Photon-initiated processes at high mass

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PDF4LHC meeting, CERN, 13 Sep 2016

In collaboration with Valery Khoze and Misha Ryskin

Outline

- Photon PDF: motivation/previous approaches.
- Importance of the coherent component: our work.
- Predictions for the LHC/FCC.
- LUXqed: comparison.

The photon PDF

• In era of high precision phenomenology at the LHC: NNLO calculations rapidly becoming the 'standard'. However:

$$\alpha_S^2(M_Z) \sim 0.118^2 \sim \frac{1}{70} \qquad \alpha_{\rm QED}(M_Z) \sim \frac{1}{130}$$

$\longrightarrow$ NLO EW and NNLO QCD corrections can be comparable in size.

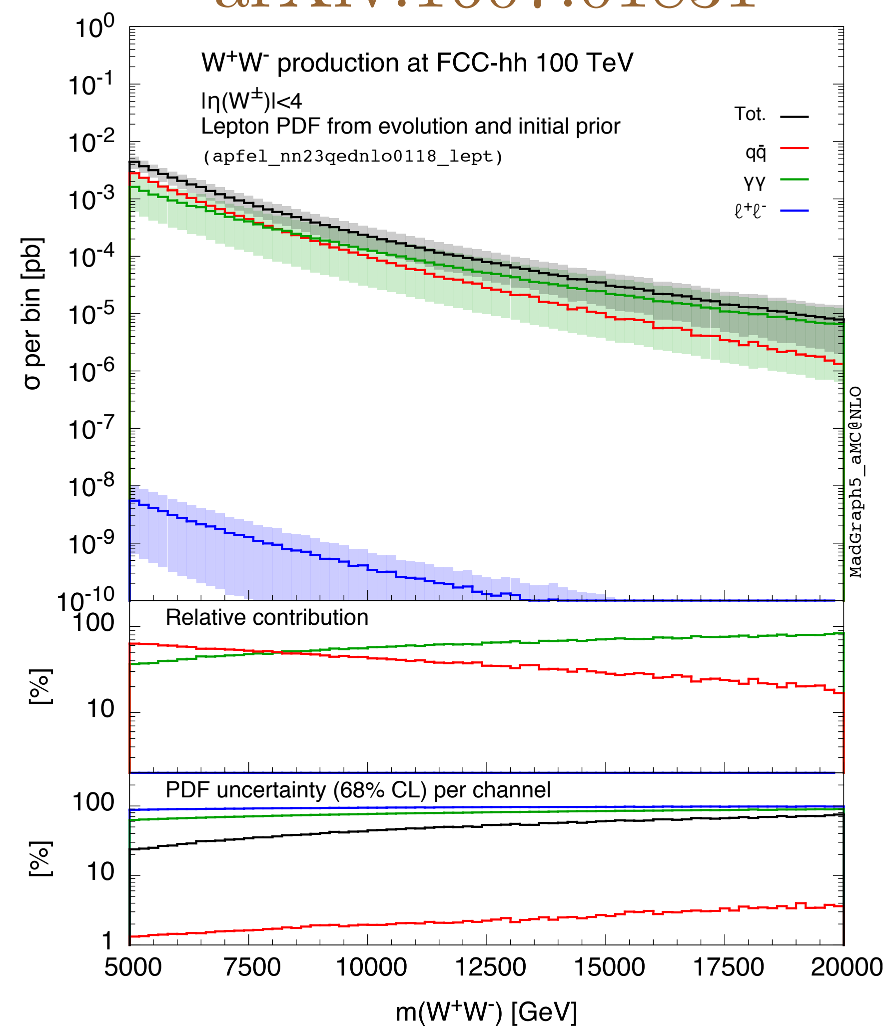
• Thus at this level of accuracy, must consider a proper account of EW corrections. At LHC these can be relevant for a range of processes (W, Z, WH, ZH, WW, $t\bar{t}$, jets...).

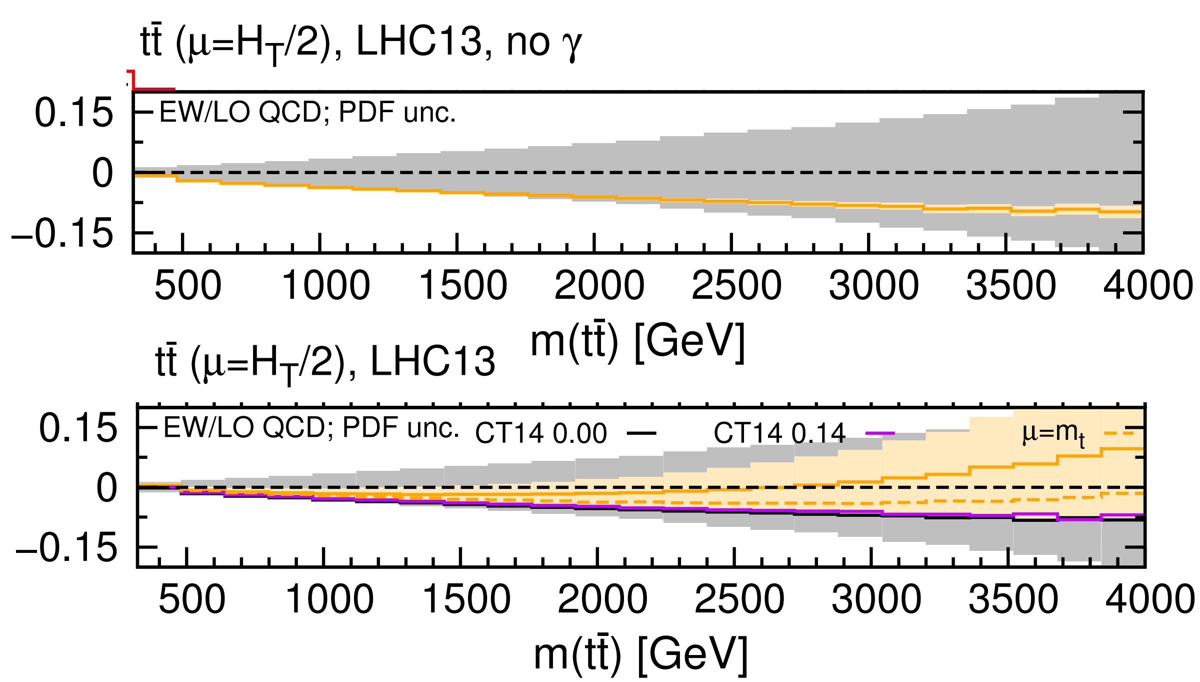
• For consistent treatment of these, must incorporate QED in initial state: QED corrections to DGLAP evolution and a photon PDF.

Recent Studies

- Resurgence of interest in photon-initiated contribution to Drell-Yan (1606.00523, 1606.06646, 1607.01831), WW (1607.01831) and $t\bar{t}$ (1606.01915) at LHC and FCC.

arXiv:1607.01831





arXiv:1606.01915

- Contribution from photon initial state potentially quite large, within quoted uncertainties. Is this the case?

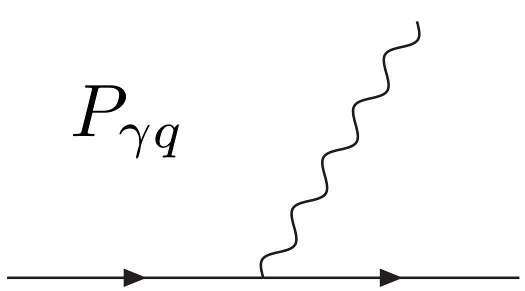
The photon PDF

- As with other partons, the photon obeys a DGLAP evolution equation:

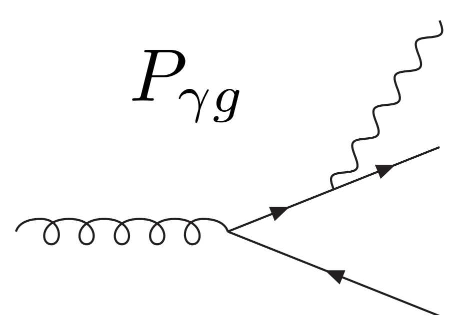
$$\gamma(x,\mu^2) = \gamma(x,Q_0^2) + \int_{Q_0^2}^{\mu^2} \frac{\alpha(Q^2)}{2\pi}\frac{dQ^2}{Q^2}\int_x^1 \frac{dz}{z}\bigg(P_{\gamma\gamma}(z)\gamma(\frac{x}{z},Q^2)$$
$$+\sum_q e_q^2 P_{\gamma q}(z) q(\frac{x}{z},Q^2) + P_{\gamma g}(z) g(\frac{x}{z},Q^2)\bigg)\,, \qquad \text{NLO in QCD}$$

- Thus PDF at scale μ given in terms of:
  - PDF at starting scale $Q_0 \sim 1\,\mathrm{GeV}$.
  - Evolution term, due to emission from quarks up to scale μ.

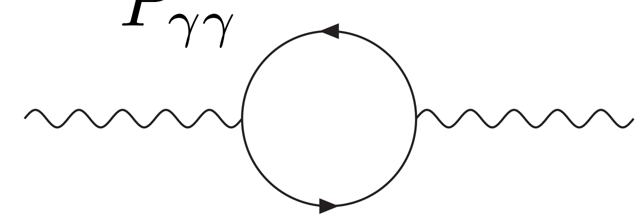
$P_{\gamma q}$



$P_{\gamma g}$



$P_{\gamma\gamma}$



- Question: how do we determine the starting distribution $\gamma(x,Q_0^2)$?

Previous approaches

arXiv:1308.0598

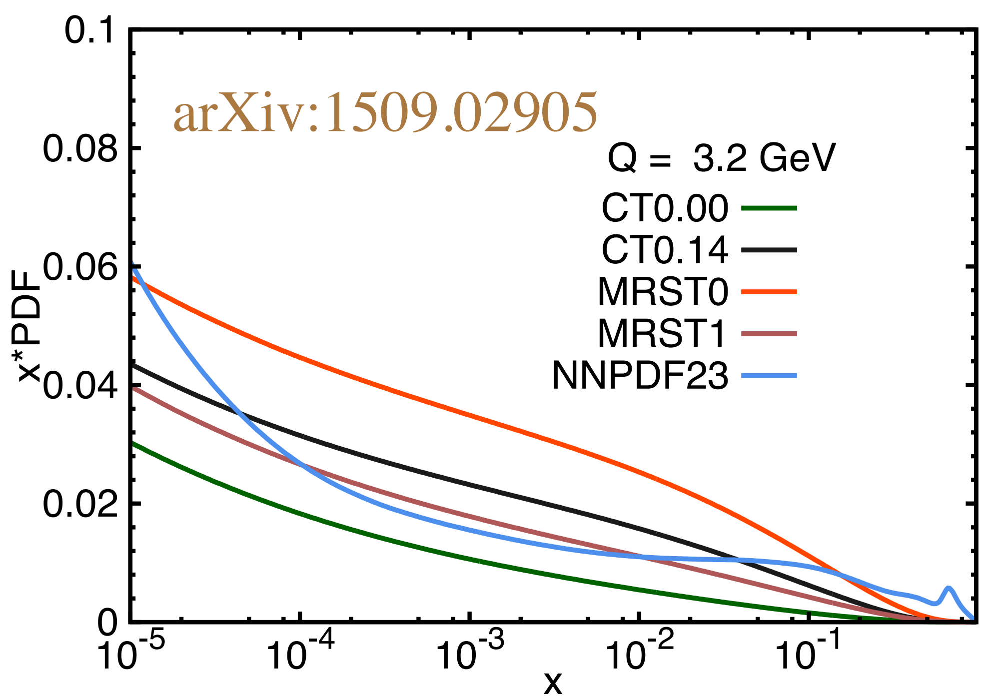
- NNPDF2.3QED: treat photon as we would quark and gluons. Freely parametrise $\gamma(x, Q_0)$ and fit to DIS and some LHC W, Z data. Uncertainties (so far) remain large.

hep-ph/0411040

- MRST2004QED: first set to include QED contributions. Model assumed, with $\gamma(x, Q_0^2)$ generated by one-photon emission off valence quarks at LL. Results compared to ZEUS isolated photon DIS.

arXiv:1509.02905

- CT14QED: 'Radiative ansatz', similar to MRST2004QED model, but with additional freedom. Fit to ZEUS isolated photon DIS.



- Comparing these different sets reveals apparently large uncertainties.

$\longrightarrow$ However: have we included all of the available information?

Recent Studies

PDFs and QED: other work

$p \to p\gamma$

- QED is long range force: at low scales ($\sim$ low photon virtuality/large wavelength) the photon sees the entire EM charge of the proton, and 'coherent' process, with proton intact after emission, is dominant. Must include this contribution!

A.D. Martin, M.G. Ryskin, arXiv:1406.2118
M. Gluck, C. Pisano, E. Reya, hep-ph/0206126

- We have recently applied this approach to photon-initiated processes at high mass, semi-exclusive processes, and diphoton resonance production.

RIP

LHL, V.A. Khoze, M.G. Ryskin, arXiv:1601.03372, 1601.07187, 1607.4635

IPPP/16/67
August 2, 2016

Photon–initiated processes at high mass

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Abstract

We consider the influence of photon–initiated processes on high–mass particle production. We discuss in detail the photon PDF at relatively high parton x, relevant to such processes, and evaluate its uncertainties. In particular we show that, as the dominant contribution to the input photon distribution is due to coherent photon emission, at phenomenologically relevant scales the photon PDF is already well determined in this region, with the corresponding uncertainties under good control. We then demon-

IPPP/16/01
April 20, 2016

The photon PDF in events with rapidity gaps

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Abstract

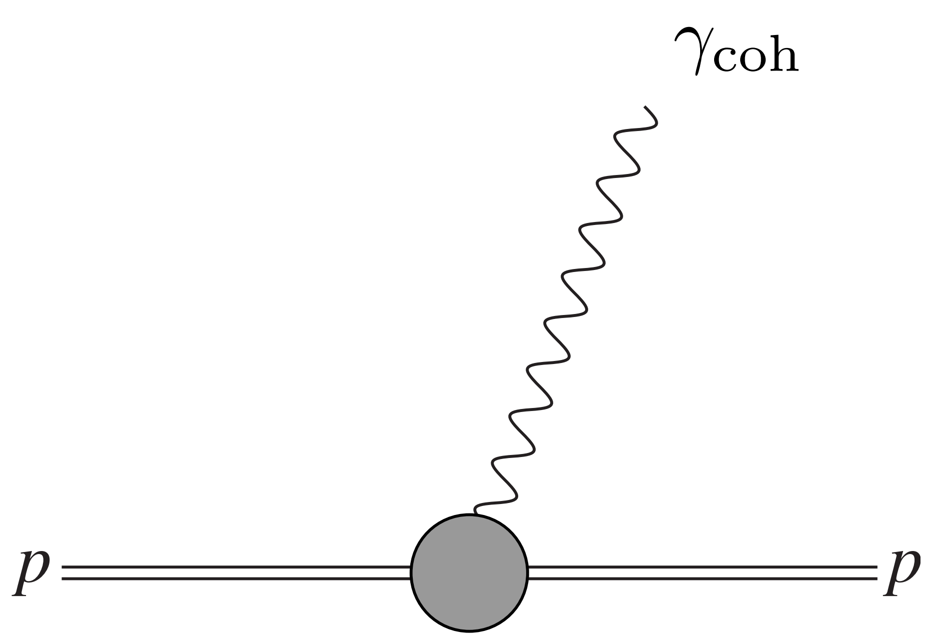
We consider photon–initiated events with large rapidity gaps in proton–proton collisions, where one or both protons may break up. We formulate a modified photon PDF that accounts for the specific experimental rapidity gap veto, and demonstrate how the soft survival probability for these gaps may be implemented consistently. Finally, we present some phenomenological results for the two–photon induced production of lepton and W boson pairs.

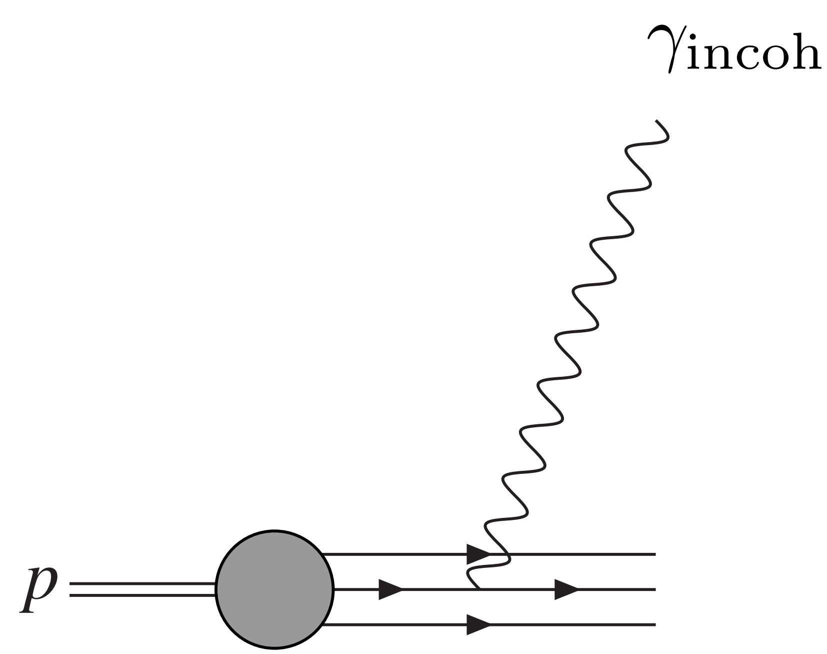
The starting distribution

- Photon at $Q_0 \sim 1\,\mathrm{GeV}$ given as sum of 'coherent' and 'incoherent' terms:

$$\gamma(x, Q_0^2) = \gamma_{\rm coh}(x, Q_0^2) + \gamma_{\rm incoh}(x, Q_0^2)$$

  - Coherent: due to elastic $p \to p\gamma$ emission $\Rightarrow$ extremely well understood.
  - Incoherent: emission from individual quarks. Some theoretical guidance, but known less precisely.





Coherent photon emission

- The part of $\gamma(x, Q_0^2)$ due to coherent photon emission is given by

γ transverse mom. Equivalent photon

$$\gamma_{\rm coh}(x, Q_0^2) = \frac{1}{x}\frac{\alpha}{\pi}\int_0^{Q^2<Q_0^2} \frac{{\rm d}q_t^2}{q_t^2 + x^2 m_p^2}\left(\frac{q_t^2}{q_t^2 + x^2 m_p^2}(1-x)F_E(Q^2) + \frac{x^2}{2}F_M(Q^2)\right)$$

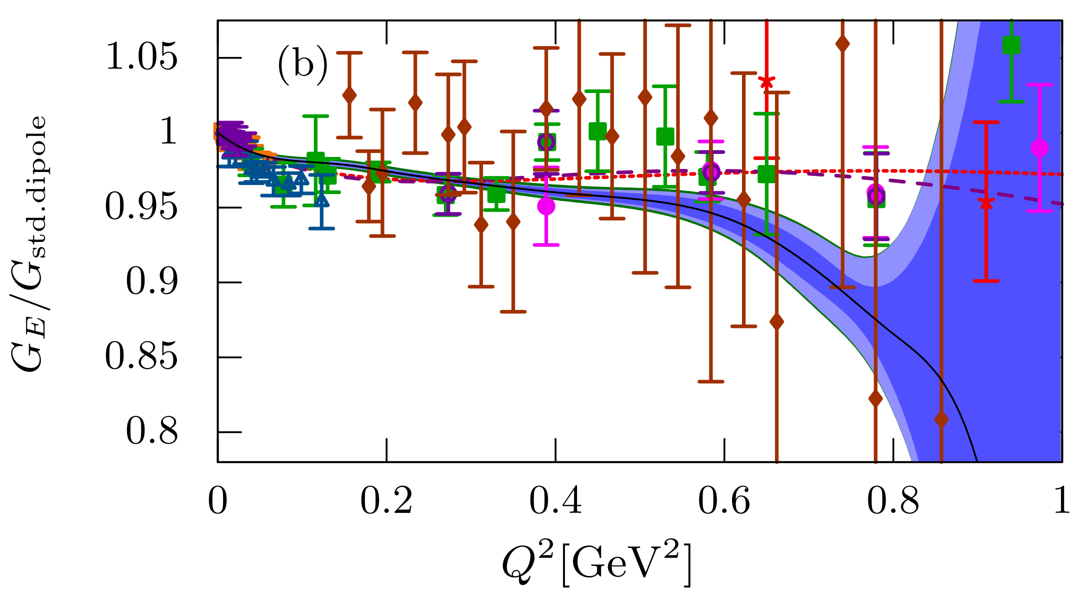
where F_E/F_M are the proton electric/magnetic form factors. Precisely measured from elastic ep scattering, in terms of `dipole' form factors:

Elastic $\Rightarrow$ steeply falling

$$G_E^2(Q_i^2) = \frac{G_M^2(Q_i^2)}{7.78} = \frac{1}{\left(1 + Q_i^2/0.71{\rm GeV}^2\right)^4}$$

- Most precise measurements show deviations from dipole, but $< 1\%$ level effects (apart from at highest x). Extended parameterisations ('double-dipole' etc) available- should include in future fits.

A1 Collaboration, arXiv:1307.6227



Incoherent photon emission

- In addition, there will be some contribution to $\gamma(x, Q_0^2)$ due to emission from the individual quarks, as in CT/MRST.

- For now take simple phenomenological approach: freeze the quark PDFs for $Q < Q_0$, but must include form factor for incoherent emission to avoid double counting with coherent piece:

$$\gamma_{\rm incoh}(x, Q_0^2) = \frac{\alpha}{2\pi} \int_x^1 \frac{{\rm d}z}{z} \left[\frac{4}{9} \underbrace{u_0}_{u+\overline{u}} \left(\frac{x}{z}\right) + \frac{1}{9} d_0 \left(\frac{x}{z}\right) \right] \frac{1+(1-z)^2}{z} \int_{Q^2_{\rm min}}^{Q_0^2} \frac{{\rm d}Q^2}{Q^2 + m_q^2} \underbrace{(1 - G_E^2(Q^2))}_{\text{form factor}} \;,$$

quarks frozon at Q_0 (include strange as well)

- $u, d \downarrow$ as $Q^2 \downarrow$ for relevant x, $\Rightarrow$ freezing corresponds to upper limit.

- Consider simple model here, but in a more complete treatment, it is this object - $\gamma_{\rm incoh}(x, Q_0^2)$ - that should be fit.

Input photon PDF

- Photon PDF at Q_0 given as sum of coherent and incoherent terms:

$$\gamma(x,Q_0^2)=\gamma_{\rm coh}(x,Q_0^2)+\gamma_{\rm incoh}(x,Q_0^2)$$

- Consider momentum fraction of proton at Q_0 due to two contributions:

$$p_\gamma=\int {\rm d}x\, x\gamma(x,Q_0^2)$$

- Find: $p_\gamma^{\rm coh}=0.15\%$ $\quad p_\gamma^{\rm incoh.}=0.05\%$ $\quad$ NNPDF3.0QED: $p_\gamma=(1.26\pm 1.26)\%$

- Recall our incoherent term is upper limit $\Rightarrow$ at least $\sim 75\%$ of photon PDF is known very precisely. Entirely expected: at low Q^2 the dominant mechanism for γ emission from a proton is coherent.

Predictions

Solving the DGLAP equation

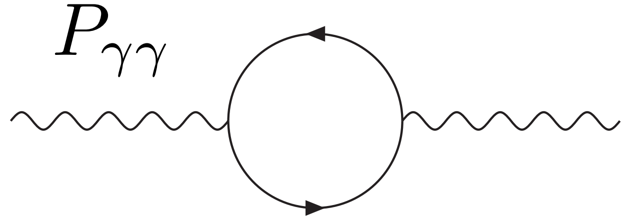
- Returning to photon DGLAP evolution equation:

$$\gamma(x,\mu^2) = \gamma(x,Q_0^2) + \int_{Q_0^2}^{\mu^2} \frac{\alpha(Q^2)}{2\pi}\frac{dQ^2}{Q^2}\int_x^1 \frac{dz}{z}\bigg(P_{\gamma\gamma}(z)\gamma(\frac{x}{z},Q^2)$$
$$+\sum_q e_q^2 P_{\gamma q}(z) q(\frac{x}{z},Q^2) + P_{\gamma g}(z) g(\frac{x}{z},Q^2)\bigg)\,,$$

NLO in QCD

- As $\alpha \ll 1$ we can simplify to very good approx: take q and g as independent of γ .

- The self-energy contribution $P_{\gamma\gamma}(z) \sim \delta(1-z)$ and therefore this term on RHS of DGLAP $\sim \gamma(x,Q^2)$ i.e. at same x as LHS.



$\longrightarrow$ Can solve the photon DGLAP equation.

Solving the DGLAP equation

- We find:

$$\gamma(x,\mu^2) = \gamma(x,Q_0^2)\, S_\gamma(Q_0^2,\mu^2) + \int_{Q_0^2}^{\mu^2} \frac{\alpha(Q^2)}{2\pi}\frac{dQ^2}{Q^2}\int_x^1 \frac{dz}{z}\bigg(\sum_q e_q^2 P_{\gamma q}(z) q(\frac{x}{z},Q^2)$$
$$+ P_{\gamma g}(z) g(\frac{x}{z},Q^2)\bigg)\, S_\gamma(Q^2,\mu^2)\ ,$$

i.e. we have: $\gamma(x,\mu^2) \equiv \gamma^{\rm in}(x,\mu^2) + \gamma^{\rm evol}(x,\mu^2)$

$\longrightarrow$ Photon PDF at scale μ given separately in terms of:

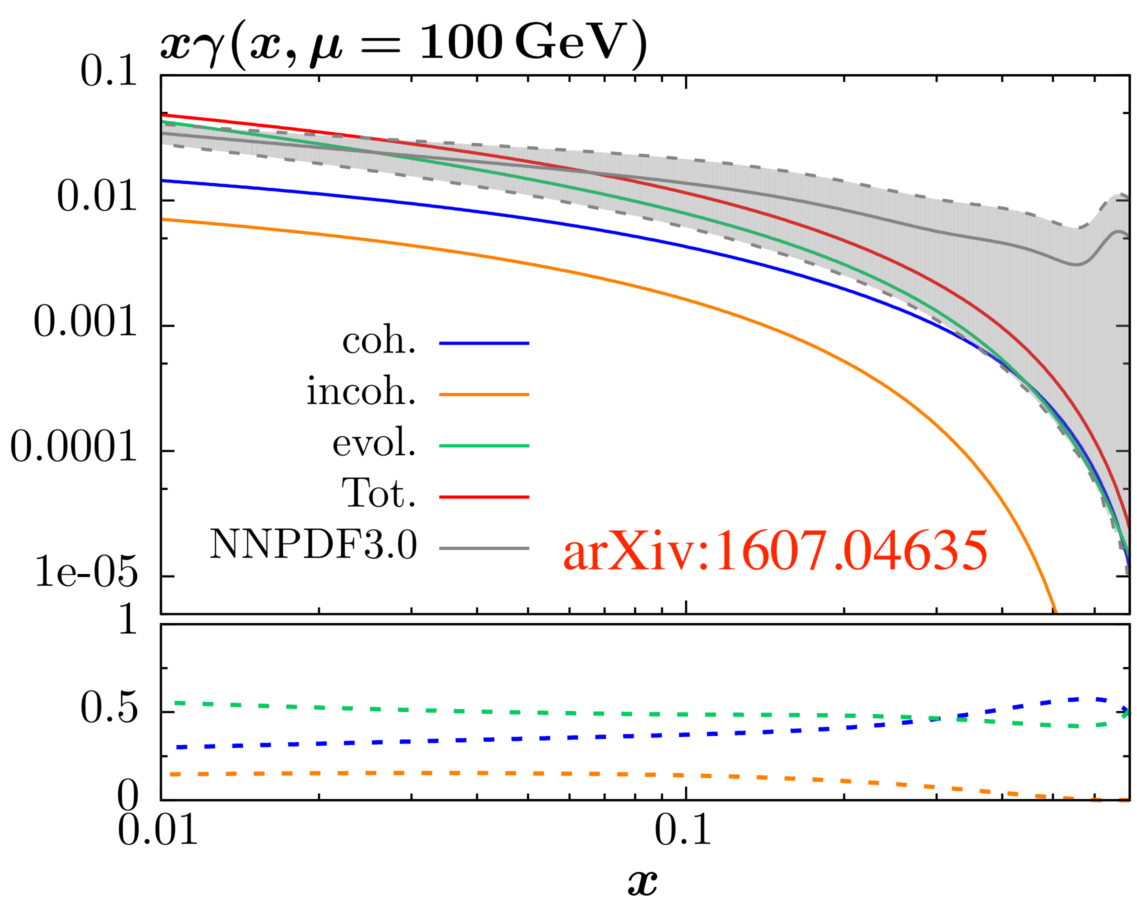
- $\gamma^{\rm in}(x,\mu^2)$: component due to low scale $Q^2 < Q_0^2 \sim 1\,{\rm GeV}^2$ emission.
- $\gamma^{\rm evol}(x,\mu^2)$: component due to high scale DGLAP emission from quarks.

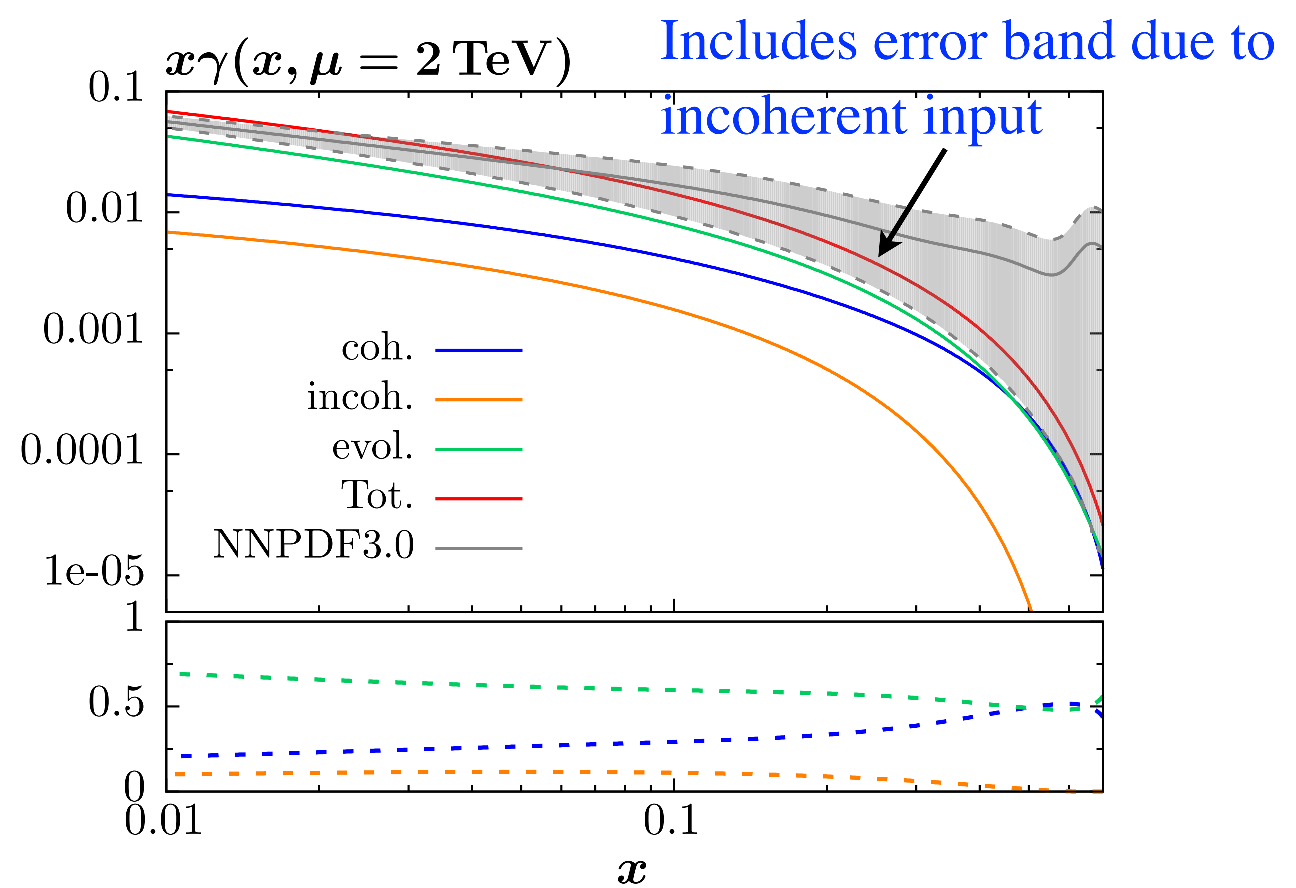
- Sudakov factor $S_\gamma(Q_0^2,\mu^2)$ is prob. for no emission between Q_0^2 and μ^2 :

$$S_\gamma(Q_0^2,\mu^2) = \exp\left(-\frac{1}{2}\int_{Q_0^2}^{\mu^2}\frac{{\rm d}Q^2}{Q^2}\frac{\alpha(Q^2)}{2\pi}\int_0^1 {\rm d}z \sum_{a=q,l} P_{a\gamma}(z)\right)$$

PDF comparison

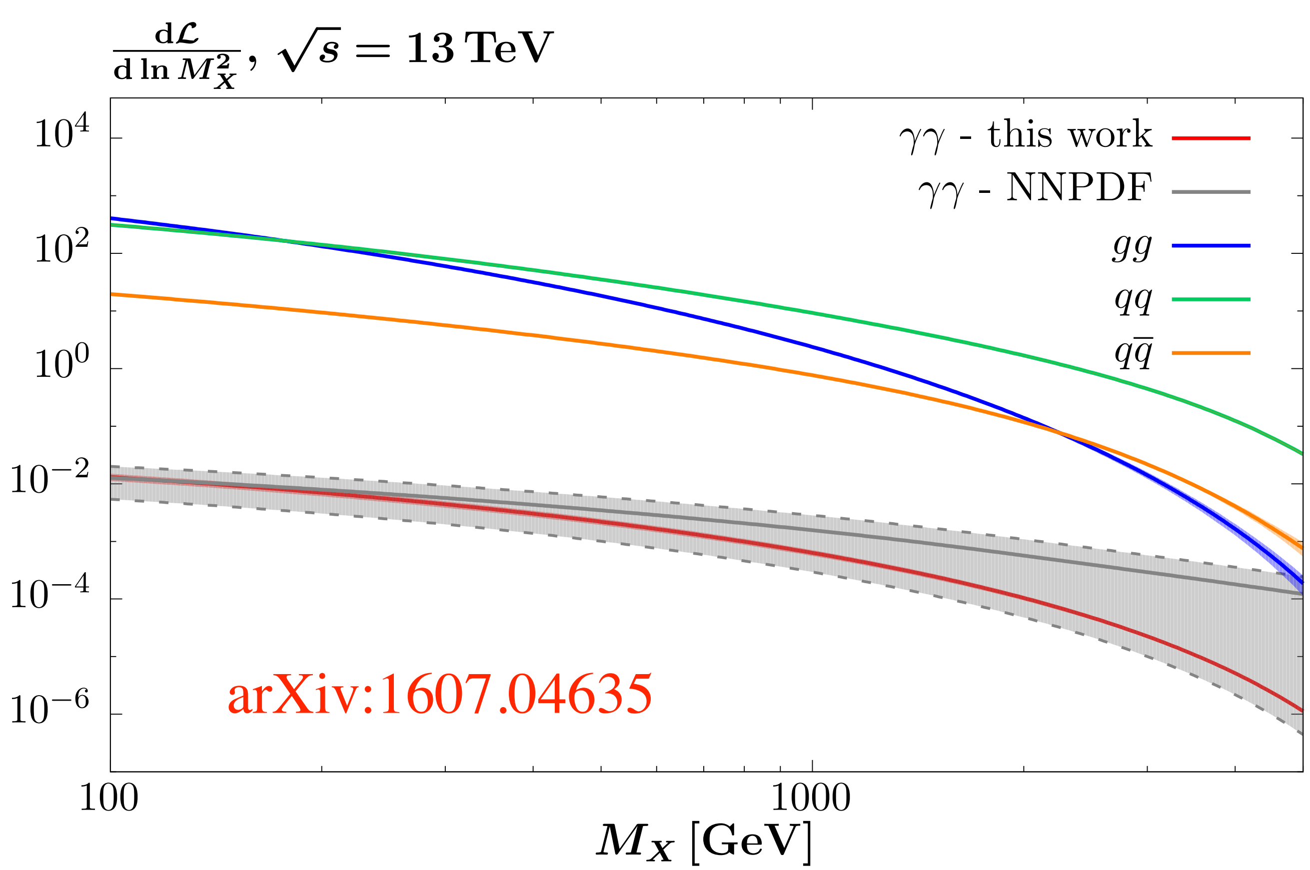
- Consider photon PDF at high scale μ :
  - $x \downarrow$: dominated by evolution. Uncertainty under good control.
  - $x \uparrow$: input component more important.
- NNPDF has huge uncertainties at higher x .
- But in our physical approach this is not the case. Prediction lies on lower end of NNPDF uncertainty band.

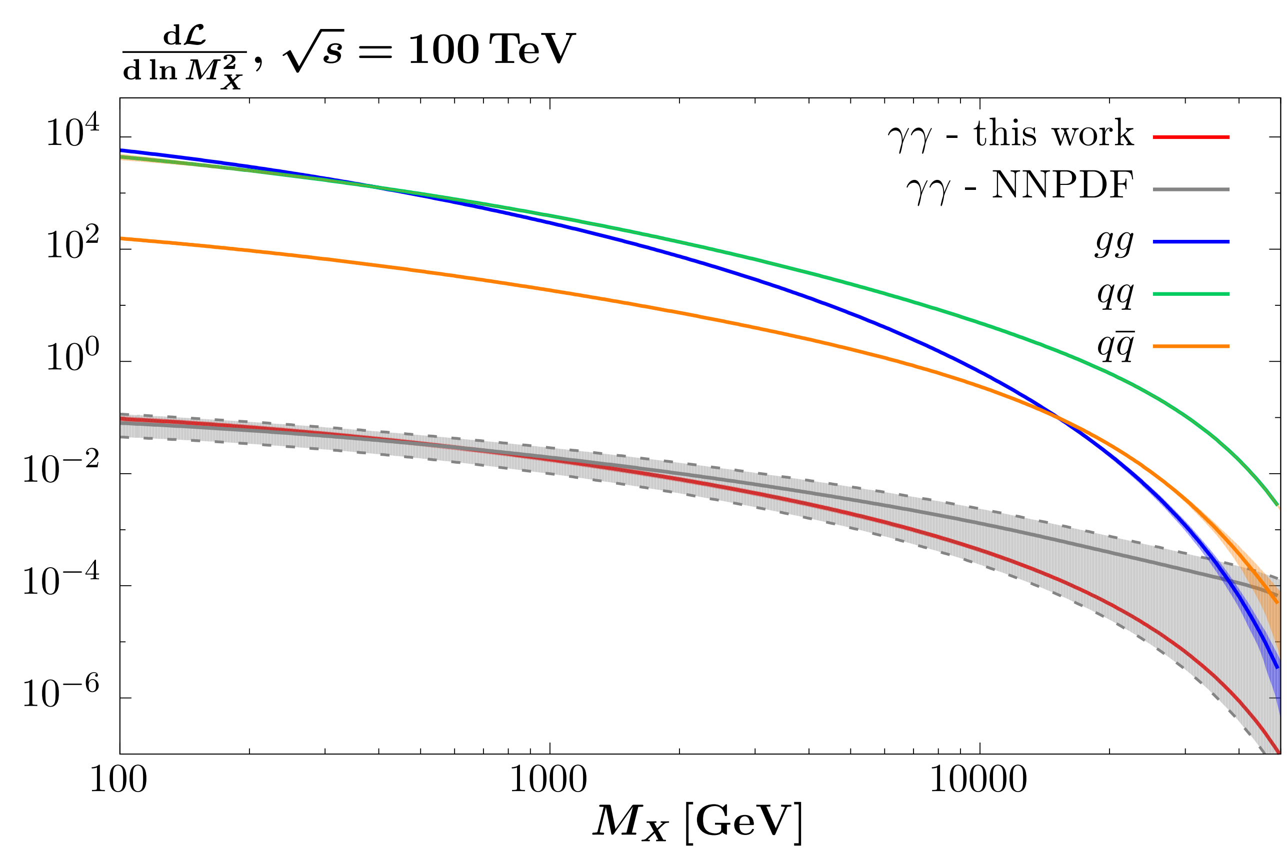




PDF luminosities

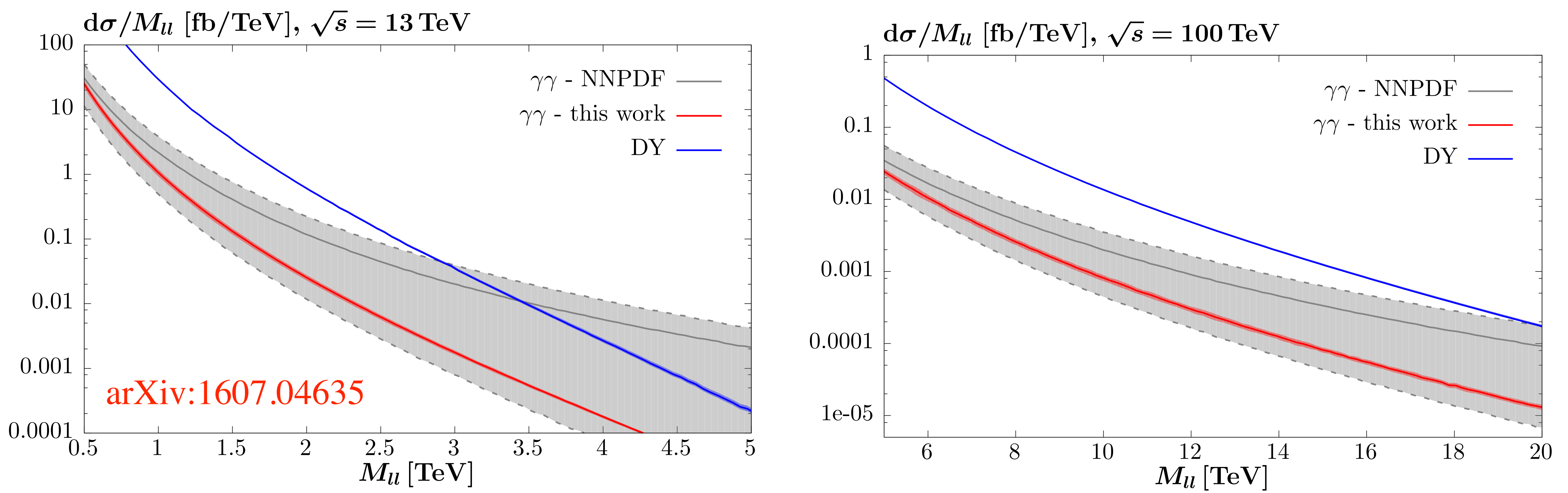
- Consider parton-parton luminosities at LHC and FCC.
- Previous result translates to large uncertainty and potentially large luminosity at high mass. q, g fall much more steeply than central γ NNPDF prediction.
- Our approach: scaling very similar to $qq/q\bar{q}$, with gg only slightly stepper. Uncertainties fairly small, again a lower end of NNPDF band.





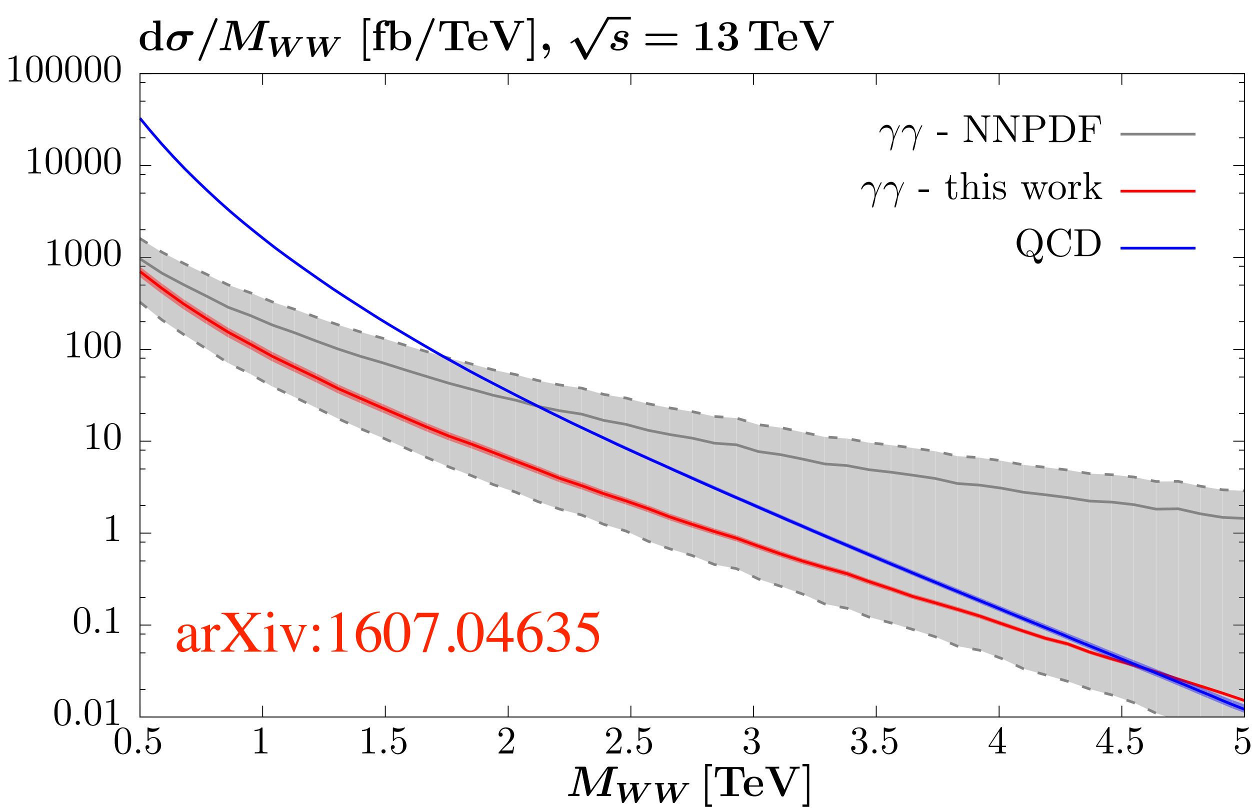
Drell-Yan production

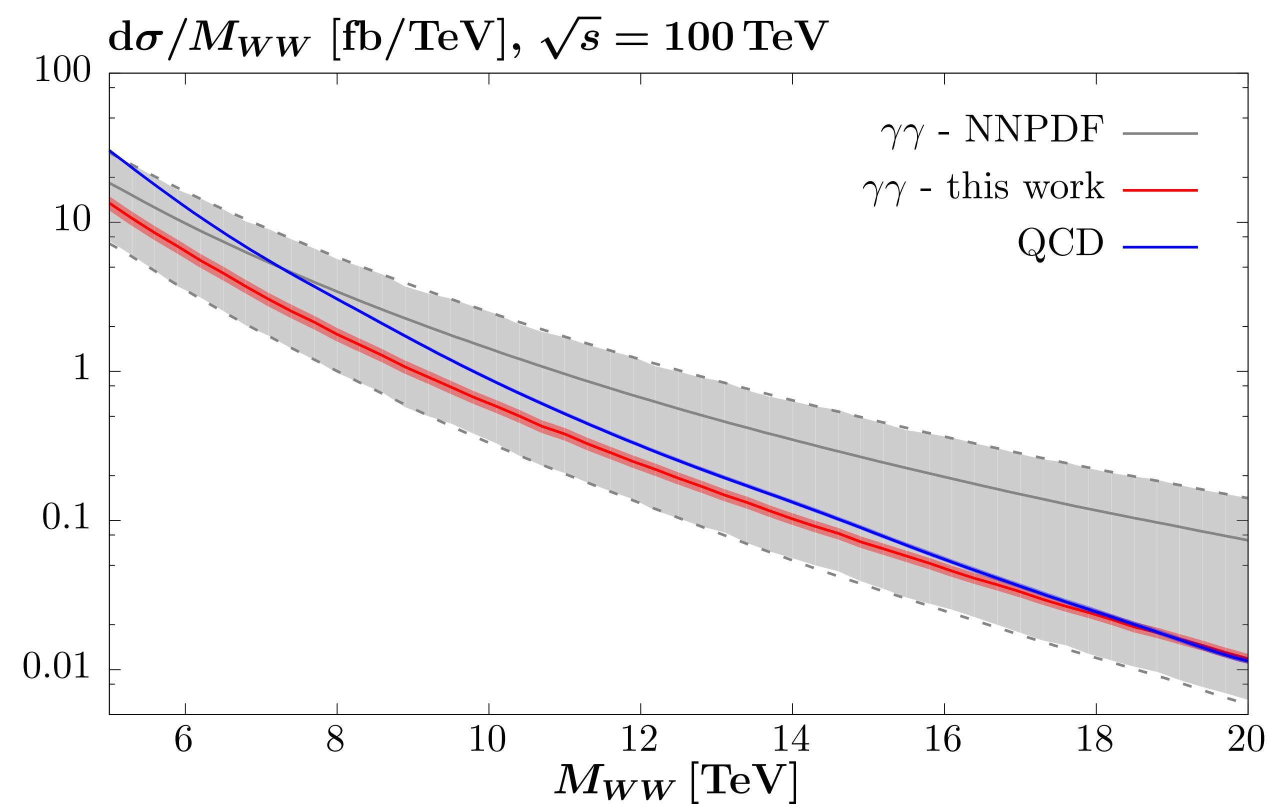
- Consider lepton pair production at LHC/FCC. As M_{ll} increases find central NNPDF $\gamma\gamma$ prediction becomes sizeable/dominant. Discussed in detail in 1606.00523, 1606.06646, 1607.01831.
- Follows directly from previous slide: relatively gentle decrease of NNPDF $\gamma\gamma$ luminosity at higher mass.
- We find this is not expected. Photon-initiated contribution $\lesssim 10\%$.



W^+W^- production

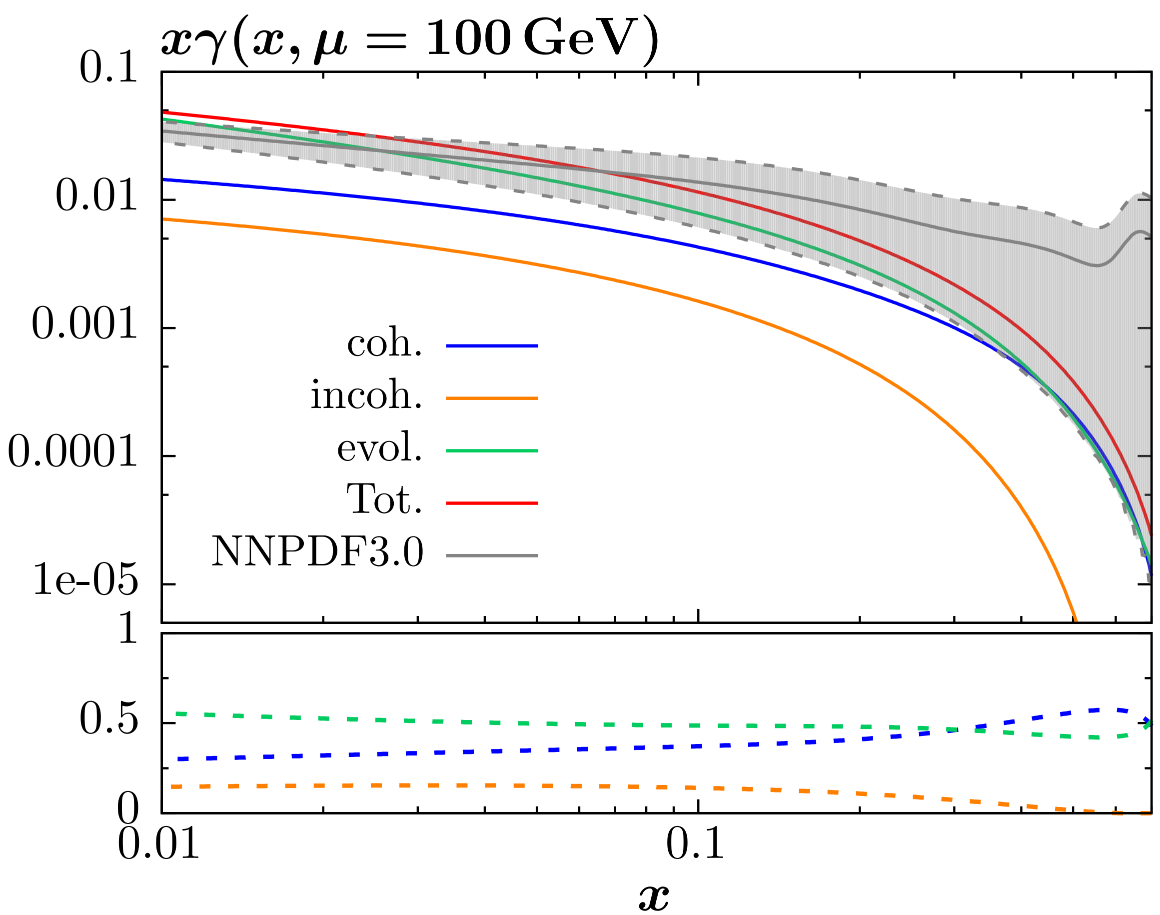
- Similar story for W^+W^- production: our results at lower end of NNPDF uncertainty band.
- However here the photon-initiated contribution is still quite large (caveat: depends somewhat on cuts).





Constraint from ATLAS data

- Recent ATLAS measurement of double-differential DY, extending to high mass $M_{ll} < 1500\,\mathrm{GeV}$. Sensitive to photon PDF.
- Bayesian reweighting exercise clearly disfavours larger NNPDF2.3 predictions $\Rightarrow$ consistent with our results.
- ATLAS data only sensitive to higher x, constraint as $x \downarrow$ largely artefact of reweighting. Would be interesting to include this in fit.



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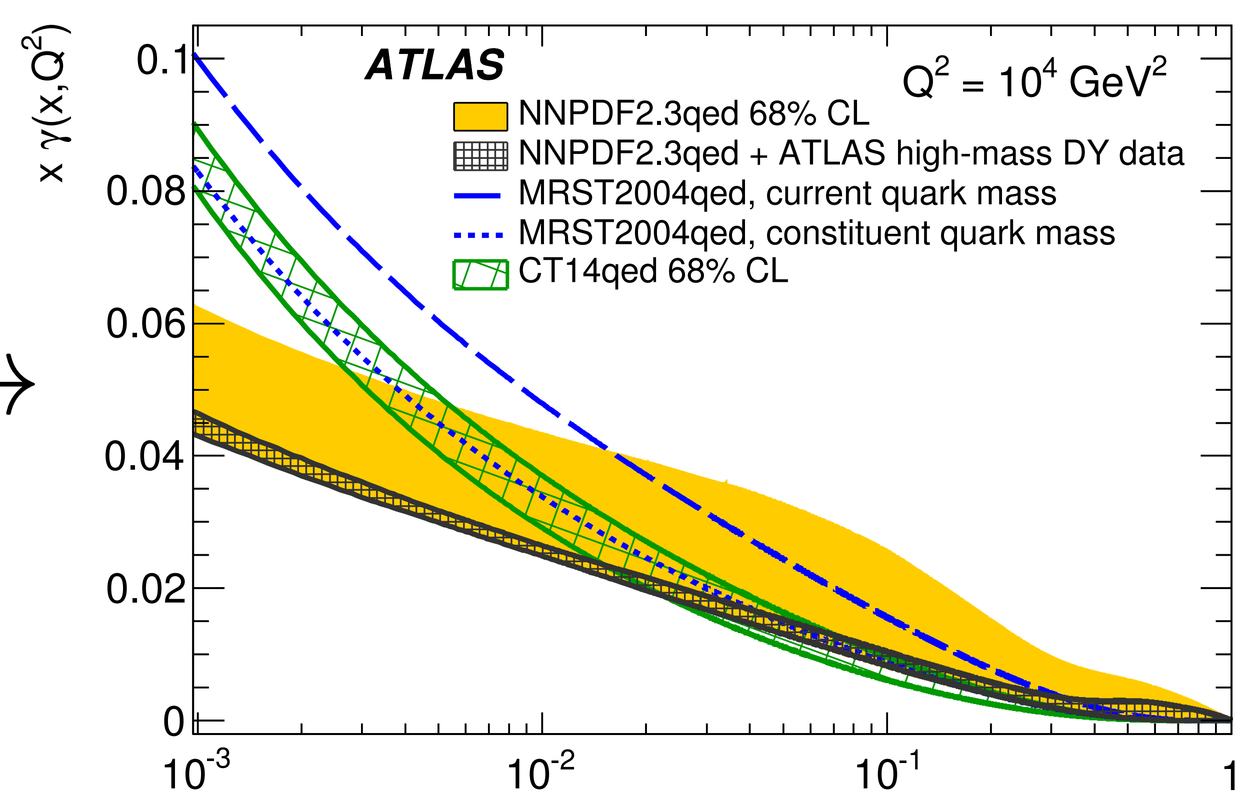

LUXqed: comparison

LUXqed

- Recent study of arXiv:1607.04266:

CERN-TH/2016-155

How bright is the proton?
A precise determination of the photon PDF

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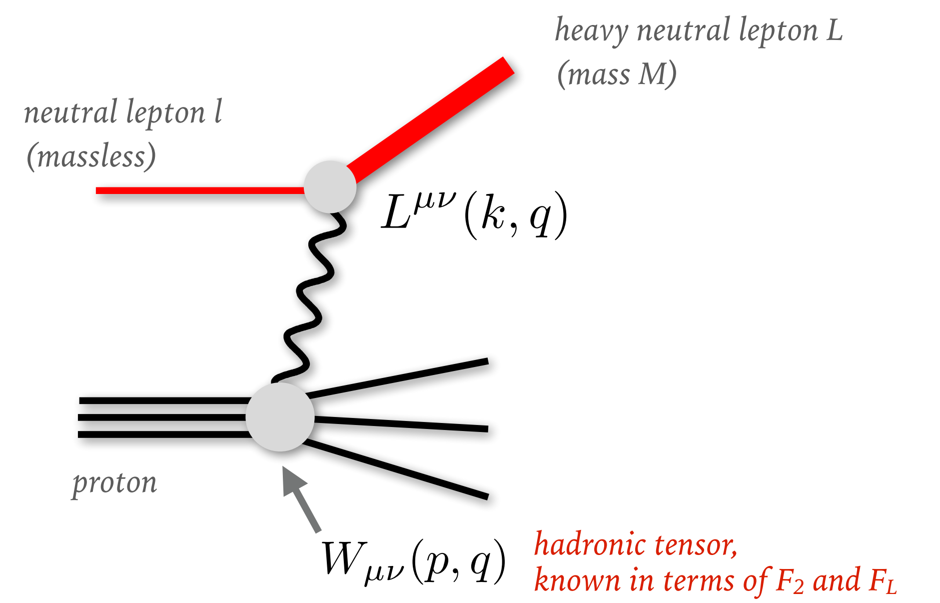
[3] *INFN, Sezione di Milano Bicocca, 20126 Milan, Italy*
[4] *Rudolf Peierls Centre for Theoretical Physics, 1 Keble Road, University of Oxford, UK*

- Show how photon PDF can be expressed in terms of F_2 and F_L. Use measurements of these to provide well constrained `LUXqed` photon PDF.

$$xf_{\gamma/p}(x,\mu^2) = \frac{1}{2\pi\alpha(\mu^2)}\int_x^1 \frac{dz}{z}\left\{\int_{\frac{x^2m_p^2}{1-z}}^{\frac{\mu^2}{1-z}} \frac{dQ^2}{Q^2}\alpha^2(Q^2)\right.$$
$$\left[\left(zp_{\gamma q}(z)+\frac{2x^2m_p^2}{Q^2}\right)F_2(x/z,Q^2) - z^2F_L\left(\frac{x}{z},Q^2\right)\right]$$
$$\left. - \alpha^2(\mu^2)z^2F_2\left(\frac{x}{z},\mu^2\right)\right\}, \quad (6)$$



LUXqed - making connection (1)

- While the formalism may appear different, in fact connection to our results can be quite simply made. Divide Q^2 integral into $Q^2 < Q_0^2 \sim 1\,\mathrm{GeV}^2$ and $Q^2 > Q_0^2$ regions.
- $Q^2 > Q_0^2$: keep on leading $\ln \mu^2/Q_0^2$ term and $Q^2 \gg m_p^2$

$$
\begin{aligned}
xf_{\gamma/p}(x,\mu^2) = \frac{1}{2\pi\alpha(\mu^2)} \int_x^1 \frac{dz}{z} \Bigg\{ \int_{\frac{x^2 m_p^2}{1-z}}^{\frac{\mu^2}{1-z}} \frac{dQ^2}{Q^2} \alpha^2(Q^2) \\
\left[\left(zp_{\gamma q}(z) + \cancel{\frac{2x^2 m_p^2}{Q^2}} \right) F_2(x/z, Q^2) - z^2 F_L\left(\frac{x}{z}, Q^2\right) \right] \\
\cancel{- \alpha^2(\mu^2) z^2 F_2\left(\frac{x}{z}, \mu^2\right)} \Bigg\}, \quad (6)
\end{aligned}
$$

- Take LO in α_S for simplicity, then:

LL

$$
xf_{\gamma/p}(x,\mu^2) \to x \int_x^1 \frac{\mathrm{d}z}{z} \int_{Q_0^2}^{\mu^2} \frac{\mathrm{d}Q^2}{Q^2} \frac{\alpha(Q^2)}{2\pi} \frac{\alpha(Q^2)}{\alpha(\mu^2)} p_{\gamma q}(z) \sum e_q^2\, q\left(\frac{x}{z}, Q^2\right) \;,
$$

Cutoff

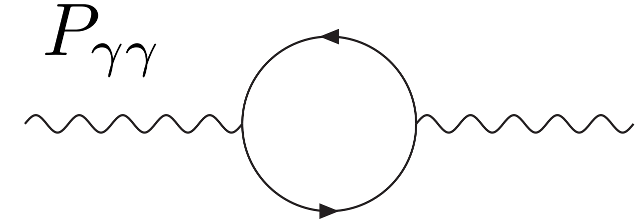
LUXqed - making connection (2)

$$xf_{\gamma/p}(x,\mu^2) = x\int_x^1 \frac{\mathrm{d}z}{z}\int_{Q_0^2}^{\mu^2}\frac{\mathrm{d}Q^2}{Q^2}\frac{\alpha(Q^2)}{2\pi}\frac{\alpha(Q^2)}{\alpha(\mu^2)}P_{\gamma q}(z)\sum e_q^2\, q\left(\frac{x}{z},Q^2\right)\ ,$$

- What about $\alpha(Q^2)/\alpha(\mu^2)$ term? Recall Sudakov factor:

$$S_\gamma(Q_0^2,\mu^2) = \exp\left(-\frac{1}{2}\int_{Q_0^2}^{\mu^2}\frac{\mathrm{d}Q^2}{Q^2}\frac{\alpha(Q^2)}{2\pi}\int_0^1 \mathrm{d}z\sum_{a=q,\,l}P_{a\gamma}(z)\right)$$

$P_{\gamma\gamma}$



comes from resumming self-energy contribution to DGLAP.

- Connection to running of α. Find: $S_\gamma(Q^2,\mu^2) = \dfrac{\alpha(Q^2)}{\alpha(\mu^2)} + O(\alpha)$

$\longrightarrow$ Recover precisely the LO $Q^2 > Q_0^2$ term in DGLAP evolution:

$$\gamma(x,\mu^2) = \gamma(x,Q_0^2)\,S_\gamma(Q_0^2,\mu^2) + \int_{Q_0^2}^{\mu^2}\frac{\alpha(Q^2)}{2\pi}\frac{dQ^2}{Q^2}\int_x^1\frac{dz}{z}\Big(\sum_q \underline{e_q^2 P_{\gamma q}(z) q(\frac{x}{z},Q^2)}$$
$$+ P_{\gamma g}(z) g(\frac{x}{z},Q^2)\Big)\,\underline{S_\gamma(Q^2,\mu^2)}\ ,$$

Caveat: omits influence of γ on quarks/gluons.

LUXqed - making connection (3)

- To compare approaches, divide Q^2 integral into $Q^2 < Q_0^2 \sim 1\,\mathrm{GeV}^2$ and $Q^2 > Q_0^2$ regions:

$$F_2^{\rm el}(x,Q^2) = \frac{[G_E(Q^2)]^2 + [G_M(Q^2)]^2\tau}{1+\tau}\delta(1-x)\,,$$
$$F_L^{\rm el}(x,Q^2) = \frac{[G_E(Q^2)]^2}{\tau}\delta(1-x)\,,$$

- $Q^2 > Q_0^2$ - standard DGLAP ($=\gamma^{\rm evol}$).
- $Q^2 < Q_0^2$ - separates into:
  - 'Elastic' = coherent component. Treatment very similar.
  - 'Inelastic' = incoherent component. Treatment different.

$$x f_{\gamma/p}(x,\mu^2) = \frac{1}{2\pi\alpha(\mu^2)}\int_x^1 \frac{dz}{z}\Bigg\{\int_{\frac{x^2m_p^2}{1-z}}^{\frac{\mu^2}{1-z}} \frac{dQ^2}{Q^2}\alpha^2(Q^2)$$
$$\left[\left(zp_{\gamma q}(z) + \frac{2x^2m_p^2}{Q^2}\right)F_2(x/z,Q^2) - z^2F_L\left(\frac{x}{z},Q^2\right)\right]$$
$$-\alpha^2(\mu^2)z^2F_2\left(\frac{x}{z},\mu^2\right)\Bigg\}, \quad (6)$$

LUXqed

$$\gamma(x,\mu^2) \equiv \gamma^{\rm in}(x,\mu^2) + \gamma^{\rm evol}(x,\mu^2)$$
$$\gamma(x,Q_0^2) = \gamma_{\rm coh}(x,Q_0^2) + \gamma_{\rm incoh}(x,Q_0^2)$$

HKR

LUXqed - incoherent component

- The incoherent component is extracted from fit to low Q^2 structure function data $p \to \gamma X$. Divided into two pieces:

    - Continuum ($W^2 \gtrsim 3.5\,\mathrm{GeV}^2$) : take HERMES fit to structure function data from various experiments, extending to $Q^2 = 0$ (photoproduction).

    - Resonance region ($W^2 \lesssim 3.5\,\mathrm{GeV}^2$): consider two different fits to world data.

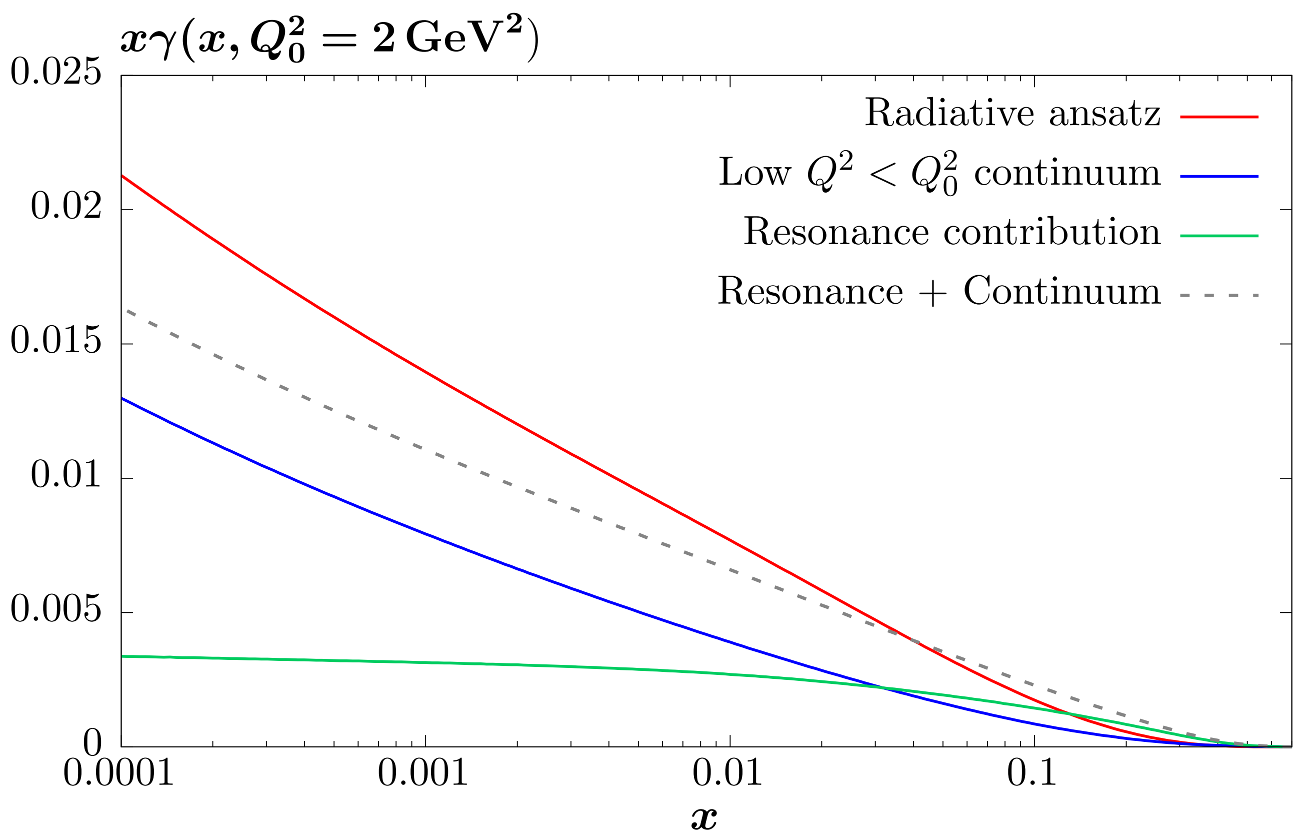
$\longrightarrow$ Places important constraints.

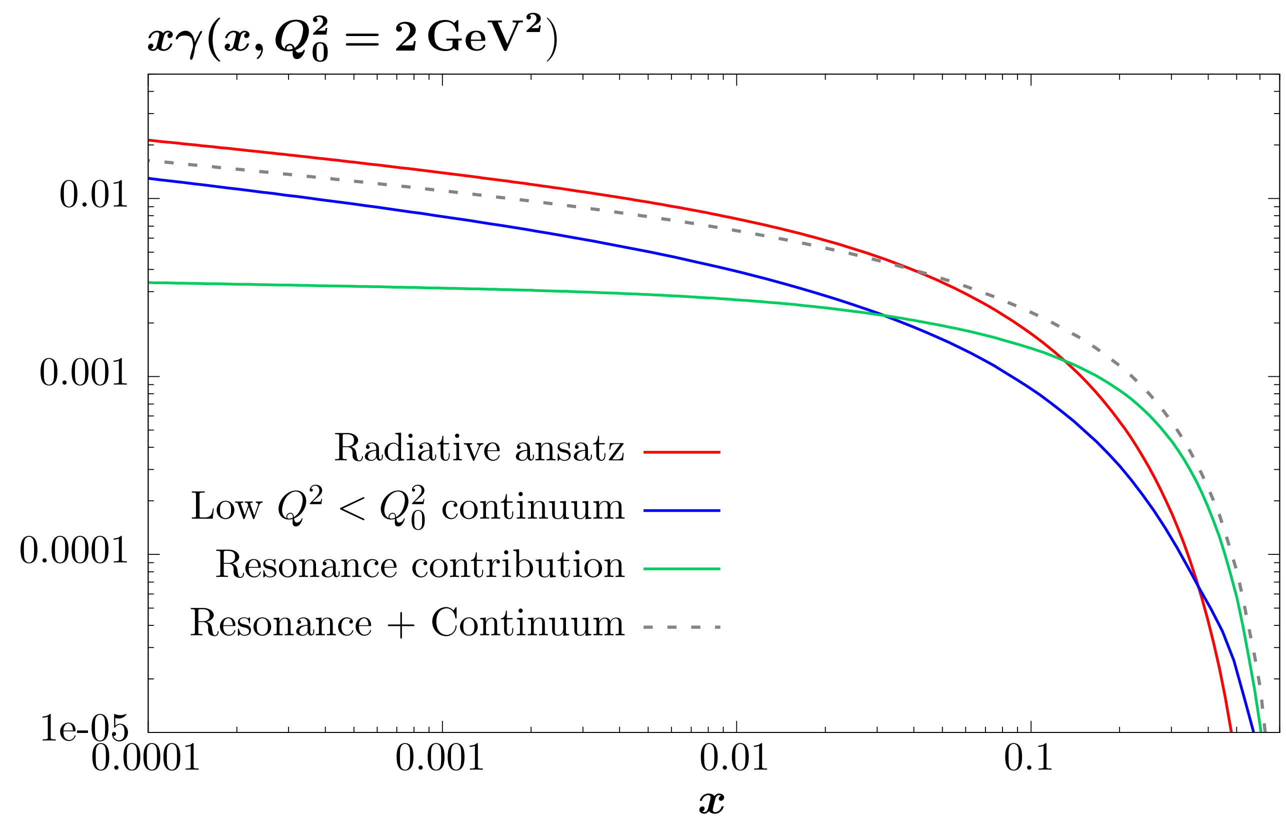
- Using connection made in previous slides, can compare our approach with this.

LUXqed - comparison (1)

- Compare photon at Q_0 in our approach ('radiative ansatz') and using low Q^2 structure function data:
  - Continuum contribution less than the $\sim$ upper bound set by our model, and similar in shape.
  - But resonance contribution flatter ($W^2 \sim Q^2/x$) and exceeds our result at higher x .

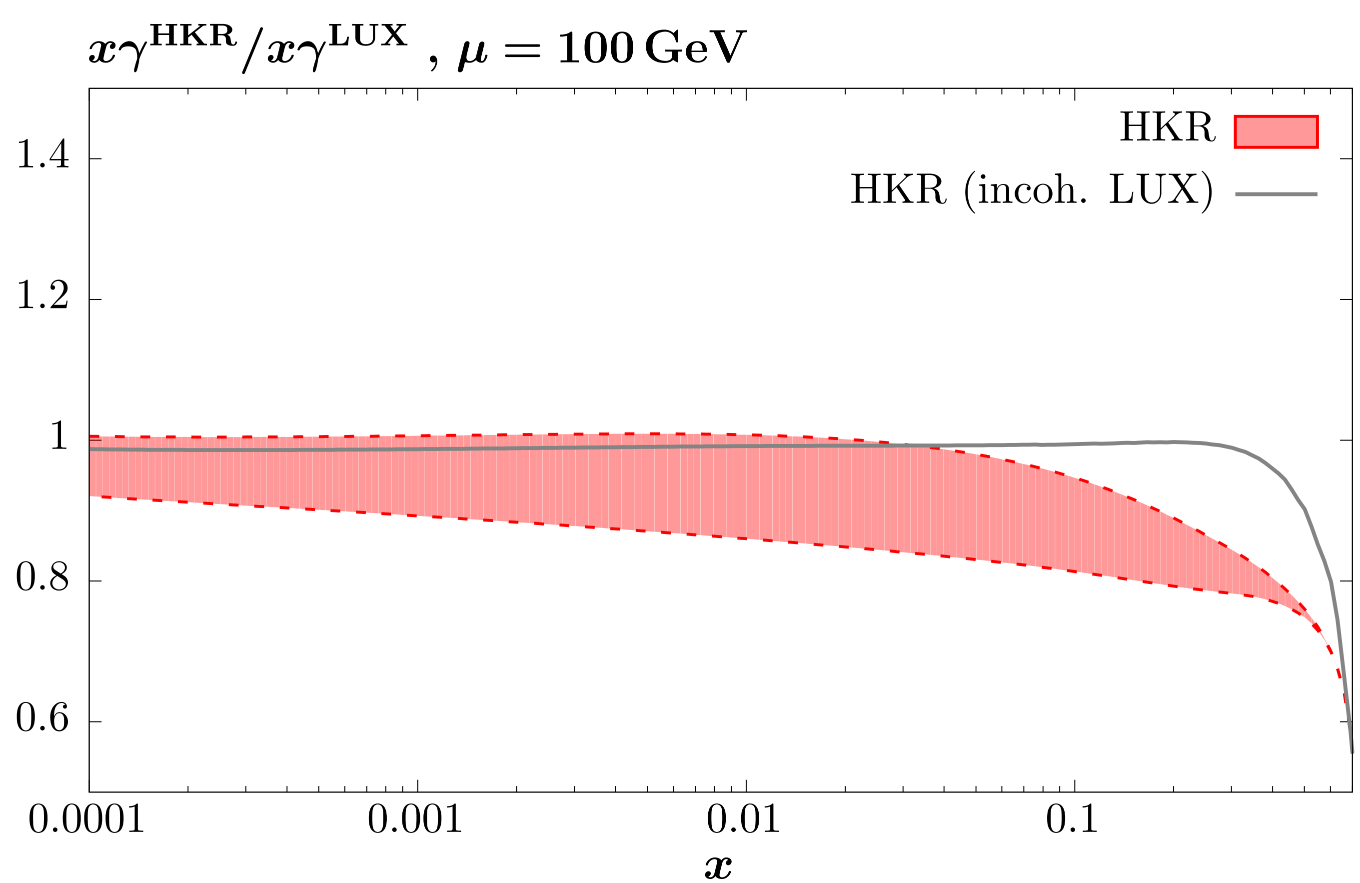
'Christy-Bosted' fit





LUXqed - comparison (2)

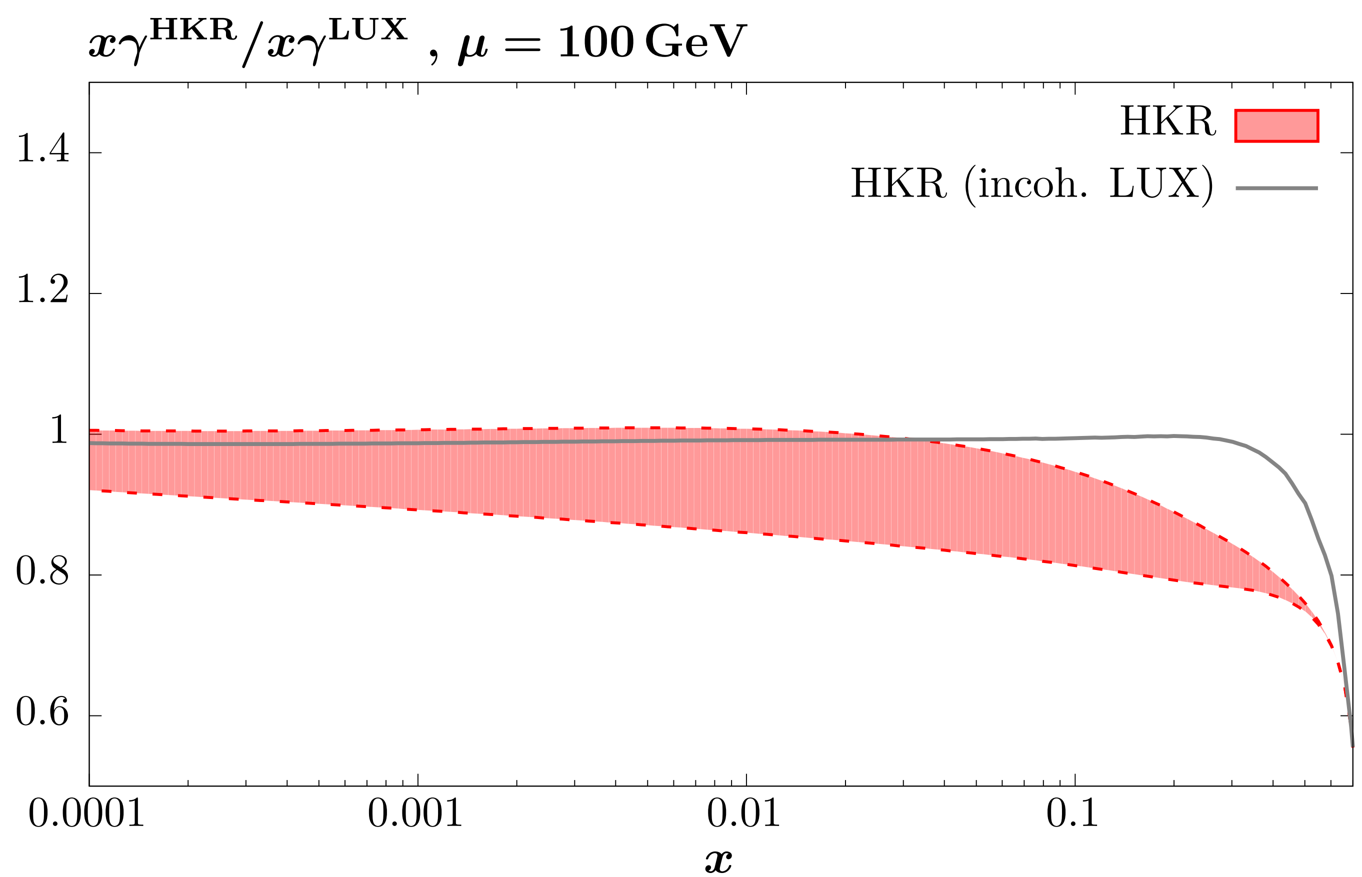
- Consider ratio of PDFs at $\mu = 100\,\mathrm{GeV}$. Lower end of HKR band given by setting $\gamma_{\rm incoh} = 0$ (for illustration).
- Complete consistency found at lower x, but deviation as $x \uparrow$ (resonance contribution).
- Check: result of our approach + incoherent calculated using structure function data within $O(\%)$ of LUXqed over all relevant x.



Photon PDF: outlook

- Have demonstrated that standard PDF approach very close to LUXqed when taking same data input for $\gamma(x, Q_0^2)$.

$\longrightarrow$ Possible to unify approaches. Consider constraints from both LHC and low Q^2 structure function data. Full treatment of uncertainties and coupled DGLAP evolution.



Conclusions

• As NNLO QCD precision becomes the standard, the increasing relevance of electroweak corrections is clear. Important part of this is photon-initiated processes: requires the introduction of a photon PDF.

• Previous approaches: either completely agnostic (NNPDF) or introduce model for photon emission off quarks (MRST/CT).

• Crucial to include coherent $p \to p\gamma$ emission term as well: dominant contribution, leads to sizeable reduction in uncertainties.

• Considering W^+W^- and l^+l^- production at LHC/FCC, the potential dominance of photon-initiated mechanism not supported.

• Outlook: MMHT work ongoing, using approach outlined above in global fit context.

• LUXqed: new approach, but connection can be made.