Unraveling the proton structure with high-precision QCD at the LHC

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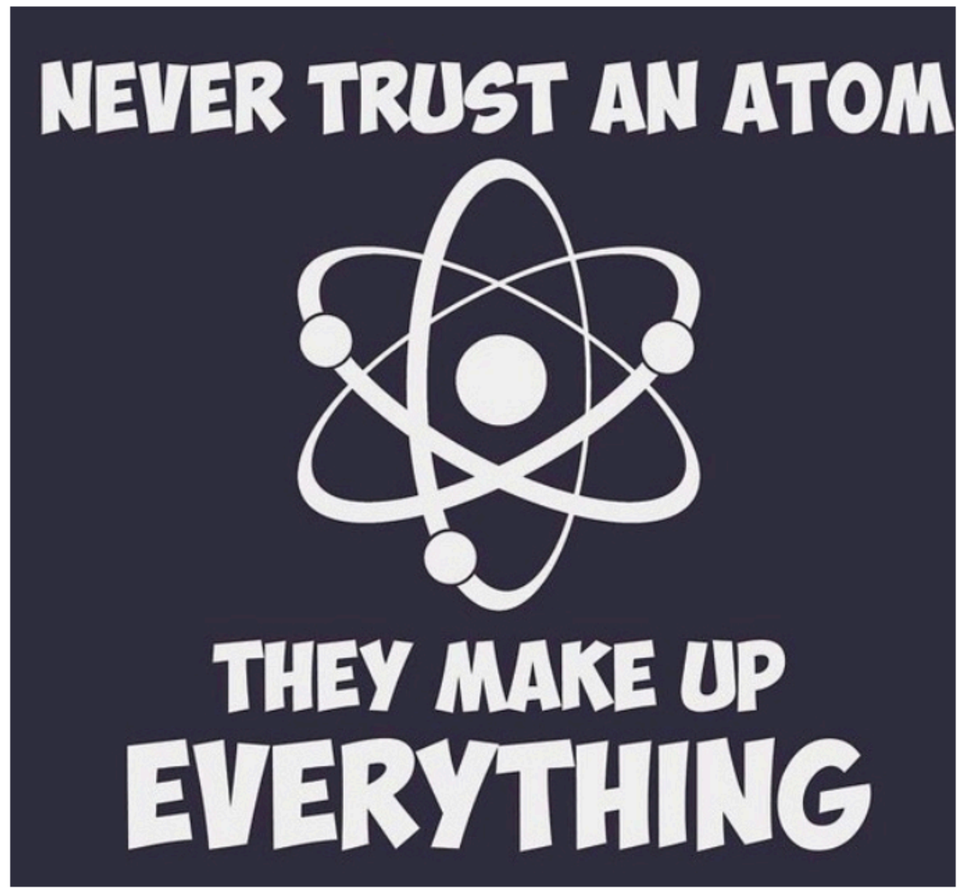
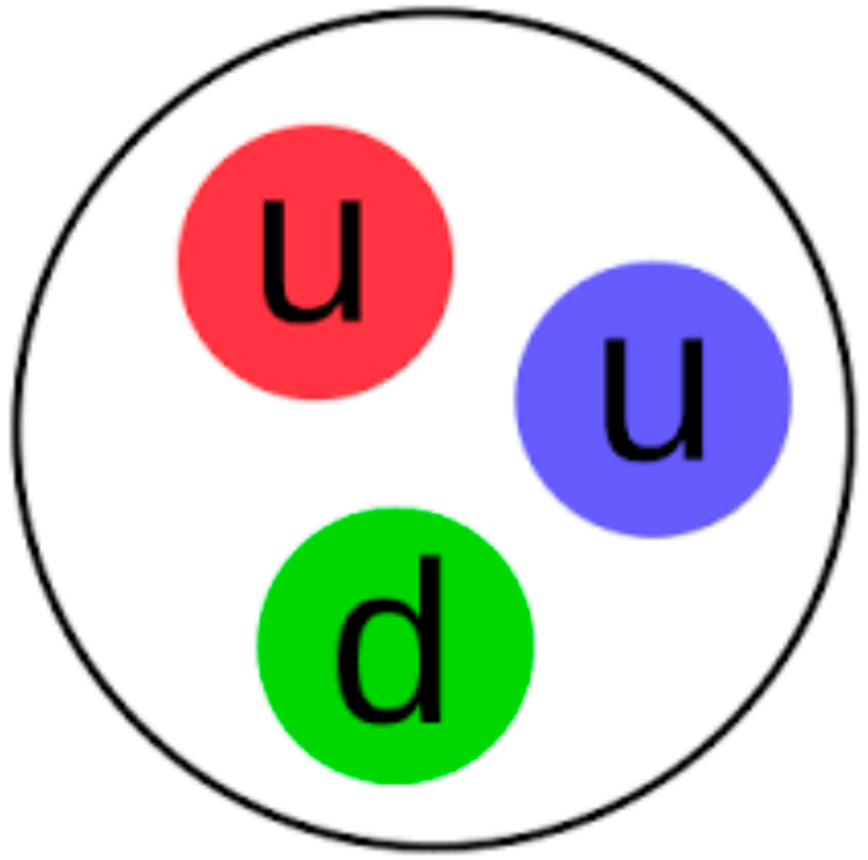
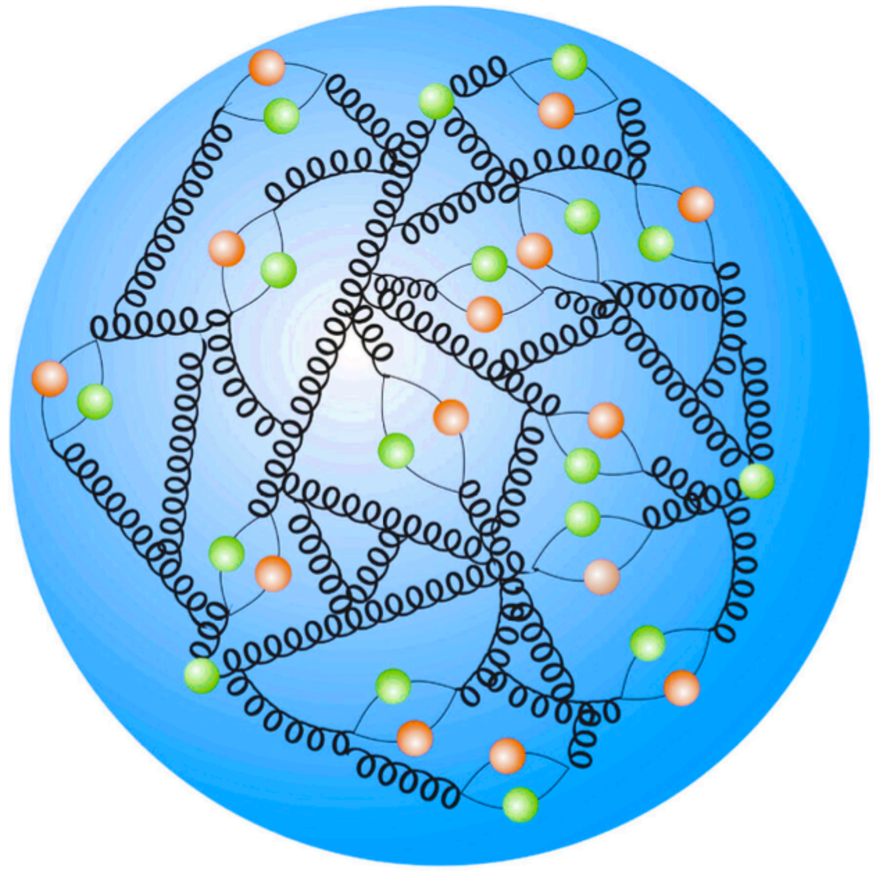
Introduction & Motivations

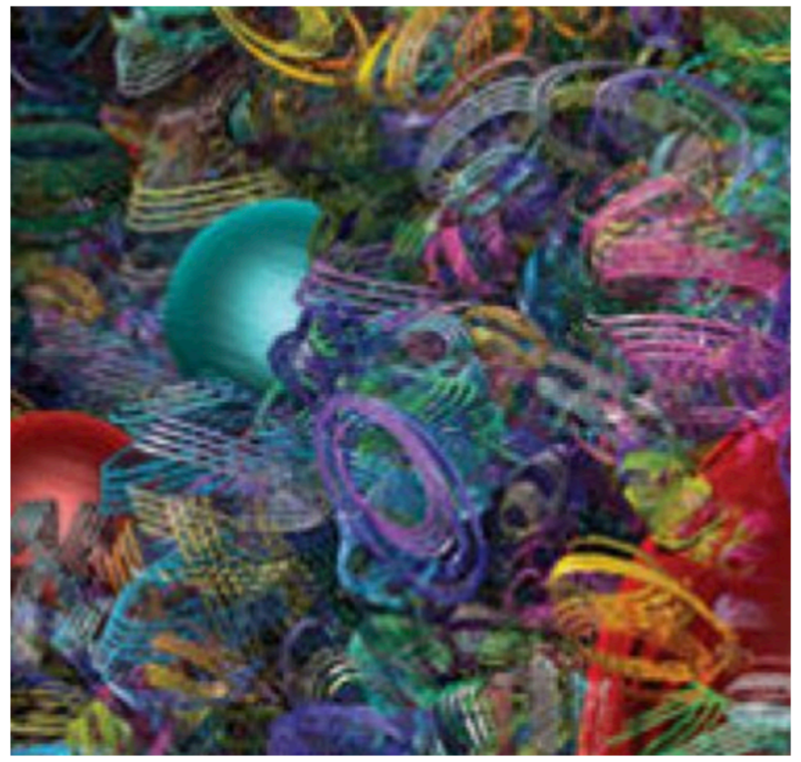
Protons despite of being so common are a perfect example to study quantum mechanics.

What a proton is depends on the resolution at which is probed.









$E \ll 1$ GeV	$E \approx 1$ GeV	$E \approx 50$ GeV	$E \approx 1$ TeV
Point like particle	**Valence quarks**	**Quark sea, gluons**	**Heavy quarks, photon**

Introduction & Motivations

Sum on all flavors

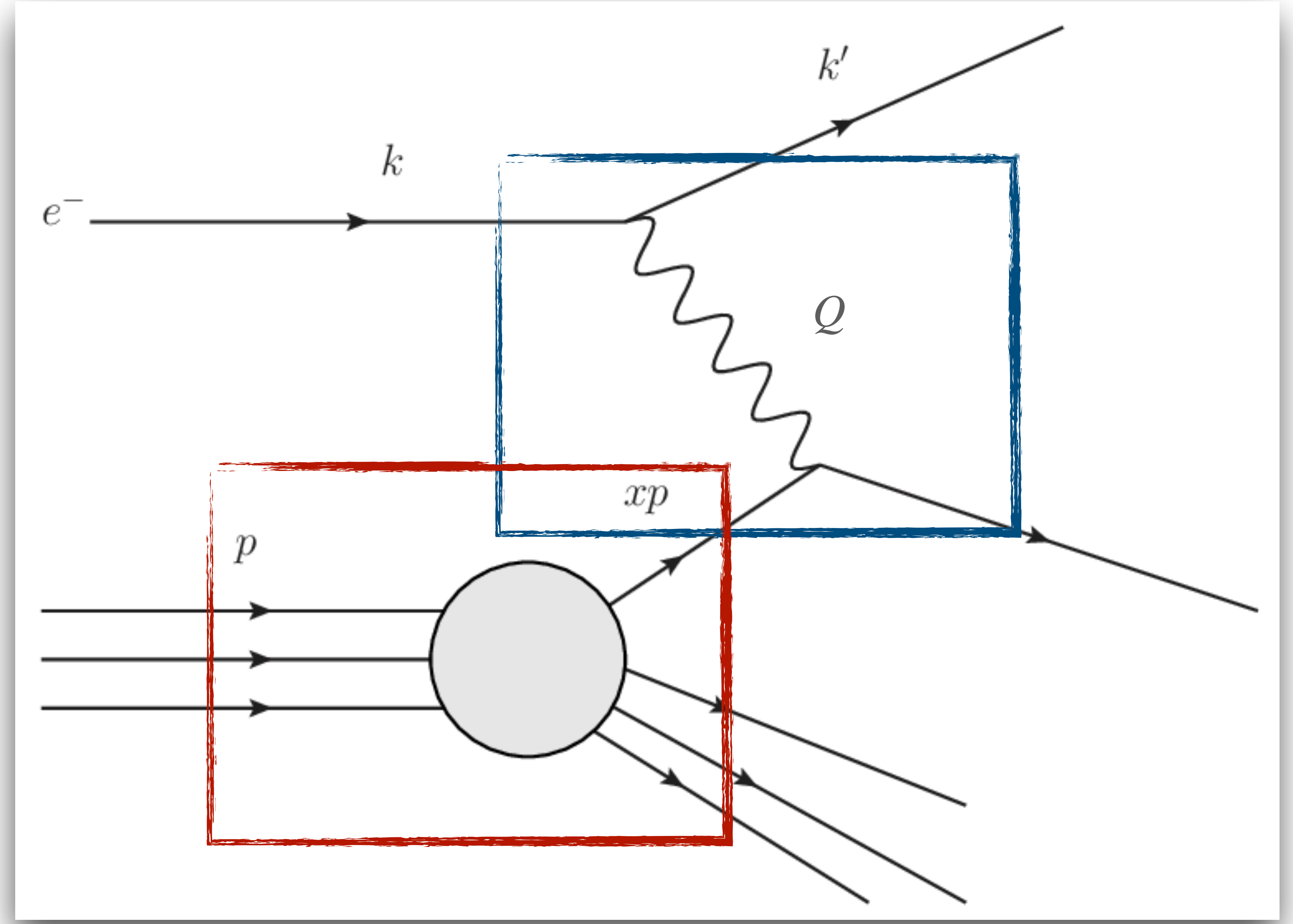
factorisation theorem for DIS

$$\sigma(x,Q^2) = \sum_i^{n_f} \int_x^1 \frac{dz}{z} f_i(z,\mu^2)\ \hat{\sigma}\left(\frac{x}{z}, \frac{Q^2}{\mu^2}, \alpha_s\right) + \mathcal{O}\left(\frac{1}{Q^2}\right)$$

Observable (cross section)

Parton Distribution Function (PDF)

Partonic Matrix Element

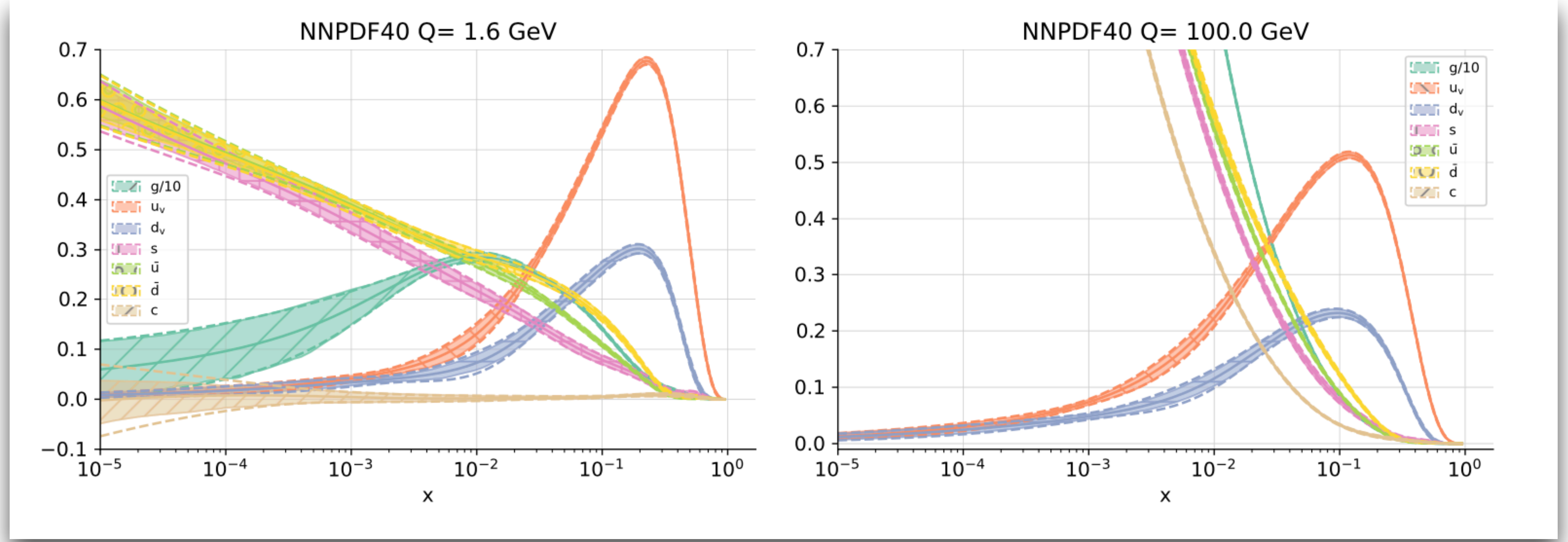


A Deep Inelastic Scattering (DIS) process:
$p\ e^- \to e^- + X$

- A generalisation of this theorem holds for pp collisions. Predictions LHC observes relies on two main ingredients: **PDFs** and **Partonic Matrix Elements (PME)**.
- To reach higher accuracy we need to compute radiative corrections on the PME, of which QCD ones are generally the largest contribution.
- In the last years many **LHC processes $(2 \to 1)$** have been calculated up to QCD at N3LO.

$$\sigma = \alpha_s \sigma_{LO} + \alpha_s^2 \sigma_{NLO} + \alpha_s^3 \sigma_{NNLO} + \alpha_s^4 \sigma_{N3LO} + \mathcal{O}(\alpha_s^5)$$

The proton in a snapshot



- PDFs (beyond LO) **are not directly observables** but are functional probability distribution and depend on the momentum faction x and on an energy scale Q^2.
- PDFs are **non perturbative objects** thus can not be computed using standard pQCD.
- PDFs are generally **extracted from High Energy data**.
- Many independent determination by different groups (CTEQ, MSHT, NNPDF, HERAPDFs)

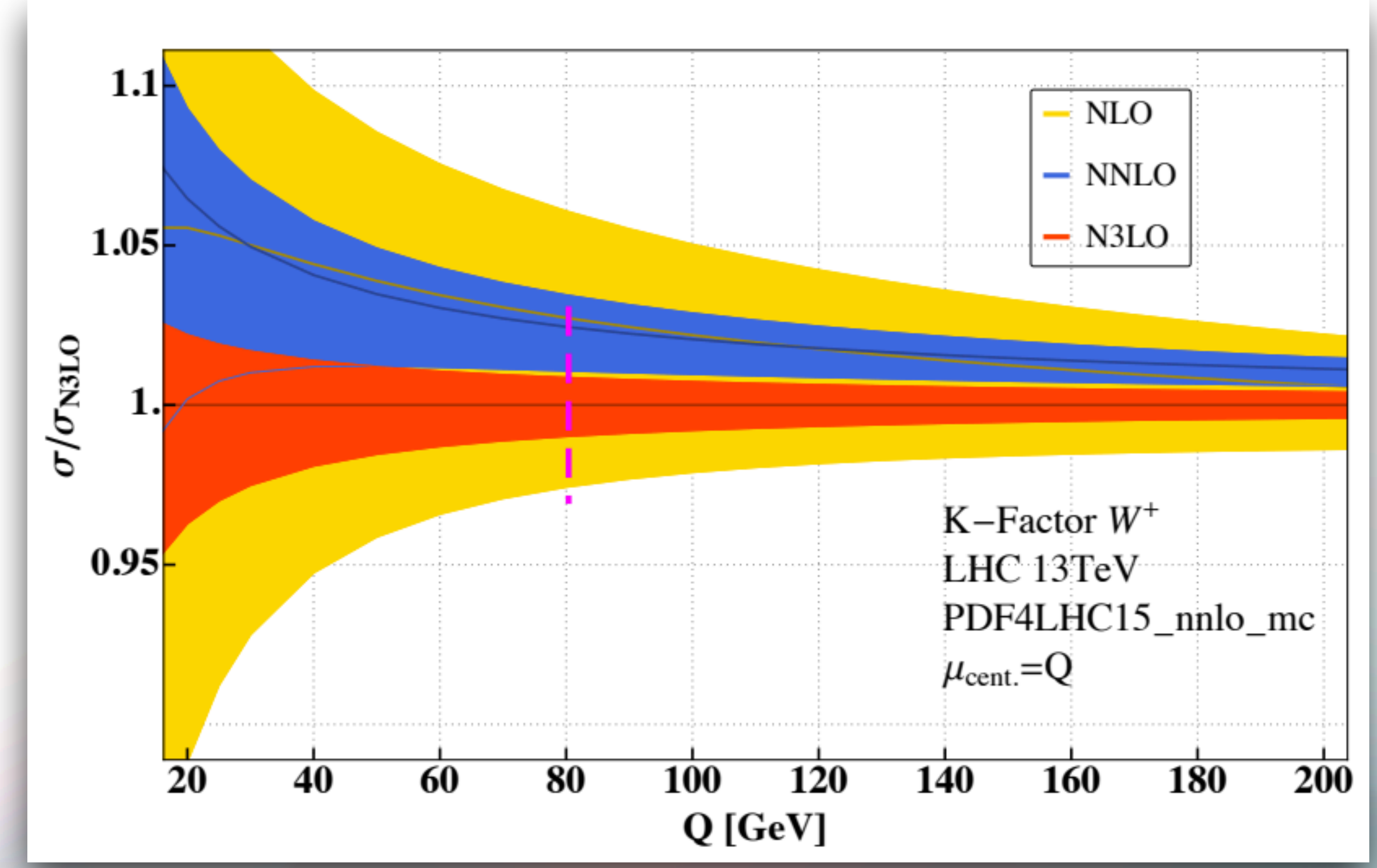
However during a PDF fit several **theoretical inputs are also needed**:

- The accuracy at which these ingredients (splitting functions, partonic coefficients) are computed determines the PDF accuracy.
- State of the art PDFs are determined at NNLO in pQCD.

How can we improve PDF determination?

➡ PDFs are still at NNLO accuracy in QCD, need to go **aN3LO**.

➡ Inclusion of **theory uncertainties** while determining PDFs is relevant at this level of accuracy.



From Duhr, Dulat, Mistleberger [arxiv:2007.13313]

PDFs determination @ aNNNLO

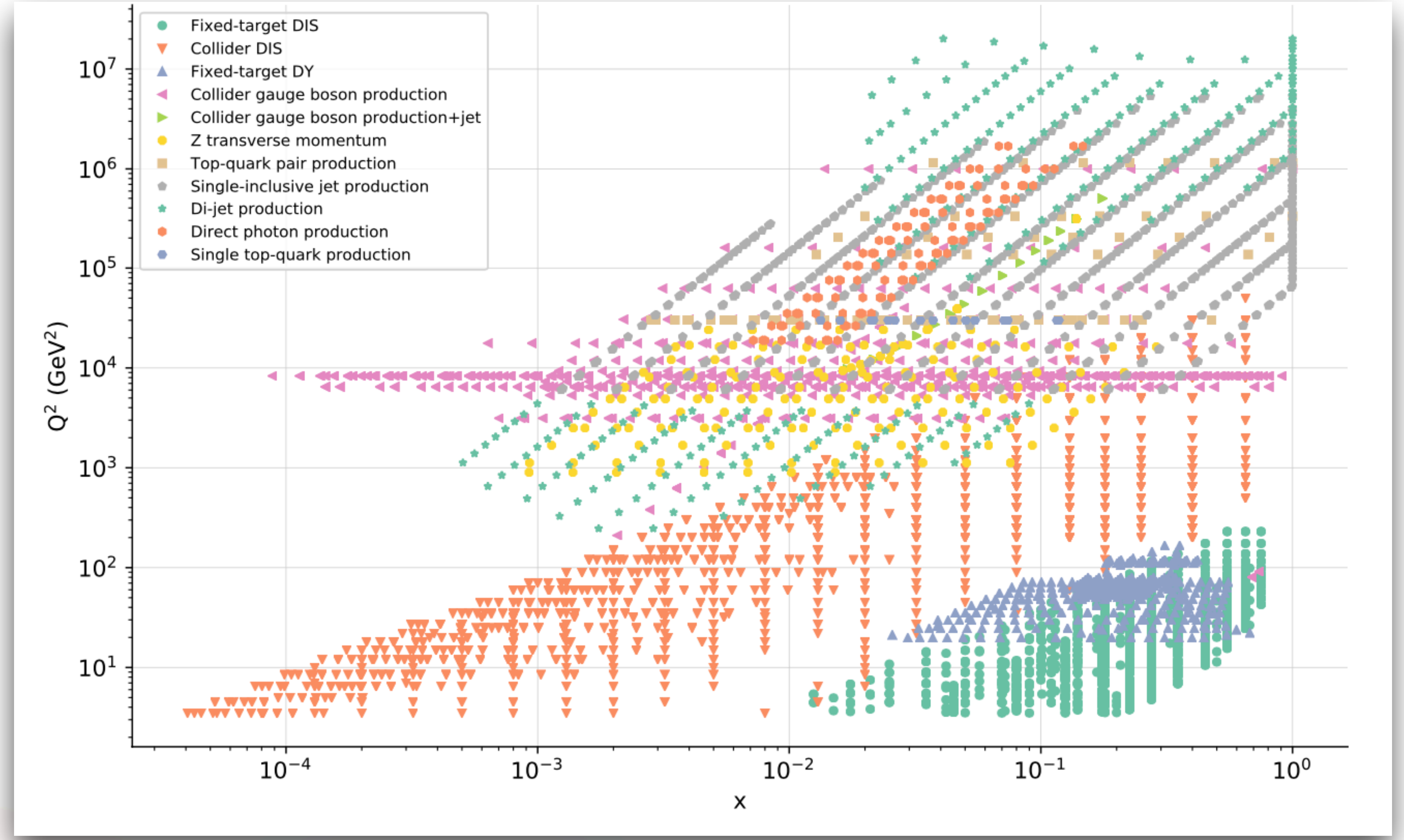
Several theoretical inputs are needed in a PDF fit:

1. The main ingredient are the **QCD splitting functions** which controls the DGLAP evolution.

$$Q^2 \frac{d}{dQ^2} f_i(x,Q) = \int_x^1 \frac{dz}{z} P_{ij}(\frac{x}{z},Q)\, f_j(x,Q)$$

2. **VFNS matching conditions** for each running component.
3. **DIS partonic coefficients** functions, accounting for massive corrections when possible.
4. **Hadronic coefficients**: which can be included mainly through *k-factors*.

The NNPDF4.0 kinematic coverage



PDFs determination @ aN3LO

Several theoretical inputs are needed in a PDF fit:

1. The main ingredient are the **QCD splitting functions** which controls the DGLAP evolution.

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

2. **VFNS matching conditions** for each running component.
3. **DIS partonic coefficients** functions, accounting for massive corrections when possible.
4. **Hadronic coefficients**: which can be included mainly through *k-factors*.

➡ Construct reliable approximations from existing calculations.

➡ Determine theory uncertainties both from:

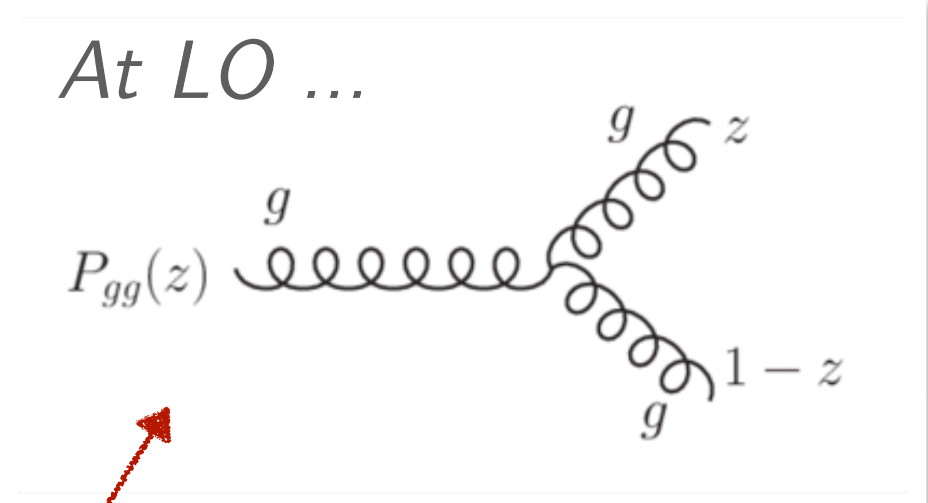
Incomplete Higher Order corrections IHOU

Missing Higher Order corrections MHOU

Not all of them are yet available at N3LO

PDF evolution @ aN3LO

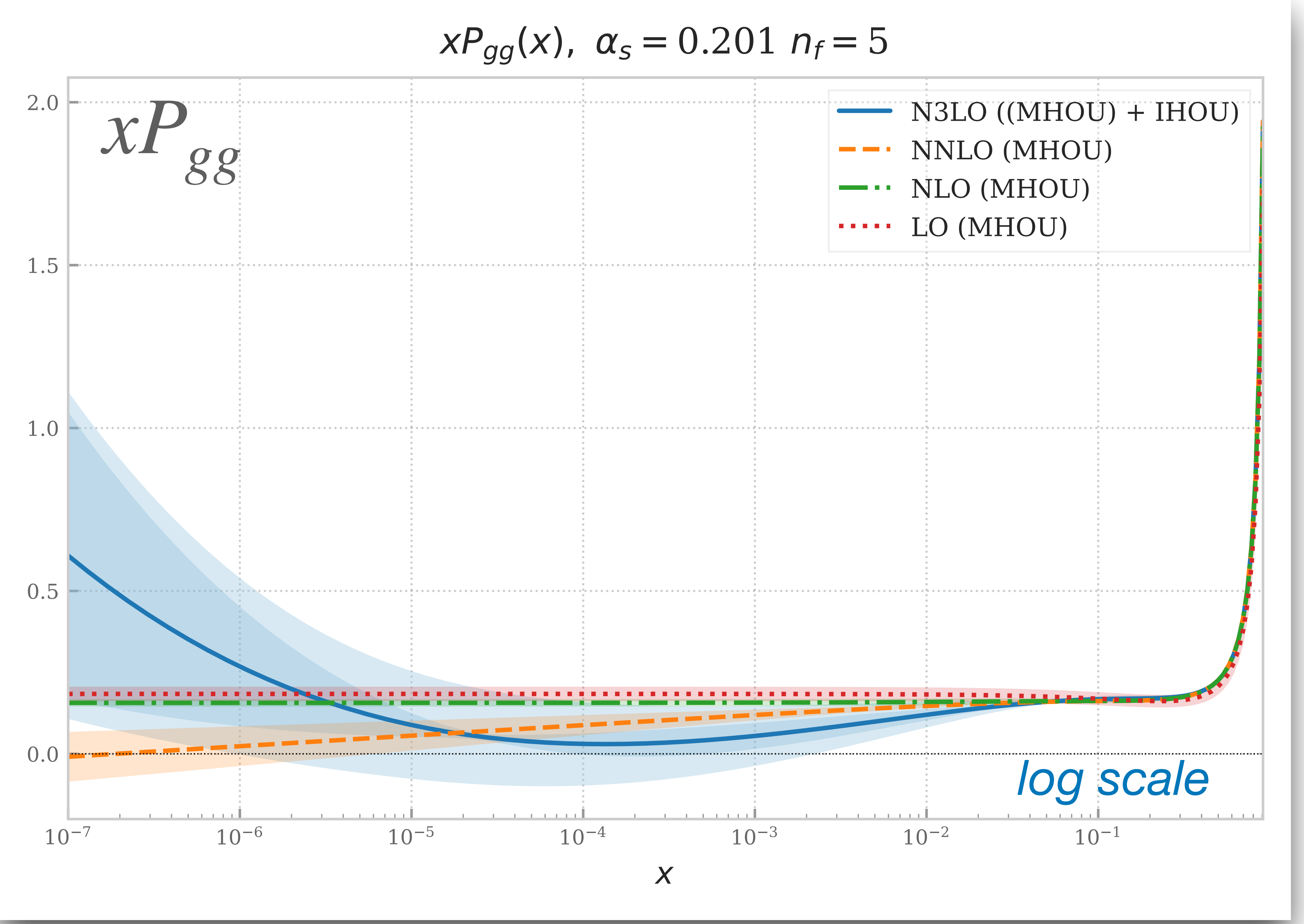
- **Splitting functions** are the kernel of DGLAP equations which governs the scale dependency of the PDFs
- Analytical calculations of the complete N3LO spitting functions are not available yet.

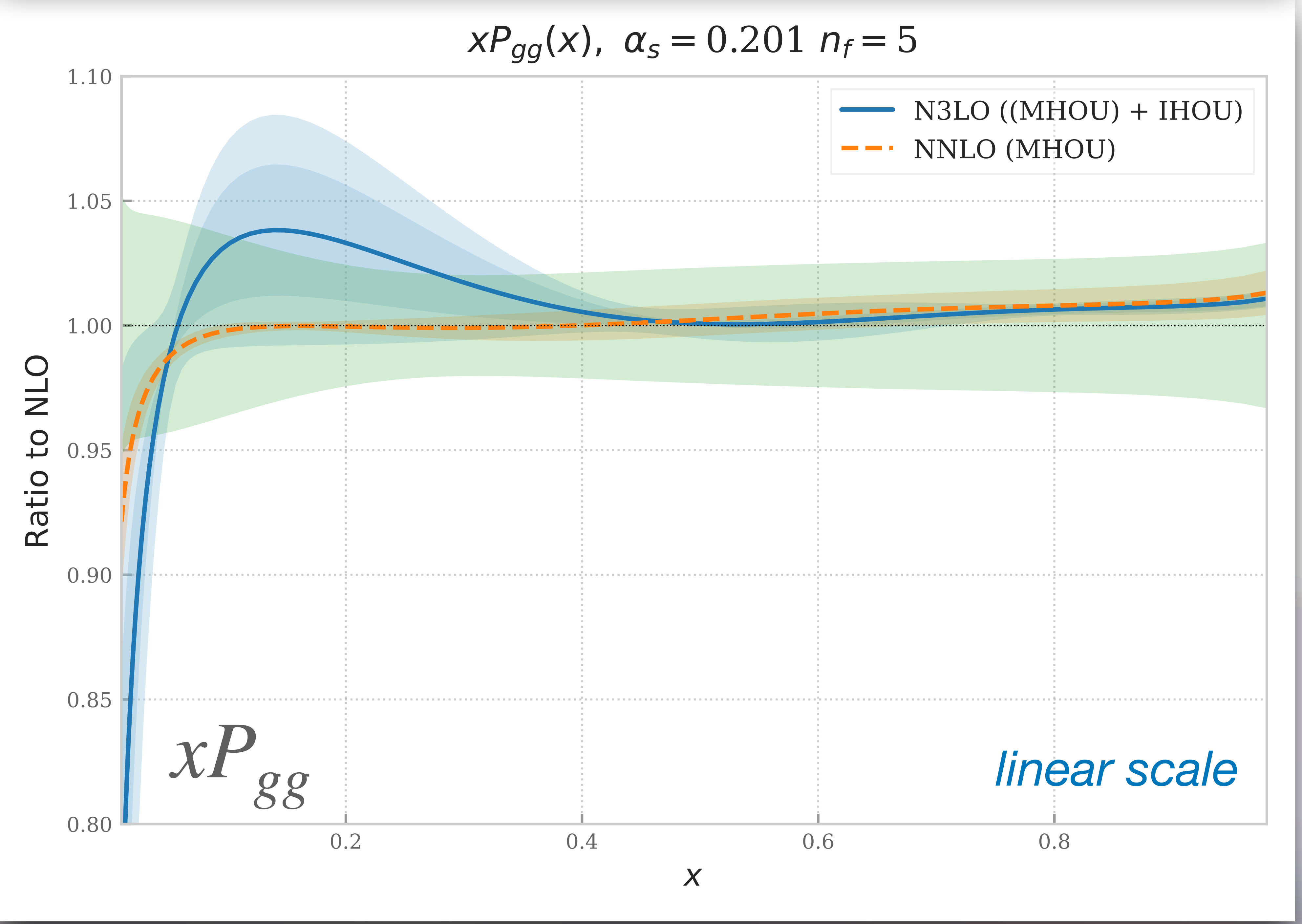


$$Q\frac{d}{dQ}f_i(x,Q) = \int_x^1 \frac{dz}{z} P_{ij}\left(\frac{x}{z},\alpha_s(Q)\right) f_j(x,Q)$$

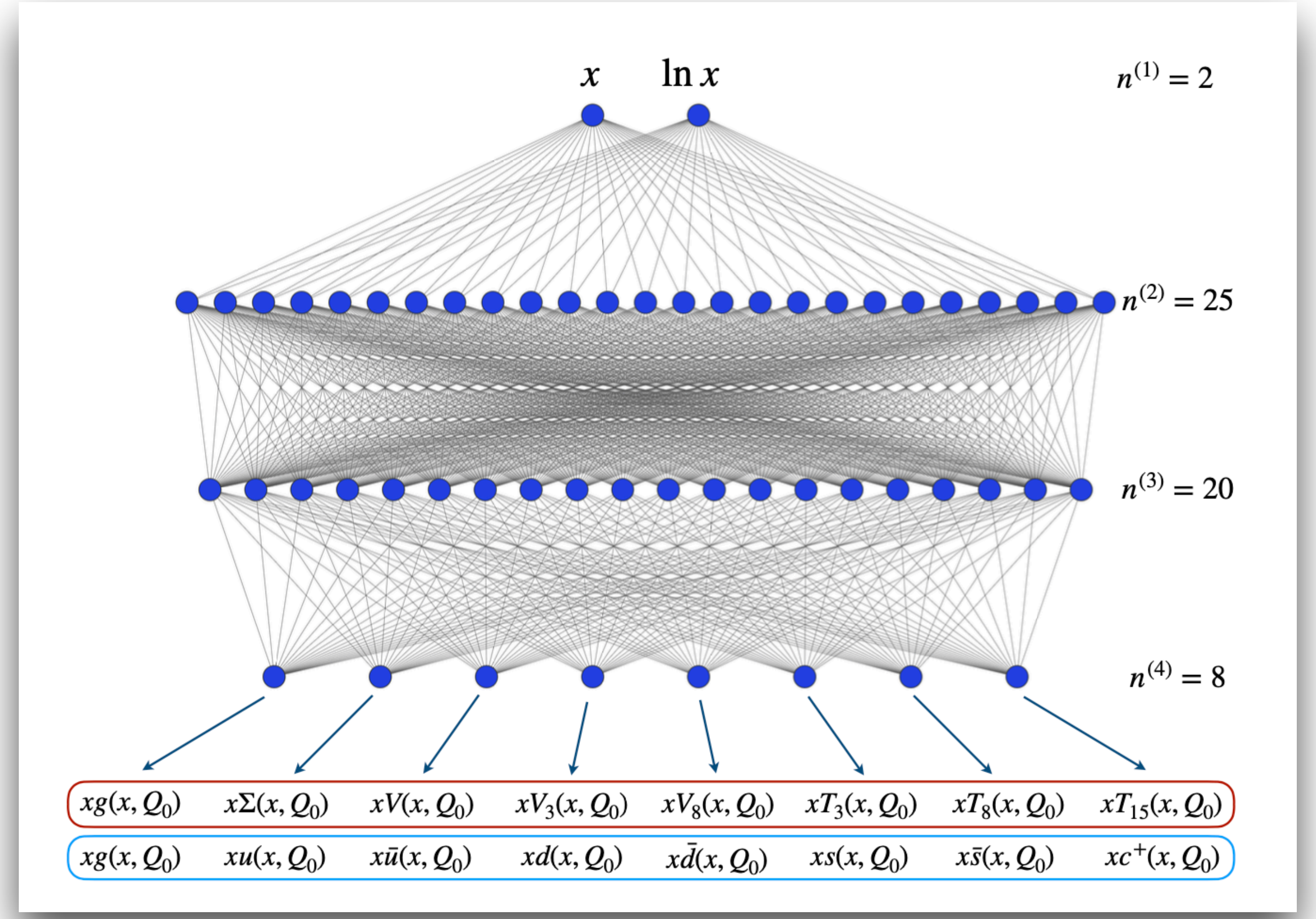
DGLAP equations for PDFs

- Approximation is done using only theoretical inputs.
- Large logs $1/x\ln^2(x)$, $1/x\ln(x)$ arise at N3LO.
- NNLO MHOU are not enough in small-x region. While pQCD is converging nicely in the large-x region.
- IHOU are not negligible.





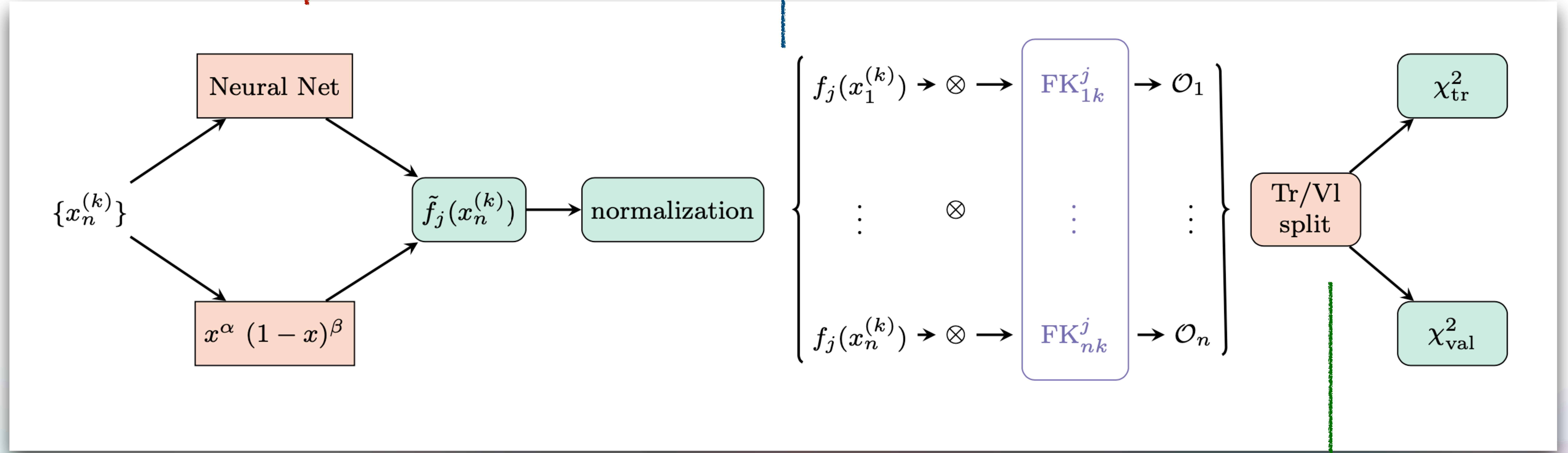
The NNPDF fitting methodology



1. PDFs are parametrised in $n_f = 4,\ Q_0 = 1.65\ GeV$ using a **neural net:**

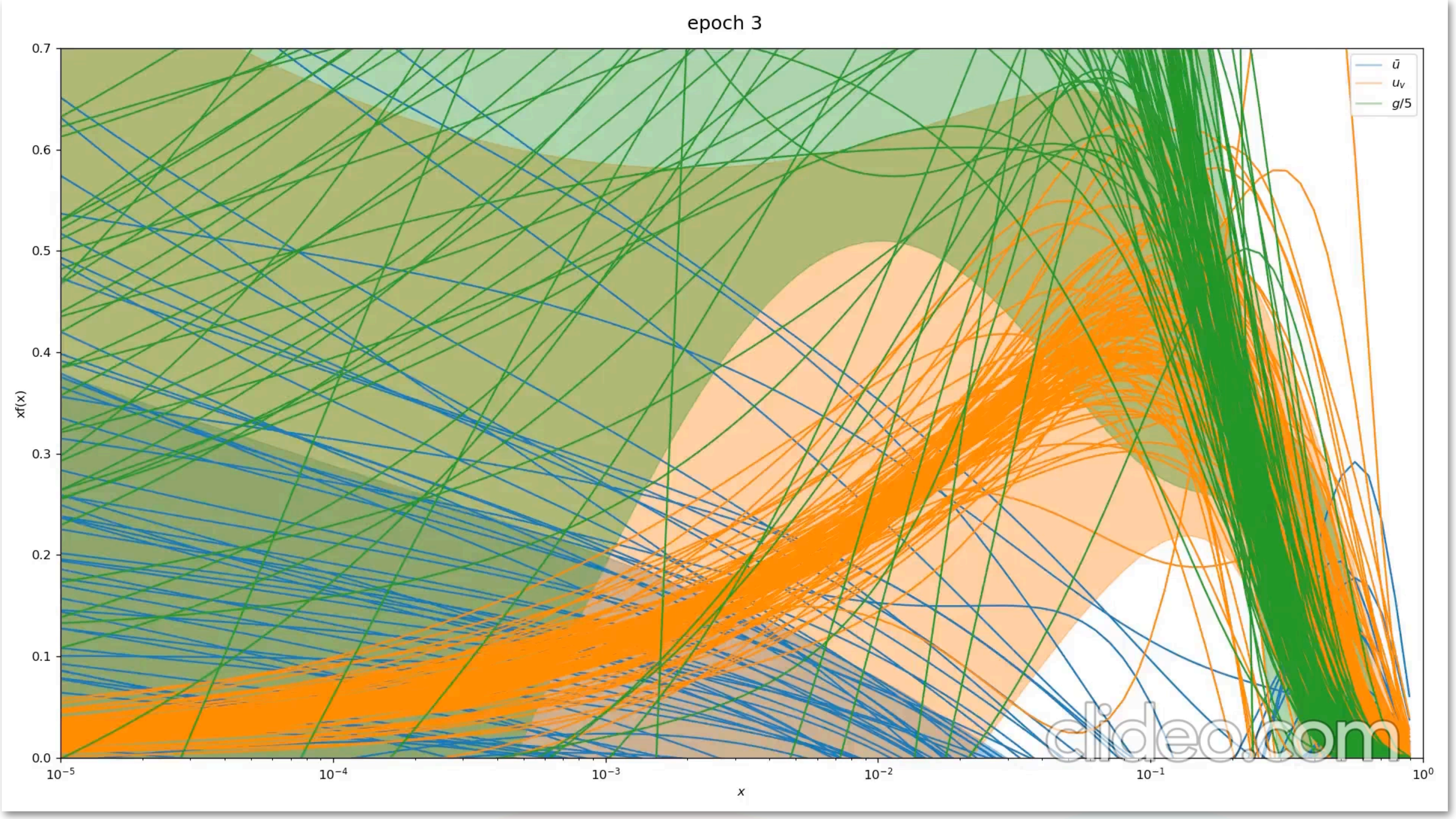
$$f_i(x) = x^{a_i}(1-x)^{b_i} NN(\theta, x, \log(x))_i$$

2. **Convolution** with Partonic coefficients



3. **Minimisation**: compare to data

Let’s run it!

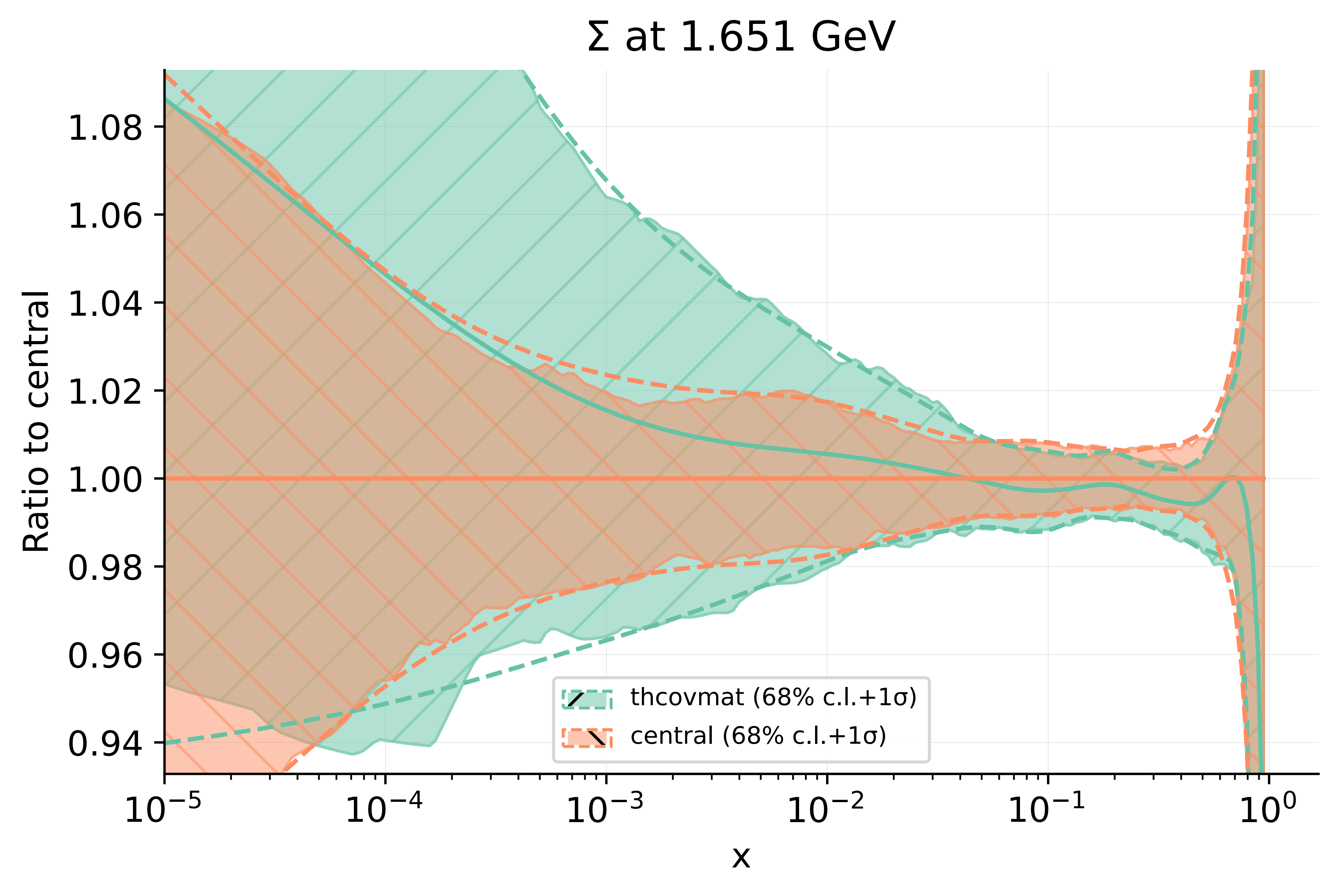


https://data.nnpdf.science/animations/replicas_uncertainty_singlefigure.mp4

Impact of MHOU theory uncertainties

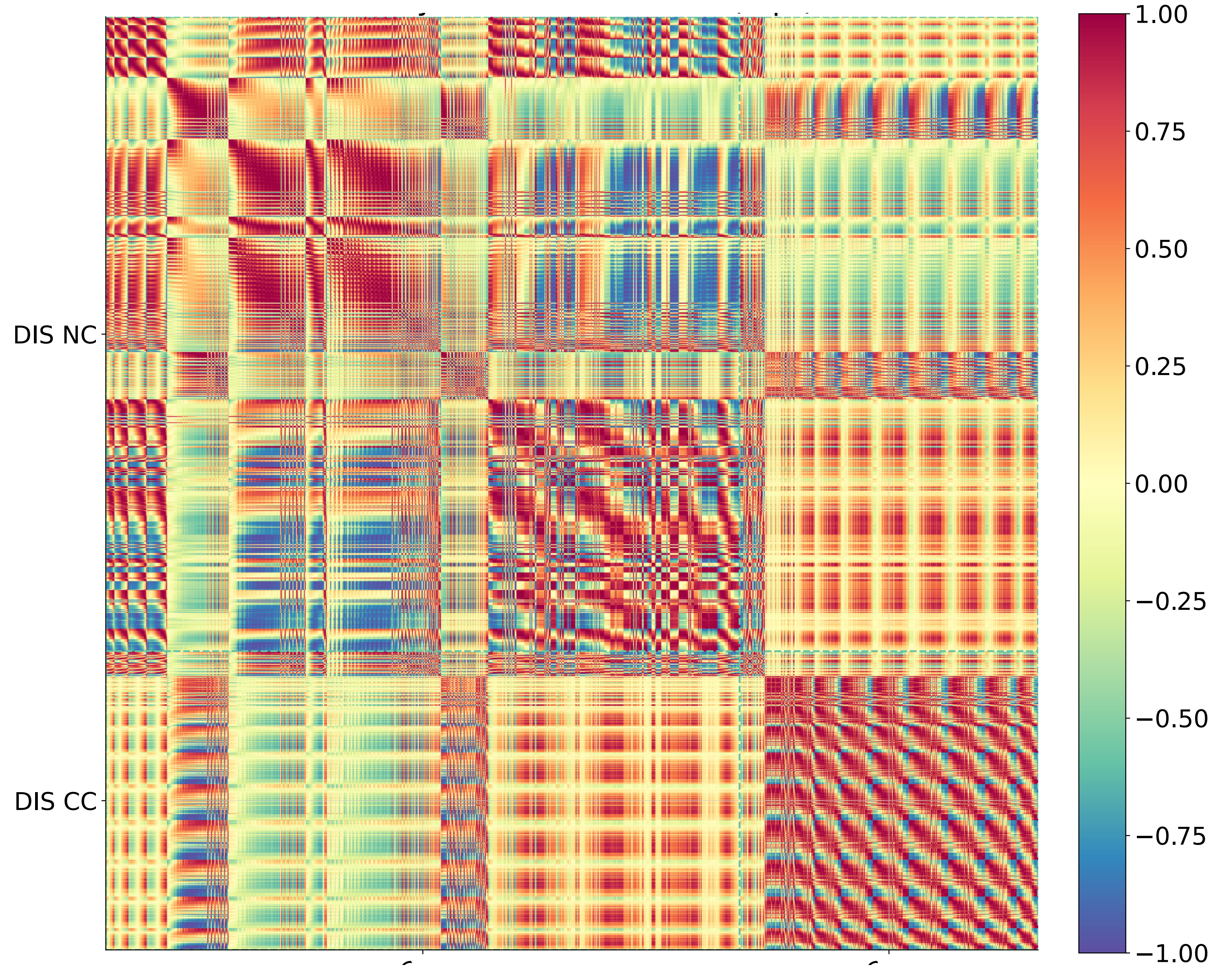
- **Factorization scale variations** are introduced during the DGLAP evolution.
- **Renormalization scale variations** are retained inside the coefficient functions and varied differently for different kind of processes.
- Theory uncertainties add correlations between datasets, which are not taken into account in the experimental covariance mat.
- Effects on the PDF fit are non-trivial.

$$\Sigma = \sum_{i=1}^{n_f} (q_i + \bar{q}_i)$$

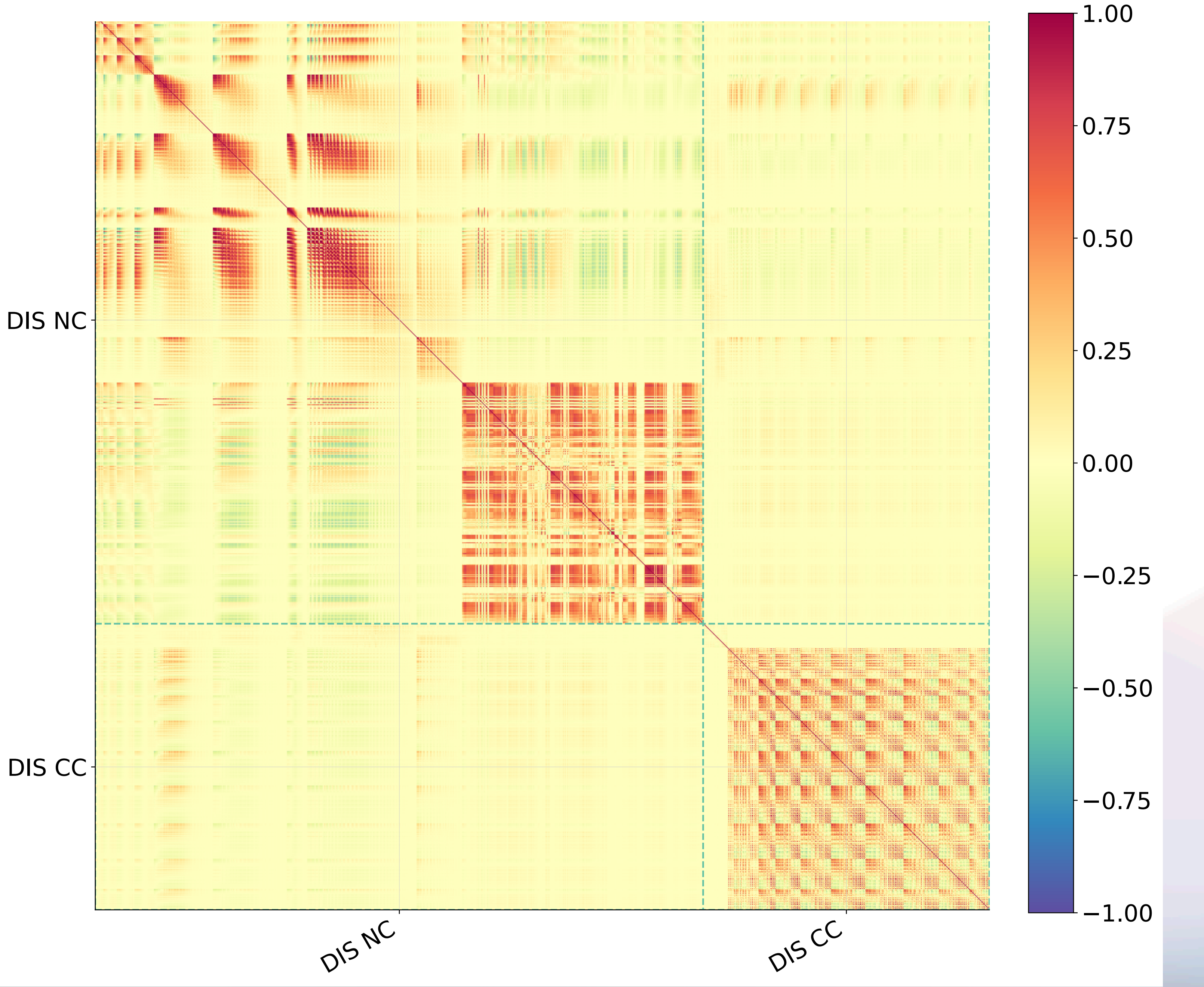


Ratio of NNLO Singlet PDFs ***with and w/o MHOU***

MHOU correlations NNLO



Exp + MHOU correlations NNLO



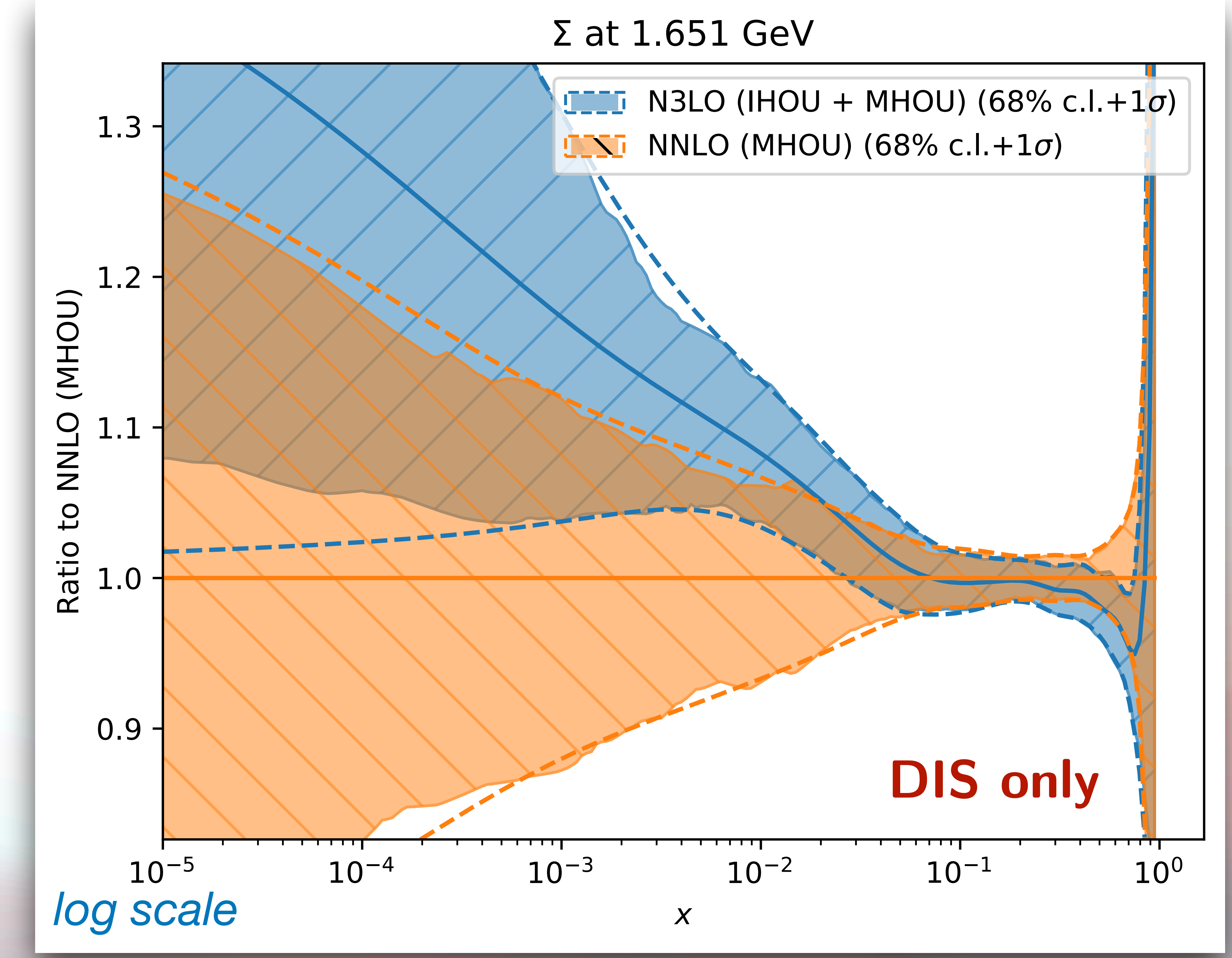
Towards aN3LO PDFs fits

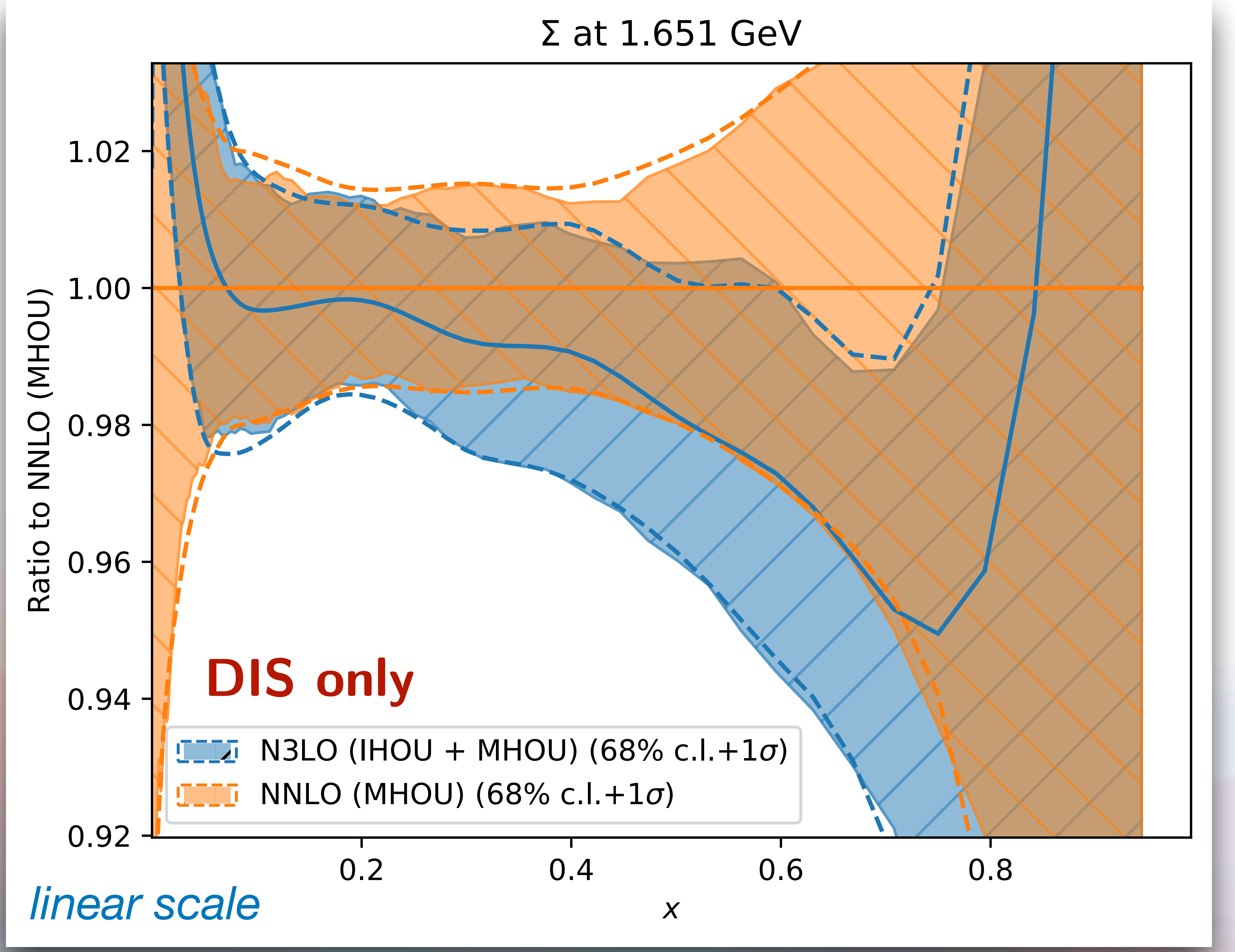
- First runs of **aN3LO DIS only** fits show a quite visible impact of N3LO corrections in the **small-x** region for gluon g and Singlet Σ.

- At large-x PDFs are compatible within one sigma with NNLO.

$$\Sigma = \sum_{i=1}^{n_f} (q_i + \bar{q}_i)$$

*Ratio of Singlet PDFs **N3LO vs NNLO** with MHOU*





Summary & Outlook

You can find us at:

https://github.com/NNPDF

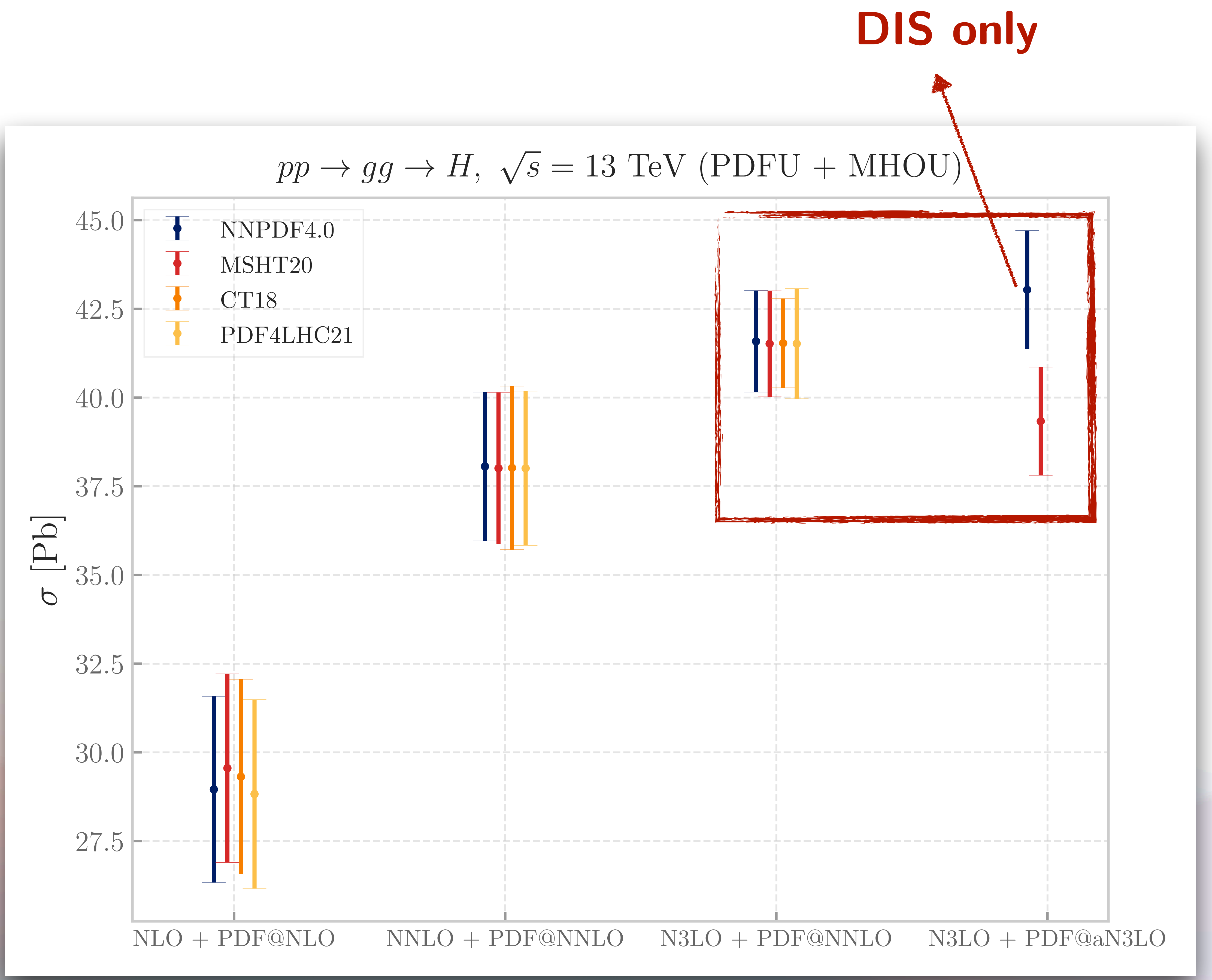
https://nnpdf.mi.infn.it/

Accurate determination of PDFs is crucial for LHC phenomenology.

Our research group is active on different topics regarding nuclear and proton structure determination. Main topics we are working on:

- **Proton PDFs** with MHOU and aN3LO.
- **Neutrino structure functions** and FPF.
- Combined **Nuclear** and **Polarised** PDFs.
- **Methodological studies** for PDFs fitting.
- Intrinsic Charm.

For LHC users:
new NNPDF releases are coming soon:
4.0 MHOU, 4.0 aN3LO, 4.0 QED
...stay tuned!



Thank you!