The LUX approach to the photon PDF

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- The Master Equation
- The LUX PDF set
- Structure functions data
- Elastic data
- Uncertainties
- Some applications
- LUX and Hoppet resources
- Conclusions

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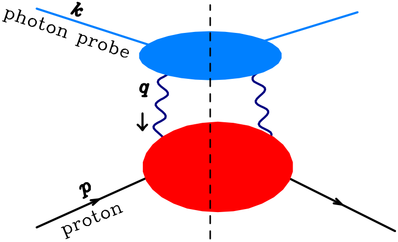
The Master Equation



$$\sigma = \int \frac{\mathrm{d}^4 q}{(2\pi)^4} \frac{e^4_{\mathrm{phys}}(q^2)}{q^4}$$
$$\times \langle k|\tilde{J}_p{}^{\mu}(-q) J_p^{\nu}(0)|k\rangle$$
$$\times \langle p|\tilde{J}_\mu(q) J_\nu(0)|p\rangle$$

Kinematics constraints:

$$Q^2 = -q^2 > 0,$$
$$0 < x_{\mathrm{bj}} = Q^2/(2p\cdot q) \leq 1.$$

- Same kinematic restrictions as in DIS.
- $\frac{1}{4\pi}\langle p|\tilde{J}_\mu(q) J_\nu(0)|p\rangle = -g_{\mu\nu} F_1(Q^2, x_{\mathrm{bj}}) + \frac{p^\mu p^\nu}{p\cdot q} F_2(Q^2, x_{\mathrm{bj}}) + \ldots$
  (Notice: full F_1 and F_2, not only inelastic)
- Photon induced process can be given in terms of F_1, F_2
- Hence: the photon PDF must be calculable in terms of F_1, F_2.

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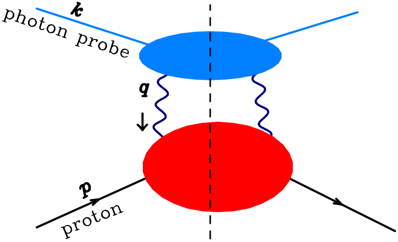

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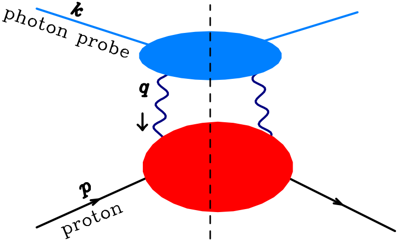

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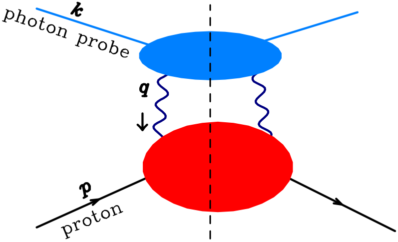

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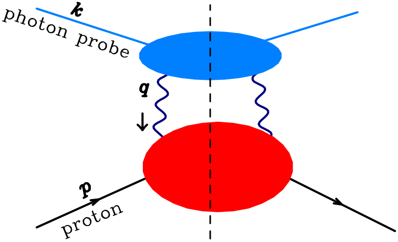

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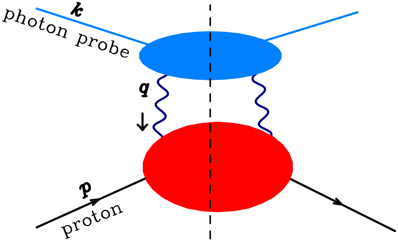

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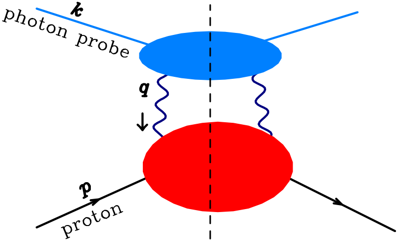

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- Take a BSM interaction of the form $\frac{e}{\Lambda}\bar{l}[\gamma^\mu, \gamma^\nu]LF_{\mu\nu} + \mathrm{cc}$, l massless, L massive with mass M, both neutral.
- Compute the cross section with the Master Formula
- Compute the cross section with the Parton Model formula
- Extract f_γ by identifying the two cross sections.

We obtain in the $\overline{\mathrm{MS}}$ scheme at NLO:

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$$xf_{\gamma/p}(x,\mu^2) = \frac{1}{2\pi}\int_x^1 \frac{dz}{z}\Bigg\{ -\overbrace{\alpha(\mu^2) z^2 F_2\left(\frac{x}{z},\mu^2\right)}^{\overline{\rm MS}\ \text{correction}}$$

$$+\underbrace{\int_{\frac{x^2 m_p^2}{1-z}}^{\overbrace{\frac{\mu^2}{1-z}}^{\overline{\rm MS}}} \frac{dQ^2}{Q^2}}_{\mathcal{O}(\log\frac{\mu^2}{m_p^2})} \frac{\alpha^2(Q^2)}{\alpha(\mu^2)}\left[\left((1+(1-z)^2)+\frac{2x^2m_p^2}{Q^2}\right)F_2(x/z,Q^2) - z^2 F_L\left(\frac{x}{z},Q^2\right)\right]\Bigg\}.$$

- $f_\gamma \approx \alpha \log\frac{\mu^2}{m_p^2} \approx \alpha/\alpha_s$ relative to $f_{u/d}$ ($\alpha_s(\mu^2) \approx 1/\log\frac{\mu^2}{\Lambda^2}$).
- $Q^2 \approx m_p^2$ region formally of order α, i.e. NLO (as $\overline{\rm MS}$ term).
- Straightforward to improve at NNLO in α_s (Master Equation is exact, compute the parton model process at NNLO)
- Also accurate at $(\alpha/\alpha_s)^2$, provided that $\alpha(Q^2)$ and F_2 include leading log electromagnetic evolution.
- Valid at all μ's: MUST match evolution accuracy with one extra α_s. Agrees with De FLorian, Sborlini, Rodrigo $\alpha\alpha_s$ splitting functions, arXiv:1512.00612.

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Use:

Ideal use:

- Get $F_{2/L}$ at low Q^2 from available data.
- PDF global fit, including EM evolution, with the photon density constrained by the previous equation, $F_{2/L}$ taken from data at low Q^2 and computed from the PDF's at high Q^2

Much can be done without performing a dedicated global fit. However, if we aim at NLO accuracy:

- Low Q^2 region cannot be neglected.
- $(\alpha/\alpha_s)^2$ terms arising from the evolution of QED coupling cannot be neglected $(\alpha(m_\mu^2))/\alpha(M_Z^2) \approx 0.94)$
- $(\alpha/\alpha_s)^2$ terms arising from the QED evolution of the quarks are small, just do something minimal to account for them.

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Ideal use:

- Get $F_{2/L}$ at low Q^2 from available data.
- PDF global fit, including EM evolution, with the photon density constrained by the previous equation, $F_{2/L}$ taken from data at low Q^2 and computed from the PDF's at high Q^2

Much can be done without performing a dedicated global fit. However, if we aim at NLO accuracy:

- Low Q^2 region cannot be neglected.
- $(\alpha/\alpha_s)^2$ terms arising from the evolution of QED coupling cannot be neglected $(\alpha(m_\mu^2))/\alpha(M_Z^2) \approx 0.94)$
- $(\alpha/\alpha_s)^2$ terms arising from the QED evolution of the quarks are small, just do something minimal to account for them.

The LUX PDF set

- Start from a standard set (e.g. PDF4LHC15_nnlo_100);
- Compute the photon PDF at $\mu = 100\,\mathrm{GeV}$, with the low Q^2 component determined from A1, CLAS and Hermes GD11-P fits, and the high Q^2 part determined from the input PDF with standard NNLO coefficient functions.
- Evolve down to 10 GeV, including QED evolution only for splitting processes that affect the photon: $P_{\gamma q}$, $P_{\gamma g}$, $P_{\gamma\gamma}$ (with $\alpha\alpha_s$ terms included).
- Fix the momentum sum rule by rescaling the gluon (a factor of 0.99299 is needed).
- Evolve up including full QED evolution (with $\alpha\alpha_s$ terms included).

This procedure is such that the structure functions at a scale of 10 GeV, where they are strongly data constrained, remain consistent with the new pdf set, while the $(\alpha/\alpha_s)^2$ due to photon radiation are included in the quark distributions at high scale.

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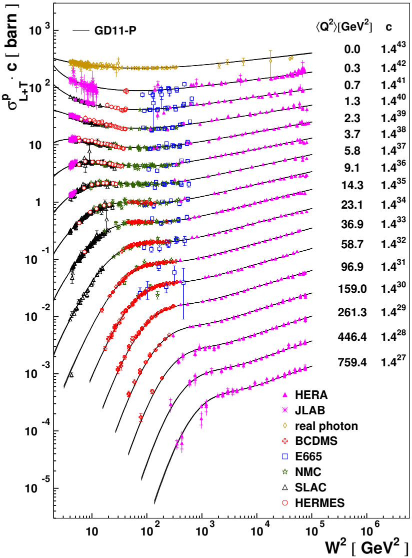

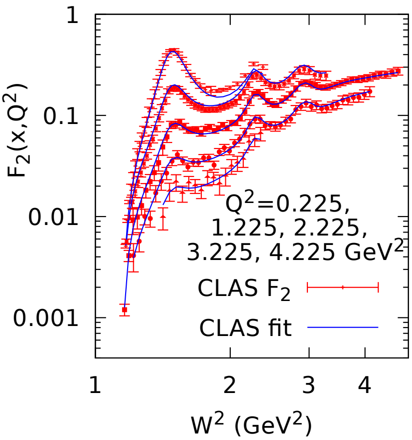

Fitted data from $Q^2 = 0.225$ to 4.725 in steps of $0.05\,\mathrm{GeV}^2$.

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

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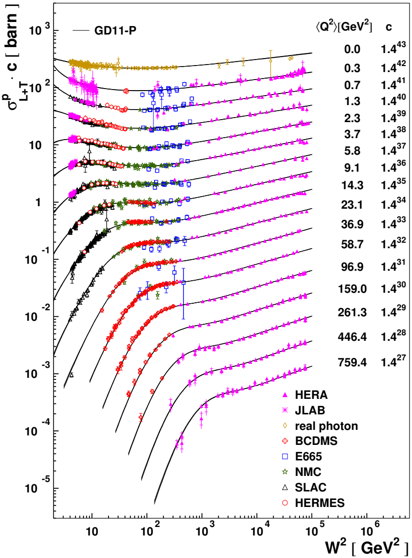

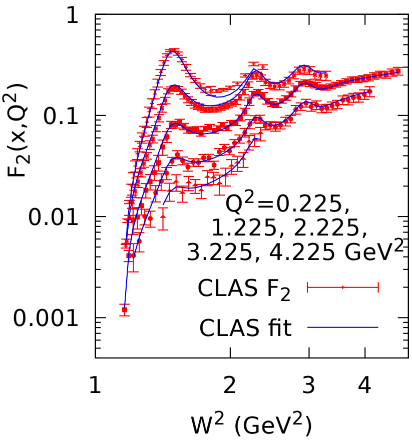

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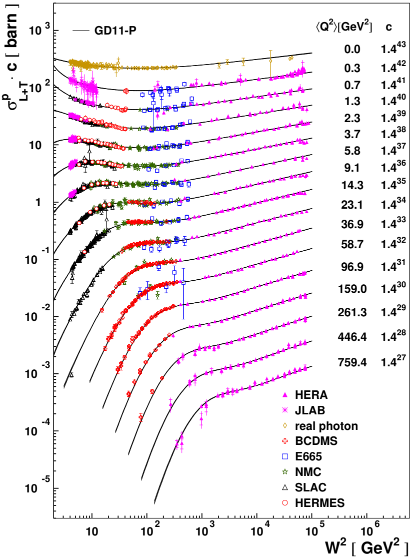

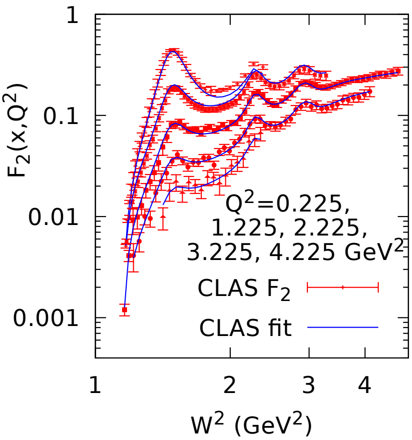

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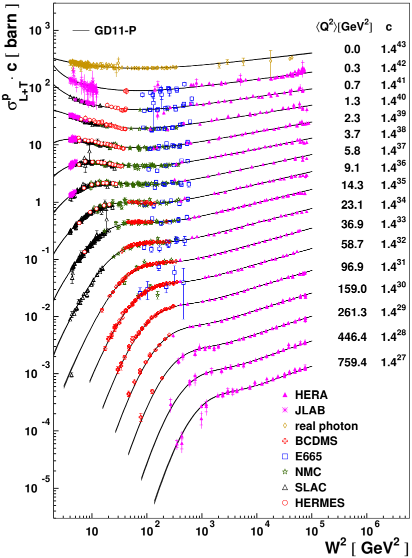

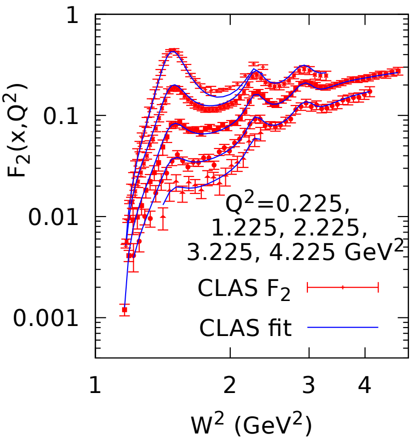

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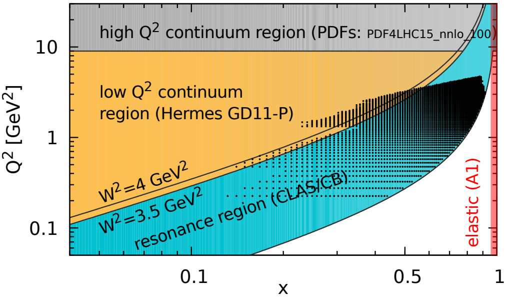
- Low Q^2 continuum essentially covered by data.
- F_2 and F_L must vanish as Q^2 and Q^4 at constant W (by analiticity of $W^{\mu\nu}$).



Also:

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

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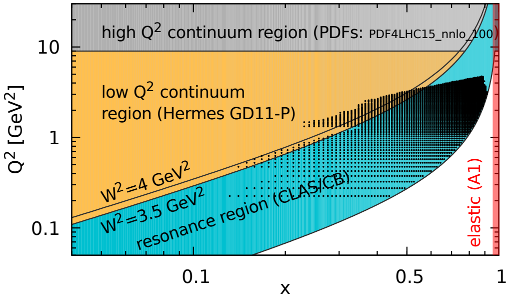

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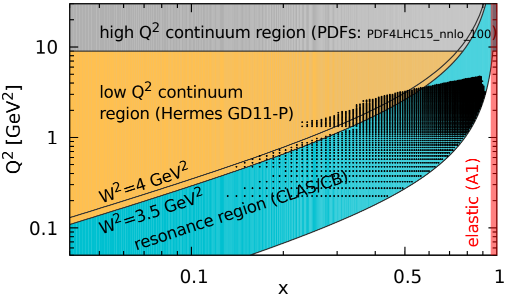

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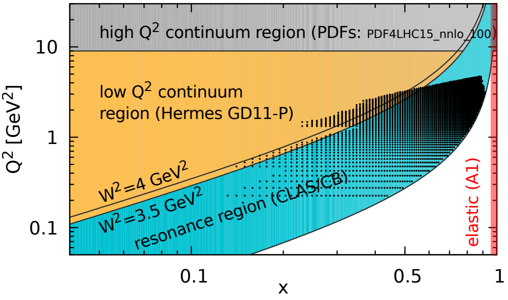

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$$F_2^{\rm el} = \frac{G_E^2(Q^2) + G_M^2(Q^2)\tau}{1+\tau}\,\delta(1-x),$$
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with $\tau = Q^2/(4m_p^2)$. In the dipole approximation

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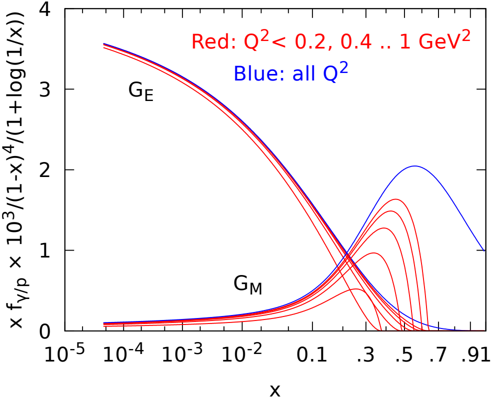

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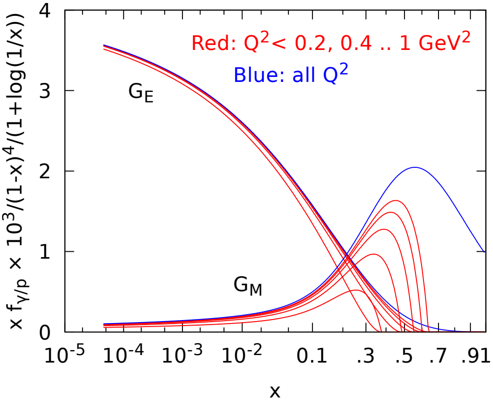

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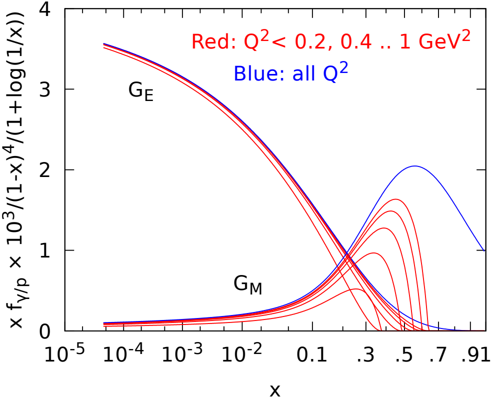

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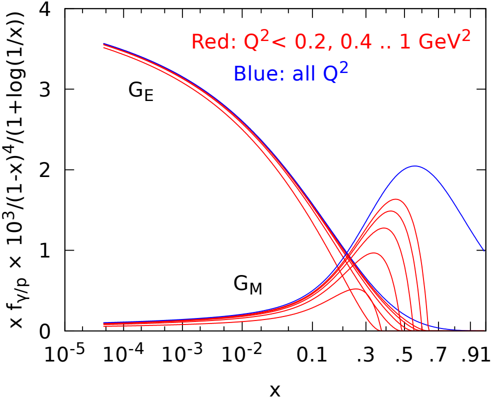

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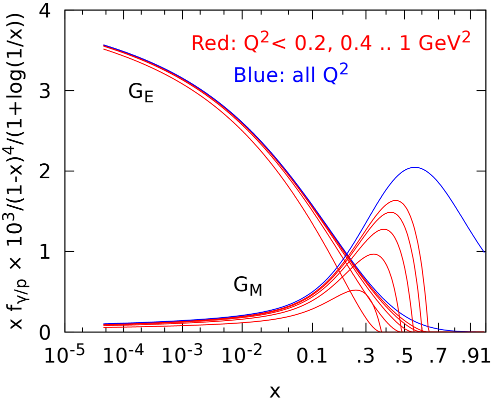

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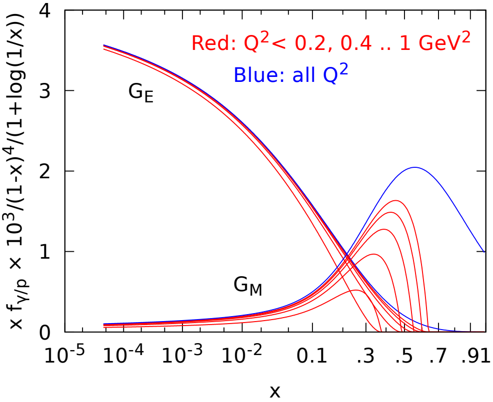

Elastic Data, A1 experiment and World data

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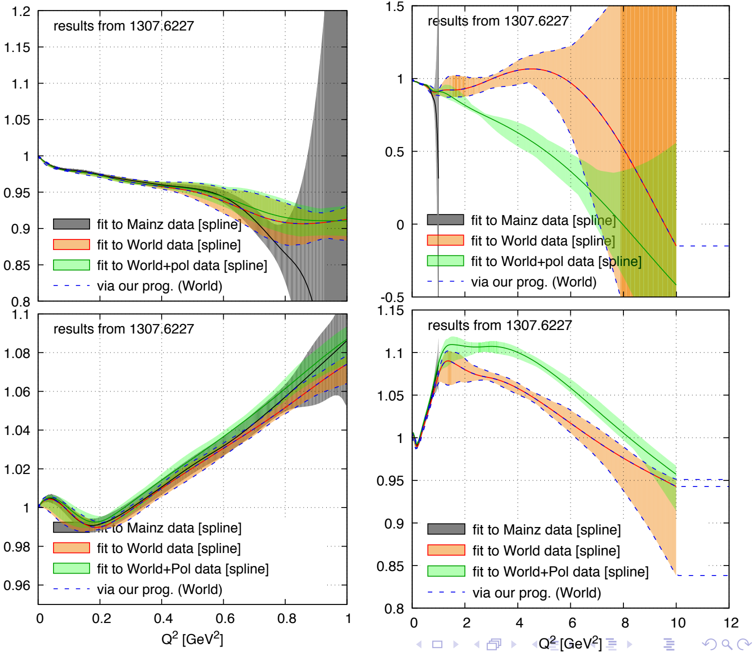
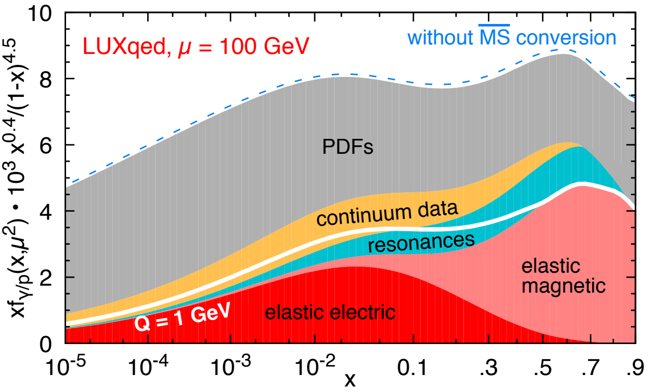


Contributions to f_γ:



- $Q^2 > 9\,GeV^2$, computed from standard PDF sets
- Important elastic component. Magnetic prevails for $x > 0.2$.
- Continuum and resonance contributions not negligible
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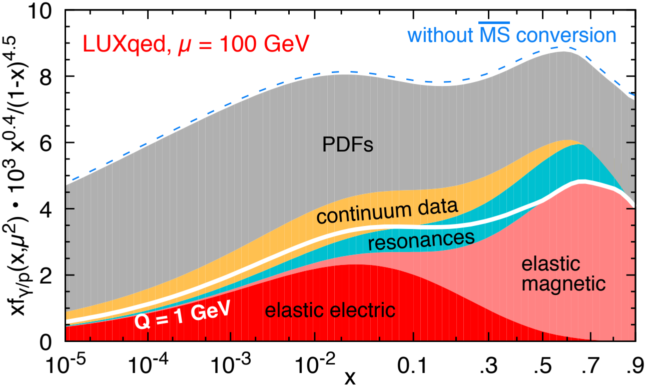

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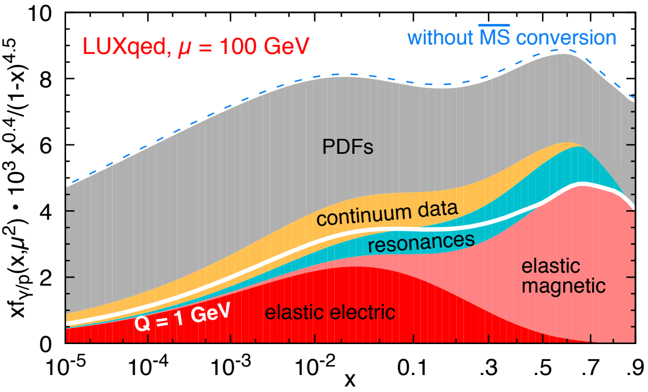

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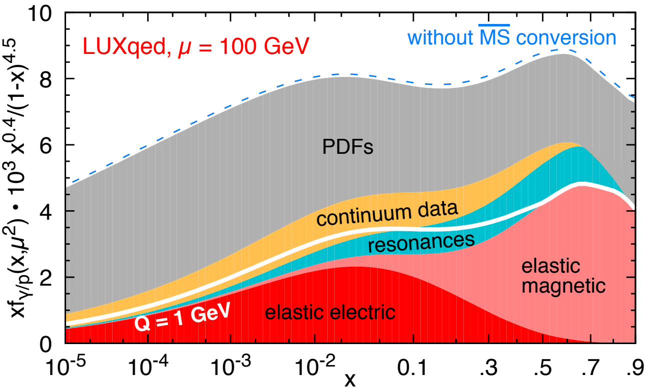

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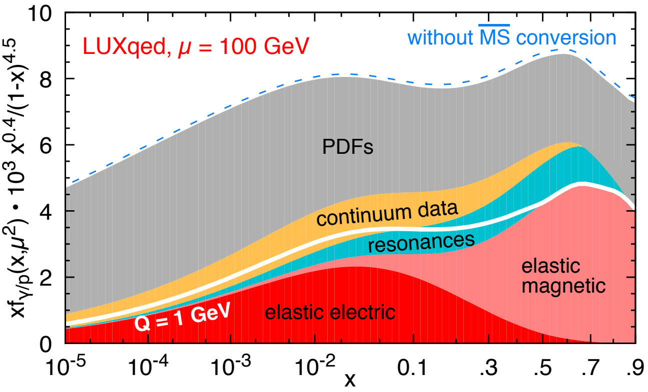
- Very important contribution from $Q^2 < 1\, GeV^2$.

Contributions to f_γ:



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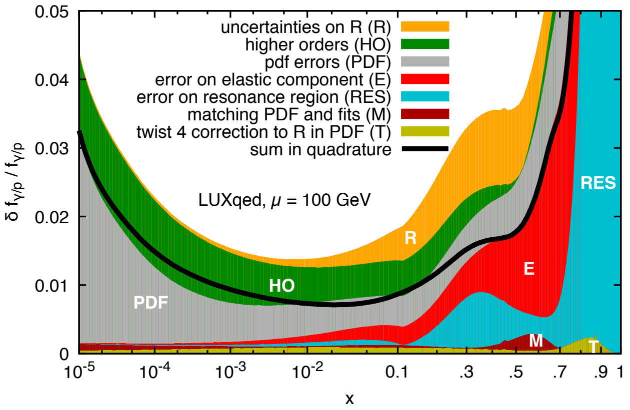
Uncertainties



- At small x, higher order effects and PDF's dominate the error.
- At large x, elastic and resonant region dominant.
- Total uncertainty at the percent level.
  Further improvements possible!

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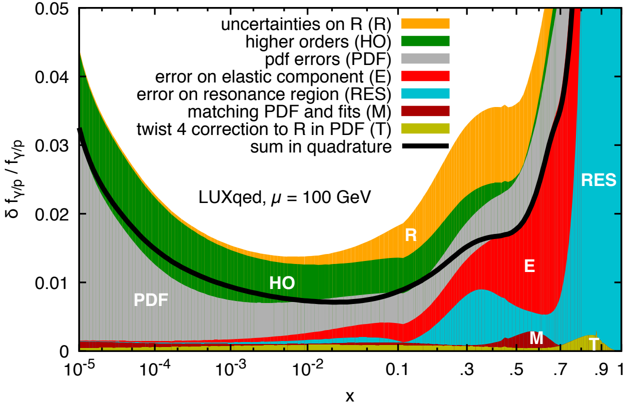

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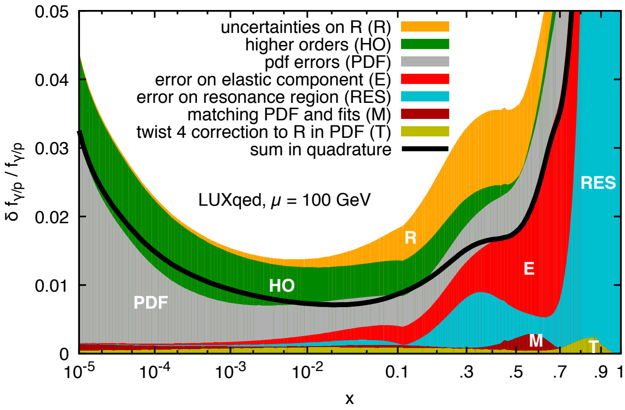

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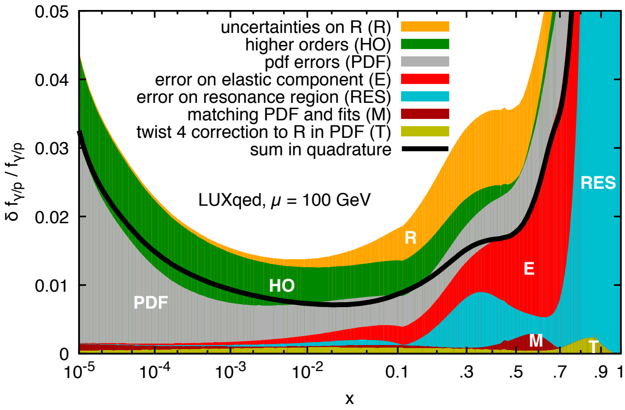

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Uncertainties included in LUX

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).
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- 106: Start using PDF's from $Q^2 = 5$ rather than $9\,\mathrm{GeV}^2$.
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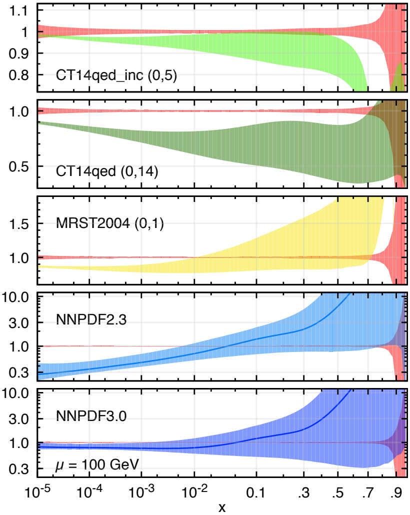
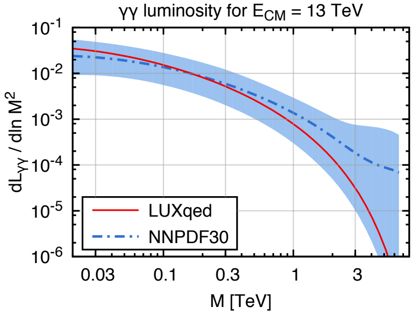




Since it only relies upon knowledge of the quark distributions, the LUX method achieves by far better precision than other methods.

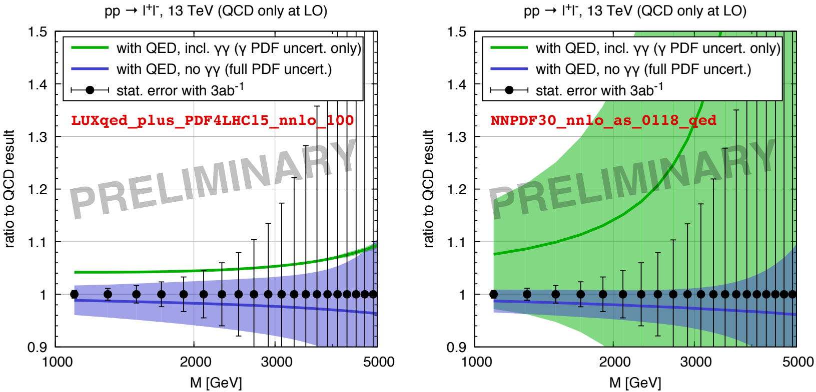
Approaches that use some lepton scattering information (in particular `CT14qed_inc`) do achieve better precision (note different y axis in panel).

APPLICATION TO HIGGS PHYSICS

$pp \to H W^+ (\to l^+ \nu) + X$ 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)

di-lepton spectrum



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

RESOURCES

- LUXqed_plus_PDF4LHC15_nnlo_100 set available from LHAPDF
- 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)

Conclusions

- Photon PDF can be extracted with great precision from available knowledge of proton structure function and form factors.
- The needed low Q^2 data is available thanks to extensive low and intermediate energy Nuclear Physics studies.
- Our study aimed at NLO precision including terms suppressed by one power of α_s or by a power of α/α_s relative to the leading term. This leads to precisions at the percent level.
- The study of structure functions and form factors at low energy is still ongoing in the Nuclear Physics Community (further progress will come).
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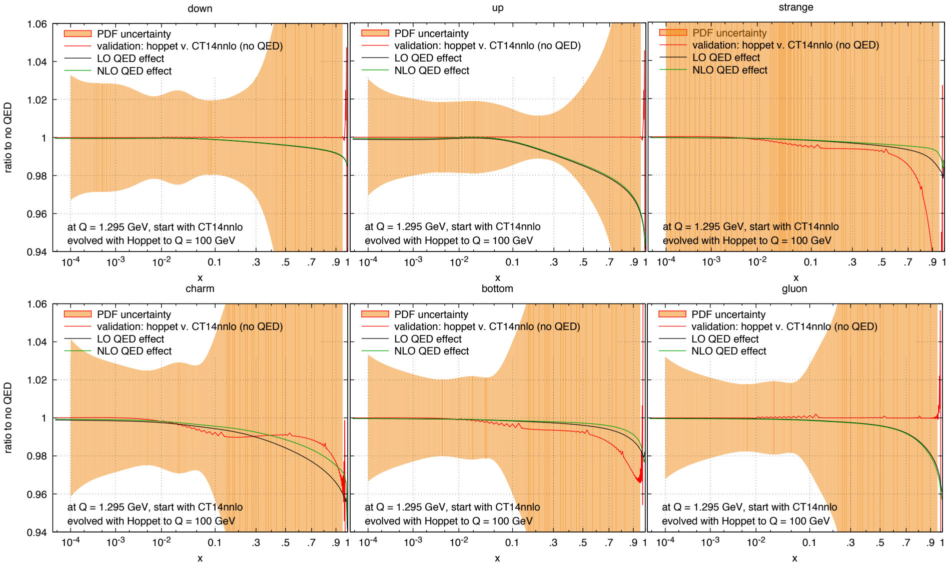
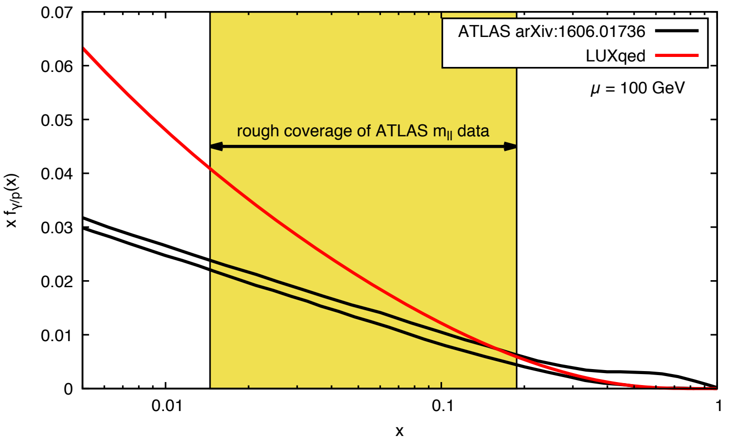
EXTRA SLIDES

Impact of QED evolution



ratio of ATLAS photon (1606.01736) to LUXqed



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