Rapidity gap survival factors caused by remnant fragmentation for $W^+W^-$ pair production via $\gamma^*\gamma^* \rightarrow W^+W^-$ subprocess with photon transverse momenta.

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Abstract

We calculate the cross section for $pp \rightarrow W^+W^-$ in the recently developed $k_T$-factorisation approach, including transverse momenta of the virtual photons. We focus on processes with single and double proton dissociation. The hadronisation of proton remnants is performed with PYTHIA 8 string fragmentation model, assuming a simple quark-diquark model for proton. Highly excited remnant systems hadronise producing particles that can be vetoed in the calorimeter. We calculate associated effective gap survival factors. The gap survival factors depend on the process, mass of the remnant system and collision energy. The rapidity gap survival factor due to remnant fragmentation for double dissociative (DD) collisions ($S_{R,DD}$) is smaller than that for single dissociative (SD) process ($S_{R,SD}$). We observe approximate factorisation: $S_{R,DD} \approx (S_{R,SD})^2$, when imposing rapidity veto.

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I. INTRODUCTION

The processes with partonic $\gamma\gamma \rightarrow O_1O_2$ ($O_1$ and $O_2$ being electroweak states) subprocesses become recently very topical. Experimentally they can be separated from other competing processes by imposing rapidity gaps around the electroweak vertex. Both charged lepton pairs $l^+l^-$ [1–5] and electroweak gauge bosons $W^+W^-$ [6, 7] were recently studied experimentally at the Large Hadron Collider. In particular processes with $W^+W^-$ are of special interest as here one can study e.g. anomalous quartic gauge boson coupling [8, 9]. Precise data may therefore provide a useful information allowing to test the Standard Model in a sector, which is so far not accessible otherwise.

There are, in general, different categories of such processes depending on whether the proton stays intact or undergoes an electromagnetic dissociation (see e.g. [10, 11]).

The $W^+W^-$ production in proton-proton processes via the $\gamma\gamma \rightarrow W^+W^-$ subprocess was recently studied in collinear [12] and transverse momentum dependent factorisation [13] approaches.

Without additional requirements it is impossible to separate the $\gamma\gamma \rightarrow W^+W^-$ mechanism from $q\bar{q} \rightarrow W^+W^-$, $gg \rightarrow W^+W^-$ or higher-order QCD processes. To enhance the sample for the wanted mechanism one may impose a rapidity gap condition around the $e^+\mu^-$ or $e^-\mu^+$ vertex.

In Fig. 1 we show a schematic picture of the single and double dissociative two-photon processes. In our recent paper [13] we have shown that rather large photon virtualities and large mass proton excitation are characteristic for the $\gamma\gamma \rightarrow W^+W^-$ induced processes. The highly excited hadronic systems hadronise producing (charged) particles that may destroy the rapidity gap around the $e^+\mu^-$ or $e^-\mu^+$ vertex. The minimal requirement is to impose a condition of no charged particles in the main ATLAS or CMS trackers.

We will focus on such effects in the present letter. The hadronisation of the proton remnants will be performed and conditions on charged particles will be imposed. Our main

![Diagram](image_url)

FIG. 1: The single and double dissociative mechanisms discussed in the present letter.

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1 The $e^+e^-$ or $\mu^+\mu^-$ final states seems less useful due to contamination by the Drell-Yan processes.
aim is to estimate gap survival factor associated with the remnant hadronisation which destroys the rapidity gap. Dependence on kinematic variables will be studied.

As has been stressed in [14], the ordinary collinear photon parton distribution functions (PDFs) – which imply a fully inclusive sum over remnant final states – cannot be used if additional gap requirements are imposed on the final states. For this purpose, in Ref. [14] a concept of “photon PDF in events with rapidity gaps” was introduced. There a requirement, that the parton emissions related to evolution do not contaminate the central rapidity region is implemented. The authors tried to answer the question how to approximately modify the collinear photon PDF to include rapidity gap requirement(s) used in modern experiments. The calculations in [14] are kept at the parton level, and no explicit remnant hadronisation effects were discussed there.

Remnant fragmentation is not the only effect that can destroy the rapidity gap. There are also possible interactions between remnant systems $X$ and $Y$ which can produce additional particles, for a recent review, see [15]. The gap survival factors for these processes are beyond the scope of the present letter. For recent estimates in photon induced processes, see e.g. [14, 16, 17].

II. SKETCH OF OUR CALCULATIONAL SCHEME

We calculate cross section for the $pp \rightarrow W^+W^-$ reaction with double proton dissociation as:

$$\frac{d\sigma(pp \rightarrow XW^+W^-Y)}{dy_+dy_-d^2p_+^zd^2p_-^zdM_XdM_Y} = x_1x_2 \frac{d\gamma(x_1,k_{1\perp},M_X)}{dM_X} \frac{d\gamma(x_2,k_{2\perp},M_Y)}{dM_Y} \times$$

$$\times \frac{1}{16\pi^2(x_1x_2s)^2} \sum_{\lambda_{W^+},\lambda_{W^-}} |M(\lambda_{W^+},\lambda_{W^-};k_{1\perp},k_{2\perp})|^2 \delta^{(2)}(p_+^+ + p_-^- - k_{1\perp} - k_{2\perp}). \quad (2.1)$$

Here $y_{\pm}$ are the rapidities and $p_{\perp}^\pm$ the transverse momenta of $W^\pm$ bosons. The $M_X$-dependent photon fluxes can be decomposed into fluxes corresponding to the relevant proton staying intact or dissociating (see Fig. 1):

$$\frac{d\gamma(x_1,k_{1\perp},M_X)}{dM_X} = \gamma_{el}(x_1,k_{1\perp})\delta(M_X - m_p) + \frac{d\gamma_{inel}(x_1,k_{1\perp},M_X)}{dM_X} \theta(M_X - (m_p + m_\pi)),$$

(2.2)

and similarly for $(x_1,k_{1\perp},M_X) \rightarrow (x_2,k_{2\perp},M_Y)$, so that the cross section for single dissociative process is less differential, as one of the two integrations over the remnant masses is unnecessary. These photon fluxes can be understood as a type of fully unintegrated parton distributions [18]. They allow us to generate events containing remnants of mass $M_X, M_Y$. The details of the relation of the photon fluxes to proton structure functions and the used matrix element $M(\lambda_{W^+},\lambda_{W^-};k_{1\perp},k_{2\perp})$ can be found in [13] and references therein.

We use an implementation of the above process in CepGen [19] for the Monte-Carlo generation of unweighted events.

The hadronisation of remnant states $X$ and/or $Y$ systems is performed using the Lund fragmentation algorithm implemented in PYTHIA 8 [20], and interfaced to CepGen. We model the incoming photon as emitted from a valence (up) quark collinear to the incoming
proton direction. Other flavour combinations are also expected to contribute to the process, but we observe the kinematics of the outgoing $X$ and $Y$ systems is not sensitive to this choice. The fractional quark momentum $x_{Bj}$ is determined event-by-event from the photon virtuality $Q^2$ and the relevant remnant mass $M_X$ through:

$$x_{Bj} = \frac{Q^2}{Q^2 + M_X^2 - m_p^2}.$$  

We check the condition for each “stable” (pions, kaons, protons, . . .) charged particle produced in the hadronisation of the $X$ and $Y$ remnants:

$$-\eta_{\text{cut}} < \eta^\text{ch} < +\eta_{\text{cut}}.$$  \hspace{1cm} (2.3)

Each event for which at least one charged particle fulfils condition (2.3) is discarded. We introduce the ratio:

$$S_R(\omega) = \frac{N_{\text{accepted}}(\omega)}{N_{\text{all}}(\omega)},$$  \hspace{1cm} (2.4)

where $\omega$ denotes a set of kinematic variables describing details of the reaction. $S_R(\omega)$ can be considered a phase-space-point-dependent rapidity gap survival factor associated with remnant(s) fragmentation. For example we will show such number for different ranges of masses of the produced system both for double and single dissociation.

### III. NUMERICAL RESULTS

Here we wish to present some results of our Monte Carlo simulations. We consider separately the case of double dissociation as well as the case of single dissociation. The most important ingredient of our calculation is realistic hadronisation of the proton remnants, which allows to estimate gap survival factor associated with spoiling the rapidity gap in the central pseudorapidity region, assumed here to be $-2.5 < \eta < 2.5$, by individual (charged!) particles. This corresponds to a realistic situation relevant for recent CMS [6] and ATLAS [7] measurements.

As mentioned in the Introduction, in the present letter we will not discuss effects related to soft interactions between remnants. They are rather small and similar for different categories of processes (elastic-elastic, elastic-inelastic, inelastic-inelastic). In general, they are expected to be dependent on the $W^+W^-$ invariant mass $M_{WW}$ [16, 17] as well as collision-energy dependent [17]. It was shown e.g. in [13] that:

$$\sigma(\text{inel.-inel.}) > \sigma(\text{inel.-el.}) + \sigma(\text{el.-inel.}) > \sigma(\text{el.-el.}).$$  \hspace{1cm} (3.1)

Can this ordering be changed when the rapidity gap requirement is taken into account? As will be shown below, absorption effects are the biggest for inelastic-inelastic processes, so that in principle the ordering in (3.1) can be changed when a rapidity veto is imposed.

#### A. Double dissociation

We start from the largest contribution, in the inclusive case, the inelastic-inelastic (double dissociative) [13] processes. In this case both remnants fragment and we have to include
FIG. 2: Two-dimensional \((\eta_{ch}^{X}, \eta_{ch}^{Y})\) distribution for four different windows of \(M_{WW}\): \((2M_{W}, 200 \text{ GeV})\), \((200, 500 \text{ GeV})\), \((500, 1000 \text{ GeV})\), \((1000, 2000 \text{ GeV})\). The square shows pseudorapidity coverage of ATLAS or CMS inner tracker.

their fragmentation simultaneously. In Fig. 2 we show two-dimensional distributions in pseudorapidity of particles from \(X\) \((\eta_{ch}^{X})\) and \(Y\) \((\eta_{ch}^{Y})\) for different ranges of masses of the centrally produced system. For illustration we show by the thin square the region relevant for ATLAS and CMS pseudorapidity coverage. One can see that the gap survival weakly depends on the invariant mass of the centrally produced system.

We quantify this effect, see Table I, by showing average remnant rapidity gap factors for different ranges of \(M_{WW}\) masses. The remnant rapidity gap survival factor at fixed \(\eta_{cut}\) becomes larger at higher collision energies. We hope this can be verified by the new data for \(\sqrt{s} = 13\ \text{TeV}\). We will leave it for future studies.

In Fig. 3 we show the distribution in \(\eta_{cut}\) for the double dissociation process. We predict a strong dependence on \(\eta_{cut}\). It would be valuable to perform experimental measurements...
TABLE I: Average rapidity gap survival factor related to spoiling the rapidity gap for double dissociative contributions by proton remnant fragmentation for different ranges of \(M_{WW}\) masses. All uncertainties are statistical only.

| Contribution          | \(S_{R,DD}(\mid \eta^{ch} \mid < 2.5)\) |
|-----------------------|----------------------------------------|
|                      | 8 TeV | 13 TeV |
| \((2M_{WW}, 200 \text{ GeV})\) | 0.586(1) | 0.601(2) |
| \((200, 500 \text{ GeV})\) | 0.629(1) | 0.649(1) |
| \((500, 1000 \text{ GeV})\) | 0.673(2) | 0.705(2) |
| \((1000, 2000 \text{ GeV})\) | 0.697(5) | 0.763(6) |
| full range            | 0.617(1) | 0.646(1) |

FIG. 3: 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 \(\sqrt{s} = 8\) TeV (left) and 13 TeV (right) with different \(\eta_{\text{cut}}\).

B. Single dissociation

We repeat a similar analysis for the single dissociative process. In Fig. 4 we show the rapidity distribution of charged particles produced in the fragmentation of the X system. The contamination of the detector is only weakly correlated with the mass of the centrally produced system.

Again we quantify the effect by showing the average remnant rapidity gap survival factor for the same windows of \(M_{WW}\). The conclusions here are similar as for the double dissociation, except that the effect of destroying the rapidity gap is smaller.

In Table II we show the rapidity gap survival factor for single dissociation processes and those values squared. By comparing to the results collected in Table I we observe that with good precision:

6
Contribution & \( S_{R,SD}(|\eta_{ch}| < 2.5) \) & \( (S_{R,SD})^2 (|\eta_{ch}| < 2.5) \) & 8 TeV & 13 TeV & 8 TeV & 13 TeV \\
(2M_{WW}, 200 \text{ GeV}) & 0.763(2) & 0.769(2) & 0.582(4) & 0.591(4) \\
(200, 500 \text{ GeV}) & 0.787(1) & 0.799(1) & 0.619(2) & 0.638(2) \\
(500, 1000 \text{ GeV}) & 0.812(2) & 0.831(2) & 0.659(3) & 0.691(3) \\
(1000, 2000 \text{ GeV}) & 0.838(7) & 0.873(5) & 0.702(12) & 0.762(8) \\
full range & 0.782(1) & 0.799(1) & 0.611(2) & 0.638(2) \\

\( S_{R,DD} \approx (S_{R,SD})^2 \). (3.2)
FIG. 5: 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 $\sqrt{s} = 8$ TeV (left) and 13 TeV (right).

FIG. 6: Rapidity gap survival factor for $|\eta^{ch}| < 2.5$ (top row) and $|\eta^{ch}| < 5$ (bottom row) as a function of the upper limit set on $M_X$, the remnant system invariant mass, for single dissociation.

ing the gap and avoiding the more complicated Monte Carlo simulations of the remnant hadronisation.

The hadronisation part is independent of the system centrally produced. Hence, this method can be used to perform calculations for processes for which there are no direct procedures to perform full Monte Carlo simulations.
IV. CONCLUSIONS

In the present letter we discuss the quantity called “remnant gap survival factor” for the $pp \rightarrow W^+W^-$ reaction initiated via photon-photon fusion. We use a recent formalism developed for the inclusive case \cite{13} which includes transverse momenta of incoming photons. This formalism has been supplemented here by including remnant fragmentation that can spoil the rapidity gap usually used to select the wanted subprocess of interest. We quantify this effect by defining the remnant gap survival factor which in general depends on the reaction, kinematic variables and details of the experimental set-ups. We discuss dependence on invariant mass of the produced $W^+W^-$ central system. We find different values for double and single dissociative processes. In general, $S_{R,DD} < S_{R,SD}$ and $S_{R,DD} \approx (S_{R,SD})^2$. Furthermore the larger $\eta_{cut}$ (upper limit on charged particles pseudorapidity) the smaller rapidity gap survival factor $S_R$, both for double and single dissociation. Finally the effect becomes smaller for larger collision energies. We have found that the crucial variable for $S_R$ is (are) masses of the final protonic systems.

The present approach is a step towards realistic modelling of gap survival in photon induced interactions and definitely requires further detailed studies and comparisons to the existing and future experimental data. In the present analyses we have neglected other effects such as soft interactions or multiple-parton interactions (see e.g. \cite{13, 21}). More detailed studies including such effects in a consistent manner will be given elsewhere.

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