The photon PDF

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Based on
A. Manohar, P. Nason, G. P. Salam, GZ
PRL 117 (2016) 242002 and 1708.01256

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The photon PDF of the proton

- Protons in LHC beams are fast moving charged particles
- For point-like charged particles the electromagnetic field (the distribution of photons) was computed by Fermi, Weizsäcker and Williams in the 1920-1930s
- But protons are not elementary and made up of quarks/gluons

Ausstrahlung bei Stößen sehr schneller Elektronen.

Von **C. F. v. Weizsäcker,** zur Zeit in Kopenhagen.

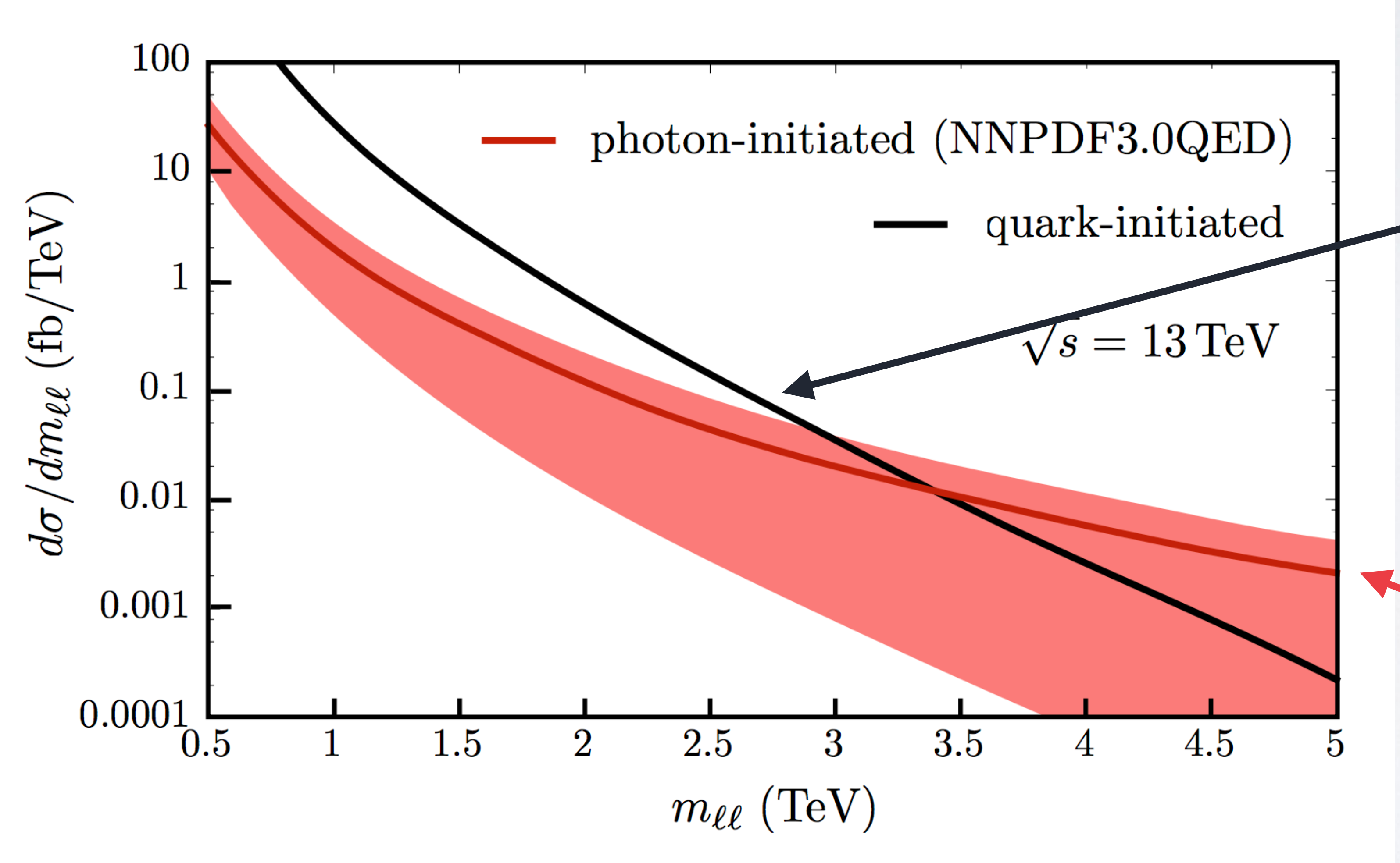
(Eingegangen am 28. Februar 1934.)

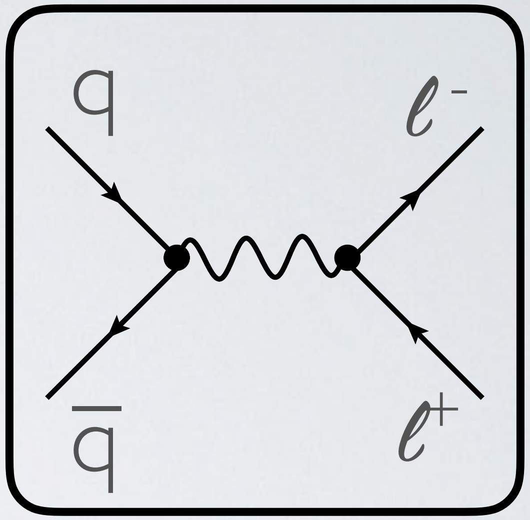
Die vorliegende Arbeit ist die Ausarbeitung der Resultate einiger Diskussionen, die vom September 1933 an im Kopenhagener Institut unter Leitung von Herrn Prof. N. Bohr stattfanden, und zu denen vor allem die Herren G. Beck, W. Heisenberg, L. Landau, E. Teller und E. J. Williams wesentliche Beiträge lieferten. — Ich möchte diese Gelegenheit gern benutzen, um Herrn Prof. Bohr für die schöne und fruchtbare Zeit, die ich in seinem Institut zubringen durfte, meinen herzlichsten Dank auszudrücken.

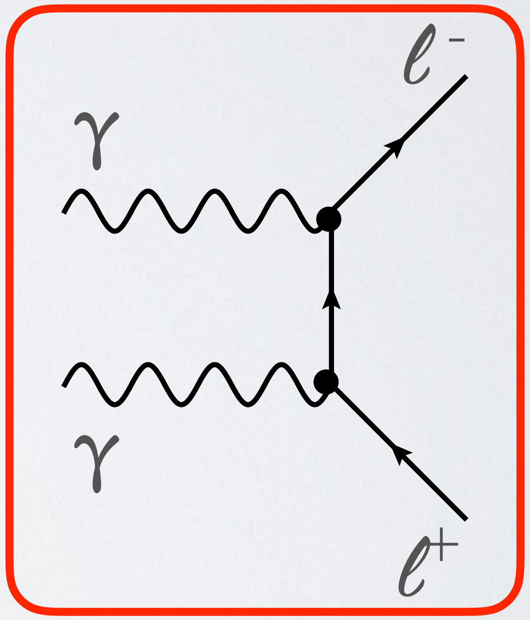
A fundamental question is what is the electromagnetic field associated to fast moving protons. This is the photon parton distribution function (PDF) of the proton

Does the photon PDF matter?

Example: Drell-Yan production







cf. also 1607.04635

Poor knowledge of photon PDF impacts both New Physics searches and precision physics

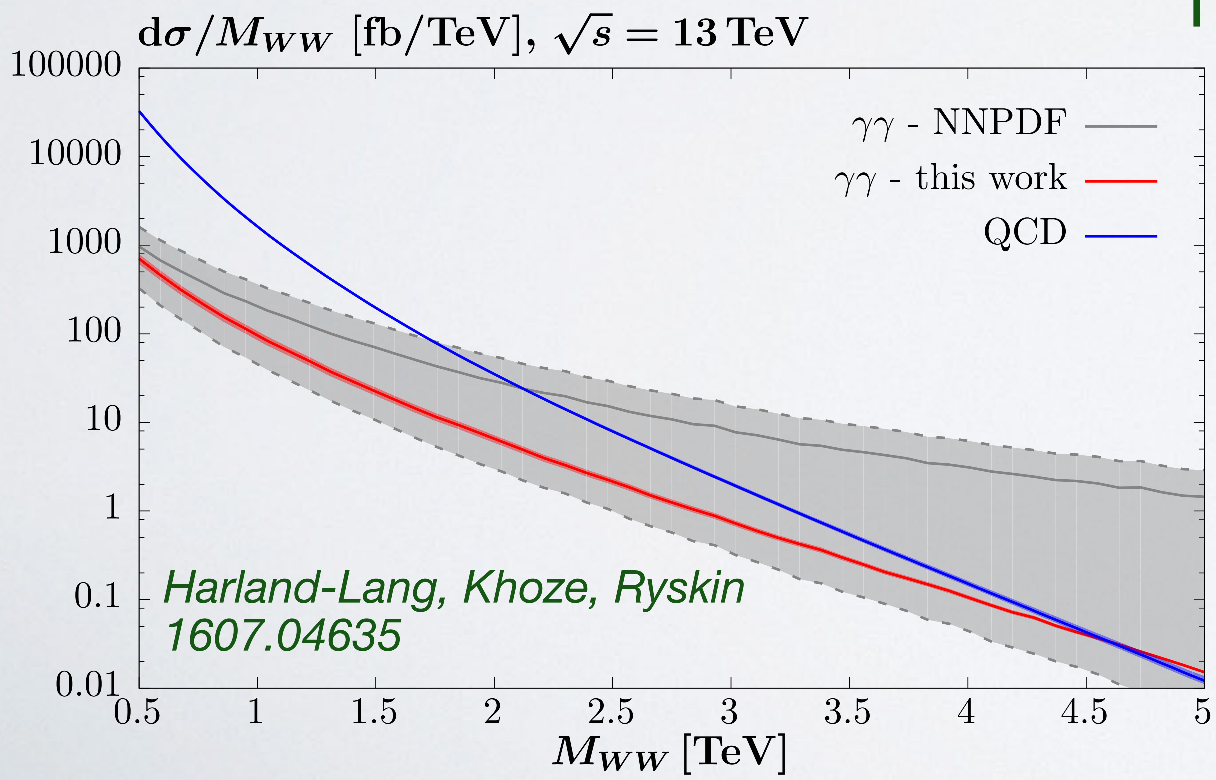
Where else do photons enter?

- Electroweak corrections to almost any process
- Largest uncertainty on VBF Higgs and WH (±few %)
- top production
- VV production

LHC-HXSWG YR4

Pagani, Tsinikos, Zaro, arXiv:1606.01915

1409.1803, 1510.08742, 1603.04874, 1601.07787, 1605.03419, 1604.04080,1607.04635, …

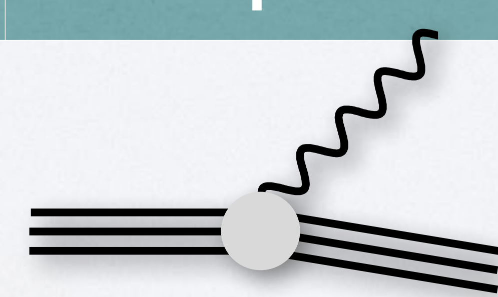


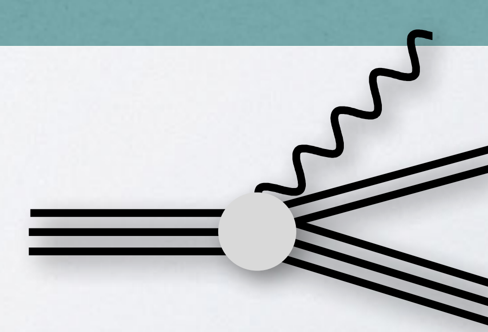
γγ (NNPDF) 100× larger than qq

Approaches to photon PDF

	elastic	inelastic	in LHAPDF?
Gluck Pisano Reya 2002	dipole	model	✘
MRST2004qed	✘	model	✓
NNPDF23qed	no separation; fit to data		✓
CT14qed	✘	model (data-constrained)	✓
CT14qed_inc	dipole	model (data-constrained)	✓
Martin Ryskin 2014	dipole (only electric part)	model	✘
Harland-Lang, Khoze Ryskin 2016	dipole	model	✘

elastic: Budnev, Ginzburg, Meledin, Serbo, 1975

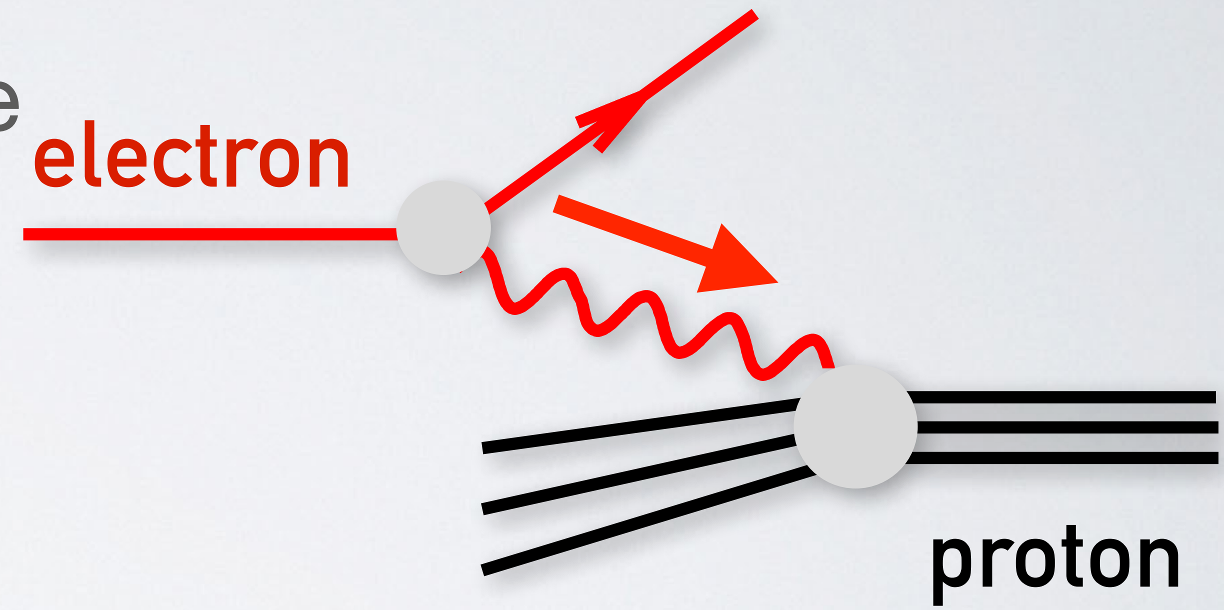




Photon PDF determination

Here I will discuss a model-independent photon PDF determination based on precise DIS data

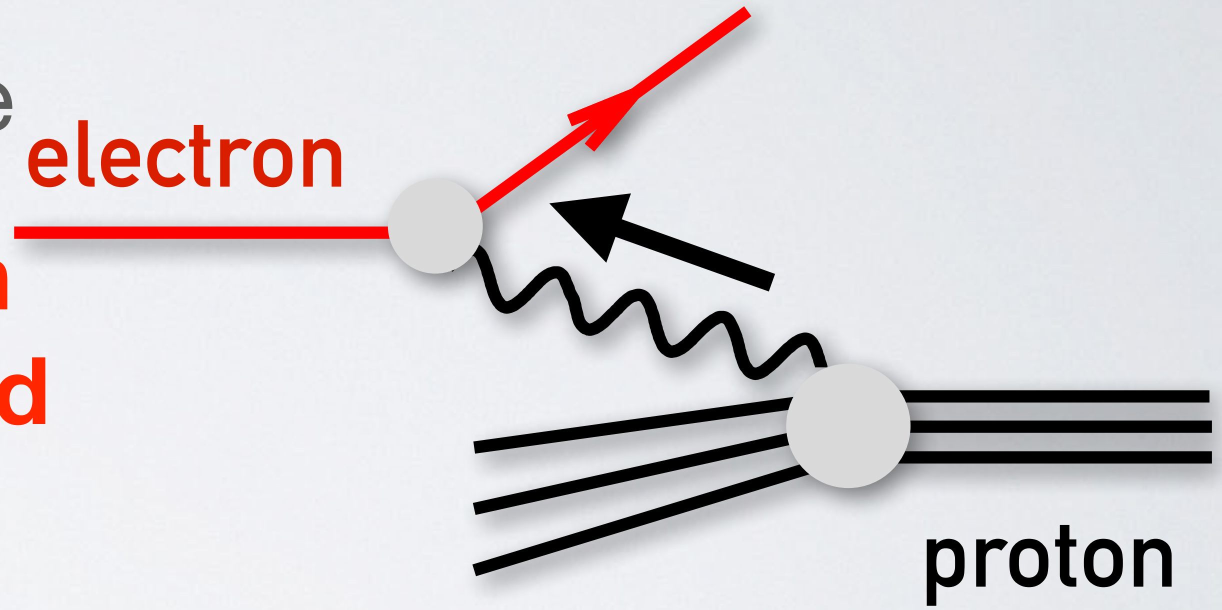
- Usually DIS seen as photons from e^- probing proton structure



Photon PDF determination

Here I will discuss a model-independent photon PDF determination based on precise DIS data

- Usually DIS seen as photons from e^- probing proton structure
- But **can be viewed as electron probing proton's photonic field**
- Everything about unpolarized EM electron–proton interaction encoded in two structure functions $F_2(x,Q^2)$ & $F_L(x,Q^2)$



$$\frac{d\sigma}{dxdQ^2} = \frac{4\pi\alpha^2}{xQ^4}\left(\left(1 - y + \frac{y^2}{2}\left(1 + 2x^2\frac{m_p^2}{Q^2}\right)\right)F_2(x,Q^2) - \frac{y^2}{2}F_L(x,Q^2)\right)$$

Photon PDF determination

Here I will discuss a model-independent photon PDF determination based on precise DIS data

Study a hypothetical ("BSM") heavy-neutral lepton production process and calculate it in two ways

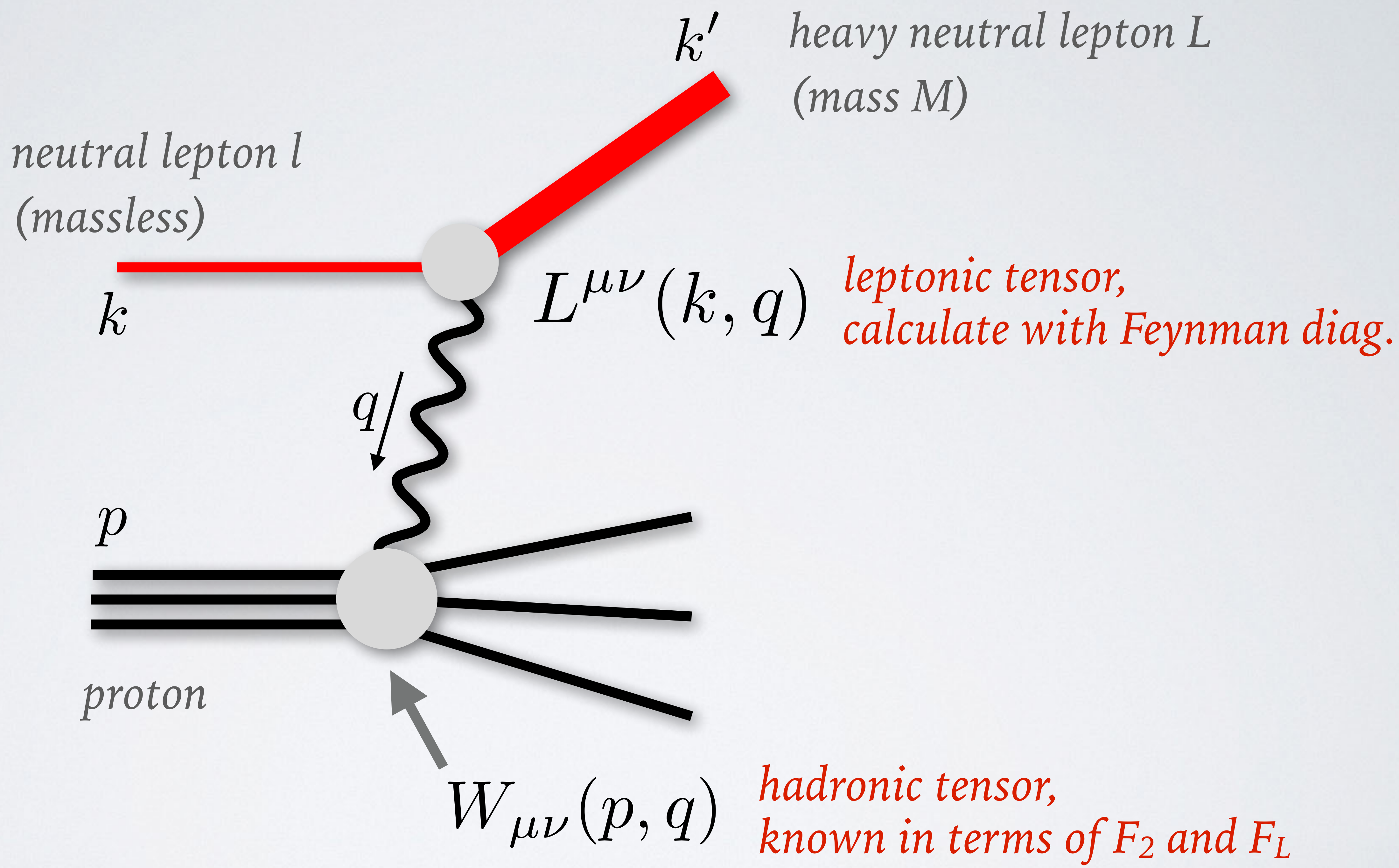
(1) in terms of structure functions (known)
(2) in terms of photon distribution (unknown)

Equivalence gives us photon distribution

Manohar, Nason, GPS & Zanderighi, arXiv:1607.04266
[use of BSM inspired by Drees & Zeppenfeld, PRD39(1989)2536]

STEP 1

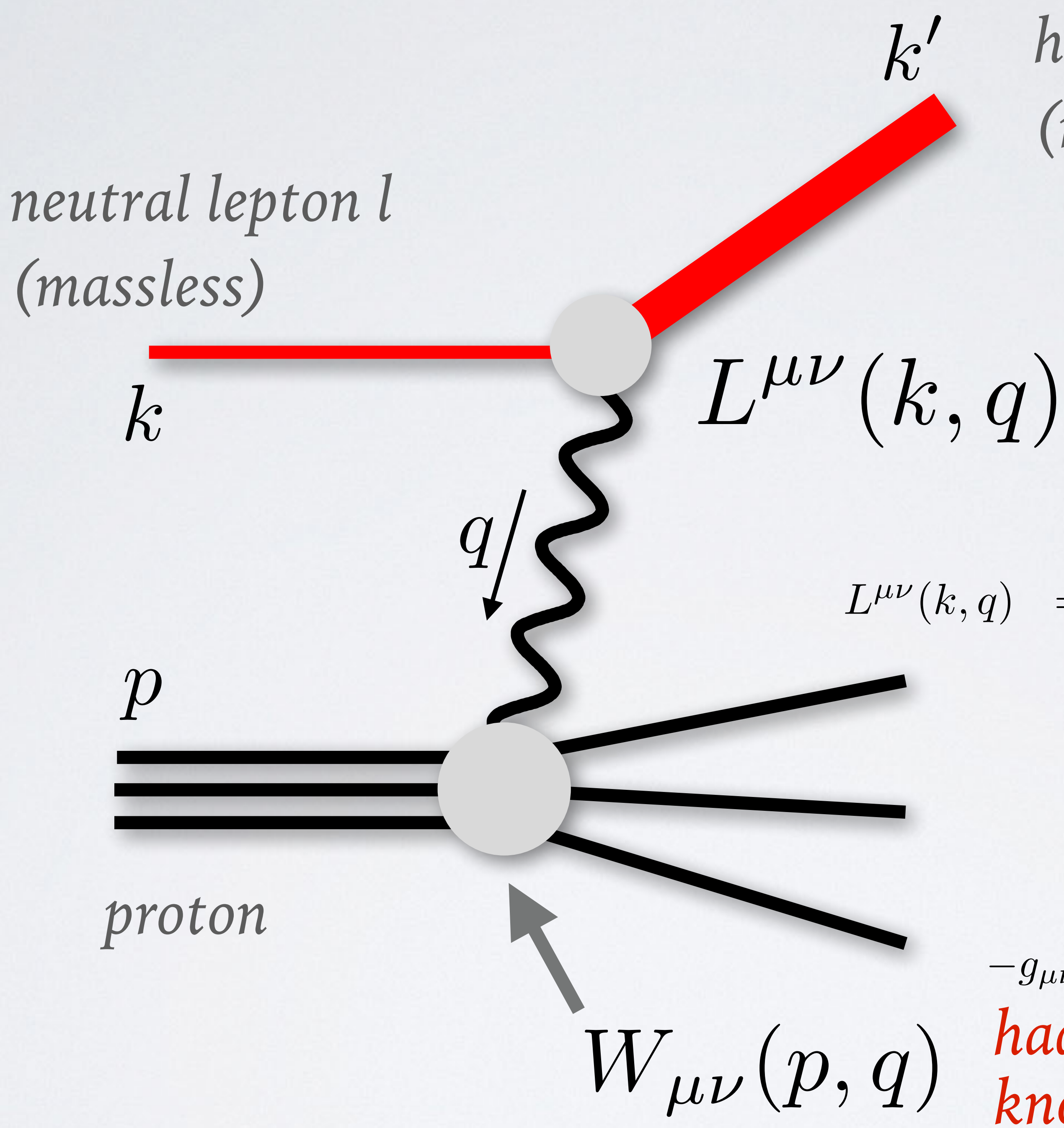
work out a cross section (exact) in terms of F_2 and F_L struct. fns.



$$\sigma = \frac{1}{4p\cdot k}\int \frac{d^4q}{(2\pi)^4 q^4} e_{\rm ph}^2(q^2)\left[4\pi W_{\mu\nu}\,L^{\mu\nu}(k,q)\right] \times 2\pi\delta((k-q)^2 - M^2)$$

STEP 1

work out a cross section (exact) in terms of F_2 and F_L struct. fns.



leptonic tensor,
calculate with Feynman diag.

$$\mathcal{L}_{\text{int}} = (e/\Lambda)\overline{L}\,\sigma^{\mu\nu}F_{\mu\nu}\,l$$

$$L^{\mu\nu}(k,q) \quad = \tfrac{1}{2}(e_{\text{ph}}^2(q^2)/\Lambda^2)\text{Tr}\left(\not{k}'\,[\not{q},\gamma^\mu]\,(\not{k}'+M)\,[\gamma^\nu,\not{q}]\right)$$

$$Q^2 = -q^2$$

$$x_{\text{Bj}} = \frac{Q^2}{2p.q}$$

$$-g_{\mu\nu}F_1(x_{\text{Bj}},Q^2) + \frac{p_\mu p_\nu}{p.q}F_2(x_{\text{Bj}},Q^2) + \cdots$$

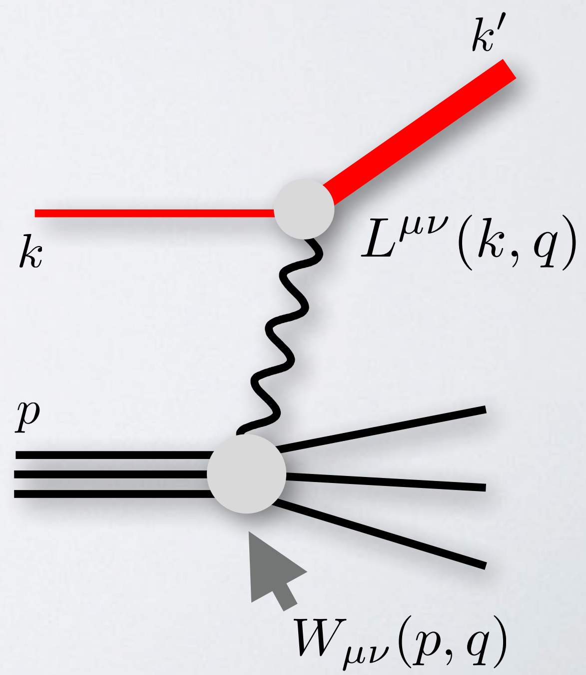
hadronic tensor,
known in terms of F_2 and F_L

$$\sigma = \frac{1}{4p\cdot k}\int \frac{d^4q}{(2\pi)^4 q^4} e_{\text{ph}}^2(q^2)\left[4\pi W_{\mu\nu}\,L^{\mu\nu}(k,q)\right] \times 2\pi\delta((k-q)^2 - M^2)$$

Cross-section using F_2 and F_L

- Lagrangian of interaction: (magnetic moment coupling) $\mathcal{L}_{\rm int} = (e/\Lambda)\overline{L}\,\sigma^{\mu\nu} F_{\mu\nu}\, l$
- Using neutral leptons and taking Λ large, ensures that only single-photon exchange is relevant
- **Answer is exact up to 1/Λ corrections**

$$\sigma = \frac{c_0}{2\pi}\int_x^{1-\frac{2xm_p}{M}} \frac{dz}{z}\int_{Q^2_{\rm min}}^{Q^2_{\rm max}} \frac{dQ^2}{Q^2}\alpha^2_{\rm ph}(-Q^2)\Bigg[\Bigg(2-2z+z^2 + \frac{2x^2m_p^2}{Q^2} + \frac{z^2Q^2}{M^2} - \frac{2zQ^2}{M^2} - \frac{2x^2Q^2m_p^2}{M^4}\Bigg)F_2(x/z,Q^2) + \left(-z^2 - \frac{z^2Q^2}{2M^2} + \frac{z^2Q^4}{2M^4}\right)F_L(x/z,Q^2)\Bigg]$$

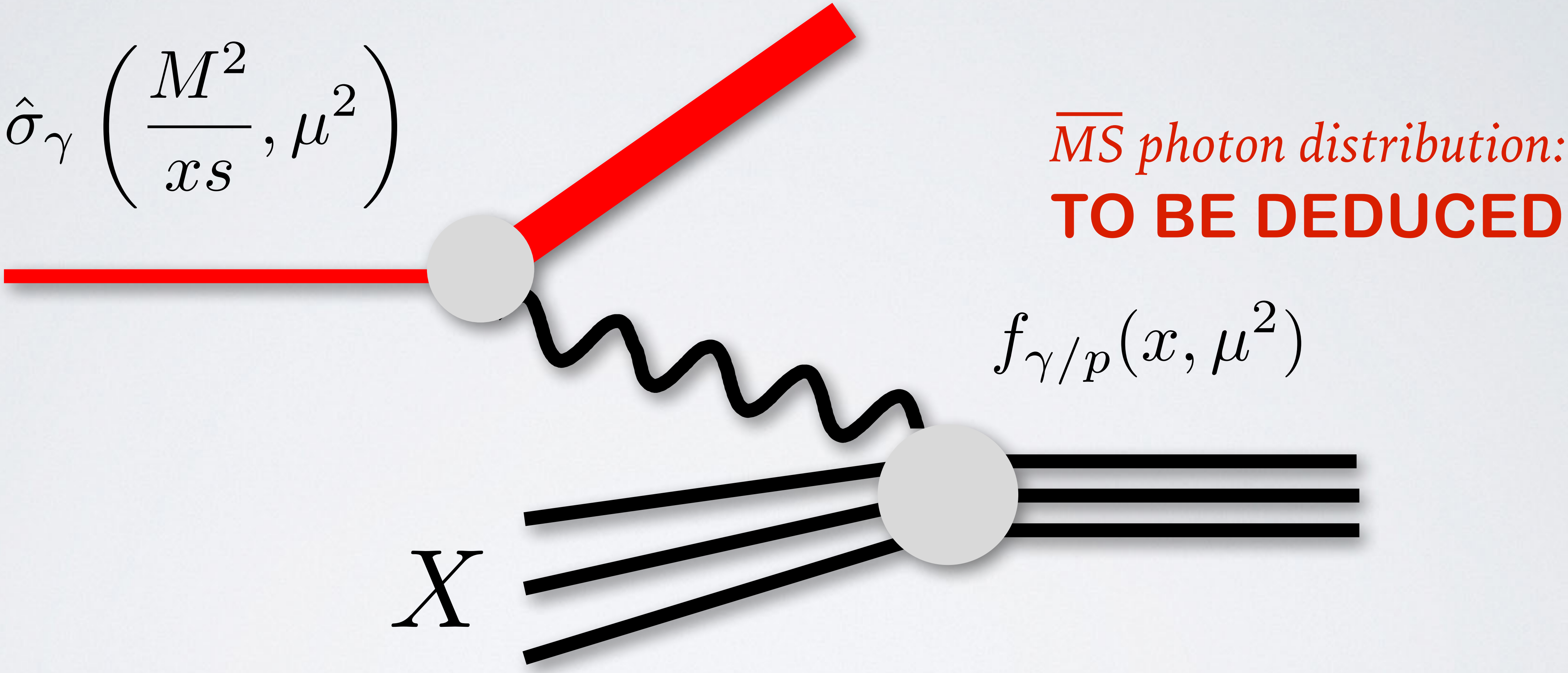


$$c_0 = 16\pi^2/\Lambda^2$$

STEP 2

work out same cross section in terms of a photon distribution

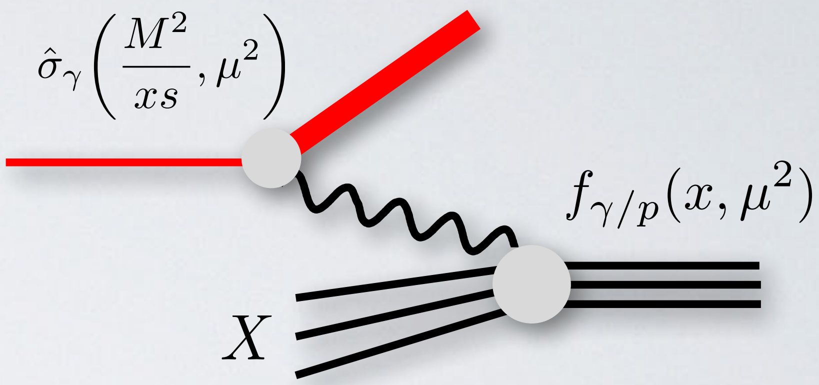
hard-scattering cross section
calculate in collinear factorisation



$$\sigma = c_0 \sum_a \int \frac{dx}{x}\, \hat{\sigma}_a\left(\frac{M^2}{xs}, \mu^2\right) x f_{a/p}\left(x, \mu^2\right)$$

Cross-section using PDFs

- ➤ Hard cross section driven by the photon distribution at LO



$$\hat{\sigma}_a(z, \mu^2) = \alpha(\mu^2)\delta(1-z)\delta_{a\gamma} + \frac{\alpha^2(\mu^2)}{2\pi}\left[-2 + 3z + zp_{\gamma q}(z)\ln\frac{M^2(1-z)^2}{z\mu^2}\right]\sum_{i\in\{q,\bar{q}\}} e_i^2\delta_{ai} + \ldots$$

- ➤ Quarks and gluons come in at higher orders

Accuracy

- Take quark and gluon distributions ~ O(1)
- α is QED coupling, α_s is QCD coupling, $L = \ln \mu^2/m_p^2$
  - Take $L \sim 1/\alpha_s$, so all $(\alpha_s L)^n \sim 1$
  - Think of $\alpha \sim (\alpha_s)^2$
- To first order, photon distribution ~ (αL)
- We aim to control all terms:
  - $\alpha L\, (\alpha_s L)^n$ [LO]
  - $\alpha_s\, \alpha L\, (\alpha_s L)^n \equiv \alpha(\alpha_s L)^n$ [NLO — extra α_s or $1/L$]
  - $\alpha^2 L^2\, (\alpha_s L)^n$ [NLO — extra $\alpha\, L$]
- Matching done at large M^2 and μ^2 to eliminate higher twists

STEP 3

equate them to deduce the photon distribution (LUXqed)

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

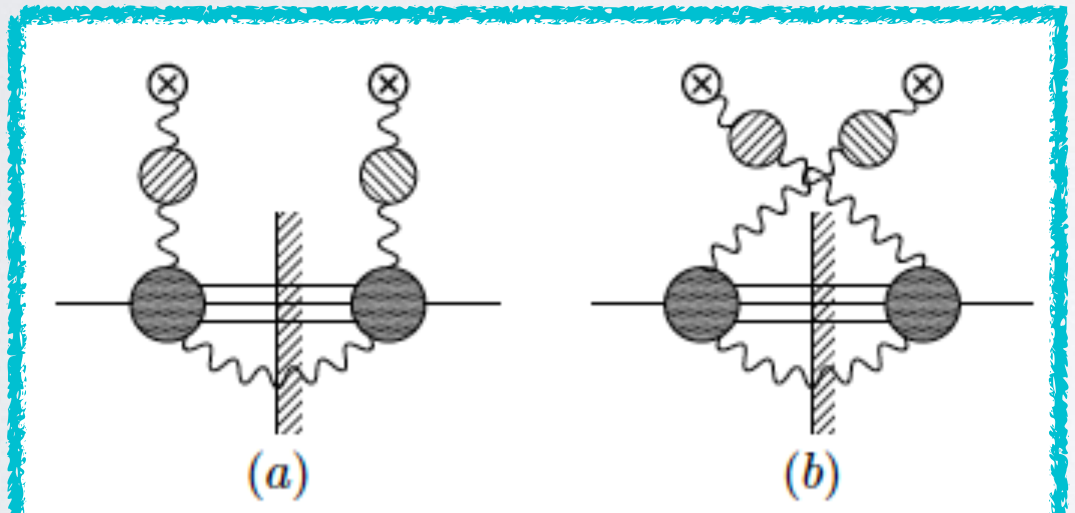
Result is in the MSbar scheme & reproduces the $O(\alpha\alpha_s)$ QED splitting functions of Florian, Rodrigo, Sborlini [2015]

NB: obtain same result regardless of hard probe

Alternative approach

It is also possible to compute the photon PDF starting from its definition in terms of operators: matrix element on the proton state of operators that count the number of photons of a given momentum fraction.

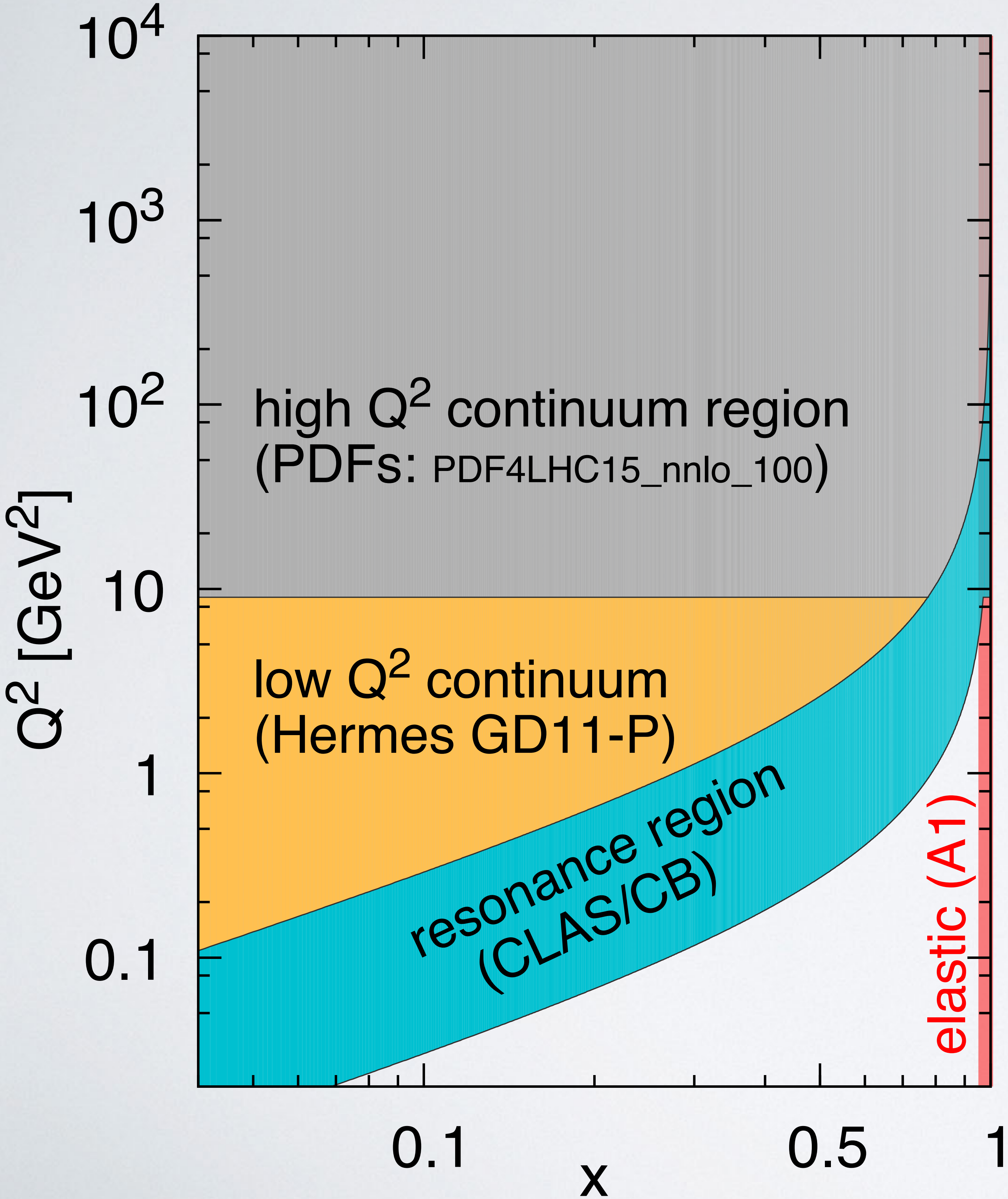
$$f_\gamma(x,\mu^2) = -\frac{1}{4\pi x p^+}\int_{-\infty}^{\infty} dw e^{-ixwp^+} \langle p|F^{n\lambda}(wn)F^{n}{}_{\lambda}(0) + F^{n\lambda}(0)F^{n}{}_{\lambda}(wn)|p\rangle_c$$



Key observation: the interaction of the photon with the proton is exactly the definition of the hadronic tensor

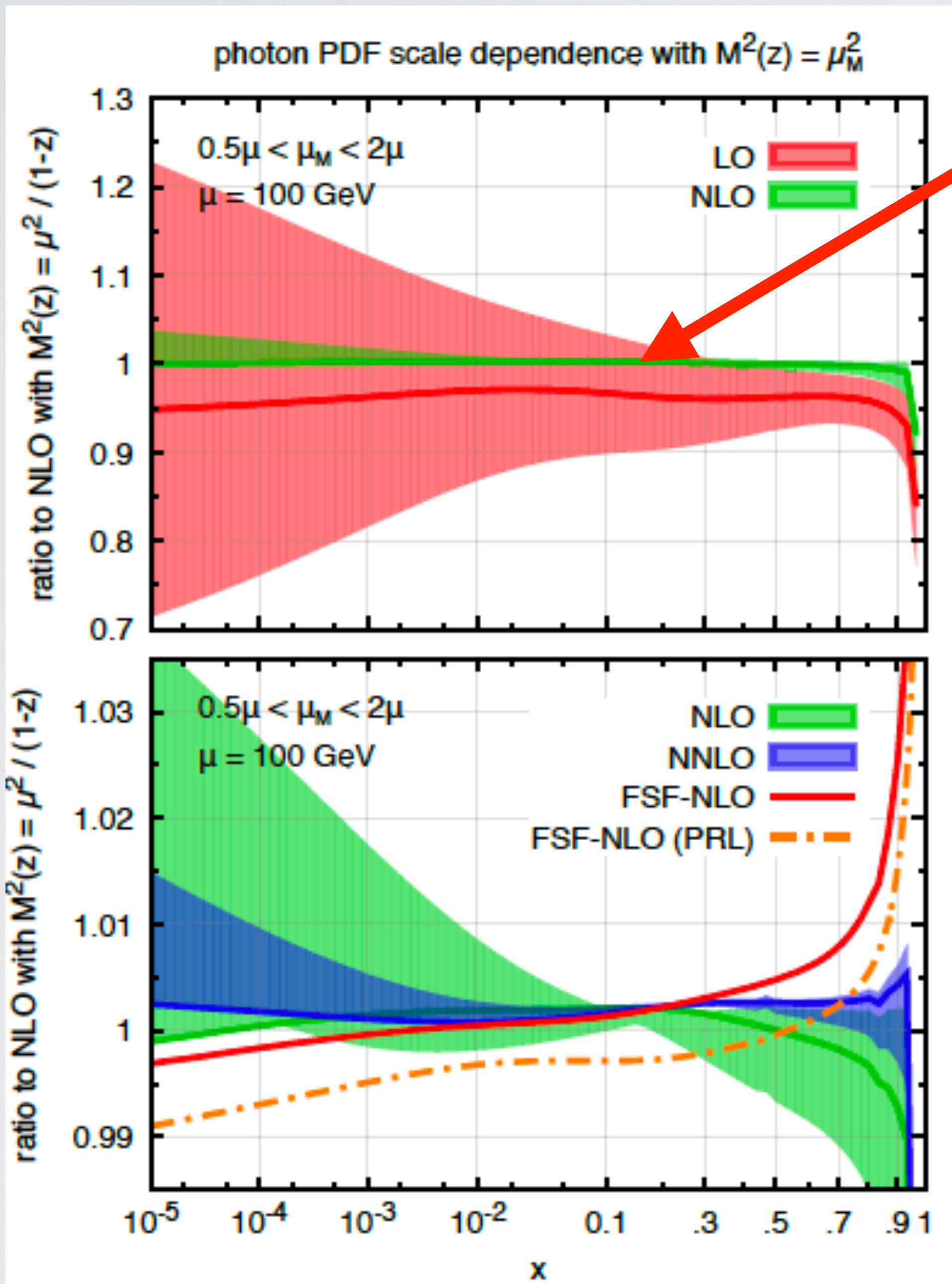
- In fact, it is simpler to compute higher-order QCD corrections starting from this approach
- QCD corrections to one order higher (NNLO) recently computed in 1708.01256

Data input



- *x*, Q^2 plane naturally breaks up into regions with different physical behaviours and data sources
- We don't use F_2 and F_L data directly, but rather various fits to data

Impact of NNLO

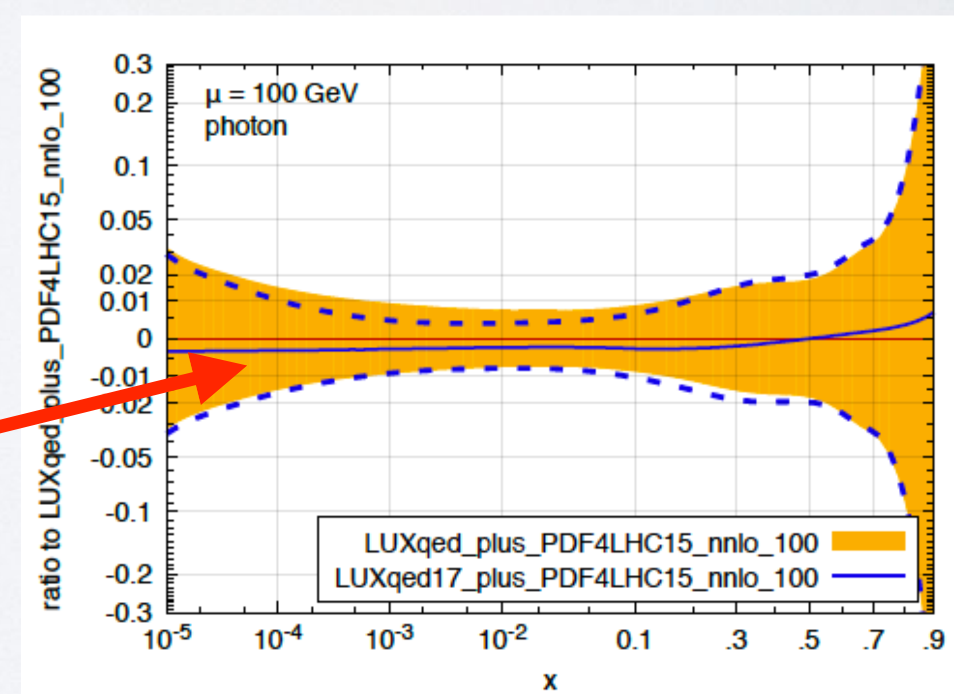


Considerable reductions of scale uncertainty already at NLO

(Previous estimates of the photon PDF were at best LO accurate…)

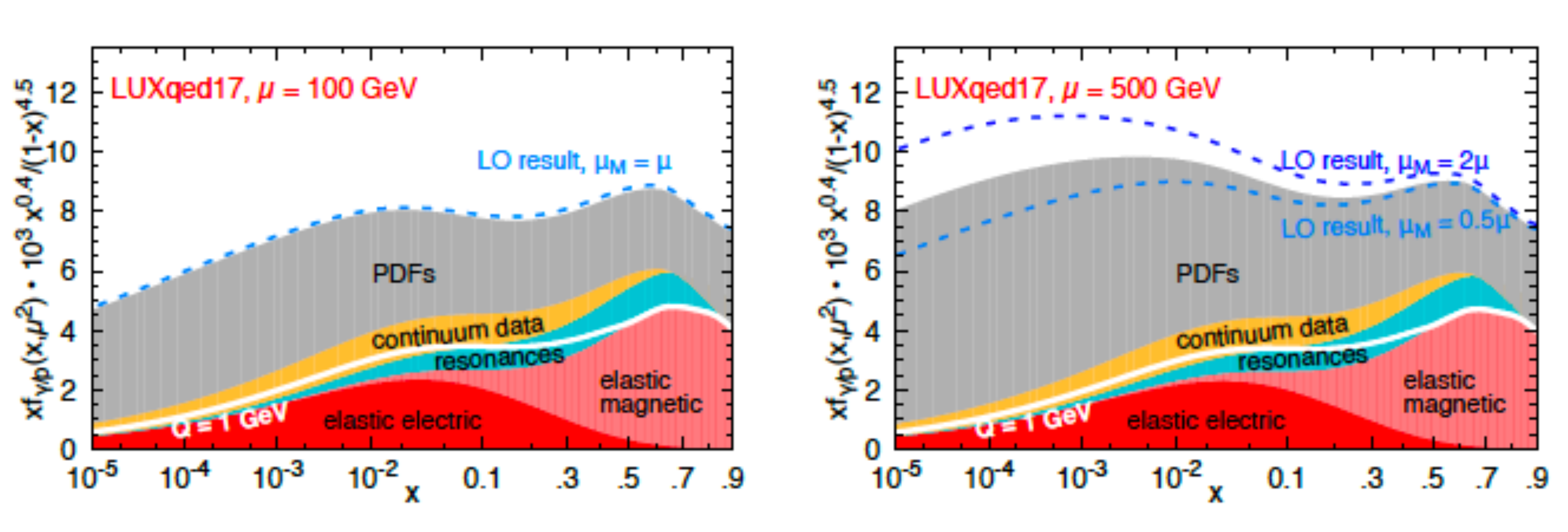
LUXqed17 differs from LUXqed in

- the choice of a scale
- including expansion of structure functions (rather than full expressions)



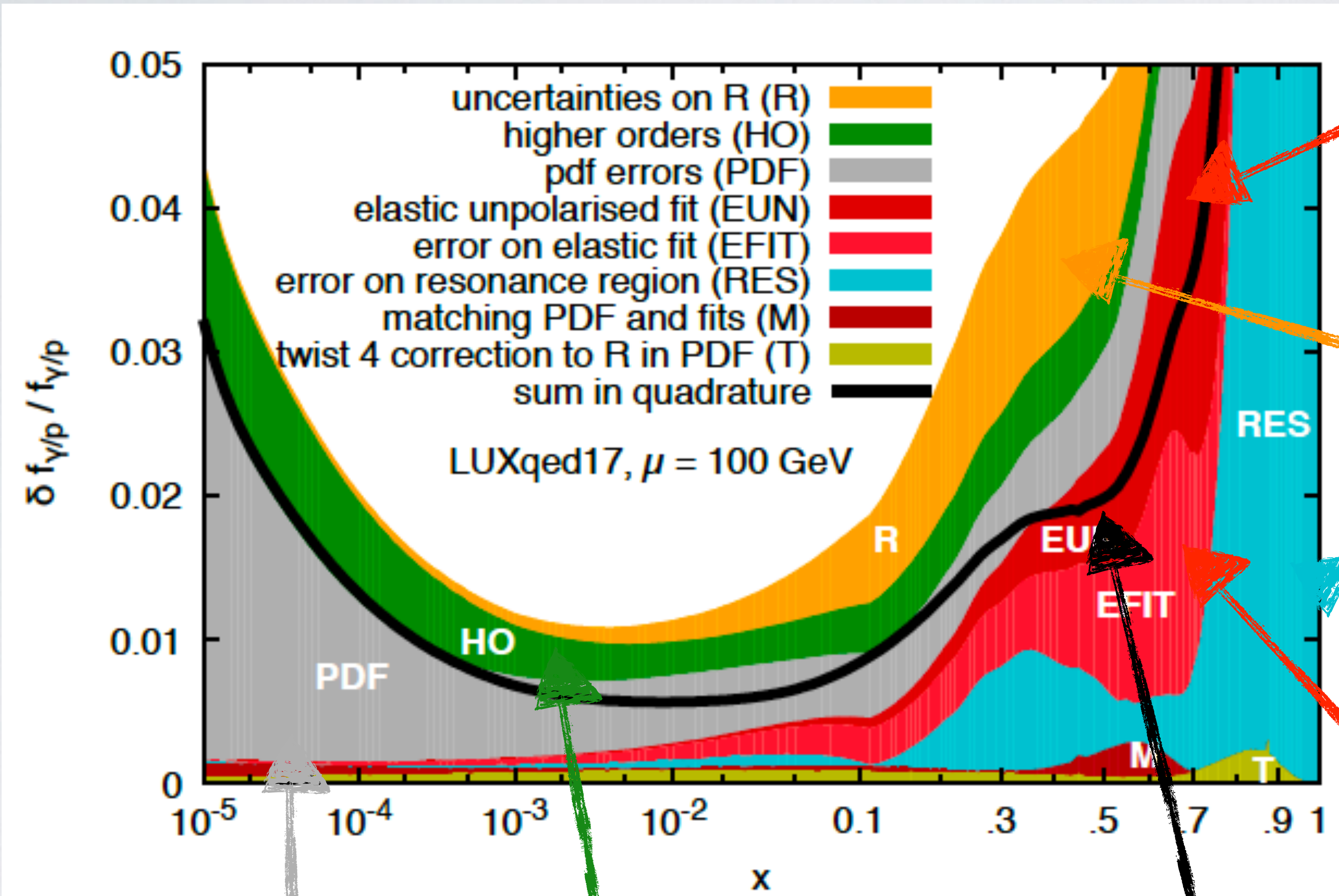
Difference well within quoted uncertainty

Contributions to the PDF



Uncertainties

linearly stacked uncertainties by source



Error on unpolarised fit

±50% on R ($\sim F_L/(F_2\text{-}F_L)$) in low-$Q^2$ continuum and resonance regions

replace CLAS resonance fit with Christy-Bosted

uncertainty on elastic component (quoted ⊕ unpol./pol.)

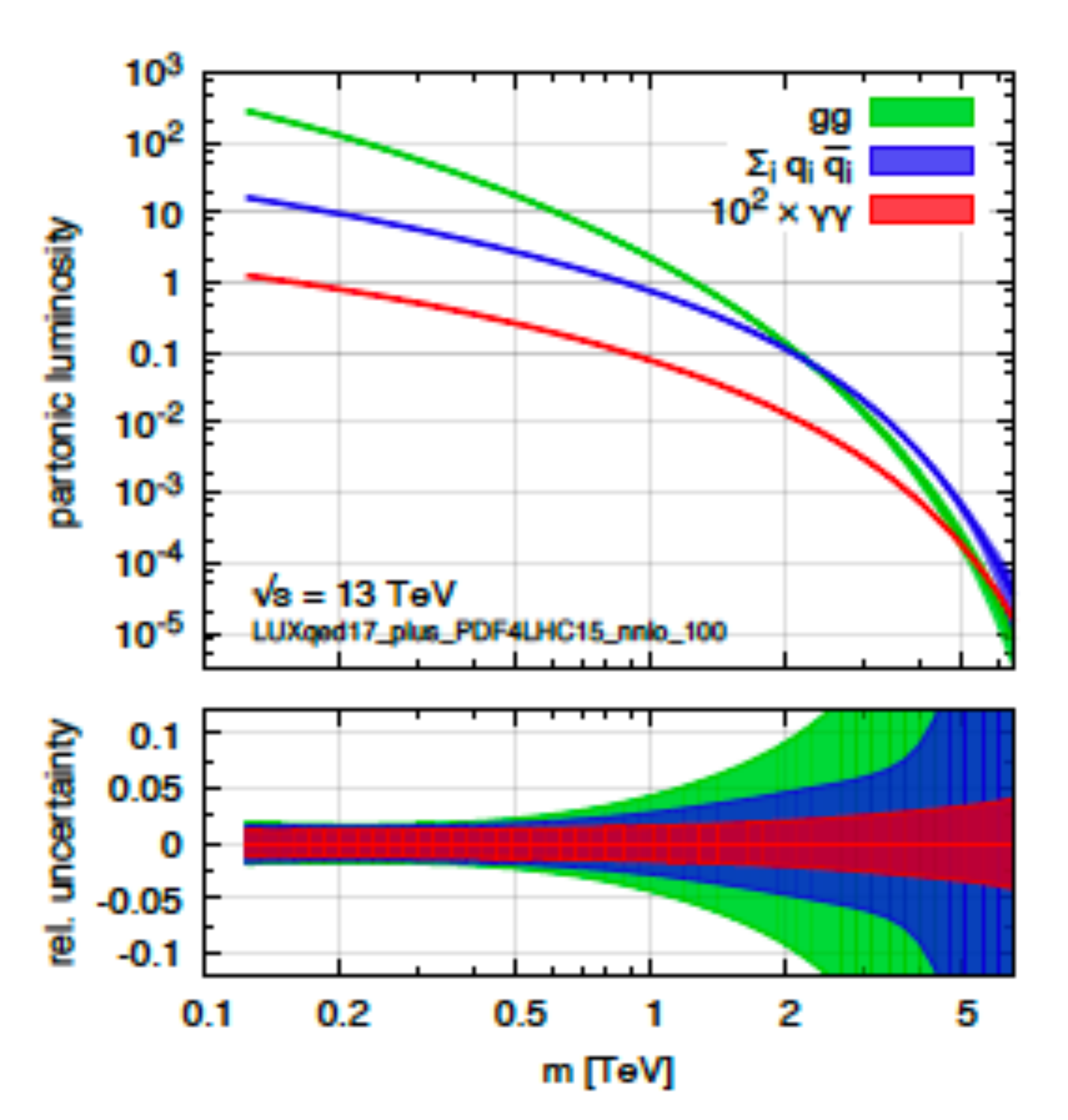
standard PDF uncertainty

treatment of upper limit of Q^2 integral ($\mu^2/(1\text{-}z)$ v. μ^2)

final total uncertainty ~ 1 – 2%
(sum in quad. of all sources)

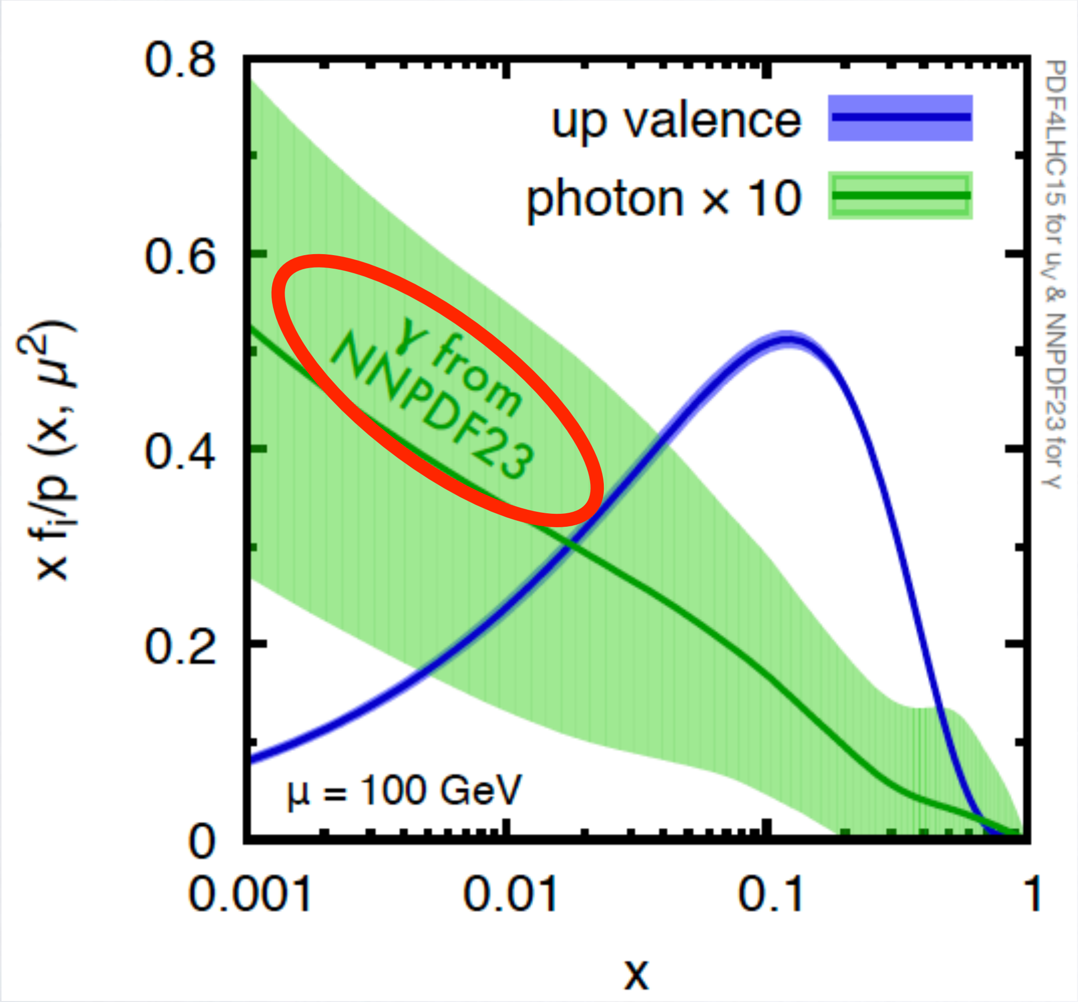
Uncertainties

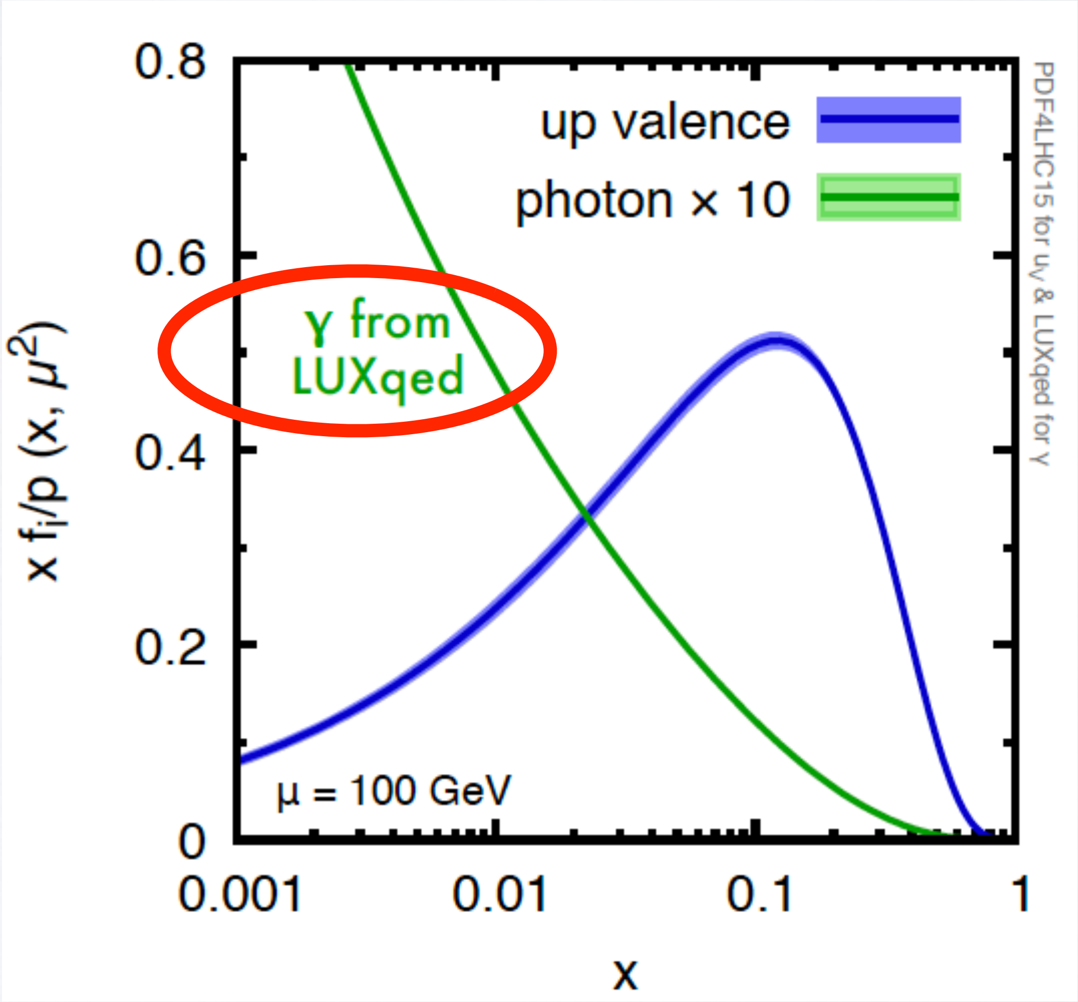
Photon becomes the best known parton in the proton



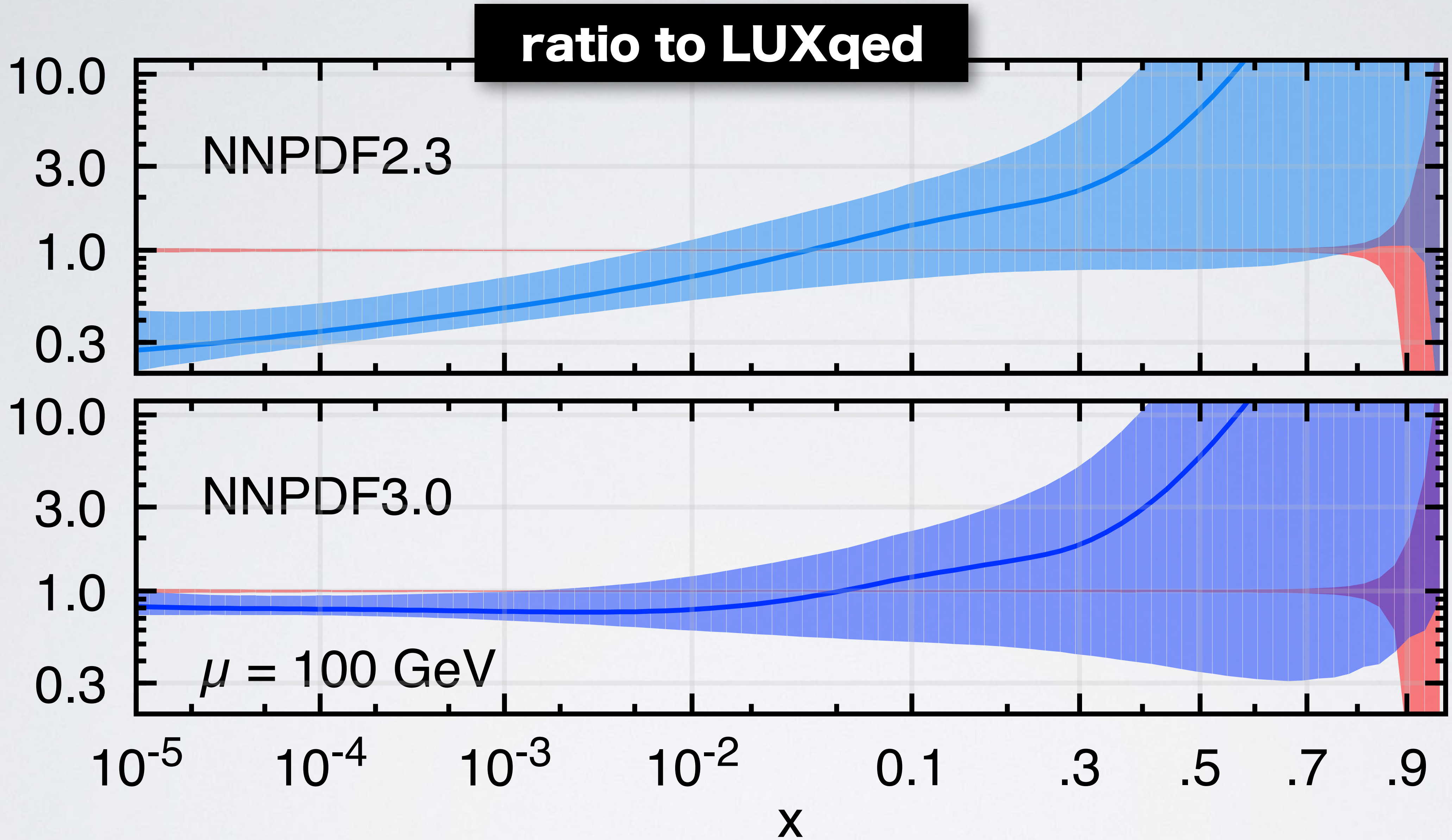
Uncertainties

Photon becomes the best known parton in the proton





Comparison to other PDFs



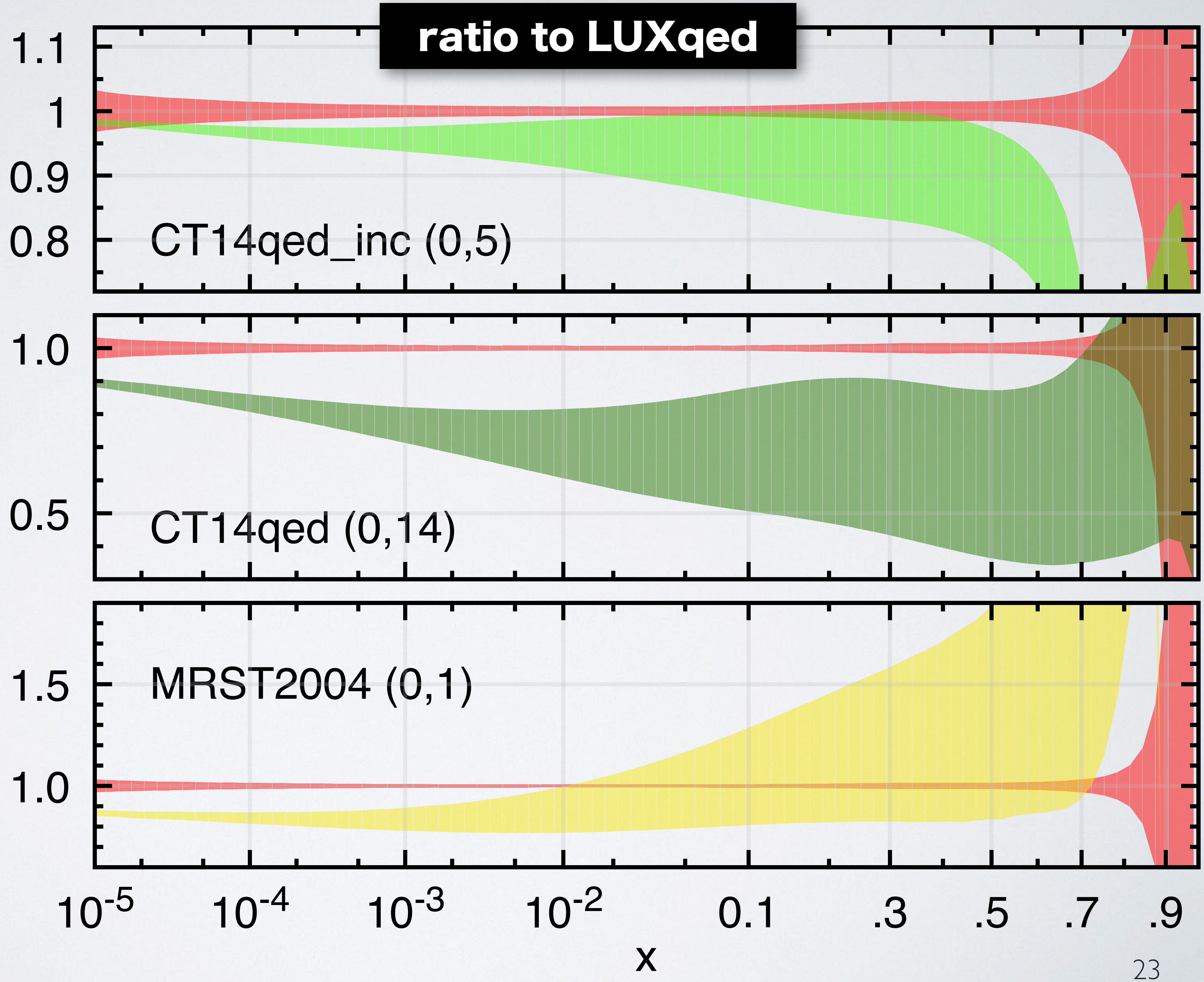
central NNPDF result much higher at large x
(but consistent within errors)

at small x, with corrected evolution (NNPDF30), about 20% smaller

Comparison to other PDFs

Others are numerically closer

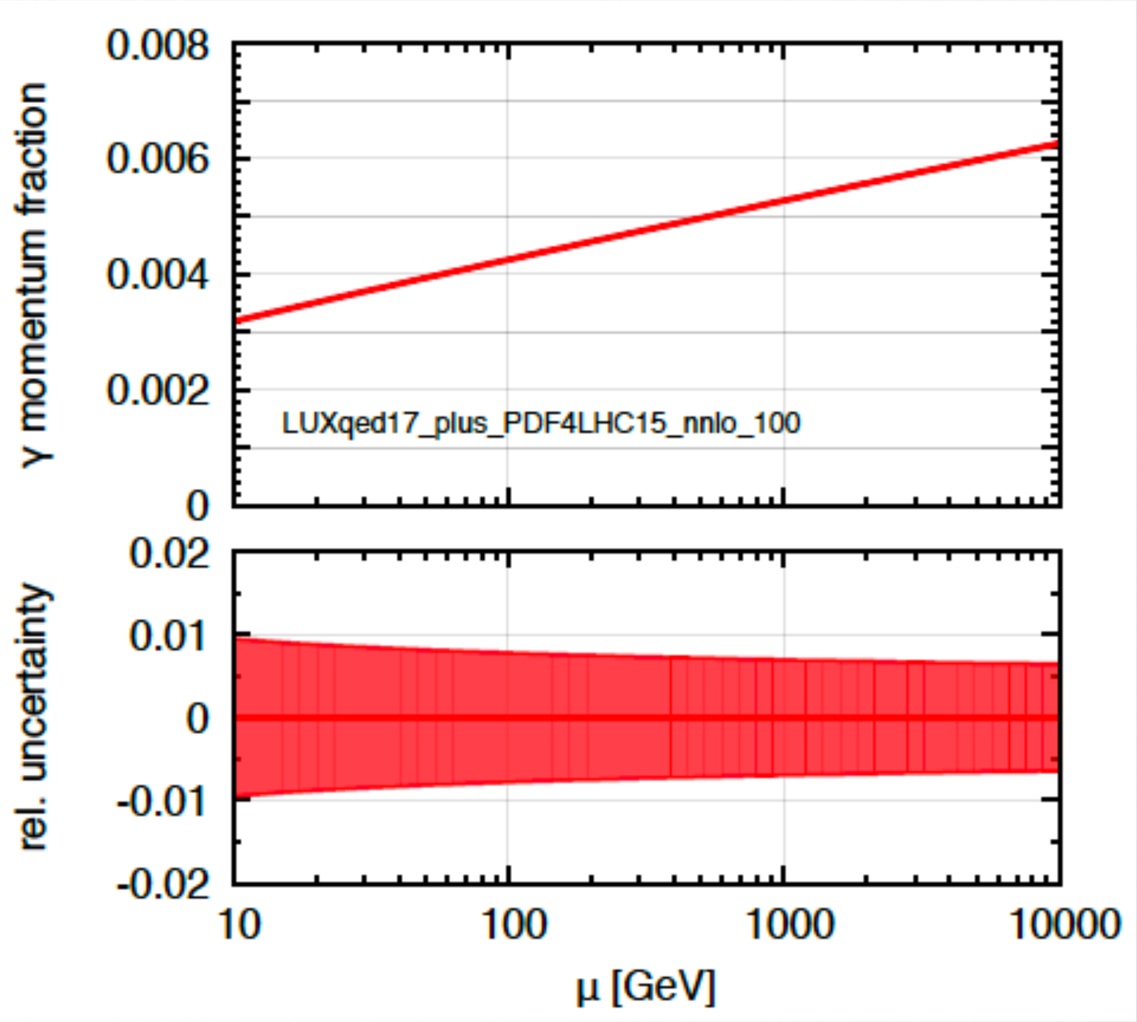
Error bands don't always overlap with LUXqed, but within ~10-20%



What is the momentum fraction carried by the photon?

Momentum fraction in % (μ = 100 GeV)

gluon	46.8 ± 0.4
valence u	18.2 ± 0.3
valence d	7.5 ± 0.2
light sea quarks	20.7 ± 0.4
charm	2.5 ± 0.1
bottom	2.5 ± 0.1
photon	0.426 ± 0.003

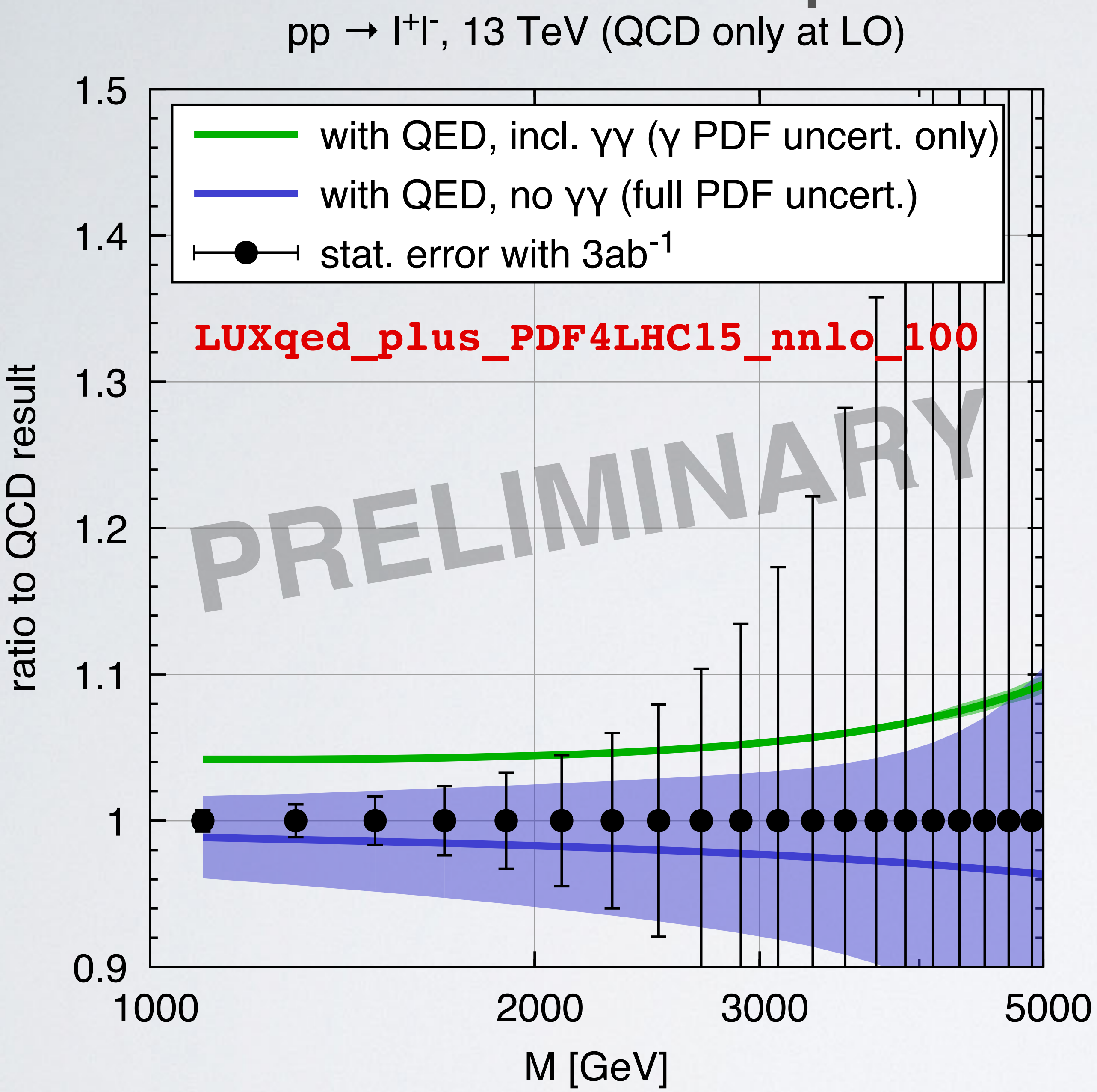


Application to Higgs

$pp \to H W^+ (\to l^+ \nu) + X$ at 13 TeV	
non-photon induced contributions	91.2 ± 1.8 fb
photon-induced contribs (NNPDF23)	$6.0^{+4.4}_{-2.9}$ fb
photon-induced contribs (LUXqed)	4.4 ± 0.1 fb

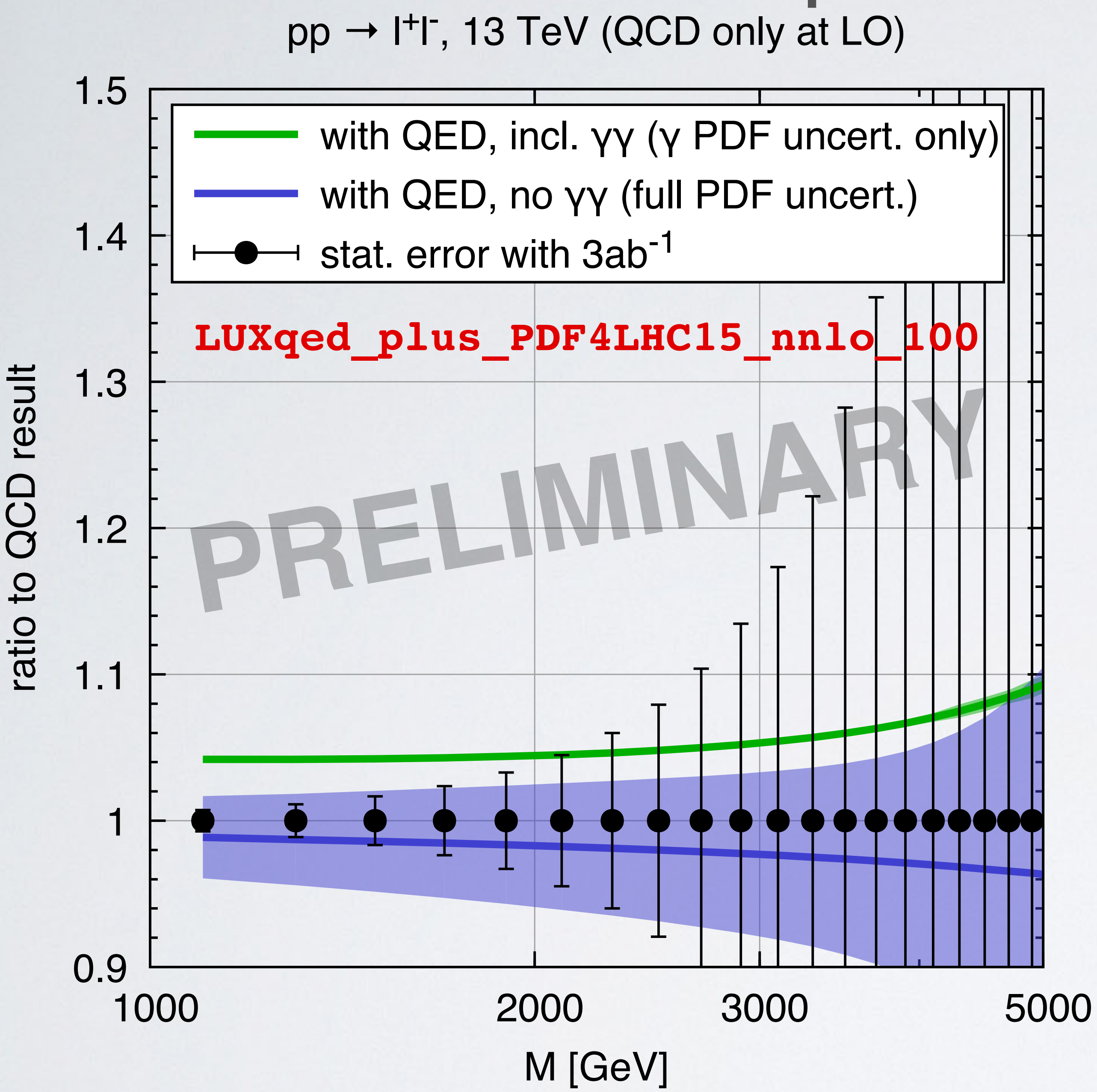
non-photon numbers from LHCHXSWG (YR4)
including PDF uncertainties

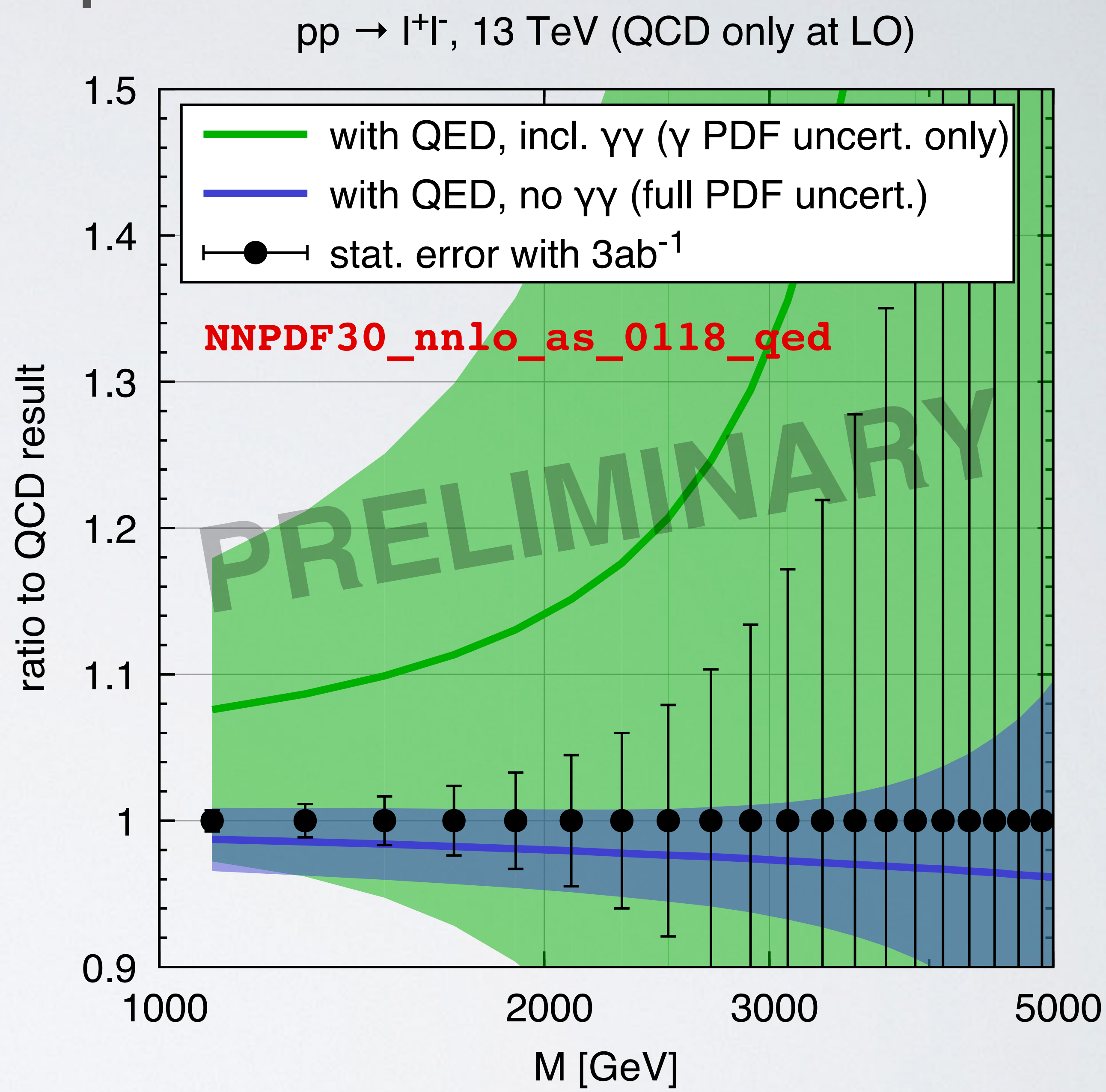
Di-lepton spectrum



LUXQED photon has few % effect on di-lepton spectrum and negligible uncertainties

Di-lepton spectrum





LUXQED photon has few % effect on di-lepton spectrum and negligible uncertainties

Conclusions

- the photon content of the proton matters both for precision physics and LHC searches
- distribution of photons in the proton depends on the **non-perturbative QCD** physics of the proton
- but **perturbative calculations** allow us to deduce the photon density from measured (non-pert.) proton structure functions
- photon PDF determined using data with 1-2% precision
- LUXqed17_plus_PDF4LHC15_nnlo_100 set available from LHAPDF (plus additional plots and validation info available from http://cern.ch/luxqed)

Conclusions

“If you think about it, it's awesome: we are made of protons, and protons are, in some part, made of light... And now we know how much of it.”

blog post by Tommaso Dorigo