High-precision measurements of proton-proton bremsstrahlung at 190 MeV
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Monte-Carlo Simulations

An important tool used in detector design and in understanding data, is Monte-Carlo simulations. The simulations for this experiment have been performed with GEANT 3.21 [28], which is a part of the CERN software libraries.

The GEANT software is capable of simulating the trajectory and estimating the energy deposition of particles between 10 keV and 1 TeV through a complex geometry. A simulation in GEANT goes in two steps. The first step is the definition of the geometry. In this step, a geometry is defined by placing objects in a master reference system. Every object consists of a certain material, whose properties are important for the transport of particles. The second step is the actual transport through the geometry, which is done on an event-by-event basis. For each event, GEANT has to know the type of particles to be transported, the starting position of the particles and their momentum vectors. In the case of \( pp\gamma \), an event consists of two protons and one photon, which start at the center of the target. Their momenta are supplied by an event generator, which generates events according to either the phase-space distribution, or a distribution based on a soft-photon approximation. GEANT transports these particles through the geometry in finite steps and keeps track of their position, energy, energy deposition, generation of other particles like photons or \( e^+e^- \) pairs etc. At each step a routine is called where the user can decide what to do with the information.

The mechanisms which play a role in the transport of particles through matter depend on the type of particle and its energy. For photons the predominant mechanisms are Compton-scattering and pair production. Also, the photoelectric effect and Rayleigh scattering are simulated, but they hardly contribute at the photon energies relevant for this work. Electrons and positrons interact via multiple scattering, ionization/\( \delta \)-ray produc-
tion and bremsstrahlung. For positrons annihilation is included as well. The simulation of proton/neutron transport is done with inclusion of multiple scattering, ionization/δ-ray production and hadronic interactions. The simulation of hadronic interactions in GEANT is performed either via the FLUKA [56] or the GEISHA [57] codes. The differential cross sections produced by these codes, are not more accurate than 30% for the energy range of 1 MeV to 400 MeV. This is not too severe since the hadronic interactions are not predominant in the transport of charged particles. Nonetheless, some care has to be taken in interpreting the results of GEANT, when hadronic interactions are expected to be of importance.

For the bremsstrahlung experiments which are subject of this thesis, two geometries were implemented, which simulate the response of the SALAD and TAPS detectors in the supercluster and block configurations. The simulations were performed for two reaction channels: proton-proton elastic scattering and proton-proton bremsstrahlung. These will be addressed separately in the following sections.

\section{Simulations for elastic scattering}

The predominant background process in \(pp\gamma\) measurements is proton-proton elastic scattering. With GEANT, one can estimate the background trigger rate due to this process. Since the cross sections and analyzing powers of elastic proton-proton scattering are very well known, this process is used to determine the luminosity and the beam polarization.

At the incident energy of 190 MeV, the kinematics of elastic scattering can be regarded as non-relativistic, in which case the opening angle of the two protons is always 90°. Due to relativity the opening angle varies between 87° and 90°. The maximum opening angle subtended by SALAD is 55°, resulting in the fact that only one of the two protons of an elastic-scattering event is able to reach SALAD. This has been a very important consideration in the design of the detector, since the \(pp\gamma\)-trigger requires a coincidence of two protons in SALAD.

The trigger condition on SALAD side is that \(N_E - N_V \geq 2\) (see section 3.1.1). When one elastically-scattered proton traverses SALAD, it will normally fire one element in the energy detector and one element in the veto detector, implying that \(N_E - N_V = 0\). Two or more protons traversing SALAD will not change this condition. However, there are three other possibilities of importance which can spoil this scenario.

1. \((p,n)\) reaction. A proton can collide with a nucleus in the scintillator and produce a neutron, for example via knockout or charge exchange. The residual proton energy (if any) may not be enough to reach the veto detector, while the neutron may escape without any deposit of energy. In this case \(N_E - N_V = 1\).

2. \((p,p)\) reaction. A proton can scatter off a nucleus in the scintillator. The new direction of the proton may be such that it fires two neighboring energy detector elements and no veto element. In this case \(N_E - N_V = 2\).
Table 4.1: The probability for the different track scenarios of elastic protons in SALAD at an incident energy of 190 MeV.

<table>
<thead>
<tr>
<th>Case</th>
<th>( N_E )</th>
<th>( N_V )</th>
<th>Probability [%] (GEANT)</th>
<th>Probability [%] (Data)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>1</td>
<td>1</td>
<td>77</td>
<td>77</td>
</tr>
<tr>
<td>1</td>
<td>1</td>
<td>0</td>
<td>17</td>
<td>14</td>
</tr>
<tr>
<td>2</td>
<td>2</td>
<td>0</td>
<td>3</td>
<td>4</td>
</tr>
<tr>
<td>3</td>
<td>2</td>
<td>1</td>
<td>3</td>
<td>5</td>
</tr>
</tbody>
</table>

Figure 4.1: The observed trigger rate as a function of beam current along with the predicted rate. The dash-dotted curve is the results of a double random coincidence and is therefore roughly proportional to the square of the beam current. The dotted curve is roughly proportional to the cube of the beam current, since it is the results of a triple random coincidence. The solid curve depicts the sum of the two contributions.

3. Crossover. Due to straggling a proton can cross over from one energy detection element to the other, and fire one veto element. In this case \( N_E - N_V = 1 \).

A random coincidence between situations 1&1, 3&3 and 1&3 will produce a valid trigger on SALAD side. Situation 2 produces the trigger with only one proton. In Table 4.1, the probability for each track scenario is shown as simulated with GEANT and as found in the data. In order to make a fair comparison with the data, the GEANT tracks are selected on the number of detector elements they fire, and not on the interaction mechanism. The agreement between the simulation and the data is rather good, taking into account the rather high systematical errors on the hadronic interactions in GEANT.

Having the probability for the occurrence of the tracks, one can estimate the rate of the \( p p \gamma \) candidate, due to the elastic channel. The derivation of this estimate is described in appendix B. In Fig. 4.1 the two components of the predicted trigger rate are plotted as a function of the beam current. The first component (dash-dotted line) consists of an
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elastic track where \( N_E = 2 \) and \( N_V = 0 \) in random coincidence with a TAPS-trigger. This contribution is roughly proportional to the square of the beam current and is therefore the dominant contribution at lower beam currents. The second component (dotted line) consists of two random tracks in SALAD delivering each \( N_E - N_V = 1 \) in random coincidence with a TAPS-trigger. This contribution is roughly proportional to the cube of the beam current. This contribution is therefore negligible at lower beam currents but becomes sizeable at a beam current close to 10 nA. The total trigger rate (solid line) is the sum of these two rates. It can be seen that this rate is in very good agreement with the observed trigger rate (diamonds). The observed rates are taken from Ref. [52].

4.2 Simulations for \( pp\gamma \)

Simulations on the proton-proton bremsstrahlung channel have been performed with the aim to investigate the resolution of the SALAD and TAPS detectors and the effect these resolutions have on the reconstruction of the \( pp\gamma \) kinematics. As input for this reconstruction, the polar and azimuthal angles of the two protons and the polar angle of the photon are used. The precision to which these five angles are measured, is the subject of the next two sections. The precision with which proton and photon energies are measured can be evaluated with data, by comparing the measured and reconstructed values. This latter comparison is performed in chapter 5.

4.2.1 The angular resolution of SALAD

The angular resolution of SALAD for charged particles is determined by two parameters. The first parameter is the intrinsic resolution of the wire chamber, which is determined by the distance between the wires and the distance from the chamber to the target. The second parameter is the amount of straggling of the charged particles. The combination of these two effects has been investigated with GEANT. The accuracy to which the scattering angles can be determined is dependent on the position in the wire chamber and on the energy of the charged particle. Proton-proton bremsstrahlung events are generated according to the phase-space distribution. The events are then tracked through the setup with GEANT, thus providing “measured” scattering angles, which will deviate to some extent from the true scattering angles. The effective resolution of SALAD is obtained by inspecting the difference between the true angle and the “measured” angle. The resulting distribution is a gaussian, with its central value at zero and with a certain standard deviation. This is depicted in Fig. 4.2. Since the angular resolution is dependent upon the position in the wire chamber, and the straggling is energy dependent, the resolution has to be investigated as a function of these two parameters. The results are listed in Table 4.2, where three different regions in the wire chamber have been selected, the first region \( (9° - 11°) \) being close to the central hole. The second region \( (15° - 17°) \) is a circle where the whole azimuthal angular range is still covered. The last region \( (21° - 23°) \) is in the corner of the chamber, where the azimuthal angular range is not complete anymore. Furthermore, three different energy regions have been selected, which are characteristic for
4.2. SIMULATIONS FOR PPγ

Figure 4.2: *The difference between the true and “measured” values of the polar and azimuthal angles of a proton detected in SALAD. Events have been selected where $15^\circ \leq \theta \leq 17^\circ$ and $60 \text{MeV} < E < 70 \text{MeV}$. The curves plotted along with the histograms are the fitted gaussian distributions, whose means ($\mu$), and standard deviations ($\sigma$) are indicated.*

Table 4.2: *The angular resolution of the SALAD detector for protons, for three different energy ranges and for three different polar angular ranges.*

<table>
<thead>
<tr>
<th>Proton energy [MeV]</th>
<th>$9^\circ \leq \theta \leq 11^\circ$</th>
<th>$15^\circ \leq \theta \leq 17^\circ$</th>
<th>$21^\circ \leq \theta \leq 23^\circ$</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>$\sigma_\theta$ [deg]</td>
<td>$\sigma_\phi$ [deg]</td>
<td>$\sigma_\theta$ [deg]</td>
</tr>
<tr>
<td>30 - 40</td>
<td>0.25</td>
<td>1.42</td>
<td>0.25</td>
</tr>
<tr>
<td>60 - 70</td>
<td>0.19</td>
<td>1.08</td>
<td>0.17</td>
</tr>
<tr>
<td>90 - 100</td>
<td>0.17</td>
<td>0.95</td>
<td>0.16</td>
</tr>
</tbody>
</table>
the energy range of protons originating from \( pp\gamma \) events. The polar angular resolution is almost independent of the polar angle, but since the low-energy protons suffer more from straggling, the resolution changes by more than 30\% from low energies to high energies. The azimuthal angular resolution shows, of course, the same energy dependence, but shows in addition a dependence on the polar angle. From a simple geometrical consideration, a \( 1/\sin \theta \) dependence can be deduced, which is consistent with the simulated resolutions.

4.2.2 The angular resolution of TAPS

The photon momentum vector is estimated via the method of linear energy weighting, as defined in Eq. (3.1). Since the angle \( \theta_\gamma \) is input for the \( pp\gamma \)-reconstruction algorithm, some care has to be taken for the precision to which this angle can be measured. One of the inputs for the measurement of \( \theta_\gamma \) is the positions of the firing crystals, \( \vec{r}_i \). The most straightforward way of defining the position vector of a BaF\(_2\) crystal is the front-face center. This definition, however, would introduce a systematical error in the momentum vector reconstruction, since an electromagnetic shower penetrates the crystals to some extent and places the center of energy deposition at a different position than the point of impact. This is depicted in Fig. 4.3. The thus-introduced systematical error can be removed by adding an effective penetration depth to the position of the BaF\(_2\) crystal. This depth is in principle dependent on the photon energy. However, the photon spectrum, accepted by the supercluster setup, is rather mono-energetic (see e.g. Fig. 5.7). Therefore, the effective depth for this experiment is not considered to be energy dependent. A simulation has been performed, where the “measured” scattering angle \( \theta_{\text{meas}} \) for different depths is compared with the true scattering angle \( \theta_{\text{true}} \). When the distribution of

Figure 4.3: Top view of a photon hitting the taps detector (not to scale). If the front-face center of the BaF\(_2\) crystals is taken, a systematical error is introduced in the determination of \( \theta \) (dashed vector).
4.2. SIMULATIONS FOR PPγ

Table 4.3: The mean (μ) and standard deviation (σ) of the θtrue - θmeas distribution for different effective depths and different regions of θγ.

<table>
<thead>
<tr>
<th>Depth [cm]</th>
<th>130° ≤ θ &lt; 140°</th>
<th>140° ≤ θ &lt; 150°</th>
<th>150° ≤ θ &lt; 160°</th>
<th>160° ≤ θ &lt; 170°</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>1.7</td>
<td>1.1</td>
<td>2.5</td>
<td>1.5</td>
</tr>
<tr>
<td>1</td>
<td>1.2</td>
<td>1.1</td>
<td>2.0</td>
<td>1.5</td>
</tr>
<tr>
<td>2</td>
<td>0.7</td>
<td>1.1</td>
<td>1.4</td>
<td>1.5</td>
</tr>
<tr>
<td>3</td>
<td>0.2</td>
<td>1.2</td>
<td>0.9</td>
<td>1.5</td>
</tr>
<tr>
<td>4</td>
<td>-0.3</td>
<td>1.2</td>
<td>0.4</td>
<td>1.4</td>
</tr>
<tr>
<td>5</td>
<td>-0.8</td>
<td>1.2</td>
<td>-0.1</td>
<td>1.5</td>
</tr>
<tr>
<td>6</td>
<td>-1.3</td>
<td>1.2</td>
<td>-0.5</td>
<td>1.5</td>
</tr>
</tbody>
</table>

θtrue − θmeas is fitted to a gaussian distribution, this delivers a centroid of the gaussian (μ) and a standard deviation (σ). To optimize the vector reconstruction, one has to tune μ to zero. The results for μ and σ for the supercluster configuration are listed in Table 4.3. It is clear that the effective depth of 4 cm gives the best overall result. Since the penetration depth is a parameter in the z-direction, it does not affect the measurement of φγ. The distribution of φtrue − φmeas should have a centroid consistent with zero, which is confirmed by the simulations.

In the analysis of the block geometry a penetration depth should, in principle, be applied. The different blocks, however, are placed such that the front face of the BaF2 crystals is nearly perpendicular to the photon vector. In the ideal case, where the photon impinges perpendicular on the front face of a BaF2 crystal, the angles θ and φ are both independent of the effective depth. For the block geometry, the centroid of the θtrue − θmeas distribution never exceeds 0.8°. Since even this worst-case value is very small with respect to the FWHM of the distribution, it is concluded that no significant gain in angle measurement would be obtained, if an effective depth were applied, for this geometry.

4.2.3 The efficiency of the reconstruction algorithm

In the off-line analysis, ppγ events are identified via kinematical reconstruction. Based on the measured polar and azimuthal angles of the protons and the polar angle of the photon, the energies of the two protons and the energy and azimuthal angle of the photon can be calculated. This reconstruction method is described in detail in section 2.1.1. However, an arbitrary combination of angles will, in general, not produce a valid solution of Eq. (2.9). Since the angles measured in background events are uncorrelated, this provides a major reduction of the background. On the other hand, one can misidentify valid ppγ events as background events, due to resolution problems. From GEANT one can obtain “measured” values for the scattering angles, θ and φ, and one can try to reconstruct the remaining kinematic variables with them. This reconstruction is successful for
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Figure 4.4: A plot of the function $f(p_A)$ as given by Eq. 4.1 for a problem case. The solid line shows the function when the true scattering angles have been used. The dash-dotted line shows the function for the same event, but now with the “measured” scattering angles.

Figure 4.5: The spectrum of the minima of $f(p_A)$ (see Eq. (4.1)) for the problem cases. These constitute 8% of the total data. The minima have been normalized with the beam momentum $p_b^2$. 
most events, but for about 8% of the \( pp\gamma \) events, no solution of Eq. (2.9) can be found. A problem case is illustrated in Fig. 4.4, where the difference between the right-hand side of Eq. (2.9) minus the left-hand side is plotted as a function of \( p_A \):

\[
f(p_A) = \left( p_A \sin \theta_A - p_B \sin \theta_B \right)^2 + 4p_A p_B \sin \theta_A \sin \theta_B \sin^2 \Phi - \frac{k^2 \sin^2 \theta_\gamma}{p_A^2}
\]  

(4.1)

where \( p_B \) and \( k \) are functions of \( p_A \), given by Eq. (2.7) and Eq. (2.6). This is done for a certain combination of scattering angles. A solution of the kinematics is found, when \( f(p_A) \) equals zero. The solid line shows the result when the true combination of the scattering angles is used, whereas the dash-dotted line shows the result with the “measured” scattering angles. In those cases, where no solution is found, due to resolution problems, one can estimate the solution as the \( \text{minimum} \) of Eq. (2.9), if this minimum is close to zero. In Fig. 4.5 the minima of Eq. (4.1) have been plotted for the problem cases, as they have been found with GEANT. The values of the minima have been expressed in units of the square of the beam momentum, in order to remove the dependence on the incident beam energy. During the off-line data analysis, the reconstruction is considered to be successful, when \( \text{min} \{ f(p_A) \}/p_e^2 \leq 0.05 \). In this case, \( p_A \) is set to the value where \( f \) is minimal. As can be seen from Fig. 4.5, no good \( pp\gamma \) events are lost with this procedure.