

Diffraction pQCD mechanism of exclusive production of W^+W^- pairs in proton-proton collisions

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We present a study of central exclusive production of W^+W^- pairs in proton-proton collisions at the LHC. We compare the contribution of the $\gamma\gamma \rightarrow W^+W^-$ mechanism with a new mechanism of exclusive diffractive production through the $gg \rightarrow W^+W^-$ subprocess with intermediate virtual Higgs boson and quark box diagrams. The amplitude for the latter process is expressed in terms of the off-diagonal unintegrated gluon distribution functions. Several observables related to this process are calculated. The phase space integrated diffractive contribution when separated is only a small fraction of fb compared to 115.4 fb of the $\gamma\gamma$ -contribution without absorption. This opens a possibility of efficient searches for anomalous boson γW^+W^- and $\gamma\gamma W^+W^-$ couplings due to new physics beyond Standard Model.

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1. Introduction

Central exclusive production (CEP) processes $pp \rightarrow p + X + p$, where X stands for a centrally produced system separated from the two very forward protons by large rapidity gaps, provide a very promising way to investigate both QCD dynamics and new physics in hadron collisions.

We focus on central exclusive production of W^+W^- pairs in high-energy proton-proton collisions [1]. The $\gamma\gamma$ -contribution for the purely exclusive production of W^+W^- was already considered in the literature. The diffractive production and decay of Higgs boson into the W^+W^- pair was discussed in Ref. [2], and the corresponding cross section turned out to be smaller than that for the $\gamma\gamma$ -contribution. Provided this is the case, the W^+W^- pair production signal would be particularly sensitive to New Physics contributions in the $\gamma\gamma \rightarrow W^+W^-$ subprocess [3, 4] and $pp \rightarrow ppW^+W^-$ reaction is an ideal case to study experimentally γW^+W^- and $\gamma\gamma W^+W^-$ couplings¹.

The linear collider would be a good option to study the couplings of gauge bosons in the distant future. For instance in Ref.[6] the anomalous coupling in locally $SU(2) \times U(1)$ invariant effective Lagrangian was studied. Other models also lead to anomalous gauge boson coupling. Similar analysis has been considered recently for $\gamma\gamma \rightarrow ZZ$ [7]. These previous analyses strongly motivate our present detailed study on a competitive diffractive contribution. The $pp \rightarrow pW^+W^-p$ process going through the diffractive QCD mechanism with the $gg \rightarrow W^+W^-$ subprocess (shown in Fig. 1) naturally constitutes a background for the exclusive electromagnetic $pp \rightarrow p(\gamma\gamma \rightarrow W^+W^-)p$ process. We consider not only the mechanism with intermediate Higgs boson but also box contributions never estimated in exclusive processes. We discuss the interference effects within the Standard Model as potentially important irreducible background for the $\gamma\gamma \rightarrow W^+W^-$ signal relevant for a precision study of anomalous couplings. Thus, our numerical estimates provide minimal limit for the central exclusive WW production signal.

Corresponding measurements will be possible to perform at the ATLAS detector with the use of very forward FP220 detectors [3]. In order to quantify to what extent the QCD mechanism competes with the “signal” from the $\gamma\gamma$ fusion, we calculate both contributions and compare them as a function of several relevant phase space variables.

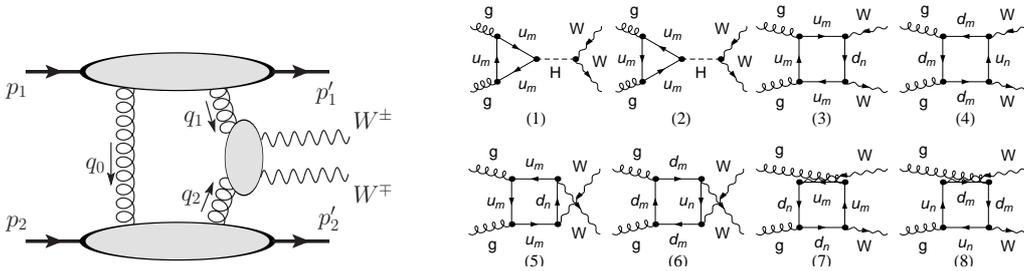


Figure 1: Diagram for the central exclusive WW pair production in pp collisions (left panel) and representative diagrams of the hard subprocess $gg \rightarrow W^\pm W^\mp$ (right panel).

¹Some more subtle aspects of the beyond Standard Model anomalous couplings were discussed e.g. in [5].

2. Formalism

2.1 Diffractive mechanism of exclusive W^+W^- pair production

We write the amplitude of the diffractive process, which at high energy is dominated by its imaginary part, as

$$\mathcal{M}_{\lambda_+, \lambda_-}(s, t_1, t_2) \simeq is \frac{\pi^2}{2} \int d^2 q_{0\perp} V_{\lambda_+, \lambda_-}(q_1, q_2, k_+, k_-) \frac{f_g(q_0, q_1; t_1) f_g(q_0, q_2; t_2)}{q_{0\perp}^2 q_{1\perp}^2 q_{2\perp}^2}, \quad (2.1)$$

where $\lambda_{\pm} = \pm 1, 0$ are the polarisation states of the produced W^{\pm} bosons, respectively, $f_g(r_1, r_2; t)$ is the off-diagonal unintegrated gluon distribution (UGDF), which depends on the longitudinal and transverse components of both gluons momenta (see [1] for more details). In the calculations we use the GJR NLO collinear gluon distribution [8] which allow to use very low $q_{\perp, cut}^2 = 0.5 \text{ GeV}^2$.

The momenta of intermediate gluons are given by Sudakov decompositions in terms of the incoming proton four-momenta $p_{1,2}$

$$\begin{aligned} q_1 &= x_1 p_1 + q_{1\perp}, & q_2 &= x_2 p_2 + q_{2\perp}, & 0 < x_{1,2} < 1, \\ q_0 &= x' p_1 - x' p_2 + q_{0\perp} \simeq q_{0\perp}, & x' &\ll x_{1,2}, \end{aligned} \quad (2.2)$$

where $x_{1,2}, x'$ are the longitudinal momentum fractions for active (fusing) and color screening gluons, respectively, such that $q_{\perp}^2 \simeq -|q_{\perp}|^2$. In the forward proton scattering limit, we have

$$t_{1,2} = (p_{1,2} - p'_{1,2})^2 \simeq p_{1,2\perp}^2 \rightarrow 0, \quad q_{\perp} \equiv q_{0\perp} \simeq -q_{1\perp} \simeq q_{2\perp}. \quad (2.3)$$

It is convenient to introduce the Sudakov expansion for W^{\pm} boson momenta

$$k_+ = x_1^+ p_1 + x_2^+ p_2 + k_{+\perp}, \quad k_- = x_1^- p_1 + x_2^- p_2 + k_{-\perp} \quad (2.4)$$

leading to

$$x_{1,2} = x_{1,2}^+ + x_{1,2}^-, \quad x_{1,2}^+ = \frac{m_{+\perp}}{\sqrt{s}} e^{\pm y_+}, \quad x_{1,2}^- = \frac{m_{-\perp}}{\sqrt{s}} e^{\pm y_-}, \quad m_{\pm\perp}^2 = m_W^2 + |k_{\pm\perp}|^2, \quad (2.5)$$

in terms of W^{\pm} rapidities y_{\pm} and transverse masses $m_{\pm\perp}$. For simplicity, in actual calculations we work in the forward limit given by Eq. (2.3), which implies that $k_{+\perp} = -k_{-\perp}$.

The gauge-invariant $gg \rightarrow W_{\lambda_+}^+ W_{\lambda_-}^-$ hard subprocess amplitude $V_{\lambda_+, \lambda_-}(q_1, q_2, k_+, k_-)$ is given by the light cone projection

$$V_{\lambda_+, \lambda_-} = n_{\mu}^+ n_{\nu}^- V_{\lambda_+, \lambda_-}^{\mu\nu} = \frac{4}{s} \frac{q_{1\perp}^{\nu}}{x_1} \frac{q_{2\perp}^{\mu}}{x_2} V_{\lambda_+, \lambda_-, \mu\nu}, \quad q_1^{\nu} V_{\lambda_+, \lambda_-, \mu\nu} = q_2^{\mu} V_{\lambda_+, \lambda_-, \mu\nu} = 0, \quad (2.6)$$

where $n_{\mu}^{\pm} = p_{1,2}^{\mu} / E_{p, cms}$ and the center-of-mass proton energy $E_{p, cms} = \sqrt{s}/2$. We adopt the definition of gluon transverse polarisation vectors proportional to the transverse gluon momenta $q_{1,2\perp}$, i.e. $\varepsilon_{1,2} \sim q_{1,2\perp} / x_{1,2}$. The helicity matrix element in the previous expression reads

$$V_{\lambda_+, \lambda_-}^{\mu\nu}(q_1, q_2, k_+, k_-) = \varepsilon^{*,P}(k_+, \lambda_+) \varepsilon^{*,\sigma}(k_-, \lambda_-) V_{\rho\sigma}^{\mu\nu}, \quad (2.7)$$

in terms of the Lorentz and gauge invariant $2 \rightarrow 2$ amplitude $V_{\rho\sigma}^{\mu\nu}$ and W boson polarisation vectors $\varepsilon(k, \lambda)$, which can be defined easily in the pp center-of-mass frame with z -axis along the proton beam (see [1]). The matrix element V_{λ_+, λ_-} contains twice the strong coupling constant $g_s^2 = 4\pi\alpha_s$. We take the running coupling constant $\alpha_s(\mu_{hard}^2 = M_{WW}^2)$ which depends on the invariant mass of WW pair taken as a hard renormalisation scale of the process. In the calculations we use the reduced form of the four-body phase space [1, 9].

2.2 Electromagnetic $\gamma\gamma \rightarrow W^+W^-$ mechanism

In the Weizsäcker-Williams approximation, the total cross section for the $pp \rightarrow pp(\gamma\gamma \rightarrow W^+W^-)$ can be written as in the parton model

$$\sigma = \int dx_1 dx_2 f_1^{WW}(x_1) f_2^{WW}(x_2) \hat{\sigma}_{\gamma\gamma \rightarrow W^+W^-}(\hat{s}), \quad (2.8)$$

where we take the Weizsäcker-Williams equivalent photon fluxes of protons from Ref. [10]. The elementary tree-level cross section for the $\gamma\gamma \rightarrow W^+W^-$ subprocess can be written in the compact form in terms of the Mandelstam variables (see e.g. Ref. [11]). To calculate differential distributions the following parton formula can be used

$$\frac{d\sigma}{dy_+ dy_- d^2 p_{W\perp}} = \frac{1}{16\pi^2 \hat{s}^2} x_1 f_1^{WW}(x_1) x_2 f_2^{WW}(x_2) \overline{|\mathcal{M}_{\gamma\gamma \rightarrow W^+W^-}(\hat{s}, \hat{t}, \hat{u})|^2}, \quad (2.9)$$

where the momentum fractions of the fusing gluons $x_{1,2}$ are defined in Eq. (2.5).

2.3 Inclusive production of W^+W^- pairs (gluon-gluon fusion)

In the lowest order of pQCD the inclusive cross section can be written as [1]

$$\frac{d\sigma}{dy_+ dy_- d^2 p_{W\perp}} = \frac{1}{16\pi^2 \hat{s}^2} x_1 g(x_1, \mu_F^2) x_2 g(x_2, \mu_F^2) \overline{|\mathcal{M}_{gg \rightarrow W^+W^-}(\lambda_1, \lambda_2, \lambda_+, \lambda_-)|^2}. \quad (2.10)$$

3. Results

The main results emerging from our analysis are presented in Fig. 2. We compare distributions of W boson for the electromagnetic $\gamma\gamma \rightarrow W^+W^-$ and diffractive $gg \rightarrow W^+W^-$ mechanisms. For a reference, we show also inclusive cross section ($gg \rightarrow W^+W^-$ contribution only) which is five orders of magnitude bigger than the exclusive counterpart. The two-photon induced contribution is almost three orders of magnitude larger than the diffractive contribution, in which all polarization components for W^+ and W^- have been included. It is completely opposite than for $pp \rightarrow pHp$, $pp \rightarrow pQ\bar{Q}p$ [12] or $pp \rightarrow pMp$ (e.g. light/heavy quarkonia production [13, 14, 15]) CEP processes. The standard relative suppression is due to soft gap survival probability factor ($S_g \sim 0.03$ for diffractive contribution versus $S_g \sim 1$ for two-photon contribution), and due to a suppression by the Sudakov form factor (see e.g. [1]) calculated at very large scales, here at $\mu_{hard} = M_{WW}$. The main difference compared to other cases is that in the diffractive case the leading contribution comes from loop diagrams while in the two-photon case already from tree level diagrams.

The distribution in W^+ (W^-) transverse momentum for exclusive diffractive production is much steeper than that for the electromagnetic contribution. The diffractive contribution peaks at

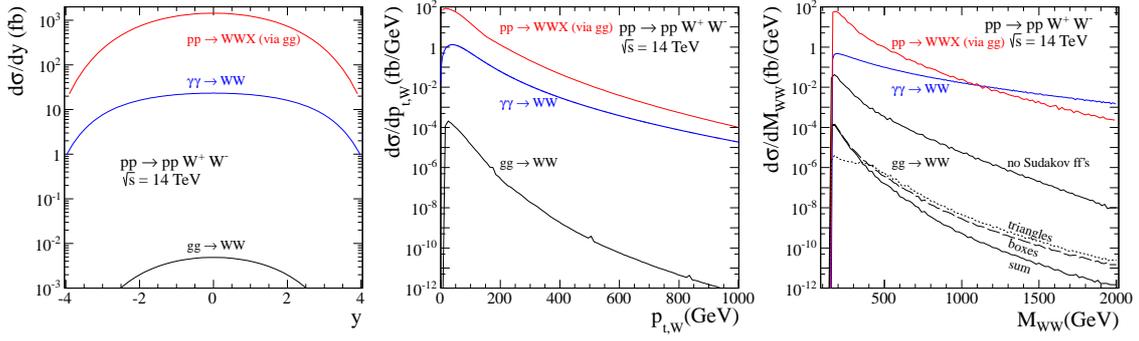


Figure 2: Distribution in W bosons rapidity (left panel), transverse momentum of one of the W bosons (central panel) and W^+W^- invariant mass (right panel). The diffractive contribution is shown by the bottom line while the $\gamma\gamma \rightarrow W^+W^-$ contribution by the middle line. The top line corresponds to the inclusive gluon-initiated $pp \rightarrow W^+W^-X$ component. On the right panel the result when the Sudakov form factor is put to one is shown.

$p_{t,W} \sim 25$ GeV while for the $\gamma\gamma \rightarrow W^+W^-$ mechanism the maximum is at $p_{t,W} \sim 40$ GeV. The exclusive cross section for $\gamma\gamma$ -contribution is at large $p_{t,W} \sim 1$ TeV smaller only by one order of magnitude than the inclusive $gg \rightarrow W^+W^-$ component. The situation could be more favorable if New Physics would be at the game [3].

The distribution for the diffractive component drops quickly with the M_{WW} invariant mass. As can be seen from the figure, the Sudakov form factor lowers the cross section by a large factor. The larger M_{WW} the larger the damping. We show the full result (boxes + triangles) and the result with boxes only which would be complete if the Higgs boson does not exist. At high invariant masses, the interference of boxes and triangles decreases the cross section. The distribution for the $\gamma\gamma$ -component drops very slowly with M_{WW} and at $M_{WW} > 1$ TeV the corresponding cross section is even bigger than the $gg \rightarrow W^+W^-$ component to inclusive production of W^+W^- pairs.

4. Conclusions

We have performed a complete calculation of the QCD diffractive contribution to the exclusive $pp \rightarrow pW^+W^-p$ process for the first time in the literature with the full one-loop (leading order) $gg \rightarrow W^+W^-$ matrix element. Two mechanisms have been considered. First mechanism is a virtual (highly off-shell) Higgs boson production and its subsequent transformation into real W^+W^- pair. Second mechanism relies on the formation of intermediate quark boxes. We have calculated corresponding amplitudes using computer program package FormCalc [16]. We have made a first estimate of the cross section using amplitudes in the forward limit “corrected” off-forward using a simple exponential (slope dependent) extrapolation. We have shown that extra box diagrams, even though they are larger than the resonant diagrams, constitute a negligibly small background for a precision study of anomalous couplings.

Differential distributions in the W^\pm transverse momentum, rapidity and W^+W^- pair invariant mass have been calculated and compared with corresponding distributions for the discussed in the literature $\gamma\gamma \rightarrow W^+W^-$ mechanism. The contribution of triangles with the intermediate Higgs bo-

son turned out to be smaller than the contribution of boxes taking into account recent very stringent limitations on Higgs boson mass from the Tevatron and LHC data. We have found that, in contrast to exclusive production of Higgs boson or dijets, the two-photon fusion dominates over the diffractive mechanism for small four-momentum transfers squared in the proton lines as well as in a broad range of W^+W^- invariant masses, in particular, for large M_{WW} . Estimated theoretical uncertainties cannot disfavor this statement. The large M_{WW} region is damped in the diffractive model via scale dependence of the Sudakov form factor.

One could focus on the diffractive contribution by imposing lower cuts on t_1 and/or t_2 using very forward detectors on both sides of the interaction point at distances of 220 m and 420 m as planned for future studies at ATLAS and CMS. The corresponding cross section is, however, expected to be extremely low.

The unique situation of the dominance of the $\gamma\gamma \rightarrow W^+W^-$ contribution over the diffractive one opens a possibility of independent tests of the Standard Model as far as the triple-boson γWW and quartic-boson $\gamma\gamma WW$ coupling is considered. It allows also stringent tests of some Higgsless models as discussed already in the literature (see e.g. Ref. [3]).

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