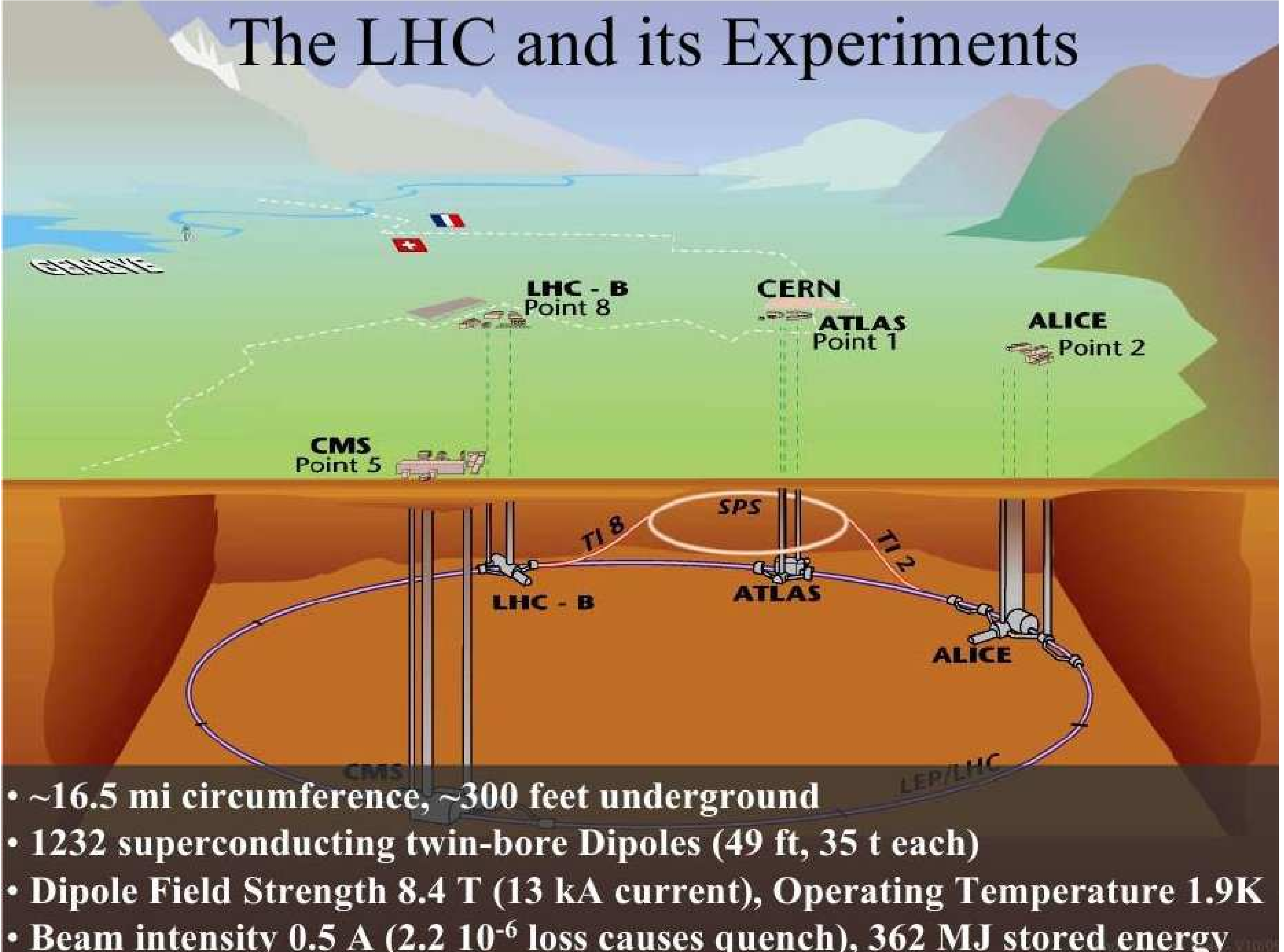
PROTON STRUCTURE
THE LAST LIGHT PARTON

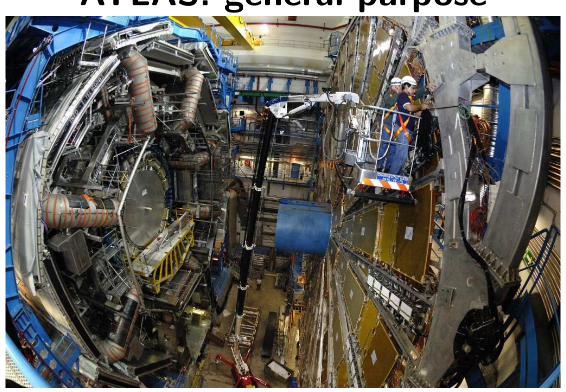
Gavin Salam, CERN
with Aneesh Manohar, Paolo Nason and Giulia Zanderighi

Particle Physics Seminar
University of Zurich and ETH Zurich
20 September 2016

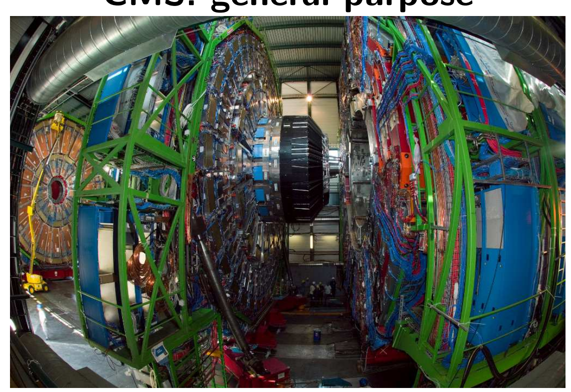
LHC — TWO ROLES — A DISCOVERY MACHINE AND A PRECISION MACHINE



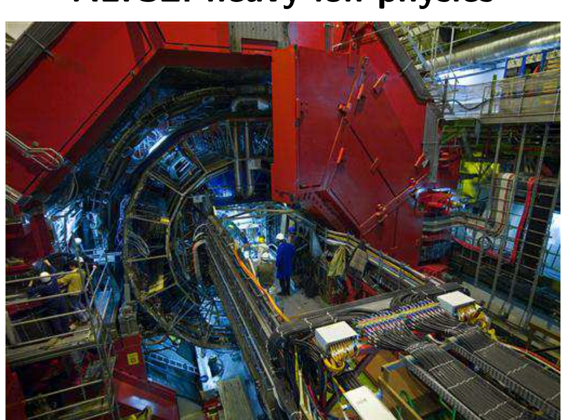
ATLAS: general purpose



CMS: general purpose

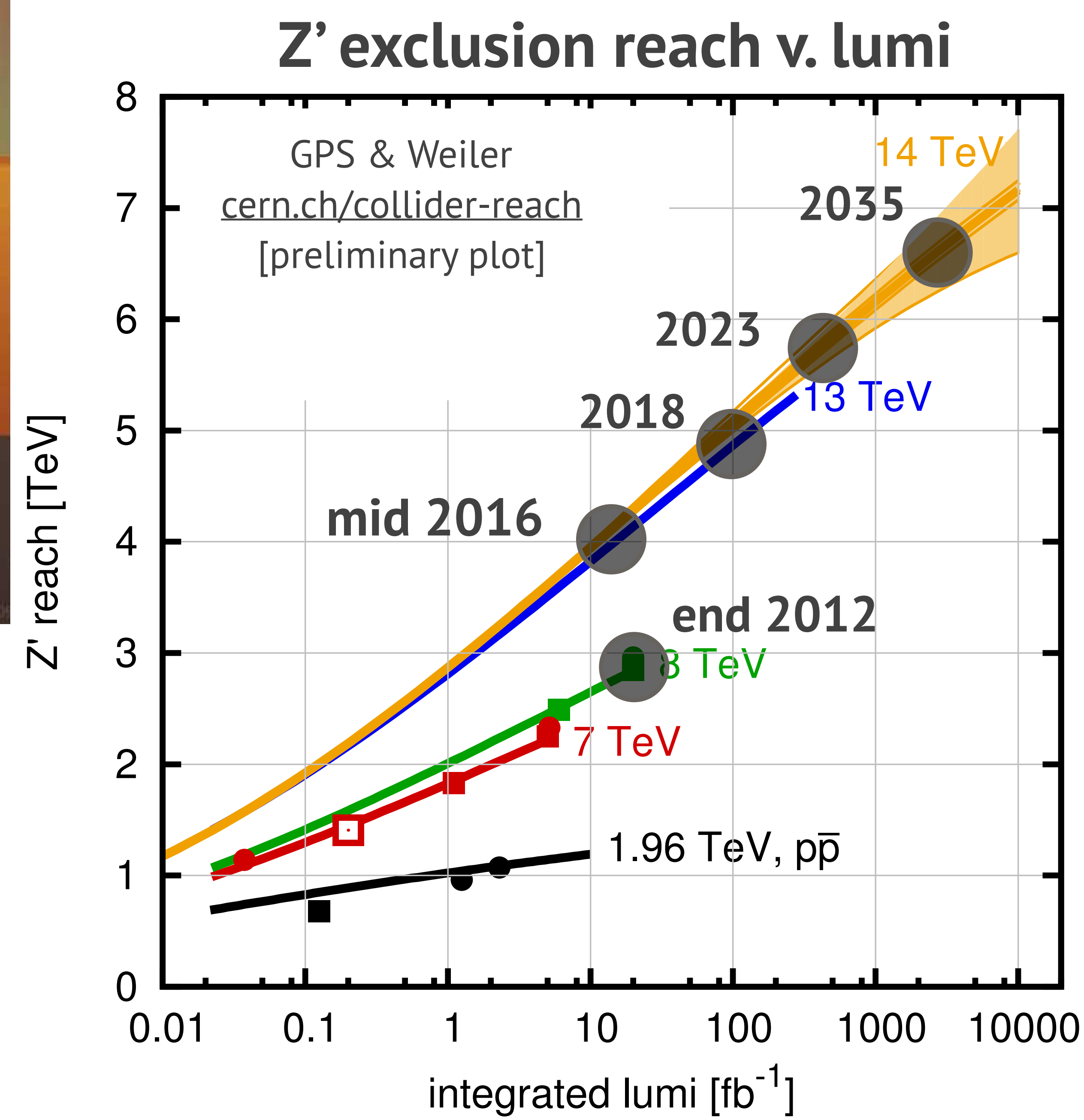


ALICE: heavy-ion physics



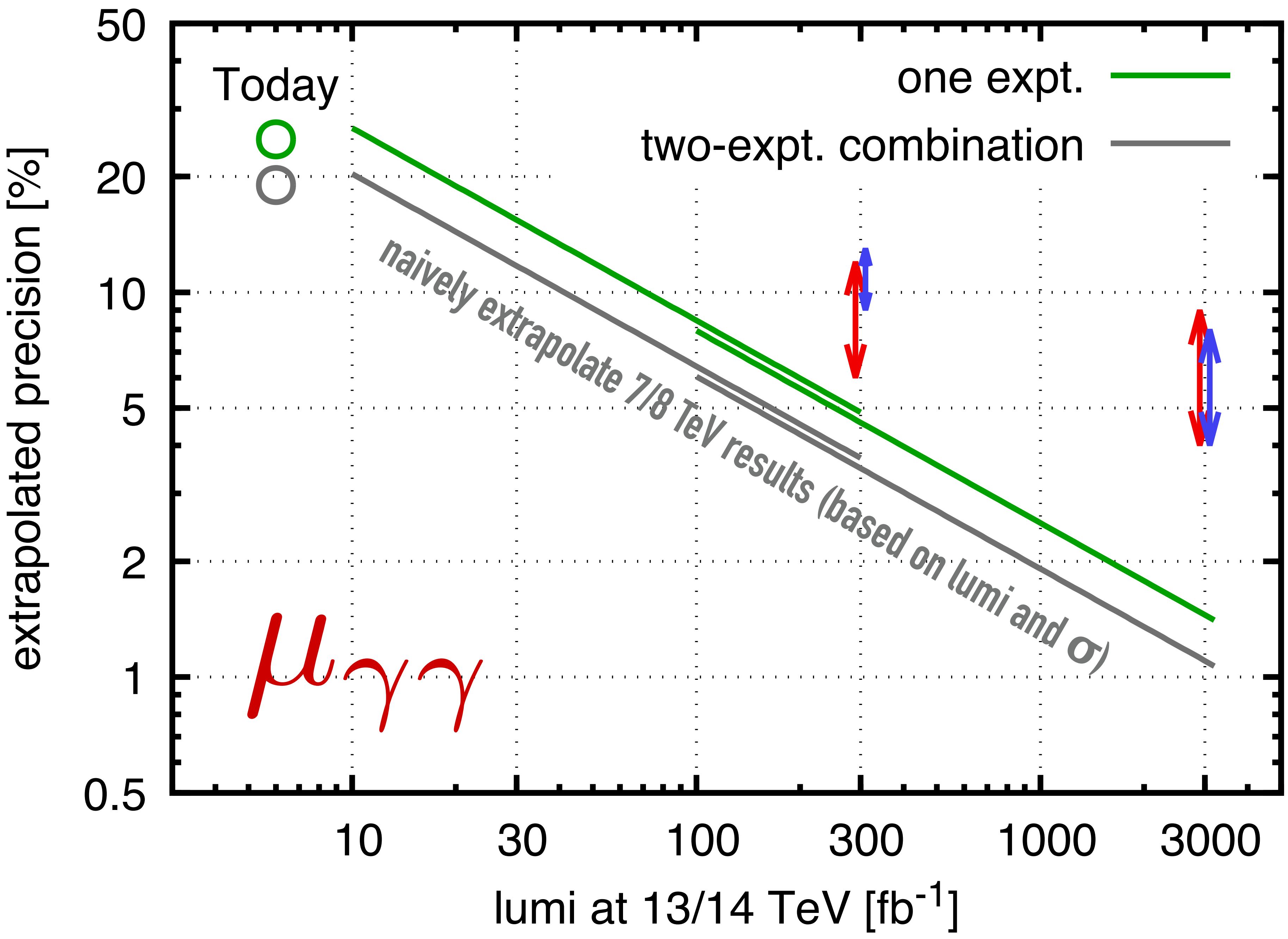
LHCb: B-physics

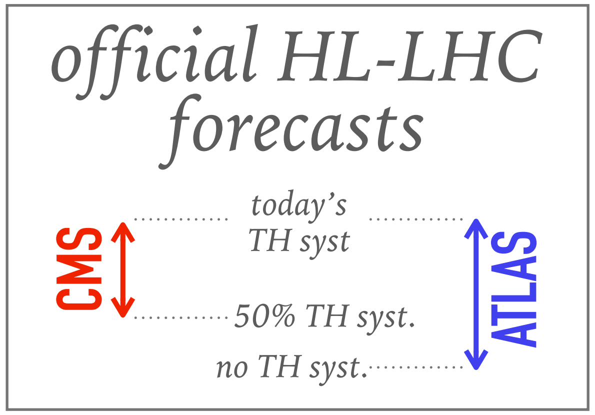
+ TOTEM, LHCf



Increase in luminosity brings discovery reach and precision

LONG-TERM HIGGS PRECISION?

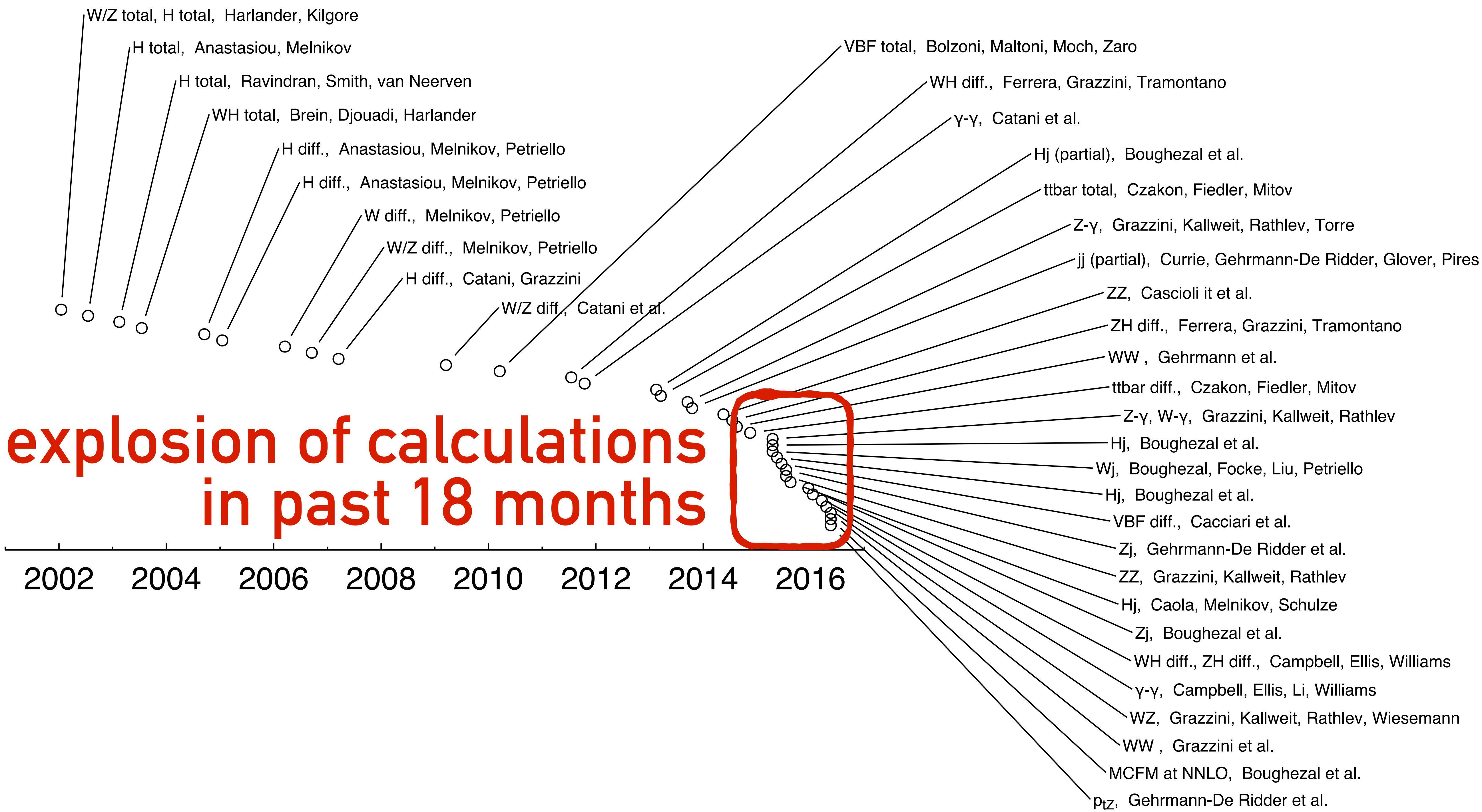




Naive extrapolation suggests LHC has long-term potential to do Higgs physics at **1% accuracy**

NNLO hadron-collider calculations v. time

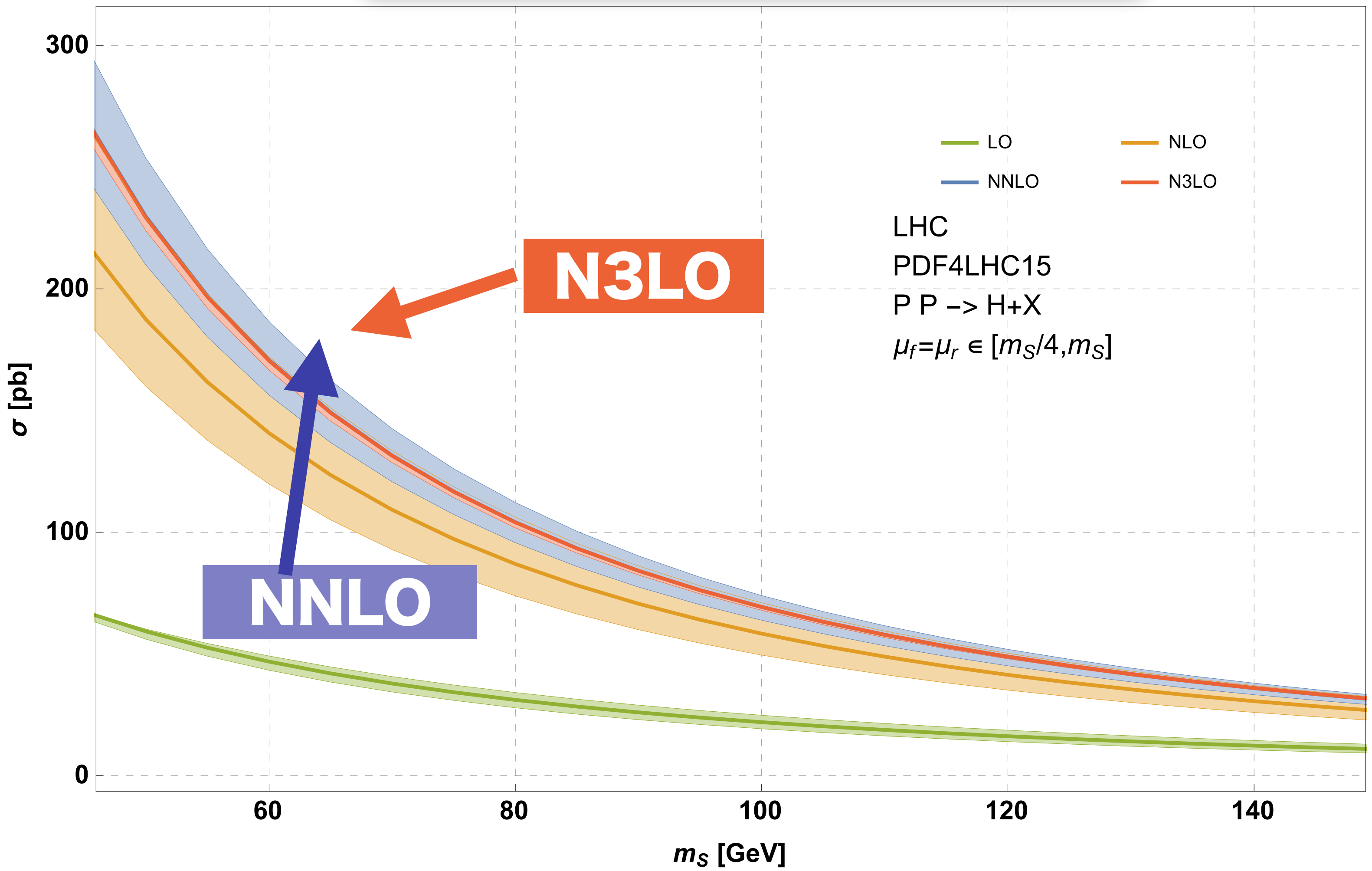
let me know of any significant omissions



N3LO

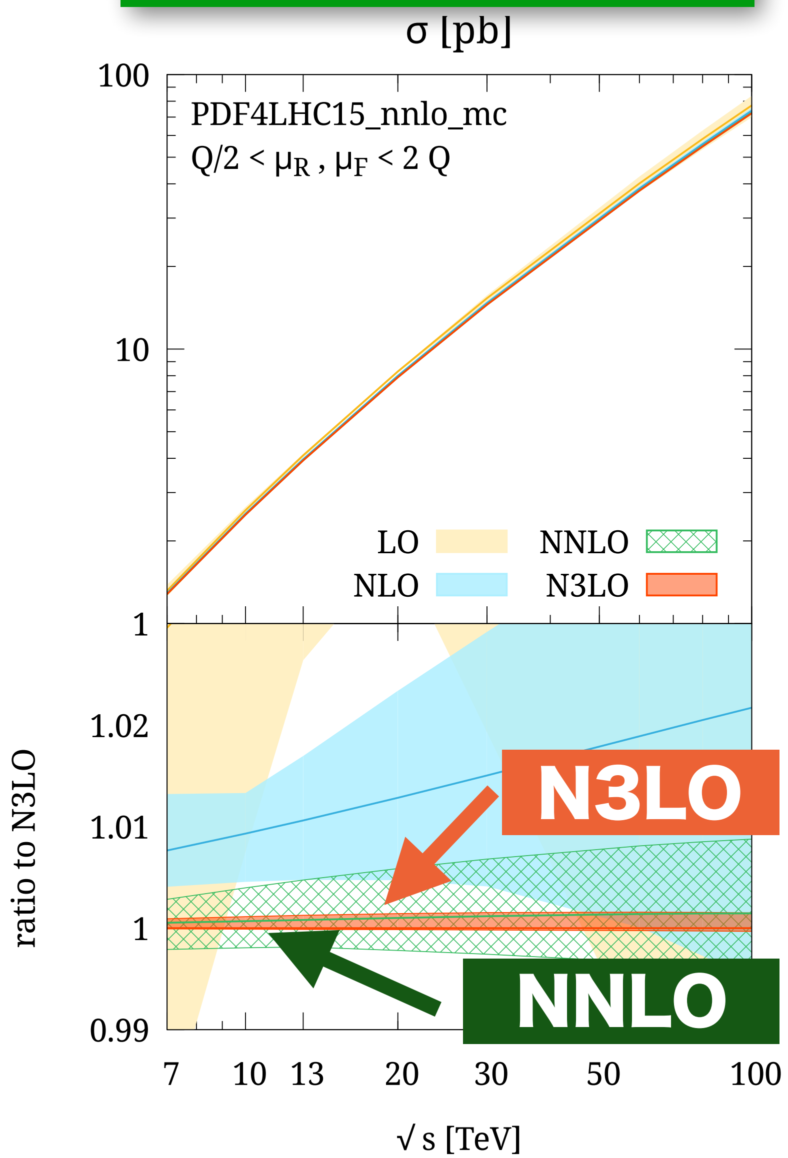
Anastasiou et al, 1602.00695

N3LO ggF Higgs

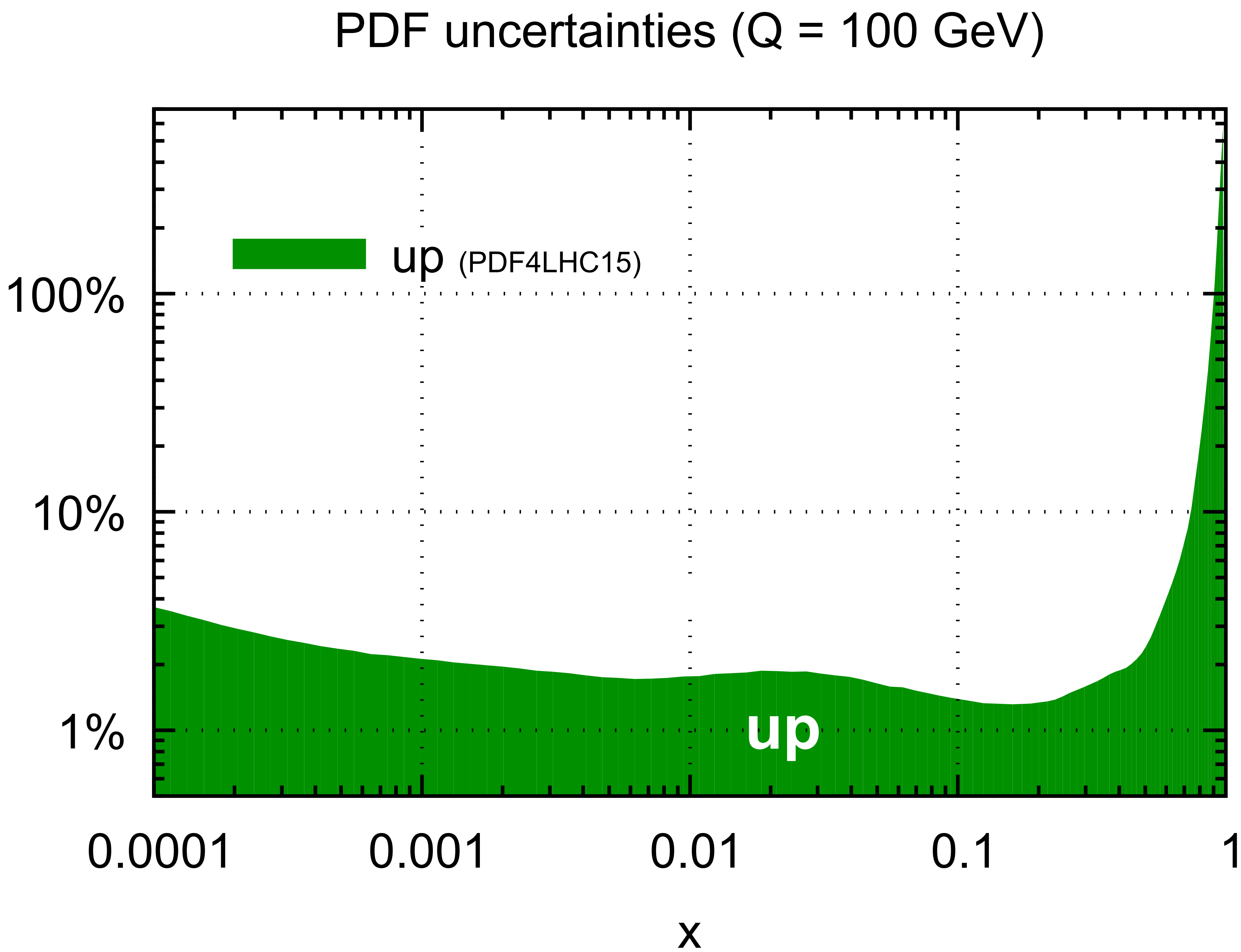


Dreyer & Karlberg, 1606.00840

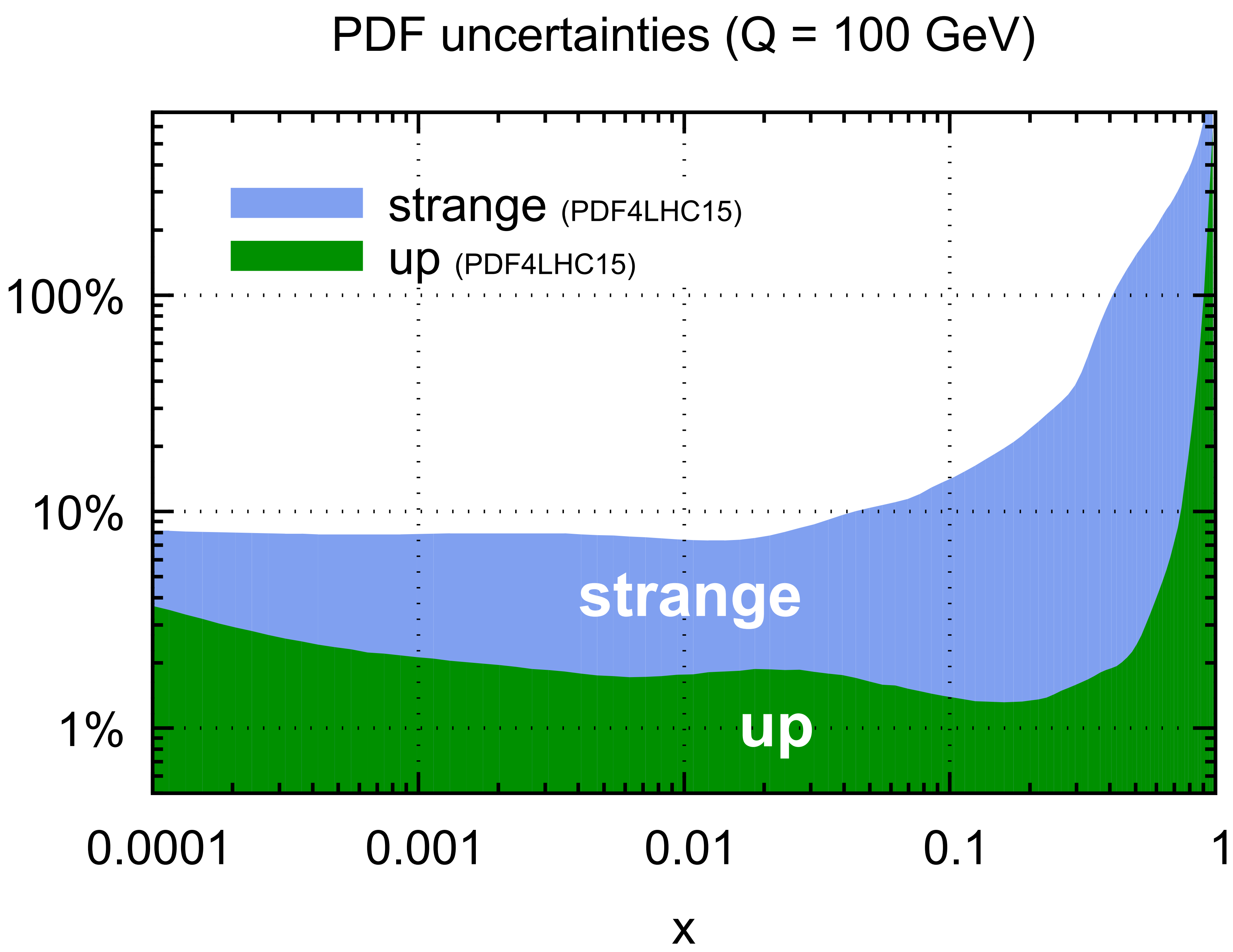
N3LO VBF Higgs



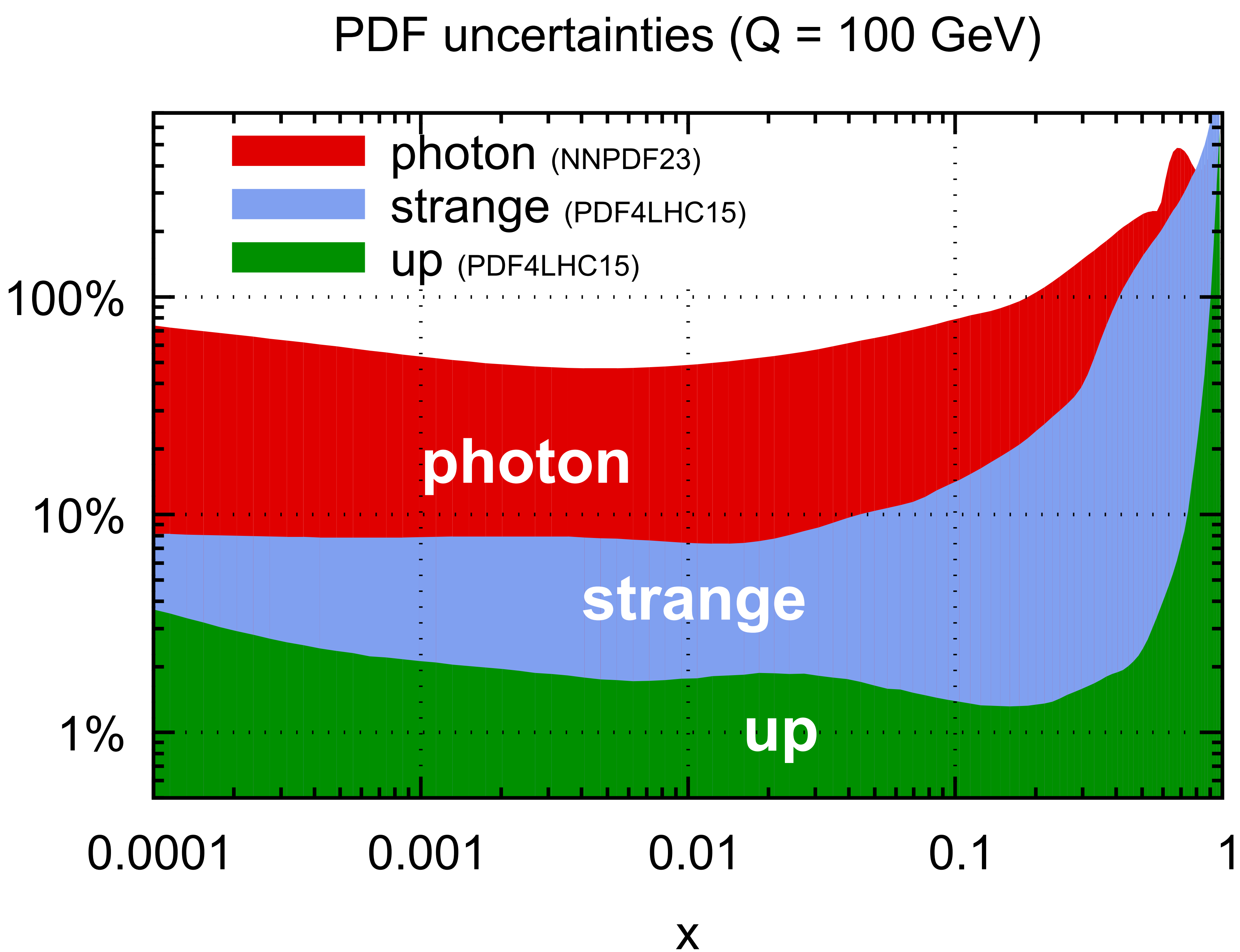
how well do we know the parton distributions?



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



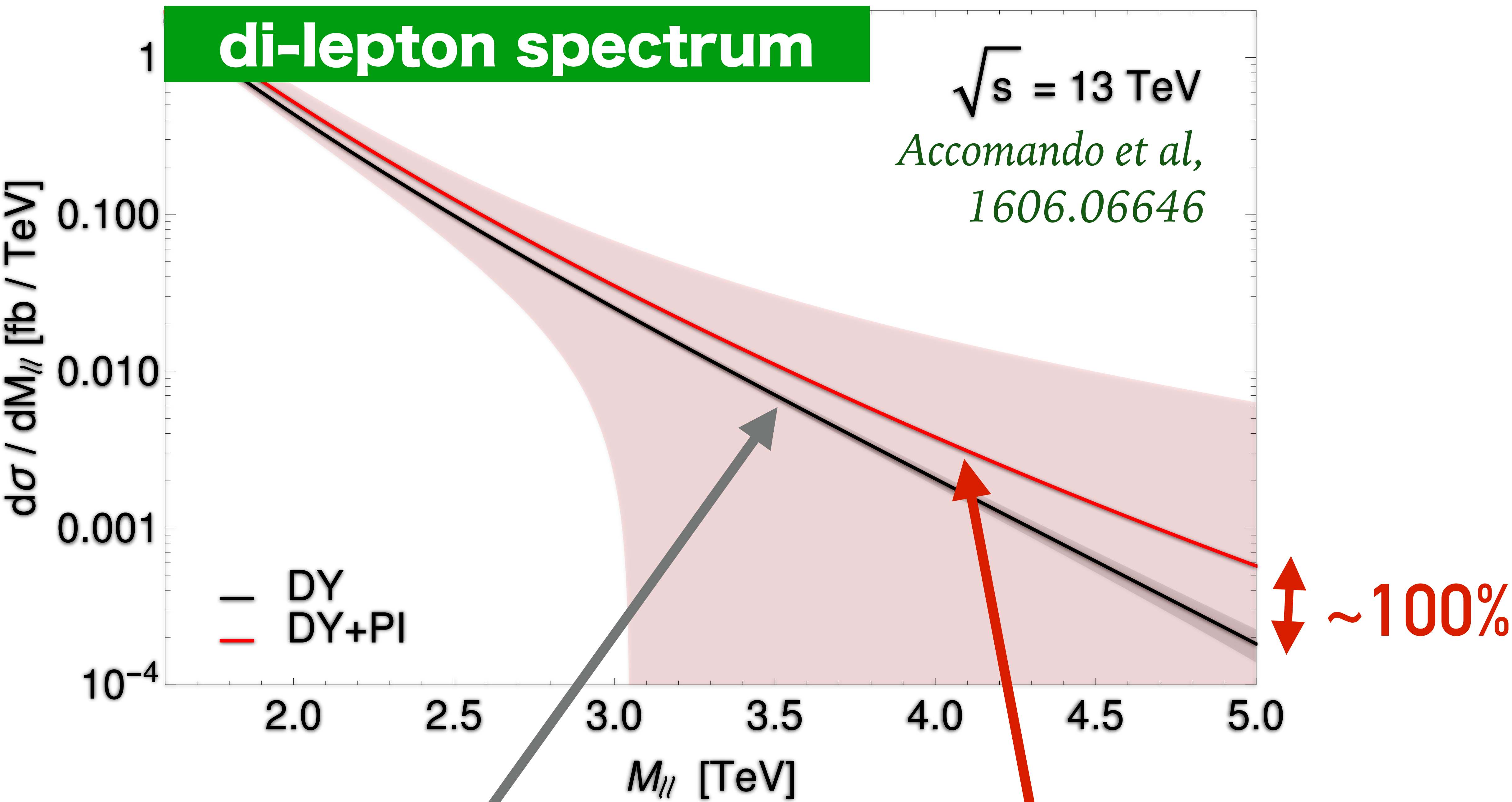
- core partons (up, down, gluon) are quite well known ~2%
- strangeness ~10%



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

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

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

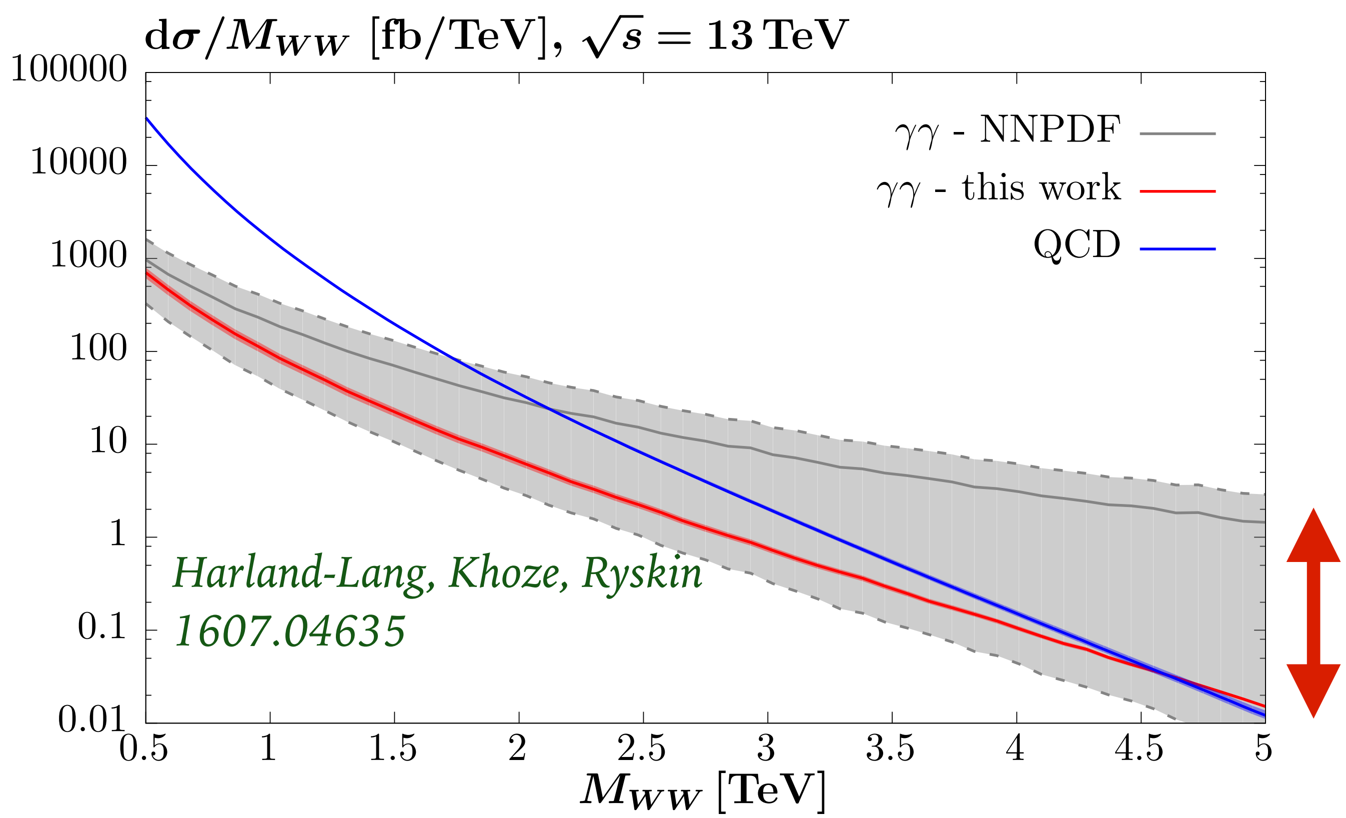


normal DY contribution

photon-induced contribution and uncertainty [NNPDF23]

where else does the photon come in?

- Electroweak corrections to almost any process
- Largest uncertainty on VBF Higgs and WH (±few %)
  LHC-HXSWG YR4
- top production *Pagani, Tsinikos, Zaro, arXiv:1606.01915*
- constraints on tqγ coupling *Goldouzian & Clerbaux, 1609.04838*
- VV production *1409.1803, 1510.08742, 1603.04874, 1601.07787, 1605.03419, 1604.04080,1607.04635, …*



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

photon-induced corrections to $pp \to HW^+$

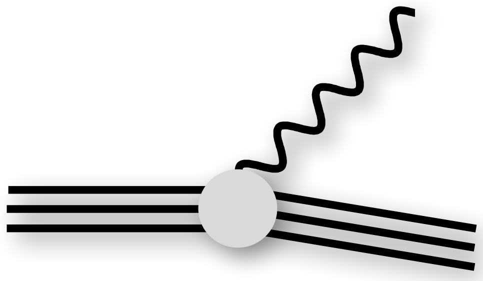
$pp \to H W^+ (\to l^+ \nu) + X$ at 13 TeV	
non-photon induced contributions	91.2 ± 1.8 fb
photon-induced contribs (NNPDF23)	$6.0^{+4.4}_{-2.9}$ fb

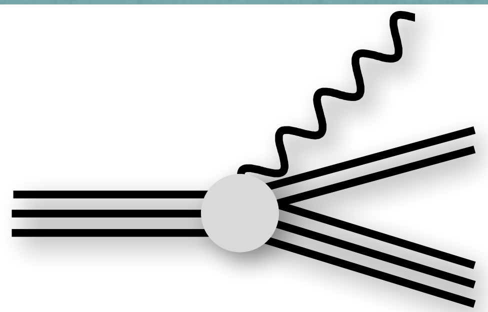
non-photon numbers from LHCHXSWG (YR4)
including PDF uncertainties

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 SHOULDN'T NEED A MODEL

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

YOU SHOULDN'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)

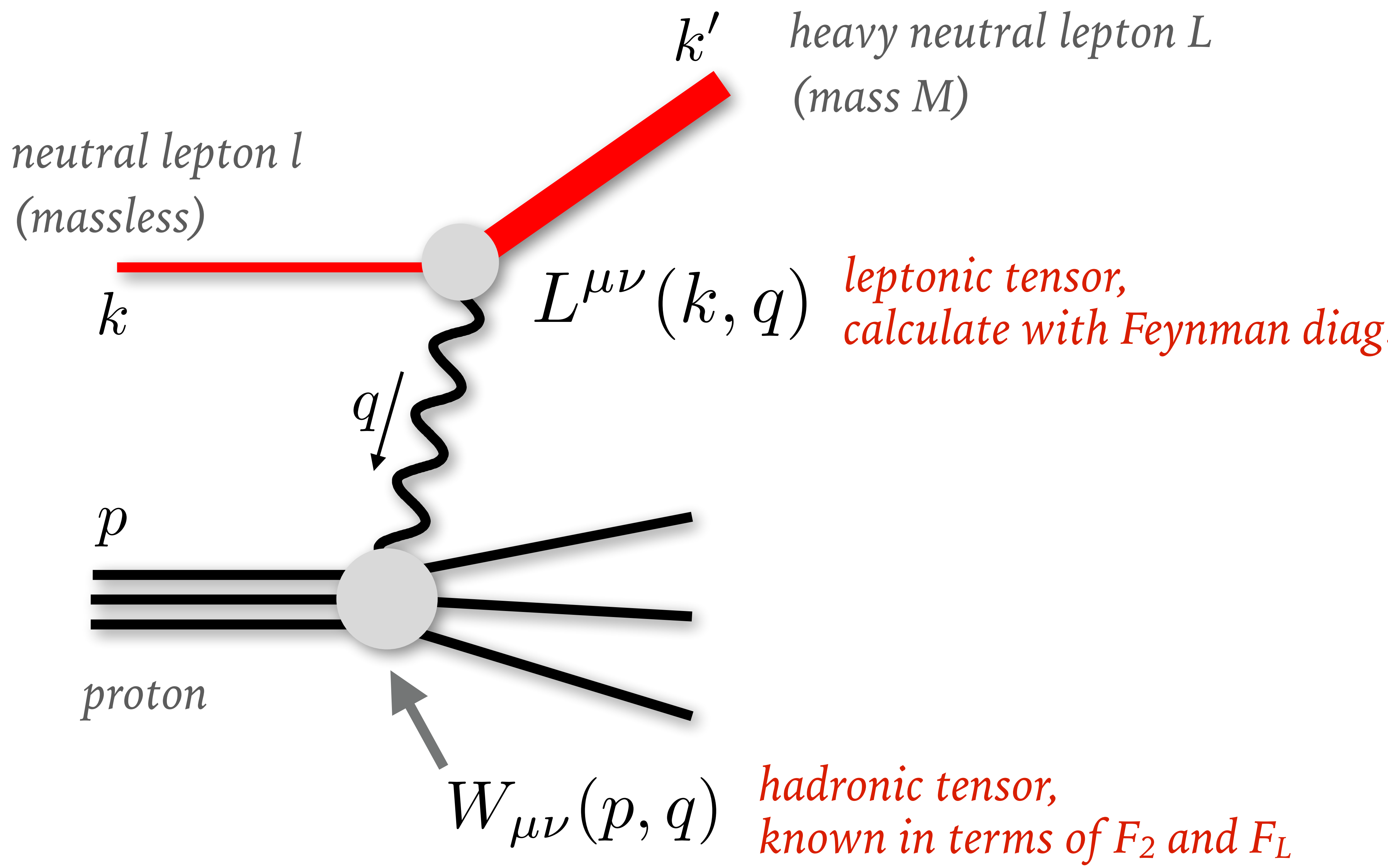
Equivalence gives us photon distirbution

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

calculation

STEP 1

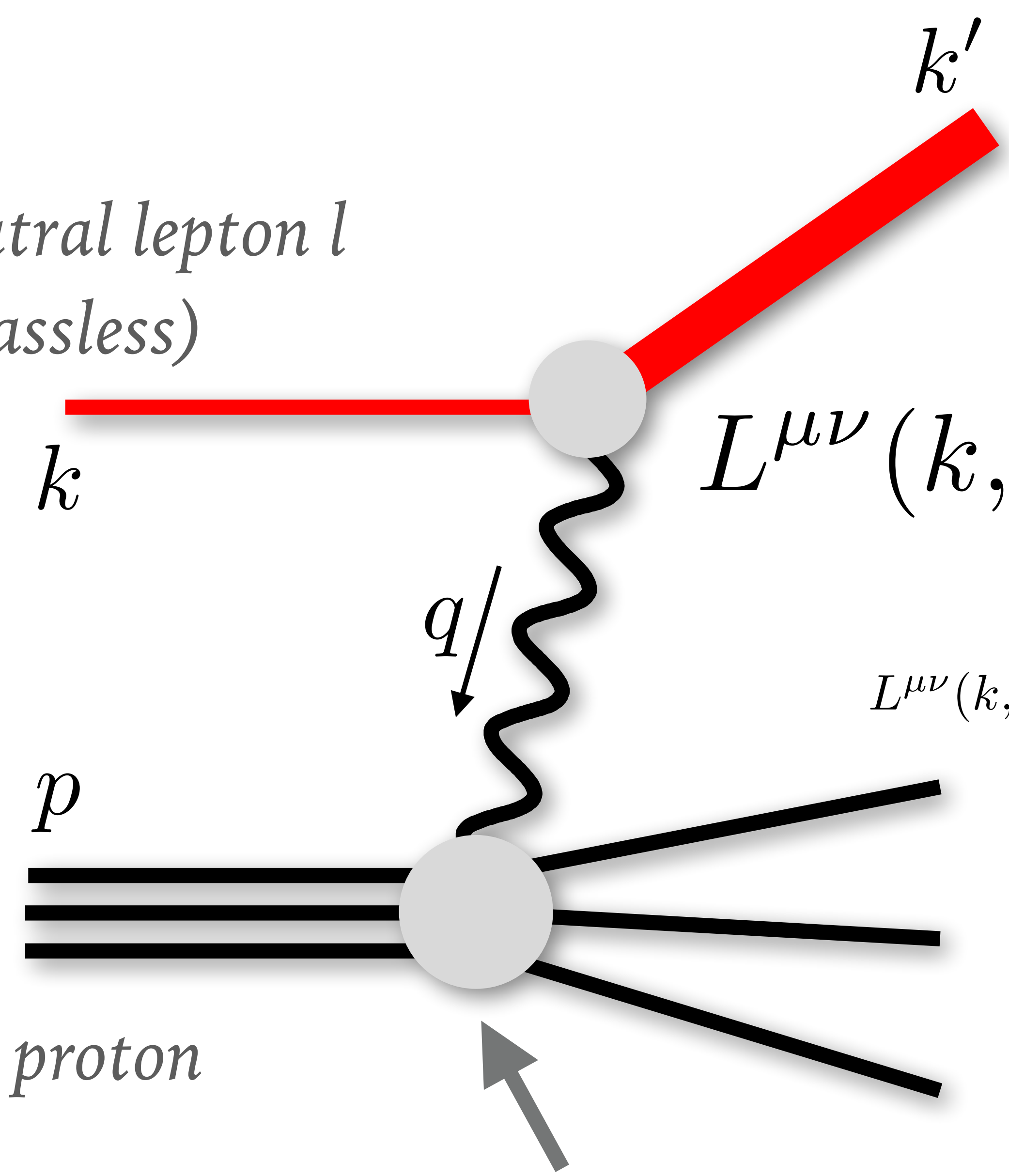
work out a cross section (exact) in terms of F_2 and F_L struct. fns.



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

STEP 1

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



$L^{\mu\nu}(k,q)$ *leptonic tensor, calculate with Feynman diag.*

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

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

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

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

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

$W_{\mu\nu}(p,q)$ *hadronic tensor, known in terms of F_2 and F_L*

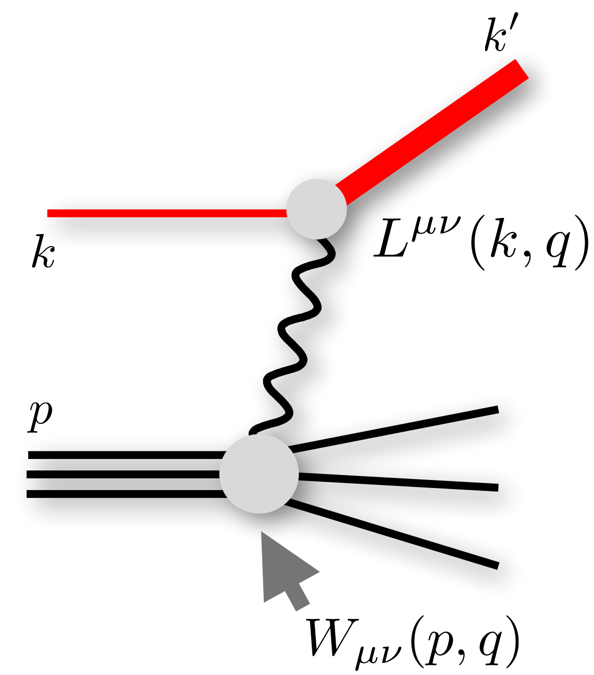
$$\sigma = \frac{1}{4p\cdot k}\int \frac{d^4q}{(2\pi)^4 q^4} e_{\rm ph}^2(q^2)\left[4\pi W_{\mu\nu}\,L^{\mu\nu}(k,q)\right] \times 2\pi\delta((k-q)^2 - M^2)$$

Cross section in terms of structure functions

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

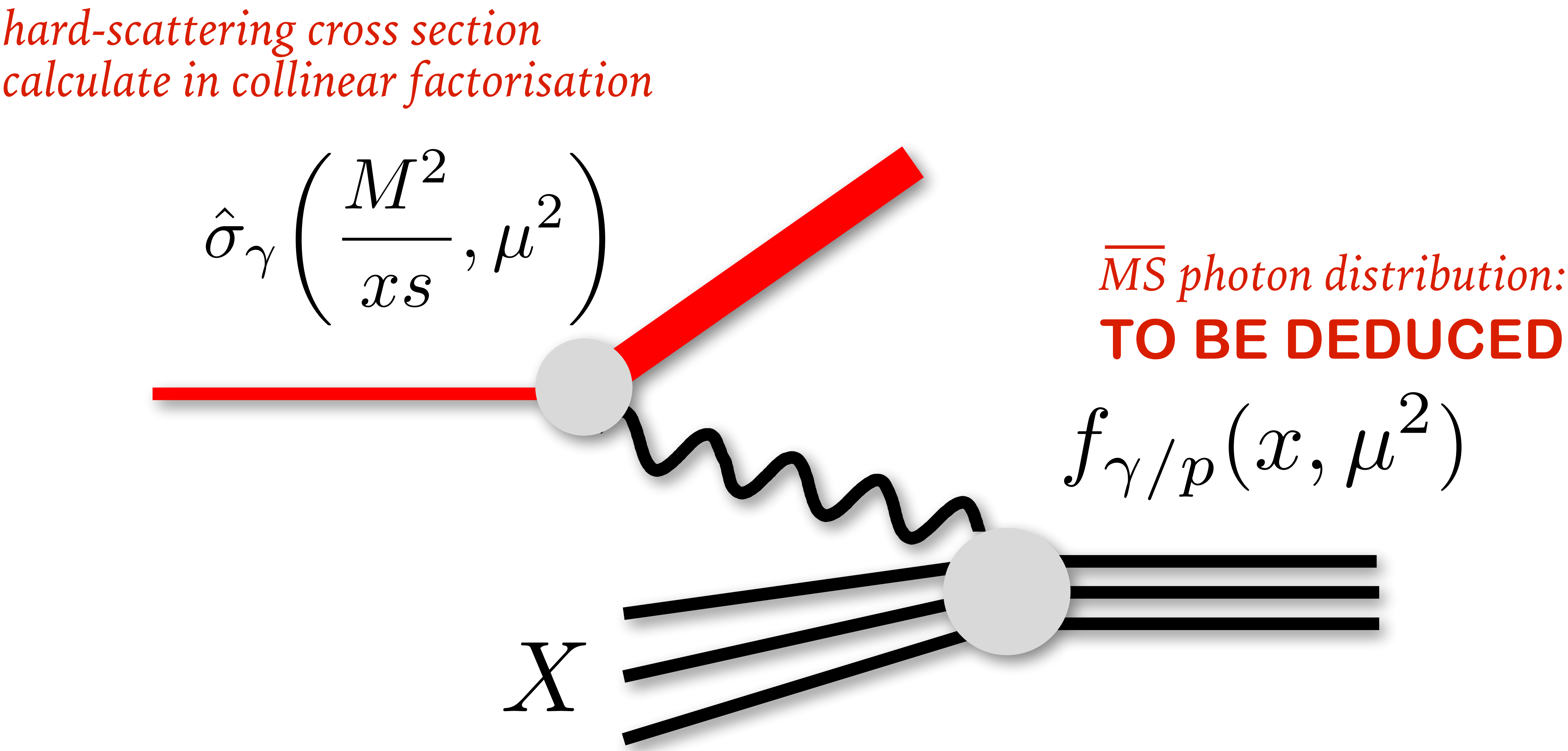
$$\sigma = \frac{c_0}{2\pi}\int_x^{1-\frac{2xm_p}{M}} \frac{dz}{z}\int_{Q^2_{\min}}^{Q^2_{\max}} \frac{dQ^2}{Q^2}\alpha^2_{\text{ph}}(-Q^2)\left[\left(2-2z+z^2 + \frac{2x^2m_p^2}{Q^2} + \frac{z^2Q^2}{M^2} - \frac{2zQ^2}{M^2} - \frac{2x^2Q^2m_p^2}{M^4}\right)F_2(x/z,Q^2) + \left(-z^2 - \frac{z^2Q^2}{2M^2}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

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



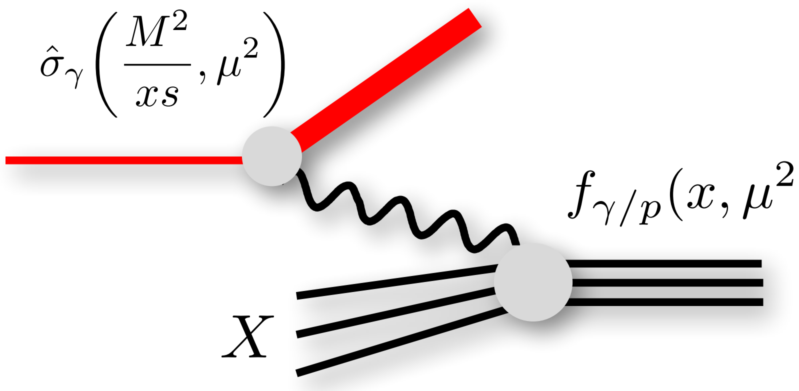
STEP 2

work out same cross section in terms of a photon distribution



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

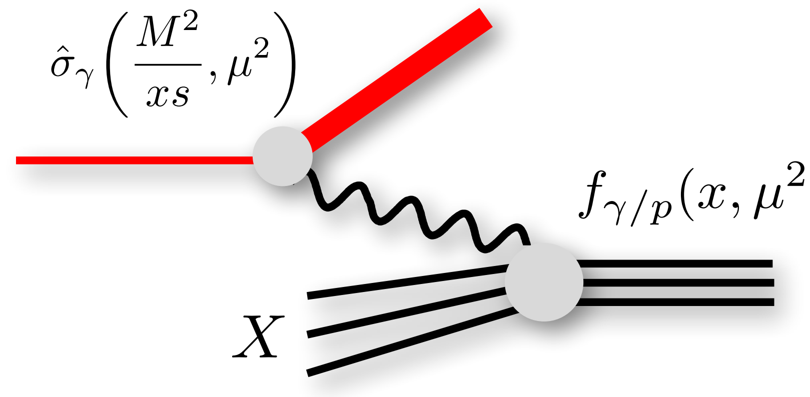
Cross section in terms of structure functions



➤ Hard cross section driven by the photon distribution at LO

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

Cross section in terms of structure functions



- Hard cross section driven by the photon distribution at LO

$$\hat{\sigma}_a(z, \mu^2) = \alpha(\mu^2)\delta(1-z)\delta_{a\gamma} + \frac{\alpha^2(\mu^2)}{2\pi}\left[-2 + 3z + \right.$$

$$\left. + z p_{\gamma q}(z) \ln \frac{M^2(1-z)^2}{z\mu^2}\right] \sum_{i \in \{q, \bar{q}\}} e_i^2 \delta_{ai} + \ldots$$

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

STEP 3

equate them to deduce the photon distribution (LUXqed)

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

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)

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

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

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

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

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

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

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

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

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

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

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

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

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:

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

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

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

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

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 an 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)

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

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

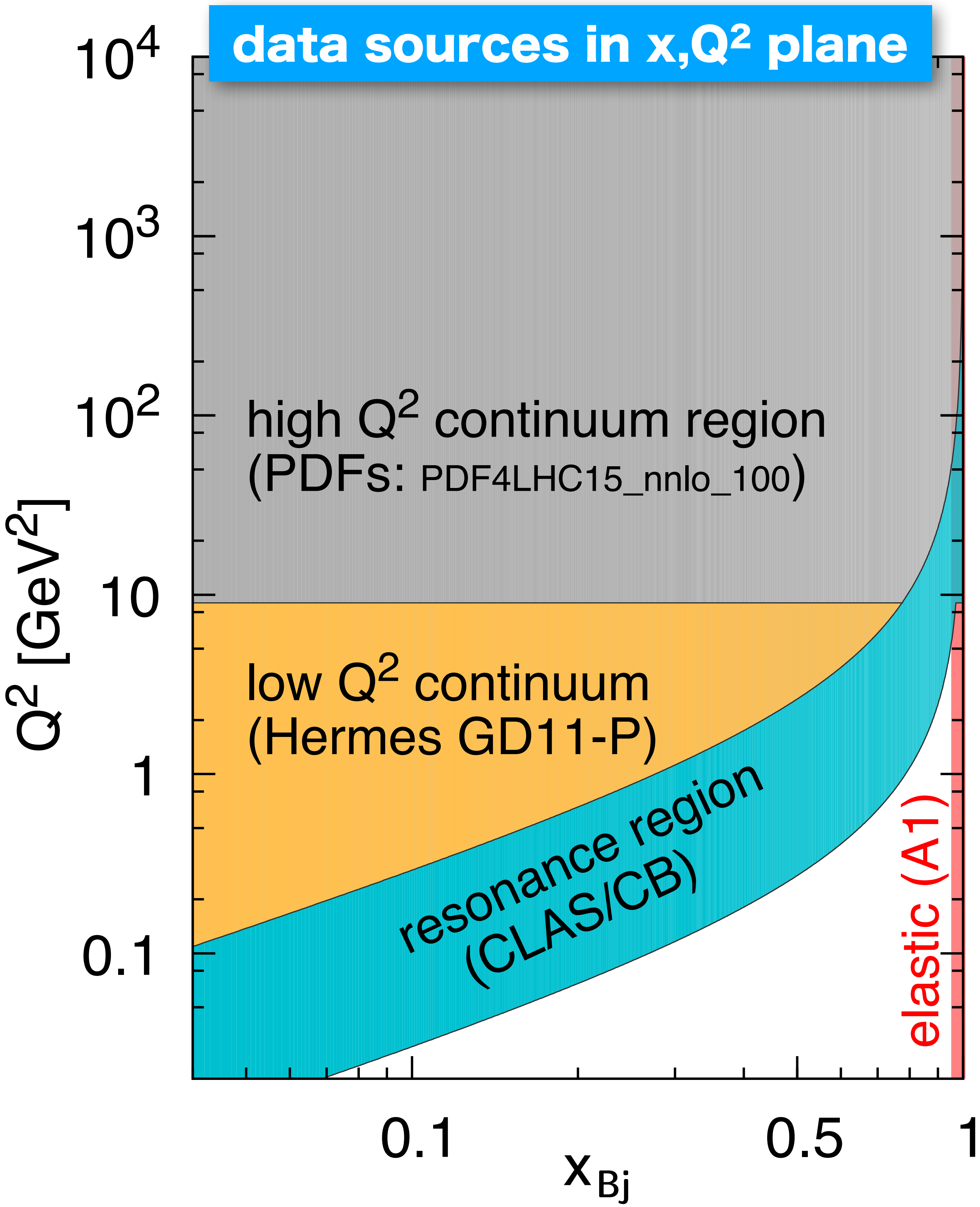
$$P^{(1,1)}_{\gamma\gamma} = (2\pi)^2 b_\alpha^{(1,2)} \delta(1-x) = -C_F N_C \sum_q e_q^2 \delta(1-x)$$

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

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

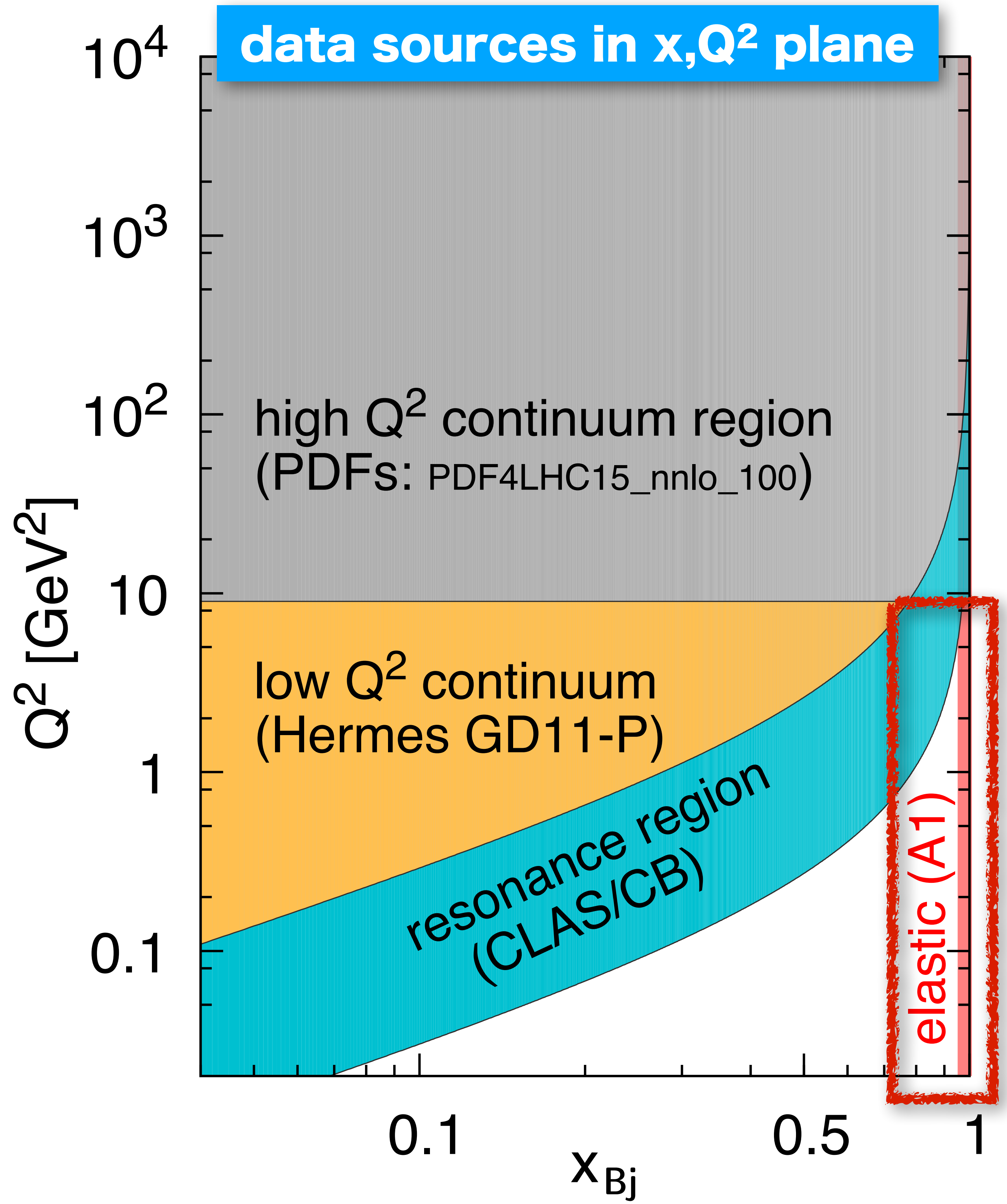
for $O(\alpha\, \alpha_s)$ terms, arXiv:1512.00612

data inputs

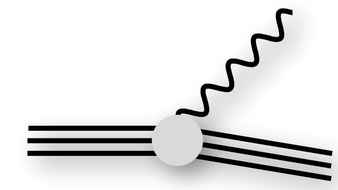


DATA

- 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



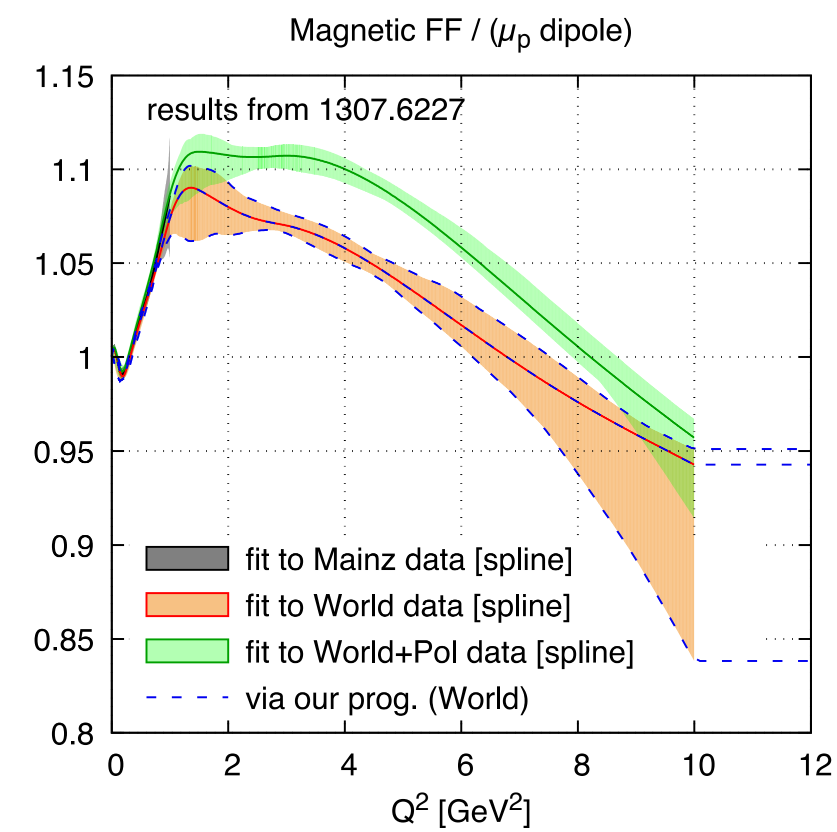
ELASTIC COMPONENT



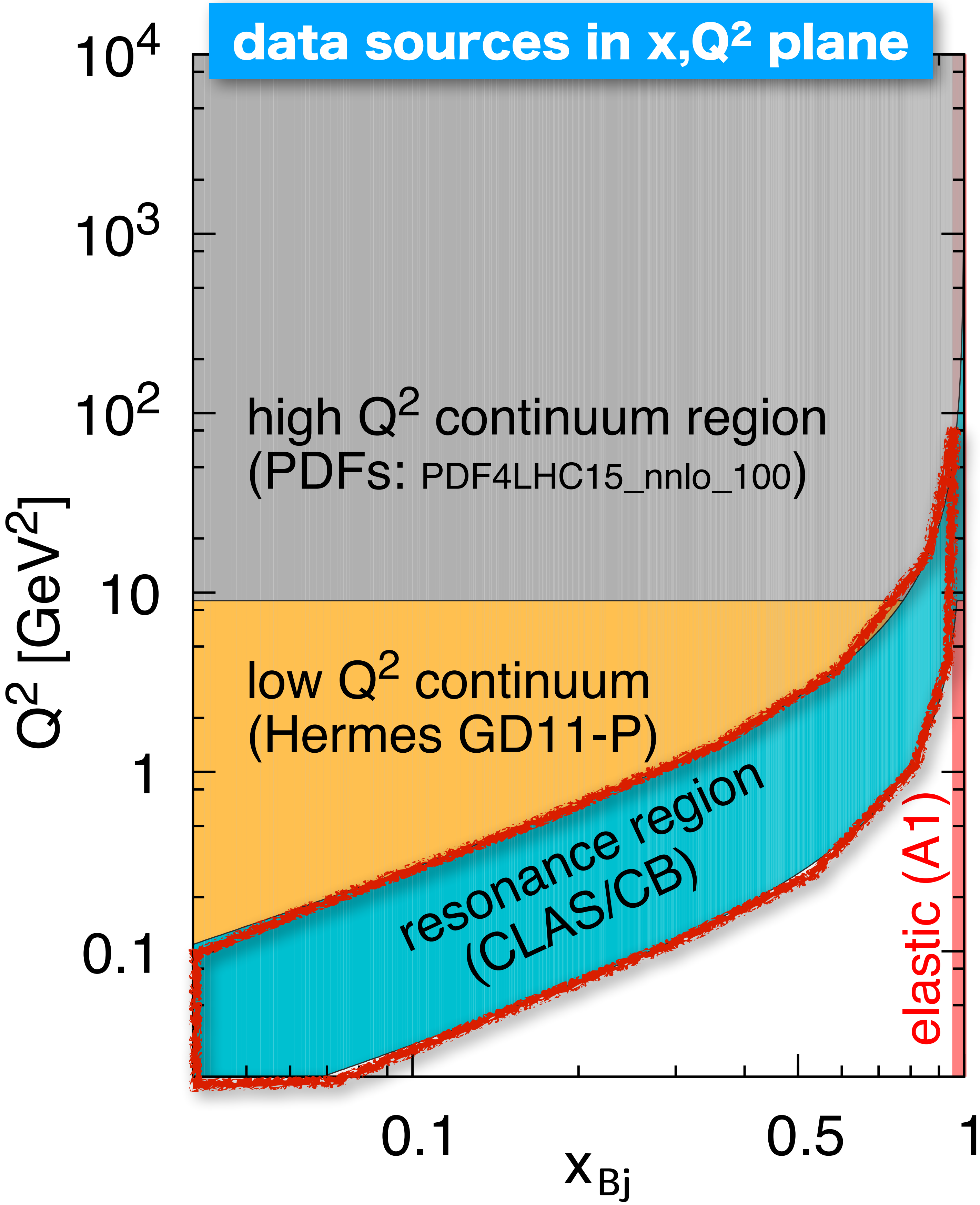
- Elastic component of $F_{2/L}$ lives at $x=1$
- Express in terms of Sachs Form factors

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

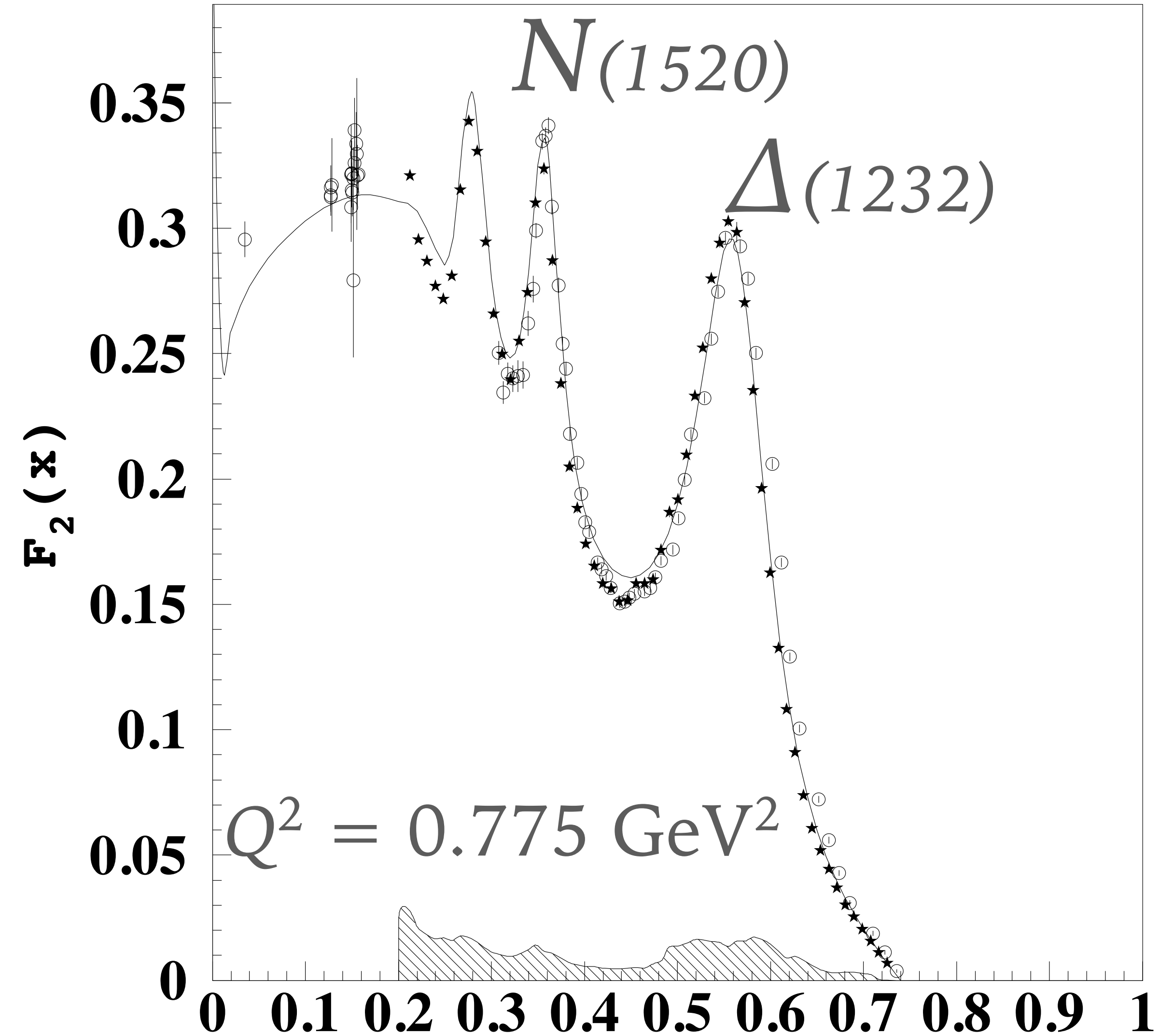
$$F_L^{\rm el} = \frac{[G_E(Q^2)]^2}{\tau}\delta(1-x)\,, \quad \tau = Q^2/(4m_p^2)$$

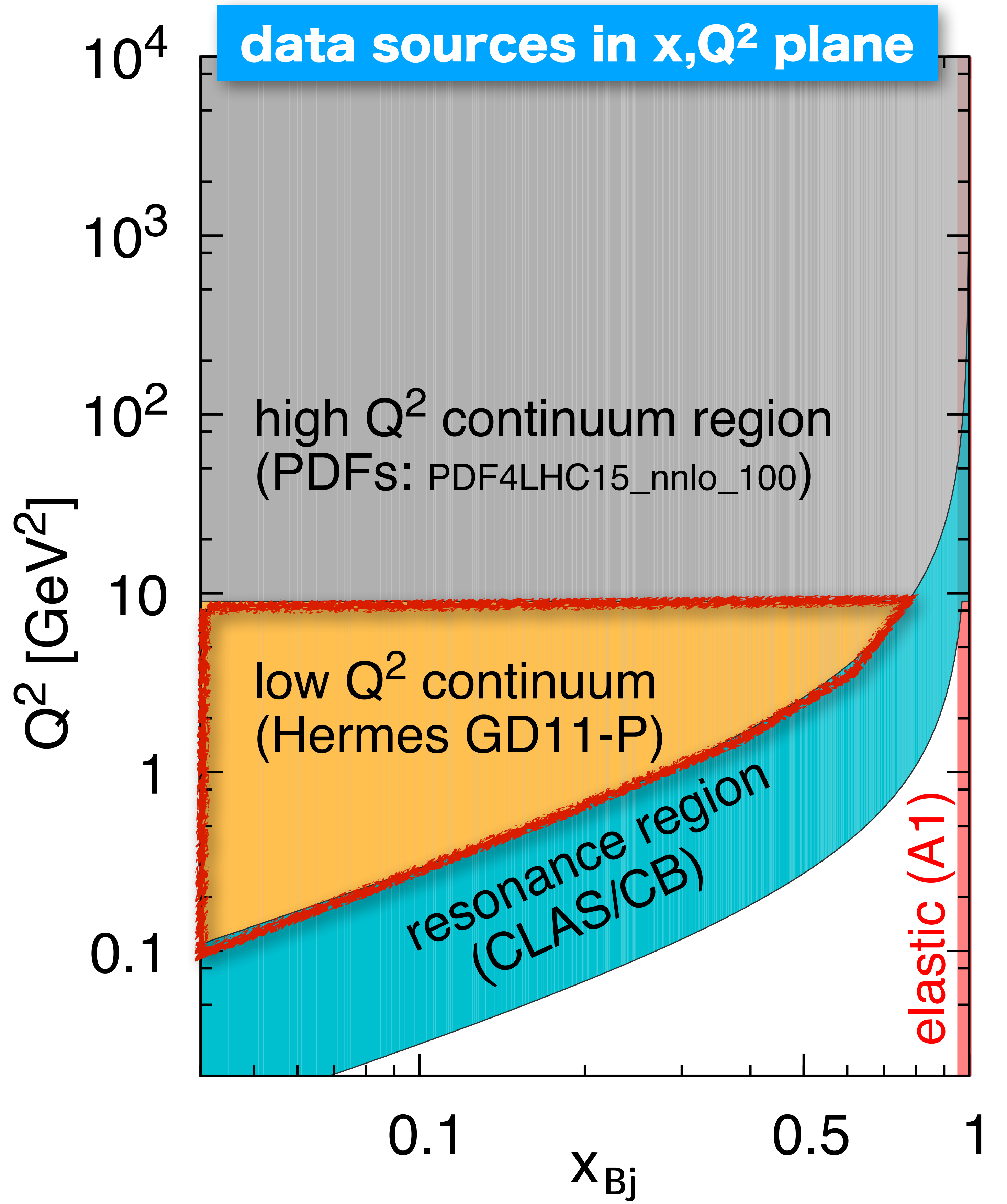


RESONANCE COMPONENT



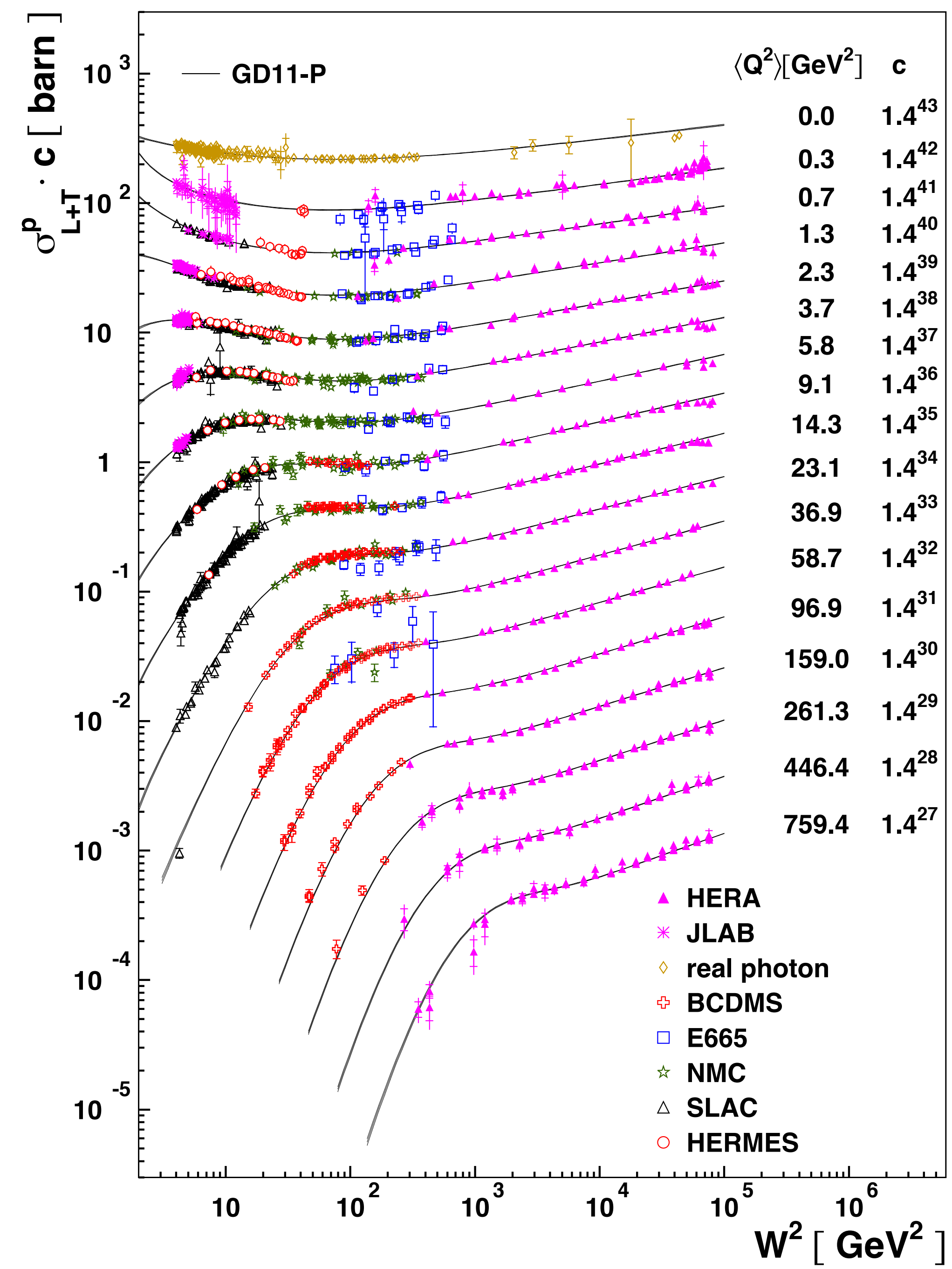
- proton gets excited, e.g. to $\Delta \rightarrow p\pi$ and higher resonances
- relevant for $(m_p+m_\pi)^2 < W^2 < 3.5\text{GeV}^2$

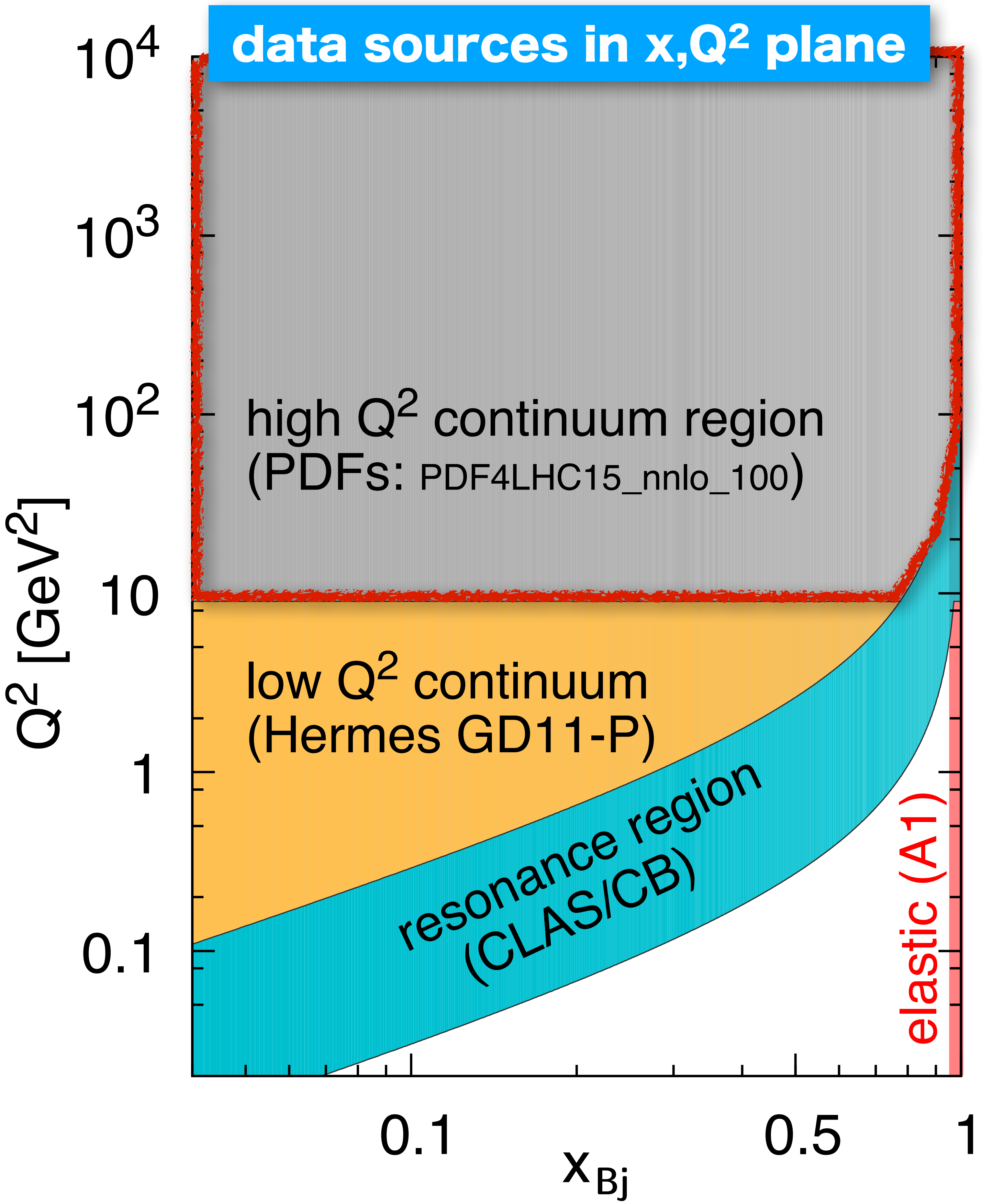




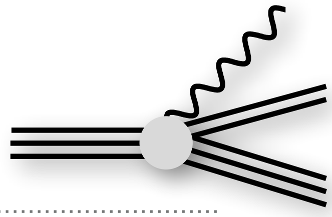
CONTINUUM COMPONENT

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

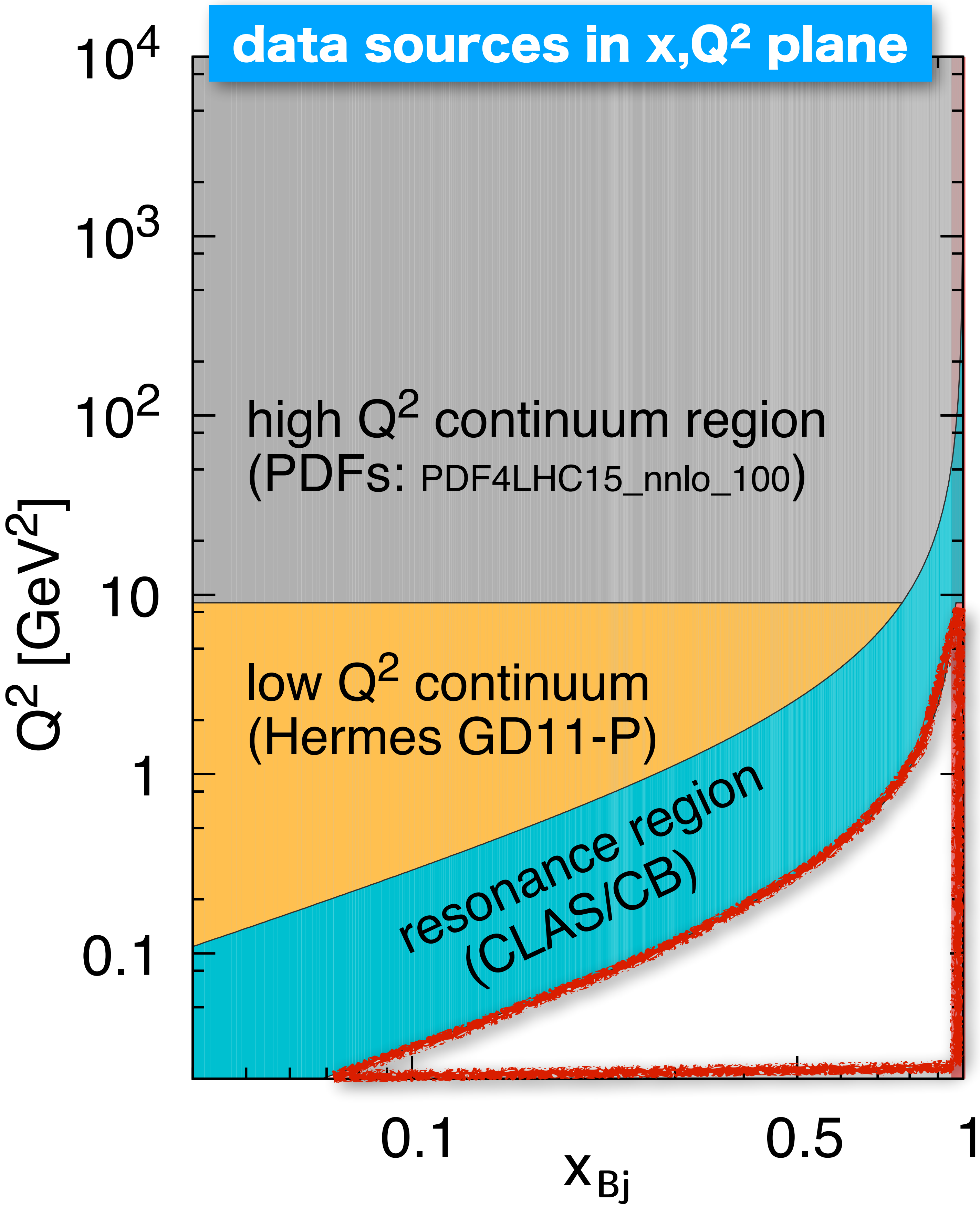




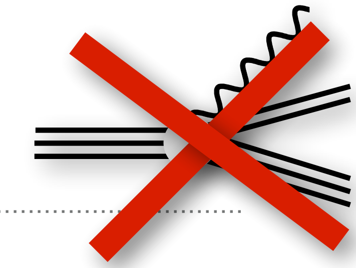
CONTINUUM COMPONENT



- 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)



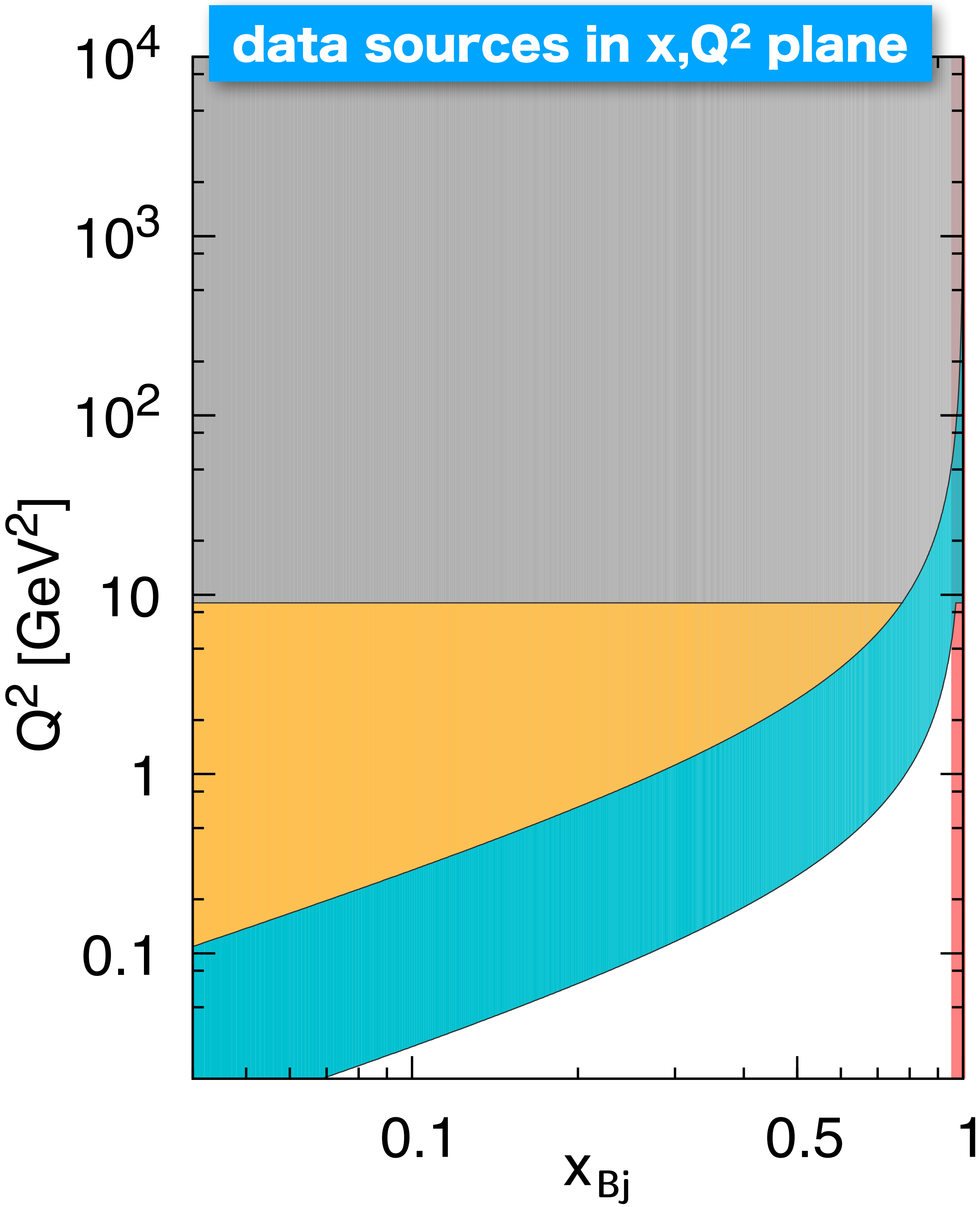
EMPTY AREA



- kinematically inaccessible region: hadronic final-state mass W in range

$$m_p < W < m_p + m_\pi$$

- i.e. the QCD mass gap
- [at higher order in QED, beyond our accuracy, can be filled with photon radiation]

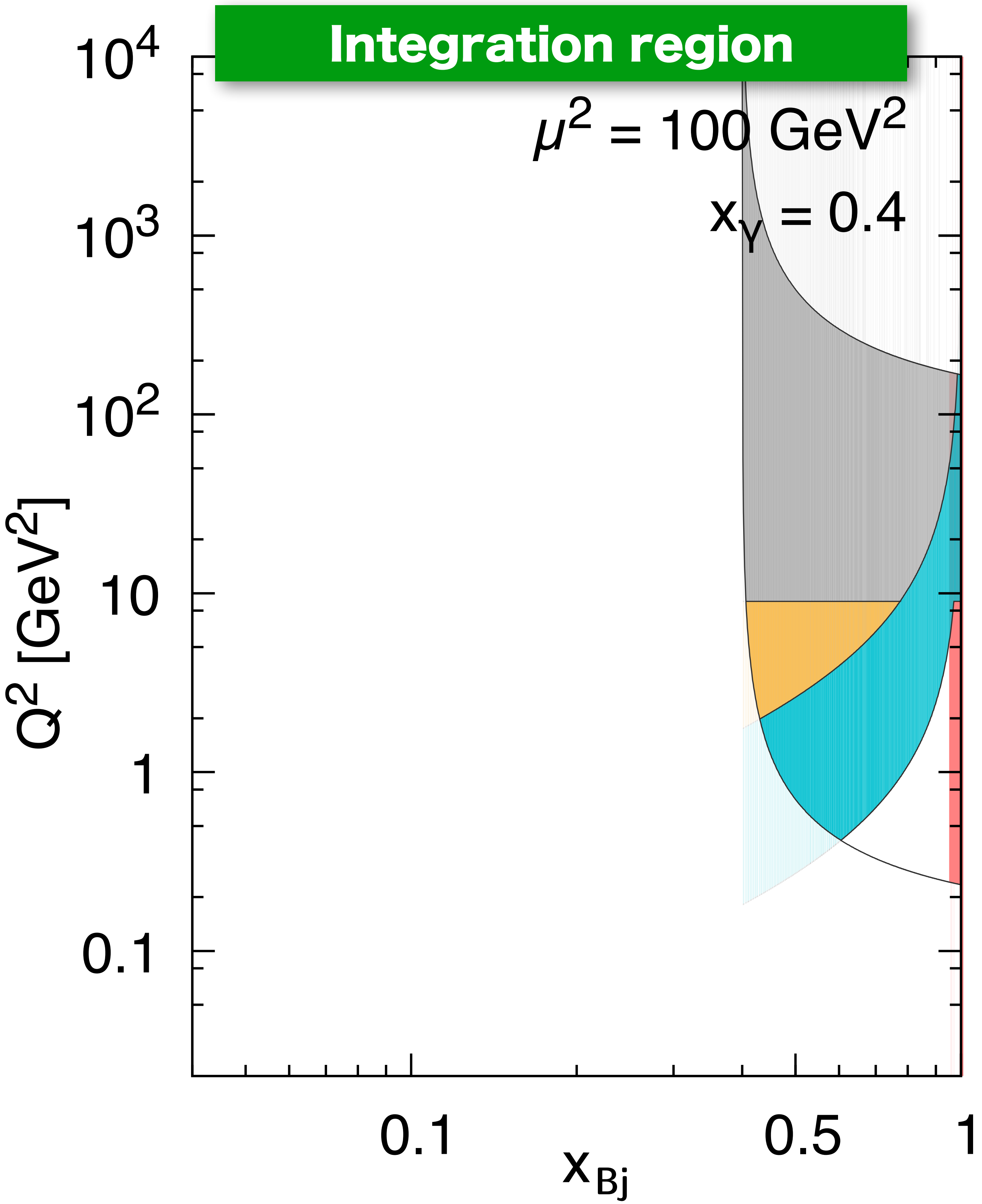


INTEGRATION REGION

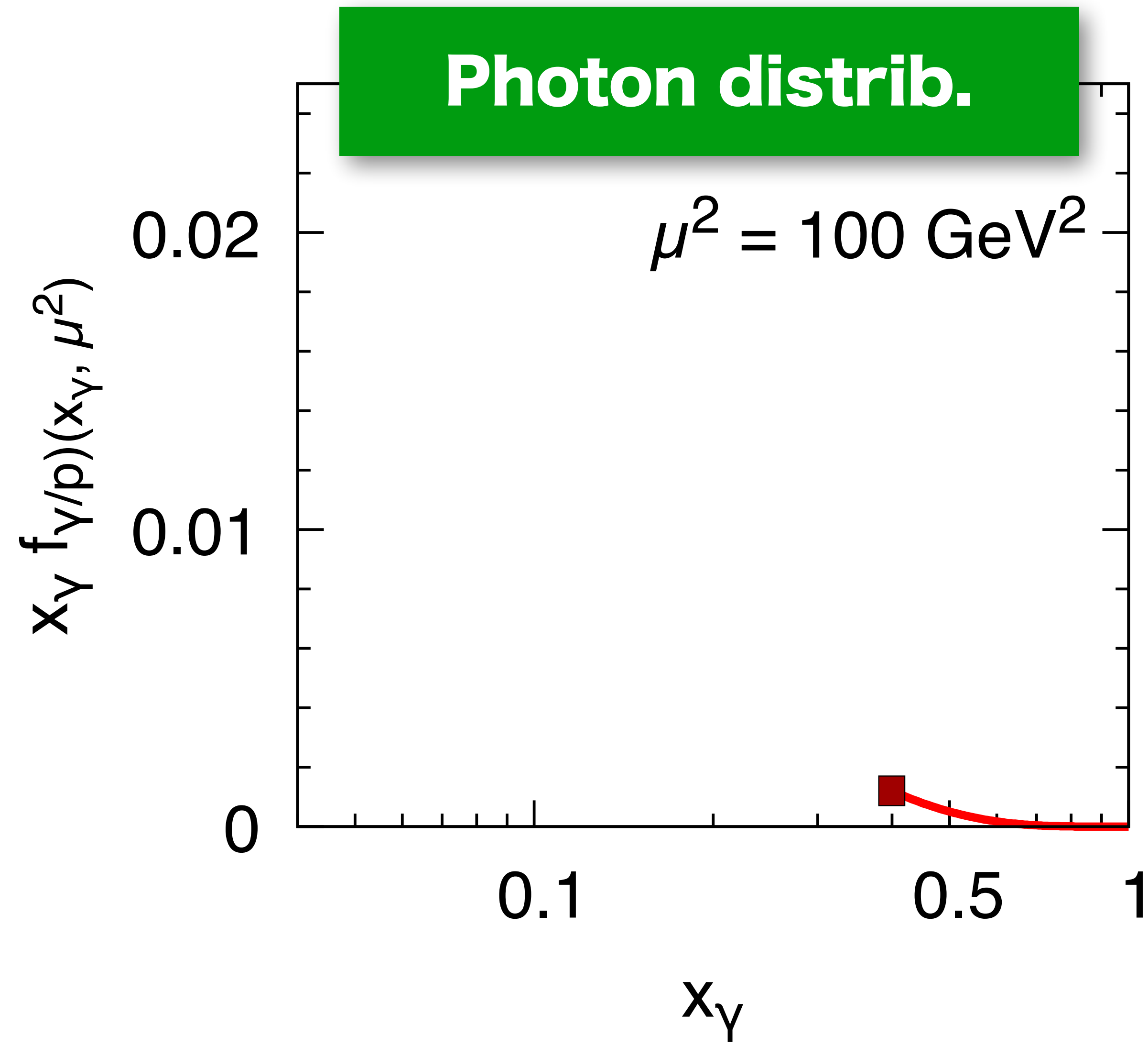
- depends on momentum fraction of the photon (x_γ) and factorisation scale (μ^2)

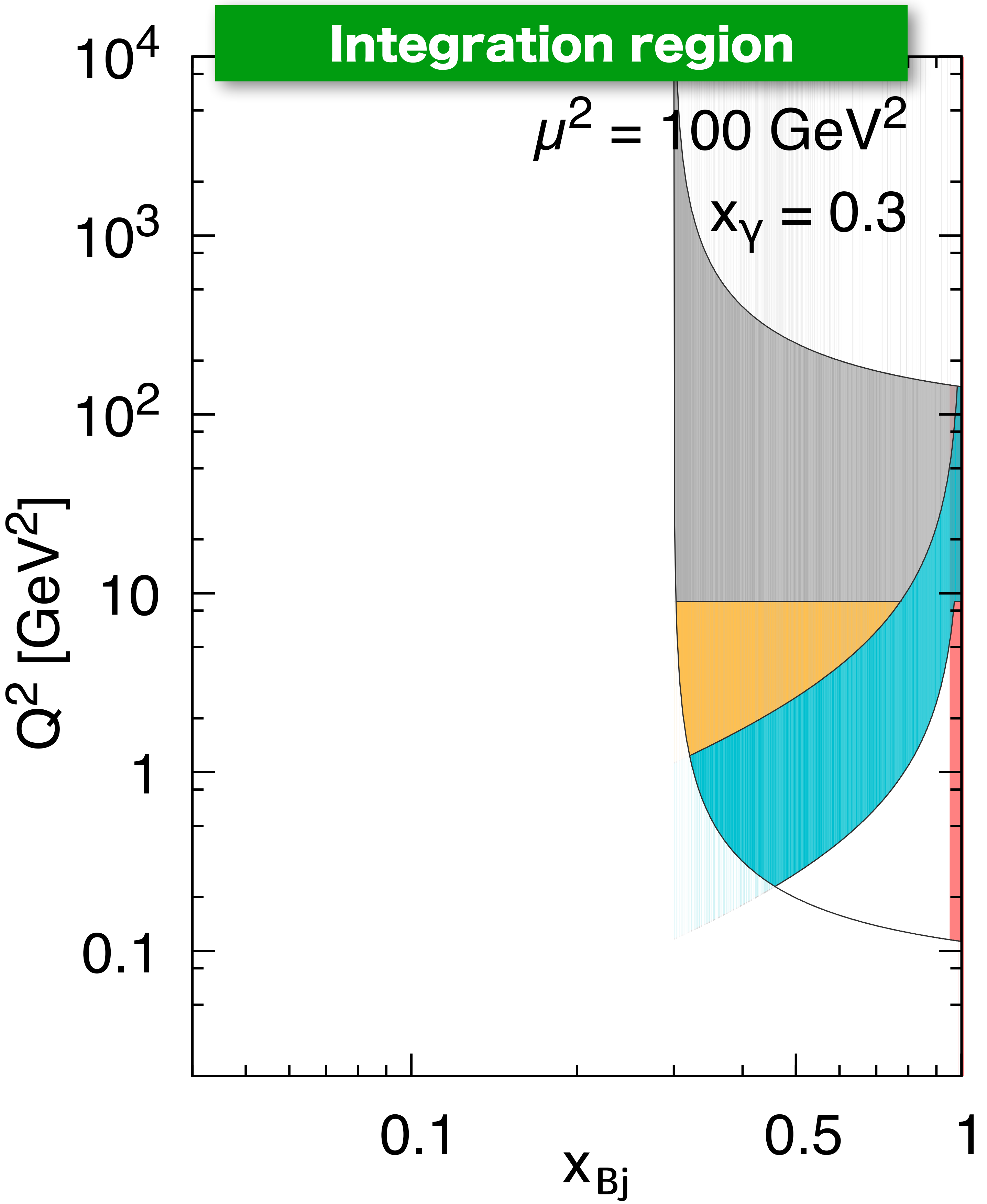
$$x f_{\gamma/p}(x,\mu^2) = \frac{1}{2\pi\alpha(\mu^2)} \int_x^1 \frac{dz}{z} \left\{ \int_{\frac{x^2 m_p^2}{1-z}}^{\frac{\mu^2}{1-z}} \frac{dQ^2}{Q^2} \alpha^2(Q^2) \left[\left(z p_{\gamma q}(z) + \frac{2x^2 m_p^2}{Q^2} \right) F_2(x/z, Q^2) - z^2 F_L\left(\frac{x}{z}, Q^2\right) \right] - \alpha^2(\mu^2)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

INTEGRATION REGION



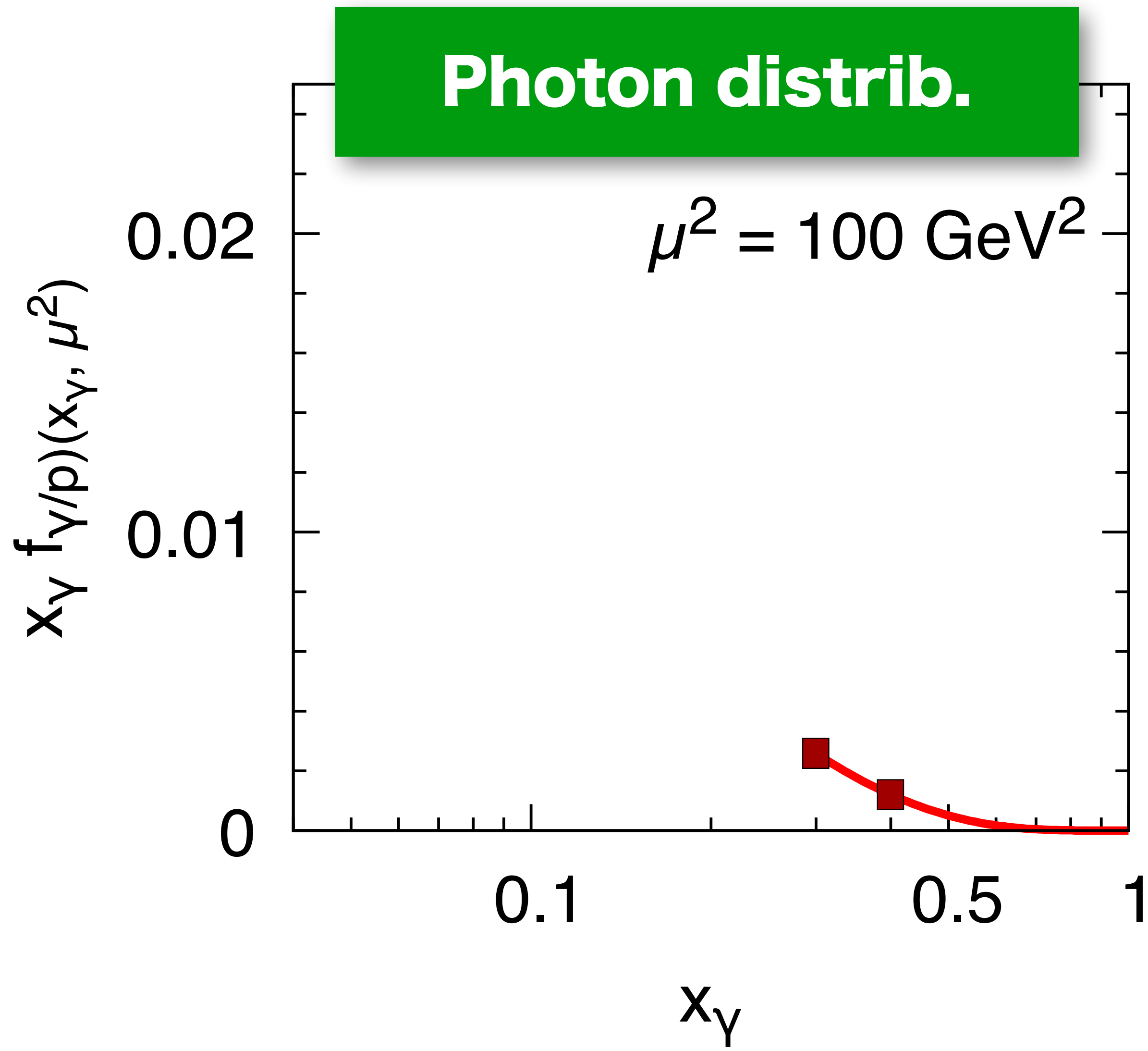
- depends on momentum fraction of the photon (x_γ) and factorisation scale (μ^2)



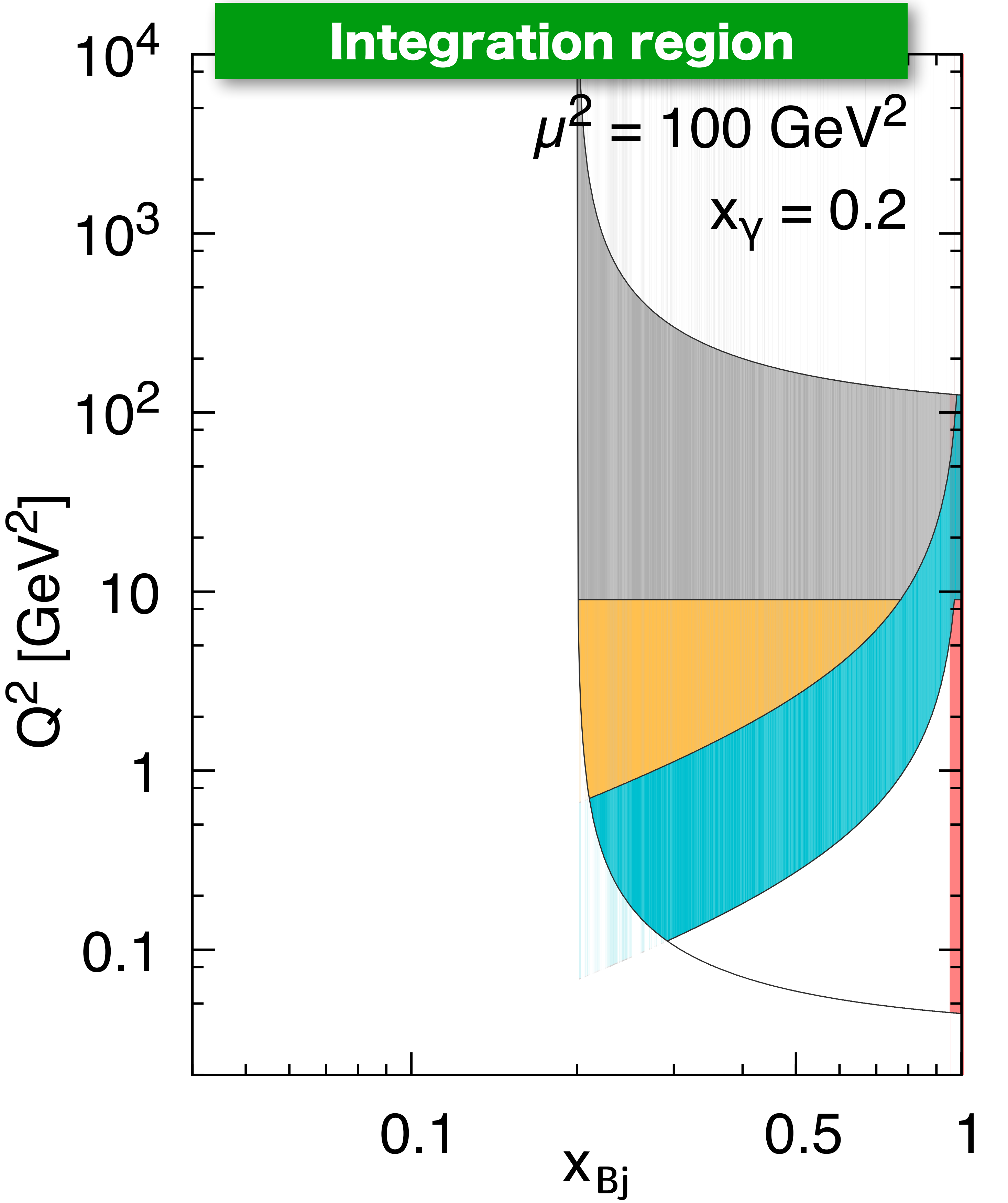


INTEGRATION REGION

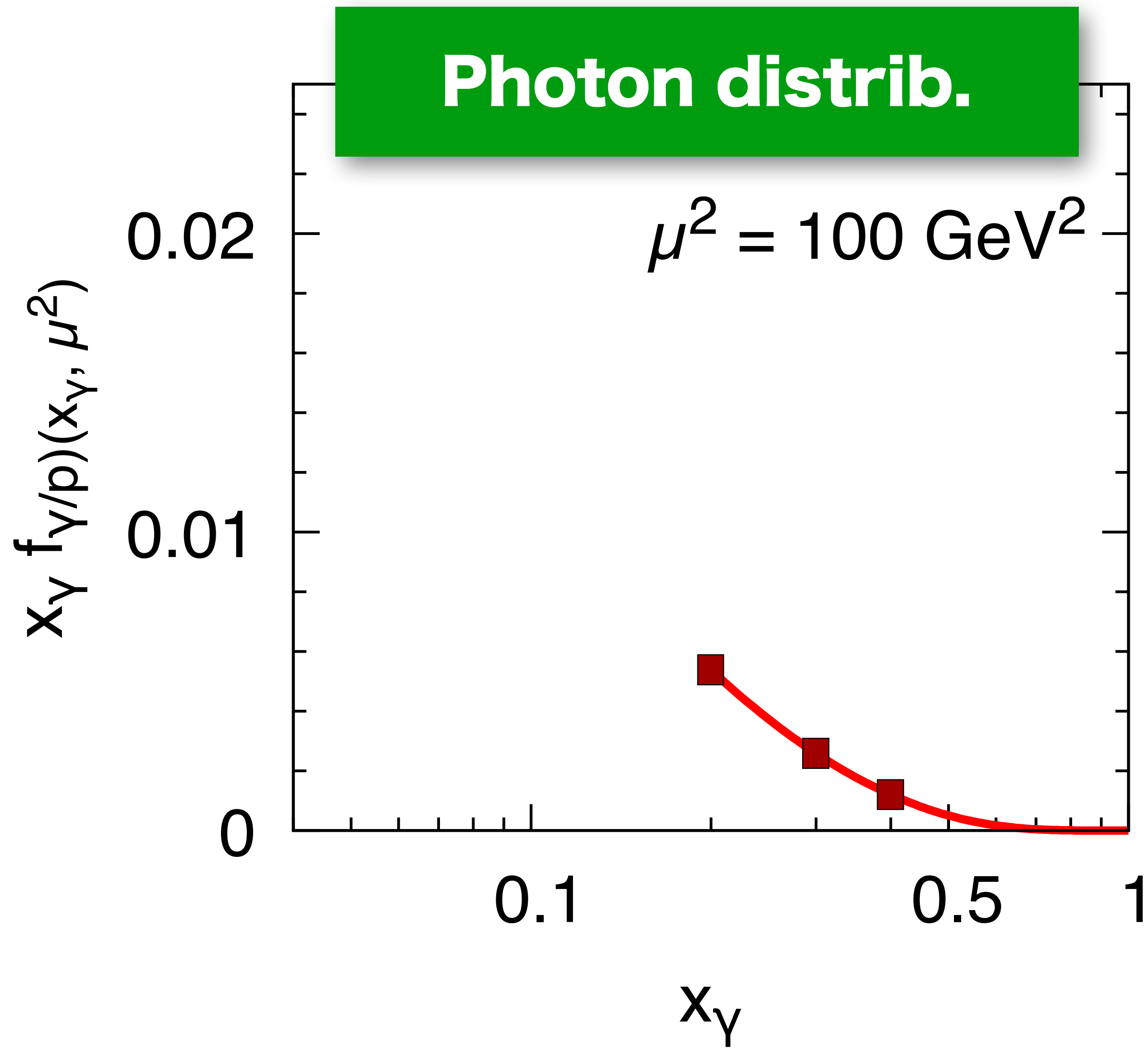
- depends on momentum fraction of the photon (x_γ) and factorisation scale (μ^2)

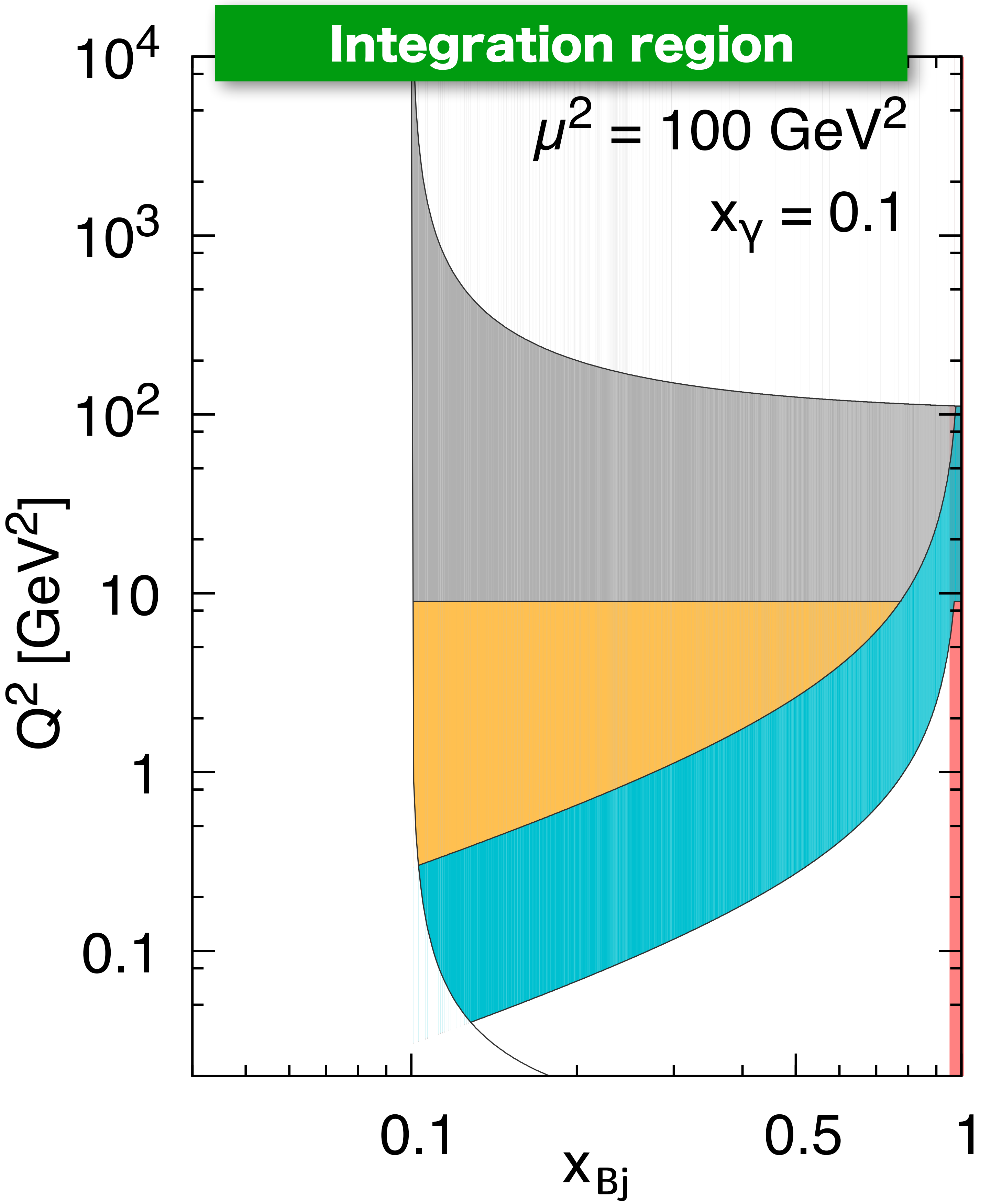


INTEGRATION REGION



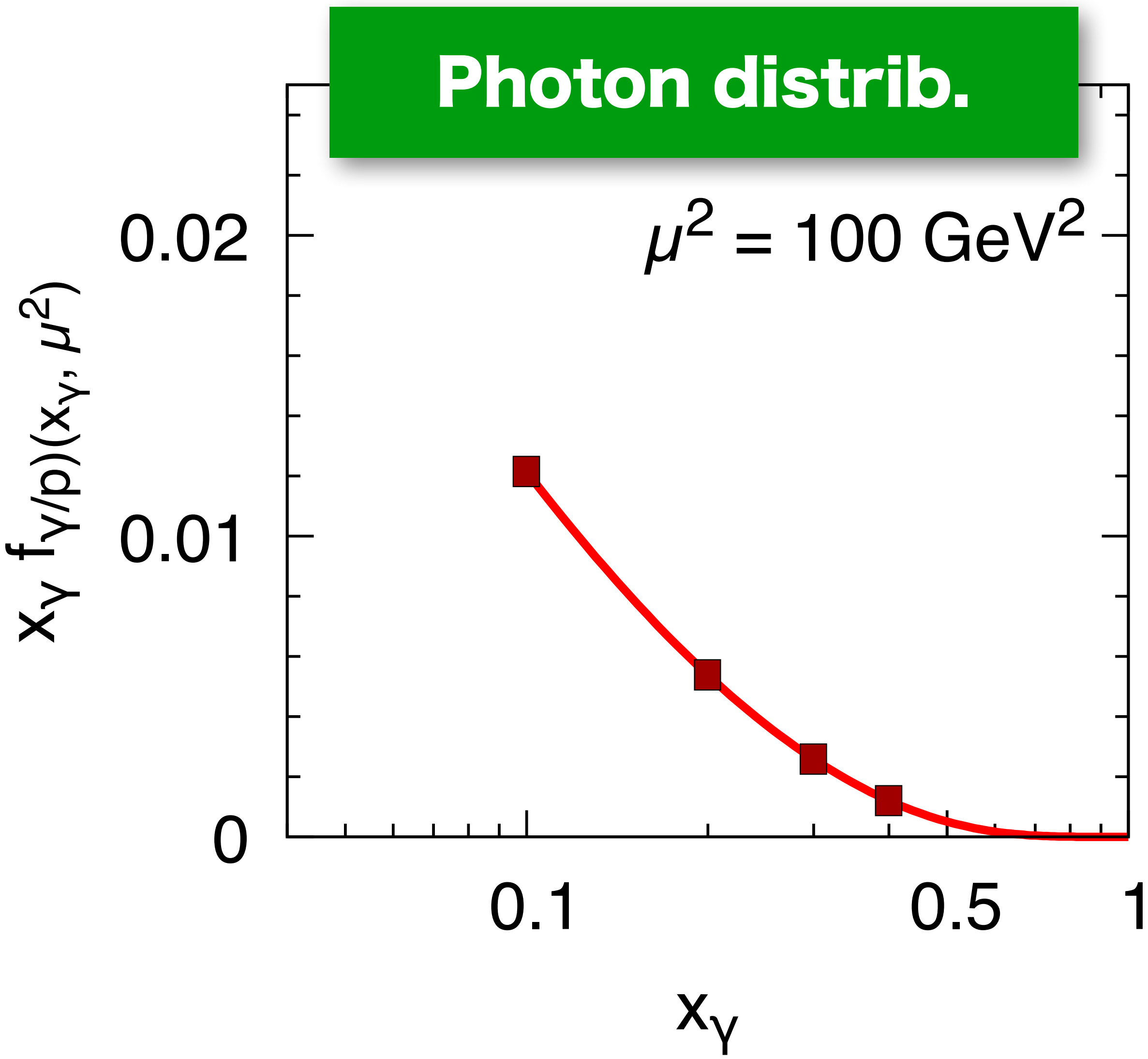
- depends on momentum fraction of the photon (x_γ) and factorisation scale (μ^2)



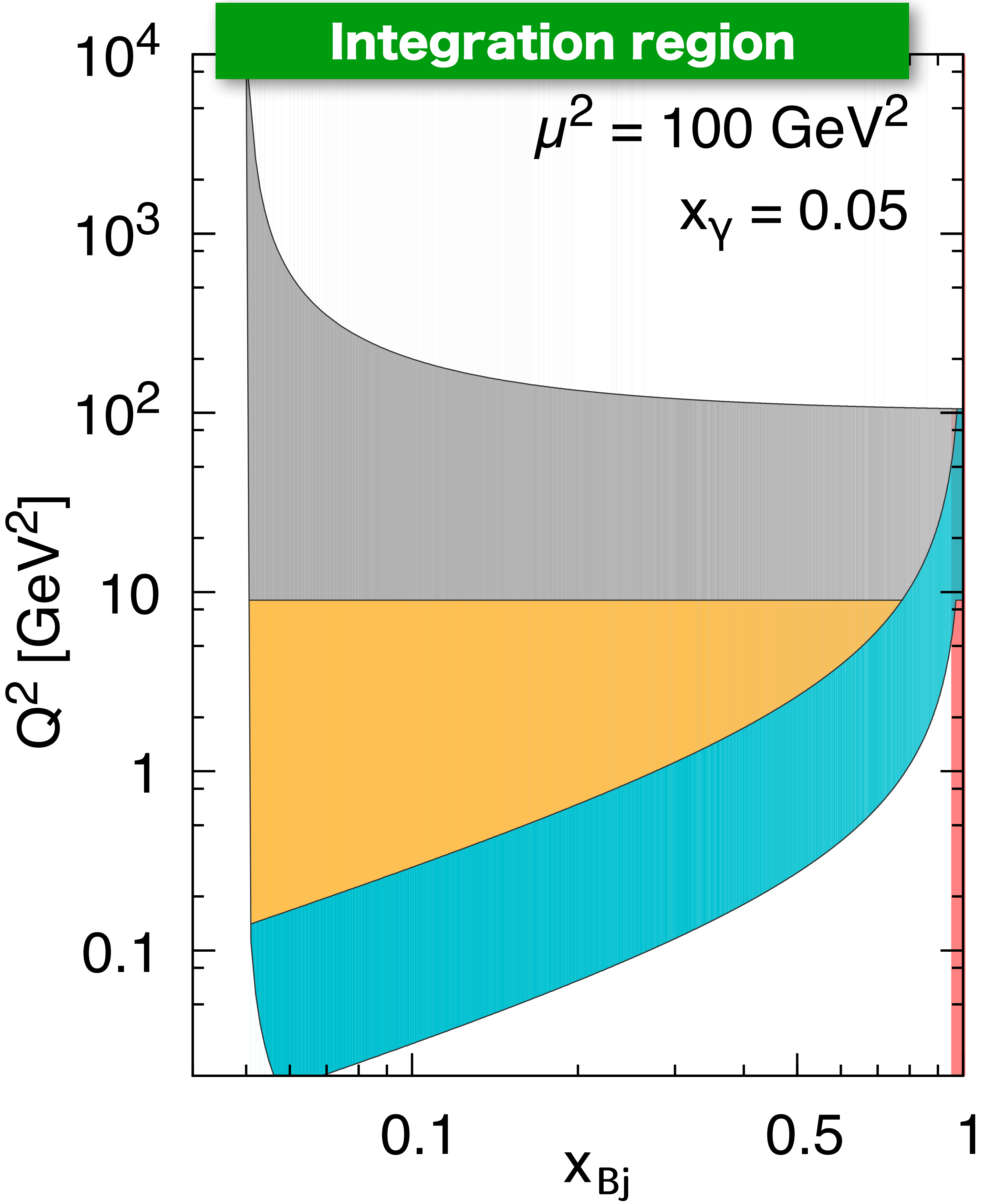


INTEGRATION REGION

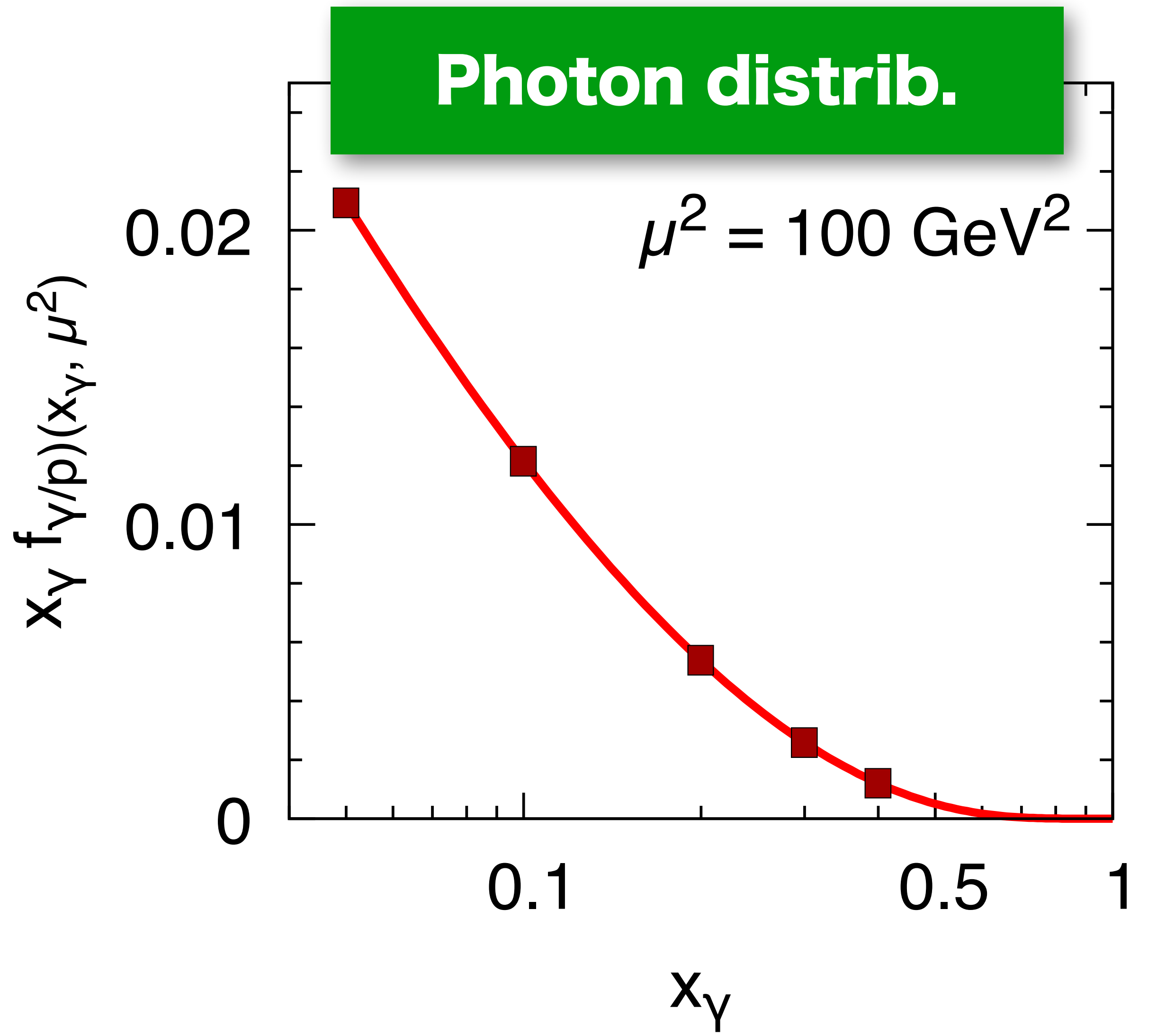
- depends on momentum fraction of the photon (x_γ) and factorisation scale (μ^2)



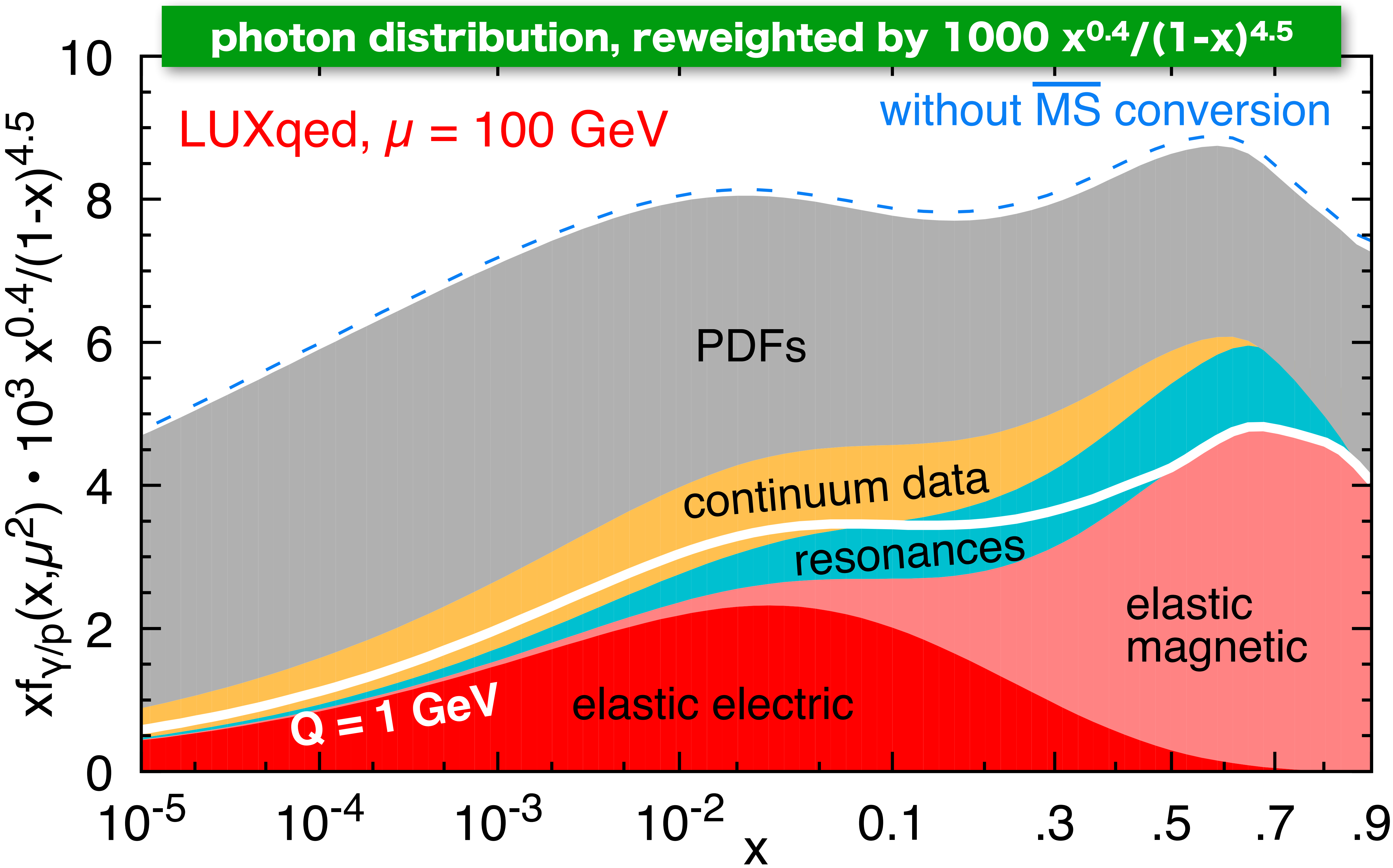
INTEGRATION REGION



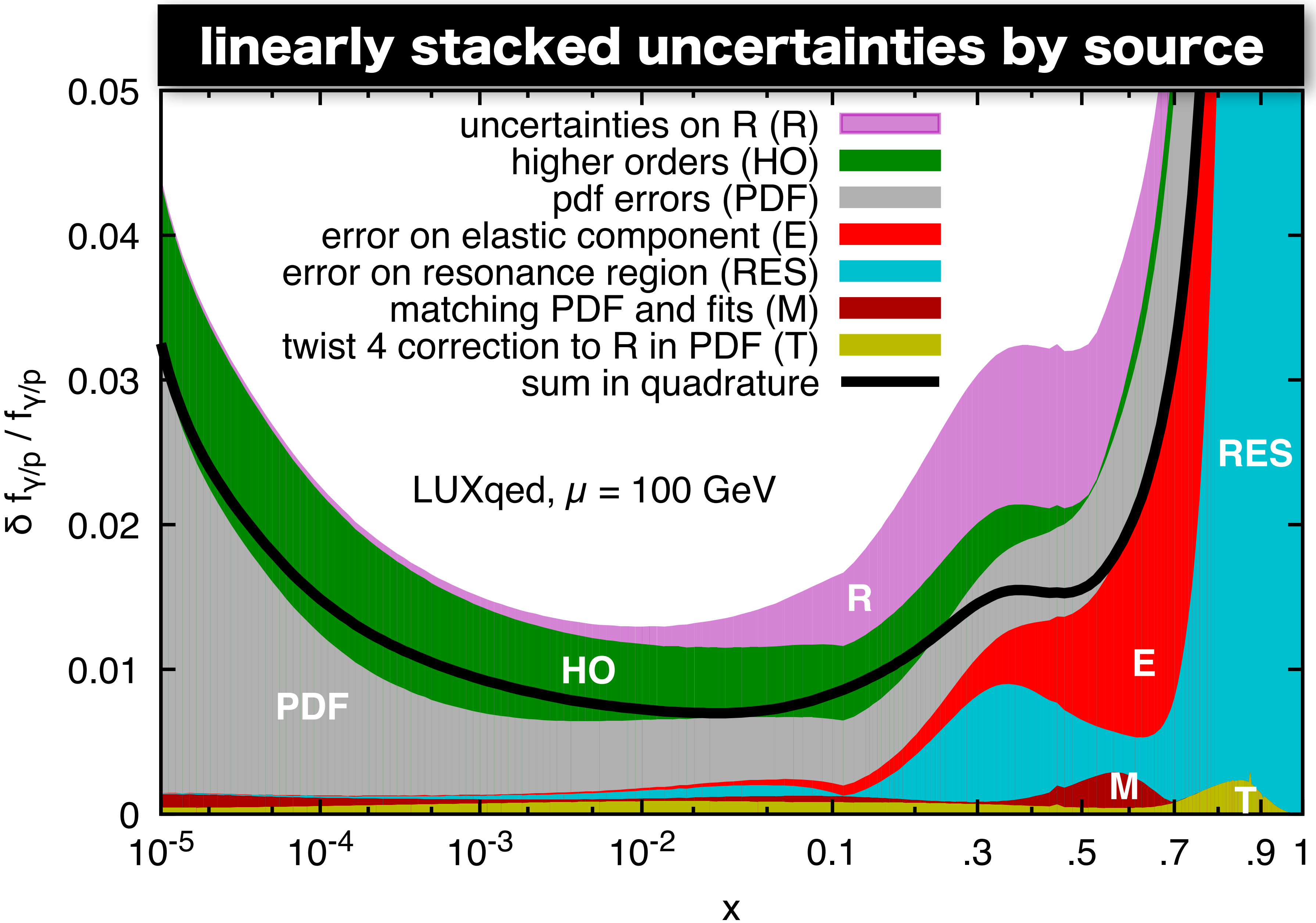
- depends on momentum fraction of the photon (x_γ) and factorisation scale (μ^2)



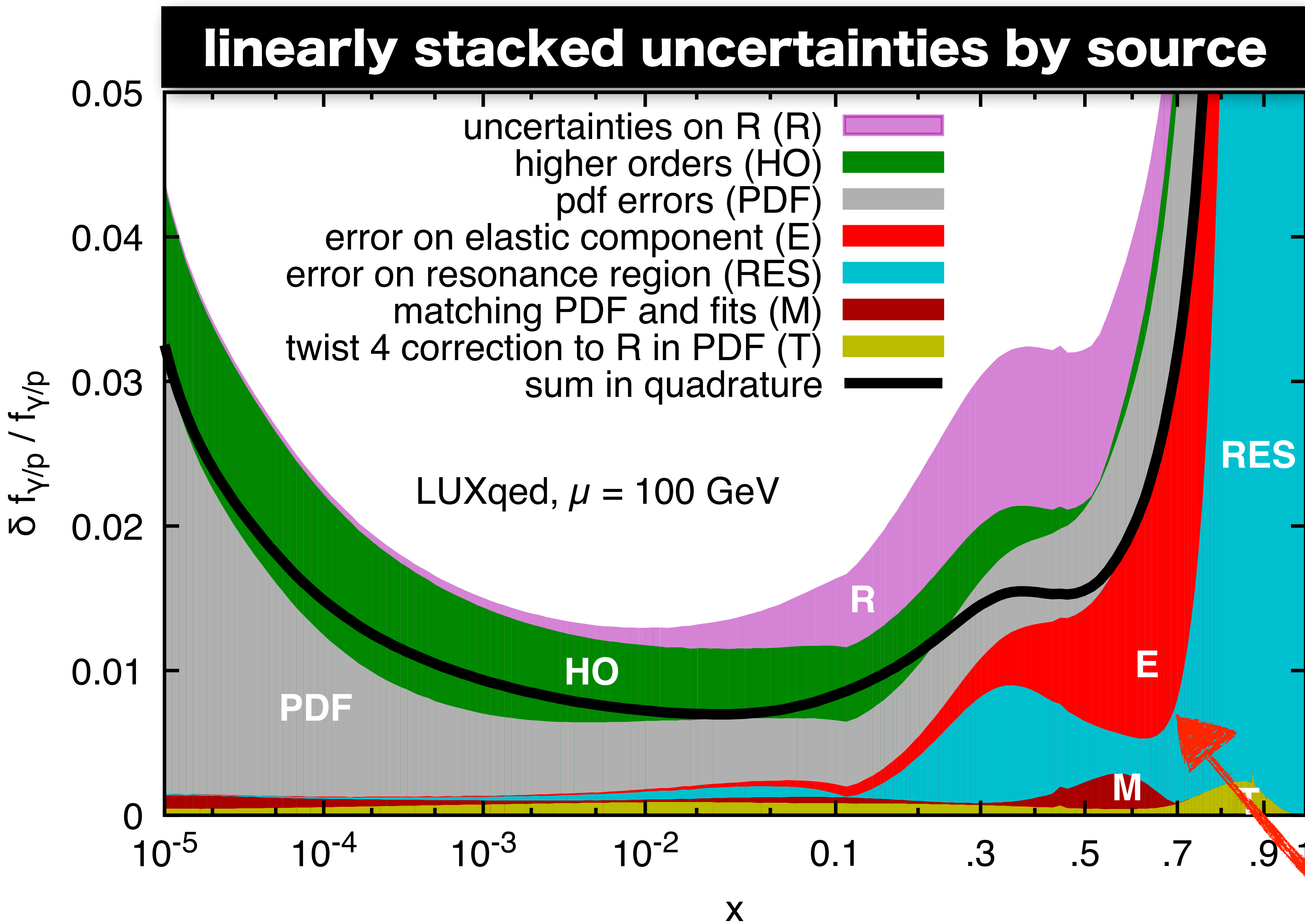
SEPARATE CONTRIBUTIONS TO PHOTON PDF



photon uncertainties (aim to be conservative & pragmatic)

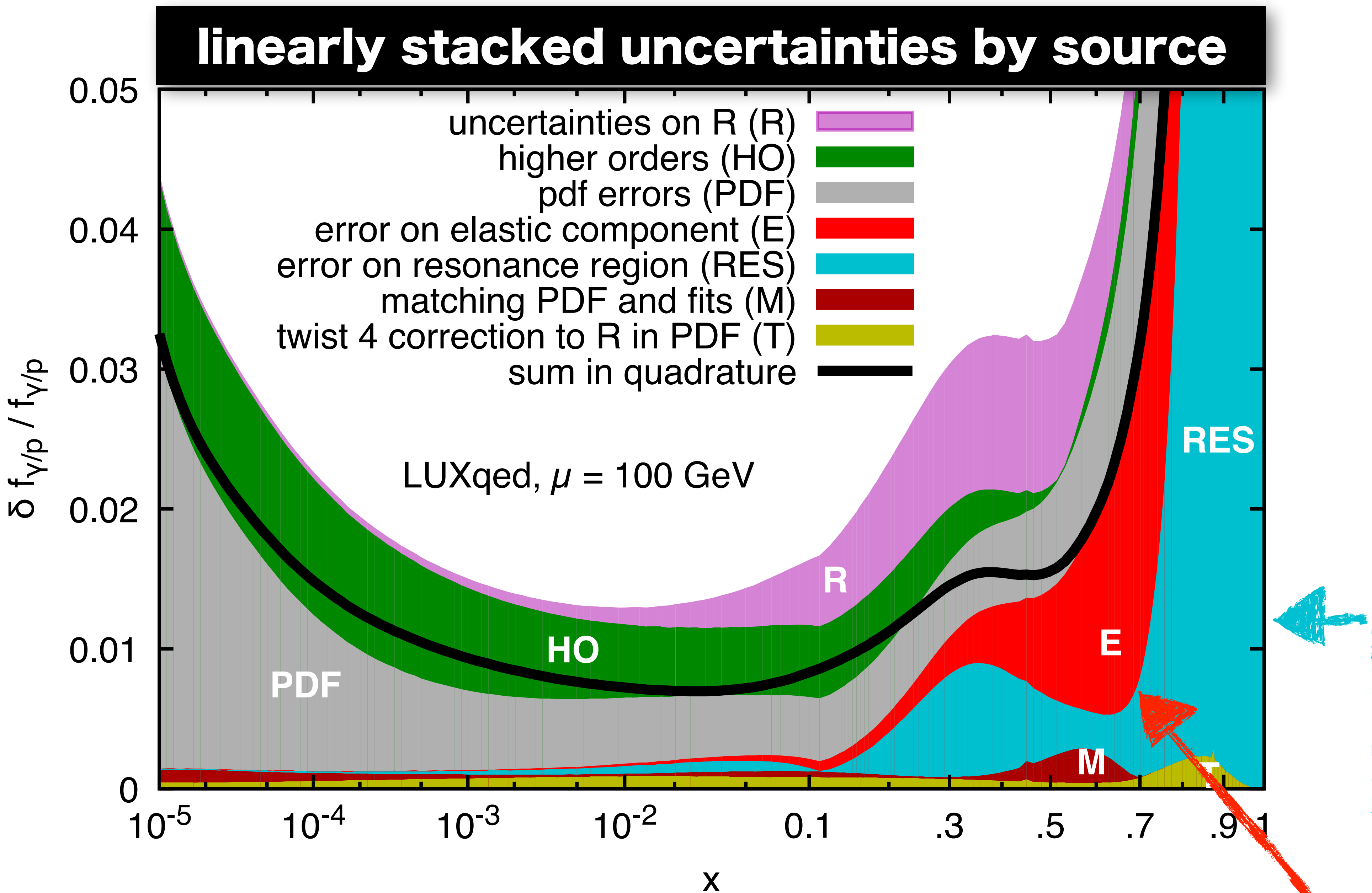


photon uncertainties (aim to be conservative & pragmatic)



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

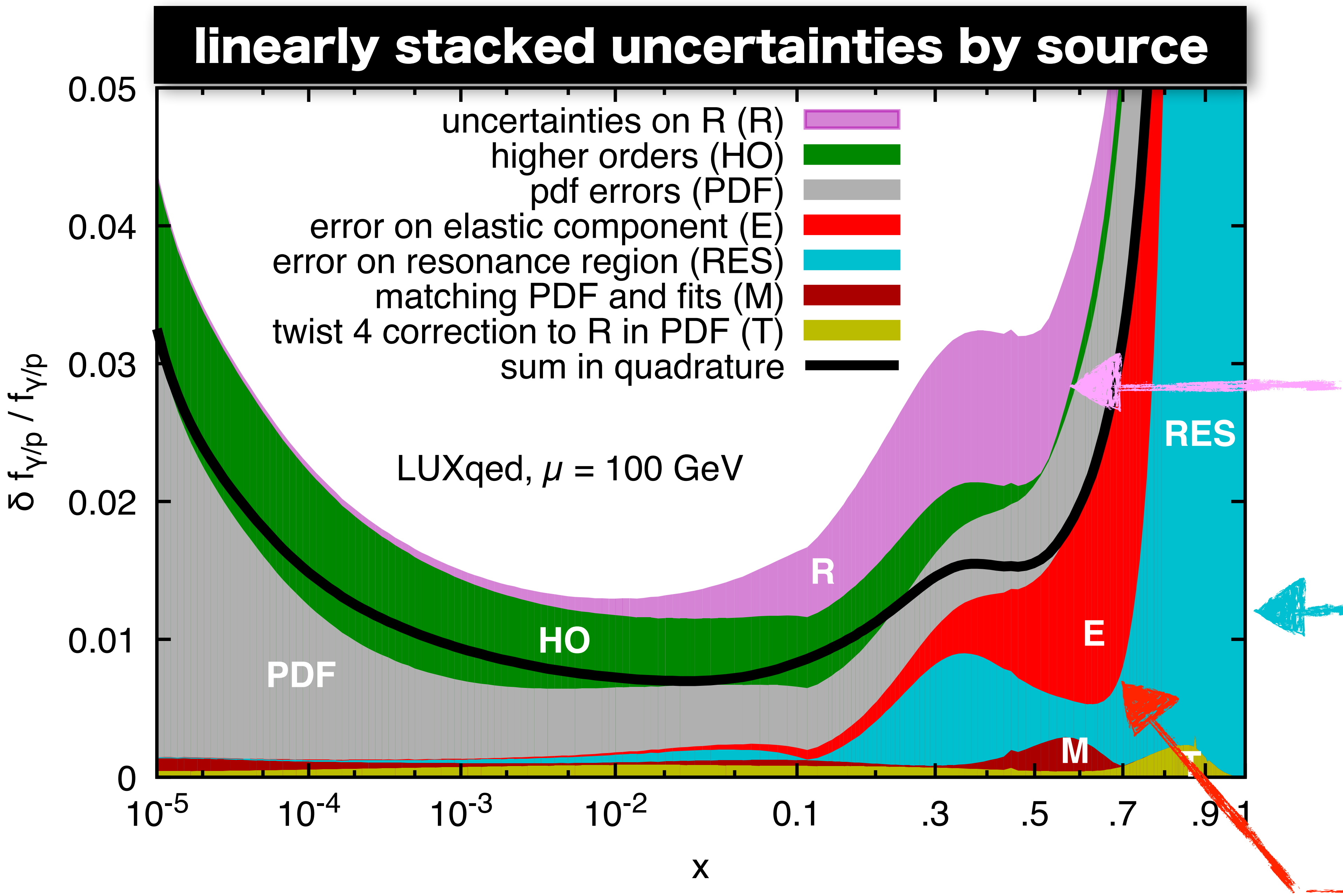
photon uncertainties (aim to be conservative & pragmatic)



replace CLAS resonance fit with Christy-Bosted

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

photon uncertainties (aim to be conservative & pragmatic)

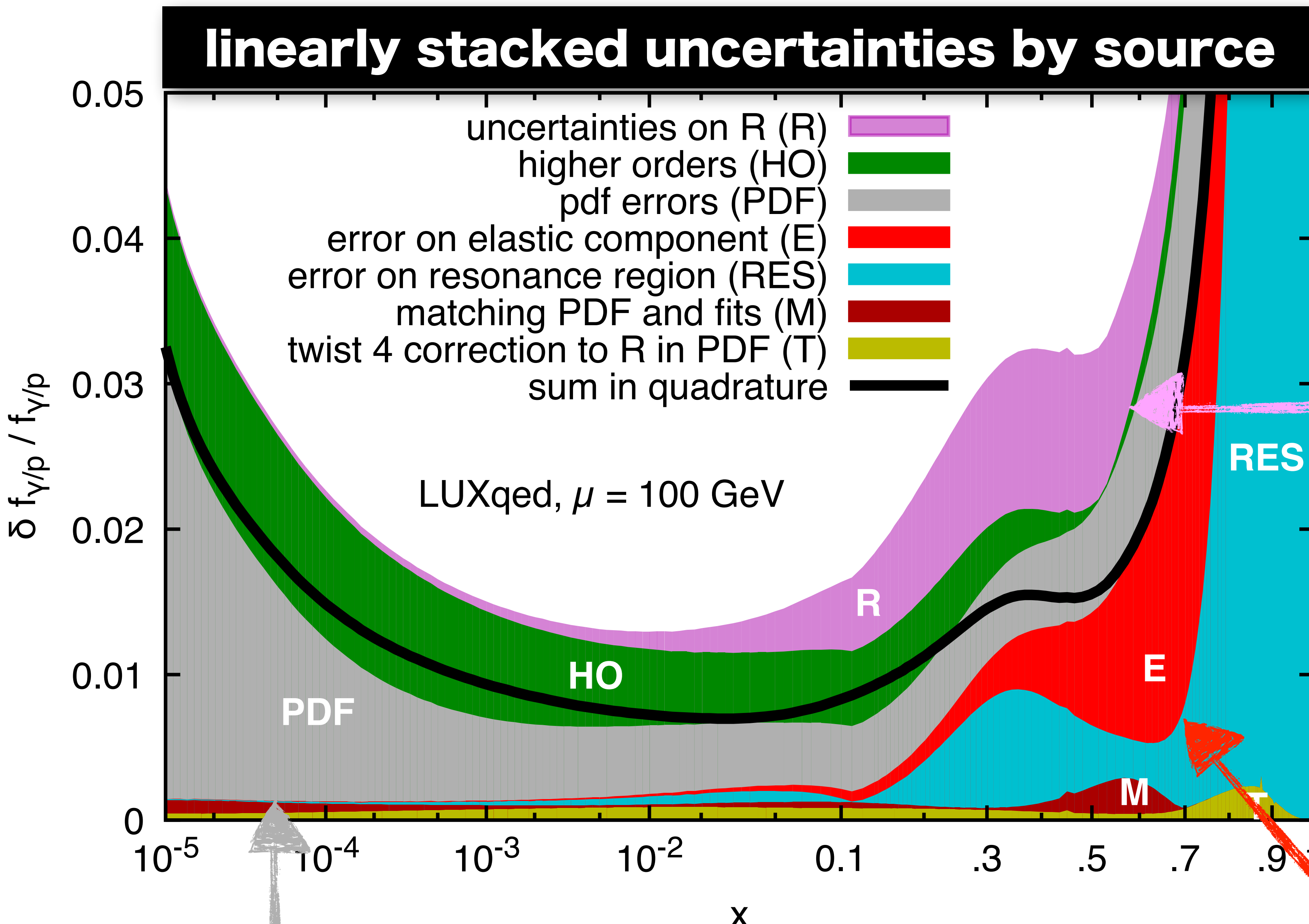


±50% on R ($\sim F_L/(F_2-F_L)$) in low-Q^2 continuum and resonance regions

replace CLAS resonance fit with Christy-Bosted

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

photon uncertainties (aim to be conservative & pragmatic)



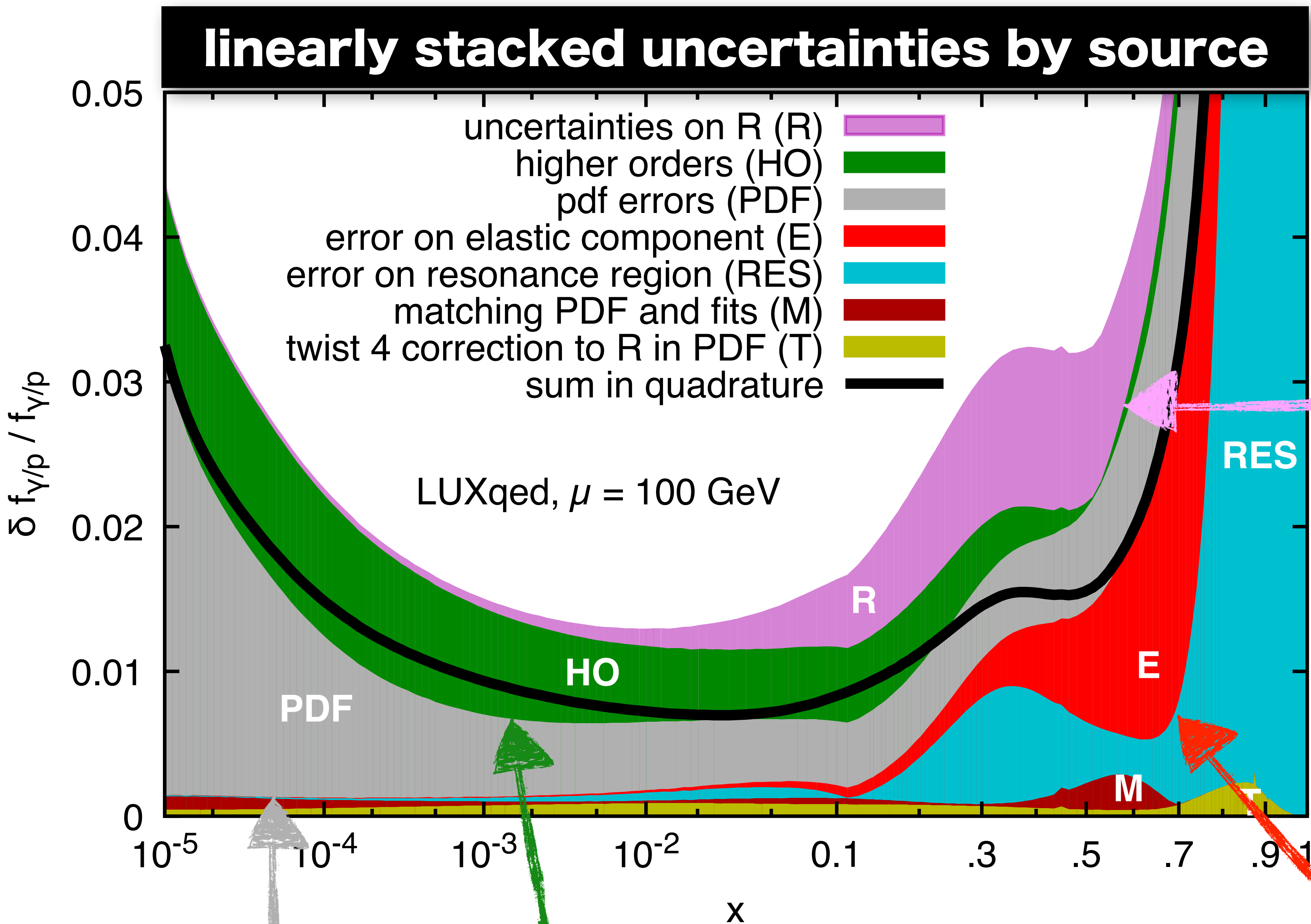
±50% on R ($\sim F_L/(F_2\text{-}F_L)$) in low-$Q^2$ continuum and resonance regions

replace CLAS resonance fit with Christy-Bosted

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

standard PDF uncertainty

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

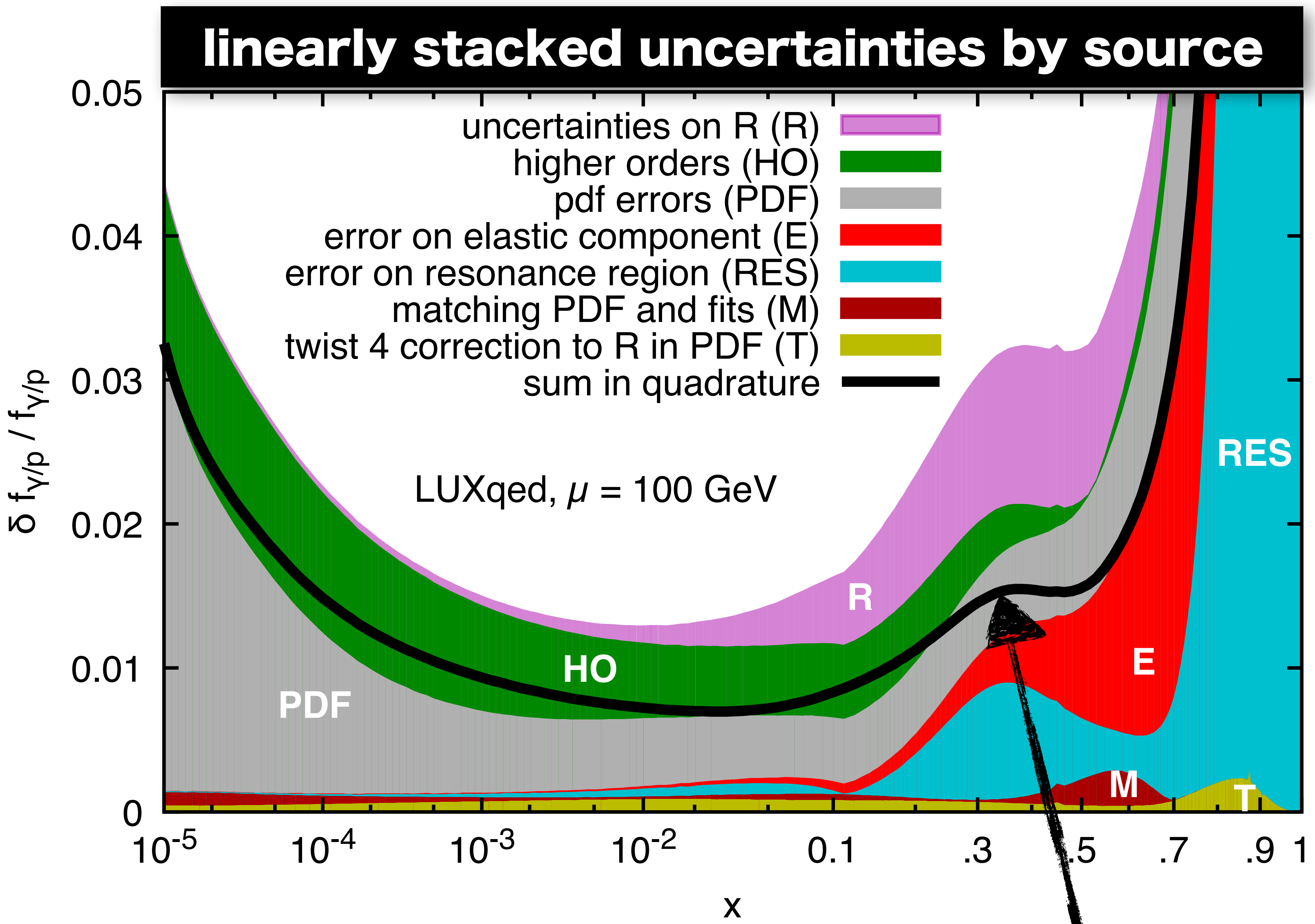
replace CLAS resonance fit with Christy-Bosted

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)



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

Uncertainties included in LUX

Added members with variations in photon PDF calculation:

- 0-100: original PDF members (PDF4LHC15_nnlo_100)
- 101: Replace CLAS parametrization of resonance region with Christy-Bosted one. (Becomes particuarly crazy al large x).
- 102: rescale R in low Q^2 region by 1.5.
- 103: rescale R in high-Q^2 region with a higher-twist component.
- 104: Use 'World" elastic fit from A1: no polarization data, no fit to Two Photon Exchange effects.
- 105: Use lower edge of elastic fit error band.
- 106: Start using PDF's from $Q^2 = 5$ rather than $9\,\mathrm{GeV}^2$.
- 107: Upper limit of integration in f_γ formula changed to μ^2 instead of $\mu^2/(1-z)$, with suitable correction of $\overline{\mathrm{MS}}$ term.

All errors are taken as symmetric.

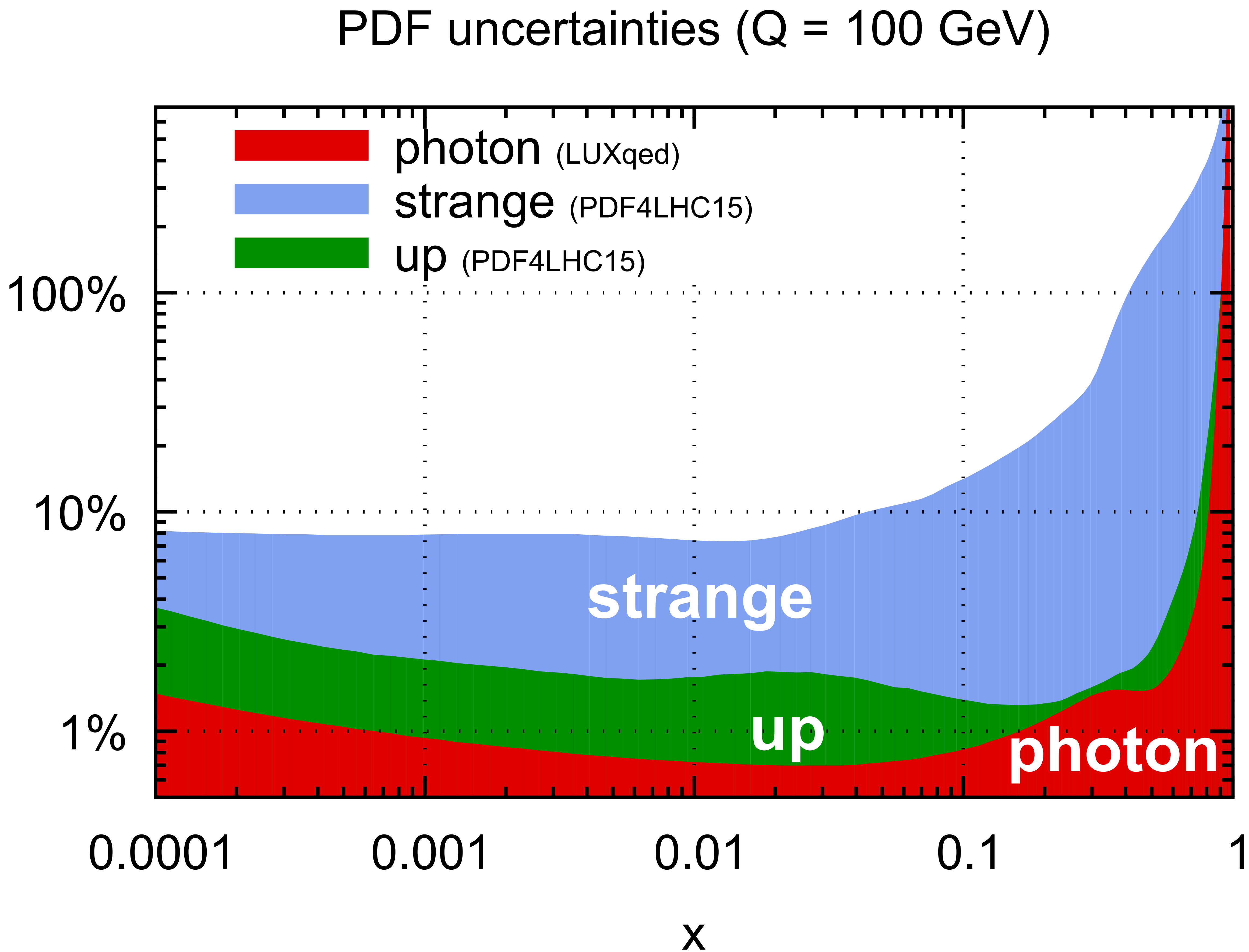
PDF valid for μ > 10 GeV (related to PDF4LHC15 issues)

PHOTON PDF ESTIMATES (not exhaustive)

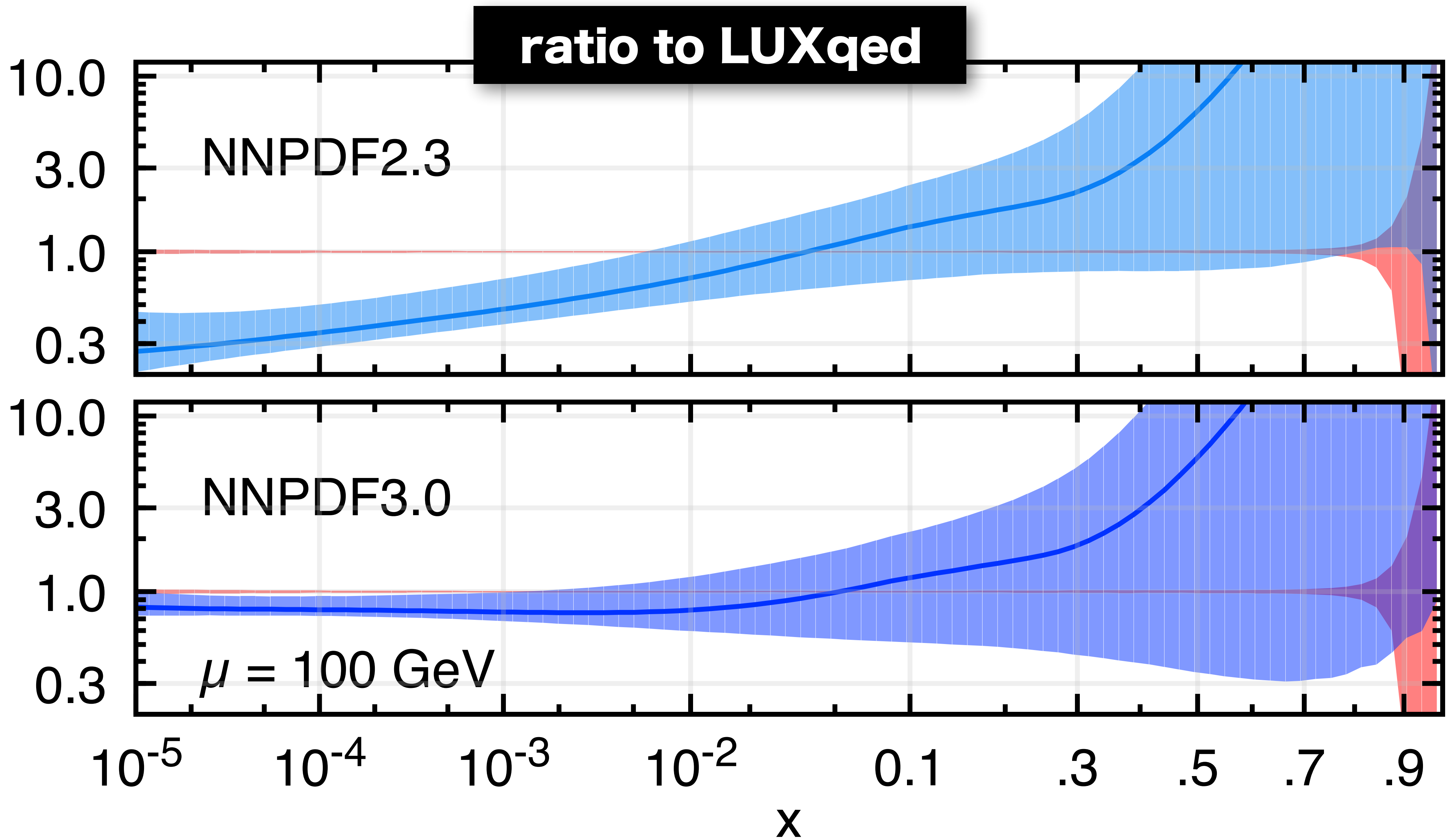
	elastic	inelastic	in LHAPDF?
Gluck Pisano Reya 2002	dipole	model	✘
MRST2004qed	✘	model	✓
NNPDF23qed	no separation; fit to data		✓
CT14qed	✘	model (data-constrained)	✓
CT14qed_inc	dipole	model (data-constrained)	✓
Martin Ryskin 2014	dipole (only electric part)	model	✘
Harland-Lang, Khoze Ryskin 2016	dipole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

examine result

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



other PDFs v. LUXqed



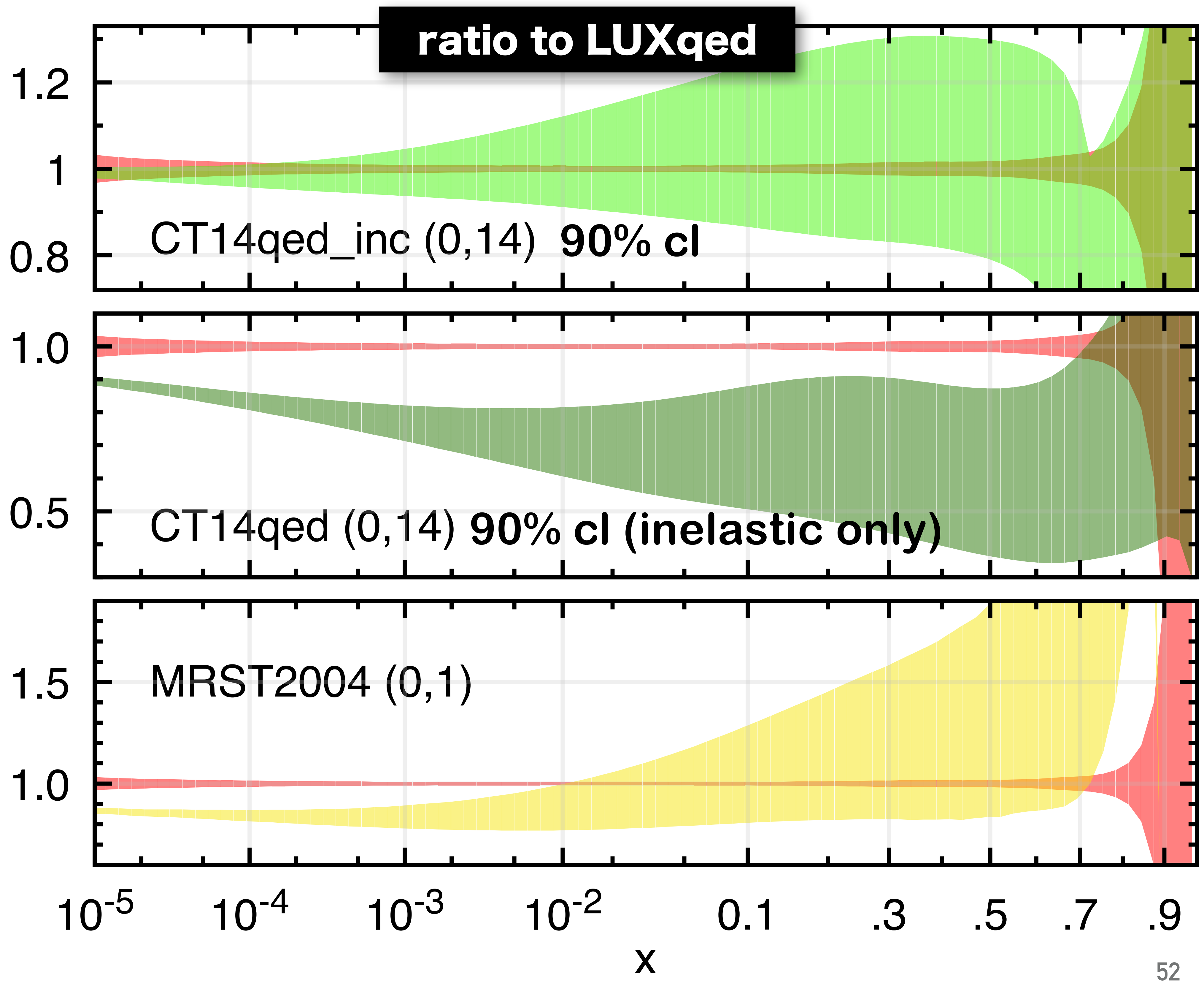
central NNPDF result much higher at large x (but consistent within errors)

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

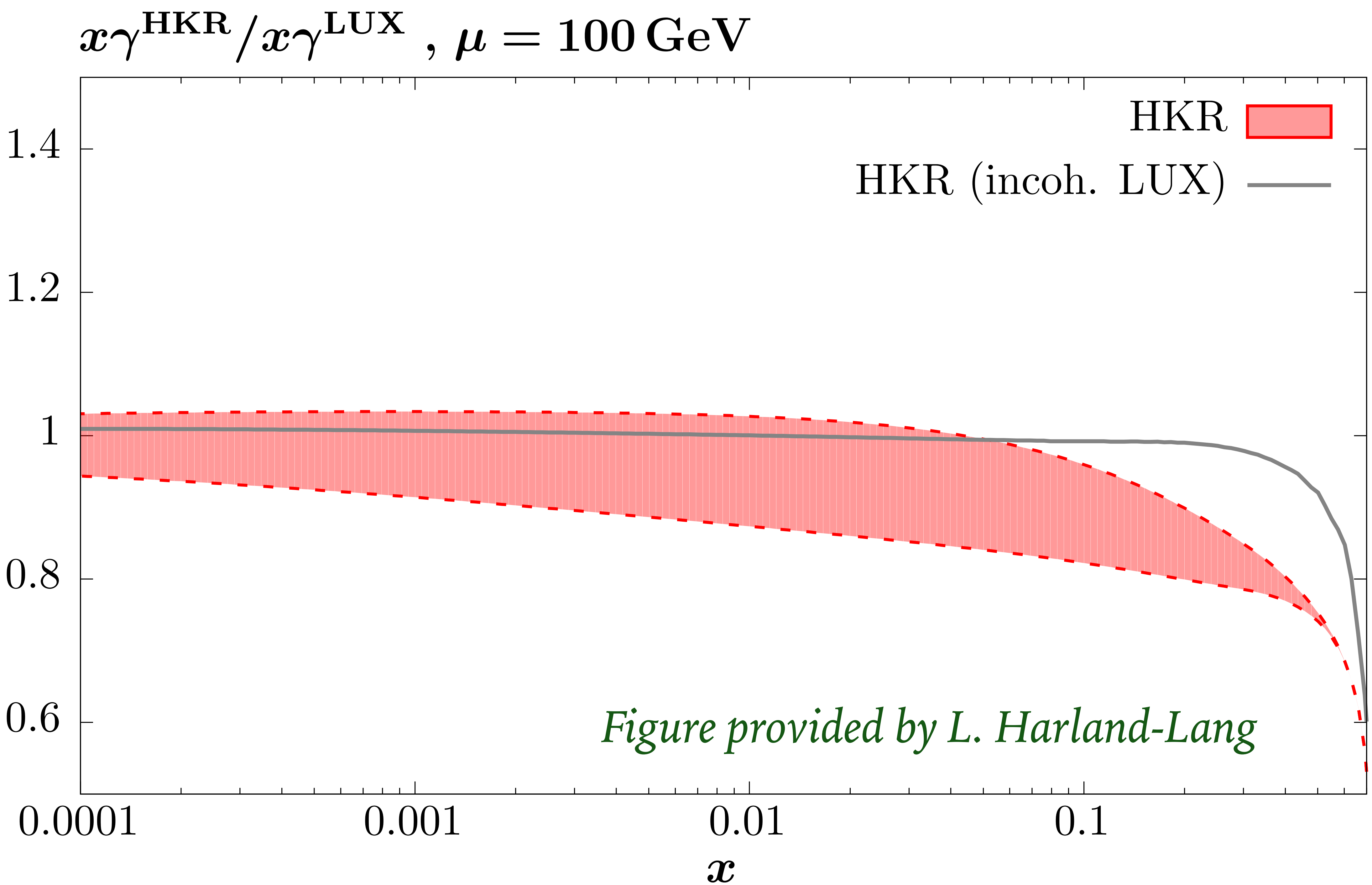
other PDFs v. LUXqed

Others are numerically closer

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

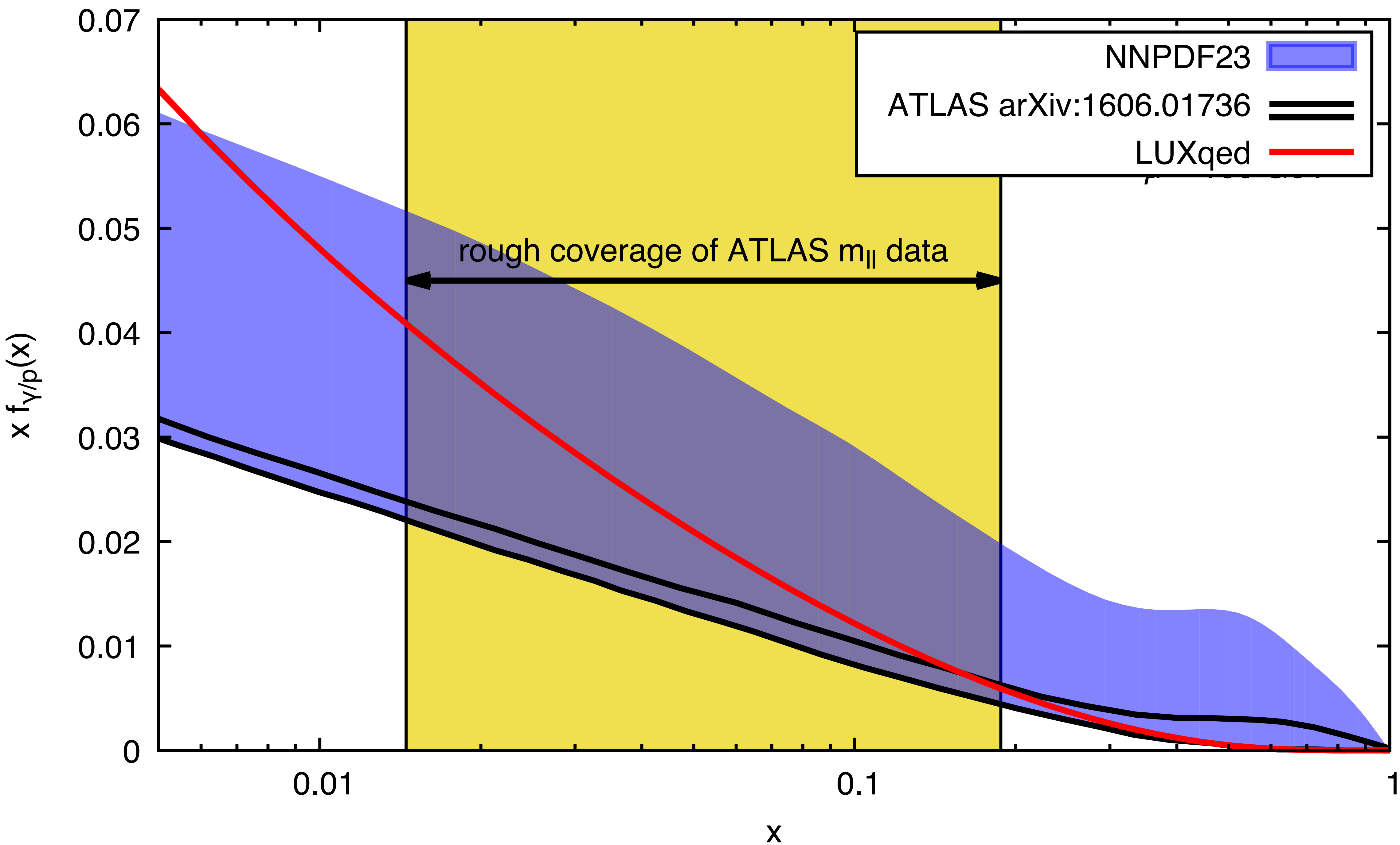


ratio of HKR (1607.04635) to LUXqed



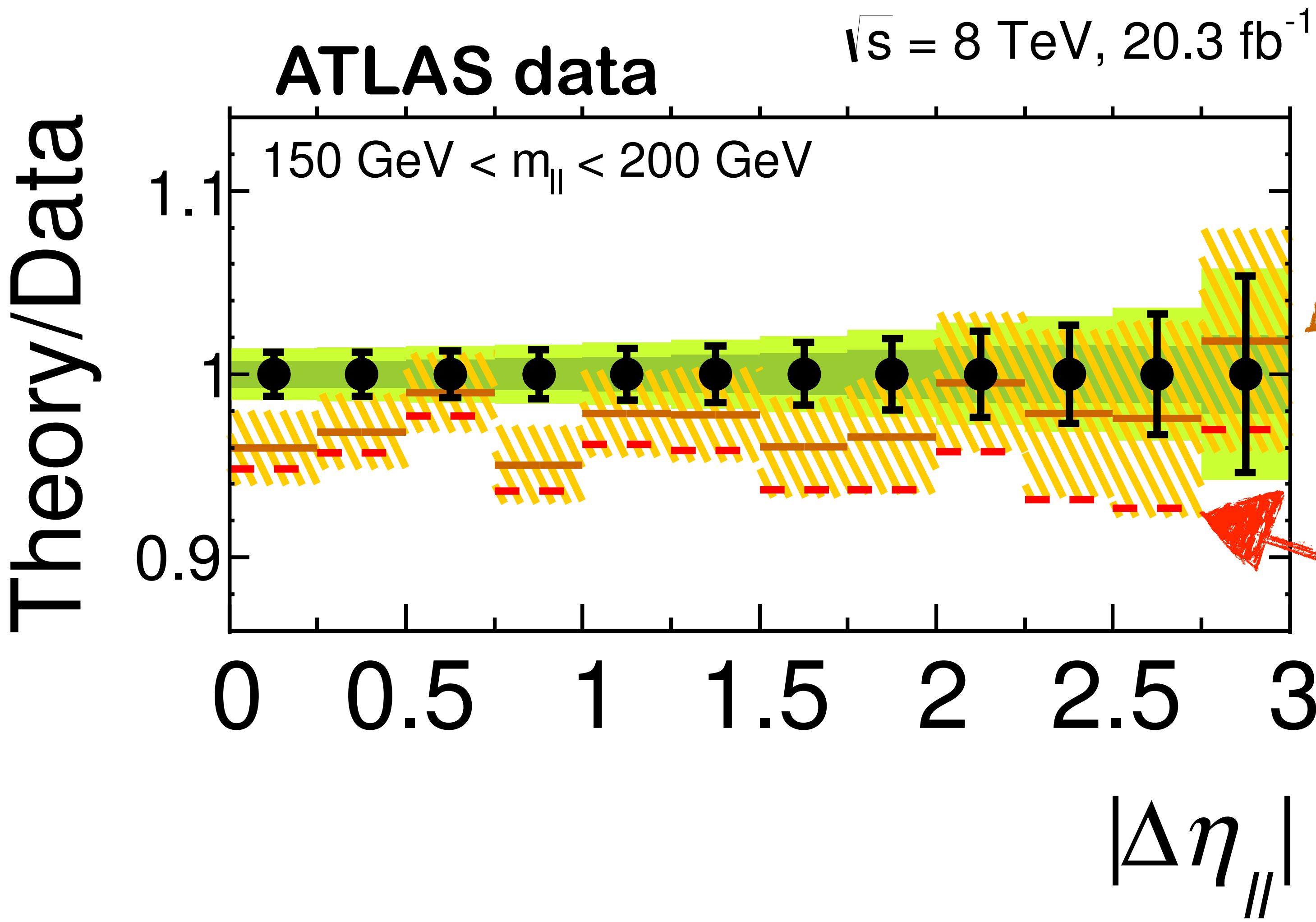
HKR based on elastic contribution (dipole approx) + model for inelastic part + evolution

ATLAS photon (1606.01736): DY-driven reweighting of NNPDF23



ATLAS result based on reweighting of NNPDF23 with high-mass (M_{ll} > 116 GeV) data

ATLAS DRELL-YAN DATA (1606.01736)



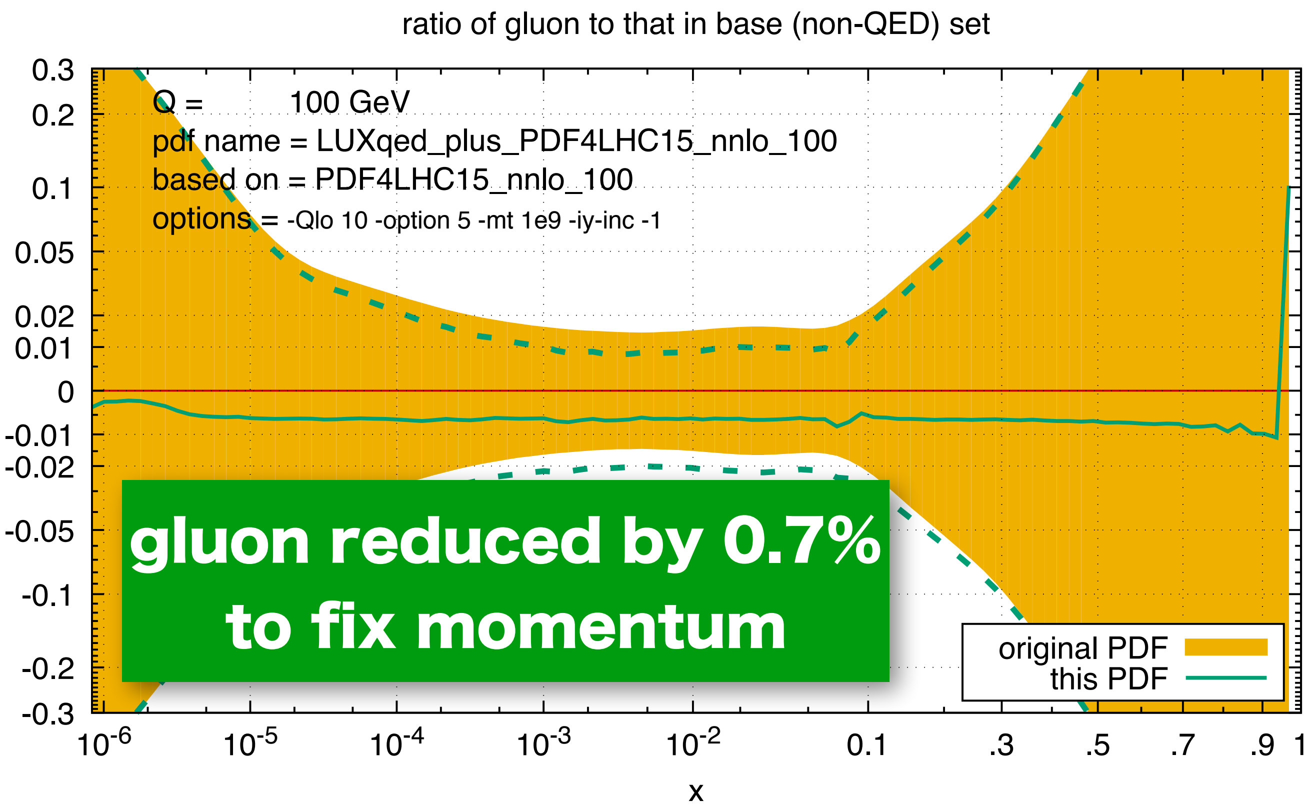
MMHT2014 QCD partons + NNPDF23 photon (and full uncertainties)

MMHT2014 without photon-induced contrib

MATCHING PROCEDURE FOR FULL SET OF PARTONS

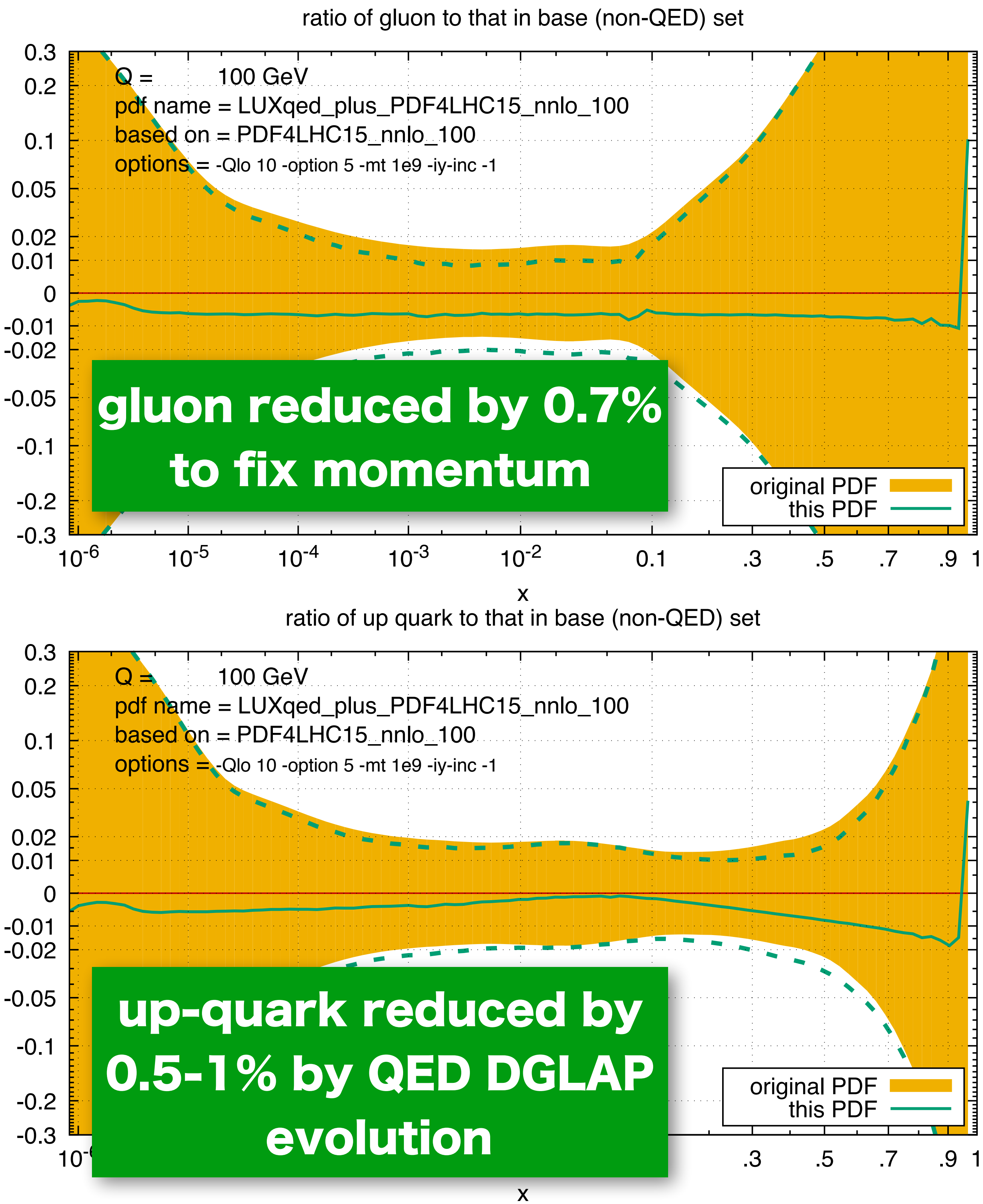
- evaluate master eqn. for $\mu = 100$ GeV (with default `PDF4LHC15_nnlo` partons)
- Do $O(\alpha\alpha_s)$ photon evolution down to $\mu = 10$ GeV (other partons: pure QCD evln.)
- Adjust momentum sum-rule by rescaling gluon $g(x) \to 0.993 g(x)$
- Evolve back up with NNLO-QCD & $O(\alpha\alpha_s)$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

MATCHING PROCEDURE FOR FULL SET OF PARTONS



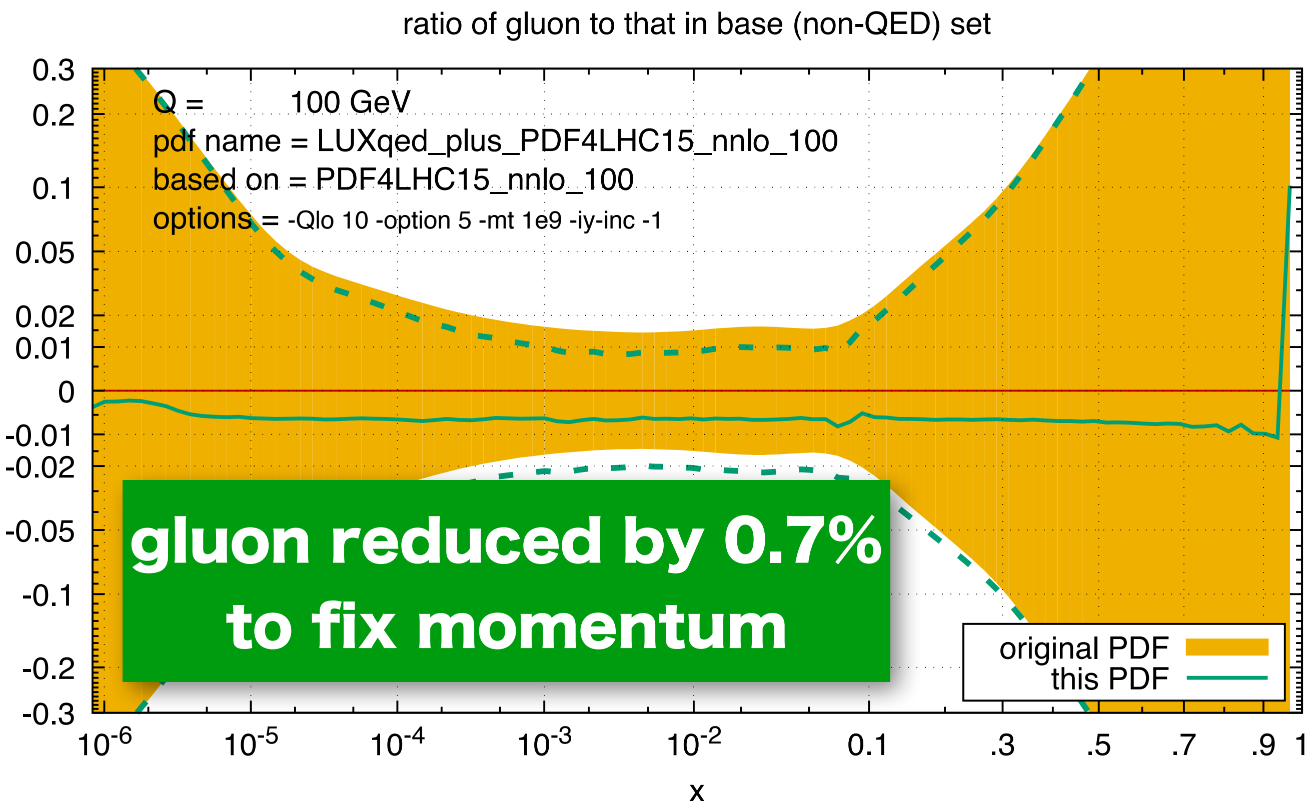
- evaluate master eqn. for $\mu = 100$ GeV (with default `PDF4LHC15_nnlo` partons)
- Do $O(\alpha\alpha_s)$ photon evolution down to $\mu = 10$ GeV (other partons: pure QCD evln.)
- Adjust momentum sum-rule by rescaling gluon $g(x) \to 0.993 g(x)$
- Evolve back up with NNLO-QCD & $O(\alpha\alpha_s)$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

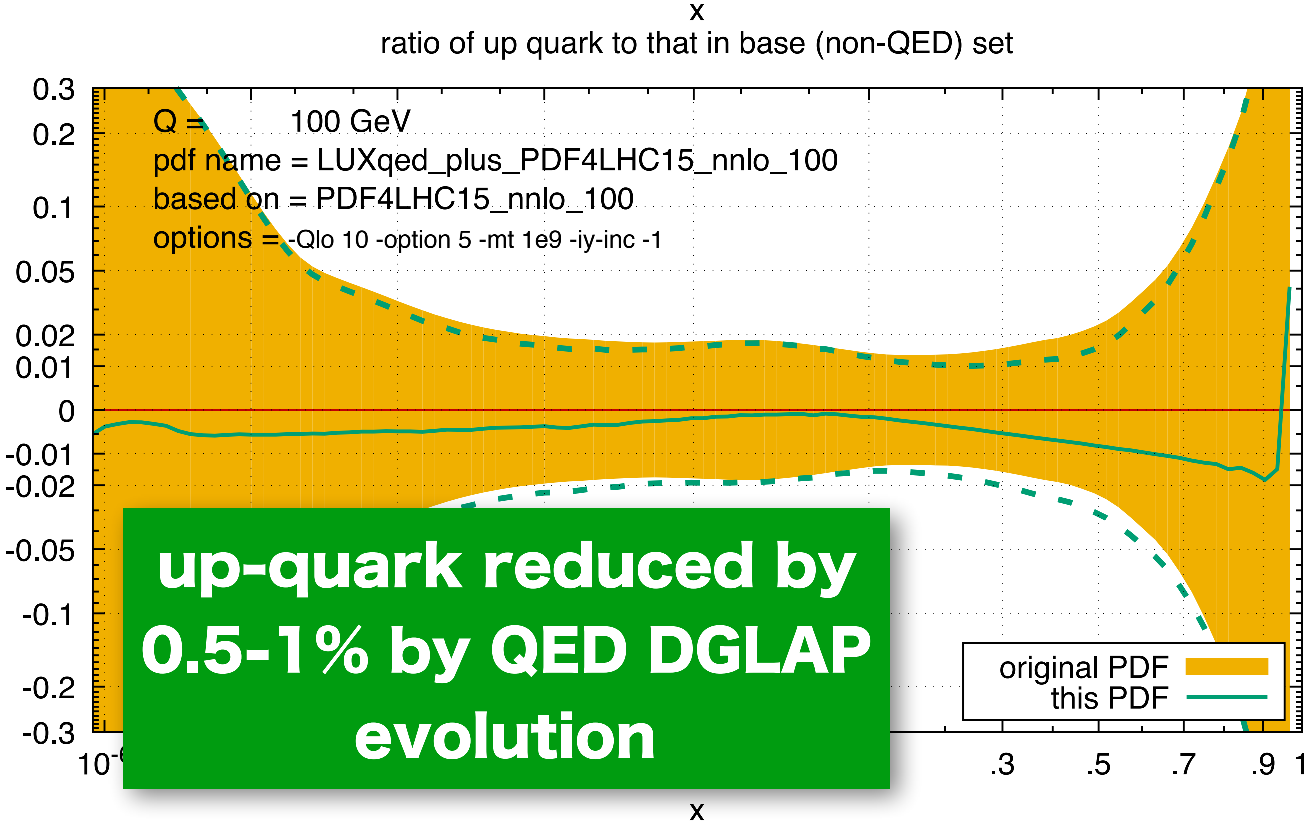
MATCHING PROCEDURE FOR FULL SET OF PARTONS



- 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

MATCHING PROCEDURE FOR FULL SET OF PARTONS

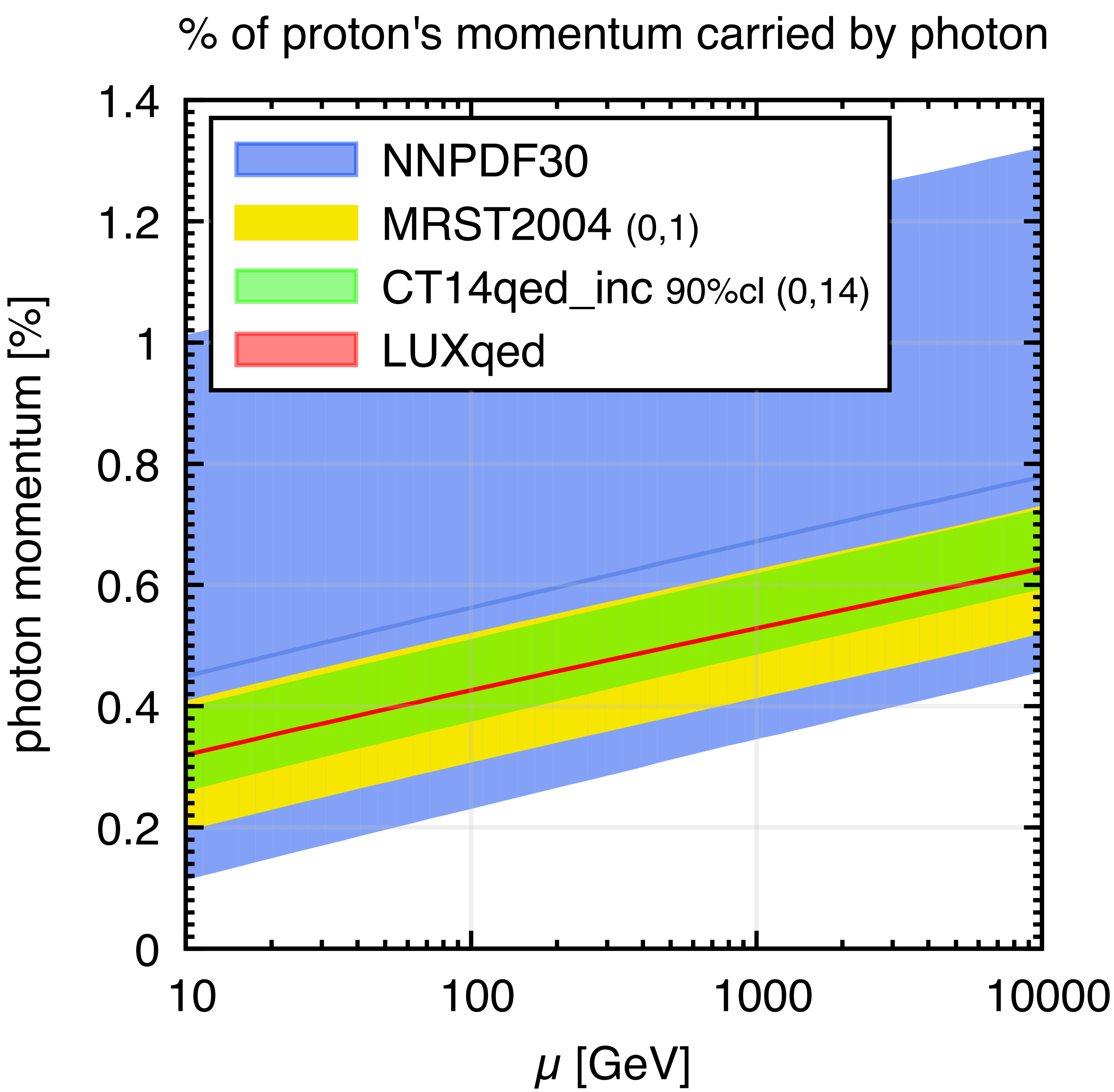




- evaluate master eqn. for $\mu = 100$ GeV (with default `PDF4LHC15_nnlo` partons)
- Do $O(\alpha\alpha_s)$ photon evolution down to $\mu = 10$ GeV (other partons: pure QCD evln.)
- Adjust momentum sum-rule by rescaling gluon $g(x) \to 0.993 g(x)$
- Evolve back up with NNLO-QCD & $O(\alpha\alpha_s)$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

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

MOMENTUM CARRIED BY PHOTON



momentum (μ = 100 GeV)	
gluon	46.8 ± 0.4%
up valence	18.2 ± 0.3%
down valence	7.5 ± 0.2%
light sea quarks	20.7 ± 0.4%
charm	4.0 ± 0.1%
bottom	2.5 ± 0.1%
photon	0.426 ± 0.003%

`LUXqed_plus_PDF4LHC15_nnlo_100`

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

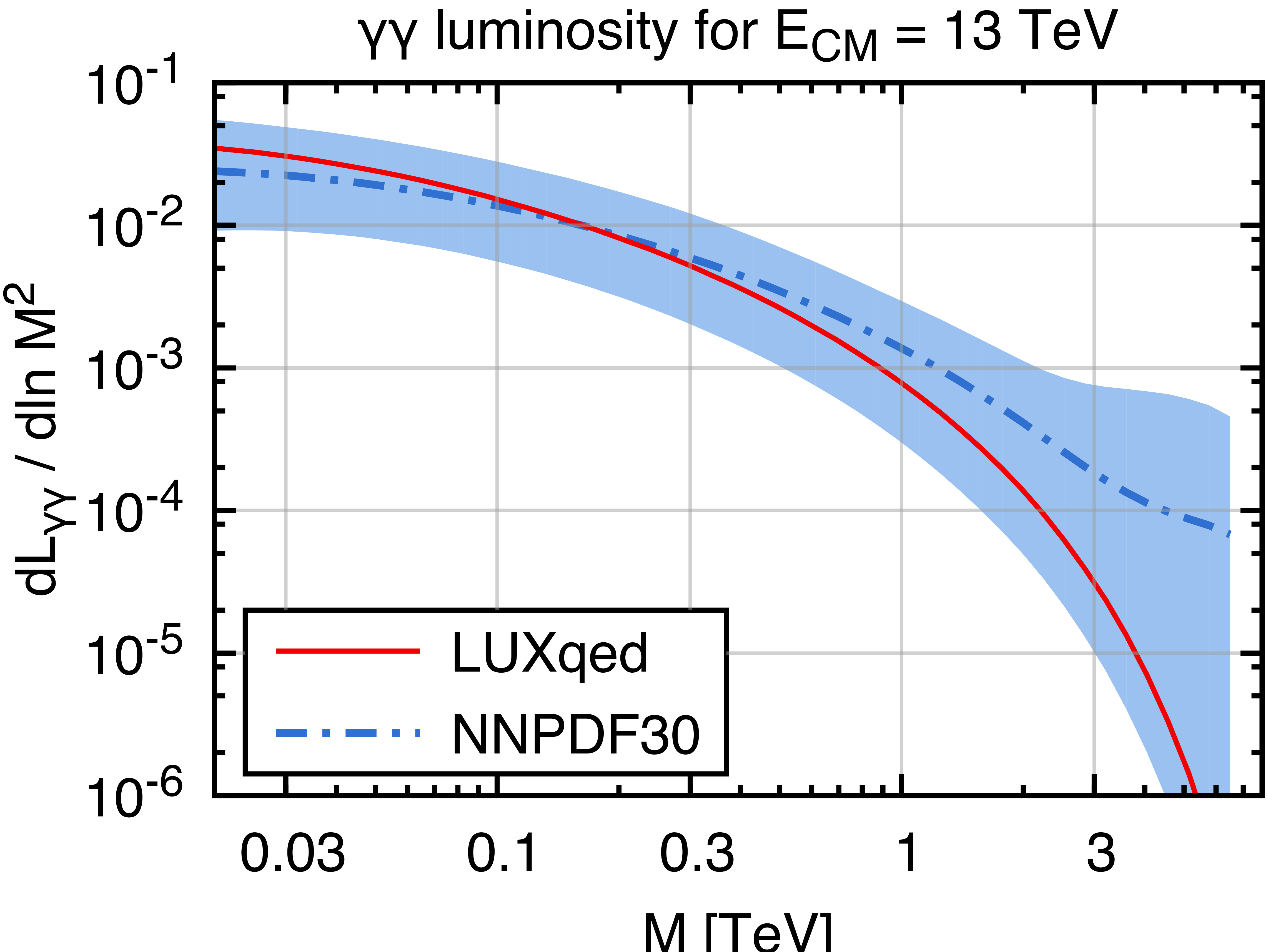
PDF valid for $\mu > 10$ GeV (related to PDF4LHC15 issues)

applications

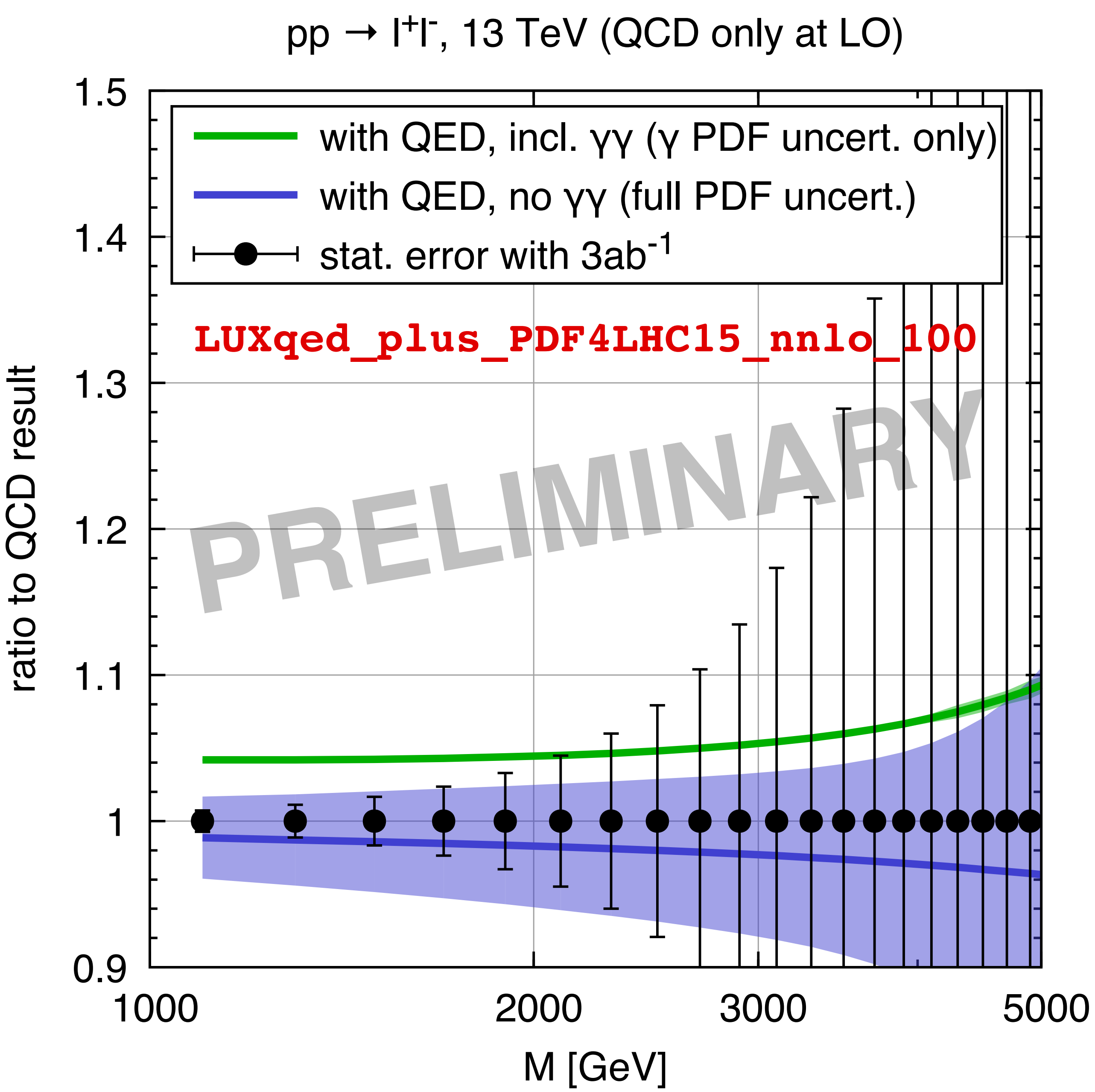
$pp \to H W^+ (\to l^+ \nu) + X$ at 13 TeV	
non-photon induced contributions	91.2 ± 1.8 fb
photon-induced contribs (NNPDF23)	$6.0\ ^{+4.4}_{-2.9}$ fb
photon-induced contribs (LUXqed)	4.4 ± 0.1 fb

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

γγ luminosity

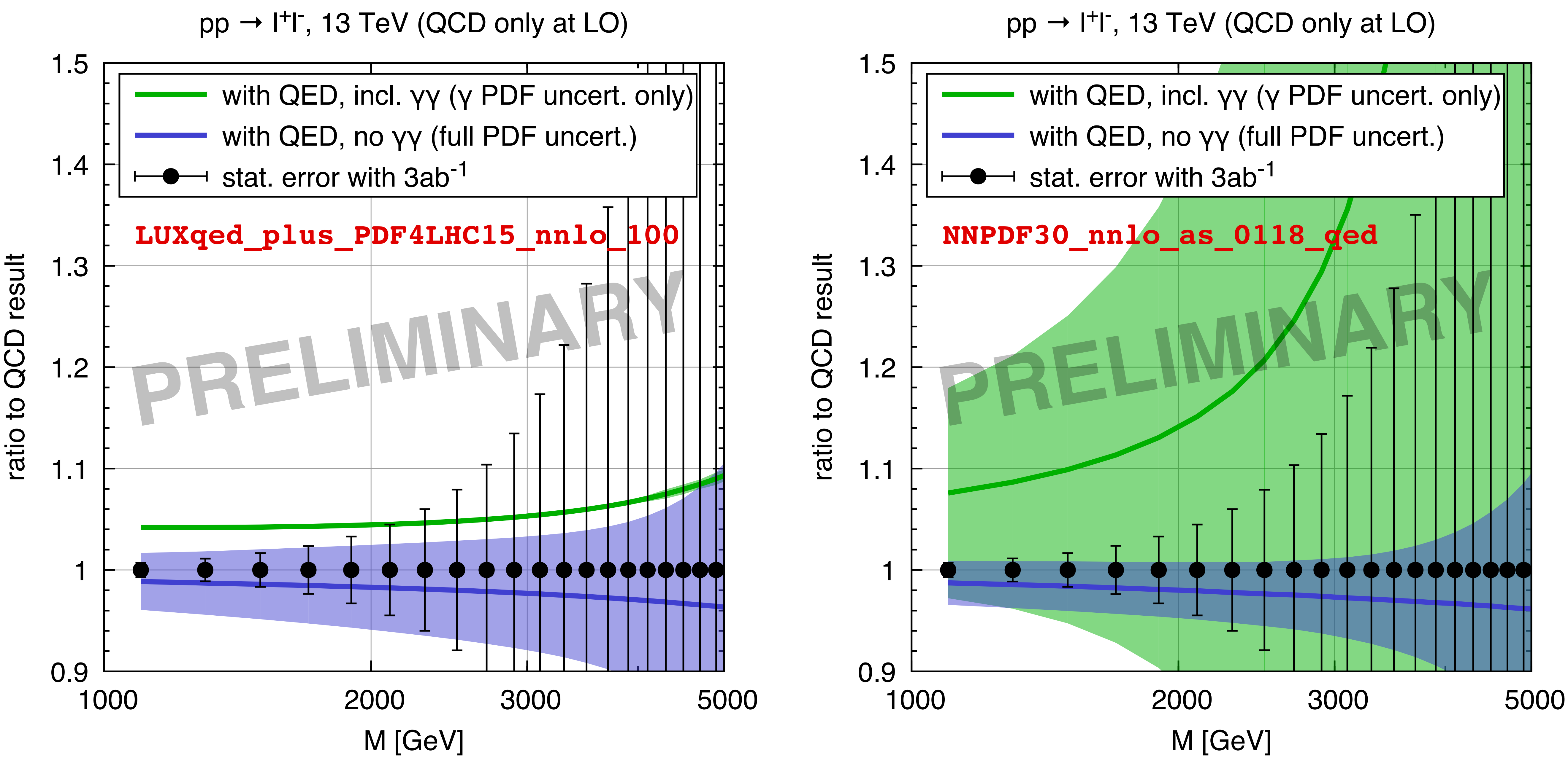


di-lepton spectrum with 3ab^{-1}



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

di-lepton spectrum with $3ab^{-1}$



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

conclusions & resources

RESOURCES

- `LUXqed_plus_PDF4LHC15_nnlo_100` set available from LHAPDF (for $\mu > 10$ GeV)
- Additional plots and validation info available from http://cern.ch/luxqed
- Preliminary version of HOPPET DGLAP evolution code with QED (order α and $\alpha\alpha_s$) corrections available from hepforge:

```
svn checkout http://hoppet.hepforge.org/svn/branches/qed hoppet-qed
```

(look at `tests/with-lhapdf/test_qed_evol_lhapdf.f90` for an example; interface may change, documentation missing)

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
- We've done just NLO (equiv. $\alpha\,\alpha_s$ in splitting functions), but higher theoretical should be accessible (e.g. α^2, $\alpha\,\alpha_s{}^2$) — open question of whether data can follow (and whether we need it)

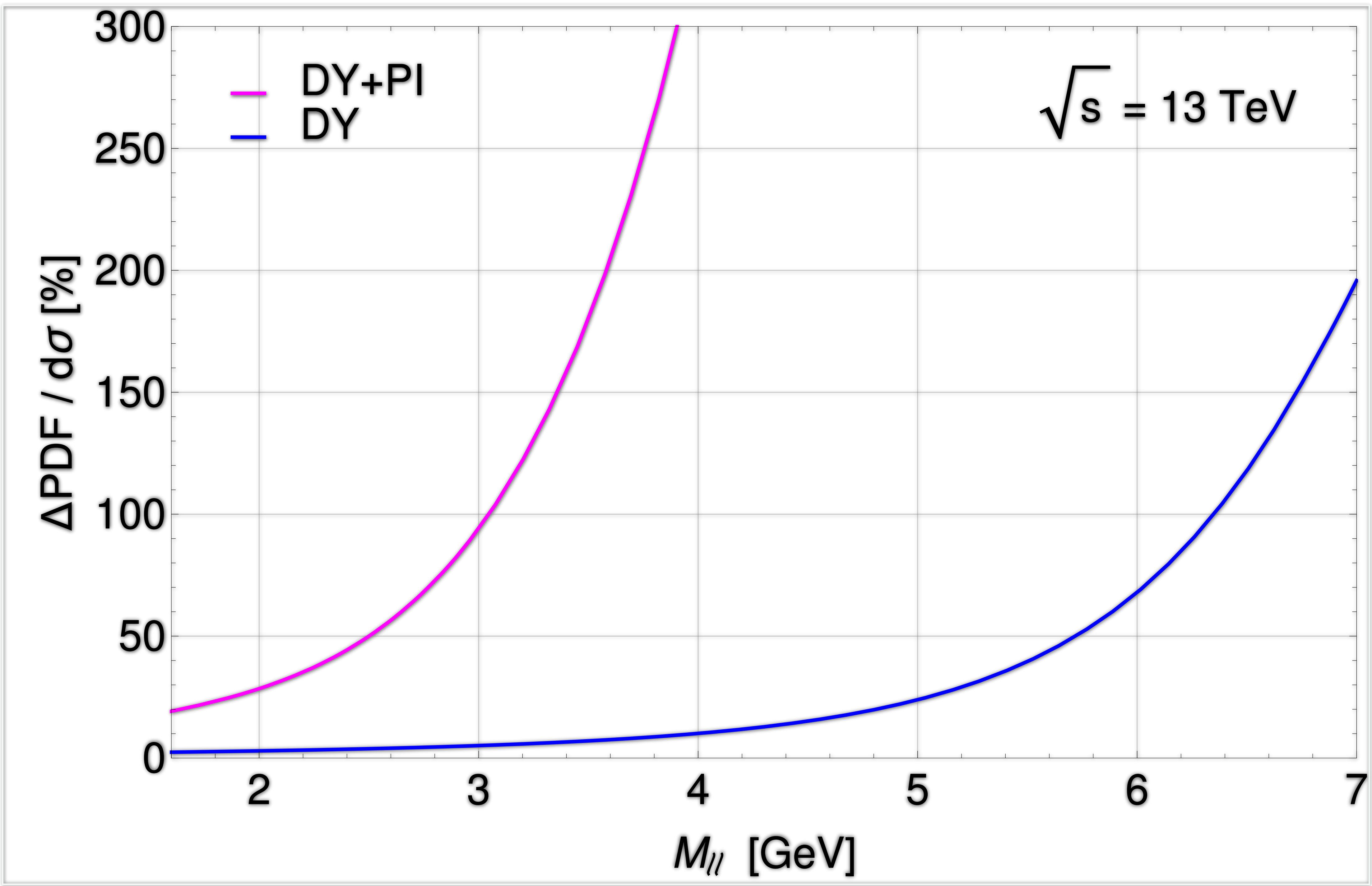
"If you think about it, it's awesome: we are made of protons, and protons are, in some part, made of light... And now we know how much of it."

blog post by Tommaso Dorigo

extra slides

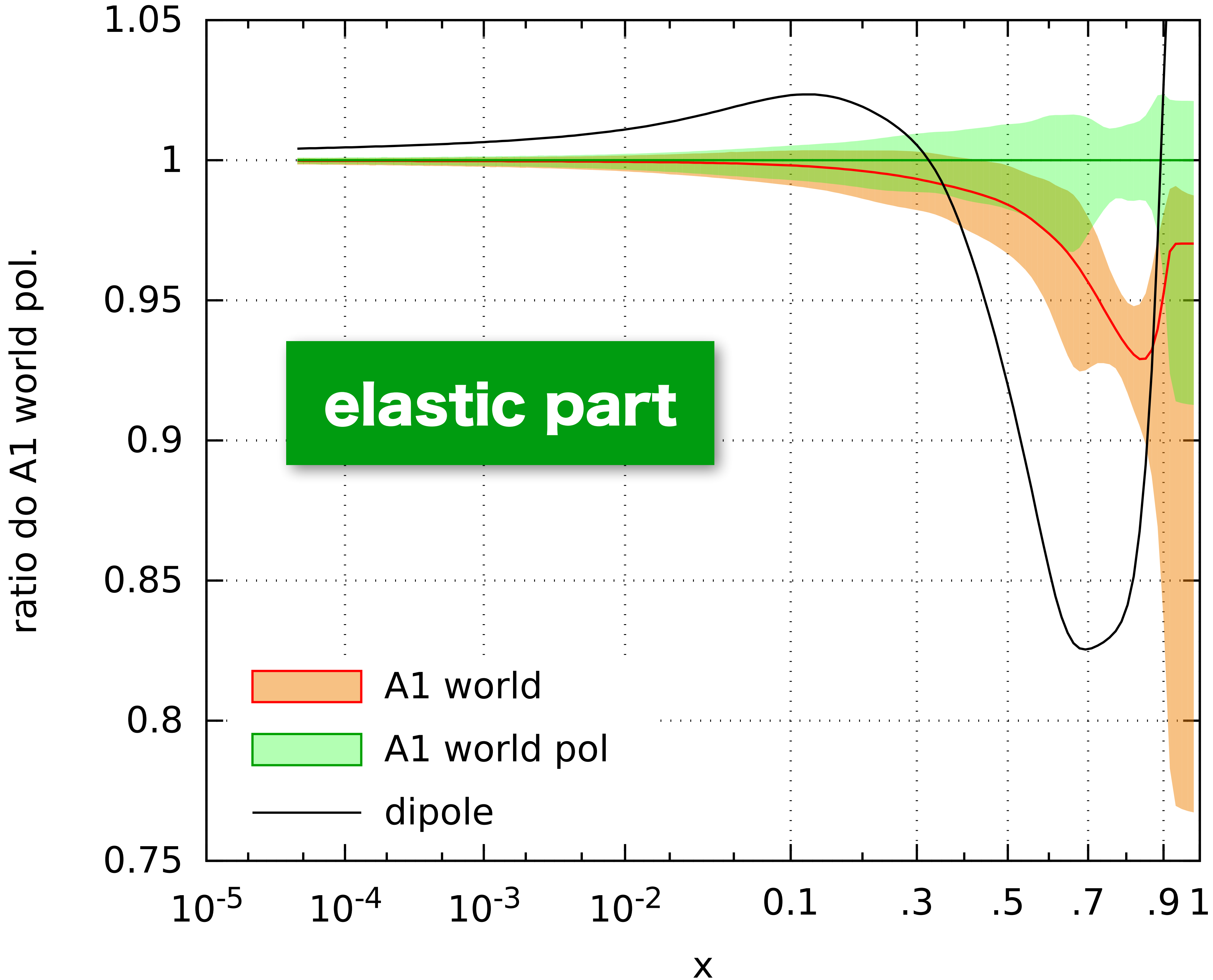
1606.06646v1

Elena Accomando,[1,2,*] Juri Fiaschi,[1,2,†] Francesco Hautmann,[2,3,‡]
Stefano Moretti,[1,2,§] and C.H. Shepherd-Themistocleous[1,2,¶]



input data & procedures

ELASTIC COMPONENT & COMPARISON TO “DIPOLE” MODEL

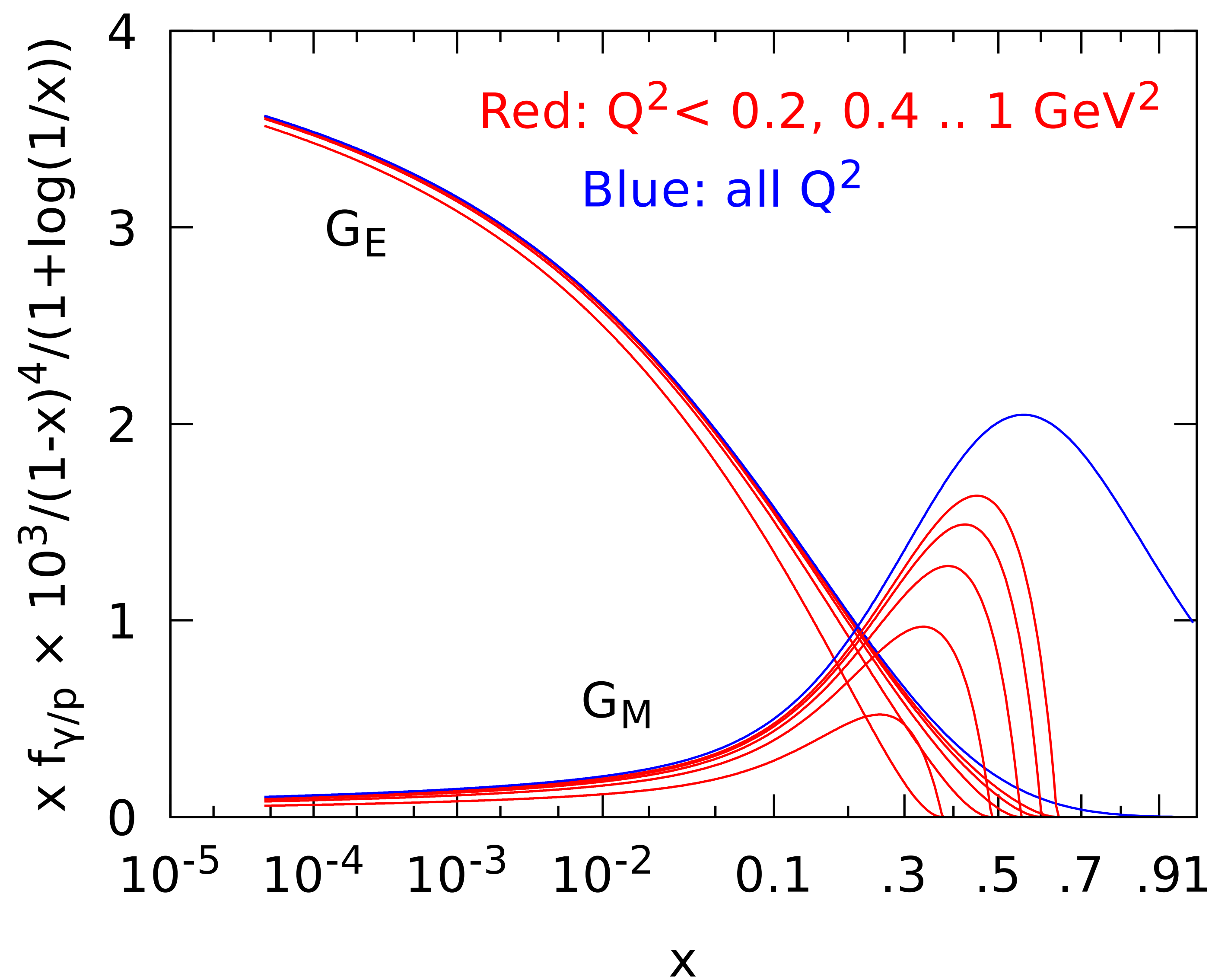


The elastic contribution to f_γ is

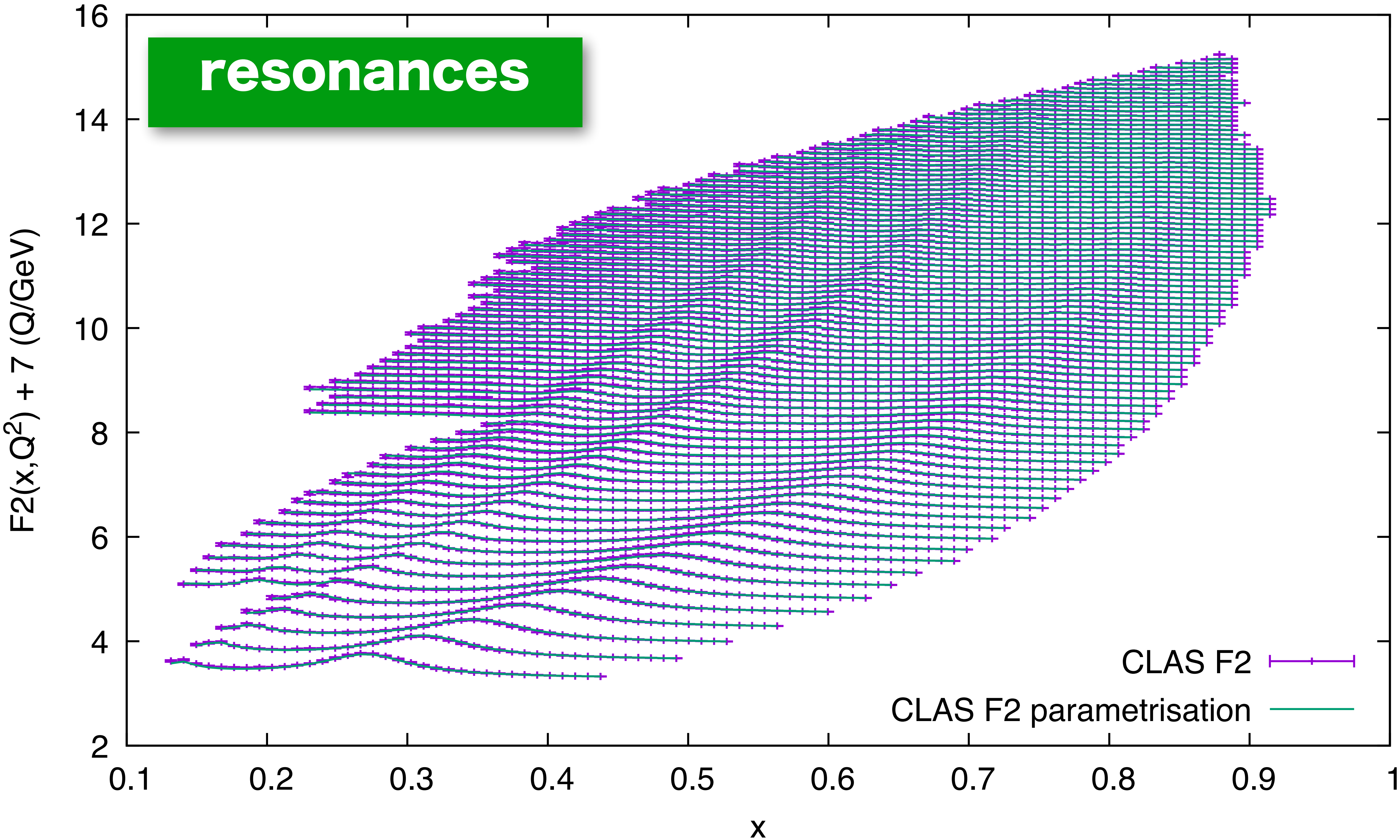
$$xf_\gamma^{\rm el}(x,\mu^2) = \frac{1}{2\pi}\int_{\frac{x^2m_p^2}{1-x}}^{\frac{\mu^2}{1-x}} \frac{{\rm d}Q^2}{Q^2}\frac{\alpha^2(Q^2)}{\alpha(\mu^2)}\left\{\left(1-\frac{x^2m_p^2}{Q^2(1-x)}\right)\frac{2(1-x)G_E^2(Q^2)}{1+\tau} + \left(2-2x+x^2+\frac{2x^2m_p^2}{Q^2}\right)\frac{G_M^2(Q^2)\tau}{1+\tau}\right\}.$$

Dipole approximation, ($\mu\to\infty$ in figure.)

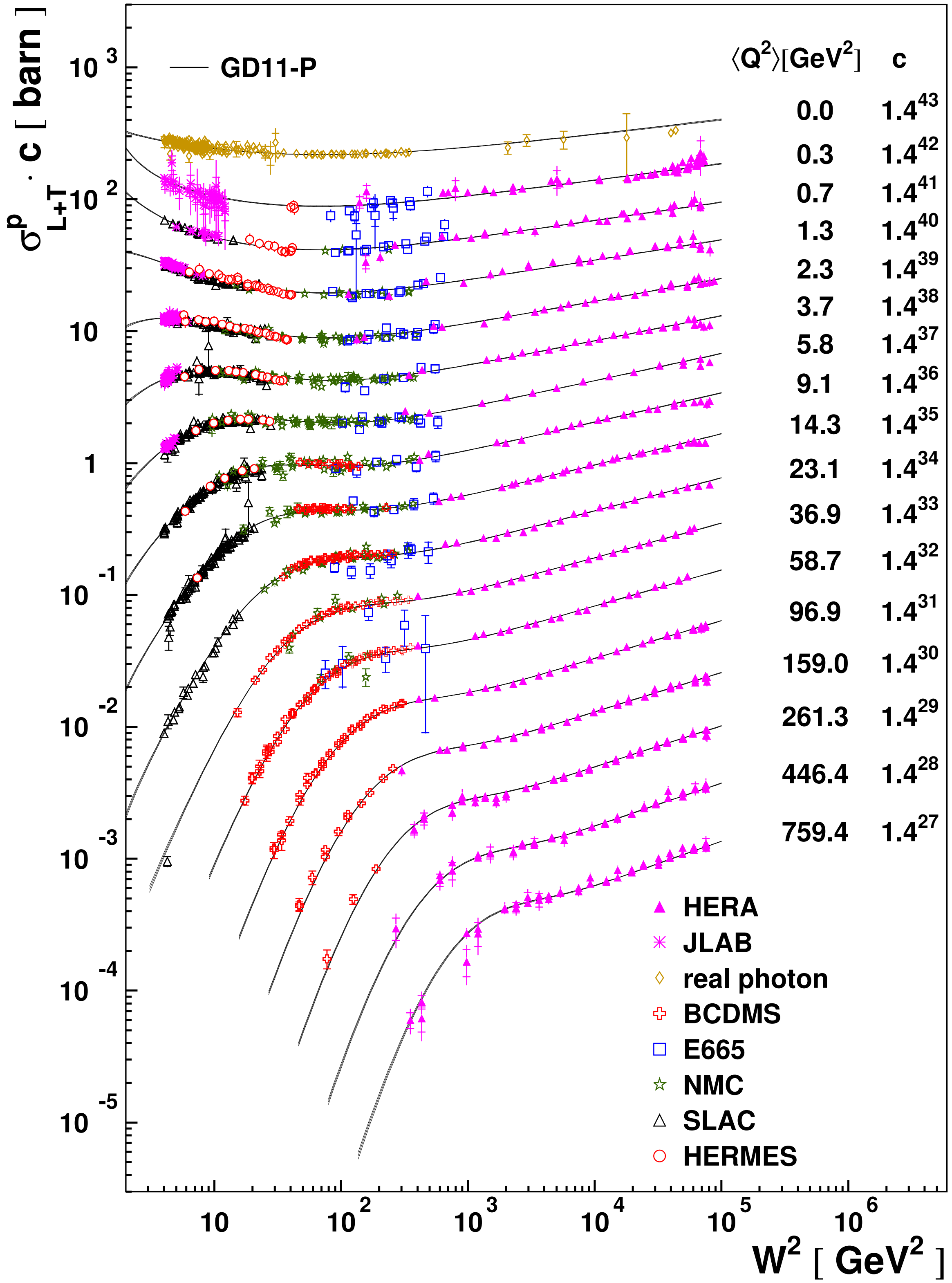
- Mostly G_E at small x.
- Mostly G_M at large x.
- Mostly from $Q^2 < 1 GeV$.

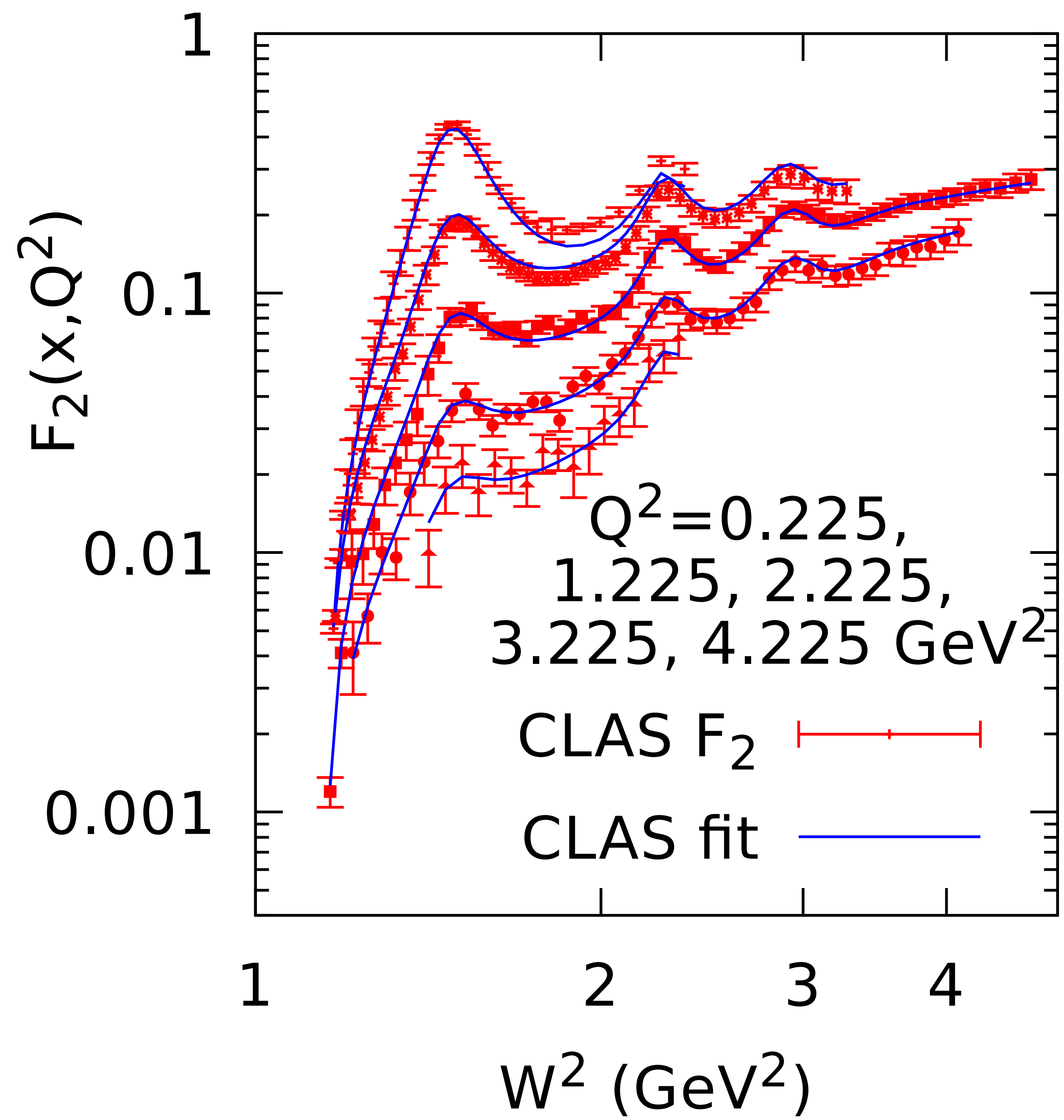


CLAS DATA



resonances
F2(x,Q²) + 7 (Q/GeV)
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
CLAS F2
CLAS F2 parametrisation





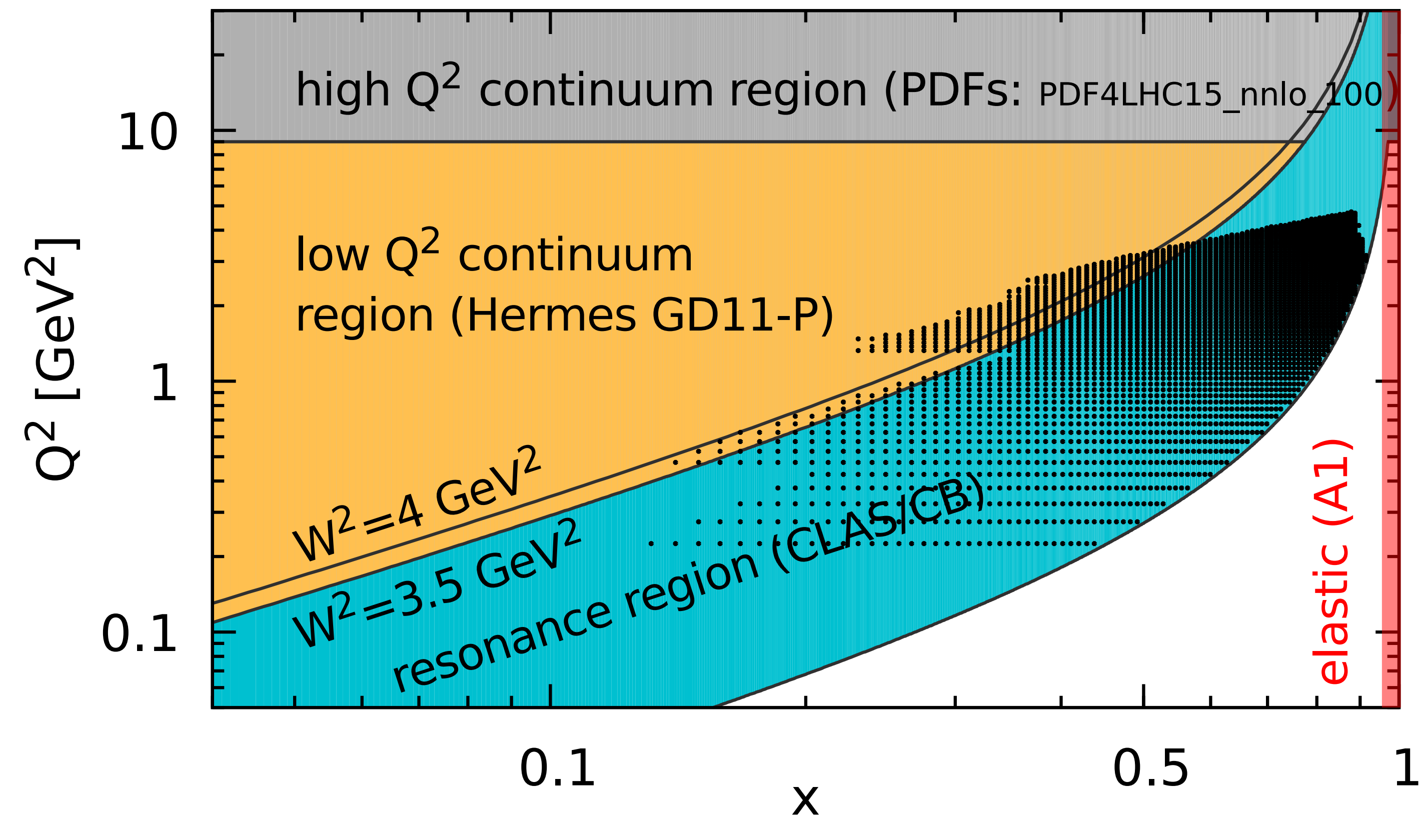
Fitted data from $Q^2 = 0.225$ to 4.725 in steps of $0.05\,\mathrm{GeV}^2$.

Hermes fit: we are interested in the region $Q^2 < 10\,\mathrm{GeV}^2$.

Continuum data region: $4\ \mathrm{GeV}^2 < W^2 \lesssim 10^5\mathrm{GeV}^2$ $(x \to 10^{-4})$.

Inelastic Data coverage

- Low Q^2 continuum essentially covered by data.
- F_2 and F_L must vanish as Q^2 and Q^4 at constant W (by analiticity of $W^{\mu\nu}$).

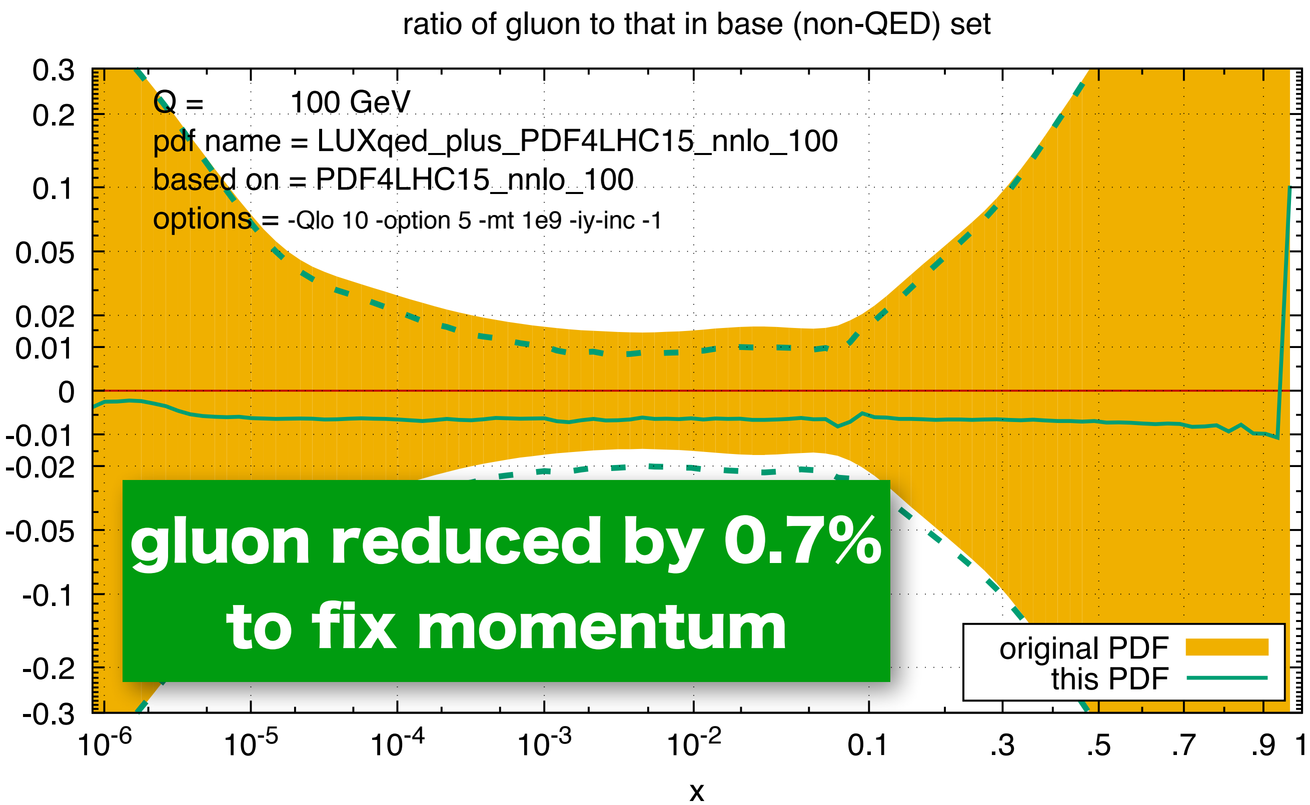


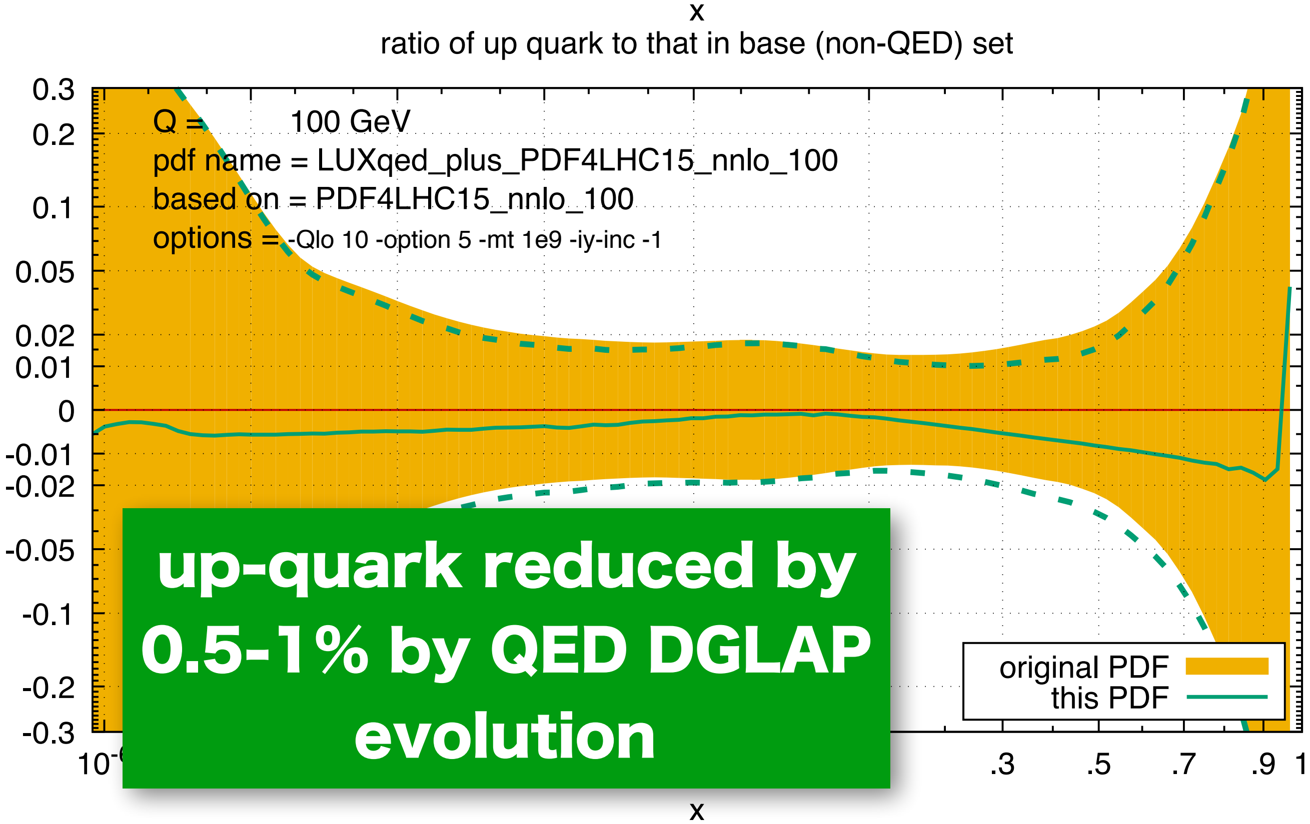
Also:

$$F_2(x, Q^2) = \frac{1}{4\pi^2\alpha}\frac{Q^2(1-x)}{1+\frac{4x^2m_p^2}{Q^2}}(\sigma_T(x, Q^2)+\sigma_L(x, Q^2)) \underset{Q^2\to 0}{\Longrightarrow} \frac{Q^2\sigma_{\gamma p}(W)}{4\pi^2\alpha^2}.$$

At small Q^2, $\sigma_T \Longrightarrow \sigma_{\gamma p}(W)$, becoming a function of W only (the *CM* energy in photoproduction), and σ_L vanishes.
Photoproduction data included in Hermes and Christy-Bosted parametrizations.

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

comparisons to others

γγ luminosity