Parton Distributions with QED corrections and LHC phenomenology

Juan Rojo
CERN, PH Division, TH Unit

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Parton distributions with QED corrections

- The theoretical accuracy of NLO/NNLO QCD calculations, together with the increasing precision of LHC data, imply that **QED and electroweak corrections** are an essential input for many important observables: **W, Z, WW, high-mass jets and tt, W/Z + jets, W mass determination ....**

- **Consistency** with the partonic matrix elements requires **PDF sets with both QCD and QED corrections** in the DGLAP evolution kernels

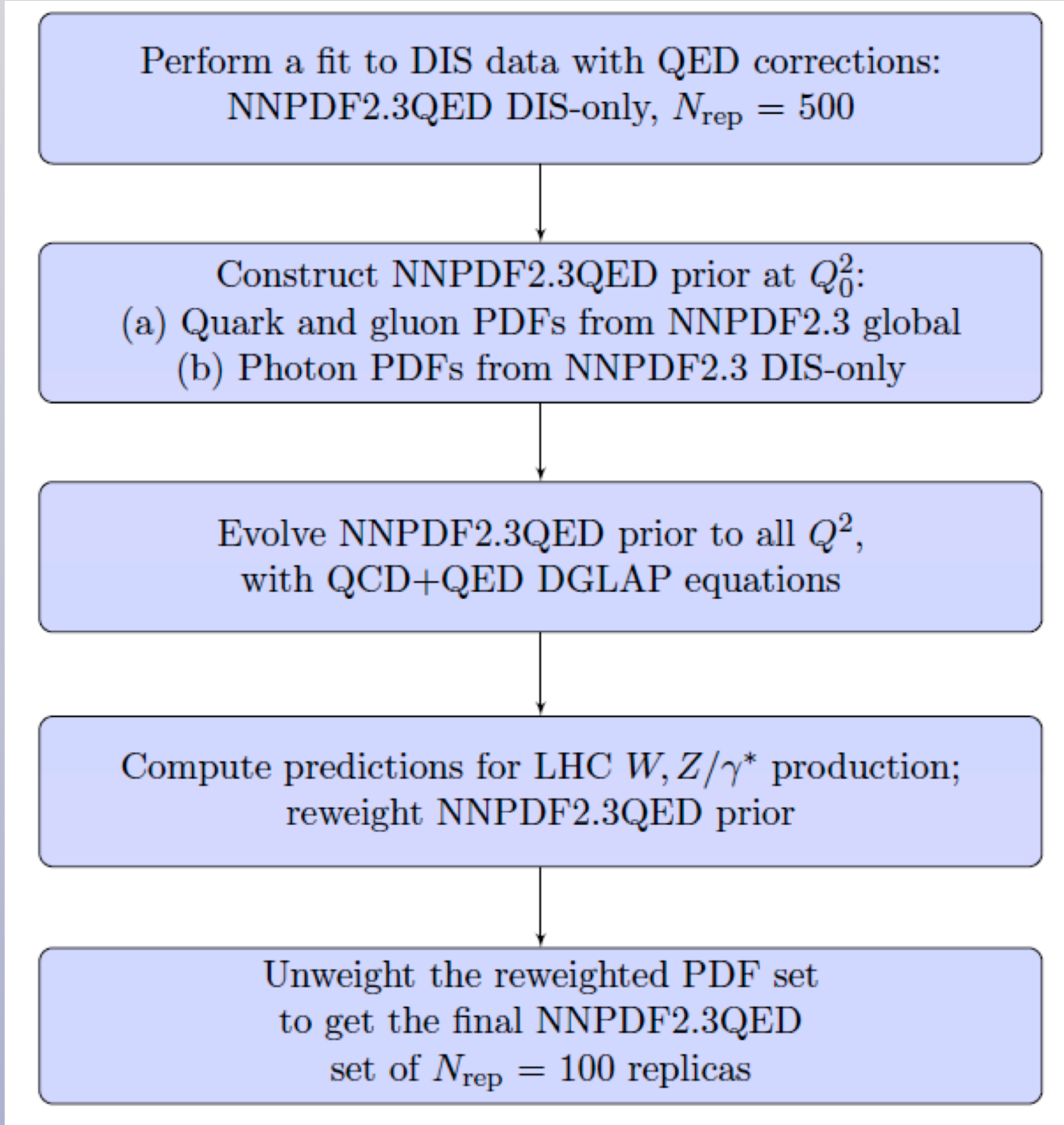
$$Q^2 \frac{\partial}{\partial Q^2} f(x,Q^2) = \left[\frac{\alpha(Q^2)}{2\pi} P^{\rm QED} + \frac{\alpha_s(Q^2)}{2\pi} P^{\rm QCD} \right] \otimes f(x,Q^2),$$

- In addition to the modified kernels, the QED collinear singularity leads to the need to introduce **the photon PDF ɣ(x,Q)**, which mixes with the quark PDFs and, as other PDFs, **requires to be determined from experimental data**

$$\begin{aligned} \nu^2 \frac{\partial}{\partial \nu^2} \gamma(x,\nu) &= \frac{\alpha(\nu)}{4\pi} \left[\left(\sum_i N_c e_i^2 \right) P_{\gamma\gamma}^{(0)}(x) \otimes \gamma(x,\nu) + \sum_i e_i^2 P_{\gamma q}^{(0)}(x) \otimes q_i(x,\nu) \right] \\ \nu^2 \frac{\partial}{\partial \nu^2} q_i(x,\nu) &= \frac{\alpha(\nu)}{4\pi} \left[N_c e_i^2 P_{q\gamma}^{(0)}(x) \otimes \gamma(x,\nu) + e_i^2 P_{qq}^{(0)}(x) \otimes q_i(x,\nu) \right] , \end{aligned}$$

- Up to recently the only PDF set with QED effects was **MRST04QED,** which on top of being by now outdated in terms of data and theory, did not fit ɣ(x,Q) from data but rather **used model assumptions,** and provided **no uncertainty estimates**

NNPDF2.3QED: General Strategy



NNPDF Collaboration
arXiv:1308.0598

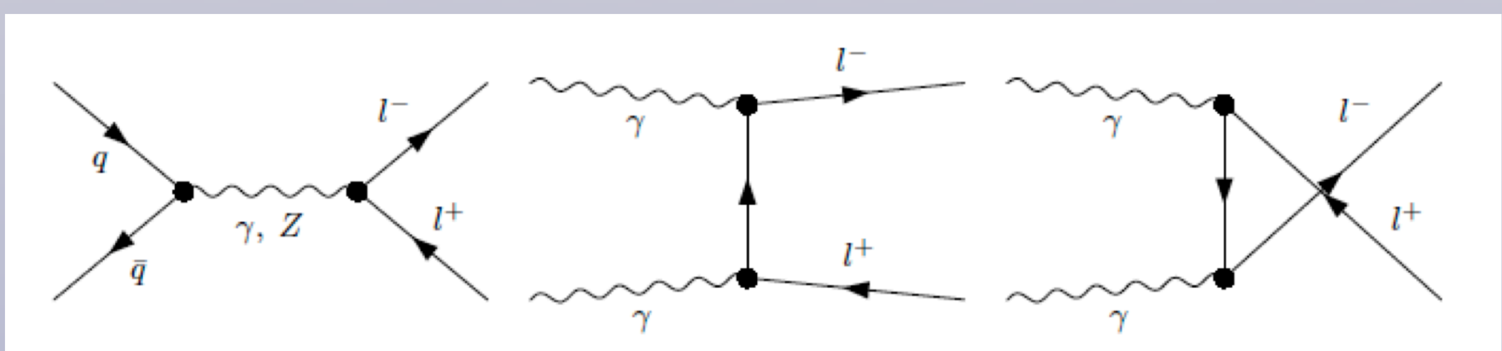
- The photon PDF **ɣ(x,Q)** is parametrized with a 2-5-3-1 Neural Network (37 parameters) and **fitted to data**: avoid **any model assumption**
- First step is a QCD+QED fit to DIS only data: huge uncertainties on **ɣ(x,Q)** due to lack of direct constraints
- Attach the fitted **ɣ(x,Q)** to the NNPDF2.3 set, and **reweight with LHC vector boson production data** directly sensitive to **ɣ initiated diagrams**
- Justified by mild correlation between **ɣ(x,Q)** and **q(x,Q), g(x,Q)**
- Final result is the **NNPDF2.3QED** set, which includes QED effects, and the photon PDF **ɣ(x,Q)** directly constrained **by LHC data**

Photon-initiated processes at the LHC

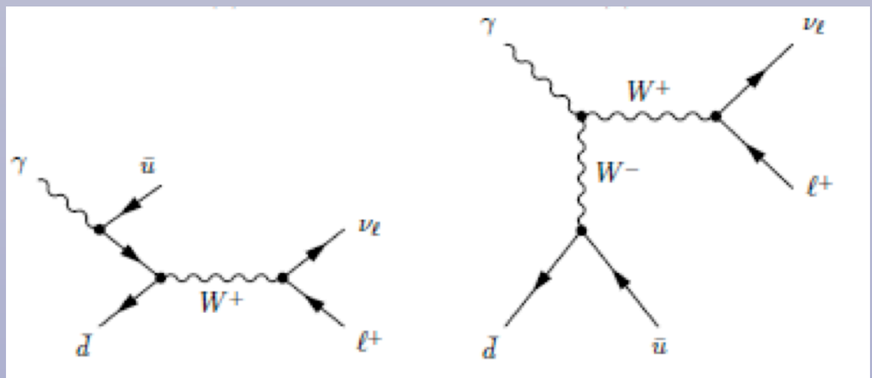
- In our approach, the **key constraints** come from precise **LHC electroweak vector boson** production data, directly sensitive to photon-initiated contributions

Dataset	Observable	Ref.	$N_{\rm dat}$	$[\eta_{\rm min}, \eta_{\rm max}]$	$[M_{\rm ll}^{\rm min}, M_{\rm ll}^{\rm max}]$
LHCb γ^*/Z Low Mass	$d\sigma(Z)/dM_{ll}$	[48]	9	[2,4.5]	[5,120] GeV
ATLAS W, Z	$d\sigma(W^{\pm}, Z)/d\eta$	[49]	30	[-2.5,2.5]	[60,120] GeV
ATLAS γ^*/Z High Mass	$d\sigma(Z)/dM_{ll}$	[50]	13	[-2.5,2.5]	[116,1500] GeV

- The relative contribution of **γγ/γq** wrt **qq** increases far from the W/Z peaks (s-channel resonance): **low-mass and high-mass Drell-Yan** production are the more constraining measurements for **γ(x,Q)**



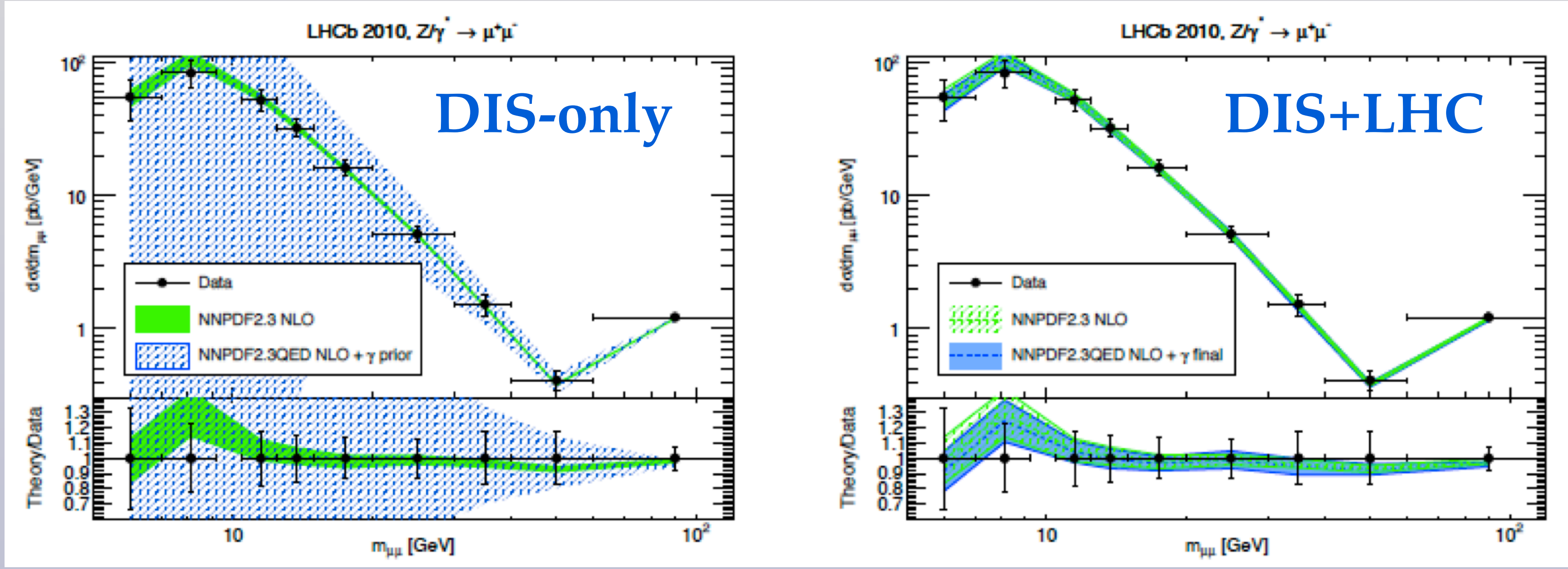
qq and γγ contributions to l+l- final state



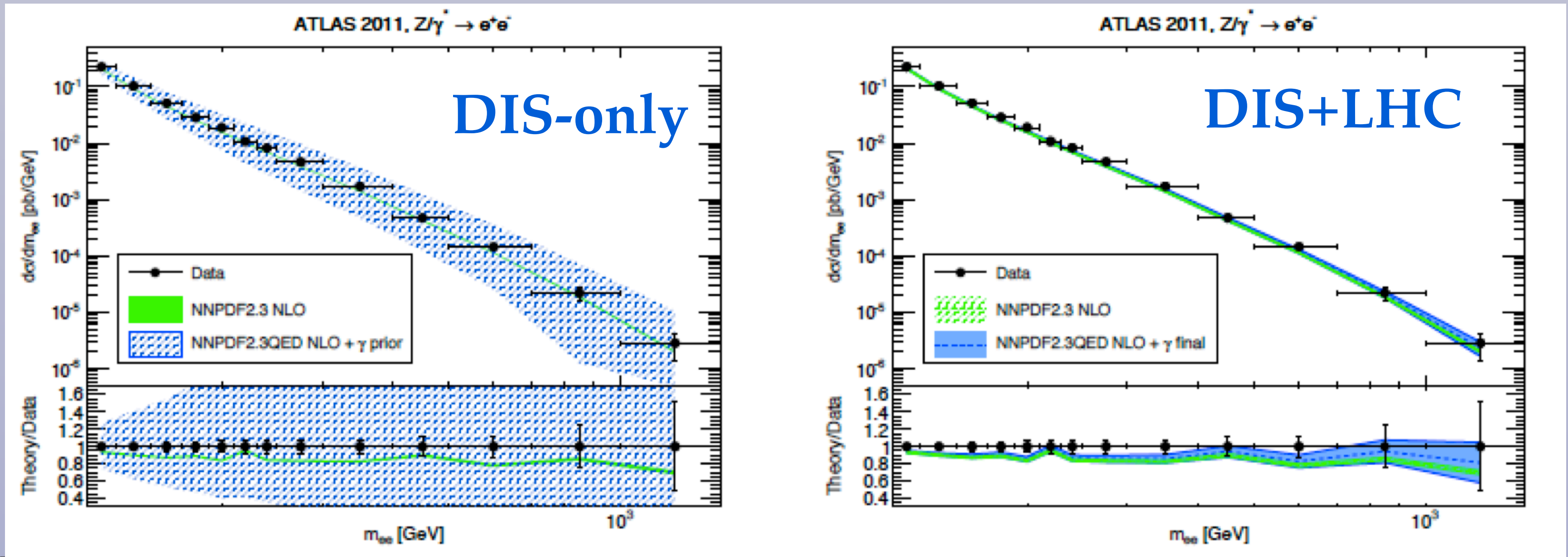
γq contributions to lν final state

Pinning down $\gamma(x,Q)$ with LHC data

Huge uncertainties in **γ(x,Q)** from **DIS-only fit**, substantially reduced by **LHC Drell-Yan data**

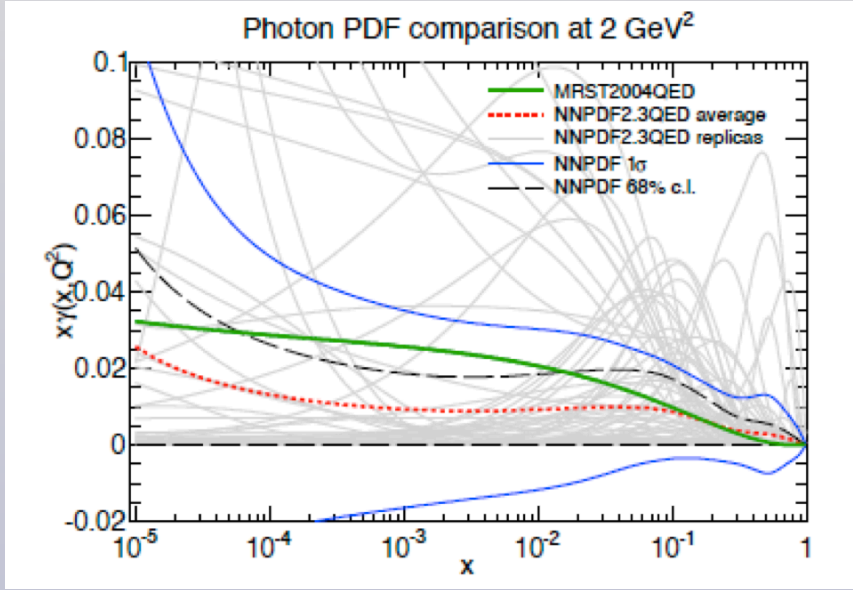


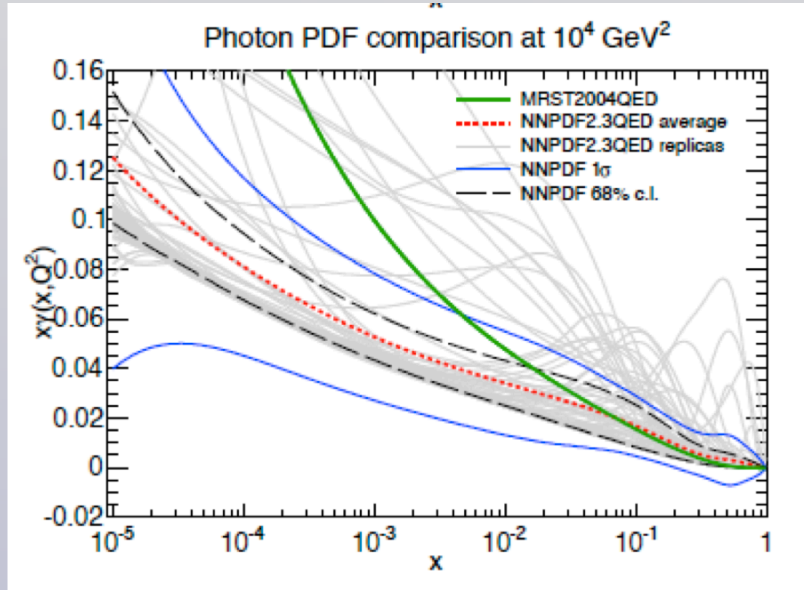
Low-mass Drell-Yan: constraints on small-x **γ(x,Q)**

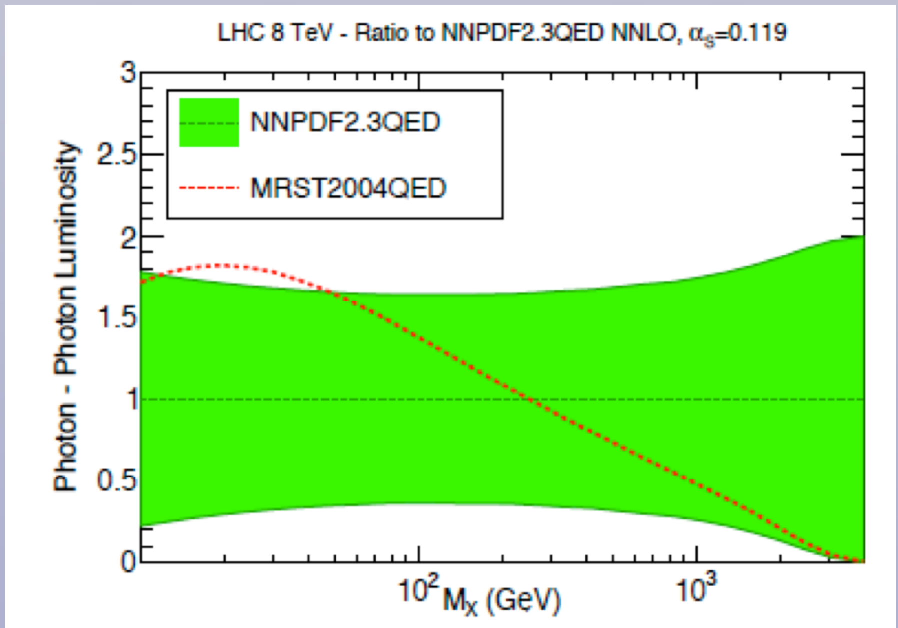


High-mass Drell-Yan: constraints on large-x **γ(x,Q)**

NNPDF2.3QED: Results







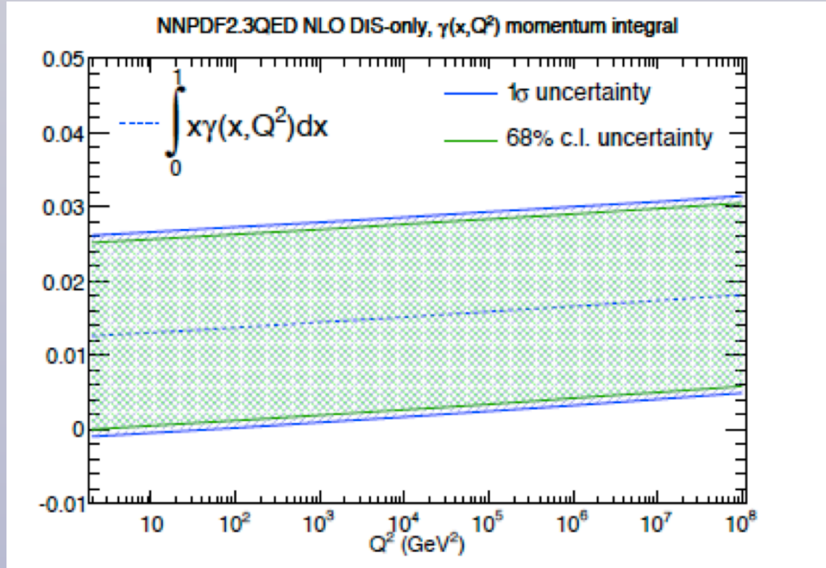
- Large uncertainties on **γ(x,Q),** in particular at small and large-x, from the **lack of direct constraints**
- MRST04QED typically **within 1-sigma** of NNPDF2.3QED, rather smaller **γγ** luminosity at high masses, r**elevant for BSM searches**
- Probability distribution for **γ(x,Q) highly non-gaussian**: 1-sigma and 68% CL very different

The momentum fraction of the photon PDF

- The size of the photon PDF allowed by experimental data can be quantified by its **contribution to the proton's momentum sum rule**

$$\int_0^1 dx\, x \left\{ \sum_i q_i(x,\mu,\nu) + g(x,\mu,\nu) + \gamma(x,\mu,\nu) \right\} = 1$$

- From the DIS fit, the **photon can contribute 1%-2%** to the total momentum, with a mild dependence on the resolution scale

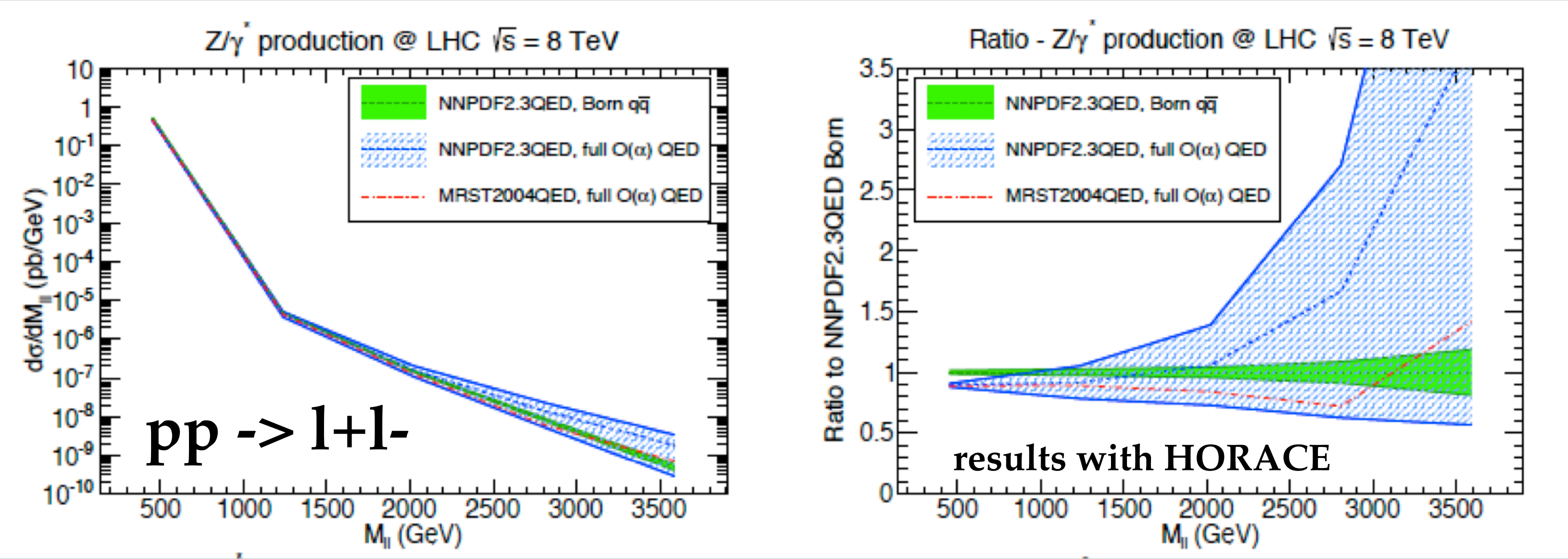


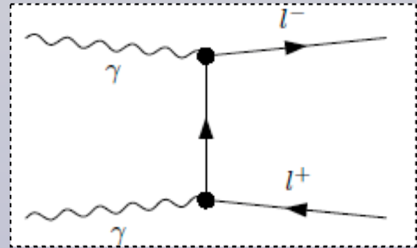
- With the **constraints from LHC data**, the preferred momentum fraction is around **0.5%**, still compatible with zero within uncertainties

	NLO	NNLO .
$\gamma;\ Q^2 = 2\ \mathrm{GeV}^2$	(0.42 ± 0.42) %	$(0.34 \pm 0.34)\%$
$\gamma;\ Q^2 = 10^4\ \mathrm{GeV}^2$	(0.68 ± 0.42) %	$(0.61 \pm 0.34)\%$

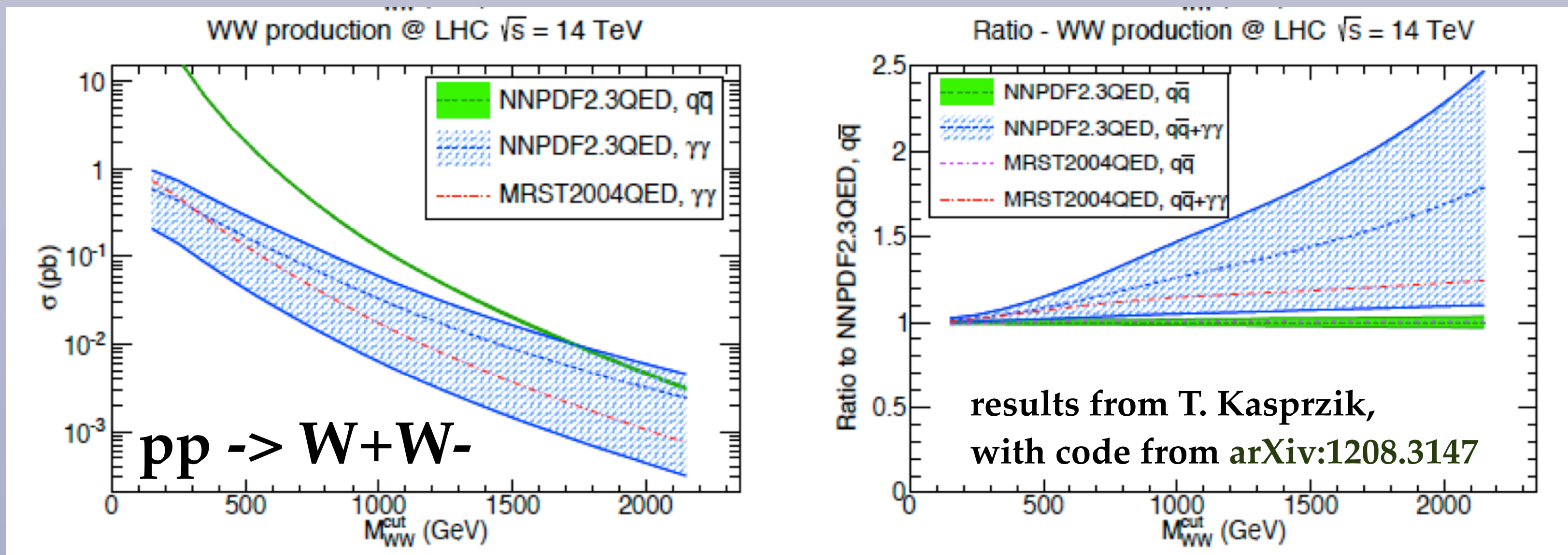
Implications for LHC pheno

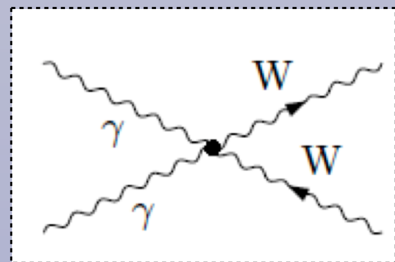
- **High-mass Drell-Yan production** is affected by large theory uncertainties from our lack of knowledge of **$\gamma(x,Q)$:** for BSM searches at **M_{ll} = 2(3) TeV**, the increase in cross-section due to **QED corrections** can be as large as **40% (150%)**. Important to derive reliable exclusion limits.





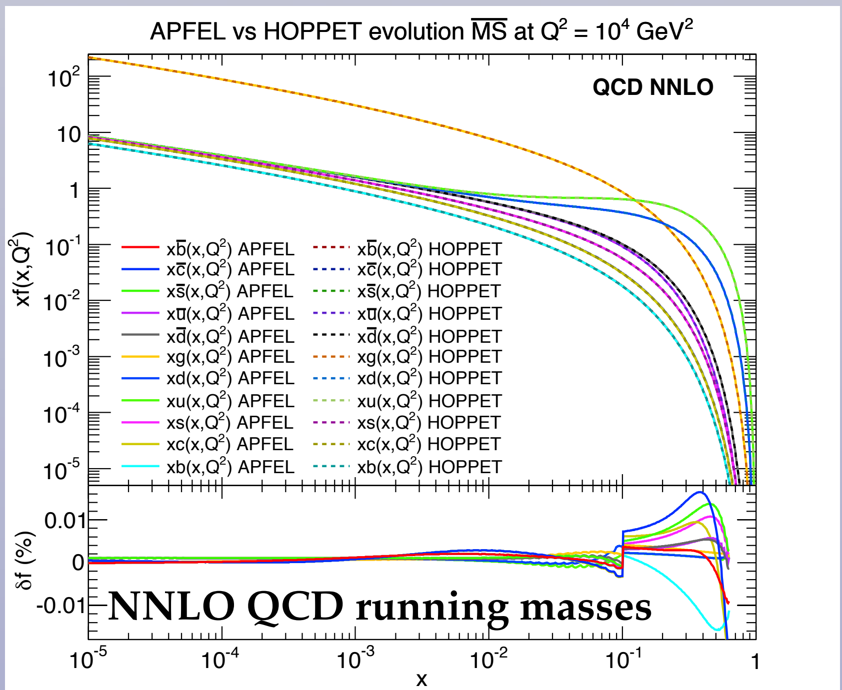
- **High-mass WW production** also affected by large corrections from **photon-initiated diagrams**: they can be **> 100%** at LHC14 for invariant masses **M_{WW} > 2 TeV**

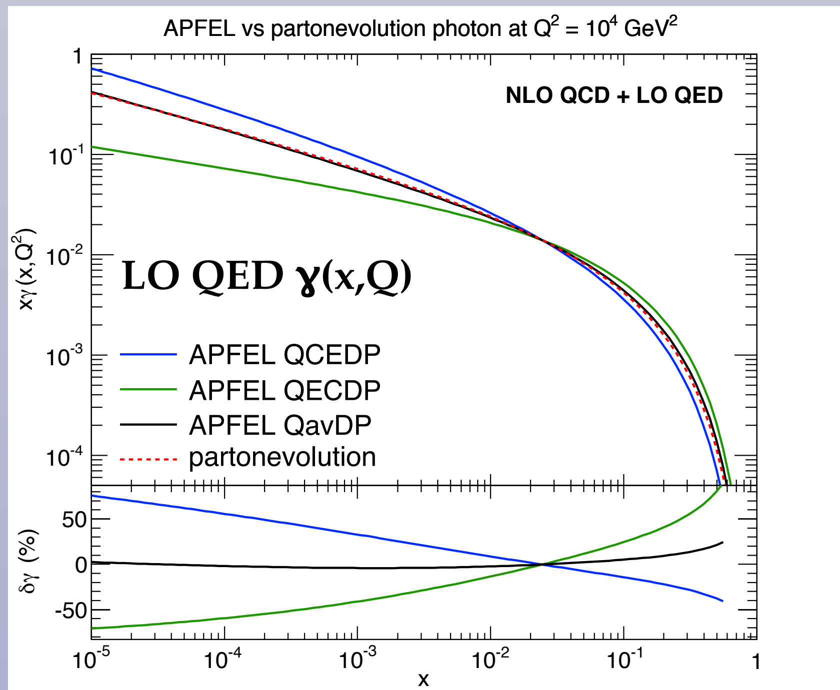




The APFEL package

- As a spin-off of the **NNPDF2.3QED sets**, we also developed the **APFEL** (**A** **P**DF **E**volution **L**ibrary with QED corrections) package **(V. Bertone, S. Carrazza and J. R., arxiv:1310.1394)**
- **APFEL** is a **new PDF evolution code** which allows to solve DGLAP equations up to **NNLO in QCD and LO in QED** in the **variable-flavor number** scheme, with both **pole** and **running masses**
- A range of options for **truncating the combined QCD+QED equations** is available, which differ by subleading terms: explore perturbative uncertainties from **missing QED higher orders**
- **APFEL** is written in Fortran77/C++/Python, and is available from **apfel.hepforge.org**
- **Validated** with public QCD and QED evolution codes: **HOPPET, MRST04QED, partonevolution**





The APFEL package

- **APFEL** allows to **systematically explore** the ambiguity inherent in solving the combined QCD+QED evolution equations, with different choices leading to different results that while **perturbatively equivalent**, can numerically differ by a large amount, specially for **γ(x,Q)**

- The first ambiguity concerns the order in which the (factorized) QCD and QED evolution are performed

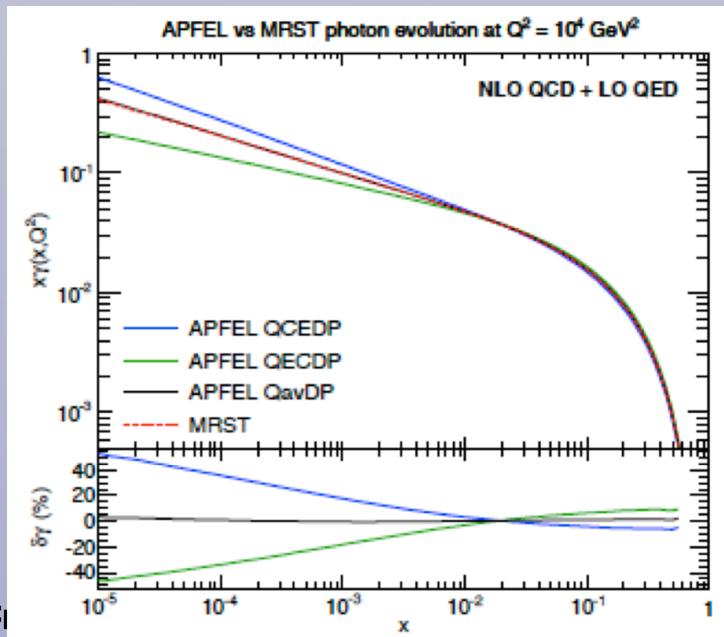
$$\Gamma^{\rm QCED}(\mu,\mu_0;\nu,\nu_0) \equiv \Gamma^{\rm QED}(\nu,\nu_0)\otimes\Gamma^{\rm QCD}(\mu,\mu_0)\,,$$
$$\Gamma^{\rm QECD}(\mu,\mu_0;\nu,\nu_0) \equiv \Gamma^{\rm QCD}(\mu,\mu_0)\otimes\Gamma^{\rm QED}(\nu,\nu_0)\,,$$

$$[\Gamma^{\rm QCD},\Gamma^{\rm QED}] = \mathcal{O}(\alpha\alpha_s)$$

- The second ambiguity, present in **VFN schemes**, is the choice of the ordering when crossing **heavy quark thresholds**

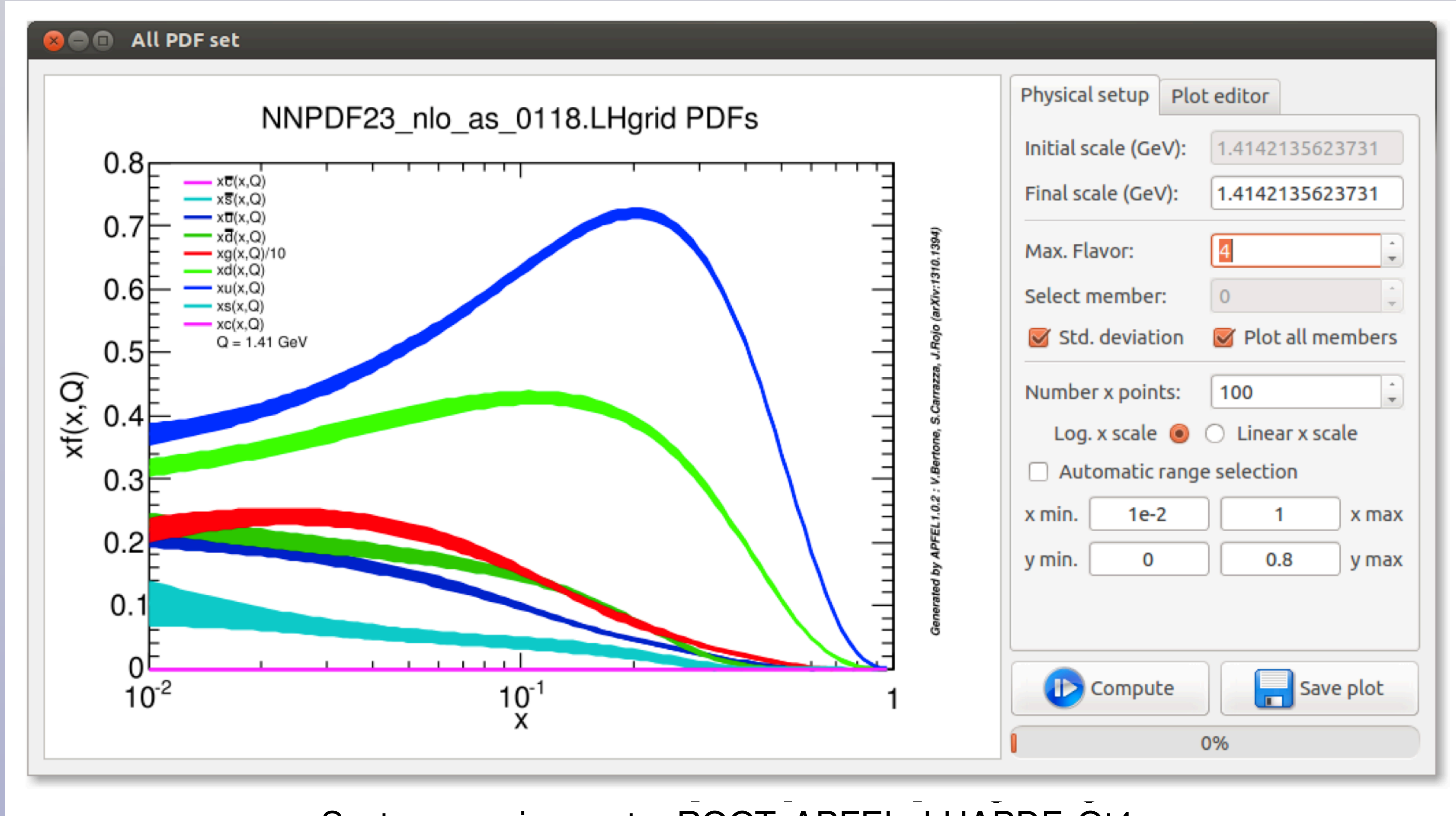
- The solution when **all possible orderings are averaged** is found to be closer to **MRST04QED** and partonevolution

$$\begin{aligned} \mathbf{q}(\mu,\nu) &= \Big\{ [\Gamma^{\rm QED,(4)}(\nu,m_c)\otimes\Gamma^{\rm QCD,(4)}(\mu,m_c)]\otimes \\ &\quad [\Gamma^{\rm QED,(3)}(m_c,\nu_0)\otimes\Gamma^{\rm QCD,(3)}(m_c,\mu_0)] \Big\}\otimes\mathbf{q}(\mu_0,\nu_0) \\ &\equiv \Gamma^{\rm QCEDP}(\mu,\mu_0;\nu,\nu_0)\otimes\mathbf{q}(\mu_0,\nu_0)\,, \end{aligned}$$



The APFEL package

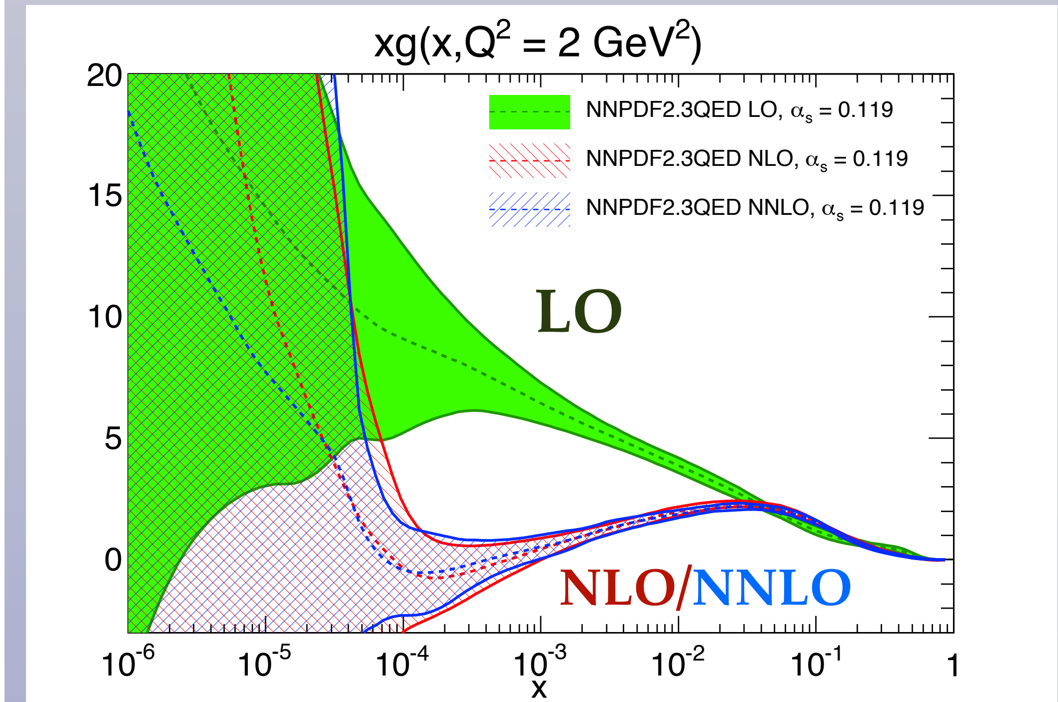
- Soon to release **v2.0.0** (PDF4LHC next week), which includes, on top of **combined QCD+QED PDF evolution**, the computation of **DIS structure functions** in the **FONLL GM-VFN** scheme (NC and CC)
- In addition, a user-friendly **Graphical User Interface** will be available, providing a **complete toolbox for PDF analysis**: comparison plots of PDF and luminosities, easy plot customization, ...

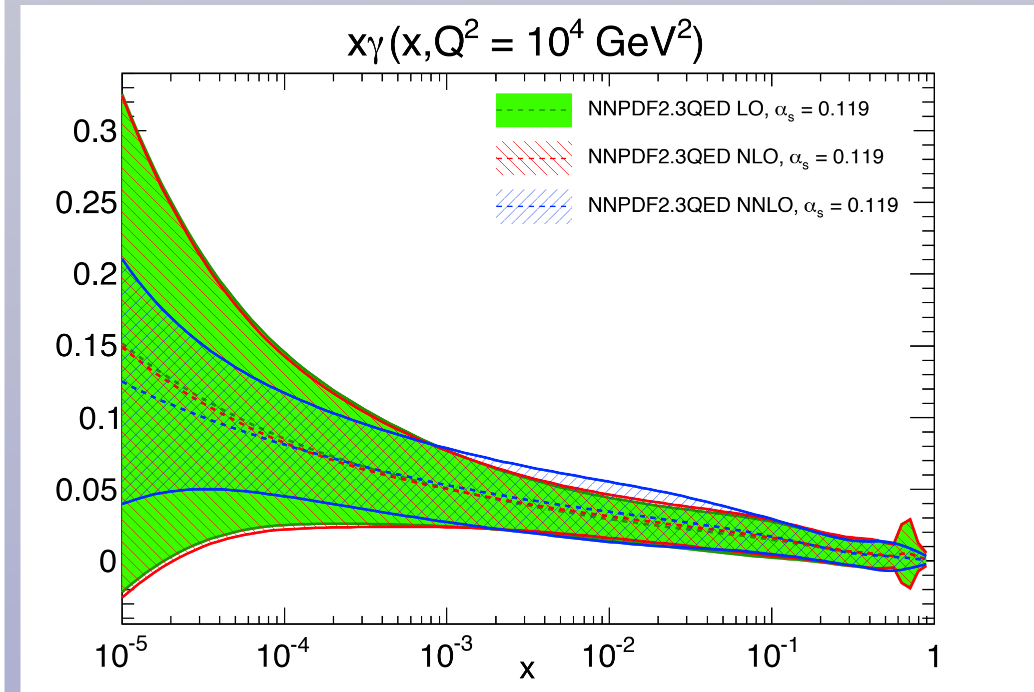


System requirements: ROOT, APFEL, LHAPDF, Qt4

Leading order PDFs with QED effects

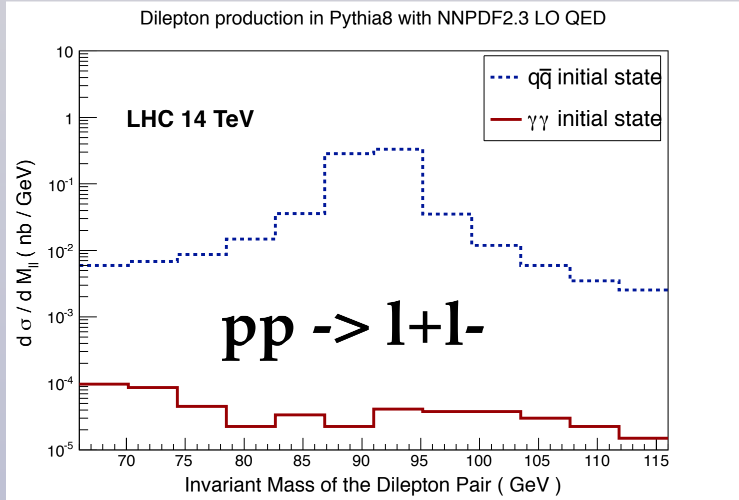
- **Leading Order PDFs** are an important ingredient for LO Event Generators.
- On top of NLO/NNLO sets, we recently derived also for the first time a **LO QCD+QED PDF** set: **NNPDF2.3QED LO (S. Carrazza, S. Forte and J.R., arXiv:1311.5887)**
- Such set would be required for consistently including **QED and EW effects in parton showers**
- The NNPDF2.3QED sets are now available as **stand-alone internal sets** in **Pythia8,** and a specific **Pythia8 tune** based on NNPDF2.3LO QED is being produced
- The **LO gluon** differs substantially from the NLO/NNLO ones, while the dependence of the **photon PDF $\gamma(x,Q)$** on the perturbative order is very mild

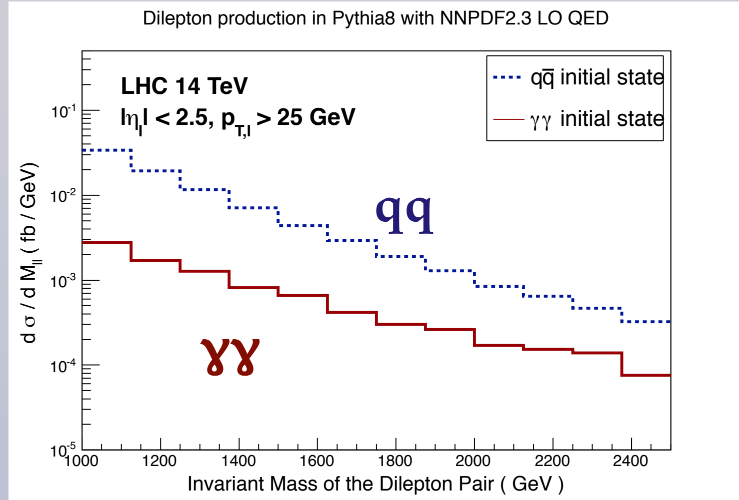


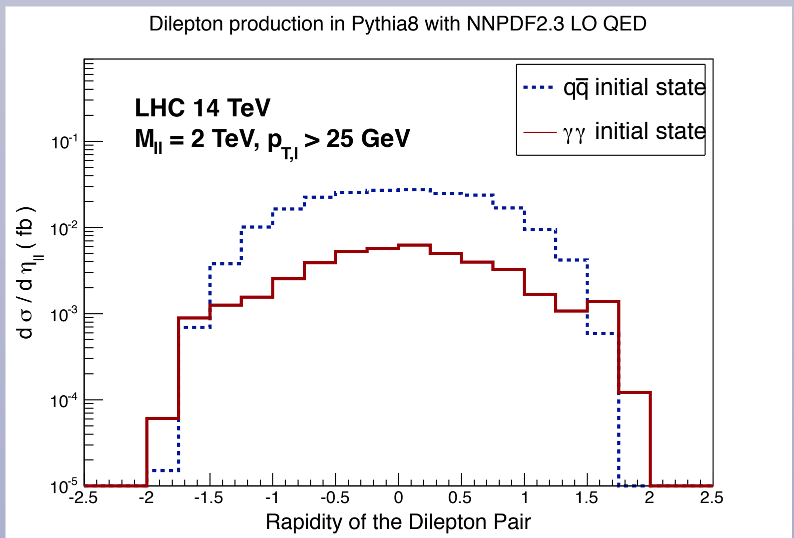


Leading order PDFs with QED effects

- As an illustration of **NNPDF2.3QED LO**, we have generated LHC **dilepton (l+l-) events** in **Pythia8**, taking into account both **qq** and **γγ** initial states
- Contribution of **γγ** initial state below permille level in the Z peak, but becomes large, **O(10-50%) for the high-mass tail**. Important background for electroweak BSM searches







- The **different production kinematics** (s-channel to qq, t-channel for **γγ**) can be clearly distinguished in the **angular distributions of the dilepton pair**
- At high invariant masses, the **γγ** contribution becomes **dominant at forward rapidities**
- Such measurement would be very constraining to pin down the photon PDF **γ(x,Q)**

Summary and outlook

- **Parton Distributions** with **QED corrections** are an important ingredient for LHC pheno
- **NNPDF2.3QED** is the **first PDF set** to include both **NNLO QCD and LO QED effects** and to provide an **unbiased determination of the photon PDF** from LHC data
- Important pheno implications, both for **precision SM measurements** and as backgrounds for **BSM searches** in processes like **high-mass Drell-Yan or WW production,** where photon-initiated contributions can be substantial
- NNPDF2.3QED LO available as internal PDF set in **Pythia8, dedicated tune** in progress
- **APFEL** is a flexible and robust **public PDF evolution code** that easily allows to perform the **combined QCD+QED evolution**, and provides **many useful tools** in the context of PDF fits
- Next steps towards even more accurate PDFs with QED/EW corrections:
  - Constraints from **more HERA/LHC data** to **reduce the uncertainties** on the photon PDF
  - Inclusion of **pure electroweak effects** in PDF evolution,
  - Developing the **tools** to include **combined QCD+QED/EW calculations** directly into a PDF fit: **applgrid** interface to **aMCatNLO** in progress

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Thanks for your attention!