PHOKHARA version 5.0

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Abstract

Electron–positron annihilation into hadrons is one of the basic reactions of particle physics. The radiative return [1, 2] offers the unique possibility for a measurement of this quantity over a wide range of energies. The large luminosity of present ϕ- and B-factories easily compensates for the additional factor of α due to the emission of a hard photon. PHOKHARA is a Monte Carlo event generator which simulates this process at next-to-leading order (NLO) accuracy. Versions 1.0 and 2.0 were based on a NLO treatment of the corrections from initial-state radiation (ISR). Those are independent of the final-state channel. Version 3.0 incorporates NLO corrections to final-state radiation (FSR) for pion pair production. The version 4.0 of PHOKHARA includes nucleon pair production and NLO corrections to FSR for muon pairs. The present version (PHOKHARA version 5.0) includes $\pi^+\pi^-\pi^0$ and kaon pair (K^+K^- and $K^0\bar{K}^0$) production as new channels, and radiative ϕ decay contributions to the reaction $e^+e^- \to \pi^+\pi^-\gamma$.

1 Introduction

The first version of the Monte Carlo event generator (PHOKHARA version 1.0 [3]) incorporates ISR only at NLO [4], with $\pi^+\pi^-\gamma(\gamma)$ and $\mu^+\mu^-\gamma(\gamma)$ as final states, and was designed to simulate configurations with photons emitted at relatively large angles, $\theta^2 \gg m_e^2/s$. Its second version (PHOKHARA version 2.0 [5]) extends the validity of the program into the small angle region [6, 7], incorporates FSR at leading order (LO) for $\pi^+\pi^-$ and $\mu^+\mu^-$ final states, and includes four-pion final states (without FSR) in the formulation described in detail in [8].

The third version of the generator (PHOKHARA version 3.0 [9]), allows simultaneous emission of one photon from the initial state and one photon from the final state, requiring only one of them to be hard. This includes in particular the radiative return to $\pi^+\pi^-(\gamma)$ and thus the measurement of the (one-photon) inclusive $\pi^+\pi^-$ cross section. The influence of collinear lepton pair radiation has been investigated in [10, 11].

Recent experimental results indeed demonstrate the power of the method and indicate that a precision of one per cent or better is within reach. In view of this progress a further improvement of our theoretical understanding seems to be required. To meet that requirements PHOKHARA version 4.0 [12, 13]), introduced production of nucleon pairs (proton-antiproton and neutron-antineutron) as new channels, and FSR for muon pair production at NLO. Some improvements were also incorporated to better describe FSR at NLO for pion pair production. The effect of photon vacuum polarization was also implemented.

The recent version of PHOKHARA (version 5.0) was a continuation of that effort. New hadronic channels were introduced, mainly $\pi^+\pi^-\pi^0$ and kaon pairs (K^+K^- and $K^0\bar{K}^0$) [14], and in addition the radiative ϕ decay contributions to the reaction $e^+e^- \to \pi^+\pi^-\gamma$ was incorporated [15] to improve description of that process when running at ϕ-factory (DAPHNE) energy. The old parameterization of the pion form factor [16] was changed to one based on a dual resonance model [17]. The new form factor is supposed to describe data up to $Q^2 \sim 10$ GeV^2 (although very recent experimental results [18] seem to indicate that the rate is still underestimated for large Q^2). The vacuum polarization was taken from [19], however the contributions from narrow resonances ($\omega, \phi, J/\psi$ etc.), which should be parameterised separately, were taken out from the original code. Linear interpolation of the 'continuum' contribution is used instead in the region of narrow resonances, which were reintroduced as additional separate contributions (only ω and ϕ in the present version). Many additional aspects of the radiative return and PHOKHARA Monte Carlo event generator was discussed in [21].

2 The program

PHOKHARA is written is FORTRAN 77. Real variables and functions are defined `double precision`. Complex numbers and functions are defined `complex*16`. The present distribution consist of the following files:

- **phokhara_5.0.f** : the main program.
- **phokhara_5.0.inc** : defines some variables and `COMMON` blocks which are used by most of the subroutines in the main program.
- **input_5.0.dat** : all the constants and specific parameters needed for the generation are given through this file. The values of these input parameters can be varied by the user.
- **vac_pol_hc1.f** : vacuum polarization from Ref. [19] changed as described in the Introduction
- **common.f** : file containing `COMMON` blocks used by vac_pol_hc1.f
- **seed.dat** : contains the seed used to initialize `RANLUX`, the double precision random number generator [20]. After each generation run a new seed is stored in this file.
- **ranlxd.c** : double precision `RANLUX` code (in C)[20]
- **ranlxd.h, ranlux_fort.c** : interface FORTRAN–C for RANLUX
- **testlxf.for** : test program for RANLUX
- **seed_prod.for** : seed 'production' for running RANLUX
- **guide.ps, notes.ps** : description of RANLUX
- **README** : short description how to compile and link PHOKHARA and test RANLUX
- **Makefile** : for compiling and linking PHOKHARA

Further information and updates of the program can be find in the following web address:
`http://cern.ch/grodrigo/phokhara`

3 Input file

The interaction of the user with the program is made through the file **input_4.0.dat**. It defines some physical constants and the specific parameters needed for the generation. The values of these parameters can be changed by the user. Some new variables have been included.

`nges` – number of events which shall be generated. The number of events accepted and returned in the output file depends on the kinematical constraints, the energy of the collision and the generated final state. Typically, the acceptance rate varies between 30% and a few per cent.

`nm` – number of events used to scan the integrand and find its maximum. A preliminary scan is maid to find the maximum(s) of the integrand(s) before the true generation starts. The value of the maximum used in the generation phase is slightly greater than this approximated maximum.

`outfile` – name of the output file where the four-momenta of the particles of the accepted events are stored.

`iprint` – whether the four-momenta of the generated events is printed (`iprint=1`) or not (`iprint=0`) through subroutine `writeevent` in the output file `outfile`.

`nlo` – whether the program should provide predictions at LO (`nlo=0`) or NLO (`nlo=1`).

`w` – energy cutoff of soft photon emission, normalized to the centre-of-mass energy. The physical result is independent of its value. Recommended value $w = 10^{-4}$.

`pion` – which final state channel shall be simulated:

`pion=0` : $\mu^+\mu^-$
`pion=1` : $\pi^+\pi^-$
`pion=2` : $2\pi^0\pi^+\pi^-$
`pion=3` : $2\pi^+2\pi^-$
`pion=4` : $p\bar{p}$
`pion=5` : $n\bar{n}$
`pion=6` : K^+K^-
`pion=7` : $K^0\bar{K}^0$
`pion=8` : $\pi^+\pi^-\pi^0$

`fsr` – only ISR is simulated (`fsr=0`), FSR is included at LO without ISR–FSR interference (`fsr=1`) or with ISR–FSR interference (`fsr=2`). The ISR–FSR interference is included only when the program is running in LO mode.

`fsrnlo` – includes (`fsrnlo=1`) or not (`fsrnlo=0`) simultaneous emission of one photon from the initial state and one photon from the final state, and the corresponding virtual corrections. Only in the two-pions, two charged kaons and two-muons modes.

`ivac` – vacuum polarization on (`ivac=1`) or off (`ivac=0`).

`tagged` – at least one photon is tagged (`tagged=0`) inside the angular region defined by the angular cuts `phot1cut` and `phot2cut`. In the untagged mode (`tagged=1`), the hadrons are tagged and the angular and energy cuts are applied on the missing energy-momentum.

`FF_Pion` – choice between Breit-Wigner parameterisation of the pion form factor: Kühn-Santmaria parameterisation (`FF_Pion=0`) or Gounaris-Sakurai parameterisation (`FF_Pion=1`)

`f0_model` – three different models for radiative ϕ-decays: KK model [15] (`f0_model=0`), no structure [15] (`f0_model=1`), radiative ϕ-decays not included (`f0_model=2`), Cesare Bini (KLOE) - private communication (`f0_model=3`).

The next set of parameters defines physical constants: coupling constants, masses, and decay widths. The following values are used by default:

$1/\alpha$ = 137.03599911 – fine structure constant

m_e = 0.51099906 $\cdot 10^{-3}$ GeV – electron mass

m_p = 0.938271998 GeV – proton mass

m_n = 0.93956533 GeV – neutron mass

m_μ = 0.1056583568 GeV – muon mass

$m_{\pi^\pm}$ = 0.13957018 GeV – charged pion mass

m_{π^0} = 0.1349766 GeV – neutral pion mass

$m_{K^\pm}$ = 0.493677 GeV – charged kaon mass

m_{K^0} = 0.497672 GeV – neutral kaon mass

For the parameterization of the form factors more constants are needed and their values are explicitly given in the subroutine `input`.

The remaining set of parameters defines the specific experimental settings:

`E` – centre-of-mass energy (GeV).

`q2min` – minimal squared invariant mass of the system formed by the hadrons and the tagged photon (GeV^2).

`q2_min_c` – minimal squared invariant mass of the hadronic/muonic system (GeV^2).

`q2_max_c` – maximal squared invariant mass of the hadronic/muonic system (GeV^2).

`gmin` – minimal energy of the tagged photon (GeV).

`phot1cut` – lower cut on the azimuthal angle of the tagged photon (degrees).

`phot2cut` – upper cut on the azimuthal angle of the tagged photon (degrees).

`pi1cut` – lower cut on the azimuthal angle of the muons or hadrons (degrees).

`pi2cut` – upper cut on the azimuthal angle of the muons or hadrons (degrees).

All the kinematical cuts are given in the centre-of-mass system of the initial particles. The azimuthal angles are defined with respect to the positron momentum.

The program offers the possibility of presenting various differential distributions as histograms. If this option is used, the name of the output file where the histograms are stored and the attributes of each histogram must be given.

`title(i)` – title of histogram `i`

`xlow(i)` – lower edge in x for histogram `i`

`xup(i)` – upper edge in x for histogram `i`

`bins(i)` – number of bins for histogram `i`

where `i=1,...,20`.

4 Output

PHOKHARA presents the output information in several forms and saves it in different files.

The four-momenta of the particles of the accepted events are stored in the file given by `outfile`. The format of the output is determined by the subroutine `writeevent(pion)` and can be changed by the user. All the momenta are given in the centre-of-mass system of the colliding electron and positron.

The subroutine `inithisto` books the histograms being based on the information given by the input file. The subroutine `endhisto(fname)` fills the histograms at the end of the generation run and save the result in the output file. The histogram information is stored in the intermediate steeps of the calculation in the matrix `histo(i,j)`, where `i` identifies the histogram number and `j` the bin and the user can use its favourite histograming tool simply modifying the subroutines `inithisto` and `endhisto`, where the initialisation and filling the histograms take place.

By default only the Q^2 distribution, where Q^2 is the squared invariant mass of the hadronic (muonic) system, is calculated. The contribution from single photon events is stored in histogram `1`. The contribution from two photon events is stored in histogram `2`. The final Q^2 distribution is given by the sum of both results. Other differential distributions can be defined though the subroutine `addiere(wgt,qq,i)`, where `wgt` is the weight of the event, `qq` is the value of Q^2 and `i` is equal to 1 for single photon events and 2 for two photon events. The four-momenta of the events are given by the matrix `momenta(i,0:3)`, where `i=1,...,7`, for the positron, the electron, the two real photons (for single photon events `momenta(4,0:3)` is set to zero), the virtual photon converting into hadrons, the $\pi^+(\mu^+, \bar{p}, \bar{n}, K^+, K^0)$ and $\pi^-(\mu^-, p, n, K^-, \bar{K}^0)$ respectively. In the three pion channel `i=6,7,8` for the $\pi^+\pi^-\pi^0$ respectively. And in the four pion channels `i=6,...,9` for the $\pi^0\pi^0\pi^-\pi^+$ and $\pi^+\pi^-\pi^-\pi^+$ respectively. This matrix can be used by the user to define other differential distributions.

At the end of the run, PHOKHARA displays also the total number of accepted events, the value of the cross section, the value of the scanned maximum(s) and the biggest value of the integrand(s) found during the Monte Carlo generation. The last should be always smaller than the scanned maximum. If during the generation a value of the integrand is found to be bigger than the scanned maximum, a warning is given. Then, the number of events used for the initial scan should be increased.

5 Forthcoming features

- Full one-loop radiative corrections for muon production.
- Simulation of narrow resonances (J/ψ and $\psi(2S)$) in all generated channels
- Simulation of other exclusive hadronic channels.
- FSR for three pion production

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