pp scattering at the LHC with the lepton pair production and one proton tagging

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Introduction

- Searching for New Physics in muon pairs production at very high energies at the LHC is of a great interest.
- The ATLAS collaboration has managed to measure the cross sections of proton-tagged dilepton production (arXiv:2009.14537).
- The analytical formulas describing the fiducial cross-section of the lepton pair production in *pp* scattering via $\gamma\gamma$ fusion mechanism are provided.
- The derivation is based on the modified equivalent photon approximation (EPA).
- Obtained formulas allow to perform numerical calculation instead of using Monte-Carlo method.
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Elastic case: $pp \to \gamma\gamma \to p\mu\mu p$

- Here the both protons don't decay $\to$ the EPA can be used.
- This leads to the restriction on the virtuality of the emitted photon: $Q^2 < \hat{q}^2 = (0.2\ GeV)^2$.
- Since the protons are not fundamental particles one should take into account their form-factors.

The spectrum of photons radiated by proton

$$n_p(\omega) = \frac{2\alpha}{\pi\omega} \int\limits_0^\infty \frac{D(Q^2)}{Q^4} q_\perp^3 \, \mathrm{d}q_\perp, \qquad (1)$$

where $Q^2 \equiv -q^2 = q_\perp^2 + \omega^2/\gamma^2$ is the photon 4-momentum squared, $\gamma = E_p/m_p \approx 6.93 \cdot 10^3$ is the Lorentz factor of the proton.

Elastic case: $pp \to \gamma\gamma \to p\mu\mu p$

The value $D(Q^2)$ is a combination of form-factors:

$$D(Q^2) = \frac{G_E^2(Q^2) + \frac{Q^2}{4m_p^2} G_M^2(Q^2)}{1 + \frac{Q^2}{4m_p^2}}, \tag{2}$$

where $G_E(Q^2)$ and $G_M(Q^2)$ are the Sachs electric and magnetic form factors and in the dipole approximation:

$$G_E(Q^2) = \frac{1}{(1 + Q^2/\Lambda^2)^2}, \;\; G_M(Q^2) = \frac{\mu_p}{(1 + Q^2/\Lambda^2)^2}. \tag{3}$$

- $\Lambda^2 = \frac{12}{r_p^2} = 0.66$ GeV^2,
- $\mu_p = 2.79$ is the proton magnetic moment
- $r_p = 0.84$ fm is the proton charge radius

Elastic case: $pp \to \gamma\gamma \to p\mu\mu p$

Substituting (3) $\to$ (2) $\to$ (1) one obtains for the spectrum of equivalent photons the following *analytical* expression:

$$n_p(\omega) = \frac{\alpha}{\pi\omega}\left\{\left(1 + 4u - (\mu_p^2 - 1)\frac{u}{v}\right)\ln\left(1 + \frac{1}{u}\right) - \right.$$
$$- \frac{24u^2 + 42u + 17}{6(u+1)^2} - \frac{\mu_p^2 - 1}{(v-1)^3}\left[\frac{1 + u/v}{v - 1}\ln\frac{u+v}{u+1} - \right.$$
$$\left. - \frac{6u^2(v^2 - 3v + 3) + 3u(3v^2 - 9v + 10) + 2v^2 - 7v + 11}{6(u+1)^2}\right], \tag{4}$$

where

$$u = \left(\frac{\omega}{\Lambda\gamma}\right)^2,\ v = \left(\frac{2m_p}{\Lambda}\right)^2.$$

Elastic case: $pp \to \gamma\gamma \to p\mu\mu p$

In EPA the cross section for the lepton pair production can be written as following

$$\sigma(pp \to p\ell^+\ell^- p) = \int\limits_0^\infty \int\limits_0^\infty \sigma(\gamma\gamma \to \ell^+\ell^-)\, n_p(\omega_1)\, n_p(\omega_2)\, \mathrm{d}\omega_1\, \mathrm{d}\omega_2, \tag{5}$$

where $\sigma(\gamma\gamma \to \ell^+\ell^-)$ is the cross section for the production of a lepton pair in a collision of two real photons with energies ω_1 and ω_2.

Elastic case: $pp \to \gamma\gamma \to p\mu\mu p$

In order to calculate the fiducial cross-section the ATLAS experimental constraints on the phase space volume must be imposed:

- $p_{i,T} > \hat{p}_T = 15\ GeV$ for muons ($\hat{p_T} = 18\ GeV$ for electrons), where $p_{i,T}$ is a transversal momentum of a lepton l_i.
- $\eta_i < \hat{\eta} = 2.4$ for muons ($\hat{\eta} = 2.47$ for electrons), where η_i is a pseudorapidity of a lepton l_i.
- $p_T \equiv p_{1,T} \approx p_{2,T}$ since sum of the transversal momenta of photons $\sqrt{Q^2} \lesssim \hat{q} = 0.2\ GeV$.
- $20\ GeV < W < 70\ GeV$ and $W > 105\ GeV$, where W is an invariant mass of a muon pair.
- $0.035 < \xi < 0.08 \to 227$ GeV$< \omega < 520$ GeV, where ξ is a fraction of the energy that the proton loses. The given range of values allows the proton to hit the forward detector.

Elastic case: $pp \to \gamma\gamma \to p\mu\mu p$

In order to calculate the expression (5) with experimental cuts one should introduce explicitly the integration over W, p_T and η. For this purpose it is convenient to perform a substitution $(\omega_1, \omega_2) \to (W, y)$ in the following way

- $W^2 = 4\omega_1\omega_2$ (when both photons are almost real);
- $y = \frac{1}{2} \ln \frac{\omega_1}{\omega_2}$.

Integration over p_T can be performed with help of the following formula:

$$\frac{\mathrm{d}\sigma(\gamma\gamma \to \ell^+\ell^-)}{\mathrm{d}p_T} = \frac{8\pi\alpha^2}{W^2 p_T} \cdot \frac{1 - 2p_T^2/W^2}{\sqrt{1 - 4p_T^2/W^2}},$$

Elastic case: $pp \to \gamma\gamma \to p\mu\mu p$

Integration over η is equivalent to the integration over y since there is a pure kinematical relation between them:

$$\hat{y} = \hat{\eta} + \frac{1}{2} \ln \frac{1 - \sqrt{1 - 4p_T^2/W^2}}{1 + \sqrt{1 - 4p_T^2/W^2}}.$$

Introducing the photon-photon luminosity one obtains the following integral:

$$\frac{\mathrm{d}\hat{L}}{\mathrm{d}W} = \frac{W}{2} \int\limits_{-\hat{y}}^{\hat{y}} n_p\left(\tfrac{W}{2}\,\mathrm{e}^{y}\right)\, n_p\left(\tfrac{W}{2}\,\mathrm{e}^{-y}\right)\,\mathrm{d}y.$$

A few words about inelastic case: $pp \to \gamma\gamma \to p\mu\mu X$

- Here one of the protons disintegrates $\to$ the EPA can't be used to describe this proton. It can be modified within the approach of the scattering amplitudes helicity representation.
- Virtuality of the photon emitted by this proton isn't small $\to$ integration over Q^2 must be performed using experimental cuts up to $\hat{p}_T^{\ell\ell} \equiv 5$ GeV.
- Within a parton framework one has to consider proton-quark collision and sum over all quarks so as:

$$\sigma(pp \to p + \ell^+\ell^- + X) = \sum_q \sigma(pq \to p + \ell^+\ell^- + q).$$

Also the integration should be performed with parton density functions (PDF) over the variable of fraction of proton energy the quark possesses x.

Numerical results

- Elastic case:

$$\sigma_{\text{fid}}(pp \to p + \mu^+\mu^- + p) = 8.6 \text{ fb},$$
$$\sigma_{\text{fid}}(pp \to p + e^+e^- + p) = 10.1 \text{ fb}.$$

- Inelastic case:

$$\sigma_{\text{fid}}(pp \to p + \mu^+\mu^- + X) = 9.2 \text{ fb},$$
$$\sigma_{\text{fid.}}(pp \to p + e^+e^- + X) = 11 \text{ fb}.$$

- Total elastic-inelastic cross-section is

$$\tilde{\sigma}^{\text{fid.}}_{\mu\mu+p} = 18 \pm 2 \text{ fb},$$
$$\tilde{\sigma}^{\text{fid.}}_{ee+p} = 21 \pm 2 \text{ fb}.$$

- ATLAS results:

$$\sigma^{\text{exp.}}_{\mu\mu+p} = 7.2 \pm 1.6 \text{ (stat.)} \pm 0.9 \text{ (syst.)} \pm 0.2 \text{ (lumi.) fb},$$
$$\sigma^{\text{exp.}}_{ee+p} = 11.0 \pm 2.6 \text{ (stat.)} \pm 1.2 \text{ (syst.)} \pm 0.3 \text{ (lumi.) fb}$$

Survival factor

- The so-called *survival factor* $S(b)$ takes into account the diminishing of the cross sections due to breaking of both protons occurring when the protons scatter with small impact parameter b.
- For elastic case this factor provides 10% diminishing. It can be taken into account without Monte-Carlo simulations and calculated in the following work: arXiv:2106.14842.
- For inelastic case this factor provides 50% diminishing (arXiv:2107.02535).
- Taking into account what is said above it is seen that the derived formulas are in agreement with the experimental data at the level of $2-3$ standard derivations.