EDMS Document Number: **2439884**
Rev: 1.0- Status: Released

ORGANISATION EUROPEENNE POUR LA RECHERCHE NUCLEAIRE
EUROPEAN ORGANIZATION FOR NUCLEAR RESEARCH
Laboratoire Européen pour la Physique des Particules
European Laboratory for Particle Physics

Occupational Health & Safety and Environmental Protection Unit

Technical Note
16 November 2020

Implementation of ICRP116 Fluence to Effective Dose Conversion Coefficients in a FLUKA user routine

prepared by:	**verified by:**	**approved by:**
D. Bozzato (HSE-RP-AS)	R. Froeschl (HSE-RP-AS)	R. Froeschl (HSE-RP-AS)

CERN-OPEN-2023-009
16/11/2020

Summary

The estimation of the effective dose from the prompt radiation of a high energy and mixed radiation field is an important aspect of radiation protection at accelerator facilities. At present, it is possible to estimate effective dose from external irradiation with the FLUKA Monte Carlo code using conversion coefficients as suggested by ICRP *Publication 74* and as calculated by M. Pelliccioni.

This Technical Note describes the methodology with which the latest sets of conversion coefficients from the ICRP *Publication 116* for neutrons, protons, charged pions, muons, photons, electrons and positrons have been implemented in a FLUKA user routine for converting fluence to effective dose for different external irradiation geometries during radiation transport. The conversion coefficients for several other particles, e.g. kaons and sigmas, are approximated by the conversion coefficients for particles having a similar radiological effect, as it has been done in the past.

Modifications

Revisions	Date	Pages	Description
1.0	16.11.2020	all	Creation of document

Contents

1 Introduction

1.1 Effective dose and conversion coefficients

The effective dose is one of the primary radiation protection quantities recommended in the ICRP *Publication 103* [1] and is the fundamental quantity used in the regulatory framework. As it was defined in ICRP *Publication 60* [2], the effective dose E is the weighted sum of tissue equivalent doses:

$$E = \sum_T w_T \sum_R w_R D_{T,R} = \sum_T w_T H_T \qquad (1)$$

where $D_{T,R}$ is the mean absorbed dose in an organ or tissue T from radiation R, w_T is the tissue weighting factor chosen to represent the contributions of individual organs and tissues to the overall radiation detriment ($\sum_T w_T = 1$) and w_R the radiation weighting factor. The unit of the effective dose is the sievert (Sv) and this quantity is not directly measurable but can only be estimated once the exposure conditions are known.

Since the ICRP *Publication 74* [3], additional radiation types have been considered and ICRP *Publication 116* [4] has issued new sets of coefficients for external radiation exposure that were computed taking into account the updated radiation weighting factors and tissue weighting factors based on the latest available scientific information regarding the biological consequences of radiation exposure. For the ICRP calculations, the Reference Male and Female phantoms were also employed: these are based on tomographic images and composed of voxels and were defined and formally adopted as a standard in the ICRP *Publication 110* [5].

The analysis of the differences between the new set of coefficients and the previous one for external exposure conditions is presented in ICRP *Publication 116* with great detail for each particle type. The most important aspects are:

- the differences in the photons, electrons and positron coefficients with respect to the tabulated values in ICRP *Publication 74* are not greater than 20%-30% and are largely attributable to specific aspects of the computational phantoms employed.
- larger differences are observed for low and high energy neutrons mainly due to the change in the energy dependent radiation weighting factors.
- for protons and charged pions a radiation weighting factor of 2 has been proposed and for muons a factor of 1 (values that are consistent with the radiation weighting factors computed and recommended by M. Pelliccioni [6]).
- a set of coefficients for alpha particles was also issued even though, at least for application other than space ones, they are of less importance due to their short range in tissue at typical energies.

Within the scope of their use, since issued by an international authority, the coefficients have to be considered as reference data and therefore without uncertainty.

1.2 Possible irradiation geometries

The fluence to effective dose conversion coefficients were calculated by different ICRP Task Groups for idealized whole body irradiation using the official ICRP computational phantoms and following the recommendations of ICRP *Publication 103*.

Depending on the orientation of the body with respect to the incoming radiation, the dose to the organs can differ significantly. For this reason, there are sets of coefficients for different irradiation geometries:

- **Anterior-Posterior (AP) and Posterior-Anterior (AP) geometries** The radiation is incident in a direction orthogonal to the long axis of the body respectively on the front (AP) and on the back (PA) of the body. These conditions approximate, for particular and known body orientation, the irradiation by the radiation field produced by a distant source.
- **Left Lateral (LLAT) and Right Lateral (RLAT) irradiation geometries** In this case, the radiation is incident in a direction orthogonal to the long axis of the body on the left side (LLAT) or on the right side (RLAT) of the body. These conditions approximate, for particular and known body orientation, the irradiation by the radiation field produced by a distant source.
- **Rotational irradiation geometry** In this condition, the body is irradiated by a parallel beam of ionising radiation which rotates at uniform rate around the long axis of the body from a direction orthogonal to the long axis. It can well approximate the irradiation by a planar source or the situation in which a person moves randomly in a radiation field.
- **Isotropic irradiation geometry** Is an irradiation condition in which the particle fluence per solid angle does not depend on the direction and the location in space. It is typical of highly scattered radiation or can well approximate the external exposure from a large cloud of radioactive gas.
- **WORST irradiation geometry** The WORST (Working Out the Radiations Shielding Thickness) [7] irradiation condition does not represent a real irradiation geometry. It is the most conservative case for radiation studies in which the body orientation is not known. The coefficients for this case are the maximum between the available irradiation geometries. In general the Anterior-Posterior irradiation geometry gives the highest values at lower energies, while at higher energies the Isotropic irradiation condition, due to the greater path of primary and secondary particles in the phantom, gives the highest contribution (especially in the case of hadrons).

2 Implementation in FLUKA user routine

The fluence to effective dose conversion coefficients that were implemented in FLUKA [8, 9] by S. Roesler [7] for AP, ROT and WORST irradiation geometries are data tables based on fits to coefficients suggested by ICRP *Publication 74* for low energies and to values calculated by M. Pelliccioni [10]. For each irradiation geometry two sets had been implemented: one based on radiation weighting factors recommended by ICRP *Publication 60* and one based on radiation weighting factors proposed by M. Pelliccioni [6].

Using a similar approach, the ICRP *Publication 116* fluence to effective dose conversion coefficients for external radiation exposure have been implemented in a FLUKA user routine as data tables for discrete energy values. The energy points are equally spaced in a logarithmic scale chosen to have ten points per each decade. To produce such data tables, the procedure recommended by ICRP *Publication 116* was followed: a cubic spline was used to interpolate between the ICRP tabulated coefficients in a log-log scale.

The tabulated data from ICRP are limited to $10\,\mathrm{GeV}$ with the only exception of charged pions for which the maximum tabulated energy is $200\,\mathrm{GeV}$. For LHC applications, the way higher energies are treated is an important aspect. Considering that at very high energies the interaction lengths are approximately constant while the energy of the secondaries (hence their path in the organs) is greater, a linear extrapolation based on the high energy trend was implemented up to $10\,\mathrm{TeV}$. This solution seems physically sound and reproduces well the high energy behaviour also observed in the previously implemented sets of coefficients which included also few points at very high energy.

The data tables obtained in this way have been implemented in a FLUKA user routine based on `fluscw.f`[1] which returns the appropriate fluence to effective dose coefficient in $\mathrm{pSv\,cm^2}$ and applies it to fluence as scored by `USRBIN`, `USRTRACK` and `USRBDX` estimators.

Different sets have been implemented for AP, PA, ISO and WORST irradiation geometries. The choice of the desired set to be applied is done through the `SDUM` of the scoring card, a string in the form ED<irradiation_geometry>, where <irradiation_geometry> can be `AP`, `PA`, `ISO` or `WORST` (for example, `EDISO` will apply fluence to effective dose conversion coefficients for an isotropic irradiation). For protons, photons and neutrons also sets for LLAT, RLAT and ROT irradiation geometries are implemented for dedicated applications. Since these sets were not provided for all the particles, they are by default disabled and an appropriate flag in the routine has to be set in order to enable them before compiling: even in the latter case, a zero weighting will be applied when requesting these sets if a particle is not a proton, photon or neutron. This is an important aspect to be considered since, for example, the photon exposure is always accompanied by secondary electrons and positrons.

Regarding the attribution of the correct coefficient, once the routine is called, the `SDUM` is checked and the proper data table is used. At this stage if LLAT, RLAT or ROT sets are requested without being enabled, the run is stopped. When the particle energy is between two energy points, a linear interpolation in log-log scale is performed between the tabulated data. If the energy is greater than the maximum energy of $10\,\mathrm{TeV}$, the coefficient corresponding to the maximum energy is assigned. If the particle energy is below the lowest tabulated value for that particle a zero weighting is applied with the exception of neutrons and photons for which the lowest tabulated values is used.

Since they were provided in ICRP *Publication 116*, coefficients for Helium-4 ions are also implemented. Except for space applications, it is very unlikely to have Helium-4 ions exceeding few MeV and, at these energies, their range in tissue is so small that they do not pose significant problems for external irradiation. For this reason, if the contribution of Helium-4 ions has to be taken into account, the sets have to be enabled by a proper flag before compiling the routine.

[1] The user routine which applies the coefficients is an improvement of the same routine that had been implemented for the application of the fluence conversion coefficients method to the radiological characterization [11–13]. Estimation of effective dose and user of conversion coefficients from `SETDATA.txt` can be performed in the same run.

In the radiation fields of high energy accelerators there could be other particles to be considered but for which no fluence to effective dose conversion coefficients have been provided yet. The same approach as the one adopted by S. Roesler [7] was followed: the coefficients of another particle having a similar radiological effect are used for these particles. The different conversion coefficient sets for different particle types are summarized in table 1. All other particles are weighted with 0.

Particle Type	**Set of conversion coefficients (ICRP116)**	**Particle Type**	**Set of conversion coefficients (ICRP116)**
proton	proton	anitproton	proton
electron	electron	antineutron	neutron
positron	positron	positive kaon	positive pion
photon	photon	negative kaon	negative pion
neutron	neutron	lamda	neutron
positive muon	positive muon	antilambda	neutron
negative muon	negative muon	negative sigma	negative pion
positive pion	positive pion	positive sigma	positive pion
negative pion	negative pion		

Table 1: Summary of the fluence to effective dose conversion coefficient sets implemented for different particle types. All other particles are weighted with 0.

Figures 1 to 10 show for each particle type and irradiation geometry the fluence to effective dose conversion coefficients for external exposure as implemented in the FLUKA user routine. The ICRP *Publication 116* tabulated data and the values calculated by M. Pelliccioni, both with the radiation weighting factors from ICRP *Publication 60* (as recommended by ICRP *Publication 74*) and with the ones recommended by M. Pelliccioni, are shown on each plot when available. The fits implemented in the FLUKA routine are labelled in a similar way as described before, with an added specification for the particle type, i.e. the set are named, just for plotting purposes, as ED<particle><irradiation_geometry>. For a given particle type, the sets for all the irradiation geometries are also shown in a single plot for comparison.

3 Conclusion

The way in which the fluence to effective dose conversion coefficients for external exposure issued in ICRP *Publication 116* have been implemented in a FLUKA user routine was the discussed in the present Technical Note.

As illustrated in figures 1 to 10, there are no significant changes for electrons, photons and muon coefficients. Notably there is a difference in the positrons coefficients from those of electrons at lower energies (at least below 10 MeV) where annihilation photons give a larger contribution to the dose of deep seated organs. The coefficients for protons, neutrons and pions are in line with values from M. Pelliccioni obtained with his recommended radiation weighting factors: indeed, the current radiation weighting factors, at least at high energy, are equivalent to those proposed by M. Pelliccioni. Differences in neutron coefficients at lower energy have been attributed in ICRP *Publication 116* by the change in the function describing the energy dependence of the radiation weight. The superimposition of the implemented fits with the old coefficients from Pelliccioni is also an additional confirmation of the soundness of the linear extrapolation at energies higher than 10 GeV.

The validation of the implementation of the coefficients and the comparison of the effective dose estimated with the ICRP *Publication 116* and the FLUKA built-in estimators has been performed for a simple test case and the main results have been presented in a separate Technical Note [14].

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[5] International Commission on Radiological Protection. *Adult Reference Computational Phantoms*, 2009. ICRP Publication 110, Ann. ICRP 39(2).

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[10] M. Pelliccioni. *Overview of Fluence-to-Effective Dose and Fluence-to-Ambient Dose Equivalent Conversion Coefficients for High Energy Radiation Calculated Using the FLUKA Code*. *Radiation Protection Dosimetry*, 88(4):279–297, 2000.

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[13] Fluence conversion coefficients code GitLab repository.

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Appendices

Appendix A

Conversion coefficients from fluence to effective dose

The fluence to effective dose conversion coefficients for external exposure for different particle types and irradiation geometries as implemented in the FLUKA user routine are shown in the following Appendix.

The ICRP *Publication 116* tabulated data and the values calculated by M. Pelliccioni both with the radiation weighting factors from ICRP *Publication 60* (as recommended by ICRP *Publication 74*) and with the ones recommended by M. Pelliccioni are shown on each plot when available.

The fits implemented in the FLUKA routine are labelled in a similar way as described before, with an added specification for the particle type, i.e. the set are named, just for plotting purposes, as ED<particle><irradiation_geometry>. For a given particle type, the sets for all the irradiation geometries are also shown in a single plot for comparison.

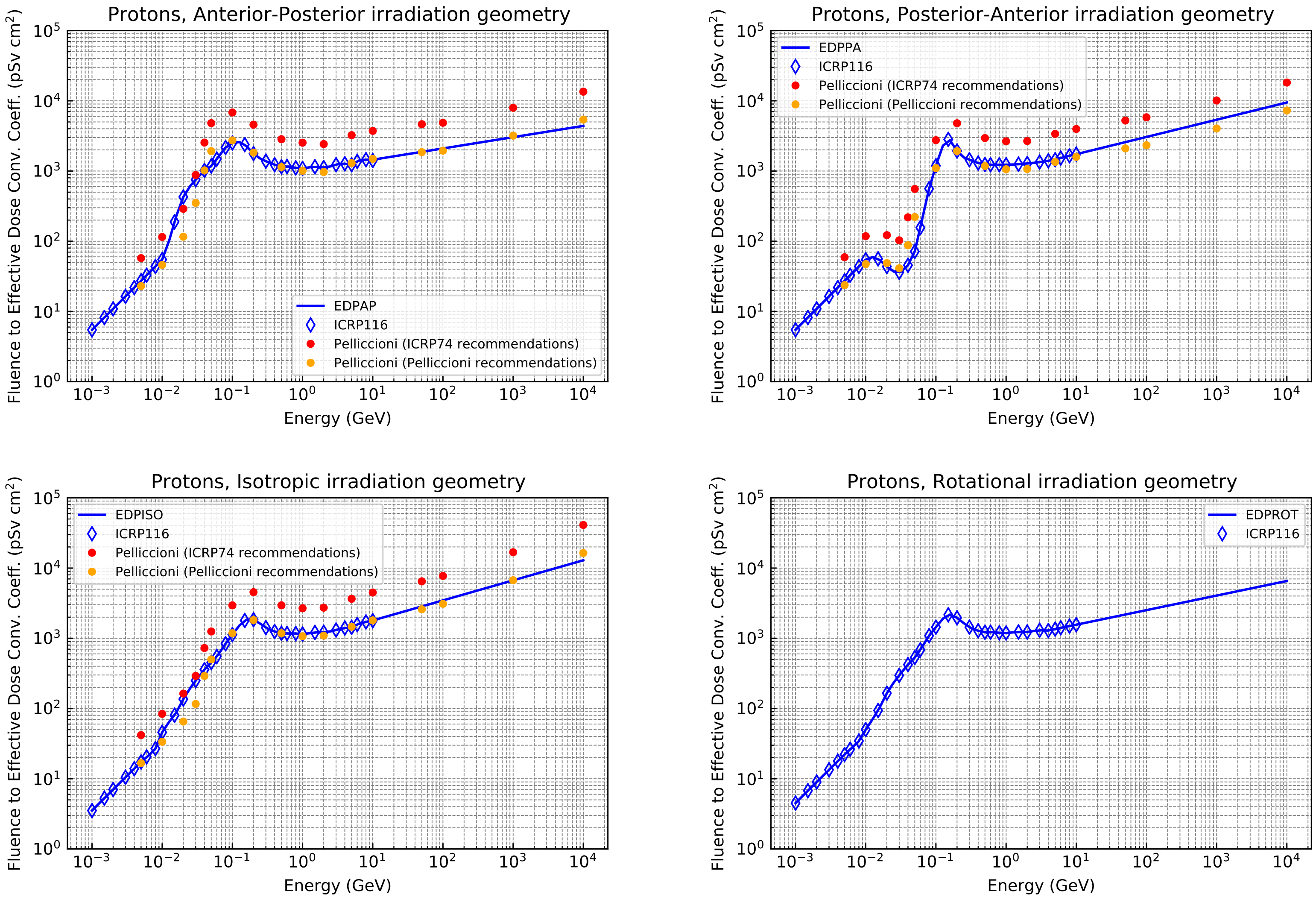


Figure 1: Conversion coefficients from fluence to effective dose for protons. Values from ICRP *Publication 116* are shown together with M. Pelliccioni calculation for the available irradiation geometries.

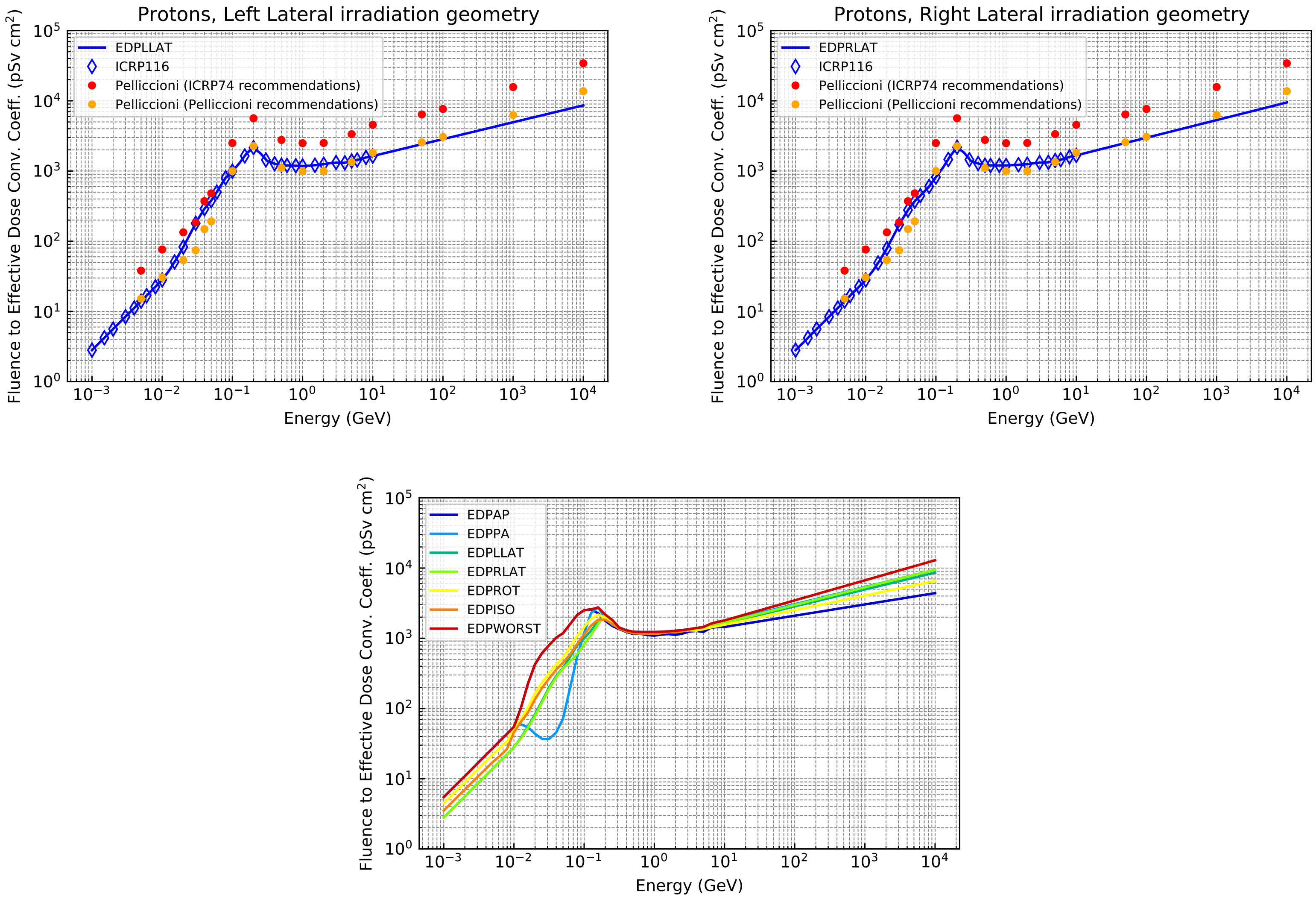


Figure 1: (Continued) Conversion coefficients from fluence to effective dose for protons. Values from ICRP *Publication 116* are shown together with M. Pelliccioni calculation for the available irradiation geometries.

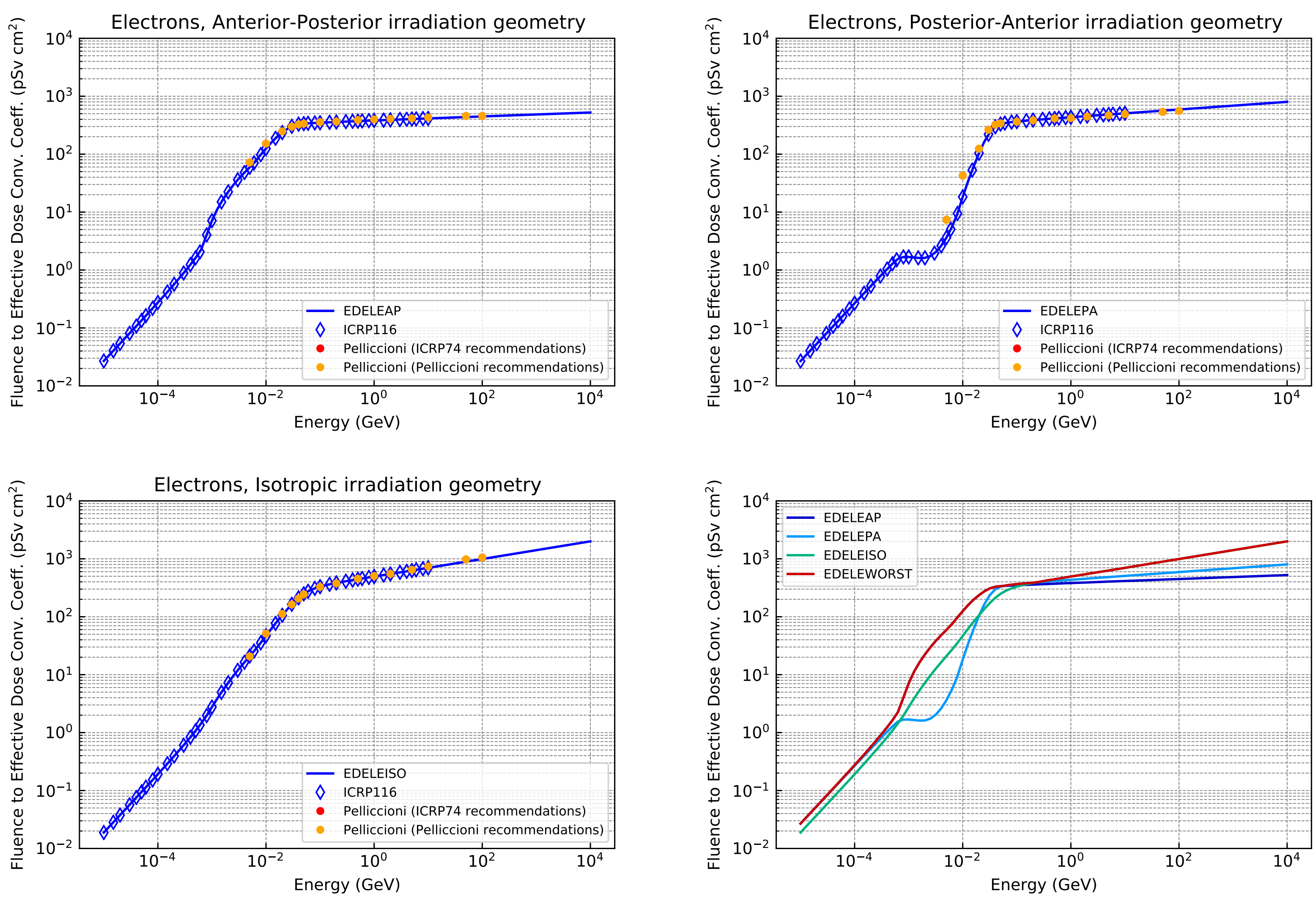


Figure 2: Conversion coefficients from fluence to effective dose for electrons. Values from ICRP *Publication 116* are shown together with M. Pelliccioni calculation for the available irradiation geometries.

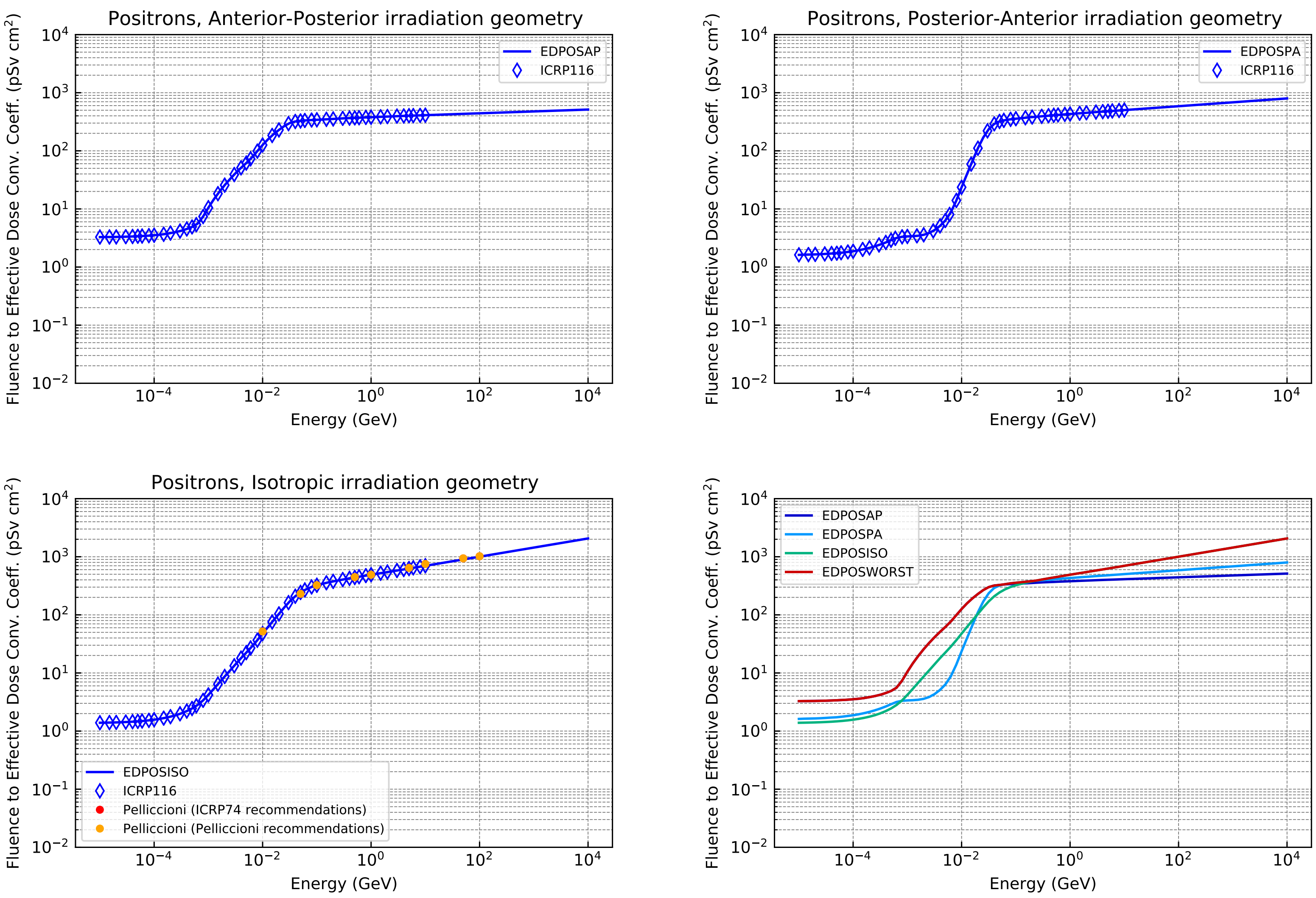


Figure 3: Conversion coefficients from fluence to effective dose for positrons. Values from ICRP *Publication 116* are shown together with M. Pelliccioni calculation for the available irradiation geometries.

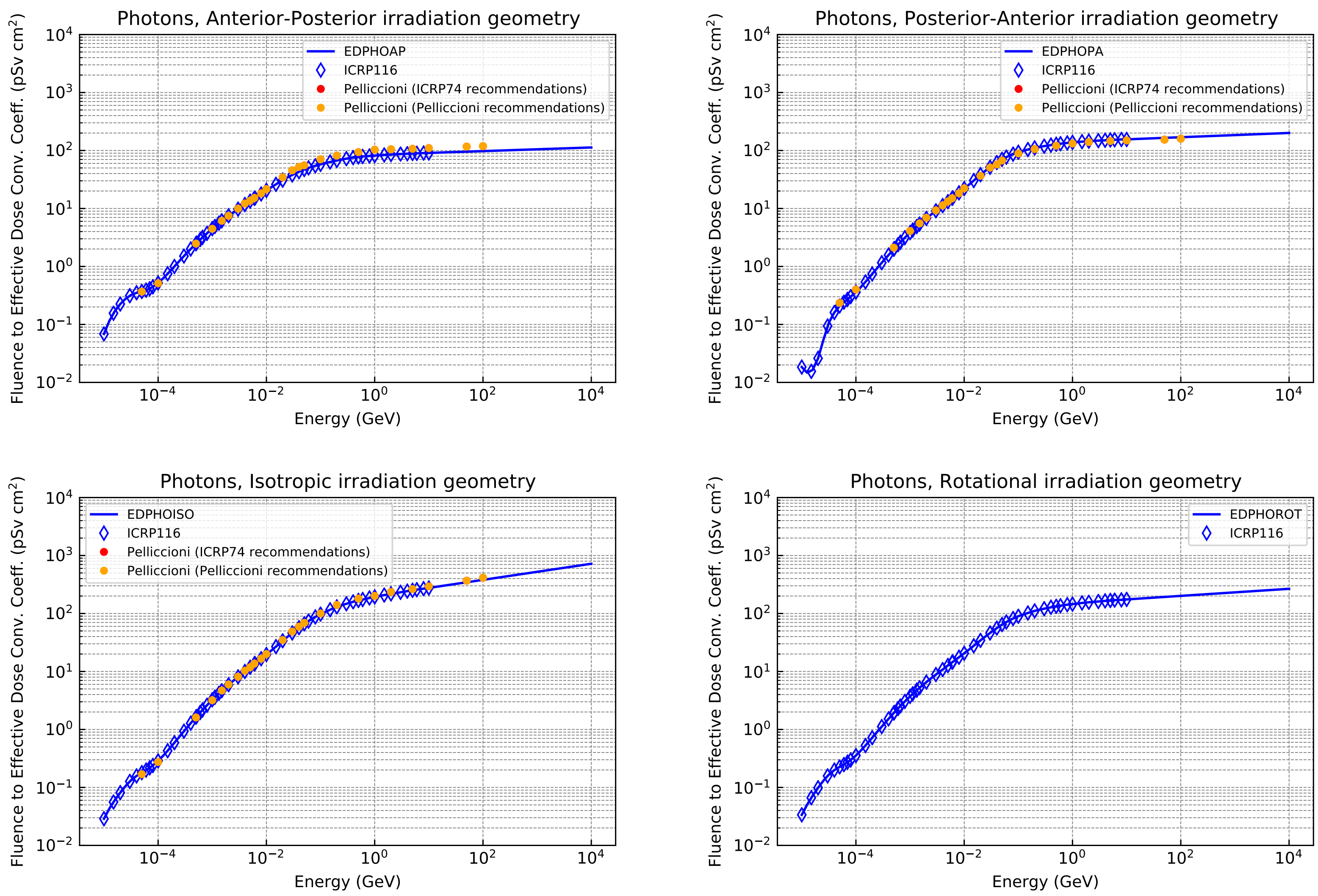


Figure 4: Conversion coefficients from fluence to effective dose for photons. Values from ICRP *Publication 116* are shown together with M. Pelliccioni calculation for the available irradiation geometries.

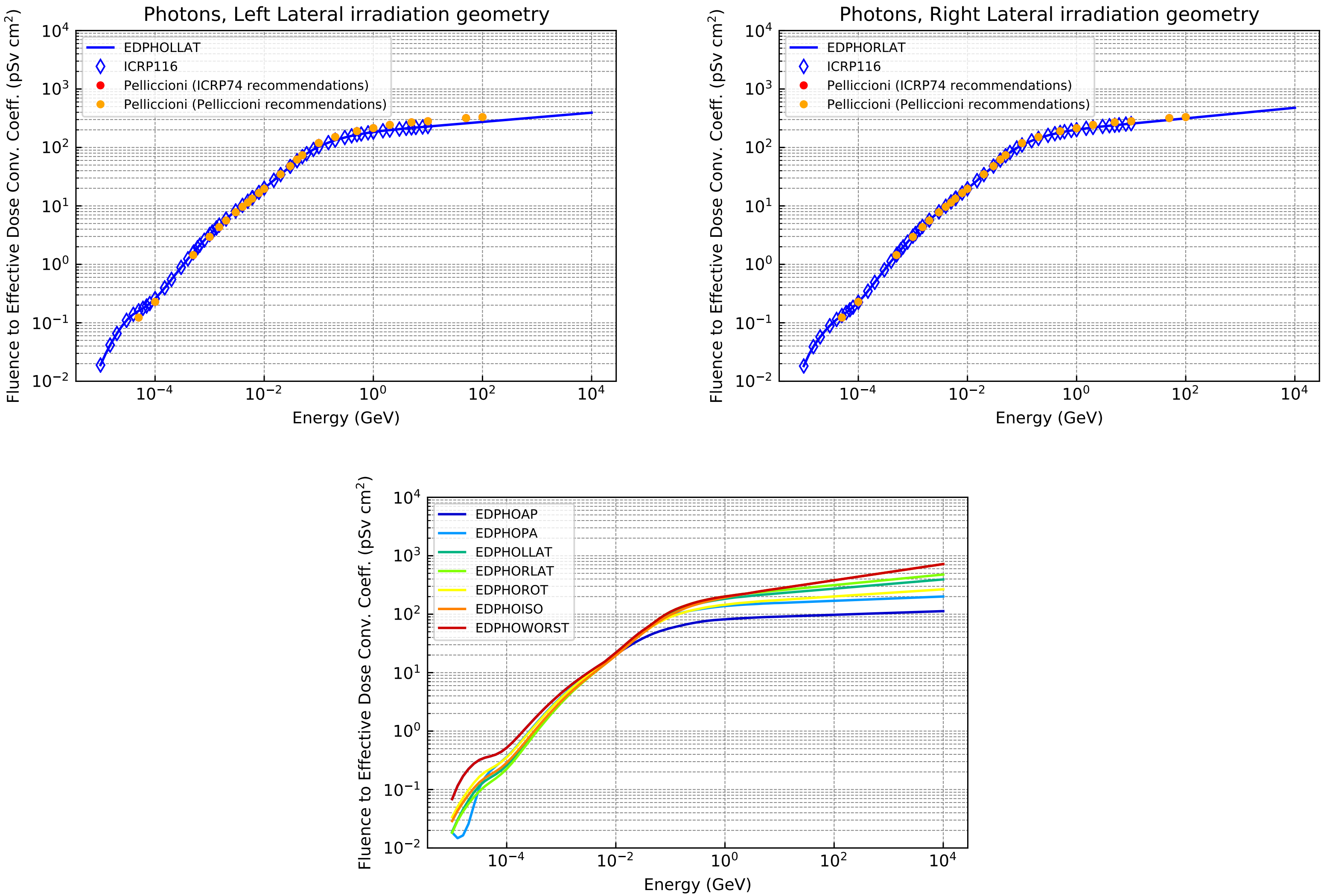


Figure 4: (Continued) Conversion coefficients from fluence to effective dose for neutrons. Values from ICRP *Publication 116* are shown together with M. Pelliccioni calculation for the available irradiation geometries.

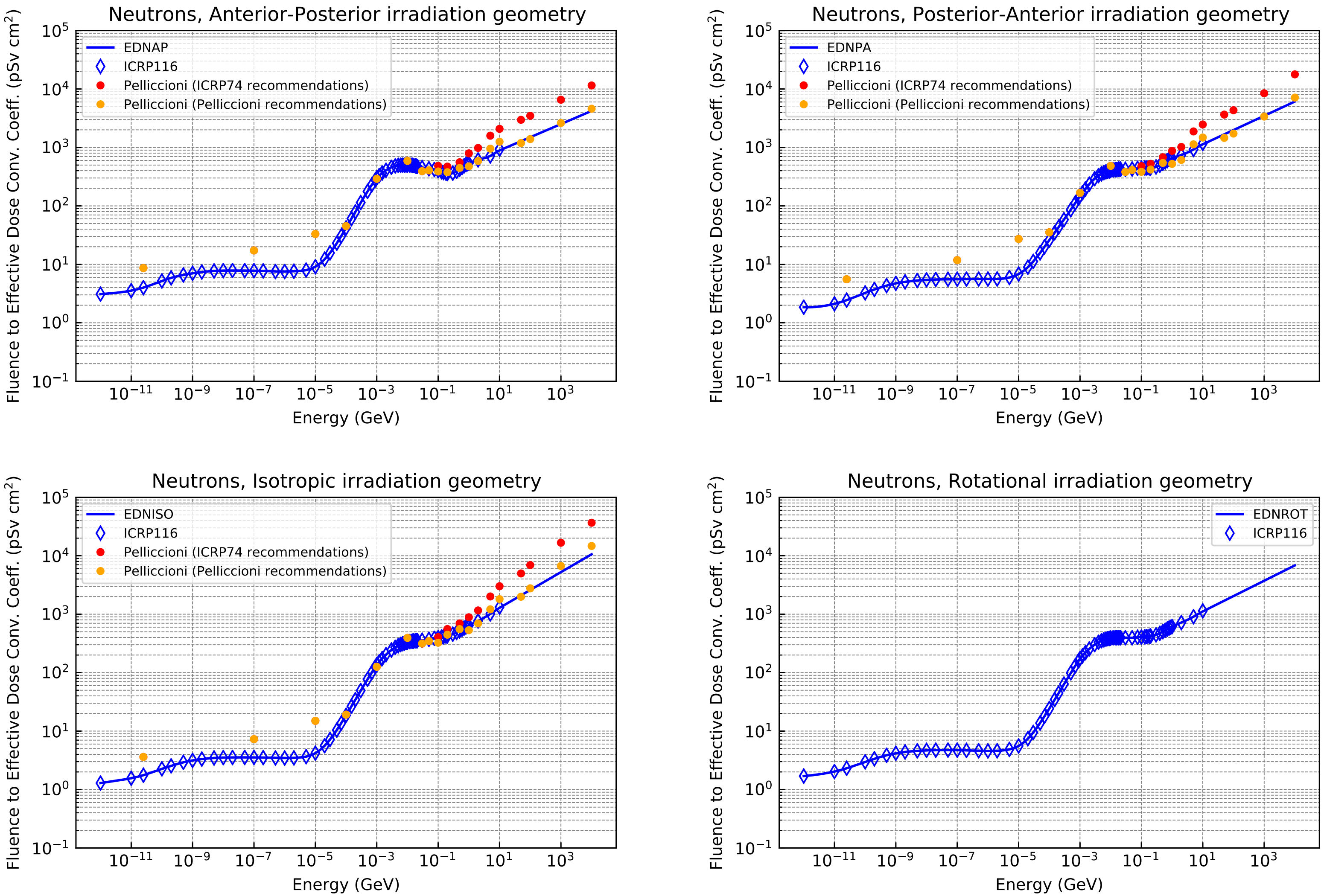
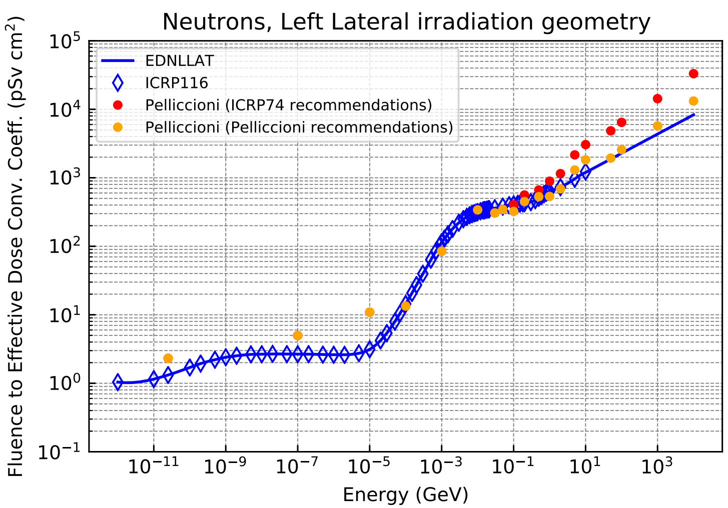
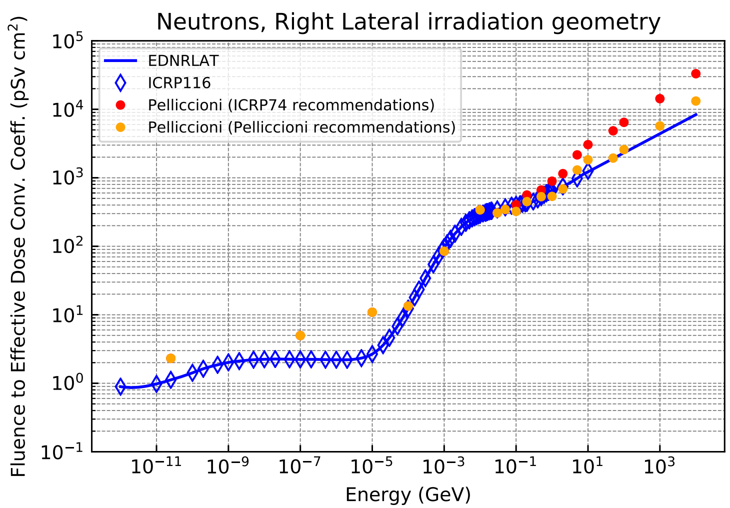


Figure 5: Conversion coefficients from fluence to effective dose for neutrons. Values from ICRP *Publication 116* are shown together with M. Pelliccioni calculation for the available irradiation geometries.





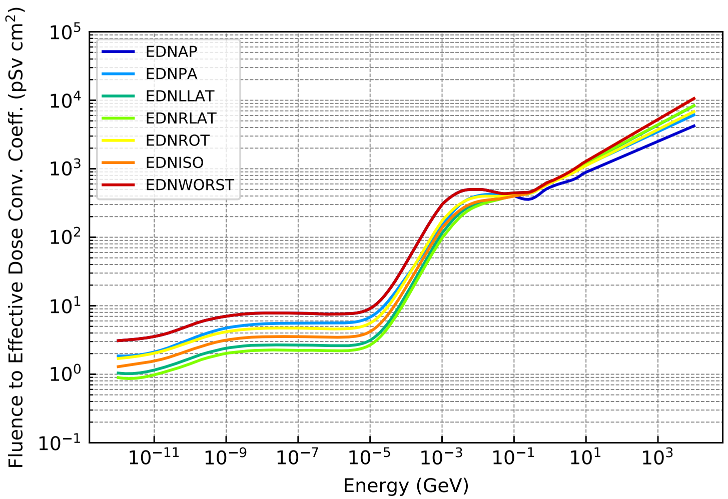


Figure 5: (Continued) Conversion coefficients from fluence to effective dose for neutrons. Values from ICRP *Publication 116* are shown together with M. Pelliccioni calculation for the available irradiation geometries.

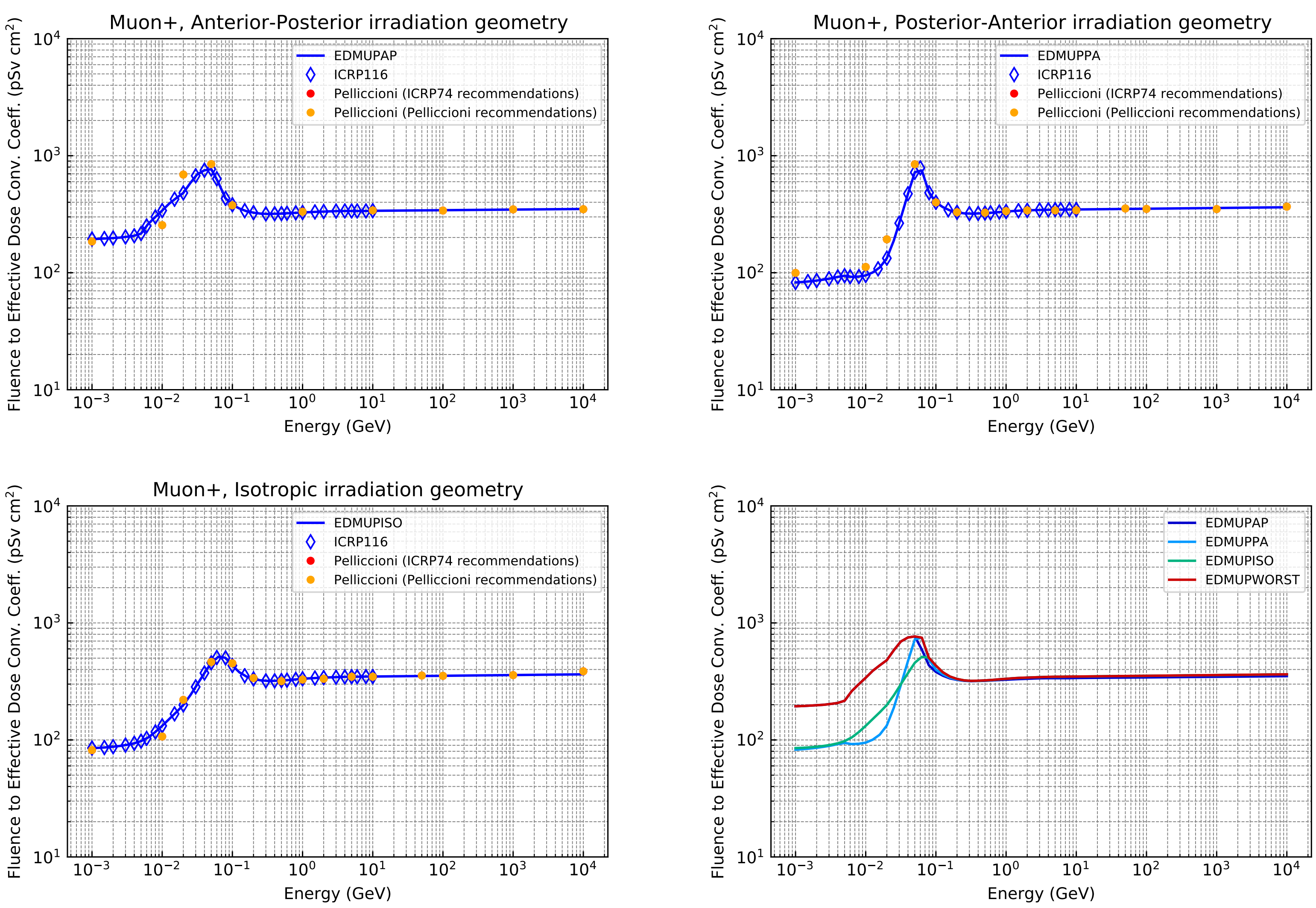


Figure 6: Conversion coefficients from fluence to effective dose for μ^+. Values from ICRP *Publication 116* are shown together with M. Pelliccioni calculation for the available irradiation geometries.

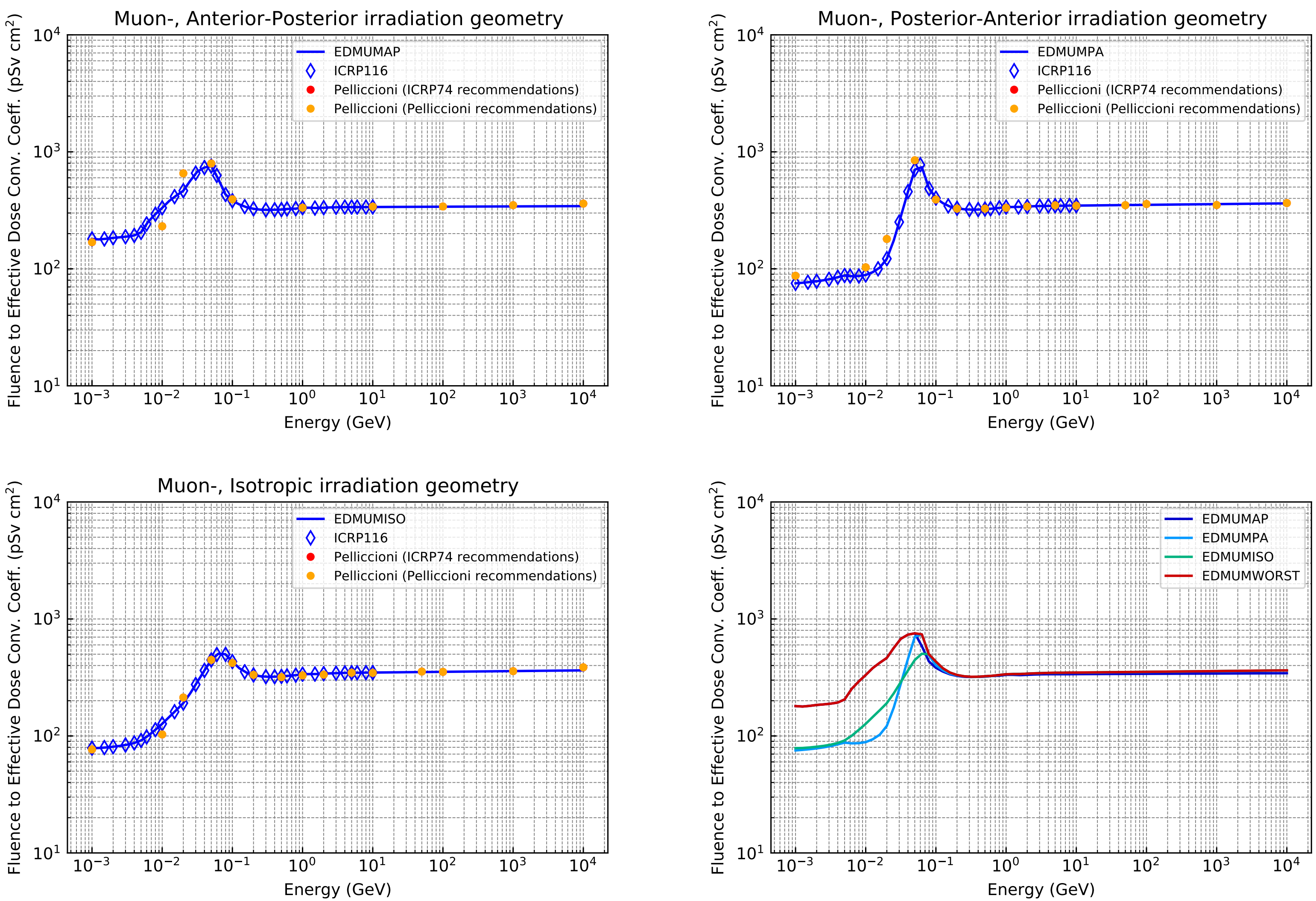


Figure 7: Conversion coefficients from fluence to effective dose for μ^-. Values from ICRP *Publication 116* are shown together with M. Pelliccioni calculation for the available irradiation geometries.

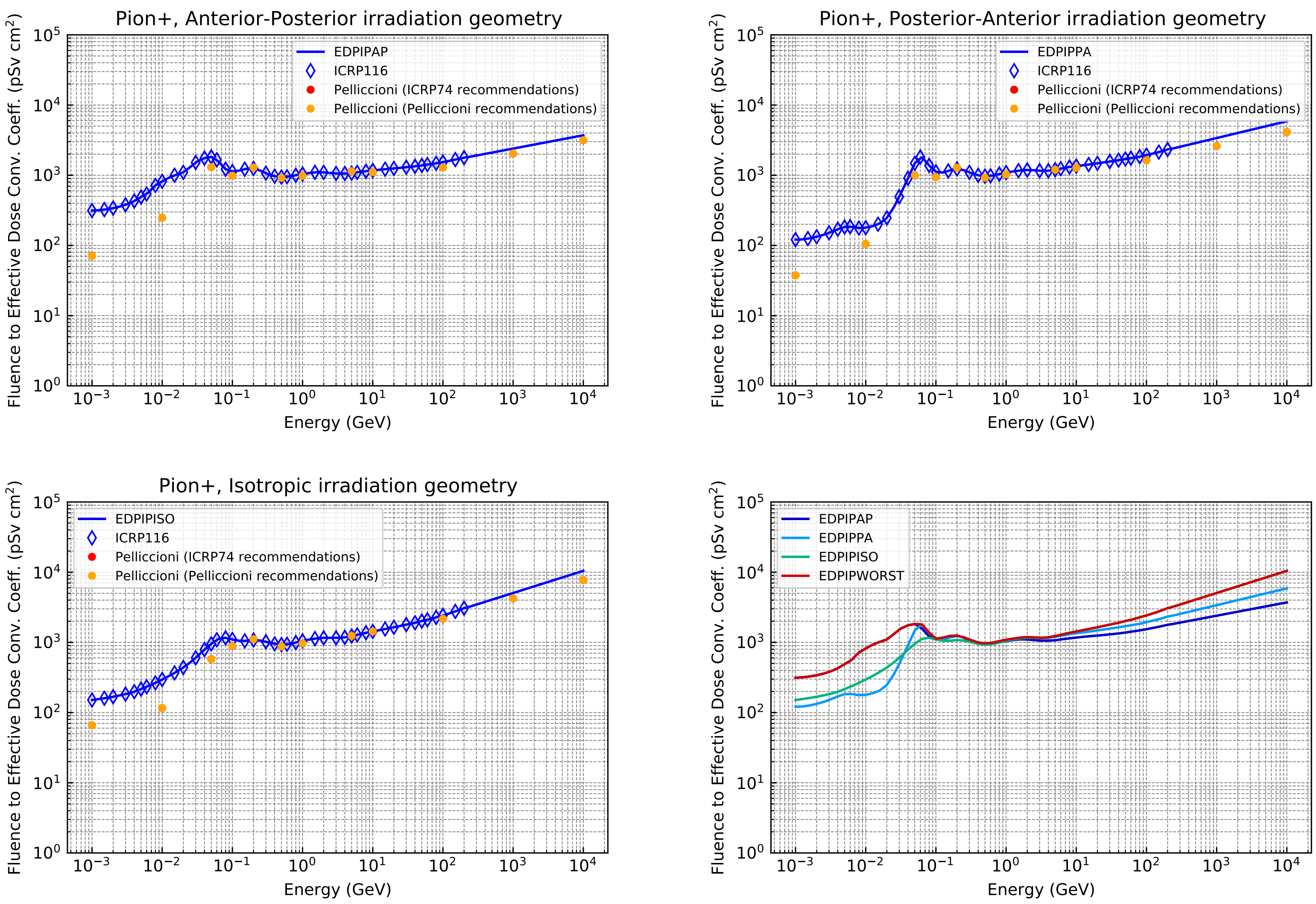


Figure 8: Conversion coefficients from fluence to effective dose for π^+. Values from ICRP *Publication 116* are shown together with M. Pelliccioni calculation for the available irradiation geometries.

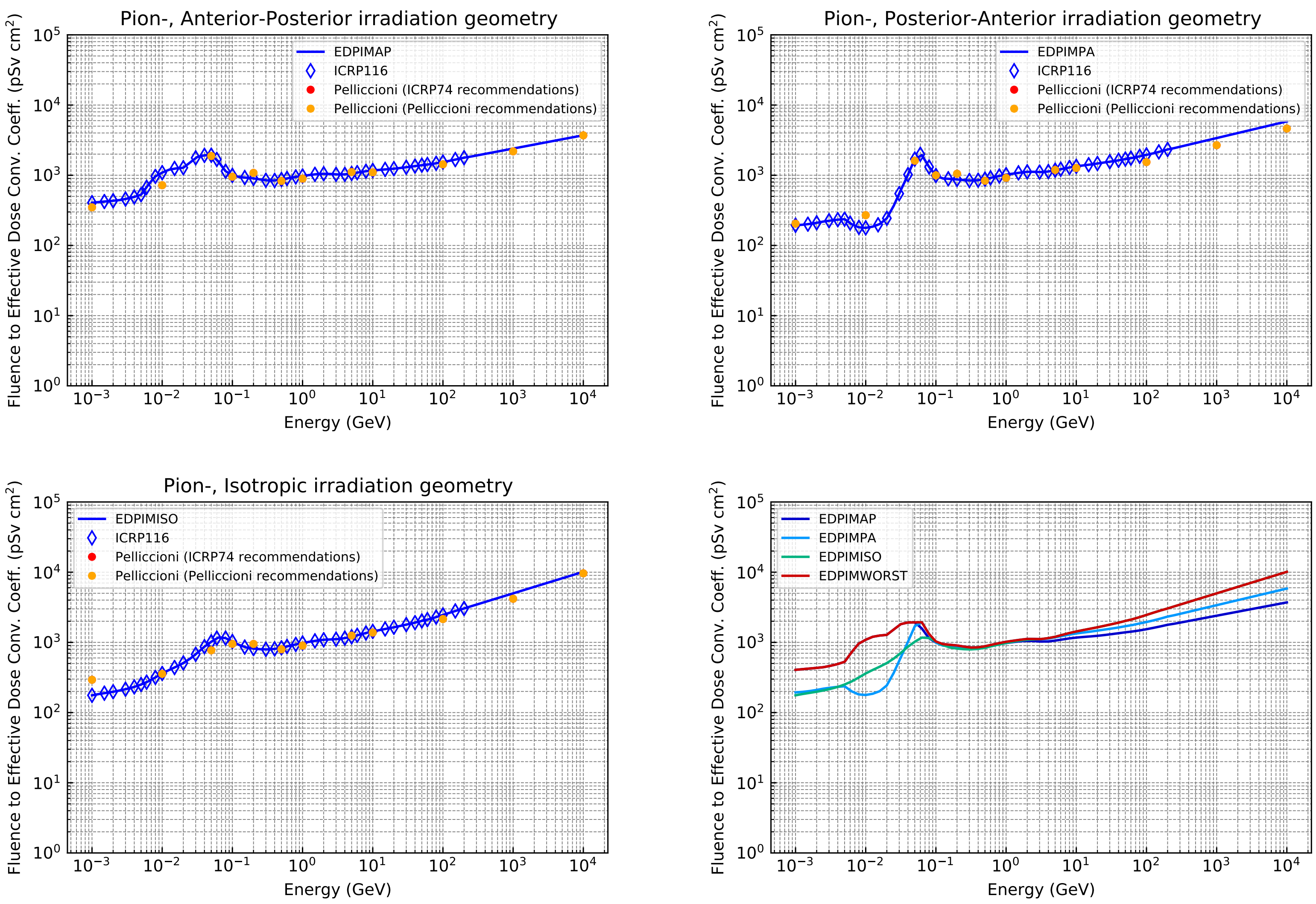


Figure 9: Conversion coefficients from fluence to effective dose for π^{-}. Values from ICRP *Publication 116* are shown together with M. Pellicciono calculation for the available irradiation geometries.

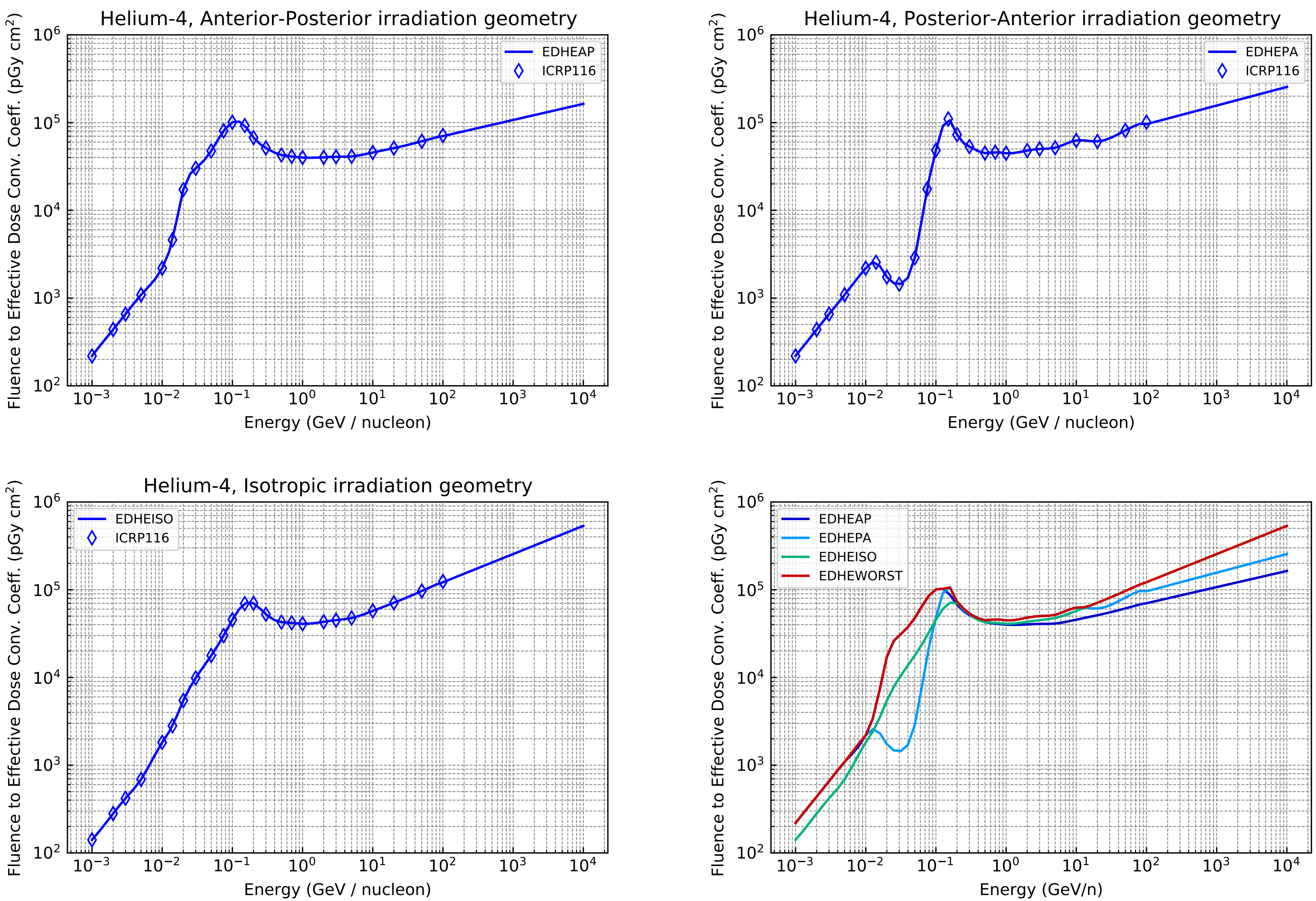


Figure 10: Conversion coefficients from fluence to effective dose for He-4. Values from ICRP *Publication 116* are shown together with M. Pelliccioni calculation for the available irradiation geometries.