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deq99.f - A FLUKA user-routine converting fluence into effective dose and ambient dose equivalent

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Summary

Conversion coefficients from fluence into effective dose and ambient dose equivalent are implemented as a FLUKA user-routine for incident neutrons, protons, charged pions, muons, photons and electrons. The coefficients are based on fits to values for discrete energies as suggested by ICRP74 and as calculated by M. Pelliccioni *et al.* with FLUKA.

Keywords: Effective dose, ambient dose equivalent, fluence-to-dose conversion coefficients, FLUKA.

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1 Effective dose coefficients

The effective dose E is the sum of the weighted equivalent doses in all tissues and organs of the human body. It is given by the expression

$$E = \sum_T w_T \times H_T \tag{1}$$

where H_T is the equivalent dose in tissue or organ T and w_T is the weighting factor for tissue T. The equivalent dose H_T is given by

$$H_T = \sum_R w_R \times D_{T,R} \tag{2}$$

where $D_{T,R}$ is the average absorbed dose from radiation R in tissue T and w_R is the radiation weighting factor of radiation R.

The effective dose depends on the irradiation geometry. Coefficients for three different geometries are implemented in `deq99.f`:

1. **Anterior-Posterior** irradiation geometry (AP). This has been the standard irradiation geometry for over 40 years.
2. **Rotational** irradiation geometry (RT): It represents typical situations in an accelerator environment. Where specific values are not available for this particular geometry, the coefficients are defined as the mean values of those for Anterior-Posterior, Posterior-Anterior, Right-Lateral and Left-Lateral irradiation geometries. It has been verified that these mean values approximate well those for the rotational irradiation geometry.
3. **WORST** irradiation geometry (WT): At a certain energy the coefficient is defined as the maximum value of the coefficients for Anterior-Posterior, Posterior-Anterior, Right-Lateral and Left-Lateral irradiation geometries. "WORST" stands for "Working Out Radiation Shielding Thicknesses" as these coefficients are typically used for shielding design. It is the most pessimistic irradiation geometry which has to be used in studies of accident situations where the orientation of the body is not known.

The implementation in `deq99.f` is based on spline-fits to coefficients suggested by ICRP74 [1] for low energies and to values calculated by M. Pelliccioni. [2] In the latter case, $D_{T,R}$ has been obtained with FLUKA [3, 4] using an anthropomorphic phantom and a broad parallel beam of the respective particle type. The coefficients include tissue weighting factors as recommended by ICRP60 [5]. For each irradiation geometry, two sets of conversion coefficients are implemented in `deq99.f`, one based on radiation weighting factors w_R recommended by ICRP60 [5] and a second one which uses factors proposed by Pelliccioni [6]. They differ at higher energies, *e.g.*, in case of protons with energies above 2 MeV ICRP60 recommends a value of 5 while Pelliccioni proposes a value of 2 (see Ref. [6] for further details).

The effective dose conversion coefficients are shown in Figs. 1-14. Symbols denoted with "Pelliccioni-1" refer to coefficients based on w_R of ICRP60, while those denoted with "Pelliccioni-2" are based on the recommendations of Pelliccioni for w_R. The spline-fits implemented in `deq99.f` are labelled with a five-character string as follows

E<irradiation-geometry>< w_R-set>

where <irradiation-geometry> can be "AP", "RT" or "WT" and < w_R-set> is either "74" (ICRP values) or "MP" (Pelliccioni values). For example, "EWTMP" denotes the effective dose conversion coefficients for the WORST irradiation geometry and Pelliccioni radiation weighting factors.

2 Ambient dose equivalent coefficients

The ambient dose equivalent $H^*(10)$ at the point of interest in the actual radiation field is the dose equivalent which would be generated in the associated oriented and expanded radiation field at a depth of 10 mm on the radius of the ICRU sphere (30 cm diameter tissue equivalent) which is oriented opposite to the direction of incident radiation.

Again, the implementation in `deq99.f` is based on spline-fits to coefficients suggested by ICRP74 [1] for low energies and to values calculated by M. Pelliccioni with FLUKA. [2] The ambient dose equivalent coefficients for all considered particle types are also shown in Figs. 1-14. The sets are labelled with "AMB74".

3 Implementation as FLUKA user-routine

The effective dose and ambient dose equivalent conversion coefficients are implemented as FLUKA user-routine (function `FLUSCW`). This user-routine is called prior to any fluence scoring in FLUKA with the actual particle type and energy as argument. It returns a factor, to be specified by the user inside the routine, here the appropriate fluence-to-dose equivalent conversion coefficient in units of pSv×cm^2, and applies it to fluence as the scored quantity. The respective conversion coefficient sets are selected by the user by means of the `SDUM` input character string with the above mentioned labeling scheme, *e.g.*, "EWTMP".

The fits are not implemented in analytical form but as data tables with coefficients for discrete energy values between a minimum and a maximum energy. Double-logarithmic interpolation is performed within the energy bins. If the routine is called for a particle with an energy above the maximum energy of the tabulated grid (typically 10 TeV) the conversion coefficient corresponding to the maximum energy is assigned. On the other hand, if the routine is called for a particle with an energy below the minimum energy of the tabulated grid (which varies with the particle types, see the graphs in Figs. 1-14) it is assigned zero weight, except for neutrons and photons where the coefficient of the lowest tabulated energy is used.

Conversion coefficients are assigned to the most important particle types for typical transport calculations (see column 1 in Table 1), others are assigned zero weight. If no conversion coefficient set is implemented for one of the important particles it is approximated with the one of a particle of similar radiological effect, *e.g.*, kaons are assigned pion conversion coefficients. Conversion coefficients for negatively and positively charged muons are practically identical. Therefore, only one spline-fit is implemented for both charges in `deq99.f`. No specific recommendations were given by Pelliccioni for the radiation factors for photons and electrons. Thus, the routine returns identical factors for both sets of w_R, *e.g.*, for EWT74 and EWTMP. Table 1 summarizes the conversion coefficients implemented in `deq99.f`.

Table 1: Summary of conversion coefficient sets implemented and used for different particle types. The symbol "*" in "E*74" and "E*MP" refers to the labels for the different irradiation geometries, "AP","RT" and "WT". The symbol "x" means that the conversion coefficient set is implemented, while "-" denotes that it is not implemented and zero weighting is returned.

Particle type	Conversion coefficient set	E*74	E*MP	AMB74
proton	proton	x	x	x
antiproton	proton	x	x	x
electron	electron	x	E*74	x
positron	electron	x	E*74	x
photon	photon	x	E*74	x
neutron	neutron	x	x	x
antineutron	neutron	x	x	x
positive muon	muon	E*MP	x	x
negative muon	muon	E*MP	x	x
positive pion	positive pion	x	x	x
negative pion	negative pion	x	x	x
positive kaon	positive pion	x	x	x
negative kaon	negative pion	x	x	x
lambda	neutron	x	x	x
antilambda	neutron	x	x	x
negative sigma	negative pion	x	x	x
positive sigma	positive pion	x	x	x
others	-	-	-	-

References

[1] International Commission on Radiological Protection, “Conversion Coefficients for use in Radiological Protection against External Radiation”, ICRP Publication 74, Ann. ICRP 26, Pergamon Press (1996).

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[6] M. Pelliccioni, “Radiation weighting factors and high energy radiation”, Radiation Protection Dosimetry 80 (1998) 371-378.

[7] A. Ferrari, M. Pelliccioni and M. Pillon, “Fluence to effective dose and effective dose equivalent conversion coefficients for photons from 50 keV to 10 GeV”, Radiation Protection Dosimetry 67 (1996) 245-251.

[8] A. Ferrari, M. Pelliccioni and M. Pillon, “Fluence to effective dose and effective dose equivalent conversion coefficients for electrons from 5 MeV to 10 GeV”, Radiation Protection Dosimetry 69 (1997) 97-104.

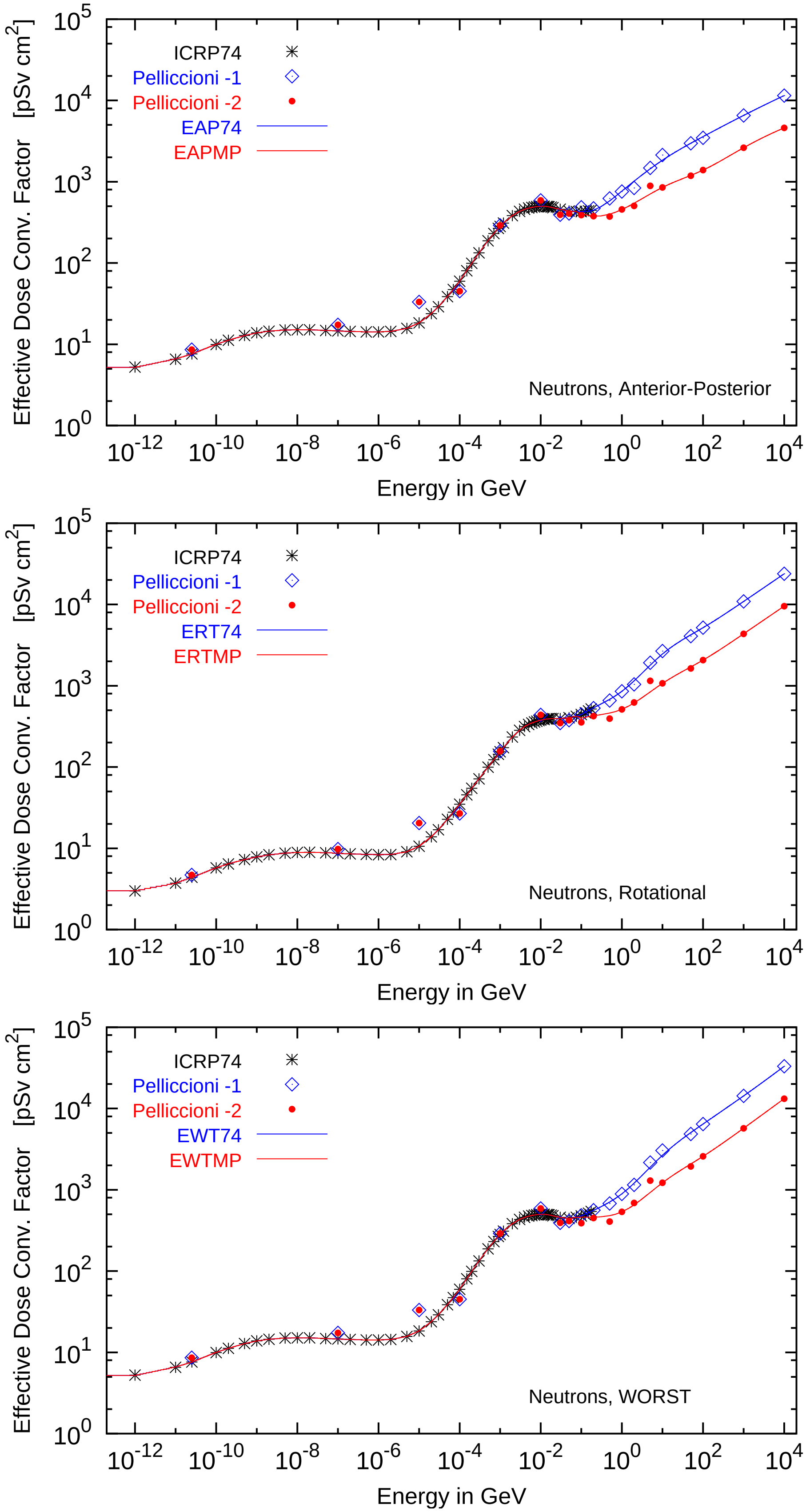


Figure 1: Conversion coefficients from fluence to effective dose for neutrons. Values recommended by ICRP below 180 MeV (Table A.41 in Ref. [1]) are shown together with coefficients calculated by Pelliccioni (Table A1.6 in Ref. [2]) and fitted curves as implemented in `deq99.f`. Values are given for anterior-posterior, rotational and WORST irradiation geometries.

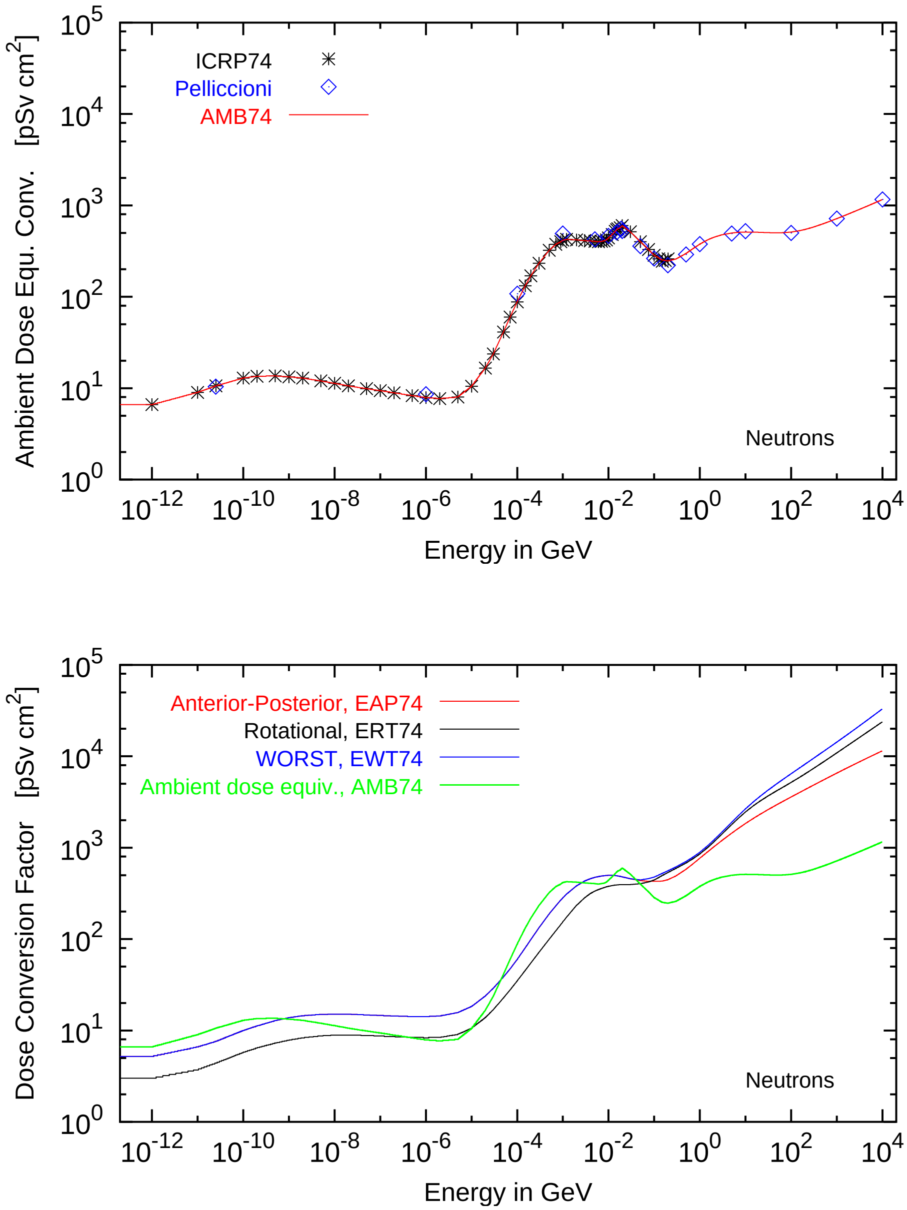


Figure 2: Conversion coefficients from fluence to ambient dose equivalent for neutrons (upper panel). Values recommended by ICRP below 200 MeV (Table A.42 in Ref. [1]) are shown together with coefficients calculated by Pelliccioni (Table A2.6 in Ref. [2]) and a fitted curve as implemented in `deq99.f`. The lower panel compares the different effective dose and the ambient dose equivalent conversion coefficient fits with each other.

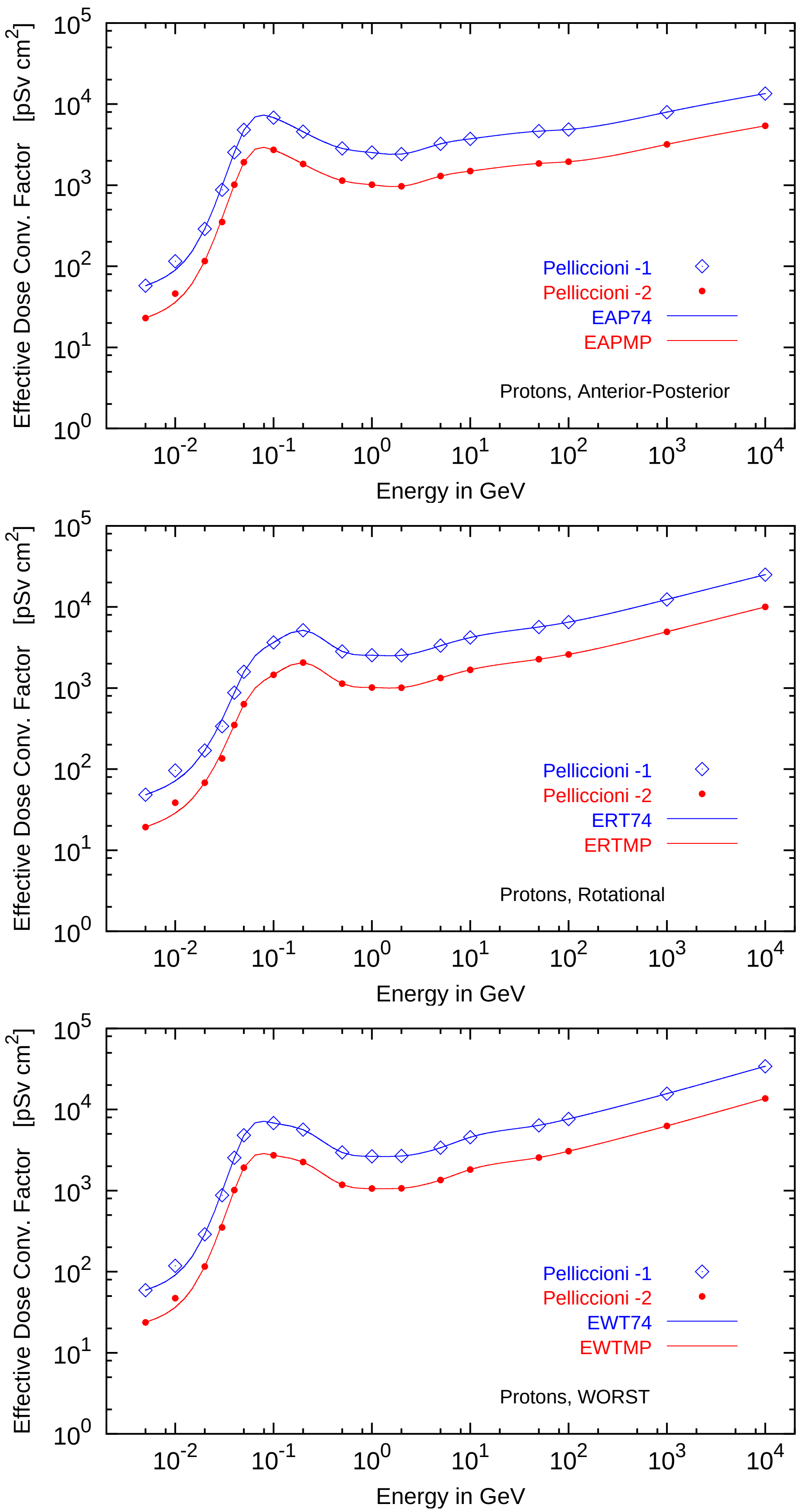


Figure 3: Conversion coefficients from fluence to effective dose for protons. Values calculated by Pelliccioni (Table A1.7 in Ref. [2]) and fitted curves as implemented in `deq99.f` are shown for anterior-posterior, rotational and WORST irradiation geometries.

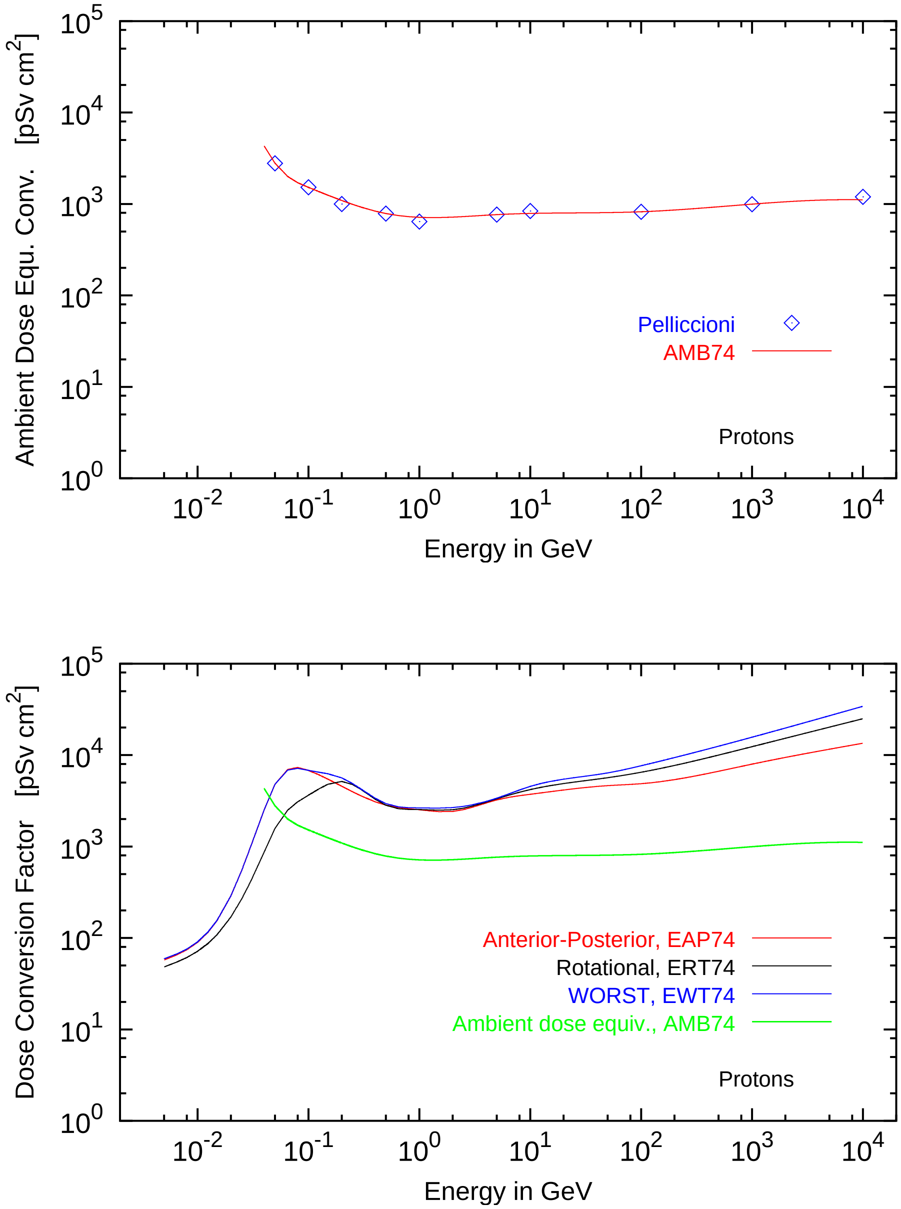


Figure 4: Conversion coefficients from fluence to ambient dose equivalent for protons (upper panel). Values calculated by Pelliccioni (Table A2.7 in Ref. [2]) are shown together with a fitted curve as implemented in `deq99.f`. The lower panel compares the different effective dose and the ambient dose equivalent conversion coefficient fits with each other.

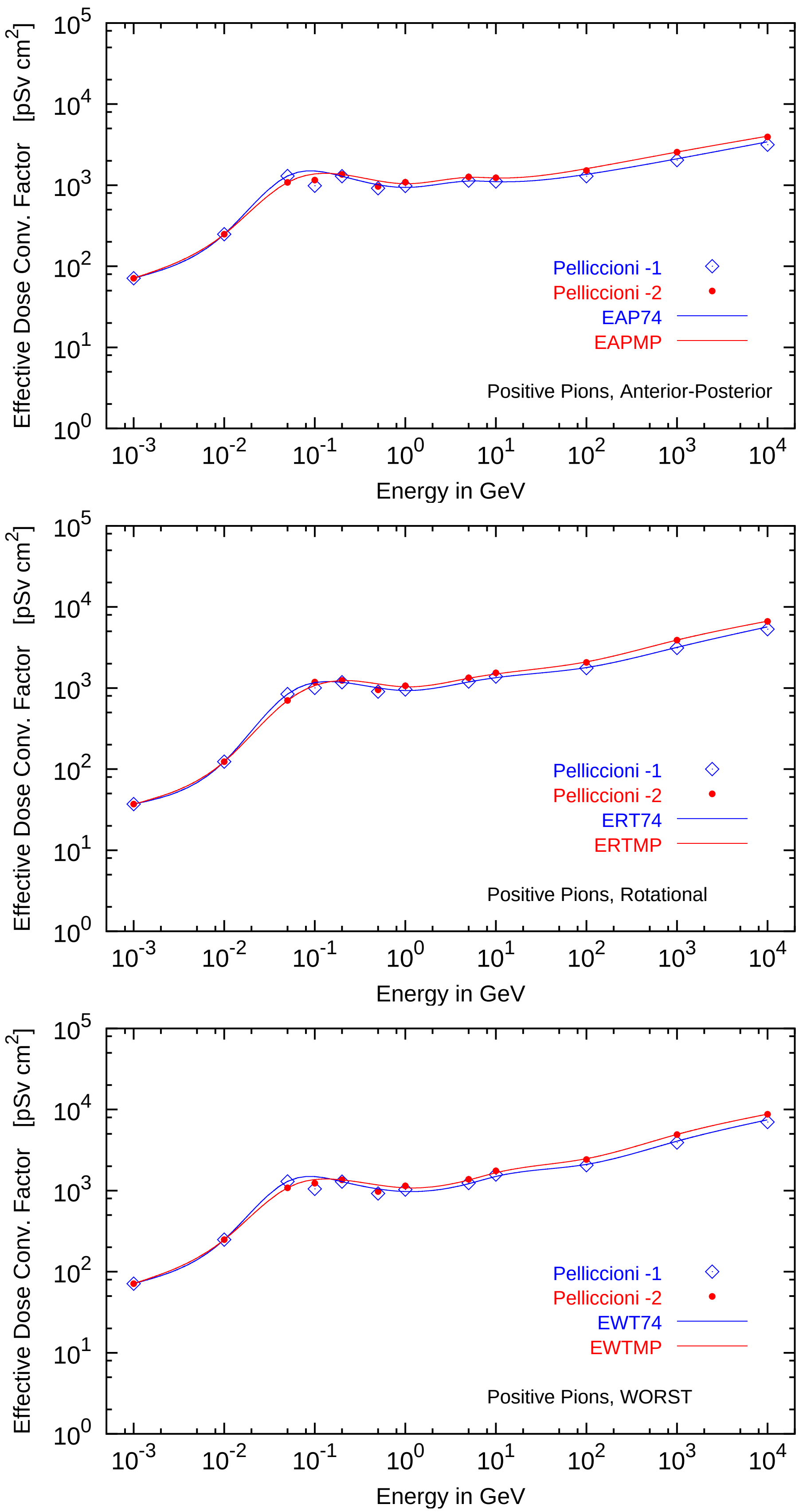


Figure 5: Conversion coefficients from fluence to effective dose for positively charged pions. Values calculated by Pelliccioni (Table A1.9 in Ref. [2]) and fitted curves as implemented in `deq99.f` are shown for anterior-posterior, rotational and WORST irradiation geometries.

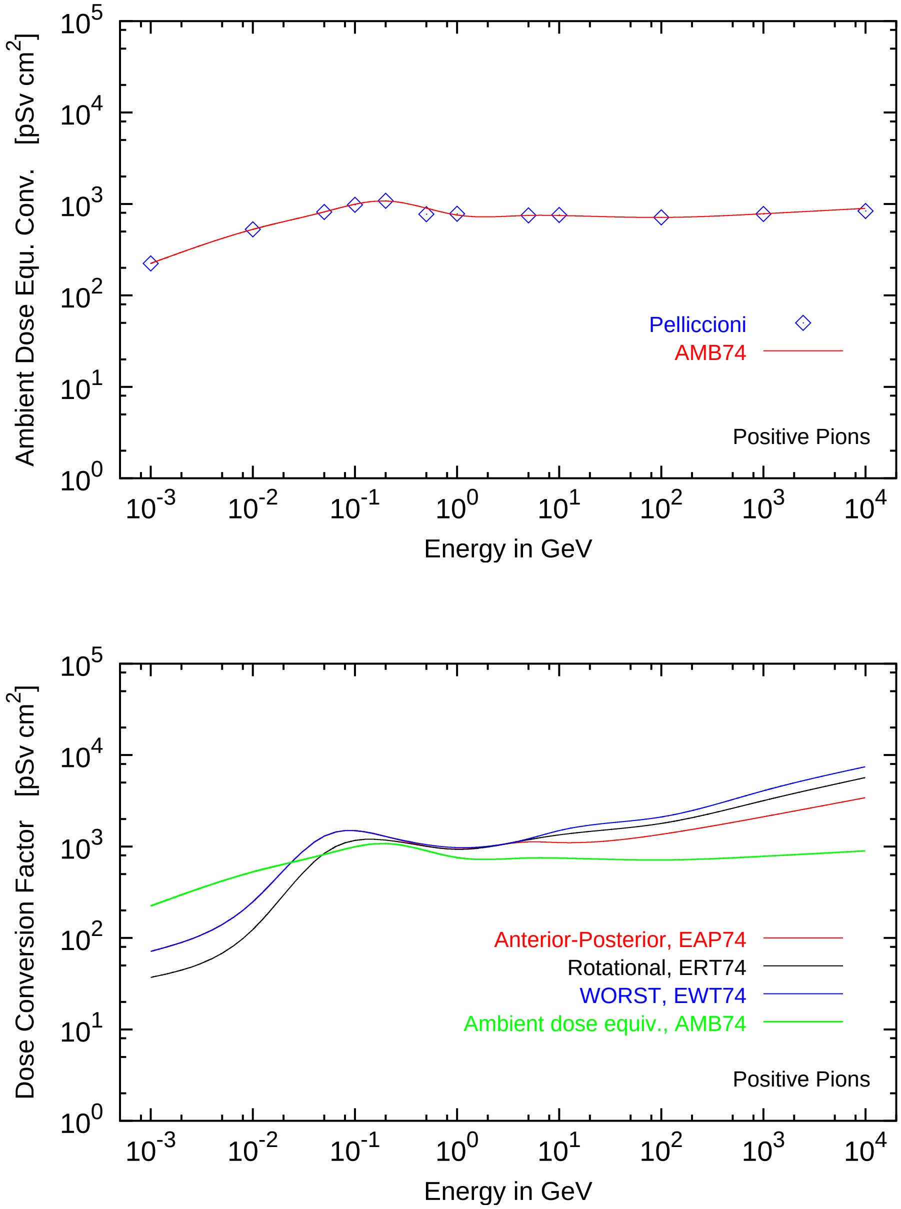


Figure 6: Conversion coefficients from fluence to ambient dose equivalent for positively charged pions (upper panel). Values calculated by Pelliccioni (Table A2.9 in Ref. [2]) are shown together with a fitted curve as implemented in `deq99.f`. The lower panel compares the different effective dose and the ambient dose equivalent conversion coefficient fits with each other.

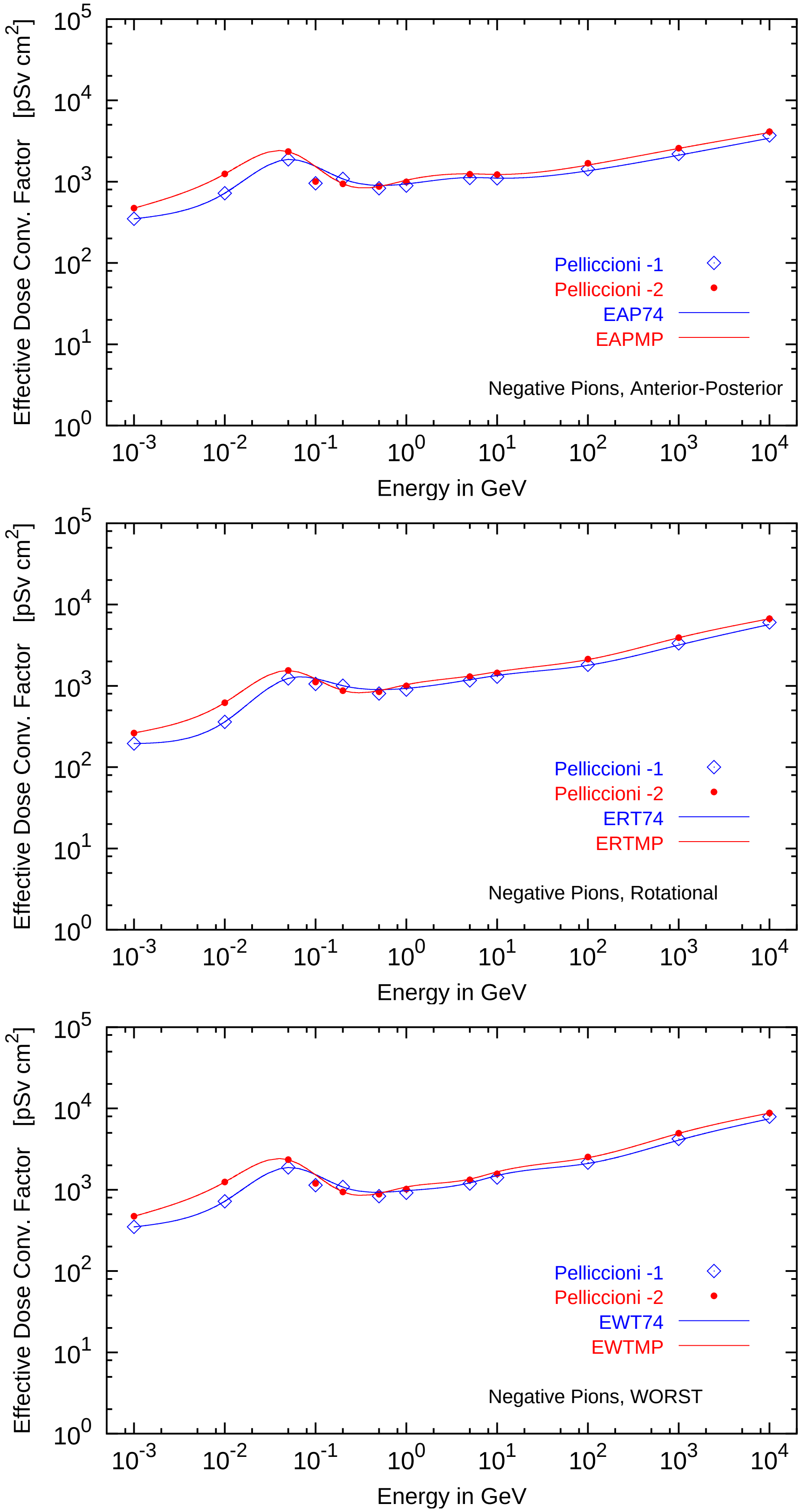


Figure 7: Conversion coefficients from fluence to effective dose for negatively charged pions. Values calculated by Pelliccioni (Table A1.8 in Ref. [2]) and fitted curves as implemented in `deq99.f` are shown for anterior-posterior, rotational and WORST irradiation geometries.

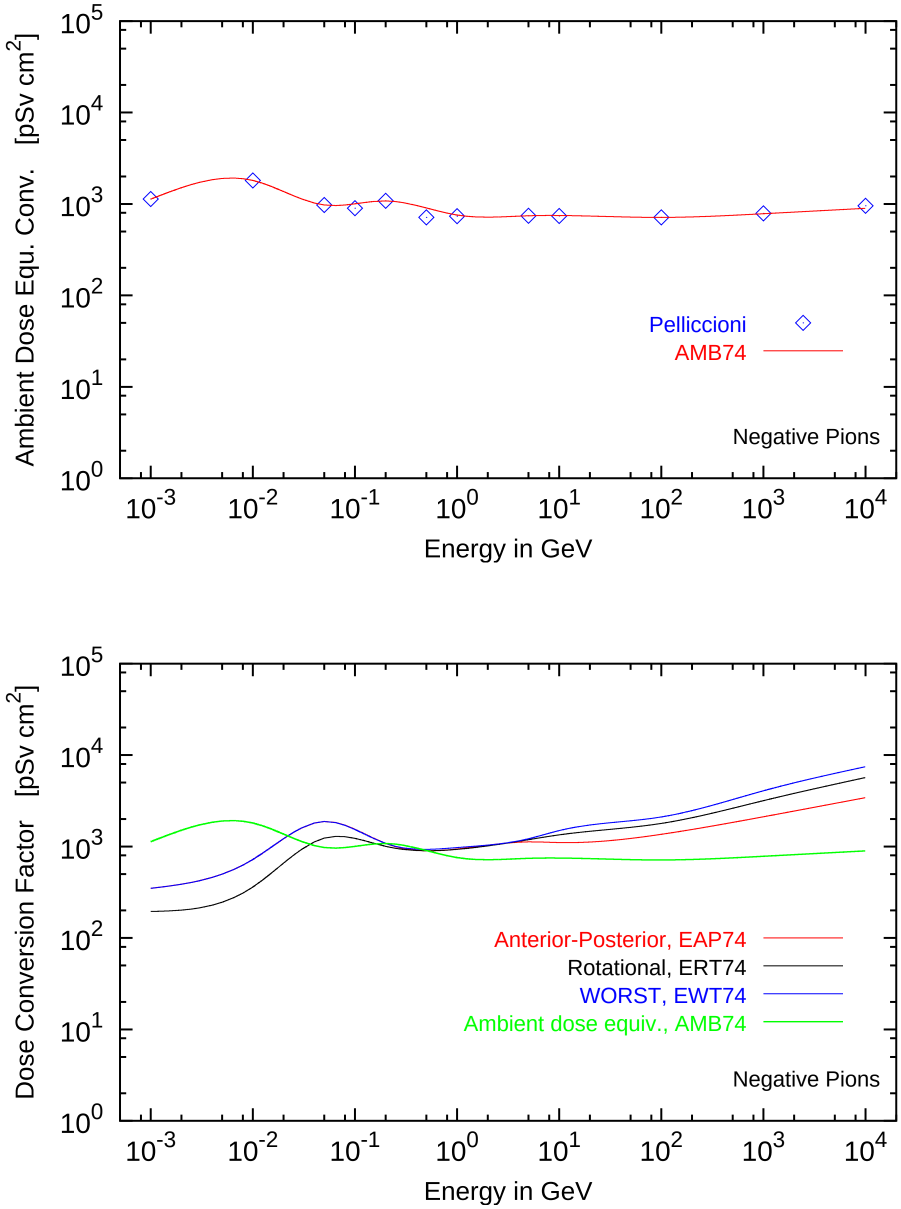


Figure 8: Conversion coefficients from fluence to ambient dose equivalent for negatively charged pions (upper panel). Values calculated by Pelliccioni (Table A2.8 in Ref. [2]) are shown together with a fitted curve as implemented in `deq99.f`. The lower panel compares the different effective dose and the ambient dose equivalent conversion coefficient fits with each other.

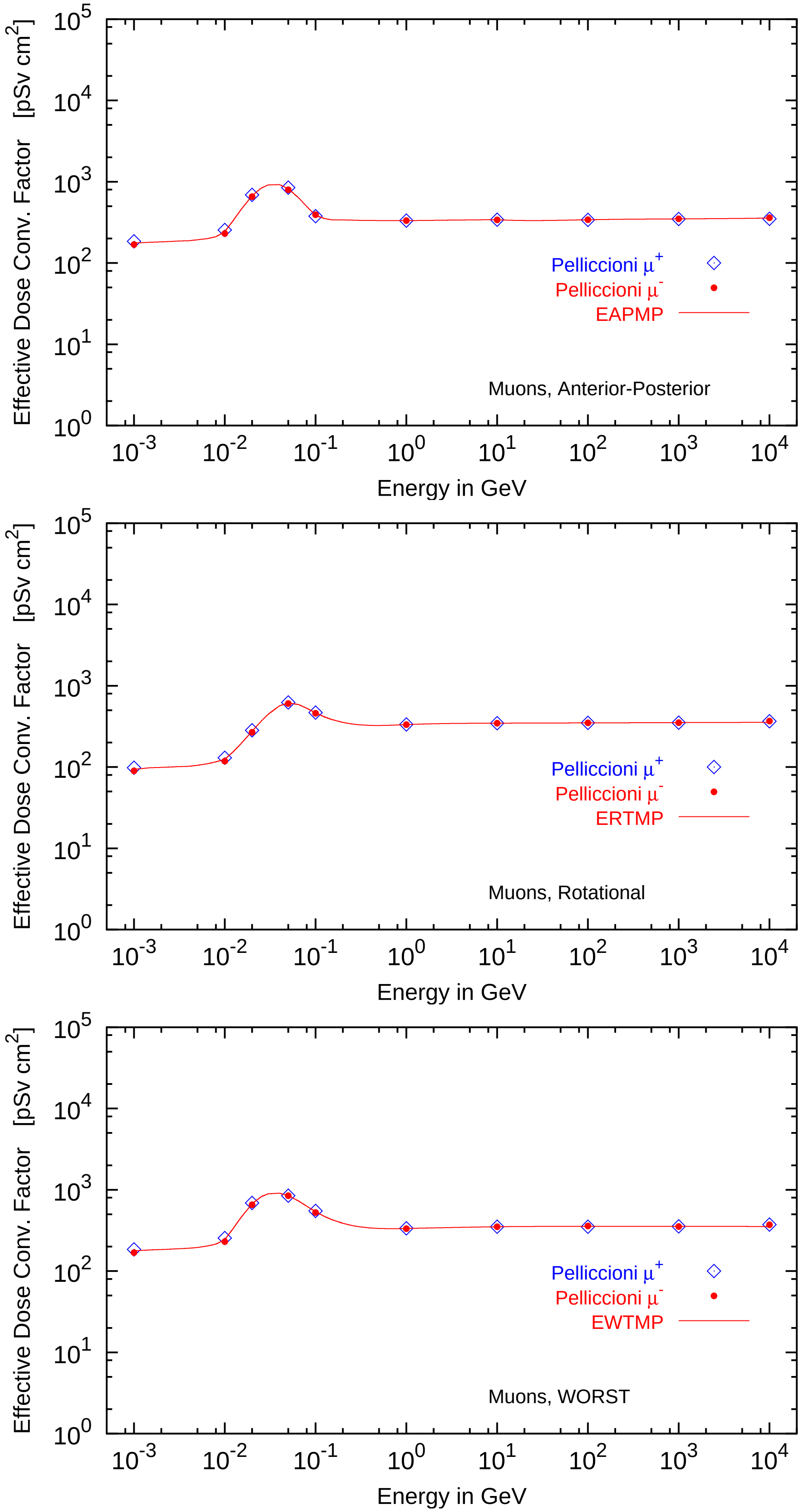
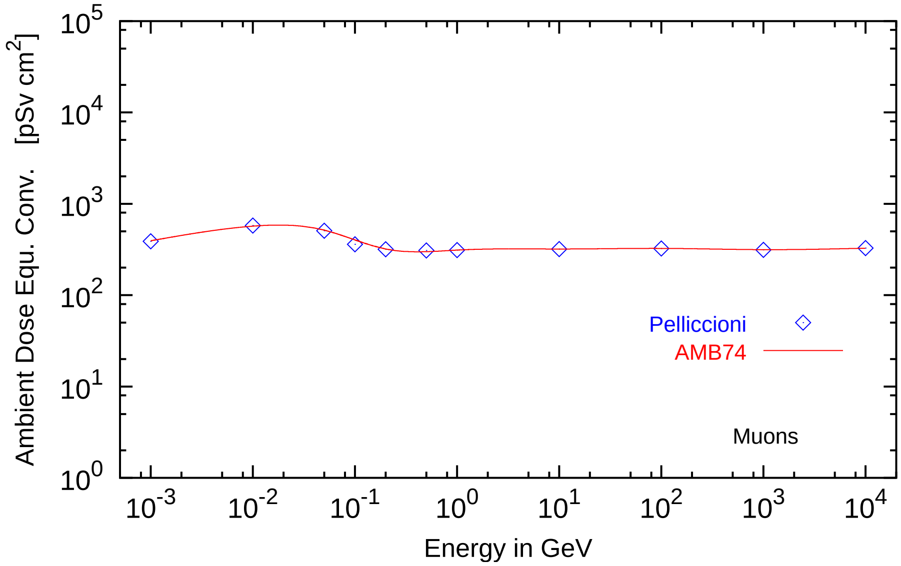


Figure 9: Conversion coefficients from fluence to effective dose for muons. Values calculated by Pellicicioni (Table A1.4 for negatively charged muons and Table A1.5 for positively charged muons, respectively, in Ref. [2]) and fitted curves as implemented in `deq99.f` are shown for anterior-posterior, rotational and WORST irradiation geometries.



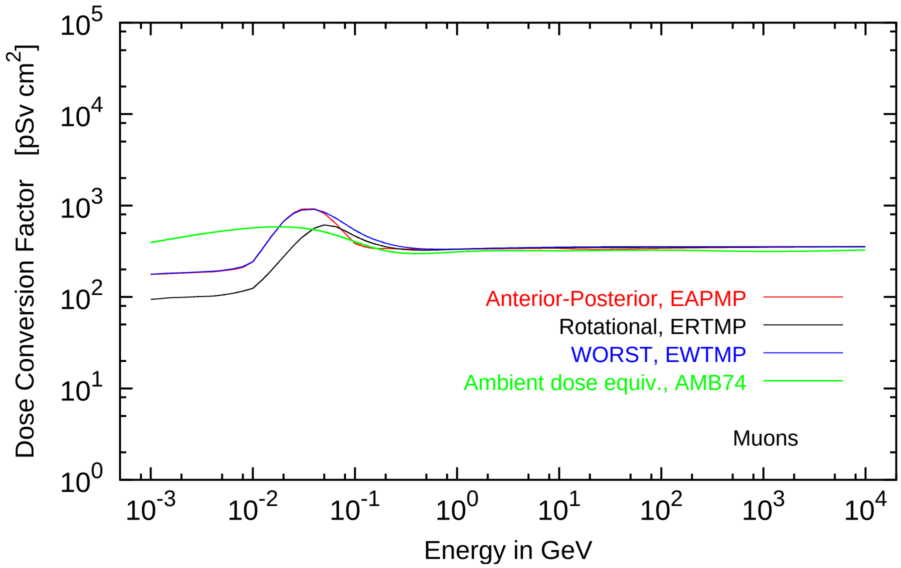


Figure 10: Conversion coefficients from fluence to ambient dose equivalent for muons (upper panel). Values calculated by Pelliccioni (Table A2.4 for negatively charged muons and Table A2.5 for positively charged muons, respectively, in Ref. [2]) are shown together with a fitted curve as implemented in `deq99.f`. The lower panel compares the different effective dose and the ambient dose equivalent conversion coefficient fits with each other.

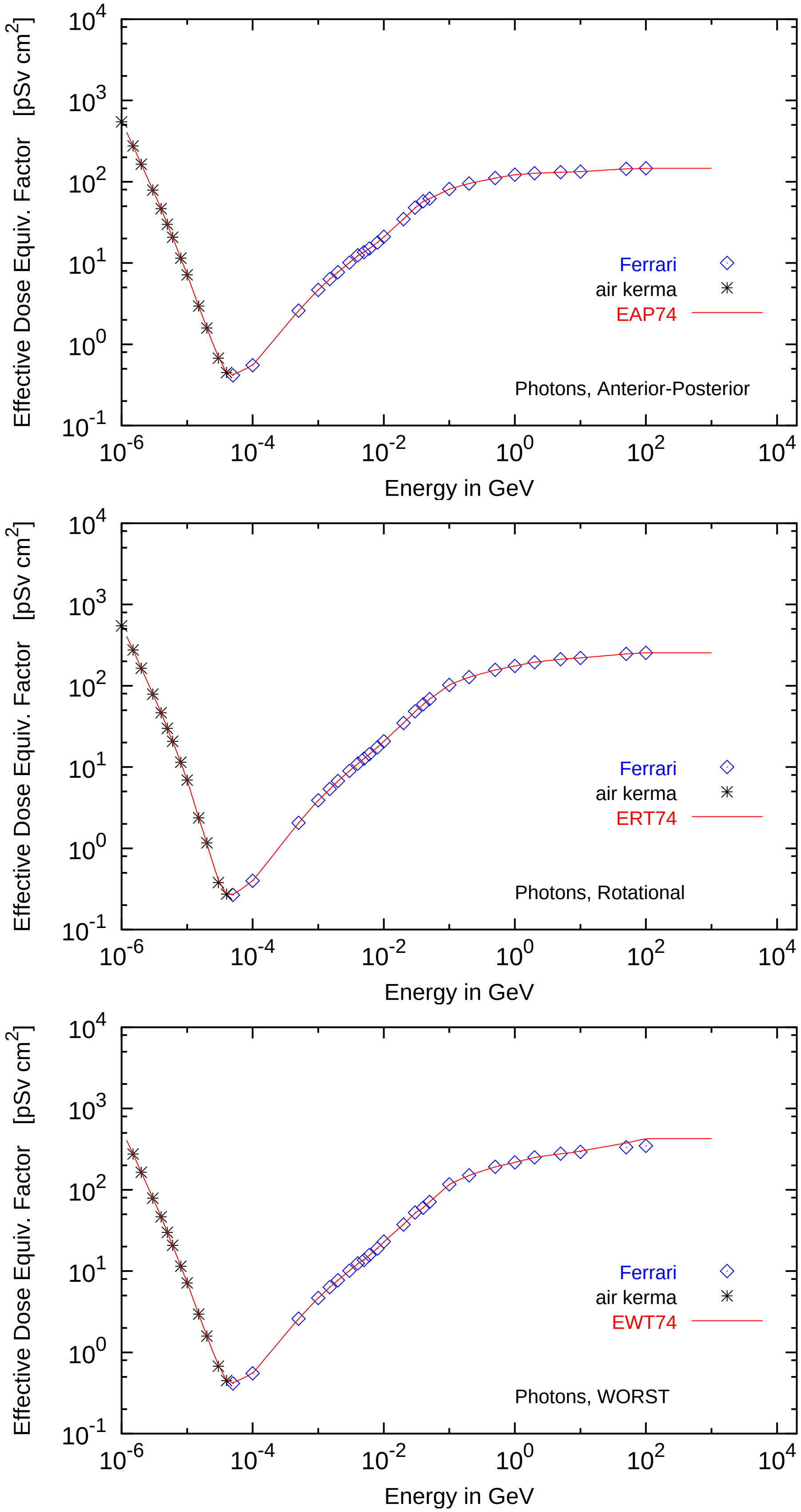


Figure 11: Conversion coefficients from fluence to effective dose equivalent for photons. Values calculated by Ferrari (Table 1 in Ref. [7]) and fitted curves as implemented in `deq99.f` are shown for anterior-posterior, rotational and WORST irradiation geometries. Below 50 keV conversion coefficients for air kerma per unit fluence are used.

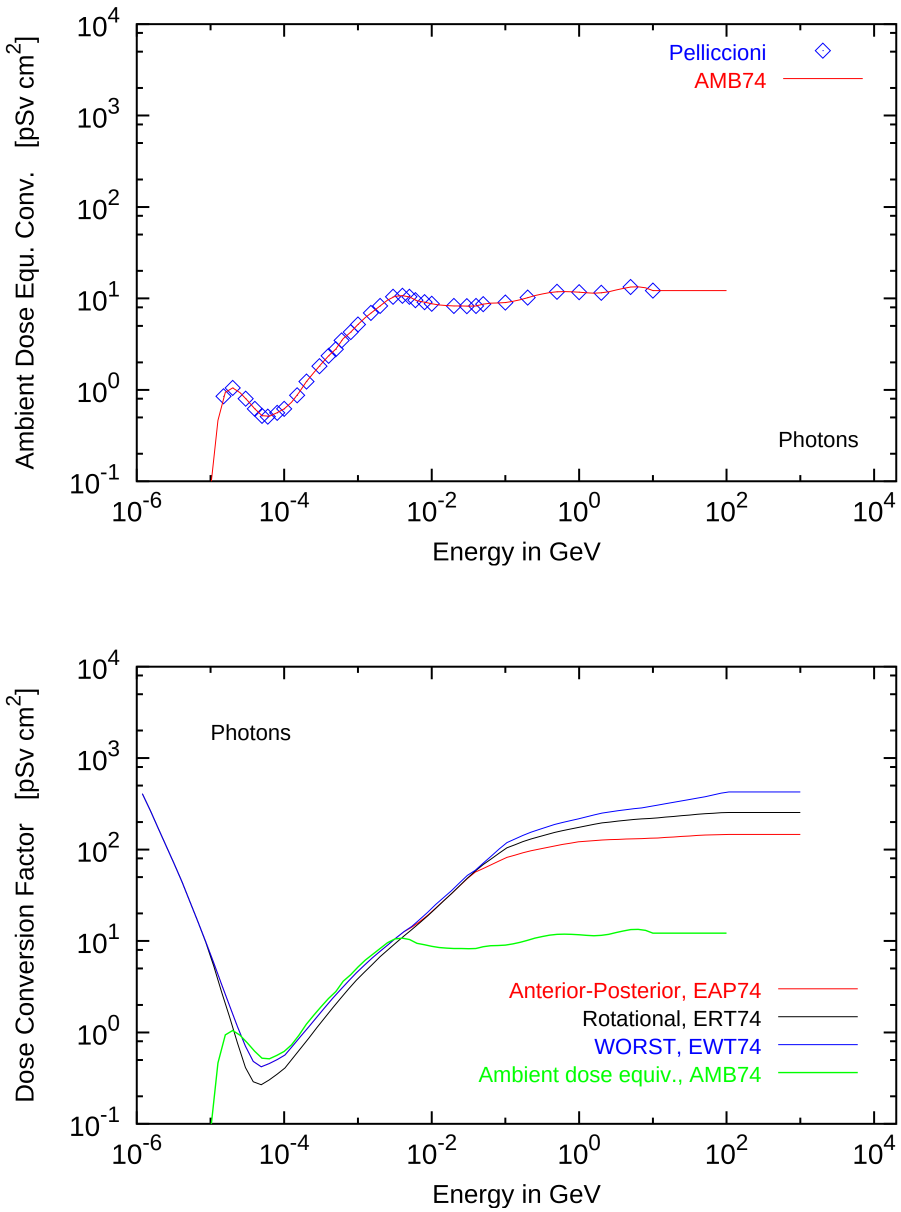


Figure 12: Conversion coefficients from fluence to ambient dose equivalent for photons (upper panel). Values calculated by Pelliccioni (Table A2.1 in Ref. [2]) are shown together with a fitted curve as implemented in `deq99.f`. The lower panel compares the different effective dose and the ambient dose equivalent conversion coefficient fits with each other.

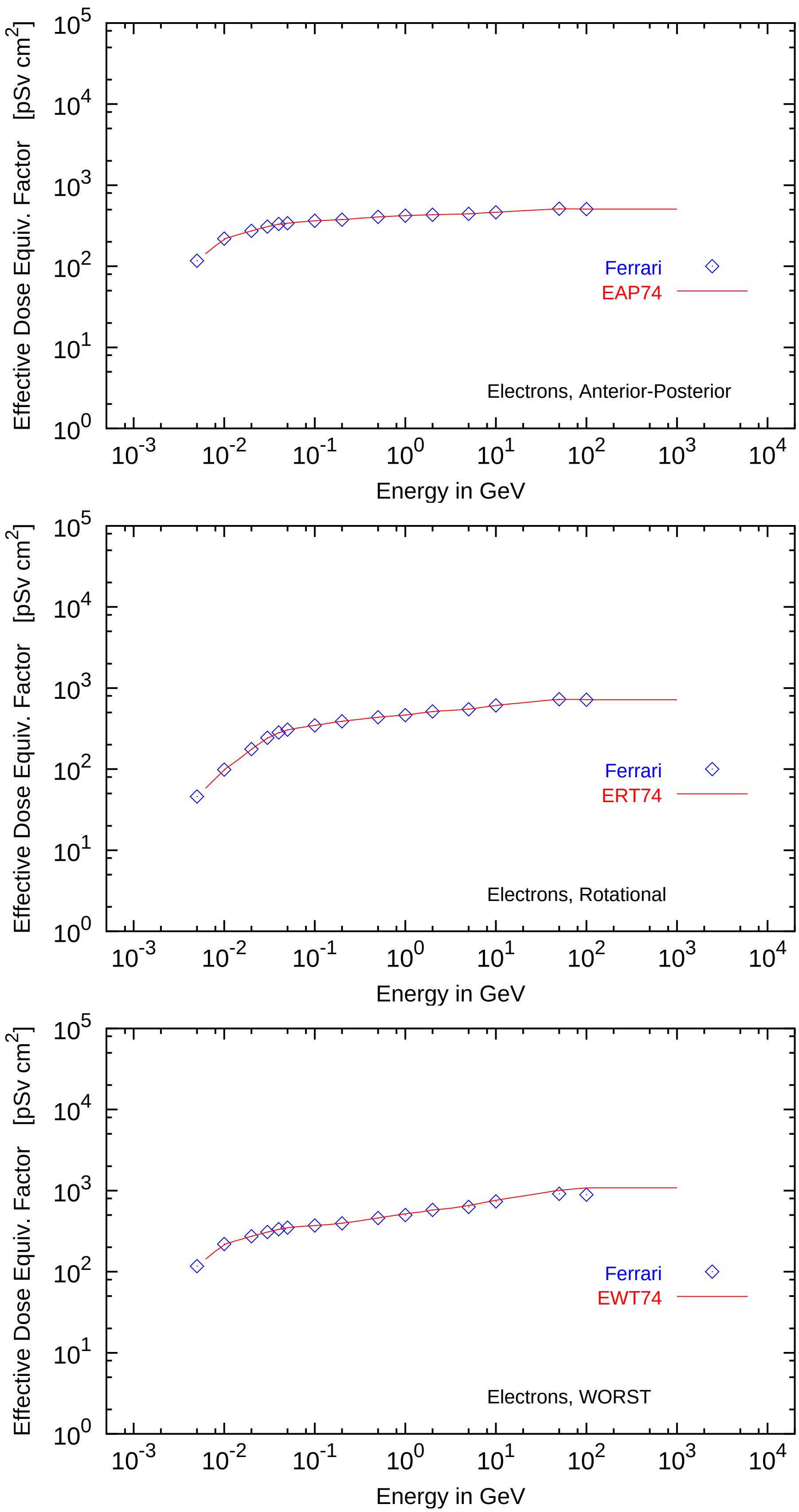


Figure 13: Conversion coefficients from fluence to effective dose equivalent for electrons. Values calculated by Ferrari (Table 1 in Ref. [8]) and fitted curves as implemented in `deq99.f` are shown for anterior-posterior, rotational and WORST irradiation geometries.

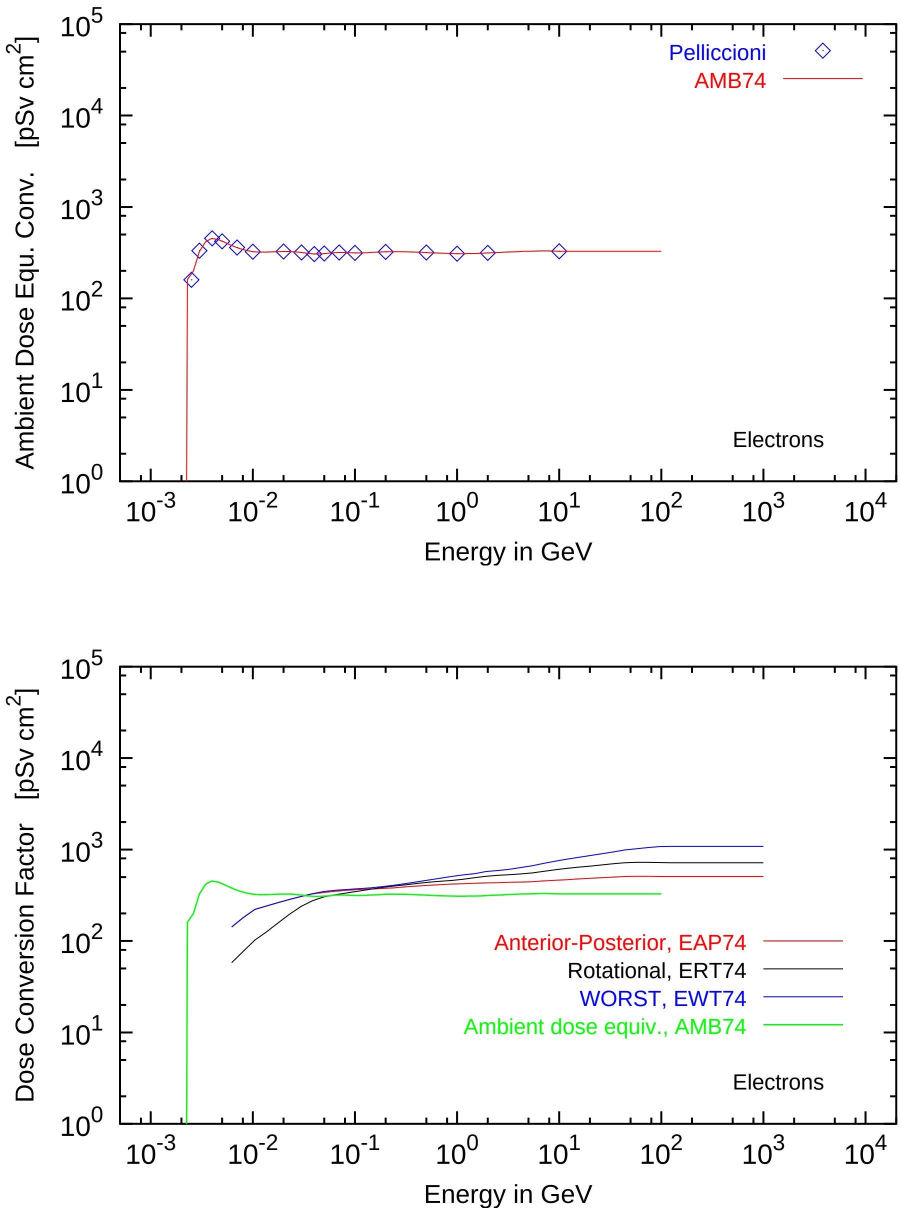


Figure 14: Conversion coefficients from fluence to ambient dose equivalent for electrons (upper panel). Values calculated by Pelliccioni (Table A2.2 in Ref. [2]) are shown together with a fitted curve as implemented in `deq99.f`. The lower panel compares the different effective dose and the ambient dose equivalent conversion coefficient fits with each other.