

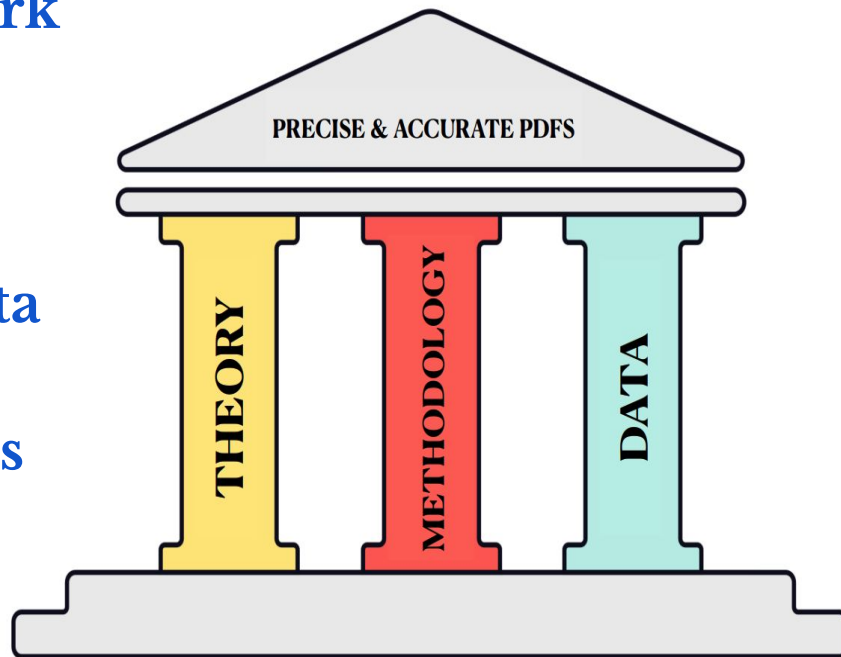
28 Sep. 2026 - Oxford - QCD@LHC
Kamil Laurent

Towards the NNPDF 4.1 global PDF analysis



Overview of the Talk

1. The NNPDF Framework
2. Theory Advances
3. New Experimental Data
4. Methodology Advances



NNPDF Timeline

2027	NNPDF4.1	[WIP]
07/2026	Z pT resummation and PDF determination	[arXiv:2607.19183]
05/2026	Hyperopt. with ensemble regression	[arXiv:2605.31482]
03/2026	Top mass from a global PDF analysis	[arXiv:2603.28865]
02/2026	PDFs and theory parameters	[arXiv:2602.24005]
11/2025	alpha_s extractions without PDF refitting are biased	[arXiv:2511.22561]
11/2025	Higher twist and jet power corrections	[arXiv:2511.14387]
11/2025	Parametrisation scale invariance of PDF fits	[arXiv:2511.09284]
06/2025	alpha_s determination with aN3LO $\otimes$ QED $\otimes$ MHOU	[arXiv:2506.13871]
03/2025	Closure test with inconsistencies	[arXiv:2503.17447]
03/2025	NNPDFpol2.0 - helicity dependent PDFs	[arXiv:2503.11814]

01/2025	Implications of NNPDF4.0 for LHC	[arXiv:2501.10359]
11/2024	Combination of aN3LO PDFs (w/ MSHT)	[arXiv:2411.05373]
10/2024	Ensemble-based hyperoptimisation	[arXiv:2410.16248]
06/2024	NNPDF4.0 for MC event generators	[arXiv:2406.12961]
06/2024	NNPDF4.0 aN3LO $\otimes$ QED $\otimes$ MHOU	[arXiv:2406.01779]
02/2024	NNPDF4.0 aN3LO	[arXiv:2402.18635]
01/2024	NNPDF4.0 NNLO $\otimes$ MHOU	[arXiv:2401.10319]
01/2024	NNPDF4.0 QED	[arXiv:2401.08749]
02/2023	Pipeline - industrialisation of theory predictions	[arXiv:2302.12124]
08/2022	Intrinsic charm	[arXiv:2208.08372]
09/2021	NNPDF4.0 (main release)	[arXiv:2109.02653]

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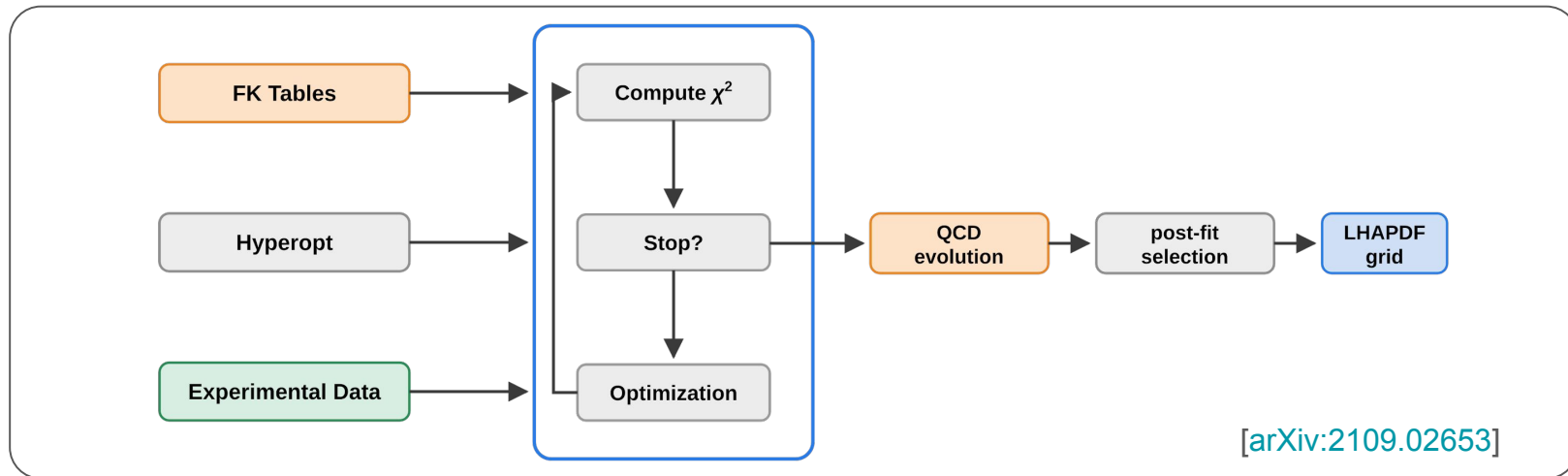
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The NNPDF 4.x Framework

The inverse problem (DIS):

$$\sigma_{exp} \longleftrightarrow \sigma = \sum_a \hat{\sigma}_a(\mu^2) \otimes f_a(\mu^2)$$

The NNPDF framework:

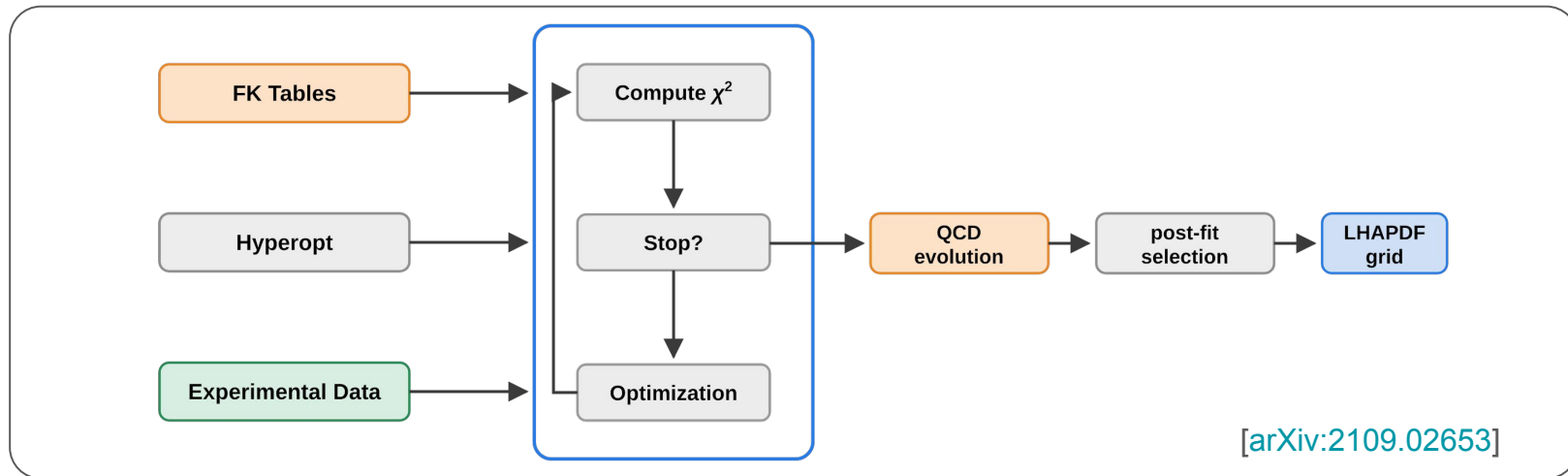


The NNPDF 4.x Framework

The inverse problem (DIS):

$$\sigma_{exp} \longleftrightarrow \sigma = \sum_{a,b} \hat{\sigma}_a(\mu^2) \otimes E_{ab}(\mu^2 \leftarrow Q_0^2) \otimes f_b(Q_0^2)$$

The NNPDF framework:

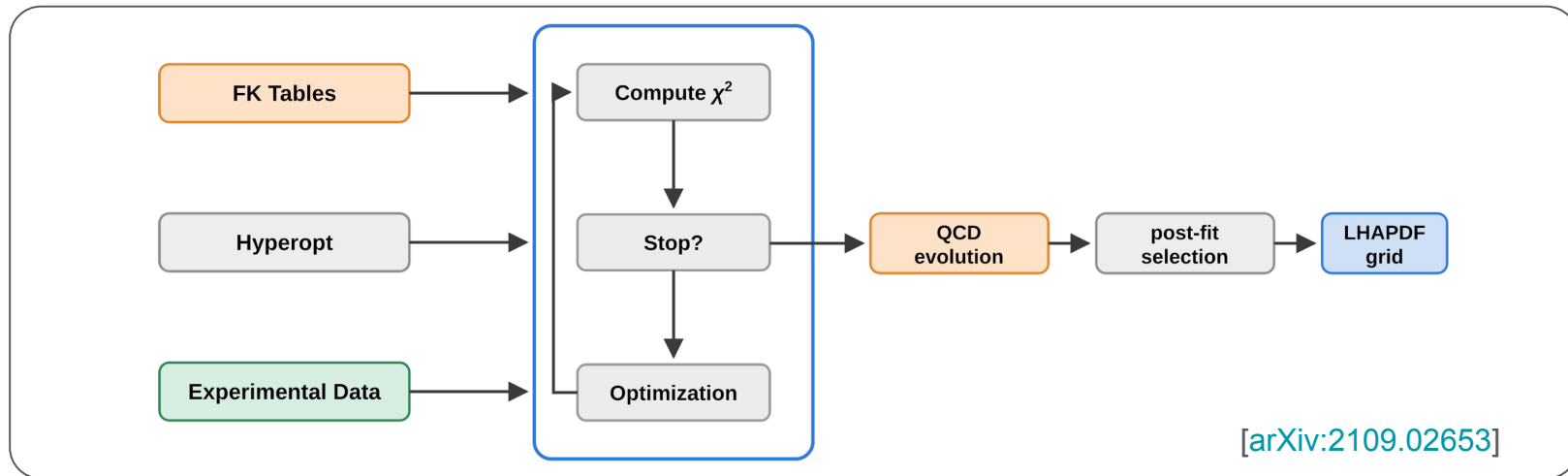


The NNPDF 4.x Framework

The inverse problem (DIS):

$$\sigma_{exp} \longleftrightarrow \sigma = \sum_{a,b} \hat{\sigma}_a(\mu^2) \otimes E_{ab}(\mu^2 \leftarrow Q_0^2) \otimes f_b(Q_0^2)$$

The NNPDF framework:



Theory Advances

New Theory Features in NNPDF4.1

Included in partial releases

01/2024	NNPDF4.0 QED	[arXiv:2401.08749]
01/2024	NNPDF4.0 NNLO $\otimes$ MHOU	[arXiv:2401.10319]
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Released with NNPDF4.1

11/2025	Higher twist and jet power corrections	[arXiv:2511.14387]
07/2026	Z pT resummation and PDF determination	[arXiv:2607.19183]
	EW corrections (k-factors)	[WIP]

EW corrections, required for high precision at LHC, need an extension of the proton PDF set:

- photon PDF
 $\gamma(x, Q^2)$
- QED splitting functions in PDF evolution
 $\mathcal{O}(\alpha), \mathcal{O}(\alpha\alpha_S), \mathcal{O}(\alpha^2)$

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MHOU are in many cases compatible with experimental uncertainties.

- Estimate of MHOU through variations of (μ_R, μ_F)
- We use a theory covariance matrix $C = C_{exp} + C_{th}$

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	EW corrections (k-factors)	[WIP]

Hard-scattering cross-sections at N3LO need PDFs determined at the same perturbative order to make predictions with the same accuracy.

- aN3LO for splitting functions and massive DIS coefficient functions
- IHOU added to theory covariance

New Theory Features in NNPDF4.1

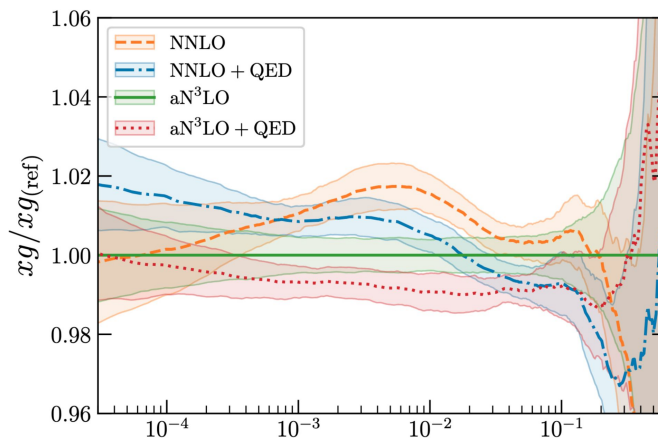
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	EW corrections (k-factors)	[WIP]

State of the art PDF set that combines the previous advancements.



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	EW corrections (k-factors)	[WIP]

- Exact NNLO computations replace k-factors
- C_{th} improved with higher twist (DIS) and linear power corrections (jets)
- Resummation relevant even for $p_T > 30 \text{ GeV}$ in Z p_T data at 13 TeV
- EW corrections included as k-factors

Perturbative Orders

NNPDF4.0
arXiv:2109.02653

NNPDF4.1
WIP

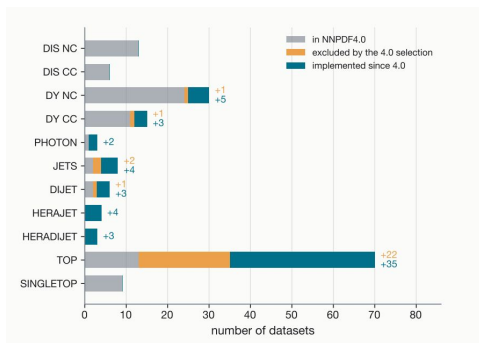
$\sigma_b^{(k)}(x_l, \mu_j^2)$	DIS: NNLO hadronic: NNLO k-factors	DIS: aN3LO hadronic: NNLO
$\text{EKO}_{a,i}^{b,l,j}$	NNLO	aN3LO QCD $\otimes$ NLO QED
EW corrections	Cuts	k-factors
$\text{FK}_a(x_i; \mu_0^2)$	NNLO k-factors	- aN3LO QCD $\otimes$ QED - EW k-factors - Z_{PT} resummation
Theory Uncertainties	Nuclear	4.0 + MHOU + IHOU + HT/PC

$$\text{FK}_a(x_i; \mu_0^2) = \sum_{b,j,k,l} \alpha_s^{n+k}(\mu_j^2) \text{EKO}_{a,i}^{b,l,j} \sigma_b^{(k)}(x_l, \mu_j^2)$$

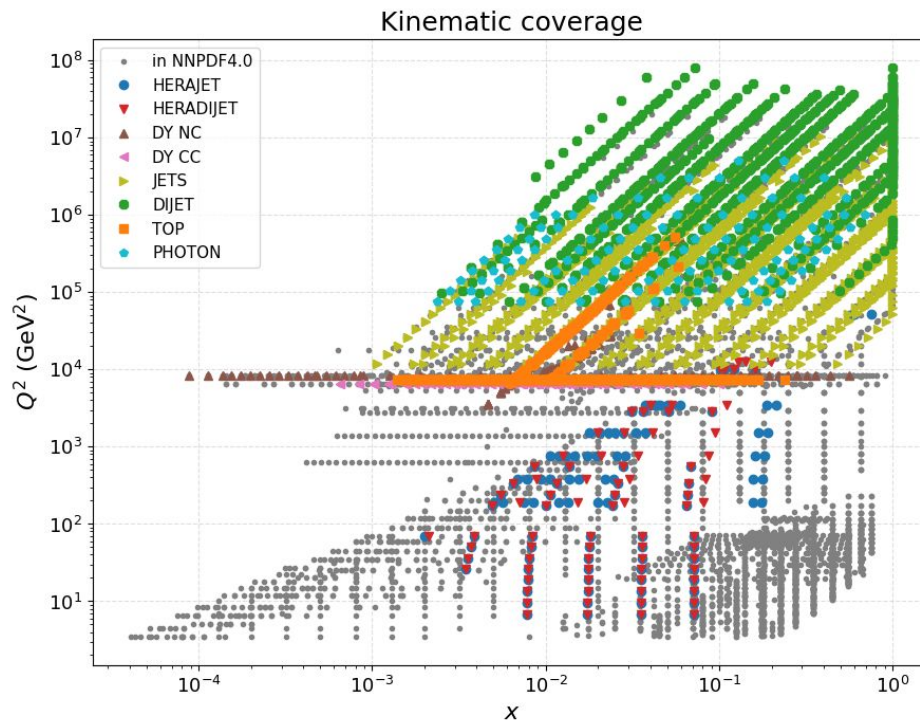
New Experimental Data

New Experimental Data

At now around 50 new datasets and 800 new data points.



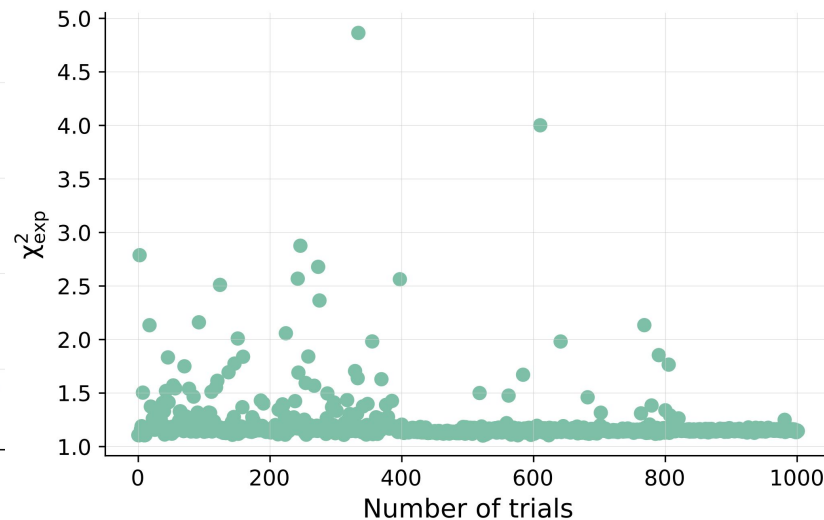
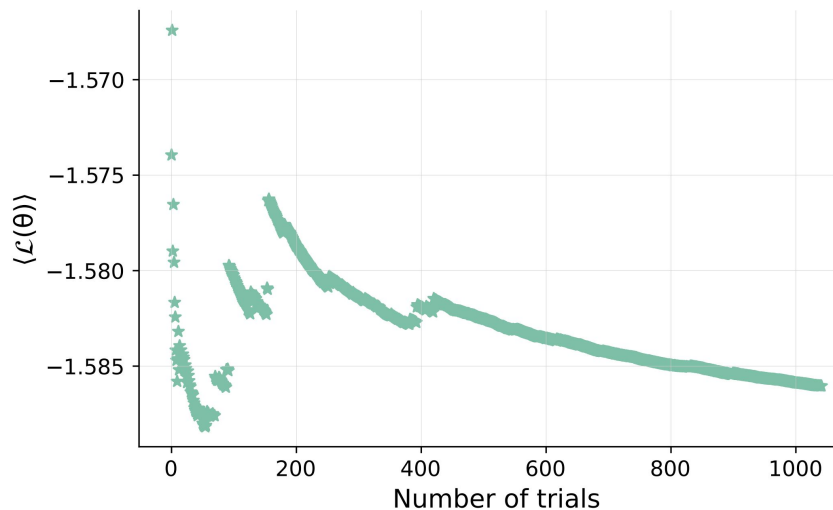
Process	NNPDF4.0	NNPDF4.1	4.1 conservative
DIS NC	13 / 2100	13 / 2100	13 / 2100
DIS CC	6 / 989	6 / 989	6 / 989
DY NC	24 / 735	30 / 903	24 / 613
DY CC	11 / 157	15 / 222	9 / 115
HERAJET	0 / 0	4 / 121	4 / 121
HERADIJET	0 / 0	3 / 83	3 / 83
JETS	2 / 356	8 / 928	4 / 377
DIJET	2 / 144	6 / 658	2 / 226
TOP	14 / 64	70 / 566	54 / 374
SINGLETOP	9 / 17	9 / 17	9 / 17
PHOTON	1 / 53	3 / 177	3 / 177
Total	82 / 4615	167 / 6764	131 / 5192



Methodology Advances

Ensemble Based Hyperoptimisation

$$\mathcal{L}^{(i)}(\theta) = \left(y^{(i)} - \bar{T}^{(i)}\right)^T \left(C_y^{(i)} + C_{\text{PDF}}^{(i)}\right)^{-1} \left(y^{(i)} - \bar{T}^{(i)}\right) + \log \det \left(C_y^{(i)} + C_{\text{PDF}}^{(i)}\right)$$



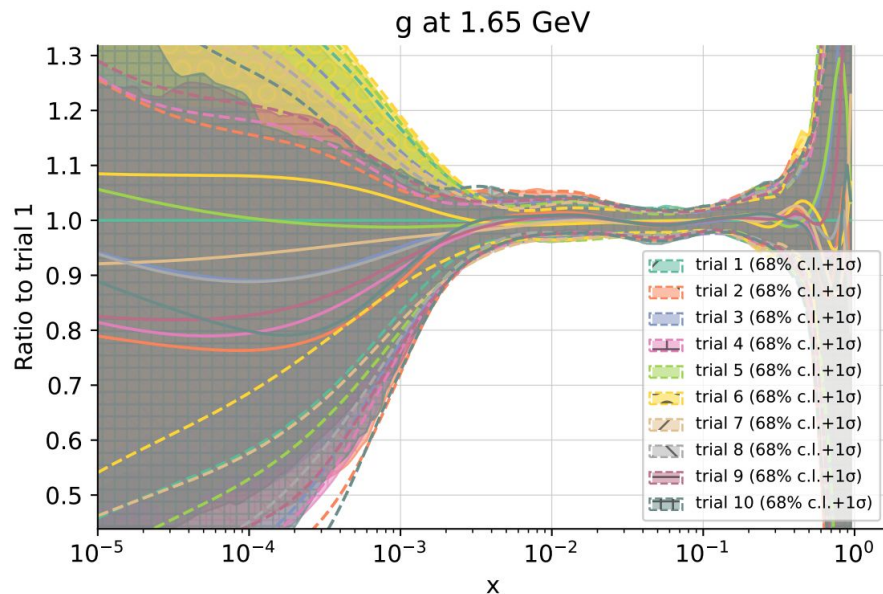
Hyperoptimising on the faithfulness of the uncertainty

[\[arXiv:2605.31482\]](https://arxiv.org/abs/2605.31482)

Ensemble Based Hyperoptimisation

NNPDF4.1:

- MC replicas extracted from many methodologies
- methodological uncertainty estimate

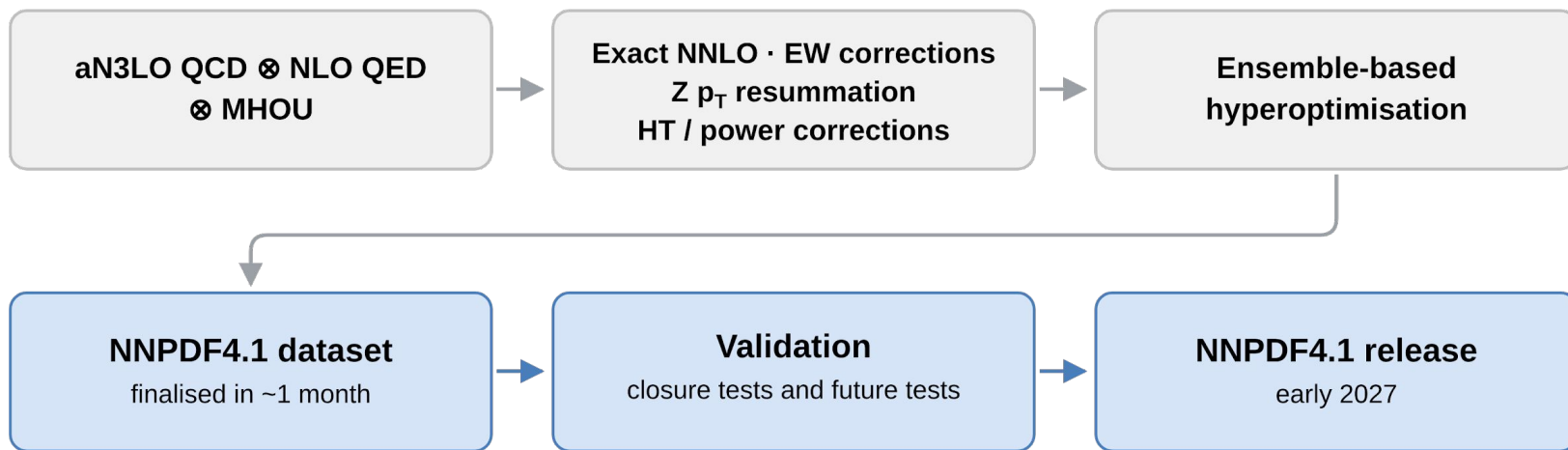


[[arXiv:2410.16248](https://arxiv.org/abs/2410.16248)]

[[arXiv:2605.31482](https://arxiv.org/abs/2605.31482)]

Conclusions and Outlook

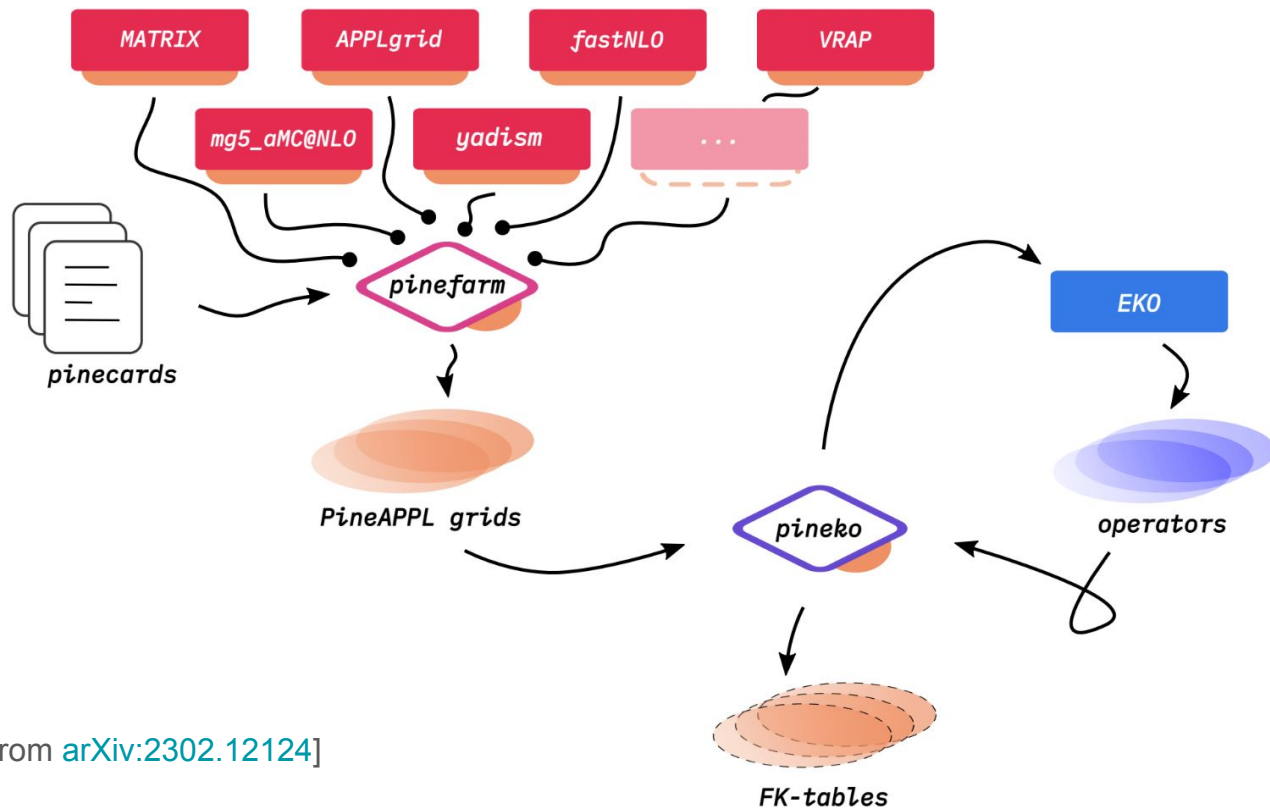
We aim to release the **NNPDF4.1 PDF SET** in Q1 2027.



Thank You!

~ Backup Slides ~

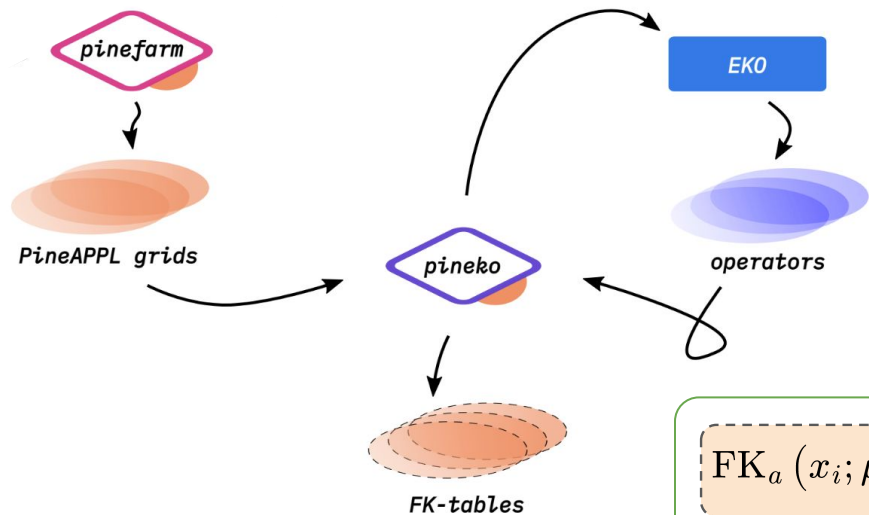
Pipeline Framework (open source)



[image from [arXiv:2302.12124](https://arxiv.org/abs/2302.12124)]

Pipeline for Theory Input

$$\sigma = \sum_{i,j,k} \sum_a f_a(x_i, \mu_{Fj}^2) \alpha_s^{n+k}(\mu_{Rj}^2) \sigma_a^{(k)}(x_i, \mu_{Fj}^2, \mu_{Rj}^2)$$



for PDF fits

$$\sigma = \sum_i \sum_a f_a(x_i; \mu_0^2) \text{FK}_a(x_i; \mu_0^2)$$



$$\text{FK}_a(x_i; \mu_0^2) = \sum_{b,j,k,l} \alpha_s^{n+k}(\mu_j^2) \text{EKO}_{a,i}^{b,l,j} \sigma_b^{(k)}(x_l, \mu_j^2)$$

[arXiv:2302.12124]

New Theory Features in NNPDF4.1

Included in partial releases

01/2024	NNPDF4.0 QED	[arXiv:2401.08749]
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	EW corrections (k-factors)	[WIP]

$$F_2^p(x, Q^2) = F_2^{p, \text{LT}}(x, Q^2) \left(1 + \frac{H_2^p(x)}{Q^2} \right)$$

$$\frac{d\sigma_{\text{jet}}}{dp_T dy} = \left[\frac{d\sigma_{\text{jet}}}{dp_T dy} \right]_{\text{pert}} \left(1 + \frac{H_j(y)}{p_T} \right)$$

New Theory Features in NNPDF4.1

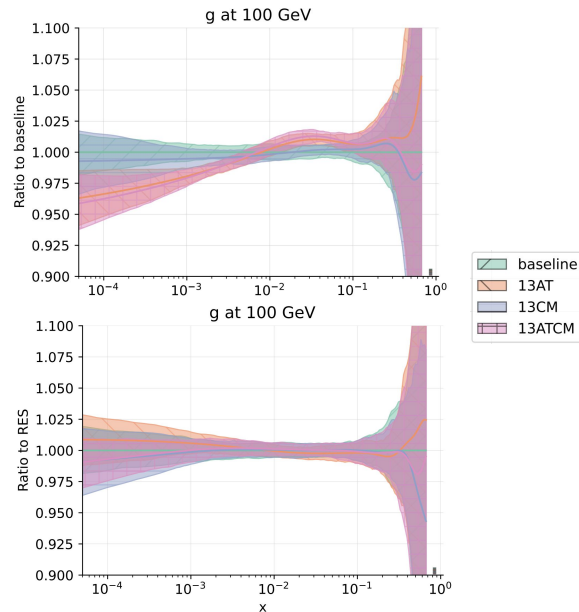
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Resummation effects are important even for $p_T > 30 \text{ GeV}$



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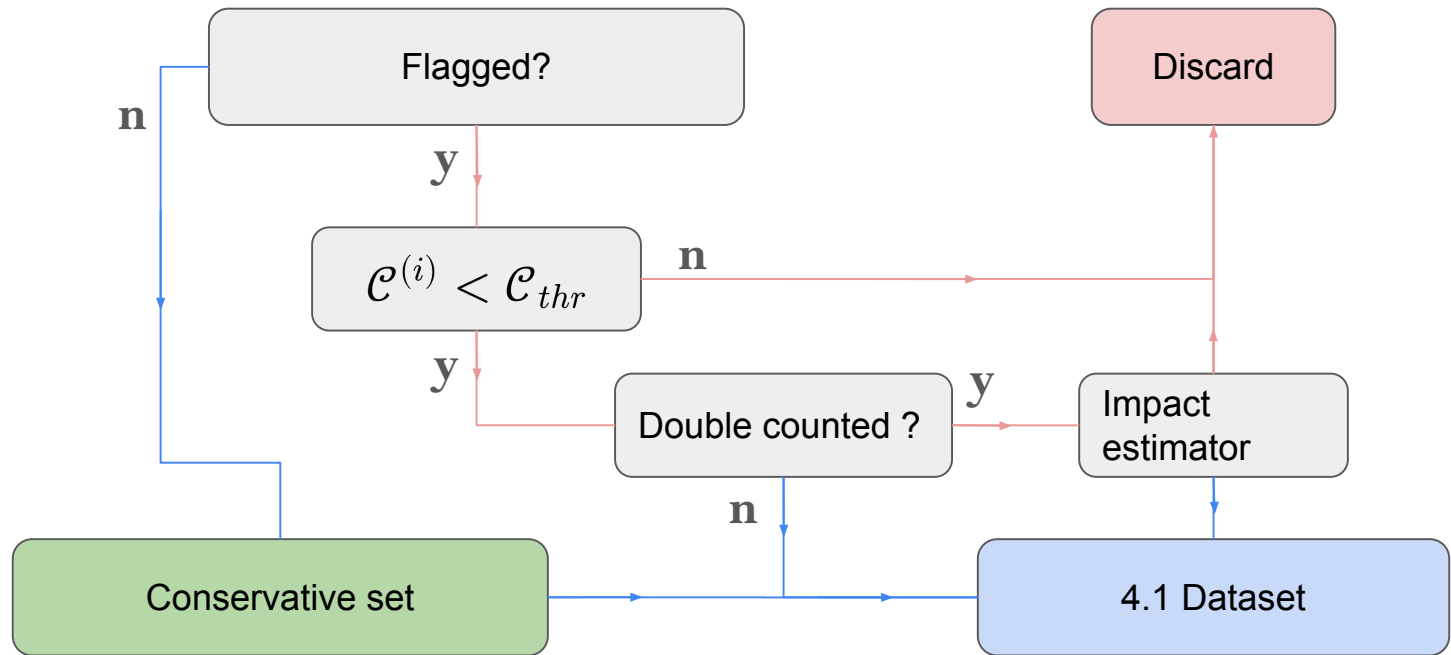
We add EW k-factor, without including corrections that are already been subtracted by experimental data.

New vs Old Data

Process	NNPDF4.0	NNPDF4.1	4.1 conservative
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Total	82 / 4615	167 / 6764	131 / 5192

Process	New in 4.1	New in conservative
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DY CC	4 / 60	1 / 2
HERAJET	4 / 121	4 / 121
HERADIJET	3 / 83	3 / 83
JETS	6 / 697	2 / 146
DIJET	4 / 514	1 / 136
TOP	57 / 513	41 / 321
PHOTON	2 / 124	2 / 124
Total	86 / 2221	57 / 957

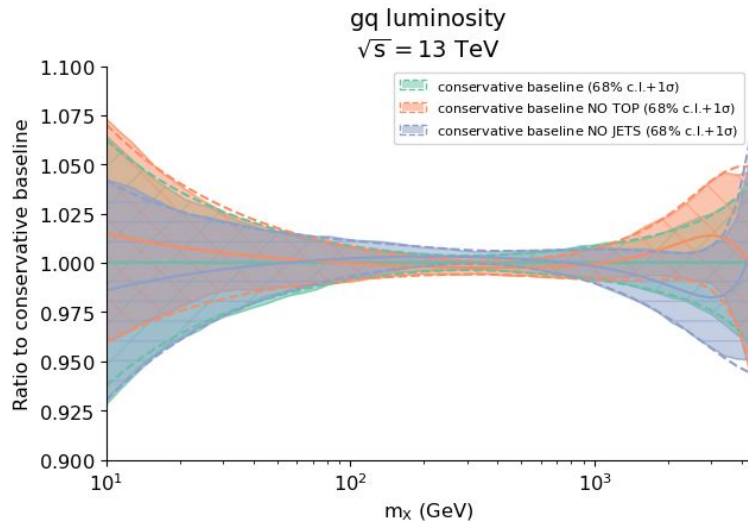
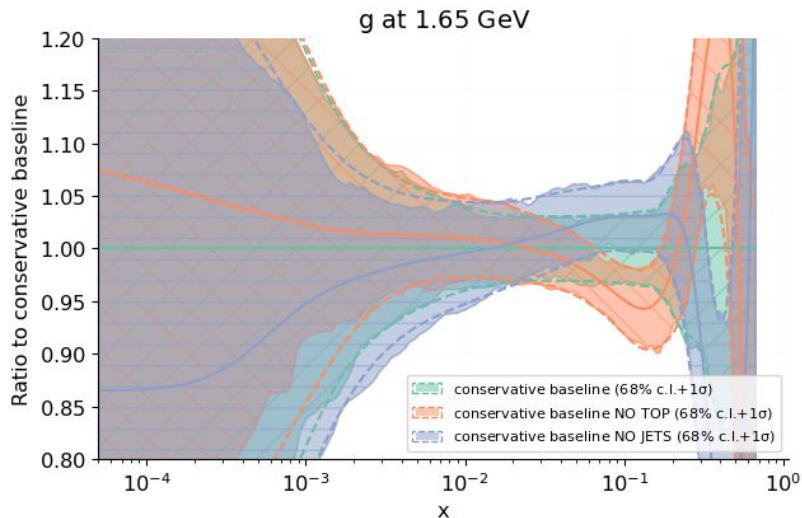
Determining the 4.1 Dataset



A procedure for dataset selection.

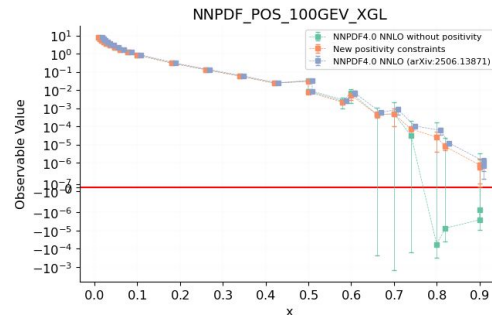
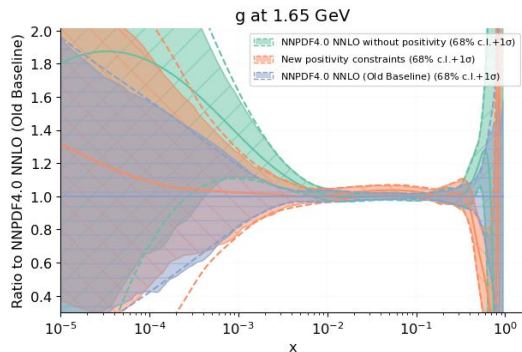
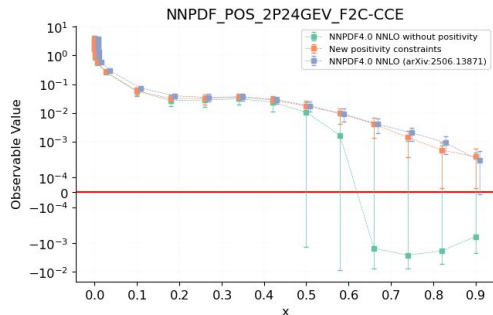
Determining the 4.1 Dataset

We are able to produce a conservative PDF set, and we do not expect major changes in this set after the dataset selection procedure.



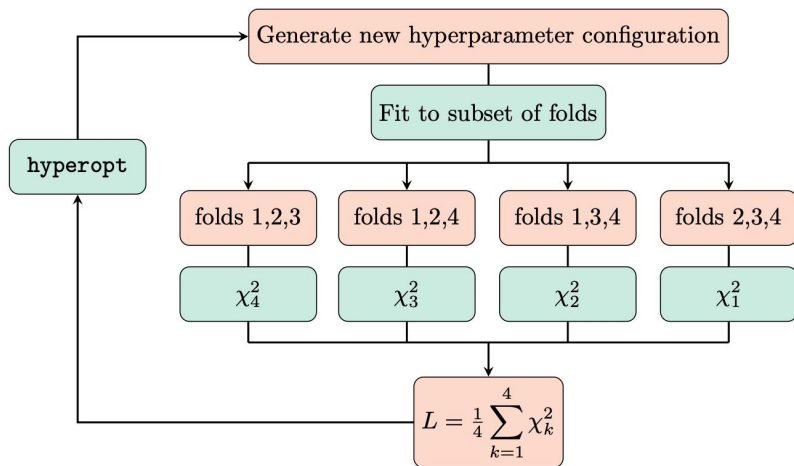
New Positivity Settings

	NNPDF4.0 arXiv:2109.02653	NNPDF4.1 WIP
Observables	$F_2^u, F_2^d, F_2^s, F_2^c, F_L$ $\sigma_{\text{DY}, u\bar{u}}, \sigma_{\text{DY}, d\bar{d}}, \sigma_{\text{DY}, s\bar{s}},$	/
PDF	$u, \bar{u}, s, \bar{s}, d, \bar{d}, g$	$u, \bar{u}, s, \bar{s}, d, \bar{d}, c, \bar{c}, g$
Scale	$Q^2 = 5 \text{ GeV}^2$	quarks: $Q^2 = 10^4 \text{ GeV}^2$ gluon: $W^2 = 10 \text{ GeV}^2$



Ensemble Based Hyperoptimisation

$$\mathcal{L}^{(i)}(\theta) = \left(y^{(i)} - \bar{T}^{(i)}\right)^T \left(C_y^{(i)} + C_{\text{PDF}}^{(i)}\right)^{-1} \left(y^{(i)} - \bar{T}^{(i)}\right) + \log \det \left(C_y^{(i)} + C_{\text{PDF}}^{(i)}\right)$$



$$\mathcal{L}(\theta) = \frac{1}{k} \sum_i \mathcal{L}^{(i)}(\theta)$$

Closure Test and Future Test

The NNPDF4.1 fitting framework will be benchmarked with closure tests and future tests.

Are the uncertainties statistically faithful?

Can the PDF set describe physics outside of the extrapolation region?