PROCEEDINGS OF SCIENCE

Central $\mu^+\mu^-$ production via photon-photon fusion in proton-proton collisions with proton dissociation

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We report a study on the description of two-photon production of dimuons in proton-proton collisions. We focus on the region of high transverse momentum of the muon pairs, where contributions from proton dissociative events are important. Here one must go beyond the Weizsäcker-Williams approximation of collinear photons and take the photon transverse momenta into account. The resulting formalism in the high-energy limit can be understood as a type of k_T-factorization where the transverse momentum dependent photon fluxes play the role of "unintegrated" photon densities. The calculation of the unintegrated photon fluxes for dissociative events requires knowledge of proton structure functions in a broad range of $x_{\rm Bj}$ and Q^2, which we will discuss.

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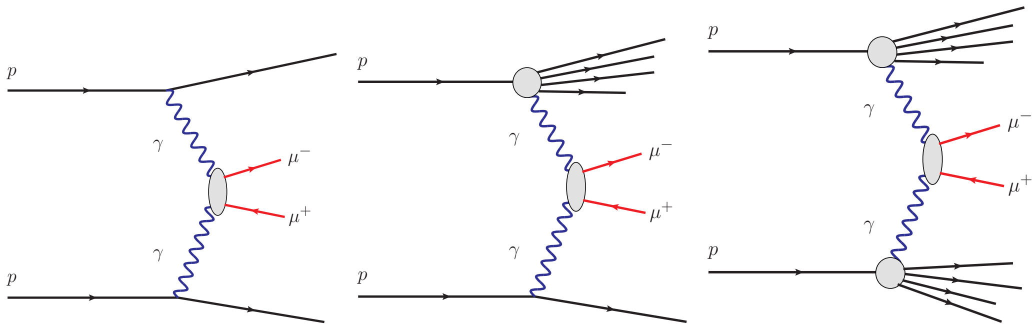

Figure 1: Mechanisms of lepton pair production throught $\gamma\gamma$-fusion: elastic-elastic, elastic-inelastic and inelastic-inelastic processes.

1. Introduction

Recently, there has been much interest in exclusive processes at high energies, in which the incoming protons emerge intact in the final state and some simple system is produced in the central region. In practice, due to the incomplete instrumentation of detectors one has to include also the dissociation of protons (see figure 1). Here we analyze the QED process of muon-pair production (see e.g. [1]), in which case inelastic dissociation is -at least in principle- calculable in terms of measured proton structure functions. Having the spin one, photon exchanges can contribute to the same event topologies as the Pomeron exchange.

2. Formalism

Much useful information on the two-photon mechanism of particle production is found in [2]. Here however we are interested in distributions fully differential in muon variables, and it is best to start from scratch from the direct evaluation of Feynman diagrams. We are interested in a case where the final state lepton pair is separated by a large rapidity from all other final state particles, which is a typical feature of the high-energy limit. In such a limit, the cross section differential in the lepton rapidities $y_\pm$ and transverse momenta $\vec{p}_{T\pm}$ can be written in the form familiar from the k_T–factorization [3]:

$$\frac{d\sigma(AB \to Xl^+l^-Y)}{dy_+dy_-d^2\vec{p}_{T+}d^2\vec{p}_{T-}} = \int \frac{d^2\vec{q}_{T1}}{\pi\vec{q}_{T1}^{\,2}} \frac{d^2\vec{q}_{T2}}{\pi\vec{q}_{T2}^{\,2}} \mathscr{F}^{(i)}_{\gamma^*/A}(x_1,\vec{q}_{T1})\, \mathscr{F}^{(j)}_{\gamma^*/B}(x_2,\vec{q}_{T2}) \frac{d\sigma^*(p_+,p_-;\vec{q}_{T1},\vec{q}_{T2})}{dy_+dy_-d^2\vec{p}_{T+}d^2\vec{p}_{T-}}\,. \tag{2.1}$$

where the longitudinal momentum fractions of photons are calculated from

$$x_1 = \frac{m_{\perp+}}{\sqrt{s}}e^{y_+} + \frac{m_{\perp-}}{\sqrt{s}}e^{y_-}\,,\, x_2 = \frac{m_{\perp+}}{\sqrt{s}}e^{-y_+} + \frac{m_{\perp-}}{\sqrt{s}}e^{-y_-}\,,\, m_{\perp\pm} = \sqrt{\vec{p}_{T\pm}^{\,2} + m_l^2}\,.$$

The important quantities are the unintegrated photon densities $\mathscr{F}^{(\mathrm{el/inel})}_{\gamma^*/A}(x,\vec{q}_T)$ which read explicitly

$$\mathscr{F}^{(\mathrm{el})}_{\gamma^*/A}(x,\vec{q}_T) = \frac{\alpha_{\mathrm{em}}}{\pi}(1-x)\left[\frac{\vec{q}_T^{\,2}}{\vec{q}_T^{\,2}+x^2m_A^2}\right]^2 \frac{4m_p^2G_E^2(Q^2)+Q^2G_M^2(Q^2)}{4m_p^2+Q^2}\left(1-\frac{Q^2-\vec{q}_T^{\,2}}{Q^2}\right)\,, \tag{2.2}$$

for the elastic, coherent contribution. It is calculated in terms of the proton electric and magnetic formfactors $G_{E,M}(Q^2)$, and

$$\mathscr{F}^{(\mathrm{inel})}_{\gamma^*/A}(x,\vec{q}_T) = \frac{\alpha_{\mathrm{em}}}{\pi}(1-x)\int_{M^2_{\mathrm{thr}}}^{\infty} \frac{dM_X^2 F_2(M_X^2,Q^2)}{M_X^2+Q^2-m_p^2}\Big(1-\frac{Q^2-\vec{q}_T{}^2}{Q^2}\Big)\Big[\frac{\vec{q}_T{}^2}{\vec{q}_T{}^2+x(M_X^2-m_A^2)+x^2m_A^2}\Big]^2, \tag{2.3}$$

for the inelastic contribution in which the proton breaks up into a system of invariant mass M_X, over which we integrate here. It is a property of the high-energy limit that fluxes of transverse and longitudinal virtual photons are equal and only the structure function $F_2 = 2xF_1 + F_L$ appears.

The other ingredient of our calculation is the off-shell cross section for the fusion of virtual photons, which reads [1]:

$$\frac{d\sigma^*(p_+,p_-;\vec{q}_{T1},\vec{q}_{T2})}{dy_1 dy_2 d^2\vec{p}_{T+} d^2\vec{p}_{T-}} = \frac{\alpha^2_{\mathrm{em}}}{\vec{q}_{T1}^{\,2}\vec{q}_{T2}^{\,2}}\sum_{\lambda,\bar\lambda}\Big|B_{\lambda\bar\lambda}(p_+,p_-;q_1,q_2)\Big|^2\delta^{(2)}(\vec{q}_{T1}+\vec{q}_{T2}-\vec{p}_{T+}-\vec{p}_{T-}).$$

If we parametrize the lepton four-momenta in terms of their Sudakov-parameters as

$$p_\pm = \alpha_\pm p_1 + \beta_\pm p_2 + p_{\pm\perp},\, \beta_\pm = \frac{\vec{p}_{T\pm}^{\,2}+m^2}{\alpha_\pm s}, \tag{2.4}$$

the off-shell cross section takes a particularly simple form in terms of the variables [4]:

$$z_\pm = \frac{\alpha_\pm}{\alpha},\, \vec{k}_T = z_-\vec{p}_{T+} - z_+\vec{p}_{T-}\,. \tag{2.5}$$

The familiar structures

$$\begin{aligned}\Phi_0 &= \frac{1}{(\vec{k}_T+z_+\vec{q}_{T2})^2+\varepsilon^2} - \frac{1}{(\vec{k}_T-z_-\vec{q}_{T2})^2+\varepsilon^2}\,,\\ \vec{\Phi}_T &= \frac{\vec{k}_T+z_+\vec{q}_{T2}}{(\vec{k}_T+z_+\vec{q}_{T2})^2+\varepsilon^2} - \frac{\vec{k}_T-z_-\vec{q}_{T2}}{(\vec{k}_T-z_-\vec{q}_{T2})^2+\varepsilon^2}\,,\end{aligned} \tag{2.6}$$

with $\varepsilon^2 = m_l^2 + z_+z_-\vec{q}_{T1}^{\,2}$, enter the off-shell matrix element:

$$\begin{aligned}\sum_{\lambda,\bar\lambda}\Big|B_{\lambda\bar\lambda}(p_+,p_-;q_1,q_2)\Big|^2 &= 2z_+z_-\vec{q}_{T1}^{\,2}\Big[\underbrace{4z_+^2z_-^2\vec{q}_{T1}^{\,2}\Phi_0^2}_{L} + \underbrace{(z_+^2+z_-^2)\vec{\Phi}_T{}^2 + m_l^2\Phi_0^2}_{T}\\ &+ \underbrace{\Big[\vec{\Phi}_T\times\frac{\vec{q}_{T1}}{|\vec{q}_T|}\Big]^2 - \Big(\frac{\vec{\Phi}_T\cdot\vec{q}_{T1}}{|\vec{q}_{T1}|}\Big)^2}_{TT'} + \underbrace{4z_+z_-(z_+-z_-)\Phi_0(\vec{q}_{T1}\vec{\Phi}_T)}_{LT}\Big]\end{aligned} \tag{2.7}$$

We indicated the terms corresponding to photon 1 being in the longitudinal or transverse polarization states and the respective interference contributions.

3. Selected Results

The results shown here were obtained using a standard dipole parametrization for the elastic formfactors, and the Szczurek-Uleshchenko parametrization [5] for F_2. We use two sets of cuts:

[1]Note that (the transverse) virtual photons carry the linear polarizations parallel to $\vec{q}_{T1},\vec{q}_{T2}$, and the averaging over photon polarizations is in fact effected by the azimuthal integrations in eq.(2).

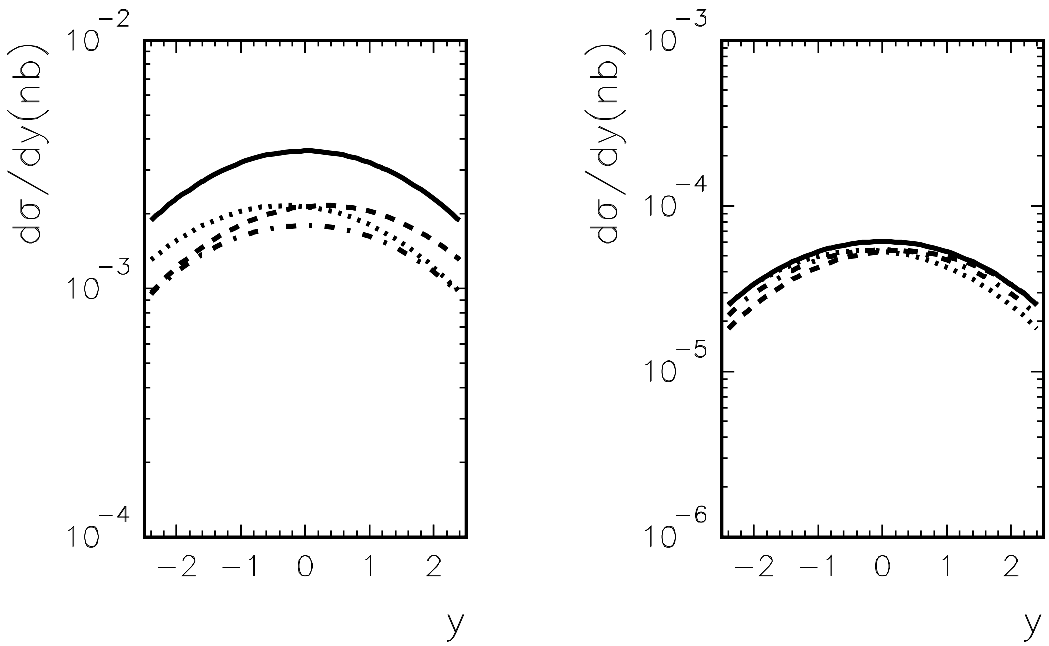

Figure 2: Muon rapidity distributions for low-p_T (left) and high-p_T (right) cuts. We show separately the elastic-elastic (solid), elastic-inelastic (dashed), inelastic-elastic (dotted) and inelastic-inelastic (dash-dotted) mechanisms at $\sqrt{s}$ = 7 TeV.

the low-p_T cut, $p_T > 3\,\mathrm{GeV}$ and the high-p_T cut $p_T > 15\,\mathrm{GeV}$. The former is typical, say for an analysis of (semi-)exclusive Υ-production, while the latter for an analysis of the $\gamma\gamma \to W^+W^-$ process [6]. For the rapidities of muons we take $|y_\pm| < 2.5$, and the mass of the excited state M_X in the inelastic processes varies according to $m_p + m_\pi \leq M_X \leq 1\,\mathrm{TeV}$.

In figure 2 we show the rapidity distribution of muons separately for the elastic-elastic (solid line), elastic-inelastic (dashed line), inelastic-elastic (dotted line) and inelastic-inelastic (dash-dotted line) mechanisms at $\sqrt{s}$ = 7 TeV. We observe that inelastic cross sections are large. The shape of the elastic-inelastic and inelastic-elastic distributions are asymmetric around $y = 0$. This reflects the fact that the photon inducing the breakup tends to be harder than the one coupling to the elastic vertex. Transverse momentum distributions of muons are shown in figure 3. Here we observe that p_T distributions in the inelastic-elastic case are broader than in the elastic-elastic collisions. In the inelastic-inelastic events the muon p_T-distribution is still harder. This shows that virtual photons contribute to the p_T of muons. We also show the distribution in invariant mass of the $\mu^+\mu^-$-pair. Here the most striking feature is that for the inelastic-elastic and inelastic-inelastic collisions, the invariant mass distributions extend below $M = 2p_T^{\rm cut}$. This is possible for pairs which carry a finite transverse momentum $\vec{p}_{T\,sum} = \vec{p}_{T+} + \vec{p}_{T-}$. As expected the effect of these pairs is strongest for the inelastic-inelastic case. Obviously it cannot be described in the standard Weizsäcker-Williams approach using collinear photons.

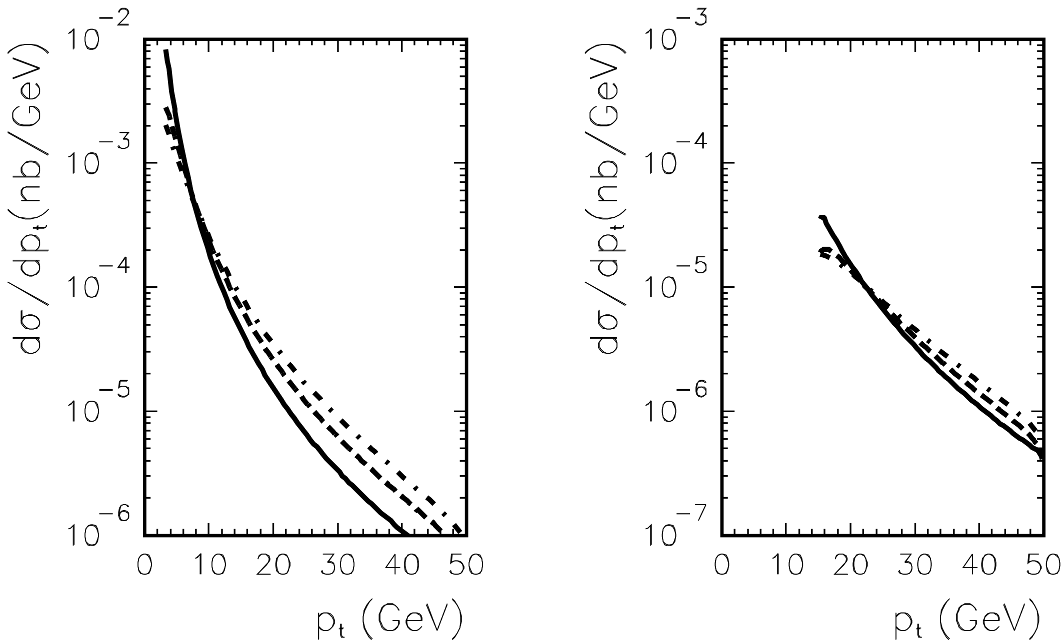

Figure 3: Muon transverse momentum distributions for low-p_T (left) and high-p_T (right) cuts. We show separately the elastic-elastic (solid), elastic-inelastic (dashed), inelastic-elastic (dotted) and inelastic-inelastic (dash-dotted) mechanisms at $\sqrt{s}$ = 7 TeV.

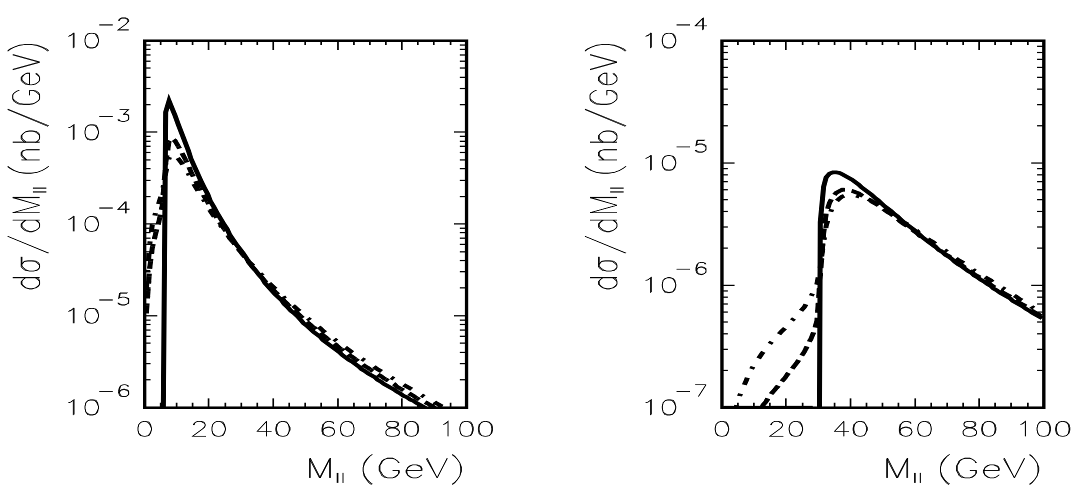

Figure 4: Invariant mass distributions of the $\mu^+\mu^-$-pair for low-p_t (left) and high-p_t (right) cuts. We show separately the elastic-elastic (solid), elastic-inelastic (dashed), inelastic-elastic (dotted) and inelastic-inelastic (dash-dotted) mechanisms at $\sqrt{s}$ = 7 TeV.

4. Conclusion

We have reviewed the production of muon pairs by the $\gamma\gamma$-fusion mechanism in proton-proton collisions at LHC energies. Three different classes of processes (elastic-elastic, elastic-inelastic and inelastic-inelastic) have been discussed. We proposed a method to calculate all three of the above processes, which is the QED analogue to the familiar k_T-factorization.

Here we have shown transverse momentum and rapidity distributions of muons, as well as distributions in dimuon invariant mass and in the transverse momentum of the muon pair. Imposing cuts on muon transverse momenta, all the three event classes elastic-elastic, elastic-inelastic, and inelastic-inelastic) give contributions of similar magnitude. While the elastic-elastic contribution is well under control, the inelastic contributions are subjected to uncertainties of the order of 20% or even more for some regions of correlation observables.

Different regions of phase space of the muon pair are sensitive to structure functions in different ranges of $x_{\rm Bj}$ and Q^2. Unfortunately, at present there is no single set of structure functions available in the literature which accurately treats all regions of $x_{\rm Bj}$ and Q^2.

The contribution from $\gamma\gamma$-fusion to a specific final state can be enhanced by imposing the condition of no charged particles coming from the same vertex (see e.g. [1]). The inelastic processes then become very important. However, one should still include absorption effects into the calculation. While some early discussion of absorptive effects in lepton pair production do exist [7], these studies concentrate on an entirely different kinematic region than we do in this work.

We leave the investigation of absorptive corrections and a possibility of their direct measurement to future studies.

References

[1] CMS Collaboration, JHEP **01** (2012) 052, JHEP **11** (2012) 080,

[2] V.M. Budnev, I.F. Ginzburg, G.V. Meledin, V.G. Serbo, Phys. Rept. **15** (1975) 181.

[3] G. Silveira, L. Forthomme, J. Hollar, K. Piotrzkowski, W. Schäfer & A. Szczurek, to appear.

[4] E. Bartos, S. R. Gevorkyan, E. A. Kuraev and N. N. Nikolaev, Phys. Rev. **A66**, 042720 (2002), arxiv:hep-ph/0109281.

[5] A. Szczurek and V. Uleshchenko, Eur. Phys. J. **C12** (2000) 663; Phys. Lett. **B475** (2000) 120, arxiv:hep-ph/9911467.

[6] CMS Collaboration, JHEP **07** (2013) 116.

[7] V.A. Khoze, A.D. Martin, R. Orava, M.G. Ryskin, Eur. Phys. J. **C19** (2001) 313, arxiv:hep-ph/0010163.