Ref.TH.3720-CERN

THE PRODUCTION OF GAUGE BOSON PAIRS BY $p\bar{p}$ COLLIDERS

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A B S T R A C T

The simultaneous production of two gauge bosons from the set (W, Z, γ, γ^*) by $p\bar{p}$ colliders is considered. The dynamical characteristics of the lowest order 2-parton contributions are analyzed. The 4-parton background is small. The significance of $W\gamma$ (and also $Z^0\gamma$) production in unravelling possible W , Z substructure is stressed.

^{*)} The author thanks the CERN Theoretical Physics Division for its kind hospitality.

The recent experimental observation of the weak intermediate vector bosons W and Z at the CERN $p\bar{p}$ collider has opened the possibility for their detailed study¹⁾. Besides the particularities of their decay modes, one may hope to gain more insight into their production modes. The present results do not signal any disagreement with the predictions of the Weinber-Salam model²⁾; one therefore might be tempted to go further and to ask about the experimental verification of its characteristic triple gauge boson coupling, such as, for instance, $WW\gamma$ or Z^0WW . Obviously the cross-sections are much smaller.

Such questions have been followed up in several significant papers by analyzing the production of gauge boson pairs W^+W^- , W^-Z^0 , $W^- \gamma$ at pp and $p\bar{p}$ colliders³⁾ and the triple gauge boson coupling was found to be of importance. Furthermore, the $W^- \gamma$ channel involves the (anomalous) magnetic dipole and electric quadrupole moments of the W boson, causing a zero in the angular distribution of the parton cross-section⁴⁾ if their $SU_2 \times U_1$ values are chosen.

Since earlier cross-section estimates suffer from the deficiency of using scale independent momentum distributions a careful re-analysis is justified. With the present study we aim to broaden our goal by analyzing the production of any pair of gauge bosons out of the set Z^0 , $W^\pm$, γ , γ^* . The γ stands for an on-shell photon and $\gamma^*(\rightarrow \ell^+\ell^-)$ symbolizes massive lepton-pair production. We thus analyze the dynamical characteristics of the lowest order weak and electromagnetic production of two gauge bosons initiated by 2 partons (similar to Figs. 1a-c), and we determine the background originating from the 4-parton processes (Figs. 1d,e) whose relevance in the production of large- p_T hadron jets has recently been recognized⁵⁾. The identification of a W or Z , together with another gauge boson, via a pair of hadron jets is likely to become possible⁶⁾. We therefore also estimate the cross-section size for the production of one gauge boson accompanied by a pair of quark/gluon jets (Fig. 1e) with a mass cut of $M_{jj} \geq 70$ GeV being imposed.

The set of investigated 2-parton processes is

$$q\bar{q} \rightarrow Z^0 Z^0, \quad W^+ W^-, \quad W^- Z^0 \quad (1)$$

$$q\bar{q} \rightarrow Z^0 \gamma, \quad W^- \gamma, \quad \gamma\gamma, \quad \gamma^* \gamma \quad (2)$$

with the parton cross-sections given in Refs. 3) and 7). Those processes in (1) and (2) which involve a W are asymmetric under $t \leftrightarrow u$ exchange whereas all others remain invariant. The processes (1) have a relatively broad t dependence and vanish as the phase space boundaries are reached whereas all processes (2) become highly singular. The $W\gamma$ production involves the W anomalous magnetic moment K with its value fixed by $SU_2 \times U_1$ to unity.

Similarly, the list of analyzed background 4-parton processes reads

$$(qq)_1 + (q\bar{q})_2 \rightarrow Z^0 Z^0, \quad W^- W^-, \quad W^+ W^-, \quad W^- Z^0 \quad (3)$$

$$(qq)_1 + (\bar{q}\bar{q})_2 \rightarrow Z^0 + \gamma j, W^- + \gamma j, \gamma^* + \gamma j \quad (4)$$

$$(qq)_1 + (\bar{q}\bar{q})_2 \rightarrow Z^0 + j_1 j_2, W^- + j_1 j_2, \gamma^* + j_1 j_2 \quad (5)$$

where j stands for a quark/gluon jet, and the rates for γ^* always involve $\mu^+ \mu^-$ (or $e^+ e^-$) production. Hadronic 2-jet production proceeds via eight subprocesses whose parton cross-sections are found in Ref. 8). For the hadronic production of direct photons we refer to Ref. 9).

Choosing as kinematical variables the rapidities y_i and the transverse momentum q_t of the final state particles, the differential cross-section for the processes (1) and (2) reads

$$d\sigma \equiv d\sigma/dy_1 dy_2 dq_t^2 = \quad (6)$$

$$x_1 x_2 \sum_q \left[\hat{d}\sigma_{\hat{t}} u(x_1, Q^2) \bar{u}(x_2, Q^2) + \hat{d}\sigma_{\hat{u}} \bar{u}(x_1, Q^2) u(x_2, Q^2) \right]$$

where $\hat{d}\sigma_x \equiv \hat{d}\sigma/d\hat{t}(x)$ stands for the parton cross-section of the particular subprocess. $\hat{s}, \hat{t}, \hat{u}$ are the Mandelstam variables of the subprocess, and the usual parton kinematics applies¹⁰⁾. The differential cross-section of the 4-parton processes (Figs. 1d,e) reads

$$d\sigma = \sum_{q,g} (d\sigma_{12} d\sigma_{34} / \pi R^2) \cdot V(x_1, x_3) \cdot V(x_2, x_4) \quad (7)$$

where $d\sigma_{ij}$ represents the 2-parton cross-section. For each of the two subprocesses the parton kinematics applies separately. Obviously, the processes (3)-(5) are more easily calculated by directly integrating over the momentum fractions x_i if there is no explicit q_t dependence.

The $V(x_1, x_3)$ represent the momentum distributions of two constituents. We use the simple ansatz

$$V(x_1, x_3) = u(x_1, Q_1^2) \cdot u(x_3, Q_1^2) \cdot (1-x_1-x_3) \cdot \theta(1-x_1-x_3) \quad (8)$$

where the $u(x_1, Q_1^2)$ are the single quark/gluon momentum distributions involving (leading-log) QCD corrections¹¹⁾. We have explicitly verified that this form constitutes an excellent approximation to the generalized Kuti-Weisskopf model (KWG)¹²⁾. This model assumes the infinity of quarks in the nucleon to be uncorrelated apart from a strict observation of momentum conservation; the confinement effects on each constituent type are described by the "primitive structure functions". This attempt at the multi-quark distributions has been successfully applied to the soft-hadronic processes¹³⁾.

The scale Q^2 in the single parton momentum distributions is chosen to be $Q^2 \equiv \hat{s}$ if at least one of the final state particles has a large mass, and $Q^2 \equiv 2 \hat{s}\hat{t}\hat{u}/(\hat{s}^2 + \hat{t}^2 + \hat{u}^2)$ if both are massless.

The factor πR^2 in the denominator of Eq. (7) represents the total hadronic cross-section which is the estimate of the size of a hadron. The reason for this

factor is as follows : given that a pair of constituents interacts, the probability that there is a second interaction process is proportional to the flux factor of the accompanying quarks ; these are confined to the hadrons and their flux is thus inversely proportional to the area of a hadron. A more accurate estimate requires more detailed information on the hadron structure. In our subsequent analysis we choose : $\pi R^2 = 100 \text{ GeV}^{-2}$.

The sum $\Sigma_{q/g}$ is taken over all quark/gluon combinations.

Within the above-sketched framework we have carried out a detailed analysis of the dynamical particularities of the processes in (1) and (2). We have also assessed the influence of the set of 4-parton processes in (3-5) ; the importance of the analogous 2-parton reactions should eventually also be clarified¹⁴).

In Fig. 2a¹⁵) we present the integrated cross-sections of the 2-parton processes (1) and (2). All reactions involving a "direct" photon reveal a strongly peaked angular distribution of the parton cross-section. We therefore set the lower transverse momentum cut-off at $p_T = 5, 10 \text{ GeV}$ in agreement with the typical transverse momentum thresholds imposed by the experiments. For clarity of presentation we connected the two curves of the same process at their upper and lower ends of the overall centre-of-mass energy $\sqrt{s}$. The $\ell^+\ell^-$ -mass of γ^* production was chosen at $M_{\gamma^*} = 10 \text{ GeV}$.

The cross-section estimates for $\gamma\gamma$, $\gamma^*\gamma$, $Z^0\gamma$, Z^0Z^0 production are based on the (Abelian) quark exchange diagrams (Figs. 1a,b). The non-Abelian graph Fig. 1c (additional to Figs. 1a,b) exercises a non-negligible influence in $W^-\gamma$, W^+W^- , W^-Z^0 production. The latter two processes, calculated without Fig. 1c, would in fact be significantly larger since the interference term $\text{Re}(T_a + T_b) \cdot T_c^*$ is negative. We notice a strong threshold onset for processes with large final state masses which, above 1 TeV, changes to a steady rise in $\sqrt{s}$. At $\sqrt{s} = 540 \text{ GeV}$, typical cross-section values are :

$$\sigma(\gamma\gamma, Z^0\gamma, W^-\gamma) = (10^{-34}, 3 \cdot 10^{-36}, 10^{-36}) \text{ cm}^2 \quad (9)$$

whereas all others are at least one order of magnitude lower. If $\sigma(\gamma^*\gamma)$ is compared with Z, W production, the leptonic branching ratios $\text{BR}(W \rightarrow \ell\nu) \sim 8\%$, $\text{BR}(Z^0 \rightarrow \ell^+\ell^-) \sim 3\%$ should be taken into account. All final state modes generated by $W^- \leftrightarrow W^+$ lead to the same cross-sections.

In Fig. 2b we expose the integrated cross-sections of the 4-parton processes in (3)-(5). Our earlier remarks on the transverse momentum cut-off of the "direct" photon production γj , and on the γ^* mass apply here in the same way. Our results reveal that at $\sqrt{s} = 540 \text{ GeV}$ the 4-parton production of two gauge bosons is insignificant, at most a few per cent of the analogous 2-parton process. This is understood as follows : suppose the quarks/gluons in a nucleon are completely uncorrelated and therefore $d\sigma_4 = d\sigma_1 \cdot d\sigma_2 / \pi R^2$, where $d\sigma_{1,2}$ is the hadronic cross-section of each

of the two 2-parton processes. Thus, the size of $d\sigma_1$ determines the importance of $d\sigma_4$. If the nucleon constituents, however, are correlated, the 2-parton momentum distributions and the δ fall-off of the integrated parton cross-sections determine the size of $d\sigma_4$. The available energy is distributed by the 2-parton distributions among the two subprocesses with the typical x -values being fixed by the momenta (and/or masses) of the final state particles/jets. The 2-parton distributions impose the constraints due to the limited number of valence flavours and they properly enforce the strong fall-off if the available nucleon momentum is used up : $x_1 + x_3 \rightarrow 1$.

Note that this production mechanism also allows for W^-W^- and W^+W^+ production which otherwise, in the familiar framework, could not occur.

The stronger cross-section rise of the processes $W^- + \gamma j$ etc., with increasing $\sqrt{s}$, is partially explained by the above arguments ; the strong increase of the gluon distribution at low x in $gq \rightarrow \gamma q$ enforces this trend.

Assuming that W and Z could be identified via their two-jet decay modes, we aim, by indicating the cross-section for $W^- + jj$ etc., (Fig. 1e), at a background estimate for the signal such as $W^+ + (W^- \rightarrow) j_1 j_2$. We have for this reason imposed the mass cut-off $M_{jj} \geq 70$ GeV and the lower transverse momentum cut-off $p_T \geq 10$ GeV for each jet. Assuming the branching ratio $BR(W \rightarrow jj) \sim 75\%$ we notice that the background from the four-parton process is substantial.

If the constraint on the invariant 2-jet mass is released, the cross-section increases by more than an order of magnitude. Since at $\sqrt{s} = 540$ GeV $\sigma(W^- + jj) \sim 10^{-35}$ cm², one may expect that 1% of all events involving a W are accompanied by a pair of large- p_T jets. One $q\bar{q}$ pair annihilates to create the W and simultaneously a second quark/gluon pair annihilates to produce the final state jet pair (Fig. 1e). In our calculations we have imposed on the latter the lower transverse momentum cut-off $p_T = 10$ GeV; reducing further this value leads to an even bigger cross-section !

We now focus on the dynamical particularities of the 2-parton processes of (1) and (2). We have analyzed the most important kinematical distributions, and we discuss in the following their essential features.

In Fig. 3a we expose the (constituent) centre-of-mass angular distribution. We impose a lower transverse momentum cut-off $p_T \geq 10$ GeV for the processes involving a "direct" photon. The cross-section fall-off close to the phase space boundaries is due to the constraint

$$\hat{s} \geq (\sqrt{(p_T/\sin\theta)^2 + M_1^2} + \sqrt{(p_T/\sin\theta)^2 + M_2^2})^2 \quad (10)$$

which in earlier analyses has been ignored.

The most striking aspect here is the dip in the $W^- \gamma$ (and also $W^+ \gamma$) angular distribution. If the anomalous magnetic moment of the W is set to $K = +1$, as

required by strict $SU_2 \times U_1$, the parton cross-section reveals a zero at $\cos\theta_{CM} = -(1 + 2e_q)$. The e_q is the charge fraction of the quark initiating the reaction. This zero was shown to be a consequence of a factorizability of the amplitude into one factor which contains the dependence on the charge or other internal-symmetry indices, and another which contains the dependence on the spin or polarization indices. Necessary ingredients are one massless boson and a gauge trilinear coupling^{16 a)}. This insight was subsequently generalized to a large class of single-photon tree amplitudes involving derivative couplings as prescribed by gauge theory^{16 b)}. Similar zeros are expected in $W \rightarrow q\bar{q}\gamma$ and $q\bar{q} \rightarrow WZ$, but $W^- \gamma$ seems to offer the best possibility in the search for such a zero.

If the W and Z^0 are no longer pointlike, one may expect the magnetic dipole, the electric quadrupole and the charge radius

$$\mu_W = e(1 + K + \rho)/2M_W, \quad Q_W = -e(K - \rho)/M_W^2, \quad R_W^2 = (K + \rho)/M_W^2 \quad (11)$$

to be different from their $SU_2 \times U_1$ value $K = 1, \rho = 0$; the intermediate vector bosons would thus be composed of very massive constituents¹⁸⁾. Besides the anomalous magnetic moment K there is a new parameter ρ which allows for the independent variation of μ_W and Q_W ; K and ρ are unknown. For illustration purposes we have set $K = -1$ and notice that the dip disappears. As $K \rightarrow -3$ the fully integrated cross-section grows by a factor 2. If $\rho = 1$ these features would be significantly enforced⁴⁾. One also may expect significant changes in W^+W^- , W^-Z^0 and $Z^0\gamma$ production, although a first analysis of $q\bar{q} \rightarrow \gamma^*$, $Z'^0 \rightarrow Z^0 + \gamma$ ¹⁹⁾ revealed for reasonable parameters a cross-section below the $Z^0\gamma$ curve in Fig. 2a; notice that the interference effects were, however, ignored²⁰⁾. The experimental search for such features seems to us of utmost importance. For a detailed theoretical study of $W^- \gamma$ production with subsequent ev decay we refer to Ref. 21).

The asymmetry seen in the W^+W^- and W^-Z^0 (and also W^+Z^0) curves of Fig. 3a reflects the angular behaviour of the parton cross-sections. Note also the symmetry between the W^- and the W^+ distributions.

The rapidity distributions were determined when assuming for the "direct" photon the lower transverse momentum cut-off $p_T \geq 10$ GeV. The W and Z rapidities are in the range $-1.5 \lesssim y_W \lesssim +1.5$ centred roughly around zero, whereas those of γ and γ^* extend to $-2.5 \lesssim y_\gamma \lesssim +2.5$. Typical values for the single rapidity distributions $d\sigma/dy_i$ at $y_i = 0$ of the processes (1) $\equiv (Z^0Z^0, W^+W^-, W^-Z^0)$ and (2) $\equiv (Z^0\gamma, W^- \gamma, \gamma\gamma, \gamma^*\gamma)$ are

$$d\sigma/dy_{i=1}(1) = (10^{-38}, 10^{-37}, 5 \cdot 10^{-39}) \text{ cm}^2 = d\sigma/dy_{i=2}(1) \quad (12)$$

$$d\sigma/dy_{i=1}(2) = (10^{-36}, 5 \cdot 10^{-37}, 10^{-35}, 3 \cdot 10^{-39}) \text{ cm}^2 \quad (13)$$

$$d\sigma/dy_{i=2}(2) = (6 \cdot 10^{-37}, 10^{-37}, 10^{-35}, 3 \cdot 10^{-35}) \text{ cm}^2 \quad (14)$$

The i refers to the first and second particles of the final state pair. If their masses are significantly different one notices a difference in the $i = 1$ and 2 cross-sections due to the different rapidity ranges. The γ -rapidity distribution of $W^- \gamma$ has its maximum around $y_2(\gamma) = -1.1$ and reveals an asymmetry of almost an order of magnitude in the cross-section values of the negative and positive rapidity ranges. The same, though less pronounced, feature is observed in $W^- Z^0$ production with its maximum point at $y_{Z^0} = +0.2$. It is a consequence of the fact that x_2 diminishes and x_1 grows as y_2 increases from negative to positive values. One therefore gradually passes through the maximum of the $d(x_1)\bar{u}(x_2)$ combination for W^- production, which for $x_2 \sim 0.3$ lies around $y_2(\gamma) \sim -1.0$ and $y_2(Z^0) \sim 0$. The corresponding distributions with $W^- \rightarrow W^+$ are obtained by $y \rightarrow -y$ reflection. The $\cos\theta_{CM}$ dip of $W^- \gamma$ is not recognizable via the single particle distributions. Changing the anomalous magnetic moment $K \rightarrow -1$, the cross-section increases in the central region by a factor 3. This discrepancy significantly increases as the transverse momentum cut-off grows, reaching almost an order of magnitude for $p_T \geq 30$ GeV.

We have carried out correlation studies on the double rapidity distributions imposing $y_1 = 0, \pm y_2$ and noticed that the above discussed features are enforced. The $W^- \gamma$ dip appears for all the above rapidity constraints except if $y_1 = y_2$ is imposed; all curves then show the familiar smooth rapidity plateau. We illustrate with Fig. 3b a typical case. Thus, selecting $W^- \gamma$ events with the $y_2(\gamma)$ rapidity around the origin should reveal the dip in the region close to $y_1(W) \sim -0.5$. In $W^- \gamma, W^- Z^0$ and $W^+ W^-$ we notice again the asymmetry between the positive and negative rapidity ranges.

All information on the rapidity distributions is drained from the laboratory angular distributions which show a universal $d\sigma/d\cos\theta_{Lab} \sim (\cos\theta_{Lab})^{-3}$ divergence towards the phase space boundaries: $\cos\theta_{Lab} = \pm 1$. Full divergence of the processes involving a "direct" photon is prevented by the transverse momentum cut-off $p_T \geq 10$ GeV which enforces a turnover of these distributions towards zero. In the region $|\cos\theta_{Lab}| \lesssim 0.8$ all curves show a flat valley and are almost parallel. Differences between the different production channels manifest themselves mostly towards the two extremes where the cross-sections grow over 1-2 orders of magnitude. Thus, the laboratory angular distributions do not offer much insight into the dynamics.

In Fig. 4a we show the transverse momentum dependence of the processes (1) and (2), and Fig. 4b we show the cross-section fall-off with increasing invariant mass ($M^2 \equiv \hat{s}$) of the two final state particles.

From Fig. 4a we infer: the transverse momentum dependence $d\sigma/dq_t$ of all processes in (1) shows a very broad distribution with maximum around $q_t \sim 25$ GeV, which gradually decreases as q_t reaches large values and which rapidly vanishes

as $q_t \rightarrow 0$. The W^+W^- cross-section is typically $\sim 4 \cdot 10^{-39}$ cm²/GeV whereas Z^0Z^0 , W^-Z^0 are one order of magnitude below. All processes involving a "direct" photon are strongly peaked as $q_t \rightarrow 0$ and rapidly decrease over several orders of magnitude as q_t gets large. At $q_t \sim 10$ GeV the $W^- \gamma$, $Z^0 \gamma$ processes are typically $\sim 2 \cdot 10^{-37}$ cm²/GeV; similarly $\gamma\gamma$ production is $\sim 10^{-35}$ cm²/GeV and $\gamma^* \gamma$ production is $\sim 3 \cdot 10^{-39}$ cm²/GeV. The q_t -decrease of the latter two processes is stronger than the decrease of the former two.

From the mass distribution in Fig. 4b we deduce an almost (universal) exponential fall-off in M after the initial threshold onset of each process which is determined by Eq. (10) with $\sin\theta = 1$. Typically cross-section values of the processes (1), (2) near their thresholds are

$$d\sigma/dM (1) = (4 \cdot 10^{-40}, 4 \cdot 10^{-39}, 2 \cdot 10^{-40}) \text{ cm}^2/\text{GeV} \quad (15)$$

$$d\sigma/dM (2) = (7 \cdot 10^{-38}, 3 \cdot 10^{-38}, 2 \cdot 10^{-36}, 6 \cdot 10^{-40}) \text{ cm}^2/\text{GeV} \quad (16)$$

We have also indicated the changes if the triple couplings are dropped. We notice in W^-Z^0 an increase of almost an order of magnitude and in W^+W^- an increase of a factor 3. As we change K from its $SU_2 \times U_1$ value to -1 we notice a small cross-section change in the threshold region.

The assumptions and approximations, carefully discussed in our study on 4-jet production⁵⁾, apply also to the present investigation. Since here we are mostly concerned with the production of very massive objects, the next-to-leading QCD corrections are less influential²²⁾. Our results for $W + jj$ etc., might change by typically a factor < 3 which also includes the uncertainties due to the gluon distributions. As we go to $\sqrt{s} \sim 1$ TeV, the uncertainties will grow due to the unknown low x behaviour of the sea quark distribution. The $\gamma\gamma$, $\gamma^* \gamma$, as well γg productions have box graph contributions which might also lead to a slight change of our results.

The foregoing study was intended as an exploratory analysis of two gauge boson production. At $\sqrt{s} = 540$ GeV, $(Z^0 \gamma, W^- \gamma)$ production is $\sim 10^{-36}$ cm², W^+W^- is one and (Z^0Z^0, W^-Z^0) are two orders of magnitude below; there is little contamination from the 4-parton processes. An increase of $\sqrt{s}$ to 620 GeV, or even very much higher, increases substantially the rates. Whilst going to $\sqrt{s} = 2$ TeV one may expect a gain of two orders of magnitude in the production of a gauge boson pair and of three orders of magnitude for $W + jj$, etc. The $W^- \gamma$ (and possibly also $Z^0 \gamma$) production shows an interesting structure in its CM-angular distribution as well as in the rapidity correlations which could reveal unexpected features of the intermediate vector bosons.

ACKNOWLEDGEMENTS

I would like to thank P. Jenni and M. Jacob for the careful reading of the manuscript and helpful suggestions. I have profited from discussions with R. Kinnunen, and I am grateful for some independent checks. Professor C. Joseph, with his kind help, has made this study possible.

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FIGURE CAPTIONS

- 1 a-c The 2-parton production of gauge boson pairs by the Abelian graphs (a), (b), and the non-Abelian diagram (c).
- 1 d,e The 4-parton production of a gauge boson pair (d), and one gauge boson with a pair of quark/gluon jets (e) where the mass cut $M_{jj} \geq 70$ GeV is imposed.
- 2a The integrated cross-section for the 2-parton production of a gauge boson pair with a transverse momentum cut-off : $p_T(\gamma) = 5, 10$ GeV for the processes involving a "direct" photon. The Drell-Yan mass is $M_{\gamma^*} = 10$ GeV.
- 2b The integrated cross-section for the 4-parton production of a gauge boson pair, one gauge boson with a "direct" photon accompanied by a quark/gluon jet , or one gauge boson and a pair of quark/gluon jets. The transverse momentum cut-off $p_T(\gamma) = 10$ GeV is applied whenever a "direct" photon or a quark/gluon jet is produced. $M_{\gamma^*} = 10$ GeV.
- 3a The (constituent) centre-of-mass angular distribution of the processes (1) and (2). The $p_T(\gamma) = 10$ GeV and $M_{\gamma^*} = 10$ GeV.
- 3b The rapidity correlations of the 2-parton processes (1) and (2) with the rapidity of the second particle fixed at $y_2 = 0$. The $p_T(\gamma) = 10$ GeV and $M_{\gamma^*} = 10$ GeV.
- 4a The transverse momentum dependence of the 2-parton processes in (1) and (2). The $p_T(\gamma) = 10$ GeV and $M_{\gamma^*} = 10$ GeV.
- 4b The invariant mass distribution of the final state gauge boson pair in (1) and (2) with $p_T(\gamma) = 10$ GeV and $M_{\gamma^*} = 10$ GeV. The dashed curves indicate the cross-section modifications if the triple gauge coupling is ignored, or if the W anomalous magnetic moment is $K = -1$.

- Figure 1 -

(b)

- Figure 2 -

- Figure 3 -

(a)

Fig. 4

(b)

- Figure 4 -