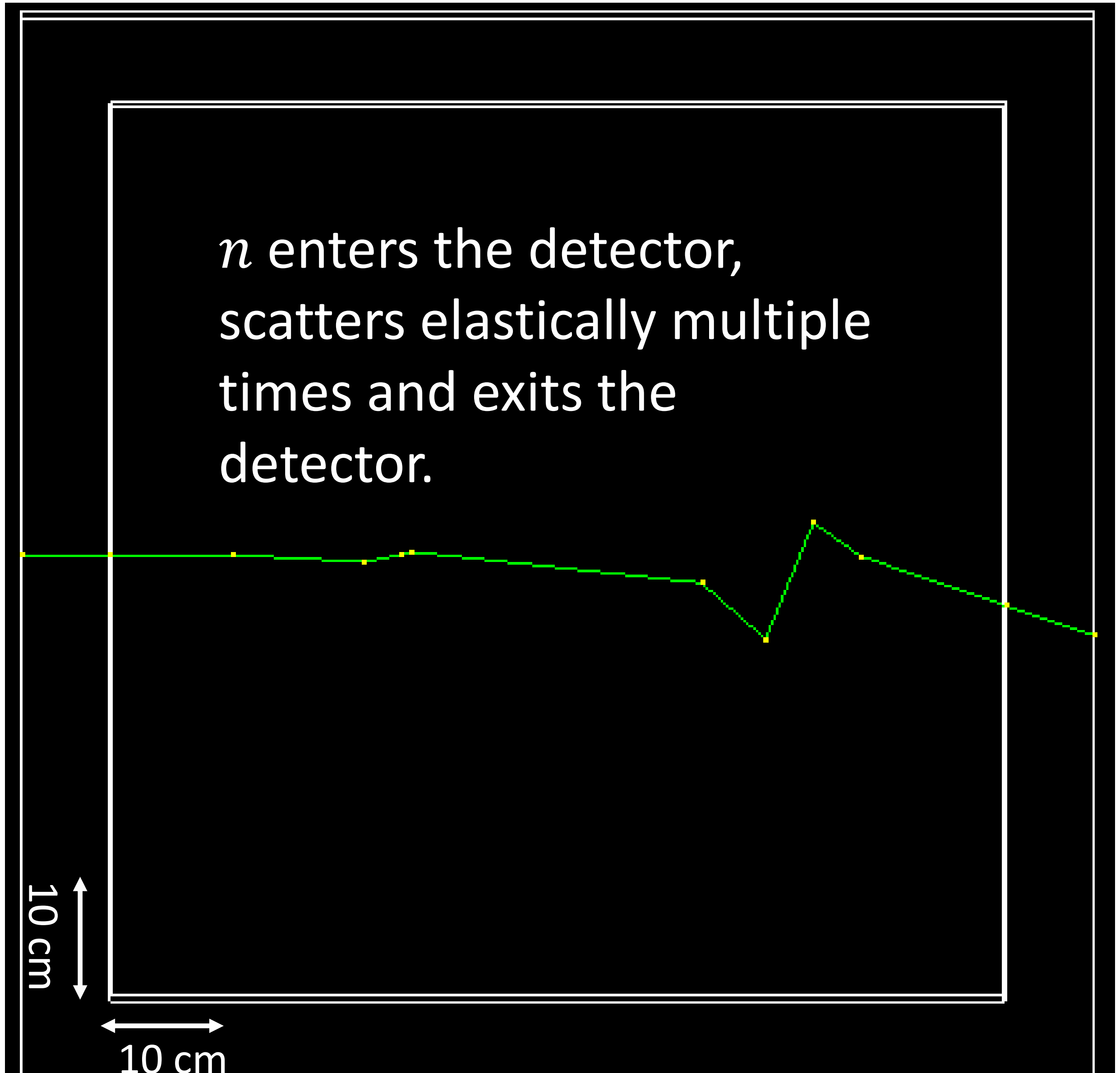
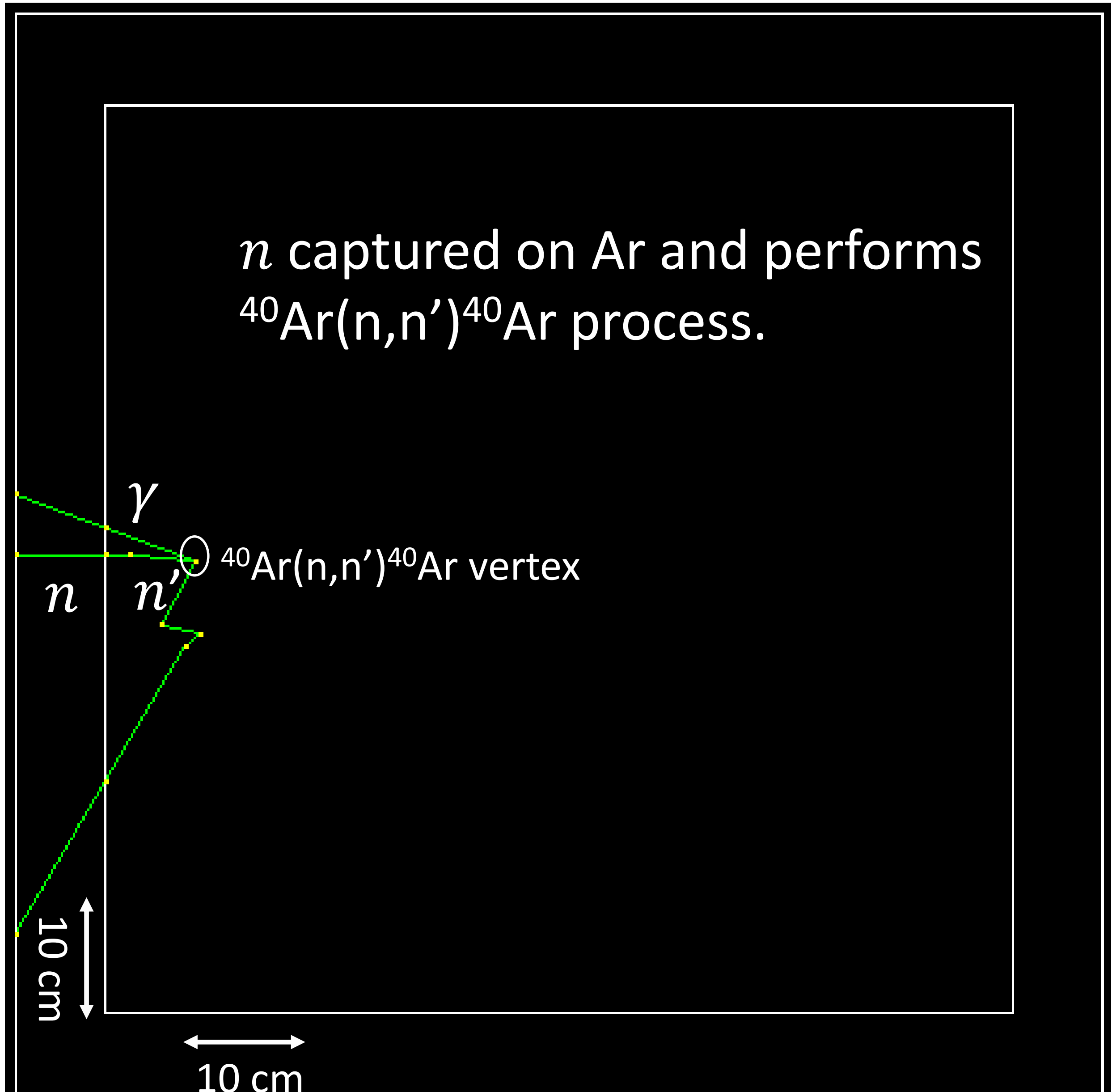
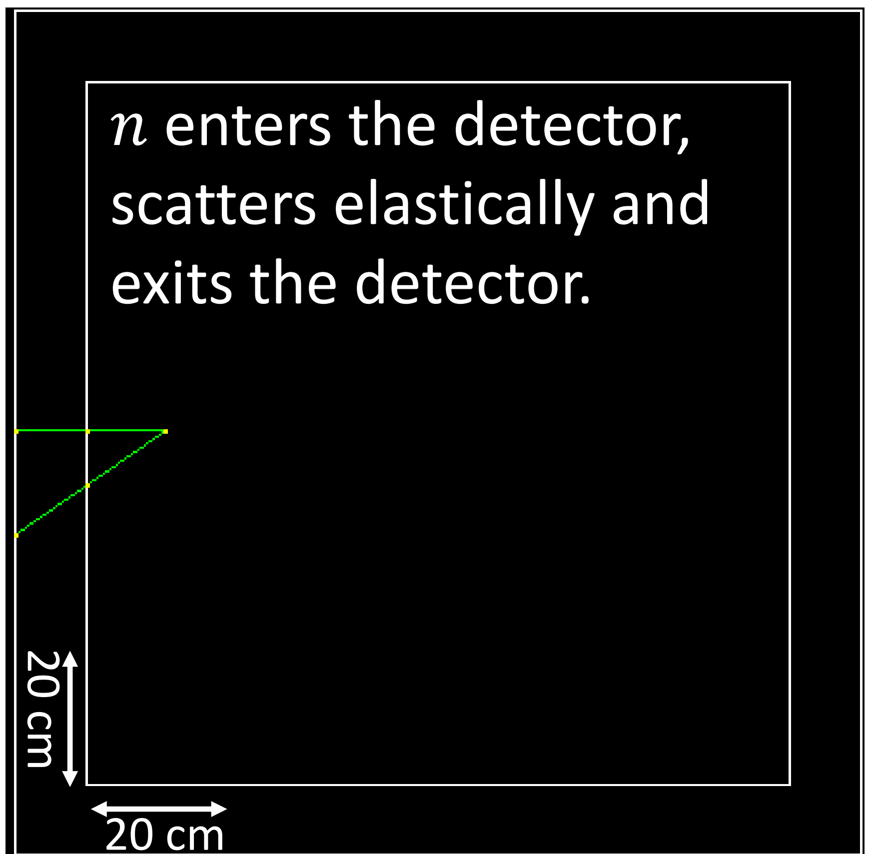
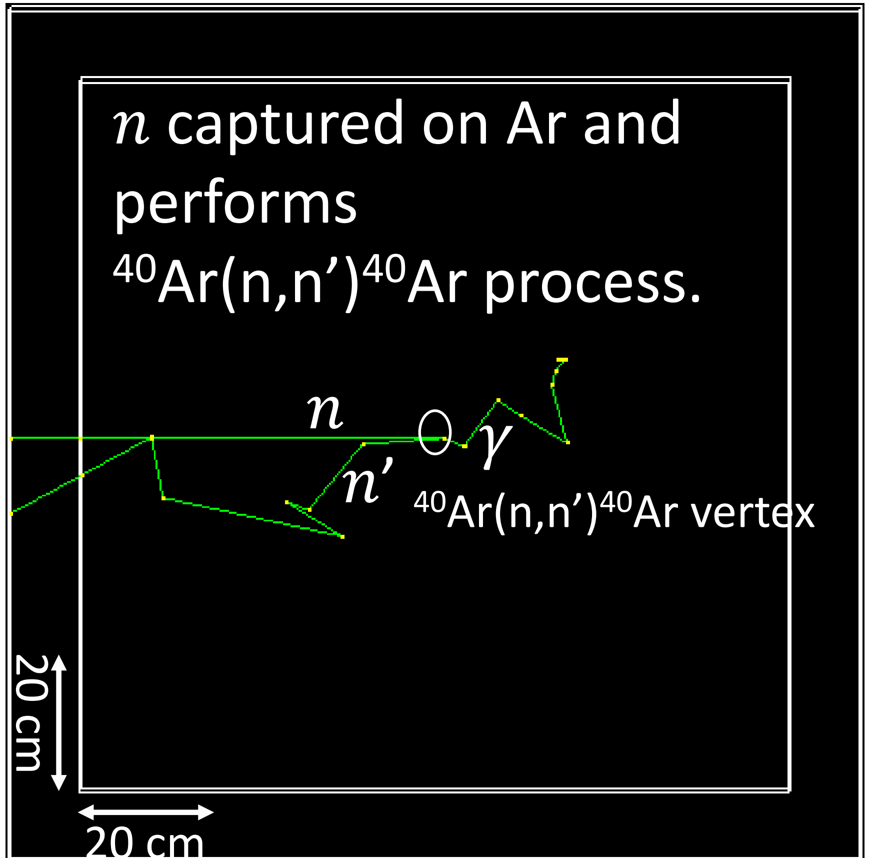
Examples of 2.5 MeV neutron interaction sequence in LArTPC

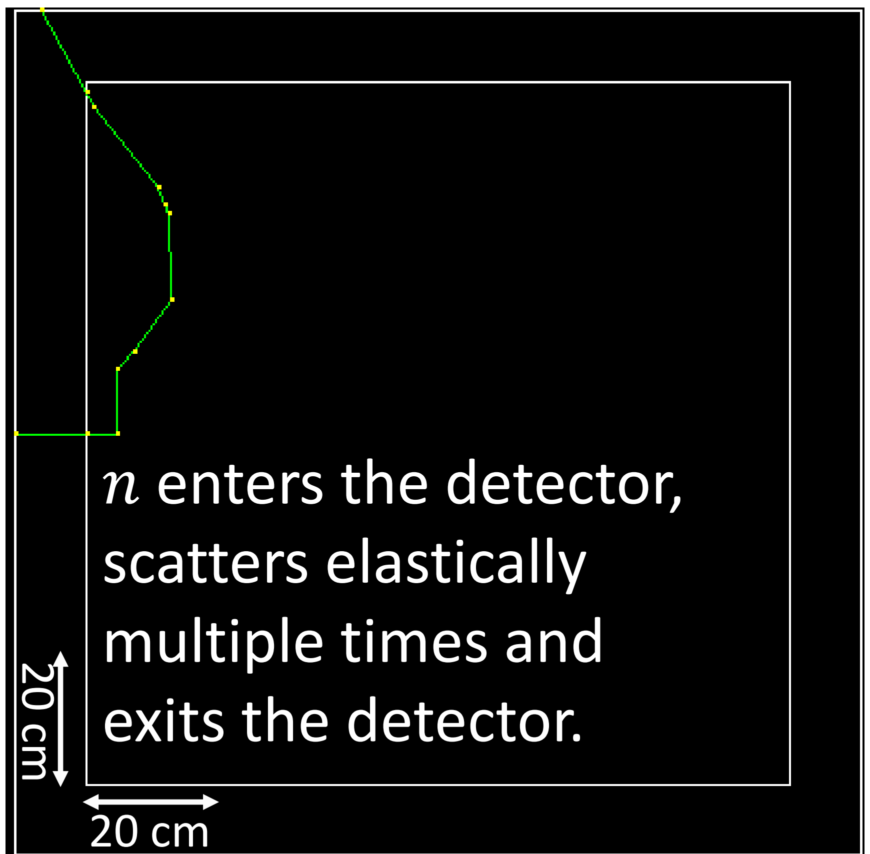


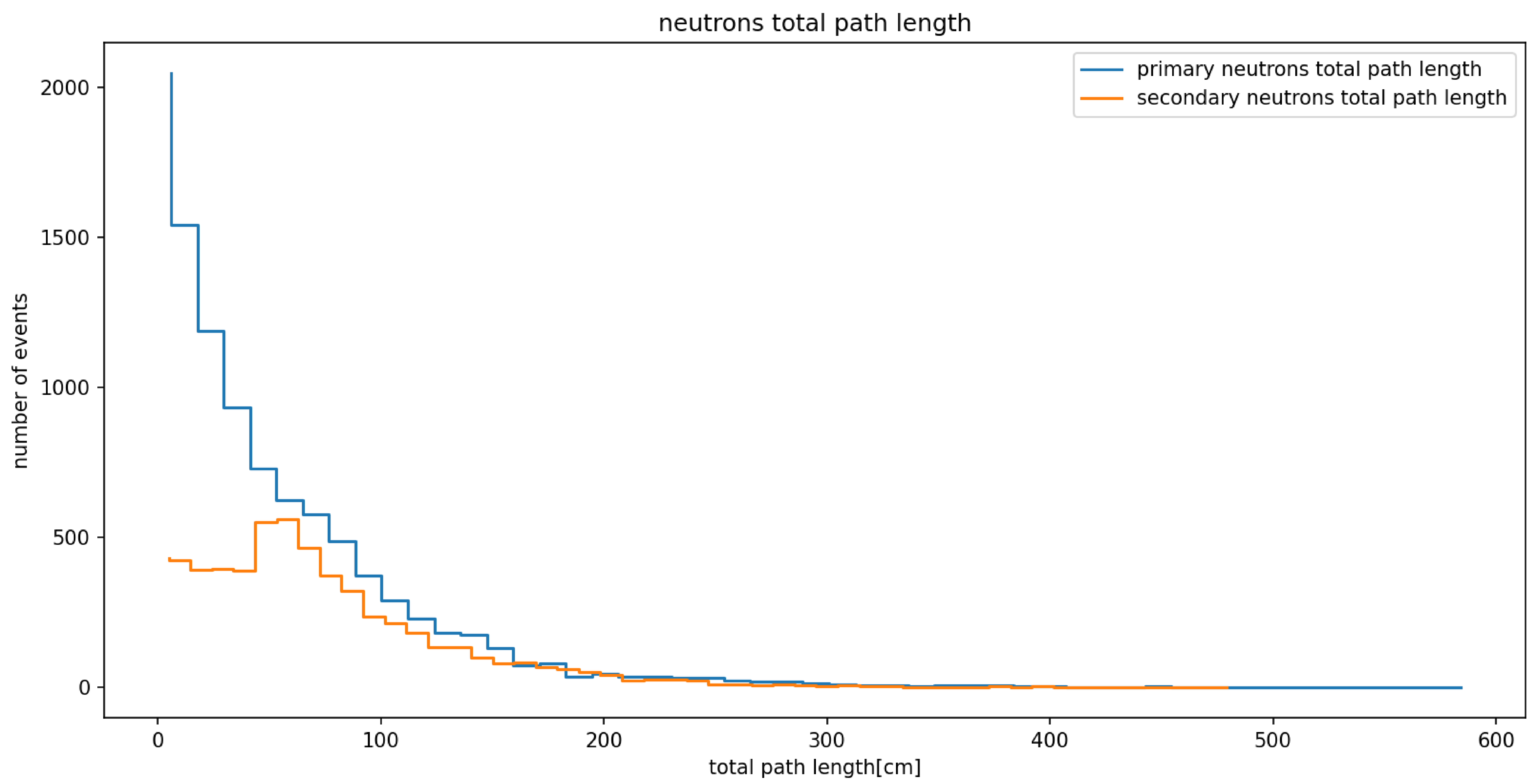


Examples of 2.5 MeV neutron interaction sequence in LArTPC

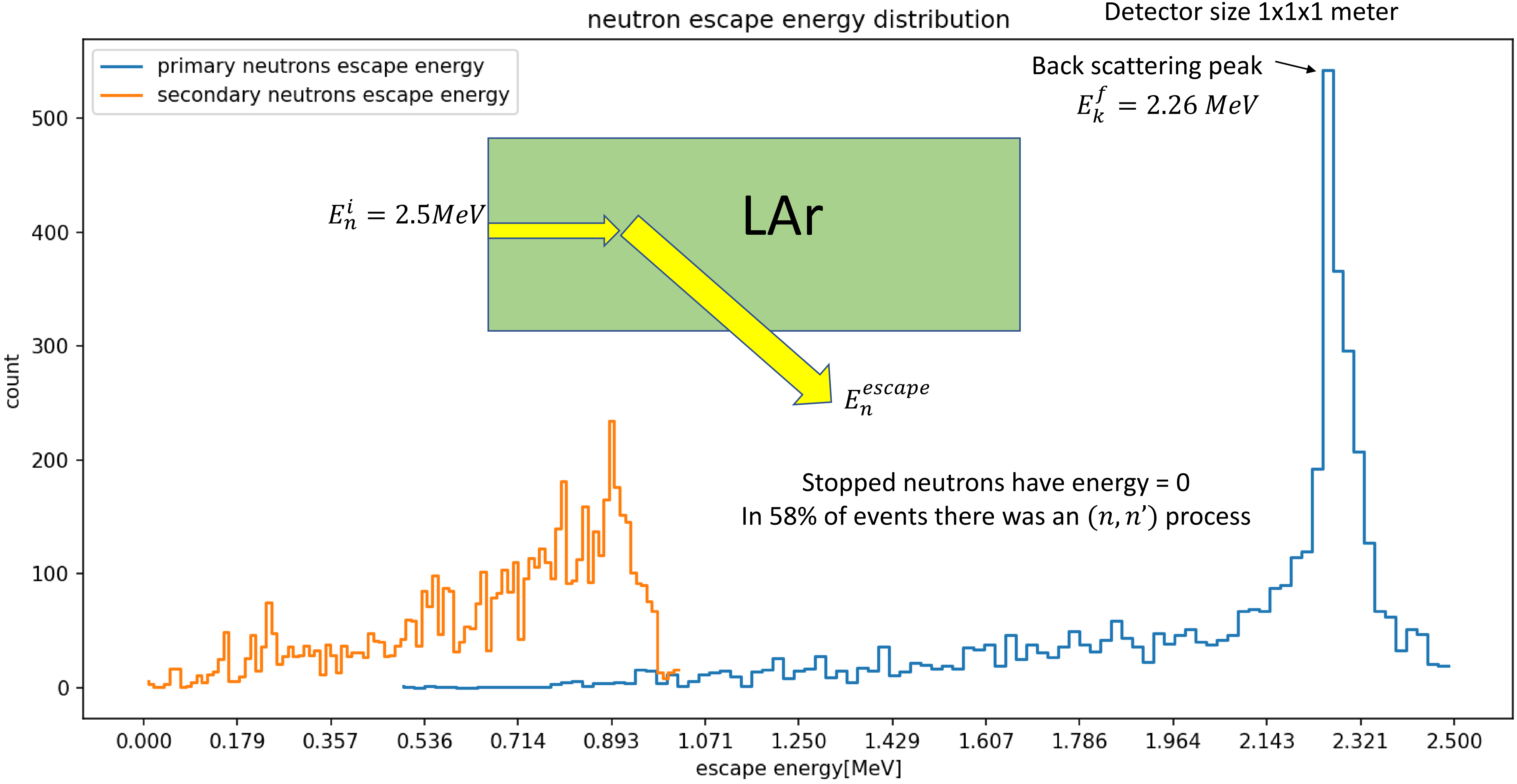




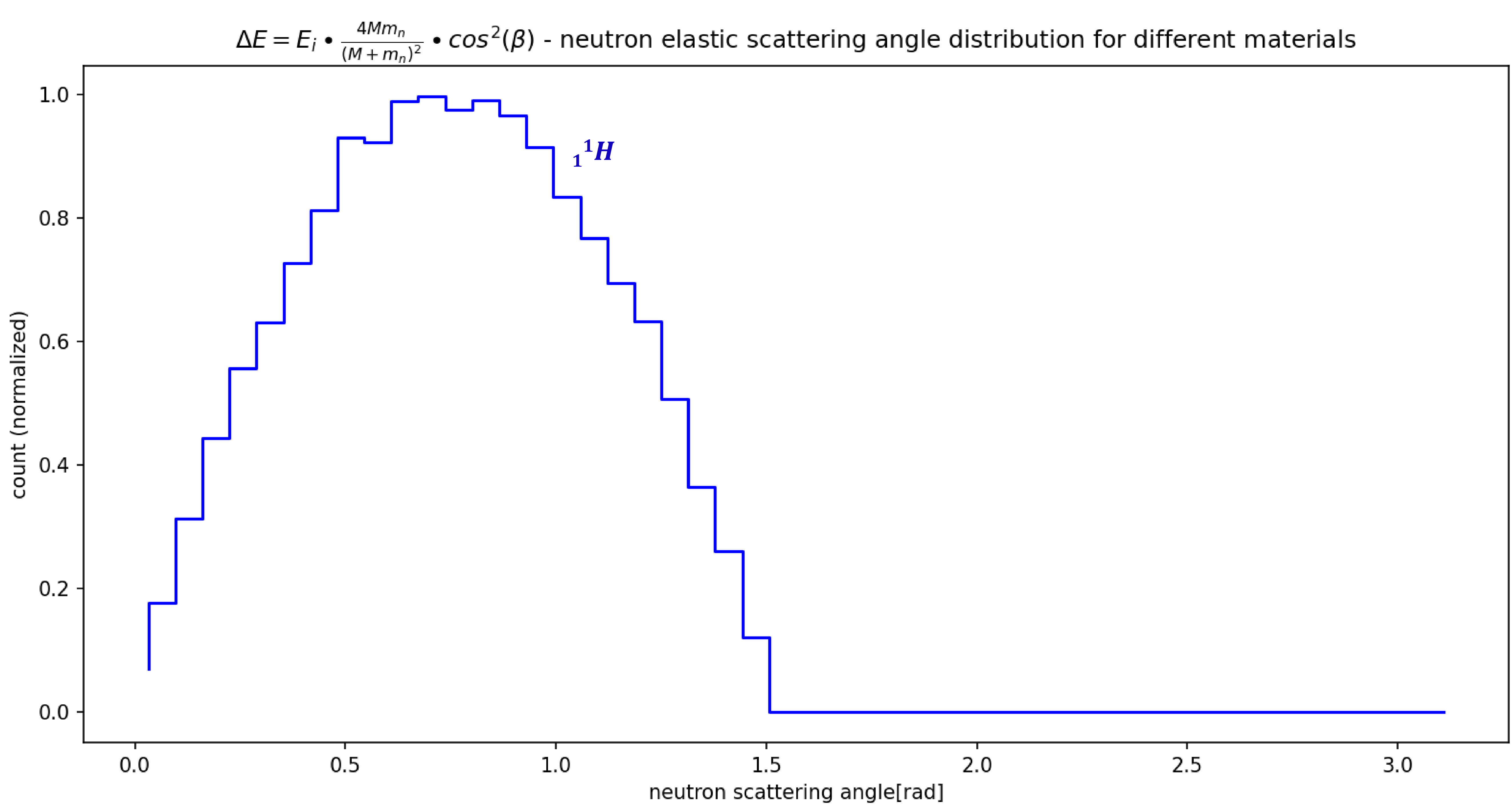




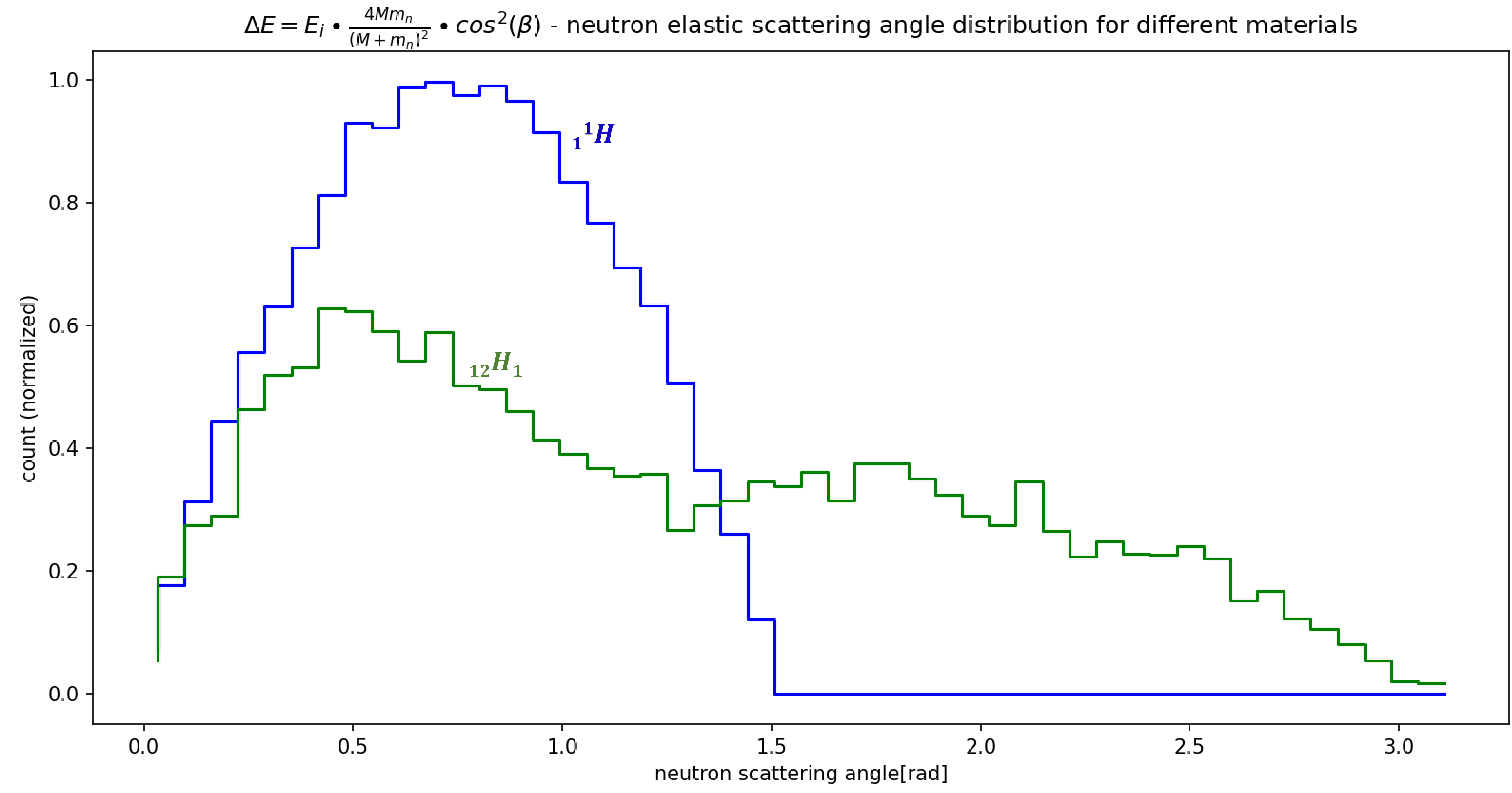
neutrons total path length
primary neutrons total path length
secondary neutrons total path length
number of events
0
500
1000
1500
2000
0
100
200
300
400
500
600
total path length[cm]



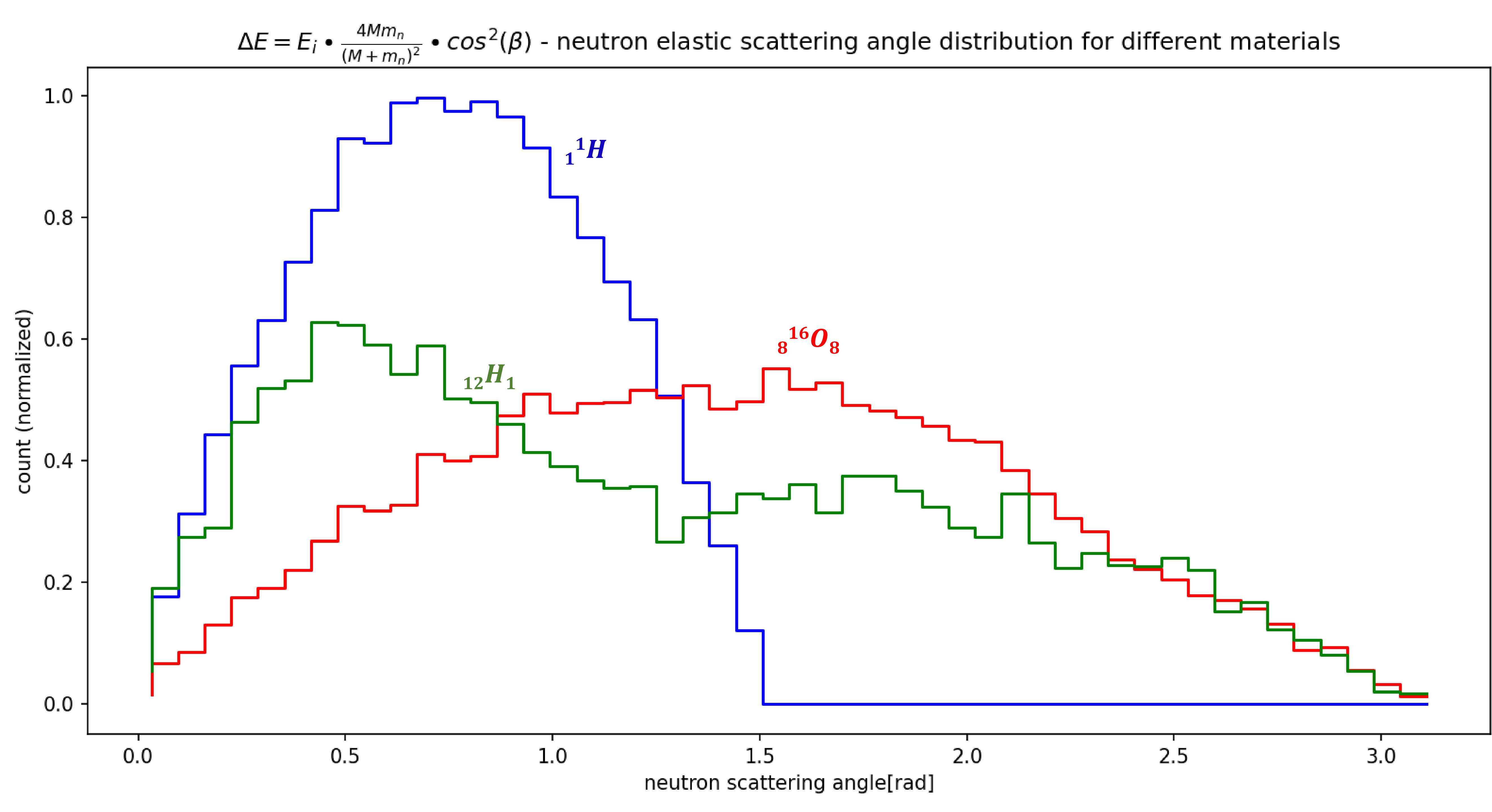
neutron escape energy distribution
Detector size 1x1x1 meter
primary neutrons escape energy
secondary neutrons escape energy
Back scattering peak
$E_k^f = 2.26\ MeV$
LAr
$E_n^i = 2.5 MeV$
E_n^{escape}
Stopped neutrons have energy = 0
In 58% of events there was an (n, n') process
count
escape energy[MeV]
0
100
200
300
400
500
0.000
0.179
0.357
0.536
0.714
0.893
1.071
1.250
1.429
1.607
1.786
1.964
2.143
2.321
2.500



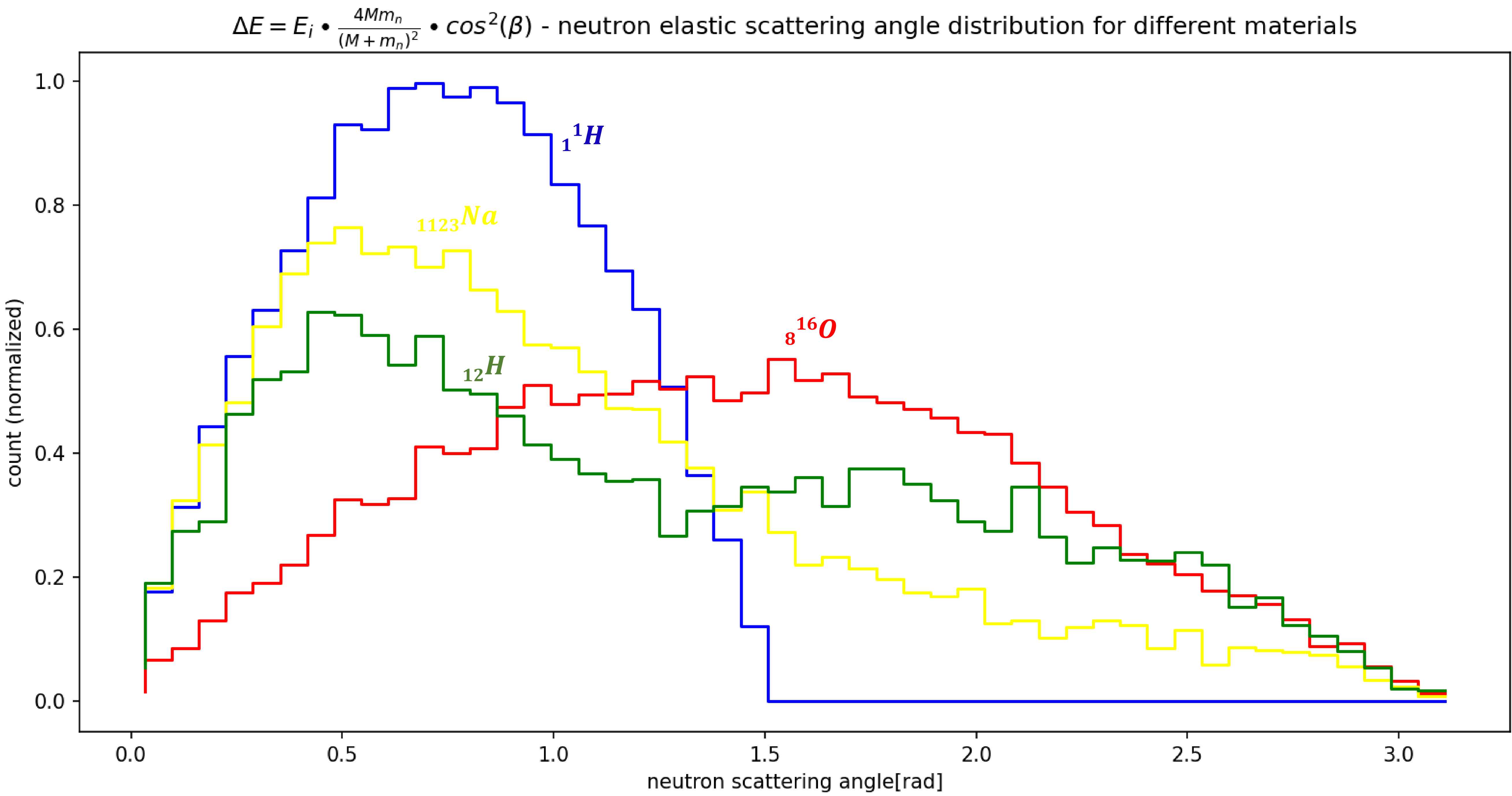
$\Delta E = E_i \bullet \frac{4Mm_n}{(M+m_n)^2} \bullet cos^2(\beta)$ - neutron elastic scattering angle distribution for different materials
$_1^1H$
count (normalized)
0.0
0.2
0.4
0.6
0.8
1.0
0.0
0.5
1.0
1.5
2.0
2.5
3.0
neutron scattering angle[rad]



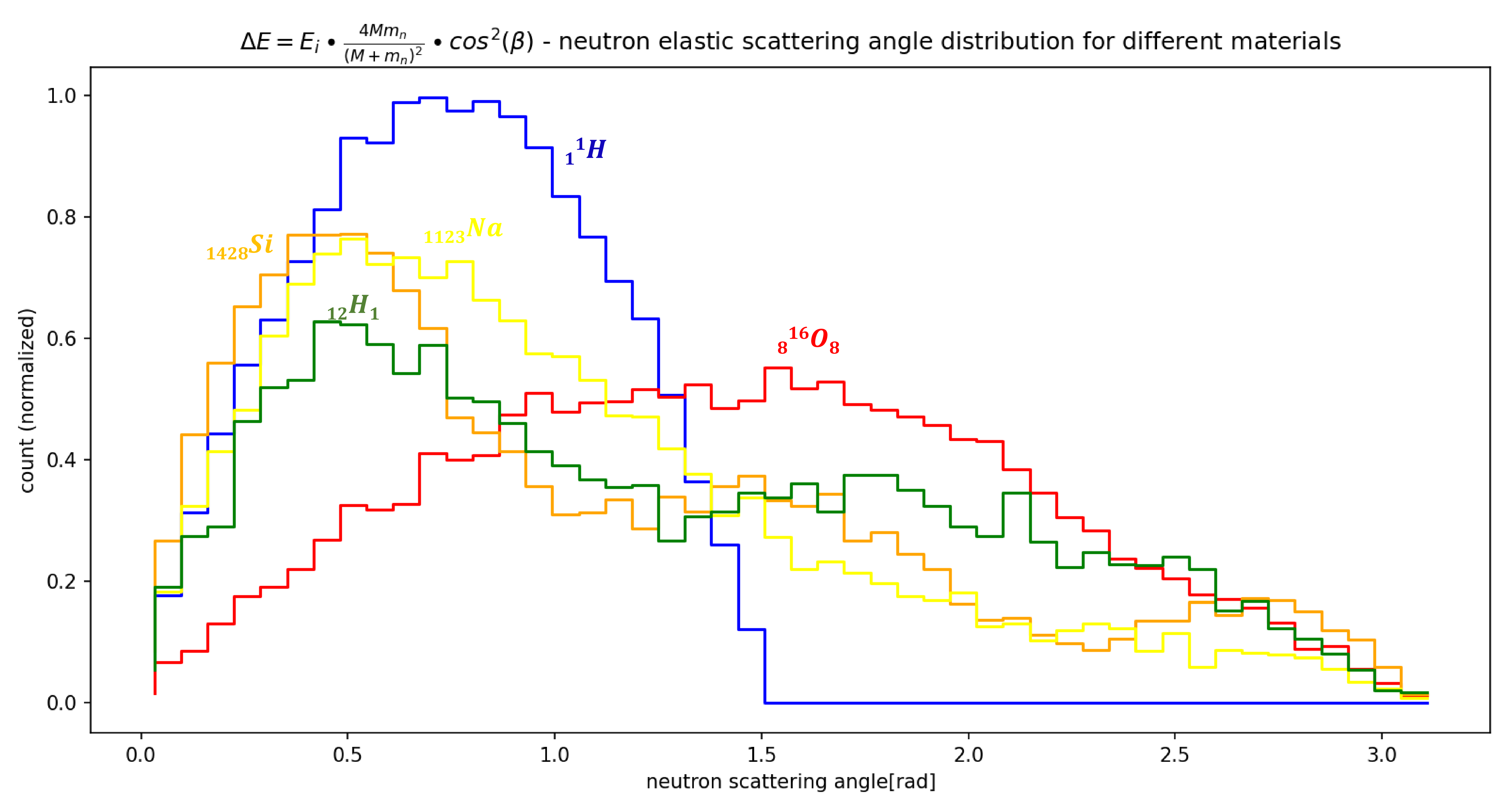
$\Delta E = E_i \bullet \frac{4Mm_n}{(M+m_n)^2} \bullet cos^2(\beta)$ - neutron elastic scattering angle distribution for different materials
$_1{}^1H$
$_{12}H_1$
count (normalized)
neutron scattering angle[rad]
0.0
0.2
0.4
0.6
0.8
1.0
0.0
0.5
1.0
1.5
2.0
2.5
3.0



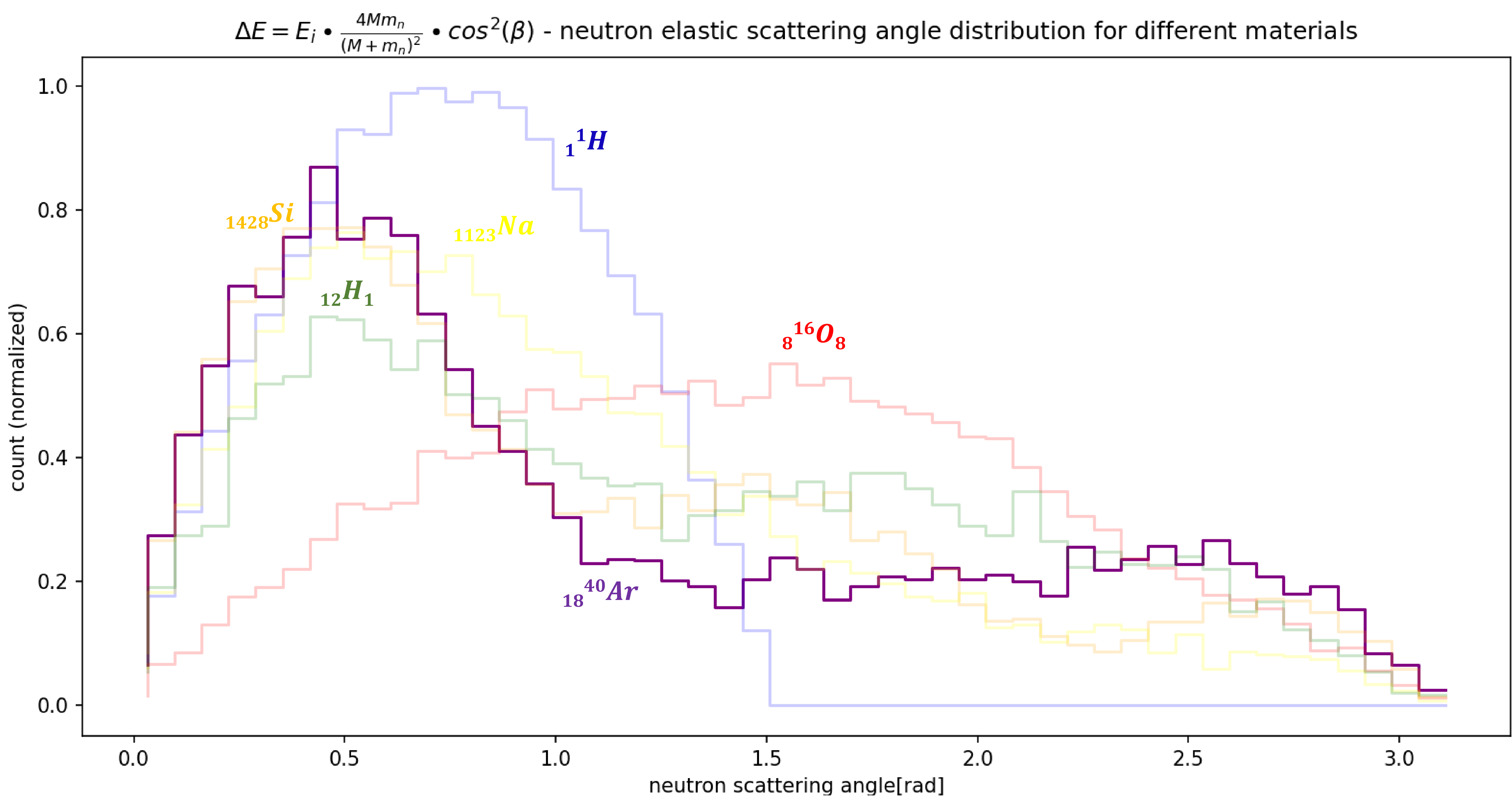
$\Delta E = E_i \bullet \frac{4Mm_n}{(M+m_n)^2} \bullet cos^2(\beta)$ - neutron elastic scattering angle distribution for different materials
count (normalized)
neutron scattering angle[rad]
$_1{}^1H$
$_8{}^{16}O_8$
$_{12}H_1$
0.0
0.2
0.4
0.6
0.8
1.0
0.0
0.5
1.0
1.5
2.0
2.5
3.0



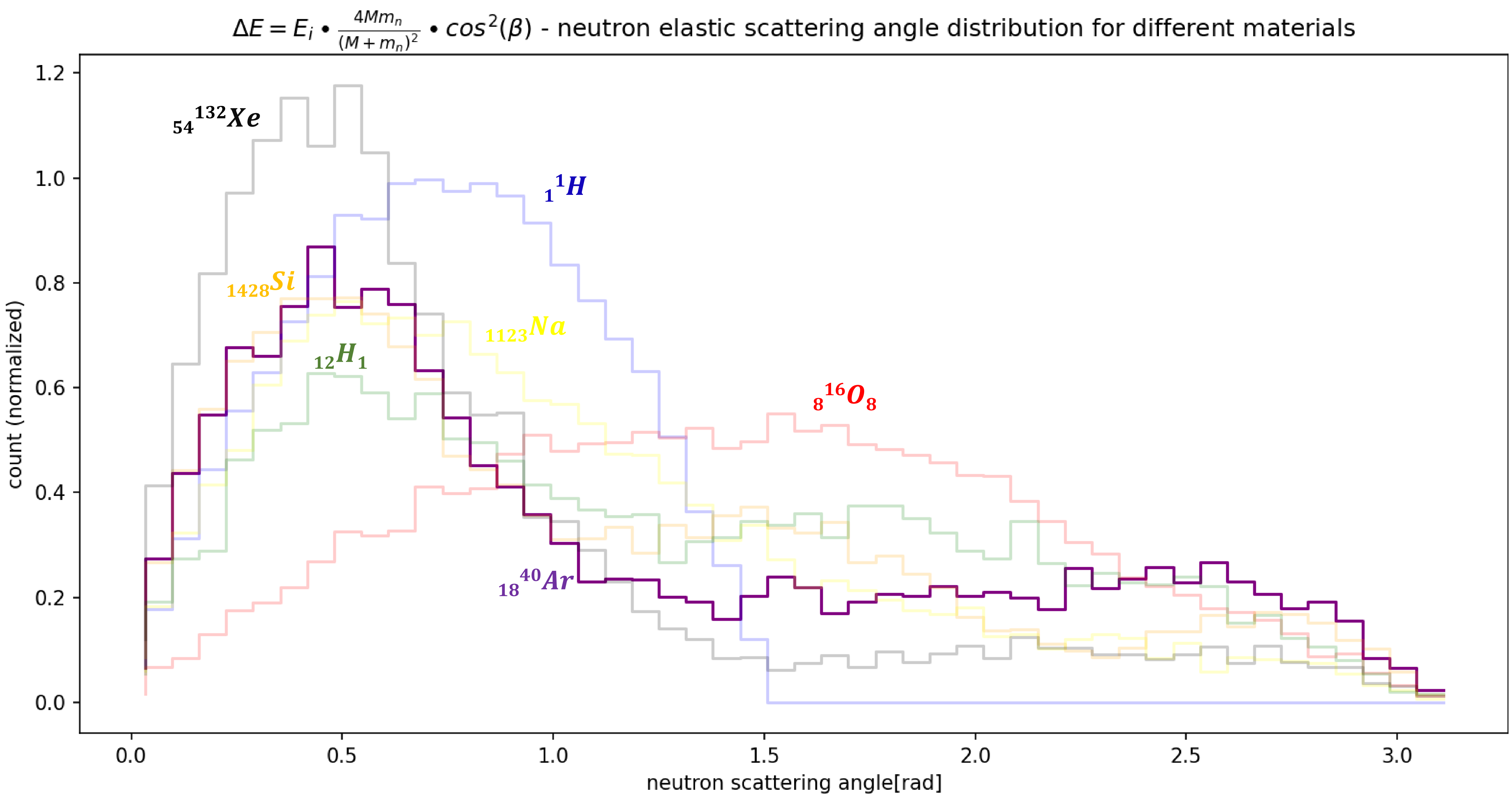
$\Delta E = E_i \bullet \frac{4Mm_n}{(M+m_n)^2} \bullet cos^2(\beta)$ - neutron elastic scattering angle distribution for different materials
count (normalized)
neutron scattering angle[rad]
1.0
0.8
0.6
0.4
0.2
0.0
0.0
0.5
1.0
1.5
2.0
2.5
3.0
$_1{}^1H$
$_{11}{}^{23}Na$
$_1{}^2H$
$_8{}^{16}O$



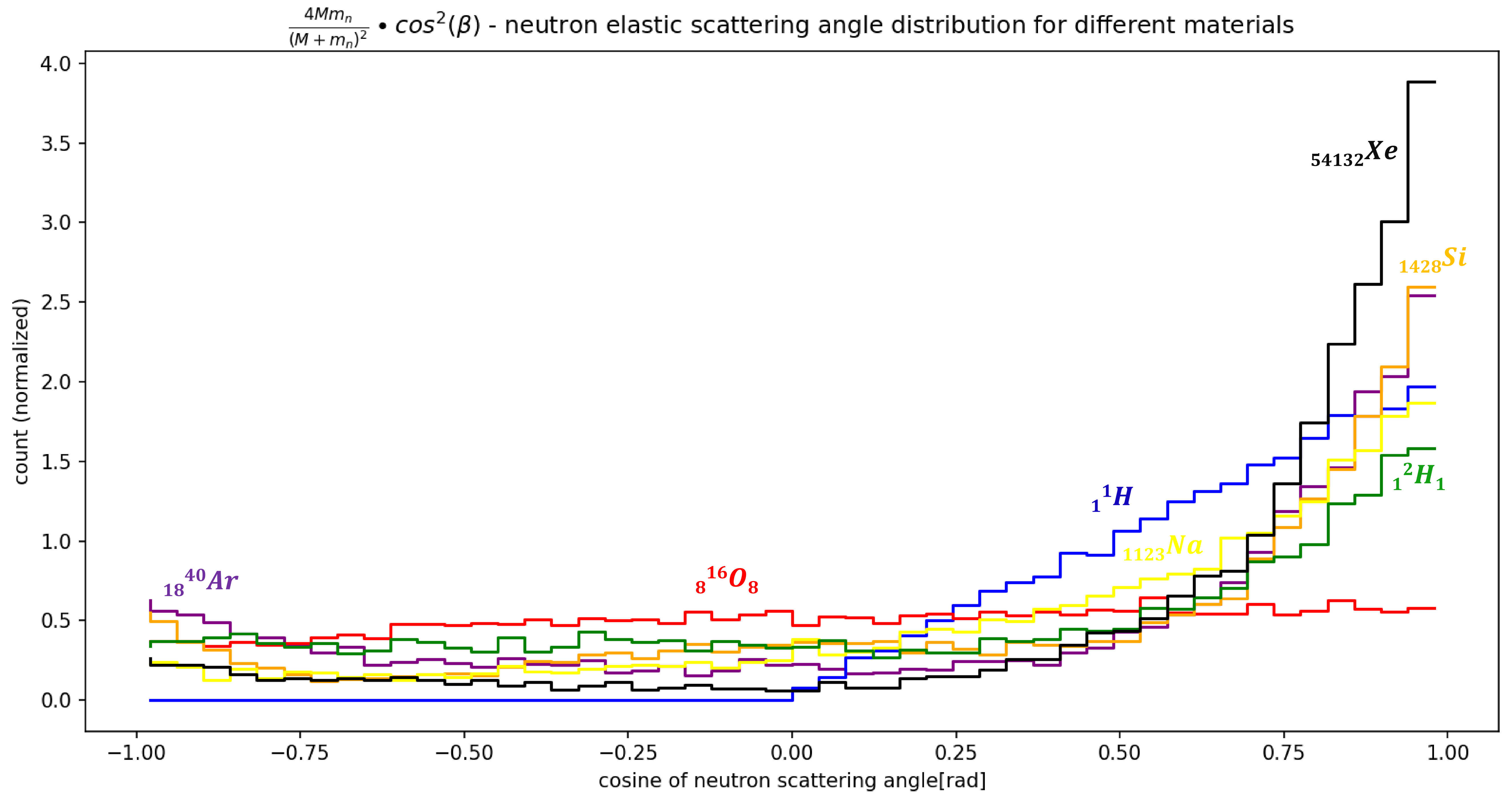
$\Delta E = E_i \bullet \frac{4Mm_n}{(M+m_n)^2} \bullet cos^2(\beta)$ - neutron elastic scattering angle distribution for different materials
count (normalized)
neutron scattering angle[rad]
$_1{}^1H$
$_{1428}Si$
$_{1123}Na$
$_{12}H_1$
$_8{}^{16}O_8$
0.0
0.2
0.4
0.6
0.8
1.0
0.0
0.5
1.0
1.5
2.0
2.5
3.0



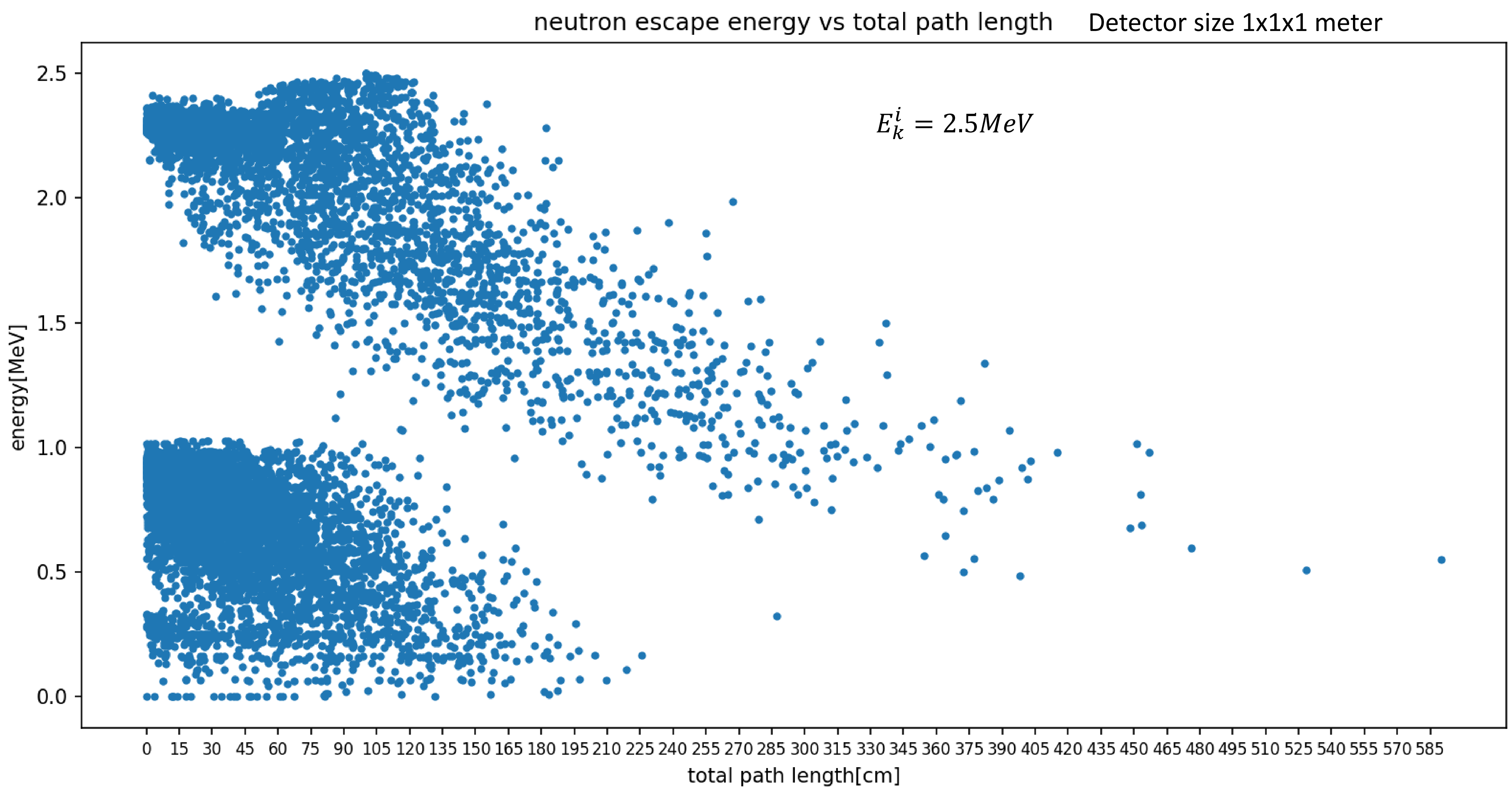
$\Delta E = E_i \bullet \frac{4Mm_n}{(M+m_n)^2} \bullet cos^2(\beta)$ - neutron elastic scattering angle distribution for different materials
$_{1}{}^{1}H$
$_{1428}Si$
$_{1123}Na$
$_{12}H_{1}$
$_{8}{}^{16}O_{8}$
$_{18}{}^{40}Ar$
count (normalized)
0.0
0.2
0.4
0.6
0.8
1.0
0.0
0.5
1.0
1.5
2.0
2.5
3.0
neutron scattering angle[rad]

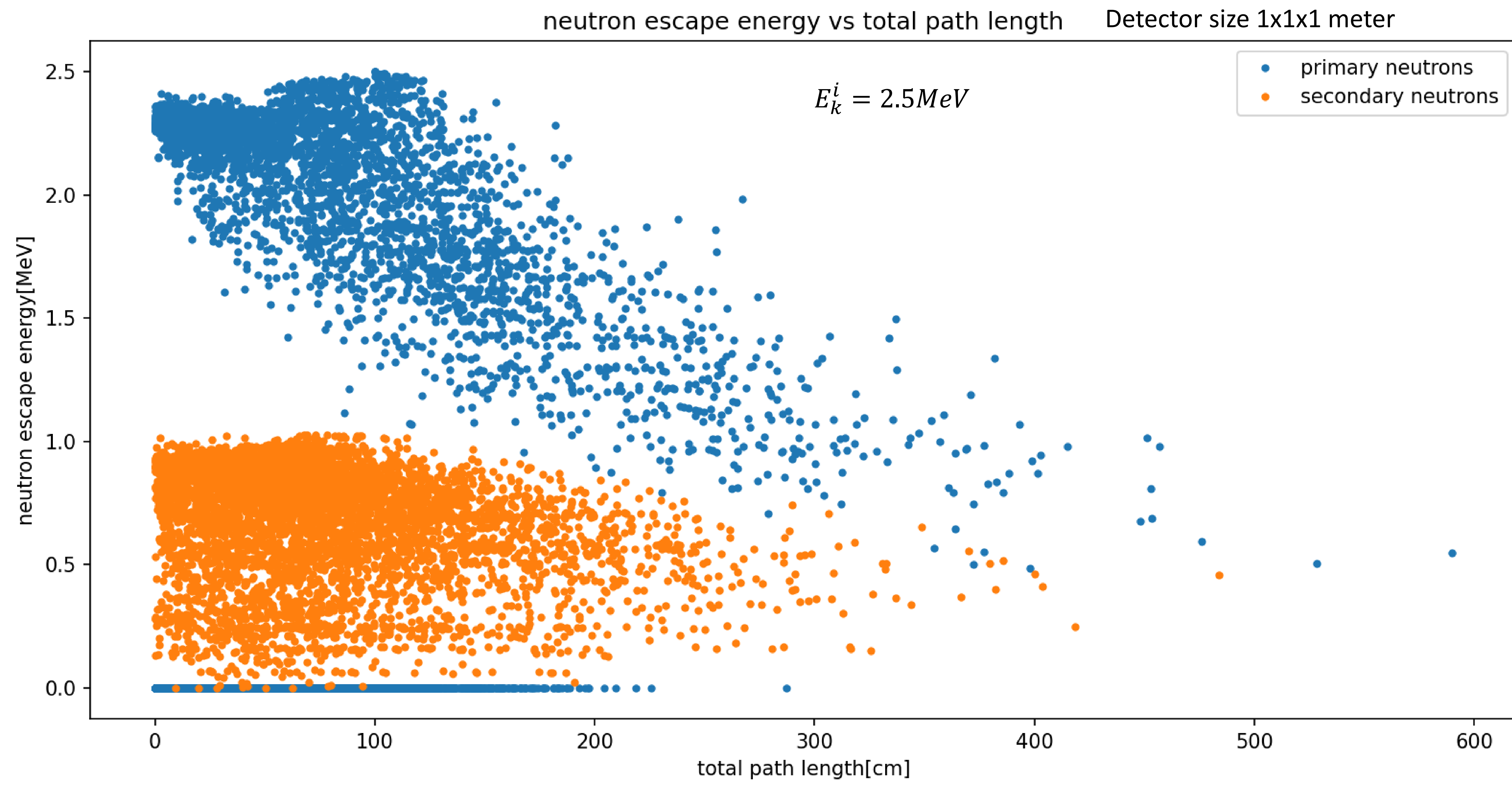


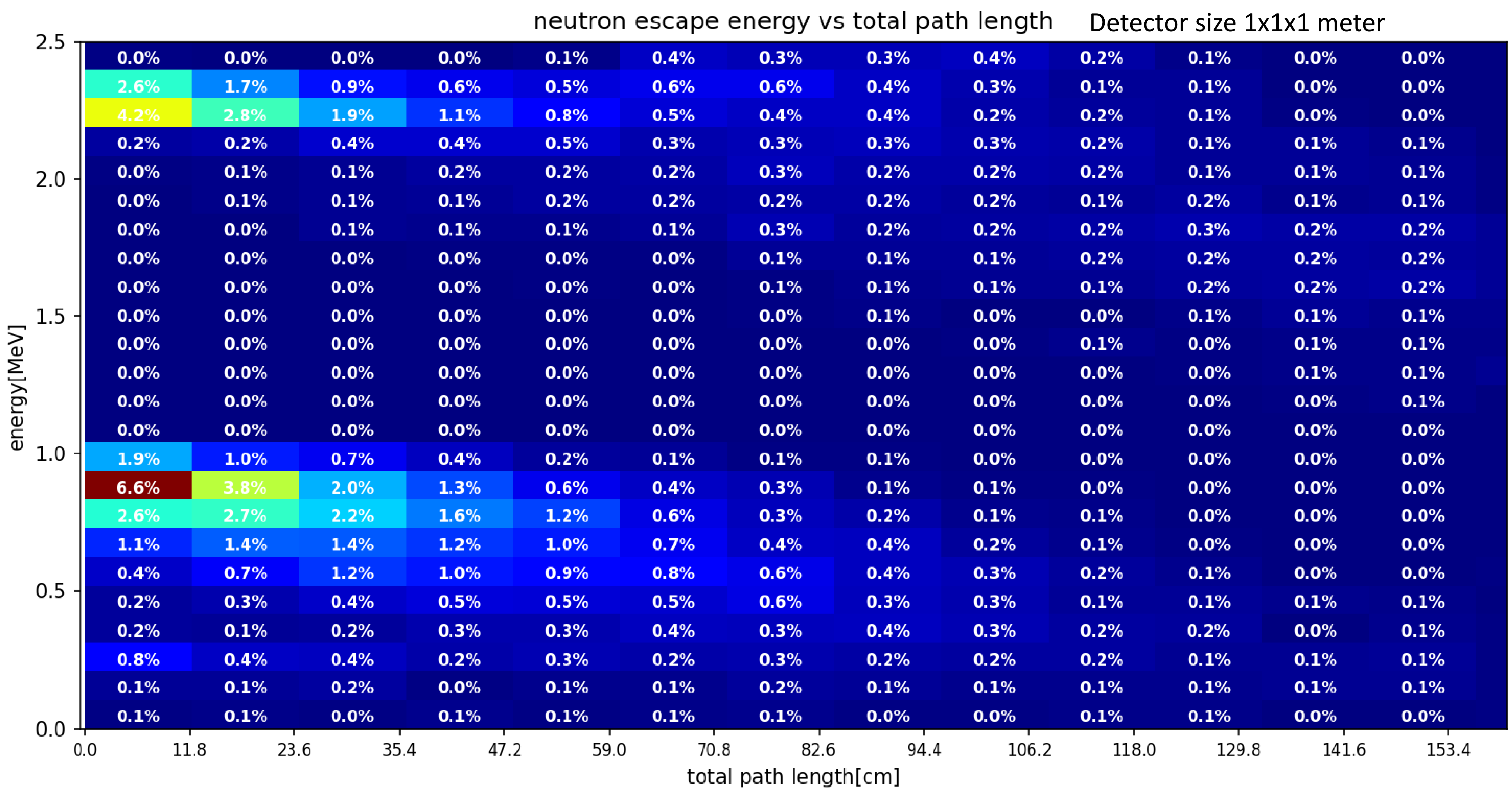
$\Delta E = E_i \bullet \frac{4Mm_n}{(M+m_n)^2} \bullet cos^2(\beta)$ - neutron elastic scattering angle distribution for different materials
${}_{54}{}^{132}Xe$
${}_{1}{}^{1}H$
${}_{14}{}^{28}Si$
${}_{11}{}^{23}Na$
${}_{12}H_{1}$
${}_{8}{}^{16}O_{8}$
${}_{18}{}^{40}Ar$
count (normalized)
neutron scattering angle[rad]
1.2
1.0
0.8
0.6
0.4
0.2
0.0
0.0
0.5
1.0
1.5
2.0
2.5
3.0

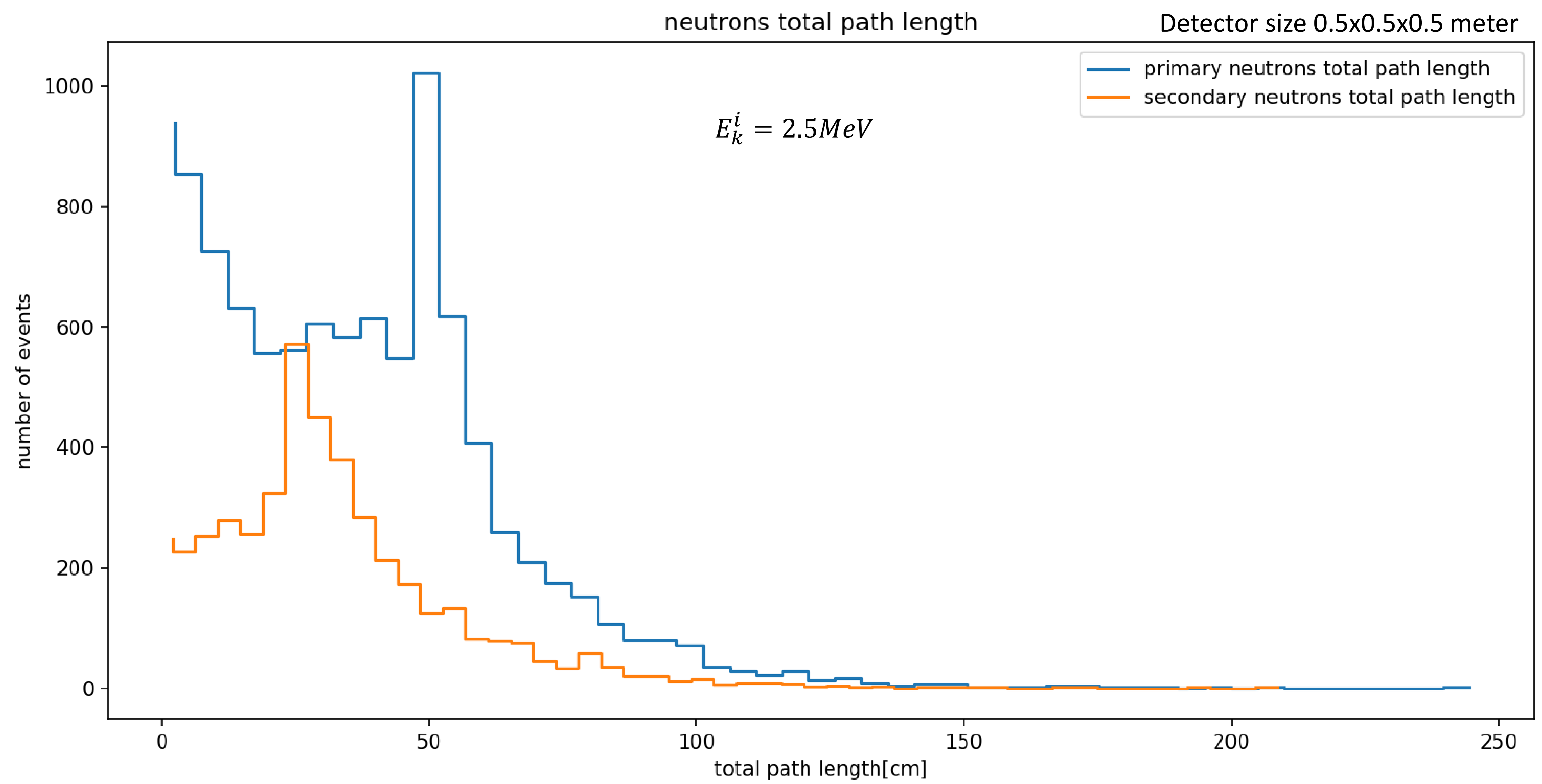


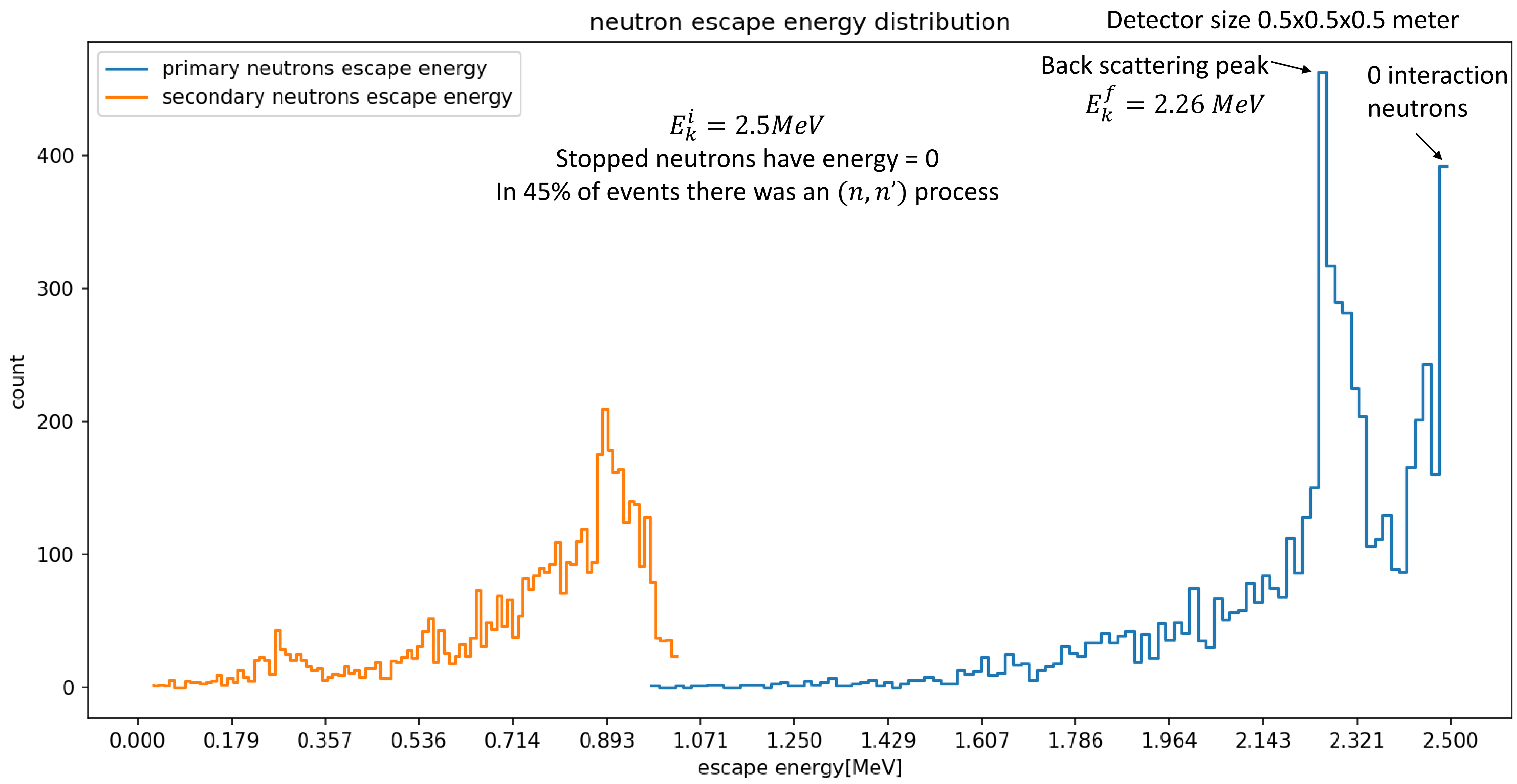
$\frac{4Mm_n}{(M+m_n)^2} \bullet cos^2(\beta)$ - neutron elastic scattering angle distribution for different materials
count (normalized)
cosine of neutron scattering angle[rad]
$_{54132}Xe$
$_{1428}Si$
$_1{}^2H_1$
$_1{}^1H$
$_{1123}Na$
$_{18}{}^{40}Ar$
$_8{}^{16}O_8$

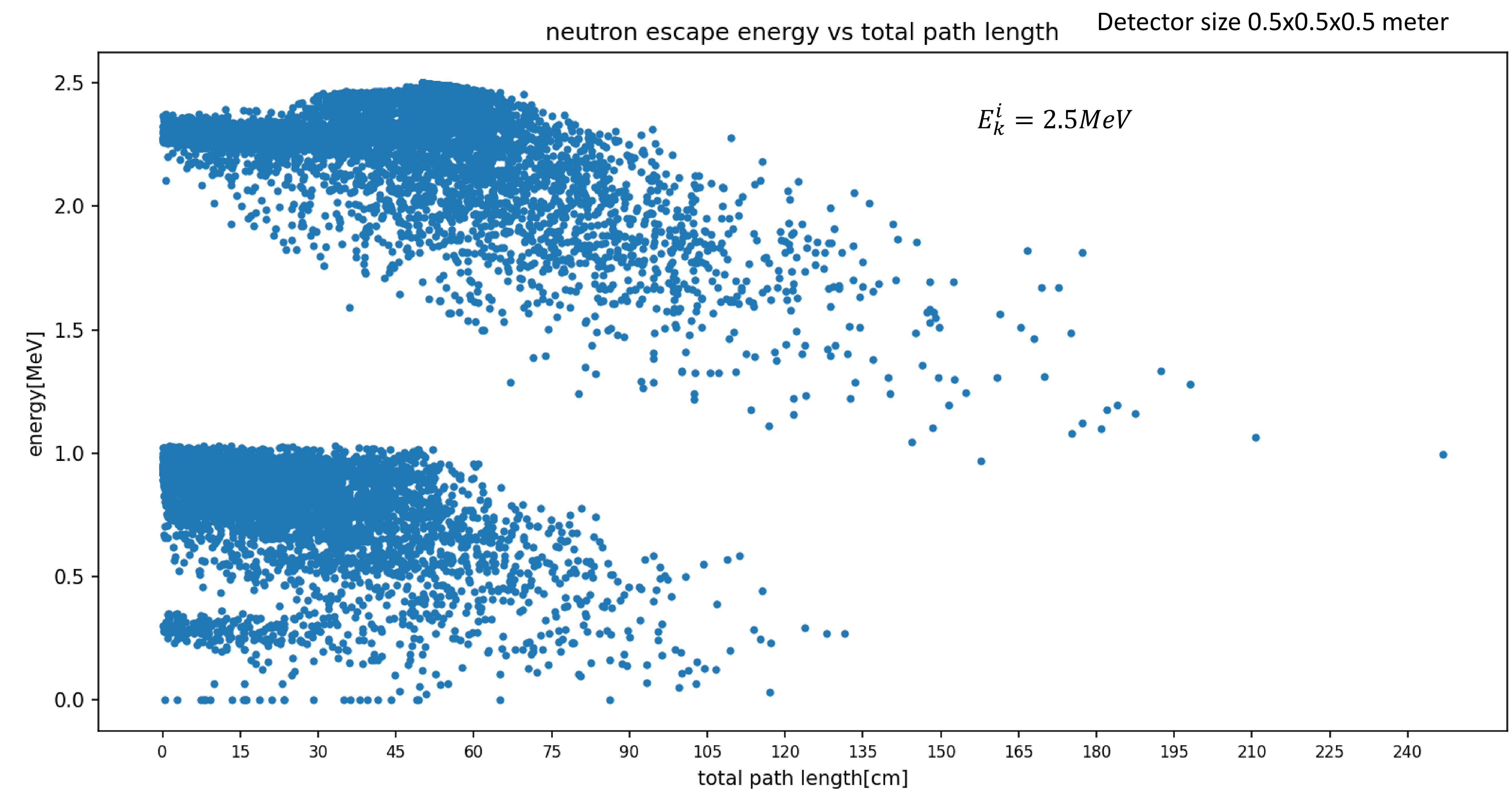

neutron escape energy vs total path length
Detector size 1x1x1 meter
$E_k^i = 2.5MeV$
energy[MeV]
total path length[cm]
2.5
2.0
1.5
1.0
0.5
0.0
0 15 30 45 60 75 90 105 120 135 150 165 180 195 210 225 240 255 270 285 300 315 330 345 360 375 390 405 420 435 450 465 480 495 510 525 540 555 570 585


neutron escape energy vs total path length
Detector size 1x1x1 meter
$E_k^i = 2.5MeV$
primary neutrons
secondary neutrons
neutron escape energy[MeV]
total path length[cm]
2.5
2.0
1.5
1.0
0.5
0.0
0
100
200
300
400
500
600

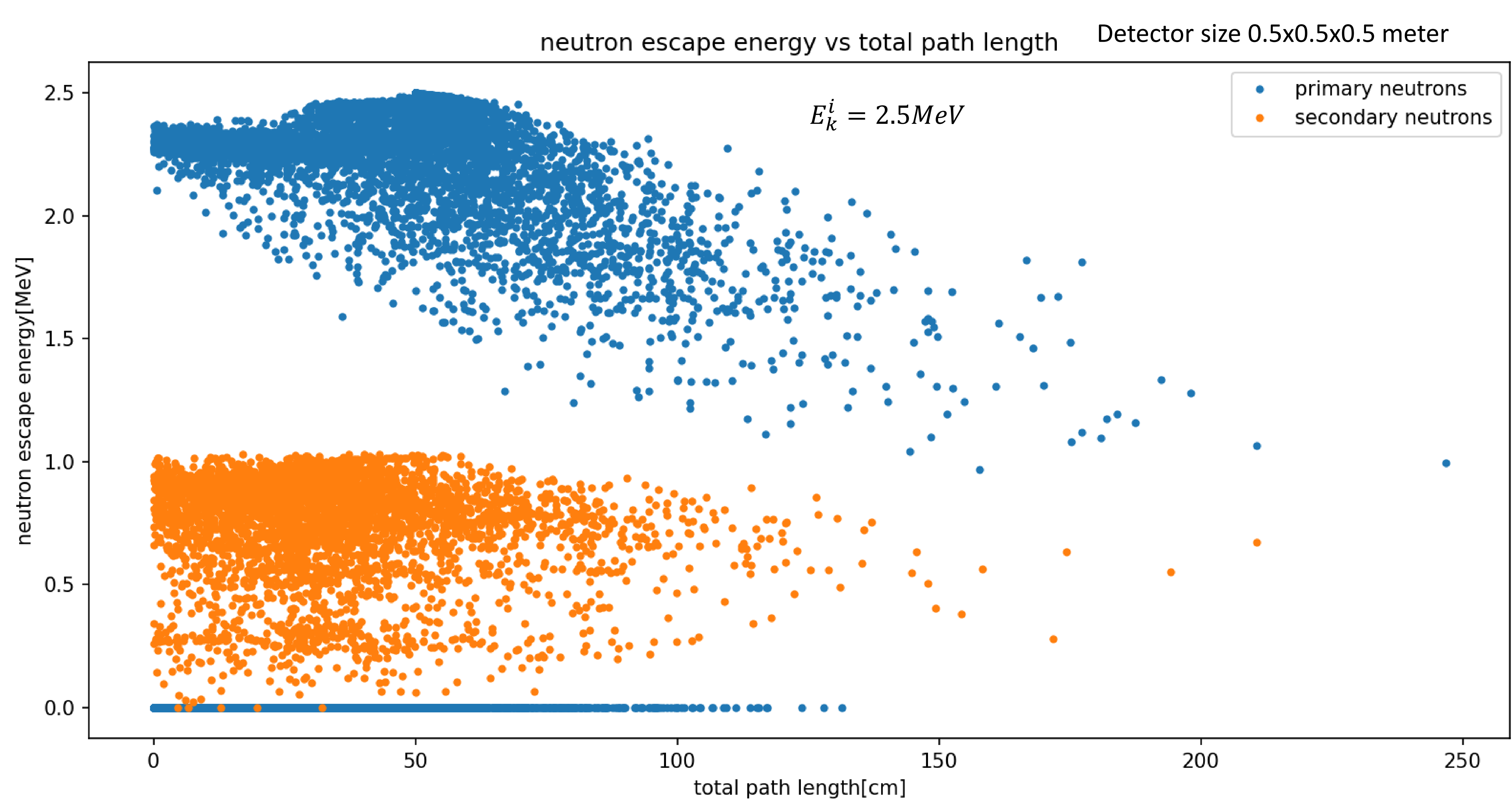

neutron escape energy vs total path length
Detector size 1x1x1 meter
0.0% 0.0% 0.0% 0.0% 0.1% 0.4% 0.3% 0.3% 0.4% 0.2% 0.1% 0.0% 0.0%
2.6% 1.7% 0.9% 0.6% 0.5% 0.6% 0.6% 0.4% 0.3% 0.1% 0.1% 0.0% 0.0%
4.2% 2.8% 1.9% 1.1% 0.8% 0.5% 0.4% 0.4% 0.2% 0.2% 0.1% 0.0% 0.0%
0.2% 0.2% 0.4% 0.4% 0.5% 0.3% 0.3% 0.3% 0.3% 0.2% 0.1% 0.1% 0.1%
0.0% 0.1% 0.1% 0.2% 0.2% 0.2% 0.3% 0.2% 0.2% 0.2% 0.1% 0.1% 0.1%
0.0% 0.1% 0.1% 0.1% 0.2% 0.2% 0.2% 0.2% 0.2% 0.1% 0.2% 0.1% 0.1%
0.0% 0.0% 0.1% 0.1% 0.1% 0.1% 0.3% 0.2% 0.2% 0.2% 0.3% 0.2% 0.2%
0.0% 0.0% 0.0% 0.0% 0.0% 0.0% 0.1% 0.1% 0.1% 0.2% 0.2% 0.2% 0.2%
0.0% 0.0% 0.0% 0.0% 0.0% 0.0% 0.1% 0.1% 0.1% 0.1% 0.2% 0.2% 0.2%
0.0% 0.0% 0.0% 0.0% 0.0% 0.0% 0.0% 0.1% 0.0% 0.0% 0.1% 0.1% 0.1%
0.0% 0.0% 0.0% 0.0% 0.0% 0.0% 0.0% 0.0% 0.0% 0.1% 0.0% 0.1% 0.1%
0.0% 0.0% 0.0% 0.0% 0.0% 0.0% 0.0% 0.0% 0.0% 0.0% 0.0% 0.1% 0.1%
0.0% 0.0% 0.0% 0.0% 0.0% 0.0% 0.0% 0.0% 0.0% 0.0% 0.0% 0.0% 0.1%
0.0% 0.0% 0.0% 0.0% 0.0% 0.0% 0.0% 0.0% 0.0% 0.0% 0.0% 0.0% 0.0%
1.9% 1.0% 0.7% 0.4% 0.2% 0.1% 0.1% 0.1% 0.0% 0.0% 0.0% 0.0% 0.0%
6.6% 3.8% 2.0% 1.3% 0.6% 0.4% 0.3% 0.1% 0.1% 0.0% 0.0% 0.0% 0.0%
2.6% 2.7% 2.2% 1.6% 1.2% 0.6% 0.3% 0.2% 0.1% 0.1% 0.0% 0.0% 0.0%
1.1% 1.4% 1.4% 1.2% 1.0% 0.7% 0.4% 0.4% 0.2% 0.1% 0.0% 0.0% 0.0%
0.4% 0.7% 1.2% 1.0% 0.9% 0.8% 0.6% 0.4% 0.3% 0.2% 0.1% 0.0% 0.0%
0.2% 0.3% 0.4% 0.5% 0.5% 0.5% 0.6% 0.3% 0.3% 0.1% 0.1% 0.1% 0.1%
0.2% 0.1% 0.2% 0.3% 0.3% 0.4% 0.3% 0.4% 0.3% 0.2% 0.2% 0.0% 0.1%
0.8% 0.4% 0.4% 0.2% 0.3% 0.2% 0.3% 0.2% 0.2% 0.2% 0.1% 0.1% 0.1%
0.1% 0.1% 0.2% 0.0% 0.1% 0.1% 0.2% 0.1% 0.1% 0.1% 0.1% 0.1% 0.1%
0.1% 0.1% 0.0% 0.1% 0.1% 0.1% 0.1% 0.0% 0.0% 0.1% 0.1% 0.0% 0.0%
2.5
2.0
1.5
1.0
0.5
0.0
energy[MeV]
0.0 11.8 23.6 35.4 47.2 59.0 70.8 82.6 94.4 106.2 118.0 129.8 141.6 153.4
total path length[cm]


neutrons total path length
Detector size 0.5x0.5x0.5 meter
primary neutrons total path length
secondary neutrons total path length
$E_k^i = 2.5MeV$
number of events
1000
800
600
400
200
0
0
50
100
150
200
250
total path length[cm]

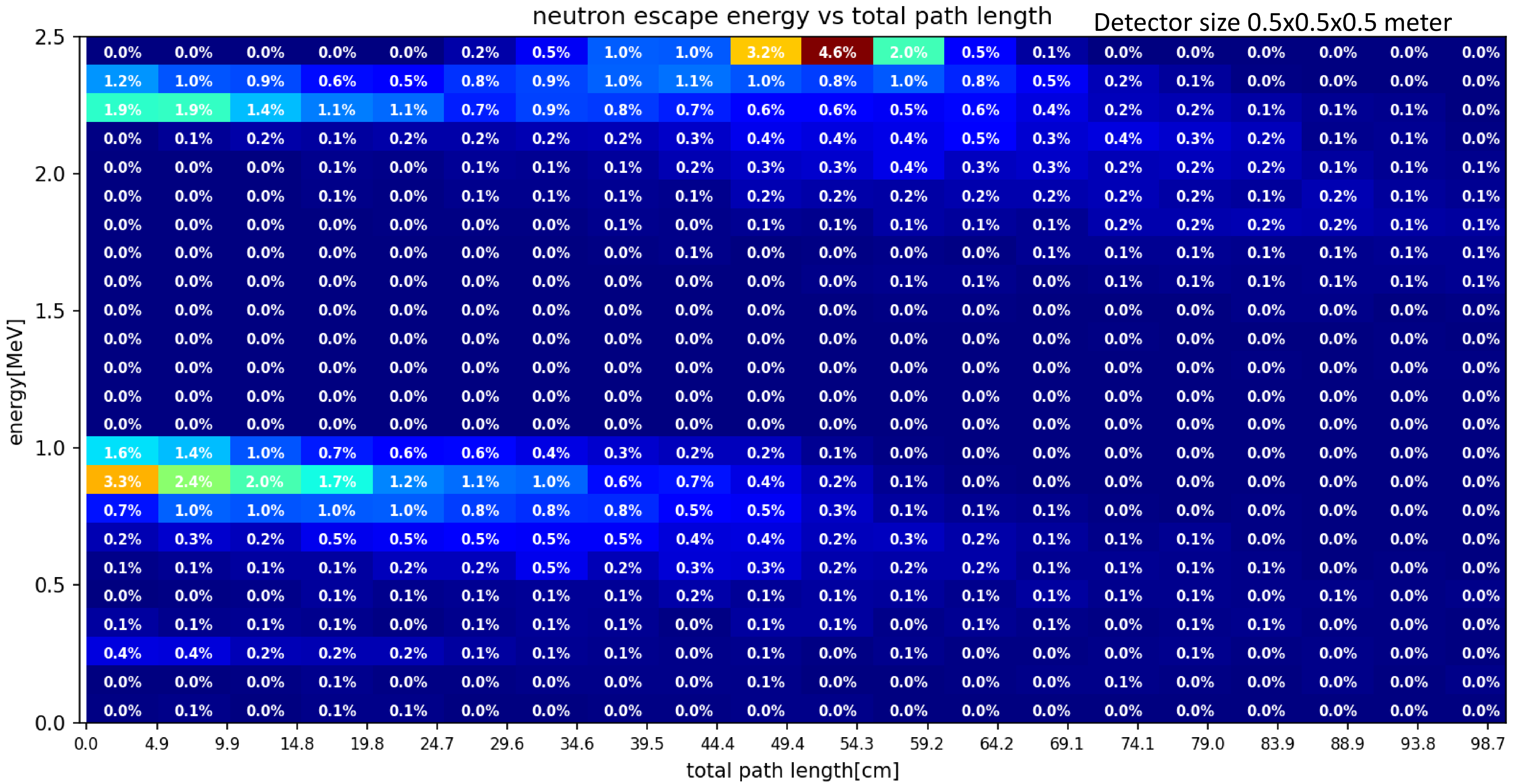

neutron escape energy distribution
Detector size 0.5x0.5x0.5 meter
primary neutrons escape energy
secondary neutrons escape energy
$E_k^i = 2.5MeV$
Stopped neutrons have energy = 0
In 45% of events there was an (n, n') process
Back scattering peak
$E_k^f = 2.26\ MeV$
0 interaction neutrons
count
0
100
200
300
400
0.000
0.179
0.357
0.536
0.714
0.893
1.071
1.250
1.429
1.607
1.786
1.964
2.143
2.321
2.500
escape energy[MeV]



neutron escape energy vs total path length
Detector size 0.5x0.5x0.5 meter
$E_k^i = 2.5MeV$
energy[MeV]
0.0
0.5
1.0
1.5
2.0
2.5
0
15
30
45
60
75
90
105
120
135
150
165
180
195
210
225
240
total path length[cm]



neutron escape energy vs total path length
Detector size 0.5x0.5x0.5 meter
$E_k^i = 2.5MeV$
primary neutrons
secondary neutrons
neutron escape energy[MeV]
total path length[cm]
0.0
0.5
1.0
1.5
2.0
2.5
0
50
100
150
200
250


neutron escape energy vs total path length
Detector size 0.5x0.5x0.5 meter
energy[MeV]
2.5
2.0
1.5
1.0
0.5
0.0
0.0% 0.0% 0.0% 0.0% 0.0% 0.2% 0.5% 1.0% 1.0% 3.2% 4.6% 2.0% 0.5% 0.1% 0.0% 0.0% 0.0% 0.0% 0.0% 0.0%
1.2% 1.0% 0.9% 0.6% 0.5% 0.8% 0.9% 1.0% 1.1% 1.0% 0.8% 1.0% 0.8% 0.5% 0.2% 0.1% 0.0% 0.0% 0.0% 0.0%
1.9% 1.9% 1.4% 1.1% 1.1% 0.7% 0.9% 0.8% 0.7% 0.6% 0.6% 0.5% 0.6% 0.4% 0.2% 0.2% 0.1% 0.1% 0.1% 0.0%
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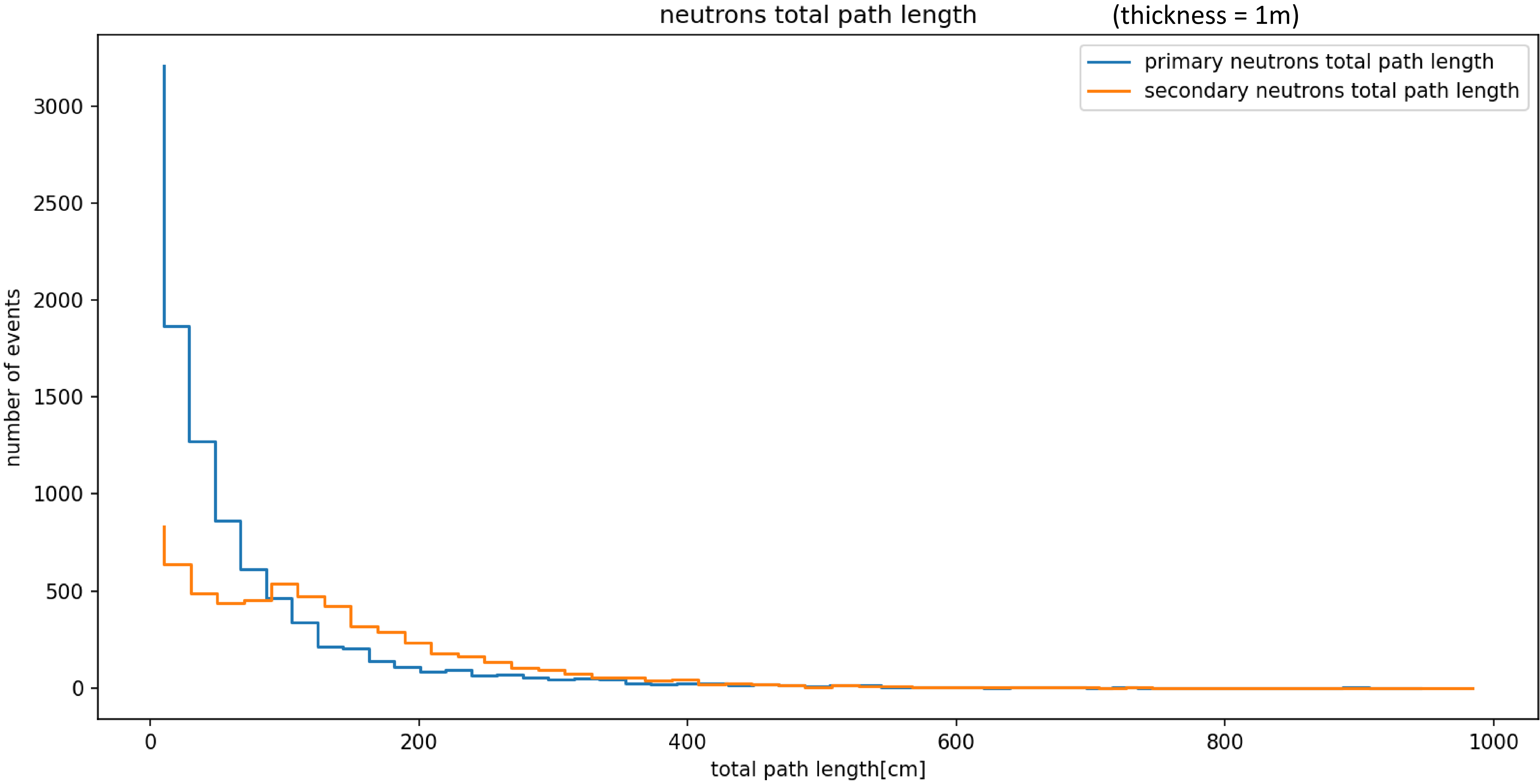
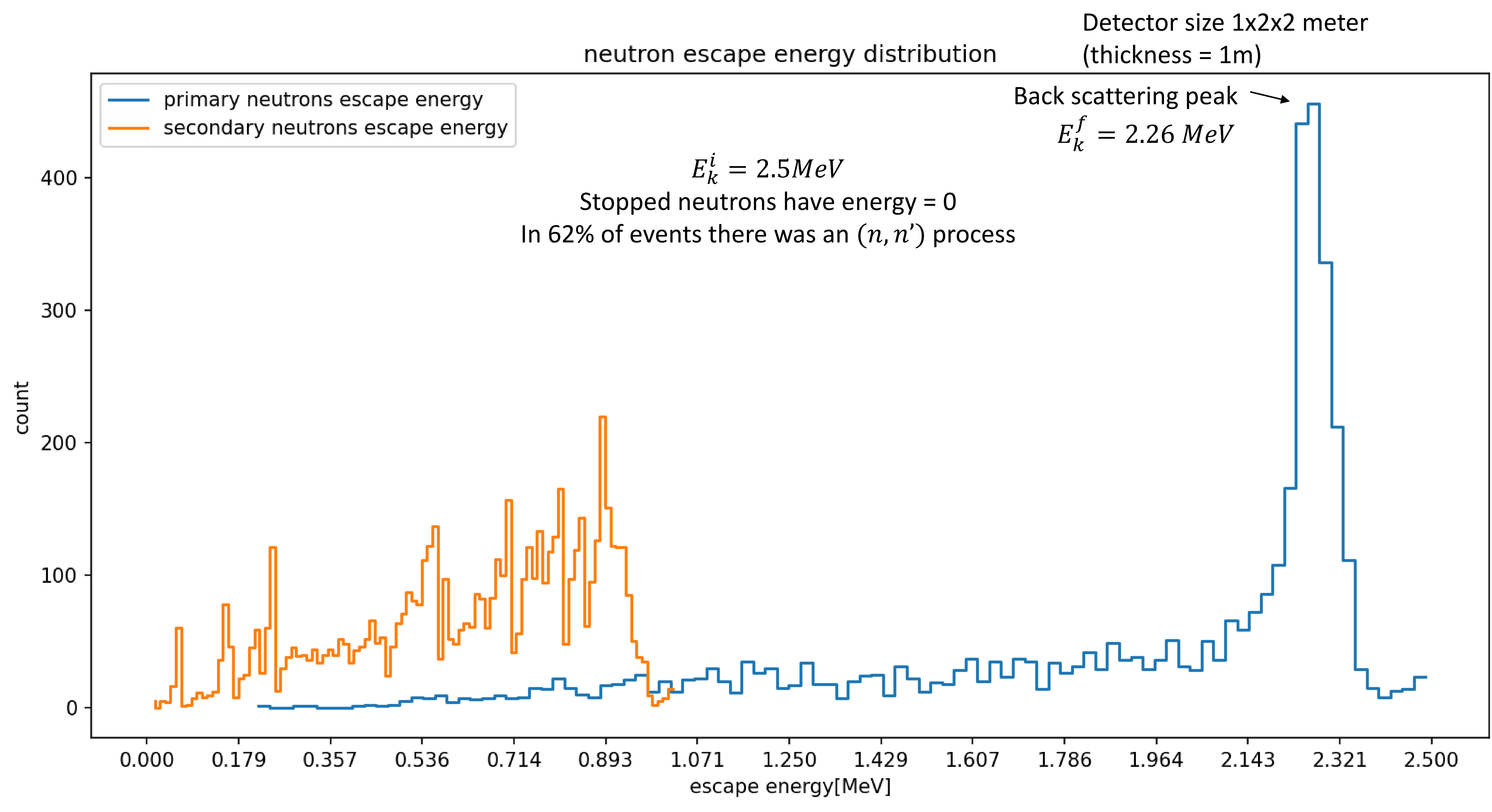
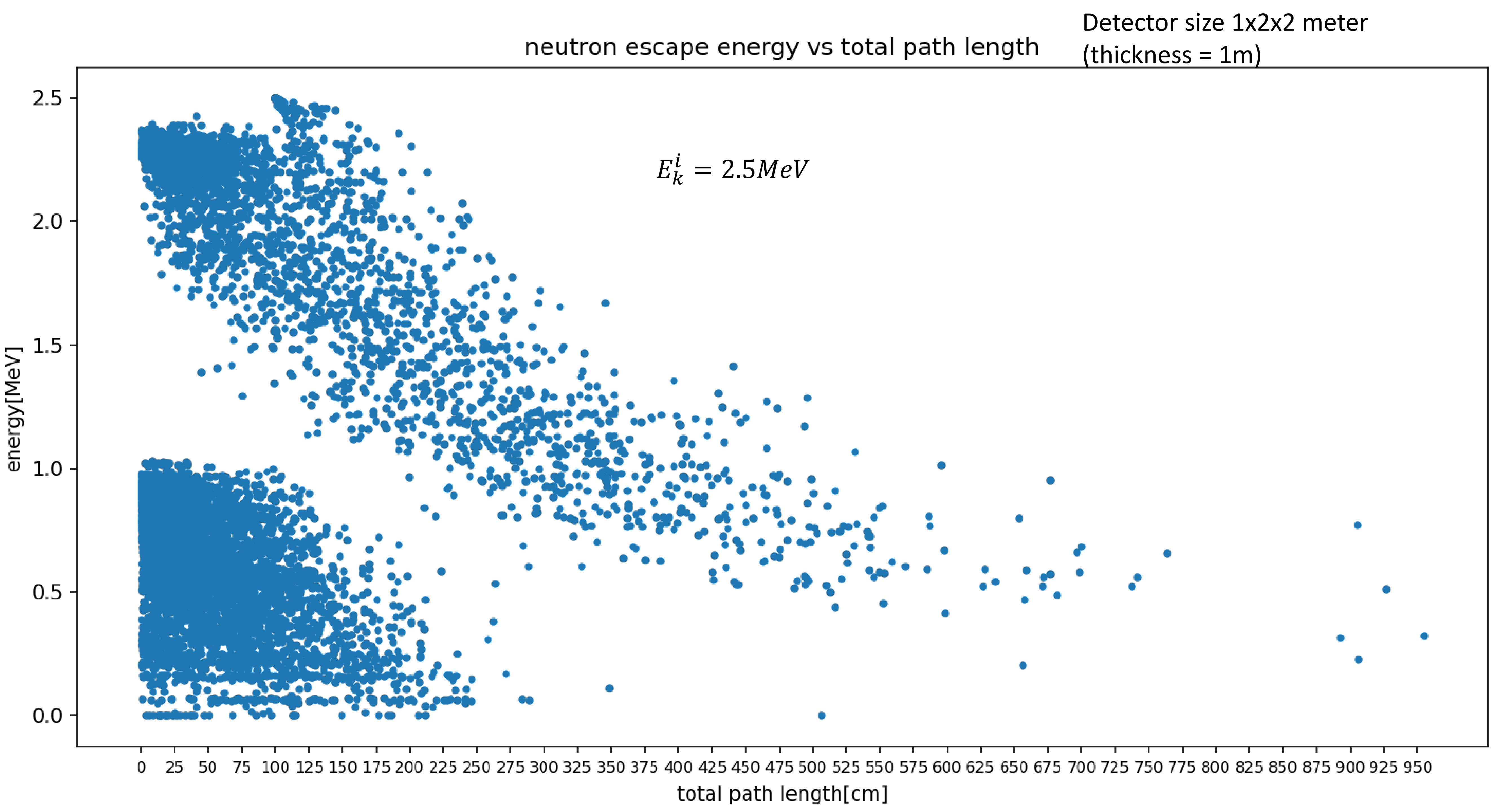
1.6% 1.4% 1.0% 0.7% 0.6% 0.6% 0.4% 0.3% 0.2% 0.2% 0.1% 0.0% 0.0% 0.0% 0.0% 0.0% 0.0% 0.0% 0.0% 0.0%
3.3% 2.4% 2.0% 1.7% 1.2% 1.1% 1.0% 0.6% 0.7% 0.4% 0.2% 0.1% 0.0% 0.0% 0.0% 0.0% 0.0% 0.0% 0.0% 0.0%
0.7% 1.0% 1.0% 1.0% 1.0% 0.8% 0.8% 0.8% 0.5% 0.5% 0.3% 0.1% 0.1% 0.1% 0.0% 0.0% 0.0% 0.0% 0.0% 0.0%
0.2% 0.3% 0.2% 0.5% 0.5% 0.5% 0.5% 0.5% 0.4% 0.4% 0.2% 0.3% 0.2% 0.1% 0.1% 0.1% 0.0% 0.0% 0.0% 0.0%
0.1% 0.1% 0.1% 0.1% 0.2% 0.2% 0.5% 0.2% 0.3% 0.3% 0.2% 0.2% 0.2% 0.1% 0.1% 0.1% 0.1% 0.0% 0.0% 0.0%
0.0% 0.0% 0.0% 0.1% 0.1% 0.1% 0.1% 0.1% 0.2% 0.1% 0.1% 0.1% 0.1% 0.1% 0.1% 0.1% 0.0% 0.1% 0.0% 0.0%
0.1% 0.1% 0.1% 0.1% 0.0% 0.1% 0.1% 0.1% 0.0% 0.1% 0.1% 0.0% 0.1% 0.1% 0.0% 0.1% 0.1% 0.0% 0.0% 0.0%
0.4% 0.4% 0.2% 0.2% 0.2% 0.1% 0.1% 0.1% 0.0% 0.1% 0.0% 0.1% 0.0% 0.0% 0.0% 0.1% 0.0% 0.0% 0.0% 0.0%
0.0% 0.0% 0.0% 0.1% 0.0% 0.0% 0.0% 0.0% 0.0% 0.1% 0.0% 0.0% 0.0% 0.0% 0.1% 0.0% 0.0% 0.0% 0.0% 0.0%
0.0% 0.1% 0.0% 0.1% 0.1% 0.0% 0.0% 0.0% 0.0% 0.0% 0.0% 0.0% 0.0% 0.0% 0.0% 0.0% 0.0% 0.0% 0.0% 0.0%
0.0 4.9 9.9 14.8 19.8 24.7 29.6 34.6 39.5 44.4 49.4 54.3 59.2 64.2 69.1 74.1 79.0 83.9 88.9 93.8 98.7
total path length[cm]

Detector size 1x2x2 meter
(thickness = 1m)

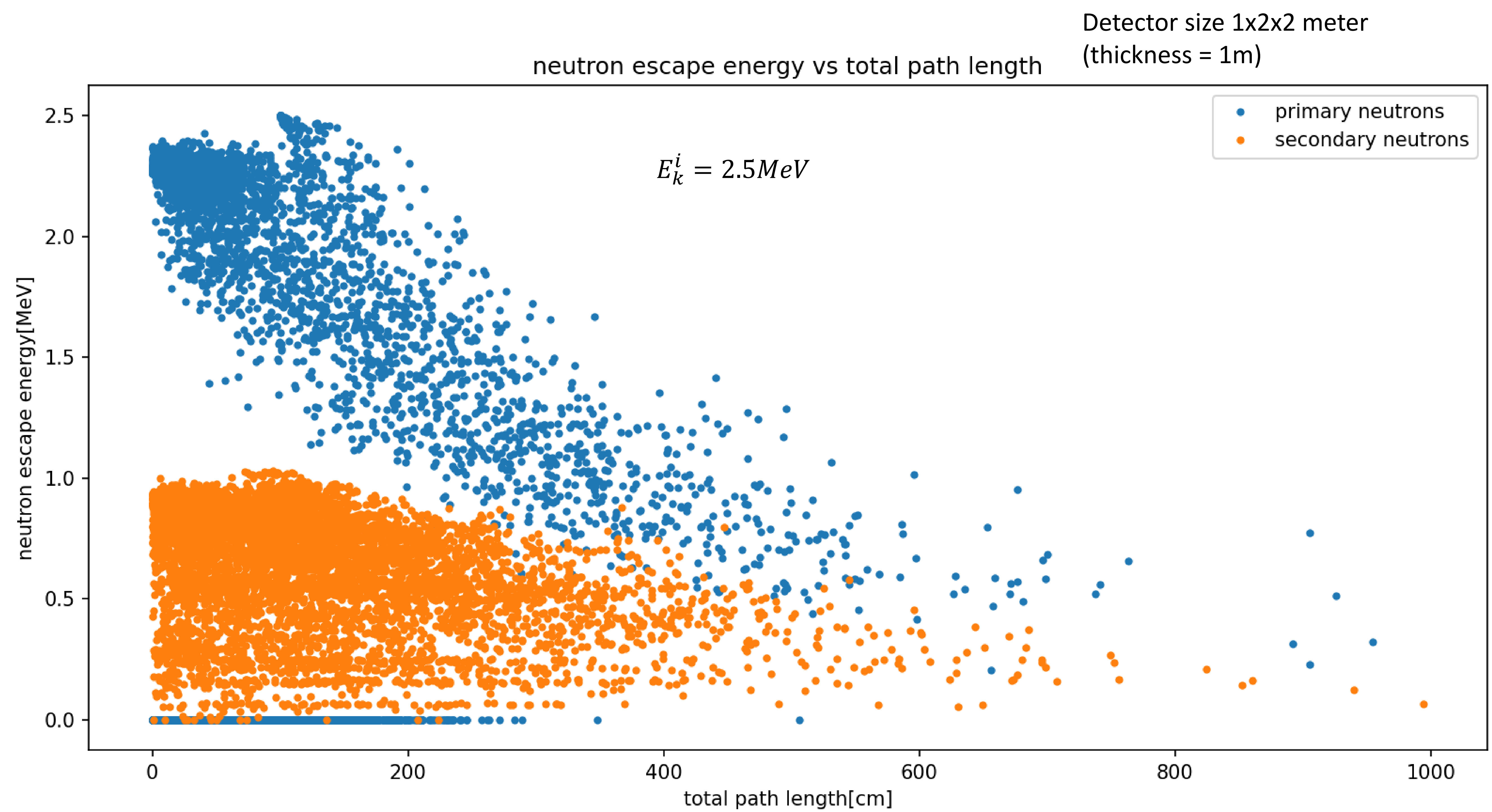




Detector size 1x2x2 meter
(thickness = 1m)
neutron escape energy distribution
primary neutrons escape energy
secondary neutrons escape energy
Back scattering peak
$E_k^f = 2.26\ MeV$
$E_k^i = 2.5MeV$
Stopped neutrons have energy = 0
In 62% of events there was an (n, n') process
count
0
100
200
300
400
0.000
0.179
0.357
0.536
0.714
0.893
1.071
1.250
1.429
1.607
1.786
1.964
2.143
2.321
2.500
escape energy[MeV]



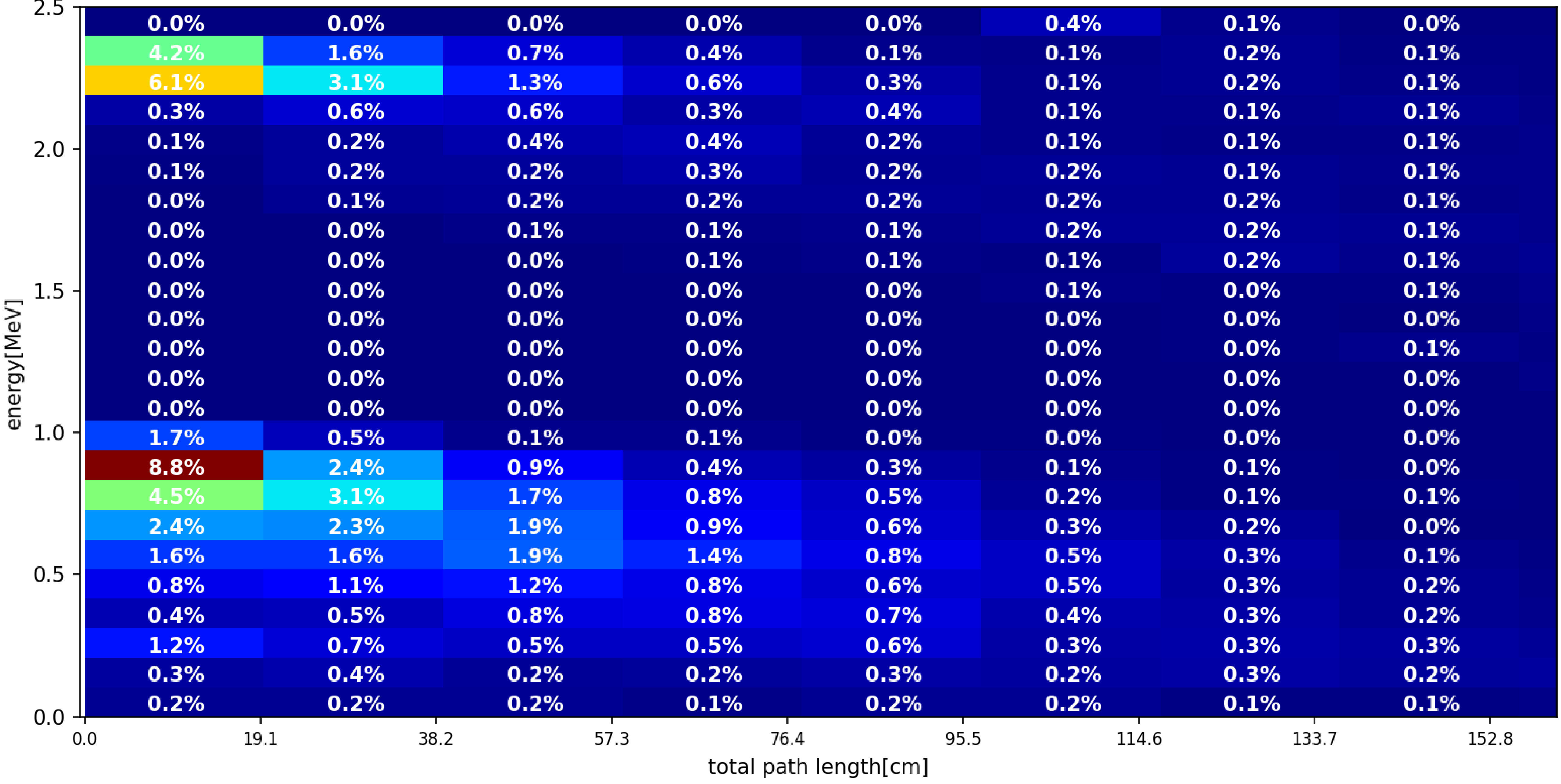
neutron escape energy vs total path length
Detector size 1x2x2 meter
(thickness = 1m)
$E_k^i = 2.5MeV$
energy[MeV]
total path length[cm]
0.0
0.5
1.0
1.5
2.0
2.5
0 25 50 75 100 125 150 175 200 225 250 275 300 325 350 375 400 425 450 475 500 525 550 575 600 625 650 675 700 725 750 775 800 825 850 875 900 925 950


Detector size 1x2x2 meter
(thickness = 1m)
neutron escape energy vs total path length
primary neutrons
secondary neutrons
$E_k^i = 2.5MeV$
neutron escape energy[MeV]
total path length[cm]
0.0
0.5
1.0
1.5
2.0
2.5
0
200
400
600
800
1000

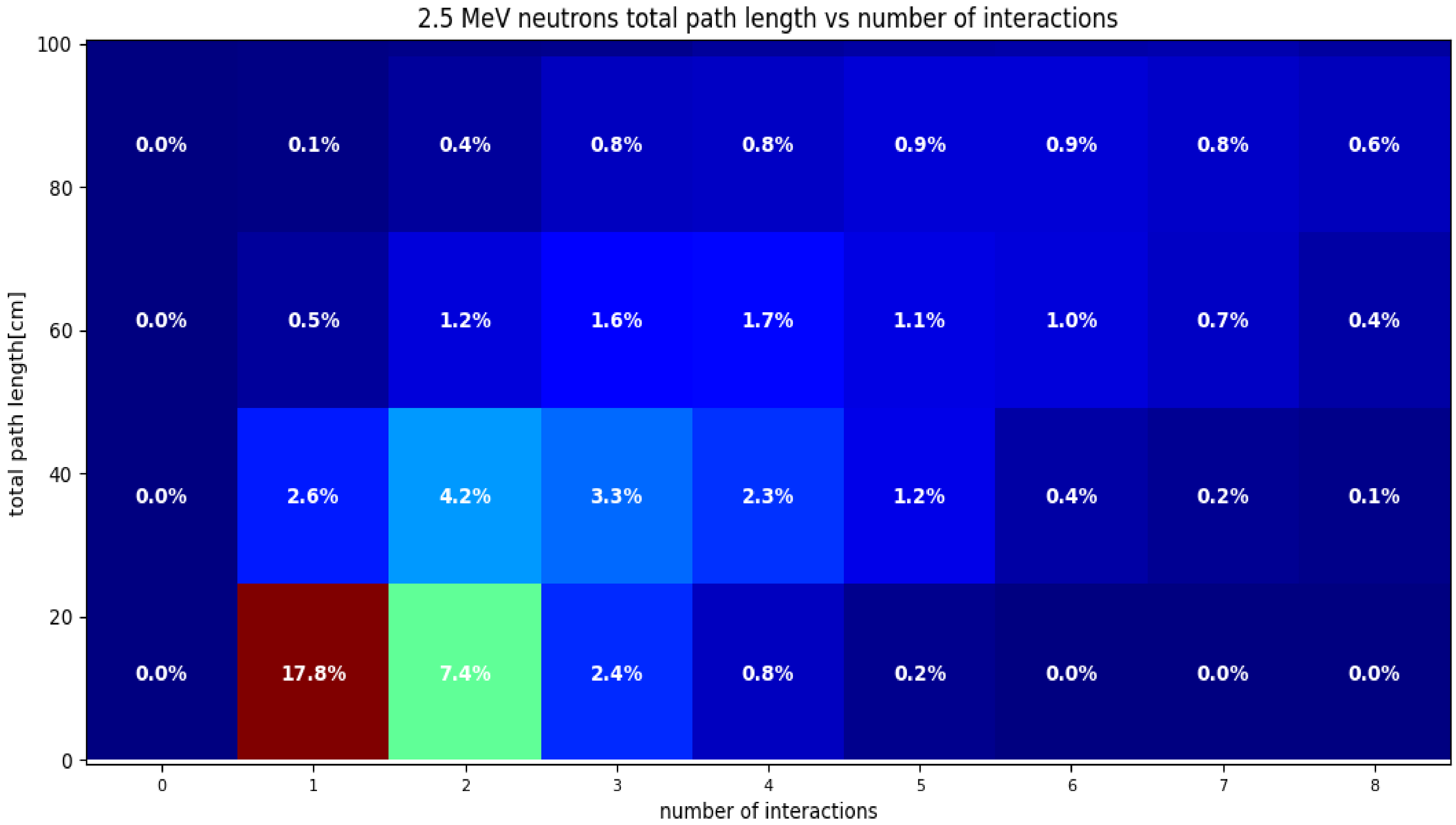
Only for primary neutrons (didn’t perform (n,n’))

Detector size 1x2x2 meter
(thickness = 1m)

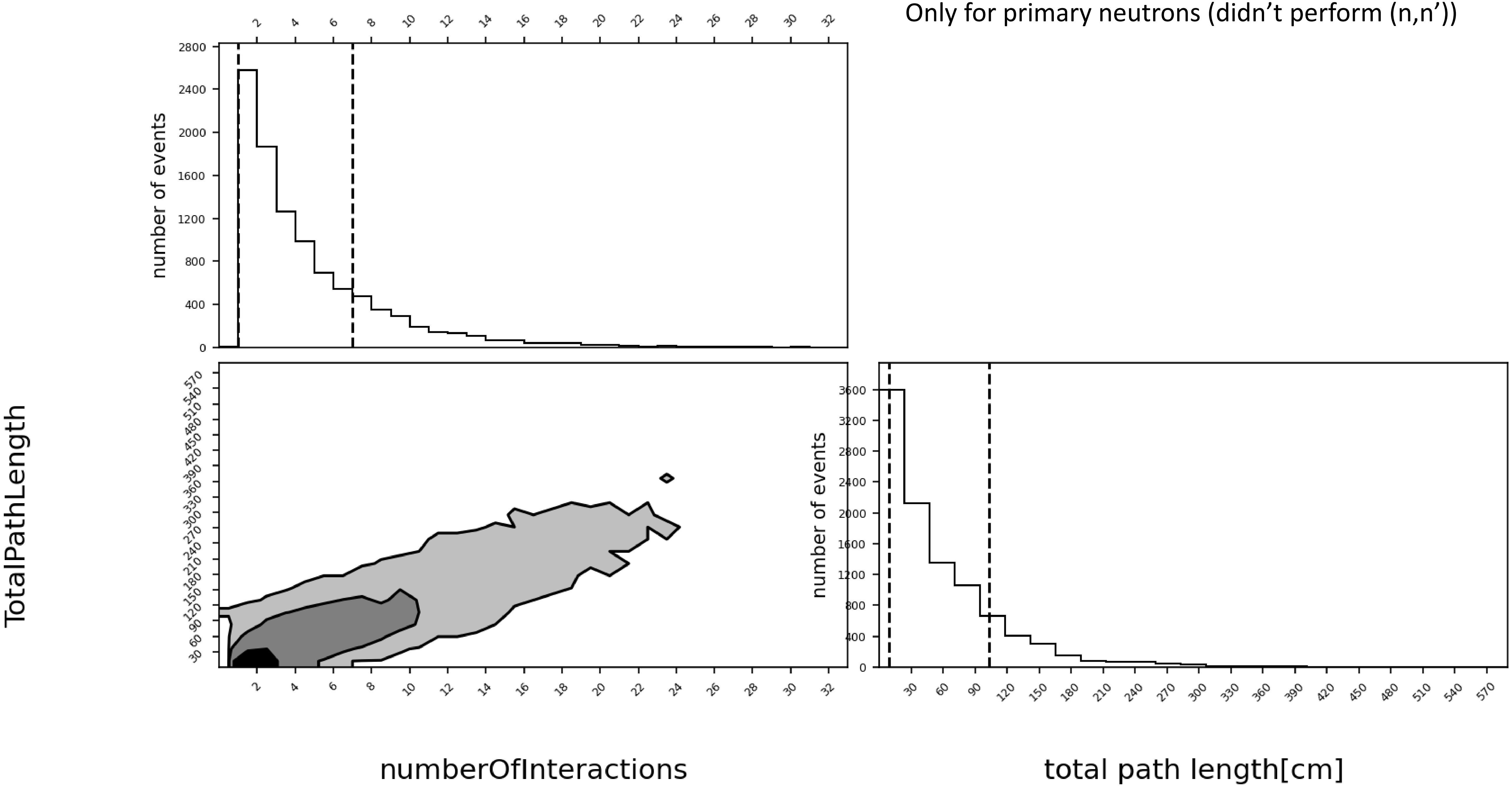
neutron escape energy vs total path length

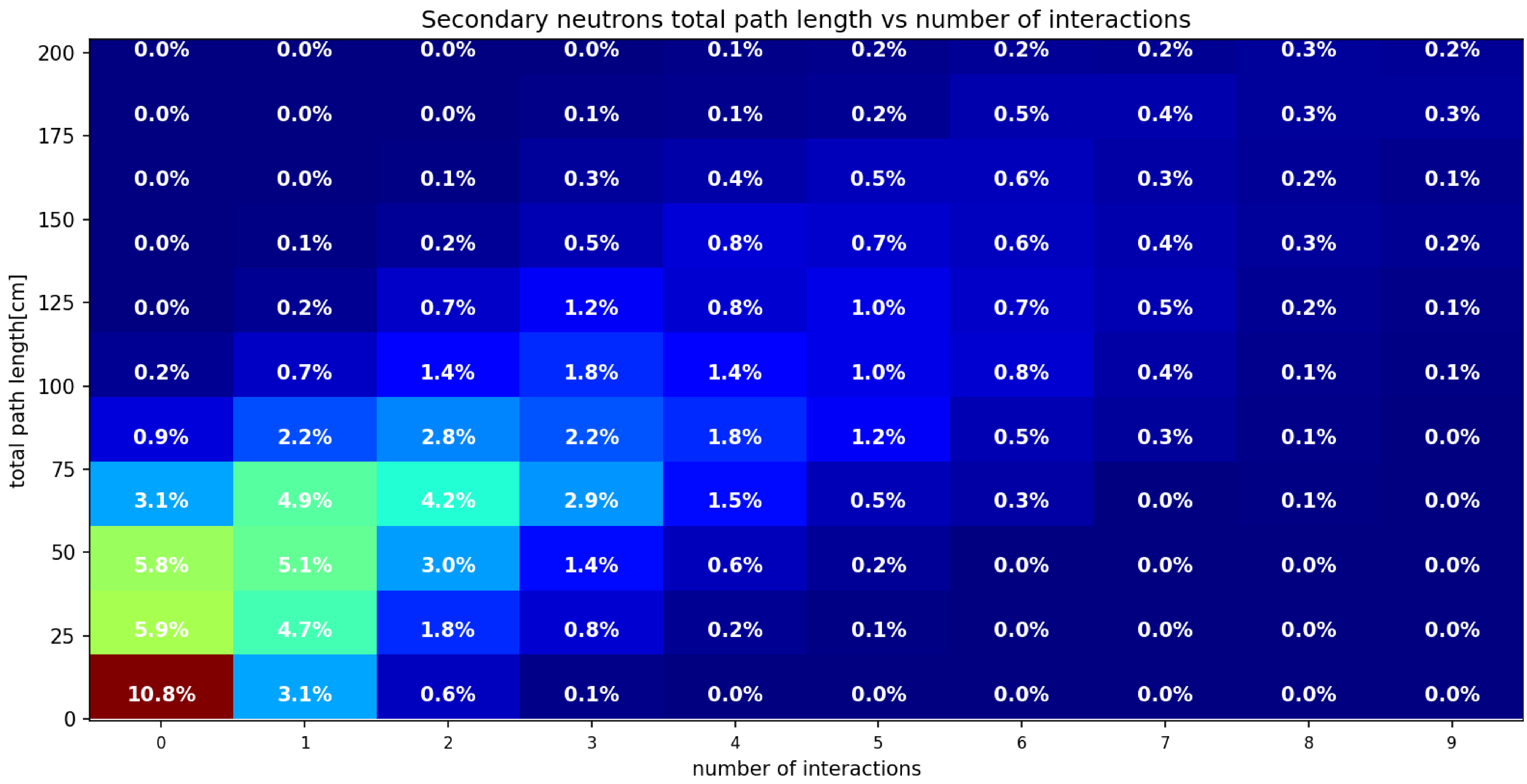


Only for primary neutrons (didn't perform (n,n'))

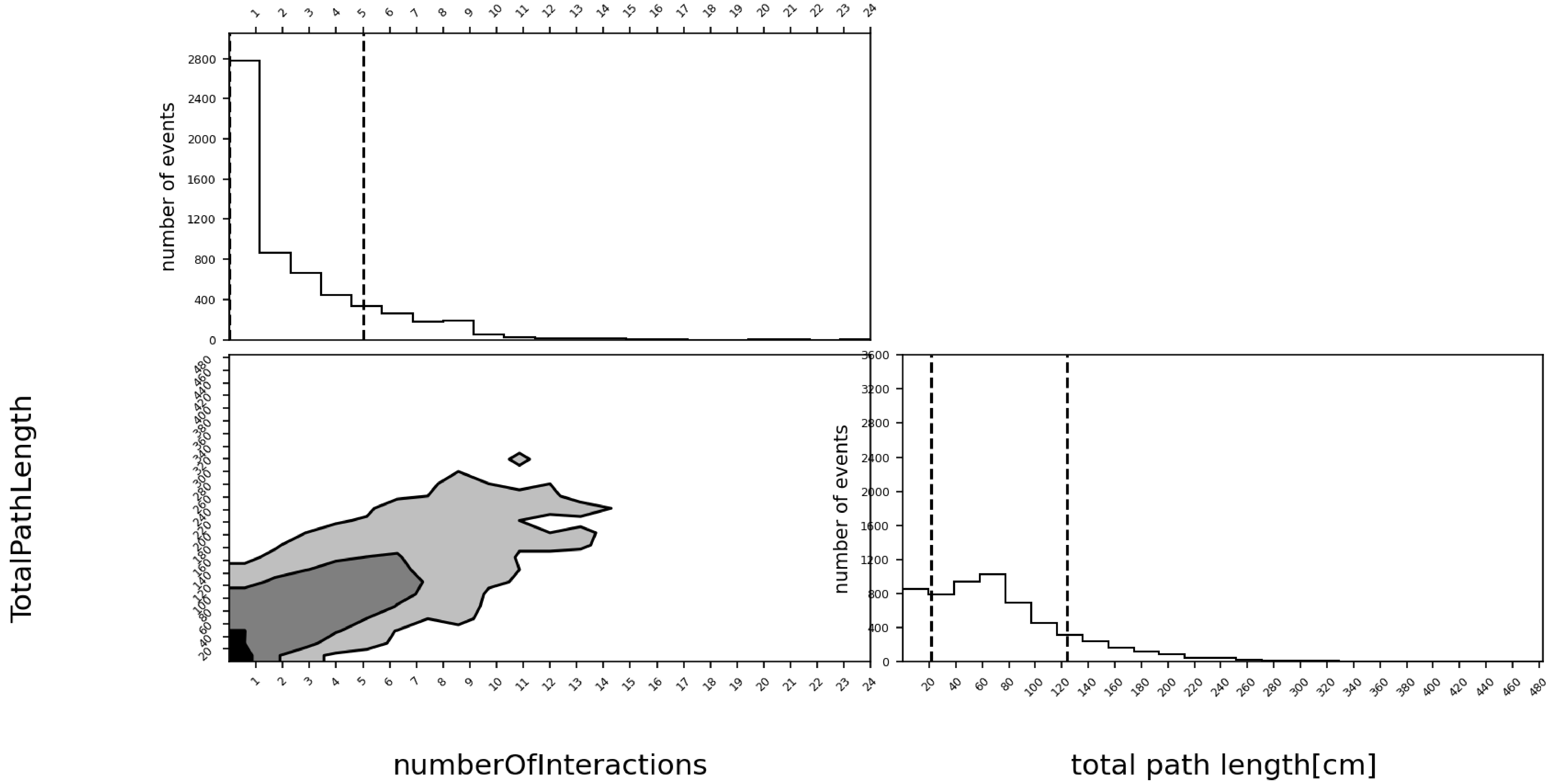


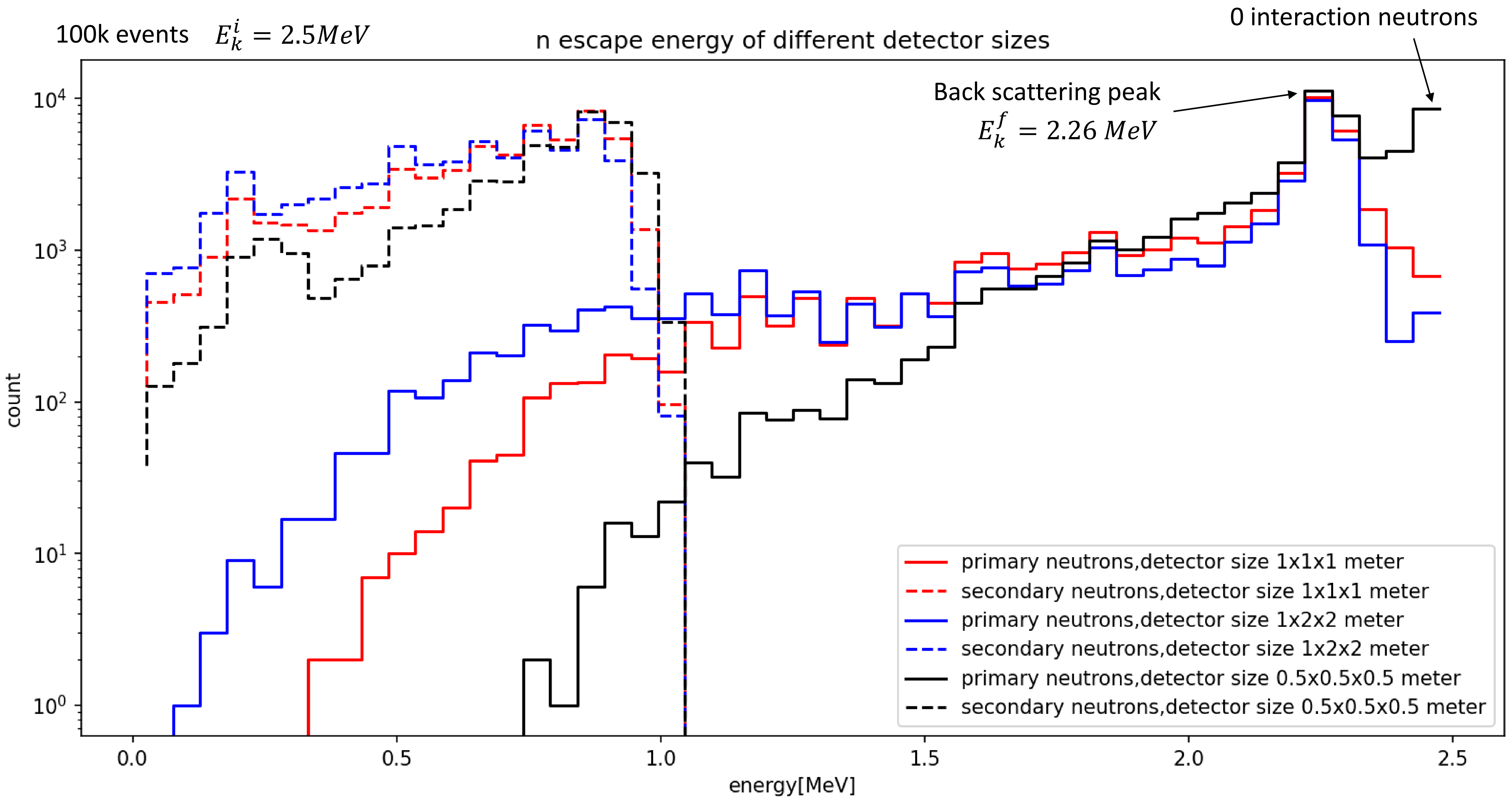
Only for primary neutrons (didn’t perform (n,n’))



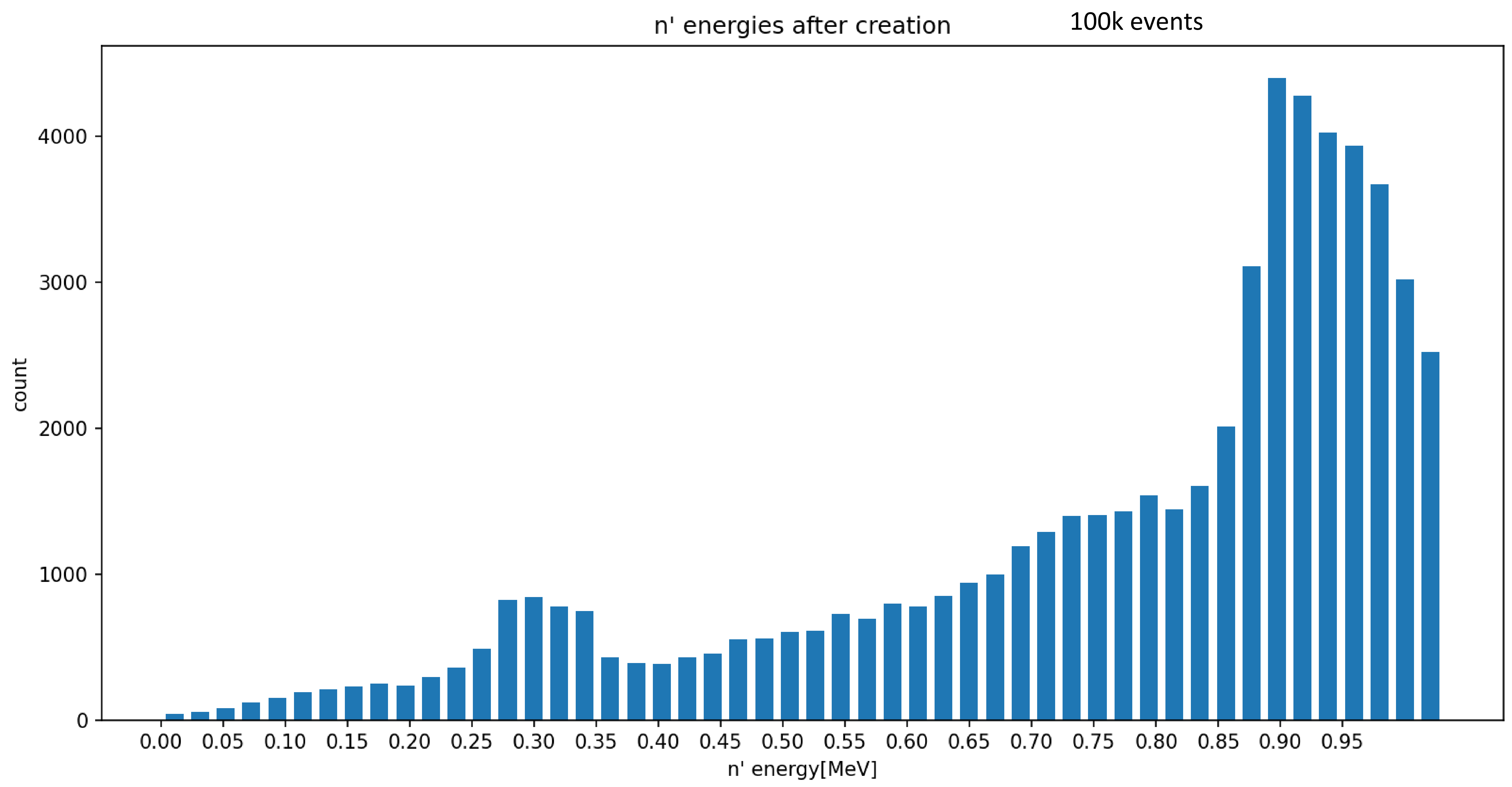


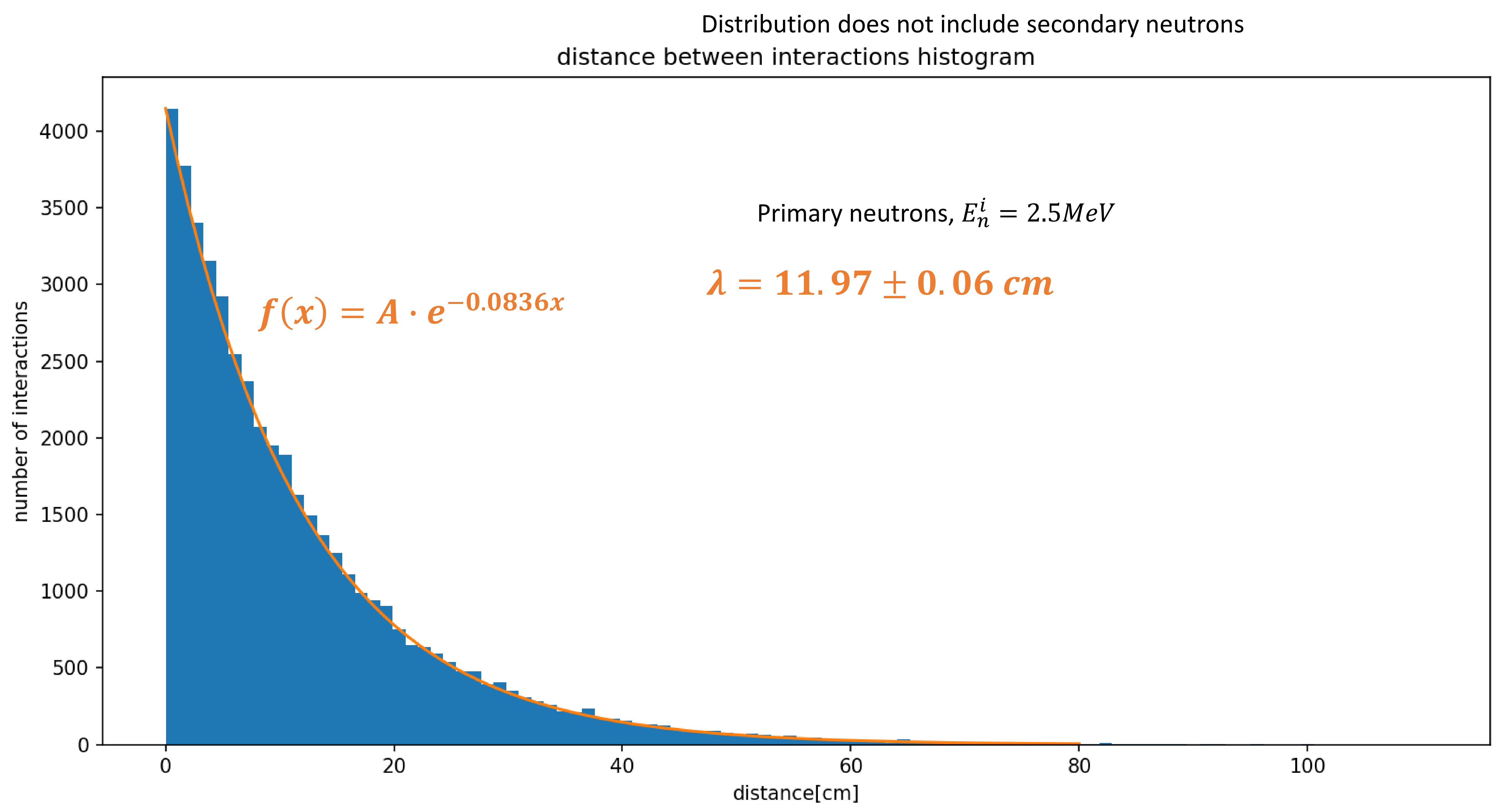
Secondary neutrons total path length vs number of interactions
total path length[cm]
number of interactions
200
175
150
125
100
75
50
25
0
0
1
2
3
4
5
6
7
8
9
0.0% 0.0% 0.0% 0.0% 0.1% 0.2% 0.2% 0.2% 0.3% 0.2%
0.0% 0.0% 0.0% 0.1% 0.1% 0.2% 0.5% 0.4% 0.3% 0.3%
0.0% 0.0% 0.1% 0.3% 0.4% 0.5% 0.6% 0.3% 0.2% 0.1%
0.0% 0.1% 0.2% 0.5% 0.8% 0.7% 0.6% 0.4% 0.3% 0.2%
0.0% 0.2% 0.7% 1.2% 0.8% 1.0% 0.7% 0.5% 0.2% 0.1%
0.2% 0.7% 1.4% 1.8% 1.4% 1.0% 0.8% 0.4% 0.1% 0.1%
0.9% 2.2% 2.8% 2.2% 1.8% 1.2% 0.5% 0.3% 0.1% 0.0%
3.1% 4.9% 4.2% 2.9% 1.5% 0.5% 0.3% 0.0% 0.1% 0.0%
5.8% 5.1% 3.0% 1.4% 0.6% 0.2% 0.0% 0.0% 0.0% 0.0%
5.9% 4.7% 1.8% 0.8% 0.2% 0.1% 0.0% 0.0% 0.0% 0.0%
10.8% 3.1% 0.6% 0.1% 0.0% 0.0% 0.0% 0.0% 0.0% 0.0%


number of events
TotalPathLength
numberOfInteractions
number of events
total path length[cm]



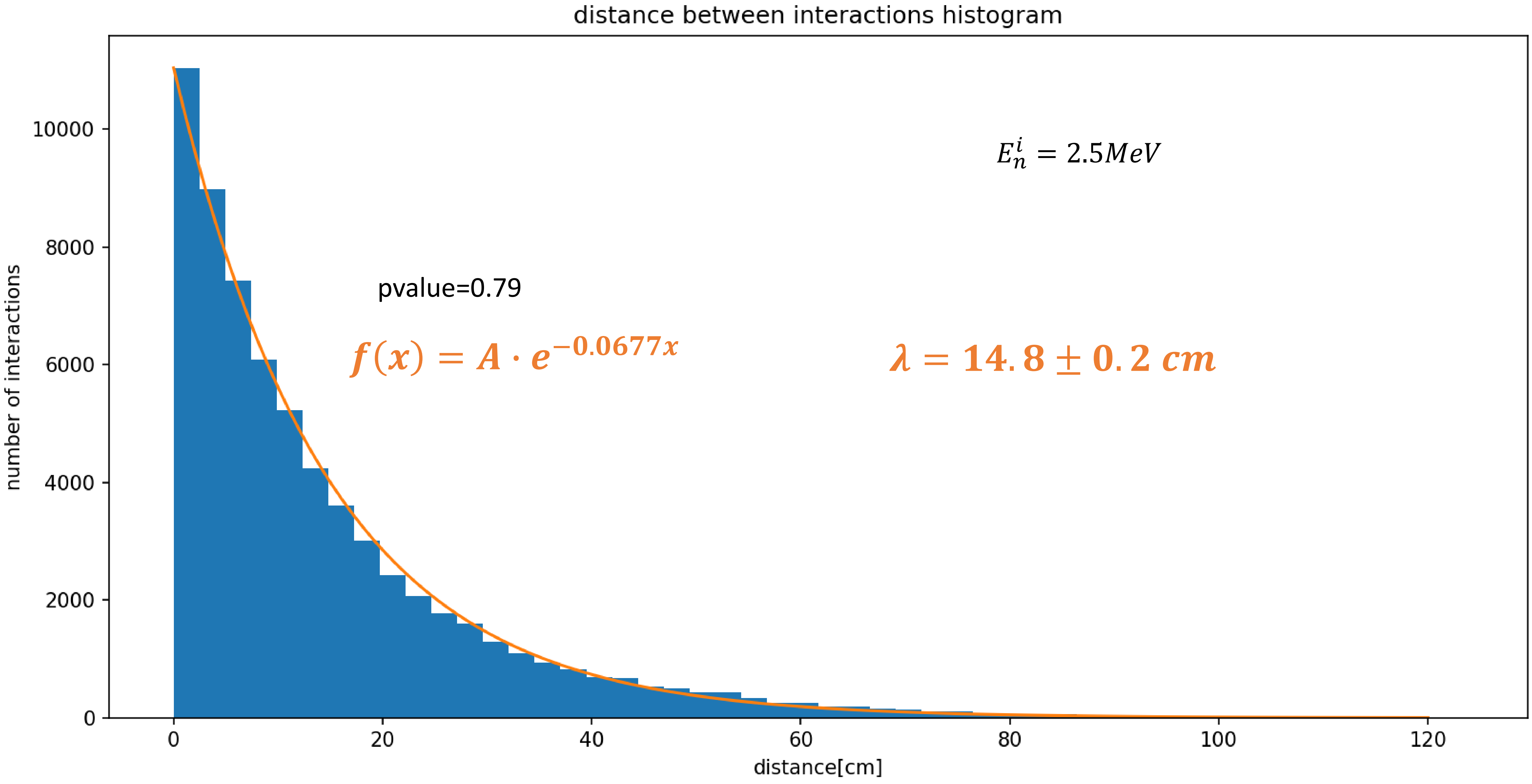
100k events $E_k^i = 2.5MeV$
n escape energy of different detector sizes
0 interaction neutrons
Back scattering peak
$E_k^f = 2.26\ MeV$
count
energy[MeV]
10^4
10^3
10^2
10^1
10^0
0.0
0.5
1.0
1.5
2.0
2.5
primary neutrons,detector size 1x1x1 meter
secondary neutrons,detector size 1x1x1 meter
primary neutrons,detector size 1x2x2 meter
secondary neutrons,detector size 1x2x2 meter
primary neutrons,detector size 0.5x0.5x0.5 meter
secondary neutrons,detector size 0.5x0.5x0.5 meter


n' energies after creation
100k events
count
4000
3000
2000
1000
0
0.00
0.05
0.10
0.15
0.20
0.25
0.30
0.35
0.40
0.45
0.50
0.55
0.60
0.65
0.70
0.75
0.80
0.85
0.90
0.95
n' energy[MeV]

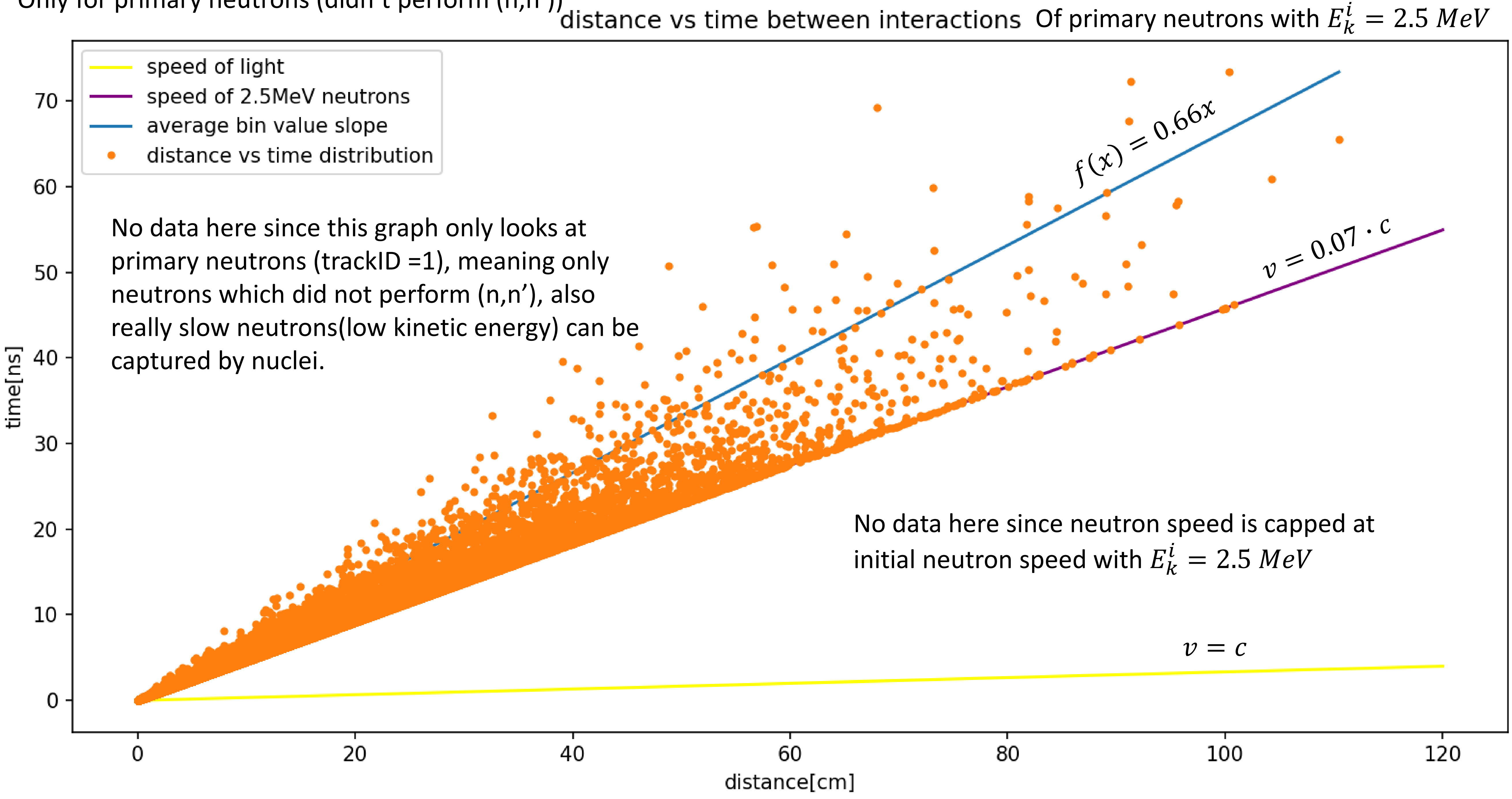


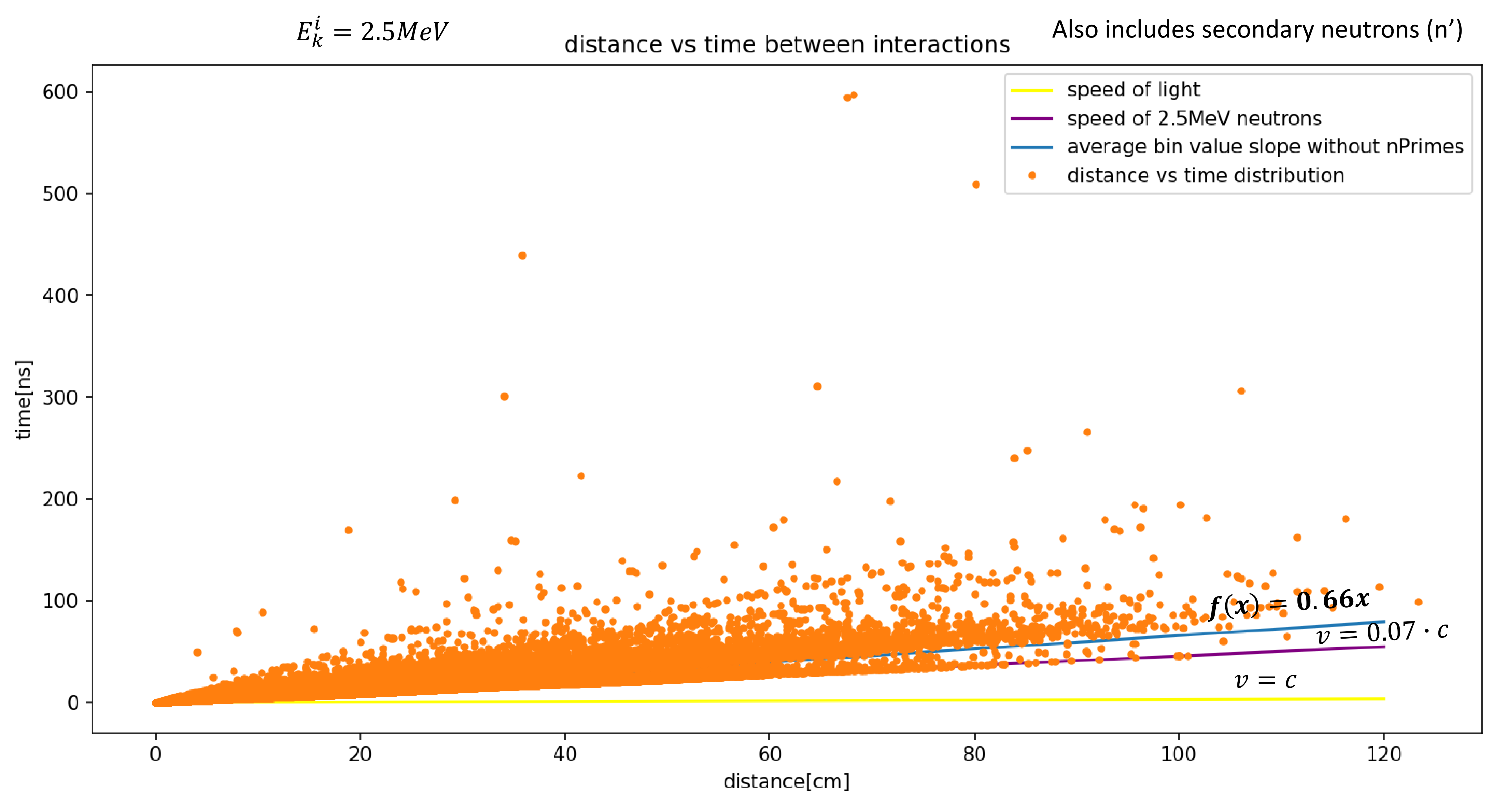
Distribution does not include secondary neutrons
distance between interactions histogram
Primary neutrons, $E_n^i = 2.5MeV$
$\lambda = 11.97 \pm 0.06\ cm$
$f(x) = A \cdot e^{-0.0836x}$
number of interactions
distance[cm]
0
500
1000
1500
2000
2500
3000
3500
4000
20
40
60
80
100

Distribution also includes secondary neutrons



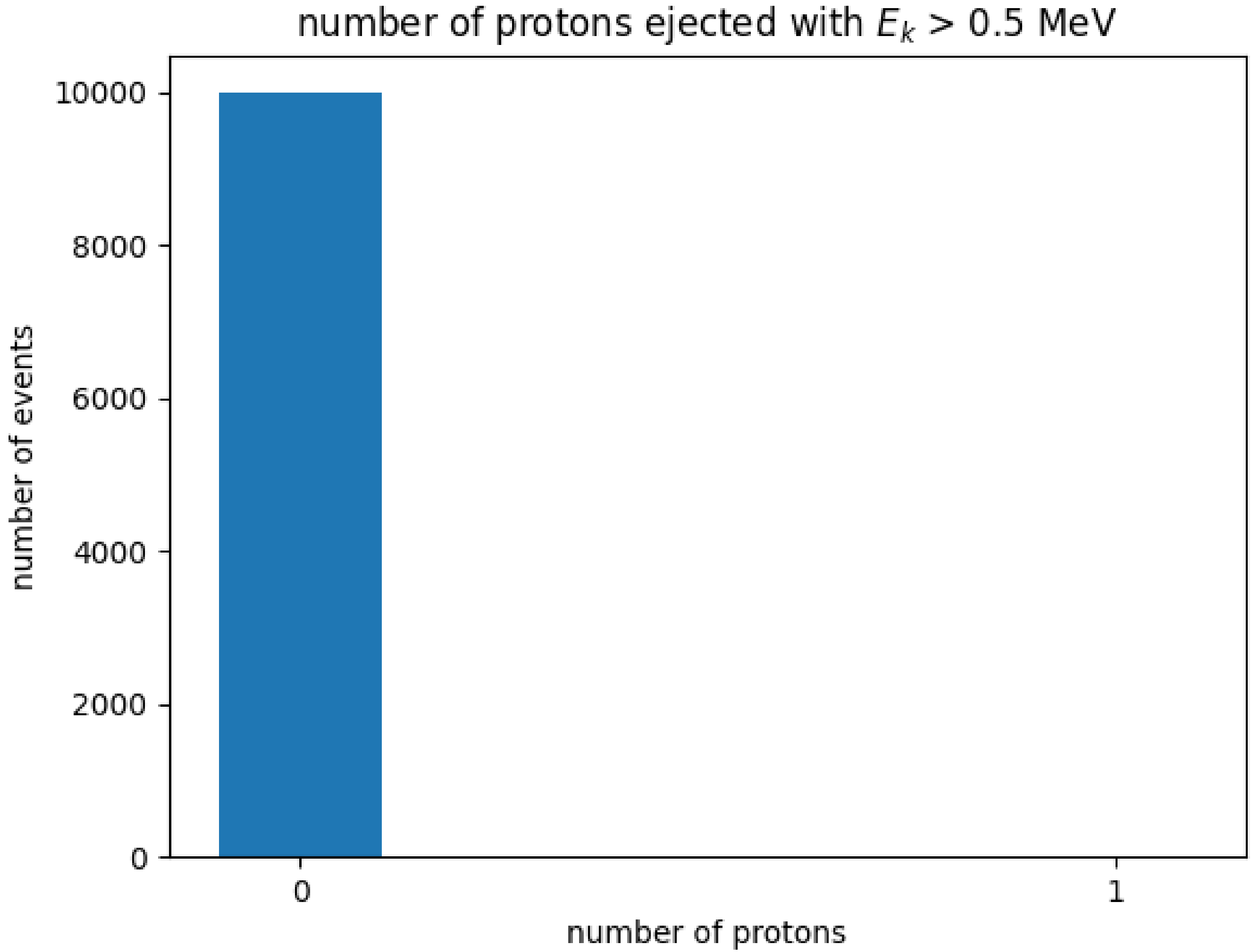
Only for primary neutrons (didn't perform (n,n'))

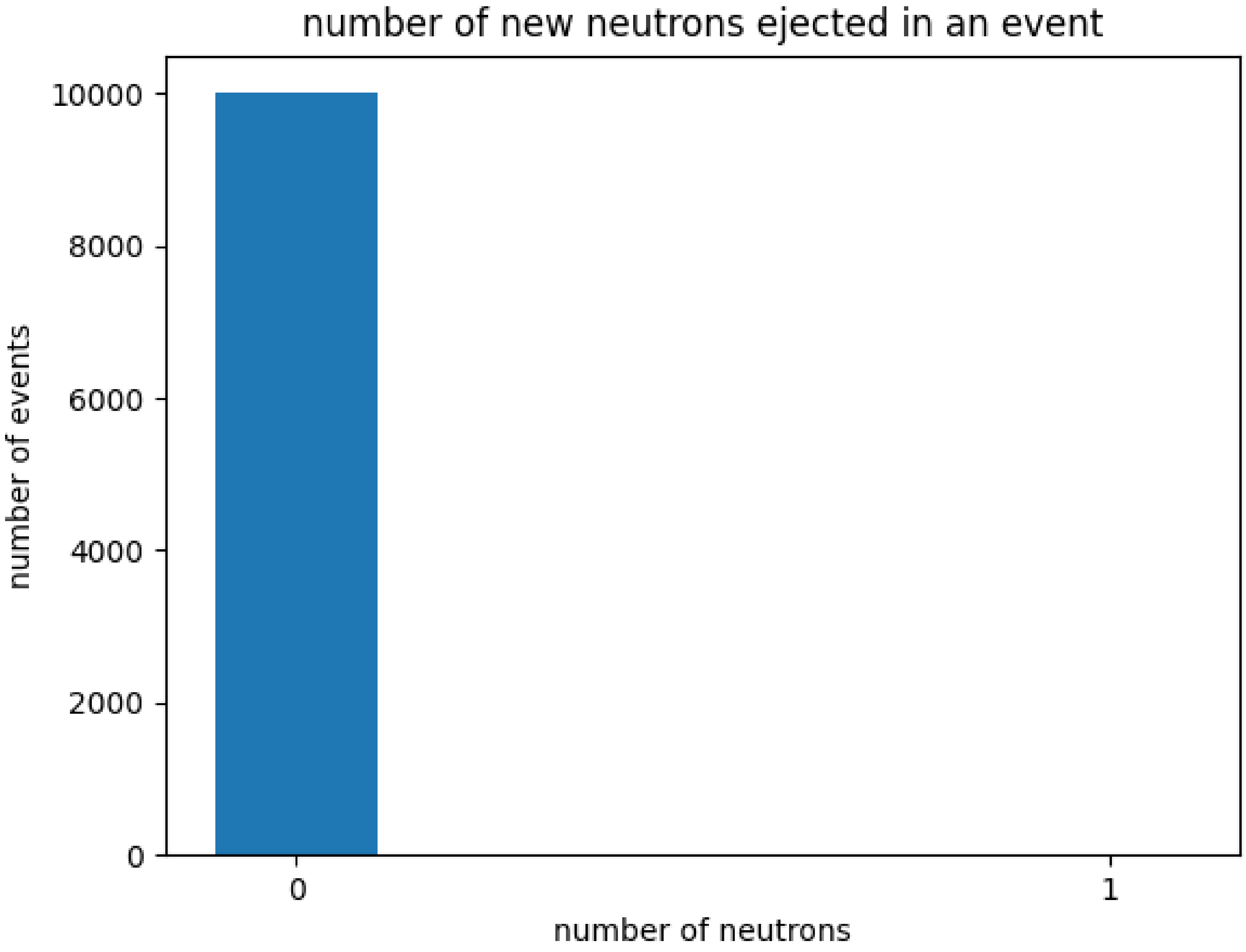


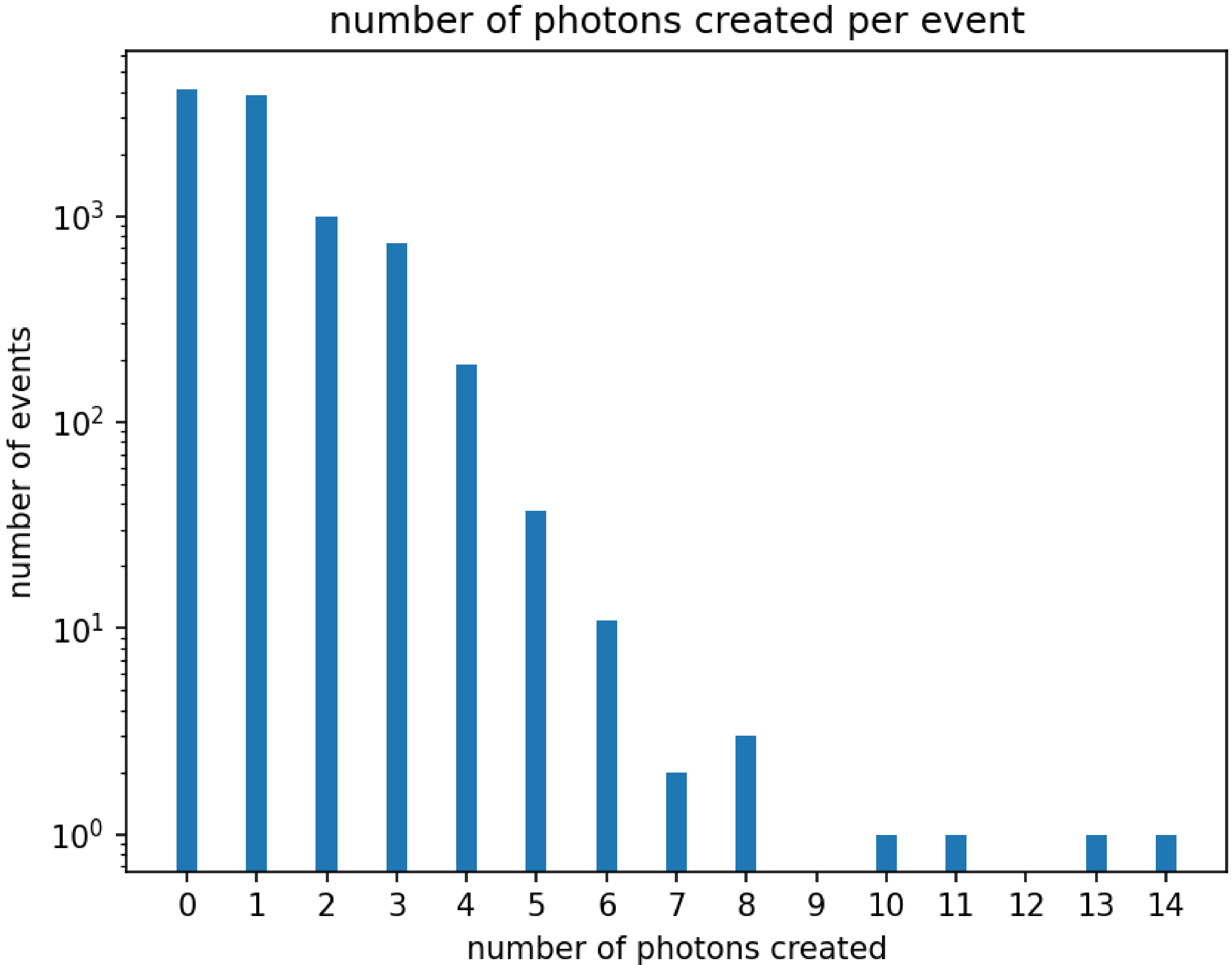


$E_k^i = 2.5MeV$
distance vs time between interactions
Also includes secondary neutrons (n')
speed of light
speed of 2.5MeV neutrons
average bin value slope without nPrimes
distance vs time distribution
$f(x) = 0.66x$
$v = 0.07 \cdot c$
$v = c$
time[ns]
distance[cm]
0
100
200
300
400
500
600
0
20
40
60
80
100
120

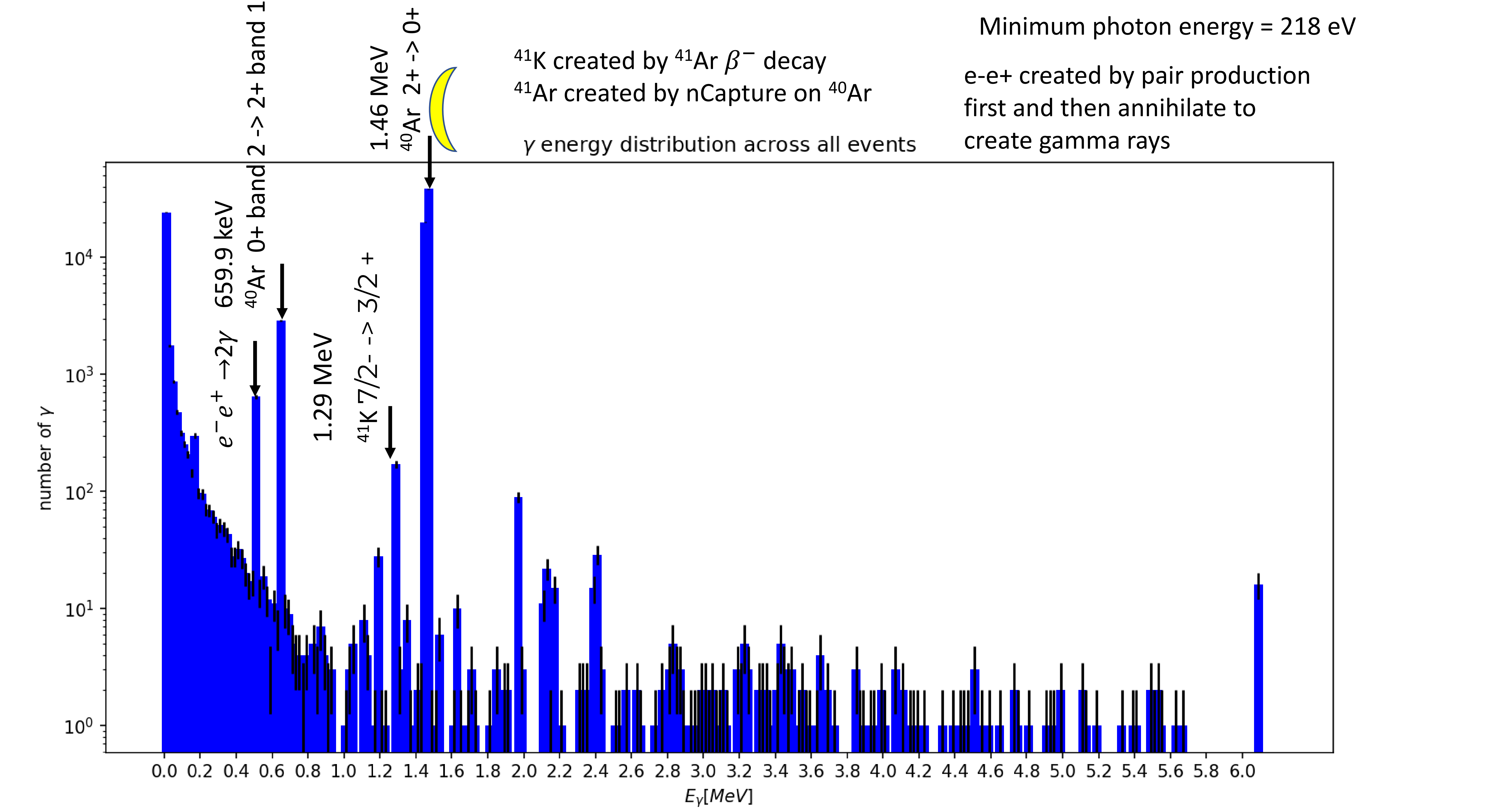
No protons exit the detector, though some are created in (n,p) process with Argon 36



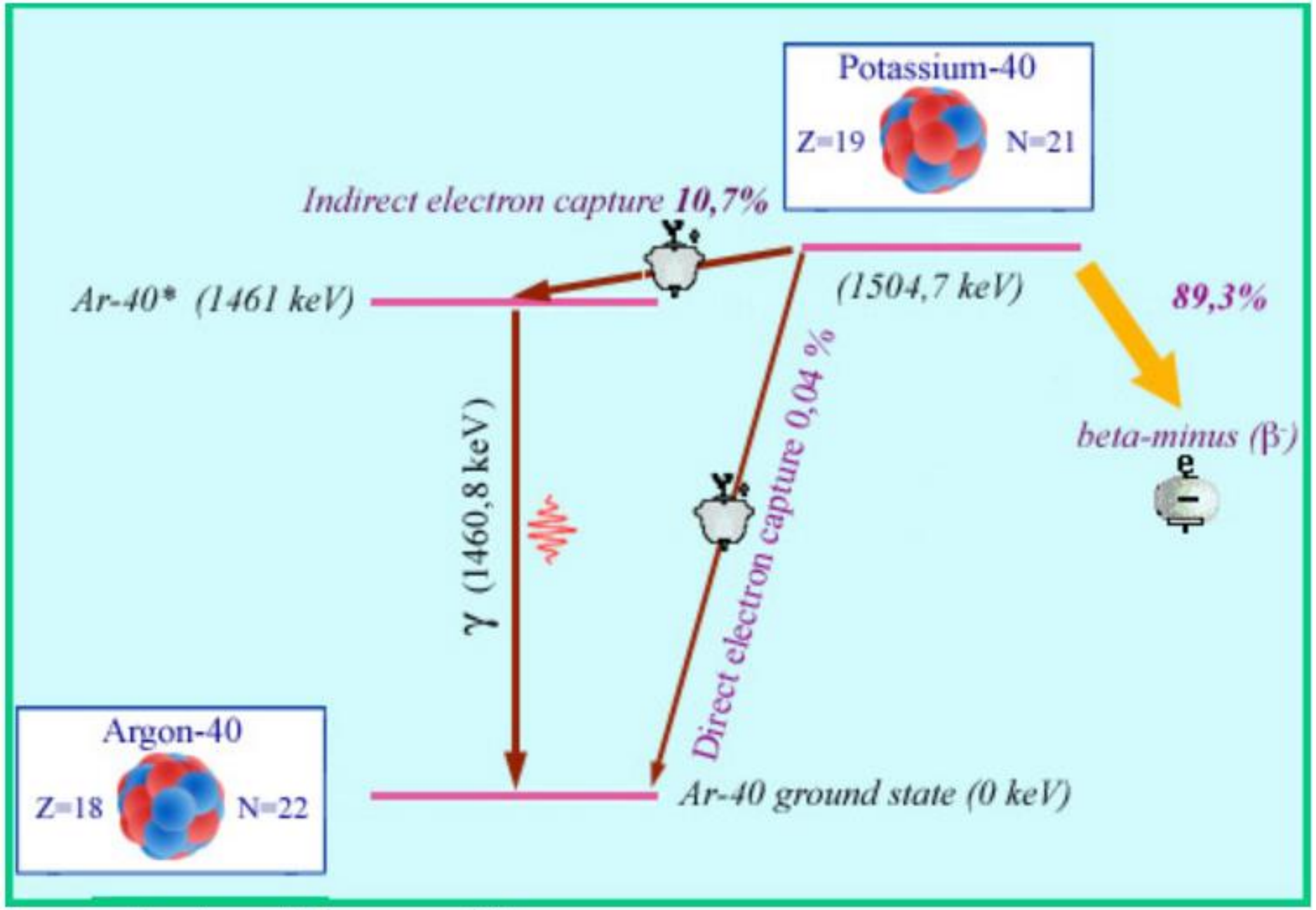

number of new neutrons ejected in an event
10000
8000
6000
4000
2000
0
0
1
number of events
number of neutrons



number of photons created per event
number of events
number of photons created
10^0
10^1
10^2
10^3
0
1
2
3
4
5
6
7
8
9
10
11
12
13
14

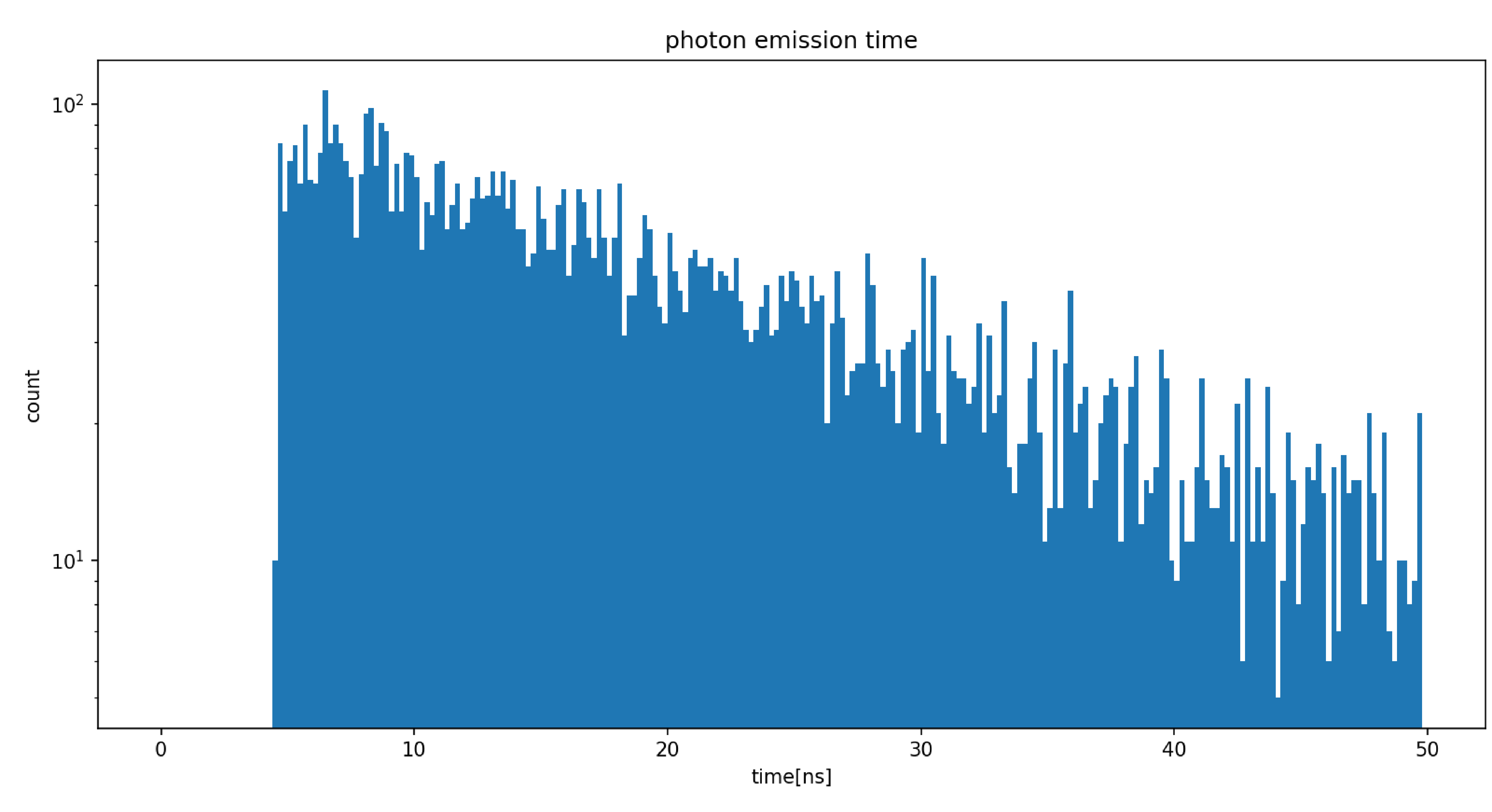


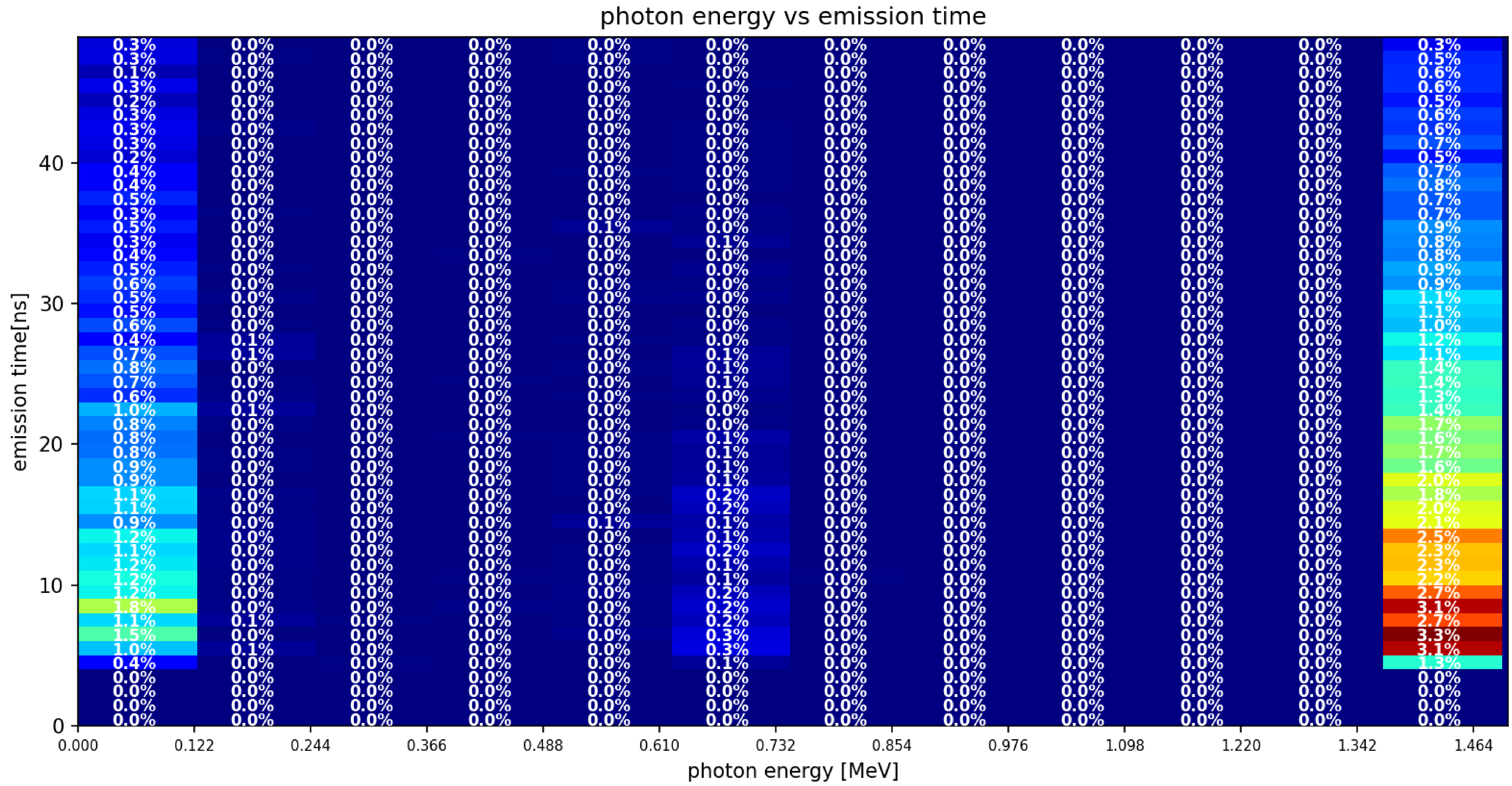
Minimum photon energy = 218 eV
^{41}K created by ^{41}Ar β^- decay
^{41}Ar created by nCapture on ^{40}Ar
γ energy distribution across all events
e-e+ created by pair production first and then annihilate to create gamma rays
1.46 MeV
^{40}Ar 2+ -> 0+
^{40}Ar 0+ band 2 -> 2+ band 1
659.9 keV
$e^-e^+ \rightarrow 2\gamma$
1.29 MeV
^{41}K 7/2- -> 3/2 +
number of γ
E_γ[MeV]

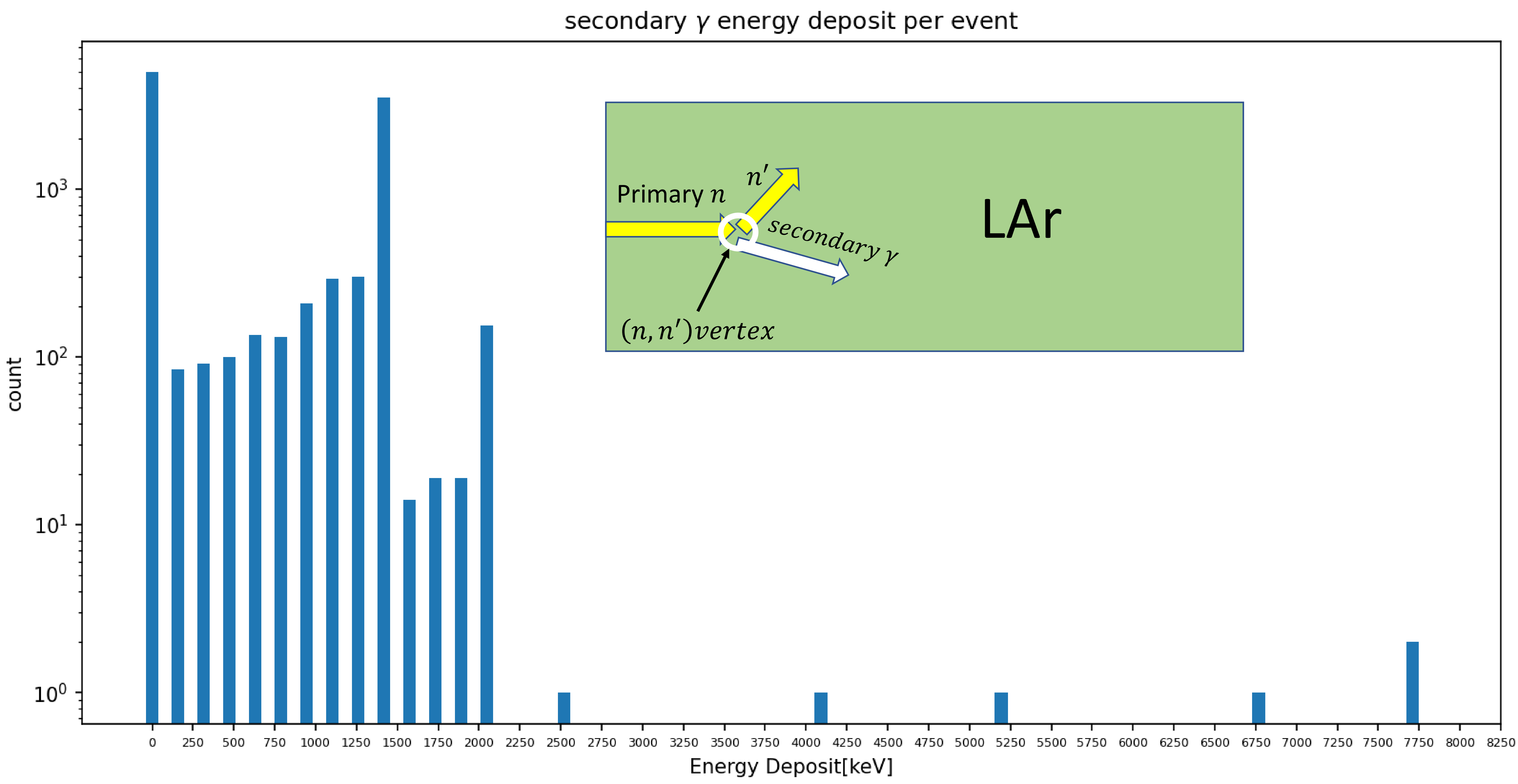


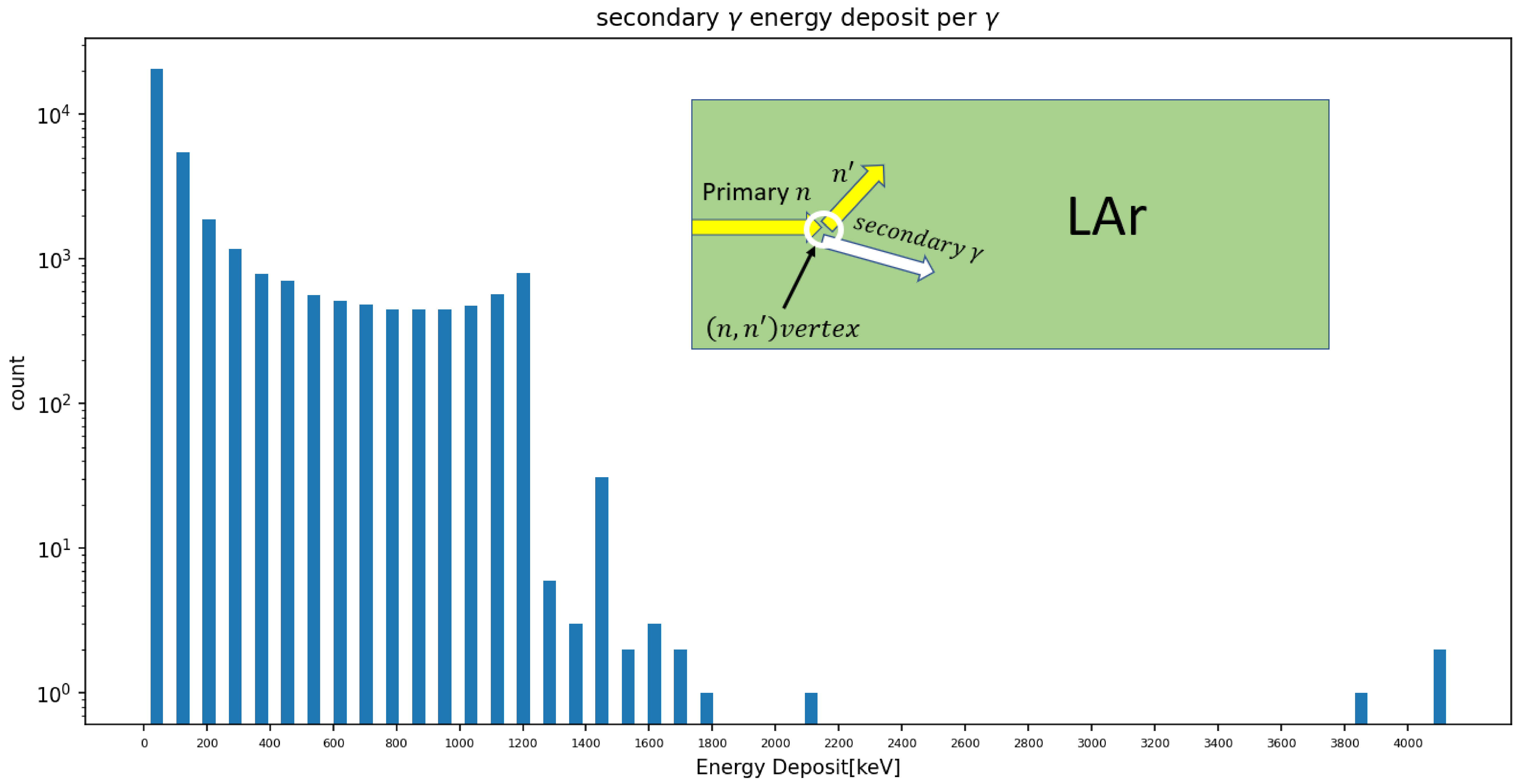
From potassium 40 to argon 40

The electron capture which causes potassium 40 to transform into argon 40 in its ground state takes place in only 0.04% of cases. Far more frequently (10.68% of the time), an indirect capture leads to an excited argon atom which needs to return to its ground state by emitting a gamma ray at an energy of 1.46 MeV. Without this characteristic gamma ray,

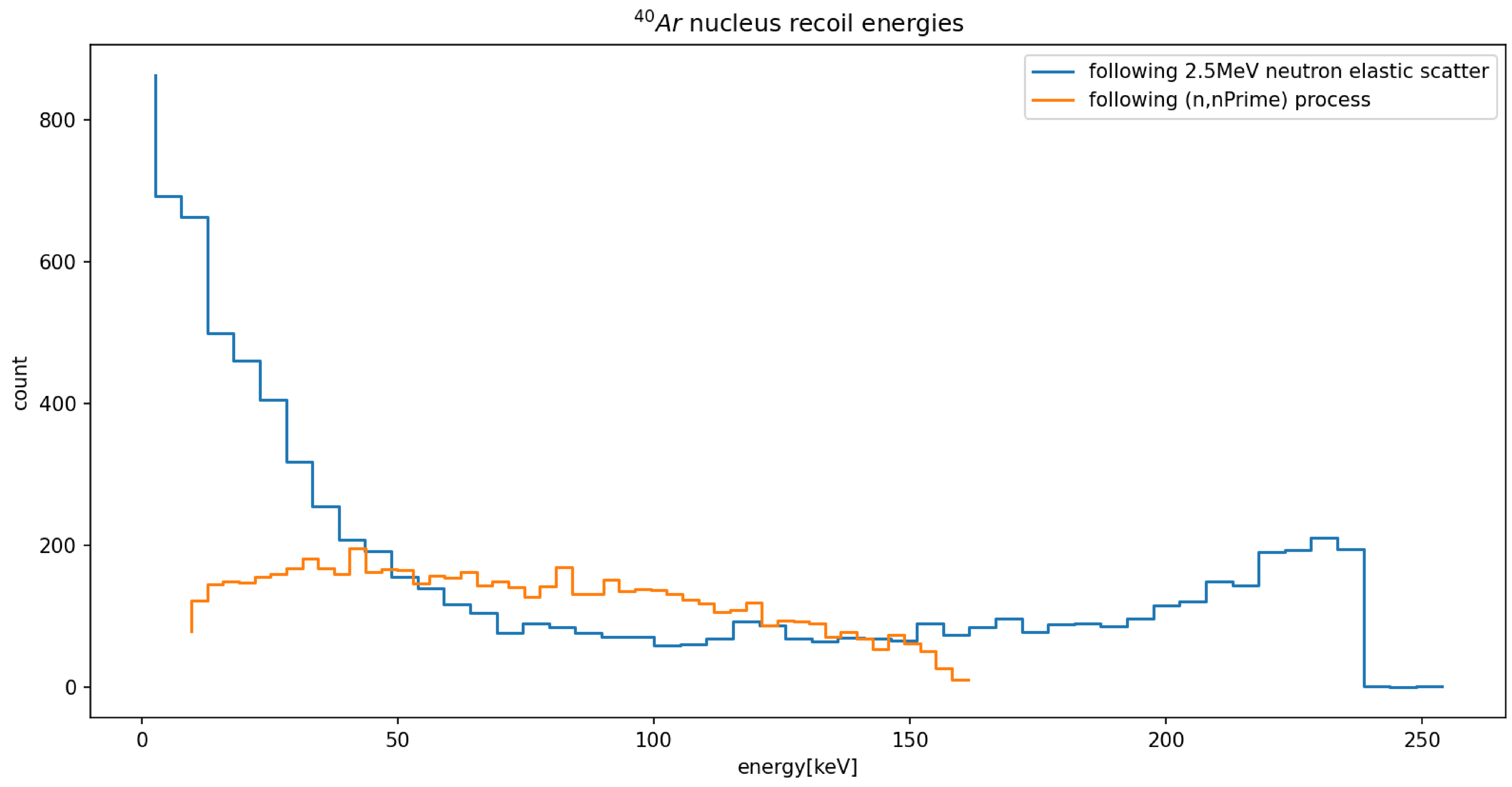

photon emission time
count
10^2
10^1
0
10
20
30
40
50
time[ns]


photon energy vs emission time
emission time[ns]
photon energy [MeV]
0
10
20
30
40
0.000
0.122
0.244
0.366
0.488
0.610
0.732
0.854
0.976
1.098
1.220
1.342
1.464

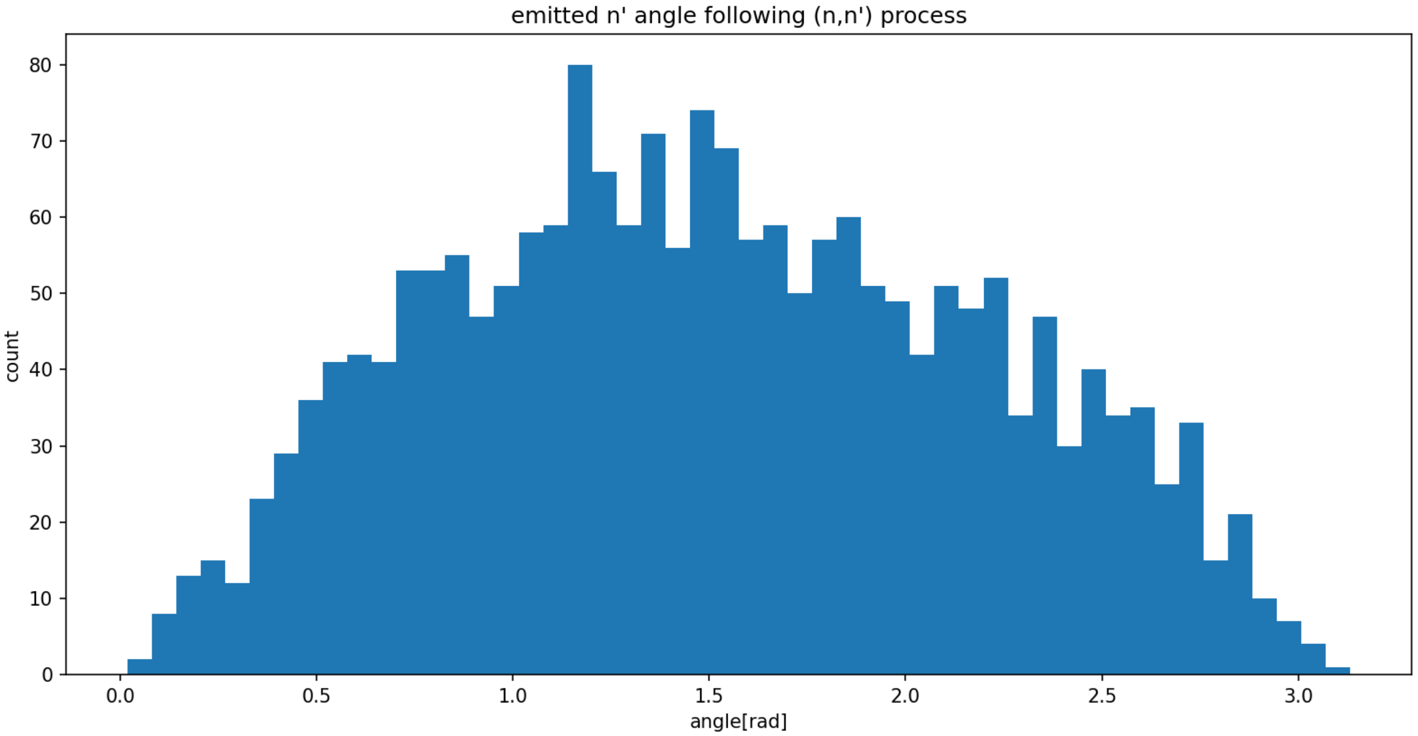

secondary γ energy deposit per event
count
Energy Deposit[keV]
Primary n
n'
secondary γ
(n, n')vertex
LAr

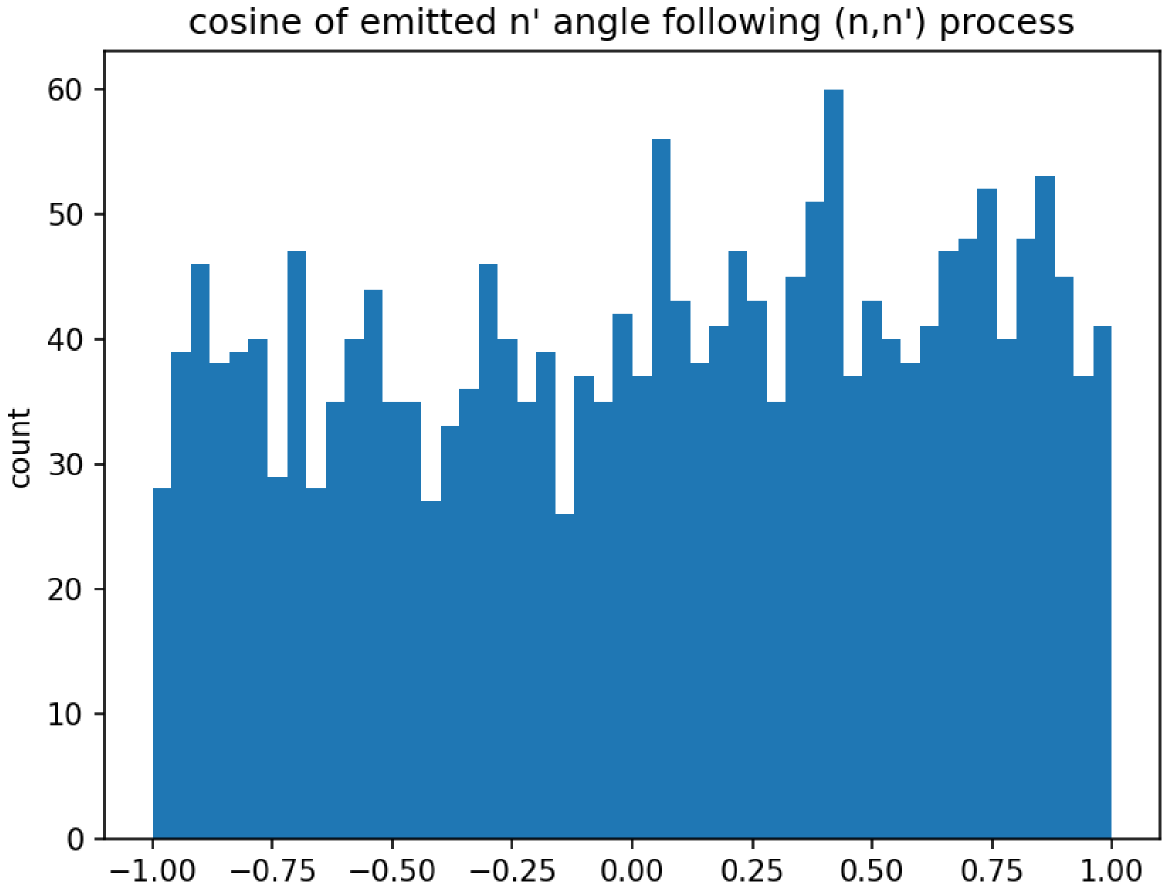


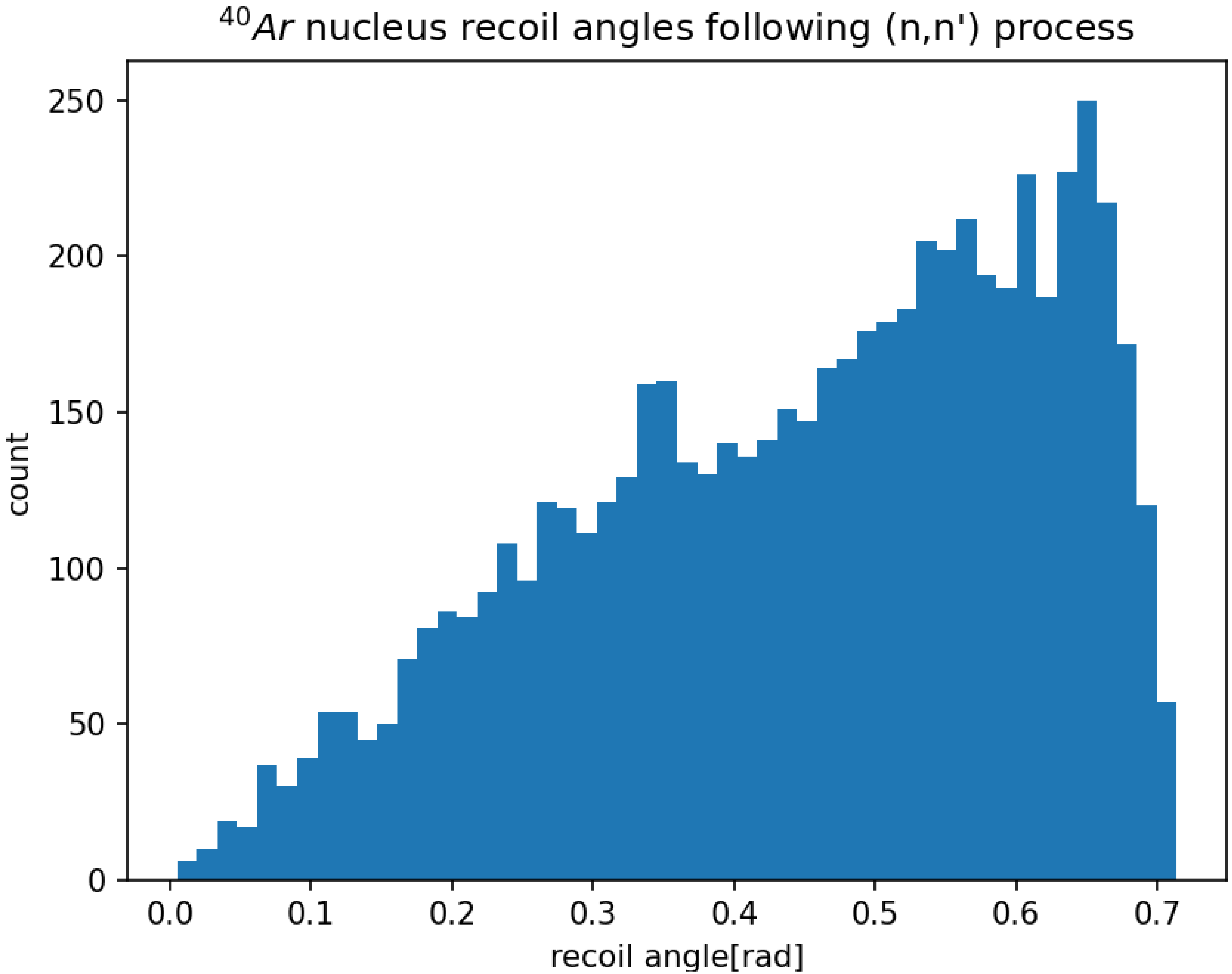
secondary γ energy deposit per γ
count
10^4
10^3
10^2
10^1
10^0
0
200
400
600
800
1000
1200
1400
1600
1800
2000
2200
2400
2600
2800
3000
3200
3400
3600
3800
4000
Energy Deposit[keV]
Primary n
n'
secondary γ
$(n, n')vertex$
LAr

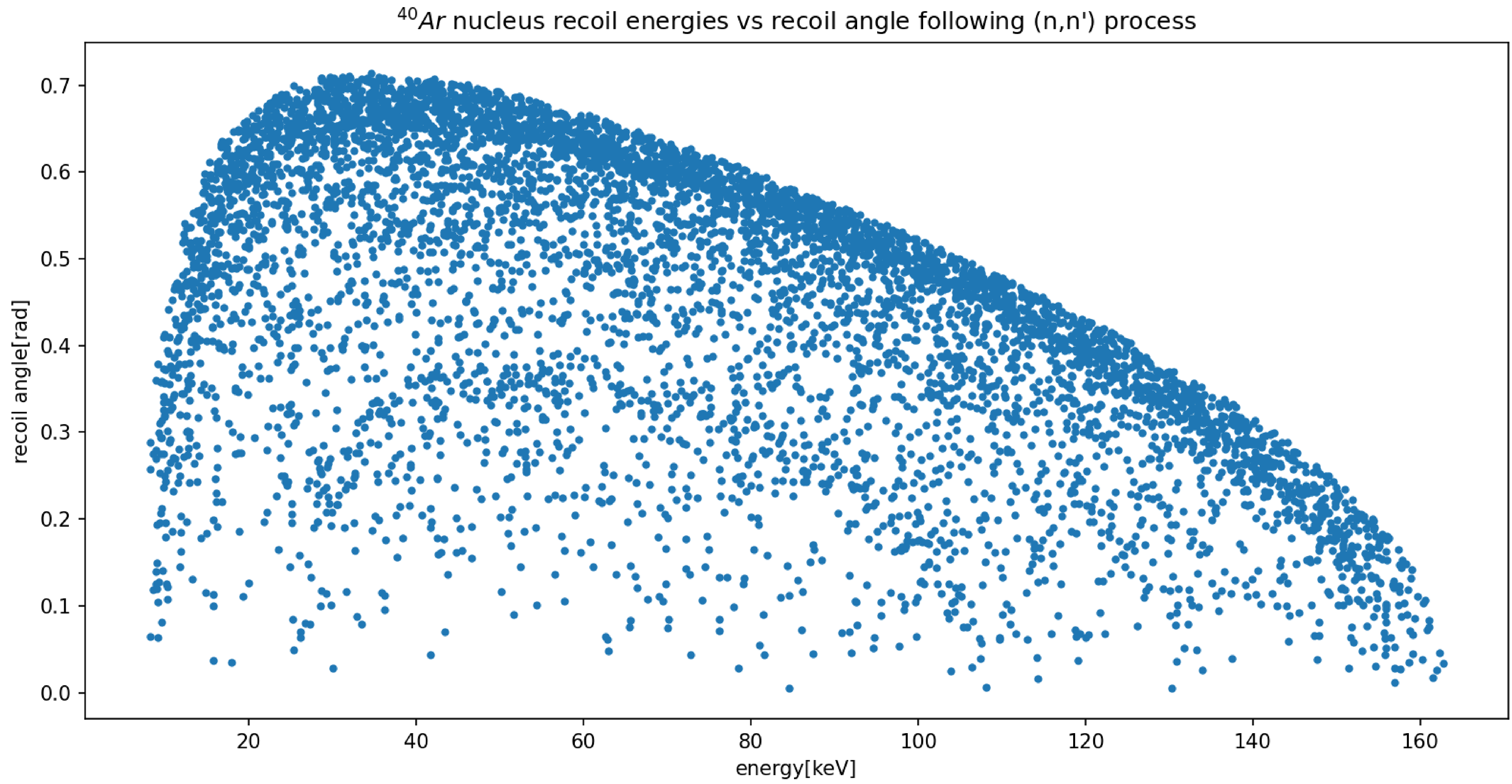


^{40}Ar nucleus recoil energies
following 2.5MeV neutron elastic scatter
following (n,nPrime) process
count
0
200
400
600
800
0
50
100
150
200
250
energy[keV]


emitted n' angle following (n,n') process
count
angle[rad]
0
10
20
30
40
50
60
70
80
0.0
0.5
1.0
1.5
2.0
2.5
3.0

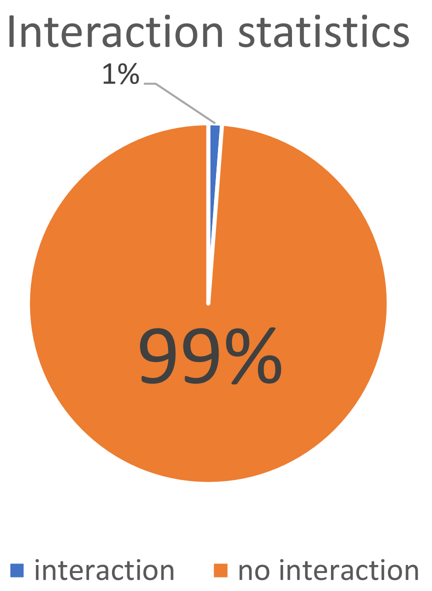

cosine of emitted n' angle following (n,n') process
count
0
10
20
30
40
50
60
−1.00
−0.75
−0.50
−0.25
0.00
0.25
0.50
0.75
1.00


^{40}Ar nucleus recoil angles following (n,n') process
count
0
50
100
150
200
250
0.0
0.1
0.2
0.3
0.4
0.5
0.6
0.7
recoil angle[rad]



^{40}Ar nucleus recoil energies vs recoil angle following (n,n') process
recoil angle[rad]
0.0
0.1
0.2
0.3
0.4
0.5
0.6
0.7
energy[keV]
20
40
60
80
100
120
140
160

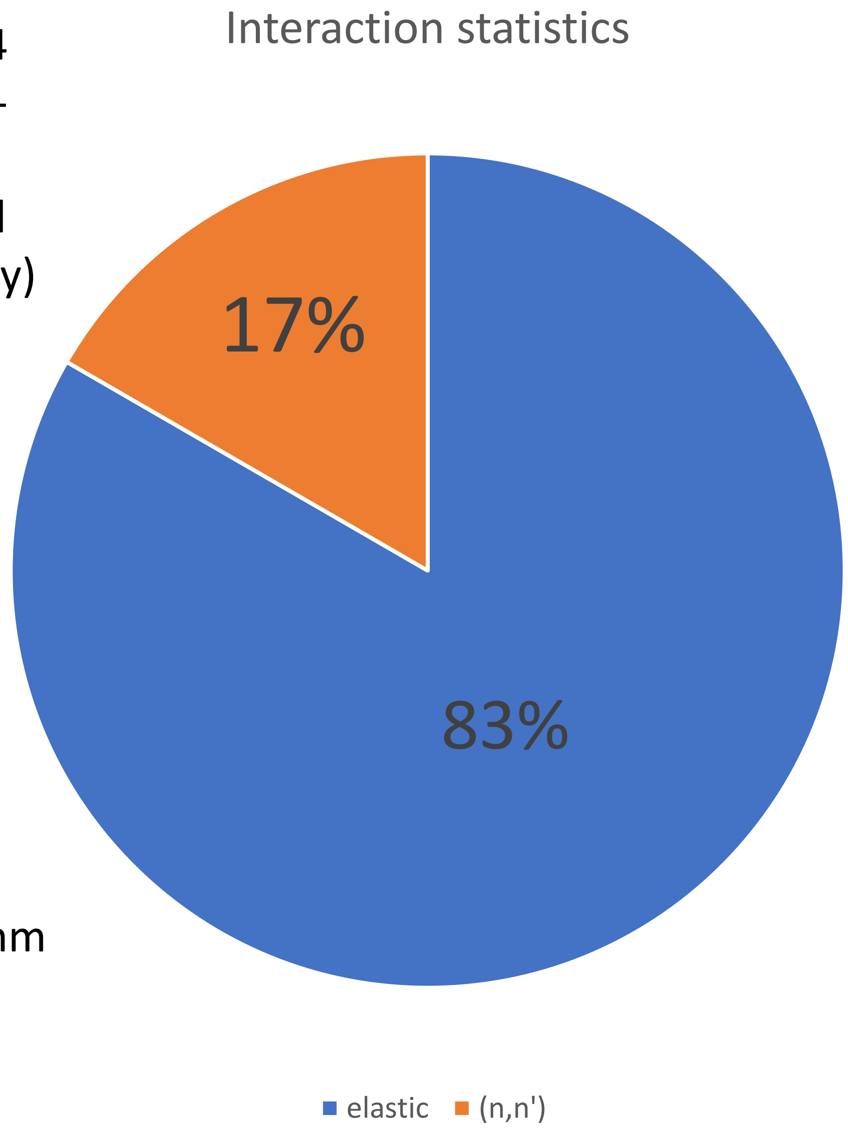
Creus et al. , *JINST* 10 (2015)



neutron

Our geant4 simulation- Emulating the LAr cell size(roughly)

50 mm



Consequence - In the paper they neglect inelastic scatters because they use elastic kinematics in order to calculate nucleus recoil, and thus in 17% of events they have an error in their calculations.

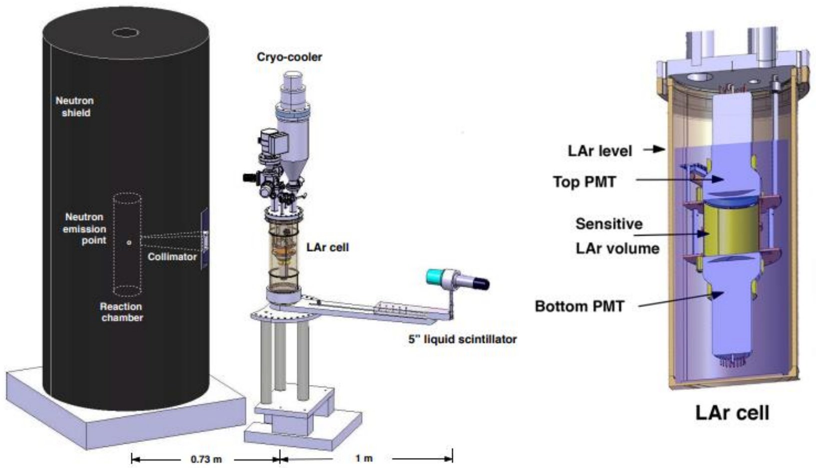
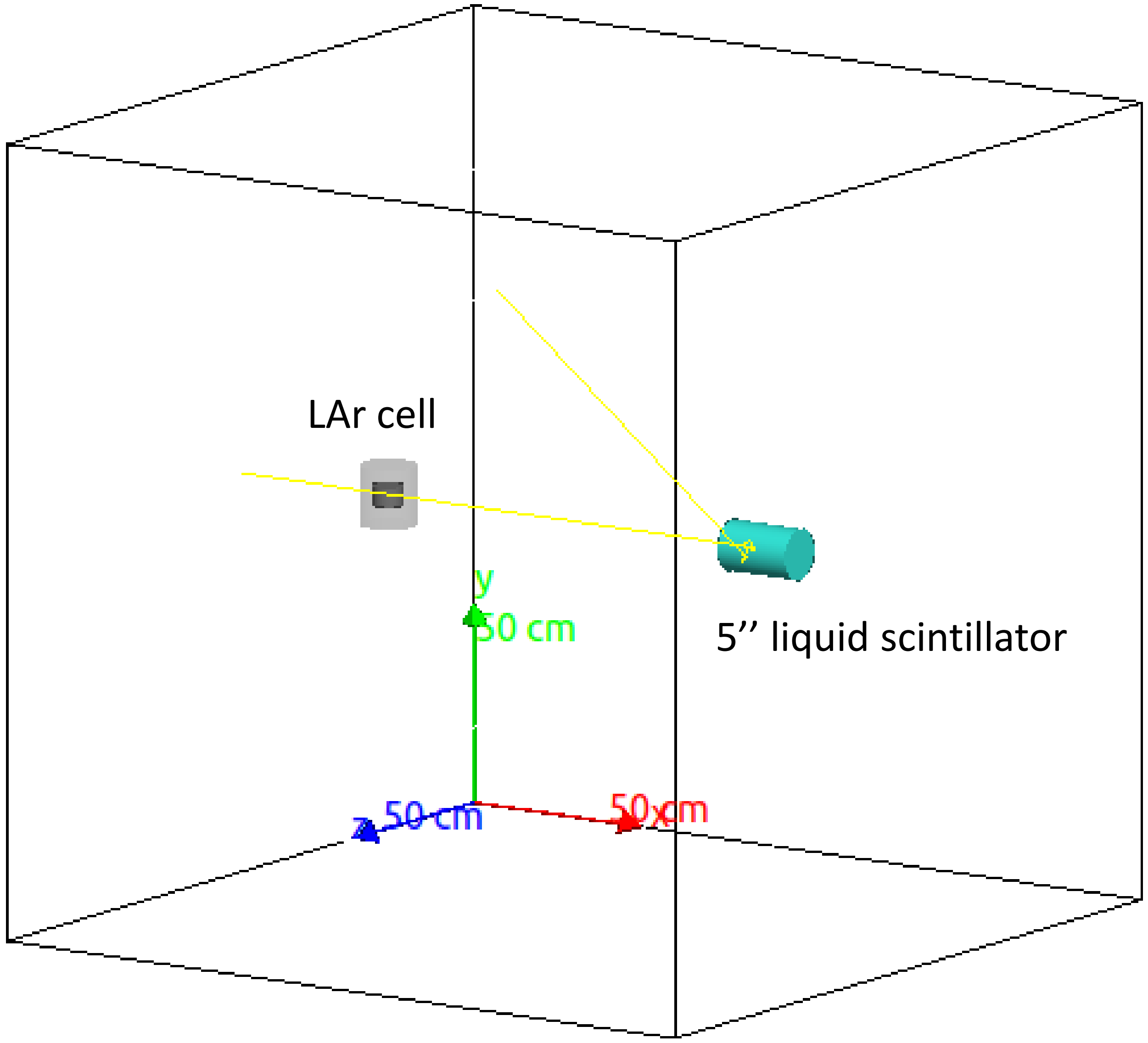


Figure 3. Left: neutron gun, argon cell and liquid scintillation counter used to measure L_{eff} in LAr. Right: sketch of the LAr cell with its vacuum chamber (see text).

clear recoils, relative to electrons, between 11 keV and 120 keV in liquid argon. Single elastic neutron-argon scattering dominates thanks to the small active volume of our argon cell and the well collimated neutron beam, while the contamination from neutron inelastic scattering is negligible. A χ^2 minimization is performed leaving L_{eff} and the energy resolution as free parameters. The

?

My geant4 simulator



Article experimental setup

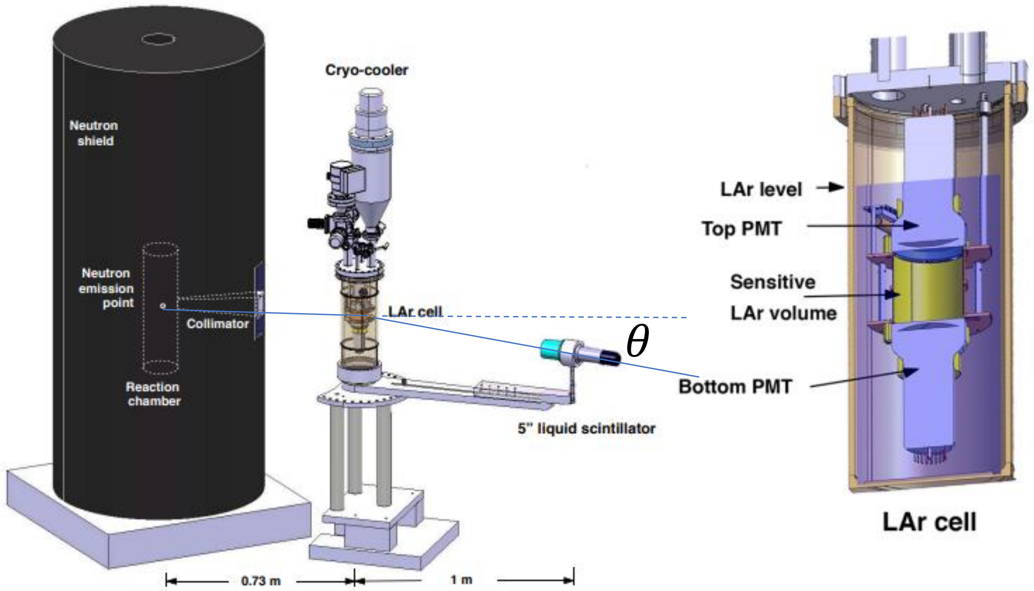
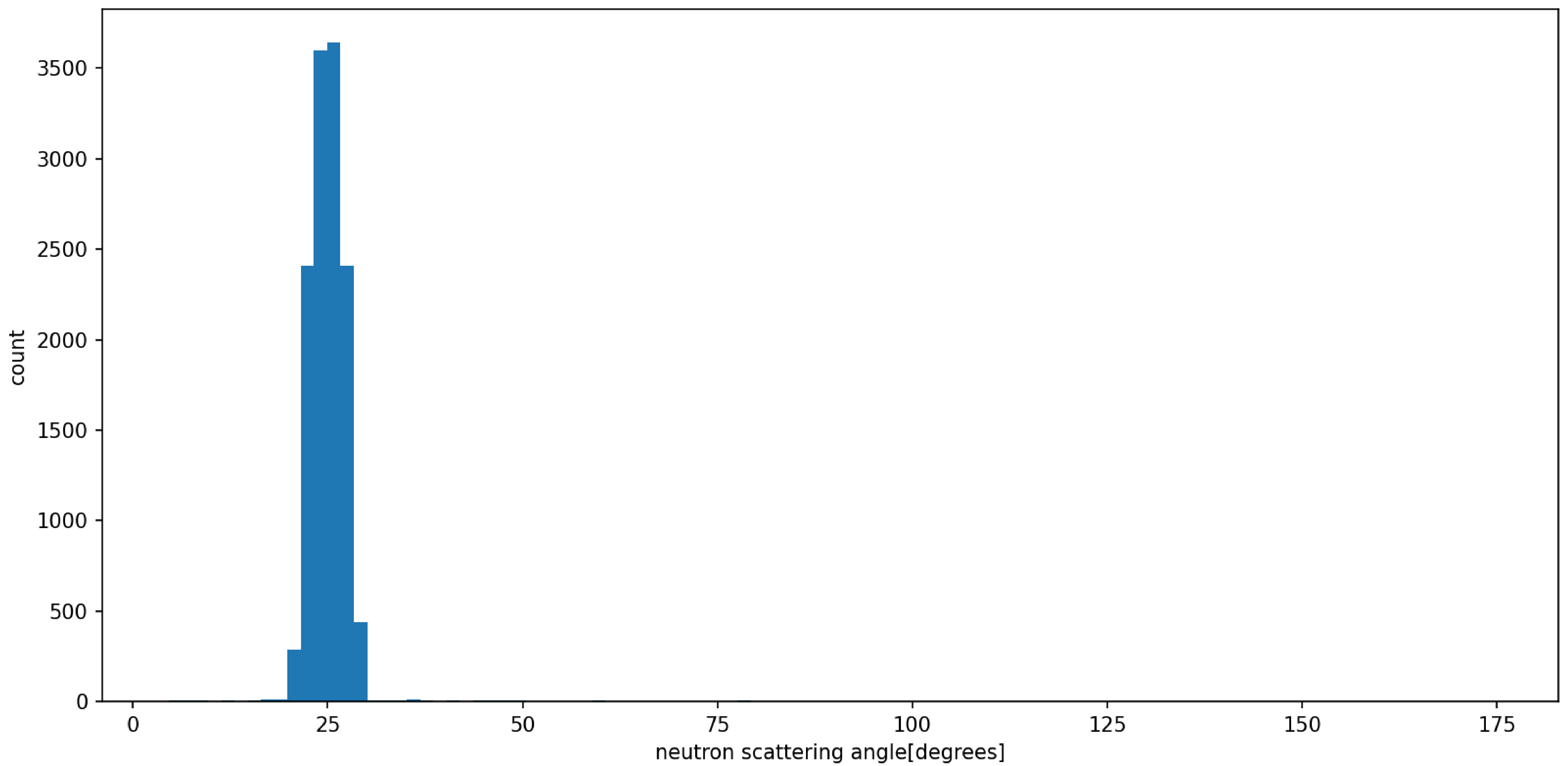


Figure 3. Left: neutron gun, argon cell and liquid scintillation counter used to measure L_{eff} in LAr. Right: sketch of the LAr cell with its vacuum chamber (see text).

in the experiment there is also a 1.5mm aluminium layer around the sensitive volume of LAr, but the effect on the neutrons is minimal(sub percent)

Also, in reality the beam is collimated into 0.2% 4pi steradians which gives an effective surface area of $0.013\ [cm^2]$ of neutrons hitting the LAr, and in my simulator I use a pencil beam (0 width)



count
3500
3000
2500
2000
1500
1000
500
0
0
25
50
75
100
125
150
175
neutron scattering angle[degrees]

Article experimental setup

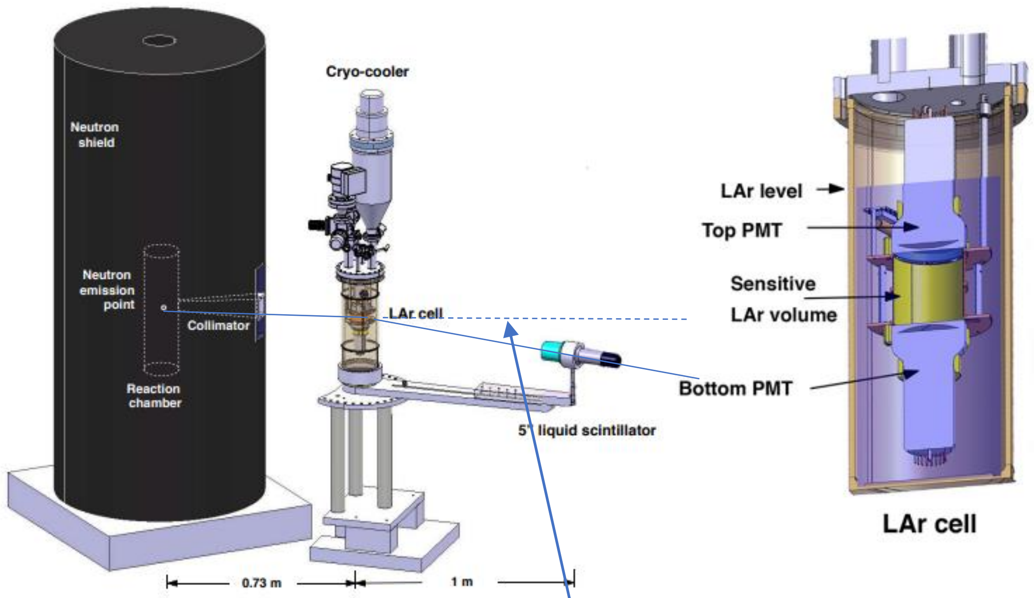
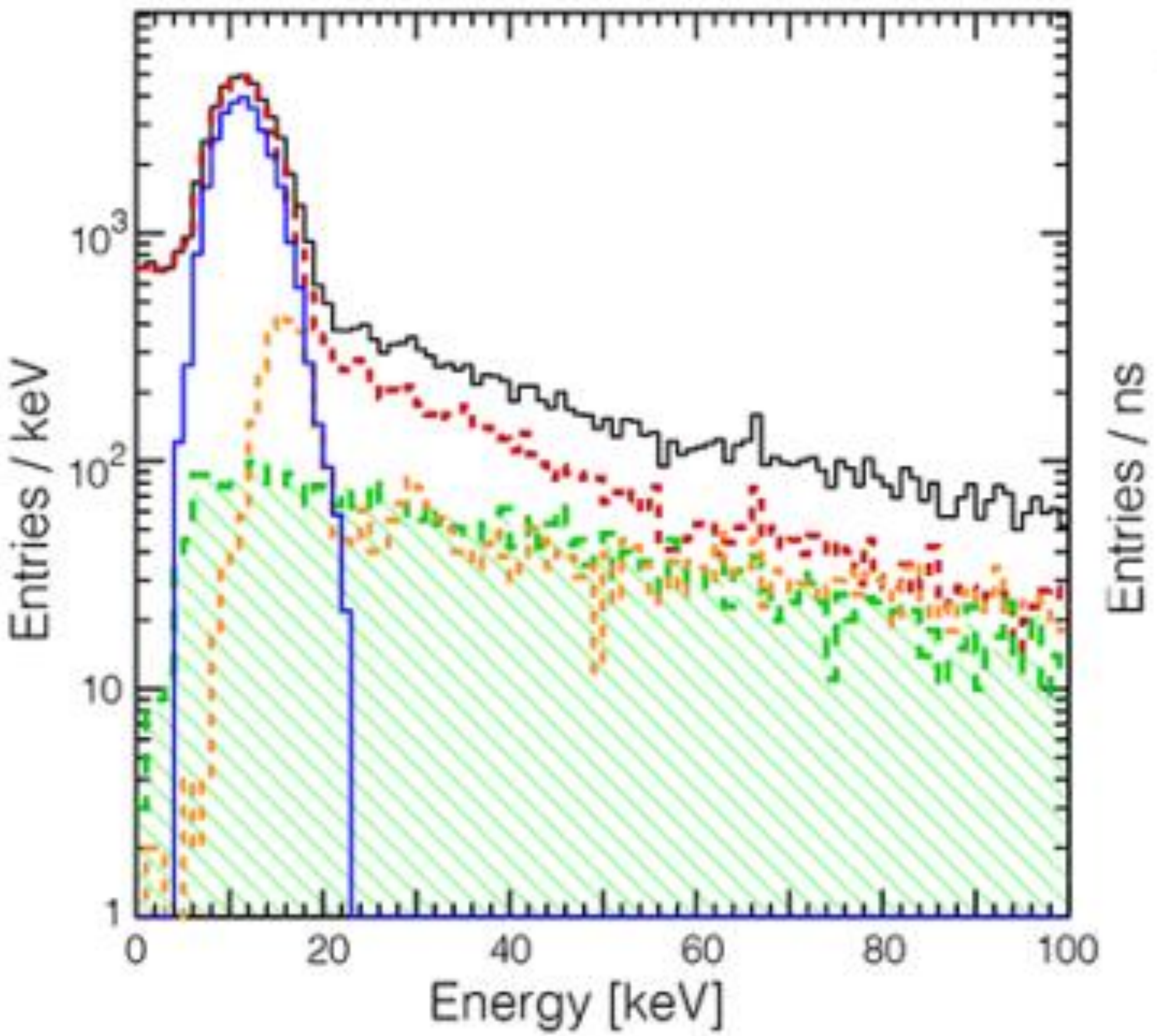
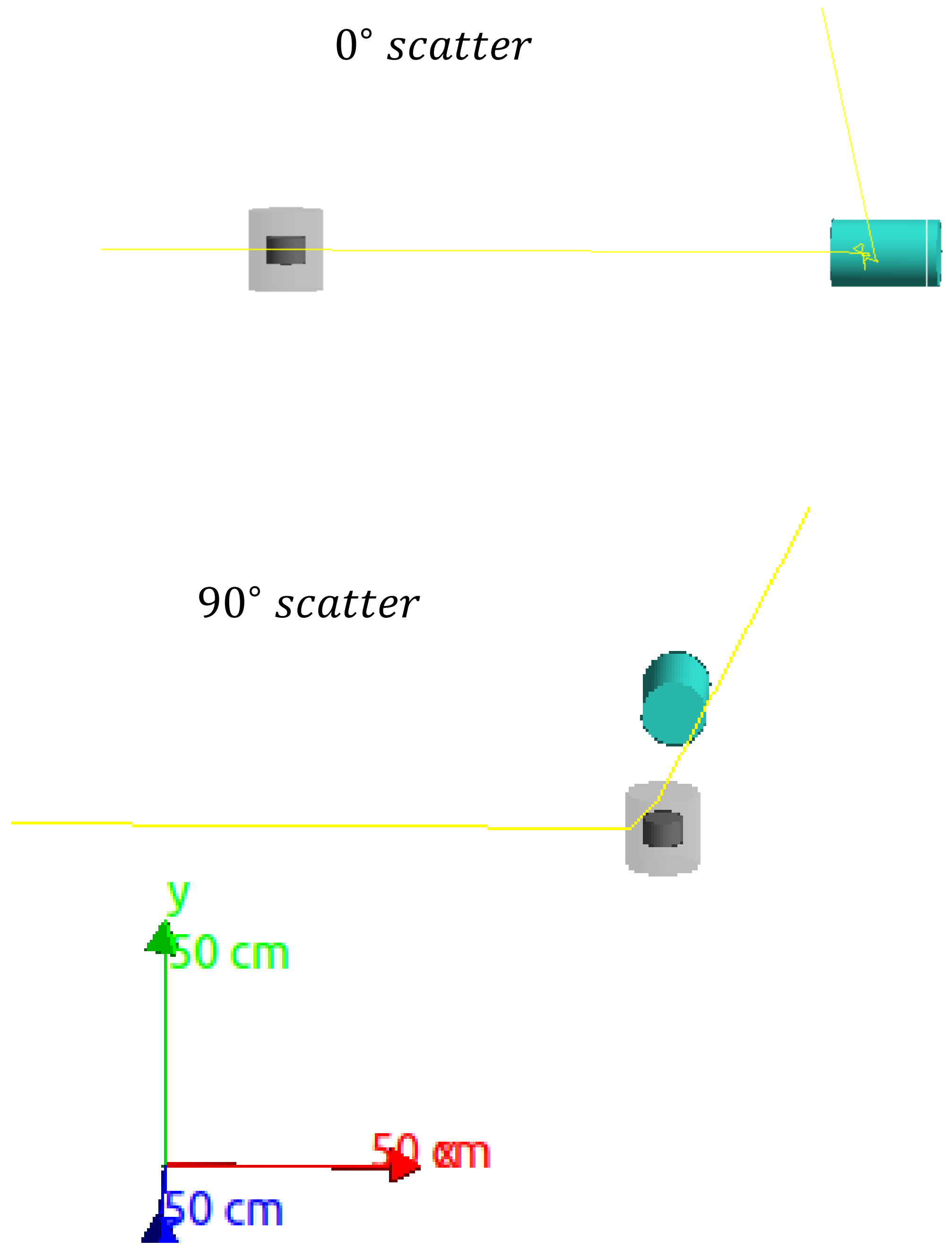


Figure 3. Left: neutron gun, argon cell and liquid scintillation counter used to measure L_{eff} in LAr. Right: sketch of the LAr cell with its vacuum chamber (see text).

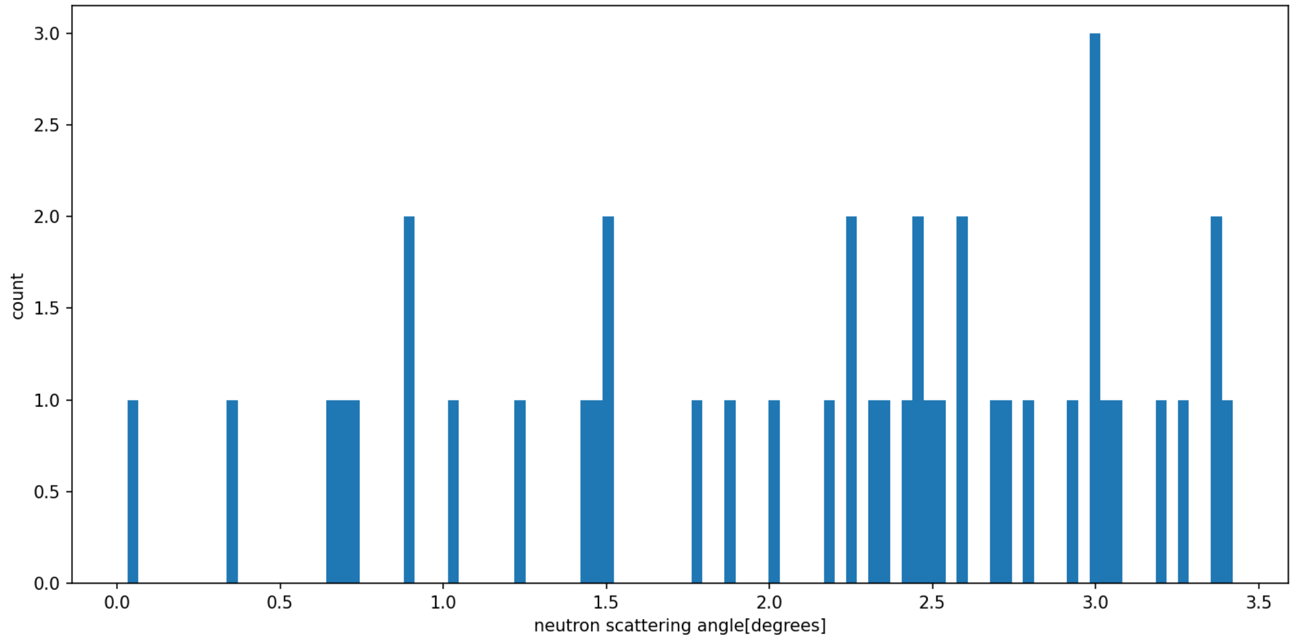
$\theta = 25^{\circ}$

Nucleus E_{recoil} dist.

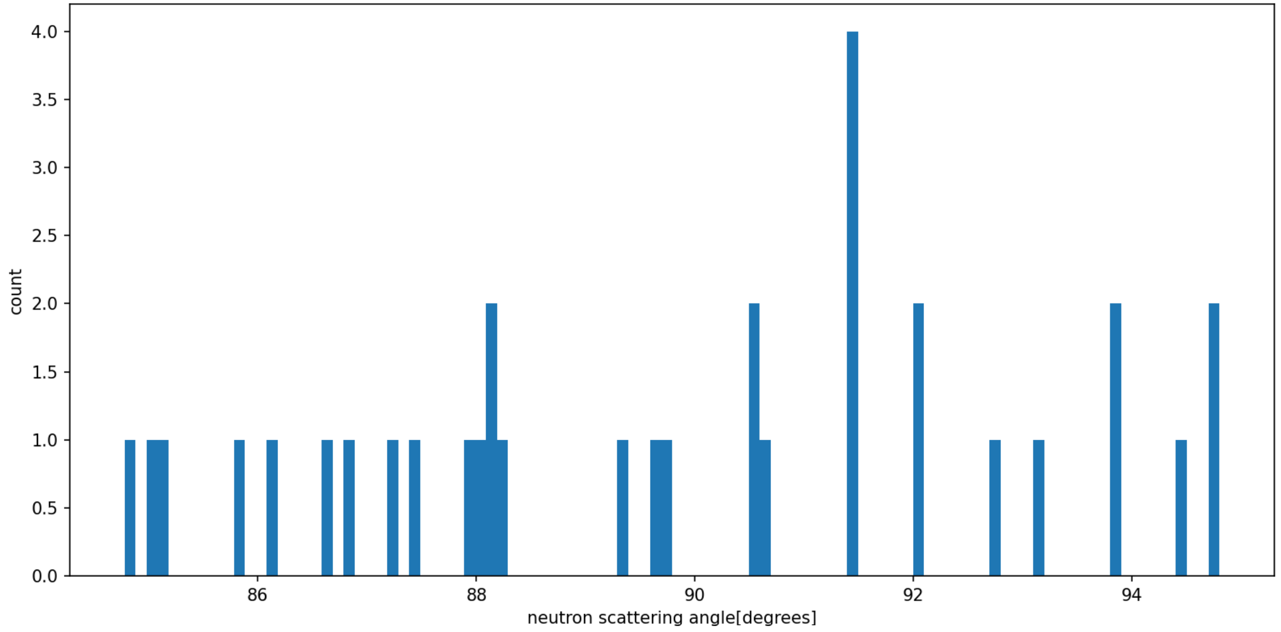




0° scatter
90° scatter
y
50 cm
50 cm
50 cm

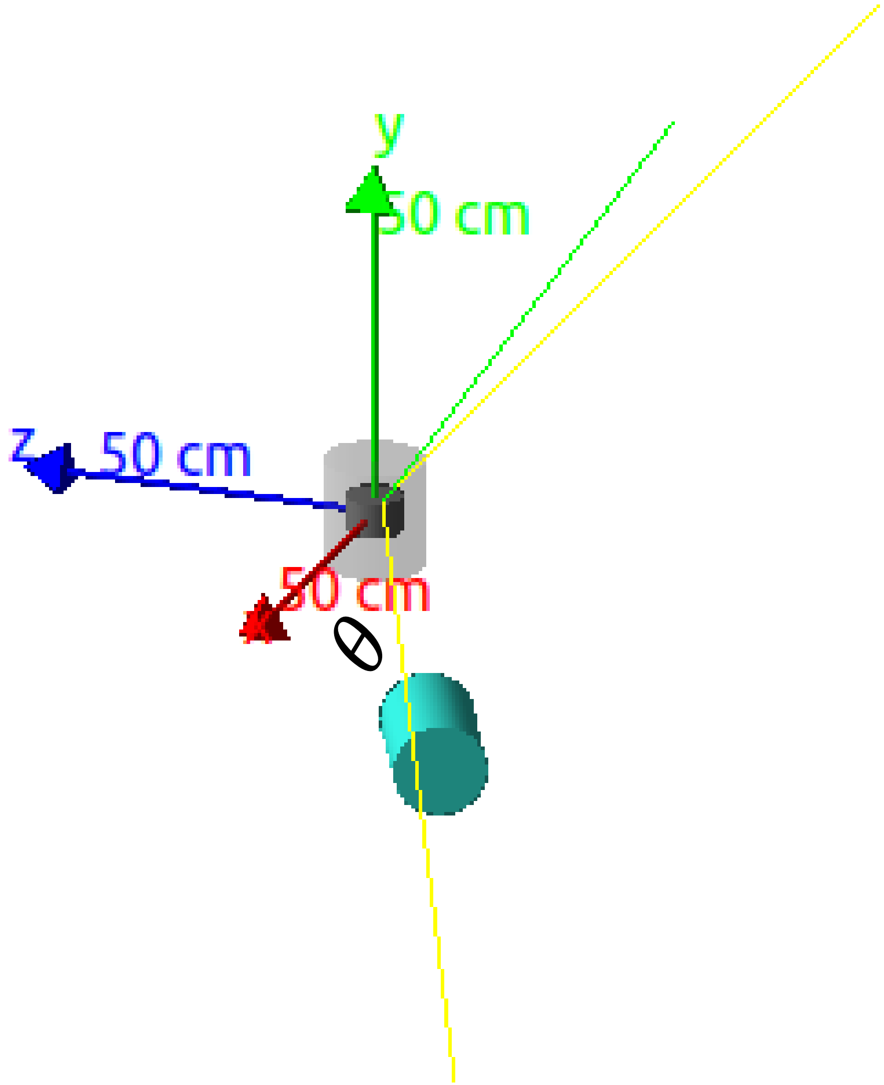


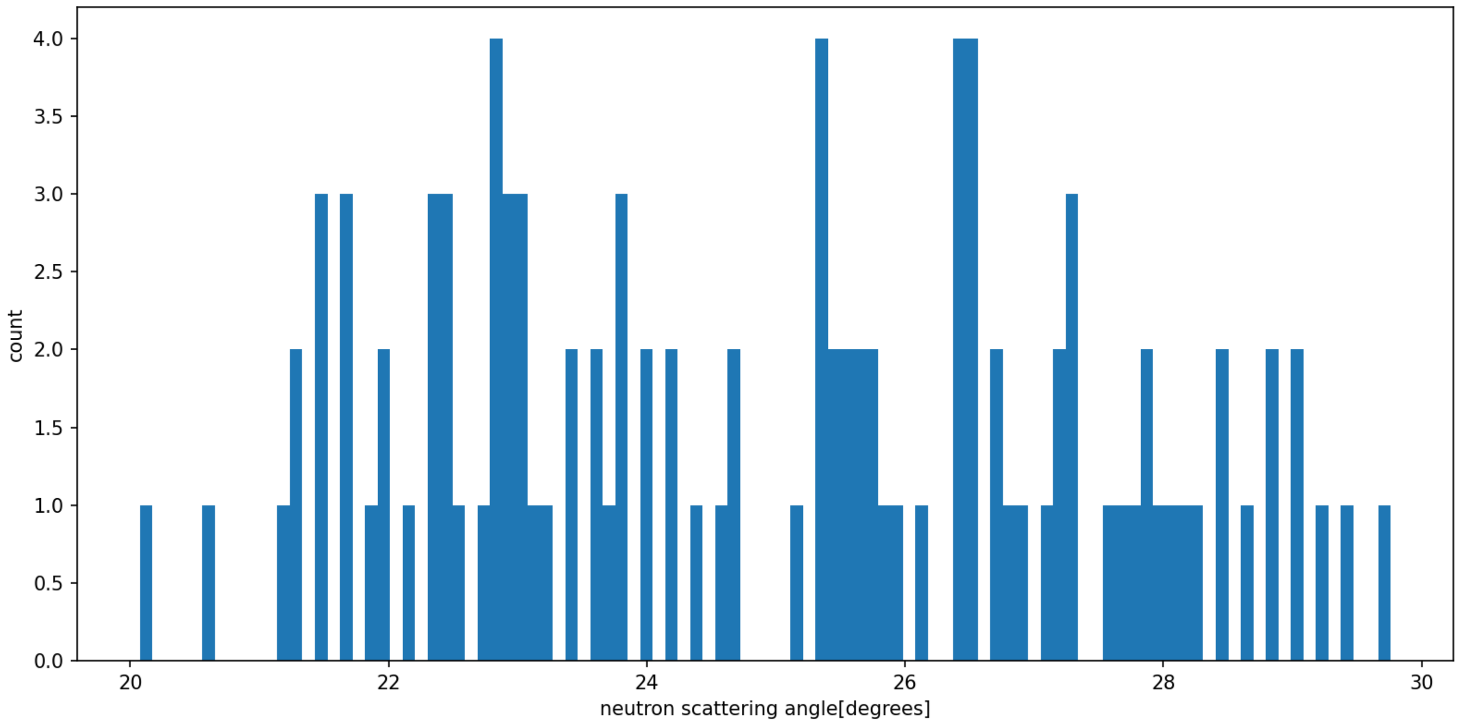
count
neutron scattering angle[degrees]



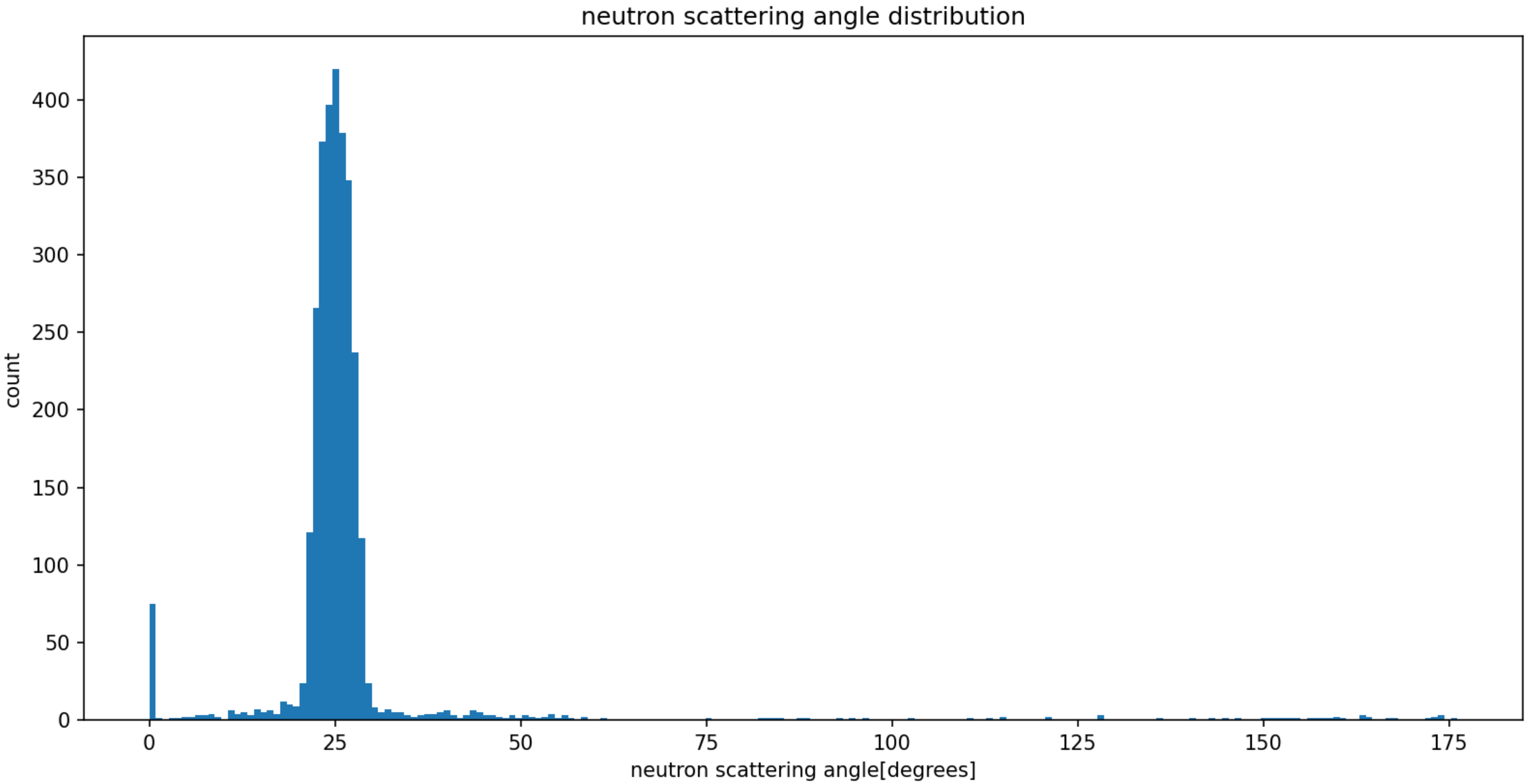
count
neutron scattering angle[degrees]

$25° \; scatter$

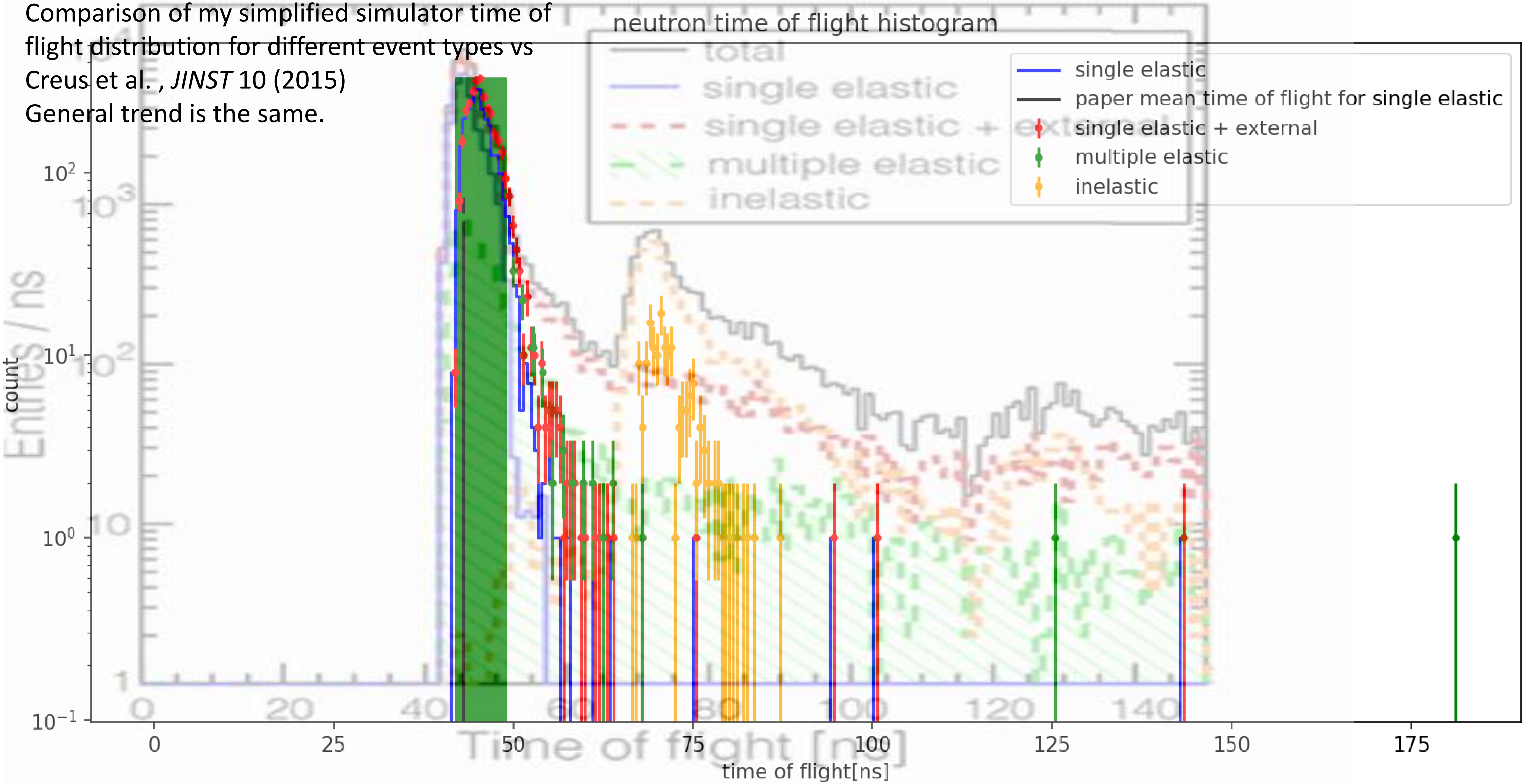




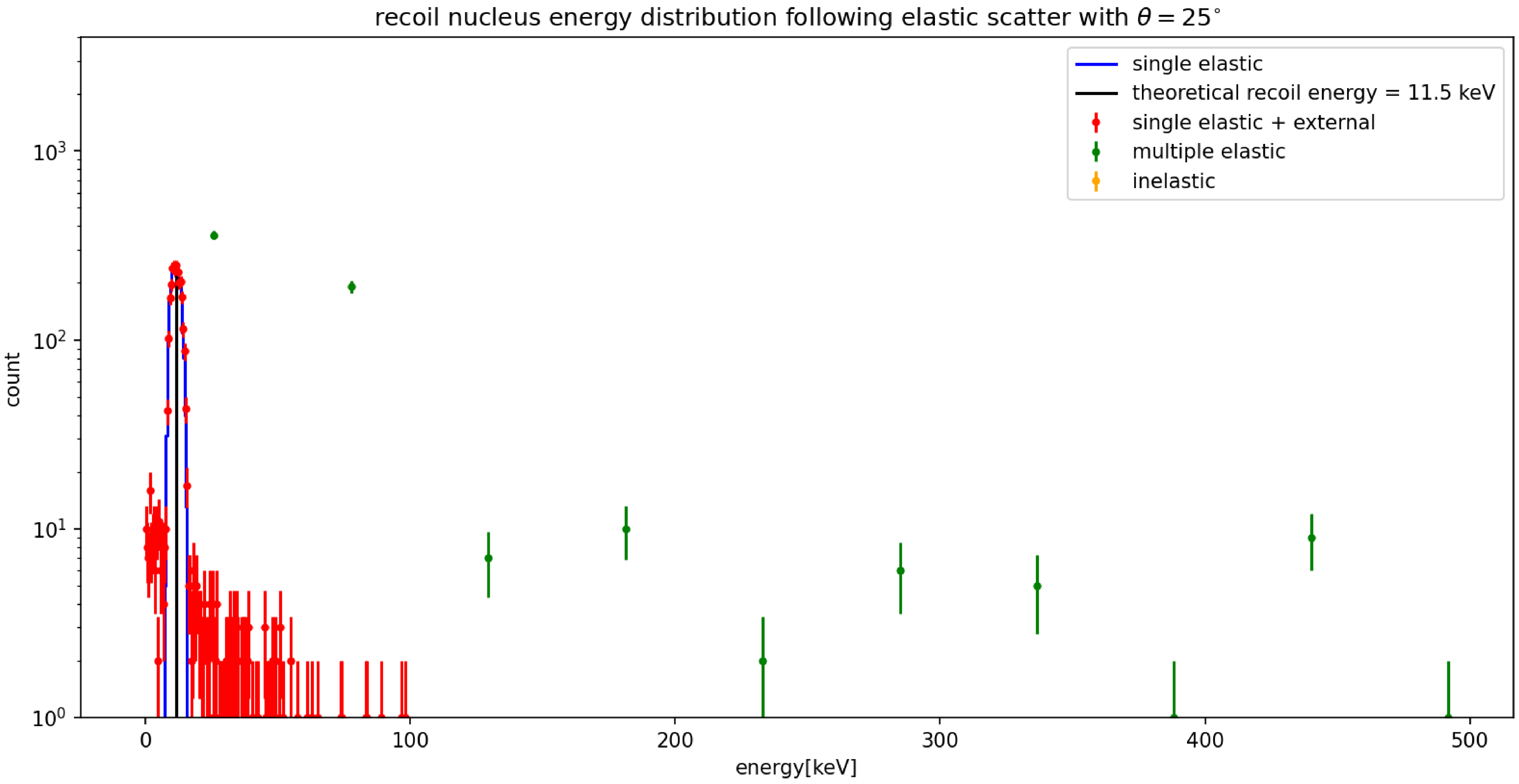
Liquid scintillator placed at 25° angle relative to LAr cell,
Showing the neutron scattering angle distribution within the active volume of the cell without external scatters

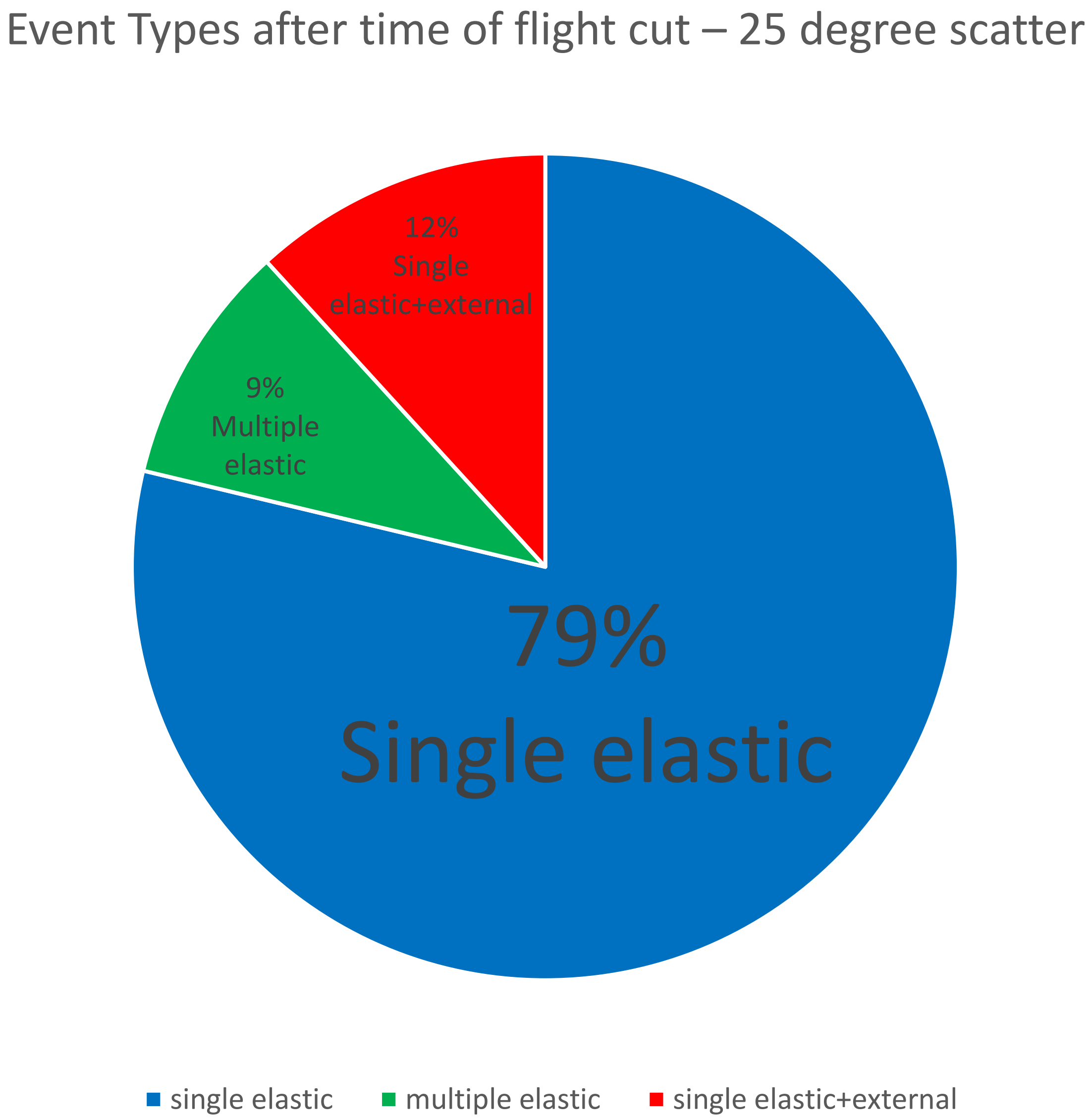


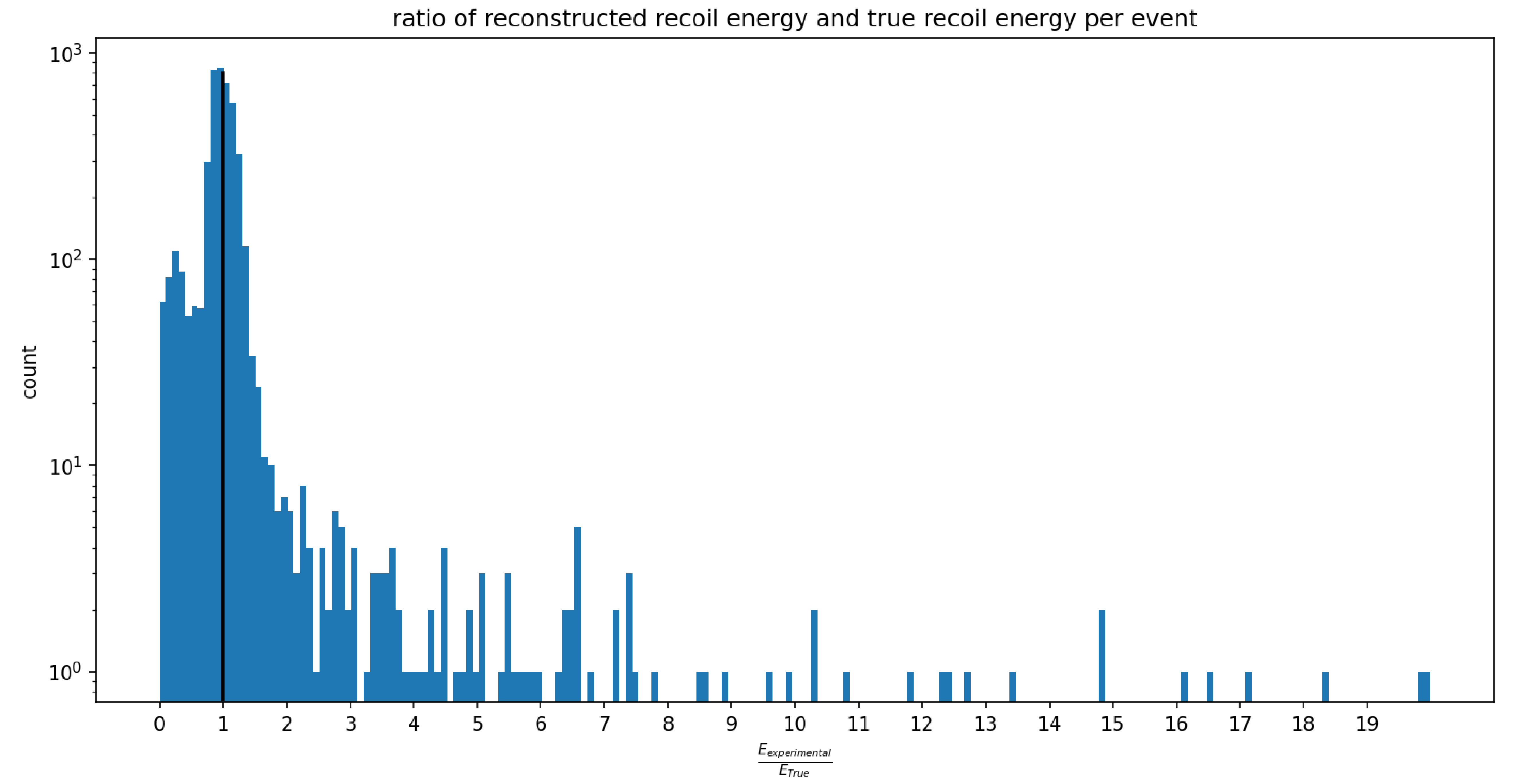
Comparison of my simplified simulator time of flight distribution for different event types vs Creus et al. , *JINST* 10 (2015)
General trend is the same.



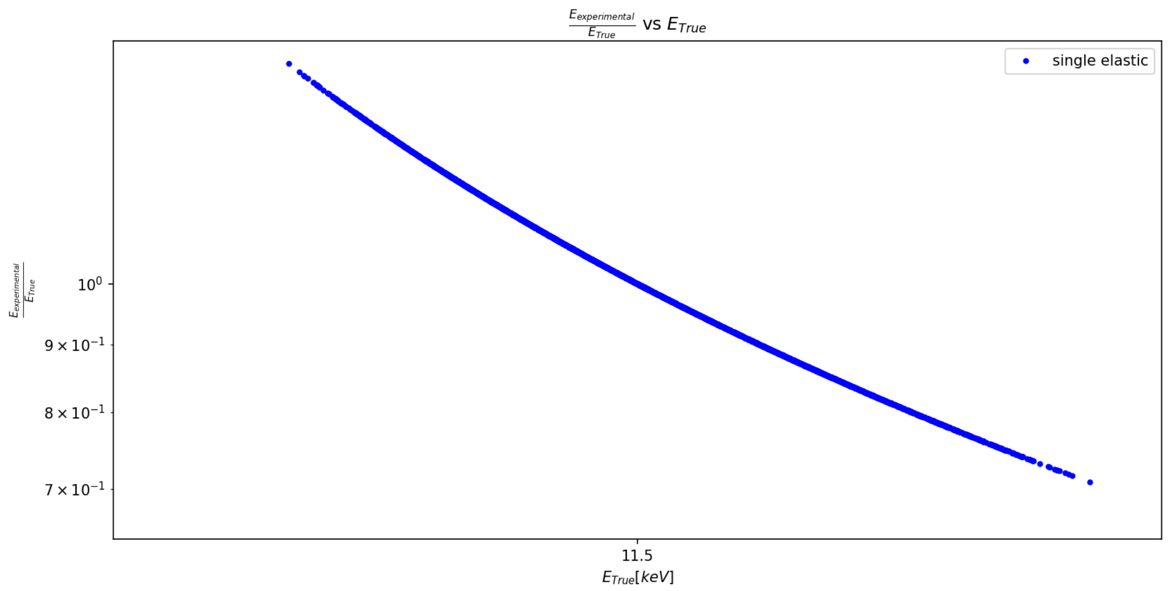
After time of flight cut - $42\ [ns] < time < 49\ [ns]$



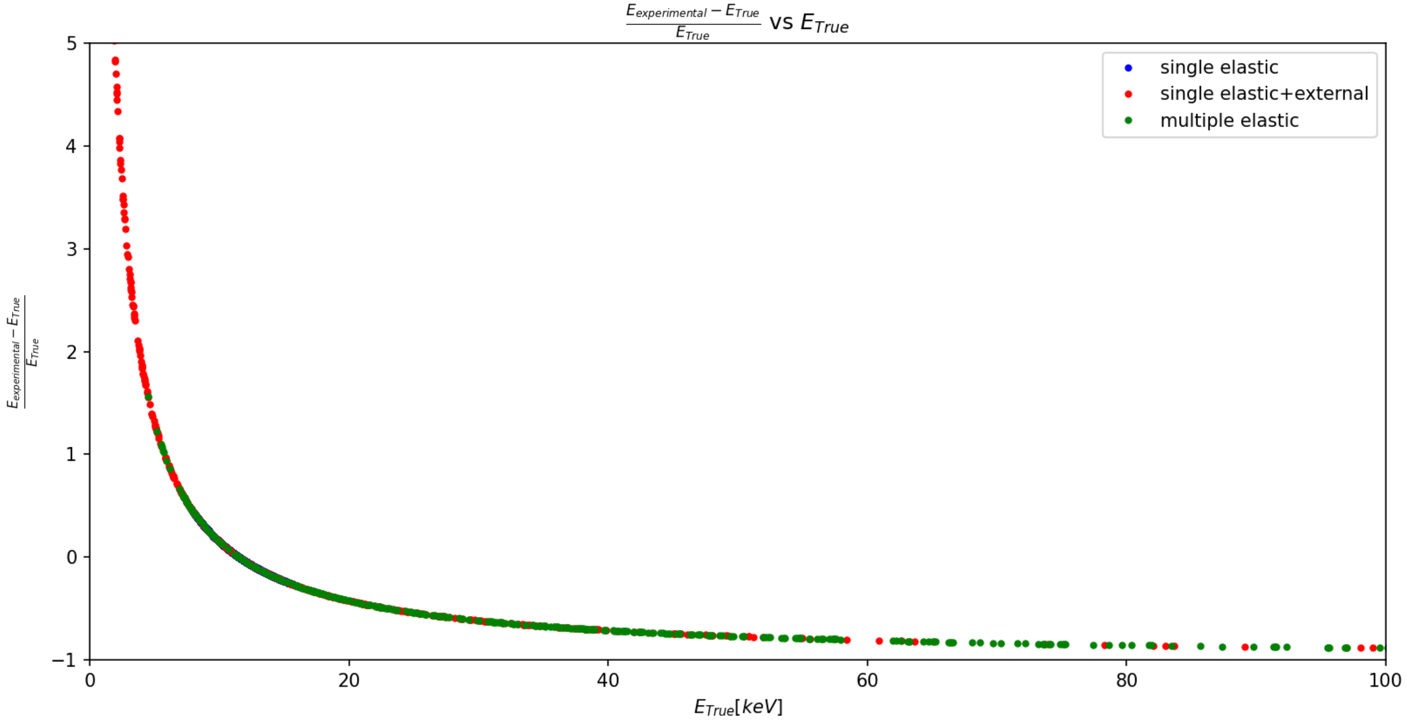

Event Types after time of flight cut – 25 degree scatter
12%
Single
elastic+external
9%
Multiple
elastic
79%
Single elastic
single elastic
multiple elastic
single elastic+external



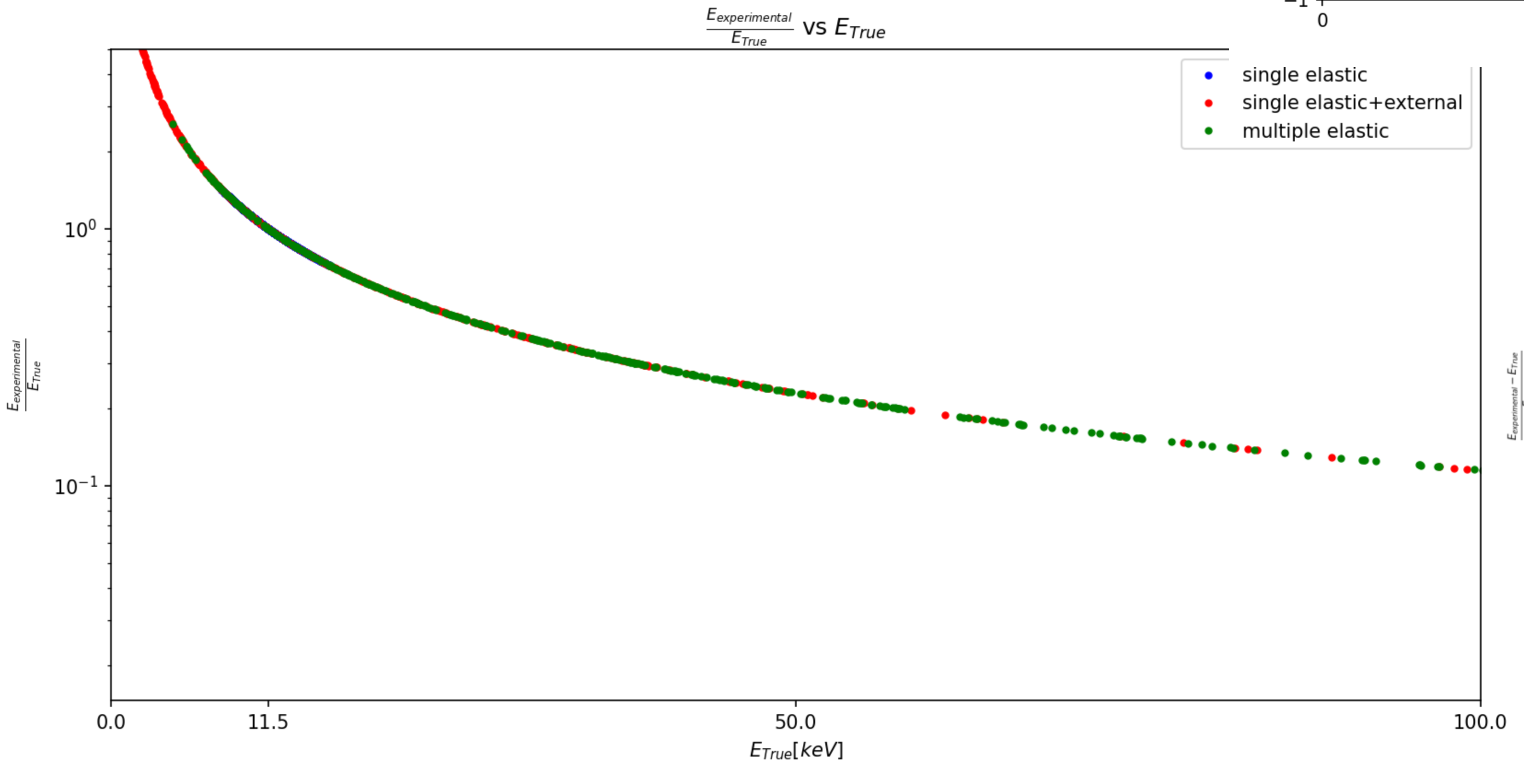
ratio of reconstructed recoil energy and true recoil energy per event
count
10^3
10^2
10^1
10^0
0
1
2
3
4
5
6
7
8
9
10
11
12
13
14
15
16
17
18
19
$\frac{E_{experimental}}{E_{True}}$



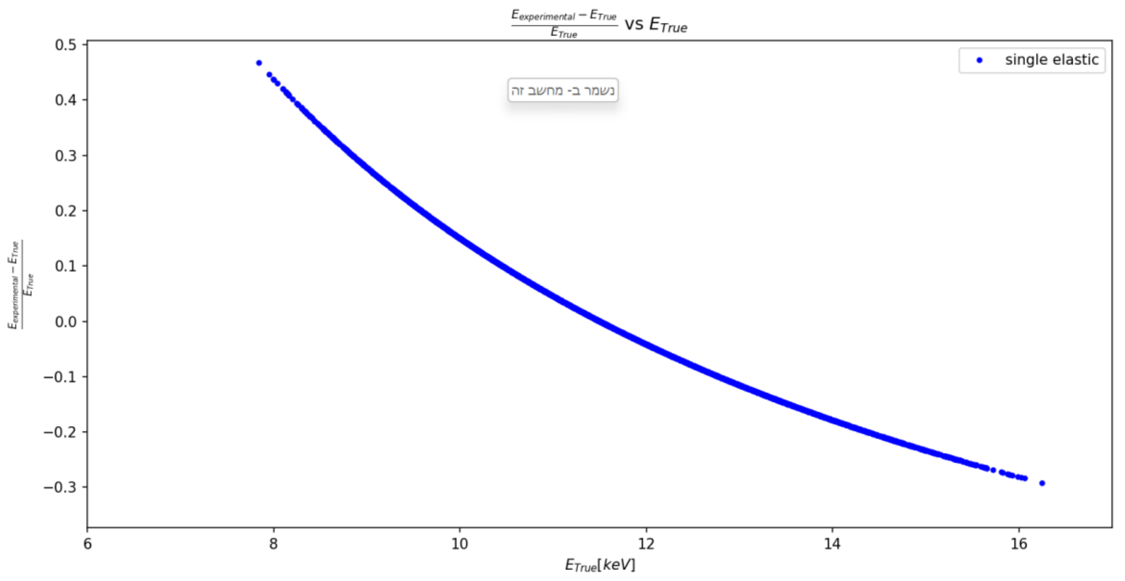
$\frac{E_{experimental}}{E_{True}}$ vs E_{True}
single elastic
$\frac{E_{experimental}}{E_{True}}$
10^0
9×10^{-1}
8×10^{-1}
7×10^{-1}
11.5
$E_{True}[keV]$



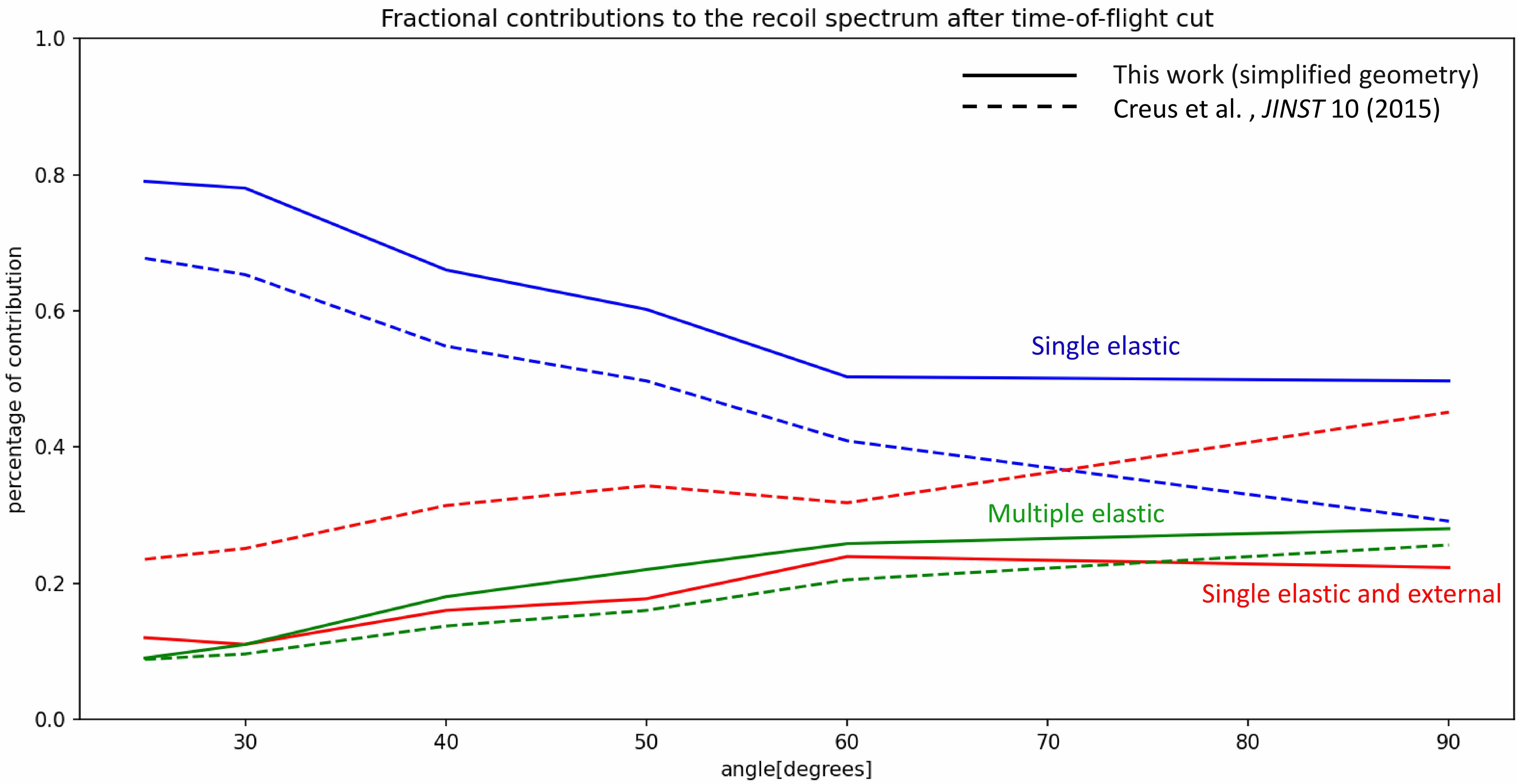
$\frac{E_{experimental}-E_{True}}{E_{True}}$ vs E_{True}
single elastic
single elastic+external
multiple elastic
$\frac{E_{experimental}-E_{True}}{E_{True}}$
5
4
3
2
1
0
−1
0
20
40
60
80
100
$E_{True}[keV]$



$\frac{E_{experimental}}{E_{True}}$ vs E_{True}
single elastic
single elastic+external
multiple elastic
$\frac{E_{experimental}}{E_{True}}$
10^0
10^{-1}
0.0
11.5
50.0
100.0
$E_{True}[keV]$

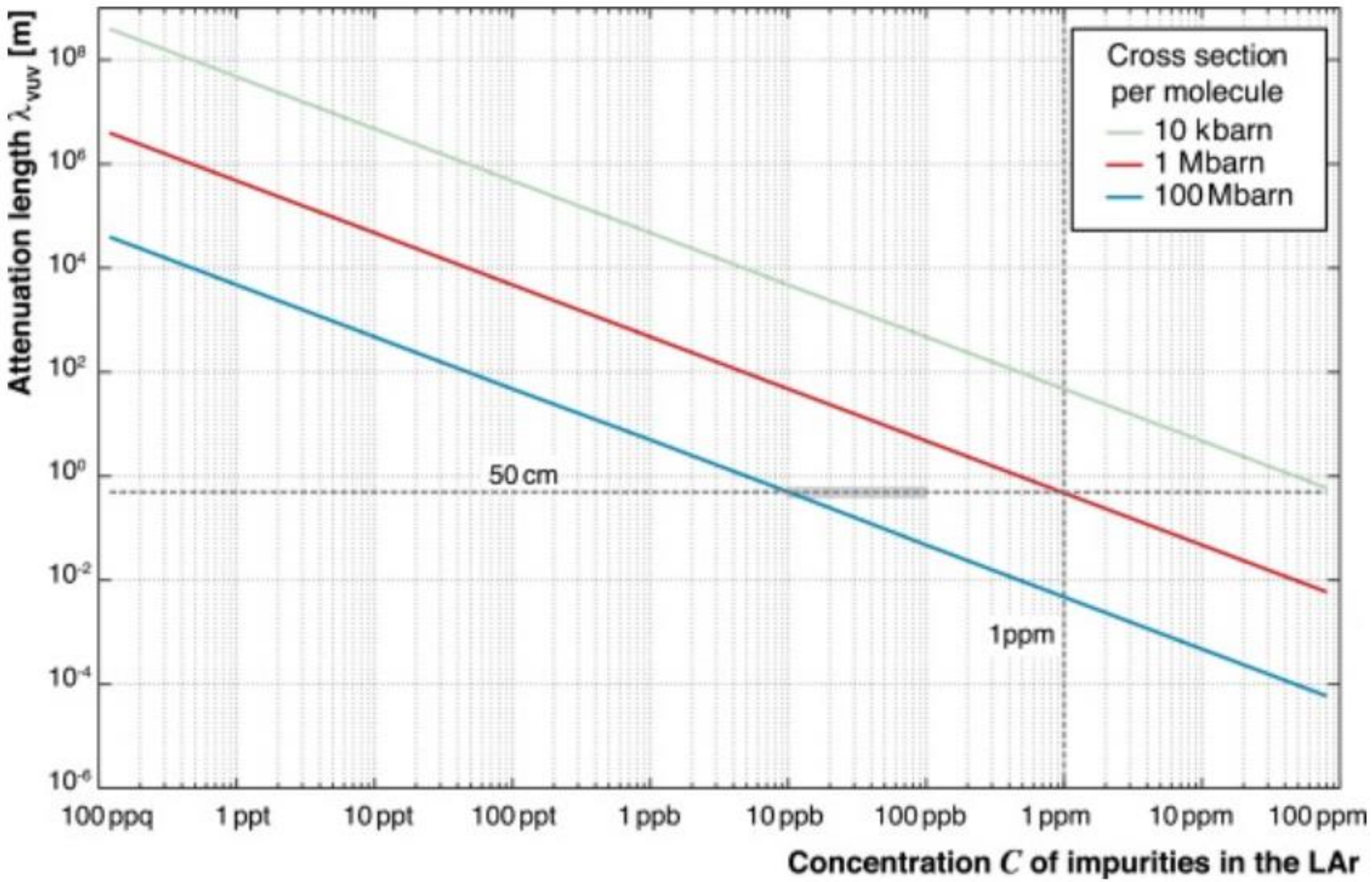


$\frac{E_{experimental}-E_{True}}{E_{True}}$ vs E_{True}
single elastic
נשמר ב- מחשב זה
$\frac{E_{experimental}-E_{True}}{E_{True}}$
0.5
0.4
0.3
0.2
0.1
0.0
−0.1
−0.2
−0.3
6
8
10
12
14
16
$E_{True}[keV]$



Fractional contributions to the recoil spectrum after time-of-flight cut
This work (simplified geometry)
Creus et al. , *JINST* 10 (2015)
Single elastic
Multiple elastic
Single elastic and external
percentage of contribution
angle[degrees]
1.0
0.8
0.6
0.4
0.2
0.0
30
40
50
60
70
80
90

https://www.sciencedirect.com/science/article/pii/S0927650516302341



In order to make sure we understand how to properly set the required parameters for scintillation light in geant4, we first want to make some sanity checks.

First and foremost, we want to see that the distribution of the amount of scintillation photons created matches the parameter we set for the SCINTILLATIONYIELD.

Doing this we run into a problem – we don’t seem to get the right amount of photons.

The following slides explain why that is

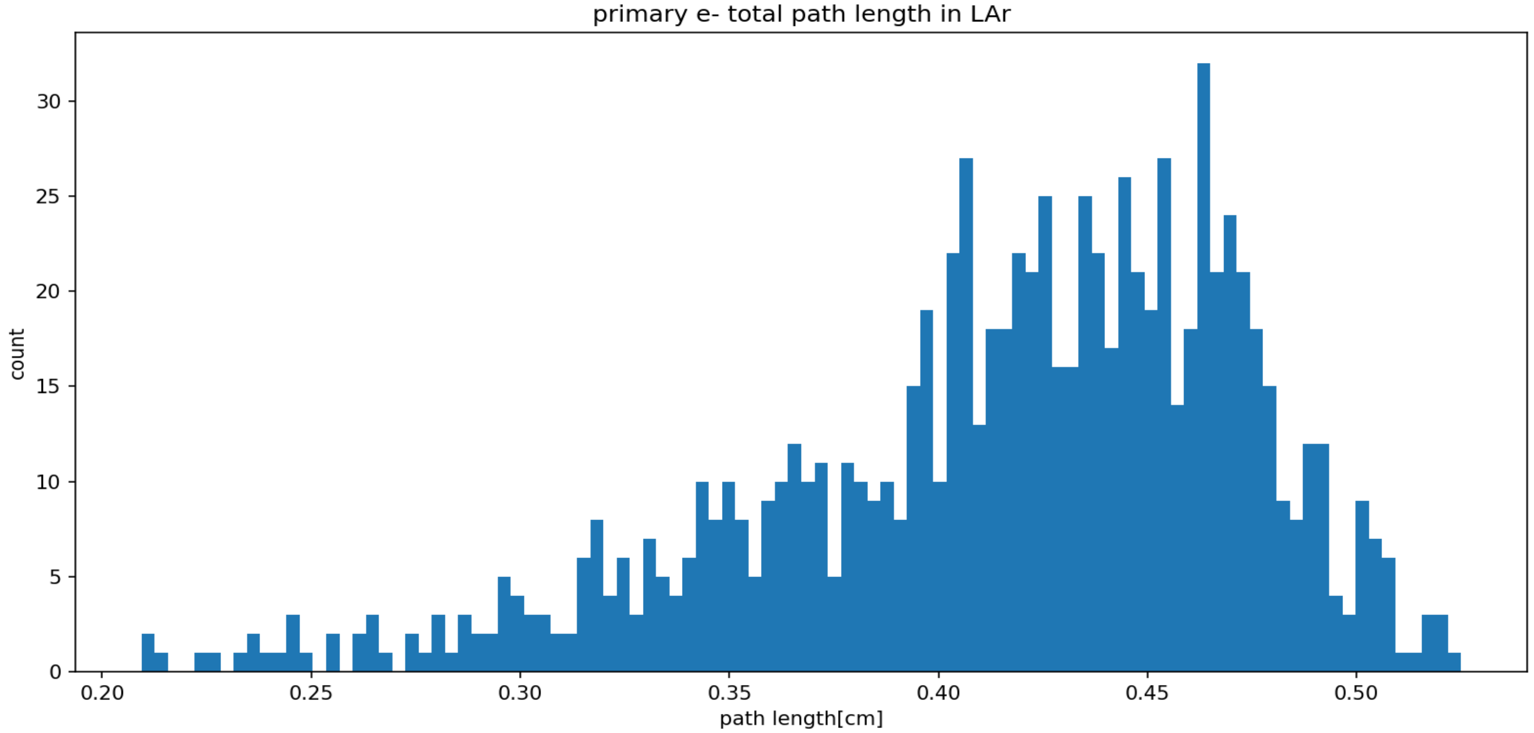
When setting the SCINTILLATIONYIELD of a material in geant4, geant takes into account the birks constant when calculating how many scintillation photons to produce in an event, even for electrons. This means you will see fewer scintillation photons than your input parameter.

Even if you set birks constant = 0, the physics package overrides and sets the LAr birks constant = 0.032 mm/MeV
This tracks according to the data we gathered – using the average path length of the primary electron in the detector(with $E_{k_i} = 1MeV$), we can calculate the light yield attenuation assuming birks constant = 0.032 using:

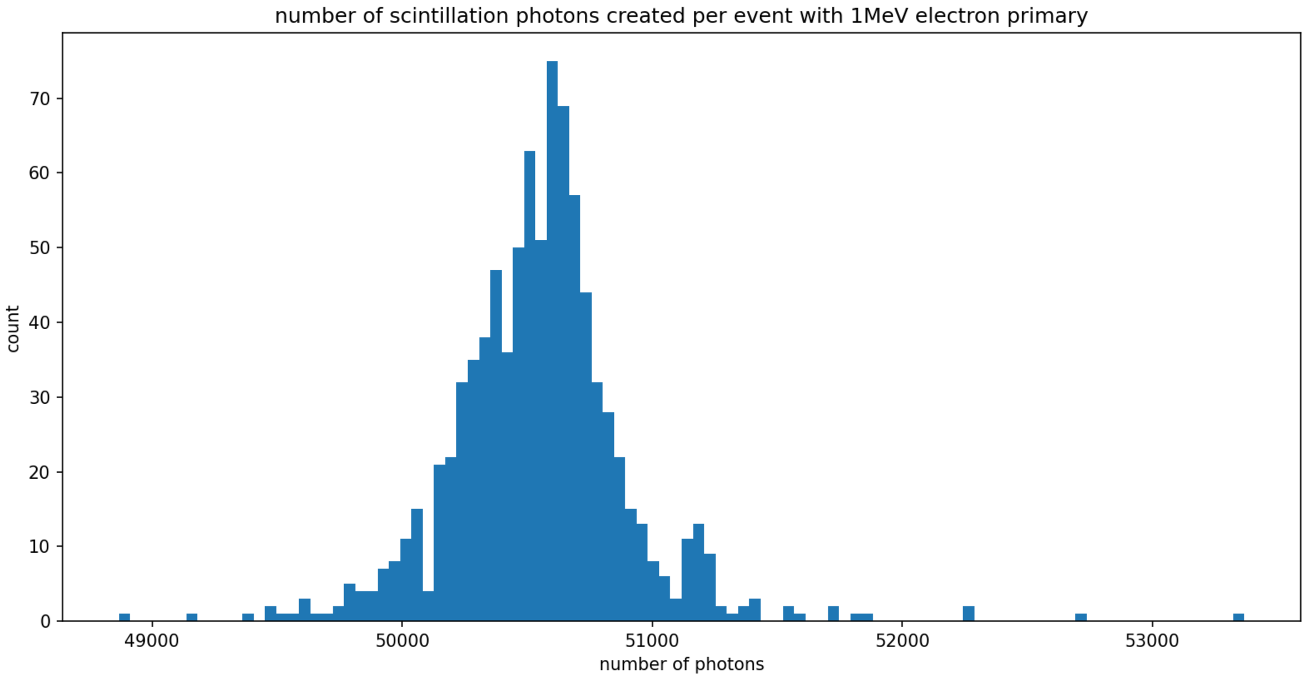
$$attenuation = \frac{1}{1+0.032 \cdot avg.path\ length} = 1.007 - 1.009$$

if you can the amount of scintillation photons per event, you can deduce the attention of the light yield by $\frac{51000}{num\ of\ scint\ photons}$

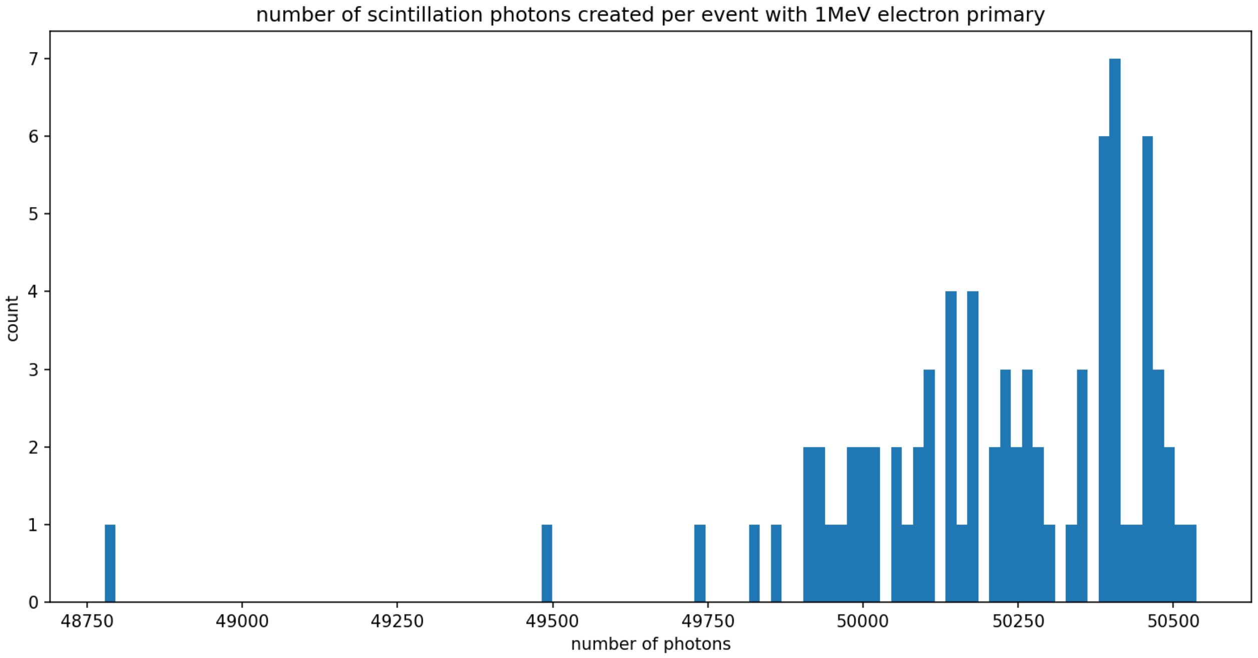
This comes out to be around 1.012 when checking each photon individually by its track and 1.008 using the process vector->GetNumPhotons method.



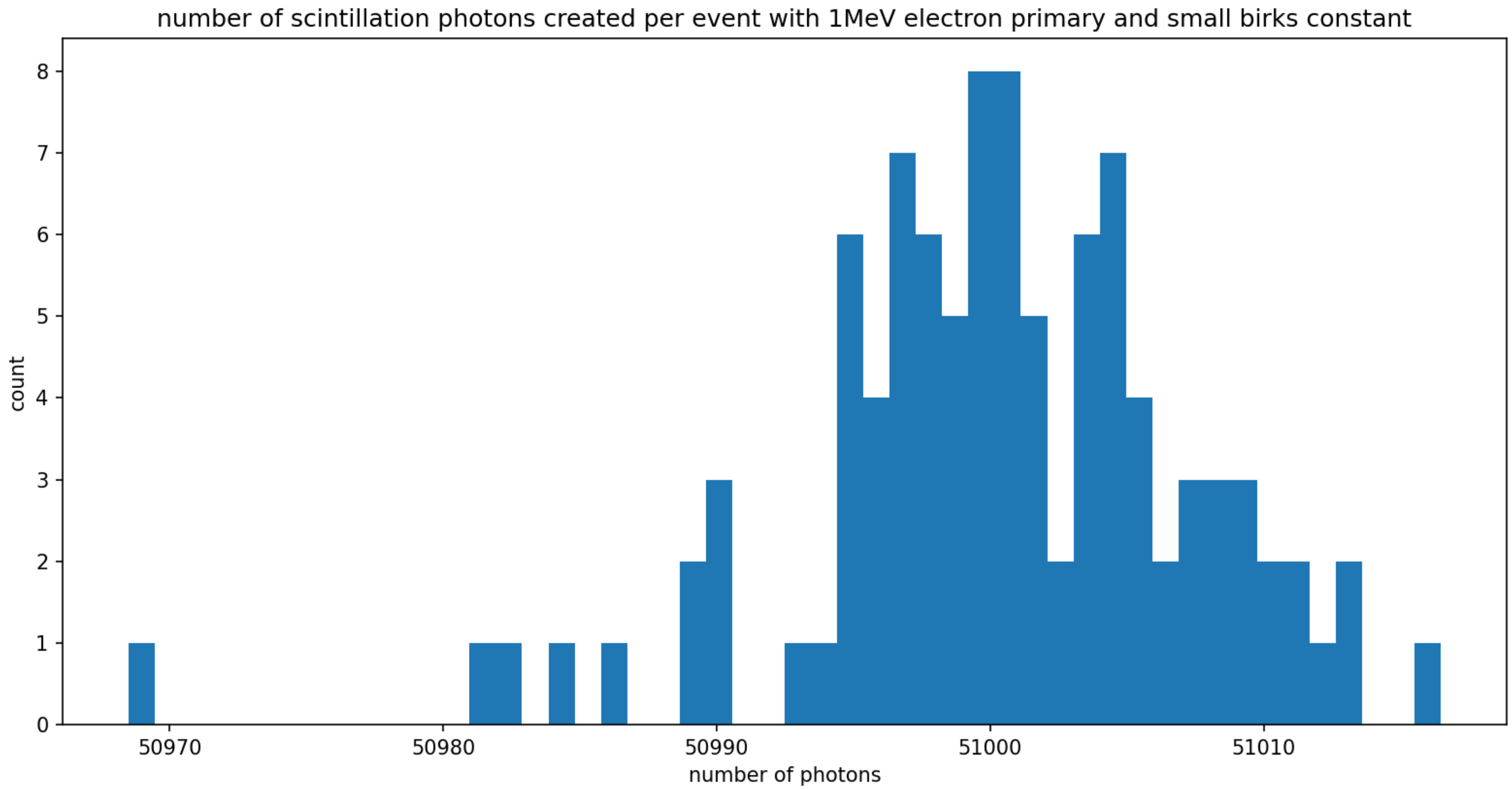
Using processVector->getNumPhotons



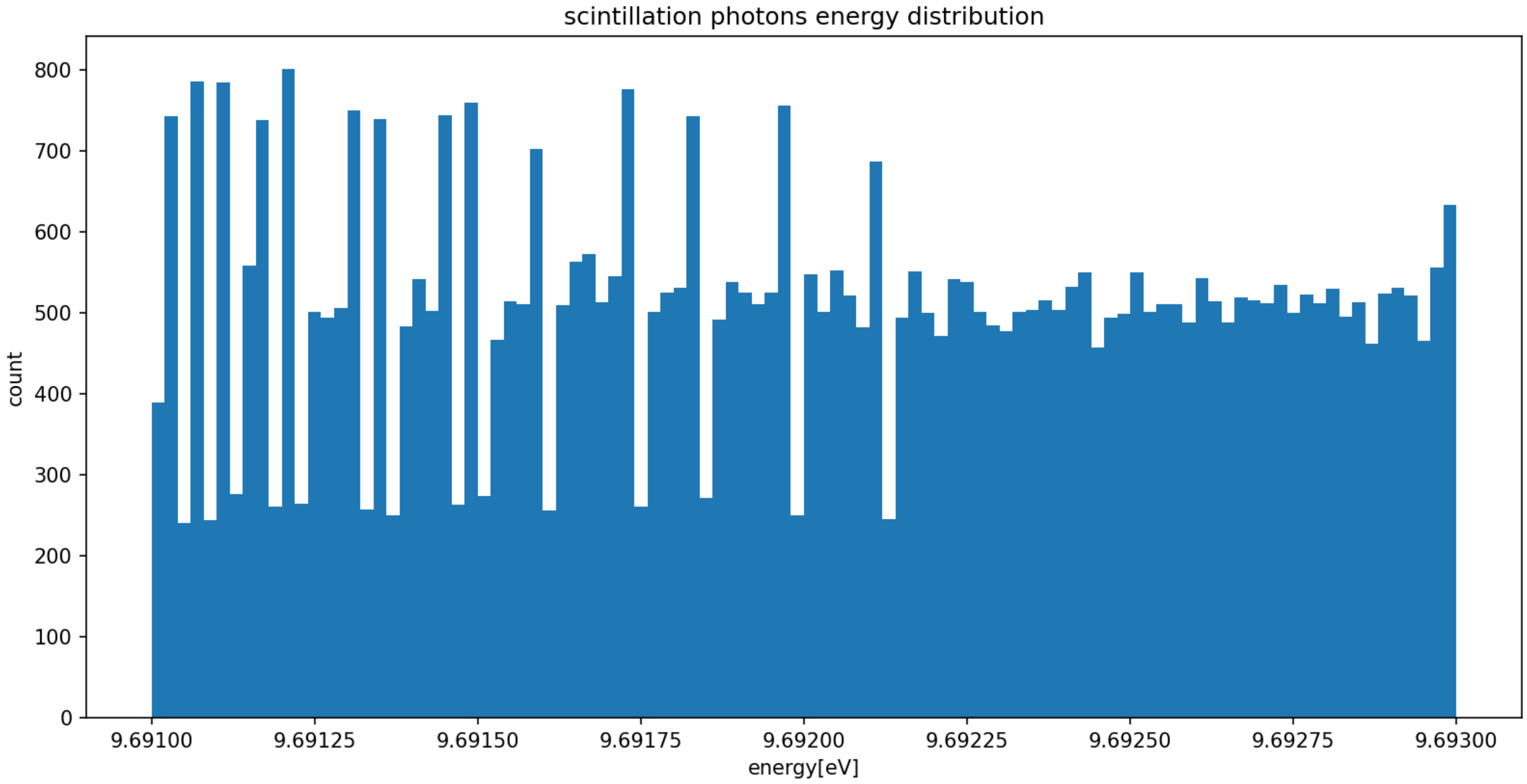
Checking each track individually



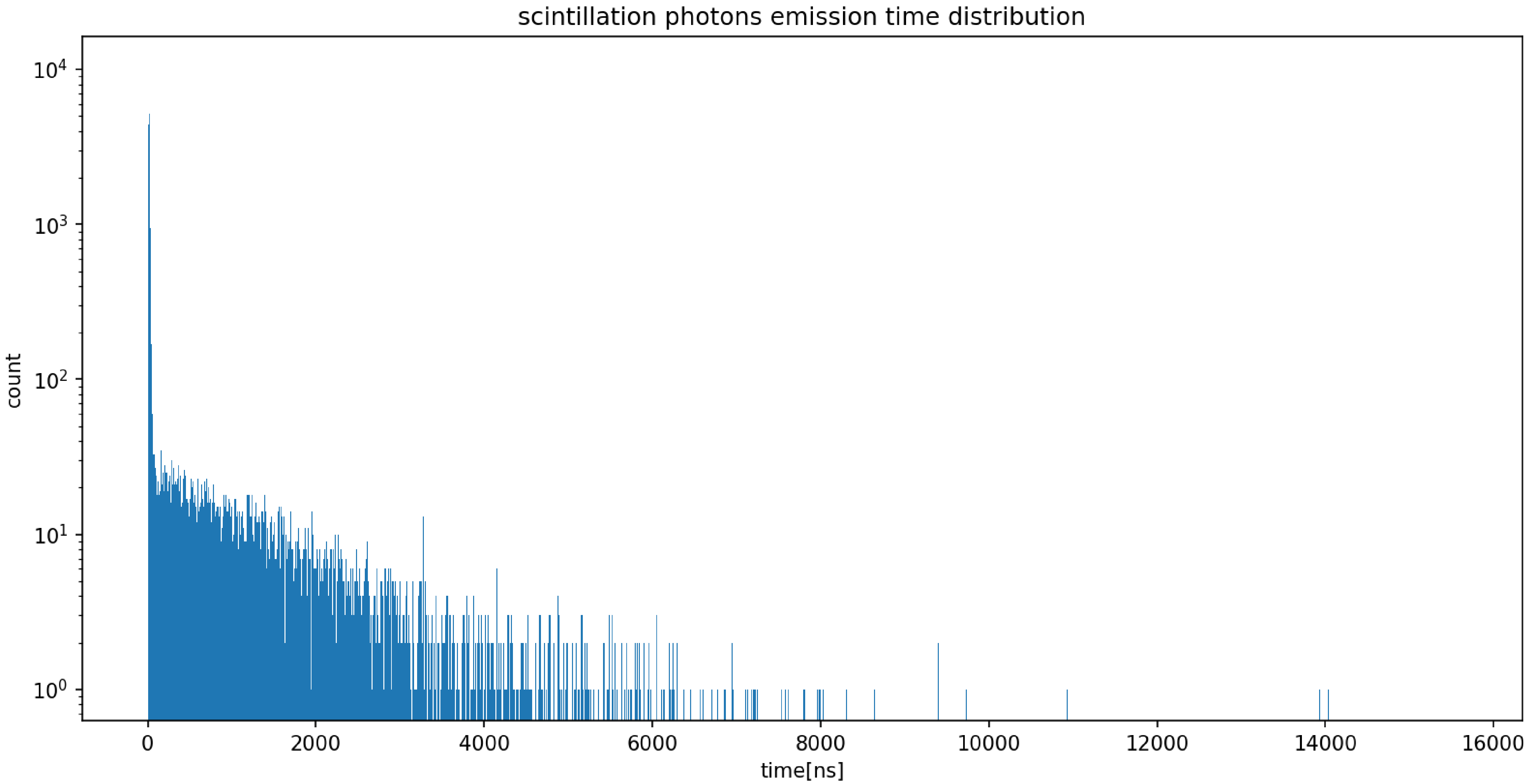
Finally, when setting birks constant to a really small number, but not 0, so that the physics package does not override it, you see a distribution centered around 51000 photons per event as expected:

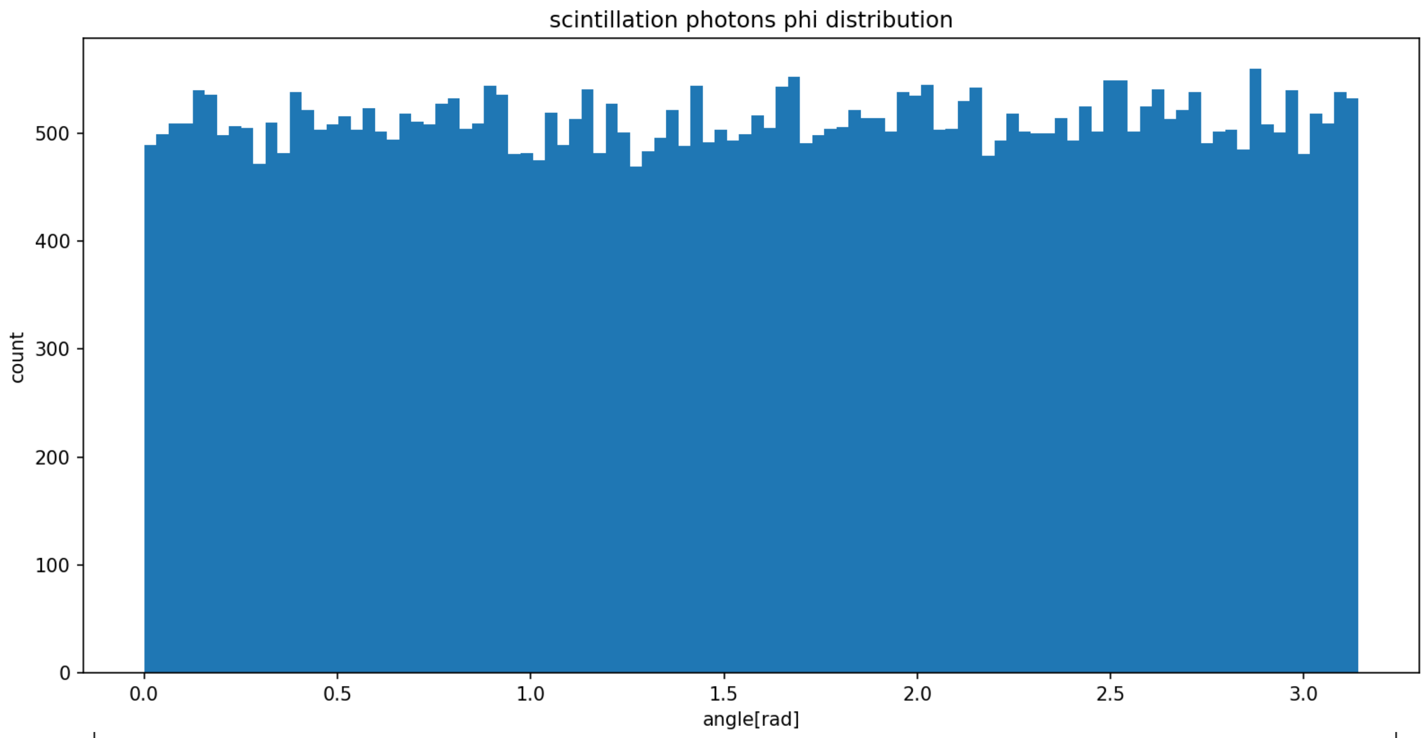


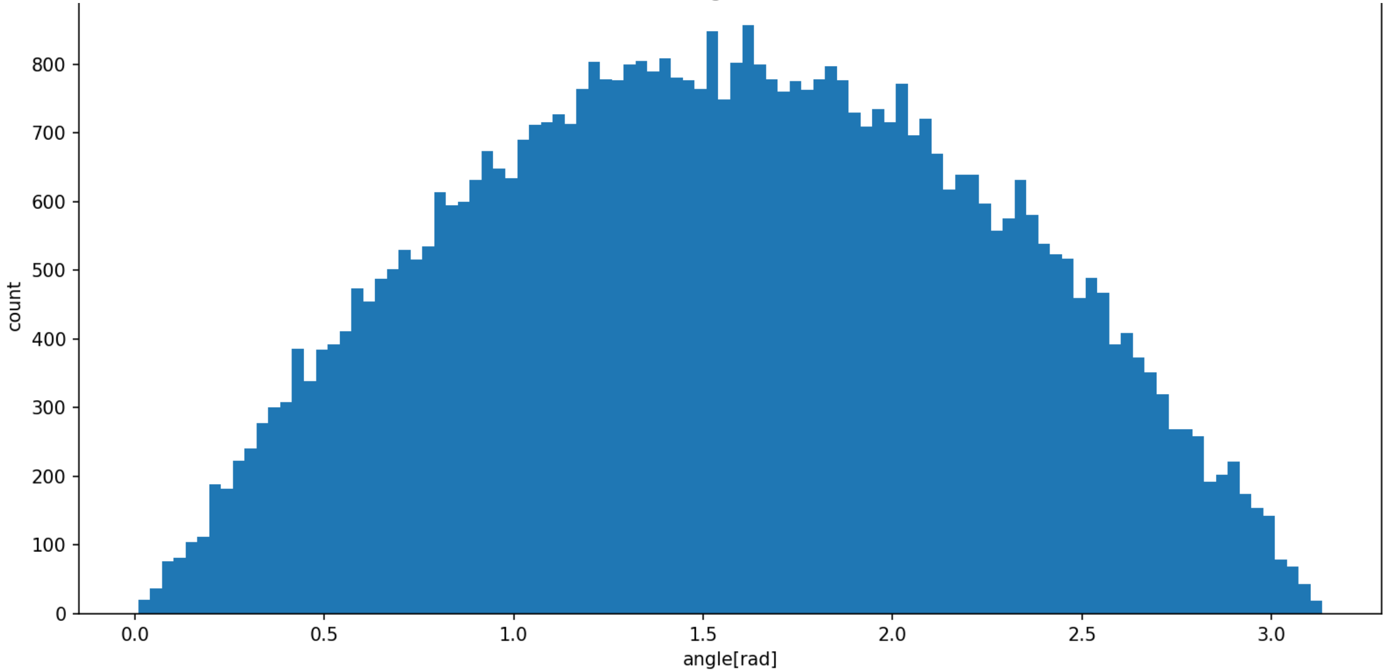
Moving on, we want to perform extra sanity checks. We start by firing a 1 MeV electron directly in the center of our LAr cylinder.
Firstly, the emitted scintillation photons' wavelength – this distribution matches the parameters we set – centered around 128nm wavelength for the emission spectra.



Next, looking at the emission timing of the scintillation photons, with fast component set to 7ns and slow component set to 1500ns:

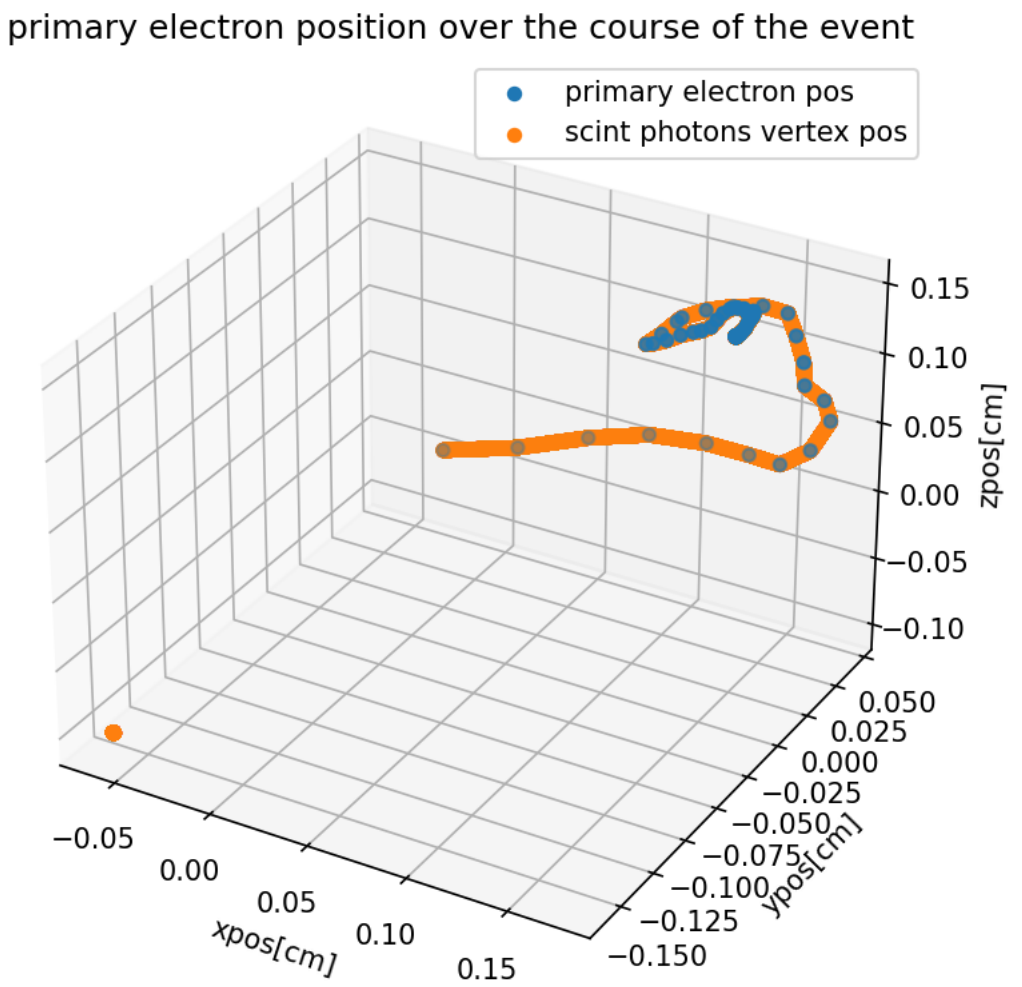






Next, the scintillation photons' angular distribution, separated to spherical angles θ and ϕ.

And finally, looking at the positions in which the scintillation photons were created and seeing they roughly match the track of the primary electron:

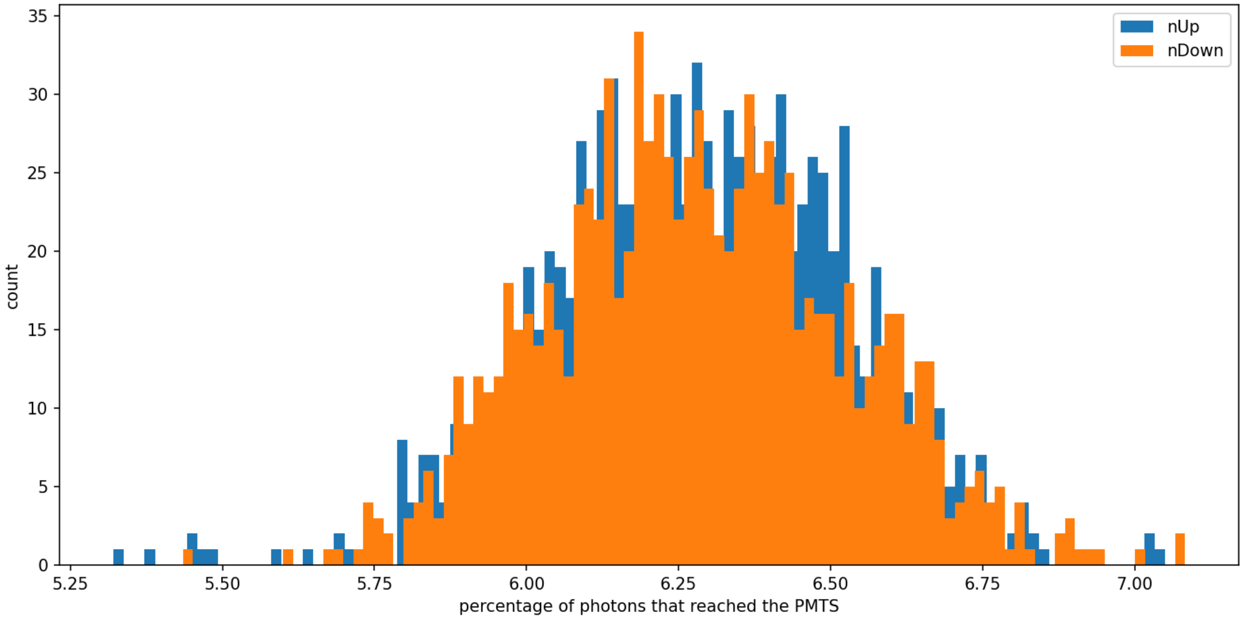


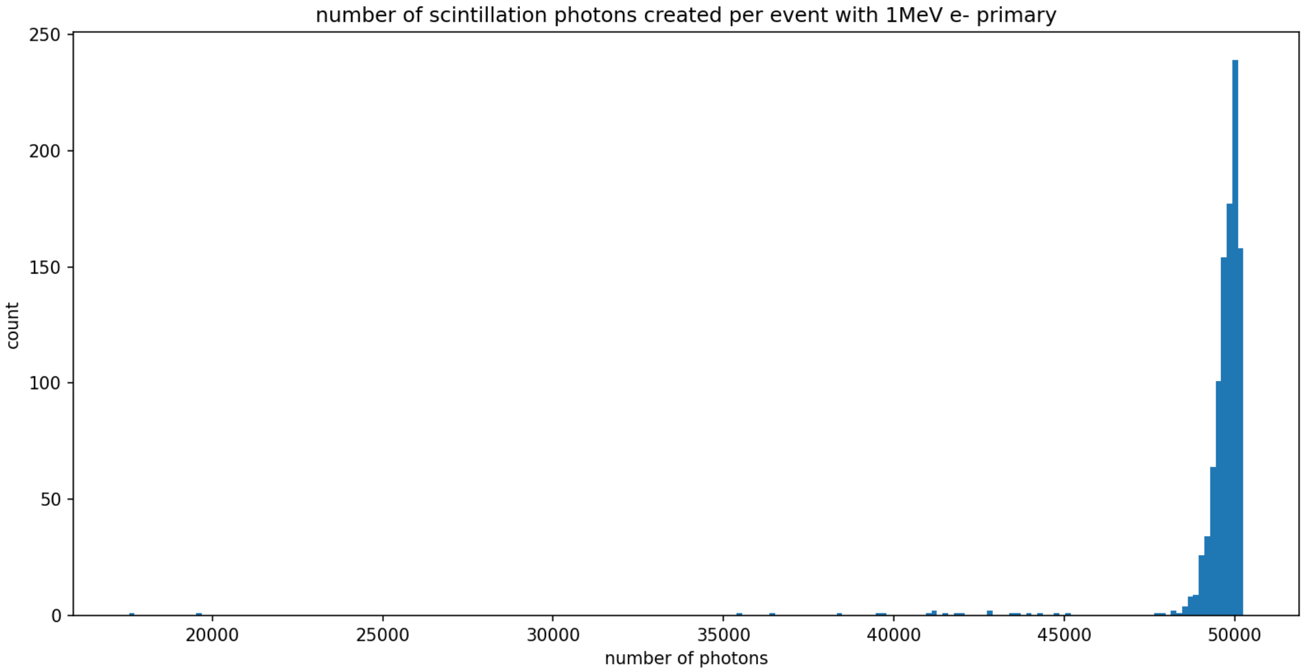
Now we can safely move on to try and fully recreate the findings of Creus et al.

We first try to emulate PMTS and coincidence between them in the following way – we ask how many photons reached each base of the LAr cylinder (in their research there are 2 PMTS surrounding each base), and in order to take into account the QE of the TPB and PMT we roll a random number in a uniform distribution in the range (0,1) and if it is < 0.25 we say the photon was absorbed inside the pmt.

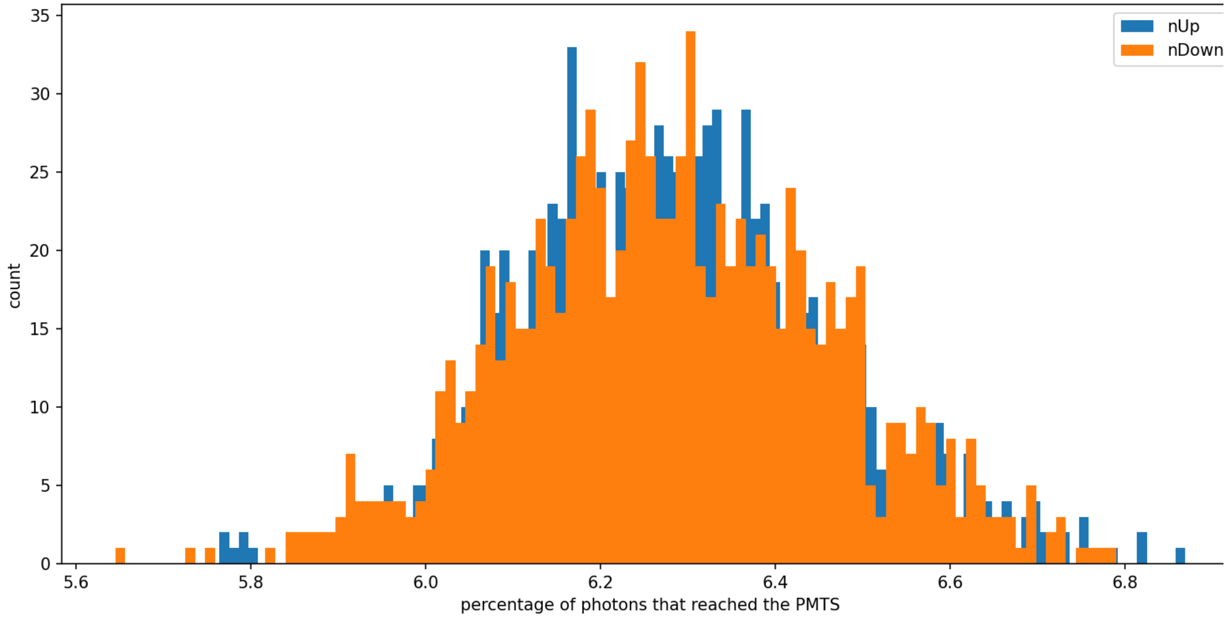
In order to ask if there was coincidence between the PMTs, we look at the time difference of photons reaching the top PMT and the bottom PMT, and if in an event we get a time difference that is smaller than $\frac{c}{n*h}$ (where c is the speed of light, n is the refractive index of LAr , and h is the height of the cylinder), we say that there is coincidence in the event.

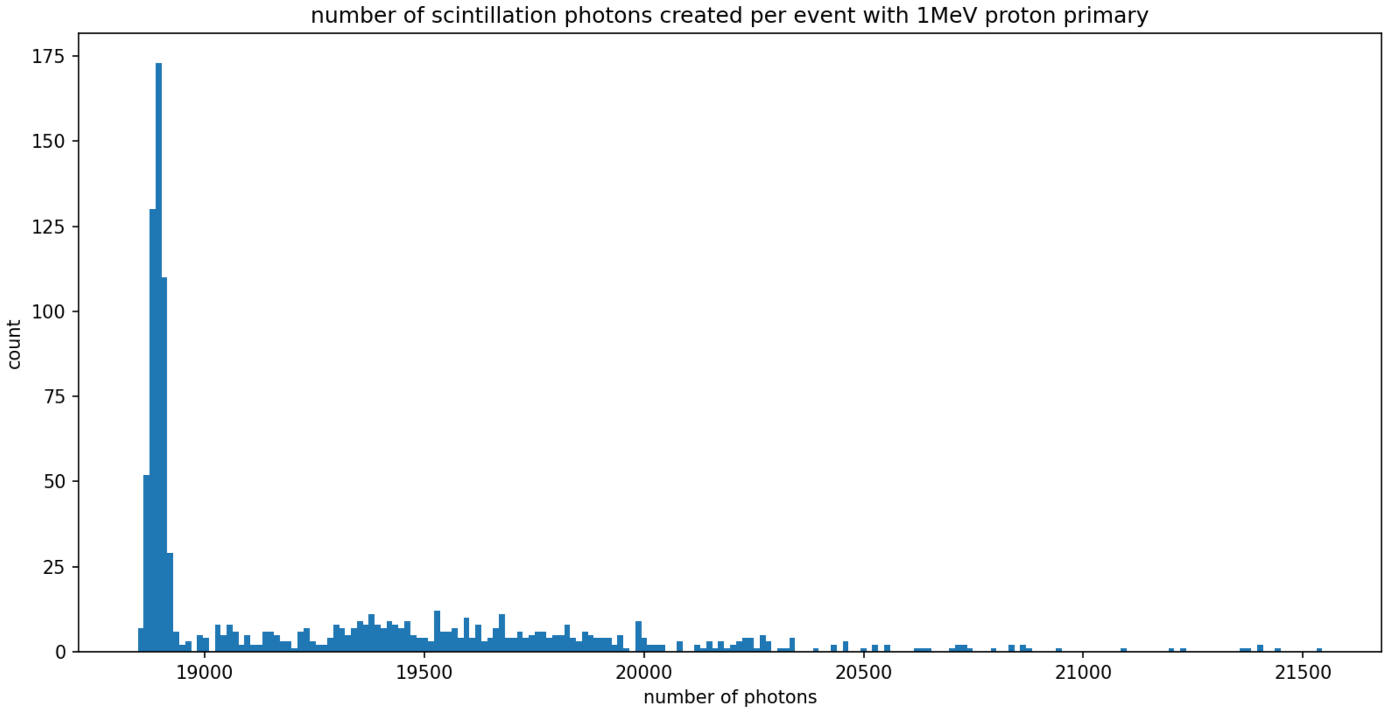
The following plots are for a primary electron:





The following plots are for a primary proton:





The rest of the plots are pretty similar to the electron plots. The main difference is in the positions in which the scintillation photons are created – a proton primary deposits most of its energy over a very short distance relative to the electron, and so all scintillation photons are created very close to the center of the LAr cylinder (that is also the reason the scintillation yield is smaller for a proton relative to an electron)