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Muon pair production via the photon fusion at the LHC: weak interaction corrections

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We consider muon pair production in pp collisions in semiexclusive processes. In the leading order this process is described by $\gamma\gamma$ fusion. We consider the correction due to γZ fusion and demonstrate that it is small, at the level of a few percent. However, we show that with the help of kinematic cuts the relative contribution of weak interaction corrections can be enhanced and reach the level of 20%.

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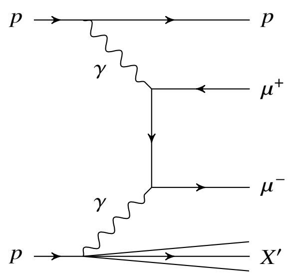


Figure 1: One of the diagrams describing inelastic part of the semiexclusive process.

1. Introduction

Ultraperipheral collisions (UPC) are events when source particles interact with their electromagnetic fields and remain intact after the collision. UPC is an excellent source of clean events for checking Standard Model and studying New Physics in $\gamma\gamma$ fusion. Let us note the following features of UPC: it is possible to detect protons in forward detectors to reconstruct full kinematics; it is accessible analytically with equivalent photons approximation (EPA); formulae can be easily adopted for new particles (γ couples to electric charge).

However, for the scattered proton to remain intact the square of the 4-momentum of the emitted photon (or Z boson) $Q^2 \equiv -q^2$ should not considerably exceed $(200\text{ MeV})^2$, since for larger Q^2 the cross section is suppressed by the elastic form factor [1, Appendix A]. Thus, for the relative γZ contribution in respect to $\gamma\gamma$ fusion we get:

$$Q^2 \lesssim (200\text{ MeV})^2 \quad \Rightarrow \quad \frac{Q^2}{M_Z^2 + Q^2} \sim 10^{-5}, \tag{1}$$

where M_Z is the Z boson mass. Therefore, the weak interaction contribution is negligible in case of UPC.

Both the CMS and the ATLAS collaborations reported [2, 3] observation of the reaction of lepton pair (e^+e^- or $\mu^+\mu^-$) production when *one* of the scattered protons is detected (that is why it is called semiexclusive) by forward detectors (the CMS–TOTEM precision proton spectrometer or the ATLAS Forward Proton Spectrometer). The other proton can remain intact or disintegrate. In the latter case (see Fig. 1) the following experimental cuts were imposed in muons case in [3]:

- $p_T > 15$ GeV — transverse momentum of each muon.
- $|\eta| < 2.4$ — pseudorapidity of each muon.
- $p_T^{\mu\mu} < 5$ GeV — net transverse momentum of muon pair.
- 20 GeV $< W <$ 70 GeV or $W >$ 105 GeV — invariant mass of muon pair.
- At least one proton hits a forward detector.

See our recent paper [4] with formulas and numerical estimates of the cross sections measured in [3].

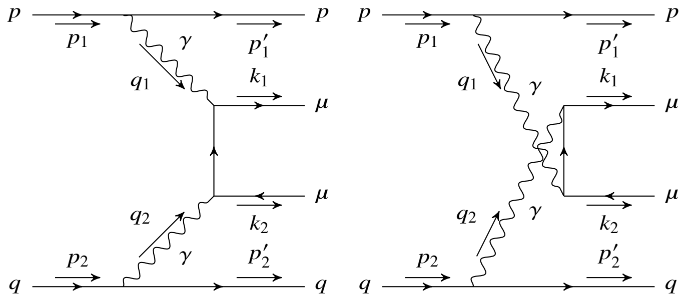


Figure 2: Diagrams corresponding to the $\mu^+\mu^-$ production via $\gamma\gamma$ fusion.

For photon emitted by the survived proton we have $Q_1^2 \ll (200\text{ MeV})^2$, therefore, for $\left(p_T^{\mu\mu}\right)^2 \gg 1\text{ GeV}^2$ we have $Q_2^2 \approx \left(p_T^{\mu\mu}\right)^2$ and

$$\frac{Q^2}{M_Z^2 + Q^2} \approx \frac{\left(p_T^{\mu\mu}\right)^2}{M_Z^2 + \left(p_T^{\mu\mu}\right)^2} \lesssim 10^{-3}. \tag{2}$$

Therefore, in this case weak interaction contribution is also negligible.

However, what if we remove these cuts? If only one of the protons remains intact while the second one disintegrates producing a hadron jet then substitution of the photon emitted by the second proton by a Z boson may lead to numerically noticeable corrections. This is so since the value of Q^2 is now bounded from above only by the invariant mass of the produced muon pair W (for $Q^2 > W^2$ the cross section of muon pair production via $\gamma\gamma$ fusion is suppressed as a power of W^2/Q^2, see (14)). In this way the contribution from the Z boson exchange being proportional to $\left[Q^2/(M_Z^2 + Q^2)\right]^2$ can become noticeable for $W^2 \gtrsim M_Z^2$.

When no cuts applied the inelastic part prevail over the quasielastic one, see for example our paper [5], so in what follows we consider only inelastic part of the cross section.

This talk is based on paper [6] written in collaboration with E. K. Karkaryan, V. A. Novikov, A. N. Rozanov, M. I. Vysotsky, E. V. Zhemchugov.

The paper is organized as follows. In Section 2 the necessary formulae for the $\gamma\gamma$ fusion processes are presented. In Section 3 the contribution from γZ fusion is discussed as well as its interference with $\gamma\gamma$ fusion; the results of numerical evaluation are also presented in this Section. In Section 4 we conclude.

2. $\gamma\gamma$ fusion

Since the virtuality of one photon can be significant, the EPA approximation can not be applied in its traditional form. Therefore special consideration is required. We closely follow [4] and the review of two-photon particle production [7].

Main contribution to the inelastic part of the cross section can be found within the parton approximation, i.e. considering quasielastic collisions of proton and quark from disintegrating proton (see Fig. 2). In this way we get:

$$\sigma_{\text{inelastic}}(pp \to p\mu^+\mu^- X) = \sum_q \sigma(pq \to p\mu^+\mu^- q) \tag{3}$$

where we sum over valent u and d and sea quarks.

The cross section for two-photon production can be written in the following way

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

where the leading factor 2 takes into account the symmetrical process where the other proton survives, α is the fine structure constant, Q_q is the charge of quark q, $\rho^{(1)}_{\mu\nu}$ and $\rho^{(2)}_{\mu\nu}$ are the density matrices of the photons, $M_{\alpha\beta}$ is the amplitude for $\gamma\gamma^*\to\mu^+\mu^-$ process, $\mathrm{d}\Gamma$ is the phase space of the muon pair, m_p is the proton mass, $f_q\left(x,Q_2^2\right)$ is the parton distribution function (PDF) for quark q, x is the fraction of the momentum of the disintegrating proton carried by the quark, $Q_2^2=-q_2^2$, E_1' and E_2' are the energies of the proton and the quark after the collision.

For the density matrix $\rho^{(1)}$ originating from the elastically scattered proton we have (see Eqs. (25-27) from [4]):

$$\rho^{(1)}_{\mu\nu}=-\left(g_{\mu\nu}-\frac{q_{1\mu}q_{1\nu}}{q_1^2}\right)G_M^2(Q_1^2)-\frac{(2p_1-q_1)_\mu(2p_1-q_1)_\nu}{q_1^2}D\left(Q_1^2\right), \quad (5)$$

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

Here $Q_1^2=-q_1^2$, and $G_E\left(Q_1^2\right)$, $G_M\left(Q_1^2\right)$ are the Sachs form factors of the proton. For the latter we use the dipole approximation:

$$G_E\left(Q^2\right)=\frac{1}{\left(1+Q^2/\Lambda^2\right)^2},\quad G_M\left(Q^2\right)=\frac{\mu_p}{\left(1+Q^2/\Lambda^2\right)^2},\quad \Lambda^2=\frac{12}{r_p^2}=0.66\ \mathrm{GeV}^2, \quad (6)$$

where $\mu_p=2.79$ is the proton magnetic moment and $r_p=0.84$ fm is the proton charge radius [8].

The density matrix of the photon emitted by the quark is

$$\rho^{(2)}_{\alpha\beta}=-\frac{1}{2q_2^2}\mathrm{Tr}\{\hat{p}_2^{'}\gamma_\alpha\hat{p}_2\gamma_\beta\}=-\left(g_{\alpha\beta}-\frac{q_{2\alpha}q_{2\beta}}{q_2^2}\right)-\frac{(2p_2-q_2)_\alpha(2p_2-q_2)_\beta}{q_2^2}. \quad (7)$$

It is convenient to consider the lepton pair production in the basis of virtual photon helicity states. In the center of mass system (c.m.s.) of the colliding photons, we have $q_1=(\tilde{\omega}_1,0,0,\tilde{q})$, $q_2=(\tilde{\omega}_2,0,0,-\tilde{q})$,

$$\rho_i^{\mu\nu}=\sum_{a,b}\left(e_i^{a\mu}\right)^*e_i^{b\nu}\rho_i^{ab}, \quad (8)$$

$$\rho_i^{ab}=(-1)^{a+b}e_i^{a\mu}\left(e_i^{b\nu}\right)^*\rho_i^{\mu\nu}, \quad (9)$$

where $e_i^{a\mu}$ is the standard set of orthonormal 4-vectors orthogonal to q_i, $a,b\in\{\pm1,0\}$, and ρ_i^{ab} are the density matrices in the helicity representation. The amplitudes of the lepton pair production in the helicity basis M_{ab} appear from the following equation:

$$\begin{aligned}\rho_1^{\mu\nu}\rho_2^{\alpha\beta}M_{\mu\alpha}M^*_{\nu\beta} = (-1)^{a+b+c+d}\rho_1^{ab}\rho_2^{cd}M_{ac}M^*_{bd} = \\ = \rho^{(1)}_{++}\rho^{(2)}_{++}|M_{++}|^2 + \rho^{(1)}_{++}\rho^{(2)}_{--}|M_{+-}|^2 + \rho^{(1)}_{++}\rho^{(2)}_{00}|M_{+0}|^2 + \\ + \rho^{(1)}_{--}\rho^{(2)}_{++}|M_{-+}|^2 + \rho^{(1)}_{--}\rho^{(2)}_{00}|M_{-0}|^2 + \rho^{(1)}_{--}\rho^{(2)}_{--}|M_{--}|^2. \end{aligned} \tag{10}$$

Matrix elements of the photon density matrices in the helicity representation for transverse polarizations were found in [4] (see also [7, 9]). For the first photon we have:

$$\rho^{(1)}_{++} = \rho^{(1)}_{--} \approx D\left(Q_1^2\right)\frac{2E^2 q^2_{1\perp}}{\omega_1^2 Q_1^2}, \tag{11}$$

where E is the proton energy in the c.m.s. of the colliding protons, $q_{1\perp}$ is the transversal momentum of the photon and ω_1 is its energy in the same system. For the second photon which is emitted by the quark with the initial energy xE, $0 < x < 1$, we have:

$$\rho^{(2)}_{++} = \rho^{(2)}_{--} = \frac{2x^2E^2q^2_{2\perp}}{\omega_2^2 Q_2^2}, \quad \rho^{(2)}_{00} = \frac{4x^2E^2q^2_{2\perp}}{\omega_2^2 Q_2^2}. \tag{12}$$

Due to simple form of (11) and (12), the expression (10) simplifies so the cross section of $\gamma\gamma^* \to \mu^+\mu^-$ factors out. In this way we get:

$$\frac{\mathrm{d}\sigma_{pq\to p\mu^+\mu^-q}}{\mathrm{d}W} = W\int\limits_{\frac{W^4}{36\gamma^2 s}}^{s-W^2}\sigma_{\gamma\gamma^*\to\mu^+\mu^-}\left(W^2, Q_2^2\right)\mathrm{d}Q_2^2\int\limits_{\frac{1}{2}\ln\left(\frac{W^2+Q_2^2}{s}\cdot\max\left(1,\frac{m_p^2}{9Q_2^2}\right)\right)}^{\frac{1}{2}\ln\frac{s}{W^2+Q_2^2}} n_p(\omega_1)\frac{\mathrm{d}n_q(\omega_2)}{\mathrm{d}Q_2^2}\mathrm{d}y, \tag{13}$$

where W is invariant mass of the muon pair and

$$\sigma_{\gamma\gamma^*\to\mu^+\mu^-} = \sigma_{TT} + \sigma_{TS}, \tag{14}$$

$$\sigma_{TS} \approx \frac{16\pi\alpha^2 W^2 Q_2^2}{\left(W^2+Q_2^2\right)^3}, \quad \sigma_{TT} \approx \frac{4\pi\alpha^2}{W^2}\left[\frac{1+Q_2^4/W^4}{\left(1+Q_2^2/W^2\right)^3}\ln\frac{W^2}{m^2} - \frac{\left(1-Q_2^2/W^2\right)^2}{\left(1+Q_2^2/W^2\right)^3}\right], \tag{15}$$

$$\omega_1 = \sqrt{W^2+Q_2^2}\cdot e^{y}/2, \quad \omega_2 = \sqrt{W^2+Q_2^2}\cdot e^{-y}/2, \tag{16}$$

$$n_p(\omega_1) = \frac{\alpha}{\pi\omega_1}\int\limits_0^\infty \frac{D(Q_1^2)q^2_{1\perp}\mathrm{d}q^2_{1\perp}}{Q_1^4}, \quad \text{(can be integrated analytically; see [6])} \tag{17}$$

$$\frac{\mathrm{d}n_q(\omega_2)}{\mathrm{d}Q_2^2} = \frac{\alpha Q_q^2}{\pi\omega_2}\int\limits_{\sqrt{\frac{W^2+Q_2^2}{s}}\cdot e^{-y}\cdot\max\left\{1,\frac{m_p}{3\sqrt{Q_2^2}}\right\}}^{1}\frac{Q_2^2-(\omega_2/3x\gamma)^2}{Q_2^4}f_q\left(x,Q_2^2\right)\mathrm{d}x. \tag{18}$$

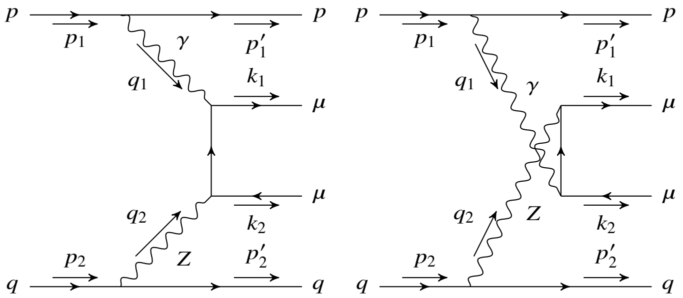


Figure 3: Diagrams for γZ fusion.

3. γZ fusion

To take into account γZ fusion we should add diagrams in Fig. 3 to ones shown in Fig. 2 getting 4 diagrams in leading order in total[1]. In Eq. (4) $\rho^{(1)}_{\alpha\beta}$ does not change but in addition to $\rho^{(2)}_{\alpha\beta}$ we get $\tilde{\rho}^{(2)}_{\alpha\beta}$ for interference of $\gamma\gamma$ and γZ diagrams and $\tilde{\tilde{\rho}}^{(2)}_{\alpha\beta}$ for the square of the γZ diagrams:

$$\tilde{\rho}^{(2)}_{\alpha\beta} = -\frac{1}{2q_2^2}\left[\frac{g_V^q}{2}\,\mathrm{Tr}\{\hat{p}_2'\gamma_\alpha\hat{p}_2\gamma_\beta\} + \frac{g_A^q}{2}\,\mathrm{Tr}\{\hat{p}_2'\gamma_\alpha\hat{p}_2\gamma_\beta\gamma_5\}\right], \tag{19}$$

$$\tilde{\tilde{\rho}}^{(2)}_{\alpha\beta} = -\frac{1}{2q_2^2}\,\mathrm{Tr}\left\{\hat{p}_2'\left(\frac{g_V^q}{2}\gamma_\alpha + \frac{g_A^q}{2}\gamma_\alpha\gamma_5\right)\hat{p}_2\left(\frac{g_V^q}{2}\gamma_\beta + \frac{g_A^q}{2}\gamma_\beta\gamma_5\right)\right\}, \tag{20}$$

where g_V^q and g_A^q are vector and axial couplings of Z boson to the quark q.

Calculating matrix elements of $\tilde{\rho}^{(2)}_{ab}$ in the helicity representation according to (9), in the limit $xE/\omega_2 \gg 1$ we get:

$$\tilde{\rho}^{(2)}_{ab} \approx \frac{g_V^q}{2}\rho^{(2)}_{ab}, \quad \tilde{\tilde{\rho}}^{(2)}_{ab} \approx \frac{(g_V^q)^2 + (g_A^q)^2}{4}\rho^{(2)}_{ab}. \tag{21}$$

For the sum of all four diagrams we have:

$$\mathcal{A} = A_\mu \cdot \bar{p}'\gamma_\mu p/q_1^2,\; A_\mu = \frac{eQ_q}{q_2^2}\bar{q}'\gamma_\alpha q M^\gamma_{\mu\alpha} + \frac{e}{s_W c_W (q_2^2 - M_Z^2)}\bar{q}'\left[\frac{g_V^q}{2}\gamma_\alpha + \frac{g_A^q}{2}\gamma_\alpha\gamma_5\right] q M^Z_{\mu\alpha}, \tag{22}$$

where $s_W \equiv \sin\theta_W$ and $c_W \equiv \theta_W$, θ_W is the weak mixing angle, and for the $\gamma\gamma \to \mu^+\mu^-$ and $\gamma Z \to \mu^+\mu^-$ amplitudes we have:

$$M^\gamma_{\mu\alpha} = Q_\mu^2 e^2\left[\bar{\mu}\gamma_\mu\frac{1}{\hat{k}_1 - \hat{q}_1 - m}\gamma_\alpha\mu + \bar{\mu}\gamma_\alpha\frac{1}{\hat{q}_1 - \hat{k}_2 - m}\gamma_\mu\mu\right], \tag{23}$$

$$M^Z_{\mu\alpha} = \frac{Q_\mu e^2}{s_W c_W}\left\{\frac{g_V^\mu}{2}\left[\bar{\mu}\gamma_\mu\frac{1}{\hat{k}_1 - \hat{q}_1 - m}\gamma_\alpha\mu + \bar{\mu}\gamma_\alpha\frac{1}{\hat{q}_1 - \hat{k}_2 - m}\gamma_\mu\mu\right] + \frac{g_A^\mu}{2}[\gamma_\alpha \to \gamma_\alpha\gamma_5]\right\} =$$

$$= \frac{1}{s_W c_W}\frac{g_V^\mu}{2Q_\mu}M^\gamma_{\mu\alpha} + \frac{Q_\mu e^2}{s_W c_W}\frac{g_A^\mu}{2}\left[\bar{\mu}\gamma_\mu\frac{1}{\hat{k}_1 - \hat{q}_1 - m}\gamma_\alpha\gamma_5\mu + \bar{\mu}\gamma_\alpha\gamma_5\frac{1}{\hat{q}_1 - \hat{k}_2 - m}\gamma_\mu\mu\right], \tag{24}$$

[1]Let us note that these are not the only possible tree diagrams, there are also bremsstrahlung-like diagrams producing photon/Z boson with the invariant mass of the pair. These diagrams were considered in [10] for processes where both protons were allowed to disintegrate. We believe that these diagrams are not that essential, at least, when W is not close to M_Z (see cut on W from [3] provided in Section 1), however, it certainly deserves a more detailed study.

where g_V^μ and g_A^μ are muon vector and axial couplings, $Q_\mu = -1$ is the muon electric charge which was not substituted for generality.

For the square of the amplitude we get (see details in [6]):

$$|\mathcal{A}|^2 \equiv \varkappa \left|\mathcal{A}_{\gamma\gamma}\right|^2, \quad \varkappa\left(Q_2^2\right) = 1 + 2\cdot\frac{g_V^\mu}{Q_\mu}\cdot\frac{g_V^q}{Q_q}\cdot\lambda + \frac{\left(g_V^\mu\right)^2+\left(g_A^\mu\right)^2}{Q_\mu^2}\cdot\frac{\left(g_V^q\right)^2+\left(g_A^q\right)^2}{Q_q^2}\cdot\lambda^2, \tag{25}$$

$$\lambda \equiv \frac{1}{(2s_W c_W)^2\left(1+M_Z^2/Q_2^2\right)}, \tag{26}$$

where $\mathcal{A}_{\gamma\gamma}$ is the amplitude via $\gamma\gamma$ fusion only.

Therefore the modification of (13) is very simple: one should insert $\varkappa\left(Q_2^2\right)$ under integration over Q_2^2.

The accuracy of (13) is at the level of 20%. The different sources contributing to this uncertainty are discussed in [6]. Let us stress that this uncertainty appears mostly due to effects of low-Q^2 physics and it does not affect the absolute value of the correction.

Results of numerical calculation are shown in Fig. 4. The weak interaction correction does not exceed a few percent. The reason for that is clear: all scales of Q_2^2 in (13) are equally important while for the weak interaction correction only the domain $M_Z^2 \lesssim Q_2^2 \lesssim W^2$ is relevant.

The weak interaction correction is more pronounced when we set the lower limit on Q_2^2, $Q_2^2 > \hat{Q}_2^2$, closer to the electroweak scale, M_Z^2. For $\hat{Q}_2 \gg 1$ GeV it means a cut on the total transverse momentum of the produced pair, $p_T^{\mu\mu} > \hat{Q}_2$. Such a selection is both theoretically and experimentally clean. From the theory side we have no complications due to low-Q^2 physics. From the experiment side this selection means high-p_T events with two distinguishable muons (at least for $W \gtrsim \hat{Q}_2$ since the cross section is additionally suppressed for $Q_2^2 > W^2$, see (14)). The results for $\hat{Q}_2 = 30,\ 50,\ 70$ GeV are shown in Fig. 5. We see that the correction reaches 20 %.

In the limit $Q_2^2 \gg M_Z^2$ the function $\varkappa(Q_2^2)$ reaches its maximum value:

$$\varkappa\left(Q_2^2\right) \approx 1 + 2\cdot\frac{g_V^\mu}{Q_\mu}\cdot\frac{g_V^q}{Q_q}\cdot\frac{1}{(2s_W c_W)^2} + \frac{\left(g_V^\mu\right)^2+\left(g_A^\mu\right)^2}{Q_\mu^2}\cdot\frac{\left(g_V^q\right)^2+\left(g_A^q\right)^2}{Q_q^2}\cdot\frac{1}{(2s_W c_W)^4} \approx \tag{27}$$
$$\approx \begin{cases} 1.35 & \text{for} \quad q = u,\ \bar{u},\ c,\ \bar{c}; \\ 2.76 & \text{for} \quad q = d,\ \bar{d},\ s,\ \bar{s},\ b,\ \bar{b}. \end{cases}$$

However, to get an idea of what the correction in principle might be, one should know how much up- and down-type quarks contribute to the cross section in photon–photon fusion. We calculated individual contributions of each quark into the cross section (13). For $\hat{Q}_2 = 70$ GeV and $W = 20$ GeV, up-type quarks combined $(u + \bar{u} + c + \bar{c})$ give 78 % (and this value slowly depends on W). Consequently, the asymptotic value of the enhancement is $0.78\cdot 1.35 + 0.22\cdot 2.76 \approx 1.6$.

4. Conclusions

For ultraperipheral collisions weak interaction correction is negligible. In case of semi-exclusive process weak interaction correction to the lepton pair production gives few percent increase of the production cross section. When the lower limit on the net transverse momentum of the produced pair is set, the correction goes up and can reach 20 %.

Numerical calculations were performed with the help of `libepa` [11].

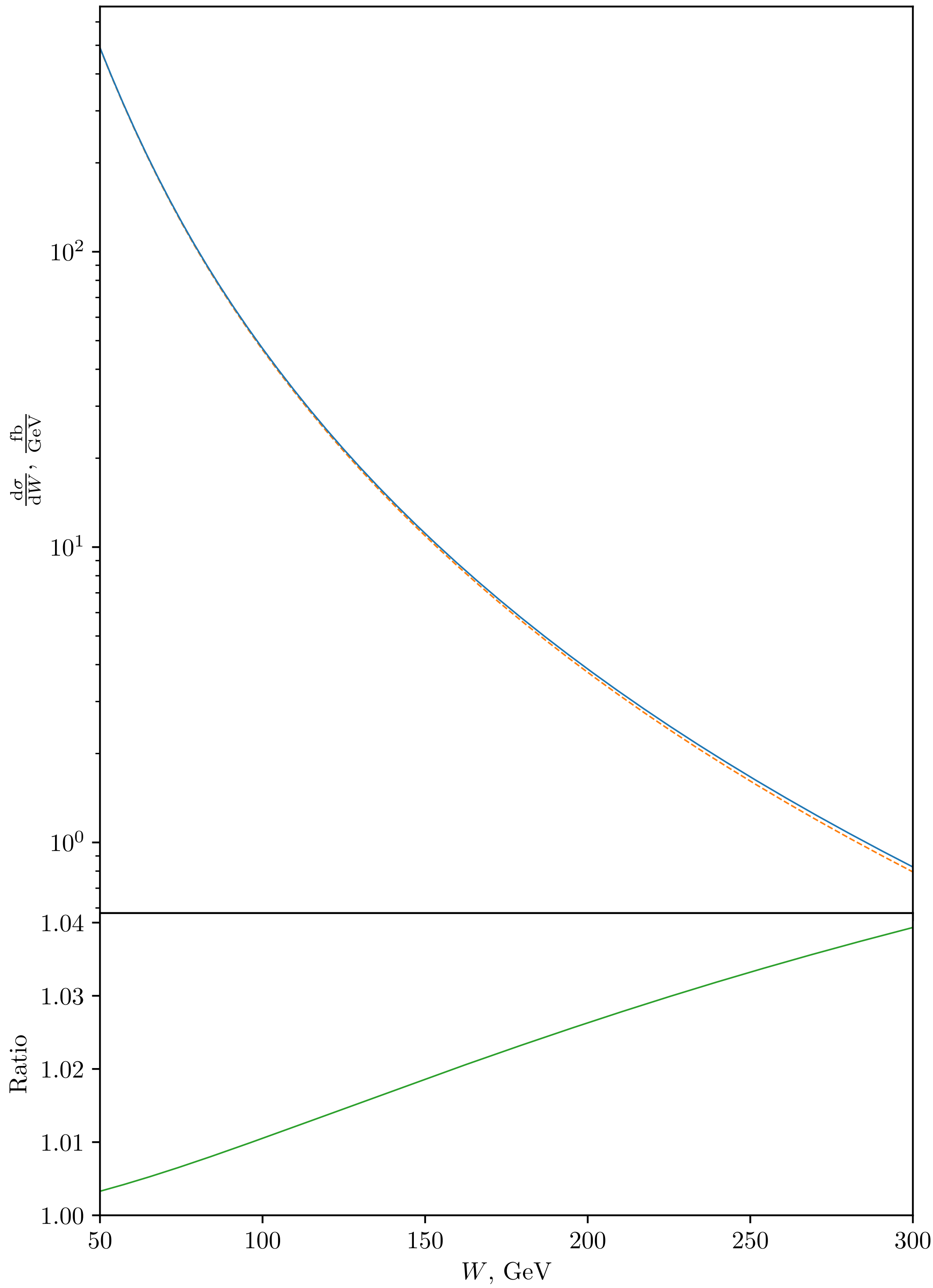
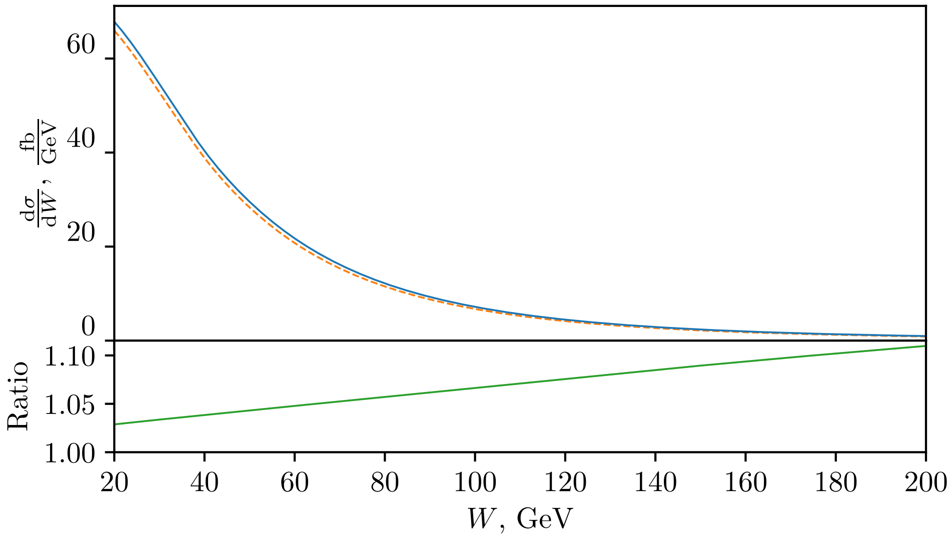
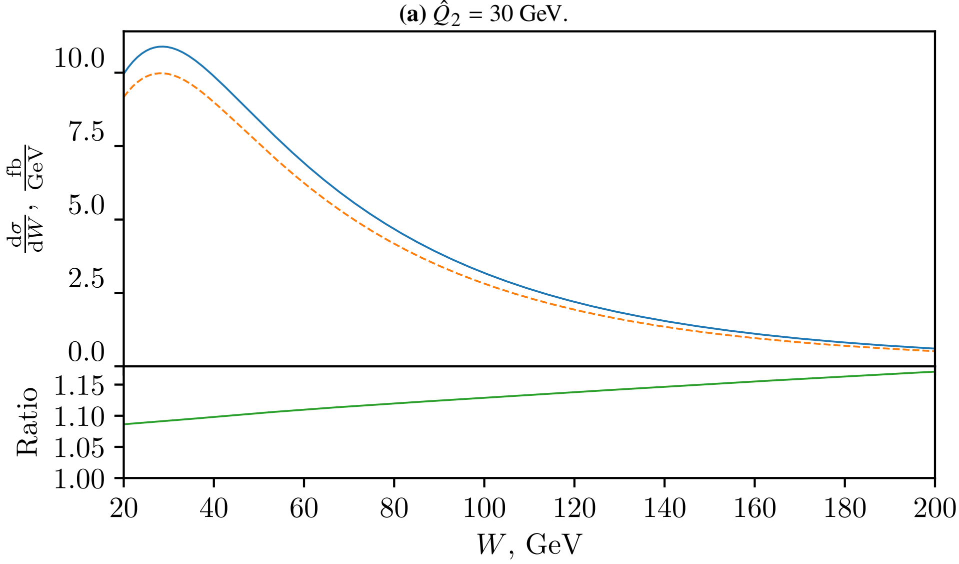


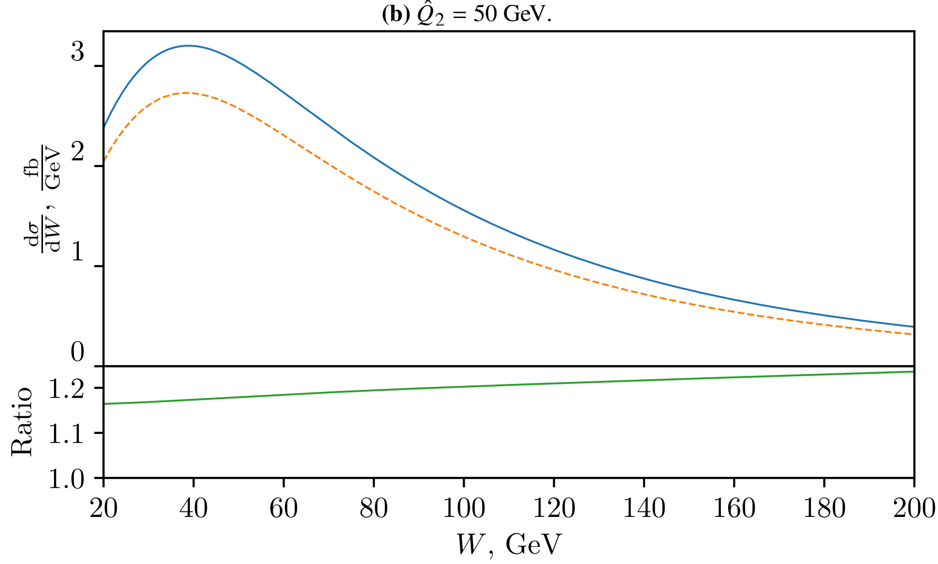
Figure 4: *Upper plot:* differential cross section of the photon fusion only (orange dashed line) and with the weak interaction correction taken into account (blue solid line). *Lower plot:* their ratio.



(a) $\hat{Q}_2$ = 30 GeV.



(b) $\hat{Q}_2$ = 50 GeV.



(c) $\hat{Q}_2$ = 70 GeV.

Figure 5: Differential cross sections for different lower limits on Q_2^2. Styles and colors of the lines are the same as in Fig. 4.

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References

[1] M.I. Vysotsky and E.V. Zhemchugov, *Equivalent photons in proton–proton and ion–ion collisions at the Large Hadron Collider*, *Phys. Usp.* **62** (2019) 910 [1806.07238].

[2] CMS, TOTEM collaboration, *Observation of proton-tagged, central (semi)exclusive production of high-mass lepton pairs in pp collisions at 13 TeV with the CMS-TOTEM precision proton spectrometer*, *JHEP* **07** (2018) 153 [1803.04496].

[3] ATLAS collaboration, *Observation and Measurement of Forward Proton Scattering in Association with Lepton Pairs Produced via the Photon Fusion Mechanism at ATLAS*, *Phys. Rev. Lett.* **125** (2020) 261801 [2009.14537].

[4] S.I. Godunov, E.K. Karkaryan, V.A. Novikov, A.N. Rozanov, M.I. Vysotsky and E.V. Zhemchugov, *pp scattering at the LHC with the lepton pair production and one proton tagging*, *Eur. Phys. J. C* **82** (2022) 1055 [2207.07157].

[5] S.I. Godunov, E.K. Karkaryan, V.A. Novikov, A.N. Rozanov, M.I. Vysotsky and E.V. Zhemchugov, *Forward Proton Scattering in Association with Muon Pair Production via the Photon Fusion Mechanism at the LHC*, *JETP Lett.* **115** (2022) 59 [2112.01870].

[6] S.I. Godunov, E.K. Karkaryan, V.A. Novikov, A.N. Rozanov, M.I. Vysotsky and E.V. Zhemchugov, *Weak interaction corrections to muon pair production via the photon fusion at the LHC*, *Phys. Rev. D* **108** (2023) 093006 [2308.01169].

[7] V.M. Budnev, I.F. Ginzburg, G.V. Meledin and V.G. Serbo, *The Two photon particle production mechanism. Physical problems. Applications. Equivalent photon approximation*, *Phys. Rept.* **15** (1975) 181.

[8] E. Tiesinga, P.J. Mohr, D.B. Newell and B.N. Taylor, *CODATA recommended values of the fundamental physical constants: 2018**, *Rev. Mod. Phys.* **93** (2021) 025010.

[9] A. Dobrovolskaya and V. Novikov, *On heavy Higgs boson production*, *Z. Phys. C* **52** (1991) 427.

[10] L.A. Harland-Lang, *Physics with leptons and photons at the LHC*, *Phys. Rev. D* **104** (2021) 073002 [2101.04127].

[11] E.V. Zhemchugov, S.I. Godunov, E.K. Karkaryan, V.A. Novikov, A.N. Rozanov and M.I. Vysotsky, *libepa – a C++/Python library for calculations of cross sections of ultraperipheral collisions*, 2311.01353.