Probing photonic content of the proton using photon-induced dilepton production in $p + \mathrm{Pb}$ collisions at the LHC

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Abstract

We propose a new experimental method to validate photon parton distribution function (PDF) inside the proton at LHC energies. It is based on the measurement of dilepton production from the $\gamma p \to \ell\ell + X$ reaction in proton–lead collision configuration. These experimental conditions guarantee relatively clean environment, both in terms of reconstruction of the final state and in terms of possible background. We firstly calculate the cross sections for this process with collinear photon PDFs, where we identify correct choice of the scale, in analogy to deep inelastic scattering. We then include the virtuality of probed photon in the calculations, based on modern parametrizations of deep inelastic structure functions. We find the potential measurement of this process is accessible by LHC experiments.

I. INTRODUCTION

Precise calculations of various electroweak reactions in pp collisions at the LHC need to account for, on top of the higher-order corrections, the effects of photon-induced subprocesses. The relevant examples are the production of lepton pairs [1–5] or pairs of electroweak bosons [6–13].

Recently, a precise photon distribution inside the proton has been evaluated in Ref. [14]. This approach provides a model-independent determination of the photon PDF (embedded in so-called LUXqed distribution) and it is based on proton structure function and elastic form factor fits in electron–proton scattering.

Up to date, there are no experimentally clean processes identified that would allow to either strongly constrain or verify the calculations. For example, the extraction of photon PDF from isolated photon production in deep inelastic scattering (DIS) [15] or from inclusive $pp \to \ell\ell + X$ reaction [2, 16, 17] is limited due to large QCD background. On contrary, the elastic part of the photon PDF is verified via exclusive $\gamma\gamma \to \ell\ell$ process, measured in pp collisions by ATLAS [18, 19], CMS [20, 21] and recently by CMS+TOTEM [22] collaborations.

We therefore propose a new experimental method to constrain photonic content of the proton. Thanks to the large fluxes of quasi-real photons from the Pb ion at the LHC, the photon-induced dilepton production in $p+\text{Pb}$ collision configuration is a very clean way to probe photon PDF. This process is shown schematically in Fig. 1, where by analogy to DIS, two leading-order diagrams can be identified. Since the photon flux from the ion scales with Z^2 and QCD-induced cross-sections scale approximately with A, the amount of QCD background is greatly reduced comparing to pp case.

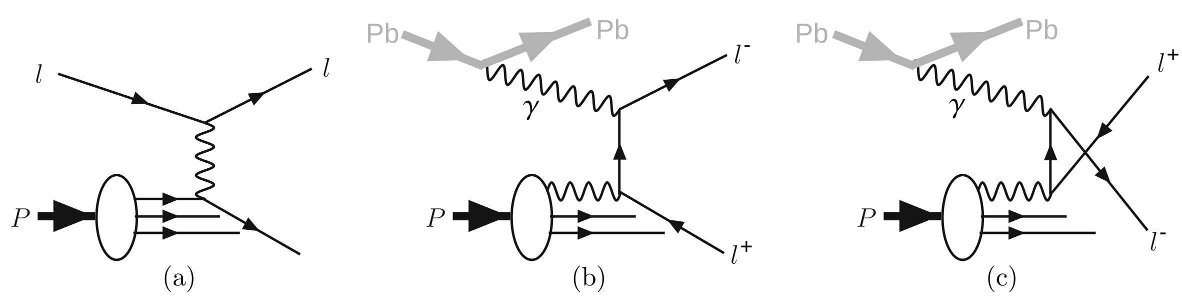

FIG. 1: Schematic graphs for deep inelastic scattering, $\ell p \to \ell + X$ (a) and photon-induced dilepton prodcution, $\gamma p \to \ell\ell + X$, in t-channel (b) and u-channel (c).

Moreover, as this process does not involve the exchange of color with the photon-emitting nucleus, no significant particle production is expected in the rapidity region between the dilepton system and the nucleus. The photon-emitting nucleus is also expected to produce no neutrons because the photons couple to the entire nucleus. Thus, a combination of a rapidity gap and zero neutrons in the same direction provide straightforward criteria to identify these events experimentally.

II. FORMALISM

A. Elastic vertices

In this work we are only interested in the elastic vertices on the nucleus side.

We recall, that for the proton, we can express the photon flux through the electric and magnetic form factors $G_E(Q^2)$ and $G_M(Q^2)$ of the proton:

$$W_T^{\rm el}(M_X^2, Q^2) = \delta(M_X^2 - m_p^2)\, Q^2 G_M^2(Q^2)\,,\; W_L^{\rm el}(M_X^2, Q^2) = \delta(M_X^2 - m_p^2) 4m_p^2 G_E^2(Q^2)\,. \quad (1)$$

The contribution to the photon flux is then again obtained by contracting

$$\frac{p^\mu p^\nu}{s^2}\, W_{\mu\nu}^{\rm el}(M_X^2, Q^2) = \delta(M_X^2 - m_p^2)\Big[\Big(1 - \frac{z}{2}\Big)^2 \frac{4m_p^2 G_E^2(Q^2) + Q^2 G_M^2(Q^2)}{4m_p^2 + Q^2} + \frac{z^2}{4} G_M^2(Q^2)\Big] \quad (2)$$

For the nucleus, we follow [23], and replace

$$\frac{4m_p^2 G_E^2(Q^2) + Q^2 G_M^2(Q^2)}{4m_p^2 + Q^2} \longrightarrow Z^2 F_{\rm em}^2(Q^2)\,. \quad (3)$$

We neglect the magnetic form factor in the following. (It even rigorously vanishes for spinless nuclei.)

For the ^{208}Pb nucleus, we use the realistic formfactor from the STARLIGHT MC.

$$F_{\rm em}(Q^2) = \frac{3}{(QR_A)^3}\Big\{ \sin(QR_A) - QR_A \cos(QR_A)\Big\} \frac{1}{1 + a^2 Q^2}\,. \quad (4)$$

Here

$$R_A = 1.1 A^{1/3}\,{\rm fm}\,,\; a = 0.7\,{\rm fm},\; Q = \sqrt{Q^2}\,. \quad (5)$$

Variable	Requirement
lepton transverse momentum, p_{T}^{ℓ}	> 4 GeV
lepton pseudorapidity, $\lvert\eta^{\ell}\rvert$	< 2.4
dilepton invariant mass, $m_{\ell\ell}$	> 10 GeV

TABLE I: Definition of the fiducial region used in the studies.

Therefore we obtain the elastic flux

$$\mathcal{F}^{\mathrm{el}}_{\gamma^* \leftarrow A}(z, \boldsymbol{q}) = \frac{Z^2 \alpha_{\mathrm{em}}}{\pi} \, (1-z) \left(\frac{\boldsymbol{q}^2}{\boldsymbol{q}^2 + z(M_X^2 - m_A^2) + z^2 m_A^2} \right)^2 F^2_{\mathrm{em}}(Q^2) \, . \tag{6}$$

For ^{208}Pb the charge is $Z = 82$.

III. EXAMPLE EXPERIMENTAL CONFIGURATION AND POSSIBLE BACKGROUND SOURCES

We assume collision setup from recent pPb run at the LHC, carried out at the centre-of-mass energy per nucleon pair $\sqrt{s_{NN}} = 8.16$ TeV. Since the energy per nucleon in the proton beam is larger than in the lead beam, the nucleon–nucleon centre-of-mass system has a rapidity in the laboratory frame of $+0.465$.

As an example of method's applicability, we will use the geometry of ATLAS [24] and CMS [25] detectors in the following. We also consider dimuon-channel only, however the integrated results for ee and $\mu\mu$ channels can be obtained by simply multiplying all cross-sections by a factor of two.

We start with applying minimum transverse momentum requirement of 4 GeV to both muons. This requirement is imposed to ensure high lepton reconstruction and triggering efficiency. Moreover, due to limited acceptance of the detectors, each muon is required to have a pseudorapidity (η^{ℓ}) that satisfies $|\eta^{\ell}| < 2.4$ condition. Our calculations are carried out for a minimum dilepton invariant mass $m_{\ell\ell} = 10$ GeV. Such a choice is due to removal of possible contamination from $\Upsilon(\to \ell\ell)$ photoproduction process. Summary of all selection requirements is presented in Table I

Possible background for this process can arise from inclusive lepton-pair production, e.g.

from Drell–Yan [26] process. This processes would lead to disintegration of the incoming ion, and zero-degree calorimeters (ZDC) [27, 28] can be used to veto very-forward-going neutral fragments which would allow to fully reduce this background. Another background can arise from diffractive interactions, hence possibly mimicking signal topology. However, since the nucleus is a fragile object (with the nucleon binding energy of just 8 MeV) even the softest diffractive interaction will likely result in the emission of a few nucleons from the ion, detectable in the ZDC.

Another background category is the photon-induced process with resolved photon, i.e. $\gamma p \to Z/\gamma^* X$ reaction. Here, the rapidity gap is expected to be smaller than in the signal process due to the additional particle production associated with the "photon remnant". Any other residual contamination of this process can be controlled using dedicated region, with a dilepton invariant mass around the Z-boson mass.

IV. RESULTS WITH COLLINEAR PHOTON-PDFS

We start with the calculation of the elastic contribution, $p\text{Pb} \to p\text{Pb}\ell\ell$. In this case the photon flux becomes:

$$f_\gamma^p(x,\mu) = f_\gamma^p(x) \tag{7}$$

and the following parameterization is used []:

$$f_\gamma^p(x) = \frac{\alpha}{\pi}\left(\frac{1-x+0.5x^2}{x}\right)\left(\frac{A+3}{A-1}\log A - \frac{17}{6} - \frac{4}{3A} + \frac{1}{6A^2}\right) , \tag{8}$$

where $A = 1 + \frac{Q_0^2(1-x)}{xm_p^2}$ and $Q_0^2 = 0.71\ \text{GeV}^2$.

The results for the elastic case are cross-checked with the calculation from STARlight MC and a good agreement is found: $\sigma_{fid}^{\text{el}} = 17.5$ nb, whereas $\sigma_{fid}^{\text{STARlight}} = 17.0$ nb. Both calculations are also corrected by a factor $S^2 = 0.96$ which takes into account the requirement that there be no hadronic interactions between the proton and the ion. This is calculated using STARlight, where the hard-sphere proton–nucleus requirement [29] is used.

Next, for the inelastic case ($\gamma p \to \ell\ell X$), several recent parameterizations of the photon parton distributions are studied: CT14qed [15], LUXqed17 [30] and NNPDF3.1luxQED [31]. Comparison of several lepton kinematic distributions between different photon-PDFs are shown in Fig. **??**. The integrated fiducial cross-sections are summarized in Tab. **??**.

(some discussion here...)

It should be made clear, that the calculations with collinear photons (at lowest order) produce leptons that are back-to-back in transverse kinematics. Therefore, to take the effect of inelastic photon virtuality into account, a dedicated parton shower algorithm should be used.

(mention we don't want to do extra PS; we would rather stick to kt factorization)

V. RESULTS INCLUDING PHOTON TRANSVERSE MOMENTUM

VI. DISCUSSION

We take the opportunity to calculate expected number of events for realistic assumption on total integrated luminosity. based on the previous pPb runs at the LHC, we assume $\int L dt = 200\ \mathrm{nb}^{-1}$.

(show some table(s) here)

VII. SUMMARY

In summary, we propose a method that would unambiguously allow to test and constrain the photon parton distribution at LHC energies.

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