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

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Introduction

- **Electroweak corrections** are important for precise calculations of cross sections in different processes.
- **Photon distributions** become topical in last years. Mostly collinear approach was discussed.
- $\gamma\gamma \rightarrow l^+l^-$ was measured by ATLAS and CMS.
- $\gamma\gamma \rightarrow W^+W^-$ testing physics beyond Standard Model anomalous boson couplings.
  Pierzchala, Piotrzkowski and Chapon, Royon and Kepka
- $\gamma\gamma \rightarrow W^+W^-$ important contribution to large $M_{WW}$
  (M. Łuszczak, A. Szczurek, Ch. Royon).
- $\gamma\gamma \rightarrow W^+W^-$ can be separated by imposing rapidity gap condition (ATLAS and CMS).
Dilepton production


Presented here papers

- M. Łuszczak, W. Schäfer and A. Szczurek, “Production of $W^+ W^-$ pairs via $\gamma^* \gamma^* \rightarrow W^+ W^-$ subprocess with photon transverse momenta”, JHEP05 (2018) 064.


- M. Luszczak, L. Forthomme, W. Schäfer and A. Szczurek. “Production of $t\bar{t}$ pairs via $\gamma\gamma$ fusion with photon transverse momenta and proton dissociation”, JHEP02 (2019) 100.
Formalism

Master formula:

$$\frac{d\sigma^{(i,j)}}{dy_1 dy_2 d^2 p_1 d^2 p_2} = \int \frac{d^2 q_1}{\pi q_1^2} \frac{d^2 q_2}{\pi q_2^2} F^{(i)}_{\gamma^*/A} \left( x_1, q_1 \right) F^{(j)}_{\gamma^*/B} \left( x_2, q_2 \right) \frac{d\sigma^* \left( p_1, p_2; q_1, q_2 \right)}{dy_1 dy_2 d^2 p_1 d^2 p_2},$$

(1)

As for $k_t$-factorization approach in gluon-gluon induced processes

$i,j = \text{elastic, inelastic}$

$$x_1 = \sqrt{\frac{p_1^2 + m_W^2}{s} e^{y_1}} + \sqrt{\frac{p_2^2 + m_W^2}{s} e^{y_2}} ,$$

$$x_2 = \sqrt{\frac{p_1^2 + m_W^2}{s} e^{-y_1}} + \sqrt{\frac{p_2^2 + m_W^2}{s} e^{-y_2}} .$$

(2)
Mechanisms discussed in the presentation
Elementary process, diagrams

t-, u- and contact diagrams
Matrix elements

Elementary off-shell cross section:

\[
\frac{d\sigma^*(p_1, p_2; q_1, q_2)}{dy_1 dy_2 d^2 p_1 d^2 p_2} = \frac{1}{16\pi^2(x_1 x_2 s)^2} \sum_{\lambda_W^+ \lambda_W^-} |M(\lambda_W^+, \lambda_W^-)|^2 \delta^{(2)}(p_1 + p_2 - q_1 - q_2),
\]

(3)

Helicity-dependent off-shell matrix elements

\[
M(\lambda_W^+ \lambda_W^-) = \frac{1}{|\vec{q}_\perp^1||\vec{q}_\perp^2|} \sum_{\lambda_1 \lambda_2} (\vec{e}_\perp(\lambda_1) \cdot \vec{q}_\perp^1)(\vec{e}_\perp^*(\lambda_2) \cdot \vec{q}_\perp^2)M(\lambda_1, \lambda_2; \lambda_W^+, \lambda_W^-)
\]
\[
= \frac{1}{|\vec{q}_\perp^1||\vec{q}_\perp^2|} \sum_{\lambda_1 \lambda_2} q_\perp^1_1 q_\perp^1_2 e_i(\lambda_1)e_i^*(\lambda_2) \cdot M(\lambda_1, \lambda_2; \lambda_W^+, \lambda_W^-),
\]

(4)

Initial and final state helicity-dependent matrix elements were discussed in:
O. Nachtmann, F. Nagel, M. Pospischil and A. Utermann,
Matrix elements

Auxiliary formula:

\[ q'_{\perp 1} q'_{\perp 2} = \frac{1}{2} \delta_{ij} (\vec{q}_{\perp 1} \cdot \vec{q}_{\perp 2}) + \frac{1}{2} (q'_{\perp 1} q'_{\perp 2} + q'_{\perp 1} q'_{\perp 2} - \delta_{ij} (\vec{q}_{\perp 1} \cdot \vec{q}_{\perp 2})) + \frac{1}{2} (q'_{\perp 1} q'_{\perp 2} - q'_{\perp 1} q'_{\perp 2}) \]

\[ = \frac{1}{2} \delta_{ij} (\vec{q}_{\perp 1} \cdot \vec{q}_{\perp 2}) + \frac{1}{2} t_{ij}^{kl} q_{\perp 1} q_{\perp 2} + \frac{1}{2} \epsilon_{ij} [\vec{q}_{\perp 1}, \vec{q}_{\perp 2}] . \] (5)

\[ k_t\)-factorization W-boson helicity dependent matrix elements:

\[ M(\lambda_{W^+} \lambda_{W^-}) = \frac{1}{|\vec{q}_{\perp 1}||\vec{q}_{\perp 2}|} \left\{ (\vec{q}_{\perp 1} \cdot \vec{q}_{\perp 2}) \cdot \left( M(;++; \lambda_{W^+} \lambda_{W^-}) + M(--; \lambda_{W^+} \lambda_{W^-}) \right) \right. 
\] 
\[ - i[\vec{q}_{\perp 1}, \vec{q}_{\perp 2} \left( M(;++; \lambda_{W^+} \lambda_{W^-}) - M(--; \lambda_{W^+} \lambda_{W^-}) \right) \right. 
\] 
\[ - \left( q^x_{\perp 1} q^x_{\perp 2} - q^y_{\perp 1} q^y_{\perp 2} \right) \left( M(;++; \lambda_{W^+} \lambda_{W^-}) + M(--; \lambda_{W^+} \lambda_{W^-}) \right) 
\] 
\[ - iq^x_{\perp 1} q^y_{\perp 2} + q^y_{\perp 1} q^x_{\perp 2} \right) \left( M(;++; \lambda_{W^+} \lambda_{W^-}) - M(--; \lambda_{W^+} \lambda_{W^-}) \right) . \] (6)
Photon fluxes

Inelastic flux:

\[
F_{\gamma* \rightarrow A}^{\text{in}}(z, q) = \frac{\alpha_{\text{em}}}{\pi} \left\{ (1 - z) \left( \frac{q^2}{q^2 + z(M_X^2 - m_p^2) + z^2 m_p^2} \right)^2 \frac{F_2(x_{Bj}, Q^2)}{Q^2 + M_X^2 - m_p^2} \right.

+ \frac{z^2}{4x_{Bj}^2} \frac{q^2}{q^2 + z(M_X^2 - m_p^2) + z^2 m_p^2} \left( \frac{2x_{Bj}F_1(x_{Bj}, Q^2)}{Q^2 + M_X^2 - m_p^2} \right) \bigg],
\]

(7)

Ingredients: \( F_1 \) and \( F_2 \) structure functions

Elastic flux:

\[
F_{\gamma* \rightarrow A}^{\text{el}}(z, q) = \frac{\alpha_{\text{em}}}{\pi} \left\{ (1 - z) \left( \frac{q^2}{q^2 + z(M_X^2 - m_p^2) + z^2 m_p^2} \right)^2 \frac{4m_p^2 G_E^2(Q^2) + Q^2 G_M^2(Q^2)}{4m_p^2 + Q^2} \right.

+ \frac{z^2}{4} \frac{q^2}{q^2 + z(M_X^2 - m_p^2) + z^2 m_p^2} G_M^2(Q^2) \bigg].
\]

(8)

Ingredients: Electromagnetic form factors

Collinear-factorization approach

\[ \frac{d\sigma^{(i,j)}}{dy_1 dy_2 d^2p_T} = \frac{1}{16\pi^2(x_1 x_2 s)^2} \sum_{i,j} x_1 \gamma^{(i)}(x_1, \mu^2) x_2 \gamma^{(j)}(x_2, \mu^2) |M_{\gamma\gamma \rightarrow W^+W^-}|^2. \]  

(9)

Longitudinal momentum fractions:

\[ x_1 = \sqrt{\frac{p_T^2 + m^2_W}{s}} \left( \exp(y_1) + \exp(y_2) \right), \]
\[ x_2 = \sqrt{\frac{p_T^2 + m^2_W}{s}} \left( \exp(-y_1) + \exp(-y_2) \right). \]  

(10)
Parametrizations of structure functions of proton

ALLM parametrization

- H. Abramowicz, E. M. Levin, A. Levy and U. Maor,

\[
F_2(x, Q^2) = \frac{Q^2}{Q^2 + m_0^2} \left( F_2^P(x, Q^2) + F_2^R(x, Q^2) \right)
\]

FFJLM parametrization

- R. Fiore, A. Flachi, L. L. Jenkovszky, A. I. Lengyel and V. K. Magas,

\[
I m\alpha(s) = s^\delta \sum_n c_n \left( \frac{s - s_n}{s} \right)^{R e\alpha(s_n)} \cdot \theta(s - s_n)
\]
\[
R e\alpha(s) = \alpha(0) + \frac{s}{\pi} PV \int_0^\infty ds' \frac{I m\alpha(s')}{s'(s' - s)}
\]
Parametrizations of structure functions of proton

SU parametrization

- A. Szczurek, V. Uleshchenko,

\[ F_N^2(x, Q^2) = F_{N,VDM}^2(x, Q^2) + F_{N,part}^2(x, Q^2) \]

\[ F_{N,VDM}^2(x, Q^2) = \frac{Q^2}{\pi} \sum_V \frac{M_V^4 \cdot \sigma_{VN}^{tot}(s^{1/2})}{\gamma_V^2 (Q^2 + M_V^2)^2} \cdot \Omega_V(x, Q^2) \]

\[ F_{N,part}^2(x, Q^2) = \frac{Q^2}{Q^2 + Q_0^2} \cdot F_{2 \text{asymp}}^2(\bar{x}, \bar{Q}^2) \]
LUX-like structure function

Recently LUX QED parametrization was proposed.

- a newly constructed parametrization, which at $Q^2 > 9 \text{ GeV}^2$ uses an NNLO calculation of $F_2$ and $F_L$ from NNLO MSTW 2008 partons. It employs a useful code by the MSTW group to calculate structure functions. At $Q^2 > 9 \text{ GeV}^2$ this fit uses the parametrization of Bosted and Christy in the resonance region, and a version of the ALLM fit published by the HERMES Collaboration for the continuum region. It also uses information on the longitudinal structure function from SLAC. As the fit is constructed closely following LUX QED work we call this fit LUX-like.
# Results, integrated cross sections

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

**Table:** Cross sections (in pb) for different contributions and different F2 structure functions: LUX, ALLM97 and SU, compared to the relevant collinear distributions with MRST04 QED and LUXqed distributions.
$k_t$-factorization result similar to the collinear (for the same structure function (LUX-like))
old MRST04-QED colliner approach predicted larger cross section.
Results, inelastic-inelastic contribution

\[ p p \rightarrow W^+ W^- X \quad \sqrt{s} = 8 \text{ TeV} \]

\[ p p \rightarrow W^+ W^- X \quad \sqrt{s} = 13 \text{ TeV} \]

-6 \leq y_{WW} \leq 6

\[ \frac{d\sigma}{dp_T} \text{ (nb/GeV)} \]

\[ p_T \text{ (GeV)} \]

-6 \leq y_{WW} \leq 6

\[ \frac{d\sigma}{dp_T} \text{ (nb/GeV)} \]

\[ p_T \text{ (GeV)} \]
Results, inelastic-inelastic contribution

Similar results at midrapidities
Results, inelastic-inelastic contribution

\[ p p \rightarrow W^+ W^- X \quad \sqrt{s} = 8\,\text{TeV} \]

\[ p p \rightarrow W^+ W^- X \quad \sqrt{s} = 13\,\text{TeV} \]

Delta function for collinear approach
But difficult to measure!
Results, different components

$p p \rightarrow W^+ W^- X$  \( |s| = 8 \text{ TeV} \)

\[
\frac{d\sigma}{dM_{WW}} (\text{nb}/\text{GeV})
\]

\[
\begin{array}{c}
\text{in-in LUX-like} \\
\text{el-in (or in-el) LUX-like} \\
\text{el-el (B)} \\
\text{in-in collinear LUX} \\
\text{el-in (or in-el) collinear LUX} \\
\text{el-el (DZ)}
\end{array}
\]

\( 0 \leq M_{WW} \leq 2000 \) GeV

\( -6 \leq y_{WW} \leq 6 \)

\( p p \rightarrow W^+ W^- X$  \( |s| = 13 \text{ TeV} \)

\[
\frac{d\sigma}{dM_{WW}} (\text{nb}/\text{GeV})
\]

\[
\begin{array}{c}
\text{in-in LUX-like} \\
\text{el-in (or in-el) LUX-like} \\
\text{el-el Budnev} \\
\text{in-in collinear LUX} \\
\text{el-in (or in-el) collinear LUX} \\
\text{el-el DZ}
\end{array}
\]

\( 0 \leq M_{WW} \leq 2000 \) GeV

\( -6 \leq y_{WW} \leq 6 \)
Results, different components

In collinear approach all of them are Dirac delta functions
Results, different components

\[ p p \rightarrow W^+ W^- X \hspace{0.5cm} \sqrt{s} = 8 \text{ TeV} \]

\[ p p \rightarrow W^+ W^- X \hspace{0.5cm} \sqrt{s} = 13 \text{ TeV} \]

LUX-like structure functions
Results, rapidity distance between $W$ bosons

Very broad distribution, spin-1 exchange
Results, correlation variables

Large virtualities of photons, contradicts collinear approach
Similar pattern for different parametrizations of structure functions
Results, correlation variables

Large $M_{WW}$ large $|t_1|$ or $|t_2|$ - strongly virtual photons
Results, correlation variables
There seem to be a correlation between $M_X$ and $M_Y$
When one is large, the second seems rather small
needs more attention.
Results, correlation variables

For $\sqrt{s} = 13$ TeV similar pattern
Results, spin decompositions

<table>
<thead>
<tr>
<th>contribution</th>
<th>8 TeV</th>
<th>13 TeV</th>
</tr>
</thead>
<tbody>
<tr>
<td>TT</td>
<td>0.405</td>
<td>0.950</td>
</tr>
<tr>
<td>LL</td>
<td>0.017</td>
<td>0.046</td>
</tr>
<tr>
<td>LT + TL</td>
<td>0.028 + 0.028</td>
<td>0.052 + 0.052</td>
</tr>
<tr>
<td>SUM</td>
<td>0.478</td>
<td>1.090</td>
</tr>
</tbody>
</table>

**Table**: 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.
Results, spin decompositions

\[ \frac{d\sigma}{dM_{WW}} (\text{nb/GeV}) \]

Inelastic-elastic

LUX-like

\[ p p \rightarrow W^+ W^- X \]

\[ \sqrt{s} = 8 \text{ TeV} \]

\[ 6 \leq -y_{WW} \leq 6 \]

\[ p p \rightarrow W^+ W^- X \]

\[ \sqrt{s} = 13 \text{ TeV} \]

\[ 6 \leq -y_{WW} \leq 6 \]
Results, longitudinal structure function

\[ p p \rightarrow W^+ W^- X \quad \sqrt{s} = 8 \text{ TeV} \]

\[ p p \rightarrow W^+ W^- X \quad \sqrt{s} = 13 \text{ TeV} \]

Small effect, decreasing the cross section
Gap survival for purely exclusive process

\[ \langle S^2(M_{H^+H^-}) \rangle \]

\[ pp \rightarrow ppH^+H^- \]


similar studies: Dynadal, Schoeffel and Harland-Lang, Khoze, Ryskin

No dependence on rapidity gap size !!!
Gap survival related to (mini)jet emissions

Figure: The single and double dissociative mechanisms.

The remnant fragmentation with PYTHIA 8
Including only parton emission is already quite good.
(see also Harland-Lang, Khoze, Ryskin, Eur.Phys.J.C76 (2016) 255. (collinear photons)).
General consideration

It was shown (Luszczak et al.) that without any gap survival effects:

\[ \sigma(\text{inel.-inel.}) > \sigma(\text{inel.-el.}) + \sigma(\text{el.-inel.}) > \sigma(\text{el.-el.}) . \]  

(11)

Can this ordering be changed when the rapidity gap requirement is taken into account?

\[ S_R(\eta_{\text{cut}}) = 1 - \frac{1}{\sigma} \int_{-\eta_{\text{cut}}}^{\eta_{\text{cut}}} \frac{d\sigma}{d\eta_{\text{jet}}} d\eta_{\text{jet}}, \]  

(12)
Distribution of the extra jet

Figure: Jet rapidity distribution for $F_2$ using a LO partonic distribution at large $Q^2$. The solid line is a sum of all contributions. The dashed line is for the valence component and the dotted line is for the sea component.
Gap survival factor associated with jet emission

Figure: Gap survival factor associated with the jet emission and defined by Eq. (12). The solid line is for the full model, the dashed line for the valence contribution and the dotted line for the sea contribution.
Particles in the jet

Figure: Distribution of charged particles in the single dissociative case for $u$ (black solid line) and $d$ (red dotted line) quarks with respect to $\eta_{\text{jet}}$. 
Double dissociation

CepGen simulation, $\gamma\gamma\rightarrow W^+W^-$ (DD), $\sqrt{s} = 13$ TeV

$160 < M_{WW} < 200$ GeV

$200 < M_{WW} < 500$ GeV

$500 < M_{WW} < 1000$ GeV

$1000 < M_{WW} < 2000$ GeV
Gap survival factors for SD and DD processes

### Table: Average rapidity gap survival factor related to remnant fragmentation for single dissociative and double dissociative contributions for different ranges of $M_{WW}$. All uncertainties are statistical only.

<table>
<thead>
<tr>
<th>2*Contribution</th>
<th>$S_{R,SD}(\mid \eta^{ch} \mid &lt; 2.5)$</th>
<th>$(S_{R,SD})^2(\mid \eta^{ch} \mid &lt; 2.5)$</th>
<th>$S_{R,DD}(\mid \eta^{ch} \mid &lt; 2.5)$</th>
</tr>
</thead>
<tbody>
<tr>
<td>($2M_{WW}$, 200 )</td>
<td>0.763(2) 0.769(2)</td>
<td>0.582(4) 0.591(4)</td>
<td>0.586(1) 0.601(2)</td>
</tr>
<tr>
<td>(200, 500 )</td>
<td>0.787(1) 0.799(1)</td>
<td>0.619(2) 0.638(2)</td>
<td>0.629(1) 0.649(1)</td>
</tr>
<tr>
<td>(500, 1000 )</td>
<td>0.812(2) 0.831(2)</td>
<td>0.659(3) 0.691(3)</td>
<td>0.673(2) 0.705(2)</td>
</tr>
<tr>
<td>(1000, 2000 )</td>
<td>0.838(7) 0.873(5)</td>
<td>0.702(12) 0.762(8)</td>
<td>0.697(5) 0.763(6)</td>
</tr>
<tr>
<td>full range</td>
<td>0.782(1) 0.799(1)</td>
<td>0.611(2) 0.638(2)</td>
<td>0.617(1) 0.646(1)</td>
</tr>
</tbody>
</table>
Gap survival for double dissociation

Figure: Gap survival factor for double dissociation as a function of the size of the pseudorapidity veto applied on charged particles emitted from proton remnants, for the diboson mass bins defined in the text and in the figures for $\sqrt{s} = 8$ (left) and 13 (right).

We predict a strong dependence on $\eta_{\text{cut}}$. It would be valuable to perform experimental measurements with different $\eta_{\text{cut}}$. 
Gap survival for single dissociation

Figure: $\eta_{ch}$ distribution for single dissociative process for four different windows of $M_{WW}$: $(2M_W, 200)$, $(200, 500)$, $(500, 1000)$, $(1000, 2000)$, and for $\sqrt{s} = 8$ (left) and 13 (right). The lines show pseudorapidity coverage of ATLAS or CMS detector.
Factorization

\[ S_{R,DD} \approx (S_{R,SD})^2 . \]  \hspace{1cm} (13)

Such an effect is naively expected when the two fragmentations are independent, which is the case by the model construction. Soft processes will violate the factorisation
Gap survival

Figure: Gap survival factor for single dissociation as a function of the size of the pseudorapidity veto applied on charged particles emitted from proton remnants, for the diboson mass bins defined in the text and in the figures for $\sqrt{s} = 8$ (left) and 13 (right).
Figure: Rapidity gap survival factor for $|\eta^{\text{ch}}| < 2.5$ and $|\eta^{\text{ch}}| < 5$ as a function of the upper limit set on $M_X$, the remnant system invariant mass, for single dissociation.
A comment on the role of soft effects

So far we have not included the soft gap survival factors. They are relatively easy to calculate only for double elastic (DE) contribution (Lebiedowicz, Szczurek). For the “soft” gap survival factors we expect:

\[ S_{\text{soft}}(DD) < S_{\text{soft}}(SD) < S_{\text{soft}}(DE) \]  \hspace{1cm} (14)

Some estimates of phase space averaged values were presented (Harland-Lang, Khoze, Ryskin). A precise kinematics-dependent calculation of soft gap survival factor requires further studies. We expect that the soft gap survival factors may violate the relation \( S_R(DD) = (S_R(SD))^2 \) for the combined (remnant+soft) rapidity gap survival factors.
$pp \to t\bar{t}$ processes via $\gamma\gamma$ fusion

Figure: Classes of processes discussed included. From left to right: elastic-elastic, inelastic-elastic (or equivalently, elastic-inelastic), and inelastic-inelastic contributions.
## Total cross sections

<table>
<thead>
<tr>
<th>Contribution</th>
<th>No cuts</th>
<th>$y_{\text{jet}}$ cut</th>
</tr>
</thead>
<tbody>
<tr>
<td>elastic-elastic</td>
<td>0.292</td>
<td>0.292</td>
</tr>
<tr>
<td>elastic-inelastic</td>
<td>2*0.544</td>
<td>2*0.439</td>
</tr>
<tr>
<td>inelastic-elastic</td>
<td>0.983</td>
<td>0.622</td>
</tr>
<tr>
<td>inelastic-inelastic</td>
<td></td>
<td></td>
</tr>
<tr>
<td>all contributions</td>
<td>2.36</td>
<td>1.79</td>
</tr>
</tbody>
</table>

**Table:** Cross section in fb at $\sqrt{s} = 13$ TeV for different components (left column) and the same when the extra condition on the outgoing jet $|y_{\text{jet}}| > 2.5$ is imposed.
**Figure:** Rapidity distribution of $t$ or $\bar{t}$ for different components defined in the figure.
Figure: Transverse momentum distribution of $t$ or $\bar{t}$ for different components defined in the figure.
Applying jet veto

Figure: $t\bar{t}$ 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.
Further distributions

**Figure:** Distribution in the mass of the dissociated system for single dissociation (left) and double dissociation (right). We show result without and with the rapidity gap condition.
Photon virtualities

Figure: Photon virtuality distribution for different components defined in the figure.
Photon virtualities

Figure: The two-dimensional $\frac{d^2\sigma}{d\log_{10}(-t_1)d\log_{10}(-t_2)}$ distribution as a function of $\log_{10}(-t_1), \log_{10}(-t_2)$ in nb for the inelastic-inelastic contribution. Here $Q_i^2 = -t_i \cdot 1 \text{ GeV}^2$. 
Invariant masses

Figure: The two-dimensional $\frac{d^2\sigma}{dM_X dM_Y}$ distribution as a function of $M_X \times M_Y$ in nb/GeV$^2$ for the inelastic-inelastic contribution.
Figure: Distribution in $M_X$ for different windows of $M_Y$ (left) and as a function of $M_Y$ for different windows of $M_X$ (right)

\[ \frac{d\sigma(M_X, M_Y)}{dM_X dM_Y} = Cf(M_X)f(M_Y). \]
Consequences of photon transverse momenta

Figure: Distribution in transverse momentum of the $t$ and $\bar{t}$ pairs for elastic - elastic, inelastic-elastic (elastic-inelastic) and inelastic-inelastic contributions for LUX-like structure function.
Gap survival factor

\[ S_R(\eta_{\text{cut}}) = 1 - \frac{1}{\sigma} \int_{-\eta_{\text{cut}}}^{\eta_{\text{cut}}} \frac{d\sigma}{d\eta_{\text{jet}}} d\eta_{\text{jet}}, \]  

(16)
Gap survival factor

Figure: The two-dimensional $\frac{d^2\sigma}{d\eta_{\text{jet1}} d\eta_{\text{jet2}}}$ distribution as a function of $\eta_{\text{jet1}}, \eta_{\text{jet2}}$ in nb. The left panel shows distribution without cuts and the right panel with cuts on $\eta_{\text{jet1}}$ and $\eta_{\text{jet2}}$. 
Figure: Gap survival factor for single and double dissociation as a function of the size of the pseudorapidity veto applied on the recoiling jet emitted from proton remnants.
Conclusions on $W^+ W^-$

- Helicity-dependent matrix elements derived by Nachtmann et al. were used.
- 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 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 $Q^2$ have been observed, raising questions about the reliability of...
Conclusions. $W^+ W^-$

- We have presented a decomposition of the cross section into different polarizations of both $W$ bosons. It has been shown that the $TT$ (both $W$ transversely polarized) contribution dominates and constitutes a little bit 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 quantified the effect of inclusion of longitudinal structure function into the transverse momentum dependent fluxes of photons. A rather small, approximately $M_{WW}$ - independent, effect was found.

- The discussed here $\gamma\gamma \rightarrow W^+ W^-$ mechanism leads to rather large rapidity separations of $W^+$ and $W^-$ boson
Conclusions on gap survival factor

- We have discussed the quantity called "remnant gap survival factor" for the $pp \rightarrow W^+ W^-$ 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 discussed the role of valence and sea contributions.
- 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 $\eta_{\text{cut}}$ (upper limit on charged particles pseudorapidity), the smaller rapidity gap survival factor $S_R$. This holds both for the single and double dissociation.
Conclusions, $t\bar{t}$

- We have calculated cross sections for $t\bar{t}$ production via $\gamma\gamma$ mechanism in $p\ p$ 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. 
  $$\sigma_{t\bar{t}}^{ela-ela} < \sigma_{t\bar{t}}^{SD} < \sigma_{t\bar{t}}^{DD}.$$ 

- We have calculated several differential distributions. Some of them are not accessible in standard EPA.

- We have shown that large photon virtualities come into the game. 
  In EPA one has on-shell photons.

- Gap survival factor due to proton remnant dissociation(s) have been calculated for different intervals of rapidity veto. 
  In our approach $S_{DD}^{DD} = (S_{R}^{SD})^2$.

- The gap destroying effects reverse order of contributions. 
  (this should be observed in experiments with rapidity gaps).
Outlook

So far we have calculated $\gamma\gamma \to W^+ W^-$ inclusive cross section.

ATLAS and CMS measure leptons and check rapidity gaps.
Include decays of $W$ bosons:
$W^+ \to \mu^+$, $W^- \to e^-$ or
$W^+ \to e^+$, $W^- \to \mu^-$
Consistent inclusion of soft (rapidity gap size dependent) gap survival factors together with those included here.