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

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Abstract

We propose a new experimental method to validate photon-PDF of the proton at LHC energies.

1. Introduction

A significant fraction of proton-proton collisions at the LHC involves quasi-real photon interactions.

... [3]

As the signal 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.

2. Formalism

2.1. 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 [2], and replace

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

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.

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

Here

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

Therefore we obtain the elastic flux

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

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

3. Example experimental configuration and possible background sources

As an example of method's applicability, we will use the geometry of ATLAS and CMS 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

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 1: Definition of the fiducial region used in the studies.

choice is due to removal of possible contamination from $\Upsilon(\rightarrow \ell\ell)$ photoproduction process. Summary of all selection requirements is presented in Table 1

Possible background for this process can arise from inclusive lepton-pair production, e.g. from Drell–Yan [5] process. This processes would lead to disintegration of the incoming ion, and zero-degree calorimeters (ZDC) [4, 1] 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 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. $\gamma p \rightarrow Z/\gamma^{*} X$ 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.

4. Results with collinear photon-PDFs

We start with the calculation of the elastic contribution, $p+\mathrm{Pb} \rightarrow p+\mathrm{Pb}\ell\ell$. 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 $A = 1 + \frac{Q_0^2(1-x)}{x m_p^2}$ and $Q_0^2 = 0.71\ \mathrm{GeV}^2$.

The results for the elastic case are cross-checked with the calculation from STARlight MC and a good agreement is found: $\sigma_{fid}^{\mathrm{el}} = 17.5$ nb, whereas $\sigma_{fid}^{\mathrm{STARlight}} = 17.0$ 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 [6] is used.

Next, for the inelastic case ($\gamma p \to \ell\ell$), several recent parameterizations of the photon parton distributions are studied: CT14qed [], LUXqed17 [] and NNPDF3.1luxqed []. 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 this; we would rather stick to kt factorization)

5. Results including photon transverse momentum

6. Discussion

7. Summary

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

References

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