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Booklet of Contributions

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Content

Simulations with MC generators for $e^+e^-(X)$ processes

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The Monte Carlo generator EKHARA [1] was published recently and the source code is available online at the web-site reported in [2]. It is suitable for running simulations of processes like $e^+e^- \to e^+e^-X$ via $\gamma\gamma$ interactions, where $X = \pi^0, \eta, \eta', \pi^+\pi^-$. Several amplitude models are available for this study; among these, the one of interest has been the double-octet model, which makes better predictions compared to single-octet model or Vector Meson Dominance model in the evaluation of the rates of these processes. The explicit calculations are performed and well explained in [2]. The performances of EKHARA in running simulations of $e^+e^- \to e^+e^-\pi^0$ and $e^+e^- \to e^+e^-\eta$ have been checked in the experiment BES-III (e^+e^- collider at Beijing, China) [3], and have being compared with data: the analyses are currently going ahead.

The implementation of EKHARA in the official BES-III code was not easy, due to the fact that it makes use of quadrupole precision variables; in order to run such a code, which is written in fortran, one needs to upload on his machine a particular version of fortran, Intel-fortran [4], and follow the policy for usage and academic purposes.

Simulations have been shown with the EKHARA fortran code, on the channels $e^+e^- \to e^+e^-X$ via $\gamma\gamma$ interactions, where $X = \pi^0, \eta, \eta'$, setting the energy in the center of mass at 3.77 GeV, in the hypothesis that (A) one outcoming lepton is tagged, (B) both outcoming leptons are tagged, or (C) none of them. To tag a lepton in an angular range means to define an angular range where it is supposed to be detected. In the simulation here performed, the angular range under study has been $[21.6;158.4]^0$. The result is that we expect a cross section hundred times higher in the case we do not tag any lepton; however in the experiments BaBar [5] and Belle [6], which published results of these analyses, the good reconstruction of the final state was possible by tagging one of the 2 outcoming leptons; we can tag even both, but in this case we definitively need high statistics, otherwise the analysis is not feasible. The simulations performed for these analyses show that in BES-III it is possible to cover the range of low momentum transfer Q^2, which was not possible to analyze in the past experiments due to the limitations of the trigger conditions. The range of $Q^2 \in$ [0;2] GeV^2 is the most important to analyze, from theoretical point of view, to give contribution to the precise determination of the light-by-light hadronic contribution to the measurement of (g-2)$_\mu$. We know that the muon anomaly, from theoretical point of view, can be written as sum of three main contributions. One of these, the hadronic contribution, soffers for lack of precision. The Feynman diagram of the decay $e^+e^- \to e^+e^-X$ via $\gamma\gamma$ interactions, where $X = \pi^0, \eta, \eta'$, is suitable for this kind of search. The goal of these analyses in BES-III will be the measurement of the form factor $F(Q^2) * Q^2$ vs Q^2, which will give important input to the theory in the range of Q$^2 \in$ [0;2] GeV^2 to better understanding the muon anomaly.

EKHARA does not include radiative corrections, yet. Radiative corrections represent an important feature as they can have a significant impact in the precision of the measurement that one wishes to perform. In the particular analyses under exam, the solution adopted is to define a variable as below:

$$r_\gamma = \frac{\sqrt{s}-E^*_{eP}-p^*_{eP}}{\sqrt{s}}$$

where:

$\sqrt{s}$ is the energy in the center of mass;
E^*_{eP}. Let's assume to tag the outcoming electron in the decay $e^+e^- \rightarrow e^+e^-\pi^0$. The tagged eletron and the pseudoscalar meson (P), e.g. π^0, are fully reconstructed. The tagged electron is scattered at large angle. We can easy identify the non tagged (and non reconstructed) positron in this decay assuming that it will be scattered at very small angle. So, if we select properly a very small angular range where the positron will be scattered, we are pretty sure to identify it in a unique way. The system of the tagged electron + the reconstructed pseudoscalar meson is labeled here as eP system. In this respect, E^*_{eP} represents the energy in the center of mass of this system.
$p^*_{e\pi}$ is the momentum in the center of mass of the system eP.

The characteristic of the variable r_γ is its symmetic gaussian distribution, in the hypothesis that no radiative corrections occur. In fact, the measured value and the true value of the transfer momentum Q^2 are not the same quantitiy, but:

$$Q^2_{meas} = Q^2_{true}(1 + r_\gamma)$$

Ideally r_γ is suppsed to be 0; but in the real world, it is distributed around 0, and it is skewed to the right depending on how strong the radiative corrections affect the final result. By applying the proper selection cuts to this variable, we can reject mainly the combinatorial background which affects this analysis, and also the ISR background which is not part of our signal distribution. We also cut on the cosin of the small scattering angle θ_{eP} of the non tagged positron, indeed, in order to identify the non reconstructed particle of this event and reject mainly all combinatorial background. The main background here is the Virtual Compton Scattering (VCS), and the selection on θ_{eP} and r_γ are mandatory requests to reject this kind of background: the VCS cross section (e.g. process $e^+e^- \rightarrow e^+e^-\gamma$) is thousand times higher than the cross section of the process under study. We learn this lesson from the BaBar analysis on the same decay channel [7], while the experiment Belle adopted another solution to take in proper consideration the radiative corrections [8]: they used the Monte Carlo generator Rabhat [9], which includes radiative corrections at NLO and solves the problem of the divergences by using the numerical integrator BASE/SPRING [10]. The new version of BASE/SPRING divides the space in ipercubes, and it is able to isolate the singularity which can occur in the calculation. It can do integrations up to 50 variables. The combination of BASE/SPRING to Rabhat reproduces the data distributions very well.

A good Monte Carlo generator, which includes radiative corrections at NLO and it is suitable for the analysis of e^+e^- to $e^+e^-, \mu^+\mu^-, \gamma\gamma, \pi^+\pi^-$, is Babayaga at NLO [11], availabe and documented online [12]. However, all simulations here shown are in e^+e^- colliders. The question can be if all these Monte Carlo generators are suitable for studying processes like $p\bar{p} \to e^+e^-$, as for the future experiment $\bar{P}ANDA$ [13], and how important are the radiative corrections in this case. A preliminary work on the rare decay $p\bar{p} \to Y \to e^+e^-$ with the PandaRoot framework was shown. The physics case under study in this particular contest has been the interference between Y(4260) and Y(4160), and how important are radiative effects at NLO and NNLO in this case. The Monte Carlo simulations have been performed by using the Mone Carlo generator EvtGen, and PHOTOS [14]. Reconstruction efficiency is found high in $p\bar{p} \to Y(4160) \to e^+e^-$ and $p\bar{p} \to Y(4260) \to e^+e^-$. An angular distribution analysis is needed to study the interference effect. This work in $\bar{P}ANDA$ is at the beginning.

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Overview of the Radiative Corrections Plan for OLYMPUS

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The OLYMPUS experiment aims to measure a quantity that is itself a radiative correction: the hard two-photon exchange (TPE) contribution to the elastic ep scattering cross section. As this measurement should be at the 1% level, other radiative corrections need to be carefully taken into account. By measuring the e^+p to e^-p cross section ratio, the contribution from unwanted elastic corrections is reduced since, at the order α^3, only the TPE interference terms have an odd lepton charge dependence. However, inelastic (bremsstrahlung) corrections must also be accounted for, and the interference terms between radiation off of the lepton and radiation off of the proton also have an odd lepton charge dependence and are thus very important.

The standard radiative corrections are typically given by the formulas of Mo and Tsai [1] or Maximon and Tjon [2]. Both have relatively simple analytic forms but rely on the validity of the soft photon approximation. These papers quantify the amount of cancellation between elastic and inelastic terms with a single experimental parameter, ΔE, which is the maximum amount of energy a scattered lepton can lose and still be detected as elastic. However, since OLYMPUS reconstructs both the outgoing lepton and proton, and requires great precision, this single parameter ΔE is too crude of a quantization of our separation of elastic and inelastic events. We would like to take into account our full experimental acceptance, all detector efficiencies, and even the analysis cuts we make. Thus, a radiative Monte Carlo is necessary. No longer limited by the need for analytic equations, we can then use a full calculation of the first order bremsstrahlung without approximation.

A key component of our radiative corrections plan is the use of run information in our generator. Run information includes things like beam energy, beam position, beam slope, and which parts of the drift chambers were powered down at any given time – all of which affect our acceptance. Our radiative generator uses this information to produce events that mirror what was happening in the actual data. Then, we use a Geant4 Monte Carlo and digitization (adding in detector effects) to produce simulated raw data in the same format as our real data. Then, the exact same software that is used for our event reconstruction and analysis can be used as part of our simulation. We produce two sets of results: one with our real data, and one with simulation that includes everything but hard TPE. By combining the, we can extract just the hard TPE part.

The OLYMPUS generator plugin is designed to make it easy to swap different physics codes in and out. The static "outer" part of the generator handles the interfacing with the raw data files to get the run info and the production of the appropriate vertex distribution. The "inner" part does the initial event generation and cross section calculation. This design makes it easy for us to use and compare different radiative generators. For example, the radiative generator ESEPP [3], which was written for the Novosibirsk VEPP-3 TPE experiment, has already been fully implemented in our framework.

We are also developing our own radiative generator code. This differs from ESEPP in that it produces weighted events. Because of this, we have freedom in which kinematic distribution we sample from. We can use importance sampling: approximating the shape of the cross section carefully in regions that are likely to pass our elastic cuts (yielding almost constant event weights), and reducing the sampling in regions that are likely to be rejected. This is important because the Geant4 propagation of our generated events is by far the slowest part, computationally, of our entire analysis chain and the bremsstrahlung cross section is very large for events with high external photon energy.

Another benefit of using a weighted generator that we plan to take full advantage of is that it allows us to use multiple weights. Since Geant4 propagation is slow, it is undesirable to generate more events than absolutely needed. Thus, to test how different choices at the generator level affect our final radiative correction, we can simply produce multiple cross section calculations for each event and carry them along in parallel. We can use this, for example, to study if our choice of proton form factors (which affect the bremsstrahlung correction) has a significant impact on our final result. We can also use this technique to produce two results: one with the Mo and Tsai definition of "hard TPE" and one with the Maximon and Tjon definition, while barely increasing the amount of computational effort required.

In general, the OLYMPUS collaboration is taking a cautious approach to radiative corrections, as they are particularly important for our measurement. We are making sure we understand and can justify all of the physics that goes into our generator. Additionally, our simulation framework allows us to take into account acceptance and efficiency effects as comprehensively as possible. Finally, we are doing careful comparisons with the generators used by other TPE experiments to ensure that all experiments produce results with consistent radiative corrections.

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Simulating Internal Bremsstrahlung in the OLYMPUS Radiative Generator

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The OLYMPUS Experiment aims to measure the ratio of positron-proton to electron proton elastic scattering cross sections, in order to determine the contribution from hard two-photon exchange. This technique is sensitive to radiative effects that are odd in the sign of the lepton charge, so the interference of electron bremsstrahlung and proton bremsstrahlung must be taken into account accurately. OLYMPUS will implement radiative corrections using a Monte Carlo simulation, and a generator is being developed. In this talk, I presented the requirements for a suitable generator, the method for calculating bremsstrahlung cross sections, and how these calculations are implemented.

The OLYMPUS Experiment, which ran at the DORIS storage ring at DESY, concluded its data taking runs in 2012. The experiment was performed by colliding a 2.01 GeV lepton beam against a fixed, unpolarized, hydrogen target. The beam species was changed once per day between electrons and positrons. The scattered lepton and the recoiling proton from an elastic collision were detected in coincidence with a toroidal magnetic spectrometer. The luminosity was monitored with a redundant system of Møller/Bhabha calorimeters and forward elastic scattering telescopes. Over 4 fb^{-1} of integrated luminosity was collected, which exceeded the design goal of 3.7 fb^{-1}.

Isolating hard two-photon exchange amounts to isolating one radiative correction from a host of others. The technique of alternating between electron and positron beams is sensitive to any effects that are odd in the lepton charge sign. There are three classes of such effects. The first is the one of interest, hard two-photon exchange. The second is soft two-photon exchange, which is accounted for in standard radiative corrections, albeit with slightly different approximations from correction to correction. The third is the interference between bremsstrahlung from the lepton and bremsstrahlung from the proton. Bremsstrahlung is more difficult to take into account because the added photon(s) change the kinematics of the outgoing particles. The simple approach of integrating over lepton energy loss (or alternatively in missing mass) within an acceptance window is not sufficient for OLYMPUS, which has no such well-defined acceptance. The OLYMPUS analysis will rely on cuts in many different variables. For that reason, it makes sense for OLYMPUS to use the Monte Carlo method to simulate radiative effects, and to study how they propagate through the analysis.

The OLYMPUS group at MIT is developing a radiative generator. The design follows the approach used in the recent Mainz precision form factor measurements, but with a revised treatment of bremsstrahlung, since the bremsstrahlung interference is crucial for OLYMPUS. The Mainz generator has not been fully described in a publication yet. However, an outline of the algorithm can be found in references [1, 2]. The MIT generator is currently not release-ready, and components are still being tested. The goal is to eventually release the code to the community.

The MIT generator includes a calculation of the bremsstrahlung cross section. The first step is to perform a tree-level single-photon, calculation numerically, including the diagrams where a photon is emitted from a lepton leg, and those where a photon is emitted from a proton leg. The amplitudes are added coherently to produce interference. No soft-photon approximation is made. The evolution of the proton form factors are taken into account at every proton vertex. The photon can be emitted in all directions, i.e. no peaking approximation is made. The off-shell proton current is approximated by the on-shell current. We modify the single-photon cross section with an exponentiated correction factor, taken from one of the standard radiative corrections [3, 4, 5] to approximate the effect of bremsstrahlung at higher orders.

To generate an event, the generator needs to produce values for θ_l, ϕ_l, θ_γ, ϕ_γ, and ΔE_l from suitable probability distributions, and then to weight the event by the corrected cross section, divided by the probability density for the values for the kinematic variables. The convergence of the simulation depends on having weights that are close to uniform. For that reason, the photon direction is sampled from a distribution that approximates the peaks around the incoming and outgoing lepton. The energy loss of the electron, ΔE_l, is sampled from a power law distribution, chosen from a standard correction (taken from [3, 4, 5]). This approach has an added benefit of producing a weight that hides the IR-divergence of the bremsstrahlung cross section. No separation between an "elastic region" and an "inelastic region" is needed. See references [1, 2] for more details on the procedure.

In summary, radiative corrections must be carefully taken into account in the OLYMPUS analysis, and bremsstrahlung is especially important. The MIT group is developing a radiative generator that calculates the bremsstrahlung cross section without using common approximations like the soft-photon approximation or the peaking approximation. When the generator is ready, the goal is to distribute the code publicly.

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Status of the Novosibirsk TPE experiment

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Unaccounted two-photon exchange (TPE) effects are considered to be the most likely cause of the discrepancy between the Rosenbluth and polarization transfer methods of measuring the proton electromagnetic form factors. The TPE effects can be studied experimentally by measuring the ratio $R = \sigma(e^+p)/\sigma(e^-p)$ of the positron-proton to electron-proton elastic scattering cross sections. Such measurements were recently carried out by our group at the VEPP–3 storage ring (Novosibirsk, Russia) and, independently, by two other collaborations — OLYMPUS (Hamburg, Germany) and CLAS (Newport News, VA, USA). Here we report on the status of the Novosibirsk TPE experiment (see [1, 2] for details).

The measurement was performed at two different beam energies: 1.6 GeV (Run I) and 1.0 GeV (Run II). A hydrogen internal gas target with a thickness of about 10^{15} at./cm^2 was used. Electron and positron beams were alternated regularly in order to suppress the effects of any slow drift in time of the target thickness and detection efficiency. The scattered electron/positron and the recoil proton were registered in coincidence by a wide-aperture non-magnetic detector. The lepton scattering angles were $15°-25°$ and $55°-75°$ in the first run and $65°-105°$ in the second run. Thus, the experiment covered the range of the four-momentum transfer squared up to $Q^2 \approx 1.5$ GeV^2 and the values of the virtual-photon polarization parameter ε down to 0.2.

Preliminary results (as of October 2013) of the Novosibirsk TPE experiment are shown in Fig. 1 in comparison with previously available data and some theoretical/phenomenological predictions [3–8]. For our data points (the red circles), the error bars correspond to the statistical errors, while the hashed areas show the kinematic ranges and estimated systematic uncertainties of the measurement. The standard lowest-order QED radiative corrections are taken into account using a `Geant4` simulation and the `ESEPP` event generator [9]. It should be noted that some minor experimental corrections have not been applied yet. The final results of the experiment are expected in 2014.

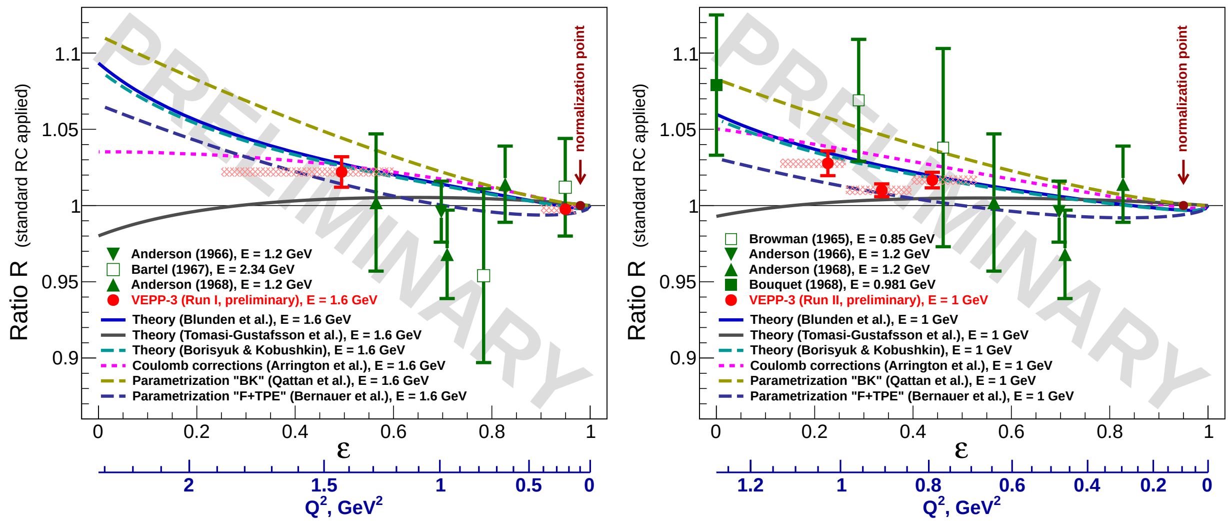

Figure 1: Preliminary results of the first (left side) and second (right side) runs.

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ESEPP: an event generator for elastic scattering of electrons and positrons on protons

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ESEPP (which is an acronym for Elastic Scattering of Electrons and Positrons on Protons) is a new multipurpose event generator, developed for Monte Carlo simulation of unpolarized elastic scattering of charged leptons (e^-, e^+, μ^-, and μ^+) on protons. It takes into account the lowest-order QED radiative corrections to the Rosenbluth cross section including the first-order bremsstrahlung process beyond the soft-photon and ultrarelativistic approximations. The source code of ESEPP is freely available under the GNU GPL license and can be found at the web page [1]. The event generator may be useful for several ongoing and planned experiments, such as the two-photon exchange experiments (VEPP–3, OLYMPUS, and CLAS) and the new measurements of the proton charge radius (PRad and MUSE).

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Radiative Corrections : selected comments

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1. The lowest order radiative corrections to the Born amplitude for $e+p->e+p$ elastic scattering, excluding the two photon exchange amplitude and ignoring the real photon emission by the proton, vanish in an incluseve experimental set-up. It means that only the electron and proton in the final states are seen and full integration on (possible) real photon is performed.

   This can be demonstrated (and the proof is rigorous in QED [2]) considering the analytical properties of the forward elastic scattering amplitude, which is related to the cross section through optical theorem. Sum rules can be derived for hadrons [3]. The relevant sum rules include such a characteristics of proton as its electric radii, anomalous magnetic moment and the photoproduction cross sections on proton. Sum rules are fulfilled with rather good accuracy.

   Usually radiative corrections are decomposed in soft (real and virtual) and hard photon emission, which can be calculated separately, analytically and numerically. One has to introduce two auxiliary parameters λ a fictitious photon mass, which is necessary to regularise infrared singularity and ΔE, set by the experiment as the energy boundary for the definition of 'soft' and 'hard' photon. This statement is based on the Bloch-Nordsieck theorem [1]: the probability that only a finite number of photons escapes the detection is zero. The observed cross section is very close to the cross section where all radiative corrections are ignored: "*the total probability of a given change in the motion of the electron is unaffected by the interaction with radiation, and the mean number of emitted quanta is infinite in such a way that the mean radiated energy is equal to the energy radiated classically in the corresponding trajectory*". The factorisation of the soft photon term is justified by the different energy scale of the soft and hard photon emission.

2. RC at all order of perturbation theory, in the leading logarithm approximation (LLA) can be calculate in the frame of the lepton structure function method [4] and have been applied to elastic *ep* scattering in Ref. [5]. Non leading terms, suppressed by (α/π) including two photon exchange or interference between initial and final states, may by computed as a 'K-factor'.

3. RC depend strongly on the experimental set-up, in particular the ΔE cut for soft photon emission. However, in a set up where the electron is detected in a calorimeter, it is impossible to disentangle the emission of soft and hard collinear photons *i.e.*,

emitted along the scattered electron. The structure function method takes this into account as the integrated emission factor becomes unity. Note that measuring the recoil protons, one has no restriction on electron emission.

4. Charge asymmetry in $e^{\pm}p$ elastic scattering, $A \sim 4\alpha \ln(E\theta/\Delta E)$ arises from the contribution of intermediate proton state due to the interference of Born and the imaginary part of box amplitude. The contribution of π and N intermediate state (Δ, $N*$ resonances) have opposite signs and one order smaller magnitude.

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General considerations - useful references

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The problem of the calculation of radiative corrections is a longstanding question in hadron physics [1].

Taking into account photon emission at first order (α^3), among the possible diagrams, one has to take into account the interference between one and two photon exchange (box) diagram. Recently the importance of this mechanism has been object of experimental and theoretical efforts. It was observed already in the 70's [2] that the simple rule of α-counting for the estimation of the relative role of two-photon contribution to the amplitude of elastic eh-scattering (h is a hadron), may not hold at large momentum transfer. The argument for the possible increase of the relative role of two-photon exchange at large momentum transfer follows from the fact that this momentum has to be equally shared between the two photons, which results in a non negligeable two-photon amplitude. This effect could then manifest at relatively small momentum transfer - of the order of 1 GeV^2 - especially in the region of diffractive minima and would be even larger for ed-elastic scattering and for heavier nuclei (like ^3He or ^4He), due to the steeper decreasing of the deuteron form factors.

Model independent considerations on two photon exchange in ep elastic scattering can be found in Refs. [3], and for the crossed processes $\bar{p}+p\to e^++e^-$ and $e^++e^-\to\bar{p}+p$ in Refs. [5] and [4] respectively.

In experiment as DVCS and ep elastic scattering a precise calculation of 'standard' QED radiative corrections appears essential before extracting any information on the proton structure [6, 7].

The emission from the proton is usually neglected, however its interference with the electron emission may have serious consequences on aspects as angular asymmetries and nonlinearities in the relevant distributions. It has been shown that in ep elastic scattering, such asymmetries are of the same order and usually larger than odd effects induced by possible two photon exchange [8].

Concerning form factors (FFs) extraction, attention was driven to final state radiation (FSR) in $e^++e^-\to\bar{p}+p(\gamma)$ in Ref. [9]. In the reaction $\bar{p}+p\to e^++e^-$, an analysis with the PHOTOS package [10], as implemented in PANDARoot (the software of the PANDA experiment at FAIR [11] both for simulation and analysis) was performed and compared to the existing calculations [12, 13]. PHOTOS allows to apply the correction to simulated events from final state radiation (FSR), in leading log approximation (LLA). It appears that simulations agree with the calculations, concerning even terms. On the other hand PHOTOS does not contain the interference between initial and final state emissions, which is the main source of angular asymmetry. [8]. The feature that RC depend on the electron angle in Lab system [14] is well reproduced by PHOTOS.

Present experiments for extraction the nucleon structure, are mostly multi-particle detection and coincidence experiments, with large coverage detectors, both in angle and in momentum acceptance. This fact, together with the achievable precision, makes the calculation of radiative corrections (RC) critical for extracting experimental results in ep elastic scattering as well as $\bar{p}+p \leftrightarrow e^+e^-$. A (precise) calculation of RC should be complemented by a Monte Carlo application, embedded in the analysis programs. This arises numerical and formal problems of divergences and instabilities which should be solved jointly by experts, experimentalists and theoreticians.

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