Z boson contribution into the muon pair production in semi-exclusive proton-proton collisions at the LHC

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Introduction

- Searching for New Physics in proton-proton collisions at very high energies at the LHC is of a great interest.
- Possible indicator of the New Physics is a muon anomolous magnetic moment.
- The possible New Physics might manifest itself more significantly in muons interactions with large invariant mass.
- The effects coming from Z boson correction to the leading process of the pp scattering via $\gamma\gamma$ fusion will be investigated.
- The results are contained in the following paper: *"Weak interaction corrections to muon pair production via the photon fusion at the LHC Phys. Rev. D 108, 093006 (2023)*. arXiv:2308.01169

Results for semi-exclusive e/m muon pair production

- Quasielastic 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 cross-section is

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

"pp scattering at the LHC with the lepton pair production and one proton tagging". Eur. Phys. J. C 82, 1055 (2022).

- ATLAS results:

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

Phys. Rev. Lett. 125, 261801 (2020).

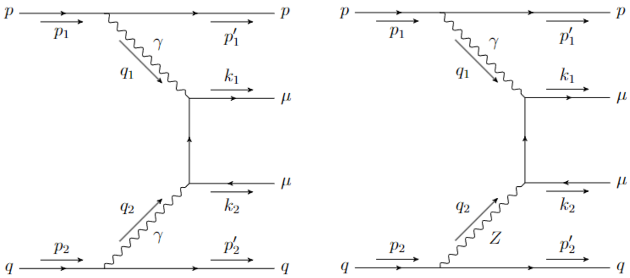
- Taking into account *survival factor* $S(b)$ leads to agreement with the experimental data at the level of $2 - 3$ standard derivations.

Feynman diagrams for Z contribution

- Proton survives $\to$ upper bound on Z virtuality $Q^2 \to$ $\to$ Z impact suppressed as $\hat{Q}^2/M_Z^2 \sim 10^{-5}$.
- Proton disintegrates $\to$ perform calculation within the parton model:

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

- Two types of terms: 1) the interference between $\gamma\gamma$ and γZ; 2) pure γZ.



Master formula for $pq \to p\mu^+\mu^- q$

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

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

  where Q_q is a quark charge, $\rho^i_{\mu\nu}$ is a vector boson density matrix, $M_{\mu\alpha}$ is the amplitude of $\gamma\gamma/\gamma Z \to \mu\mu$ process, x is a fraction of the proton momentum carried by quark q and $f_q(x, Q_2^2)$ is a parton distribution function (PDF).
- It is convenient to work in helicity representation:

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

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

Photon density matrices

Photon density matrix can be written as:

$$\rho^{(1)}_{++} = \rho^{(1)}_{--} \approx D\left(Q_1^2\right)\frac{2E^2 q_{1\perp}^2}{\omega_1^2 Q_1^2},$$

for the $pp\gamma$ vertex and

$$\rho^{(2)}_{++} = \rho^{(2)}_{--} \approx \frac{2x^2 E^2 q_{2\perp}^2}{\omega_2^2 Q_2^2}, \quad \rho^{(2)}_{00} \approx \frac{4x^2 E^2 q_{2\perp}^2}{\omega_2^2 Q_2^2},$$

for the $qq\gamma$ vertex. Here $q_{i\perp}^2 \approx Q_i^2 - \omega_i^2/\gamma^2$ and $D(Q_1^2)$ is a combination of Sachs form factors of the proton:

$$D\left(Q_1^2\right) = \frac{G_E^2\left(Q_1^2\right) + \left(Q_1^2/4m_p^2\right)G_M^2\left(Q_1^2\right)}{1 + Q_1^2/4m_p^2}.$$

Z boson density matrices

- Z interaction with quarks looks like:

$$\Delta L_{qqZ} = \frac{e}{s_W c_W}\left[\frac{g_V^q}{2}\bar{q}\gamma_\alpha q + \frac{g_A^q}{2}\bar{q}\gamma_\alpha\gamma_5 q\right] Z_\alpha, \quad s_W \equiv \sin\theta_W,$$
$$c_W \equiv \cos\theta_W, \quad g_V^q = T_3^q - 2Q_q s_W^2, \quad g_A^q = T_3^q.$$

- Under approximation $\omega_2/xE \ll 1$ one obtains for the interference density matrix:

$$\tilde{\rho}_{ab}^{(2)} \approx \frac{g_V^q}{2}\rho_{ab}^{(2)},$$

and for the Z only:

$$\tilde{\tilde{\rho}}_{ab}^{(2)} \approx \frac{\left(g_V^q\right)^2 + \left(g_A^q\right)^2}{4}\rho_{ab}^{(2)},$$

where $\rho_{ab}^{(2)}$ is a photon density matrix in the helicity representation.

Z contribution into the amplitude $M_{\gamma\gamma+\gamma Z}$

- The following statements can be proved:
  1. Interference between the processes due to vector and axial-vector interaction is identically zero.
  2. The square of the amplitude with the axial coupling equals that with the vector coupling (under approximation $W \gg m_\mu$, W is muon pair invariant mass).
- This leads us to a simple factorization of the correction due to weak interaction in the total amplitude:

$$|M_{\gamma\gamma+\gamma Z}|^2 \equiv \varkappa |M_{\gamma\gamma}|^2,$$

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

Helicity amplitudes

The following expressions for the diferent polarizations can be obtained:

$$|M_{+0}|^2 + |M_{-0}|^2 = (4\pi\alpha)^2 \frac{32 Q_2^2}{W^2\left(1 + Q_2^2/W^2\right)^2} \varkappa.$$

When $Q_2^2 = 0$ the square $|M_{\pm 0}|^2 = 0$.

$$|M_{+-}|^2 + |M_{-+}|^2 = (4\pi\alpha)^2 \frac{4\sin^2\theta\left(1 + \cos^2\theta\right)}{\left(1 + Q_2^2/W^2\right)^2} \times$$
$$\times \left[\frac{1}{1 - v\cos\theta} + \frac{1}{1 + v\cos\theta}\right]^2 \varkappa,$$

where $v = \sqrt{1 - 4m_\mu^2/W^2}$. For $\theta = 0, \pi$ the $|M_{\pm\mp}|^2 = 0$ due to the helicity conservation.

Chiral anomaly

- For the $++$ polarizations (and $--$ in the same way) one can write:

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

- In the limit $m_\mu \ll W$ the term $[...] \sin^2\theta = 0$ when $\theta = 0, \pi$ **but** the term in curly braces $\{...\} \neq 0$ and gives finite contribution into the cross section. It is the manifestation of the chiral anomaly.

Master formula for $pp \to p\mu\mu X$ with Z correction

Substituting density matrices and amplitude into the master formula and summing over all valent and sea quarks q one obtains:

$$\frac{d\sigma_{pp\to p\mu^+\mu^- X}}{dW} = \frac{4\alpha W}{\pi} \sum_q Q_q^2 \int\limits_{\frac{W^4}{36\gamma^2 s}}^{s} \frac{\sigma_{\gamma\gamma^*\to\mu^+\mu^-}(W^2, Q_2^2)}{(W^2+Q_2^2)Q_2^4} \cdot \varkappa\left(Q_2^2\right) \cdot dQ_2^2 \times$$

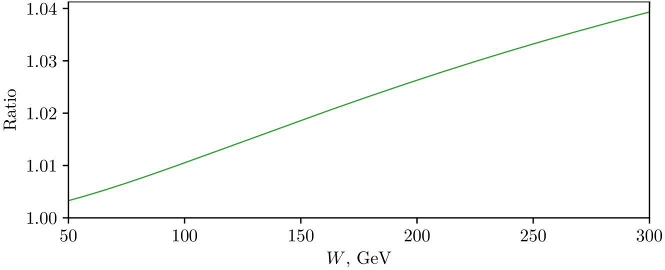
$$\times \int\limits_{\frac{W^2+Q_2^2}{s}\cdot\max\left(1, \frac{m_p}{3\sqrt{Q_2^2}}\right)}^{1} dx\, f_q(x, Q_2^2) \int\limits_{\frac{1}{2}\ln\left(\frac{W^2+Q_2^2}{x^2 s}\cdot\max\left(1,\frac{m_p^2}{9Q_2^2}\right)\right)}^{\frac{1}{2}\ln\frac{s}{W^2+Q_2^2}} \omega_1 n_p(\omega_1)\left[Q_2^2 - (\omega_2/3x\gamma)^2\right] dy$$

where y is a rapidity of a muon pair $y = (1/2)\ln\omega_1/\omega_2$, $\gamma = E/m$ and $n_p(\omega_1)$ is a modified equivalent photon spectrum of a proton:

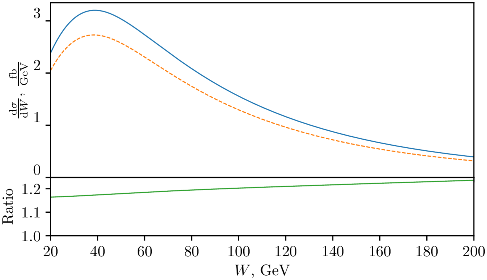
$$n_p(\omega_1) = \frac{\alpha}{\pi\omega_1} \int\limits_0^\infty \frac{D(Q_1^2)\, q_{1\perp}^2\, dq_{1\perp}^2}{Q_1^4}.$$

Value of the Z boson 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 contribution of Z boson into the semi-exclusive muon pair production in the ultrarelativistic proton-proton collisions at the LHC was investigated.
- Analytical formulas describing weak interaction correction into the cross section of $pp \to p\mu\mu X$ process were obtained.
- It was shown by means of helicity representation for the amplitudes that $M_{\pm\pm}$ term contains chiral anomaly.
- The numerical integration was performed with help of the special library *libepa*.
- It was shown that with the larger lower limit on $p_T^{\mu\mu}$ the contribution goes up to 20%.