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Quartic Anomalous Couplings in $e\gamma$ Colliders

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We study the production of gauge boson pairs at the next generation of linear e^+e^- colliders operating in the $e\gamma$ mode. The processes $e\gamma \to VV'F$ ($V, V' = W$, Z, or γ and $F = e$ or ν) can give valuable information on possible deviations of the quartic vector boson couplings from the Standard Model predictions. We establish the range of the new couplings that can be explored in these colliders based on a 3σ effect in the total cross section. We also present several kinematical distributions of the final state particles that could manifest the underlying new dynamics. Our results show that an $e\gamma$ collider can extend considerably the bounds on anomalous interactions coming from oblique radiative corrections and from direct searches in e^+e^- colliders.

I. INTRODUCTION

The Standard Model (SM) of electroweak interactions has so far explained all the available experimental data extremely well [1]. From LEP data, we can witness the agreement between theory and experiment at the level of 1%, which is a striking confirmation of the $SU(2)_L \times U(1)_Y$ invariant interactions involving fermions and gauge bosons. However, some predictions of the SM have not yet been object of direct experimental observation, such as the symmetry breaking mechanism and the interaction among the gauge bosons. In particular, the structure of the trilinear and quartic vector boson couplings is completely determined by the non-abelian gauge structure of the model, and a detailed study of these interactions can either confirm the local gauge invariance of the theory or indicate the existence of new physics beyond the SM.

The triple and quartic gauge-boson vertices, in the scope of gauge theories, have a common origin and possess a universal strength. In the SM they are constrained by the $SU(2)_L \times U(1)_Y$ gauge invariance, and for a given process, there are important cancellations between the bad high energy behaviour of the various amplitudes, which leads to a final result that is consistent with the unitarity requirements.

In a more general context, the quartic anomalous couplings can be related to the low energy limit of heavy state exchange giving rise to an effective contact interactions, whereas trilinear couplings are modified by integrating out heavy fields. Therefore, it is possible to build extensions of the SM where the trilinear couplings remain equal to the SM ones, while the quartic vertices are modified. For instance, the introduction of a new heavy scalar singlet, that interacts strongly with the Higgs sector of the SM, enhances the four vector-boson interaction, without affecting neither the triple vector boson coupling nor spoiling the SM predictions for the ρ parameter [2]. Further examples include the Higgs-less models [3] where the breaking of the $SU(2)_L \times U(1)_Y$

symmetry is realized nonlinearly, leading to the appearance of large anomalous four gauge boson vertices.

One of the main goals of LEP II at CERN will be the study of the reaction $e^+e^- \to W^+W^-$ which will furnish bounds on possible anomalous $W^+W^-\gamma$ and W^+W^-Z interactions [4]. Within the SM framework, it will be also possible to constrain indirectly the four-vector-boson interactions since the $SU(2)_L \times U(1)_Y$ local gauge symmetry connects trilinear and quartic vertices. Nevertheless, the test of a wide class of models, that predicts only quartic anomalous vector boson interactions, will have to rely on the direct measurements of reactions such as $e^+e^- \to VVV$, $\gamma+\gamma \to VV$, or $e+\gamma \to VV'F$ ($V, V' = W$, Z, or γ and $F = e$ or ν). This, of course, cannot be done at LEP II due to its limited available center of mass energy.

The planned next generation of linear e^+e^- colliders (NLC) will have enough center of mass energy to study directly quartic vertices through the production of three gauge boson [5–7], and will offer further independent tests of the SM. Moreover, at the NLC it will be possible to transform an electron beam into a photon one through the laser backscattering mechanism [8, 9]. This kind of process will allow the NLC to operate in three different modes: e^+e^-, $e\gamma$, and $\gamma\gamma$. This versatility opens up the opportunity to perform a deeper analysis of the anomalous couplings, mainly for those new interactions involving photons. In fact, the study of the anomalous vertices $W^+W^-\gamma\gamma$ and $Z^0Z^0\gamma\gamma$ has been carried out in Ref. [10] assuming the $\gamma\gamma$ mode for NLC, where the sensitivity to anomalous couplings is improved by two orders of magnitude when compared to the e^+e^- mode results.

It is important to point out that the laser backscattering mechanism leads to the total loss of the electron (positron) beam in an e^+e^- linear collider. Consequently, the experimental collaborations of the NLC will have to decide in which mode they want to operate the collider, *i.e.* either in the e^+e^-, $e\gamma$ or $\gamma\gamma$ mode, and it is essential to study comparatively the capabilities of each of these setups to explore new physics.

In this work we study the capability of an e^+e^- linear collider, operating in the $e\gamma$ mode, to search for anomalous four-gauge-boson interactions. We restrict ourselves to the analyses of effective lagrangians that contain at least one photon and that do not exhibit a trilinear coupling associated to it since, in this case, they cannot be indirectly probed at LEP II. This search for anomalous couplings is carried out through the study of the reactions

$$e + \gamma \rightarrow W^+ + W^- + e \qquad [WWE]\,, \tag{1a}$$

$$e + \gamma \rightarrow Z^0 + \gamma + e \qquad [ZGE]\,, \tag{1b}$$

$$e + \gamma \rightarrow Z^0 + Z^0 + e \qquad [ZZE]\,, \tag{1c}$$

$$e + \gamma \rightarrow W^- + \gamma + \nu \qquad [WGN]\,, \tag{1d}$$

$$e + \gamma \rightarrow W^- + Z^0 + \nu \qquad [WZN]\,, \tag{1e}$$

that receive contributions from the quartic vertices $W^+W^-\gamma\gamma$, $W^+W^-Z^0\gamma$, and $Z^0Z^0\gamma\gamma$. Some of these reactions, assuming SM couplings for all particles, were recently considered in Ref. [11].

The outline of this paper is as follows. In Sec. II we exhibit the chosen effective operators that gives rise to the anomalous couplings and we discuss low energy constraints coming from oblique radiative corrections. Section III contains a brief description and expressions for the laser backscattering mechanism as well as the discussion about the cross sections. Our results for several relevant kinematical distributions of the final state particles are shown in Sec. IV, and we summarize our conclusions in Sec. V.

II. ANOMALOUS QUARTIC COUPLINGS: LOW ENERGY CONSTRAINTS

In this work, we study some operators that generate anomalous quartic vector-boson vertices. We consider genuinely quartic operators, that is, operators which do not induce new trilinear vertices. With this choice, the strength of the quartic vertices cannot be constrained, for instance, by LEP II bounds on the anomalous trilinear vertices. Furthermore, since we are interested in probing anomalous couplings in an $e\gamma$ collider, we concentrate on operators that involve at least one photon.

In constructing effective operators associated to such anomalous couplings we employ the formalism of Ref. [12]. We require the existence of a custodial $SU(2)_{WI}$ symmetry, which forbids any contribution to the ρ parameter. We must also require that the phenomenological lagrangians are invariant under local $U(1)_{em}$ symmetry. The lowest order operators that comply with the above requirements and give genuinely quartic couplings, involving at least one photon, are of dimension six. If we restrict our analyses to C and P conserving interactions, it is easy to see that there are two independent operators involving two photons [5]

$$\mathcal{L}_0 = -\frac{\pi\alpha}{4\Lambda^2}\, a_0\, F^{\mu\nu} F_{\mu\nu} W^{(i)\alpha} W^{(i)}_{\alpha} \;, \tag{2}$$

$$\mathcal{L}_c = -\frac{\pi\alpha}{4\Lambda^2}\, a_c\, F^{\mu\alpha} F_{\mu\beta} W^{(i)}_{\alpha} W^{(i)\beta} \;, \tag{3}$$

and one operator exhibiting just one photon

$$\mathcal{L}_n = i\frac{\pi\alpha}{4\Lambda^2}\, a_n\, \epsilon_{ijk} W^{(i)}_{\mu\alpha} W^{(j)}_{\nu} W^{(k)\alpha} F^{\mu\nu} \;, \tag{4}$$

where $W^{(i)}$ is the $SU(2)_{WI}$ triplet and $F^{\mu\nu}$ is the electromagnetic field strength. When written in terms of the physical fields W^+, W^-, and $Z^0 = W^3 \cos\theta_W$, the effective lagrangians (2,3) give rise to anomalous $W^+W^-\gamma\gamma$ and $Z^0Z^0\gamma\gamma$ couplings while (4) generates a new $W^+W^-Z^0\gamma$ vertex. The $Z^0Z^0\gamma\gamma$ vertex is particularly interesting since it is absent in the SM.

It is important to analyze the possible low-energy constraints on these lagrangians due to their one-loop contribution to the vacuum polarization diagrams (oblique corrections). In principle, $\mathcal{L}_n$ contributes only to the $Z\gamma$ two-point function at the one-loop level, and in consequence to $\sin\overline{\theta}_W$, whose definition is based on the Z^0 asymmetries. However, such contribution is proportional to the W momentum in the loop, and consequently the loop integral vanishes. Therefore there are no low-energy constraints on $\mathcal{L}_n$.

The lagrangians $\mathcal{L}_0$ and $\mathcal{L}_c$ contribute to the photon, W, and Z two point functions. Due to the structure of the lagrangians, the contributions to the W and Z self-energies are constant, *i.e.* they do not dependent on the external momentum, and are related by the $SU(2)_{WI}$ custodial symmetry

$$\Pi_{WW(0,c)}(q^2) = c_w^2 \Pi_{ZZ(0,c)}(q^2) , \tag{5}$$

where $c_w = \cos\theta_W$. Therefore, as expected, they do not contribute to the ρ parameter, and also their contribution to $\sin\overline{\theta}_W$ vanishes.

Since these lagrangians preserve the local $U(1)_{em}$ symmetry, the photon self-energy has the form

$$\Pi_{\gamma\gamma(0,c)}(q^2) = q^2 \Pi'_{\gamma\gamma(0,c)} , \tag{6}$$

where $\Pi'_{\gamma\gamma(0,c)}$ is constant due to the explicit form of the anomalous interactions. Therefore, there is no contribution to the running of the electromagnetic coupling either.

However, $\mathcal{L}_0$ and $\mathcal{L}_c$ affect the value of Δr, meaning that the S and U parameters of Ref. [13, 14] or, equivalently, ϵ_2 and ϵ_3 in notation of Ref. [15] are modified. In order to estimate this effect, we evaluate $\Pi'_{\gamma\gamma(0,c)}$ using a gauge-invariant cutoff regularization [16]

$$\Pi'_{\gamma\gamma 0} = \frac{2\pi\alpha a_0}{\Lambda^2}\Big[-\frac{M_W^2}{8\pi^2}\left(1+\frac{1}{2c_w^4}\right)+\frac{3M_W^2}{16\pi^2}\ln\frac{\Lambda^2}{M_W^2}+\frac{3M_W^2}{32\pi^2c_w^4}\ln\frac{\Lambda^2c_w^2}{M_W^2}-\frac{\Lambda^2}{16\pi^2}\left(1+\frac{1}{2c_w^2}\right)\Big]\,,$$

$$\Pi'_{\gamma\gamma c} = \frac{2\pi\alpha a_c}{\Lambda^2}\Big[-\frac{M_W^2}{128\pi^2}\left(1+\frac{1}{2c_w^4}\right)+\frac{3M_W^2}{64\pi^2}\ln\frac{\Lambda^2}{M_W^2}+\frac{3M_W^2}{128\pi^2c_w^4}\ln\frac{\Lambda^2c_w^2}{M_W^2}$$
$$-\frac{\Lambda^2}{32\pi^2}\left(1+\frac{1}{2c_w^2}\right)-\frac{3\Lambda^4}{64\pi^2M_W^2}\Big]\,.$$

The cutoff Λ can be identified with the scale of the new physics appearing in the lagrangian, whereas the coefficients a_0 and a_c remain arbitrary. In the following, we choose for the sake of definiteness $\Lambda = M_W$. Using the definitions of S and U of Ref. [14], which for the new contributions reduce to the original definitions of Ref. [13], we obtain

$$(\Delta S)_0 = 0.17\ a_0 \quad , \quad (\Delta U)_0 = 0.051\ a_0\,,$$
$$(\Delta S)_c = 0.055\ a_c \quad , \quad (\Delta U)_c = 0.016\ a_c\,. \tag{7}$$

The present experimental values for the S and U parameters can be found in Ref. [14] while the SM contributions can be found in Ref. [16]. Assuming $m_{top} = 130$ GeV and $m_H = 1000$ GeV, the one sigma result for ΔS is

$$-0.77 < \Delta S < 0.11\,. \tag{8}$$

Comparing the theoretical results (7) with the experimental ones (8), we obtain, at the one sigma level, the following constraints.

$$-4.5 < a_0 < 0.64$$
$$-11 < a_c < 5.8$$

As we show in this paper, the bounds on $a_{0,c}$ coming from low energy data are one to two orders of magnitude (depending on the top and Higgs masses) weaker than the accelerator limits that are obtained via the study of vector boson production in $e\gamma$ collisions.

III. LASER BACKSCATTERING AND CROSS SECTION

The most promising mechanism to generate a hard photon beam in an e^+e^- linear collider is the laser backscattering. When soft photons from a few eV laser collide with an electron or positron beam, a large flux of photons, carrying a great amount of the parent fermion energy, is generated. The spectrum of the laser backscattered photons is [9]

$$F_L(x) \equiv \frac{1}{\sigma_c}\frac{d\sigma_c}{dx} = \frac{1}{D(\xi)}\left[1 - x + \frac{1}{1-x} - \frac{4x}{\xi(1-x)} + \frac{4x^2}{\xi^2(1-x)^2}\right] , \qquad (9)$$

with

$$D(\xi) = \left(1 - \frac{4}{\xi} - \frac{8}{\xi^2}\right)\ln(1+\xi) + \frac{1}{2} + \frac{8}{\xi} - \frac{1}{2(1+\xi)^2} ,$$

where σ_c is the Compton cross section, $\xi \simeq 4E\omega_0/m_e^2$, m_e and E are the electron mass and energy respectively, and ω_0 is the laser photon energy. The fraction x represents the ratio between the scattered photon and initial electron energy for the backscattered photons traveling along the initial electron direction. The maximum possible value of x is

$$x_{\max} = \frac{\omega_{\max}}{E} = \frac{\xi}{1+\xi} , \qquad (10)$$

with $\omega_{\max}$ being the maximum scattered photon energy.

It is interesting to notice that $x_{\max}$ grows with the laser and the electron energy. However, ω_0 should be less than $m_e^2/\omega_{\max}$ in order to avoid that the interaction of laser photons and backscattered ones create a pair e^+e^-, which would reduce the conversion of electrons to photons. In our calculation we have chosen the laser energy in order to maximize the backscattered photon energy without spoiling the luminosity. This can be accomplished by taking $\xi = 2(1+\sqrt{2}) \simeq 4.8$. With this choice, the photon spectrum exhibits a peak close to its maximum which occurs at $x_{max} \simeq 0.83$.

The total cross sections are obtained by folding the elementary cross sections with the photon distribution

$$\sigma(s) = \int_0^{x_{max}} dx \; F_L(x) \; \hat{\sigma}_{VV'F}(\hat{s}) \; , \tag{11}$$

where $\hat{\sigma}_{VV'F}$ are the cross sections, evaluated at $\hat{s} = xs$, for the reactions $e\gamma \rightarrow VV'F$, with $V, V' = W$, Z, or γ and $F = e$ or ν.

The analytical evaluation of the cross section $\hat{\sigma}_{VV'F}$ for each of the subprocesses (1a–1e) is very lengthy and tedious despite being straightforward. In order to perform these calculations in a efficient way, we used a numerical method similar to the one described in Ref. [6]. We verified explicitly that our amplitudes are Lorentz invariant and $U(1)_{em}$ gauge invariant. The numerical integrations were performed using a Monte Carlo routine [17], and we tested our results against possible statistical fluctuations.

IV. DOUBLE VECTOR BOSON PRODUCTION: DISTRIBUTIONS AND RESULTS

Now we have all the necessary ingredients to perform a detailed study of the production of two gauge boson in $e\gamma$ colliders, taking into account anomalous quartic couplings. First of all, we analyzed the effect of the anomalous couplings on the total cross section of the processes (1a–1e). The anomalous couplings a_0 and a_c contribute to the processes WWE, ZGE, ZZE, and WGN while the coupling a_n participate only of the processes WWE and WZN. The anomalous cross sections for these processes are quadratic functions of the parameters a_i $(i = 0, \; c, \; n)$ *i.e.*

$$\sigma_{AN} \;=\; \sigma_{SM} \;+\; a_i \, \sigma^i_{int} \;+\; a_i^2 \, \sigma^i_{ano} \; , \tag{12}$$

where σ_{SM} is the Standard Model cross section and σ_{int} (σ_{ano}) is the interference (pure anomalous) contribution. We present in Table I the values of $\sigma_{SM,int,ano}$ for the interactions 2–4, assuming that only one anomalous coupling is different from zero at one time. For events containing a photon in the final state, we imposed a cut on the photon transverse momentum $p_T^\gamma > 15$ GeV, which not only guarantees that our results are free of infrared divergences but also mimics the performance of a typical electromagnetic calorimeter. As an illustration of the typical behaviour of σ_{AN}, we exhibit in Fig. 1 the total cross section for the process WWE as a function of a_c and a_n.

From the Table I we learn that WWE and ZZE are the most sensitive processes to a_0 and a_c. In the WWE case, the SM cross section is larger than the crossed channel $e^+e^- \rightarrow W^+W^-\gamma$ by more than one order of magnitude [5], due to the t-channel photon exchange diagrams [19] that dominates in the former case. These diagrams involves the anomalous quartic coupling making this process very sensitive to a_0 and a_c. For the process ZZE, the SM calculation does not contain a t-channel photon exchange. However, the introduction of the anomalous couplings $Z^0Z^0\gamma\gamma$ gives rise to this kind of contribution, making ZZE very sensitive to the anomalous couplings, despite the small value of its SM cross section. We should notice that for the process ZGE, the $a_{0,c}$ anomalous coupling also introduces a new contribution, due to the vertex $Z^0Z^0\gamma\gamma$, that has a Z exchange in the t-channel. Nevertheless, in the effective Z approximation [20], we note that the enhancement is at most proportional to $\ln(s/M_Z^2)$ for the exchange of transverse Z's, and consequently the ZGE becomes almost insensitive to the anomalous couplings.

The WWE production turned out to be rather insensitive to the anomalous coupling a_n since the anomalous vertex $W^+W^-Z^0\gamma$ does not contribute to the dominant diagrams of this process, which are the ones involving the exchange of a photon in the t-channel. In fact, in the effective Z and γ approximations we can see that the anomalous contribution is suppressed by a factor $\ln(s/M_Z^2)/\ln(s/m_e^2)$ in relation to the dominant terms. In spite of the cross section for WZN being smaller than the one for WWE, the process WZN is the most sensitive to this anomalous coupling.

In order to quantify the effect of the new couplings, we define the statistical significance ($\mathcal{S}$) of the anomalous signal

$$\mathcal{S} = \frac{|\sigma_{AN} - \sigma_{SM}|}{\sqrt{\sigma_{SM}}} \sqrt{\mathcal{L}} \,, \tag{13}$$

which can be easily evaluated using the parametrization (12) with the coefficients given in Table I. We list in Table II the values of the anomalous couplings that correspond to a 3σ effect for the different processes, assuming an integrated luminosity $\mathcal{L} = 10$ fb^{-1} for the associated e^+e^- collider. We checked that our results do not change by more than a factor of 2 if we adopt realistic values for the efficiency of the vector boson reconstruction and increase the value of $\mathcal{S}$ to 5.

We can see from Table II that the 3σ limits for the a_0 and a_6 couplings are approximately one order magnitude better than the limits one can get in the e^+e^- mode [5, 18]. Our limits are of the same order than the ones obtained through the reaction $\gamma\gamma \to W^+W^-$ with unpolarized beams [10, 18] and are within a factor of 5 of the ones from the reaction $\gamma\gamma \to Z^0Z^0$ [10, 18]. On the other hand, we must stress that the anomalous a_n vertex can not be studied so well in the $\gamma\gamma$ mode of the collider since it contributes only to processes like $\gamma\gamma \to W^+W^-Z^0$ which have a smaller phase space. From what we learnt above, we also expect that the attainable limits at e^+e^- to be much worse than the ones from $\gamma\gamma$ and $e\gamma$.

The study of the anomalous couplings through the total cross section of the different processes is the crudest thing that can be done. In principle, the shapes and values of the kinematical distributions can be used to increase the sensitivity to the anomalous couplings, improving consequently the bounds on the new couplings and yielding further information. In Figs. 2 to 4 we compare some SM distributions for the ZZE process with the ones corresponding to the anomalous coupling $a_0 = 0.028$, which gives a 3σ deviation in the total cross section. From these figures, we can see that the effect of the anomalous interactions in the distributions is more than a mere overall normalization. For instance, Fig. 2 exhibits the energy and transverse momentum distributions for Z and e, and shows that the existence of an anomalous coupling favors the production of higher p_T vector bosons.

More dramatic is the difference in the angular (or rapidity) distribution of the final particles, as seen in Fig. 3. In the SM, the final electron goes preferentially in the opposite direction of the initial electron, as in a "Compton-like" process. However, the anomalous a_0 coupling contributes with a new photon t-channel, which is dominated by low transfer momenta. This effect makes the electron go mainly in the forward direction and leads to an electron angular distribution which is very distinct from the one expected in the SM. The distributions in the angle between the final particles and the invariant-mass distribution of the ZZ pair are shown in Fig. 4. We see that the effect of the anomalous coupling is to increase the average angle between the Z's while, at the same time, to reduce the average angle between the Z and the electron. Furthermore, the anomalous interaction also favors higher invariant masses for the ZZ pairs, since the new couplings are proportional to the photon momentum, which are very large in the case of backscattered photons.

Despite the large sensitivity of the ZZE process to the anomalous couplings $a_{0,c}$, we verified that the anomalous 3σ distributions for the couplings a_0 and a_c are indistinguishable, since all the cases give rise to distributions that exhibit the same general behaviour. Therefore, the analysis of the process ZZE can only indicate the existence of anomalous couplings, but not their origins and explicit form.

We also verified that in the case of the WWE process, the deviations from the SM predictions for the kinematical distributions is equivalent to the ZZE process. In spite of giving looser bounds on the anomalous couplings, the WWE process has a large cross section which can give rise to a substantial statistic.

In Figs. 5-7 we exhibit some distributions for the WZN process for the SM and also including the anomalous coupling $a_n = 0.74$, which corresponds to a 3σ deviation in the total cross section. We verified that, in this process, the behaviour of the anomalous distributions for the 3σ limits ($a_n = 0.74$ and $a_n = -1.2$) are basically the same, and consequently they are indistinguishable. One interesting property of the a_n anomalous vertex is that its intensity is linearly related to the photon momentum, and consequently its contribution to the processes is more important for highly energetic photons, whose energy is close to the maximum of the laser backscattering spectrum. Therefore, the presence of the anomalous vertex increases the available energy for the reaction causing the distribution of momenta and energy of the final gauge bosons to be shifted towards high energy (see Figs. 5 and 6). This argument allows us to conclude that the invariant mass distributions of the vector bosons are also increased at high invariant masses, as can be seen from Fig. 7.

V. SUMMARY AND CONCLUSIONS

In this paper we studied the capability of an e^+e^- collider, operating in the $e\gamma$ mode to search for anomalous four-gauge-boson interactions. We concentrated on those that contain at least one photon and that do not exhibit a trilinear coupling associated to the it, and required the anomalous lagrangians to be invariant under a custodial $SU(2)_{WI}$ and under local $U(1)_{em}$ symmetries. One interesting property of the interactions we analyzed is that the available low energy constraints on these anomalous couplings are very loose.

The search for anomalous couplings has been performed through the analyses of production of gauge boson pairs, $e\gamma \to VV'F$ ($V, V' = W$, Z, or γ and $F = e$ or ν). Our results show that ZZE and WWE are the most sensitive processes to the anomalous couplings involving two photons, a_0 and a_6. The 3σ limits on these couplings obtained from the study of the total cross section for the $VV'F$ production are approximately one order magnitude better than the limits using the e^+e^- mode [5] and a factor of 5 worse than the limits coming from the $\gamma\gamma$ mode [10]. The anomalous coupling a_n, which only involves one photon in the quartic vertex, cannot be efficiently studied in the $\gamma\gamma$ or e^+e^- modes of the collider, being WZN the process most sensitive to it.

The bottom line of our work is that an e^+e^- collider operating in the $e\gamma$ mode will be able to increase substantially the potential of analyses of anomalous four-gauge-boson interactions with respect to the e^+e^- mode. Despite of the $e\gamma$ mode being more sensitive to the presence of further contributions to the standard model, it will be a hard task to discriminate the form and origin of the new contributions.

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APPENDIX A: FEYNMAN RULES

We present in this appendix the Feynman rules for the anomalous interactions $\mathcal{L}_0$

(Eq. 2), $\mathcal{L}_c$ (Eq. 3), and $\mathcal{L}_n$ (Eq. 4). Our conventions are that all the momenta are incoming to the vertex. The interactions $\mathcal{L}_0$ and $\mathcal{L}_c$ give rise to anomalous contributions to $W^{+\,\mu}(p_+) - W^{-\,\nu}(p_-) - \gamma^\alpha(p_1) - \gamma^\beta(p_2)$ given by

$$i\frac{2\pi\alpha}{\Lambda^2}\, a_0\, g_{\mu\nu}\ \left[g_{\alpha\beta}\,(p_1{\cdot}p_2) - p_{2\alpha}p_{1\beta}\right]\ , \tag{A1}$$

and

$$i\frac{\pi\alpha}{2\Lambda^2}\, a_c \Big[(p_1{\cdot}p_2)\,(g_{\mu\alpha}\, g_{\nu\beta} + g_{\mu\beta}\, g_{\alpha\nu}) + g_{\alpha\beta}\ (p_{1\mu}p_{2\nu} + p_{2\mu}p_{1\nu}) \\ - p_{1\beta}\,(g_{\alpha\mu}\, p_{2\nu} + g_{\alpha\nu}\, p_{2\mu}) - p_{2\alpha}\,(g_{\beta\mu}\, p_{1\nu} + g_{\beta\nu}\, p_{1\mu})\Big]\ , \tag{A2}$$

respectively. The contributions of these lagrangians to the anomalous $Z^0 - Z^0 - \gamma - \gamma$ vertex is obtained by multiplying the above results by $1/\cos^2\theta_W$ and making $W \to Z$.

The interaction $\mathcal{L}_n$ yields a contribution to $W^{+\,\mu}(p_+) - W^{-\,\nu}(p_-) - \gamma^\alpha(p_1) - Z^\beta(p_2)$ given by

$$i\frac{\pi\alpha}{4\cos\theta_W\Lambda^2}\, a_n \Big\{ g_{\mu\beta}\ [g_{\nu\alpha}\ p_1{\cdot}(p_2 - p_+) - p_{1\nu}(p_2 - p_+)_\alpha] \\ - g_{\nu\beta}\ [g_{\mu\alpha}\ p_1{\cdot}(p_2 - p_-) - p_{1\mu}(p_2 - p_-)_\alpha] \\ + g_{\mu\nu}\ [g_{\alpha\beta}\ p_1{\cdot}(p_+ - p_-) - (p_+ - p_-)_\alpha p_{1\beta}] \\ - p_{2\mu}\,(g_{\alpha\nu}\ p_{1\beta} - g_{\alpha\beta}\ p_{1\nu}) + p_{2\nu}\,(g_{\alpha\mu}\ p_{1\beta} - g_{\alpha\beta}\ p_{1\mu}) \\ - p_{-\beta}\,(g_{\alpha\mu}\ p_{1\nu} - g_{\alpha\nu}\ p_{1\mu}) + p_{+\beta}\,(g_{\alpha\nu}\ p_{1\mu} - g_{\alpha\mu}\ p_{1\nu}) \\ - p_{+\nu}\,(g_{\alpha\beta}\ p_{1\mu} - g_{\alpha\mu}\ p_{1\beta}) + p_{-\mu}\,(g_{\alpha\beta}\ p_{1\nu} - g_{\alpha\nu}\ p_{1\beta})\Big\}\ . \tag{A3}$$

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[19] We checked that the total cross section for the process $e + \gamma \to W^+ + W^- + e$ is very well approximated by the reaction $e+\gamma \to e+\gamma+(\gamma)_b \to W^+ + W^- + e$, with the bremsstrahlung photon $(\gamma)_b$ described by the equivalent photon (Weizsäcker-

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TABLES

TABLE I. Parameters characterizing the anomalous cross sections in fb for the different processes and interactions.

	WWE	ZGE	ZZE	WGN	WZN
σ_{SM}	3797.	378.	9.91	457.	71.9
σ^0_{int}	1361.	−0.0976	0.982	1.38	—
σ^0_{ano}	8005.	20.7	3697.	67.6	—
σ^c_{int}	959.	−0.673	0.960	−17.4	—
σ^c_{ano}	657.	9.65	318.	31.6	—
σ^n_{int}	0.118	—	—	—	4.01
σ^n_{ano}	2.88	—	—	—	9.22

TABLE II. Intervals for a_0, a_c, and a_n corresponding to a deviation $\leq 3\sigma$ in the total cross section. We also exhibit the difference ($\Delta\sigma$) between the anomalous cross sections and the SM ones in fb for a 3σ effect.

	WWE	ZGE	ZZE	WGN	WZN
a_0	(−0.21, 0.036)	(−0.94, 0.95)	(−0.029, 0.028)	(−0.56, 0.54)	—
a_c	(−1.5, −1.4) and (−0.064, 0.059)	(−1.3, 1.4)	(−0.098, 0.095)	(−0.57, 1.1)	—
a_n	(−4.5, 4.5)	—	—	—	(−1.2, 0.74)
$\|\Delta\sigma\|$	58.	18.	3.0	20.	8.0

FIGURES

FIG. 1. Total cross section for the process WWE as a function of the anomalous couplings a_c (dotted line) and a_n (solid line). The 3σ interval around the SM value of the cross section is marked by horizontal dashed lines. We assumed an integrated luminosity $\mathcal{L} = 10\ \text{fb}^{-1}$ for the e^+e^- collider.

FIG. 2. Energy and transverse momentum distributions for Z and e in the process ZZE. The dotted line is the SM prediction and the solid line is the anomalous distribution for the positive 3σ limit $a_0 = 0.028$.

FIG. 3. Angle with the beam pipe and rapidity distributions for Z and e in the process ZZE. The conventions are the same as in Fig. 2.

FIG. 4. Distribution in the angle between the final particles and invariant mass distribution of the ZZ pair in the process ZZE. The conventions are the same as in Fig. 2.

FIG. 5. Energy distribution for W and Z in the process WZN. The dotted line is the SM prediction and the solid line is the anomalous distribution for the positive 3σ limit $a_n = 0.74$.

FIG. 6. Transverse momentum distribution for W, Z and missing (neutrino) in the

process WZN. The conventions are the same as in Fig. 5.

FIG. 7. Distribution of the angle between the gauge bosons and invariant mass distribution of the gauge bosons in the process WZN. The conventions are the same as in Fig. 5.

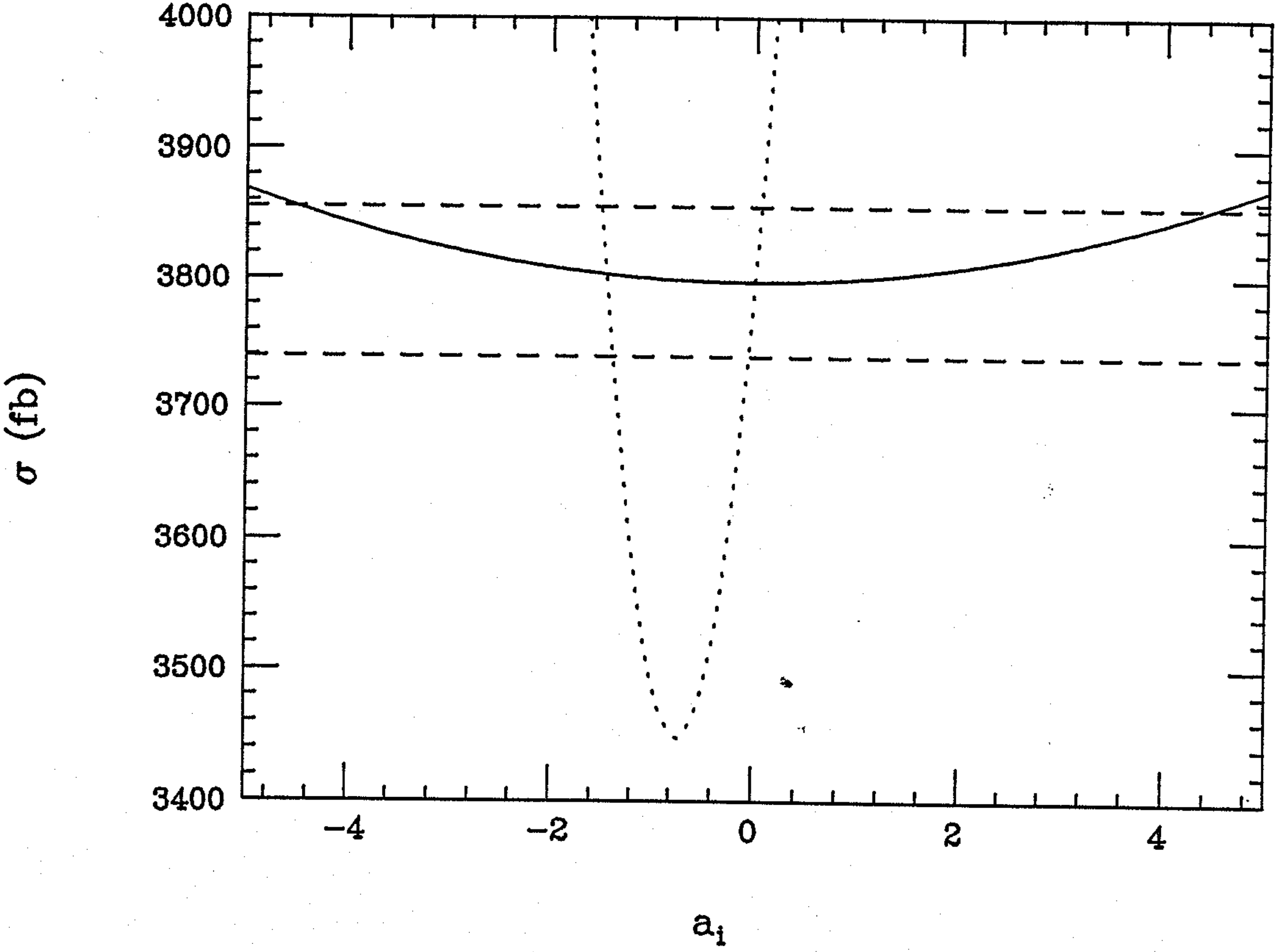
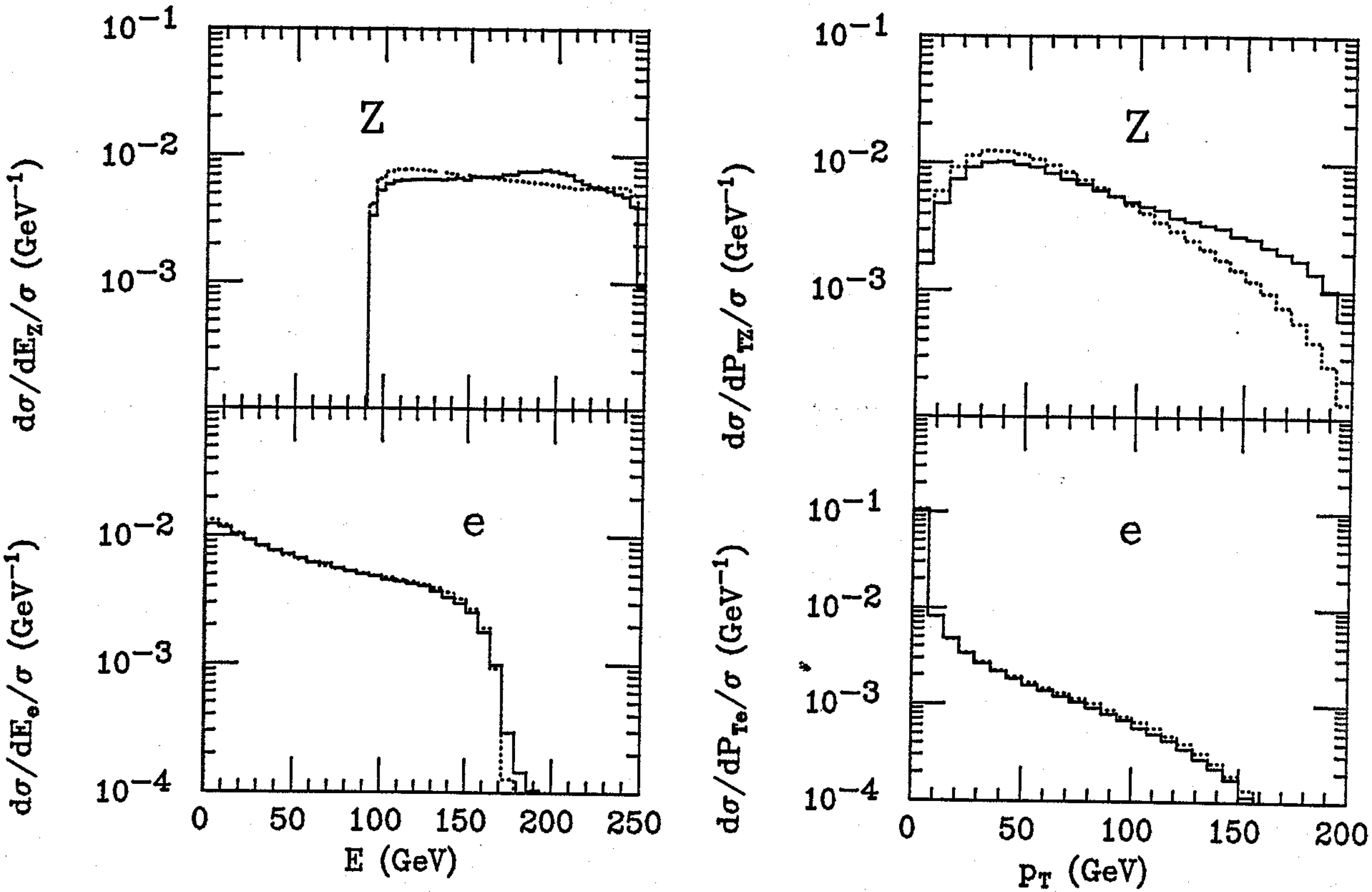


Fig. 1



Z
e
Z
e
$d\sigma/dE_Z/\sigma$ (GeV^{-1})
$d\sigma/dE_e/\sigma$ (GeV^{-1})
$d\sigma/dP_{TZ}/\sigma$ (GeV^{-1})
$d\sigma/dP_{Te}/\sigma$ (GeV^{-1})
10^{-1}
10^{-2}
10^{-3}
10^{-4}
0
50
100
150
200
250
E (GeV)
p_T (GeV)

Fig. 2

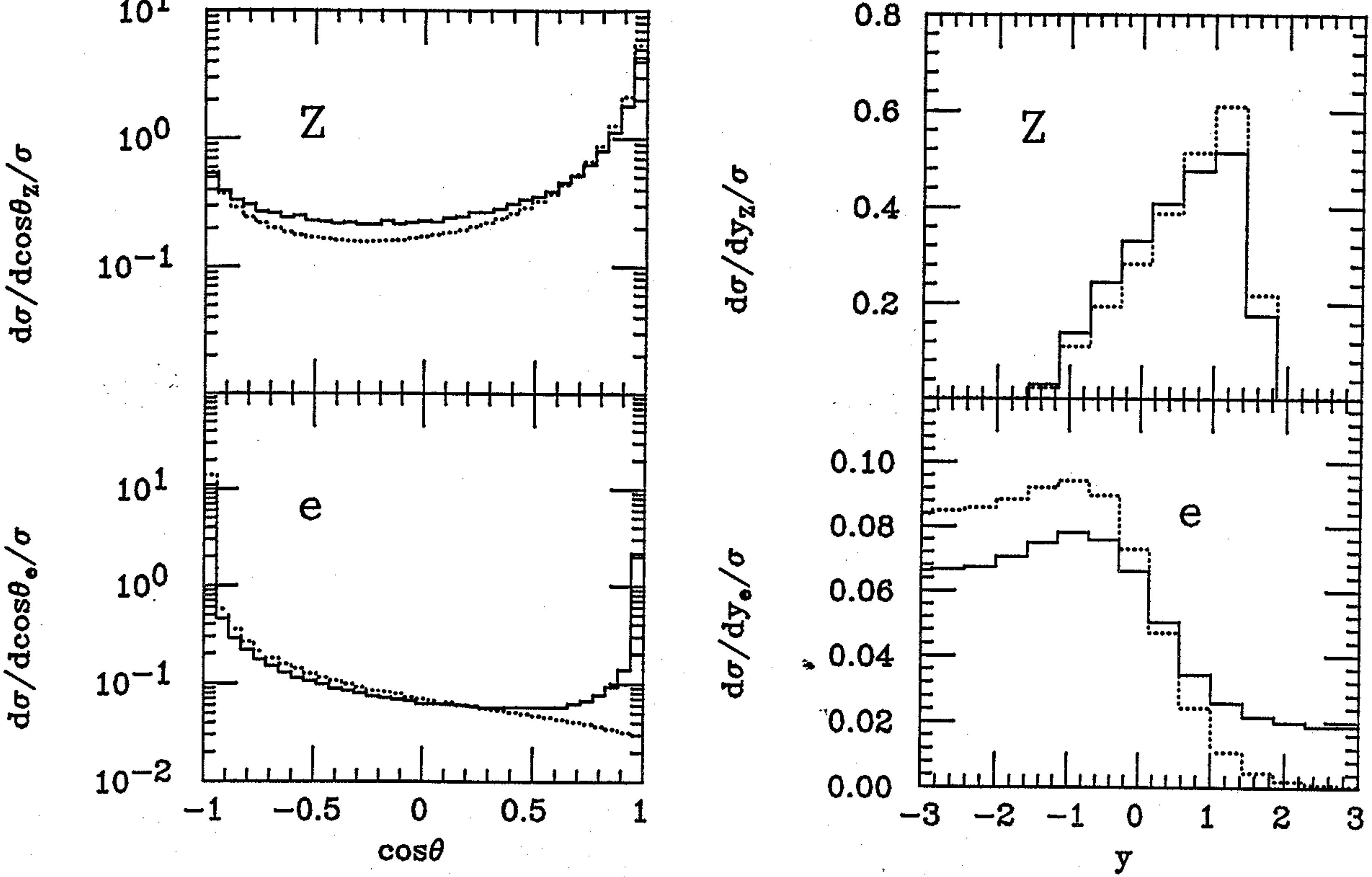
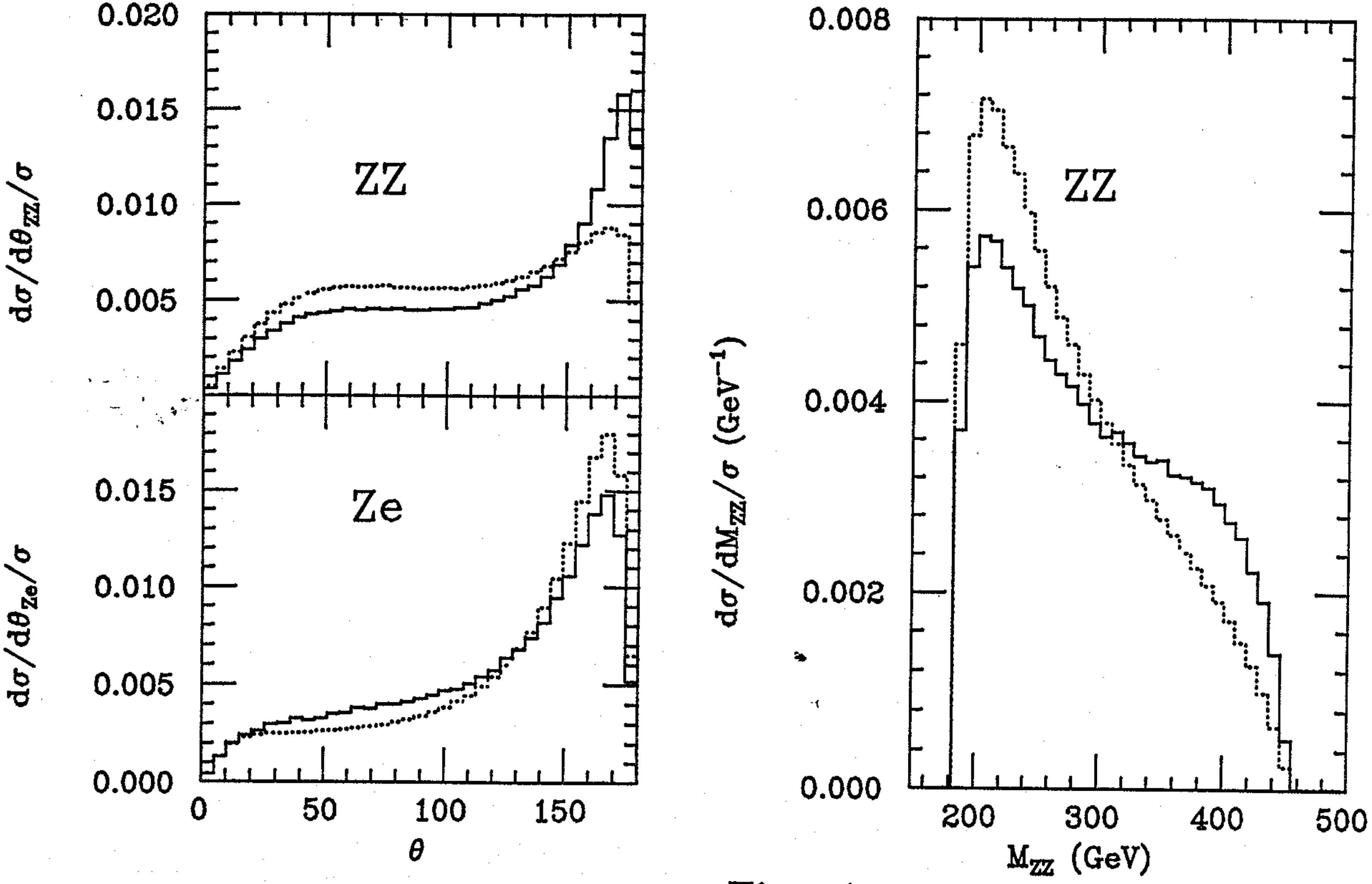


Fig. 3



0.020
0.015
0.010
0.005
ZZ
dσ/dθ_ZZ/σ
0.015
0.010
0.005
0.000
Ze
dσ/dθ_Ze/σ
0
50
100
150
θ
0.008
0.006
0.004
0.002
0.000
ZZ
dσ/dM_ZZ/σ (GeV^-1)
200
300
400
500
M_ZZ (GeV)

Fig. 4

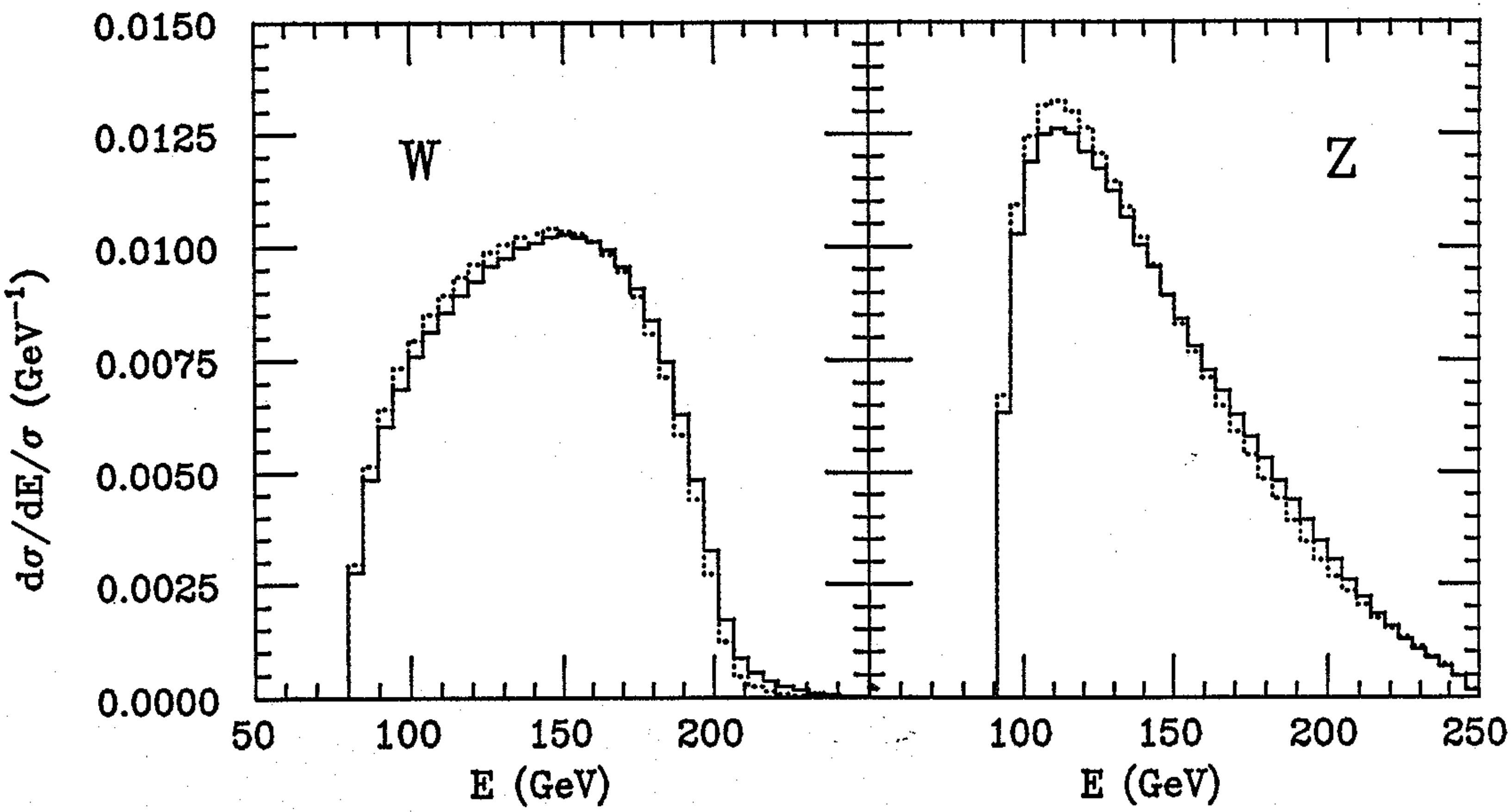
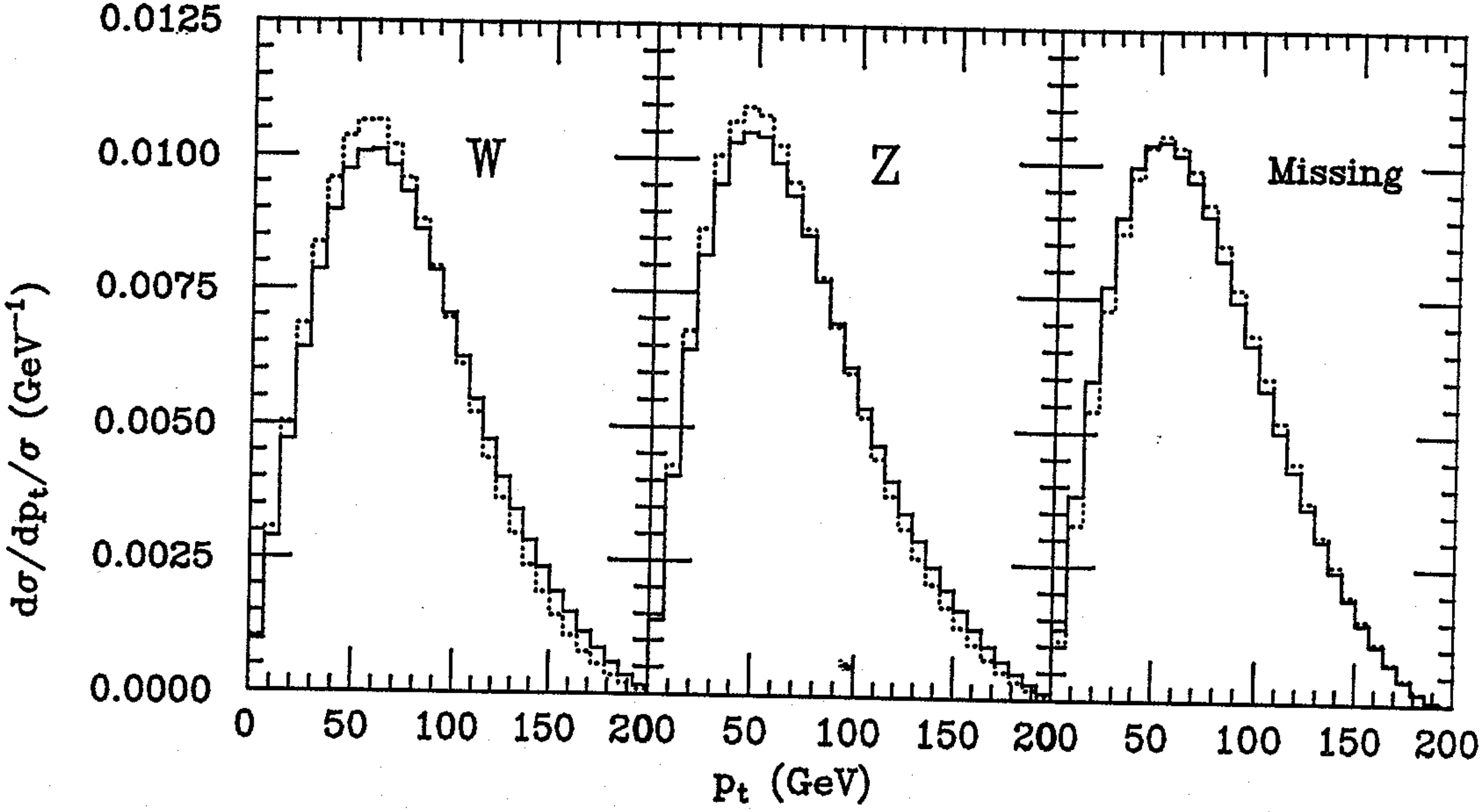

0.0150
0.0125
0.0100
0.0075
0.0050
0.0025
0.0000
dσ/dE/σ (GeV^-1)
W
Z
50
100
150
200
250
E (GeV)
E (GeV)

Fig. 5



0.0125
0.0100
0.0075
0.0050
0.0025
0.0000
dσ/dp_t/σ (GeV^-1)
W
Z
Missing
0
50
100
150
200
50
100
150
200
50
100
150
200
p_t (GeV)

Fig. 6

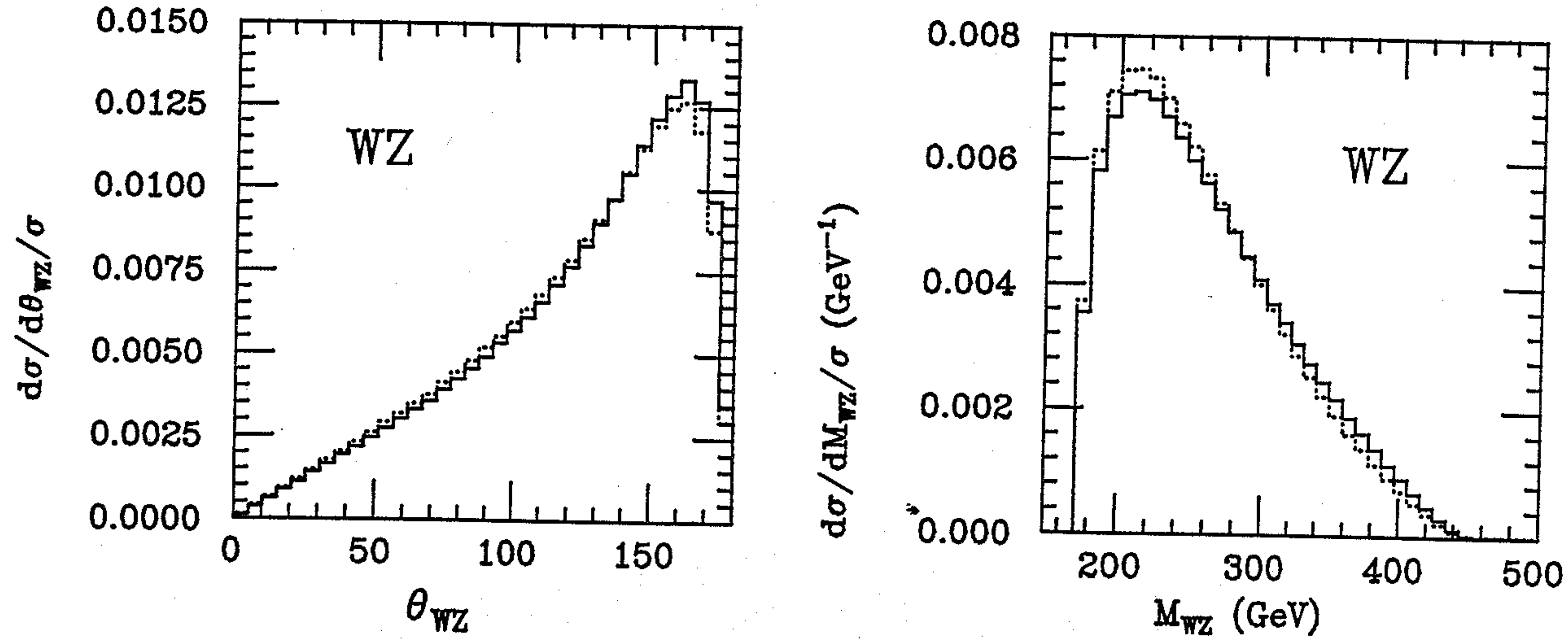

WZ
0.0150
0.0125
0.0100
0.0075
0.0050
0.0025
0.0000
0
50
100
150
$d\sigma/d\theta_{WZ}/\sigma$
θ_{WZ}
WZ
0.008
0.006
0.004
0.002
0.000
200
300
400
500
$d\sigma/dM_{WZ}/\sigma$ (GeV^{-1})
M_{WZ} (GeV)

Fig. 7