Initial State Radiation: A success story

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The investigation of events with Initial State Radiation (ISR) and subsequent Radiative Return has become an impressively successful and guiding tool in low and intermediate energy hadron physics with electron-positron colliders: it allows to measure hadronic cross sections and the ratio $R$ from threshold up to the maximum energy of the colliders running at fixed energy, to clarify reaction mechanisms and reveal substructures (intermediate states and their decay mechanisms) and to search for new highly excited mesonic states with $J^{PC}=1^{--}$. While being discussed since the sixties-seventies ISR became a powerful tool for experimentalists only with the development of EVA-PHOKHARA [1], a Monte Carlo generator developed over almost 10 years, while increasing its complexity, which is user friendly, flexible and easy to implement into the software of existing detectors.

1. INITIAL STATE RADIATION:

The idea

The idea to use Initial State Radiation to measure hadronic cross sections from the threshold up to the maximum energy of colliders with fixed energies $\sqrt{s}$, to reveal reaction mechanisms and to search for new mesonic states consists in exploiting the process $e^+e^- \rightarrow \text{hadrons} + n\gamma$ to reduce the centre of mass energies of the colliding electrons and positrons and consequently the energy squared $M_{\text{hadr}}^2 = s - 2\sqrt{s}E_{\gamma}$ of the final state by emitting 1 or more photons. The method is particularly well suited for the modern meson factories like $D\Lambda\Phi$NE, PEP-II, KEKB covering the energy regions up to 1.02 GeV and up to 10.6 GeV, respectively (restricted for the latter actually up to 4...5 GeV if hard photons are detected). A big advantage of the ISR method are the low point-to-point systematic errors of the hadronic energy spectra because the luminosity, the energy of the electrons and positrons and many of the various contributions to the detection efficiencies are determined once for the whole spectrum. As a consequence the overall normalization error is the same for all energies of the hadronic system. The term Radiative return alternately used for ISR refers to the appearance of pronounced resonances (e.g. $\rho, \omega, \phi, J/\psi, Z$) with energies below the collider energy (see Fig. 1, taken from Ref. [16]). Reviews and updated results can be found in the Proceedings of the International Workshops in Pisa (2003) [2], Novosibirsk (2006) [4] and the present ones in Frascati (2008).

2. INITIAL STATE RADIATION:

The history

2.1. The pre-EVA-PHOKHARA era

Calculations of ISR date back to the sixties-seventies of the 20th century. For example photon emission for muon pair production in electron-positron collisions has been calculated in Ref.
for the 2π-final state in Ref. [5], resonances $(\rho, \omega, \phi)$ have been implemented in Ref. [7], the excitation of $\psi(3100)$ and $\psi'(3700)$ in Ref. [8], and the possibility to determine the pion form factor was discussed in Ref. [9]. The application of ISR to the new high luminosity meson factories, originally to determine the hadronic contribution to vacuum polarization, more specifically the pion form factor, has materialized in the late nineties. It has started with calculations of ISR for the colliders DAΦNE, PEP-II, KEKB [10][11][12]. See also Refs. [13][14] for calculations of radiative corrections for pion and kaon production below energies of 2 GeV. An impressive example of ISR is the Radiative Return to the region of the Z-resonance at LEP 2 with collider energies around 200 GeV [15], (see Fig. 1).

Figure 1. Initial State Radiation and the cross section $\sigma$ as function of centre of mass energy $\sqrt{s}$, courtesy PDG Ref. [10].

2.2. Eva, PHOKHARA: determination of hadronic cross sections, the muon magnetic anomaly and the running fine structure constant

ISR became a powerful tool for the analysis of experiments at low and intermediate energies only with the development of Eva-Phokhara, a Monte Carlo generator which is user friendly, flexible and easy to implement into the software of the existing detectors [12]. The generator was applied to an experiment to determine the cross section $e^+e^- \rightarrow \pi^+\pi^-\gamma$ from the reaction threshold up to the maximum energy for the first time with the detector KLOE at DAΦNE [17][18][19]. The original motivation was and is still the determination of the hadronic contribution to the vacuum polarization from hadronic cross sections.

2.2.1. The hadronic contribution to the anomalous magnetic moment of the muon $a_{\mu}^{\text{had}}$

The determination of the hadronic contribution to the vacuum polarization, which arises from the coupling of virtual photons to quark-antiquark-pairs $\gamma^* \rightarrow q\bar{q} \rightarrow \gamma^*$, is possible by measuring the cross section of electron positron annihilation into hadrons with a real photon emitted in the initial state $e^+e^- \rightarrow \gamma\gamma^* \rightarrow \text{hadrons} \gamma$. It is of great importance for the interpretation of the precision measurement of the anomalous magnetic moment of the muon $a_{\mu}$ in Brookhaven (E821) [20] and for the determination of the value of the running fine structure constant at the $Z^0$ resonance $a(m_Z^2)$, contributing to precision tests of the standard model of particle physics, see for details Jegerlehner [21], also this conference [22]. The Novosibirsk groups CMD - 2 and SND [23][24][25] pioneered the measurements of hadronic cross sections by changing the collider energy (energy scan). The ISR method represents an alternate, independent and complementary way to determine those cross sections with different systematic errors.

2.2.2. KLOE: Determination of $e^+e^- \rightarrow \pi^+\pi^-\gamma$ by emission of photons in the initial state, radiative return to the resonances $\rho$ and $\omega$

The hadronic vacuum polarization below 2.5 GeV can be determined only experimentally because calculations within perturbative QCD are unrealistic, calculations on the lattice are not yet available with necessary accuracy, and calculations in the framework of chiral perturbation theory are restricted to values close to the $2\pi$-threshold. With the maximum energy of 1.02 GeV of DAΦNE almost 70% of the hadronic correction can be determined due to the dominance of the $\rho$-resonance. This correction was previously based on the measurement of the $e^+e^- \rightarrow \pi^+\pi^-$ reaction of the Novosibirsk groups [23][24] by an energy scan.

The KLOE collaboration has carried out two
analyses: In the so called small photon angle analysis the cross section $e^+e^- \rightarrow \pi^+\pi^-\gamma$ has been measured between 0.6 and 1.0 GeV with a statistical error of less than 0.2 % and a systematical error of 1.2 %. Two pions have been detected in the drift chamber in the angular interval $50^\circ < \theta_\pi < 130^\circ$ with excellent momentum resolution, disregarding the photon. However, an additional constraint for the missing photon angle $\theta_\gamma = \theta(|p(\pi^-)+p(\pi^+)|) < 15^\circ$, $\theta_\gamma > 165^\circ$ has been required. As a consequence of this restricted phase space only the $M_{\pi\pi}$ region between 0.3 and 1.0 GeV$^2$ is populated. The advantage of the small angle analysis is negligible background from resonant (\phi- )decays ($e^+e^- \rightarrow \phi \rightarrow \pi^+\pi^-\gamma$, $e^+e^- \rightarrow \phi \rightarrow f_0\gamma \rightarrow \pi^+\pi^-\gamma$) and from final state radiation.

In the large photon angle analysis the cross section $e^+e^- \rightarrow \pi^+\pi^-\gamma$ can be measured down to the $2\pi$ threshold. In addition to the two pions also photons are detected in the angular interval $50^\circ < \theta_\gamma < 130^\circ$ with an energy of $E_\gamma > 50 MeV$. This analysis is hindered by large resonant background and final state radiation which can be overcome by reducing the energy of $DA\Phi NE$ below the $\phi$-resonance.

The results of both analyses agree very well. The hadronic correction to the vacuum polarization for $a_\mu$ obtained in the small angle analysis using the data of 2001 (140 pb$^{-1}$ in the interval $0.35 < M_{\pi\pi}^2 < 0.95$ GeV$^2$) is $a_\mu^{\pi\pi} = (388.7 \pm 0.8_{\text{stat}} \pm 4.9_{\text{syst}}) \cdot 10^{-10}$ $^{[19]}$. The total systematic error of $a_\mu^{\pi\pi}$ of 1.3% includes an experimental systematic error of 0.9% and a theoretical systematical error of 0.9 % taken in quadrature.

An update (mainly due to a revised $Bhabha$ cross section to determine the luminosity $^{[25]}$) resulted in $a_\mu^{\pi\pi} = (384.4 \pm 0.8_{\text{stat}} \pm 4.9_{\text{syst}}) \cdot 10^{-10}$. Using the data of 2002 (240 pb$^{-1}$) the small angle analysis gave $a_\mu^{\pi\pi} = (386.3 \pm 0.86_{\text{stat}} \pm 3.9_{\text{syst}}) \cdot 10^{-10}$ with a noticeably reduced statistical and systematic error. In the large angle analysis a value of $a_\mu^{\pi\pi} = (252.5 \pm 0.6_{\text{stat}} \pm 2.0_{\text{syst,f0}} \cdot 10^{-10}$ is obtained for a restricted region $0.50 < M_{\pi\pi}^2 < 0.85$ GeV$^2$ covering mainly the $\rho$-resonance to be compared with the result of the small angle analysis of the 2002 data in the same energy interval of $a_\mu^{\pi\pi} = (255.4 \pm 0.4_{\text{stat}} \pm 2.5_{\text{syst}}) \cdot 10^{-10}$ $^{[27]}$. The main problem of the large angle analysis is the large systematic (model dependent) error from the contribution of the $f_0$ from the radiative decay of the $\phi$ according to $e^+e^- \rightarrow \phi \rightarrow f_0\gamma \rightarrow \pi^+\pi^-\gamma$ at low values of $M_{\pi\pi}^2$. The KLOE ISR data and the (energy scan) results from Novosibirsk $^{[23,24,25]}$ agree within the error bars (Fig. $^{[2]}$).

![Figure 2. Comparison of data from KLOE $^{[19]}$, CMD2, SND $^{[23,24,25]}$.](image)

2.2.3. BaBar, Belle: Determination of $e^+e^- \rightarrow hadrons \gamma$ by emission of photons in the initial state, radiative return to $\rho, \omega, \phi, ..., J/\psi, ...$

Soon after the application of EVA-PHOKHARA to KLOE $^{[17]}$ the BaBar collaboration also started the investigation of hadron final states with ISR $^{[29]}$. In recent years a plethora of final states has been studied, starting with the reaction $e^+e^- \rightarrow J/\psi \gamma \rightarrow \mu^+\mu^-\gamma$ $^{[30]}$. While detecting a hard photon the upper energy for the hadron cross sections is limited to roughly 4.5 GeV. Final states with 3, 4, 5, 6 charged and neutral pions , 2 pions and 2 kaons, 4 kaons, 4 pions and 2 kaons, with a $\phi$ and a $f_0(980)$, $J/\psi$ and 2 pions or 2 kaons, pions and $\eta$, kaons and $\eta$, but also baryonic final states with protons and...
antiprotons, $Λ^0$ and $Λ^+$, $Λ^0$ and $Σ^0$, $Σ^+$ and $Σ^-$, $D$ and $D^*$-mesons, etc. have been investigated \[31,32\]. In preparation are final states with 2 pions, 2 kaons. Particularly important final states are those with 4 pions which contribute significantly to the muon anomalous magnetic moment and which were poorly known before the ISR measurements \[32\]. The BaBar results for the 4π- final states are not only consistent with previous ones but rather represent the best measurements for $E_{cm} < 0.75$ GeV, are competitive for 0.75÷1.4 GeV, are the best ones for 1.4÷2.0 GeV and the only measurement for $E_{cm} > 2.0$ GeV. Detailed analyses allow the identification of intermediate states and consequently the study of the reaction mechanisms. For instance, in the case of the final state with 2 charged and 2 neutral pions ($e^+e^- \rightarrow π^+π^-π^0π^0γ$) the intermediate states $ωπ^0$ and $a_1(1260)π$ dominate, while also $ρ^0ρ^0$ and $ρ^0f_0(980)$ have been seen. The final state with 5 pions proceeds to about 20% via $π^+π^-η$ or $ρη$ and to about 40% by $π^+π^-ω$, the rest being $ρ^0ρ^+π^-$. For more details see \[32\].

More recently also Belle joined the ISR programme with emphasis on final states containing mesons with hidden and open charm: $J/ψ$ and $ψ(2S)$, $D$ and $D^*$ \[33,34\].

### 2.4. EVA-PHOKHARA and BaBar: Baryon form factors $e^+e^- \rightarrow BBγ$

Also baryonic final states with protons and antiprotons, $Λ^0$ and $Λ^+$, $Λ^0$ and $Σ^0$, $Σ^+$ and $Σ^-$ have been investigated in agreement with previous measurements, but with significantly improved statistics. The effective proton form factor shows some nontrivial structures at invariant $pp$ masses of 2.25 and 3.0 GeV, so far unexplained \[43,44\].

### 3. Summary

Being discussed since the sixties/seventies ISR became a powerful tool for experimentalists only with the development of EVA-PHOKHARA by J. H. Kühn, H. Czyż, G. Rodrigo and collaborators \[12\], a Monte Carlo generator developed over almost 10 years, while increasing its complexity, which is user friendly, flexible and easy to implement into the software of the existing detectors. The ISR method was originally thought to be an alternative to energy scans to determine hadronic cross sections from the reaction threshold to the maximum centre of mass energy of fixed energy meson $(φ, τ/charm, B)$- factories in order to determine the hadronic contribution to the muon magnetic anomaly $a_μ^{had}$ and to the running fine structure constant $α(m_Z^2)$, and it was very successful in that respect. But being more than a poor man’s alternative to scan energies it turned out to be an extremely useful tool to clarify reaction mechanisms and to reveal substruc-
tures (intermediate states and their decay mechanisms) leading to more and more hadronic final states, a plethora at \( B \)-factories. Statistical errors have been dramatically reduced. Systematic errors are under better and better control. Finally it has opened a totally new and unexpected access to highly excited states (with \( J^{PC} = 1^{--} \)) the structure of which is not yet known.

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