Including QED corrections in PDFs fits

The NNPDF4.0QED PDFs set

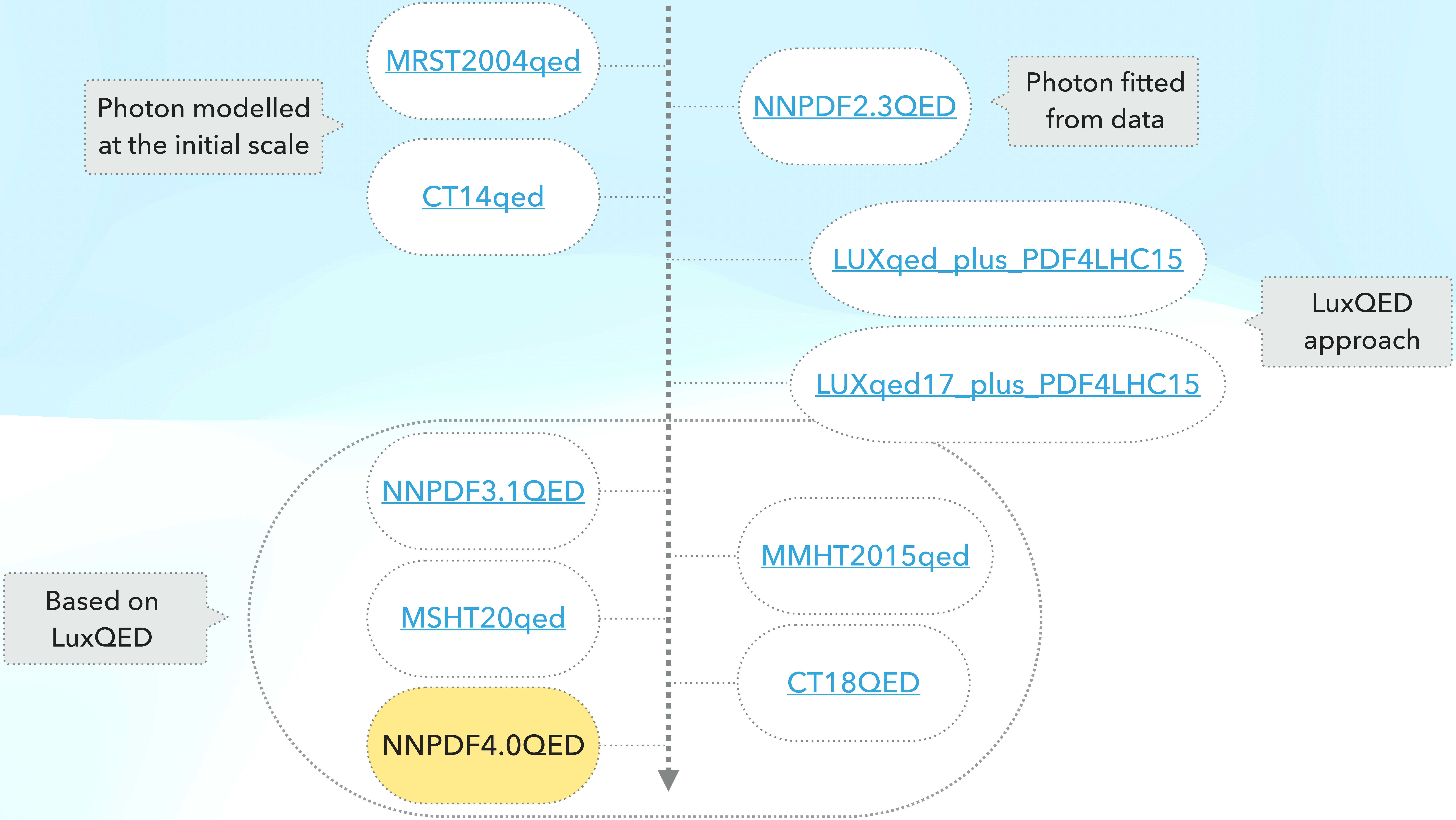
Niccolò Laurenti, on behalf of the NNPDF collaboration, QCD@LHC23

Summary

- ☑ Introduction
- ☑ Adding QED to a PDF fit
- ☑ Results
- ☑ Impact on phenomenology
- ☑ Conclusions

INTRODUCTION

Introduction: QED fits done in the past



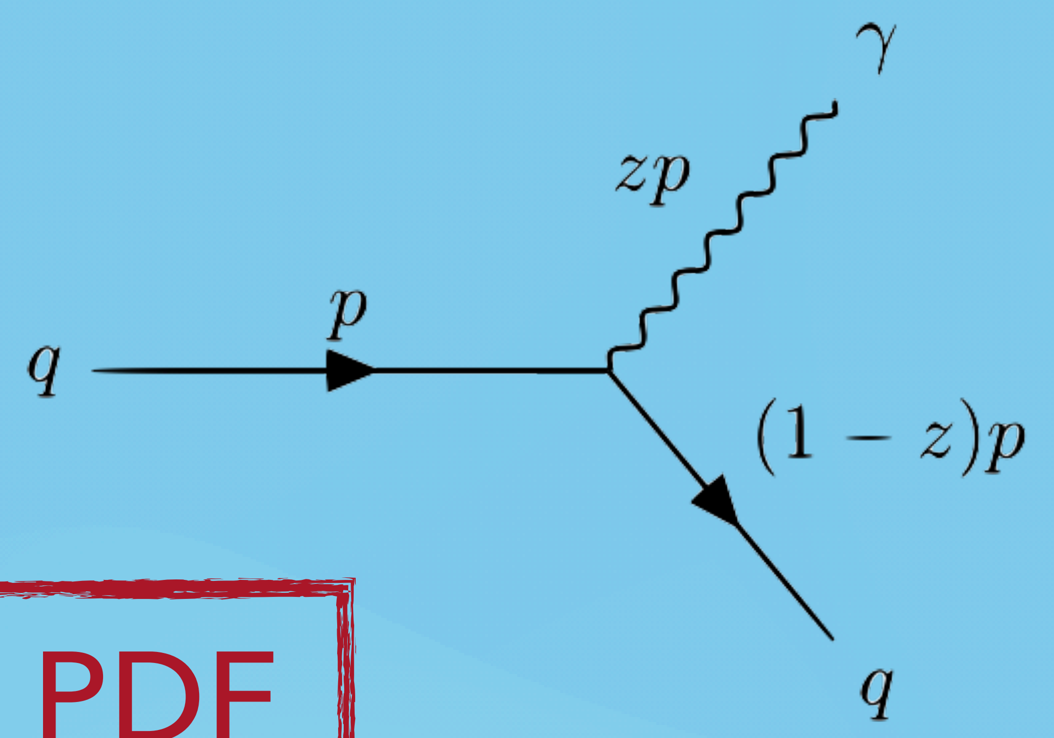
ADDING QED TO A PDF FIT

Adding QED: motivation

$\alpha \sim \mathcal{O}(\alpha_s^2) \sim \mathcal{O}(1\%)$

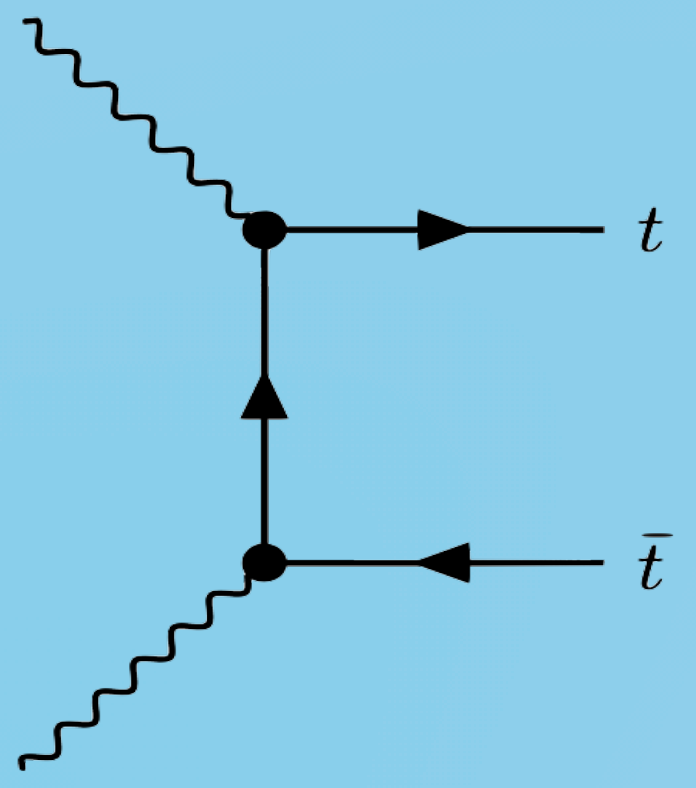
percent correction

quarks can emit photons



we get a photon PDF

For some processes we can't neglect photon induced contributions



starts at $\mathcal{O}(\alpha_s^0)$

In some kinematical regions QED corrections are important

see phenomenology section

Adding QED: corrections to DGLAP

$$\mu^2 \frac{d}{d\mu^2} f_i(x,\mu^2) = \sum_{j=q,\bar{q},g,\gamma} \int_x^1 \frac{dz}{z} P_{ij}\left(\frac{x}{z}, \alpha_s(\mu^2), \alpha(\mu^2)\right) f_j(z,\mu^2) \quad i = q, \bar{q}, g, \gamma$$

$$P_{ij}(\alpha_s, \alpha) = P_{ij}(\alpha_s) + \tilde{P}_{ij}(\alpha_s, \alpha)$$

pure QED and QCD⊗QED terms

$$\alpha P_{ij}^{(0,1)} + \alpha_s \alpha P_{ij}^{(1,1)} + \alpha^2 P_{ij}^{(0,2)} + \ldots$$

$$\alpha_s P_{ij}^{(0)} + \alpha_s^2 P_{ij}^{(1)} + \alpha_s^3 P_{ij}^{(2)} + \ldots$$

pure QCD terms

Gluon couples in the same way to all quarks

Photon couples in different ways to up-like and down-like quarks

More difficult to diagonalize (see next slide)

Adding QED: corrections to DGLAP

Solving the system

Pure QCD case

$$\mu^2 \frac{d}{d\mu^2} \begin{pmatrix} g \\ \Sigma \end{pmatrix} = \begin{pmatrix} P_{gg} & P_{gq} \\ P_{qg} & P_{qq} \end{pmatrix} \otimes \begin{pmatrix} g \\ \Sigma \end{pmatrix}$$

$$\mu^2 \frac{d}{d\mu^2} V = P_{ns,v} \otimes V$$

$$\mu^2 \frac{d}{d\mu^2} f_{ns,\pm} = P_{ns,\pm} \otimes f_{ns,\pm}$$

$$\Sigma = \sum_{i=1}^{n_f} q_i^+ \quad V = \sum_{i=1}^{n_f} q_i^-$$

$$q^\pm = q \pm \bar{q}$$

$$f_{ns,\pm} = \begin{cases} u^\pm - d^\pm \\ u^\pm + d^\pm - 2s^\pm \\ u^\pm + d^\pm + s^\pm - 3c^\pm \\ u^\pm + d^\pm + s^\pm + c^\pm - 4b^\pm \\ u^\pm + d^\pm + s^\pm + c^\pm + b^\pm - 5t^\pm \end{cases}$$

QCD⊗QED case

$$\mu^2 \frac{d}{d\mu^2} \begin{pmatrix} g \\ \gamma \\ \Sigma \\ \Sigma_\Delta \end{pmatrix} = \mathbf{P_s} \otimes \begin{pmatrix} g \\ \gamma \\ \Sigma \\ \Sigma_\Delta \end{pmatrix}$$

$$\mu^2 \frac{d}{d\mu^2} \begin{pmatrix} V \\ V_\Delta \end{pmatrix} = \mathbf{P_v} \otimes \begin{pmatrix} V \\ V_\Delta \end{pmatrix}$$

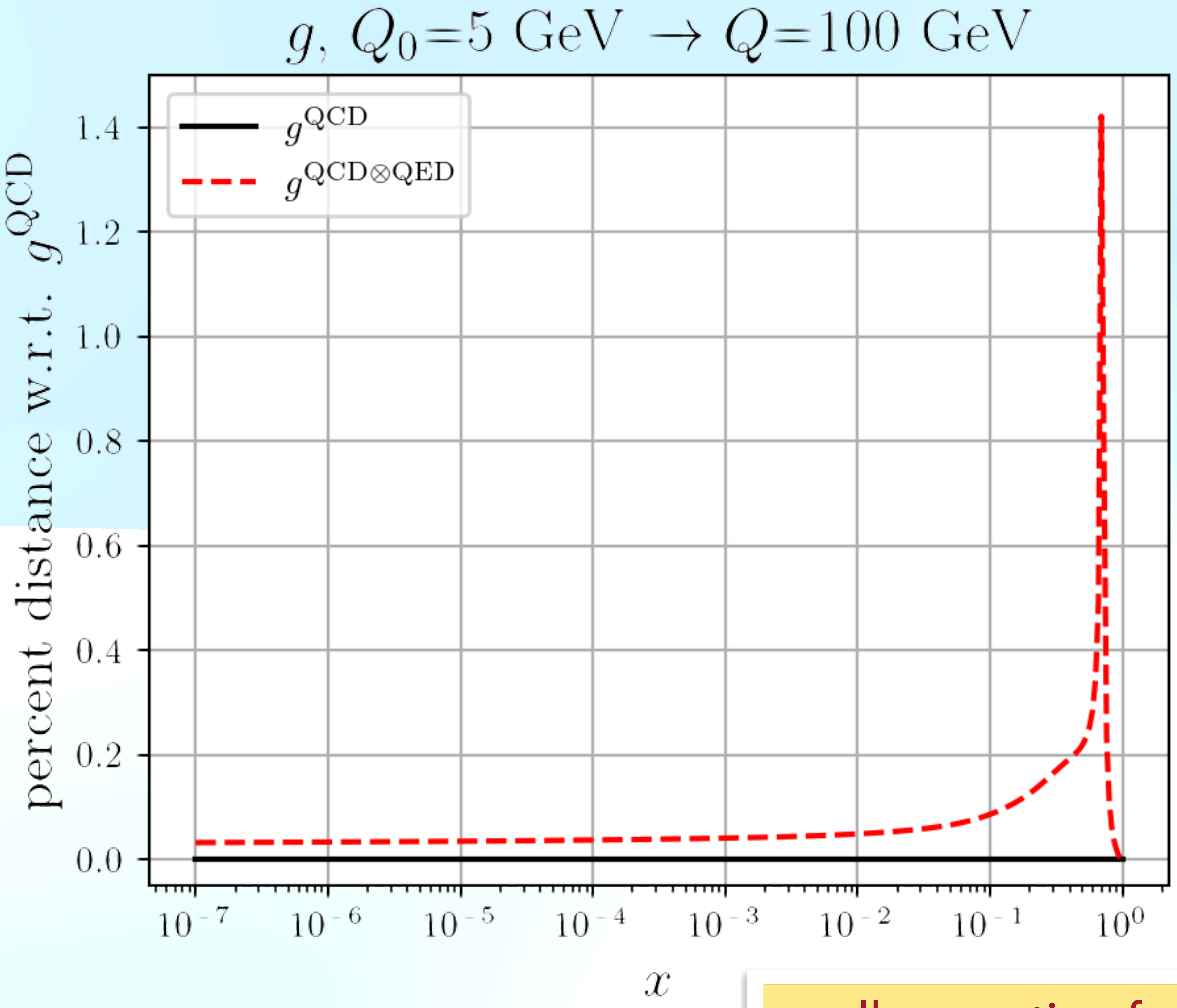
$$\mu^2 \frac{d}{d\mu^2} f_{ns,\pm}^{u/d} = \left(P_{ns,\pm} + \tilde{P}_{ns,\pm}^{u/d} \right) \otimes f_{ns,\pm}^{u/d}$$

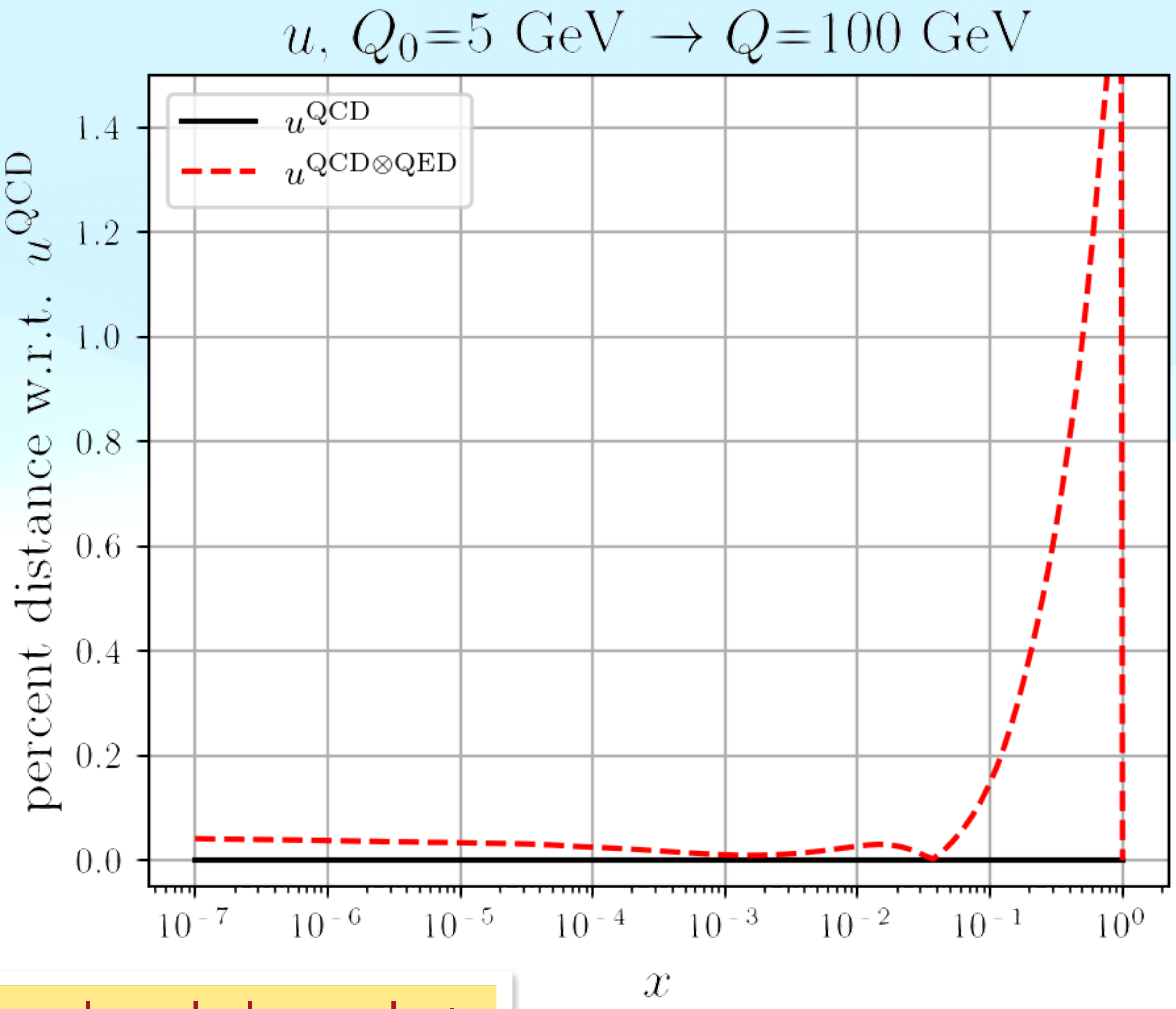
$$f_{ns,\pm}^u = \begin{cases} u^\pm - c^\pm \\ u^\pm + c^\pm - 2t^\pm \end{cases} \quad f_{ns,\pm}^d = \begin{cases} d^\pm - s^\pm \\ d^\pm + s^\pm - 2b^\pm \end{cases}$$

$$\Sigma_\Delta = \frac{n_d}{n_u} \sum_{i=1}^{n_u} u_i^+ - \sum_{i=1}^{n_d} d_i^+ \quad V_\Delta = \frac{n_d}{n_u} \sum_{i=1}^{n_u} u_i^- - \sum_{i=1}^{n_d} d_i^-$$

Adding QED: corrections to DGLAP

Numerical results





small correction for quark and gluon…but needed for the evolution of the photon!

Adding QED: photon PDF

- Photon PDF is obtained from LuxQED approach [Manohar, Nason, Salam, Zanderighi, 2016]

$$x\gamma(x,\mu^2) = \frac{1}{2\pi\alpha(\mu^2)} \int_x^1 \frac{dz}{z} \left\{ \int_{\frac{m_p^2 x^2}{1-z}}^{\frac{\mu^2}{1-z}} \frac{dQ^2}{Q^2} \alpha^2(Q^2) \left[\left(z P_{\gamma q}(z) + \frac{2x^2 m_p^2}{Q^2} \right) F_2(x/z, Q^2) - z^2 F_L(x/z, Q^2) \right] - \alpha^2(\mu^2) z^2 F_2(x/z, \mu^2) \right\}$$

$$F_{2,L} = \sum_i C_{2,L,i} \otimes f_i$$

γ depends on the other PDFs!!

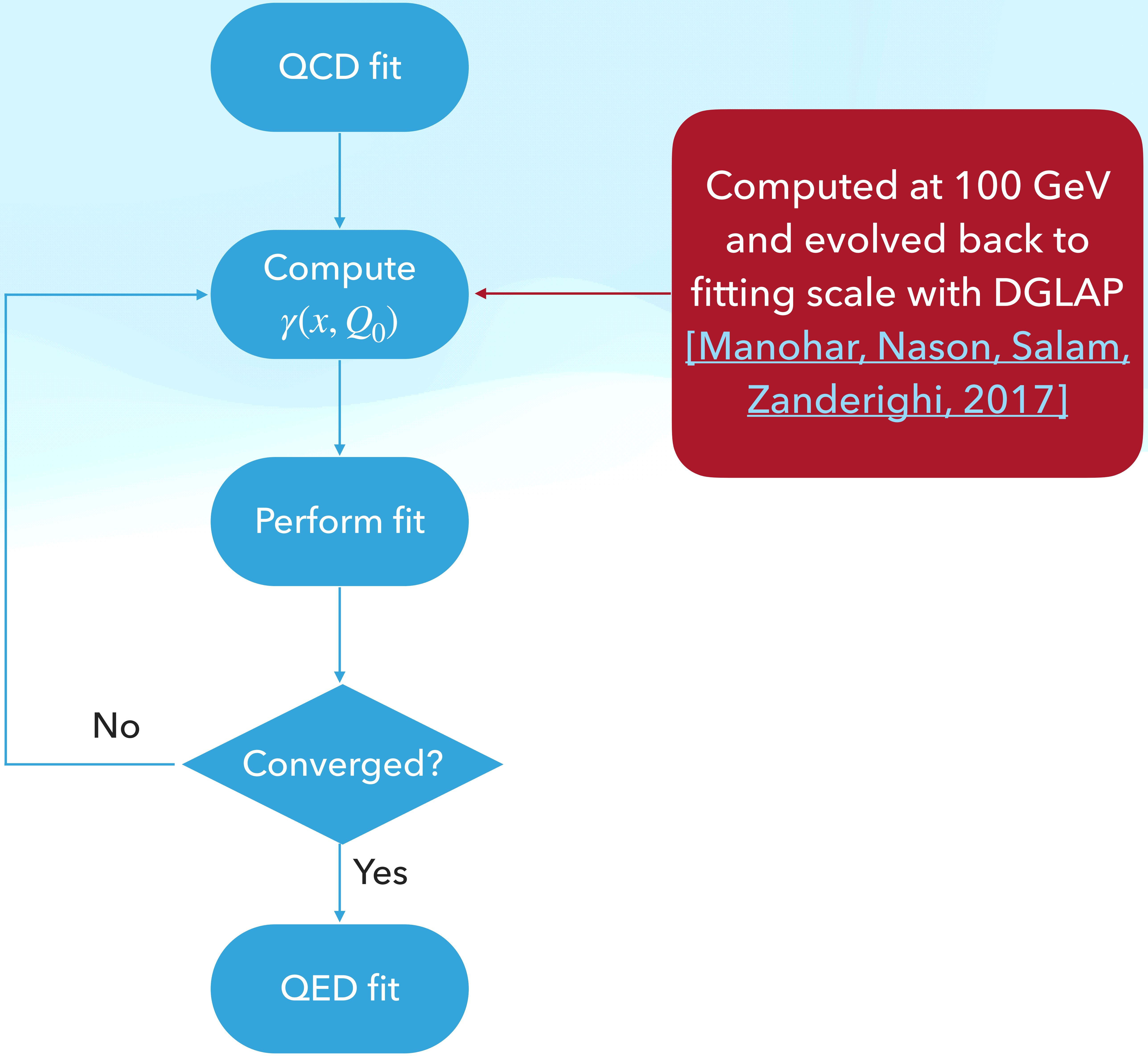
- γ modifies the momentum sum rules:

$$\int_0^1 dx\, x \left(\Sigma(x,Q^2) + g(x,Q^2) + \gamma(x,Q^2) \right) = 1$$

Adding QED: iteration

LuxQED formula gives a constraint between γ and the other PDFs

Such constraint is implemented iteratively



RESULTS OF THE FIT

Results of the fit: **remark**

No photon-initiated contributions in theory predictions

Chosen dataset cuts points in which they are important

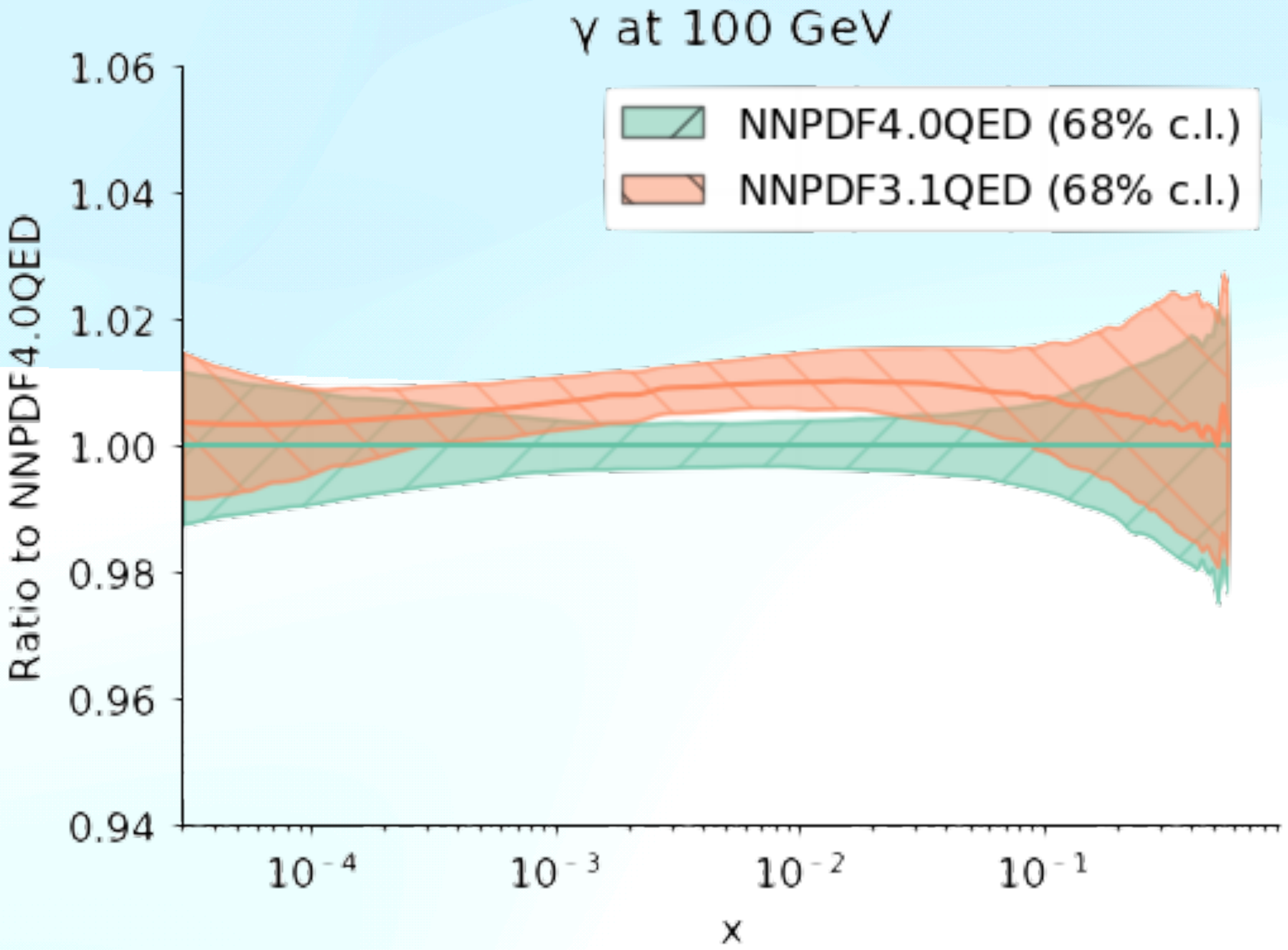
QED corrections enter in the fit through momentum sum rule and DGLAP evolution

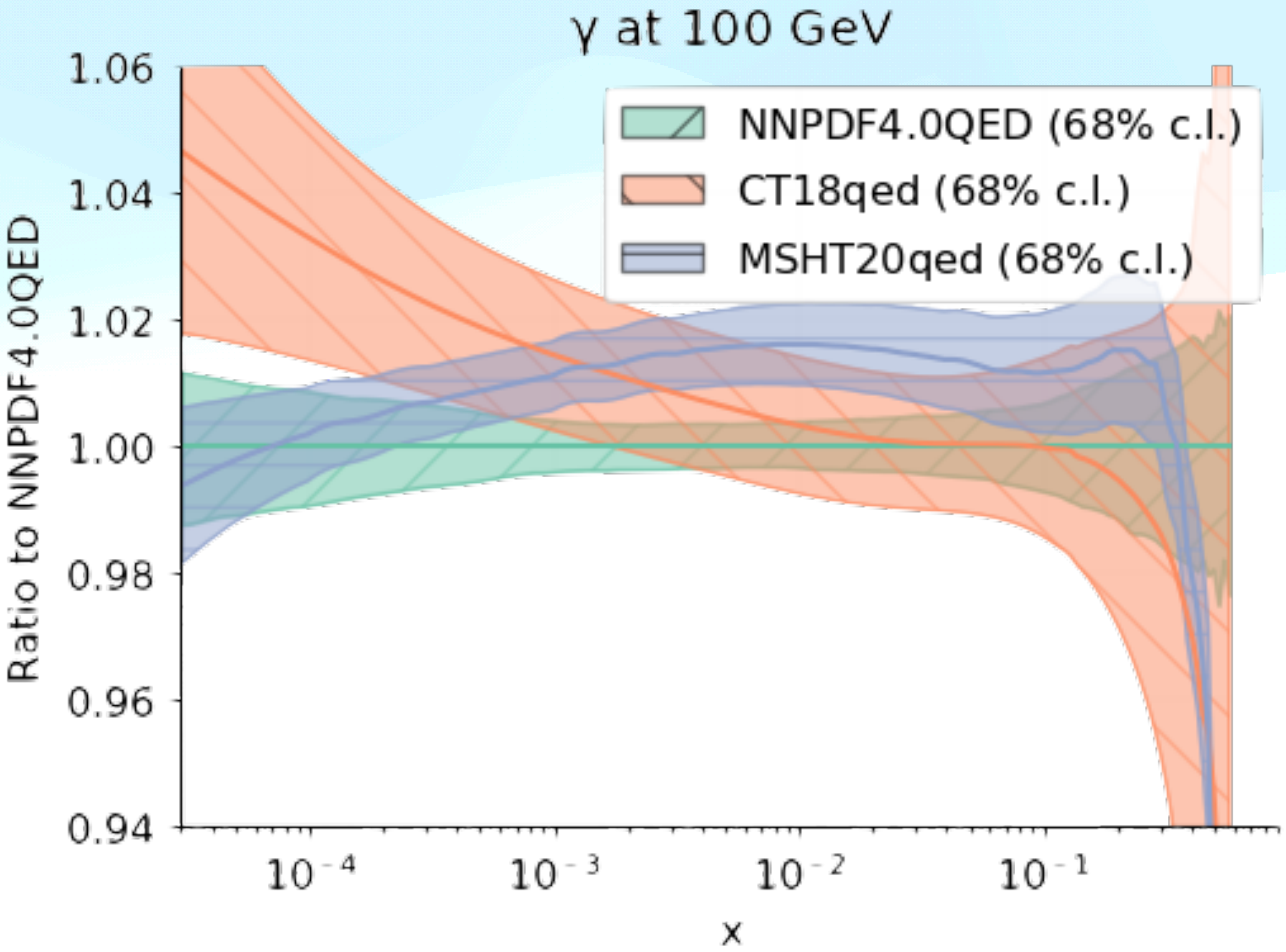
Future development

Add photon-initiated contributions and add data points in which they are important

Results of the fit: photon

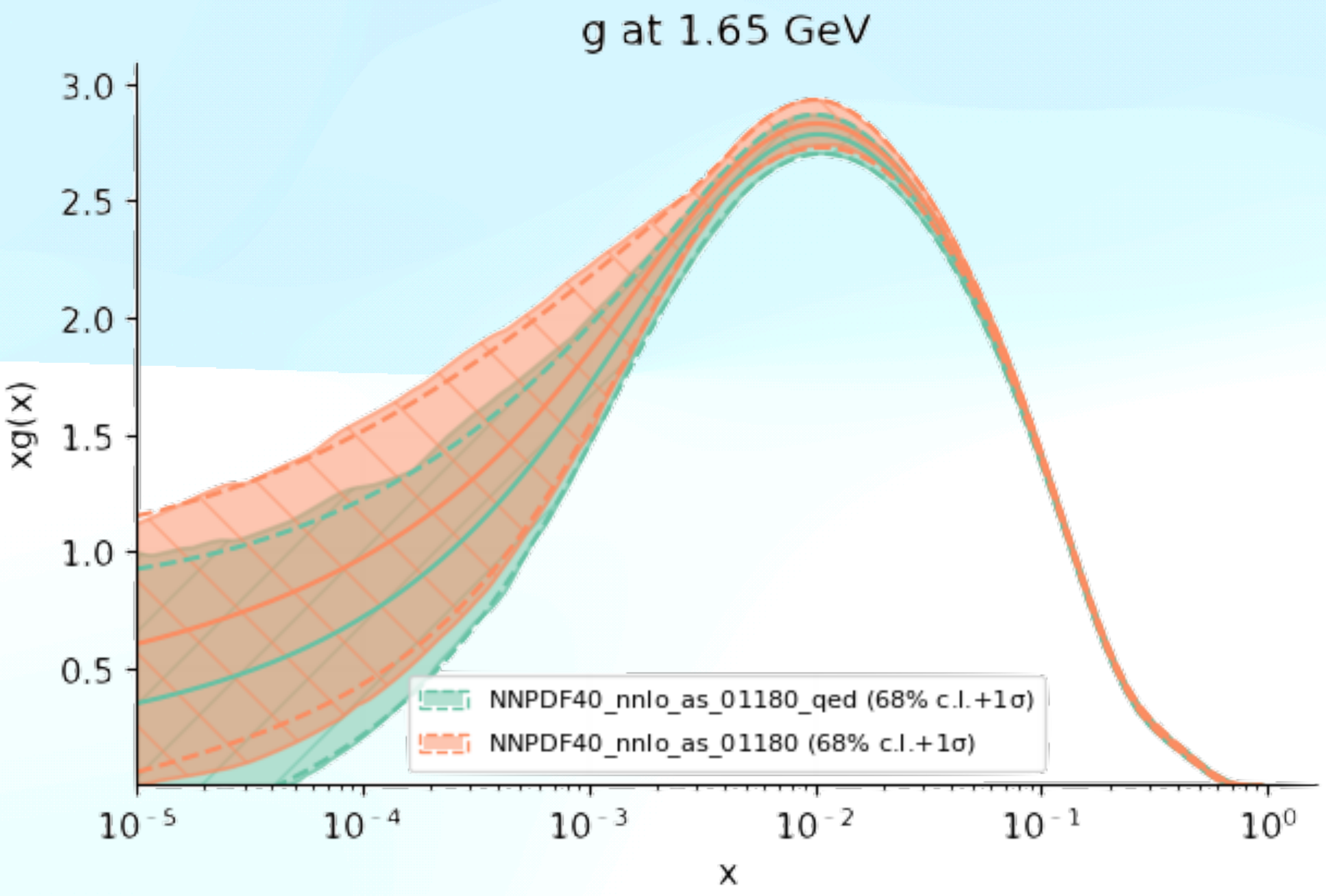
Comparison with other QED fits

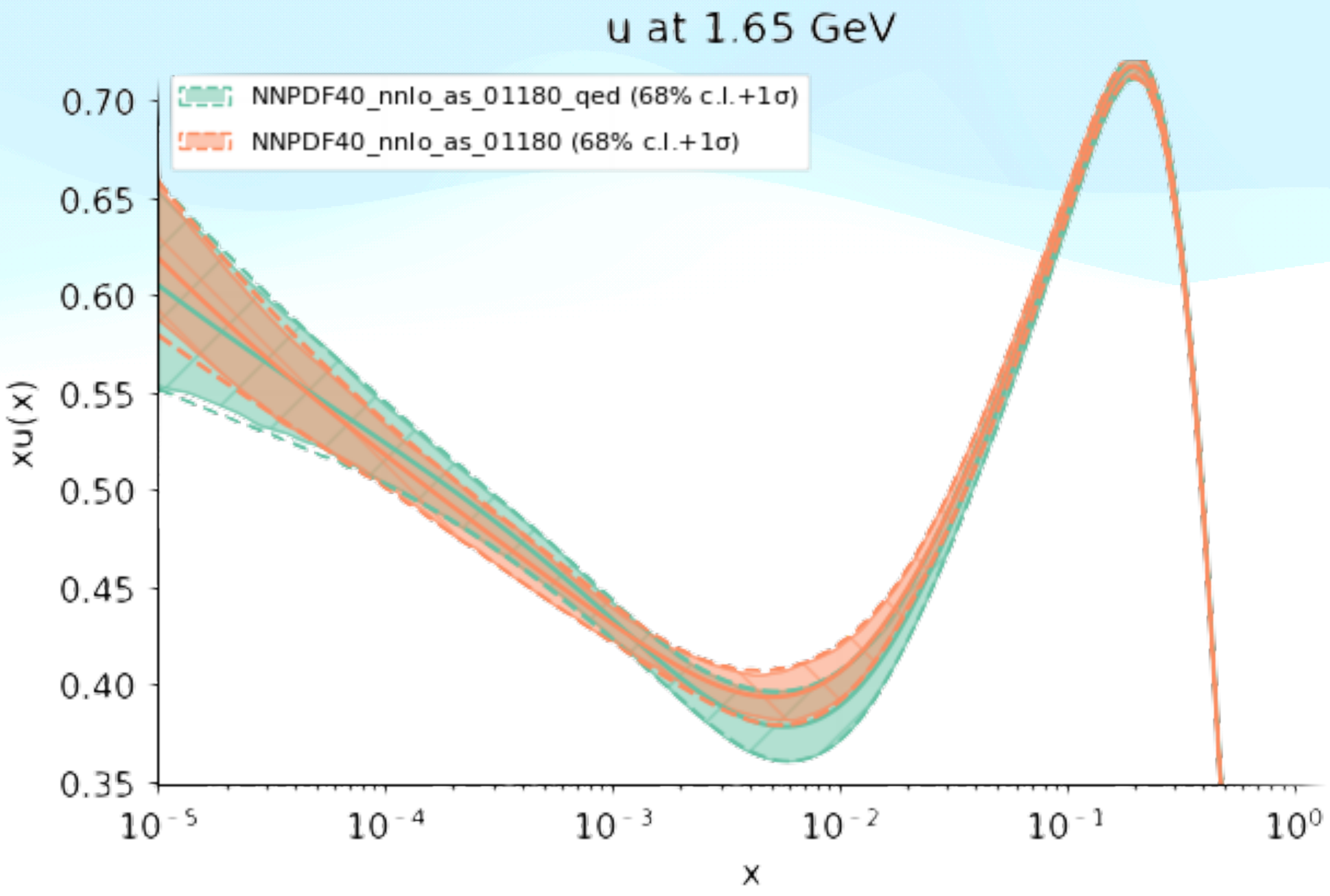




Results of the fit: quarks and gluon

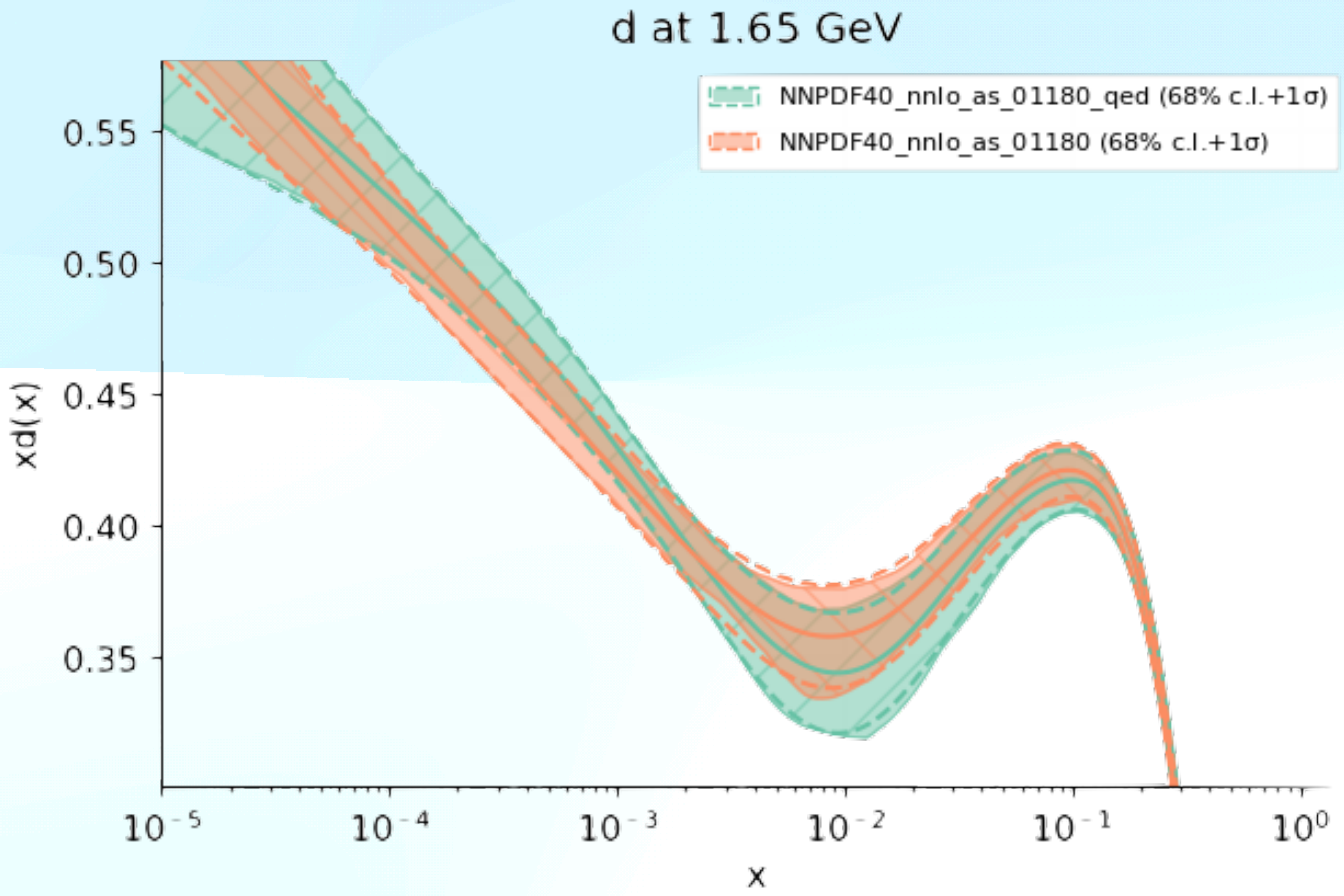
Comparison with NNPDF4.0

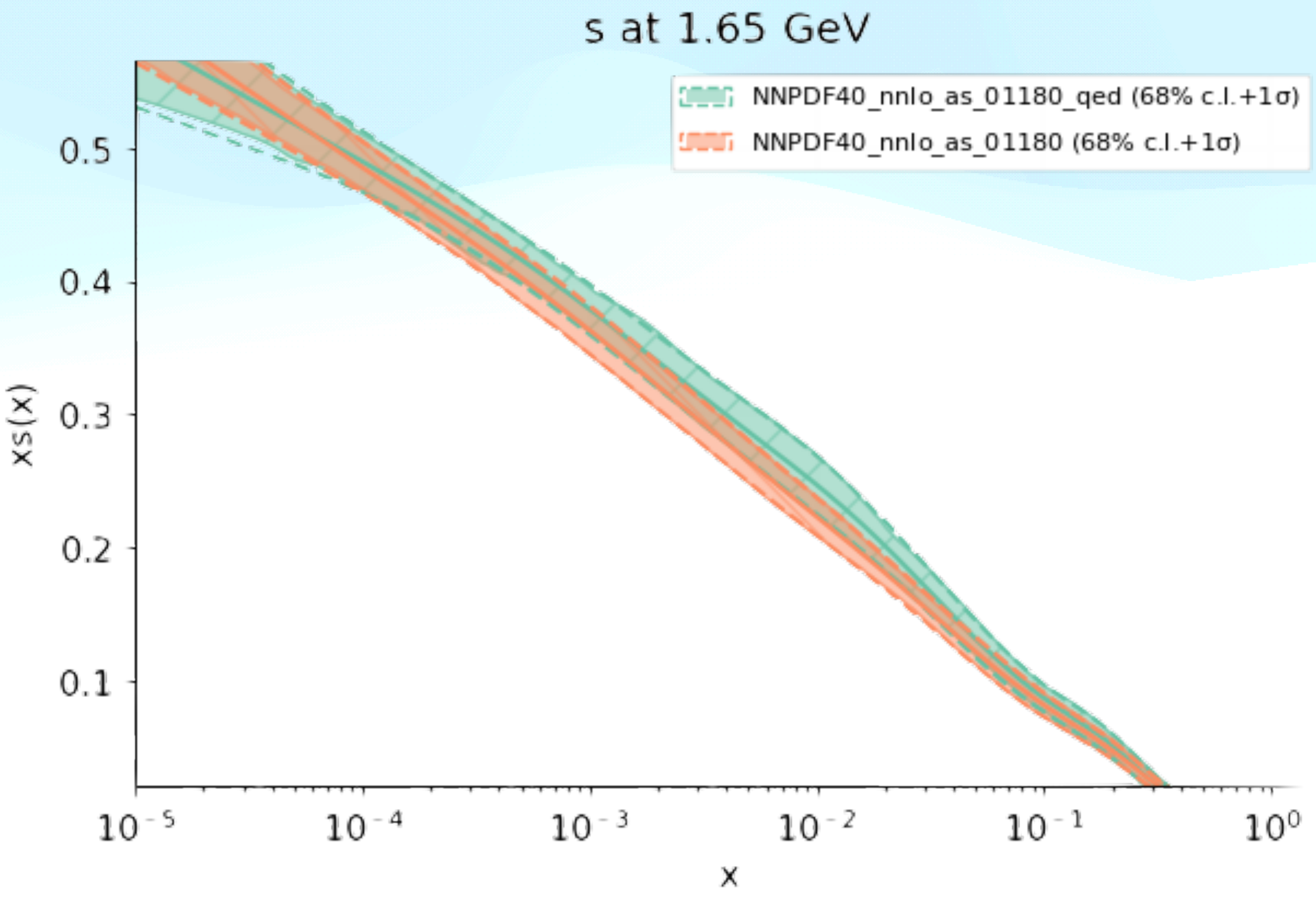




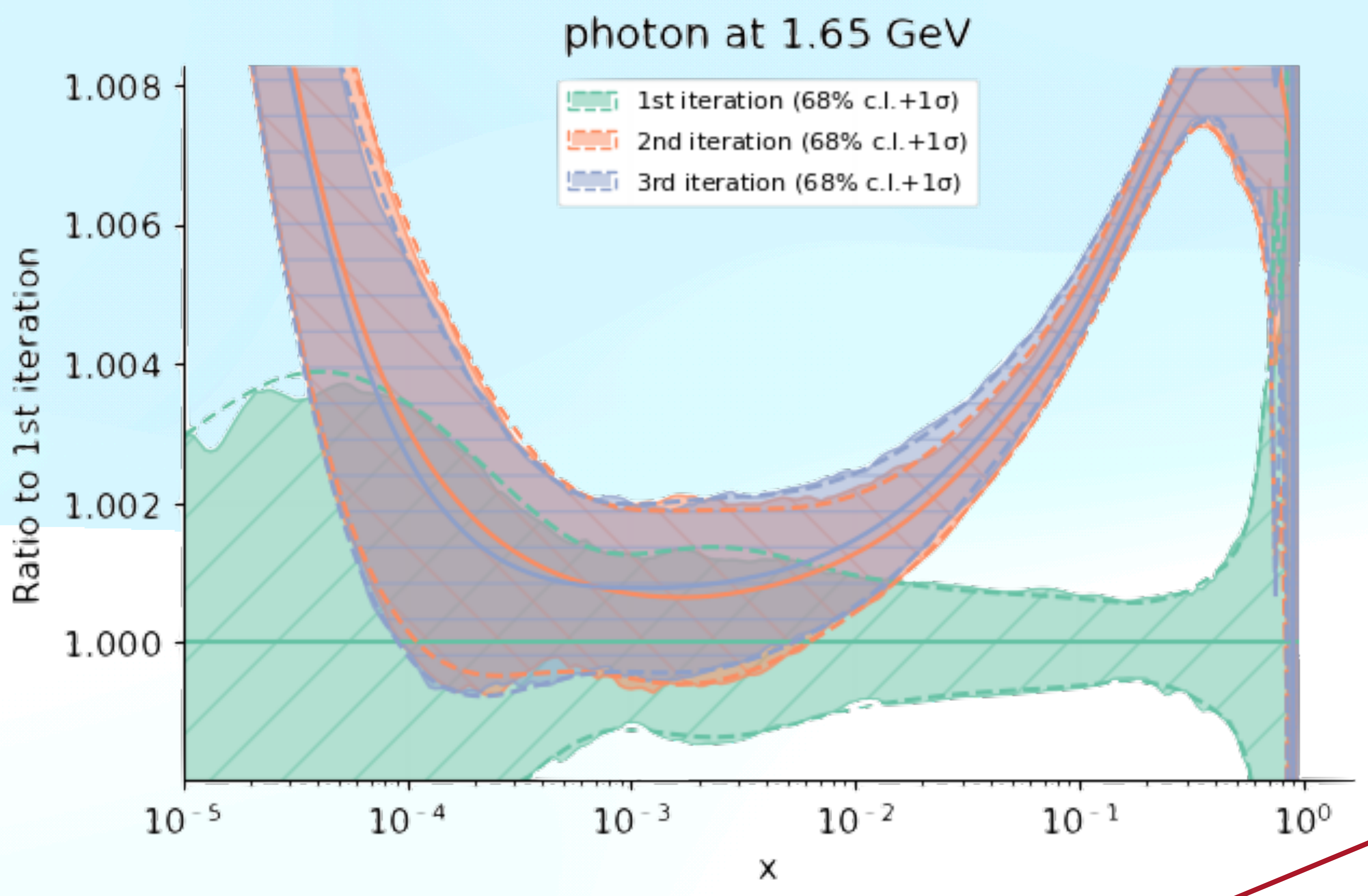
Results of the fit: quarks and gluon

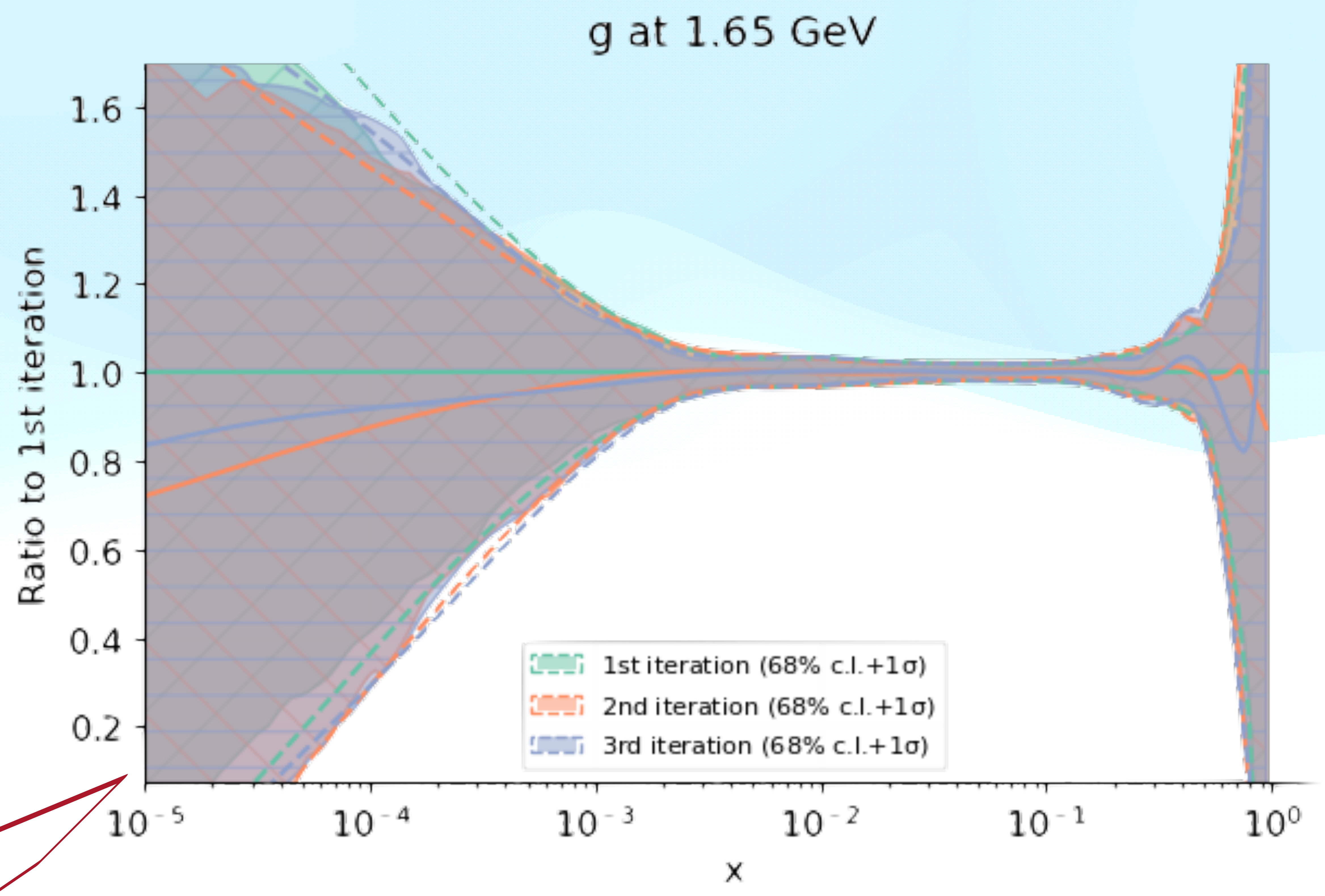
Comparison with NNPDF4.0





Results of the fit: iteration

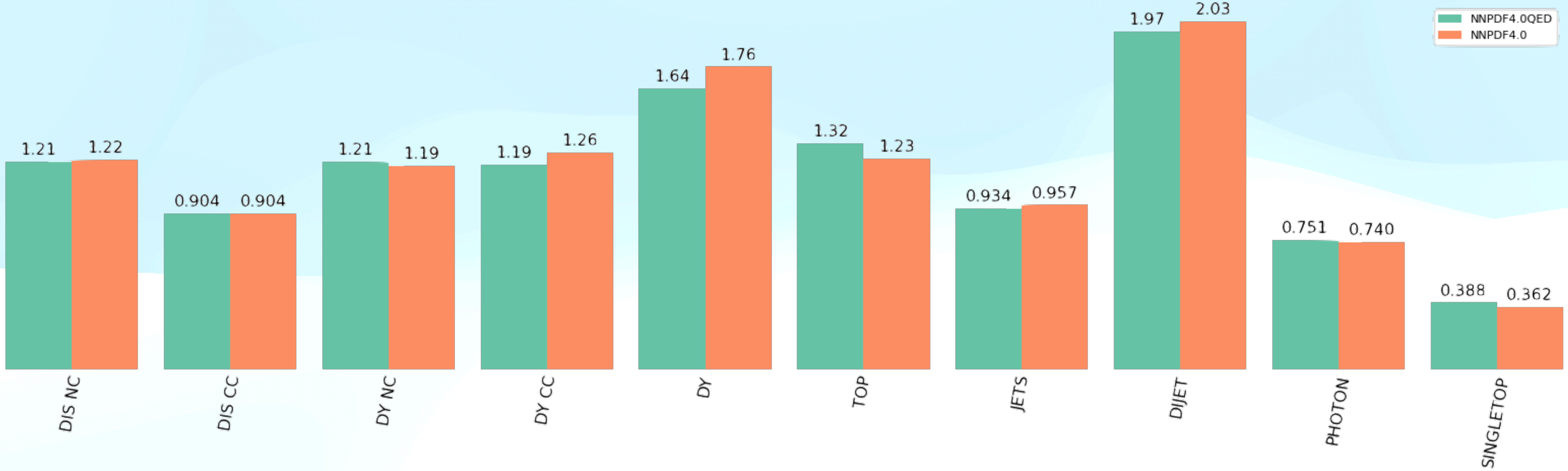




Two iterations are enough for the fit to converge!

Results of the fit: **fit quality**

χ^2 by processes:



Few words on a new pipeline

NNPDF4.0

Based on

`APFEL`

`APFELgrid`

`APPLgrid`

NNPDF4.0QED

Based on

`EKO`

`Pinefarm` new tools!

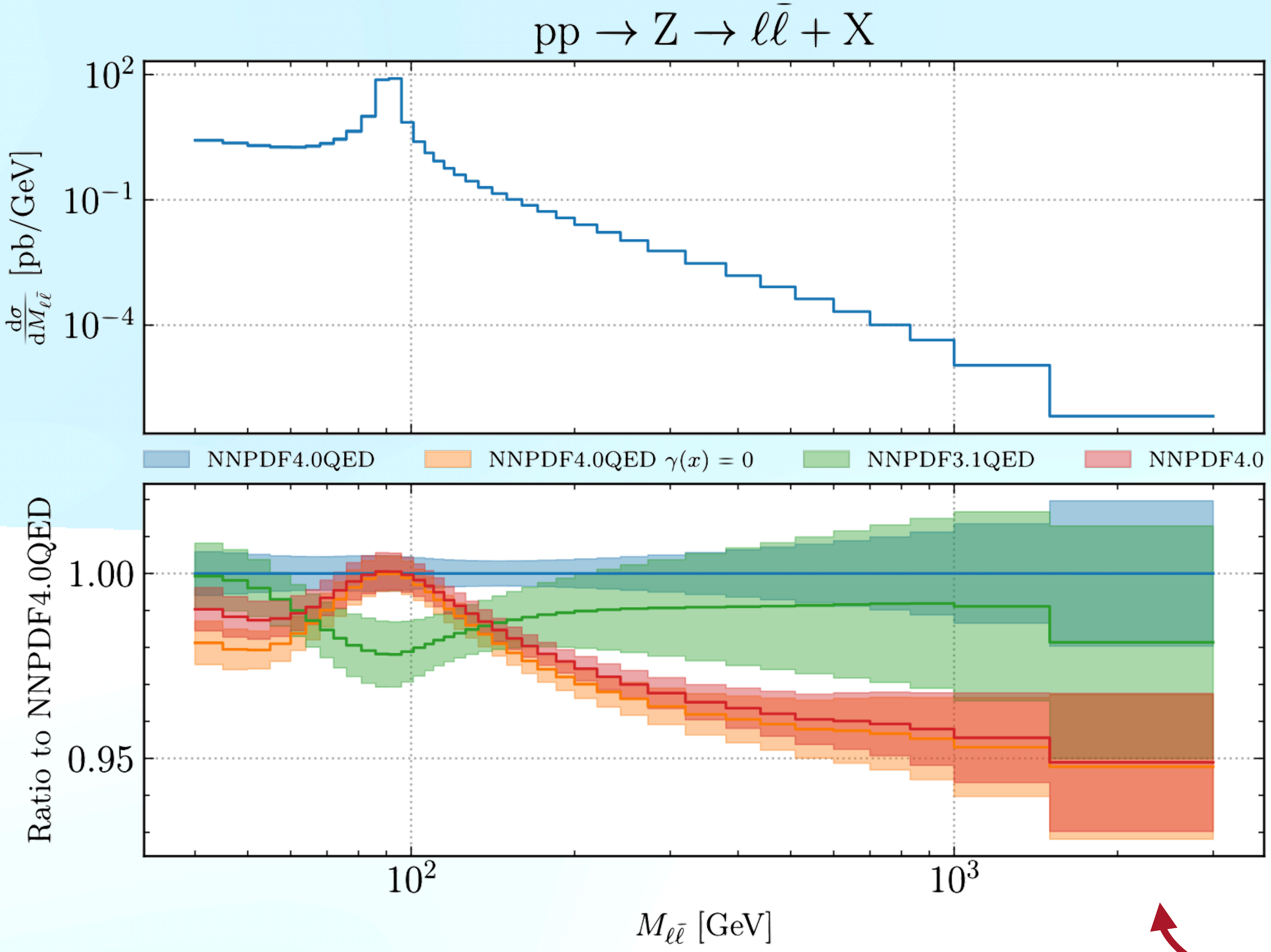
`PineAPPL`

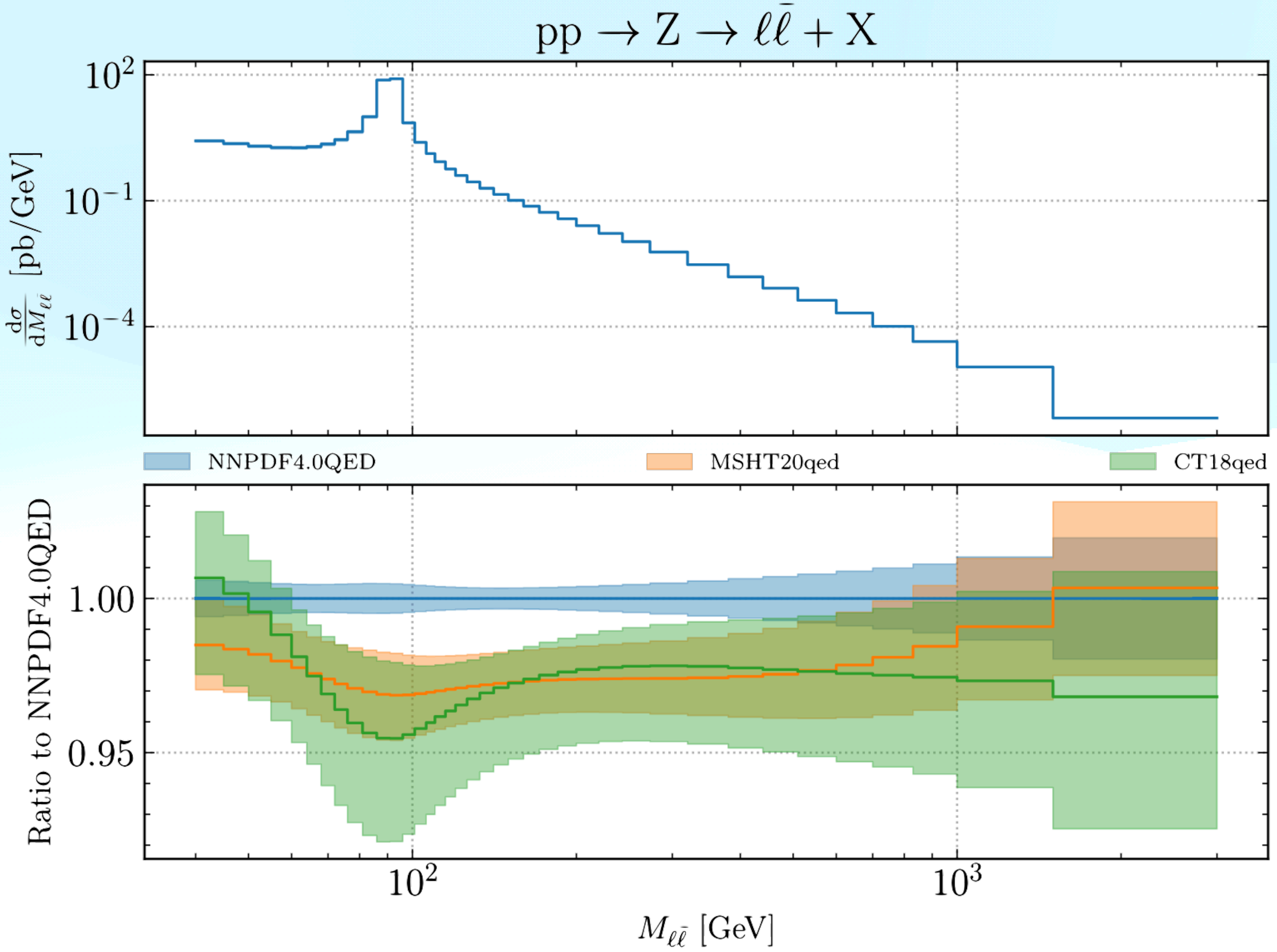
It will allow photon induced contributions in the theory predictions!

See "Pineline: Industrialization of High-Energy Theory Predictions" by A. Barontini

IMPACT ON PHENOMENOLOGY

Impact on phenomenology: inclusive Drell-Yan production





In this section photon-induced channels have been included

In the high invariant mass region QED corrections are not negligible!

Impact on phenomenology: weak boson production

In the high p_T region QED corrections are not negligible!

SUMMARY AND CONCLUSIONS

Summary and conclusions

- ☑ We can add QED corrections to PDF fitting, getting a photon PDF
- ☑ The photon PDF is compatible with the most recent QED fits
- ☑ Quarks and gluon are almost unchanged (the photon PDF is small)
- ☑ There are processes in which photon initiated contributions are not negligible
- ☑ Soon we will be able to add such processes in our theory predictions

Thanks for your attention!!

BACKUP SLIDES

Solving DGLAP

Singlet and Valence sectors

$$\mathbf{P}_\mathrm{s} = \begin{pmatrix} P_{gg} + \tilde{P}_{gg} & \tilde{P}_{g\gamma} & P_{gq} + \langle \tilde{P}_{gq} \rangle & \nu_u \tilde{P}_{g\Delta q} \\ \tilde{P}_{\gamma g} & \tilde{P}_{\gamma\gamma} & \langle \tilde{P}_{\gamma q} \rangle & \nu_u \tilde{P}_{\gamma \Delta q} \\ 2n_f (P_{qg} + \langle \tilde{P}_{qg} \rangle) & 2n_f \langle \tilde{P}_{q\gamma} \rangle & P_{qq} + \langle \tilde{P}^{\mathrm{ns},+}_q \rangle + \langle e_q^2 \rangle^2 \tilde{P}_\mathrm{ps} & \nu_u \tilde{P}^{\mathrm{ns},+}_{\Delta q} + \nu_u e^2_{\Delta q} \langle e_q^2 \rangle \tilde{P}_\mathrm{ps} \\ 2n_f \nu_d \tilde{P}_{\Delta q g} & 2n_f \nu_d \tilde{P}_{\Delta q \gamma} & \nu_d \tilde{P}^{\mathrm{ns},+}_{\Delta q} + \nu_d e^2_{\Delta q} \langle e_q^2 \rangle \tilde{P}_\mathrm{ps} & P_{\mathrm{ns},+} + \{ \tilde{P}^{\mathrm{ns},+}_q \} + \nu_u \nu_d (e^2_{\Delta q})^2 \tilde{P}_\mathrm{ps} \end{pmatrix}$$

$$\mathbf{P}_\mathrm{v} = \begin{pmatrix} P_{\mathrm{ns},V} + \langle \tilde{P}^{\mathrm{ns},-}_q \rangle & \nu_u \tilde{P}^{\mathrm{ns},-}_{\Delta q} \\ \nu_d \tilde{P}^{\mathrm{ns},-}_{\Delta q} & P_{\mathrm{ns}-} + \{ \tilde{P}^{\mathrm{ns},-}_q \} \end{pmatrix}$$

$$\nu_{u/d} = \frac{n_{u/d}}{n_f}, \quad \langle \tilde{P}^{\mathrm{ns},\pm}_q \rangle = \nu_u \tilde{P}^{\mathrm{ns},\pm}_u + \nu_d \tilde{P}^{\mathrm{ns},\pm}_d,$$

$$\{ \tilde{P}^{\mathrm{ns},\pm}_q \} = \nu_d \tilde{P}^{\mathrm{ns},\pm}_u + \nu_u \tilde{P}^{\mathrm{ns},\pm}_d, \quad \tilde{P}^{\mathrm{ns},\pm}_{\Delta q} = \tilde{P}^{\mathrm{ns},\pm}_u - \tilde{P}^{\mathrm{ns},\pm}_d$$

Solving DGLAP

Solution of the non-diagonal sectors

$\mu^{2(n)} = \mu^2$

$$\mathbf{E}_S(\mu^2 \leftarrow \mu_0^2) = \mathscr{P} \exp\left(-\int_{\log \mu_0^2}^{\log \mu^2} \gamma_S(\alpha_s(\mu'^2), \alpha(\mu'^2)) d \log \mu'^2 \right) \simeq \prod_{k=0}^{n-1} \mathbf{E}_S(\mu^{2(k+1)} \leftarrow \mu^{2(k)})$$

$$\gamma(N) = -\int_0^1 dz\, z^{N-1} P(z)$$

Solved in Mellin space

$$\mathbf{E}_S(\mu^{2(k+1)} \leftarrow \mu^{2(k)}) = \exp\left(-\gamma_S(\alpha_s(\mu^{2(k+1/2)}), \alpha(\mu^{2(k+1/2)}))\Delta \log \mu^{2(k)}\right)$$

$$\log \mu^{2(k+1/2)} = \frac{\log \mu^{2(k+1)} + \log \mu^{2(k)}}{2}$$

$$\Delta \log \mu^{2(k)} = \log \mu^{2(k+1)} - \log \mu^{2(k)}$$

Computation of the photon

Why the LuxQED formula is used at 100 GeV?

LuxQED neglects higher twist corrections $\mathcal{O}\left(\frac{\Lambda}{\mu}\right)$

For low μ, the integral is dominated by low Q^2 structure functions

non-perturbative!