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Production of W^+W^- and $t\bar{t}$ pairs via photon-photon processes in proton-proton collisions

Antoni Szczurek[∗†]
Institute of Nuclear Physics PAN, Kraków
E-mail: antoni.szczurek@ifj.edu.pl

Marta Luszczak
Rzeszów University, Rzeszów
E-mail: luszczak@ur.edu.pl

We review our recent results for production of W^+W^- and $t\bar{t}$ pairs via photon-photon fusion. A theoretical approach is presented in short. We include transverse momenta of photons when calculating fluxes of photons. Then we discuss our results for cross section (total and differential) for W^+W^- production. Results for different parametrizations of proton structure functions are used to calculate inelastic fluxes of photons. A discussion on rapidity gap survival probability due to remnant fragmentation is presented. A similar discussion is presented for $t\bar{t}$ production.

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∗Speaker.
†A footnote may follow.

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1. Introduction

It was realized rather recently that the electroweak corrections are important for precise calculations of cross sections in different processes. The $pp \to W^+W^-$ process is a good example (see e.g. [1]). Then $\gamma\gamma \to W^+W^-$ is the most important subprocess. This subprocess is important also in the context of searches beyond Standard Model [2, 3]. By imposing special conditions on the final state this contribution can be observed experimentally [4, 5].

In [6, 7] we developed a formalism for calculating $pp \to l^+l^-$ processes proceeding via photon-photon fusion. In [8] we used the same technique to calculate cross section for $pp \to W^+W^-$ reaction proceeding via photon-photon fusion. In order to make reference to real "measurements" of the photon-photon contribution one has to include in addition the gap survival probability caused by extra emissions. In [9] we concentrated on the effect related to remnant fragmentation and its destroying of the rapidity gap.

In [10] we calculated cross section for the photon-photon contribution for the $pp \to t\bar{t}$ reaction including also effects of gap survival probability.

Here we briefly review our results obtained in [8, 9, 10].

2. Our approach

In our analyses we included different categories of processes shown in Fig.2.

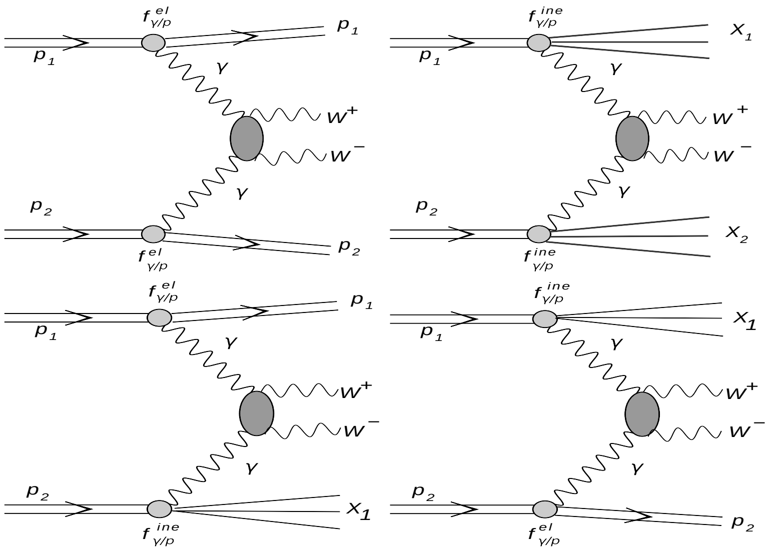

Figure 1: Diagrams representing different categories of photon-photon induced mechanisms for production of W^+W^- pairs.

In contrast to other authors, in our approach we include transverse momenta of (virtual) photons. Then the differential cross section for W^+ and W^- production can be written as:

$$\frac{d\sigma^{(i,j)}}{dy_1 dy_2 d^2\vec{p}_{T1} d^2\vec{p}_{T2}} = \int \frac{d^2\vec{q}_{T1}}{\pi\vec{q}_{T1}^{\,2}} \frac{d^2\vec{q}_{T2}}{\pi\vec{q}_{T2}^{\,2}} \mathscr{F}^{(i)}_{\gamma^*/A}(x_1,\vec{q}_{T1}) \mathscr{F}^{(j)}_{\gamma^*/B}(x_2,\vec{q}_{T2}) \frac{d\sigma^*(p_1,p_2;\vec{q}_{T1},\vec{q}_{T2})}{dy_1 dy_2 d^2\vec{p}_{T1} d^2\vec{p}_{T2}} \quad (2.1)$$

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where i, j = elastic, inelastic and the longitudinal momentum fractions are expressed in terms of rapidities and transverse momenta of W bosons.

-

$$
\begin{aligned}
x_1 &= \sqrt{\frac{\vec{p}_{T1}^{\,2} + m_W^2}{s}} e^{y_1} + \sqrt{\frac{\vec{p}_{T2}^{\,2} + m_W^2}{s}} e^{y_2} \,, \\
x_2 &= \sqrt{\frac{\vec{p}_{T1}^{\,2} + m_W^2}{s}} e^{-y_1} + \sqrt{\frac{\vec{p}_{T2}^{\,2} + m_W^2}{s}} e^{-y_2} \,.
\end{aligned} \tag{2.2}
$$

The elementary $\gamma\gamma \to W^+W^-$ processes in the Standard Model are shown in Fig.2.

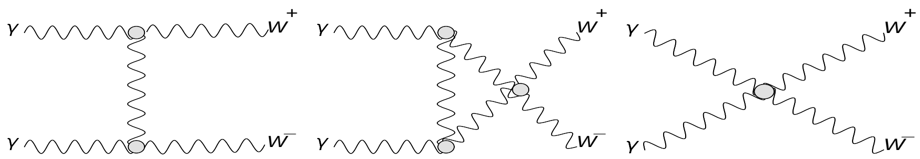

Figure 2: Different Feynman diagrams for photon-photon induced mechanisms for production of W^+W^- pairs.

The elementary off-shell cross section in (2.1) is written as:

$$
\frac{d\sigma^*(p_1, p_2; \vec{q}_{T1}, \vec{q}_{T2})}{dy_1 dy_2 d^2\vec{p}_{T1} d^2\vec{p}_{T2}} = \frac{1}{16\pi^2 (x_1 x_2 s)^2} \sum_{\lambda_{W^+}\lambda_{W^-}} |M(\lambda_{W^+}, \lambda_{W^-})|^2 \, \delta^{(2)}(\vec{p}_{T1} + \vec{p}_{T2} - \vec{q}_{T1} - \vec{q}_{T2}) \,.
$$

Above the helicity-dependent off-shell matrix elements were calculated as:

$$
\begin{aligned}
M(\lambda_{W^+}\lambda_{W^-}) &= \frac{1}{|\vec{q}_{\perp 1}||\vec{q}_{\perp 2}|} \sum_{\lambda_1 \lambda_2} (\vec{e}_\perp(\lambda_1) \cdot \vec{q}_{\perp 1})(\vec{e}_\perp^{\,*}(\lambda_2) \cdot \vec{q}_{\perp 2}) \mathscr{M}(\lambda_1, \lambda_2; \lambda_{W^+}, \lambda_{W^-}) \\
&= \frac{1}{|\vec{q}_{\perp 1}||\vec{q}_{\perp 2}|} \sum_{\lambda_1 \lambda_2} q_{\perp 1}^i q_{\perp 2}^j \, e_i(\lambda_1) e_j^*(\lambda_2) \mathscr{M}(\lambda_1, \lambda_2; \lambda_{W^+}, \lambda_{W^-}) \,.
\end{aligned} \tag{2.3}
$$

Initial and final state helicity-dependent matrix elements were discussed e.g. in [11]. The k_t-factorization W-boson helicity dependent matrix elements were calculated with the help of the above [8].

The unintegrated inelastic flux of photons is expressed as:

$$
\begin{aligned}
\mathscr{F}^{\mathrm{in}}_{\gamma^* \leftarrow A}(z, \vec{q}_T) &= \frac{\alpha_{\mathrm{em}}}{\pi} \Big\{ (1-z) \Big(\frac{\vec{q}_T^{\,2}}{\vec{q}_T^{\,2} + z(M_X^2 - m_p^2) + z^2 m_p^2} \Big)^2 \frac{F_2(x_{\mathrm{Bj}}, Q^2)}{Q^2 + M_X^2 - m_p^2} \\
&+ \frac{z^2}{4x_{\mathrm{Bj}}^2} \frac{\vec{q}_T^{\,2}}{\vec{q}_T^{\,2} + z(M_X^2 - m_p^2) + z^2 m_p^2} \frac{2x_{\mathrm{Bj}} F_1(x_{\mathrm{Bj}}, Q^2)}{Q^2 + M_X^2 - m_p^2} \Big\} \,,
\end{aligned} \tag{2.4}
$$

The main ingredients of the formula are F_1 and F_2 proton structure functions.

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contribution	8 TeV	13 TeV
LUX-like		
$\gamma_{el}\gamma_{in}$	0.214	0.409
$\gamma_{in}\gamma_{el}$	0.214	0.409
$\gamma_{in}\gamma_{in}$	0.478	1.090
ALLM97 F2		
$\gamma_{el}\gamma_{in}$	0.197	0.318
$\gamma_{in}\gamma_{el}$	0.197	0.318
$\gamma_{in}\gamma_{in}$	0.289	0.701
SU F2		
$\gamma_{el}\gamma_{in}$	0.192	0.420
$\gamma_{in}\gamma_{el}$	0.192	0.420
$\gamma_{in}\gamma_{in}$	0.396	0.927
LUXqed collinear		
$\gamma_{in+el}\ \gamma_{in+el}$	0.366	0.778
MRST04 QED collinear		
$\gamma_{el}\gamma_{in}$	0.171	0.341
$\gamma_{in}\gamma_{el}$	0.171	0.341
$\gamma_{in}\gamma_{in}$	0.548	0.980
Elastic- Elastic		
$\gamma_{el}\gamma_{el}$ (Budnev)	0.130	0.273
$\gamma_{el}\gamma_{el}$ (DZ)	0.124	0.267

Table 1: Cross sections (in *pb*) for different contributions and different F_2 structure functions: LUX, ALLM97 and SU, compared to the relevant collinear distributions with MRST04 QED and LUXqed distributions.

The unintegrated elastic flux of photons is expressed as:

$$\mathscr{F}^{\mathrm{el}}_{\gamma^*\leftarrow A}(z,\vec{q}_T) = \frac{\alpha_{\mathrm{em}}}{\pi}\Big\{(1-z)\left(\frac{\vec{q}_T^{\,2}}{\vec{q}_T^{\,2}+z(M_X^2-m_p^2)+z^2m_p^2}\right)^2\frac{4m_p^2G_E^2(Q^2)+Q^2G_M^2(Q^2)}{4m_p^2+Q^2} + \frac{z^2}{4}\frac{\vec{q}_T^{\,2}}{\vec{q}_T^{\,2}+z(M_X^2-m_p^2)+z^2m_p^2}G_M^2(Q^2)\Big\}\,. \tag{2.5}$$

In this case the main ingredients are G_E and G_M electromagnetic form factors of proton.

To calculate inelastic fluxes of photons one needs numerical representation of structure functions of protons. Different parametrizations of F_2 structure functions are available in the literature, see e.g. [12, 13, 14].

3. Results

The integrated cross sections obtained in our approach are collected in Table 1.

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Without any gap survival effects:

$$\sigma(inel.-inel.) > \sigma(inel.-el.) + \sigma(el.-inel.) > \sigma(el.-el.)\ . \tag{3.1}$$

Many differential distributions were calculated in [8]. Here, in Fig.3, we show only invariant mass distribution for double dissociation processes (inelastic-inelastic) for different parametrizations of the structure functions from the literature.

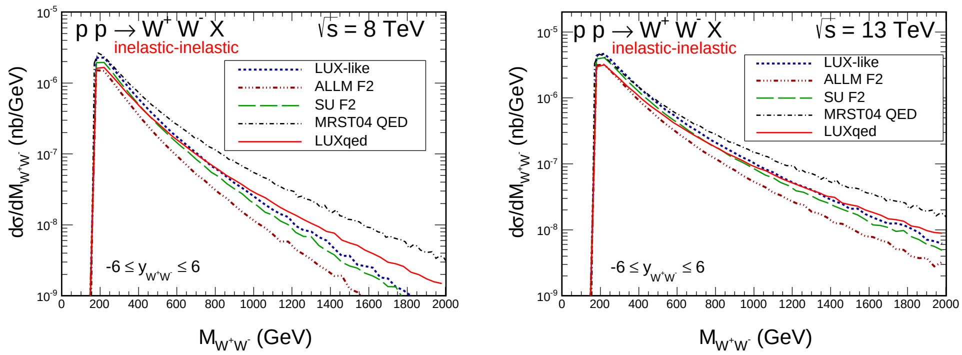

Figure 3: M_{WW} invariant mass distribution for double dissociative contribution obtained with different parametrizations of structure functions.

The k_t-factorization result is similar to the collinear one for the same structure function (LUX-like). The rather old MRST04-QED collinear approach [15] predicted larger cross section. The reasons were discussed in [8].

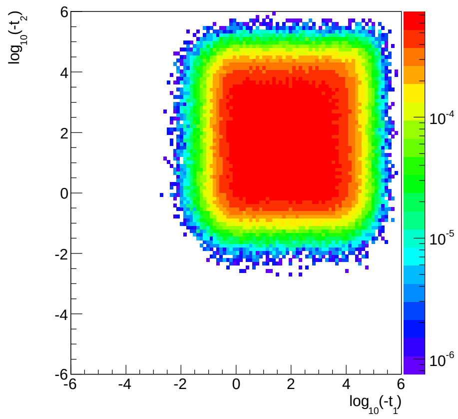

Figure 4: Two-dimensional distribution in $(log_{10}(Q_1^2), log_{10}(Q_2^2))$ for double dissociative process.

As an example in Fig.3 we show distribution in virtualities of photons. Rather large virtualities of photons come into game. The large virtualities of photons seem to contradict collinear approach.

Our formalism allows to calculate contributions depending on helicities of W^+ and W^- bosons. The results are collected in Table 2 for two different collision energies. Clearly the TT contribution dominates.

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contribution	8 TeV	13 TeV
TT	0.405	0.950
LL	0.017	0.046
LT + TL	0.028 + 0.028	0.052 + 0.052
SUM	0.478	1.090

Table 2: Contributions of different polarizations of W bosons for the inelastic-inelastic component for the LUX-like structure function. The cross sections are given in *pb*.

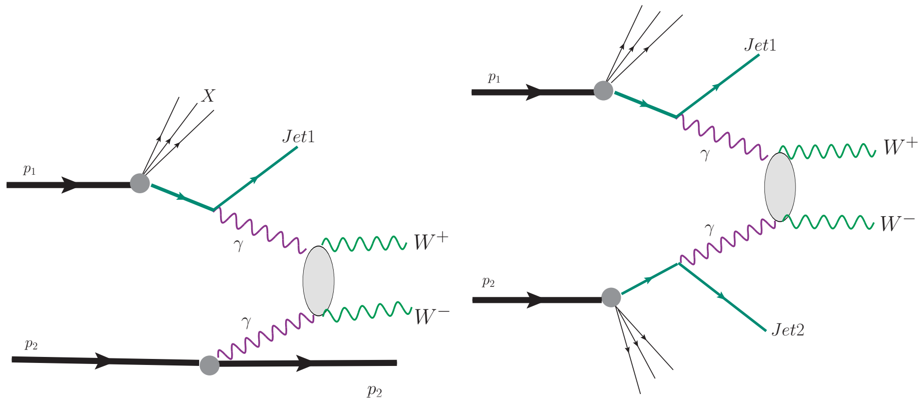

Figure 5: Schematic representation of the single and double dissociative mechanisms. Jets are shown explicitly.

	8 *TeV*	13 *TeV*	8 *TeV*	13 *TeV*	8 *TeV*	13 *TeV*
$(2M_{WW}, 200\ GeV)$	0.763(2)	0.769(2)	0.582(4)	0.591(4)	0.586(1)	0.601(2)
$(200, 500\ GeV)$	0.787(1)	0.799(1)	0.619(2)	0.638(2)	0.629(1)	0.649(1)
$(500, 1000\ GeV)$	0.812(2)	0.831(2)	0.659(3)	0.691(3)	0.673(2)	0.705(2)
$(1000, 2000\ GeV)$	0.838(7)	0.873(5)	0.702(12)	0.762(8)	0.697(5)	0.763(6)
full range	0.782(1)	0.799(1)	0.611(2)	0.638(2)	0.617(1)	0.646(1)

Table 3: Average rapidity gap survival factors: $S_{R,SD}(|\eta^{ch}| < 2.5)$, $(S_{R,SD})^2\,(|\eta^{ch}| < 2.5)$, $S_{R,DD}(|\eta^{ch}| < 2.5)$ related to remnant fragmentation for *single dissociative* and *double dissociative* contributions for different ranges of M_{WW}.

The remnant fragmentation [9] was done with the help of PYTHIA 8 program. Including only parton (jet) emission is already a quite good approximation.

The gap survival probability for single dissociative process is calculated as:

$$S_R(\eta_{\rm cut}) = 1 - \frac{1}{\sigma}\int_{-\eta_{\rm cut}}^{\eta_{\rm cut}} \frac{d\sigma}{d\eta_{\rm jet}} d\eta_{\rm jet} \,. \tag{3.2}$$

A schematic representation of remnant fragmentation(s) with explicit jet is shown in Fig.5. Jet emissions were considered also in [17].

The gap survival factor associated with jet emission is shown in Fig.6.

Fig.7 illustrates how gap survival factor is destroyed by particle (hadron) emission for double dissociative process.

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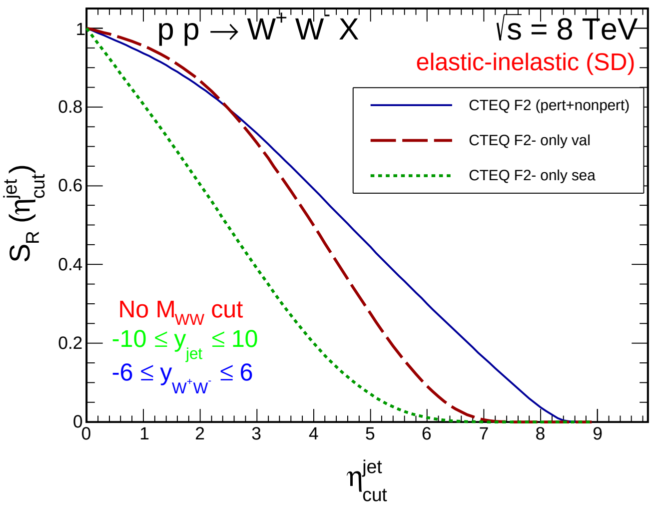

Figure 6: Gap survival factor for single dissociative process associated with the jet emission. The solid line is for the full model, the dashed line for the valence contribution and the dotted line for the sea contribution.

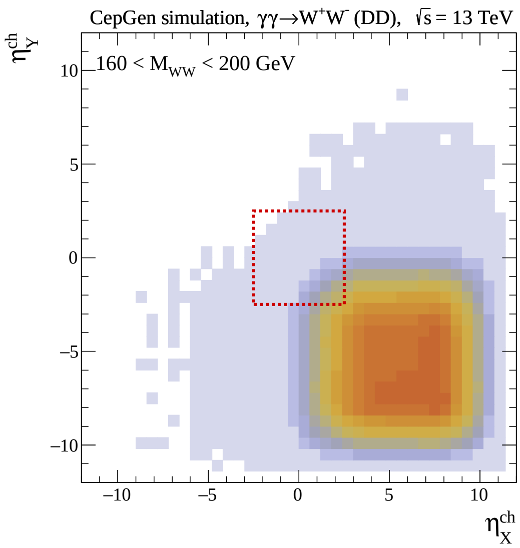

Figure 7: Two-dimensional $(\eta_X^{\mathrm{ch}}, \eta_Y^{\mathrm{ch}})$ distribution for a selected window of M_{WW}. The square shows pseudorapidity coverage of ATLAS or CMS inner tracker.

We find (see also Table 1)

$$S_{R,DD} \approx (S_{R,SD})^2 \ . \tag{3.3}$$

Such an effect is naively expected when the two fragmentations are independent, which is the case by the model construction. The soft processes will most probably violate the factorisation. There is, however, no formalism which allows to calculate the gap survival probabability for these processes as a function of rapidity gap window. So far we have not included the soft gap survival factors. They are relatively easy to calculate only for double elastic (DE) contribution [16]. For the "soft"

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Contribution	No cuts	$y_{\rm jet}$ cut
elastic-elastic	0.292	0.292
elastic-inelastic	0.544	0.439
inelastic-elastic	0.544	0.439
inelastic-inelastic	0.983	0.622
all contributions	2.36	1.79

Table 4: Cross section for $t\bar{t}$ production in fb at $\sqrt{s}$ = 13 TeV for different components (left column) and the same when the extra condition on the outgoing jet $|y_{\rm jet}| > 2.5$ is imposed.

gap survival factors we expect:

$$S_{soft}(DD) < S_{soft}(SD) < S_{soft}(DE)\ . \tag{3.4}$$

Finally we wish to show also similar results for $pp \to t\bar{t}$ reaction. In Table 3 we show integrated cross sections for different categories of processes. Rather small cross sections are obtained. It is not clear at present whether such a process can be identified experimentally.

As an example we show $t\bar{t}$ invariant mass distribution for inclusive case as well as when extra veto on (mini)jet is imposed. The inclusion of rapidity gap veto reduces the cross section. Whether the cross section corresponding to the photon-photon fusion can be measured requires special dedicated studies.

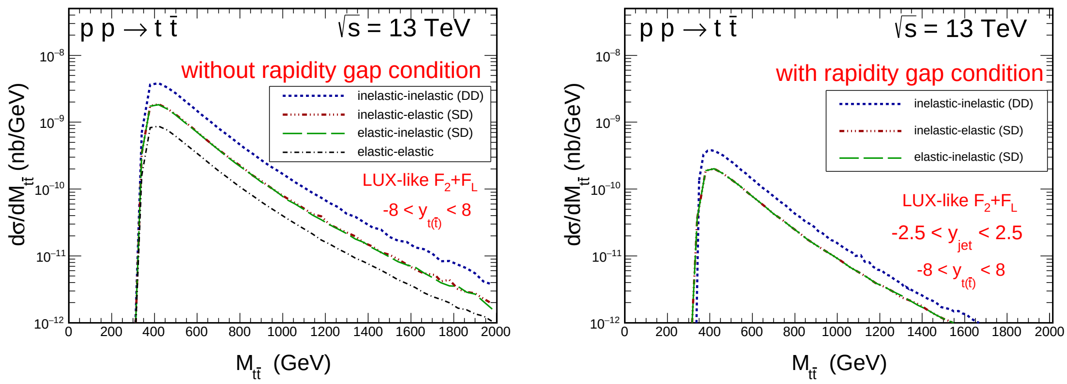

Figure 8: $t\bar{t}$ invariant mass distribution for different components defined in the figure. The left panel is without imposing the condition on the struck quark/antiquark and the right panel includes the condition.

4. Conclusions

Helicity-dependent matrix elements for $\gamma^*\gamma^* \to W^+W^-$ (off-shell photons) have been derived and used in the calculation of cross sections for $pp \to W^+W^-$ reaction. We have obtained cross section of about 1 pb for the LHC energies. This is about 2 % of the total integrated cross section dominated by the quark-antiquark annihilation and gluon-gluon fusion. Different combinations of the final states (elastic-elastic, elastic-inelastic, inelastic-elastic, inelastic-inelastic) have been considered. The unintegrated photon fluxes were calculated based on modern parametrizations of the

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proton structure functions from the literature. Several differential distributions in W boson transverse momentum and rapidity, WW invariant mass, transverse momentum of the WW pair, mass of the remnant system have been presented. Several correlation observables have been studied. Large contributions from the regions of large photon virtualities Q_1^2 and/or Q_2^2 have been found putting in question the reliability of leading-order collinear-factorization approach. We have presented a decomposition of the cross section into different polarizations of both W bosons. It has been shown that the TT (both W transversly polarized) contribution dominates and constitutes more than 80 % of the total cross section. The LL (both W longitudinally polarized) contribution is interesting in the context of studying WW interactions or searches beyond the Standard Model. We have quantifield the effect of inclusion of longitiudinal structure function into the transverse momentum dependent fluxes of photons. A rather small, approximataly M_{WW} - independent, effect was found.

We have discussed the quantity called "remnant gap survival factor" for the $pp \to W^+W^-$ reaction initiated via photon-photon fusion. We have calculated the gap survival factor for single dissociative process on the parton level. In such an approach the outgoing parton (jet/mini-jet) is responsible for destroying the rapidity gap. We have found that the hadronisation only mildly modifies the gap survival factor calculated on the parton level. This may justify approximate treatment of hadronisation of remnants. We have found different values for double and single dissociative processes. In general, $S_{R,DD} < S_{R,SD}$ and $S_{R,DD} \approx (S_{R,SD})^2$. We expect that the factorisation observed here for the remnant dissociation and hadronisation will be violated when the soft processes are explicitly included. The larger $\eta_{\rm cut}$ (upper limit on charged particles pseudorapidity), the smaller rapidity gap survival factor S_R. This holds both for the double and the single dissociation. The present approach is a first step towards a realistic modelling of gap survival in photon induced interactions and definitely requires further detailed studies and comparisons to the existing and future experimental data.

We have also calculated cross sections for $t\bar{t}$ production via $\gamma\gamma$ mechanism in pp collisions including photon transverse momenta and using modern parametrizations of proton structure functions. The contribution to the inclusive $t\bar{t}$ is only about 2.5 fb. We have found $\sigma_{tt}^{ela-ela} < \sigma_{tt}^{SD} < \sigma_{tt}^{DD}$. We have calculated several differential distributions. Some of them are not accessible in standard equivalent photon approximation. As for W^+W^- production we have shown that rather large photon virtualities come into the game.

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