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Test und Einbau des Bhabha Ereignisgenerators Babayaga@NLO in die Software-Umgebung des *BaBar* Experimentes

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Diplomarbeit

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ZUSAMMENFASSUNG

Das *BaBar* Experiment befindet sich am Stanford Linear Accelerator Center, SLAC, in Stanford, USA. Am derzeit längsten Linearbeschleuniger der Welt werden Elektronen auf 9 GeV und Positronen auf 3.1 GeV beschleunigt und in zwei übereinanderliegenden Speicherringen, der PEP-II B-Fabrik, eingespeist. Die resultierende Schwerpunktsenergie von 10.58 GeV ermöglicht die Erzeugung der $\Upsilon(4S)$ Resonanz, die anschließend fast ausschließlich in zwei B-Mesonen zerfällt. Außerdem werden Quark-Antiquark-Paare wie $c\overline{c}$, $s\overline{s}$, $d\overline{d}$, $u\overline{u}$ erzeugt sowie Leptonenpaare e^+e^-, $\mu^+\mu^-$ oder $\tau^+\tau^-$.

Das wesentliche Ziel von *BaBar* ist die Untersuchung der CP-Asymmetrie im Zerfall neutraler B-Mesonen. Weitere Aufgaben bestehen in der Messung der CKM-Matrixelemente, Analysen seltener B-Zerfälle sowie Studien von Mesonen mit c- und b- Quarkinhalt.

Mit der Analysemethode des 'Radiative Return' kann auch bei PEP-II der hadronische Wirkungsquerschnitt über einen weiten Energiebereich < 5 GeV gemessen werden. Ein von den einfallenden Leptonen ausgesandtes Photon bewirkt eine Absenkung der effektiven Schwerpunktsenergie des Leptonenpaares. Für diese und weitere Untersuchungen, wie z.B. den τ-Analysen, ist es notwendig, die Luminosität des PEP-II Speicherringes genau zu kennen.

Die Luminosität wird unter Verwendung folgender Referenzreaktionen gemessen, wobei der *BaBar* Detektor selbst zur Messung herangezogen wird, da an modernen Teilchenfabriken kein dedizierter Luminositäts-Counter bei kleinen Polarwinkeln technisch realisierbar ist:

$$e^+e^- \rightarrow e^+e^-(\gamma)$$

$$e^+e^- \rightarrow \mu^+\mu^-(\gamma)$$

$$e^+e^- \rightarrow \gamma\gamma$$

Die $\gamma\gamma$-Reaktion wird dabei nur verwendet, um zeitabhängige Veränderungen der Luminosität bzw. zeitabhängige Effekte wie Detektoralterung aufzudecken. Derzeit ist diese Luminositätsmessung durch die Kenntnis des theoretischen Wirkungsquerschnittes von Bhabha-Reaktionen limitiert.

In der aktuellen Luminositätsmessung wird der Bhabha Ereignisgenerator *BHWIDE* verwendet. Dieser berechnet absolute Wirkungsquerschnitte in dem für Luminositätsmessungen typischen Phasenraumvolumen bei Polarwinkeln zwischen 40° und 140° mit einer theoretischen Präzision von 0.5%. Der erste Teil dieser Diplomarbeit besteht aus einem Vergleich dieses Generators mit dem neu entwickelten Ereignisgenerator *Babayaga@NLO*, der dazu in der Lage ist, Wirkungsquerschnitte auf 0.1% genau zu berechnen. Beide Ereignisgeneratoren beinhalten alle 'Next to Leading Order (NLO)'- Korrekturen. Die unterschiedlichen Präzisionen von *BHWIDE* und *Babayaga@NLO* kommen durch eine jeweils andere Herangehensweise in der Auswahl der Korrekturen höherer Ordnung zustande. Um die Wichtigkeit der Vollständigkeit dieser $\mathcal{O}(\alpha)$-Korrekturen in Störungstheorie zu verdeutlichen, wurde ebenfalls die Vorgängerversion *Babayaga.3.5*, die nicht alle NLO-Korrekturen beinhaltet, in die Vergleichsstudie mitaufgenommen.

Der Beitrag der Vakuum Polarisation zum absoluten Wirkungsquerschnitt lässt sich nicht berechnen da sich QCD Korrekturen bei kleinen Energien nicht in Störungsrechnung bestimmen lassen. Die Werte hierfür wurden empirisch bestimmt und in die Ereignisgeneratoren implementiert. Deshalb wurde die Vergleichsstudie zwischen *BHWIDE* und *Babayaga@NLO* sowohl mit wie auch ohne Vakuum Polarisationskorrekturen durchgeführt. Es hat sich jedoch im Verlauf der Studie herausgestellt, dass die Effekte der unterschiedlichen Vakuum Polarisation auf die differentiellen Wirkungsquerschnitte keinen nennenswerten Einfluss haben.

Bei der Untersuchung der differentiellen Wirkungsquerschnitte ist folgender Trend festzustellen: Im typischen Phasenraumvolumen der Luminositätsbestimmung bei *BABAR* unterscheiden sich die Verteilungen von *BHWIDE* und *Babayaga@NLO* nur minimal. Es sind Unterschiede von maximal bis zu $(0.2 \pm 0.1)\%$ feststellbar. Diese Unterschiede kompensieren sich zum Teil im absoluten Wirkungsquerschnitt. Trotzdem war es sinnvoll, den neuen hochpräzisen Ereignisgenerator *Babayaga@NLO* in die *BABAR* Software Umgebung einzubauen, um die maximale theoretische Präzision der Wirkungsquerschnittsbestimmung sicherzustellen.

Der *Babayaga@NLO* FORTRAN Code wurde im Rahmen dieser Diplomarbeit in die *BABAR* C^{++} Software Umgebung eingebaut. Bei der Implementierung galt die grundlegende Philosophie, so wenig vom ursprünglichen

Programm wie möglich zu verändern.

Der Zufallszahlengenerator kann per Option bei Aufruf von *Babayaga@NLO* ausgewählt werden. Der im ursprünglichen Programm verwendete Zufallszahlengenerator RANLUX wurde ebenfalls in die *BABAR* Umgebung eingebaut. Diese Einbindung war sehr hilfreich um zu überprüfen, ob der Einbau der *Babayaga@NLO* Software korrekt war. Es musste in den Zwischenschritten verifiziert werden, dass die erzeugten Ereignisse immer noch den Ereignissen der ursprünglichen Version entsprechen, wenn man diese mit dem gleichen SEED und identischen Randbedingungen erzeugt. Dies wurde ebenfalls für die finale Version verifiziert.

Um die Produktionsgeschwindigkeit von *Babayaga@NLO* zu erhöhen wurde der Ereignisgenerator durch den sogenannten 'default' Modus erweitert. Verwendet man die 'default'-Optionen für das Phasenraumvolumen der kinematischen Variablen der ausgehenden Leptonen, kann durch bereits abgespeicherte Parameter ein großer Teil der Initialisierungsroutine übersprungen werden. Werden nicht-'default'-Werte gewählt, müssen diese Parameter zunächst in der Initialisierungsroutine berechnet werden und *Babayaga@NLO* produziert die Ereignisse wieder mit der ursprünglichen Geschwindigkeit.

Der *Babayaga@NLO* Ereignisgenerator ist nun komplett in die *BABAR* Software-Umgebung eingebunden. Dies ermöglicht u.a. eine Verbesserung der Luminositätsbestimmung bei *BABAR* mit weitreichenden Konsequenzen für viele Physik-Analysen, insbesondere im Bereich der 'Radiative Return'-Analysen und für τ-Analysen.

Es wird bald eine neue Version von *Babayaga@NLO* verfügbar sein, die zusätzlich den $\mu^+\mu^-$- und $\gamma\gamma$-Kanal beinhaltet. Durch eine Verbesserung der theoretischen Präzision des $\mu^+\mu^-$-Kanals kann man den Gesamtfehler für die Präzision der Luminositätsbestimmung in diesem Kanal auf die gleiche Grössenordnung wie den e^+e^--Kanal drücken. Dies würde die Genauigkeit der Luminositätsmessung noch weiter verbessern. Deshalb ist es empfehlenswert, diesen neuen Ereignisgenerator ebenfalls in die *BABAR* Software Umgebung einzubauen, sobald er zur Verfügung steht.

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Test and implementation of the Bhabha event generator Babayaga@NLO into the *BaBar* software environment

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Diploma Thesis

at the Faculty for Physics
of the University of Karlsruhe (TH)

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SUMMARY

The BABAR experiment is located at the Stanford Linear Accelerator Center, SLAC, USA. The longest linear accelerator in the world injects electrons of 9 GeV and positrons of 3.1 GeV in the PEP-II collider. The resulting center of mass (CM) energy of 10.58 GeV has been chosen in order to create the $\Upsilon(4S)$ resonance, which almost exclusively decays into a B-meson pair. In addition quark-antiquark pairs like $c\overline{c}$, $s\overline{s}$, $d\overline{d}$, $u\overline{u}$ are produced as well as the lepton pairs e^+e^-, $\mu^+\mu^-$ or $\tau^+\tau^-$.

The primary physics goal of the BABAR experiment is the systematic study of *CP*-violating asymmetries in the decay of neutral B mesons to *CP*-eigenstates. In addition, measurements of the CKM-matrix elements, analyses of rare B-decays as well as studies of mesons with c- and b-quark content are performed.

With the Radiative Return method it is even possible to measure hadronic cross sections over a wide energy range < 5 GeV. One of the incoming leptons emitted photons leads to a lowering of the effective CM energy of the corresponding lepton pair. For these Initial State Radiation and many other analyses, as the τ-analyses, it is necessary to know the PEP-II luminosity as precise as possible. In modern particle factories a dedicated luminosity-counter cannot be built for the small polar angular region. Therefore, the BABAR detector is also used for the luminosity measurement. The luminosity is measured using the following reference reactions:

$$e^+e^- \rightarrow e^+e^-(\gamma)$$

$$e^+e^- \rightarrow \mu^+\mu^-(\gamma)$$

$$e^+e^- \rightarrow \gamma\gamma$$

The $\gamma\gamma$-reaction is only used to show time-dependent variations of the luminosity and the detector conditions such as ageing effects. At present the luminosity measurement is limited by the precision on the knowledge of the theoretical cross-section of the Bhabha reactions.

In the actual luminosity measurement *BHWIDE* is used to simulate

Bhabha events. It calculates absolute cross sections in the typical phase space volume for luminosity measurements with a theoretical precision of 0.5%. The first part of this diploma thesis consists of a comparison study between this generator and the newly developed event generator *Babayaga@NLO* which determines cross sections with a precision of 0.1%. Both event generators include all Next to Leading Order (NLO) corrections. The different precision of *BHWIDE* and *Babayaga@NLO* are the result of a different approach in the selection procedure of other higher order corrections. To demonstrate the importance of including all $\mathcal{O}(\alpha)$-corrections in perturbation theory, the previous version of *Babayaga* (version 3.5), which has not all $\mathcal{O}(\alpha)$-corrections implemented, is also included in the comparison study.

The vacuum polarization contribution to the cross section is not calculable since it is not possible to determine QCD corrections at low energies with perturbation theory. The values for the vacuum polarization are empirically determined and implemented in the event generators. To determine only the differences due to the theoretical models between *BHWIDE* and *Babayaga@NLO*, the comparison study was also done without vacuum polarization. Realizing, however, that the effect of vacuum polarization does not have a remarkable influence on the differences between the differential cross sections of the two event generators, only the comparison including all corrections is discussed in detail in this diploma thesis.

In the investigation of the differential cross sections the following trend is noticeable: in the typical phase space volume of the luminosity measurement at *BaBar* there are only very small differences between *BHWIDE* and *Babayaga@NLO*. They are up to $0.2 \pm 0.1\%$. These differences, however, almost compensate in the absolute cross section. It was reasonable to implement this new, high precision event generator in the *BaBar* software environment to improve the maximum theoretical precision of the cross section determination.

During this diploma thesis the *Babayaga@NLO* FORTRAN code was implemented in the *BaBar* C^{++} software environment. The philosophy was to change as few code of the program as possible.

It is possible to choose the random number generator when running the *Babayaga* code at *BaBar* . The original random number generator RANLUX, had to be replaced by a standard *BaBar* random number generator. Keeping RANLUX as an option in *Babayaga@NLO* enables, however, to ensure that the insertion of the code was correct. It was verified in each step of the inclusion that the produced events were exactly the same as in the stand-alone version, if they are produced with the same SEED and identical boarder conditions. This was verified for the final version.

In order to increase the speed of *Babayaga@NLO*, the event generator was expanded by the so-called 'default'-mode. In case the user applies the default values for the selection cuts on the kinematic variables of the outgoing leptons, precomputed quantities are used in the initialization routine. However, if non-'default' values for the run-time-parameters are chosen, the event production is performed with the original speed.

The *Babayaga@NLO* event generator is now completely implemented in the *BABAR* software environment. This allows an improvement in the luminosity determination at *BABAR* with extensive consequences for many physics analyses, especially in the sector of 'Radiative Return' and muon analyses.

In the not so distant future there will be a new version of *Babayaga@NLO* available which includes the $\mu^+\mu^-$- and $\gamma\gamma$-channel in addition. With an improvement of the theoretical precision of the $\mu^+\mu^-$-channel, it is possible to reduce the total error of the precision of the luminosity measurement in this channel to the same order as in the e^+e^--channel. This would lead to a further improvement of the luminosity measurement. Therefore it should be recommended to also implement this event generator in the *BABAR* software environment as soon as it will be available.

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Chapter 1

Motivation

The PEP-II B Factory is an asymmetric e^+e^- collider operating at a center of mass (CM) energy of 10.58 GeV, the mass of the $\Upsilon(4S)$ resonance. This resonance decays almost exclusively to $B^0\overline{B}^0$ and B^+B^- pairs and is thus ideally suited for the study of B meson decays with the *BABAR* experiment, which is located in the interaction region of the collider.

The primary physics goal is the systematic study of *CP*-violating asymmetries in the decay of neutral B mesons to *CP* eigenstates. As one of its most important results *BABAR* has measured in the golden decay channel $B^0 \rightarrow J/\psi\, K^0_S$ the angle β of the CKM unitary triangle and has proven like this for the first time that there are *CP*-violating effects not only in the kaon-system, but also in the B-system. This measurement is continuously updated with the increasing statistics ($\sin 2\beta = 0.7222 \pm 0.040 \pm 0.023$ [2]). Other measurements are performed in order to extract also the other two CKM-angles γ and α.

BABAR has also a broad physics program beyond *CP*-physics, including measurements of decays of τ-leptons and mesons including b and c quarks. Recent measurements of the muon anomaly a_μ at the Brookhaven National Laboratory with a precision of 0.5 ppm [3] have led to renewed interest in accurate measurements of the cross section for e^+e^- annihilation into hadrons. Hadronic contributions to the photon spectral functions due to quark loops are not calculable in the framework of perturbative QCD (pQCD). However, the hadronic contribution of the spectral function is connected by unitarity to the cross section for $e^+e^- \rightarrow$ hadrons. Thus a dispersion relation can be derived, giving the contribution to a_μ as an integral over the hadronic cross section. Similarly the hadronic contribution to the running of the electromagnetic fine structure constant at the Z-pole $\Delta\sigma_{hadr}(s)$ is not calculable

within pQCD at low energies and is also obtained by means of a dispersion relation. Current electroweak precision tests at the scale $s = M_Z^2$ are limited by the precision of the order of 1% by which the hadronic piece to the running of α is known [4].
It is not a simple task to measure the hadronic cross sections $\sigma_{hadr} = \sigma(e^+e^- \rightarrow hadrons)$ at *BABAR* [5]. As mentioned PEP-II runs at a fixed center of mass (CM) energy of 10.58 GeV. An energy scan for the hadronic cross section measurements is therefore not feasible. A new method, the so called Radiative Return has to be used. Hereby events in which one of the incoming leptons has emitted a photon in the initial state are investigated. These are the Initial State Radiation (ISR) events. As a result the invariant mass M_{hadr} of the hadronic system is reduced and therefore the hadronic cross section in the energy range $M_{hadr} < \sqrt{s}$ becomes accessible. This measured *radiative* cross section $\sigma(e^+e^- \rightarrow hadrons + \gamma)$ has to be related to the *non-radiative* cross section $\sigma(e^+e^- \rightarrow hadrons)$. This can be achieved by the use of the theoretical radiator function H(M_{hadr}^2). The relation is described in equation 1.1.

$$M_{hadr}^2 \cdot \frac{d\sigma_{hadrons+\gamma}}{dM_{hadr}^2} = \sigma_{hadr} \cdot H(M_{hadr}^2) \tag{1.1}$$

The radiator function describes the process of ISR with a precision of 0.5%. It has been computed up to Next to Leading Order (NLO) by the Monte-Carlo generator PHOKHARA [6]. In order to use this method a normalization method is needed. The integrated luminosity is perfectly suited to be used in order to perform the requested normalization of the hadronic cross sections. Another possibility is the normalization with $\mu^+\mu^-\ \gamma$ events. There are, however, deviations up to 3% in measurements of hadronic cross sections between the $\mu^+\mu^-\ \gamma$ and the $\int \mathcal{L}(t)dt$ normalization method. These differences have to be further investigated. This improvement is especially needed for the measurement of the $\pi^+\pi^-(\gamma)$-channel with a precision better than 1%.

The BABAR measurement of the $\pi^+\pi^-\pi^+\pi^-$ cross section with the Radiative Return method is displayed in figure 1.1. The BABAR result has very high statistics and is nicely confirmed in the low energy region ($E_{CM} < 1.5\,\text{GeV}$) by previous, energy scan experiments. For the first time the $\pi^+\pi^-\pi^+\pi^-$ cross section is also measured in the energy range $2.5\,\text{GeV} < E_{CM} < 4.5\,\text{GeV}$. An overview over other ISR analyses at BABAR can be found in [4]

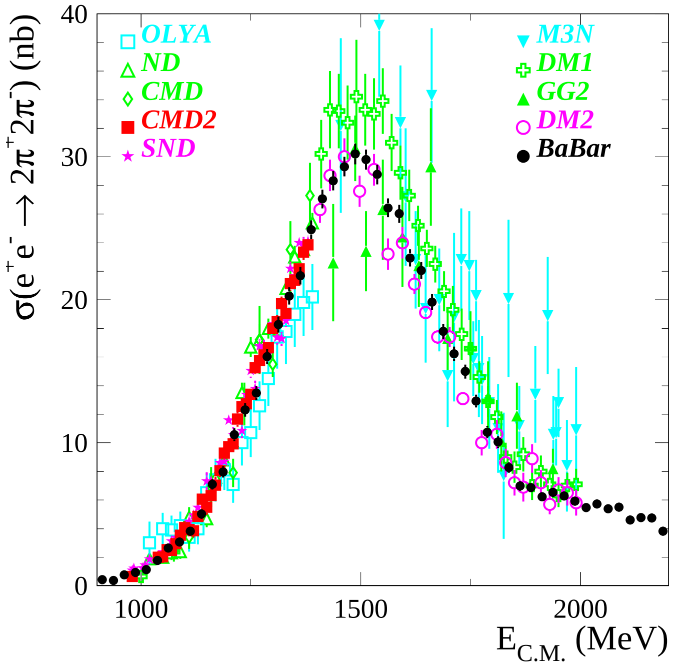

Figure 1.1: Measurements of the $\pi^+\pi^-\pi^+\pi^-$ cross section with different experiments

A precise knowledge of the luminosity is also of importance in the study of τ-analyses, e.g. the measurement of branching fractions of τ decays into hadrons. The total error of 1.4% concerning the branching fraction of the $\pi^+\pi^-\pi^-\nu$-channel is dominated by the 0.9% error of the actual luminosity determination [7]. Therefore the luminosity needs to be known with a very high precision.

In the following chapters the PEP-II facility and the BABAR detector are described. Then the actual luminosity measurement of PEP-II and existing event generators are discussed in detail. As a next step, the result from a comparison between different event generators are presented. Finally the implementation process of the Bhabha event generator *Babayaga@NLO* into the *BaBar* software environment is described.

Chapter 2

The *BABAR* Experiment

2.1 The Asymmetric PEP-II Collider

The PEP-II (Positron Electron Project) facility consists of two independent storage rings. Electrons are stored in the high-energy ring. The electron beam has an energy of 9 GeV, while the low-energy ring stores 3.1 GeV positrons. The term "asymmetric" refers to the fact that the electron and positron energies are not equal.

This results in a collision Center of Mass CM energy of 10.58 GeV and a forward boost of the CM frame, which is crucial for a precise measurement of the $B\overline{B}$ decay displacement (Δz) [9]. Injection is achieved by extracting electrons and positrons at collision energies from the Stanford Linear Collider (SLC) and transporting each of them in a dedicated bypass line. The low-emittance SLC beams are used for the injection process. The collider was completed in July 1998. Since then an integrated luminosity $\mathcal{L}_{int} = \int \mathcal{L}(t)dt$ of about 400 fb^{-1} was achieved

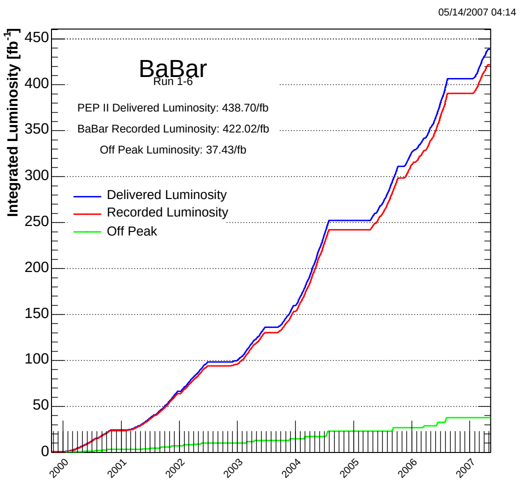

Figure 2.1: Run1 - Run6 integrated luminosity of PEP-II as a function of time

(figure 2.1) with an instantaneous luminosity $\mathcal{L}$ of up to 1.2 $10^{34}\,\mathrm{cm}^{-2}\mathrm{s}^{-1}$. A new detector had to be constructed in order to study those high-intensity collisions: the *BABAR* detector.

2.2 The *BABAR* Detector

Superb vertex resolution and very good particle identification were the most important criteria in the development of the five detection units forming the *BABAR* detector. The tracking system of the experiment consists of a silicon vertex detector and a cylindrical drift chamber. Particle identification is accomplished by means of a newly developed technology called DIRC. Additional detector components are an electromagnetic calorimeter and a muon system, the instrumented flux return. The angular acceptance for the entire experiment is determined by the vertex detector, which is limited by machine components. In the following, the subsystems of the *BABAR* detector, ordered from the inside out, are described [8, 9].

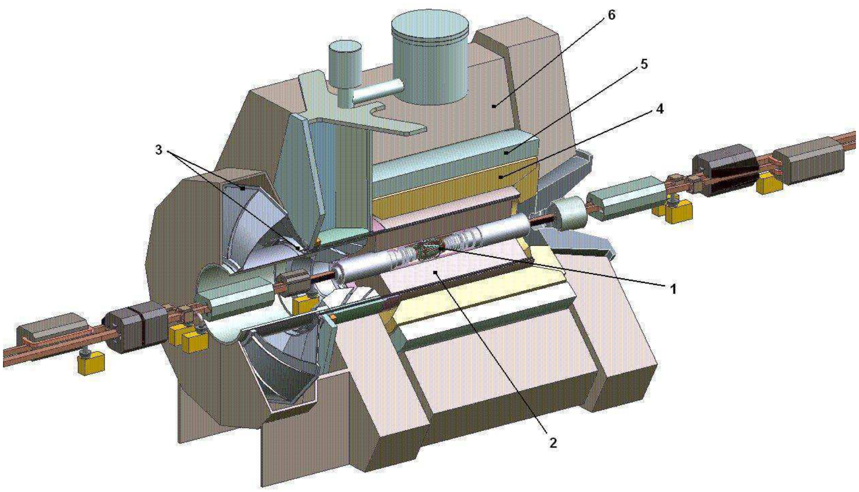

Figure 2.2: The *BABAR* detector components: 1) Silicon Vertex Detector (SVT); 2) Drift Chamber (DCH); 3) Detector of Internally Reflected Cherenkov light (DIRC); 4) Electromagnetic Calorimeter (EMC); Solenoid; 6) Instrumented Flux Return (IFR)

2.2.1 Silicon Vertex Detector

The vertex detector is the only tracking device inside the 20 cm radius of the inner mechanical structure, the so called support tube. It is used to measure precisely both impact parameters for charged tracks (the z-component with σ_z=65 μm and the transversal r - ϕ coordinates with σ_r=65 μm); these measurements are used to determine the difference in decay times of the two B^0 mesons. This is for example needed in order to determine the time-dependent *CP*-asymmetry with BABAR. The vertex detector also provides the measurements of production angles, given momentum information from the drift chamber. Finally, charged particles with a transverse momentum p_t between 40 MeV/c and 100 MeV/c are tracked only with the vertex detector, which must therefore provide a good pattern recognition. The vertex detector consists of five layers of double-sided silicon strip detectors. The inner three layers are ordered in a barrel geometry with detectors parallel to the beam pipe. The outer two layers combine barrel detectors in the central region with wedge detectors forward and backward. The detector can track particles with a polar angle in the laboratory frame of up to 20.1° in the forward direction and of up to 150.2° in the backward direction.

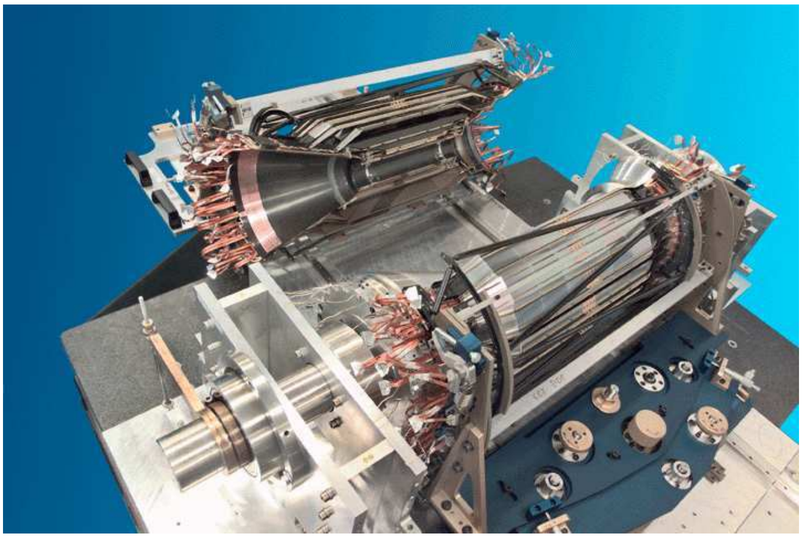

Figure 2.3: Silicon Vertex Tracker

2.2.2 Drift Chamber / Central Tracker

The second component of the tracking system is the drift chamber, which is used primarily to achieve excellent momentum resolution (σ_{p_t}/p_t=0.47%) and pattern recognition for charged particles with $p_t > 100\,\mathrm{MeV}/c$. It also supplies information for the charged track trigger and a measurement of $\mathrm{d}E/\mathrm{d}x$ for particle identification. The chamber extends in radius from 22.5 cm, just outside the support tube to 80 cm. For most particles of interest at PEP-II, the optimum momentum resolution is achieved by having a continuous tracking volume with a minimum amount of material to minimize the effect of multiple scattering. By using a helium-based gas mixture with low mass wires and a magnetic field of 1.5 T, very good momentum resolution can be obtained. The forward edge of the chamber is situated 1.66 m from the interaction point, which makes it possible to obtain reasonable momentum resolution down to the limit of forward acceptance 17.2°.

Figure 2.4: Drift Chamber during wire staping

A design of four axial and six stereo superlayers, each consisting of four individual layers, was chosen as the baseline design for the drift chamber. The chamber is constructed to minimize the amount of material in front of the particle identification and calorimeter systems in the heavily populated forward direction. The readout electronics are mounted only on the back end of the chamber and the endplates are designed as truncated cones.

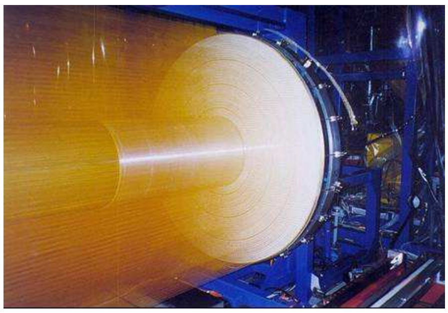

Figure 2.5: Drift Chamber with all wires strung

2.2.3 Barrel Particle ID: DIRC

There are two primary goals for the particle identification system. One is to identify kaons beyond the momentum range where the dE/dx information in the Drift Chamber can be used. The other one is to identify pions from few body decays. A new detector technology was required to achieve these goals. A Detector of Internally Reflected Cherenkov radiation (DIRC) is used in the barrel region.

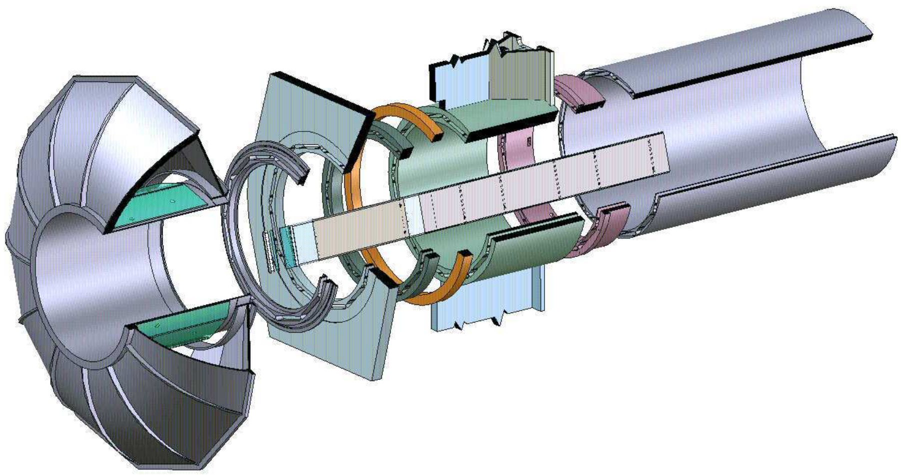

Figure 2.6: DIRC

Cherenkov light is produced in 144 quartz bars with the dimension 1.75 x 3.5 cm^2, each 4.9 m long with a refraction index of $n = 1.474$. In order to produce Cherenkov radiation, particles have to travel through the quartz bars with a velocity v higher than the speed of light in this medium. The emitted radiation forms a light cone with an opening angle depending on n and v:

$$\cos\alpha = \frac{c}{nv} \tag{2.1}$$

There is a characteristic correlation between the angle α and the momentum of a particle. Using momentum information of other detector components, it is possible to determine the identity of the particle emitting the Cherenkov light. The light is transferred by total internal reflection to a large water tank outside the backward end of the magnet. Finally it is observed by an array of photomultiplier tubes at the outside of the tank, where images governed by the Cherenkov angle are formed. A mirror at the forward end of the bars reflects the forward-going light, preserving the angular information (see fig. 2.7).

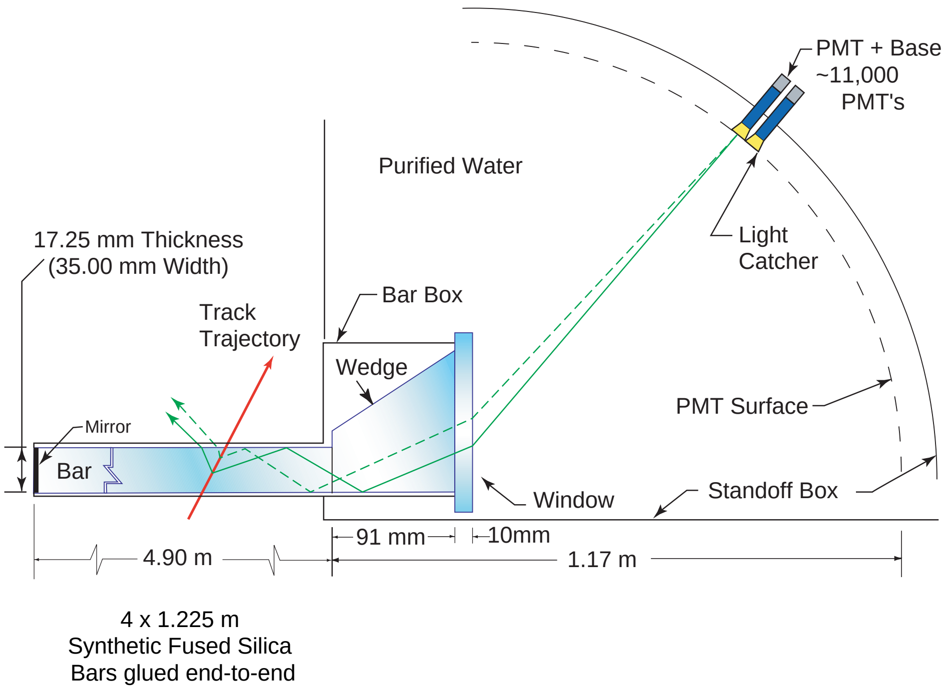

Figure 2.7: Principle of the Detector of Internally Reflected Cherenkov radiation

2.2.4 Electromagnetic Calorimeter

The electromagnetic calorimeter has an excellent energy resolution ($\sigma_E/E = 3.0\%$) down to very low photon energies. This is provided by a fully projective CsI(TI) crystal calorimeter, which has very good energy and angular resolution and retains a high detection efficiency at the lowest relevant photon energies. The calorimeter consists of a cylindrical barrel section with an inner radius of 90.5 cm and a conical forward endcap. The barrel calorimeter contains 5880 trapezoidal crystals; the forward endcap calorimeter contains 900 crystals. Each crystal is readout by two independent silicon photodiodes. Electronic noise and beam-related backgrounds dominate the resolution at low photon energies, while shower leakage from the rear of the crystals dominates at higher energies.

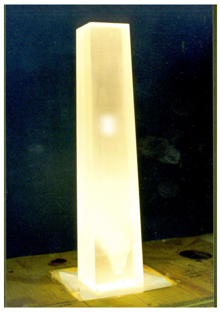

Figure 2.8: CsI(TI) crystal in light

2.2.5 Instrumented Flux Return

The IFR is designed to separate pions from muons for momenta greater than 0.5 GeV/c; it also has the capability to detect and provide coordinate information on neutral hadrons. The magnetic flux return iron is divided into 18 layers whose thickness increases outwards from 2 to 10 cm for a total thickness of 55-60 cm. The gaps between iron plates are filled with active detectors, originally only consisting of Resistive Plate Chambers (RPCs). The RPCs are now systematically replaced by Limited Streamer Tubes (LSTs) since a significant efficiency drop of the RPCs with time has been observed. Both RPCs and LSTs provide two-dimensional position information in each plane with a resolution of 1-2 cm. Muons produce a track through most, if not all, of the IFR layers with a 90% muon detection efficiency, while most pions interact in the EMC or IFR steel (6-8% mis-identification).

2.2.6 Solenoid

Figure 2.9: Solenoid superconductive magnet

To achieve good momentum resolution without increasing the tracking volume and therefore calorimeter cost, it is necessary to have a magnetic field of 1.5 T. The magnet coil is therefore of superconducting design, with an inner radius of 1.40 m for the coil dewar and a cryostat length of 3.85 m. The implementation of non-standard features like a special segmentation of the iron was necessary because of the IFR and the complications caused by the DIRC readout in the backward direction.

2.3 The *BABAR* Software

2.3.1 Packages

The organization of the *BABAR* analysis software is done by using packages. Each package - consisting of several files - performs one well-defined task. This task is for example to find calorimeter clusters or the simulation of the drift chamber response. Every package has its own library and include files. Most packages are dependent from each other. For example the GEANT simulation of *BABAR* only works as a group of individual subsystem simulation packages, that do not work individually. There exist several different types of packages. By the usage of core reconstruction packages raw detector signals data is transformed into particle candidates. One of the intentions of this diploma thesis was is to build the simulation package *Babayaga*. It generates simulated events in the same format as real data. Finally, there are user analysis packages. They take the reconstructed and simulated data provided by the core reconstruction and simulation packages. These analysis packages then organize and store this data in a format that is useful for a certain user's analysis.

The organization of the *BABAR* software allows most users to deal with only two packages: an *analysis* package and the *workdir* package. In the analysis package for instance the user writes a selection code, which runs on data or Monte Carlo and which writes as an output either ntuples or histograms. The analysis package calls other required packages needed to perform the analysis. The user, however, rarely has to deal directly with any of the other packages. Compiling the *BABAR* code will create the application of the analysis package. Finally the workdir package is used to run this analysis package's specific application.

There exist many different *BABAR* analysis packages, each optimized for a certain type of analysis. For sure, an analysis package for studies of semileptonic decays will store mostly information about the lepton and will compute lepton-related quantities. On the other hand, an analysis package for studies of charm decays may use the same database of event information, but computes and stores only variables relevant to charm decays.

2.3.2 Modules

The *BABAR* code and therefore also the *BABAR* packages are built from objects called modules. In this process each module uses a certain dataset to perform one specific well-defined task. There are many different kind of modules. Some modules, so called input modules, read data from the database or get Monte Carlo simulation information. Others load certain detector conditions, make the reconstruction of particles or perform particle identification. Many filter modules are used to perform the user's analysis. In addition there are output-modules to manage histograms and ntuples. For each analysis task one module is created whenever the task has to be performed. Whenever an analysis job is run, an object called framework is created by the application of the analysis. Within this framework modules are strung together into a certain order called the analysis path. Then the framework passes data from one module to the next one, until the last module of the analysis path is reached. In each module one certain task is performed on data.

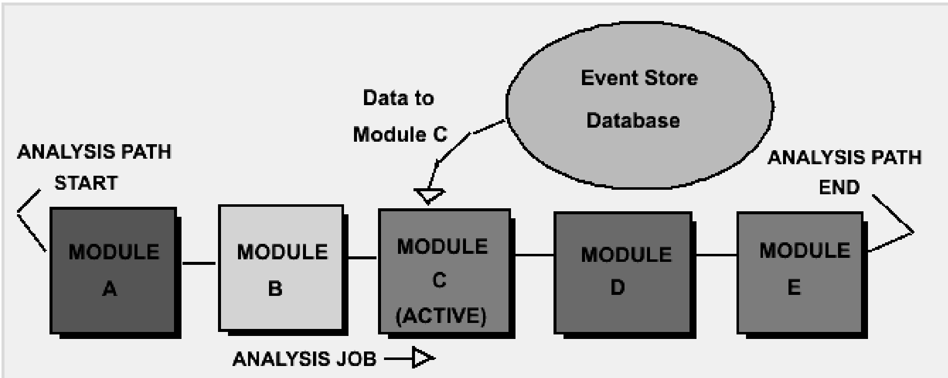

Figure 2.10: Analysis Sequence

In figure 2.10 a typical analysis job is shown. Each module has its turn while it can use the data before the framework passes the data on to the next module. The analysis job will be finished when the framework reaches the output module: this is module E in figure 2.10. Usually an analysis job uses hundreds of modules. Each module is a member of the C++ class AppModule [10]. Each member of this class must have three important member functions:

- beginJob (AbsEvent *)
- event (AbsEvent *)
- endJob (AbsEvent *)

At the very beginning of a job, the function beginJob() is executed once. Similarly, the function endJob() is executed at the end of a job. The actual module specific task is performed in the event() function. For each event belonging to a run, the event() function is executed once.

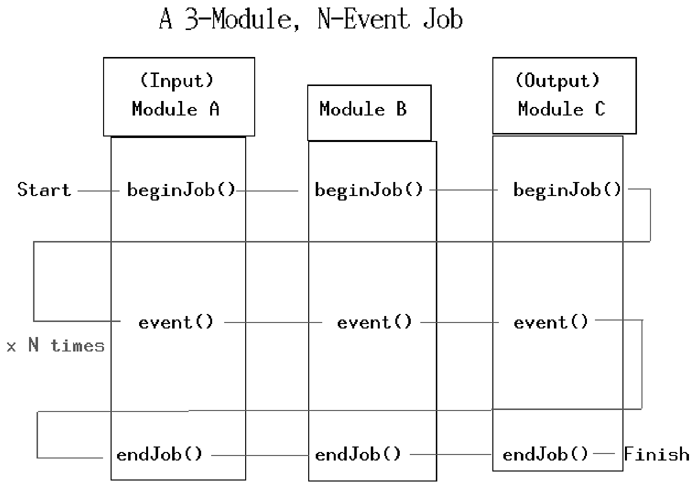

Figure 2.11: Run order of a 3-module job with N events

In figure 2.11 the order of execution in a job with N events is displayed. In the beginning of the job the beginJob() function of each module is called in the order given by the analysis path. Afterwards the event() function is called once for each of the N events. It is important to mention, that in this process, the analysis path is transversed N times instead of executing one module N times before continuing with the next module. After having gone N times through the analysis path in the event() function, the endJob() is called once for each module and the job finishes. Modules have important features, which are briefly summarized in the following:

- **Run-time parameters:** They can be reset for each analysis job. This is a great advantage over normal C++ parameters, which can be changed only by recompiling and relinking the code.
- **Paths and sequences:** Modules can be organized into an ordered list of related modules called sequence that perform a defined task that is too big for just one module. Similarly, a path is an ordered list of modules and sequences. The complete analysis path is then built from smaller paths, sequences, and modules.
- **Enable and Disable:** Modules can easily be turned on or off at

run-time. By default modules are enabled.

2.3.3 Tcl-files

Once the *BABAR* code is compiled and the executables for a certain package are built, a tcl-file serves as the user's interface, in which the task of the application is defined. There is more than one possible analysis path, because there is more than one way to put the modules together in order to create an analysis path. Tcl scripts activate and set up the analysis paths in the *BABAR* applications. They also can be used in order to disable modules or change the run-time parameters of a module.

Chapter 3

Bhabha Scattering, Event Generation and Luminosity Measurement

In this chapter the need to implement the newly developed Bhabha event generator *Babayaga@NLO* into the *BABAR* production framework is motivated. An introduction to the actual luminosity determination at the *BABAR* experiment is given. The Bhabha event generator currently used for the luminosity measurement at *BABAR*, the *BHWIDE* code, has a claimed theoretical accuracy of approximately 0.5%. The theoretical error of *Babayaga@NLO* is estimated to be 0.1% according to [12].
In the following, the Born cross section σ_{born} is calculated analytically. This result can be used as a first technical check of *Babayaga@NLO*. Then the working principles of event generators in general and the differences between the so called weighted and unweighted events are discussed. Finally the higher order corrections of *BHWIDE*, *Babayaga@NLO*, and an older version of *Babayaga* (*Babayaga.3.5*) are described and the differences in the theoretical approximations are stated.

3.1 Luminosity Determination

The luminosity is usually measured at e^+e^- colliders by counting theoretically well-known QED-processes and normalizing them to the cross section, as shown in the relations 3.1 and 3.2:

$$\mathcal{L}_{int} = N_{ev}/\sigma_{vis} \tag{3.1}$$

$$\sigma_{vis} = \epsilon \cdot \sigma_{theo} \tag{3.2}$$

σ_{vis} is the visible cross section in a certain phase space region and N_{ev} is the number of events observed for a certain reference reaction. σ_{theo} is the theoretically calculated cross section and ϵ the efficiency to identify the corresponding event in the experiment in this phase space region. To determine the value of ϵ a full detector simulation is needed. It is evident that this is only a powerful method, if the theoretical cross section can be predicted with very high precision. Also the detector simulation must be known very precisely and validated by the use of real data. If those two conditions are fulfilled, the redundancy offered by the use of many different reactions is a powerful tool in order to minimize systematic errors.

3.1.1 The *BABAR* Reference Reactions

In the *BABAR* experiment the luminosity is measured using the following QED reactions:

$$e^+e^- \to e^+e^-(\gamma) \tag{3.3}$$

$$e^+e^- \to \mu^+\mu^-(\gamma) \tag{3.4}$$

$$e^+e^- \to \gamma\gamma \tag{3.5}$$

Process 3.5 is only considered in order to reveal time dependent variations of the detector and trigger acceptances, because of the comparatively low accuracy in the theoretical and experimental precision for the $\gamma\gamma$ events.

The main challenges for a precise luminosity measurement in *BABAR* are:

- Over the last decade the theoretical interest has been focused on Bhabha scattering at LEP or even higher energies. The generators used in those studies have not been written for the $\Upsilon(4S)$ energy region. The generators for sub-LEP energies have also been not well supported and dated. Recently a new, very precise event generator, *Babayaga@NLO* [12] was developed. The goal of my diploma thesis is to replace the old generator, *BHWIDE* [13], currently used in the *BaBar* framework by this new one.

- There is no dedicated luminosity detector in *BaBar*, as it was used for instance for the luminosity determination at LEP, for which counters at small polar angles with respect to the beam axis were installed. Therefore large parts of the *BaBar* detector must be used for the measurements. This demands a good knowledge of detector material in order to make a precise detector simulation over a large volume.

3.1.2 Precision of Actual Luminosity Measurement

The luminosity of the Run 1, Run 2 and Run 3 data sample at the *BaBar* experiment is $(125.2 \pm 1.2) fb^{-1}$. It is determined with an error of 0.94% [11]. Table 3.1 shows the precision of the luminosity measurement for the different reference reactions. The precision of the final luminosity calculation is dominated by the systematic uncertainty on the event generators in the Monte Carlo production. Especially in the $\mu^+\mu^-$-channel the total error is totally dominate by the theoretical known cross-section. The event generator BKQED contains all NLO order corrections, however, has no Next to Next Leading Order (NNLO) correction implemented in its code.

$e^+e^- \rightarrow$	exp. error	theo. error	total error	event generator
e^+e^- (γ)	0.7 %	0.7 %	1.0 %	*BHWIDE* [13]
$\mu^+\mu^-$ (γ)	0.5 %	1.4 %	1.5 %	BKQED [14]
$\gamma\gamma$	1.6 %	2.0 %	2.6 %	BKQED [14]

Table 3.1: Experimental and theoretical errors for different reference reactions used for the *BaBar* luminosity measurement.

The reference reaction which leads to the most precise luminosity determination is Bhabha scattering. Here the experimental and theoretical errors are the same (0.7%). The Bhabha sample that was used for this measurement has to fulfill the following selection criteria:

- two differently charged tracks
- polar angle θ between icoming e^+e^- beam directions and charged track 1 and 2:

  $cos(\theta_{1,CMS}) < 0.7$ & $cos(\theta_{2,CMS}) < 0.65$

- energy of track 1 and 2:

  $E_{1,CMS}/E_{Beam} > 0.75$ & $E_{2,CMS}/E_{Beam} > 0.50$

- 3-dimensional angle (acolinearity) between the two charged tracks:

  $|acol - 180°| < 30°$

- energy fraction deposited in the EMC of track 1 and 2:

  $E_1/P_1 > 0.7$ & ($E_2/P_2 > 0.4$ OR $E_2/P_2 = 0$)

With the implementation of *Babayaga@NLO* the theoretical error in the e^+e^- (γ) channel of 0.7% will decrease to approximately 0.1% or using a more conservative estimate to 0.2%. The authors of *Babayaga@NLO* are currently working on a new event generator that also includes the $\mu^+\mu^-$ (γ) and the $\gamma\gamma$ channel. The total error of the $\mu^+\mu^-$ (γ) channel of 1.5% is dominated by the theoretical error of 1.4%. An improvement of the theoretical error in this channel has therefore a strong influence on the luminosity determination in general. The precision in the $\mu^+\mu^-$ (γ) channel would be comparable to the dominating Bhabha channel. It should be therefore strongly be recommended to also include this event generator in the BABAR software environment when it will be available.

3.2 Born Approximation

It is helpful to consider the simplest case for Bhabha scattering: no photon is present in the final state and only the Leading Order (LO) contribution, represented by the following Feynman diagrams, are taken into account:

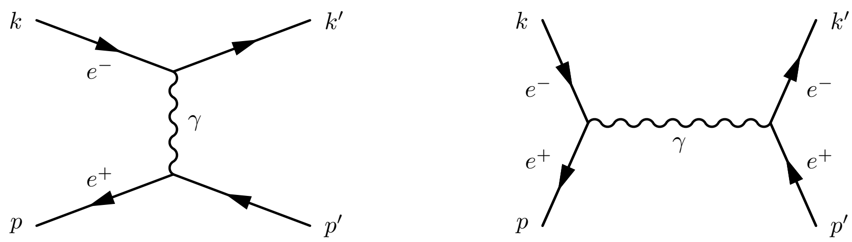

Figure 3.1: t-channel and s-channel Leading Order Feynman diagrams

Using the Feynman rules, relation 3.6 for the spin average of the invariant amplitude $\mathcal{M}$ is obtained:

$$\overline{|\mathcal{M}|^2} = \frac{e^4}{16\pi s}(\frac{s^2+u^2}{t^2} + \frac{2u^2}{ts} + \frac{u^2+t^2}{s^2}) \qquad (3.6)$$

with the Mandelstam variables: $s \equiv (k+p)^2$, $t \equiv (k-k\prime)^2$ and $u \equiv (k-p\prime)^2$. The first term corresponds to the almost completely dominating t-channel or scattering diagram. The last term describes the s-channel or annihilation process and the middle term reflects the interference between the scattering and annihilation amplitude. In the CM frame, equation 3.7, relating the differential cross section and the invariant amplitude $\mathcal{M}$ for a two body process, is found. Neglecting the electron mass, simple relations between the Mandelstam variables and the scattering angle θ according to equations 3.8 and 3.9 can be obtained:

$$\frac{d\sigma}{d\Omega} = \frac{1}{64\pi^2 s}\frac{p_f}{p_i}\overline{|\mathcal{M}|^2} \qquad (3.7)$$

$$t \simeq -\frac{1}{2}(1-\cos\theta)s \qquad (3.8)$$

$$u \simeq -\frac{1}{2}(1+\cos\theta)s \qquad (3.9)$$

Now formula 3.7 can be expressed in terms of $\cos\theta$:

$$\frac{d\sigma}{d\cos\theta} = \frac{e^4}{16\pi s}\{\frac{4+(1+\cos\theta)^2}{(1-\cos\theta)} - \frac{(1+\cos\theta)^2}{1-\cos\theta} + \frac{1}{2}(1+\cos^2\theta)\} \qquad (3.10)$$

The relative s-channel contribution increases with larger polar angles. The event generator gives us a certain number of events N($\Delta\cos\theta$), in a certain interval $\Delta\cos\theta$, which can be compared to equation 3.10 with the help of equation 3.11.

$$\frac{N(\Delta\cos\theta)}{\Delta\cos\theta} = \frac{d\sigma}{d\cos\theta}\frac{N_{Tot}}{\sigma_{Tot}} \qquad (3.11)$$

This is used in chapter 4.2 to give a crude test of the *Babayaga@NLO* event generator.

3.3 Corrections to Born Approximation

To approach the physical cross section of Bhabha scattering, a variety of corrections to the Born approximation have to be taken into account. The most important corrections are the electromagnetic Next to Leading Order

NLO corrections. They are Initial State Radiation, Final State Radiation and diagrams containing one loop. They have to be considered in the t-channel as well as in the s-channel. FSR in the s-channel is illustrated in figure 3.3. The Feynman diagrams of all other NLO corrections (real and virtual) can be found in appendix A.1. *BHWIDE* and *Babayaga@NLO* include the complete set of NLO corrections.

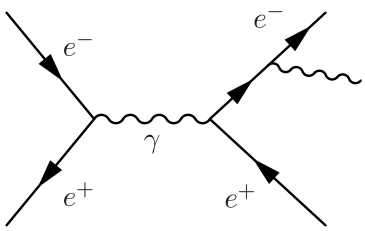

Figure 3.2: Final State Radiation in s-channel

The Next to Next to Leading Order corrections NNLO are combinations of the NLO corrections: for example two ISR photons, one loop and one ISR photon, and so on (examples are shown in appendix A.2).

Those higher order Feynman diagrams have been treated differently in the *BHWIDE* and *Babayaga@NLO* Bhabha event generators. *BHWIDE* uses the YFS formalism to exponentiate exact $\mathcal{O}(\alpha)$ corrections.
Babayaga@NLO is built on a Parton Shower technique allowing to include essentially the leading logarithmic corrections to the cross section up to all orders of α [1].

Moreover, weak corrections have also to be considered. Figure 3.3 shows the weak leading order correction in the t-channel.

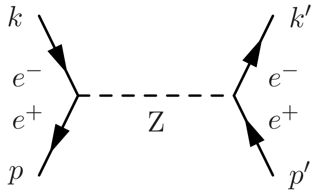

Figure 3.3: Weak LO correction in t-channel

All the effects discussed until now are calculated at high precision using perturbation theory. However the strong interaction effect of the hadronic vacuum polarization cannot be calculated because of the fact that QCD correction cannot be treated in perturbation theory. It is phenomenologically obtained from data by applying the dispersion relation between

$\sigma(e^+e^- \rightarrow hadrons)$ and the hadronic vacuum polarization (Feynman diagram in appendix A.2)[15]. It might be different for the two generators, since the data for the *BHWIDE* corrections is not up to date. Therefore in this study the event generators have also been compared with each other without the effect of vacuum polarization.

3.4 Event Generation

In this section the process of event generation and cross section determination will be explained. In order to generate physical events *Babayaga@NLO* performs the following four steps:

- read input parameters
- production of weighted events
- production of unweighted physical events
- output of simulation results

3.4.1 Input of Parameters

Either by using an input card or interactively the user has to set the following parameters in order to generate Bhabha events with *Babayaga@NLO*:

ecms	center of mass energy E_{CMS}, in GeV
thmin	minimum scattering angle θ_{min} for e^- and e^+, in $^\circ$ in CM frame
thmax	maximum scattering angle θ_{max} for e^- and e^+, in $^\circ$ in CM frame
zmax	maximum $e^\pm$ acollinearity angle, *acol* in $^\circ$ in CM frame
emin	minimum energy $E_{min,lep}$ for e^- and e^+, in GeV
nev	number of events N_{ev} to be generated
eps	sets the soft/hard photon energy separator, in $E_{CMS}/2$ units
ord	photonic radiative corrections: 'born','alpha' or 'exp'
model	radiative corrections: 'matched' is recommended by the authors
seed	the seed for the RANLUX random number generator
nphot	only a fixed number of nphot (hard) photons are generated
nwrite	output files in 'path' are written every nwrite events
nsearch	nsearch events are generated to find the maximum value of the cross section, after which also events unweightening is started
sdmax	the starting maximum value for the cross section (FMAX)

3.4.2 Weighted Events

In the phase of weighted events production the kinematic variables of the final state particles can in principle be chosen randomly according to arbitrary distributions. In order to make the later process of unweighting more effective, those distributions should resemble the actual physical distribution as much as possible. Since the real distribution is not known, the Born distribution is a good first approximation. This distribution is for sure not the correct physical distribution but only an approximation to it.

A so-called weight, which reflects the distribution, is associated to the event. Once this event is selected, a small phase space volume ΔV around it is chosen. The square of the matrix-element $|\mathcal{M}(\Delta V)|^2$ in this volume element is determined and precise corrections in the small phase space volume around this event are obtained. These correction factors determine the precise weight of this event.

The dependence of the cross section on a certain kinematic variable is nothing else than the probability distribution of this variable, multiplied with the integrated cross section. Knowing the corrected weight that reflects the probability to chose this particular event in this phase space volume and the differential cross section in this volume, allows us to estimate the absolute cross section event by event.

In detail the production phase includes the following steps: In a first step the polar scattering angle θ is chosen according to a probability distribution that resembles the Born probability distribution. It is important to clarify that this event is chosen according to a certain probability distribution which is not flat. A certain weight has to be attributed to this event which reflects this a-priory arbitrary probability distribution. As mentioned before, the better the chosen probability distribution agrees with the actual final probability distribution, the more effective the event selection will be in the end.

The azimuthal angle ϕ is chosen from a flat distribution and a weight of $\frac{1}{2\pi}$ as a weight is determined for each event. The weight agrees for all events, due to the rotational symmetry of the outgoing lepton's final probability distribution.

Now, in a second step, the volume element ΔV in the multi-particle Lorentz invariant phase space around this event is calculated.

In a third step, the number of photons is chosen. The number of photons is distributed according to a poissonian function and the corresponding weights are chosen accordingly.

Now a certain energy is attributed to the photons. After a decision-making process by which lepton the photon was emitted, the kinematic variables of the leptons get corrected in order to still satisfy the momentum and energy conservation laws. Again corresponding weights are determined.

In a final step the higher order corrections for this event are determined numerically with a so called Parton Shower technique. This complex process calculates $|\mathcal{M}(\Delta V)|^2$ and gives as a result a further weight correction of our final event.

The final weight of an event reflects, how probable it was to receive this single event $P(event)$. Having the phase space volume element ΔV and the squared matrix element $|\mathcal{M}(\Delta V)|^2$, it is now possible to calculate the cross section of this phase space volume according to equation 3.12.

$$\sigma_{theo}(\Delta V) = |\mathcal{M}(\Delta V)|^2 \cdot \Delta V \tag{3.12}$$

Finally the determination of the absolute cross section for this process is obtained with equation 3.13.

$$\sigma_{theo,tot} = \sigma_{theo}(\Delta V) \cdot P(event) \tag{3.13}$$

3.4.3 Unweighted Events

As discussed in the previous section, the weighted events are generated according to a chosen probability function in the beginning, which is actually not the real physical distribution. In order to reflect the real distribution, the final weights have to be taken into account. The more improbable our event is, the higher the final weight of the event will be. Basically in the weighted events production phase the multi-particle Lorentz invariant phase space is scanned for the events with the highest weights. This highest value is increased by 10 percent, saved as variable FMAX and used in the unweightening phase to produce the physical events with the following hit and miss technique:

One event with a corresponding weight is created as before according to the weighted distributions. A random number between 0 and 1 is created and multiplied with FMAX. If the resulting number is smaller than the weight of the event, the event will be accepted; otherwise it will be rejected.

It can then be ensured, that our final events are distributed according to physical distributions including the Parton Shower corrections. A problem occurs, if the weight of an event is bigger than FMAX. Then this event is chosen for sure, but the other events should have been chosen with a lower probability in respect to this event because the value for FMAX should have been larger. These so called overflow events increase the error on the cross section. This can be prevented by choosing a large number of events in the weighted events production phase.

3.4.4 Output of Simulation Results

The kinematic variables of the unweighted events can now be saved in ntuples and the corresponding cross section is printed on the screen as well as in a file corresponding to the ntuple.

Chapter 4

Comparison of *Babayaga@NLO* with Other Event Generators

In this chapter the cross section dependence on some selected kinematical variables of *Babayaga@NLO* are compared to the result of the so-far standard generator for Bhabha events in *BABAR* , BHWIDE, as well as to an older *Babayaga* version, Babayaga.3.5.

As a first step, a comparison of the absolute cross section simulated by the three event generators for different selection cuts is performed. For the computation of the data samples a center of mass energy of 10.576 GeV is used as needed for PEP-II. There are neither requirements made on the maximum number of created photons nor on the acolinearity, the angle between the outgoing electron and the outgoing positron.

In a second step, the differential cross sections of the data samples of the three different event generators are investigated.

Finally the results of this comparison study are summarized.

4.1 Absolute Cross Section

In the following the absolute cross sections of the weighted events of the different event generators are compared among each other. The weighted cross section is more precise than the unweighted one because of the higher statistics.

4.1.1 Excluding Vacuum Polarization

As discussed before, the hadronic vacuum polarization cannot be calculated by the means of perturbation theory. It is therefore phenomenologically obtained from data that is continuously being updated. Considering the fact that the generators do not include the same hadronic vacuum polarization corrections (see Feynman-diagrams in figure A.6), the absolute cross sections are also compared to each other without this effect. In such a way one can be sure that one only considers the differences in handling higher order corrections between the different generators.

However, for the *BHWIDE* generator it is not a simple task to switch off only the vacuum polarization. It is more convenient to switch off the weak corrections at the same time. That is not the intended task. Therefore in a first analysis the importance of the weak corrections have to be investigated. When comparing the resulting cross sections with weak interaction contributions off to the cross section including all corrections, it is clear that the effect of weak interaction is in the sub-permil range and therefore negligible for this study. This can be seen in table 4.1.

angular range (CM)	cross section [nb]	
	BHWIDE with WC	*BHWIDE* without WC
15°-165°	119.53±0.08	119.5±0.1
30°-150°	24.22±0.02	24.17±0.02
40°-140°	11.660±0.008	11.67±0.03
50°-130°	6.289±0.004	6.31±0.03
60°-120°	3.549±0.003	3.554±0.006
70°-110°	1.928±0.002	1.931±0.003
80°-100°	0.822±0.001	0.824±0.002

Table 4.1: Absolute cross sections dependence on θ_{lep} selection cuts with and without weak corrections (WC)

As a consequence it is now possible to compare the *BHWIDE* cross section without vacuum polarization and without weak interaction corrections with the cross section of *Babayaga@NLO* without vacuum polarization. The resulting values for the absolute cross section and different angular ranges can be seen in table 4.2.

angular range (cms)	cross section [nb]	
	BHWIDE	*Babayaga@NLO*
15°-165°	119.53±0.08	119.5±0.1
30°-150°	24.22±0.02	24.17±0.02
40°-140°	11.660±0.008	11.67±0.03
50°-130°	6.289±0.004	6.31±0.03
60°-120°	3.549±0.003	3.554±0.006
70°-110°	1.928±0.002	1.931±0.003
80°-100°	0.822±0.001	0.824±0.002

Table 4.2: Absolute cross sections dependence on θ_{lep} selection cuts, without vacuum polarization

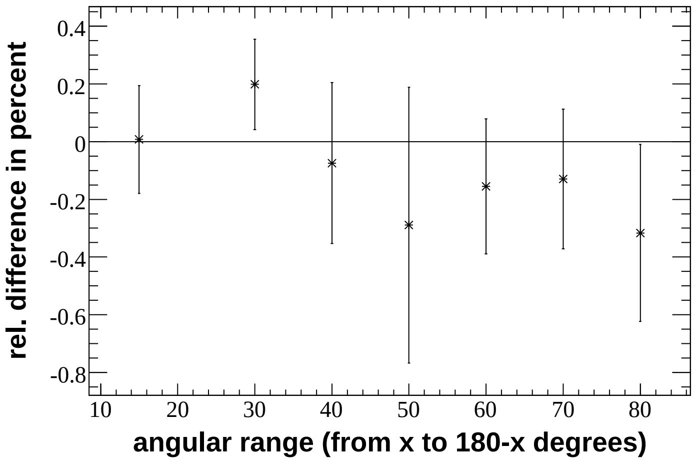

Figure 4.1: Relative difference between the *BHWIDE* and *Babayaga@NLO* cross section as function of θ_{lep} without vacuum polarization

The relative difference of the absolute cross sections simulated by *BHWIDE* and *Babayaga@NLO* are shown in figure 4.1. There is a very nice agreement between the values of the two event generators within the statistical errors.

4.1.2 Including All Corrections

As a next step the absolute cross sections including all $\mathcal{O}(\alpha)$ corrections as well as weak corrections and vacuum polarization of the three event generators are compared with each other. The results for different cuts on the polar angle θ_{lep} of the outgoing respectively incoming particles in the CM frame are shown in table 4.3.

angular range (CM)	cross section [nb] *BHWIDE*	*Babayaga@NLO*	*Babayaga.3.5*
15°-165°	124.89±0.08	124.85±0.15	127.4±0.1
30°-150°	25.57±0.02	25.51±0.03	25.89±0.02
40°-140°	12.363±0.008	12.37±0.03	12.53±0.02
50°-130°	6.690±0.005	6.71±0.03	6.754±0.009
60°-120°	3.784±0.003	3.79±0.01	3.807±0.006
70°-110°	2.060±0.002	2.062±0.003	2.071±0.003
80°-100°	0.881±0.001	0.881±0.002	0.883±0.002

Table 4.3: Absolute cross section dependence on θ_{lep} selection cuts of *BHWIDE*, *Babayaga@NLO* and *Babayaga.3.5*

There is also in this case an excellent agreement between the results for *Babayaga@NLO* and *BHWIDE*. They coincide within the statistical errors (see figure 4.2). There is however a noticeable difference in the order of 1.0% between *Babayaga@NLO* and *Babayaga.3.5*, due to the fact that *Babayaga.3.5* does not take into account all NLO corrections.

To further investigate the small differences of the event generators, the differential cross sections have to be studied.

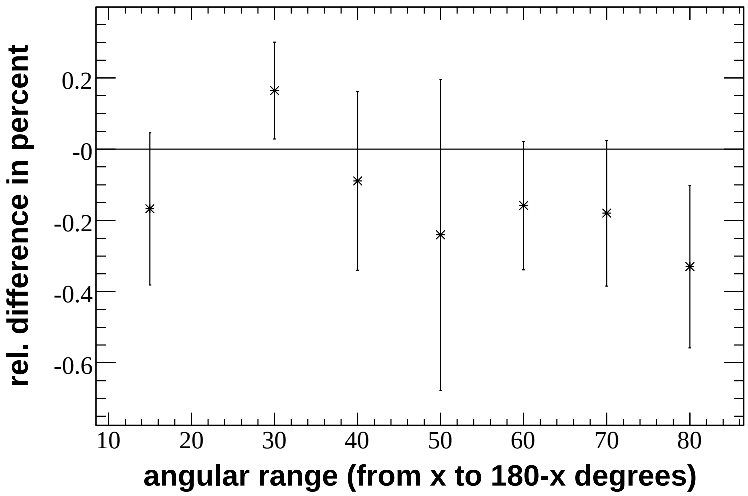

Figure 4.2: Relative difference between the *BHWIDE* and *Babayaga@NLO* cross section as function of θ_{lep} selection cuts

4.2 Differential Cross Section

In order to compare the differential cross sections, it was necessary to save ntuples with momentum information of the outgoing electron, positron, the most energetic photon and the number of produced photons. The events distributed according to the physical probability distribution, the unweighted events, have to be saved in these n-tuples.

4.2.1 Born Approximation

The simplest approximation to e^+e^- scattering is a final state without any photons, the Born approximation. In chapter 3.4 the cross section for this process is calculated analytically in dependence of the cosine of the outgoing positron's polar angle $\cos\theta_{e^+}$. Figure 4.3 shows the results for *Babayaga@NLO* in comparison to the calculated function according to equation 3.11.

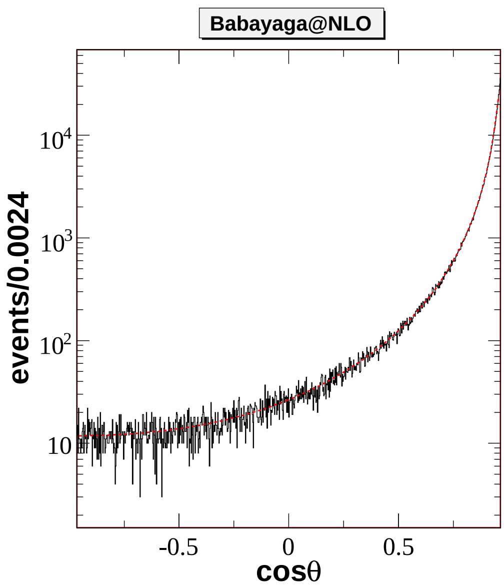

Figure 4.3: *Babayaga@NLO* differential cross section as function of θ_{pos} in the Born approximation and theoretical distribution (equ.3.11) in red

The comparison between the distribution of simulated events with the analytically calculated distribution confirms the assumption that the saved events are the unweighted physical events since the histogram created with *Babayaga@NLO* data is in perfect agreement with the function calculated in chapter 3.4. The comparison is also a technical cross check that the ntuple storage is under control.

4.2.2 Including All Corrections

The most important comparison between the data samples produced by the different event generators is the investigation of differential cross sections including all corrections. Again the older version of *Babayaga* is included in the study in order to clarify the importance of introducing all NLO terms into the event generator. The data samples are produced under the input conditions listed in table 4.4.

event generator	*BHWIDE*	*Babayaga@NLO*	*Babayaga.3.5*
CM energy E_{CMS}	10.576 GeV		
angular range of leptons scattering angle θ_{lep}	$15° < \theta_{lep} < 165°$		
number of events N_{ev}	$4.46 \cdot 10^7$	$3.0 \cdot 10^7$	$2.6 \cdot 10^7$
minimum energy of each outgoing lepton $E_{min,lep}$	0.5 GeV		
acolinearity range	$0° < acol < 180°$		
vacuum polarization	on		
weak corrections	on		

Table 4.4: Input parameters for the different event generators

Again the cross section dependence on the following variables is studied:

- polar angle θ_{lep} of the outgoing leptons
- energy of the outgoing leptons E_{lep}
- acolinearity $acol$
- scattering angle θ_{phot} of the hardest photon

Outgoing Positron

At first the angular distribution of the outgoing positron is investigated. θ is the polar angle between the outgoing positron and the beamaxis at the interaction point as shown in figure 4.4. The red area is restricted by the imposed cuts on the scattering angle of the outgoing leptons: $15° < \theta < 165°$.

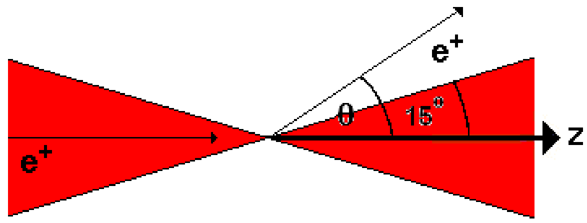

Figure 4.4: Angular production range for leptons

Already in the Born approximation the differential cross section diverges for $\theta \to 0°$. Therefore also after the inclusion of higher order corrections most of the positrons are scattered to the smallest allowed polar angles. This can be observed in figure 4.5.

There is an agreement within 0.2% between *Babayaga@NLO* and *BHWIDE* for positrons that are scattered in the angular range $15° < \theta_{e^+} < 40°$. The older version of *Babayaga*, however, shows a deviation of up to 2.0% in this region. Especially for large scattering angles, there is a strong difference of up to 40% between *Babayaga.3.5* and *Babayaga@NLO* respectively *BHWIDE*. Even in this high scattering region where only a sub-permill fraction of events can be found, there is still a quite good agreement of the order of 1% between *Babayaga@NLO* and *BHWIDE*. Also the weighted fit in the region, which is interesting for the *BABAR* luminosity determination, $40° < \theta_{e^+} < 140°$, shows a nice agreement between *Babayaga@NLO* and *BHWIDE* within the statistical limits $(0.0 \pm 0.1)\%$.

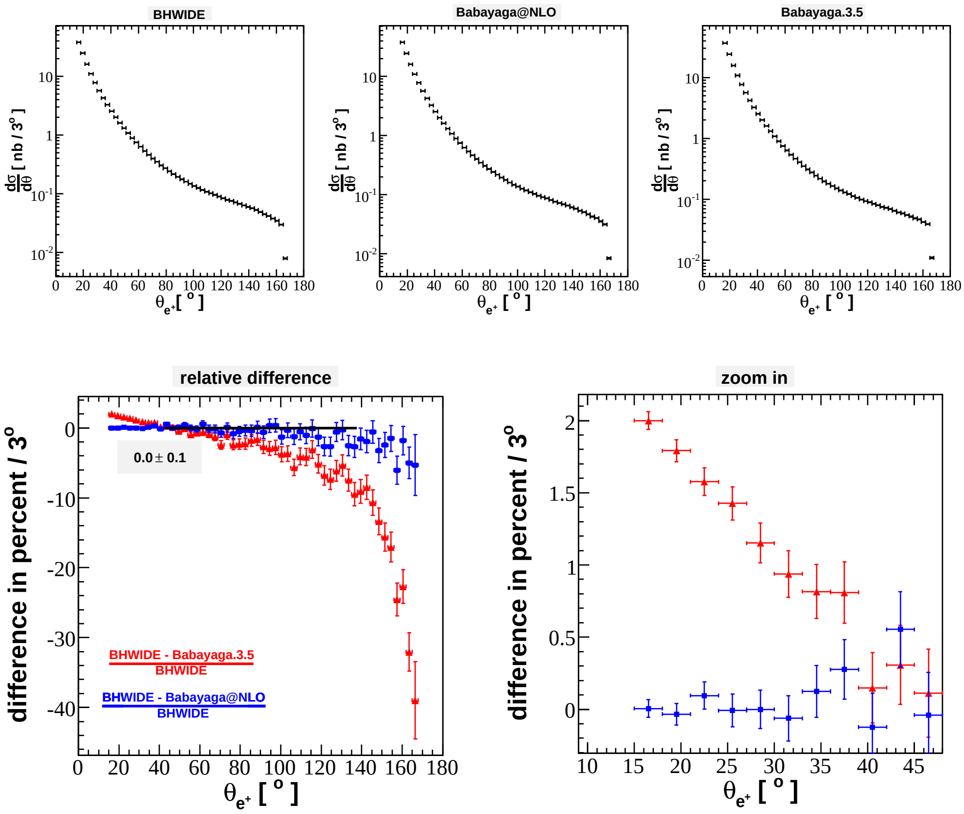

Figure 4.5: TOP: differential cross section as function of the polar angle of the scattered positron, left: *BHWIDE*, center: *Babayaga@NLO*, right: *Babayaga.3.5*, BOTTOM: relative differences (left) with zoom (right)

As the next variable the energy distributions of the outgoing positrons are investigated. In figure 4.6 an agreement within the statistical errors between *BHWIDE* and *Babayaga@NLO* can be observed when photons with energies $E_\gamma < 0.3\,\text{GeV}$ are emitted.

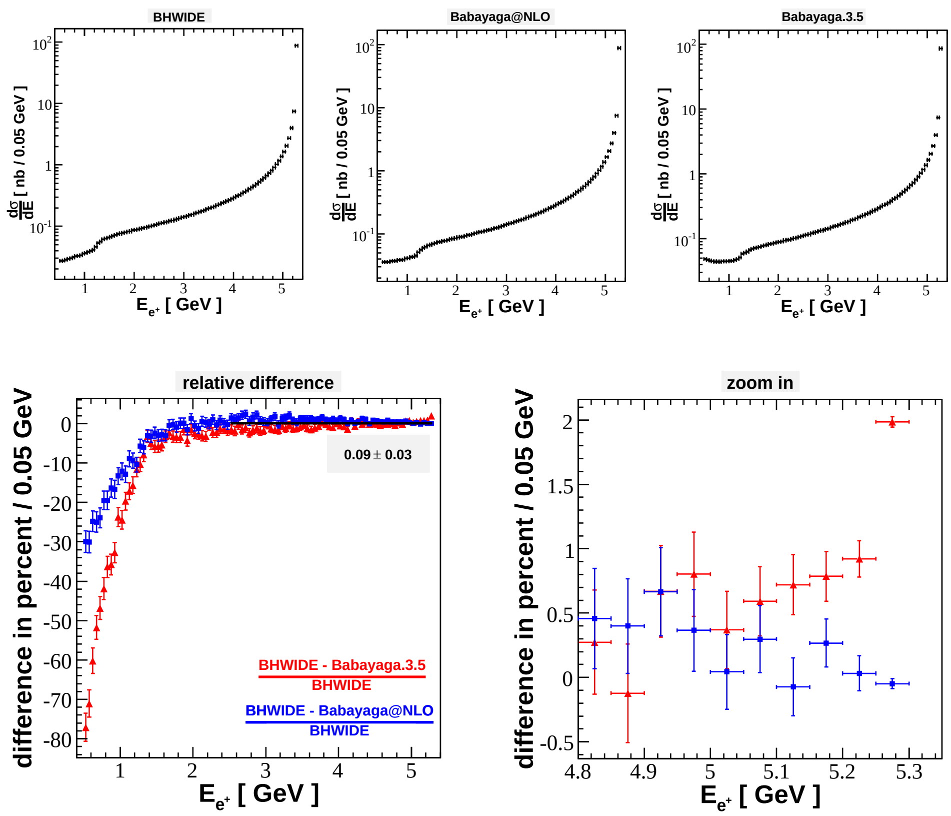

Figure 4.6: TOP: differential cross section as function of outgoing positron's energy, left: *BHWIDE*, center: *Babayaga@NLO*, right: *Babayaga.3.5*, BOTTOM: relative differences (left) with zoom (right)

The fit is applied to the events for which the positron keeps more than half of its energy, $E_{positron} > 2.6\,\mathrm{GeV}$. The fit result of $(0.09 \pm 0.08)\%$ in this, for the *BaBar* luminosity determination used region, is again almost compatible with zero. There is a sub-permill effect which implies that the *Babayaga@NLO* cross section is a little smaller in this region than the one received by *Babayaga@NLO*. In the energy region of $E_{pos,CMS} < 2\,\mathrm{GeV}$, however, the differences become in the order of 10% up to 30% for very hard emitted photons. These differences that are much smaller than the large differences up to almost 80% between *BHWIDE* and *Babayaga.3.5* do not influence the luminosity determination, since the luminosity is determined only with events in which leptons keep at least 50% of their original energy.

At $E_{out,pos} = 1.3\,\mathrm{GeV}$ a discontinuity of the distribution is observed. This is a result of the cuts applied on the polar angles of the leptons. If the outgoing electron emitted a very hard photon it's possible that it is scattered back in the cut region $\theta > 165°$.

For symmetry reasons the distributions for the outgoing electrons are similar. They can be found in the appendix B.2 for the reason of completeness.

Acolinearity

The acolinearity is the three dimensional angle between outgoing electron and positron (equation 4.1).

$$acol = \frac{360^\circ}{\pi} \frac{\vec{p'} \cdot \vec{k'}}{|\vec{p'}||\vec{k'}|} \tag{4.1}$$

The two dimensional projection of the acolinearity is shown in figure 4.7.

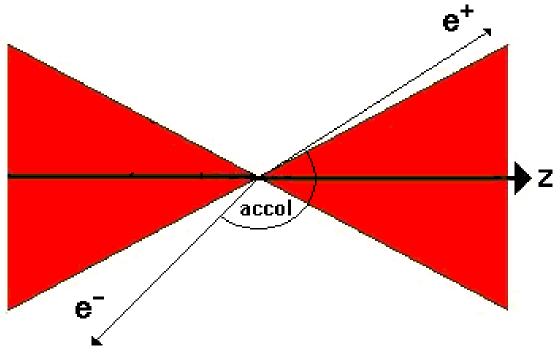

Figure 4.7: Two dimensional projection of the acolinearity

Its value reflects the energy loss of the lepton due to emitted photons. If no photon emerges, the leptons remain antiparallel. The acolinearity then is 180°.

The acolinearity dependence of the cross section can be seen in figure 4.8. In the *BaBar* luminosity determination only events with an acolinearity $acol > 150^\circ$ are considered. The weighted fit result in this area $(0.10 \pm 0.03)\%$ shows a permill deviation between *Babayaga@NLO* and *BHWIDE*. In the acolinearity region where $acol > 100^\circ$ these two event generators agree within 1% in the differential cross section. *Babayaga.3.5* shows deviations of up to 10% in the $acol > 150^\circ$ region. Also a non-physical discontinuity is discovered for all three generators at an angle of $acol \simeq 35^\circ$. The origin for this effect is the cut on the lepton polar angles when the events are produced $(15^\circ < \theta_{leptons} < 165^\circ)$.

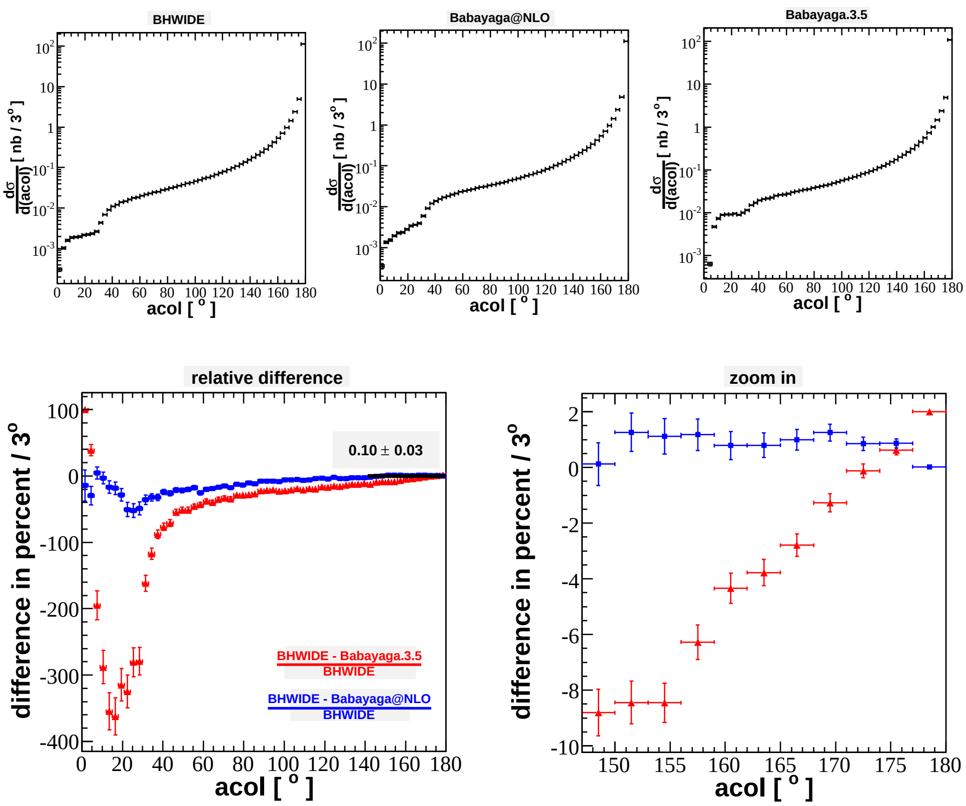

Figure 4.8: TOP: differential cross section as function of acolinearity, left: *BHWIDE*, center: *Babayaga@NLO*, right: *Babayaga.3.5*, BOTTOM: relative differences (left) with zoom (right)

Figure 4.9 shows the dependence of this discontinuity on the lepton cut angle θ_{min}.

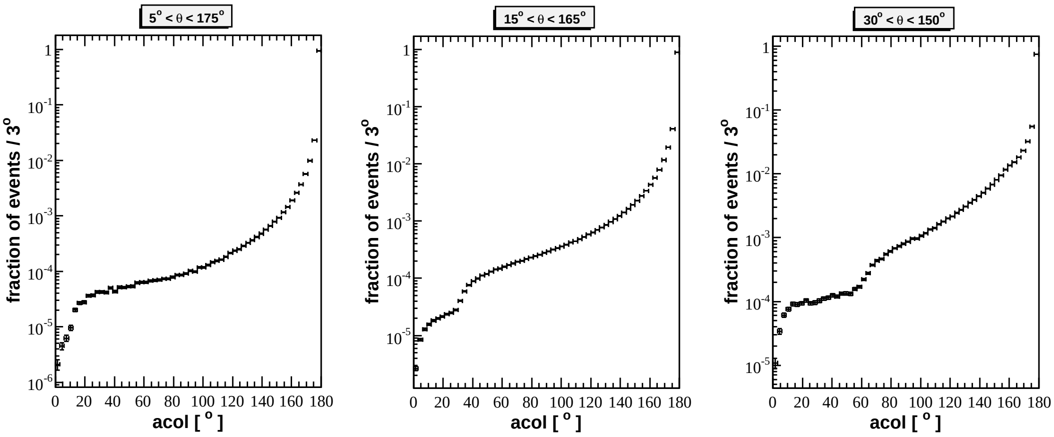

Figure 4.9: Acolinearity distribution with different cuts on the lepton scattering angles for a *BHWIDE* data sample, left: $5 < \theta < 175$, center: $15 < \theta < 165$, right: $30 < \theta < 150$

The effect always starts at an angle that is a few degrees higher than two times θ_{min}.

$$acol < 2 \cdot \theta_{min} + \epsilon \tag{4.2}$$

This can be understood, looking at figure 4.10. Like most of the positrons, the positron in this example is scattered to a small angle $\theta_{positron} = \theta_{min} + \epsilon$. Events with positrons that are scattered in the red area are rejected due to the cuts applied in the data sample production. If there is no photon emitted, the corresponding electron would be scattered in the direction of the dashed line. If however a hard photon is emitted by the electron, this electron might be scattered in the red restricted area. This effect therefore starts when the acolinearity satisfies equation 4.2

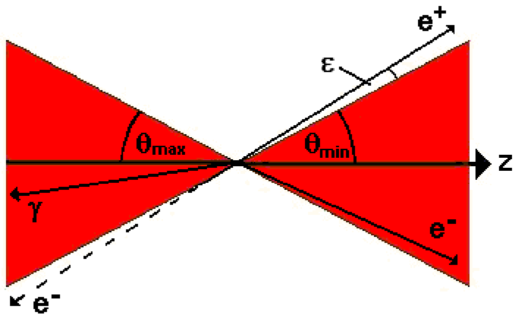

Figure 4.10: Investigation of the discontinuity in the acolinearity distributions

Hardest Photon

In figure 4.11 the distribution of number of photons N_γ is shown. *Babayaga@NLO* and *BHWIDE* coincide within a level of 2%.

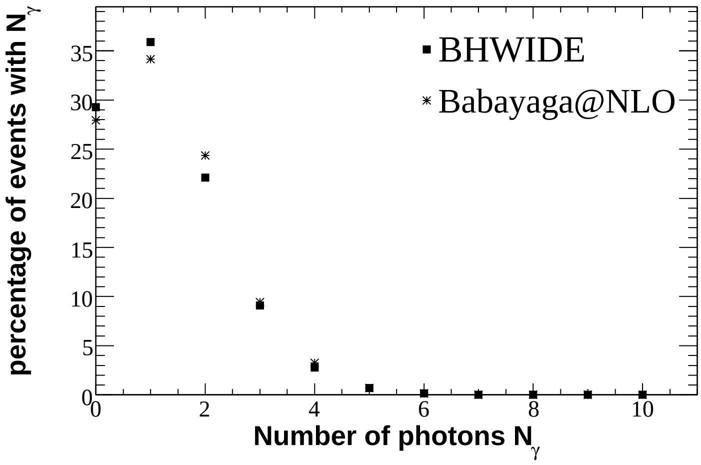

Figure 4.11: Probability to obtain a certain number of photons N_γ in the final state

The θ distribution for the hardest photon in a e^+e^- scattering event is displayed in figure 4.12. There is a minimum cut energy for the photons of 1.0 MeV. There are large relative differences between *BHWIDE* and *Babayaga@NLO* from up to 5 percent in regions with few events. There seems to be a systematic effect, in which the most energetic photon of *BH-*

WIDE has a distribution tending to a larger polar scattering angle θ than the *Babayaga@NLO* photon. This cannot be clearly seen in figure 4.12, because of the superposition of the distribution of events where the hardest photon is being emitted from the forward-going electron and the backward-going positron.

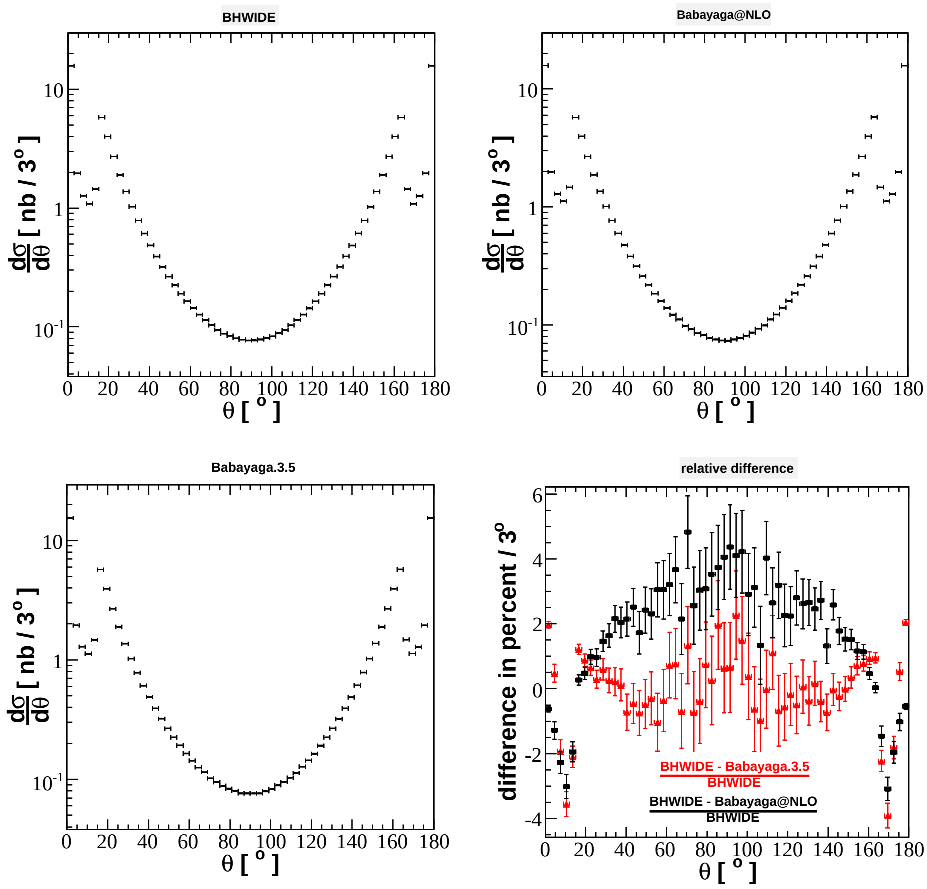

Figure 4.12: Dependence of the cross section on the polar angle of the hardest photon, TOP: *BHWIDE* (left), *Babayaga@NLO* (right), BOTTOM: *Babayaga.3.5* (left), relative differences (right)

To understand the two double peak structures in the angular distributions of the hardest photons in figure 4.12 an expected photon emission distribution of the positron is shown in figure 4.13. Photons are preferably emitted in the flight direction of the corresponding positron. Therefore the

peak in the first bin corresponds to the Initial State Radiation photons of the positrons. The second one, corresponding to the Final State Radiation peak, is created by the outgoing positrons that are preferably scattered in the small polar angle region that is not cut out by our restrictions in the data sample production.
The structure at larger angles corresponds to the ISR and FSR peaks of the incoming respectively outgoing electrons. The superposition of these two structures leads to figure 4.12.

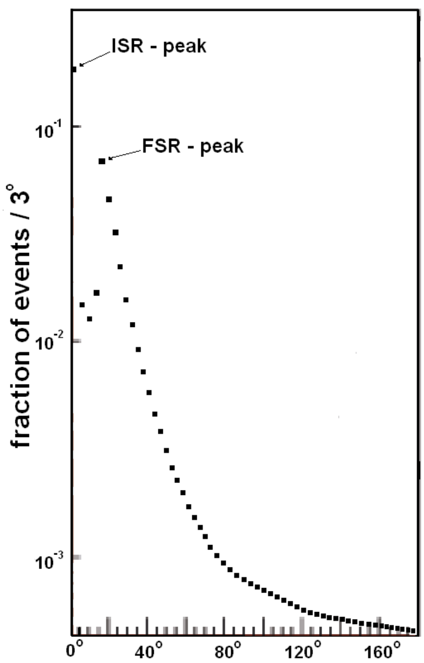

Figure 4.13: Expected polar angular distribution for photons emitted by positrons

4.3 Conclusions Concerning the Generator Comparison Studies

Babayaga@NLO and *BHWIDE* agree to the level of 1.0% in the differential distributions of the cross section in the cut selection regions interesting for the luminosity determination at *BaBar*. These deviations compensate, however, in the absolute cross section with a precision of approximately 0.1%.

An identical study concerning the differential cross sections without the effect of vacuum polarization was performed. However, the results were very similar to the results including all corrections. The assumption, that the effect of the Vacuum Polarization is only a constant factor applied to the cross section, was confirmed. In chapter 4.1 it was already shown that this shift of the absolute cross section was the same for *Babayaga@NLO* and *BHWIDE*.

Large differences from up to 20% between the two generators are seen in the sparse populated regions with very hard photon emission. It is not evident whether the *Babayaga@NLO* Parton Shower technique to approach higher order corrections or the YFS method used by *BHWIDE* is more precise in order to describe these rare events. This phase space region, however, clearly does not influence the luminosity determination at *BaBar*.

The older version *Babayaga.3.5* shows even in the phase space regions of interest for the *BaBar* luminosity determination differences from up to 10% compared to *BHWIDE* or *Babayaga@NLO*. In the absolute cross section remains a difference in the order of 1%. This reflects the importance of the inclusion of all NLO corrections into the *Babayaga* code.

Chapter 5

The Insertion of *Babayaga@NLO* into the *BaBar* Software Environment

A very important task of this diploma thesis was the insertion of the precise Bhabha event generator *Babayaga@NLO* into the *BaBar* simulation environment. The basic philosophy was to make the insertion in several steps, cross-checking in each phase whether the step procedure was correct. To make these check the original random number generator RANLUX was also included into the *BaBar* software. Like this it was possible to check that no mistake was introduced when *Babayaga@NLO* was inserted into the simulation framework of *BaBar* . If one starts the stand-alone version and the inserted one with the same SEED for the random number generator, exactly the same results must be obtained. A second important point of the insertion philosophy was to change as less code as possible during the insertion. The structure of *Babayaga* should be very similar to the original one, having in mind that *Babayaga@NLO* had to be divided into three sub-functions in order to fulfill the modular C^{++} standards of the *BaBar* software (see section 2.3.2). Having in mind these basic ideas, the main issues to handle were:

- the creation of a wrapper to establish a link between the Fortran *Babayaga@NLO* code and the C^{++} software environment of *BaBar*
- changing the structure of *Babayaga@NLO* to make it compatible with

the C^{++} standard *BABAR* modules

- the usage of a different standard *BABAR* random number generator
- improvements of the speed of the *Babayaga@NLO* data sample production
- final checks to assure that the insertion was correct

5.1 Linking *Babayaga@NLO* to *BABAR*

First, a class had to be defined in order to implement *Babayaga@NLO* generator into the *BABAR* framework. This is done with the GfiBabayaga.hh and GfiBabayaga.cc. In these files the run-time-parameters are defined. In addition elements of this class need to have the required modular structure of the *BABAR* code. This means that these elements can depend on the run-time-parameters and consist of the following three functions as described in:

- gfi_babayaga_init()
- gfi_babayaga_event()
- gfi_babayaga_final()

The Bhabha event generator *Babayaga@NLO* is written in Fortran. Therefore a link between this code and the C^{++} class structure had to be established. The file that represents this link is 'GfiBabayagaFort.F' (see appendix C.2). It satisfies the required class criteria. 'GfiBabayagaFort.F' calls the actual *Babayaga@NLO* code in three different modes, visualized in fig.5.1:

- gfi_babayaga_init() calls *Babayaga*(mode = -1)
- gfi_babayaga_event() calls *Babayaga*(mode = 0)
- gfi_babayaga_final() calls *Babayaga*(mode = 1)

In addition it passes on the run-time-parameter. As described before, run-time-parameters can be set in a Tcl file, without recompiling the code of *Babayaga@NLO*. In the corresponding Tcl file for *Babayaga@NLO*, GfiBabayaga.tcl, the user has access to the following run-time-parameters (more details in appendix C.1):

- **smearingMode:** The initial conditions of an event are given from a different program. There are smearing effects for the Center of Mass Energy E_{CMS}, which can be included in the production (true) or neglected (false)
- **minThetaLepton:** Sets the minimum polar scattering angle θ_{min} for the leptons
- **maxThetaLepton:** Sets the maximum polar scattering angle θ_{max} for the leptons
- **minEnergyLepton:** Sets the minimum energy of each outgoing lepton $E_{lep,min}$
- **maxCmsAcollinearity:** Sets a lower bound for the 3-dimensional angle *acol* between the outgoing leptons
- **minEnergyPhoton:** Sets the soft/hard photon energy separator, in $E_{CMS}/2$ units
- **nPhotonMax:** only a fixed number of (hard) photons are generated
- **photonicRadCorr:** 0 is Born approximation
1 is $\mathcal{O}(\alpha)$ approximation
2 is exponentiated (most precise)
- **runningAlpha:** switch for vacuum polarization: on (1) or off (2)
- **randomSeed:** sets seed for RANLUX number generator (more details next chapter)
- **nWeightedInitEvents:** number of weighted events to scan for FMAX

5.2 The Structure of *Babayaga@NLO*

The *Babayaga@NLO* code (see appendix C.3) has been adapted to the requested class structure. It is now dependent on the mode variable, which has three possible values:

- **gfi_babayaga_init() calls *Babayaga*(mode = -1):**

  All run-time-parameters are forwarded to *Babayaga@NLO*. The kinematic initial variables are set and the final variables are initialized in the *Babayaga*(-1) function. Also the requested number of weighted events is produced in order to find the maximum value of the weight FMAX.

- **gfi_babayaga_event() calls N_{ev} times *Babayaga*(mode = 0):**

  In the original *Babayaga@NLO* code a fixed number events is produced. Now *Babayaga@NLO* does not have this information concerning the number events that are supposed to be produced anymore. *Babayaga*(mode = 0) produces one single event each time it is called. A new veto routine was implemented that scans for an accepted unweighted event and passes the event information to the next *BABAR* module. This event routine is called N_{ev} times.

- **gfi_babayaga_final() calls *Babayaga*(mode = 1):**

  Finally a third function was created that handles the termination of event generation and gives out the standard code output on the screen.

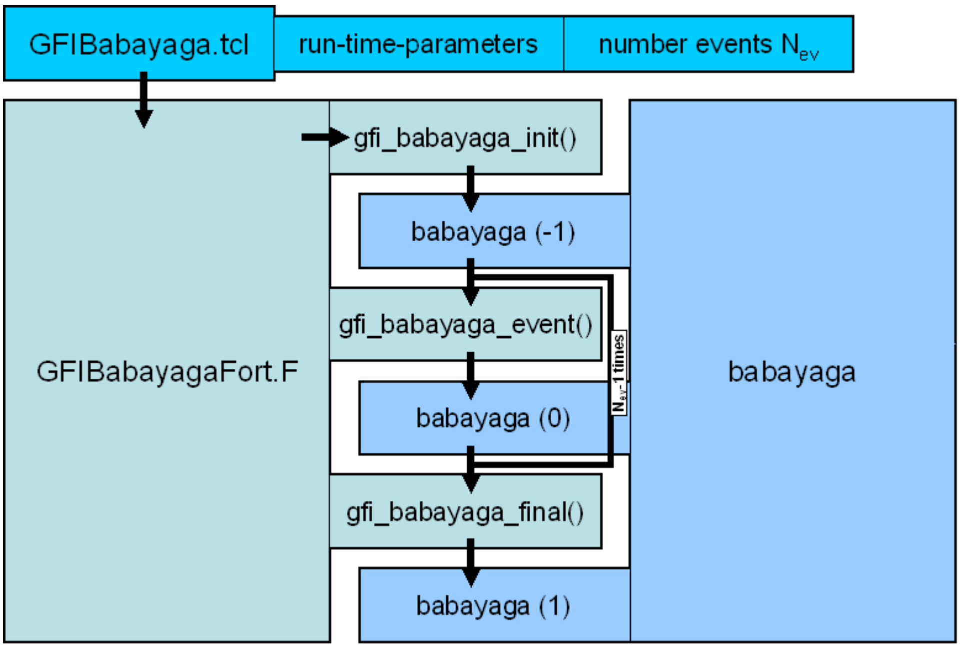

Figure 5.1: Link structure between *Babayaga@NLO* code and the *BABAR* module GfiBabayagaFort.F

5.3 Random Number Generator

The random number generator used in the Fortran *Babayaga@NLO* code is RANLUX. In the *BABAR* software environment, however, a standard *BABAR* random number generator has to be used. For Fortran code it was suggested to use the BEGRAN generator. This generator is now installed in the *Babayaga* package. The weighted events however are still produced with RANLUX, since they are only used to calculate FMAX. As soon as the unweighted production, the production of the physical events begins, BEGRAN takes over and produces the random numbers. This allows to ensure reproducability according to *BABAR* standards.

5.4 Speed Improvement of *Babayaga@NLO*

In order to increase the speed of *Babayaga@NLO* for the *BABAR* productions an additional option was implemented to the software. The so called **'Default Mode'** gets automaticaly enabled if the standard cut selections of *Babayaga@NLO* are chosen in the GfiBabayaga.tcl file. *Babayaga@NLO* will not compute the weighted events in the initialization routine anymore in order to search for this FMAX but takes a previously computed standard value. In order to receive a precision of the absolute cross section of better than one permill more than 5 million weighted events were generated in the FMAX exploration phase. Especially for productions with only a few unweighted events, a noticeable improvement of the production speed is observed with this method. The standard cut selections of *Babayaga@NLO*, with which the default mode values were computed, are:

photonicRadCorr	set 2
runningAlpha	set 1
minThetaLepton	set 15
maxThetaLepton	set 165
minEnergyLepton	set 3.0
maxCmsAcollinearity	set 180
minEnergyPhoton	set 0.0001
nPhotonMax	set -1
randomSeed	set 700253512
smearingMode	set true

5.5 Final Checks

It is still an option to use the original *Babayaga@NLO* random number generator RANLUX with the implemented code. An event by event comparison was done and it is evident that the results are the same for the stand-alone and the *BaBar* version.
It is also possible to check the correct implementation of the default mode. The weighted events are always computed with RANLUX. A sample of unweighted events was created using the same conditions as in the default mode. This sample has been compared to a sample produced in default mode. The unweighted events are in both cases produced with BEGRAN using the same seed. They are exactly the same. This means that the default mode implementation is successful, it creates the same initial conditions to produce unweighted events as the weighted event production procedure.
It is now safe to say that the implementation of *Babayaga@NLO* into the *BaBar* software environment was successful.

Chapter 6

Conclusions and Outlook

A detailed comparison of the Bhabha event generators for large angle Bhabha scattering has been performed. *BHWIDE* and *Babayaga@NLO* give the same results within a precision of 0.1% for the absolute cross section. However there are differences of the order of 1% concerning the angular distributions of the differential cross sections in the regions of interest for the *BABAR* luminosity determination. These differences almost completely compensate in the effective cross section in the phase space volume used for the luminosity measurement. Since the *Babayaga@NLO* event generator has a theoretical accuracy of approximately 0.1% and *BHWIDE* claims an accuracy of around 0.5%, it has been worthwhile to implement the *Babayaga@NLO* generator in the *BABAR* software environment, even though the precision of *BHWIDE* seemed to be underestimated.

The implementation of *Babayaga@NLO* into the *BABAR* software environment was successful. Tests were performed using the same random number generator, RANLUX, with the same seed for the implemented and stand alone version of *Babayaga@NLO*. Therefore, it was possible to confirm the correct implementation by means of an event to event comparison. The new *Babayaga@NLO* event generator will contribute to an improved luminosity determination at *BABAR*. I want to mention that a new version of *Babayaga@NLO* will be available in the near future. This version will include the $\gamma\gamma$ channel and the $\mu^+\mu^-$ channel with improved precision. Especially an improvement for the $\mu^+\mu^-$ channel is badly needed at the moment, since the total error is totally dominated by theory while $\mu^+\mu^-$ events can be selected experimentally with a similar (or even better) precision than Bhabha events.

An interesting study for which *Babayaga@NLO* will be used is a very light mass Dark Matter search at *BaBar* using the Radiative Return. A large flux of photons with the energy of the electron mass is observed coming from the center of our galaxy. The large flux of these photons is not yet understood. One possible explanation is that dark matter particles annihilate to e^+e^--pairs that later annihilate to photons:

$$\chi\overline{\chi} \rightarrow e^+e^- \rightarrow \gamma\gamma$$

If this is true there must exist a vector boson X that couples to the e^+e^--pair. The theoretical prediction for the mass of this boson is $m_X \leq 100\,\mathrm{MeV}/c^2$. Drees et al. proposed to look for this particle at the the ϕ-factory DAϕNE and B-factories. They estimate that it could be possible to detect this vector boson with the given luminosity with the *BaBar* detector [19]. It might be seen as a bump produced with ISR events, since the method of Radiative Return allows us to scan lower energy regions if an ISR-photon is emitted.

$$e^+e^- \rightarrow e^+e^-\gamma_{ISR} \rightarrow X\gamma_{ISR} \rightarrow e^+e^-\gamma_{ISR}$$

The dominating background for these events are Bhabha events, which therefore need to be theoretically understood with a high precision. The Bhabha event generator *Babayaga@NLO* seems to be ideally suited for such an analysis.

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Appendix A

Feynman Diagrams

A.1 NLO Corrections

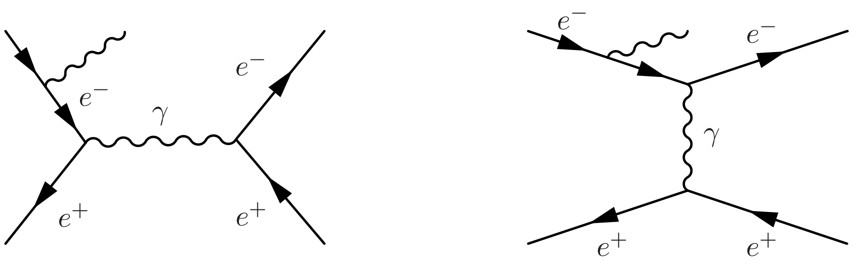

Figure A.1: Initial State Radiation in s-channel (left) and t-channel (right)

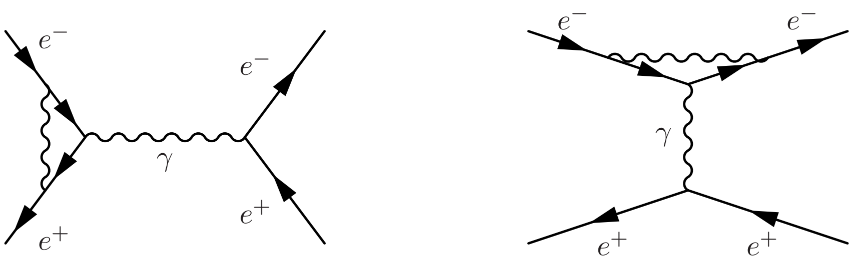

Figure A.2: Other NLO corrections

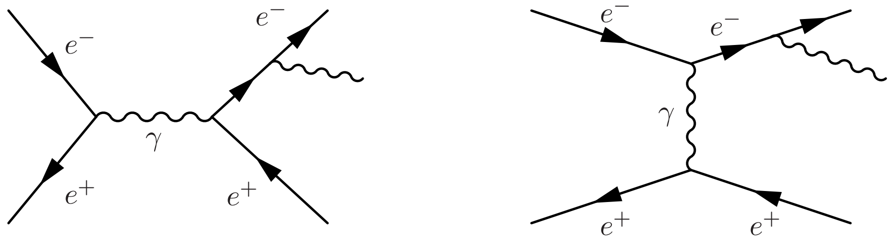

Figure A.3: Final State radiation in s-channel (left) and t-channel (right)

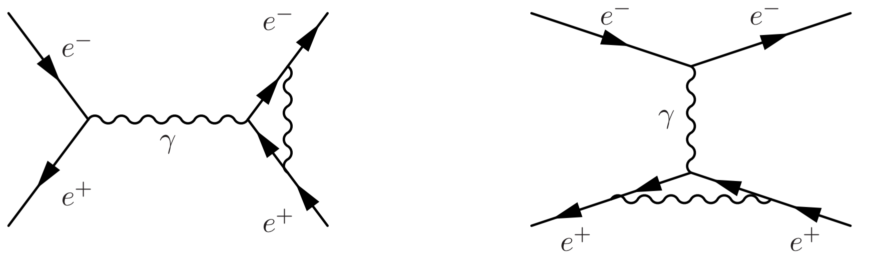

Figure A.4: Other NLO corrections

A.2 Other Corrections

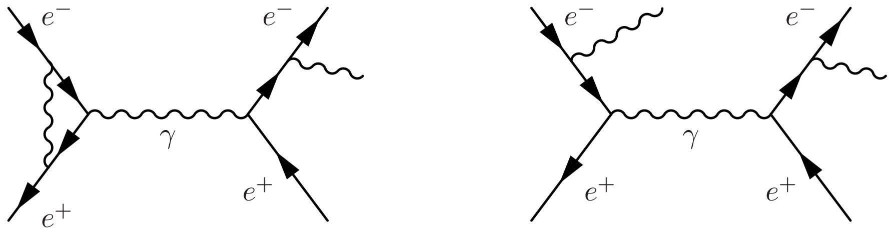

Figure A.5: Examples for NNLO corrections

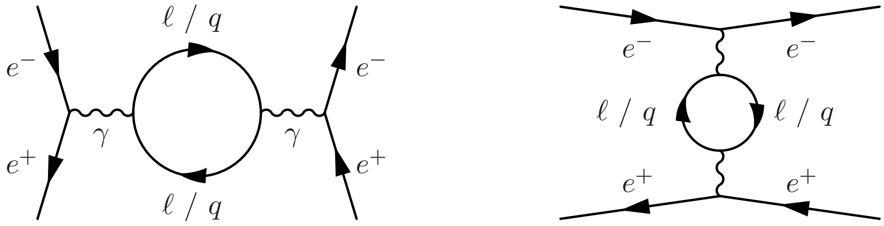

Figure A.6: Vacuum polarization in s-channel (left) and t-channel (right)

Appendix B

Comparison Plots

B.1 Angular Distribution of Outgoing Electron

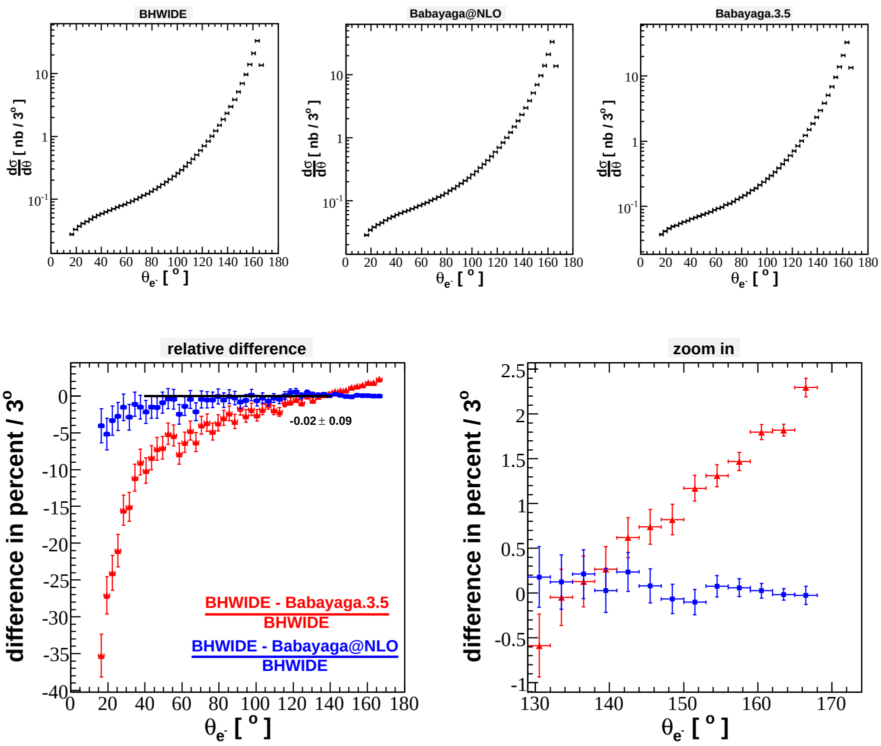

Figure B.1: TOP: differential cross section as function of the outgoing electron's polar angle, left: *BHWIDE*, center: *Babayaga@NLO*, right: *Babayaga.3.5*, BOTTOM: relative differences (left) with zoom (right)

B.2 Energy Distribution of Outgoing Electron

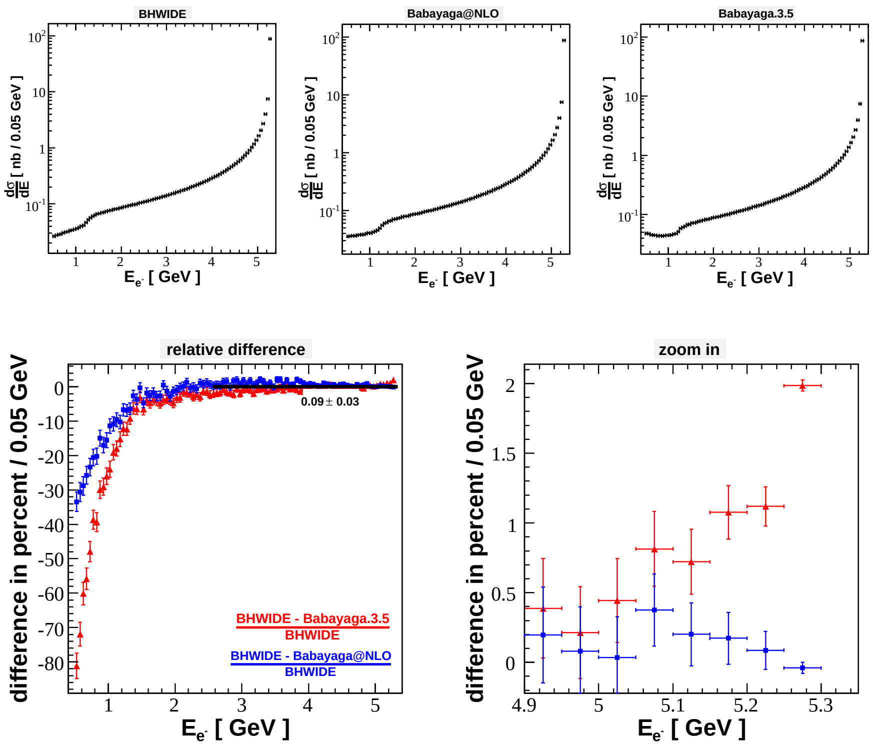

Figure B.2: TOP: differential cross section as function of the outgoing electron's energy, left: *BHWIDE*, center: *Babayaga@NLO*, right: *Babayaga.3.5*, BOTTOM: relative differences (left) with zoom (right)

Appendix C

Program Code

C.1 GfiBabayaga.tcl

```
####################################################################
#       sample tcl-file to run Babayaga@NLO event generator      #
####################################################################

sourceFoundFile ../GeneratorsQA/common.tcl

disableGenerators 0
module disable GqaMCAnalysis
module disable GqaBhwideHisto
module disable GqaBrmBbbremHisto
module disable GqaBkqedHisto

module disable GqaGamGamHist
module disable GqaAfkqedHisto
module disable GqaPhokharaHisto
module disable GqaTauHisto
module disable GqaAfkQedHisto
module disable GqaRandCheck
module disable GfiFlagLongLived

module enable GfiBabayaga
# A module to test babayaga:
##module enable GqaMCAnalysis
#path append genQA GqaBhwideHisto
```

```
# show

# set run-time parameters for the babayaga generator
#
module talk GfiBabayaga
  runRanlux set 0 ! if =1 then standard babayaga-rnd#generator
                  ! is used (set runRanlux=0 for BaBar production!)

  photonicRadCorr set 2
  runningAlpha set 1
  minThetaLepton set 15
  maxThetaLepton set 165
  minEnergyLepton set 3.0
  maxCmsAcollinearity set 180
  minEnergyPhoton set 0.0001
  nPhotonMax set -1
  randomSeed set 700253512
  nWeightedInitEvents set 5
  smearingMode set true
  show
exit

ev begin -nev 1000
exit
```

C.2 GfiBabayagaFort.F

```
 c-----------------------------------------------------------------------
c File and Version Information:
c $Id: GfiBabayagaFort.F,v 1.9 2006/12/09 00:52:09 hafner Exp $
c
c Description:
c      GfiBabayaga interface to the BaBayaga common blocks
c
c Environment:
c Software developed for the BaBar Detector at the SLAC B-Factory.
c
c Author List:
c     A. Hafner and G. Schott    Interface to the Babayaga generator
c-----------------------------------------------------------------------


c-----------------------------------------------------------------------
      SUBROUTINE gfi_babayaga_init(runRanluxint,
     &                             minThetaLepton, maxThetaLepton,
     &                             maxCmsAcollinearity, minEnergyLepton,
     &                             minEnergyPhoton, nPhotonMax,
     &                             runningAlpha, photonicRadCorr,
     &                             averageCmsEnergy,
     &                             verboseValue, nWeightedInitEvents,
     &                             randomSeed, defaultMode)
     IMPLICIT NONE

      integer runRanluxint
      integer runranluxinteger
      double precision minThetaLepton
      double precision maxThetaLepton
      double precision maxCmsAcollinearity
      double precision minEnergyLepton
      double precision minEnergyPhoton
      integer nPhotonMax
      integer runningAlpha
      integer photonicRadCorr
      double precision averageCmsEnergy
      integer verboseValue
```

```
integer nWeightedInitEvents
integer randomSeed
integer defaultmode    integer defaultmodesave
integer*8 k
double precision sdifmax
logical runranlux
double precision thmin,thmax,emin,zmax,egmin,thgmin,thgmax
integer nphotmode
double precision ecms
double precision eps
integer iwriteout,iseed,nsearch,iverbose
character*6 ord
integer iarun

double precision ecmssave

common/default/defaultmodesave
common/kblobk/k
common/realinput/sdifmax
common/rluxparam/runranlux
common/rluxsaveparam/runranluxinteger
common/expcuts/thmin,thmax,emin,zmax,egmin,thgmin,thgmax
common/nphot_mode/nphotmode
common/ecms/ecms
common/epssoft/eps
common/tclparameters/iseed,nsearch,iverbose
common/intinput/iwriteout
common/qedORDER/ord
common/ialpharunning/iarun
common/ecmssave/ecmssave

write(6,*) 'In subroutine gfi_babayaga_init'

runranlux = .true.
runranluxinteger = runRanluxint
if (defaultMode.eq.1) sdifmax = 479890.485
if (defaultMode.eq.1) k = 5000000
print*,'defaultilimode=',defaultMode
thmin = minThetaLepton
thmax = maxThetaLepton
```

```
      zmax = maxCmsAcollinearity
      emin = minEnergyLepton
      eps = minEnergyPhoton
      iseed = randomSeed
      nsearch = nWeightedInitEvents
      nphotmode = nPhotonMax
      iarun = runningAlpha
      defaultmodesave = defaultmode
      if (photonicRadCorr.eq.0) ord = 'born'
      if (photonicRadCorr.eq.1) ord = 'alpha'
      if (photonicRadCorr.eq.2) ord = 'exp'
      print*,'Setting the order to ',ord
      print*,'runRanluxint == ', runRanluxint

      ecms = averageCmsEnergy
      ecmssave = averageCmsEnergy

      call babayaga(-1)

      RETURN
      END
c-----------------------------------------------------------------------


c-----------------------------------------------------------------------
      SUBROUTINE gfi_babayaga_event( cmsEnergySmeared, betaSmearedX,
     &                               betaSmearedY, betaSmearedZ )
      IMPLICIT NONE

      double precision cmsEnergySmeared
      double precision betaSmearedX,betaSmearedY,betaSmearedZ
CC      double precision betx,bety,betz
      double precision ecms
      integer*8 k
      integer iseed,nsearch,iverbose
      double precision ecmssave

c     Smeared energy parameters
CC      common/ecmssmeared/betx,bety,betz
      common/ecms/ecms
```

```
      common/kblobk/k
      common/tclparameters/iseed,nsearch,iverbose
      common/ecmssave/ecmssave

      if (nsearch+1==k) then
      write(6,*) 'In subroutine gfi_babayaga_event'
      endif

c     Set smeared CM energy
      ecms = cmsEnergySmeared
      ecmssave = cmsEnergySmeared

CC      betx = betaSmearedX
CC      bety = betaSmearedY
CC      betz = betaSmearedZ

      call babayaga(0)
      call babtohep

      RETURN
      END
c-----------------------------------------------------------------------


c-----------------------------------------------------------------------
      SUBROUTINE gfi_babayaga_final
      IMPLICIT NONE

      write(6,*) 'In subroutine gfi_babayaga_final'

      call babayaga(1)

      RETURN
      END
c-----------------------------------------------------------------------
```

C.3 Babayaga.F

```
***************************************************
*          BaBayaga@NLO event generator           *
*     written by CMCC, last modified 5/3/2006     *
*         adapted for BaBar by GS and AH          *
***************************************************
      subroutine babayaga(mode)
      implicit double precision(a-h,o-z)

      integer mode   ! set mode: -1: init, 0:event, 1:final
      logical genend   ! stop searching for an unweighted event


      double precision sdifmax
      integer*8 k,naccepted,iwriteout
      parameter (mph=40)
      real*4 csi(1)
      dimension randvec(3)
      dimension sump(0:mph-1),sum2p(0:mph-1)
      dimension fractions(0:mph-1)
      dimension xsecp(0:mph-1),varp(0:mph-1)
      dimension pin(0:3),p1(0:3),p2(0:3),qph(mph,0:3),q(0:3)
      dimension pin1(0:3),pin2(0:3),ptmp(0:3),pbeam1(0:3),pbeam2(0:3)
      dimension p1b(0:3),p2b(0:3)
      integer isvec(25)
      character*6   ord
      character*10  model
      character*100 storefile
      character*3   eventlimiter,store

      double precision ecmsav

      integer runranluxinteger
      logical runranlux


      common/kblobk/k
      common/momentafinal/p1,p2
```

```
*** filled in the subroutine userinterface
      common/ecms/ecms
      common/ecmsav/ecmsav
      common/ecmssave/ecmssave
      common/nphot$\_$mode/nphotmode
      common/expcuts/thmin,thmax,emin,zmax,egmin,thgmin,thgmax
      common/zparameters/zm,gz,ve,ae,rv,ra,wm,s2th,gfermi,sqrt2,um
      common/epssoft/eps
      common/energiabeam/ebeam
      common/parameters/ame,convfac,alpha,pi
      common/tclparameters/iseed,nsearch,iverbose
      common/intinput/iwriteout
      common/qedORDER/ord
      common/charinput/model,eventlimiter,store,storefile
      common/realinput/sdifmax
      common/nmaxphalpha/nphmaxalpha
      common/ialpharunning/iarun
*********************************************

      common/coseni/cmax,cmin
      common/momentainitial/pin1,pin2
      common/radpattern/nph(4)

      common/forborncrosssection/phsp2b,flux2b,bornme,bornmeq2,bornmez
      common/reducedtoborn/p1b,p2b
      common/various/beta
      common/for$\_$debug/ppp(0:3),denphsp,dir3(0:3),dir4(0:3)

      common/rluxsaveparam/runranluxinteger
      common/rluxparam/runranlux

      common/babayagacommon1/am1,am2,esoft
      common/babayagacommon12/in$\_$conf$\_$spin,npoints
      common/babayagacommon2/pbeam1,pbeam2,sum,sum2,sump,sum2p
      common/babayagacommon3/sumover,sum2over,sumneg,sum2neg
      common/babayagacommon14/nphmax
      common/babayagacommon24/xsec
      common/babayagacommon34/var
      common/babayagacommon44/naccepted
      common/babayagacommon5/bornmax,phspmax,nwhenmax
```

```
      common/babayagacommon8/wmax,prodmax
      common/babayagacommon6/elmmax,nover
      common/babayagacommon8/fmax,hmeff
      common/babayagacommon7/hitpmiss,hit,istopsearch,nneg,wnpoints,qph

      print$\*$,'In main programme, mode = ',mode

c     Initialisation stage
      if (mode.eq.-1) then
         call userinterface
         print$\*$,'Setting the average CM energy to ', ecms
         ecmsav = ecms
         cmax = cos(thmin)
         cmin = cos(thmax)
$\*$     for ALPHA, not released
$\*$         call init$\_$apar
         am1 = ame
         am2 = ame
      endif

c     Set beam parameters in the init and event-generation stages
      if (mode.eq.-1.or.mode.eq.0) then

         if (k.le.nsearch) then
            ecms = ecmsav
         else
            ecms = ecmssave
         endif

      esoft = eps $\*$ ecms/2.d0

      in$\_$conf$\_$spin = 4

      pin(0) = ecms
      pin(2) = 0.d0
      pin(3) = 0.d0
      pin(1) = 0.d0

      beta = sqrt(1.d0 - 4.d0$\*$am1$\*$$\*$2/pin(0)$\*$$\*$2)
      pin1(0) = pin(0)/2.d0
```

```
      pin1(1) = 0.d0
      pin1(2) = 0.d0
      pin1(3) = beta $\*$ pin1(0)
      pin2(0) = pin(0)/2.d0
      pin2(1) = 0.d0
      pin2(2) = 0.d0
      pin2(3) = -beta $\*$ pin2(0)

      do ki = 0,3
         pbeam1(ki) = pin1(ki)
         pbeam2(ki) = pin2(ki)
      enddo
      endif ! mode=-1 or mode=0

c     Initialisation stage (continued)
      if (mode.eq.-1) then
      sum = 0.d0
      sum2 = 0.d0
      do ki = 0,mph-1
         sump(ki) = 0.d0
         sum2p(ki) = 0.d0
      enddo
      nphmax = 0
      xsec = 0.d0
      var  = 0.1d0
      naccepted = 0

      bornmax  = 0.d0
      phspmax  = 0.d0
      nwhenmax = 0
      wmax     = 0.d0
      prodmax  = 0.d0
      elmmax   = 0.d0
      nover    = 0
      hitpmiss     = 0.d0
      hit          = 0.d0
      istopsearch  = 0
      nneg         = 0
      sumover      = 0.d0
      sum2over     = 0.d0
```

```
      sumneg       = 0.d0
      sum2neg      = 0.d0
      if (store.eq.'yes') call initstorage(storefile)
      do j = 0,3
         do ki = 1,mph
            qph(ki,j) = 0.d0
         enddo
      enddo
      ng = 0

      endif  ! mode=-1

c     Event generation mode
      if (mode.eq.0) then

         genend = .false.
         do while(genend.eqv..false.)

         if (k.le.nsearch) then
            ecms = ecmsav
         else
            ecms = ecmssave
         endif

         esoft = eps $\*$ ecms/2.d0

         in$\_$conf$\_$spin = 4

         pin(0) = ecms
         pin(2) = 0.d0
         pin(3) = 0.d0
         pin(1) = 0.d0

         beta = sqrt(1.d0 - 4.d0$\*$am1$\*$$\*$2/pin(0)$\*$$\*$2)
         pin1(0) = pin(0)/2.d0
         pin1(1) = 0.d0
         pin1(2) = 0.d0
         pin1(3) = beta $\*$ pin1(0)
         pin2(0) = pin(0)/2.d0
         pin2(1) = 0.d0
```

```
         pin2(2) = 0.d0
         pin2(3) = -beta $\*$ pin2(0)
         do ki = 0,3
            pbeam1(ki) = pin1(ki)
            pbeam2(ki) = pin2(ki)
         enddo

         k = k+1

         if (k.eq.nsearch+1) then
            if (runranluxinteger.eq.1) runranlux = .true.
            if (runranluxinteger.eq.0) runranlux = .false.
         endif

         flux = 8.d0 $\*$ (ecms/2.d0)$\*$$\*$2

         call get$\_$cos$\_$fer(csi(1),cth,wcos)
         call multiplicity(eps,ecms,cth,ng,wnphot)
         sdif = wnphot$\*$wcos

! this works
c     call phasespacenew(pin,p1,p2,qph,ng,am1,am2,esoft,phsp,w,ie)
c but this works great!!
         call phasespace(pbeam1,pbeam2,p1,p2,qph,ng,am1,am2,
     .        esoft,cth,w,phsp,ie)
         if (ie.ge.1) ie = 1
         if (ng.gt.nphmax) nphmax = ng
         sdif = sdif $\*$ phsp $\*$ w
         if (ie.lt.1) then
            call cuts(p1,p2,qph,icut)
         else
            icut = 1
         endif
         ie = ie + icut
         if (icut.eq.0) naccepted = naccepted + 1

!!        ie = 1   ! uncomment  for phase space integral
         call squared$\_$matrix(model,ng,ecms,p1,p2,qph,ie,
     >        icalc,emtx,prod)
```

```
         bck  = emtx
         emtx = emtx/in$\_$conf$\_$spin ! divided by initial spin conf.
         emtx = emtx$\*$convfac/flux ! divided by the flux

         if (ie.eq.0) then
            call svfactor(model,ng,ecms,p1,p2,eps,sv,deltasv)
            sdif = sdif $\*$ sv
         else
            sdif = 0.d0
         endif

         sdif = sdif $\*$ emtx
! rescaling for Z exchange
         sdif = sdif/bornme$\*$(bornme + bornmez)
!!         emtx = 1.d0 ! uncomment  for phase space integral
         iii = 0
         if (sdif.gt.sdifmax) then
            sdifmax = sdif
            nwhenmax = ng
            iii = 1
         endif
         if (istopsearch.eq.0) then
            if (iverbose.eq.1.and.iii.eq.1) then
               call eikonal$\_$factor('multip',ng,pin1,
     .              pin2,p1,p2,q,qph,eikonal)
               call eikonal$\_$noint('multip',ng,pin1,
     .              pin2,p1,p2,q,qph,eiknoint)
               print$\*$,'=======',nph,sdif/sdifmax,eikonal/eiknoint
            endif
         endif


!! unweightening for unweighted events...
         if (k.gt.nsearch) then
            istopsearch = 1
            if (hitpmiss.lt.1.d0) then
               fmax = 1.1d0$\*$sdifmax
               print$\*$,'Starting now also unweighted generation!'
            endif
            hitpmiss = hitpmiss + 1.d0
```

```
            call BBRRANDNUM(csi,1)
            if (fmax$\*$csi(1).lt.sdif) then
               hit = hit + 1.d0
ccc               print$\*$,'k ===============',k
ccc               print$\*$,'ecms ===============',ecms
               genend = .true.  ! we found a good unweighted event
C               if (store.eq.'yes') call eventstorage(p1,p2,qph)
            endif
            if (sdif.lt.-1.d-12) then
               nneg  = nneg  + 1
               sumneg  = sumneg + abs(sdif)
               sum2neg = sum2neg + sdif$\*$$\*$2
            endif
            if (sdif.gt.fmax) then
               nover = nover + 1
               sumover  = sumover  + sdif - fmax
               sum2over = sum2over + (sdif - fmax)$\*$$\*$2

               if (iverbose.eq.1) then
                  prodom = 1.d0
                  do i = 1,ng
                     prodom = prodom$\*$qph(i,0)
                  enddo
                  call eikonal$\_$factor('multip',ng,pin1,pin2,
     .                 p1,p2,q,qph,eikonal)
                  call eikonal$\_$noint('multip',ng,pin1,pin2,
     .                 p1,p2,q,qph,eiknoint)
                  print$\*$,'.......................................'
                  print$\*$,sdif/fmax,nph,' event: ',k
                  print$\*$,eikonal/eiknoint

                  a1 = acos(p1(3)/sqrt(tridot(p1,p1)))$\*$180.d0/pi
                  a2 = acos(p2(3)/sqrt(tridot(p2,p2)))$\*$180.d0/pi
                  print$\*$,'angles and acoll',a1,a2,abs(180.d0 - a1 - a2)

                  a1 = acos(p1b(3)/sqrt(tridot(p1b,p1b)))$\*$180.d0/pi
                  a2 = acos(p2b(3)/sqrt(tridot(p2b,p2b)))$\*$180.d0/pi
                  print$\*$,'angles and acoll for born',
     .                 a1,a2,abs(180.d0 - a1 - a2)
```

```
                  if (ng.ge.1.and.sdif/fmax.gt.1.d0) then
                     sampl = 1.d0
                     do i = 1,ng
                        print$\*$,'>> ',i,' of',ng
                        do j = 0,3
                           ptmp(j) = qph(i,j)
                        enddo
                        print$\*$,ptmp(0),p1(0),p2(0)
                        pin1mod = sqrt(tridot(pin1,pin1))
                        print$\*$,acos(tridot(ptmp,pin1)/ptmp(0)/pin1mod)
     .                       $\*$180/pi
                        p1mod = sqrt(tridot(p1,p1))
                        p2mod = sqrt(tridot(p2,p2))
                        print$\*$,acos(tridot(ptmp,p1)/ptmp(0)/p1mod)$\*$180/pi
                        print$\*$,acos(tridot(ptmp,p2)/ptmp(0)/p2mod)$\*$180/pi
                        c1 = ptmp(0)$\*$pin1(0)/dotb(ptmp,pin1)
                        c2 = ptmp(0)$\*$pin2(0)/dotb(ptmp,pin2)
                        c3 = ptmp(0)$\*$p1(0)/dotb(ptmp,p1)
                        c4 = ptmp(0)$\*$p2(0)/dotb(ptmp,p2)
                        sampl = sampl$\*$(c1+c2+c3+c4)
                     enddo
                  endif
               endif
            endif
         endif
!!!!!!
         sum  = sum  + sdif
         sum2 = sum2 + sdif$\*$$\*$2

         sump(ng)  = sump(ng)  + sdif
         sum2p(ng) = sum2p(ng) + sdif$\*$$\*$2

         varbefore = var
         xsec = sum/k
         var  = sqrt(abs((sum2/k-xsec$\*$$\*$2)/k))
         tollerate = 2.d0
         if (var.gt.tollerate$\*$varbefore.and.varbefore.gt.0.d0) then
            if (iverbose.eq.1) then
               print$\*$,' '
               print$\*$,'@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@ '
```

```
               print$\*$,'Event ',k,'  ratio',var/varbefore
               print$\*$,bck       ! l'el. di matr. come esce dalla routine...
               print$\*$,'Ecms = ',pin1(0) + pin2(0)
               print$\*$,nph
               print$\*$,p1
               print$\*$,p2
               print$\*$,acos(p1(3)/sqrt(tridot(p1,p1)))$\*$180/pi
               print$\*$,acos(p2(3)/sqrt(tridot(p2,p2)))$\*$180/pi
               do j = 1,ng
                  do i = 0,3
                     ptmp(i) = qph(j,i)
                  enddo
                  print$\*$,ptmp
                  a = acos(ptmp(3)/sqrt(tridot(ptmp,ptmp)))$\*$180.d0/pi
                  a1 = acos(tridot(ptmp,p1)/ptmp(0)/sqrt(tridot(p1,p1))
     >                 )$\*$180.d0/pi
                  a2 = acos(tridot(ptmp,p2)/ptmp(0)/sqrt(tridot(p2,p2))
     >                 )$\*$180.d0/pi
                  print$\*$,'angles ',a,a1,a2
               enddo
               print$\*$,'@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@'
               print$\*$,' '
            endif
!     ! Nullifying this event....
            ratio = var/varbefore
            if (k.gt.5000000.and.ratio.gt.10) then
               print$\*$,'^^^^^^^^^^^^^^^^^^^^^^^^^^'
               print$\*$,'REJECTING THE EVENT'
               print$\*$,'^^^^^^^^^^^^^^^^^^^^^^^^^^'
               sum = sum - sdif
               sum2 = sum2 - (sdif)$\*$$\*$2
               sump(ng) = sump(ng) - sdif
               sum2p(ng) = sum2p(ng) - (sdif$\*$$\*$2)
               xsec = sum/k
               var  = sqrt((sum2/k-xsec$\*$$\*$2)/k)
               sdif = 0.d0
            endif
         endif
$\*$
         if (icalc.eq.1.and.ie.eq.0) then
```

```
            call distributions(sdif,k,p1,p2,qph)
         endif

      enddo
      endif  ! mode=0

c     Finalisation stage
      if (mode.eq.1) then

C     Creates files such as matched$\_$....txt
C            call writedistributions

!! hit or miss cross section...
            hmxsect = 0.d0
            hmerr   = 0.d0
            if (hitpmiss.gt.0.d0)  then
               print$\*$,'hitpmiss>0'
               hmeff   = hit/hitpmiss
               hmxsect = fmax$\*$hmeff
               hmerr   = fmax $\*$ sqrt(hmeff$\*$(1-hmeff)/hitpmiss)
            endif
!!

            xsec = sum/k
            var  = sqrt((abs(sum2/k-xsec$\*$$\*$2))/k)

            write(6,$\*$)' '
            write(6,'(1x,A,f12.4,A)')
     >           'Ecms (average value) =',ecmsav,' GeV'
            write(6,'(1x,A,f12.4,A)')
     >           'thmin  =',thmin$\*$180.d0/pi,' deg'
            write(6,'(1x,A,f12.4,A)')
     >           'thmax  =',thmax$\*$180.d0/pi,' deg'
            write(6,'(1x,A,f12.4,A)')
     >           'acoll. =',zmax$\*$180.d0/pi,' deg'
            write(6,'(1x,A,f12.4,A)')
     >           'emin   =',emin,' GeV'
            write(6,'(1x,A)')
     >           'ord    = '//ord
            write(6,'(1x,A)')
```

```
     >          'model  = '//model
            write(6,'(1x,A,i5)')
     >          'nphot mode =',nphotmode
            write(6,'(1x,A,i9)')
     >          'seed   =',iseed
            write(6,'(1x,A,i5)')
     >          'iarun  =',iarun
            write(6,'(1x,A,f10.9)')
     >          'eps    = ',eps
            write(6,$\*$)' '
            if (eventlimiter.eq.'w') then
               write(6,'(A,f12.0,A)')'~ Generating ', nsearch,
     .             ' weighted events ~'
            else
               write(6,'(A,f12.0,A)')'~ Generating ', hit,
     .             ' unweighted events ~'
            endif
            write(6,$\*$)' '
            write(6,$\*$)'::::::>>>>>> weighted events <<<<<<::::::'
            do i = 0,nphmax
               xsecp(i) = sump(i)/k
               varp(i)  = sqrt((abs(sum2p(i)/k-xsecp(i)$\*$$\*$2))/k)
               fractions(i) = xsecp(i)/xsec $\*$ 100.d0
               write(6,'(i2,A,f10.5,A,f10.5,A,f6.2,A)')
     :             i,' photons: ',xsecp(i),' +-',varp(i),
     :             '      (',fractions(i),' %)'
            enddo
            write(6,'(1x,A,f10.5,A,f10.5,A)')
     :          'total:   ',xsec,' +-',var,' nb'
            write(6,$\*$)' '
c            write(6,$\*$)'fractions (%)',(fractions(i),i=0,nphmax)
            eff = (1.d0$\*$naccepted)/k
c            write(6,'(1x,A,i12)')
c     :          'accepted ',naccepted
            write(6,'(1x,A,f6.2,A)')
     :          'cut points ',100.d0 - eff$\*$100,' %'
            write(6,$\*$)'::::::>>>>>>>>>>>>>>><<<<<<<<<<<<<<<::::::'
            write(6,$\*$)' '
            write(6,$\*$)'::::::>>>>>> unweighted events <<<<<<::::::'
            write(6,'(1x,A,f6.2,A)')
```

```
     :          'hit or miss efficiency ',hmeff$\*$100,' %'
           write(6,'(1x,A,f12.0,A,f12.0)')
     :          'hit+missed and hit points ',hitpmiss,' ',hit
           write(6,'(1x,A,f12.0)')
     :          'unweighted events generated ',hit
           biashit        = 0.d0
           biashitpmiss   = 0.d0
           biasneghit     = 0.d0
           biasneghitmiss = 0.d0
           sezover        = 0.d0
           errsezover     = 0.d0
           if (hit.gt.0.d0) then
              print$\*$,'hit>0'
              biashit      = 1.d0$\*$nover/hit
              biashitpmiss = 1.d0$\*$nover/hitpmiss
              biasneghit   = 1.d0$\*$nneg/hit
              biasneghitmiss = 1.d0$\*$nneg/hitpmiss
              sezover    = sumover/hitpmiss
              errsezover = (sum2over/hitpmiss - sezover$\*$$\*$2)/hitpmiss
              errsezover = sqrt(abs(errsezover))
              sezneg    = sumneg/hitpmiss
              errsezneg = (sum2neg/hitpmiss - sezneg$\*$$\*$2)/hitpmiss
              errsezneg = sqrt(abs(errsezneg))
           endif
           write(6,$\*$)' '
           write(6,'(1x,A,f10.5,A,f10.5,A)')
     :          'total (nb):   ',hmxsect,' +-',hmerr,' +'
           write(6,'(1x,A,f10.5,A,f10.5,A)')
     :          '       !!!!   ',sezover,' +-',
     :          errsezover,' (bias over fmax) +'
           write(6,'(1x,A,f10.5,A,f10.5,A)')
     :          '       !!!!   ',-sezneg,' +-',
     :          errsezneg,' (bias negative)'

           write(6,'(1x,A,f10.5,A,f10.5)')
     :          'total + biases: ',hmxsect
     :          +sezover-sezneg,' +-',hmerr+errsezover+errsezneg
           write(6,$\*$)' '
           write(6,'(1x,A,i12)')
     :          'N. points with w > fmax (bias): ',nover
```

```
            write(6,'(1x,A,f10.7,A,f10.7,A)')
     :           'bias/hit and bias/(hit+missed):',
     :           biashit$\*$100,' % and ',biashitpmiss$\*$100,' %'
            write(6,'(1x,A,i12)')
     :           'N. points with w < 0:',nneg
            write(6,'(1x,A,f10.5,A,f10.5,A)')
     :           'biases for w < 0:   ',
     :           biasneghit$\*$100,' % and ',biasneghitmiss$\*$100,' %'
            write(6,$\*$)' '
            write(6,'(1x,A,f14.6,A,f14.6)')
     :           'Upper limits fmax and sdifmax',fmax,' ',sdifmax
            write(6,'(1x,A,i3,A)')
     :           'when there were ',nwhenmax,' photons'
            write(6,$\*$)':::::>>>>>>>>>>>>>>><<<<<<<<<<<<<<<:::::'
            write(6,$\*$)' '
C       if (store.eq.'yes') call finalizestorage
      endif                     ! mode=1

      end
```

Hiermit versichere ich, die vorliegende Arbeit selbständig verfasst und nur die angegebenen Hilfsmittel verwendet zu haben.

Andreas Hafner

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