Muon pair production at the LHC with one proton tagging via $\gamma\gamma$ fusion and γZ fusion.

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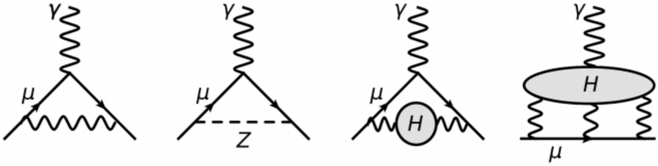
Introduction

- Searching for New Physics in muon pairs production at very high energies at the LHC is of a great interest.
- The ATLAS collaboration managed to measure the cross sections of dilepton production with one proton hitting the forward detector. *(see Phys. Rev. Lett. 125, 261801 (2020))*
- The analytical formulas describing fiducial cross section of the proton-proton scattering will be provided.
- The correction due to Z boson exchange to the leading process of the pp scattering via $\gamma\gamma$ fusion will be investigated.

Anomalous muon magnetic moment

Measurement of the Positive Muon Anomalous Magnetic Moment to 0.20 ppm (2023).

$$\vec{\mu} = g_\mu \left(\frac{e}{2m_\mu} \right) \vec{s}, \quad \textit{where} \quad g_\mu = 2(1 + a_\mu).$$



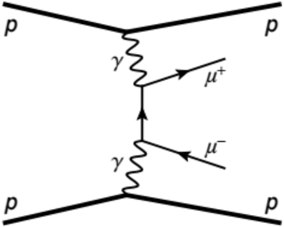
$$a_\mu(exp.) - a_\mu(SM) = (249 \pm 48) \times 10^{-11} \quad \text{with significance} \quad 5\sigma.$$

Experimental cuts

The ATLAS experimental constraints on the phase space volume are:

- $p_{i,T} > \hat{p}_T = 15\ GeV$, where $p_{i,T}$ is a transversal momentum of a muon.
- $|\eta_i| < \hat{\eta} = 2.4$, where η_i is a pseudorapidity of a muon.
- $p_T^{\mu\mu} < \hat{p}_T^{\mu\mu} = 5\ GeV$, where $p_T^{\mu\mu}$ is a transversal momentum of a muon pair.
- $20\ GeV < W < 70\ GeV$ and $W > 105\ GeV$, where W is an invariant mass of a muon pair.
- $0.035 < \xi < 0.08 \rightarrow 227\ \text{GeV} = \omega_{min} < \omega < \omega_{max} = 520\ \text{GeV}$, where ξ is a fraction of the energy that the proton loses.

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



- Here both protons don't disintegrate $\to$ the EPA can be used.

$$\sigma\left(pp \to p\mu^+\mu^- p\right) = \int_0^\infty \int_0^\infty \sigma\left(\gamma\gamma \to \mu^+\mu^-\right)\, n_p(\omega_1)\, n_p(\omega_2)\, \mathrm{d}\omega_1\, \mathrm{d}\omega_2.$$

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

- The equivalent photon spectrum is:

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

where $Q^2 = q_\perp^2 + \omega^2/\gamma^2$.

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

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

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

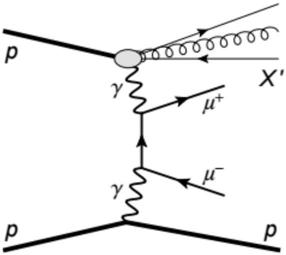
$$G_E(Q^2) = \frac{1}{(1 + Q^2/\Lambda^2)^2}, \quad G_M(Q^2) = \frac{\mu_p}{(1 + Q^2/\Lambda^2)^2}.$$

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

- $W = 4\omega_1\omega_2$.
- $y = \frac{1}{2}\ln\frac{\omega_1}{\omega_2}$, where $y = \eta + \frac{1}{2}\ln\frac{1-\sqrt{1-4p_T^2/W^2}}{1+\sqrt{1-4p_T^2/W^2}}$.
- After imposing ATLAS experimental constraints one obtains:

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

Inelastic case: $pp \to p(\gamma\gamma)p \to p\mu\mu X$



- Here one of the protons disintegrates $\to$ the EPA can't be used. The calculation can be performed within the parton model.

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

Inelastic case: $pp \to p(\gamma\gamma)p \to p\mu\mu X$

The cross-section for the reaction $pq \to p\mu\mu q$ is:

$$
\begin{aligned}
d\sigma_{pq\to p\mu^+\mu^- q} =& \frac{Q_q^2(4\pi\alpha)^2}{q_1^2 q_2^2}\rho^{(1)}_{\mu\nu}\rho^{(2)}_{\alpha\beta}M_{\mu\alpha}M^*_{\nu\beta}\times \\
& \times\frac{(2\pi)^4\delta^{(4)}(q_1+q_2-k_1-k_2)d\Gamma}{4\sqrt{(p_1p_2)^2-m_p^4}}\times \\
& \times\frac{d^3p_1^{'}}{(2\pi)^3 2E_1^{'}}\frac{d^3p_2^{'}}{(2\pi)^3 2E_2^{'}}\times f_q(x,Q_2^2)dx,
\end{aligned}
$$

where Q_q is a quark charge, $\rho^i_{\mu\nu}$ is a photon density matrix, $M_{\mu\alpha}$ is the amplitude of $\gamma\gamma^* \to \mu\mu$ process, $d\Gamma$ is a phase volume of the muon pair and $f_q(x,Q_2^2)$ is a parton distribution function (PDF).

Inelastic case: $pp \to p(\gamma\gamma)p \to p\mu\mu X$

- Changing to the photons helicity basis one obtains:

$$\rho_1^{\mu\nu}\rho_2^{\alpha\beta}M_{\mu\alpha}M^*_{\nu\beta} = (-1)^{a+b+c+d}\rho_1^{ab}\rho_2^{cd}M_{ac}M^*_{bd},$$

  where $a, b, c, d \in \{\pm 1, 0\}$

- Non-diagonal terms ($a \neq b$ *or* $c \neq d$) vanish after integration over phase space.
- For the amplitudes $|M_{\pm 0}|^2$ contribution we have:

$$|M_{\pm 0}|^2 \sim Q_2^2/W^2 \leq \left(\hat{p}_T^{\mu\mu}/W\right)^2 \ll 1.$$

- The transversal term reveals the chiral anomaly:

$$|M_{++}|^2 \sim \sin^2\theta[...] + \left\{\frac{1-v^2}{(1+v\cos\theta)^2} + \frac{1-v^2}{(1-v\cos\theta)^2}\right\}.$$

Inelastic case: $pp \to p(\gamma\gamma)p \to p\mu\mu X$

- The cross section $\sigma(\gamma\gamma \to \mu\mu)$ is a sum over transversal polarizations of photons:

$$\sigma(\gamma\gamma \to \mu\mu) = \int \frac{1}{4}\Big[|M_{++}|^2 + |M_{+-}|^2 + |M_{-+}|^2 + |M_{--}|^2\Big]\times$$
$$\times \frac{(2\pi)^4\delta^{(4)}(q_1 + q_2 - k_1 - k_2)d\Gamma}{4p_1p_2}.$$

- Similarly to the elastic case the equivalent photon spectrum of quark can be introduced:

$$n_q(\omega) = \frac{2Q_q^2\alpha}{\pi\omega}\int\limits_{\omega/E}^{1} dx \int\limits_{0}^{p_T^{\ell\ell}} dq_{2\perp}\frac{q_{2\perp}^3}{Q_2^4} f_q(x, Q_2^2).$$

Inelastic case: $pp \to p(\gamma\gamma)p \to p\mu\mu X$

- Under the approximation $\omega_1 \ll E$, $\omega_2 \ll xE$ one obtains:

$$\rho_1^{++} = \rho_2^{--} \approx D(Q_1^2) \cdot \frac{2E^2 q_{1\perp}^2}{\omega_1^2 Q_1^2},$$

$$\rho_1^{++} = \rho_2^{--} \approx \frac{2E^2 x^2 q_{2\perp}^2}{\omega_2^2 Q_2^2}.$$

- Using parton distribution functions *MSHT20nnlo_as118* (*Eur. Phys. J. C81, 341 (2021)*) provided by *LHAPDF* (*Eur. Phys. J. C75, 132 (2015)*) we get the cross section:

$$\sigma_{fid.}(pp \to p\mu^+\mu^- X) = 9.6\ fb.$$

Numerical results

- Elastic case:

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

- Inelastic case:

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

- Total elastic-inelastic cross-section is

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

- ATLAS results:

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

Survival factor

- The so-called *survival factor* $S(b)$ depending on the impact parameter b must be taken into account.
- For elastic case this factor provides 10% diminishing of the cross section. (*see JHEP 2021, 234 (2021)*)
- For inelastic case this factor provides 50% diminishing of the cross section. *(see Phys. Rev. D 104, 074009 (2021))*
- Thus the derived formulas are in agreement with the experimental data at the level of $2-3$ standard derivations.

γZ correction

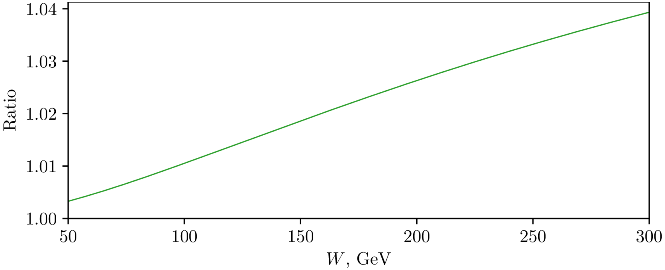
- Interference between processes due to vector and axial interaction is identically zero.
- The $|M_{\gamma Z}^{V}|^2 = |M_{\gamma Z}^{A}|^2$ in the limit $W \gg m$.
- $|M_{\gamma\gamma+\gamma Z}|^2 \equiv \varkappa |M_{\gamma\gamma}|^2$, where

$$\varkappa(Q_2^2) = 1 + 2\frac{g_V^\mu}{Q_\mu}\frac{g_V^q}{Q_q}\lambda + \frac{\left(g_A^q\right)^2 + \left(g_V^q\right)^2}{Q_\mu^2}\frac{\left(g_A^\mu\right)^2 + \left(g_V^\mu\right)^2}{Q_q^2}\lambda^2$$

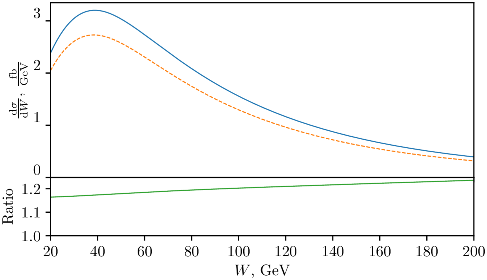
and $\lambda = \frac{1}{(2s_W c_W)^2\left(1 + M_Z^2/Q_2^2\right)}$.

γZ correction

- The ratio $\frac{(d\sigma/dW)_{\gamma\gamma+\gamma Z}}{(d\sigma/dW)_{\gamma\gamma}}$ is presented in the graph:



- If the lower limit on $p_T^{\mu\mu}$ grows the correction becomes larger:



Conclusion

- The analytical formulae for the cross section of the processes $pp \to p\mu\mu p$ and $pp \to p\mu\mu X$ were obtained.
- After implying experimental cuts on the theoretically obtained formulae the fiducial cross section was calculated.
- After taking into account the survival factor the derived formulae are in good agreement with the ATLAS results.
- The value of the γZ correction was calculated. It is shown that with the larger lower limit on $p_T^{\mu\mu}$ the contribution goes up to 20%.
- The numerical calculations were performed with the help of the library *libepa*: `https://github.com/jini-zh/libepa` developed within our group.
- The work is supported by RSF grant No. 19-12-00123-П.