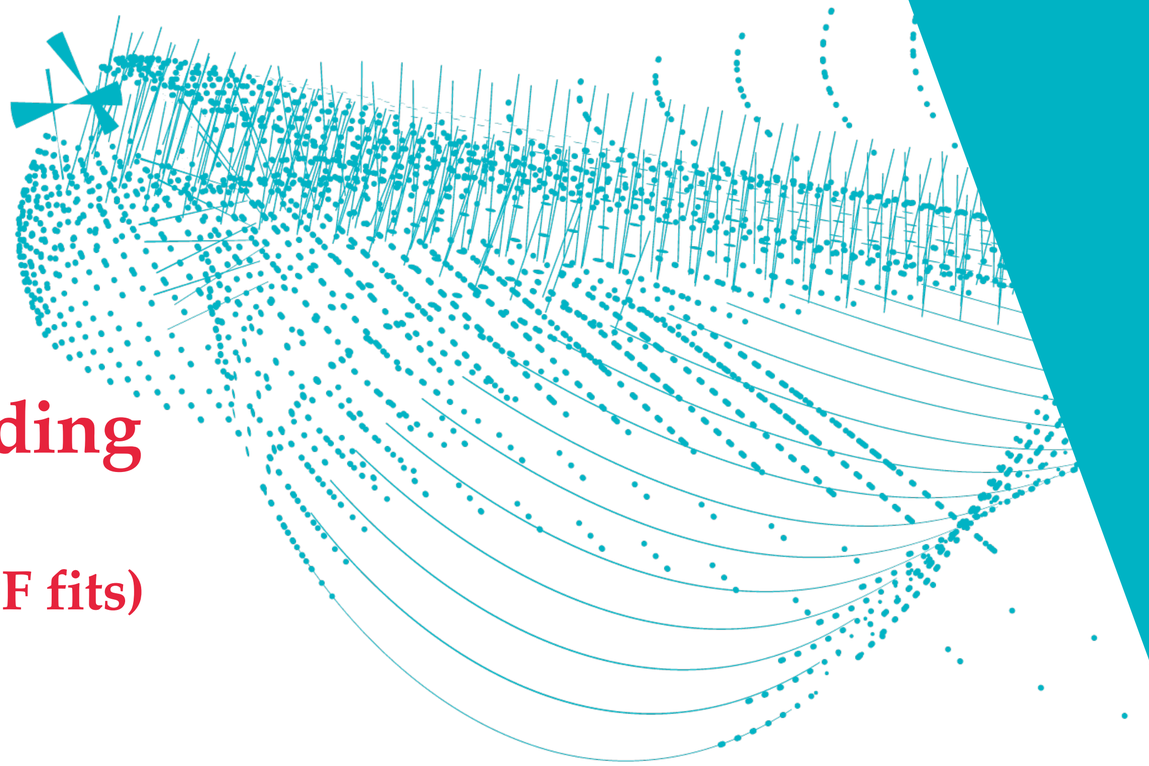
Nikhef



Precision PDF determination including photon PDF

(Towards fully including EW corrections in PDF fits)

NNPDF

Tanjona R. Rabemananjara on behalf of the NNPDF collaboration
LHCP2025, May 5th 2025
Taipei, Taiwan

VU VRIJE UNIVERSITEIT AMSTERDAM

Outline of the Talk

	Introduction & Motivations	
Part I	PDF Determination: the NNPDF Methodology	[arXiv:2109.02653; arXiv:2109.02671]
Part II	Photon-PDF Determination within the NNDPF	[arXiv:2401.08749]
Part III	Results & Implications for LHC Phenomenology	[arXiv:2401.08749; arXiv:2406.01779]
	Conclusions & Outlook	

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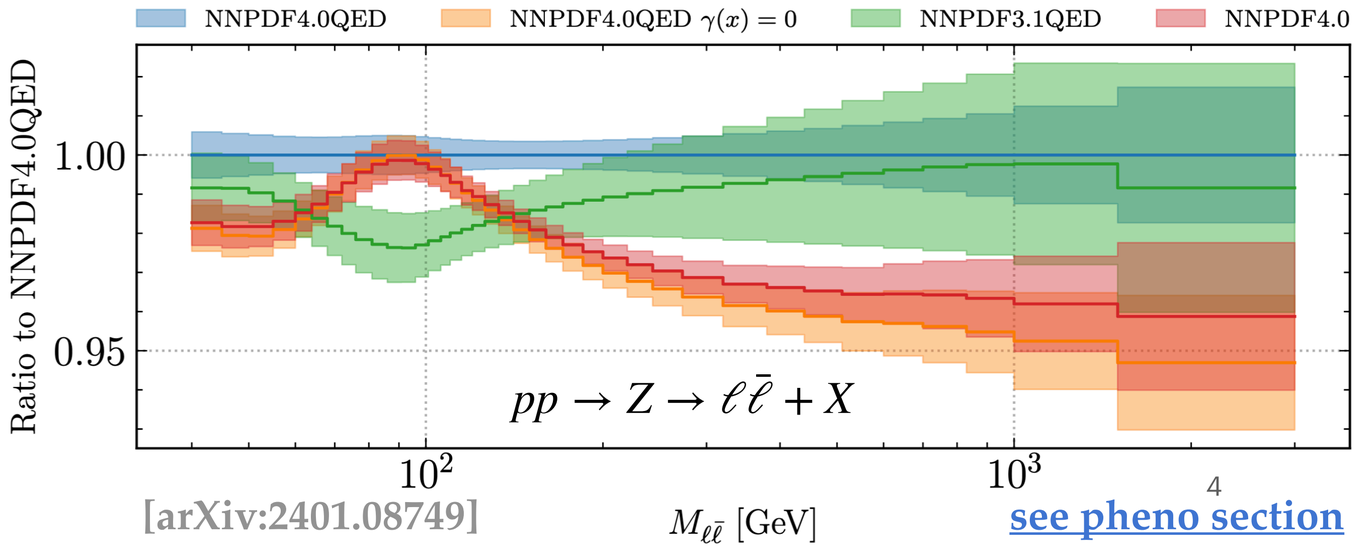
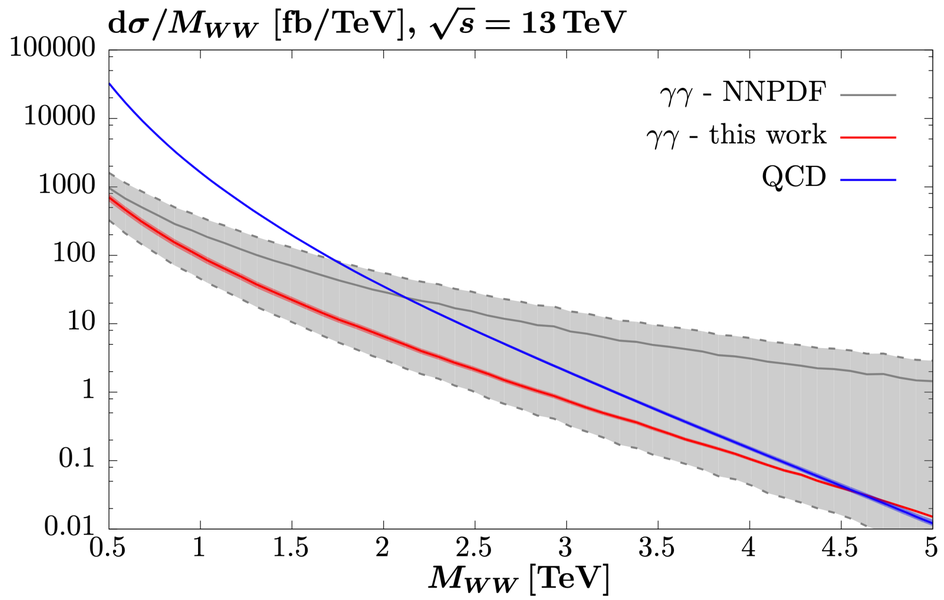
Introduction & Motivations

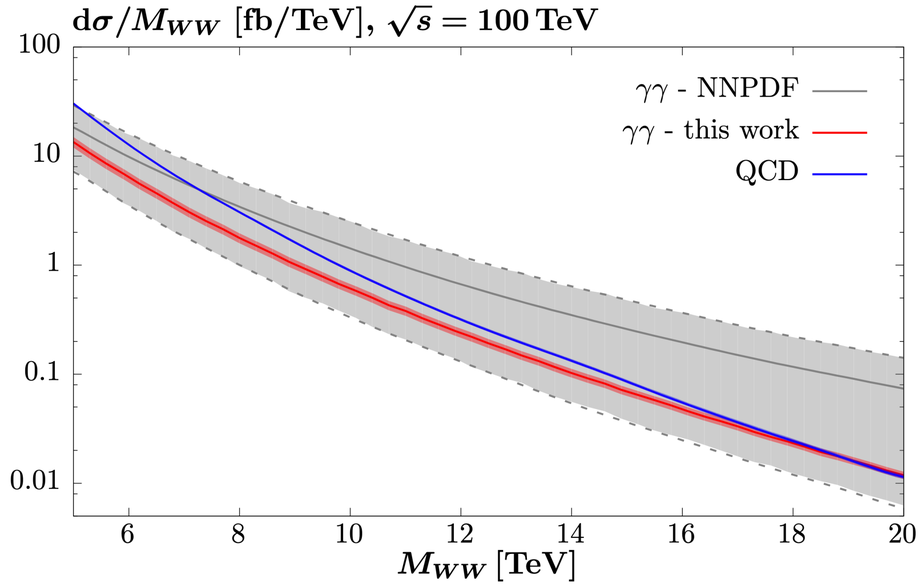
- Significant progress has been done in the determination of proton densities $\Longleftrightarrow$ **reaching precision ~1-2%**
- Photon PDF $\gamma(x, Q^2)$ **can no longer be neglected** as the determination of proton parton densities become **more accurate and precise** $\Longleftrightarrow$ $\alpha \sim \mathcal{O}(\alpha_s^2) \sim \mathcal{O}(1\%)$
- **Where do $\gamma(x, Q^2)$ PDF enter?** Electroweak corrections to almost all processes, VBF Higgs and WH, top production [D. Pagani, I. Tsinikos, M. Zaro; arXiv:1606.01915], WW production [L. A. Harland-Lang, V. A. Khoze, M. G. Ryskin; arXiv:1607.04635]
- $\gamma(x, Q^2)$ PDF is **crucial** for both **precision physics** and the **searches Beyond the Standard Model**



[arXiv:2401.08749]



[arXiv:1607.04635]



see pheno section

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PDF Determination: Formalism & Ingredients

Collinear Factorisation enables the separation between short-range and long-range physics:

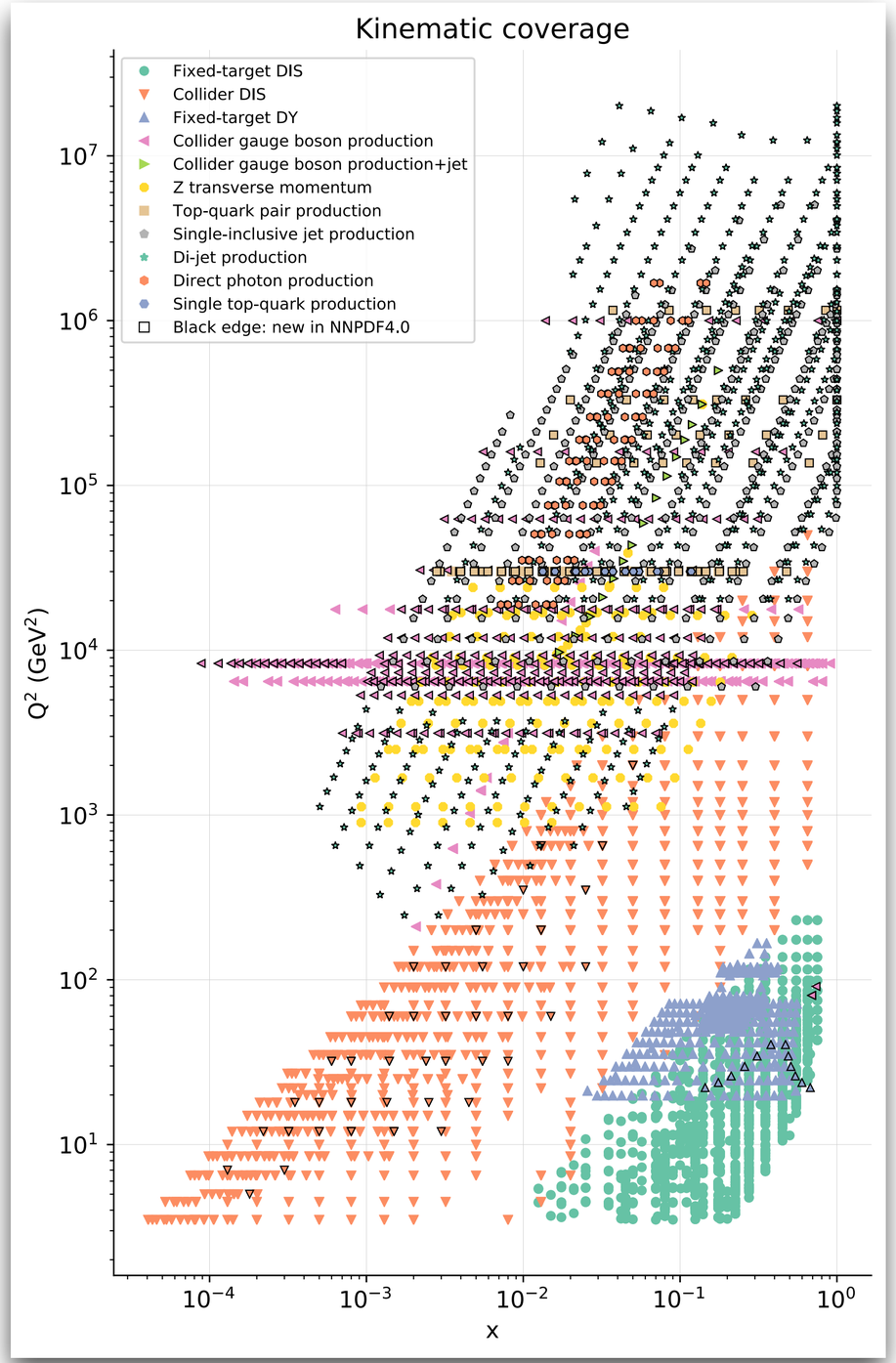
$$\mathcal{O}_{\rm LHC}(M,s) \propto \sum_{ij} \int_{M^2}^{s} d\hat{s}\, \mathscr{L}_{ij}(\hat{s},s)\hat{\mathcal{O}}_{ij}\left(\hat{s},\alpha_s(M)\right)$$

Where the Partonic luminosity directly relates to the PDFs:

$$\mathscr{L}_{ij}(Q,s) = \frac{1}{s}\int_{Q^2/s}^{1} \frac{dx}{x} f_i\left(\frac{Q^2}{sx},Q\right) f_j(x,Q)$$

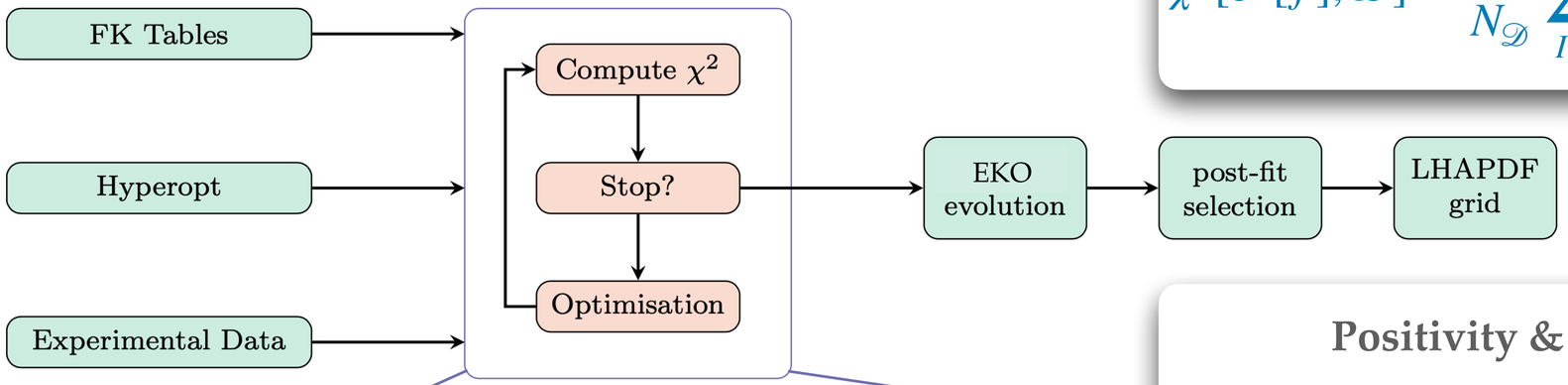
PDFs are universal and their determinations involve **three main ingredients**:

- **Experimental data** — contains $\sim \mathcal{O}(4000)$ datapoints, probe different processes and channels, include LHC Run II, etc.
- **Theory predictions** — Heavy quark schemes, NNLO (aN3LO) accuracy, MHOUs, Photon PDFs, intrinsic charm, etc.
- **Methodology** — Neural Network (NN) parametrisation, closure & future tests, uncertainty propagation, etc.



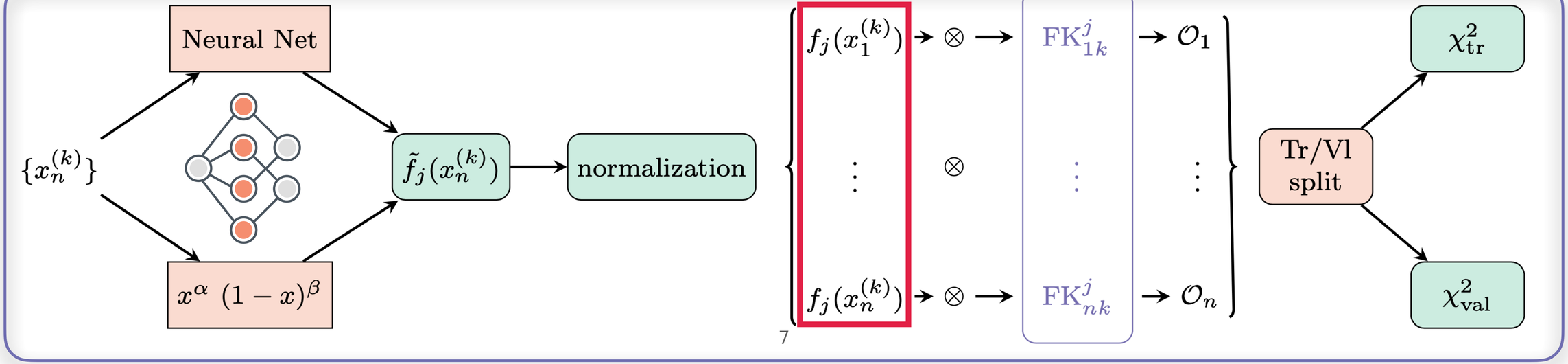
NNPDF Fitting Methodology in a Nutshell

$$\chi^2[\mathcal{T}[f],\mathcal{D}] = \frac{1}{N_{\mathcal{D}}} \sum_{I,J} \left(\mathcal{T}_I[f] - D_I\right) C_{IJ}^{-1} \left(\mathcal{T}_J[f] - D_J\right)$$



Positivity & Integrability constraints:

$$\chi^2_{\text{tot}} \to \chi^2_{\text{tot}} + \sum_{k=1}^{8} \Lambda_k \sum_{i=1}^{n_i} \mathcal{F}\left(\tilde{f}_k\left(x_i, Q^2\right)\right)$$



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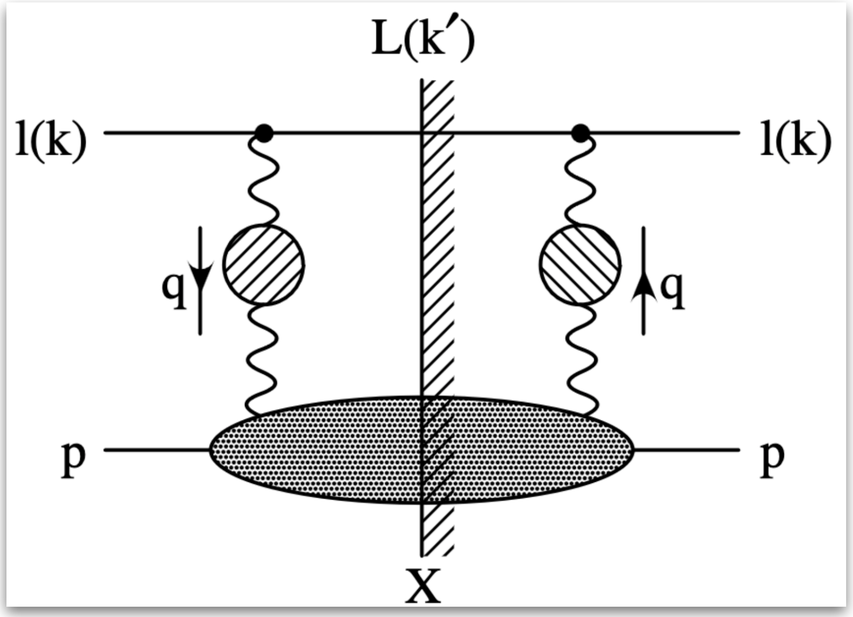
Approaches to constrain γ-PDFs

- γ-PDF is **difficult to measure** given that there are **no processes in which it enters in a dominant way**
- Historically, γ-PDF has previously been computed using **Physical** (radiation from model valence quarks) or **data-driven model** (lack of sensitive data); both of which presented major drawbacks
- **LUX formalism** A.V. Manohar, P. Nason, G.P. Salam, G. Zanderighi [arXiv:1607.04266; arXiv:1708.01256]: shows that it is possible to **strongly compute/constrain γ-PDF from currently available data**
- γ-PDF can be directly measured or computed using pQCD in the LUX formalism depending on the energy regime
- Two main changes are required to account for photons in PDF fits:
  - Modified QCD⊗QED DGLAP evolution:

$$\mu^2 \frac{df_i\left(N,\mu^2\right)}{d\mu^2} = \sum_j \gamma_{ij}\left(N,\alpha_s\left(\mu^2\right),\alpha\left(\mu^2\right)\right) f_j\left(N,\mu^2\right)$$

  - Modified QCD⊗QED Sum rules:

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



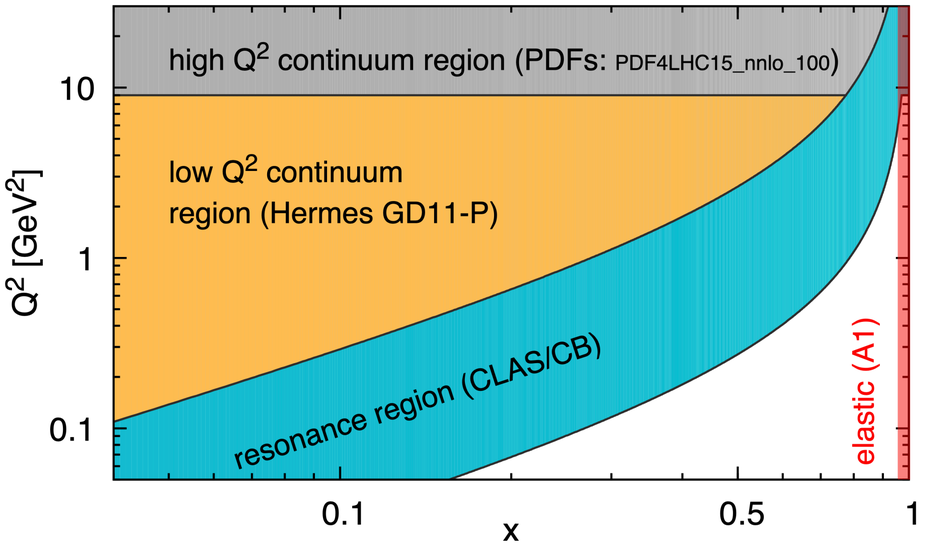
LO	$\alpha_s^1\alpha^0$	$\alpha_s^0\alpha^1$	
NLO	$\alpha_s^2\alpha^0$	$\alpha_s^1\alpha^1$	$\alpha_s^0\alpha^2$
NNLO	$\alpha_s^3\alpha^0$	$\alpha_s^2\alpha^1$	....

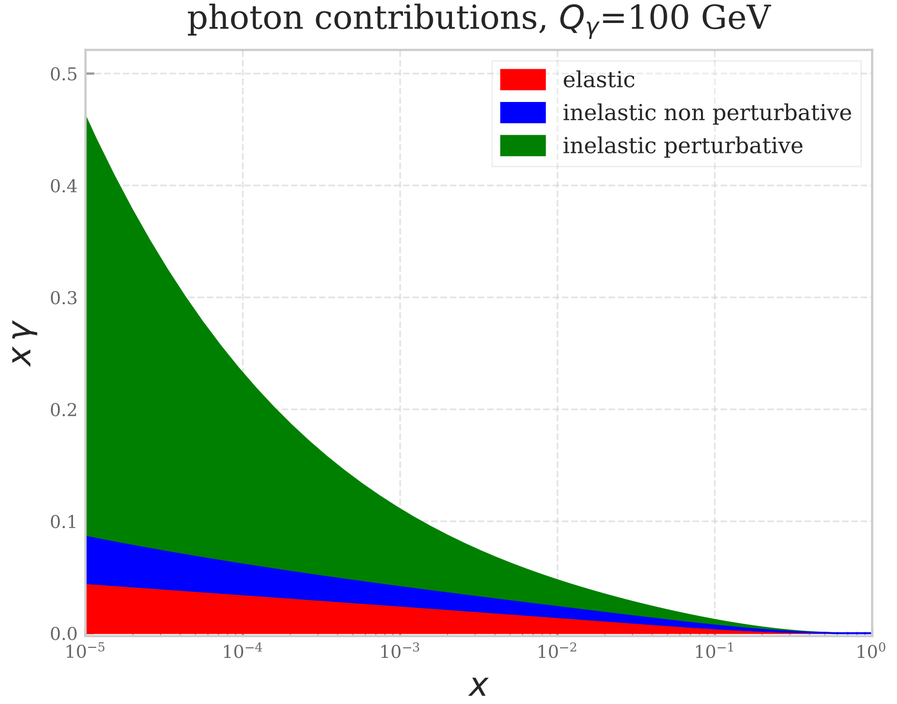
γ-PDF Determination with the LUX formalism

γ-PDFs are computed from **DIS structure functions** [arXiv:1607.04266]:

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

- Depending on the kinematic region/energy regime the structure functions are computed form: **Elastic DIS**, **Resonance**, **Shallow Inelastic**, **DIS**



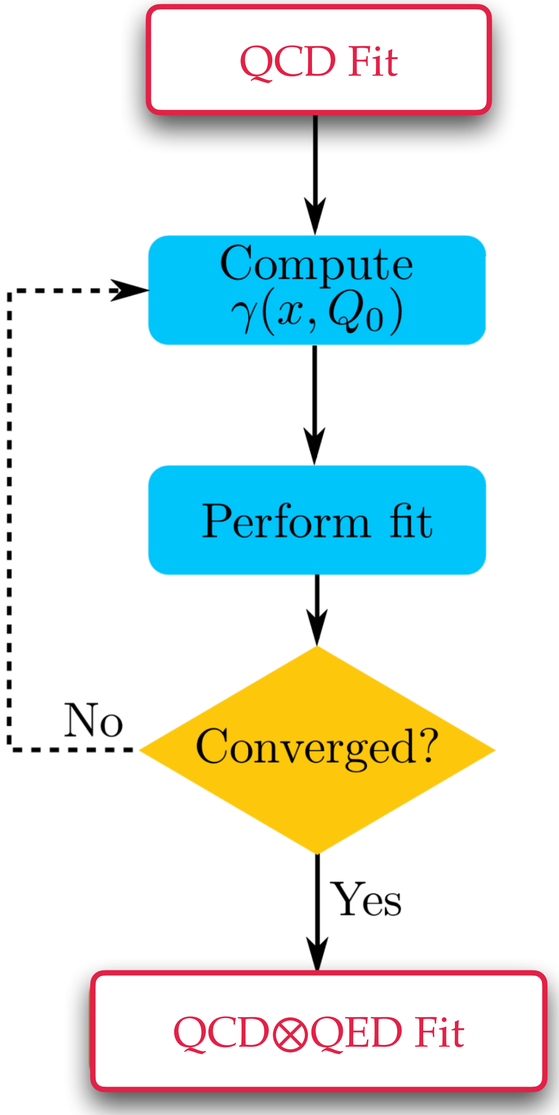


γ-PDF Determination with the LUX formalism

γ-PDFs are computed from **DIS structure functions** [arXiv:1607.04266]:

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

- Depending on the kinematic region/energy regime the structure functions are computed form: **Elastic DIS**, **Resonance**, **Shallow Inelastic**, **DIS**
- While $\gamma(x,Q^2)$ depends on the PDFs through the structure functions, it affects their determination during the iterative procedure.
- $\gamma(x,Q^2)$ is computed iteratively during the fit at $Q=100$ GeV (evolved down to $Q_0=1.65$ GeV). Such scale is chosen to minimise contributions from the low-regime and higher-twist effects
- Mixed QED⊗QCD DGLAP evolution: **more difficult to diagonalise due to how γ couples differently to up-like and down-like quarks** $\Longrightarrow$ **Unified Evolution Basis**



$a_{em}=\alpha/(4\pi)$

$F_{2,L}=\mathscr{C}^i_{2,L}\otimes f_i$

NNPDF [arXiv:1712.07053]

Solving the Mixed QCD⊗QED Evolution

Because photons couple differently to **up-like** and **down-like** quarks

$\Longleftrightarrow$

QCD⊗QED Evolution is **more difficult to Diagonalise**

NNPDF4.0QED uses a so called **Unified Evolution Basis** n_f active quarks are split into n_u and n_f flavors $(n_f = n_u + n_d)$

$$\mu^2 \frac{d}{d\mu^2} \begin{pmatrix} g \\ \gamma \\ \Sigma \\ \Sigma_\Delta \end{pmatrix} = -\mathbf{\Gamma}_s \begin{pmatrix} g \\ \gamma \\ \Sigma \\ \Sigma_\Delta \end{pmatrix}, \quad \mu^2 \frac{d}{d\mu^2} \begin{pmatrix} V \\ V_\Delta \end{pmatrix} = \mathbf{\Gamma}_V \begin{pmatrix} V \\ V_\Delta \end{pmatrix}, \quad \mu^2 \frac{d}{d\mu^2} f^{u/d}_{ns,\pm} = \left(\gamma_{ns,\pm} + \tilde{\gamma}^{u/d}_{ns,\pm} \right) f^{u/d}_{ns,\pm}$$

$$f^u_{ns,\pm} = \begin{cases} u^\pm - c^\pm \\ u^\pm + c^\pm - 2t^\pm, \end{cases} \quad f^d_{ns,\pm} = \begin{cases} d^\pm - s^\pm \\ d^\pm + s^\pm - 2b^\pm, \end{cases} \quad \Sigma_\Delta = \frac{n_d}{n_u} \sum_{i=1}^{n_u} u_i^+ - \sum_{i=1}^{n_d} d_i^+ \quad V_\Delta = \frac{n_d}{n_u} \sum_{i=1}^{n_u} u_i^- - \sum_{i=1}^{n_d} d_i^-$$

PineAPPL: Combined QCD⊗QED fast interpolation tables

PineAPPLv1: "fast and flexible theory predictions for present and future colliders"

[(Top appear soon) Tomas Jezo, Emanuele R. Nocera, Tanjona Rabemananjara, Christopher Schwan, Tanishq Sharma, Jan Wissmann]

- ☑ **Main idea was to support ELECTROWEAK corrections**
- ☑ **Interfaced to various MC Generators (MadGraph, NNLOJet, MATRIX, …)**
- ☑ **support any arbitrary number of convolutions** ⟹ supports processes such as Single Inclusive Hadron Production in *pp* (**3 convolutions**), Exclusive Particle Production in *pp* and *pPb* (**4 convolutions**), …
- ☑ support **various combinations of initial- and final-states**:

$$\{\text{Unpolarized, Polarized}\} \otimes \{\text{PDF, FF}\}$$

- ☑ supports **additional variation of Fragmentation scale** μ_a and more…

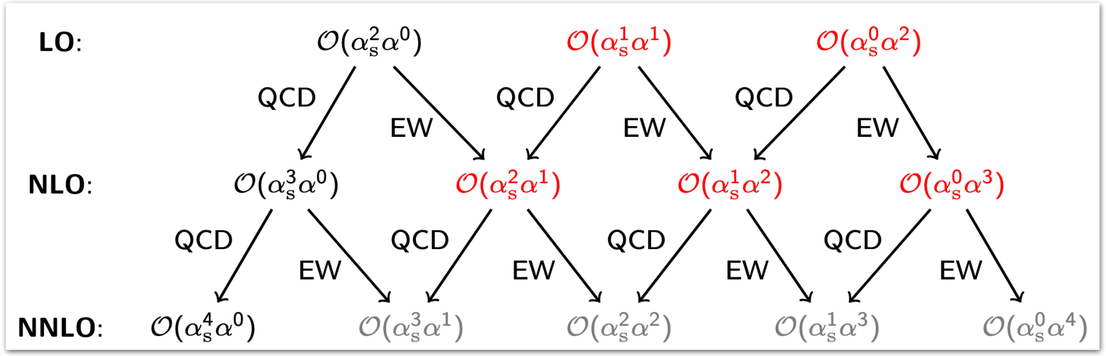
Rust passing | codecov 97% | docs passing | crates.io v1.0.0-alpha2 | Rust 1.80+

What is PineAPPL?

This repository contains programs, libraries and interfaces to read and write `PineAPPL` interpolation grids, which store theoretical predictions for high-energy collisions independently from their PDFs and the strong coupling.

PineAPPL grids are generated by Monte Carlo generators, and the grids in turn can be convolved with PDFs to produce tables and plots, such as the following one:

https://github.com/NNPDF/pineappl



Example of QCD⊗QED mixing for $pp \to t\bar{t}$

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γ-PDFs Determination: Fit Quality

- **Fit quality improves with the perturbative orders**
- **Impact of QED effects on fit quality is negligible, both globally and for individual processes**

	Dataset	NNPDF4.0 NLO		NNPDF4.0 NNLO	
		QCD×QED	QCD	QCD×QED	QCD
χ^2	Global	1.31	1.26	1.17	1.17
$\langle E_{\rm tr}\rangle_{\rm rep}$		2.47±0.07	2.41±0.06	2.27±0.06	2.28±0.05
$\langle E_{\rm val}\rangle_{\rm rep}$		2.66±0.11	2.57±0.10	2.39±0.10	2.37±0.11
$\langle \chi^2\rangle_{\rm rep}$		1.337±0.016	1.286±0.017	1.192±0.014	1.195±0.015
χ^2	DIS neutral-current	1.38	1.31	1.22	1.23
	DIS charged-current	0.94	0.92	0.90	0.90
	Drell–Yan (inclusive and with one jet)	1.56	1.56	1.30	1.31
	Top-quark pair production	2.31	1.98	1.31	1.24
	Single-top production	0.38	0.36	0.39	0.36
	Inclusive jet production	0.83	0.85	0.93	0.96
	Dijet production	1.56	1.55	1.94	2.03
	Direct photon production	0.64	0.58	0.74	0.75

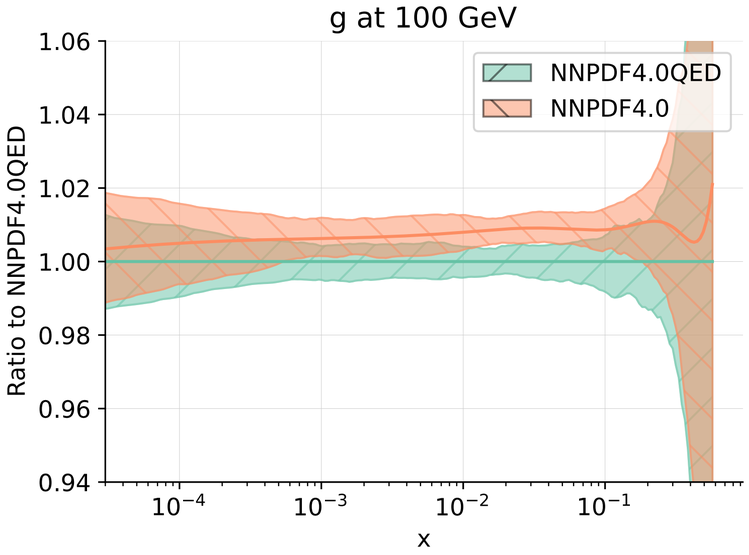
γ-initiated processes not included in theory predictions $\Longleftrightarrow$ Corresponding datasets are cut away

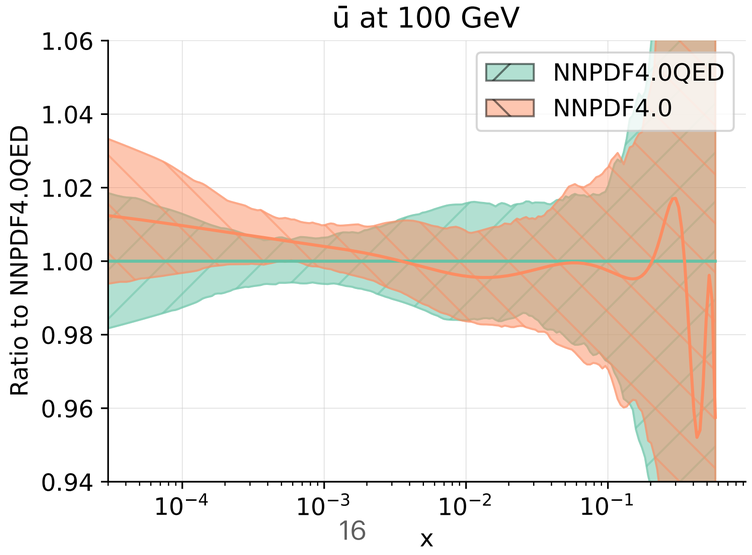
γ-PDFs Determination: PDFs w/o vs. w/ QED

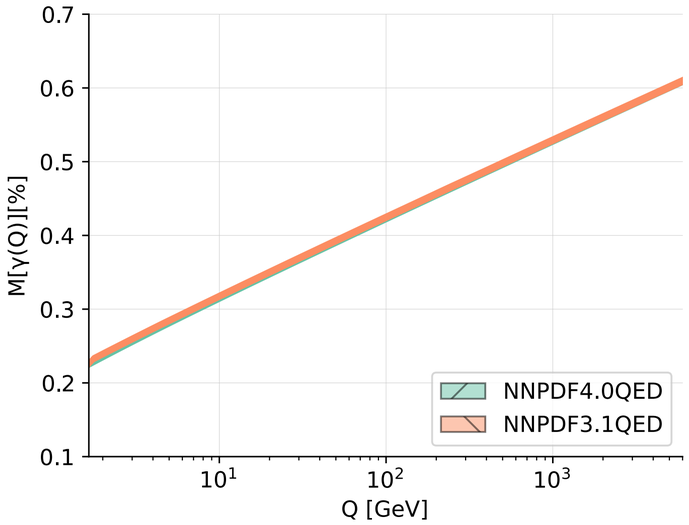
- The effect of the inclusion of QED corrections is **very mild** — and **mostly seen in the gluon PDF**
- The main impact of the photon on PDFs is through the sum rules — this is quantified by evaluating the contribution of the photon momentum fractions:

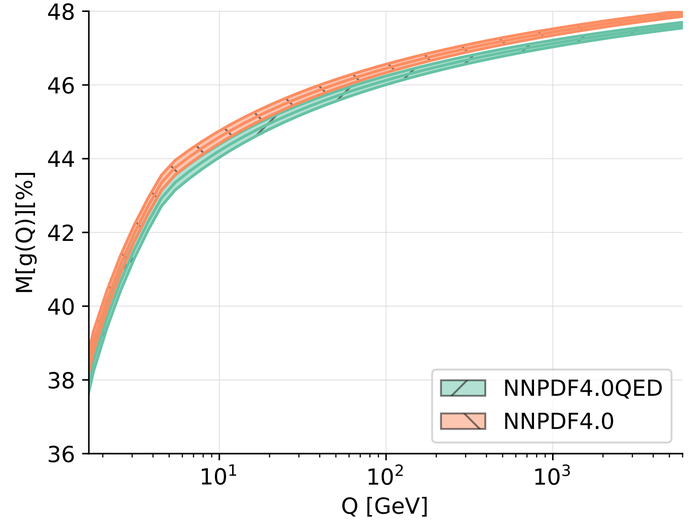
$$M[\gamma(Q)] \equiv \int_0^1 dx\, x\gamma(x, Q)$$

- The photon carries around 0.2% of the proton momentum at a low (Q~1 GeV) scale, growing logarithmically with Q up to around 0.6% at the multi-TeV scale $\Longleftrightarrow$ **depletion of the gluon momentum**

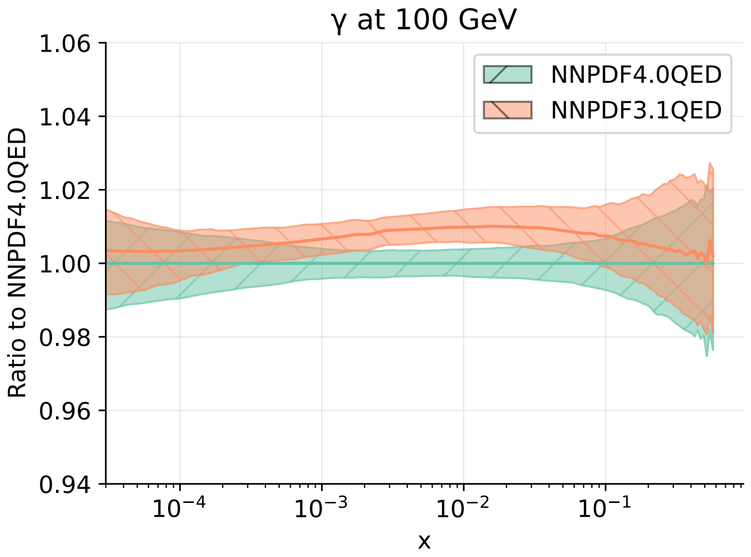


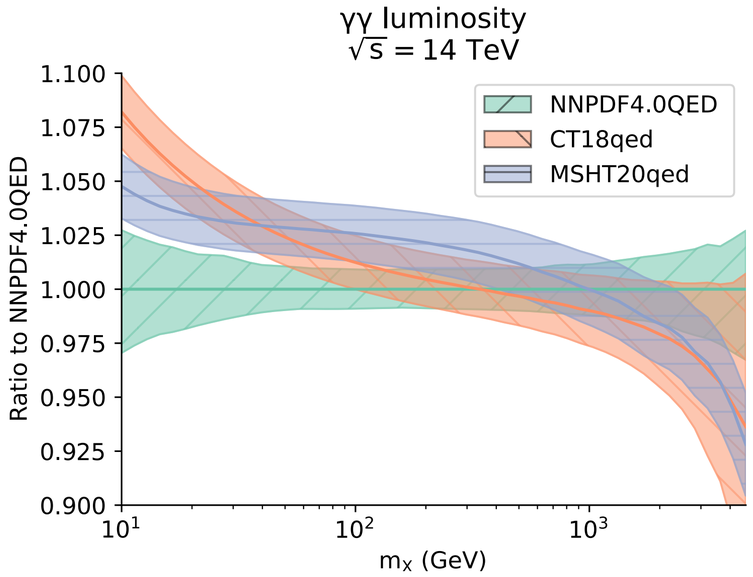


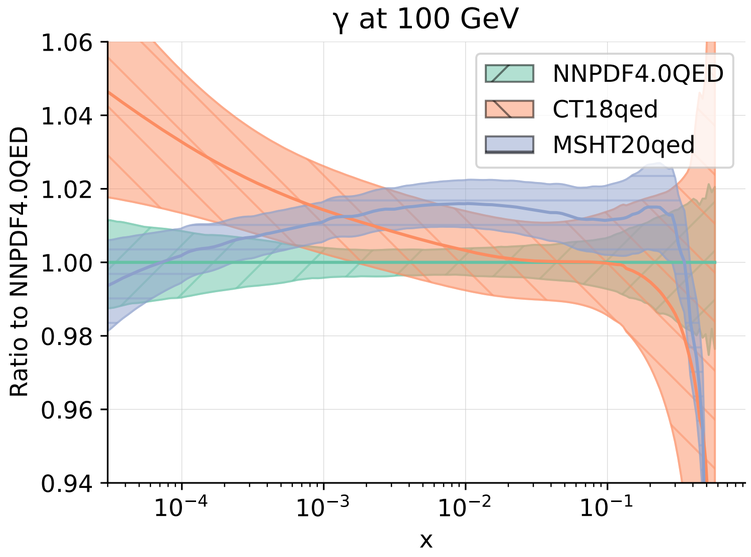


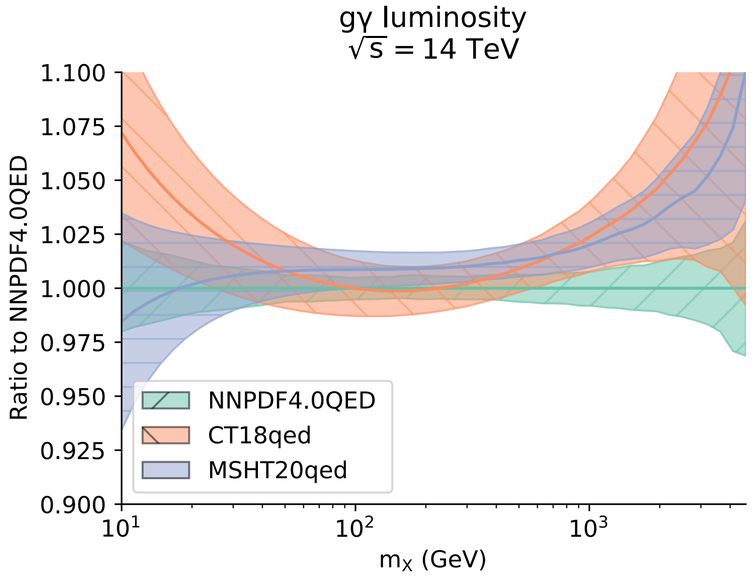


γ-PDFs Determination: Comparison to other sets



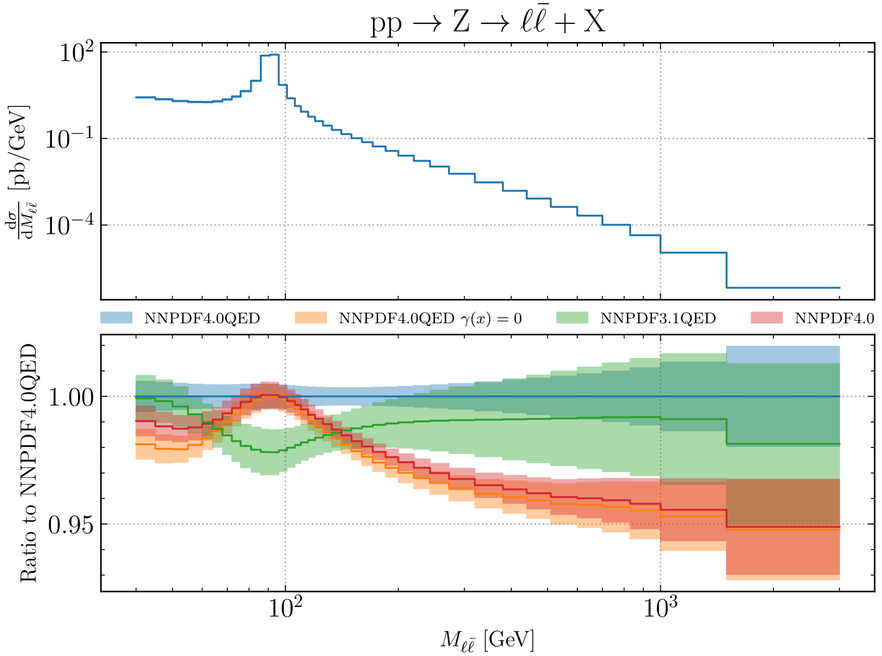


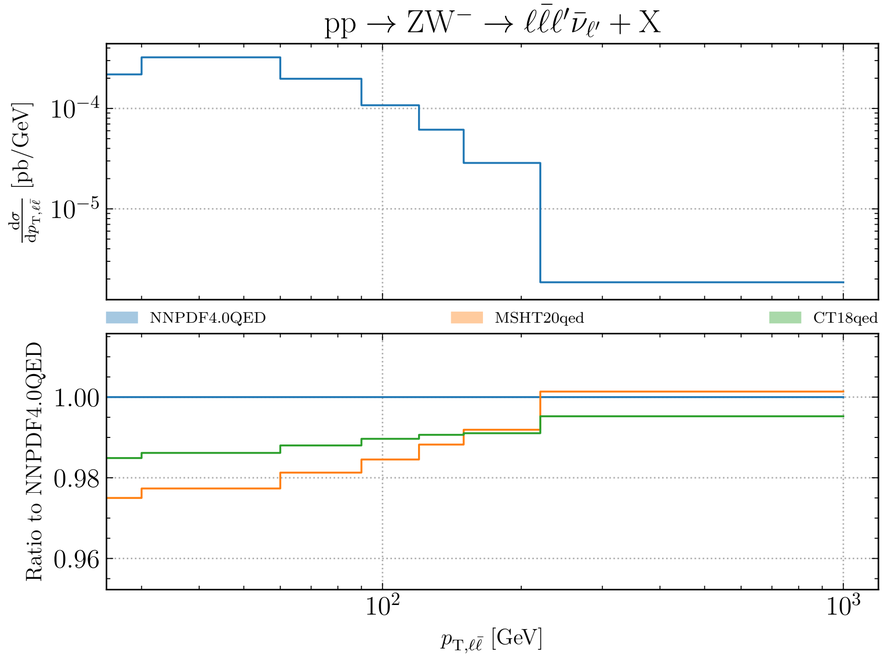


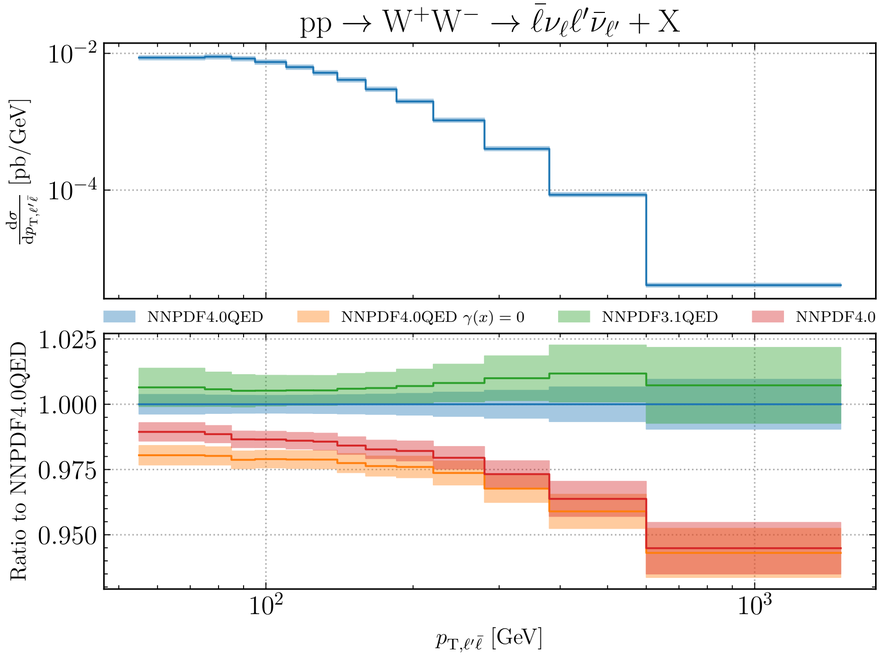


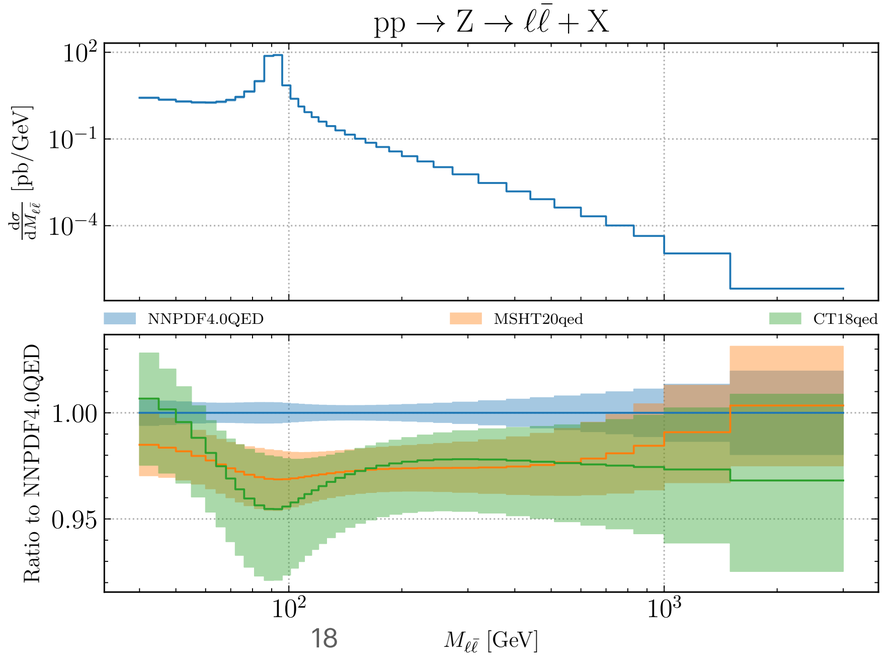
- Good agreement between with the disagreement coming from "truncated" vs. "exact" solutions of the Evolution equations
- Because all the other PDF fitting groups rely on the LUX formalism, the γ-PDFs agree well at the percent level
- Luminosity generally in agreement but differ at very small and large invariant mass

γ-PDFs Determination: Implications for LHC Phenomenology









- γ-induced processes have been included/excluded in the theory predictions for phenomenology
- Non-negligible corrections in the high-invariant mass $M_{\ell\bar{\ell}}$ and high-p_T regions

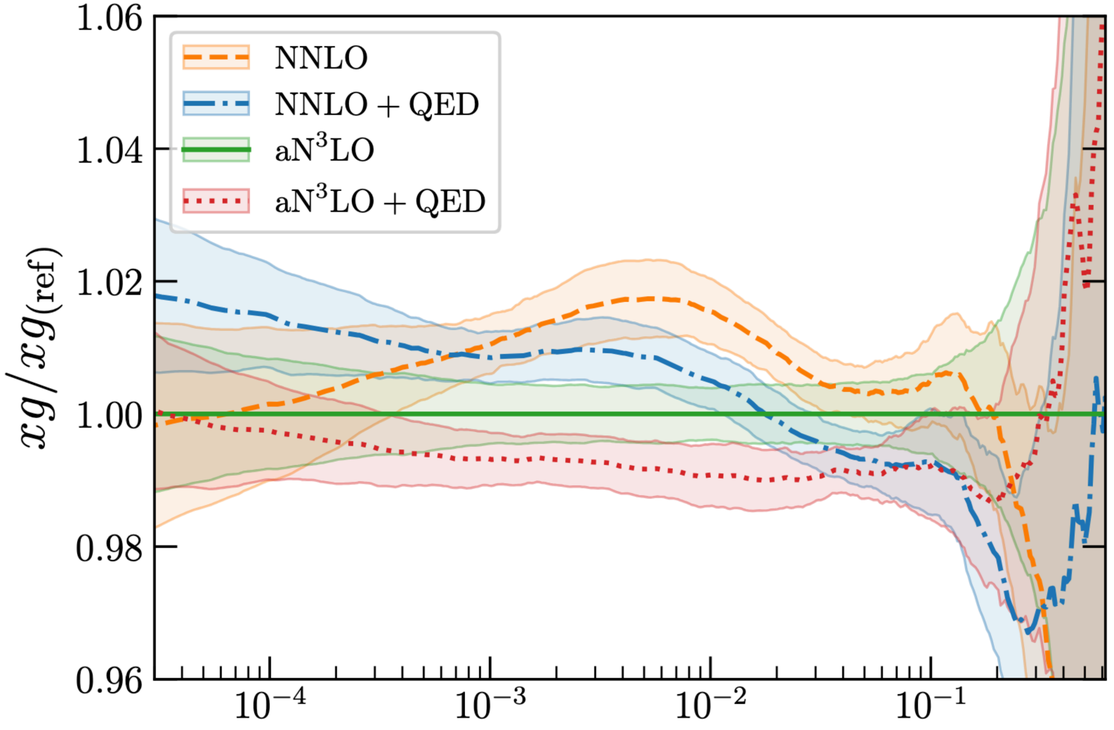
PDF Determination at "aN3LO⊗QED"

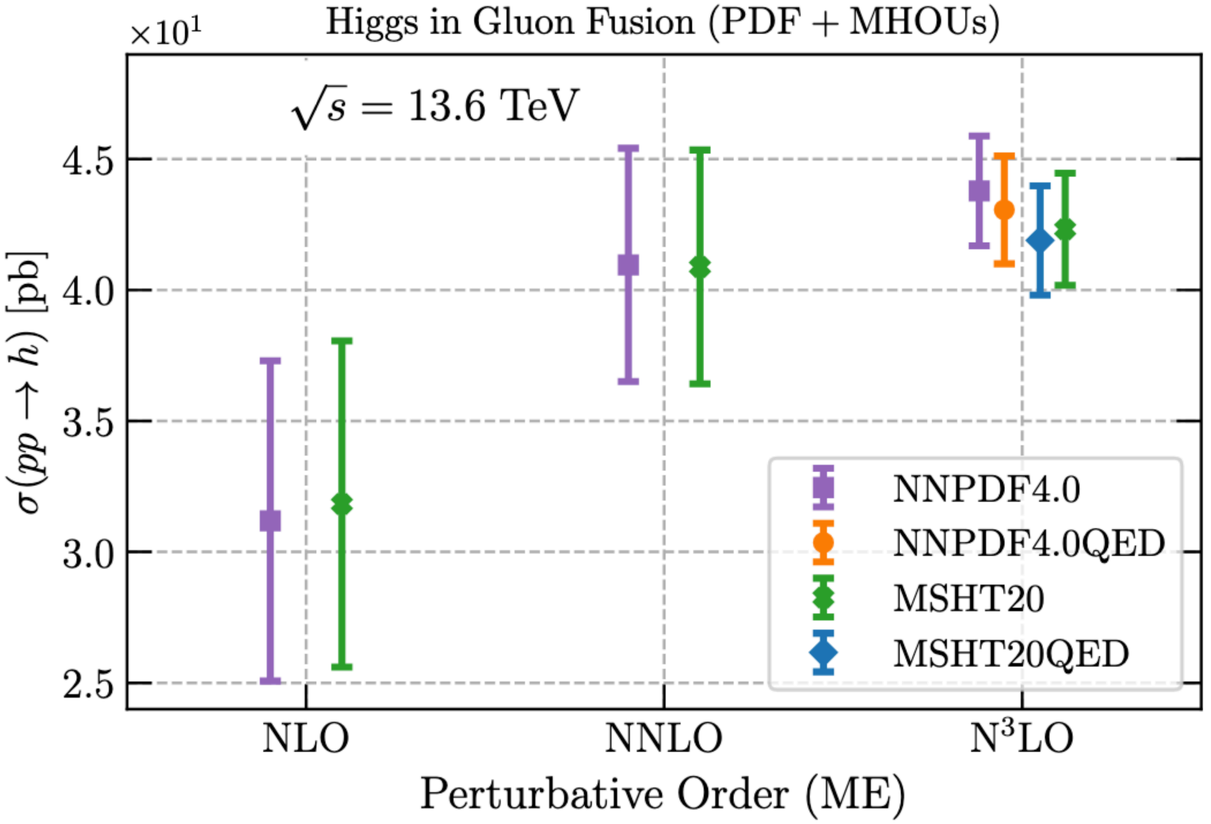
QED corrections & γ-PDF are key for LHC phenomenology:

- ❖ QED effects are of the same size as aN3LO
- ❖ Photon suppresses gluon momentum by up to 1%

Various LHC processes receive seizable γ-initiated contributions:

- ❖ aN3LO⊗QED result in a few percent suppression for ggH
- ❖ Difference between NNLO & N3LO predictions are reduced when using the appropriate PDFs at each order



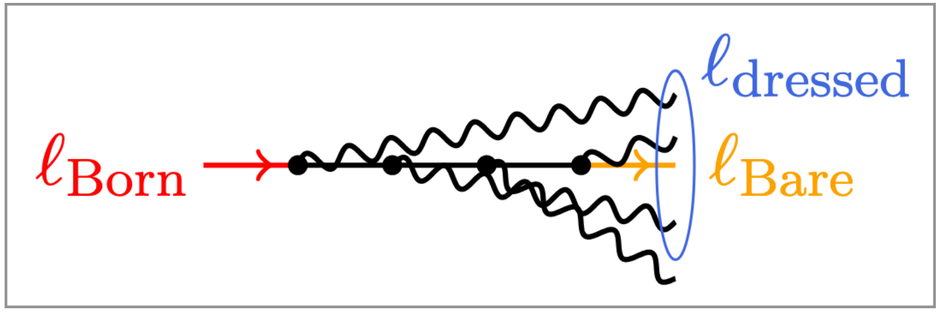


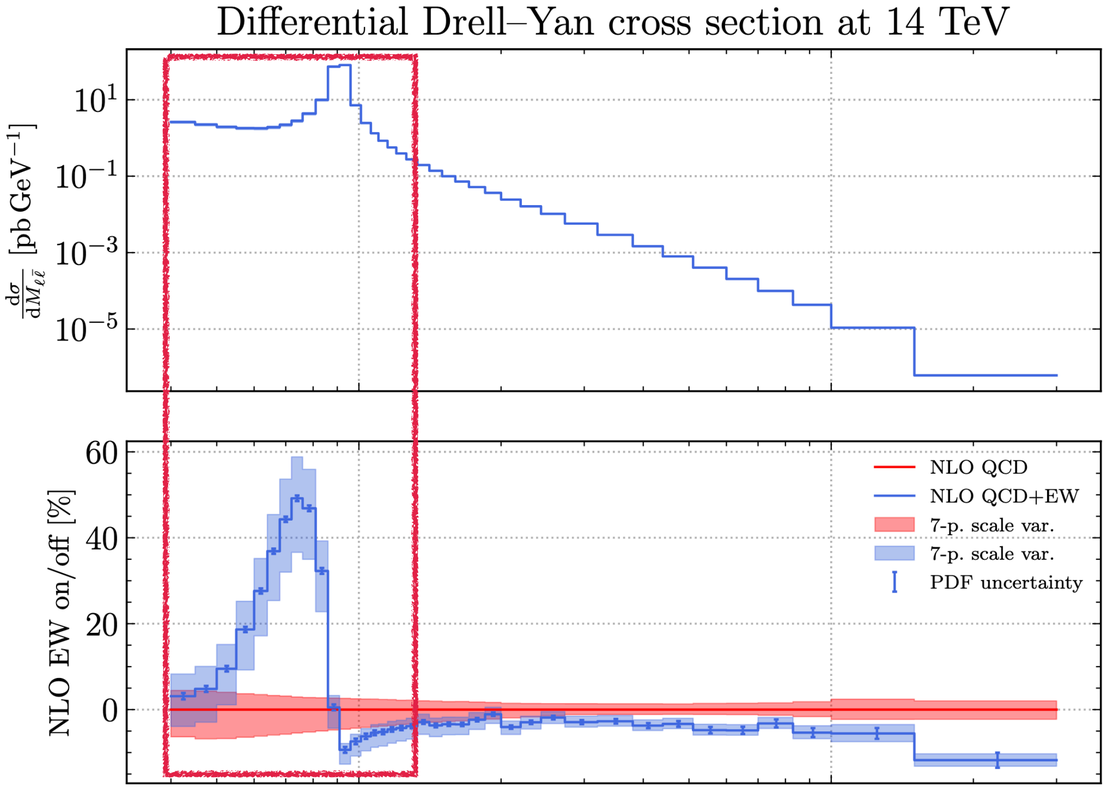
PDF fits with consistent EW corrections: Issues with Final State Radiations (FSR)

- **Pre-FSR/Born leptons data:** leptons before they radiate; comparisons for **pure QCD theory predictions**
- **Post-FSR/Dressed leptons data:** leptons with photons recombined around a radius $\Delta R_{f\gamma}$ (~ 0.1); what actual experiments measured $\Longrightarrow$ calculate shower inversion (PHOTOS) to get pre-FSR data; needed for **PDF fits with consistent EW corrections**
- **Dressing factors**

$$C_{\text{dress}} = \frac{\mathrm{d}\sigma_{\text{post-FSR}}/\mathrm{d}O}{\mathrm{d}\sigma_{\text{pre-FSR}}/\mathrm{d}\mathcal{O}}$$

- Can be **as large as 50%** for DY, for example, in the invariant mass distributions
- EW PDF determination largely depends on whether post-FSR datasets (upon removal of pre-FSR double-counting) are available
- **Post-FSR datasets are not published:** Challenges? Different treatments between muons and electrons?





Outline of the Talk

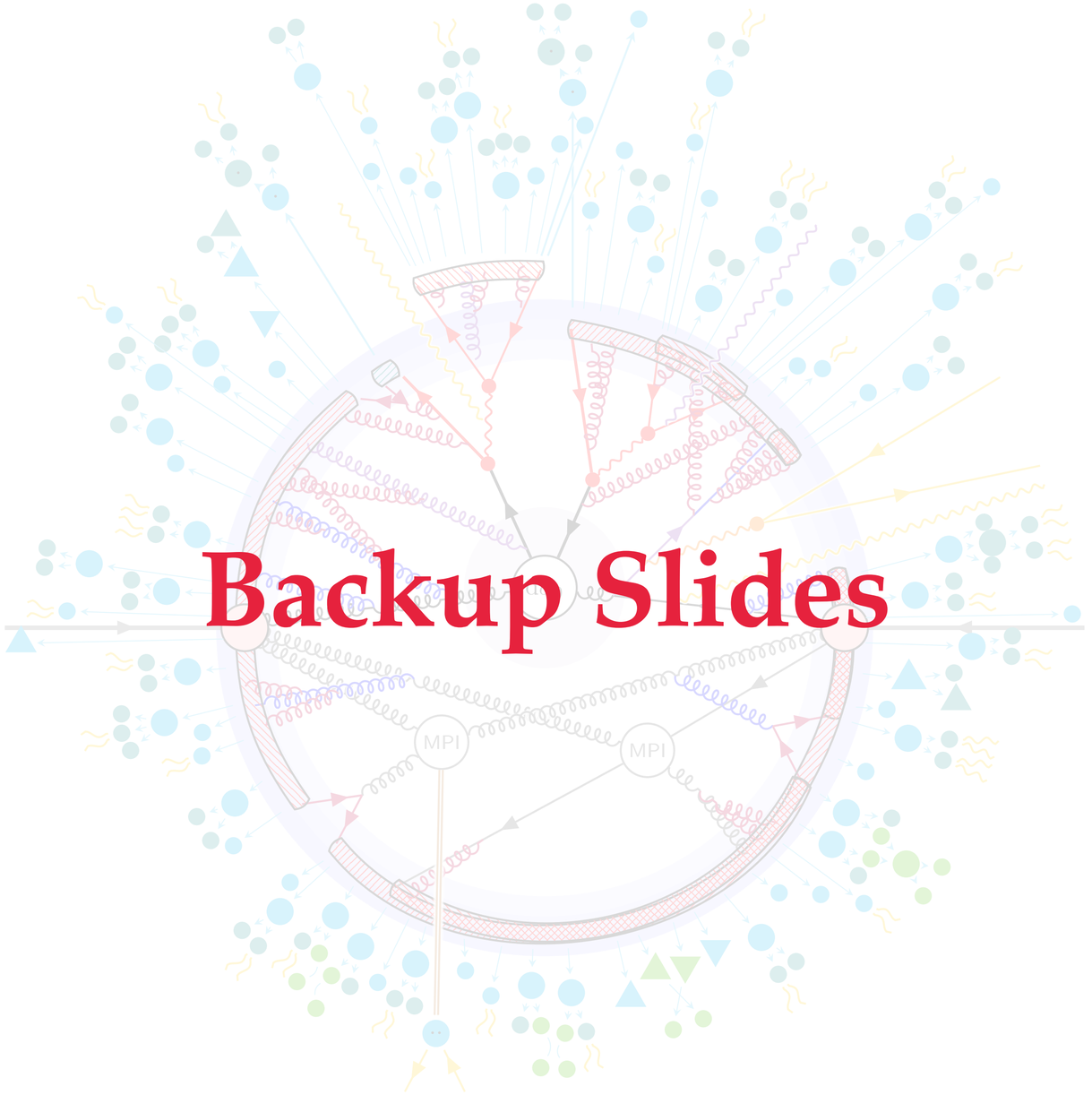
	Introduction & Motivations	
Part I	PDF Determination: the NNPDF Methodology	[arXiv:2109.02653; arXiv:2109.02671]
Part II	Photon-PDF Determination within the NNDPF	[arXiv:2401.08749]
Part III	Results & Implications for LHC Phenomenology	[arXiv:2401.08749; arXiv:2406.01779]
	Conclusions & Outlook	

Conclusions & Outlook

- The precision era at the LHC requires precise & accurate PDFs determination
- Photon PDF starts to matter for many processes at the LHC and therefore can no longer be neglected — one of such processes is DY, specifically Z boson production
- Photon PDF can be determined through the LUXQED formalism using present data reaching **high-precision ~1-2%**
- A precise and accurate determination of the photon PDF is crucial for the **searches for new physics**
- Future direction will include the determination of the photon PDF with the **inclusion of photon-initiated processes**
- Significant progress in the NNPDF global analysis for a state-of-the-art determination at **aN3LO⊗QED⊗MHOUs**

THANKS FOR YOUR ATTENTION

"Wanderer above the Sea of Fog" by Caspar David Friedrich

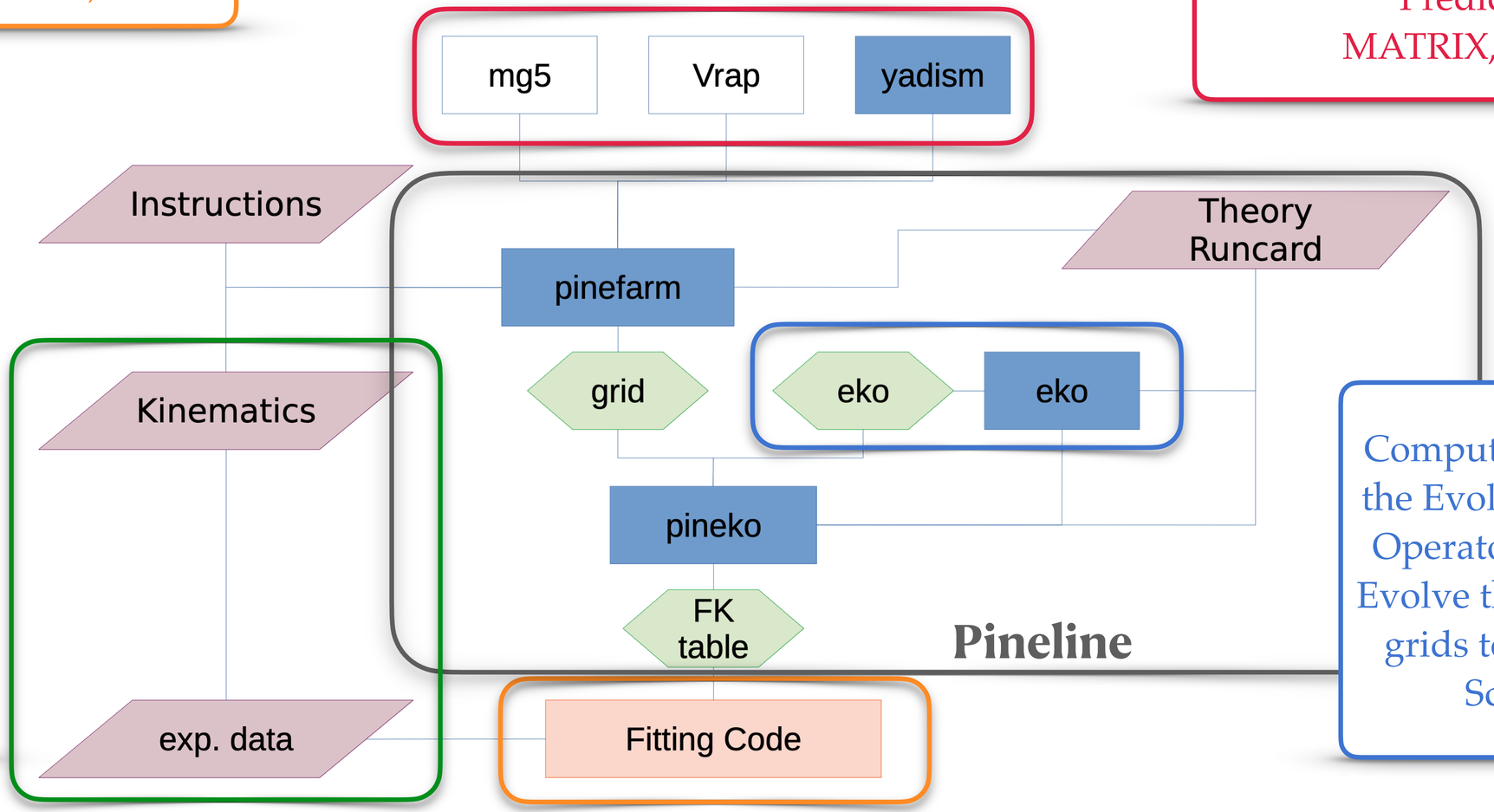


Backup Slides

A new Toolchain for PDF predictions

Fitting Code can be anything:
NNPDF, CTEQ, MSHT, etc.

Generators providing Theory Predictions
MATRIX, MCFM?

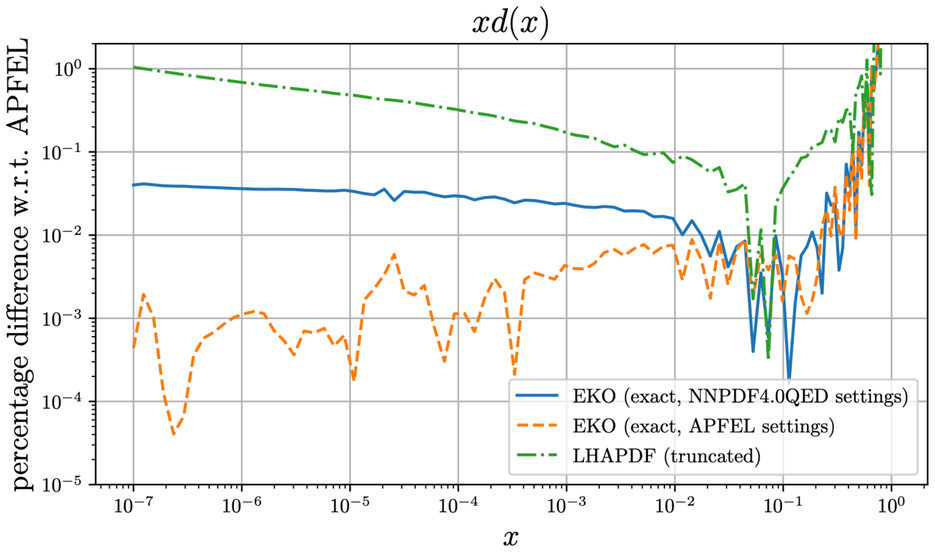


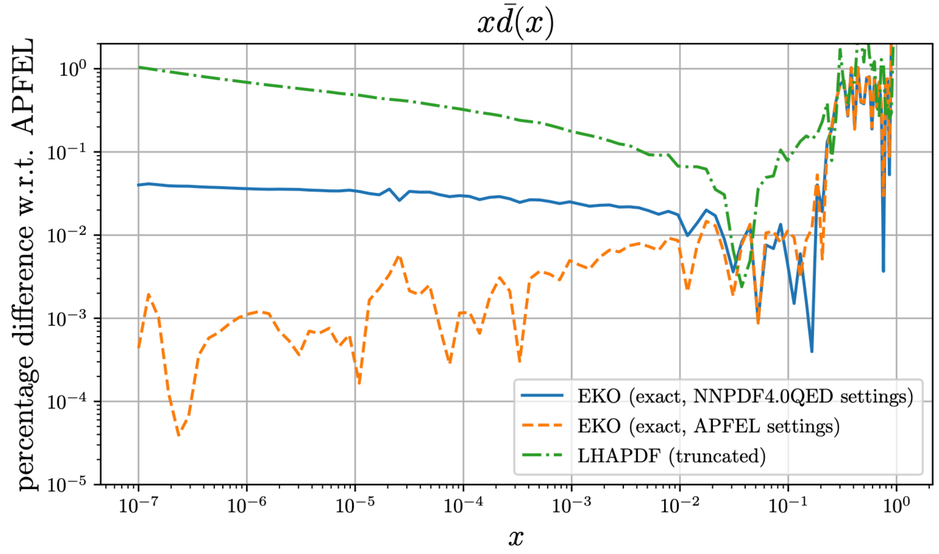
Experimental Inputs that provides the kinematics and the corresponding central values

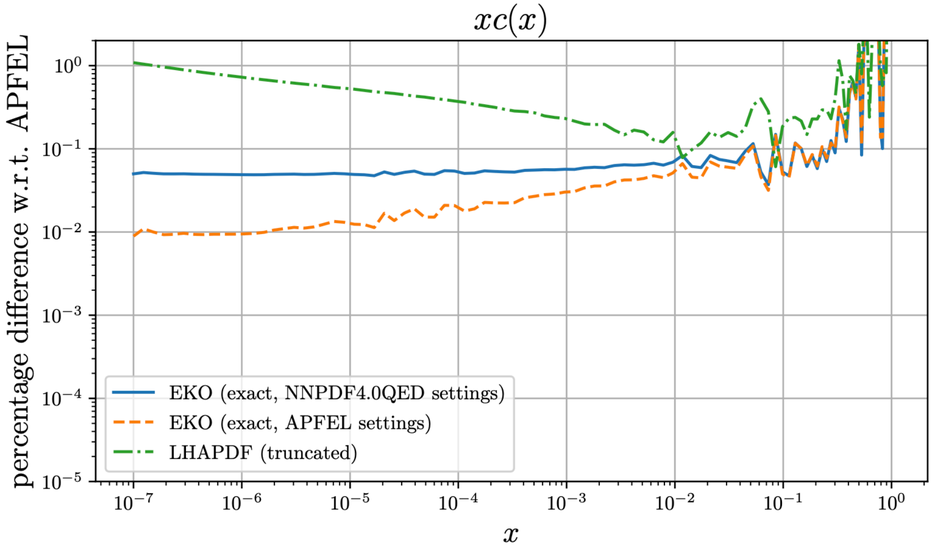
Computes/Provides the Evolution Kernel Operators (EKO) to Evolve the PineAPPL grids to the fitting Scale Q_0

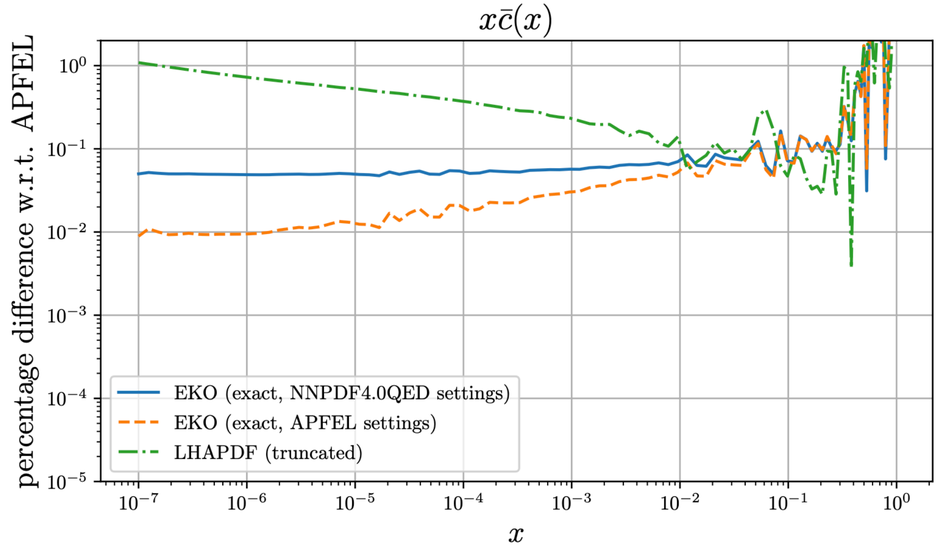
arXiv:2302.12124

QCD⊗QED Evolution









Scale Dependence of γ-PDF