# Forward proton scattering in association with muon pair production via the photon fusion mechanism at the LHC

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# Introduction

- Recent measurement of muon magnetic moment at Fermilab has confirmed the deviation from the Standard Model prediction of more than $4\sigma$.
- If it is a manifestation of New Physics, one should expect that at higher energies the deviations in the interactions of muons should be larger.
- Since ultraperipheral collisions are a source of very clean events, they can help to constrain parameters of new particles that can be responsible for this difference.
- At the LHC muon pairs are produced with high invariant masses in ultraperipheral collisions of hadrons, and this gives a chance for New Physics to be detected.
- Here analytical expressions for the cross section of the muon pair production when one of protons remain intact are provided.
- With help of the derived formulas, the cross section values can be evaluated by the standard numerical integration routines rather than Monte Carlo simulations.

# The leading order Feynman diagram for the ultraperipheral collision

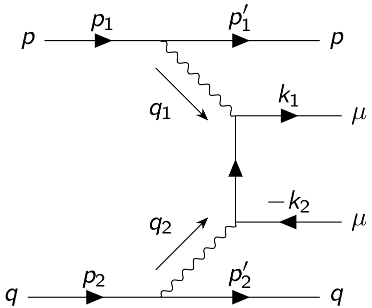


Figure 1: A $\gamma\gamma$ fusion mechanism of muon pair production.

# Cross section of $pq \to p\mu^+\mu^- q$

- Using standard Feynman rules the master formula of the process under consideration can be obtained:

$$d\sigma_{pq\to p\mu^+\mu^- q} = \frac{Q_q^2(4\pi\alpha)^2}{(q_1^2)^2(q_2^2)^2}(q_1^2\rho^{(1)}_{\mu\nu})(q_2^2\rho^{(2)}_{\alpha\beta})M_{\mu\alpha}M^*_{\nu\beta}\times \tag{1}$$

$$\times\frac{(2\pi)^4\delta^{(4)}(q_1+q_2-k_1-k_2)d\Gamma}{4\sqrt{(p_1p_2)^2-m_p^4}}\frac{d^3p_1'}{(2\pi)^3 2E_1'}\frac{d^3p_2'}{(2\pi)^3 2E_2'}.$$

- For the density matrices $\rho^{(1)}_{\mu\nu}$ we get:

$$\rho^{(1)}_{\mu\nu} = -\frac{1}{2q_1^2}Sp\{(\hat{p}_1'+m_p)\gamma_\mu(\hat{p}_1+m_p)\gamma_\nu\} = \tag{2}$$

$$= -\left(g_{\mu\nu}-\frac{q_{1\mu}q_{1\nu}}{q_1^2}\right)-\frac{(2p_1-q_1)_\mu(2p_1-q_1)_\nu}{q_1^2},$$

and a similar expression for $\rho^{(2)}_{\alpha\beta}$.

# On photon polarization

- Since the photons, emitted by the protons, are virtual they have three polarizations: two transversal ones and a longitudial (scalar) one.
- Accordnig to the signature of the described process one of the protons has to remain intact, so for the square of the momentum transfer $-q_1^2 \lesssim \hat{q}^2$, where $\hat{q} \sim \Lambda_{QCD}$.
- As for the quark, its value of the transferred momentum $-q_2^2$ is approximately bounded by the invariant mass of the muon pair $W$, because the cross section of the reaction $\gamma\gamma^* \to \mu^+\mu^-$ quickly decreases as $W^2/(-q_2^2)$.
- Thus the photon with the momentum $q_1$ is emitted quasielastically and is polarized transversally, while the photon with the momentum $q_2$ can also be longitudinally polarized.

# Density matrices approximate expressions

- The most appropriate way to deal with the density matrices is to introduce the basis of virtual photons helicity states.
- In the centre-of-mass system of colliding photons we have:

$$e^{(1)}_{\mu}(\pm 1) = \frac{1}{\sqrt{2}}(0, \mp 1, -i, 0),\ \ e^{(1)}_{\mu}(0) = \frac{i}{\sqrt{-q_1^2}}(\widetilde{q}_1, 0, 0, \widetilde{\omega}_1), \qquad (3)$$

  and similar expressions for the $e^{(2)}_{\mu}$.
- Since this set of vectors forms an orthonomal basis for othogonal to $q_{1\mu}$ ($q_{2\mu}$ respectively) subspace, we may write the following expansion:

$$\rho^{(i)}_{\mu\nu} = \sum_{a,b} [e^{(i)}_{\mu}(a)]^* e^{(i)}_{\nu}(b) \rho^{(i)}_{ab},\ \ a, b = \pm 1, 0. \qquad (4)$$

- $\rho^{(i)}_{ab}$ are the density matrices in the helicity representation, that can be approximately ($E \gg \omega_1$, $xE \gg \omega_2$) written in the following way

$$\rho^{(1)}_{++} = \rho^{(1)}_{--} = 2\frac{E^2}{\omega_1^2},\ \ \rho^{(1)}_{00} = 4\frac{E^2}{\omega_1^2},$$
$$\rho^{(2)}_{++} = \rho^{(2)}_{--} = 2\frac{x^2E^2}{\omega_2^2},\ \ \rho^{(2)}_{00} = 4\frac{x^2E^2}{\omega_2^2}. \qquad (5)$$

# Master formula for $d\sigma_{pq\to p\mu^+\mu^- q}$

- Finally we obtain

$$d\sigma_{pq\to p\mu^+\mu^- q} = \left(\frac{\alpha}{\pi}\right)^2 Q_q^2 \frac{(q_1 q_2)}{(p_1 p_2)} \sigma_{\gamma\gamma^*\to\mu^+\mu^-}(q_2^2, W) x E^2 \frac{dq_{1\perp}^2}{q_1^2} \frac{dq_{2\perp}^2}{q_2^2} \frac{d\omega_1}{\omega_1^2} \frac{d\omega_2}{\omega_2^2}. \tag{6}$$

- For the inner cross section of the muon pair production via $\gamma^*\gamma$ fusion one can write

$$d\sigma_{\gamma\gamma^*\to\mu^+\mu^-} = \frac{\sum \overline{|M|^2}\ d\cos\theta}{32\pi W^2(1 - q_2^2/W^2)},$$

$$\sum \overline{|M|^2} = \frac{1}{4}\left[|M_{++}|^2 + |M_{+-}|^2 + |M_{-+}|^2 + |M_{--}|^2 + 2|M_{+0}|^2 + 2|M_{-0}|^2\right], \tag{7}$$

where $M_{\pm\pm}$, $M_{\pm 0}$ are the amplitudes of the process $\gamma\gamma^* \to \mu^+\mu^-$ with the corresponding photons polarizations.

# Master formula for $d\sigma_{pq\to p\mu^+\mu^- q}$

- Integration over $q_{1\perp}^2$ is easily performed: $\int dq_{1\perp}^2/q_1^2 = 2\ln \hat{q}\gamma/\omega_1$, where $\gamma = E/m_p$ is the Lorentz factor of the proton.
- It is convenient to change the integration variables from the photon energies $\omega_1$ and $\omega_2$ to the square of the invariant mass of the produced pair $W^2$ and the ratio of photon energies $y = \omega_1/\omega_2$: $d\omega_1 d\omega_2 dq_{2\perp}^2 = (1/8y) dW^2 dy dQ_2^2$, where $Q_2^2 = -q_2^2$.
- Taking into consideration the upper bounds on photon energies $\omega_1 \le \hat{q}\gamma$, $\omega_2 \le xE$, we obtain the final formula:

$$\sigma_{pp\to p\mu^+\mu^- X} = 2\cdot\left(\frac{\alpha}{\pi}\right)^2 \sum_q Q_q^2 \int\limits_{\hat{W}^2}^{\infty} dW^2 \int\limits_0^{s\hat{q}/m_p - W^2} \frac{\sigma_{\gamma\gamma^*\to\mu^+\mu^-}(Q_2^2, W^2)}{W^2+Q_2^2} dQ_2^2 \times$$

$$\times \int\limits_{\frac{W^2+Q_2^2}{s\hat{q}/m_p}}^{1} f_q(x, Q_2^2) dx \int\limits_{(W^2+Q_2^2)/x^2 s}^{(2\hat{q}\gamma)^2/(W^2+Q_2^2)} \frac{dy}{y} \frac{\ln\left(\hat{q}\gamma/\omega_1\right)}{Q_2^2 + \left(\omega_2/x\gamma\right)^2}, \quad (8)$$

where $\omega_1 = \sqrt{y(W^2+Q_2^2)}/2$, $\omega_2 = \sqrt{W^2+Q_2^2}/(2\sqrt{y})$ and $f_q(x, Q_2^2)$ is the $q$-quark density function.

# Numerical result

- The differential cross section $d\sigma_{pp\to p\mu^+\mu^- X}/dW$ for $W > 12$ GeV is shown in Fig. 2

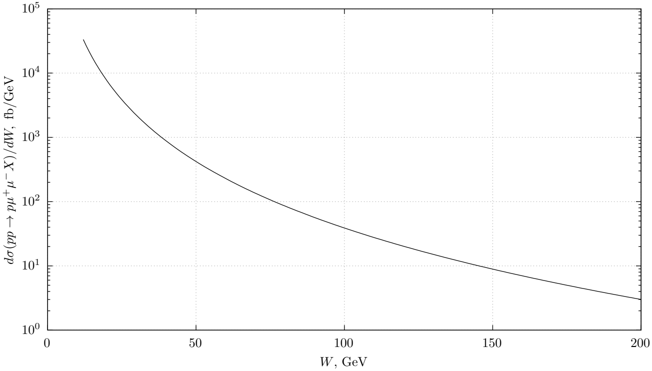


Figure 2: The spectrum $d\sigma_{pp\to p\mu^+\mu^- X}/dW$ of muon pairs produced in photons fusion with one forward proton.

- The integrated cross section in this region is

$$\sigma_{pp\to p\mu^+\mu^- X}(W > 12 \text{ GeV}) = 203 \text{ pb.} \tag{9}$$

# Conclusions

- Analytical formulas for the cross section of $\mu^+\mu^-$ pair production in semi-inclusive *pp*-scattering at the LHC were obtained.
- Numerical integration was performed and the spectrum of the produced pairs is presented in Fig. 2.
- Obtained formulas can be modified for 1) calculation of chargino production by taking into account the chargino mass, 2) ion-ion collisions and more accurate *pp*-collisions by taking into consideration form-factors and survival factors and 3) semi-inclusive processes with gauge bosons.
- Thus the theoretical description of the semi-inclusive ultraperipheral reactions provided above and future researches based on the current work are highly desirable for searches of New Physics.
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