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TREPS: A Monte-Carlo Event Generator for Two-photon Processes at e^+e^- Colliders using an Equivalent Photon Approximation

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Abstract

A description and the use of an event-generator code for two-photon processes at e^+e^- colliders, TREPS, are presented. This program uses an equivalent photon approximation in which the virtuality of photons is taken into account. It is applicable to various processes by specifying a combination of final-state particles and the angular distributions among them. A comparison of the results with those from other programs is also given.

1 Introduction

Hadron production from two-photon collisions is a powerful tool for investigating the natures of strong interactions, including the photon's hadronic structure, mechanism of hadronization, and properties of various produced resonances. The Monte-Carlo programs developed so far for two-photon processes have many varieties. For high-p_T reactions in which at least one final-state particle has a much higher p_T than the typical energy scale of strong interactions of ~ 1 GeV, an assumption that they are caused by point-like interactions among partons is considered to be valid. In this case, calculations based on QED and perturbative QCD give reasonable answers.

In low- or intermediate-p_T regions where a non-perturbative effect plays an important role, a phenomenological approach is inevitable. In this case, we must introduce various hypothetical phenomenology among the photon, intermediary resonances, and final-state particles. One of the easiest ways to make such calculations is to use an equivalent photon approximation (EPA), and inserting the interactions between the photons by hand. In EPA, the probability of photon emissions from electrons is approximately calculated by QED in its energy and Q^2 distributions, where $Q^2 \equiv -q^2$ is a sign-changed 4-momentum transfer of an electron, which represents the virtuality of the photon.

There exist some problems in dealing with virtual photons in EPA. By definition, EPA is only valid for samples in which the photons are regarded as being almost real, and all of the photons have a finite virtuality with a probability distribution, $d\mathcal{P}/dQ^2 \sim 1/Q^2$, which does not vanish very quickly at high Q^2. Therefore, we must include some effects from the photon's virtuality for reliable calculations. A virtual photon gives a finite p_T for the $\gamma\gamma$ system; this effect is introduced kinematically without ambiguity. However, the Q^2 dependence of the probability distribution ($d\mathcal{P}/dQ^2$) requires an approximation in EPA. Furthermore, since we do not know the precise dynamics of the interaction induced

by a virtual photon in each process, we must approximate the interactions of the virtual photon(s) by assuming its simple relation to those of real photons.

In the usual resonance formations, which are not forbidden in real two-photon reactions, the probability the resonance being produced by a highly virtual photon, is very small, because the probability that highly virtual photons are emitted is small in itself, and, moreover, a highly virtual photon hardly ever produces a relatively light resonance by a form-factor effect. Experimentally, we can cut away such a component from highly virtual photons by vetoing using the recoiled electron, or requiring a strict p_T balancing in the final-state particle system in exclusive measurements, and can be free from ambiguities brought about by highly virtual photons.

Here, the two-photon luminosity function ($L_{\gamma\gamma}(W)$) is defined as the probability of a two-photon emission of the $\gamma\gamma$ c.m. energy of W from a pair of beam particles,

$$L_{\gamma\gamma}(W)\Delta W = \frac{(\int \mathcal{L}dt)_{\gamma\gamma}|_W^{W+\Delta W}}{(\int \mathcal{L}dt)_{ee}},$$

where $(\int \mathcal{L}dt)_{\gamma\gamma}|_W^{W+\Delta W}$ is the corresponding integrated luminosity on the basis of $\gamma\gamma$ incident falling in a W range between W and $W+\Delta W$ (ΔW must be small so that $L_{\gamma\gamma}(W)$ does not change much), when the integrated luminosity on the basis of the incident e^+e^- $(\int \mathcal{L}dt)_{ee}$ is accumulated. The above relation leads to that between the cross sections based on $\gamma\gamma$ and e^+e^- incidents,

$$\frac{d\sigma_{ee}}{dW} = \sigma_{\gamma\gamma}(W)L_{\gamma\gamma}(W).$$

The size of the two-photon luminosity function depends on the cutoff of Q^2, ($Q^2_{\rm max}$), which is an upper limit for the integration of emitted photons with Q^2. However, when we choose a reasonable $Q^2_{\rm max}$, which is safely larger than the cut effectively applied for the experimental data, the $Q^2_{\rm max}$ dependence of $L_{\gamma\gamma}(W)$ cancels out with the variation of the experimental efficiency coming from the Q^2 cut in their product; the analysis gives a stable result for the measured cross section, $\sigma_{\gamma\gamma}(W)$.

The program described in this report, TREPS (Two-photonic REsonance Production Simulator), generates simulated events from two-photon collisions as well as the calculated values of the two-photon luminosity function. The particle combination in the final state and its invariant mass (W) are explicitly specified before the calculation. The program never generates different combinations of particles event by event in itself, although such a feature can be realized by connecting the output from TREPS to another simulator, like LUEXEC, in JETSET[1]. It also never assumes any W distribution in itself. The W distribution must be introduced explicitly by numerals before the calculation.

In Sect.2, I describe the approximations used in the EPA calculations, numerical integrations and so on in TREPS for each of the calculations of the two-photon luminosity function and event generation. The results from TREPS are compared with those from other programs in Sect.3. The use of TREPS is found in Sect.4. A summary is given in Sect.5.

2 Approximations in TREPS

TREPS adopts an EPA using the formulae given in ref. [2]. The calculations are made in a separated way from the derivation of the two-photon luminosity function and the relative weight in event generation. Thus, an explanation is given separately below of the applied approximations for each of the two parts. All of the calculations based on EPA are made and described in e^+e^- c.m. system.

2.1 Calculation of the two-photon luminosity function

The two-photon luminosity function is calculated based on Eqs.(2.33) and (2.19) in ref. [2]. In TREPS, the maximum value of Q^2 for the incident photons ($Q^2_{\rm max}$) is used instead of $\theta_{i,\rm max}$. Moreover, a high-Q^2 suppression effect (or a form-factor effect) is effectively introduced into the luminosity function by a factor $F(Q^2, W)$, where $F(Q^2, W)$ is defined by the factorized relation between the cross sections for virtual photons and the real photons, $\sigma_{\gamma^*\gamma^*}(W, Q_1^2, Q_2^2) = F(Q_1^2, W)F(Q_2^2, W)\sigma_{\gamma\gamma}(W)$. Therefore, $\ln(\frac{E(1-z)}{mz}\theta_{2,\rm max})$ in Eq. (2.19) is replaced by $\frac{1}{2}\int_{\ln\frac{m^2z^2}{1-z}}^{\ln Q^2_{\rm max}} F(e^v, W)dv$, where an integration variable, $v \equiv \ln Q^2$, is chosen. These integrations are made by Simpson's integration formula.

In the formation of a narrow resonance (R), the cross section $\sigma_{ee\to eeR}$ is proportional to $(2J+1)\Gamma_{\gamma\gamma}$,where J and $\Gamma_{\gamma\gamma}$ are the spin and two-photon decay width of the resonance, respectively. The proportional coefficient,

$$4\pi^2 L_{\gamma\gamma}(m_R)/{m_R}^2,$$

is also given by TREPS at the corresponding resonance mass, $m_R = W$.

2.2 Event Generation

The event generator in TREPS allows a virtuality for only one side of a photon. An appropriate positive value, Q_0^2, is set in the generator, which is the minimum Q^2 value that the photons in the calculation can have as finite values. Although Q_0^2 is larger than the true kinematically allowed minimum Q^2 value, ($Q^2_{\rm min}$), it is still smaller than the detectable finite scale. Q^2 is replaced for all photons with a virtuality below Q_0^2 by $Q^2 = 0$; this means that the photon and recoiled electron go to a zero-degree polar angle. The approximation which we use gives a finite Q^2 for at most one side of a photon in this meaning. Therefore, although TREPS generates detectable "single-tag" events, it does not generate "double-tag" events. In event generation, the virtualities for both photons, Q_1^2 and Q_2^2, are tentatively generated. In the case that both Q_1^2 and Q_2^2 are larger than Q_0^2, the sum $Q_1^2 + Q_2^2$ is given for the virtuality of either photon, and the other photon has zero virtuality. The same $Q^2_{\rm max}$ value as in the calculation of the $L_{\gamma\gamma}(W)$ is applied for the event generation. The probability distribution in the event generation is based on Eq. (2.19) in ref. [2] for the photon energies, and the combination (Q_1^2, Q_2^2) is subjected

to the probability function $d^2\mathcal{P}/dQ_1^2dQ_2^2$, which is proportional to

$$\frac{F(Q_1^2,W)}{Q_1^2}\frac{F(Q_2^2,W)}{Q_2^2}\{\frac{s^2+(s-W^2)^2}{2s^2}-\frac{(s-W^2)Q^2_{\rm min}}{sQ_1^2}\}\{\frac{s^2+(s-W^2)^2}{2s^2}-\frac{(s-W^2)Q^2_{\rm min}}{sQ_2^2}\}$$

in the range between $m^2z_i^2/(1-z_i) < Q_i^2 < Q^2_{\rm max}$ for $i = 1,2$, where s is the square of the total c.m. energy of e^+e^- beams, $Q^2_{\rm min} = m^2W^4/\{s(s-W^2)\}$, m the electron mass, and z_i the energy fraction of the photon relative to the beam energy. Actually, a random-number generation of the Q^2 values is made via $v \equiv \ln Q^2$, because the probability function has a steep Q^2 dependence at small Q^2.

After the generation of two photons, the kinematics in the event is precisely calculated so that the final state particles give a conserved 4-momentum and the proposed W value exactly within the accuracy of the computation.

In the production of a final-state particle with a finite mass width, the mass of the particle is chosen randomly by the simplest Breit-Wigner formula of a Lorentzian. No special care is taken for a possible phase-space effect, etc. The angular distributions for the final-state particles are subjected to user-specified formula in the two-body case, or to the phase-space distribution in three-or-more-body case.

3 Numerical Comparison with Other MC Programs

The results of TREPS were compared with those from other MC programs written for special processes, Vermaseren's generator for $e^+e^- \to e^+e^-\pi^+\pi^-$ [3] and a QED calculation for four-fermion final-state processes by Berends et al.[4], in order to check the coding and to estimate the accuracy.

The value of the two-photon luminosity function from TREPS has been compared with those derived from Vermaseren's generator at the peak of the $f_2(1270)$ resonance, $W = 1.274$ GeV. In Vermaseren's generator, the $\pi^+\pi^-$ continuum part was switched off and only the $f_2(1270)$ resonance part was calculated. The program uses a Breit-Wigner formula for the resonance formation, and the two-photon luminosity function could be determined from it by dividing $\sigma_{\gamma\gamma}$ from the Breit-Wigner formula by $d\sigma_{ee}/dW$ from the output of the program. The same high-Q^2 suppression factor, as in Vermaseren's generator, was used for $F(Q^2,W)$ in TREPS, and $Q^2_{\rm max}$ is set to 16 GeV^2. The results from both programs at three e^+e^- c.m. energies are tabulated in Table 1. The results from TREPS are smaller than those from Vermaseren's, with 2% at each of the three beam energies. Since Vermaseren's code calculates the amplitude of the whole diagram, including e^+, e^-, two photon propagators and an effective coupling of $\gamma\gamma^* f_2(1270)$, it can be concluded that the numerical calculation of the two-photon luminosity function in TREPS is correct within $\sim 2\%$ error within the validity of the model assuming that the reaction is caused by $\gamma\gamma^*$ interactions with a specified $F(Q^2,W)$.

The distribution of the momenta of the two-photon system has been compared between TREPS and the QED calculation by Berends et al.[4]. The process $e^+e^- \to e^+e^-\mu^+\mu^-$ was adopted, which was calculated by the latter code with full diagrams of the

α^4 order. The events by TREPS were generated for four different W points (0.5, 1.0, 2.0, and 3.0 GeV) at $\sqrt{s} = 10.6$ GeV. Since the generated events from the code of Berends et al. have a continuous spectrum in W, only those with W being the same as the above set of values within a 1% difference were extracted. $F(Q^2, W) = 1$ and $Q^2_{\rm max} = 1$ GeV^2 were set in TREPS. Figure 1 shows the distributions of the momentum component of the $\gamma\gamma$ system parallel to the electron beam axis ($p_z^{\gamma\gamma}$) in the e^+e^- c.m. system. Only those events in which the transverse momentum of the $\gamma\gamma$ system with respect to the beam axis ($p_T^{\gamma\gamma}$) is less than 0.1 GeV/c are accumulated here. The normalization of the number of events was made on an integrated-luminosity basis for both calculations. For normalizing the TREPS's result, the two-photon luminosity function from TREPS and the total cross sections for $\gamma\gamma \to \mu^+\mu^-$ calculated by QED of the lowest order were used. Figure 2 shows the $p_T^{\gamma\gamma}$ distribution for events with $|p_z^{\gamma\gamma}| < 2W$. We can see that the shape of the $p_z^{\gamma\gamma}$ distribution is in good agreement in the two generators at each W point. In contrast, the $p_T^{\gamma\gamma}$ distributions are considerably different at W below 1 GeV. The main reason for this is that TREPS assumes here no high-Q^2 suppression in $F(Q^2, W)$. Generally speaking, a virtual photon hardly contributes to two-photon scattering, where the momentum transfer is lower than $\sqrt{Q^2}$. Because $\sqrt{Q^2} \approx p_T^{\gamma\gamma}$, the yield is expected to be dumped at $p_T^{\gamma\gamma}$ above $W/2$. The behavior of the $p_T^{\gamma\gamma}$ dependence at small $p_T^{\gamma\gamma}$ shows a reasonable agreement in the two generators, and the discrepancy at higher Q^2 is reconciled by adopting an appropriate $F(Q^2, W)$ in TREPS. Moreover, the full calculation of $e^+e^- \to e^+e^-\mu^+\mu^-$ includes other types of diagrams than the "multi-peripheral" type, which is a true two-photon collision process. The discrepancies at the end points of the $p_z^{\gamma\gamma}$ distributions are attributed to the contribution of an "annihilation"-type diagram which has a mass singularity there. The difference in the absolute values in the $p_z^{\gamma\gamma}$ distribution corresponds to the effective difference of the two-photon luminosity function for events with $p_T^{\gamma\gamma} < 0.1$ GeV/c. They coincide within 3% at W above 1 GeV, but differ by about 7% at $W = 0.5$ GeV. This is considered to be due to the interference between the other kinds of diagrams in the full QED calculation, which has a role at low W. No other peculiar systematic shift is found between the distributions from the two generators. This implies that the momentum distribution of the two-photon system in TREPS is correct at the kinematical region where the EPA is expected to have validity.

4 Usage of TREPS

TREPS calculates the two-photon luminosity function and generates events for an explicitly specified process using a set of final-state particles at a fixed W (or a series of fixed W points). The high-Q^2 suppression effect and angular distributions are written by users in functions linked to the executable module. TREPS are written in FORTRAN77.

4.1 Input parameters

The followings are the input parameters given in an input data file:

- C.M. energy of a beam (in GeV): Half of the total c.m. energy of the e^+e^- system (E^*), i.e. the beam energy in a symmetric collider.
- Fractional three-momentum of the e^- beam in the lab. system (in GeV/c): ($p_x^{e^-}/E^*$, $p_y^{e^-}/E^*$, $p_z^{e^-}/E^*$) of the electron beam. In a symmetric collider with e^- running in the $+z$ direction, these are (0.0, 0.0, 1.0).
- Fractional three-momentum of the e^+ beam in lab. system (GeV/c): ($p_x^{e^+}/E^*$, $p_y^{e^+}/E^*$, $p_z^{e^+}/E^*$) of the positron beam. In a symmetric collider with e^- running in the $+z$ direction, these are (0.0, 0.0, -1.0). They must be consistent with the e^- beam's fractional three-momentum.
- $Q^2_{\rm max}$ (in GeV^2): Maximum virtuality of photons. This is applied in both the calculations of the two-photon luminosity function and event generation. If a negative value is specified, TREPS assumes a kinematically maximum value for each W.
- Maximum value for $|\cos\theta^*|$ in an event to be saved and a flag for the electric charge of a particle to which the cut applied: TREPS does not save the event into a disk file in the case that at least one of the final-state particles is out of the angular range specified by the maximum of the absolute value of the cosine of the polar angle in the e^+e^- c.m. system. This constraint is also applied for neutral particles (only for charged particles) in the case that a number 0 (1) is specified as the second parameter.
- Minimum value for p_T of the final-state particles in an event to be saved(in GeV/c) and a flag for the electric charge of a particle to which the cut applied: TREPS does not save the event into a disk file in the case that at least one of the final-state particles has a transverse momentum with respect to the e^- beam axis (in e^+e^- c.m. system) less than the minimum p_T value. This constraint is also applied for neutral particles (only for charged particles) in the case that a number 0 (1) is specified as the second parameter.
- Number of particles just after the two-photon collision: TREPS requires two or more produced particles just after a two-photon collision. A resonance produced by the formation from two photons does not emerge explicitly in the calculation, and it decays immediately (with a much shorter lifetime than can be detected) into two or more particles. Suppose a reaction $\gamma\gamma \to a_2^0(1320) \to \pi^+\rho^- \to \pi^+\pi^-\pi^0 \to \pi^+\pi^-\gamma\gamma$. In this example, $a_2^0(1320)$ does not emerge in the calculation. Therefore, the number of particles just after the collision is 2, i.e., π^+ and ρ^-. The existence of $a_2^0(1320)$ only affects to the angular distribution of the decay products in the calculation at each fixed W point.
- List of particle properties just after the two-photon collision: the particle code (in any appropriate standard), mass (in GeV/c^2), electric charge, $c\tau$, number of

products in the subsequent decay in this program, and the decay width (in GeV). TREPS supports the decay of a particle in only one step. In the above example, although the ρ^- decay into $\pi^-\pi^0$ can be included in TREPS, $\pi^0 \to \gamma\gamma$ can not. The decay which is supported by TREPS is always of zero lifetime, which means that particles always decay at the collision point. The $c\tau$ in the list is not used in TREPS and only has meaning for the final-state particles whose data are passed to subsequent processing.

- List of decay products: particle code, mass, electric charge, and $c\tau$ of the decay products from the particles just after the two-photon collision, in the order of the previous list. The subsequent decays or finite mass width of these particles are not supported.

- W, number of generated events, and suppression flag of the calculation of the two-photon luminosity function: Since the calculation of the two-photon luminosity function and the event generation are made separately, either of them can be suppressed by setting zero to the number of generated events or setting the suppression flag, a letter "S". The number of generated events includes those not-saved by the polar angle or p_T cuts. Calculations and event generations at different W points are possible by putting a series of two or more lines.

4.2 Functions

The following functions describe some parameter dependences of the differential cross section specified by the user.

- TPFORM: The high-Q^2 suppression factor, $F(Q^2, W)$. It is assumed that $F(Q^2, W) \leq 1$ for any $Q^2 > 0$ and $F(0, W) = 1$.

- TPANGD: The polar-angle distribution of the first particle in the list in the $\gamma\gamma$ c.m. system. It is called only in the case that the number of particles just after the two-photon collision is two. In the case that it is more than two, the phase-space distribution is assumed.

- PDECDZ: The polar-angle distribution of each first particle in the decay-product list in the parent particle's rest frame with respect to the parent's going direction. It is called only in the case that the number of the decay products is two. In the case that it is more than two, the phase-space distribution is assumed.

4.3 Further applications

The following requirements are easily satisfied by adding some code statements for each individual purpose:

- Specifying another angular distribution among three or more final-state particles.

- Adding more chain of decays.
- Connecting to other utility programs supporting particle decays as LUEXEC in JETSET [1].
- Changing the criteria for saving into a disk file.

The first two modifications can be satisfied, in principle, by adding the necessary code statements in SUBROUTINE TPUSER, which is called just after the momentum vectors of the final-state particles being obtained. The momentum vectors are represented in the e^+e^- c.m. frame in which the e^- beam is directed along the $+z$ direction. The angular distributions can be modified by rejecting a part of the events from the phase-space distribution using a hit-or-miss method along with a weight function from the square of the known scattering/decay amplitude.

Appropriate modifications at the final stage in each event loop can meet the last two requirements.

5 Summary

The Monte-Carlo event generator TREPS can treat two-photon reactions at e^+e^- colliders for a user-specified combination of final-state particles. It calculates the two-photon luminosity function and generates simulated events at a specified fixed $\gamma\gamma$ c.m. energy (W) using an equivalent photon approximation (EPA). TREPS takes the virtuality of photons into account in the approximation, and generates events in which at most one side of a photon has a finite Q^2.

The accuracy of the calculation was tested by comparisons with other kinds of programs. The accuracy of the two-photon luminosity was estimated to be 2% within the validity of the model assuming a specific Q^2 dependence of the $\gamma\gamma^*$ cross section. The momentum distributions of the two-photon system are in very good agreement with those expected from a full diagram calculation for the process $e^+e^- \to e^+e^-\mu^+\mu^-$ in a transverse momentum region of the $\gamma\gamma$ system sufficiently lower than $W/2$.

TREPS is useful for two-photon processes of various combinations of intermediary- and final-state particles. The complicated angular distribution among the final-state particles is easily introduced.

I would like to thank the colleagues of the VENUS collaboration, who gave me a chance to make experimental studies for two-photon physics. I would like to express my special thank to Mr. H.Hamasaki. He checked the code of TREPS in detail and gave me invaluable information.

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Table 1. Numerical comparison of the two-photon luminosity functions ($L_{\gamma\gamma}(W)$) at $W = 1.274$ GeV from TREPS with those from Vermaseren's program [3].

$\sqrt{s}$ (GeV)	$L_{\gamma\gamma}(W)$ from TREPS (GeV^{-1})	$L_{\gamma\gamma}(W)$ from Vermaseren's (GeV^{-1})	ratio of difference
10.6	0.00668	0.00680	−1.8%
60.0	0.0212	0.0217	−2.3%
92.0	0.0261	0.0267	−2.2%

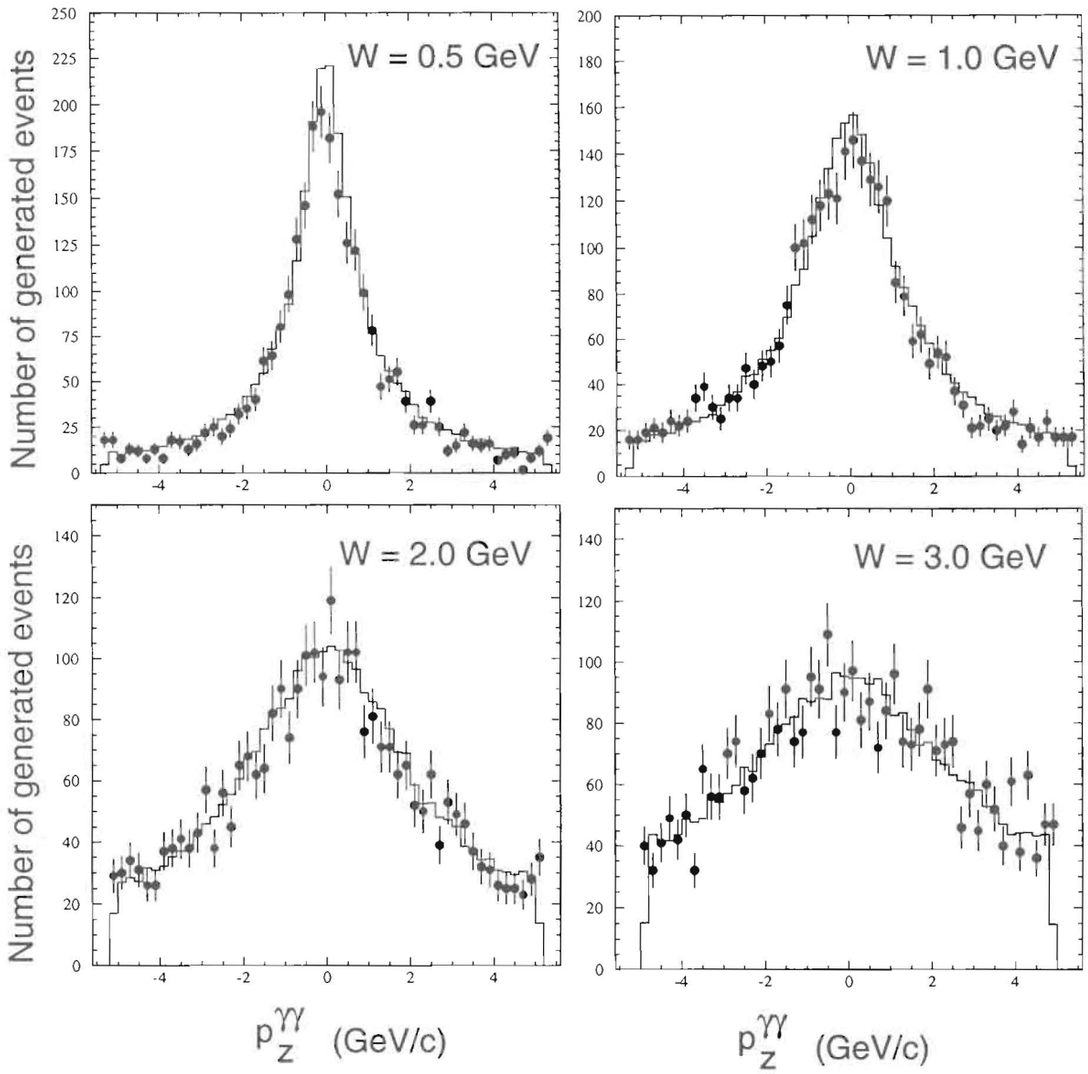

Figure 1: Distributions of the z-component of the momentum of the $\gamma\gamma$ system in the e^+e^- c.m. system ($p_z^{\gamma\gamma}$) for events from the Monte-Carlo event generators, TREPS (histograms) and Berends et al.[4](dots with error bars) at four W points. Those events with a transverse momentum with respect to the e^- beam axis ($p_T^{\gamma\gamma}$) less than 0.1 GeV/c only are accumulated. The error bars are statistical. The normalization is made on an integrated-luminosity basis.

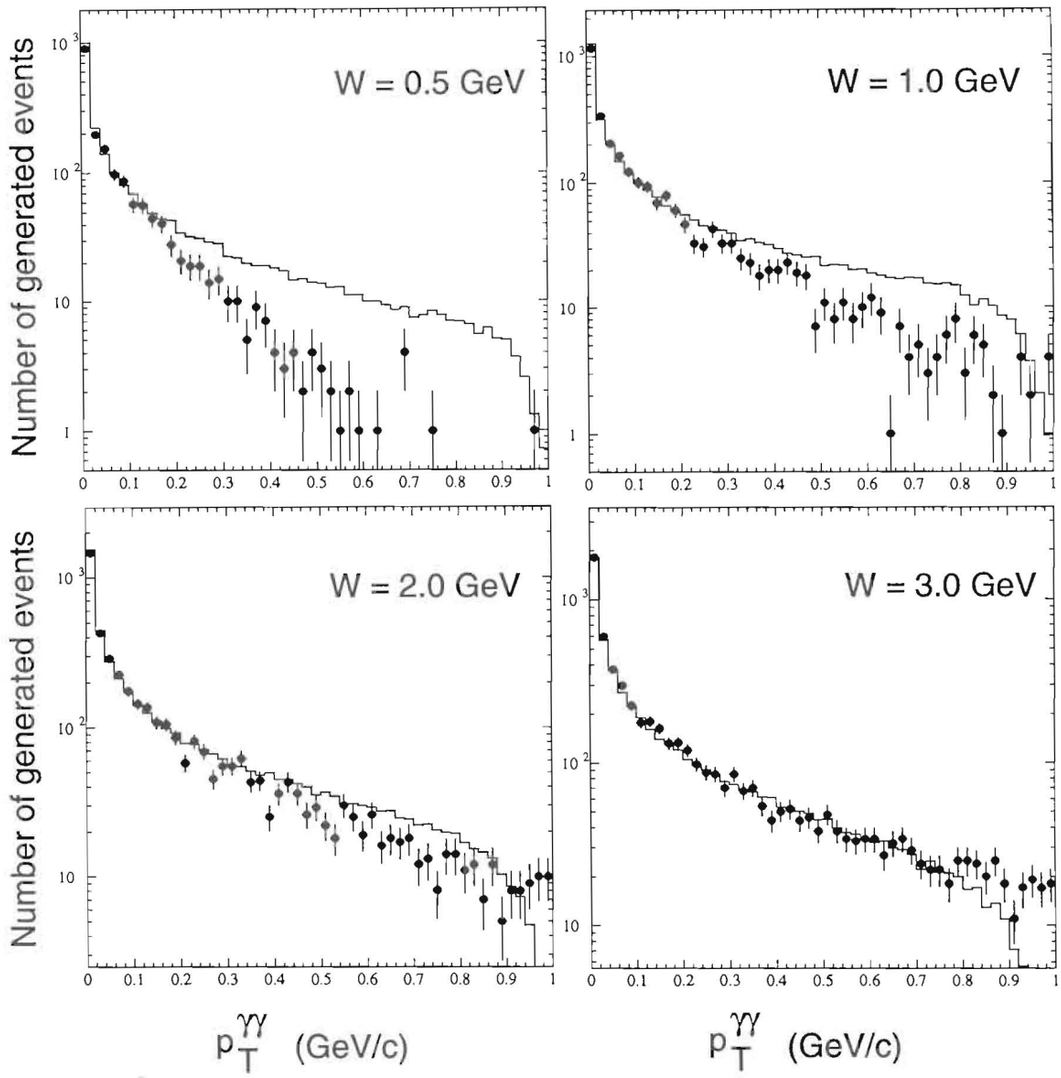

Figure 2: Distributions of the transverse component of the momentum of the $\gamma\gamma$ system in the e^+e^- c.m. system ($p_T^{\gamma\gamma}$) for events from the Monte-Carlo event generators, TREPS (histograms) and Berends et al.[4](dots with error bars) at four W points. Only those events with $|p_z^{\gamma\gamma}| \leq 2W$ are accumulated. The error bars are statistical. The normalization is made on an integrated-luminosity basis.