Final Report
TPOL Geant3 Simulation

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Abstract

This document has for goal to show what has been done with the GEANT3 Monte Carlo (MC) simulation of the TPOL polarimeter since May 2005. TPOL has for goal to measure the polarization at the electron-proton collider Hera situated at Hamburg, Germany. Two main analysis has been done since using the MC simulation. Firstly, we analyzed the parameters that could have an influence on the Analysing Power (AP) and the focus, both quantities that have a big importance in the determination of the polarization. We then tried to optimized these parameters in the simulation. Secondly, we studied the effect of the backsplash in the polarimeter. We paid a special attention to the efficiency of the detector to "measure" the y-position of the backscattered photons and thus to get an accurate η-curve. These measurements are essential to evaluate the polarization of the Hera's leptons beam.

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1-Introduction

Hera (Hadron Electron Ring Accelerator) is a lepton-proton collider situated at Desy research center, Hamburg. The two storage rings, one for the protons and one for the electrons, have a circumference of 6.3 km. That permits to accelerate the electrons and the protons up to an energy of ~30GeV and ~820GeV respectively. The collisions between these particles are use to study some phenomena in high energy physics. Polarization play a crucial role in most of these phenomena.

For this reason, two polarimeters are used to record in continue the polarization of the leptons (electrons or positrons) beam: TPOL and LPOL. TPOL measure the transversal polarization (perpendicular to the beam direction) and LPOL measure the longitudinal polarization (parallel to the beam). In order to accurately use polarization in the experimental analysis, one would wish to have an error (ΔP / P) smaller than 2%. Unfortunately, this number has not been reach yet. At the beginning of their utilization, TPOL had a systematic uncertainty of 10% and LPOL had one of 5%. At the beginning of the summer 2005, many investigations and analysis had permitted to reduce these numbers to 3,5% and 2%. Also, as it will be explain later, the polarization measured by TPOL should be the same than the one measured by LPOL. Unfortunately, LPOL measurements were systematically higher than TPOL by about 7%. Again, the TPOL group had succeed to bring down this number to less than 2%. Theses progress are encouraging, but some work has to be done in order to be able to reduce these numbers again...

One of the main tool in this processes is the Monte Carlo simulation. The GEANT software, from the CERN program library, allow one to reconstructs the geometry of a given detector and to analyze what are the expected results for different beams using a computer simulation.

The work that has to be done with the Monte Carlo simulation of the TPOL polarimeter can be separated in two big parts. The first part is to improve the quality of the simulation by making it correspond more accurately to the results we get in the real polarimeter. We do this by adding new features to the simulation and by trying to find the best defaults parameters of the simulation (absolute calibration). The second part is to use the simulation to identify problems that could occur in the setup of TPOL or in the analysis used to determine the polarization. Once the problems are identified, we can simulate solutions to see whether they solve the problem or not.

2-Polarization

2.1-How the polarization is built inside Hera's rings

The polarization of the particles in the Hera's rings is a consequence of the relativistic motion of the particles and the strong magnetic fields used. This effect is known as the Sokolov-Tenov effect [1]. As the leptons move inside the ring, they become transversely polarized through the emission of synchrotron radiation and differential up/down spin flip rate. The polarization in function of the time should follow a exponential behavior of the form:

$$P(t) = Pmax\,(1 - \exp(-\frac{t}{\tau})) \tag{1}$$

,where Pmax is the maximum polarization at equilibrium and τ is a constant called the "polarization time". Due to the constant random probability of a flip of the spin of the electrons (or positrons), we should not expect a Pmax of 100%. The theory predict a maximum polarization of 92%. Unfortunately, Pmax at Hera has an average of 40% and go rarely over 50%. Lot of efforts are deployed to bring this average number over 55%. Moreover, the polarization time constant has been measured (in 1994 and 1997) to be about 37 minutes, which mean that the polarization build fairly slowly (figure 1):

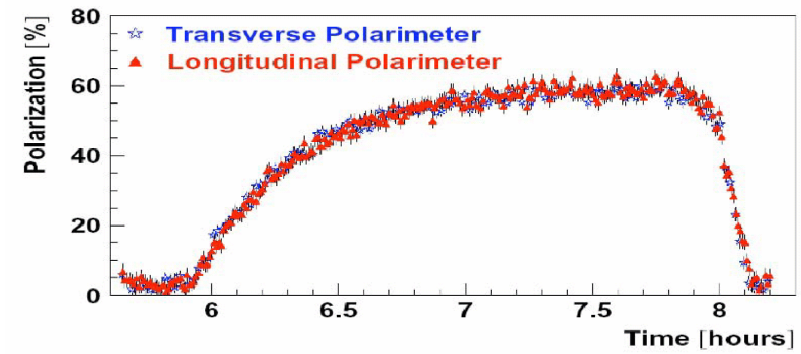

Figure 1: Polarization (in %) of the leptons in the Hera's beam as a function of the time [6]. In this plot polarization reach 60%, but it is unusual.

2.2-How the polarization is threated and used at Hera

The theory predict that the transversal polarization of the leptons should have no effect on the longitudinal collision with the protons. Experiments have indeed confirmed this reality. However, the longitudinal polarization of the leptons should affect the behavior of the collisions lepton-proton. In order to analyze this fact, spin rotators has been installed before and after each detectors, where the collisions are performed. The role of these spin rotators is precisely to change the orientation of the polarization from transversal to longitudinal and back from longitudinal to transversal. Since spin rotators only rotate the orientation of the polarization and don't affect the norm, we should measure the same polarization before and after the particles get in the detector, measurements done with TPOL, and while they are in the detector, measurements done with LPOL. To be more precise, TPOL is situated between the detectors ZEUS and H1 (far from the spin rotator and when the polarization is transversal), and LPOL is situated at HERMES (where polarization is longitudinal). See figure 2:

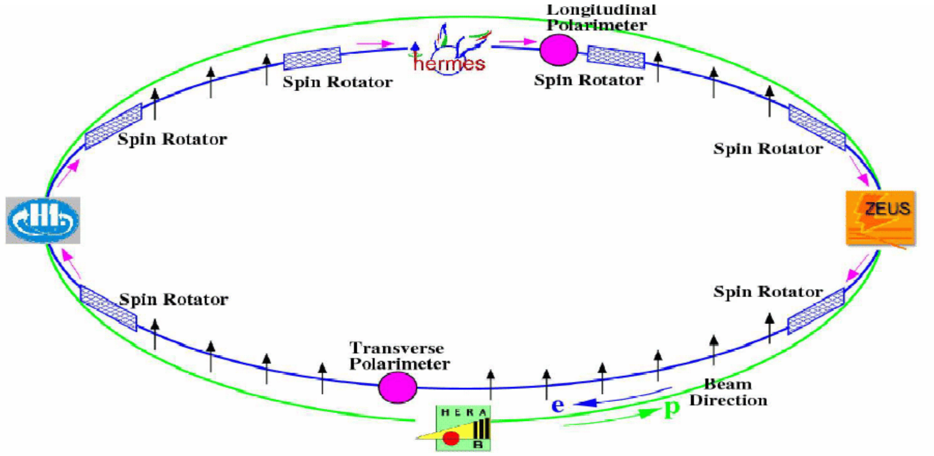

Figure 2: This scheme shows the respective position of the four detectors (Zeus, Hera B, H1, Hermes) and the two polarimeters (Transverse and Longitudinal) at the Hera ring. An vertical arrow mean that the polarization is transversal and an horizontal arrow mean that the polarization is longitudinal [8].

2.3-The determination of the polarization

In order to determine the polarization of the beam of leptons, we need to study the Compton cross section of the Compton scattering of right/left polarized photons with the leptons in the beam. The Compton cross section is given by the following equation:

$$\frac{d^2\sigma}{dEd\phi} = \Sigma_0 + S_1\Sigma_1(E)\cos 2\phi + S_3(P_Y\Sigma_{2Y}(E)\sin\phi + P_Z\Sigma_{2Z}(E))$$

$\vec{P} = (P_X, P_Y, P_Z)$ polarization vector

$\vec{S} = (S_1, S_2, S_3, S_4)$ Stokes vector

(2)

,where E is the energy, ϕ is the azimuthal angle, $\Sigma(0,1,2y,2z)$ are parameters that are function of the energy, **P**=(Px,Py,Pz) is the polarization vector for the leptons, and **S**=(S1,S2,S3,S4) is the Stokes vector for the photons [7]. Notice that the z-direction is taken to be the longitudinal direction and the y-direction is taken to be the transversal direction. Notice also that S1 correspond to the linear polarization of the photons and S3 to the circular polarization (helicity) of the photons (for left handed polarization, S3 is positive; and for right handed polarization, S3 is negative). Since we are interested in the value of Py and Pz, a quick look to the equation tell us that we should use photons with S1=0 in order to remove the "useless" second term. On the other hand, we should use a high S3, since the third term is the one we are interested in. A further analysis of this formula inform us of a big difference between the way we will have to determine the polarization Py and Pz. Putting Py=0 (and S1=0), we see that we have no more dependence over the azimuthal angle. On the other hand, if we put Pz=0 in order to analyze Py, we still have angular dependence. Thus, LPOL only need to determine the energy of the backscaterred photons, while TPOL need to determine their energy and their position. It is the main reason why TPOL has a bigger error than LPOL.

3-Setup and procedure for the TPOL polarimeter

3.1-The general setup of TPOL

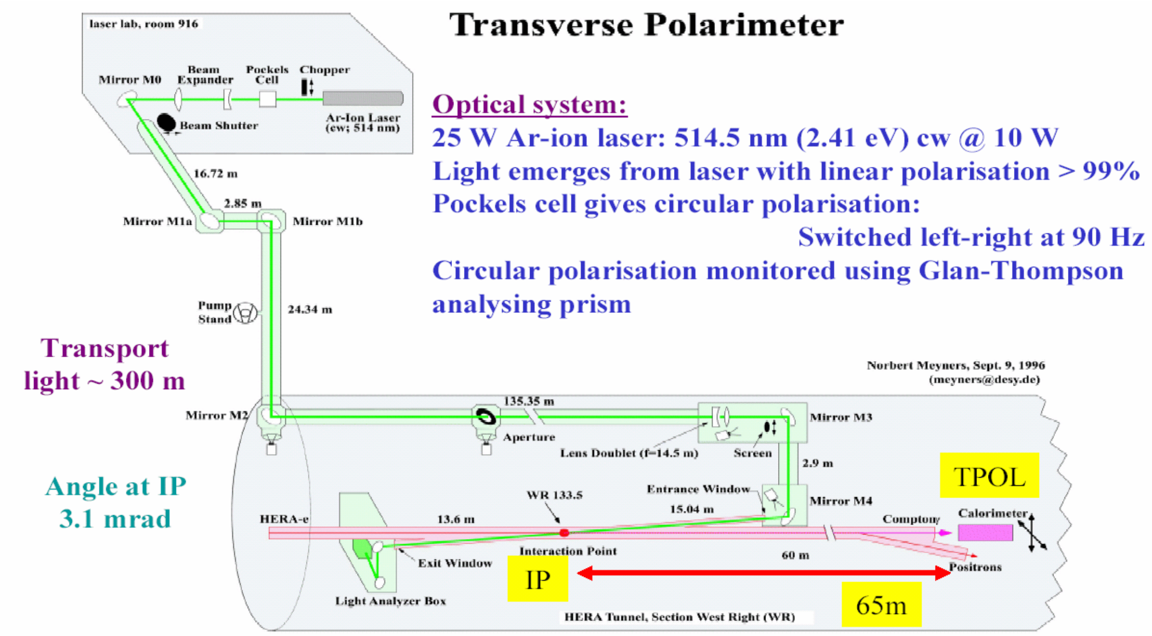

Figure 3: The general setup of the TPOL polarimeter. We can see in green the trajectory of the laser and in ping the trajectory of the lepton beam. The red dot is the position of the Compton scattering. At a distance of 65m (IP distance) to the right, is situated the calorimeter, [7].

The setup shown in figure 3 is needed to analyze the Compton cross discussed earlier. It can be resume as follow. A laser with photons of right or left helicity cross the lepton beam (electrons or positrons) at an angle of 3.1 mrad. Some of the photons get in collision with the leptons (Compton scattering). Since the momentum of the photons is a lot lower than the one of the leptons, the collision has almost not effect on the leptons. On the other hand, the photons are deviated in the same direction than the incoming leptons in a beam of small radius (Compton beam). The backscattered photons are then transport over 65m and then collected in the calorimeter. It is important to notice that they don't follow the same trajectory than the lepton. Since the photon are uncharged, they are not affected by the magnetic field that curve the trajectory of the leptons.

The Optical system used is a 25W Ar-ion laser: 514.5 nm (2.41 eV) cw @ 10W. Pockels cell are used to gives circular polarization to the photons. The helicity (left-right) of the photons coming out of the laser is switched at a rate of 90Hz. The circular polarization is monitored using Glan_Thompson analysing prism. The value of the circular polarization of the photons is greater than 99%. So we can assumed that the photons have S3=(1 or -1), [7].

3.2-The setup for the analysis of the Compton beam

The setup shown in figure 4 is necessary to the analysis of the backscattered photons:

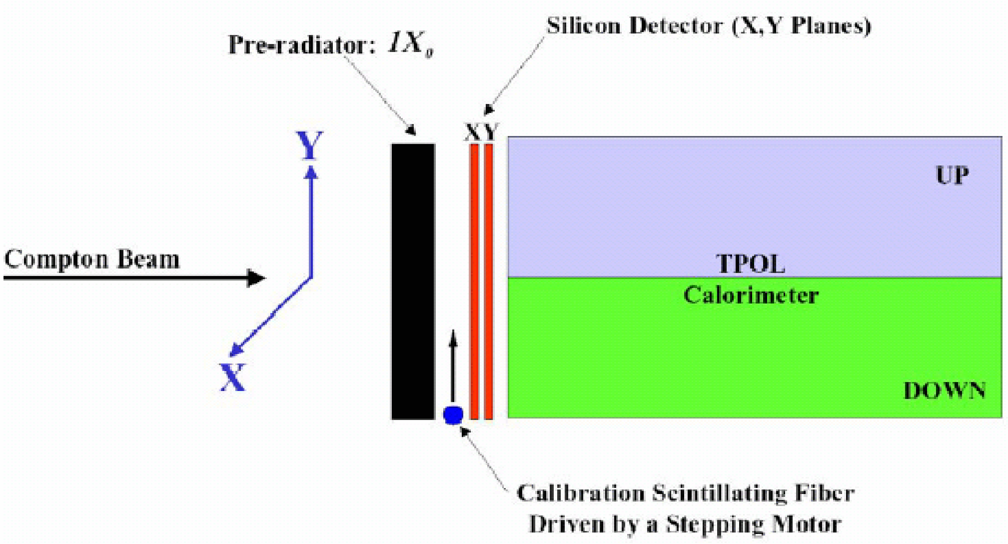

Figure 4: This figure is a "zoom" of the calorimeter and its around (side view). This setup as dimension of the order of ~10 cm which is the reason why some parts don't appear on the figure 3. There is a Pre-radiator that convert the photon into electromagnetic shower, a fiber which is used to calibrate the silicon detectors, two silicons detectors that detect the position in x and y, and finally two calorimeters (up and down) that record the asymmetry of the energy, [7].

The general idea is the following one. The Compton beam first pass trough the Pre-radiator (converter). The converter is a plate of lead with dimension (6,5,0.311)cm for (x,y,z). The role of the converter is to transform the neutral photon into charged particles (electromagnetic shower). This happens since the photons have high energy. When they interact with the atoms of lead there are formation of electrons and positrons. This "shower" of particle has a small spread (~ 0.15mm of radius) due to the high momentum of the incoming photons. Since the silicon detectors can detect charged particles, we can determine the position of the incoming photon by looking where the electromagnetic shower cross the silicon detectors.

There are two silicon detectors, one for the determination of the x position and one for the determination of the y position. Each silicon detector has strips (256 of 200 microns for the x-detector and 768 of 80 microns for the y-detector) and they are situated at ~2 cm after the converter and ~0.2 mm before the calorimeters. The energy deposited in each strip is recorded and using some cluster[1] algorithm, we can determine the position where the electromagnetic shower hit the silicon. This method for the determination of the position has two problems. It is not so accurate since some strip can be not operating: dead channel. Moreover, this is not every photon that are converted into the converter (less than 50%) which reduce considerably our statistic. Thus, this method for the acquisition of data is quite slow. We need at least 1 hour of data acquisition to be able to determine the polarization. This is too slow to be used for the on-line analysis, since the polarization can change within one hour.

This is why the calorimeters play the main role in the polarimeter TPOL. There is two calorimeters, one that record the energy deposited higher than y=0 (E_{up}) and one that record the energy deposited lower than y=0 (E_{down}). They are separated by a thin aluminum foil of ~40 microns corresponding to y=0. Each calorimeters is composed of a series of alternating lead plates and scintillator plates in the longitudinal direction (figure 5). As the electromagnetic shower goes trough the calorimeter, its energy is deposited trough the scintillator plates, which create photons that are collected one the sides (channels). The energy of the created photons is then record and when the calorimeter is

1 A cluster is a group of strips in which energy had been deposited and which stand next to each other.

well calibrated, it is possible to recover the initial energy of the backscattered photon.

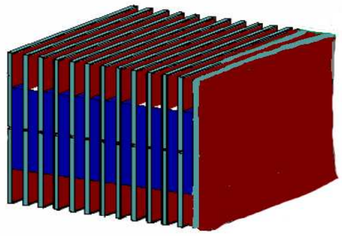

Figure 5: The calorimeters. In bruin are the leads plates and in blue are the scintillators plates

We use two calorimeters in order to be able to determine the position y of the incoming photons. Since the energy of the electromagnetic shower is not deposited in only one of the calorimeter, by looking at the quantity E_{up} and E_{down}, we can determine the position y. The parameter η, defined in equation 3, as for goal to measure this asymmetry of the energy:

$$\eta = \frac{Eup - Edown}{Eup + Edown} \tag{3}$$

The main idea is to acquire a lot of data over a long period of time and then determine the relation between η and y (curve η-y). Once this is done, we don't depend anymore on the silicon detector to find the y-position.

The remaining part of the setup is the fiber. The fiber has for use the calibration of the silicon detector. We move the fiber step by step and each time a "hit" is recorded by the fiber, we look were it hit the silicon. We can calibrate the silicon detector that way.

4-The theory

4.1-TPOL polarimeter (Py polarization)

From a deepest analysis of the Compton cross section equation, we find that the vertical position (y) of the right-handed and the left-handed photons on the cross section[2] is not the same. Moreover, this difference is a function of the polarization of the leptons. We can thus find the polarization using the fact that:

$$P_y \propto Y_l - Y_r \tag{4}$$

,where Y_l and Y_r are the vertical position of the photons on the cross section for left helicity and right helicity respectively [7]. However, as explained before, there is no efficient way to directly determine the position y of the photons on the cross section. In order to indirectly determine the the position y of the photons, we use the parameter η (equation 3).

We can then obtain the values of the polarization on-line (when the beam operated) to an acceptable accuracy using:

$$P_y = \frac{\langle \eta_l \rangle - \langle \eta_r \rangle}{AP \cdot (\Delta S3/2)} \tag{5}$$

,where AP is a constant called the Analysing Power, $\langle\eta_l\rangle$ and $\langle\eta_r\rangle$ are the average η for the photons with left and right helicity, and ΔS3 is the difference between component S3 of the circular-left and circular-right polarized photons[3]. The AP constant

2 In our case, the cross section is refers to be at the position where are the calorimeters.

3 When we refer to S3, we refer to the components of the Stoke vector defined in equation 2. Notice that perfect circular-left polarized photons have S3 = 1 and perfect circular-right polarized photons have S3 = -1. We thus often use (ΔS3 / 2) = 1.

has been determined in 1994 and 1997 using the rise-time-method. This method use the built-up time of the polarization and the maximum value that the polarization reach in the ring. From these data we determined that AP = 0.09608 $\pm$ 0.00106. Notice that when we use this formula, the following energy cut[4] is used: [5.225 GeV< E < 11.4 GeV], [4]. This formula can be use even if the Compton beam is not perfectly centered at y=0.

A more accurate method to determine the values of the polarization can be use off-line. This method make a more complete use of the Compton cross section. Without going trough the details, we fit an 3-D histogram (# of events vs energy and η) of the sum of both laser helicities (left and right). This fit has15 parameters: linear component of the laser(2), circular component of the laser(2), η-y curve (4), resolution of the energy in calorimeter, resolution of η, offset (y and η), beam size, normalization, IP distance. From this fit we can get the value of the polarization [7]. However, a fitting with 15 free parameters is not realistic. We thus have to assume we know some parameters (the 4 parameters of the η-y curves are such parameters) and keep them fixed. It is thus important to reduce the error on these parameters.

The MC simulation can help to improve the accuracy of the values for the polarization, on-line and off-line.

4.2-Focus

The focus can be interpreted as the radius of the Compton beam (beam of backscattered photons) when it reach the calorimeter (figure 6). The focus typically vary between 0.5mm and 0.6mm.

4 The energy cut is done over the total energy: ($E = E_{up} + E_{down}$).

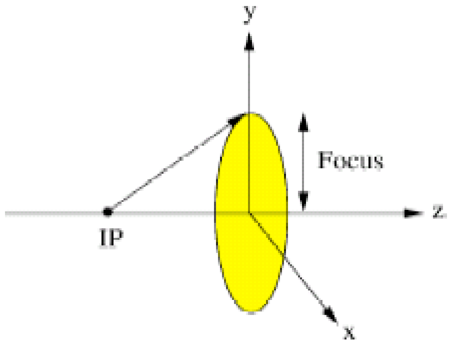

Figure 6: Physical interpretation of the focus. IP is the distance between the Compton scattering and the calorimeter.

We define the focus as follow (in mm):

$$focus = 2.1147\sqrt{\frac{RMS_l^2 + RMS_r^2}{2}} \tag{6}$$

,where RMS_l and RMS_r are the root mean square of the η_l and η_r distribution. Notice that when we use this formula, the following energy cut is used: [11.4 GeV < E < 13.775 GeV], [4].

4.3-AP and focus correlation

The study of the focus is important since a strong correlation has been found between the Analysing Power and the focus using a MC simulation in summer 2004. A correction to the AP constant is now used on-line for different value of the focus (f), which mean a more accurate determination of the polarization. The correction is given by the following equation:

$$\frac{A_0}{A} = 1 + B(f - f_0) \tag{7}$$

,where A_0=0.096 ± 0.001 is the Analysing Power from the Rise-time calibration done in 1997, B = 0.665 ± 0.010mm^{-1}, f_0 = 0.444 ± 0.010mm and A is the corrected Analysing Power, [3].

5-The MC simulation

5.1-The computer software

The MC simulation is generated using the "GEANT Simulation Tool" software from the CERN Program Library Long Writeup W5013 [10]. This program is able to simulate the trajectory and interaction of particles at high energy. The responsibility of the user is to reproduce accurately the geometry and properties of is given system; in our case, the TPOL polarimeter. The program is written in Fortran. Let's go quickly over the structure of the program. The program is divided into the following parts:

main.f: This is the main program. His role is to call the good subroutine in the good order.

gukine.f: This subroutine is responsible of the treatment of the kinematic, vertex and particles. This is in this part of the program that are treated the characteristics of the lepton and photon beam. A Gaussian distribution is used to determine the position and momentum. It is important to be aware that each simulation use the same random generator sequence, which mean that two simulations with the exact same parameters will give you the exact same results. To be more explicit, let's use this example. Suppose we keep the same parameters and run two runs of 50 000 events[5] and one run of 100 000 events. Both 50 000 events run will have the same output results, but if you add both 50 000 events run together you won't get the same output results than the 100 000 events run, since the random sequence will not get back at its beginning after 50 000 events in the 100 000 events simulation. This fact is really useful for debugging and to study the dependency of some parameter.

gustep.f: This subroutine track the particle(s) step by step and record where the energy of the particle(s) is deposited (ex: in the silicon, in the calorimeter, etc).

guout.f: This subroutine compute and records the final output results (η, position of the cluster in silicon detectors, etc). These data are store in ntuple and can be access using the software PAW [11].

ugeom.f: This subroutine describe the geometry of the polarimeter.

ugmed.f: This subroutine determine the materials and their properties used in the polarimeter.

ugffgo.f: This subroutine pass the parameter of the tpolmc.cards into the common block constants.

5 A event is consider to be a backscattered photon that hit the calorimeter.

tpolmc.cards: This cards allowed the user to change some parameters in the simulation without having to recompile the whole program. The whole cards with the "defaults parameters" (the one that we will use if we don't specify) can be seen in annex. Notice that the units used in this cards are the cm, GeV and rad. These parameters are considered to reproduce accurately the reality[6]. Here are the main "interesting" defaults parameters used:

- Polarization of the leptons in the beam = 100%
- Emittance of the HERA's beam: (in x = 54mm*urad) and (in y = 2.4mm*urad)
- S1(left) = 0.05, S1(right) = 0.05
- Energy of the lepton beam = 27.6 GeV
- Energy of the laser beam = 2.41E-9 GeV
- Angle that the laser beam cross the lepton beam = 3.1 mrad
- Dilu parameter = 0.04
- Difu parameter = 0.6
- Phot parameter = 15 000 photons/GeV

5.2-Details of the simulation

Let's explain the meaning and use of the less obvious parameters. The emittance can be interpret as the tendency of the beam to increase is radius (elliptically in the case that the emittance in x is not the same as the emittance in y). We can see that the emittance in x is taken to be about 20 time bigger than the one in y. This is due to the fact that the leptons turn in the horizontal plane, which mean that the beam is more likely to enlarge in the x direction than in the y direction (y is perpendicular to the horizontal plan).

6 A polarization of 100% is not the reality, but some explanation will be given later about this choice.

The parameter Phot (in photons/GeV) determine the quantity of photons that are created by GeV deposited in the scintillator plates. Once the photons are created, we need to determine on which side (channels) of the calorimeter they end up. This is important since each channels don't have the same gain factor and the photons that reach the aluminum plate which separate both calorimeters are considered to be lost. Obviously, the amount of photons (N) on each channels should depends on the position of the energy deposited in the calorimeter (position-dependent light collection):

$$N_{side} = N_{total} \cdot \alpha_{side} / 360^{o} \tag{8}$$

,where α is the solid angle (see left picture of figure 7). However, it is possible that some photons get absorbed in their way to the side and re-emitted in another direction. It is also possible that some photons reflect on one side and get detected on another side. It this case, we use probability to determine how the photons should be distributed on the sides (diffuse light collection). That is, for w = width between left-right side and h = height between aluminum plate and up or down[7] side, the proportion of diffuse light that end in the left/right channels should be given by h/(h+w) and the proportion that end in the up/aluminum or down/aluminum channels should be given by w/(w+h). A simpler way to think about it, is to imagine that all the diffuse light come from the center of the calorimeter. Figure 7 shows visually the difference between the position-dependent light collection and the diffuse light collection:

7 If we refer to the up calorimeter, h = distance between aluminum plate and up side. Similarly, if we refer to the down calorimeter, h = distance between aluminum plate and down side.

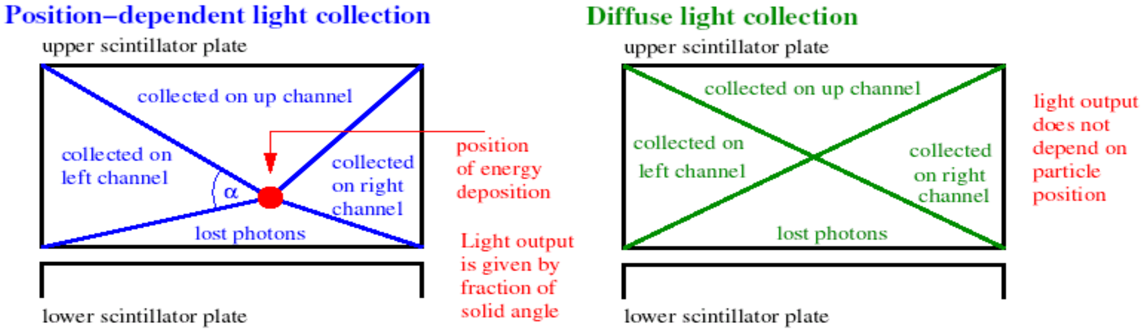

Figure 7: Front view of the up calorimeter (one of the upper scintillator plates), and part of the down calorimeter (one of the lower scintillator plate). We can see the two different ways that the light (energy) can be collected: position-dependent light collection (left) and diffuse light collection (right). The parameter Difu control the proportion of light that is collected from the diffuse light collection, [9].

The Difu parameter control the proportion of light which is collected using the probabilities principle (diffuse light collection). Finally, the parameter Dilu control the proportion of photons that cross the thin aluminum plate:

$$N_{cross} = Dilu \cdot N_{lost} \tag{9}$$

,where N_{lost} correspond to the photons that end up in the aluminum plate. Notice that the N_{cross} are all simulated to be collected in the opposite horizontal channel (ex: the photons that cross the aluminum sheet from the up-calorimeter to the down-calorimeter are collected on the down channel of the down-calorimeter, nothing on the sides).

6-Optimization of the MC simulation

6.1-Analysis with the default parameters

One of the main goal of the MC simulation is to determine what should be the Analysing Power (AP). To do that, we generate events with known polarization and ΔS3. We then analyze the η distribution for left and right polarization of the photons