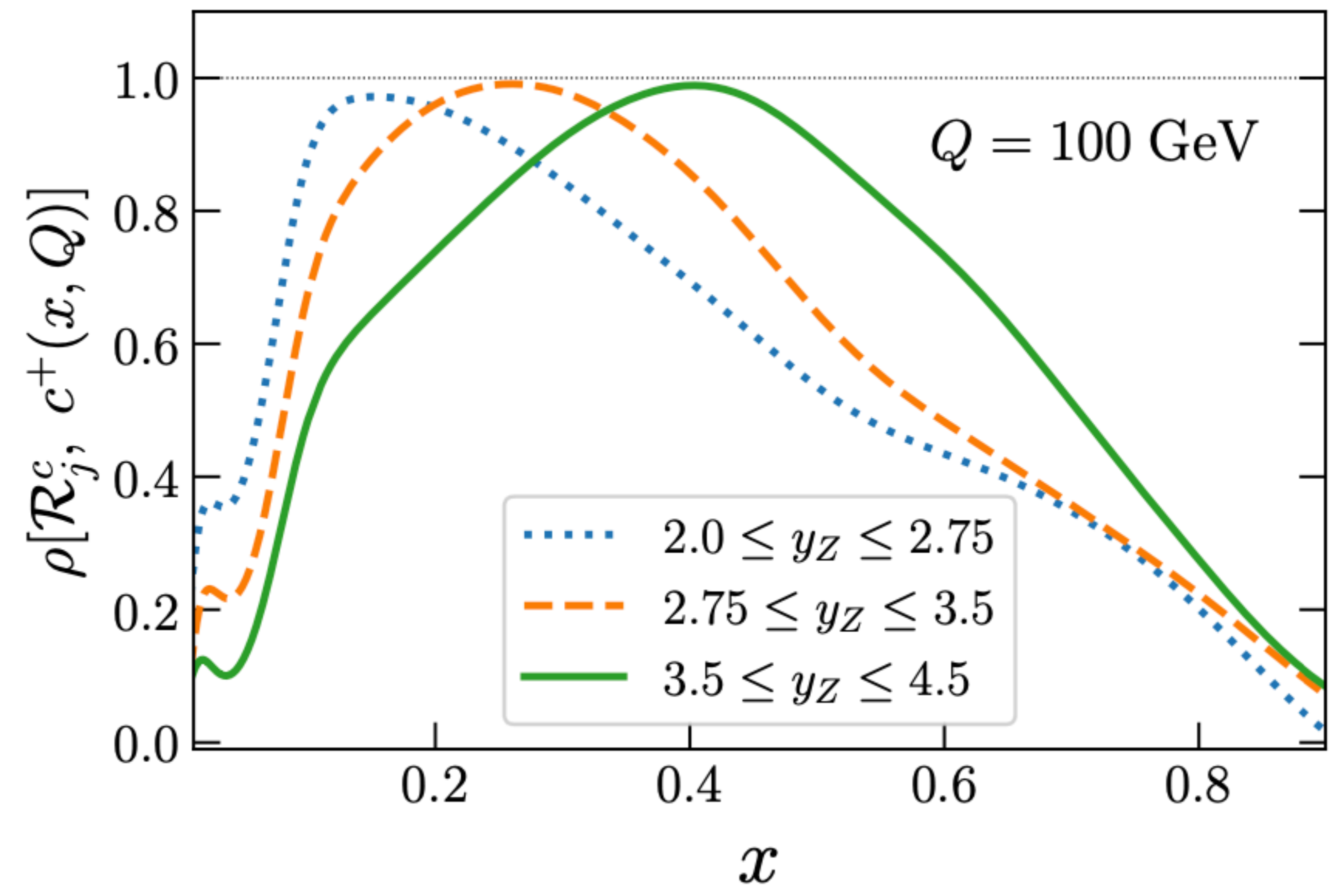
The 3FNS charm PDF displays **non-zero component** peaked at large-*x* **(3σ local significance)** identified with **intrinsic charm**

in excellent agreement with model predictions

Z+charm @ LHCb

Direct handle on the **charm content of the proton**

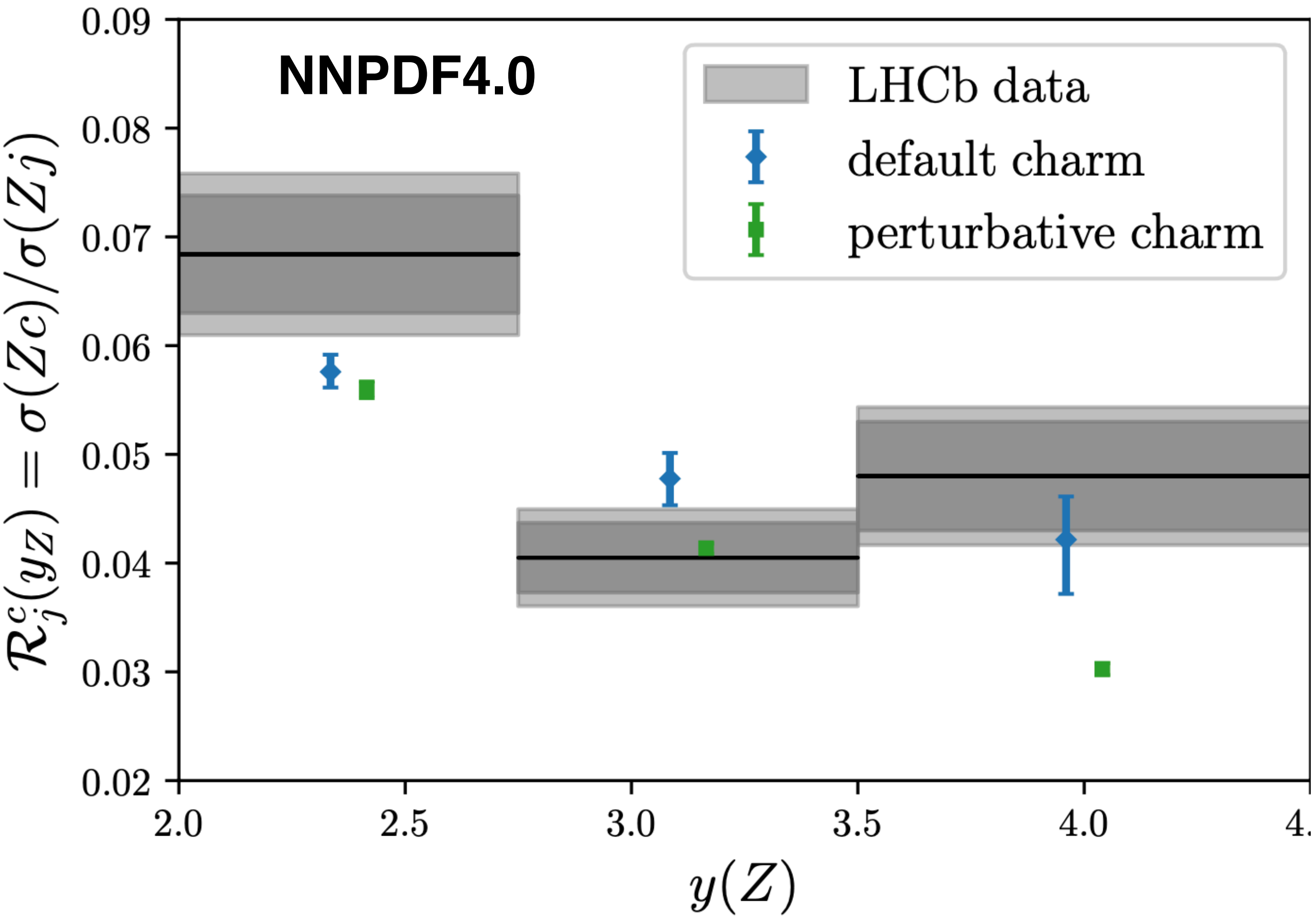


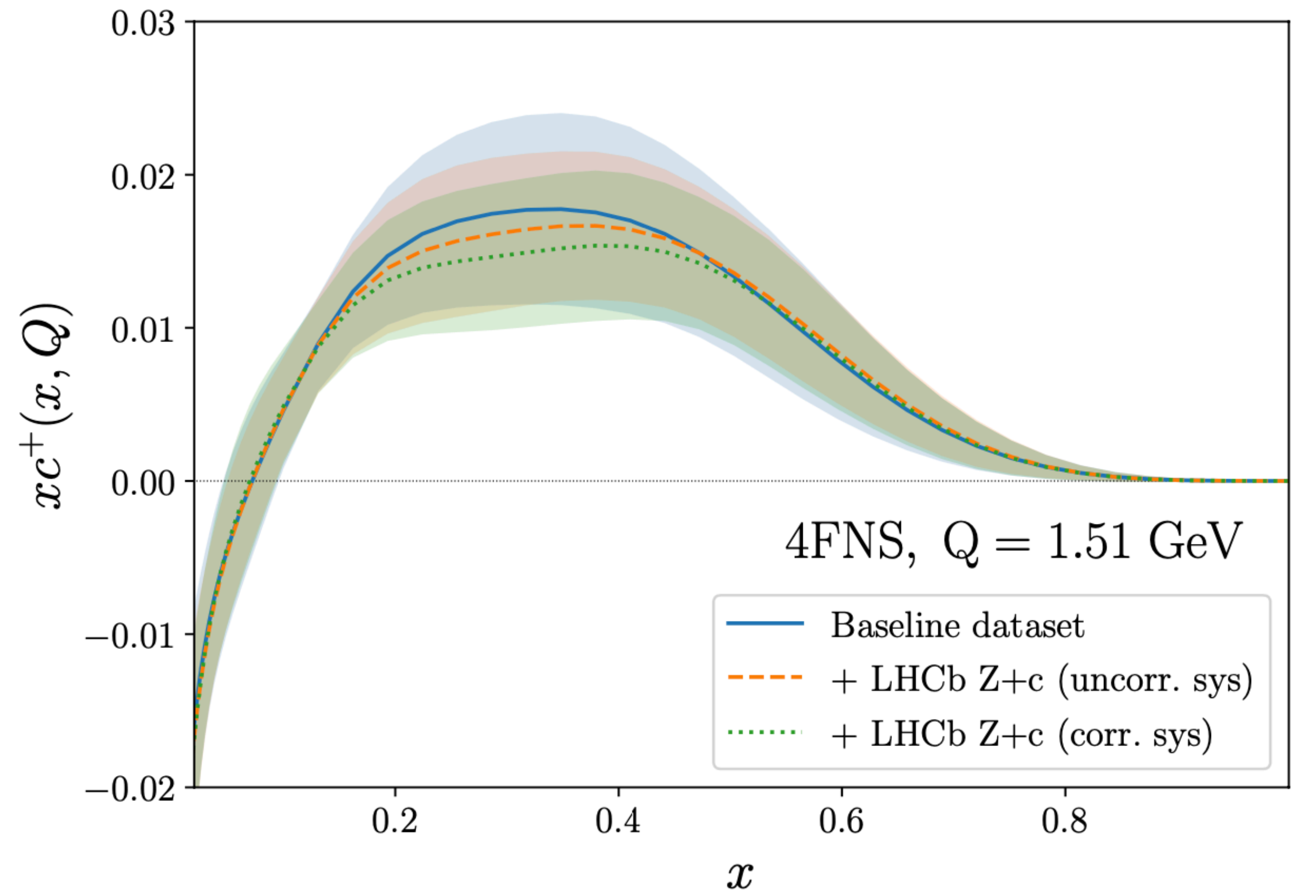


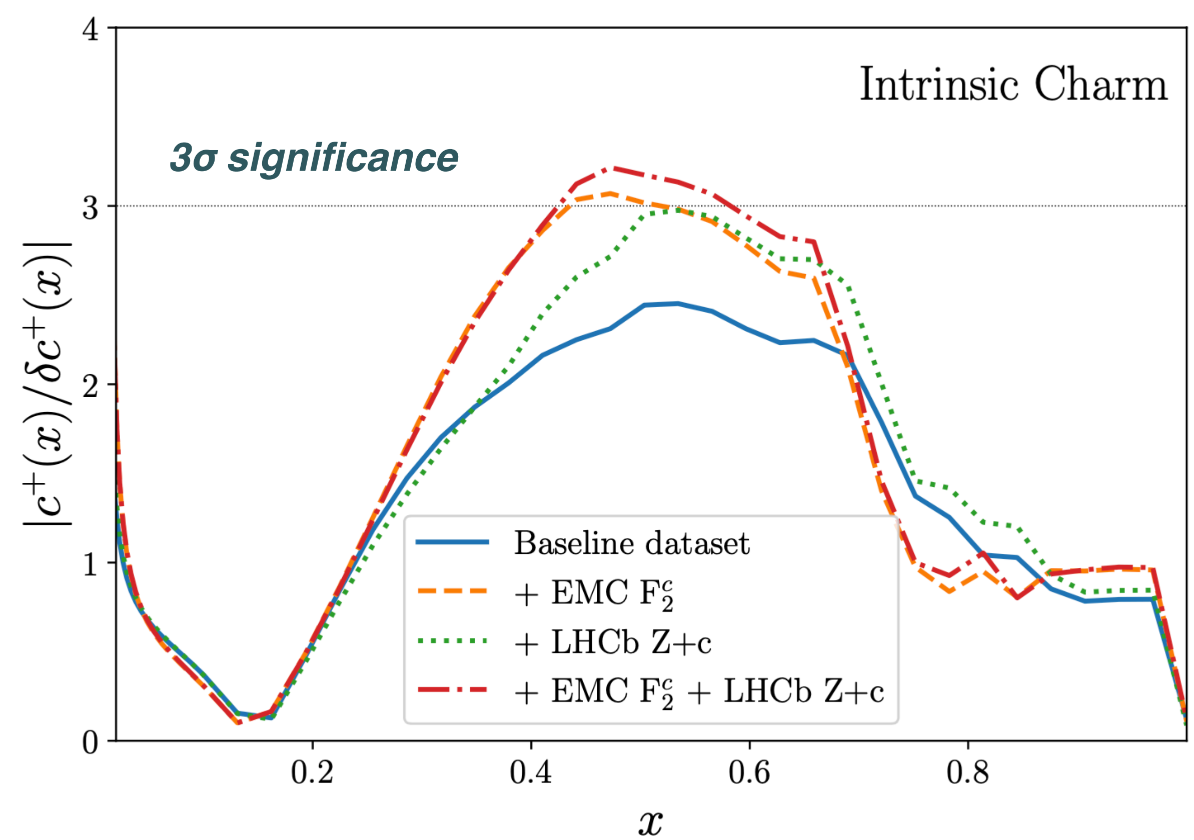
$$\mathcal{R}_j^c(y_Z) \equiv \frac{N(c \text{ tagged jets}; y_Z)}{N(\text{jets}; y_Z)} = \frac{\sigma(pp \to Z + \text{charm jet}; y_Z)}{\sigma(pp \to Z + \text{jet}; y_Z)}$$

Z+charm at forward rapidities (LHCb) sensitive to the **charm PDF up to *x*=0.5**

Z+charm @ LHCb







- A perturbative charm PDF **disagrees** with the LHCb forward Z+charm data
- LHCb data favour intrinsic charm hypothesis, with IC carrying **0.5% of proton's momentum**
- Striking consistency between **direct** (Z+c, F_2^c) **and indirect constraints** on the charm PDF

Parton Distributions: the Decade Ahead

Parton Distribution: the decade ahead

Progress in PDF determinations relies on three main pillars

Novel experimental constraints

Methodological developments

Precise theory calculations

Parton Distribution: the decade ahead

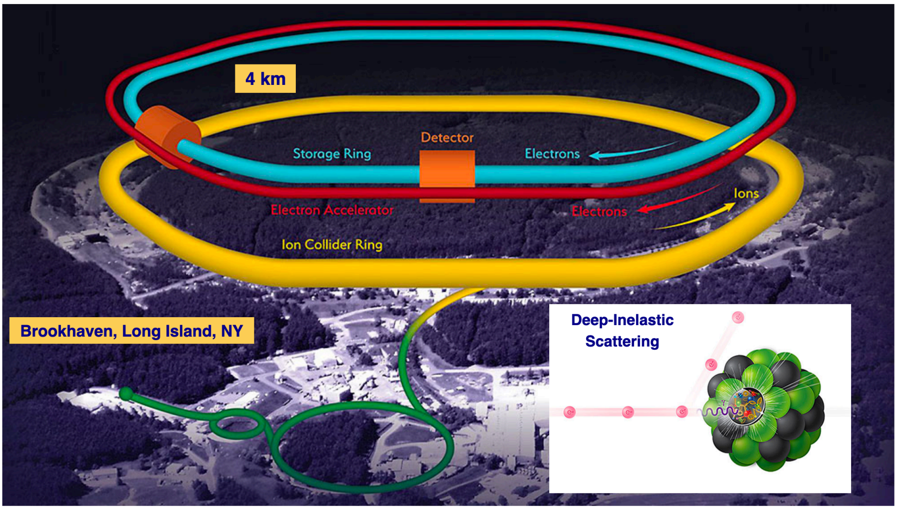
Progress in PDF determinations relies on three main pillars

Novel experimental constraints

Methodological developments

Precise theory calculations

- ☑ High-luminosity LHC
- ☑ Electron Ion Collider
- ☑ Forward Physics Facility



Parton Distribution: the decade ahead

Progress in PDF determinations relies on three main pillars

Novel experimental constraints

- ☑ High-luminosity LHC
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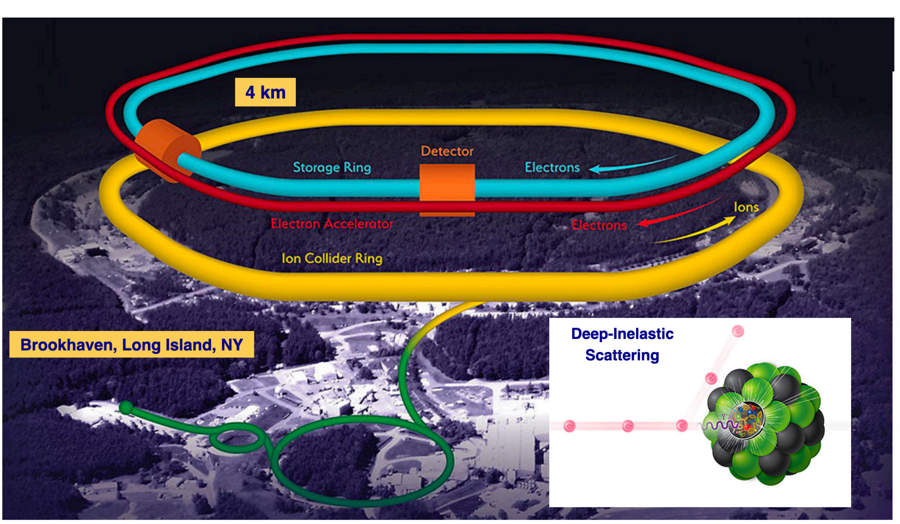
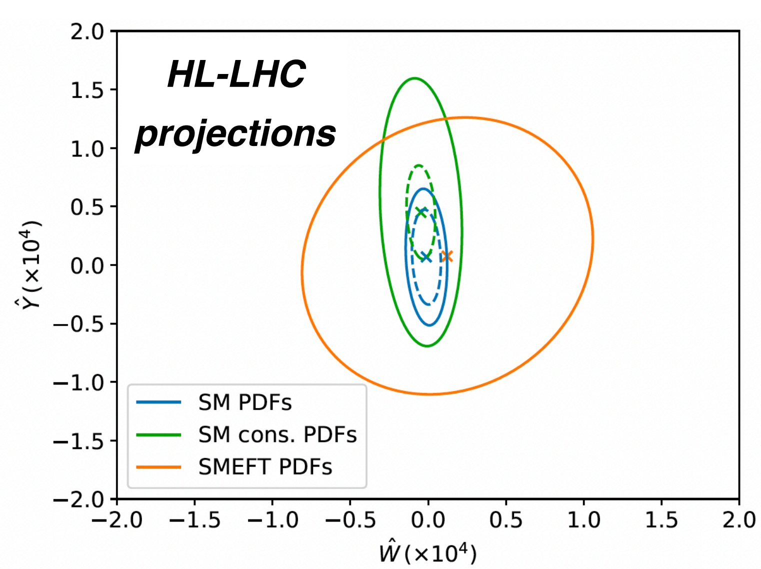


Methodological developments

- ☑ New ML techniques
- ☑ Improved fitting & statistical frameworks
- ☑ PDF & BSM joint fits
- ☑ Universal QCD fits



Precise theory calculations

Parton Distribution: the decade ahead

Progress in PDF determinations relies on three main pillars

Novel experimental constraints

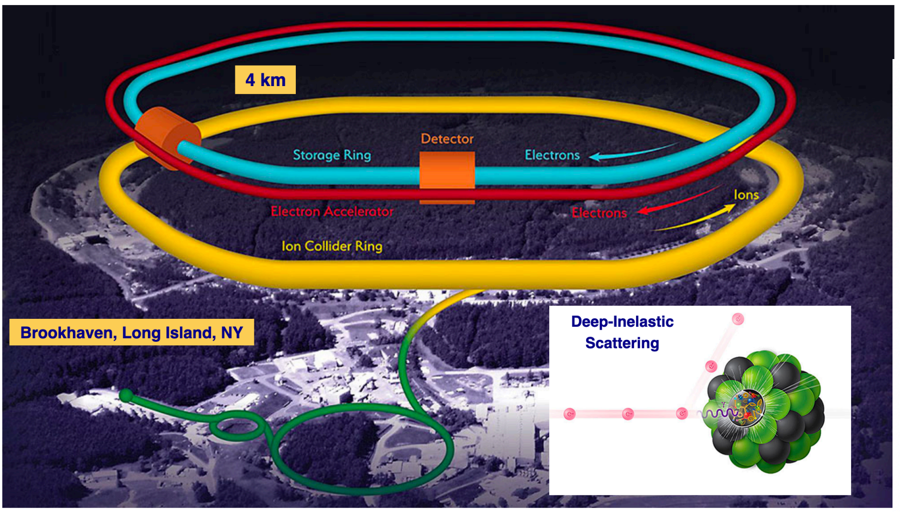
- High-luminosity LHC
- Electron Ion Collider
- Forward Physics Facility

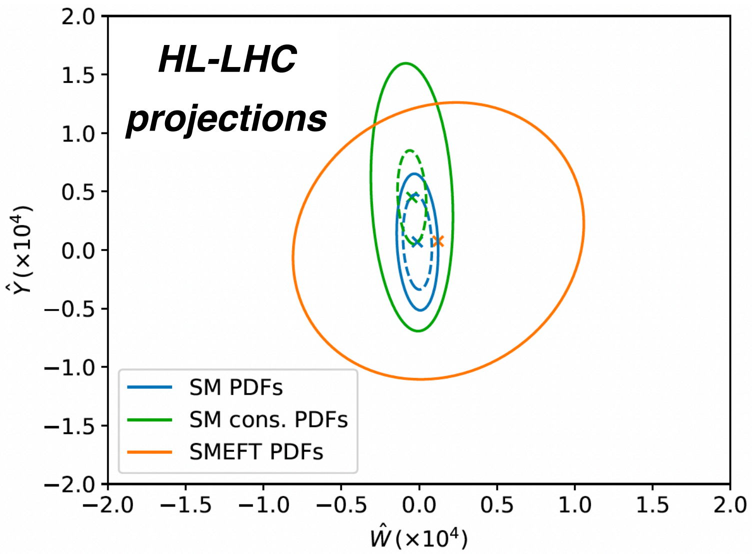
Methodological developments

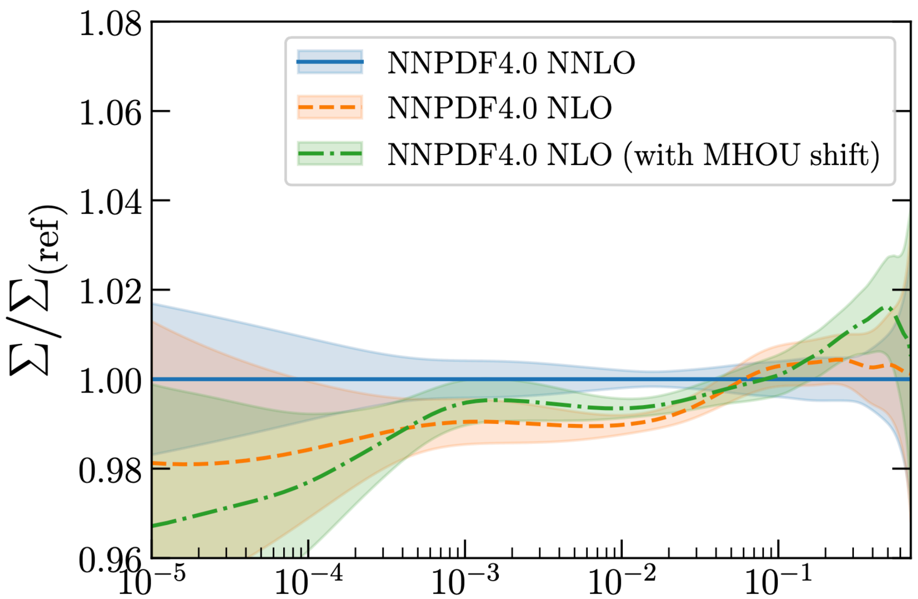
- New ML techniques
- Improved fitting & statistical frameworks
- PDF & BSM joint fits
- Universal QCD fits

Precise theory calculations

- N3LO PDFs
- Theory uncertainties
- PDFs with QED/EW

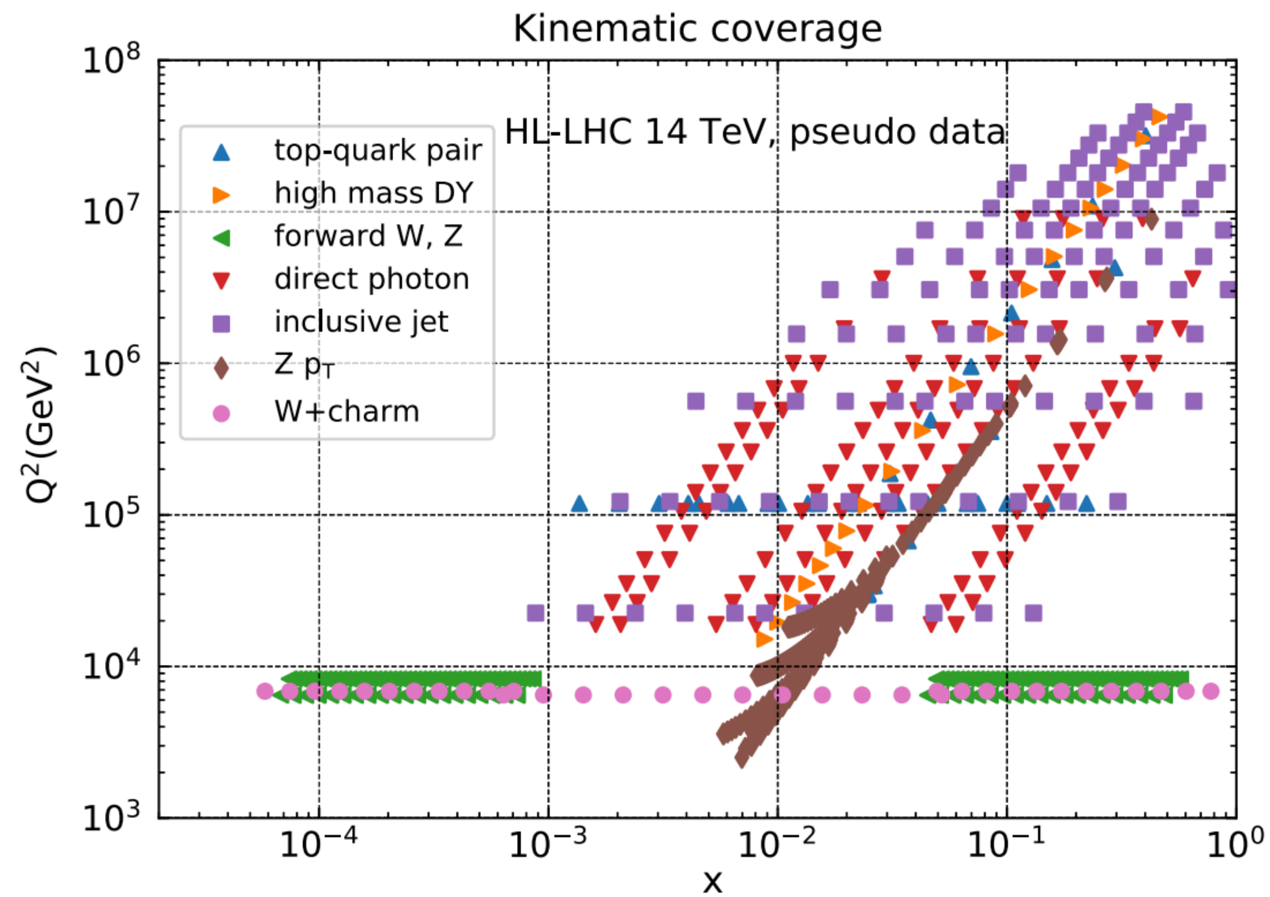






Towards ultimate PDFs at the HL-LHC

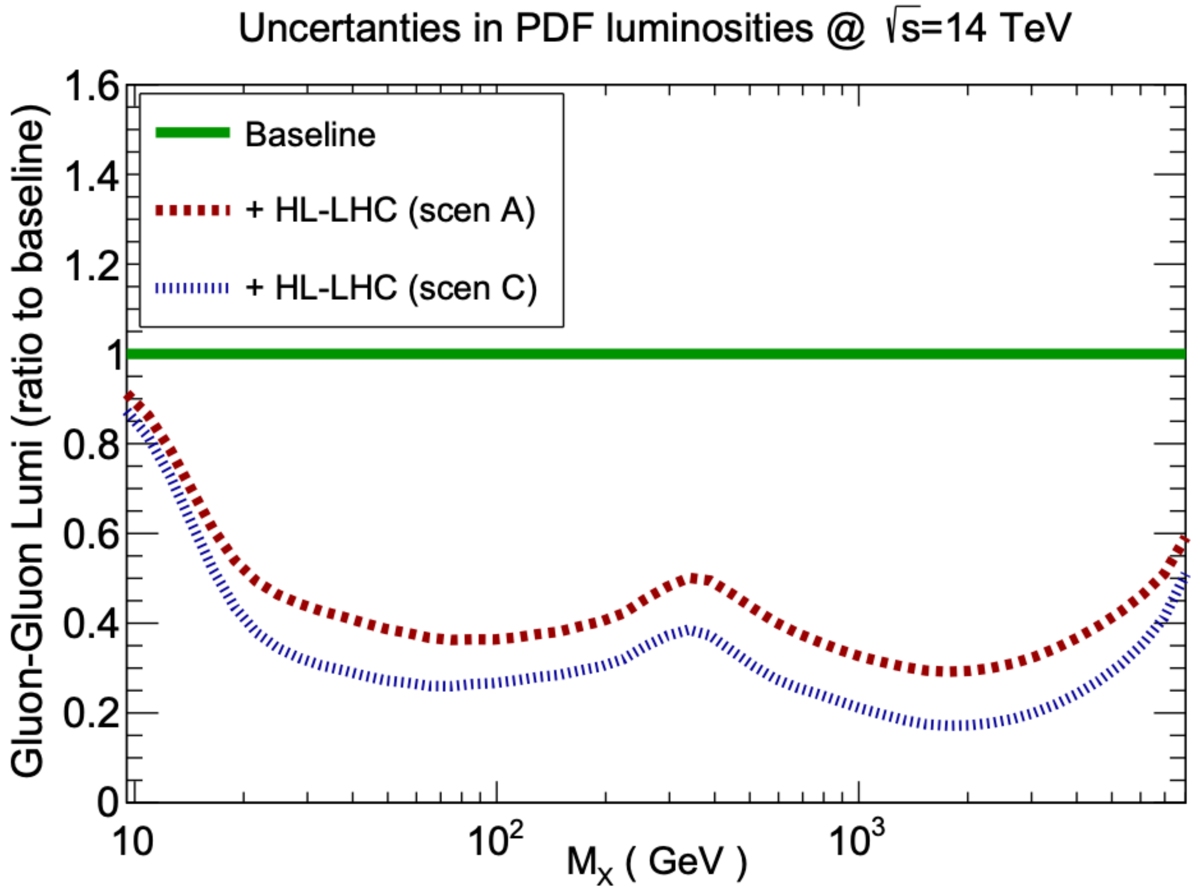
- Emphasis on processes sensitive to the **high-p$_T$ region** and not already limited by systematics
- Consider different scenarios (conservative & optimistic) for reduction of systematic errors at HL-LHC
- Quantify impact of HL-LHC data by means of the **Hessian profiling of PDF4LHC15** NNLO
- Assume ***L= 3 ab^{-1}*** for ATLAS and CMS and ***L= 0.3 ab^{-1}*** for LHCb

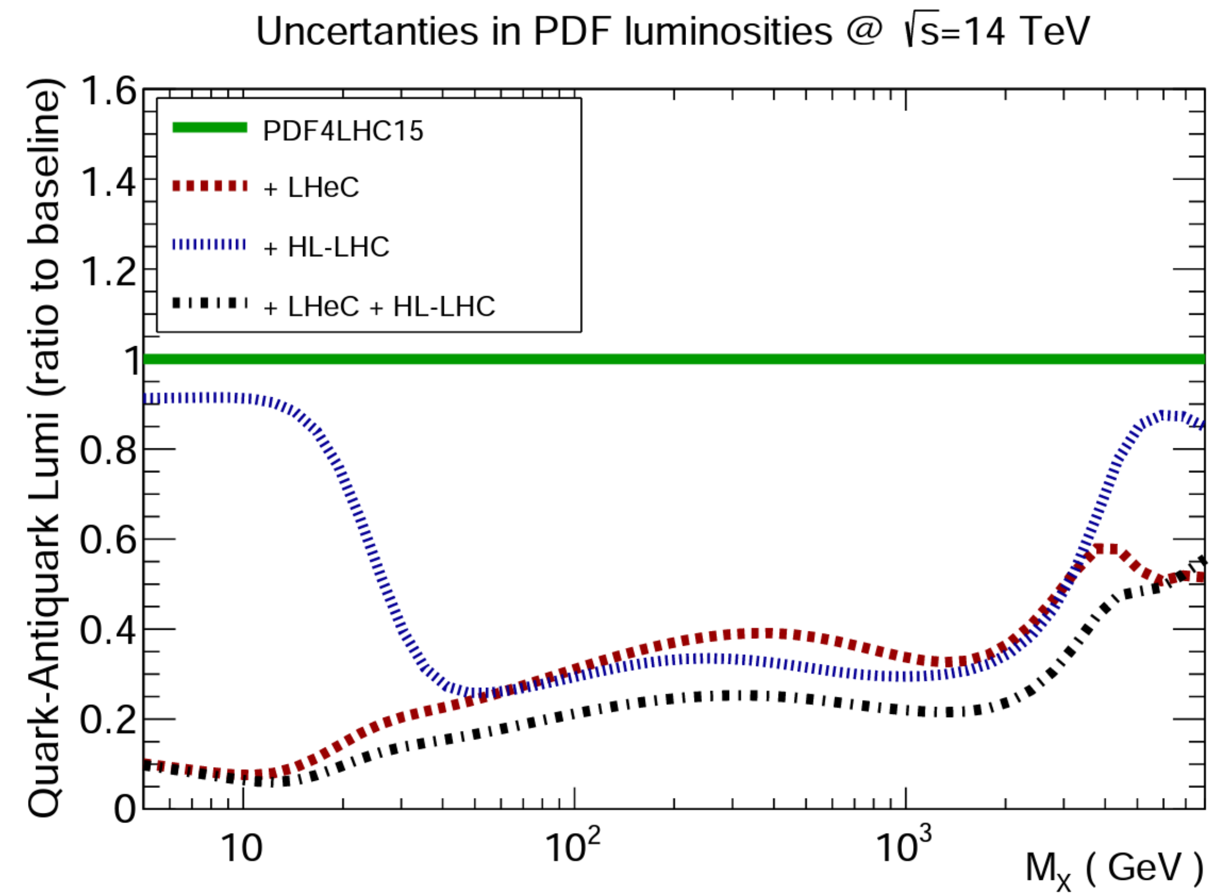


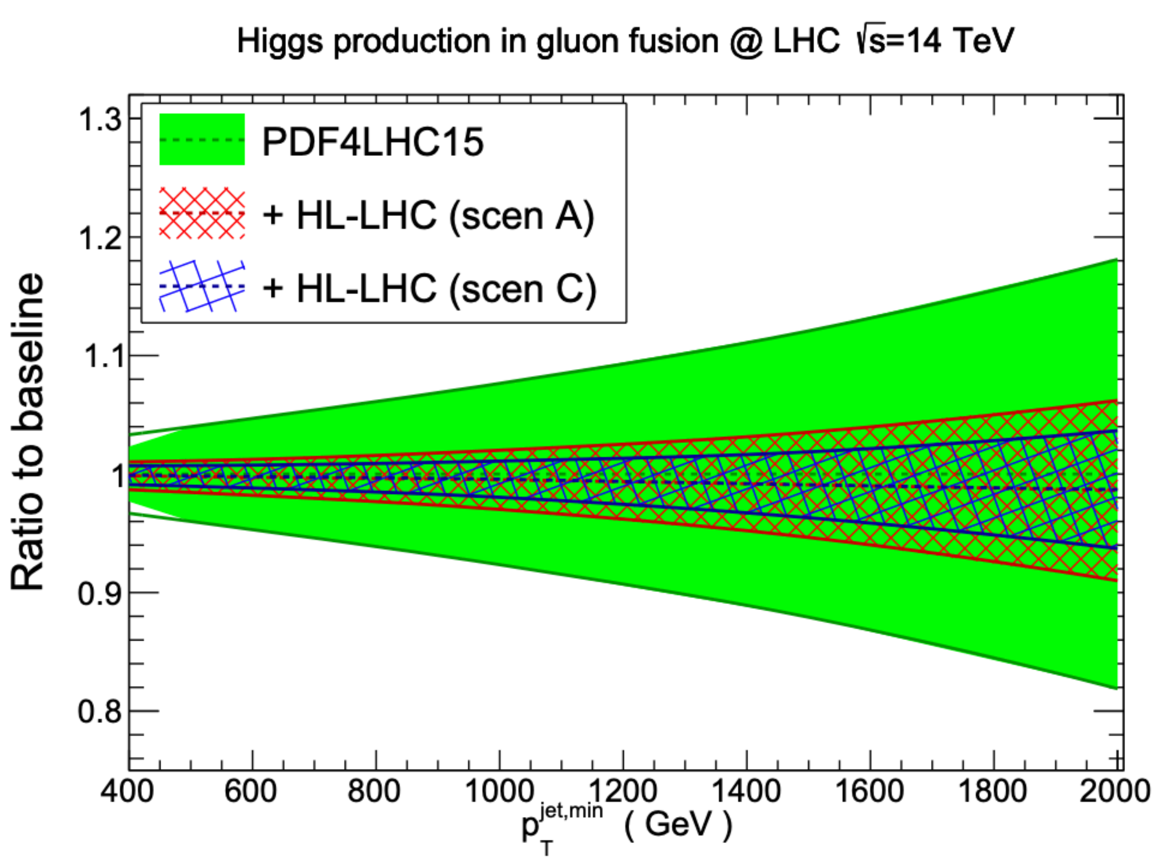
Process	Kinematics	$N_{\rm dat}$	$f_{\rm corr}$	$f_{\rm red}$	Baseline
$Z\ p_T$	$20\,\text{GeV} \le p_T^{ll} \le 3.5\,\text{TeV}$ $12\,\text{GeV} \le m_{ll} \le 150\,\text{GeV}$ $\lvert y_{ll}\rvert \le 2.4$	338	0.5	(0.4, 1)	[52] (8 TeV)
High-mass Drell-Yan	$p_T^{l1(2)} \ge 40(30)\,\text{GeV}$ $\lvert\eta^l\rvert \le 2.5,\ m_{ll} \ge 116\,\text{GeV}$	32	0.5	(0.4, 1)	[47] (8 TeV)
Top quark pair	$m_{t\bar{t}} \simeq 5\,\text{TeV},\ \lvert y_t\rvert \le 2.5$	110	0.5	(0.4, 1)	[50] (8 TeV)
W+charm (central)	$p_T^\mu \ge 26\,\text{GeV},\ p_T^c \ge 5\,\text{GeV}$ $\lvert\eta^\mu\rvert \le 2.4$	12	0.5	(0.2, 0.5)	[24] (13 TeV)
W+charm (forward)	$p_T^\mu \ge 20\,\text{GeV},\ p_T^c \ge 20\,\text{GeV}$ $p_T^{\mu+c} \ge 20\,\text{GeV}$ $2 \le \eta^\mu \le 4.5,\ 2.2 \le \eta^c \le 4.2$	10	0.5	(0.4, 1)	LHCb projection
Direct photon	$E_T^\gamma \lesssim 3\,\text{TeV},\ \lvert\eta_\gamma\rvert \le 2.5$	118	0.5	(0.2, 0.5)	[55] (13 TeV)
Forward W, Z	$p_T^l \ge 20\,\text{GeV},\ 2.0 \le \eta^l \le 4.5$ $60\,\text{GeV} \le m_{ll} \le 120\,\text{GeV}$	90	0.5	(0.4, 1)	[49] (8 TeV)
Inclusive jets	$\lvert y\rvert \le 3,\ R = 0.4$	58	0.5	(0.2, 0.5)	[61] (13 TeV)
Total		768			

Gao et al (18, 19)

Towards ultimate PDFs at the HL-LHC







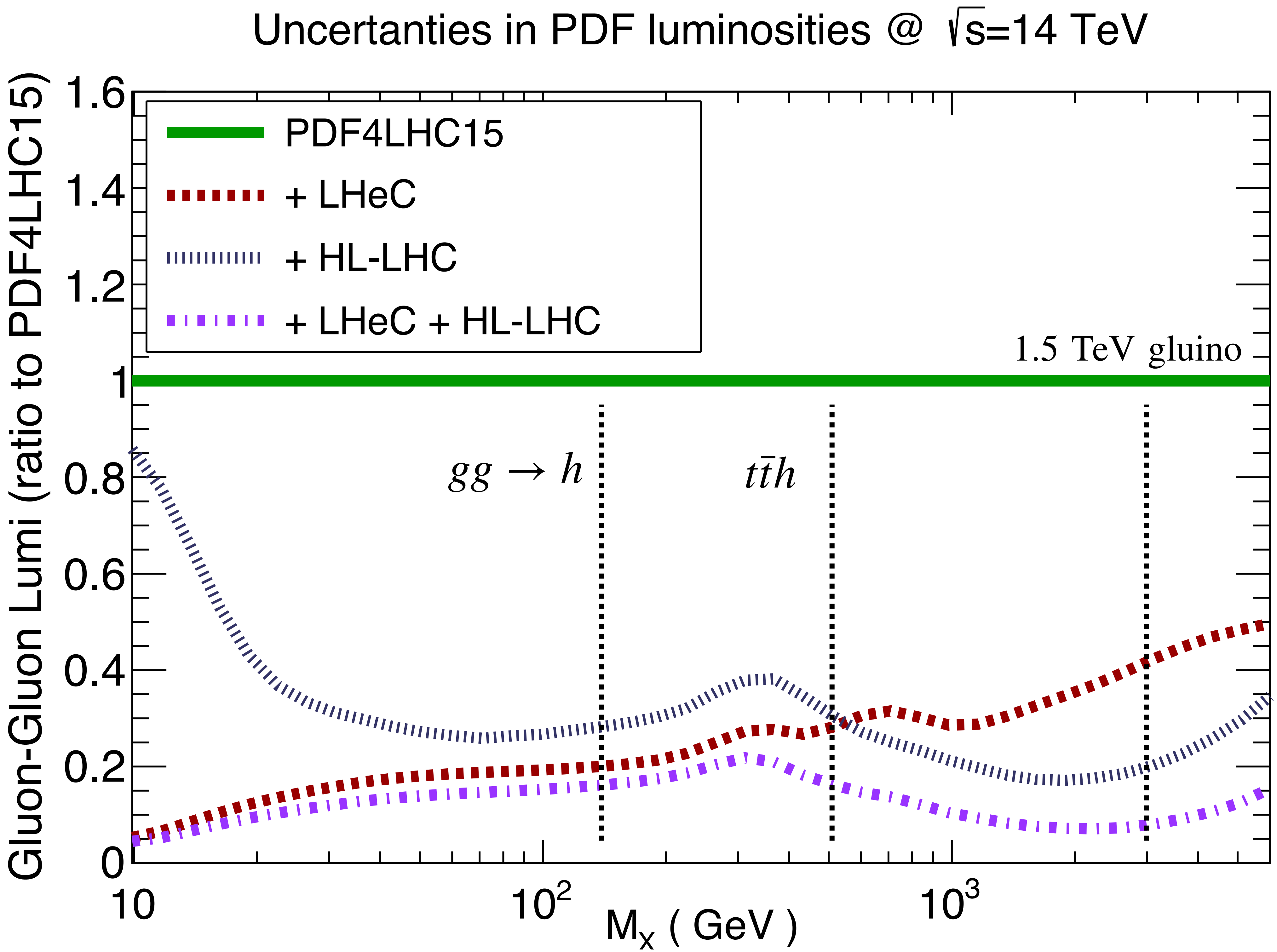
- ☑ Dedicated projections for the **HL-LHC Yellow Reports** highlight plenty of room for PDF improvements from future LHC data

- ☑ These projections account only for ``standard" processes for PDF constraints (e.g. DY, top, jets): one could do better by thinking outside the box!

- ☑ Crucial to account for **theory uncertainties**, *e.g.* MHOUs, when interpreting future LHC measurements

Towards ultimate PDFs at the HL-LHC

Compare the effects of the adding separately **LHeC and HL-LHC** to PDF4LHC15



Can New Physics hide inside the proton?

``How can you be sure you are not reabsorbing BSM physics into your PDFs?"

perhaps most frequent question I am asked in talks!

Assuming the **SM**, the theory calculations that enter a global PDF fit are:

$$\sigma_{\rm LHC}(\boldsymbol{\theta}) \propto \sum_{ij=u,d,g,\ldots} \int_{M^2}^{s} d\hat{s}\; \underbrace{\mathscr{L}_{ij}(\hat{s}, s, \boldsymbol{\theta})}_{\text{SM PDFs}}\; \widetilde{\sigma}_{{\rm SM},ij}(\hat{s}, \alpha_s(M))$$

However in the case of BSM physics, here parametrised by the **SMEFT,** the correct expression is:

$$\sigma_{\rm LHC}\left(\boldsymbol{c}, \Lambda, \boldsymbol{\theta}\right) \simeq \left(\int_{M^2}^{s} d\hat{s}\; \overbrace{\mathscr{L}_{ij}(\hat{s}, s, \boldsymbol{\theta})}^{\text{SMEFT PDFs}}\; \widetilde{\sigma}_{{\rm SM},ij}(\hat{s}, \alpha_s(M)) \right) \times \left(1 + \sum_{m=1}^{N_6} c_m \frac{\kappa_m}{\Lambda^2} + \sum_{m,n=1}^{N_6} c_m c_n \frac{\kappa_{mn}}{\Lambda^4} \right),$$

PDF parameters

SMEFT coefficients

How different are ``SM PDFs" & ``SMEFT PDFs"? Can we quantify the risk of **fitting away BSM** in PDFs?

Can New Physics hide inside the proton?

Exp.	$\sqrt{s}$ (TeV)	Ref.	$\mathcal{L}$ (fb^{-1})	Channel	1D/2D	$n_{\rm dat}$	$m_{\ell\ell}^{\rm max}$ (TeV)
ATLAS	7	[120]	4.9	e^-e^+	1D	13	[1.0, 1.5]
ATLAS (*)	8	[86]	20.3	$\ell^-\ell^+$	2D	46	[0.5, 1.5]
CMS	7	[121]	9.3	$\mu^-\mu^+$	2D	127	[0.2, 1.5]
CMS (*)	8	[87]	19.7	$\ell^-\ell^+$	1D	41	[1.5, 2.0]
CMS (*)	13	[122]	5.1	e^-e^+, $\mu^-\mu^+$ $\ell^-\ell^+$	1D	43, 43 43	[1.5, 3.0]
Total						**270 (313)**	

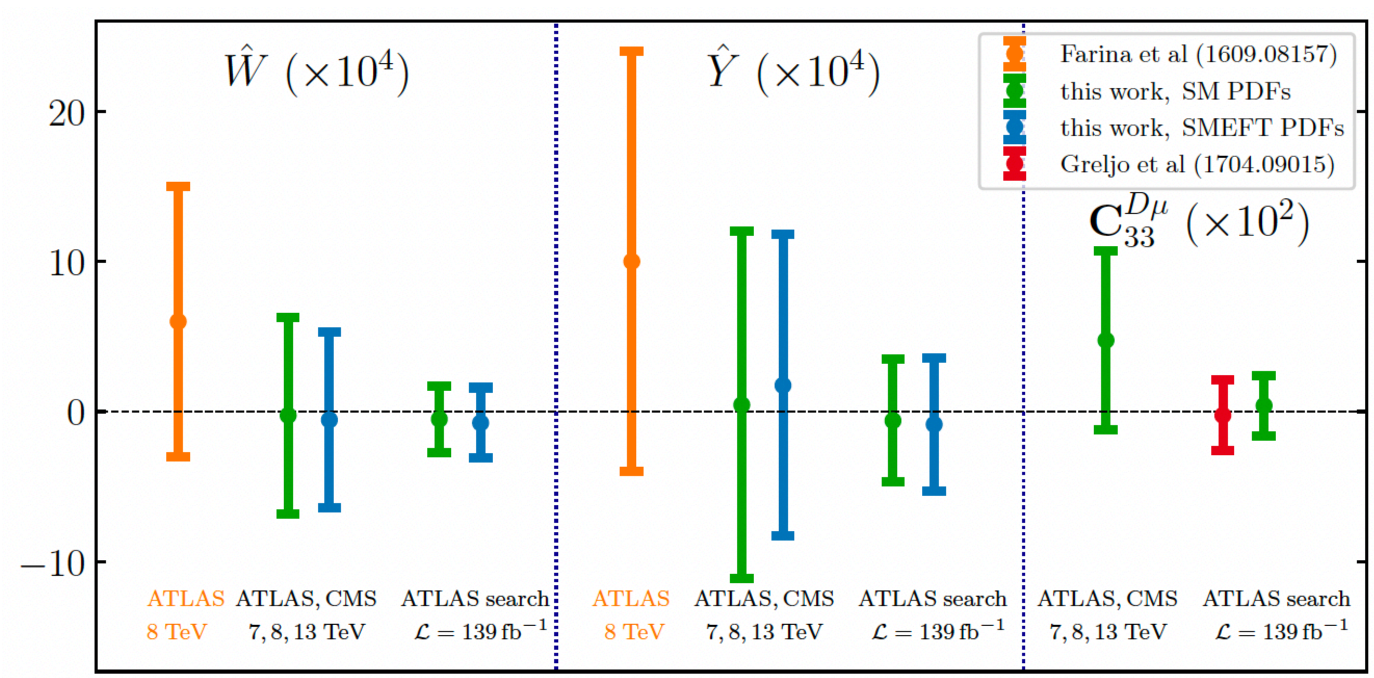
Extract PDFs from global fit where **high-mass DY cross-sections** account for EFT effects in two benchmark scenarios

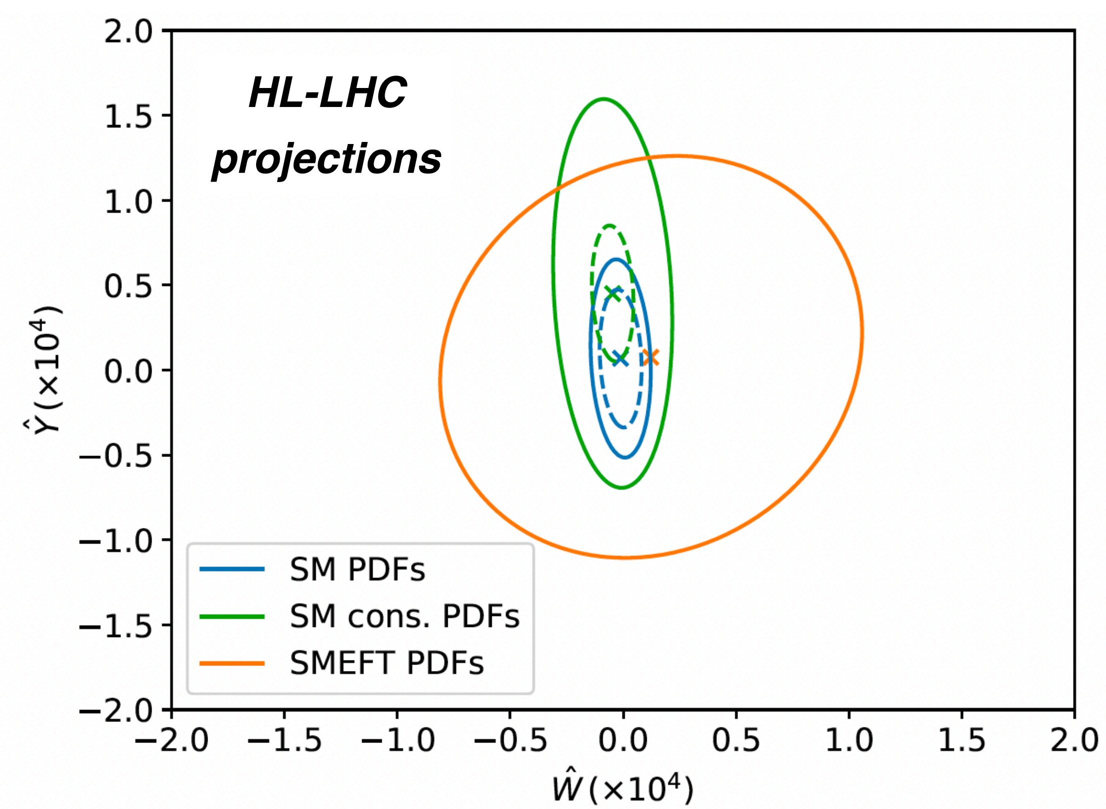
$$d\sigma_{\rm SMEFT} = d\sigma_{\rm SM} \times K_{\rm EFT}$$

$$K_{\rm EFT} = 1 + \sum_{n=1}^{n_{\rm op}} c_n R^{(n)}_{\rm SMEFT} + \sum_{n,m=1}^{n_{\rm op}} c_n c_m R^{(n,m)}_{\rm SMEFT}$$

Available data: limited interplay between PDF and EFT fits, best constraints from **searches**

HL-LHC: EFT effects, if present, would be **reabsorbed into PDFs**

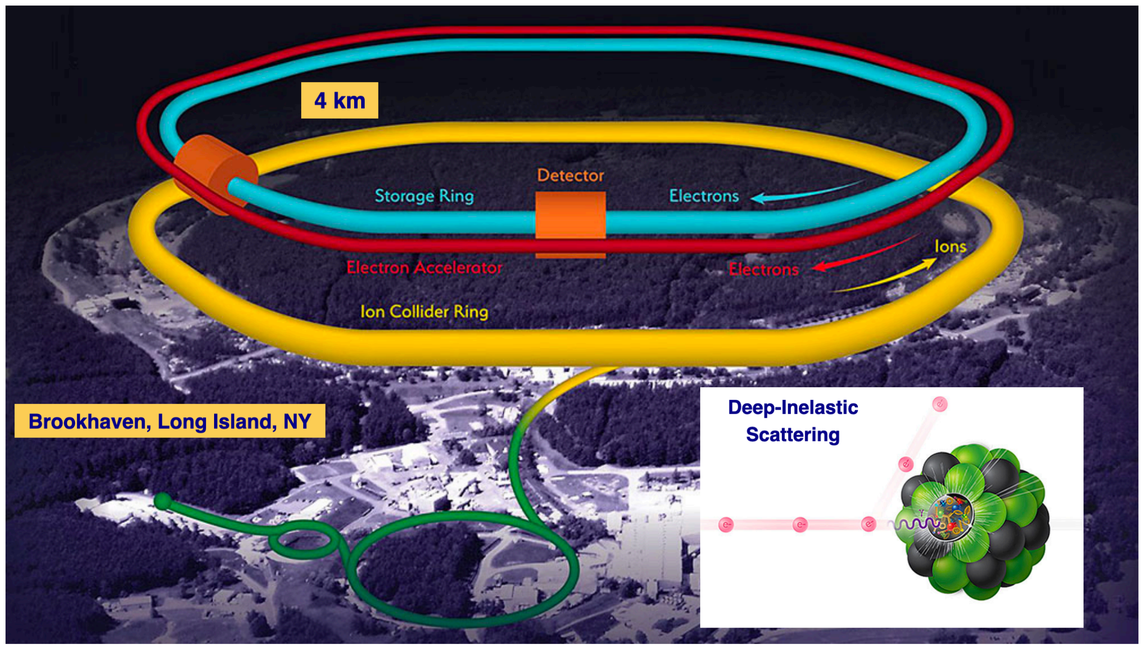


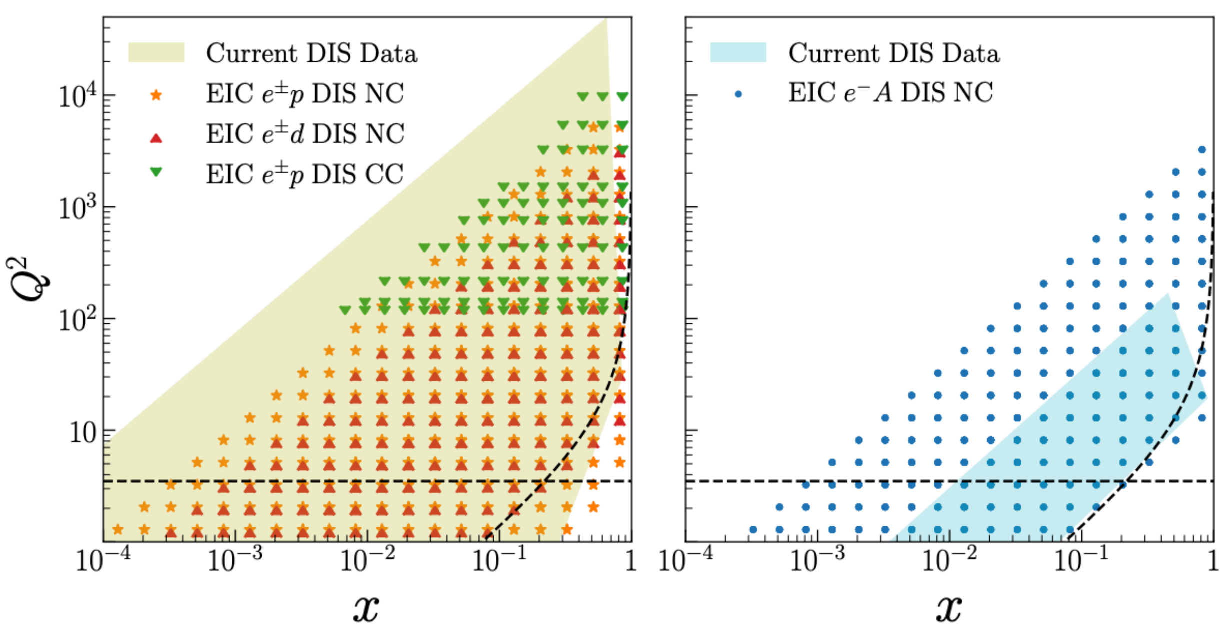


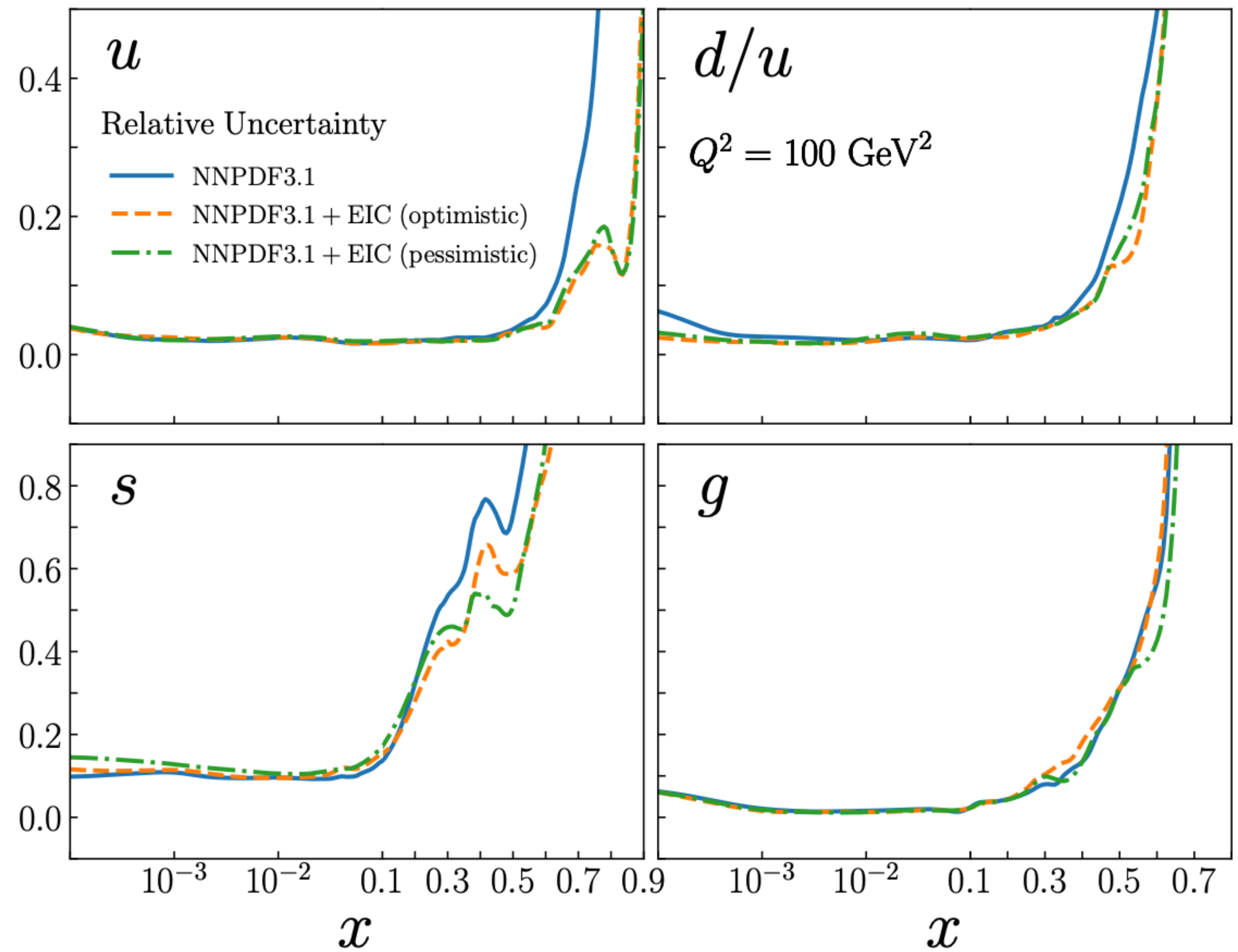
Carrazza et al 19, Greljo et al 21

Proton structure the Electron-Ion Collider

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





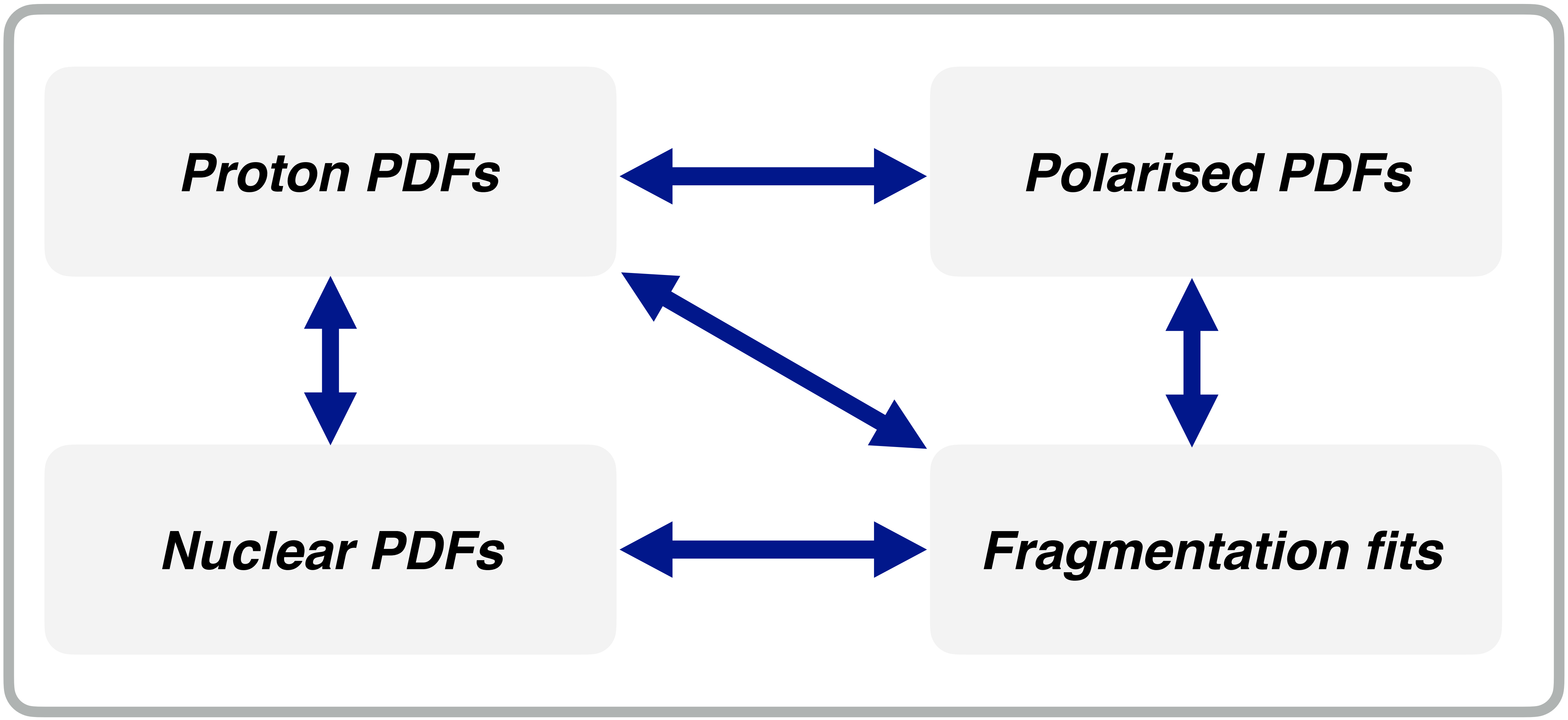


Abdul-Khalek et al (2021), EIC Yellow Report (2021)

Simultaneous extraction of PDFs, polarised PDFs, nuclear PDFs, and fragmentation functions becomes possible (actually, **required**) at the EIC

Universal QCD fits

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

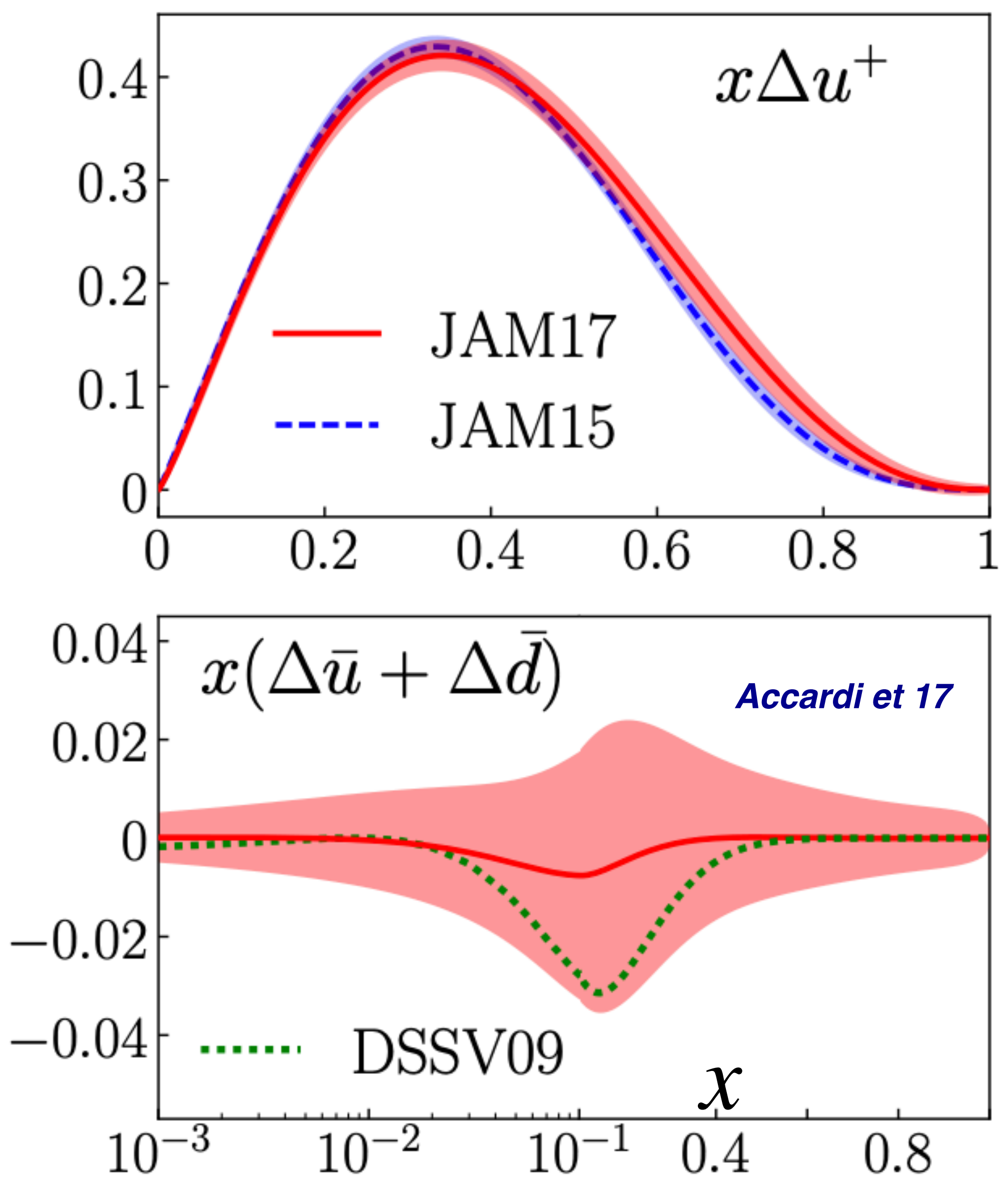


*Towards **universal/integrated global analyses** of non-perturbative QCD*

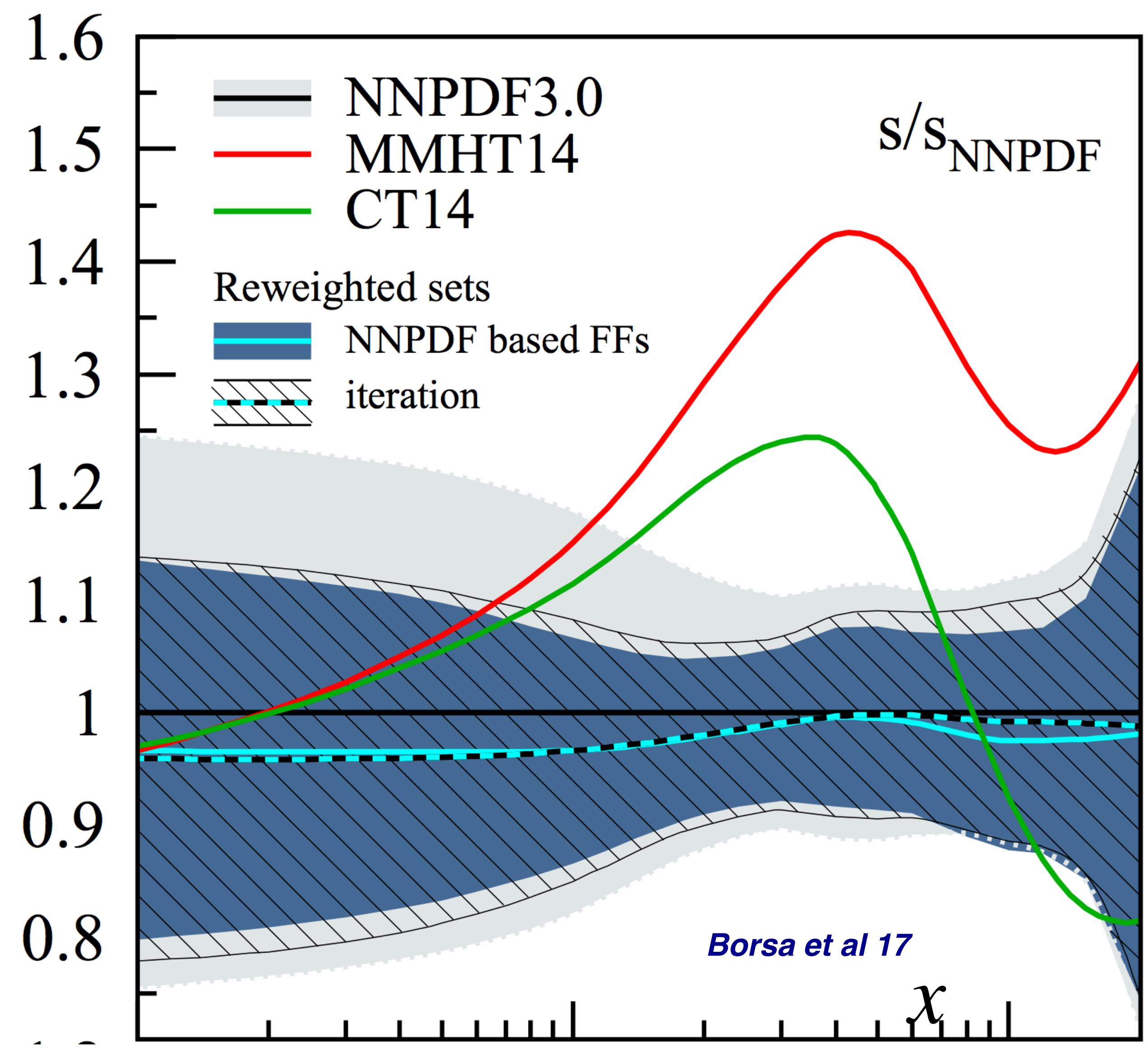
Universal QCD fits

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

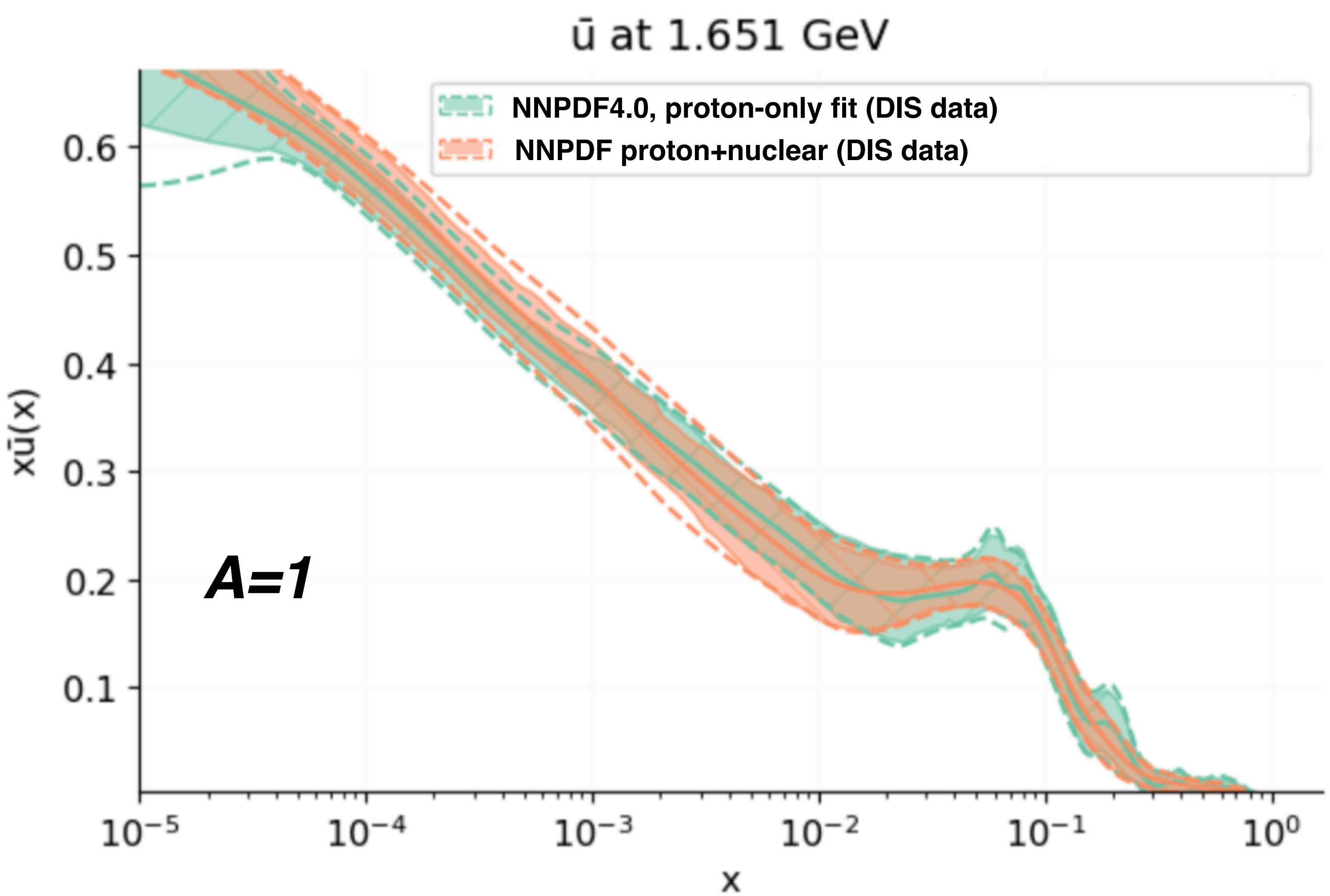
Polarised PDFs + FFs



Unpolarised PDFs + FFs

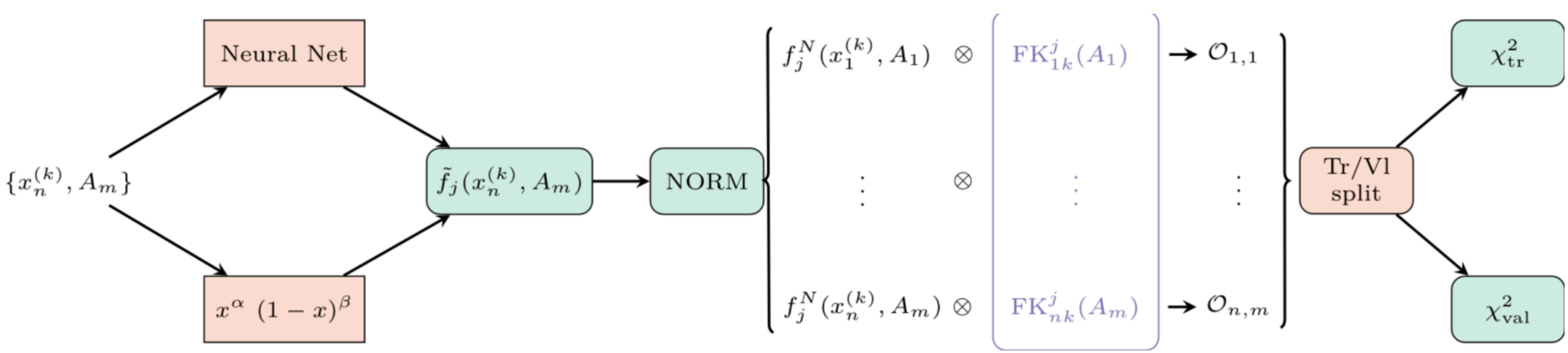


Universal QCD fits



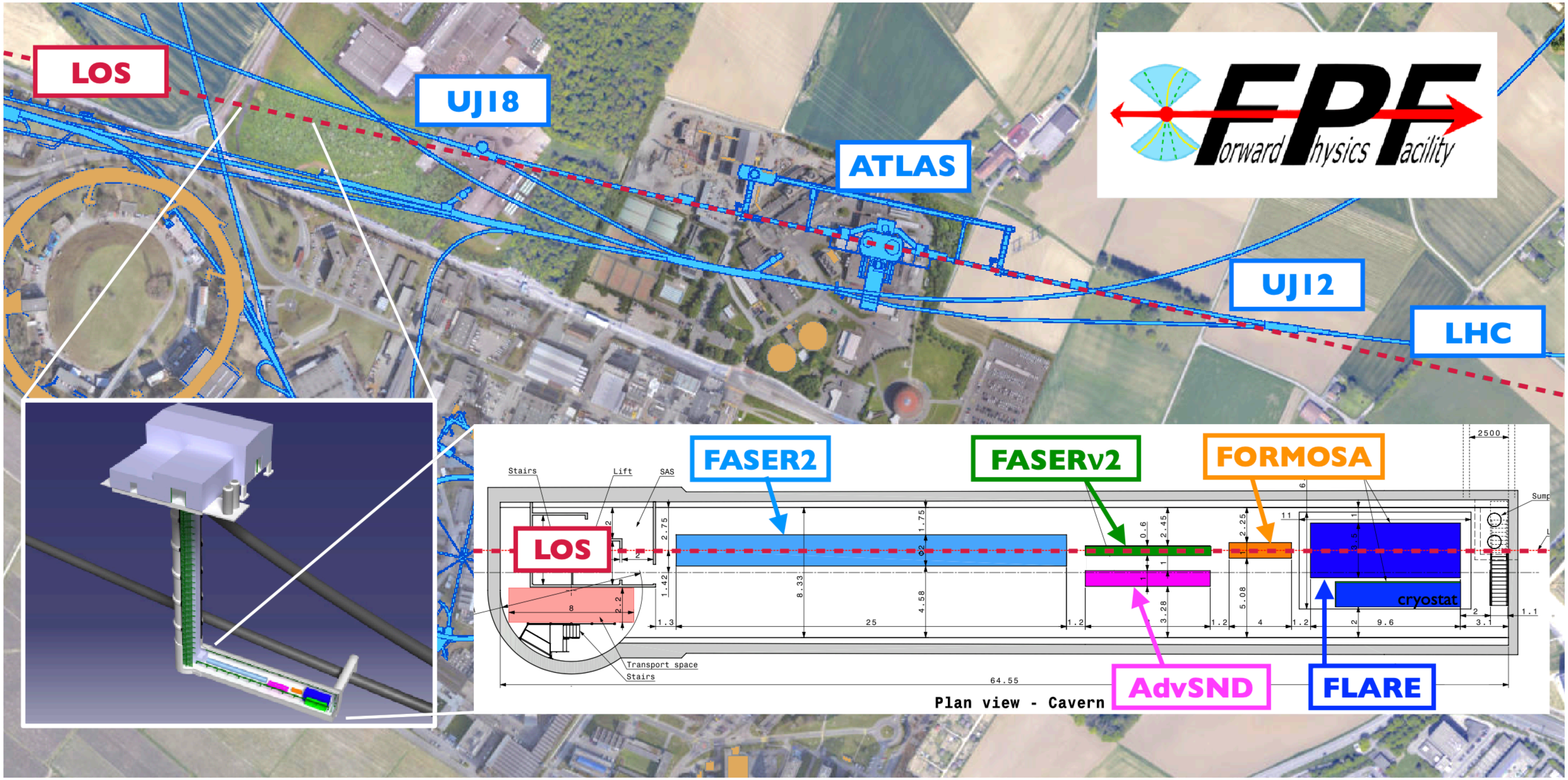
- Ongoing work towards the integration of nuclear PDF fits (nNNPDF3.0) into the NNPDF4.0 framework
- Goal: joint extraction of **PDFs from *A=1* to *A=208***
- Eventually to be extended to polarised PDFs and to FFs

Nocera, Rabemananjara, Rojo, in progress



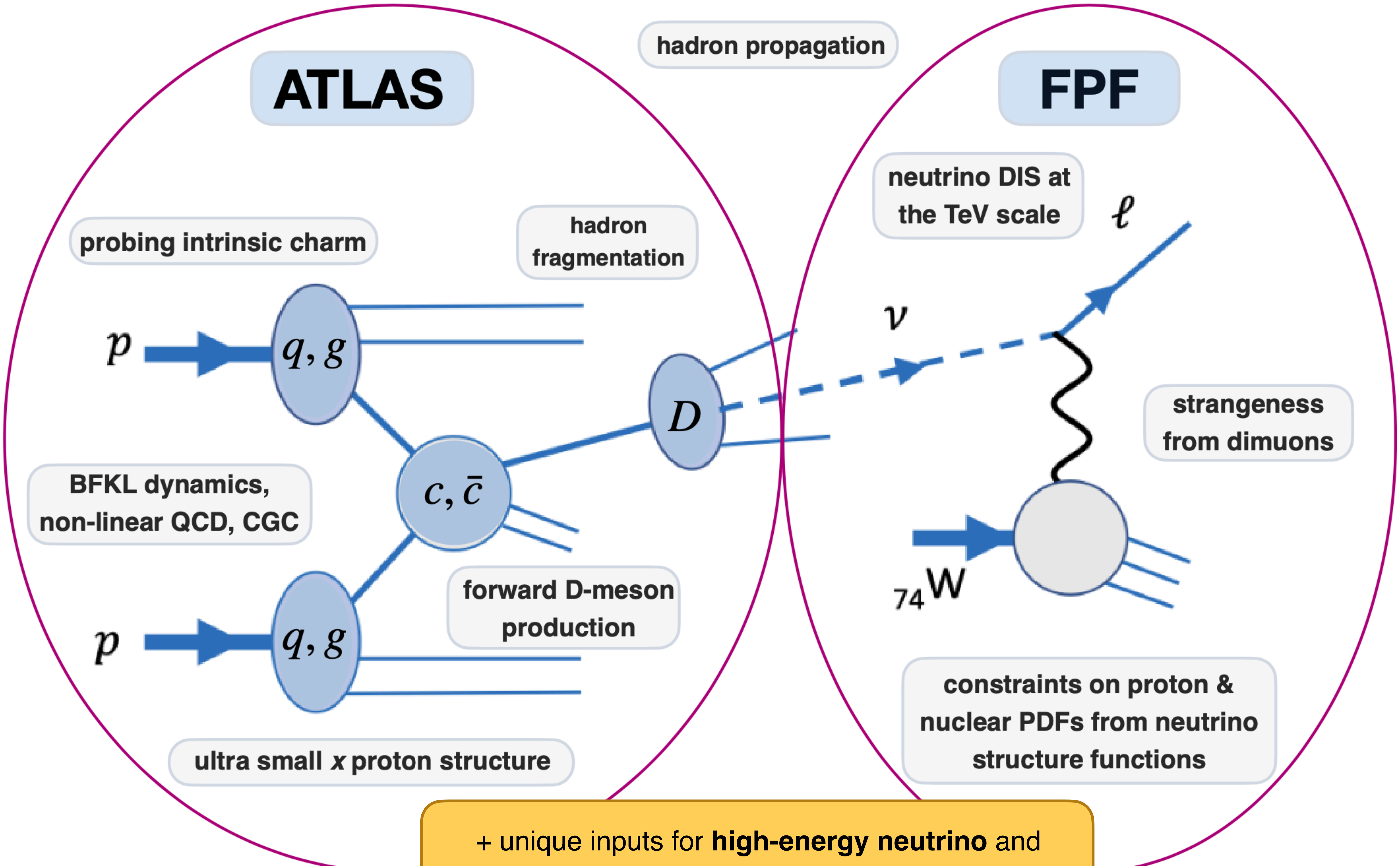
The Forward Physics Facility

A proposed new facility in a tailor-made underground cavern hosting a suite of **far-forward experiments** suitable to detect **long-lived BSM particles** and **neutrinos** produced at the **High-Luminosity LHC** (ATLAS interaction point)



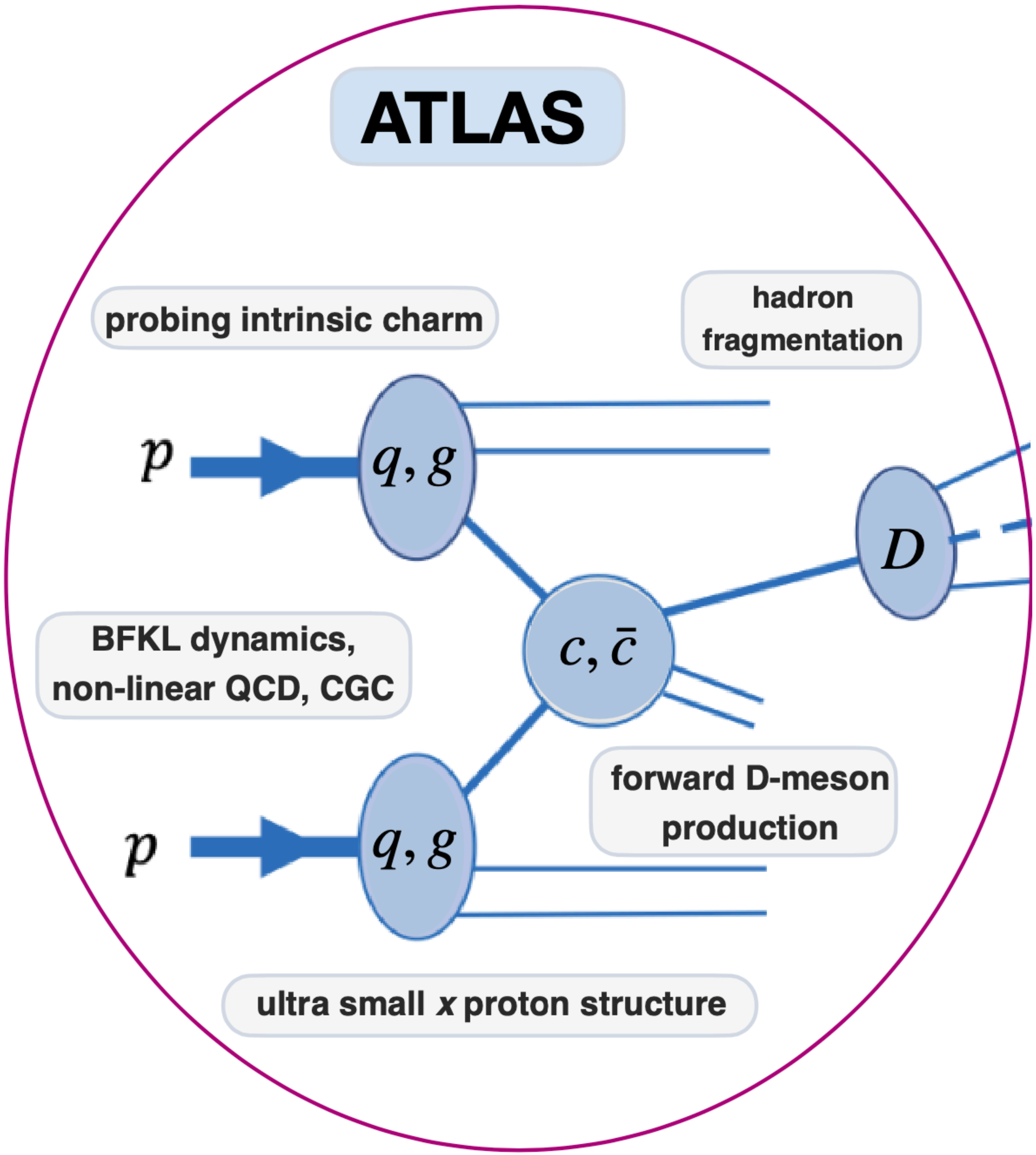
No modifications to the HL-LHC operations required!

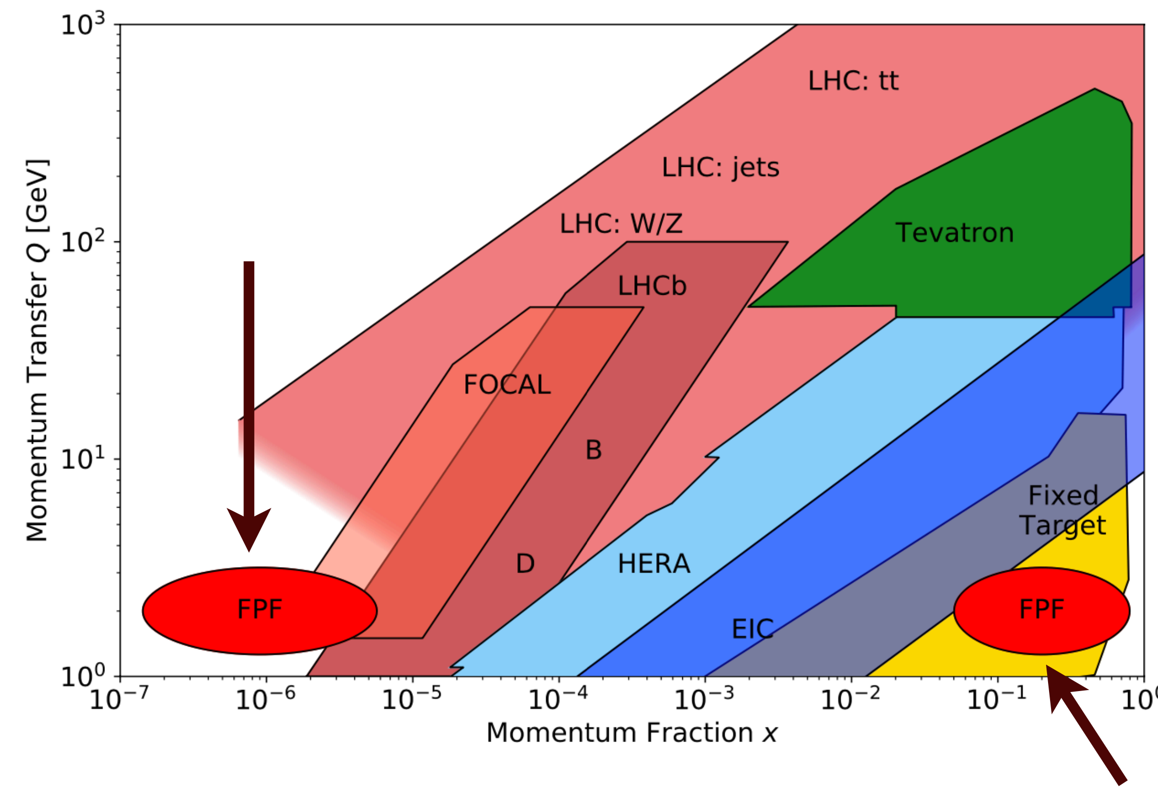
QCD at the FPF



+ unique inputs for **high-energy neutrino** and **cosmic ray** astroparticle physics experiments

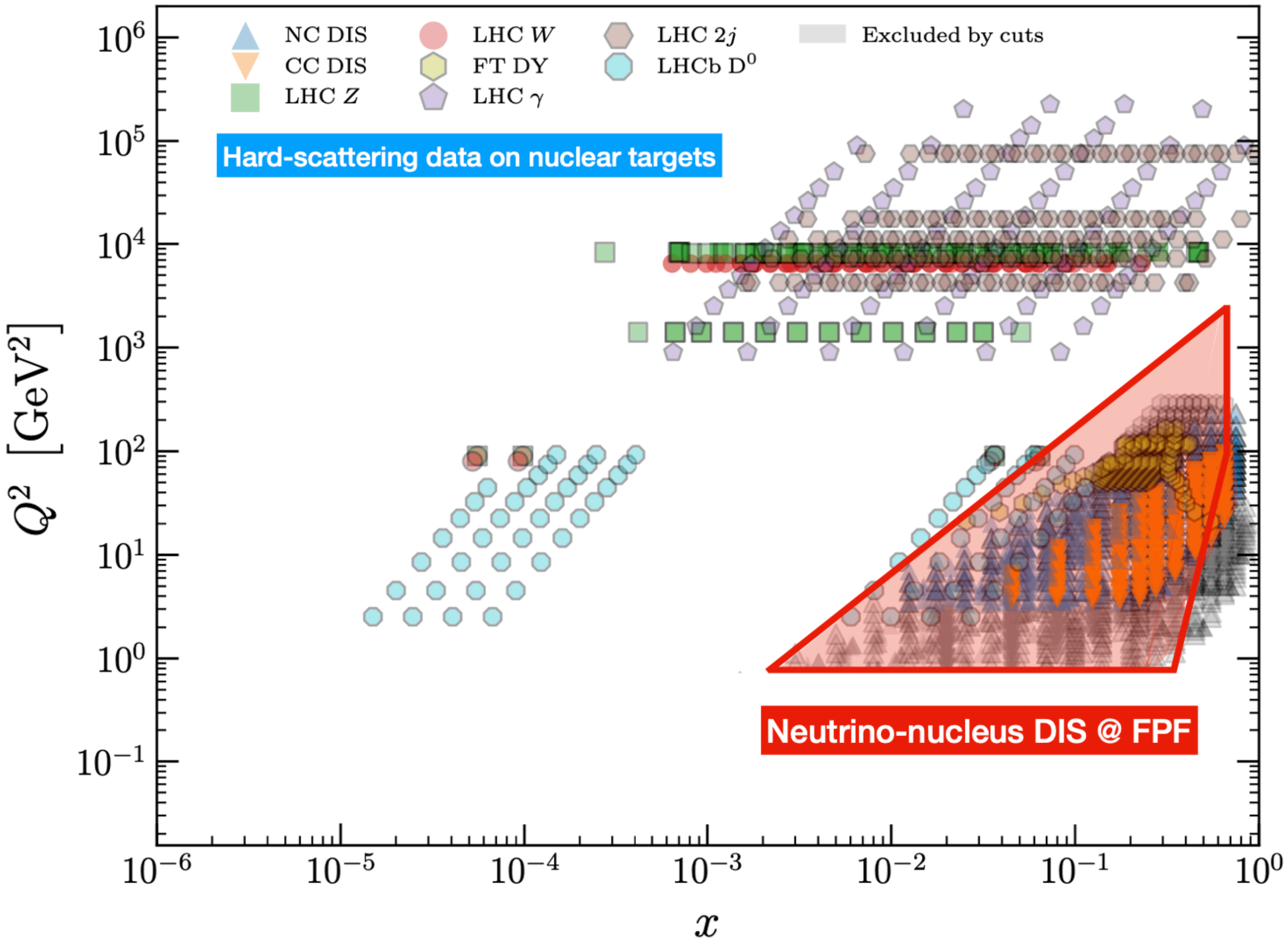
QCD at the FPF (neutrino production)



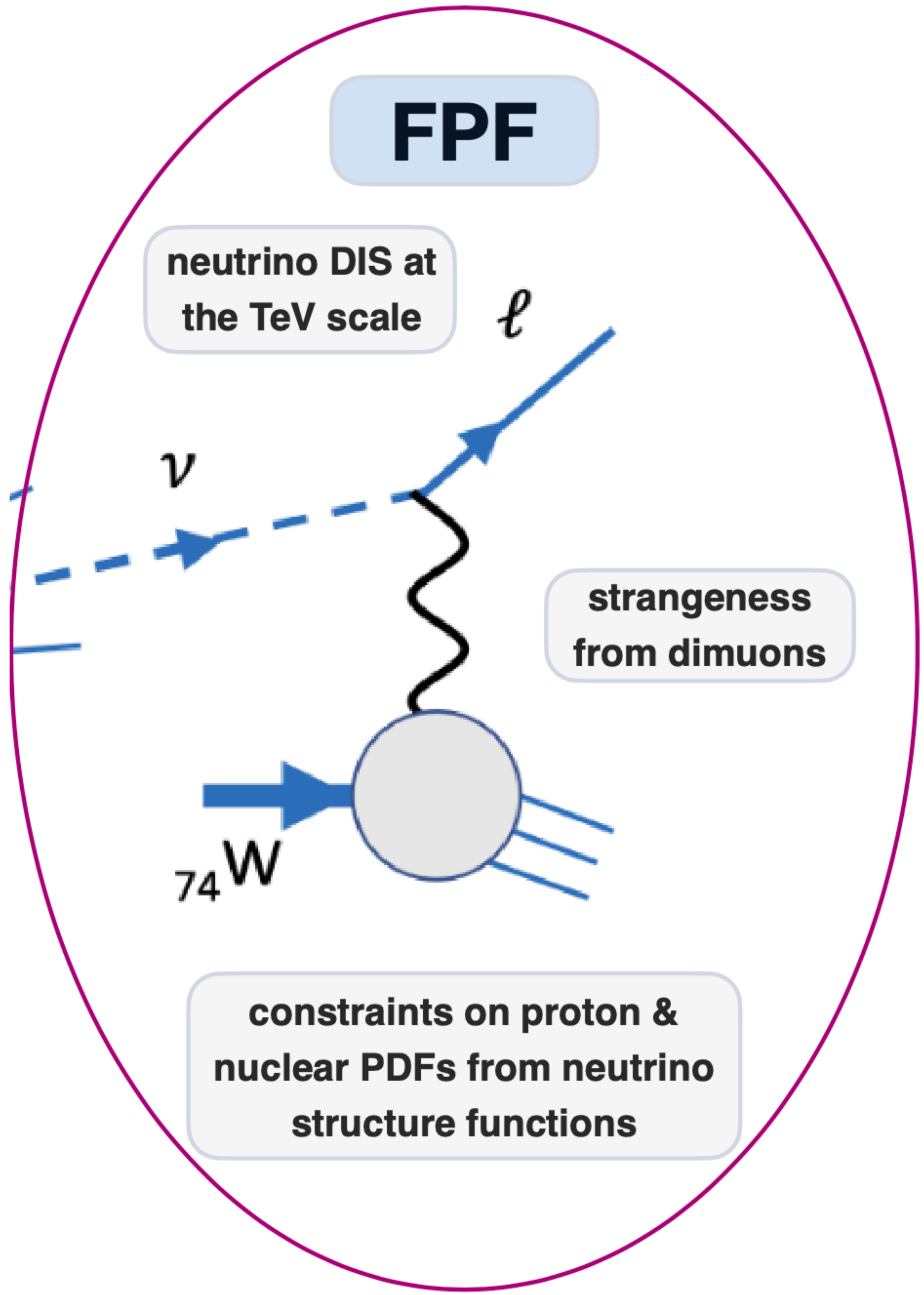


- **Forward particle production** (light hadrons & D-mesons) sensitive down to ***x*=10^{-7}**
- Ultra small-*x* proton structure & **BFKL / non-linear QCD** dynamics
- Tune models of forward hadron fragmentation (for e.g. cosmic rays)
- Constraints on **intrinsic charm** from large-*x* D-meson production

QCD at the FPF (neutrino interactions)



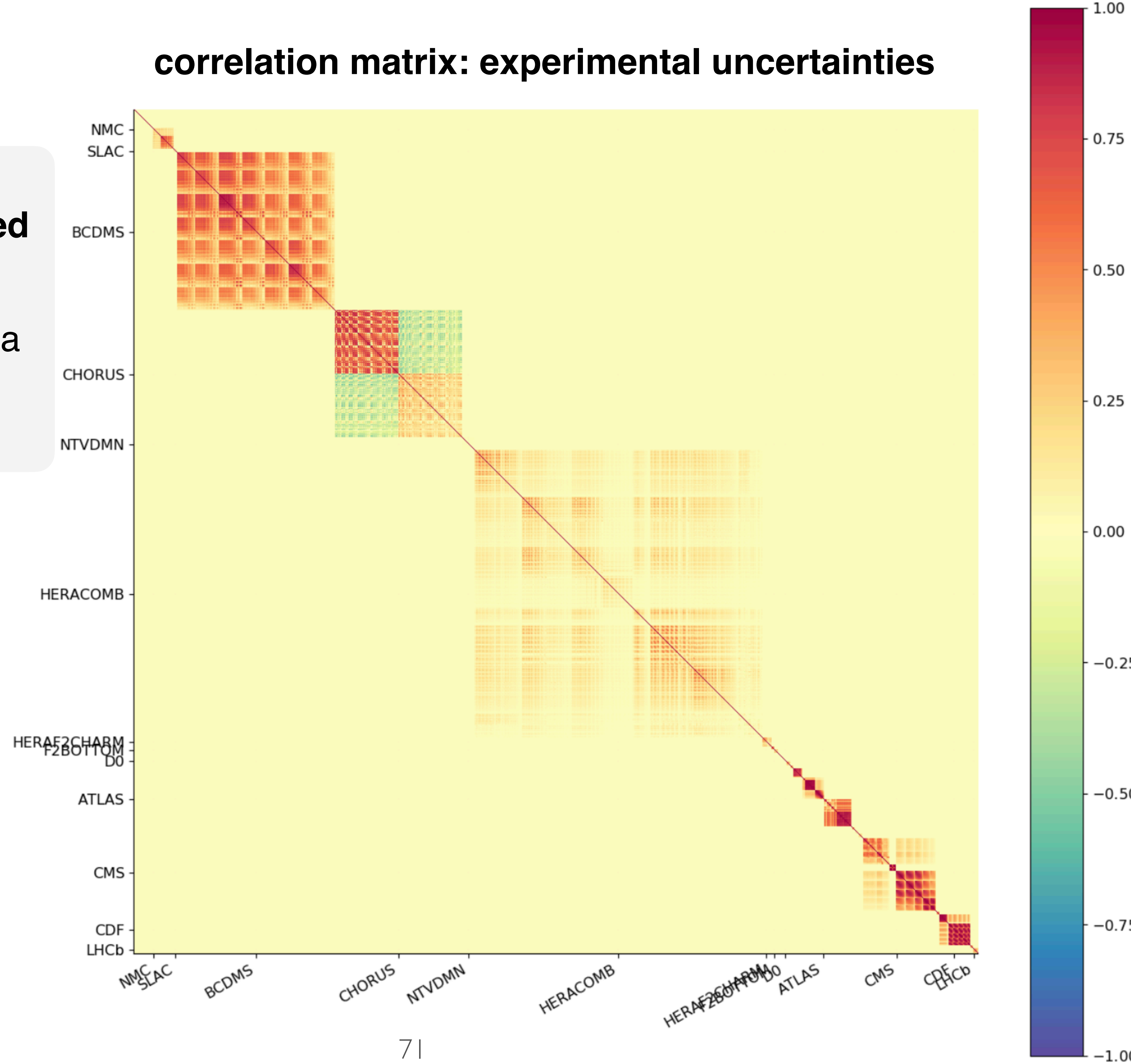
- Deep-inelastic CC scattering with **TeV neutrinos:** validate our understanding of neutrino cross-sections (relevant for oscillation experiments)
- Continue succesful program of neutrino **DIS experiments @ CERN**
- Constrain proton & nuclear **light (anti-)quark PDFs** including strangeness



QCD uncertainties in PDF fits

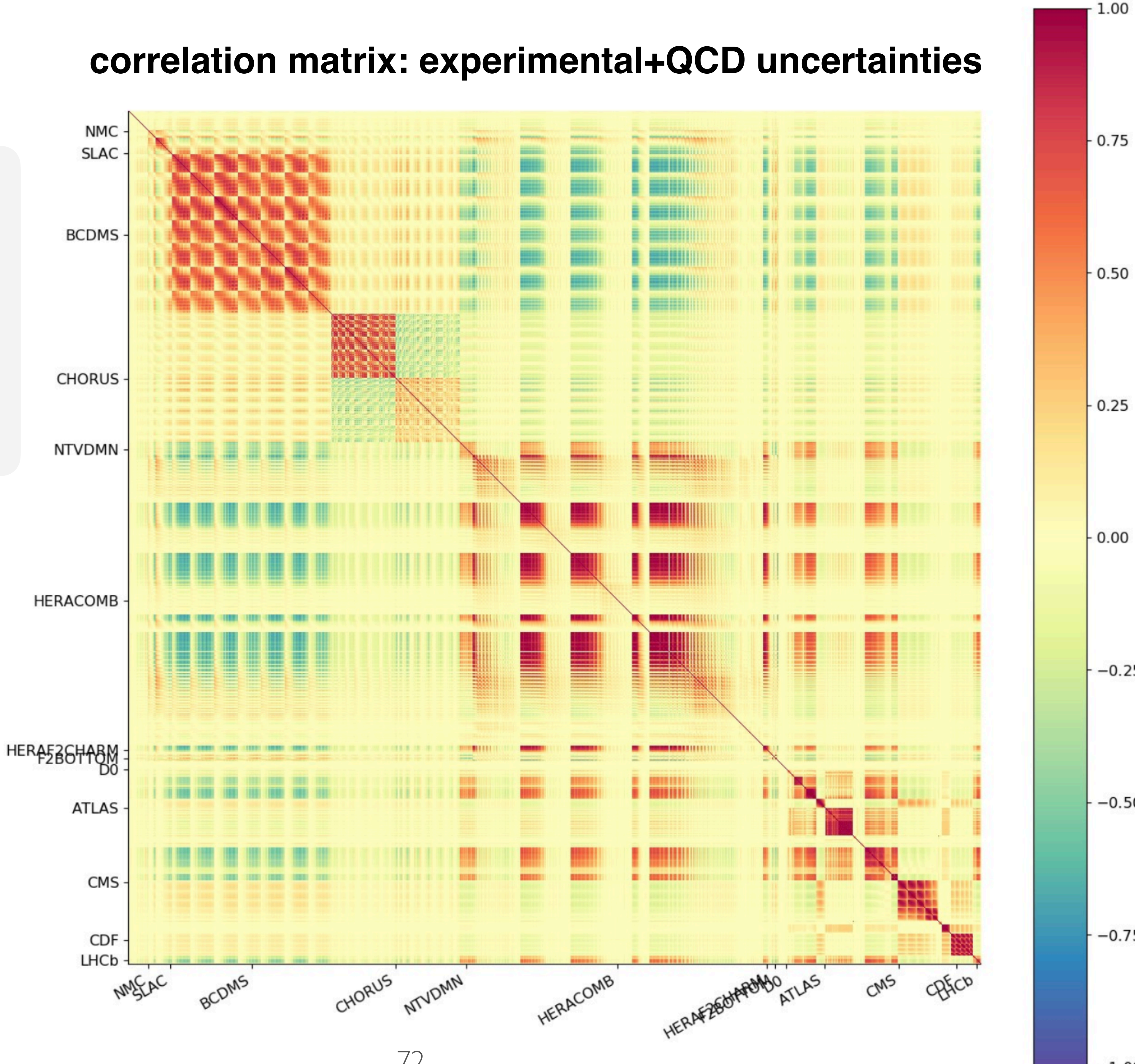
Experiment-induced correlations:

only present within a single dataset



QCD uncertainties in PDF fits

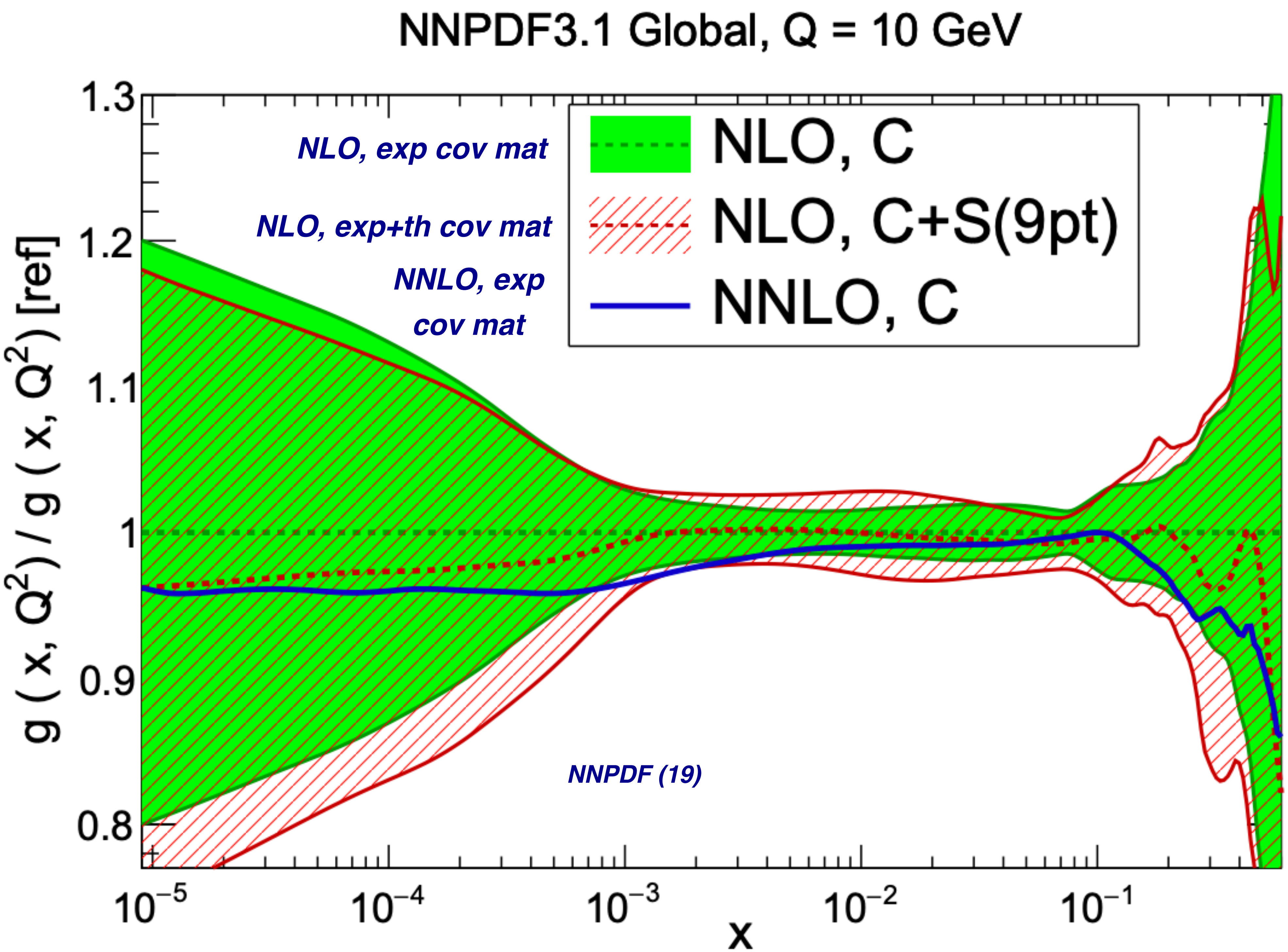
Theory-induced correlations between different experiments *e.g.* DIS and LHC



NNPDF (19)

QCD uncertainties in PDF fits

MHOUs on PDFs: increase in total uncertainties + shift in central values



extension to NNLO in the NNPDF4.0 framework in progress

Summary and outlook

- A precise understanding of the **quark and gluon structure of the proton** is a central ingredient of the physics program of the LHC

- Progress in PDF determinations leads to **precise predictions for Higgs production,** which in turn make possible a robust characterisation of the Higgs sector and searching for BSM physics

- **PDF analyses in the coming decade** will benefit from new experimental measurements at future facilities (HL-LHC, EIC, FPF, …), higher-order QCD and electroweak calculations, and methodological improvements (including new artificial intelligence techniques)