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

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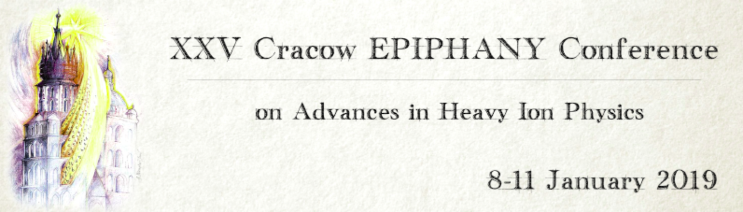


Introduction

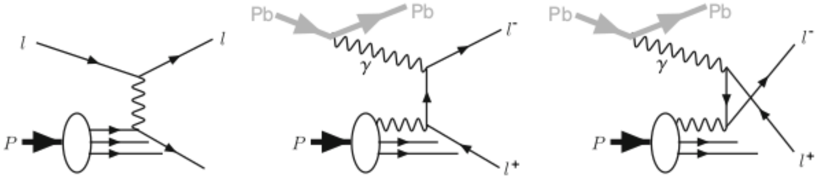
- We propose a new experimental method to probe the photon parton distribution function inside the proton (photon PDF) at LHC energies
- The method is based on the measurement of dilepton production from the $\gamma p \to \ell^+ \ell^- + X$ reaction in proton–lead collisions
- These experimental conditions guarantee 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 optimal choice of the scale, in analogy to deep inelastic scattering kinematics
- We then perform calculations including the transverse-momentum dependence of the probed photon
- Finally we estimate rates of the process for the existing LHC data samples

Introduction ($p + p$ collisions)

- 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 processes.

our contributions (M.Ł, A. Szczurek, W. Schafer)

- production of lepton pairs
  - **M. Luszczak, W. Schafer and A. Szczurek**, Phys.Rev. D93 (2016) 074018
- pairs of electroweak bosons
  - **M. Luszczak, A. Szczurek and Ch. Royon**, JHEP 1502 (2015) 098
  - **M. Luszczak, W. Schafer and A. Szczurek**, JHEP 1805 (2018) 064
  - **L. Forthomme, M. Luszczak, W. Schafer and A. Szczurek**, Phys.Lett. B789 (2019) 300-307



(a) (b) (c)

Schematic graphs for deep inelastic scattering

- (a) $\ell^{\pm} p \to \ell^{\pm} + X$
- photon-induced dilepton prodcution, $\gamma p \to \ell^{+}\ell^{-} + X$, in $p + \mathrm{Pb}$ collisions
  - (b) t-channel lepton exchange
  - (c) u-channel lepton exchange

Formalism (Elastic photon fluxes)

- elastic photons from the proton

$$\gamma_{\mathbf{el}}^{\mathbf{p}}(\mathbf{x}, \mathbf{Q^2}) = \frac{\alpha_{\rm em}}{\pi}\left[\left(1-\frac{x}{2}\right)^2 \frac{4m_p^2 G_E^2(Q^2) + Q^2 G_M^2(Q^2)}{4m_p^2 + Q^2} + \frac{x^2}{4} G_M^2(Q^2)\right]$$

- elastic photon flux for the nucleus ($\gamma_{el}^{\rm Pb}$)

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

$F_{\rm em}^2(Q^2)$ - formfactor parameterization from the STARlight MC generator

$$\mathbf{F}_{\rm em}(\mathbf{Q^2}) = \frac{3}{(QR_A)^3}\left[\sin(QR_A) - QR_A\cos(QR_A)\right]\frac{1}{1+a^2Q^2} \, ,$$

where $R_A = 1.1 A^{1/3}$ fm, $a = 0.7$ fm and $Q = \sqrt{Q^2}$.

- photon parton distribution $\gamma^{p}_{inel}(x,\mu^2)$ obeys the DGLAP equation:

$$\frac{d\gamma^{p}_{inel}(x,\mu^2)}{d\log\mu^2} = \frac{\alpha_{\rm em}}{2\pi}\int_x^1 \frac{dy}{y}\Big[\sum_q P_{\gamma\leftarrow q}(y)q(\frac{x}{y},\mu^2)+P_{\gamma\leftarrow\gamma}(y)\gamma^{p}_{inel}(\frac{x}{y},\mu^2)\Big]$$

where $q(x,\mu^2)$ is the quark PDF, e_q is the quark charge, $P_{\gamma\leftarrow q}$ is the $q\to\gamma$ splitting function, and $P_{\gamma\leftarrow\gamma}$ corresponds to the virtual self-energy correction to the photon propagator

$p+\mathrm{Pb}\to\mathrm{Pb}+\ell^+\ell^- + X$ production cross section

$$\sigma = S^2\int dx_p dx_{\rm Pb}\Big[\left(\gamma^{p}_{el}(x_p)+\gamma^{p}_{inel}(x_p,\mu^2)\right)\gamma^{\rm Pb}_{\bf el}(\mathbf{x}_{\rm Pb})\sigma_{\gamma\gamma\to\ell^+\ell^-}(x_p,x_{\rm Pb})\Big]$$

QED parton distributions

- **MRST-QED parton distributions**
  - QED-corrected evolution equations for the parton distributions of the proton

$$
\begin{aligned}
\frac{\partial q_i(x,\mu^2)}{\partial \log \mu^2} &= \frac{\alpha_S}{2\pi}\int_x^1 \frac{dy}{y}\left\{P_{qq}(y)\, q_i(\frac{x}{y},\mu^2) + P_{qg}(y)\, g(\frac{x}{y},\mu^2)\right\} \\
&+ \frac{\alpha}{2\pi}\int_x^1 \frac{dy}{y}\left\{\tilde{P}_{qq}(y)\, e_i^2 q_i(\frac{x}{y},\mu^2) + P_{q\gamma}(y)\, e_i^2 \gamma(\frac{x}{y},\mu^2)\right\} \\
\frac{\partial g(x,\mu^2)}{\partial \log \mu^2} &= \frac{\alpha_S}{2\pi}\int_x^1 \frac{dy}{y}\left\{P_{gq}(y) \sum_j q_j(\frac{x}{y},\mu^2) + P_{gg}(y)\, g(\frac{x}{y},\mu^2)\right\} \\
\frac{\partial \gamma(x,\mu^2)}{\partial \log \mu^2} &= \frac{\alpha}{2\pi}\int_x^1 \frac{dy}{y}\left\{P_{\gamma q}(y) \sum_j e_j^2\, q_j(\frac{x}{y},\mu^2) + P_{\gamma\gamma}(y)\, \gamma(\frac{x}{y},\mu^2)\right\}
\end{aligned}
$$

- **NNPDF2.3 parton distributions**
  - fit to deep-inelastic scattering (DIS) and Drell-Yan data

- **LUXqed17 parton distributions**
  - integral over proton structure functions $F_2(x, Q^2)$ and $F_L(x, Q^2)$

- unintegrated inelastic photon flux $\gamma^{p}_{inel}(x, \vec{q}_T)$:

$$\gamma^{p}_{inel}(x, \vec{q}_T) = \frac{1}{x}\frac{1}{\pi \vec{q}_T^{\,2}} \int_{M^2_{\rm thr}} dM_X^2 \mathcal{F}^{\rm in}_{\gamma^* \leftarrow p}(x, \vec{q}_T, M_X^2)$$

$$\begin{aligned}
\mathcal{F}^{\rm in}_{\gamma^* \leftarrow p}(x, \vec{q}_T) \quad &= \quad \frac{\alpha_{\rm em}}{\pi}\Big\{(1-x)\Big(\frac{\vec{q}_T^{\,2}}{\vec{q}_T^{\,2} + x(M_X^2 - m_p^2) + x^2 m_p^2}\Big)^2 \frac{F_2(x_{\rm Bj}, Q^2)}{Q^2 + M_X^2 - m_p^2} \\
&+ \quad \frac{x^2}{4x^2_{\rm Bj}} \frac{\vec{q}_T^{\,2}}{\vec{q}_T^{\,2} + x(M_X^2 - m_p^2) + x^2 m_p^2} \frac{2x_{\rm Bj} F_1(x_{\rm Bj}, Q^2)}{Q^2 + M_X^2 - m_p^2}\Big\}
\end{aligned}$$

- virtuality Q^2 of the photon depends on the photon transverse momentum ($\vec{q}_T^{\,2}$) and the proton remnant mass (M_X):

$$Q^2 = \frac{\vec{q}_T^{\,2} + x(M_X^2 - m_p^2) + x^2 m_p^2}{(1-x)}$$

Formalism (k_T-factorization approach)

- the proton structure functions require the argument

$$x_{\rm Bj} = \frac{Q^2}{Q^2 + M_X^2 - m_p^2}$$

- in practise use the pair $F_2(x_{\rm Bj}, Q^2), F_L(x_{\rm Bj}, Q^2)$

$$F_L(x_{\rm Bj}, Q^2) = \left(1 + \frac{4x_{\rm Bj}^2 m_p^2}{Q^2}\right) F_2(x_{\rm Bj}, Q^2) - 2x_{\rm Bj} F_1(x_{\rm Bj}, Q^2)$$

- F_L - the longitudinal structure function of the proton

$p + {\rm Pb} \to {\rm Pb} + \ell^+\ell^- + X$ production cross section

$$\sigma = S^2 \int dx_p dx_{\rm Pb} d\vec{q}_T \Big[\left(\gamma_{el}^p(x_p, \vec{q}_T) + \gamma_{inel}^p(x_p, \vec{q}_T)\right) \gamma_{el}^{\rm Pb}(x_{\rm Pb}) \sigma_{\gamma^*\gamma \to \ell^+\ell^-}(x_p, x_{\rm Pb}, \vec{q_T}) \Big]$$

Results with collinear photon-PDFs

Integrated fiducial cross sections for $p + \mathrm{Pb} \to \mathrm{Pb} + \ell^+\ell^- + X$ production at $\sqrt{s_{NN}} = 8.16$ TeV for different collinear photon PDF sets.

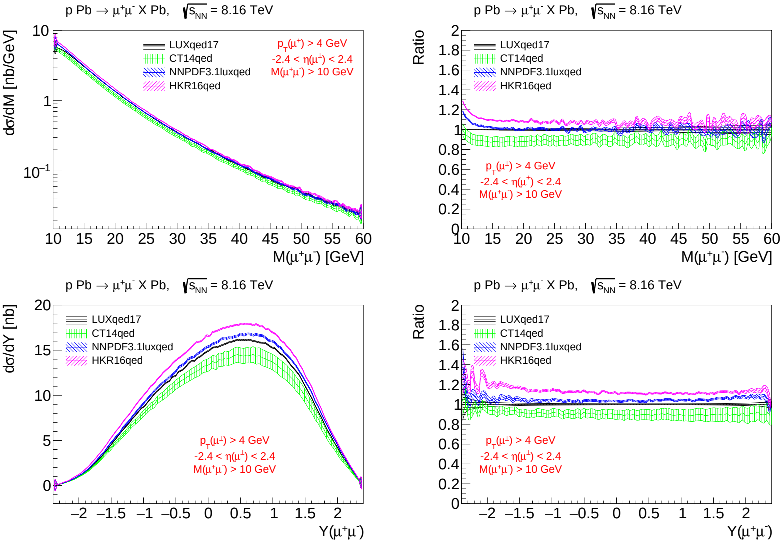
Contribution	$p_T^\ell > 4$ GeV	$p_T^\ell > 4$ GeV, $\lvert\eta^\ell\rvert < 2.4$, $m_{\ell^+\ell^-} > 10$ GeV
γ_{el}^p	44.9 nb	17.5 nb
$\gamma_{\mathrm{el}}^p + \gamma_{\mathrm{inel}}^p$ [CT14qed_inc]	98 ± 4 (PDF) nb	40 ± 2 (PDF) nb
$\gamma_{\mathrm{el}}^p + \gamma_{\mathrm{inel}}^p$ [LUXqed17]	105.8 ± 0.2 (PDF) nb	44.1 ± 0.1 (PDF) nb
$\gamma_{\mathrm{el}}^p + \gamma_{\mathrm{inel}}^p$ [NNPDF3.1luxQED]	115.6 ± 0.6 (PDF) nb	45.9 ± 0.3 (PDF) nb
$\gamma_{\mathrm{el}}^p + \gamma_{\mathrm{inel}}^p$ [HKR16qed]	121.6 nb	49.4 nb

Results using k_T-factorization approach

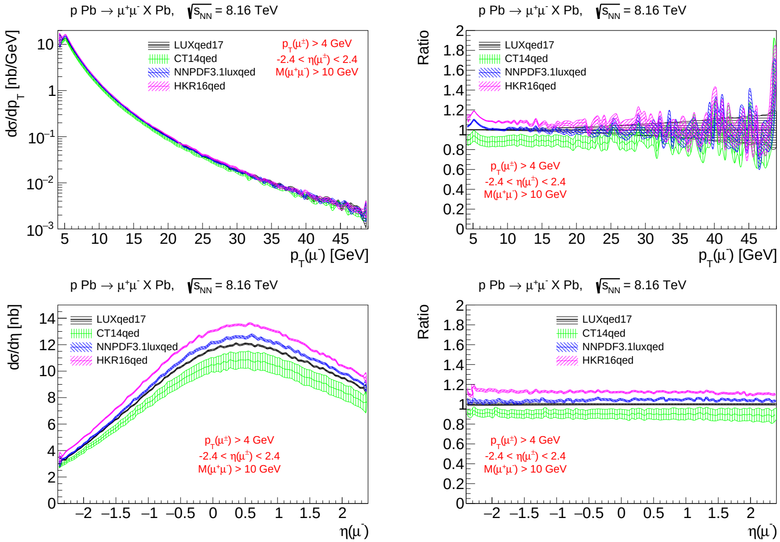
Integrated fiducial cross sections for inelastic $p + \mathrm{Pb} \to \mathrm{Pb} + \ell^+\ell^- + X$ production at $\sqrt{s_{NN}} = 8.16$ TeV for different proton structure functions.

Contribution	$p_T^\ell > 4$ GeV	$p_T^\ell > 4$ GeV, $\lvert\eta^\ell\rvert < 2.4$, $m_{\ell^+\ell^-} > 10$ GeV
$\gamma_{\rm el}^p$	47.9 nb	18.3 nb
$\gamma_{\rm inel}^p$ [LUX-like F_2]	43.6 nb	17.4 nb
$\gamma_{\rm inel}^p$ [LUX-like $F_2 + F_L$]	42.6 nb	17.1 nb
$\gamma_{\rm inel}^p$ [ALLM97 F_2]	41.7 nb	16.4 nb
$\gamma_{\rm inel}^p$ [SU F_2]	41.7 nb	16.7 nb
$\gamma_{\rm inel}^p$ [SY F_2]	40.4 nb	16.0 nb

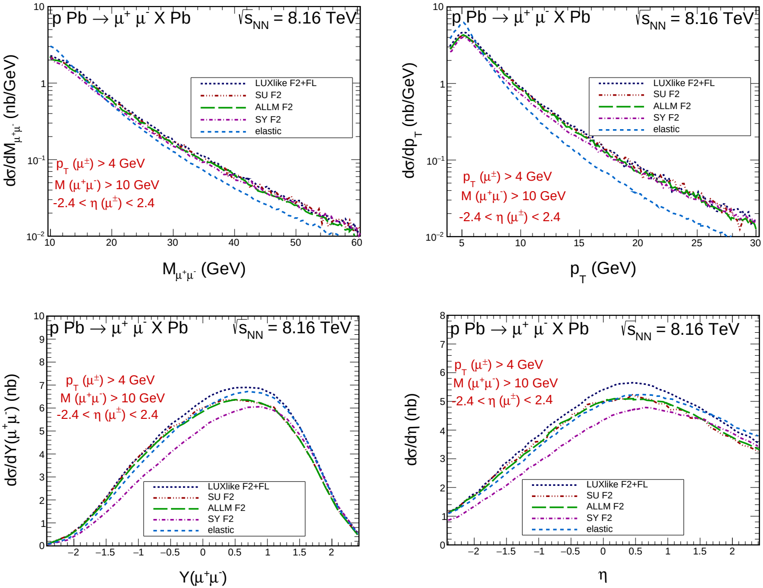
Results with collinear photon-PDFs



Results with collinear photon-PDFs



Results using k_T-factorization approach



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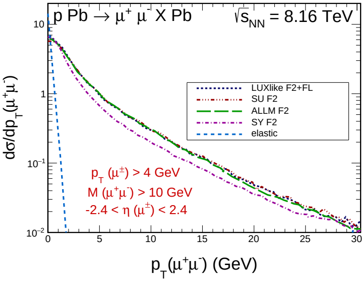
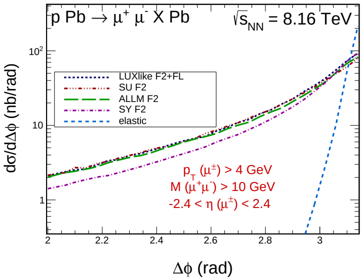
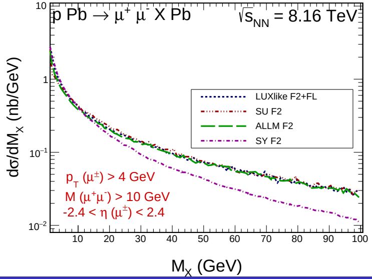
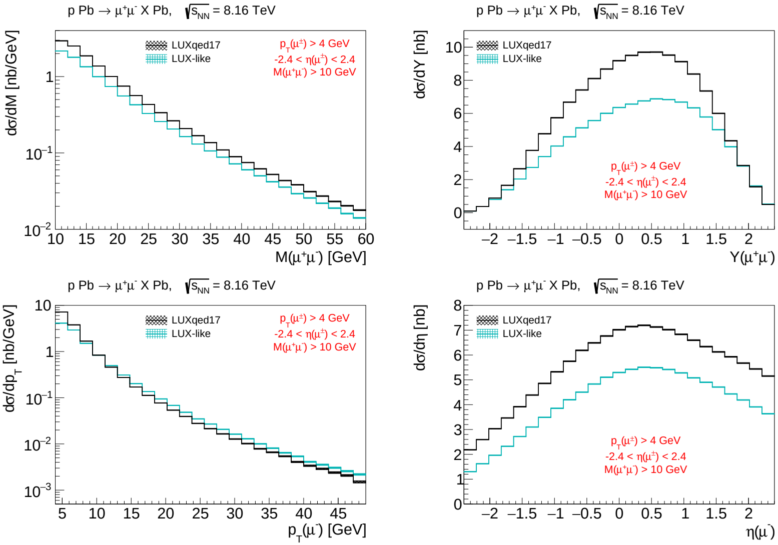






Results


p Pb → μ+μ- X Pb, √sNN = 8.16 TeV
LUXqed17
LUX-like
pT(μ±) > 4 GeV
-2.4 < η(μ±) < 2.4
M(μ+μ-) > 10 GeV
dσ/dM [nb/GeV]
M(μ+μ-) [GeV]
dσ/dY [nb]
Y(μ+μ-)
dσ/dpT [nb/GeV]
pT(μ-) [GeV]
dσ/dη [nb]
η(μ-)

Results

- We calculate expected number of events for realistic assumption on total integrated luminosity. Based on the previous $p + \mathrm{Pb}$ runs at the LHC, we assume $\int L dt = 200\ \mathrm{nb}^{-1}$.
- We also assume possible experimental efficiencies, mainly due to trigger and reconstruction of leptons, which we embed in a single correction factor $C = 0.7$.
- The data should be therefore sensitive to discriminate between the predictions based on collinear and k_T-factorization approaches, using existing datasets collected by ATLAS and CMS.

Contribution	Expected events ($C = 1$)	Expected events ($C = 0.7$)
γ^p_{el}	3600	2500
γ^p_{inel} [LUXqed17 collinear]	5600	3900
γ^p_{inel} [LUX-like $F_2 + F_L$]	3400	2400

Conclusions

- We propose a method that would allow to test and constrain the photon parton distribution at LHC energies.
- This method is based on the measurement of the cross-section for the reaction $p + \mathrm{Pb} \to \mathrm{Pb} + \ell^+\ell^- + X$, where the expected background is small comparing to the analogous process in pp collisions
- Results are shown for different choices of collinear photon PDFs, and a comparison is made with unintegrated photon distributions that include non-zero photon transverse momentum.
- Due to the smearing of dilepton transverse momentum introduced by the k_T-factorization approach, these two approaches lead to the cross sections that differ by about 30%.
- Using simple (realistic) experimental requirements on lepton kinematics, it is shown that one can expect O(3000) inelastic events with the existing datasets recorded by ATLAS/CMS at $\sqrt{s_{NN}} = 8.16$ TeV for each lepton flavour.