CLNS 03/1839
Mar 03

QMC – Quick Monte Carlo: Simulating the Two-Photon Process and Continuum e^+e^- Annihilation

Karl Berkelman

Abstract

The two-photon process is the production of a hadronic final state from the collision of two virtual photons, each emitted by one of the charged particles in an inelastic electron-positron or electron-electron scattering, that is, $ee \to ee\gamma^*\gamma^* \to ee + hadrons$. Although the $\gamma^*\gamma^* \to hadrons$ interaction is of interest in its own right, I am concerned here mainly with it as a background to the measurement of e^+e^- annihilation processes. I describe here the stand-alone Quick Monte Carlo simulation program that reproduces the general features of the untagged two-photon process or the continuum e^+e^- annihilation process. The QMC package can be used to compare inclusive final hadron spectra in those two reactions, test strategies for event selection, and estimate efficiencies.

1 Motivation

Measurements of total cross sections for e^+e^- annihilation are useful for determining the width parameters (Γ_{ee} and Γ) of the quarkonium states and for getting the $R(W)$ that is important for the understanding of muon $g-2$ and the running of α_S. An important background to the measurement in the continuum is the two-photon process. Usually the inelastically scattered beam particles are lost down the beam pipe and the hadron final states can mimic those in continuum annihilation. The total two-photon cross section at $W = 10$ GeV is 7 nb, as compared about 4 nb for annihilation.

The strategy for suppressing the two-photon rate relative to the annihilation rate has to exploit several contrasts in the two processes.

1. Because of the energy lost to the outgoing beam particles in the two-photon process, the total energy in the hadronic final state is reduced. The energy E_γ given to each photon is distributed approximately as $1/E_\gamma$, so the total visible hadron center-of-mass energy is more likely to be at the low end of the kinematically available range.

2. For the same reason, hadron multiplicities average lower for two-photon reactions relative to annihilations at the same initial beam energies.

3. The two photons are likely to have rather different energies. Thus the net longitudinal momentum of the hadrons in the lab is likely to be boosted far from zero.

4. Each photon can exist virtually as a vector meson state (ρ, ω, etc.). They interact mainly peripherally as vector mesons, exchanging a pomeron and then fragmenting. Thus, although the $\gamma^*\gamma^*$ cross section is much lower than typical hadron+hadron cross sections, the topological features of the final states are very similar: typical multiplicities, limited transverse momenta, broadly distributed longitudinal momentum, alignment along the beam axis. In contrast, continuum e^+e^- annihilation is a pointlike reaction with a well defined intermediate (timelike photon) state that decays into hadron jets aligned in any direction, with a $1 + \cos^2\theta$ distribution of jet axes.

5. Limited transverse momentum and boosted longitudinal momentum in the two-photon final states makes for small angles relative to the beam. A much larger fraction of the hadrons will escape detection relative to the annihilation case. The inelastically scattered electron and positron are most likely close to the beam line and thus not detectable.

I have written a package of Fortran routines, called QMC – Quick Monte Carlo, to quantify somewhat these generalizations and thereby enable one to optimize event selection strategy.

2 Simulation Strategy

QMC assumes that the dominant features of the two-photon process that make it different from the continuum annihilation process are mainly

- electromagnetic – generating the two photon state,
- periferal – alignment along the beam line with limited p_t,
- kinematic – the effect of the boost,

and that the subtleties of the generation of exclusive hadronic final states can therefore be approximated with inclusive distributions. Once QMC has generated the kinematics of the two-photon state with the correct energy spectra, it creates all at once the hadron final state with the right generic distributions, without going through the step-by-step quark hadronization process. QMC can also use the same hadron generation algorithm to generate e^+e^- annihilation two-jet continuum events by rotating the jet axis. That makes it possible to compare distributions in the two cases under similar assumptions.

The simulation of two-photon data in QMC subroutine TWOPHO proceeds as follows.

1. **Generate the two-photon system.** Each of the two $e^{\pm}$ beam particles radiates an almost real photon of energy fraction $x = k/E_0$ according to a probability function

$$\frac{d\mathcal{P}(x)}{dx} = \frac{1}{x}\left[(x^2 - 2x + 2)\ln[\gamma(1-x) - \tfrac{1}{2}] + \tfrac{1}{2}\,x^2 - \tfrac{1}{4}\,(2-x)^2\ln(2-x)\right],$$

where $\gamma = E_0/m_e$. Since the radiation is very strongly peaked, TWOPHO integrates over the θ_γ distribution and assumes that the photons are emitted along the beam line at $\theta_\gamma = 0$. The center-of-mass energy of the two-photon system is $W_{\gamma\gamma} = 2\sqrt{x_1 x_2}E_{beam}$, which is required to be greater than 0.5 GeV. QMC randomly rejects some choices of $W_{\gamma\gamma}$ in order to keep the distribution compatible with the known energy dependence of the cross section for $\gamma^*\gamma^* \to hadrons$ [1]. The velocity of the center of mass in the lab is $\beta = (x_1 - x_2)/(x_1 + x_2)$.

2. **Generate the hadron final state particles in the two-photon center-of-mass frame.** TWOPHO picks a random multiplicity n and a list of n pions with specified charge, E, p_t, p_z according to appropriate probability distributions. This is carried out by calling subroutine JETS, which is described in detail in a later section. The track parameters are stored in COMMON/TRAX0 and COMMON/TRAX1.

3. **Boost the hadron final state to the lab.** This consists of applying the Lorentz transformation to the E and p_z of each of the final state hadrons. The boosted track data is in COMMON/TRAX2. The outgoing electron and positron are ignored as undetectable.

4. **Decay the neutral pions.** Subroutine DKPI0 compiles a new track list (in COMMON/TRAX03 and COMMON/TRAX3) in which all the neutrals (pions) are decayed to two photons – back-to-back and isotropic in the pion rest frame – then transformed to the lab.

5. **Smear and check thresholds for the CLEO detector.** Subroutine DETECT smears the generated track parameters, p_t, $\cot\theta$, and ϕ for charged and E, θ, and ϕ for neutrals, according to their expected r.m.s. resolutions in the CLEO detector [2]. It then checks the p_t or E and the θ to see if they are in the detectable range [3][4]. By random selection it imposes a detection efficiency limit on otherwise detectable particles (now set at 95% for charged tracks and 86% for neutrals). A list of observed tracks is compiled and given in COMMON/TRAX04 and COMMON/TRAX4.

6. **Test for acceptance in the CLEO detector.** Subroutine SELECT applies the "hadronic subcollection" cuts used by Jim Pivarski [3]:

$$\langle n_c \geq N_{CMN1}\rangle \times \langle \Sigma E/W > F_{VISMN}\rangle$$

$$\times\langle\{n_c \geq N_{CMN2}\} + \{[\Sigma_n E/W > F_{NMN1}]\times[(\Sigma_n E/W < F_{NMN2}) + (E_{n,max}/W < F_{NBMN})]\}\rangle,$$

where for now $N_{CMN1} = 3$, $N_{CMN2} = 5$, $F_{VISMN} = 0.2$, $F_{NMN1} = 0.15$, $F_{NMN2} = 0.75$, and $F_{NBMN} = 0.75$ (also $\times$ means AND, $+$ means OR, $W = 2E_{beam}$, Σ_n sums over neutrals (including 20 ± 10 MeV shower energy per charged track), and $E_{n,max}$ is the energy of the most energetic neutral). The subroutine returns an argument KODE, which uses a binary bit for each failed cut; KODE $= 0$ if the event is selected. It is also possible in the main program to apply additional cuts.

7. **Calculate efficiencies and cross sections.** With the appropriate normalizations the event simulation can be thought of as a numerical integration, convoluting the two-photon emission probability distribution in $W_{\gamma\gamma}$ with the cross section for $\gamma^*\gamma^* \to$ *hadrons*. The detection efficiency is calculated in the obvious way. Applying it to the total cross section gives the effective visible cross section.

For comparison, the QMC subroutine ANNIH uses much of the same aparatus to simulate continuum annihilation $e^+e^- \to hadrons$. Instead of step 1 above, the beam electron and positron each undergo initial state radiation according to the approximate effective radiator formula:

$$\begin{aligned} \mathcal{P}(k)dk &= tdk/k \qquad && \text{for } k > 0.005E_{beam}, \\ &= 0 && \text{for } k < 0.005E_{beam}, \\ t &= \tfrac{\alpha}{\pi}\left(\ln\tfrac{W^2}{m^2} - 1\right). \end{aligned}$$

As a result the center of mass energy W_{coll} for the e^+e^- annihilation is often reduced and the collision takes place in a frame moving with respect to the lab. If the reduction in W_{coll} results in a significant enhancement in the cross section ($\propto W^{-2}$) ANNIH generates more events with the same γ^* energies as appropriate. Step 2 proceeds as before. In step 3, ANNIH rotates the entire final state so that it is aligned along a random axis instead of the z axis, and then boosts to the laboratory frame. The random axis is picked with a distribution $d\mathcal{P}(\theta_{jet})/d\Omega \propto 1 + \cos^2\theta_{jet}$. This gives a two-jet event with the correct jet axis distribution for the fragmentation of two back-to-back spin-$\frac{1}{2}$ quarks.

Note that QMC does not do an analogous initial state radiation in the TWOPHO routine. The emission of each of the two colliding photons is a low q^2 process, so that the corresponding effective radiator factor $t = (\alpha/\pi)[\ln(q^2/m^2) - 1]$ is probably negligible. The two colliding photons do not radiate in lowest order, since they are neutral.

3 The Hadron Final State

The final state hadrons are required to have the distributions in total and charged multiplicity $n,\ n_c$ and in transverse and longitudinal momenta $p_t,\ p_z$ appropriate to the available center of mass energy W. The final state must also conserve energy and momentum, $\Sigma E = W,\ \Sigma p_t = 0,\ \Sigma p_z = 0$. This is done in subroutine JETS in the following steps.

1. **Average multiplicity.** For the average *charged* multiplicity JETS uses a formula based on the PDG plot of $\overline{n}_c(W)$ from e^+e^- data [1]:

$$\overline{n}_c(W) = a_m + b_m \ln W^2 + c_m(\ln W^2)^2.$$

The coefficients are adjustable and have now the values $a_m = 2.9,\ b_m = 0.152,\ c_m = 0.203$.

2. **Multiplicity spread.** Over a wide energy range charged multiplicities obey "modified KNO scaling" [5, 6]. That is, the distribution in scaled multiplicity $z' = (n_c - \alpha)/(\overline{n}_c - \alpha)$ is observed to be independent of energy W. The appropriate α for reactions without leading beam particles is $\alpha \approx 0$. The universal distribution [6] can be described by $d\mathcal{P}/dz = a_z z^{b_z} \exp(c_z z + d_z z^2)$ with $a_z = 1.54,\ b_z = 0.506 \sim 0.5,\ c_z = 0.583,\ d_z = -0.784$. JETS approximates this by a Gaussian and pick a random z with a mean 0.9 and r.m.s. spread 0.7. The chosen charged multiplicity is then $n_c = z\overline{n}_c(W)$. The total multiplicity n is got by scaling up by the factor $f_0/(1 + f_0)$, where f_0 is the neutral fraction, taken to be 0.37.

3. **Spherical hadron state.** JETS generates n random particle momenta according to the probability distribution that will give the desired final transverse momentum spectrum, that is,
$$\frac{d\mathcal{P}}{dp} = p^2 e^{-b_p p},$$
where $b_p = 3.52$ [6]. It then assigns random isotropic polar and azimuthal angles $\theta,\ \phi$ for each particle, attempting to achieve overall balance ($\Sigma\vec{p} = 0$). The balance is usually not perfect, so JETS then rotates the ensemble of particles to put the net momentum along the $+z$ direction. JETS scales down (up) each p_z in the forward (backward) hemisphere so that $\Sigma p_z = 0$.

4. **Masses and energies.** In the present version of the program all final state particles (directly produced or coming from decays) are given the pion mass and the corresponding energies are calculated.

5. **Energy conservation.** If the total energy of the ensemble of particles generated in the previous steps is greater than W, JETS scales down all the momenta by the common factor required to get $\Sigma E = W$. If the total energy is less than W, only the *longitudinal* momentum components are scaled to achieve $\Sigma E = W$.

6. **Charges.** JETS assigns particle charges $+$, $-$, 0 at random, keeping overall charge zero and making the neutral fraction f_0 on average.

I have written a program TESTJET to exercise the JETS routine and type out event track lists (if desired) and distributions. It seems to do what it was designed to do – produce generic all-pion final states aligned along z, with the desired distributions in multiplicity and transverse momentum, and conserving energy and momentum.

The final states are quite generic, in the sense that there are no additional physics assumptions, no correlations, and no mass combinations indicating decays from intermediate particles. JETS will obviously not reproduce the peculiarities of exclusive final states as one approaches thresholds at low W. Also, the generated final states resemble $q\overline{q}$ jets; gluon jets are not generated.

4 Running QMC

I have written a Fortran main program, TESTQMC, which accepts a beam energy as typed input, and calls TWOPHO or ANNIH the desired number of times to generate either two-photon or continuum annihilation events. It can on demand type out the track information for each event or save event or track ntuples on disk. At the end it produces frequency plots of interesting kinematic variables and gives the detection efficiency and the total and detected cross sections. TESTQMC can also test other nonstandard event selection cuts. The speed is impressive, a few milliseconds per event.

Users desiring to run the QMC package have several options.

- **Run TESTQMC as is.** The sequence of TESTQMC calls to the generator routines goes as follows.

IF(IOPTION.EQ.1)THEN	! IOPTION is chosen at run time
CALL TWOPHO	! Generate a $e^+e^- \to e^+e^-\gamma^*\gamma^* \to e^+e^- pions$ event
ELSE	
CALL ANNIH	! Generate a continuum $e^+e^- \to \gamma^* \to pions$ event
ENDIF	
CALL DKPI0	! Decay the neutral pions
CALL DETECT	! Simulate CLEO acceptance, efficiency, resolution
CALL SELECT(KODE)	! Apply event selection criteria (KODE=0 if selected)

  Both the TWOPHO and ANNIH routines call the basic generator routine JETS. The files you need are `testqmc.F` containing the calling program, `qmc.F` containing the Monte Carlo subroutines, `util.F` containing some utility routines, and some CERN packages for RAN and HBOOK routines, etc. The first three files are in `/homes/cleo/kb/gamgam`. Assuming that you have copied them into your area, you can compile and link with

```
f77 -L/nfs/cern/pro/lib -lpacklib -lmathlib testqmc.F qmc.F util.F
-o testqmc.exe
```

  Then run by typing `testqmc.exe`

- **Copy and edit the Fortran in `testqmc.F`, `qmc.F`, and `util.F` and run your own version.** One option, for instance, is to use the QMC generator only as far as the output of DKPI0, then send each generated final state particle through an alternative detector simulation, for instance, a detector other than CLEO. The appropriate input to such a detector simulation would be the generated event and track information in the QMC output COMMON blocks TRAX03 and TRAX3. They look like this.

PARAMETER M=80		! dimension for track lists
COMMON/TRAX03/	MULT3,	! total multiplicity
	J3CH(I),	! track charge -1,0,1
	AMASS(I)	! mass in GeV
COMMON/TRAX3/	E3(I),	! measured energy in GeV
	P3X(I),	! measured p_x in GeV/c
	P3Y(I),	! measured p_y in GeV/c
	P3Z(I),	! measured p_z in GeV/c
	P3T(I),	! $\sqrt{p_x^2 + p_y^2}$ in GeV/c
	PHI3(I)	! $\tan^{-1}(p_y/p_x)$ in radians
	(I = 1..MULT3)	

I have written a subroutine LUJETTER (in file `kb/gamgam/qmc.F`) to convert the generator data from the above QMC format to the Lund standard format [7]:

PARAMETER M=4000		! dimension for track history lists
COMMON/LUJETS/	N,	! MULT3
	K(I,1),	! means undecayed particle
	K(I,2),	! ± 221 for $\pi^{\pm}$, 22 for γ
	K(I,3..5),	! 0
	P(I,1..3),	! P3X(I),P3Y(I),P3Z(I)
	P(I,4),	! E3(I)
	P(I,5),	! A3MASS(I)
	V(I,1..5)	! 0.
	(I=1..N)	

It can be run with the usual QMC package (omitting DETECT and SELECT) using the main program QMCLU (in file `kb/gamgam/qmclu.F`) instead of TESTQMC. There also exists somewhere a Lund subroutine LUHEPC(MCONV) (with MCONV =1) that will convert the track information in COMMON/LUJETS/ to the LEP standard HEPEVT event record format.

- **Run the standard CLEOG Monte Carlo with QMC replacing QQ.** That is, replace the QQ event generator with the QMC routines including LUJETTER but omitting DETECT and SELECT. You can then run the simulated data through the CLEO Pass1 or Pass2 event reconstruction program. This option may be available sometime in the future.

- **Write your own program to call whichever QMC routines you wish to use.**

5 Some Results

I have checked the ANNIH+DKPI0+DETECT+SELECT version of QMC against the standard CLEO Monte Carlo (CLEOG with QQ) for e^+e^- continuum production of hadron final states at $E_{beam} = 5.3$ GeV. Some comparison plots from simulated event samples satisfying the standard hadronic subcollection criteria are shown in Fig. 1. The agreement is encouraging.

Figure 2 compares some representative QMC spectra from e^+e^- annihilation and from the two-photon process for a beam energy of 5.3 GeV. Note that although the two-photon process does result in lower multiplicities and visible energies as expected, the contrasts in the e^+e^- and $\gamma^*\gamma^*$ spectra are not very striking for the events that get past the hadron subcollection cuts.

Table 2 shows cross sections at $E_{beam} = 5.3$ GeV and their slopes with respect to E_{beam}. As given in section 2 item 6, the hadron selection requirement is an AND of three conditions. For each failed requirement the SELECT routine assigns a bit: (1) charged multiplicity, (2) visible energy, and (4) a complicated set of ORs and ANDs designed to reject lepton pairs. Table 1 shows the bit sums for the 5.3 GeV annihilation and two-photon processes. Most of the annihilation events pass all the requirements; most of the two-photon events fail all the requirements, bringing the visible cross section from above the continuum annihilation down to about 4% of it.

Actually the tabulated *total* cross sections are less well defined than the corresponding *hadron selected* cross sections. Included in the total cross section are events with very low center of mass hadron energies, either because of large initial state radiation in the e^+e^- annihilation or because the two photon energies were low in the $\gamma^*\gamma^*$ collision. In both cases the cross section increases rapidly at low collision energies: $\sigma_{ee} \propto 1/W_{coll}^2$ and $\mathcal{P}_{\gamma\gamma} \propto 1/E_{\gamma_1}E_{\gamma_2}$. QMC does not handle low energy exclusive processes well; it just uses in subroutine JETS a minimum collision energy cutoff, WCOLLMN=0.5 for now. The hadron selection criteria, however, reject the very low energy events, so the corresponding visible cross section should be much less sensitive to the arbitrary threshold cutoff. Note that although the hadron selected radiative annihilation cross section is far from the total radiative annihilation cross section, it is nevertheless rather close to the naive, idealized no-radiation cross section.

Some of this lack of definition of the total cross section may also be present in the standard CLEO QQ Monte Carlo annihilation cross section. The effect of initial state radiation is to produce a spectrum of e^+e^- collision energies $\mathcal{P}(W_{coll}) \propto (W_{beams} - W_{coll})^{-1}$ that gets convoluted with the $\sigma_{cont}(W_{coll}) \propto W_{coll}^{-2}$ with the result that the net cross section would diverge if it weren't for the nonzero hadron production threshold. One has to be sure to define carefully what total cross section one is measuring. Does it include ISR events with hadron energies all the way down to threshold? Or is it the idealized (and unphysical) no-radiation hadronic cross section? What is actually in the Monte Carlo for ISR? Does it correctly generate events down to threshold, and with the correctly enhanced cross section? This is especially important in the measurement of R. This ambiguity is not present in the resonance cross section. If too much energy is radiated, the resonance cannot be produced and the ISR cuts off cleanly.

Can we do more to suppress the two-photon events? I have tried several possible additional selection criteria, taking advantage of the p_z imbalance and the low p_t in the two-photon events. The effects on the continuum annihilation and two-photon rates are given in Table 3. One novel discrimination variable, which turned out to be not very effective, is

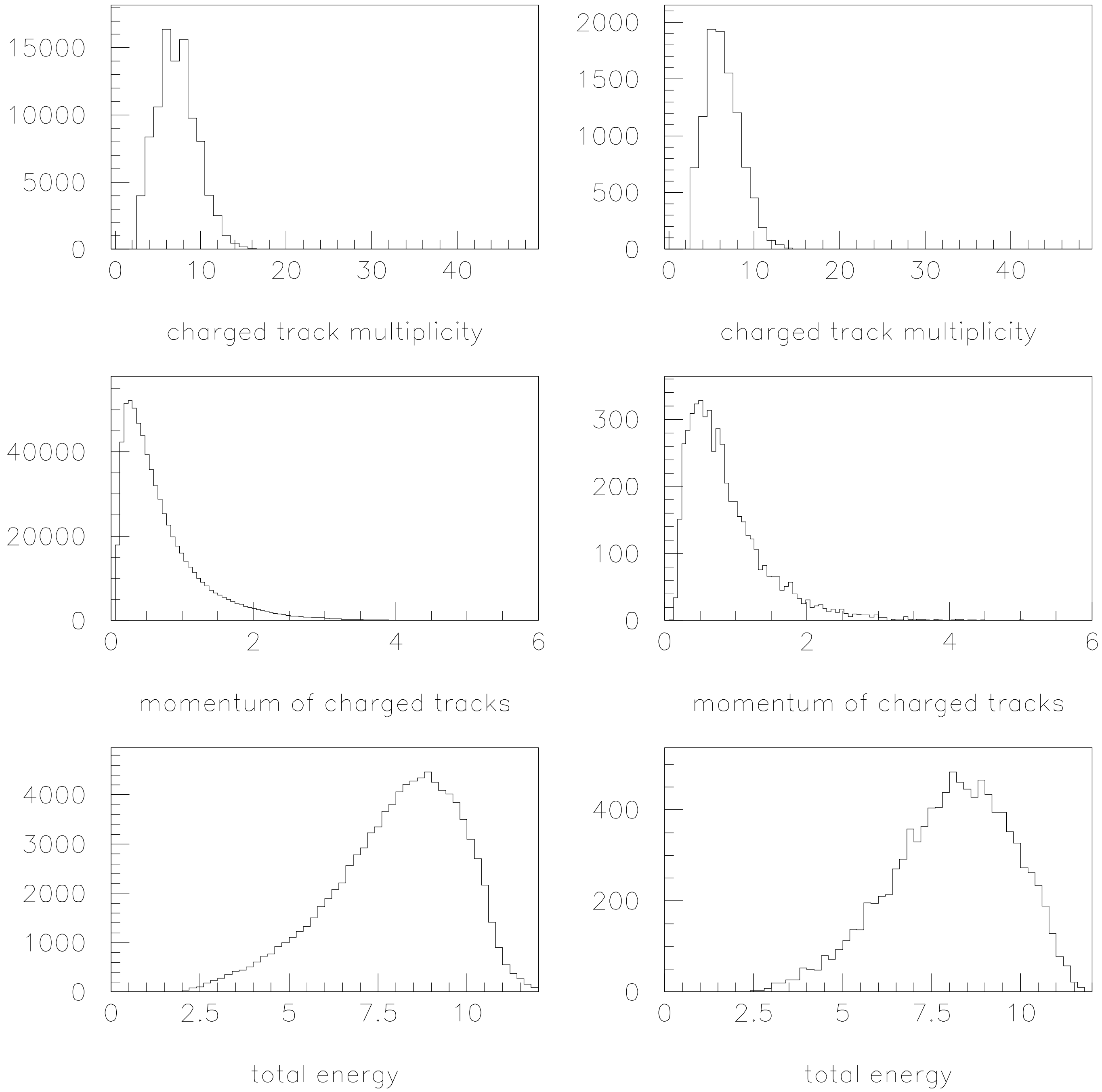

Figure 1: Comparison of some CLEO Monte Carlo (left side) and QMC (right side) spectra in hadron-selected e^+e^- continuum annihilation events at 5.3 GeV per beam. Top: visible charged multiplicity. Middle: detected track momentum in GeV/c. Bottom: visible total energy.

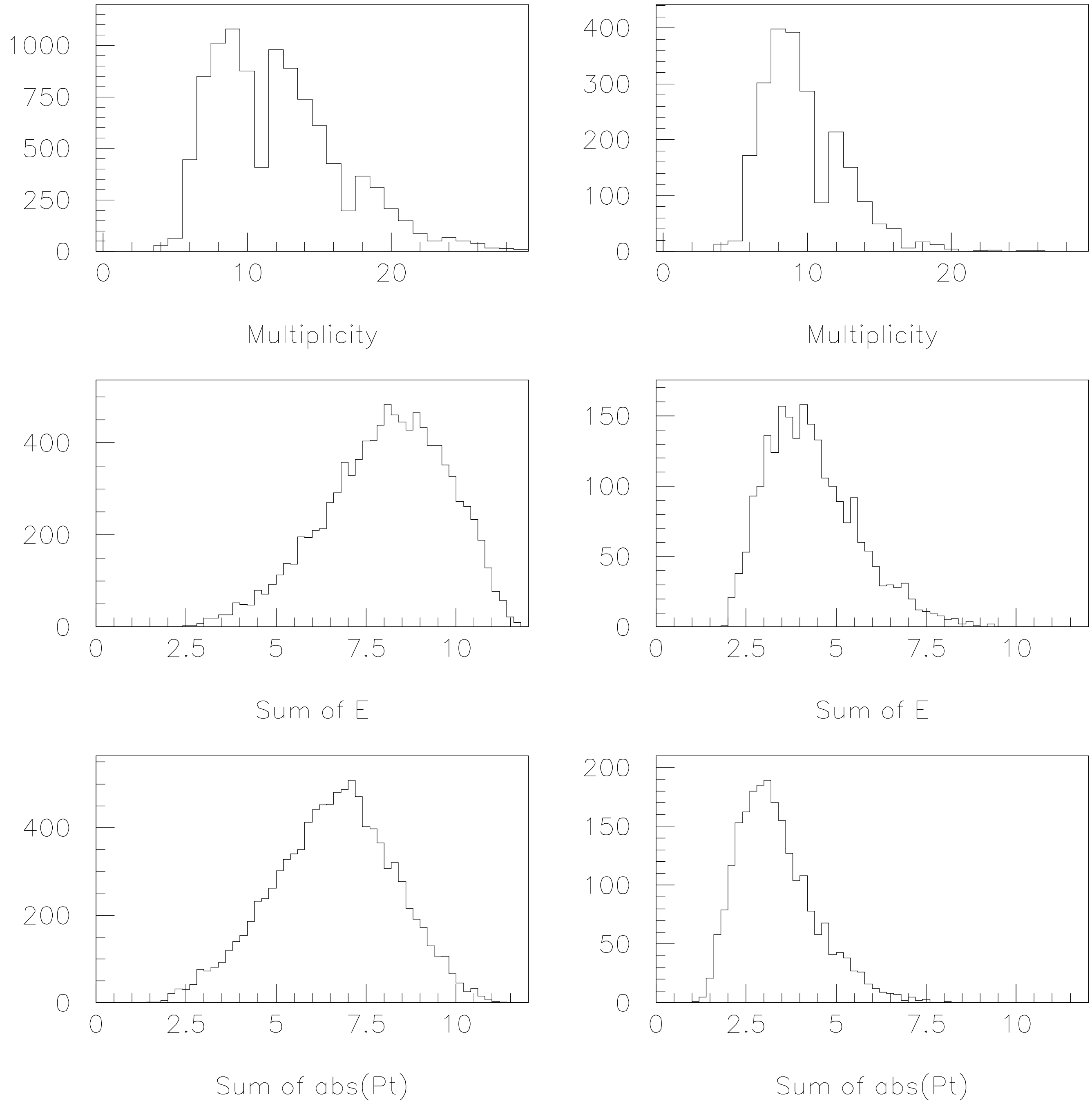

Figure 2: Comparison of some QMC spectra in hadron-selected e^+e^- continuum annihilation events (left side) and $\gamma^*\gamma^*$ events (right side). Top: total visible multiplicity. Middle: visible total energy. Bottom: visible algebraic sum of transverse momentum.

Table 1: Frequencies for the KODE bit sum returned by SELECT for $E_{beam} = 5.3$ GeV.

KODE	$e^+e^- \rightarrow hadrons$	$e^+e^- \rightarrow \gamma^*\gamma^* \rightarrow e^+e^- hadrons$
0	53.8%	2.3%
1	4.3%	0.4%
2	$< 0.1\%$	$< 0.1\%$
1+2	$< 0.1\%$	$< 0.1\%$
4	9.7%	4.0%
4+1	6.1%	1.8%
4+2	0.7%	3.1%
4+2+1	25.2%	88.3%

Table 2: Cross sections and slopes at $E_{beam} = 5.3$ GeV.

	$e^+e^- \rightarrow hadrons$	$e^+e^- \rightarrow \gamma^*\gamma^* \rightarrow e^+e^- hadrons$
σ no rad.	2.86 nb	
σ total	4.72 nb	7.16 nb
σ selected	2.54 nb	0.09 nb
selected/total	54%	1.2%
$\sigma^{-1}d\sigma/dE_{beam}$ total	-0.081 %/MeV	0.008 %/MeV
$\sigma^{-1}d\sigma/dE_{beam}$ selected	-0.074 %/MeV	0.048 %/MeV

the total visible energy E_h in whichever hemisphere (forward or backward of $\theta = 90°$) which has the lowest visible energy. I conclude that the hadron subcollection cuts already applied do about as well one can, although it may be possible to cut the two-photon background by an additional factor of two-thirds with a $\sim 1\%$ effect on the continuum annihilation signal. For the measurement of $R = \sigma_{had}/\sigma_{\mu\mu}$ around 5 GeV per beam that would imply a background/signal ratio of 2 to 3%. I suspect that it will be hard to do much better than this without introducing unacceptable systematic uncertainty in the signal efficiency.

Table 2 shows that for the measurement of a resonance cross section, $e^+e^- \rightarrow \Upsilon \rightarrow hadrons$ for instance, the background from $\gamma^*\gamma^* \rightarrow hadrons$ should not be a problem. The two-photon contribution to the hadron-selected continuum under the peak modifies its energy slope from -0.074% per MeV to $(-0.074 + \frac{0.09}{2.31}0.048) = -0.072\%$ per MeV, a rather small effect. It will be sufficient to assume the nominal continuum slope (or with a rough correction) and let the continuum magnitude float in the peak fitting.

Table 3: Efficiencies for several new cuts after the standard hadronic subcollection cuts have already been applied ($E_{beam} = 5.3$ GeV).

variable	require	e^+e^- $\rightarrow hadrons$	$e^+e^- \rightarrow \gamma^*\gamma^*$ $\rightarrow e^+e^- hadrons$
$\Sigma E/E_{beam}$	> 0.71	99%	63%
$\Sigma\|p_t\|/E_{beam}$	> 0.49	99%	73%
$\|\Sigma p_z\|/\Sigma\|p_z\|$	< 0.97	99%	95%
E_h/E_{beam}	> 0.03	99%	95%

6 Limitations

QMC has several limitations, some of which may eventually be mitigated.

Gamma angular distribution. The generated virtual photons and the outgoing e^+ and e^- should have realistic angular distributions instead of being assumed to be along the beam line. Allowing for $\theta_\gamma \neq 0$ would have an effect on the p_t and p_z distributions of the hadrons in the lab, and would permit one to simulate tagging at detectable angles. One should realize, of course, that tagged photons will be far off the mass shell and the spectrum of hadronic final states will be modified by form factor effects.

Realistic two-photon final states. QMC/TWOPHO assumes that inclusive hadronic final states in the two-photon process are like continuum e^+e^- final states, except for the kinematic effects of the energy and velocity of the $\gamma\gamma$ center-of-mass frame and the fact that the limited p_t hadronic final state that is oriented only along the beam in the two-photon case is oriented along any direction in the annihilation. One can check the QMC/ANNIH simulation against e^+e^- continuum data, but there is no reliable body of inclusive two-photon data to provide the corresponding check for the QMC/TWOPHO simulation. While you can find cuts that give you a rather pure sample for the former case, you can't for the latter. Any two-photon simulation will have to be based on plausible guesses. Even a Lund fragmentation model would be rather poorly constrained by fact.

Rare final states. In both the annihilation and two-photon cases the tails of observed inclusive distributions are populated by rare processes: energetic gluon jets, high q^2 virtual γ^*'s in the two-photon process, pointlike $\gamma^*\gamma^* \rightarrow q\overline{q}$ collisions, and such. Since QMC does not treat these processes exactly, the low-rate tails of any simulated distribution can be very wrong, even when the bulk of the distribution is essentially correct. One should not assume, as in Table 3 for example, that the program is correct when it says that a certain cut eliminates only 1% of the annihilation events.

Interaction with the CLEO detector. The QMC/DETECT subroutine does not actually track particles through the CLEO detector to simulate scattering, absorption, and the generation of secondaries. The decays, though, are already crudely accounted for, since QMC generates only the eventual final state charged pions and decay photons. One could take my lists of generated final state particles, omit the DETECT routine, instead call LUJETTER to put the particle data into the Lund format, then send the particles through the standard CLEOG detector simulation routines, produce simulated data in the CLEO detector readout format, and reconstruct with suez.

7 Acknowledgments

I am indebted to Jim Pivarski for providing plots from the standard CLEO Monte Carlo, and to Zaza Metreveli for help in adapting CLEOG to run with QMC.

References

[1] *Review of Particle Physics*, Physical Review D **66**, 010001-254 (2002)

[2] Y. Kubota et al. (CLEO), Nucl. Instr. and Methods A **320**, 66 (1992).

[3] Jim Pivarski, private communication.

[4] Brian Heltsley, *Calorimeter Systematics*, CLEO meeting, 25 Jan 03.

[5] Z. Koba, H.B. Nielsen, and P. Olesen, Nucl. Phys. B **40**, 317 (1972).

[6] G.J. Alner et al. (UA5), Physics Reports **154**, 247 (1987).

[7] T. Sjöstrand, Computer Physics Commun. **82**, 74 (1974); the long writeup version exists as hep-ph/9508391.