A Bayesian-based Method for Particle Track Identification in Low-energy Pair-creation Telescopes

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Abstract. A critical step during the data analysis of pair creation telescopes is the correct identification of the electron and positron tracks. For MEGA, an electron-tracking Compton and pair telescope optimized for energies up to 50 MeV, we describe a low-energy pair event reconstruction approach partly based on Bayesian statistics.

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INTRODUCTION

The Medium Energy Gamma-ray Astronomy telescope MEGA [1] detects gamma rays in the energy range from 400 keV up to 50 MeV via Compton scattering and pair creation. It consists of a tracker of double-sided Silicon strip detectors (0.5 mm thick, 0.47 mm pitch), where the initial scattering process takes place and where the direction of the electrons and positrons is determined, and a CsI calorimeter, which stops the secondary particles.

Considering the recovery of the energy and origin information of the measured gamma rays, MEGA has two advantages compared to GLAST: First, MEGA's double-sided strip detectors are capable of measuring positions and deposited energies in each layer, while GLAST has two perpendicularly arranged single-sided strip detectors per layer, which only give a binary signal, but no energy measurement. Second, the Silicon layers in the GLAST tracker are interleaved with tungsten foils to increase the high-energy effective area, but worsen the angular resolution and efficiency at lower energies due to increased Molière scattering and energy absorption. As consequence, MEGA can use the complete track kinematics, which greatly simplifies and improves the pair identification at low energies.

In general, this step is not straightforward due to ambiguous track sequences, additional tracks generated by bremsstrahlung, defective pixels, interactions in passive material, etc. The applied algorithm is a four-step process, which is described in the following.

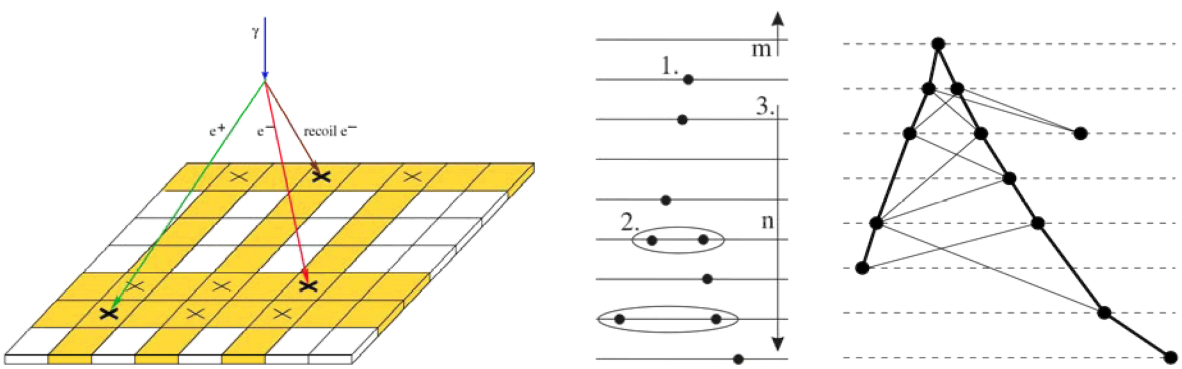

FIGURE 1. Illustrations of the different steps of the pair reconstruction: Left: Step 1, Center: Step 2, Right: Step 3

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A LOW-ENERGY ELECTRON-POSITRON PAIR RECONSTRUCTION APPROACH

In **Step 1** the strips are combined into interaction locations (see figure 1, left). For each possible interaction combination calculate a quality factor, which describes how good the energies E in the x and y strips of one individual layer of the tracker (including their uncertainties σ) correspond to having originated from the same interaction:

$$Q_C = \frac{1}{N} \sum_{i,j=1}^{N} \frac{\left(E_i^x - E_j^y\right)}{\left(\sigma_i^x\right)^2 + \left(\sigma_j^y\right)^2} \tag{1}$$

The permutation with the lowest Q_C represents the correct interaction positions. Charge sharing, defective pixels, etc. are taken into account when all possible interaction pairs are analyzed. Since the energy deposited by traversing charged particles follows a broad Landau-distribution, and due to the present energy resolution in the tracker, in roughly 10% of the cases the positions are wrongly reconstructed. However, those interactions can be corrected in Step 4 of the analysis.

In **Step 2** the vertex of electron-positron pairs are identified (see figure 1, center): The start point of the pair is always represented by a vertex-like structure, which is defined by: (1) At least one layer contains exactly one hit (the starting point of the vertex). (2) In the n following layers below the start point at least two layers contain exactly two hits. (3) There is no hit in the m layers directly above the start point (ignore if vertex is in top layers). Beyond this point, events having a vertex are treated as potential pairs, the remaining events as Compton events.

In **Step 3** an initial guess of the electron and positron paths is made (see figure 1, right): Layer-by-layer, search for the straightest continuation of the track and choose the sequence for which the quality factor from the individual direction change ($\Delta\phi$) is smallest: $Q_T = \Delta\phi^2_{e,i} + \Delta\phi^2_{p,j}$

In **Step 4** this initial guess is iterated by utilizing all available information using Bayes' statistics: While most pair creation interactions are already correctly identified after Step 3, some cases need post-processing, because e.g. Bremsstrahlung hits might have been integrated into the track, the tracks might cross, due to a failed initial step, or U-turning Compton tracks might have been misinterpreted as a pair vertex. This requires a common quality factor for the electron-positron tracks, which is determined by the probability that the measured track sequences originate from a correctly reconstructed and completely absorbed electron or positron using all possible information. This probability is best calculated via Bayesian statistics for the measurements m_i: $p(G|\cup m_i) = p(G)\, p(\cup m_i|G) / p(\cup m_i)$

It utilizes two vast data spaces whose population is determined by prior simulations. The first data space describes the correctly sequenced interaction of an electron or positron within the Silicon layer (G: "good track segment"), and the second how this signature looks like if the track segment was not generated by the passage of an electron/positron along the track (B: "bad track segment"). With this information, the following Bayesian quality factor Q_{Pair} can be calculated for the tracks:

$$Q_{Pair} = 1 - p\left(G\middle|\cup m_i\right) \approx \frac{R}{R-1} \quad \text{with } R = \frac{p\left(G\middle|\cup m_i\right)}{p\left(B\middle|\cup m_i\right)} = \frac{p(G)\cdot \prod_i p\left(m_i\middle|G\right)}{p(B)\cdot \prod_i p\left(m_i\middle|B\right)} \tag{2}$$

In the following alternative paths are investigated by changing one element at a time: track crossings, exchange, exclude, include individual hits, etc. For all those possibilities the quality factor is calculated. If any of the possibilities is better than the original one, the new track sequence is used as best guess for a new search until no further improvement can be found.

PERFORMANCE DETERMINED BY SIMULATIONS

Simulations with the MEGA satellite geometry show that at 100 MeV 98% of the pairs can be recognized correctly, 79% at 20 MeV, and 73% at 10 MeV. At lower energies (with their larger opening angles) it is harder to distinguish the pair signatures from Compton signatures. Examples of reconstructed calibration measurements with the MEGA prototype can be found in [2] and [3].

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