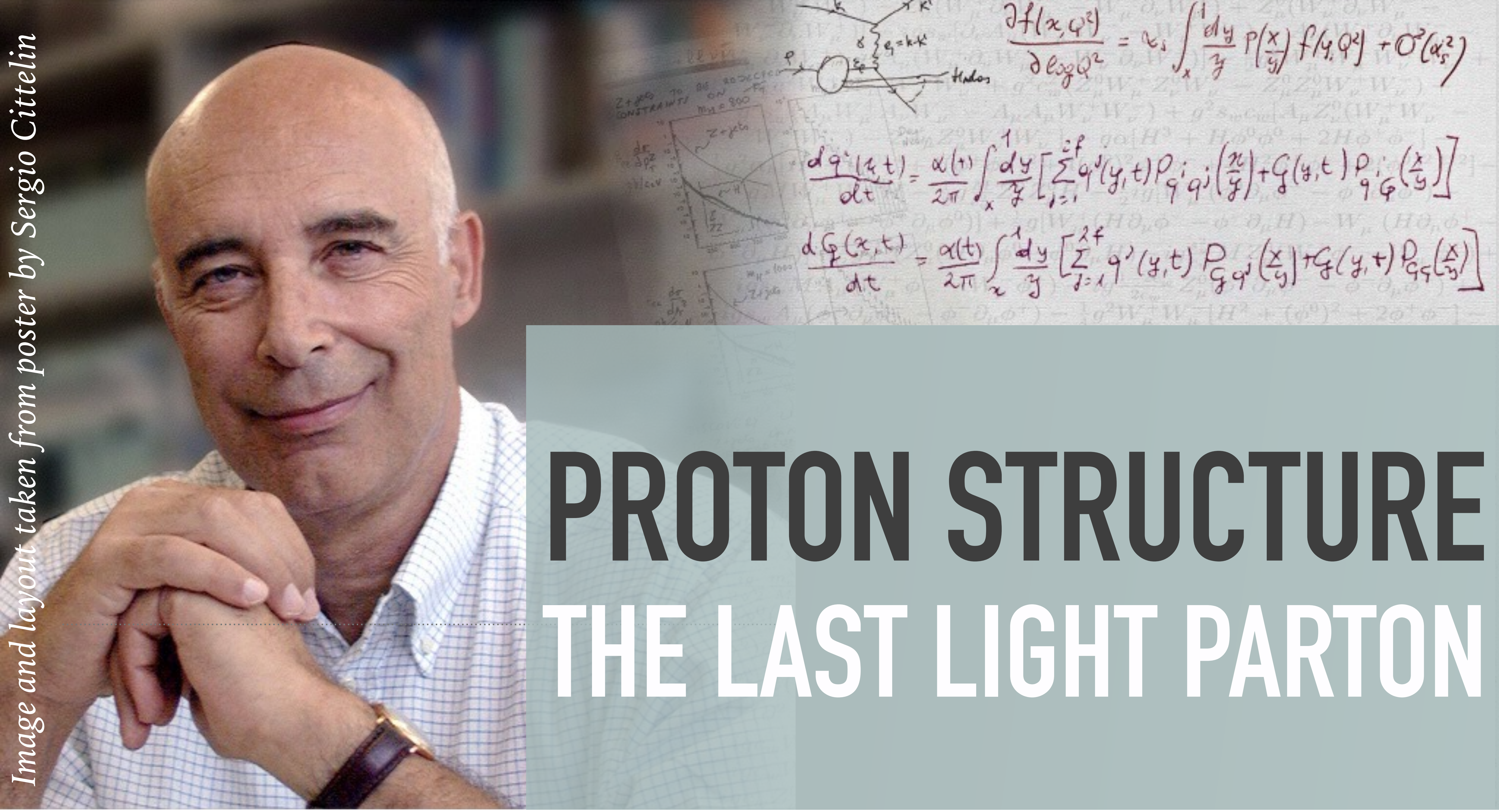


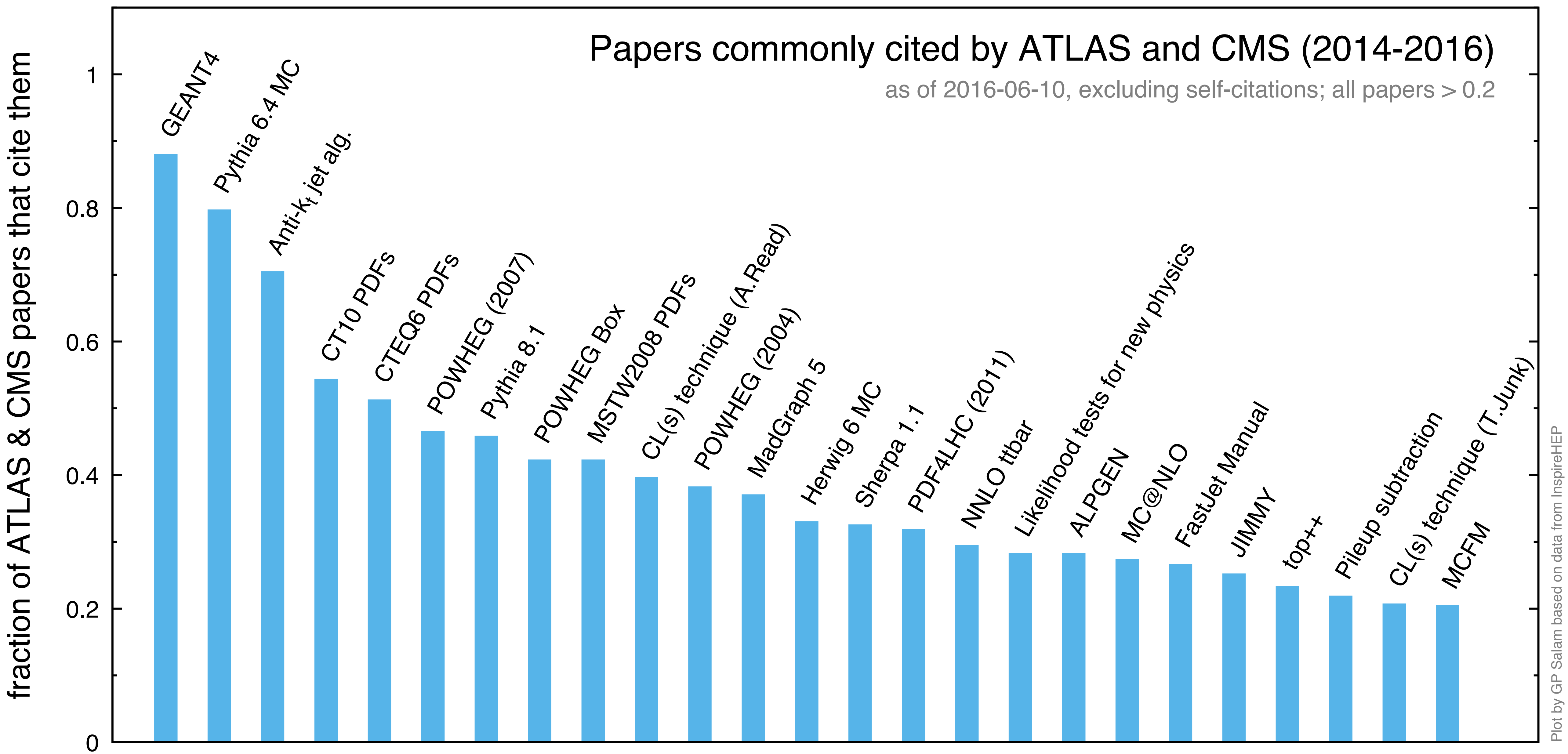
Image and layout taken from poster by Sergio Cittelin

PROTON STRUCTURE
THE LAST LIGHT PARTON

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

Guido Altarelli Memorial Session
5th International Conference on New Frontiers in Physics, Crete, July 2016

WHAT DO ATLAS & CMS USE MOST FREQUENTLY?



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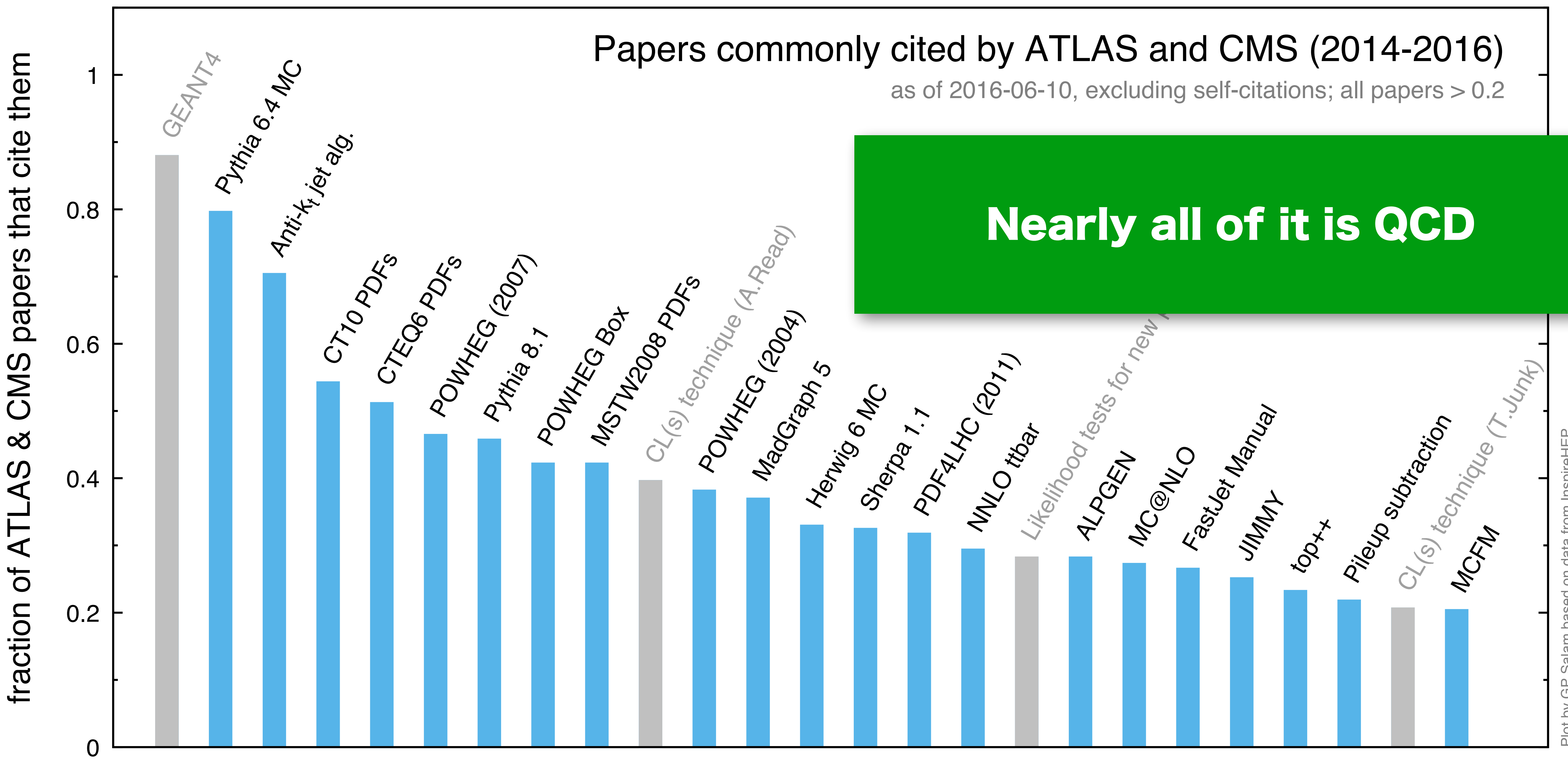
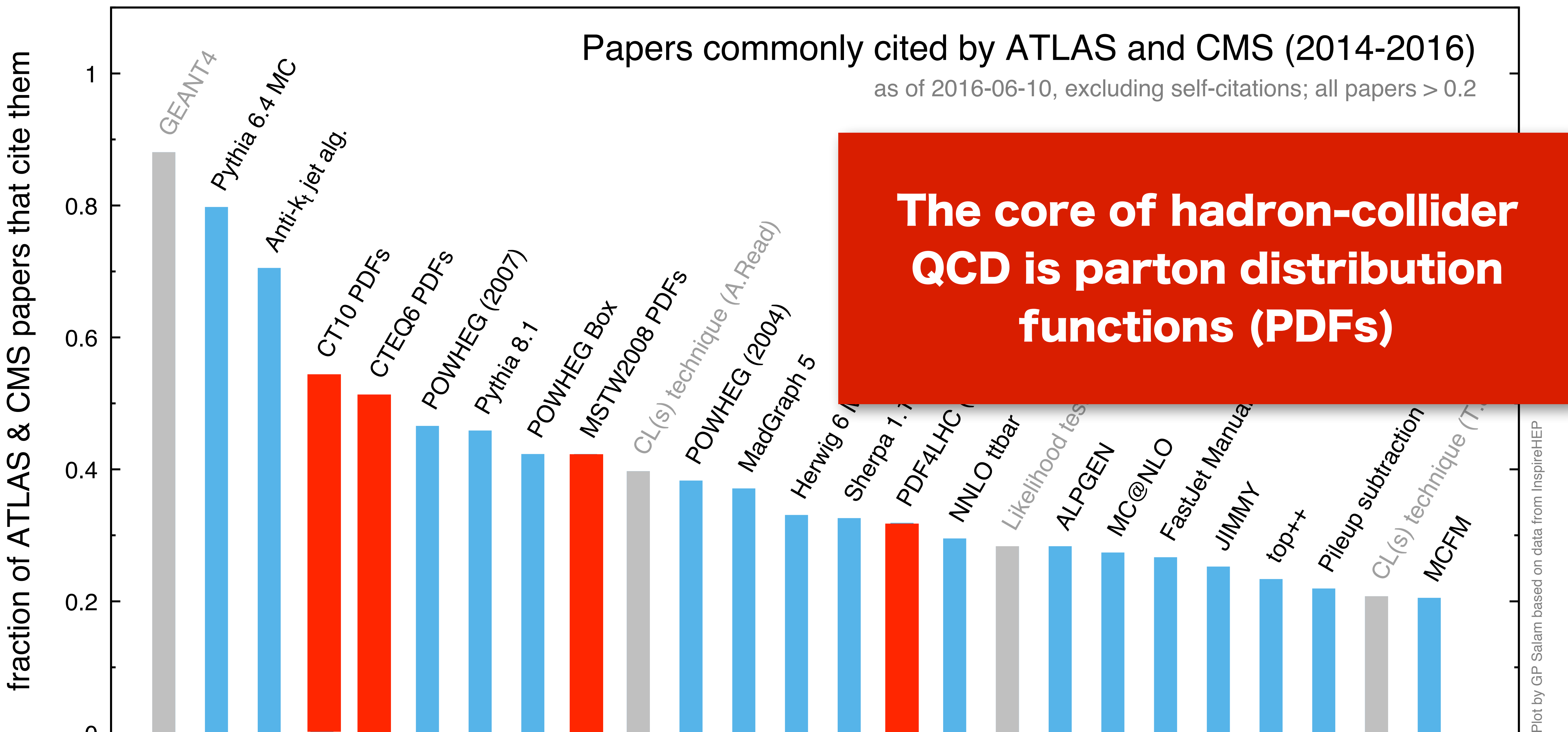


Nearly all of it is QCD

WHAT DO ATLAS & CMS USE MOST FREQUENTLY?



The core of hadron-collider QCD is parton distribution functions (PDFs)

Dokshitzer-Gribov-Lipatov-Altarelli-Parisi (DGLAP) equations

ASYMPTOTIC FREEDOM IN PARTON LANGUAGE

G. ALTARELLI *

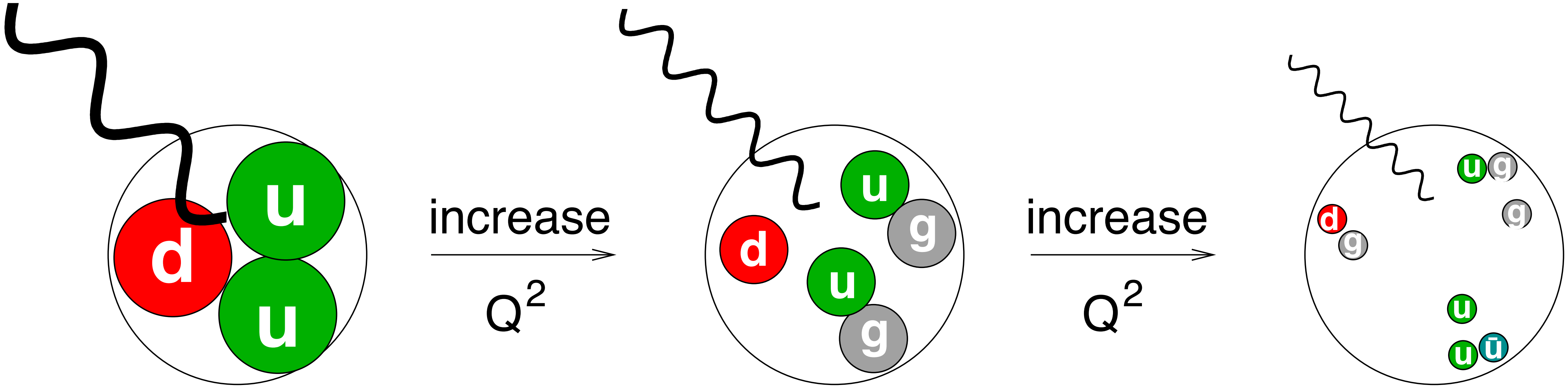
Laboratoire de Physique Théorique de l'Ecole Normale Supérieure **, *Paris, France*

G. PARISI ***

Institut des Hautes Etudes Scientifiques, Bures-sur-Yvette, France

Received 12 April 1977

A novel derivation of the Q^2 dependence of quark and gluon densities (of given helicity) as predicted by quantum chromodynamics is presented. The main body of predictions of the theory for deep-inleastic scattering on either unpolarized or polarized targets is re-obtained by a method which only makes use of the simplest tree diagrams and is entirely phrased in parton language with no reference to the conventional operator formalism.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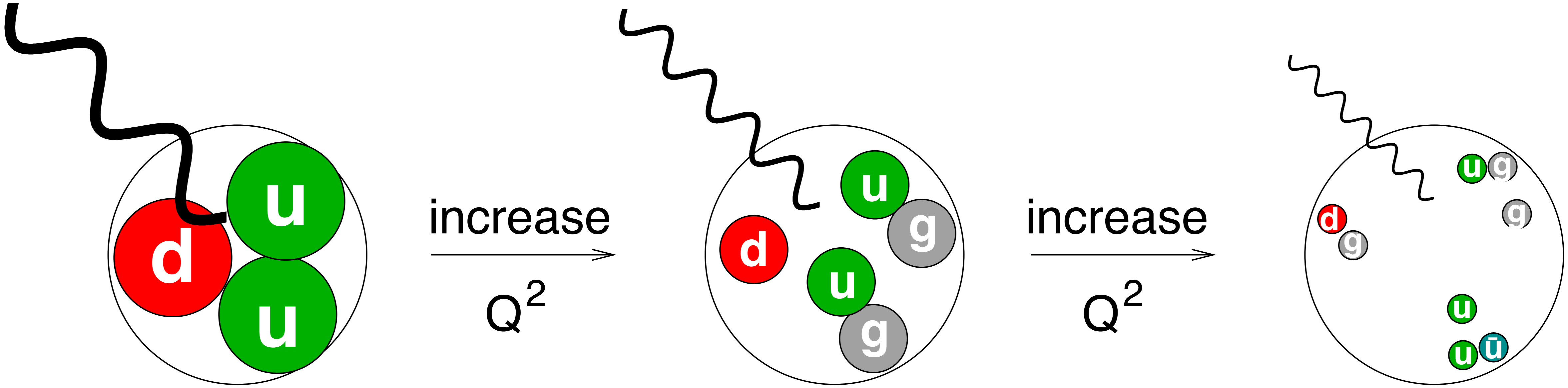
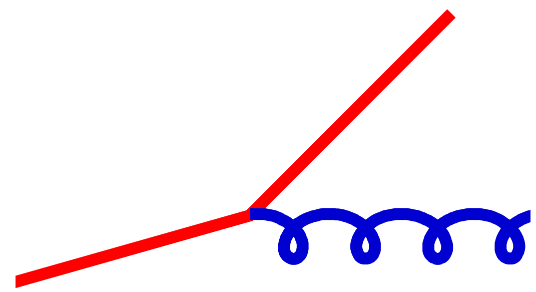
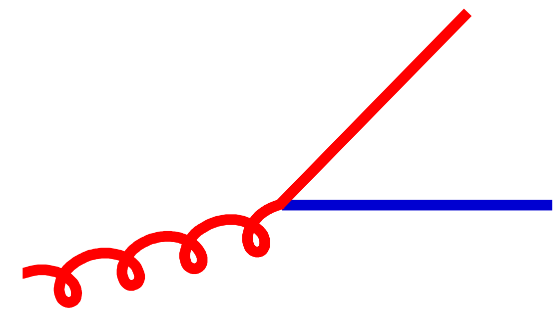
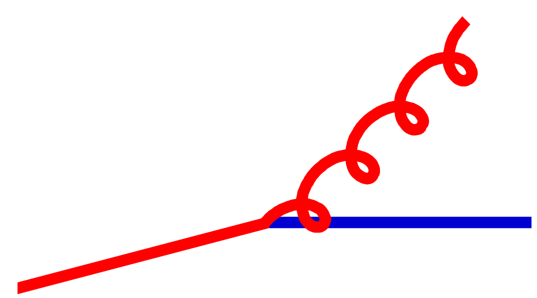


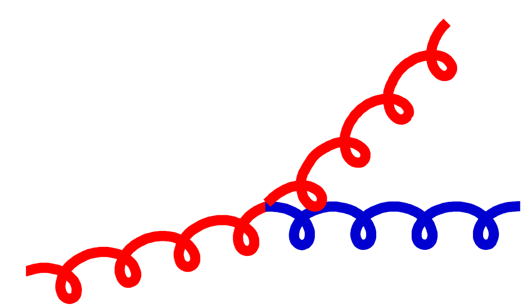




$$\frac{\mathrm{d}q^i(x, t)}{\mathrm{d}t} = \frac{\alpha(t)}{2\pi} \int_x^1 \frac{\mathrm{d}y}{y} \left[\sum_{j=1}^{2f} q^j(y, t) P_{\mathrm{q}^i \mathrm{q}^j}\left(\frac{x}{y}\right) + G(y, t) P_{\mathrm{q}^i \mathrm{G}}\left(\frac{x}{y}\right) \right],$$

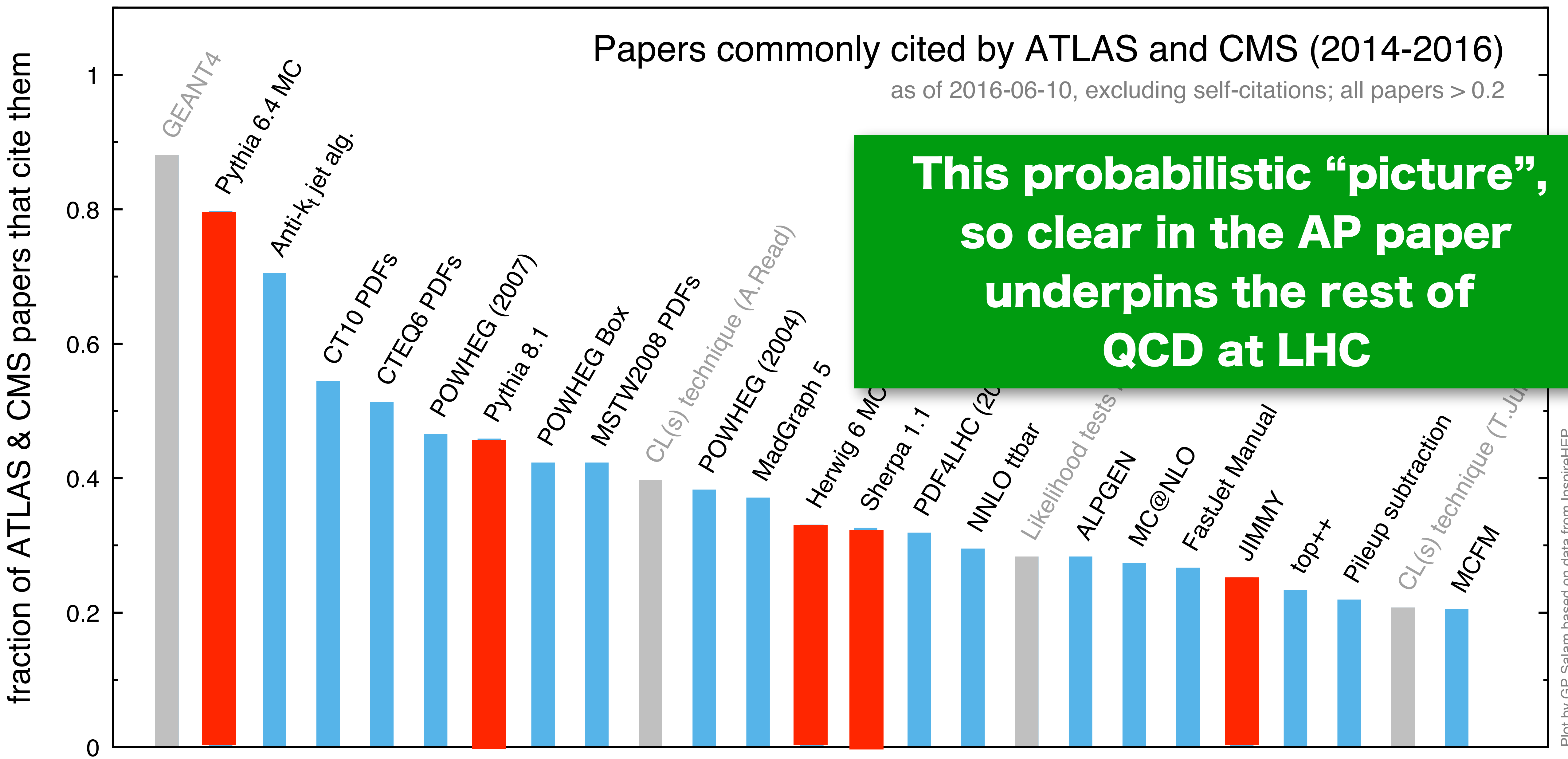
$$\frac{\mathrm{d}G(x, t)}{\mathrm{d}t} = \frac{\alpha(t)}{2\pi} \int_x^1 \frac{\mathrm{d}y}{y} \left[\sum_{j=1}^{2f} q^j(y, t) P_{\mathrm{G}\mathrm{q}^j}\left(\frac{x}{y}\right) + G(y, t) P_{\mathrm{GG}}\left(\frac{x}{y}\right) \right].$$





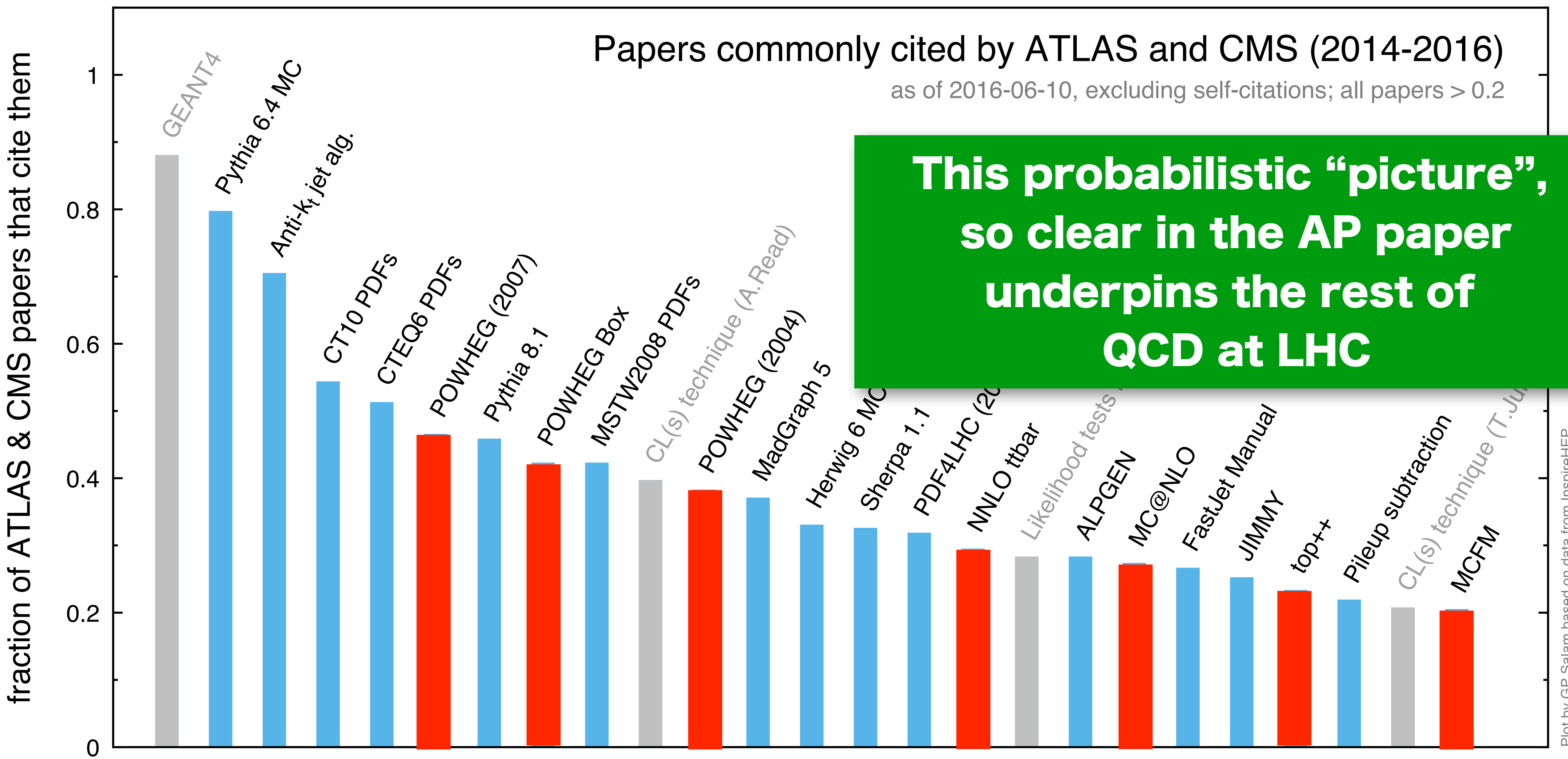
Quantum mechanics made probabilistic

WHAT DO ATLAS & CMS USE MOST FREQUENTLY?



This probabilistic “picture”, so clear in the AP paper underpins the rest of QCD at LHC

WHAT DO ATLAS & CMS USE MOST FREQUENTLY?



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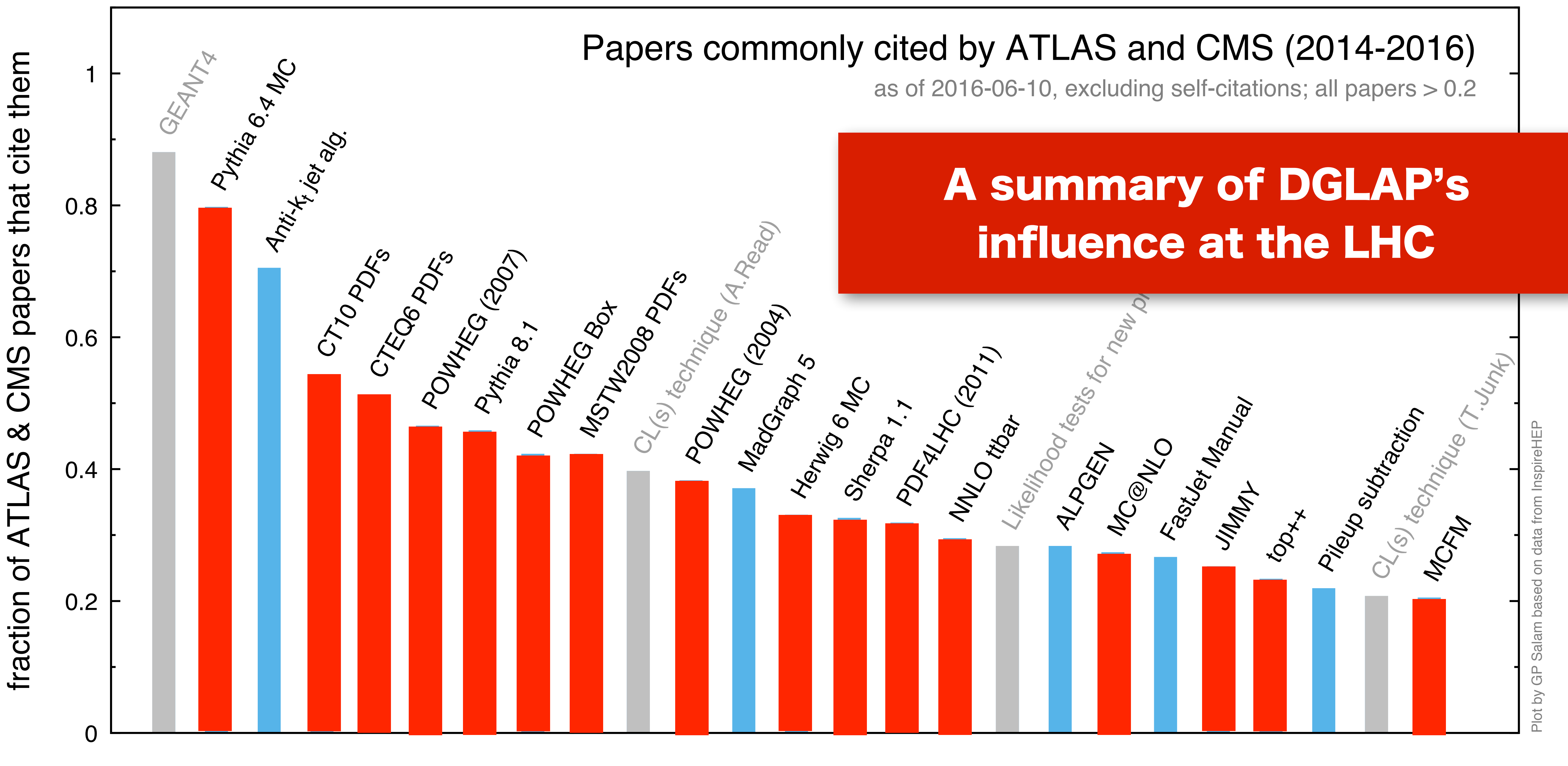
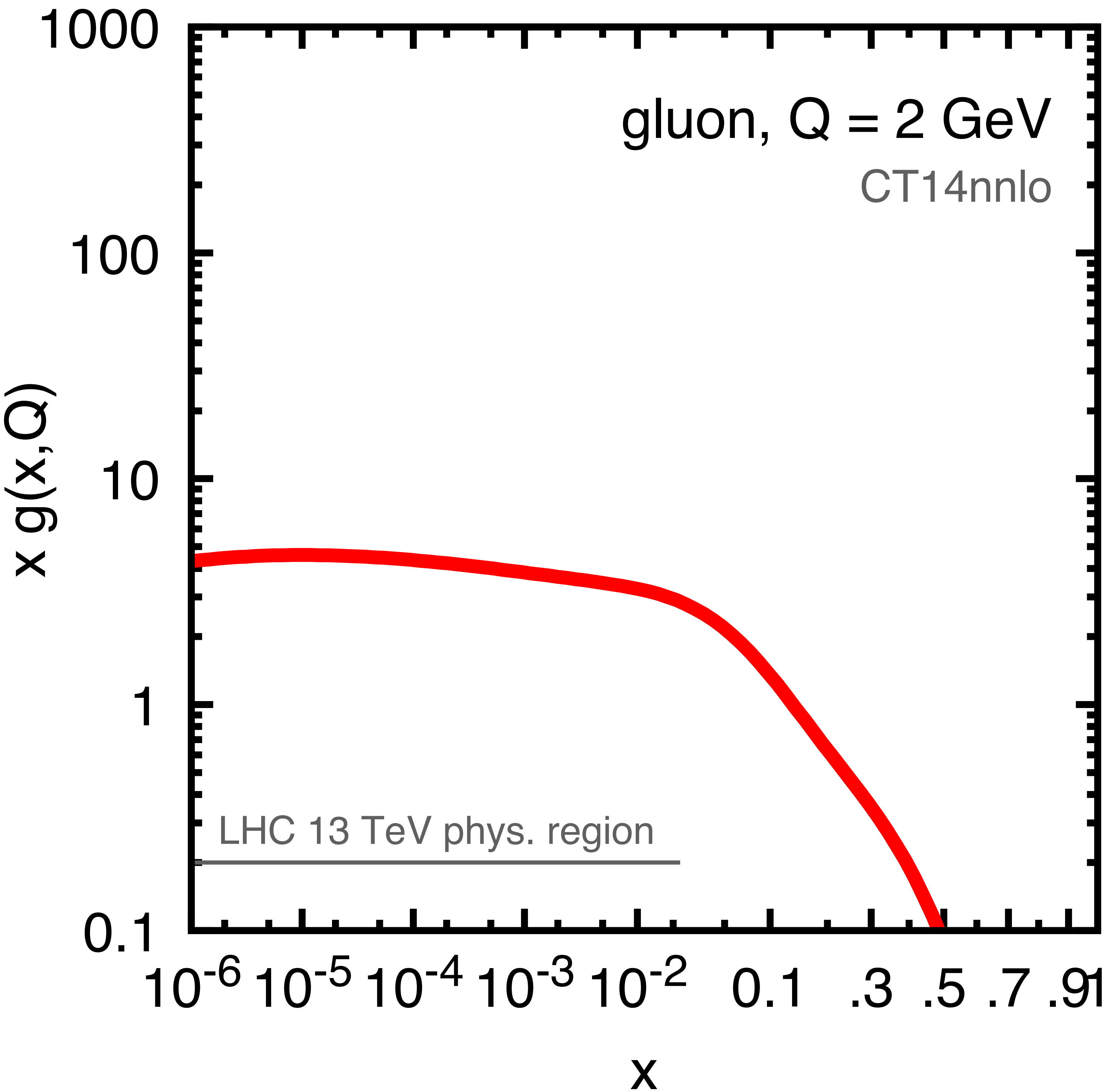
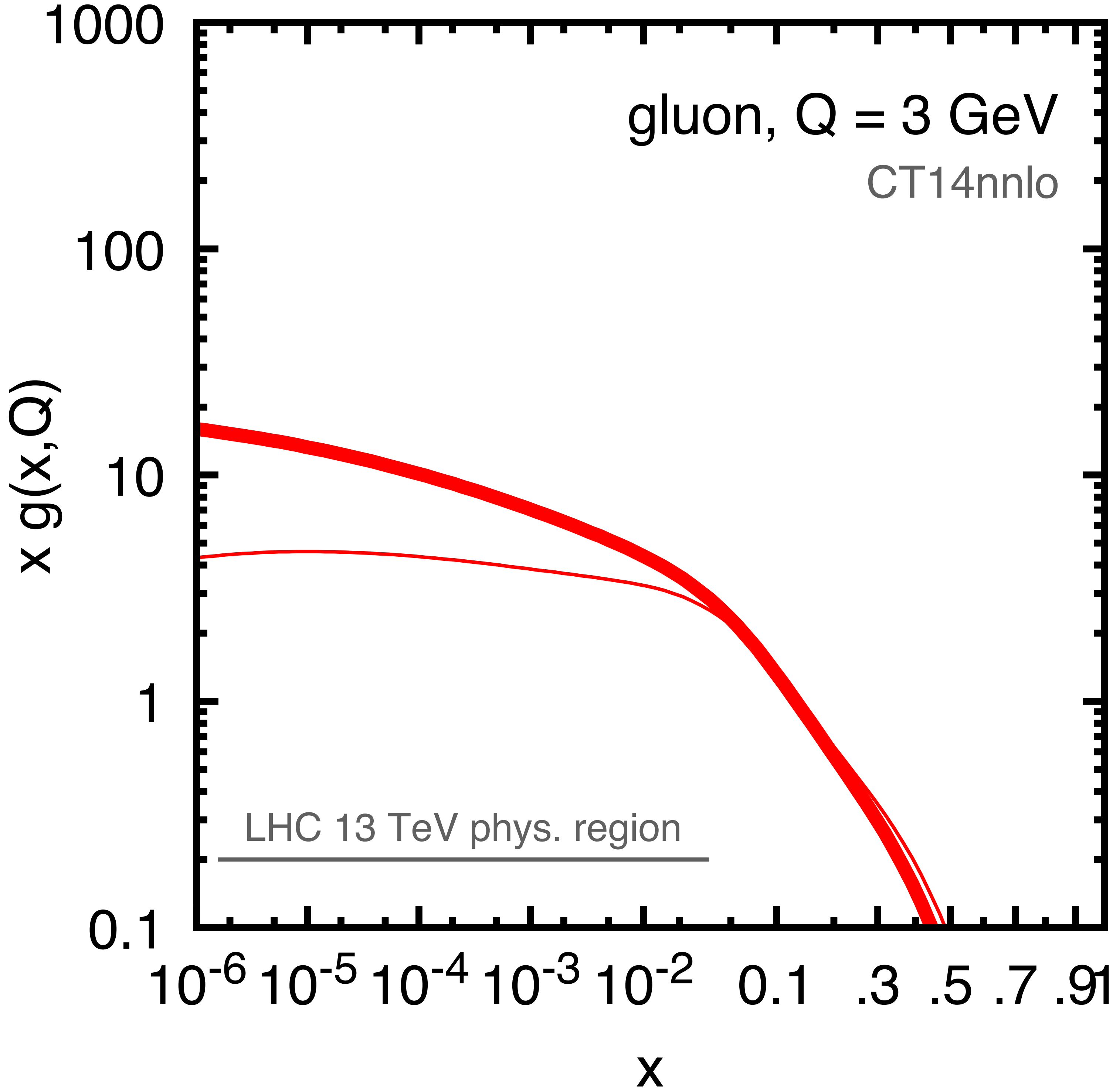


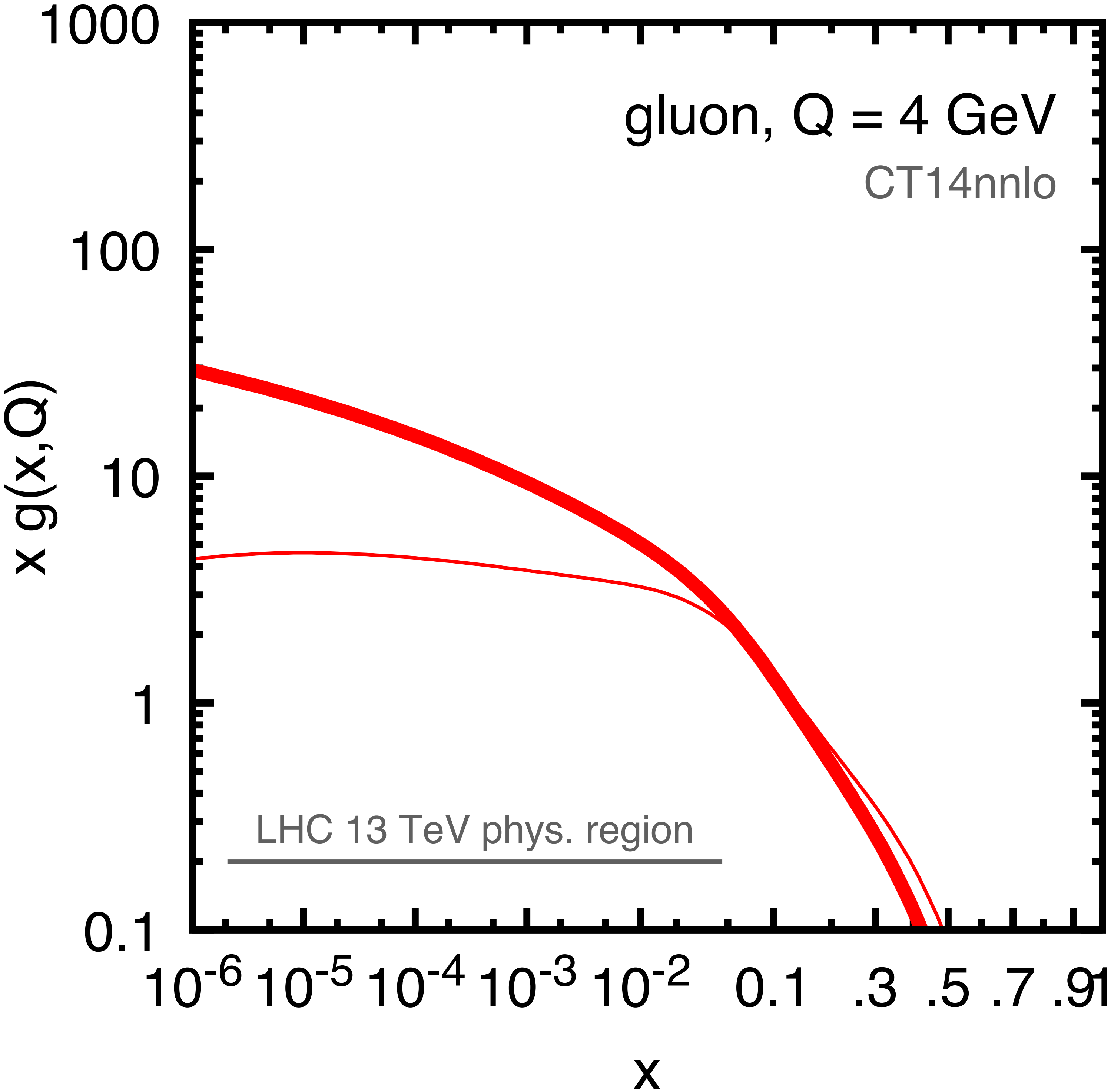
impact of DGLAP evolution from Q_0 = 2 GeV



impact of DGLAP evolution from $Q_0 = 2$ GeV



impact of DGLAP evolution from $Q_0 = 2$ GeV



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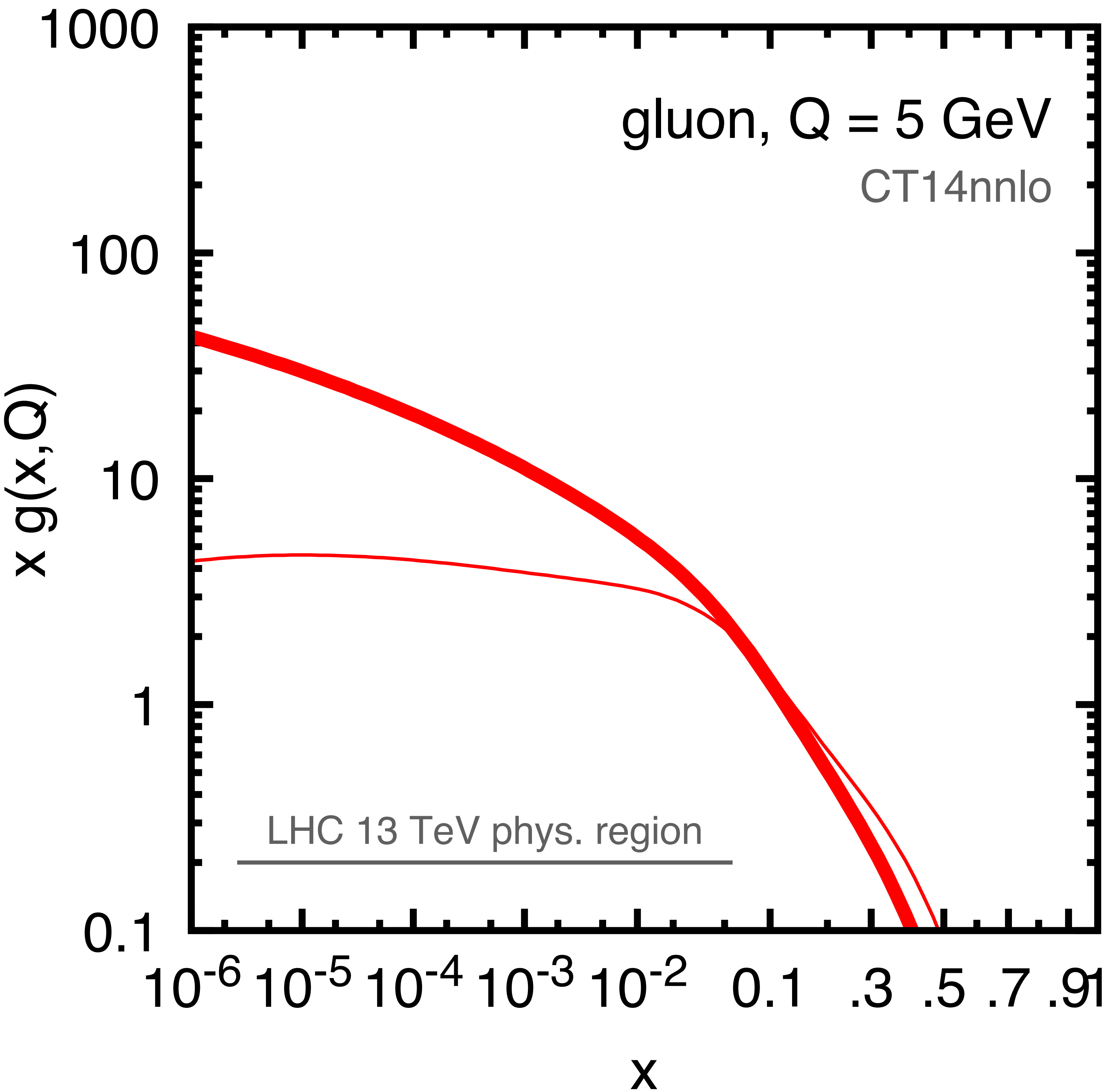
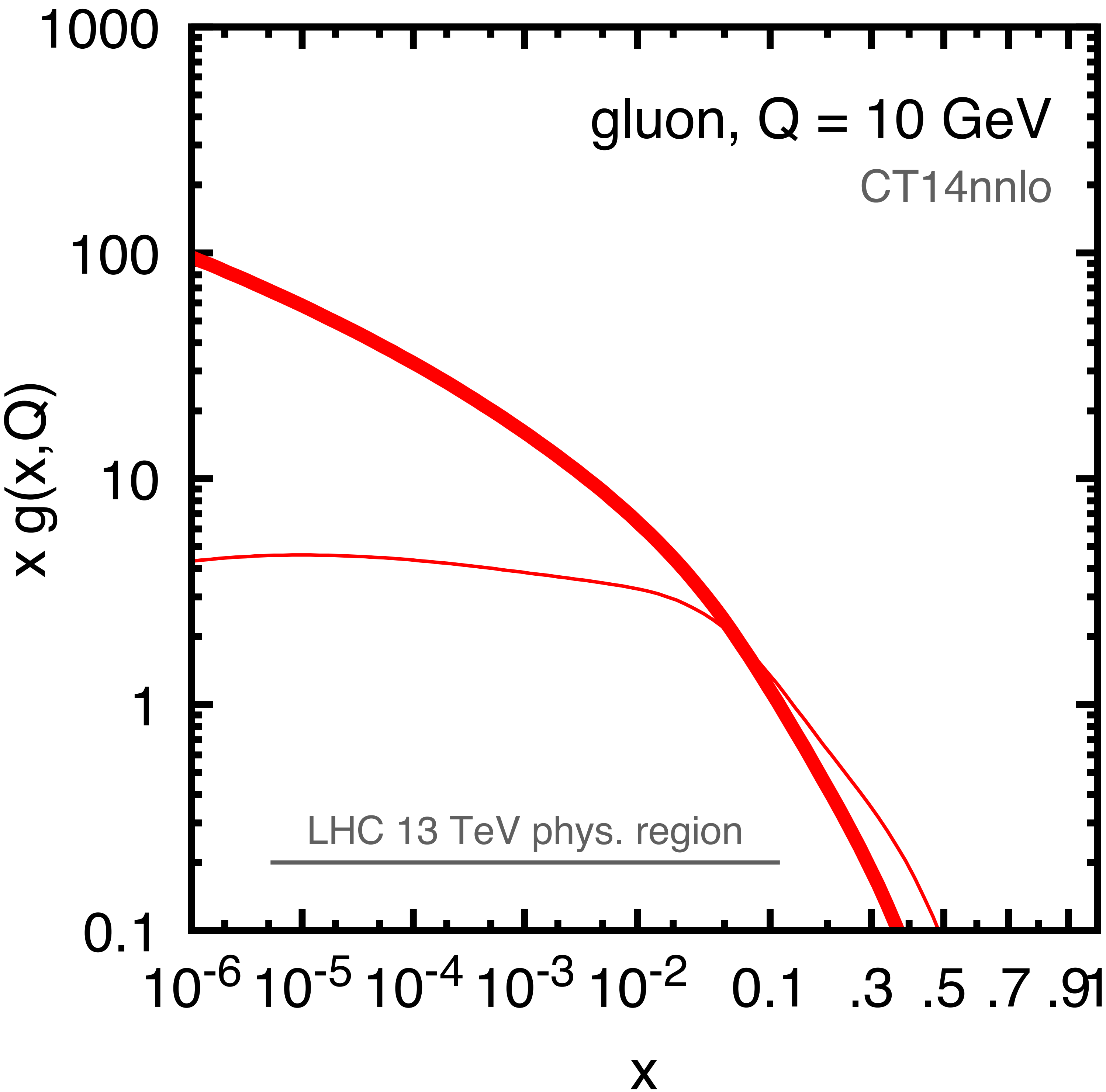
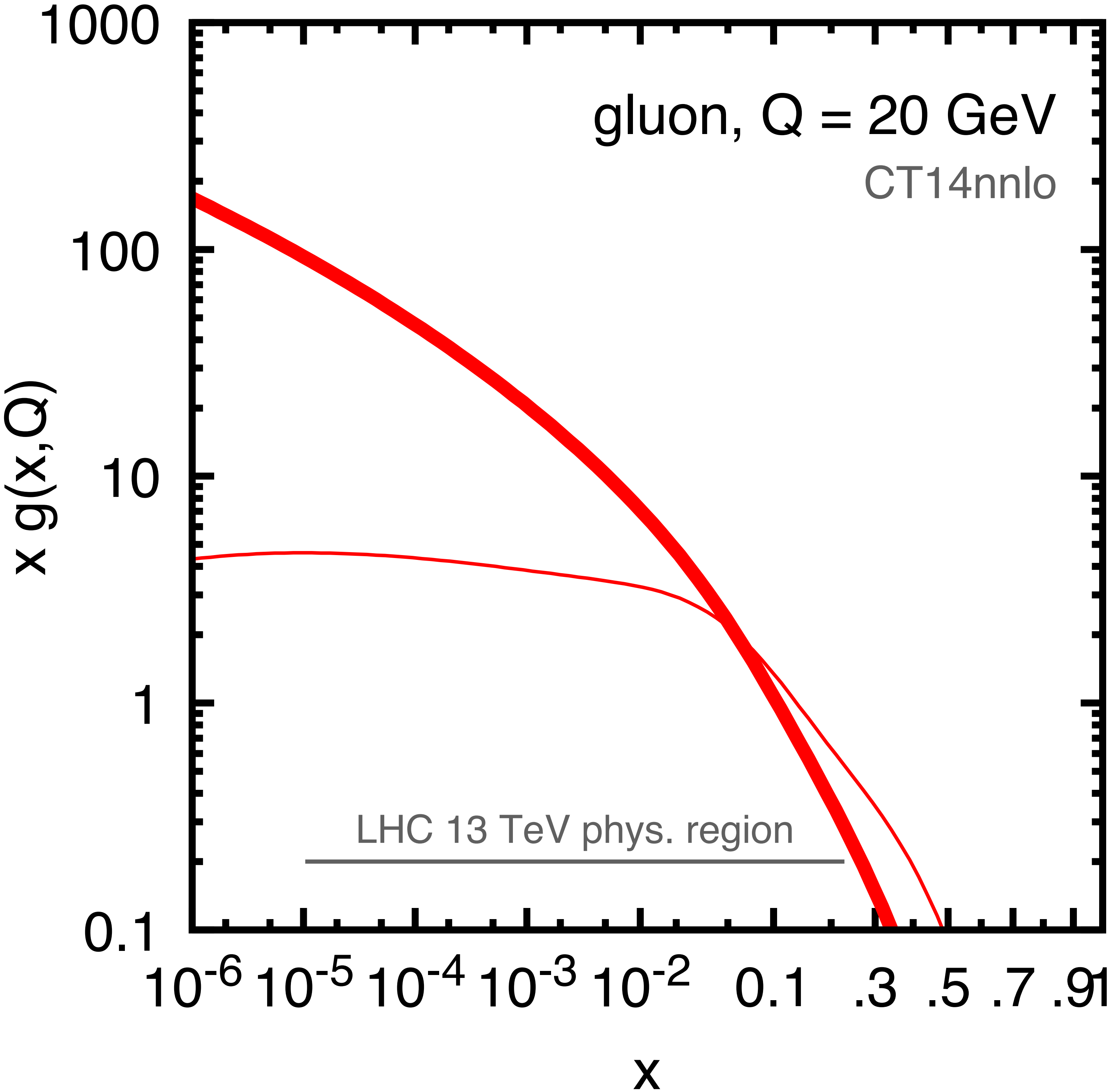


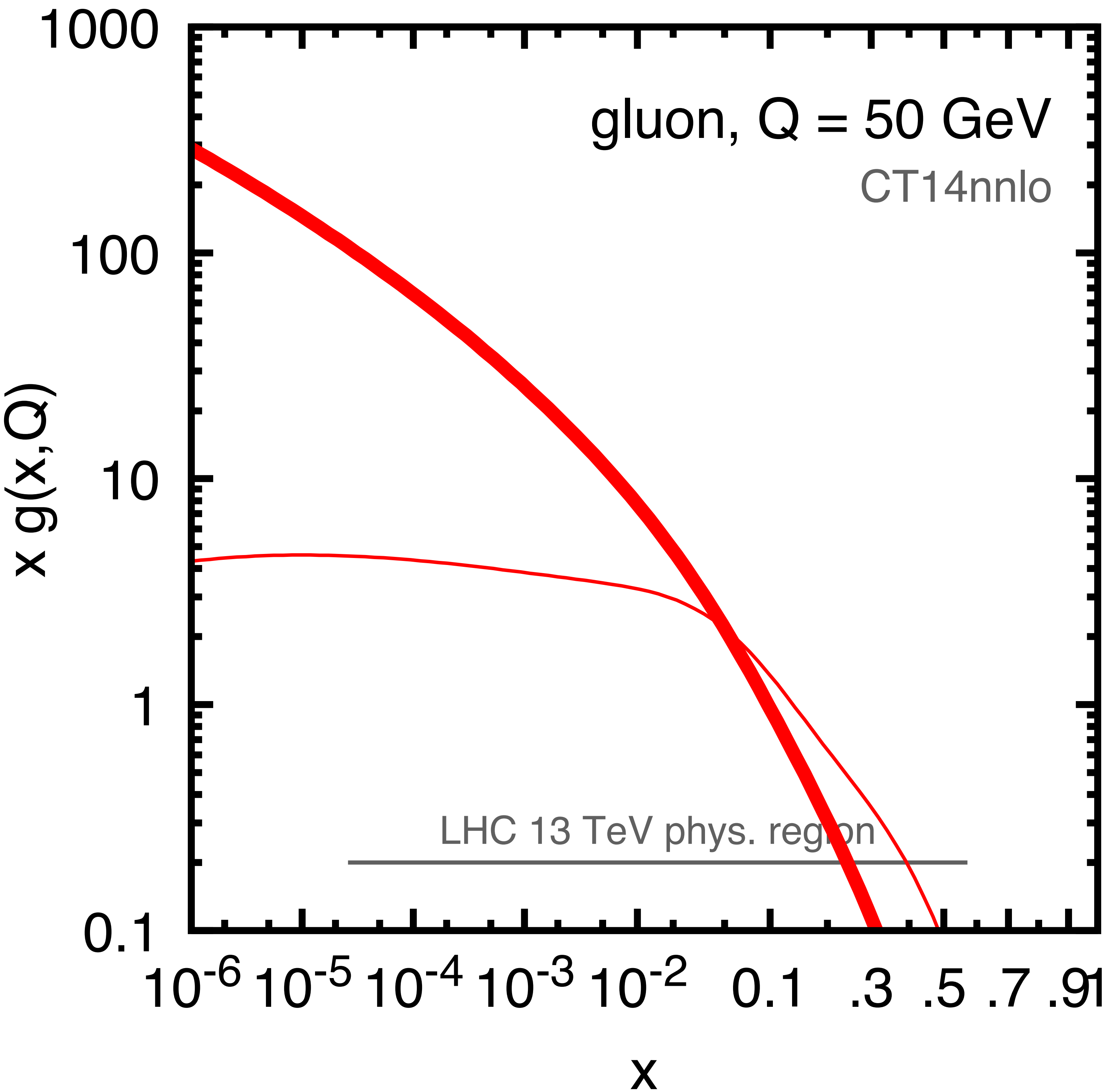
impact of DGLAP evolution from $Q_0 = 2$ GeV



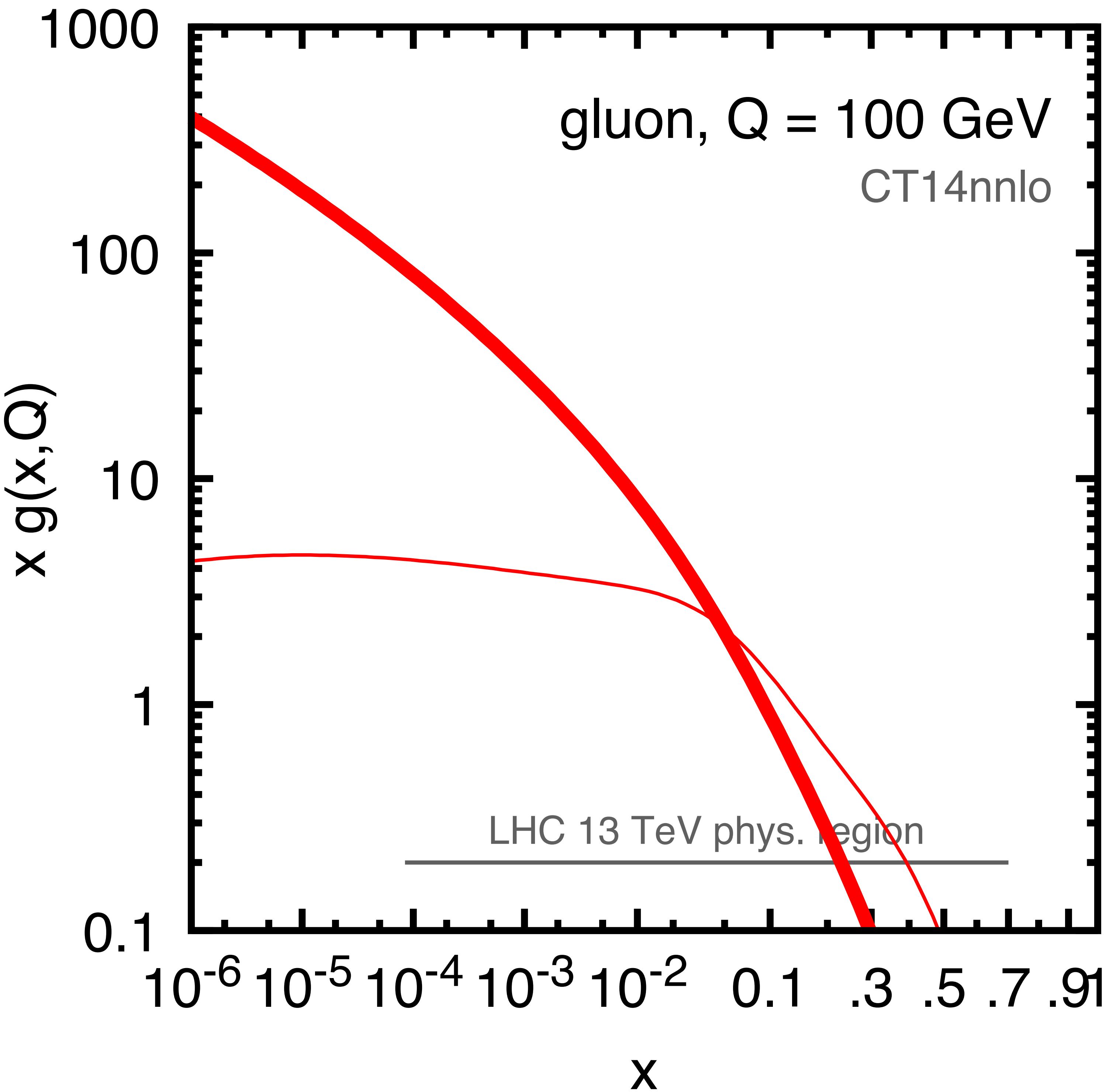
impact of DGLAP evolution from $Q_0 = 2$ GeV

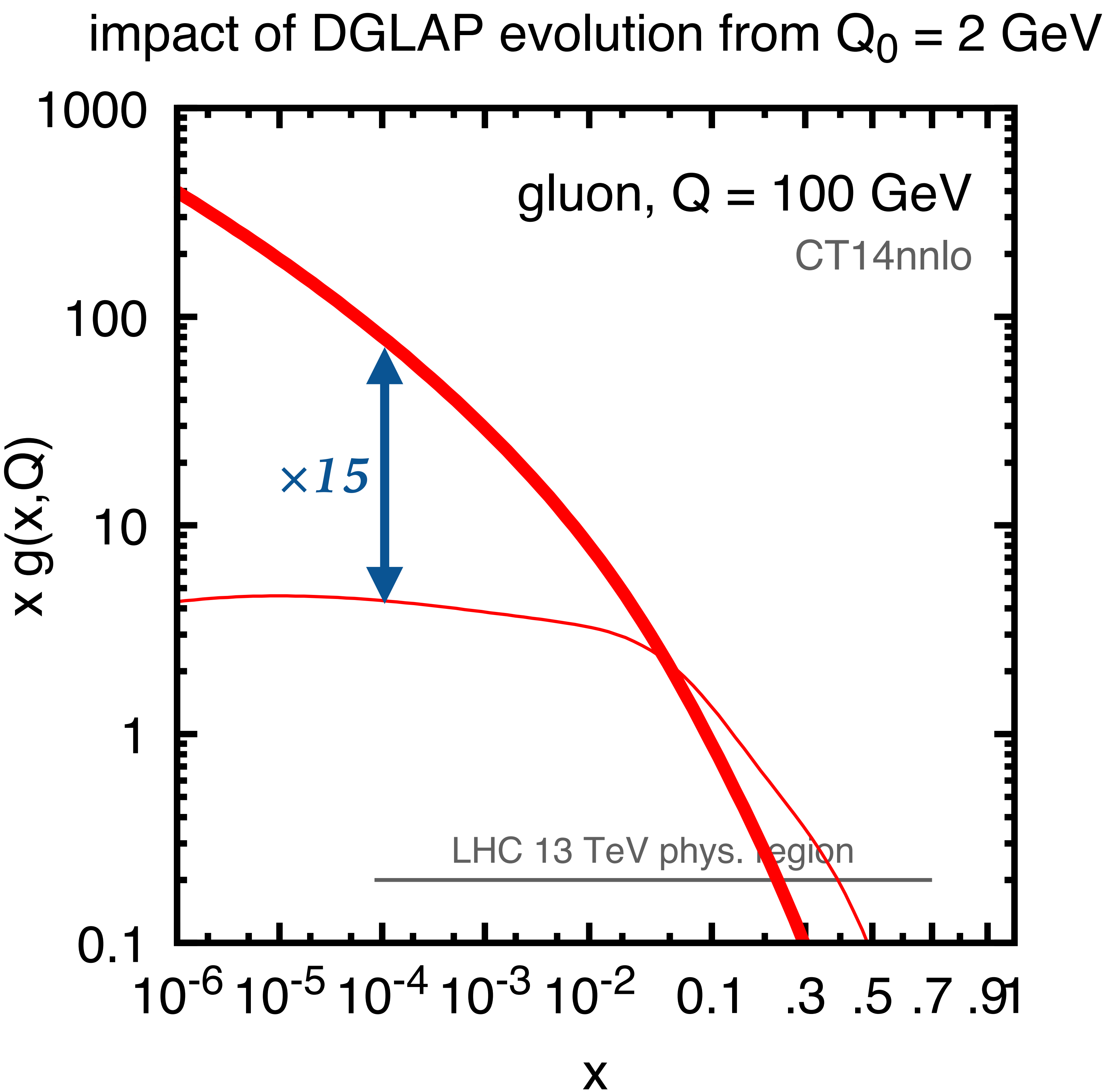


impact of DGLAP evolution from $Q_0 = 2$ GeV



impact of DGLAP evolution from Q_0 = 2 GeV



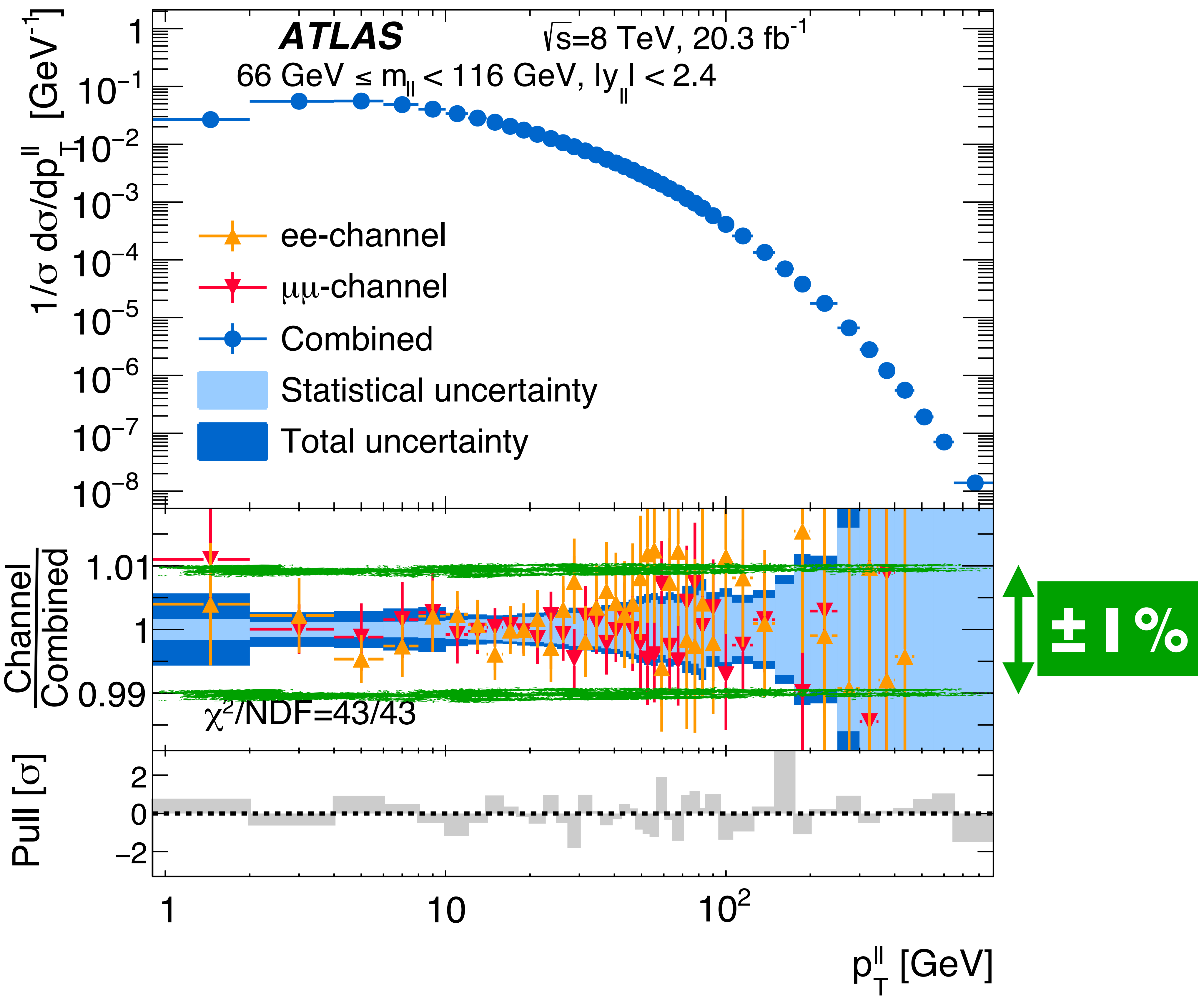


DGLAP evolution changes parton distributions by factors ~ 10

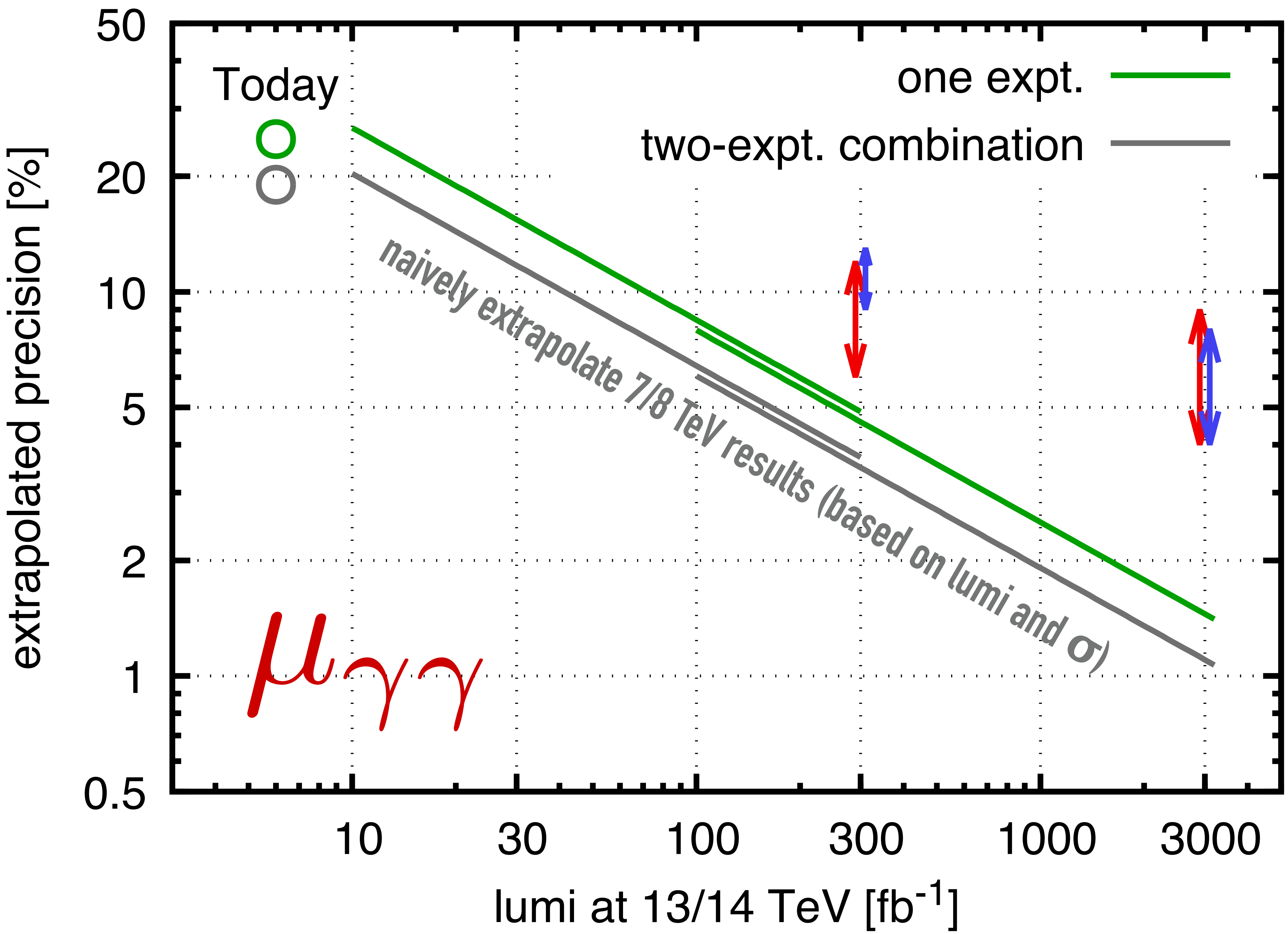
Higgs cross section (13 TeV) would be 6x smaller without DGLAP

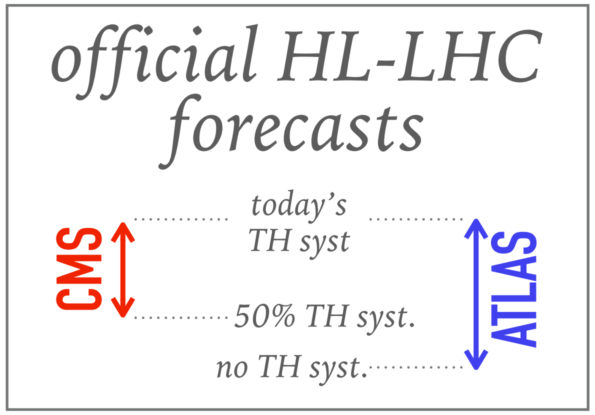
nowadays, used at NNLO, thanks to Moch, Vermaseren & Vogt

EXPERIMENTAL PRECISION TODAY CAN REACH 1%



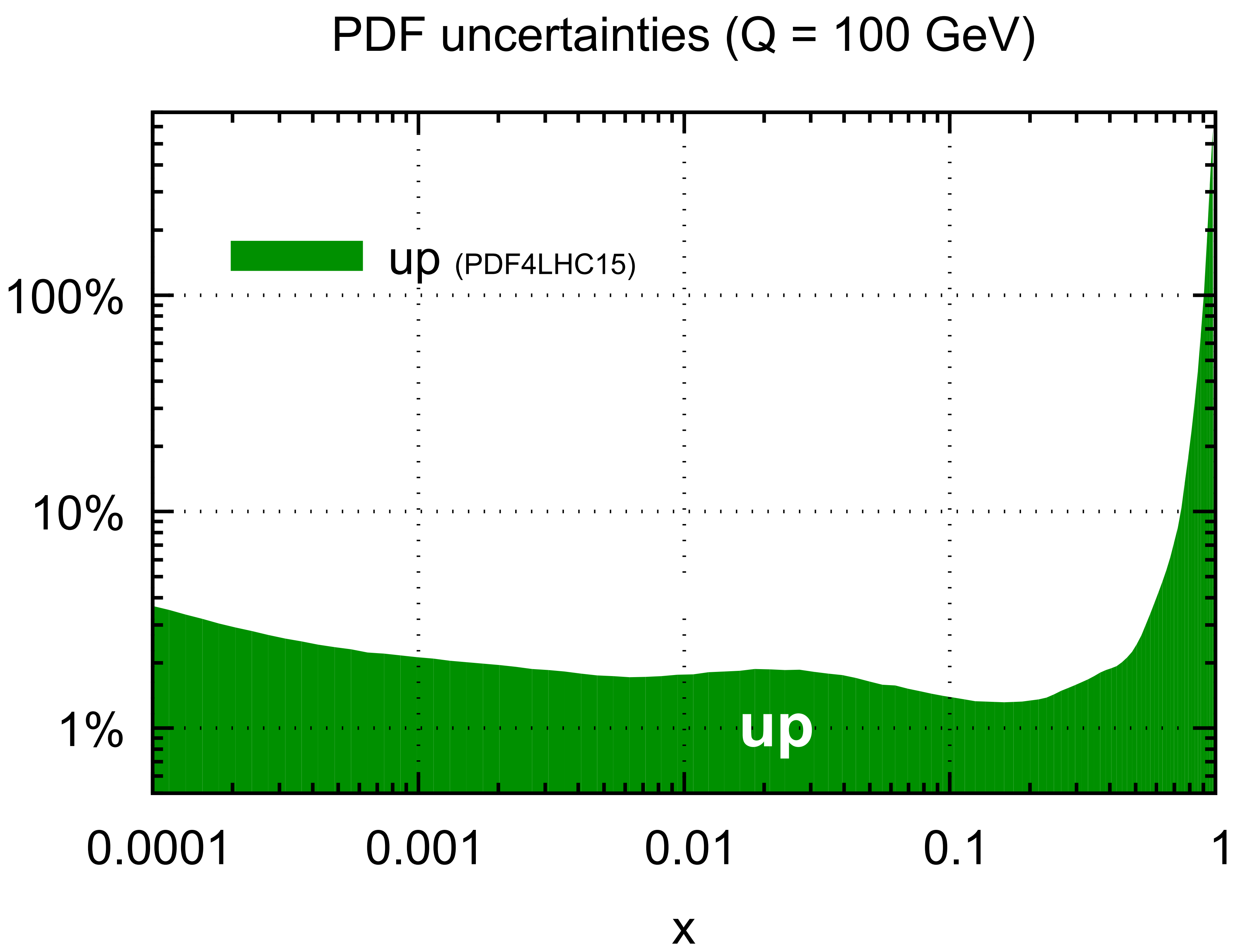
WHAT ACCURACY DO WE NEED? E.G. FOR LONG-TERM HIGGS PRECISION



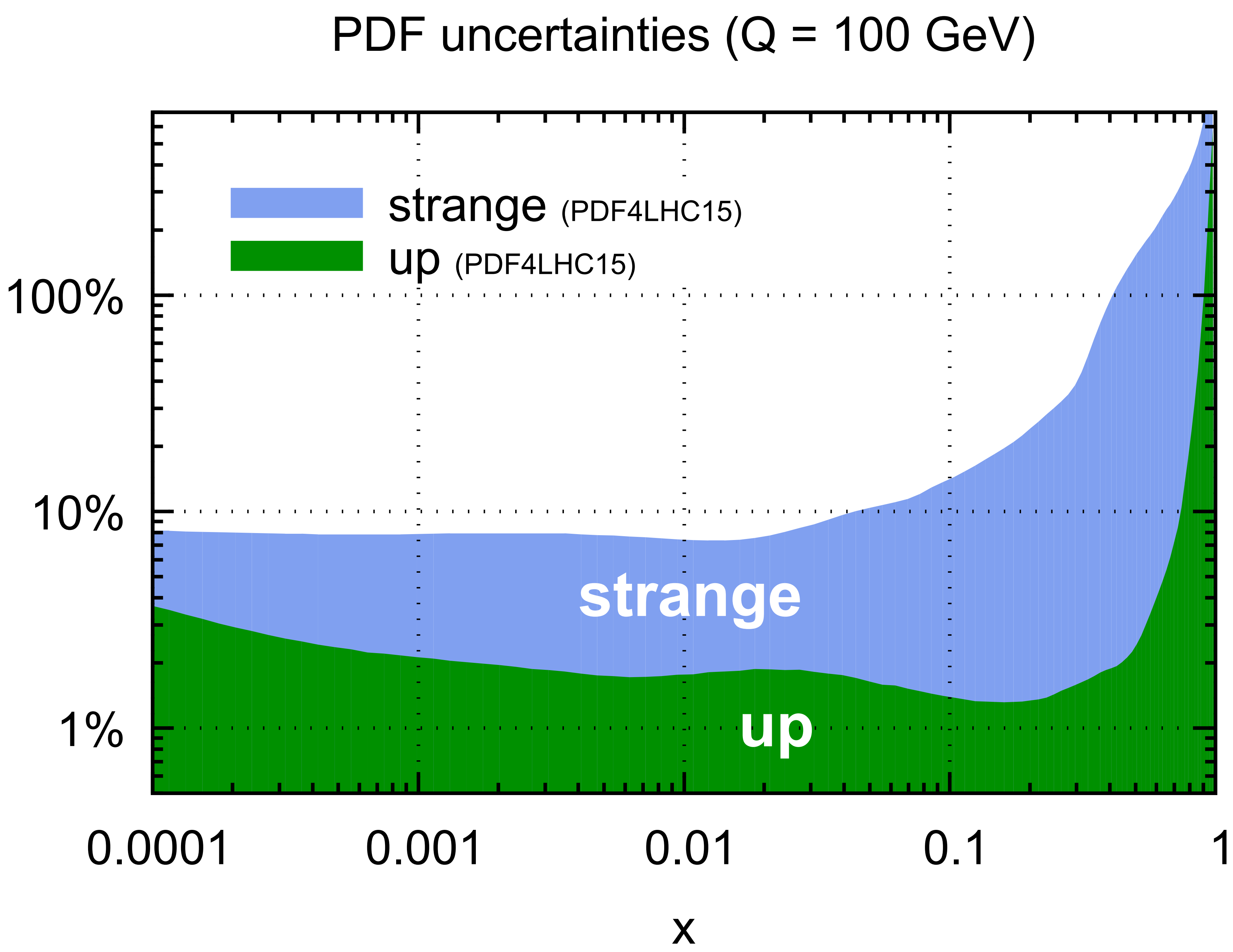


Naive extrapolation suggests LHC has long-term potential to do Higgs (and much other) physics at **1% accuracy**

how well do we know the parton distributions?

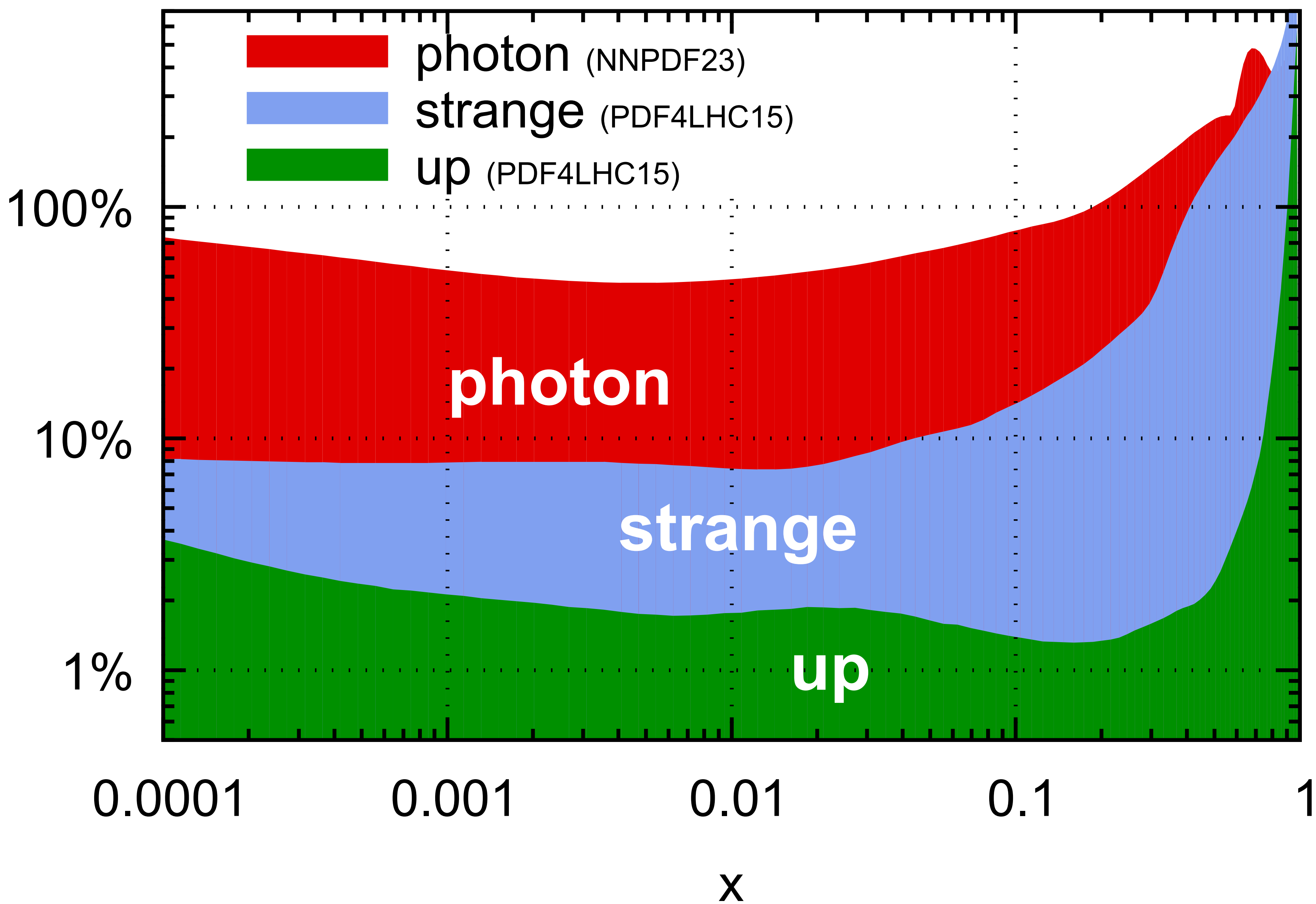


- core partons (up, down, gluon) are quite well known



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

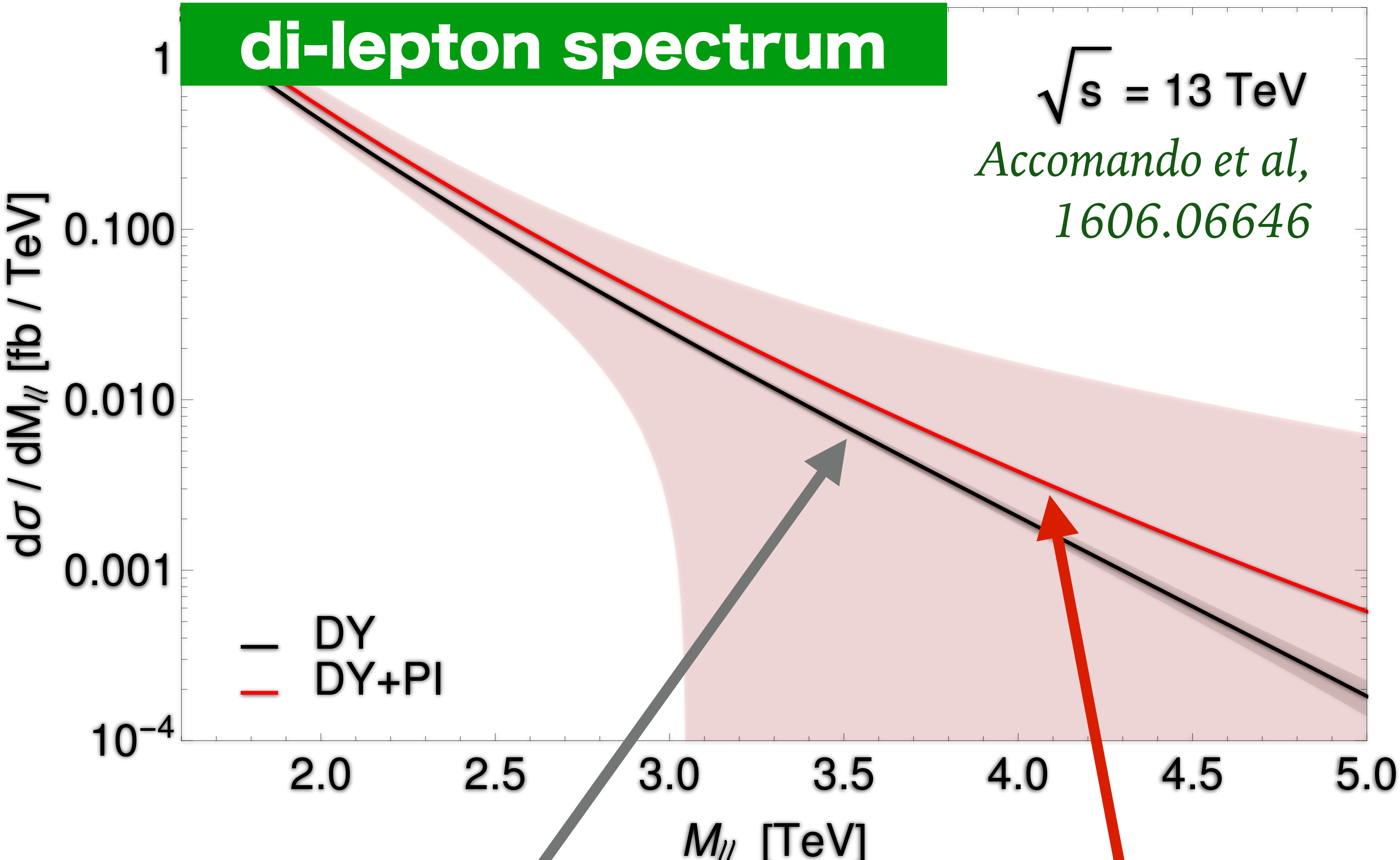
PDF uncertainties (Q = 100 GeV)



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

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

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



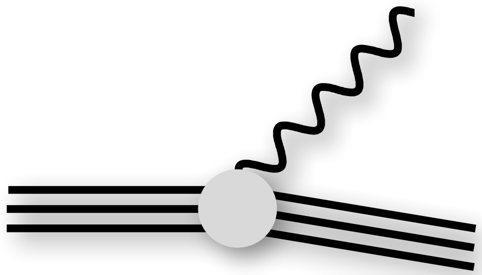
normal DY contribution

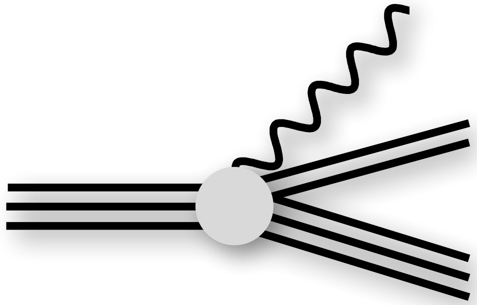
photon-induced contribution and uncertainty [NNPDF23]

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

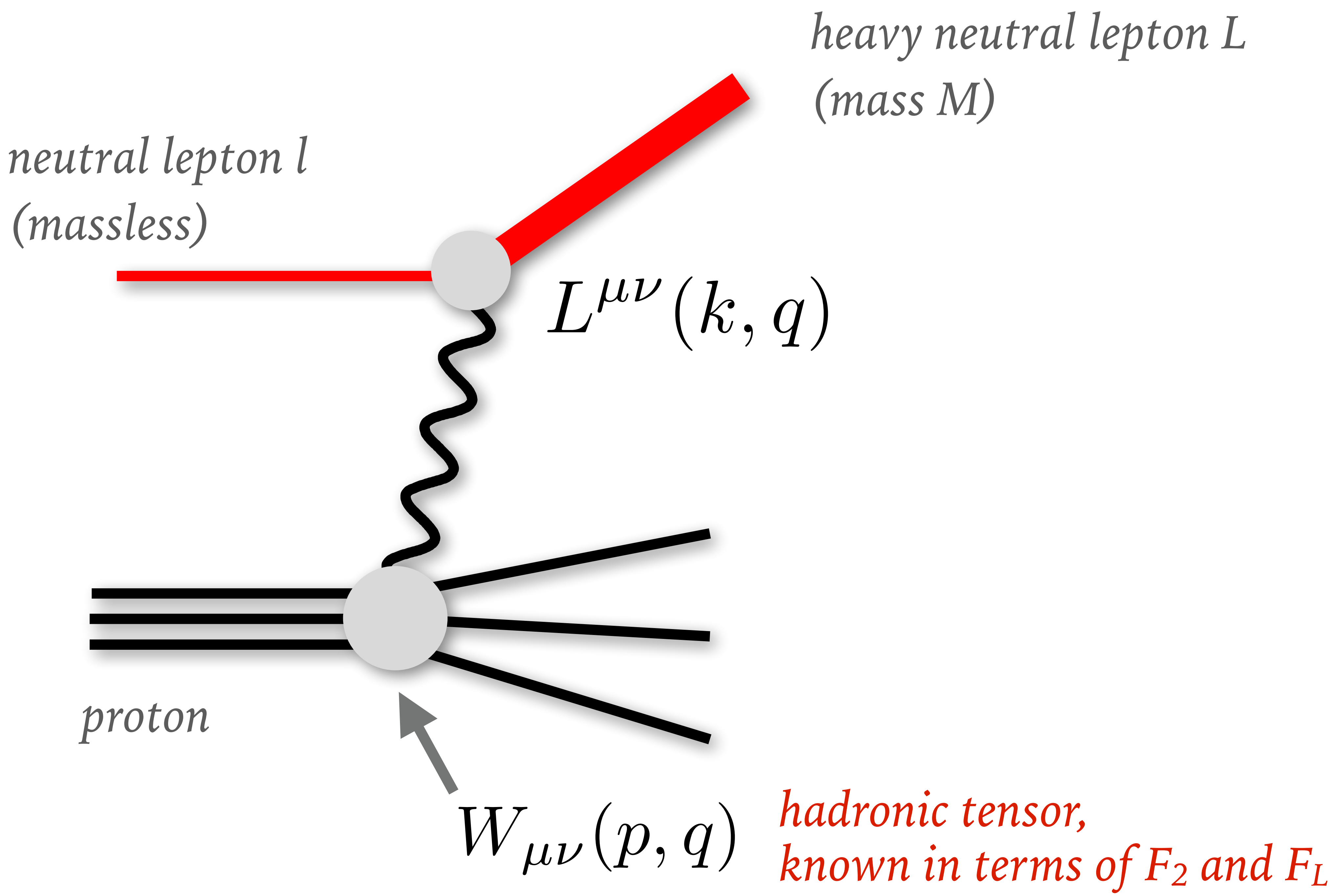
---

to extract it, we'll study a hypothetical ("BSM") heavy-neutral lepton production process

Manohar, Nason, GPS & Zanderighi, to appear

STEP 1

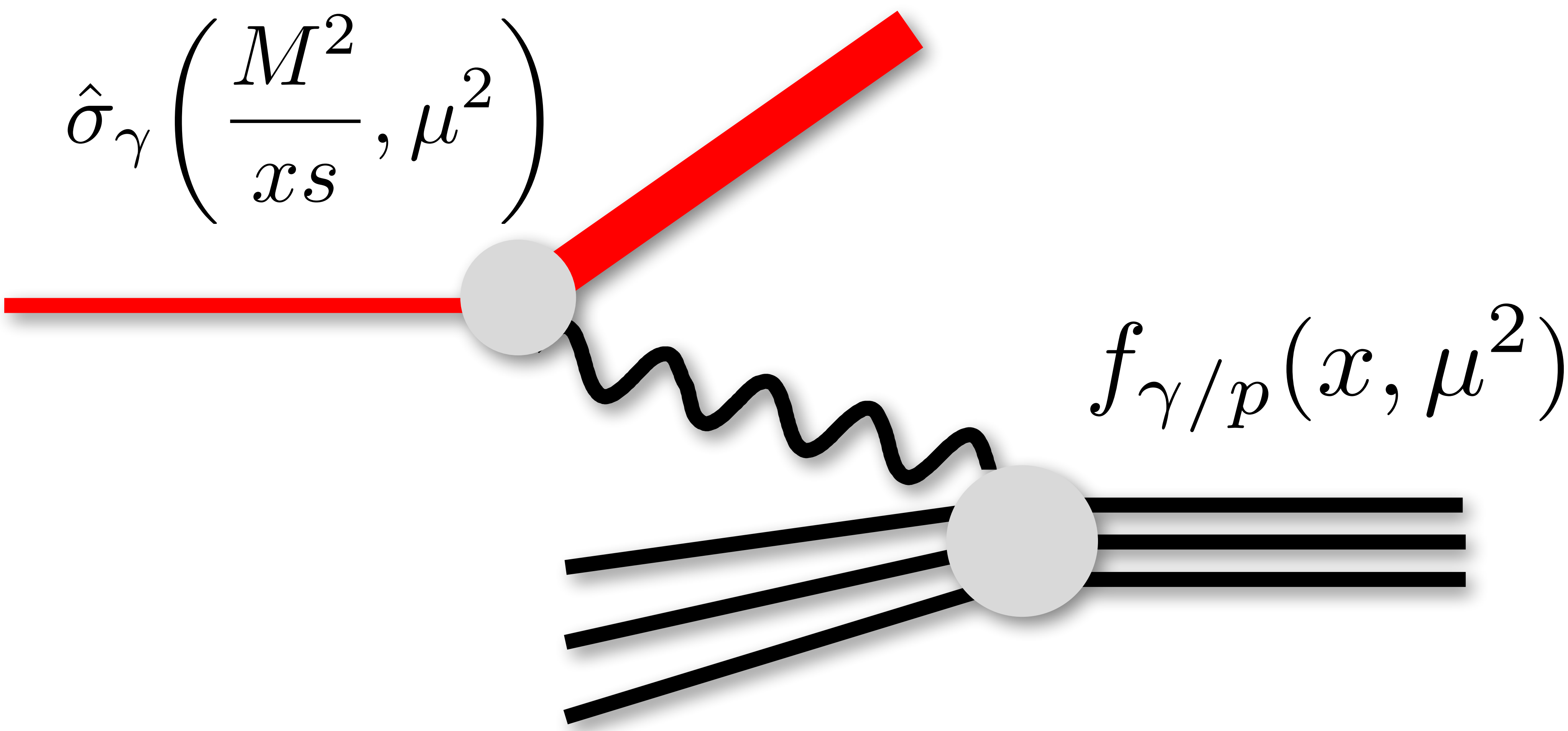
work out a cross section (exact) in terms of F_2 and F_L struct. fns.



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

STEP 2

work out same cross section in terms of a photon distribution



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

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

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

Result is in MSbar scheme & consistent with
2015 de Florian, Rodrigo, Sborlini $O(\alpha\alpha_s)$ $P_{\gamma x}$ QED split.fns.

PHOTON PDF ESTIMATES (not exhaustive)

	elastic	inelastic	in LHAPDF?
Gluck Pisano Reya 2002	dipole	model	✗
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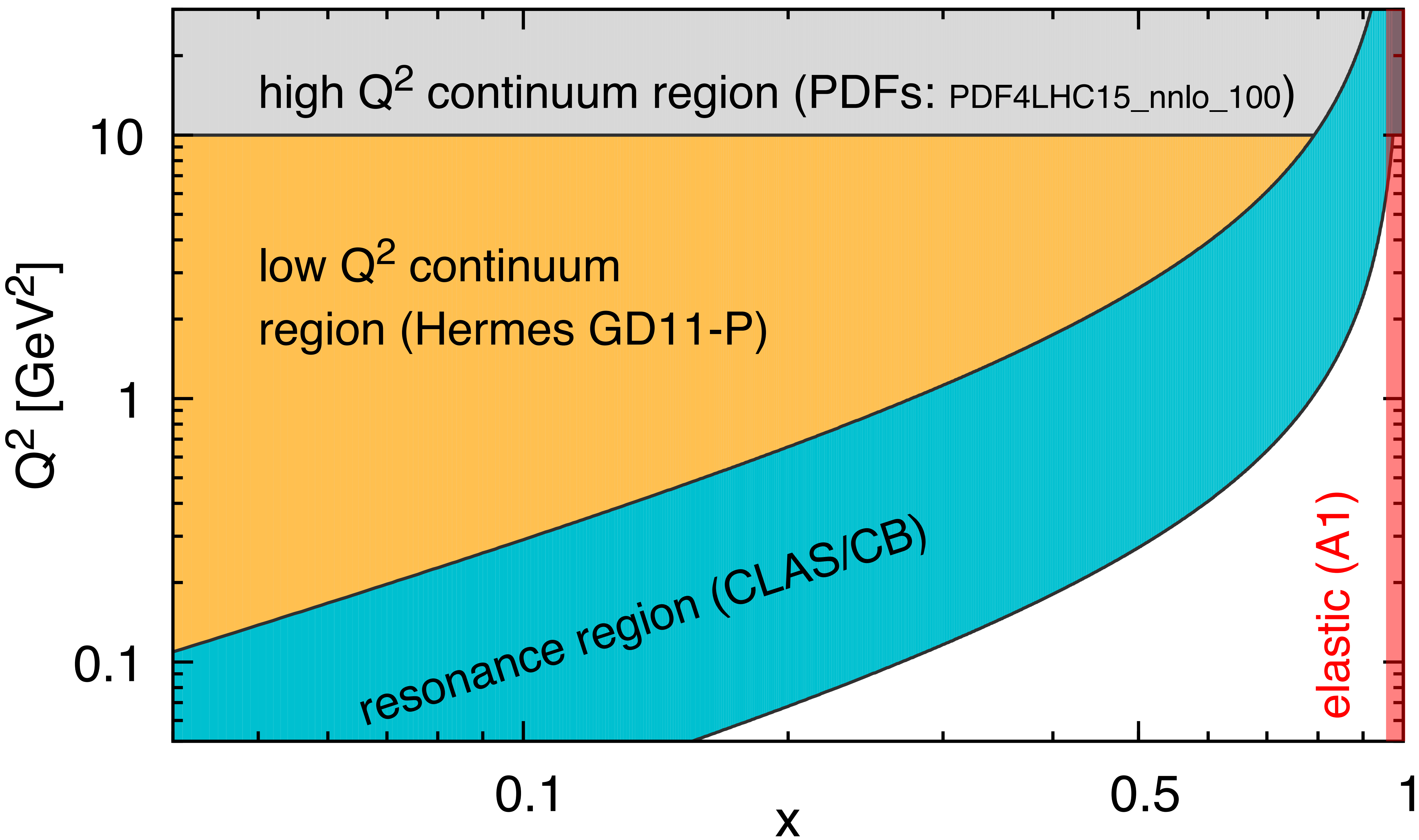
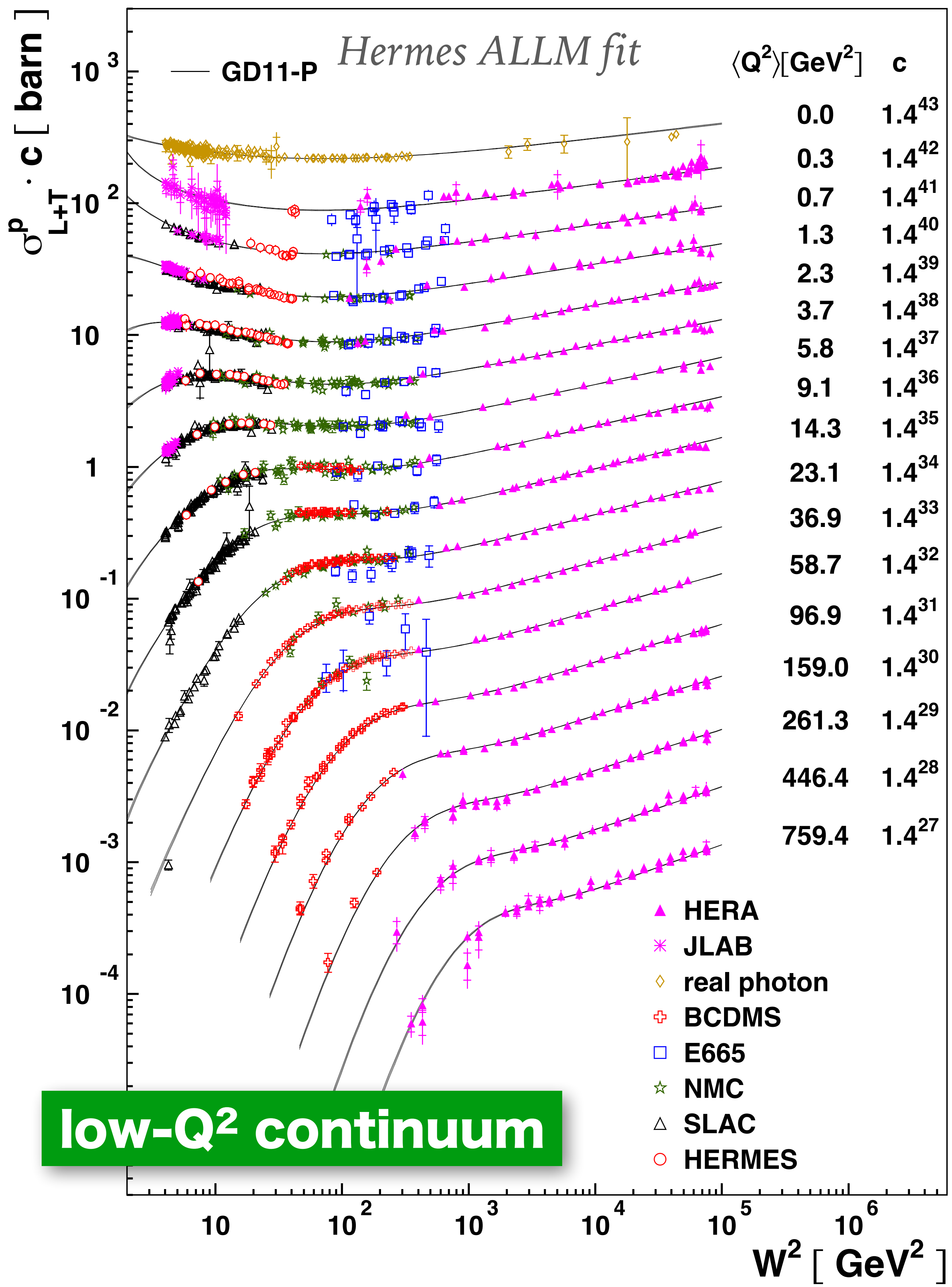
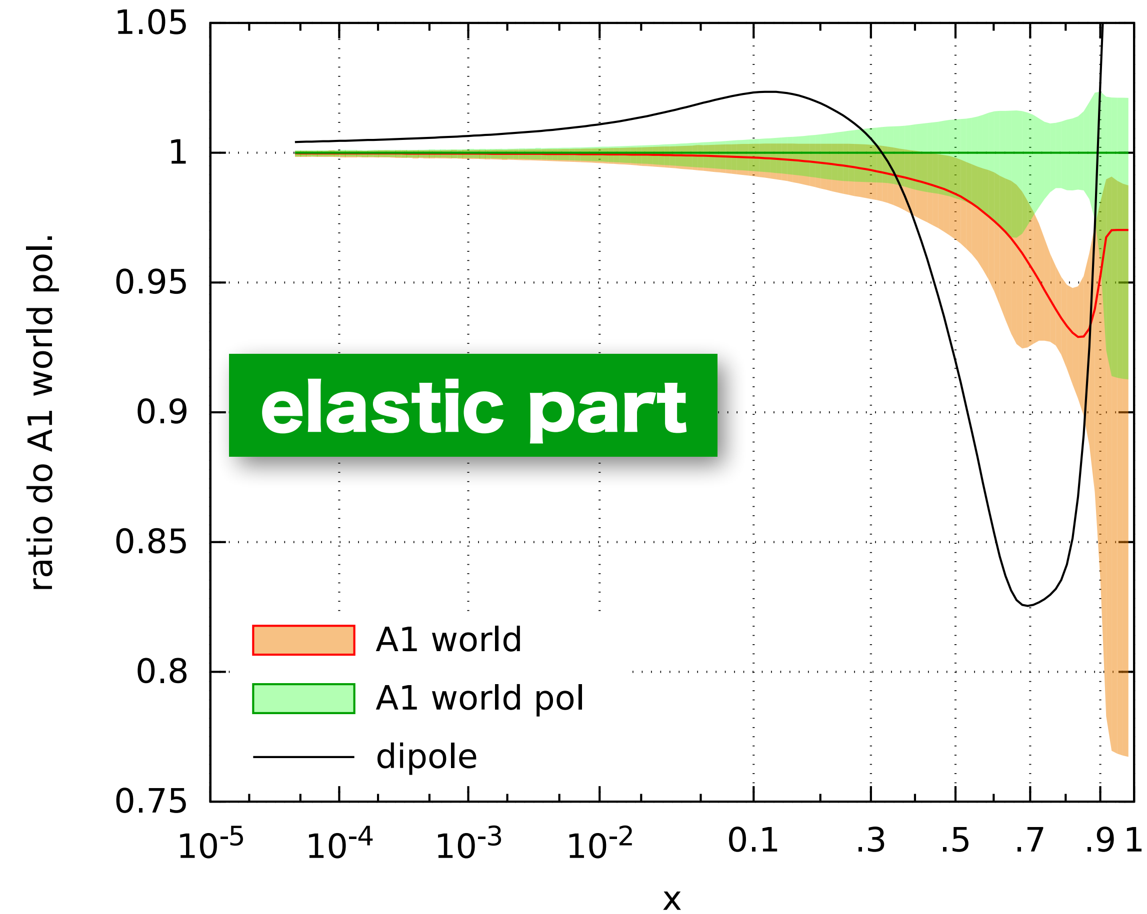
Martin Ryskin 2014	dipole (only electric part)	model	✗
Harland-Lang, Khoze Ryskin 2016	dipole	model	✗
LUXqed 2016	data	data	soon

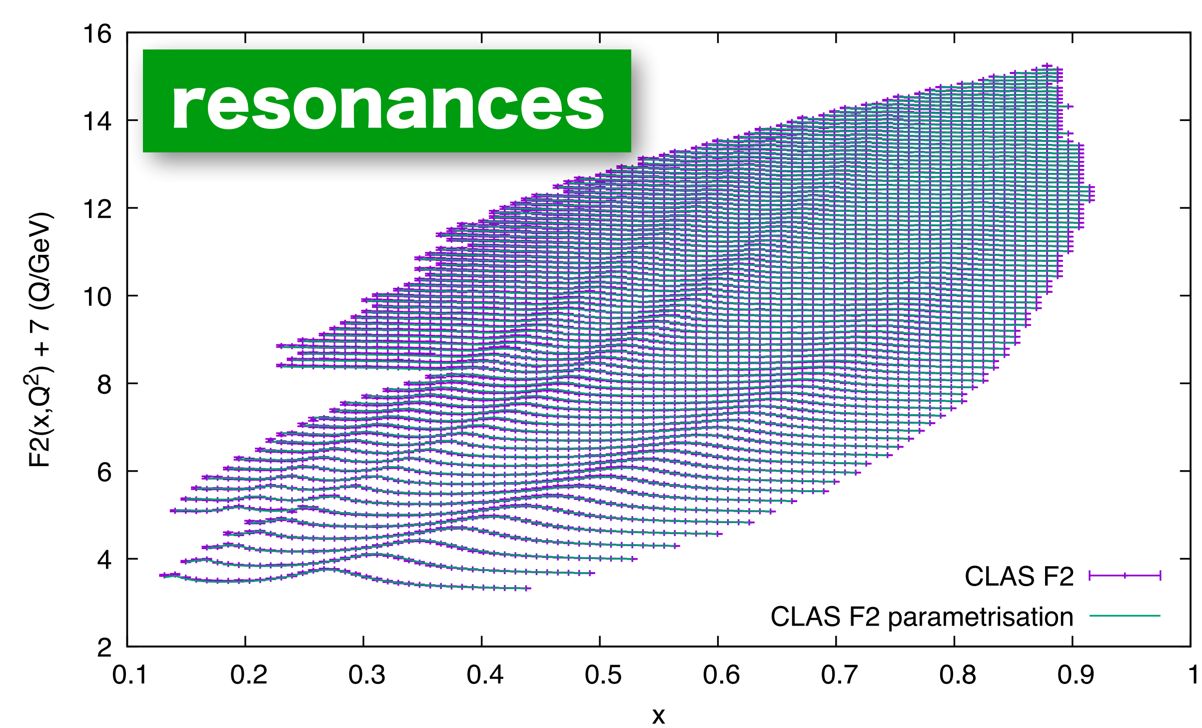
DATA SOURCES – various fits to F2, FL & elastic form factors

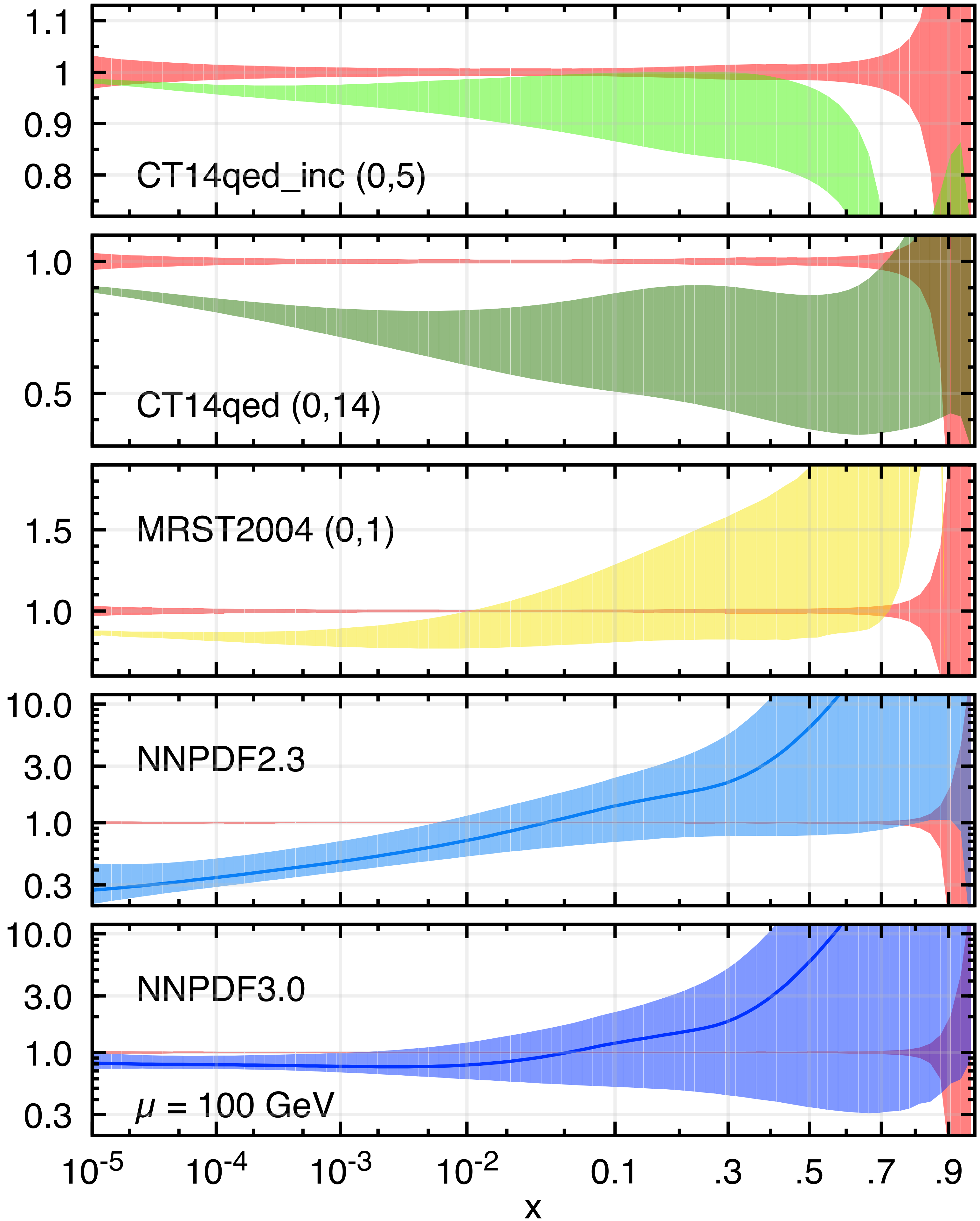


DATA SOURCES – various fits to F2, FL & elastic form factors





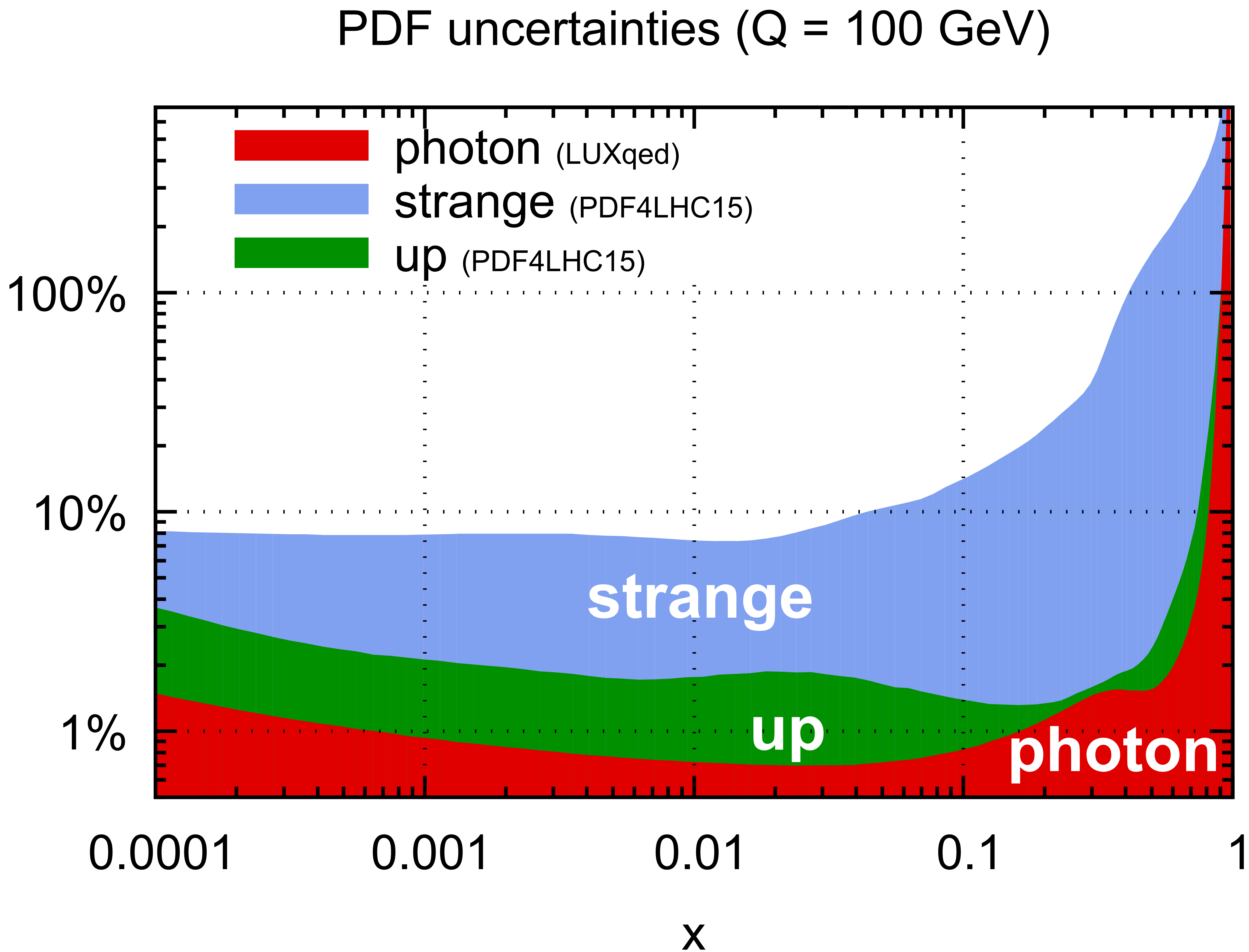




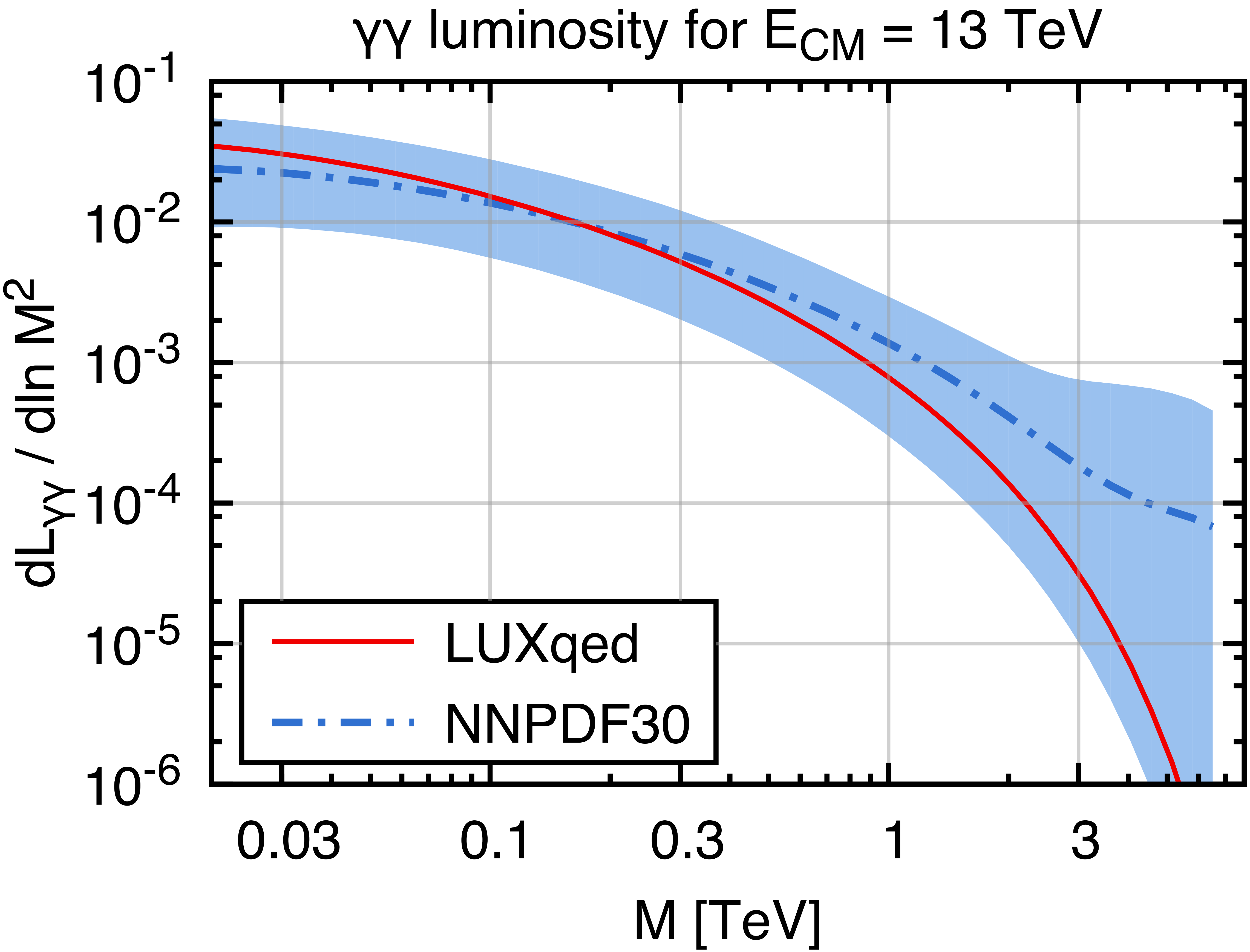
the results

ratio of some widely used PDFs to LUXqed (red)

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



γγ 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

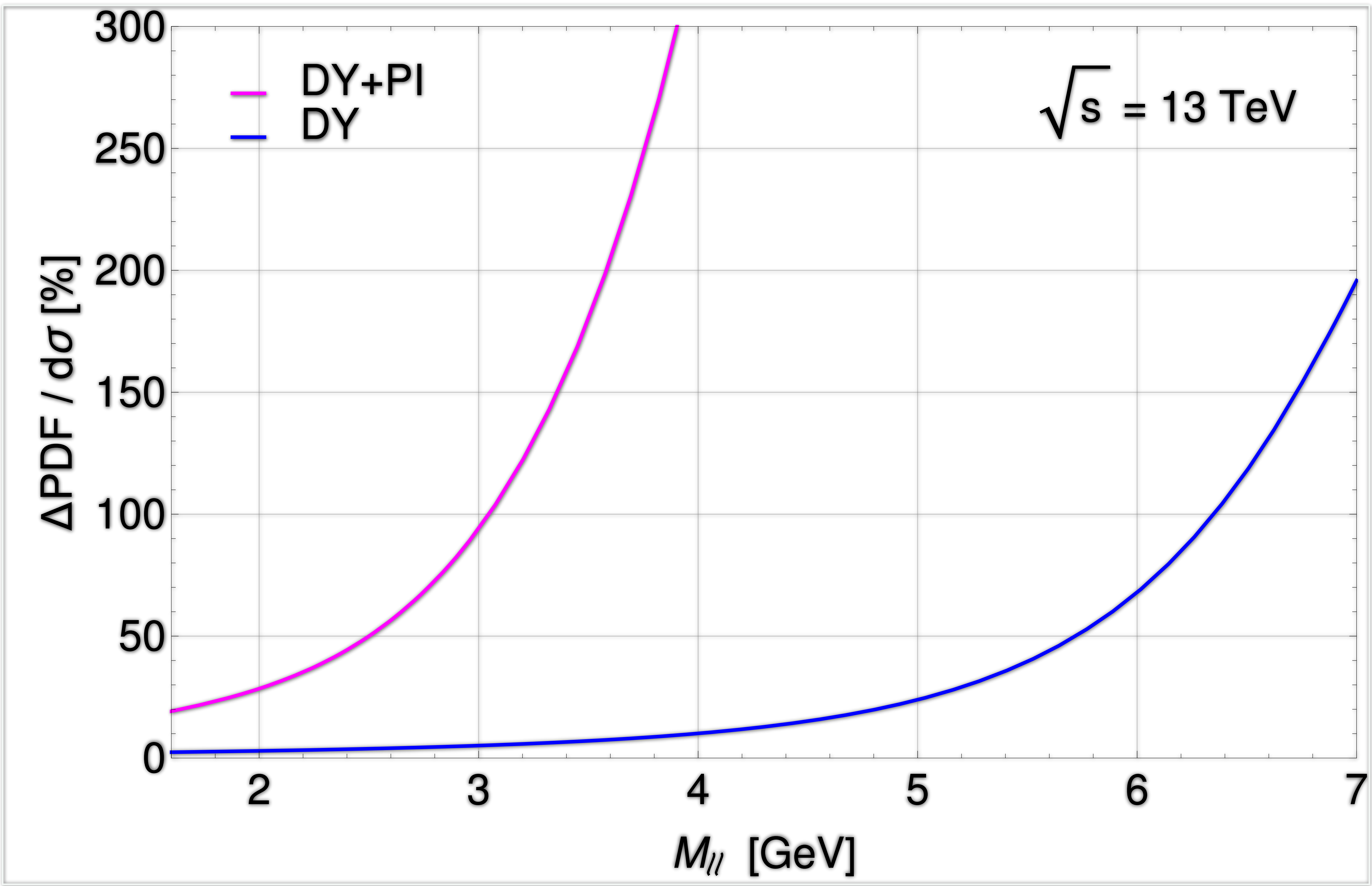
CLOSING REMARKS

- LHC physics would be unrecognisable without Guido's contributions, first and foremost the simple physical picture contained in the DGLAP equations.
- Parton distribution functions are among the crucial inputs to LHC physics, with significant open problems still to solve today.
- More generally, Guido's dedication, his combination of breadth and attention to detail, all serve as a model for what a physicist may aspire to.

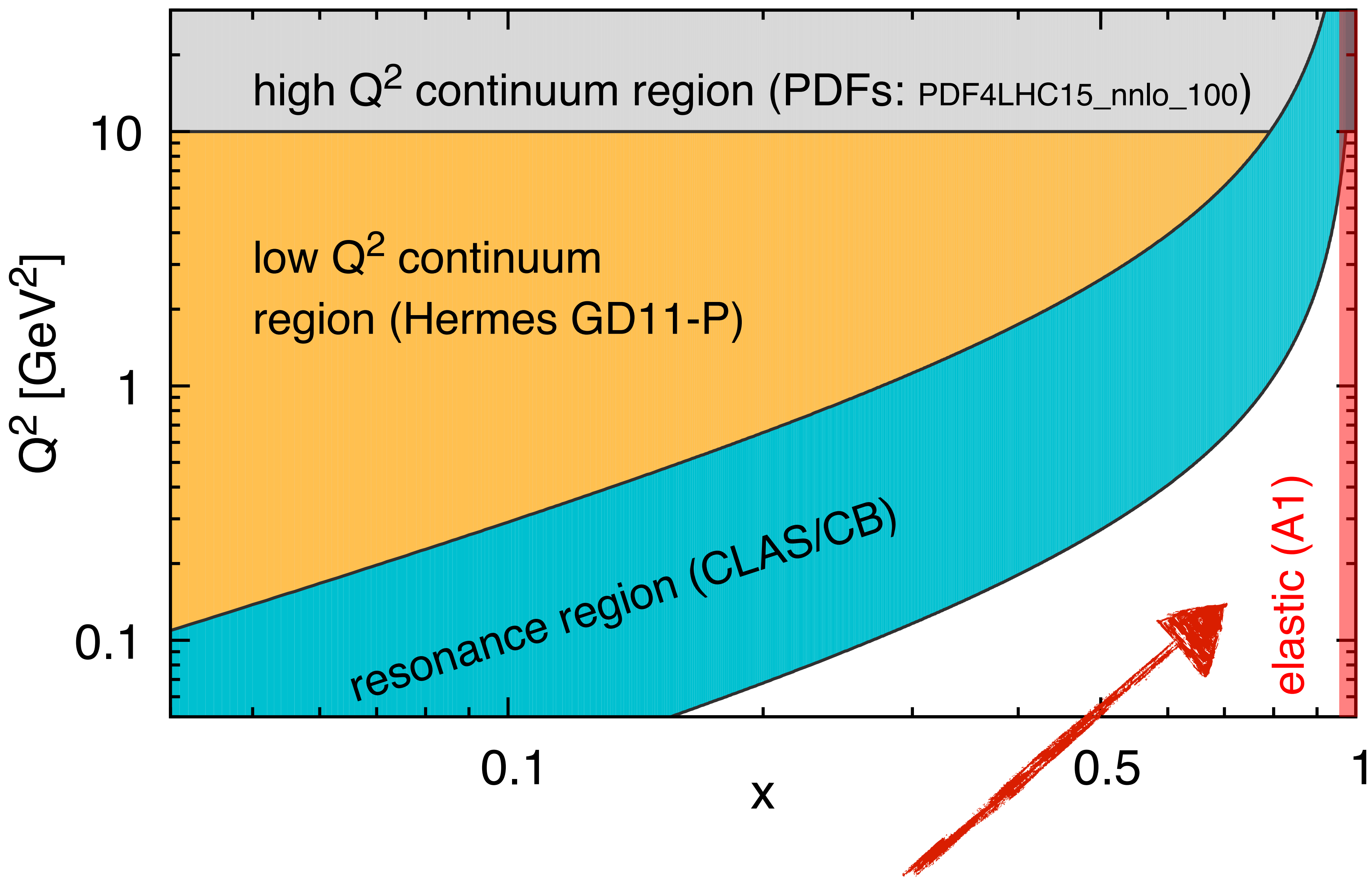
extra slides

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,¶]



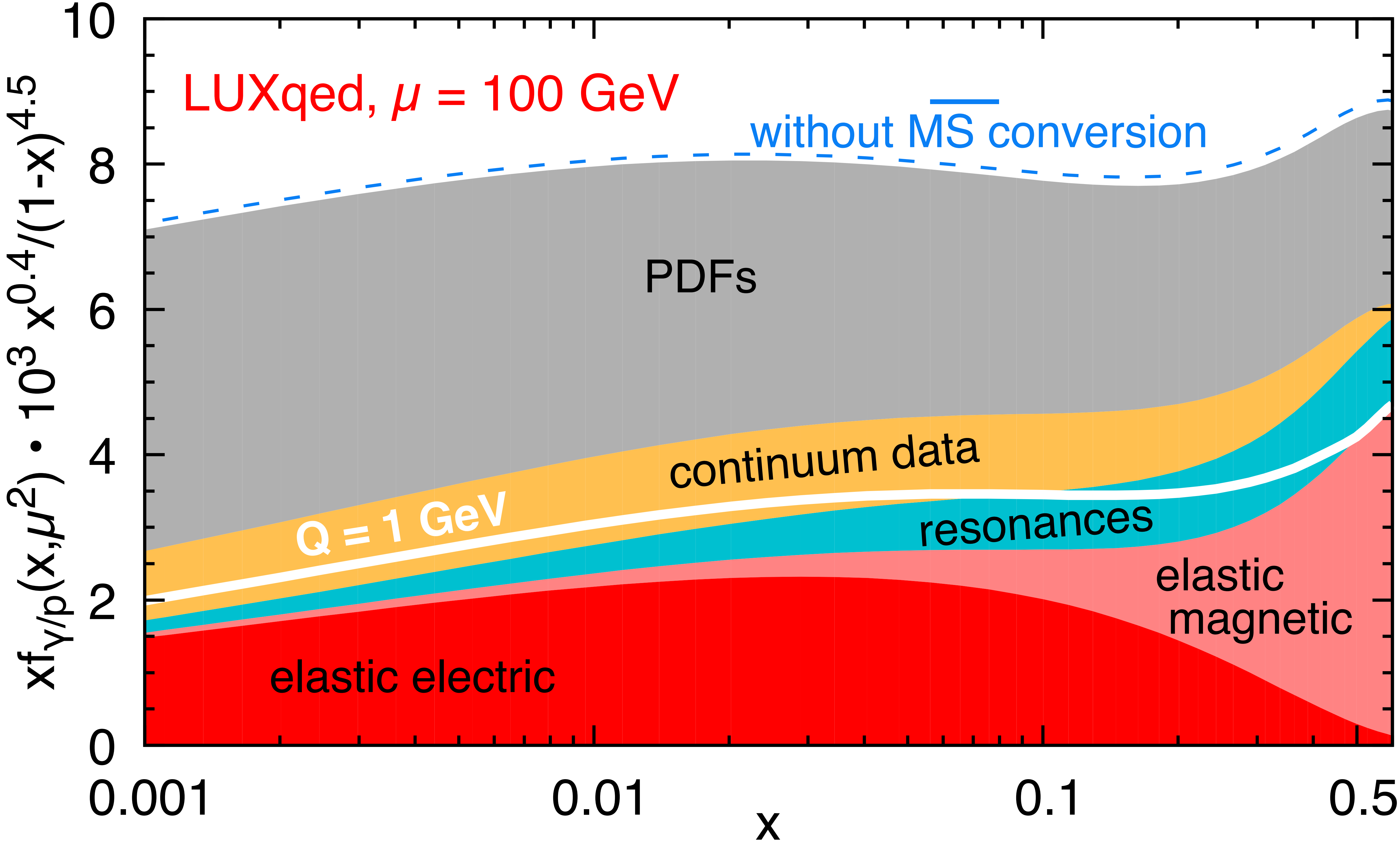
DATA SOURCES – elastic form factors



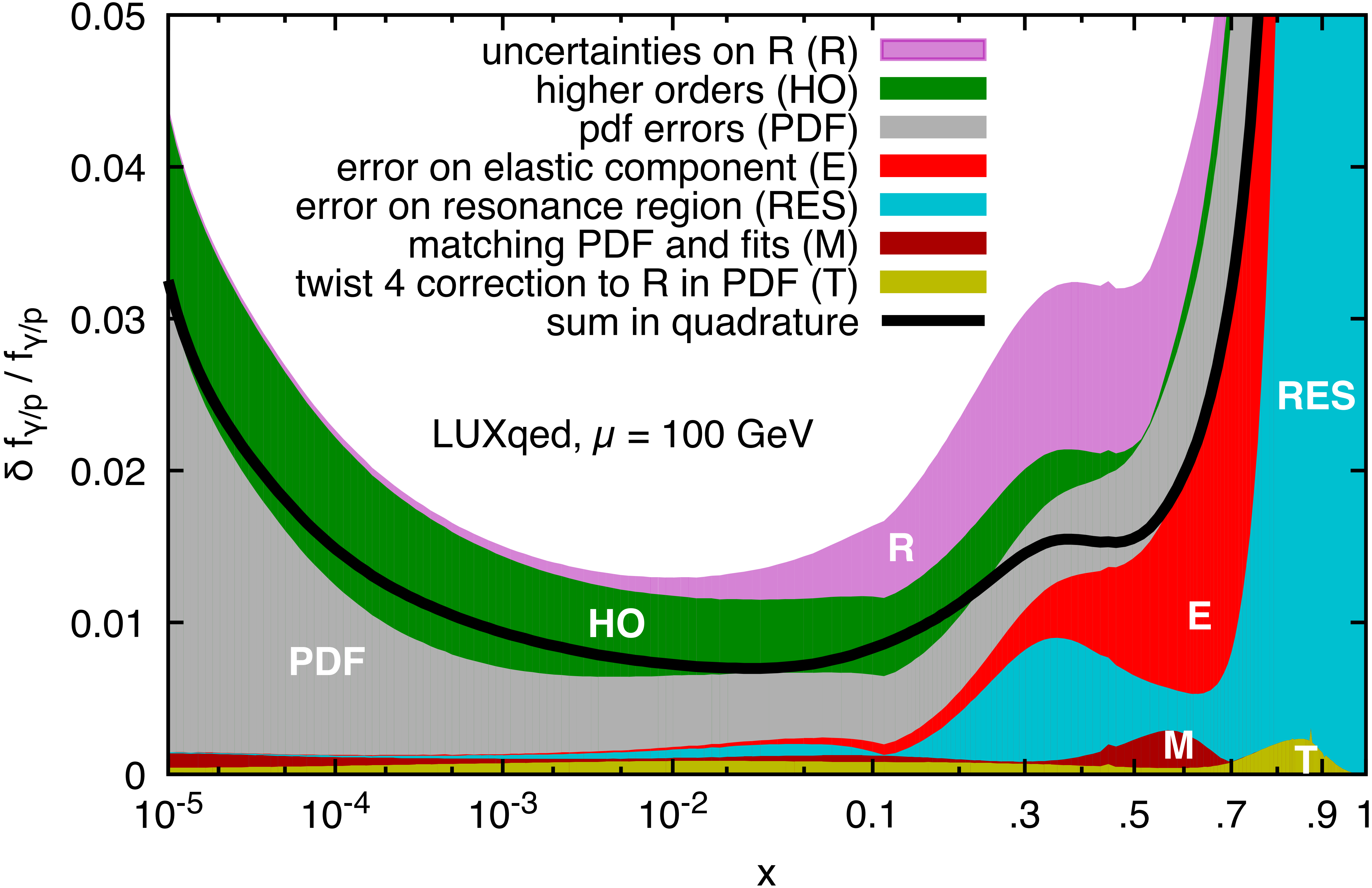
$$F_2^{\mathrm{el}} = \frac{[G_E(Q^2)]^2 + [G_M(Q^2)]^2\tau}{1+\tau}\delta(1-x)\,,$$

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

SEPARATE CONTRIBUTIONS TO PHOTON PDF



BREAKDOWN OF UNCERTAINTIES



γγ luminosity