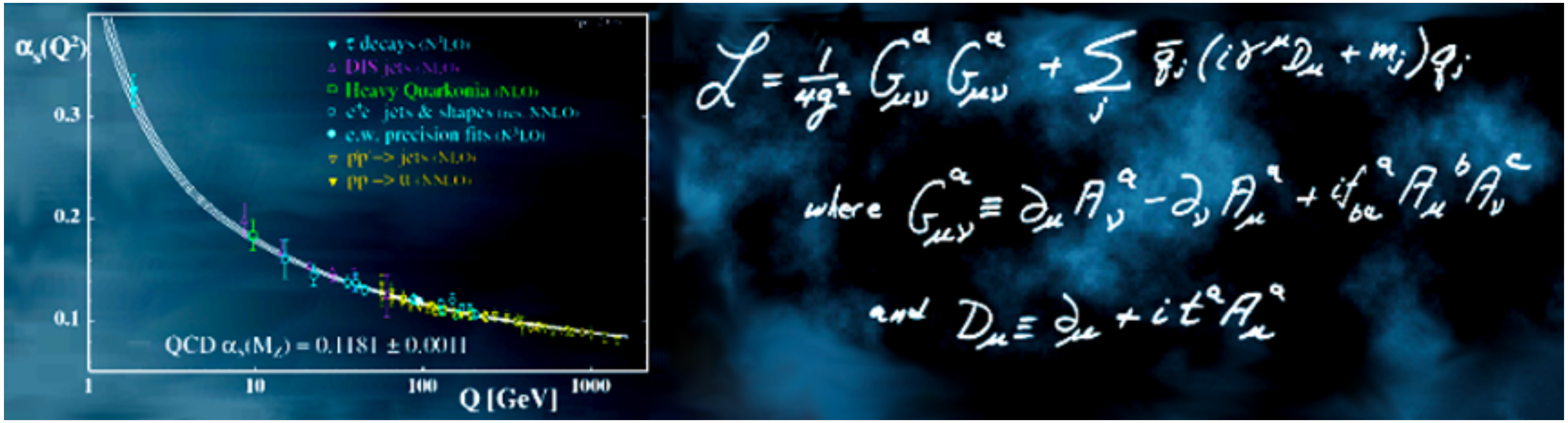
Strong coupling fits from NNPDF global analyses

Juan Rojo, VU Amsterdam & Nikhef

alphas-2022 Workshop

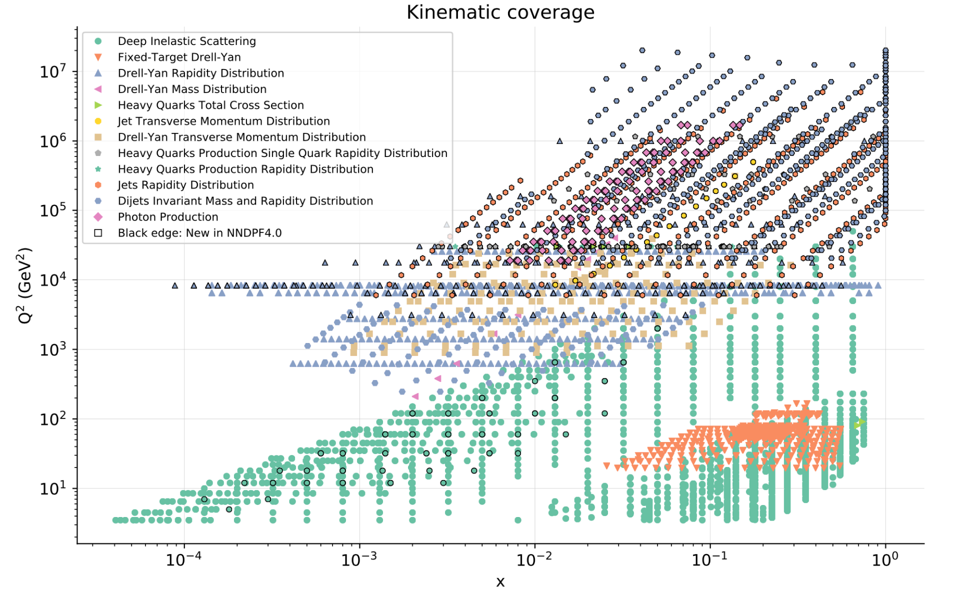
February 1st 2022



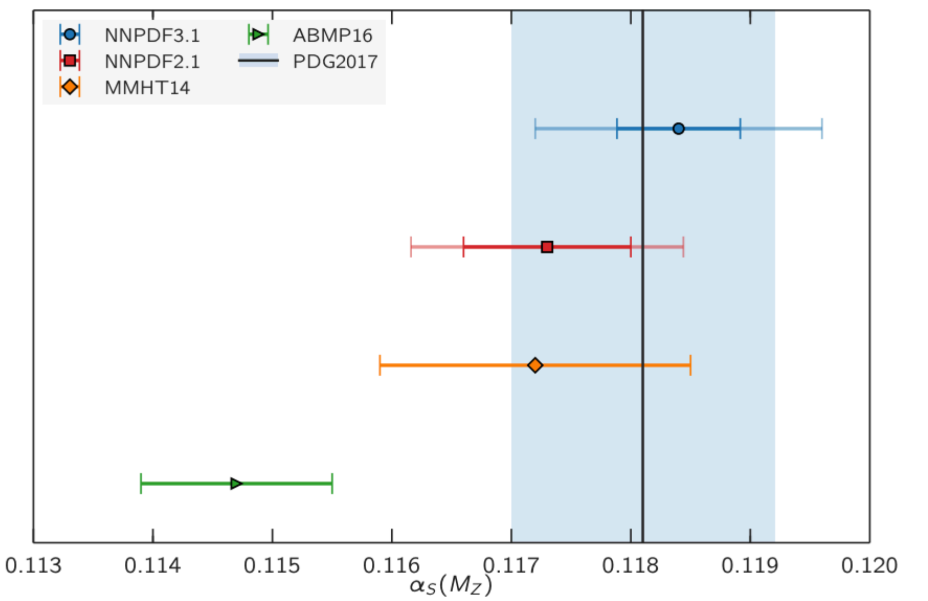
Outline

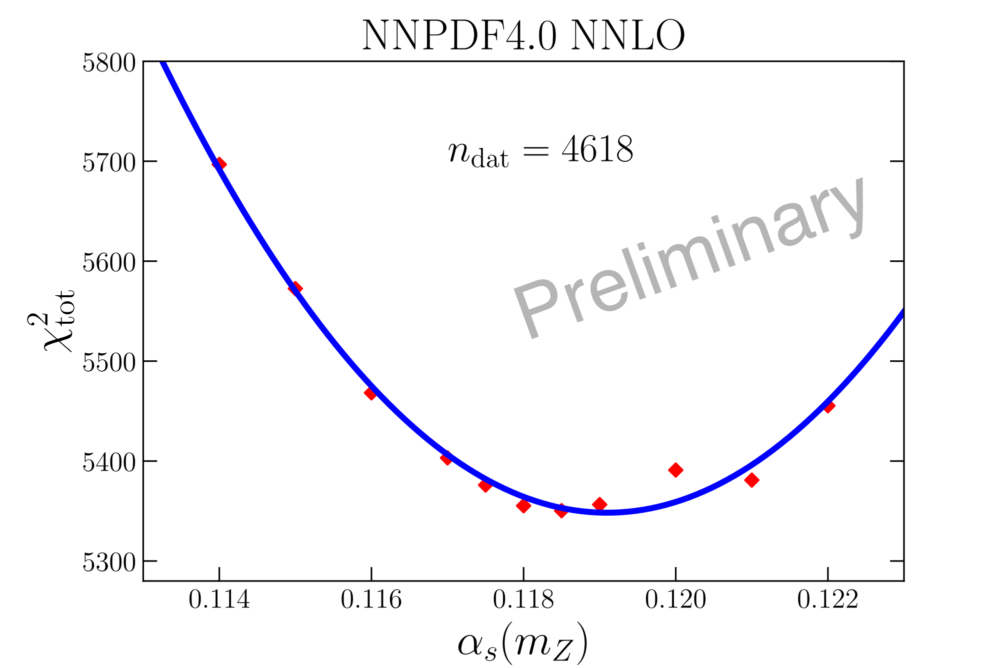
- The NNPDF4.0 global PDF analysis
- Strong coupling determination from NNPDF3.1
- Preliminary results based on NNPDF4.0
- The SimuNET strategy

NNPDF4.0: data set extension



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

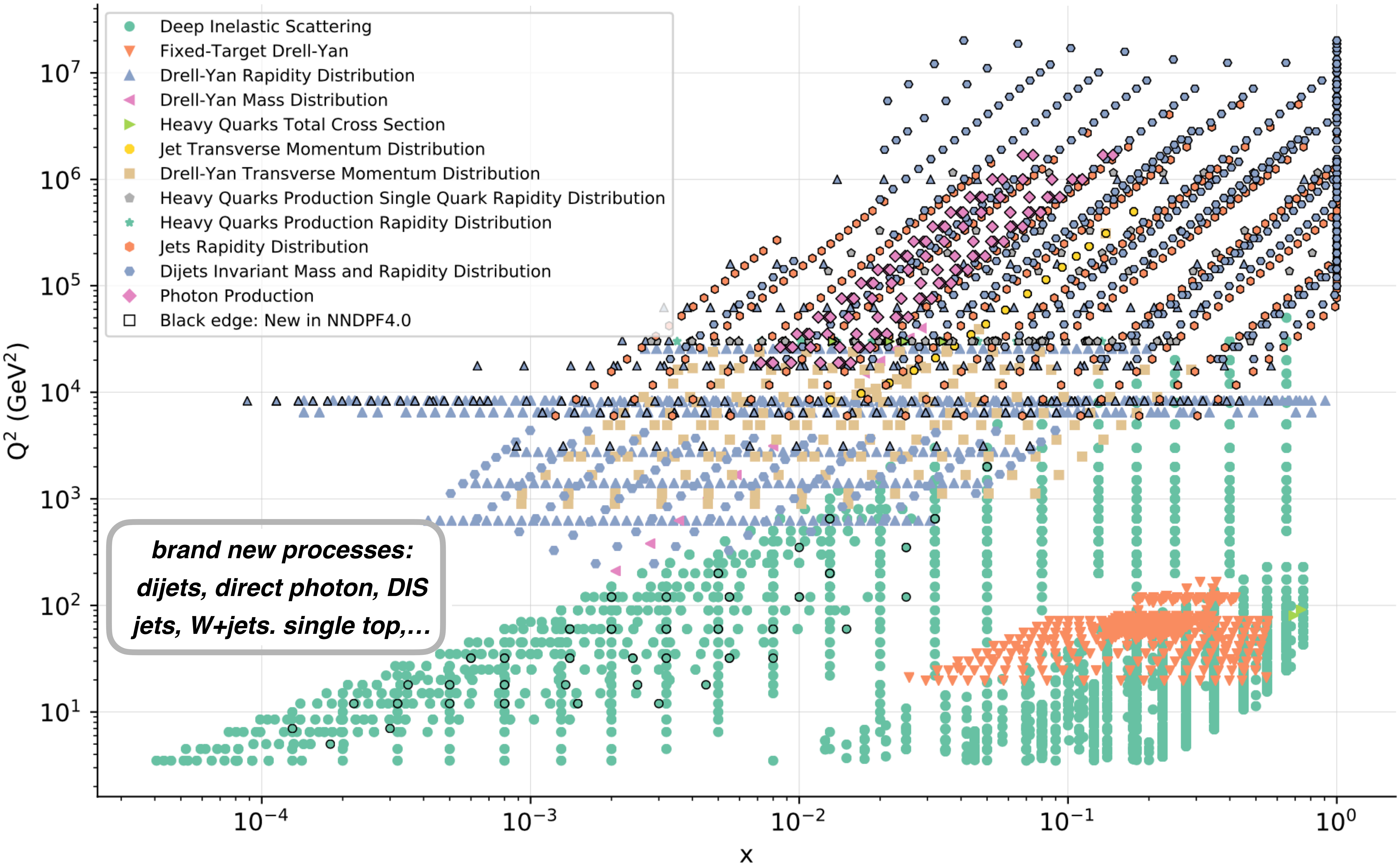




NNPDF4.0

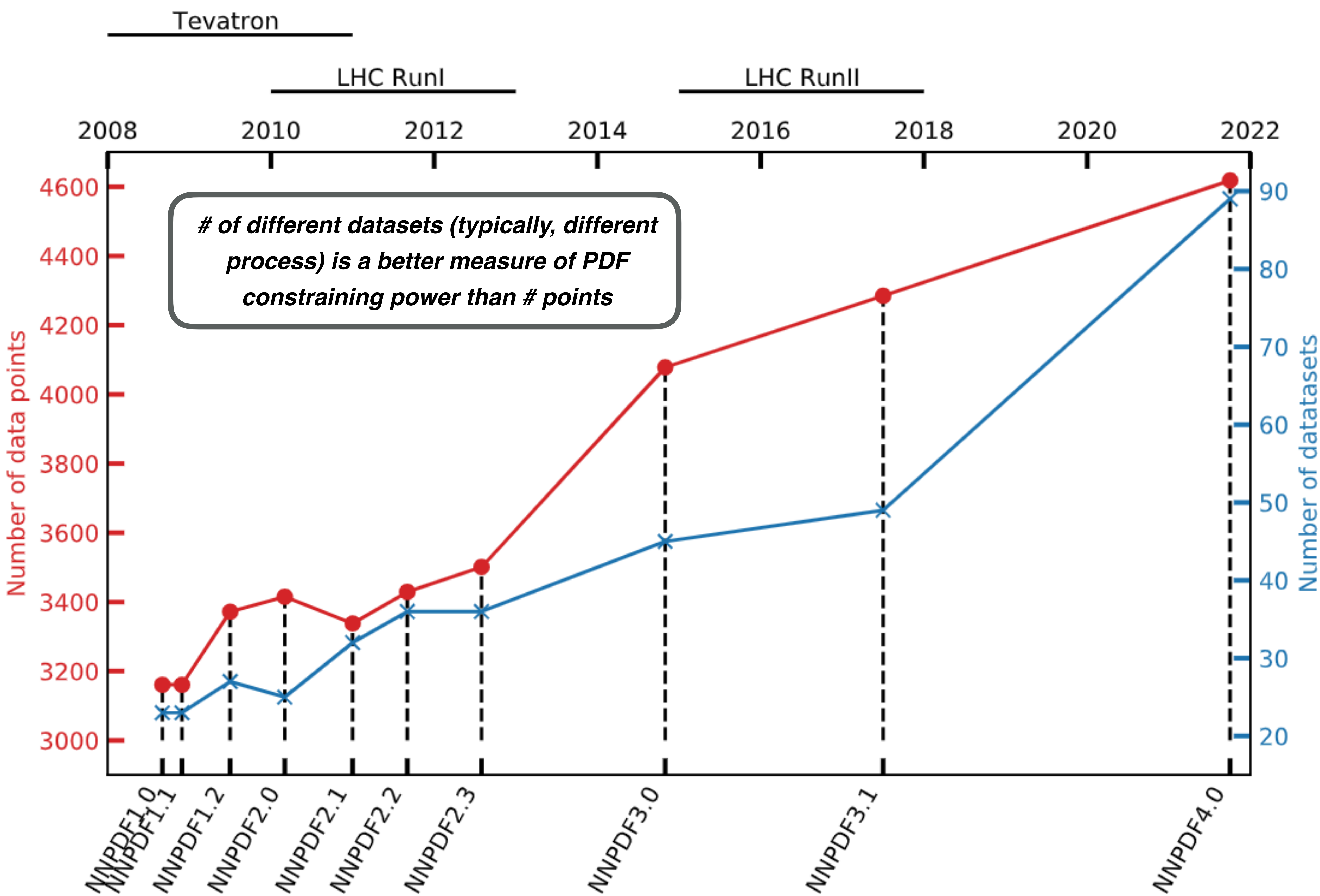
arXiv:2109.02653

The NNPDF4.0 dataset



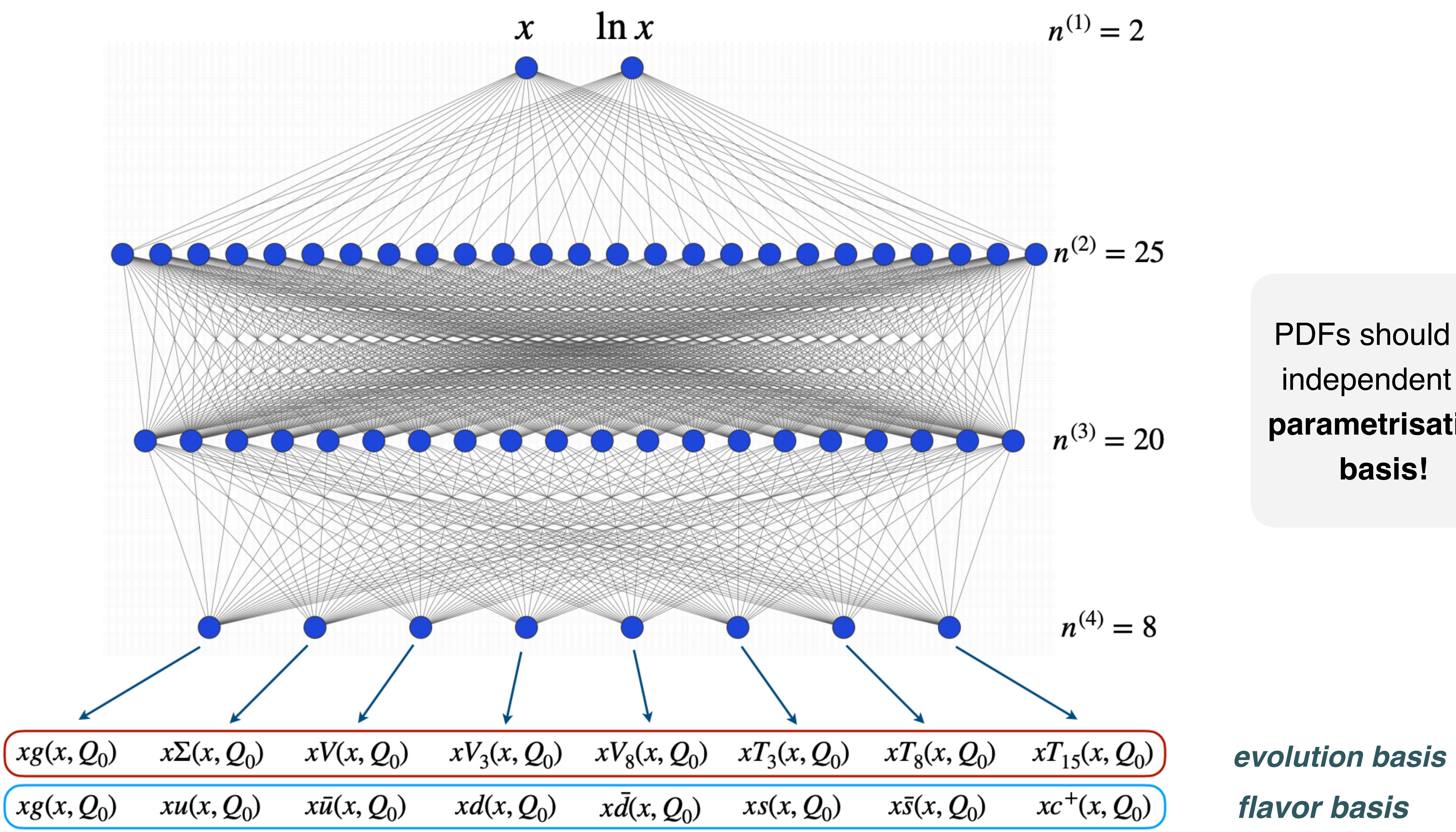
$\mathcal{O}(50)$ data sets investigated; $\mathcal{O}(400)$ data points more in NNPDF4.0 than in NNPDF3.1

From NNPDF1.0 to NNPDF4.0



Improved fitting methodology

- ☑ **Stochastic Gradient Descent** via TensorFlow for NN 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)



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

Improved fitting methodology

- **Stochastic Gradient Descent** via TensorFlow for NN training
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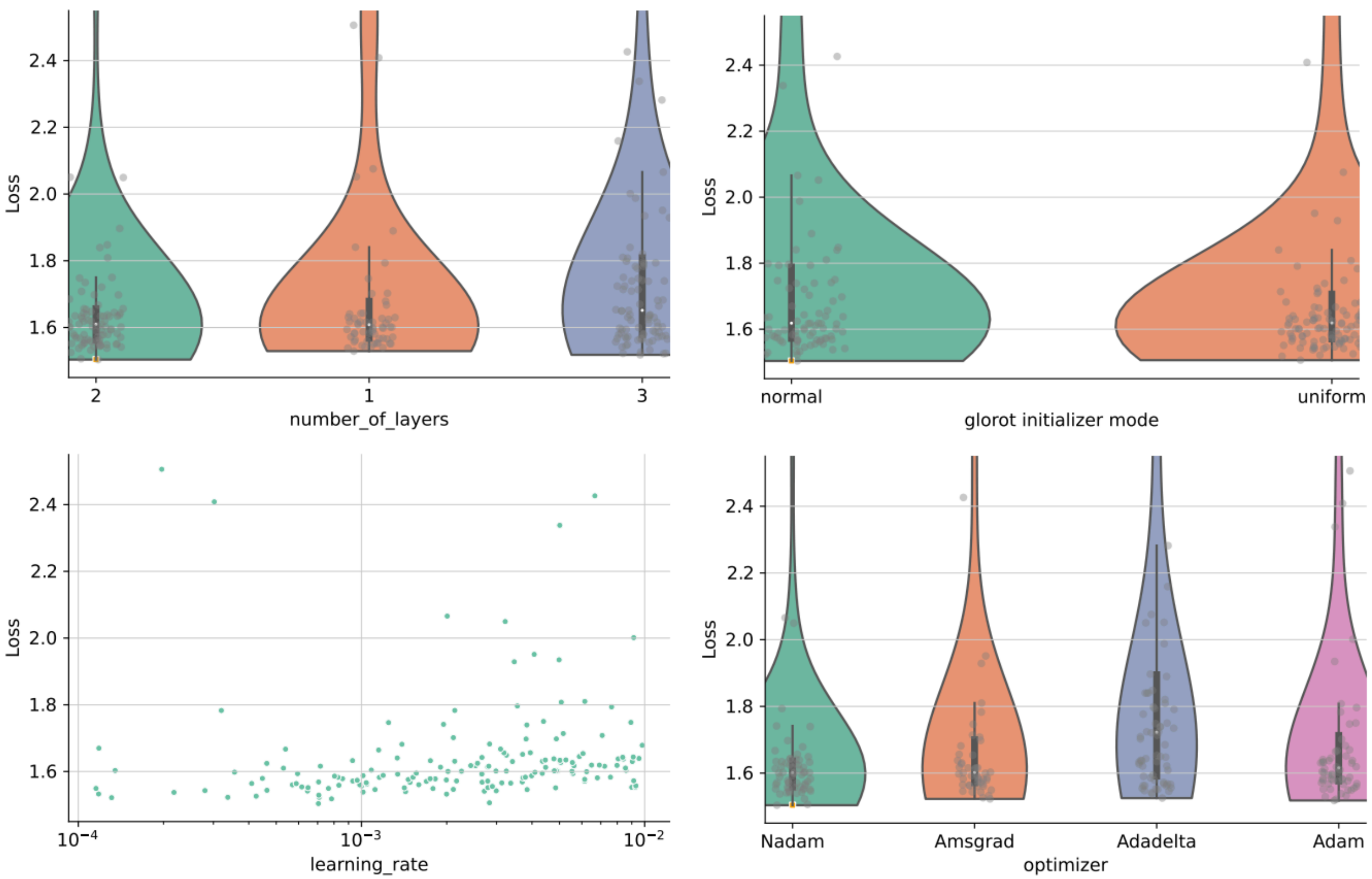
Loss (``average")

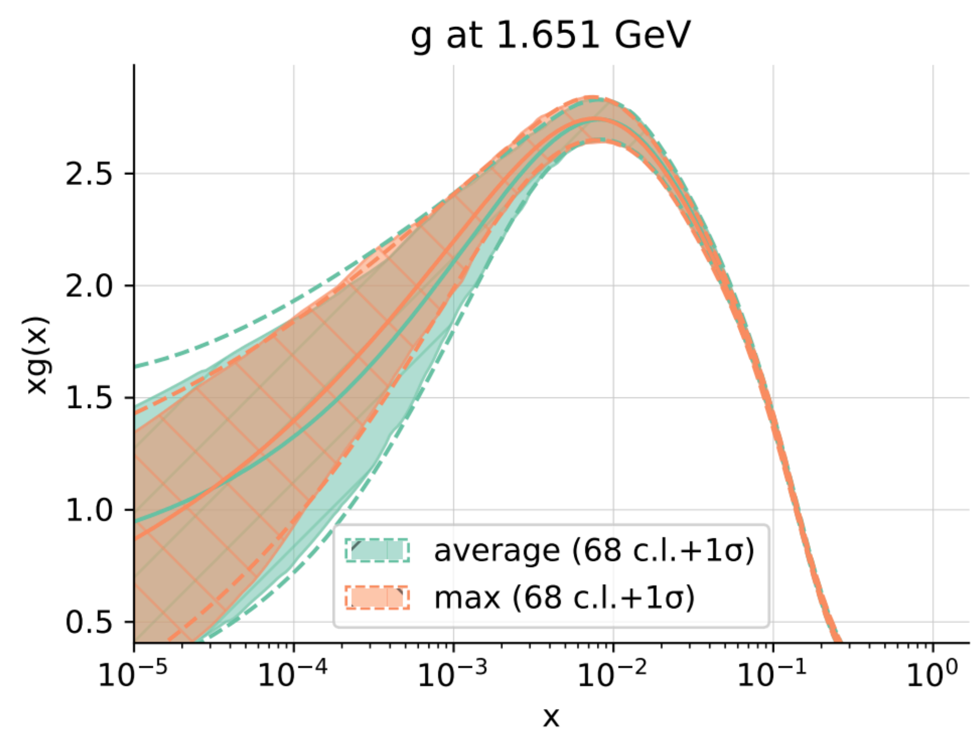
ML model hyperparams

$$\hat{\boldsymbol{\theta}} = \arg\min_{\boldsymbol{\theta}\in\boldsymbol{\Theta}} \left(\frac{1}{n_{\rm fold}} \sum_{k=1}^{n_{\rm fold}} \chi^2_k(\boldsymbol{\theta}) \right)$$

Loss (``max")

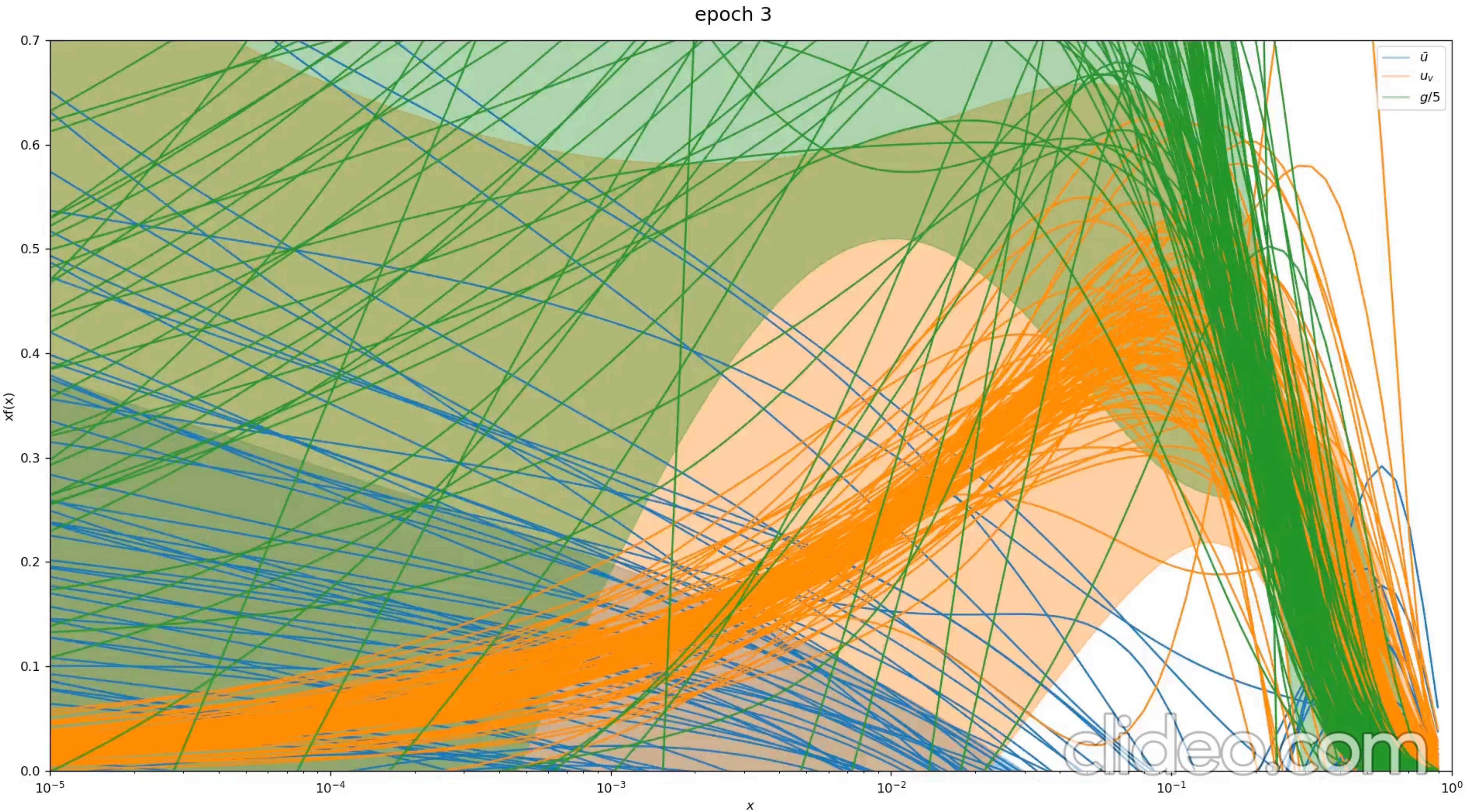
$$L = \max\left(\chi^2_1, \chi^2_2, \chi^2_3, \ldots, \chi^2_{n_{\rm fold}}\right)$$





Stability wrt hyperopt loss function

Improved fitting methodology



Illustrating the outcome of **SGD minimisation** (band: standard deviation over the MC replicas)

Closure and future tests

Closure tests

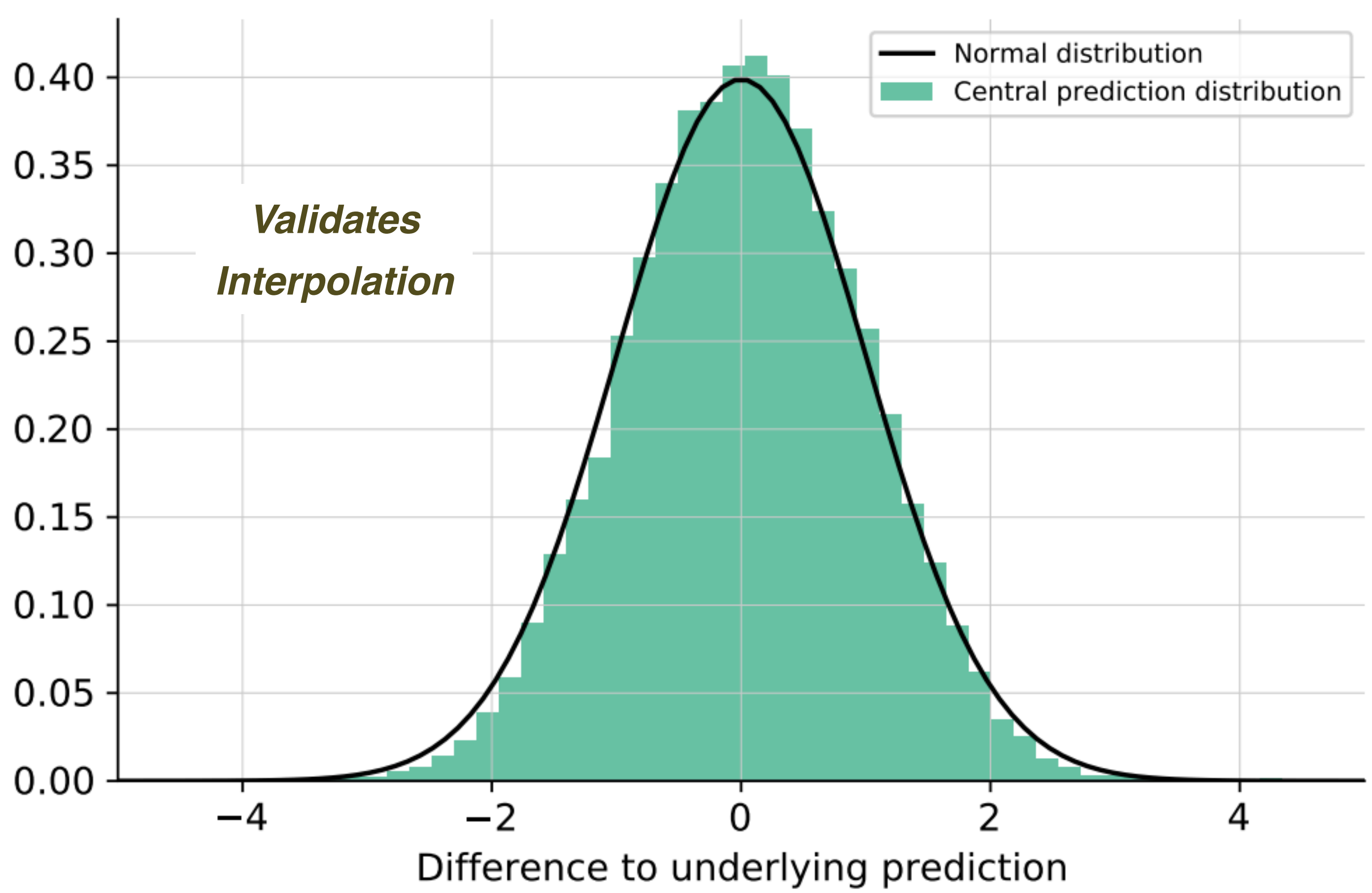
Generate **toy data** based on some known PDF, check *a posteriori* that the **true underlying law is reproduced** within errors

mean NN prediction *true central value*

generate many toys

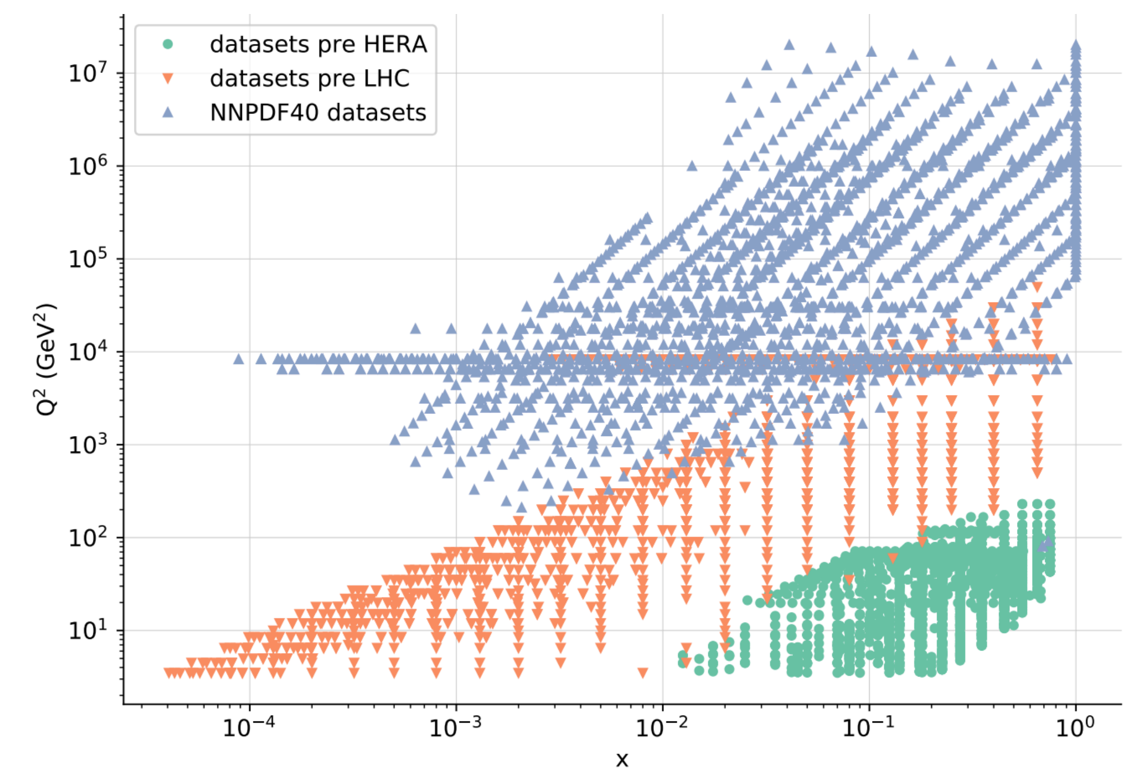
$$\delta_i^{(l)} \equiv \frac{\left(\mathbf{E}_\epsilon\left[g_i\right]^{(l)} - f_i\right)}{\sigma_i^{(l)}}$$

data index *PDF uncertainty*



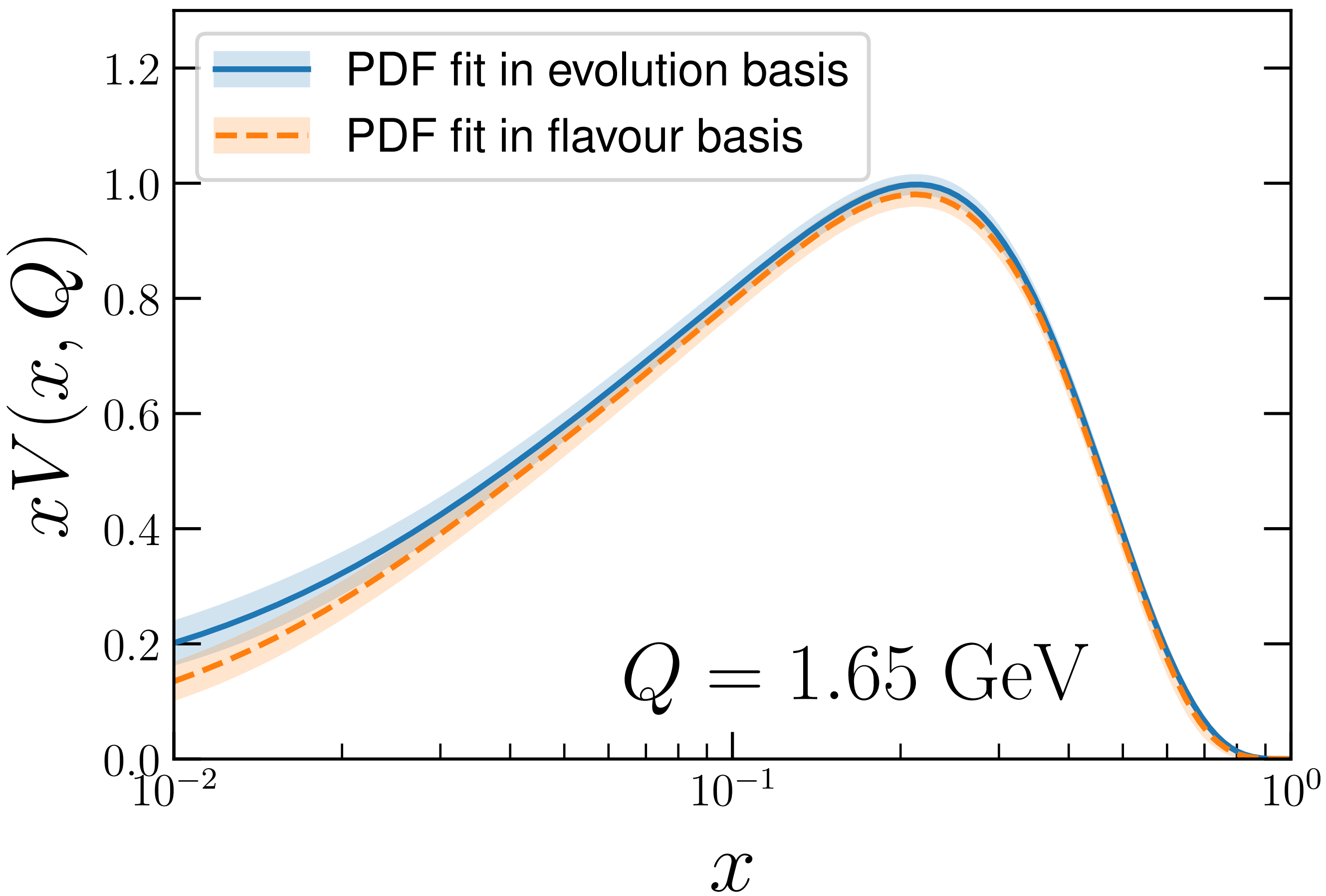
Future tests

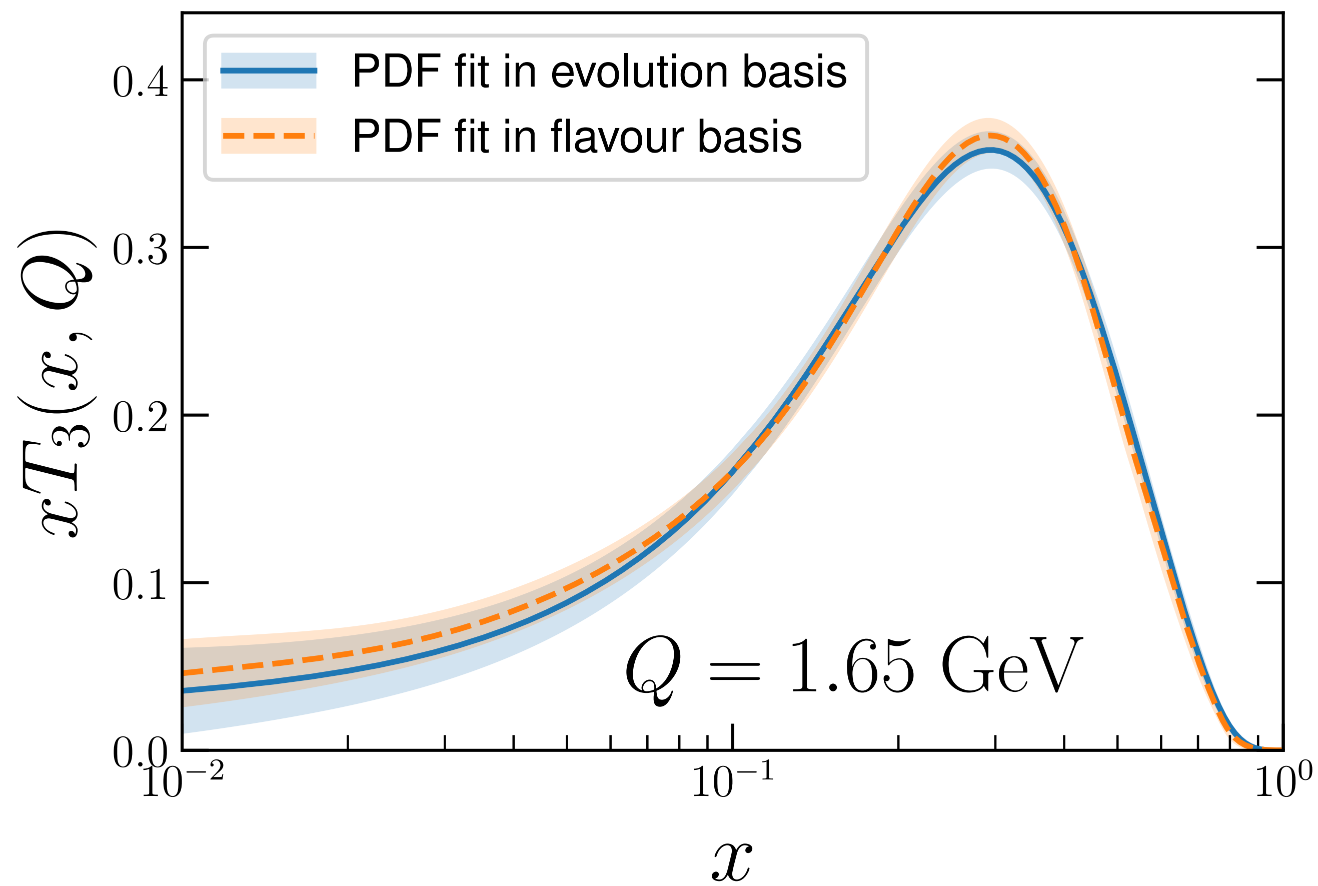
Fit data restricted to specific kinematic regions, then verify **succesful extrapolation**



Process	χ^2 pre-HERA	χ^2 pre-LHC	χ^2 Global
Fixed target NC DIS	1.05	1.18	1.23
Fixed target CC DIS	0.80	0.85	0.87
Fixed target Drell-Yan	0.92	1.27	1.59
HERA	*27.20* (**1.23**)	1.22	1.20
Collider Drell-Yan (Tevatron)	*5.52* (**1.02**)	0.99	1.11
Collider Drell-Yan (LHC)	*18.91* (**1.31**)	*2.63* (**1.58**)	1.53
Top quark production	*20.01* (**1.06**)	*1.30* (**0.87**)	1.01
Jet production	*2.69* (**0.98**)	*2.12* (**1.10**)	1.26

Parametrisation basis independence





evolution basis PDF parametrisation:

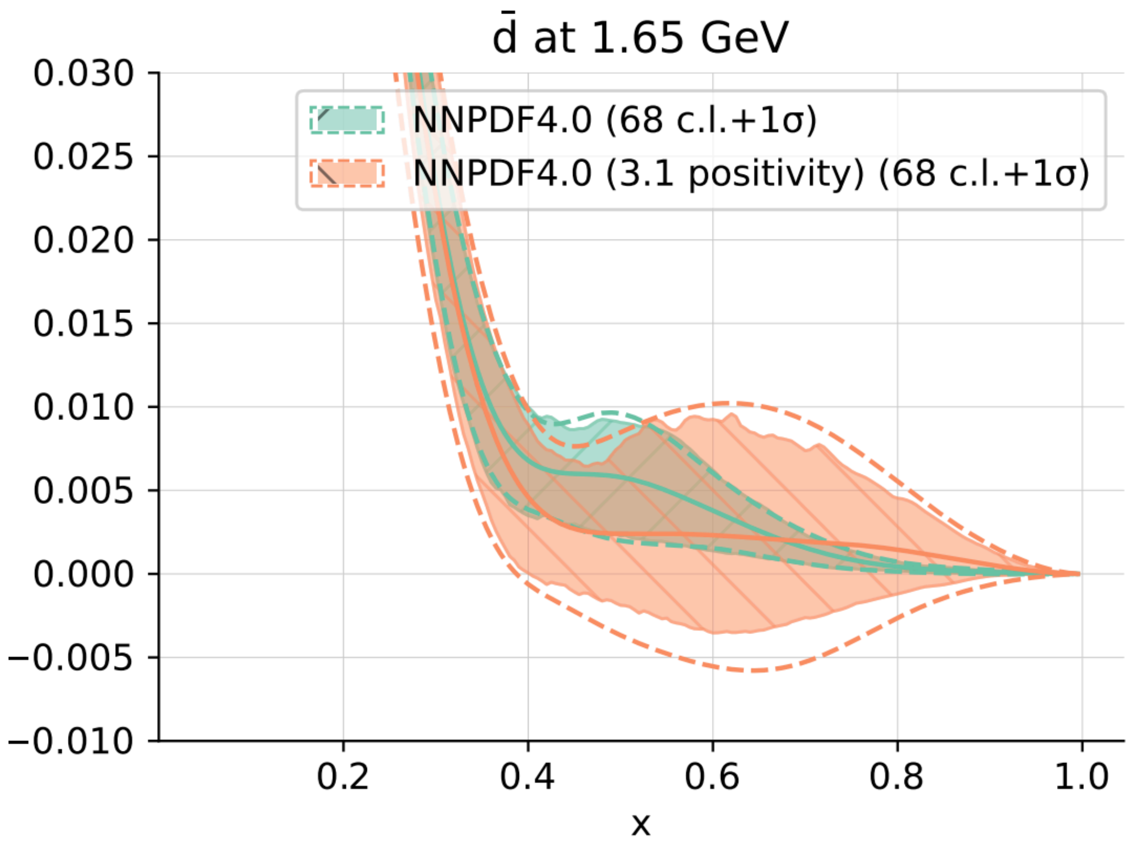
$$xV(x, Q_0) \propto \mathrm{NN}_V(x)$$
$$xT_3(x, Q_0) \propto \mathrm{NN}_{T_3}(x)$$

Radically different strategies to parametrize the **quark PDF flavour combinations** lead to identical results: ultimate test of **parametrisation independence**

flavour basis PDF parametrisation:

$$xV(x, Q_0) \propto \left(\mathrm{NN}_u(x) - \mathrm{NN}_{\bar{u}}(x) + \mathrm{NN}_d(x) - \mathrm{NN}_{\bar{d}}(x) + \mathrm{NN}_s(x) - \mathrm{NN}_{\bar{s}}(x)\right)$$
$$xT_3(x, Q_0) \propto \left(\mathrm{NN}_u(x) + \mathrm{NN}_{\bar{u}}(x) - \mathrm{NN}_d(x) - \mathrm{NN}_{\bar{d}}(x)\right)$$

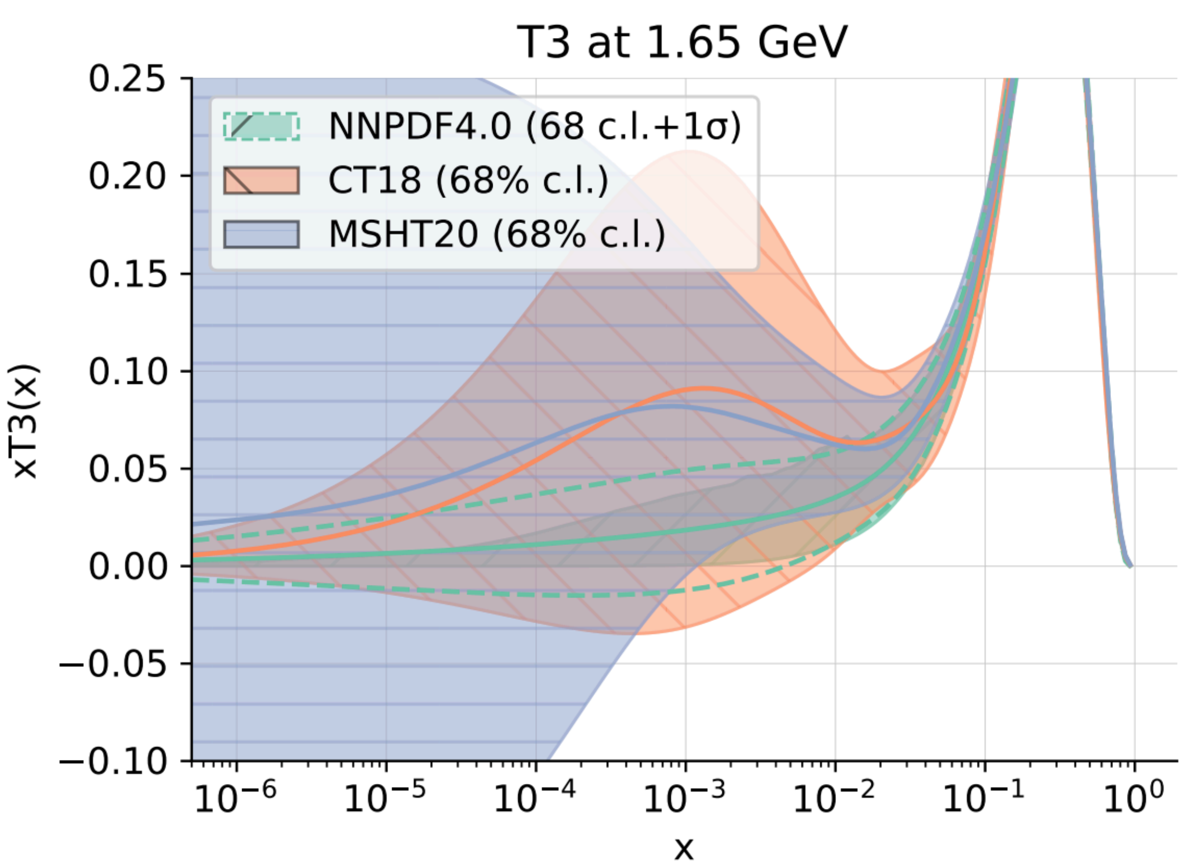
Positivity and integrability

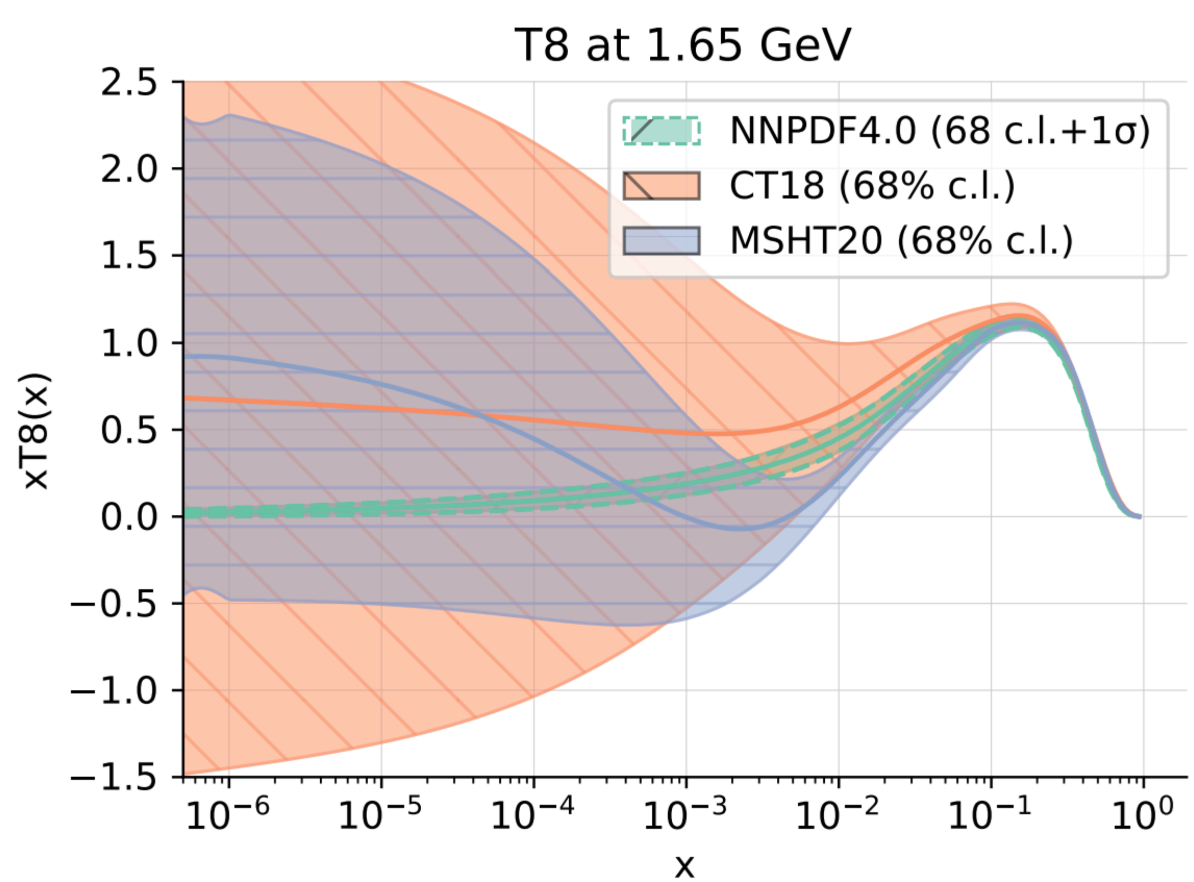


- MSbar PDFs have been shown to satisfy **positivity** requirements at all orders: **reduce large-*x* uncertainties**

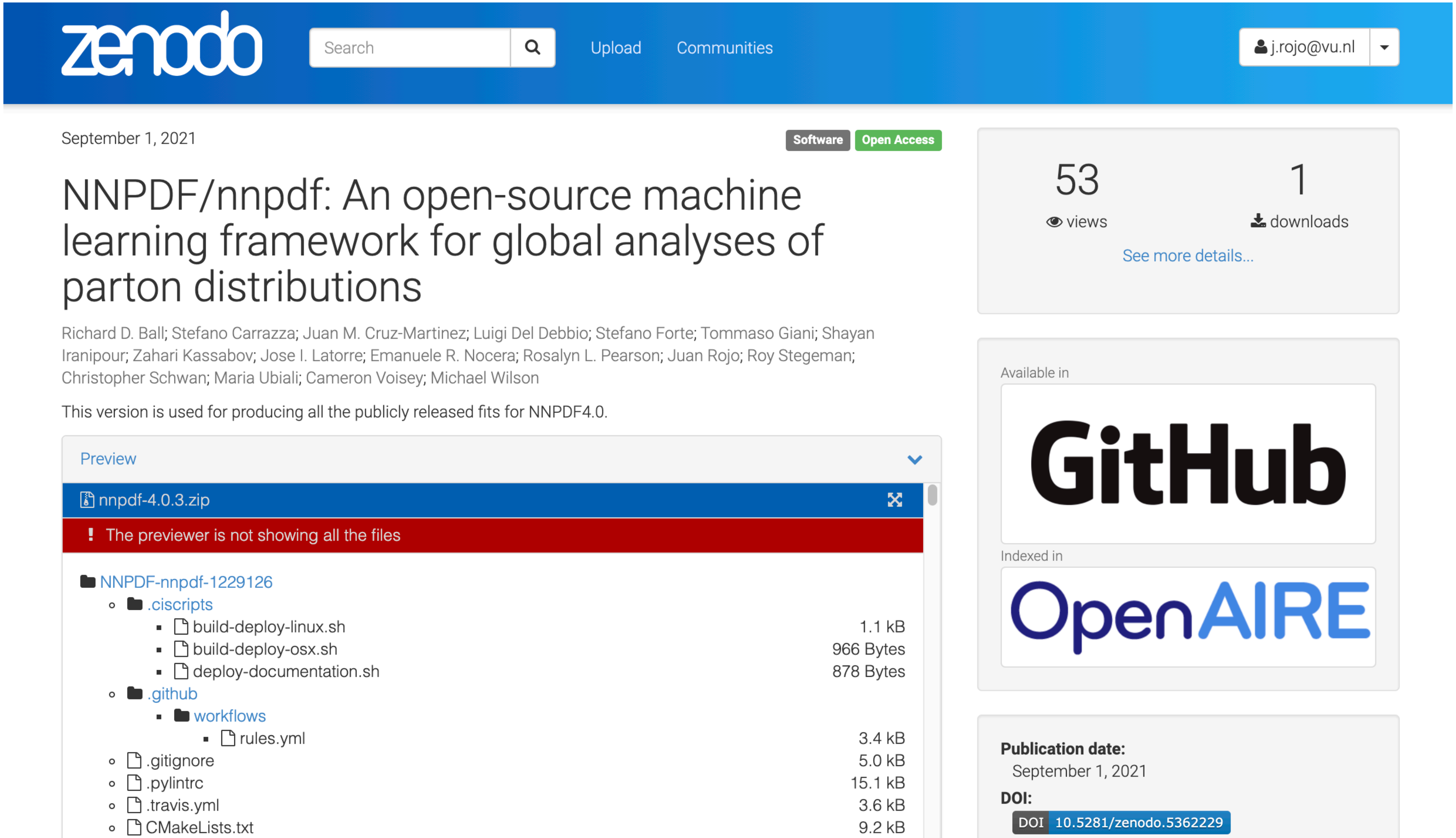
- The non-singlet quark triplet and octet should be *integrable* (e.g. Gottfried sum rule): **reduce small-*x* uncertainties**

$$T_8 = (u + \bar{u}) + \left(d + \bar{d}\right) - 2\,(s + \bar{s})$$



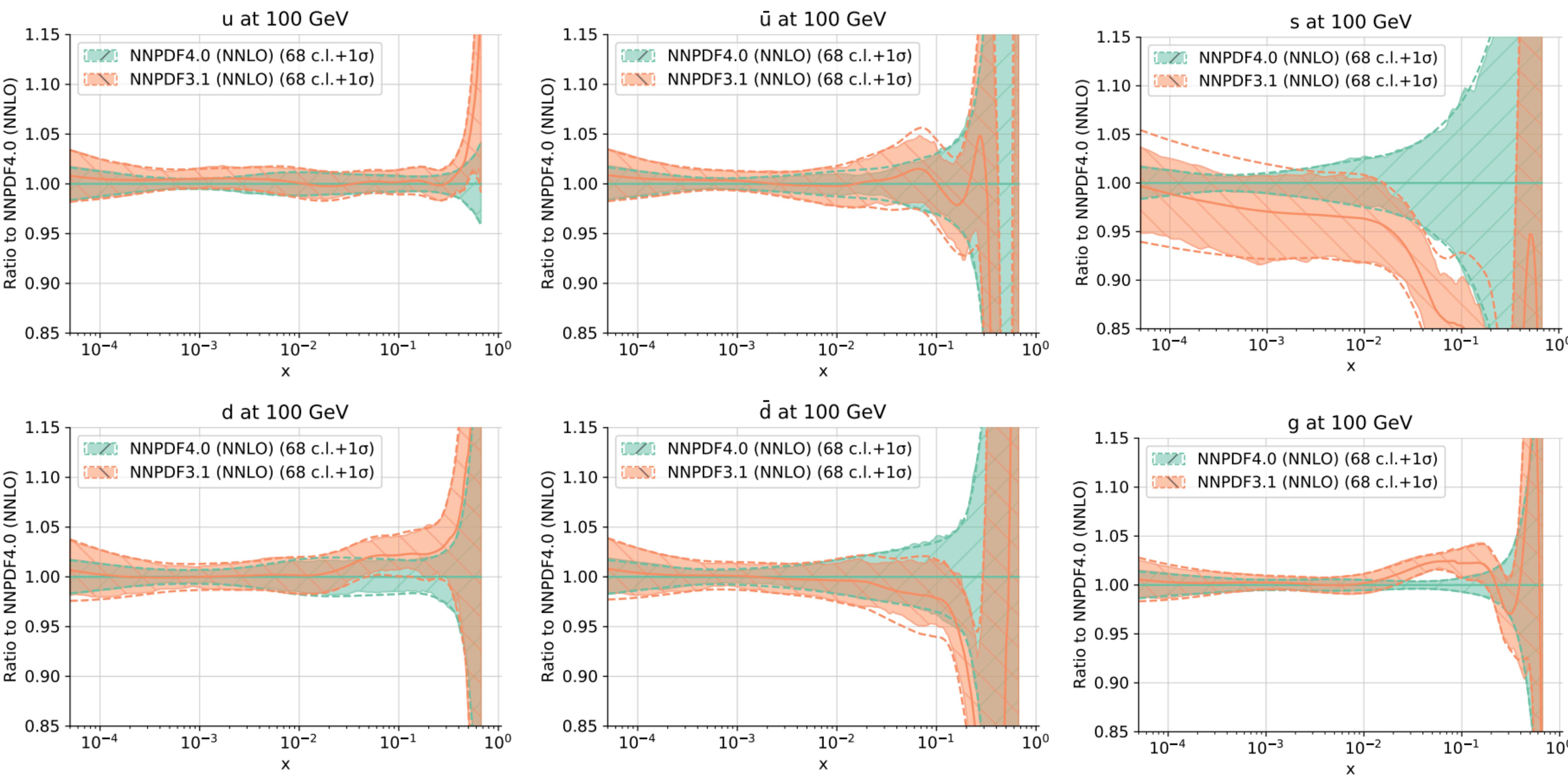


A ML open-source QCD fitting framework



The full **NNPDF machine learning fitting framework** has been publicly released open source, together with extensive documentation and user-friendly examples

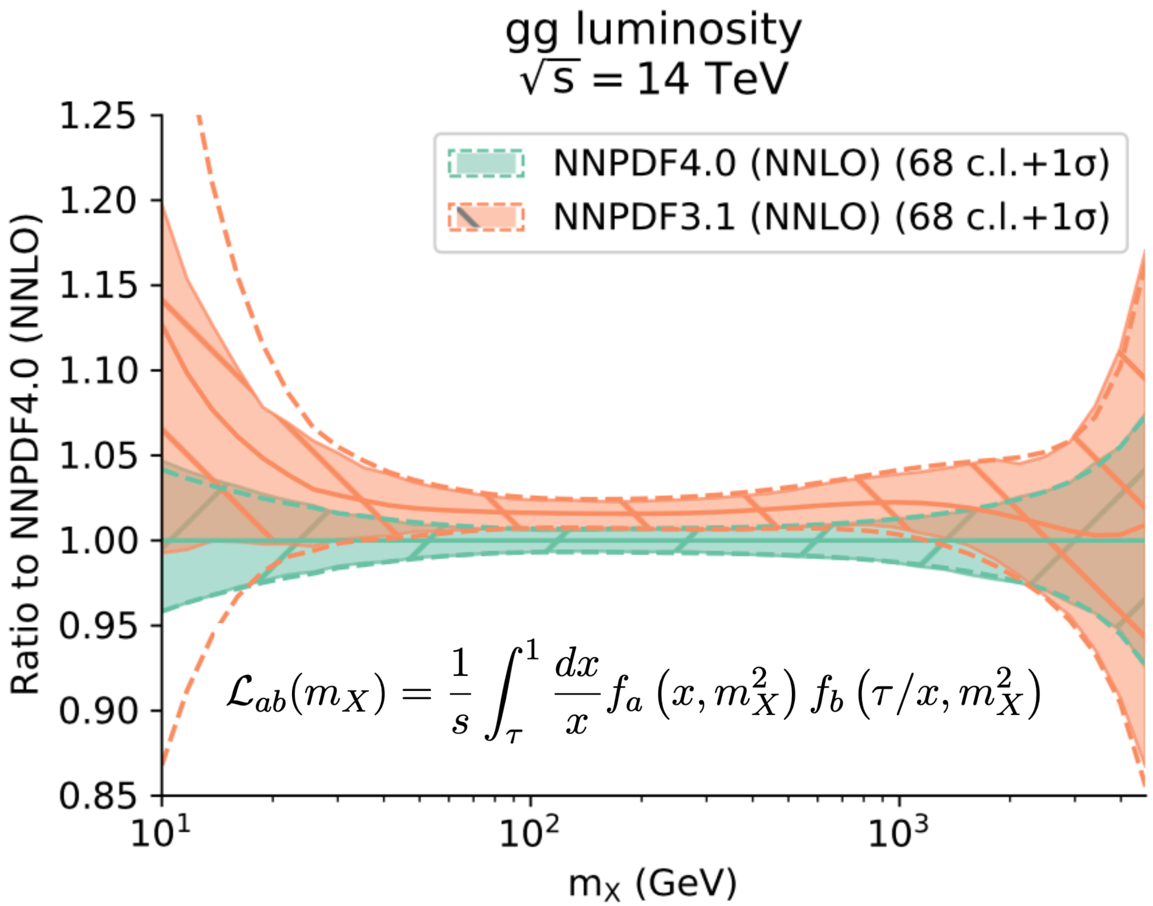
Comparison with NNPDF3.1

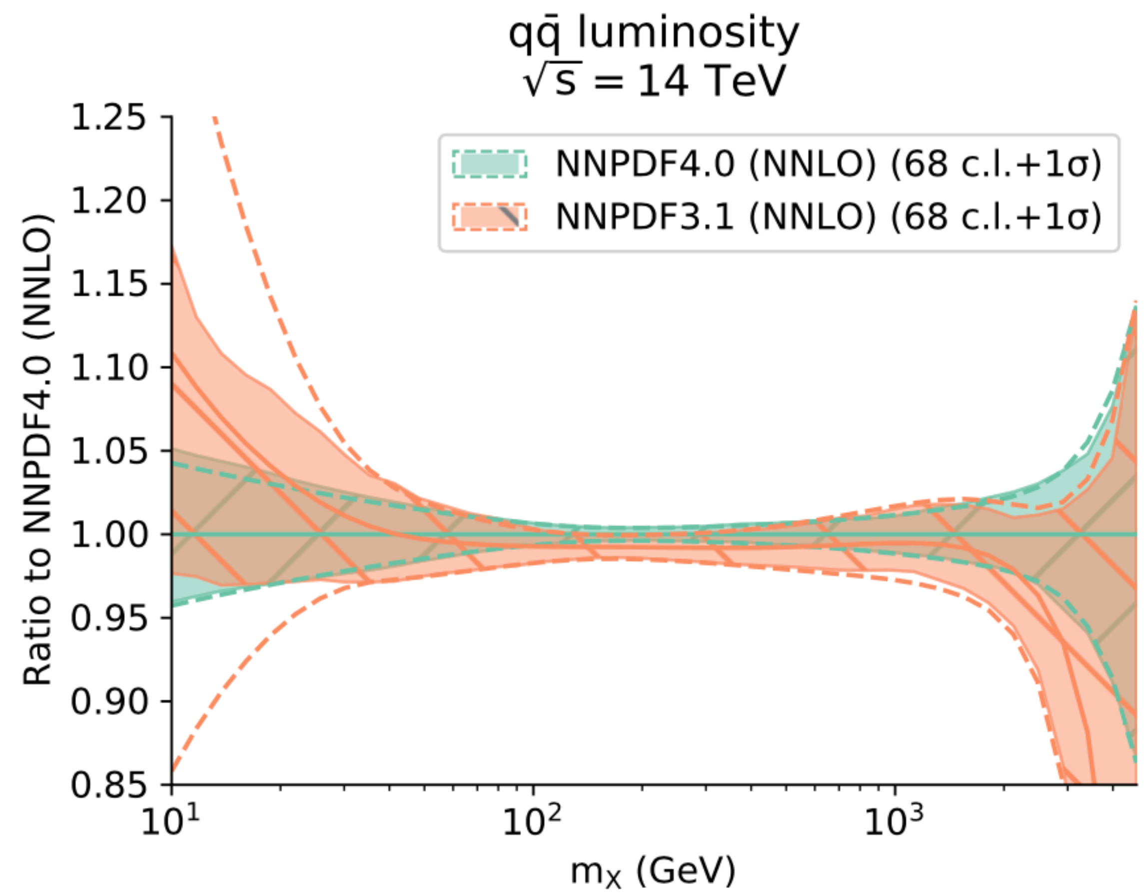


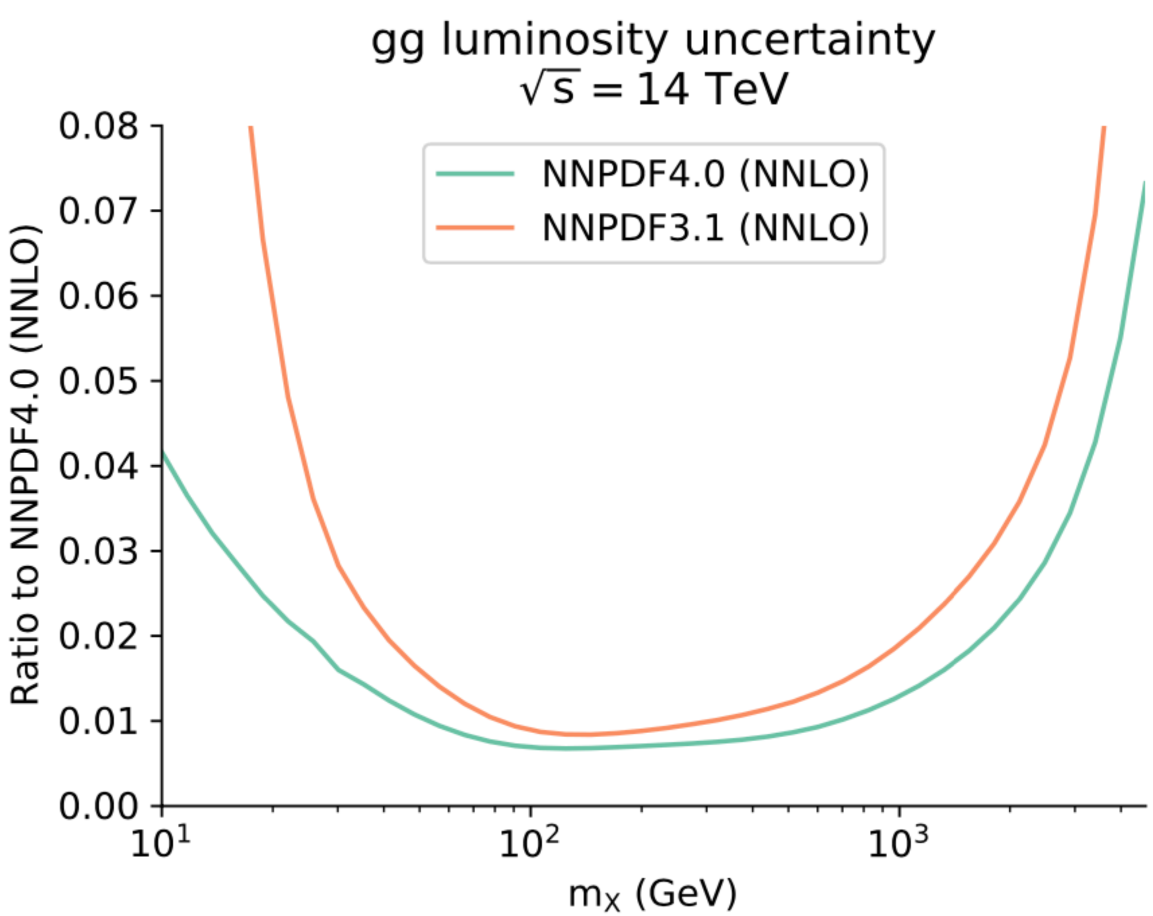
- **Good agreement** with NNPDF3.1 within uncertainties, with NNPDF4.0 being more precise

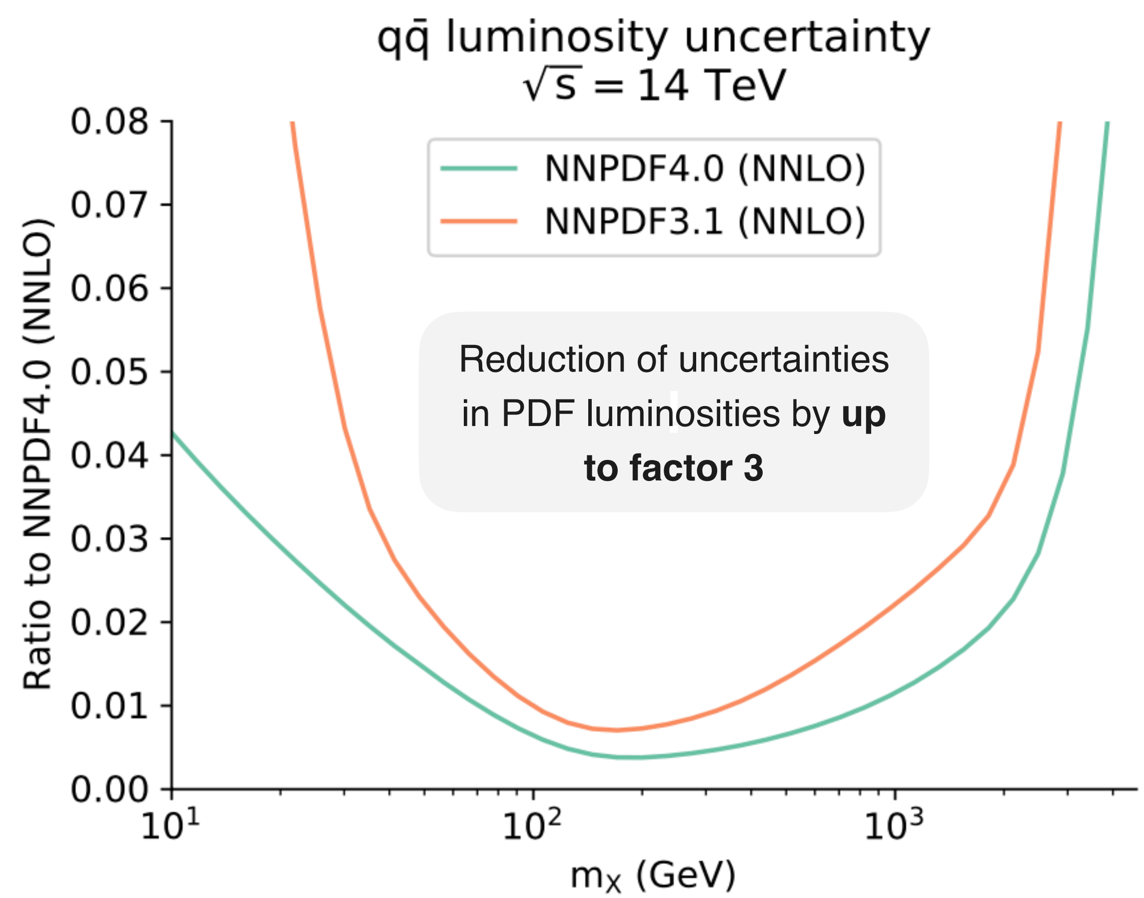
- Differences can be traced back to the **impact of specific datasets** (e.g. dijets for large-*x* gluon) or improvements in **theory calculations** (e.g. NNLO corrections in dimuon DIS for strangeness)

Comparison with NNPDF3.1





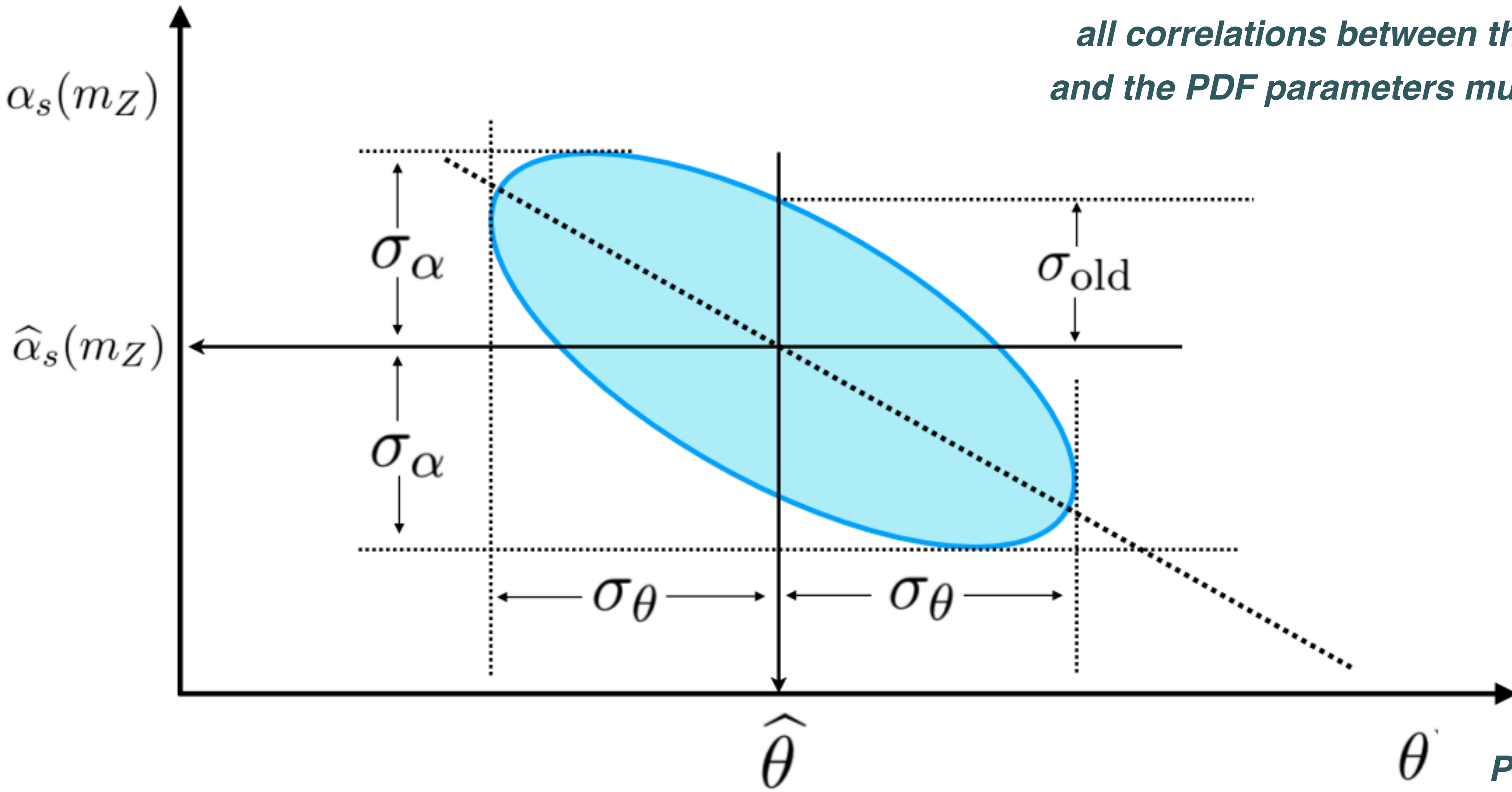




Alphas from NNPDF3.1

arXiv:1802.03398

Correlated Monte Carlo replicas



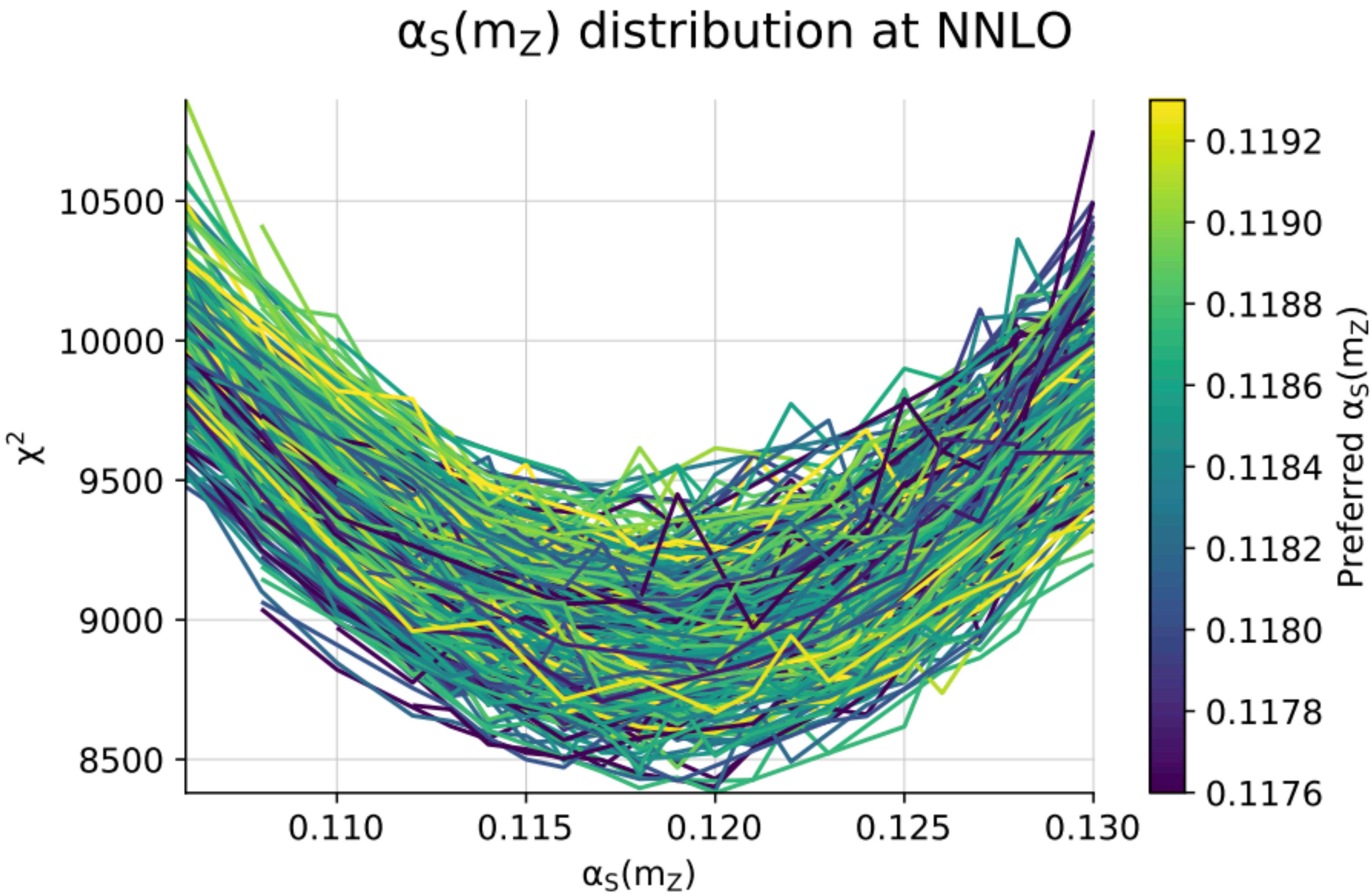
all correlations between the strong coupling and the PDF parameters must be accounted for

PDF parameter

- Most used method to extract alphas from global PDF fit is repeating analysis for a range of alphas values and then **fitting a parabolic curve**
- Within a Monte Carlo fit such as NNPDF, such parabolic fit misses part of the correlations between PDF parameters, since **the underlying data is unchanged**
- Solution is to generate **correlated Monte Carlo replicas** to fully account for this effect

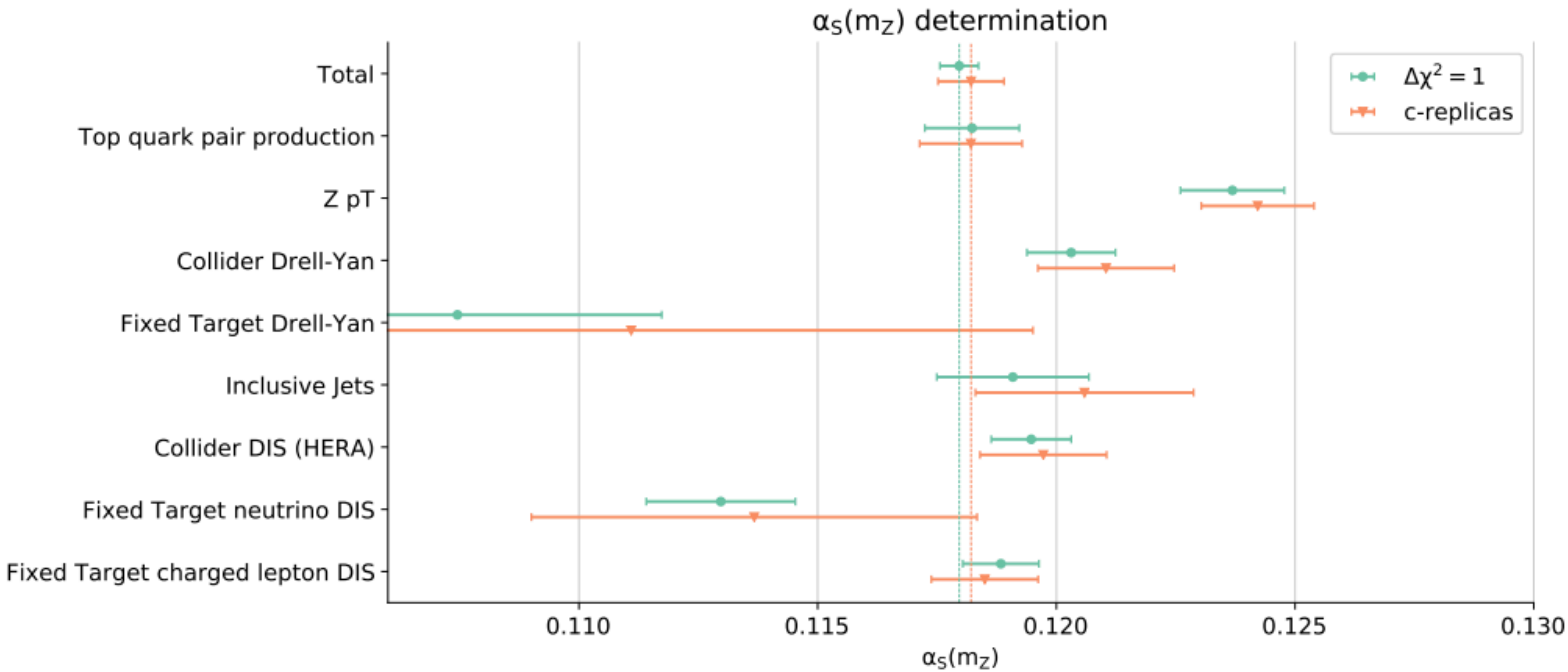
c-replicas: identical settings except for alphas value

Correlated Monte Carlo replicas



Distribution of 400 correlated replicas fitted to the NNPDF3.1 dataset

Impact of correlated Monte Carlo replicas



Within a Monte Carlo determination, neglecting correlations between replicas **underestimates the PDF uncertainty** on the strong coupling by up to a factor 2

Process sensitivity

	NLO	NNLO
Fixed-target charged lepton DIS	973	973
Fixed-target neutrino DIS	908	908
Collider DIS (HERA)	1221	1211
Fixed Target Drell-Yan	189	189
Collider Drell-Yan	378	388
Inclusive jets	164	164
Z p_T	120	120
Top quark pair production	26	26
Total	3979	3979

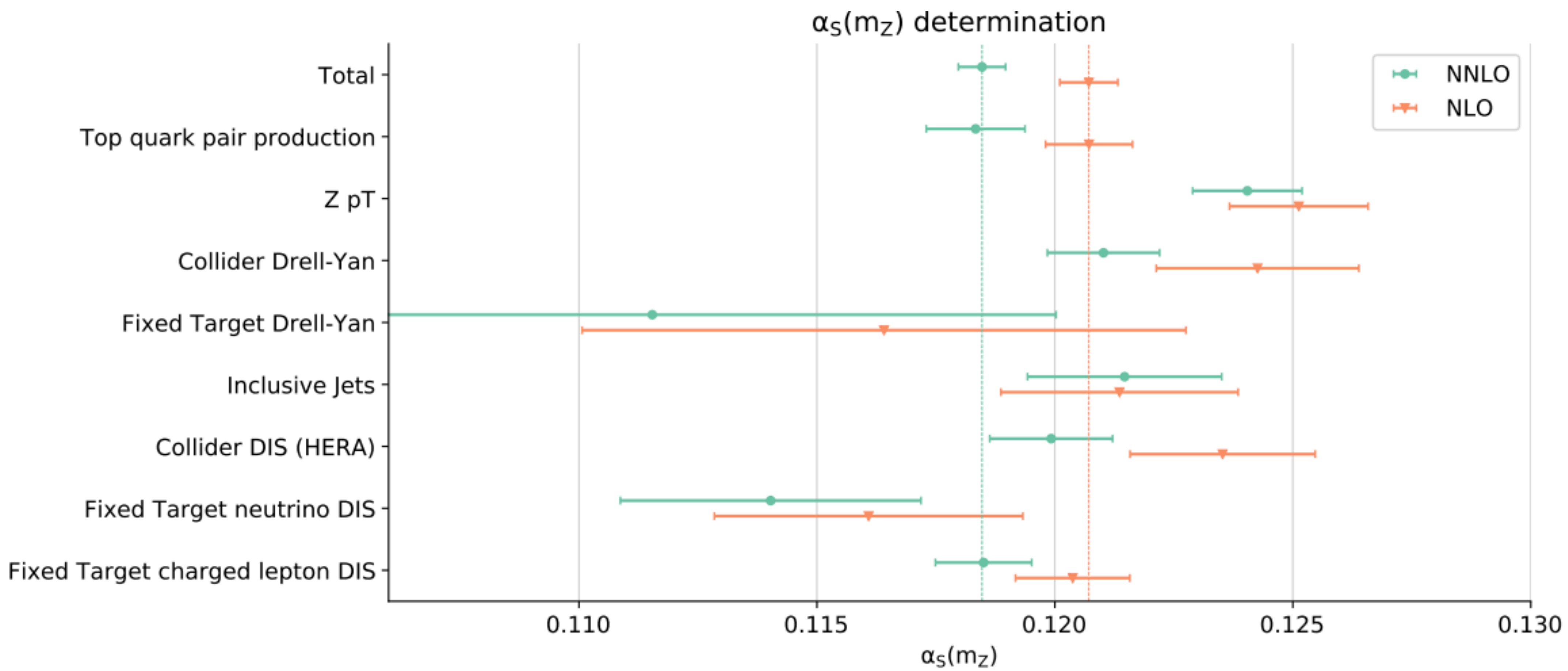
Estimate **pull from different process** by comparing alphas fits from the partial chi2s for specific datasets

Important caveats when (mis)interpreting these results as the **``preferred alphas value"** from a specific process type

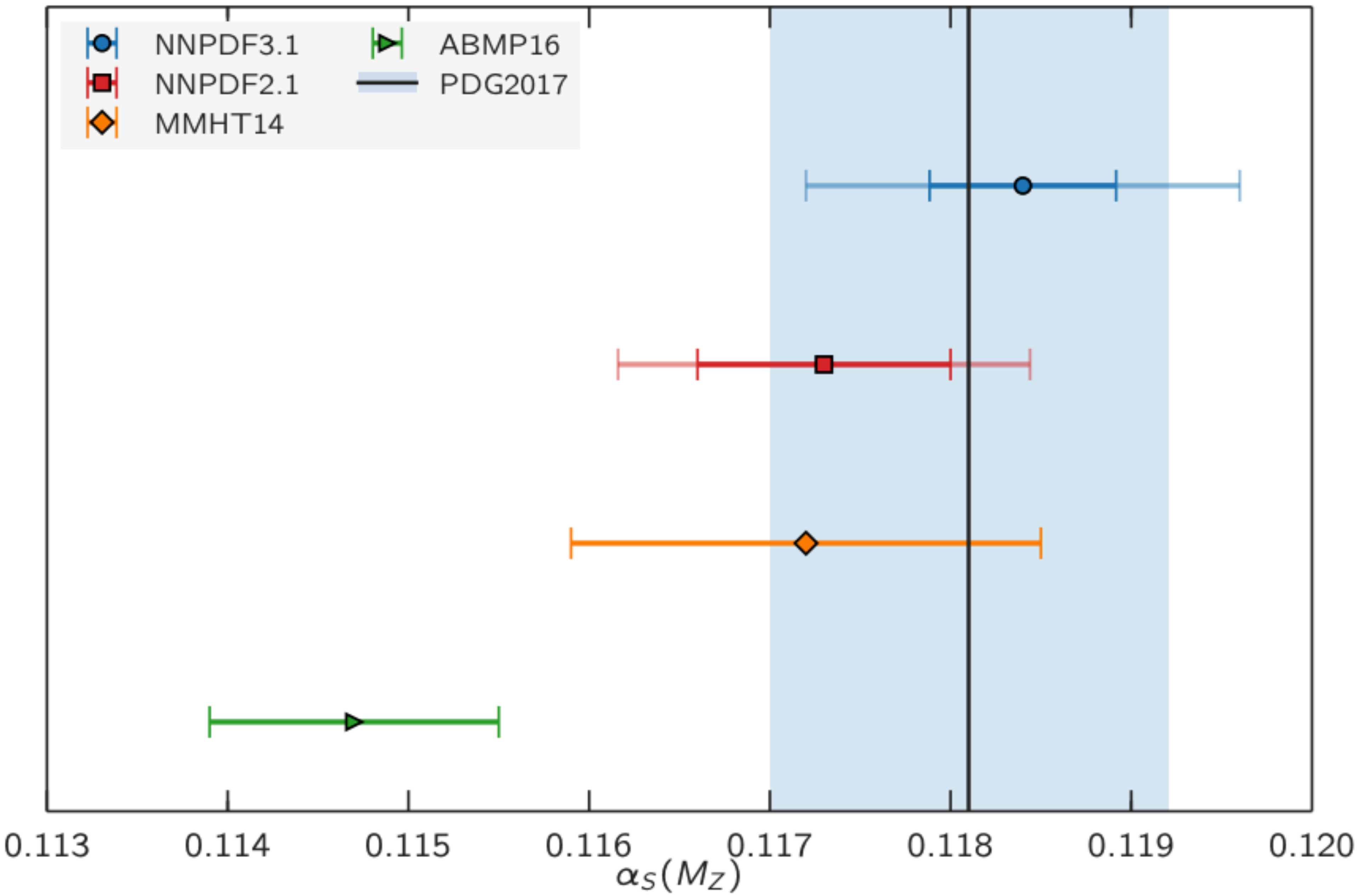
Why α_s Cannot be Determined from Hadronic Processes without Simultaneously Determining the Parton Distributions

2001.04986 [hep-ph]

Stefano Forte[1] and Zahari Kassabov[2]



NNPDF3.1-based results



$$\alpha_s^{\rm NNLO}(m_Z) = 0.1185 \pm 0.0005^{\rm exp} \pm 0.0001^{\rm meth} \pm 0.0011^{\rm th} = 0.1185 \pm 0.0012\ (1\%)\ ,$$

Good agreement with PDG average and previous NNPDF determinations

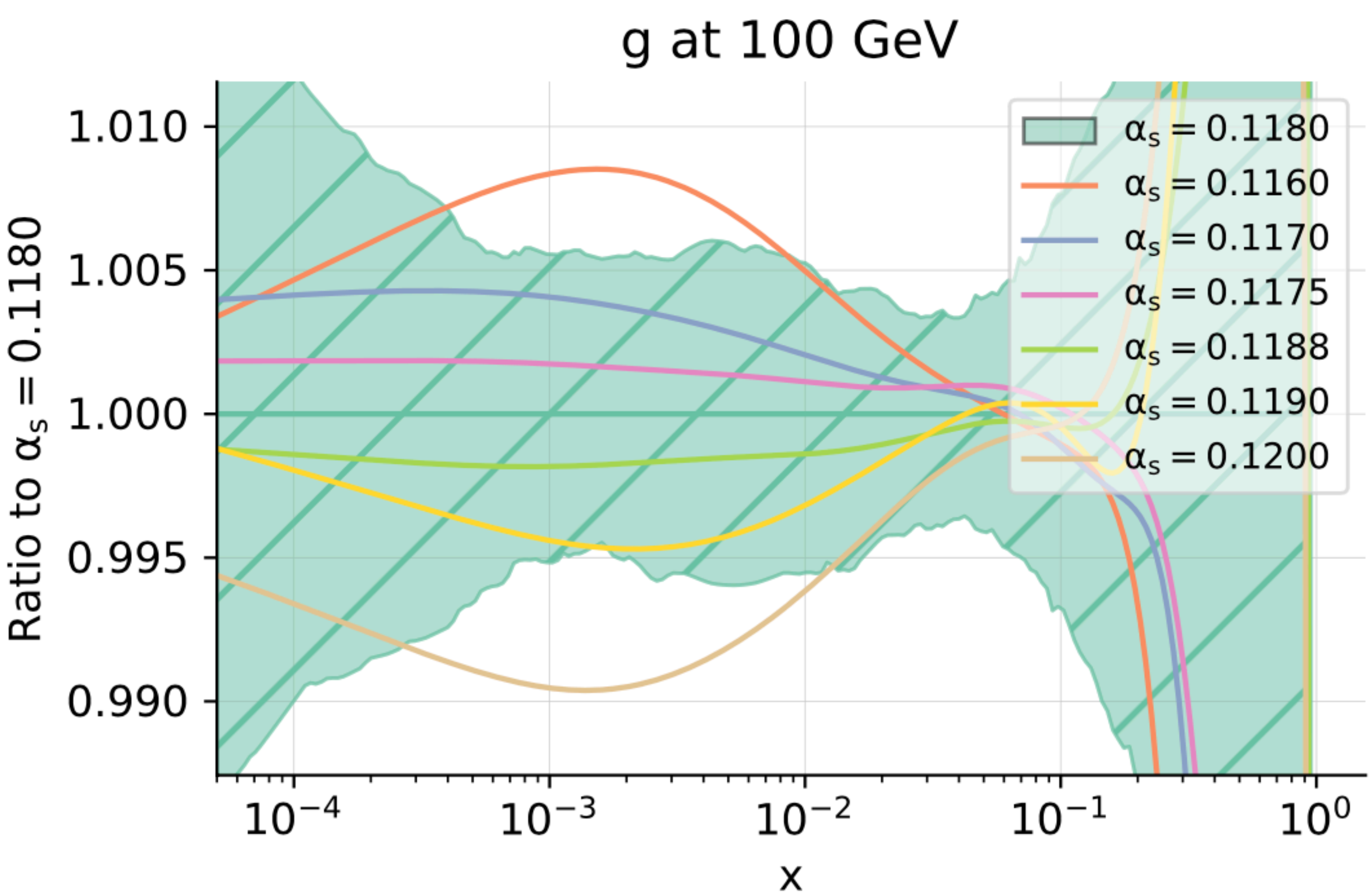
Precision limited by MHOU, here estimated as half the (NNLO-NLO) shift

Alphas from NNPDF4.0

work in progress, preliminary results!

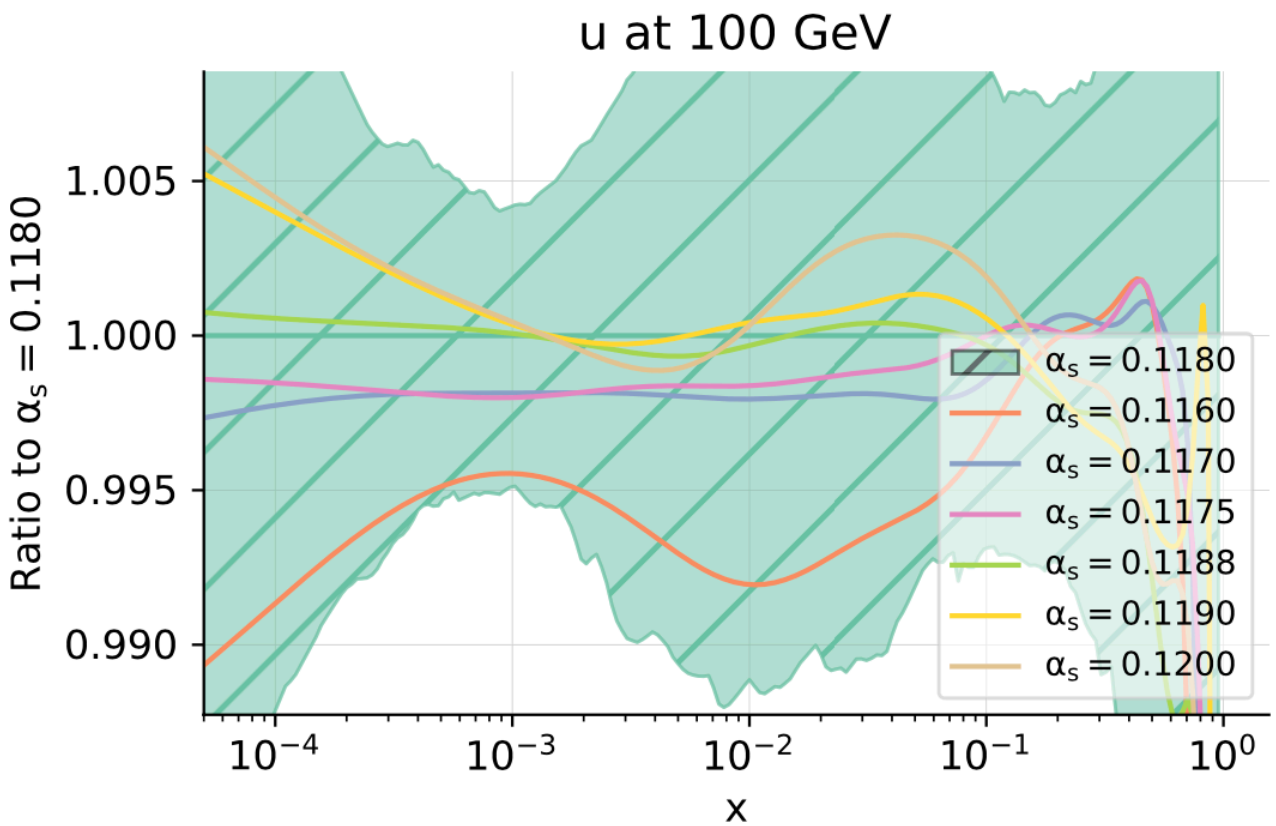
Settings

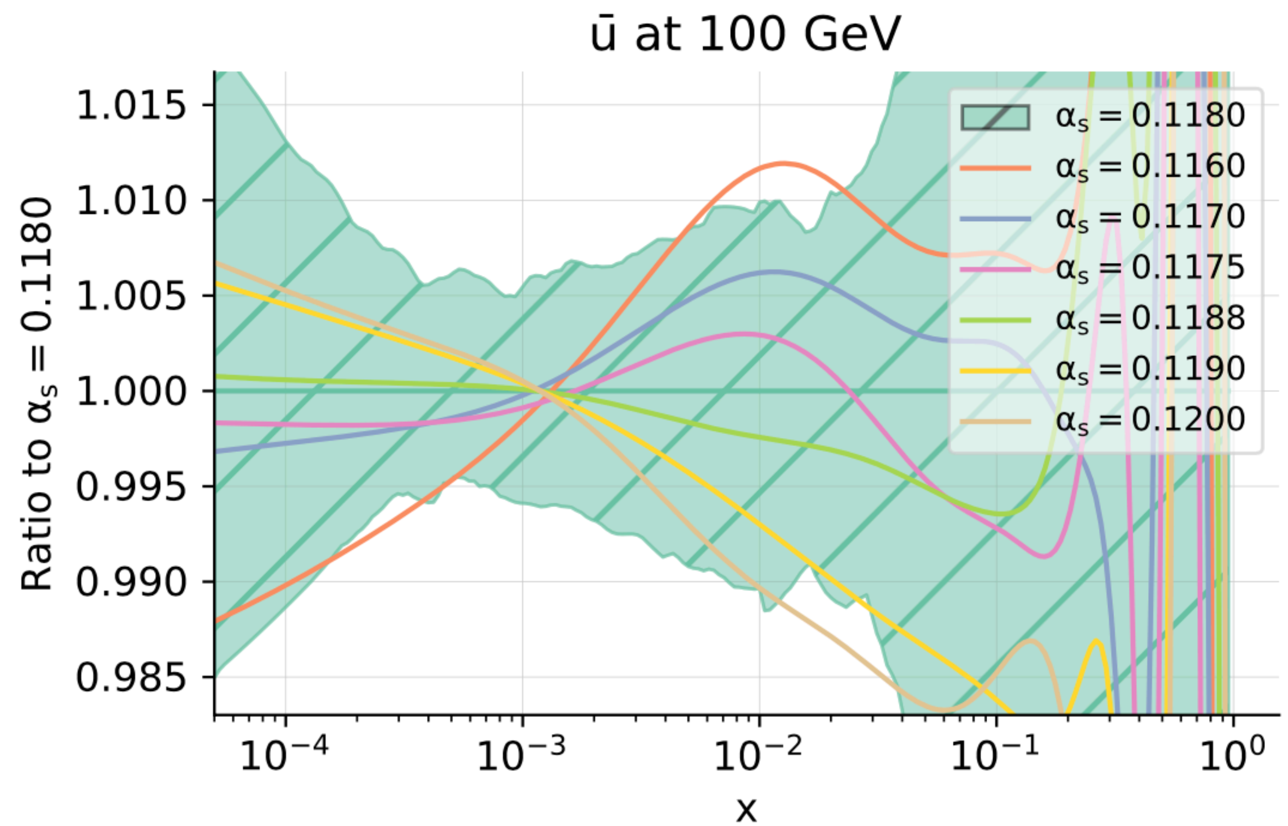
- 2 batches of correlated replicas, **200 replicas** for each alphas value
- Scan the region between **alphas=0.114** to **alphas=0.122**
- Denser coverage near the expected (PDG) minimum
- This talk: results from **parabolic fits**, results based on correlated replicas WIP



gluon PDF is (anti-) correlated to alphas at large (small) x

Settings


u at 100 GeV
Ratio to $\alpha_s = 0.1180$
x
$\alpha_s = 0.1180$
$\alpha_s = 0.1160$
$\alpha_s = 0.1170$
$\alpha_s = 0.1175$
$\alpha_s = 0.1188$
$\alpha_s = 0.1190$
$\alpha_s = 0.1200$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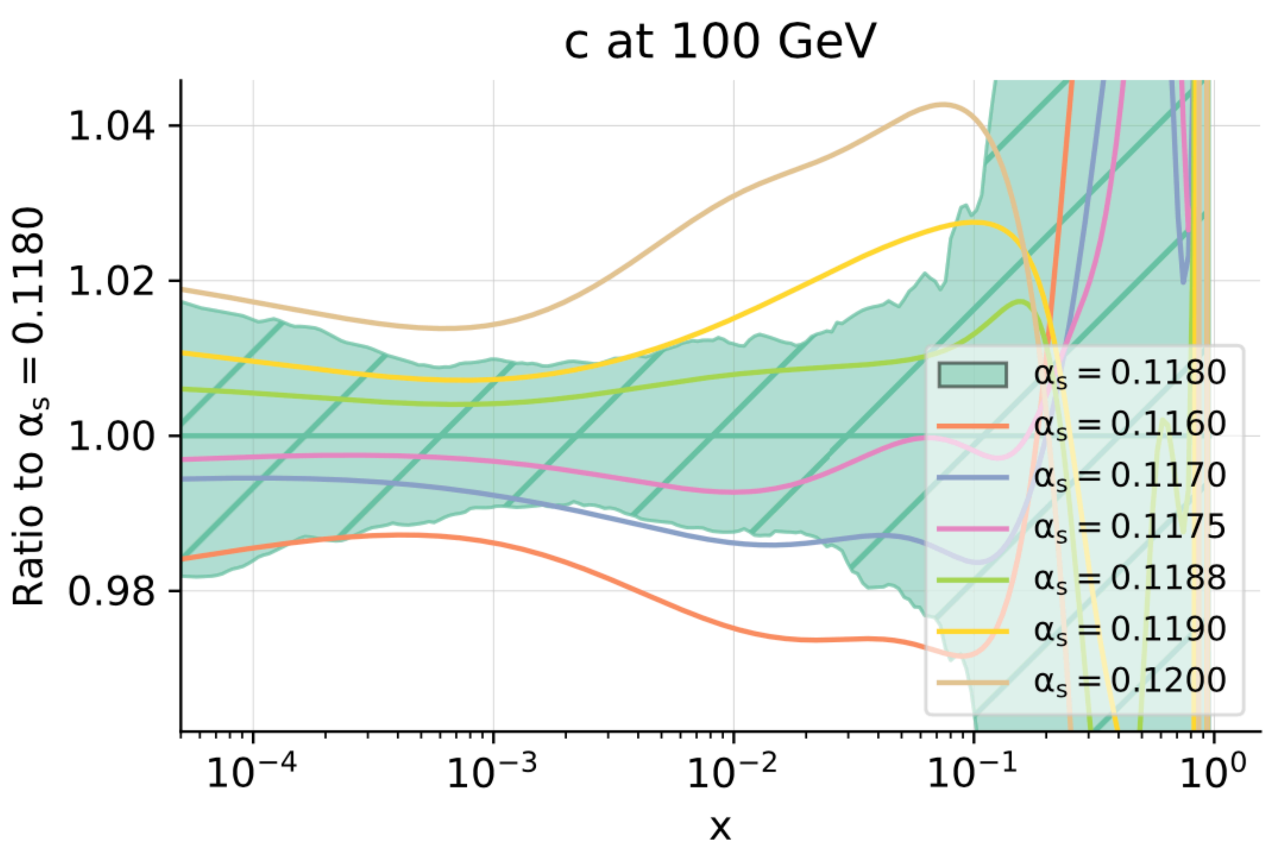
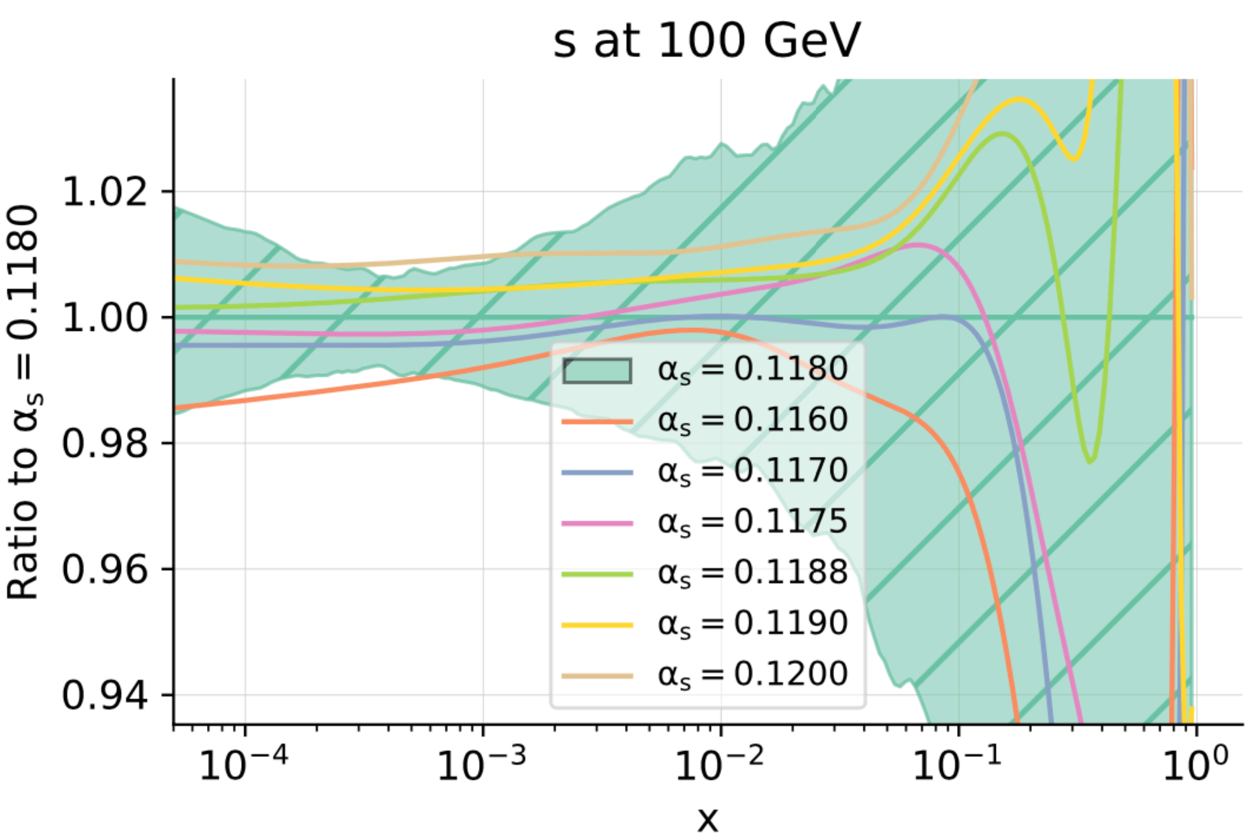
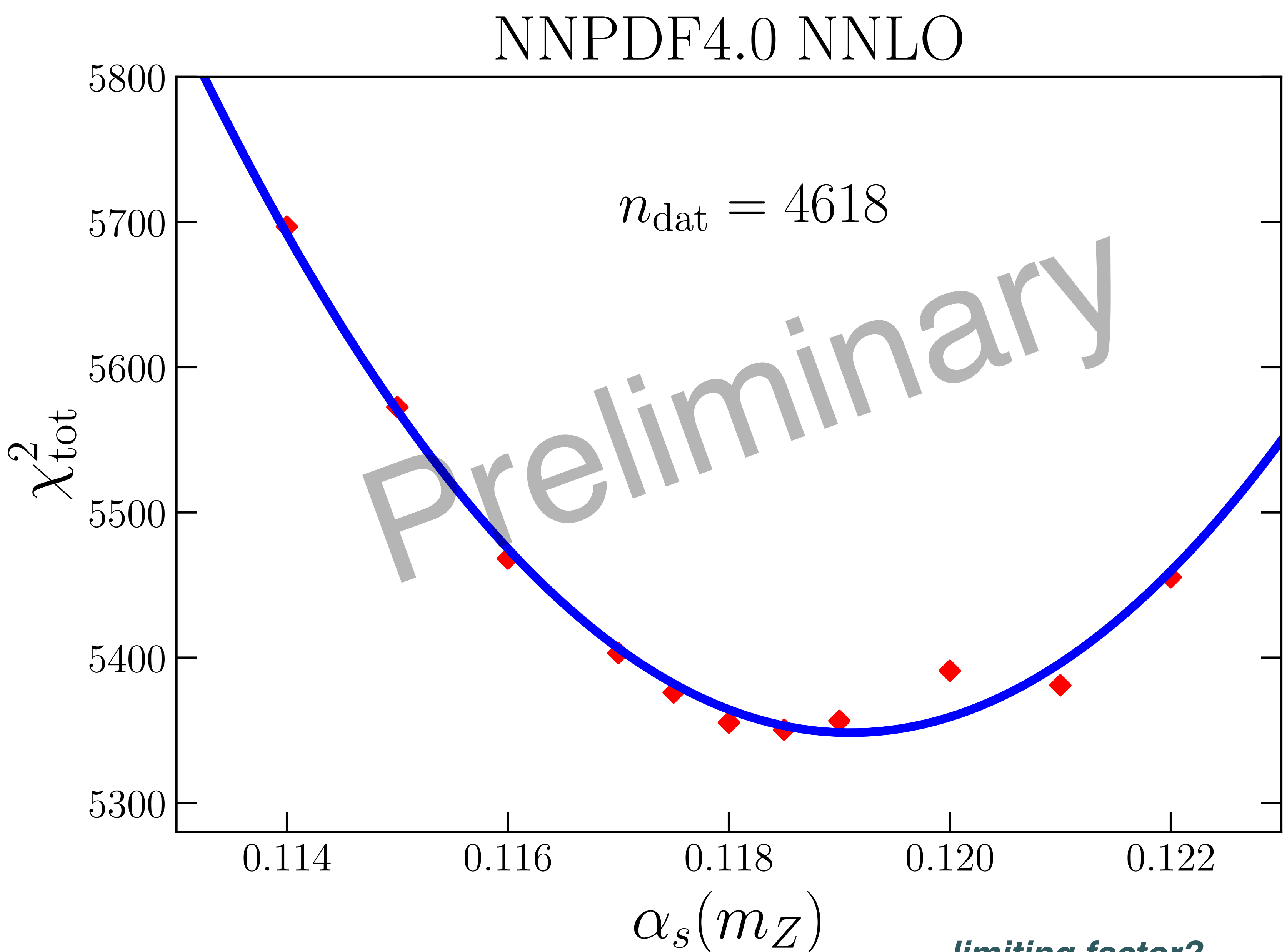

c at 100 GeV
Ratio to $\alpha_s = 0.1180$
x
$\alpha_s = 0.1180$
$\alpha_s = 0.1160$
$\alpha_s = 0.1170$
$\alpha_s = 0.1175$
$\alpha_s = 0.1188$
$\alpha_s = 0.1190$
$\alpha_s = 0.1200$


s at 100 GeV
Ratio to $\alpha_s = 0.1180$
x
$\alpha_s = 0.1180$
$\alpha_s = 0.1160$
$\alpha_s = 0.1170$
$\alpha_s = 0.1175$
$\alpha_s = 0.1188$
$\alpha_s = 0.1190$
$\alpha_s = 0.1200$

Results



limiting factor?

$$\alpha_S(m_Z) = 0.1191 \pm 0.0003_{\rm pdf} \pm (?)_{\rm meth} \pm (?)_{\rm mhou}$$

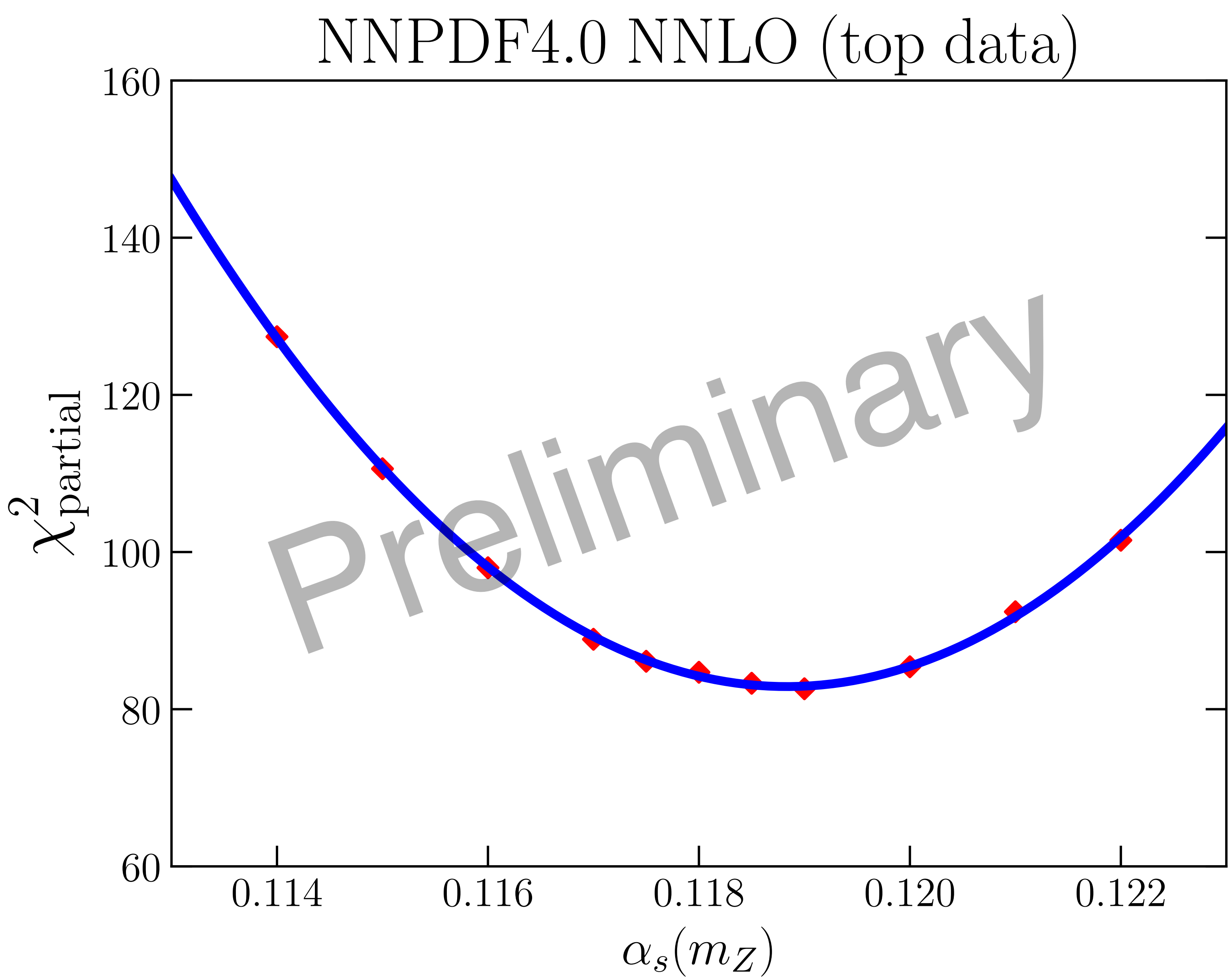
NNPDF4.0, parabolic fit

$$\alpha_S(m_Z) = 0.1185 \pm 0.0005_{\rm pdf} \pm 0.0001_{\rm meth} \pm 0.0011_{\rm mhou}$$

NNPDF3.1 correlated replicas

Good consistency with previous determination

Results



$$\alpha_S(m_Z) = 0.1196 \pm 0.0007_{\mathrm{pdf}} \pm (?)_{\mathrm{meth}} \pm (?)_{\mathrm{mhou}}$$

NNPDF4.0, parabolic fit

Consistency with global fit results

Note that this is the alphas value extracted from the **partial chi2 contribution from top quark data** in the global fit, this is **not** the value of the strong coupling preferred by top data

SimuNET

A new generation of simultaneous fits to LHC data using deep learning

arXiv:2201.07240

Shayan Iranipour, Maria Ubiali
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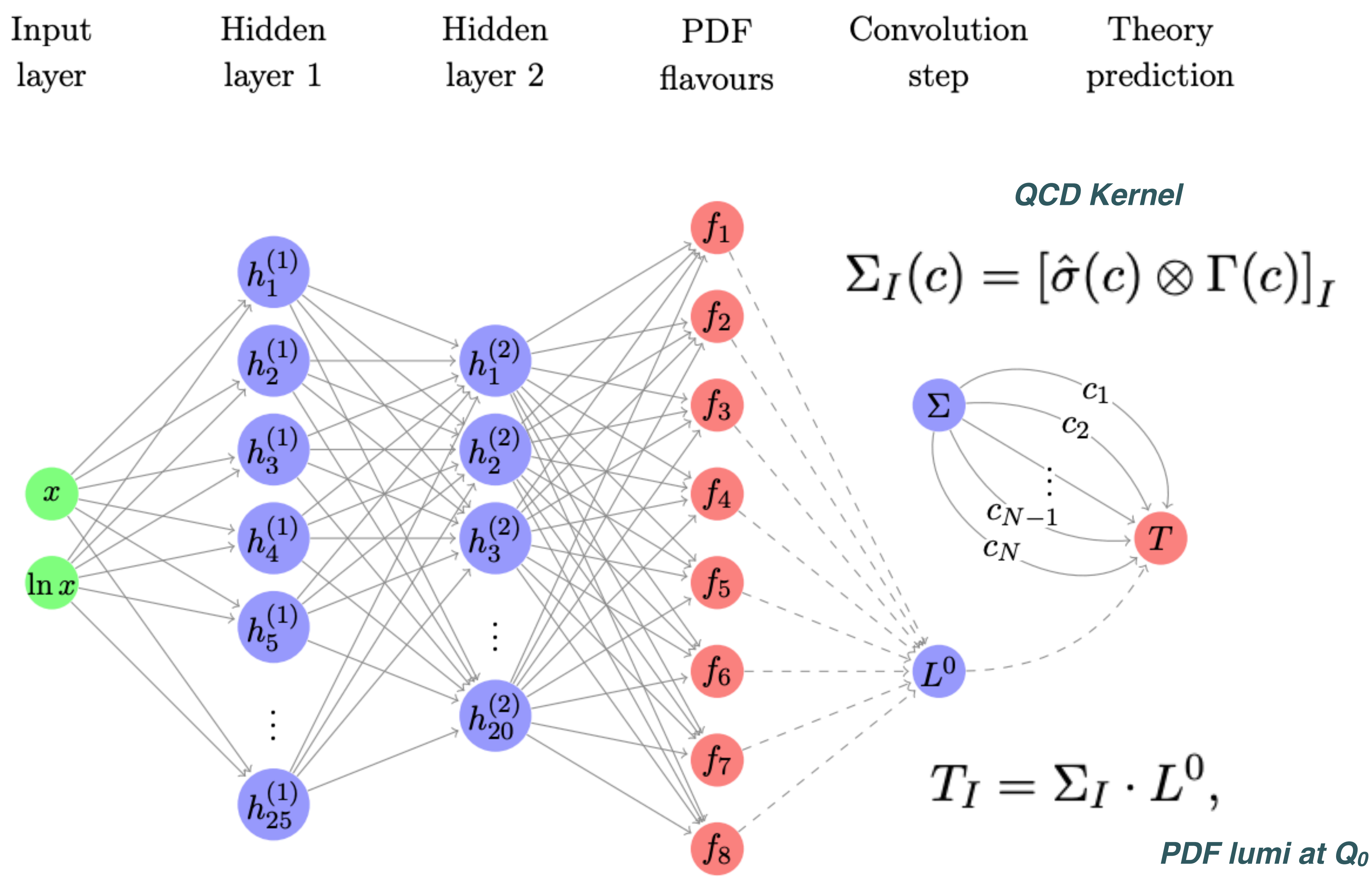
E-mail: s.iranipour@damtp.cam.ac.uk, m.ubiali@damtp.cam.ac.uk

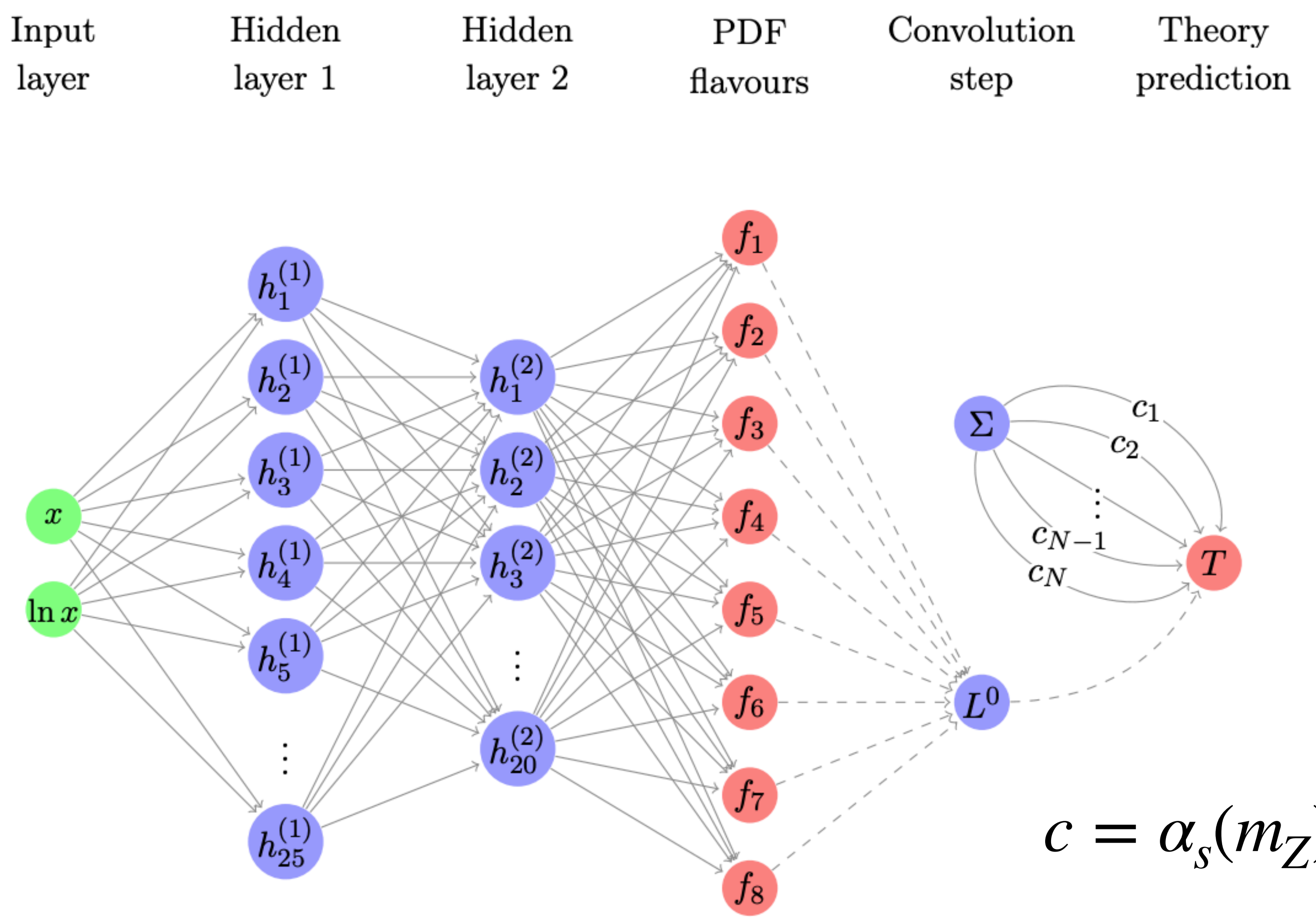
The SimuNET approach



Extend the NNPDF4.0 architecture with an **extra convolutional layer** that depends on SM (or BSM) parameters, e.g. alphas, m_c , or EFT Wilson coefficients

Simultaneous minimisation of the figure of merit wrt to PDF and SM/BSM parameters

The SimuNET approach



$c = \alpha_s(m_Z) \qquad c^* = 0.118$

$$\begin{aligned} K =& \hat{\sigma}_0 \otimes \Gamma_0 + (c - c^*)\left(\hat{\sigma}_1 \otimes \Gamma_0 + \hat{\sigma}_0 \otimes \Gamma_1\right) + \cdots \\ \equiv& K_0 + (c - c^*) K_1 + \cdots \end{aligned}$$

Linear expansion of the QCD kernels in the strong coupling

Alternatively, element-wise interpolation in alphas of the FK table elements

Work in progress, stay tuned!

Summary and outlook

- The global NNPDF4.0 fit achieves **high accuracy** in an unprecedentedly broad kinematic range, thanks so its **extensive dataset** combined with **deep-learning optimisation models**

- It is hence suitable to be deployed for the **simultaneous determination of PDFs and (B)SM parameters**, such as the strong coupling constant

- Several complementary techniques under consideration: parabolic fits, correlated replicas, the SimuNet approach, ….

- Limiting factor in alphas extractions from global fits is **robust estimate of MHOU**, which requires estimating also the **MHOUs associated to the PDFs**

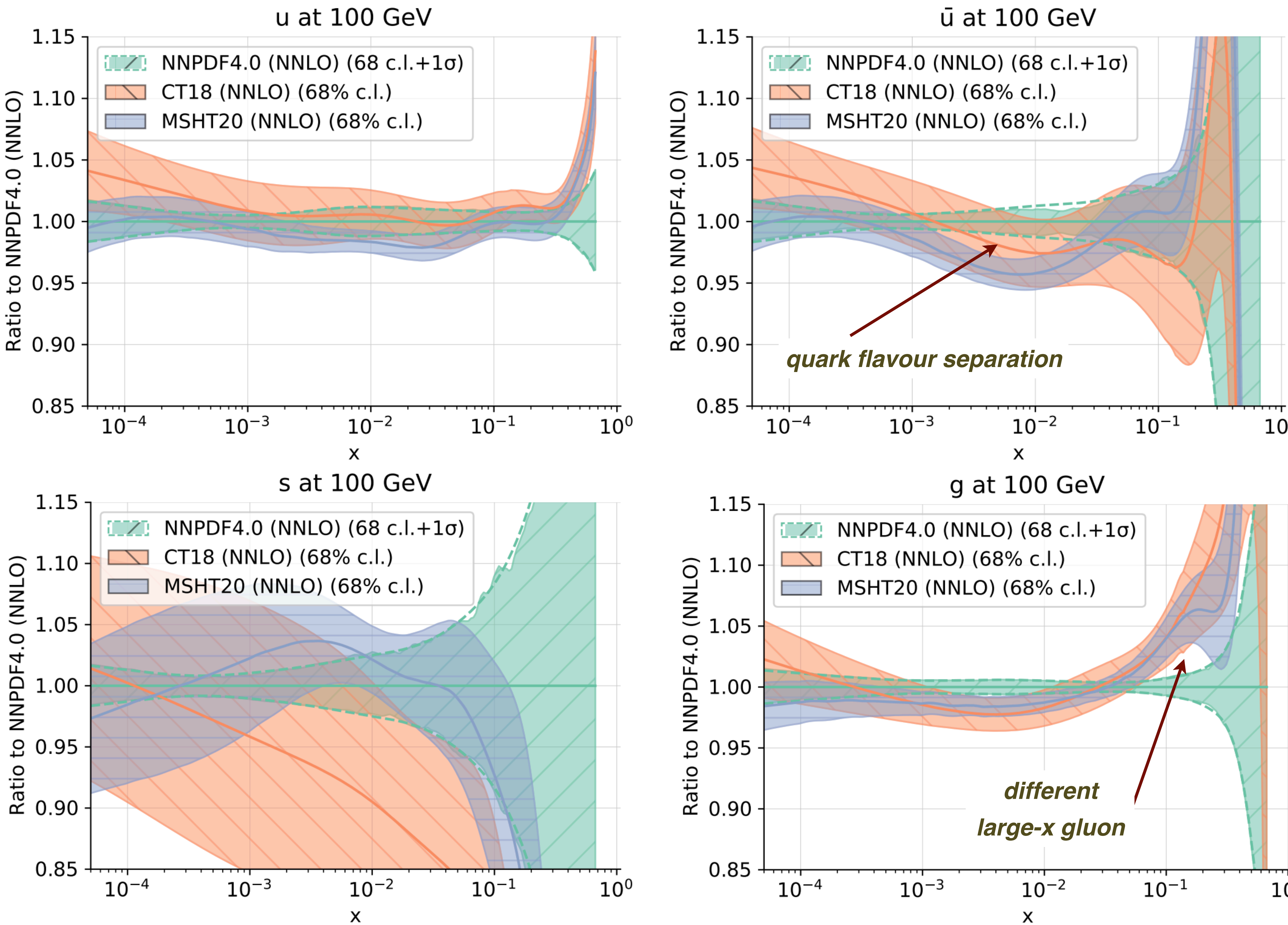
Theory Covariance Matrix approach, NNPDF 19

Stay tuned!

Extra Material

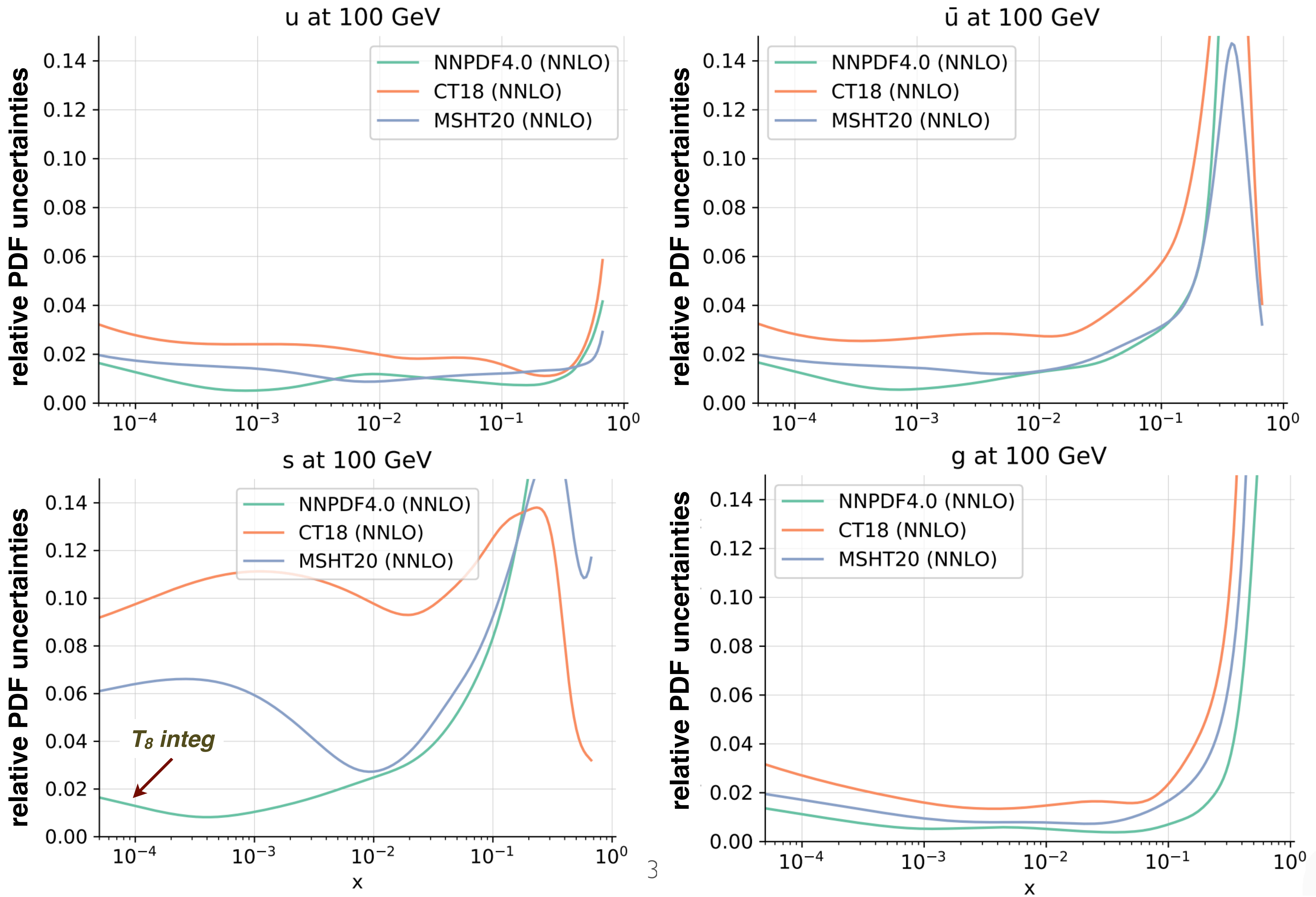
Comparison between global fits

reasonable agreement with CT18, and MSHT20, different pattern of PDF uncertainties



Comparison between global fits

different **pattern of PDF uncertainties** … $\delta_{\rm PDF}({\rm CT}) \gtrsim \delta_{\rm PDF}({\rm MSHT}) \gtrsim \delta_{\rm PDF}({\rm NNPDF})$



Comparison between global fits

… follows pattern of **input datasets**

$$\delta_{\mathrm{PDF}}(\mathrm{CT}) \gtrsim \delta_{\mathrm{PDF}}(\mathrm{MSHT}) \gtrsim \delta_{\mathrm{PDF}}(\mathrm{NNPDF})$$

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 $\sigma_{tt}^{\mathrm{tot}}$ 7, 8 TeV	[65]	✓	✓	✓	✗	✗
ATLAS $\sigma_{tt}^{\mathrm{tot}}$ 7, 8 TeV	[260–265]	✗	✗	✓	✗	✗
ATLAS $\sigma_{tt}^{\mathrm{tot}}$ 13 TeV ($\mathcal{L} = 3.2$ fb^{-1})	[66]	✓	✗	✓	✗	✗
ATLAS $\sigma_{tt}^{\mathrm{tot}}$ 13 TeV ($\mathcal{L} = 139$ fb^{-1})	[134]	✗	✓	✗	✗	✗
ATLAS $\sigma_{tt}^{\mathrm{tot}}$ 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 $\sigma_{tt}^{\mathrm{tot}}$ 5 TeV	[88]	✗	✓	✗	✗	✗
CMS $\sigma_{tt}^{\mathrm{tot}}$ 7, 8 TeV	[146]	✓	✓	✗	✗	✗
CMS $\sigma_{tt}^{\mathrm{tot}}$ 8 TeV	[271]	✗	✗	✗	✗	✓
CMS $\sigma_{tt}^{\mathrm{tot}}$ 5, 7, 8, 13 TeV	[68, 272–280]	✗	✗	✓	✗	✗
CMS $\sigma_{tt}^{\mathrm{tot}}$ 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