CERN-TH/2002-99
TTP02-05

RADIATIVE RETURN AT NLO: THE PHOKHARA MONTE CARLO GENERATOR [a]

Germán Rodrigo [1, b], Henryk Czyż [2, c] and Johann H. Kühn [1,3, d]
[1] *Theory Division, CERN, CH-1211 Geneva 23, Switzerland.*
[2] *Institute of Physics, University of Silesia, PL-40007 Katowice, Poland.*
[3] *Institut für Theoretische Teilchenphysik, Universität Karlsruhe, D-76128 Karlsruhe, Germany.*

Electron–positron annihilation into hadrons plus an energetic photon from initial state radiation allows the hadronic cross-section to be measured over a wide range of energies at high luminosity meson factories. A Monte Carlo generator called PHOKHARA has been constructed, which simulates this process at the next-to-leading order accuracy.

The total cross section for electron–positron annihilation into hadrons is one of the fundamental observables in particle physics. Its high energy behaviour provides one of the first and still most convincing arguments for the point-like nature of quarks. Its normalization was evidence for the existence of quarks of three different colours, and the recent, precise measurements even allow for an excellent determination of the strong coupling at very high and intermediate energies through the influence of QCD corrections.

Weighted integrals over the cross section with properly chosen kernels are, furthermore, a decisive input for electroweak precision tests. This applies, for example, to the electromagnetic coupling at higher energies or to the anomalous magnetic moment of the muon. Of particular importance for these two applications is the low energy region, say from threshold up to centre-of-mass (cms) energies of approximately 3 GeV and 10 GeV, respectively. Recent measurements based on energy scans between 2 and 5 GeV have improved the accuracy in part of this range. However, similar, or even further improvements below 2 GeV would be highly welcome. The region between 1.4 GeV and 2 GeV, in particular, is poorly studied and no collider will cover

[a] Work supported in part by BMBF under grant number 05HT9VKB0 and E.U. EURODAΦNE network TMR project FMRX-CT98-0169.
[b] Supported in part by E.U. TMR grant HPMF-CT-2000-00989; e-mail: german.rodrigo@cern.ch
[c] Supported in part by EC 5-th Framework, contract HPRN-CT-2000-00149; e-mail: czyz@us.edu.pl
[d] e-mail: jk@particle.uni-karlsruhe.de

this region in the near future. Improvements or even an independent cross-check of the precise measurements of the pion form factor in the low energy region by the CMD2 and DM2 collaborations would be extremely useful, since this dominates in the analysis of the muon anomalous magnetic moment.

Experiments at present electron–positron colliders operate mostly at fixed energies, albeit with enormous luminosity, with BaBar and BELLE at 10.6 GeV and KLOE at 1.02 GeV as most prominent examples. This peculiar feature allows the use of the radiative return, i.e. the reaction

$$e^+(p_1) + e^-(p_2) \to \gamma(k) + \gamma^*(Q)(\to \text{hadrons}) \ , \tag{1}$$

to explore a wide range of Q^2 in a single experiment [1,2]. Nominally masses of the hadronic system between $2m_\pi$ and the cms energy of the experiment are accessible. In practice it is useful to consider only events with a hard photon — tagged or untagged — to clearly identify the reaction, which lowers the energy significantly.

The study of events with photons emitted under both large and small angles, and thus at a significantly enhanced rate, is particularly attractive for the $\pi^+\pi^-$ final state with its clear signature, an investigation performed at present at DAΦNE [3]. Events with a tagged photon, emitted under a large angle with respect to the beam, have a clear signature and are thus particularly suited to the analysis of hadronic final states of higher multiplicity [4].

The inclusion of radiative corrections is essential for the precise extraction of the cross section, which is necessarily based on a Monte Carlo simulation. A first program, called EVA, was constructed some time ago [1]. It simulates $\pi^+\pi^-$ events and includes initial-state radiation (ISR), final-state radiation (FSR), and their interference at the leading order (LO), and the dominant radiative corrections from additional collinear radiation through structure function techniques. Four pion production were also considered [2].

The complete NLO corrections have been implemented in a new Monte Carlo generator called PHOKHARA [5]. This includes virtual and soft photon corrections [6] to the process $e^+e^- \to \gamma + \gamma^*$ and the emission of two real hard photons: $e^+e^- \to \gamma + \gamma + \gamma^*$. The current version includes ISR only and is limited to $\pi^+\pi^-\gamma(\gamma)$ and $\mu^+\mu^-\gamma(\gamma)$ as final states. The uncertainty from unaccounted higher order ISR was estimated [5] at around 0.5%. The dominant FSR contribution can be deduced from the earlier program EVA and will be implemented in the forthcoming versions of PHOKHARA. Both programs were initially designed to simulate reactions with tagged photons, i.e. at least one photon was required to be emitted under large angles. The extension of these results to untagged photon events, i.e for photons emitted at arbitrary small angles, has been recently investigated [7,8]. Due to the modular structure of PHOKHARA additional hadronic modes can be easily implemented. The modes with three and four pions are in preparation. Further information can be obtained at `http://cern.ch/german.rodrigo/phokhara`.

References

1. S. Binner, J. H. Kühn and K. Melnikov, Phys. Lett. **B459** (1999) 279 [hep-ph/9902399].
2. H. Czyż and J. H. Kühn, Eur. Phys. J. C **18** (2001) 497 [hep-ph/0008262].
3. B. Valeriani [KLOE Collaboration], these proceedings. A. Aloisio *et al.* [KLOE Collaboration], hep-ex/0107023.
4. O. Buchmüller [BABAR collaboration], these proceedings.
5. G. Rodrigo, H. Czyż, J. H. Kühn and M. Szopa, Eur. Phys. J. C DOI 10.1007/s100520200912 [hep-ph/0112184].
6. G. Rodrigo, A. Gehrmann-De Ridder, M. Guilleaume and J. H. Kühn, Eur. Phys. J. C **22** (2001) 81 [hep-ph/0106132].
7. G. Rodrigo, Acta Phys. Polon. B **32** (2001) 3833 [hep-ph/0111151].
8. J. H. Kühn and G. Rodrigo, hep-ph/0204283