New developments in PHOKHARA Monte Carlo generator *

Henryk Czyż[a], Agnieszka Grzelińska[b] and Agnieszka Wapienik[a]

a: Institute of Physics, University of Silesia, PL-40007 Katowice, Poland
b: Institut für Theoretische Teilchenphysik, Universität Karlsruhe, D-76128 Karlsruhe, Germany

(Received December 4, 2007)

The present status of the physics program, which led to the development of the Monte Carlo event generator PHOKHARA is described. The possibility of using the radiative return method in various aspects of hadronic physics, from the measurement of the hadronic cross section, to detailed investigations of the hadronic dynamics is emphasized. New results are presented showing how to measure baryon form factors using the knowledge of their spin in baryon-antibaryon production with subsequent decay.

PACS numbers: 13.40.Ks,13.66.Bc

1. Introduction

The radiative return method proposed for the first time to serve as a tool in the hadronic cross section measurement [1] requires Monte Carlo event generator(s) as theoretical input . The method relies on the factorization properties of the differential cross section with photon(s) emitted from the initial states (ISR) and the possibility to solve problems caused by the photons emitted from the final hadrons (FSR). The first tools to meet the expectations from experimental groups were developed (EVA [2], EVA4pi [3]) using the structure functions method. That was a limitation, as not only the accuracy of the codes was not adequate to fulfill the experimental expectations, but also within that framework more theoretical work is required to deal with possible double counting of the configurations,

* Presented by H. Czyż at XXXI International Conference of Theoretical Physics Matter To The Deepest: Recent Developments In Physics of Fundamental Interactions, Ustroń , 5-11 September 2007, Poland. Work supported in part by EC 6-th Framework Program under contract MRTN-CT-2006-035482 (FLAVIAnet), TARI project RII3-CT-2004-506078 and Polish State Committee for Scientific Research (KBN) under contract 1 P03B 003 28.

where the hard photon is emitted at low angles. The adopted approach in the continuation of the research program, mainly fixed order exact calculations, resulted in the development of the state-of-the-art Monte Carlo event generator PHOKHARA[4, 5, 6, 7, 8, 9], successfully used by the experimental groups BaBar, BELLE and KLOE working at meson factories. The hadronic cross section extracted using the radiative return method from the cross section of the reaction with emitted photons gives complementary information to the scan method, traditionally used for such purposes. It is needed to calculate, via dispersion relations, the anomalous magnetic moment of the muon (for recent reviews see [10]) and the running of the electromagnetic coupling (for recent review see [11]). Profiting from the huge luminosities of the meson factories one can get valuable physical information, without building new accelerators and with accuracy competitive to traditional methods, as demonstrated [12] by the KLOE collaboration. As the method allows for the extraction of the hadronic cross section for energies from a production threshold to (almost) the nominal energy of the experiment, the B-factories have an access to data in the energy regions not covered previously by other experiments. Already now many new results exist, replacing the old measurements and/or covering new energy regions, crucial for a precise evaluation of $(g-2)_\mu$ and $\alpha_{QED}(Q^2)$. The method originally developed for the hadronic cross section measurement has, however, broader applications and can be used to study the hadron dynamics. Work started in this direction in [7], where it was shown how to extract nucleon form factors. It was continued in [8], where a method to test various models of the radiative ϕ decays was proposed. Working along this line, a newly published analysis [13] shows how to use spin information on the decaying baryons to measure phase differences of their form factors.

The Monte Carlo event generator PHOKHARA 6.0 was tested intensively at each stage of its development and the proved technical precision of the code is at the level of a small fraction (0.1-0.2) of a per mill. The precision of the theoretical formulae used in the code is currently about 0.5% as far as the ISR is concerned. That accuracy is however not good enough to fully profit from more then 2 fb^{-1} data collected by KLOE [14, 15] at DAPHNE and further work is required to meet the growing expectations.

The paper starts with a short description of the radiative return method in Section 2. The present status of the physics program for the precision hadronic physics with the PHOKHARA Monte Carlo generator is outlined in Section 3. A short summary is presented in Section 4.

2. The radiative return method in short

The radiative return method relies on factorization properties of the cross section with photon emitted from the initial electron or positron

$$d\sigma(e^+e^- \to \mathrm{hadrons} + \gamma(\mathrm{ISR})) = \\ H(Q^2, \theta_\gamma)\ d\sigma(e^+e^- \to \mathrm{hadrons}, s = Q^2)\ , \quad (1)$$

where Q^2 is the invariant mass of the hadrons. A similar factorization holds also, when more than one photon is emitted from initial states. The function $H(Q^2, \theta_\gamma)$ (or a more complicated function for multi-photon emission), at relatively low energies of meson factories, is given with high accuracy by QED only and is thus well known. From this follows that a measurement of the differential (in Q^2) cross section of the reaction $e^+e^- \to \mathrm{hadrons} +$ photons allows for a cross section $\sigma(e^+e^- \to \mathrm{hadrons})$ extraction for energies from the production threshold to almost the nominal energy of a given experiment.

The presence of the contributions from photon(s) emitted from final hadrons has to be treated as a background. It has to be studied carefully as the models of photon emission from hadrons are not well established. The region of the hadron invariant masses, which is of main interest, is below 3 GeV and thus the role of the FSR at the ϕ factory DAPHNE is far more important then at B- factories (BELLE and BaBar). The reason is purely kinematical. To obtain a low invariant mass of the hadronic system one needs a very energetic photon emission at B- factories, which is not the case for the relatively low energy of ϕ- factory. The typical kinematical configuration at a B- factory is thus an energetic photon and hadrons going in opposite directions. As the FSR contributions are enhanced only in the kinematical regions, where the hadrons and photons directions overlap, the FSR is naturally suppressed at B-factories and it is not suppressed at the ϕ- factory DAPHNE, where special care is needed to deal with it. This is shown in Fig. 1, where the relative contribution of the leading order FSR corrections is plotted for the $e^+e^- \to \pi^+\pi^-\gamma$ differential cross section. Even if the FSR contribution at DAPHNE is sizable, when no event selection is used, it is relatively easy to choose an event selection, which suppresses this unwanted background. A simple choice is also shown in Fig. 1, but more sophisticated (and efficient) solutions can be found, as it was done by the KLOE collaboration in their pion form factor measurement [12]. As the leading order contributions are suppressed at B- factories by the choice of specific kinematical configurations, it is not a surprise that the next to leading corrections, which are not suppressed by that choice, are bigger then the leading corrections. They amount up to a few percent and do depend

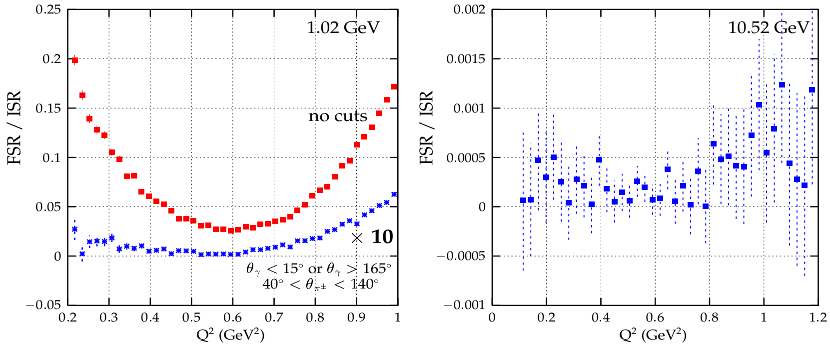

Fig. 1. The relative leading order FSR contribution to the differential, in the invariant mass of the pion pair (Q^2), cross section of the reaction $e^+e^- \to \pi^+\pi^-\gamma$ for DAPHNE and B- factories energies.

on the invariant mass of the pion pair, and therefore have to be taken into account, when aiming for a precise measurement.

For DAPHNE energies the event selection used by KLOE to suppress the FSR contributions does not allow for a measurement of the pion form factor in the threshold region. That region might be important, as the contributions from low invariant masses are enhanced by the kernel function in the dispersion relations for the muon anomalous magnetic moment. Releasing the cuts allows for measuring in the threshold region, but in the same time the model dependence of the FSR contribution becomes a serious problem [16]. Detailed studies of the FSR, also for the specific case of a ϕ-factory, where the radiative ϕ- decays play a role, were performed in many theoretical papers [6, 8, 9, 17] and that discussion will not be repeated here. One comment is, however, in order: the final solution to that problem can only come through close collaboration between theoretical and experimental groups and the analysis of both on peak and off peak data is crucial for the success of the program [16].

3. An overview of the present status of the theory research program and new challenges

The current version of the PHOKHARA 6.0 Monte Carlo event generator is a product of many years of theoretical investigations, calculations and code testing. It relies on virtual (+soft) radiative corrections to the ISR calculated in [18] and ISR hard photon corrections calculated by means of the helicity amplitudes and implemented into an efficient Monte Carlo event generator in [4, 5]. The FSR at the next to leading order was investigated, and implemented into the event generator, for muon and pion pair production in [6, 9]. In addition, very specific contributions to FSR, important at the ϕ- factory DAPHNE and coming from radiative ϕ- decays, was studied in [8]. All the implemented parts of the developed code are tested to achieve a relative technical precision of few times 10^{-4}. Independent tests were performed in [19], where the authors compared ISR contributions of muons present in PHOKHARA against the KKMC event generator [20]. An excellent agreement between non exponentiated version of the KKMC and PHOKHARA was found, while higher order corrections, not implemented yet in the PHOKHARA, give at most two per mill contributions for the invariant masses of the muons relevant for the radiative return method.

With PHOKHARA 6.0 one can now generate the following final states: $\pi^+\pi^-$, $\mu^+\mu^-$, K^+K^-, $\bar{K}^0K^0$, $\bar{p}p$, $\bar{n}n$, $\pi^+\pi^-\pi^0$, $2\pi^+2\pi^-$, $2\pi^0\pi^+\pi^-$, $\bar{\Lambda}(\to \pi^+\bar{p})\Lambda(\to \pi^-p)$, accompanied by one or two ISR photons. The FSR corrections are implemented only for $\pi^+\pi^-$, $\mu^+\mu^-$ and K^+K^-, while in the prepared new release they are implemented also for $\bar{p}p$ and $\pi^+\pi^-\pi^0$ final states. The narrow resonance (J/ψ and $\psi(2S)$) contributions to $\pi^+\pi^-$, $\mu^+\mu^-$, K^+K^-, $\bar{K}^0K^0$ will also be implemented there. The Λ pair production and decays are implemented at the leading order only [13], but as the expected number of events is modest, the accuracy of the code is sufficient for the description of this process. The spin asymmetries and spin-spin correlations of the lambdas provide information about real and imaginary parts of the lambda form factors. To measure them, one needs only the information on the angular distributions of the produced lambdas and pions coming from their decays [13]. A step towards such a measurement was done by BaBar in [21], but only a limited part of the information contained in the data was actually used.

The model describing the four pion channels was improved, based on experimental information from BaBar [22] and CMD2 [23, 24] charged mode measurements together with CLEO [25] and ALEPH [26] spectral functions. The preliminary results indicate some isospin symmetry breaking effects, if one also adds information from the preliminary BaBar measurement of the neutral mode [27].

Even if relatively few final states are implemented in the distributed version of PHOKHARA, as compared to the plethora of available final states, the implementation of the missing channels by a potential user is not difficult, at least for the ISR part, due to the modular structure of the program. This was done for example by the BELLE collaboration and used in [28].

The 0.5% accuracy of the ISR corrections in PHOKHARA will soon be the biggest contribution to the error in the pion form factor extraction by KLOE. Inclusion of the leading logarithmic corrections from the second loop to one photon emission, leading logarithmic corrections at one loop level to two photon emission and implementation of the three hard photon emission is expected to bring the accuracy to the 0.2% level and this will be the priority of the physics program of the group in the near future. It will follow the accuracy improvement [29] of the BABAYAGA code used by KLOE for the luminosity measurement.

4. Summary

The present status of the radiative return research program was outlined and plans for the near future work towards further improvements of the PHOKHARA Monte Carlo generator were sketched.

The publication is based in a big part on results obtained in collaboration with J. H. Kühn, E. Nowak-Kubat and G. Rodrigo. The authors are grateful for many useful discussions concerning experimental aspects of the radiative return method to members of the KLOE, BaBar and BELLE collaborations, mainly Cesare Bini, Achim Denig, Simon Eidelman, Wolfgang Kluge, Debora Leone, Stefan Müller, Federico Nguyen, Evgeni Solodov, Graziano Venanzoni and Ping Wang.

REFERENCES

[1] Min-Shih Chen and P. M. Zerwas, Phys. Rev. D **11** (1975) 58.

[2] S. Binner, J. H. Kühn and K. Melnikov, Phys. Lett. B **459** (1999) 279 [hep-ph/9902399].

[3] H. Czyż and J. H. Kühn, Eur. Phys. J. C **18** (2001) 497 [hep-ph/0008262].

[4] G. Rodrigo, H. Czyż, J.H. Kühn and M. Szopa, Eur. Phys. J. C **24** (2002) 71 [hep-ph/0112184].

[5] H. Czyż, A. Grzelińska, J. H. Kühn and G. Rodrigo, Eur. Phys. J. C **27** (2003) 563 [hep-ph/0212225];

[6] H. Czyż, A. Grzelińska, J. H. Kühn and G. Rodrigo, Eur. Phys. J. C **33** (2004) 333 [hep-ph/0308312].

[7] H. Czyż, J. H. Kühn, E. Nowak and G. Rodrigo, Eur. Phys. J. C **35** (2004) 527 [hep-ph/0403062].

[8] H. Czyż, A. Grzelińska and J. H. Kühn Phys. Lett. B **611** (2005) 116 [hep-ph/0412239].

[9] H. Czyż, A. Grzelińska, J. H. Kühn and G. Rodrigo, Eur. Phys. J. C **39** (2005) 411 [hep-ph/0404078].

[10] F. Jegerlehner, arXiv:hep-ph/0703125;J. Bijnens and J. Prades, Mod. Phys. Lett. A **22** (2007) 767 [arXiv:hep-ph/0702170];S. Eidelman, these proceedings.

[11] F. Jegerlehner, Nucl. Phys. Proc. Suppl. **162** (2006) 22 [arXiv:hep-ph/0608329].

[12] A. Aloisio *et al.*, [KLOE Collaboration], Phys. Lett. B **606** (2005) 12 [hep-ex/0407048].

[13] H. Czyż, A. Grzelińska and J. H. Kühn, Phys. Rev. D **75** (2007) 074026 [hep-ph/0702122].

[14] F. Ambrosino *et al.* [By KLOE Collaboration], *In the Proceedings of International Conference on Heavy Quarks and Leptons (HQL 06), Munich, Germany, 16-20 Oct 2006, pp 009* [hep-ex/0701008].

[15] D. Leone [KLOE Collaboration], Nucl. Phys. Proc. Suppl. **162** (2006) 95.

[16] A. Denig, these proceedings

[17] A. Hoefer, J. Gluza and F. Jegerlehner, Eur. Phys. J. C**24** (2002) 51, [hep-ph/0107154];G. Pancheri, O. Shekhovtsova and G. Venanzoni, Phys. Lett. B **642** (2006) 342 [hep-ph/0605244];G. Pancheri, O. Shekhovtsova and G. Venanzoni, [hep-ph/0706.3027]; K. Melnikov, F. Nguyen, B. Valeriani and G. Venanzoni, Phys. Lett. B **477** (2000) 114 [hep-ph/0001064].

[18] G. Rodrigo, A. Gehrmann-De Ridder, M. Guilleaume and J. H. Kühn, Eur. Phys. J. C **22** (2001) 81 [hep-ph/0106132]. J. H. Kühn and G. Rodrigo, Eur. Phys. J. C **25** (2002) 215 [hep-ph/0204283].

[19] S. Jadach, B. F. L. Ward and S. A. Yost, Phys. Rev. D **73** (2006) 073001 [hep-ph/0602197]; S. A. Yost, S. Jadach and B. F. L. Ward, Acta Phys. Polon. B **36** (2005) 2379 [hep-ph/0505065]; S. Jadach, Acta Phys. Polon. B **36** (2005) 2387 [hep-ph/0506180]; C. Glosser, S. Jadach, B. F. L. Ward and S. A. Yost, Phys. Lett. B **605** (2005) 123 [hep-ph/0406298].

[20] S. Jadach, B. F. L. Ward and Z. Was, Comput. Phys. Commun. **130** (2000) 260 [hep-ph/9912214].

[21] B. Aubert *et al.* [BABAR Collaboration], arXiv:0709.1988 [hep-ex].

[22] B. Aubert *et al.* [BABAR Collaboration], Phys. Rev. D **71** (2005) 052001 [hep-ex/0502025].

[23] R. R. Akhmetshin *et al.* [CMD-2 Collaboration], Phys. Lett. B **475**, 190 (2000) [arXiv:hep-ex/9912020].

[24] R. R. Akhmetshin *et al.* [CMD-2 Collaboration], Phys. Lett. B **595**, 101 (2004) [arXiv:hep-ex/0404019].

[25] K. W. Edwards *et al.* [CLEO Collaboration], Phys. Rev. D **61**, 072003 (2000) [arXiv:hep-ex/9908024].

[26] S. Schael *et al.* [ALEPH Collaboration], Phys. Rept. **421**, 191 (2005) [arXiv:hep-ex/0506072].

[27] A. Petzold, presentation at EPS Conference, Manchester 2007.

[28] X. L. Wang *et al.* [Belle Collaboration], arXiv:0707.3699 [hep-ex];C. Z. Yuan *et al.* [Belle Collaboration], arXiv:0709.2565 [hep-ex];C. Z. Yuan *et al.* [Belle Collaboration], arXiv:0707.2541 [hep-ex].

[29] G. Balossini, C. M. Carloni Calame, G. Montagna, O. Nicrosini and F. Piccinini, Nucl. Phys. B **758** (2006) 227 [hep-ph/0607181]; G. Montagna, these proceedings