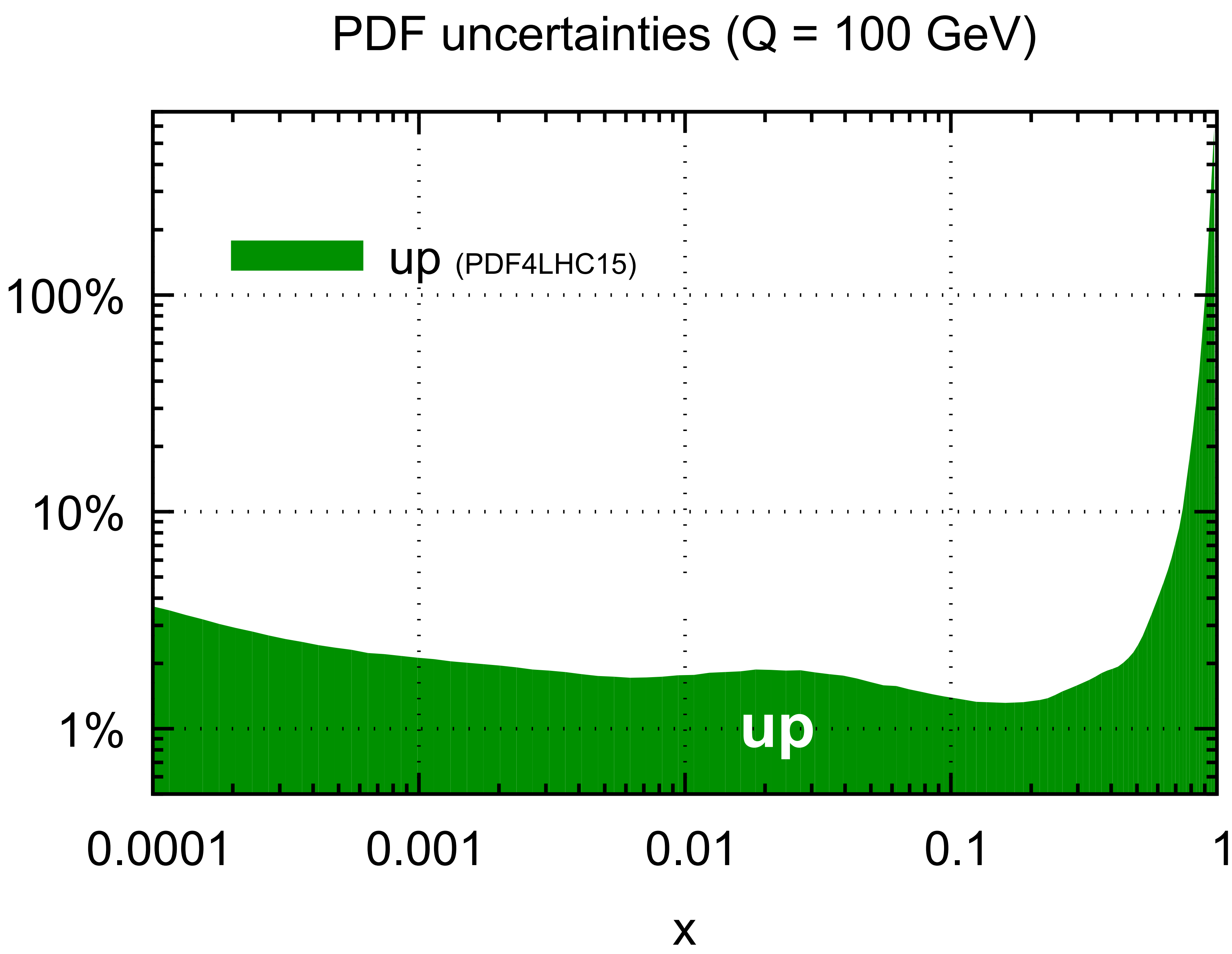
INTRODUCTION TO LUX QED

Gavin Salam, University of Oxford & All Souls College*
with Aneesh Manohar, Paolo Nason and Giulia Zanderighi,
arXiv:1607.04266 arXiv:1708.01256

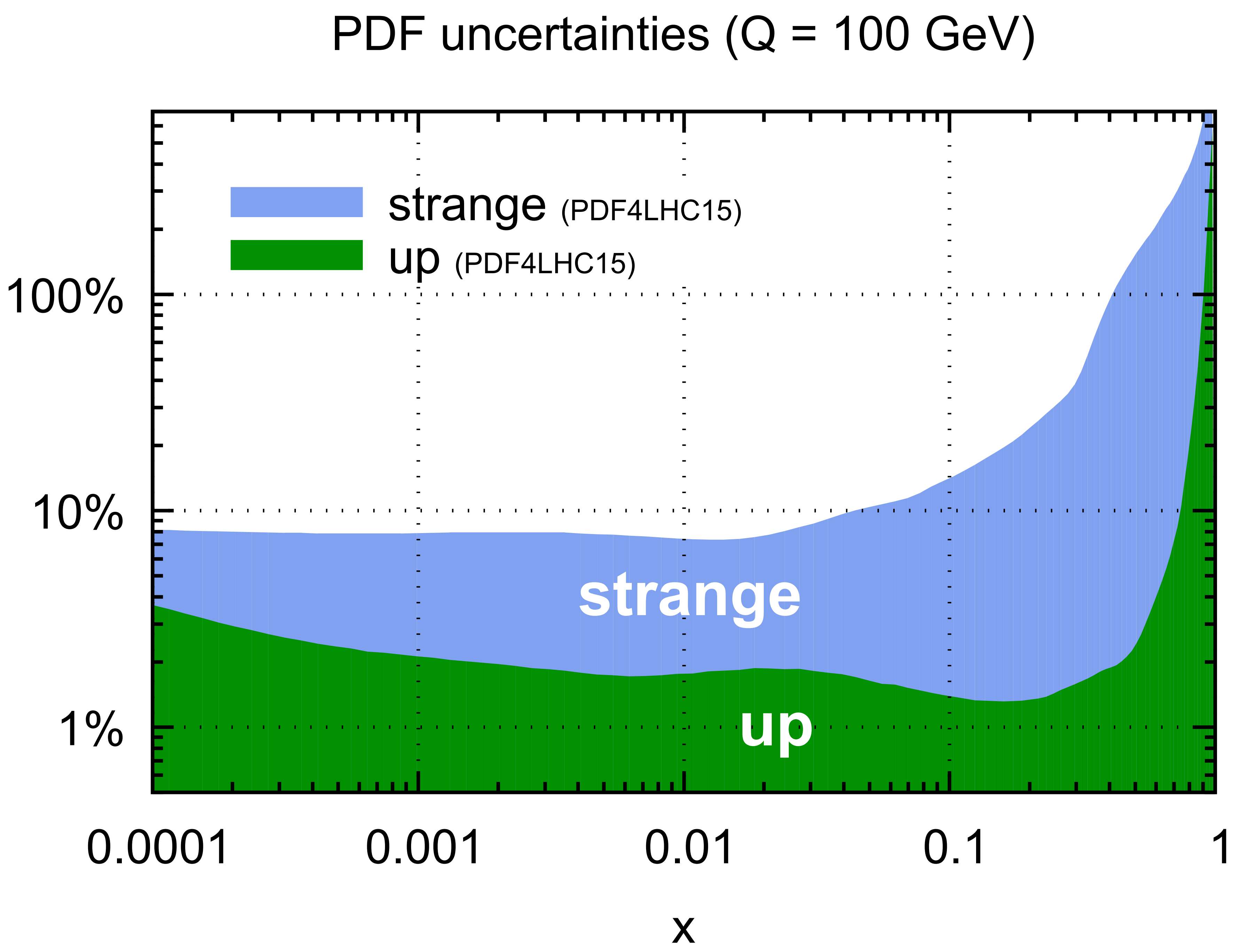
LHC EW WG General Meeting
17 December 2019

* *on leave from CERN and CNRS*

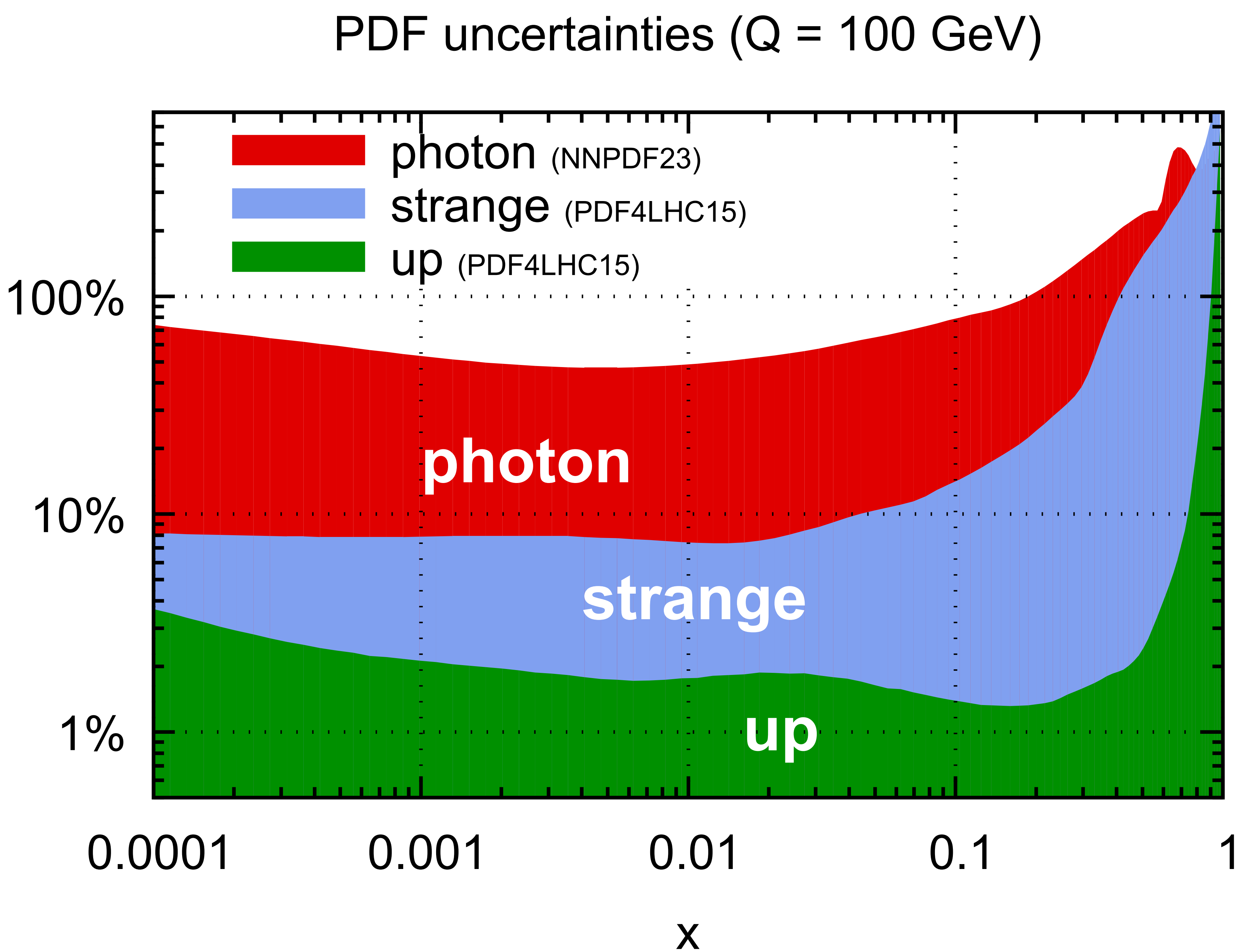
how well do (did) we know the parton distributions?



- core partons (up, down, gluon) are quite well known



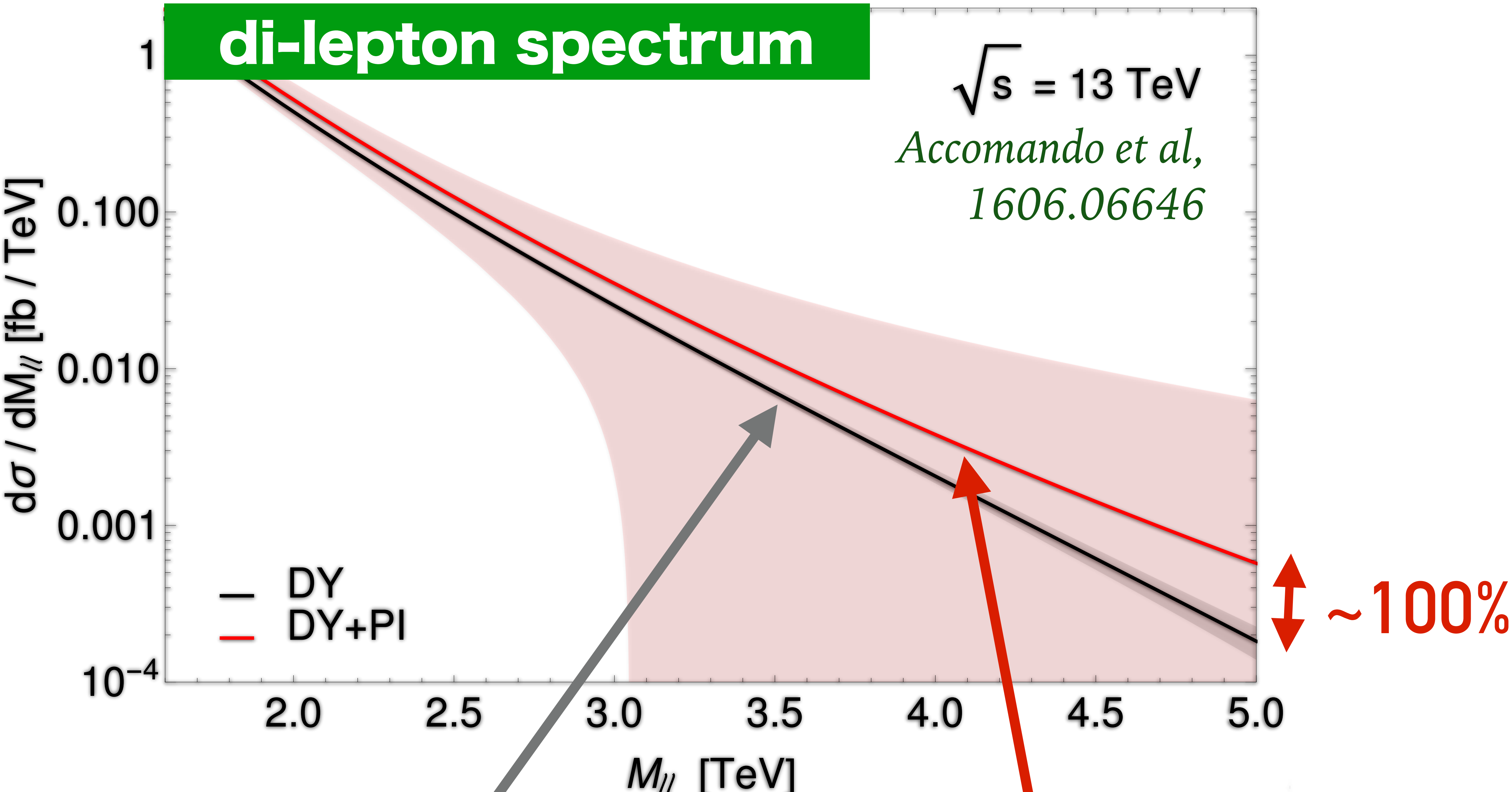
- core partons (up, down, gluon) are quite well known ~2%
- strangeness ~10%



- ➤ core partons (up, down, gluon) are quite well known ~2%
- ➤ strangeness ~10%

- ➤ one other parton, the photon, had been debated. The only model-independent determination (NNPDF23qed) had O(100%) uncertainty

IT MATTERED FOR DI-LEPTON, DI-BOSON, TTBAR, EW HIGGS, ETC.



normal DY contribution

photon-induced contribution and uncertainty [NNPDF23]

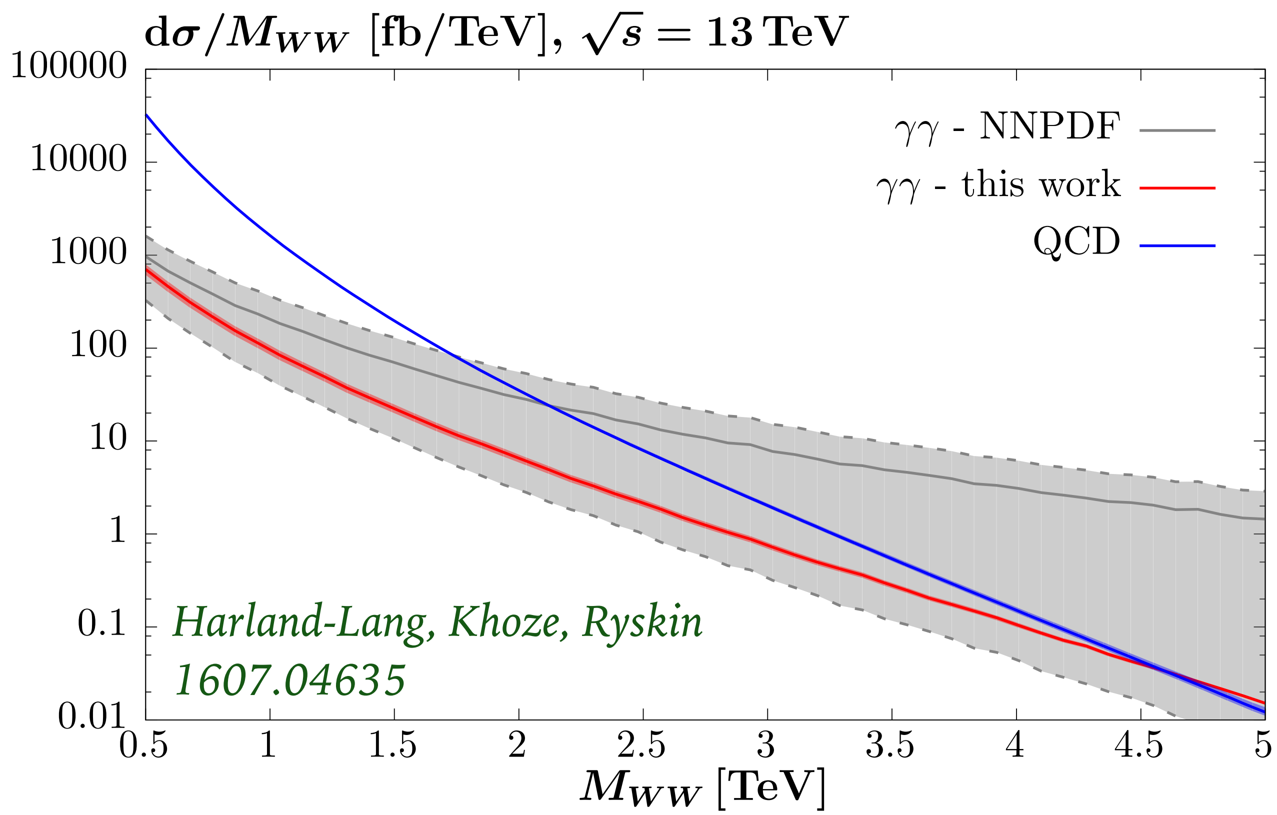
where else does the photon come in? Any time you produce charged particles

- Electroweak corrections to almost any process
- E.g. ~5% WH

LHC-HXSWG YR4

- top production *Pagani, Tsinikos, Zaro, arXiv:1606.01915*

- VV production *1409.1803, 1510.08742, 1603.04874, 1601.07787, 1605.03419, 1604.04080,1607.04635, …*

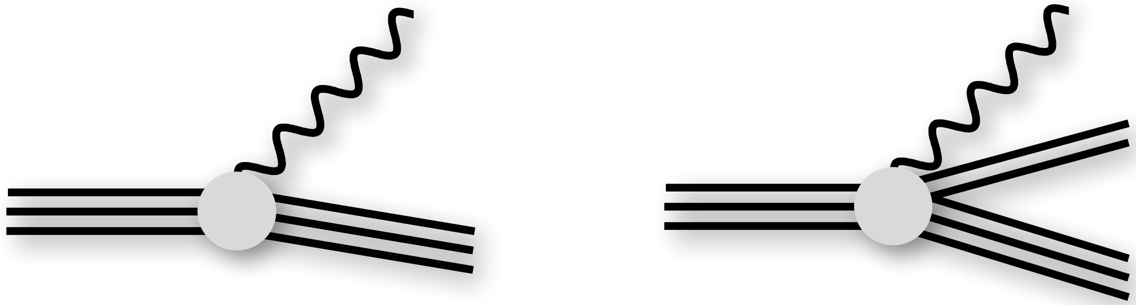


$\gamma\gamma$ (NNPDF) 100× larger than $q\bar{q}$

EARLIER PHOTON PDF ESTIMATES (not exhaustive)

	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



YOU DON'T NEED A MODEL

ep scattering (i.e. structure functions) contains all info about proton's EM field

YOU DON'T NEED A MODEL

ep scattering (i.e. structure functions) contains all info about proton's EM field

---

study hypothetical ("BSM") heavy-neutral lepton production process

Calculate it in two ways

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

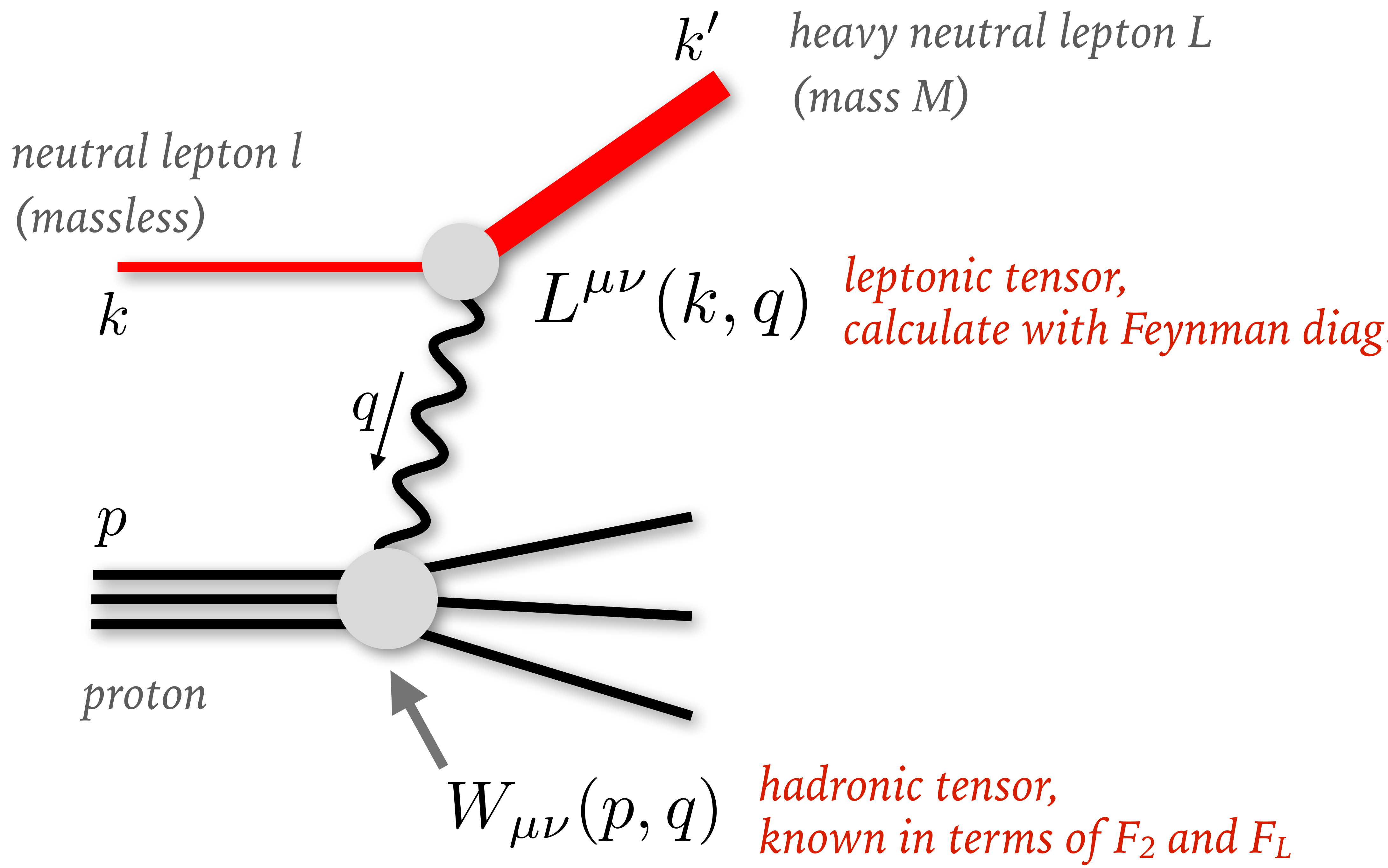
Equivalence gives us photon distirbution

Manohar, Nason, GPS & Zanderighi, arXiv:1607.04266
(use of BSM inspired by Drees & Zeppenfeld, PRD39(1989)2536)
can also use PDF operator formalism, arXiv:1708.01256

calculation

STEP 1

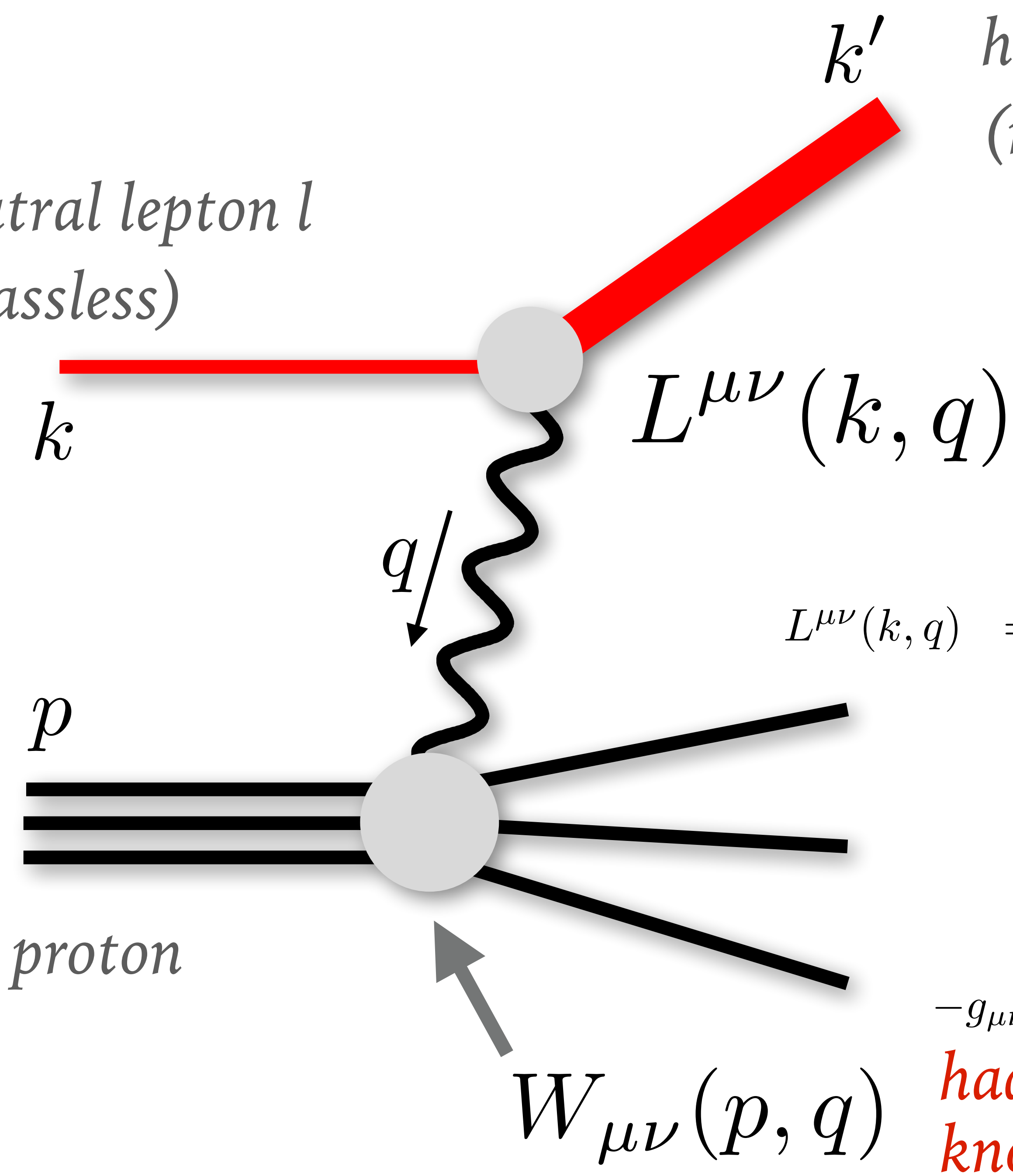
work out a cross section (exact) in terms of F_2 and F_L struct. fns.



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

STEP 1

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



heavy neutral lepton L
(mass M)

leptonic tensor,
calculate with Feynman diag.

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

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

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

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

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

hadronic tensor,
known in terms of F_2 and F_L

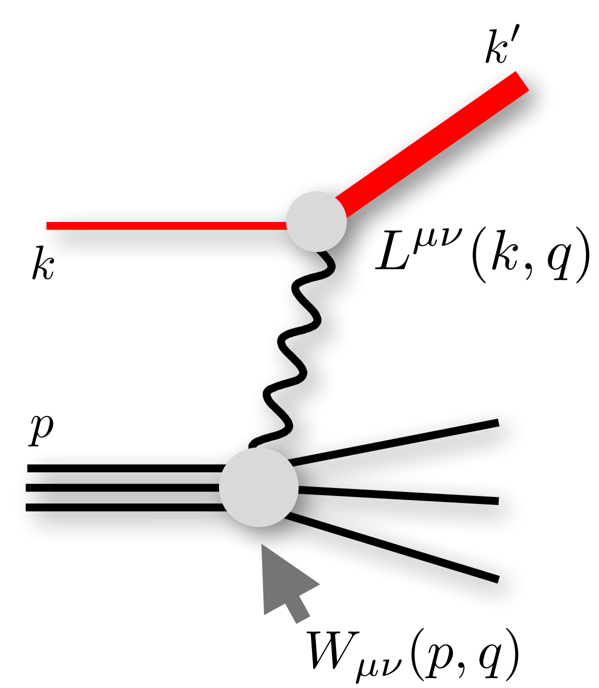
$$\sigma = \frac{1}{4p\cdot k}\int \frac{d^4q}{(2\pi)^4 q^4}e^2_{\rm ph}(q^2)\left[4\pi W_{\mu\nu}\,L^{\mu\nu}(k,q)\right]\times 2\pi\delta((k-q)^2-M^2)$$

Cross section in terms of structure functions

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

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

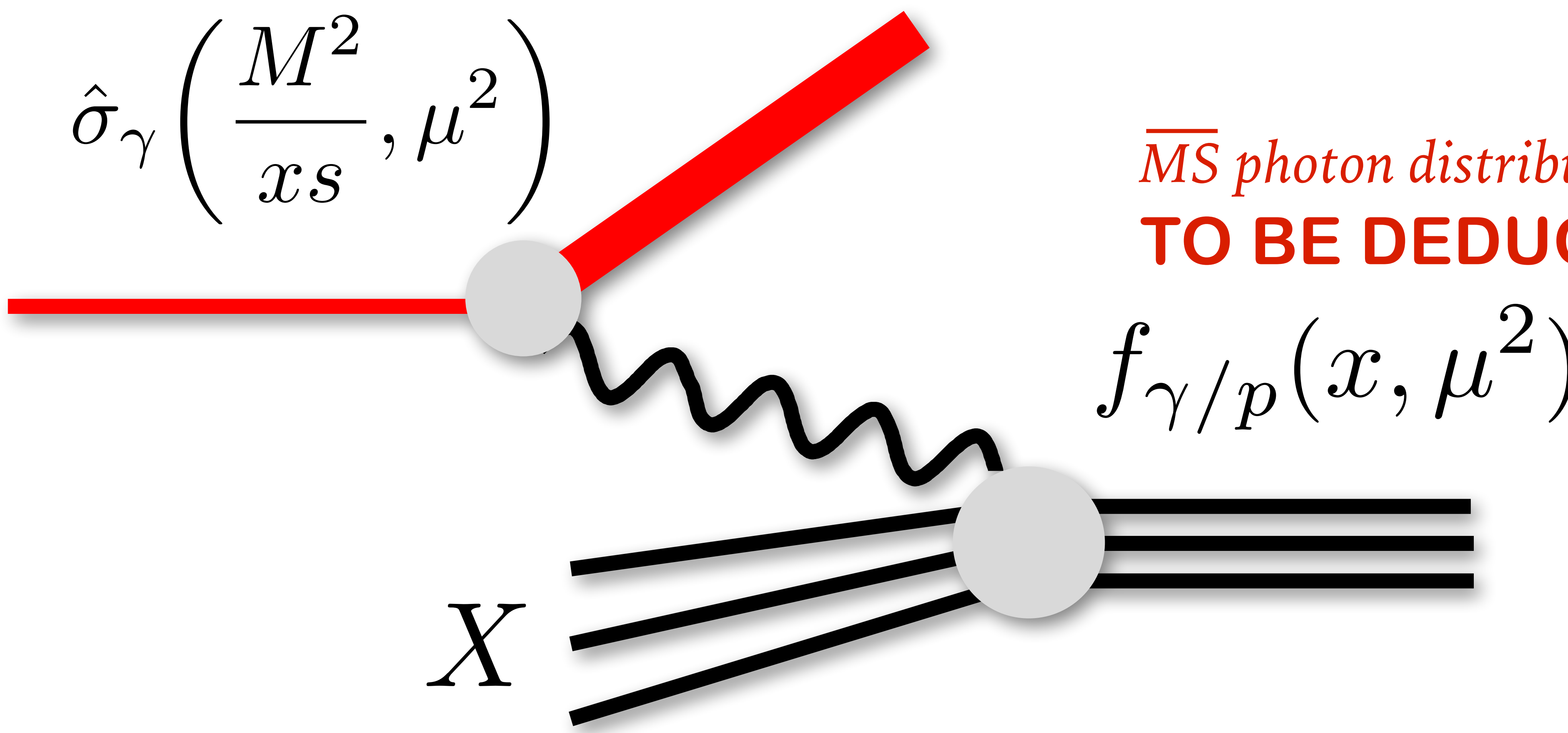
$$c_0 = 16\pi^2/\Lambda^2$$



STEP 2

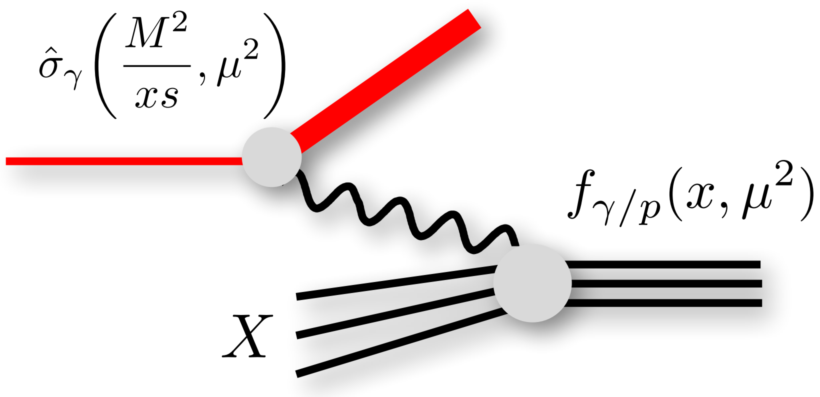
work out same cross section in terms of a photon distribution

hard-scattering cross section
calculate in collinear factorisation



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

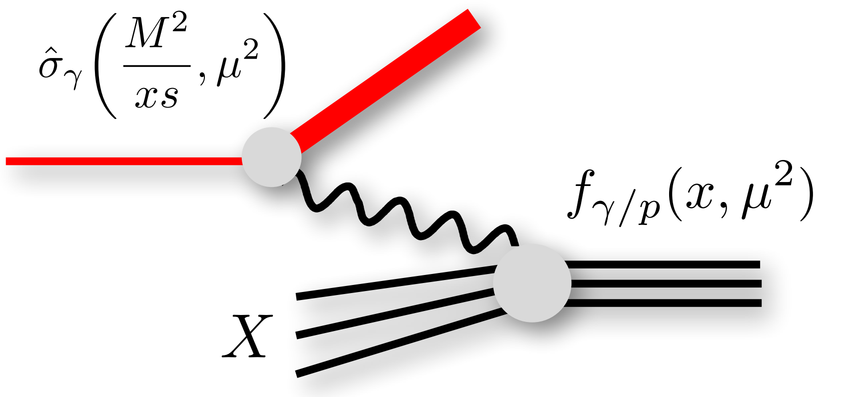
Cross section in terms of structure functions



- Hard cross section driven by the photon distribution at LO

$$\hat{\sigma}_a(z, \mu^2) = \boxed{\alpha(\mu^2)\delta(1-z)\delta_{a\gamma}}$$

Cross section in terms of structure functions



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

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

- ➤ Quarks and gluons come in at higher orders

ACCURACY AIM

- 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 $\sim (\alpha L)$
- 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 αL]
- Matching done at large M^2 and μ^2 to eliminate higher twists

STEP 3

equate them to deduce the photon distribution (LUXqed)

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

STEP 3
equate them to deduce the photon distribution (LUXqed)

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

with $F_2 \sim \sum_q e_q^2 x q(x)$ this is just (LO) DGLAP-like piece

STEP 3

equate them to deduce the photon distribution (LUXqed)

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

At low Q^2, F_2 and F_L come directly from data (non.pert.)
At high Q^2, get them from PDFs, including $O(\alpha_s)$ (NLO) terms

STEP 3
equate them to deduce the photon distribution (LUXqed)

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

Terms at boundaries are suppressed by $1/L$ (NLO)

STEP 3

equate them to deduce the photon distribution (LUXqed)

$$xf_{\gamma/p}(x,\mu^2) = \frac{1}{2\pi\alpha(\mu^2)}\int_x^1 \frac{dz}{z}\left\{\int_{\frac{x^2m_p^2}{1-z}}^{\boxed{\frac{\mu^2}{1-z}}} \frac{dQ^2}{Q^2}\alpha^2(Q^2)\right.$$

$$\left[\left(zp_{\gamma q}(z) + \frac{2x^2m_p^2}{Q^2}\right)F_2(x/z,Q^2) - z^2F_L\left(\frac{x}{z},Q^2\right)\right]$$

$$\left.\boxed{-\,\alpha^2(\mu^2)z^2F_2\left(\frac{x}{z},\mu^2\right)}\right\}$$

terms at boundary $\sim \mu^2$ ensure $\overline{\text{MS}}$ fact. scheme

STEP 3
equate them to deduce the photon distribution (LUXqed)

$$x f_{\gamma/p}(x,\mu^2) = \boxed{\frac{1}{2\pi\alpha(\mu^2)}} \int_x^1 \frac{dz}{z} \left\{ \int_{\frac{x^2 m_p^2}{1-z}}^{\frac{\mu^2}{1-z}} \frac{dQ^2}{Q^2} \boxed{\alpha^2(Q^2)} \right.$$

$$\left[\left(z p_{\gamma q}(z) + \frac{2x^2 m_p^2}{Q^2} \right) F_2(x/z, Q^2) - z^2 F_L\left(\frac{x}{z}, Q^2\right) \right]$$

$$\left. - \alpha^2(\mu^2) z^2 F_2\left(\frac{x}{z}, \mu^2\right) \right\}$$

QED running of α accounts for most $(\alpha L)^2$ effects (NLO)

(others come in the way we match to normal PDFs)

cross-checks

Cross checks & literature comparisons

- Repeat calculation for a different process (γp→H+X, via γγ→H). Intermediate results differ, **final photon distribution is identical**.

- Substitute elastic-scattering component of F_2 and F_L:

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

$$F_L^{\mathrm{el}} = \frac{[G_E(Q^2)]^2}{\tau}\delta(1-x)\,, \qquad \tau = Q^2/(4m_p^2)$$

and reproduce widely-used **Equivalent Photon Approximation** with electric (G_E) and magnetic (G_M) Sachs proton form factors

Budnev et al., Phys.Rept.15(1975)181

Cross checks & literature comparisons

- A core part of our answer

$$\left[\left(zp_{\gamma q}(z) + \frac{2x^2m_p^2}{Q^2}\right)F_2(x/z, Q^2) - z^2F_L\left(\frac{x}{z}, Q^2\right)\right]$$

appears in literature for **QED compton process ep → eγX** (but with inexact treatment of the upper and lower limits for Q^2 integration)

Anlauf et. al, CPC70(1992)97

Mukherjee & Pisano, hep-ph/0306275

- [NB other literature has expression for photon distribution in terms of F_2 and F_1 that doesn't reproduce DGLAP limit]

Luszczak, Schäfer & Szczurek, arXiv:1510.00294

Cross checks & literature comparisons

- μ^2 derivative of our answer should reproduce known DGLAP QCD-QED splitting functions
- At LO, this is trivial.
- At NLO we get relations between QED-QCD splitting functions (P) and DIS coefficient functions (C)

$$P_{\gamma q}^{(1,1)} = e_q^2 \left[p_{\gamma q} \otimes C_{2q} - h \otimes C_{Lq} + (\bar{p}_{\gamma q} - h) \otimes P_{qq}^{(1,0)} \right] ,$$

$$P_{\gamma g}^{(1,1)} = \sum_{q,\bar{q}} e_q^2 \left[p_{\gamma q} \otimes C_{2g} - h \otimes C_{Lg} + (\bar{p}_{\gamma q} - h) \otimes P_{qg}^{(1,0)} \right] ,$$

$$P_{\gamma\gamma}^{(1,1)} = (2\pi)^2 b_\alpha^{(1,2)} \delta(1-x) = -C_F N_C \sum_q e_q^2 \delta(1-x)$$

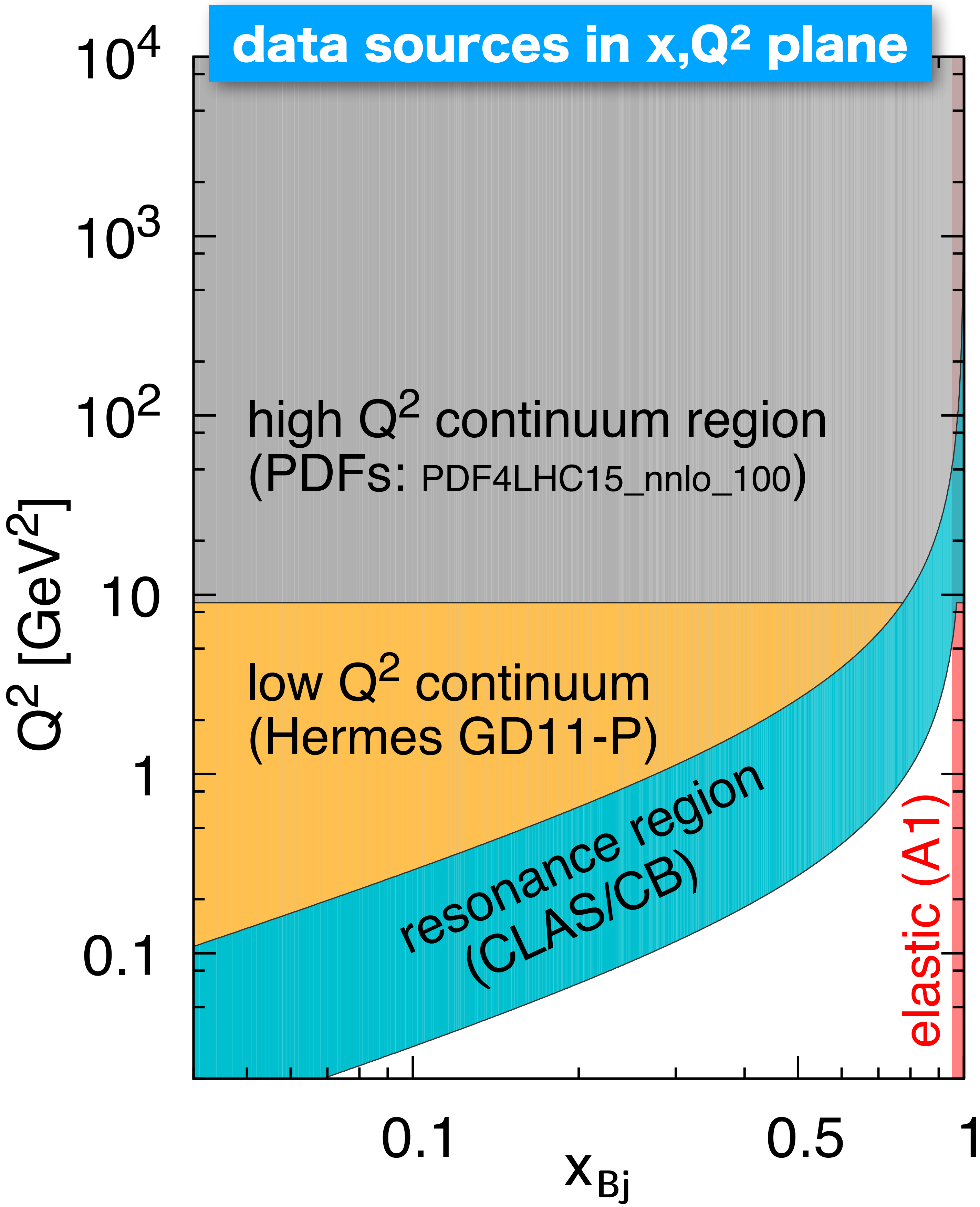
$$h(z) \equiv z \text{ and } \bar{p}_{\gamma q}(z) \equiv p_{\gamma q}(z) \ln \frac{1}{1-z}$$

- These **agree with de Florian, Sborlini & Rodrigo results**

for $O(\alpha\,\alpha_s)$ terms, arXiv:1512.00612

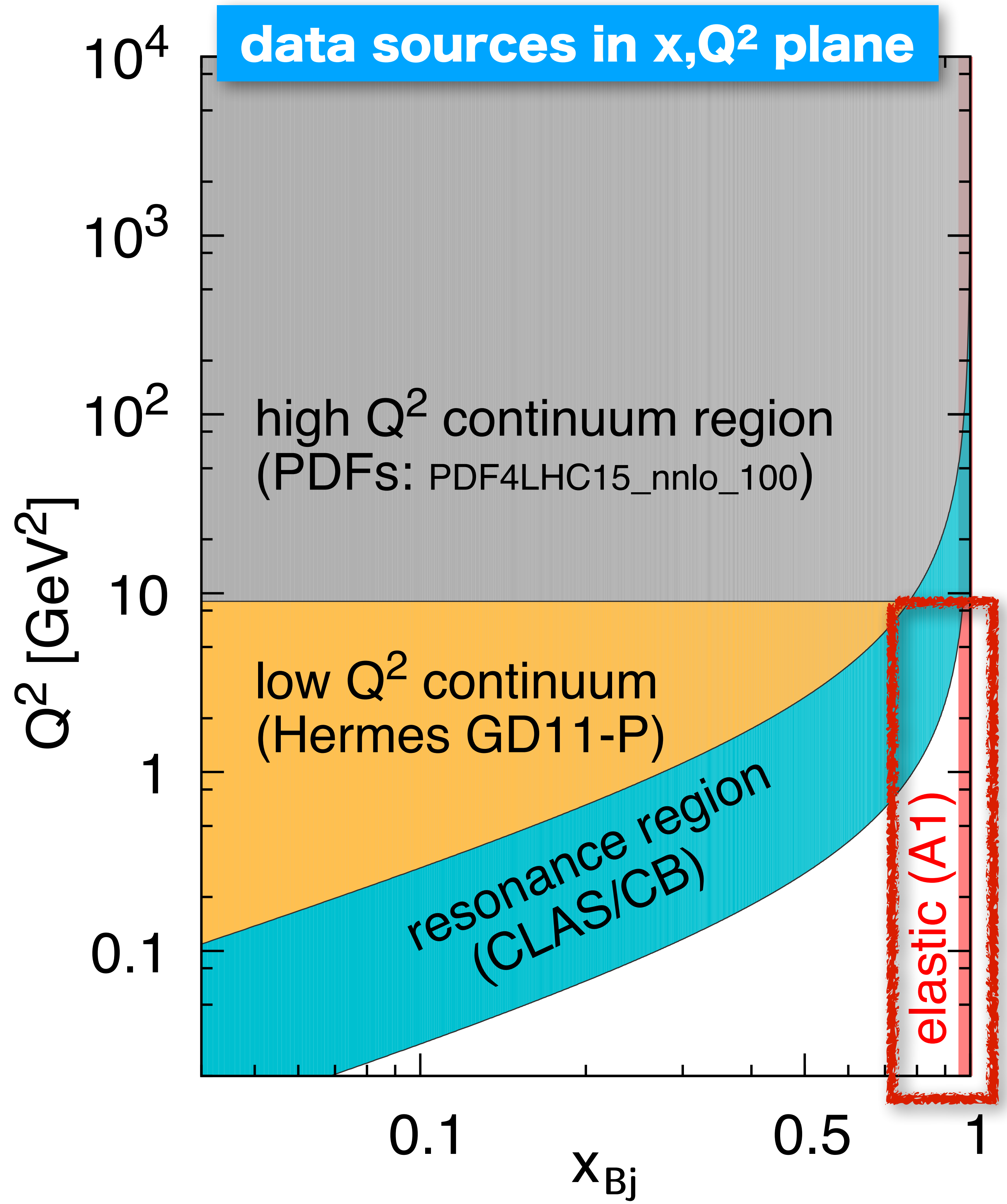
both they and we have gone to higher order — but pheno accuracy not there yet

data inputs

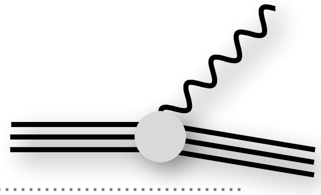


DATA

- 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



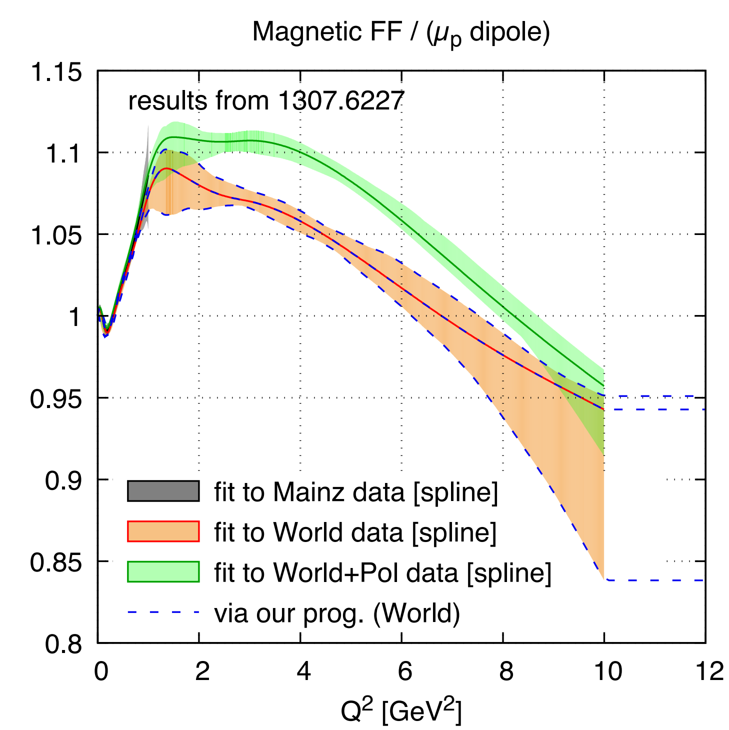
ELASTIC COMPONENT

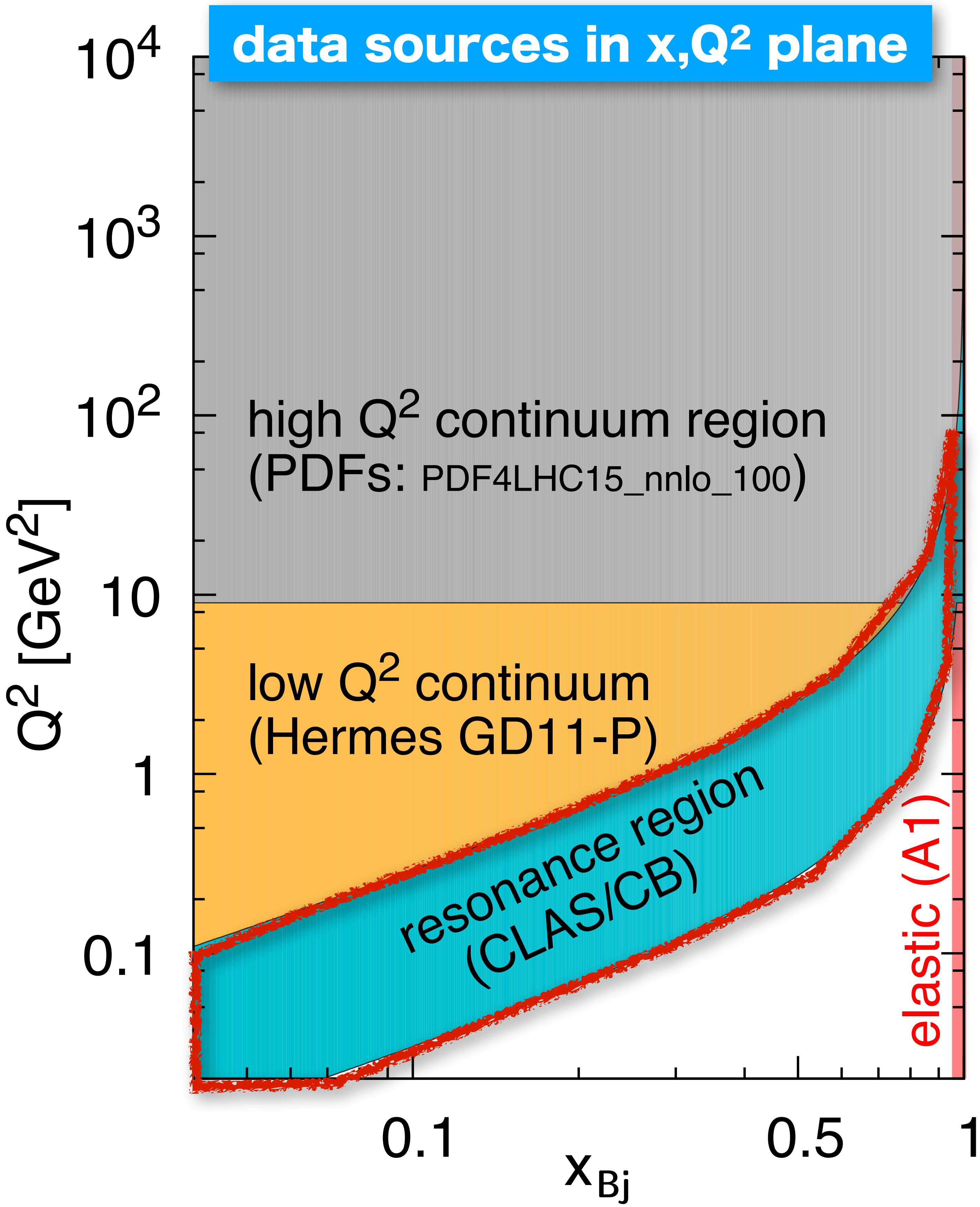


- Elastic component of $F_{2/L}$ lives at $x=1$
- Express in terms of Sachs Form factors

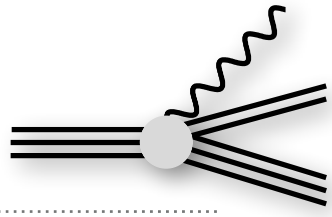
$$F_2^{\mathrm{el}} = \frac{[G_E(Q^2)]^2 + [G_M(Q^2)]^2\tau}{1+\tau}\delta(1-x)\,,$$

$$F_L^{\mathrm{el}} = \frac{[G_E(Q^2)]^2}{\tau}\delta(1-x)\,,\quad \tau \;=\; Q^2/(4m_p^2)$$

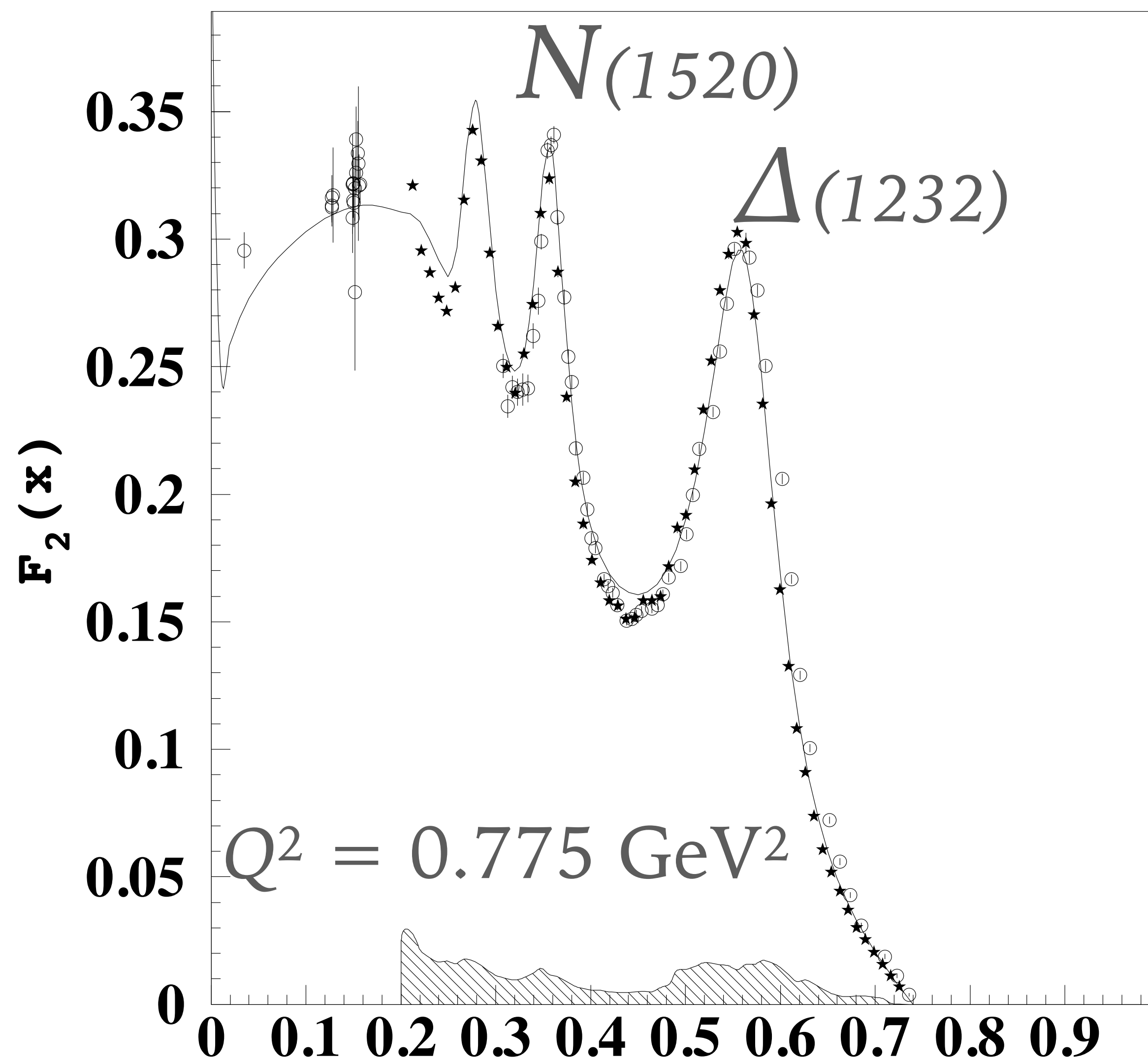


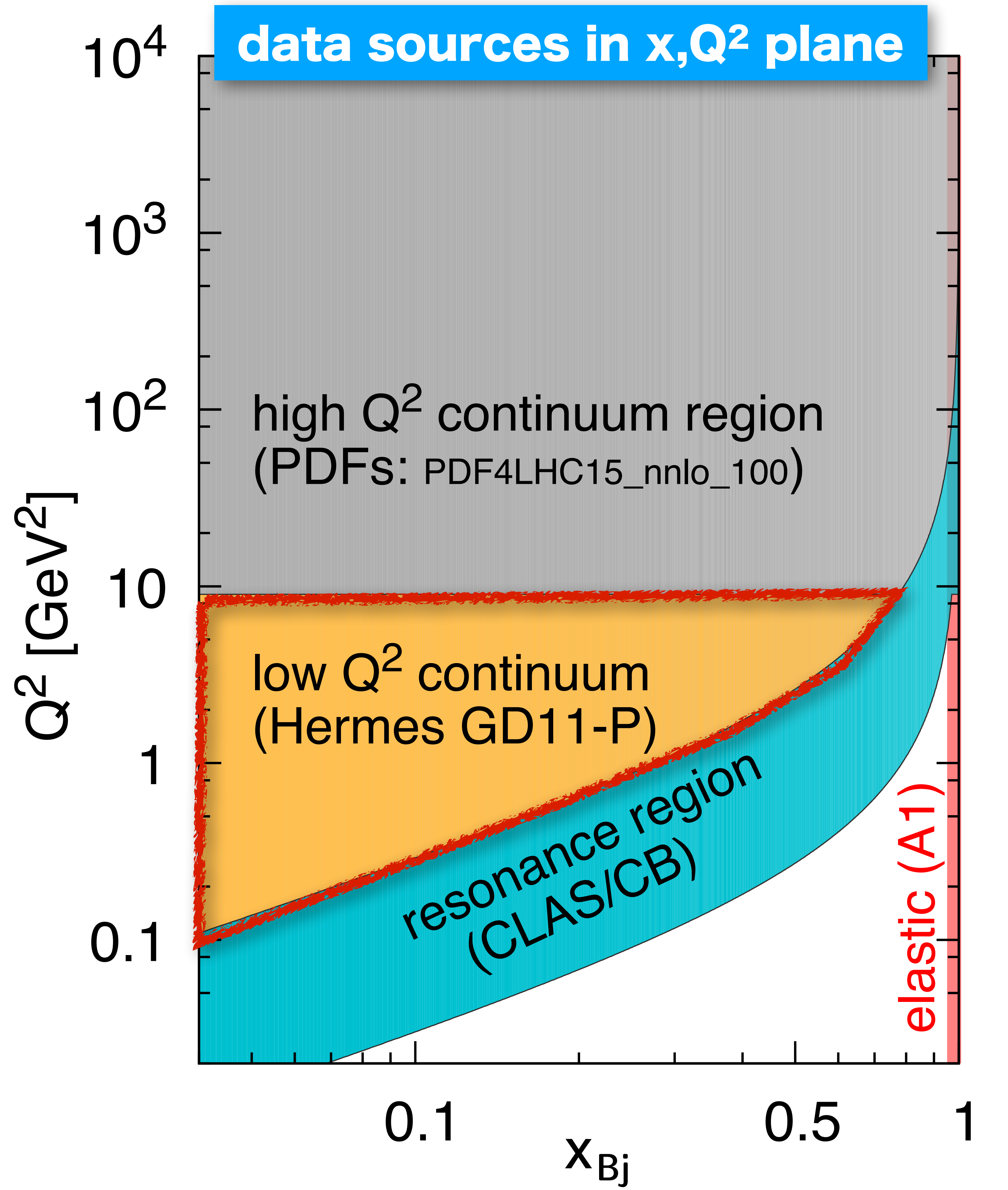


RESONANCE COMPONENT

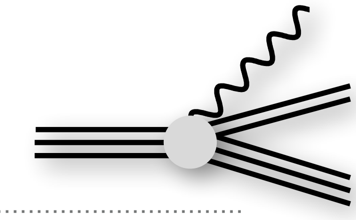


- proton gets excited, e.g. to $\Delta \rightarrow p\pi$ and higher resonances
- relevant for $(m_p+m_\pi)^2 < W^2 < 3.5\mathrm{GeV}^2$

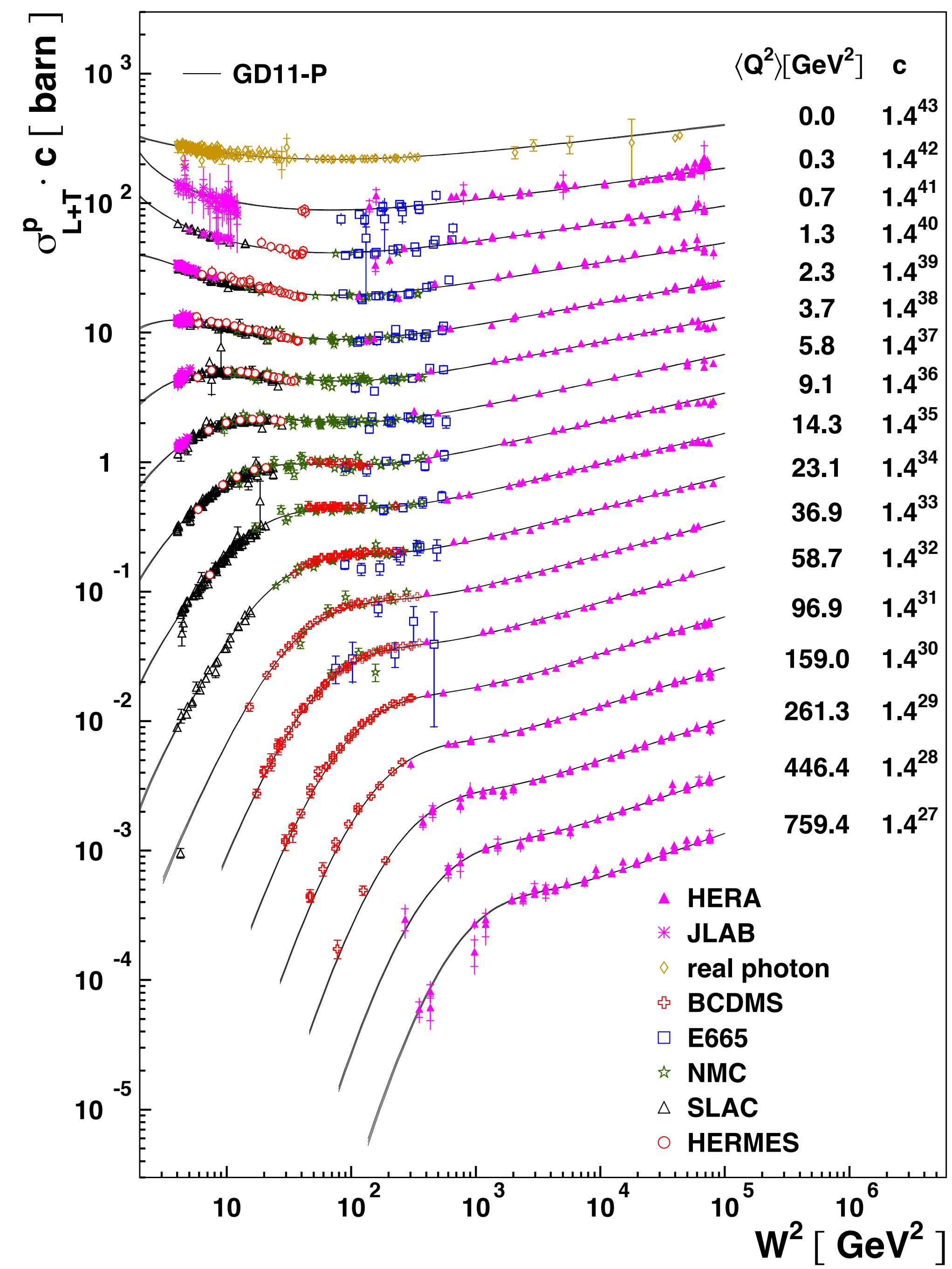




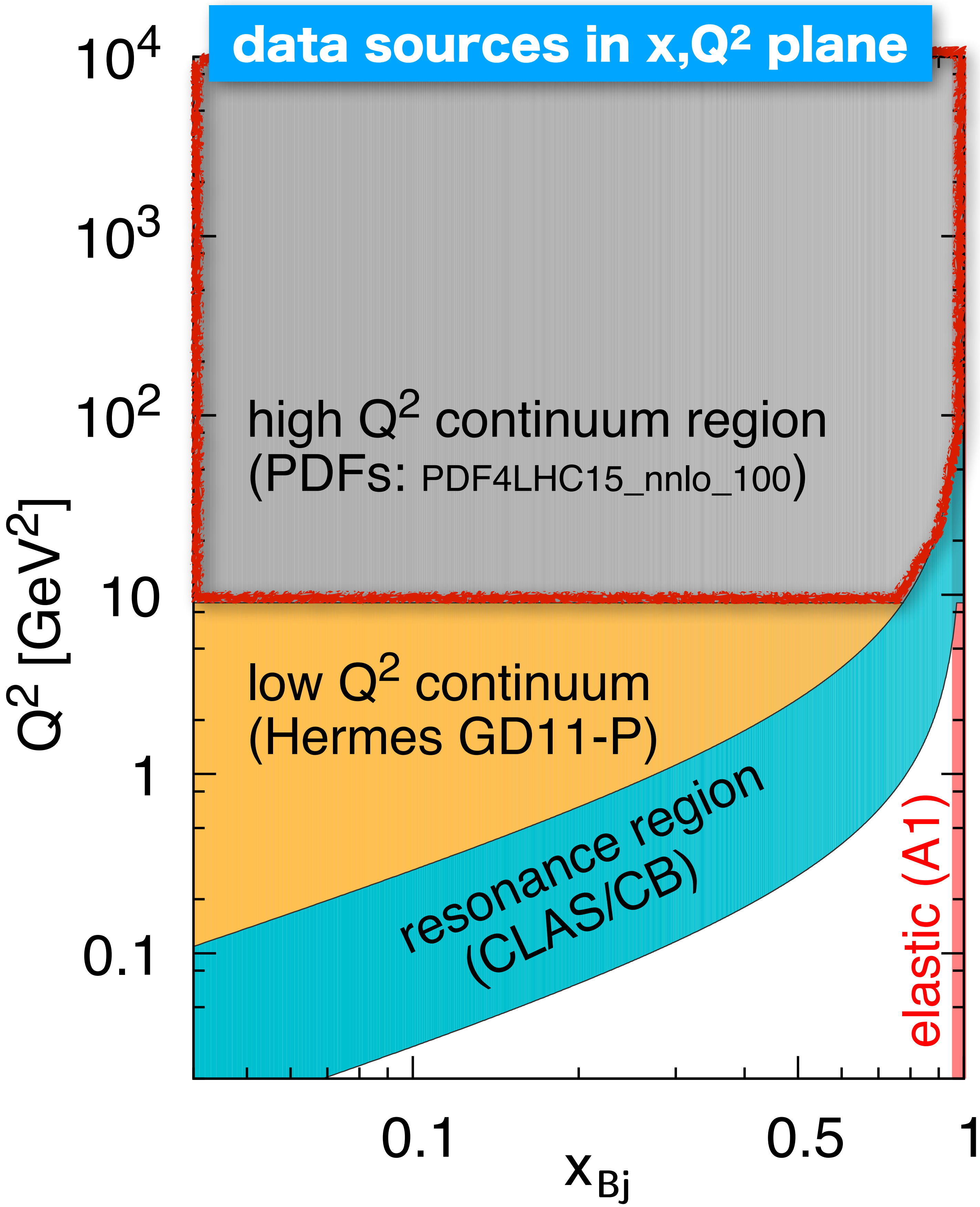
CONTINUUM COMPONENT



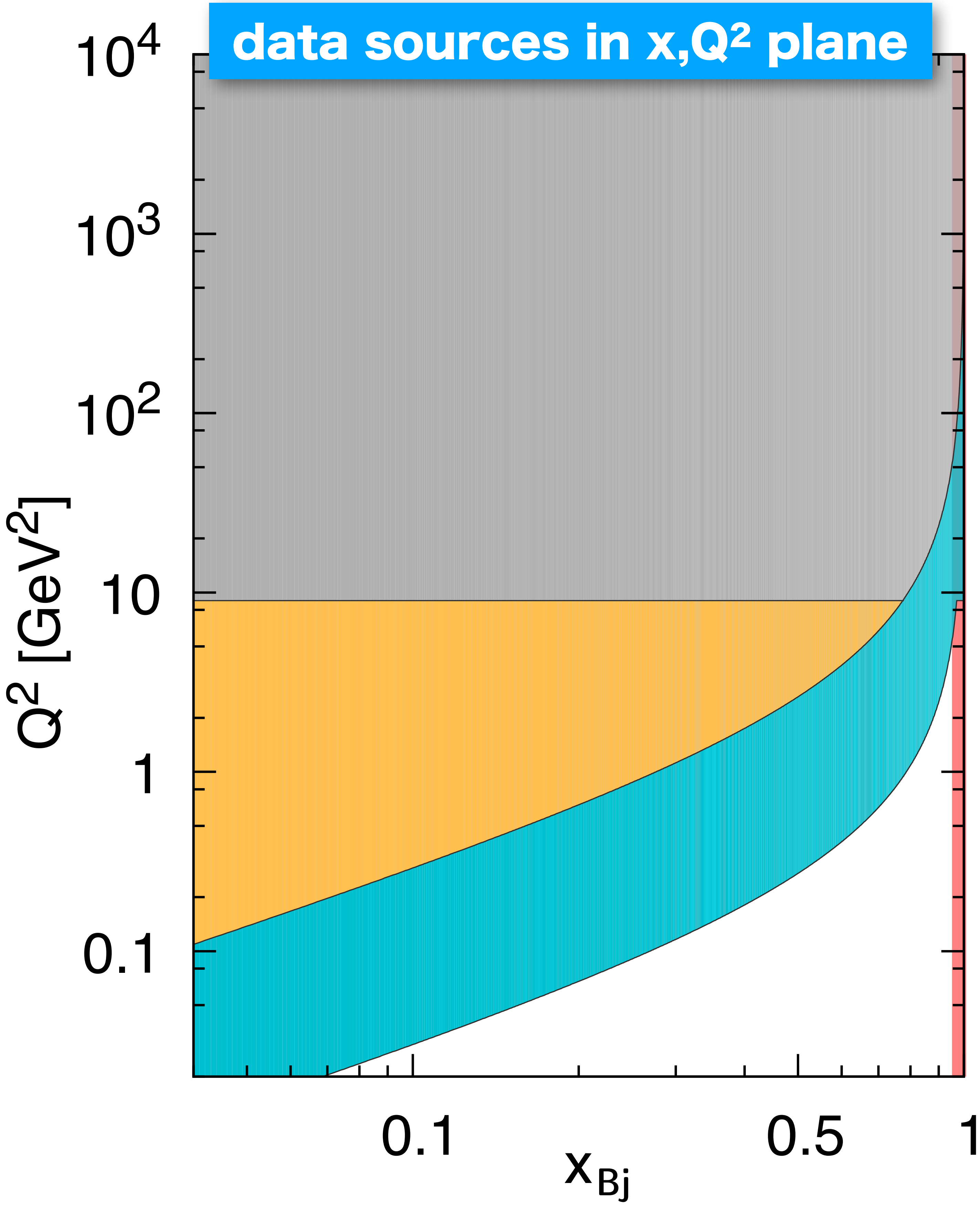
- Much data
- For $Q^2 \to 0$, $\sigma_{\gamma p}$ indep. of Q^2 at fixed W^2



CONTINUUM COMPONENT



- Less direct data for F_2 and F_L at high Q^2
- But we can reliably use PDFs and coefficient functions (up to NNLO) to calculate them
- Our default choice is PDF4LHC15_nnlo_100 (and zero-mass variable flavour-number scheme)

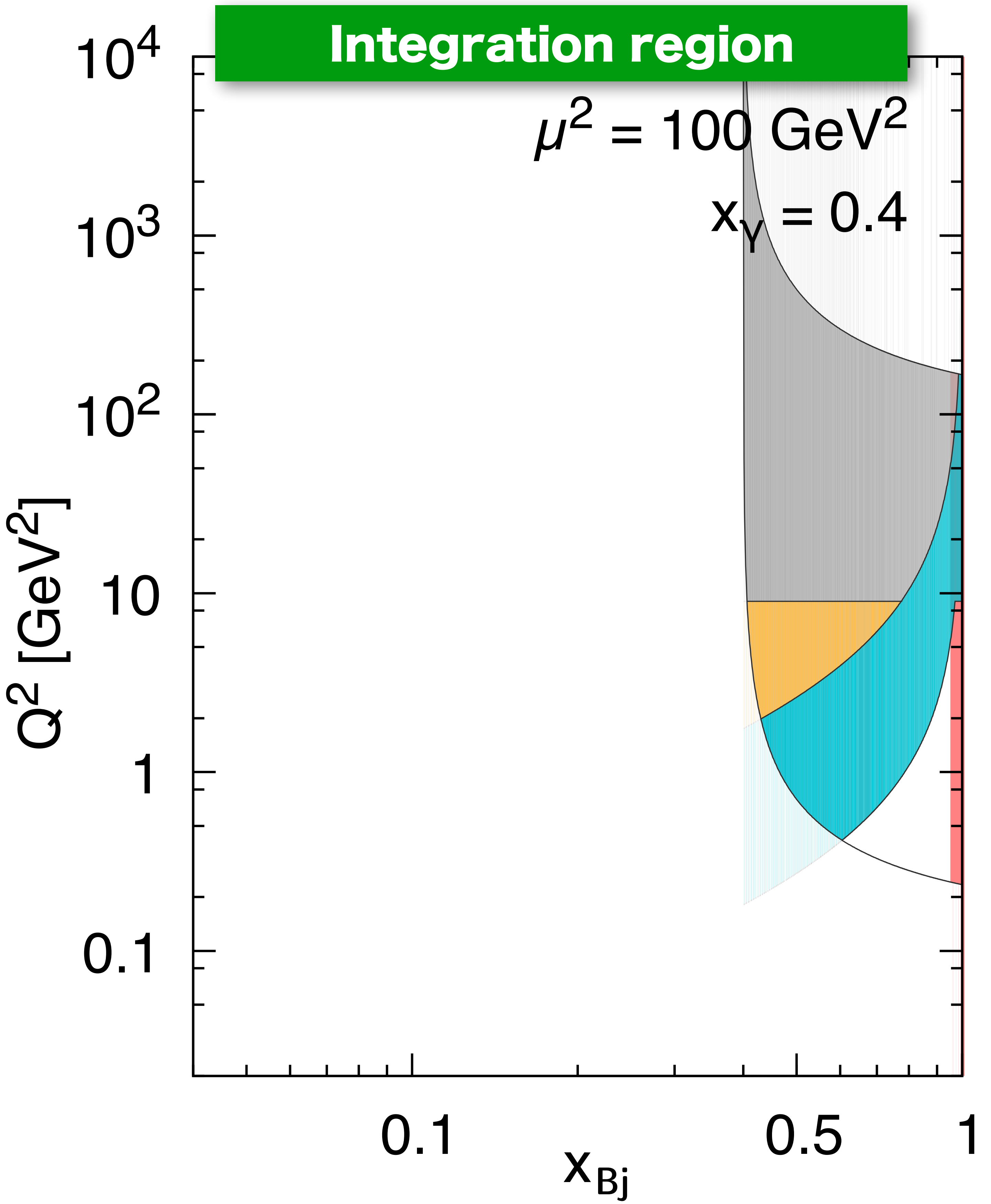


INTEGRATION REGION

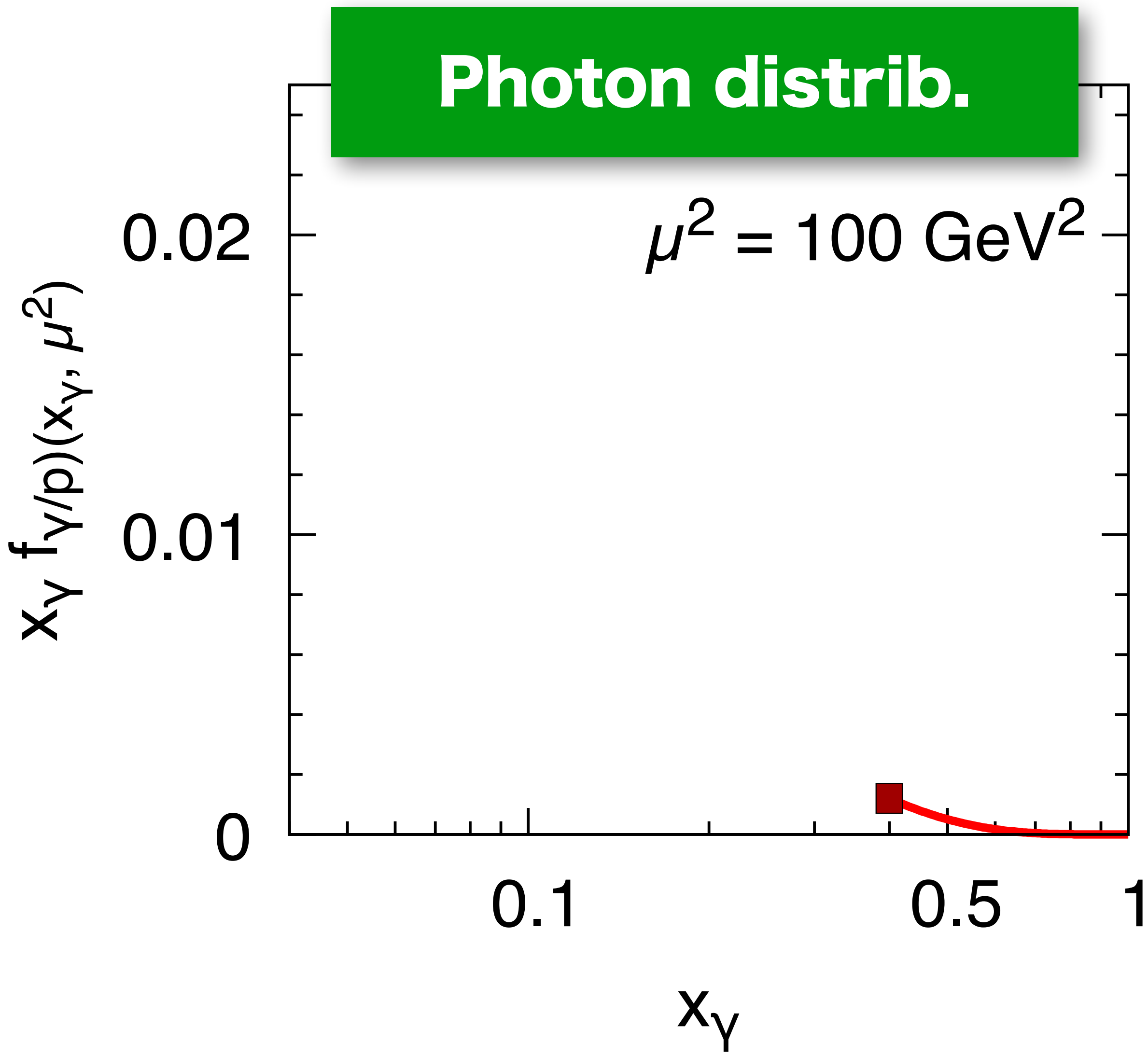
- depends on momentum fraction of the photon (x_γ) and factorisation scale (μ^2)

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

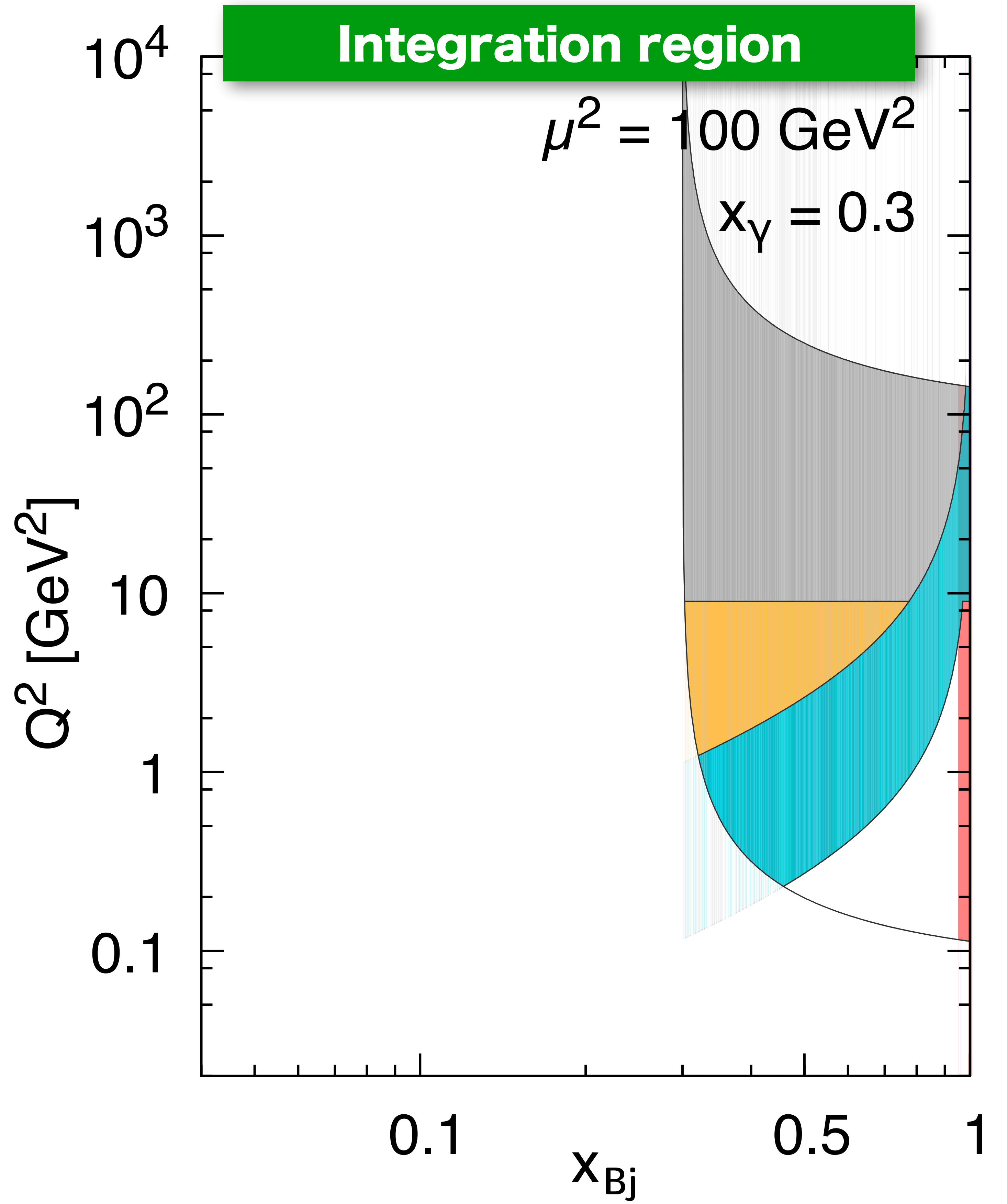
INTEGRATION REGION



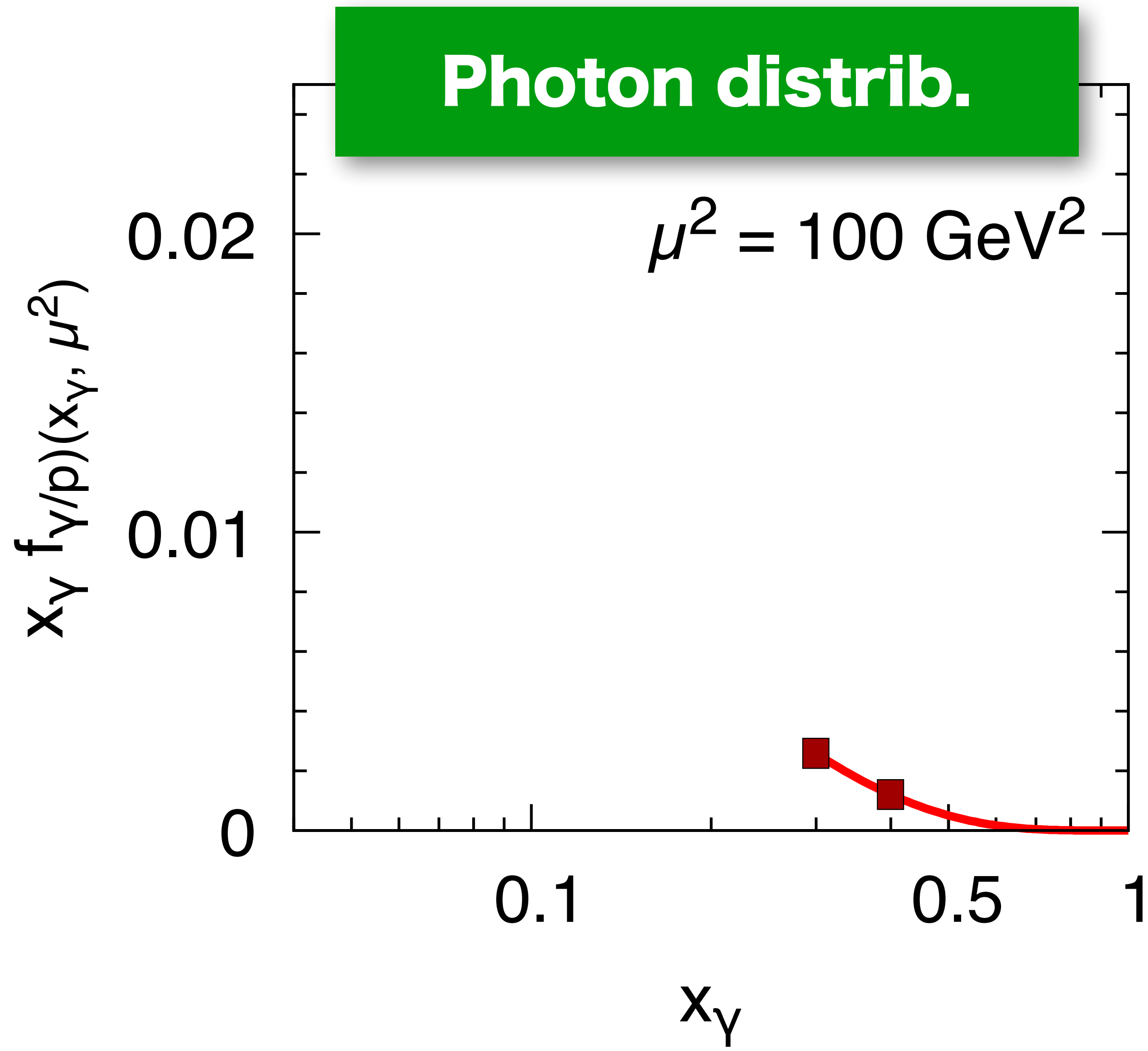
- depends on momentum fraction of the photon (x_γ) and factorisation scale (μ^2)



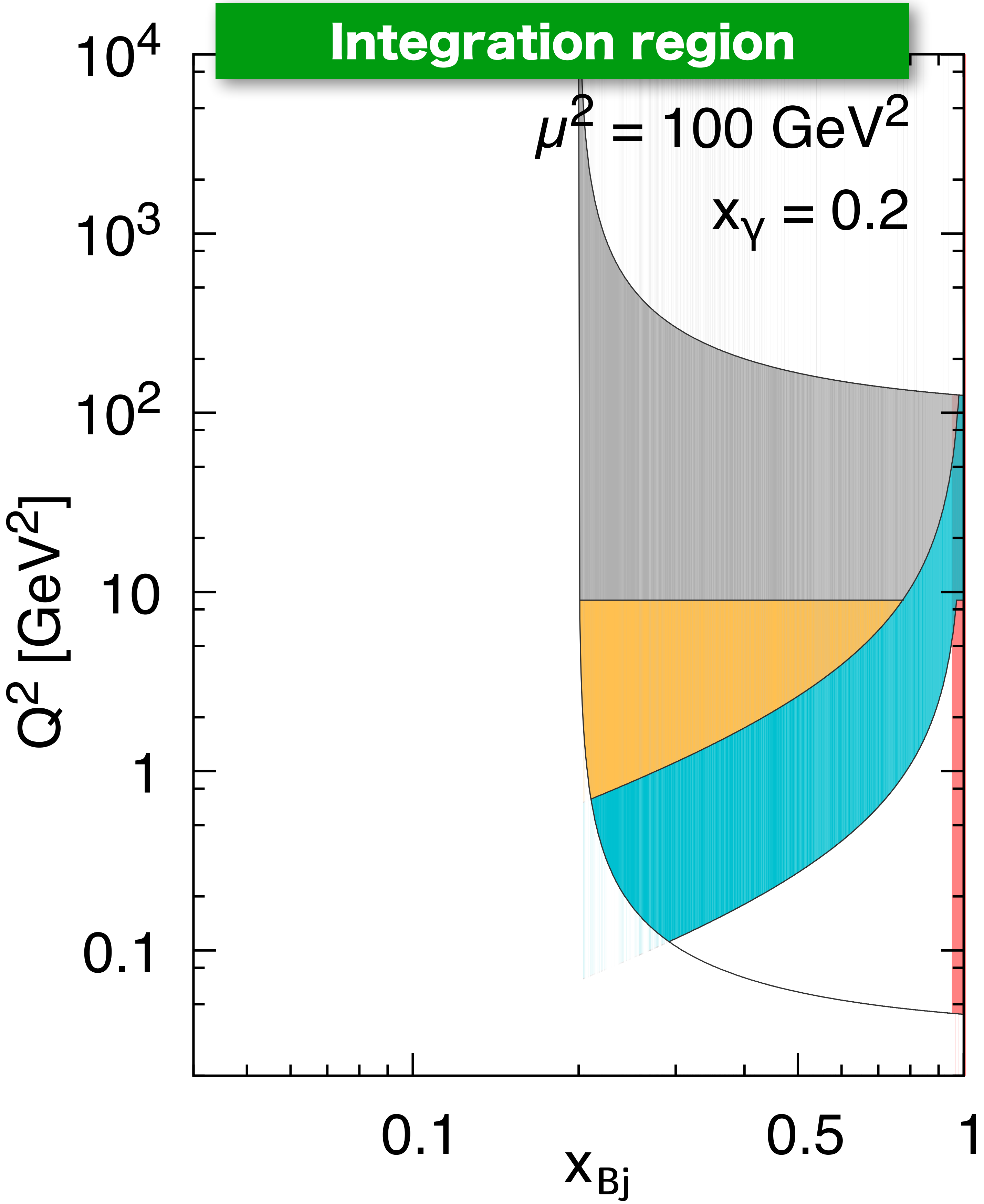
INTEGRATION REGION



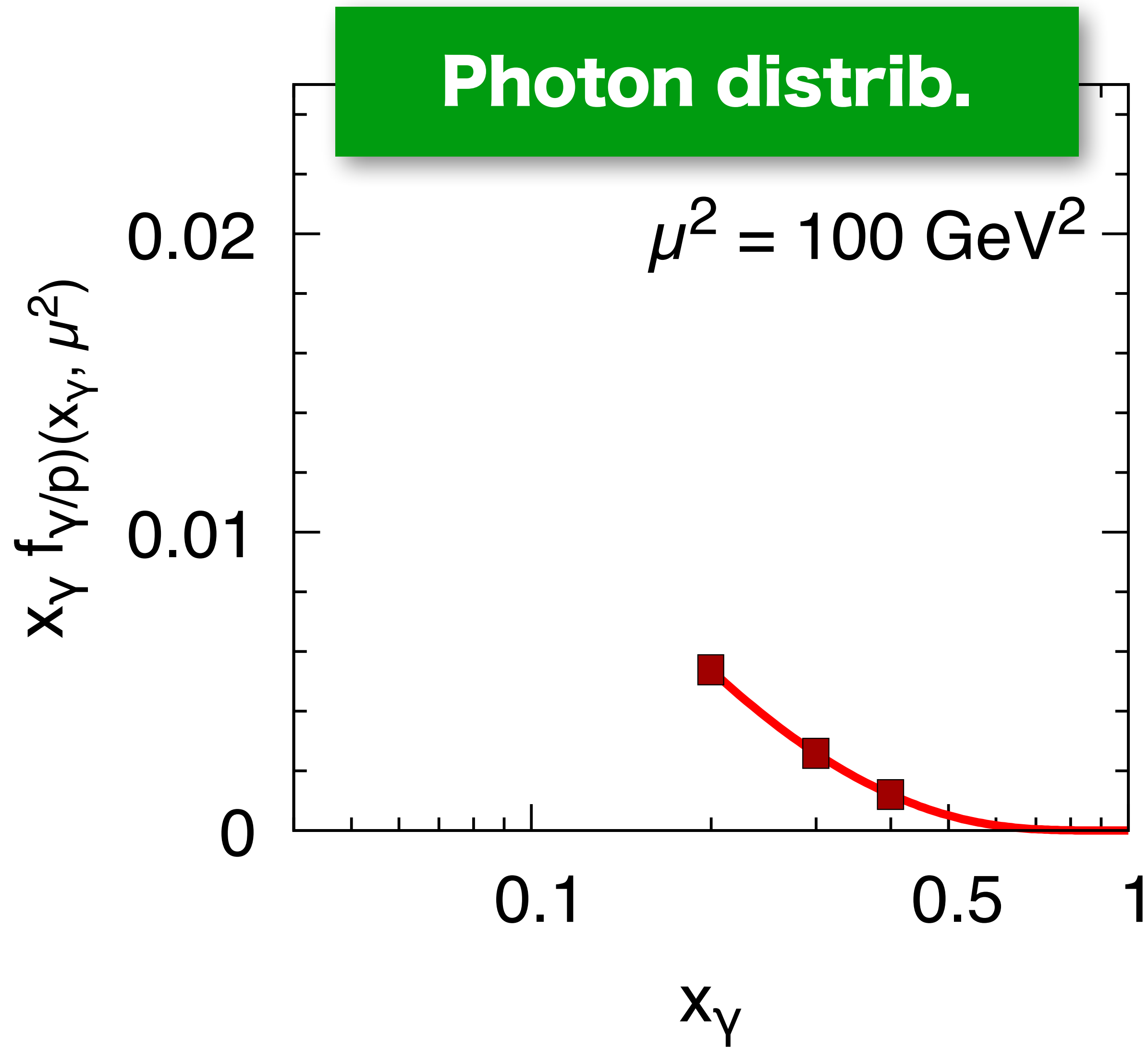
- depends on momentum fraction of the photon (x_γ) and factorisation scale (μ^2)



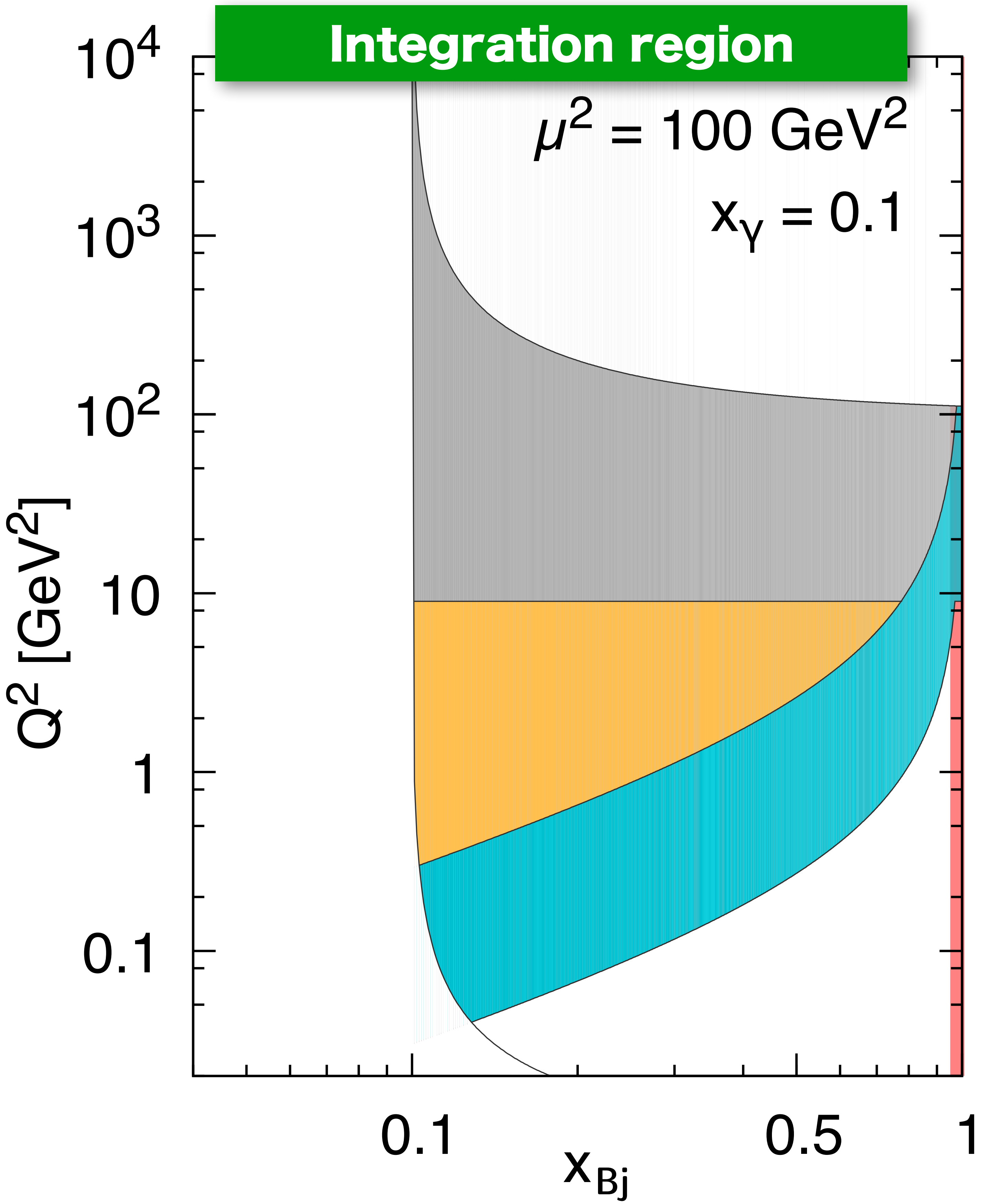
INTEGRATION REGION



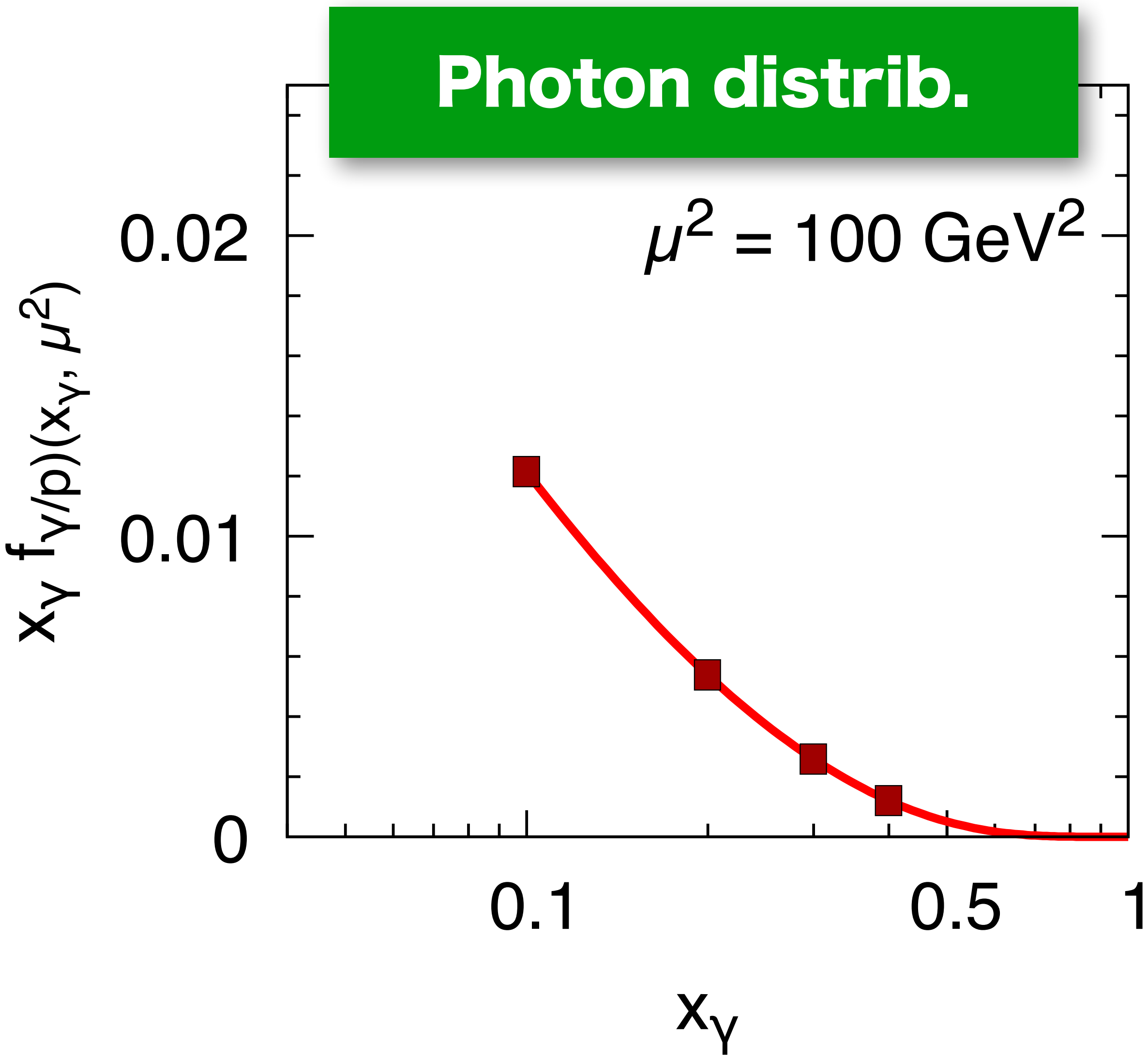
- depends on momentum fraction of the photon (x_γ) and factorisation scale (μ^2)

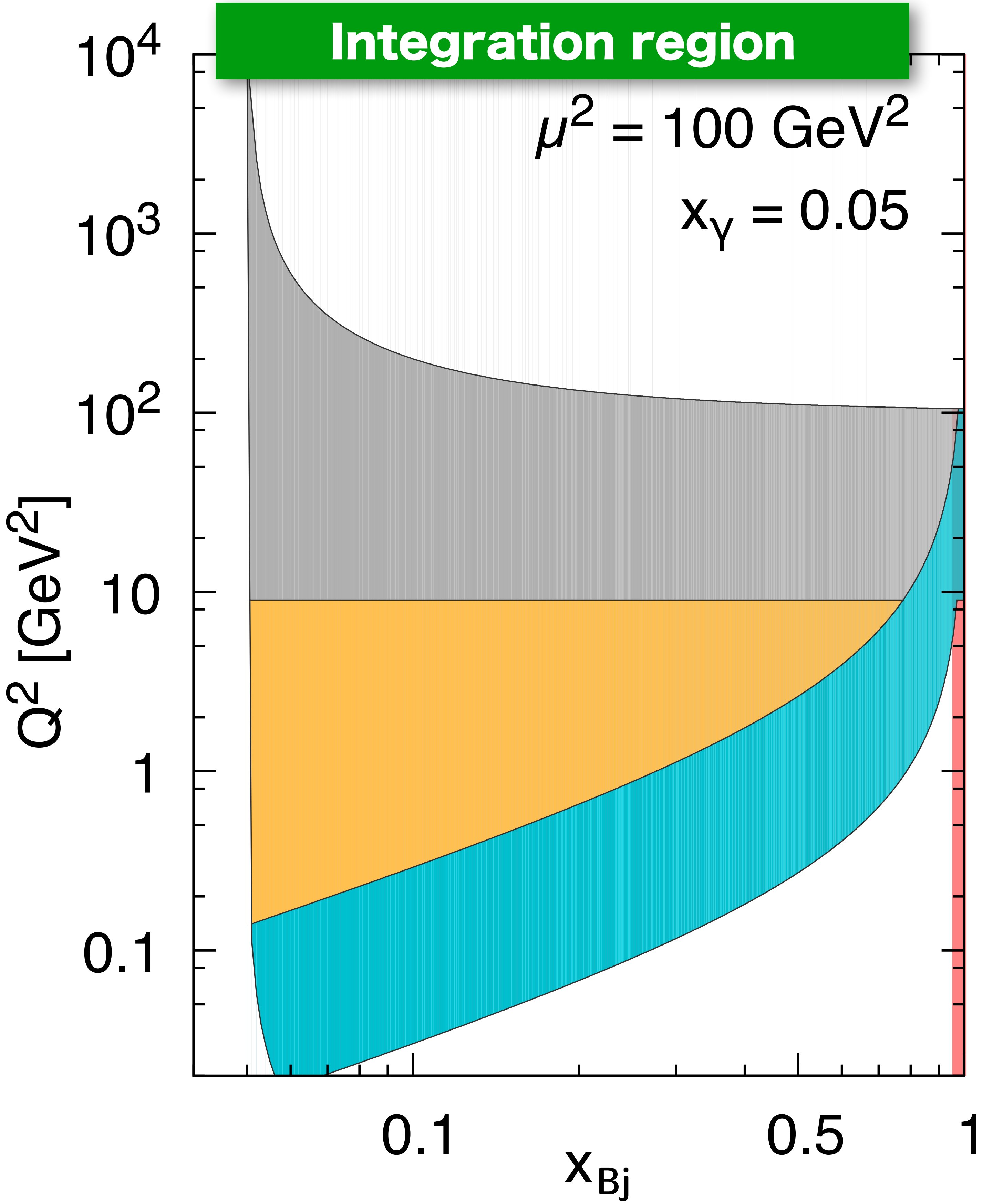


INTEGRATION REGION



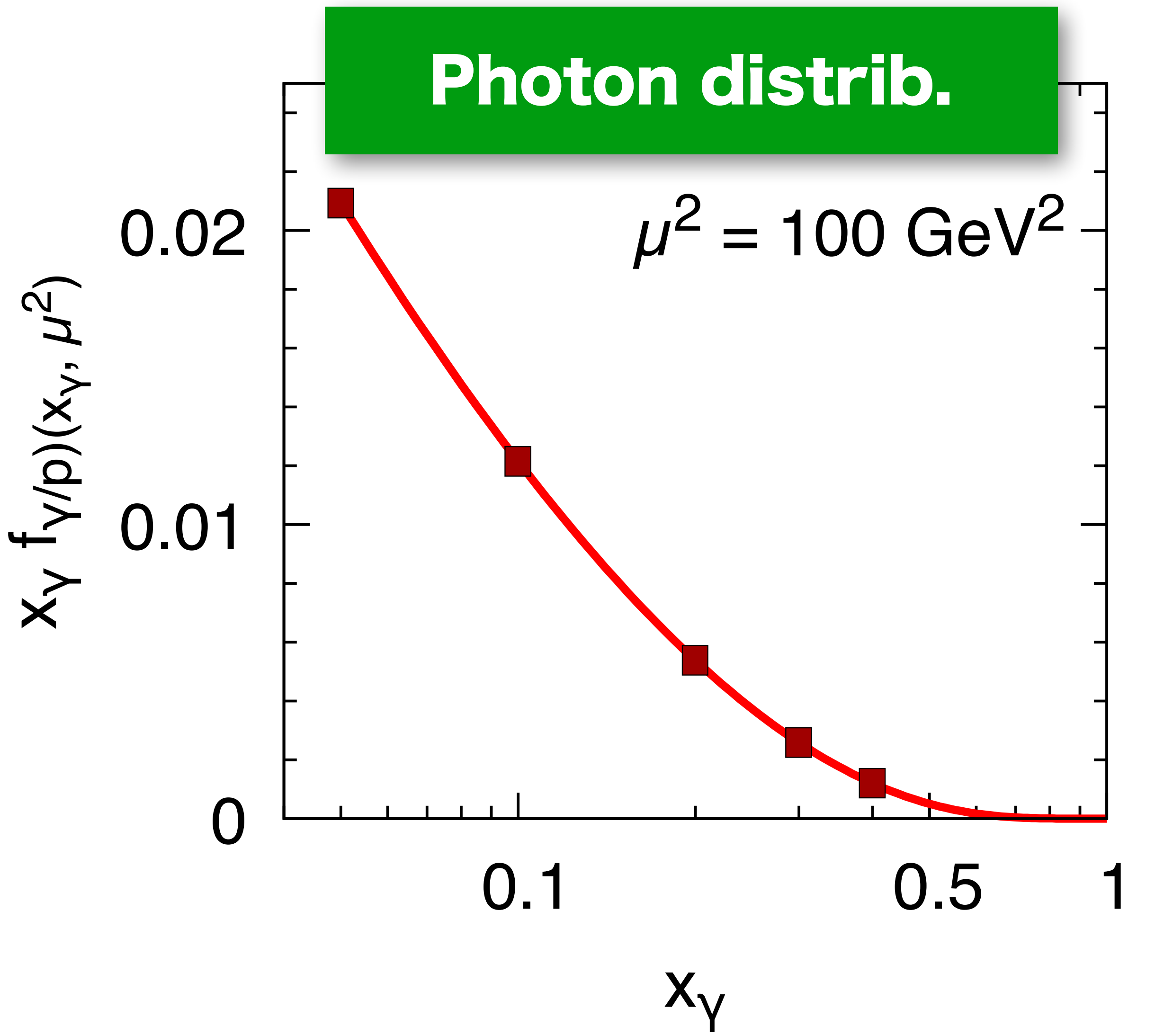
- depends on momentum fraction of the photon (x_γ) and factorisation scale (μ^2)



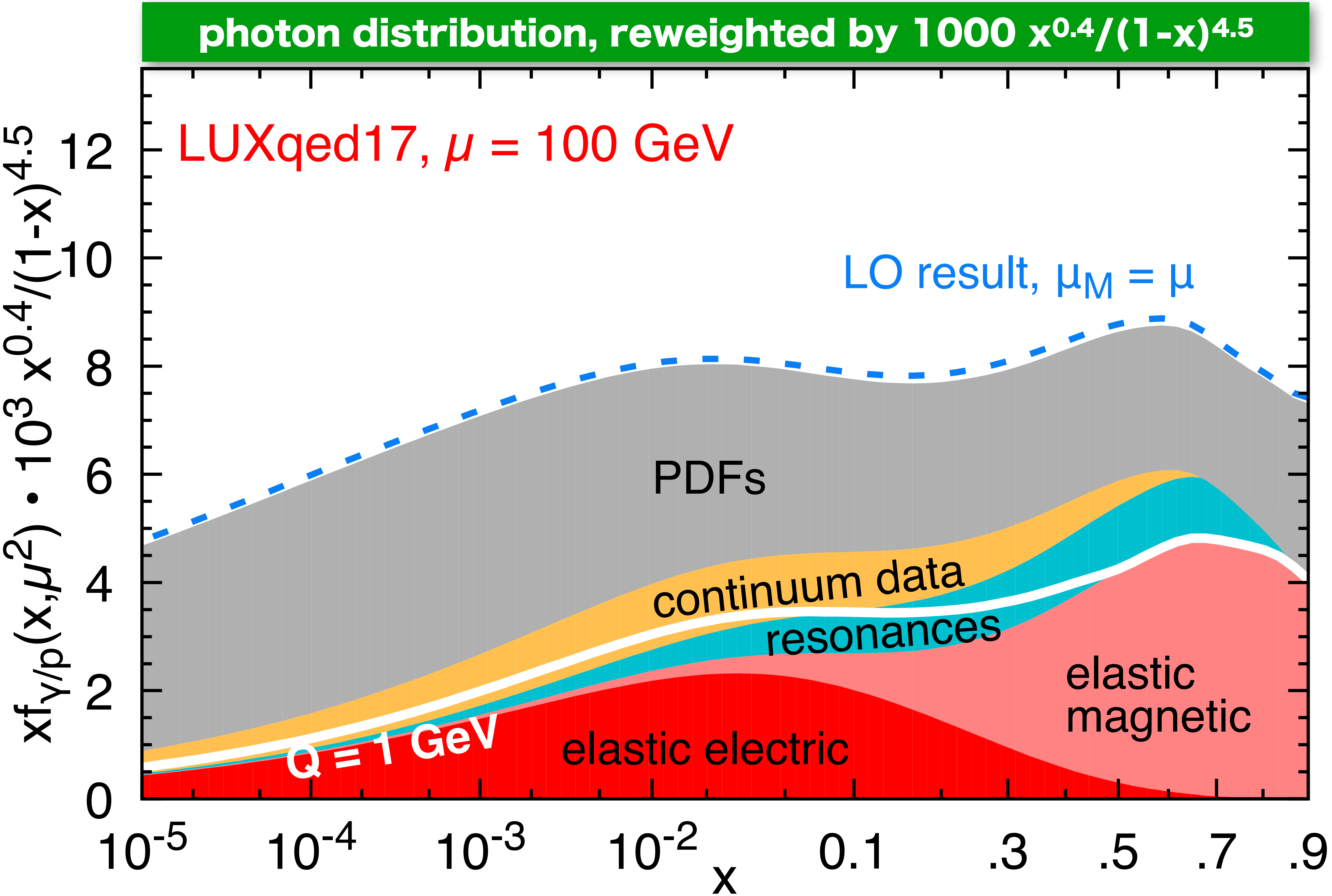


INTEGRATION REGION

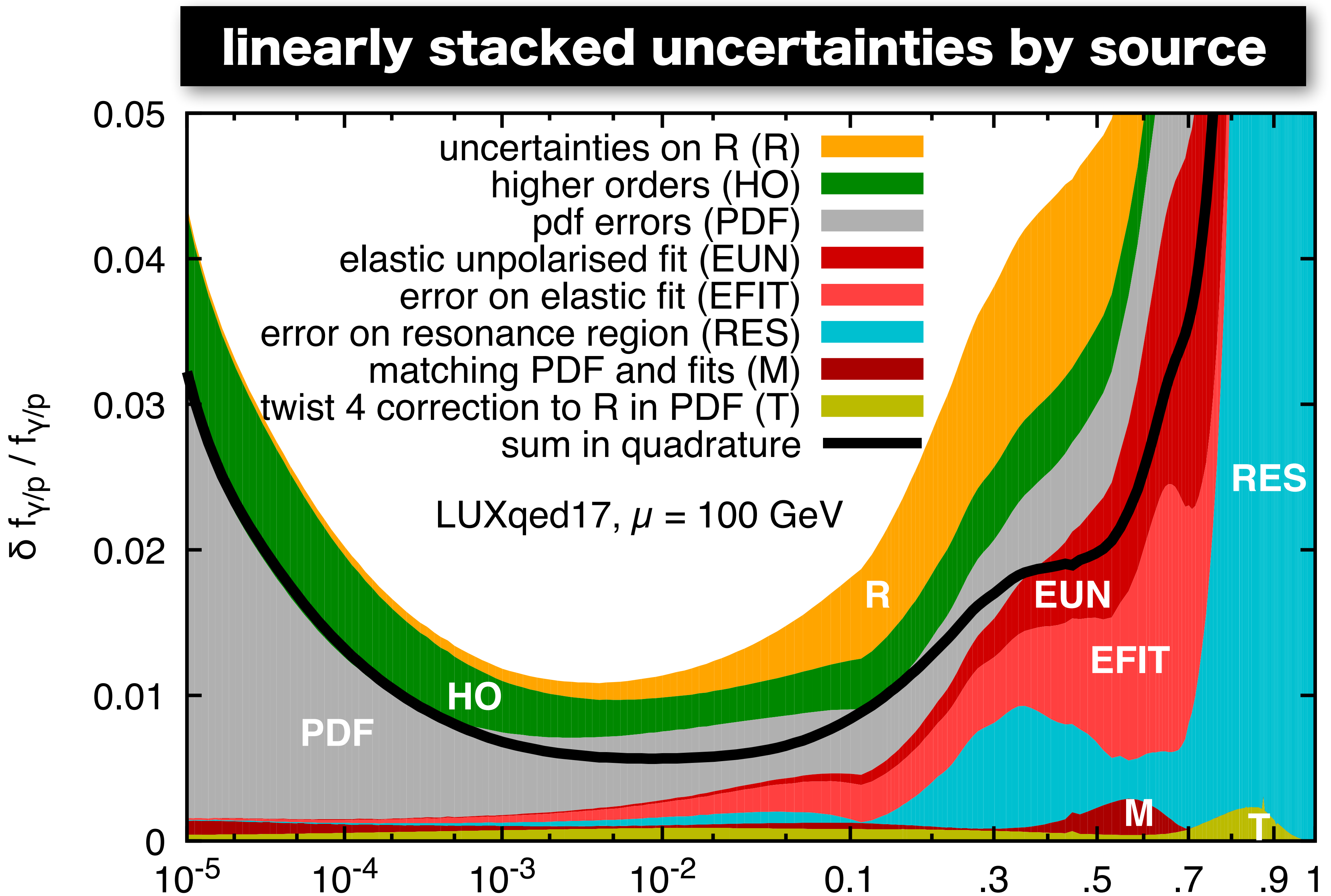
- depends on momentum fraction of the photon (x_γ) and factorisation scale (μ^2)



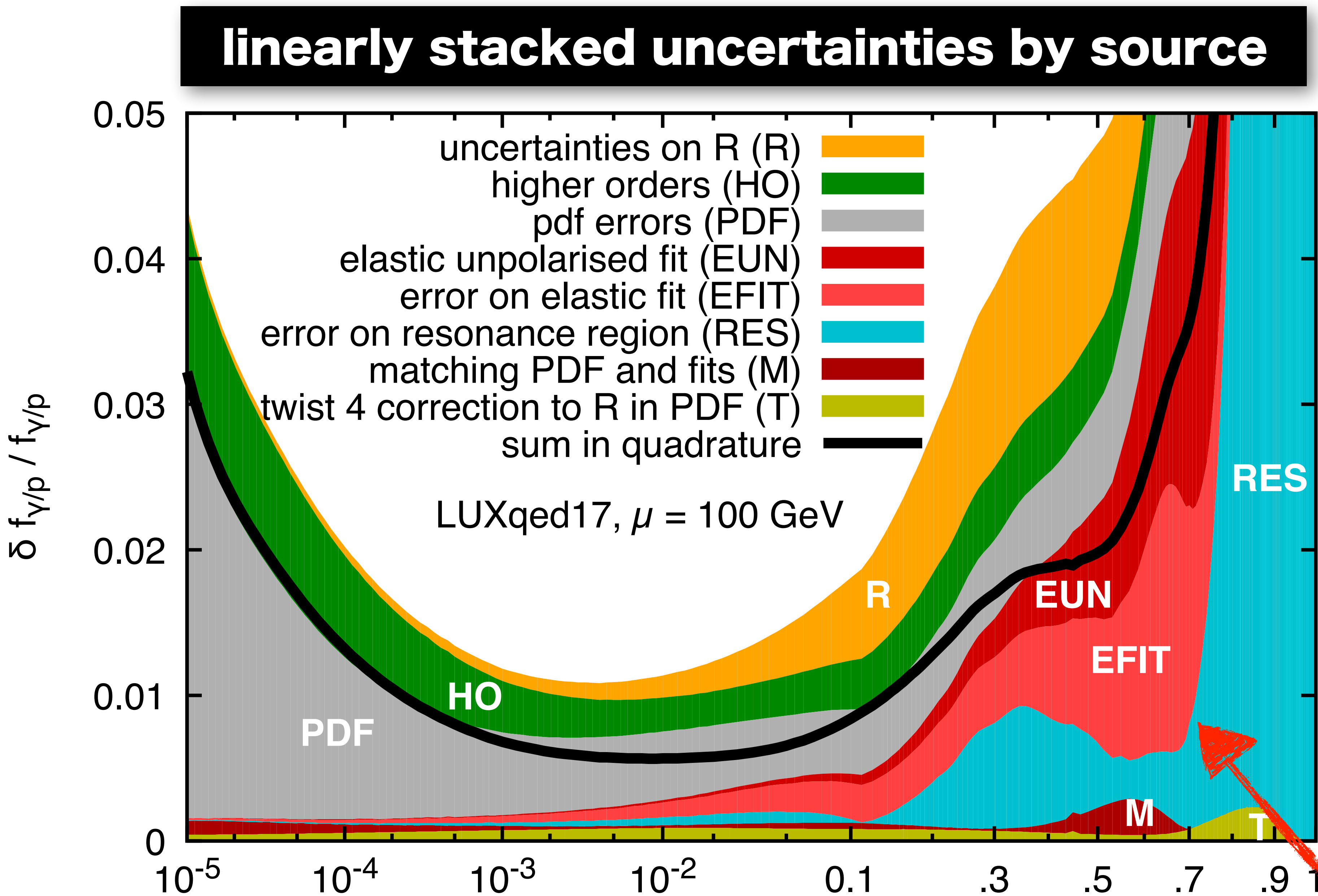
SEPARATE CONTRIBUTIONS TO PHOTON PDF



photon uncertainties (aim to be conservative & pragmatic)



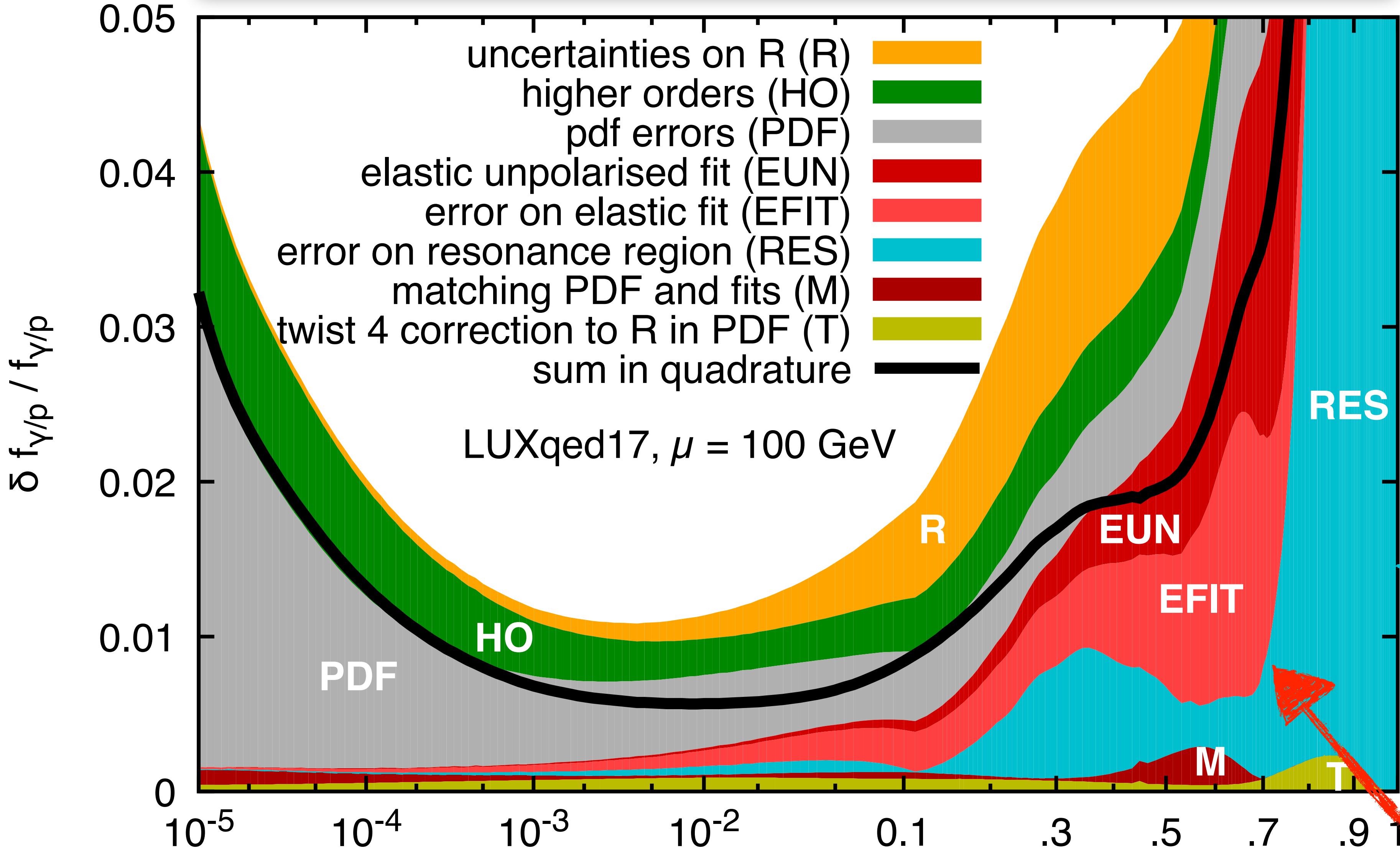
photon uncertainties (aim to be conservative & pragmatic)



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

photon uncertainties (aim to be conservative & pragmatic)

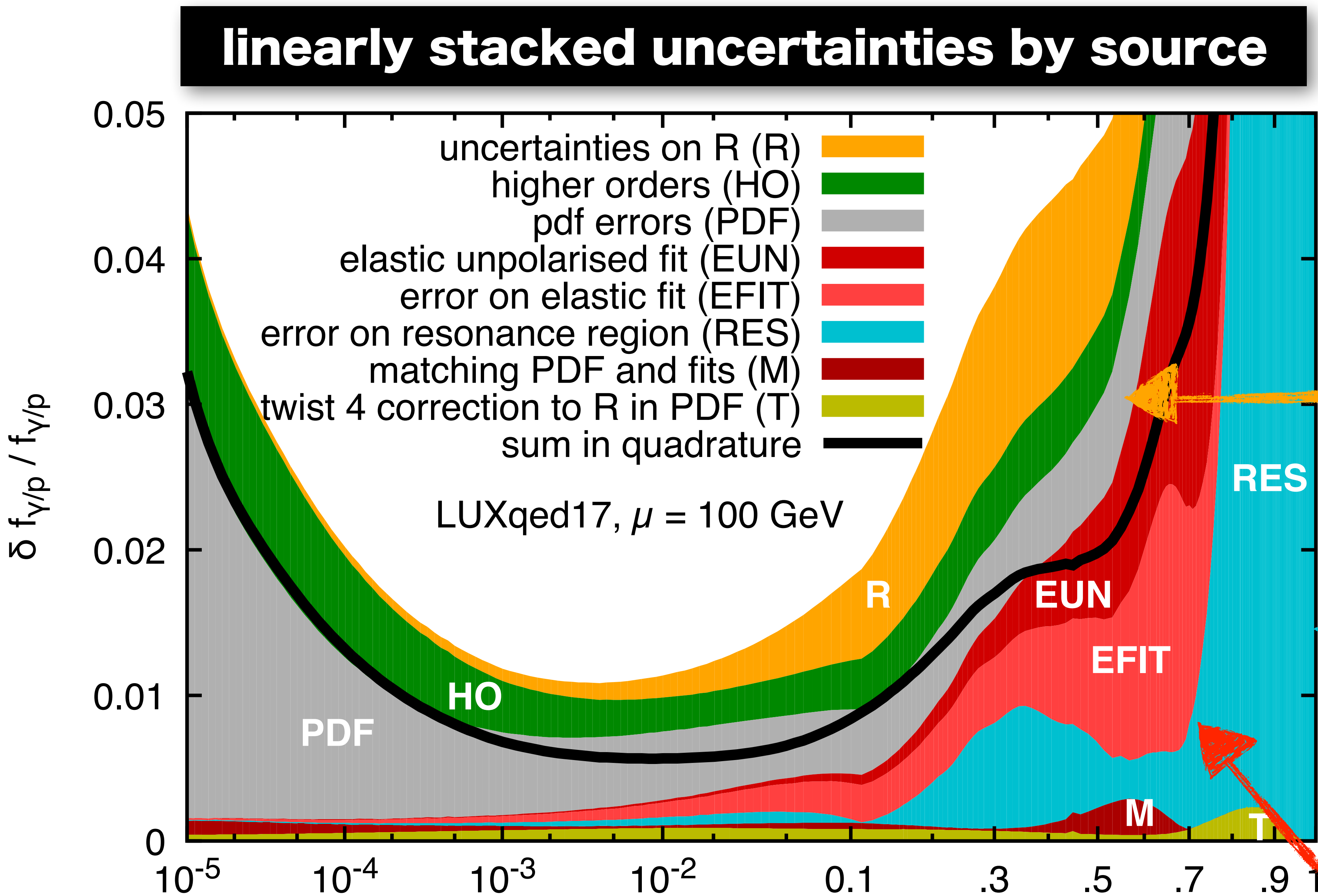
linearly stacked uncertainties by source



replace CLAS resonance fit with Christy-Bosted

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

photon uncertainties (aim to be conservative & pragmatic)

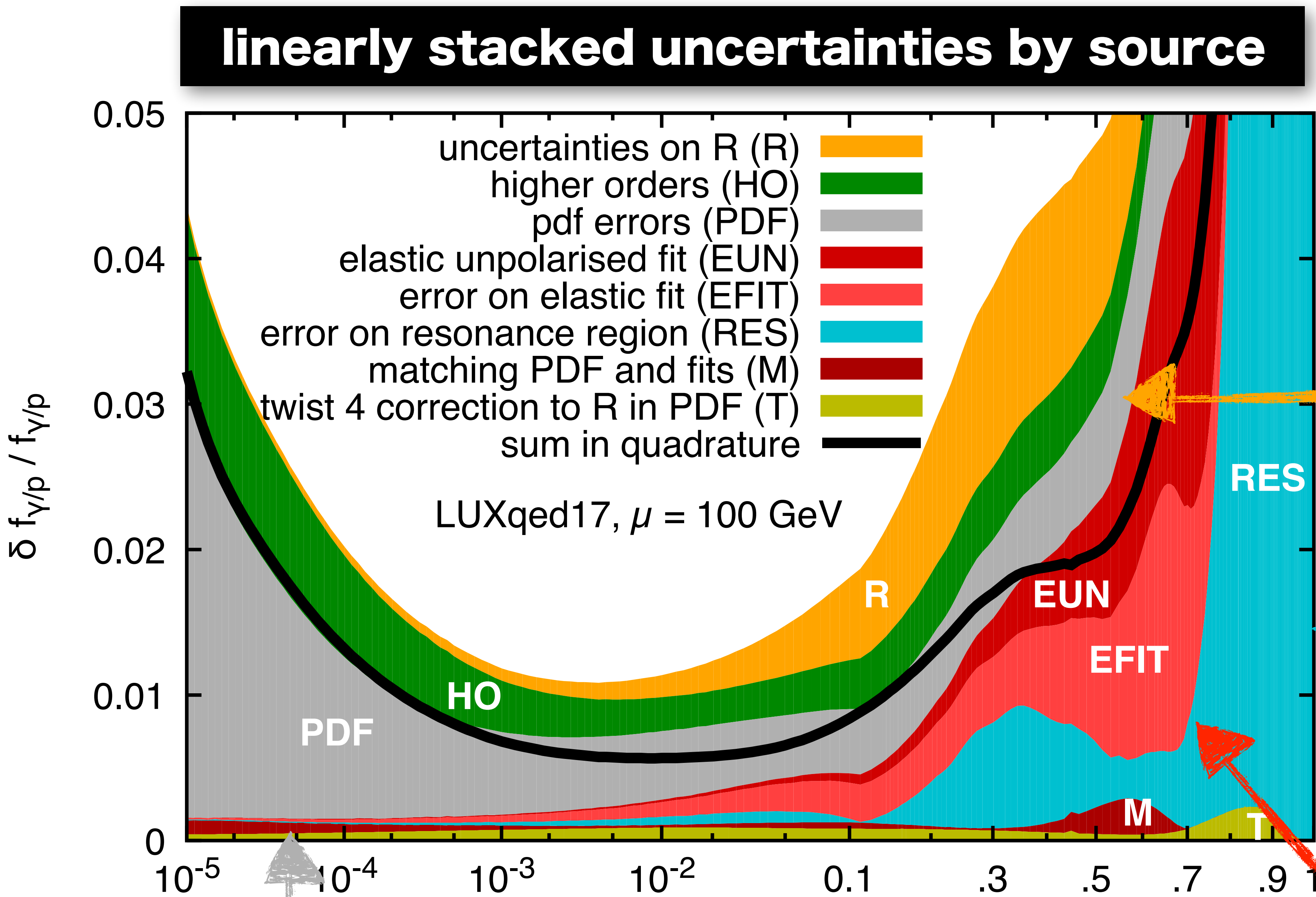


±50% on R ($\sim F_L/(F_2-F_L)$) in low-Q^2 continuum and resonance regions

replace CLAS resonance fit with Christy-Bosted

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

photon uncertainties (aim to be conservative & pragmatic)



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

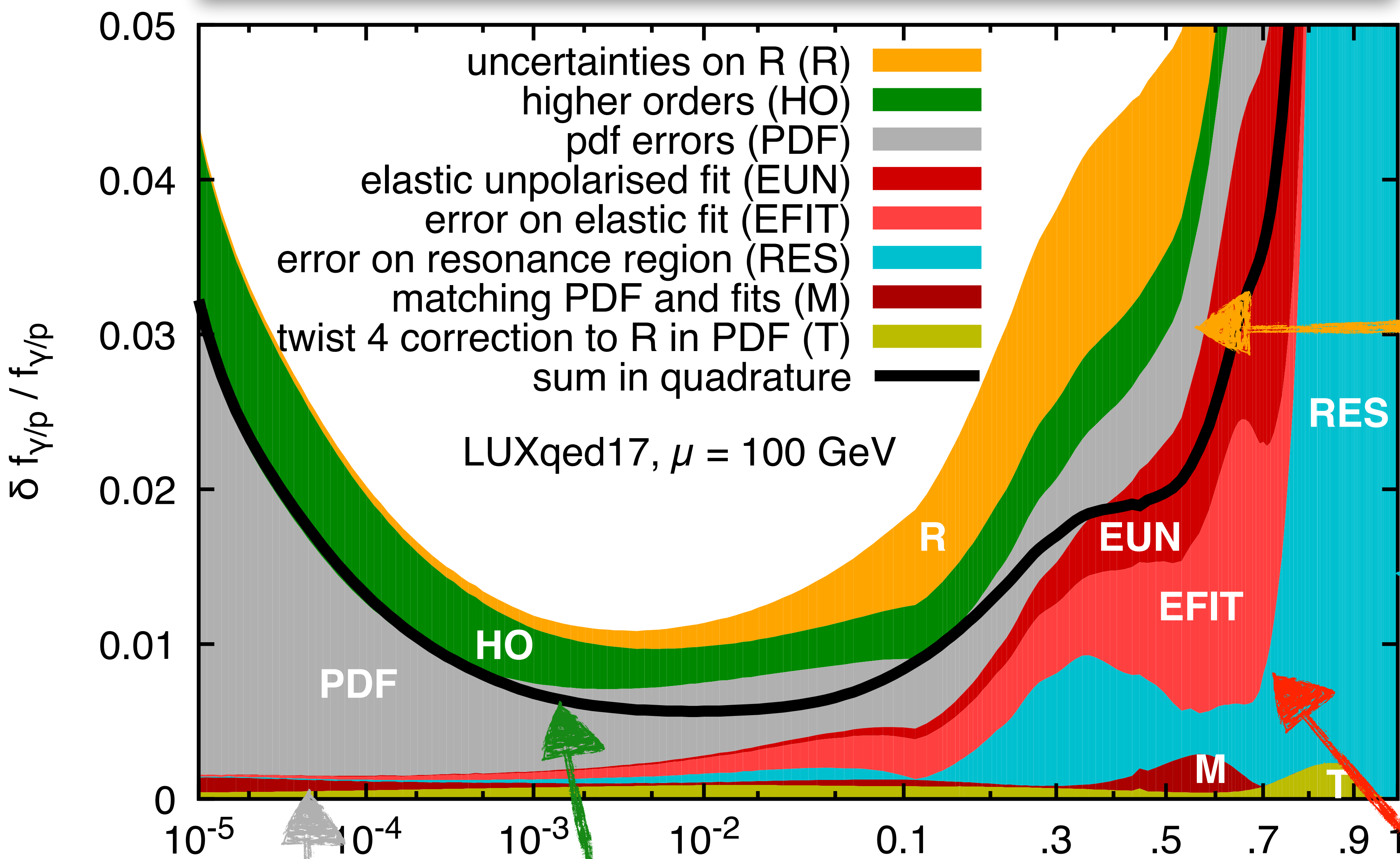
replace CLAS resonance fit with Christy-Bosted

uncertainty on elastic component (quoted $\oplus$ unpol./pol.)

standard PDF uncertainty

photon uncertainties (aim to be conservative & pragmatic)

linearly stacked uncertainties by source



$\pm 50\%$ 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

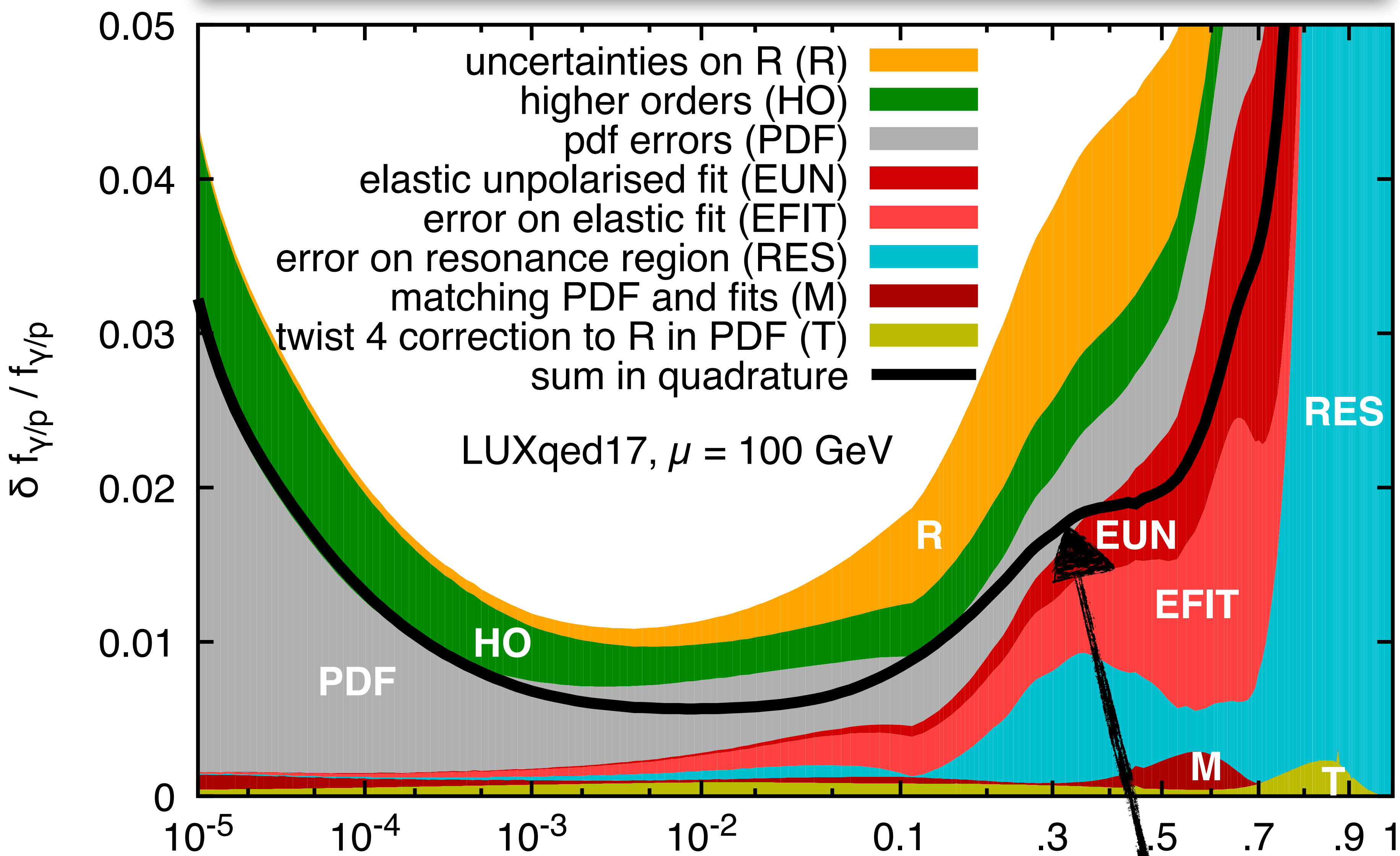
standard PDF uncertainty

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

uncertainty on elastic component (quoted $\oplus$ unpol./pol.)

photon uncertainties (aim to be conservative & pragmatic)

linearly stacked uncertainties by source



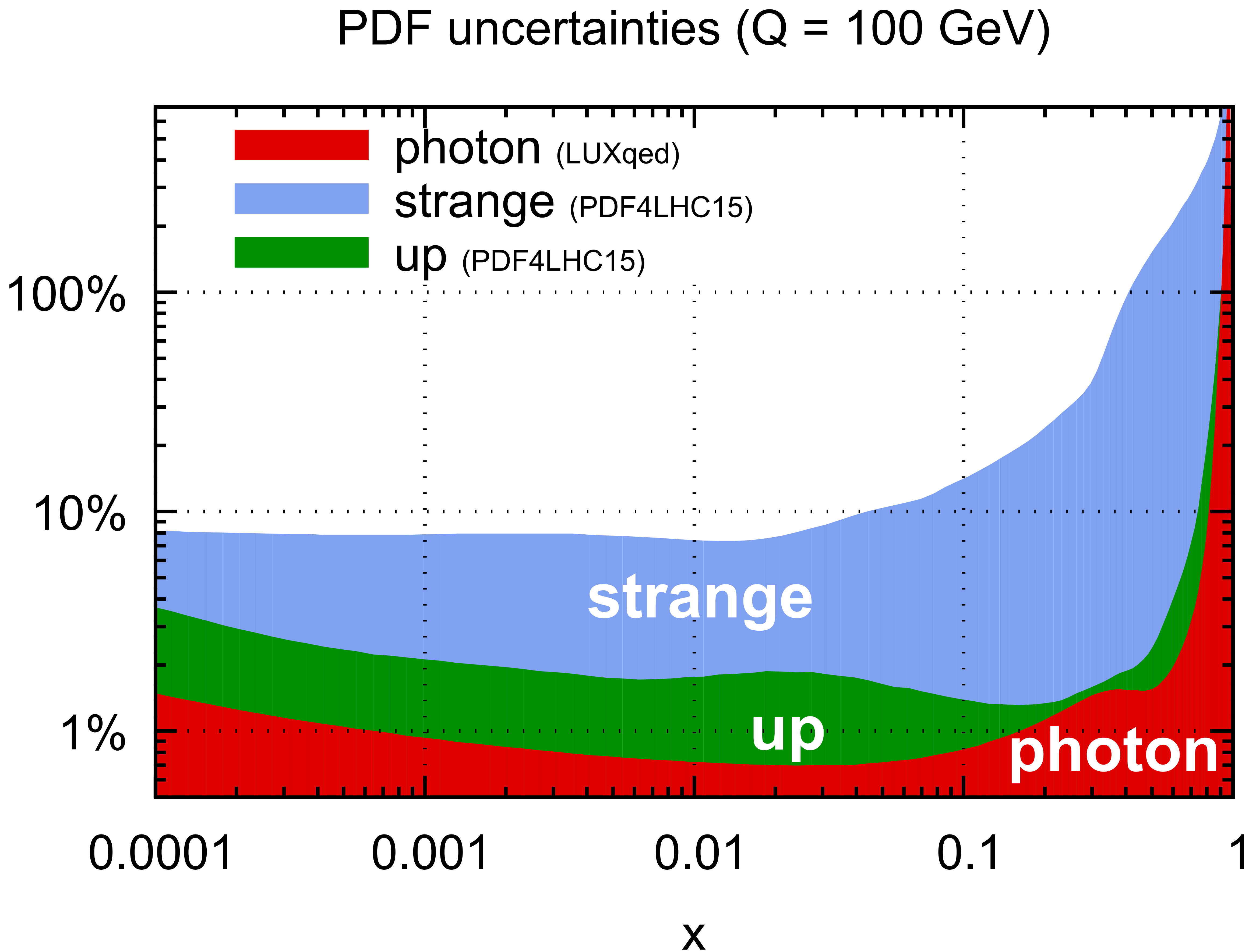
final total uncertainty ~ 1 – 2%
(sum in quad. of all sources)

PHOTON PDF ESTIMATES (not exhaustive)

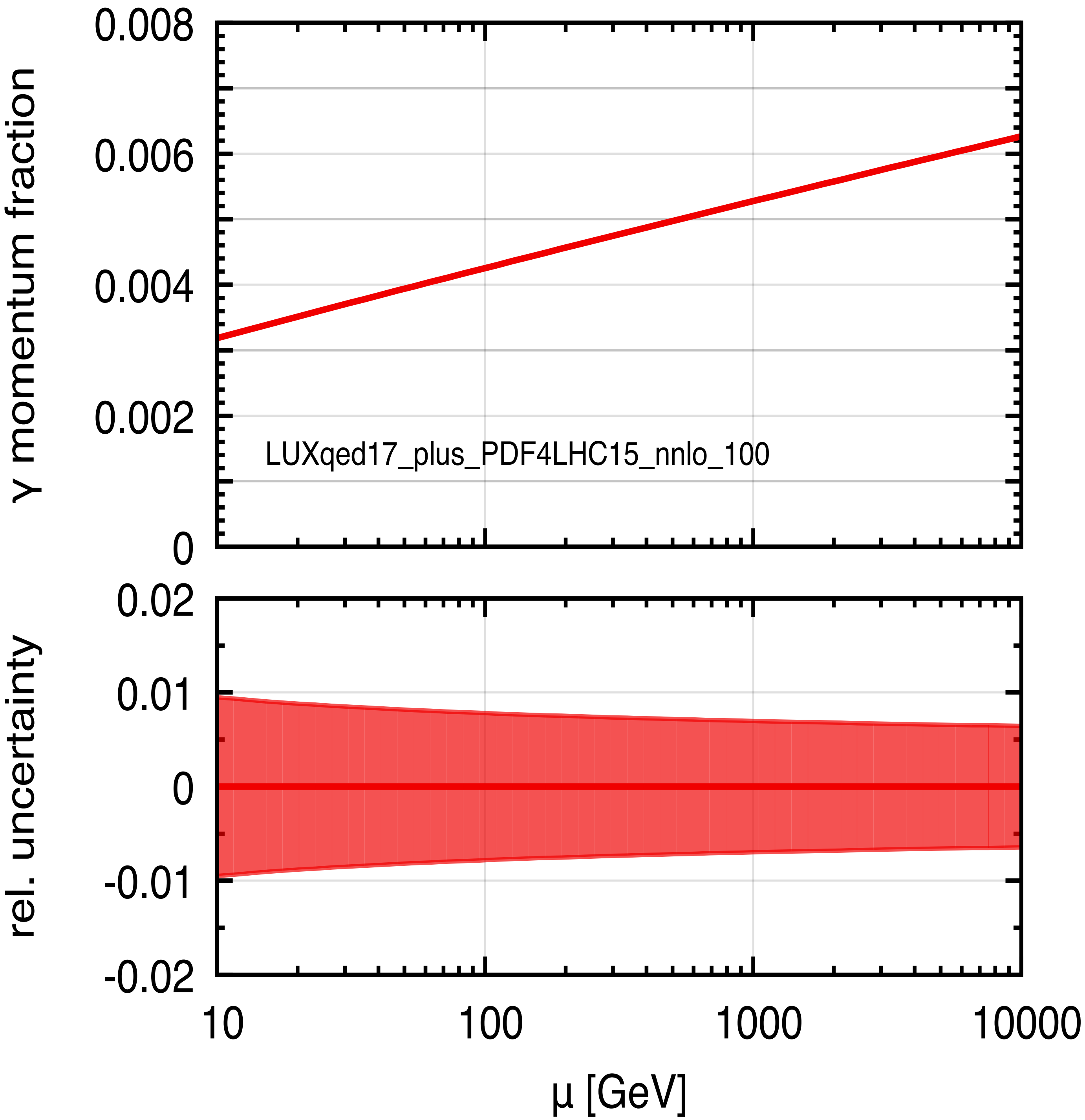
	elastic	inelastic	in LHAPDF?
Gluck Pisano Reya 2002	dipole	model	✗
MRST2004qed	✗	model	✓
NNPDF23qed	no separation; fit to data		✓
CT14qed	✗	model (data-constrained)	✓
CT14qed_inc	dipole	model (data-constrained)	✓
Martin Ryskin 2014	dipole (only electric part)	model	✗
Harland-Lang, Khoze Ryskin 2016	dipole	model	✗
LUXqed 2016/17	data	data	✓

examine result

PHOTON UNCERTAINTY (1–2%) COMPARED TO OTHER FLAVOURS



MOMENTUM CARRIED BY PHOTON



momentum (μ = 100 GeV)	
gluon	46.8 ± 0.4%
up valence	18.1 ± 0.3%
down valence	7.5 ± 0.2%
light sea quarks	20.5 ± 0.4%
charm	4.0 ± 0.1%
bottom	2.5 ± 0.1%
photon	0.425 ± 0.003%

LUXqed17_plus_PDF4LHC15_nnlo_100

(1+107 members, symmhessian, errors handled by LHAPDF out of the box)

NNPDF approach — LUXqed photon approach, refits other flavours

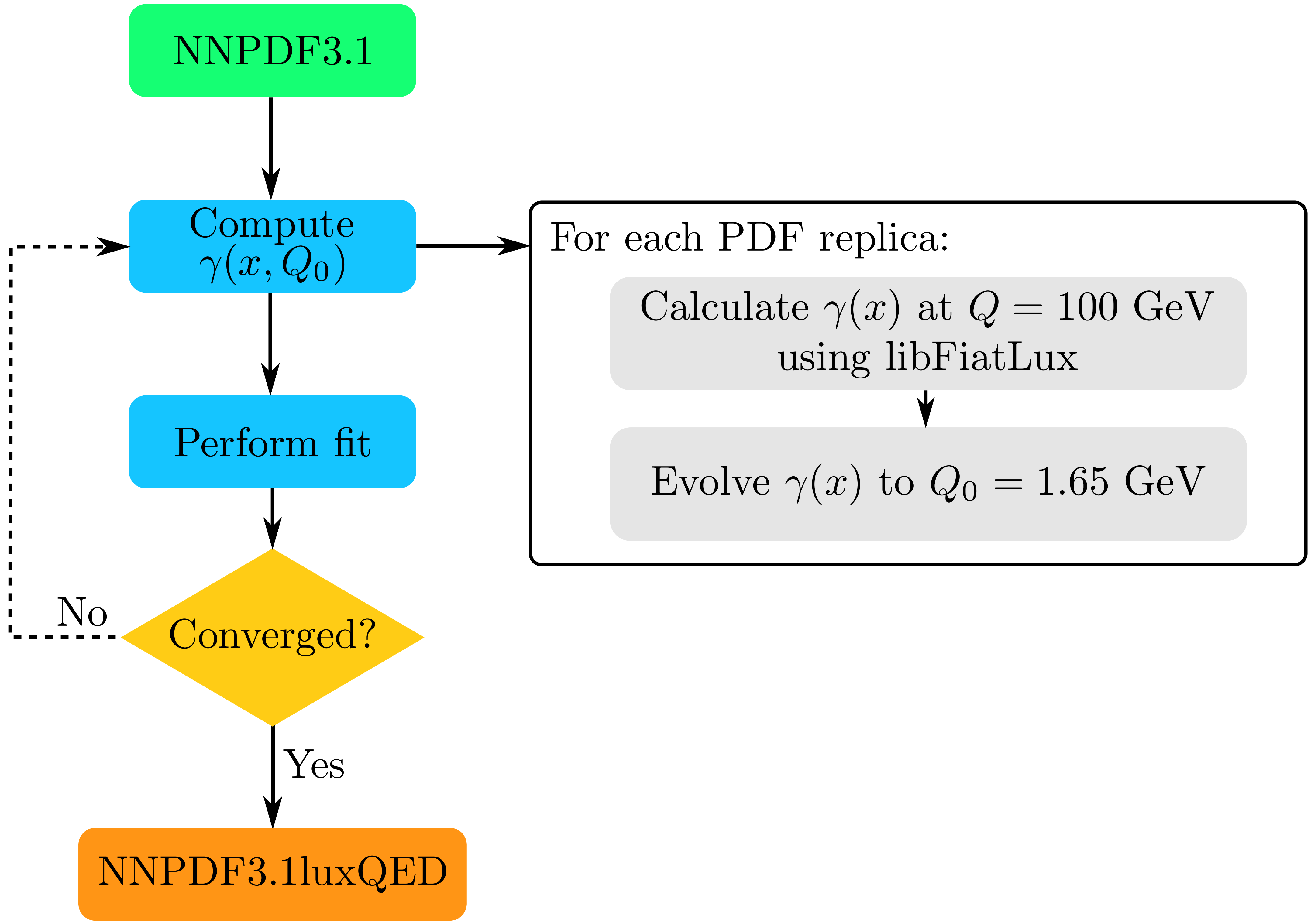
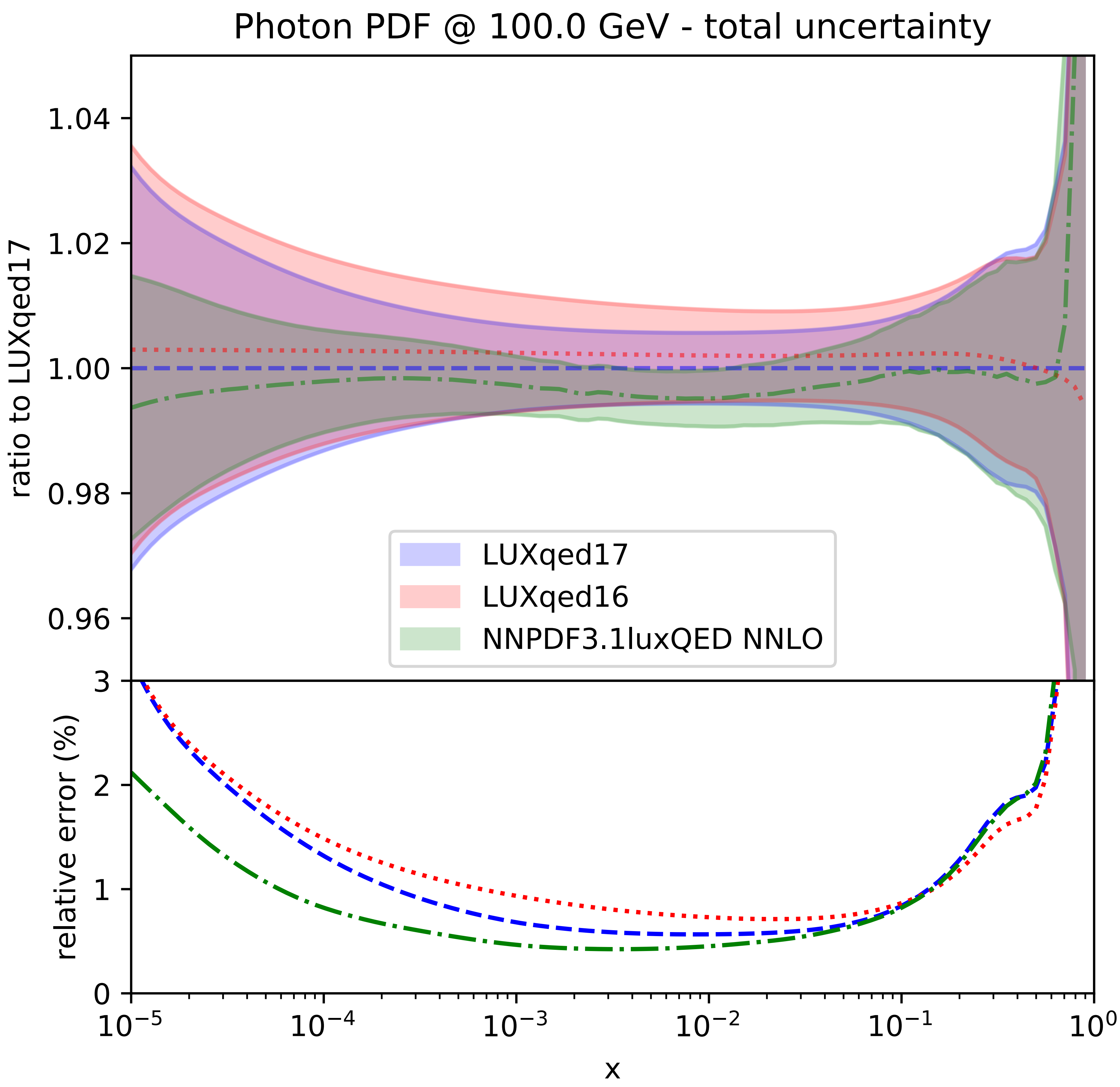
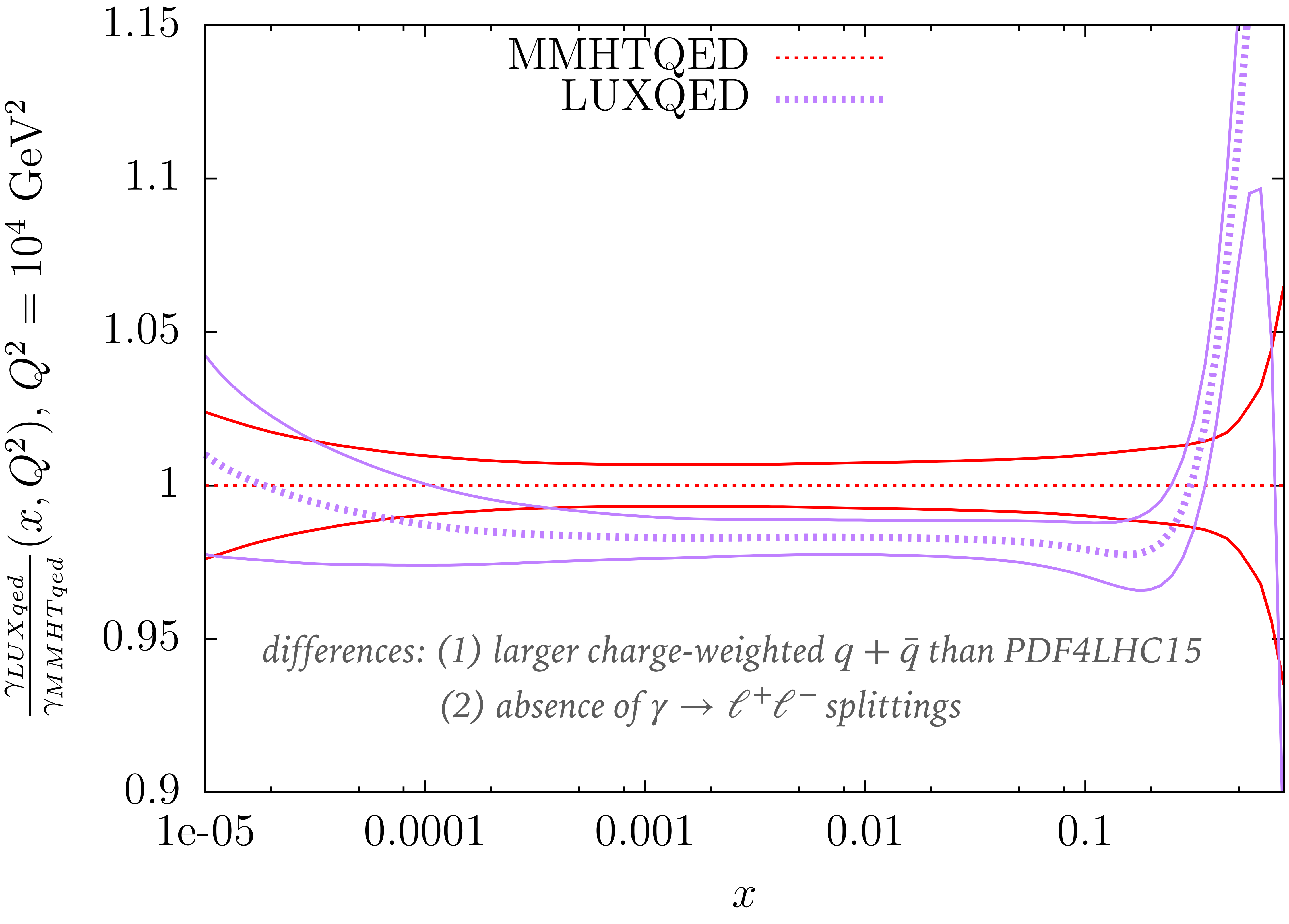


Figure 2.2. Flow diagram representing the NNPDF3.1luxQED fitting strategy. In the last iteration $n_{\rm ite}$, once the procedure has converged, the additional LUXqed17 are added to $\gamma(x, Q)$, see Sect. 2.5.

NNPDF LUXqed (1712.07053) v. our LUXqed



MMHT-framework "ad lucem" (1907.02750) v. our LUXqed



MMHT-framework "ad lucem" (1907.02750) v. our LUXqed

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

$$-z^2 F_L(x/z, Q^2) \Bigg] - \alpha^2(Q_0^2) \left(z^2 + \ln(1-z) z P_{\gamma,q}(z) - \frac{2x^2 m_p^2 z}{Q_0^2} \right) F_2(x/z, Q_0^2) \Bigg\}.$$

$$P_{\gamma,q}^{(0,1)}(z) \to P_{\gamma,q}^{(0,1)}(z) + \frac{2x^2 m_p^2}{zQ^2}.$$

$$q(x,Q^2) \to q(x,Q^2) \left(1 + \frac{A_2'}{Q^2} \int_x^1 \frac{dz}{z} C_2(z) q(\frac{x}{z}, Q^2) \right),$$

$$\delta x\gamma^{(el)}(x,Q^2) = \frac{\alpha(Q^2)}{2\pi} \frac{1}{x} \Bigg[\left(x P_{\gamma,q}(x) + \frac{2x^2 m_p^2}{Q^2} \right) \frac{[G_E(Q^2)]^2 + \tau [G_M(Q^2)]^2}{1+\tau}$$

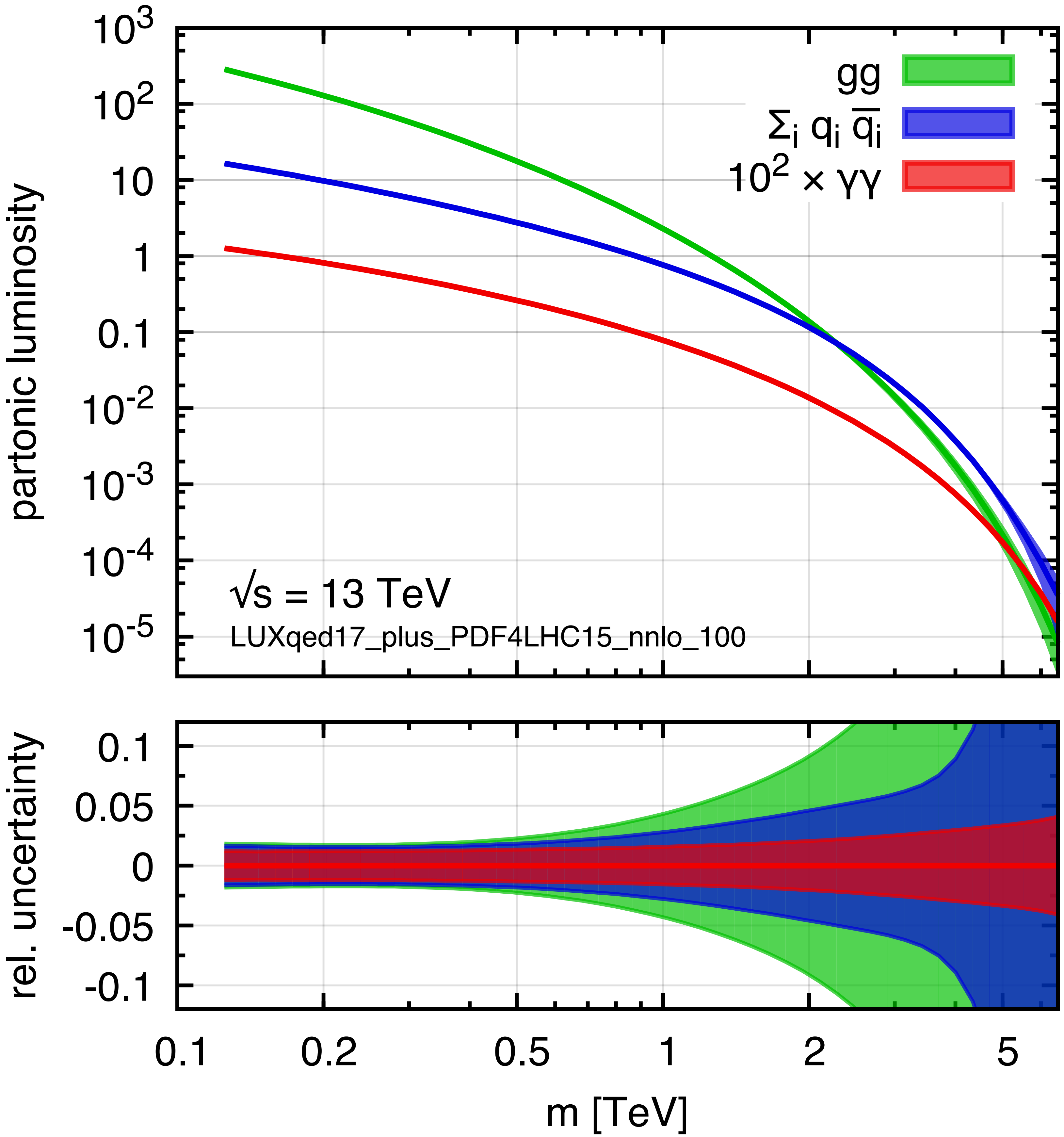
$$-x^2 \frac{[G_E(Q^2)]^2}{\tau} \Bigg].$$

$$\frac{d\gamma^{(el)}}{dt} = P_{\gamma\gamma} \otimes \gamma^{(el)} + \delta x\gamma^{(el)}.$$

formulated so as to allow evolution with photon from low scale
(whereas in LUXqed we take point of view that γ PDF makes sense only at high Q^2)

applications

PARTONIC LUMINOSITIES

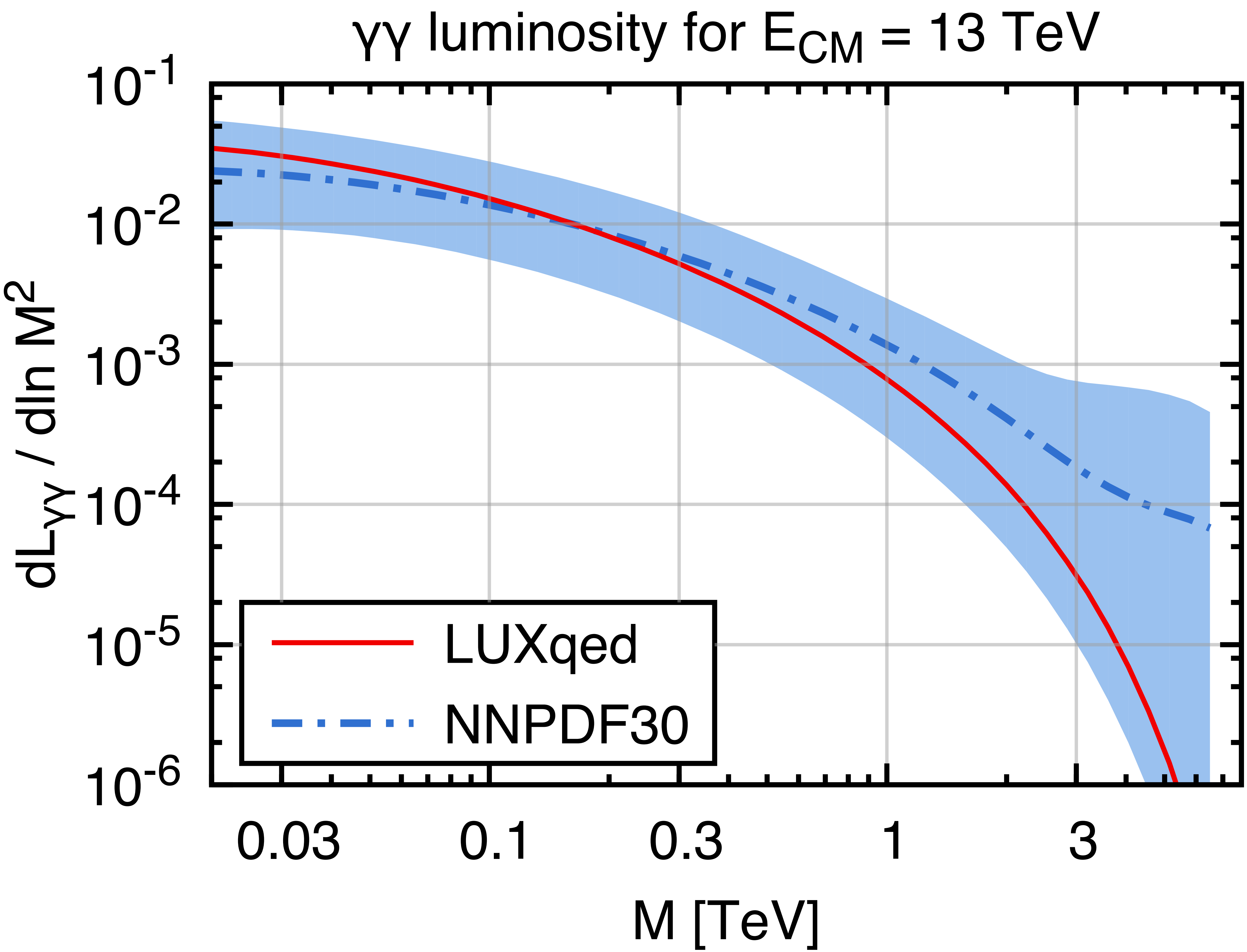


$\gamma\gamma$ luminosity is about 1000 times smaller than $q\bar{q}$ luminosity

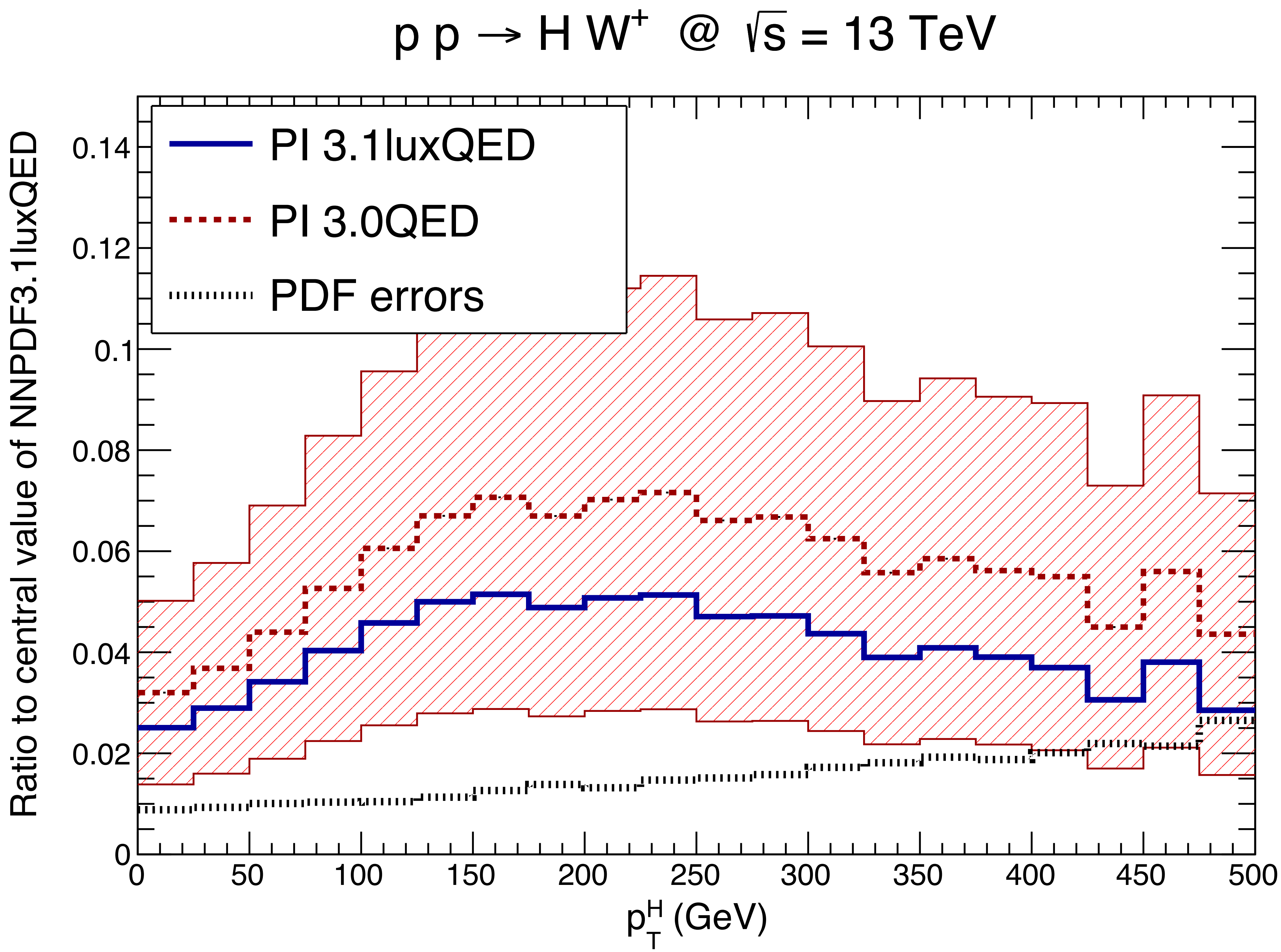
$pp \to H\,W^+ (\to l^+\nu) + X$ at 13 TeV	
non-photon induced contributions	91.2 ± 1.8 fb
photon-induced contribs (NNPDF23)	$6.0\ ^{+4.4}_{-2.9}$ fb
photon-induced contribs (LUXqed)	4.4 ± 0.1 fb

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

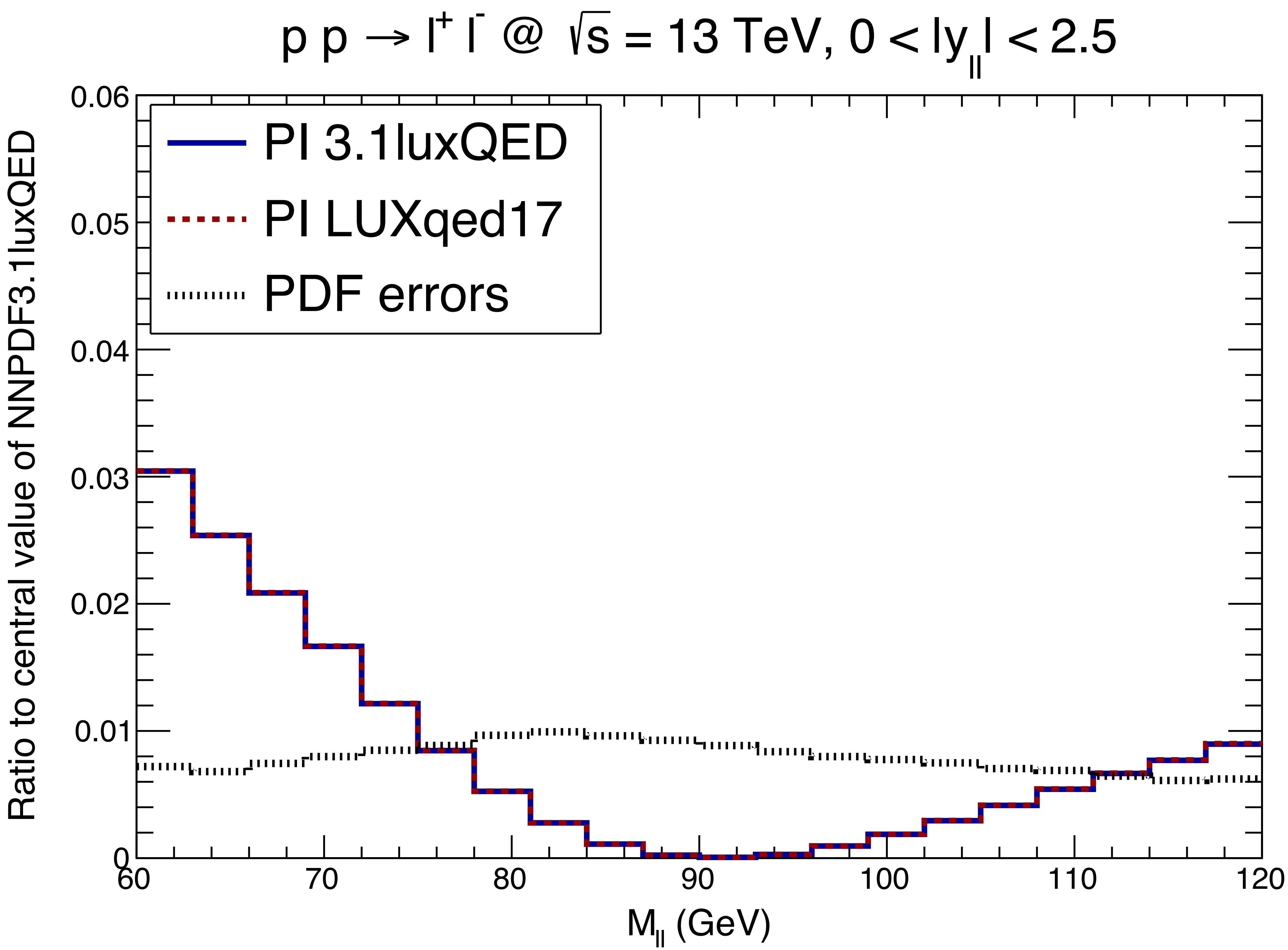
γγ luminosity



HW production (with NNPDF31-LUXqed)

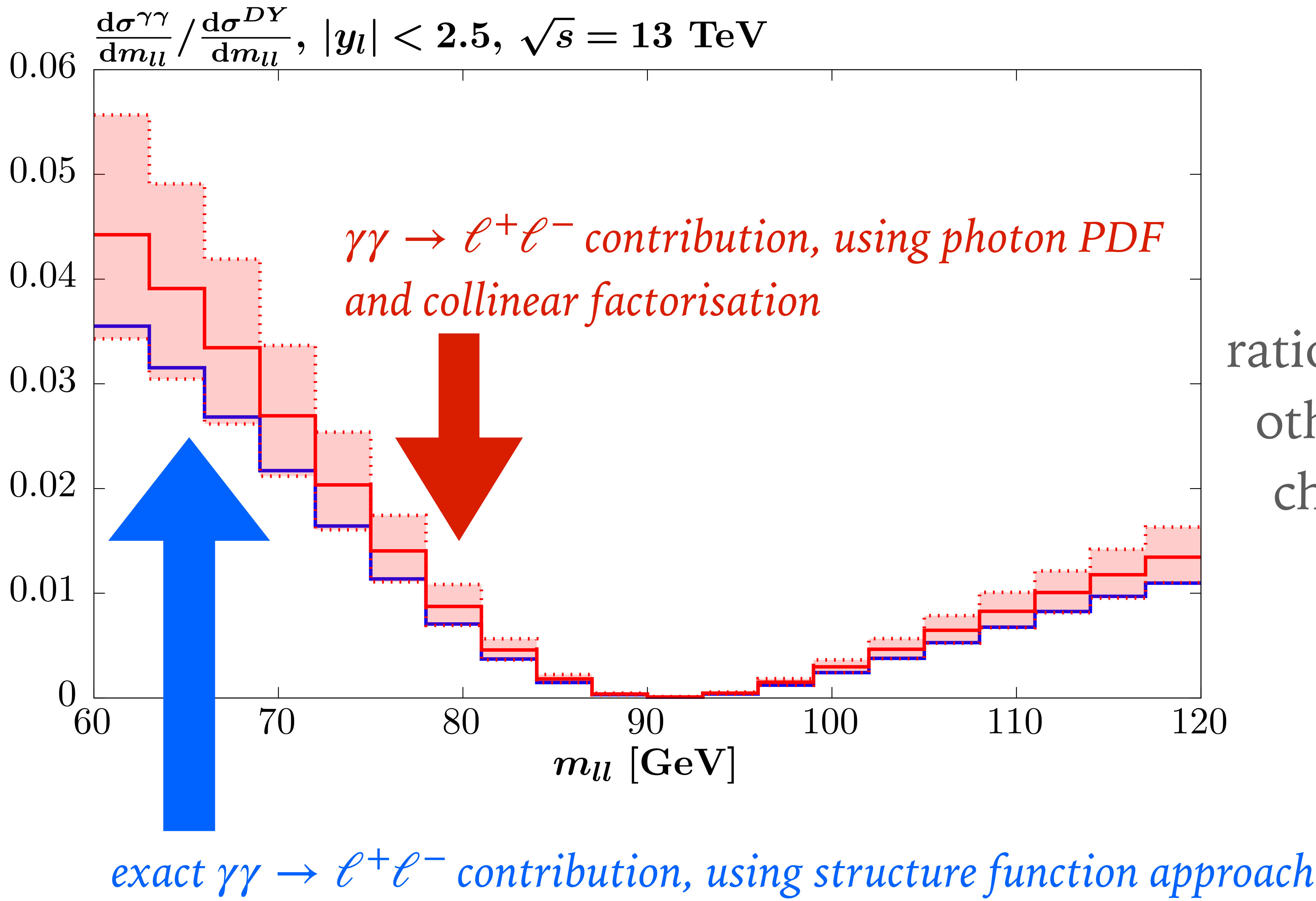


lepton-pair production (from NNPDF collab.)



ratio of γγ to other PDF channels

Harland-Lang (1910.10178): in some cases photon distribution is too indirect



ratio of γγ to other PDF channels

conclusions & resources

LHAPDF PDF sets with modern photon distributions

LUXqed17_plus_PDF4LHC15_nnlo_100
NNPDF31_nlo_as_0118_luxqed
NNPDF31_nnlo_as_0118_luxqed
MMHT2015qed_nnlo_total
MMHT2015qed_nnlo_inelastic
MMHT2015qed_nnlo_elastic

CLOSING REMARKS

- distribution of photons in the proton depends on the **non-perturbative QCD** physics of the proton
- But **perturbative QED** enables you to deduce the photon density from measured (non-pert.) proton structure functions
- photon distributions needed for some EW higher-order calculations, but not necessarily for $\gamma\gamma \to \ell^+\ell^-$

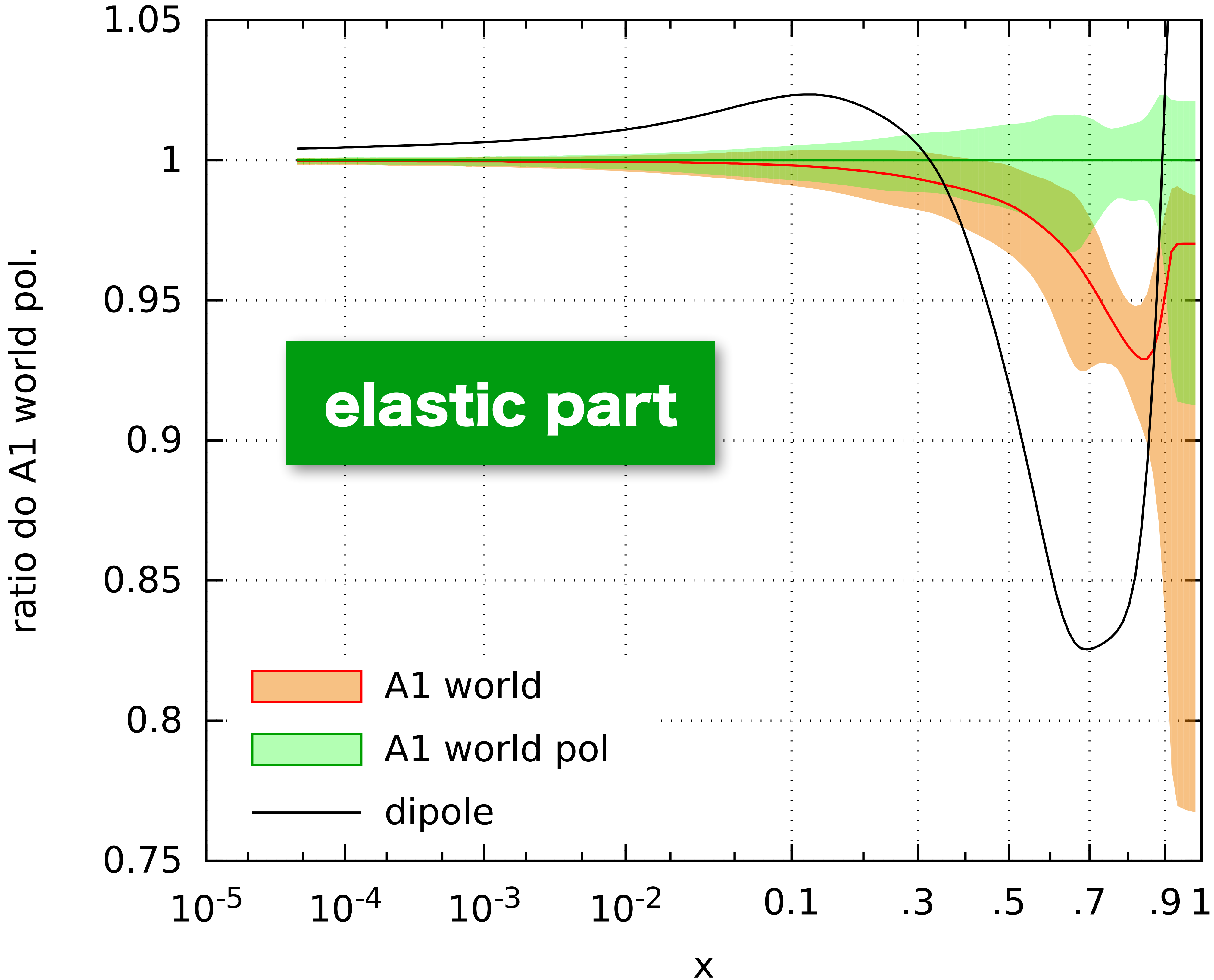
"If you think about it, it's awesome: we are made of protons, and protons are, in some part, made of light... And now we know how much of it."

blog post by Tommaso Dorigo

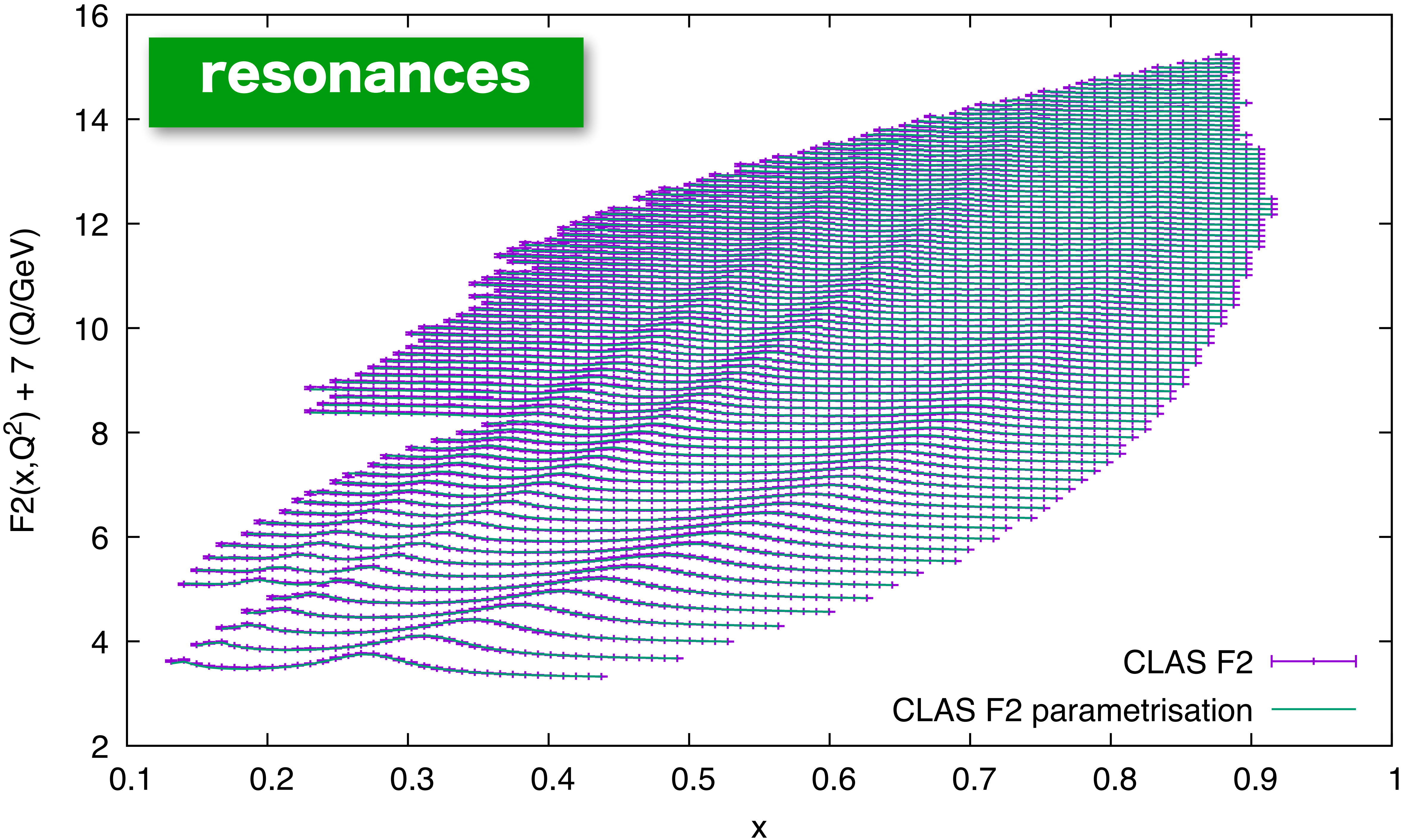
extra slides

input data & procedures

ELASTIC COMPONENT & COMPARISON TO “DIPOLE” MODEL

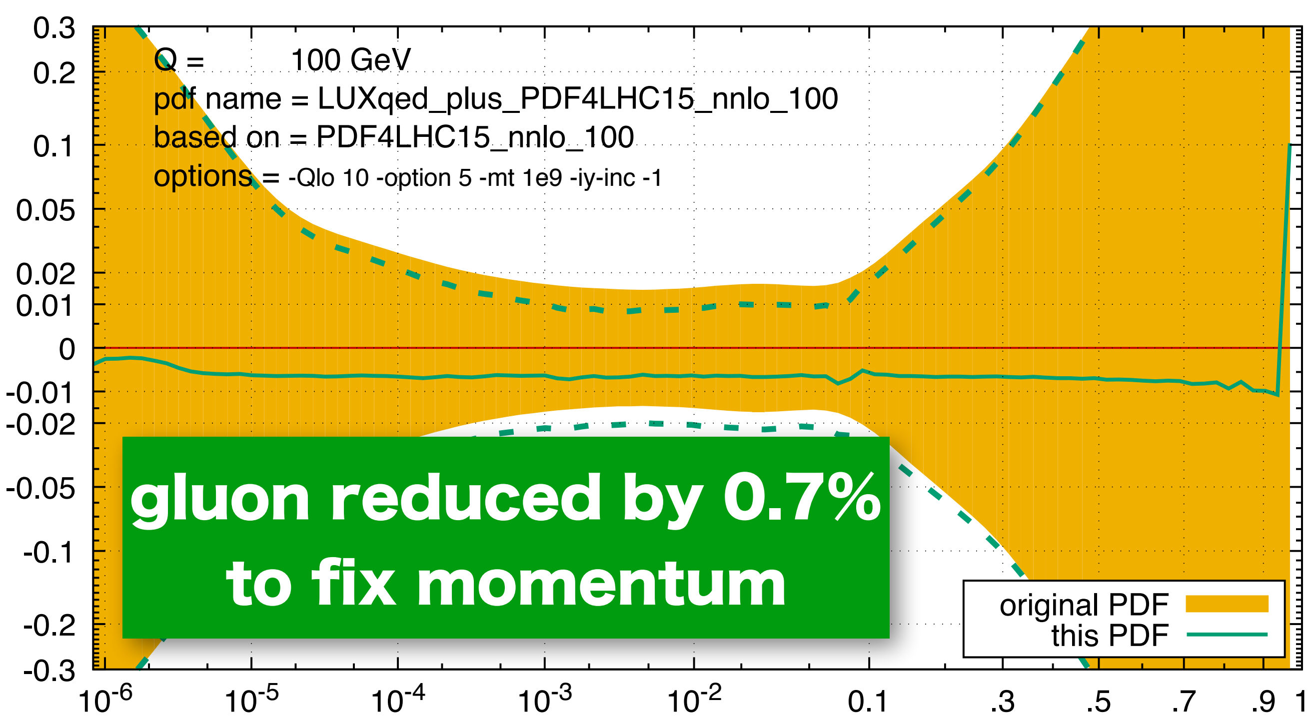


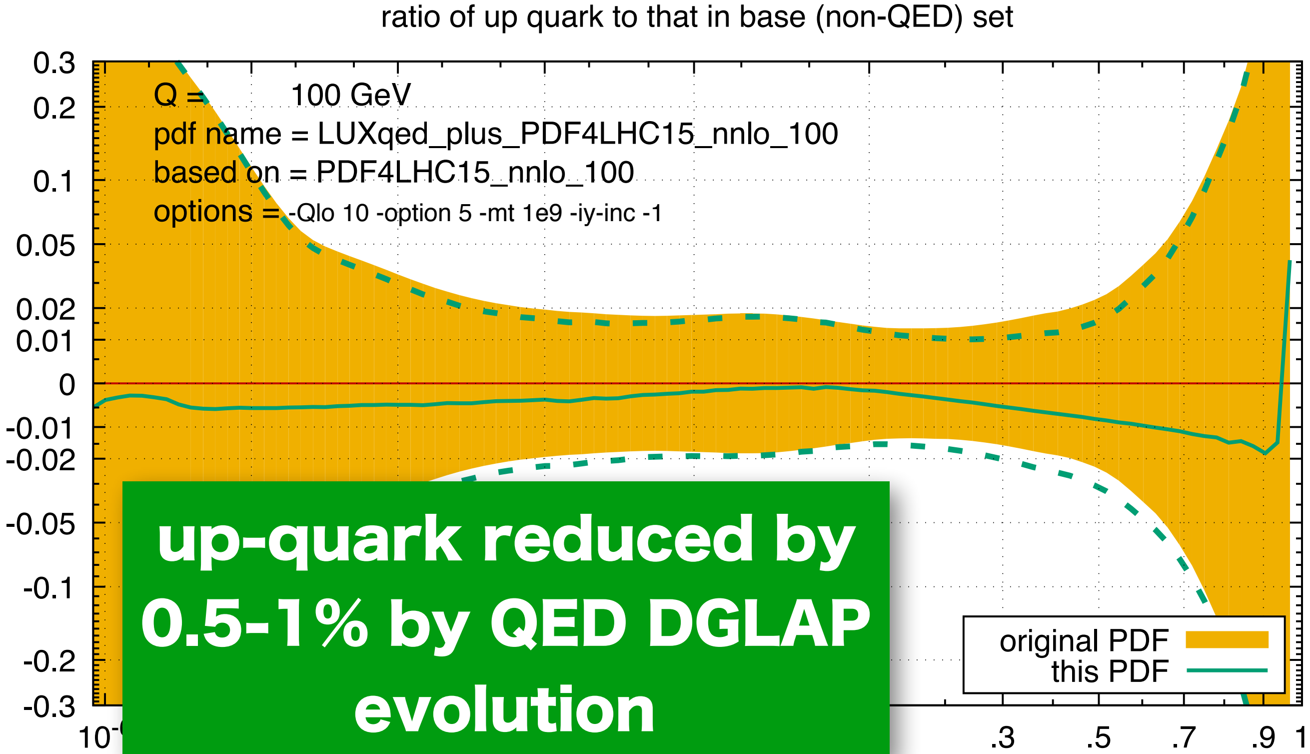
CLAS DATA



resonances
16
14
12
10
8
6
4
2
0.1
0.2
0.3
0.4
0.5
0.6
0.7
0.8
0.9
1
x
F2(x,Q^2) + 7 (Q/GeV)
CLAS F2
CLAS F2 parametrisation

MATCHING PROCEDURE FOR FULL SET OF PARTONS

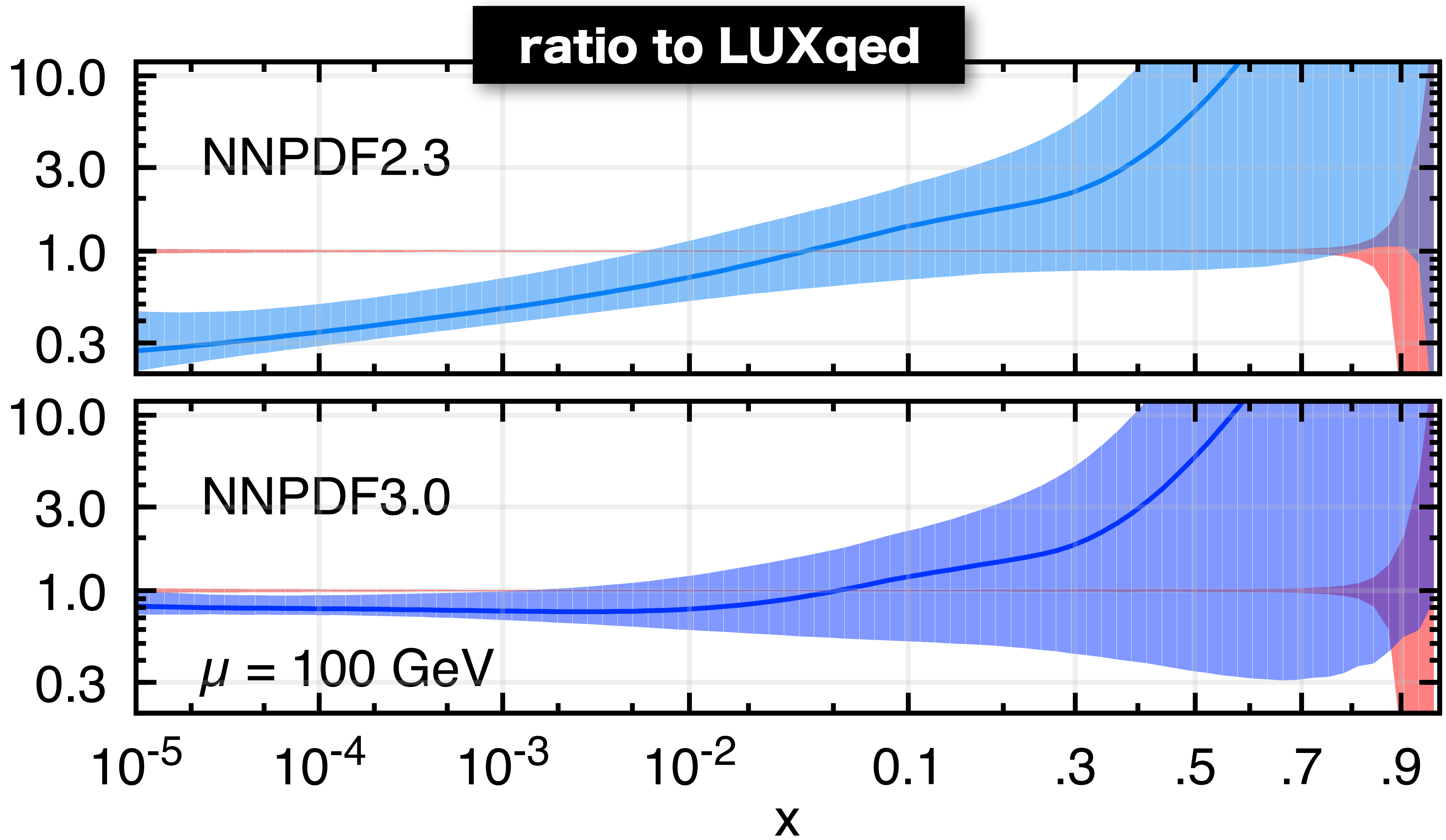




- evaluate master eqn. for $\mu = 100$ GeV (with default `PDF4LHC15_nnlo` partons)
- Do $O(\alpha\alpha_s)$ photon evolution down to $\mu = 10$ GeV (other partons: pure QCD evln.)
- Adjust momentum sum-rule by rescaling gluon $g(x) \to 0.993 g(x)$
- Evolve back up with NNLO-QCD & $O(\alpha\alpha_s)$ QED for all partons

better approach would be full PDF re-fit for QCD partons incl. EW/QED corrections & LUXqed photon

other PDFs v. LUXqed



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

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

other PDFs v. LUXqed

Others are numerically closer

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