

The polarized photon distribution function

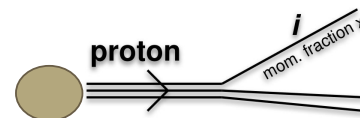
D. de Florian, L. Palma and G. F. Volonnino, *The polarized photon distribution function*, Eur. Phys. J. C **84** (2024) 905

Lucas Palma Conte

22 September 2026

PDFs

- Encodes information of structure of the nucleon as distributions in x .
- PDF are universal : the same for any process
- Fitted from data using *global fits*.
- PDFs appear in any perturbative calculation involving hadrons in the initial state.



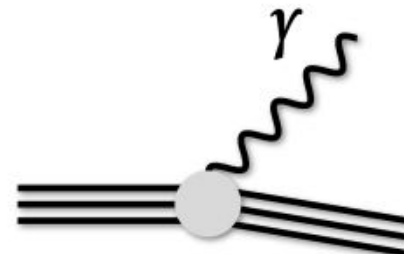
$$\sigma(ep \rightarrow eX) = \int_0^1 dz \sum_i f_i(z) \hat{\sigma}(eq_i \rightarrow eX)$$

↓ ↓

Parton Distribution Function Partonic cross section

Photon PDF

We usually hear about quark and gluon PDFs, but what about the ***photon PDF***?

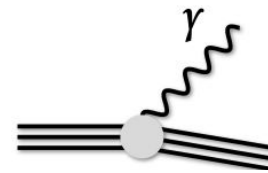


We focus on the polarized case:

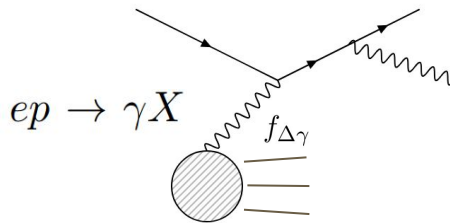
$$\Delta f_{\gamma} = f_{\gamma}^{+} - f_{\gamma}^{-}$$

Global fits are not very effective for extracting the photon PDF because it is much smaller than the quark and gluon PDFs.

Motivation



- No parameterization is available for the case of the polarized photon PDF
- QED corrections start to be important because many observables reached QCD corrections at NNLO, $\alpha_{QCD}^2 \sim \alpha_{QED} \sim \frac{1}{137}$. For this reason the PDF of the photon is a key density.
 - Calculate the evolution of polarized PDFs including QED corrections.
 - Some process are sensitive to these density, such as the productions of prompt photons in ep.

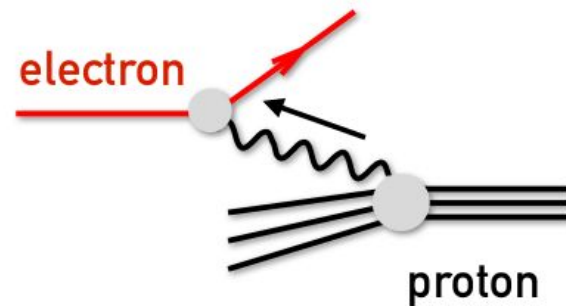


LUXqed approach: photon PDF

Extracting the photon distribution from DIS

A. Manohar, P. Nason, G. P. Salam, and G. Zanderighi, *Phys. Rev. Lett.* 117, 242002 (2016),
arXiv:1607.04266 [hep-ph]

- DIS is usually seen as a photon from electron probing proton structure, but can be viewed as an electron probing the photon PDF.
- The structure functions g_1 and g_2 encoded the information we need.



$$\frac{d^2\sigma_{LL}(x, Q^2)}{dx dQ^2} = \frac{8\pi\alpha^2 y}{Q^4} \times \left[\left(1 - \frac{y}{2} - \frac{y^2}{4}\gamma^2 \right) g_1(x, Q^2) - \frac{y}{2}\gamma^2 g_2(x, Q^2) \right]$$

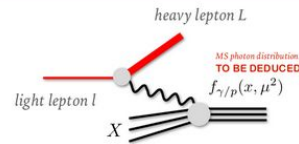
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1 Propose an auxiliary process sensitive to the photon PDF at LO

A heavy lepton L is produced in the scattering of a light lepton ℓ off the proton. At LO, the cross section is directly sensitive to the photon PDF.



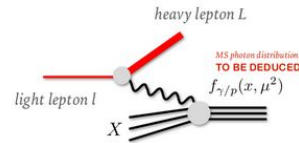
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2 Compute the process from DIS structure functions

Compute the process in terms of the structure functions g_1 and g_2 .

$$\sigma_{lp} \propto \int \frac{d^4 q}{(2\pi)^4} \frac{e^4(q^2)}{q^4} \overset{g_1, g_2}{W}^{\mu\nu}(q, p) L_{\mu\nu}(q, k)$$

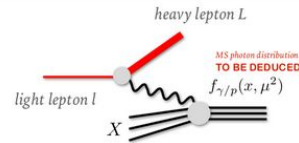
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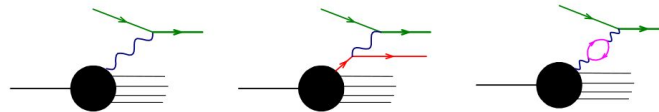
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3 Compute it in collinear factorization and match both descriptions

Compute the process using the factorization approach.

$$\sigma_{lp}(p) = \int dy \hat{\sigma}_{l\gamma}^{(0,0)}(yp) f_{\gamma}(y, \mu^2) + \frac{\alpha(\mu^2)}{2\pi} \sum_{j \in \{q, l\}} \int dy \hat{\sigma}_{lj}^{(0,1)}(yp) f_j(y, \mu^2) + \dots$$

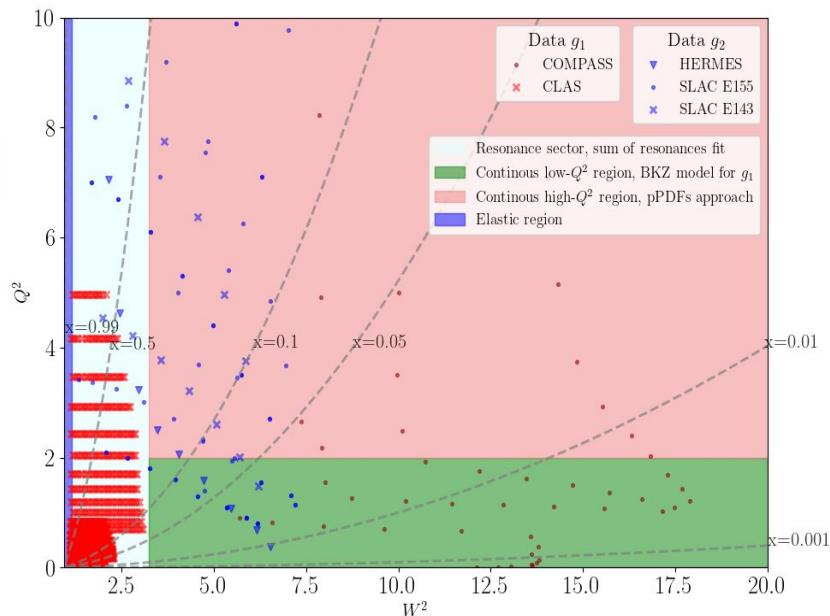


Match the two results

The polarized photon PDF

$$f_{\Delta\gamma}(x, \mu^2) = \frac{1}{2\pi\alpha(\mu^2)} \int \frac{dz}{z} \left\{ \int_{\frac{m_p^2 x^2}{(1-z)}}^{\frac{\mu^2}{1-z}} \frac{dQ^2}{Q^2} \alpha_{\text{ph}}^2(-Q^2) \right. \\ \left. \left[\left(4 - 2z - \frac{4m_p^2 x^2}{Q^2} \right) g_1(x/z, Q^2) - \left(\frac{8m_p^2 x^2}{zQ^2} \right) g_2(x/z, Q^2) \right] \right. \\ \left. + \Delta\gamma^{\overline{\text{MS}}}(x, \mu^2) \right.$$

- Must not depend in any parameter of the process.
- Necessary to know the structure functions in a wide range of parameter space.
- We divide the parameter space into regions according to the behavior of the structure functions:
Elastic, Resonance, Low-Q and High-Q.



Elastic region

$$W^2 < (m_p + m_{\pi^0})^2$$

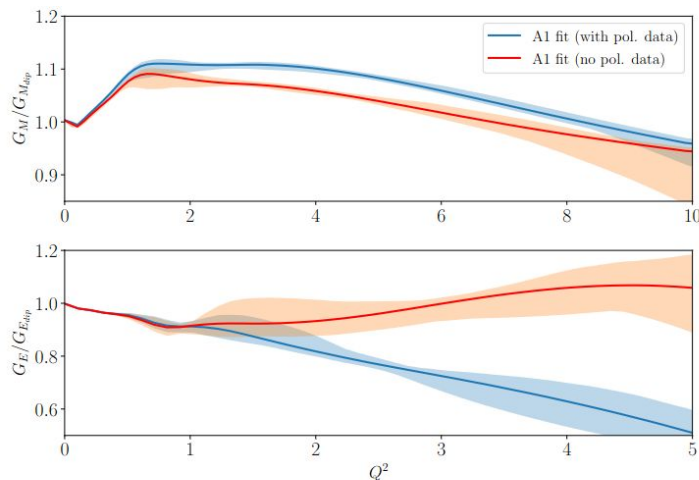
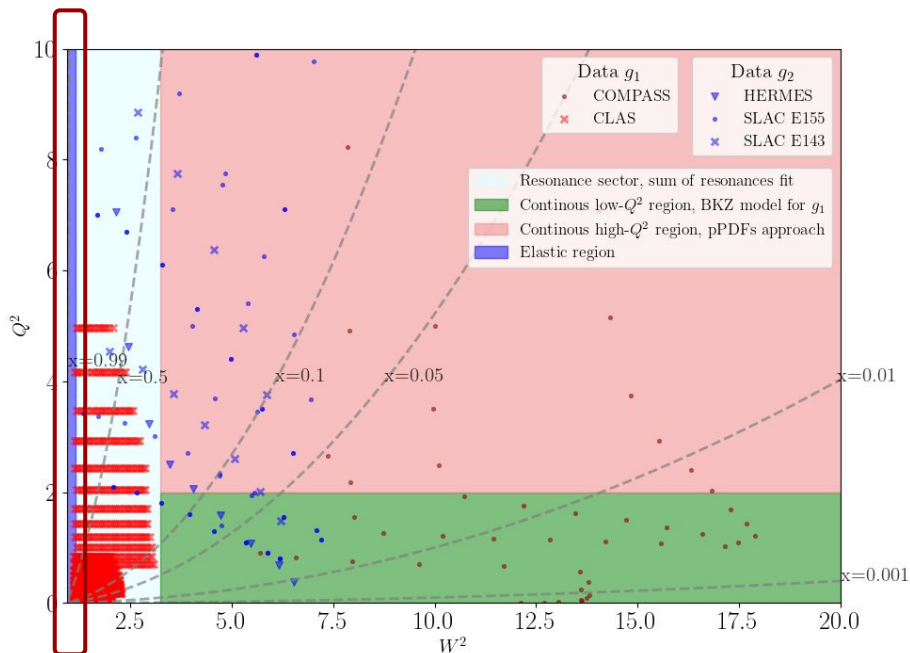
We can express g_1 and g_2 in terms of the Sachs form factors of the proton, GE and GM.

$$g_1^{\text{ela}}(x_{bj}, Q^2) = \frac{1}{2} \frac{G_E(Q^2) G_M(Q^2) + \tau G_M(Q^2)}{1 + \tau} \delta(x_{bj} - 1),$$

$$g_2^{\text{ela}}(x_{bj}, Q^2) = \frac{\tau}{2} \frac{G_E(Q^2) G_M(Q^2) - G_M(Q^2)}{1 + \tau} \delta(x_{bj} - 1),$$



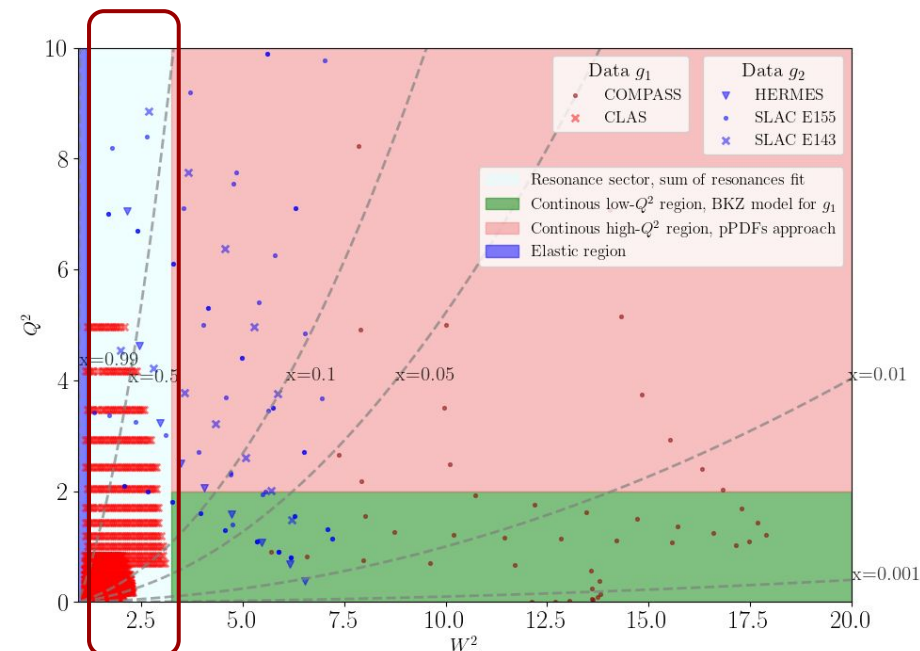
$$f_{\Delta\gamma}^{\text{el}} = \frac{1}{2\pi\alpha(\mu^2)} \int_{Q_{\text{min}}^2}^{\frac{\mu^2}{1-x}} \frac{dQ^2}{Q^2} \left\{ \alpha_{\text{ph}}^2(-Q^2) \left[\frac{G_E G_M}{1 + \tau} \left(2 - 2x - \frac{2m_p^2 x^2}{Q^2} \right) + \frac{\tau G_M^2}{1 + \tau} \left(2 - \frac{2m_p^2 x^2}{Q^2} \right) \right] \right. \\ \left. + \alpha^2(\mu^2) [2(1-x)] \frac{G_E G_M + \tau G_M^2}{1 + \tau} \right\}$$



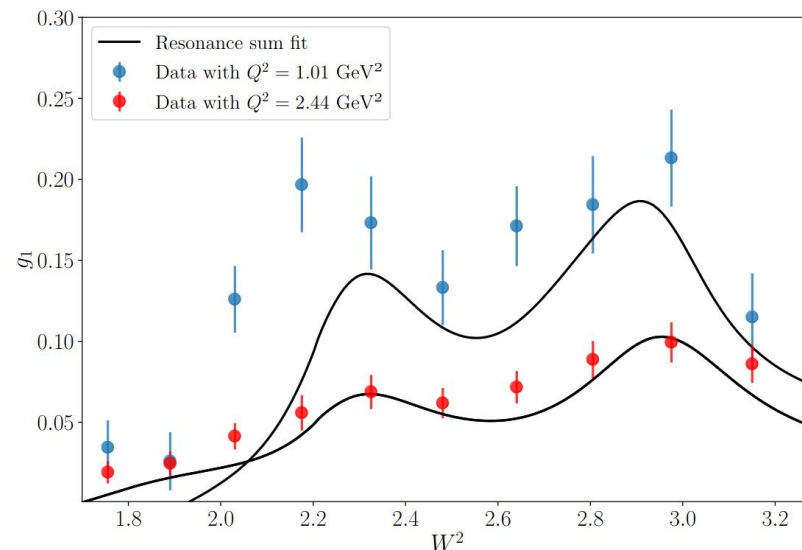
**J. C. Bernauer et al. (A1), Phys. Rev. C 90, 015206 (2014),
arXiv:1307.6227 [nucl-ex].**

Resonance region

$$(m_p + m_{\pi^0})^2 < W^2 < W_{\text{res}}^2 = 3.24 \text{ GeV}^2$$



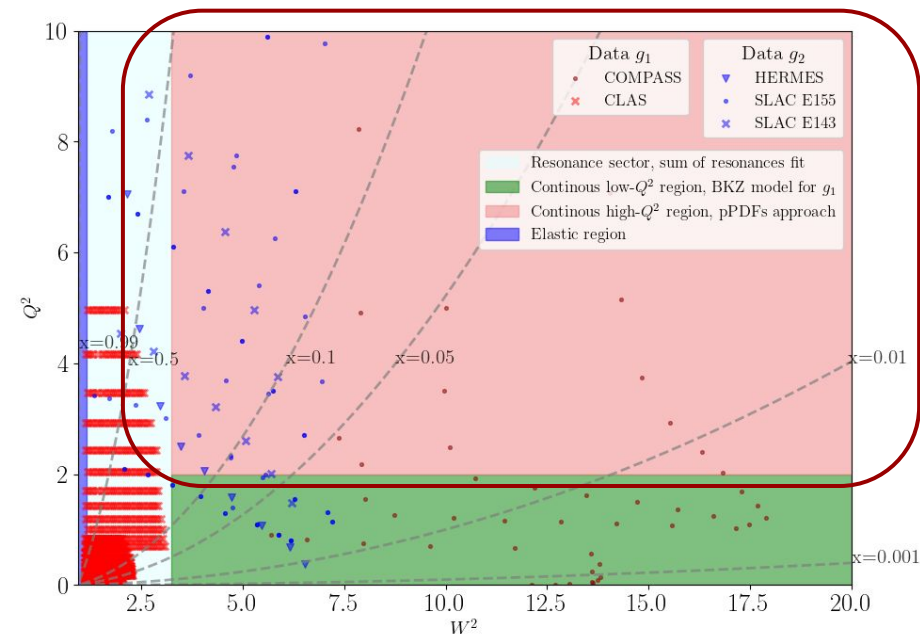
We use a model for both g₁ and g₂ based on a fit of experimental data.



Resonant contributions to polarized proton structure functions, A. N. Hiller Blin, V. I. Mokeev, and W. Melnitchouk, Phys. Rev. C 2023 107, 035202

High Q^2 region, Perturbative approach

$$Q^2 > Q_{per}^2 \text{ and } W^2 > W_{res}^2 = 3.24 \text{ GeV}^2$$

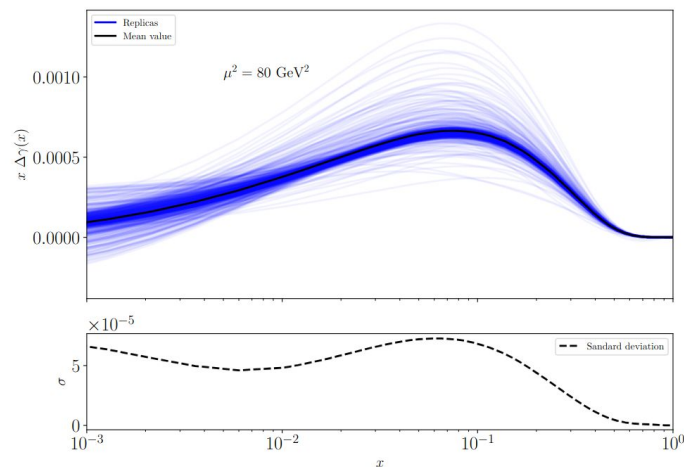


$$g_1(x, Q^2) = \sum_f \int_x^1 \frac{dz}{z} \Delta C_f^{g_1}(z, Q^2) \Delta f\left(\frac{x}{z}, Q^2\right)$$

Wandzura-Wilczek relation for g_2

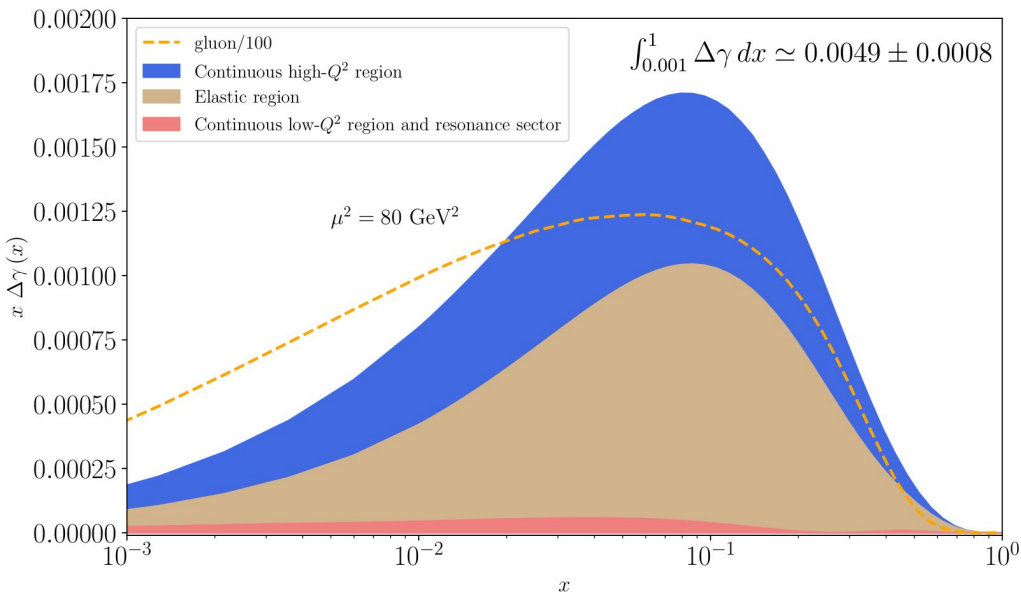
$$g_2^{WW}(x_{bj}) = -g_1(x_{bj}) + \int_{x_{bj}}^1 \frac{dy}{y} g_1(y)$$

BDSSV22 pPDF set

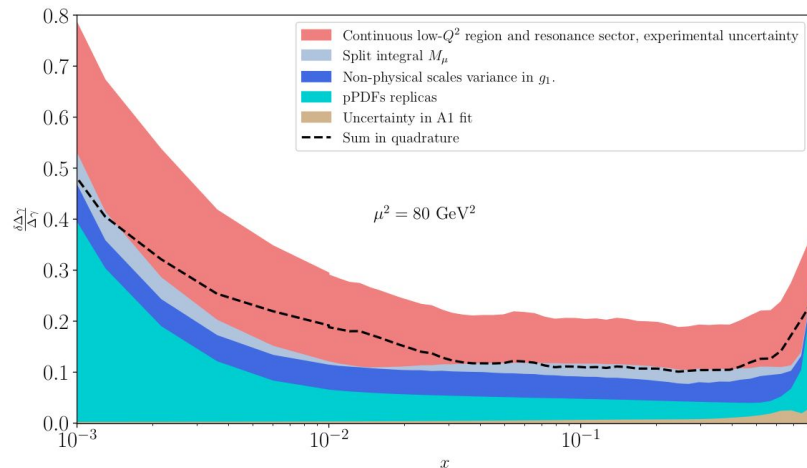


Polarized photon PDF

- The largest contributions are the perturbative and elastic region.
- The resonance and low- Q^2 regions are of a lower order.



- The largest uncertainty comes from the the low Q^2 region. These uncertainty arise from the experimental uncertainty.
- For the perturbative region the largest uncertainty arise from the PDF replicas. Also there are an uncertainty because the variation for the non physical scales.
- For the Elastic region the uncertainty is small, it arise from the experimental error in the A1 collaboration measurement of the Sachs factor.



DGLAP evolution with QED

1 Include the photon PDF in the evolution system

$$\frac{d\gamma}{dt} = \sum_f P_{\gamma f} \otimes f + \sum_f P_{\gamma \bar{f}} \otimes \bar{f} + P_{\gamma g} \otimes g + P_{\gamma\gamma} \otimes \boxed{\gamma}$$

Photon PDF
Mellin space

$$\frac{d\mathbf{E}(t, t_0)}{dt} = \mathbf{P}(\alpha_S, \alpha) \mathbf{E}(t, t_0)$$

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Photon PDF → Mellin space

$$\frac{d\mathbf{E}(t, t_0)}{dt} = \mathbf{P}(\alpha_S, \alpha) \mathbf{E}(t, t_0)$$

2 Compute the QED and mixed-order kernels

$$P_{ij} = a_S P_{ij}^{(1,0)} + a_S^2 P_{ij}^{(2,0)} + a_S^3 P_{ij}^{(3,0)} + a P_{ij}^{(0,1)} + a_S a P_{ij}^{(1,1)} + \dots$$

QED kernels computed using the Abelianization technique.

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3 Non-commuting terms

$$\mathbf{E} = \mathbf{E}^{\text{MIX}} \mathbf{E}^{\text{QED}} \mathbf{E}^{\text{QCD}}$$

$$[\mathbf{P}^{\text{QED}}, \mathbf{P}^{\text{QCD}}] \neq 0$$

Non-commuting kernels generate large term $a_S^m a^n t^l$ at high scales.

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4 Include An operators

$$\mathbf{E} = \left(1 + \sum_{i=0}^{\infty} \mathbf{A}_i \right) \mathbf{E}^{\text{MIX}} \mathbf{E}^{\text{QED}} \mathbf{E}^{\text{QCD}}$$

We reuse the pure-QCD and pure-QED evolution operators.

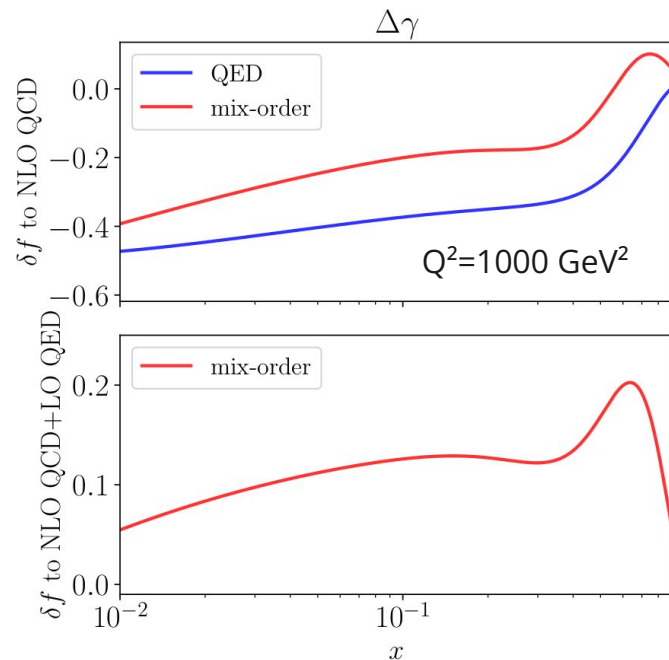
$$\frac{d\mathbf{A}_i}{dt} = \mathbf{A}_{i-1} \frac{d\mathbf{A}_0}{dt} - \left[\mathbf{A}_{i-1}, a_S \mathbf{P}^{(1,0)} + a_S^2 \mathbf{P}^{(2,0)} + a \mathbf{P}^{(0,1)} + a_S a \mathbf{P}^{(1,1)} \right]$$

Dominant tower resummed: $a_S^m a t^m$

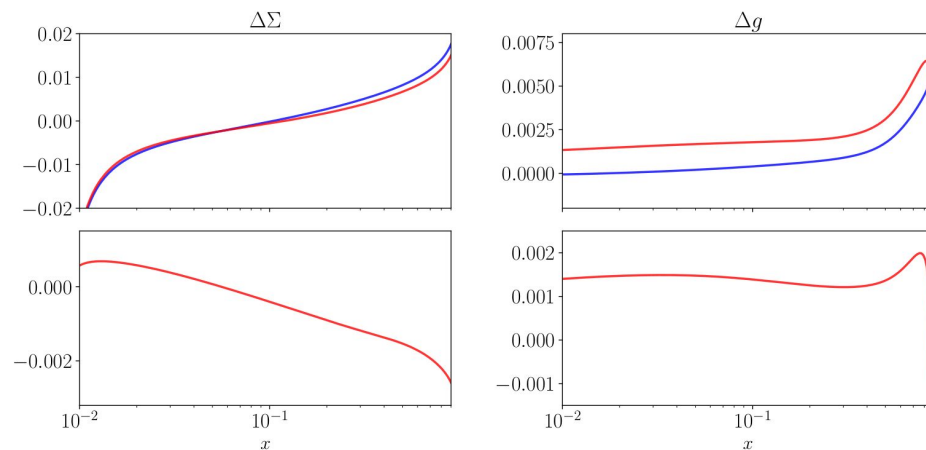
DGLAP evolution with QED

$$\delta f = \frac{f^{\mathcal{O}_1} - f^{\mathcal{O}_2}}{f^{\mathcal{O}_1}}$$

Large corrections to the polarized photon PDF



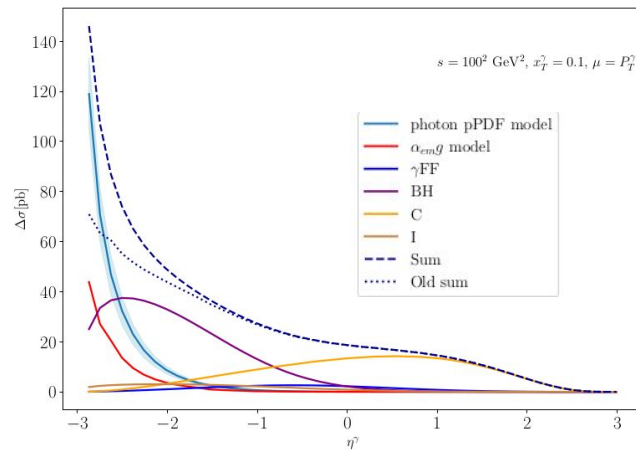
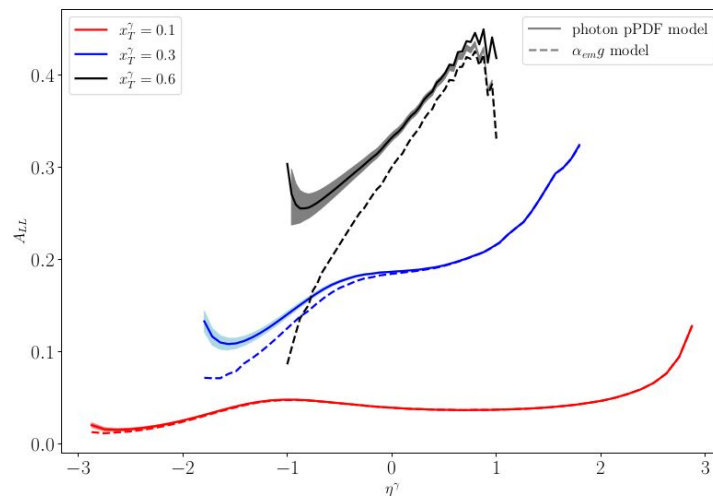
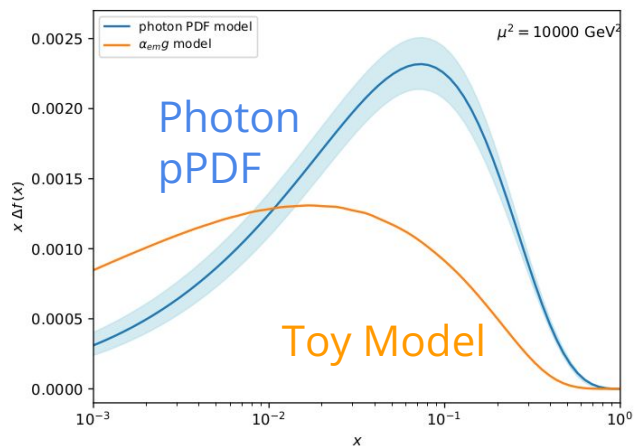
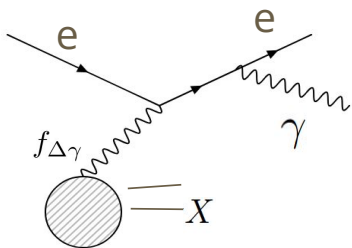
Smaller corrections for other partons



Prompt photon production ep

$$ep \rightarrow \gamma X$$

LO:



D. Rein, M. Schlegel, and W. Vogelsang, *Phys. Rev. D* 110 (2024) no.1, 014041, [arXiv:2405.04232 \[hep-ph\]](https://arxiv.org/abs/2405.04232), [doi:10.1103/PhysRevD.110.014041](https://doi.org/10.1103/PhysRevD.110.014041).

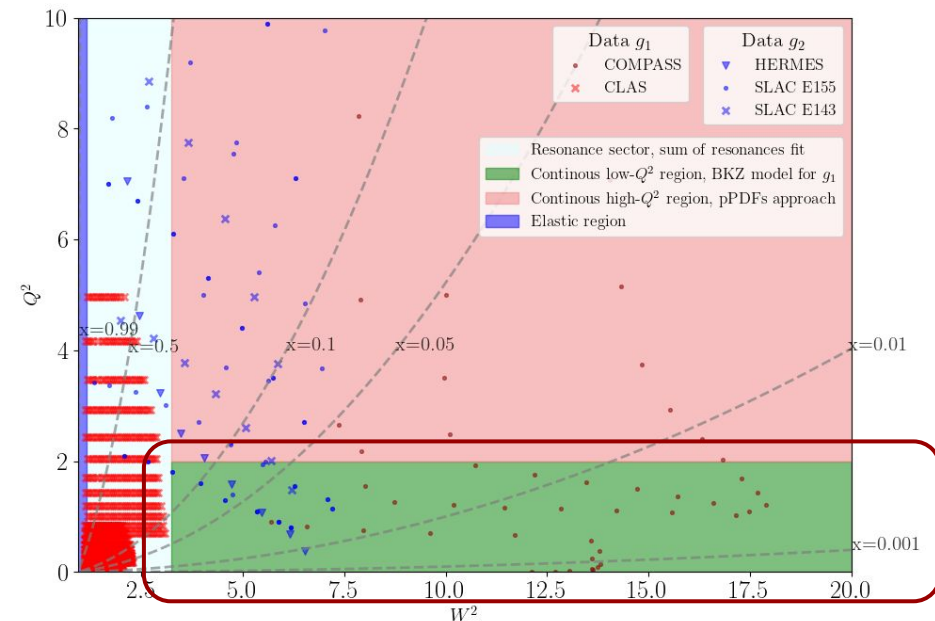
Conclusions

- We compute the polarized photon PDF using the LuxQED approach with a uncertainty of $\approx 50\%$ for low x ($x \approx 0.001$) and $\approx 10\%$ for larger x values.
- We show that the photon pPDF is of the order gluon/100.
- The first momentum is small in comparison with the quarks and gluon momentum
- We compute the mixed-order AP kernels, and solve the DGLAP equations.
- We apply the photon pPDF in Prompt Photon Production and observe significant differences with toy models.

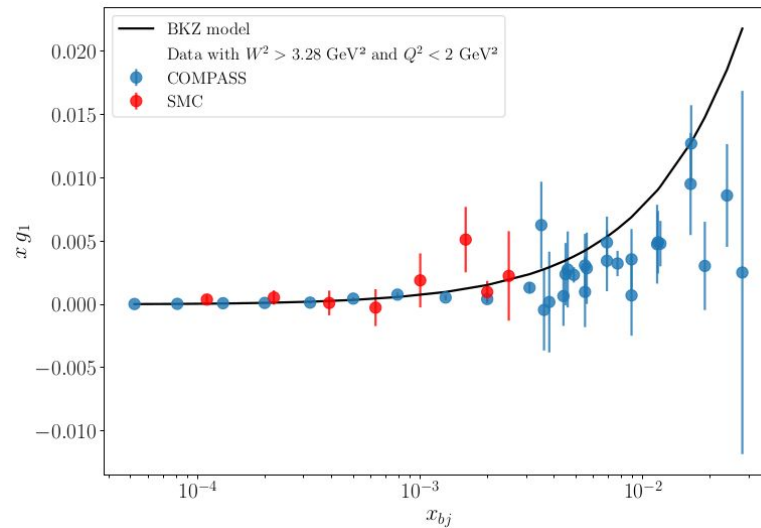
iThanks!

Low- Q^2 region

$$W^2 > W_{\text{res}}^2 \text{ and } Q^2 < Q_{\text{per}}^2 = 2 \text{ GeV}^2$$



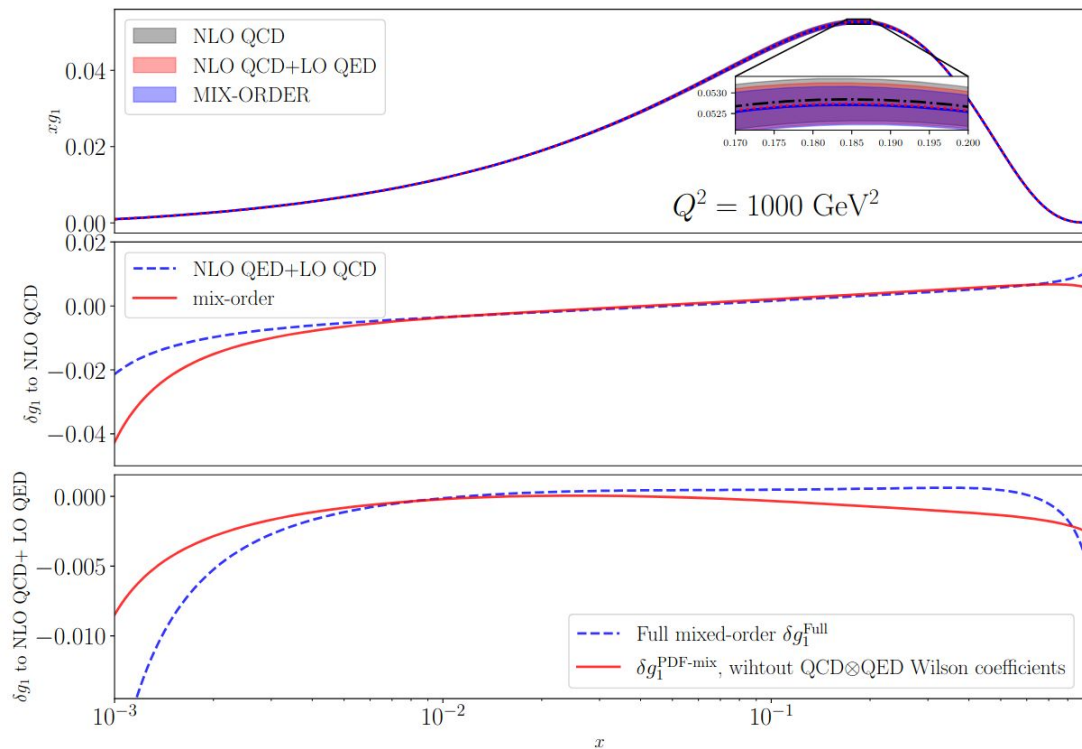
Vector Meson Dominance (VMD)



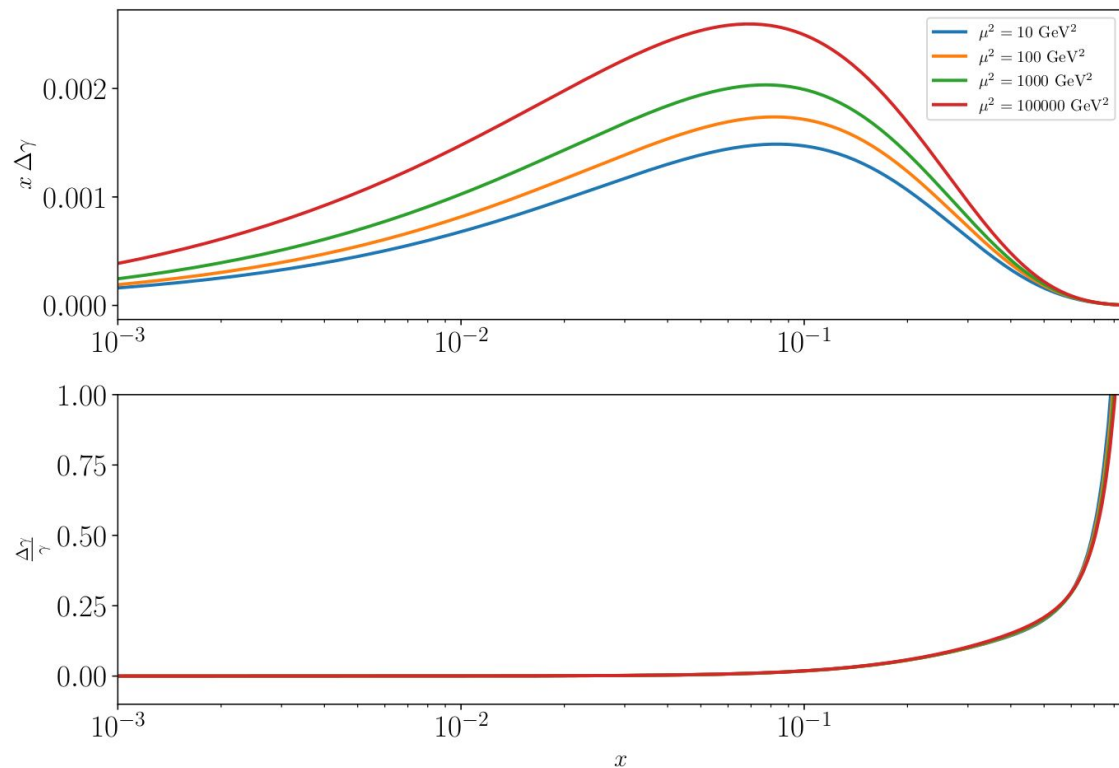
**B. M. Badelek, J. Kwiecinski, and B. Ziaja, Eur. Phys. J. C 26, 45 (2002),
arXiv:hep-ph/0206188.**

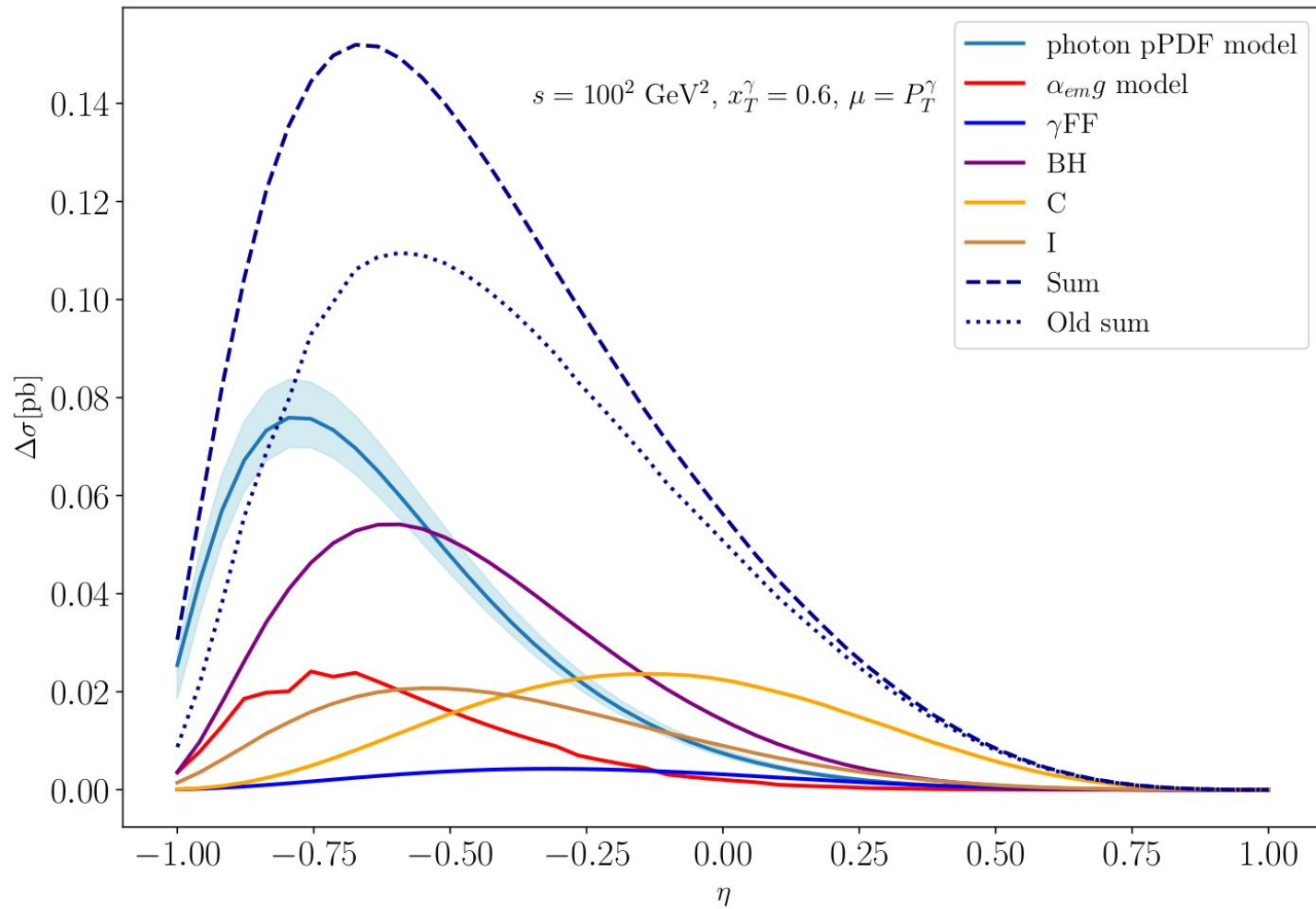
Polarized DIS

$$\begin{aligned}
 g_1(x, Q^2) = & \frac{1}{2} \sum_q e_q^2 \{ (\Delta q + \Delta \bar{q}) + 2 a_S [\Delta C_q^{(1,0)} \otimes (\Delta q + \Delta \bar{q}) + \Delta C_g^{(1,0)} \otimes \Delta g] \\
 & + 2 a [\Delta C_q^{(0,1)} \otimes (\Delta q + \Delta \bar{q}) + \Delta C_\gamma^{(0,1)} \otimes \Delta \gamma] \\
 & + 4 a_S a [\Delta C_q^{(1,1)} \otimes (\Delta q + \Delta \bar{q}) + \Delta C_g^{(1,1)} \otimes \Delta g + \Delta C_\gamma^{(1,1)} \otimes \Delta \gamma] \},
 \end{aligned}$$



Evolution photon PDF





$$\sqrt{s}=100 \text{ GeV}, x_T^Y=0.6, \mu=P_T^Y$$

$$\frac{d\sigma}{d\eta_Y dx_T^Y} [\text{pb}]$$

