Supplementary material - Figures

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Abstract. We present the simulation results of Relativistic Runaway Electron Avalanches produced in air at sea level. The data presented here results from runs of three codes used in the High Energy Atmospheric Physics community :

- Geant4 (two set-ups)
- GRRR
- REAM

The results are extracted from two simulations :

- One evaluating the probability to produce a Relativistic Runaway Electron Avalanche (RREA) from a given seed electron inside a given electric field.
- One generating a RREA from seed electrons and recording produced particles at different time and distances, and extracting important parameters from it.

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Note Concerning Geant4 Simulations

For the RREA probability simulations we set $\alpha_R = 0.001$ (c.f. main text for more information). For the RREA characteristics simulations, we use the maximum step of 1 mm for the results presented here (see main text for more information).

Medium composition

- The air is composed of 78.085% nitrogen, 20.95% oxygen and 0.965% argon,
- Absolute number density of 2.688 10^{25} m^3, equivalent to 1.293 $kg.m^3$. We always use an uniform air density.

Coordinate system and domain

- Cartesian coordinates x, y, z.
- Any field is always applied in the z (or -z) direction.
- Domain is a cylinder with radius (perpendicular to z) of 5 km and height (parallel to z) of 10 km, such that the middle of the bottom circle lies at (0,0,-5) and the middle of the top circle at (0,0,5).
- Delete particles if they fly out of the domain.

1 RREA Probability Simulation Set-up

Given an electron with a certain primary energy embedded in a background field, what is the probability that a runaway avalanche occurs?

Definition runaway avalanche

- We define a runaway avalanche if there are more or equal than 20 electrons of at least 1 MeV.

Definition of runaway avalanche probability

- The ratio of single electrons that produce a runaway avalanche over the total number of trials.
- Delete particles below threshold
- Use particle threshold of 1 keV. Positrons may however, depending on their implementation, still go into annihilation.

Domain

- The domain should be sufficiently large, such that no particle reaches the boundary

Initial energy

- The initial energy ranges between 10 keV and 1 MeV. Use a log spaced grid of at least 50 points.

Electric fields

- Use electric fields ranges between 2.10^5 V/m and 30.10^5 V/m. Use a linear spaced grid of least 50 points.
- We will produce two results. One with the field such that the initial electron is accelerated, one with the field such that the initial electron decelerates. (So +/- parallel to initial momentum)

2 RREA Characteristics Simulation Set-up

Initial seed

- Every simulation starts with 200 electrons of 100 keV.
- Particle start always in the center, i.e. (x,y,z) = (0,0,0), which their momentum directed upwards (positive z), parallel with the electric field such that they are accelerated by the field.

Energy threshold

- Take an energy threshold of 10 keV, meaning that all particles below 10 keV do not appear on the output.
- If your code is using friction for part of the spectrum, use 10 keV as the point to separate the part of friction and the part of explicit collisions.

Electric fields

- In this work we consider 12 electric fields: [6, 8, 10, 12, 14, 16, 18, 20, 22, 24, 26, 28] x $10^5\, V/m$.
- The field is oriented in the -z direction, such that the electrons are accelerated by the field upwards.

Time limit

- To avoid very large file size, a time limit must be set depending on the electric field.
- t_{stop} = [1078, 522, 351, 277, 233, 199, 179, 164, 153, 144, 135, 130] nanoseconds; each value corresponding to an electric field (following the same order).

Simulation type 1 - evolution in time

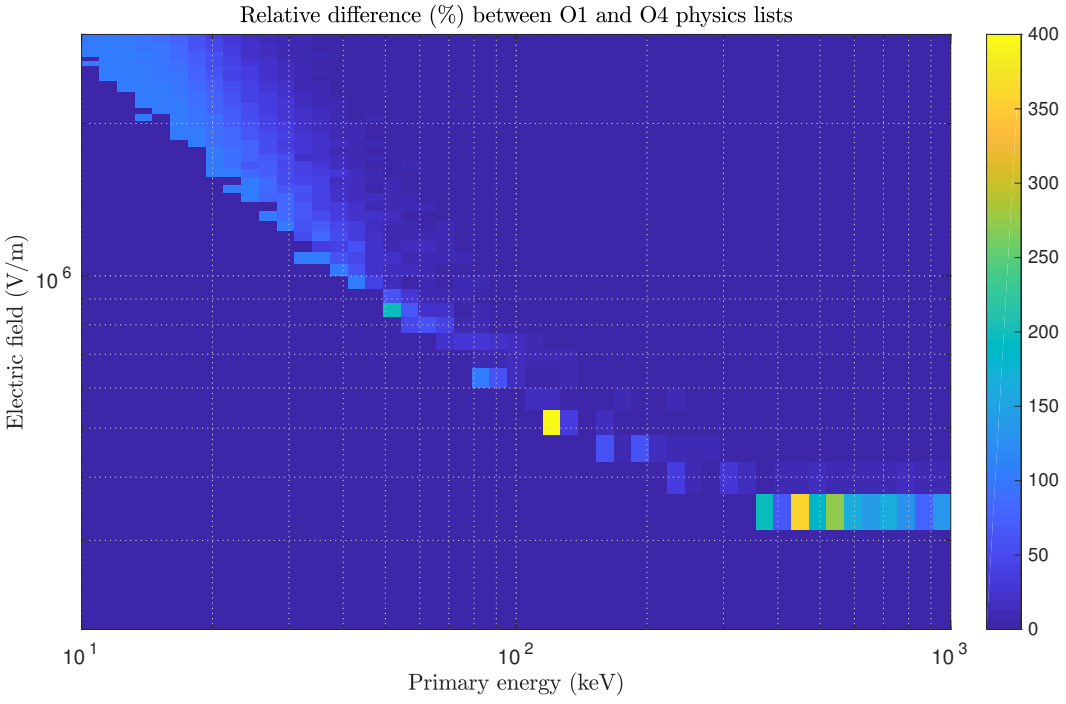
Output all particles at 32 times : t = [14., 26., 39., 51., 64., 78., 90., 102., 116., 124., 135., 144., 153., 164., 179., 199., 215., 233., 262., 277., 290., 312., 351., 406., 464., 479., 522., 599., 719., 838., 958., 1078.] nanoseconds; regardless of position.

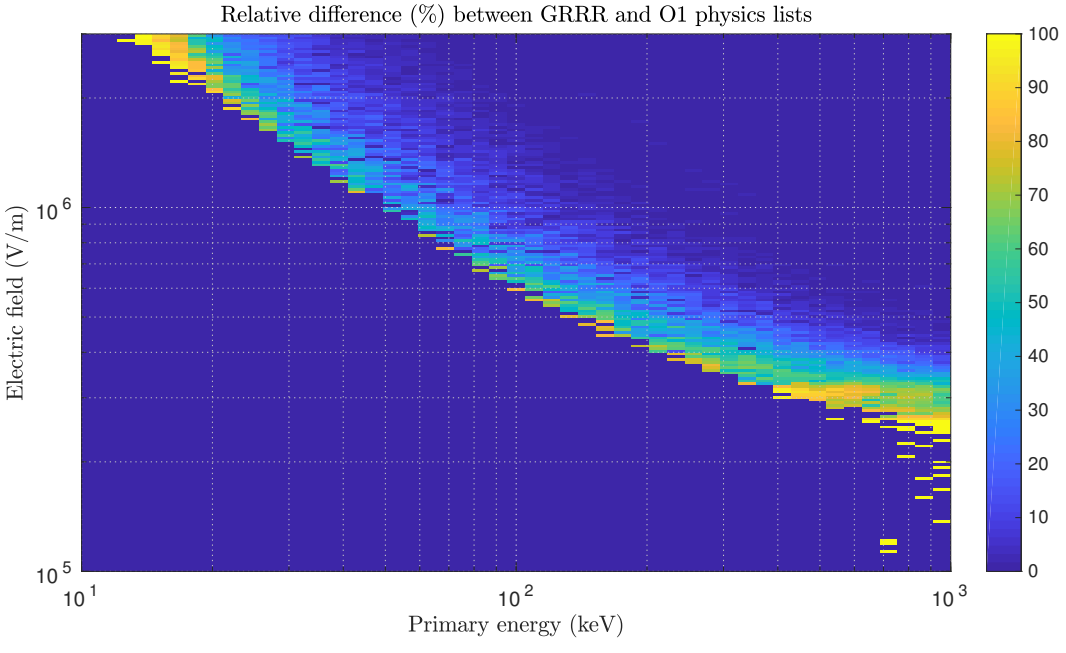
Simulation type 2 - evolution in space

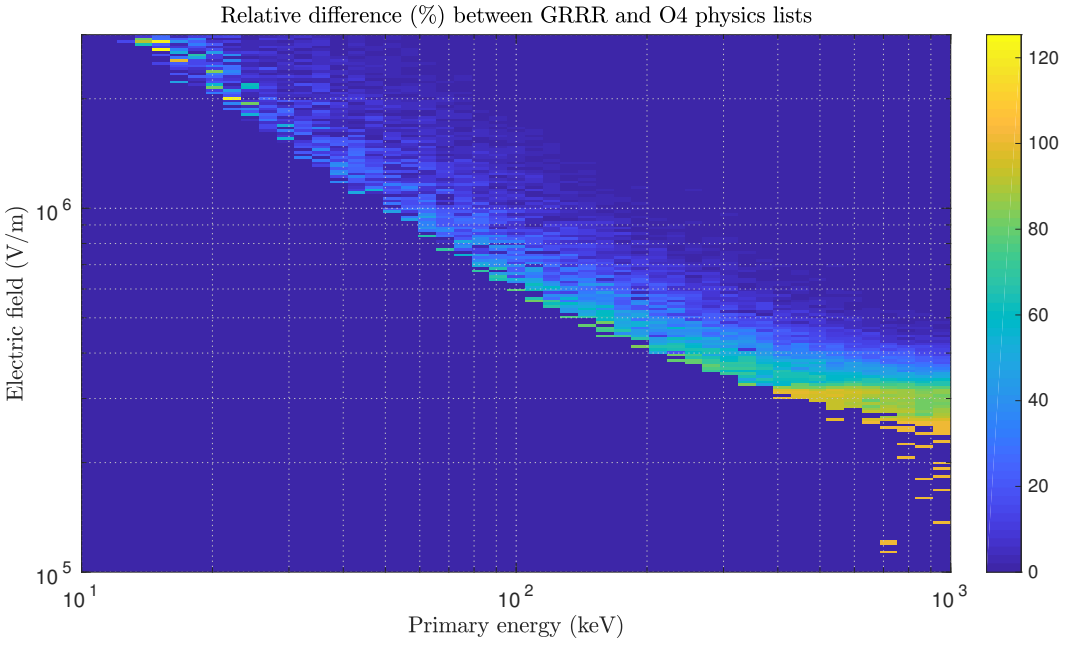
Output all particles at 32 distances : z = [4., 7., 10., 14., 17., 21., 24., 27., 31., 33., 36., 38., 41., 44., 48., 53., 57., 62., 70., 74., 77., 83., 94., 108., 124., 128., 139., 160., 192., 224., 256., 288.] meters, regardless of time of arrival.

3 RREA Probability

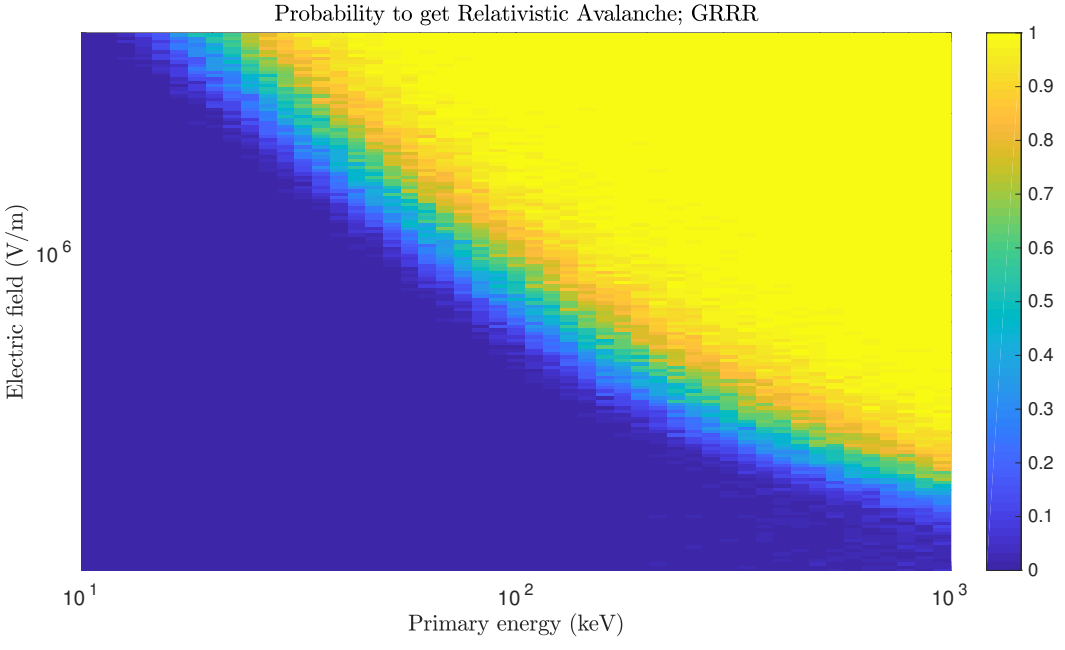
3.1 Code Comparison

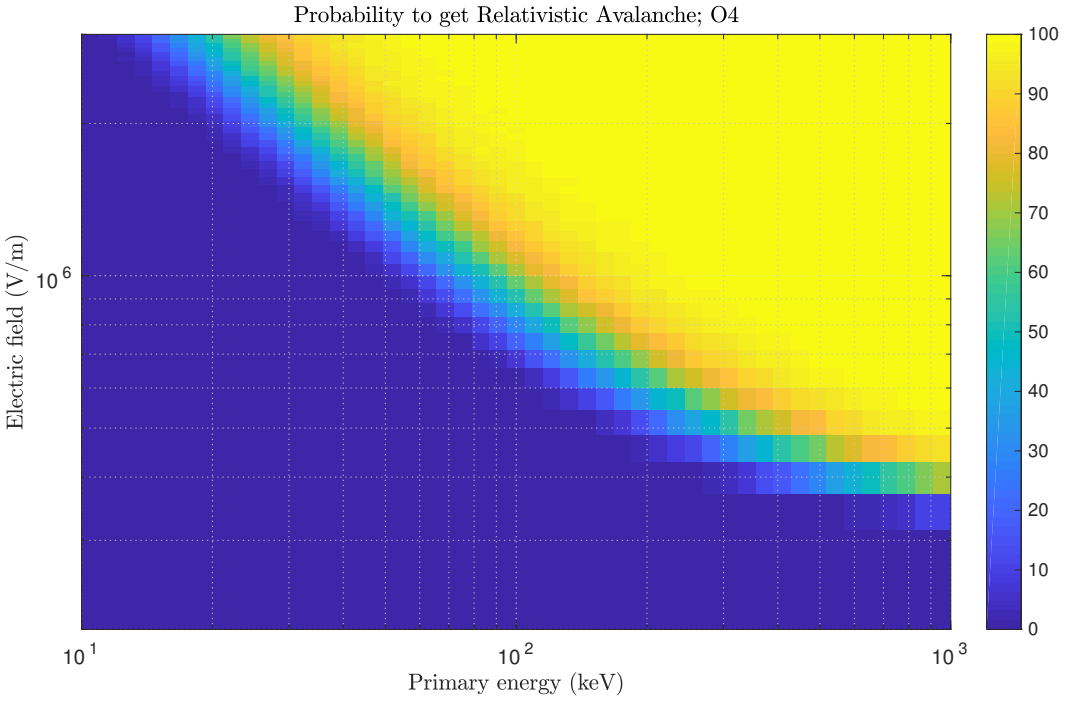


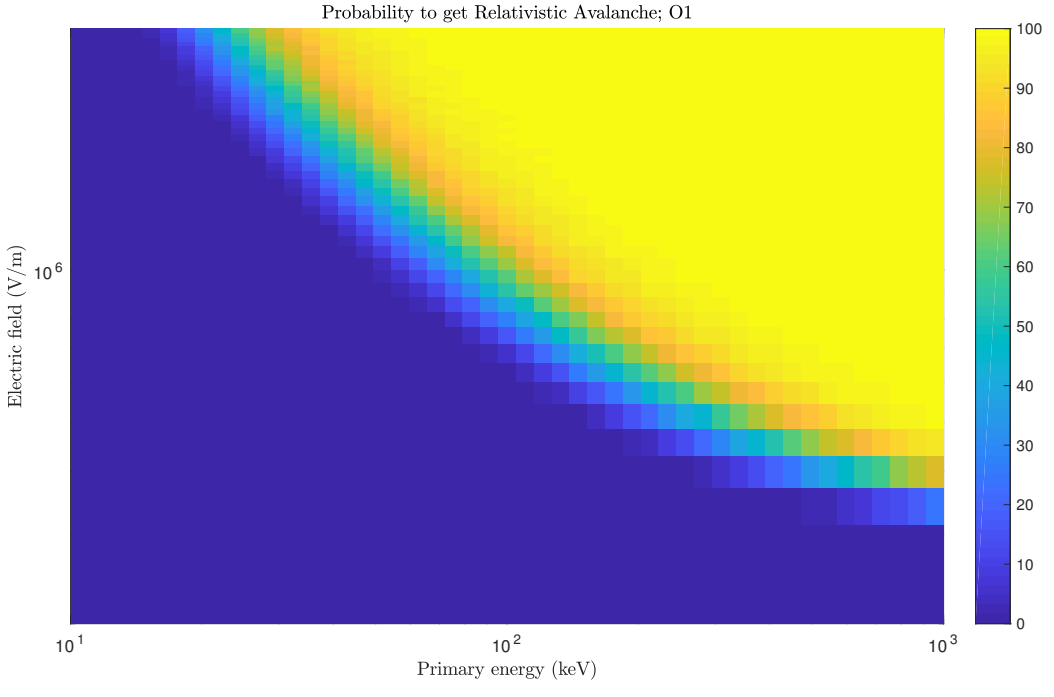




3.2 Code By Code

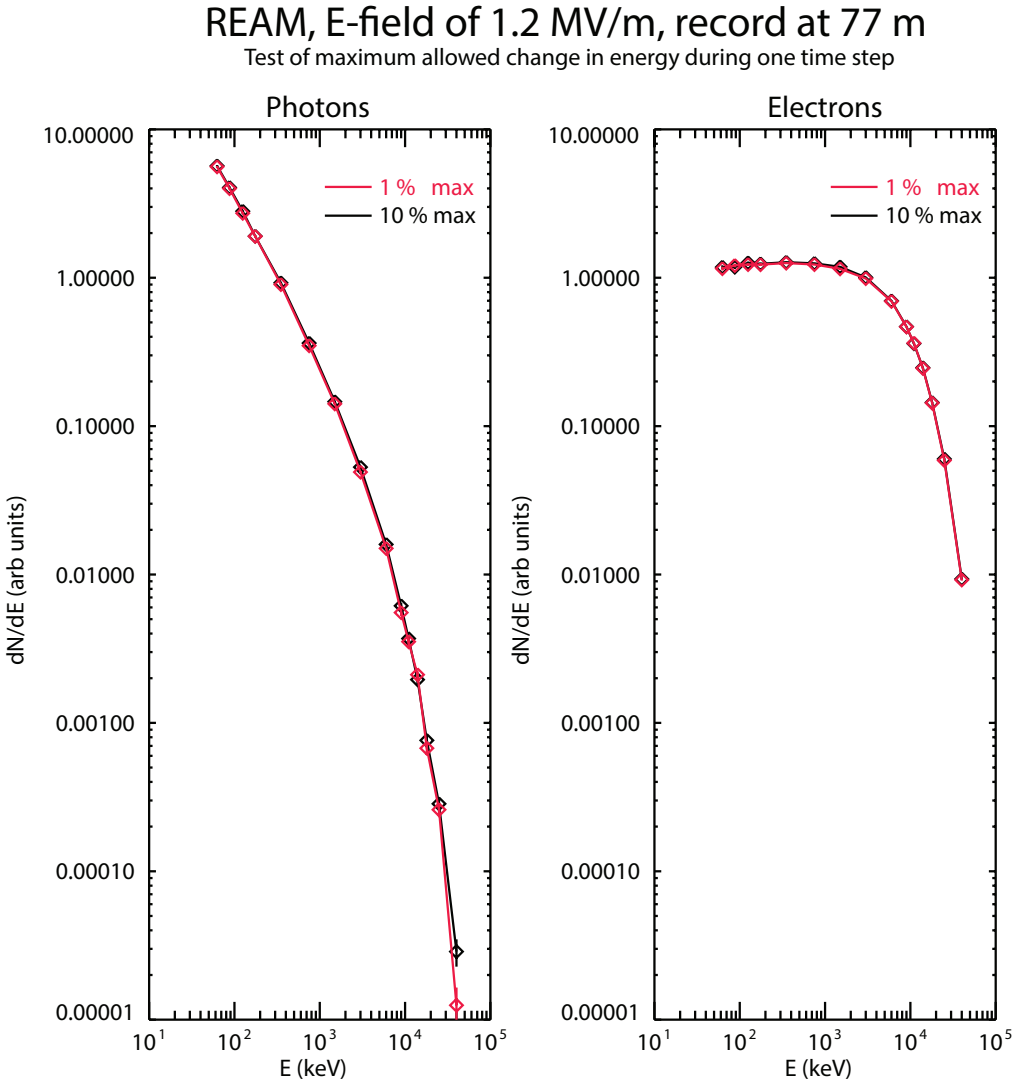



Probability to get Relativistic Avalanche; O4
Electric field (V/m)
10^6
10^1
10^2
10^3
Primary energy (keV)
100
90
80
70
60
50
40
30
20
10
0


Probability to get Relativistic Avalanche; O1
Electric field (V/m)
10^6
10^1
10^2
10^3
Primary energy (keV)
100
90
80
70
60
50
40
30
20
10
0

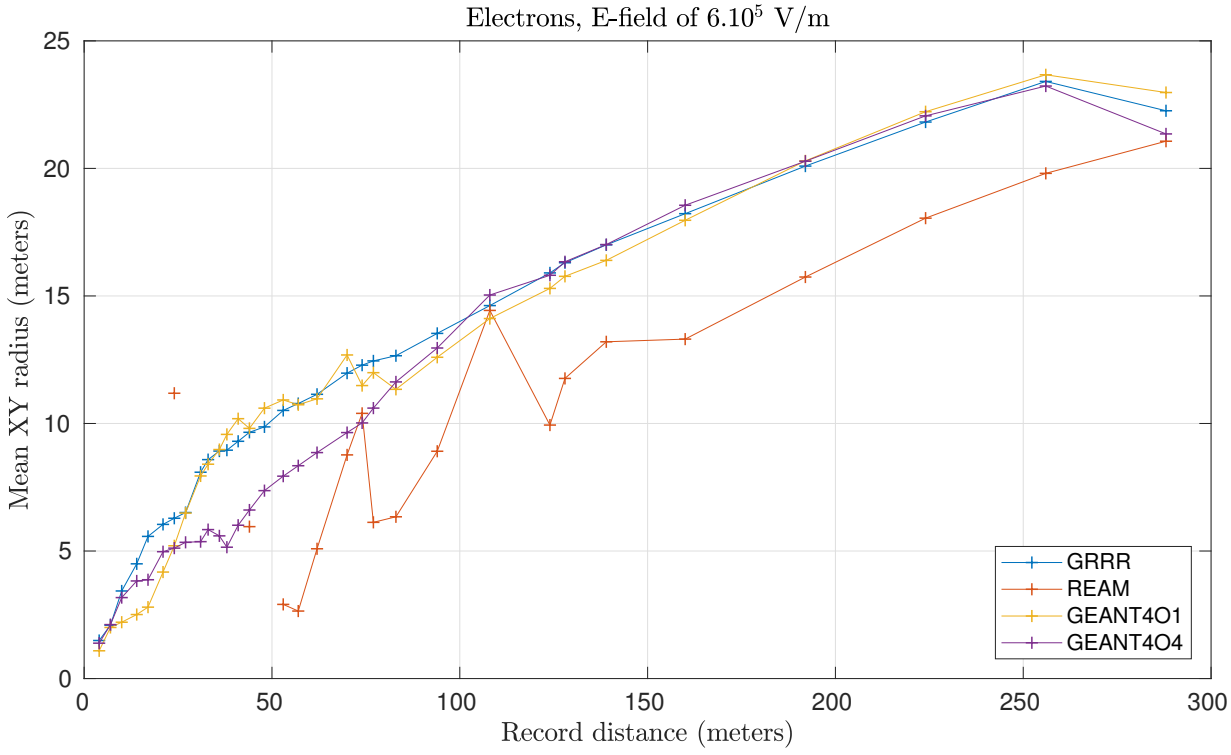
4 REAM Max Step

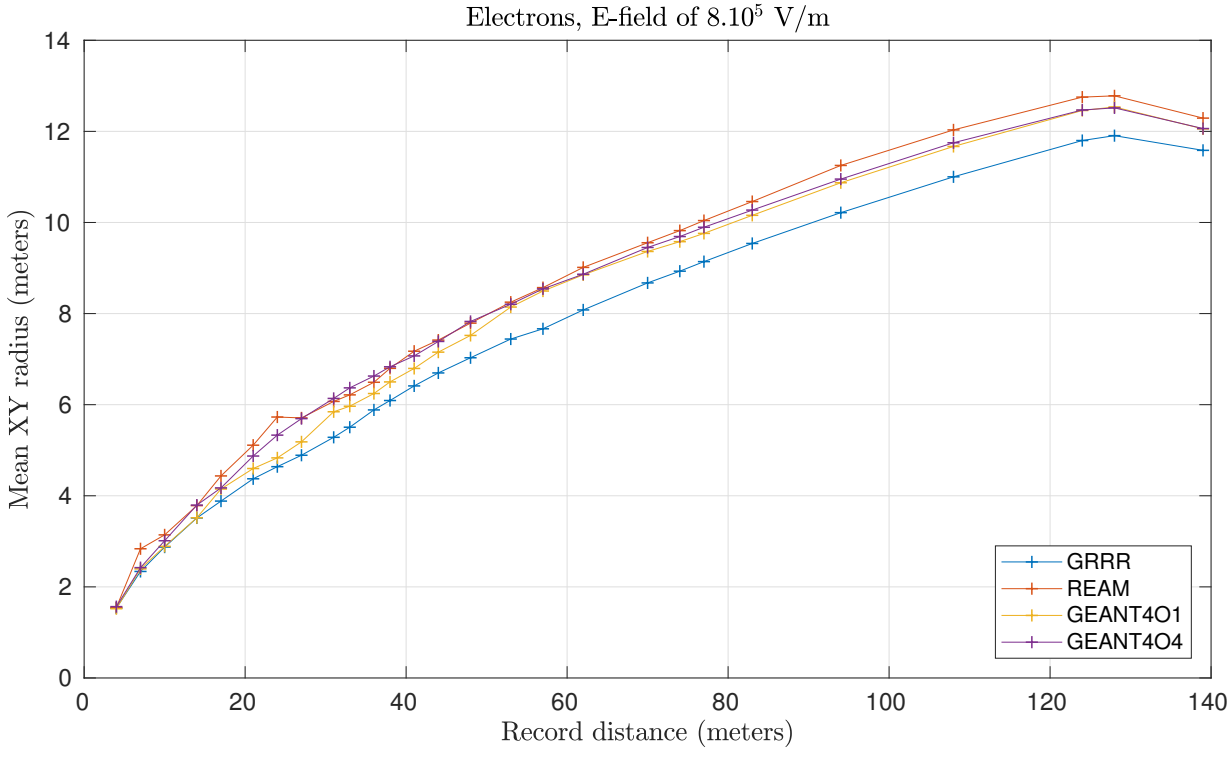
4.1 Spectra

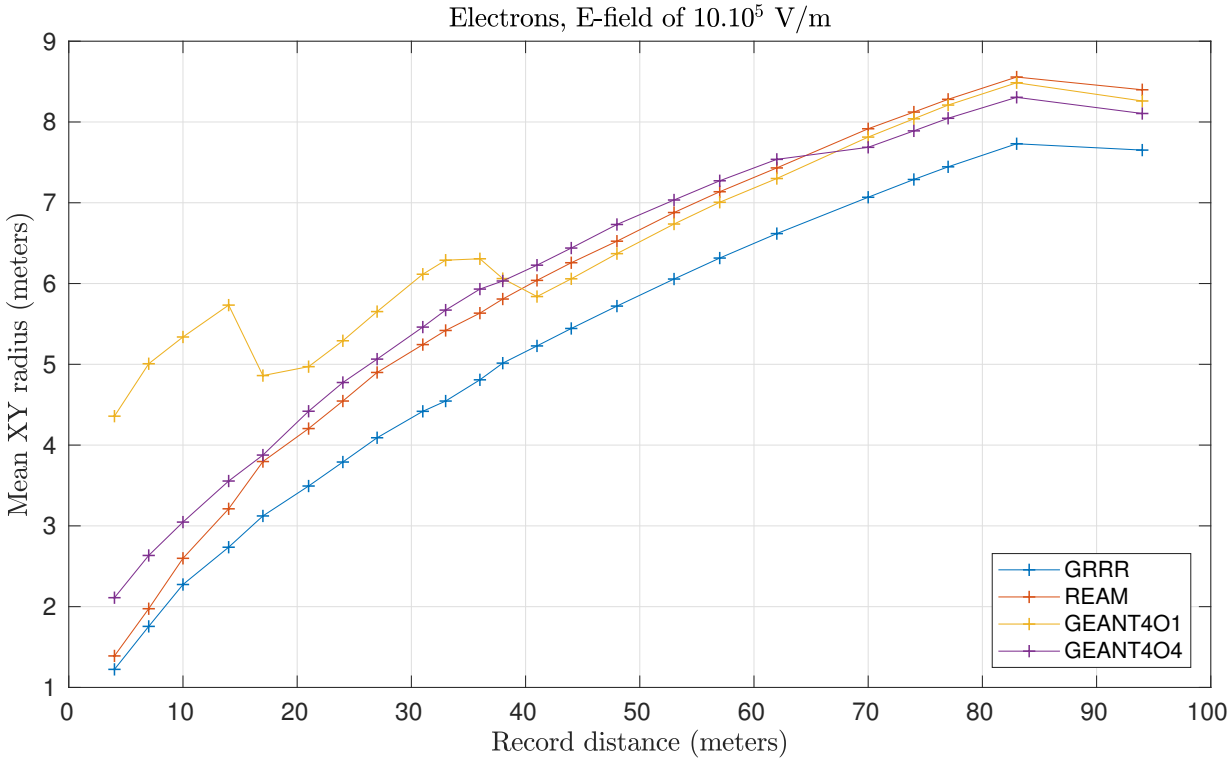


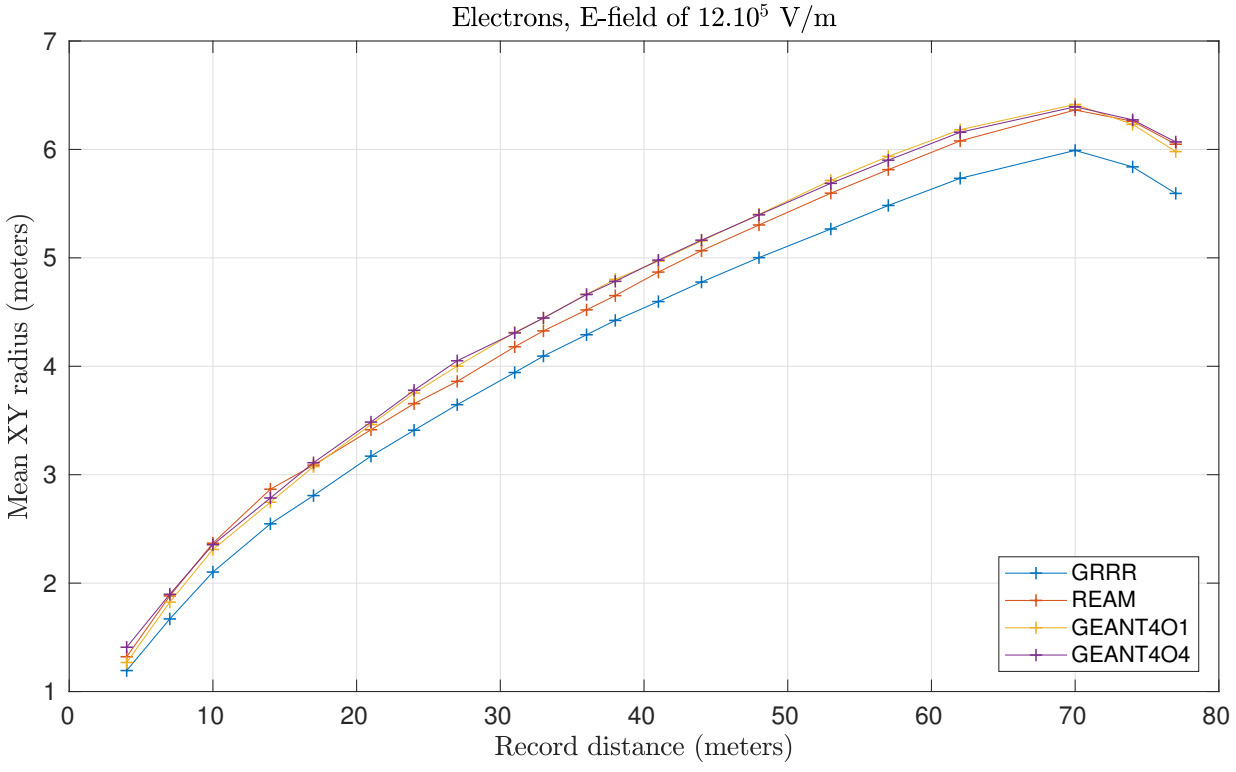
5 Mean XY Radius

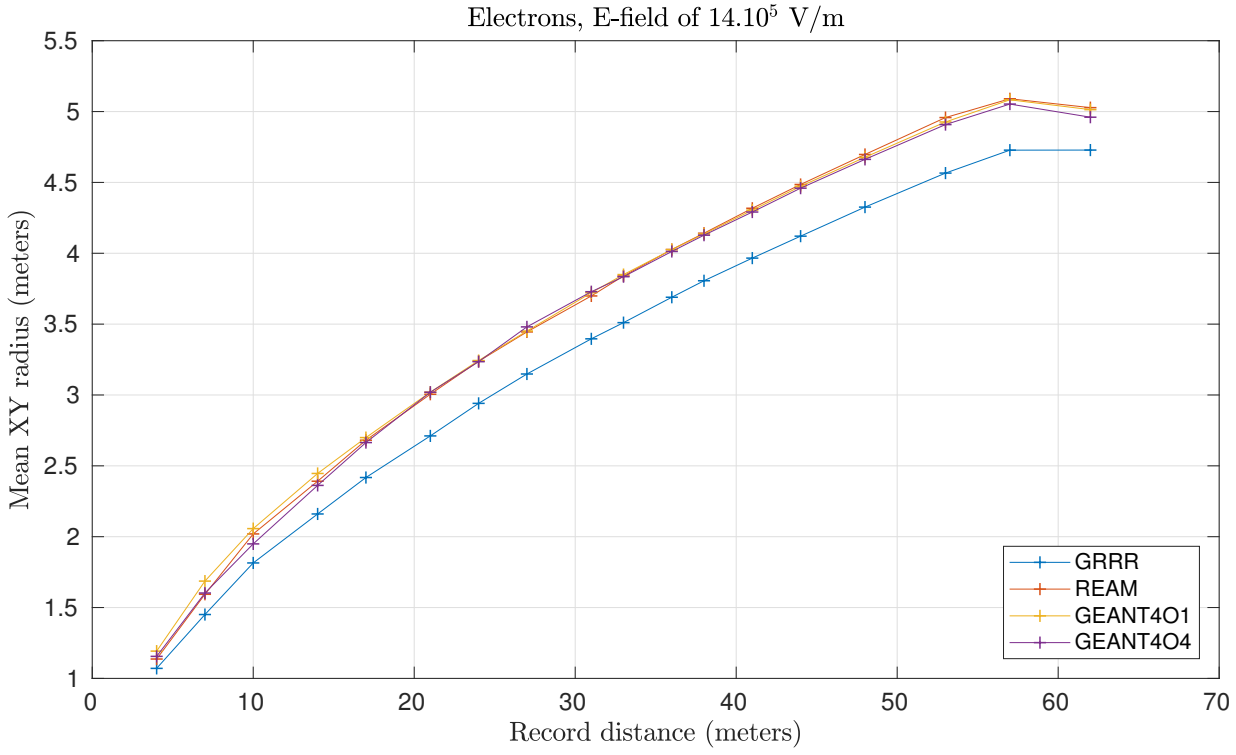
5.1 Code Comparison

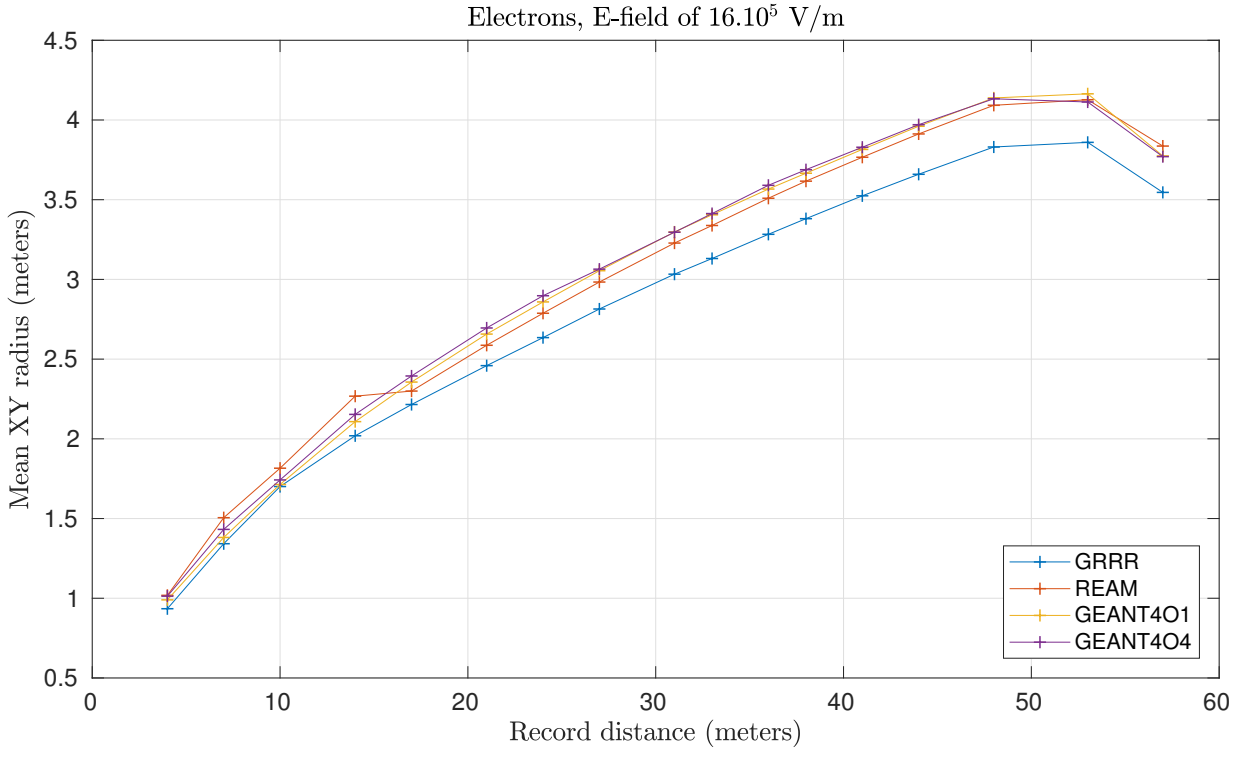


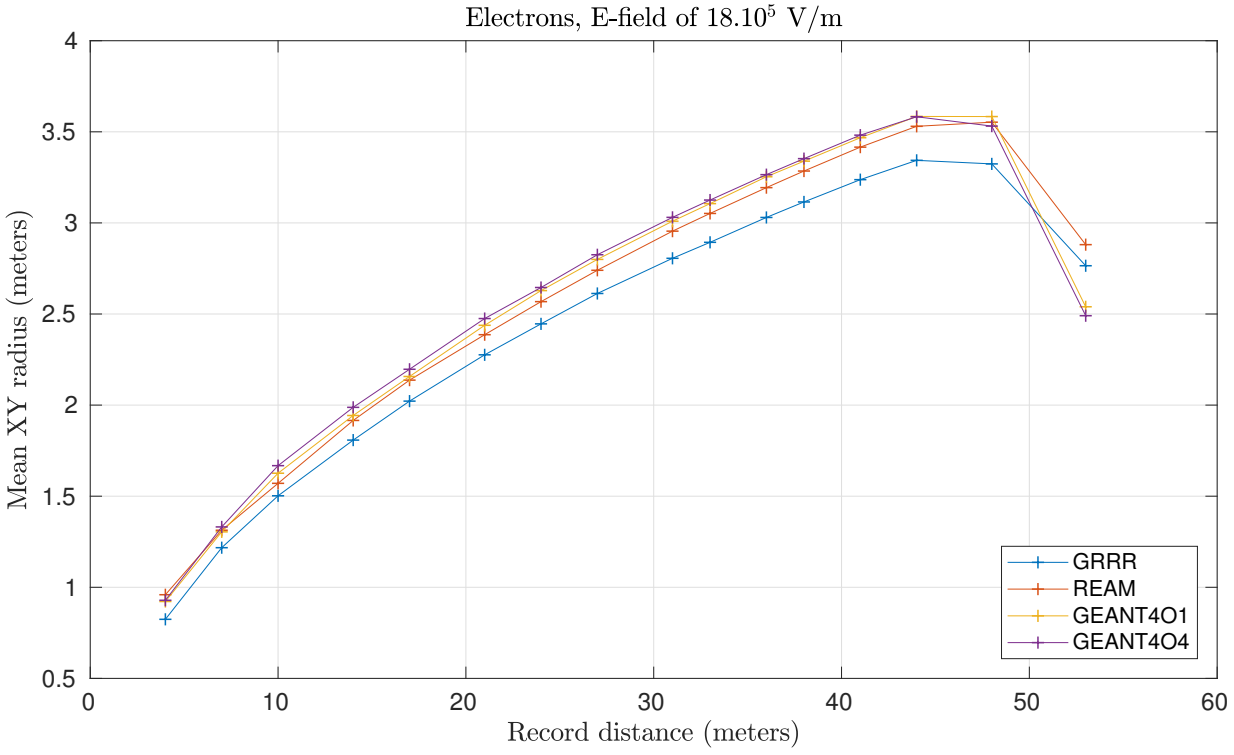


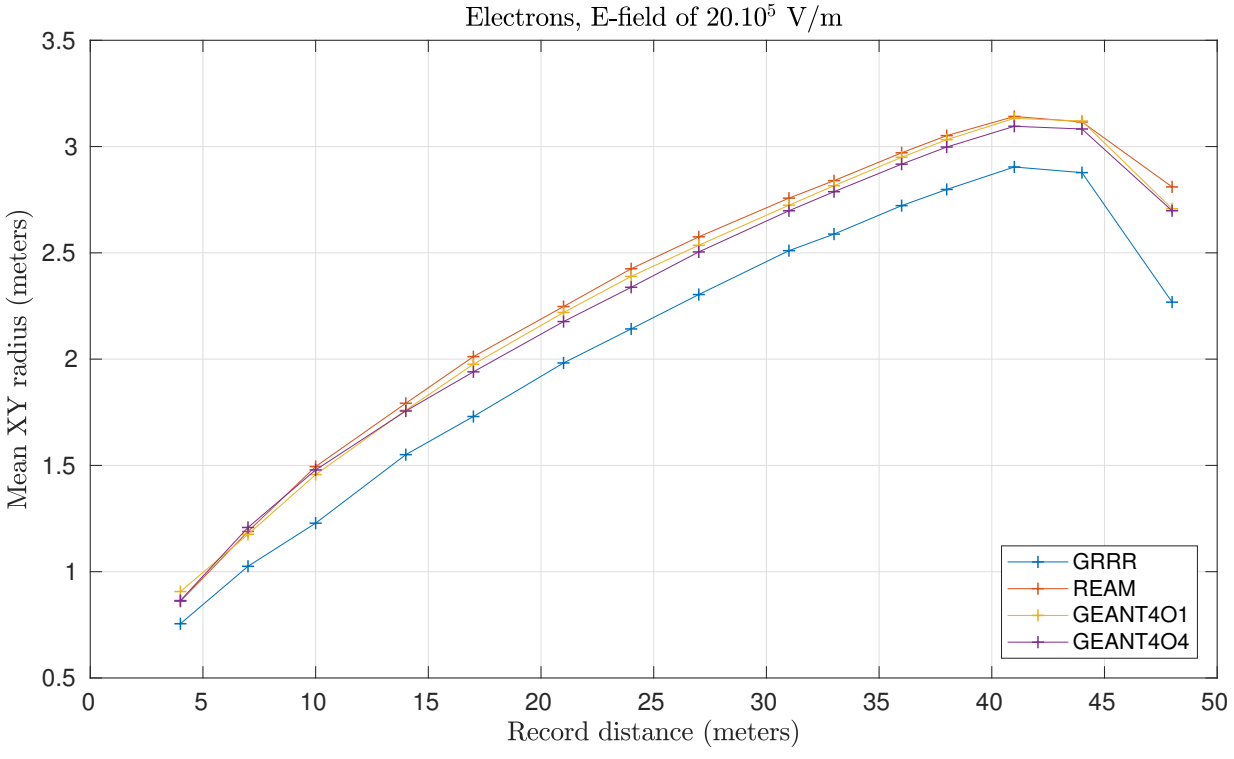

Electrons, E-field of 10.10^5 V/m
Mean XY radius (meters)
Record distance (meters)
GRRR
REAM
GEANT4O1
GEANT4O4

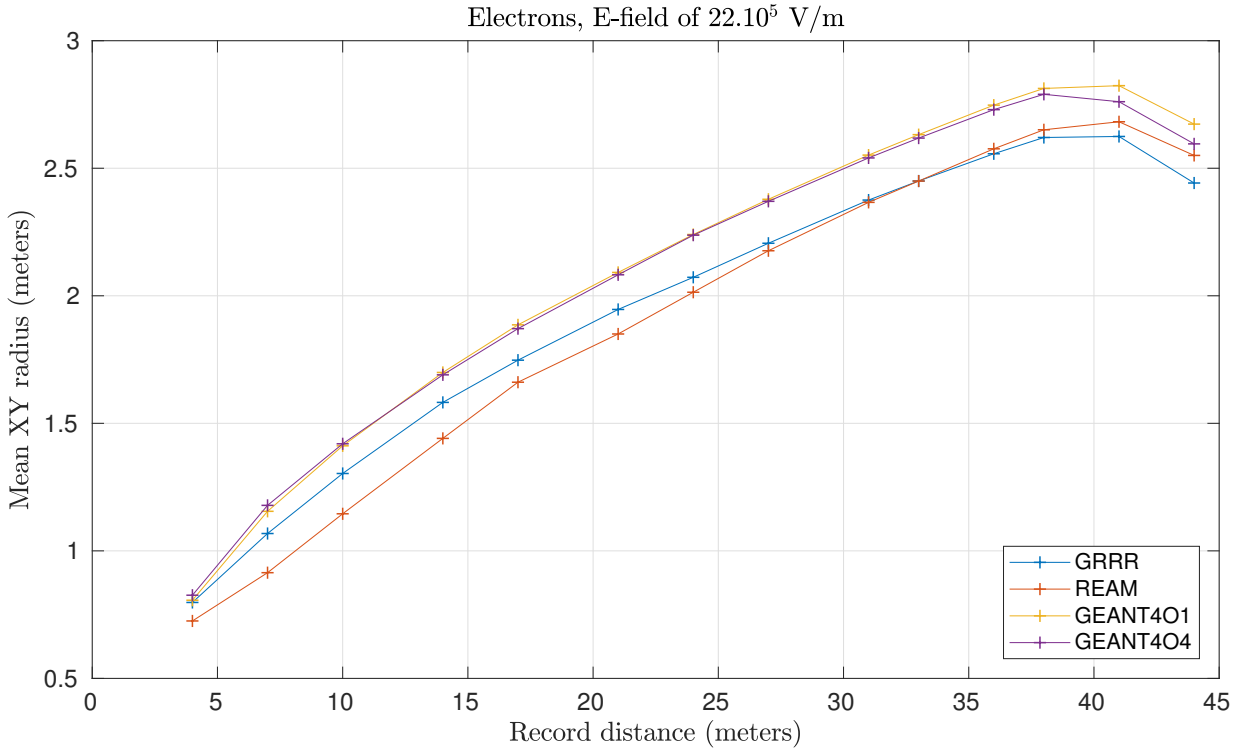

Electrons, E-field of 12.10^5 V/m
Mean XY radius (meters)
Record distance (meters)
GRRR
REAM
GEANT4O1
GEANT4O4

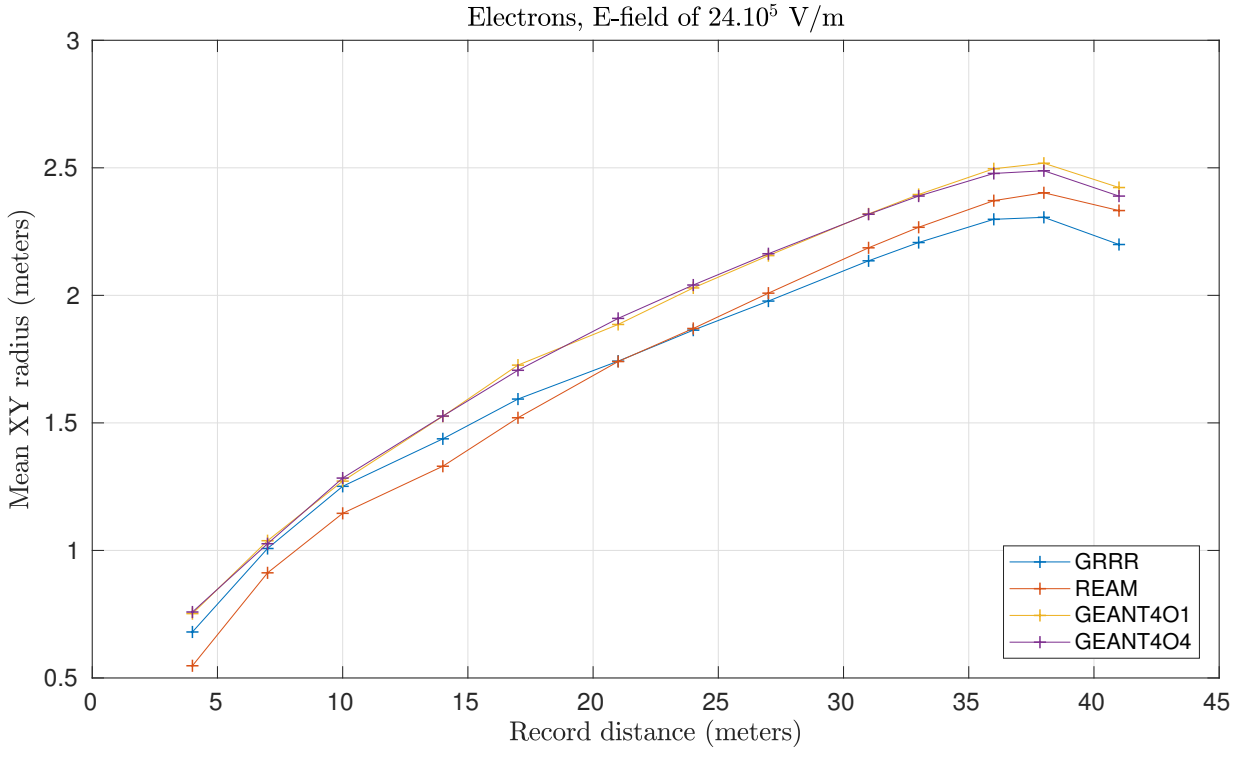

Electrons, E-field of 14.10^5 V/m
Mean XY radius (meters)
Record distance (meters)
GRRR
REAM
GEANT4O1
GEANT4O4

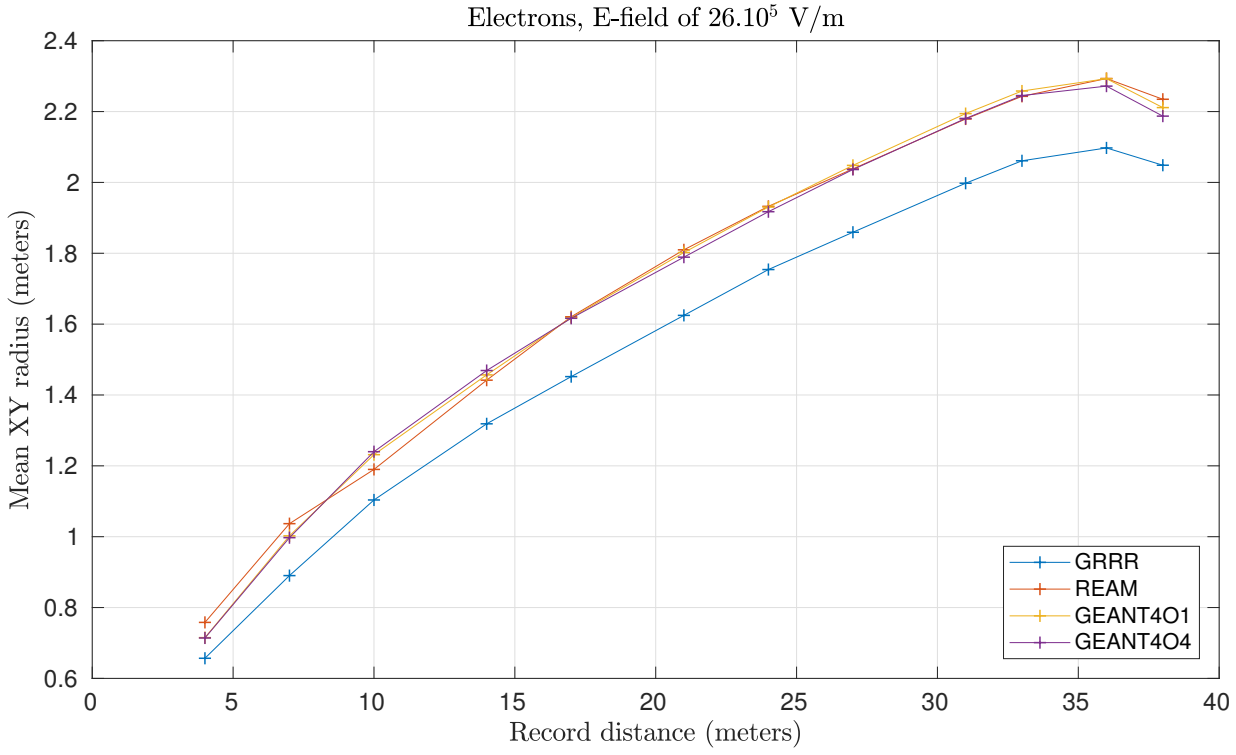

Electrons, E-field of 16.10^5 V/m
Mean XY radius (meters)
Record distance (meters)
GRRR
REAM
GEANT4O1
GEANT4O4

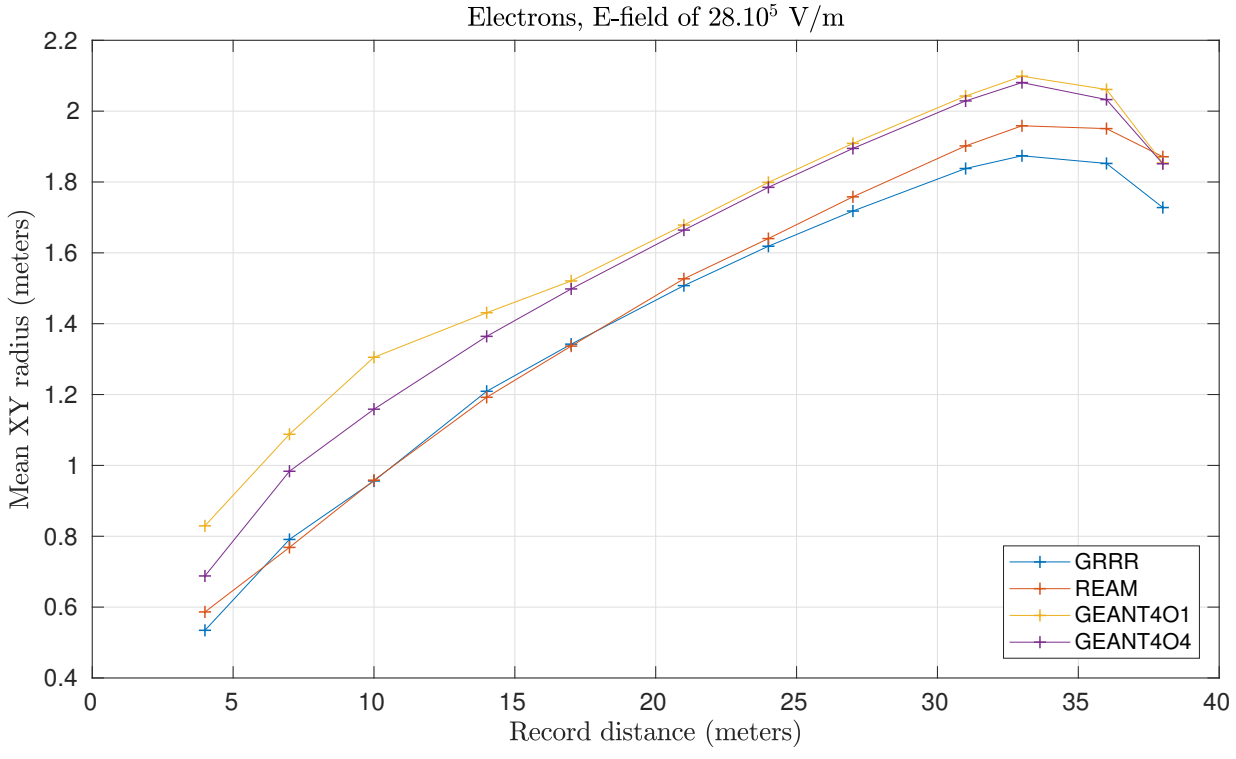

Electrons, E-field of 18.10^5 V/m
Mean XY radius (meters)
Record distance (meters)
GRRR
REAM
GEANT4O1
GEANT4O4


Electrons, E-field of 20.10^5 V/m
Mean XY radius (meters)
Record distance (meters)
GRRR
REAM
GEANT4O1
GEANT4O4

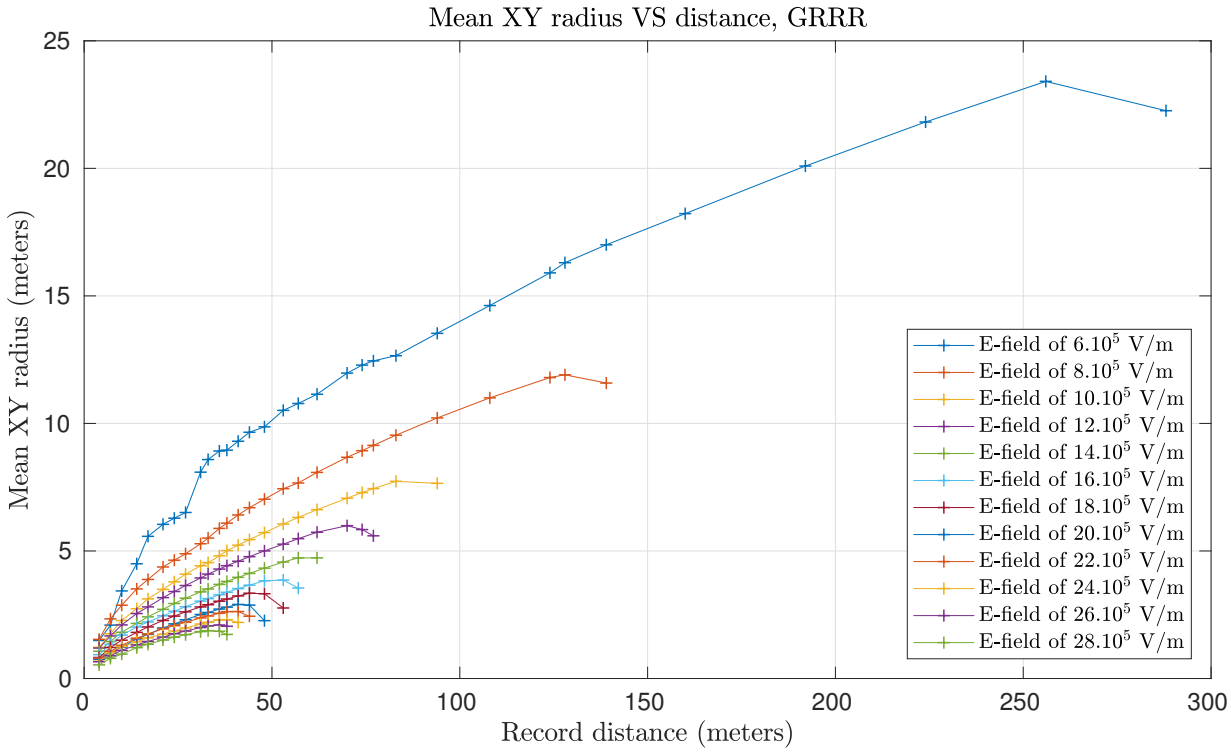

Electrons, E-field of 22.10^5 V/m
Mean XY radius (meters)
Record distance (meters)
GRRR
REAM
GEANT4O1
GEANT4O4

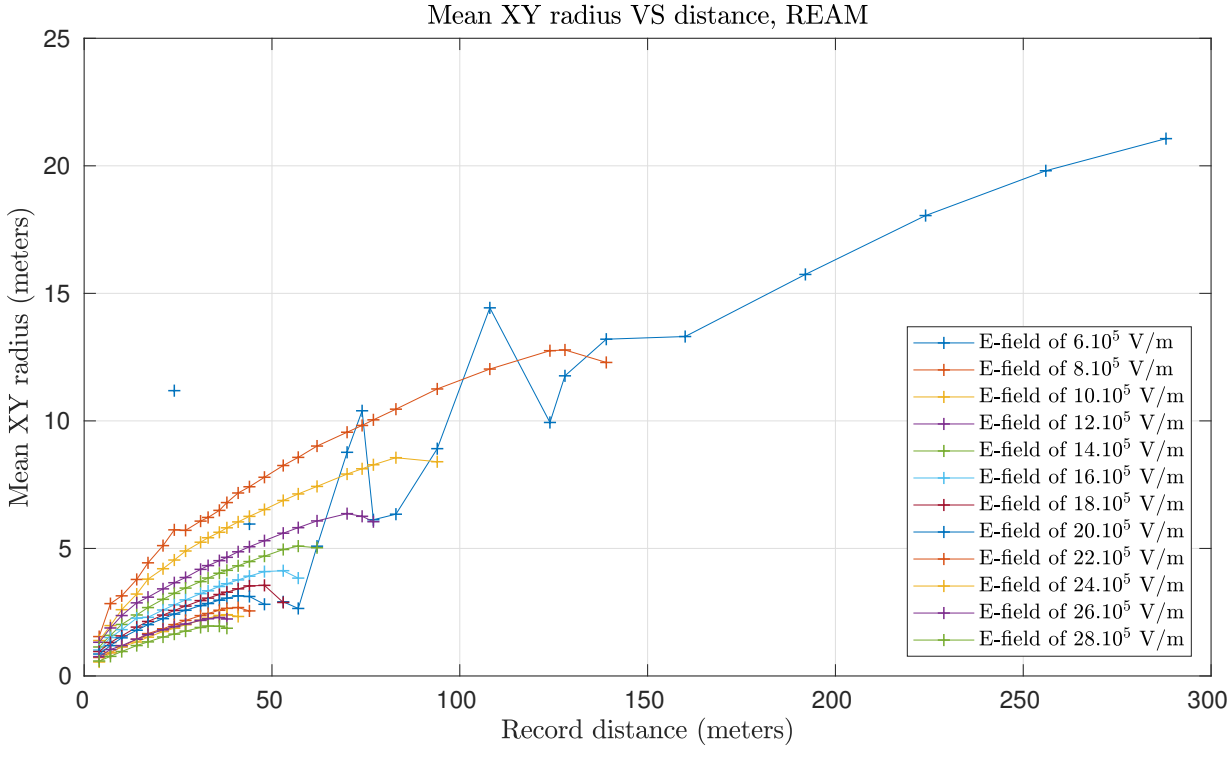

Electrons, E-field of 24.10^5 V/m
Mean XY radius (meters)
Record distance (meters)
GRRR
REAM
GEANT4O1
GEANT4O4

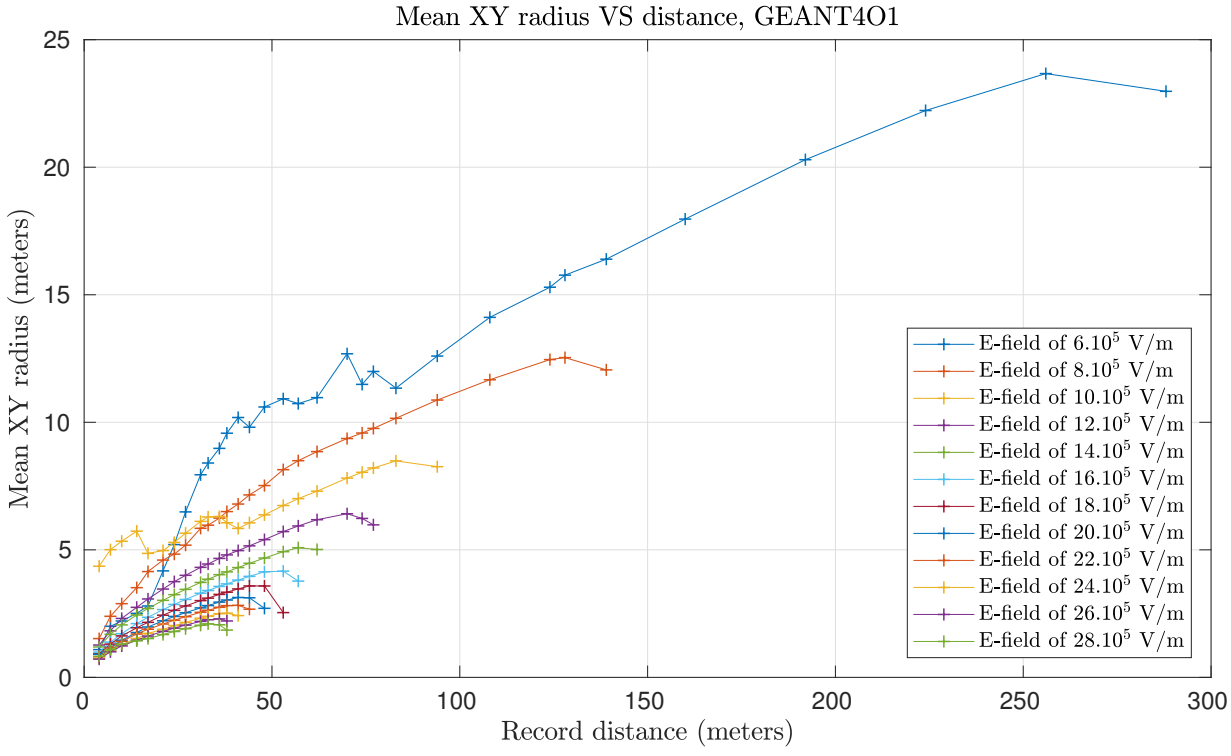

Electrons, E-field of 26.10^5 V/m
Mean XY radius (meters)
Record distance (meters)
GRRR
REAM
GEANT4O1
GEANT4O4

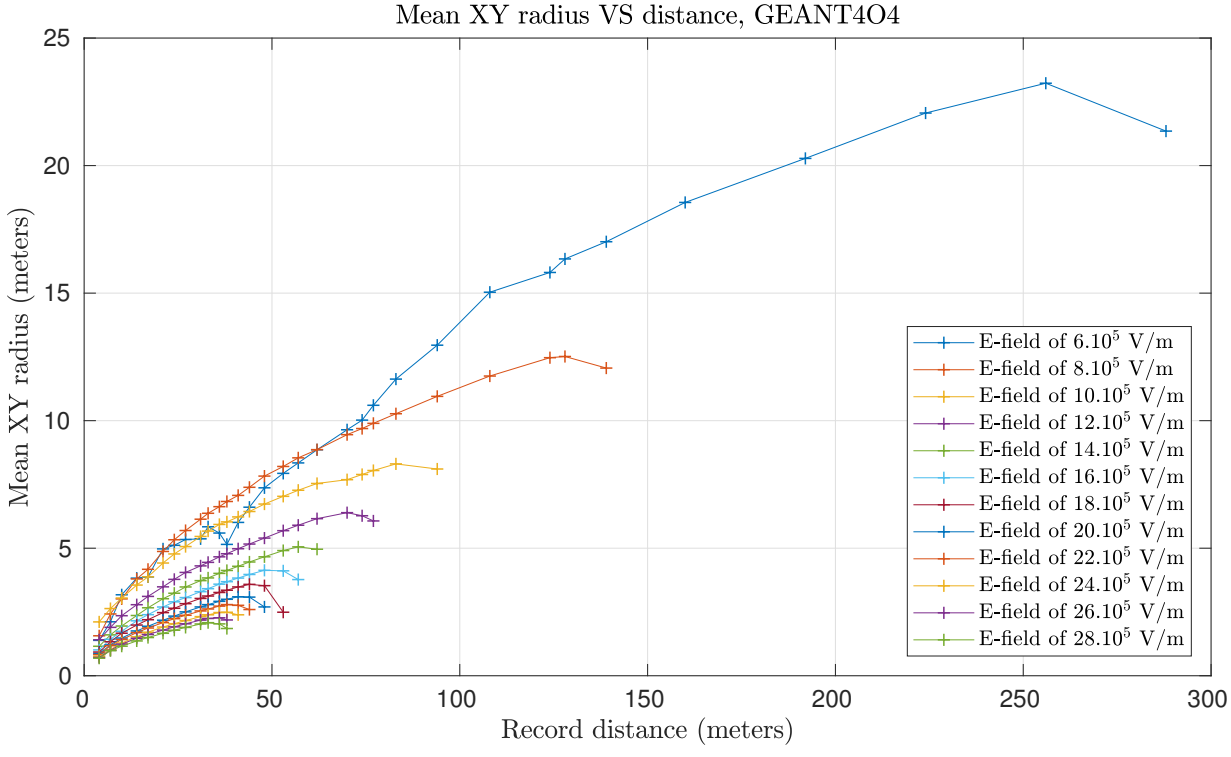

Electrons, E-field of 28.10^5 V/m
Mean XY radius (meters)
Record distance (meters)
GRRR
REAM
GEANT4O1
GEANT4O4

5.2 Code By Code



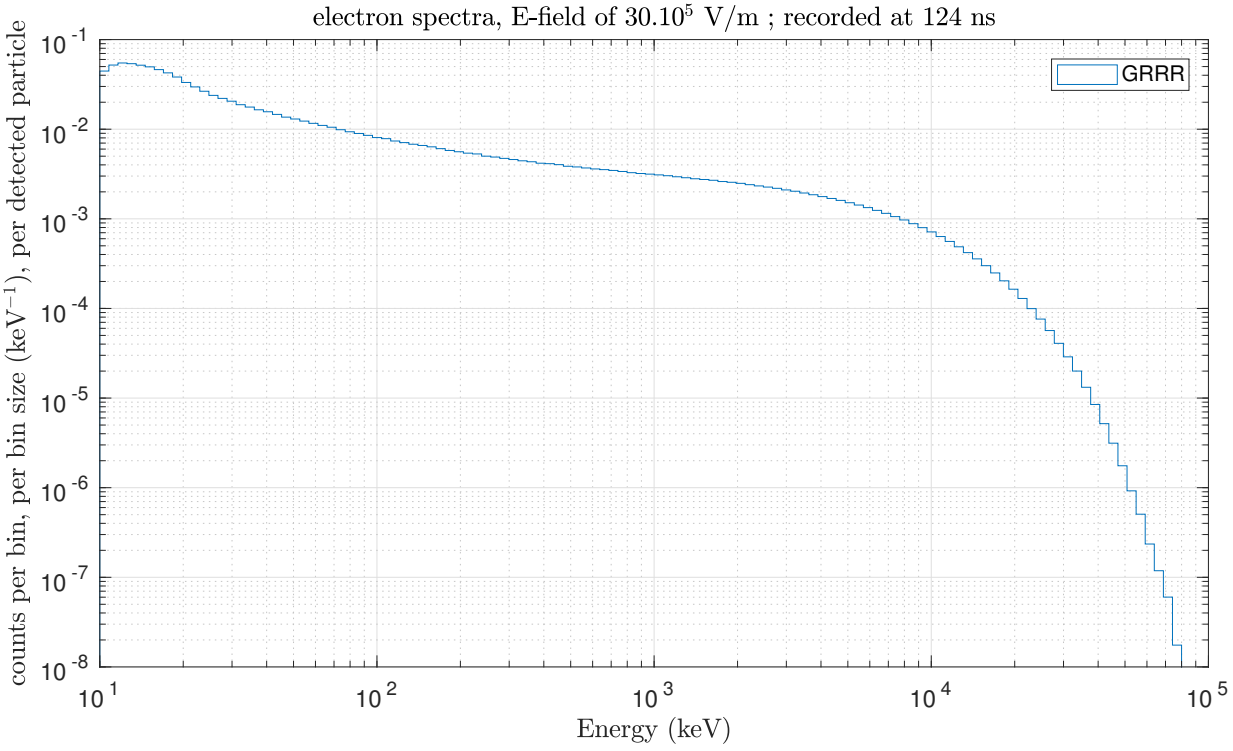


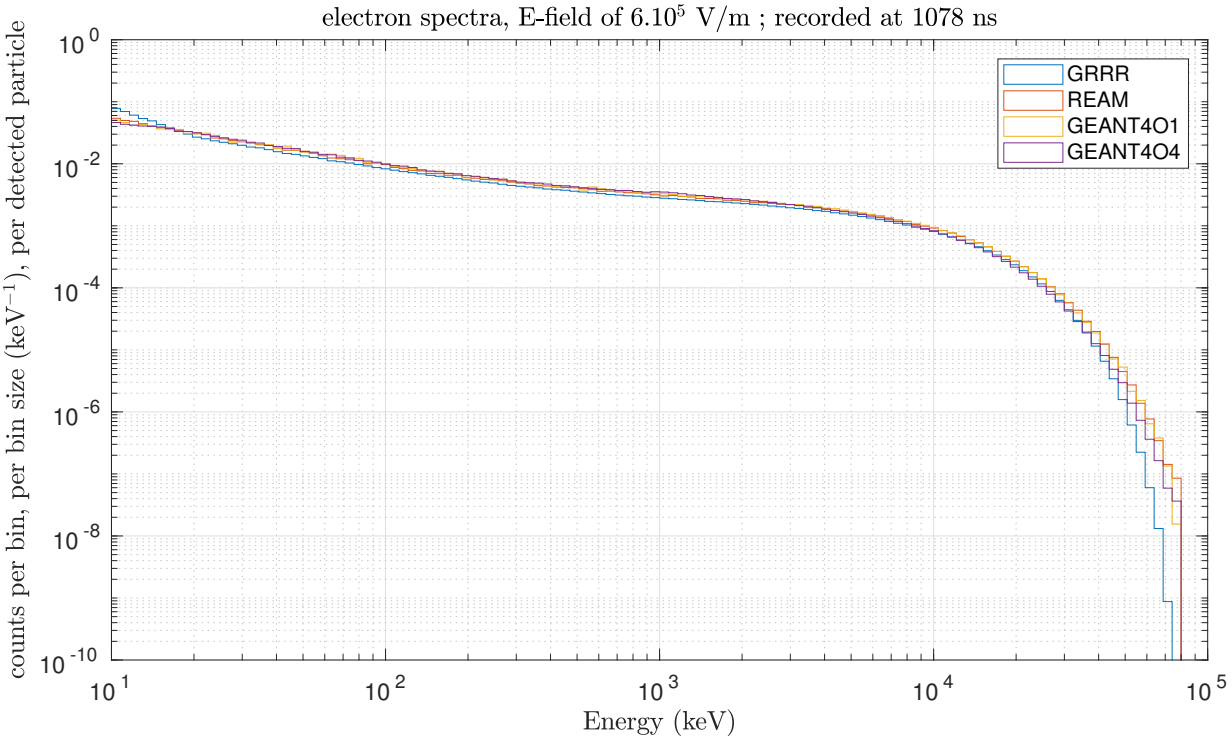

Mean XY radius VS distance, GEANT4O1
Mean XY radius (meters)
Record distance (meters)
0
5
10
15
20
25
0
50
100
150
200
250
300
E-field of 6.10^5 V/m
E-field of 8.10^5 V/m
E-field of 10.10^5 V/m
E-field of 12.10^5 V/m
E-field of 14.10^5 V/m
E-field of 16.10^5 V/m
E-field of 18.10^5 V/m
E-field of 20.10^5 V/m
E-field of 22.10^5 V/m
E-field of 24.10^5 V/m
E-field of 26.10^5 V/m
E-field of 28.10^5 V/m

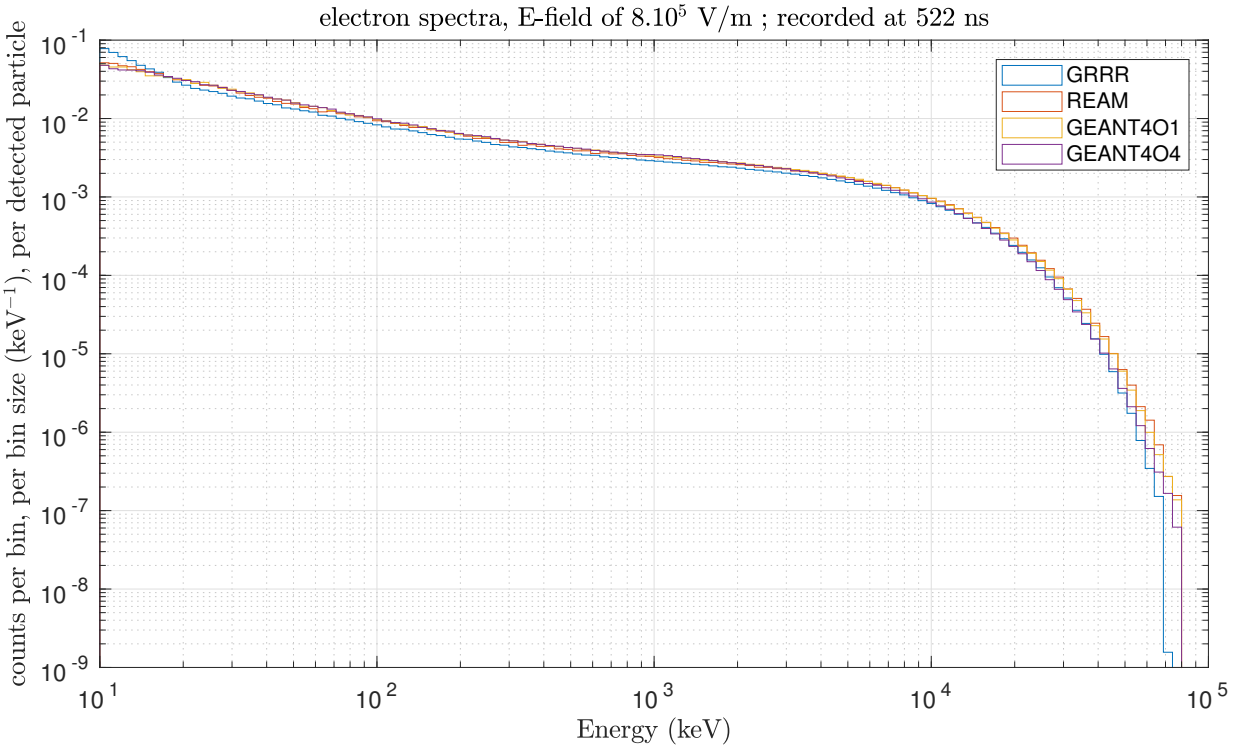

Mean XY radius VS distance, GEANT4O4
Mean XY radius (meters)
Record distance (meters)
0
5
10
15
20
25
0
50
100
150
200
250
300
E-field of 6.10^5 V/m
E-field of 8.10^5 V/m
E-field of 10.10^5 V/m
E-field of 12.10^5 V/m
E-field of 14.10^5 V/m
E-field of 16.10^5 V/m
E-field of 18.10^5 V/m
E-field of 20.10^5 V/m
E-field of 22.10^5 V/m
E-field of 24.10^5 V/m
E-field of 26.10^5 V/m
E-field of 28.10^5 V/m

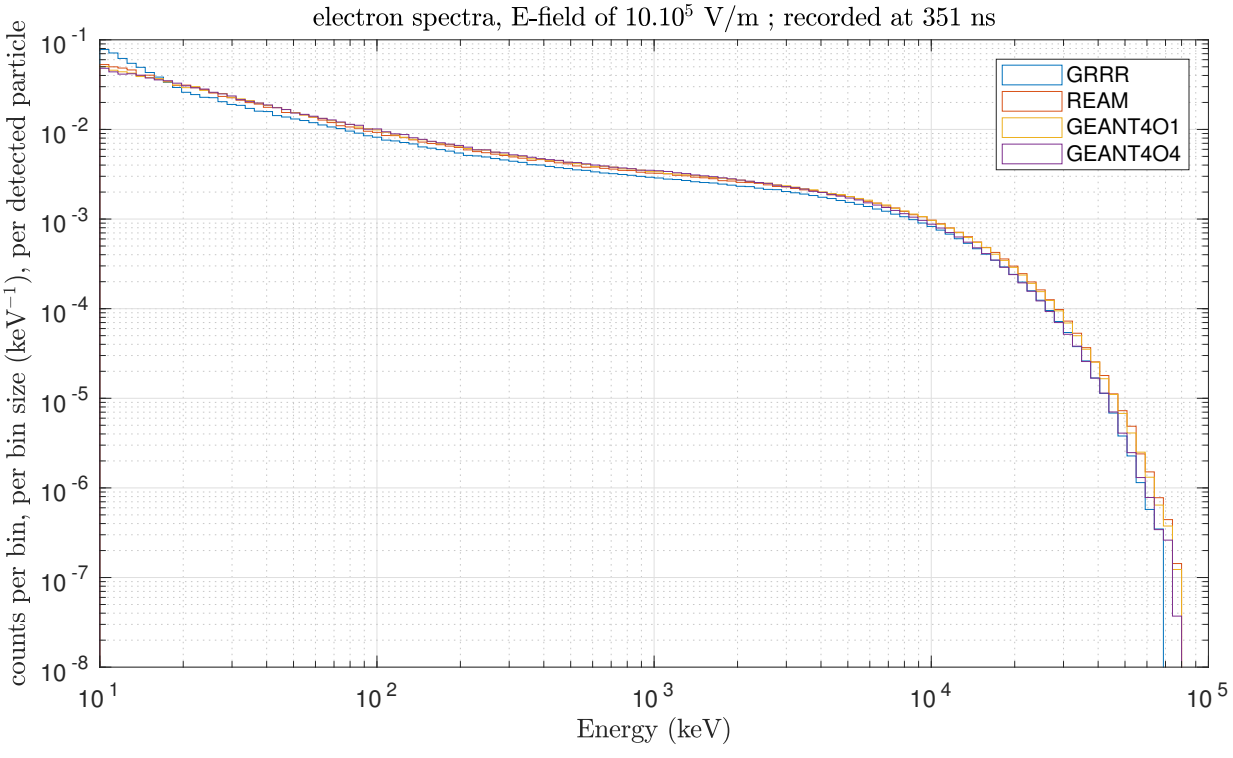
6 Spectra Comparison

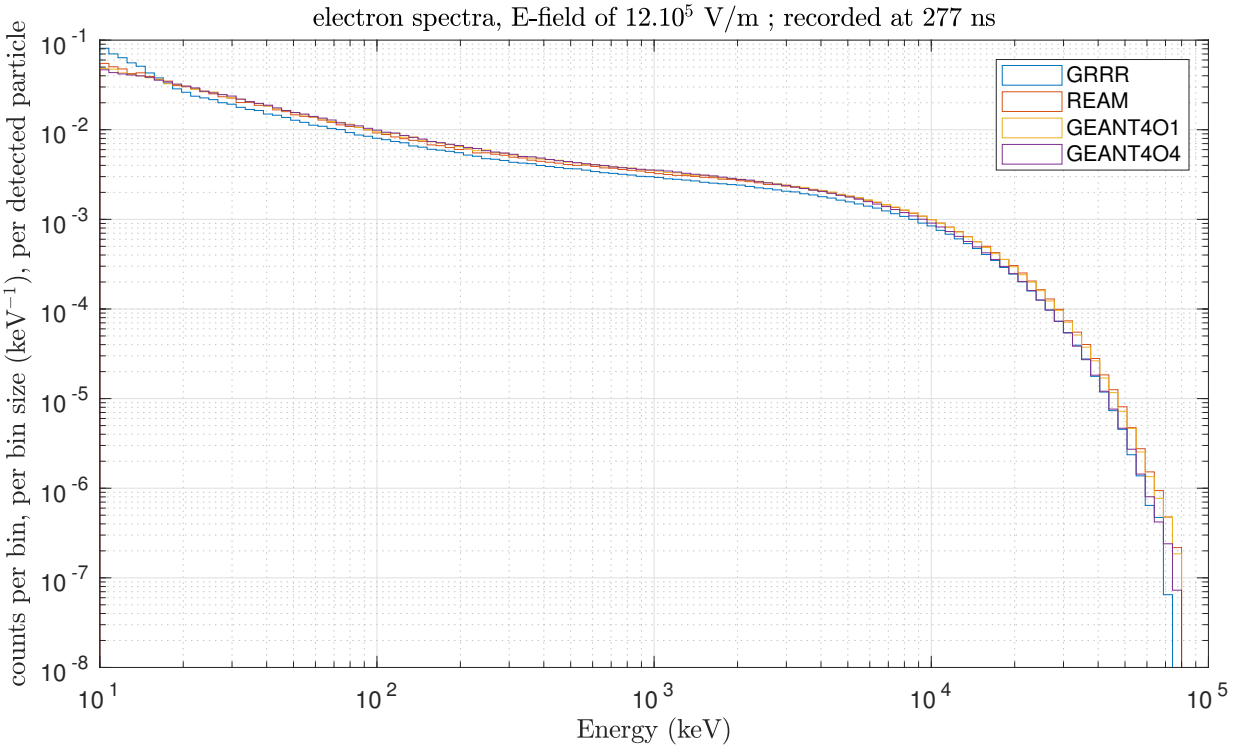
6.1 Time Record

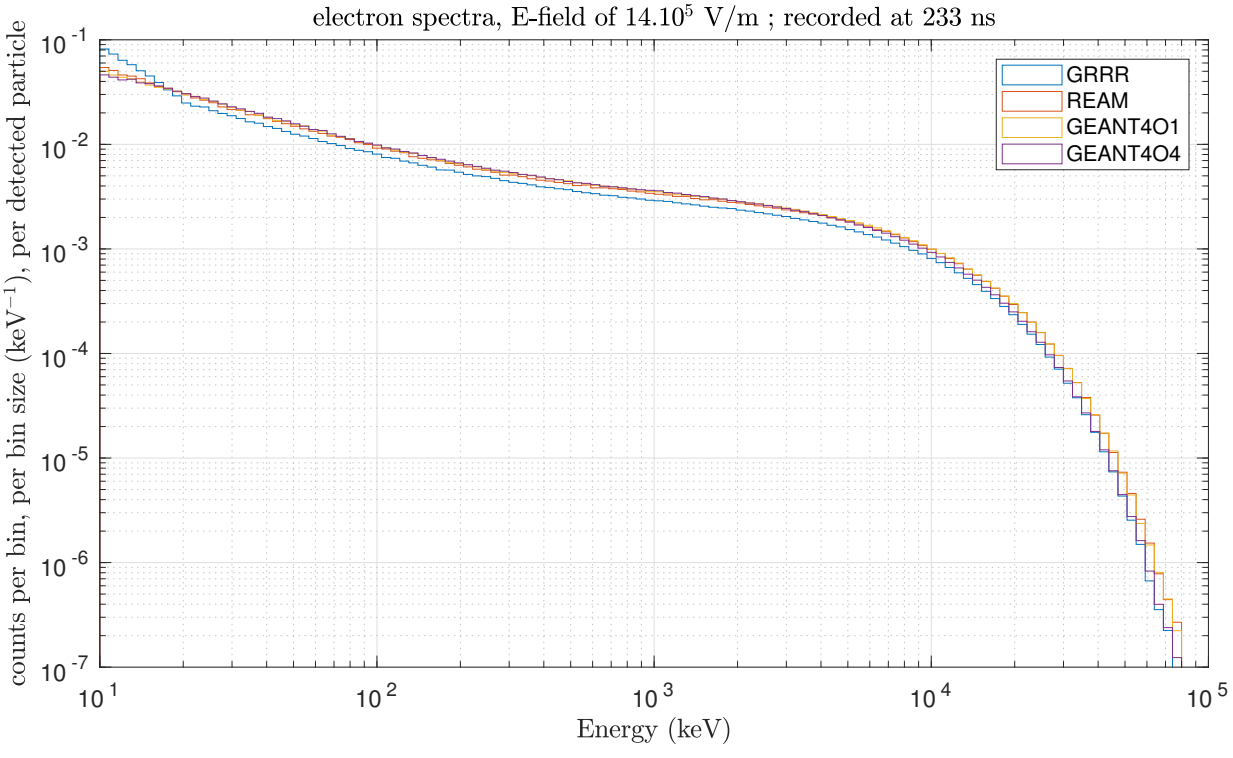


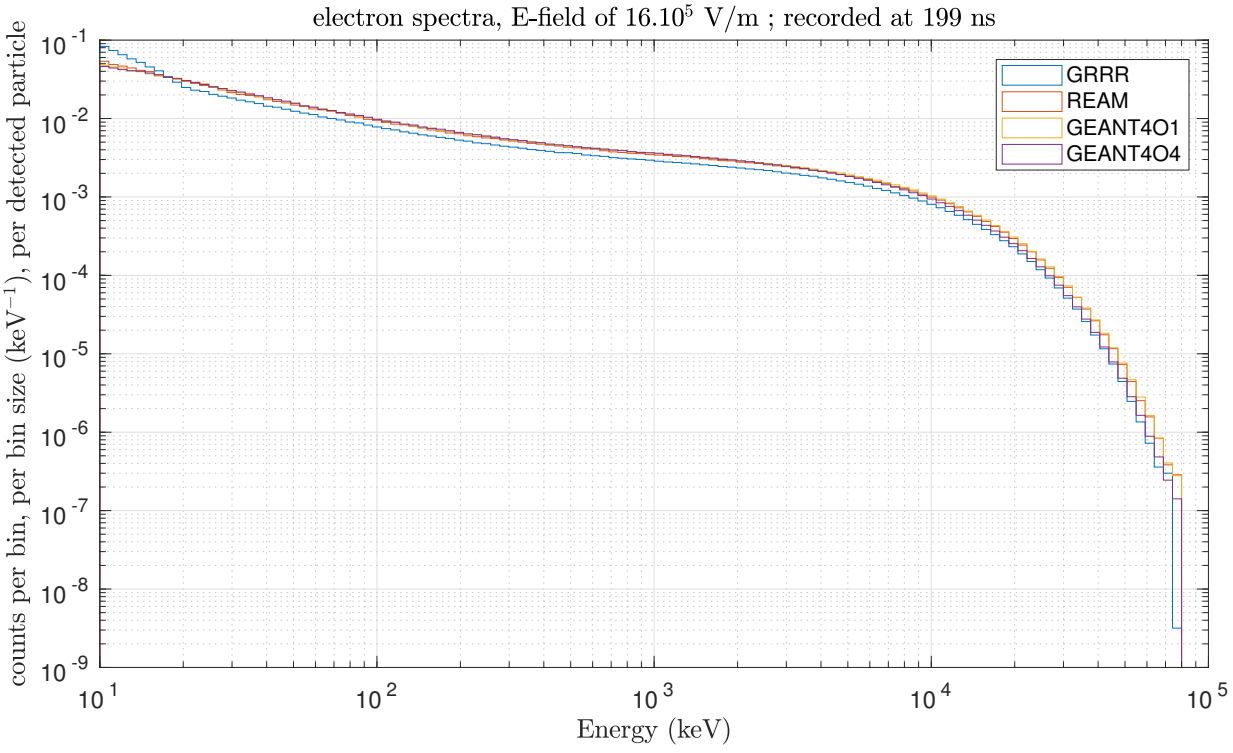


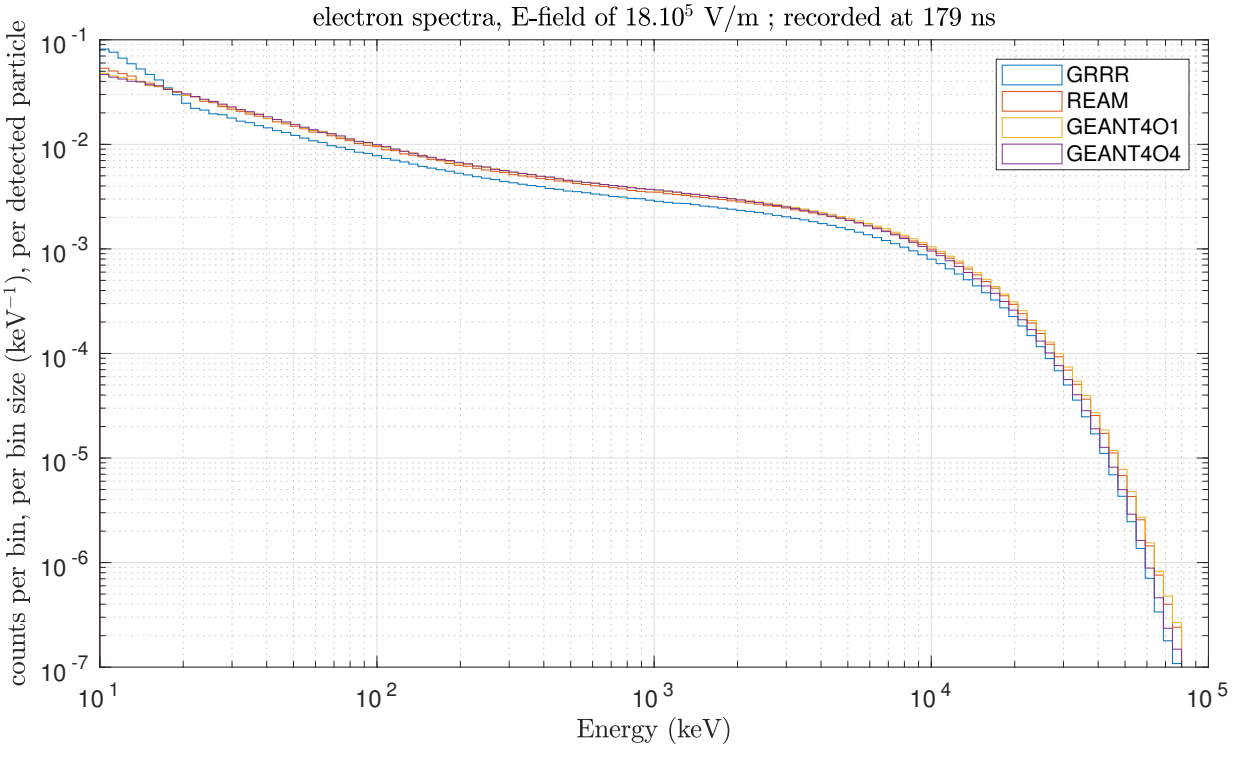

electron spectra, E-field of 8.10^5 V/m ; recorded at 522 ns
counts per bin, per bin size (keV^-1), per detected particle
Energy (keV)
GRRR
REAM
GEANT4O1
GEANT4O4

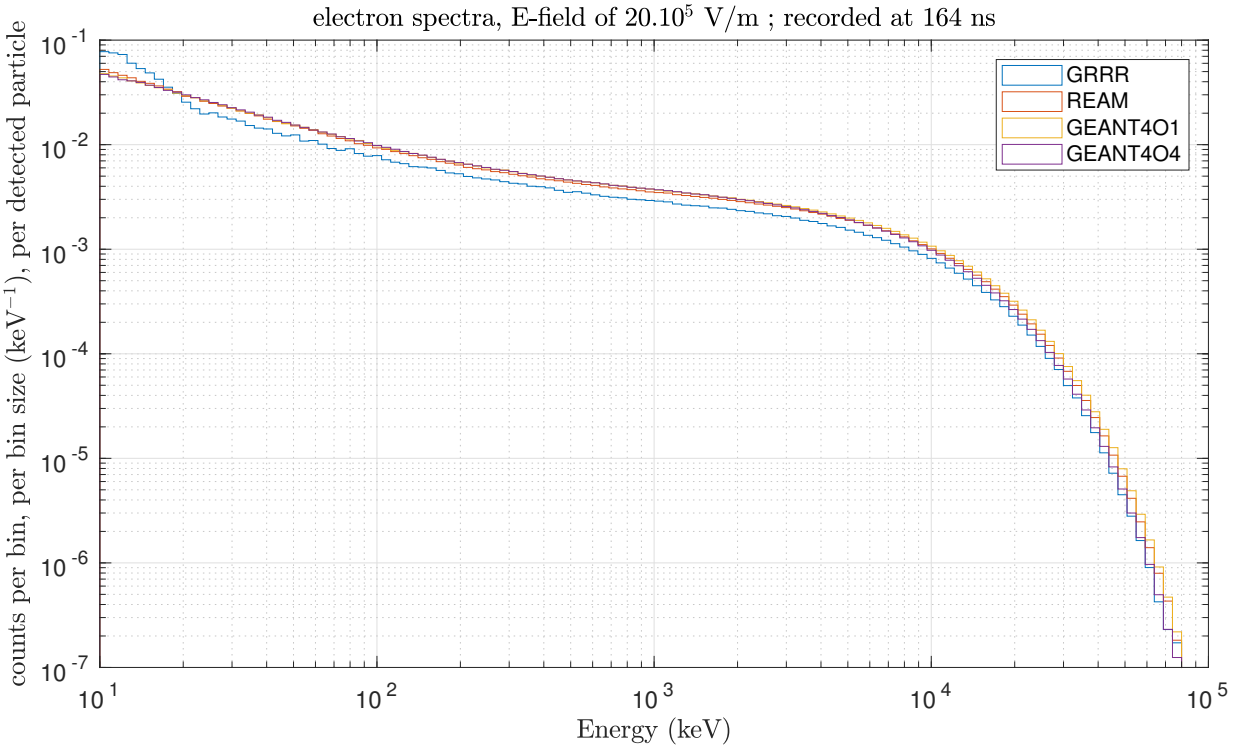

electron spectra, E-field of 10.10^5 V/m ; recorded at 351 ns
counts per bin, per bin size (keV^-1), per detected particle
Energy (keV)
GRRR
REAM
GEANT4O1
GEANT4O4

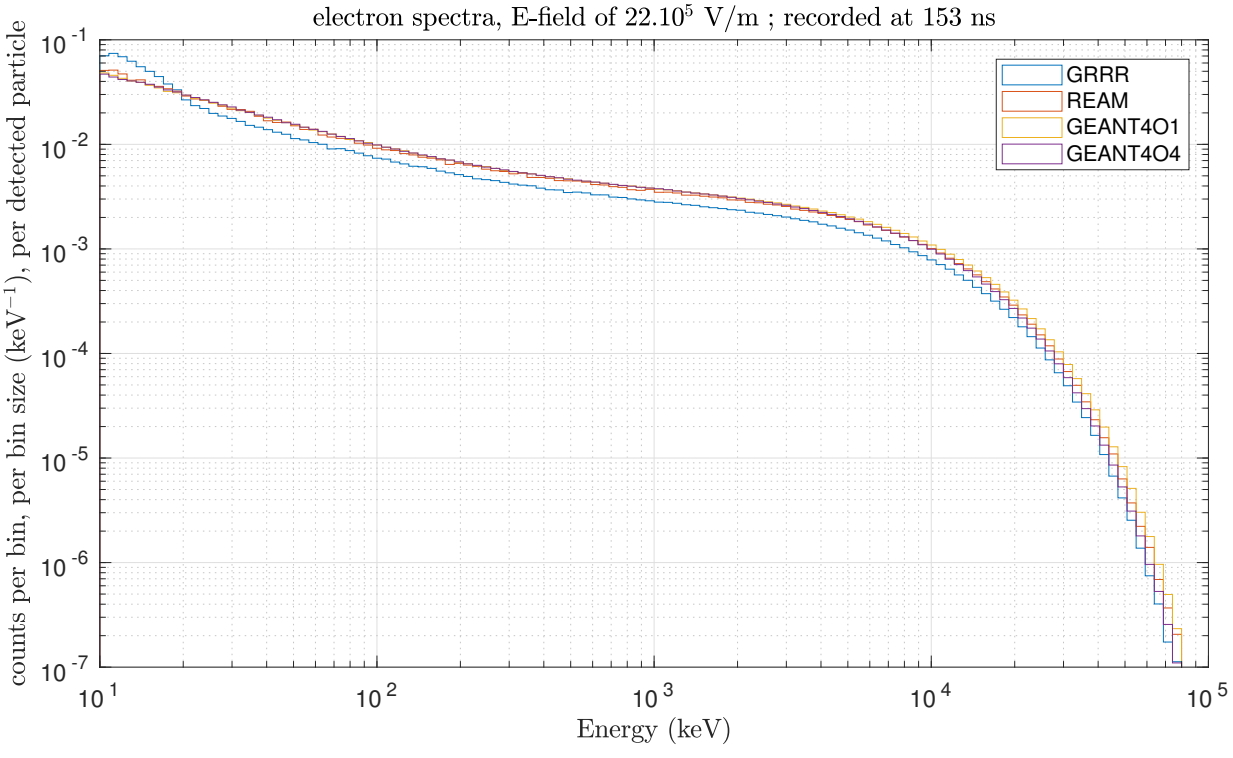

electron spectra, E-field of 12.10^5 V/m ; recorded at 277 ns
counts per bin, per bin size (keV^-1), per detected particle
Energy (keV)
GRRR
REAM
GEANT4O1
GEANT4O4

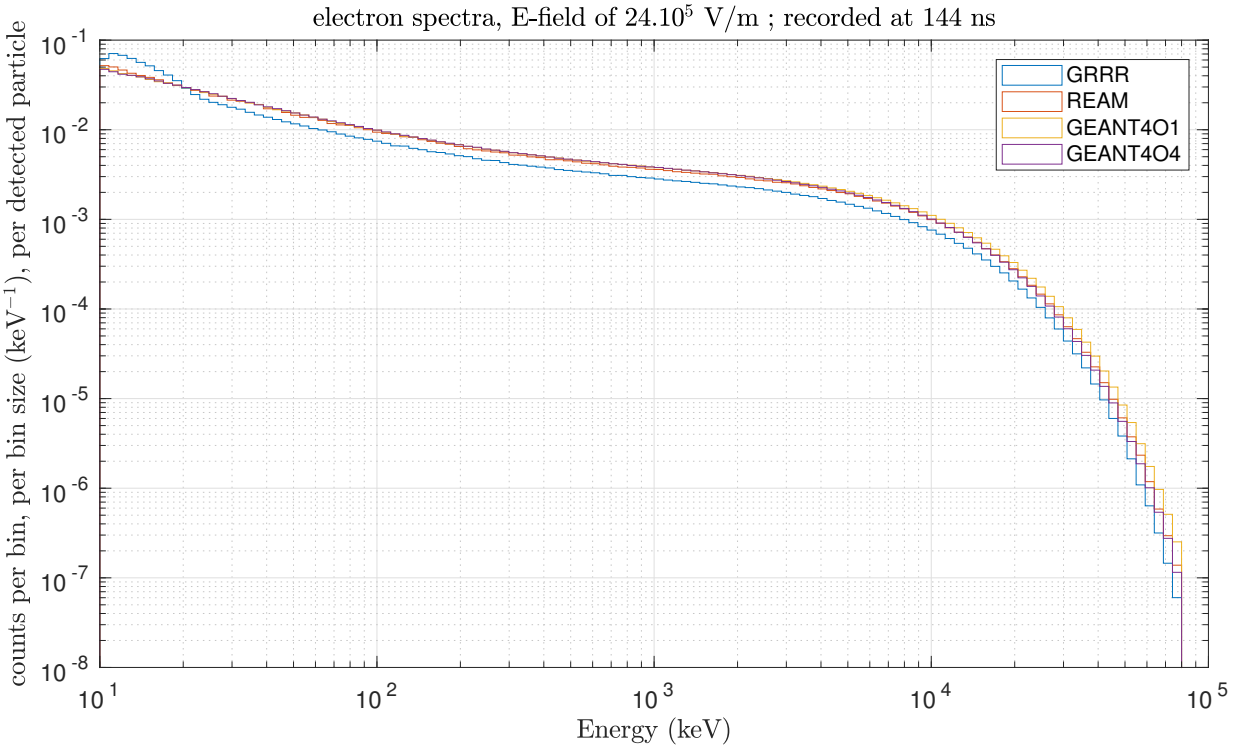

electron spectra, E-field of 14.10^5 V/m ; recorded at 233 ns
counts per bin, per bin size (keV^-1), per detected particle
Energy (keV)
GRRR
REAM
GEANT4O1
GEANT4O4

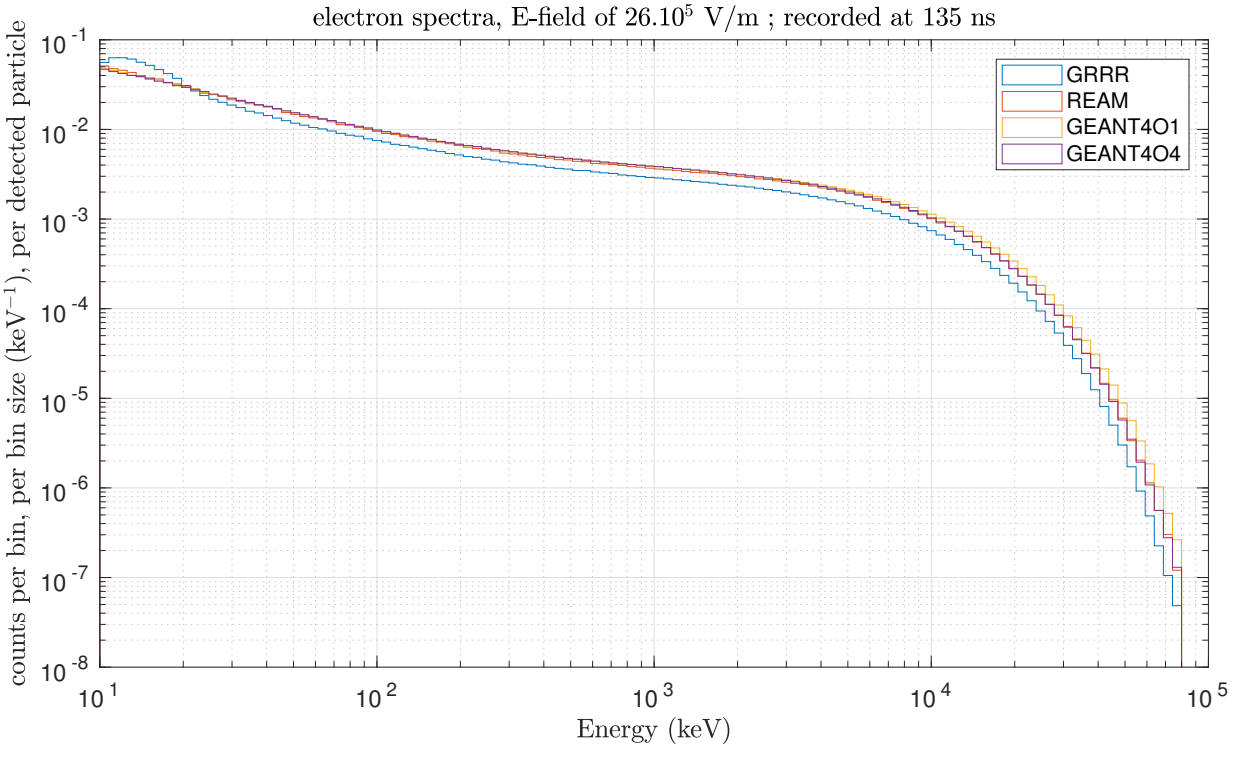

electron spectra, E-field of 16.10^5 V/m ; recorded at 199 ns
counts per bin, per bin size (keV^-1), per detected particle
Energy (keV)
GRRR
REAM
GEANT4O1
GEANT4O4

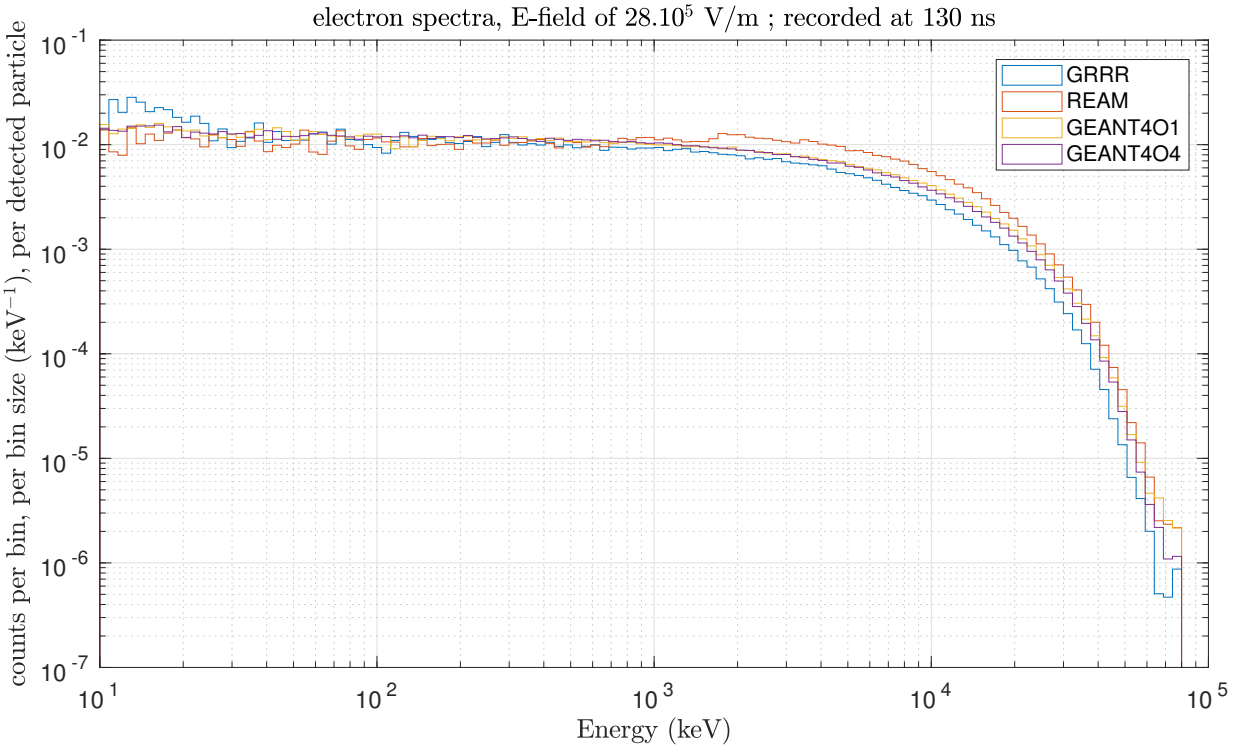

electron spectra, E-field of 18.10^5 V/m ; recorded at 179 ns
counts per bin, per bin size (keV^-1), per detected particle
Energy (keV)
GRRR
REAM
GEANT4O1
GEANT4O4

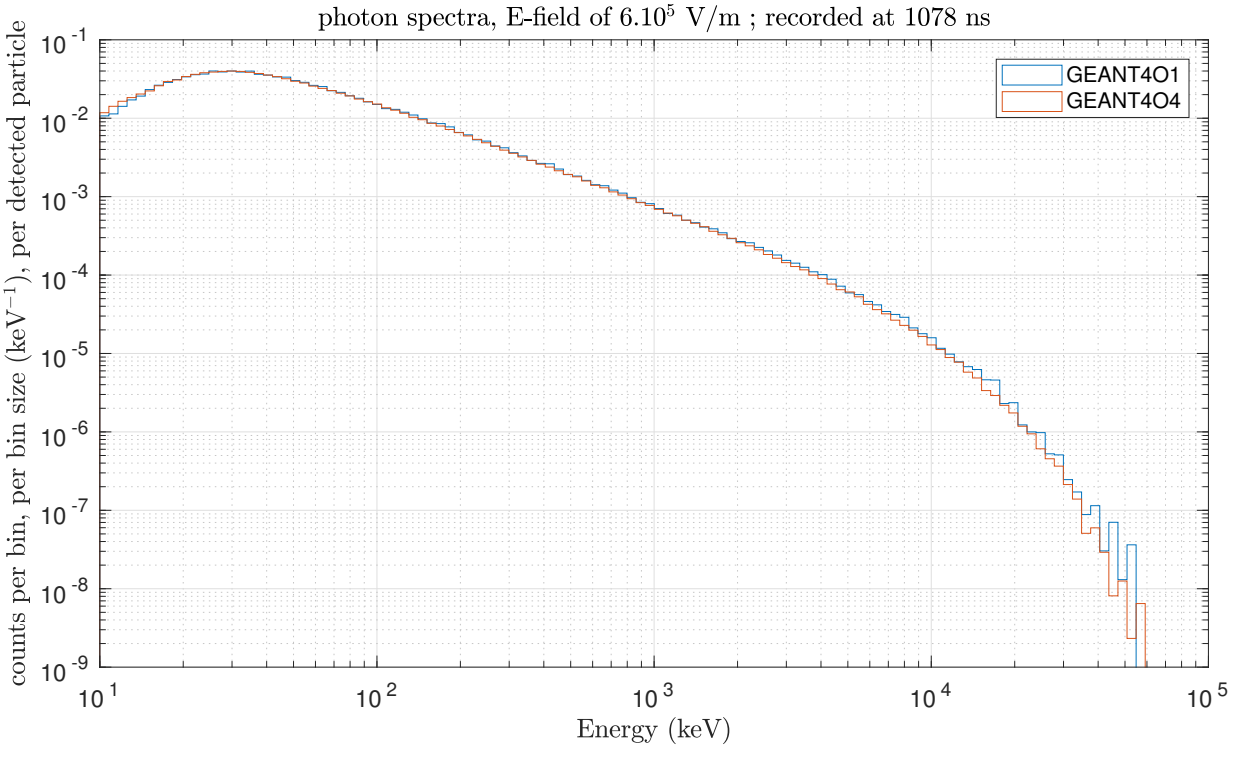

electron spectra, E-field of 20.10^5 V/m ; recorded at 164 ns
counts per bin, per bin size (keV^-1), per detected particle
Energy (keV)
GRRR
REAM
GEANT4O1
GEANT4O4

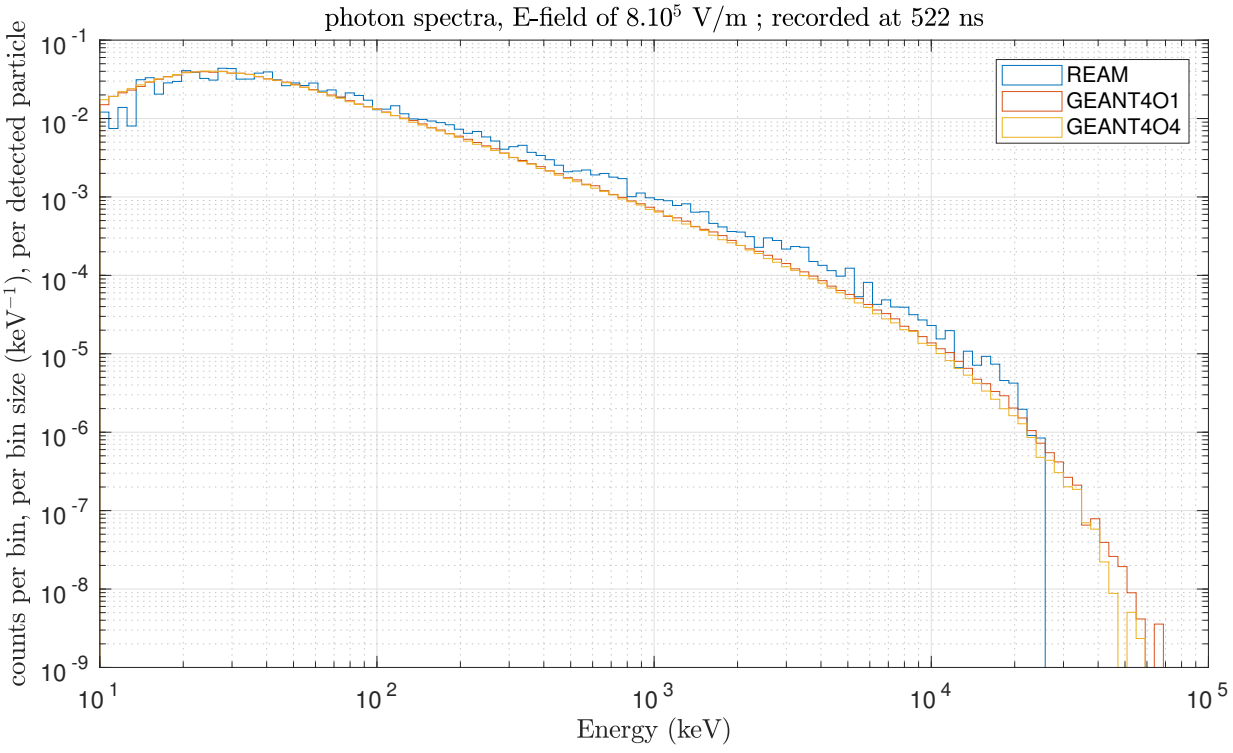

electron spectra, E-field of 22.10^5 V/m ; recorded at 153 ns
counts per bin, per bin size (keV^-1), per detected particle
Energy (keV)
GRRR
REAM
GEANT4O1
GEANT4O4

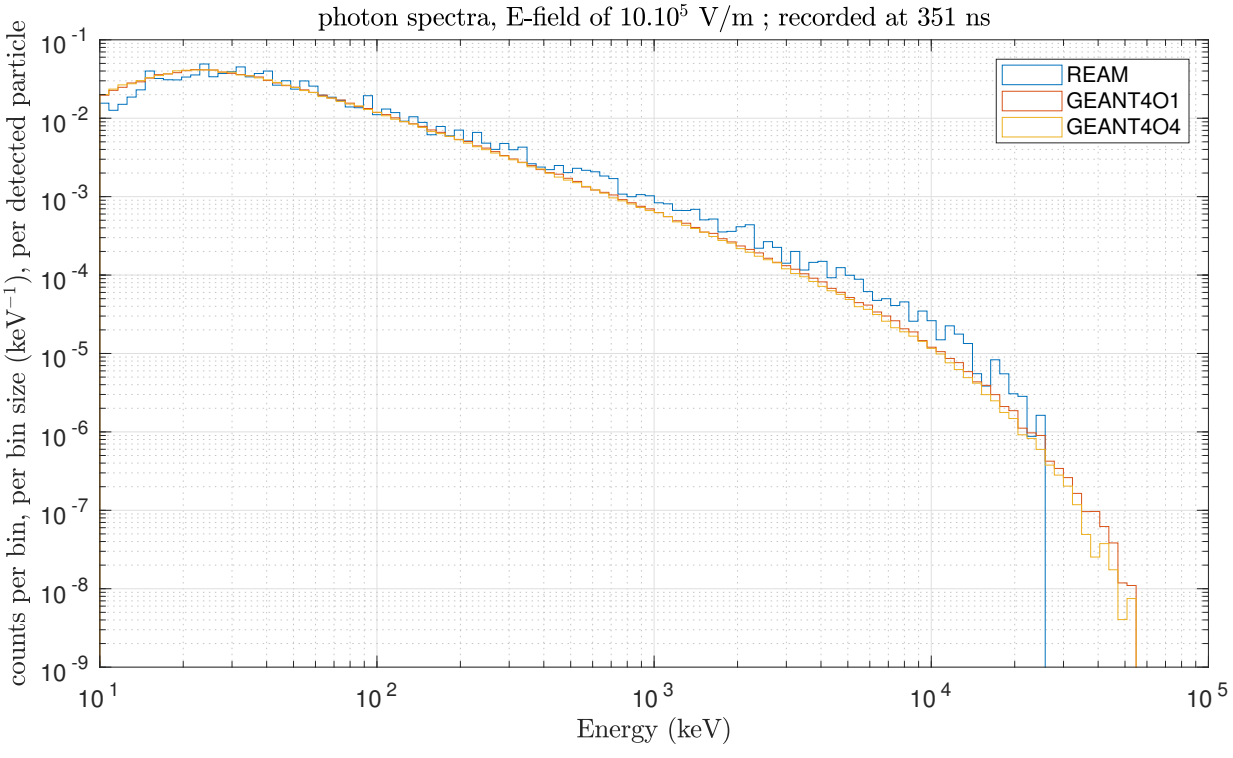

electron spectra, E-field of 24.10^5 V/m ; recorded at 144 ns
counts per bin, per bin size (keV^-1), per detected particle
Energy (keV)
GRRR
REAM
GEANT4O1
GEANT4O4

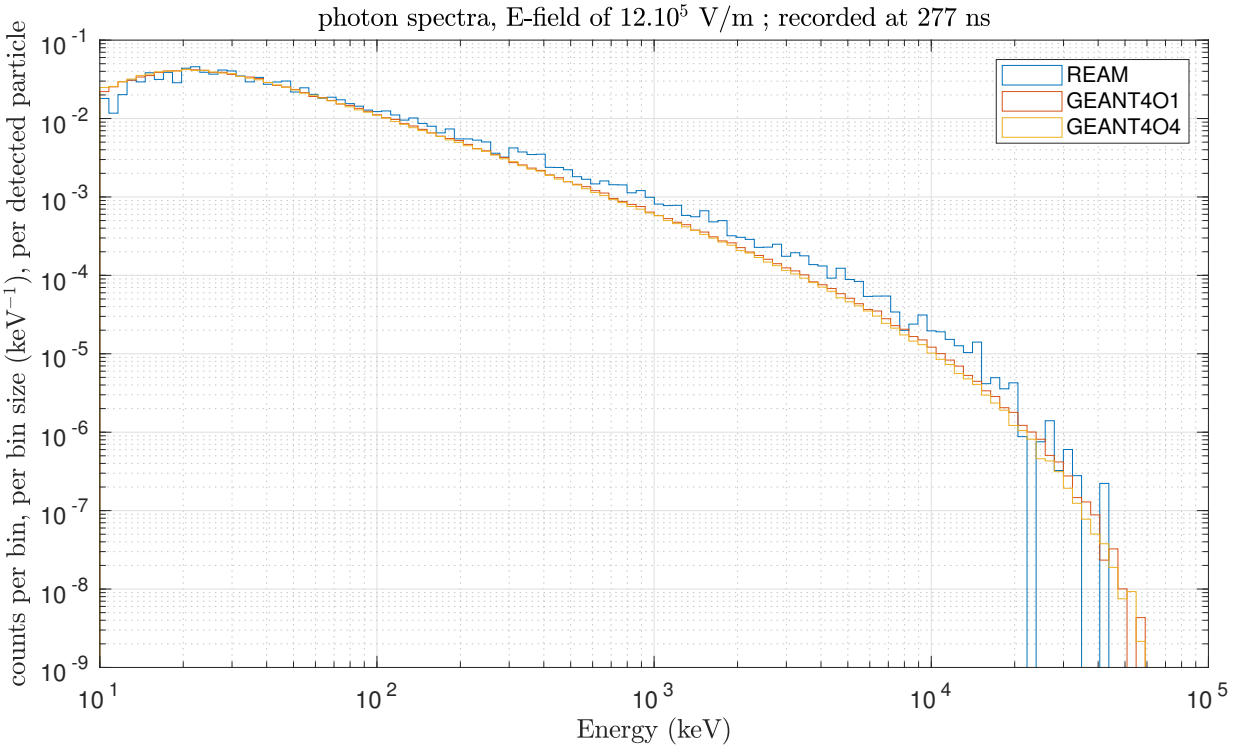

electron spectra, E-field of 26.10^5 V/m ; recorded at 135 ns
counts per bin, per bin size (keV^-1), per detected particle
Energy (keV)
GRRR
REAM
GEANT4O1
GEANT4O4

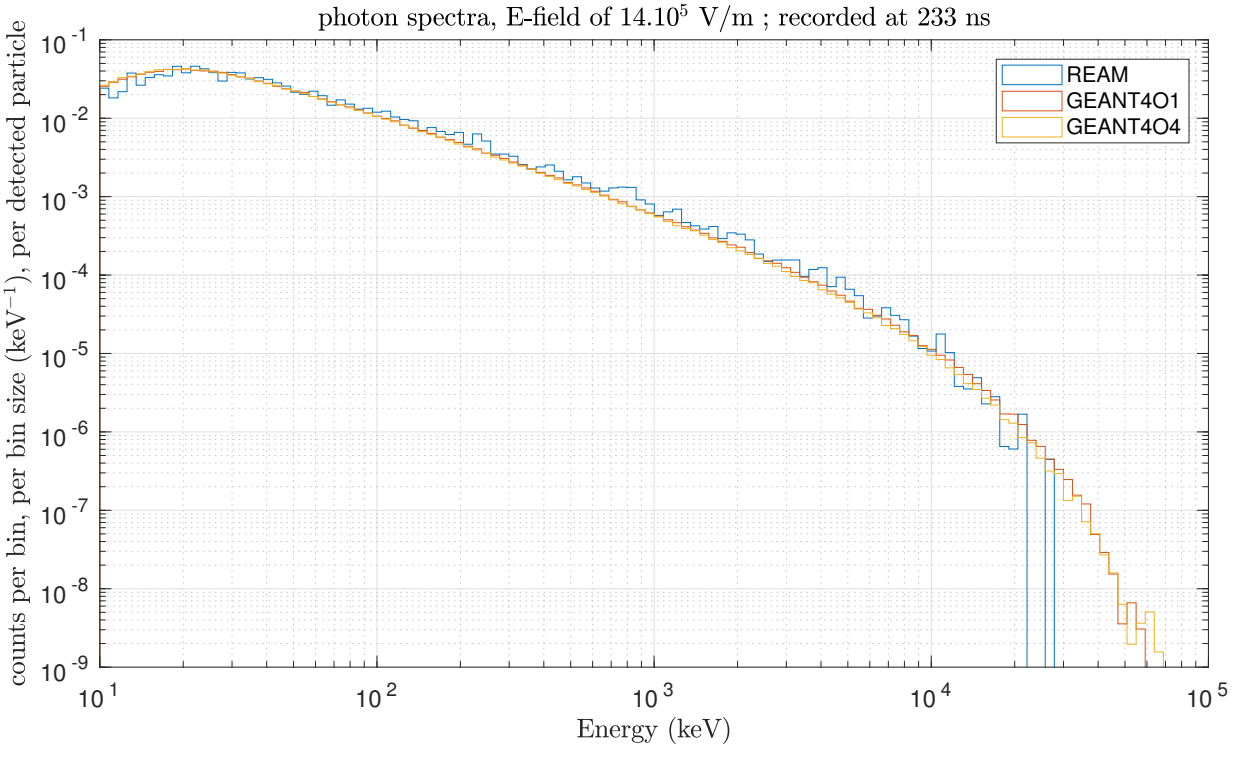

electron spectra, E-field of 28.10^5 V/m ; recorded at 130 ns
GRRR
REAM
GEANT4O1
GEANT4O4
counts per bin, per bin size (keV^-1), per detected particle
Energy (keV)

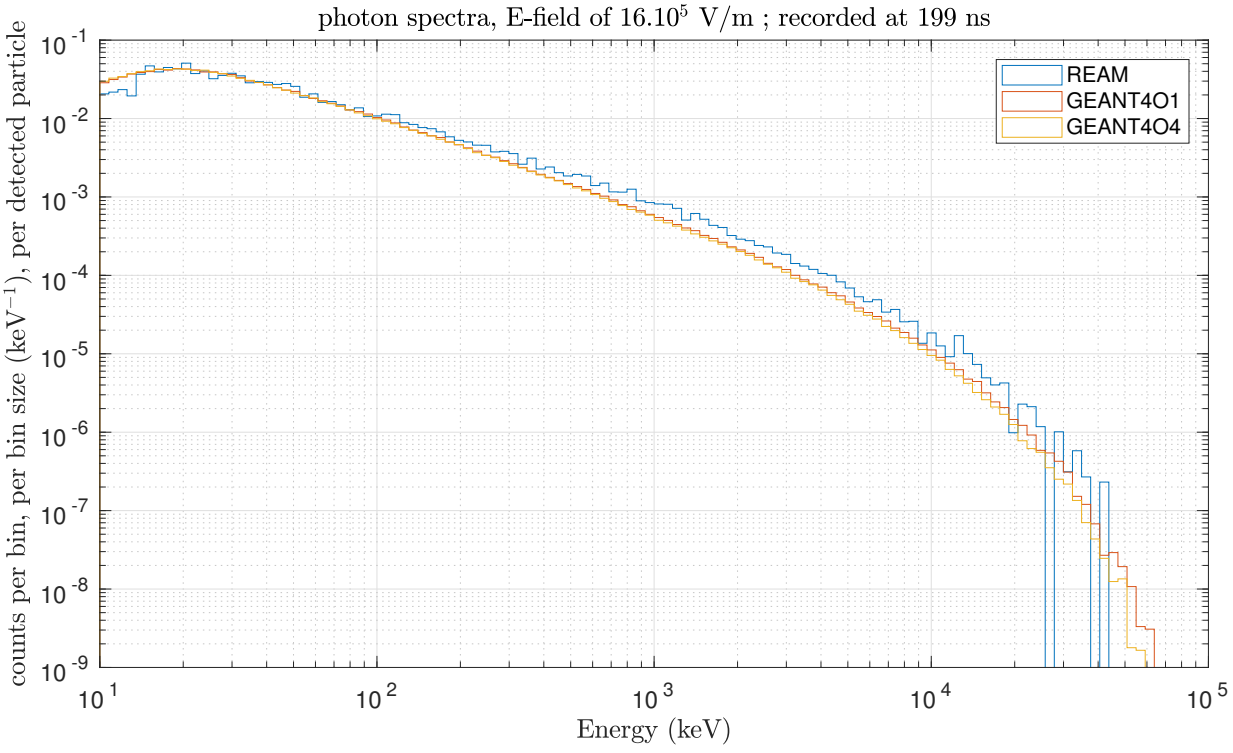

photon spectra, E-field of 6.10^5 V/m ; recorded at 1078 ns
GEANT4O1
GEANT4O4
counts per bin, per bin size (keV^-1), per detected particle
Energy (keV)

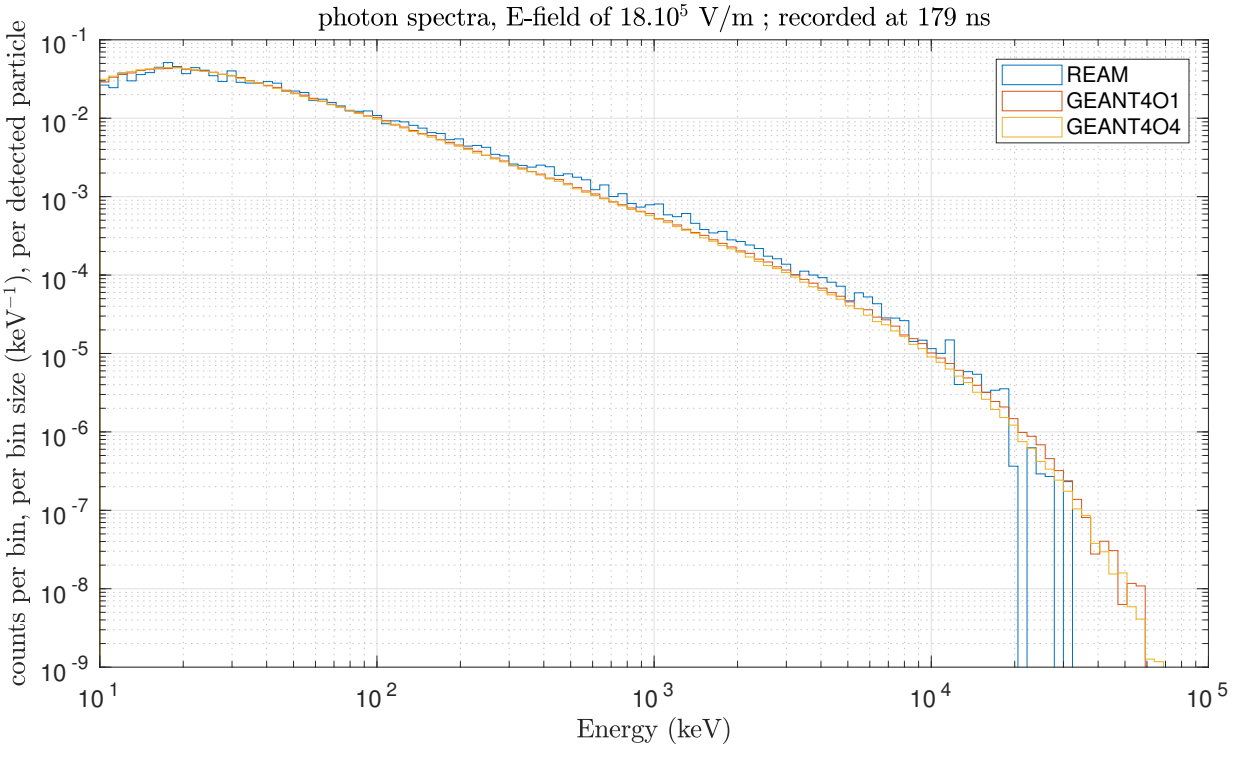

photon spectra, E-field of 8.10^5 V/m ; recorded at 522 ns
REAM
GEANT4O1
GEANT4O4
counts per bin, per bin size (keV^-1), per detected particle
Energy (keV)

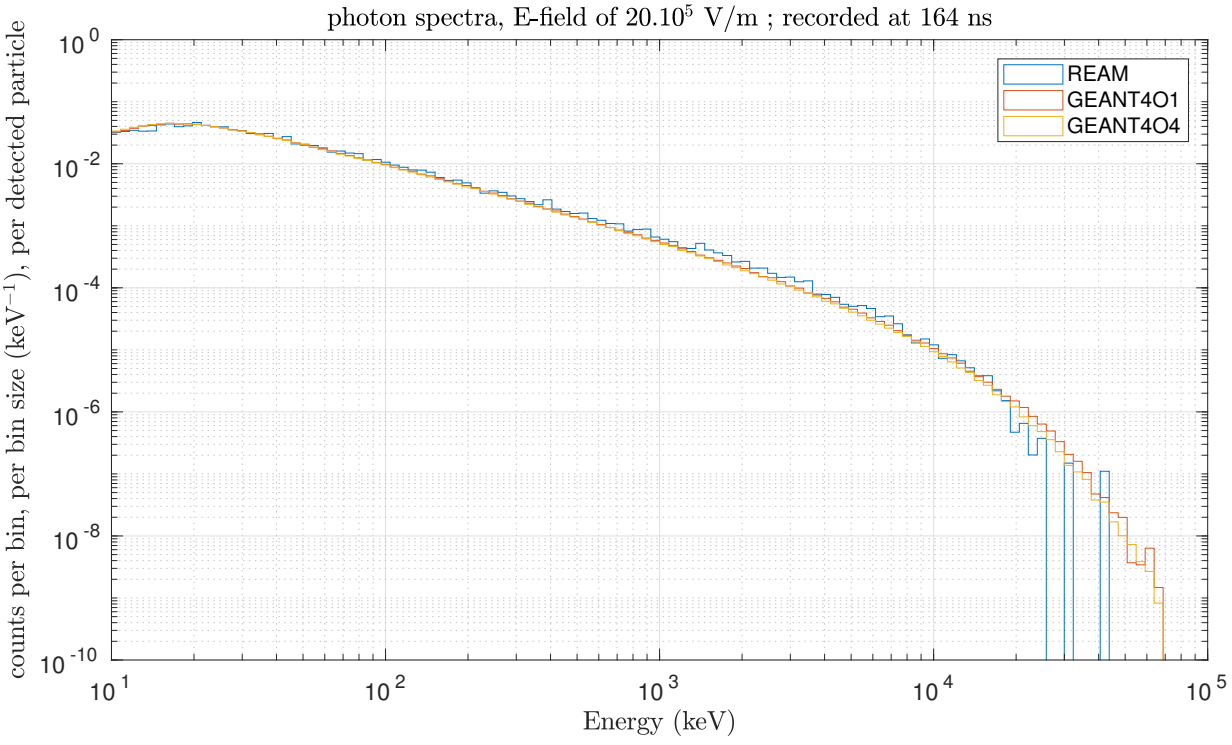

photon spectra, E-field of 10.10^5 V/m ; recorded at 351 ns
REAM
GEANT4O1
GEANT4O4
counts per bin, per bin size (keV^-1), per detected particle
Energy (keV)

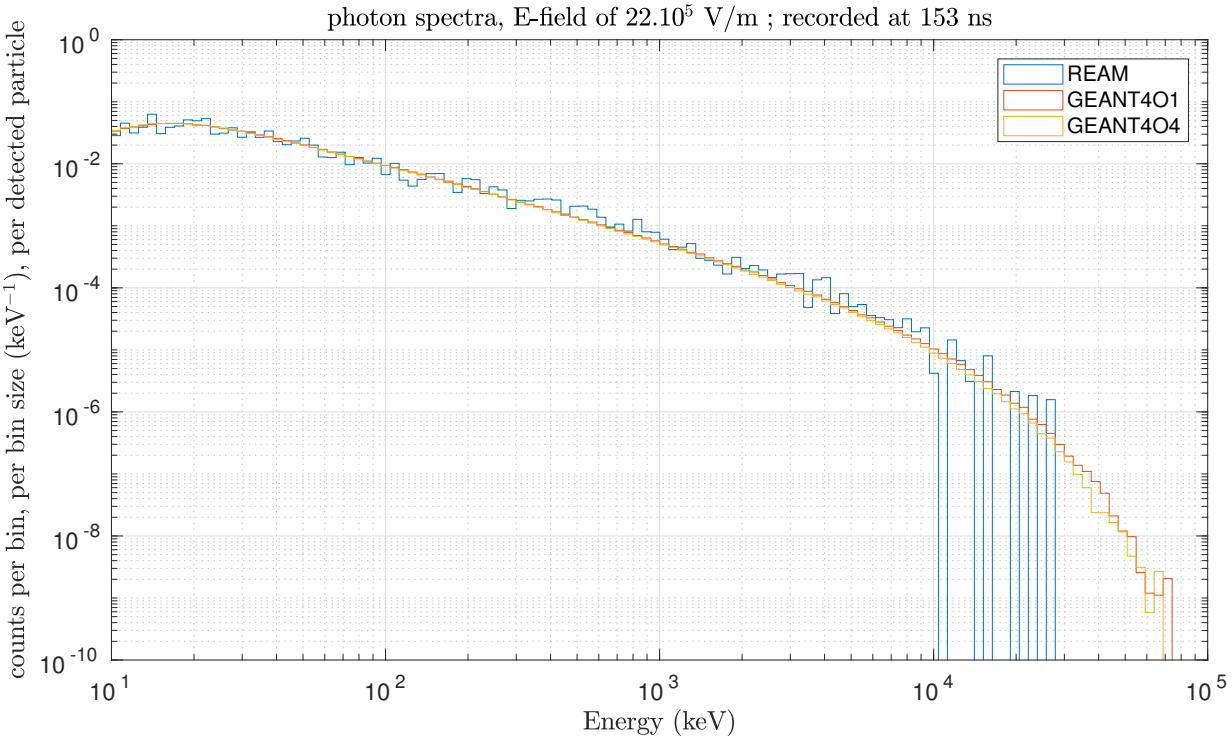

photon spectra, E-field of 12.10^5 V/m ; recorded at 277 ns
counts per bin, per bin size (keV^-1), per detected particle
Energy (keV)
REAM
GEANT4O1
GEANT4O4

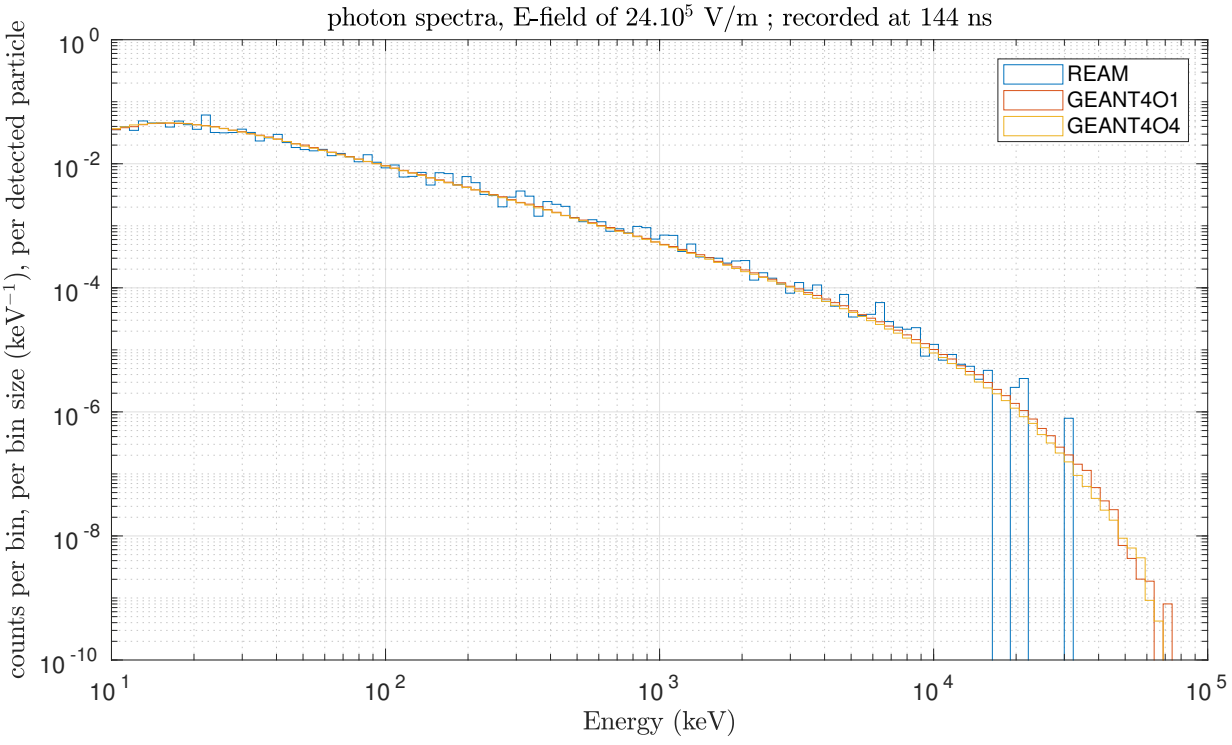

photon spectra, E-field of 14.10^5 V/m ; recorded at 233 ns
counts per bin, per bin size (keV^-1), per detected particle
Energy (keV)
REAM
GEANT4O1
GEANT4O4

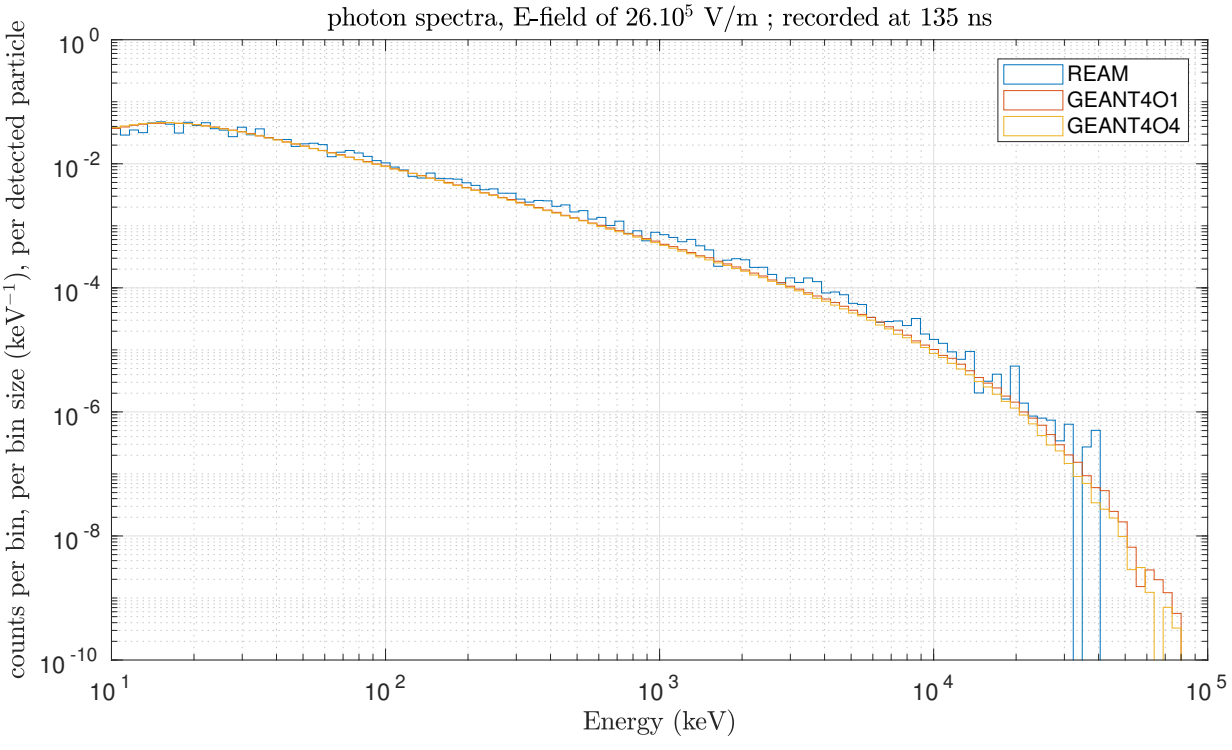

photon spectra, E-field of 16.10^5 V/m ; recorded at 199 ns
REAM
GEANT4O1
GEANT4O4
counts per bin, per bin size (keV^-1), per detected particle
Energy (keV)

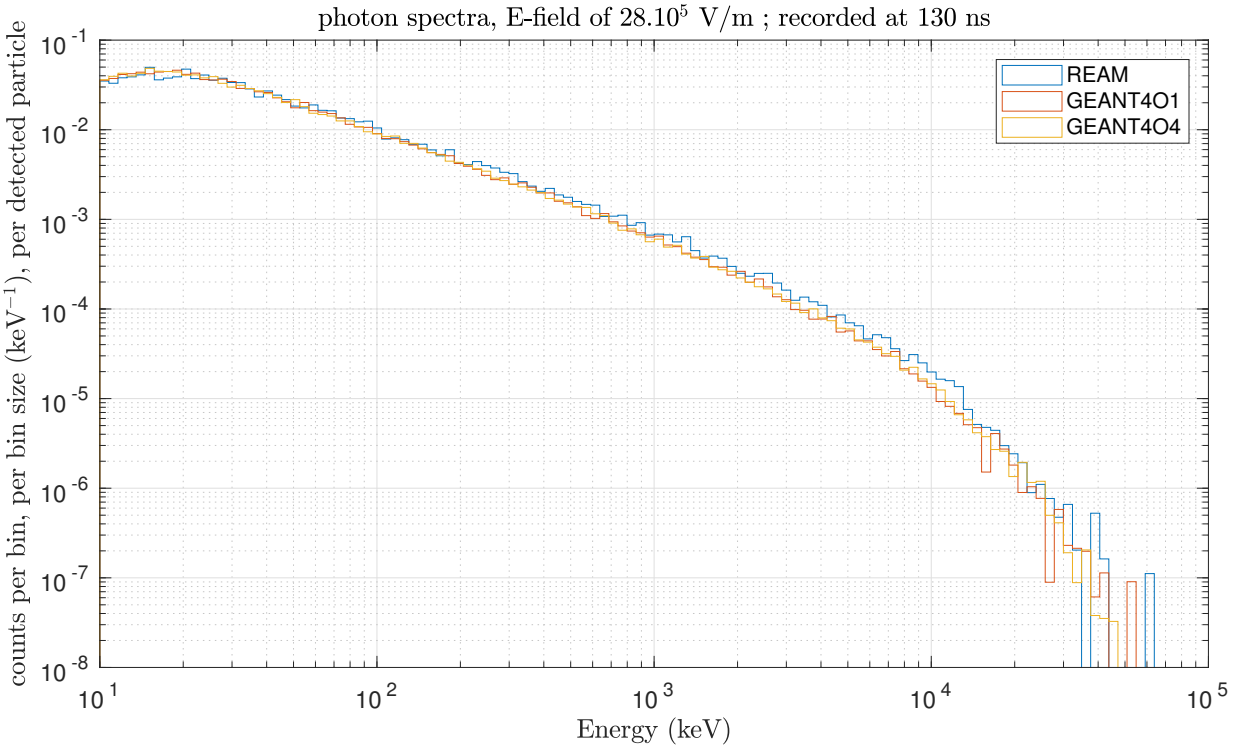

photon spectra, E-field of 18.10^5 V/m ; recorded at 179 ns
REAM
GEANT4O1
GEANT4O4
counts per bin, per bin size (keV^-1), per detected particle
Energy (keV)

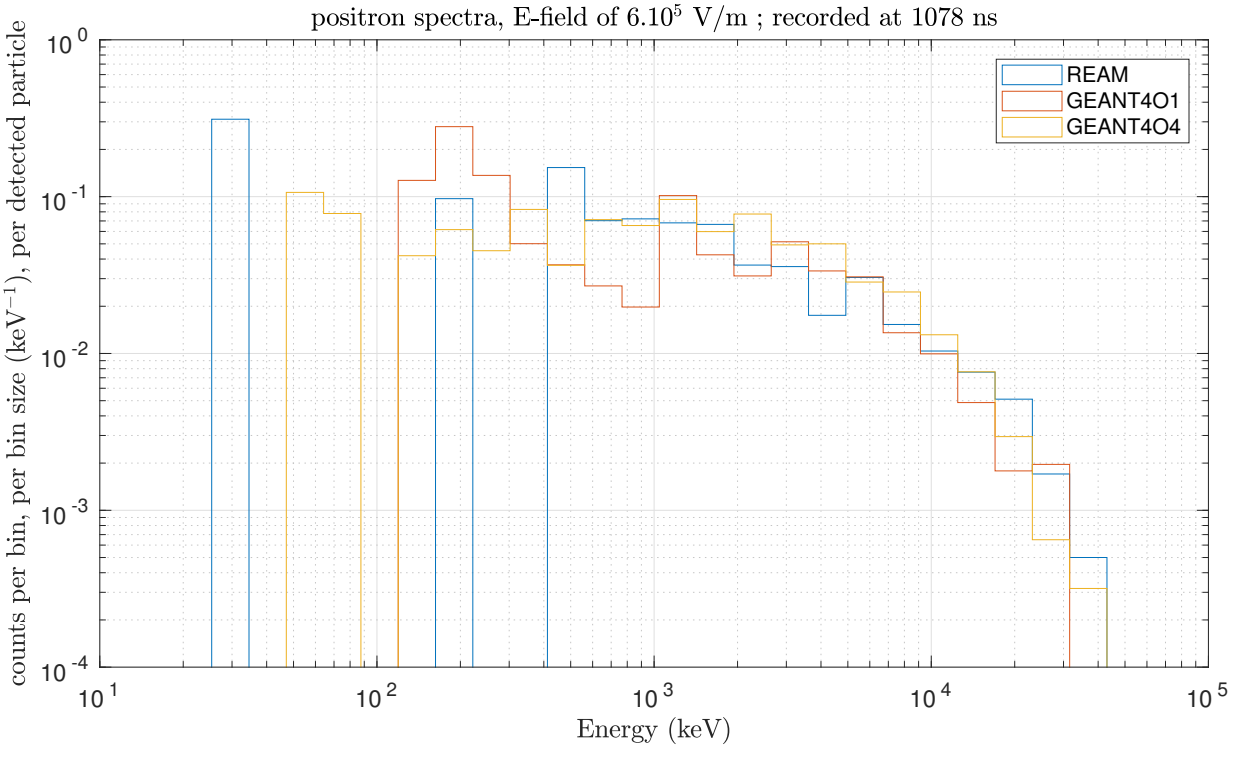

photon spectra, E-field of 20.10^5 V/m ; recorded at 164 ns
REAM
GEANT4O1
GEANT4O4
counts per bin, per bin size (keV^-1), per detected particle
Energy (keV)

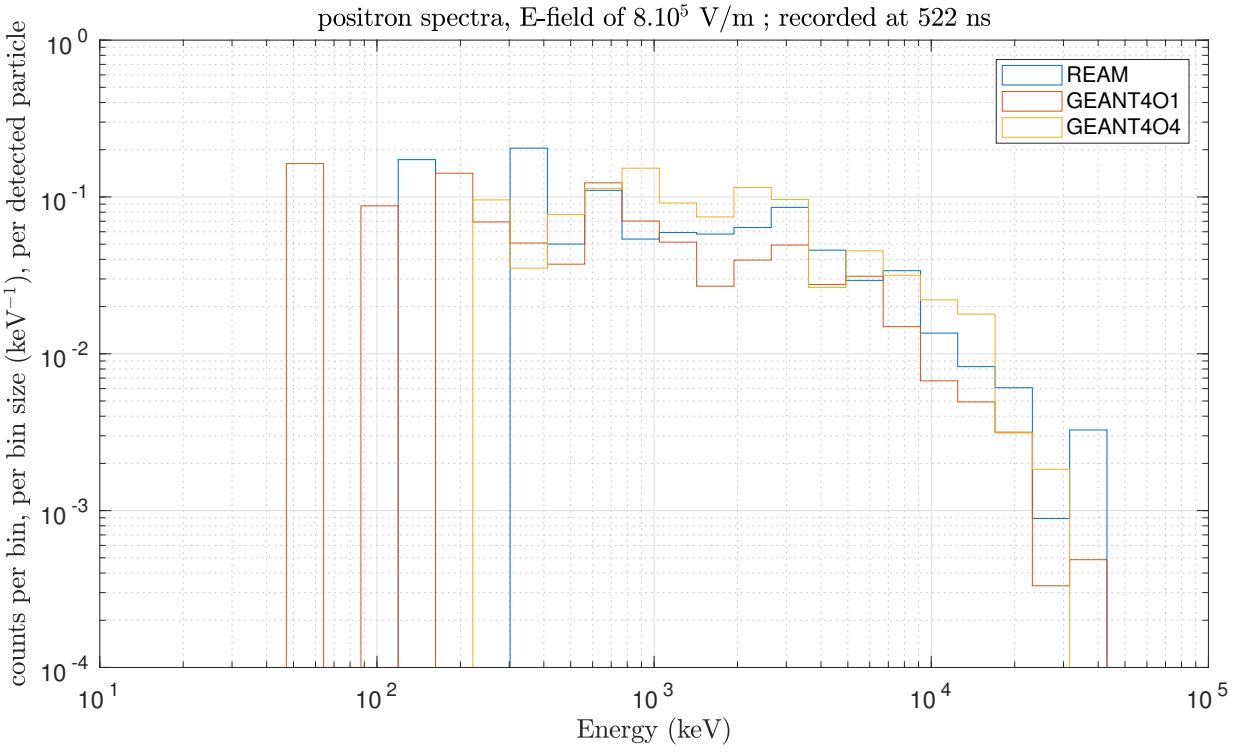

photon spectra, E-field of 22.10^5 V/m ; recorded at 153 ns
REAM
GEANT4O1
GEANT4O4
counts per bin, per bin size (keV^-1), per detected particle
Energy (keV)

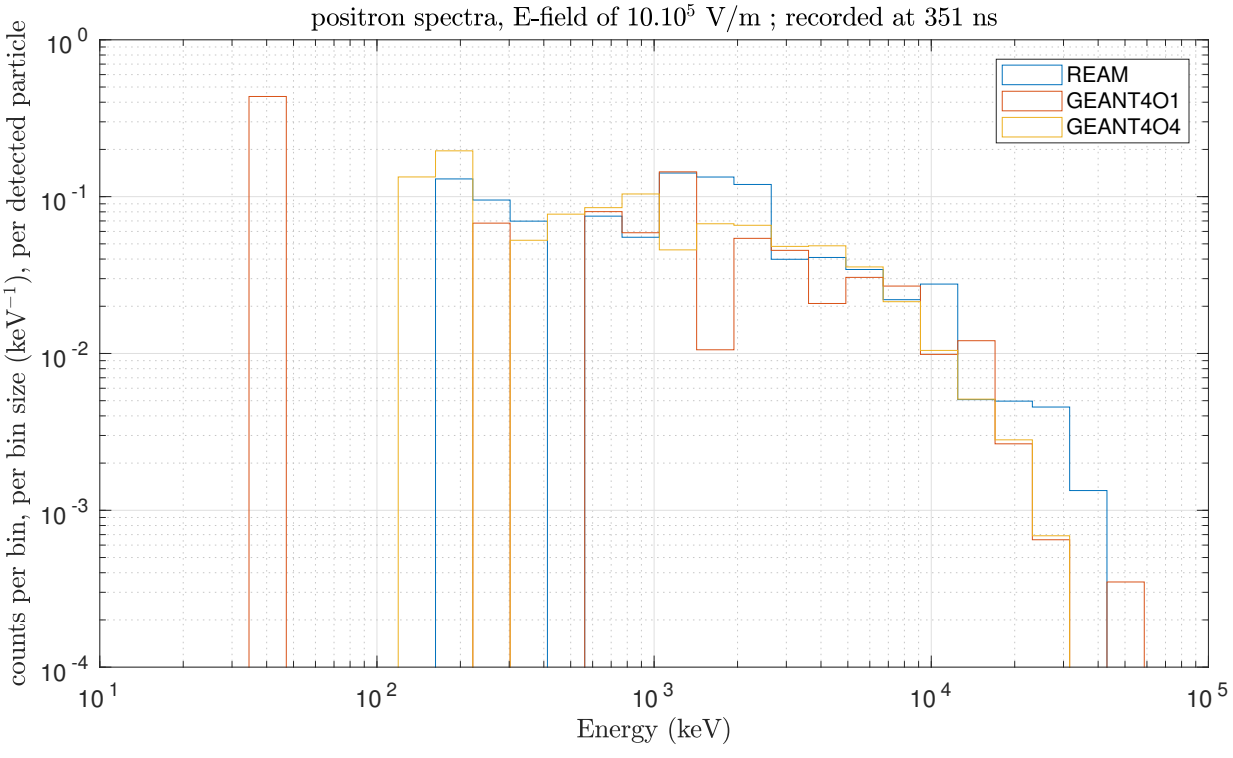

photon spectra, E-field of 24.10^5 V/m ; recorded at 144 ns
REAM
GEANT4O1
GEANT4O4
counts per bin, per bin size (keV^-1), per detected particle
Energy (keV)

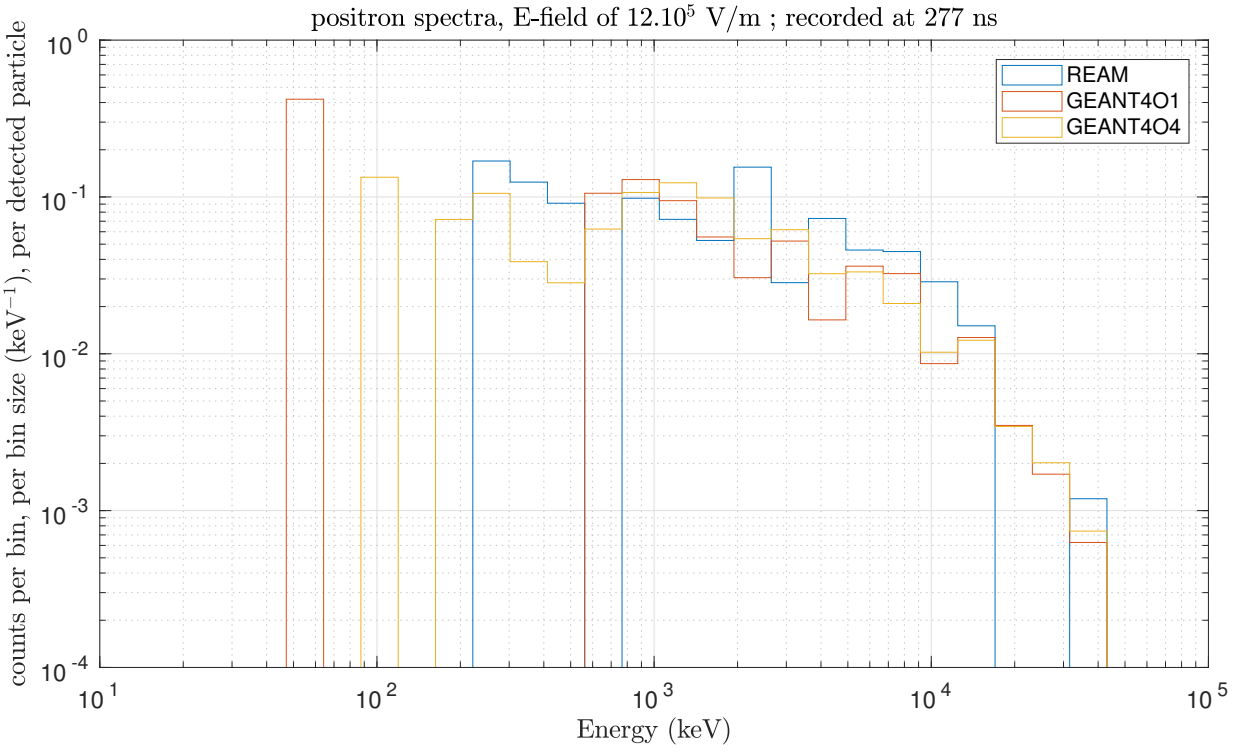

photon spectra, E-field of 26.10^5 V/m ; recorded at 135 ns
REAM
GEANT4O1
GEANT4O4
counts per bin, per bin size (keV^-1), per detected particle
Energy (keV)

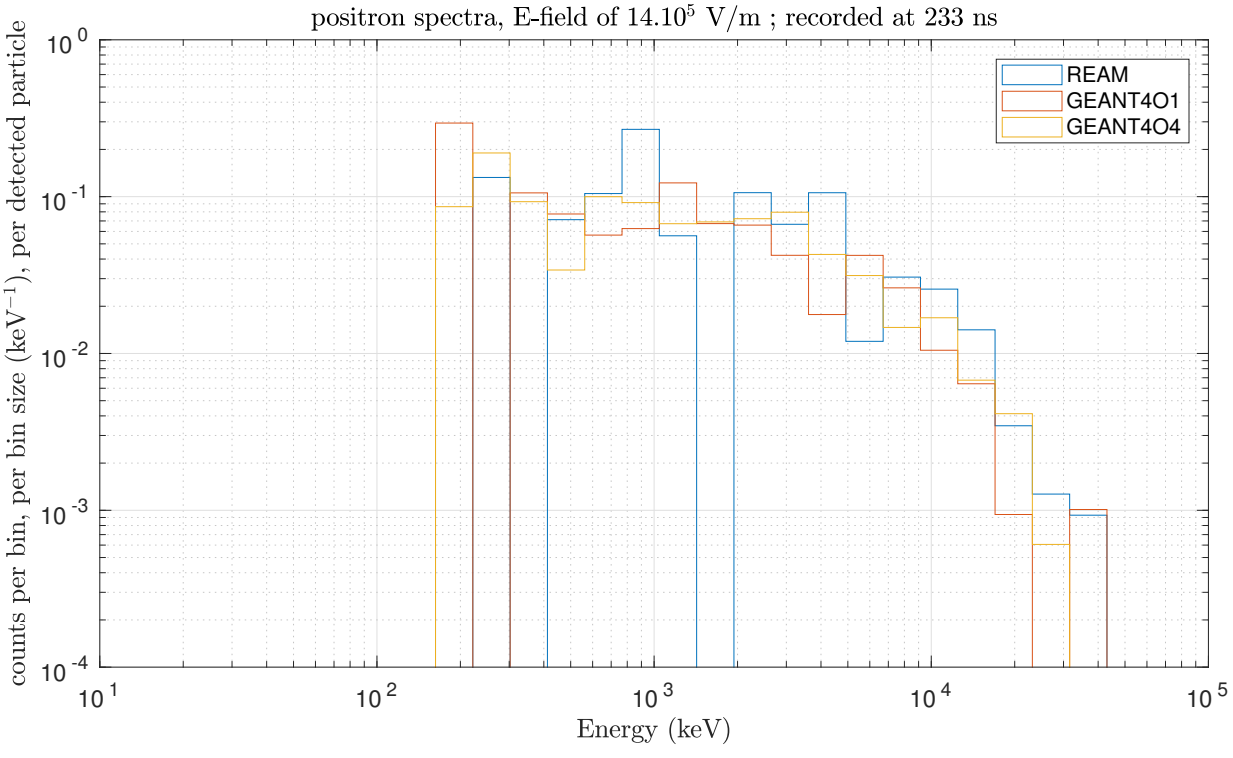

photon spectra, E-field of 28.10^5 V/m ; recorded at 130 ns
REAM
GEANT4O1
GEANT4O4
counts per bin, per bin size (keV^-1), per detected particle
Energy (keV)

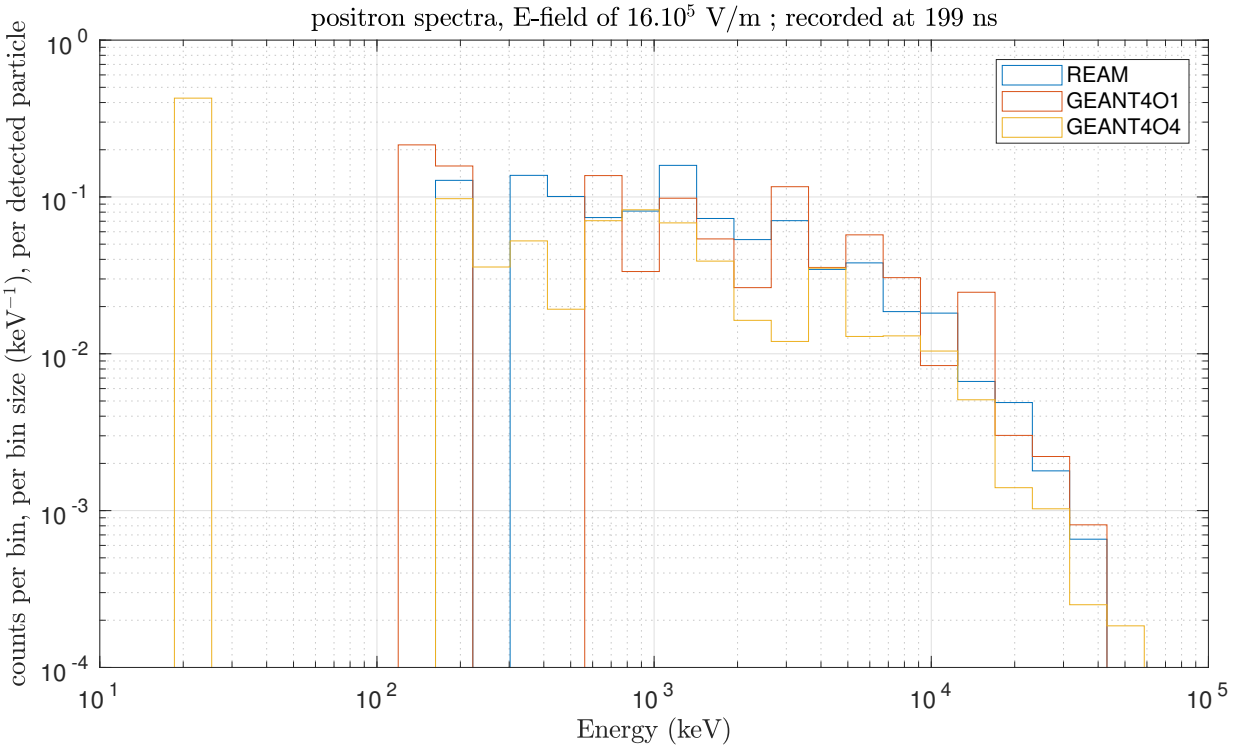

positron spectra, E-field of 6.10^5 V/m ; recorded at 1078 ns
REAM
GEANT4O1
GEANT4O4
counts per bin, per bin size (keV^-1), per detected particle
Energy (keV)

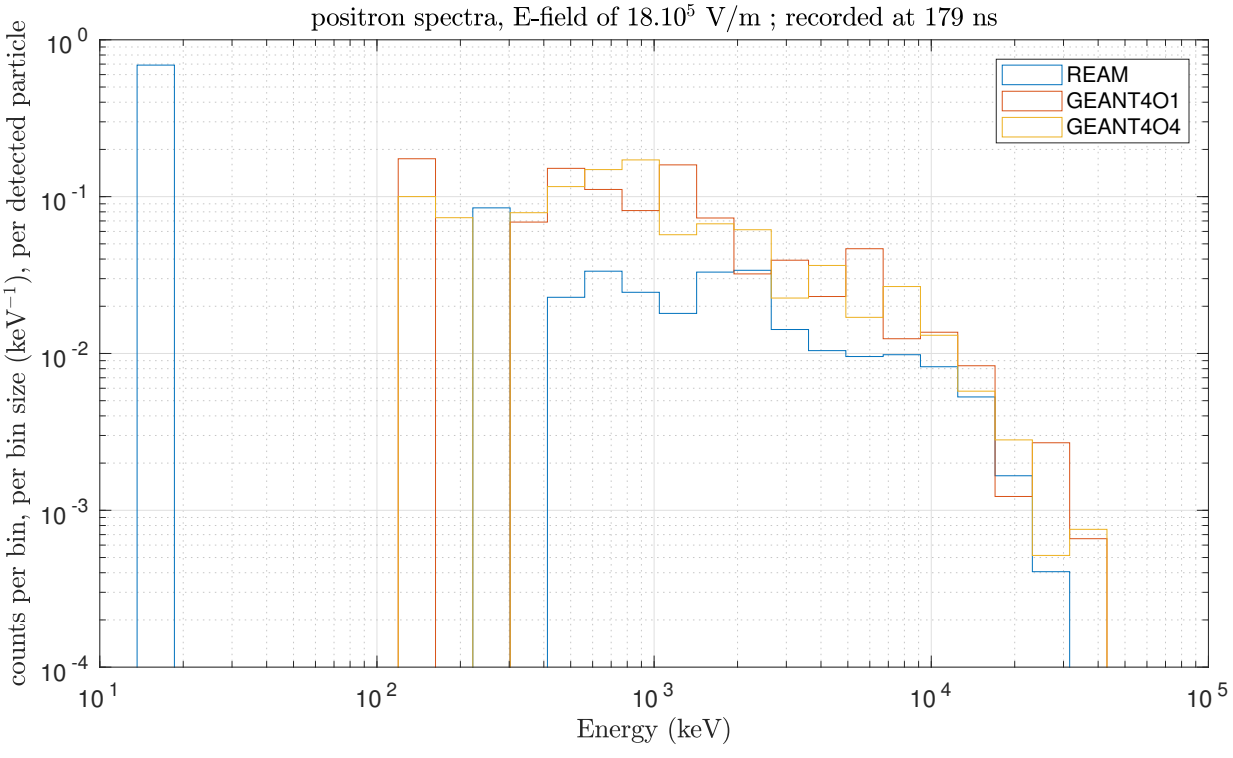

positron spectra, E-field of 8.10^5 V/m ; recorded at 522 ns
counts per bin, per bin size (keV^-1), per detected particle
Energy (keV)
REAM
GEANT4O1
GEANT4O4

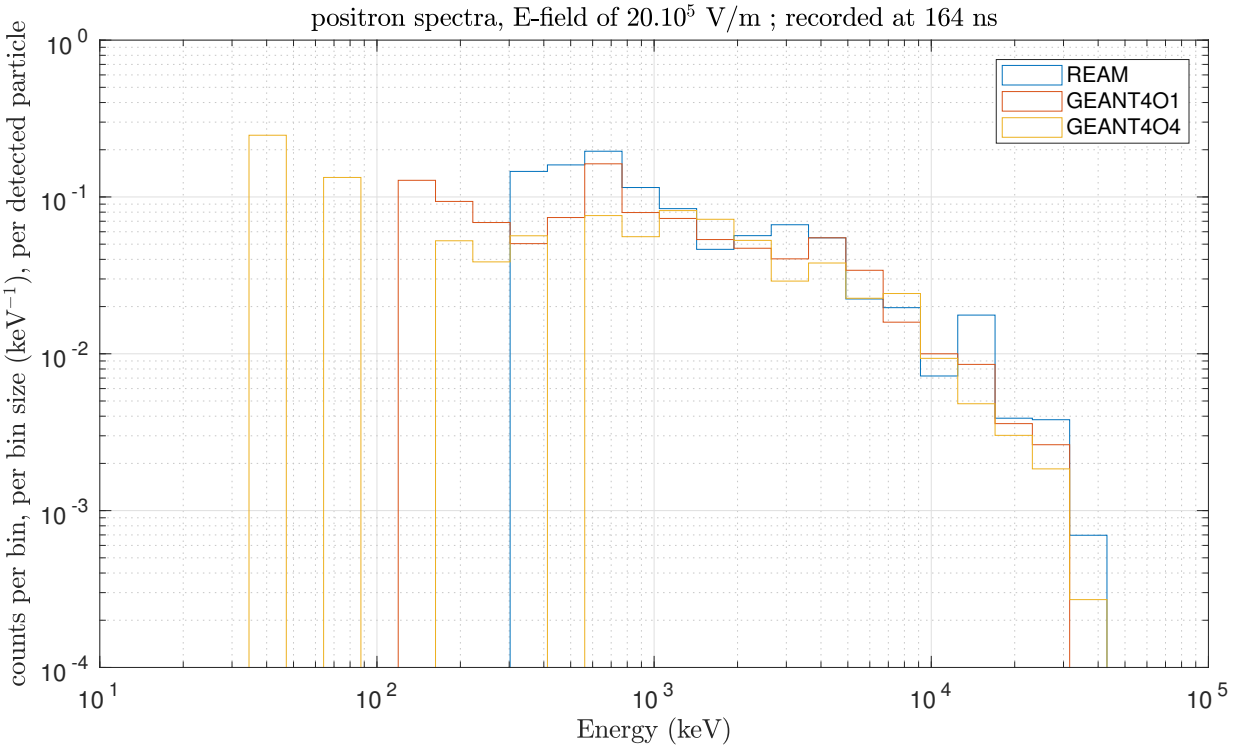

positron spectra, E-field of 10.10^5 V/m ; recorded at 351 ns
counts per bin, per bin size (keV^-1), per detected particle
Energy (keV)
REAM
GEANT4O1
GEANT4O4

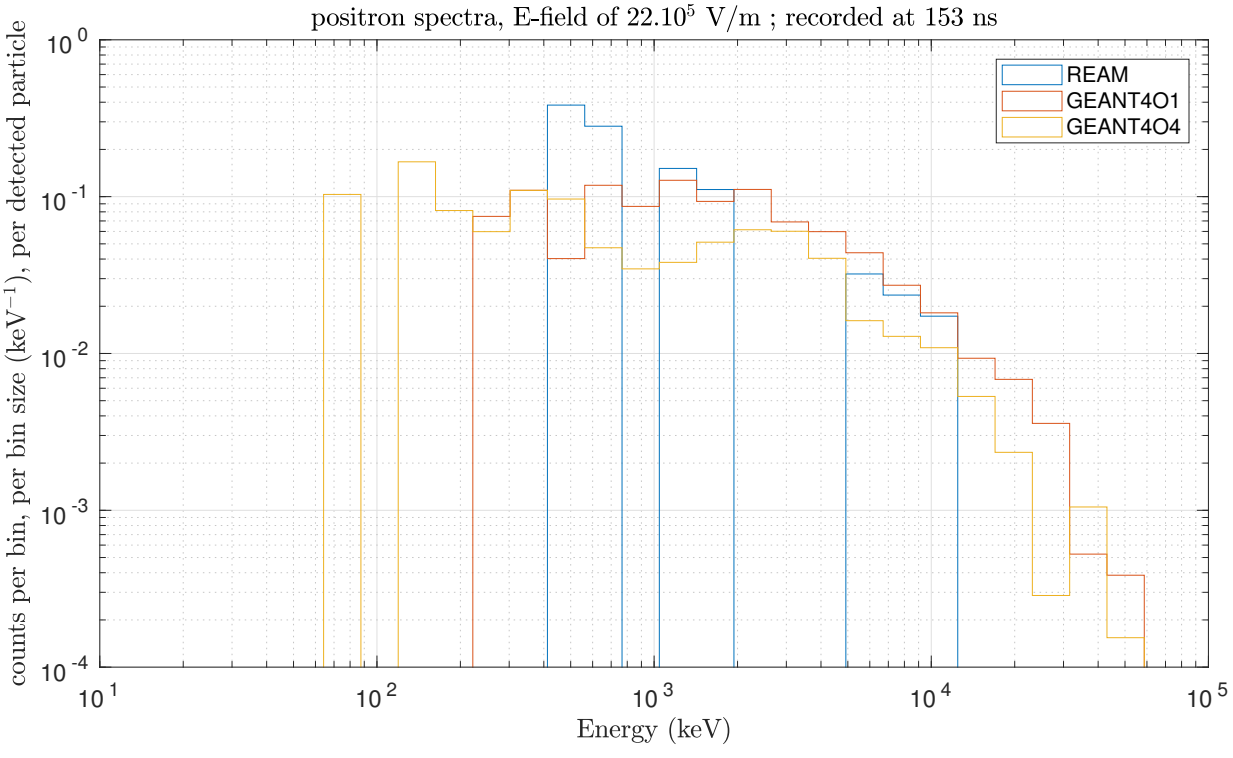

positron spectra, E-field of 12.10^5 V/m ; recorded at 277 ns
counts per bin, per bin size (keV^-1), per detected particle
Energy (keV)
REAM
GEANT4O1
GEANT4O4

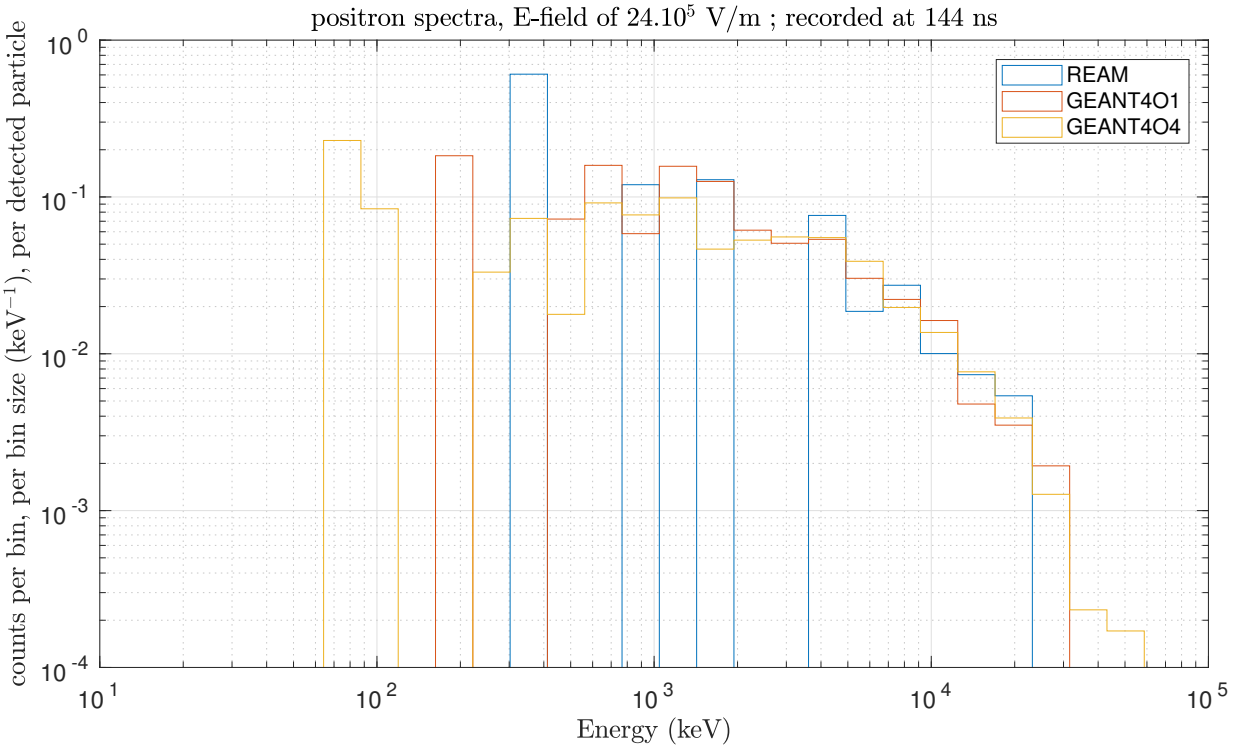

positron spectra, E-field of 14.10^5 V/m ; recorded at 233 ns
counts per bin, per bin size (keV^-1), per detected particle
Energy (keV)
REAM
GEANT4O1
GEANT4O4

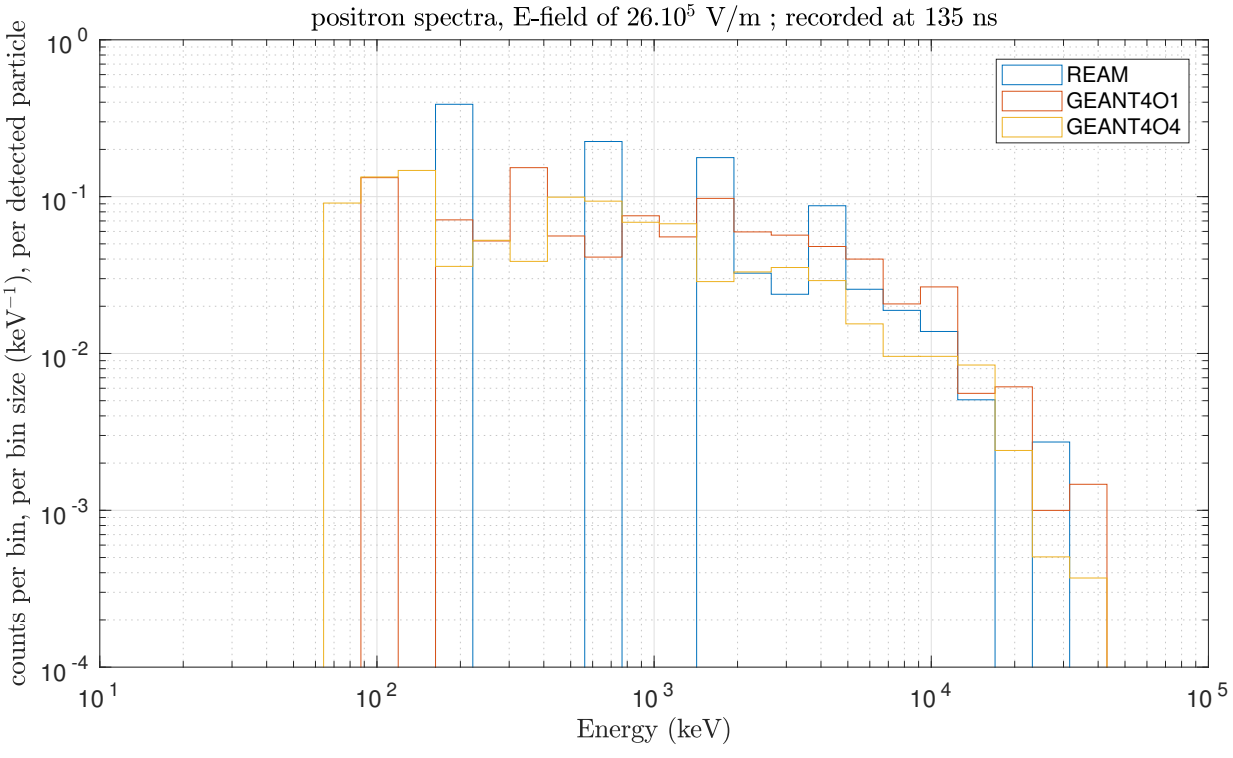

positron spectra, E-field of 16.10^5 V/m ; recorded at 199 ns
counts per bin, per bin size (keV^-1), per detected particle
Energy (keV)
REAM
GEANT4O1
GEANT4O4

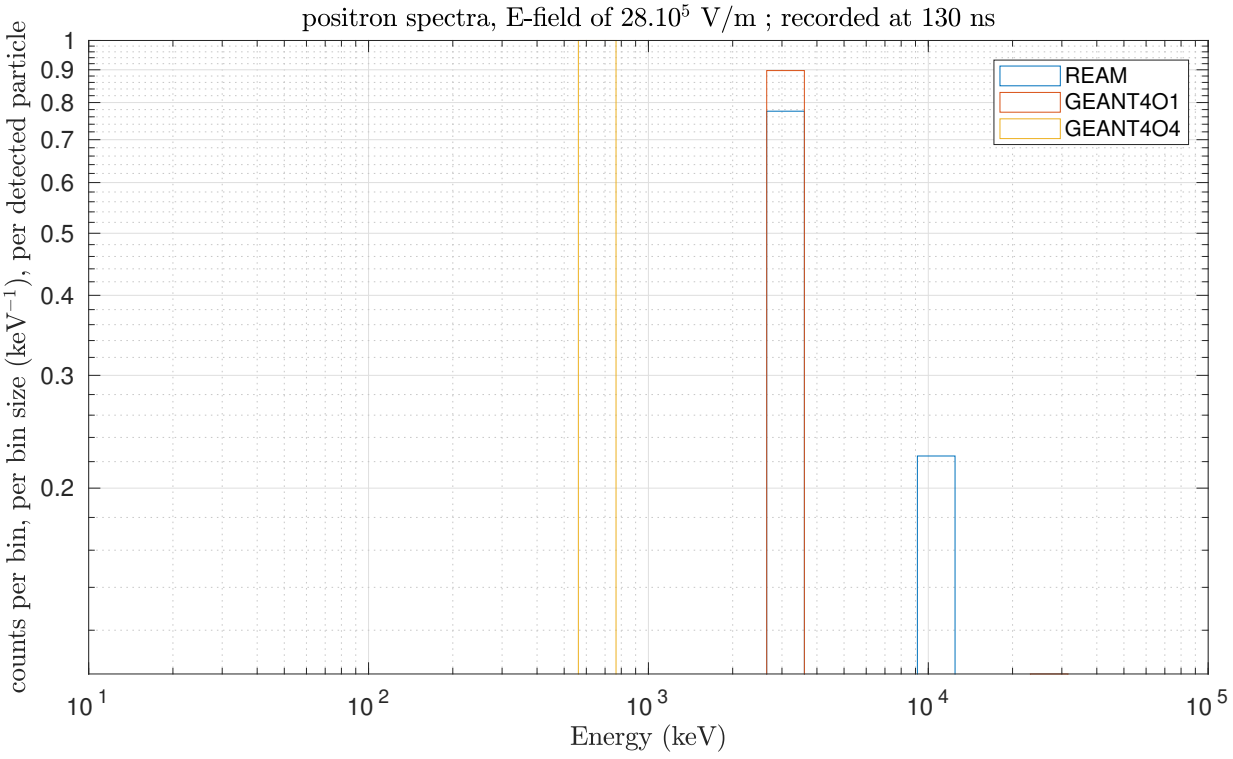

positron spectra, E-field of 18.10^5 V/m ; recorded at 179 ns
counts per bin, per bin size (keV^-1), per detected particle
Energy (keV)
REAM
GEANT4O1
GEANT4O4


positron spectra, E-field of 20.10^5 V/m ; recorded at 164 ns
REAM
GEANT4O1
GEANT4O4
counts per bin, per bin size (keV^-1), per detected particle
Energy (keV)

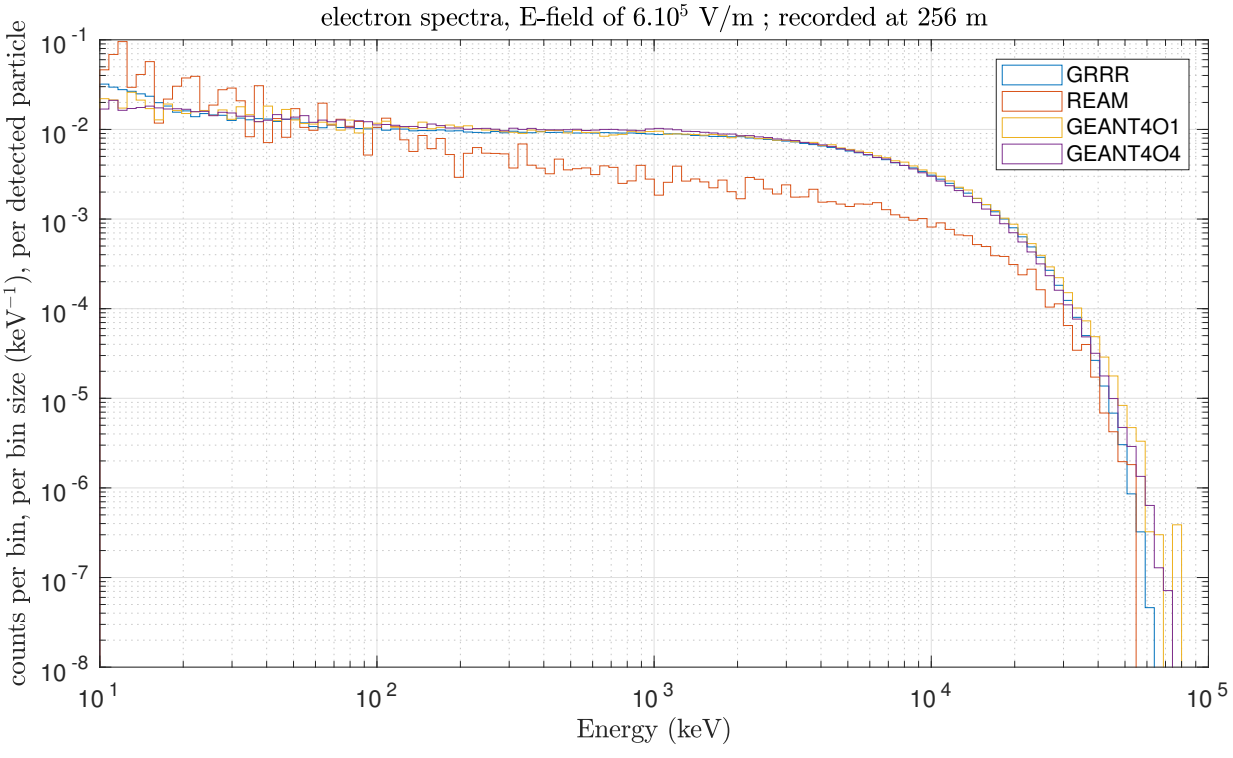

positron spectra, E-field of 22.10^5 V/m ; recorded at 153 ns
REAM
GEANT4O1
GEANT4O4
counts per bin, per bin size (keV^-1), per detected particle
Energy (keV)

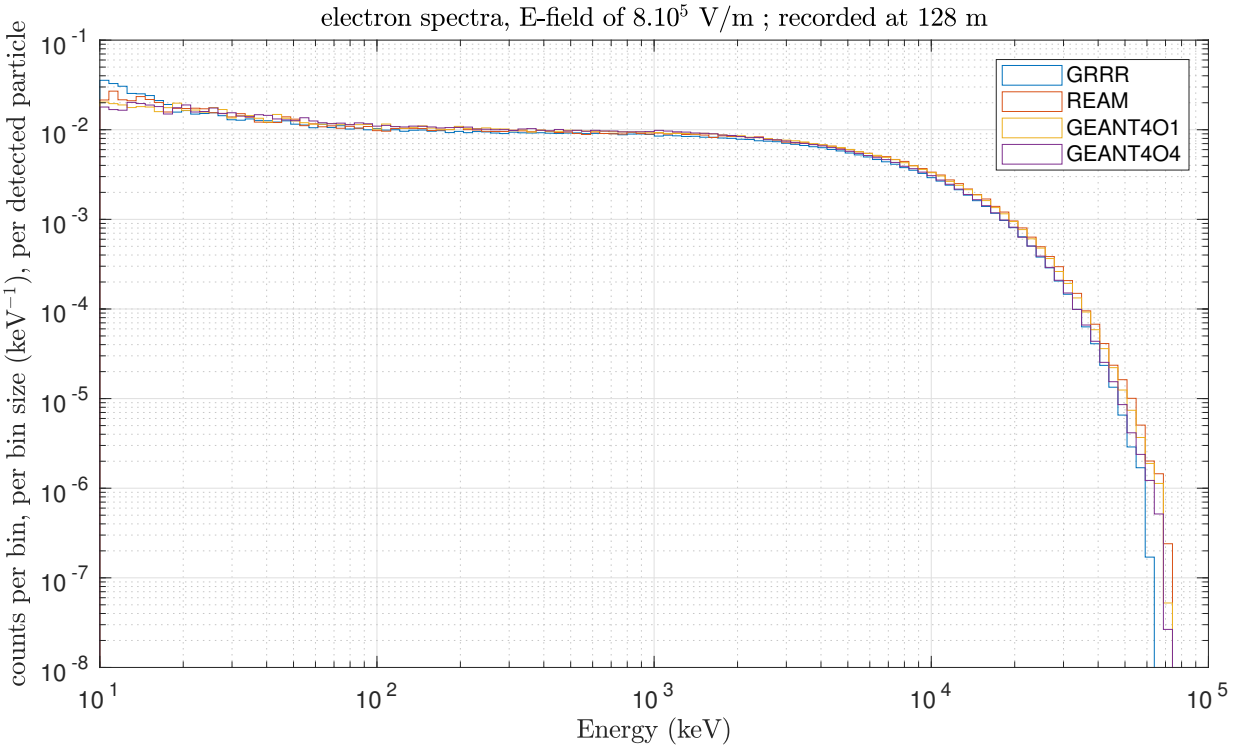

positron spectra, E-field of 24.10^5 V/m ; recorded at 144 ns
counts per bin, per bin size (keV^-1), per detected particle
Energy (keV)
REAM
GEANT4O1
GEANT4O4

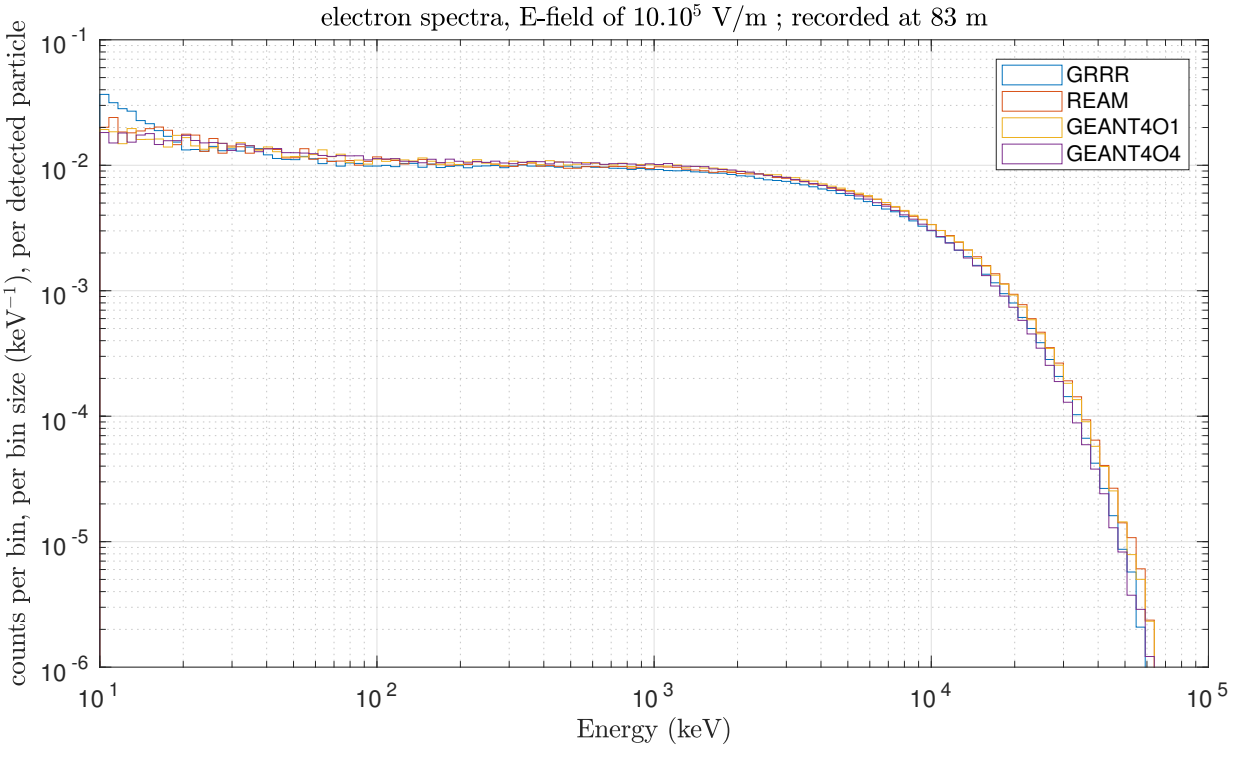

positron spectra, E-field of 26.10^5 V/m ; recorded at 135 ns
counts per bin, per bin size (keV^-1), per detected particle
Energy (keV)
REAM
GEANT4O1
GEANT4O4

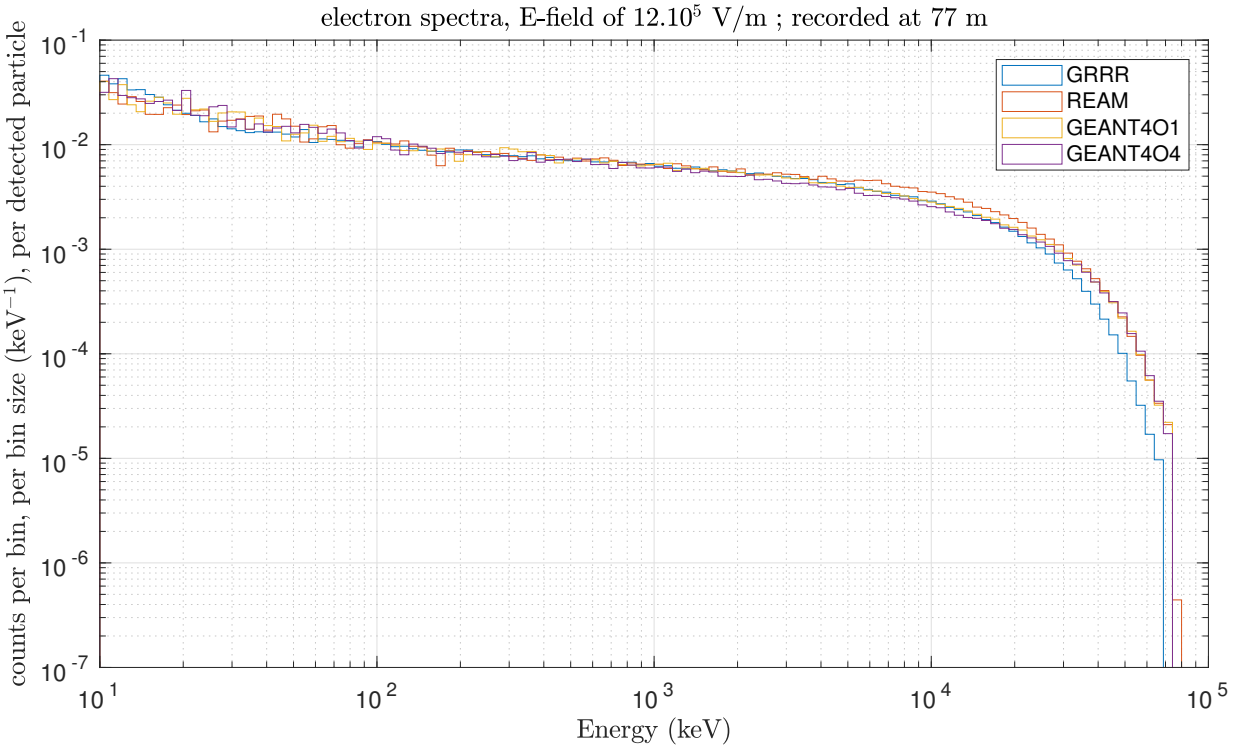


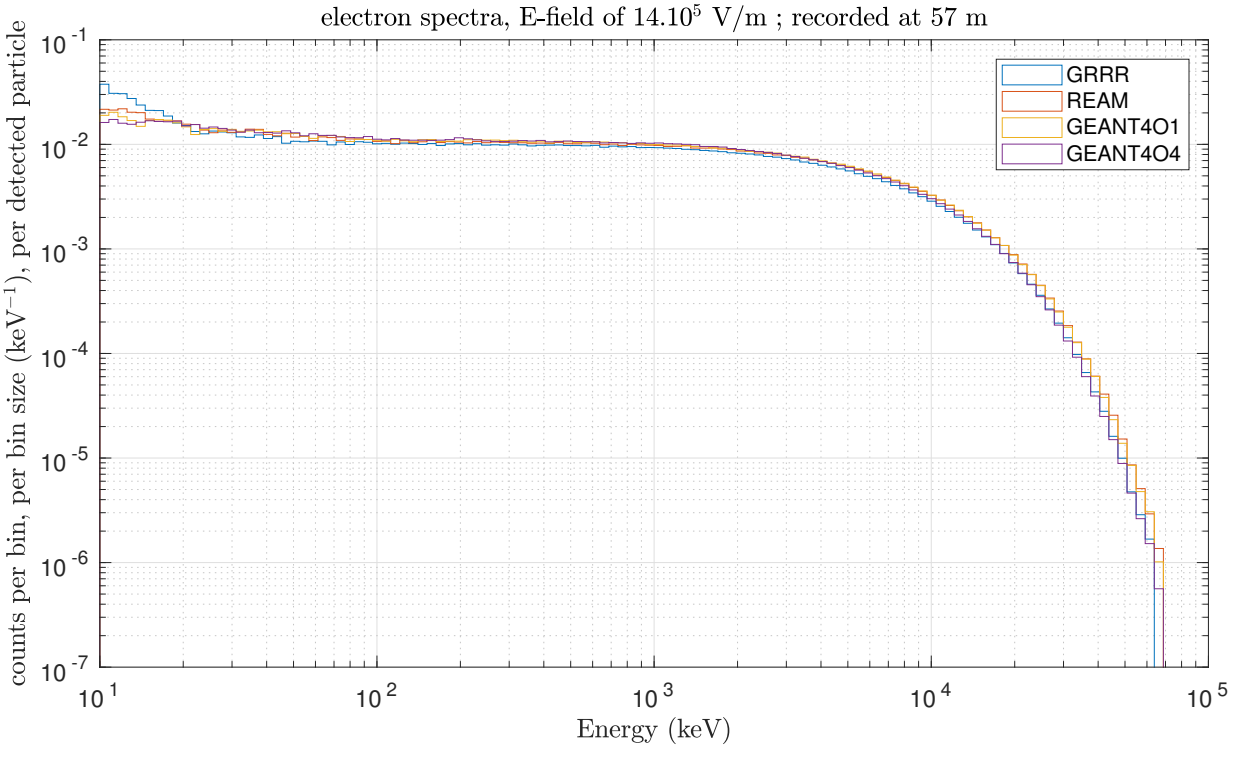
6.2 Distance Record

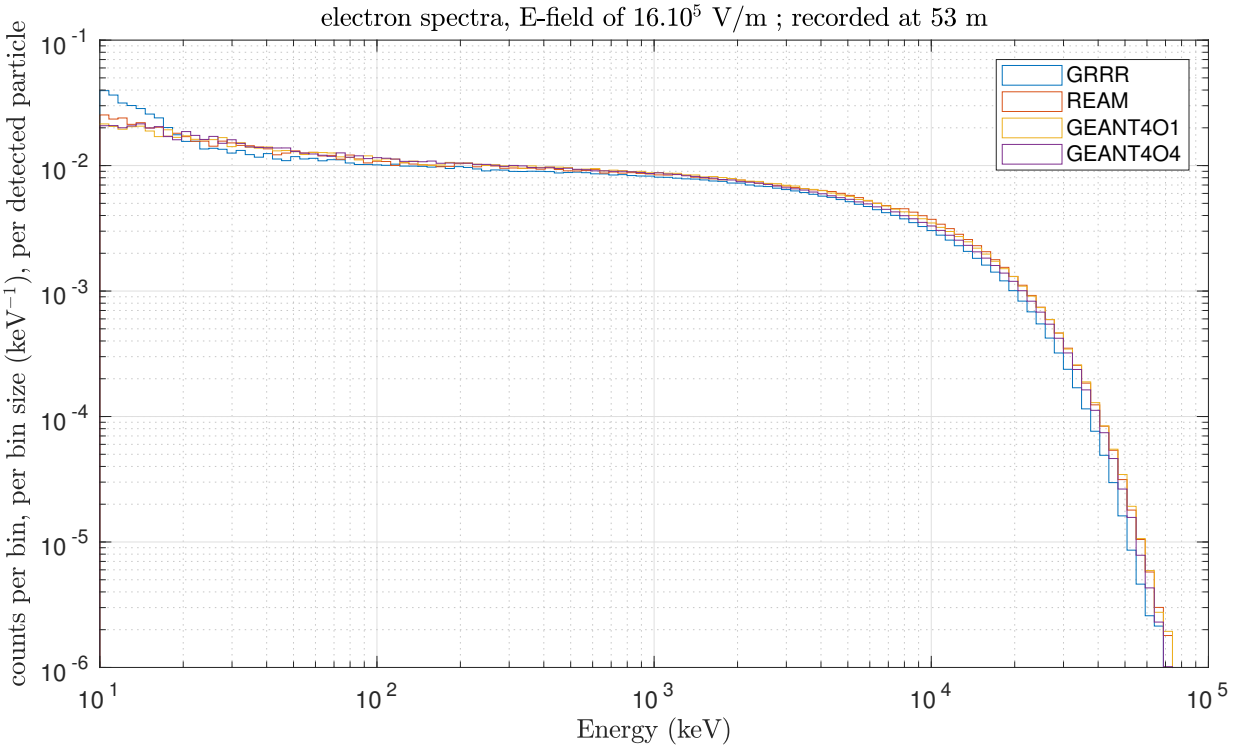


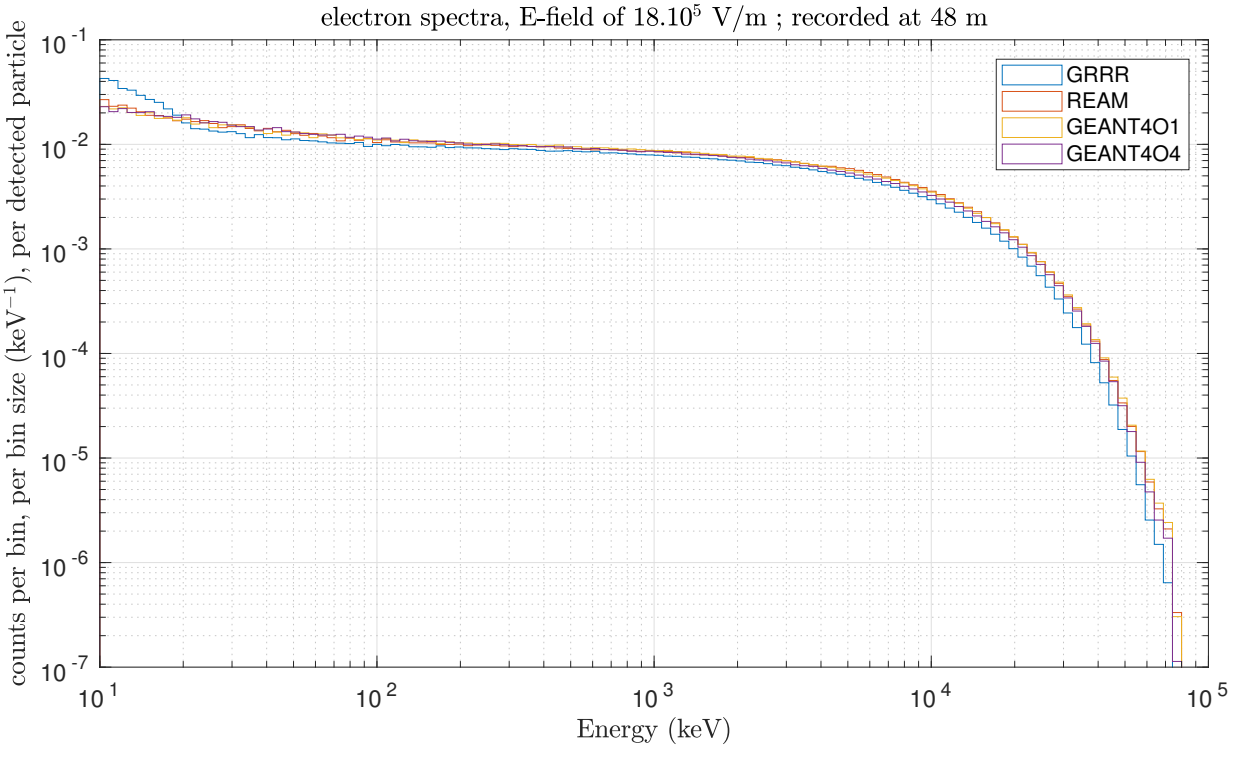

electron spectra, E-field of 8.10^5 V/m ; recorded at 128 m
counts per bin, per bin size (keV^-1), per detected particle
Energy (keV)
GRRR
REAM
GEANT4O1
GEANT4O4

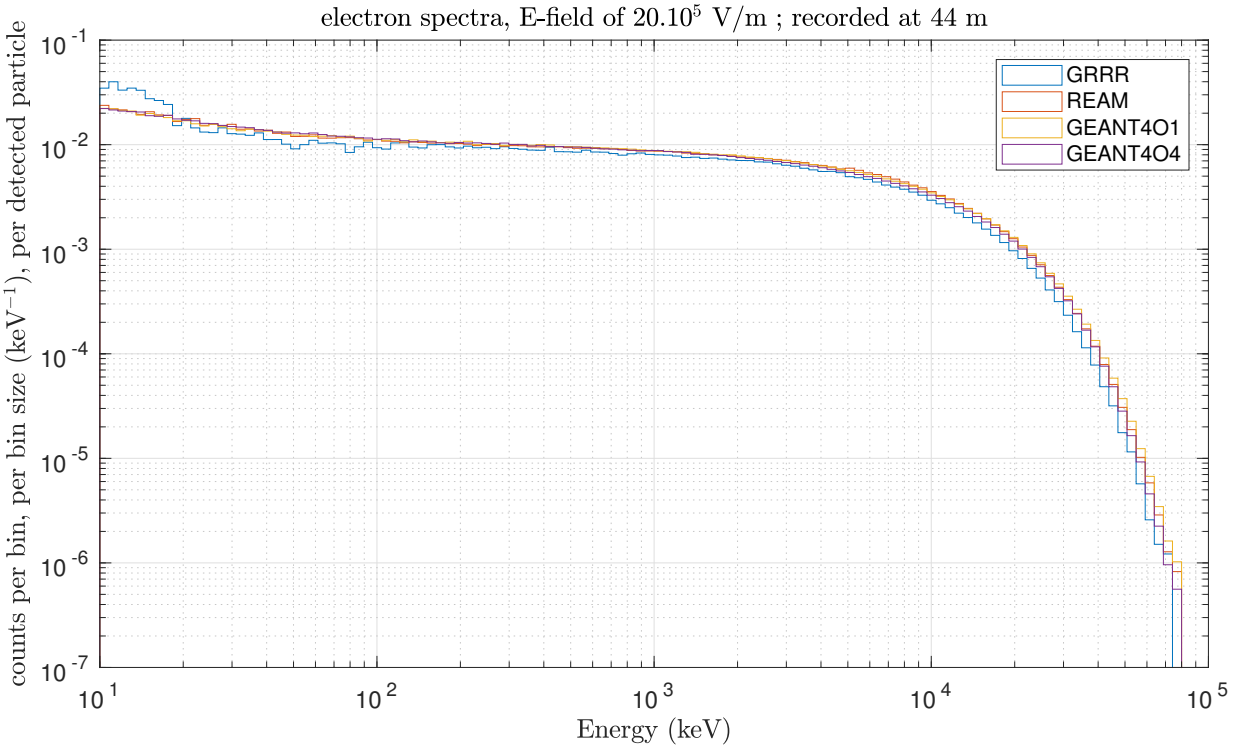

electron spectra, E-field of 10.10^5 V/m ; recorded at 83 m
counts per bin, per bin size (keV^-1), per detected particle
Energy (keV)
GRRR
REAM
GEANT4O1
GEANT4O4

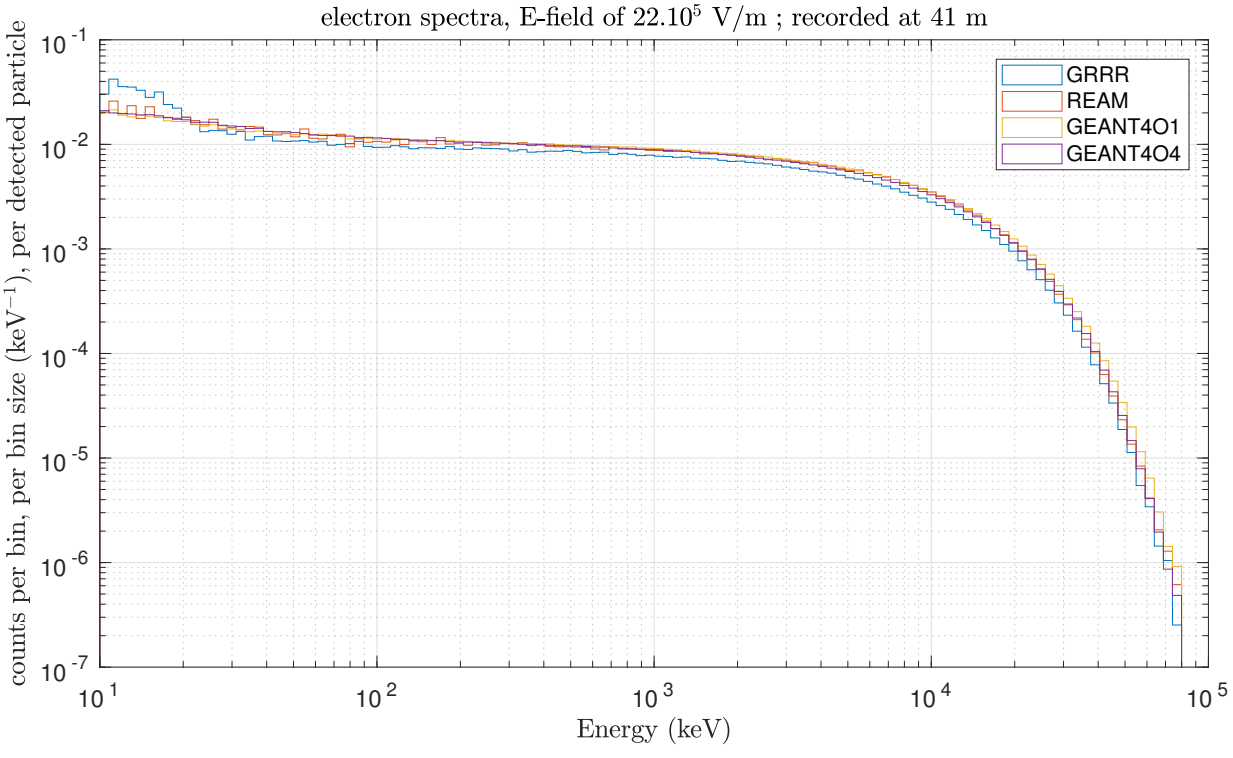

electron spectra, E-field of 12.10^5 V/m ; recorded at 77 m
counts per bin, per bin size (keV^-1), per detected particle
Energy (keV)
GRRR
REAM
GEANT4O1
GEANT4O4

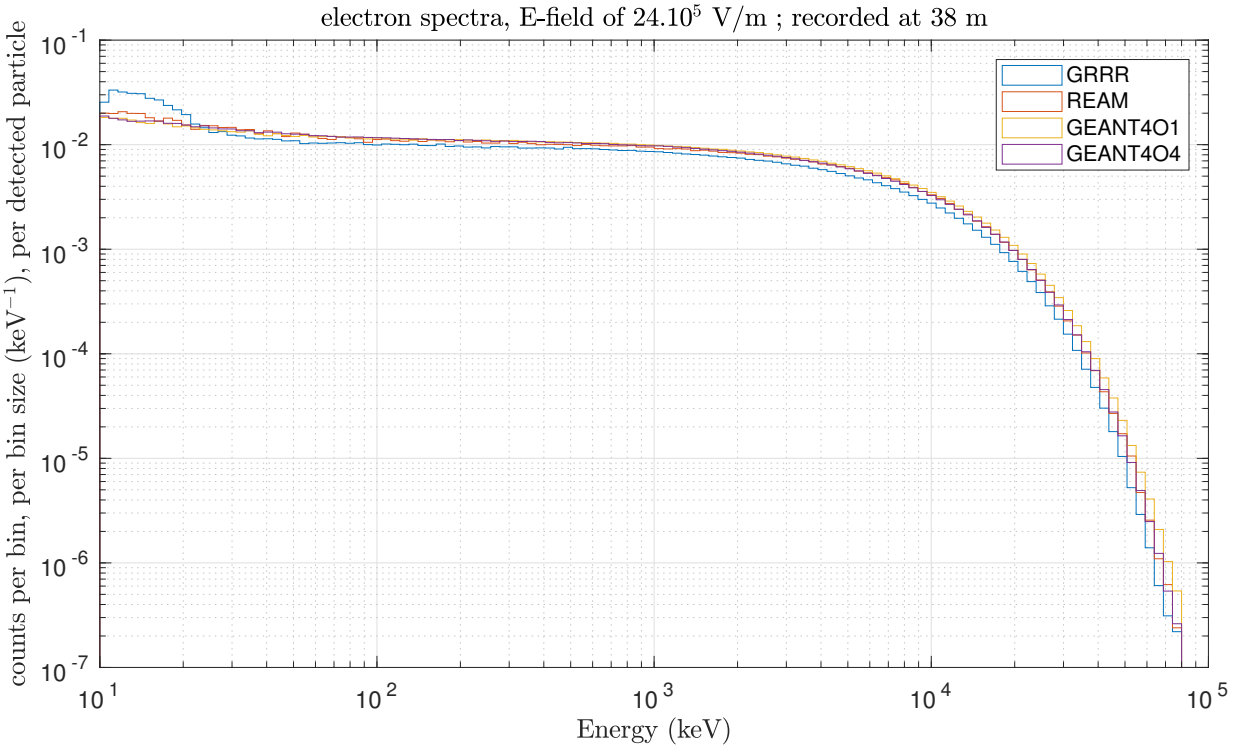

electron spectra, E-field of 14.10^5 V/m ; recorded at 57 m
counts per bin, per bin size (keV^-1), per detected particle
Energy (keV)
GRRR
REAM
GEANT4O1
GEANT4O4

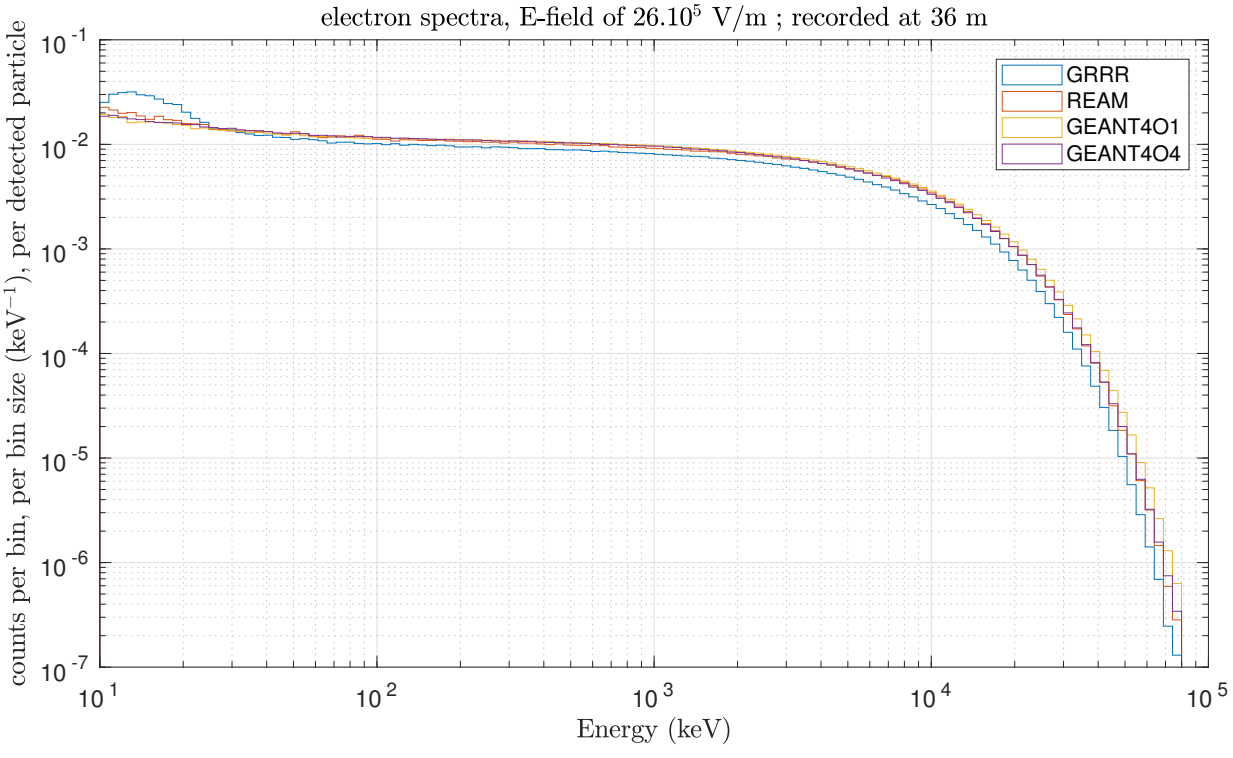

electron spectra, E-field of 16.10^5 V/m ; recorded at 53 m
counts per bin, per bin size (keV^-1), per detected particle
Energy (keV)
GRRR
REAM
GEANT4O1
GEANT4O4

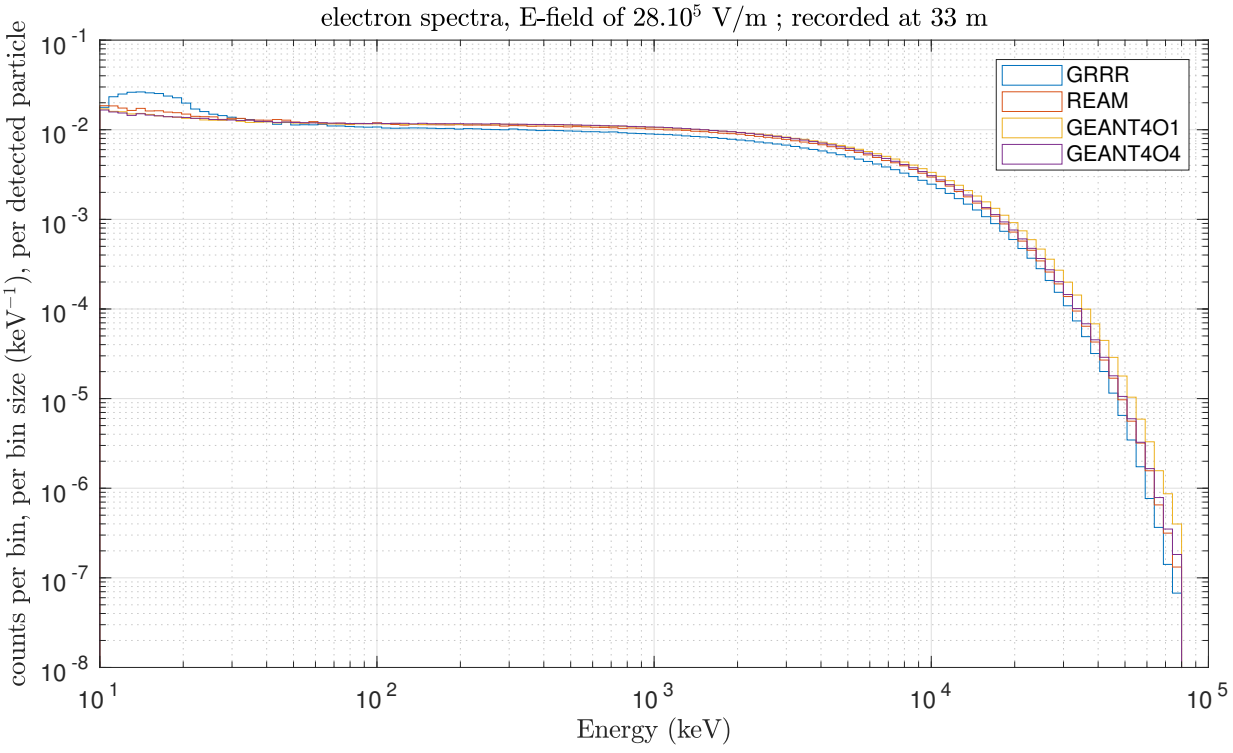

electron spectra, E-field of 18.10^5 V/m ; recorded at 48 m
counts per bin, per bin size (keV^-1), per detected particle
Energy (keV)
GRRR
REAM
GEANT4O1
GEANT4O4

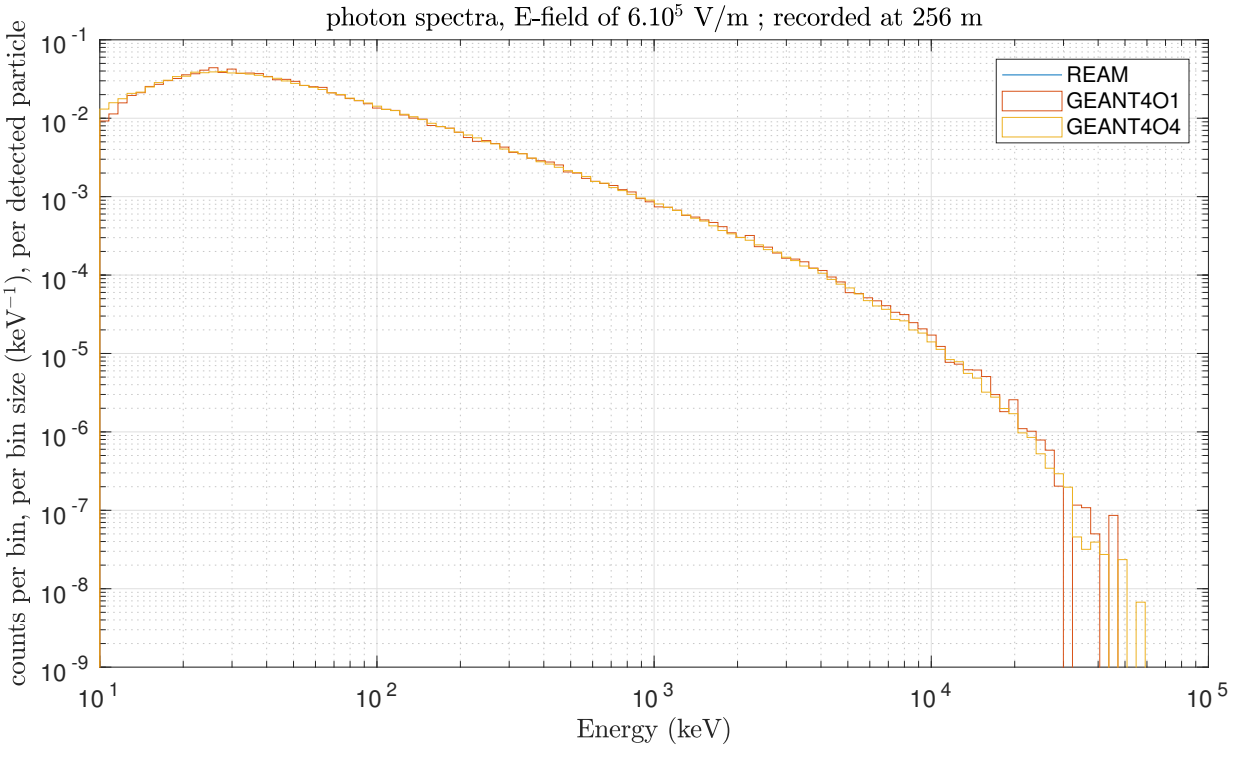

electron spectra, E-field of 20.10^5 V/m ; recorded at 44 m
counts per bin, per bin size (keV^-1), per detected particle
Energy (keV)
GRRR
REAM
GEANT4O1
GEANT4O4

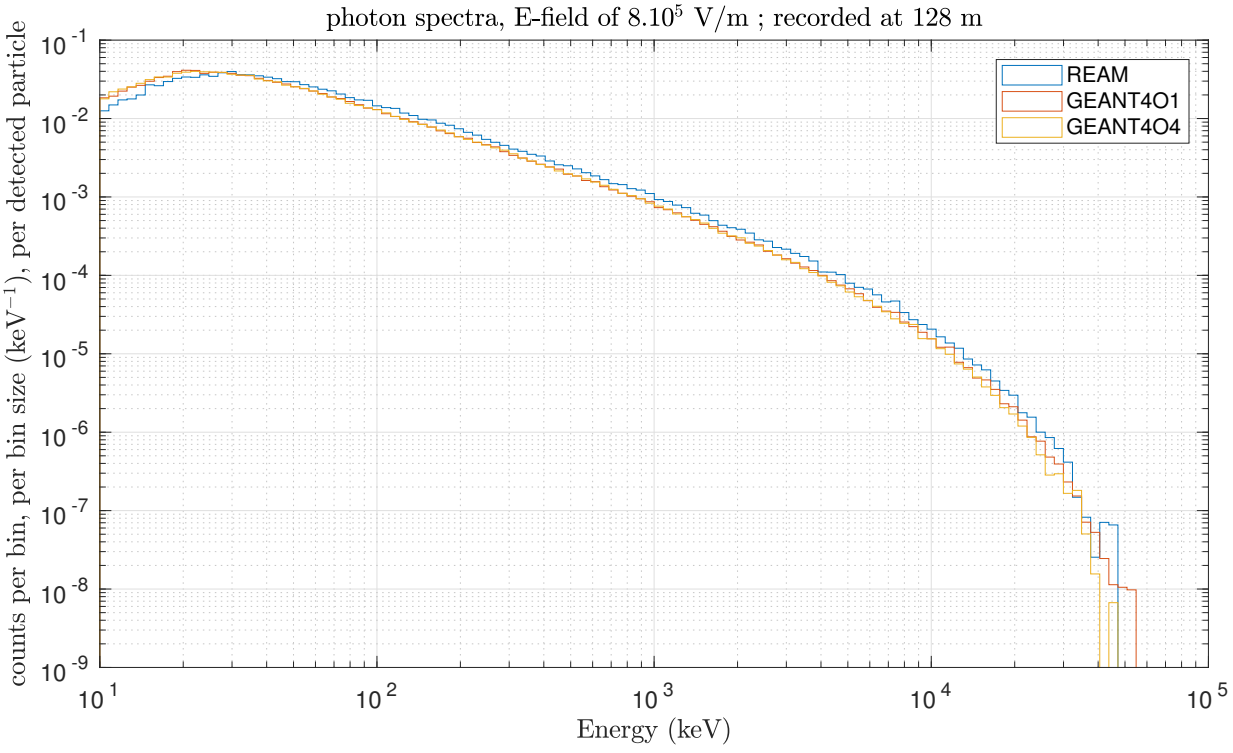

electron spectra, E-field of 22.10^5 V/m ; recorded at 41 m
counts per bin, per bin size (keV^-1), per detected particle
Energy (keV)
GRRR
REAM
GEANT4O1
GEANT4O4

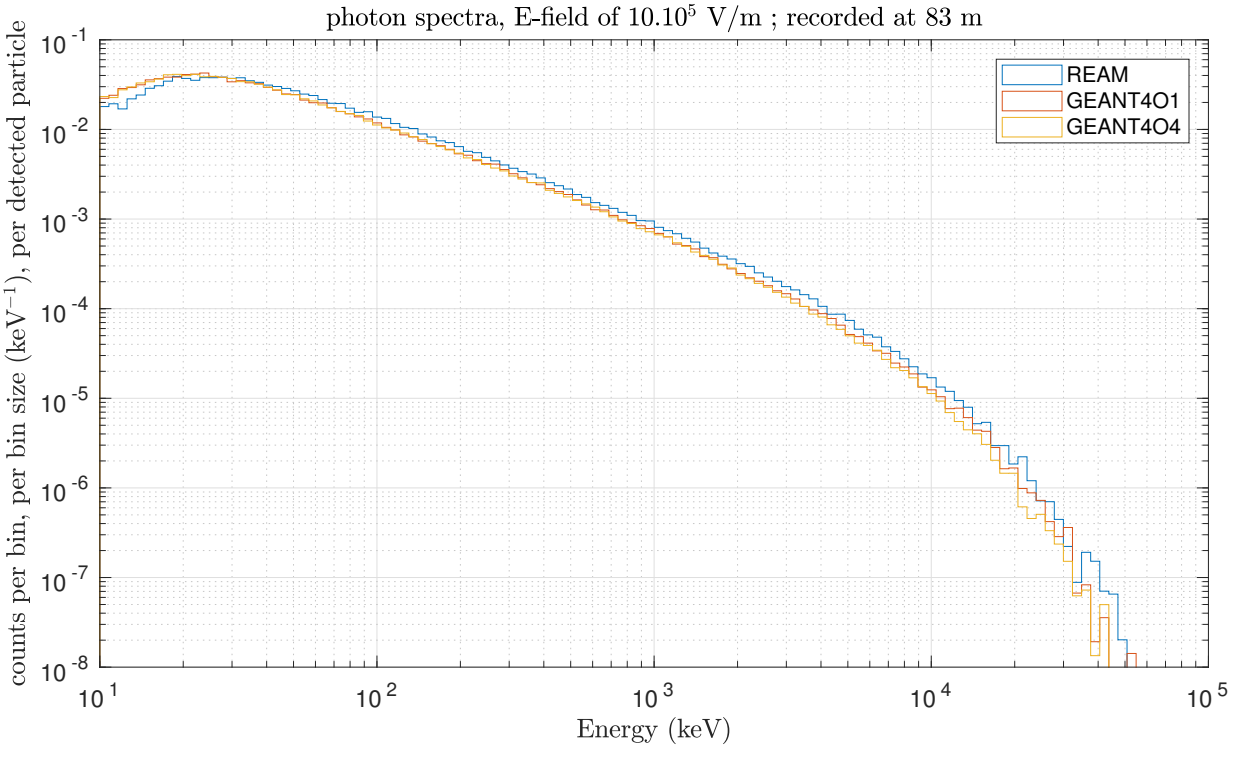

electron spectra, E-field of 24.10^5 V/m ; recorded at 38 m
counts per bin, per bin size (keV^-1), per detected particle
Energy (keV)
GRRR
REAM
GEANT4O1
GEANT4O4

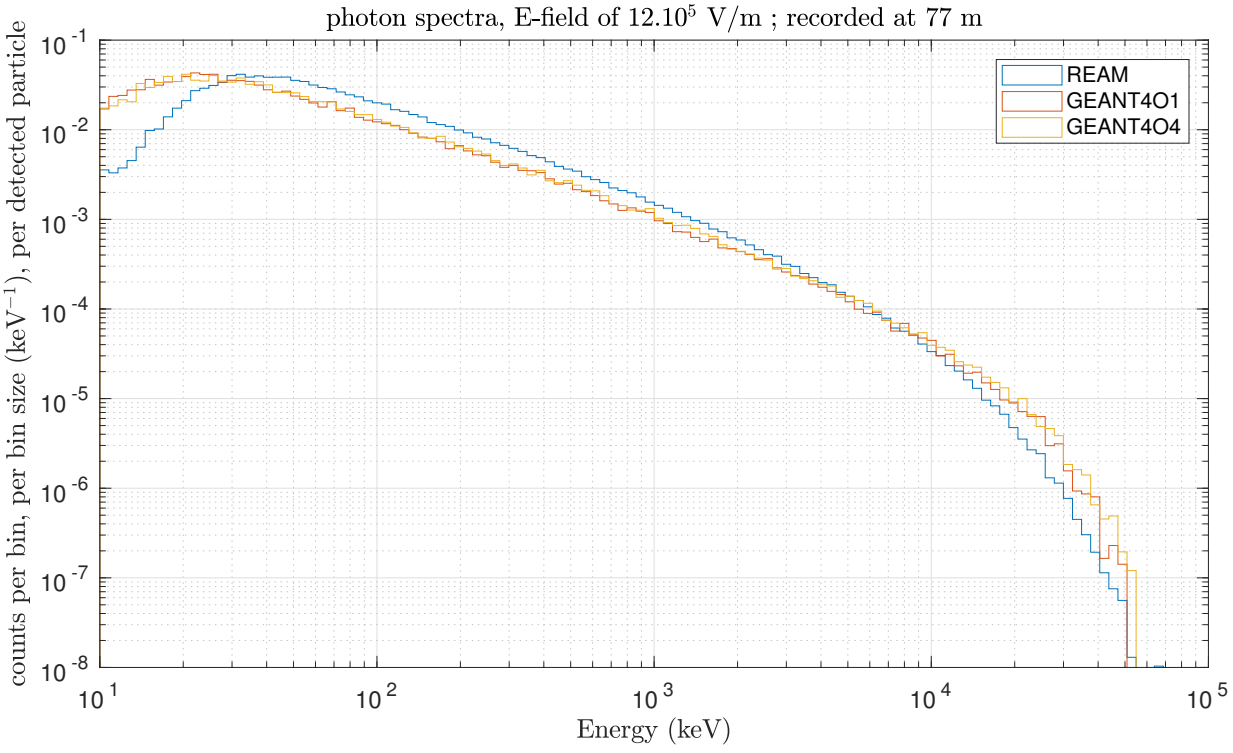

electron spectra, E-field of 26.10^5 V/m ; recorded at 36 m
counts per bin, per bin size (keV^-1), per detected particle
Energy (keV)
GRRR
REAM
GEANT4O1
GEANT4O4

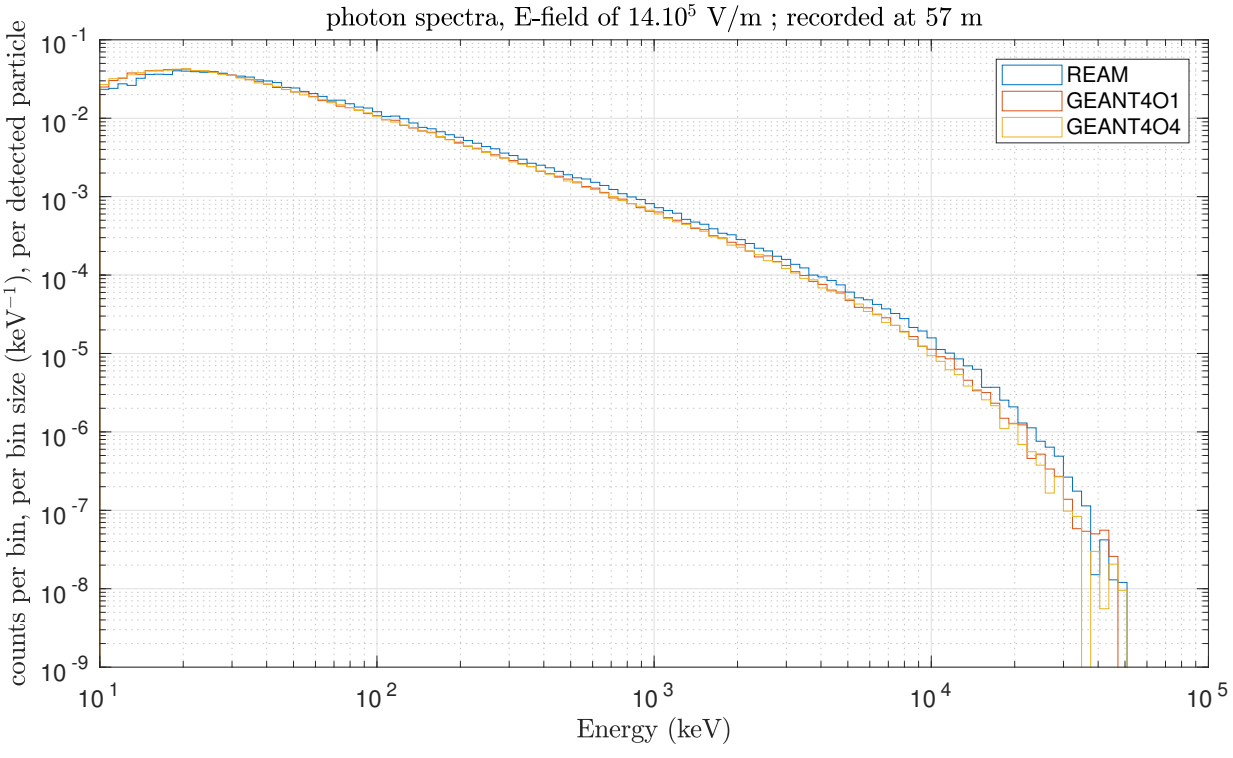

electron spectra, E-field of 28.10^5 V/m ; recorded at 33 m
GRRR
REAM
GEANT4O1
GEANT4O4
counts per bin, per bin size (keV^-1), per detected particle
Energy (keV)

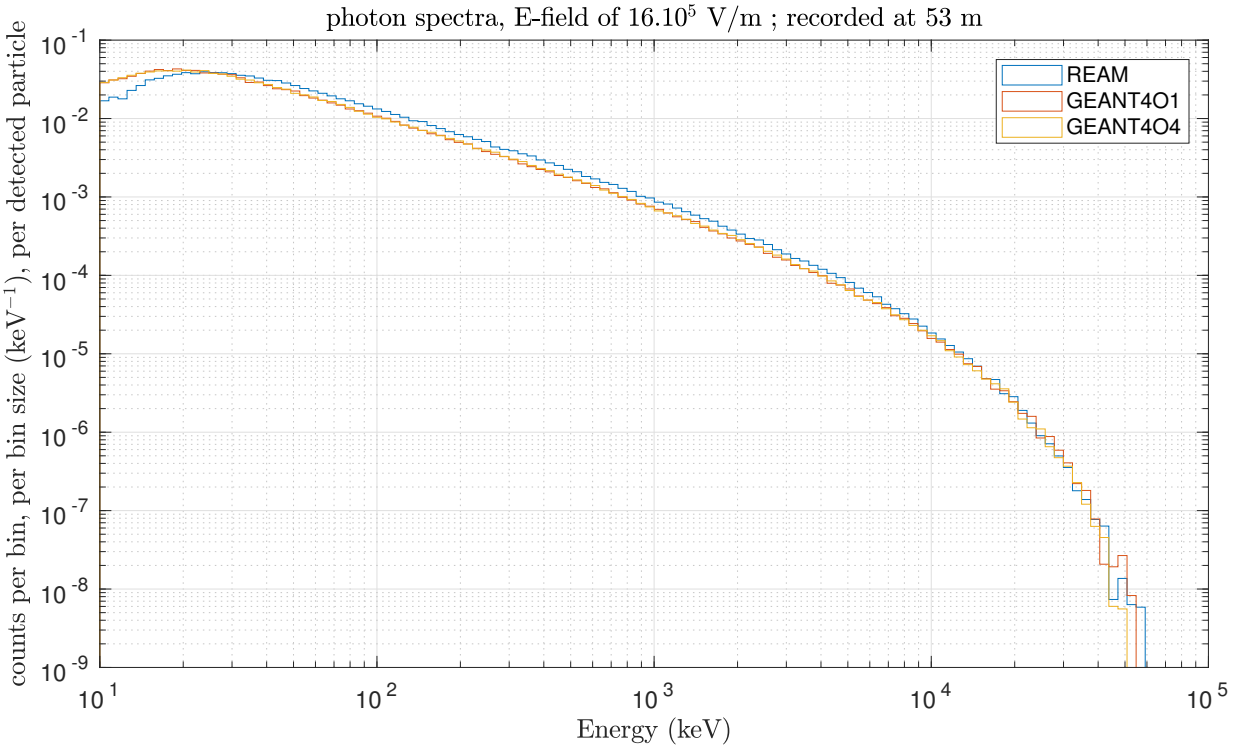

photon spectra, E-field of 6.10^5 V/m ; recorded at 256 m
REAM
GEANT4O1
GEANT4O4
counts per bin, per bin size (keV^-1), per detected particle
Energy (keV)

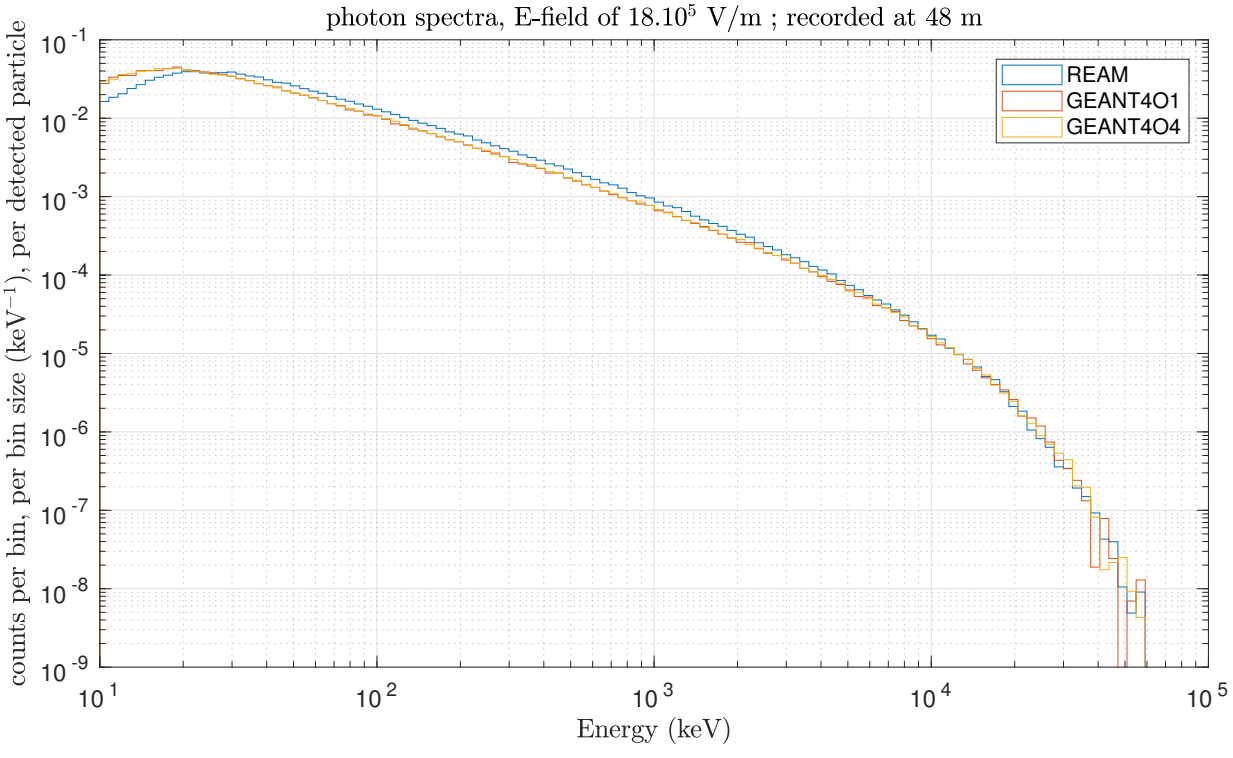

photon spectra, E-field of 8.10^5 V/m ; recorded at 128 m
counts per bin, per bin size (keV^-1), per detected particle
Energy (keV)
REAM
GEANT4O1
GEANT4O4

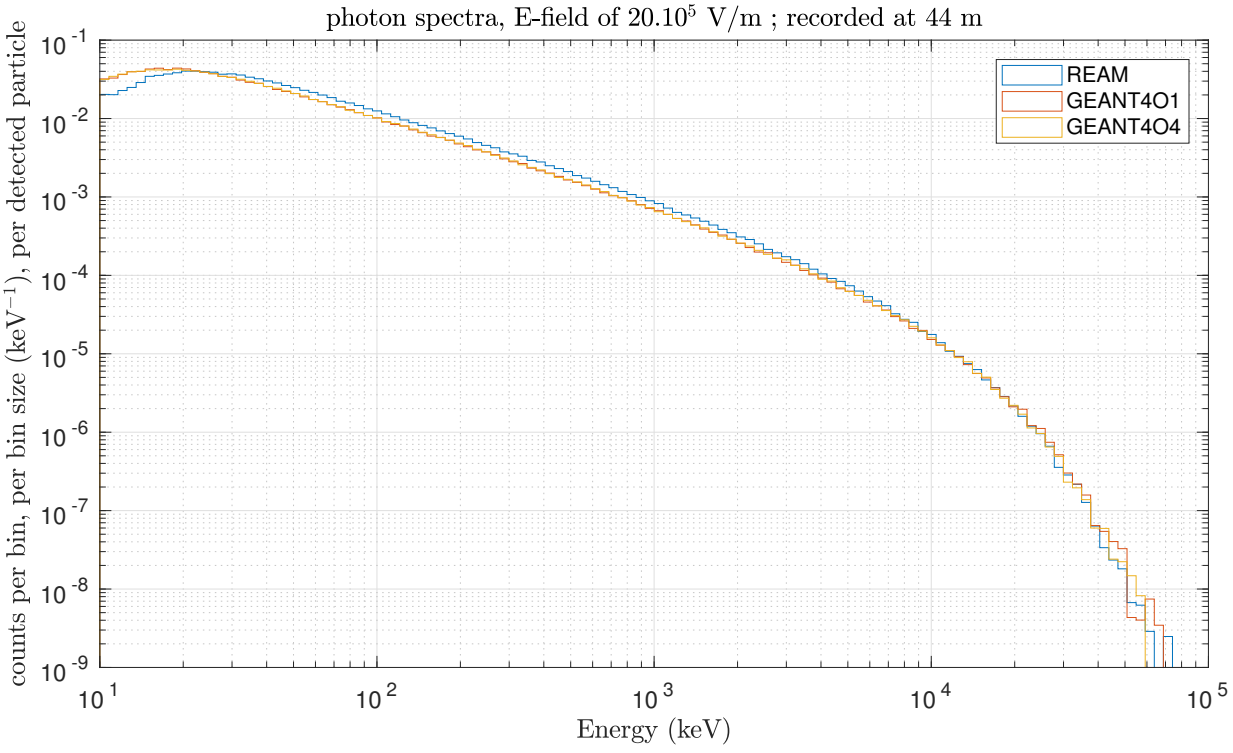

photon spectra, E-field of 10.10^5 V/m ; recorded at 83 m
counts per bin, per bin size (keV^-1), per detected particle
Energy (keV)
REAM
GEANT4O1
GEANT4O4

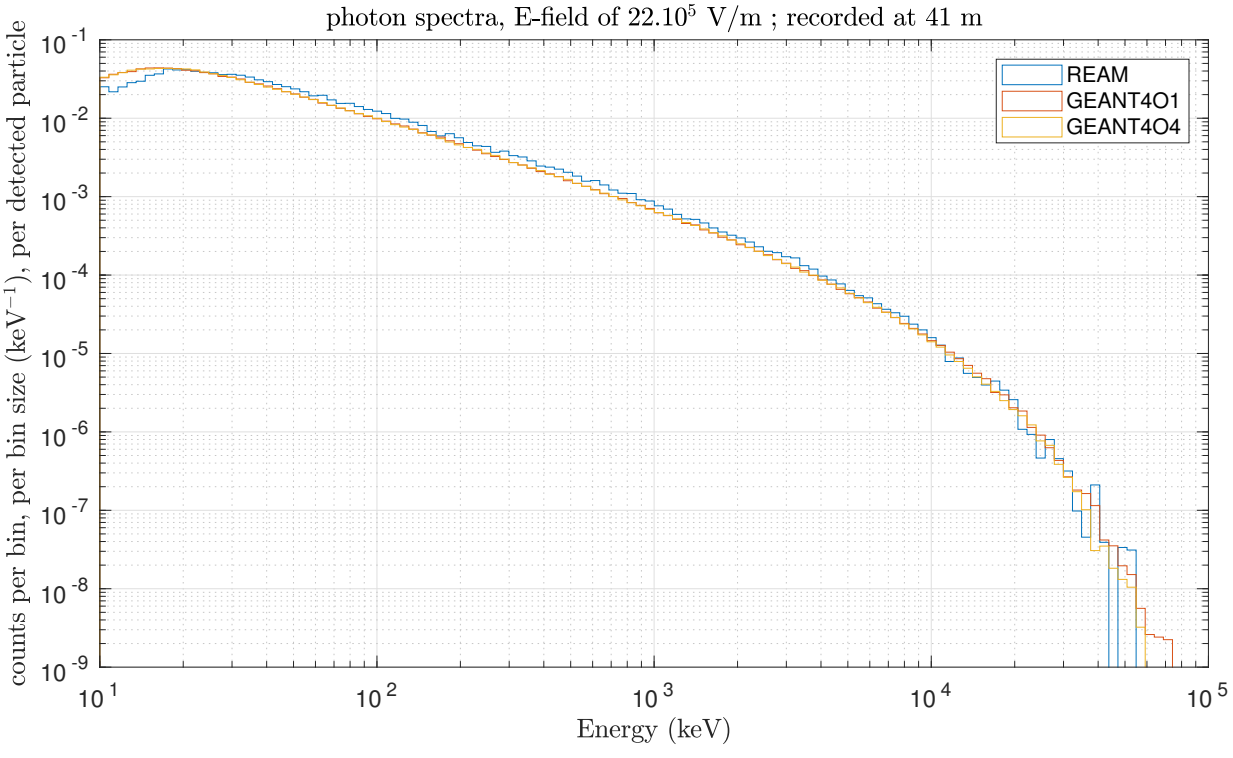

photon spectra, E-field of 12.10^5 V/m ; recorded at 77 m
REAM
GEANT4O1
GEANT4O4
counts per bin, per bin size (keV^-1), per detected particle
Energy (keV)

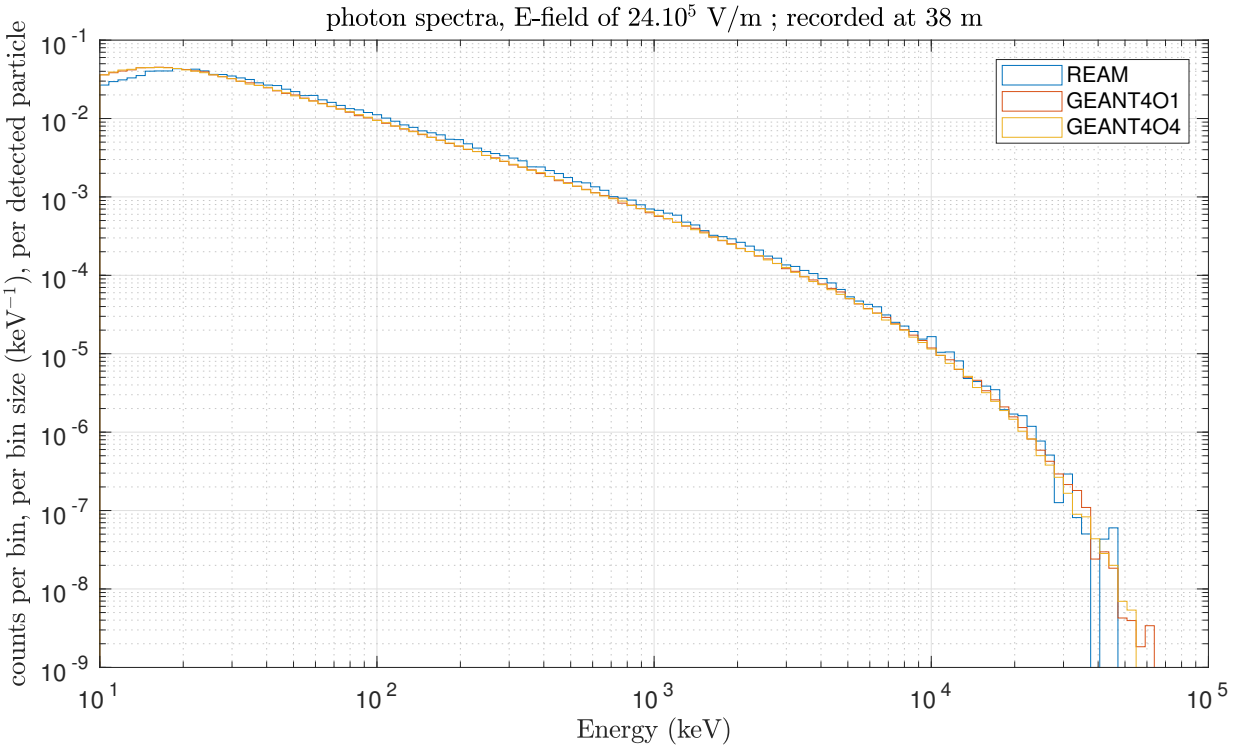

photon spectra, E-field of 14.10^5 V/m ; recorded at 57 m
REAM
GEANT4O1
GEANT4O4
counts per bin, per bin size (keV^-1), per detected particle
Energy (keV)

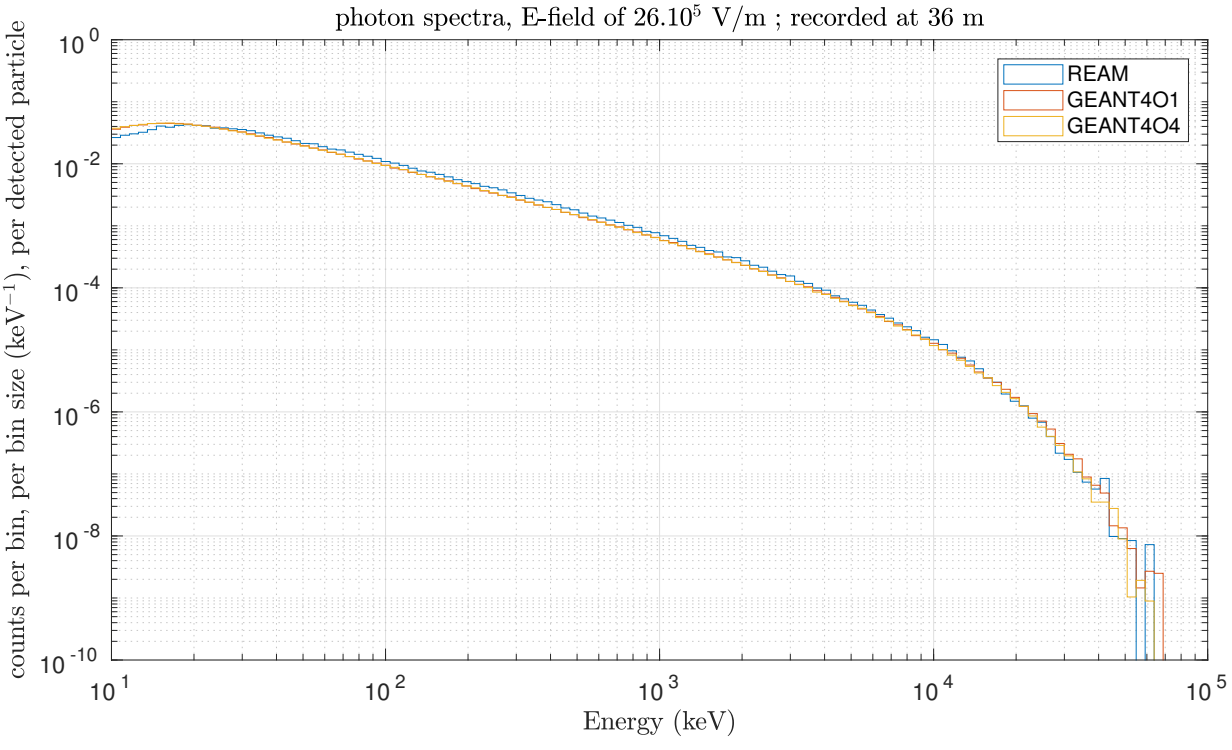

photon spectra, E-field of 16.10^5 V/m ; recorded at 53 m
counts per bin, per bin size (keV^-1), per detected particle
Energy (keV)
REAM
GEANT4O1
GEANT4O4

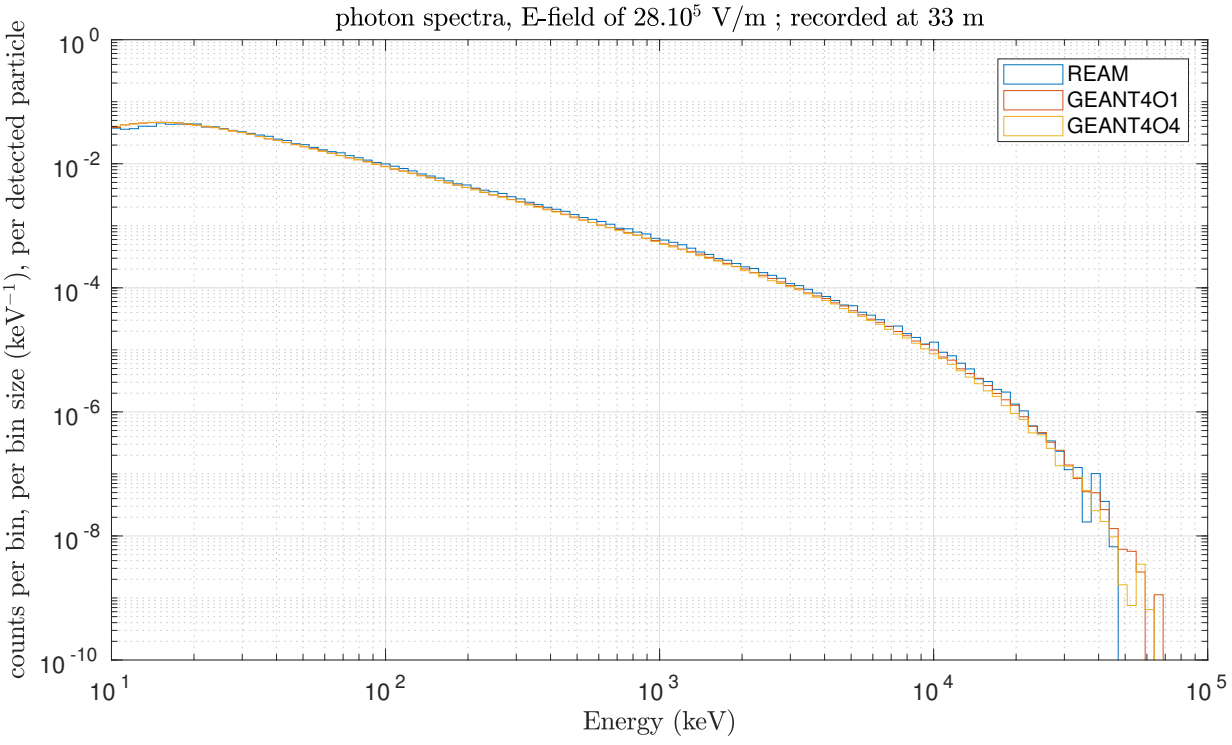

photon spectra, E-field of 18.10^5 V/m ; recorded at 48 m
counts per bin, per bin size (keV^-1), per detected particle
Energy (keV)
REAM
GEANT4O1
GEANT4O4

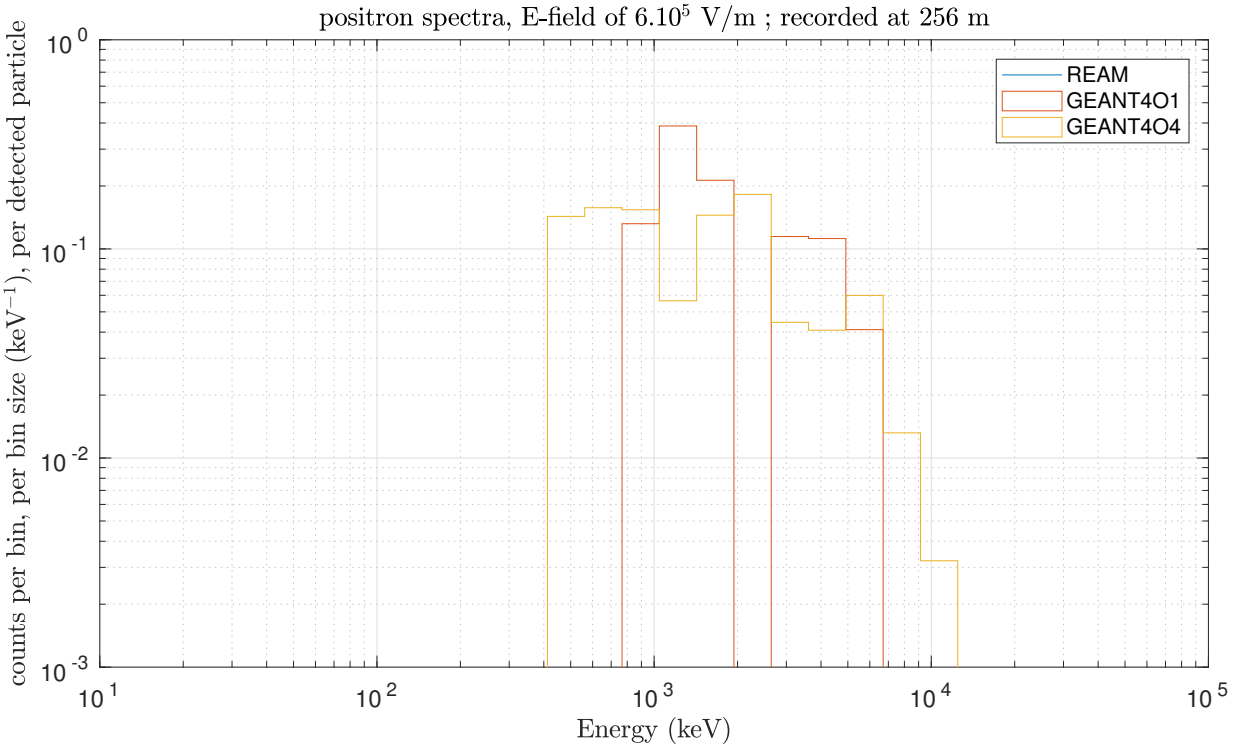

photon spectra, E-field of 20.10^5 V/m ; recorded at 44 m
REAM
GEANT4O1
GEANT4O4
counts per bin, per bin size (keV^-1), per detected particle
Energy (keV)

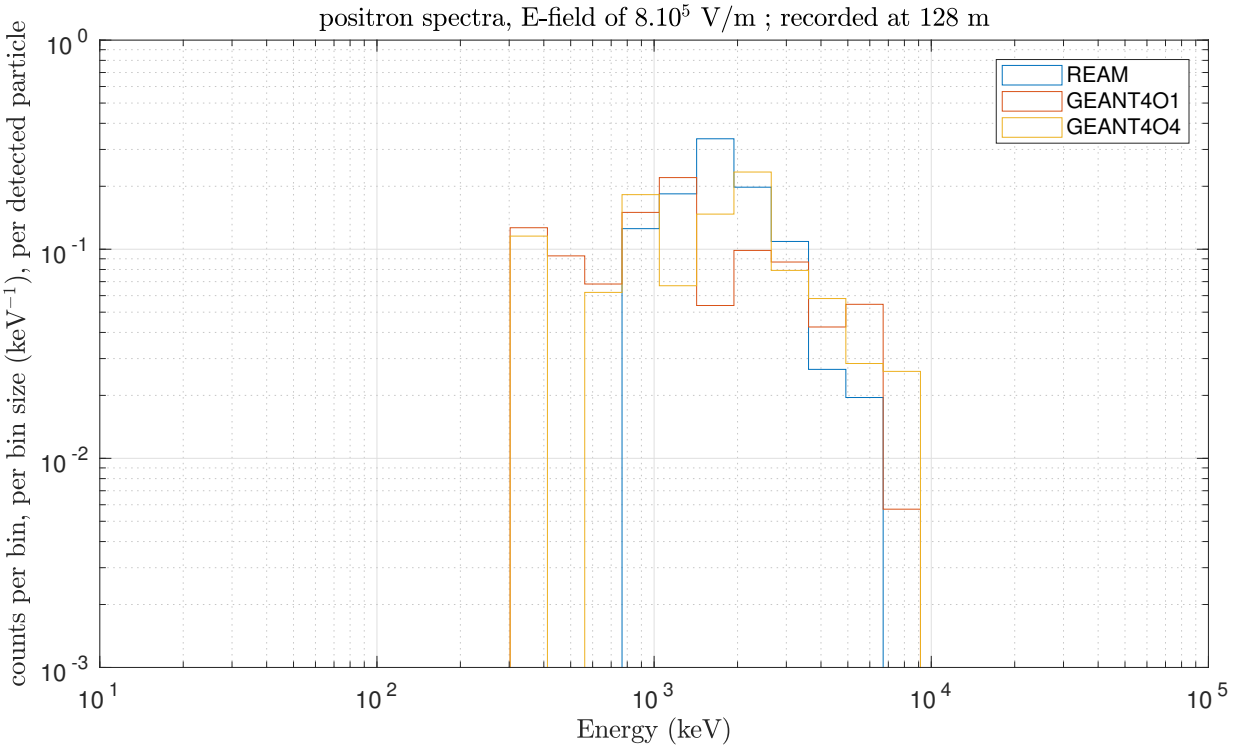

photon spectra, E-field of 22.10^5 V/m ; recorded at 41 m
REAM
GEANT4O1
GEANT4O4
counts per bin, per bin size (keV^-1), per detected particle
Energy (keV)

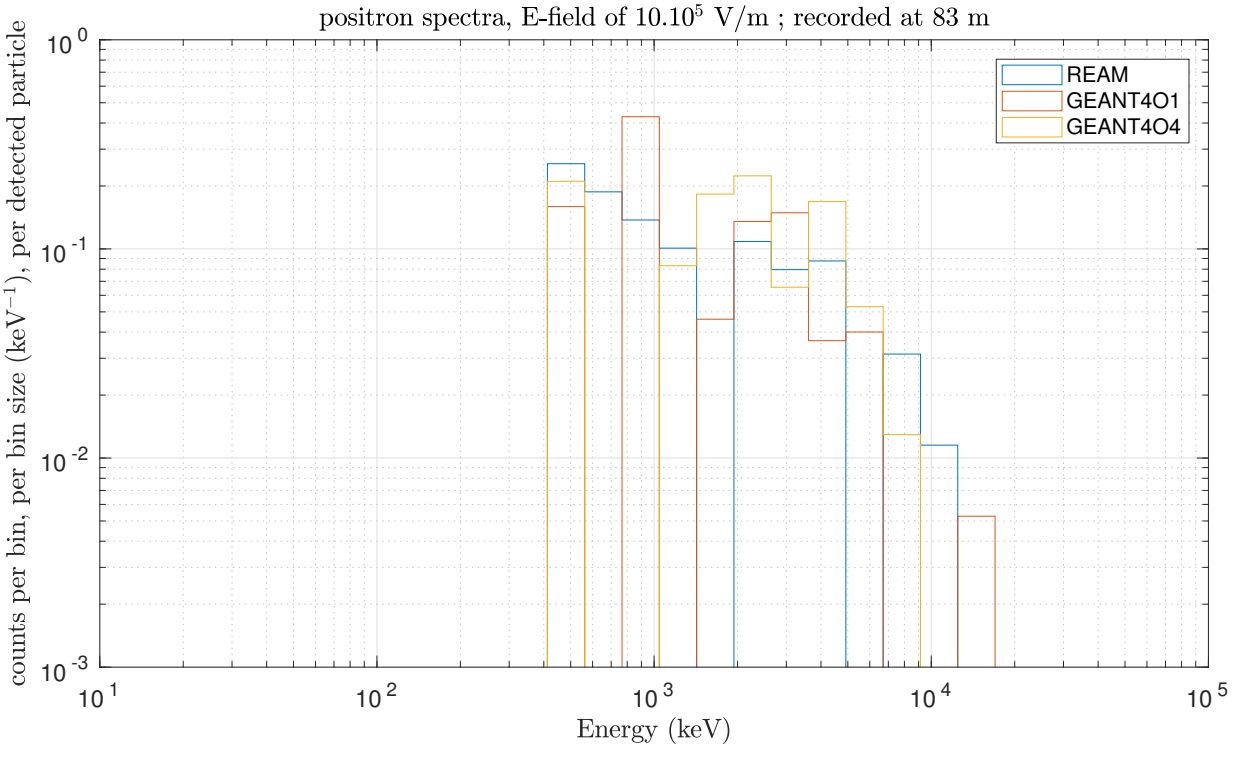

photon spectra, E-field of 24.10^5 V/m ; recorded at 38 m
REAM
GEANT4O1
GEANT4O4
counts per bin, per bin size (keV^-1), per detected particle
Energy (keV)

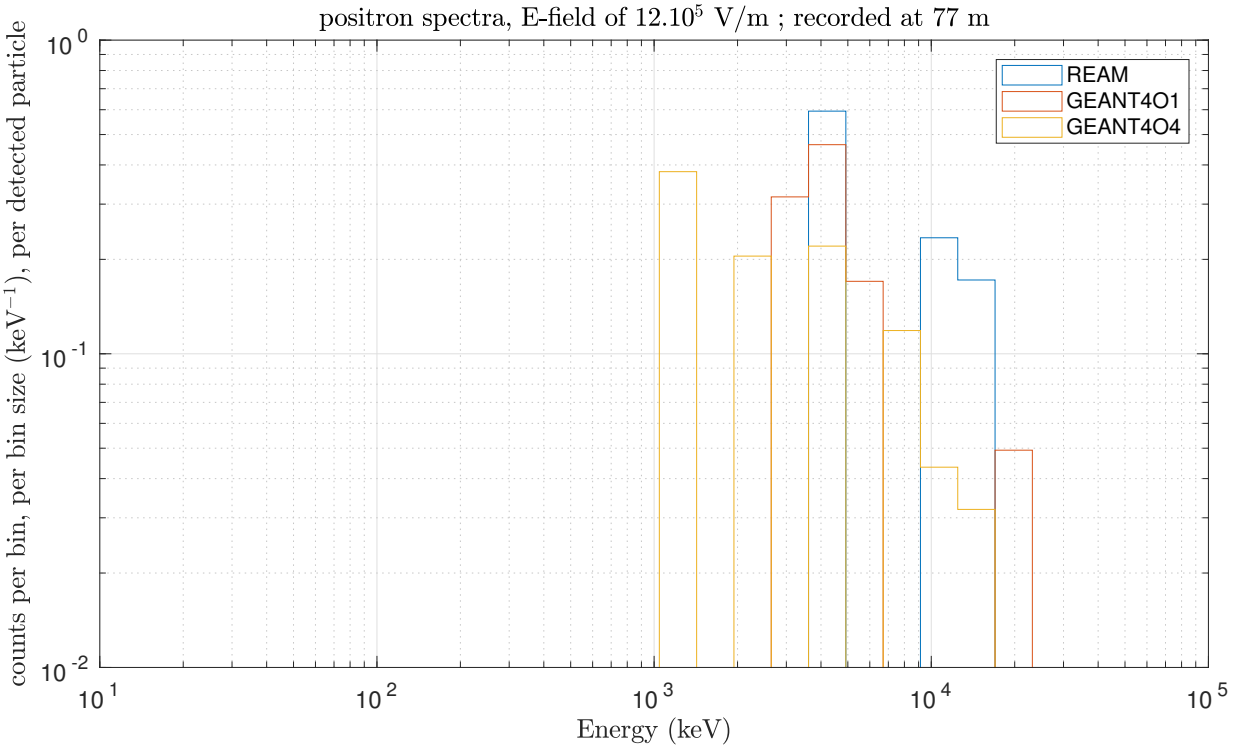

photon spectra, E-field of 26.10^5 V/m ; recorded at 36 m
REAM
GEANT4O1
GEANT4O4
counts per bin, per bin size (keV^-1), per detected particle
Energy (keV)

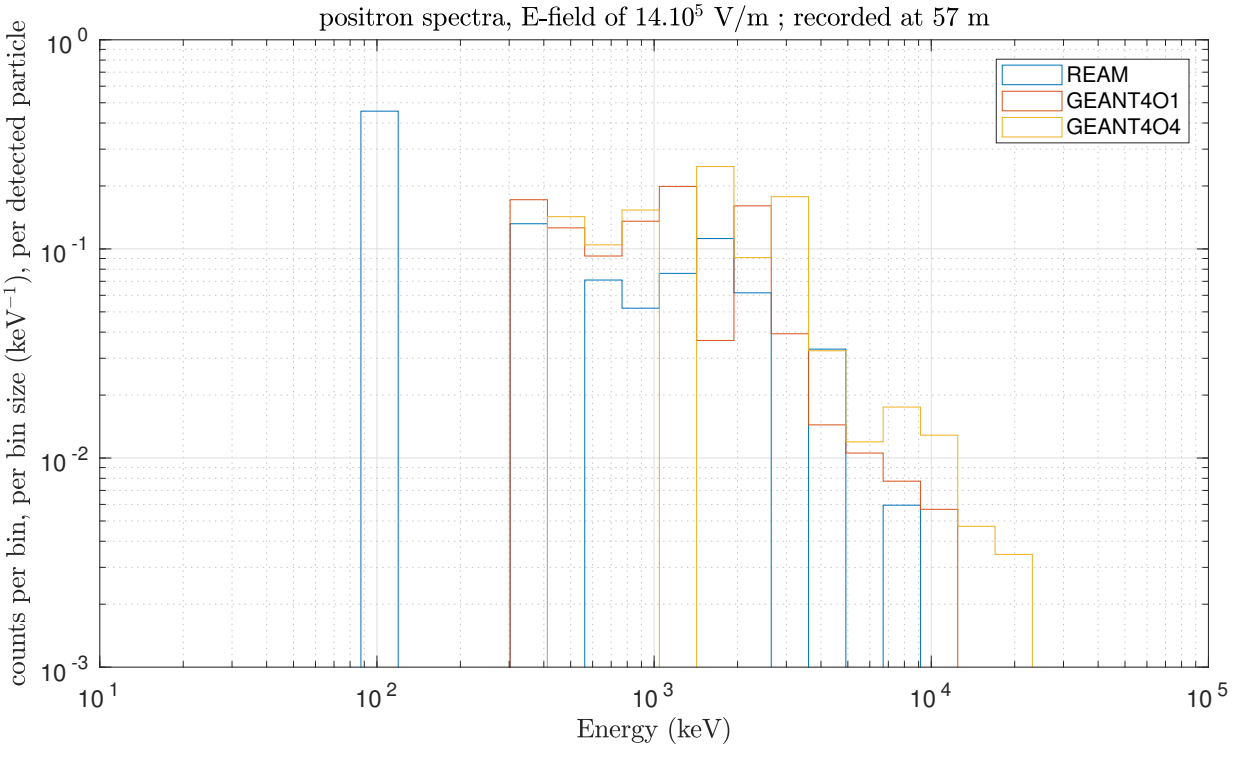

photon spectra, E-field of 28.10^5 V/m ; recorded at 33 m
REAM
GEANT4O1
GEANT4O4
counts per bin, per bin size (keV^-1), per detected particle
Energy (keV)

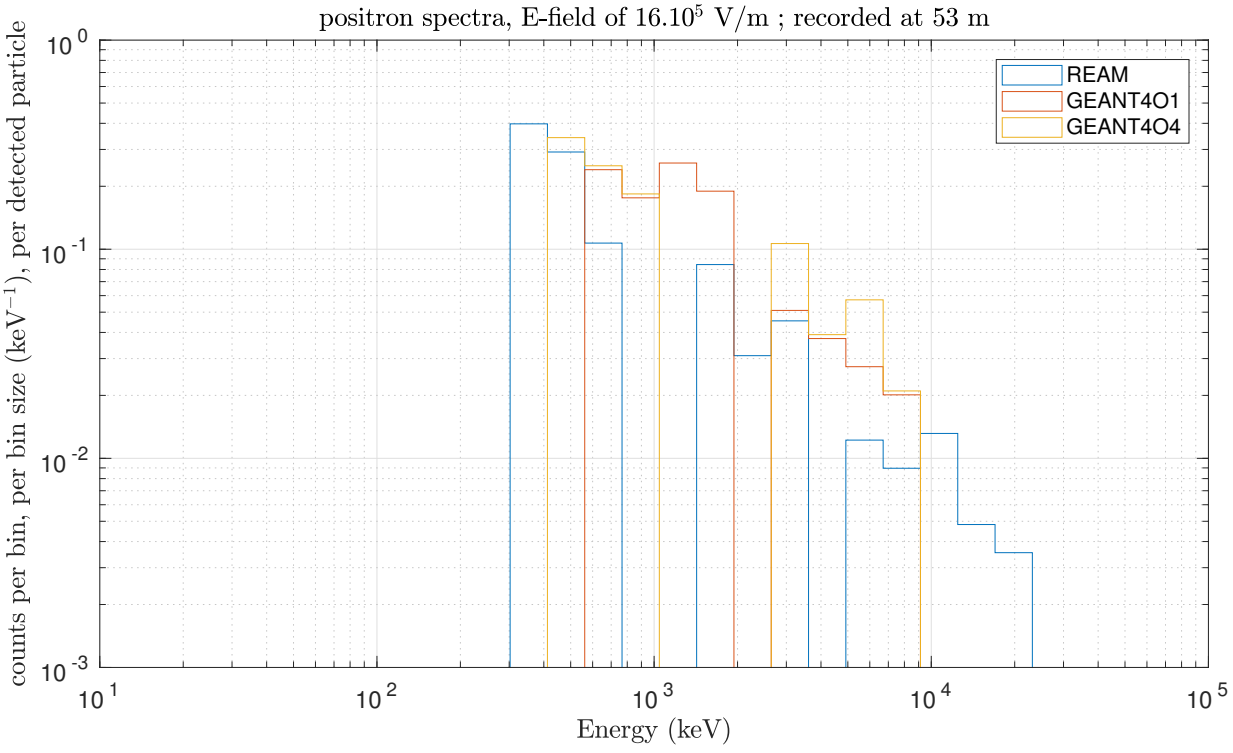

positron spectra, E-field of 6.10^5 V/m ; recorded at 256 m
REAM
GEANT4O1
GEANT4O4
counts per bin, per bin size (keV^-1), per detected particle
Energy (keV)

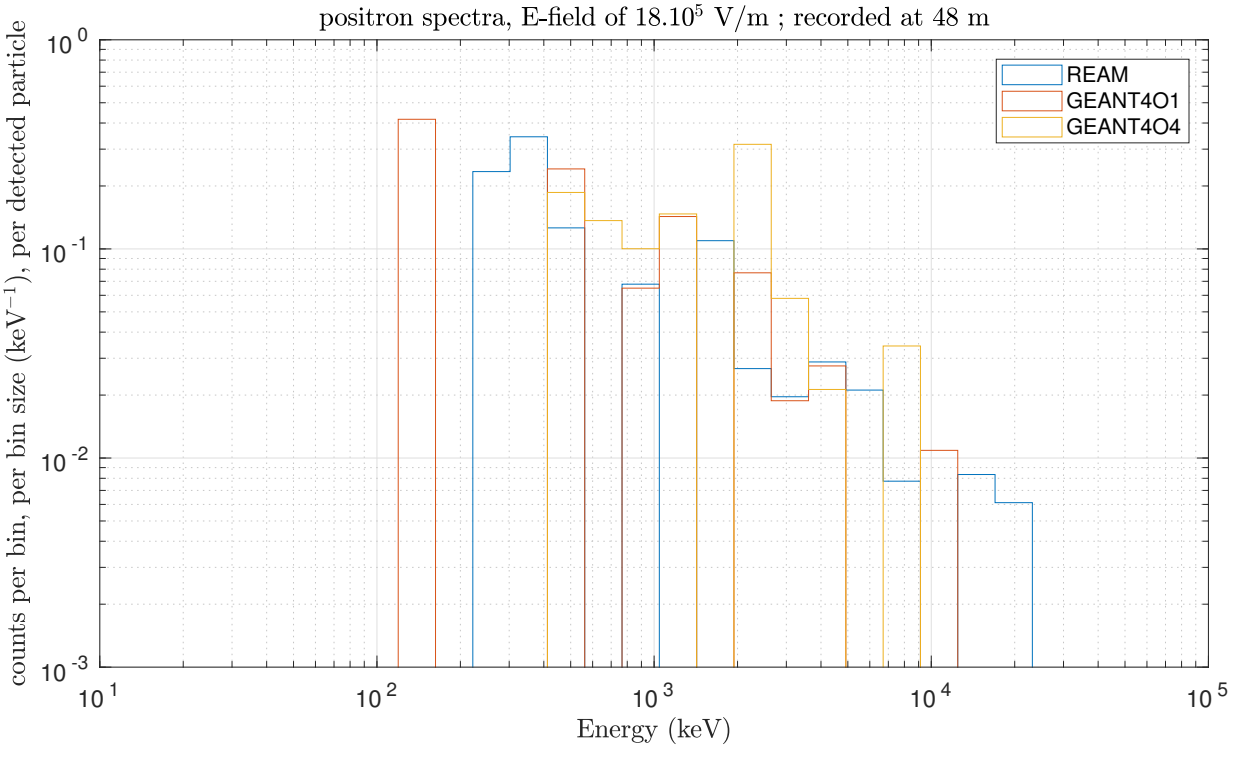

positron spectra, E-field of 8.10^5 V/m ; recorded at 128 m
counts per bin, per bin size (keV^-1), per detected particle
Energy (keV)
REAM
GEANT4O1
GEANT4O4

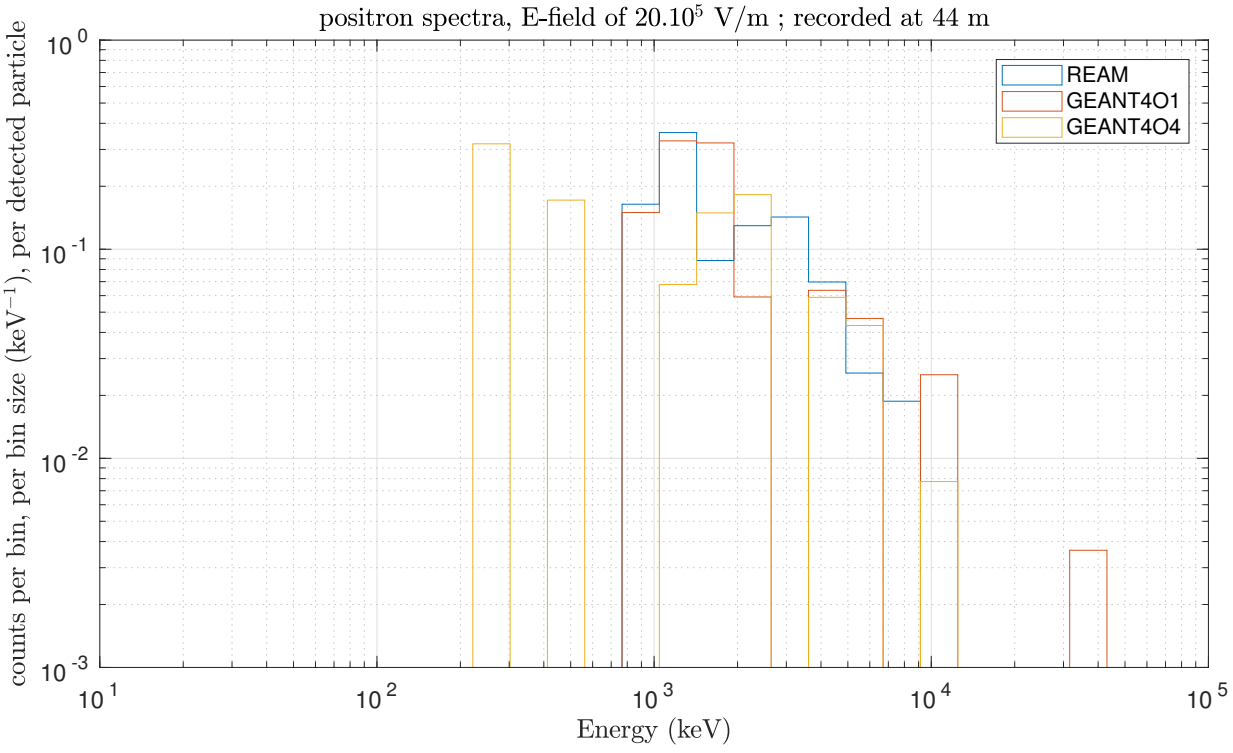

positron spectra, E-field of 10.10^5 V/m ; recorded at 83 m
counts per bin, per bin size (keV^-1), per detected particle
Energy (keV)
REAM
GEANT4O1
GEANT4O4

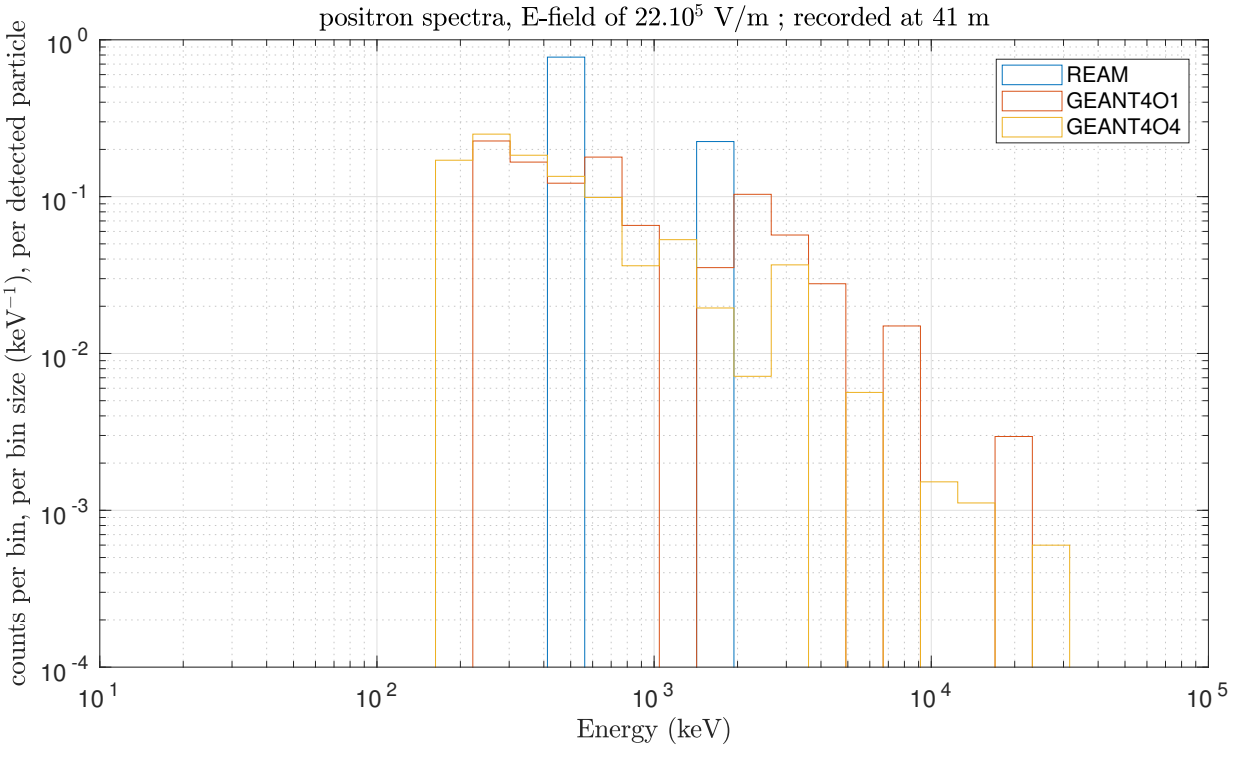

positron spectra, E-field of 12.10^5 V/m ; recorded at 77 m
counts per bin, per bin size (keV^-1), per detected particle
Energy (keV)
REAM
GEANT4O1
GEANT4O4

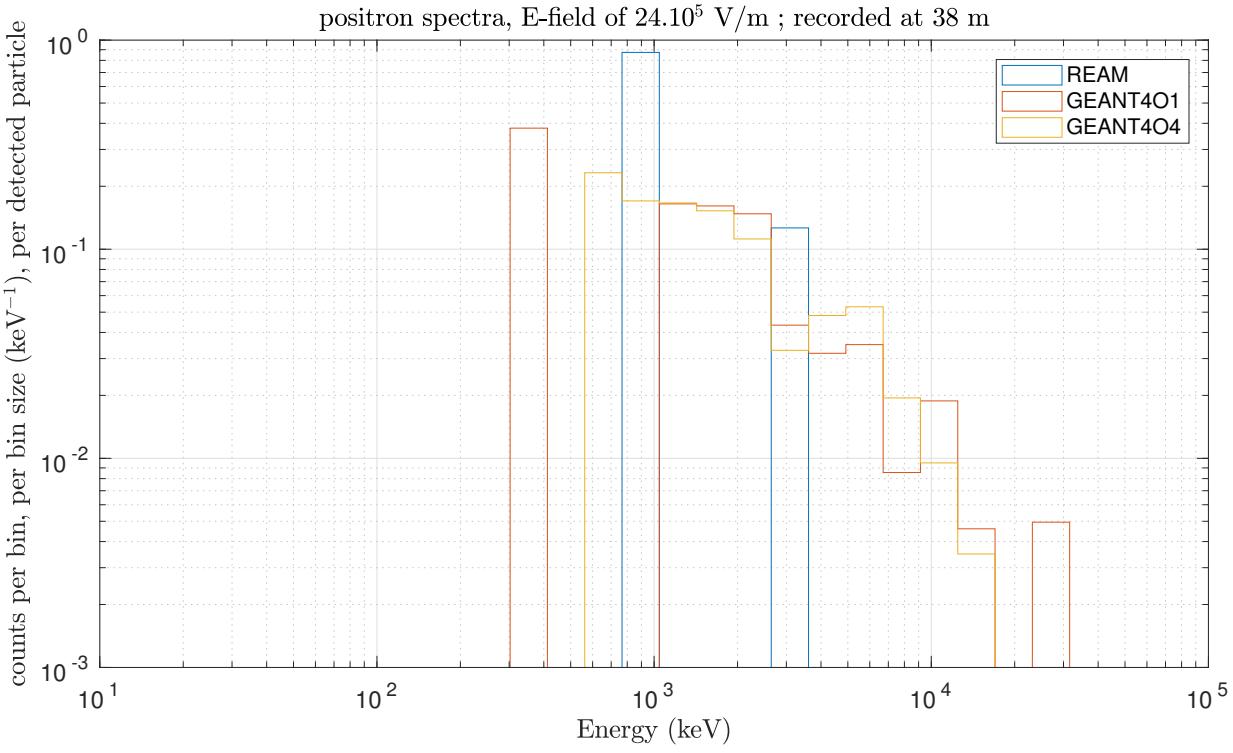

positron spectra, E-field of 14.10^5 V/m ; recorded at 57 m
counts per bin, per bin size (keV^-1), per detected particle
Energy (keV)
REAM
GEANT4O1
GEANT4O4

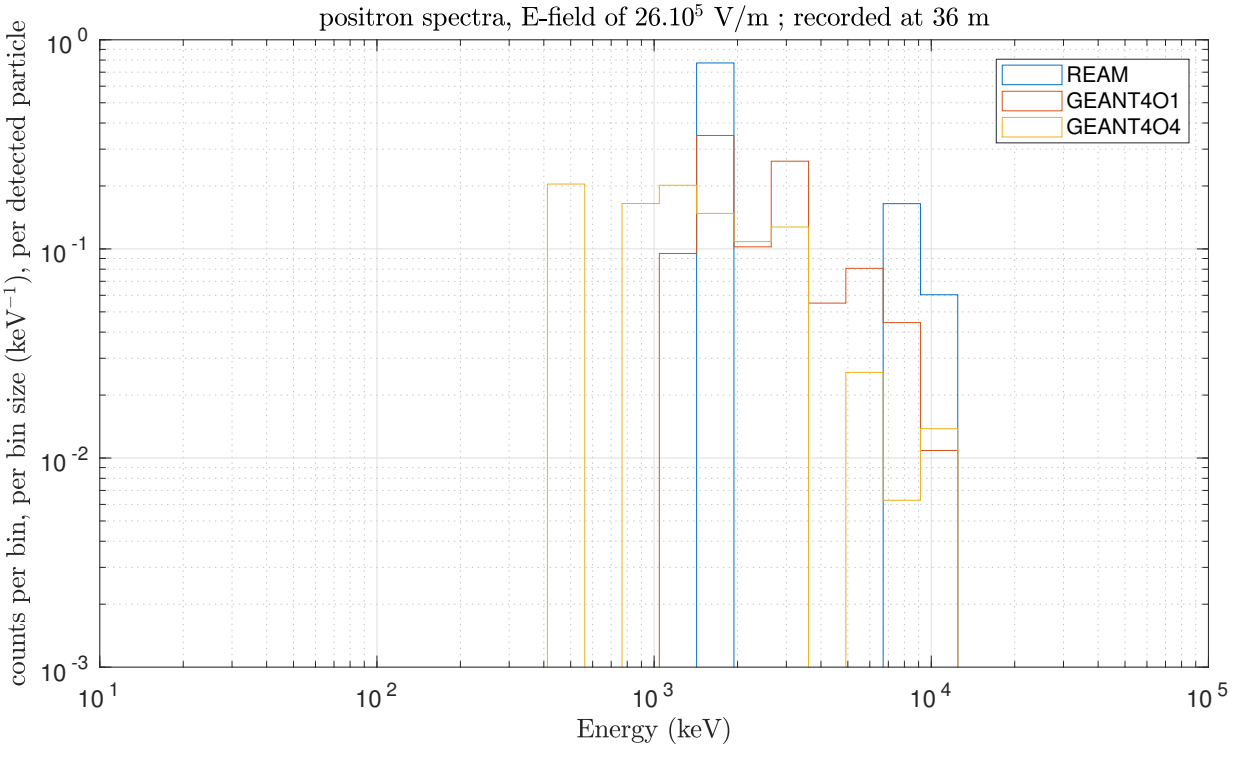

positron spectra, E-field of 16.10^5 V/m ; recorded at 53 m
counts per bin, per bin size (keV^-1), per detected particle
Energy (keV)
REAM
GEANT4O1
GEANT4O4

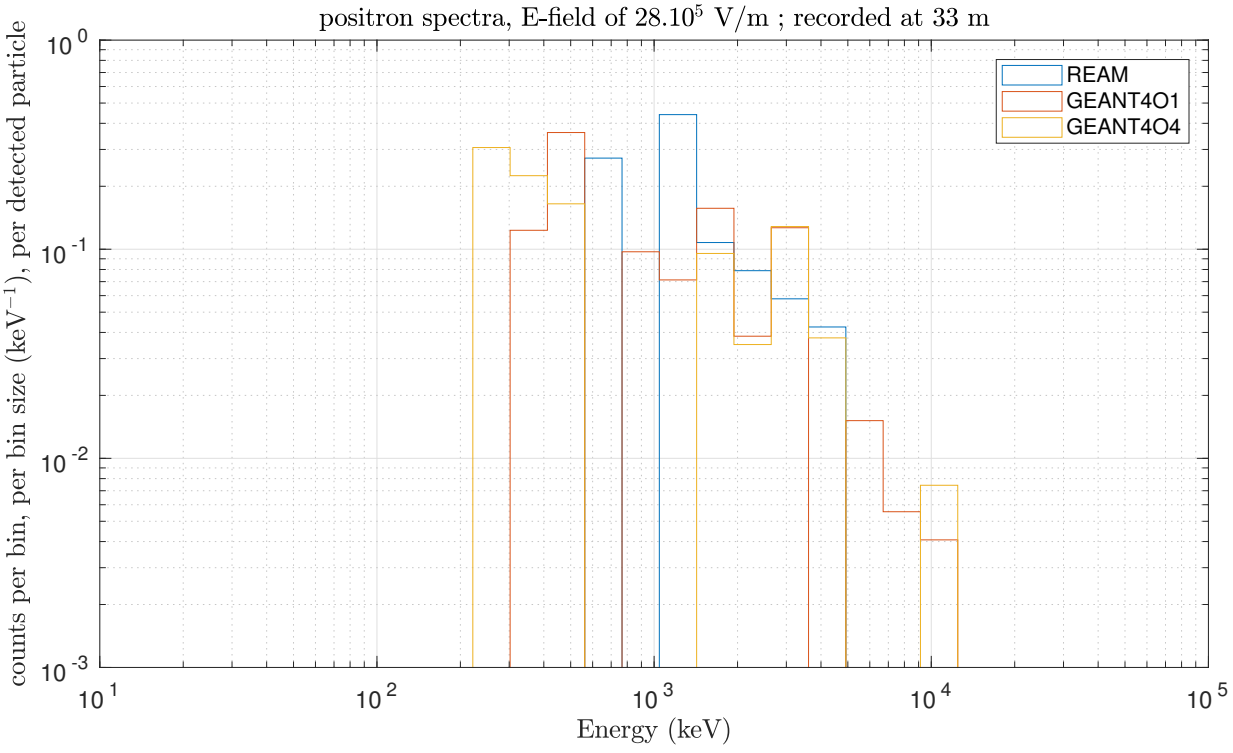

positron spectra, E-field of 18.10^5 V/m ; recorded at 48 m
counts per bin, per bin size (keV^-1), per detected particle
Energy (keV)
REAM
GEANT4O1
GEANT4O4


positron spectra, E-field of 20.10^5 V/m ; recorded at 44 m
REAM
GEANT4O1
GEANT4O4
counts per bin, per bin size (keV^-1), per detected particle
Energy (keV)


positron spectra, E-field of 22.10^5 V/m ; recorded at 41 m
REAM
GEANT4O1
GEANT4O4
counts per bin, per bin size (keV^-1), per detected particle
Energy (keV)

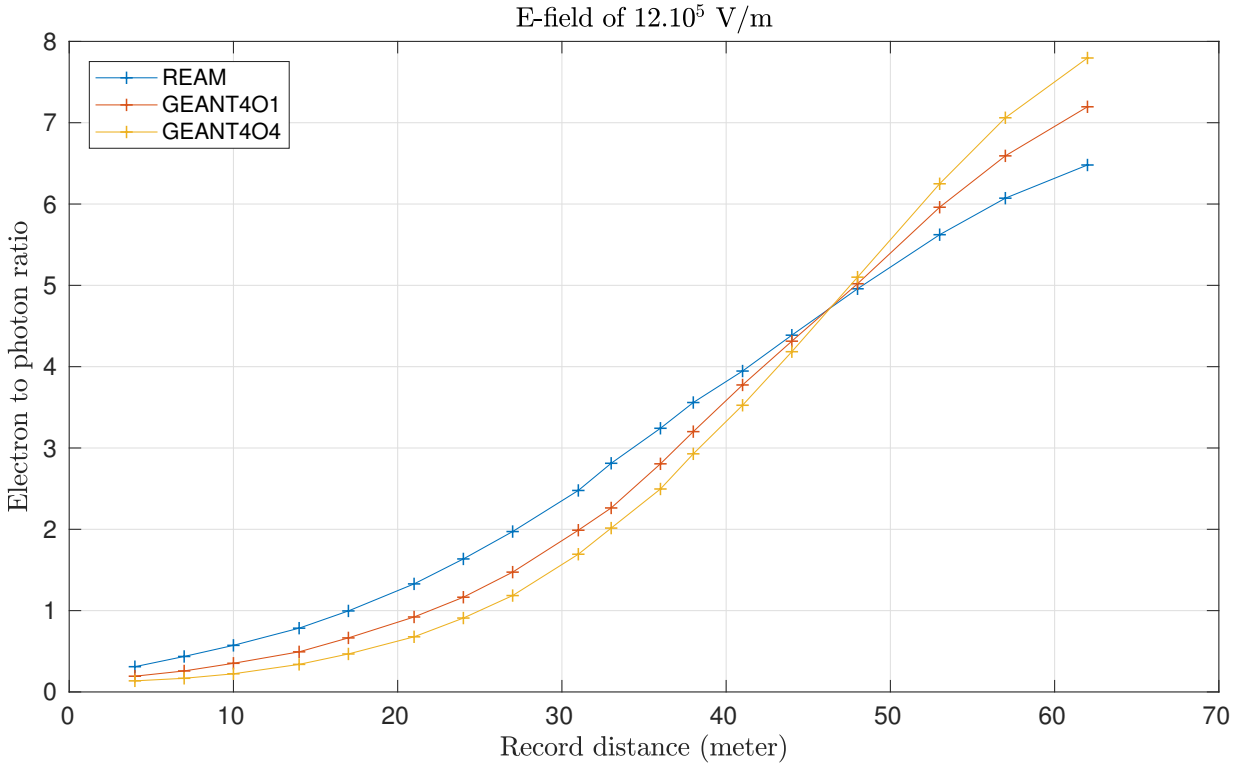

positron spectra, E-field of 24.10^5 V/m ; recorded at 38 m
counts per bin, per bin size (keV^-1), per detected particle
Energy (keV)
REAM
GEANT4O1
GEANT4O4

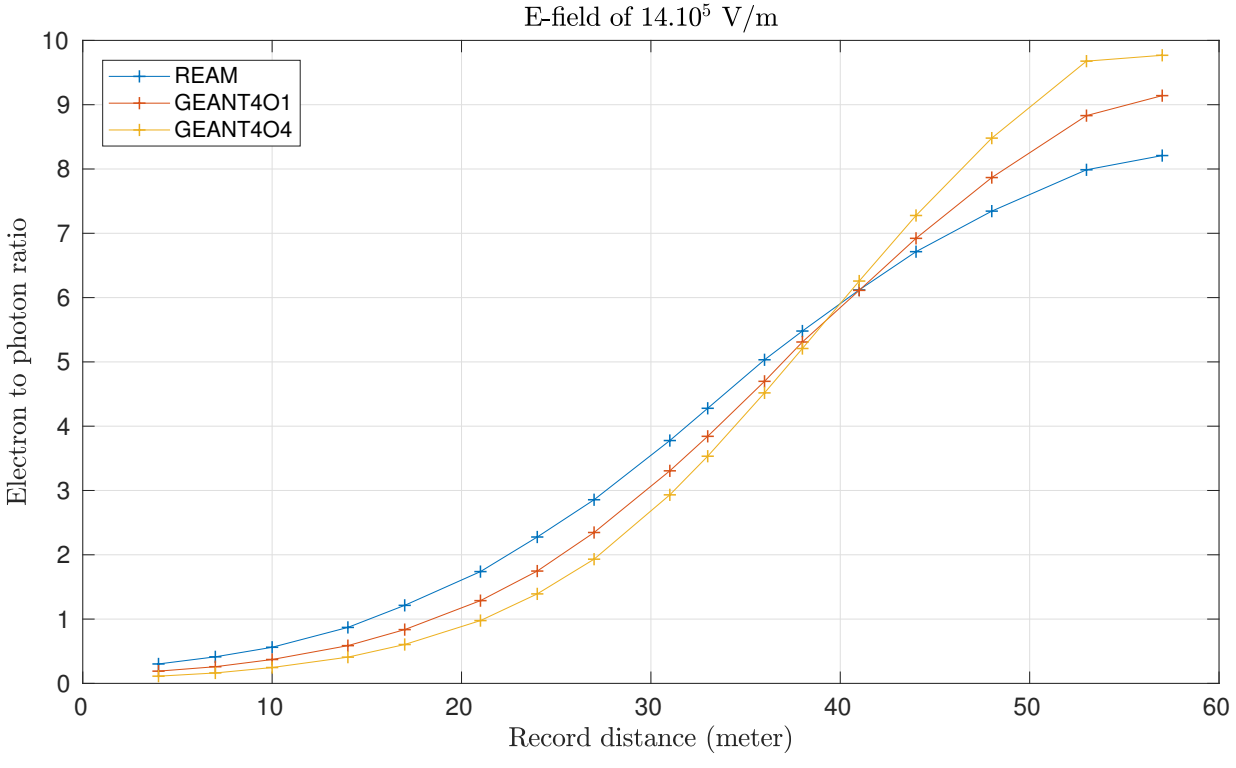

positron spectra, E-field of 26.10^5 V/m ; recorded at 36 m
counts per bin, per bin size (keV^-1), per detected particle
Energy (keV)
REAM
GEANT4O1
GEANT4O4

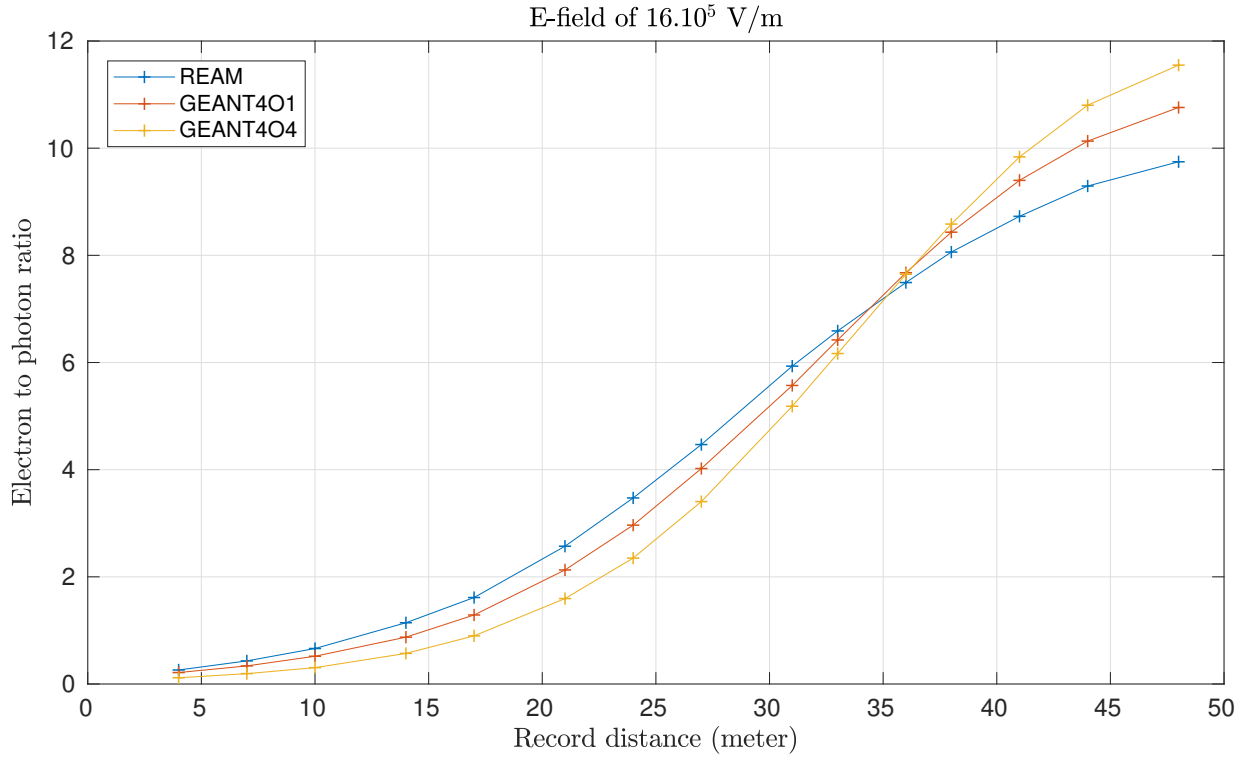

positron spectra, E-field of 28.10^5 V/m ; recorded at 33 m
counts per bin, per bin size (keV^-1), per detected particle
Energy (keV)
REAM
GEANT4O1
GEANT4O4
10^0
10^-1
10^-2
10^-3
10^1
10^2
10^3
10^4
10^5

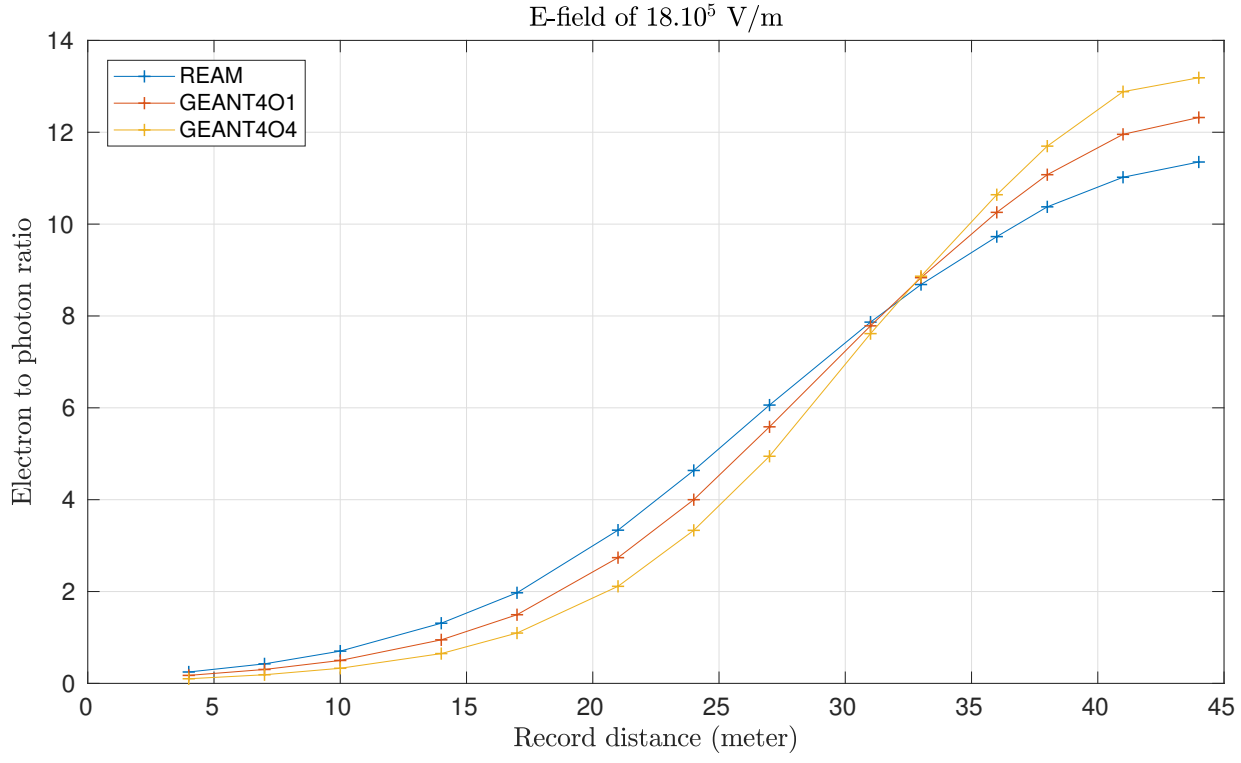
7 Electron To Photon Ratio

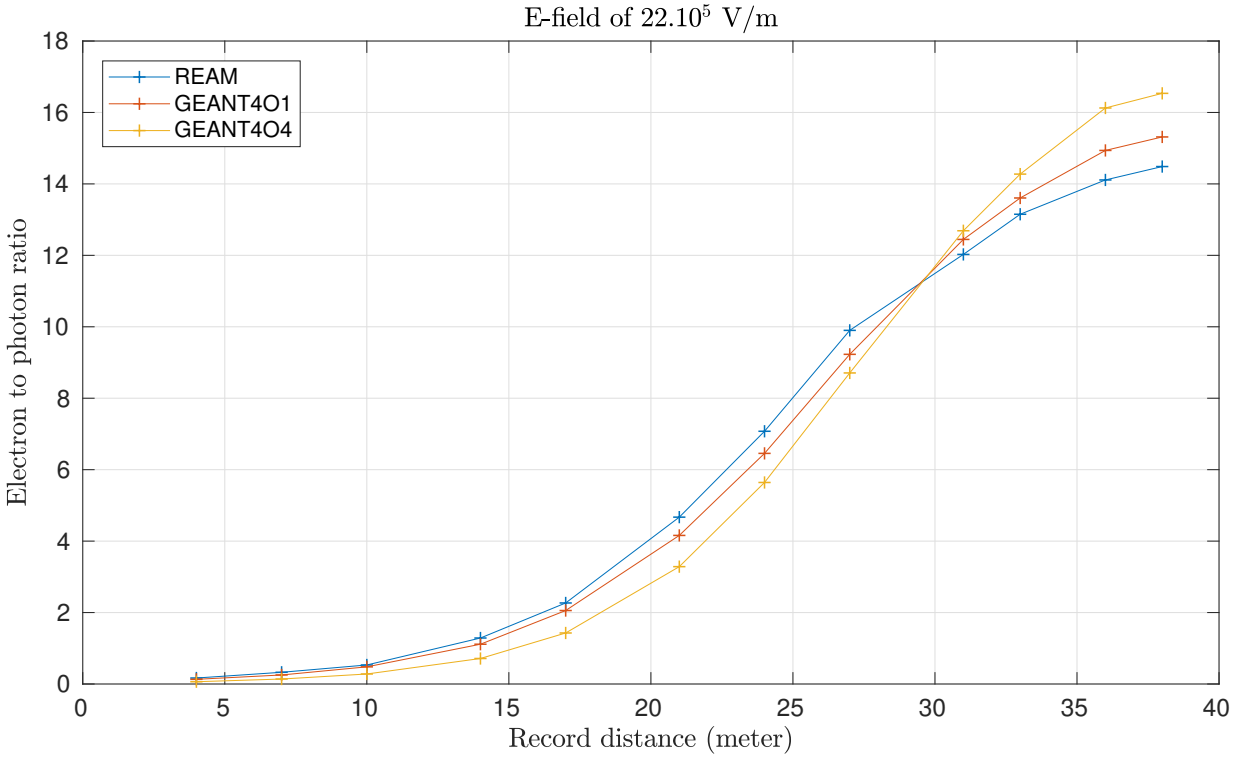
7.1 Code Comparison

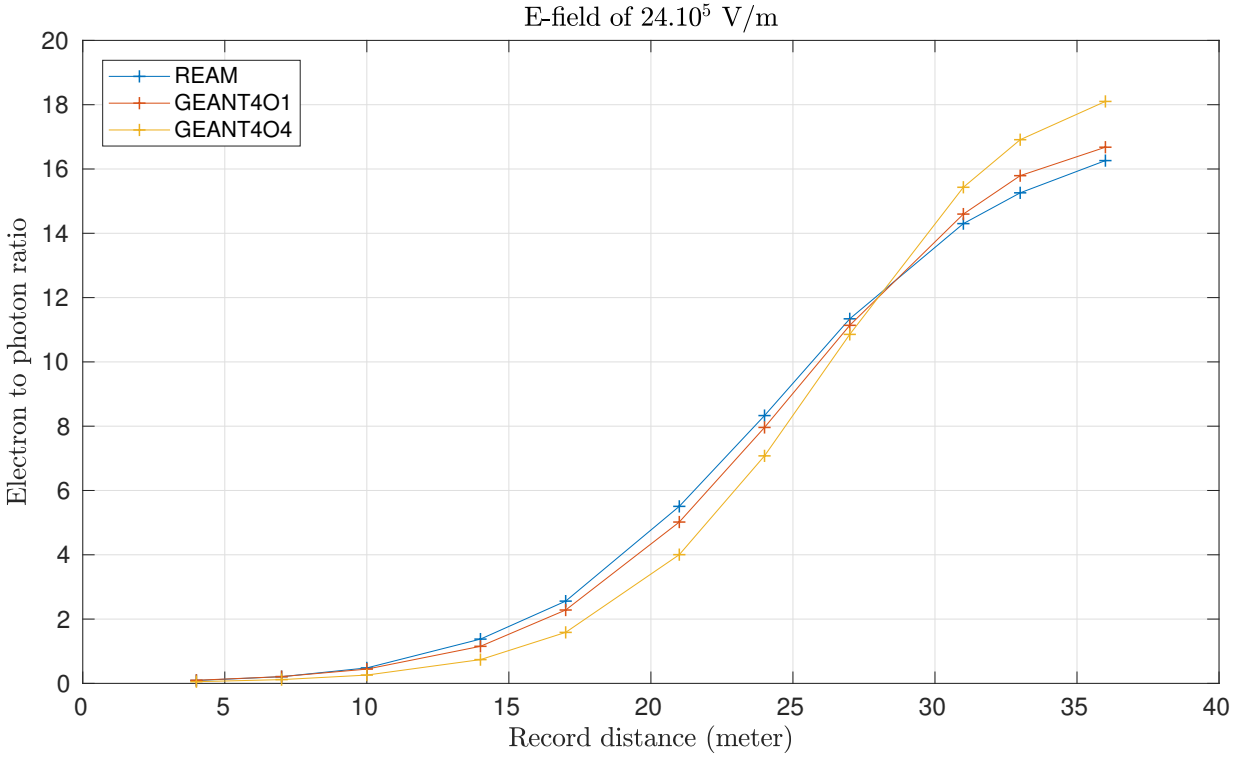


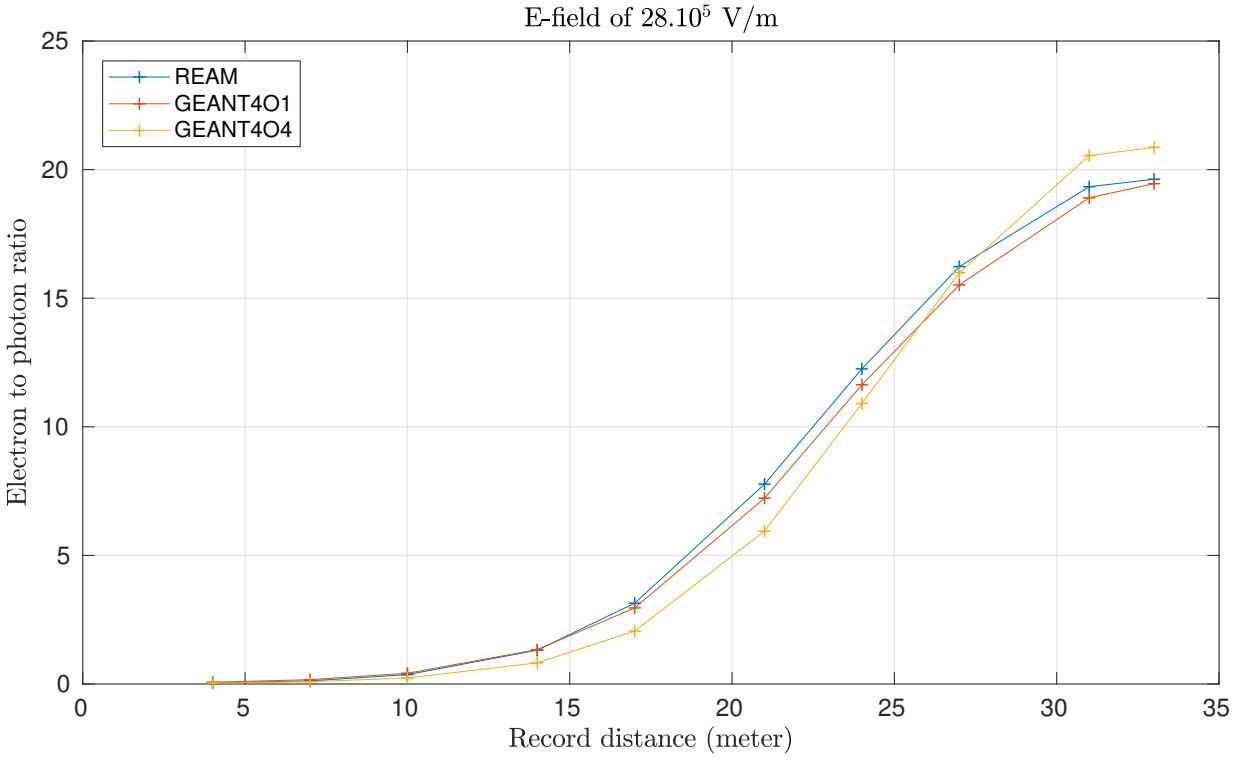


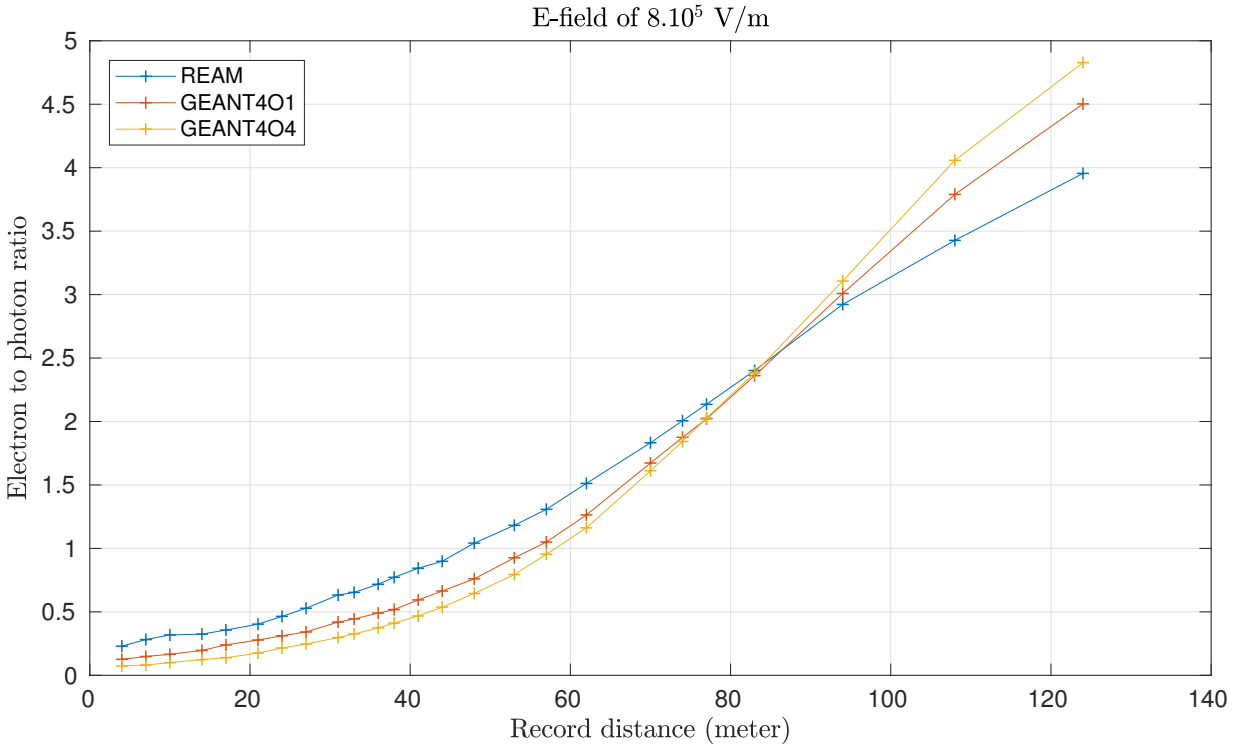

E-field of 16.10^5 V/m
REAM
GEANT4O1
GEANT4O4
Electron to photon ratio
Record distance (meter)
0
2
4
6
8
10
12
0
5
10
15
20
25
30
35
40
45
50

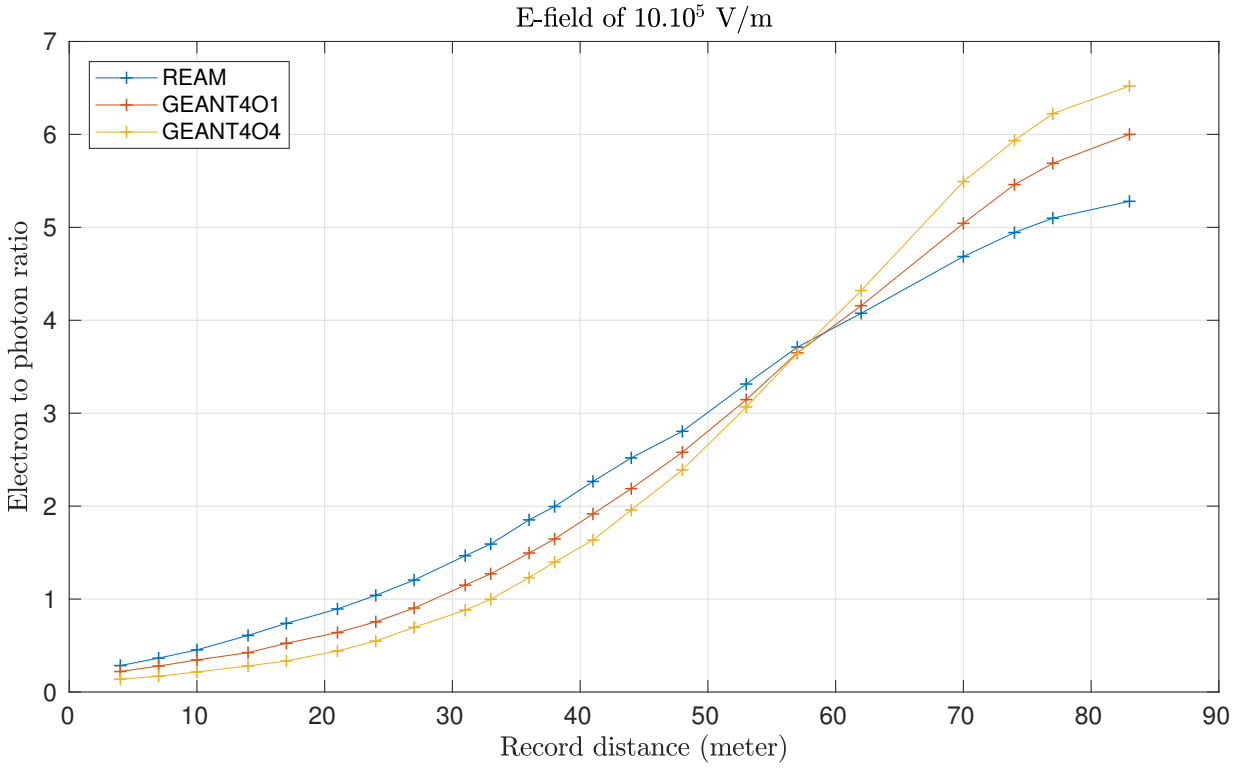

E-field of 18.10^5 V/m
REAM
GEANT4O1
GEANT4O4
Electron to photon ratio
Record distance (meter)
0
2
4
6
8
10
12
14
0
5
10
15
20
25
30
35
40
45

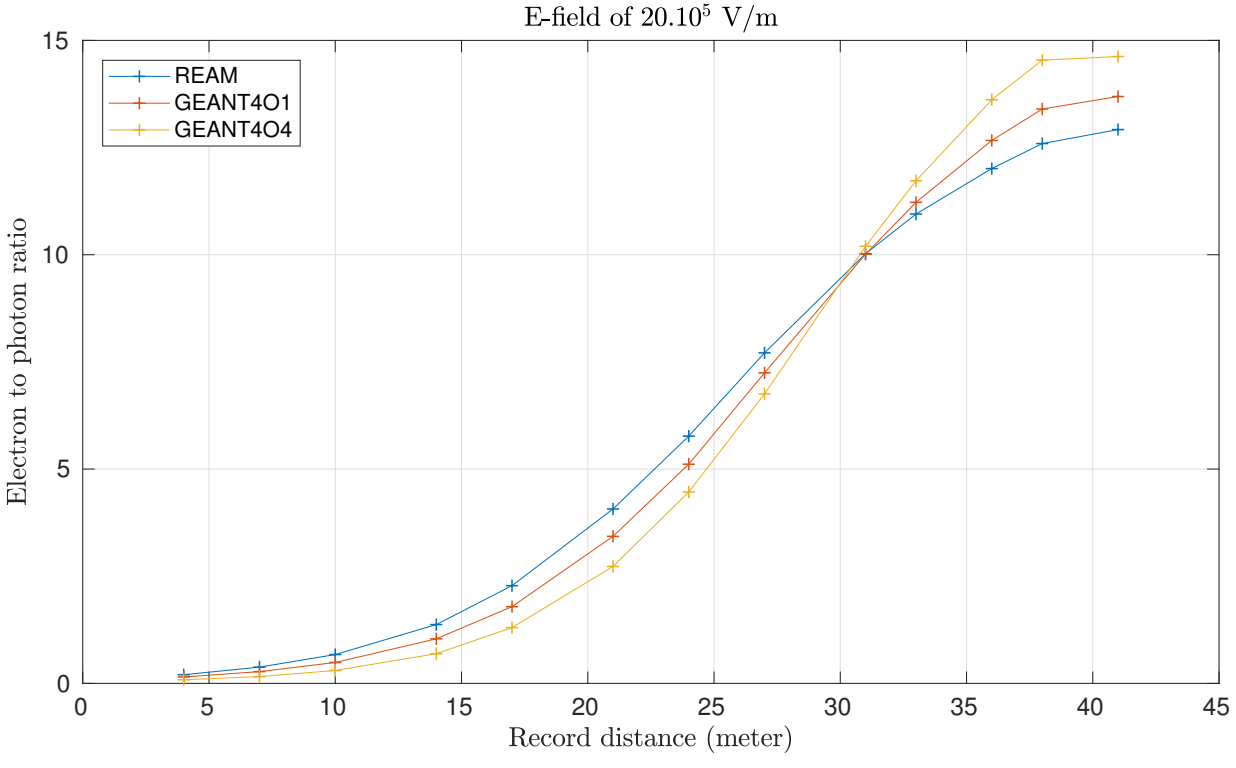

E-field of 22.10^5 V/m
REAM
GEANT4O1
GEANT4O4
Electron to photon ratio
Record distance (meter)
0
2
4
6
8
10
12
14
16
18
0
5
10
15
20
25
30
35
40

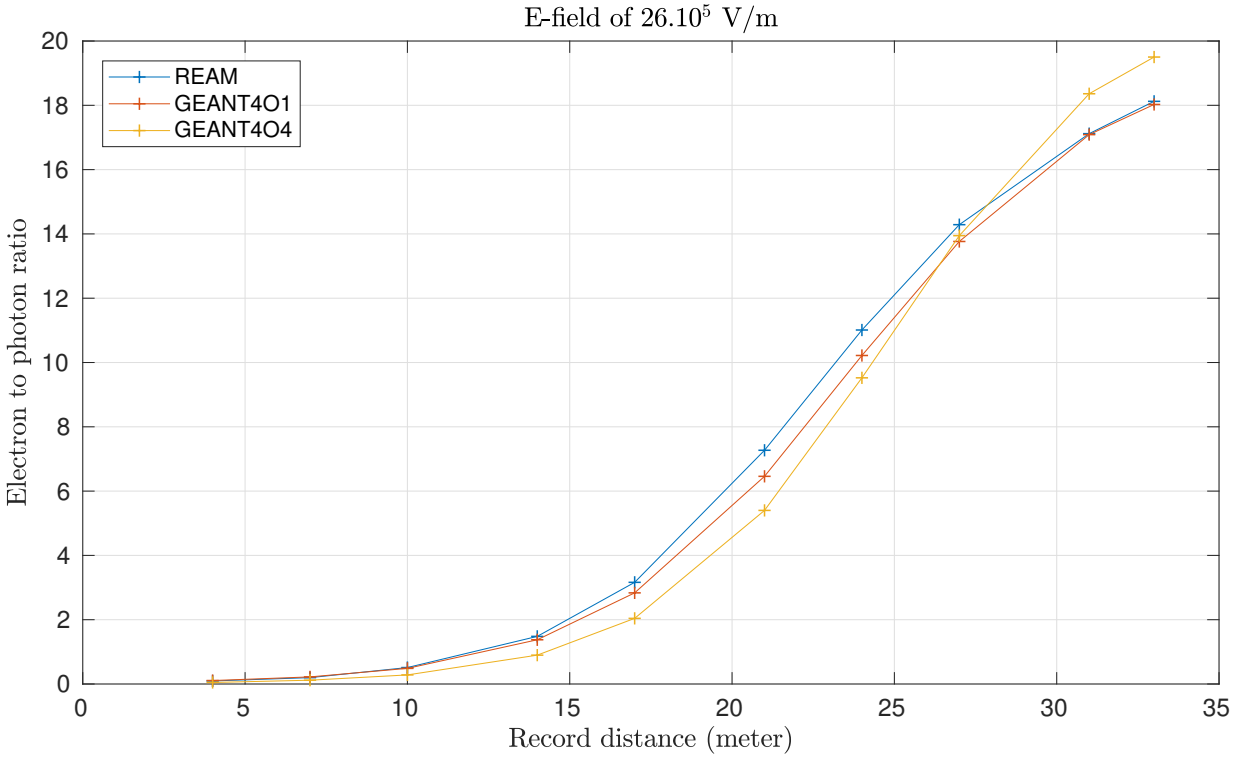

E-field of 24.10^5 V/m
REAM
GEANT4O1
GEANT4O4
Electron to photon ratio
Record distance (meter)
0
2
4
6
8
10
12
14
16
18
20
0
5
10
15
20
25
30
35
40

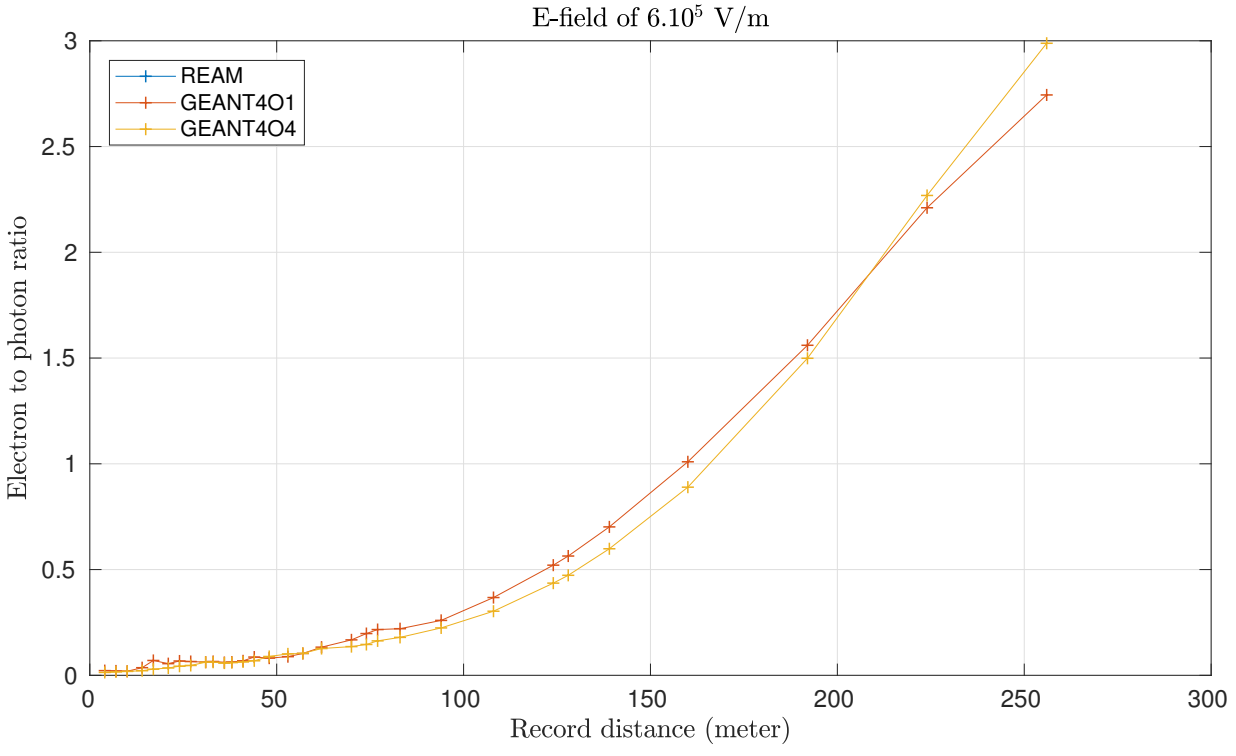

E-field of 28.10^5 V/m
REAM
GEANT4O1
GEANT4O4
Electron to photon ratio
Record distance (meter)
0
5
10
15
20
25
30
35


E-field of 8.10^5 V/m
REAM
GEANT4O1
GEANT4O4
Electron to photon ratio
Record distance (meter)
0
0.5
1
1.5
2
2.5
3
3.5
4
4.5
5
20
40
60
80
100
120
140

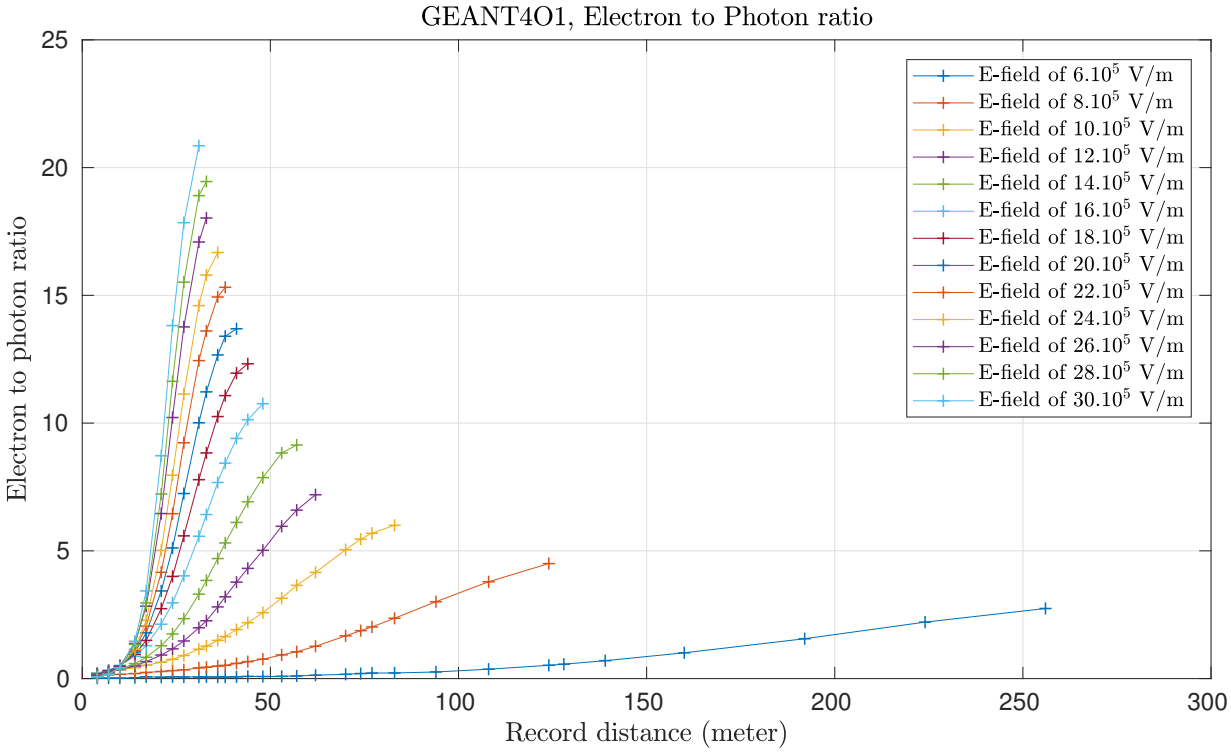

E-field of 10.10^5 V/m
REAM
GEANT4O1
GEANT4O4
Electron to photon ratio
Record distance (meter)
0
1
2
3
4
5
6
7
0
10
20
30
40
50
60
70
80
90

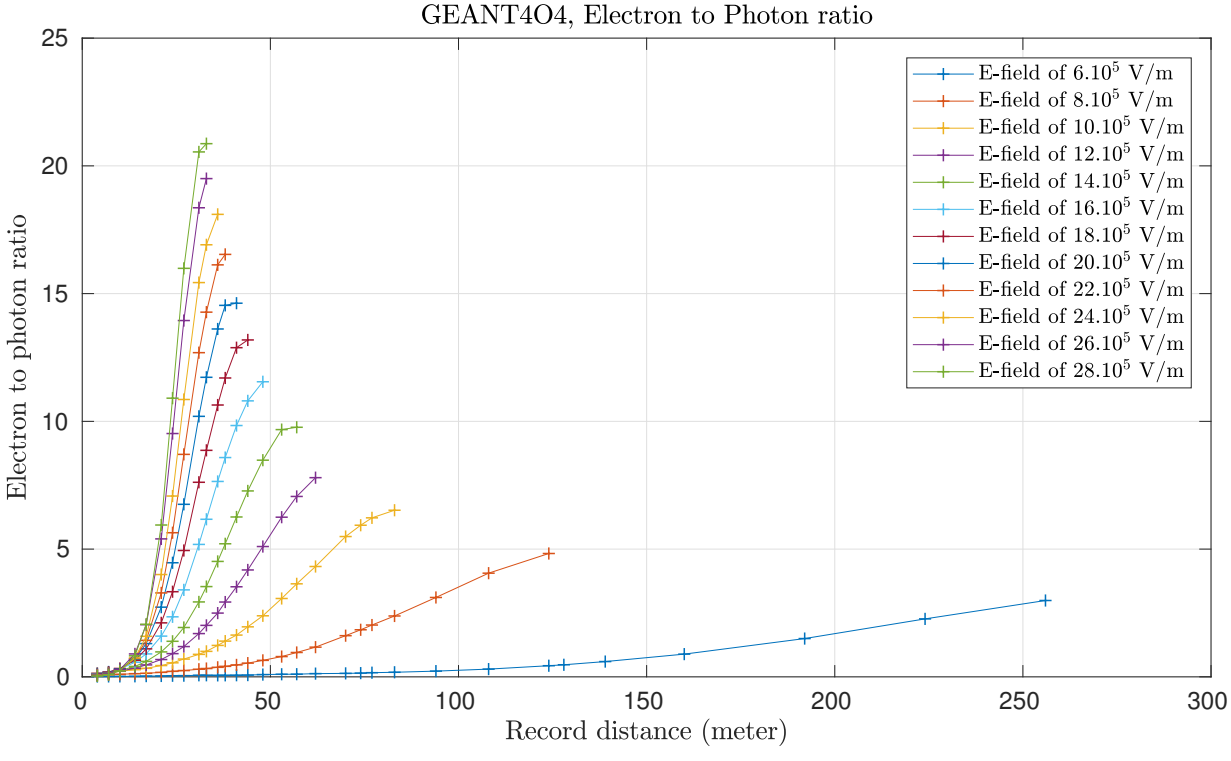

E-field of 20.10^5 V/m
REAM
GEANT4O1
GEANT4O4
Electron to photon ratio
Record distance (meter)
0
5
10
15
0
5
10
15
20
25
30
35
40
45

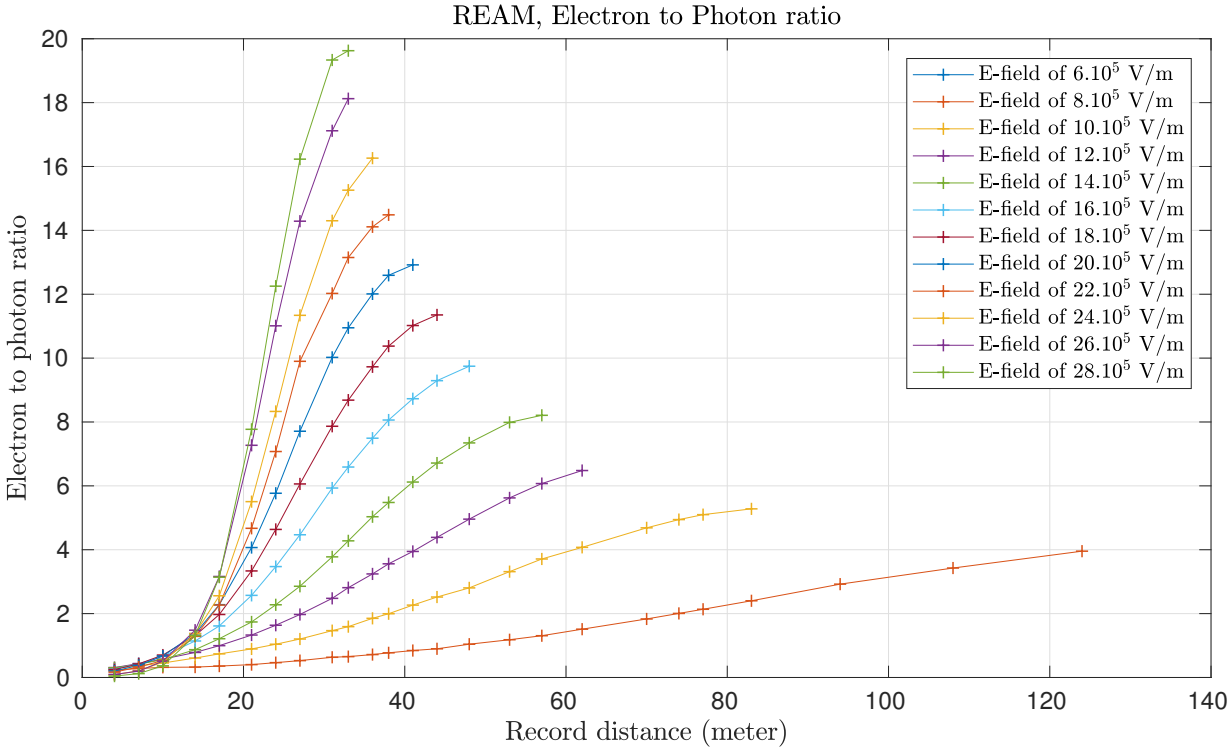

E-field of 26.10^5 V/m
REAM
GEANT4O1
GEANT4O4
Electron to photon ratio
Record distance (meter)
0
2
4
6
8
10
12
14
16
18
20
0
5
10
15
20
25
30
35


E-field of 6.10^5 V/m
REAM
GEANT4O1
GEANT4O4
Electron to photon ratio
Record distance (meter)
0
0.5
1
1.5
2
2.5
3
0
50
100
150
200
250
300

7.2 Code By Code

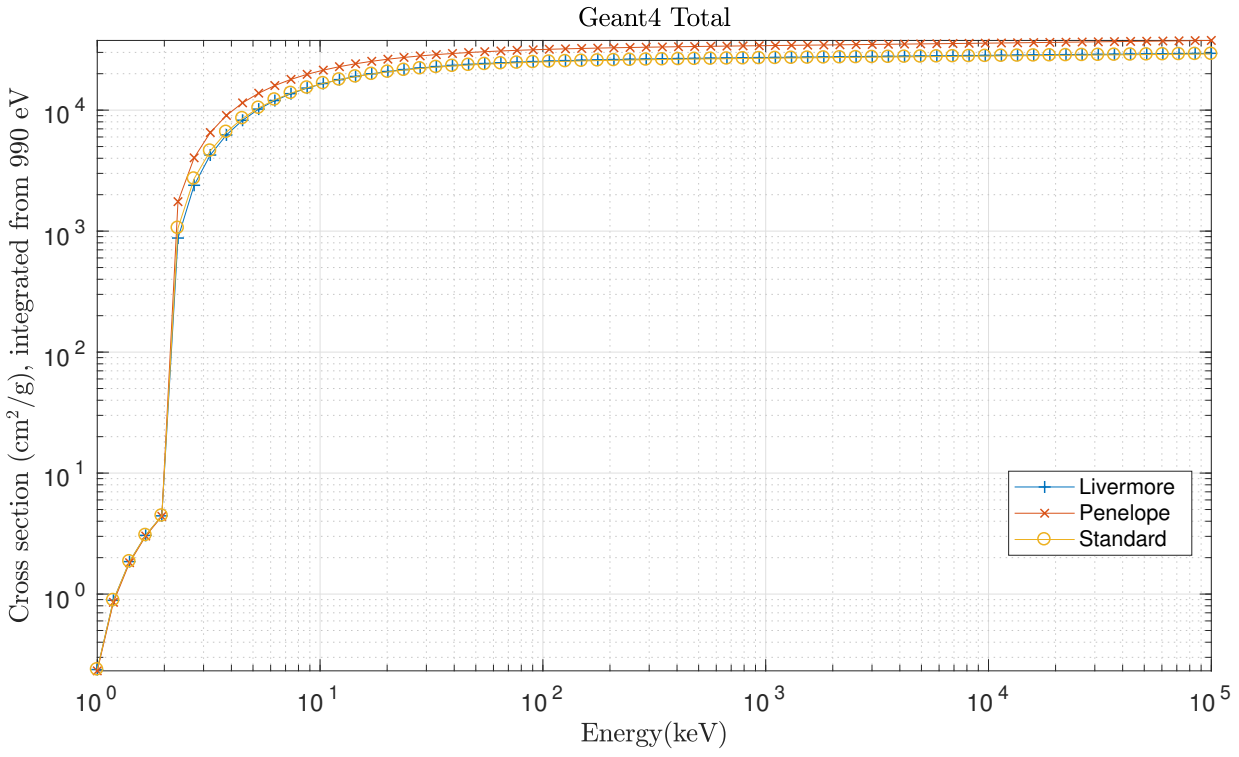




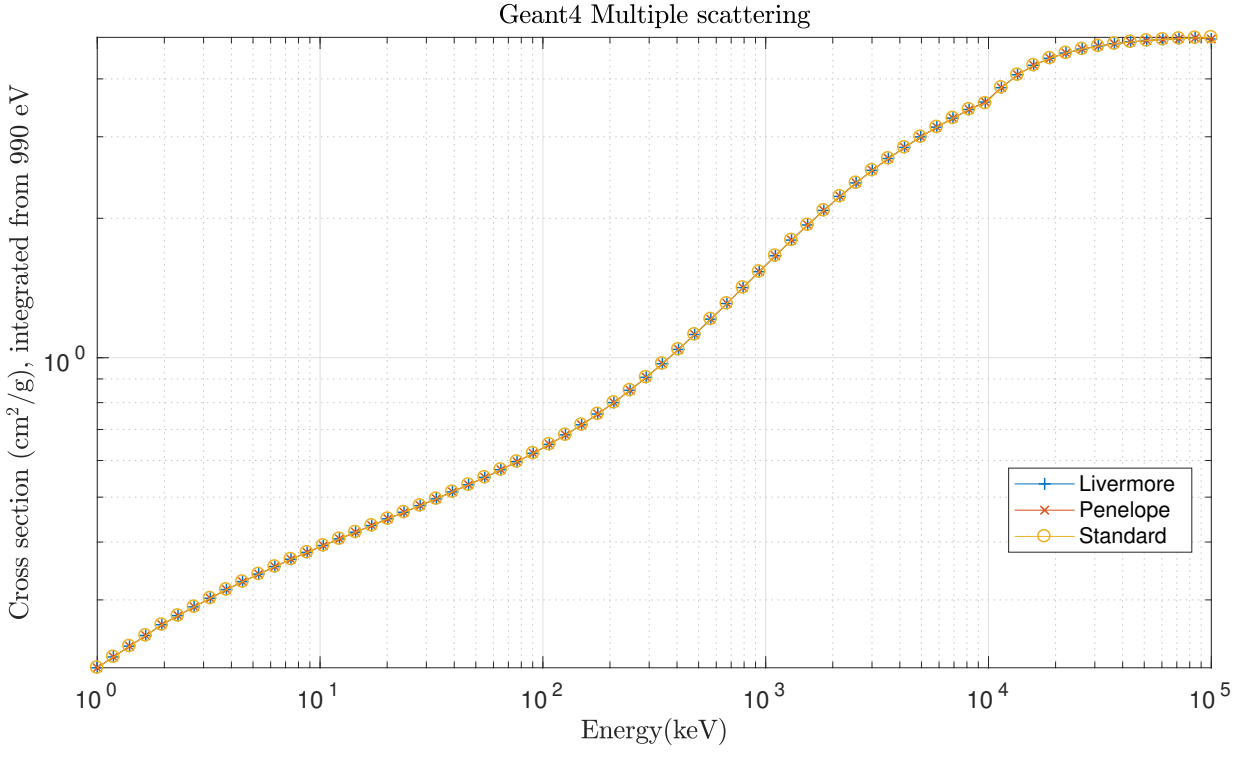

REAM, Electron to Photon ratio
Electron to photon ratio
Record distance (meter)
0
2
4
6
8
10
12
14
16
18
20
0
20
40
60
80
100
120
140
E-field of 6.10^5 V/m
E-field of 8.10^5 V/m
E-field of 10.10^5 V/m
E-field of 12.10^5 V/m
E-field of 14.10^5 V/m
E-field of 16.10^5 V/m
E-field of 18.10^5 V/m
E-field of 20.10^5 V/m
E-field of 22.10^5 V/m
E-field of 24.10^5 V/m
E-field of 26.10^5 V/m
E-field of 28.10^5 V/m

8 Geant4 Cross Sections Example Plots

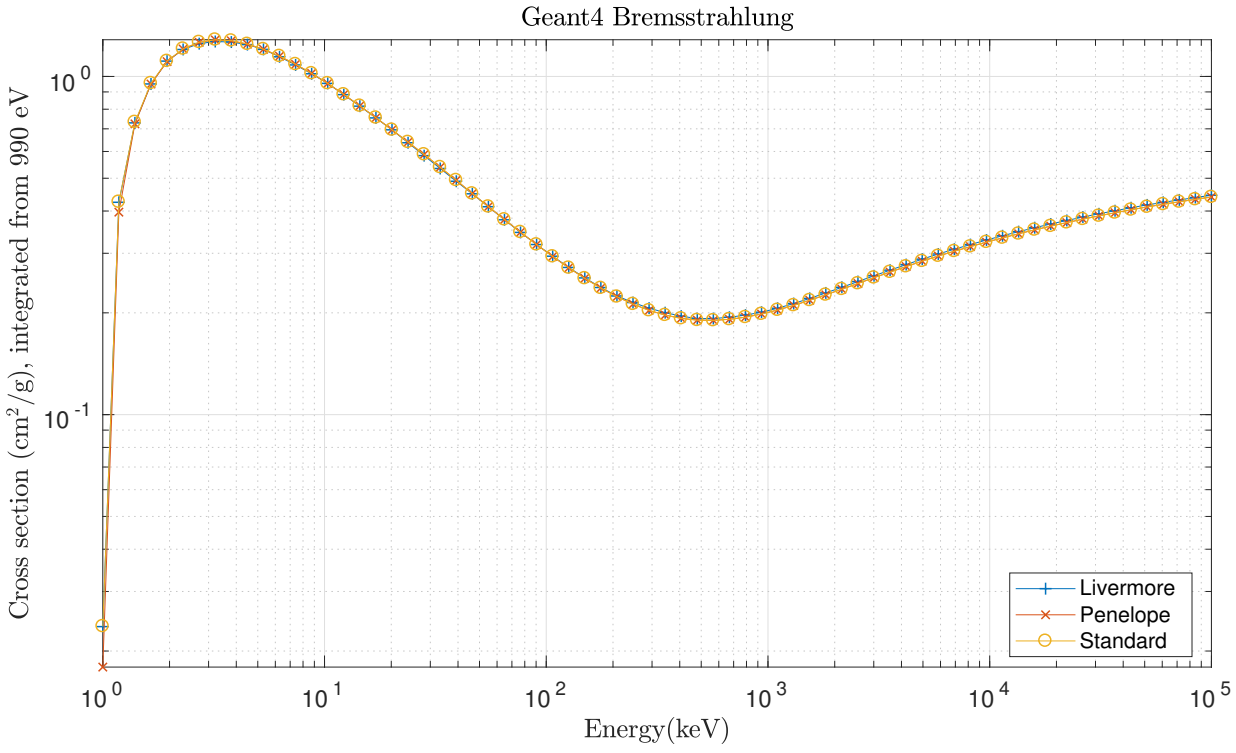
8.1 Total

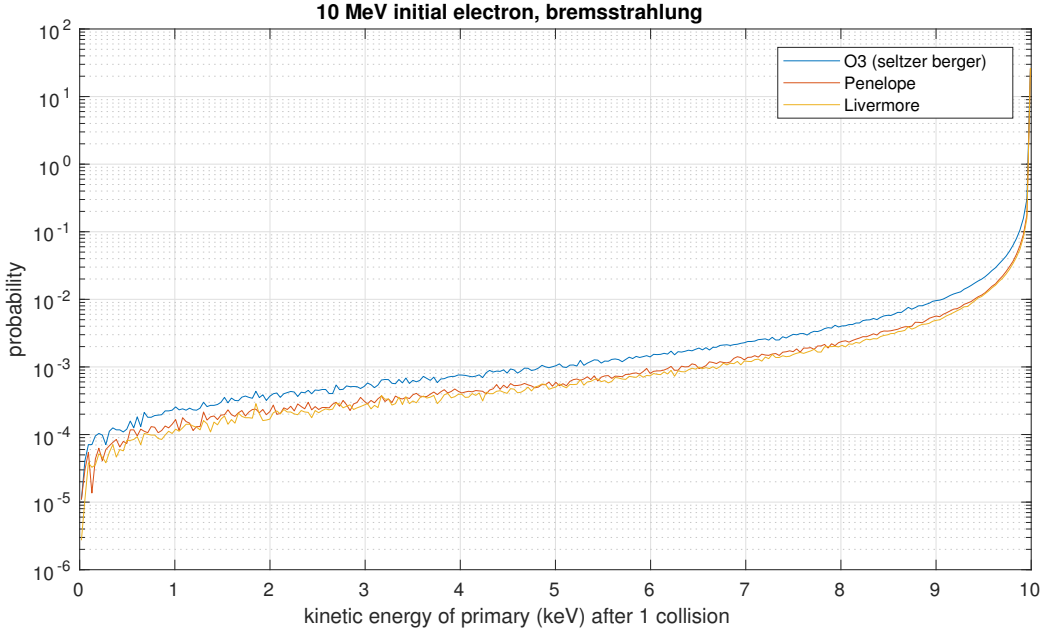


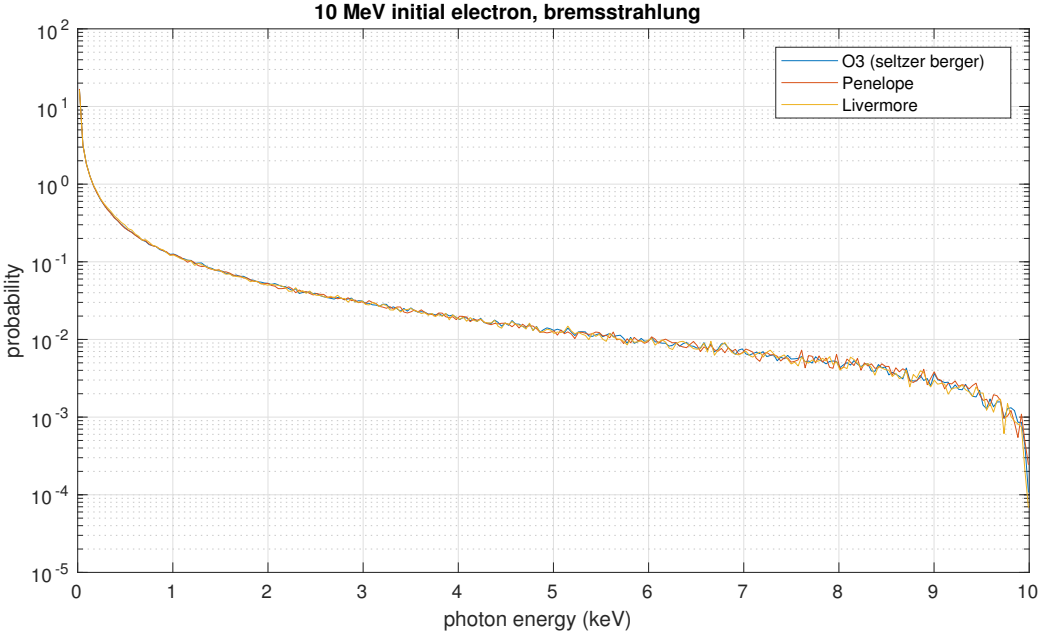
8.2 Multiple Scattering

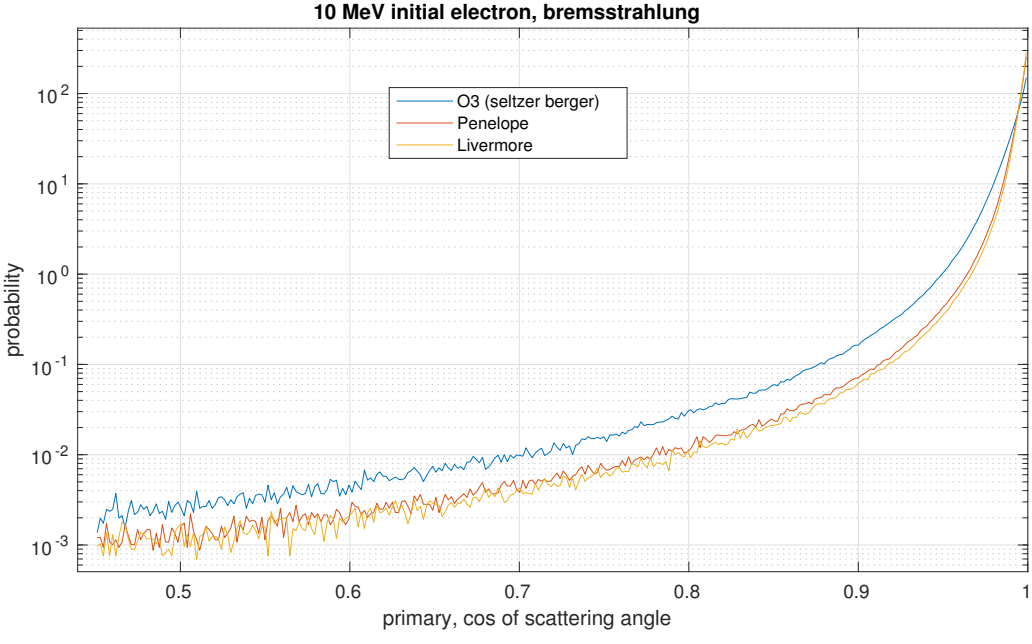


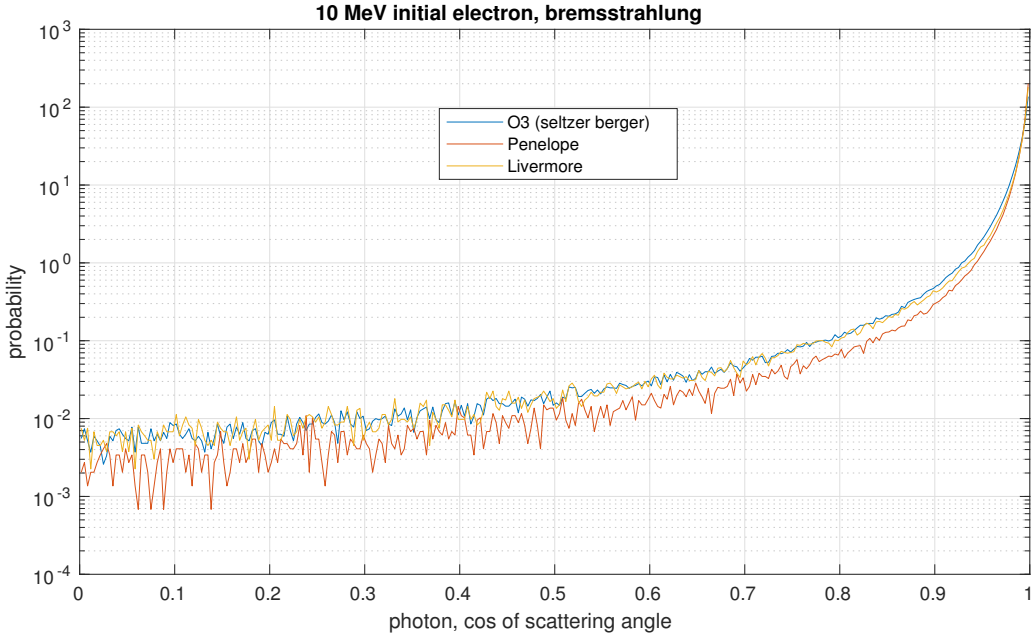
8.3 Bremsstrahlung



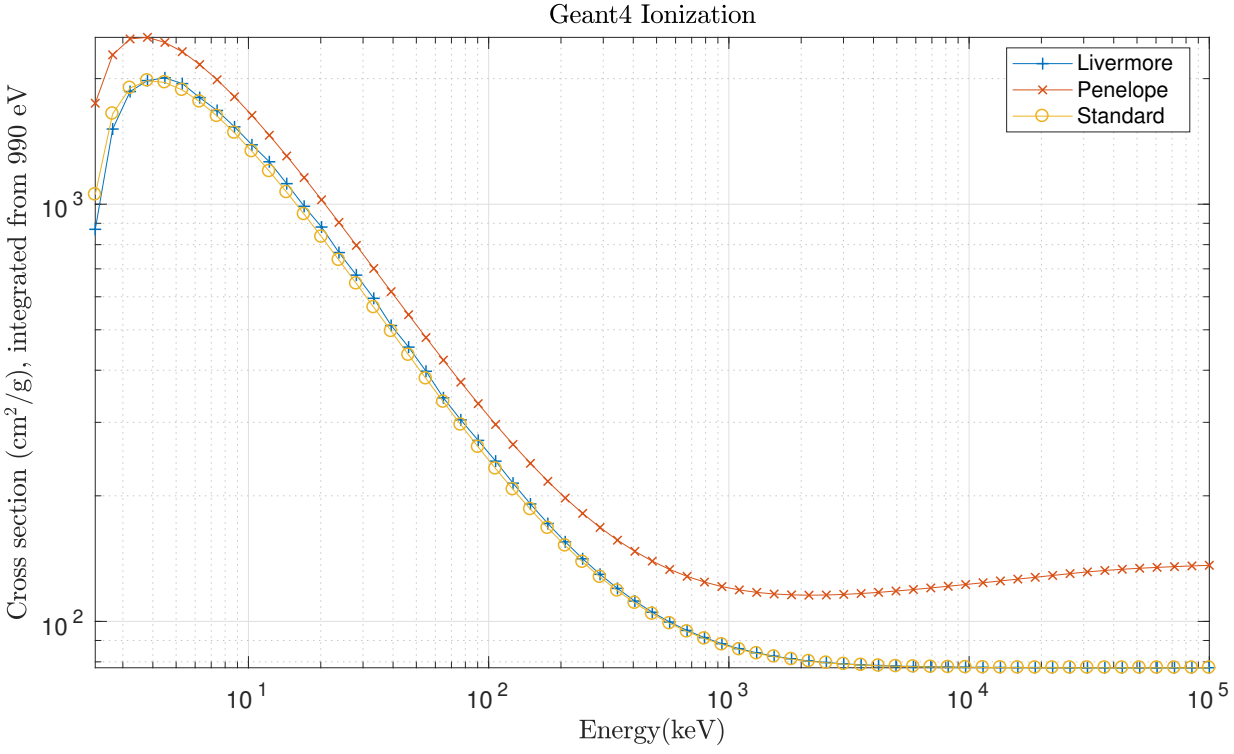


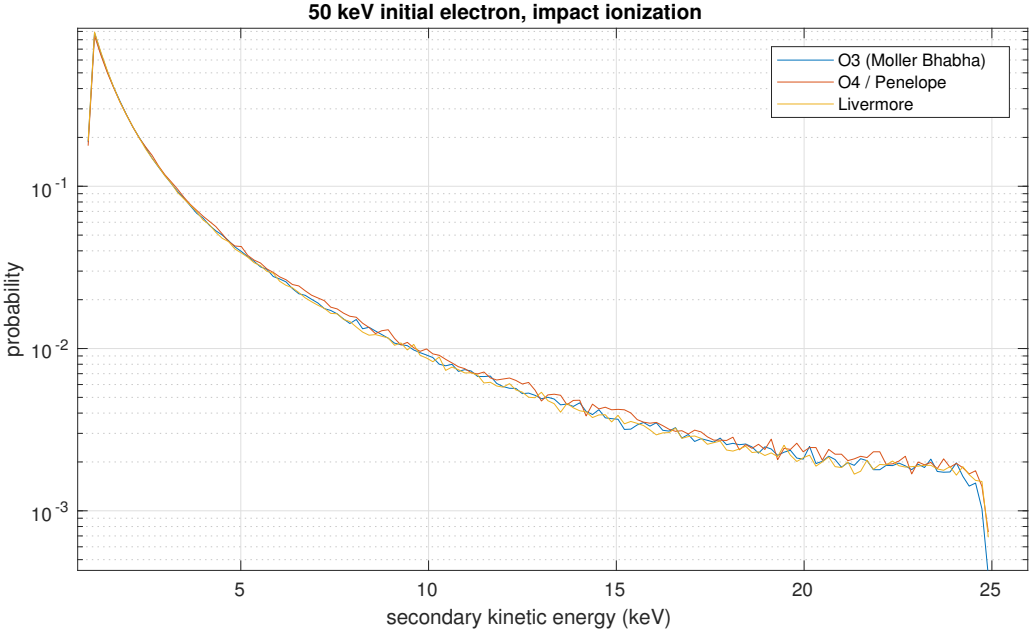

10 MeV initial electron, bremsstrahlung
O3 (seltzer berger)
Penelope
Livermore
probability
photon energy (keV)

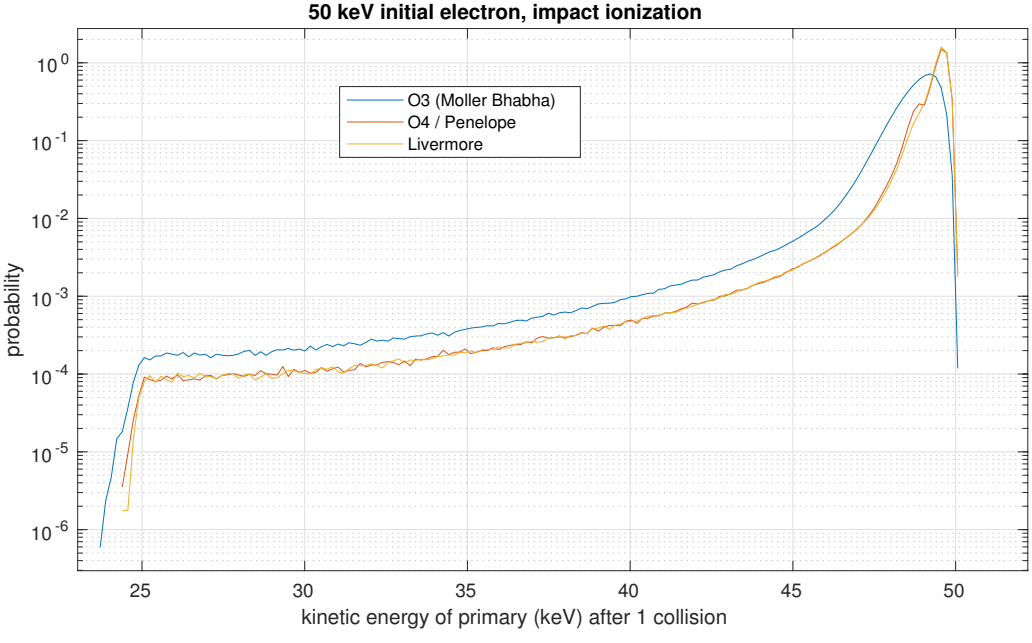

10 MeV initial electron, bremsstrahlung
O3 (seltzer berger)
Penelope
Livermore
probability
primary, cos of scattering angle

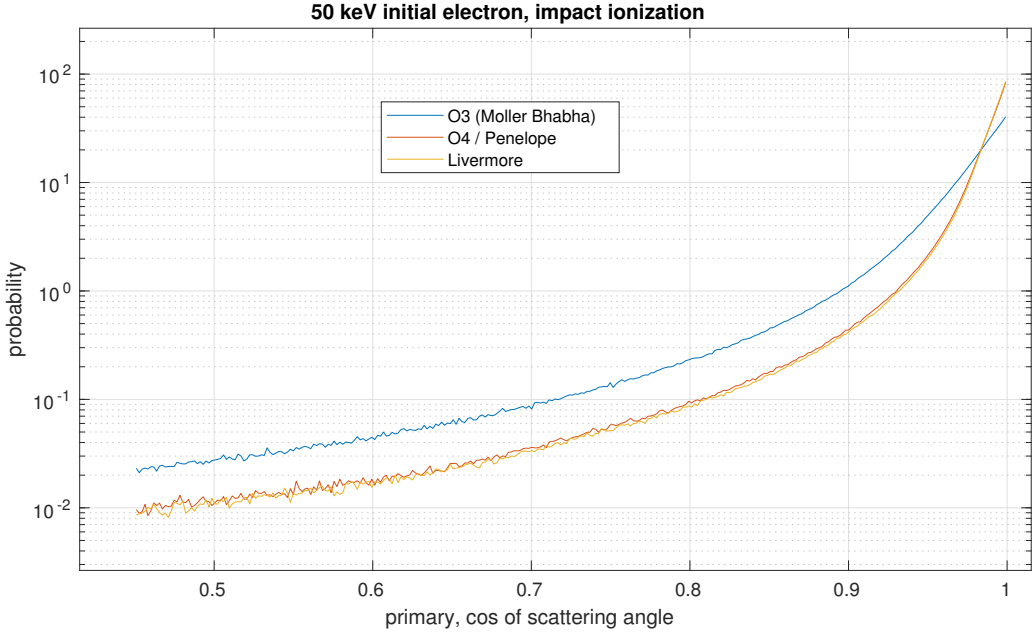


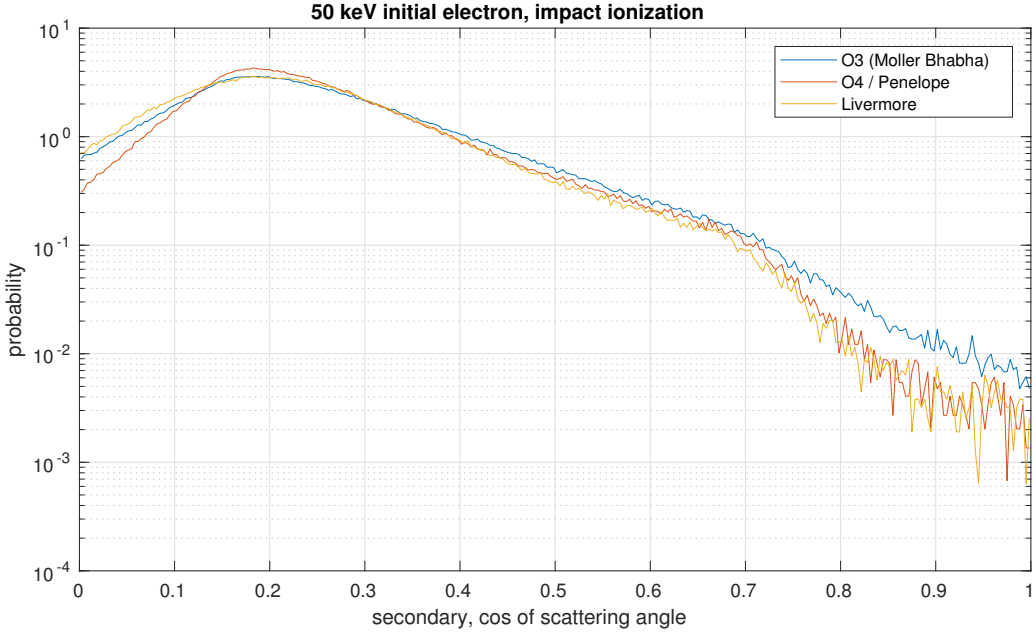
8.4 Impact Ionization



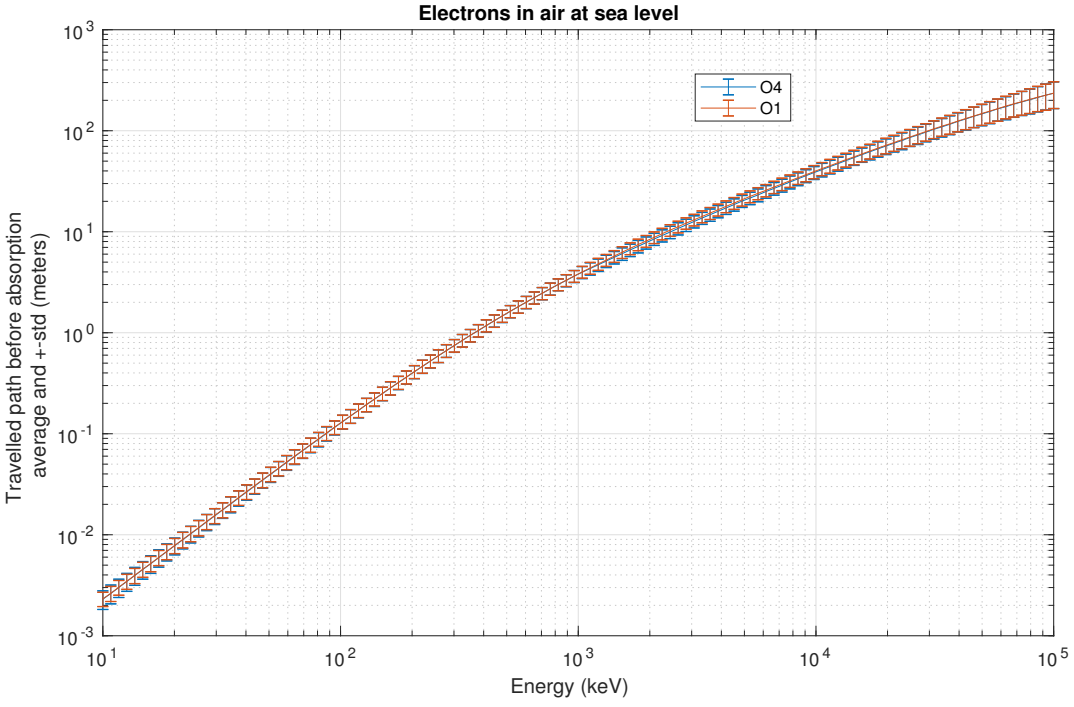

50 keV initial electron, impact ionization
O3 (Moller Bhabha)
O4 / Penelope
Livermore
probability
secondary kinetic energy (keV)

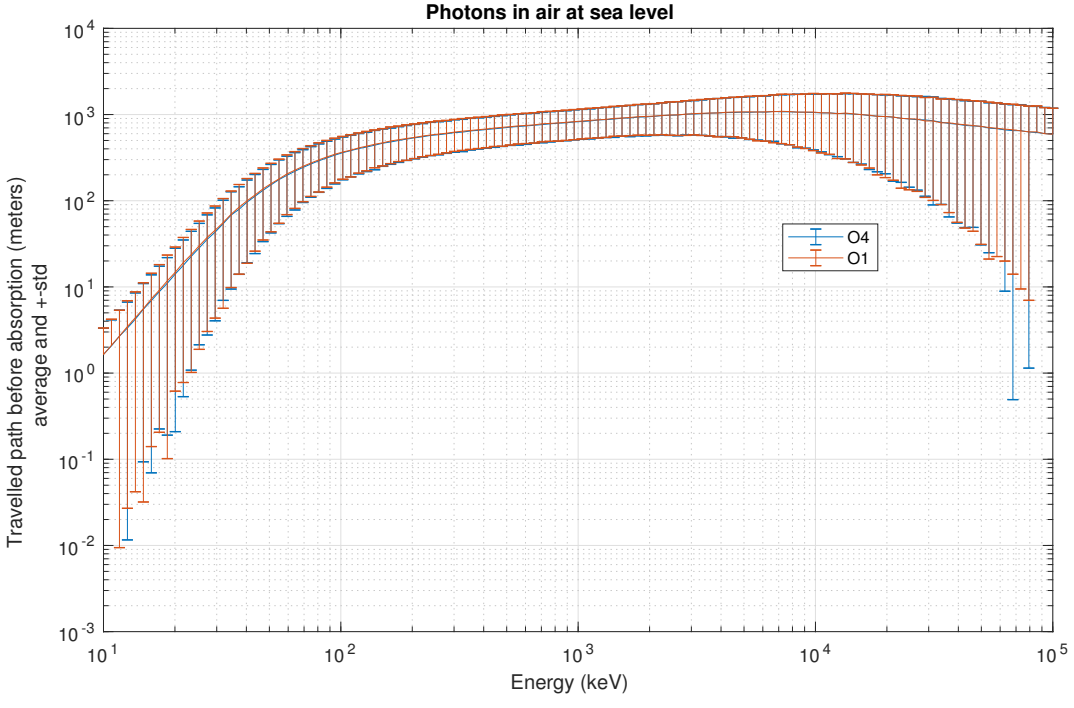

50 keV initial electron, impact ionization
O3 (Moller Bhabha)
O4 / Penelope
Livermore
probability
kinetic energy of primary (keV) after 1 collision


50 keV initial electron, impact ionization
O3 (Moller Bhabha)
O4 / Penelope
Livermore
probability
primary, cos of scattering angle


50 keV initial electron, impact ionization
O3 (Moller Bhabha)
O4 / Penelope
Livermore
probability
secondary, cos of scattering angle

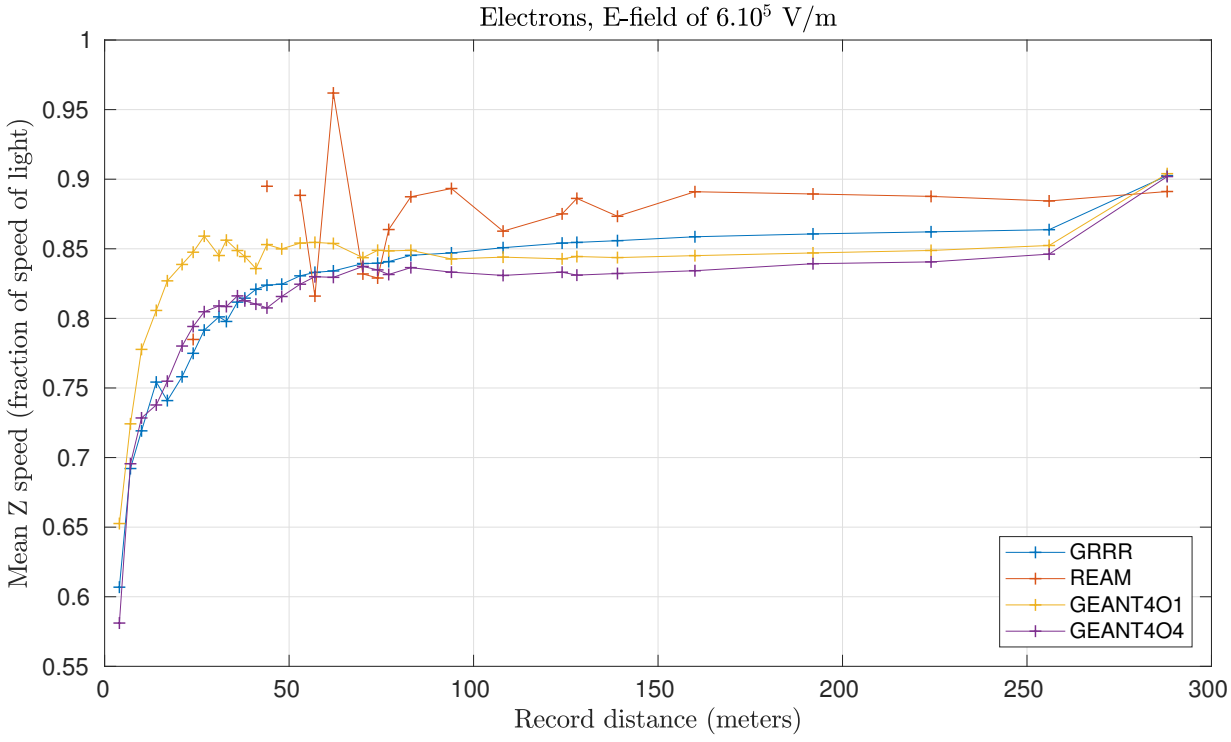
8.5 Travel Path Length

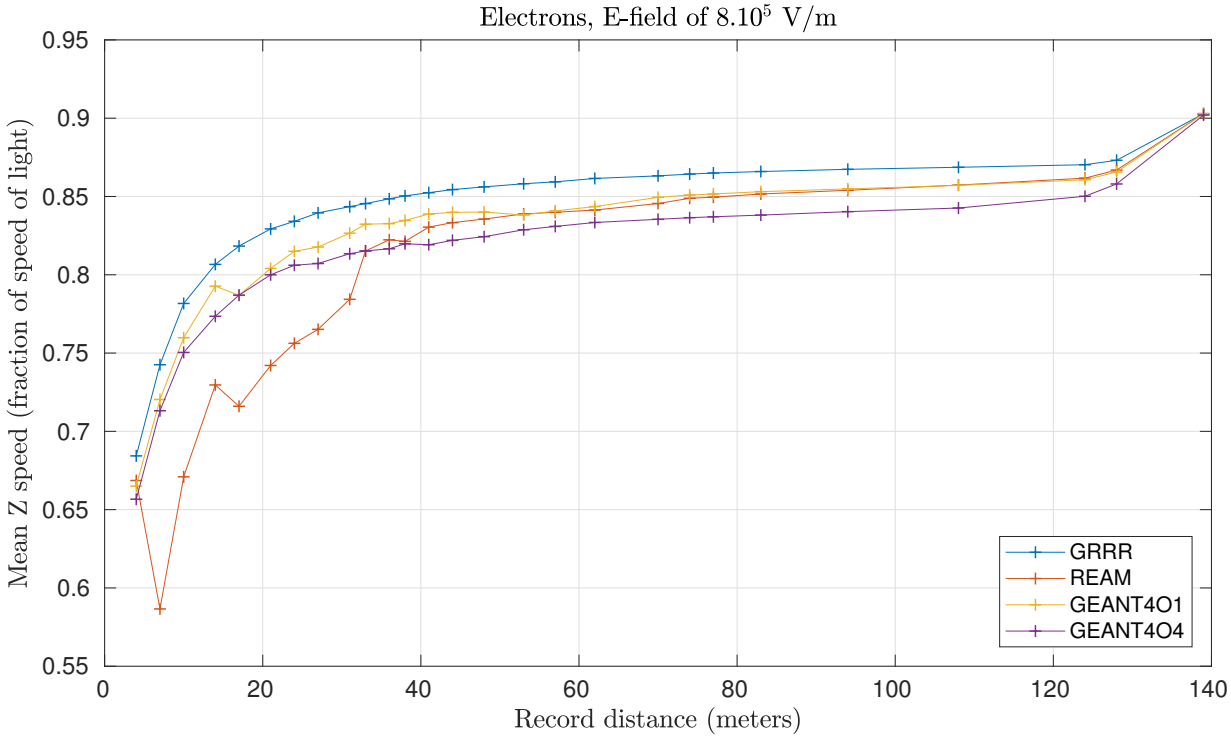


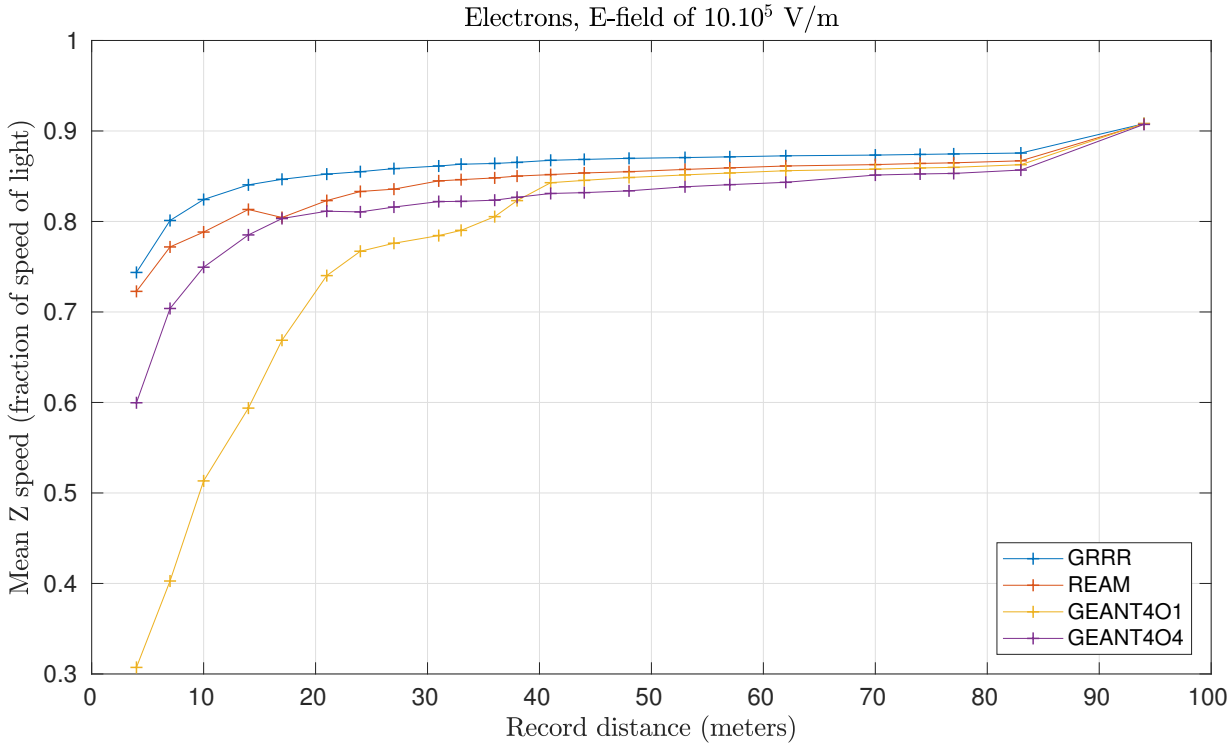


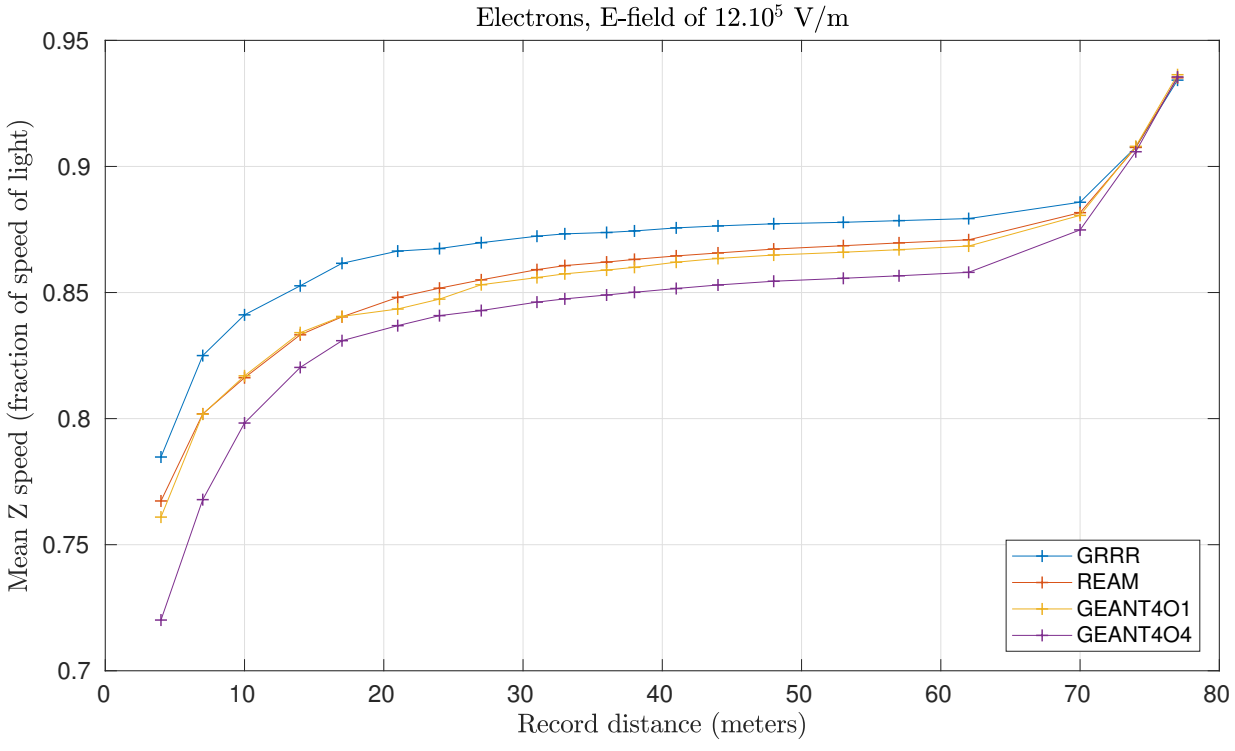
9 Mean Speed

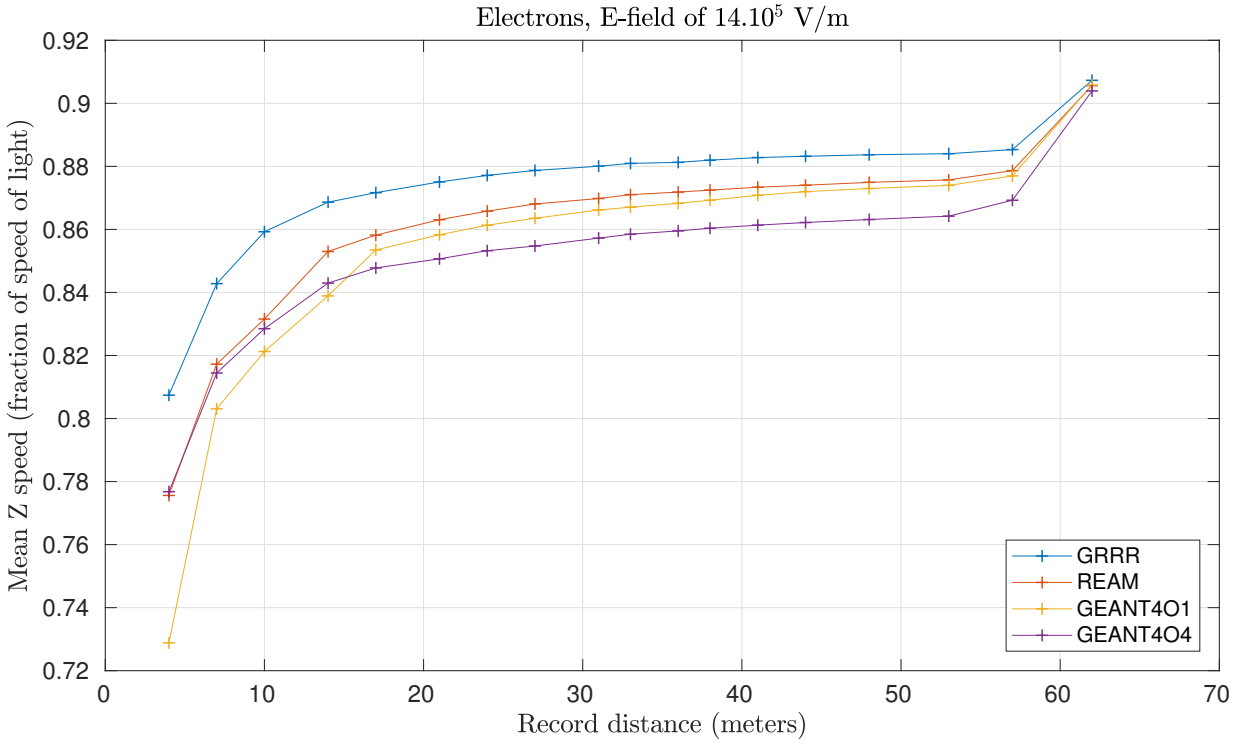
9.1 Code Comparison

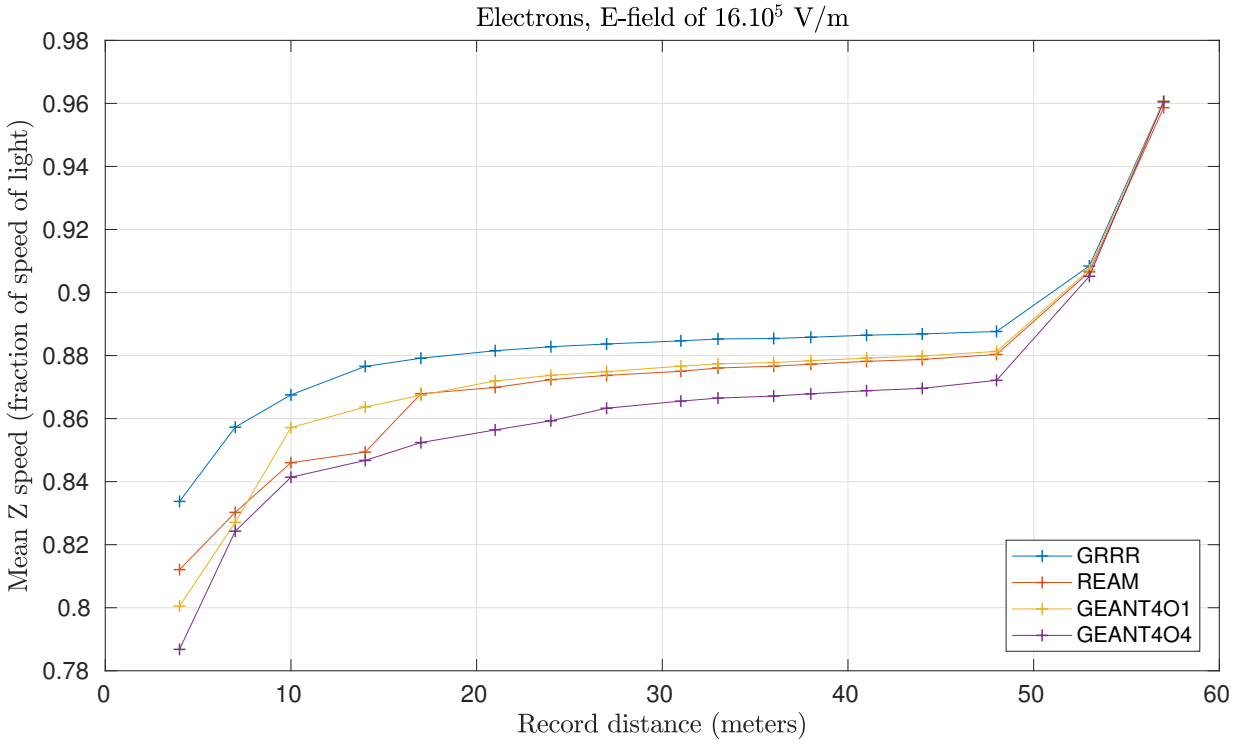


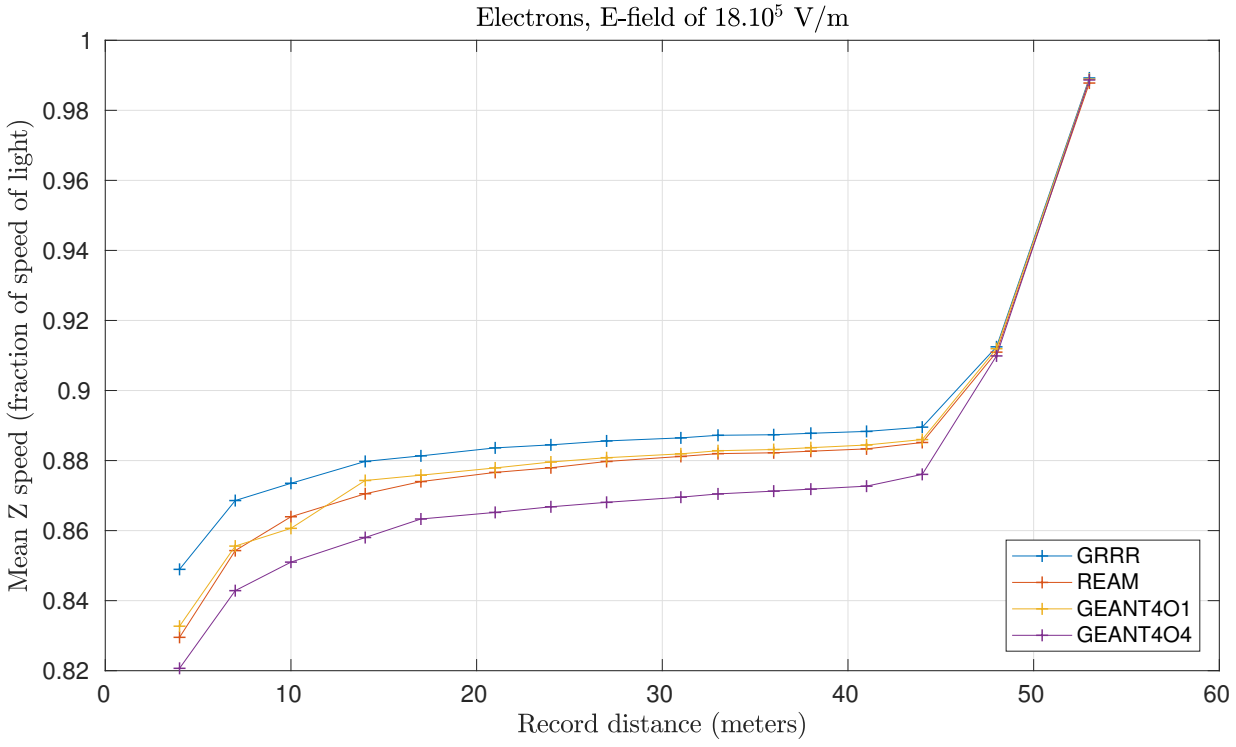


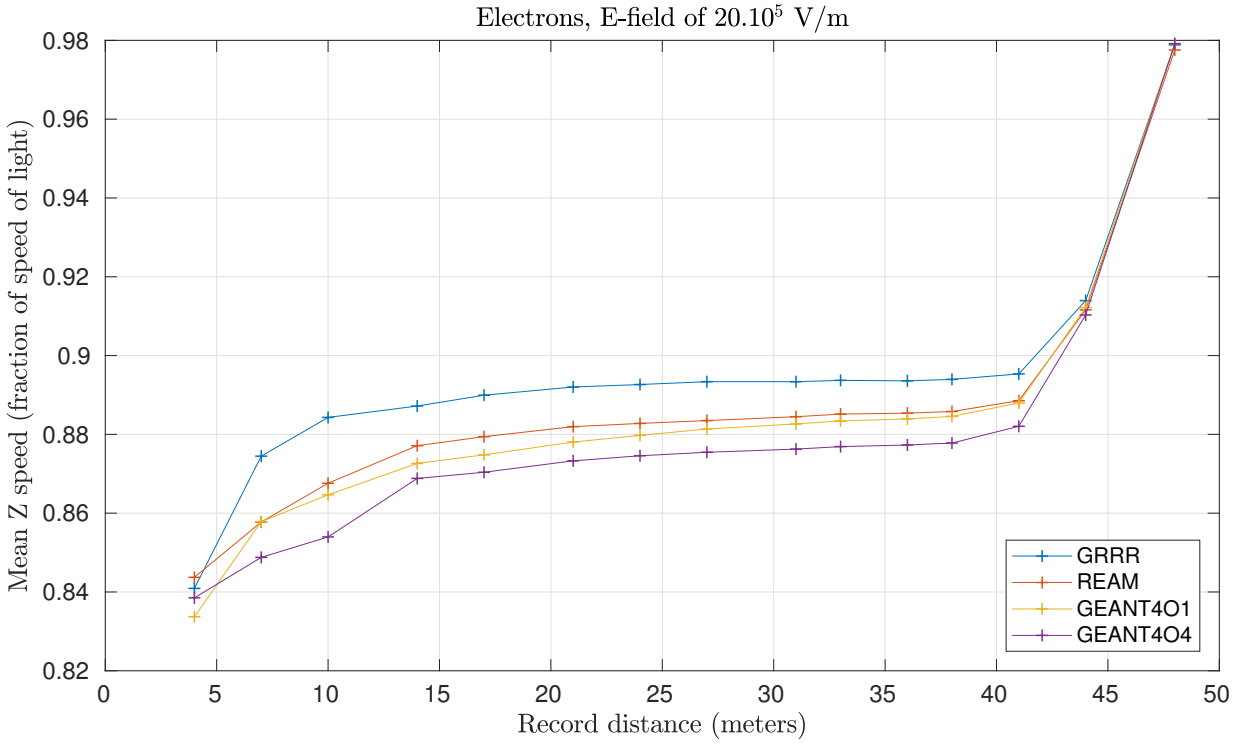

Electrons, E-field of 10.10^5 V/m
Mean Z speed (fraction of speed of light)
Record distance (meters)
GRRR
REAM
GEANT4O1
GEANT4O4

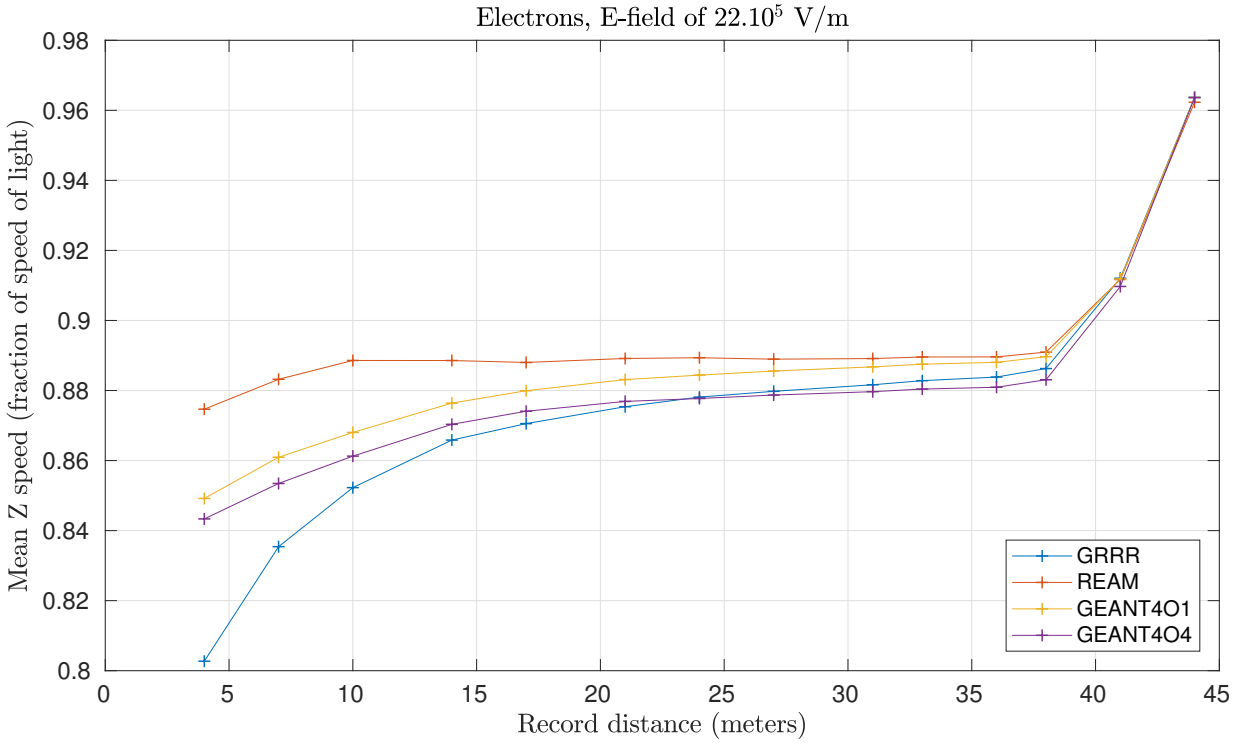

Electrons, E-field of 12.10^5 V/m
Mean Z speed (fraction of speed of light)
Record distance (meters)
GRRR
REAM
GEANT4O1
GEANT4O4

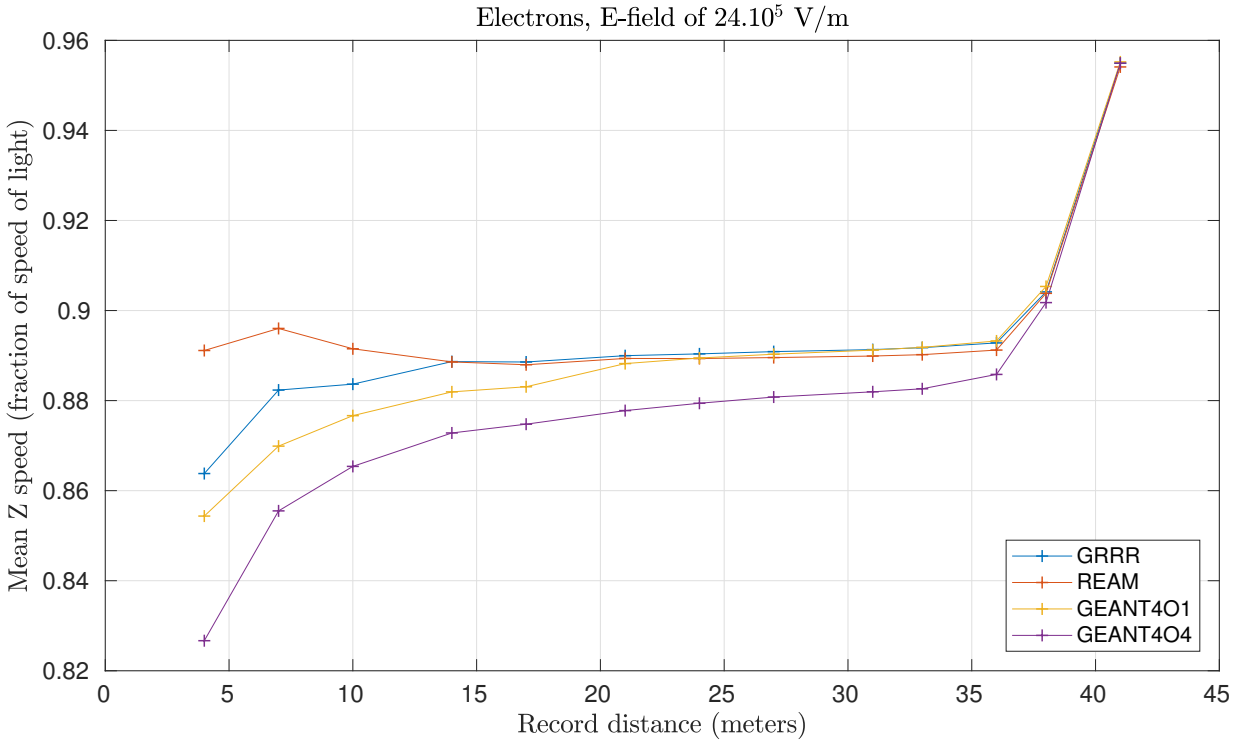

Electrons, E-field of 14.10^5 V/m
Mean Z speed (fraction of speed of light)
Record distance (meters)
0.92
0.9
0.88
0.86
0.84
0.82
0.8
0.78
0.76
0.74
0.72
0
10
20
30
40
50
60
70
GRRR
REAM
GEANT4O1
GEANT4O4

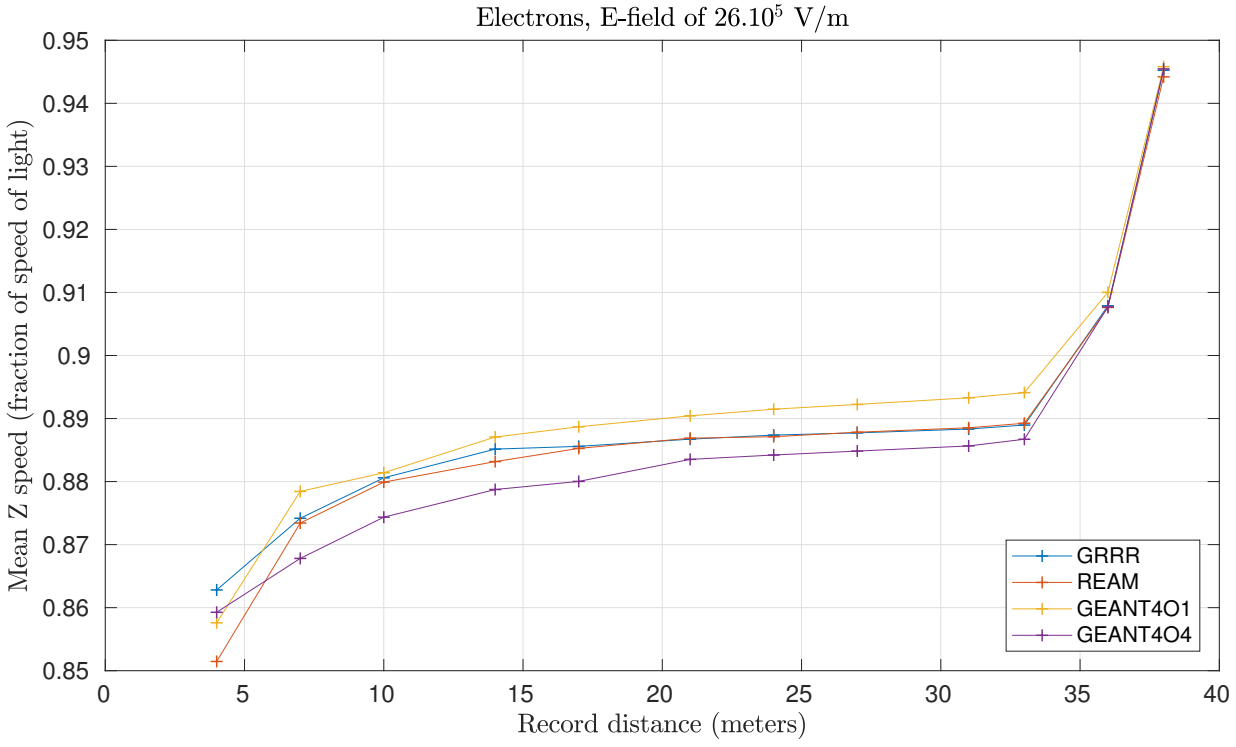

Electrons, E-field of 16.10^5 V/m
Mean Z speed (fraction of speed of light)
Record distance (meters)
0.98
0.96
0.94
0.92
0.9
0.88
0.86
0.84
0.82
0.8
0.78
0
10
20
30
40
50
60
GRRR
REAM
GEANT4O1
GEANT4O4

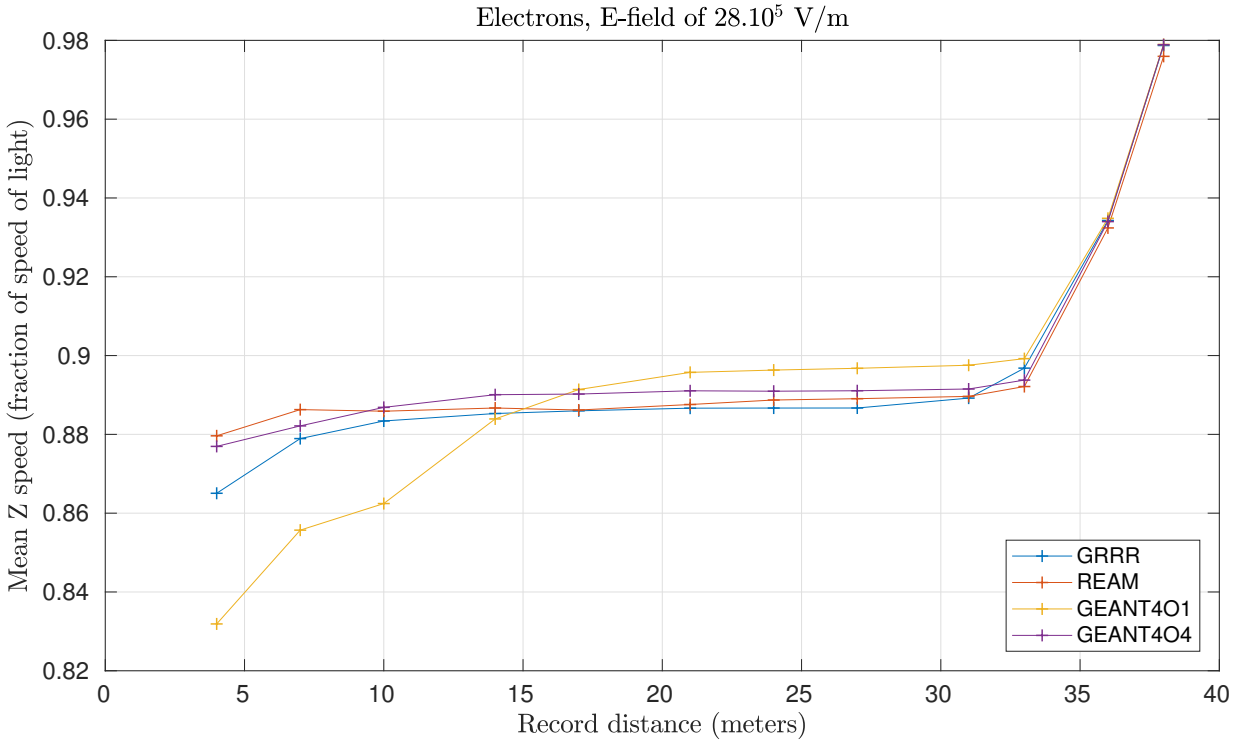

Electrons, E-field of 18.10^5 V/m
Mean Z speed (fraction of speed of light)
Record distance (meters)
GRRR
REAM
GEANT4O1
GEANT4O4


Electrons, E-field of 20.10^5 V/m
Mean Z speed (fraction of speed of light)
Record distance (meters)
GRRR
REAM
GEANT4O1
GEANT4O4

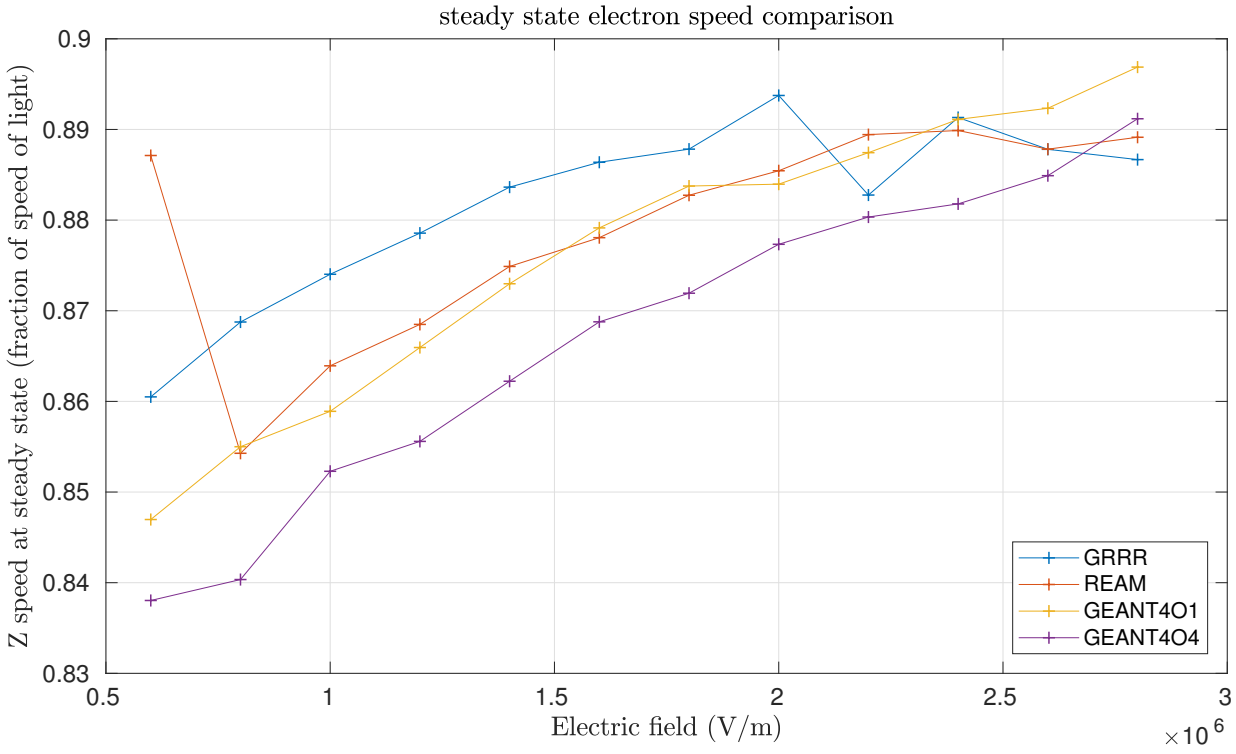

Electrons, E-field of 22.10^5 V/m
Mean Z speed (fraction of speed of light)
Record distance (meters)
GRRR
REAM
GEANT4O1
GEANT4O4


Electrons, E-field of 24.10^5 V/m
Mean Z speed (fraction of speed of light)
Record distance (meters)
GRRR
REAM
GEANT4O1
GEANT4O4

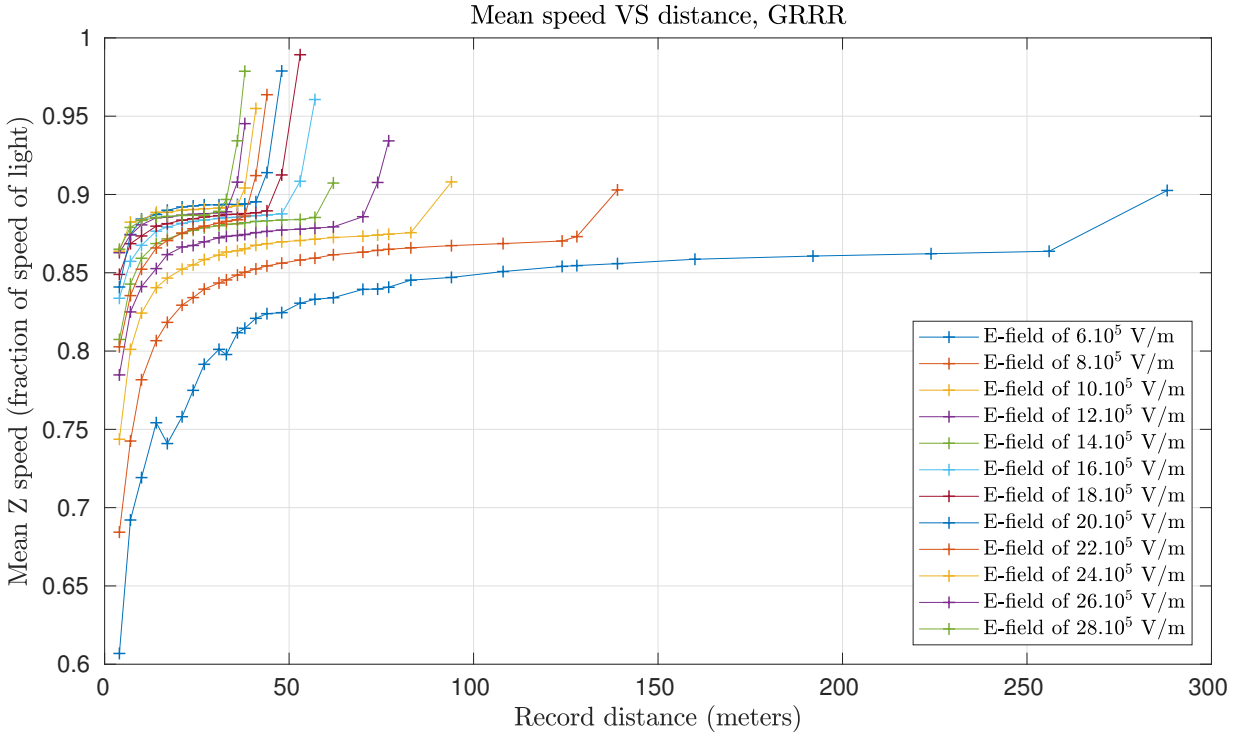

Electrons, E-field of 26.10^5 V/m
Mean Z speed (fraction of speed of light)
Record distance (meters)
0.95
0.94
0.93
0.92
0.91
0.9
0.89
0.88
0.87
0.86
0.85
0
5
10
15
20
25
30
35
40
GRRR
REAM
GEANT4O1
GEANT4O4

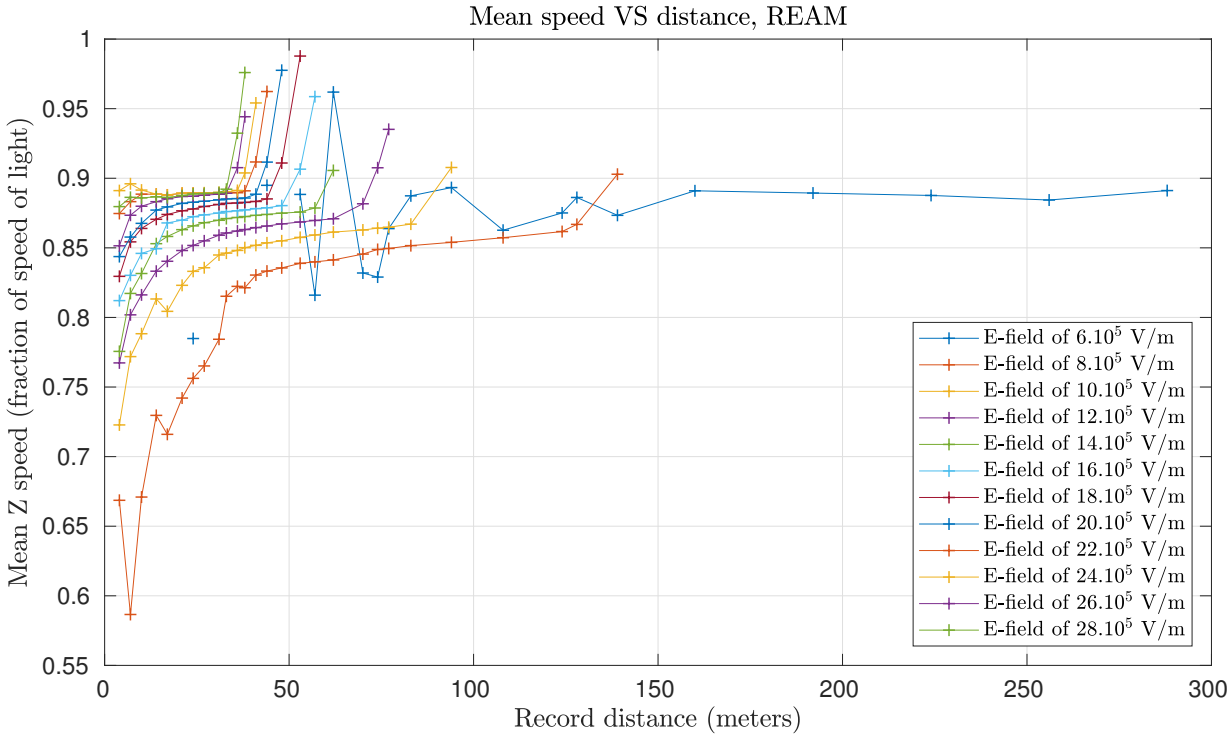

Electrons, E-field of 28.10^5 V/m
Mean Z speed (fraction of speed of light)
Record distance (meters)
0.98
0.96
0.94
0.92
0.9
0.88
0.86
0.84
0.82
0
5
10
15
20
25
30
35
40
GRRR
REAM
GEANT4O1
GEANT4O4

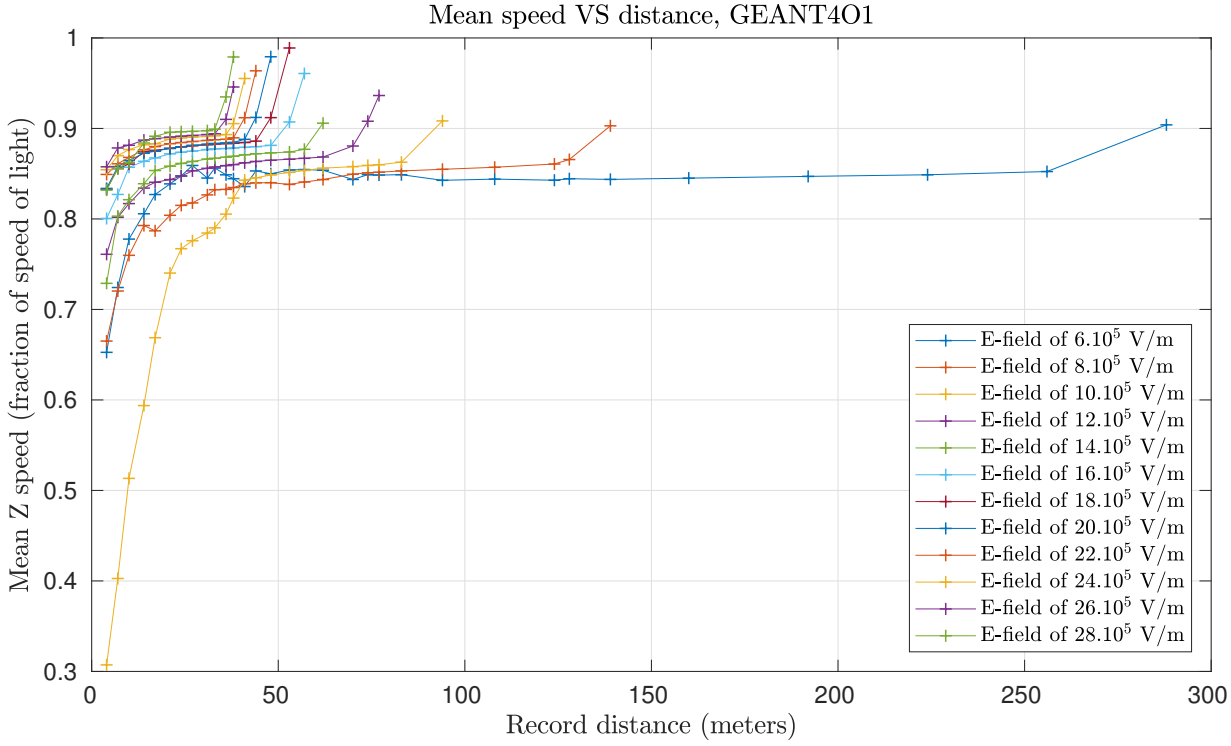
9.2 Steady State Speed Code Comparison

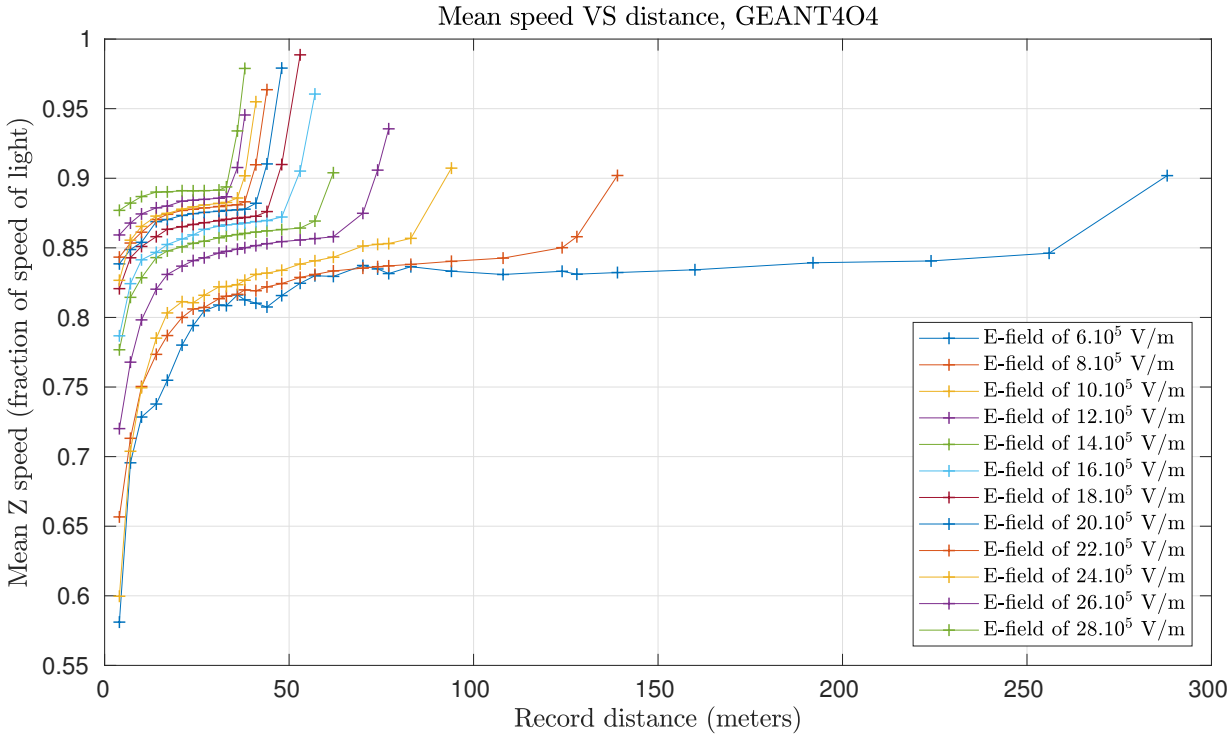


9.3 Code By Code



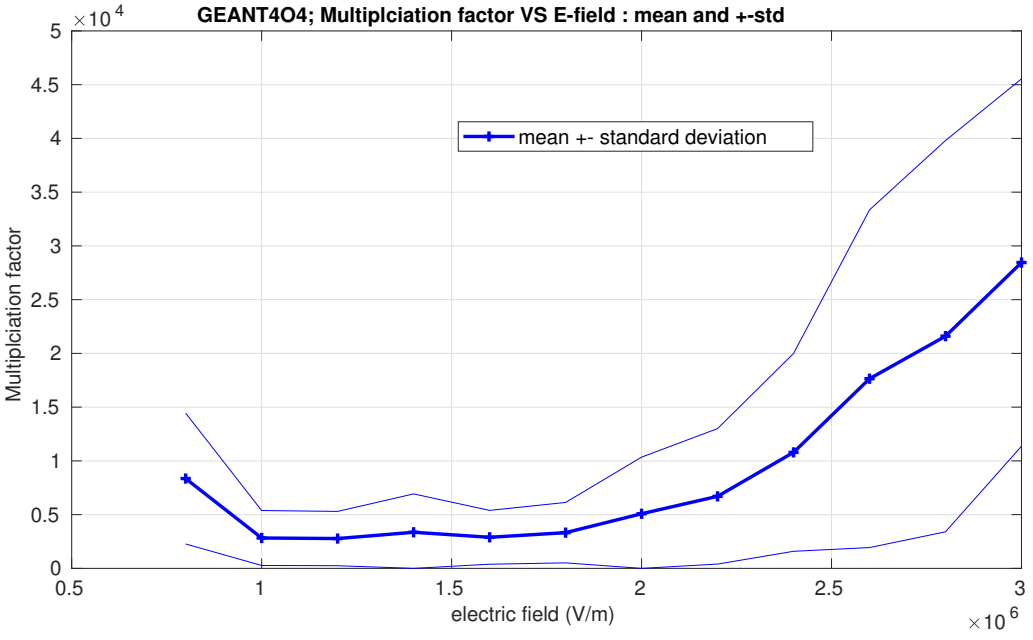

Mean speed VS distance, REAM
Mean Z speed (fraction of speed of light)
Record distance (meters)
E-field of 6.10^5 V/m
E-field of 8.10^5 V/m
E-field of 10.10^5 V/m
E-field of 12.10^5 V/m
E-field of 14.10^5 V/m
E-field of 16.10^5 V/m
E-field of 18.10^5 V/m
E-field of 20.10^5 V/m
E-field of 22.10^5 V/m
E-field of 24.10^5 V/m
E-field of 26.10^5 V/m
E-field of 28.10^5 V/m


Mean speed VS distance, GEANT4O1
Mean Z speed (fraction of speed of light)
Record distance (meters)
E-field of 6.10^5 V/m
E-field of 8.10^5 V/m
E-field of 10.10^5 V/m
E-field of 12.10^5 V/m
E-field of 14.10^5 V/m
E-field of 16.10^5 V/m
E-field of 18.10^5 V/m
E-field of 20.10^5 V/m
E-field of 22.10^5 V/m
E-field of 24.10^5 V/m
E-field of 26.10^5 V/m
E-field of 28.10^5 V/m

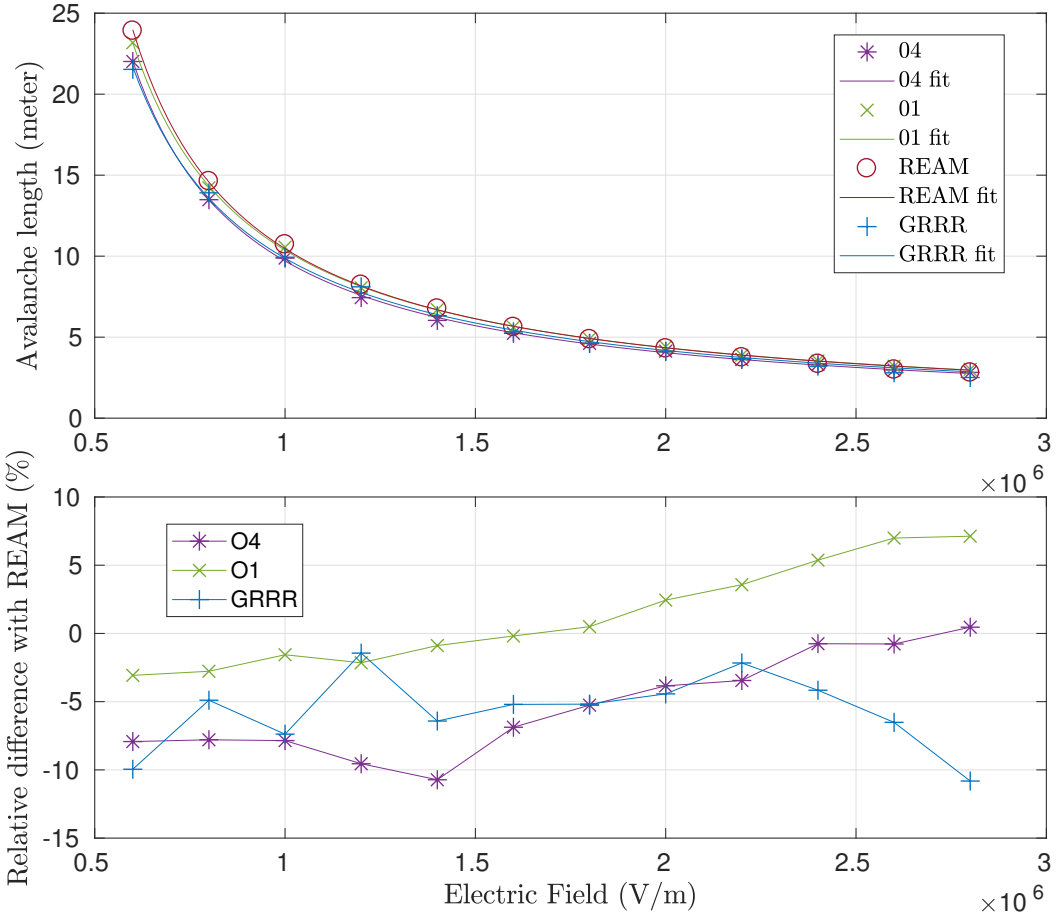

Mean speed VS distance, GEANT4O4
Mean Z speed (fraction of speed of light)
Record distance (meters)
1
0.95
0.9
0.85
0.8
0.75
0.7
0.65
0.6
0.55
0
50
100
150
200
250
300
E-field of 6.10^5 V/m
E-field of 8.10^5 V/m
E-field of 10.10^5 V/m
E-field of 12.10^5 V/m
E-field of 14.10^5 V/m
E-field of 16.10^5 V/m
E-field of 18.10^5 V/m
E-field of 20.10^5 V/m
E-field of 22.10^5 V/m
E-field of 24.10^5 V/m
E-field of 26.10^5 V/m
E-field of 28.10^5 V/m

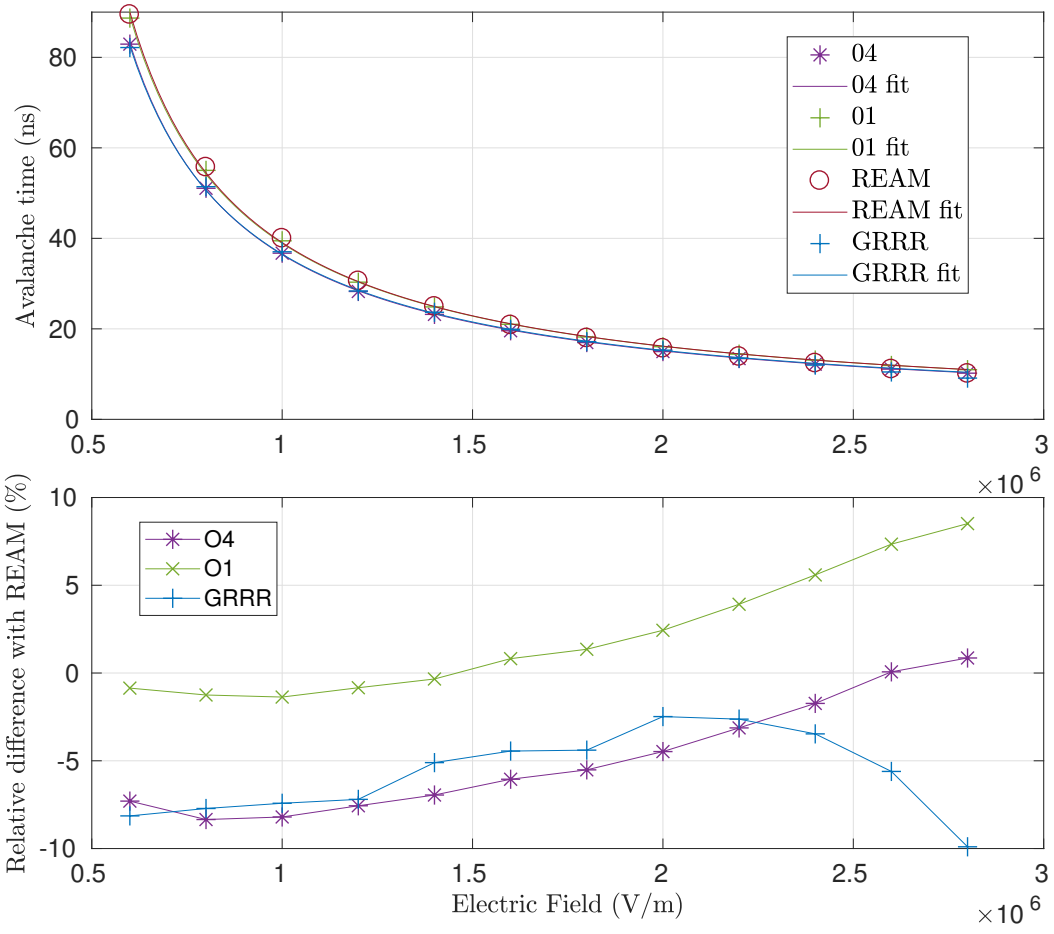
10 Multiplication Factors

10.1 Shower To Shower Fluctuations

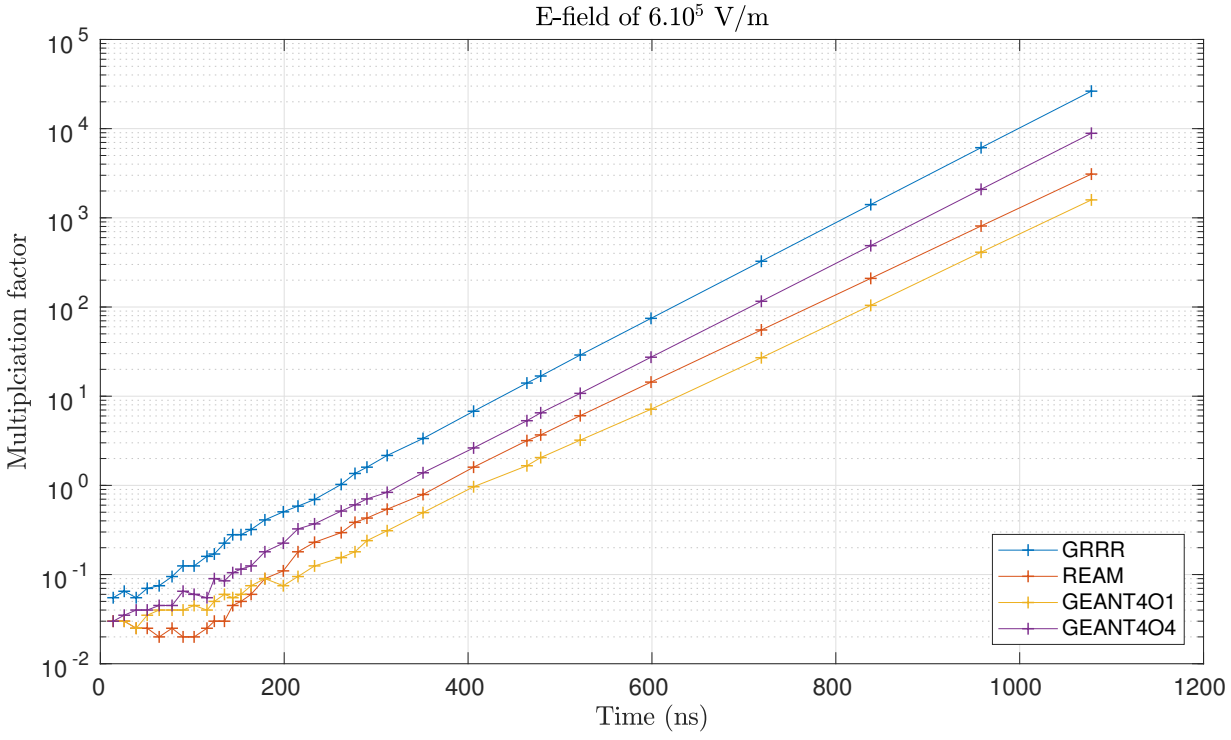


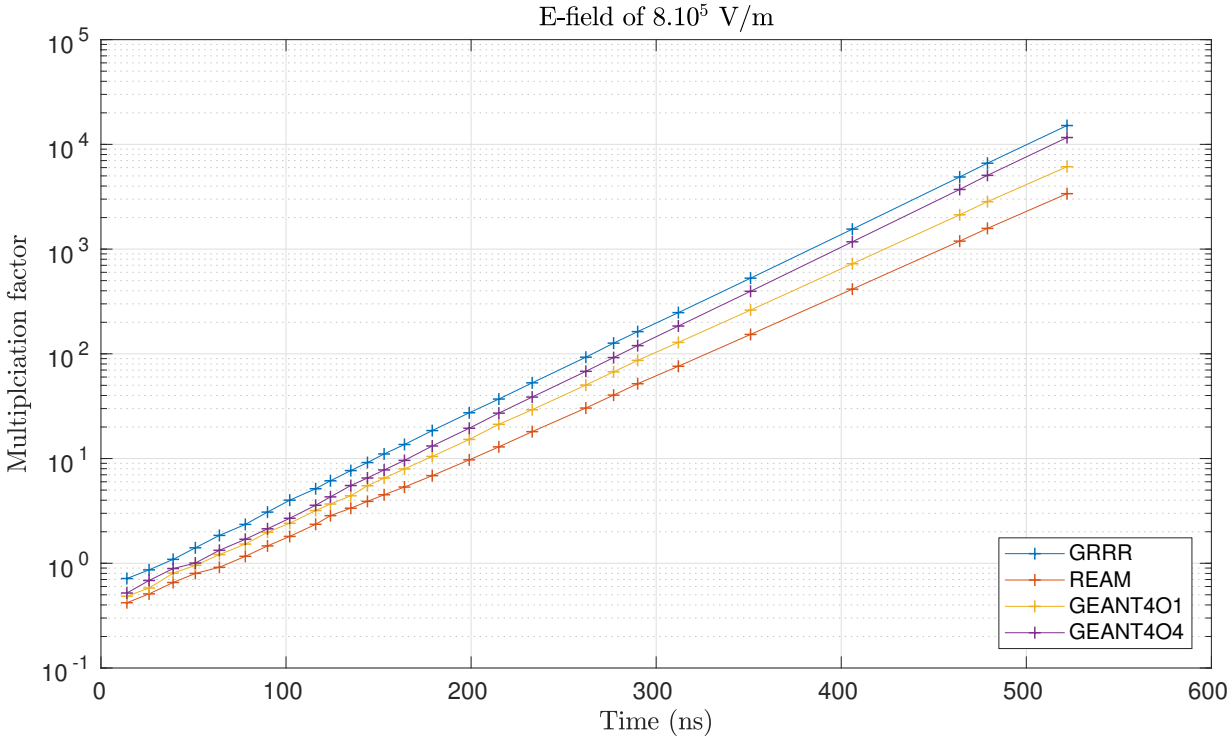
10.2 Avalanche Time And Length Code Comparison

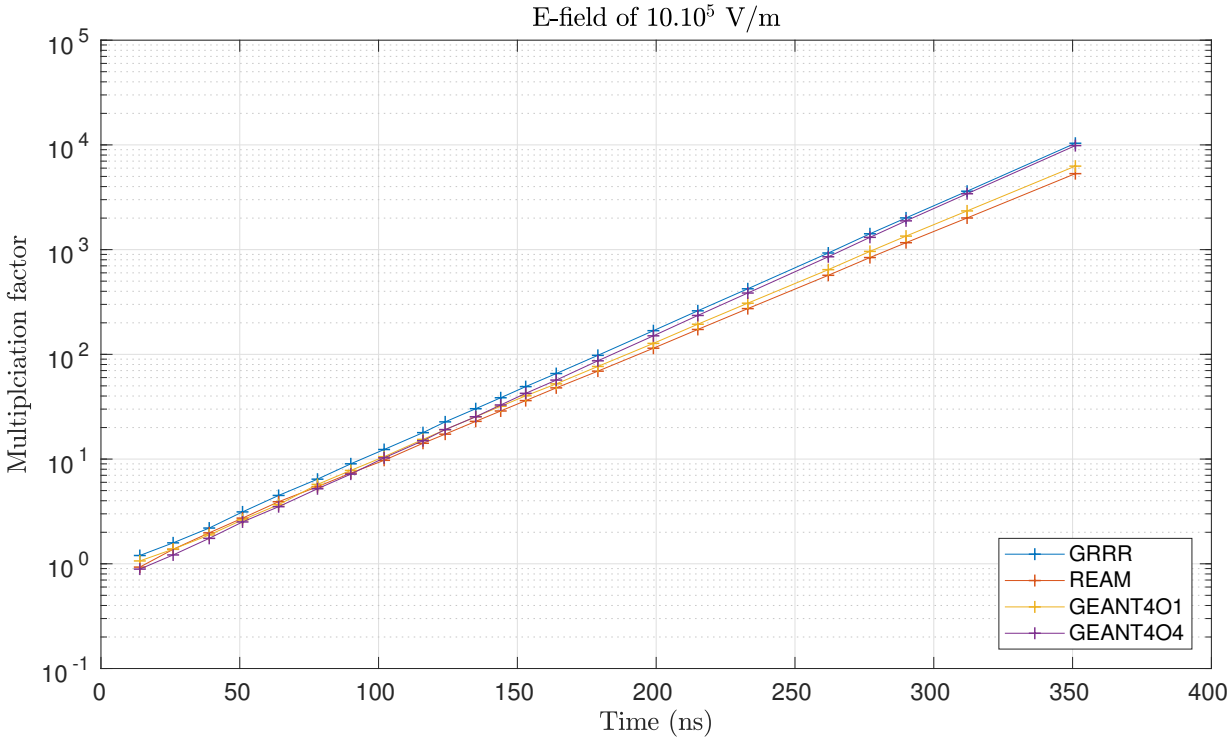


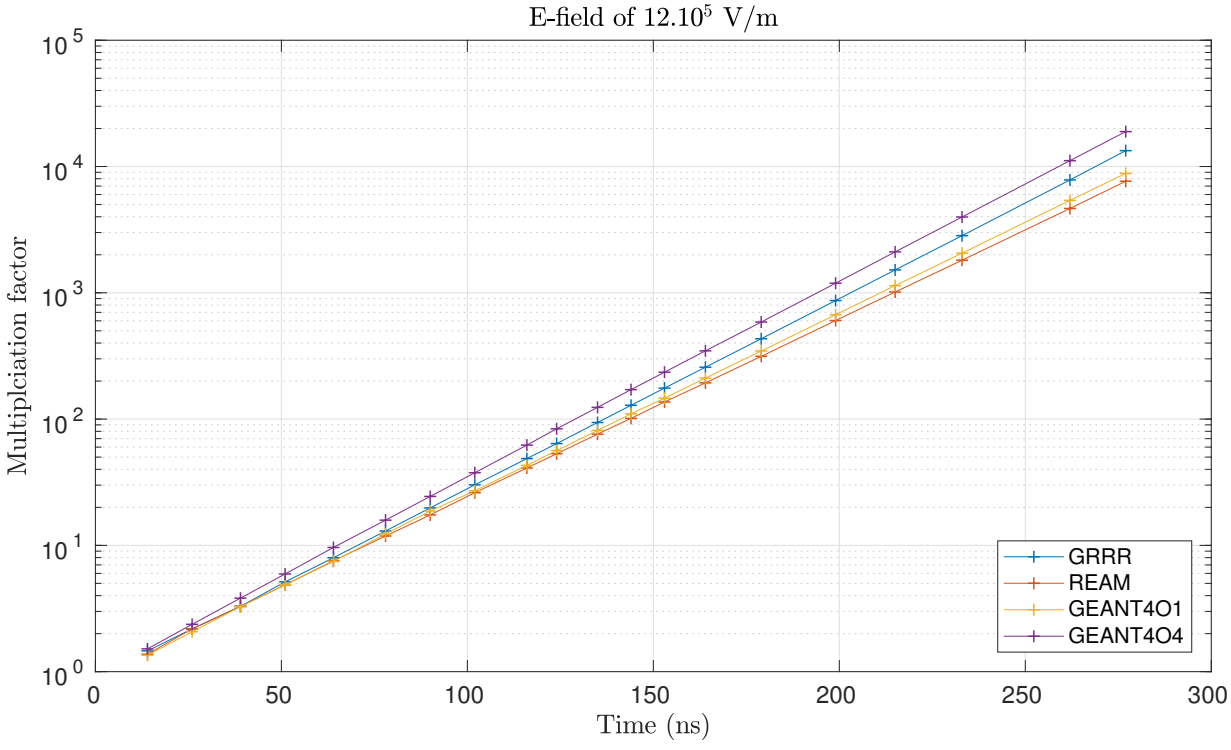

Avalanche time (ns)
04
04 fit
01
01 fit
REAM
REAM fit
GRRR
GRRR fit
×10 6
Relative difference with REAM (%)
O4
O1
GRRR
Electric Field (V/m)
×10 6

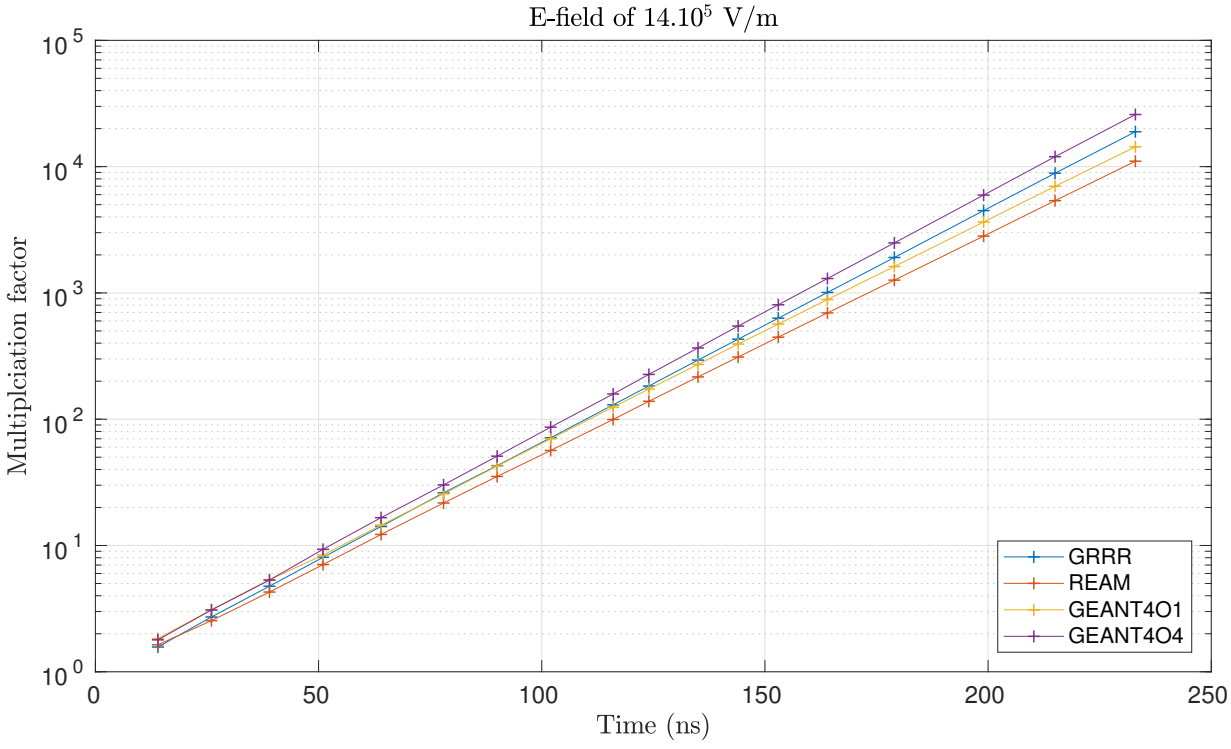
10.3 Time Record Code Comparison

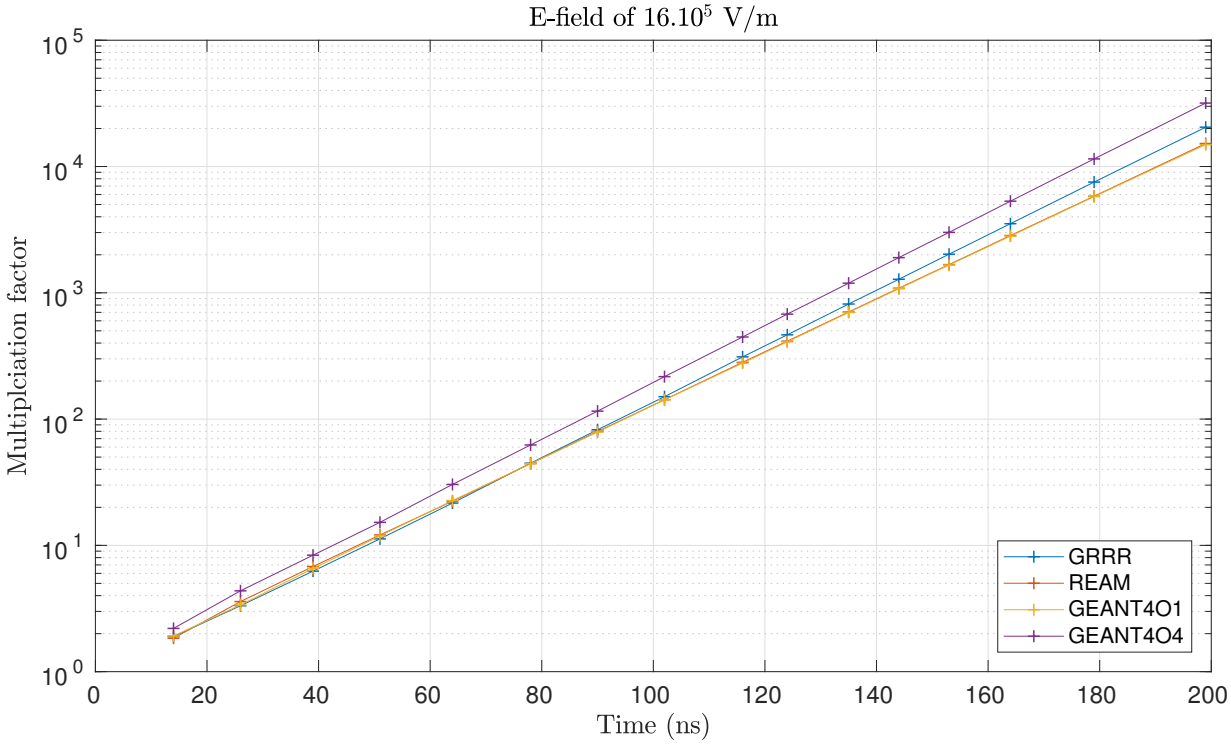


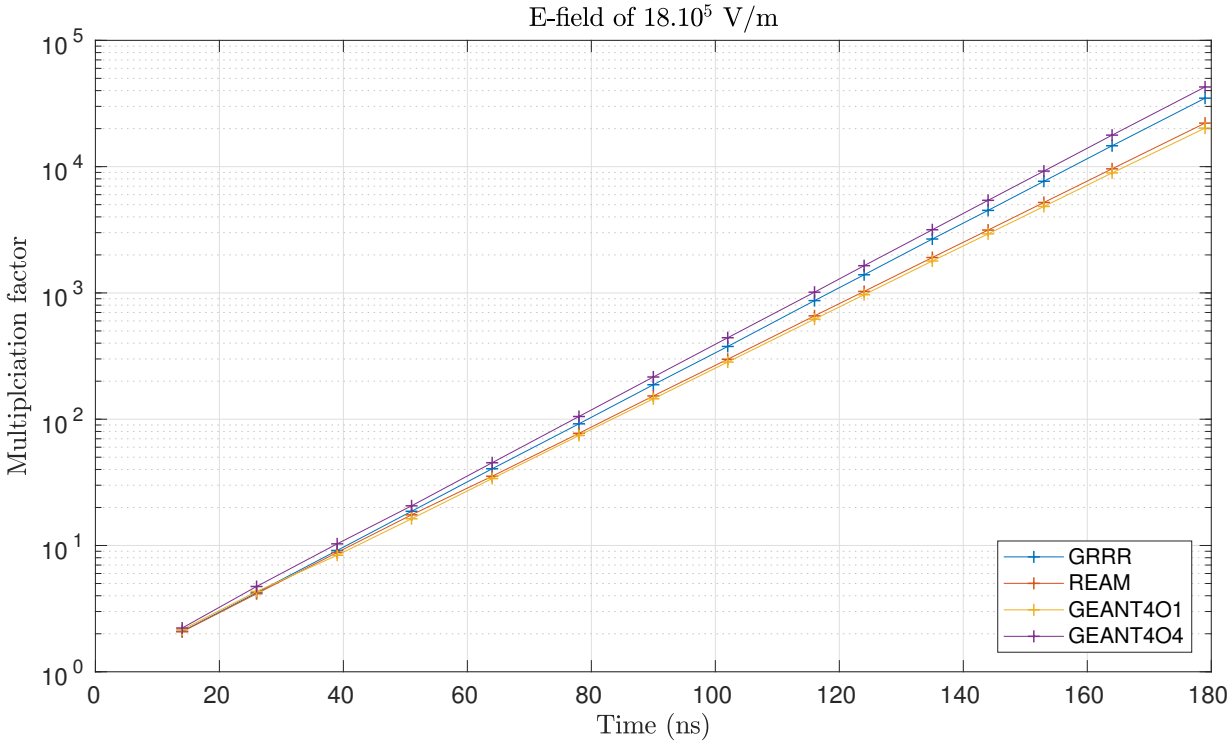


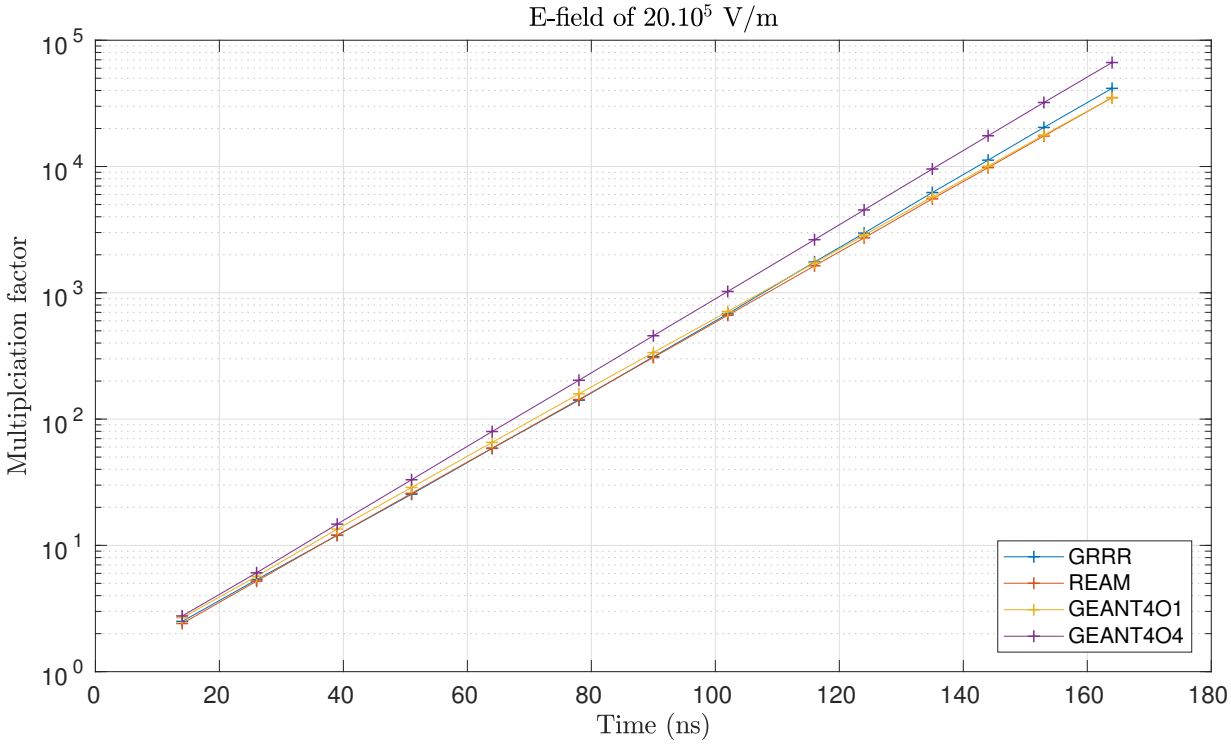

E-field of 10.10^5 V/m
Multiplciation factor
Time (ns)
GRRR
REAM
GEANT4O1
GEANT4O4

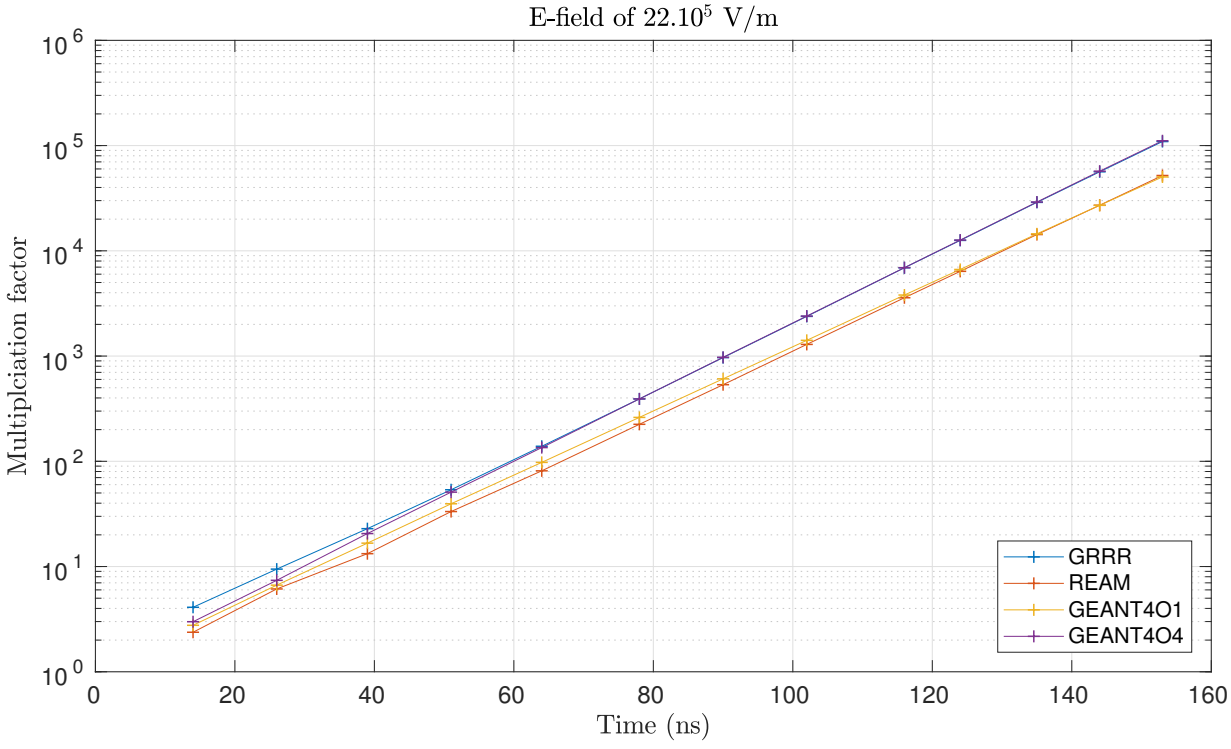

E-field of 12.10^5 V/m
Multiplciation factor
Time (ns)
GRRR
REAM
GEANT4O1
GEANT4O4

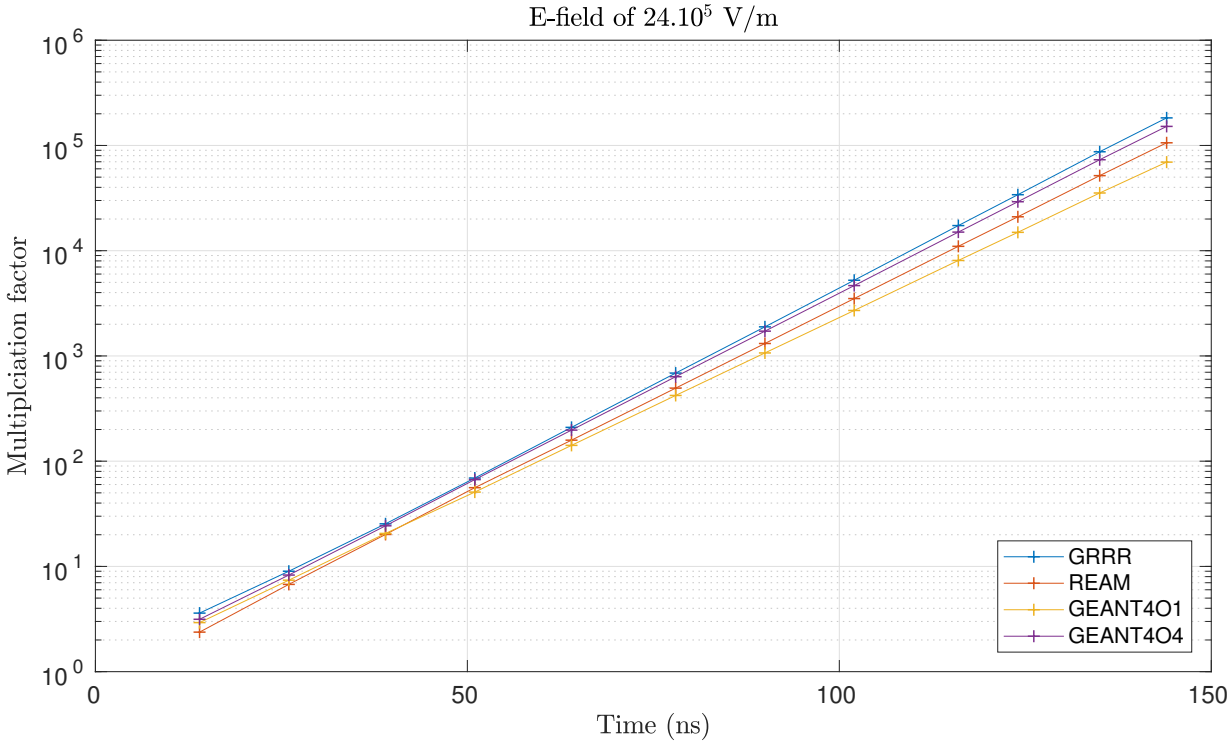

E-field of 14.10^5 V/m
Multiplciation factor
Time (ns)
GRRR
REAM
GEANT4O1
GEANT4O4

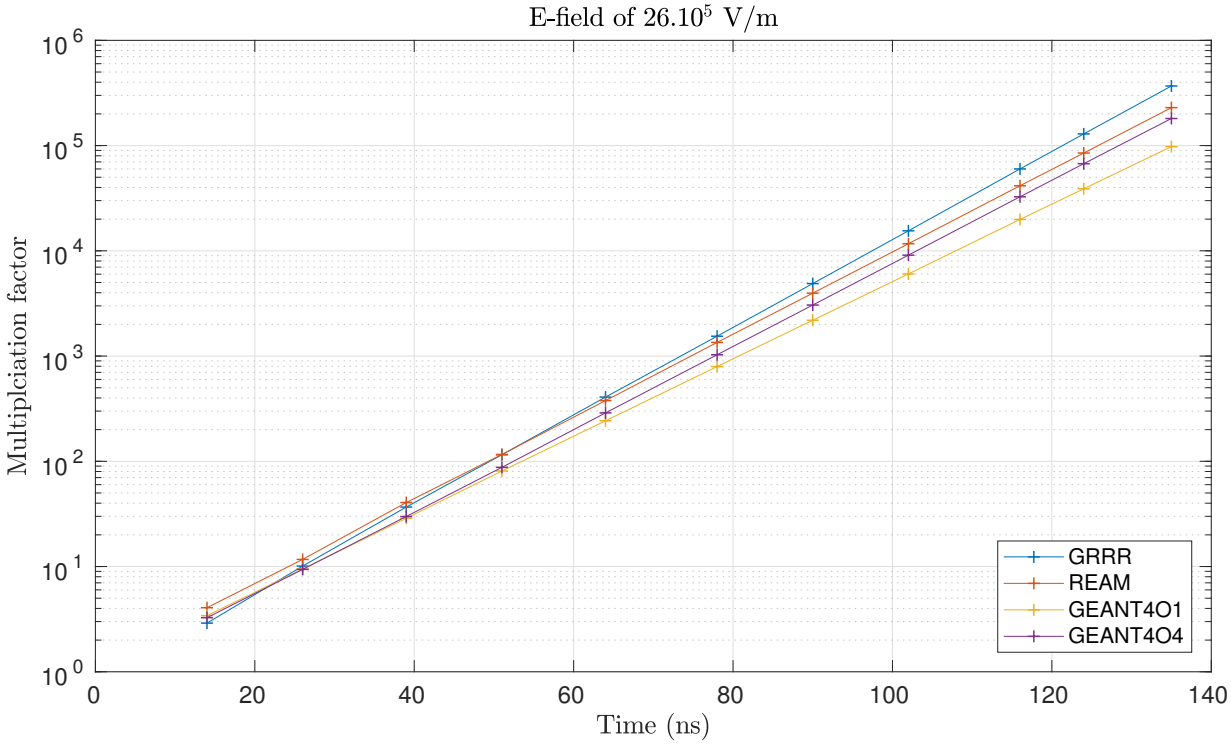

E-field of 16.10^5 V/m
Multiplciation factor
Time (ns)
GRRR
REAM
GEANT4O1
GEANT4O4

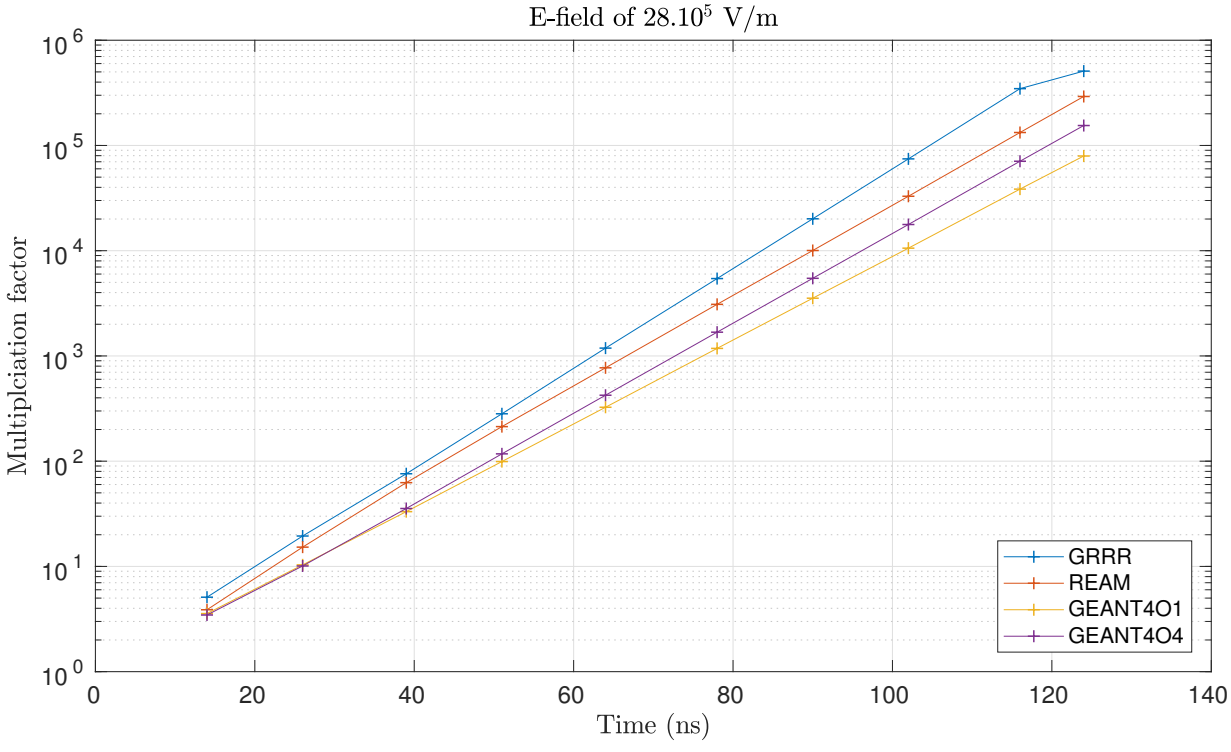

E-field of 18.10^5 V/m
Multiplciation factor
Time (ns)
GRRR
REAM
GEANT4O1
GEANT4O4

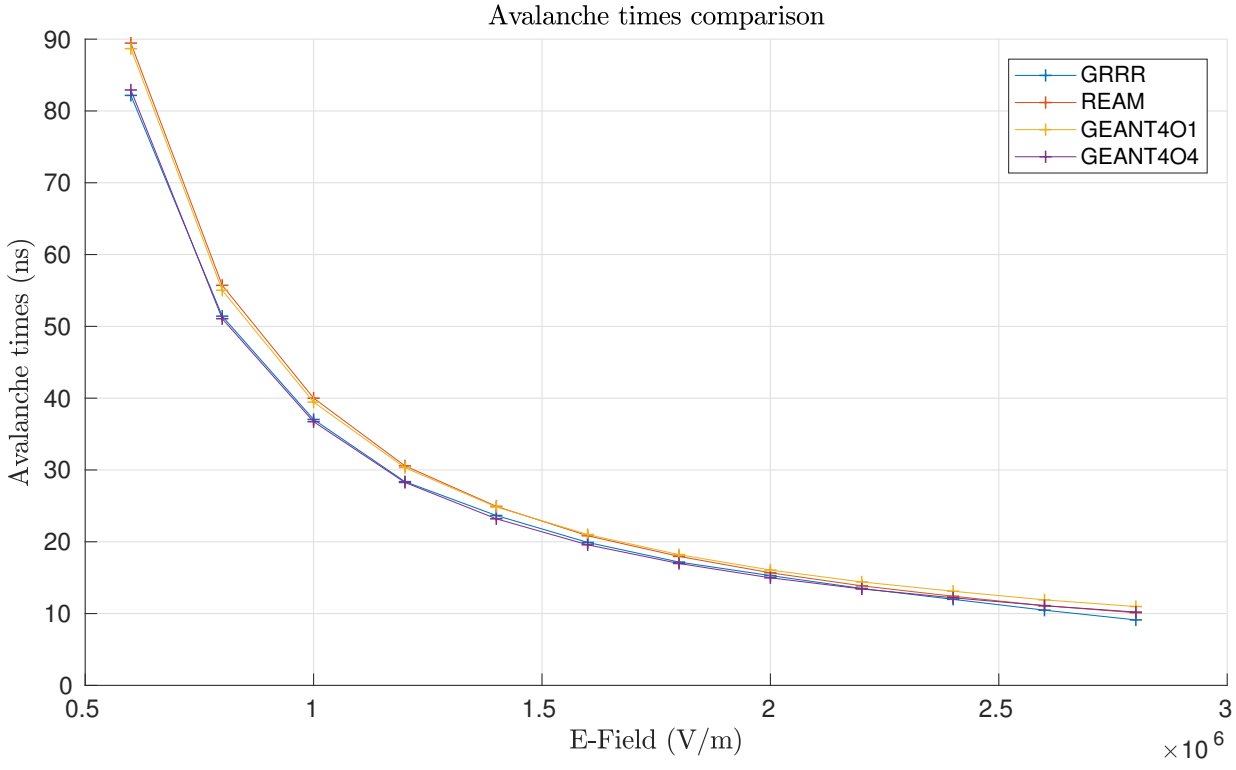

E-field of 20.10^5 V/m
Multiplciation factor
Time (ns)
GRRR
REAM
GEANT4O1
GEANT4O4


E-field of 22.10^5 V/m
Multiplciation factor
Time (ns)
GRRR
REAM
GEANT4O1
GEANT4O4

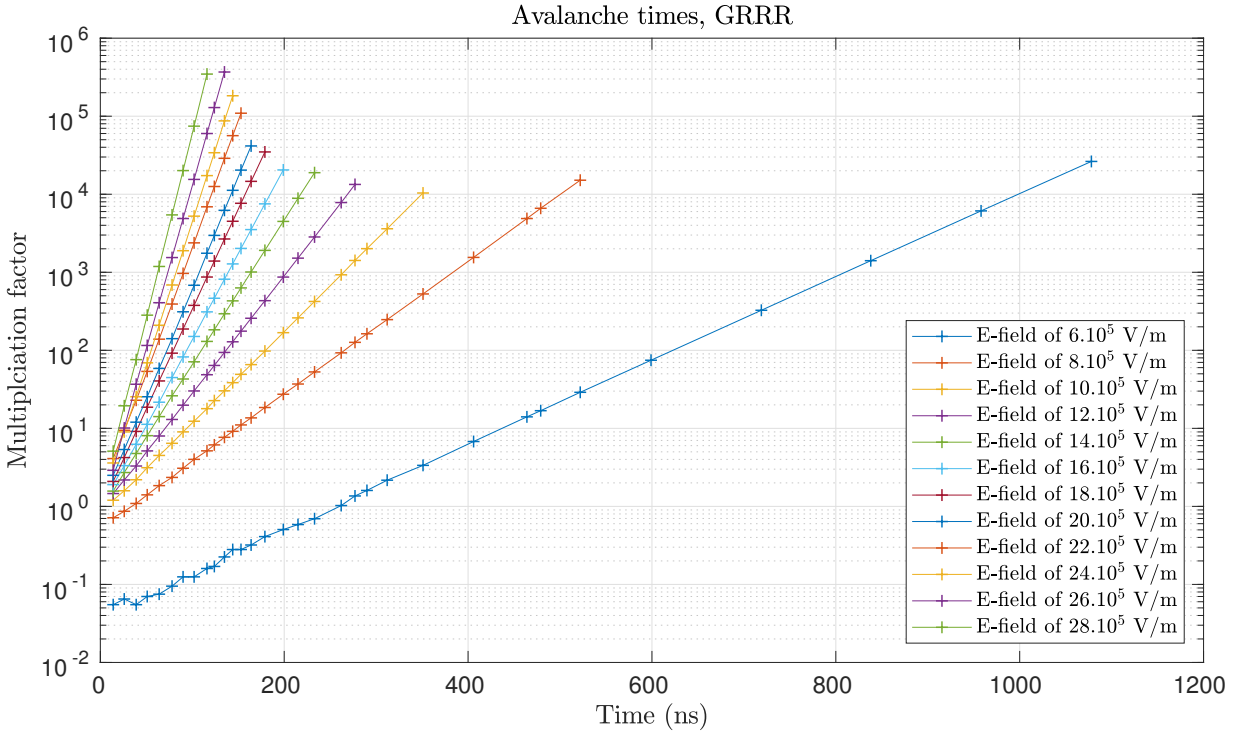

E-field of 24.10^5 V/m
Multiplciation factor
Time (ns)
GRRR
REAM
GEANT4O1
GEANT4O4

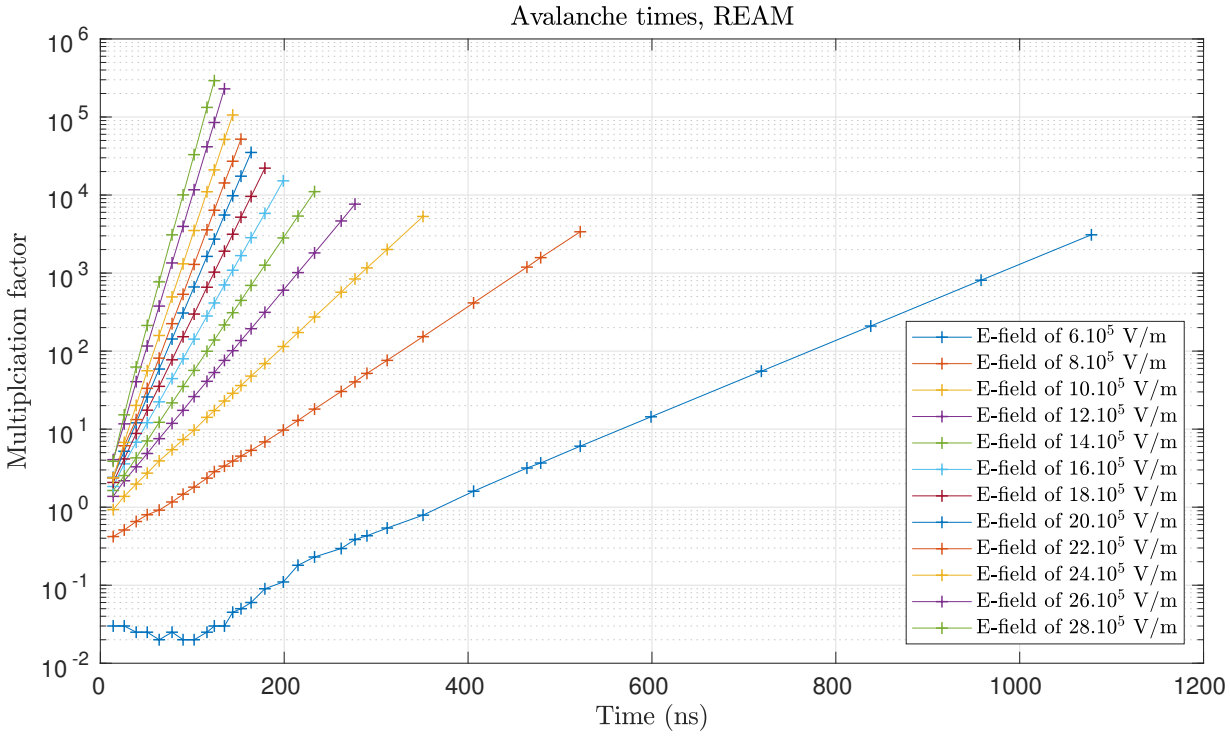

E-field of 26.10^5 V/m
Multiplciation factor
Time (ns)
GRRR
REAM
GEANT4O1
GEANT4O4

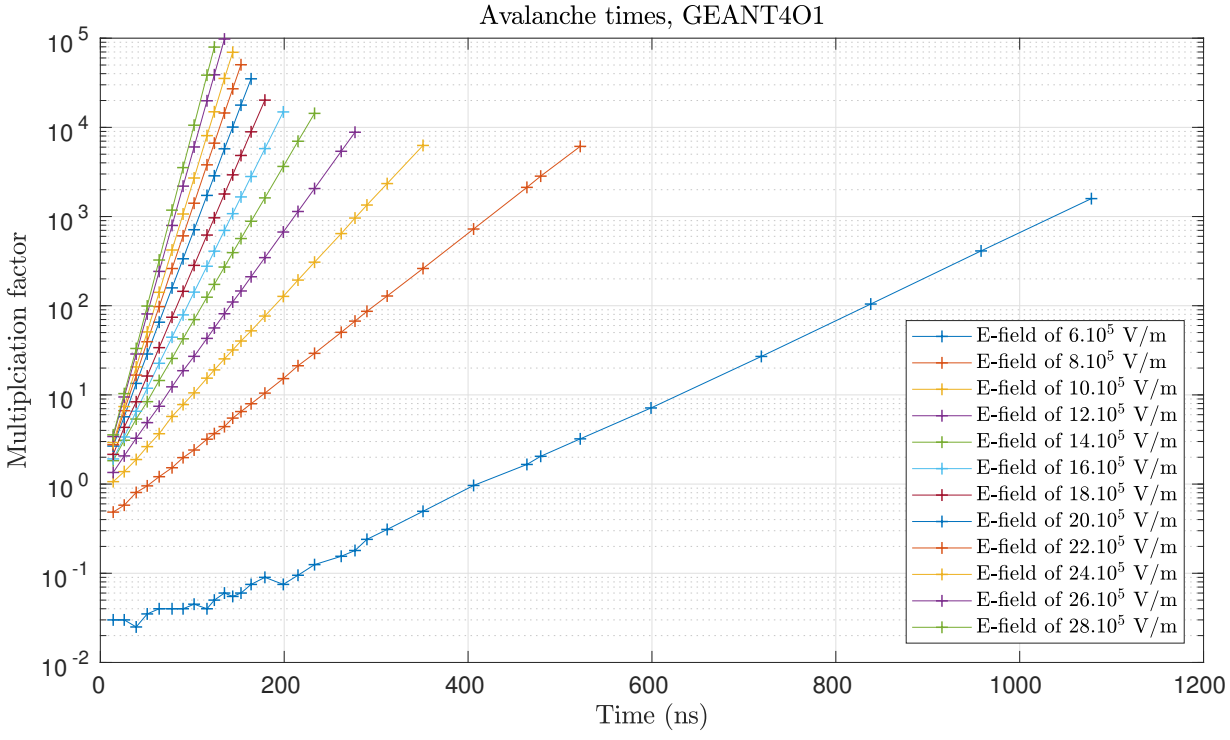

E-field of 28.10^5 V/m
Multiplciation factor
Time (ns)
GRRR
REAM
GEANT4O1
GEANT4O4

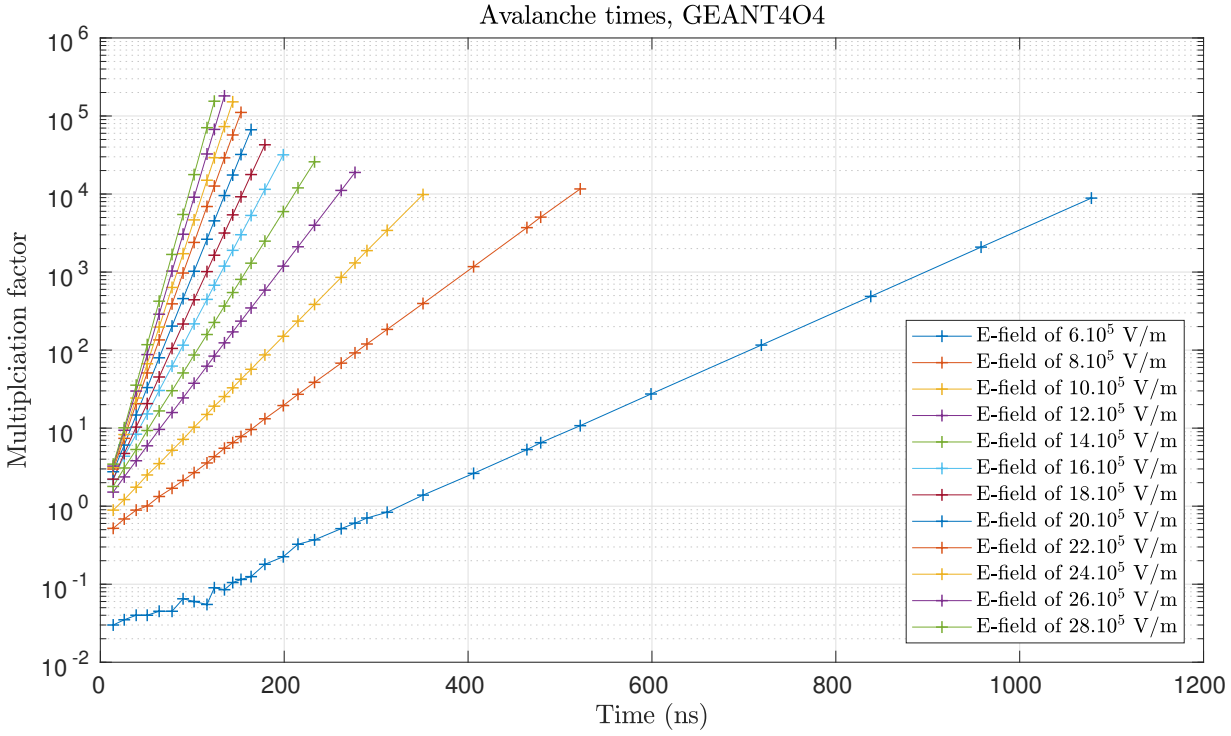


10.4 Time Record Code By Code

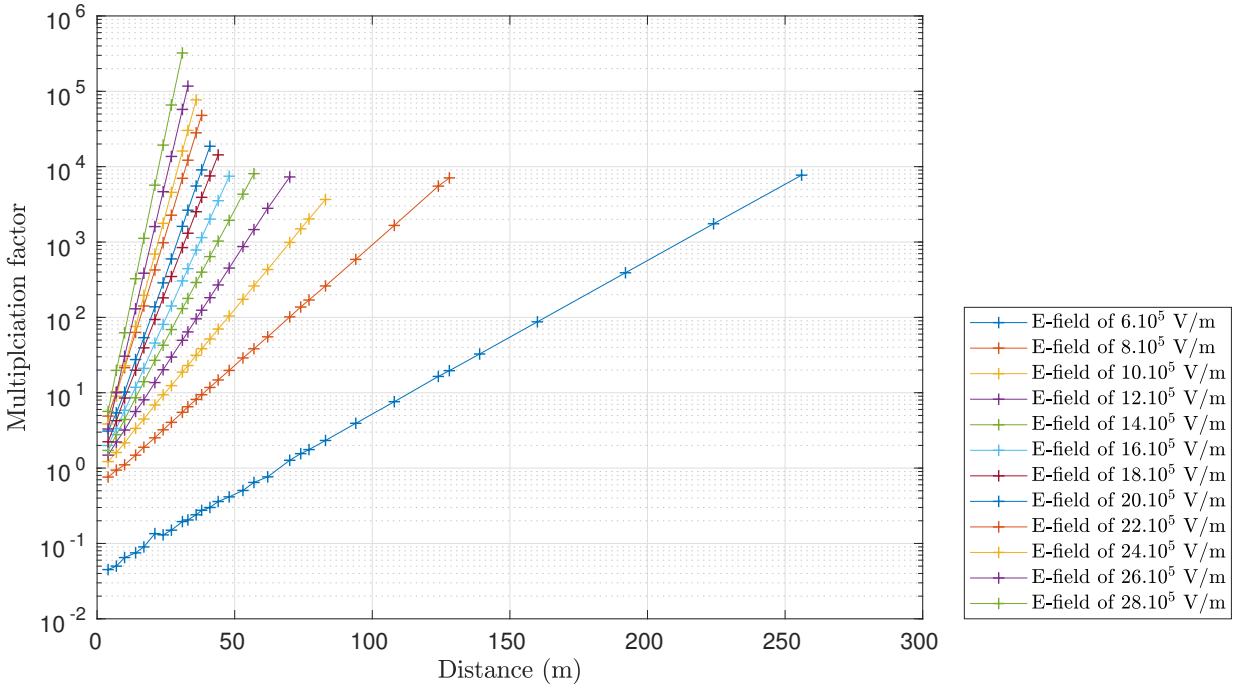


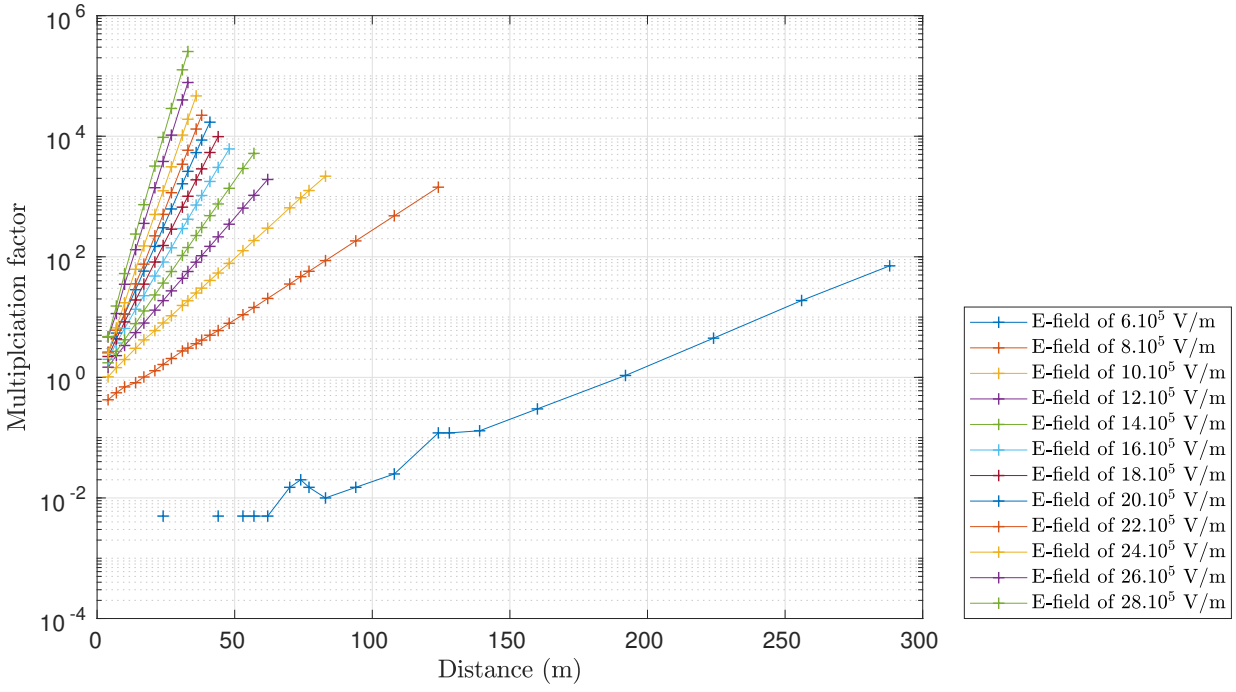

Avalanche times, REAM
Multiplciation factor
Time (ns)
E-field of 6.10^5 V/m
E-field of 8.10^5 V/m
E-field of 10.10^5 V/m
E-field of 12.10^5 V/m
E-field of 14.10^5 V/m
E-field of 16.10^5 V/m
E-field of 18.10^5 V/m
E-field of 20.10^5 V/m
E-field of 22.10^5 V/m
E-field of 24.10^5 V/m
E-field of 26.10^5 V/m
E-field of 28.10^5 V/m

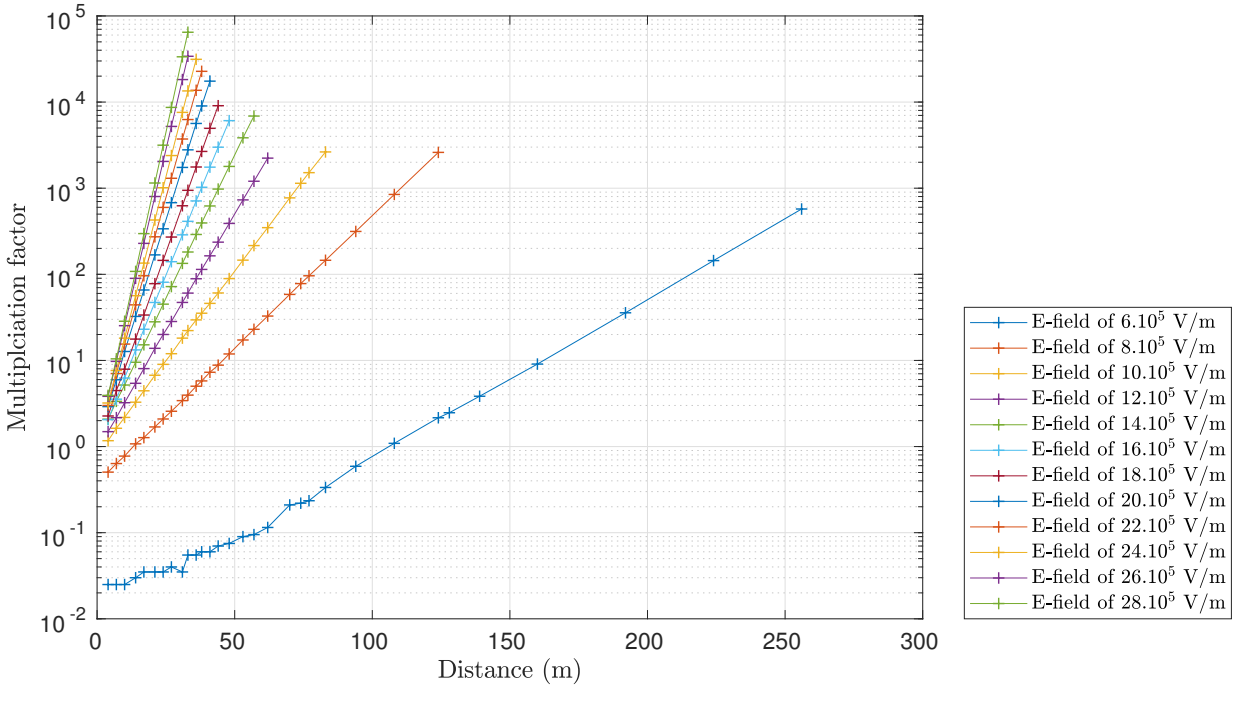

Avalanche times, GEANT4O1
Multiplciation factor
Time (ns)
E-field of 6.10^5 V/m
E-field of 8.10^5 V/m
E-field of 10.10^5 V/m
E-field of 12.10^5 V/m
E-field of 14.10^5 V/m
E-field of 16.10^5 V/m
E-field of 18.10^5 V/m
E-field of 20.10^5 V/m
E-field of 22.10^5 V/m
E-field of 24.10^5 V/m
E-field of 26.10^5 V/m
E-field of 28.10^5 V/m

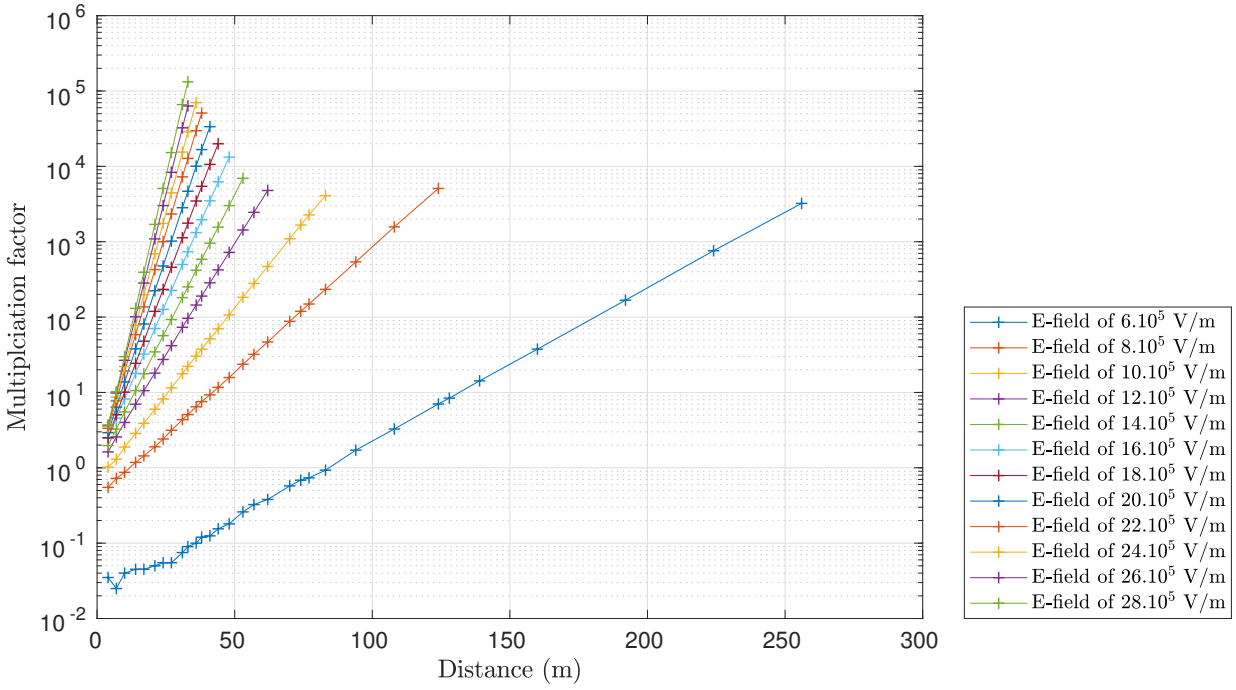


10.5 Distance Record Code By Code

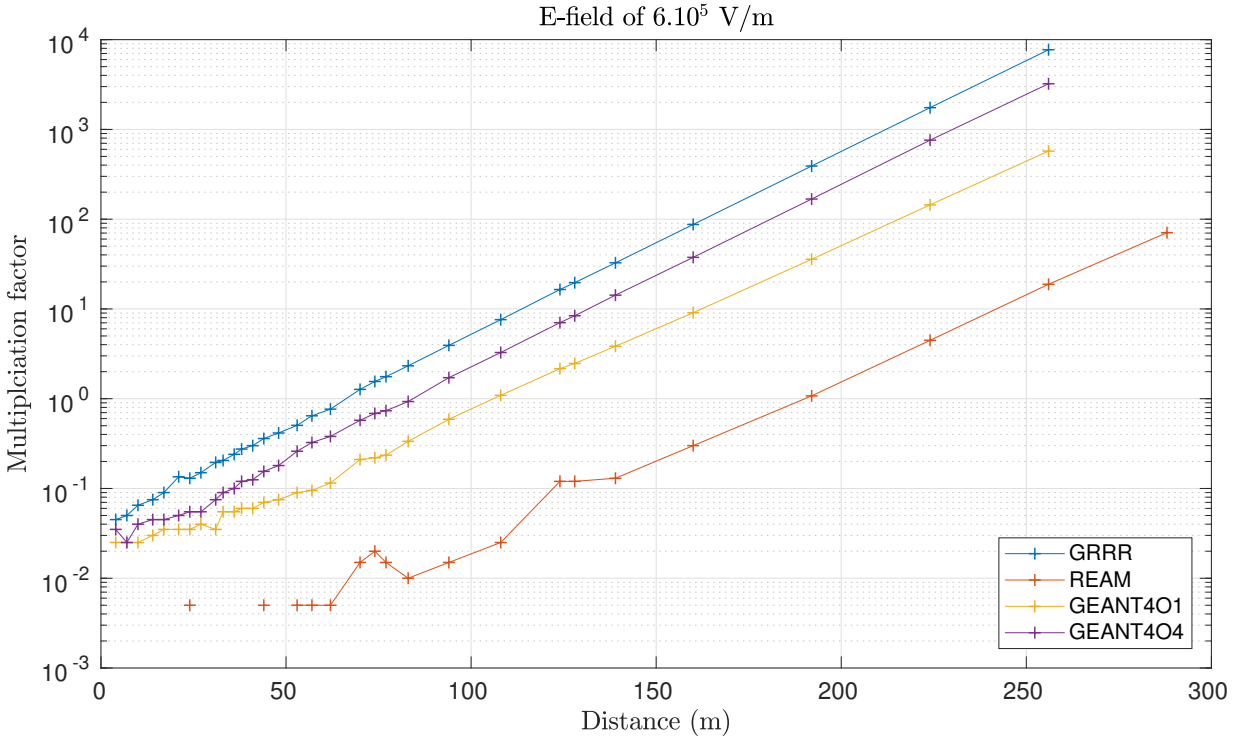


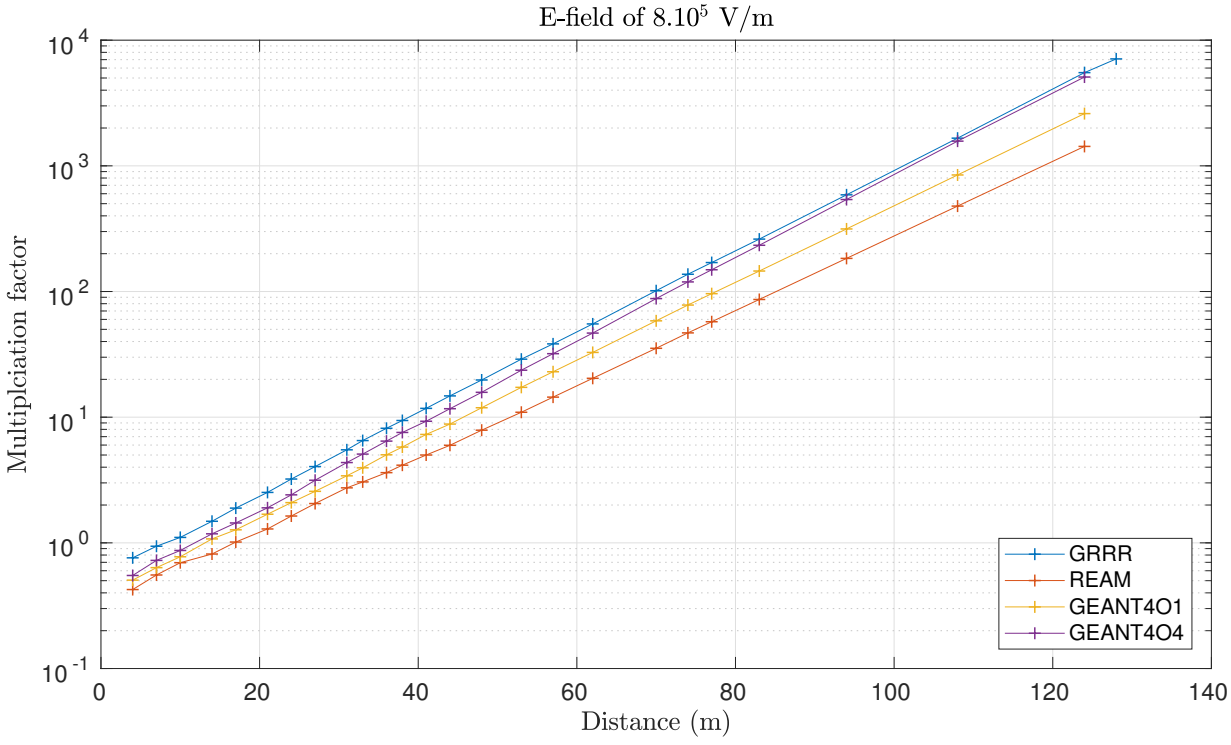

Multiplciation factor
Distance (m)
E-field of 6.10^5 V/m
E-field of 8.10^5 V/m
E-field of 10.10^5 V/m
E-field of 12.10^5 V/m
E-field of 14.10^5 V/m
E-field of 16.10^5 V/m
E-field of 18.10^5 V/m
E-field of 20.10^5 V/m
E-field of 22.10^5 V/m
E-field of 24.10^5 V/m
E-field of 26.10^5 V/m
E-field of 28.10^5 V/m

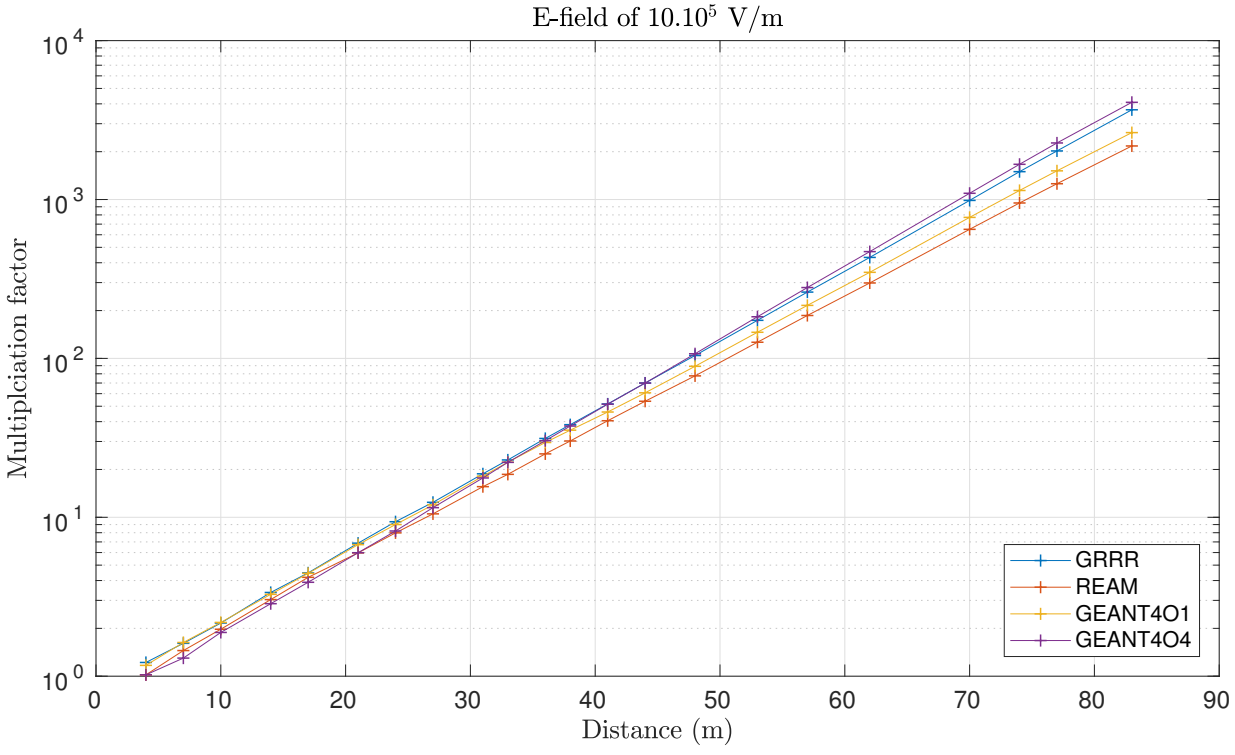

Multiplciation factor
Distance (m)
E-field of 6.10^5 V/m
E-field of 8.10^5 V/m
E-field of 10.10^5 V/m
E-field of 12.10^5 V/m
E-field of 14.10^5 V/m
E-field of 16.10^5 V/m
E-field of 18.10^5 V/m
E-field of 20.10^5 V/m
E-field of 22.10^5 V/m
E-field of 24.10^5 V/m
E-field of 26.10^5 V/m
E-field of 28.10^5 V/m

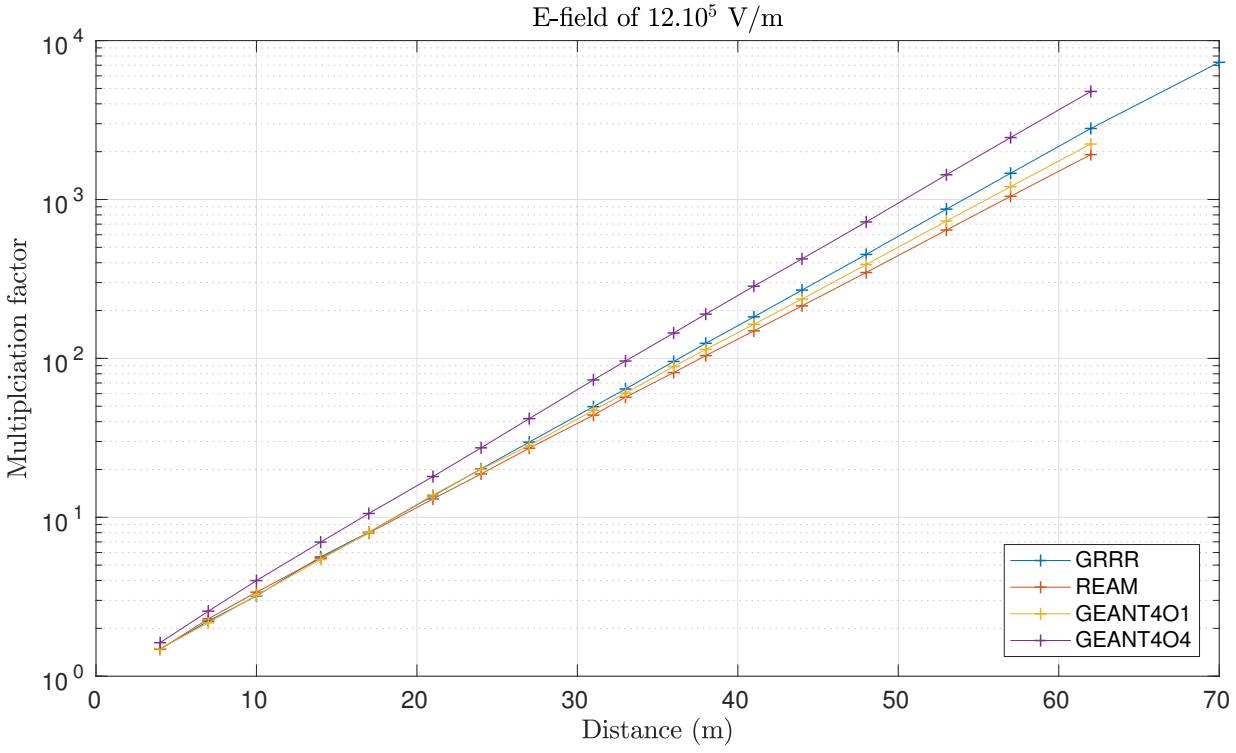


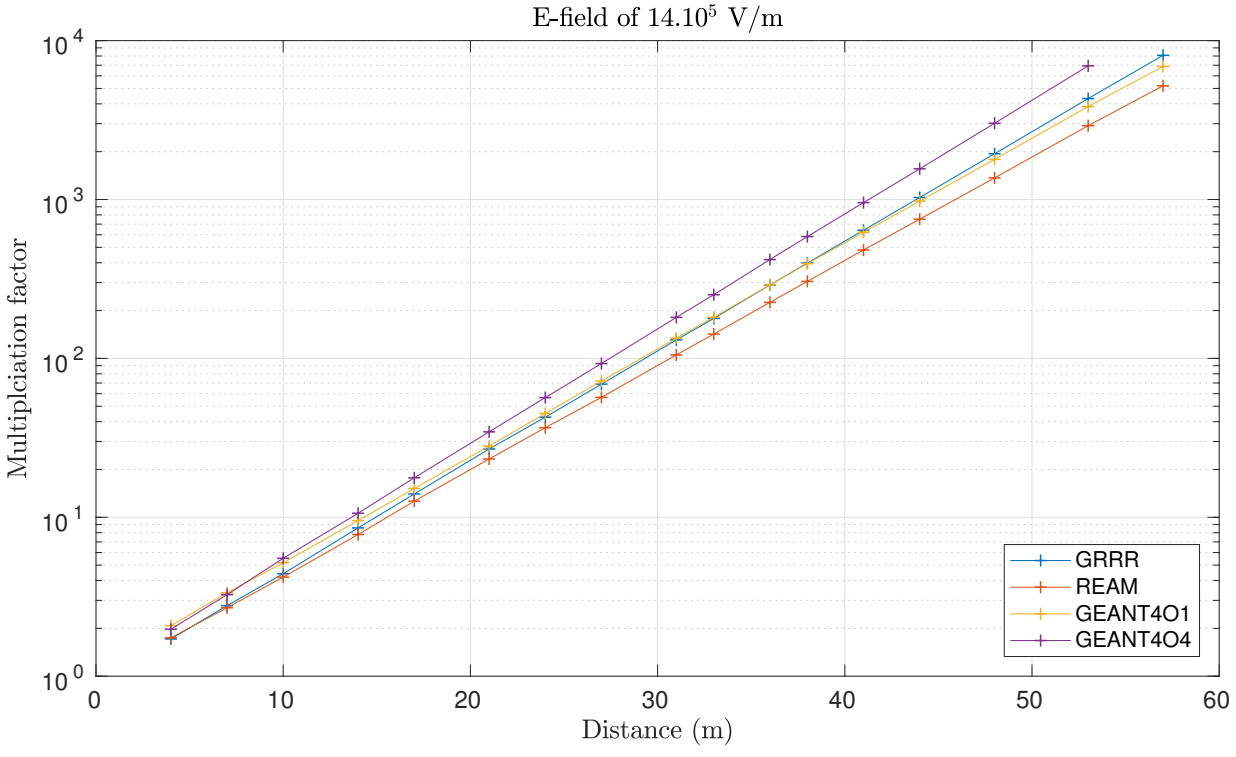
10.6 Distance Record Code Comparison

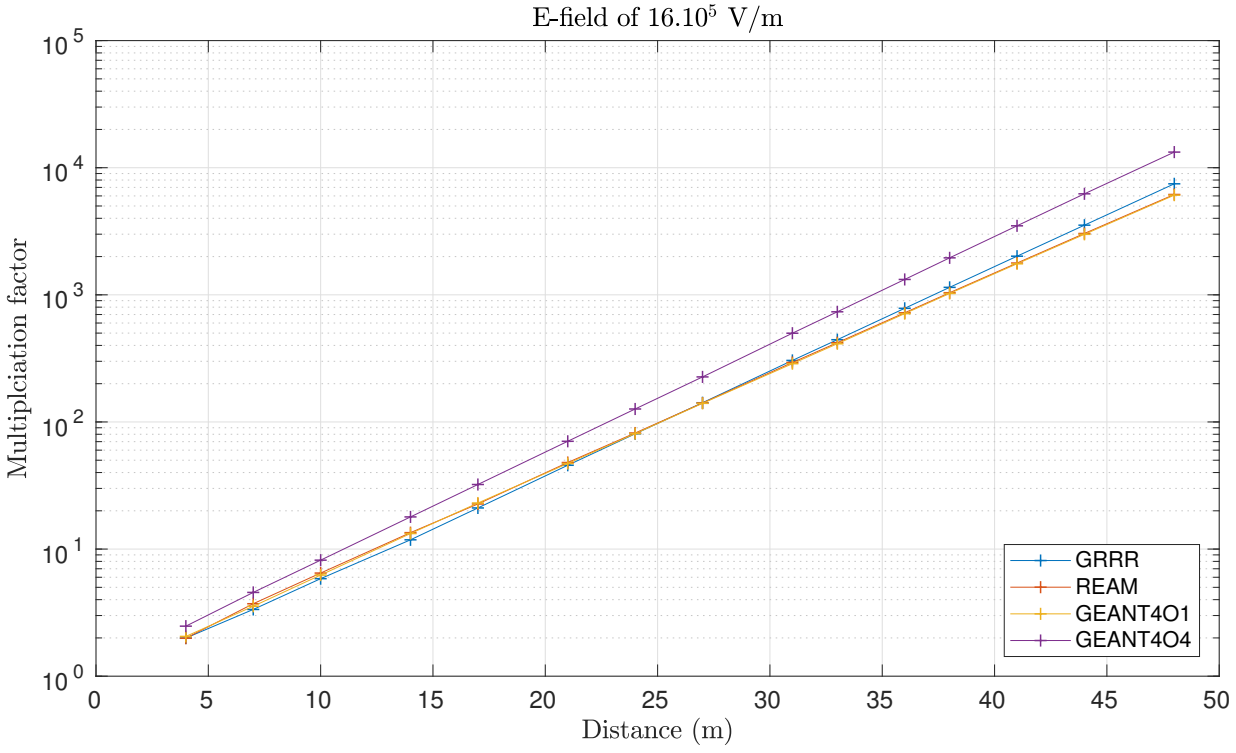


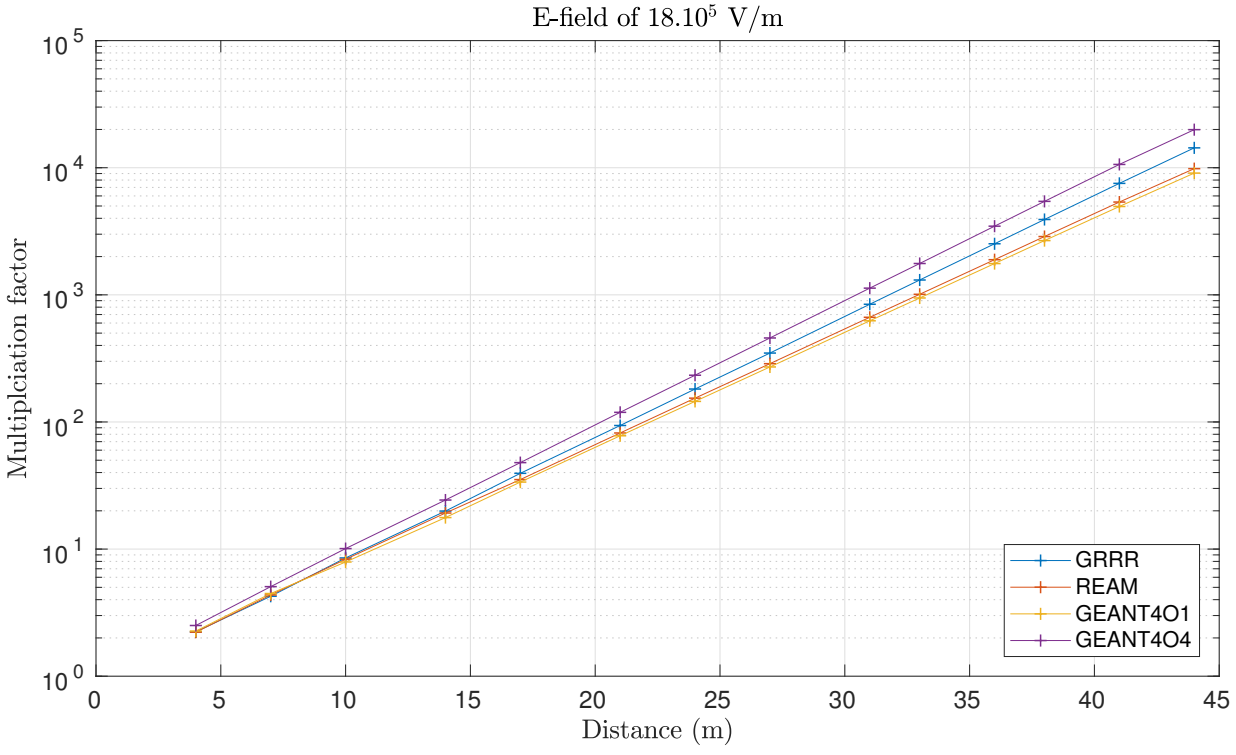

E-field of 8.10^5 V/m
Multiplciation factor
Distance (m)
GRRR
REAM
GEANT4O1
GEANT4O4

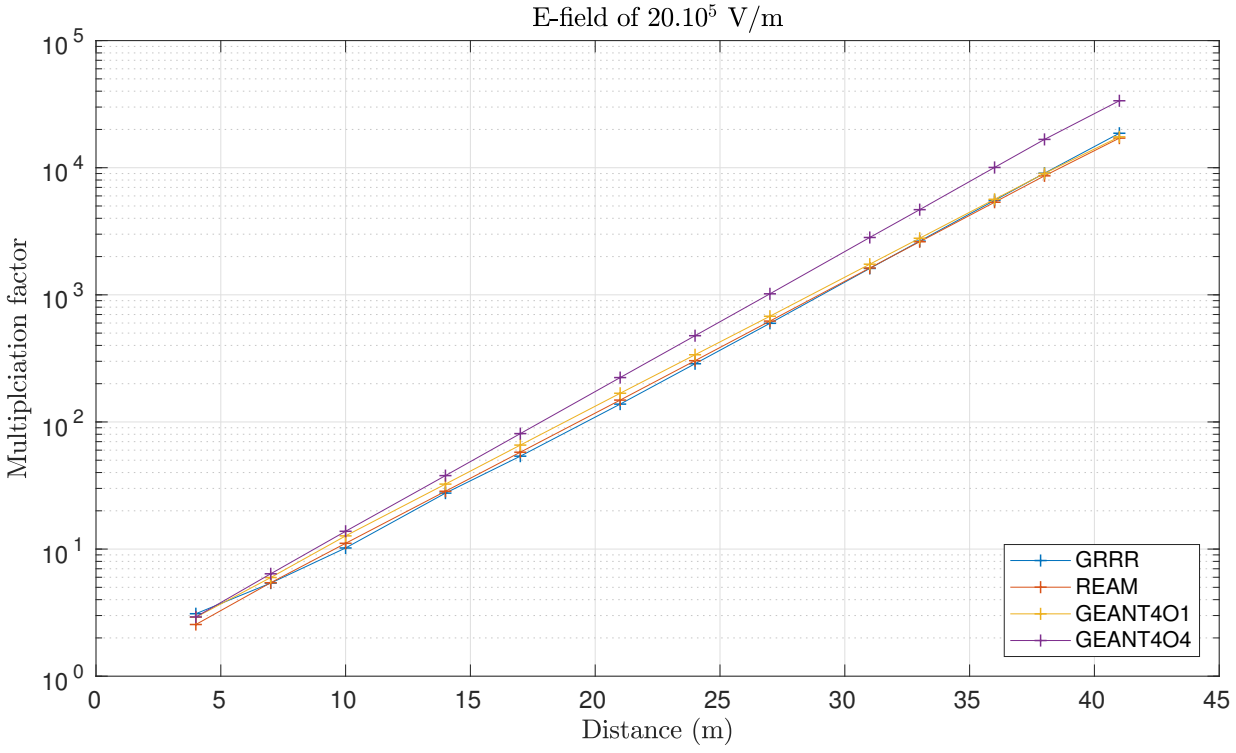

E-field of 10.10^5 V/m
Multiplciation factor
Distance (m)
GRRR
REAM
GEANT4O1
GEANT4O4

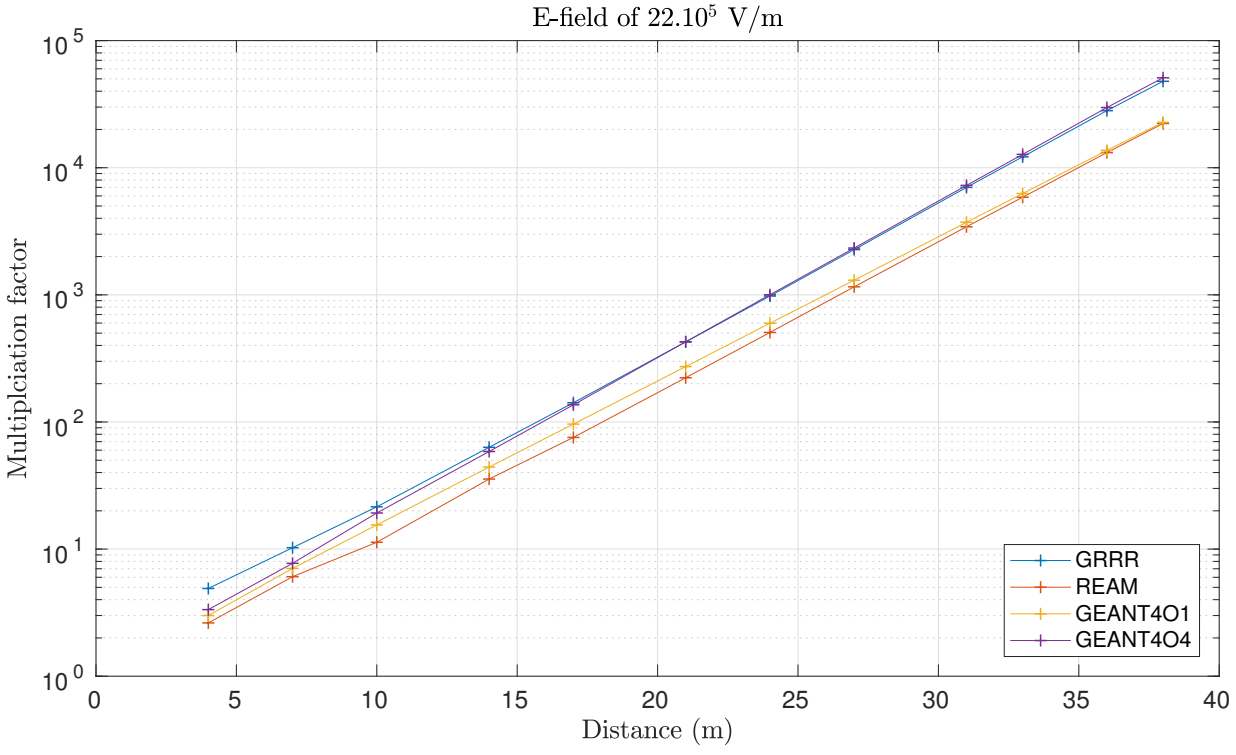

E-field of 12.10^5 V/m
Multiplciation factor
Distance (m)
GRRR
REAM
GEANT4O1
GEANT4O4

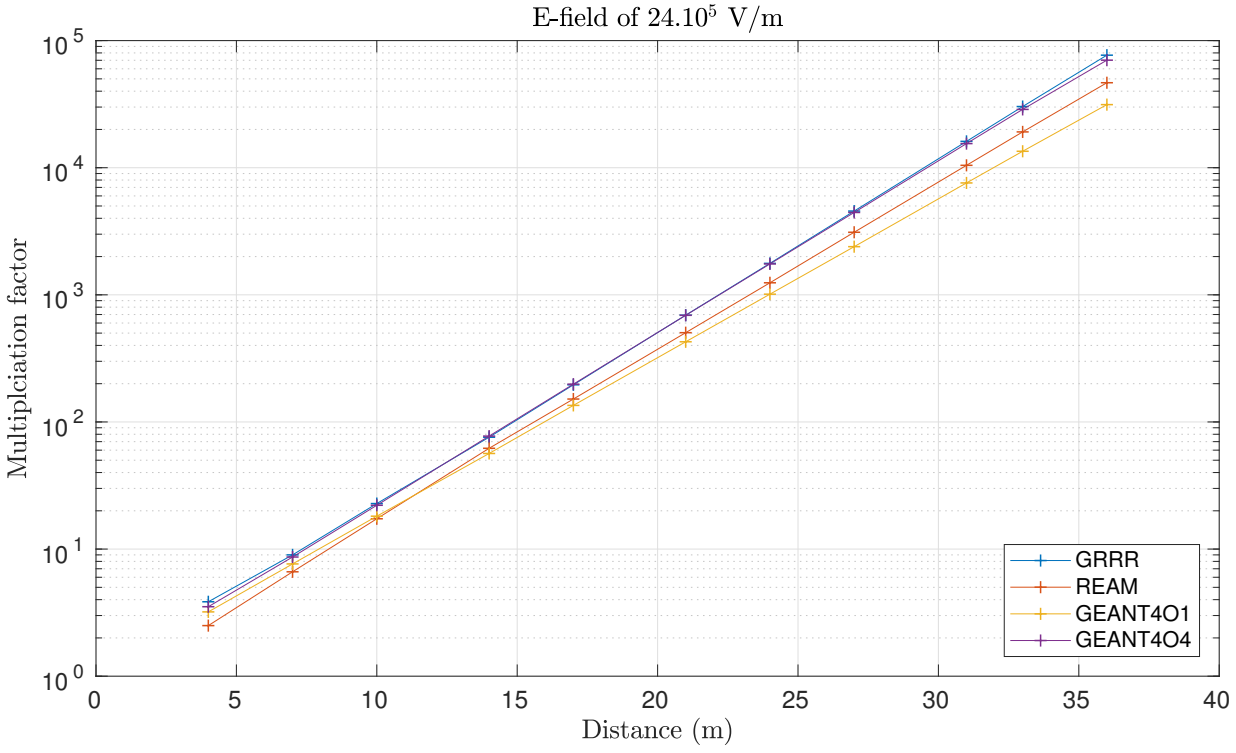

E-field of 14.10^5 V/m
Multiplciation factor
Distance (m)
GRRR
REAM
GEANT4O1
GEANT4O4

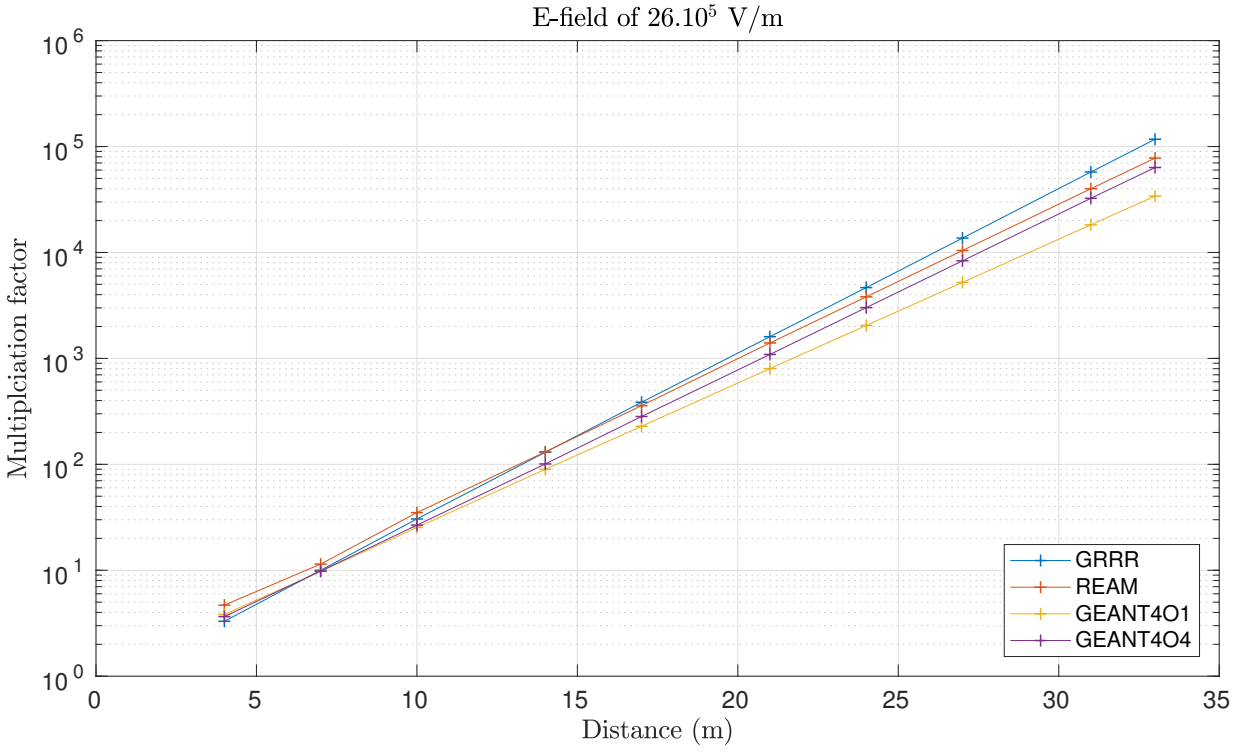

E-field of 16.10^5 V/m
Multiplciation factor
Distance (m)
GRRR
REAM
GEANT4O1
GEANT4O4

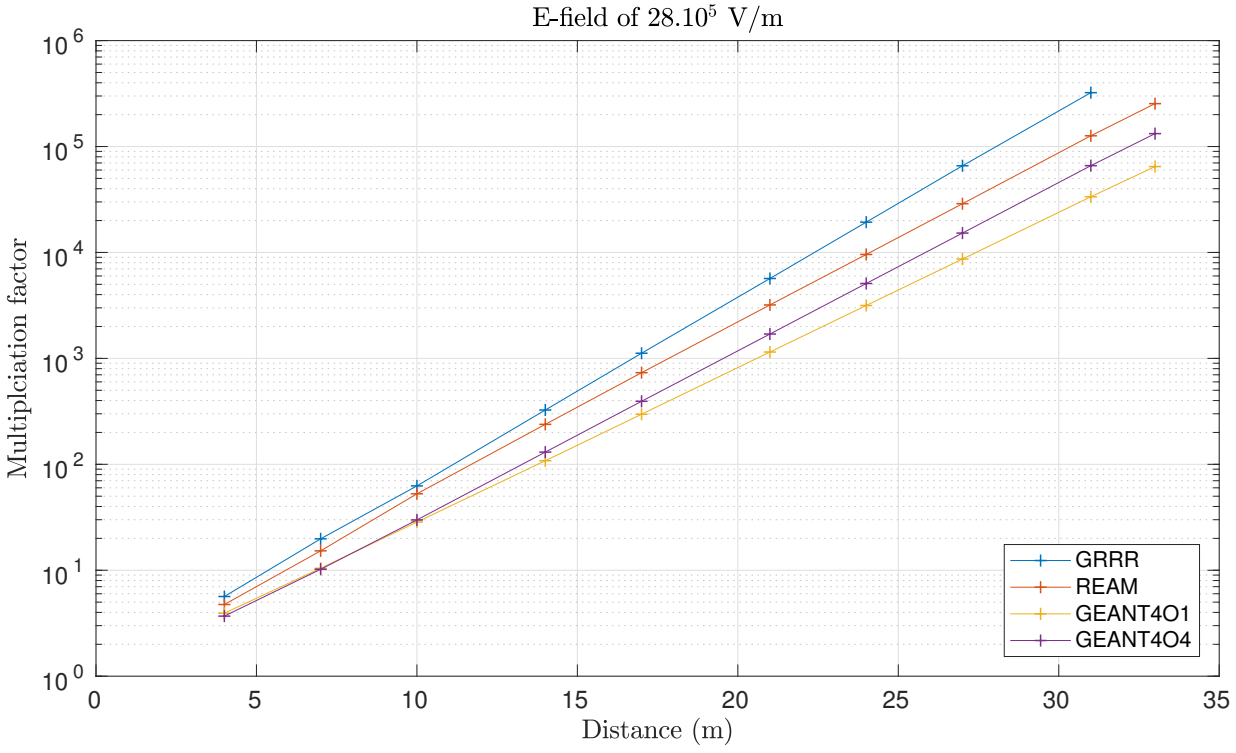

E-field of 18.10^5 V/m
Multiplciation factor
Distance (m)
GRRR
REAM
GEANT4O1
GEANT4O4

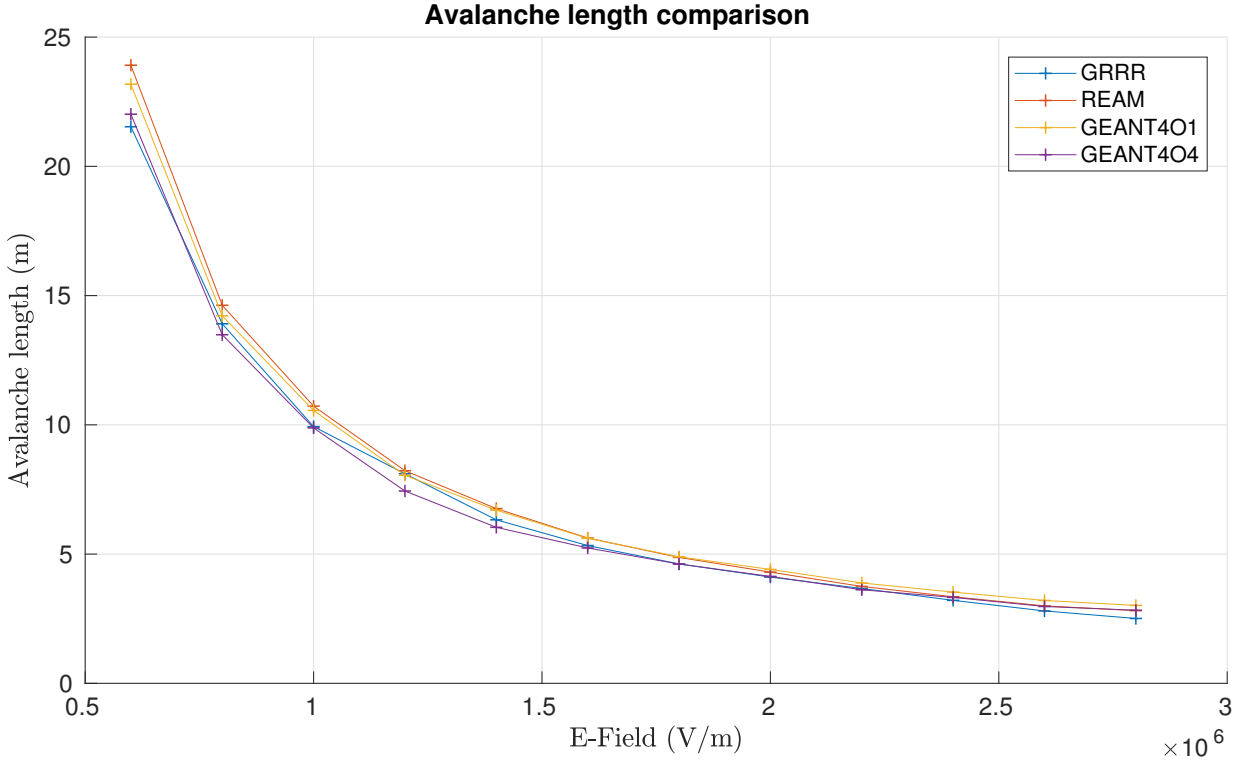

E-field of 20.10^5 V/m
Multiplciation factor
Distance (m)
GRRR
REAM
GEANT4O1
GEANT4O4


E-field of 22.10^5 V/m
Multiplciation factor
Distance (m)
GRRR
REAM
GEANT4O1
GEANT4O4


E-field of 24.10^5 V/m
Multiplciation factor
Distance (m)
GRRR
REAM
GEANT4O1
GEANT4O4

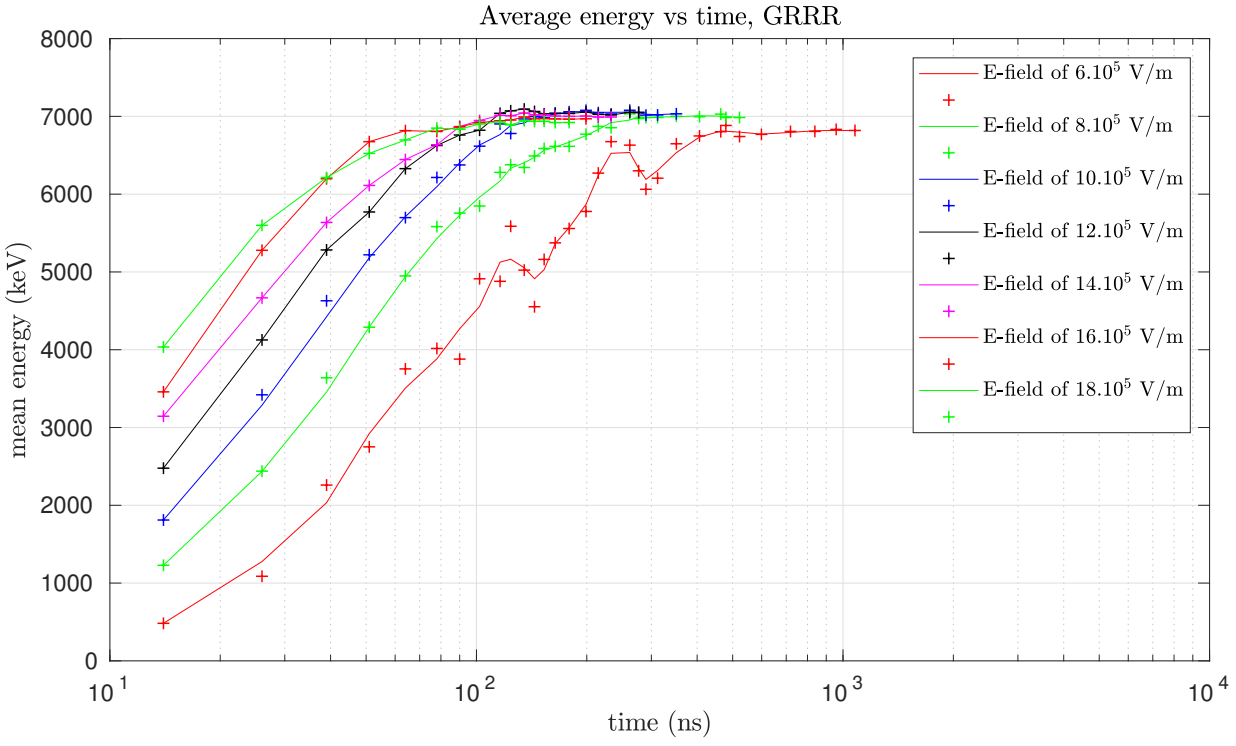

E-field of 26.10^5 V/m
Multiplciation factor
Distance (m)
GRRR
REAM
GEANT4O1
GEANT4O4

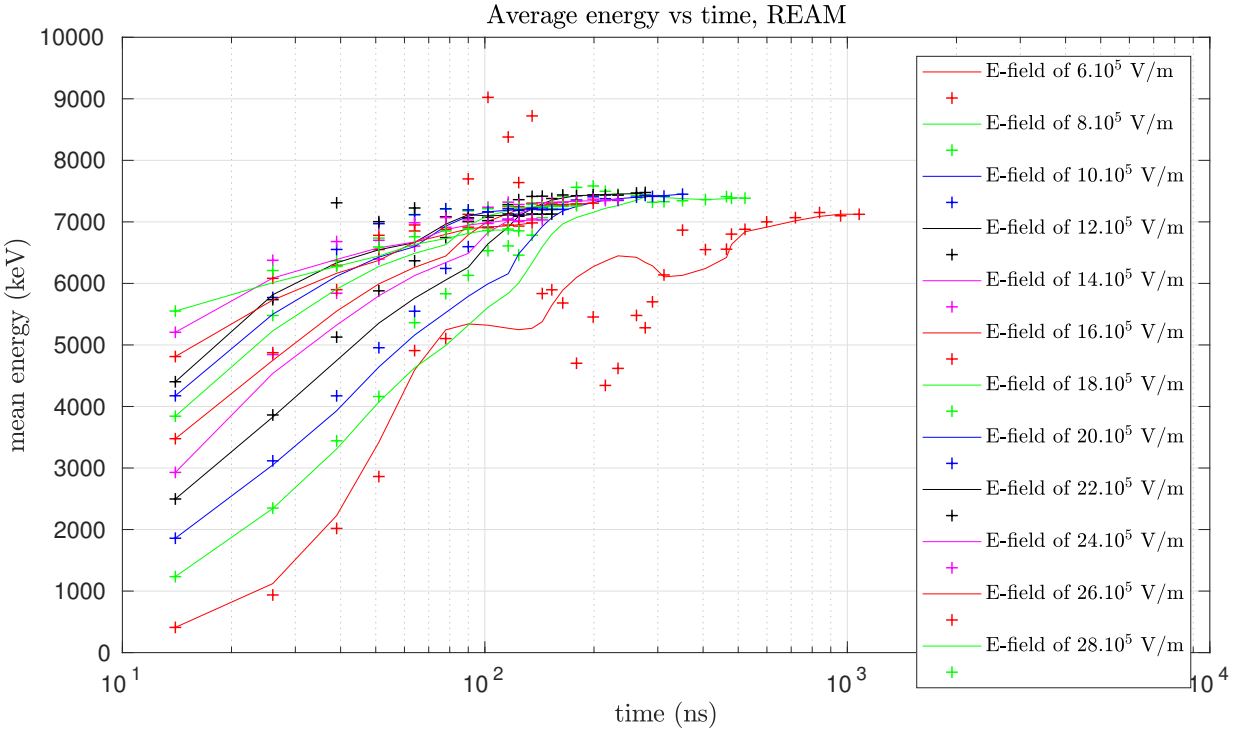

E-field of 28.10^5 V/m
Multiplciation factor
Distance (m)
GRRR
REAM
GEANT4O1
GEANT4O4

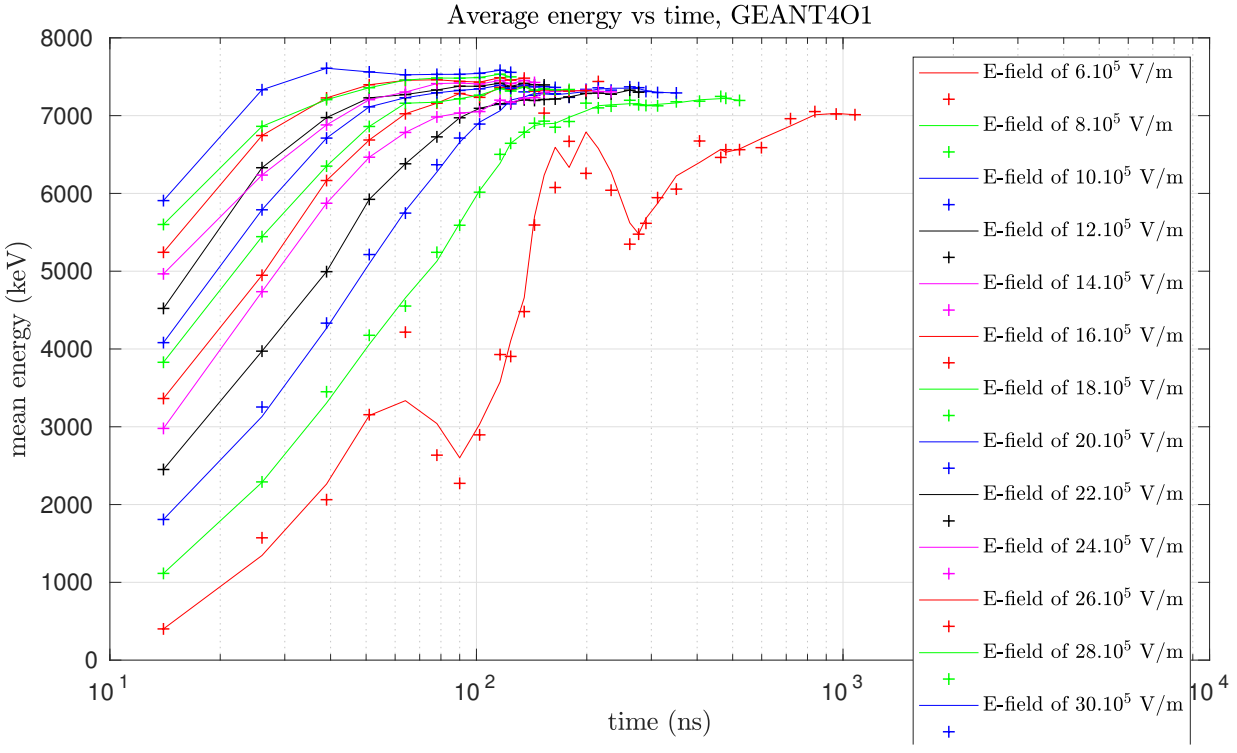

Avalanche length comparison
Avalanche length (m)
E-Field (V/m)
×10^6
GRRR
REAM
GEANT4O1
GEANT4O4

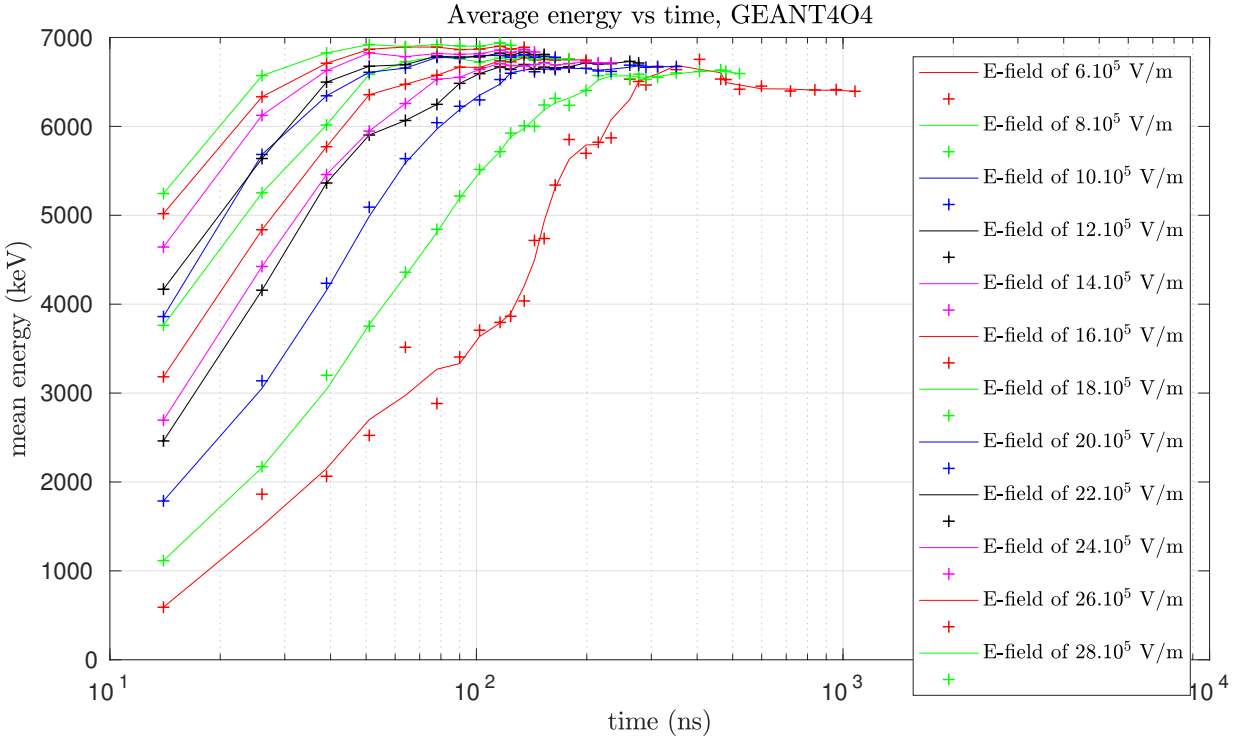
11 Time To Steady State

11.1 Average Electron Energy Evolution

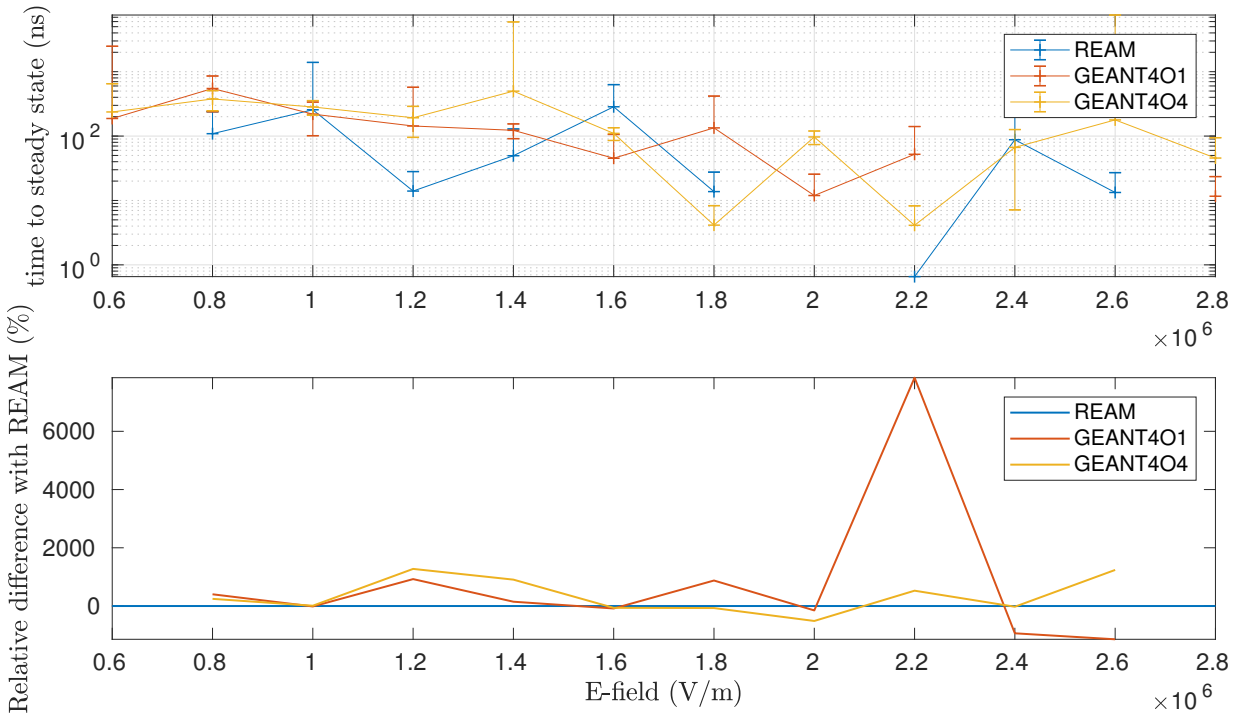


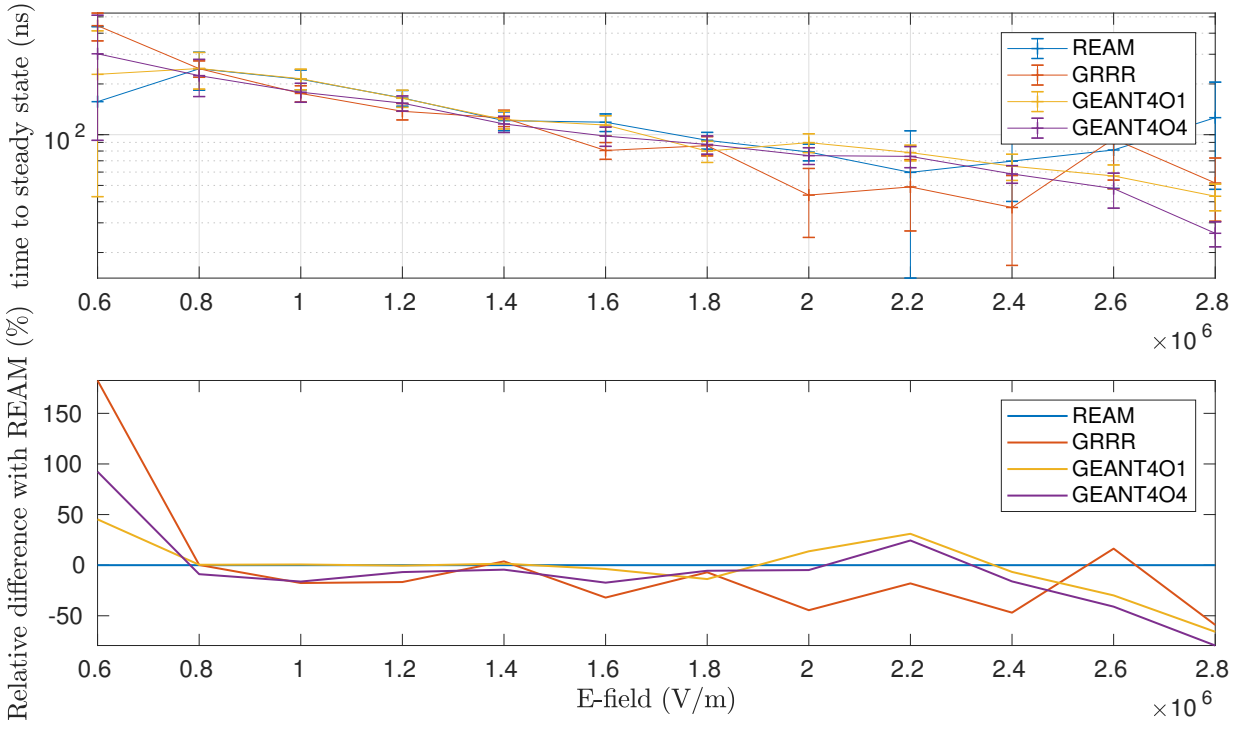



Average energy vs time, GEANT4O1
mean energy (keV)
time (ns)
E-field of 6.10^5 V/m
E-field of 8.10^5 V/m
E-field of 10.10^5 V/m
E-field of 12.10^5 V/m
E-field of 14.10^5 V/m
E-field of 16.10^5 V/m
E-field of 18.10^5 V/m
E-field of 20.10^5 V/m
E-field of 22.10^5 V/m
E-field of 24.10^5 V/m
E-field of 26.10^5 V/m
E-field of 28.10^5 V/m
E-field of 30.10^5 V/m

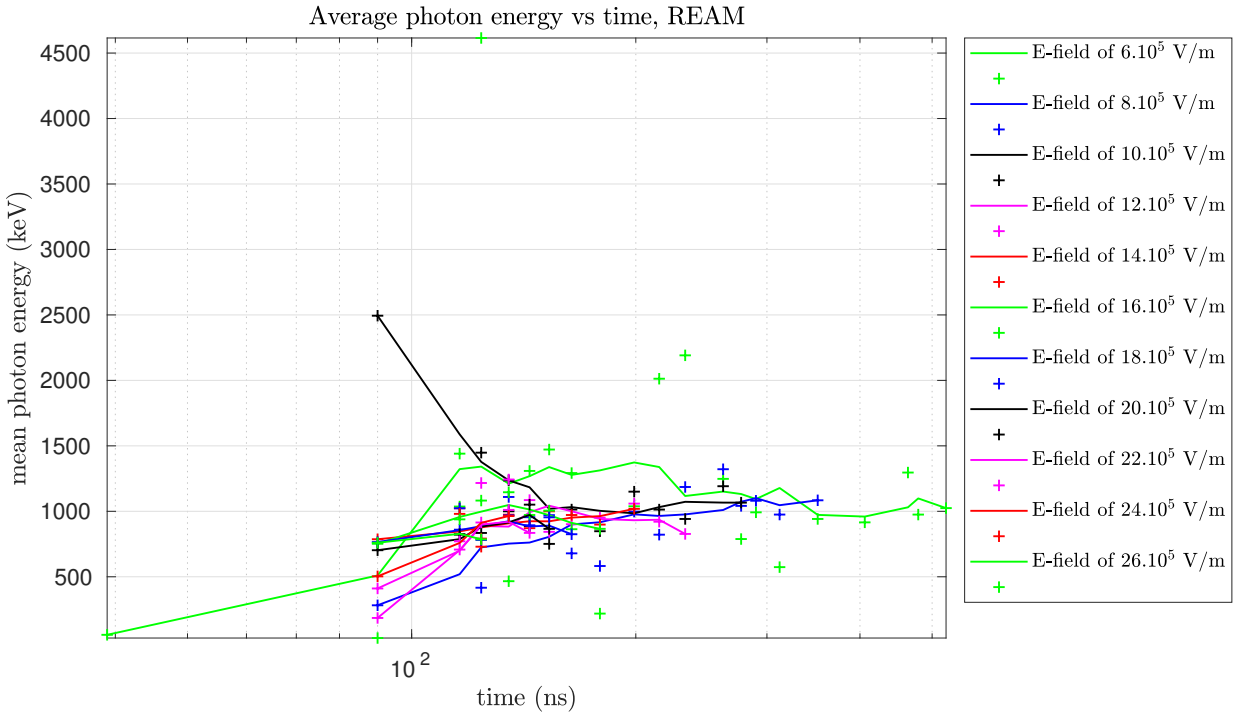

Average energy vs time, GEANT4O4
mean energy (keV)
time (ns)
E-field of 6.10^5 V/m
E-field of 8.10^5 V/m
E-field of 10.10^5 V/m
E-field of 12.10^5 V/m
E-field of 14.10^5 V/m
E-field of 16.10^5 V/m
E-field of 18.10^5 V/m
E-field of 20.10^5 V/m
E-field of 22.10^5 V/m
E-field of 24.10^5 V/m
E-field of 26.10^5 V/m
E-field of 28.10^5 V/m

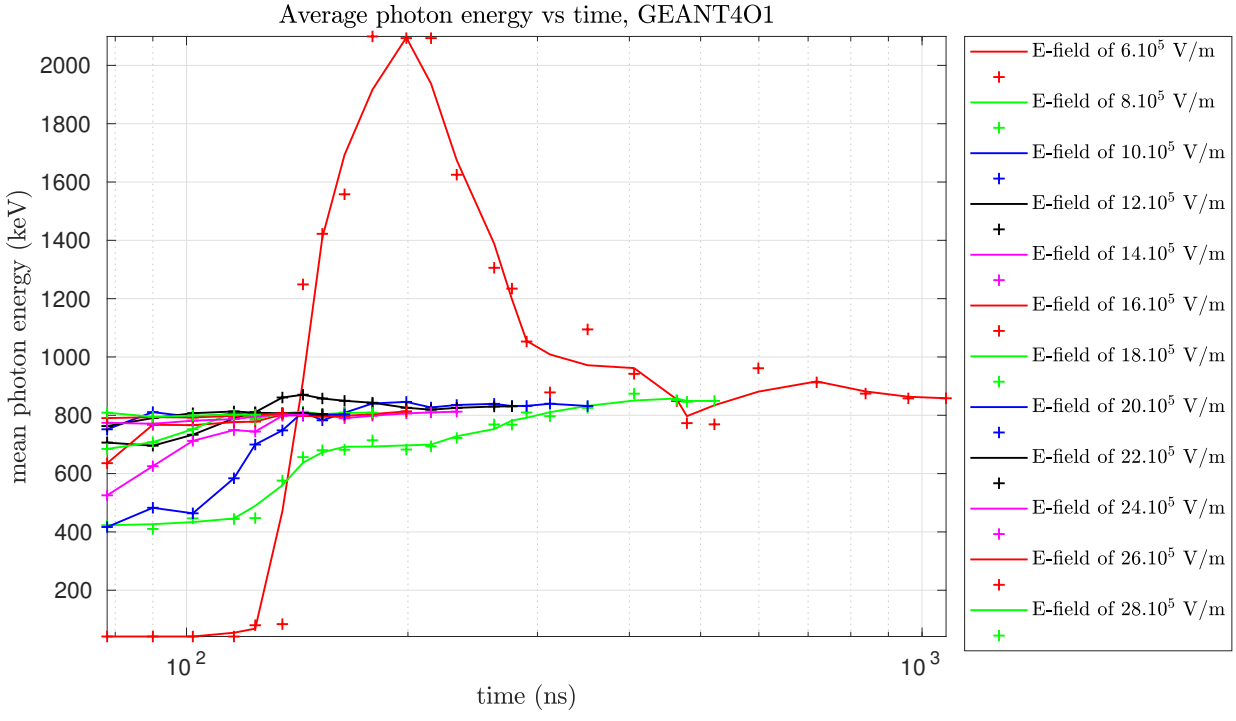
11.2 Comparison

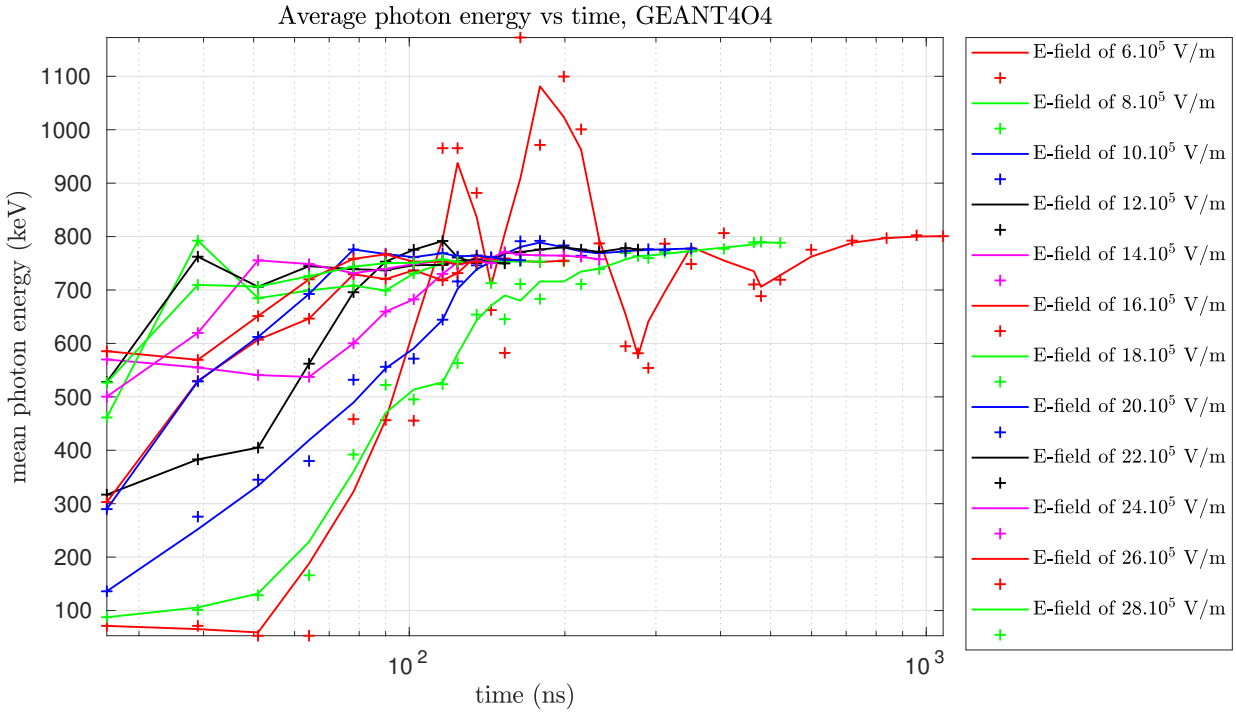


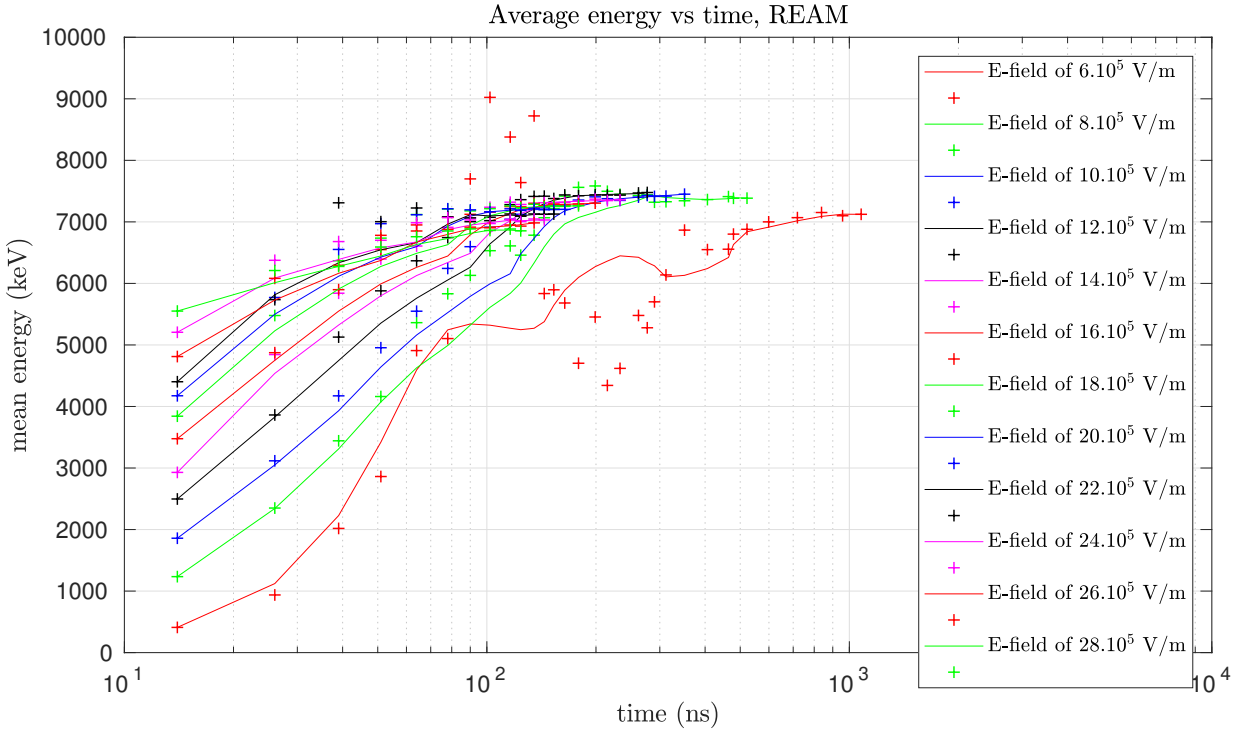


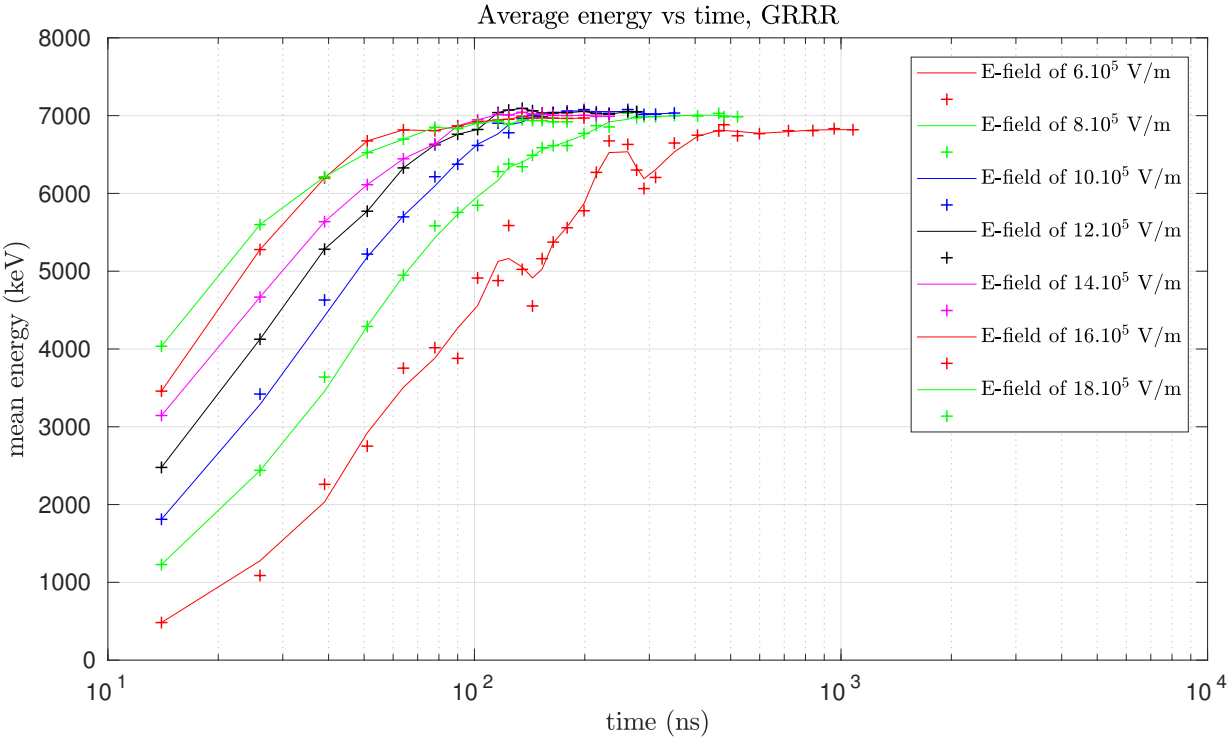
11.3 Average Photon Energy Evolution

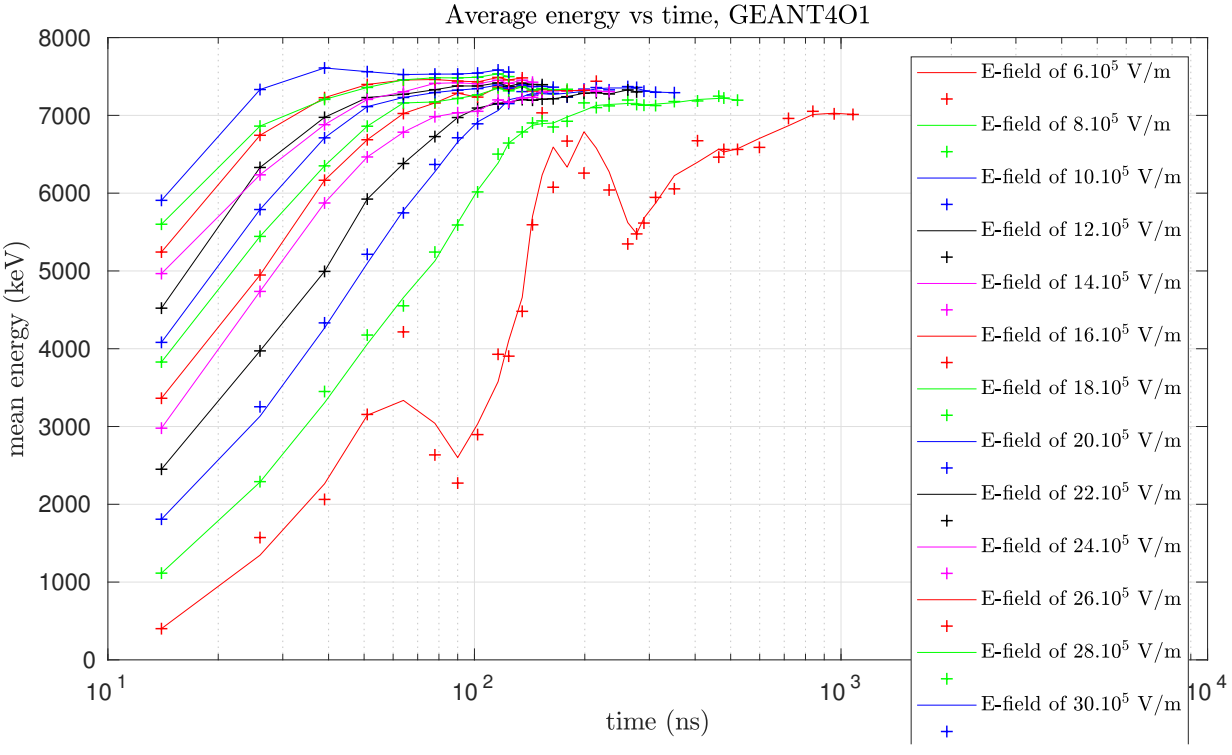


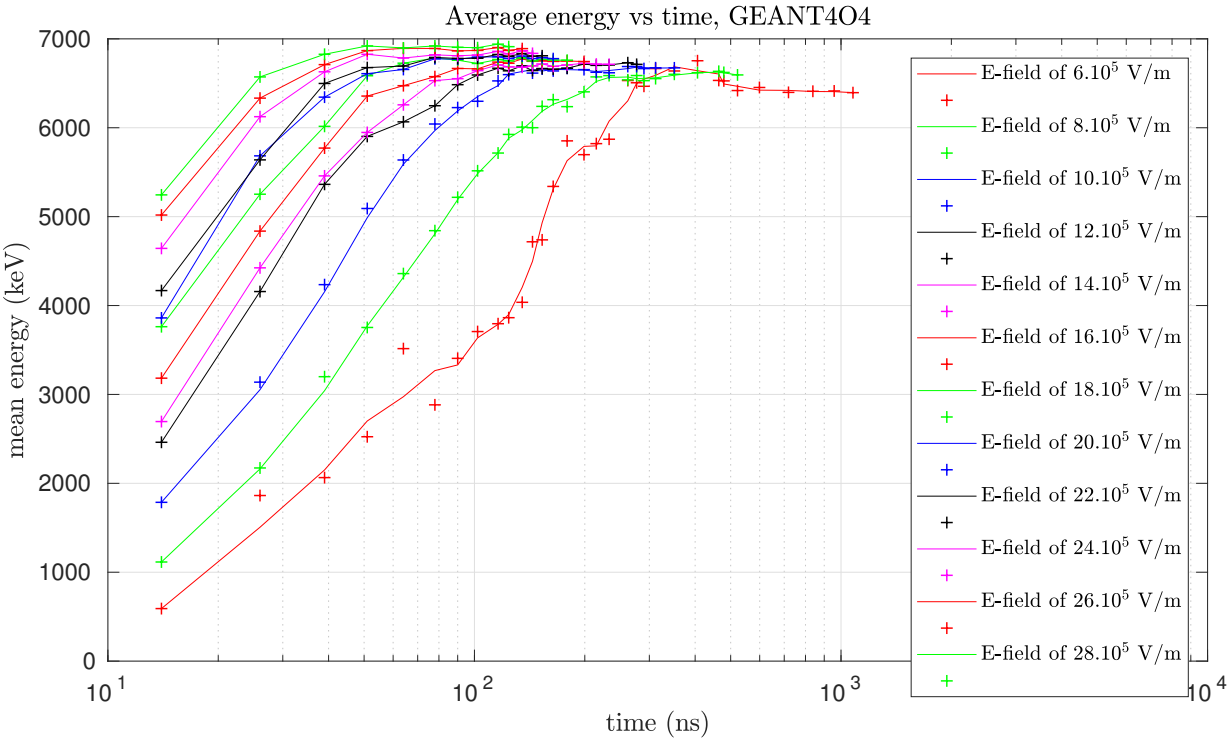



Average photon energy vs time, GEANT4O4
mean photon energy (keV)
time (ns)
E-field of 6.10^5 V/m
E-field of 8.10^5 V/m
E-field of 10.10^5 V/m
E-field of 12.10^5 V/m
E-field of 14.10^5 V/m
E-field of 16.10^5 V/m
E-field of 18.10^5 V/m
E-field of 20.10^5 V/m
E-field of 22.10^5 V/m
E-field of 24.10^5 V/m
E-field of 26.10^5 V/m
E-field of 28.10^5 V/m

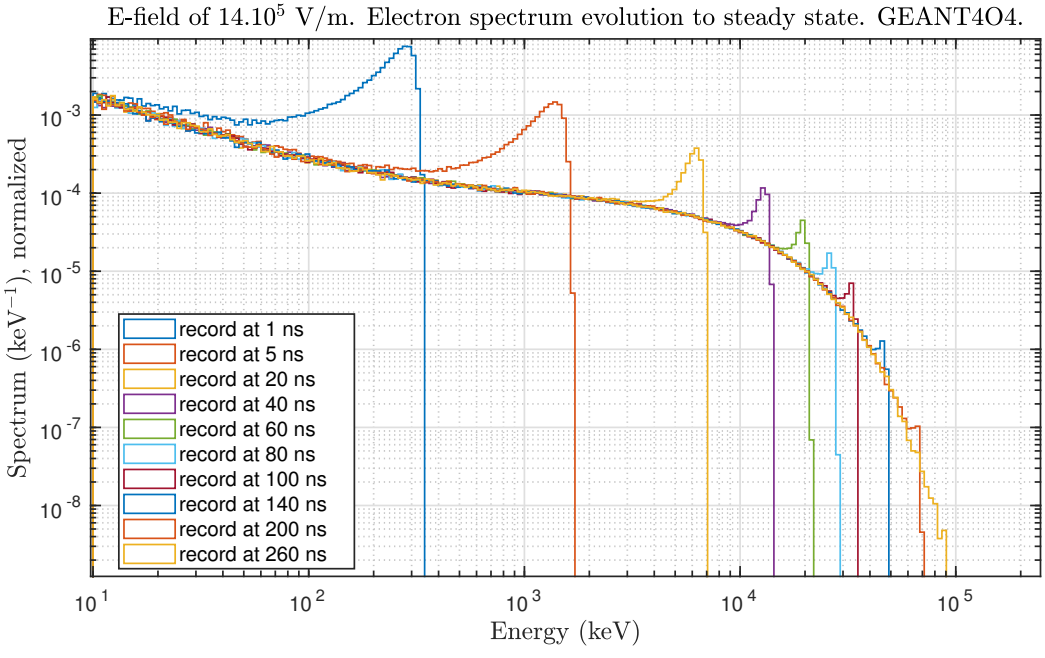

Average energy vs time, REAM
mean energy (keV)
time (ns)
E-field of 6.10^5 V/m
E-field of 8.10^5 V/m
E-field of 10.10^5 V/m
E-field of 12.10^5 V/m
E-field of 14.10^5 V/m
E-field of 16.10^5 V/m
E-field of 18.10^5 V/m
E-field of 20.10^5 V/m
E-field of 22.10^5 V/m
E-field of 24.10^5 V/m
E-field of 26.10^5 V/m
E-field of 28.10^5 V/m

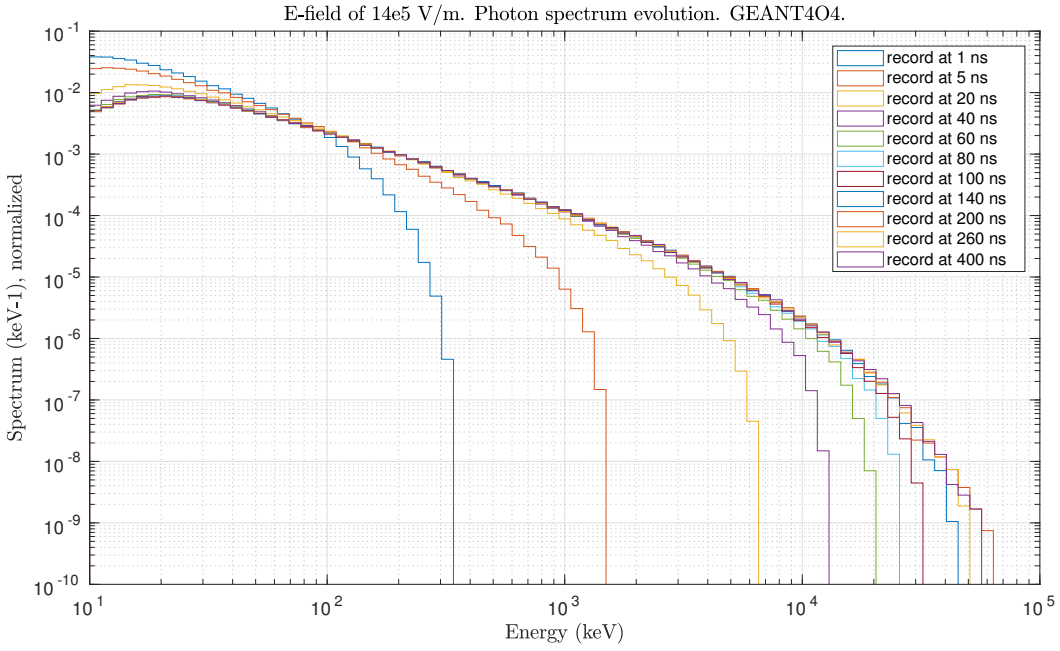

Average energy vs time, GRRR
mean energy (keV)
time (ns)
E-field of 6.10^5 V/m
E-field of 8.10^5 V/m
E-field of 10.10^5 V/m
E-field of 12.10^5 V/m
E-field of 14.10^5 V/m
E-field of 16.10^5 V/m
E-field of 18.10^5 V/m


Average energy vs time, GEANT4O1
mean energy (keV)
time (ns)
E-field of 6.10^5 V/m
E-field of 8.10^5 V/m
E-field of 10.10^5 V/m
E-field of 12.10^5 V/m
E-field of 14.10^5 V/m
E-field of 16.10^5 V/m
E-field of 18.10^5 V/m
E-field of 20.10^5 V/m
E-field of 22.10^5 V/m
E-field of 24.10^5 V/m
E-field of 26.10^5 V/m
E-field of 28.10^5 V/m
E-field of 30.10^5 V/m



11.4 Spectrum Evolution To Steady State




E-field of 14e5 V/m. Photon spectrum evolution. GEANT4O4.
Spectrum (keV-1), normalized
Energy (keV)
record at 1 ns
record at 5 ns
record at 20 ns
record at 40 ns
record at 60 ns
record at 80 ns
record at 100 ns
record at 140 ns
record at 200 ns
record at 260 ns
record at 400 ns