MSHT20qed: QED PDFs in the MSHT20 fit

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DIS 2022, 4 May 2022

T. Cridge et al., *Eur.Phys.J.C* 82 (2022) 1, 90

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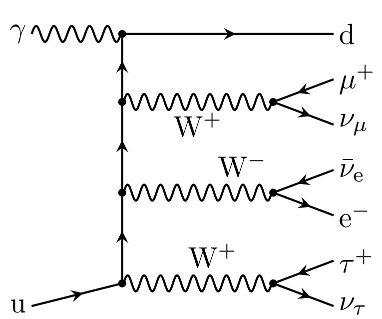
Motivation

- Heading into high precision LHC era.

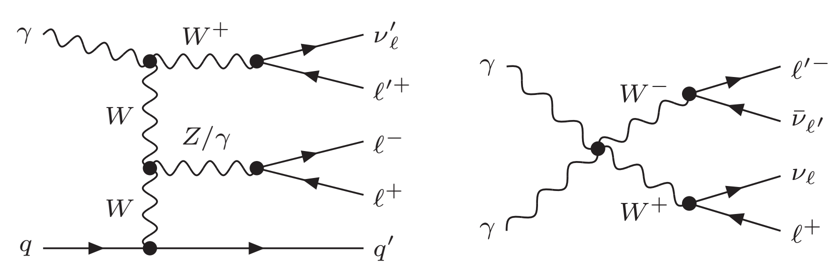
★NNLO QCD the standard for inclusive processes, but:

$$\alpha_{\rm QED}(M_Z) \sim \alpha_S^2(M_Z)$$

$\Rightarrow$ crucial to include EW effects. QED corrections a key element of this.



S. Dittmaier, G Knippen, C. Schwan, *JHEP* 02 (2020) 003



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M. Grazzini et al., *JHEP* 02 (2020) 087

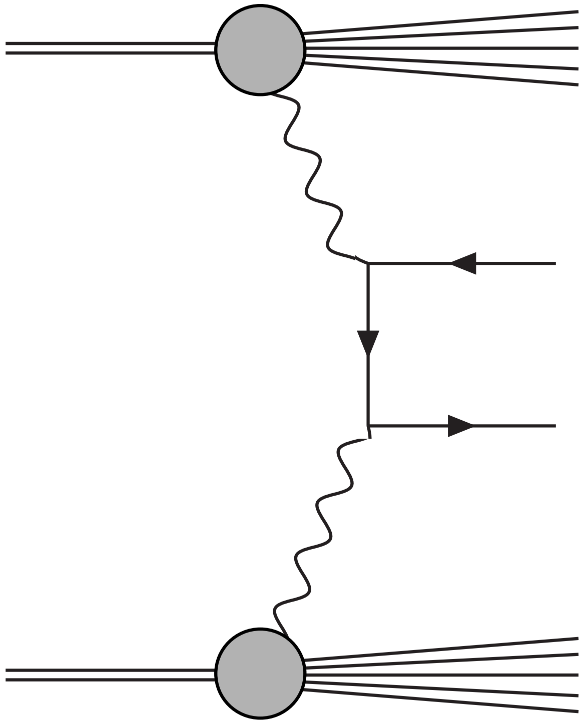
Including QED corrections in PDF fits

- These enter via QED modification to **DGLAP**:

$$P_{ij}^{(QED)} = \frac{\alpha}{2\pi} P_{ij}^{(0,1)} + \frac{\alpha \alpha_S}{(2\pi)^2} P_{ij}^{(1,1)} + \left(\frac{\alpha}{2\pi}\right)^2 P_{ij}^{(0,2)} + \ldots$$

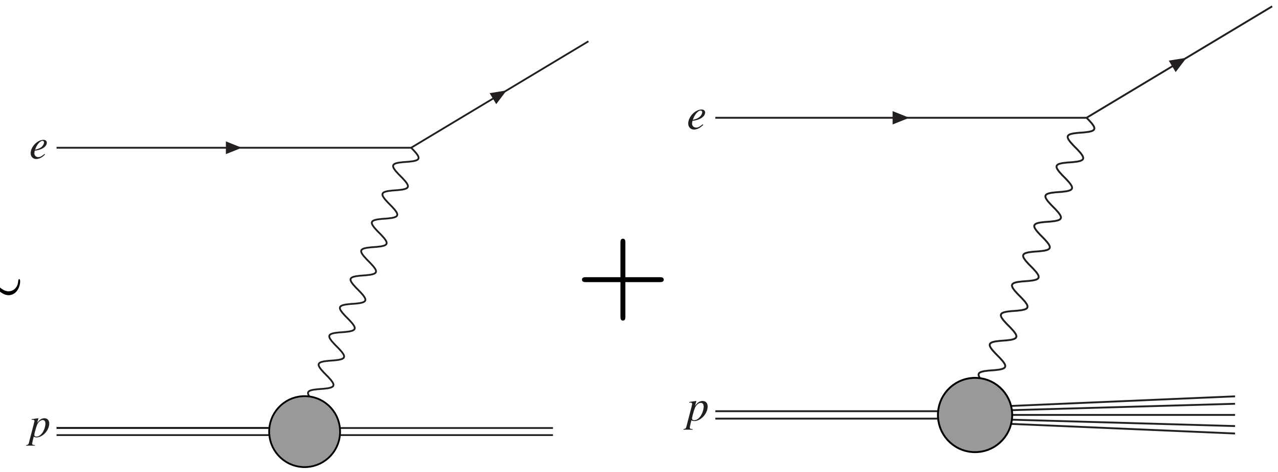
- But also require the introduction of a **photon PDF**, and inclusion of **photon-initiated** (PI) production in the corresponding cross sections.

- Historically, this were either fit agnostically or evaluated in model-dependent way.
- However, with advent of **LUXqed** work we can be more precise…



- In more detail, photon PDF given in terms of proton EM form factors and inelastic **structure functions**.

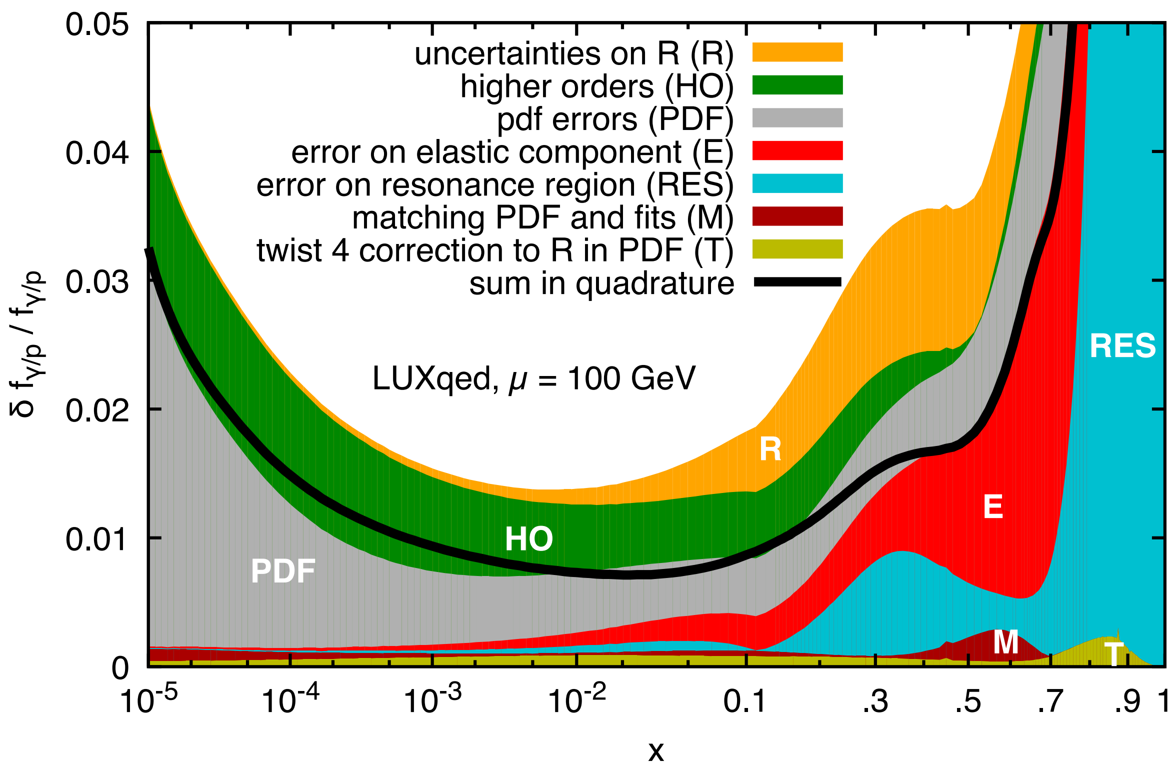
$$\gamma(x, Q^2) \sim$$



$F_{1,2}^{\rm el}$ $\quad$ $F_{1,2}^{\rm inel}$

- Idea formulated long ago, revisited over the years.

V. M. Budnev et al., Phys. Rept. 15, 181 (1975)
H. Anlauf et al., Comput. Phys. Commun. 70, 97 (1992)
J. Blumlein et al., J. Phys. G19, 1695 (1993)
A. Mukherjee and C. Pisano, Eur. Phys. J. C30, 477 (2003)
M.Luszczak at al., Phys.Rev.D93, 074018(2016)



A. Manohar et al., JHEP 1712 (2017) 046

- Put on precise footing by LUXqed:
    - ★ Extended beyond LO in α .
    - ★ Precise inputs for structure functions and hence photon PDF at high precision.

- Gives **1% level uncertainty** in derived photon PDF.

MSHT20QED

- In global PDF analysis, we can include a photon PDF a la LUXqed + suitable QED corrections to DGLAP/cross sections.
- This has been applied (different in details) by MSHT, NNPDF + CT.
- The first study by us was **MMHT14qed**.
- **MSHT20qed** is an update to this. Follows same basic idea, but with some updates + extended global dataset.

QED Parton Distribution Functions in the MSHT20 Fit

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Abstract

We present the MSHT20qed set of parton distribution functions (PDFs). These are obtained from the MSHT20 global analysis via a refit including QED corrections to the

MSHT20QED: Photon PDF

- As in **MMHT14qed** our starting point is the **LUXqed** formula, suitably modified:

$$x\gamma(x,Q_0^2) = \frac{1}{2\pi\alpha(Q_0^2)}\int_x^1 \frac{dz}{z}\bigg\{\int_{\frac{x^2 m_p^2}{1-z}}^{Q_0^2}\frac{dQ^2}{Q^2}\alpha^2(Q^2)\bigg[\bigg(zP_{\gamma,q}(z)+\frac{2x^2m_p^2}{Q^2}\bigg)F_2(x/z,Q^2) - z^2F_L(x/z,Q^2)\bigg] - \alpha^2(Q_0^2)\bigg(z^2+\ln(1-z)zP_{\gamma,q}(z)-\frac{2x^2m_p^2 z}{Q_0^2}\bigg)F_2(x/z,Q_0^2)\bigg\},$$

- Namely, we:
  - ⋆ Set $\mu_F = Q_0 = 1\,\text{GeV}$ in order to determine photon at input scale and then coupled QED DGLAP above that.
  - ⋆ To achieve this the upper limit of the first integral is modified from original formulation: $Q_0/(1-z) \to Q_0$. Then all contributions with $Q^2 > Q_0^2$ due to DGLAP.
  - ⋆ Second 'matching' term consistently modified. Though note this term is only formally relevant if NLO PI cross sections are used.

$$x\gamma(x,Q_0^2) = \frac{1}{2\pi\alpha(Q_0^2)}\int_x^1 \frac{dz}{z}\Bigg\{\int_{\frac{x^2m_p^2}{1-z}}^{Q_0^2}\frac{dQ^2}{Q^2}\alpha^2(Q^2)\Bigg[\Bigg(zP_{\gamma,q}(z)+\frac{2x^2m_p^2}{Q^2}\Bigg)F_2(x/z,Q^2)$$
$$-z^2F_L(x/z,Q^2)\Bigg] - \alpha^2(Q_0^2)\Bigg(z^2+\ln(1-z)zP_{\gamma,q}(z)-\frac{2x^2m_p^2z}{Q_0^2}\Bigg)F_2(x/z,Q_0^2)\Bigg\}\,,$$

- In brief, as in MMHT14qed our inputs for the SFs closely follow LUXqed:
  - ★ **Elastic** form factors from A1 collaboration data.
  - ★ **Inelastic** SF divided into low scale resonant (CLAS data), low scale continuum (HERMES parameterisation) and high scale continuum (NNLO pQCD) contributions.

A1 Collaboration, Phys. Rev. C90, 015206 (2014)

CLAS, M. Osipenko et al., Phys. Rev. D67, 092001 (2003)

HERMES, A. Airapetian et al., JHEP 05, 126 (2011)

- We in addition include **renormalon** corrections, relevant in low scale region.
- **Uncertainties** due to the above experimental inputs, renormalon corrections + usual eigenvector uncertainties from global fit also included.
- **32** PDF + **6** photon eigenvectors = **38** in total.

MSHT20QED: DGLAP

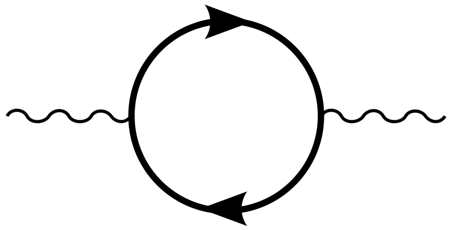
- The PDF DGLAP evolution is also suitably modified to include QED corrections:

$$P_{ij}^{(QED)} = \frac{\alpha}{2\pi} P_{ij}^{(0,1)} + \frac{\alpha\alpha_S}{(2\pi)^2} P_{ij}^{(1,1)} + \left(\frac{\alpha}{2\pi}\right)^2 P_{ij}^{(0,2)} + \ldots$$

up to $O(\alpha\alpha_S, \alpha^2)$

- This is as in MMHT14, but we now include lepton loops to $P_{\gamma\gamma}$. At $O(\alpha)$:

$$P_{\gamma\gamma} \sim \sum_i e_i^2 = N_C \sum_q^{n_F} e_q^2 + \sum_l^{n_L} e_l^2 \,.$$



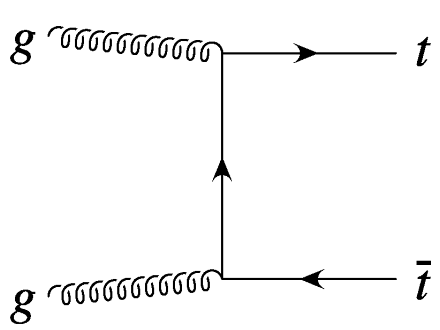
- Second term was omitted in MMHT14qed, as strictly speaking requires lepton PDFs (currently absent).
- However major impact is on photon PDF (~ 2% smaller at LHC), while momentum violation from missing lepton PDFs tiny. Hence we now include!

Backup

PI production: general comments

- In addition include PI channel for processes in fit. For MSHT these are:
  - ⋆ Inclusive jets.
  - ⋆ Top quark pair production.
  - ⋆ DIS.
  - ⋆ Lepton pair production.
- Considering the production of strongly interacting objects (jets, $t\bar{t}$), leading PI contribution simply replaces initial-state gluon with photon, e.g.:

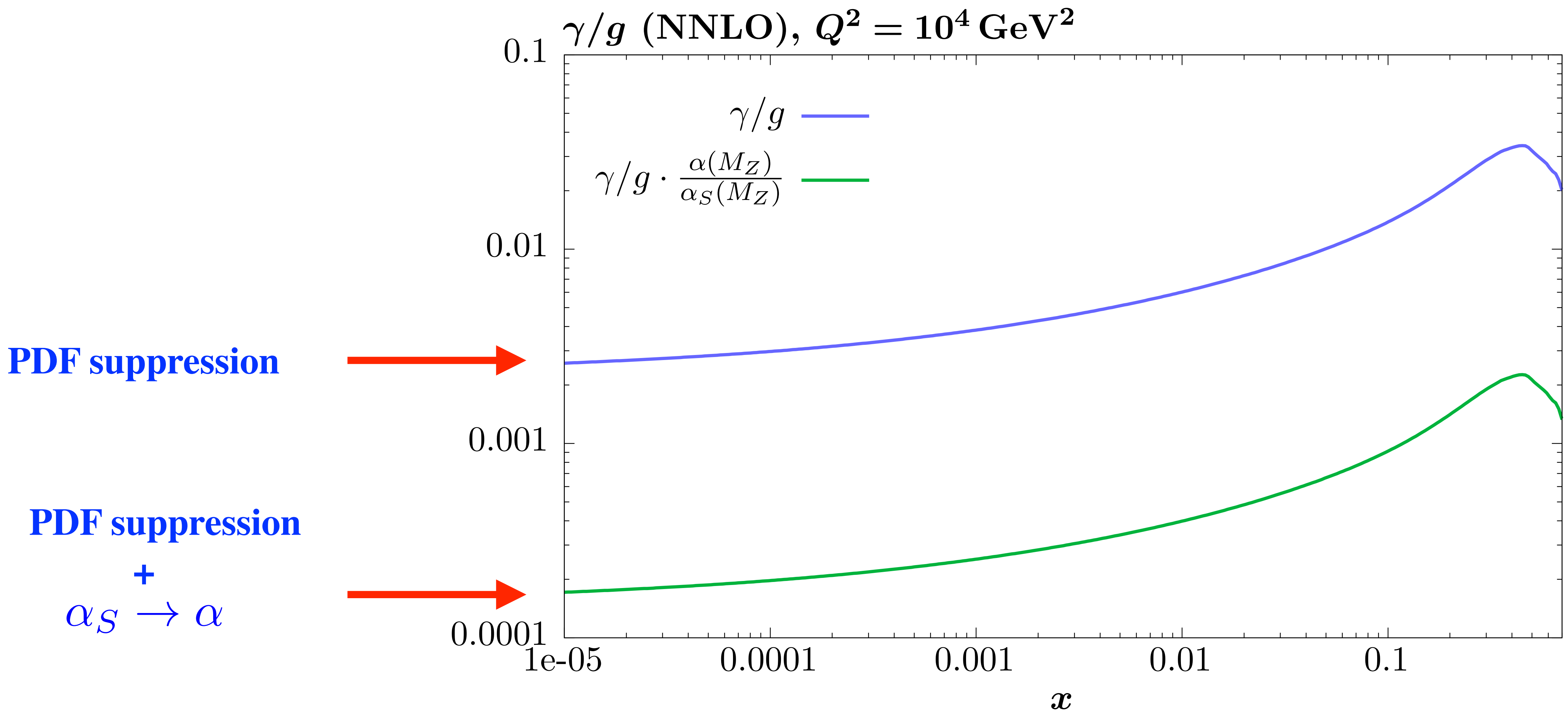
$$gg \to t\bar{t} \quad \longrightarrow \quad \gamma g \to t\bar{t}$$



- At what level do we expect PI corrections to enter?

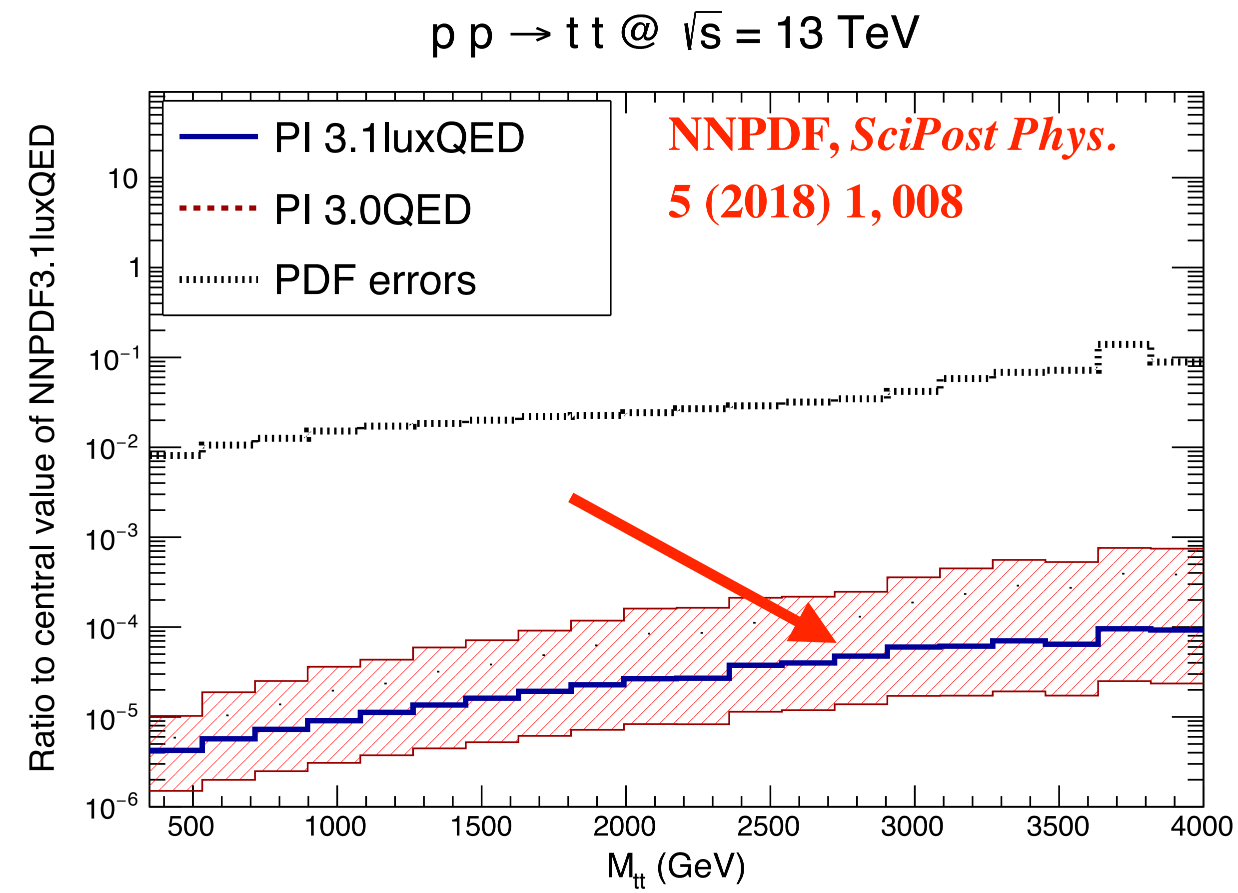
$$gg \to t\bar{t} \quad \longrightarrow \quad \gamma g \to t\bar{t}$$

- Expect from photon vs. gluon PDF, and $\alpha_S \to \alpha$ coupling in hard process



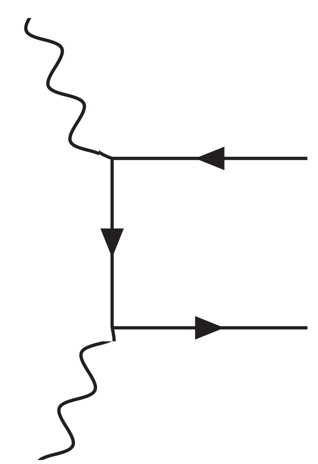
- Combination of both: PI contribution at most at **permille** level, i.e. broadly entering at same level as **N3LO** (not NNLO) QCD.

- Indeed seen in explicit calculation.
- Argument **general** for production of strongly coupled objects.
- Similar argument applies for **DIS**, with further $O(\alpha_S)$ suppression expected.



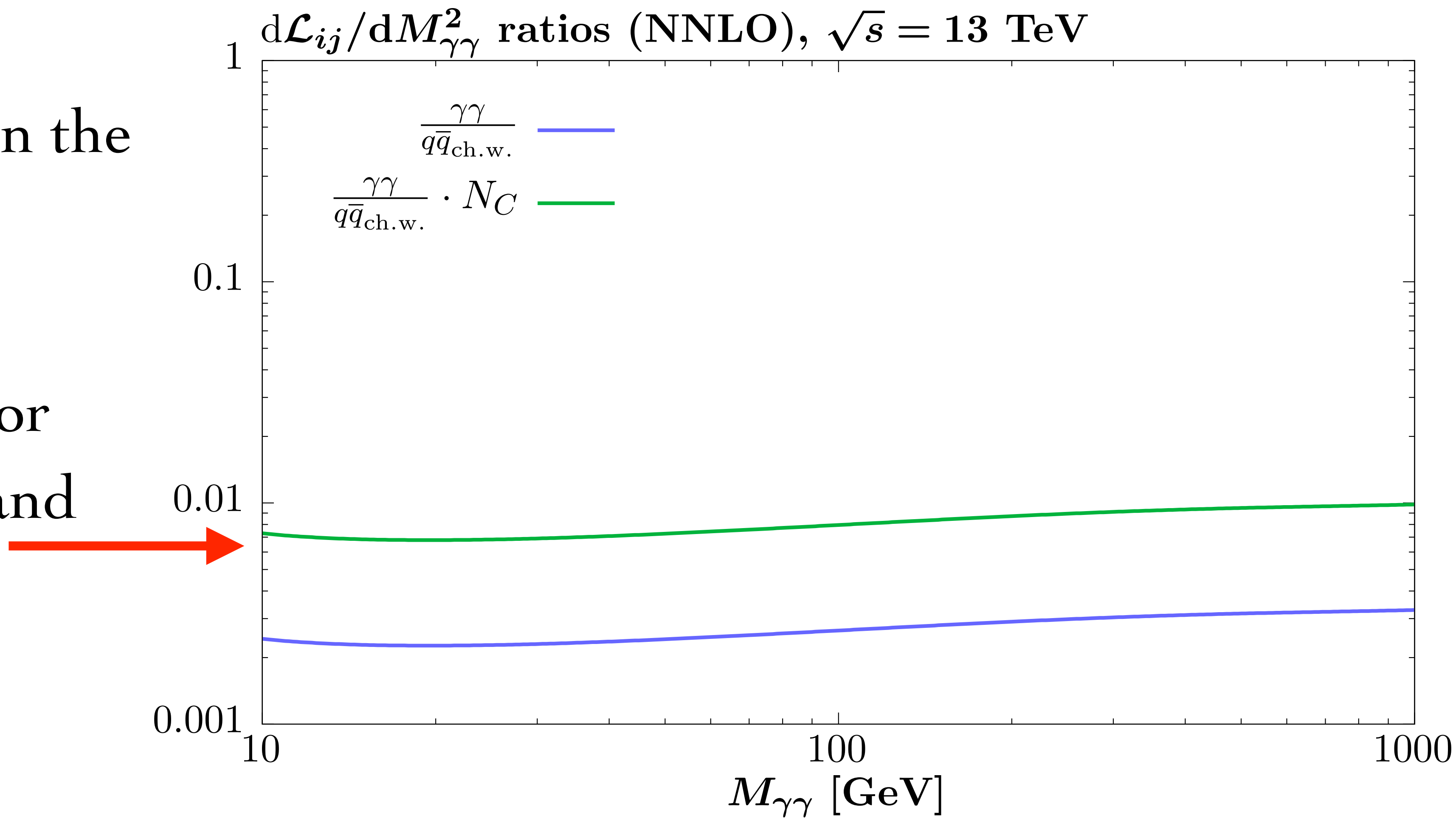
- Now turn to the production of particles with (only) EW couplings. In PDF fits currently limited to **lepton pair** production.
- In this case, the t-channel LO process is:

$$\gamma\gamma \to l^+ l^-$$



- What do we expect here?

- We are now ~ interested in the ratio of the $\gamma\gamma$ to $q\overline{q}$ luminosities.
- More precisely, account for charge weighting of DY and relative colour factor.
- Find ratio of ~1%.



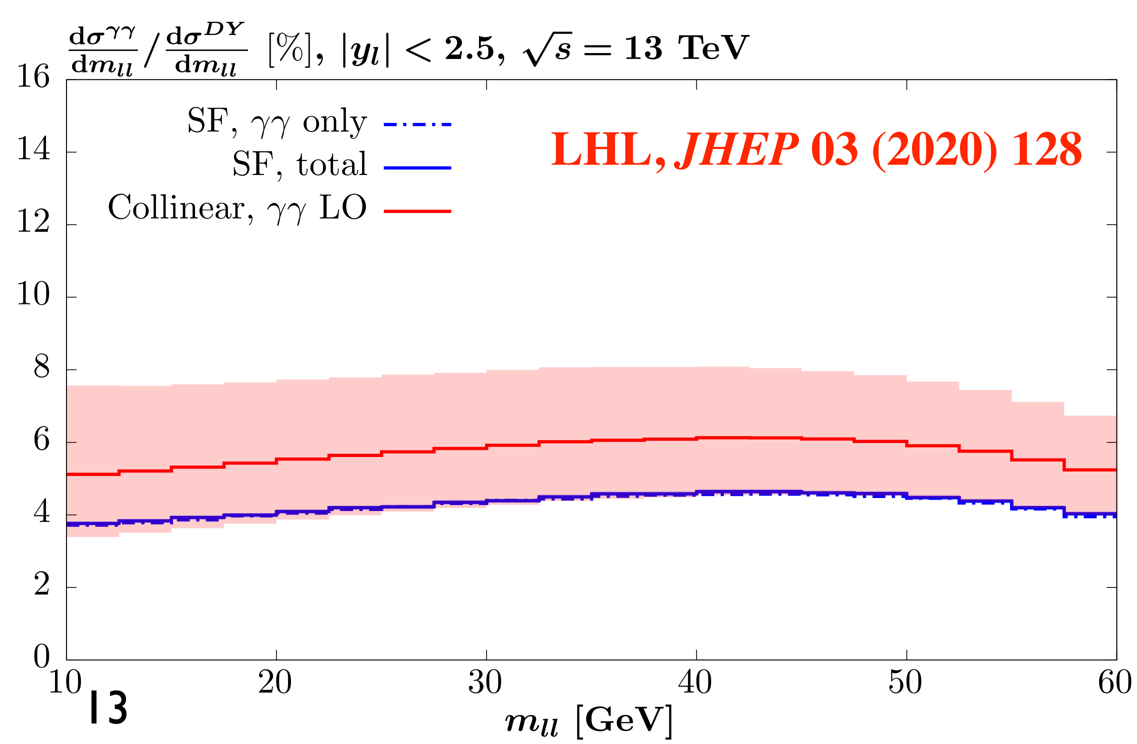
- In addition to this the PI process receives a **t-channel enhancement**, with:

$$\frac{|\mathcal{M}(\gamma\gamma \to l^+l^-)|^2}{|\mathcal{M}(q\overline{q} \to l^+l^-)|^2} \propto \frac{\hat{s}^2}{\hat{u}\hat{t}} \geq 4 \,,$$

$\Rightarrow$ PI will enter at the **~1-10%** level away from the Z peak. Indeed find this.

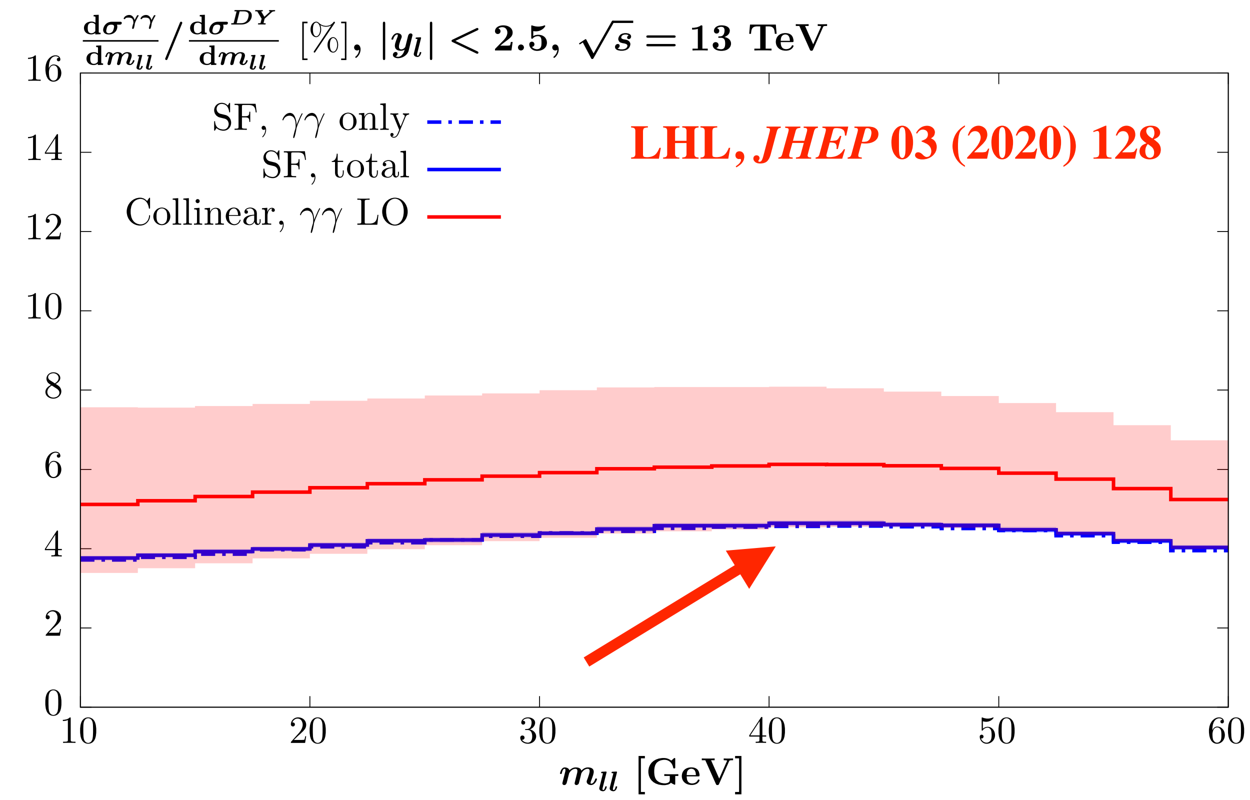
- **On peak**, same argument applies as above wrt the NLO $g \to q\overline{q}$ correction, i.e. **permille** level wrt QCD correction.

- In summary, for **strongly coupled objects** (jets, top quarks):
  - ★ PI production expected to enter at **permille** level.
  - ★ One can (should) include these as part of broader EW corrections, but **K-factor** treatment sufficient at least provided a suitable LUXqed-based photon PDF set used.
  - ★ **MSHT20qed**: include PI (+ EW) corrections using K-factors.
- By far the dominant PI contribution is to **off Z-peak lepton pair** production.
  - ★ Here contribution is ~ 1-10%. This process a (the?) key one for PDF fits to LHC data. Important to get right!
- Photon PDF a la LUX **necessary**.
- But **not sufficient**: LO process has large scale variations (as usual):



- A NLO calculation (at least) therefore necessary here.

- Alternatively, apply '**Structure Function**' calculation directly. Automatically gives **% level precision** in cross section prediction for $\gamma\gamma \to l^+l^-$ off Z-peak.



Backup

- This is applied in MSHT20qed.

- **Final caveat**: for many ATLAS datasets the $\gamma\gamma \to l^+l^-$ has been subtracted in the analysis, so cannot be included (double counting). Often done with outdated set. Clearly not to be encouraged in future!

- In the end only two sets - ATLAS high mass DY, and CMS double differential DY where we should (and do) include PI.

Results - Fit Quality

- Perform a **NNLO QCD** fit to the MSHT20 dataset, following the approach outlined in previous slides.

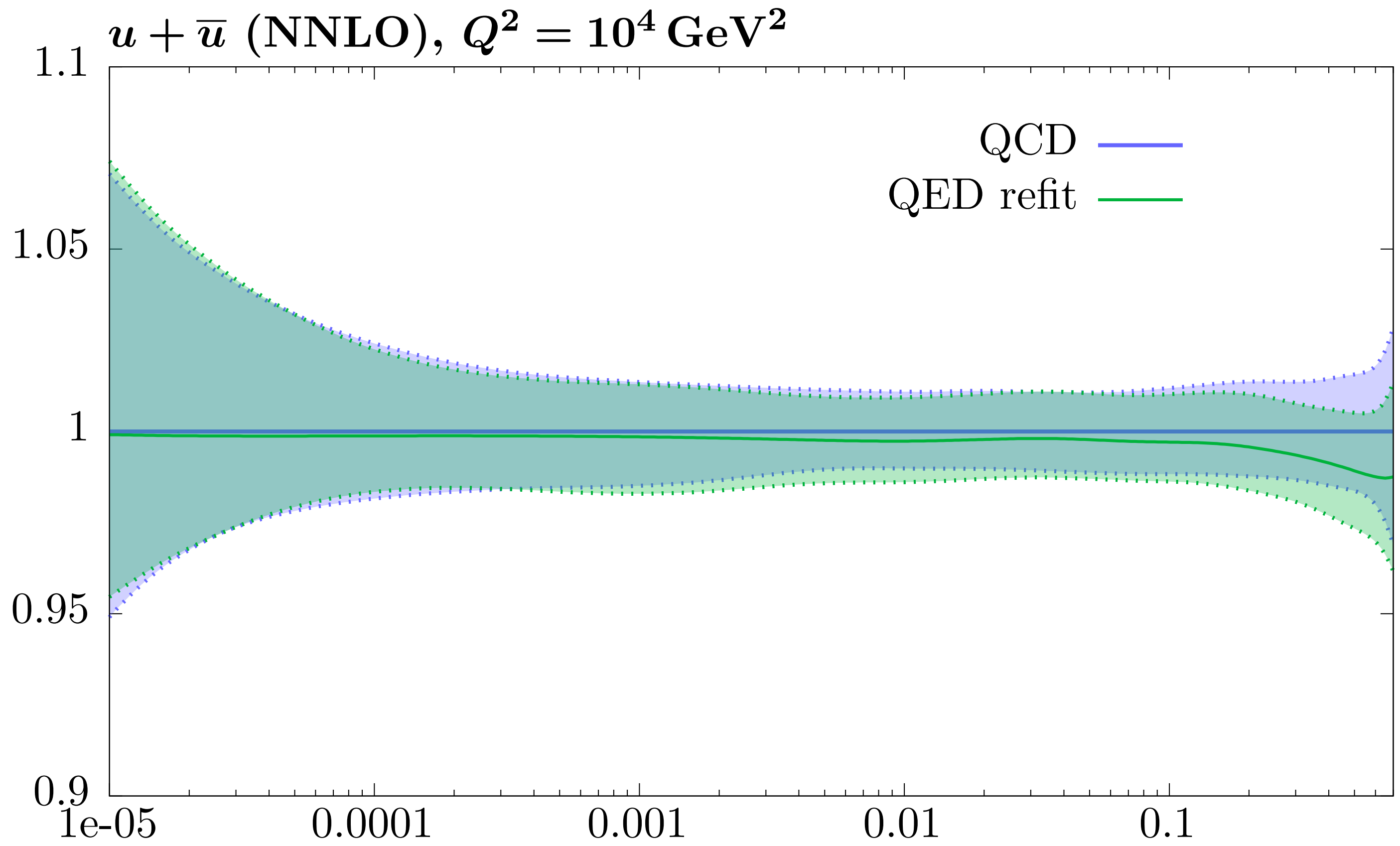
χ^2	QCD	QED	Change
Total	5111.8/4363	5136.1/4363	(+24.3)

- Find a mild **deterioration** in fit quality wrt pure QCD fit. Similar effect seen in MMHT14, though somewhat larger here.
- Broadly spread across datasets, though of note is impact on gluon-sensitive LHC processes, due to impact of QED on gluon:

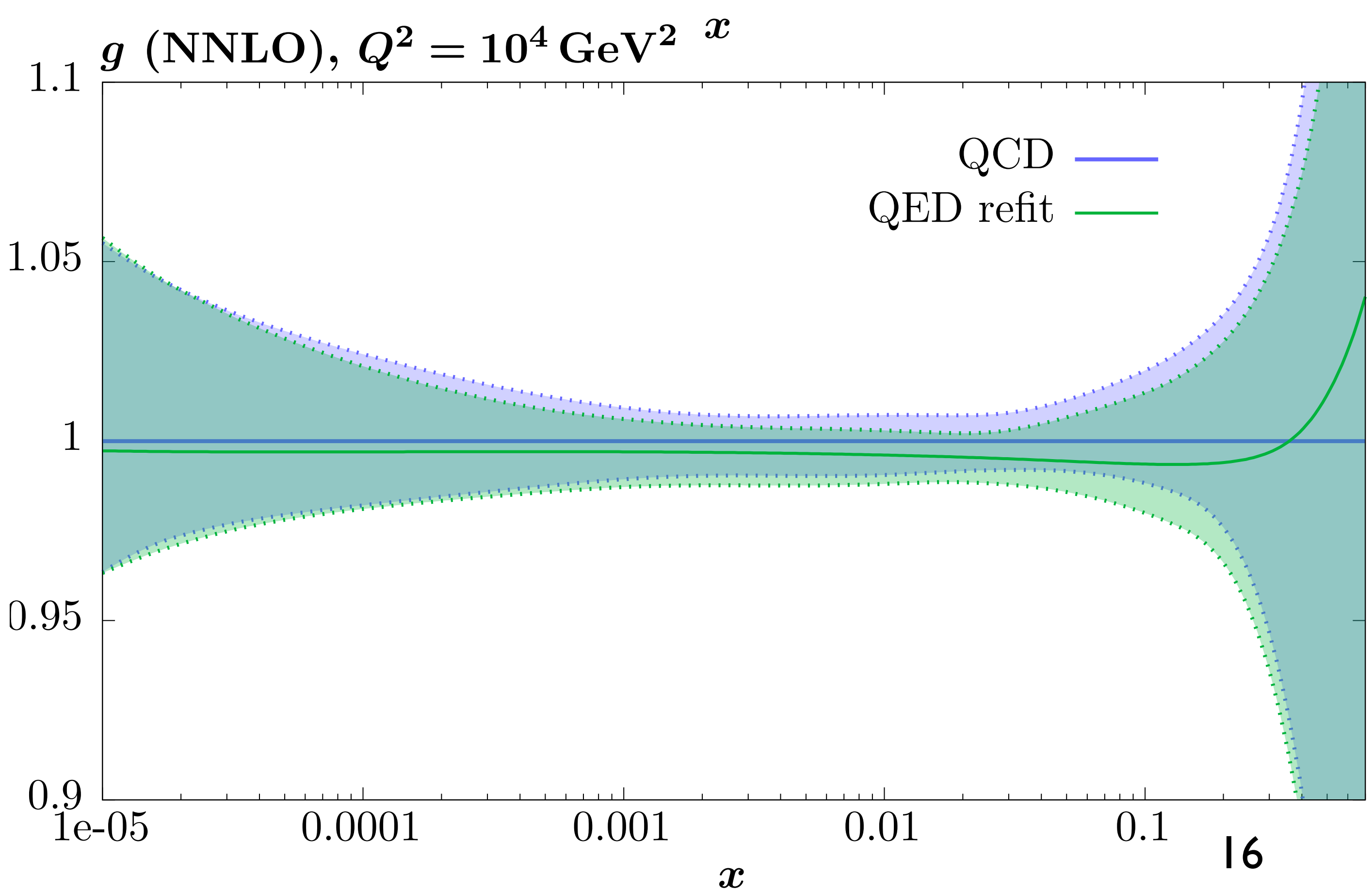
CMS 8 TeV jets [49]	262.4/174	267.9/174	(+5.5)
ATLAS 7 TeV jets [47]	221.3/140	217.8/140	(-3.5)
ATLAS 8 TeV Z p_T [52]	190.8/104	200.8/104	(+10.0)

- Find that including PI improves description of CMS 7 TeV double-differential DY by ~ 10 points. Interestingly default LO collinear calculation does not see this improvement.

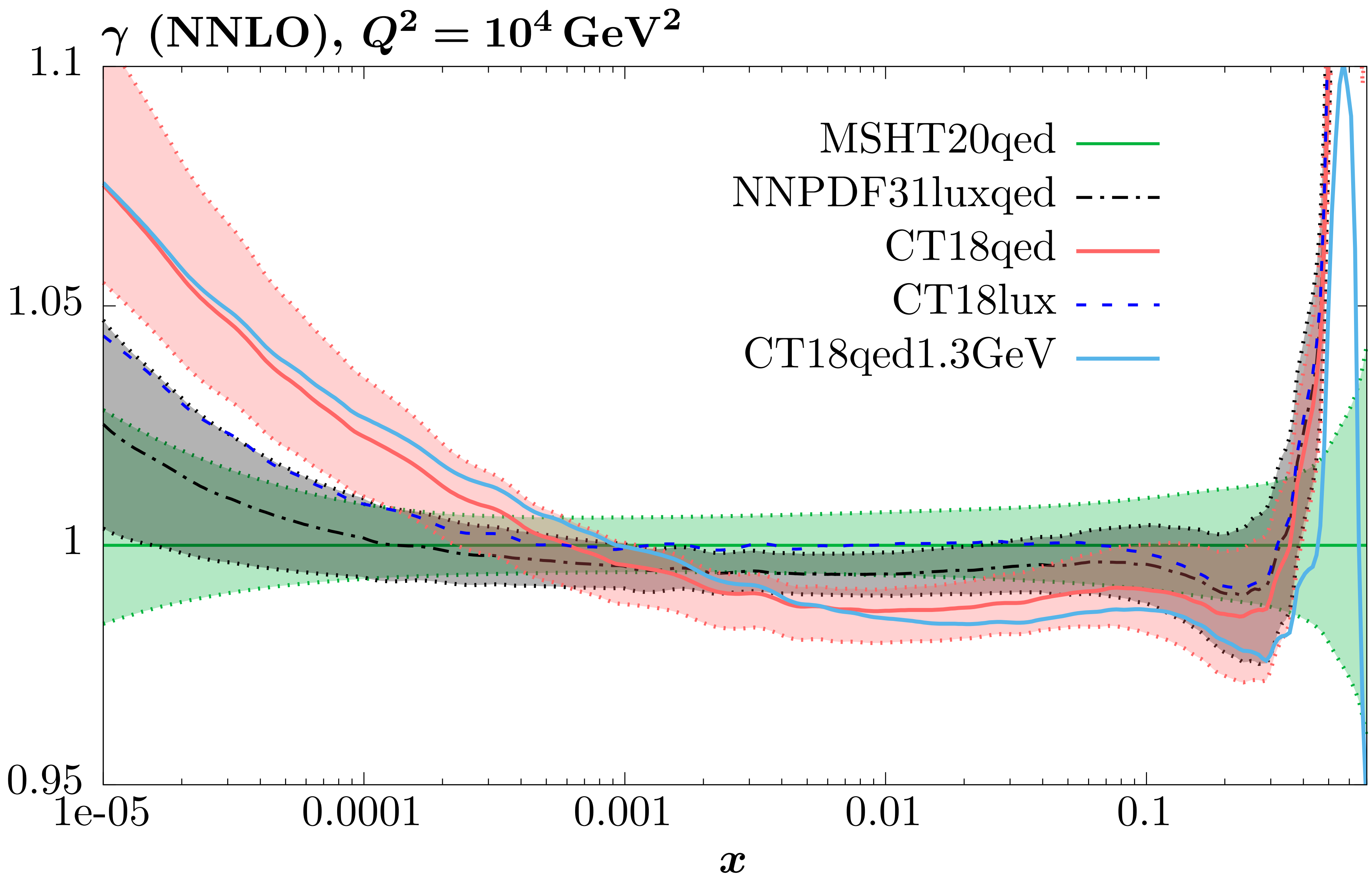
Results - PDFs



- **Reduces** $u + \overline{u}$ at high x due to $q \to q\gamma$.
- u_V (not shown) reduced at high/intermediate x .

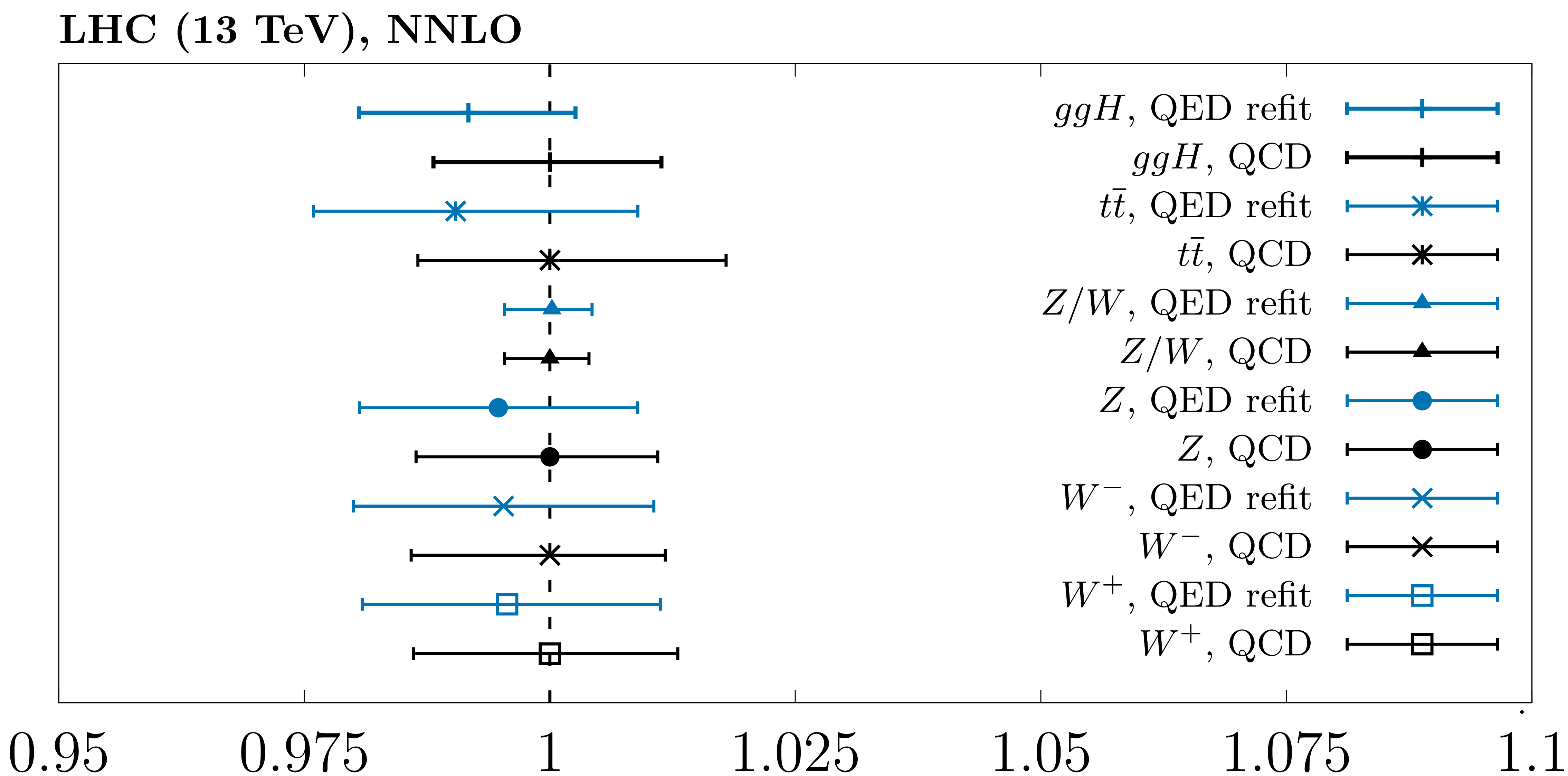


- **Gluon reduced** across wide x region due to momentum sum rule (γ carrying extra momentum).
- Increase at high x also seen by NNPDF, CT. Reason unclear (to us).



- **Broad consistency** between our result and **NNPDF, CT**.
- Enhancement at low x largely due to differing charge weighted quark singlet.
- Enhancement at high x may be due to inherent difference in our low scale approach wrt NNPDF + CT18lux.
- Indeed best agreement seen with **CT18qed1.3GeV**, which is closest to **MSHT20qed** in approach (though not perfect at highest x).

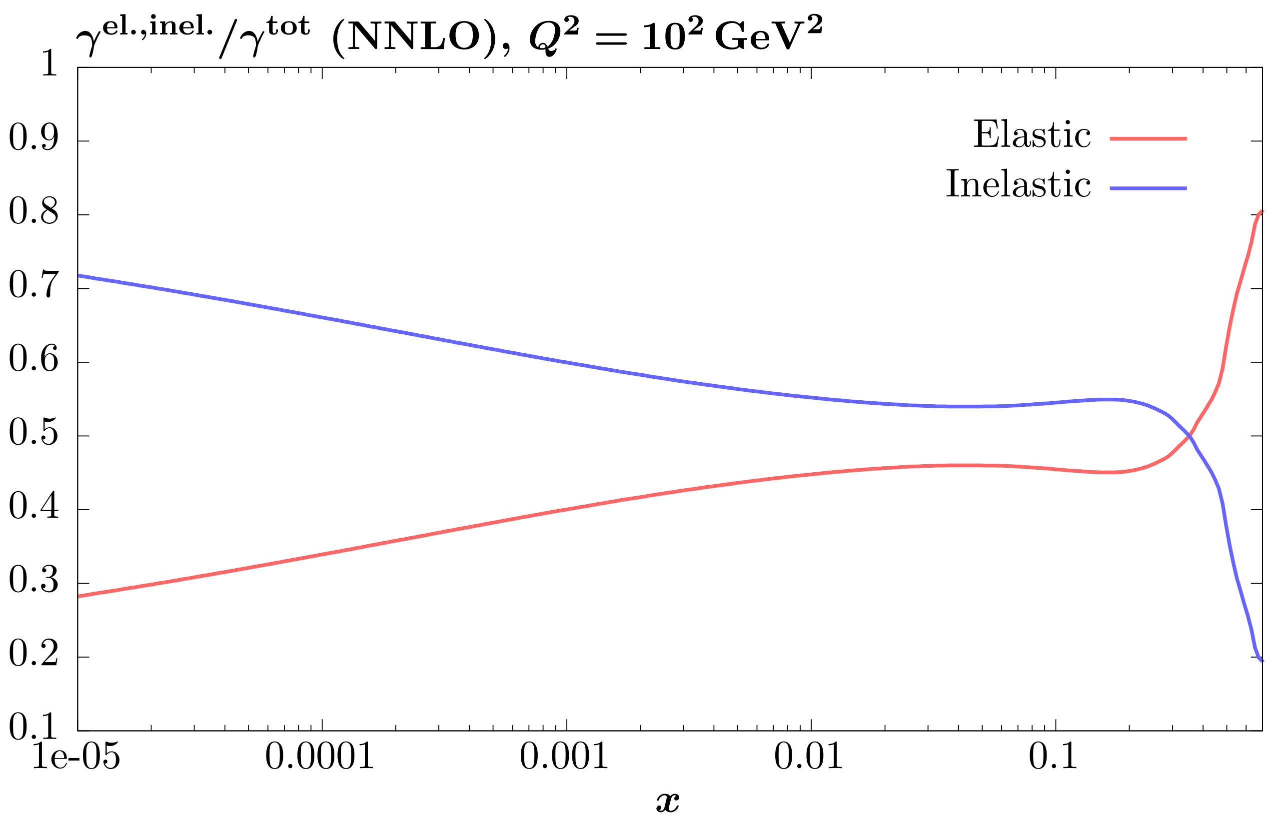
Results - Benchmark Cross Sections

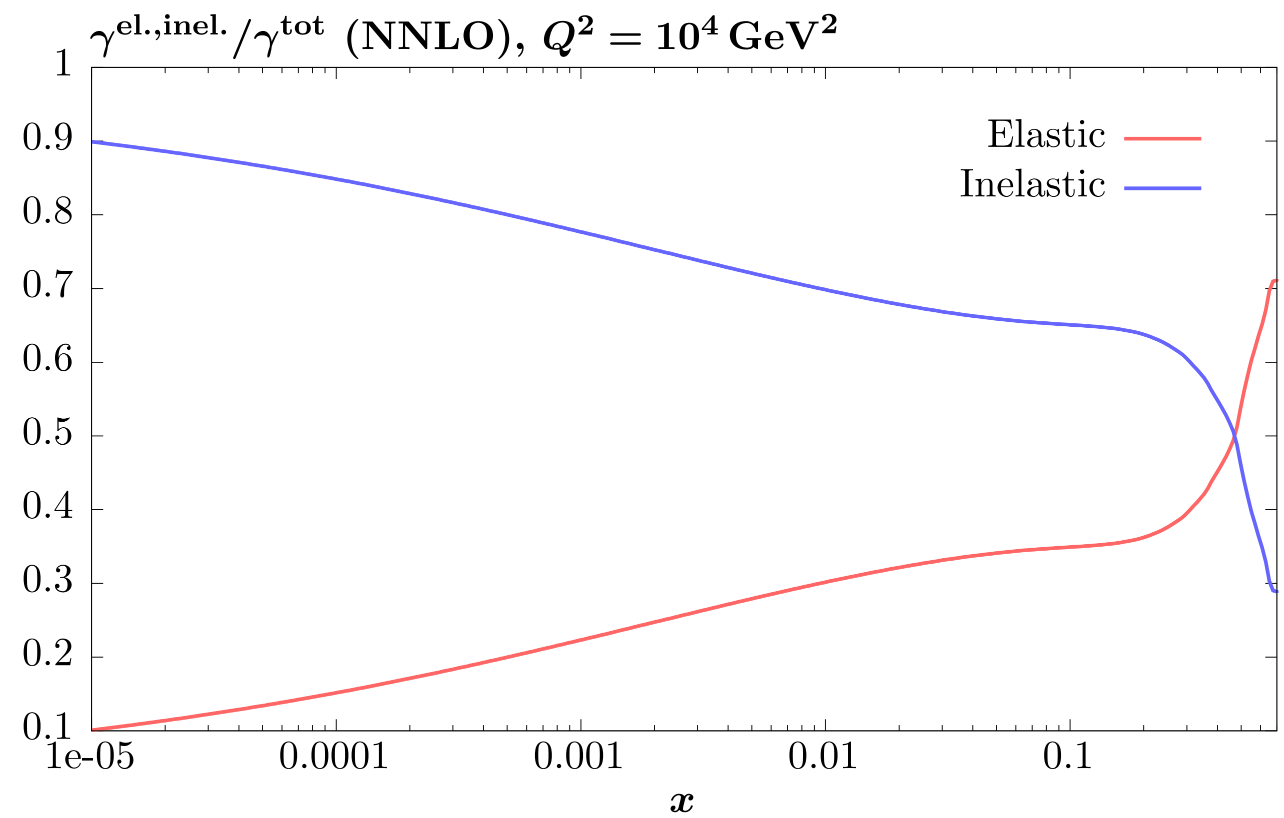


- Gluon-initiated Higgs and $t\bar{t}$ ~ 1% lower. Driven by lower gluon in QED fit.
- Similar impact on W,Z due to lower quark, W/Z ratio stable.

$\Rightarrow$ Impact smaller than but **comparable** to **PDF uncertainties**.

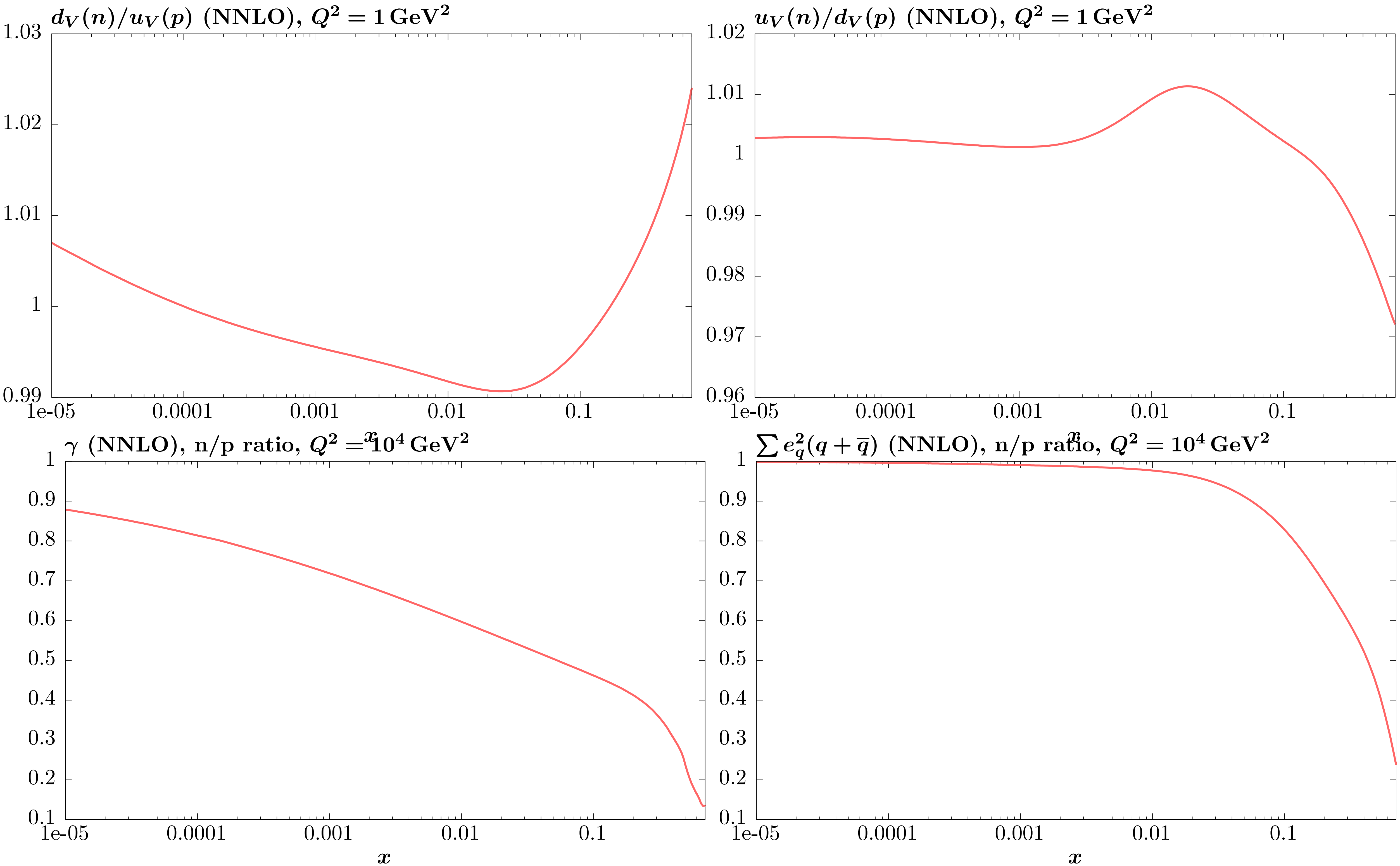
Elastic/Inelastic Breakown





- We also provide photon PDF sets with just the **elastic** and **inelastic** input photon included.
- Can be useful for dedicated studies (though care needed in interpretation).

Neutron PDFs



- As in MMHT14qed we provide a **neutron** PDF set: QED corrections lead to isospin violation and proton-neutron differences.

Summary

★ Have presented new **MSHT20qed** sets:

`MSHT20qed_nnlo`

`MSHT20qed_nnlo_elastic`
`MSHT20qed_nnlo_inelastic`

`MSHT20qed_nnlo_neutron`
`MSHT20qed_nnlo_neutron_elastic`
`MSHT20qed_nnlo_neutron_inelastic`

★ Include QED corrections to DGLAP + precision **photon PDF**.

★ Leads to a mild deterioration in fit quality, but still is more accurate!

★ Impact on PDFs + benchmark cross sections moderate but **not negligible** for precision physics.

★ PI cross sections: general discussion suggests lepton pair production key.

★ NNLO proton set, elastic/inelastic breakdown + neutron sets **available**.

Thank you for listening!

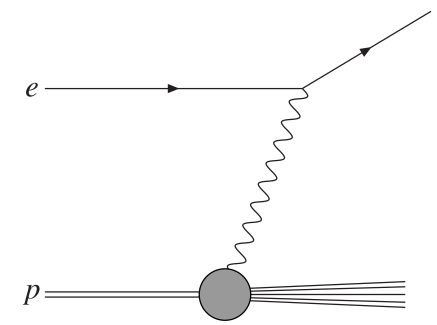
Backup

LHL, *JHEP* 03 (2020) 128

Structure Function Calculation

- Alternative approach: apply 'structure function' calculation directly.

- Structure function parameterises all physics that goes on in $\gamma p \to X$ vertex.



$$\frac{d^2\sigma}{dx\,dy} \propto L_{\alpha\beta}\, W^{\alpha\beta} \; .$$

- Use precisely same argument as for DIS to write:

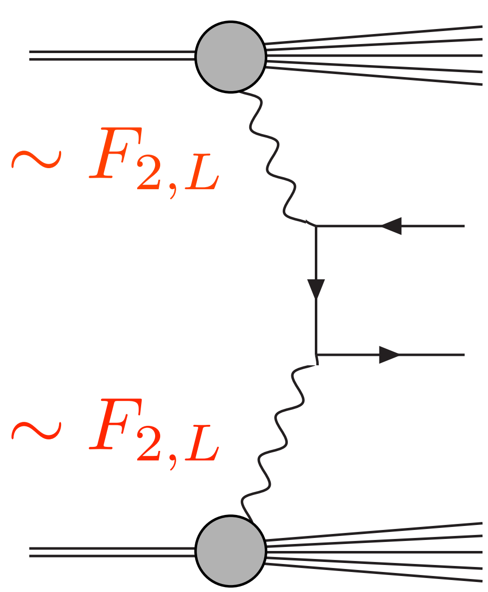
Photon x, Q^2 $\gamma^* p \to X$ $\sim \sigma(\gamma^*\gamma^* \to l^+l^-)$

$$\sigma_{pp} = \frac{1}{2s} \int \mathrm{d}x_1 \mathrm{d}x_2\, \mathrm{d}^2 q_{1_\perp} \mathrm{d}^2 q_{2_\perp} \mathrm{d}\Gamma\, \alpha(Q_1^2)\alpha(Q_2^2) \frac{\rho_1^{\mu\mu'}\,\rho_2^{\nu\nu'}\, M^*_{\mu'\nu'} M_{\mu\nu}}{q_1^2 q_2^2} \delta^{(4)}(q_1 + q_2 - p_X) \; ,$$

- Cross section given in terms of photon density matrices ρ_i :

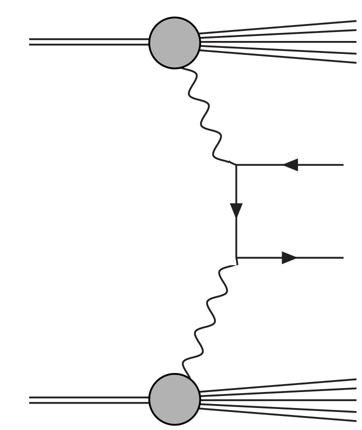
$\rho_1 \sim F_{2,L}$

$\rho_2 \sim F_{2,L}$



Uncertainties/relation to photon PDF

- Uncertainties on SF predicted l^+l^- cross section:
  - ⋆ Experimental uncertainty on $F_i^{\text{el,inel.}}$, HO corrections to $\gamma\gamma \to l^-l^+$, non-factorizable NLO EW/NNLO QCD corrections connecting beams.



- All enter at ~ 1% level or less, and no μ_F dependence

$\longrightarrow$ **Percent level precision** in predicted cross section.

- Relationship to collinear PDF? Based on expanding SF result in $\sim Q^2/M^2$.

$$\rho_1^{\mu\mu'}\rho_2^{\nu\nu'}M^*_{\mu'\nu'}M_{\mu\nu} \quad \sim \quad \gamma(x_1,\mu_F)\gamma(x_2,\mu_F^2)\sigma(\gamma\gamma\to l^+l^-) + O\left(\frac{Q^2}{m_{ll}^2}\right)$$

- At LO $Q^2 = 0$ and no control over non-zero Q^2 behaviour.
- Improves at NLO (+ …) but key point: these corrections are known before they are calculated. Already contained in the SF calculation.

$F_{1,2}^{\text{el}}$