The Photon Content of the Neutron

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Motivations

The neutron structure

- We have entered the precision era for the proton structure [2203.13923].
- How about the neutron?
- Isospin-symmetry to relate the neutron's quark-gluon PDFs.
- To what precision this isospin symmetry is preserved?
- Many isospin symmetry violation sources: QED interaction, nuclear effects.

Phenomenological relevance

- Nucleus scattering
- Neutrino-nucleus scattering: W production
- Photon initiated processes: photonic Axion-like particle production

Recall the proton's photon PDFs

The first generation

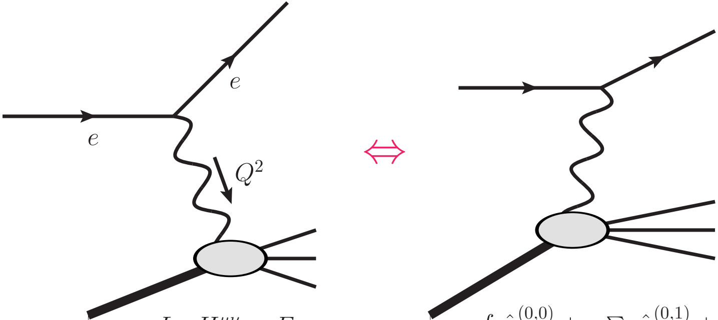
- MRST2004QED [0411040] models the photon PDF with an effective mass scale.
- NNPDF23QED [1308.0598] and NNPDF3.0QED [1410.8849] constrains photon PDF with the LHC Drell-Yan data, $q\bar{q}, \gamma\gamma \to \ell^+\ell^-$
- CT14qed_inc fits the inelastic ZEUS $ep \to e\gamma + X$ data [1509.02905], and include elastic component as well.

The second generation

- LUXqed directly takes the structure functions $F_{2,L}(x, Q^2)$ to constrain photon PDF uncertainty down to percent level [1607.04266,1708.01256]
- NNPDF3.1luxqed [1712.07053] initializes photon PDF with LUX formula at $\mu_0 = 100$ GeV (a high scale) and evolves DGLAP equation both upwardly and downwardly.
- MMHT2015qed [1907.02750] initializes photon at red $\mu_0 = 1$ GeV (a low scale) and evolve DGLAP upwardly. It's updated as MSHT20qed by the recent fit [2111.05357].
- CT18qed [2305.10733] incorporates the LUX formalism with the CT18 [1912.10053] global analysis.

The LUX formalism

- The DIS process: $ep \to e + X$



$\sigma \sim L_{\mu\nu} H^{\mu\nu} \sim F_{2,L}$ $\quad\quad$ $\sigma \sim f_\gamma \hat{\sigma}^{(0,0)}_{\ell\gamma} + \alpha \sum_j \hat{\sigma}^{(0,1)}_{\ell j} + \cdots$

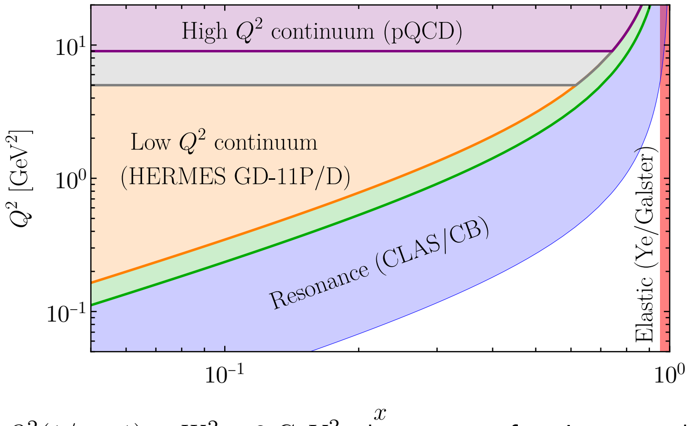
- Matching these two approaches leads to the LUX master formula [1607.04266,1708.01256]

$$x\gamma(x,\mu^2) = \frac{1}{2\pi\alpha(\mu^2)} \int_x^1 \frac{\mathrm{d}z}{z} \left\{ \int_{\frac{x^2 m_p^2}{1-z}}^{\frac{\mu^2}{1-z}} \frac{\mathrm{d}Q^2}{Q^2} \alpha^2_{\mathrm{ph}}(-Q^2) \left[\left(z p_{\gamma q}(z) + \frac{2x^2 m_q^2}{Q^2} \right) \times F_2(x/z, Q^2) - z^2 F_L(x/z, Q^2) \right] - \alpha^2(\mu^2) z^2 F_2(x/z, \mu^2) \right\}.$$

The square bracket term corresponds to the "physical factorization" scheme, while the second term is referred as the "$\overline{\mathrm{MS}}$-conversion" term.

- The structure functions $F_{2,L}$ can be directly measured, or calculated through pQCD in the high-energy regime.

Breakup of (x, Q^2) plane



- In the resonance region $W^2 = m_p^2 + Q^2(1/x - 1) < W_{\rm lo}^2 = 3\ {\rm GeV}^2$, the structure functions are taken from CLAS [0301204] or Christy-Bosted [0712.3731] fits.
- In the low-Q^2 continuum region $W^2 > W_{\rm hi}^2 = 4\ {\rm GeV}^2$, the HERMES GD11-P [1103.5704] fits with ALLM [PLB1991] functional form.
- In the high-Q^2 region ($Q^2 > Q_{\rm PDF}^2$), $F_{2,L}$ are determined through pQCD.
- The elastic form factors are taken from A1 [1307.6227] or Ye [1707.09063] fits of world data.

All these ingredients can be applied to neutron as well.

Electromagnetic form factors

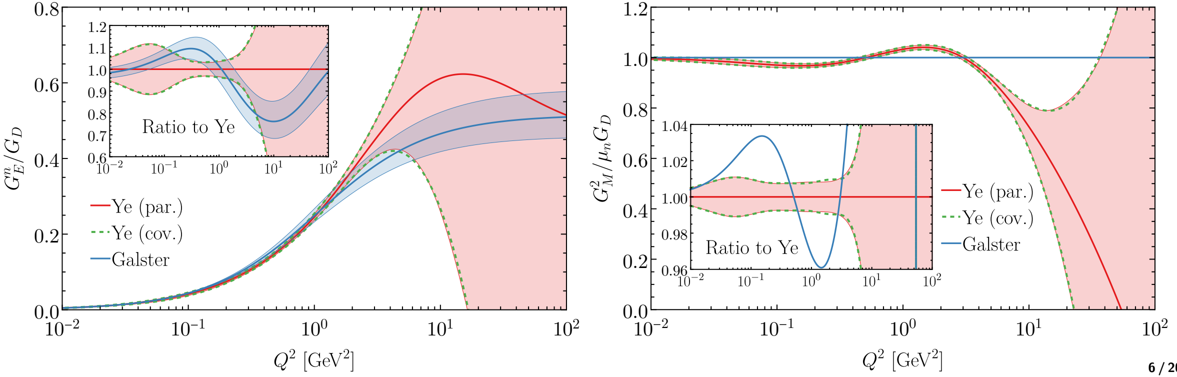
- Galster parameterization [NPB1971]

$$G_E^n(Q^2) = \frac{A\tau}{1+B\tau} G_D(Q^2), \;\; G_D(Q^2) = 1/(1+Q^2/\Lambda^2)^2,$$

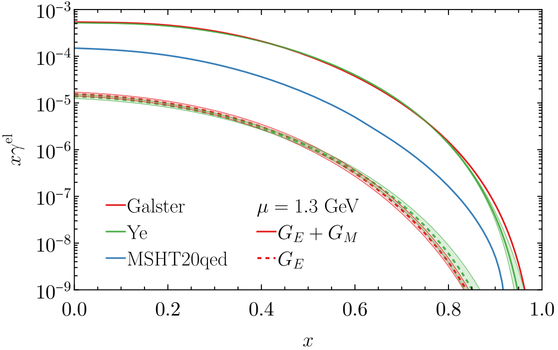
  where [Kelly, PRC2004]

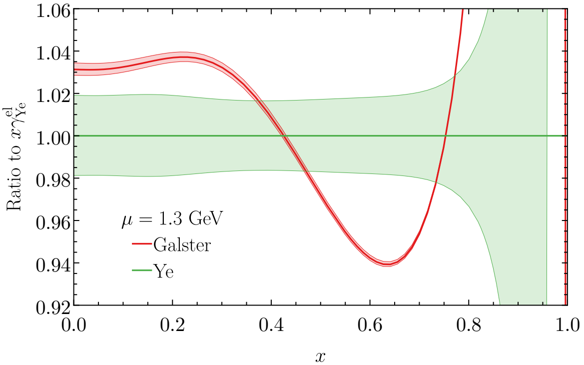
$$A = 1.70 \pm 0.04, \;\; B = 3.30 \pm 0.32$$

- Modern fit from world electron scattering data: Extracted from nuclei (e.g., D, He) [Ye et al., 1707.09063]



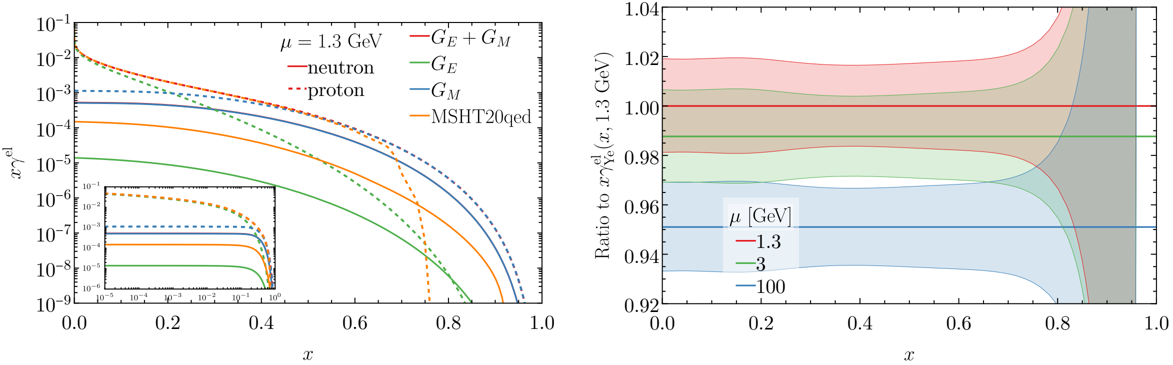
Elastic photon





- Neutron's elastic photon mainly comes from the magnetic form factor G_M
- Consistent with the zero electric charge
- MSHT20qed integrate elastic form factor up to 1 GeV and then evolve to high scale.
- We take the complete integration to $Q^2 \to \infty$, while scale dependence comes from the running coupling $\alpha(\mu^2)$.

In comparison proton's elastic photon



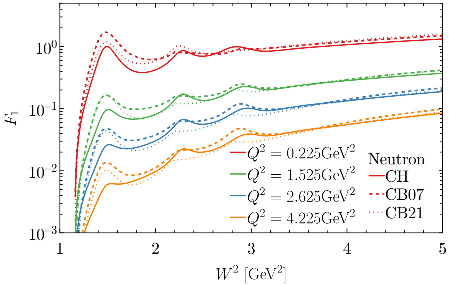
- In comparison, the proton's elastic photon is consistent with each other, except at large x due to the numerical interpolation issue.
- The proton's low-x elastic photon mainly comes from the G_E, while large-x from G_M.
- The elastic photon decrease with scale, due to $\alpha(\mu^2)$ running.

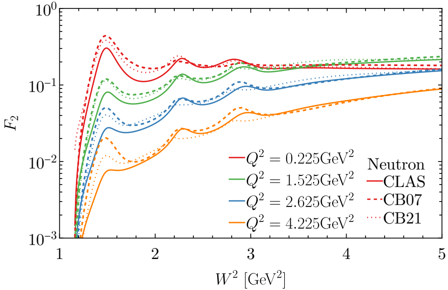
Neutron non-perturbative structure functions

Resonance:

CLAS [0301204]

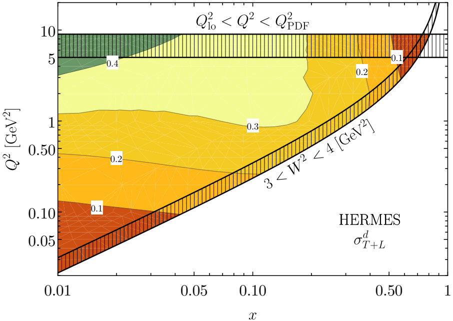
Christy-Bosted [0712.3731,0711.0159]

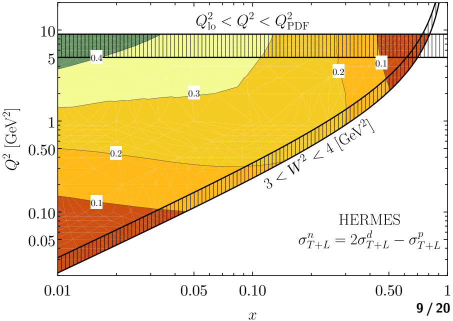




Low-Q^2 continuum:

HERMES [1103.5704]





A smooth transition

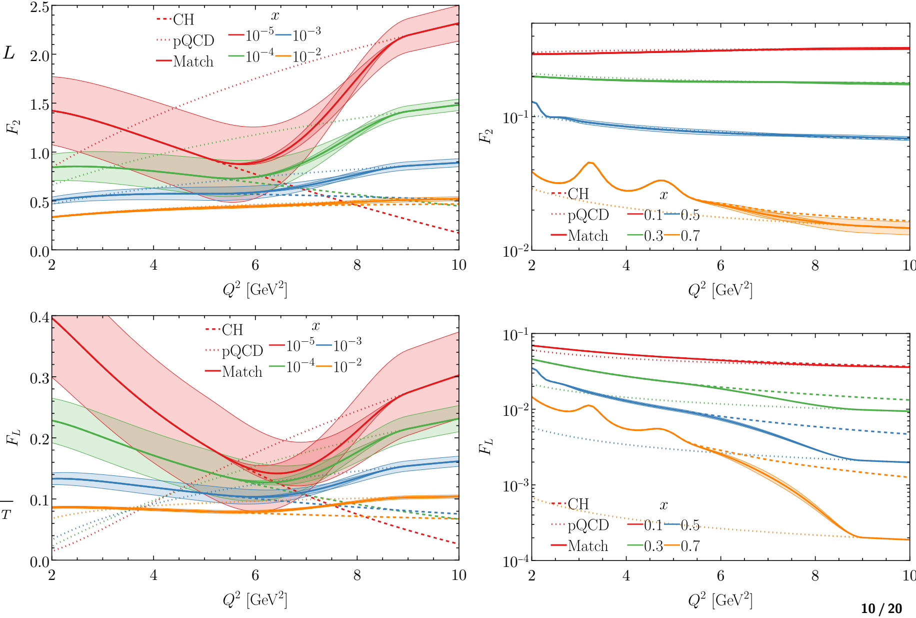
$$F_2 = \frac{1}{4\pi^2\alpha}\frac{Q^2(1-x)}{1+4x^2m^2/Q^2}\sigma_{T+L}$$

- At moderate x, HERMES can match pQCD very well.
- Large uncertainty for HERMES low-x extrapolation
- Extreme x transit to the resonance region $W^2 = Q^2(1/x-1)$

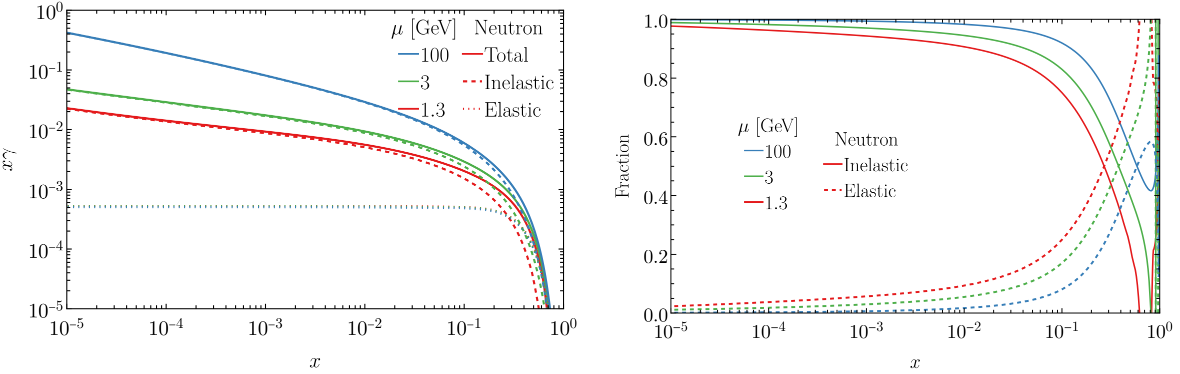
$$F_L = \left(1+\frac{4m^2x^2}{Q^2}\right)F_2\frac{R_{L/T}}{1+R_{L/T}}$$

$$R_{L/T} = R_{1998}(1\pm 50\%)$$

[9808028]

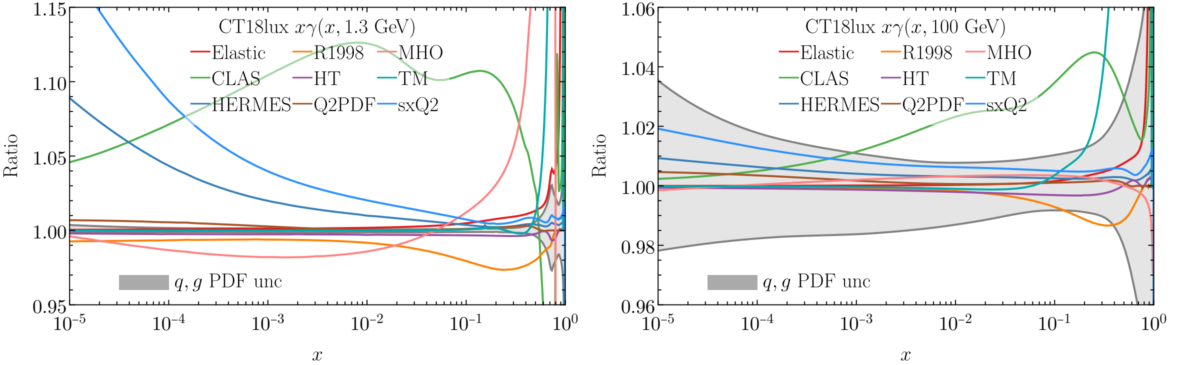


Inelastic photon



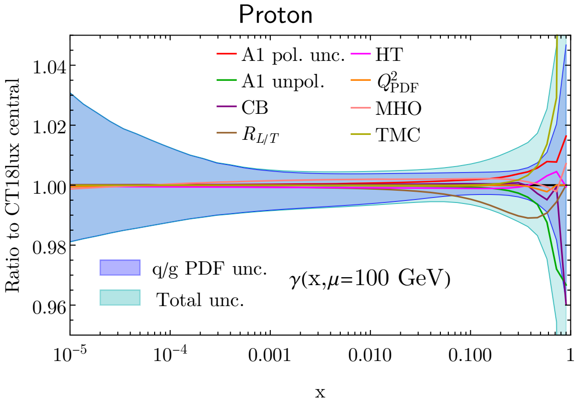
- The inelastic photon dominates.
- Elastic photon (mainly from G_M) only become relevant at very large $x(\gtrsim 0.2)$
- Inelastic photon evolves very fast

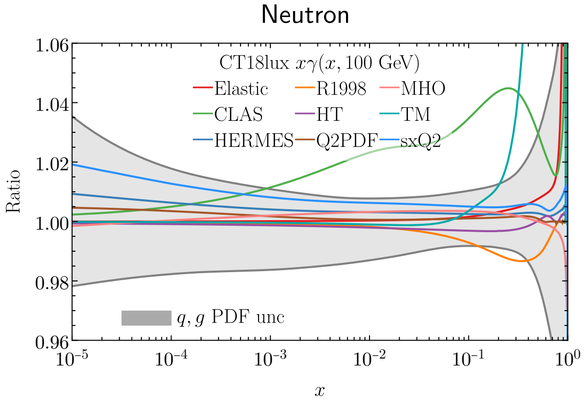
Non-perturbative uncertainties



- The resonance variation dominates at low Q^2
- The low-Q^2 non-perturbative uncertainty dies out with increasing scale, while pQCD (q, g PDF) uncertainty increase.
- Non-perturbative uncertainties remain at large x

In comparison with proton





- The proton's photon PDF uncertainty is about 1% level.
- The neutron's photon is $(2 \sim 4)\%$ in the moderate-x region.
- A significant improvement in comparison with the 1st generation of photon PDFs.

Isospin symmetry violation

Inspired by MSHT20qed

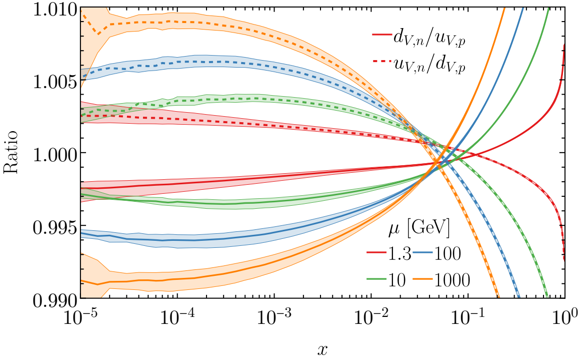
$$\varepsilon = \frac{\int \mathrm{d}x x(\gamma_p^{\mathrm{inel}}(x,\mu_0^2) - \gamma_n^{\mathrm{inel}}(x,\mu_0^2))}{\int \mathrm{d}x x\left(\frac{3}{4}u_{V,p}^{(\mathrm{QED})}(x,\mu_0^2) - 3d_{V,p}^{(\mathrm{QED})}(x,\mu_0^2)\right)}$$

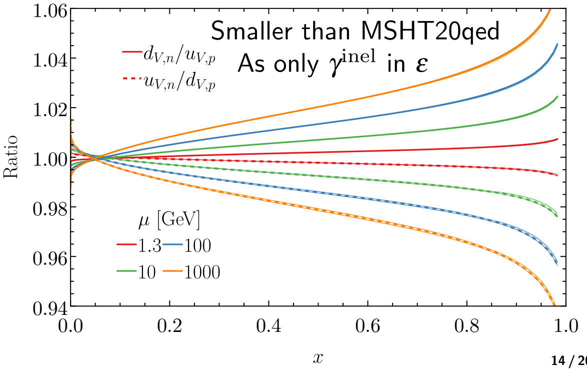
- Model the initial isospin violation with QED interaction

$$\Delta d_{V,n}(x,\mu_0^2) = d_{V,n}(x,\mu_0^2) - u_{V,p}(x,\mu_0^2) = \varepsilon\left(1 - \frac{e_d^2}{e_u^2}\right) u_{V,p}^{(\mathrm{QED})}(x,\mu_0^2),$$

$$\Delta u_{V,n}(x,\mu_0^2) = u_{V,n}(x,\mu_0^2) - d_{V,p}(x,\mu_0^2) = \varepsilon\left(1 - \frac{e_u^2}{e_d^2}\right) d_{V,p}^{(\mathrm{QED})}(x,\mu_0^2).$$

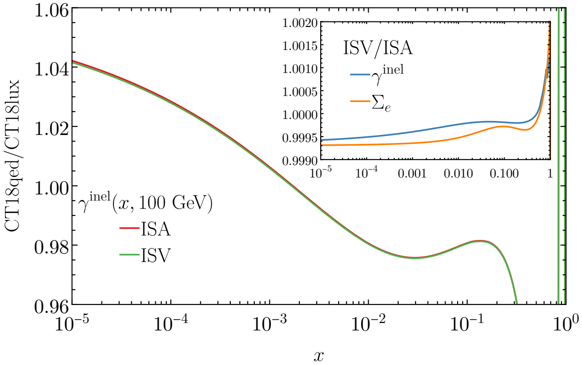
- The ε parameter can be self-consistently determined through sum rules.

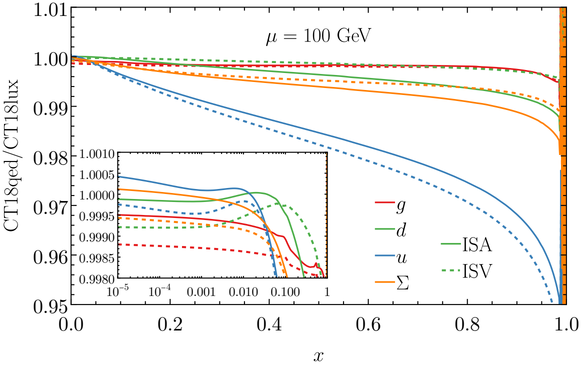




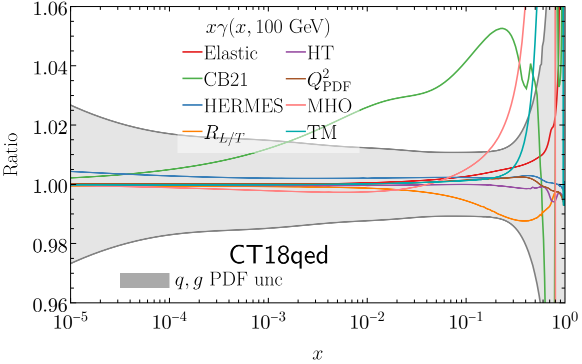
LUX vs DGLAP

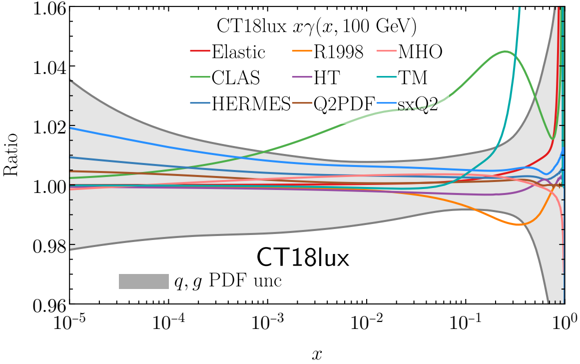
- CT18lux: directly calculate the photon PDF with the LUX formalism
- CT18qed: initialize the inelastic photon PDF with the LUX formalism at low scales, and evolve the $\mathrm{QED_{NLO}} \otimes \mathrm{QCD_{NNLO}}$ DGLAP equations up to high scales, similar to MMHT2015qed/MSHT20qed.
- CT18qed gives larger low-x photon due the evolution: $\int \mathrm{d}\log\mu^2 \frac{\alpha}{2\pi} \sum_q e_q^2 x P_{\gamma q} \otimes xq \sim F_2^{\mathrm{LO}} > F_2^{\mathrm{NNLO}}$
- Photon radiation take away the quark fraction at large x.





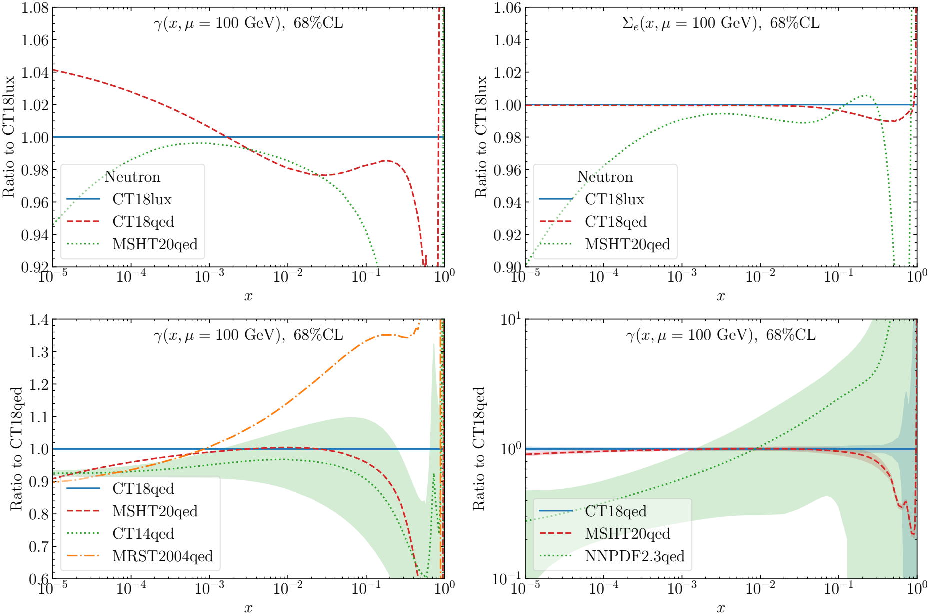
CT18qed uncertainties





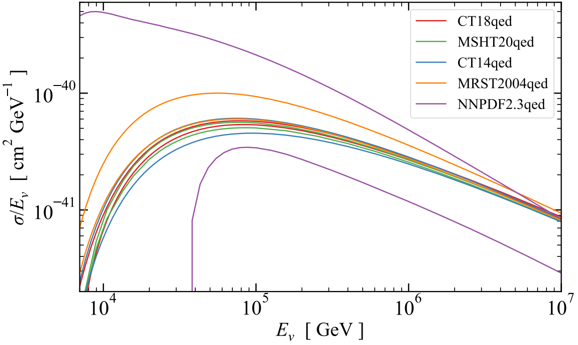
- Uncertainty consistent with the CT18lux
- The resonance uncertainty slightly increases, while the low-Q^2 non-perturbative uncertainty improves.
- The iso-spin symmetry violation effect on the photon PDF as well as the momentum sum rule is minimal.

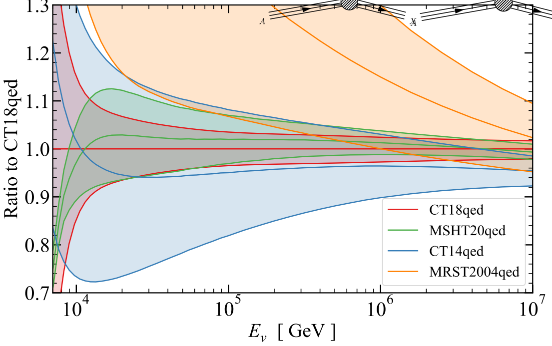
In comparison with other PDFs

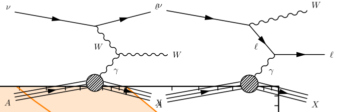


- Similarly to the proton case, CT18qed consistent with MSHT20qed at moderate x
- Low-x photon is driven by the charge weighted singlet Σ_e
- The large-x is driven by both Σ_e and non-perturbative treatment.
- Improvement with respect to 1st generation

W boson production in ν-A scattering

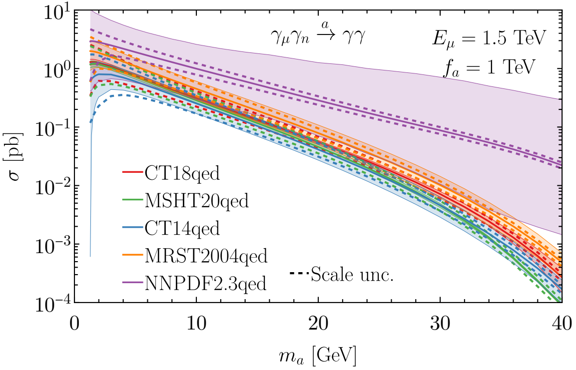


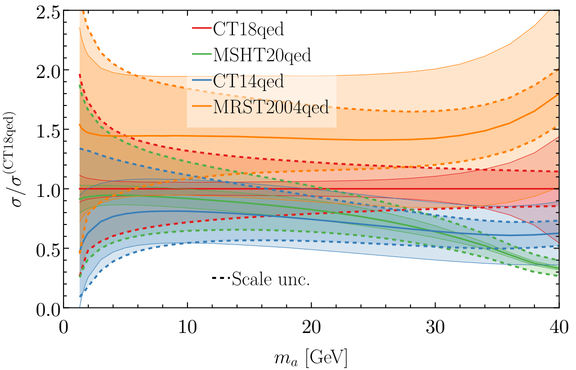




- W-boson production can be measured at in high-energy neutrino telescopes, e.g., IceCube, KM3NET, as well as collider, *i.e.*, FASER and future FPFs
- Our photon PDF directly contributes to the photon-initiated sub-process
- The photon PDF uncertainty is reduced to a percent level.

Axion-like particle production

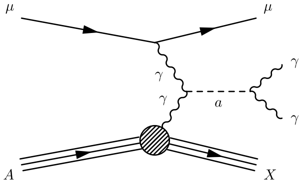




- A similar mechanism applies to photonic Axion-like particle production.
- For simplicity, we demonstrate it with the muon beam dump experiment

$$E_\mu = 1.5 \text{ TeV}, \ \sqrt{s} = \sqrt{2E_\mu m_N} = 53 \text{ GeV}.$$

- Many PDF features remain the same.



Conclusion

CT18qed is available: http://cteq-tea.gitlab.io/project/00pdfs/

- The neutron's photon content can be precisely determined by mapping the structure functions to the PDF, the LUXqed formalism.
- The elastic photon comes from the electromagnetic form factors.
- The inelastic component comes from inelastic structure functions.
- We divide the (x, Q^2) into three regions: the resonance, low-Q^2 continuum, and high-Q^2 pQCD regions.
- Similarly to the proton case, we explored two methods, LUX vs DGLAP, which give CT18lux and CT18qed, respectively. Both are consistent with each other.
- The photon PDF precision is significantly improved, with respect to the 1st generation PDFs.
- CT18qed is consistent with MHST20qed in the moderate-x region. Discrepancies were found in the low-x and large-x regions, driven by the corresponding charge-weighted singlet as well as non-perturbative treatments.
- Phenomenological implications explored with the W-boson production in the νA scattering and the photonic ALP production.
- Some future directions can be continued, such as nuclear corrections.