IL NUOVO CIMENTO **40 C** (2017) 118
DOI 10.1393/ncc/i2017-17118-2

Colloquia: SciNeGHE 2016

Characterisation and comparison of event generators for pair conversion: A crucial step for future low energy gamma telescope

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received 21 April 2017

Summary. — Gamma ray astronomy suffers from a sensitivity gap between 0.1 and 100 Mev. With high angular resolution for the electrons, it will also be possible to probe the linear polarisation of the photons. An accurate simulation is necessary to correctly design and compare these detectors. We establish baseline distributions of key kinematic variables as simulated by a 5D, exact down to threshold, and polarised event generator. We compare them to simulations with the low energy electromagnetic models available in Geant4 and in EGS5. We show that different generators give a different picture of the optimal angular resolution of pair telescopes. We also show that, of all the simulations we used, only the full 5D generator describes accurately the angular asymmetry in the case of polarised photons.

1. – Introduction

The sensitivity gap for photons between 0.1 and 100 Mev has motivated many projects for a new generation of gamma-ray space telescopes. In the high background environment, the sensitivity to point sources is directly related to the angular resolution of the telescope. The new generation of pair conversion telescopes aims therefore at improving the tracking resolution, mainly by minimising the multiple scattering inside the detector, or improving the space point resolution. Telescopes like e-ASTROGAM [1], Compair [2], and PANGU [3] propose to use silicon trackers without additional convertors, HARPO [4] and Adept [5] propose gaseous detectors, and GRAINE [6] proposes the extremely high resolution of nuclear emulsions. In all these projects, the tracking resolution is so fine, that the angular resolution for photons will be dominated by the kinematic effects of the pair production process in a large fraction of the energy range. It is therefore necessary to have a reliable event generator for pair production processes in order to properly design the telescopes.

In this paper, we shortly describe an exact generator for the pair production process in the field of a nucleus. We use it to benchmark low energy electromagnetic models available in Geant4 and in EGS5. We compare in particular the angular resolution in

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the case of high resolution tracker. Finally, we compare the description of the effect of photon polarisation when it is available. The results presented here are based on [7] and [8].

2. – An exact 5D polarised pair conversion generator

We developed a generator [9], based on the BASES/SPRING event generator [10], that instantiates the VEGAS Monte Carlo method [11]. Two methods are used to compute the 5D differential cross section. The first one uses the Bethe-Heitler analytic expression [12], the other uses a full diagram computation using the HELAS amplitude calculator [13].

This generator was cross-checked and compared to analytic formulas when available [7].

3. – Benchmarking pair conversion generators in Geant4 and EGS5

Our generator is used as a reference for comparisons of the different models available in common event generators, Geant4 and EGS5. We find that the kinematics are treated in very different ways in the various models.

The angular resolution $\sigma_{\theta,X}$ is defined as the angle around the incident photon direction, such that a fraction X of the events reconstructed from the electron and positron tracks have a deviation smaller than $\sigma_{\theta,X}$. We use $X = 68\%$, 95% and 99.7% containment which represent approximately 1σ, 2σ and 3σ. In absence of any detector effects such as multiple scattering, the resolution varies strongly between the models, as shown in fig. 1.

A more detailed study of the differences between the models can be found in [7].

4. – Polarimetry of gamma rays converting into electron-positron pairs

The polarisation of the incident gamma rays is reflected in the angular configuration of the produced tracks. The cross-section depends on the azimuthal angle ϕ as follows:

$$1 + A\cos\left(2(\phi - \phi_0)\right), \tag{1}$$

where A is called polarisation asymmetry. Several definitions of ϕ have been used in past publications. Figure 2 shows the various angles that can be defined from the pair conversion kinematics. The conversion plane angle ω is common in experimental works [6, 9, 14-17].

Figure 3 shows the measured polarisation asymmetry A using several definitions of the azimuthal angle, and the resulting uncertainty. We see that the angle $\phi_{+-} = (\phi_+ + \phi_-)/2$ is the best estimator of the polarisation [8]. It is consistent with asymptotic formulas at high and low energy.

Using this estimator, we compare the polarisation measurement from our event generator with the results obtained using the only polarised pair conversion generator available in Geant4: G4LivermorePolarizedGammaConversionModel. Figure 4 shows the measurement of the polarisation asymmetry A and the polarisation angle ϕ_0, using each generator. It is clear that not only the amplitude of the polarisation, but also the phase ϕ_0 is very poorly described under 100 Mev. Even at higher energy, A is underestimated by about 30%.

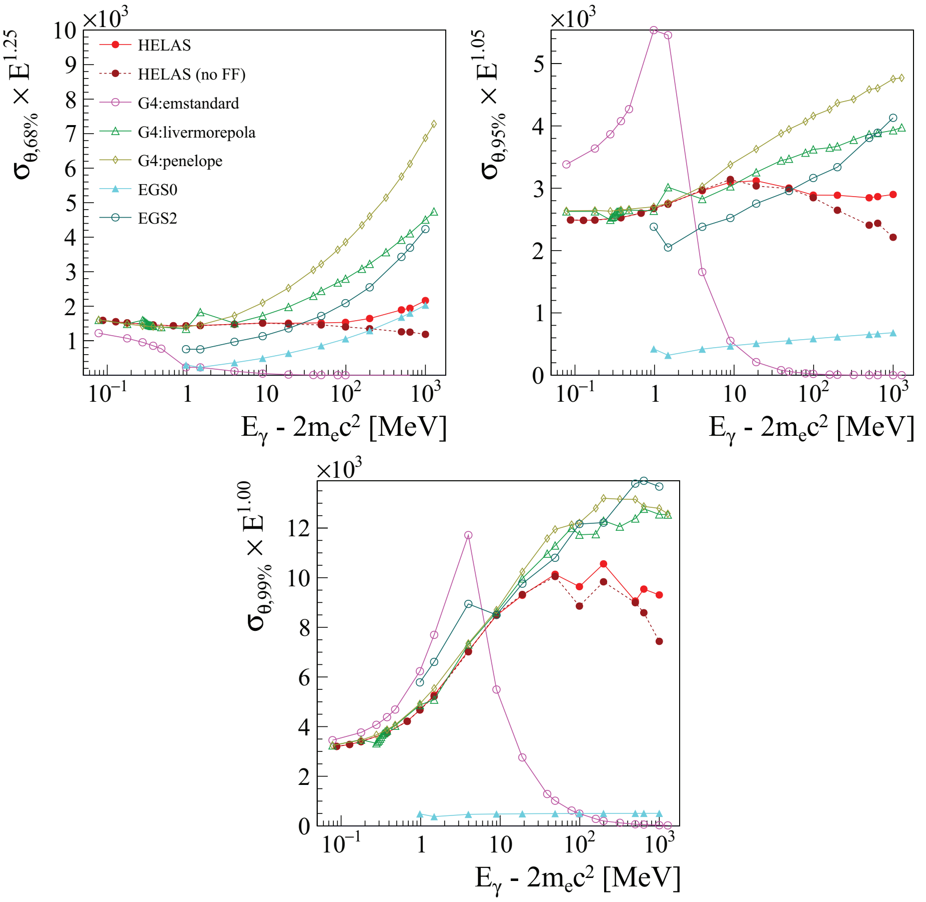

Fig. 1. – Angular resolution for the incident photon, assuming a perfect single track resolution. The 68%, 95% and 99.7% containment (respectively $1\sigma, 2\sigma$ and 3σ) can be roughly described at high energy by power laws of index 1.25, 1.05 and 1.00 respectively for the exact model (*HELAS*).

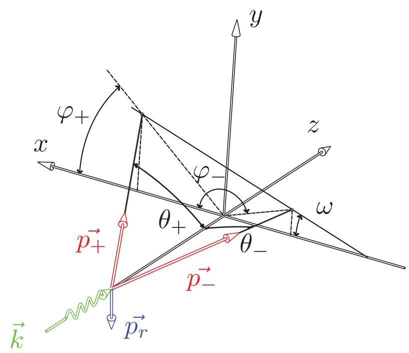

Fig. 2. – Scheme of a photon conversion.

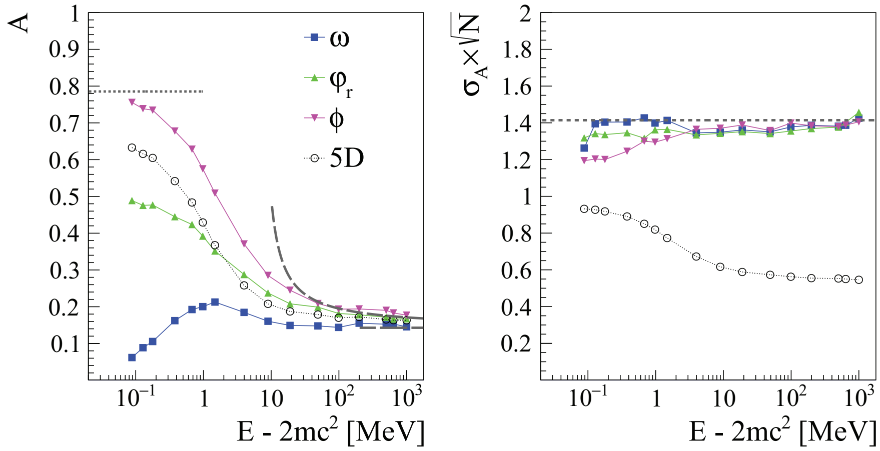

Fig. 3. – Left: measurement of the polarisation asymmetry A using several definitions of the azimuthal angle [8]. Analytic asymptotic values are shown in dashed gray lines. Right: statistical uncertainty on the measurement of the polarisation asymmetry using the different methods.

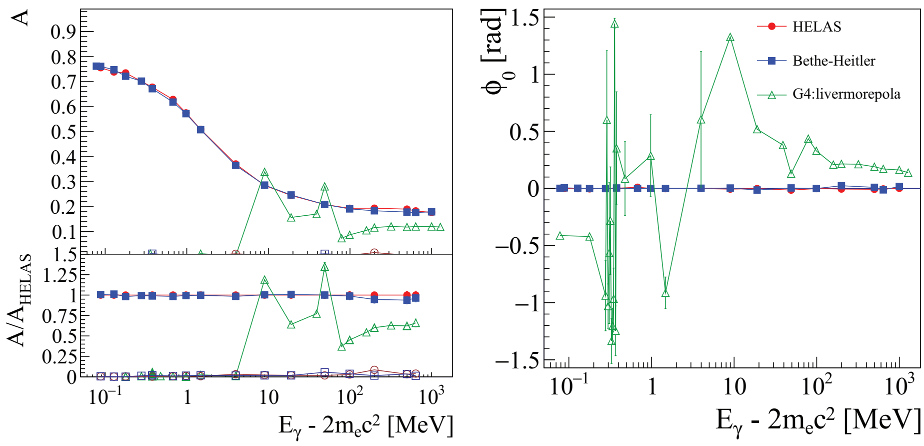

Fig. 4. – Amplitude A and phase ϕ_0 of the modulation of the distribution of the azimuthal angle ϕ. When A becomes too low ($E_\gamma < 5$ MeV for G4LivermorePolarizedGammaConversionModel), the phase ϕ_0 loses meaning. The asymptotic values of A at low and high energy are shown in dashed lines [8]. The exact model agrees very well with these functions. G4LivermorePolarizedGammaConversionModel fails to accurately describe the asymmetry, especially at low energy.

5. – Conclusion

We studied in simulations the kinematics of the conversion of gamma rays into electron-positron pairs. We developed and validated an exact 5D generator, which includes the effect of the photon polarisation. We find that the fine kinematics are poorly described by the available generators in Geant4 and EGS5. It is crucial that more accurate generators are used in the development of high resolution tracker, where these kinematics are the determining factor for the telescopes angular resolution. We also offer an optimal way to measure photon polarimetry from track directions. We find that no available event generator properly describes the effect of polarisation on the pair conversion kinematics. There are ongoing efforts to make the event generator presented here available in Geant4.

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It is a pleasure to acknowledge the support of the French National Research Agency (ANR-13-BS05-0002).

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