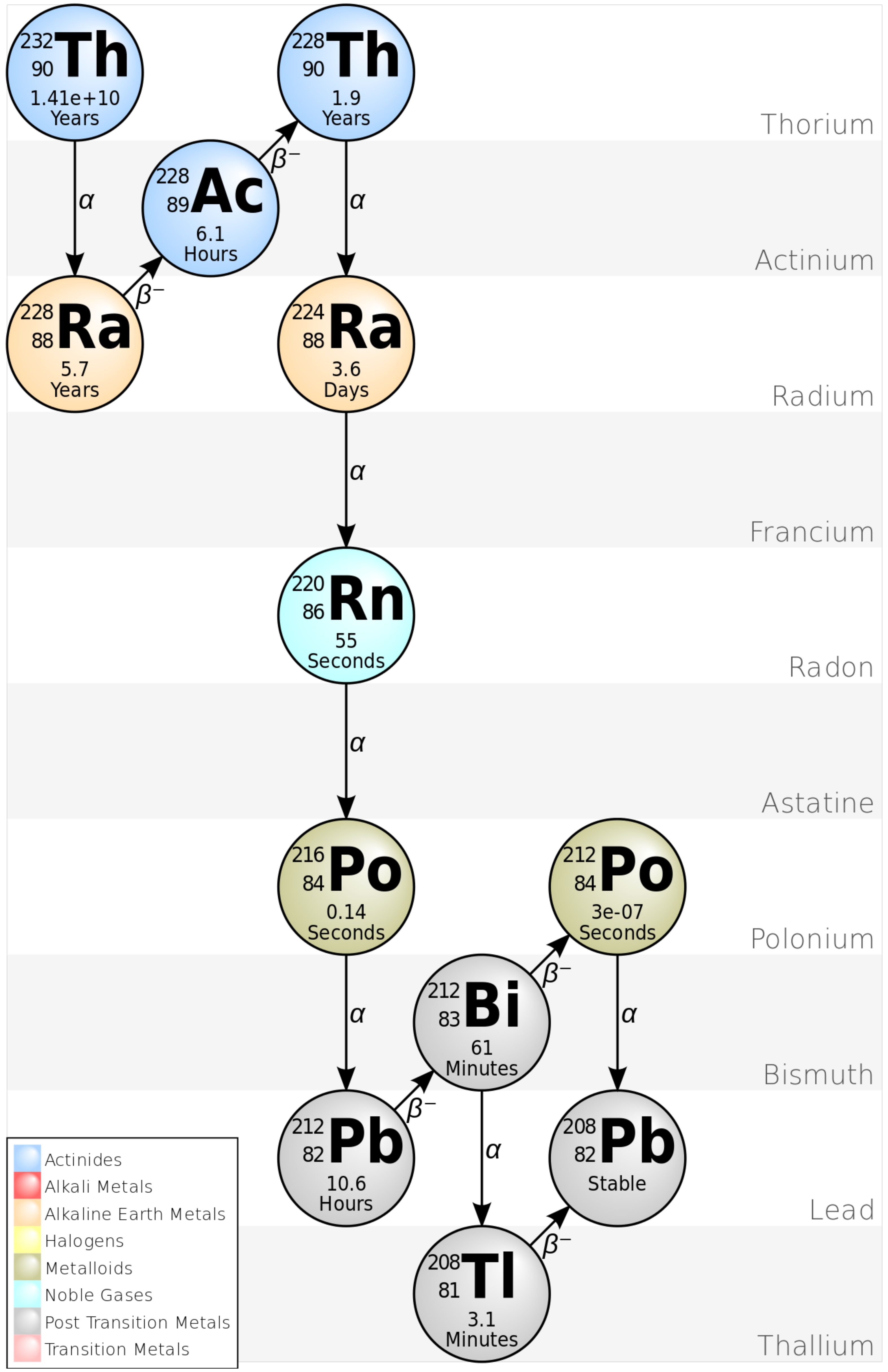
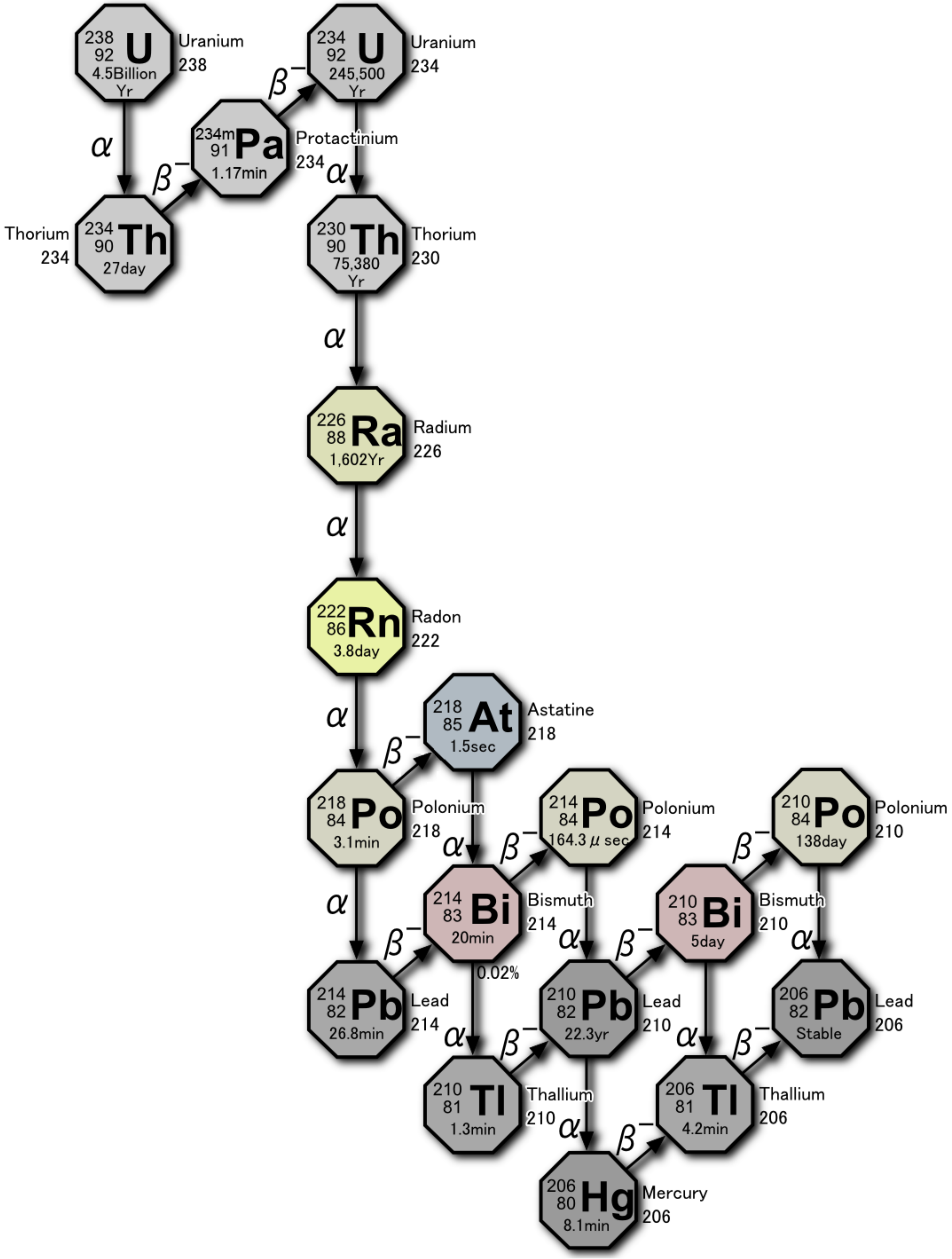
Study of Delayed Coincidences Events

NvDEx-CUPID-China collaboration group 2023 annual meeting

Shihong Fu, 17 Dicembre, 2023

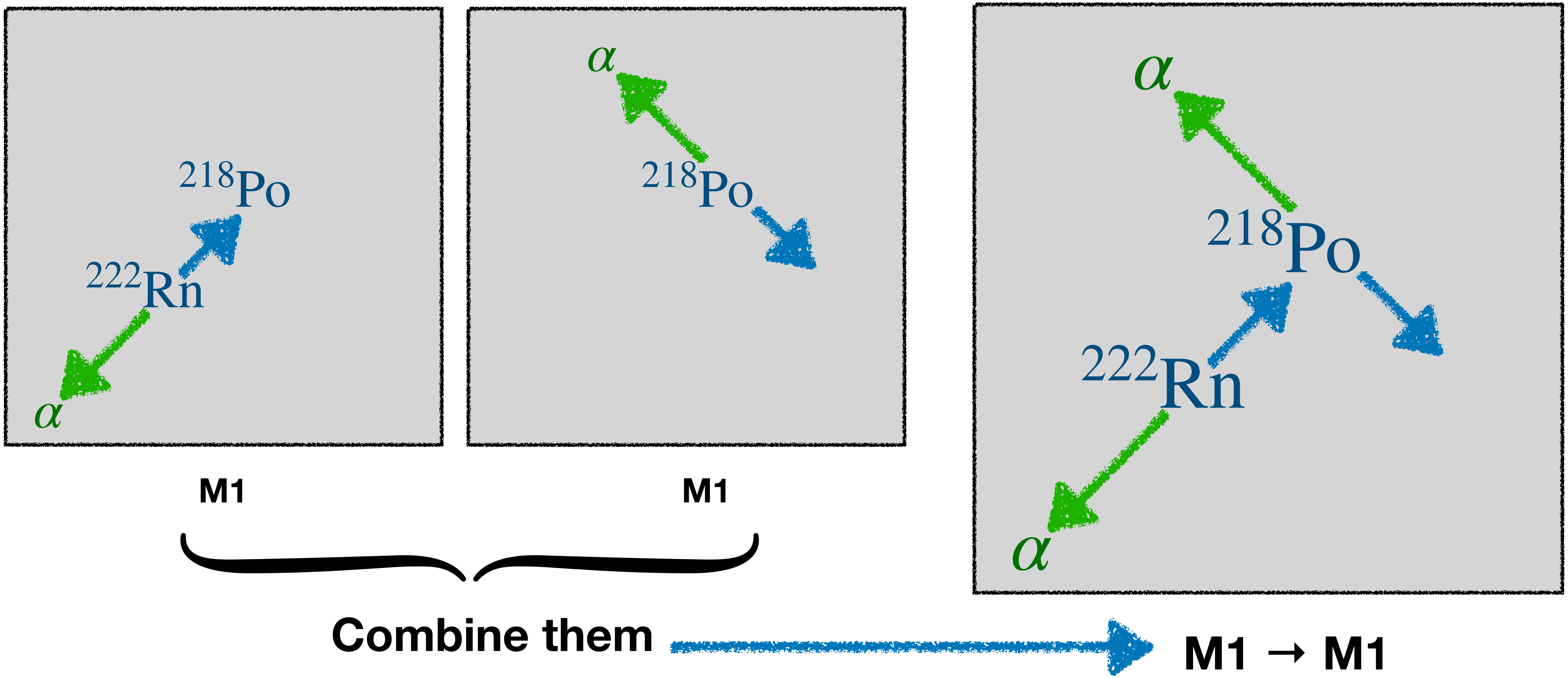
Motivation


232 90 Th 1.41e+10 Years
228 90 Th 1.9 Years
228 89 Ac 6.1 Hours
228 88 Ra 5.7 Years
224 88 Ra 3.6 Days
220 86 Rn 55 Seconds
216 84 Po 0.14 Seconds
212 84 Po 3e-07 Seconds
212 83 Bi 61 Minutes
212 82 Pb 10.6 Hours
208 82 Pb Stable
208 81 Tl 3.1 Minutes
Thorium
Actinium
Radium
Francium
Radon
Astatine
Polonium
Bismuth
Lead
Thallium
Actinides
Alkali Metals
Alkaline Earth Metals
Halogens
Metalloids
Noble Gases
Post Transition Metals
Transition Metals

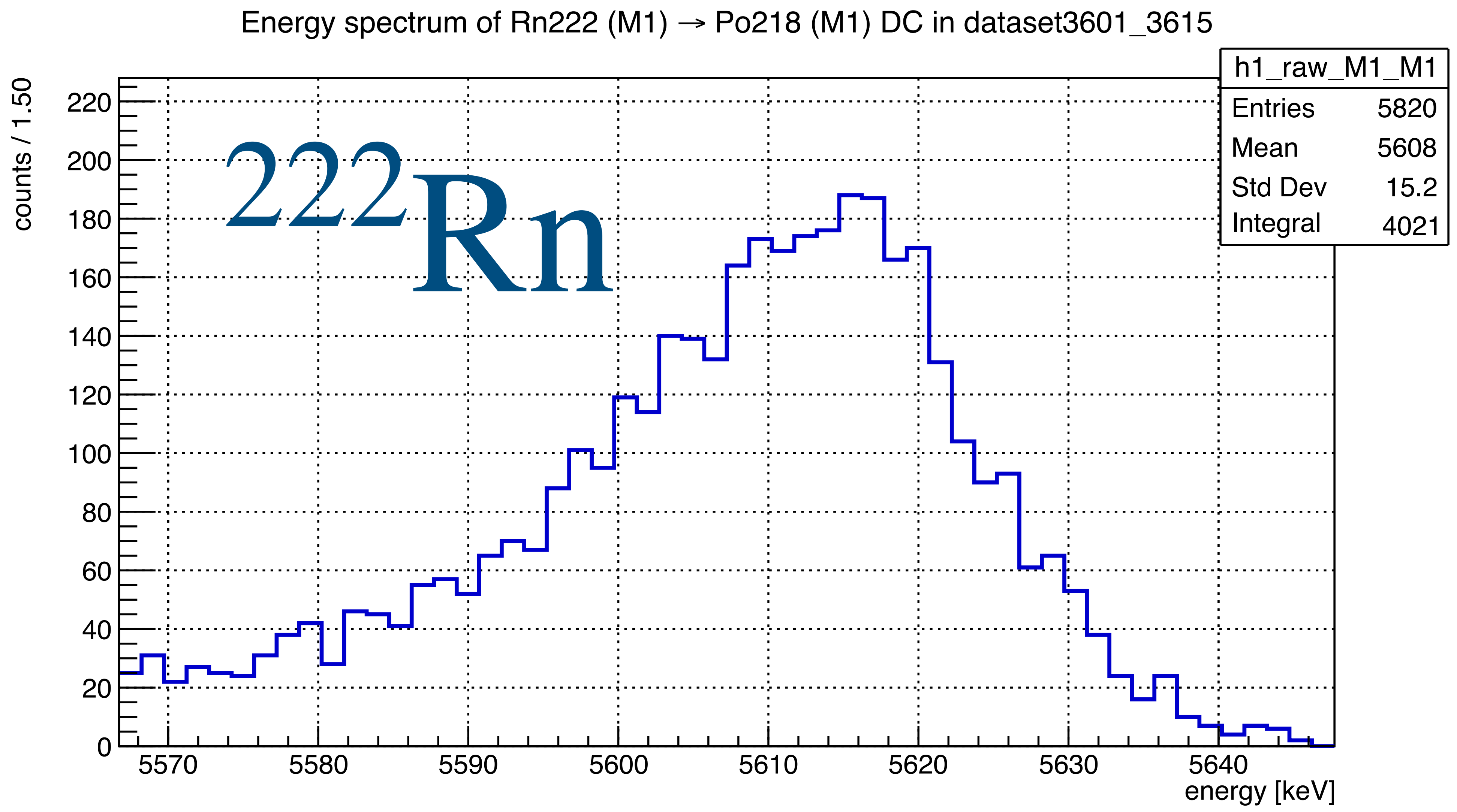

238 92 U 4.5Billion Yr Uranium 238
234 92 U 245,500 Yr Uranium 234
234m 91 Pa 1.17min Protactinium 234
234 90 Th 27day Thorium 234
230 90 Th 75,380 Yr Thorium 230
226 88 Ra 1,602Yr Radium 226
222 86 Rn 3.8day Radon 222
218 85 At 1.5sec Astatine 218
218 84 Po 3.1min Polonium 218
214 84 Po 164.3 μ sec Polonium 214
210 84 Po 138day Polonium 210
214 83 Bi 20min Bismuth 214
210 83 Bi 5day Bismuth 210
0.02%
214 82 Pb 26.8min Lead 214
210 82 Pb 22.3yr Lead 210
206 82 Pb Stable Lead 206
210 81 Tl 1.3min Thallium 210
206 81 Tl 4.2min Thallium 206
206 80 Hg 8.1min Mercury 206

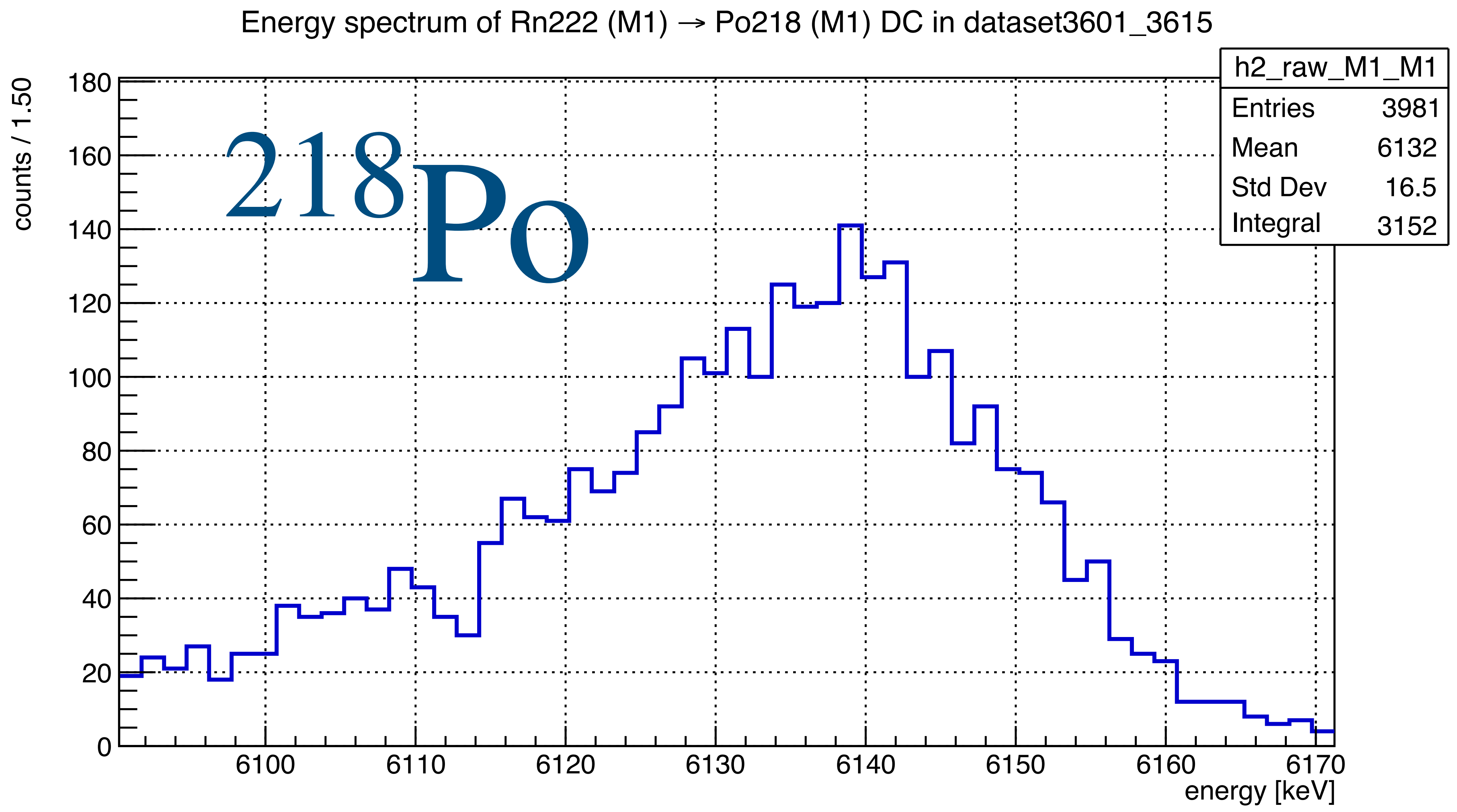
Analysis of $^{222}\mathrm{Rn} \rightarrow {}^{218}\mathrm{Po}$ DC
Case 1 : M1 → M1

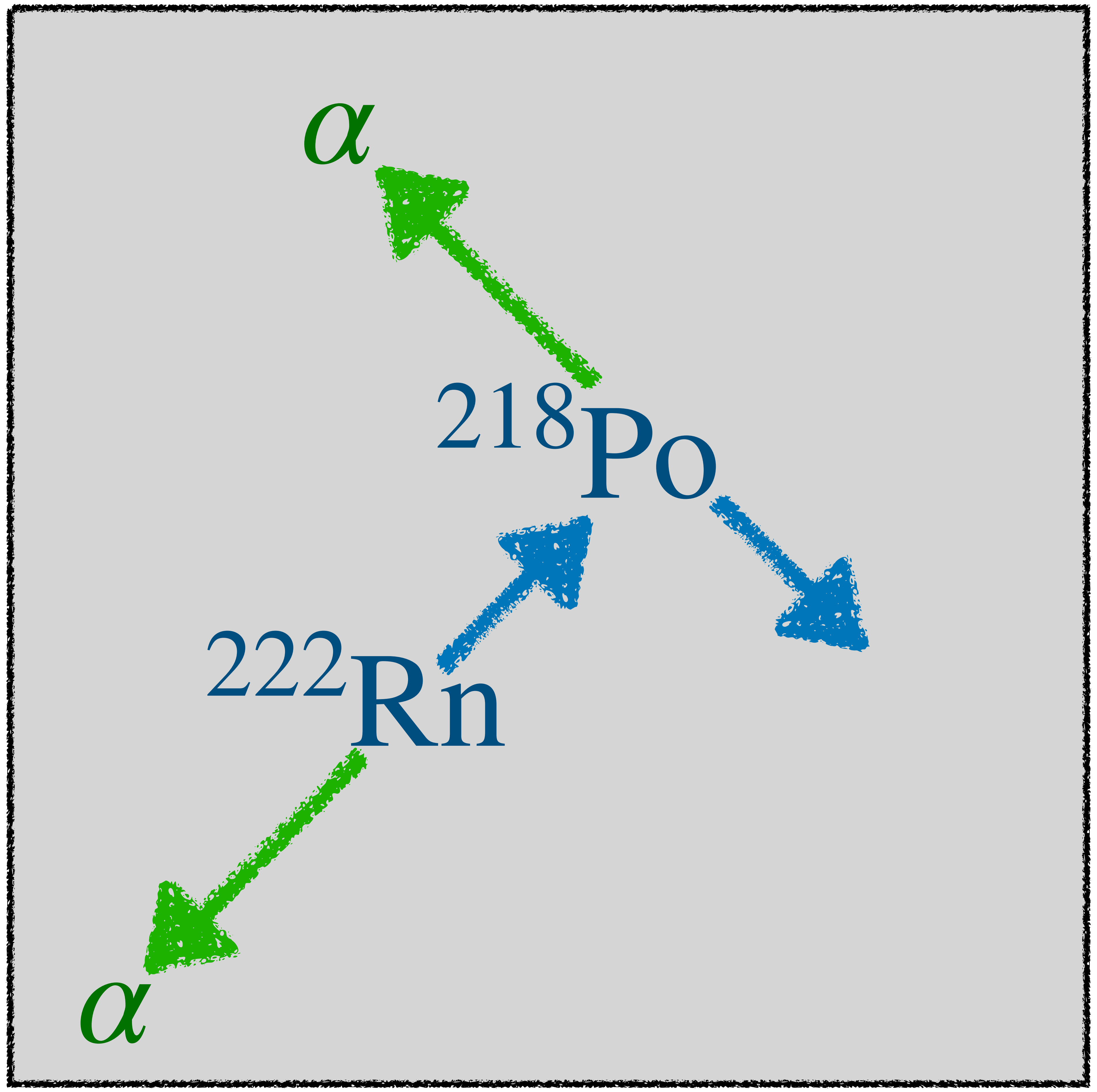
$^{222}Rn \rightarrow {}^{218}Po$ Delayed Coincidence



$^{222}Rn \rightarrow ^{218}Po$ Delayed Coincidence

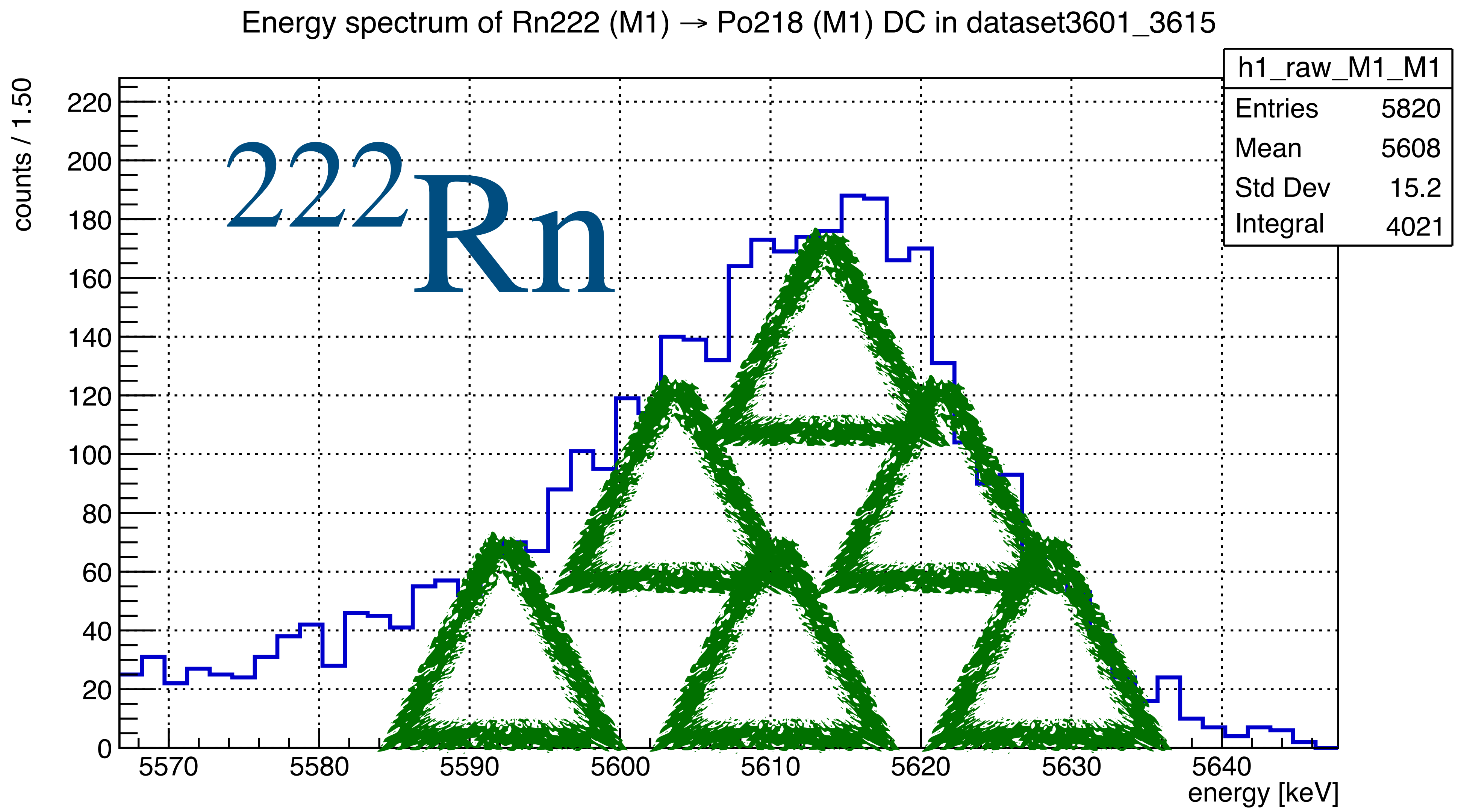


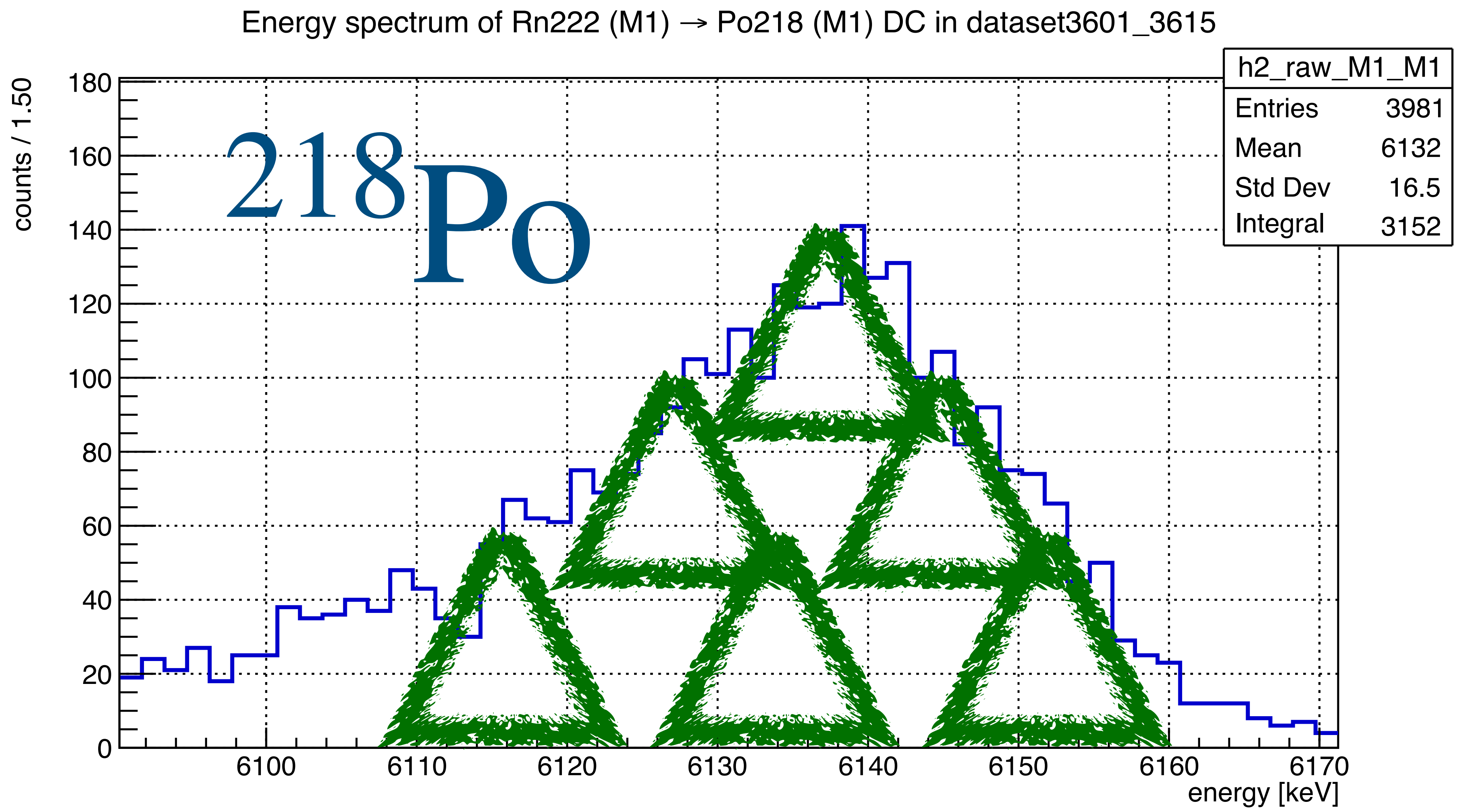


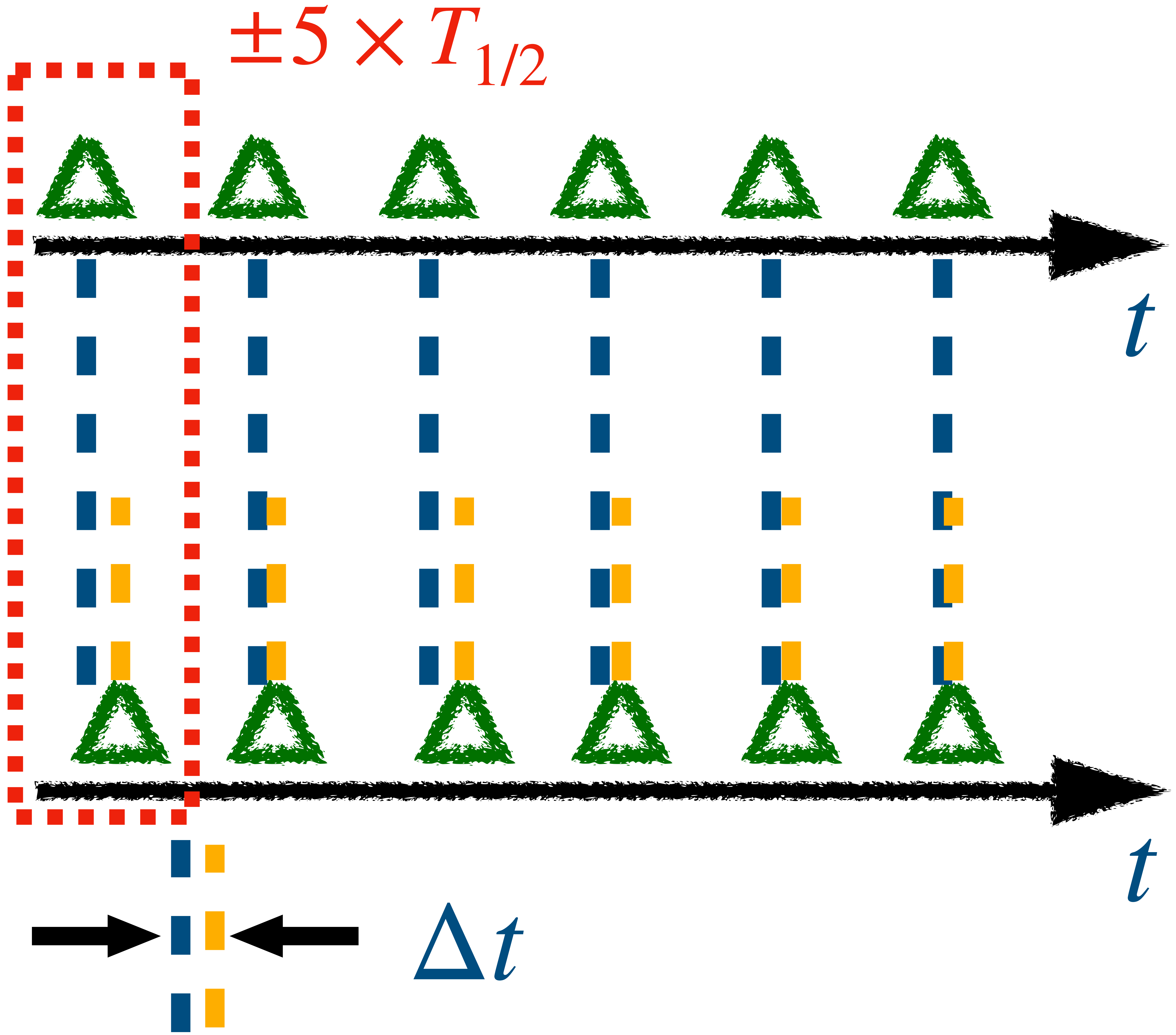


M1 → M1

$^{222}Rn \rightarrow {}^{218}Po$ Delayed Coincidence

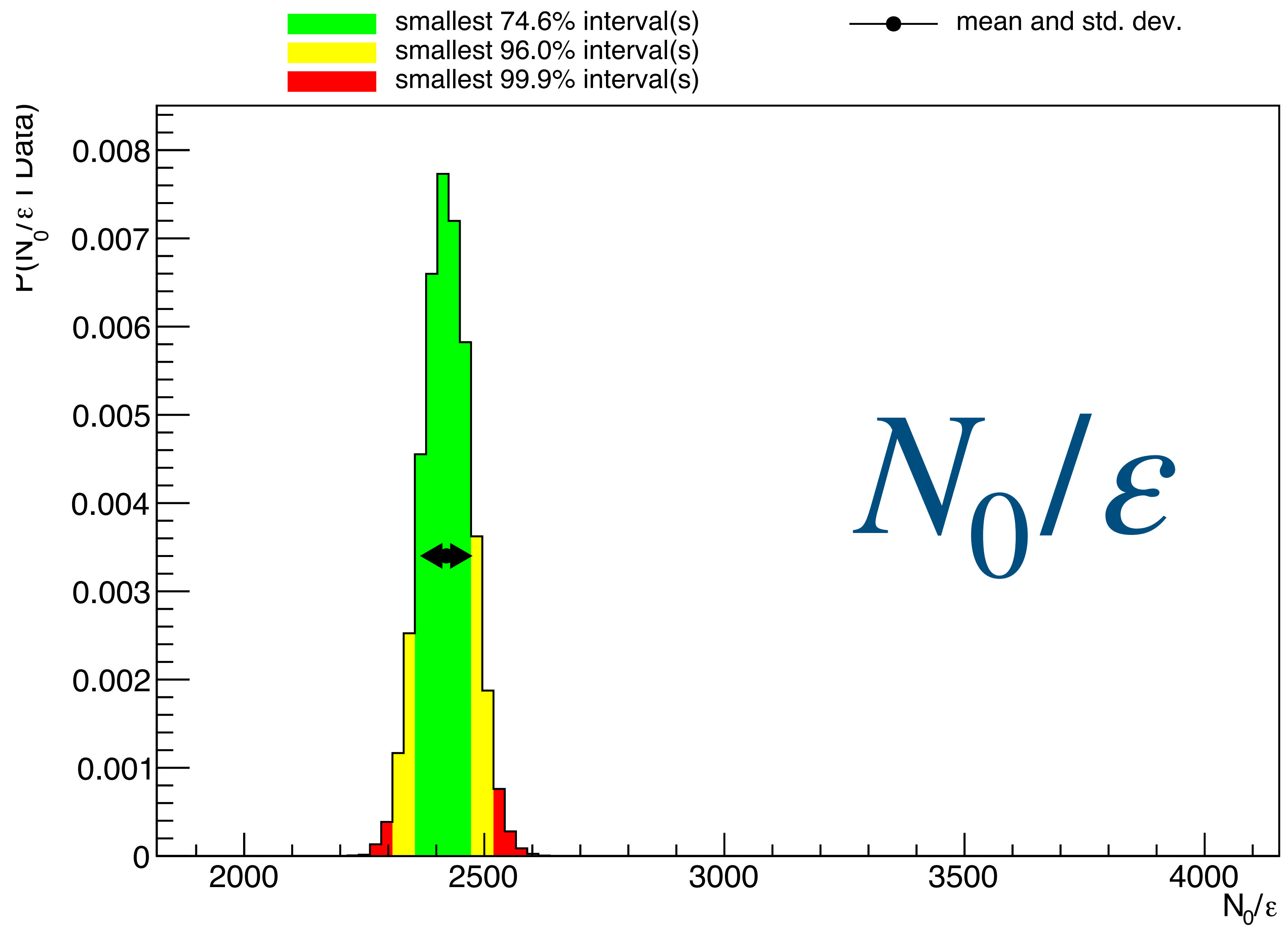


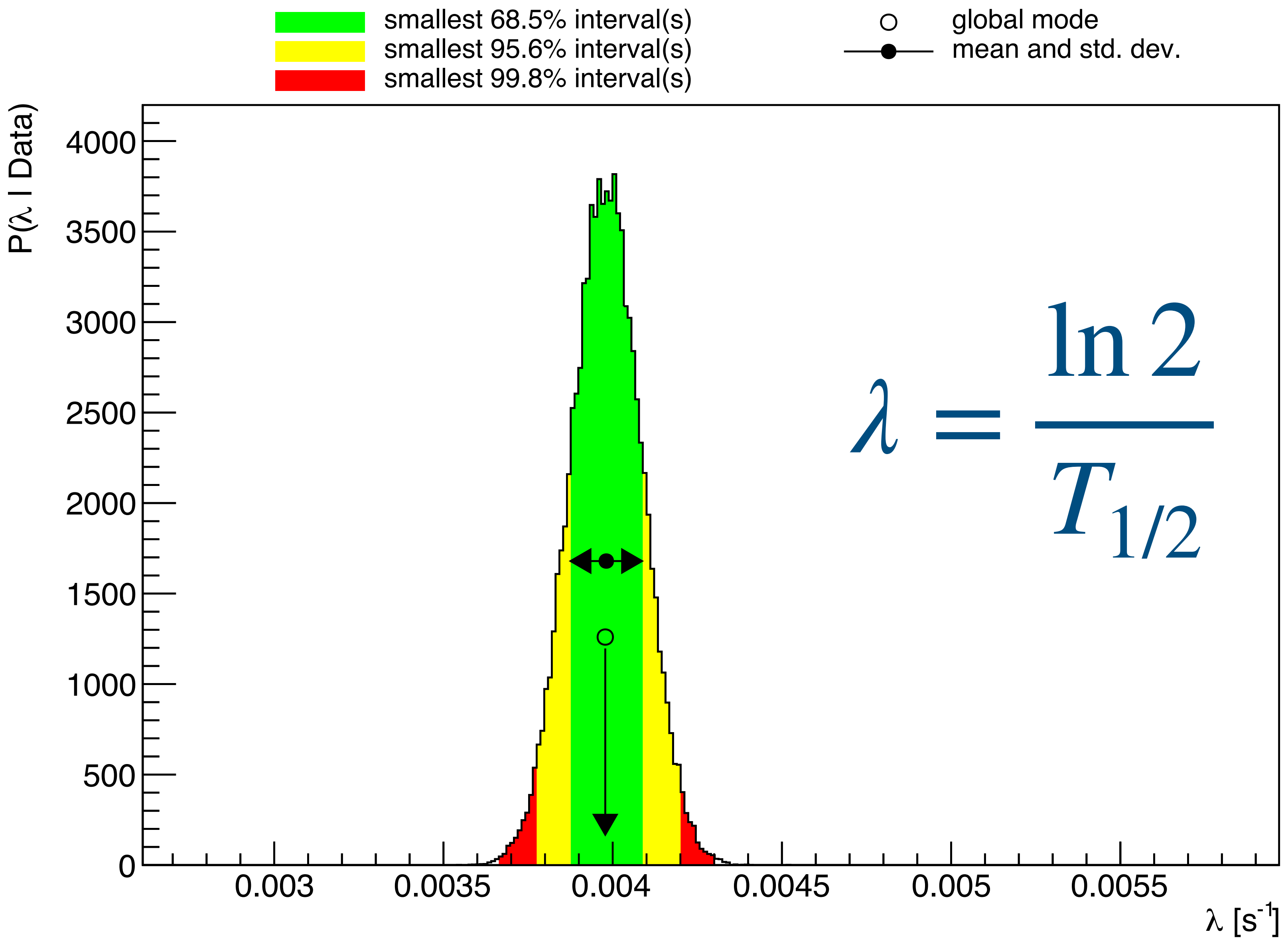


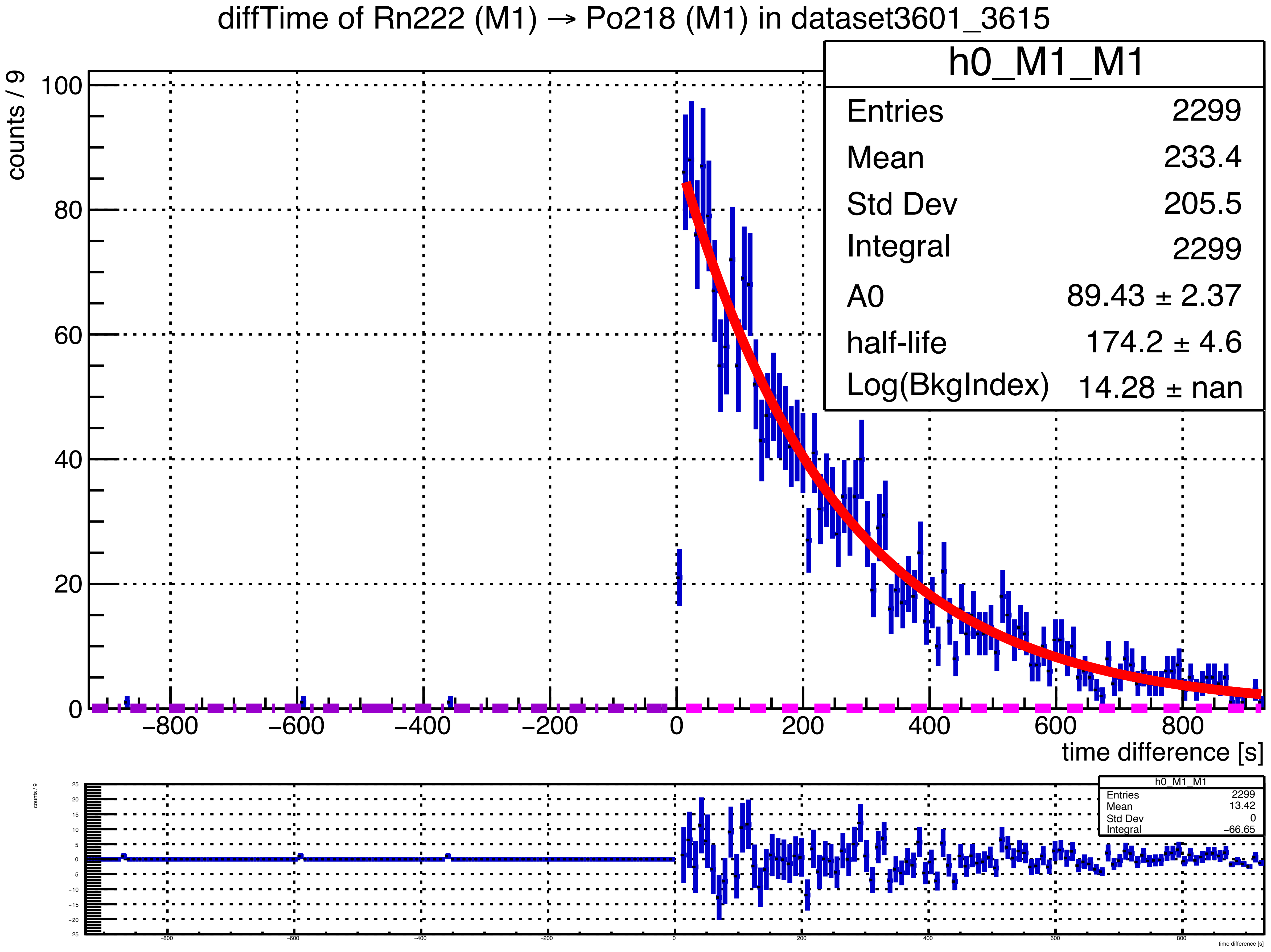


$^{222}Rn \rightarrow {}^{218}Po$

$T_{1/2} = 185.8\ \mathrm{s} \approx 3.1\ \mathrm{min}$





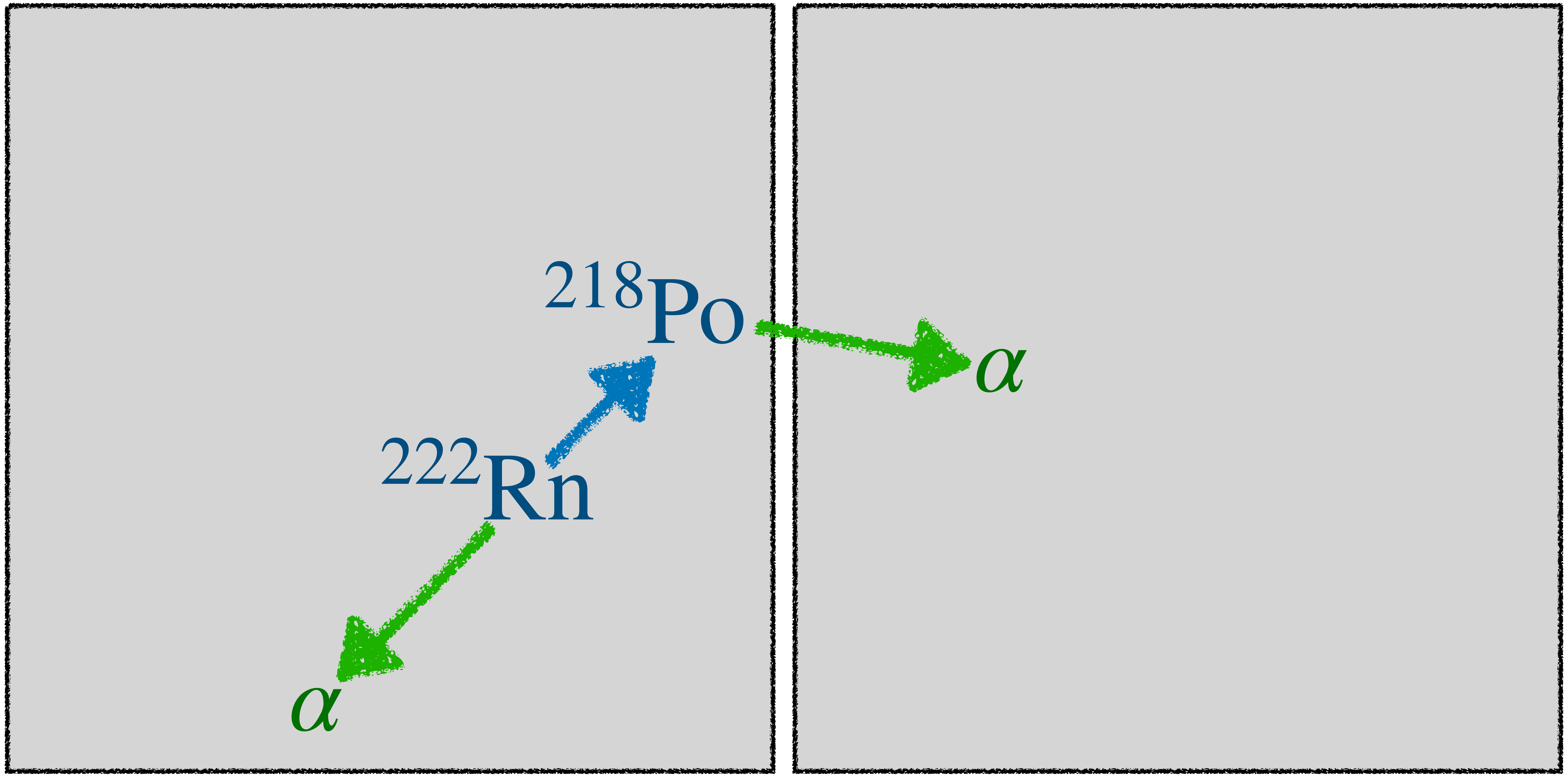


Smallest interval containing 74.6% and local mode:
(2355.5, 2472.4) (local mode at **2414.0** with rel. height 1; rel. area 1)

$$N_0/\varepsilon = 2414.0^{+58.4}_{-58.5} \quad (\varepsilon = 0.999923)$$

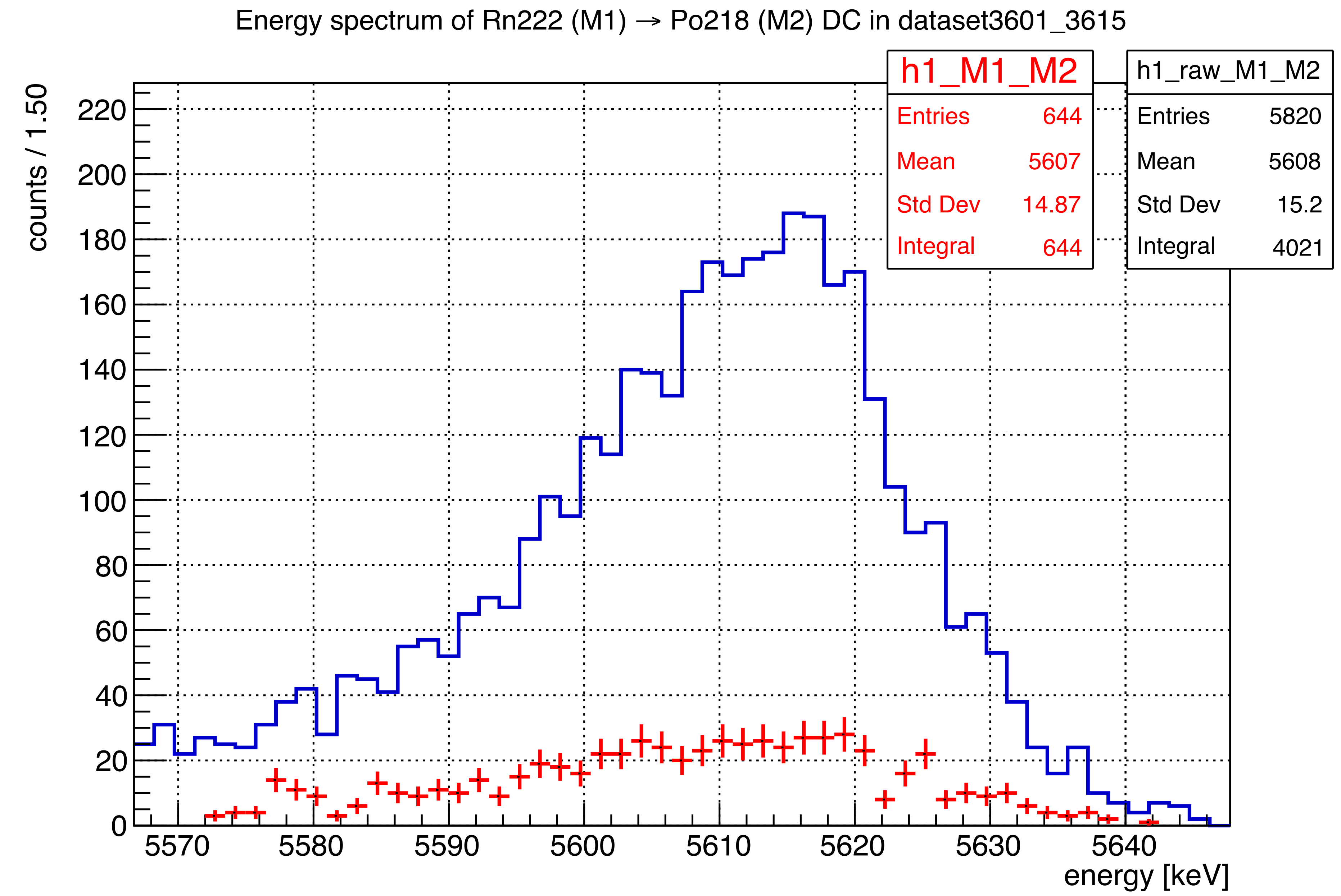
Analysis of $^{222}\mathrm{Rn} \rightarrow {}^{218}\mathrm{Po}$ DC
Case 2 : M1 → M2

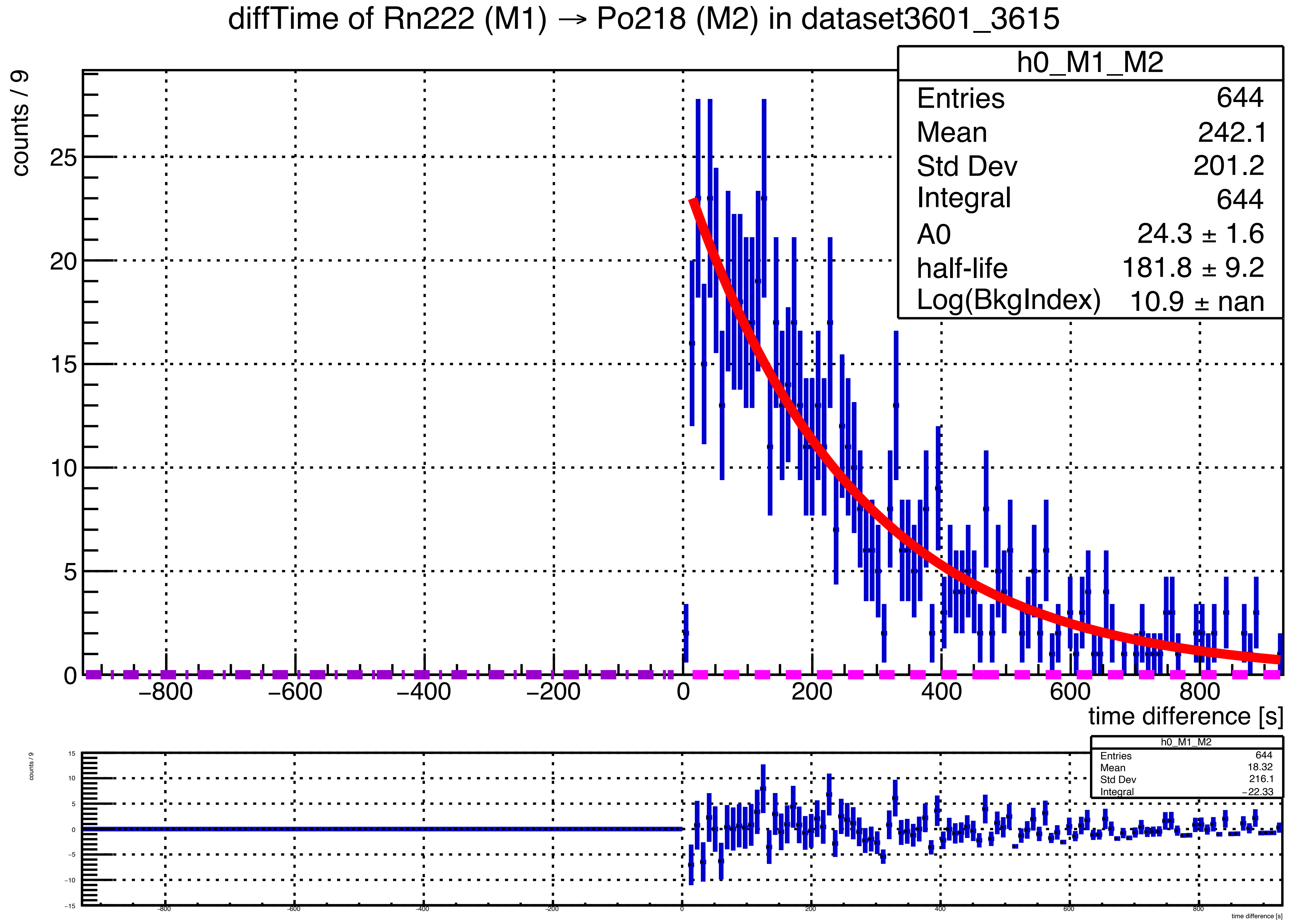
$^{222}Rn \rightarrow {}^{218}Po$ Delayed Coincidence

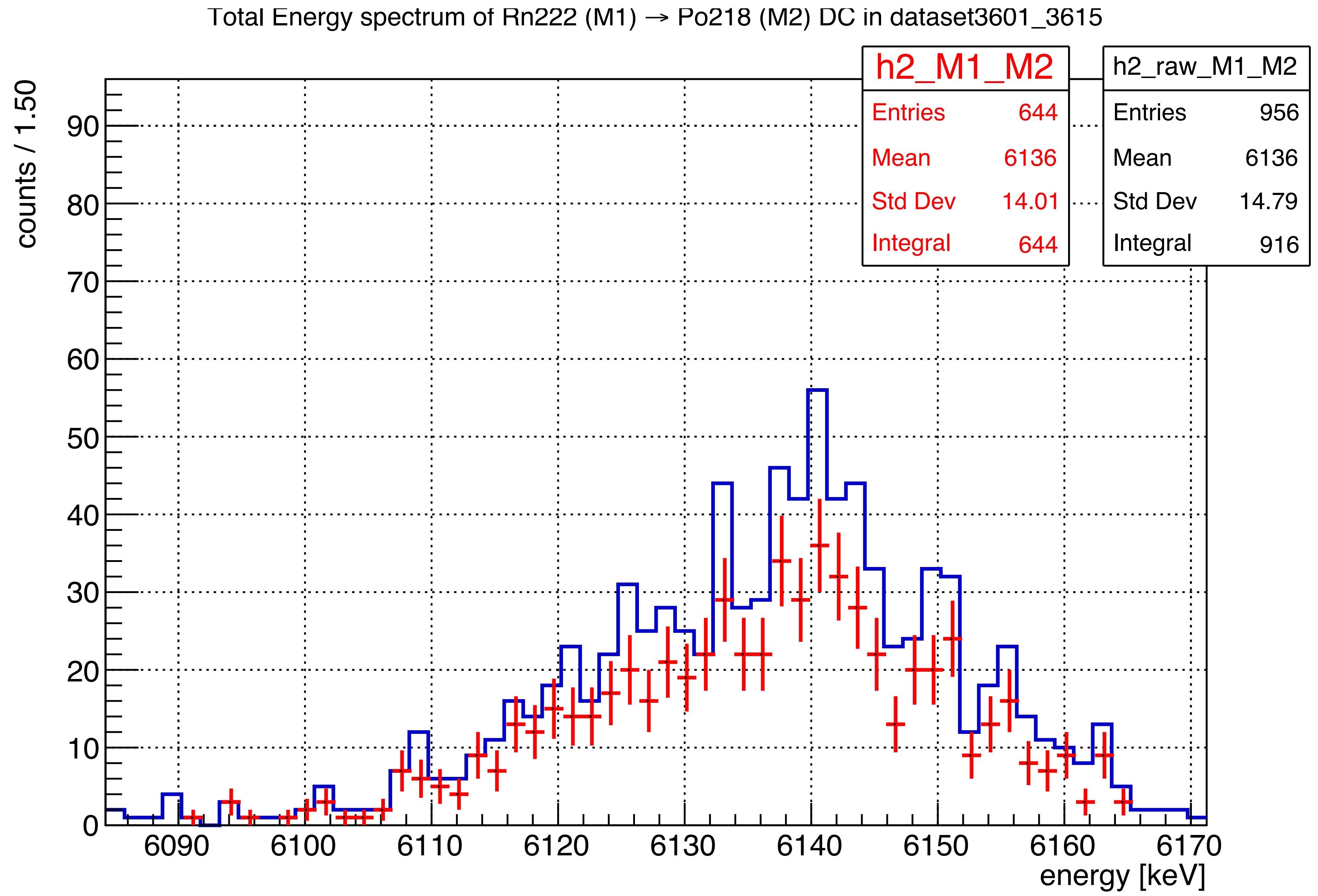


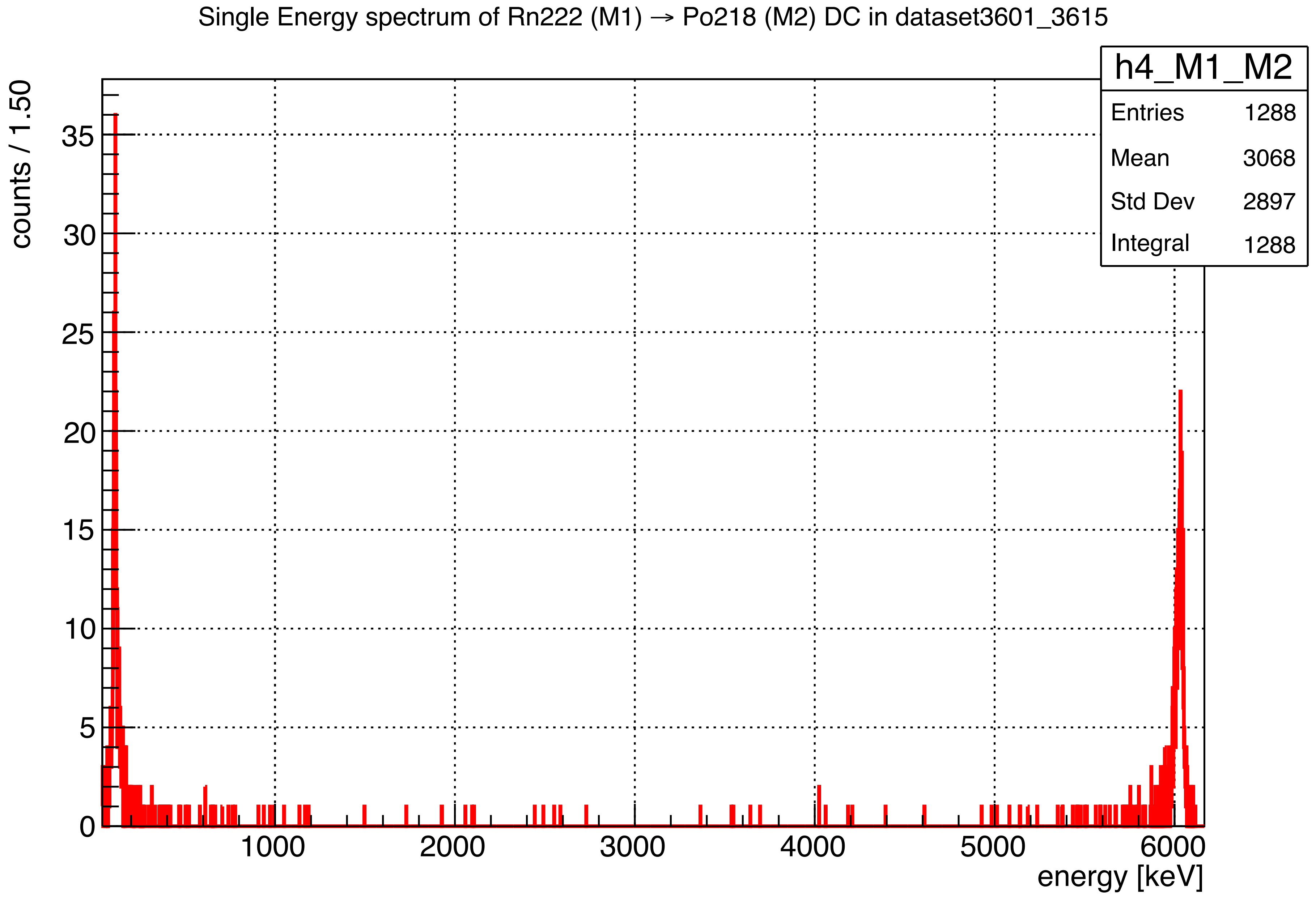
M1 → M2

$^{222}Rn \to {}^{218}Po$



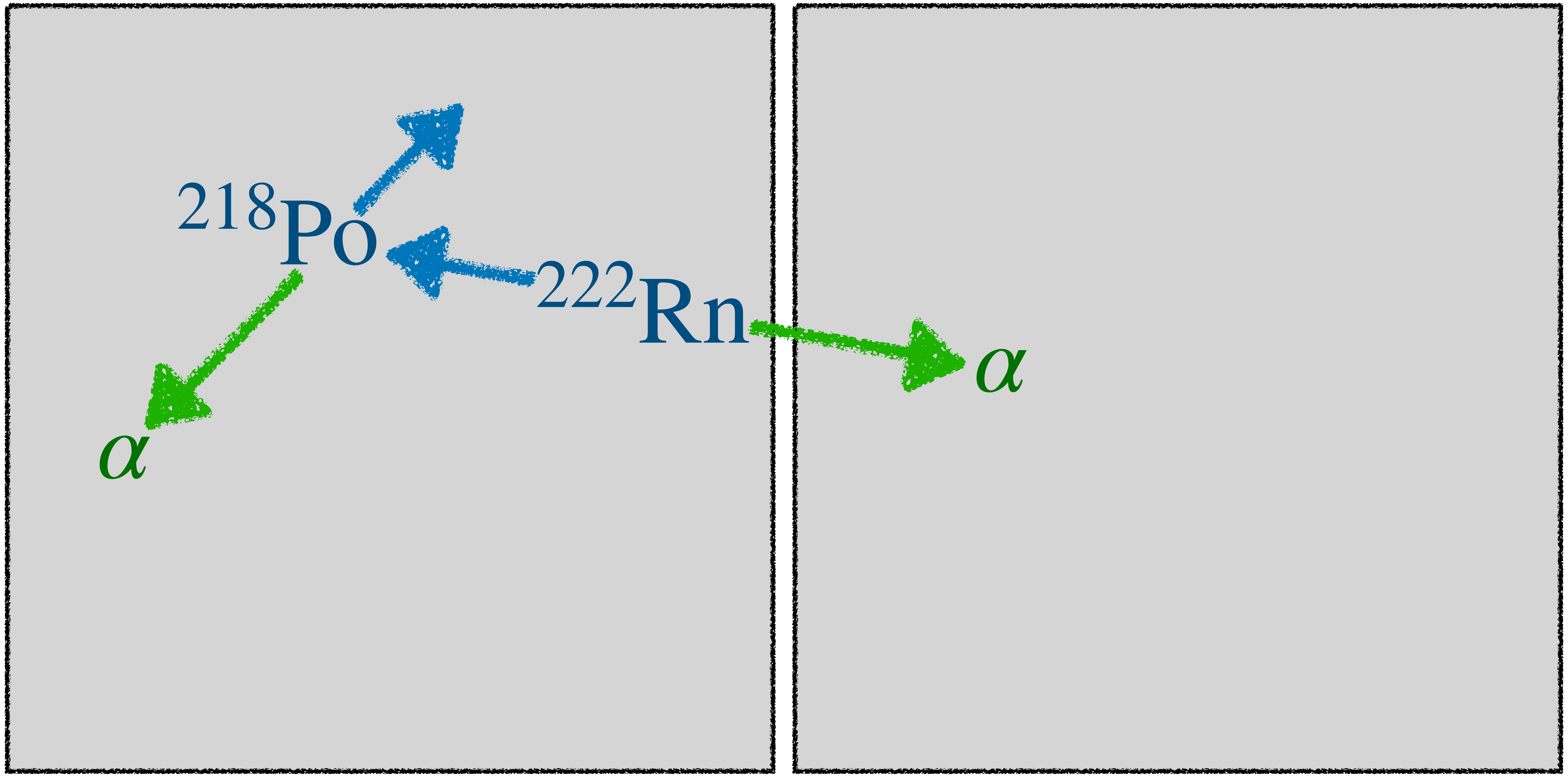






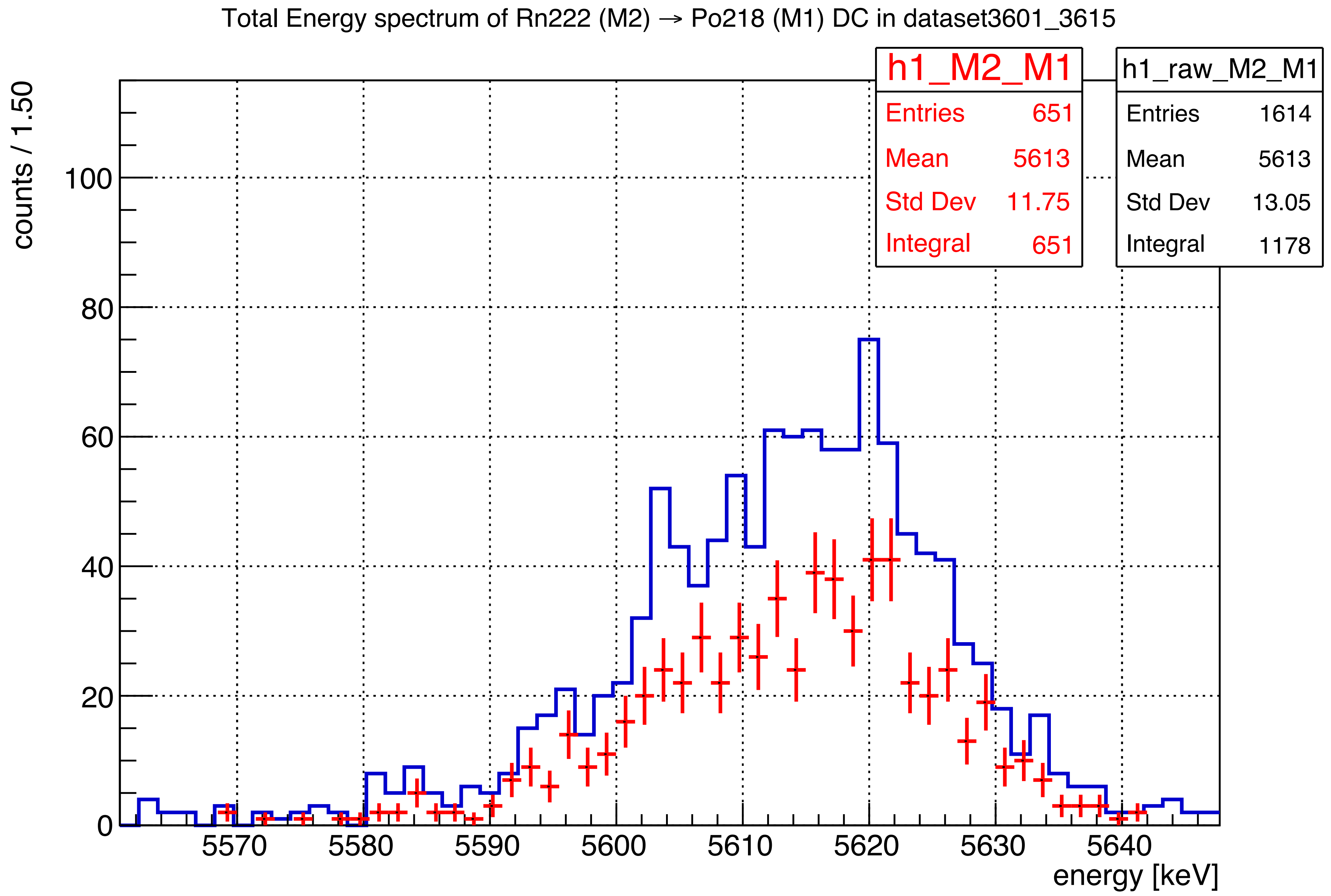
Analysis of $^{222}\mathrm{Rn} \rightarrow {}^{218}\mathrm{Po}$ DC
Case 3 : M2 → M1

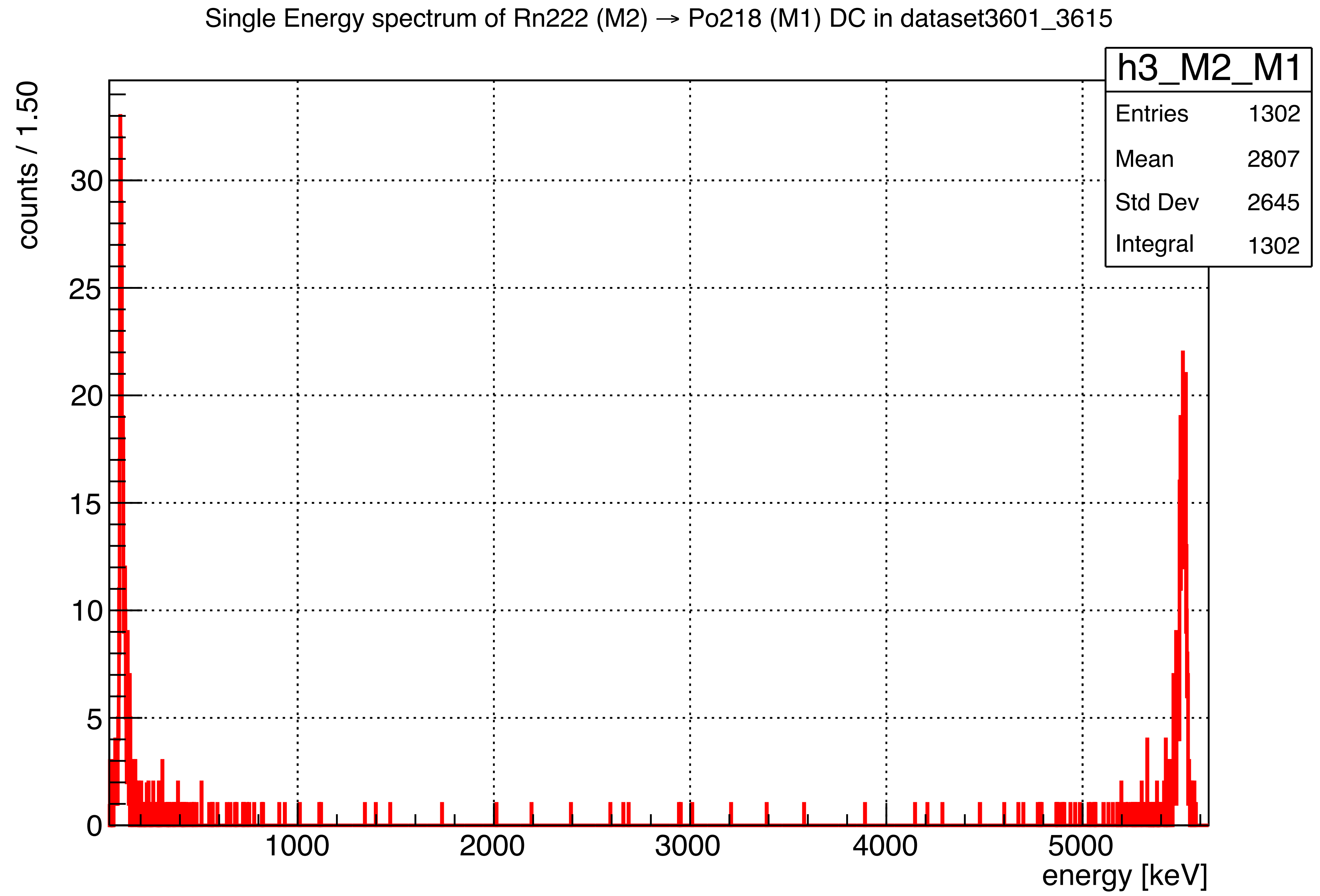
$^{222}Rn \rightarrow {}^{218}Po$ Delayed Coincidence

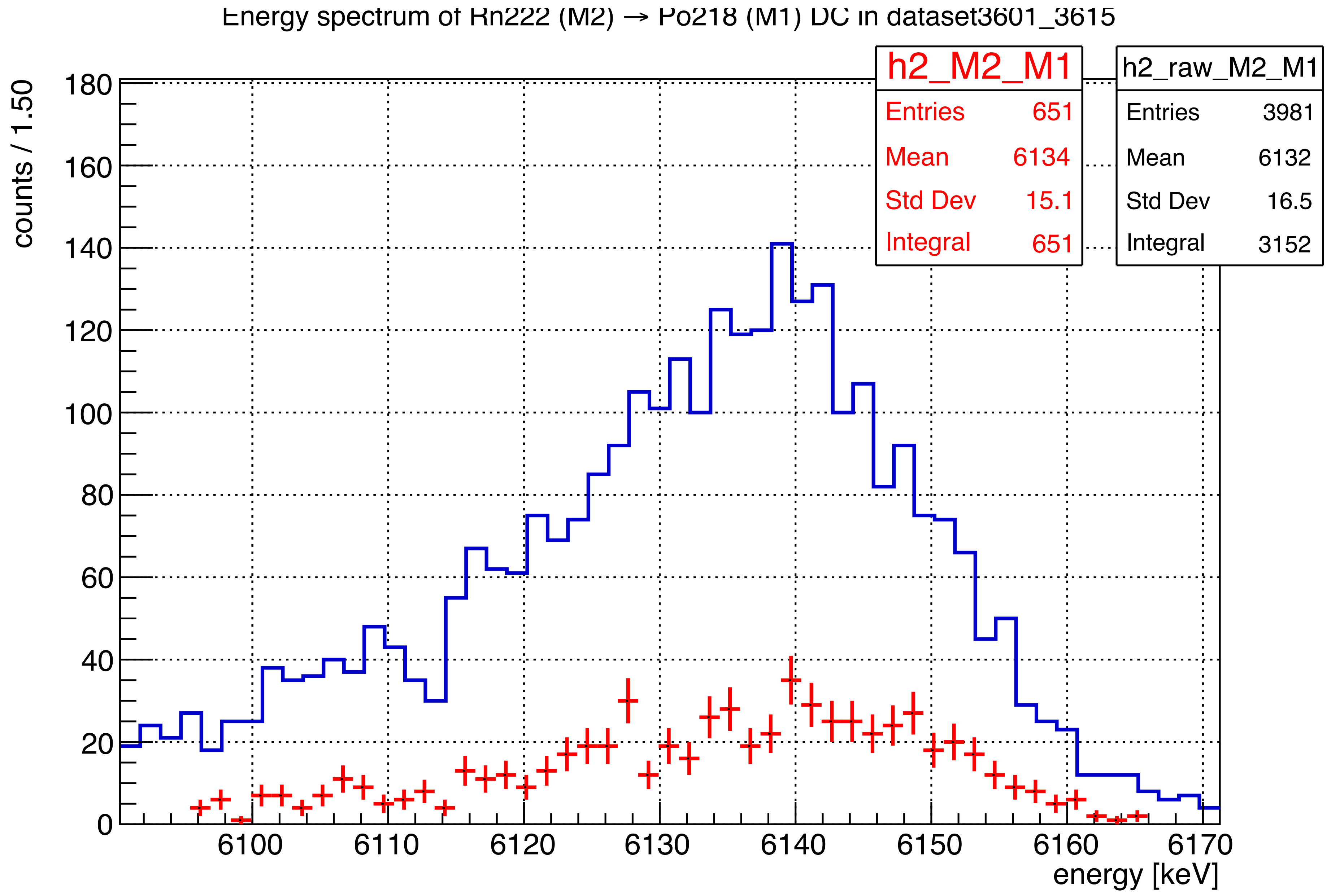


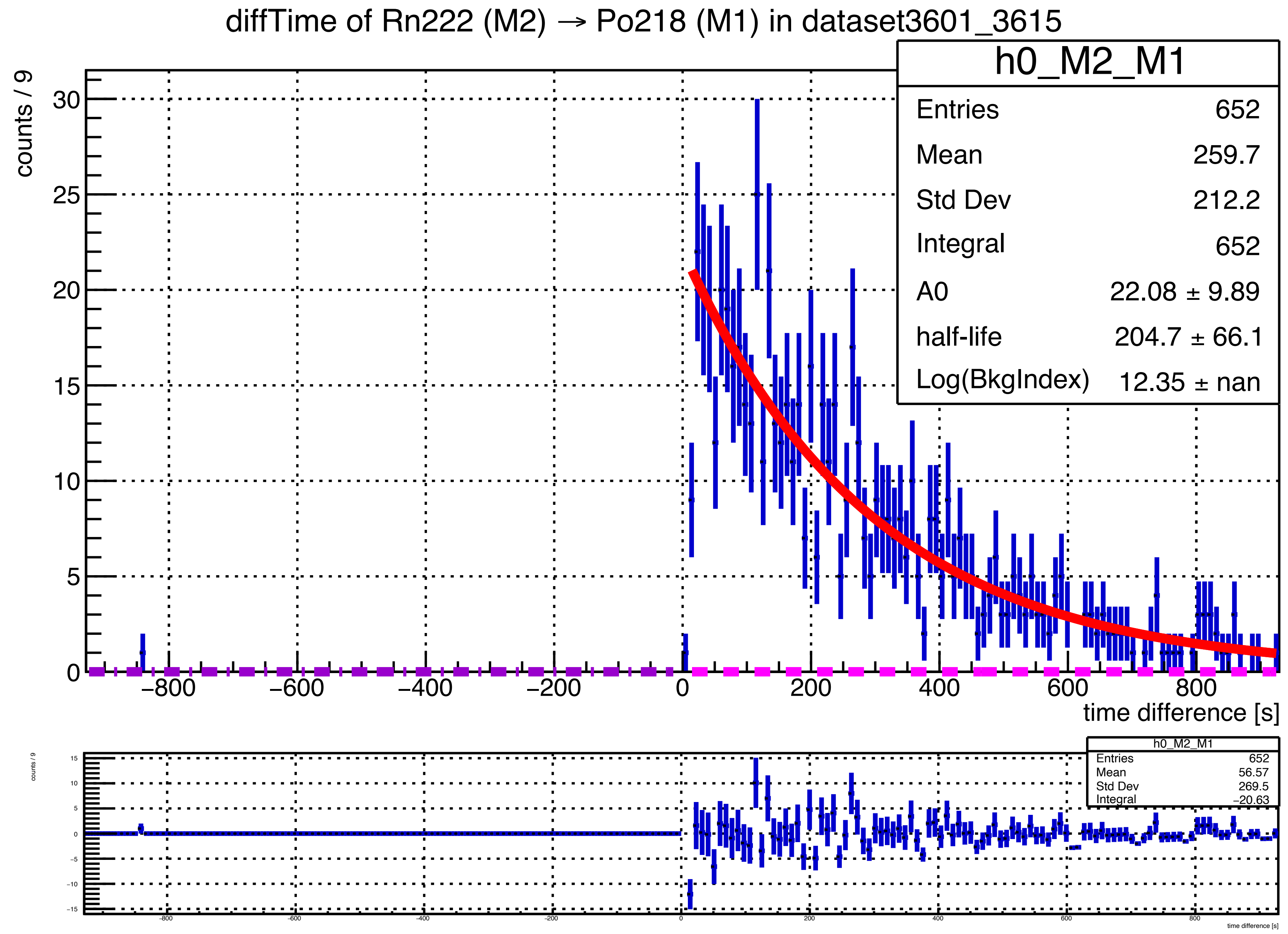
M2 → M1

$^{222}Rn \rightarrow {}^{218}Po$



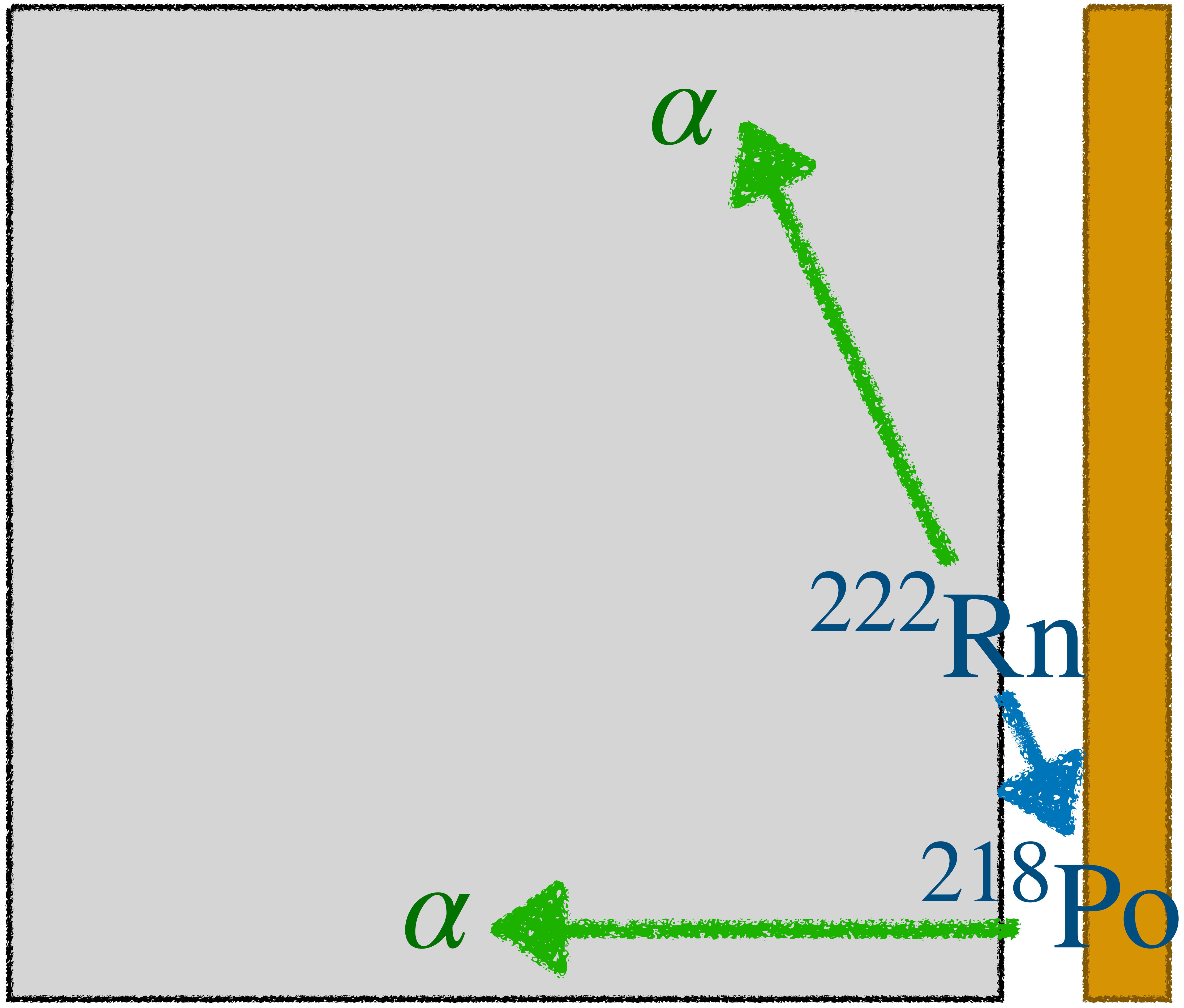




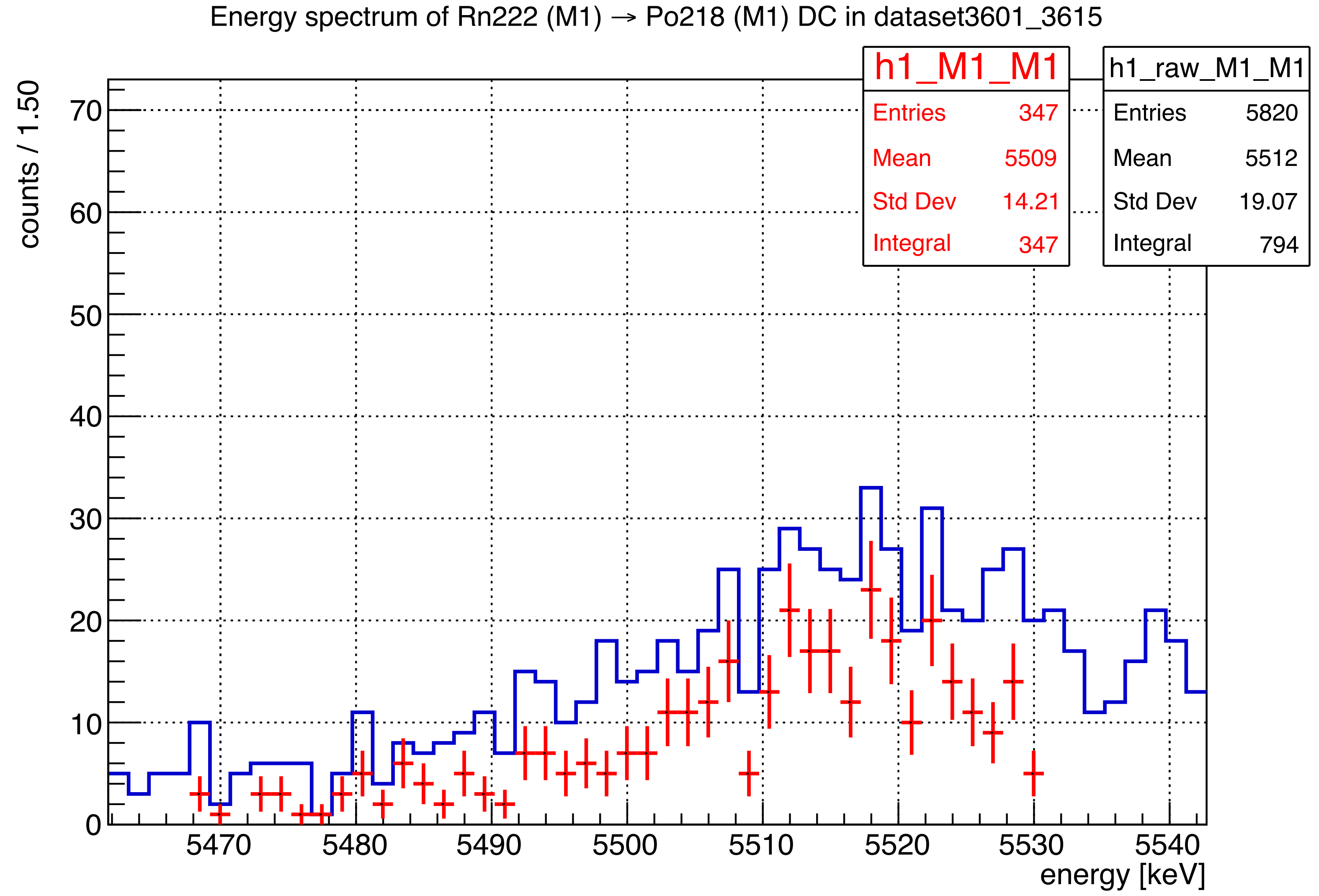


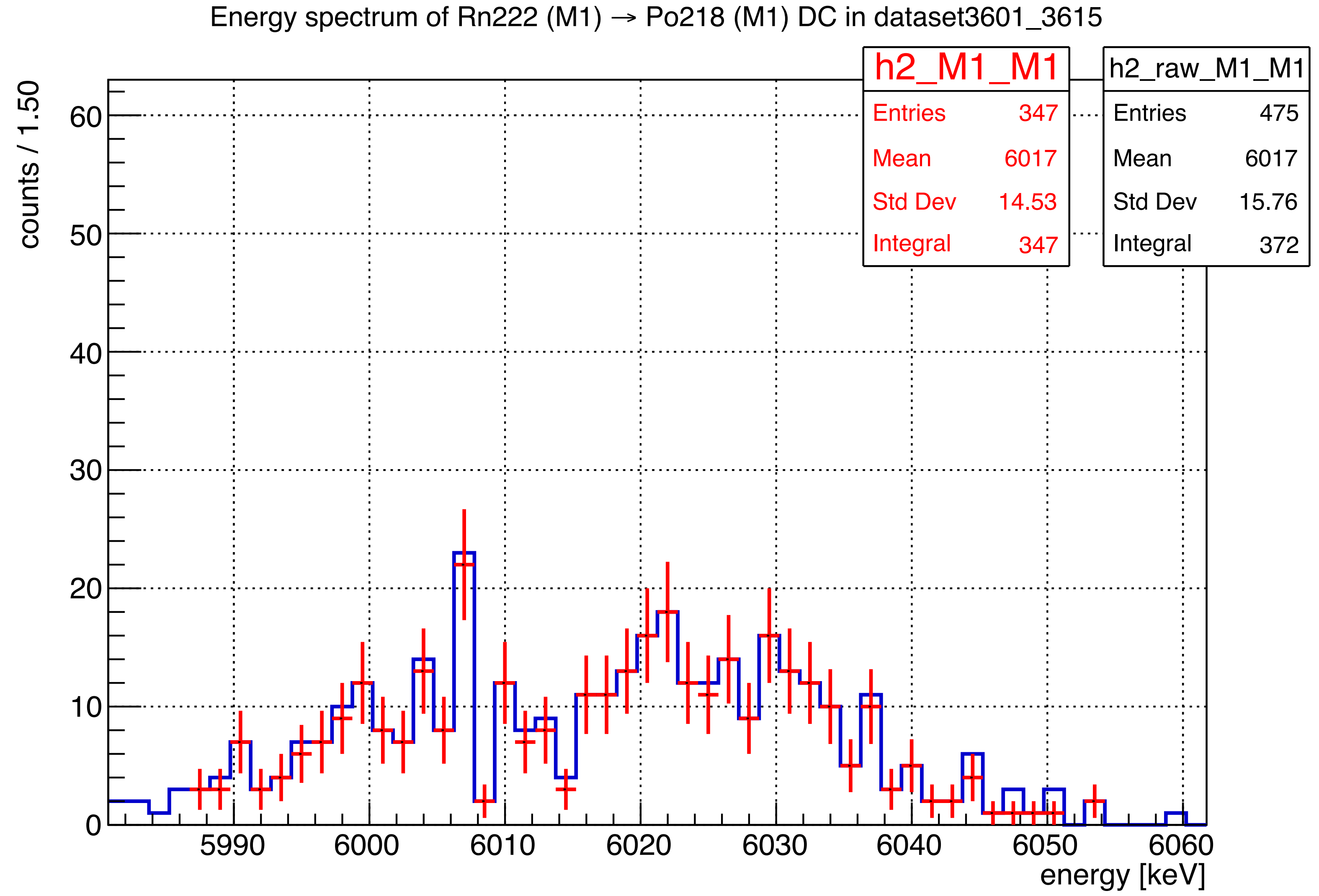
Analysis of $^{222}\mathrm{Rn} \rightarrow {}^{218}\mathrm{Po}$ DC Other Cases

$^{222}Rn(\alpha) \rightarrow {}^{218}Po(\alpha)$ Delayed Coincidence



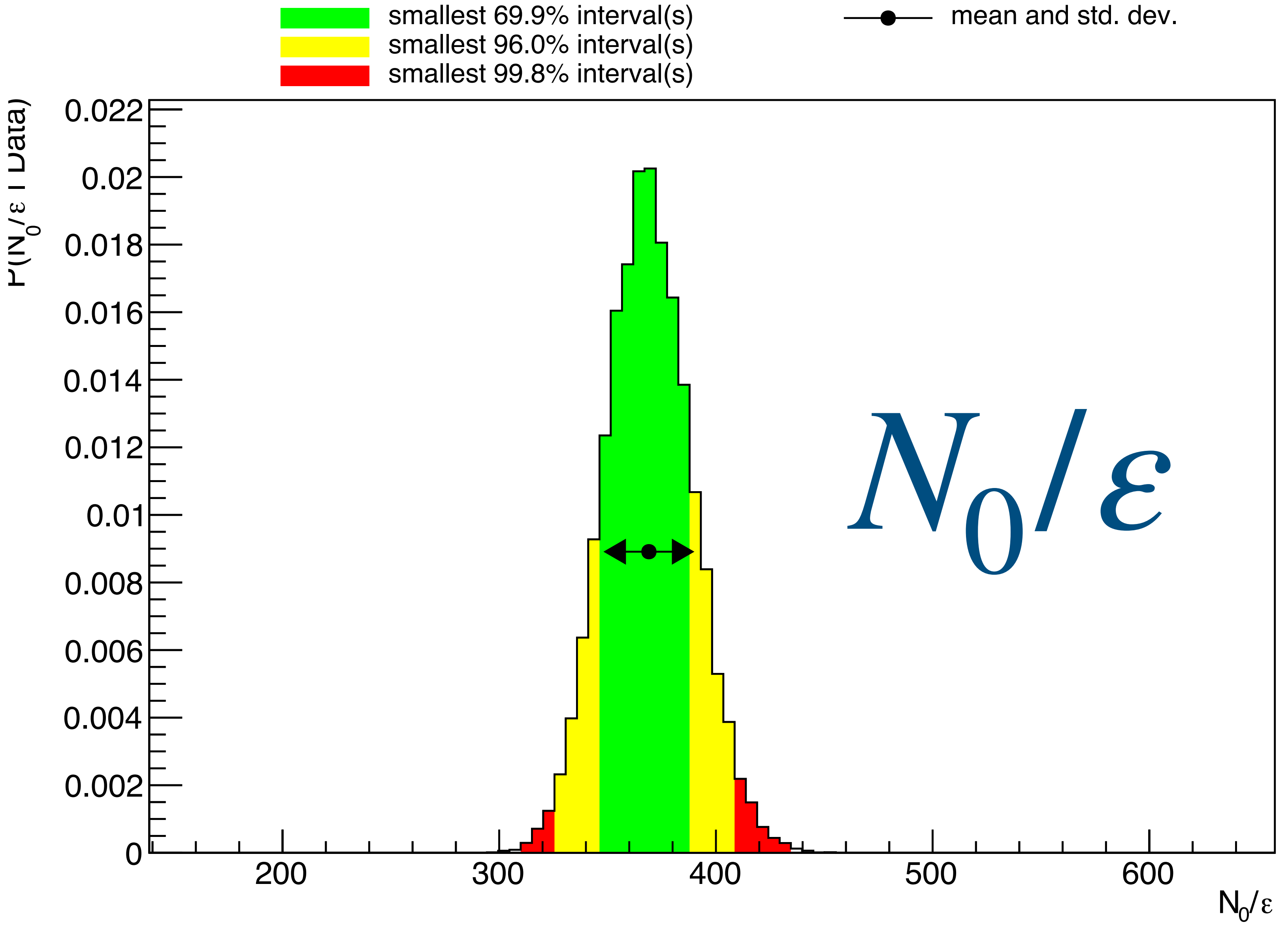
M1 → M1



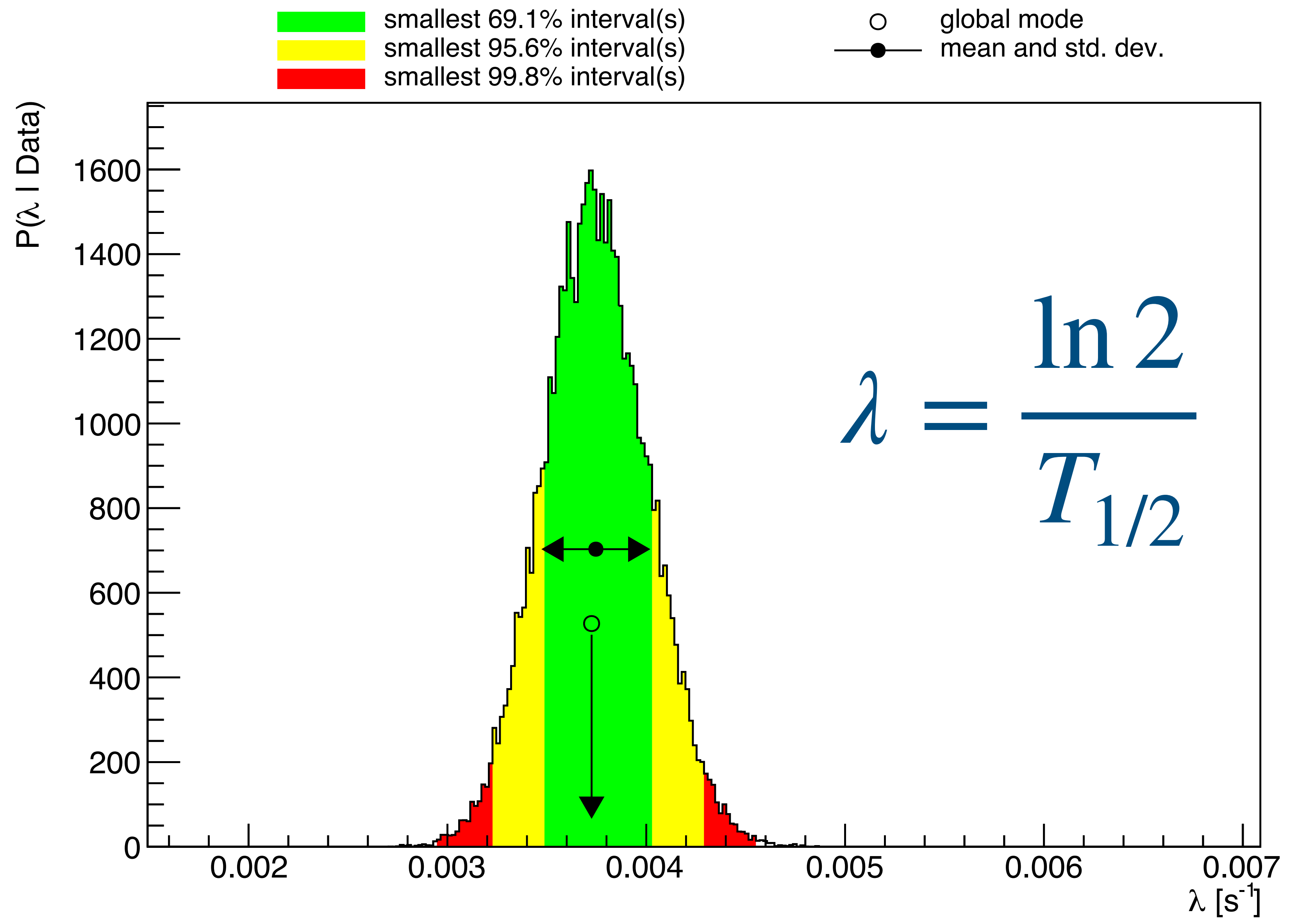


$^{222}Rn(\alpha) \rightarrow {}^{218}Po(\alpha)$

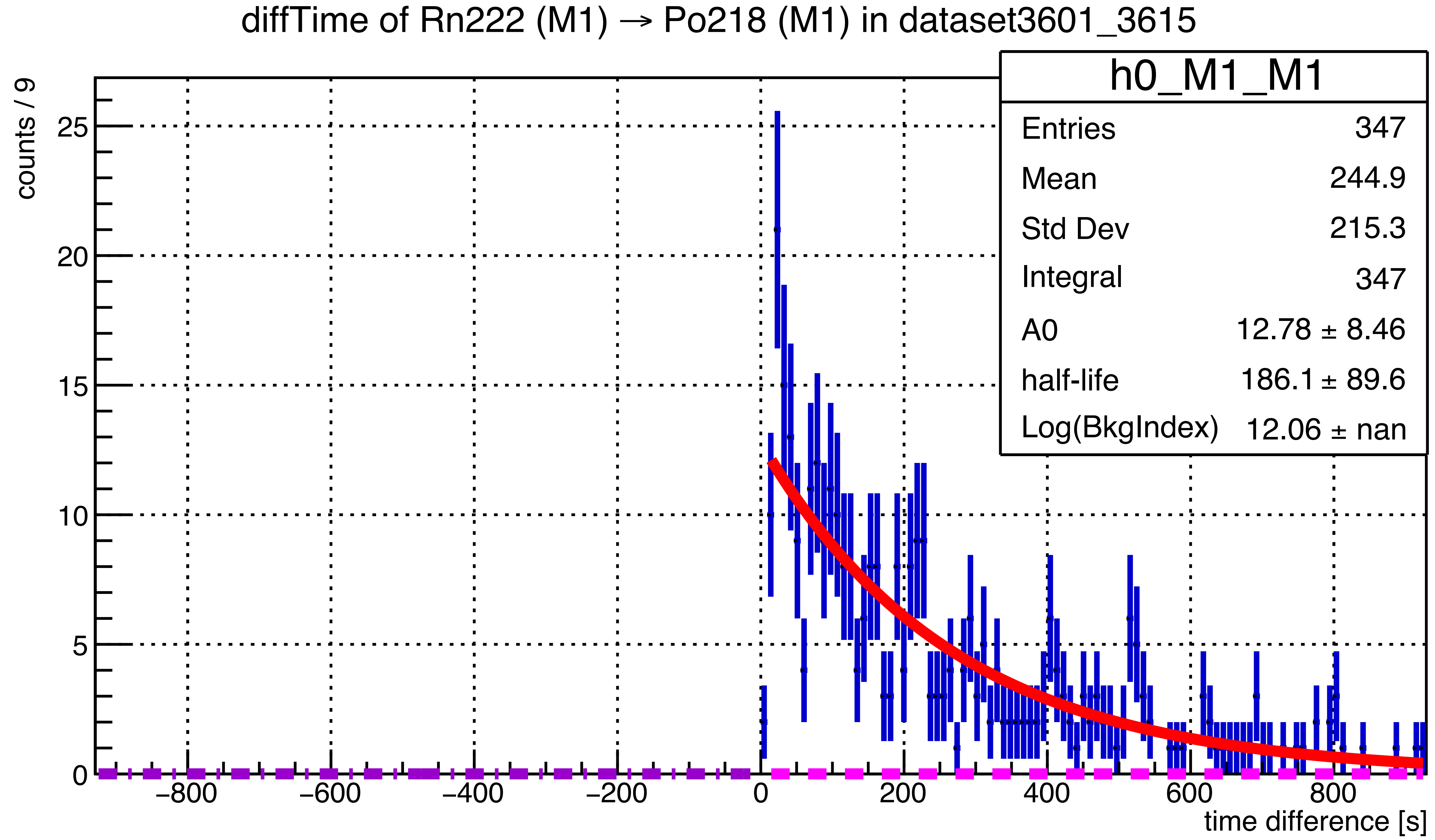
$$T_{1/2} = 185.8\ \text{s} \approx 3.1\ \text{min}$$

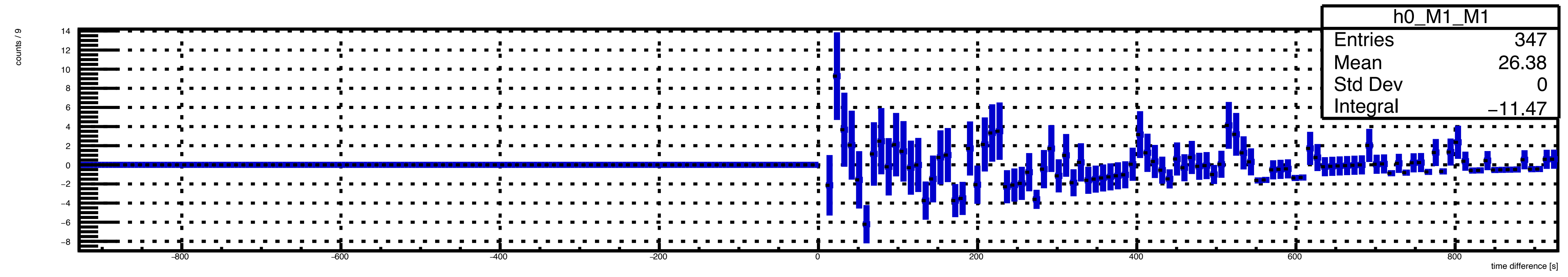


$$N_0/\varepsilon$$



$$\lambda = \frac{\ln 2}{T_{1/2}}$$

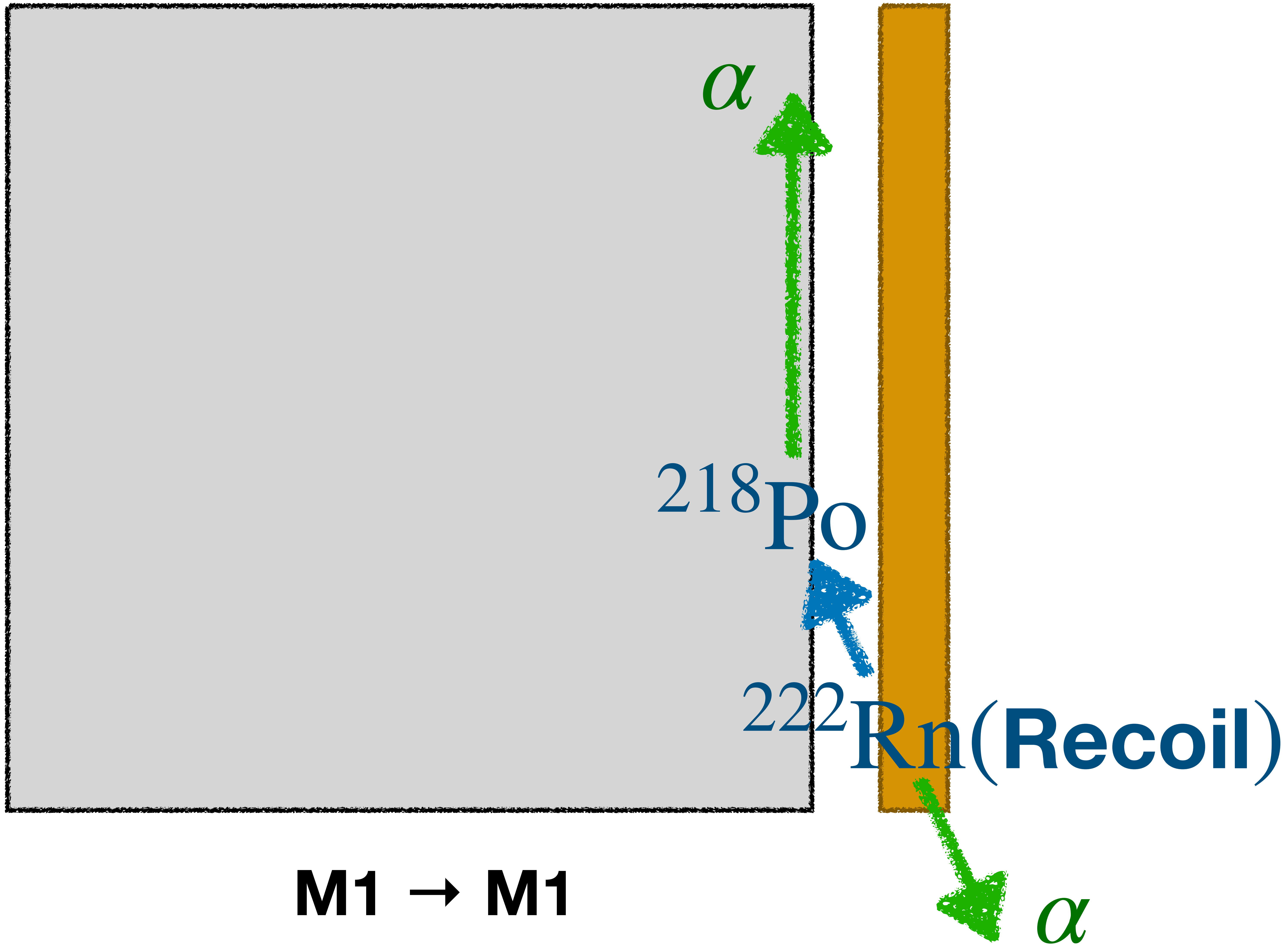




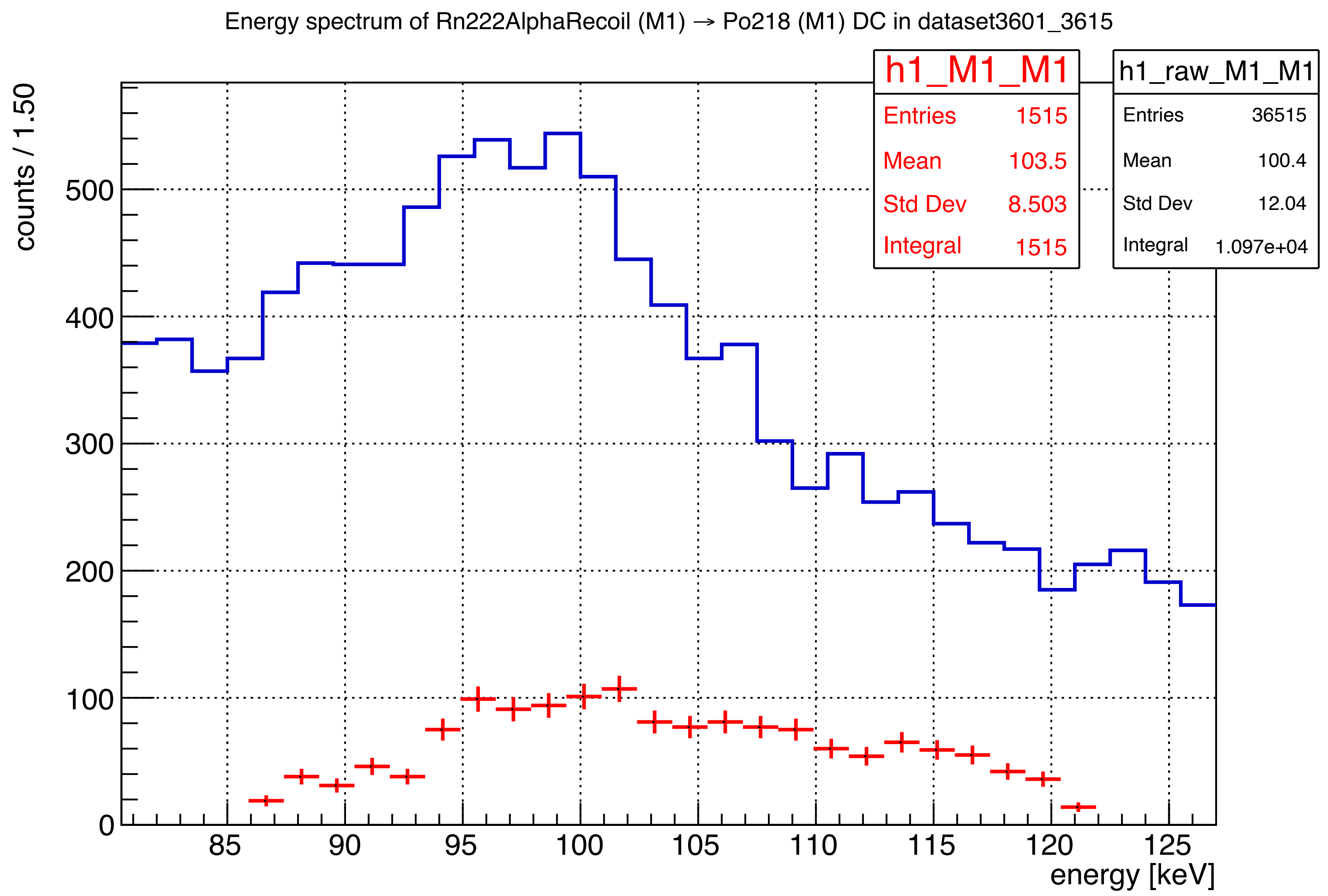
Smallest interval containing 69.9% and local mode:
(346.27, 387.83) (local mode at **369.65** with rel. height 1; rel. area 1)

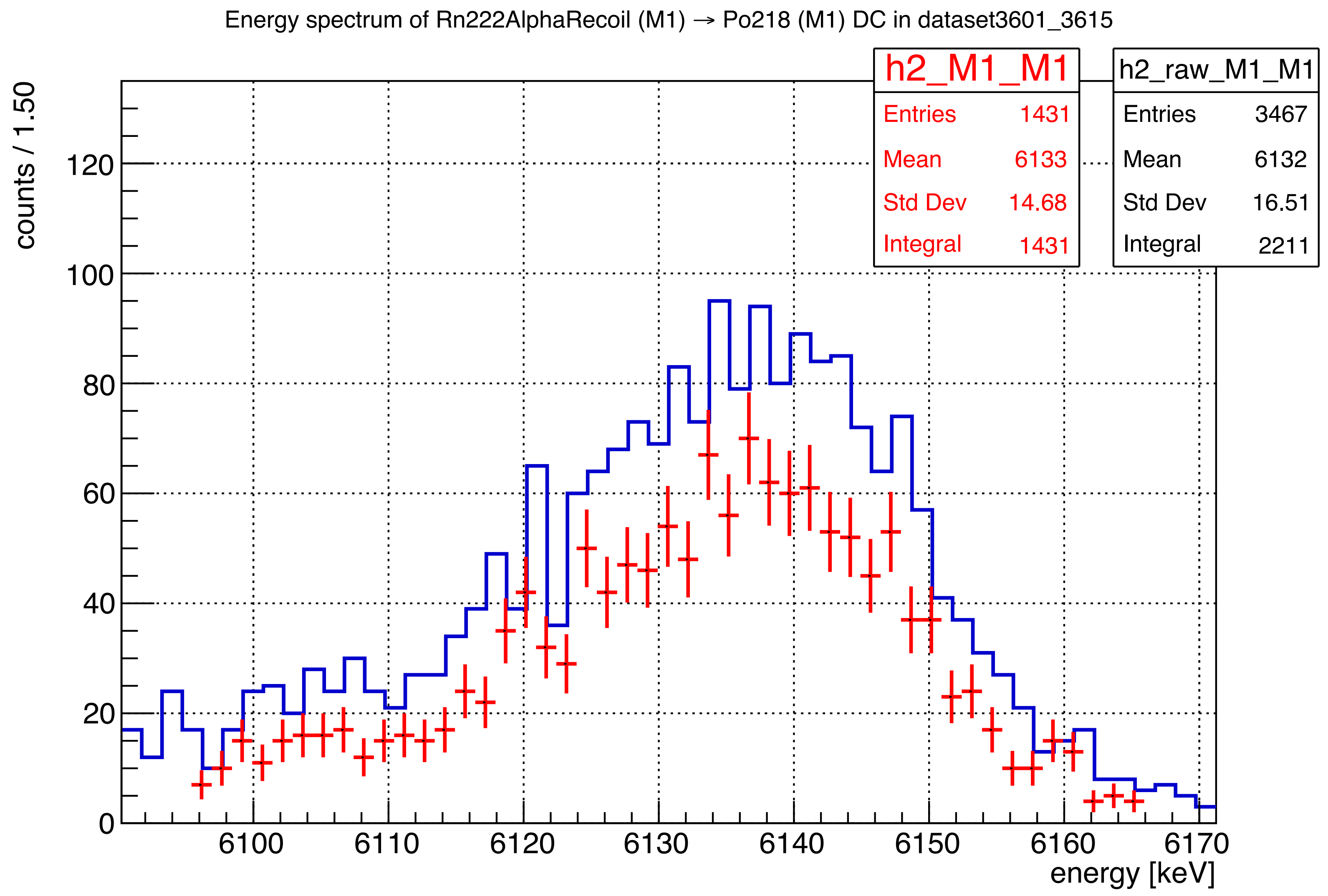
$$N_0/\varepsilon = 369.65^{+18.18}_{-23.38} \quad (\varepsilon = 0.999923)$$

^{222}Rn(Recoil) → ^{218}Po Delayed Coincidence



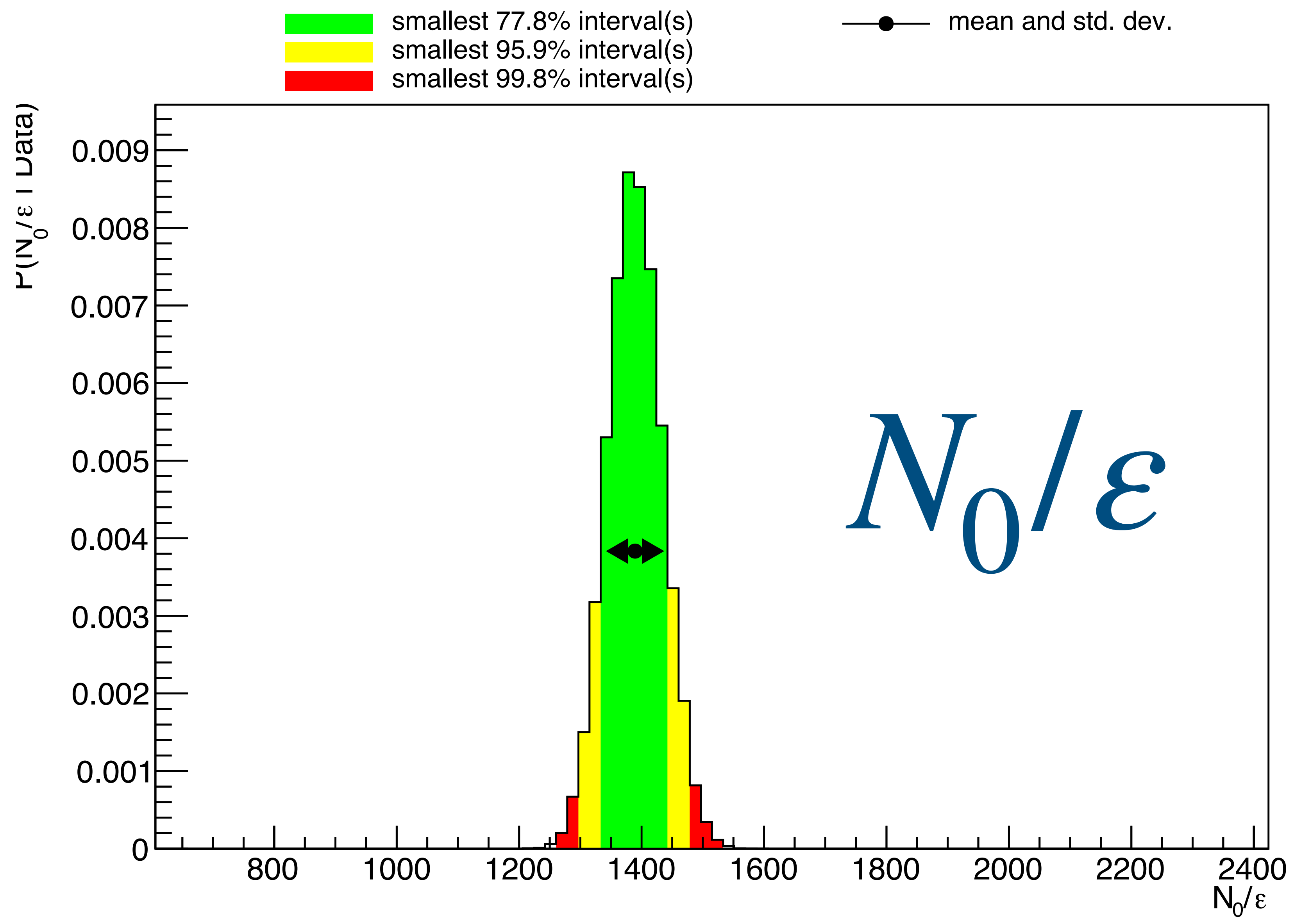
M1 → M1

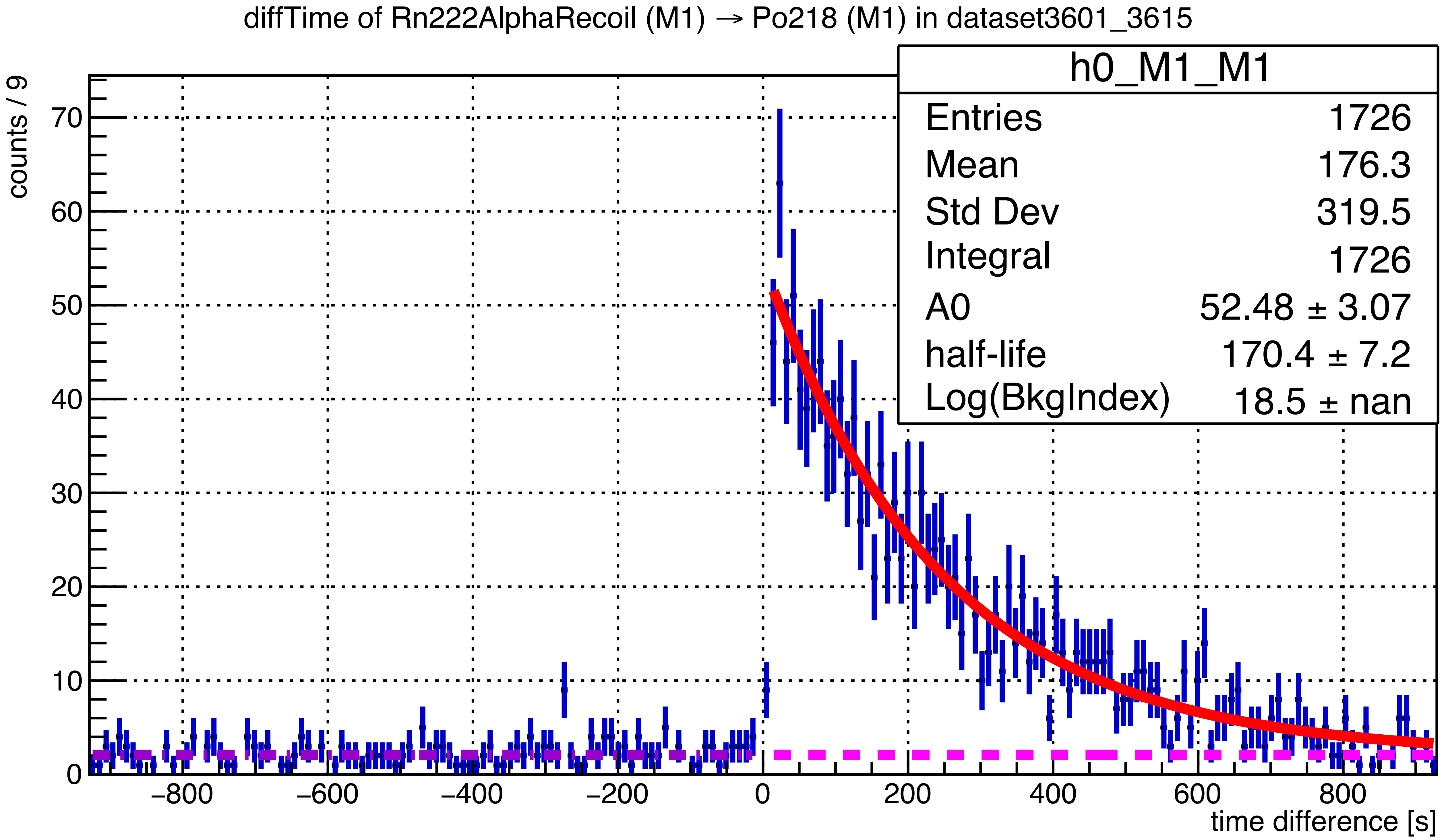


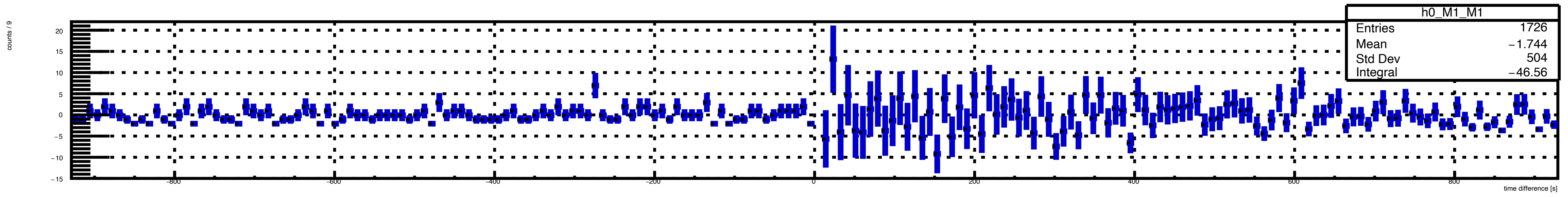


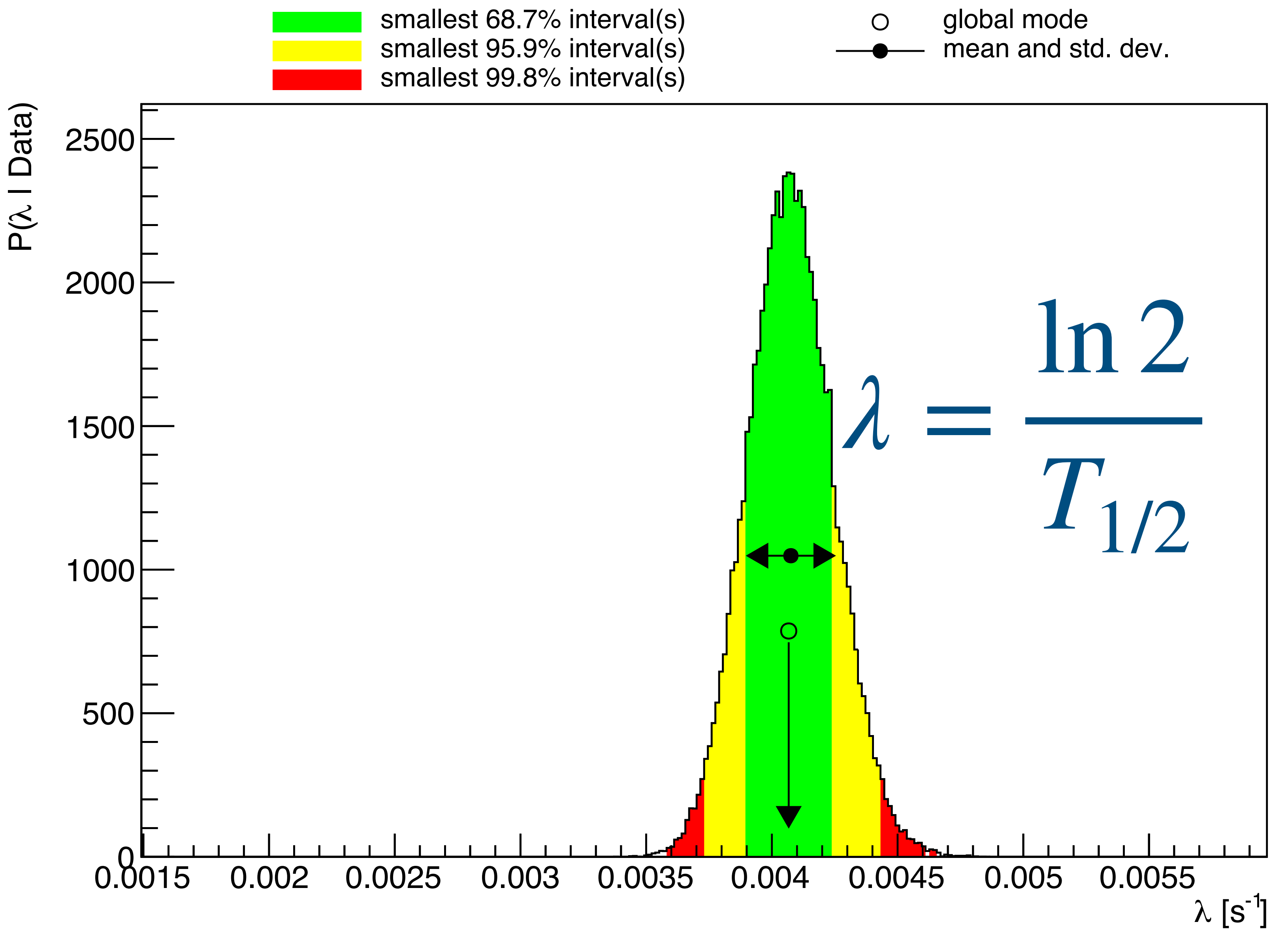
$^{222}\mathrm{Rn}(\textbf{Recoil}) \rightarrow {}^{218}\mathrm{Po}$

$$T_{1/2} = 185.8\ \mathrm{s} \approx 3.1\ \mathrm{min}$$







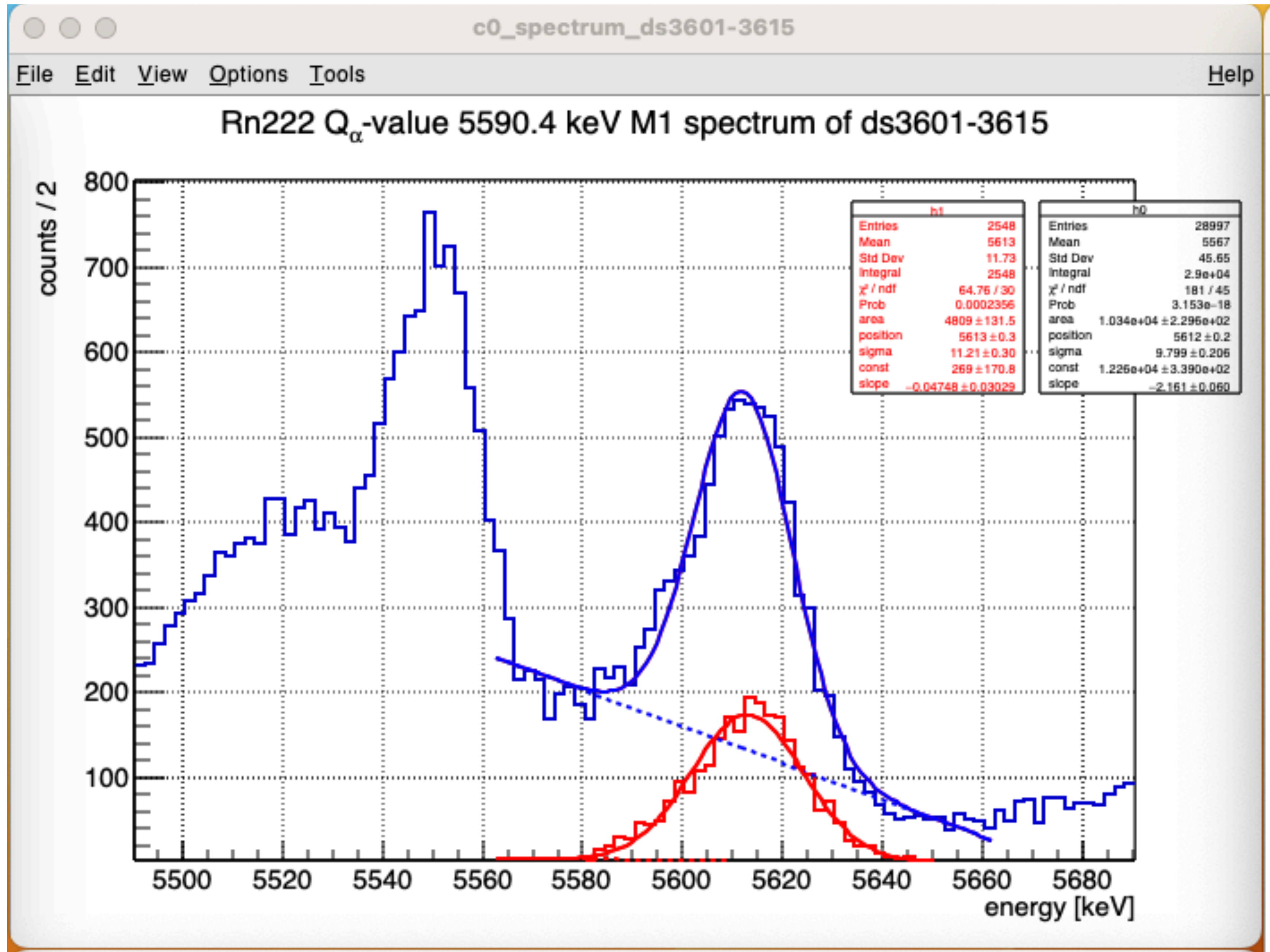


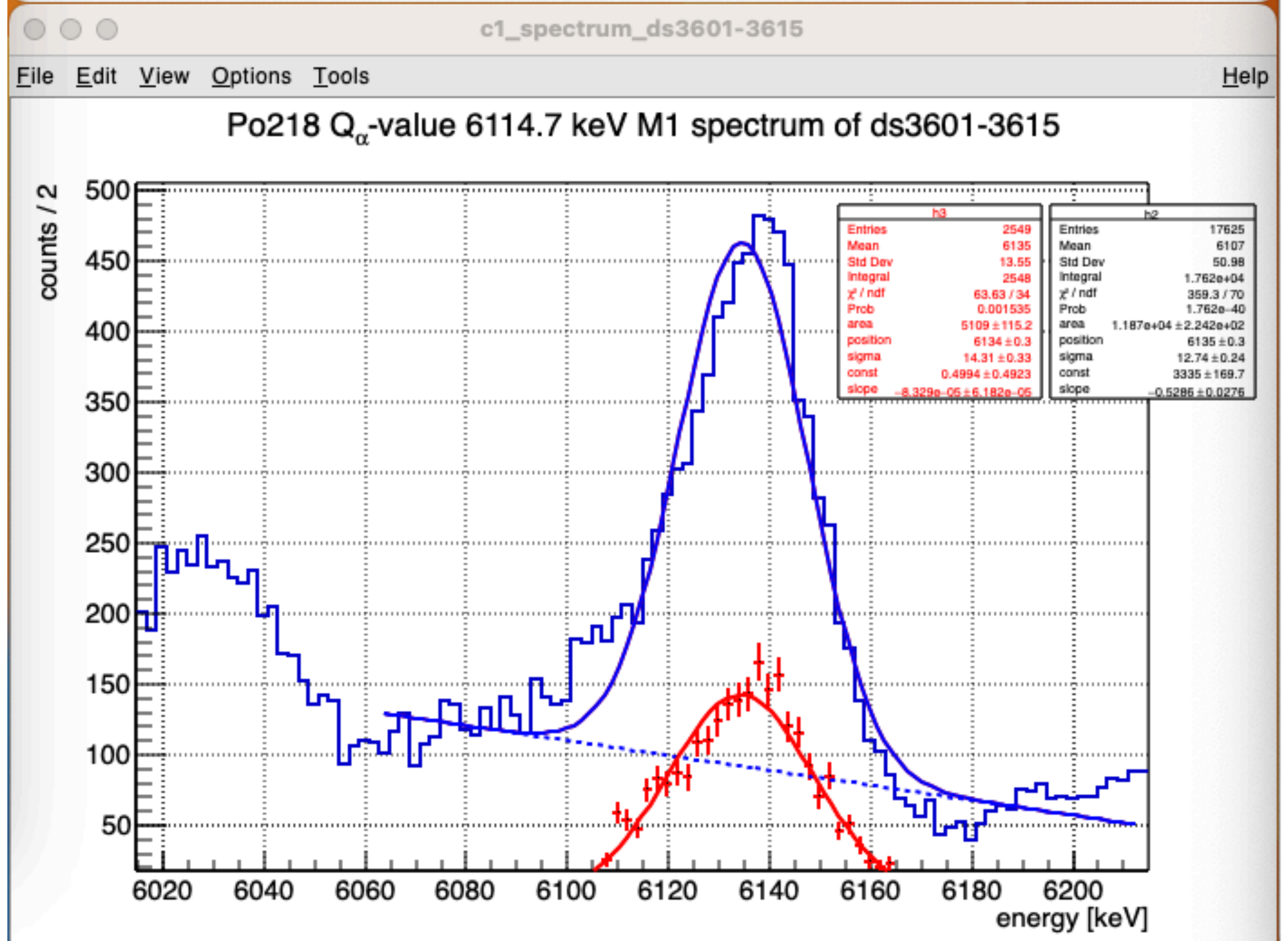
Smallest interval containing 68.2% and local mode:
(1351.3, 1442.2) (local mode at **1378.6** with rel. height 1; rel. area 1)

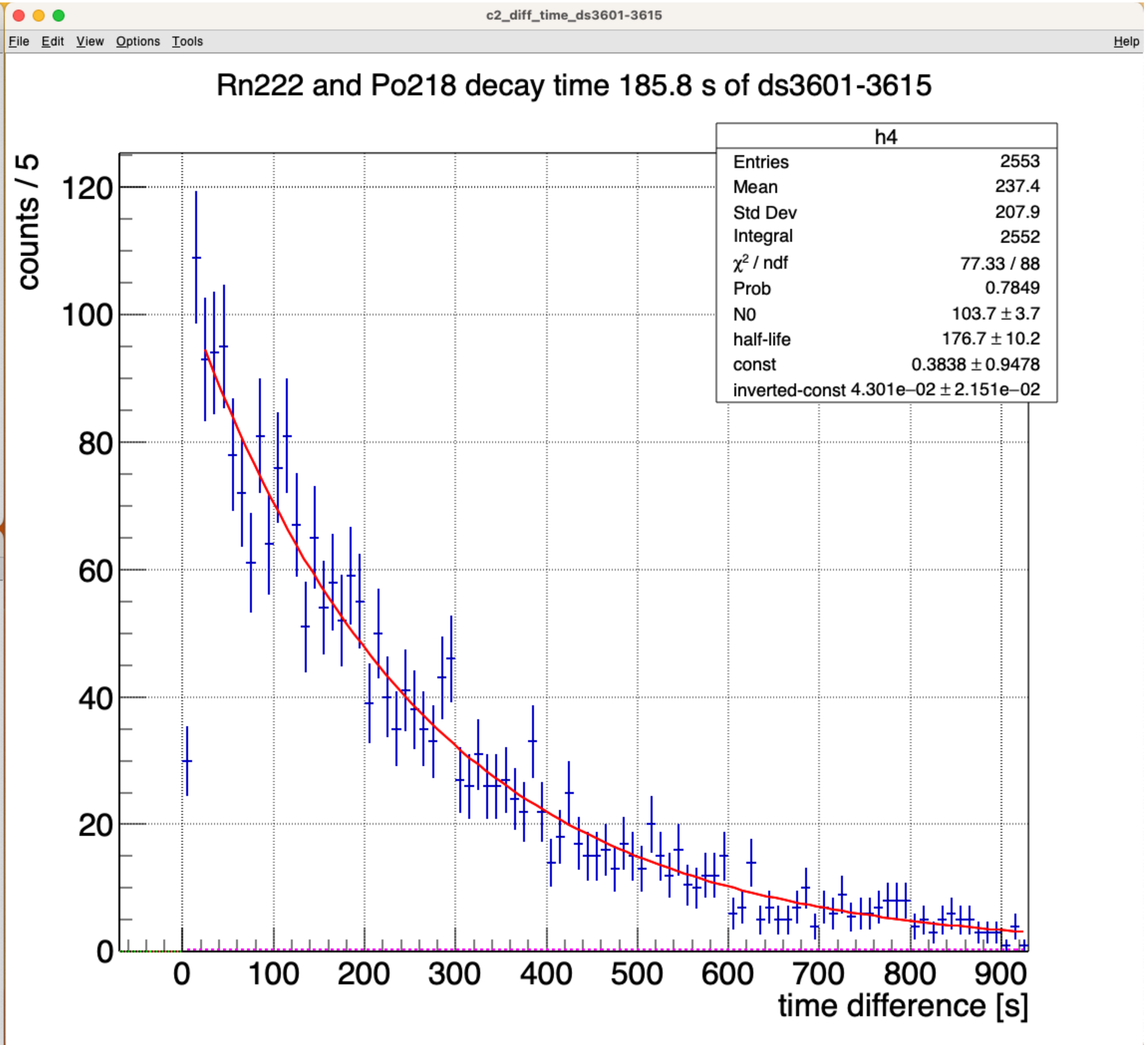
$$N_0/\varepsilon = 1378.6^{+63.6}_{-27.3} \quad (\varepsilon = 0.999923)$$

Analysis of $^{222}\mathrm{Rn} \rightarrow {}^{218}\mathrm{Po}$ DC
Wider energy cut

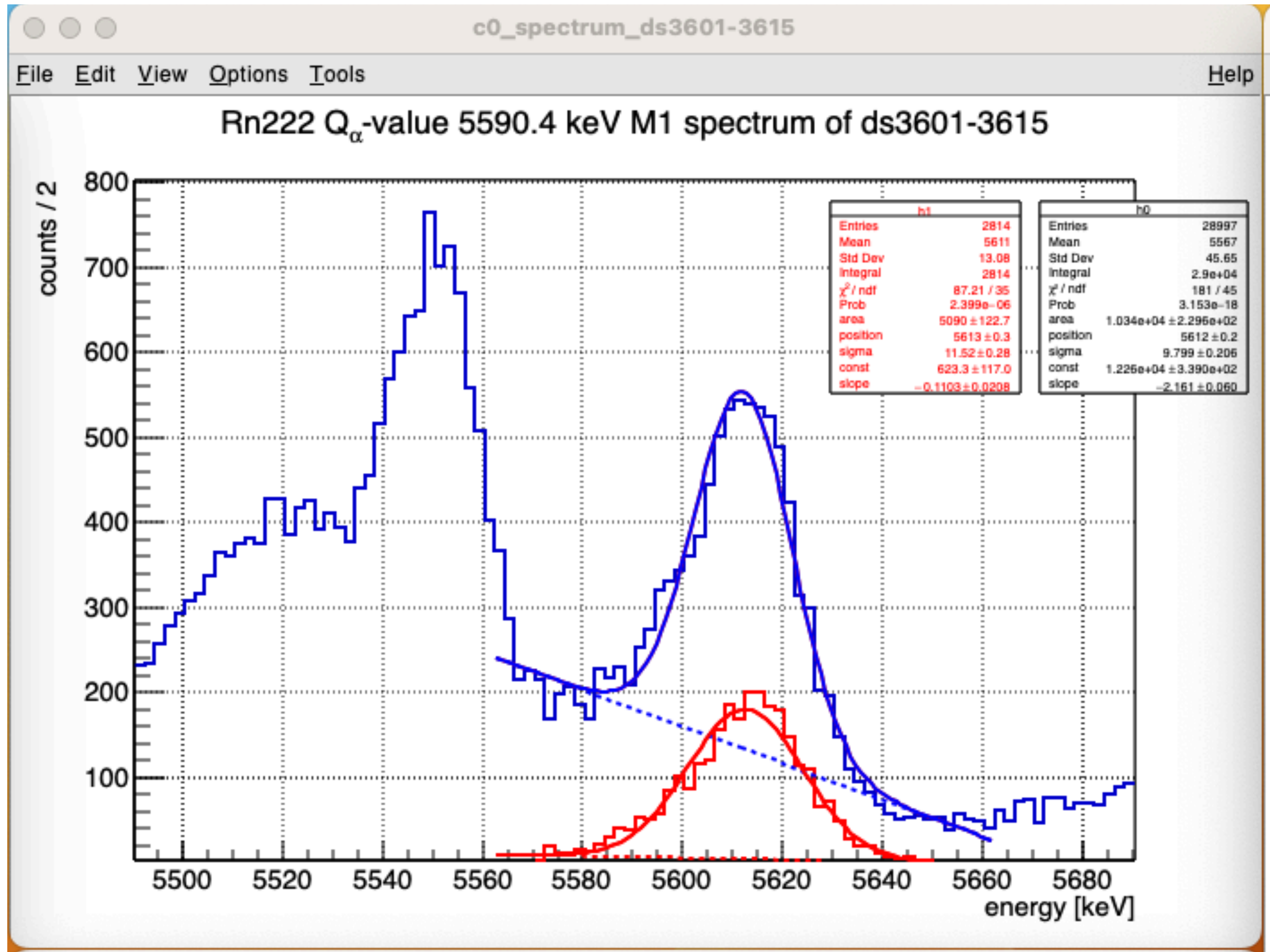
$[\ Q_\alpha \times F_Q - \Delta E\ ,\ E_{\text{high\_thresh}}\ ]$ ΔE = **30 keV**

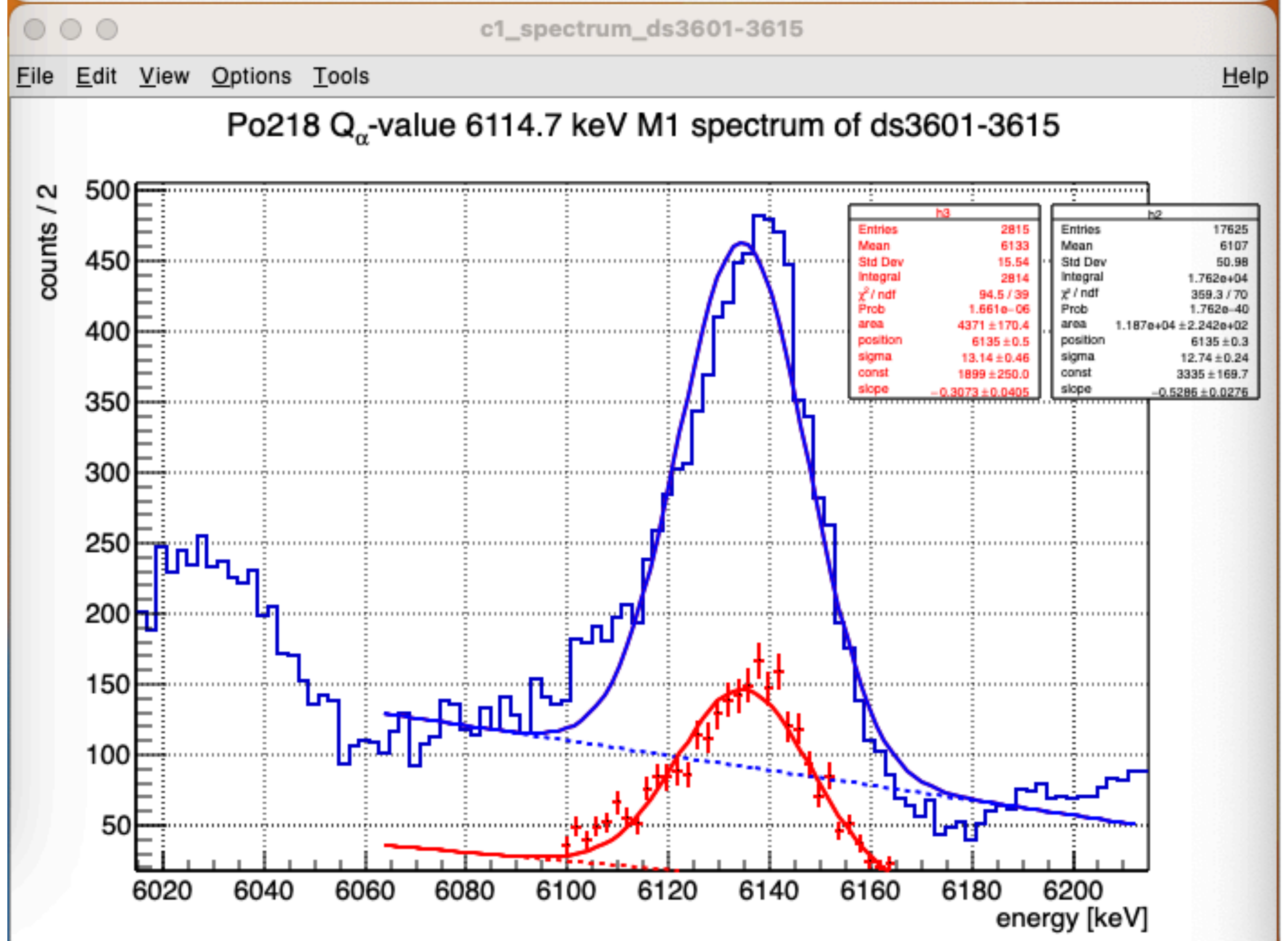


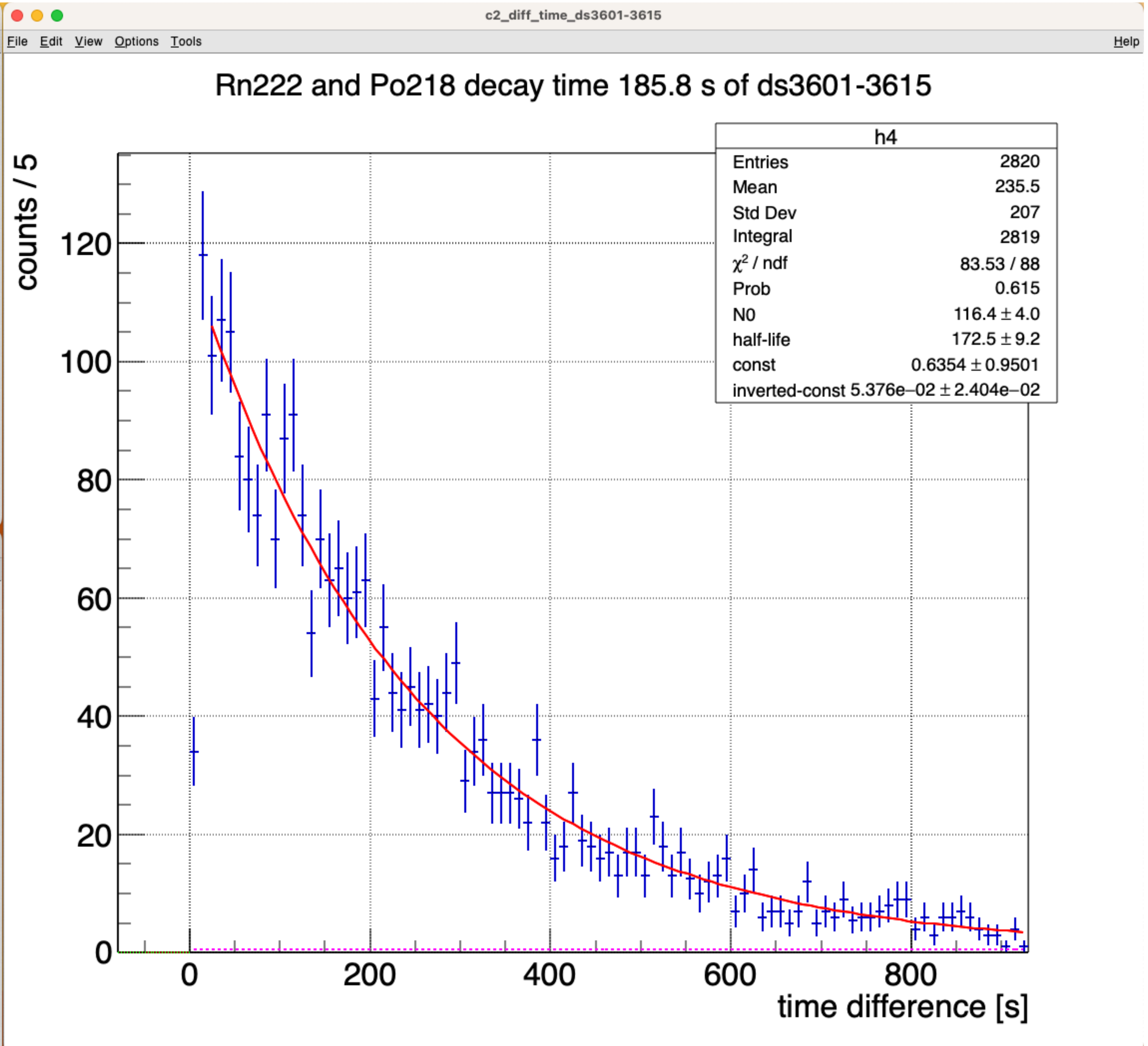




$[\ Q_\alpha \times F_Q - \Delta E\ ,\ E_{\mathrm{high\_thresh}}\ ]$ $\quad \Delta E = \mathbf{40\ keV}$

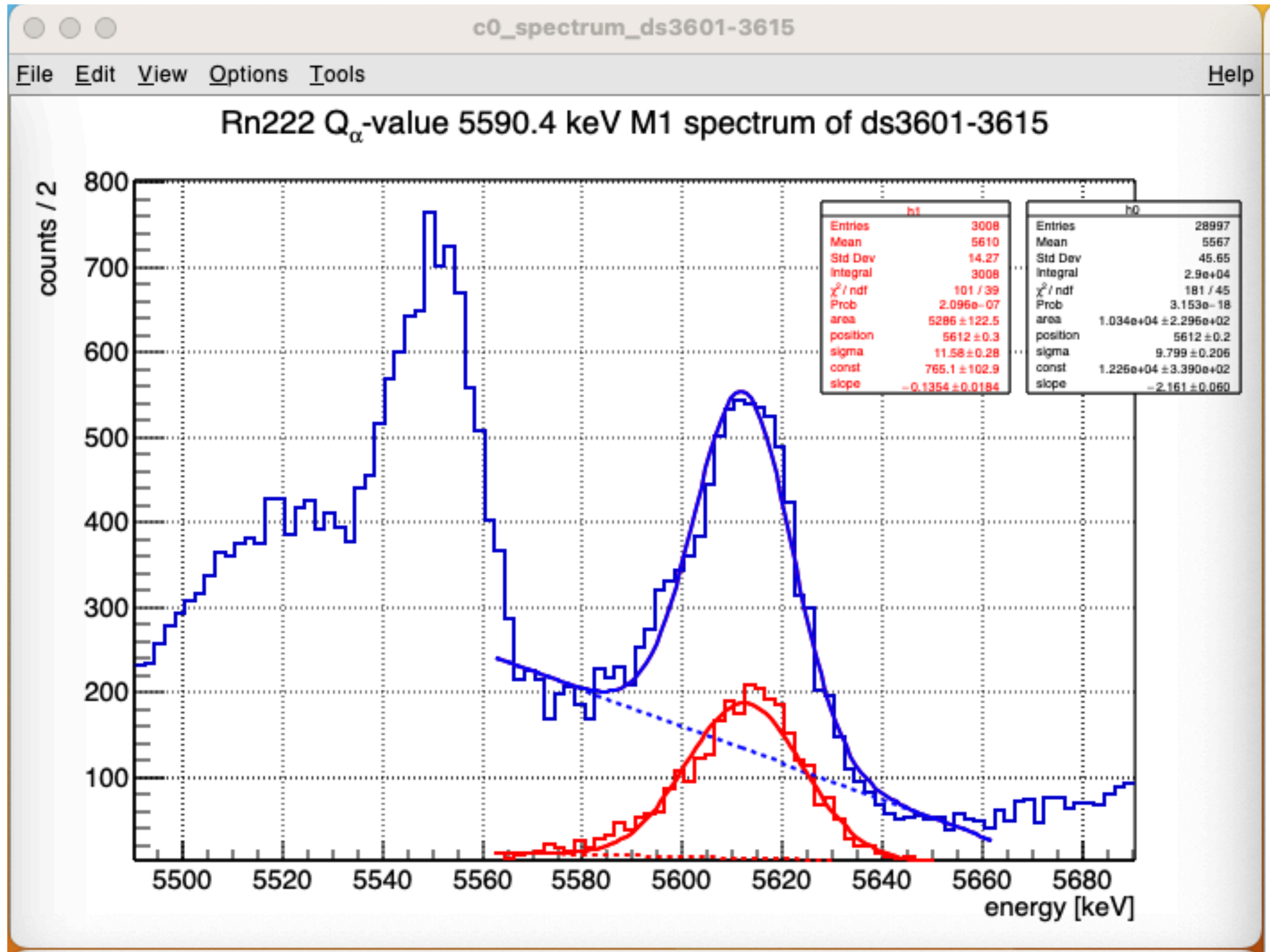


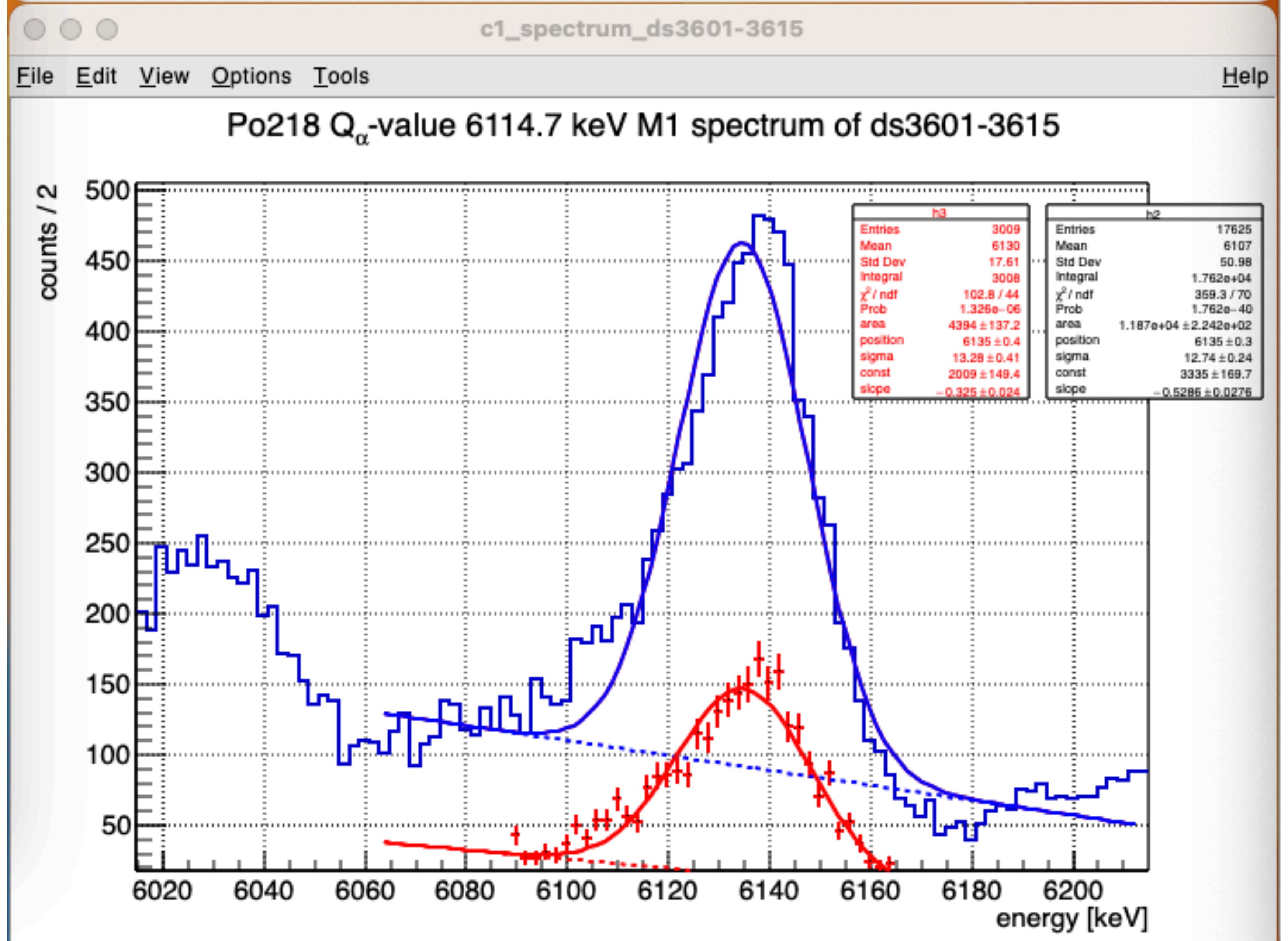


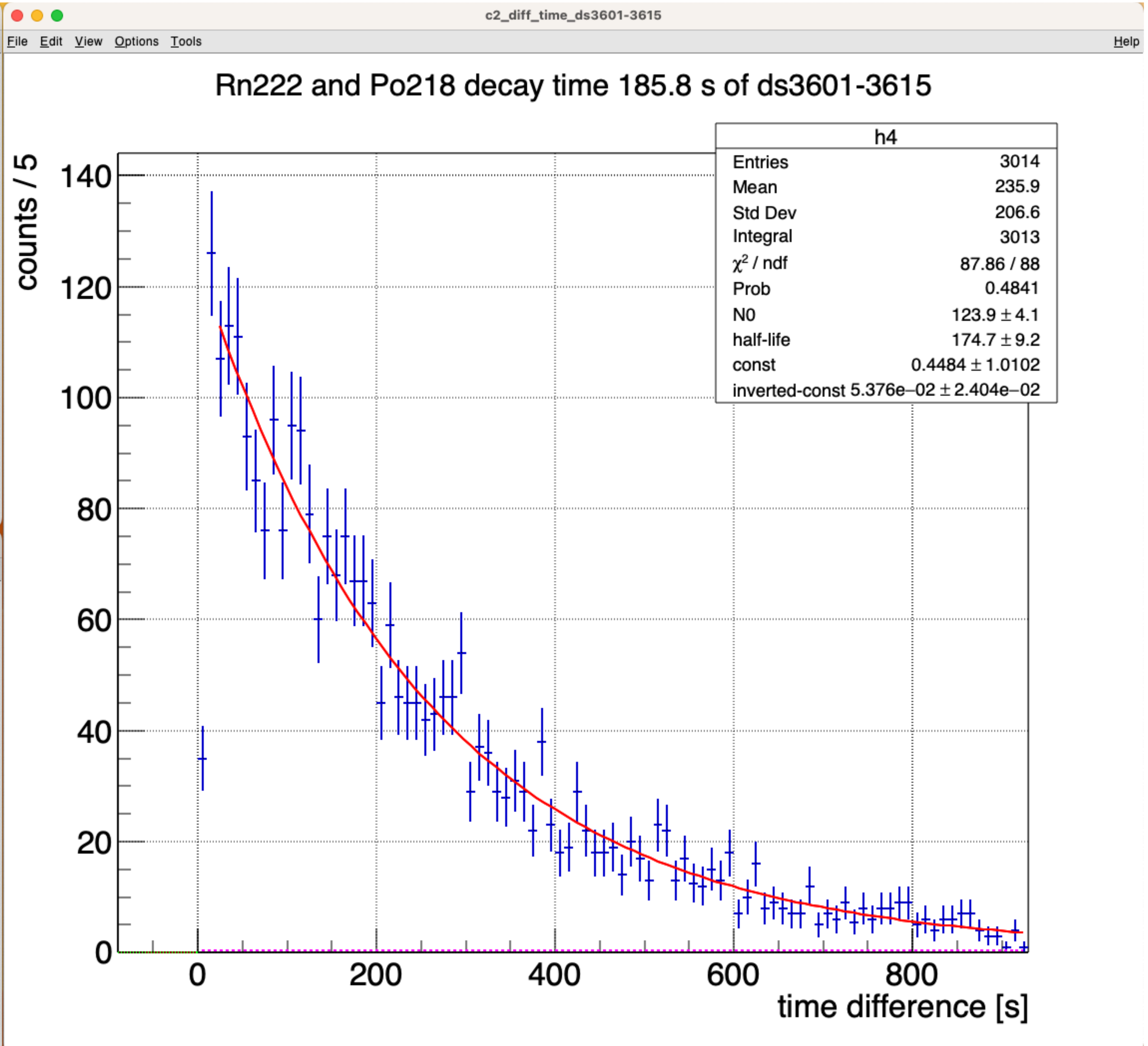


[$Q_\alpha \times F_Q - \Delta E$, $E_{\text{high\_thresh}}$]

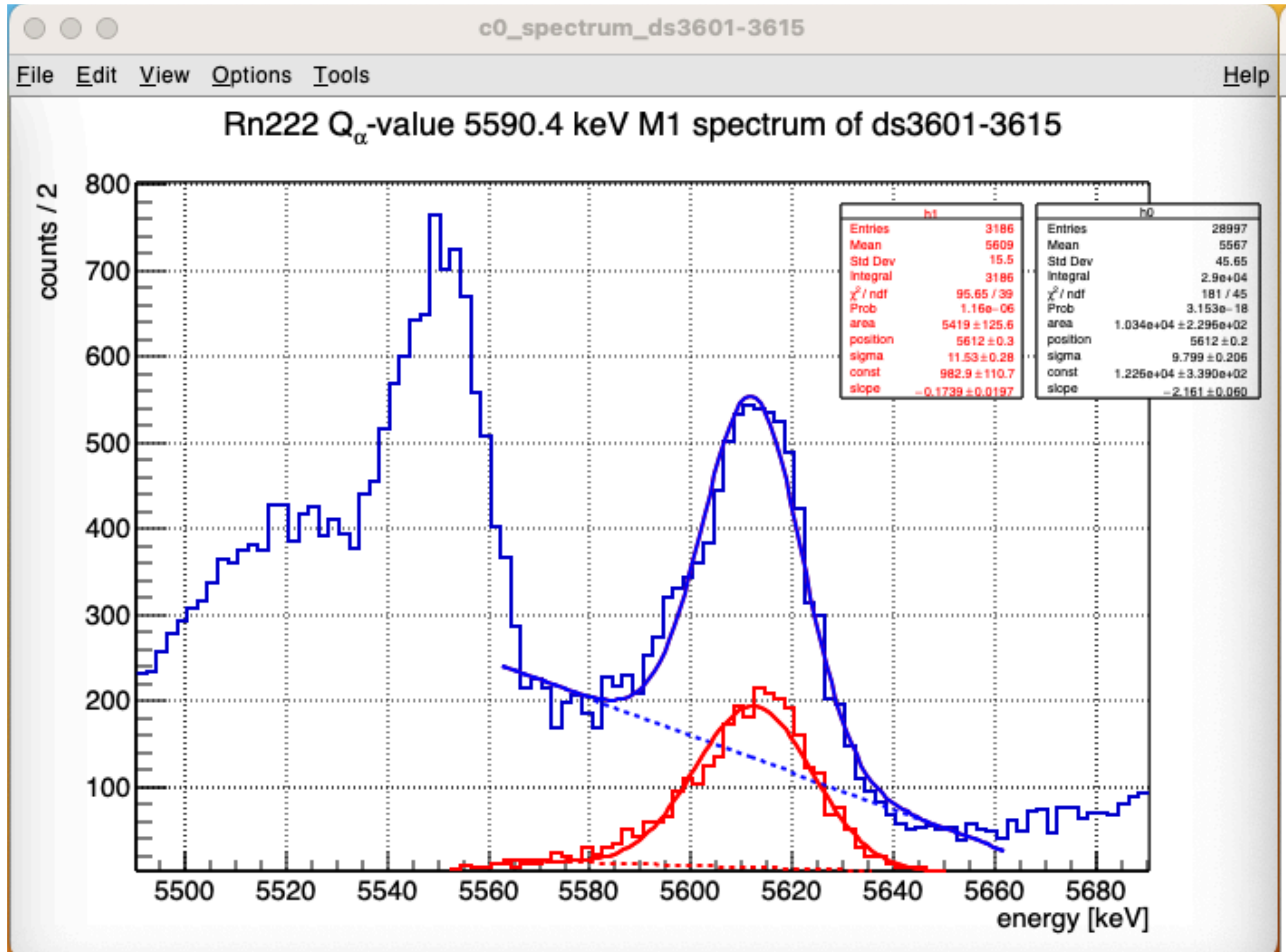
$\Delta E =$ **50 keV**

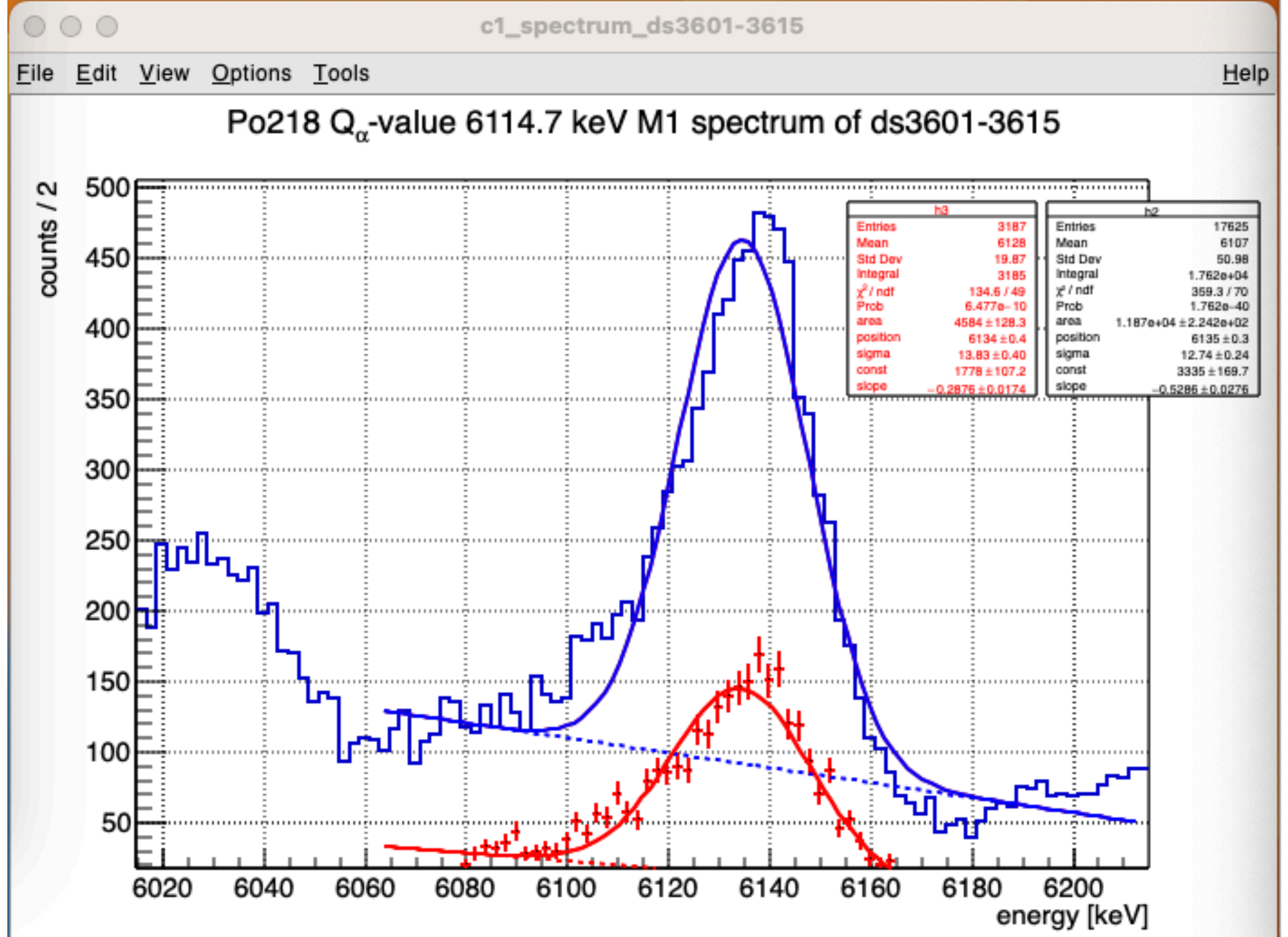


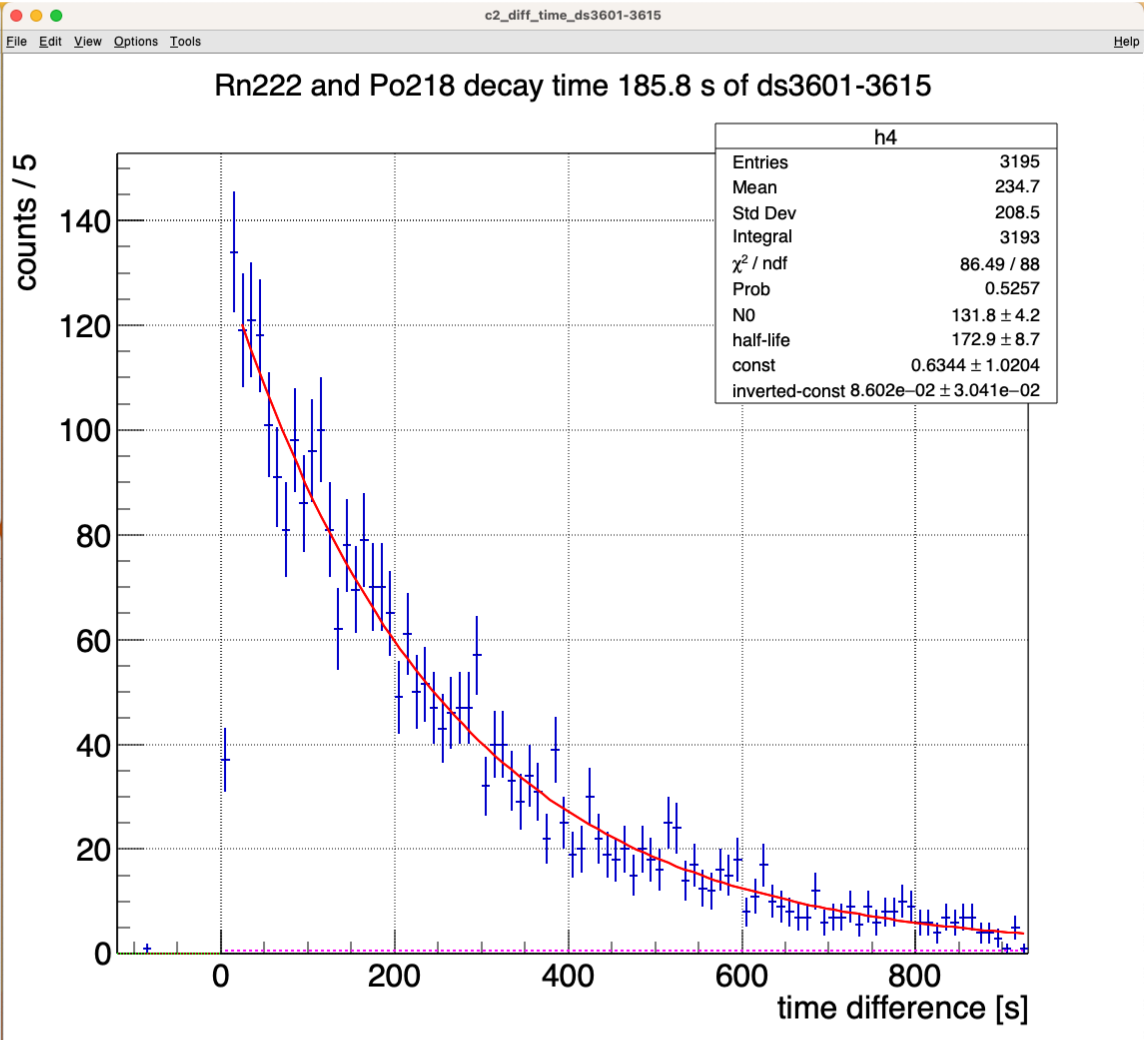




$[\ Q_\alpha \times F_Q - \Delta E\ ,\ E_{\mathrm{high\_thresh}}\ ]$ $\Delta E = $ **60 keV**

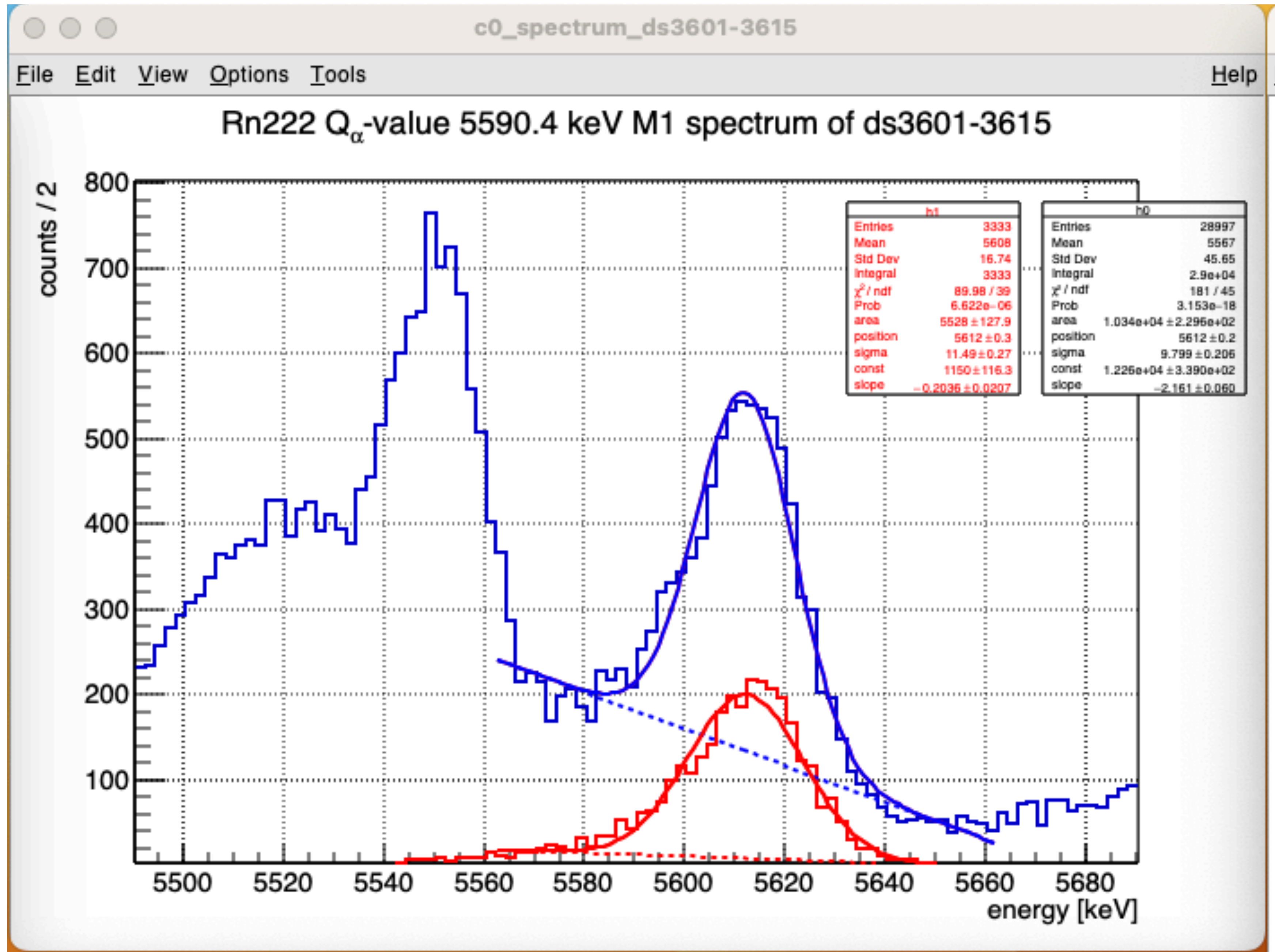


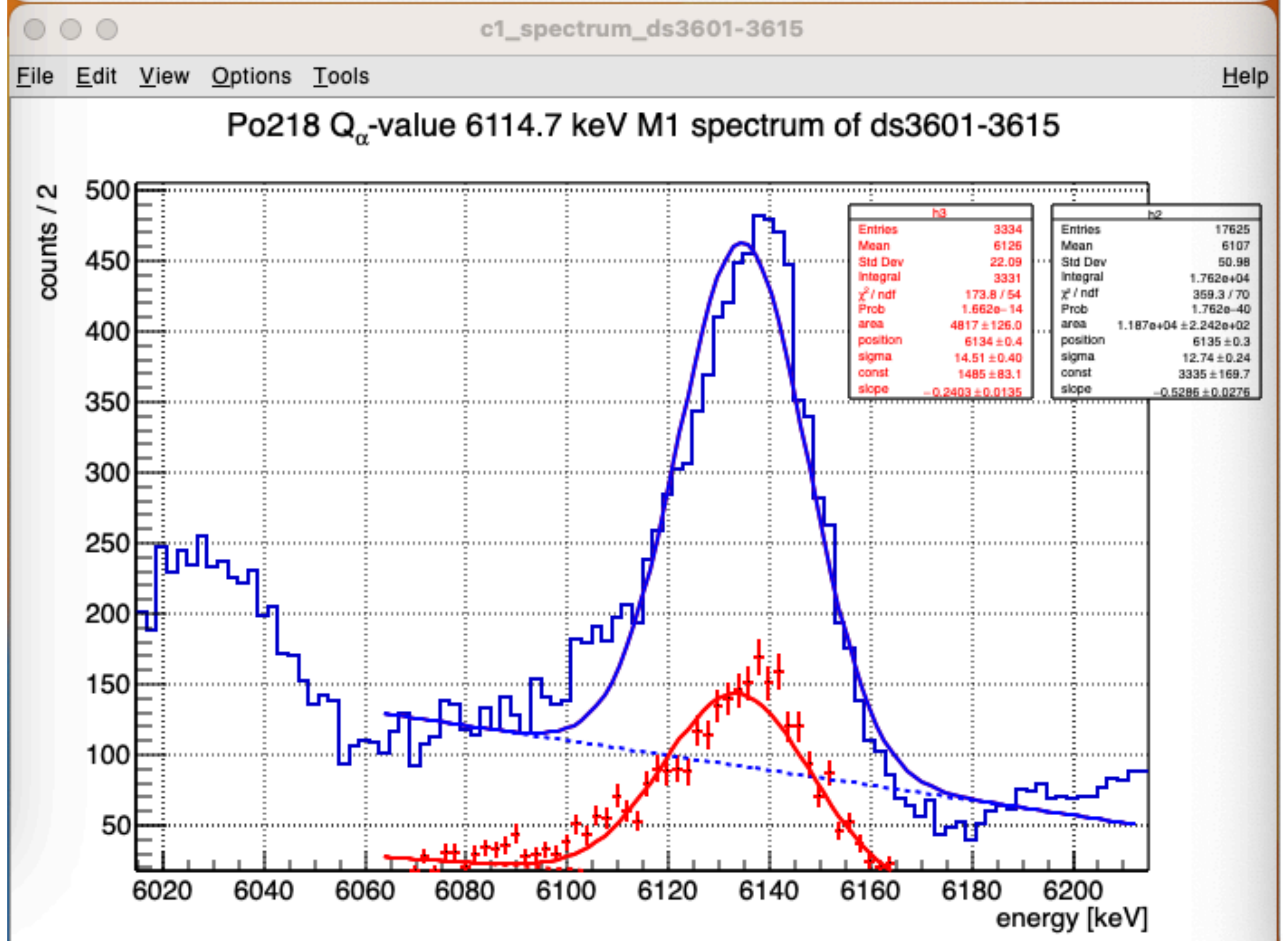


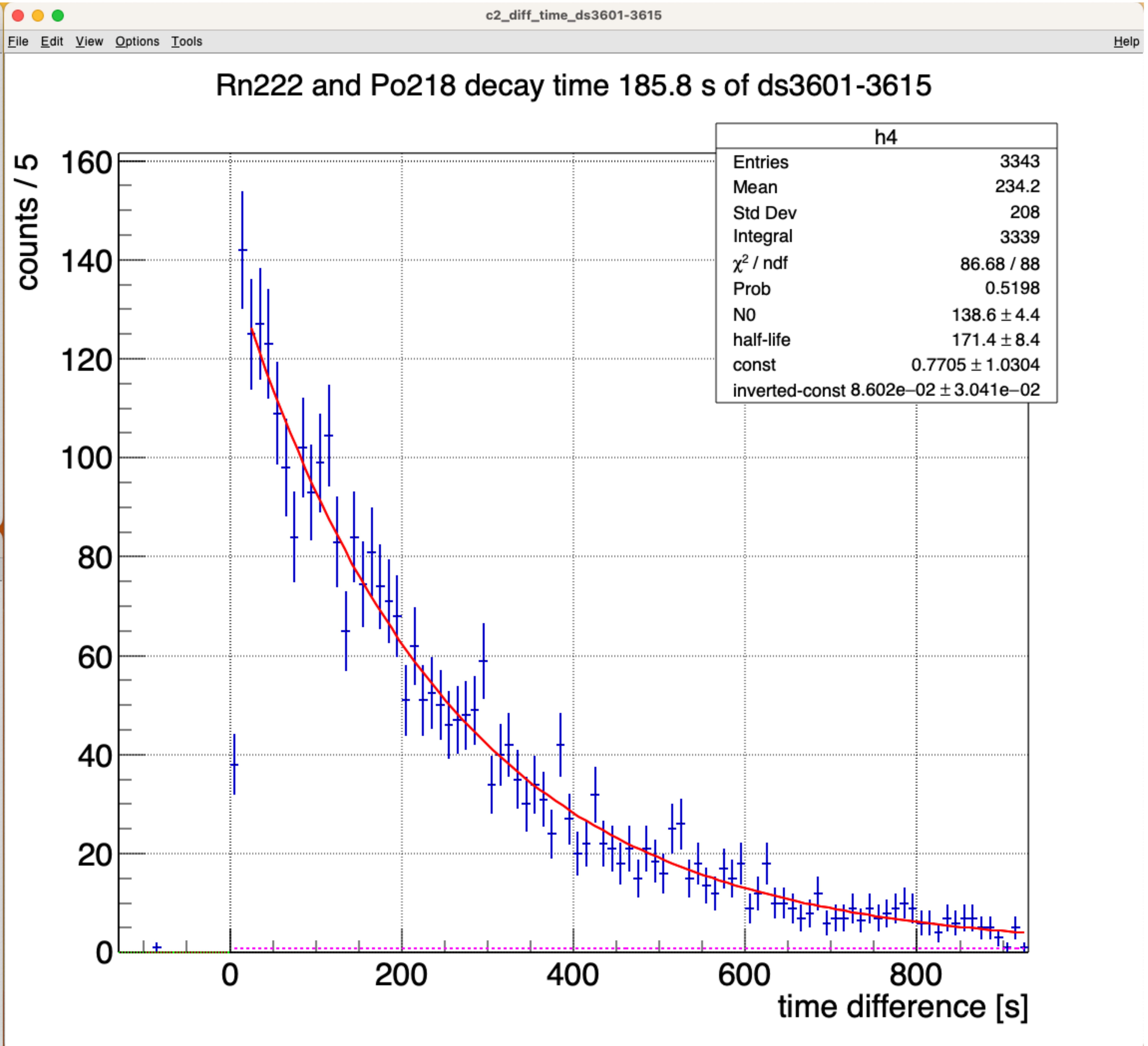


$$[\ Q_\alpha \times F_Q - \Delta E\ ,\ E_{\text{high\_thresh}}\ ]$$

$\Delta E =$ **70 keV**

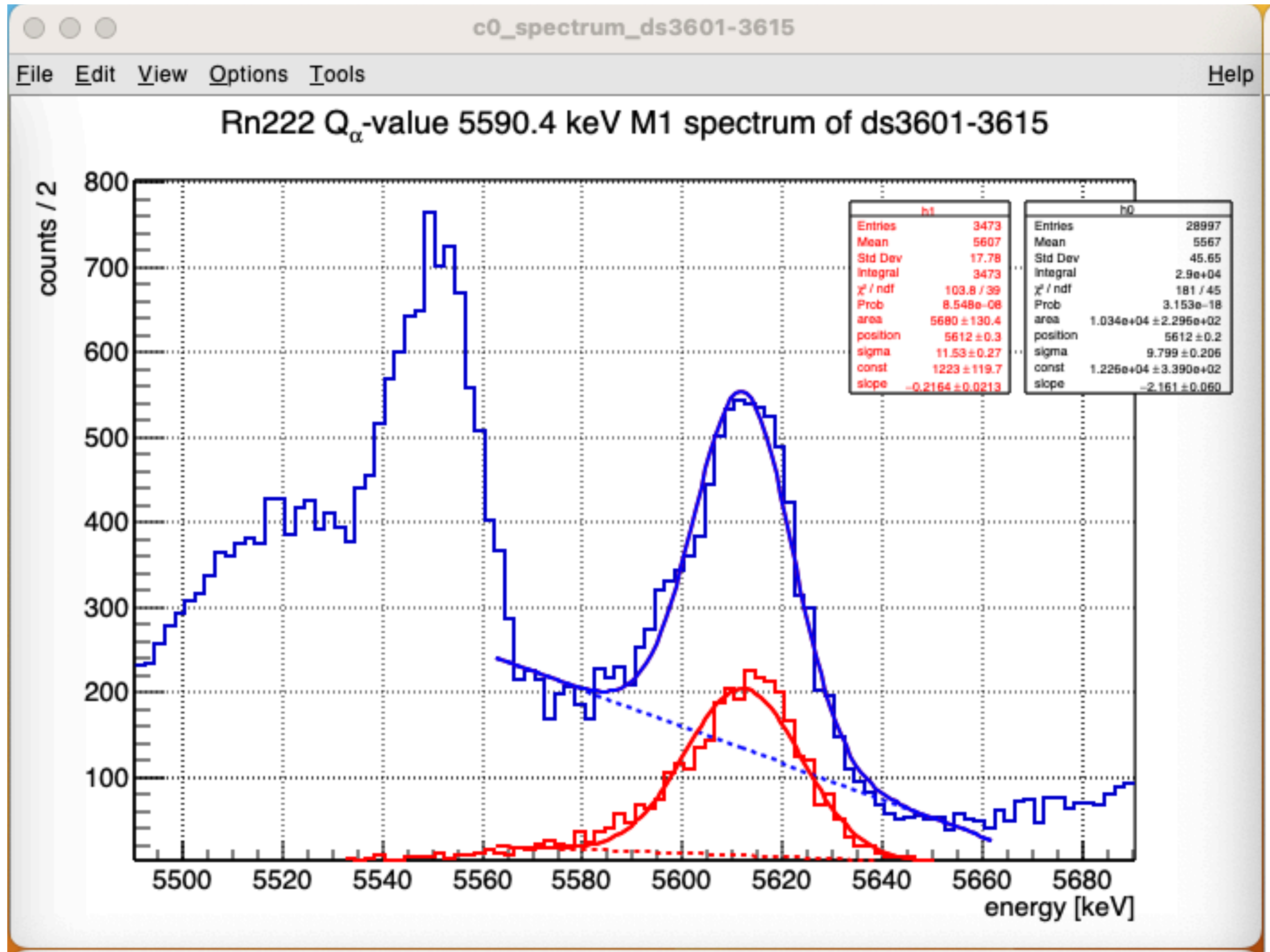


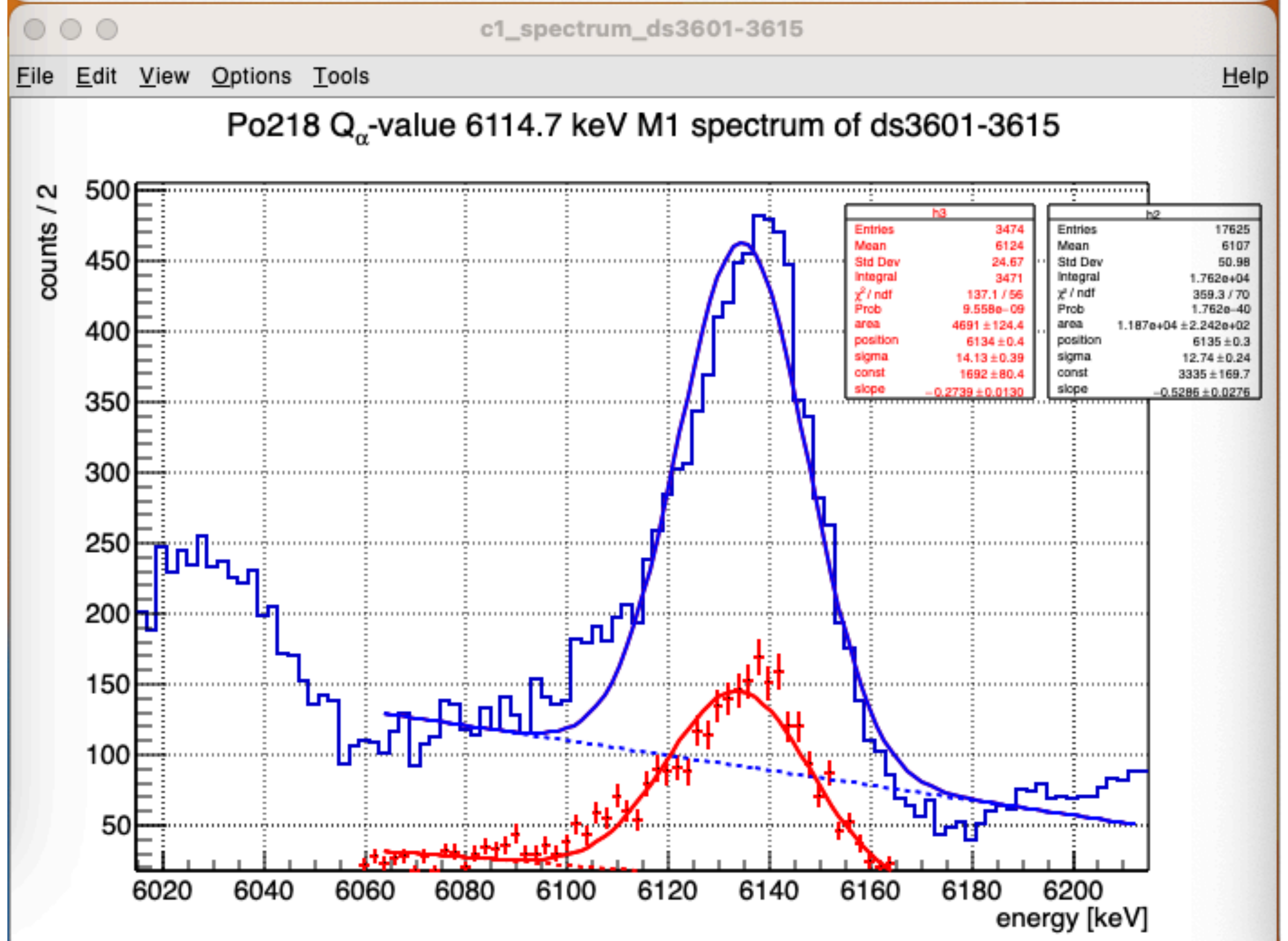


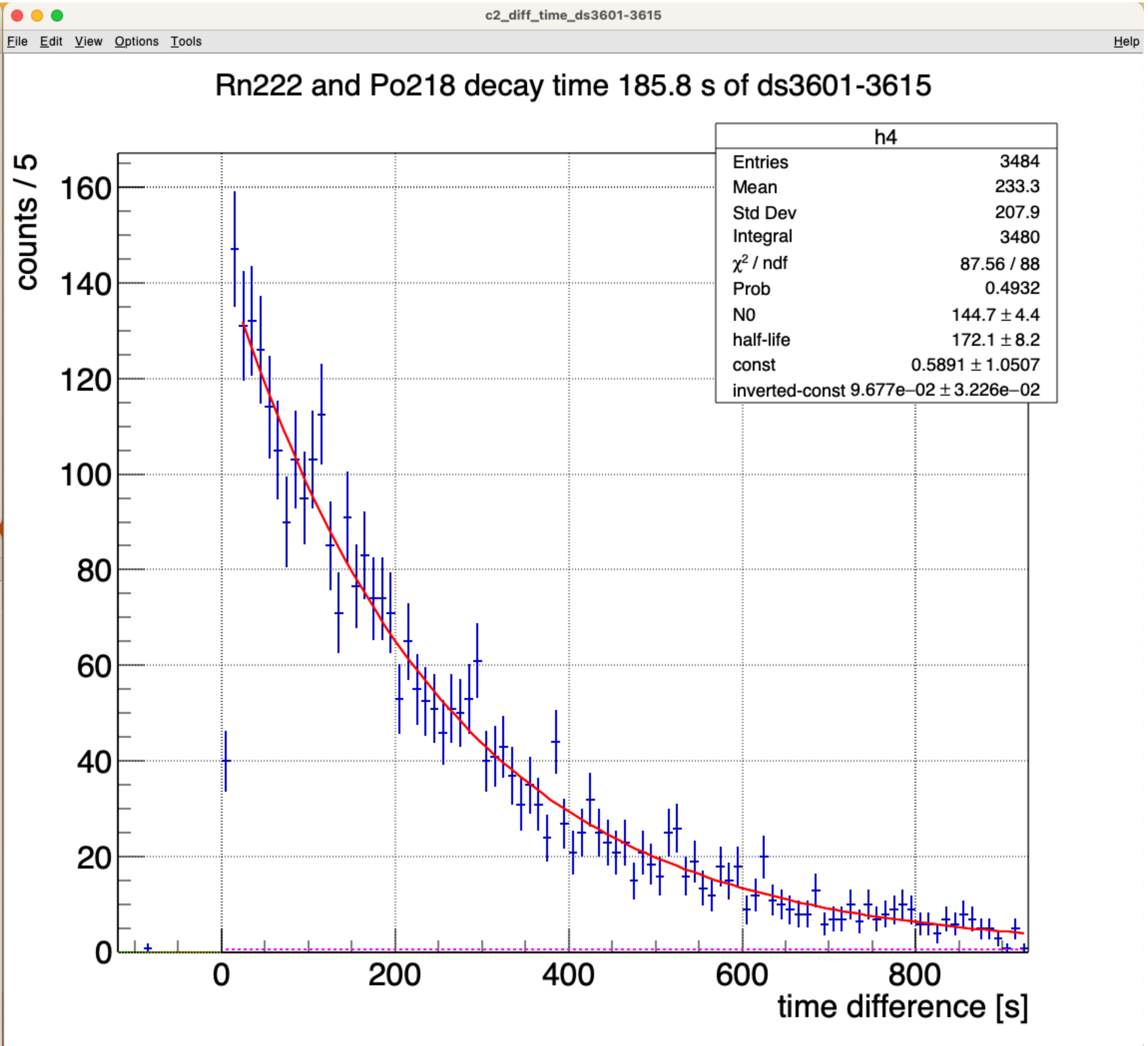


$[\; Q_\alpha \times F_Q - \Delta E \;,\; E_{\text{high\_thresh}} \;]$

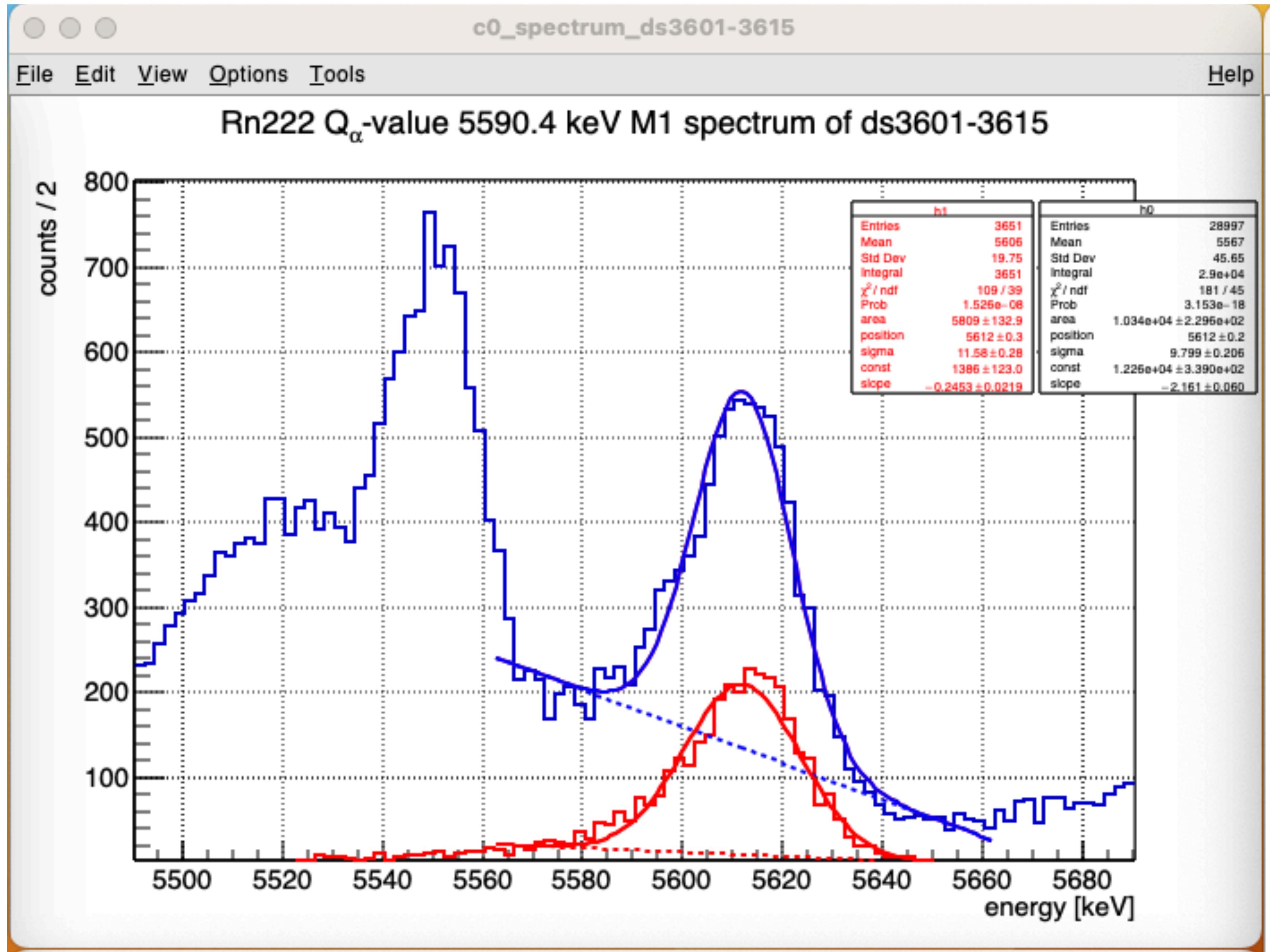
ΔE = **80 keV**

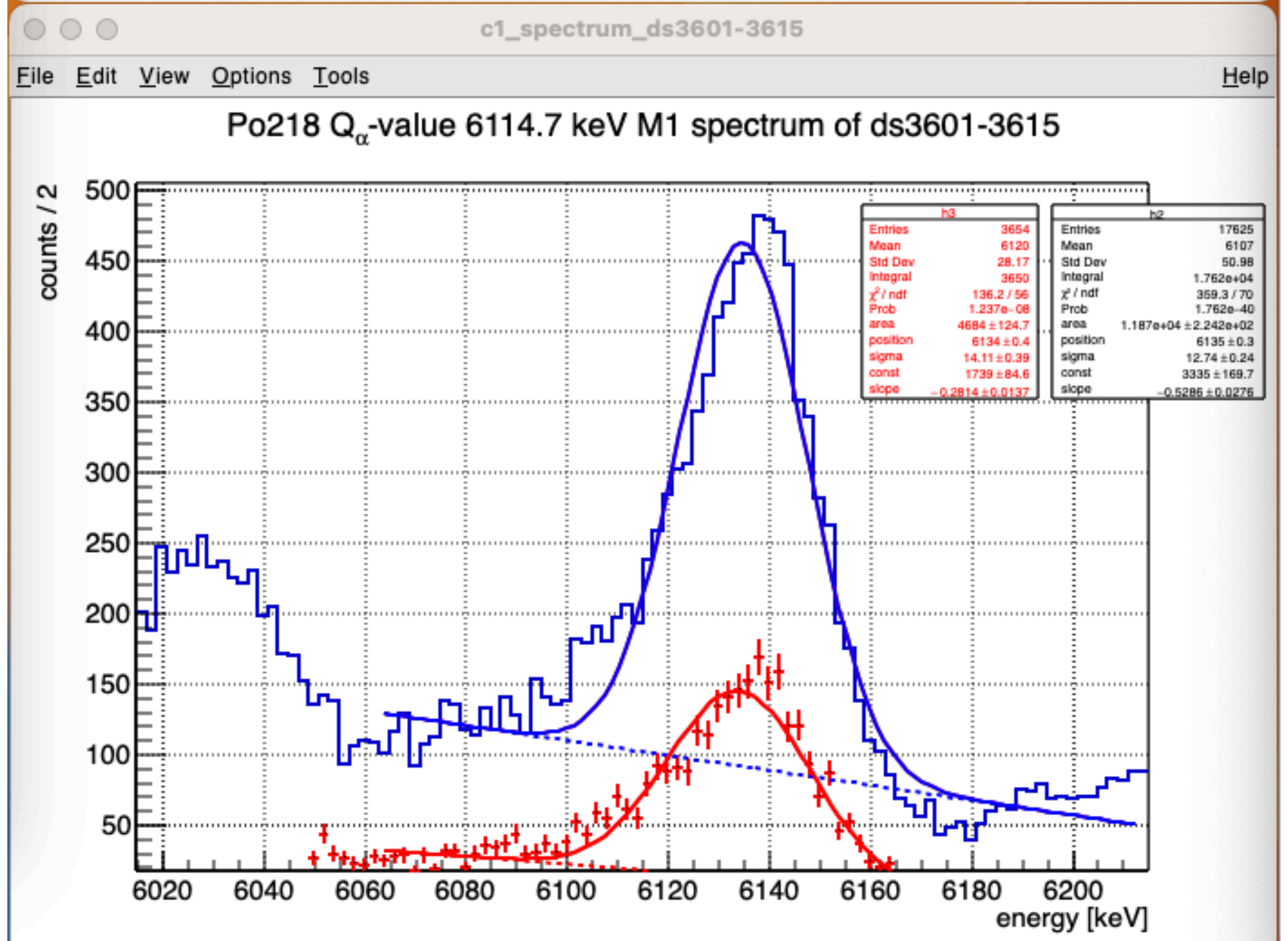


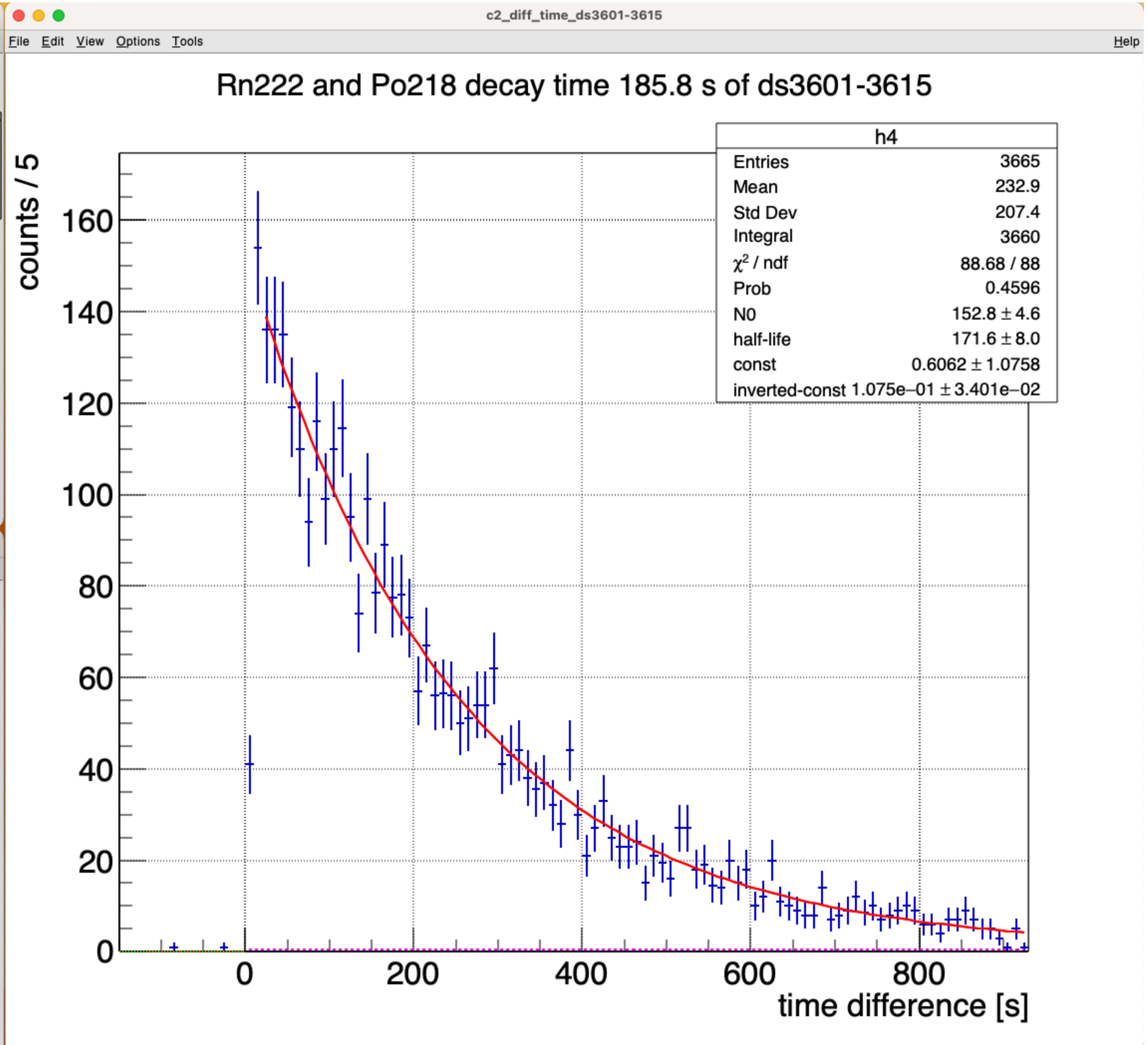




$[\ Q_\alpha \times F_Q - \Delta E\ ,\ E_{high\_thresh}\ ]$ ΔE = **90 keV**

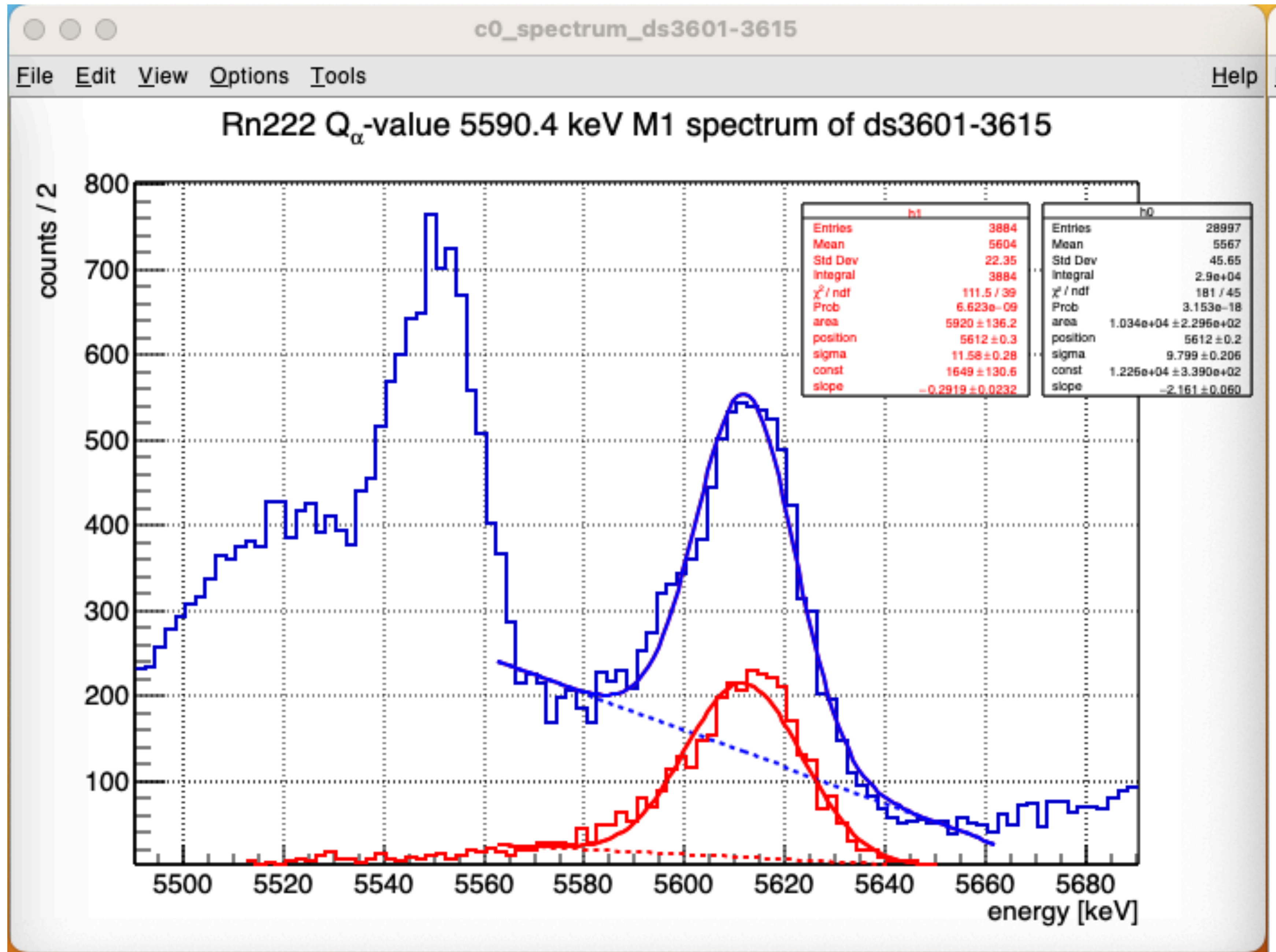


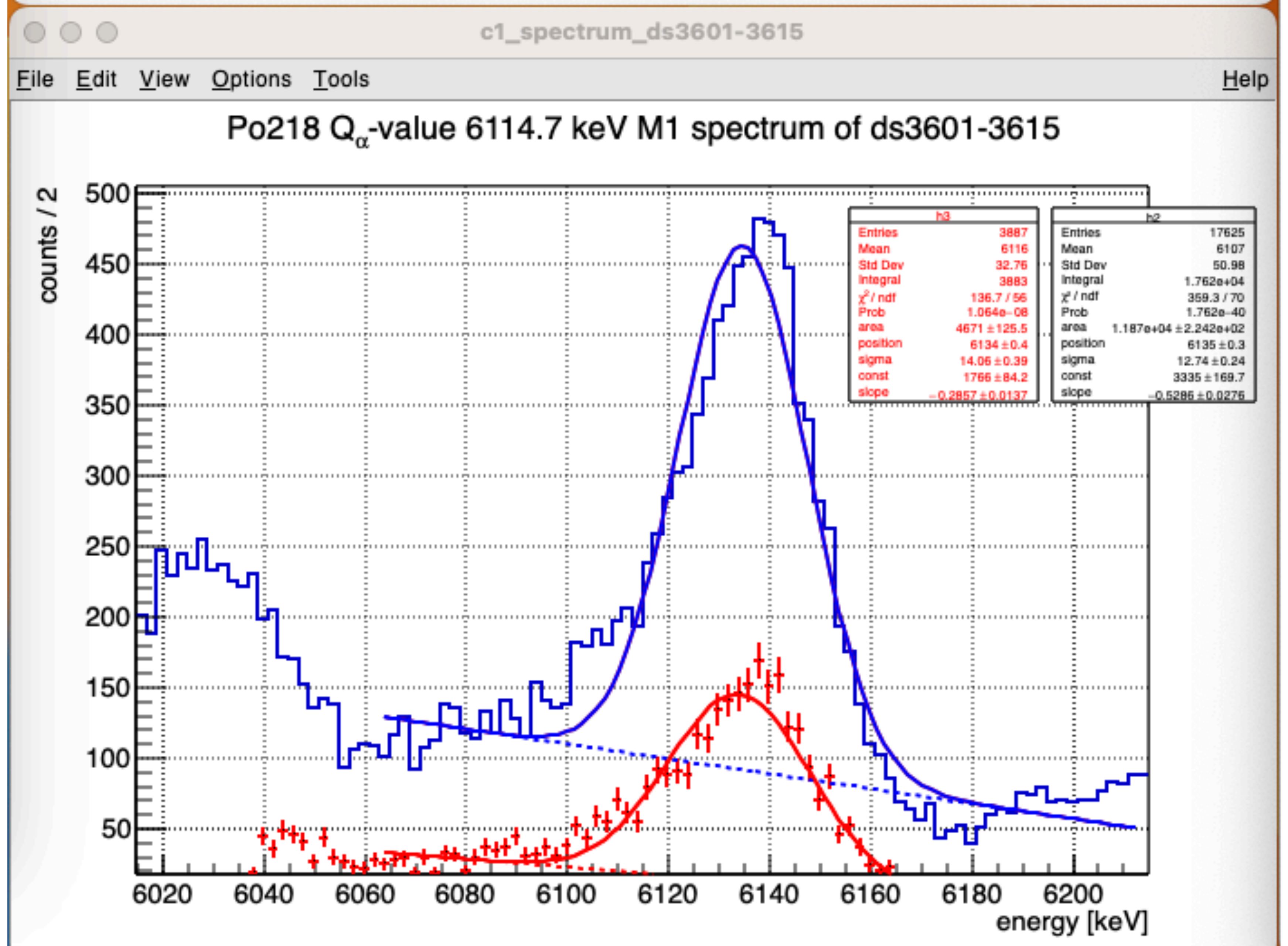


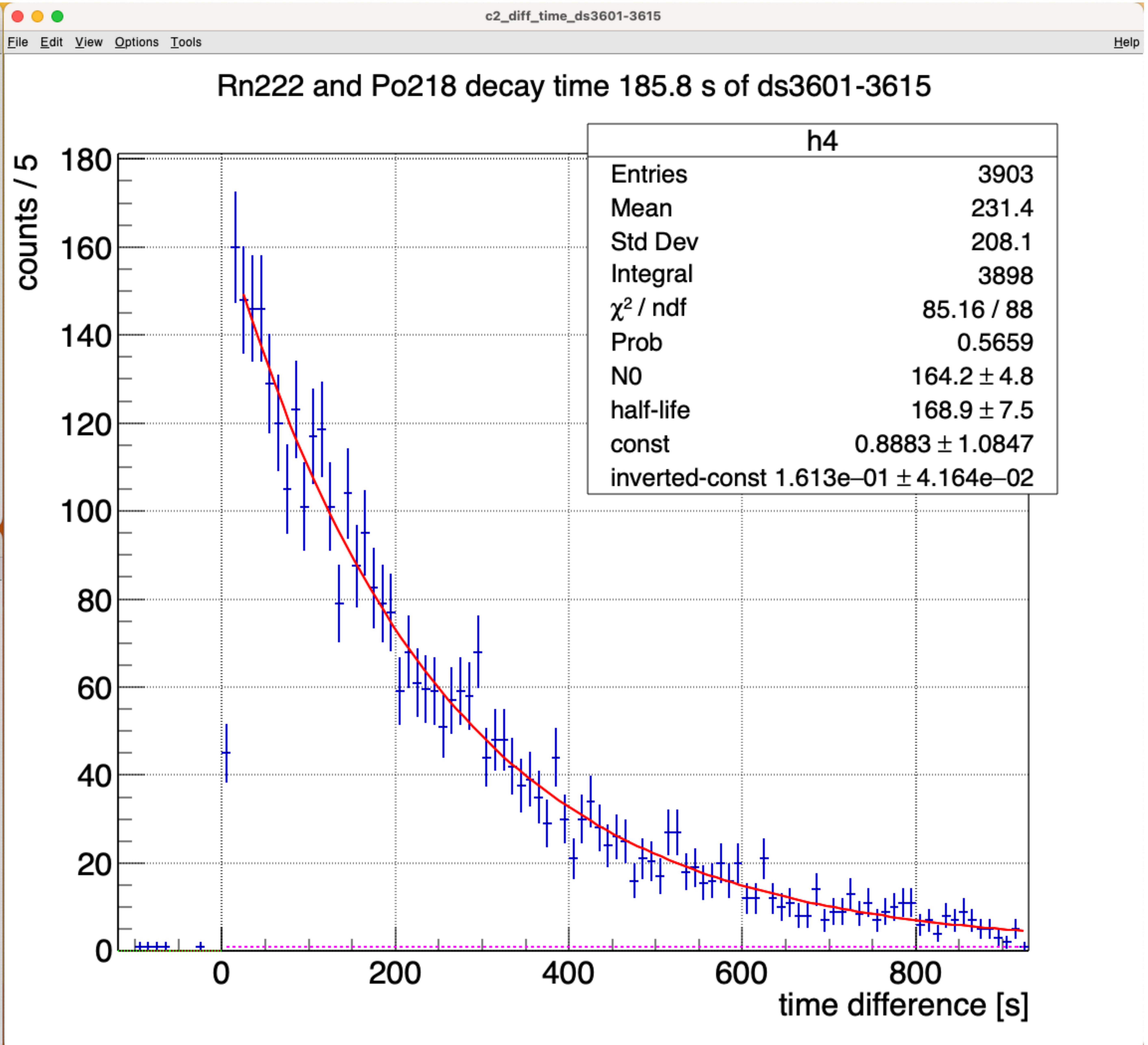


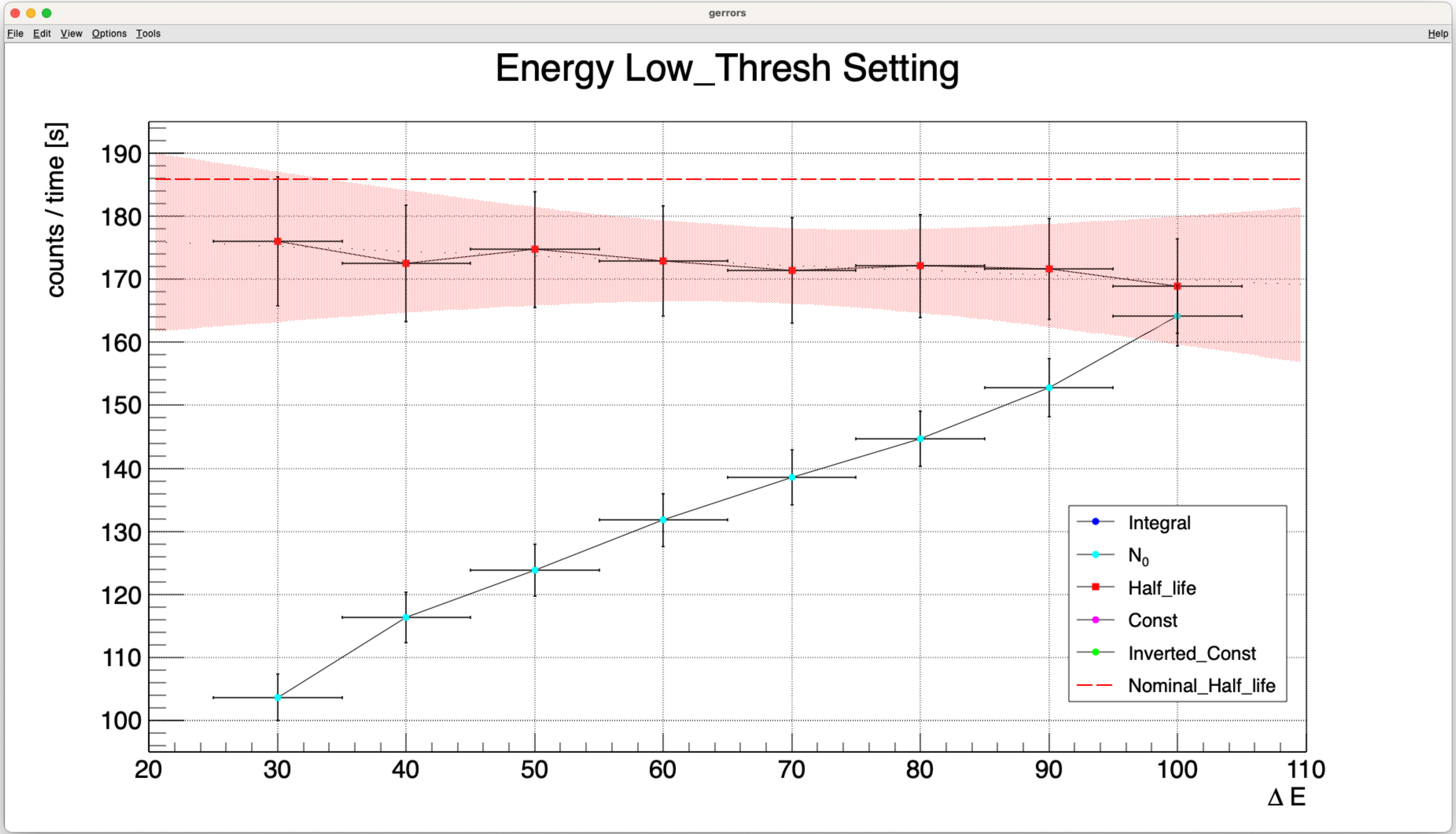
$$[\ Q_\alpha \times F_Q - \Delta E\ ,\ E_{\text{high\_thresh}}\ ]$$

$\Delta E =$ **100 keV**





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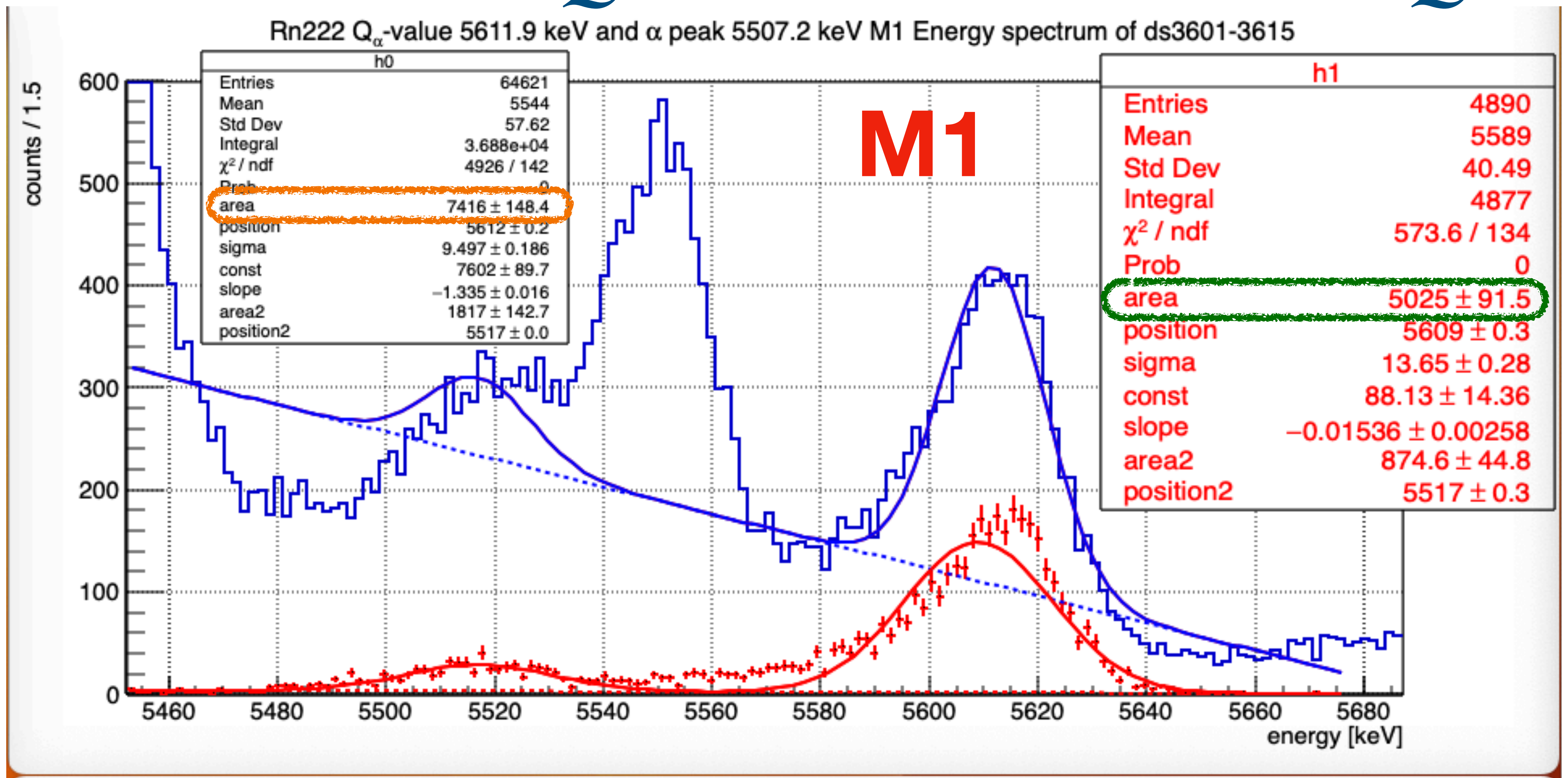
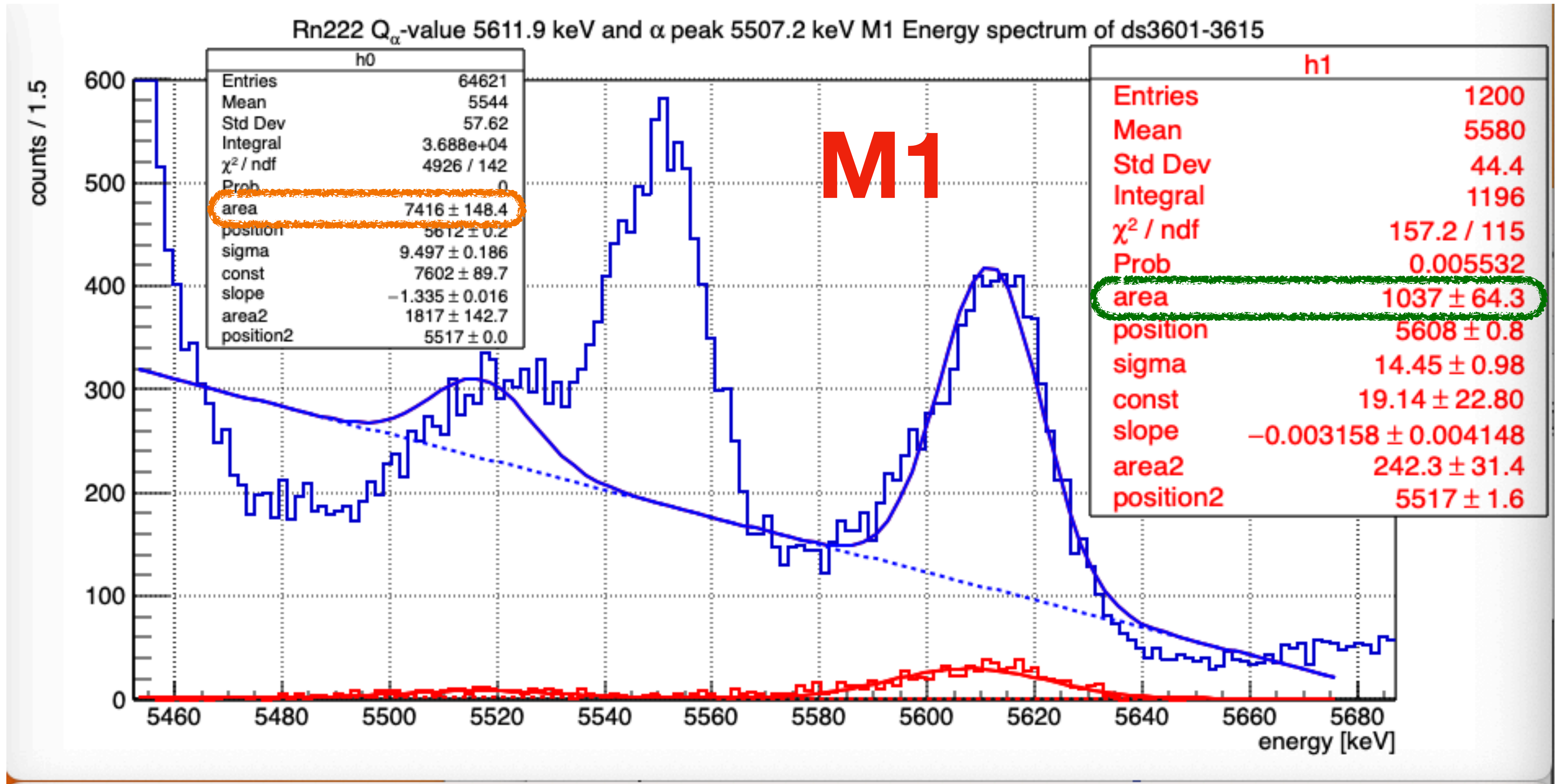
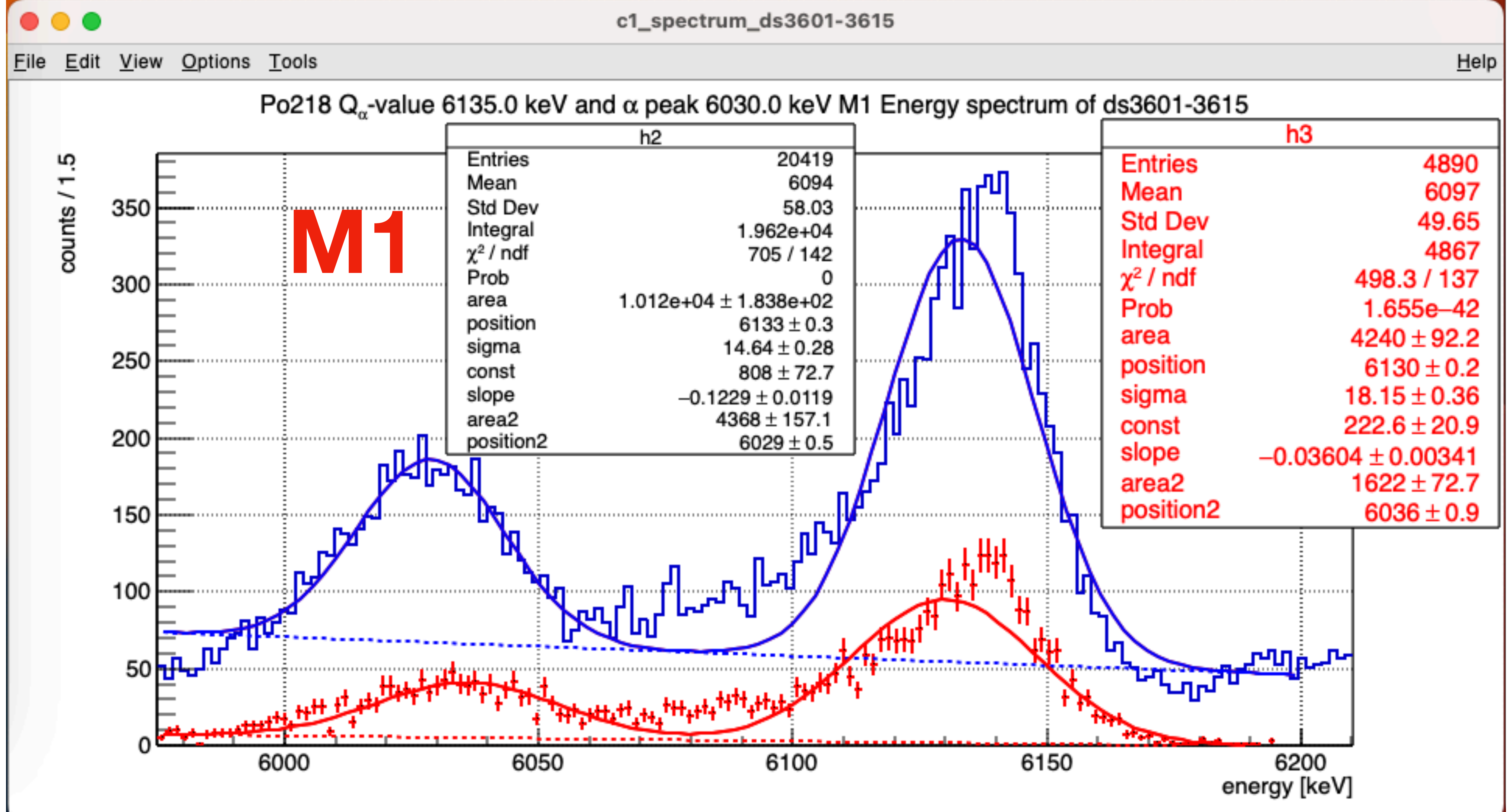
File Edit View Options Tools
Help
Energy Low_Thresh Setting
counts / time [s]
190
180
170
160
150
140
130
120
110
100
20
30
40
50
60
70
80
90
100
110
Δ E
Integral
N0
Half_life
Const
Inverted_Const
Nominal_Half_life

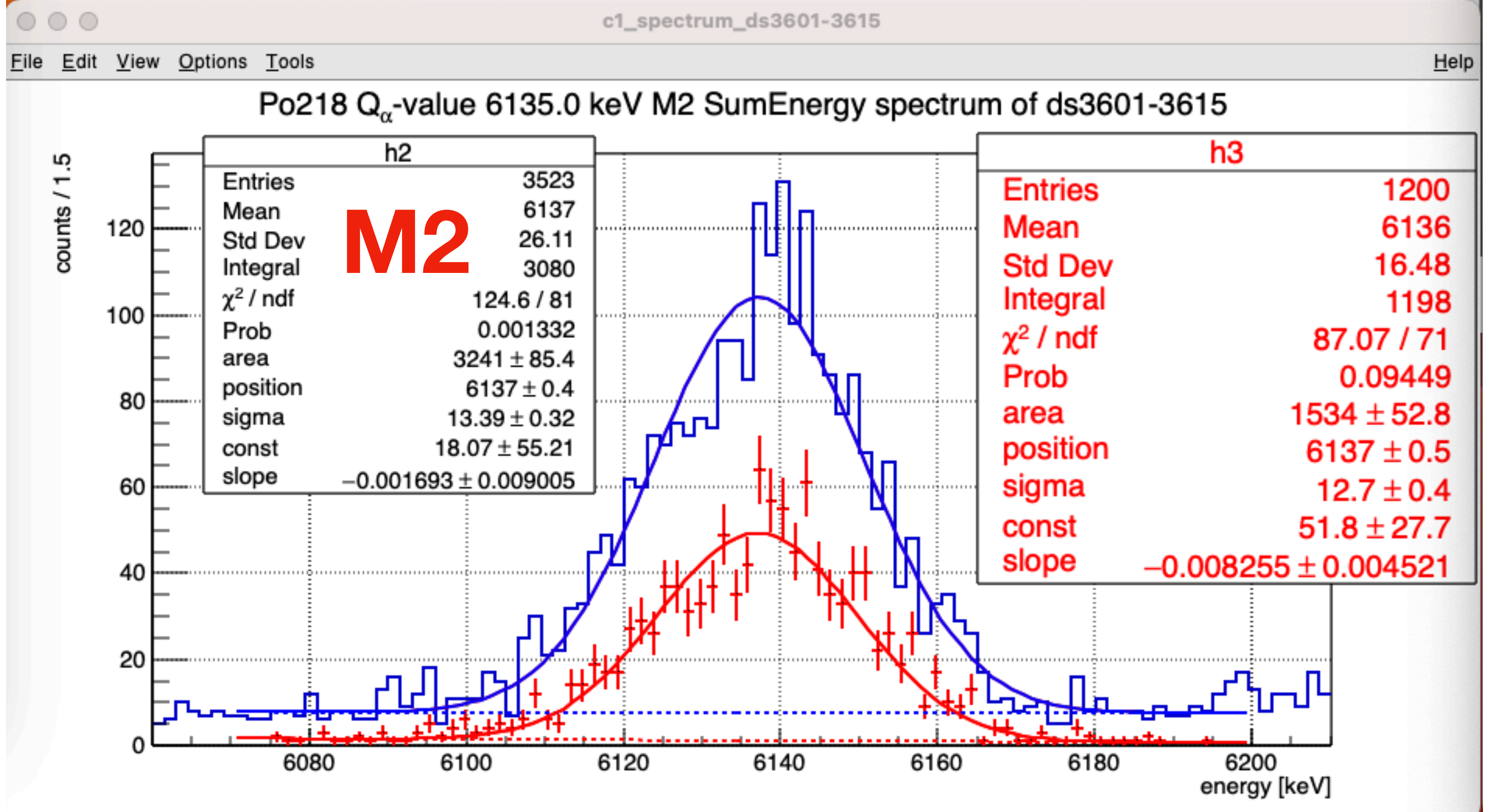
Analysis of $^{222}\mathrm{Rn} \to {}^{218}\mathrm{Po}$ DC Energy cut including α-only peak

$$[\ E_\alpha \times F_Q - \Delta E\ ,\ Q_\alpha \times F_Q + \Delta E\ ]\quad \Delta E = 60\ \text{keV}$$









Delayed Coincidence Δt background study

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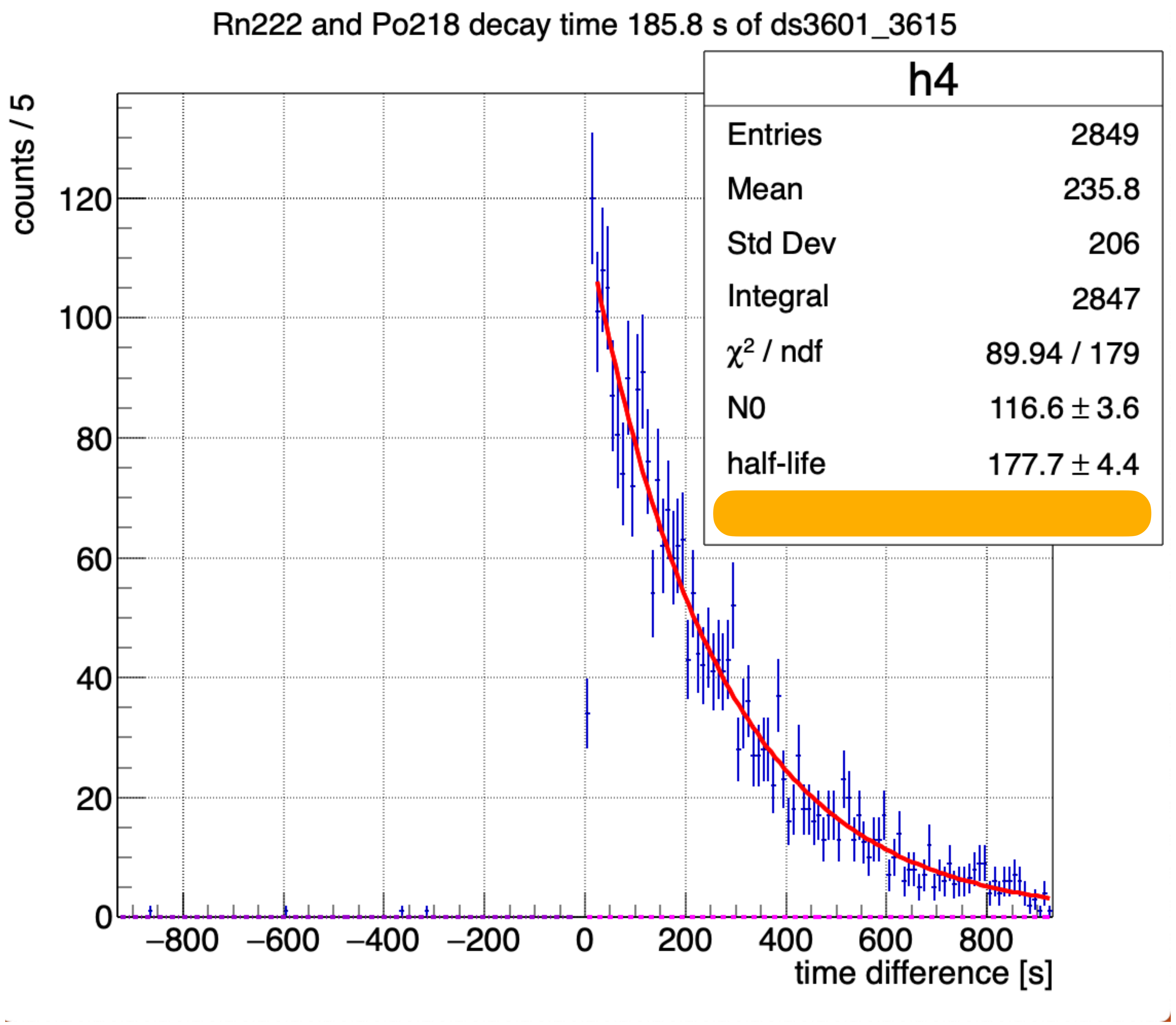
Delayed Coincidence background study

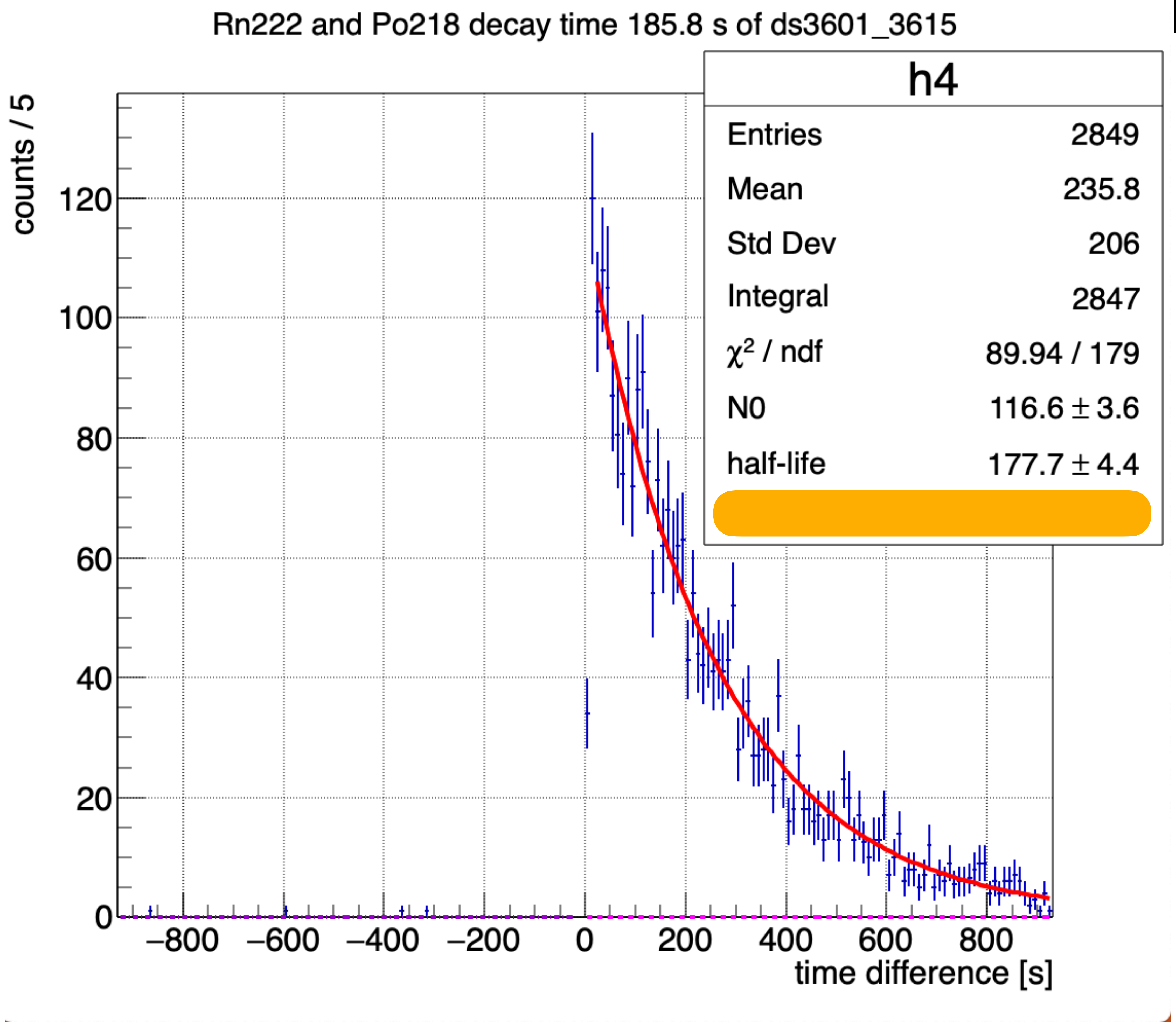
Time difference histogram



- When $\Delta t > 0$, it means that a daughter event happened after the corresponding parent event.
- For the ideal case, the Δt should follow an exponential distribution with a compatible $T_{1/2}$.
- Therefore, it is reasonable to use an exponential function to fit the results.
- $$N(\Delta t) = N_0 \times \exp\left(\frac{-\ln(2) \times \Delta t}{T_{1/2}}\right)$$

Delayed Coincidence background study

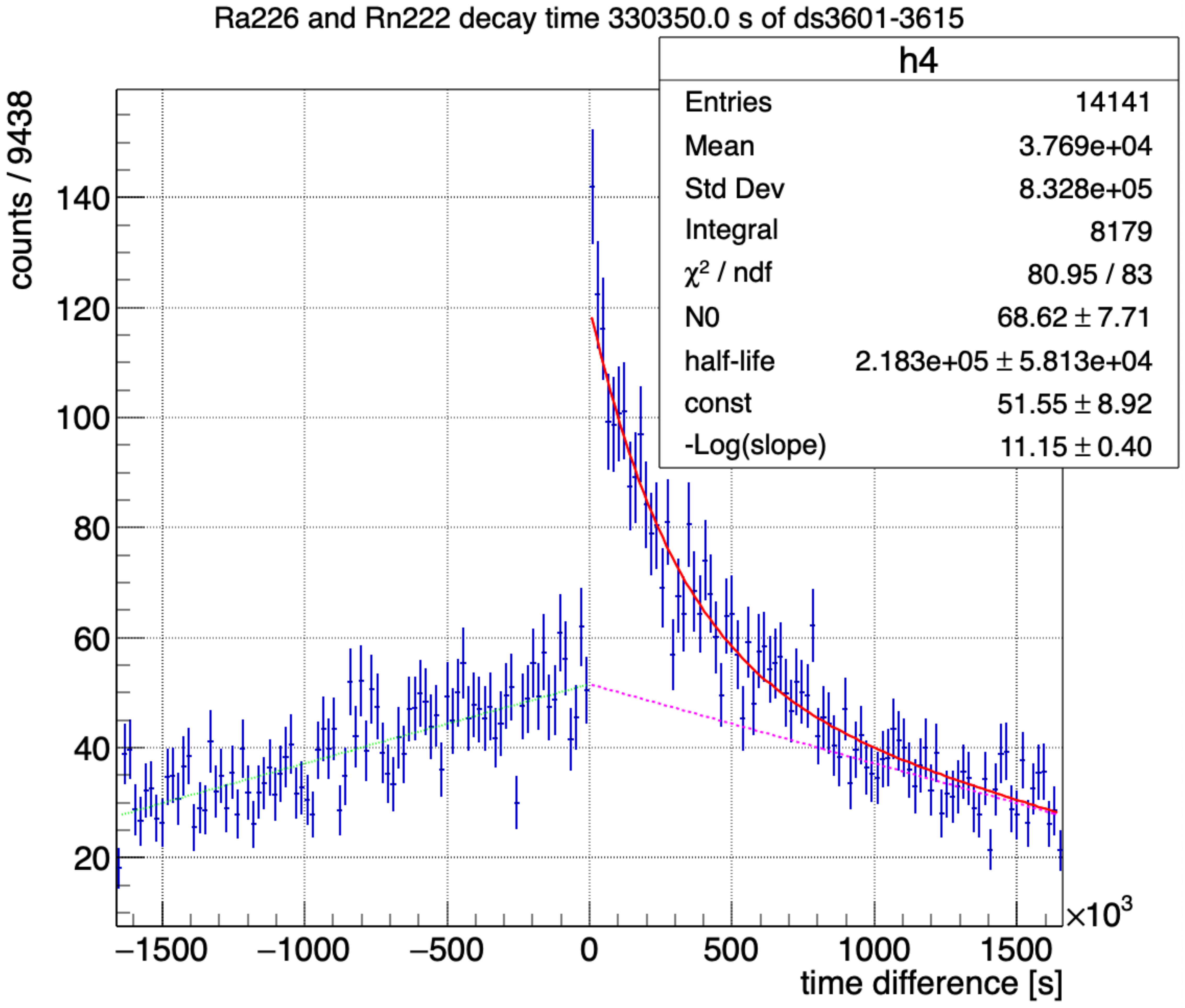
Time difference histogram



- When $\Delta t < 0$, it means that a daughter event happened before the corresponding parent event, which should not happen. So, it does not follow the exponential.
- It can be the incorrect linking among a daughter event and another event which is coming from some other sources. And equivalently, it also reflects the extent of defect on the right side.
- For this $^{222}\mathrm{Rn} \rightarrow {}^{218}\mathrm{Po}$ pair, we have quite few such events happening. Hence, in order to evaluate the background level of both sides, I added a term of constant in my function.
- $$N(\Delta t) = \begin{cases} N_0 \times \exp\left(\frac{-\ln(2) \times \Delta t}{T_{1/2}}\right) + Bkg & \Delta t > 0 \\ Bkg & \Delta t < 0 \end{cases}$$

Delayed Coincidence background study

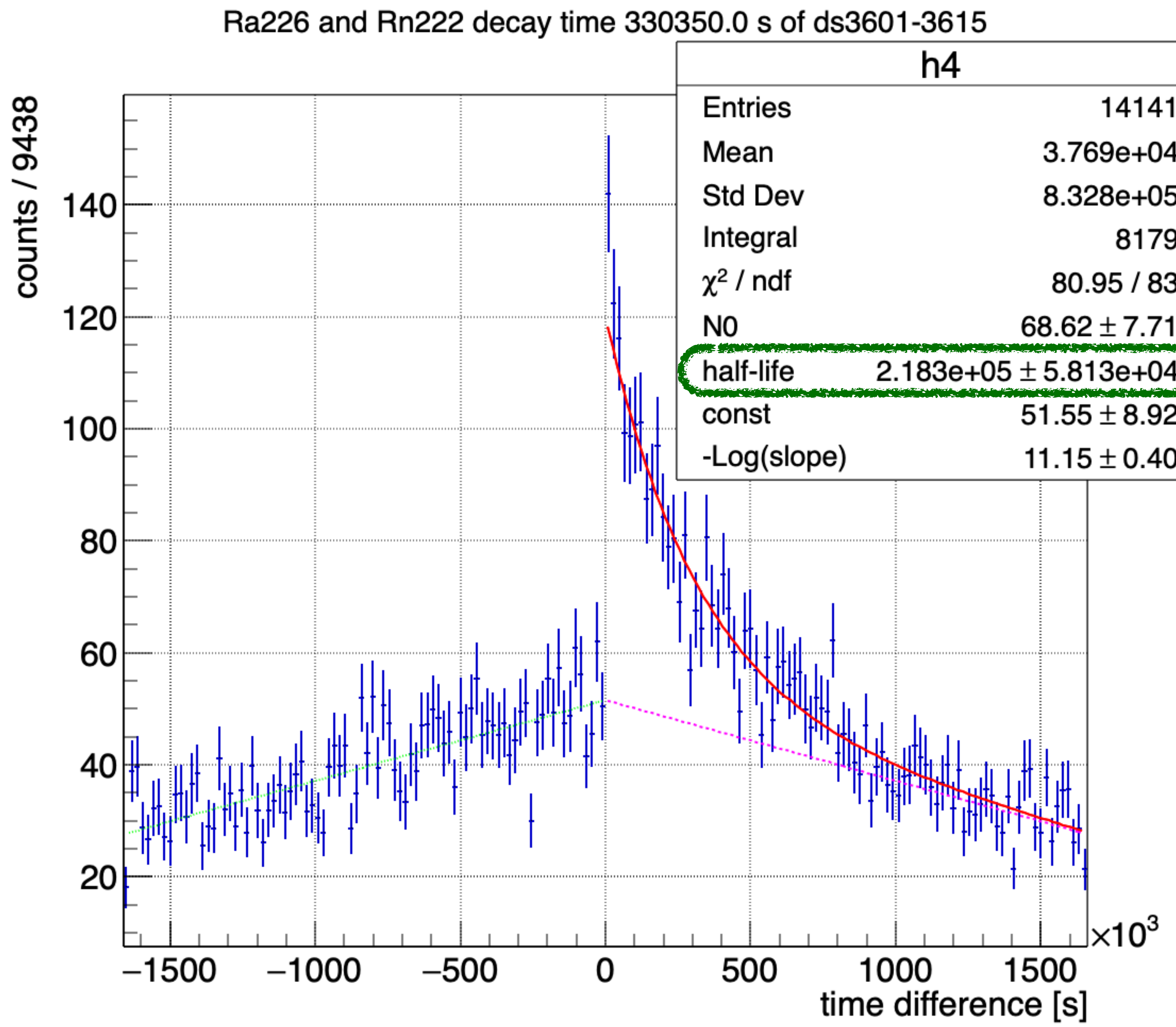
Time difference histogram

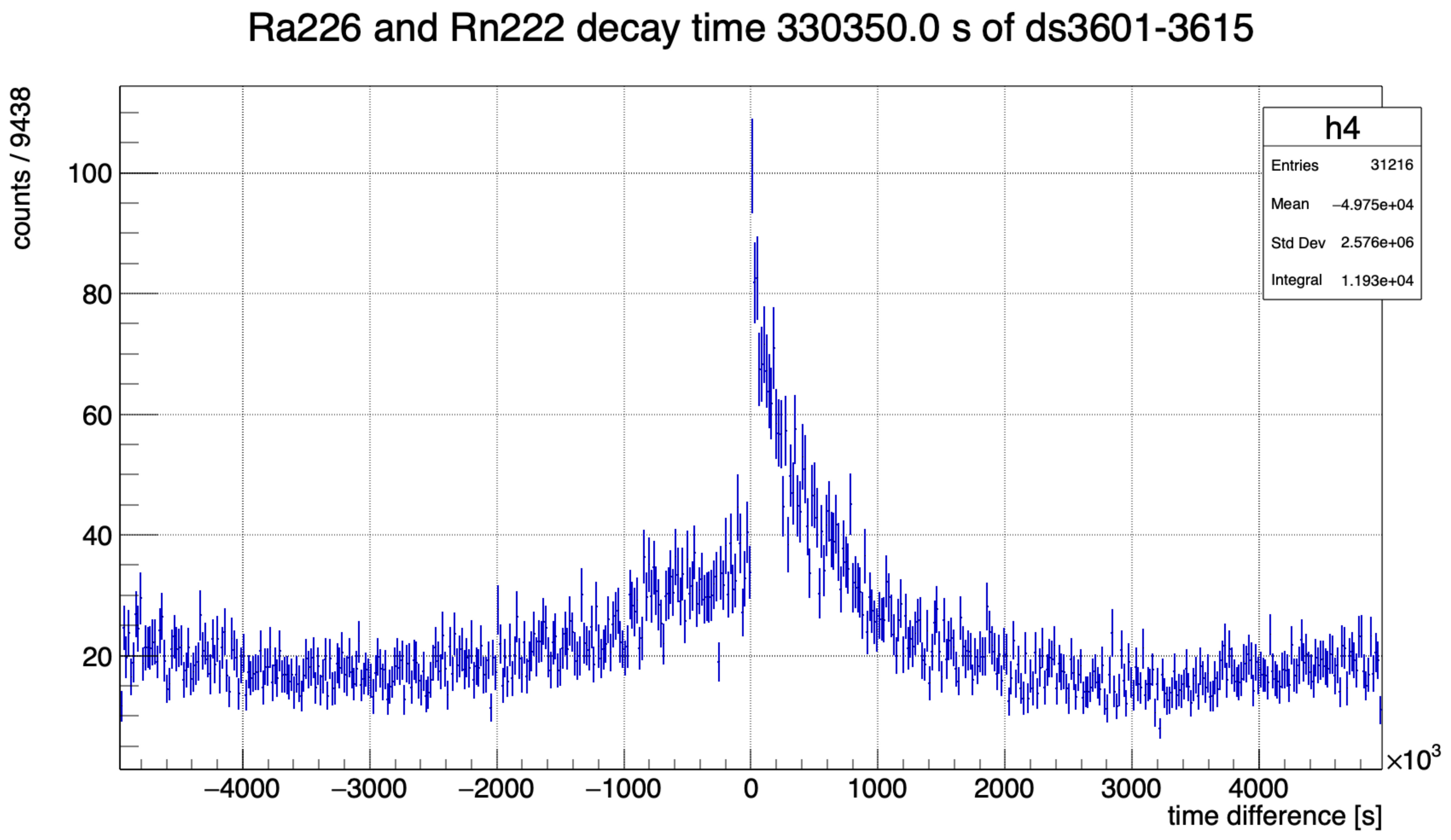


- However, for $^{226}\mathrm{Ra} \rightarrow {}^{222}\mathrm{Rn}$ pair, since the $T_{1/2}$ is ~ 3.8 days, when I search for the Delayed Coincidence events using the same method, I have much higher $\Delta t < 0$ background level.
- And the histogram shape is not constant any more. But it looks like a straight line.
- So, I decide to use a liner function for the background fitting.
- The slope is small enough, it is better to use its logarithm $[-\ln(slope)]$ to present its variation.
- $$N(\Delta t) = \begin{cases} N_0 \times \exp(\frac{-\ln(2) \times \Delta t}{T_{1/2}}) + const + slope \times \Delta t & \Delta t > 0 \\ const + \exp(-[-\ln(slope)]\ ) \times \Delta t & \Delta t < 0 \end{cases}$$

Delayed Coincidence background study

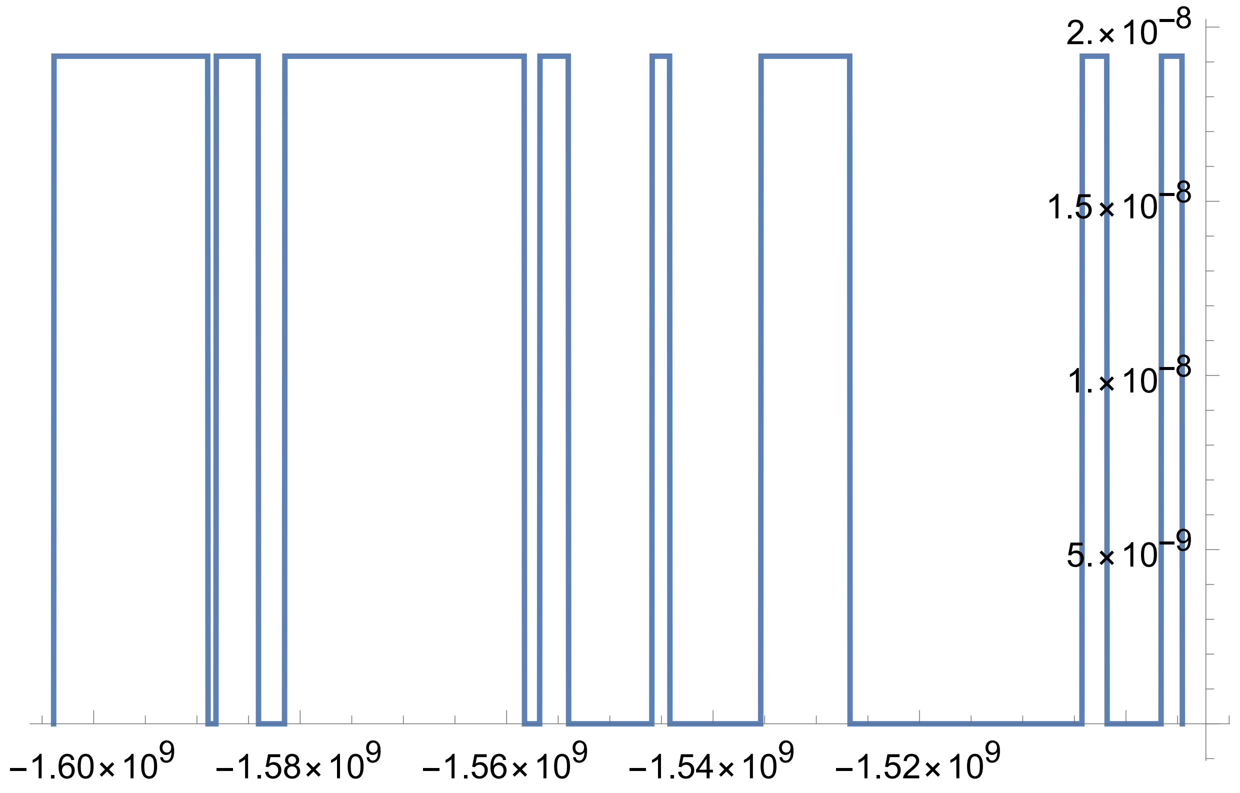
- Although, the description of background shape is very well, the fitted $T_{1/2}$ is still far away from the nominal value.
- I thought the triangular background should finish at some point, then I enlarged my Δt window limits from $5 \times T_{1/2}$ to $15 \times T_{1/2}$.
- The odd thing happened, the background starts to grow up from somewhere.



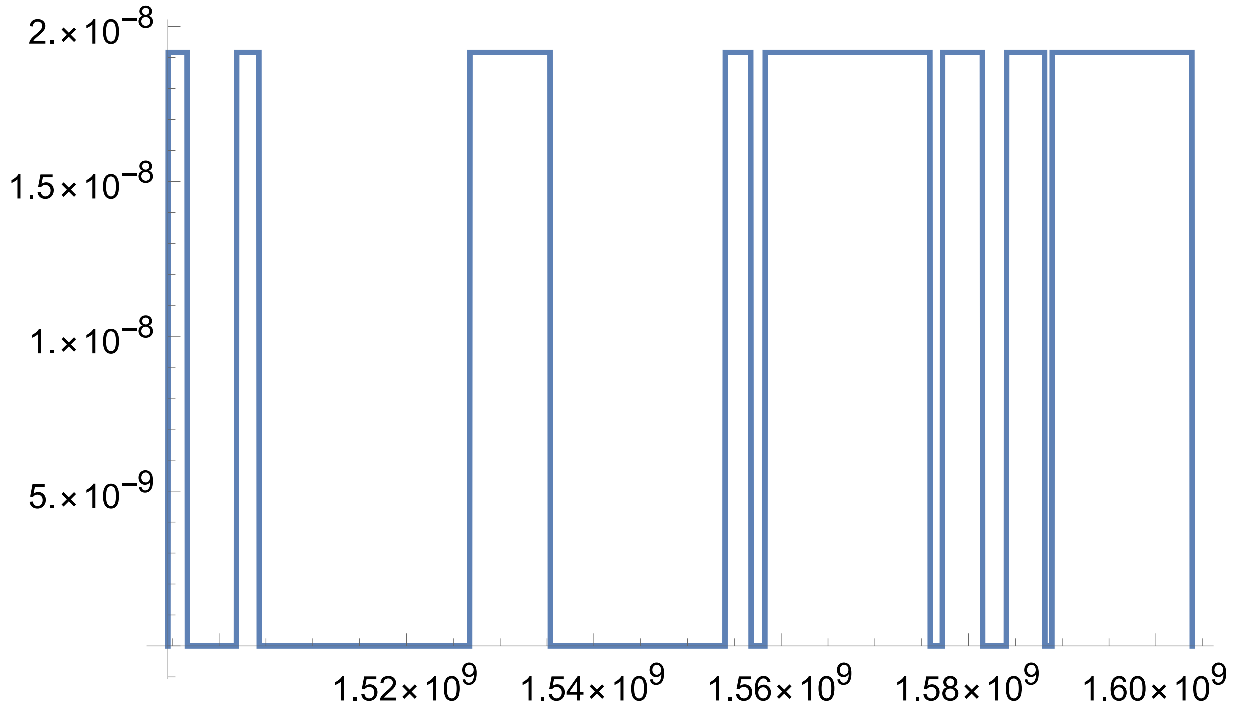


$$f_{\Delta T}(\Delta t) = \mathscr{F}^{-1}\Big\{ -\frac{1}{4\pi^2\nu^2 \cdot \text{EXPOSURE}^2} \sum_{n=1}^{15}\sum_{m=1}^{15} \Big(2\cos(2\pi\nu\cdot(T_{fn}-T_{im})) - \cos(2\pi\nu\cdot(T_{fn}-T_{fm})) - \cos(2\pi\nu\cdot(T_{in}-T_{im})) \Big) \Big\}(\Delta t)$$

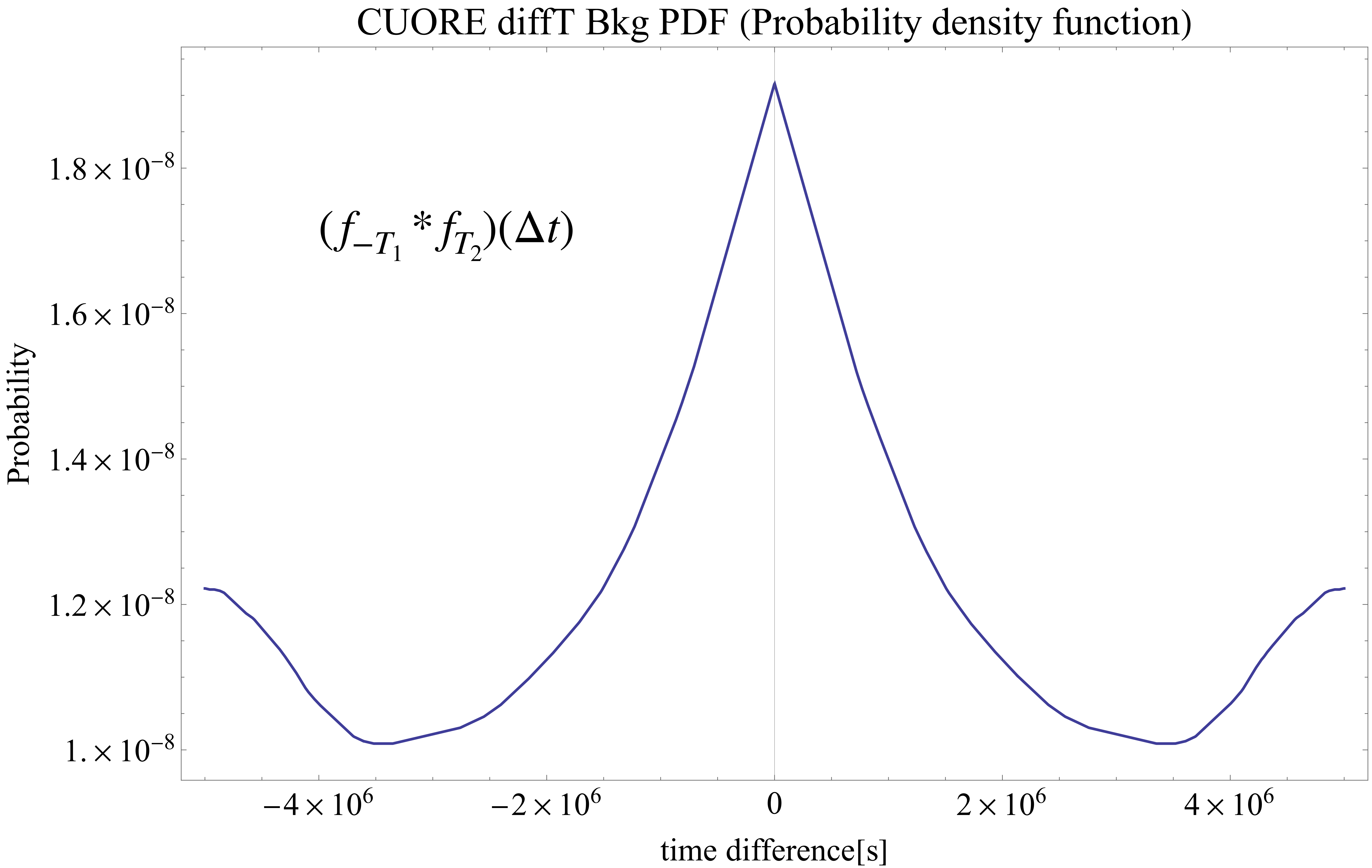
Convolution



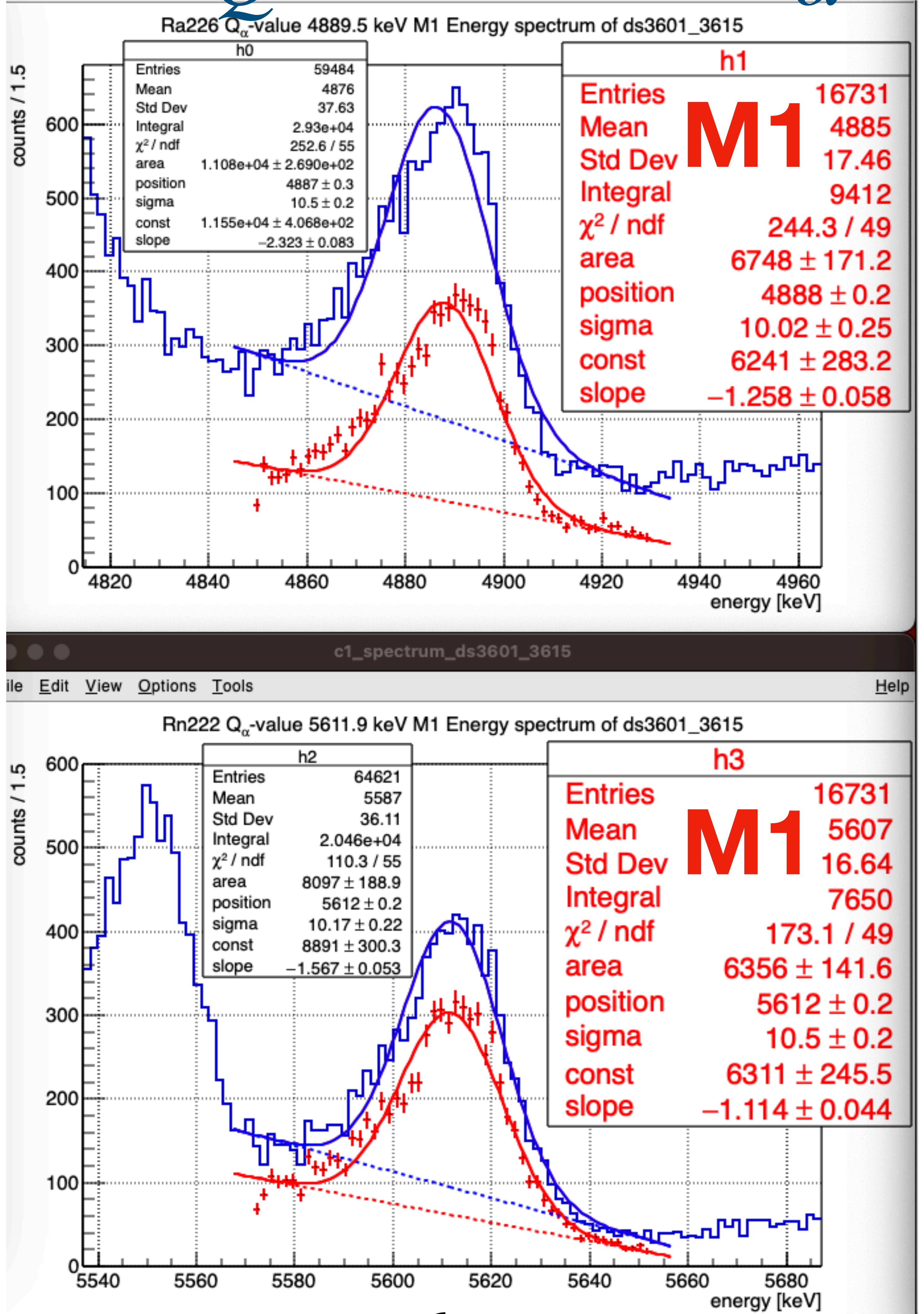
$f_{-T_1}(-t_1)$

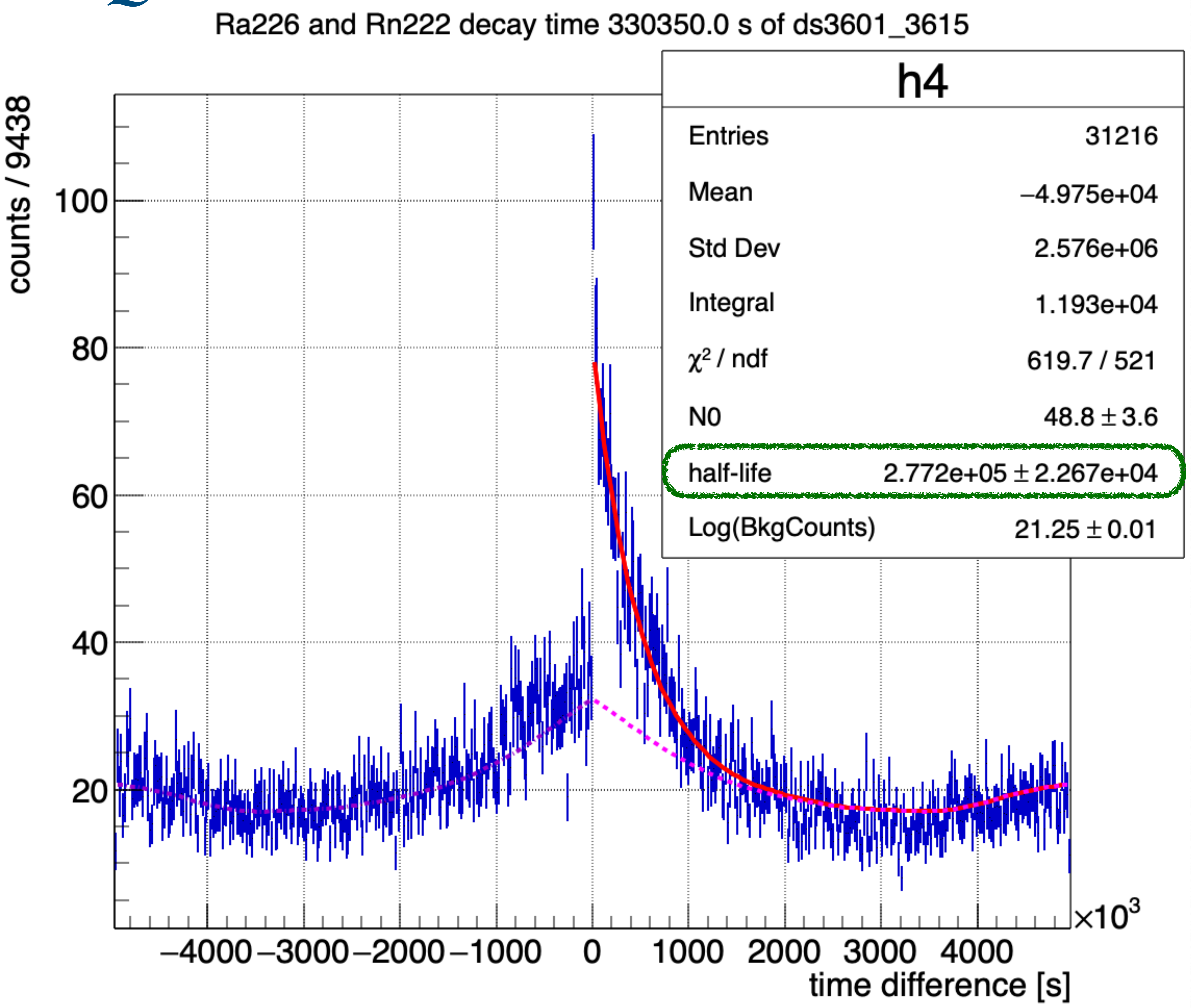


$f_{T_2}(t_2)$



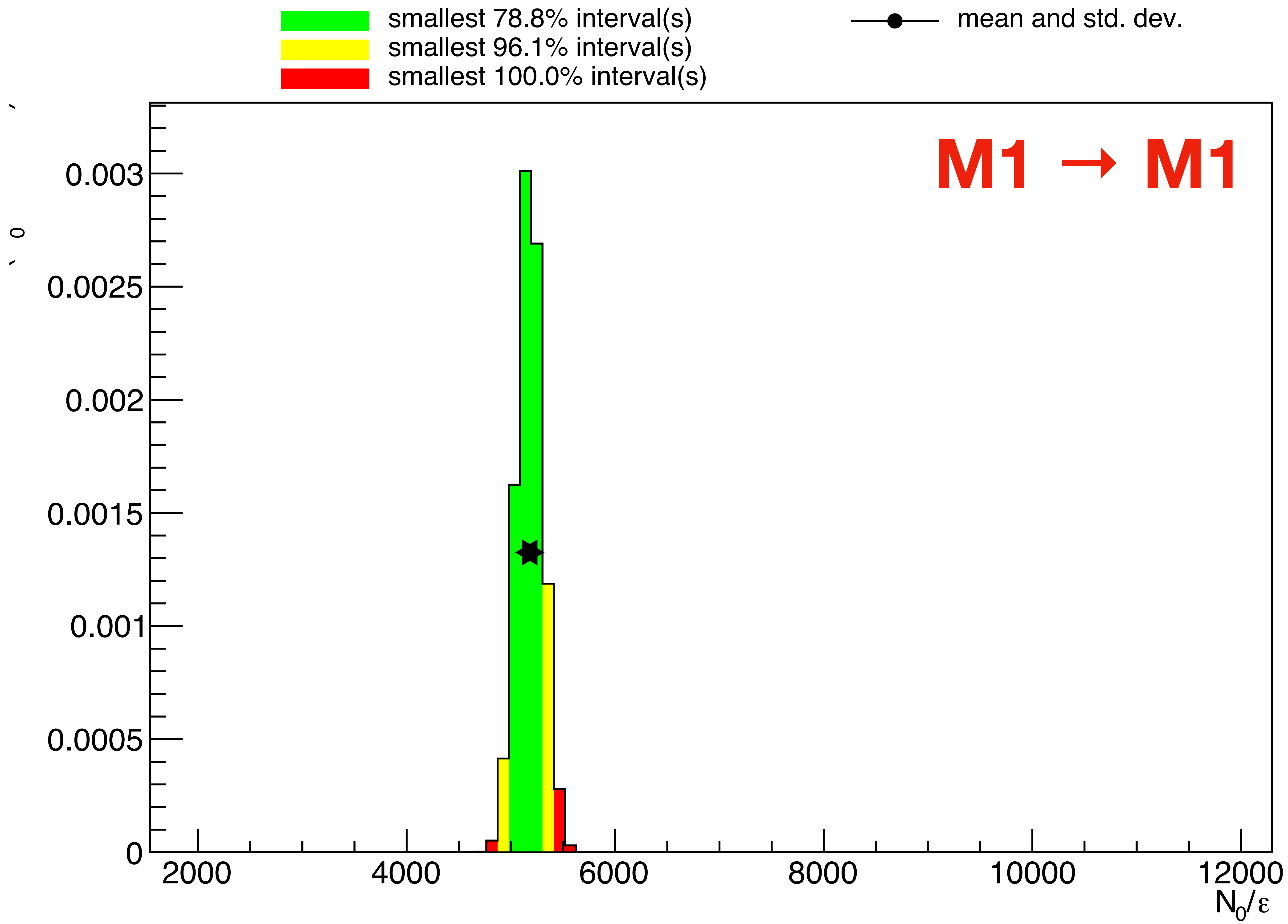
$$[\ Q_\alpha \times F_Q - \Delta E\ ,\ Q_\alpha \times F_Q + \Delta E\ ] \quad \Delta E = \textbf{40 keV}$$

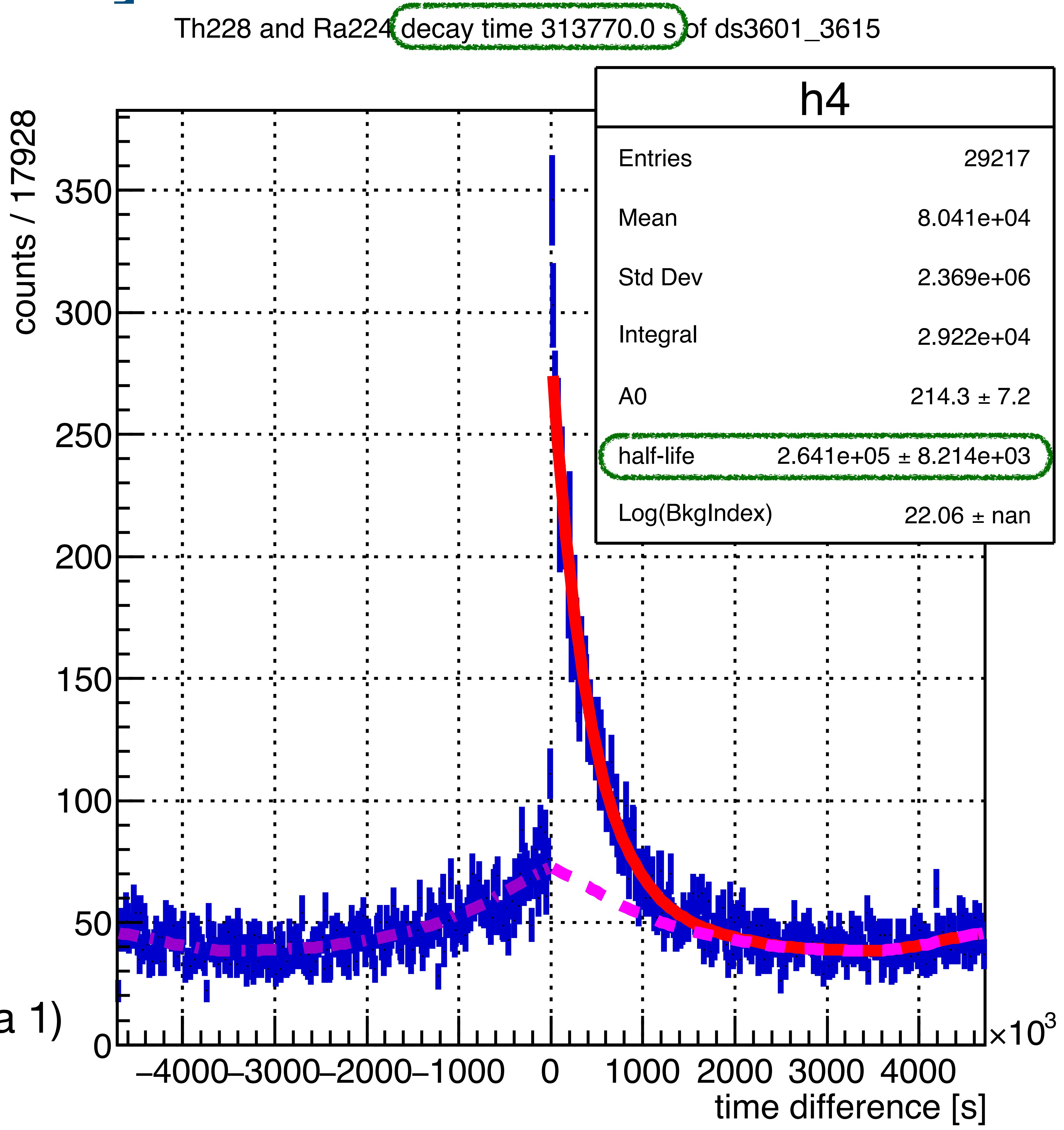




$$N(\Delta t) = \begin{cases} N_0 \times \exp\left(\dfrac{-\ln(2) \times \Delta t}{T_{1/2}}\right) + BkgCounts \times \mathrm{PDF}(\Delta t) & \Delta t > 0 \\ \exp(\ [\ln(BkgCounts)]\ ) \times \mathrm{PDF}(\Delta t) & \Delta t < 0 \end{cases}$$

$[\, Q_\alpha \times F_Q - \Delta E \,,\, Q_\alpha \times F_Q + \Delta E \,]$ $\Delta E =$ **40 keV**





Smallest interval containing 78.8% and local mode:
(4979.9, 5302.6) (local mode at **5141.2** with rel. height 1; rel. area 1)

$$N_0/\varepsilon = 5141.2^{+161.4}_{-161.3} \quad (\varepsilon = 0.878892)$$

Next work

Based on the established background function of the Δt spectrum and the non-dependence on the energy range, it is possible to match events that meet the delayed coincidence in a larger scope.

Finally, we can achieve a further distinction between events and the background within the energy range we are interested in.

Challenges

Given that all the conclusions obtained now are statistic rather than analytic. If we want to identify them event-by-event, we need to develop technologies such as machine learning.

Thanks!

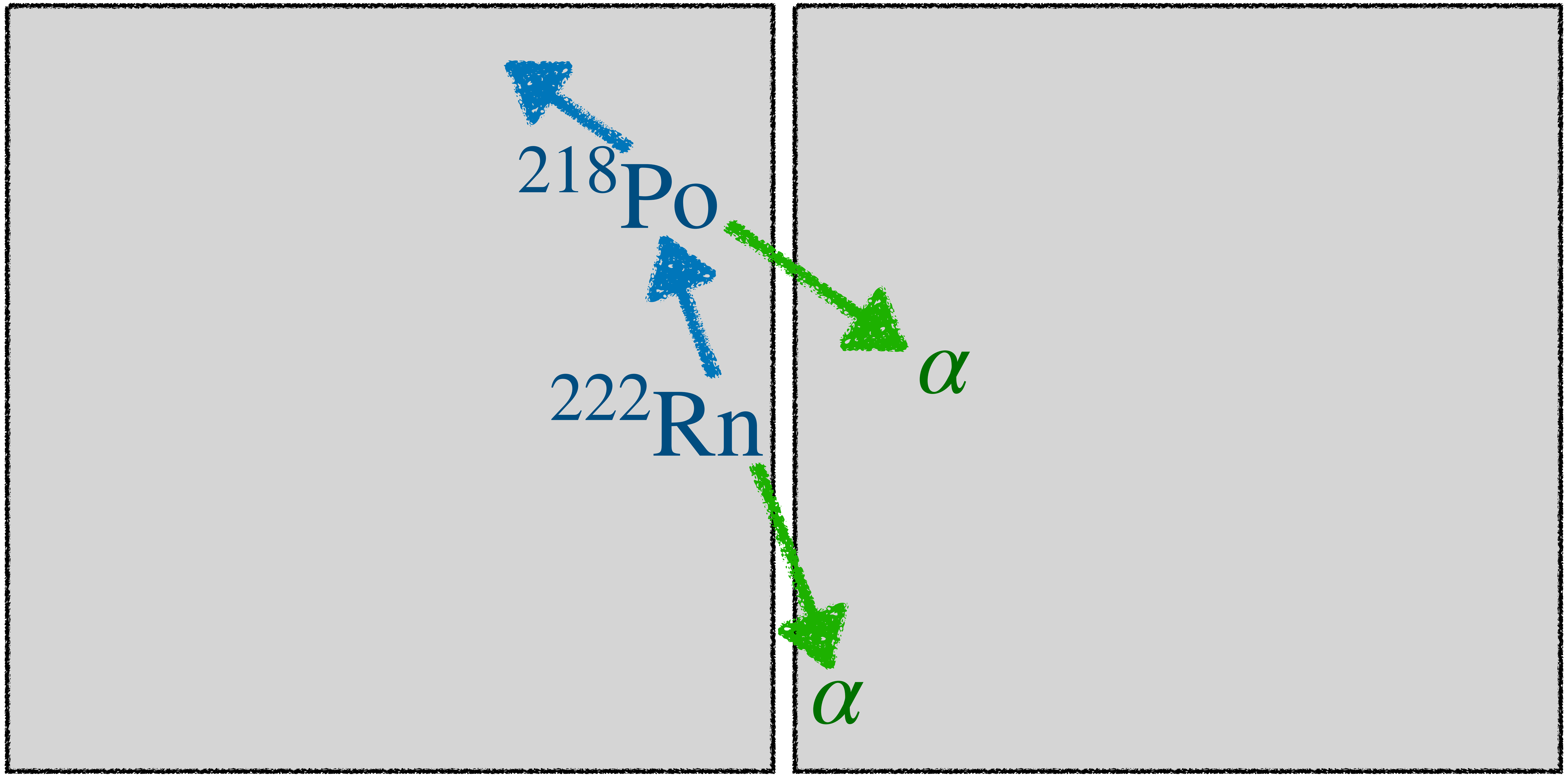
NvDEx-CUPID-China collaboration group 2023 annual meeting

Shihong Fu, 17 Dicembre, 2023

Backup

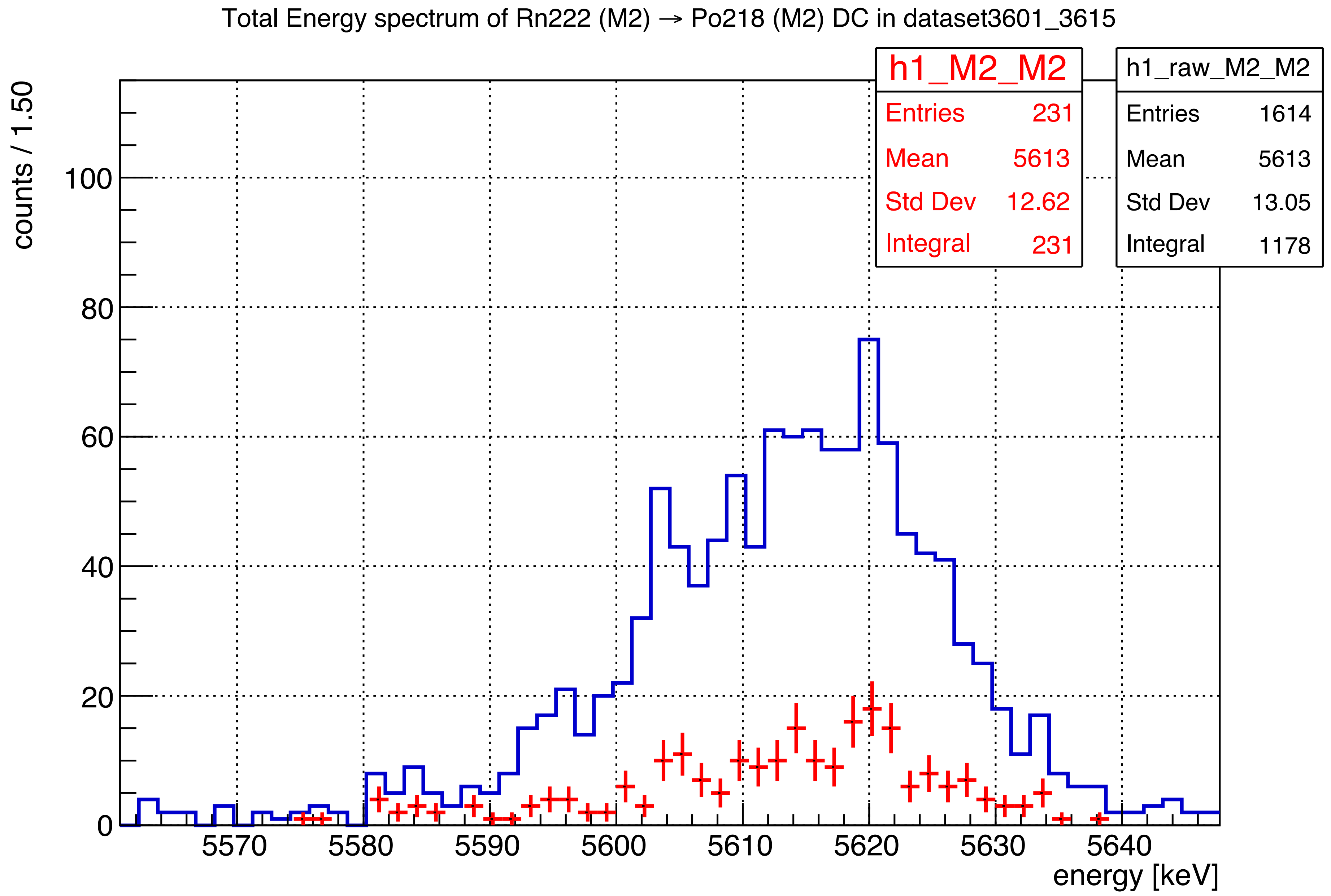
Analysis of $^{222}\mathrm{Rn} \rightarrow {}^{218}\mathrm{Po}$ DC
Case 4 : M2 → M2

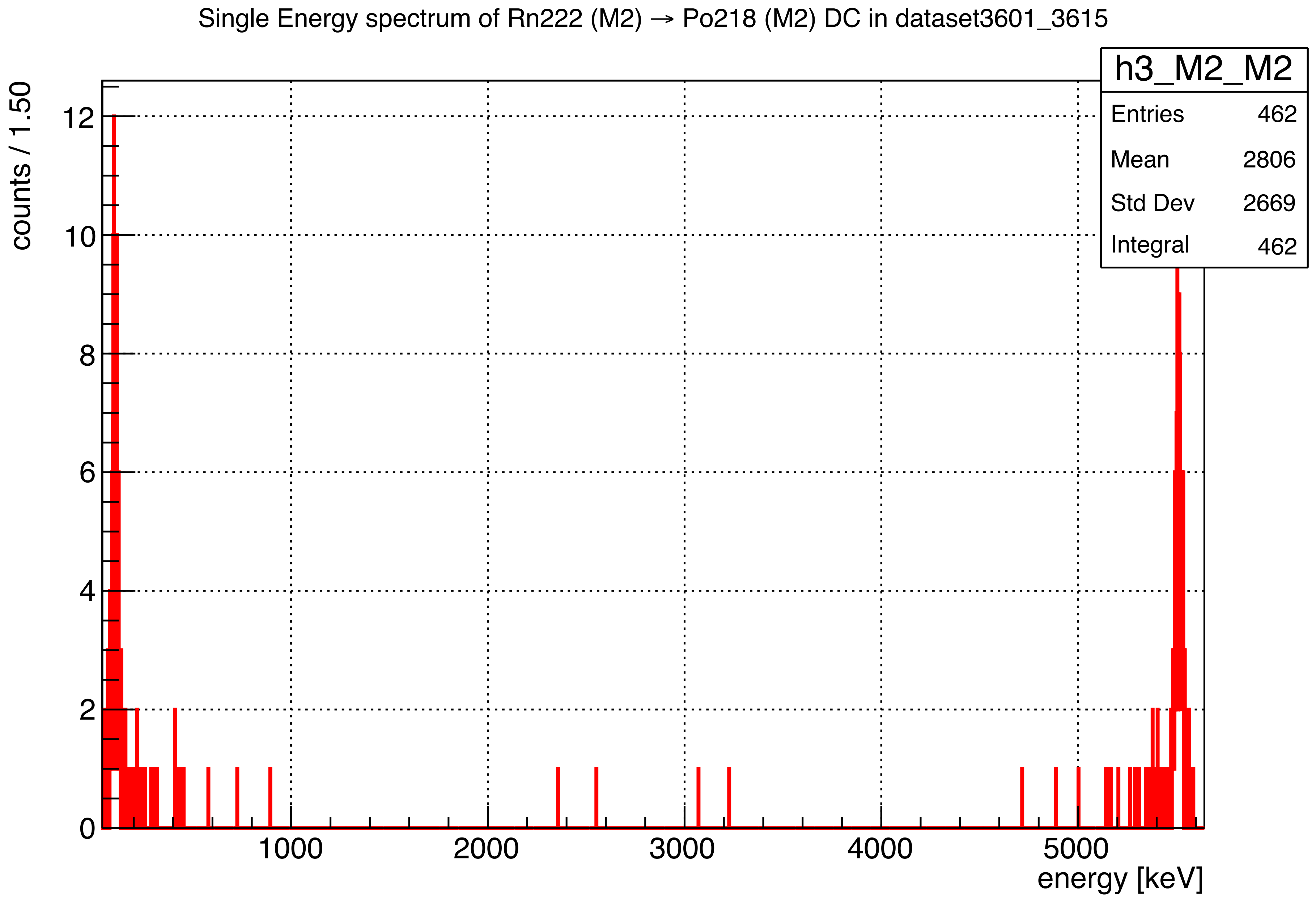
$^{222}Rn \rightarrow {}^{218}Po$ Delayed Coincidence

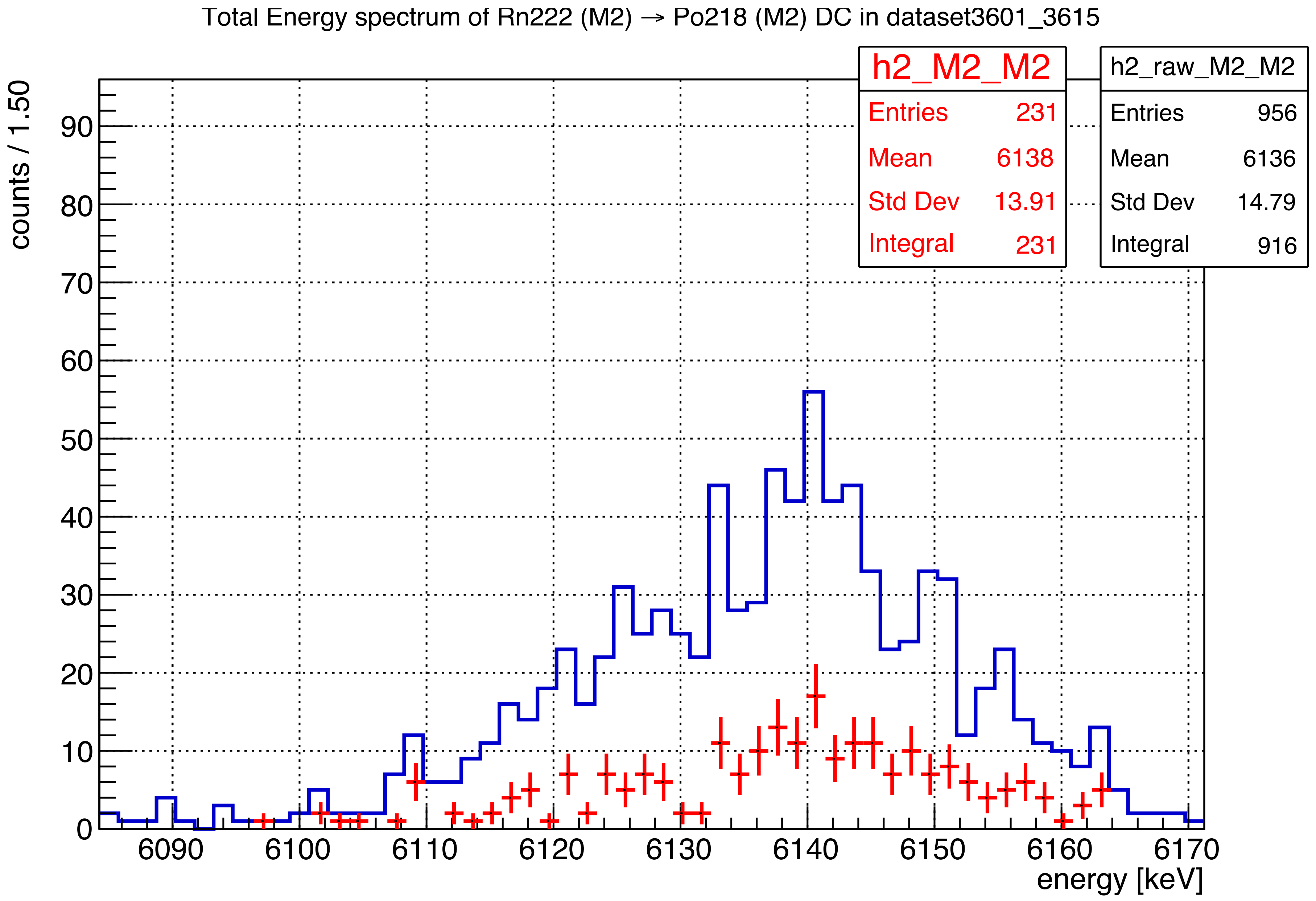


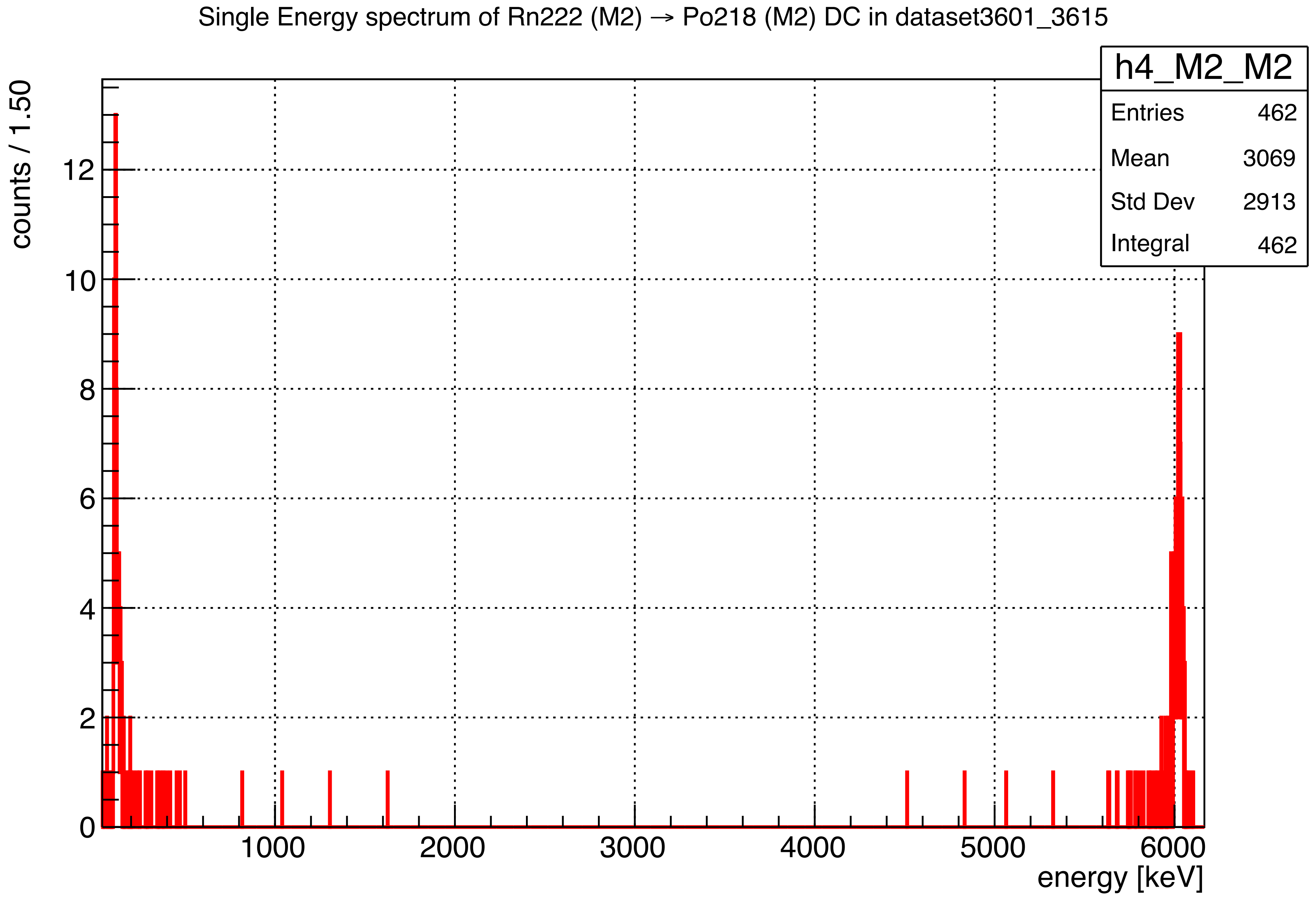
M2 → M2

$^{222}Rn \rightarrow {}^{218}Po$

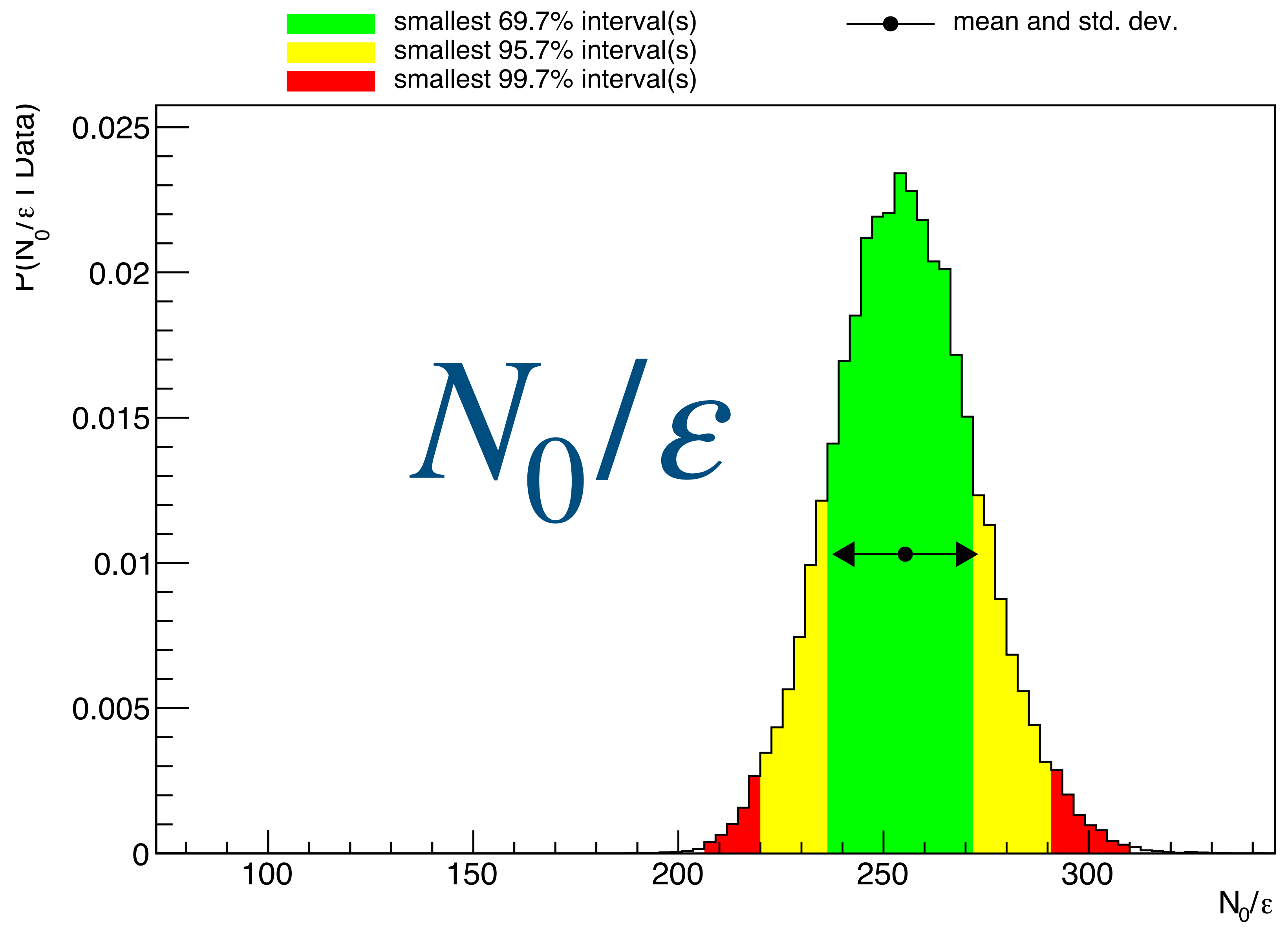




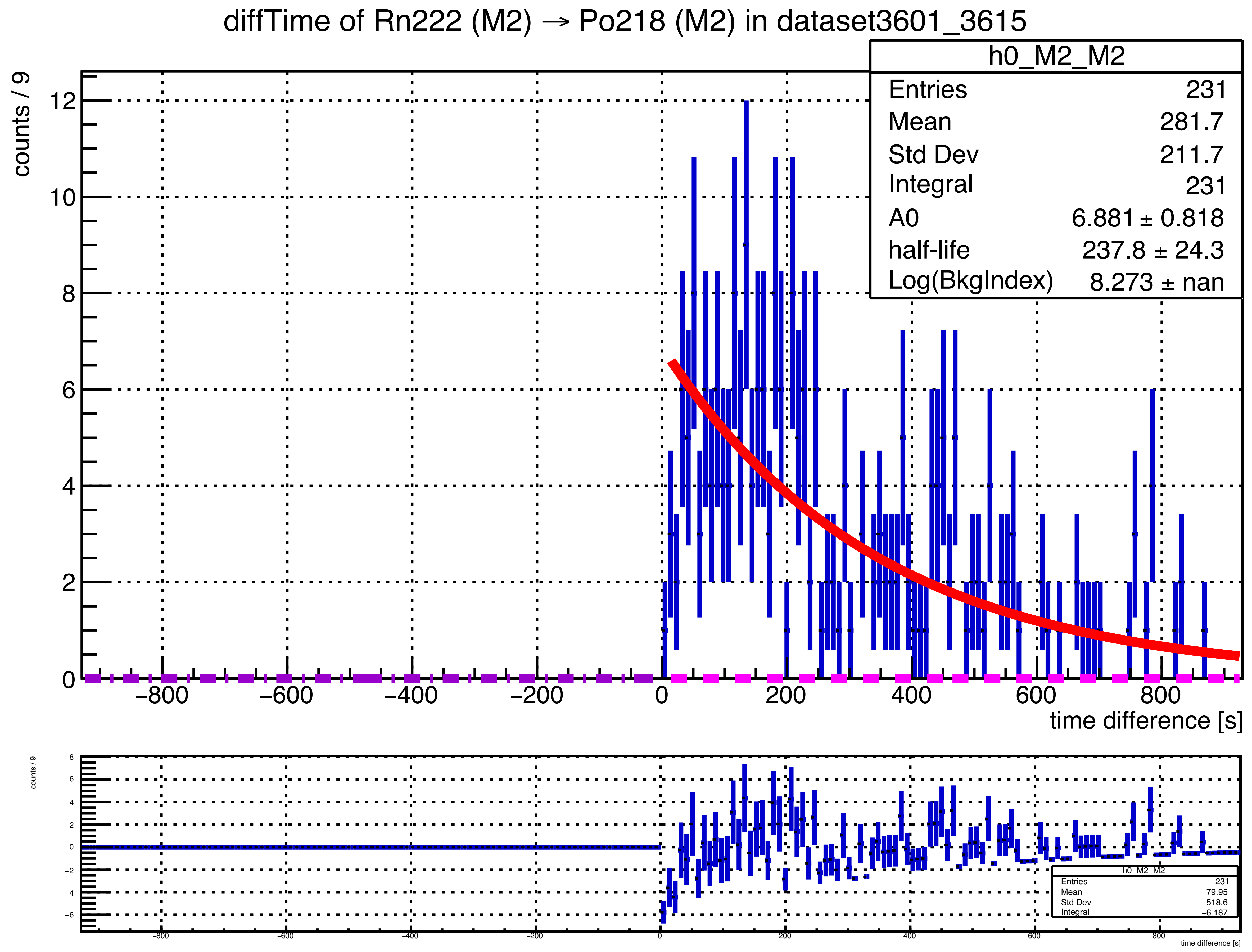


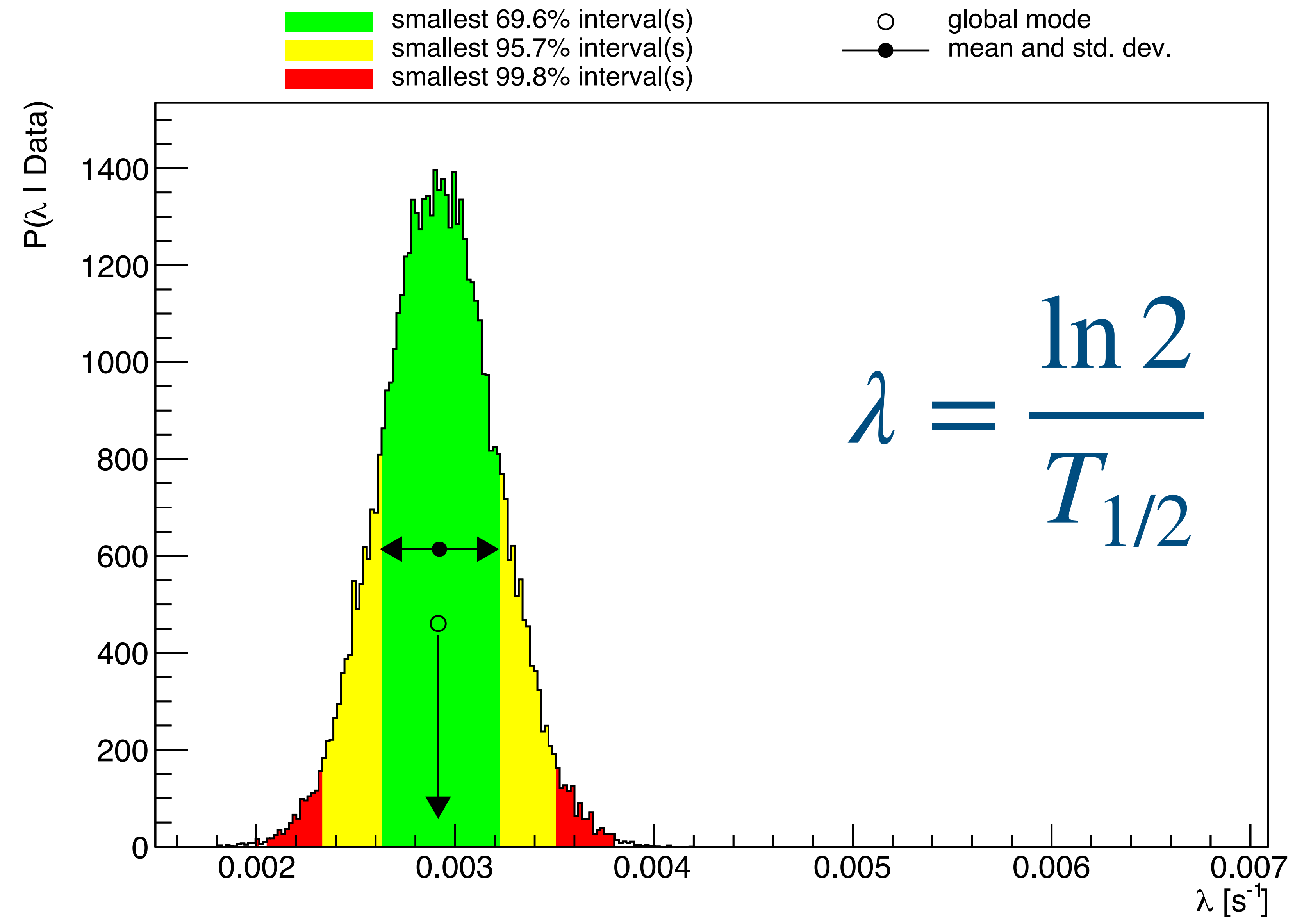


$^{222}\mathrm{Rn} \rightarrow {}^{218}\mathrm{Po}$



$$T_{1/2} = 185.8\ \mathrm{s} \approx 3.1\ \mathrm{min}$$





$$N_0/\varepsilon$$

$$\lambda = \frac{\ln 2}{T_{1/2}}$$

Smallest interval containing 69.7% and local mode:
(236.33, 271.78) (local mode at **254.06** with rel. height 1; rel. area 1)

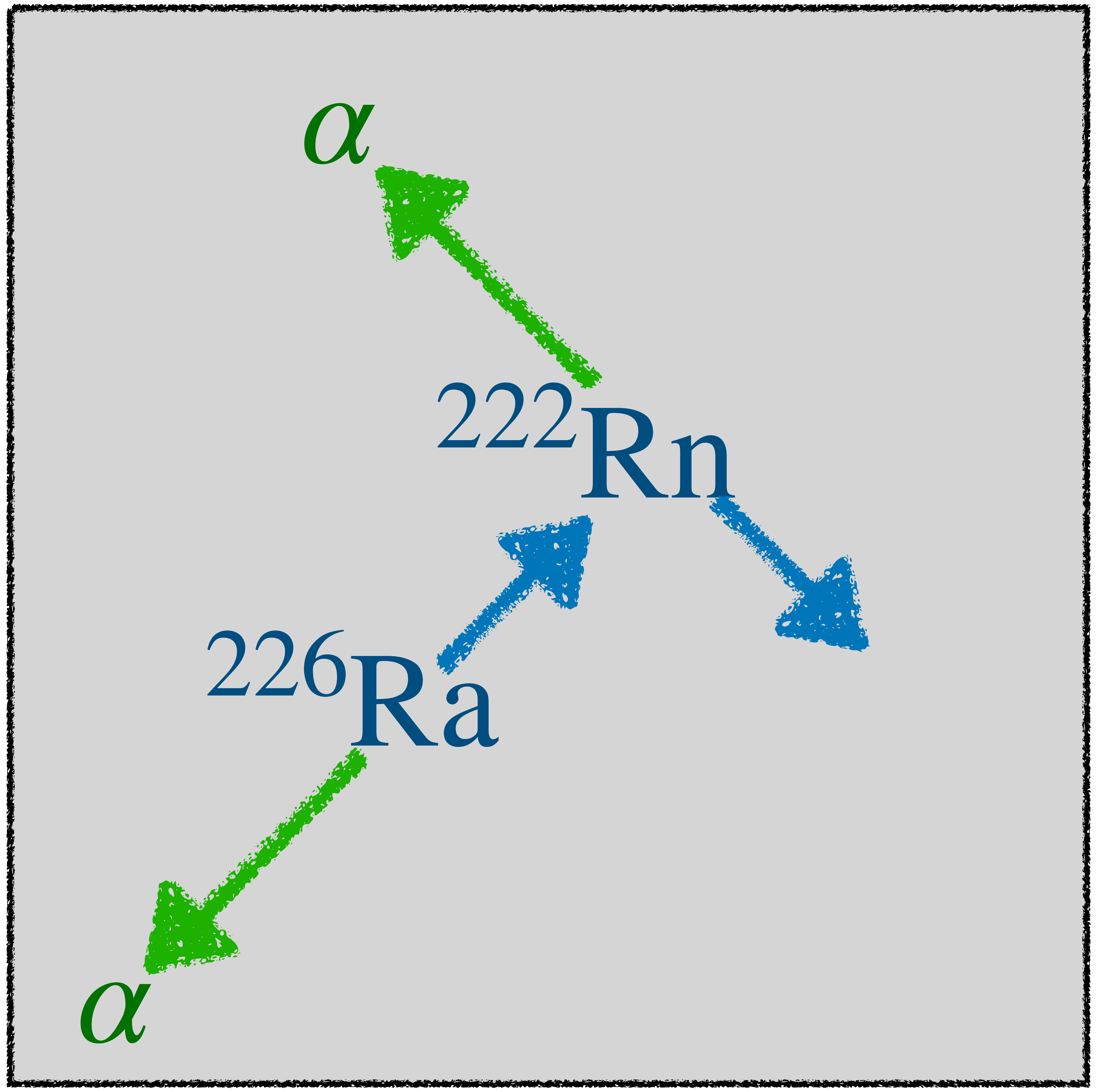
$$N_0/\varepsilon = 254.06^{+17.72}_{-17.73} \quad (\varepsilon = 0.999923)$$

Analysis of $^{226}\mathrm{Ra} \rightarrow {}^{222}\mathrm{Rn}$ DC
Case 1 : M1 → M1

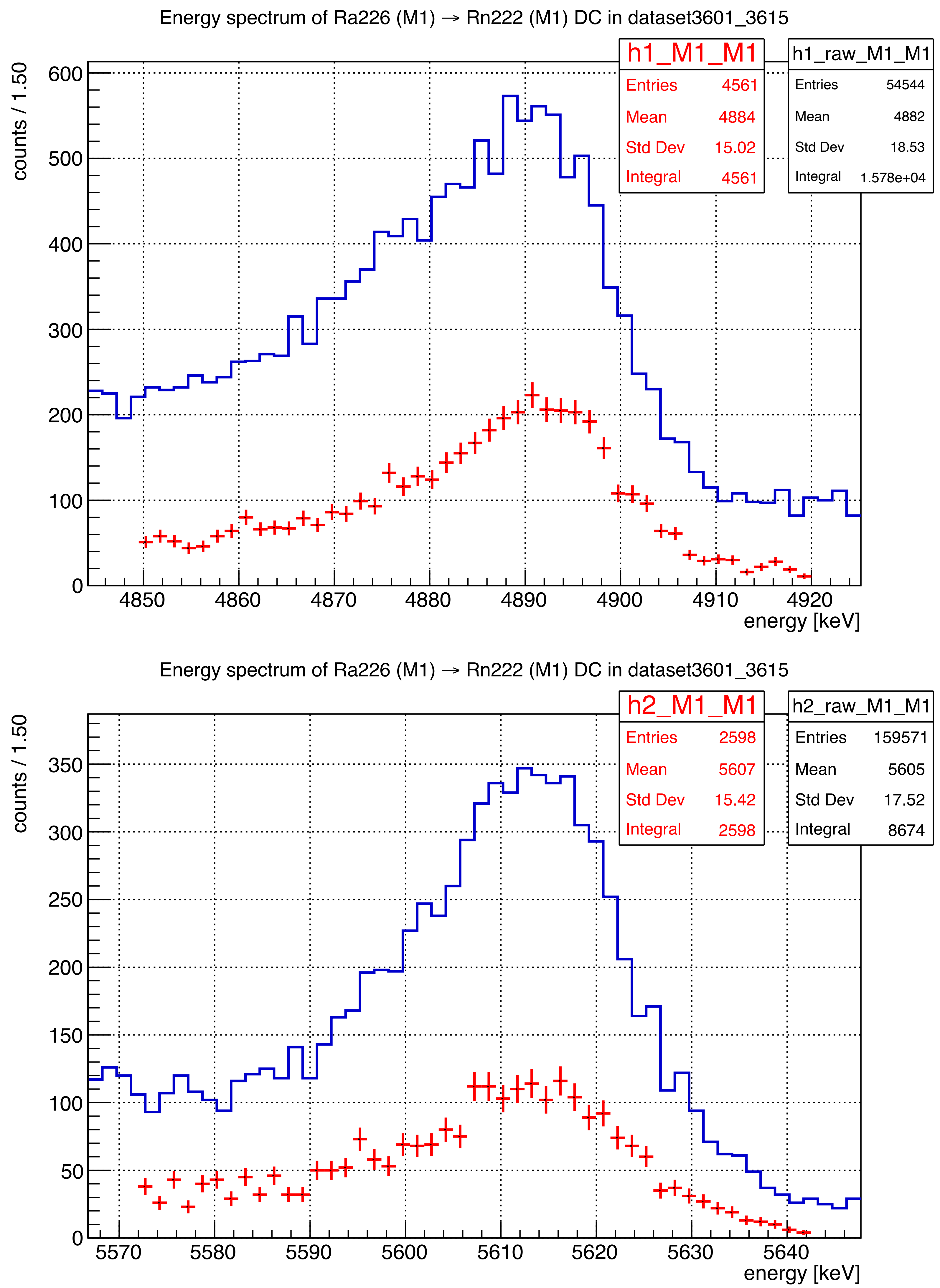
$^{226}Ra \rightarrow {}^{222}Rn$ Delayed Coincidence

Combine them → **M1 → M1**

$^{226}Ra \rightarrow {}^{222}Rn$ Delayed Coincidence

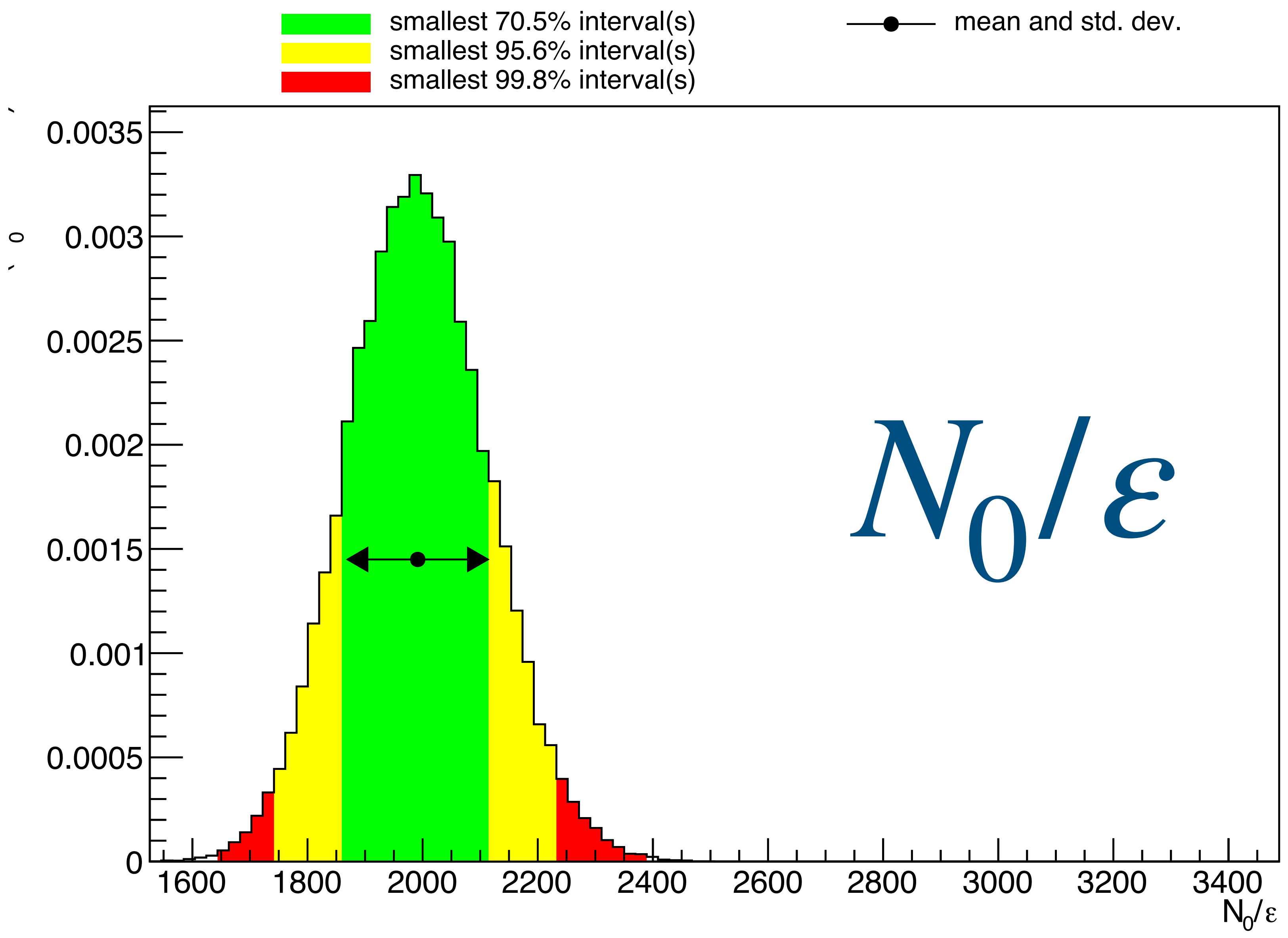


M1 → M1

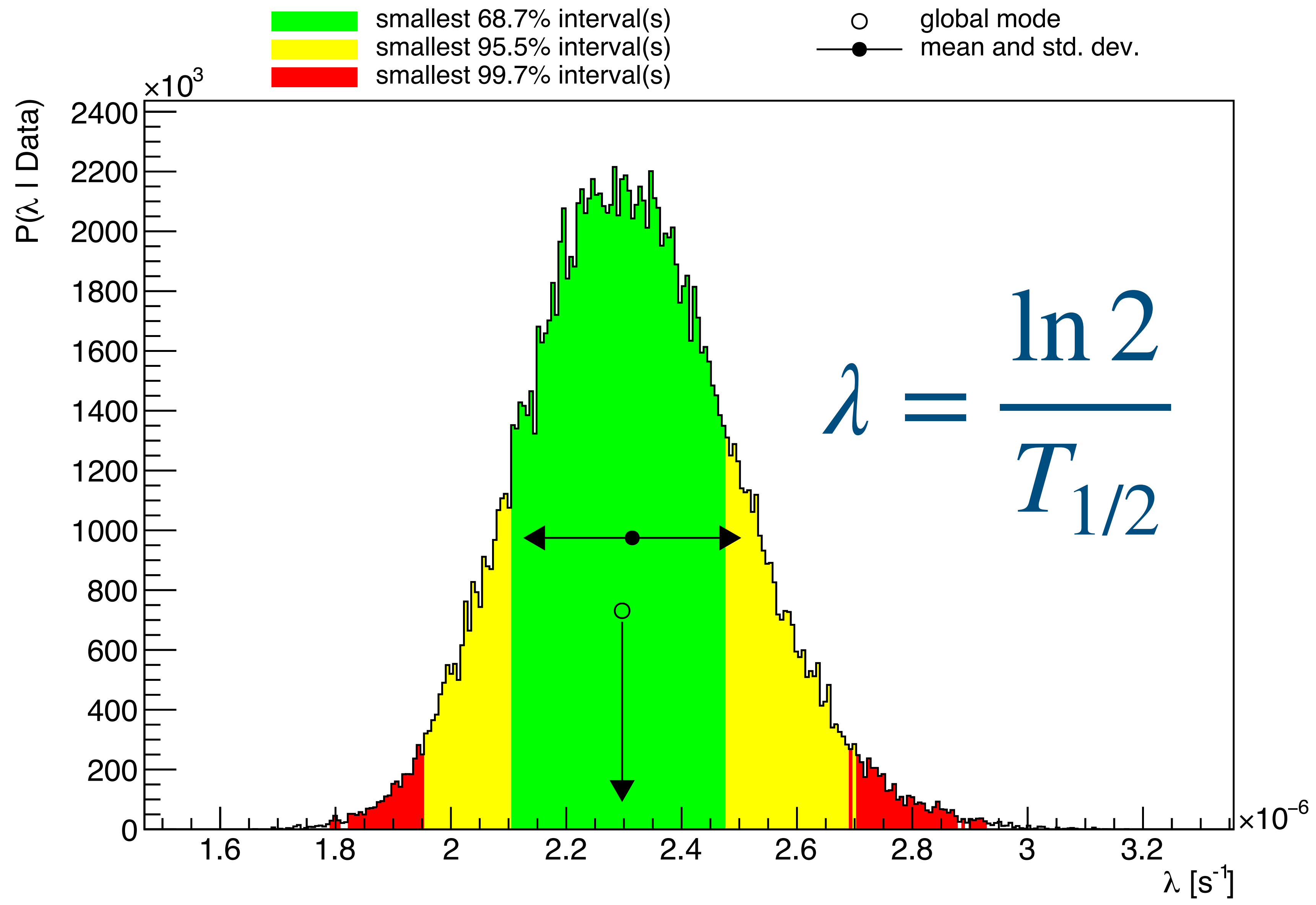


$^{226}Ra \rightarrow {}^{222}Rn$

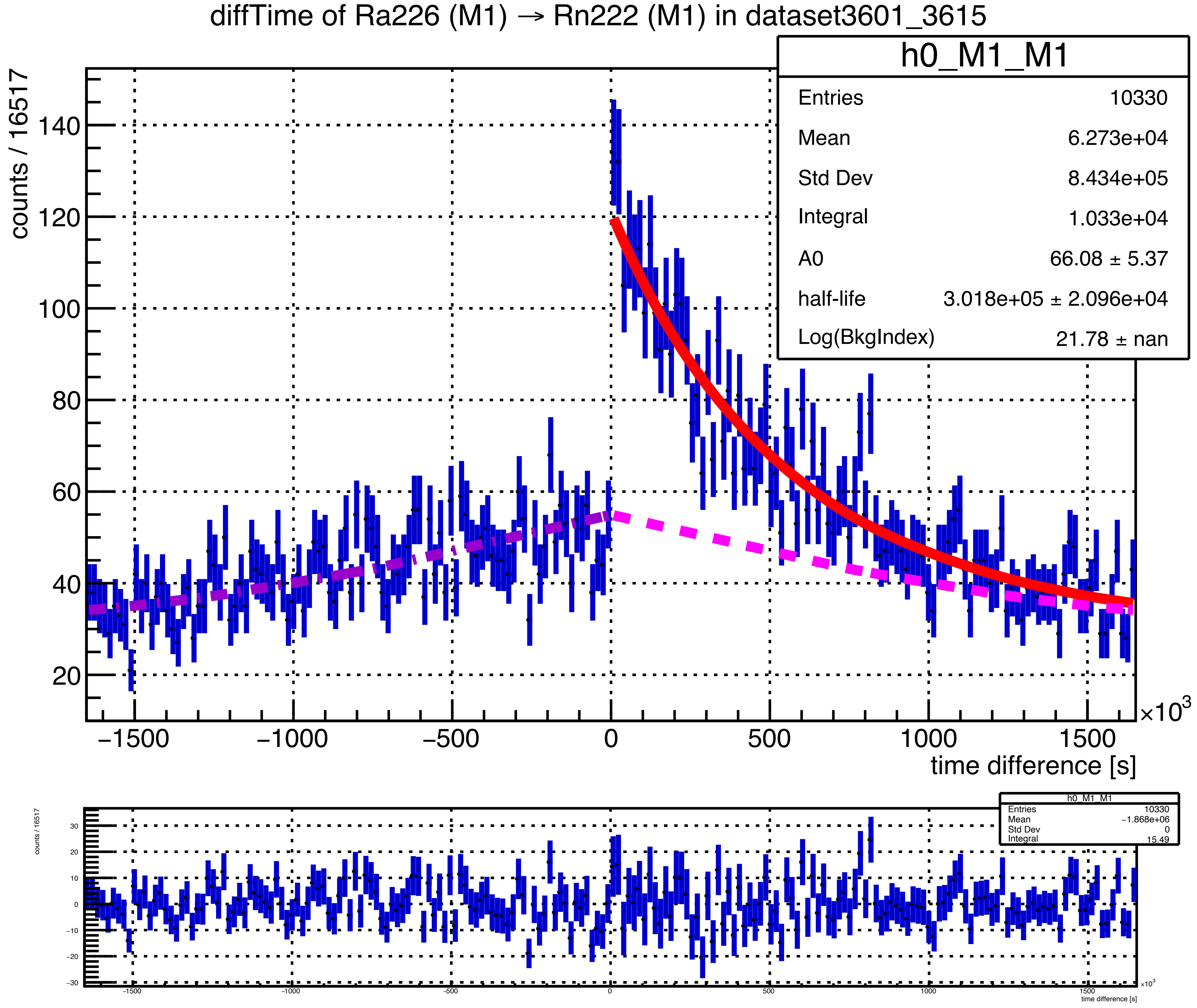
$$T_{1/2} = 313770 \text{ s} \approx 3.6 \text{ d}$$



$$N_0/\varepsilon$$



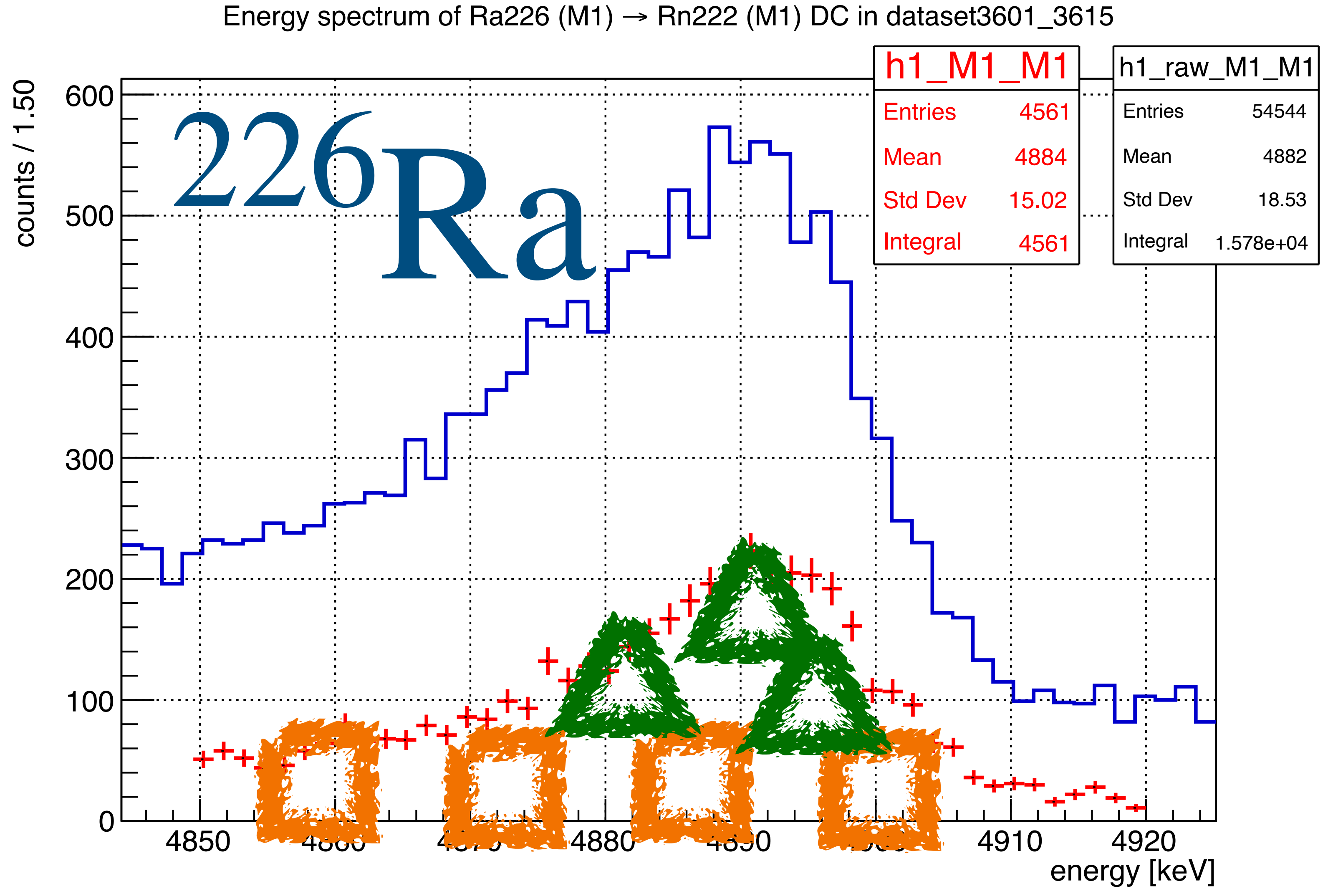
$$\lambda = \frac{\ln 2}{T_{1/2}}$$

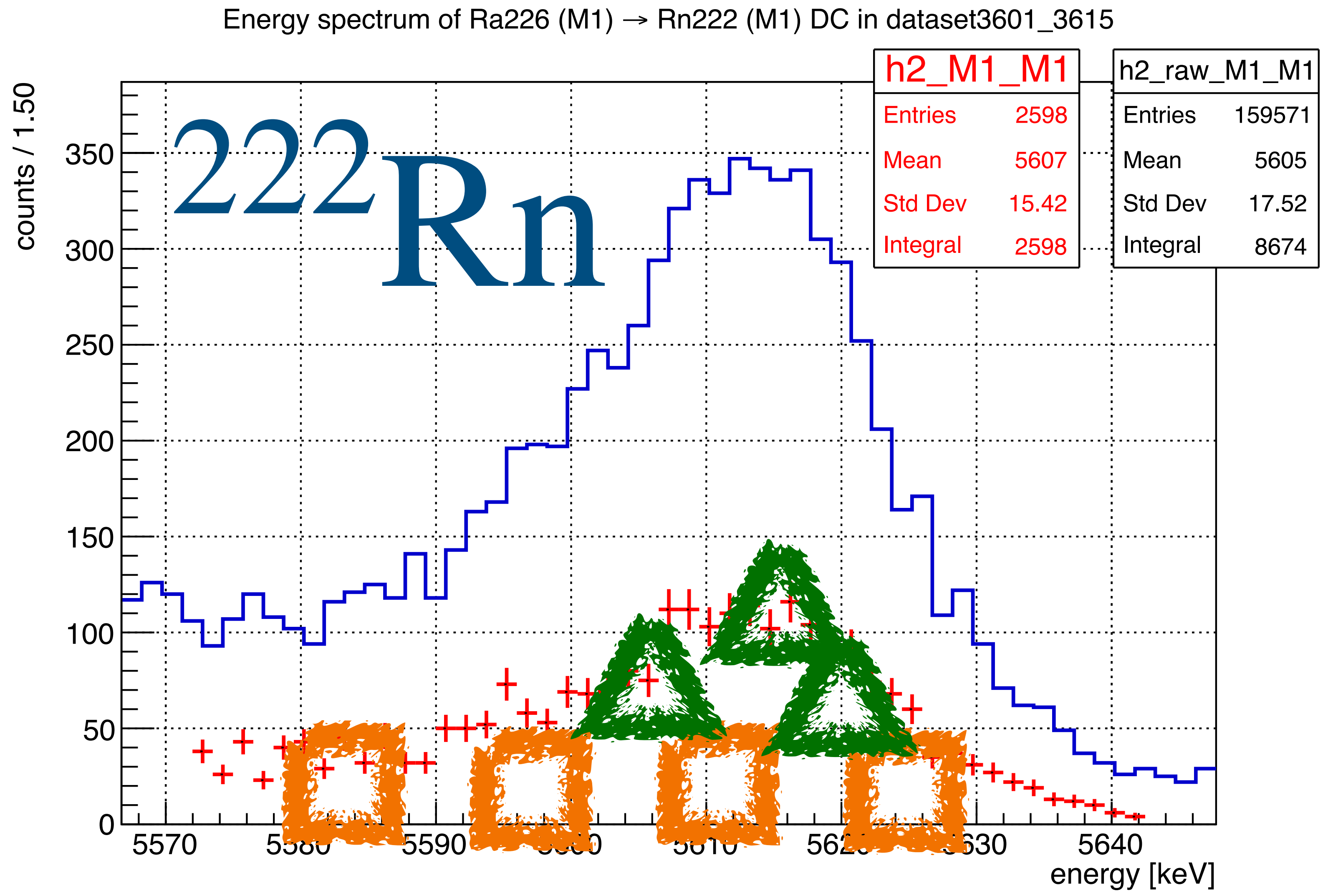


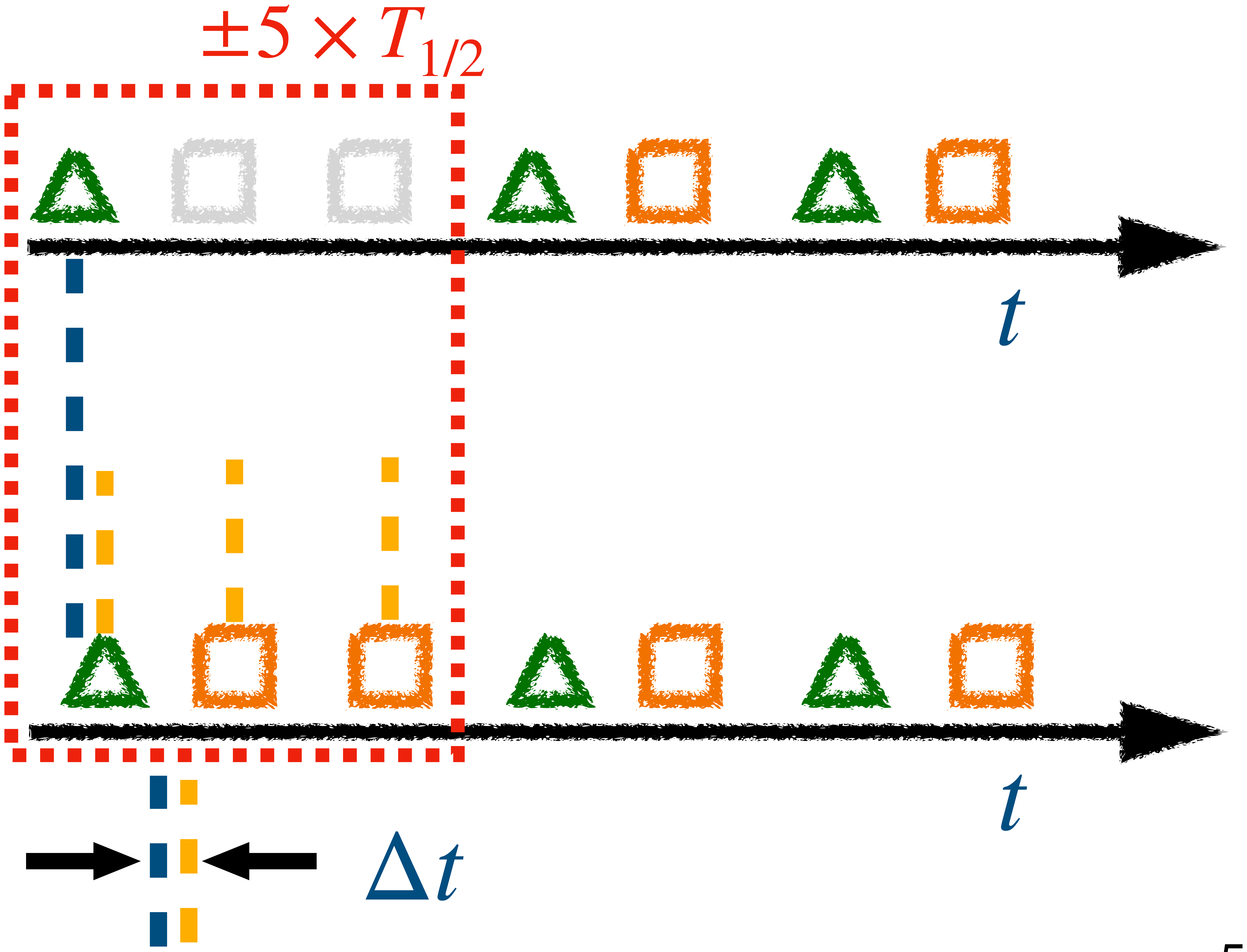
Smallest interval containing 70.5% and local mode:
(1859.5, 2114.6) (local mode at **1987.1** with rel. height 1; rel. area 1)

$$N_0/\varepsilon = 1987.1^{+127.5}_{-127.6} \quad (\varepsilon = 0.873567)$$

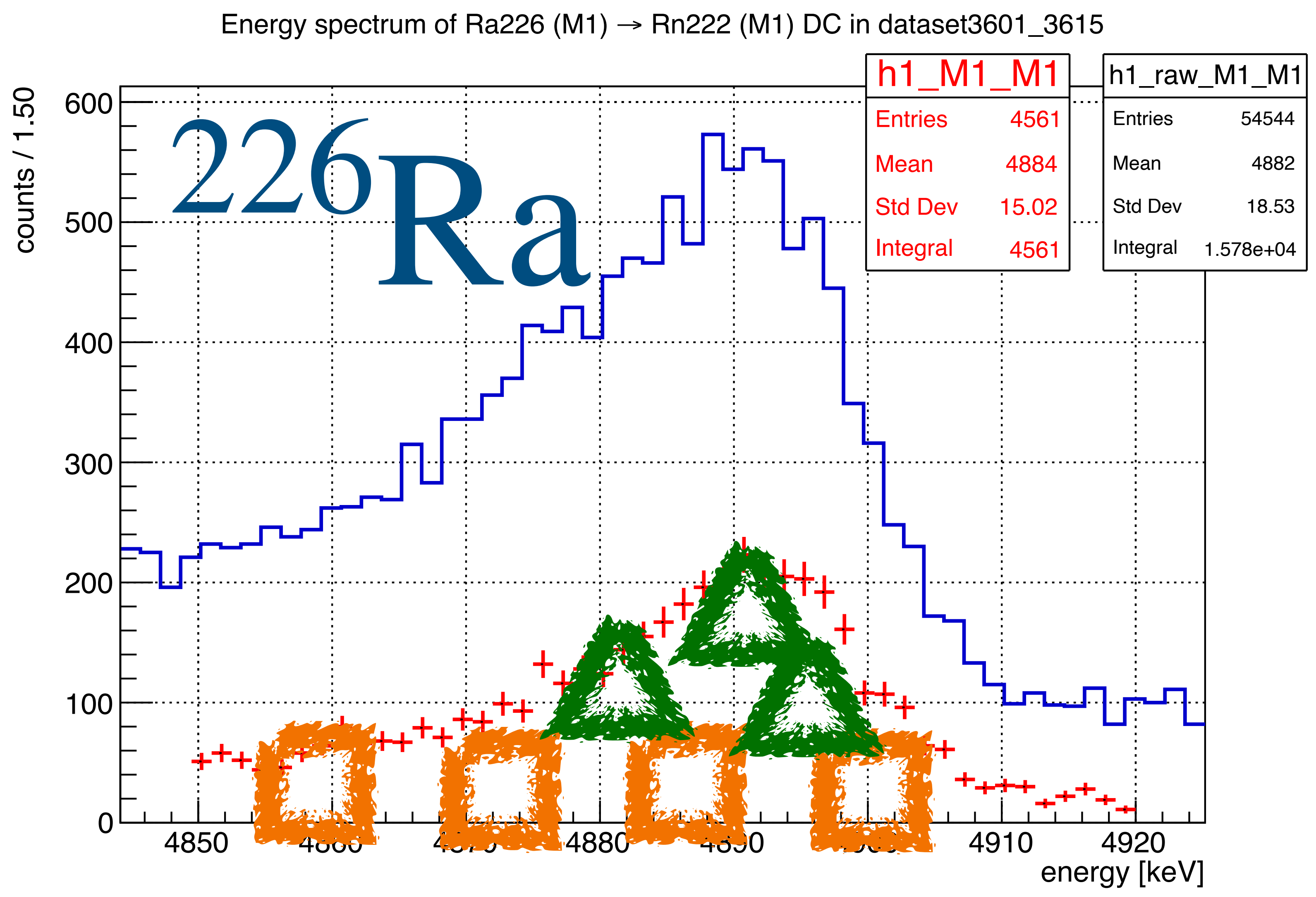
$^{226}Ra \rightarrow {}^{222}Rn$ Delayed Coincidence

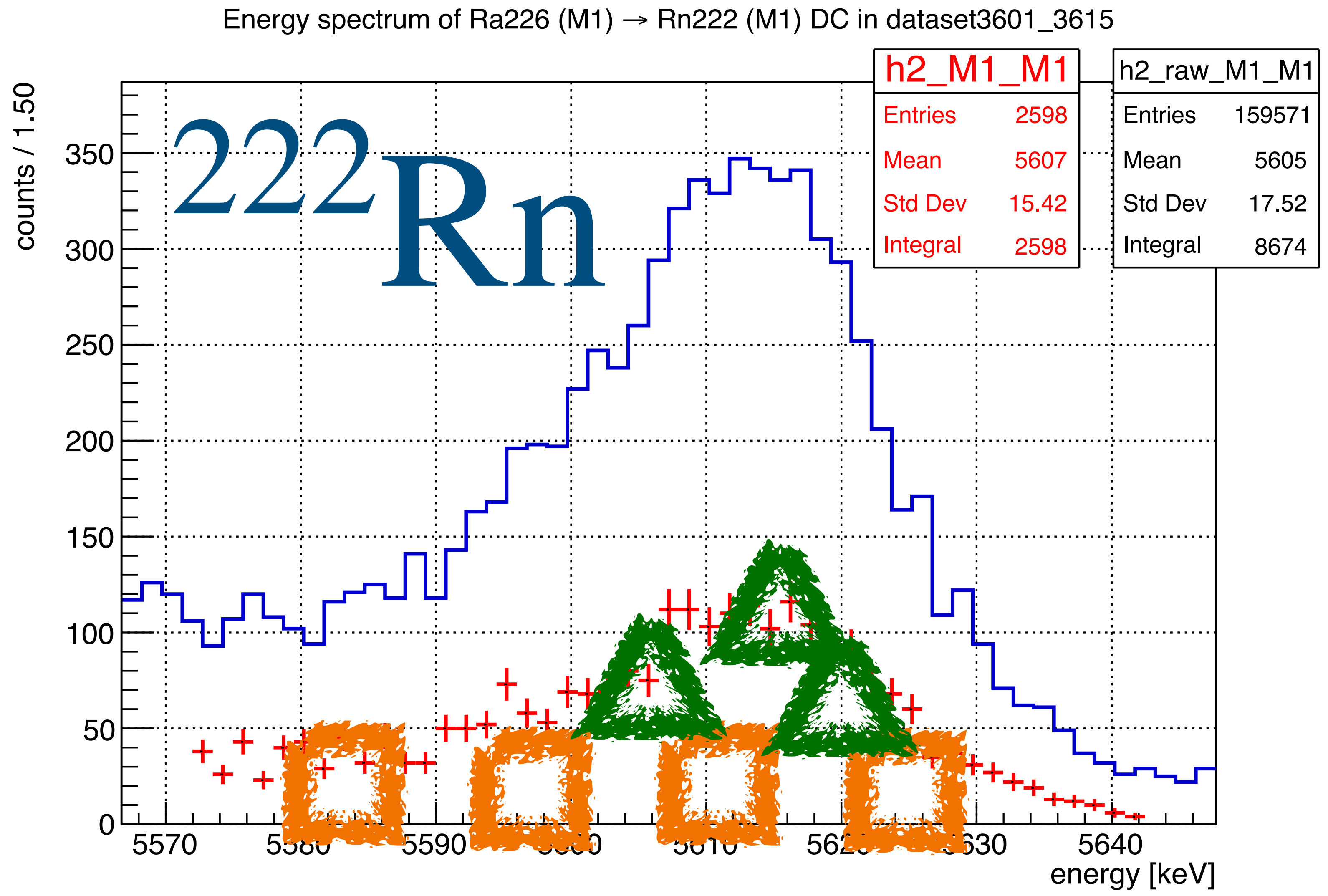


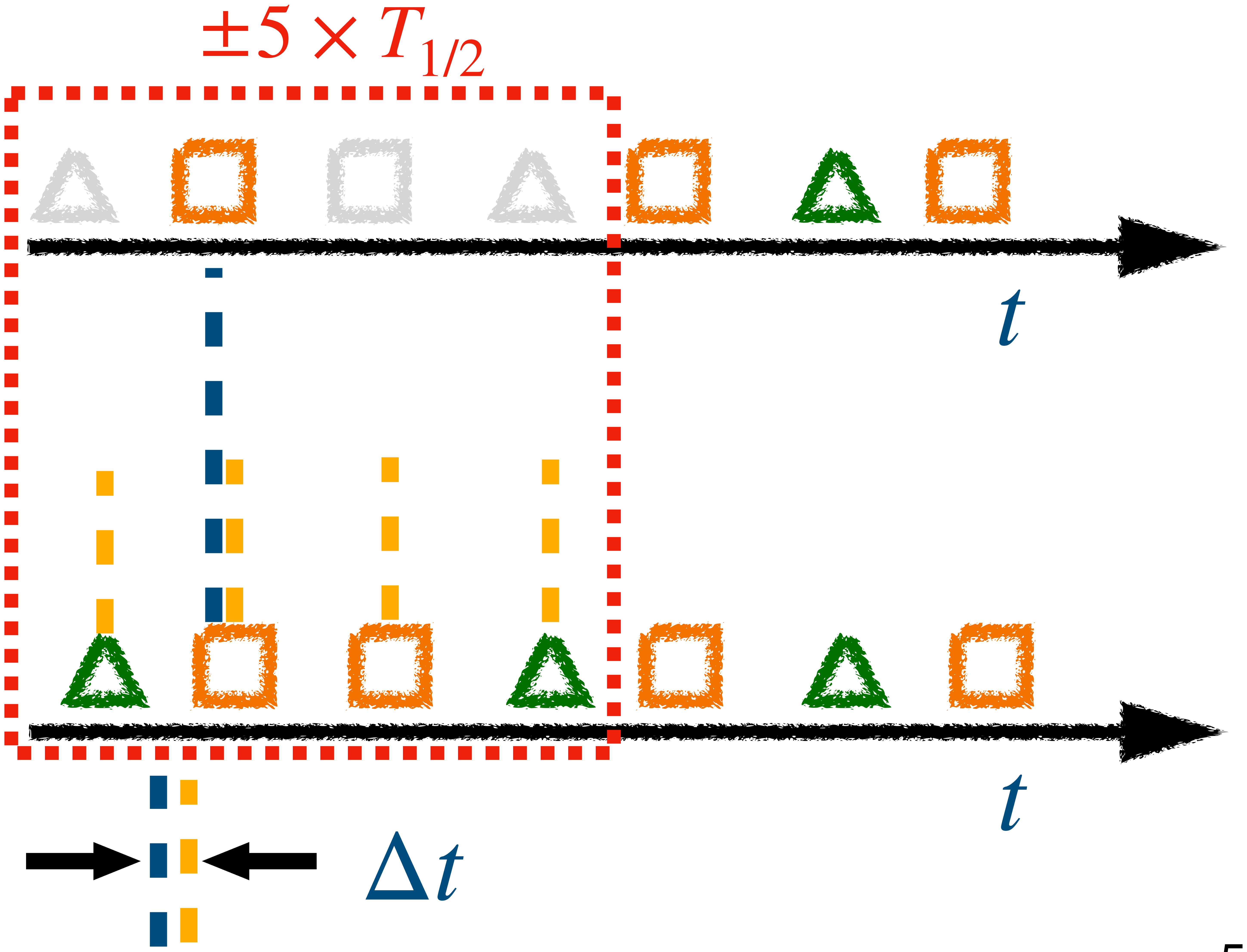




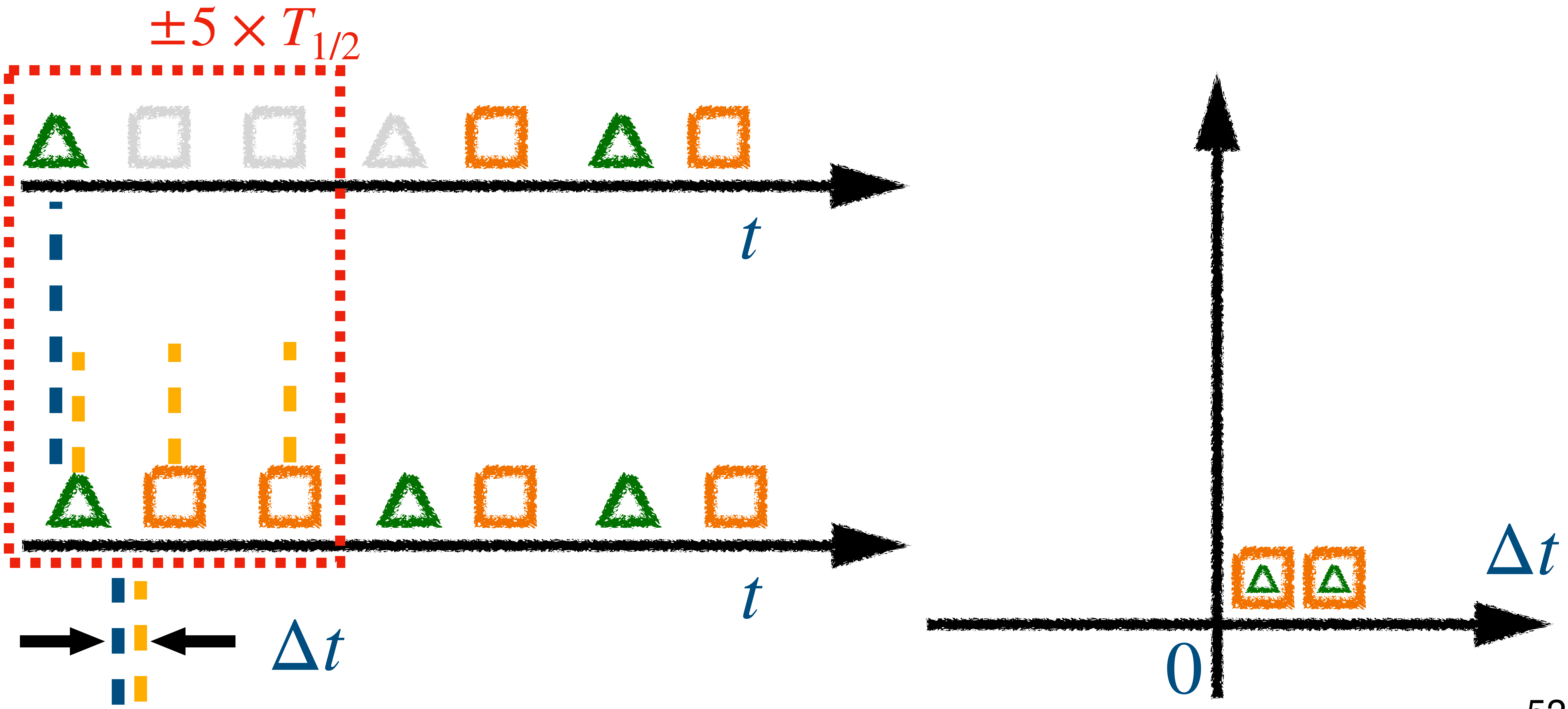
$^{226}Ra \rightarrow {}^{222}Rn$ Delayed Coincidence



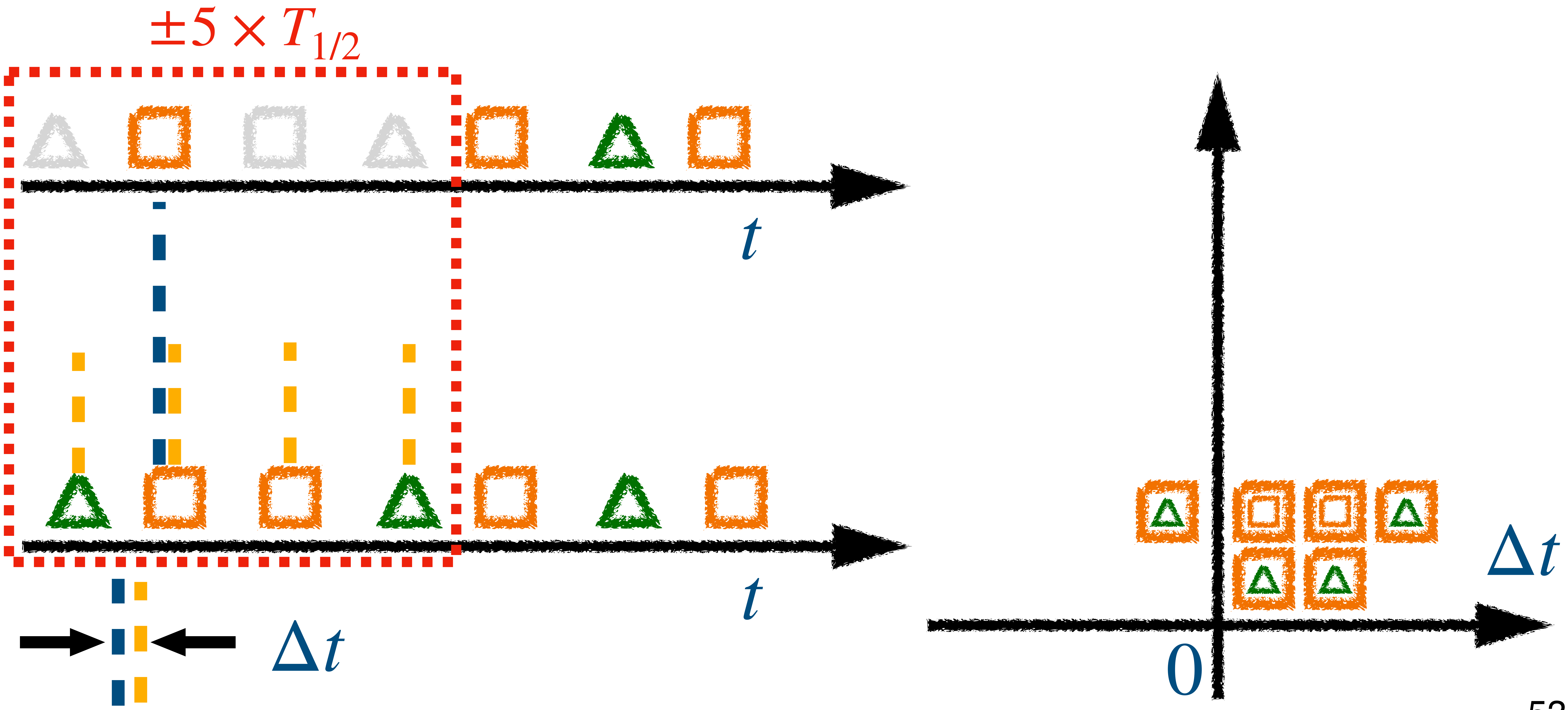




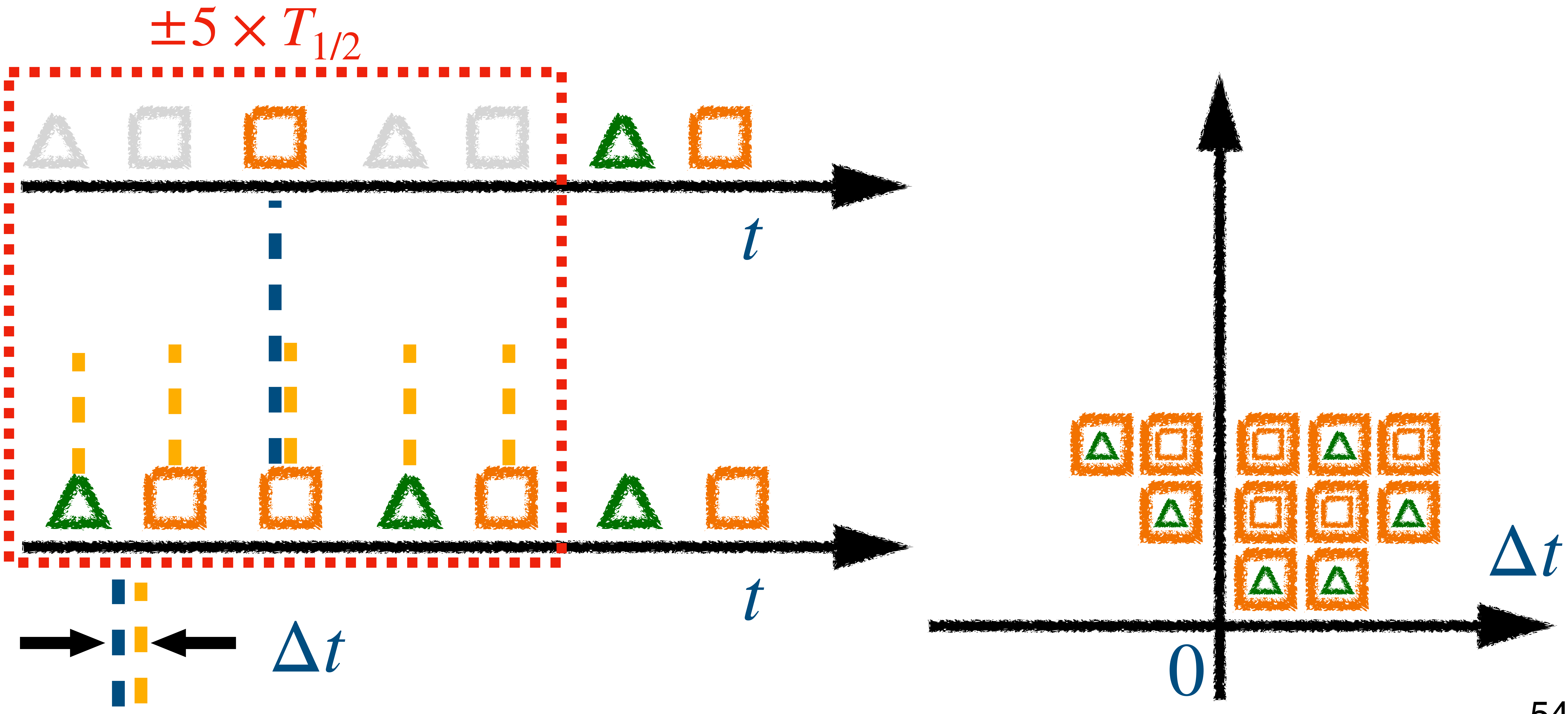
$^{226}Ra \rightarrow {}^{222}Rn$ Delayed Coincidence



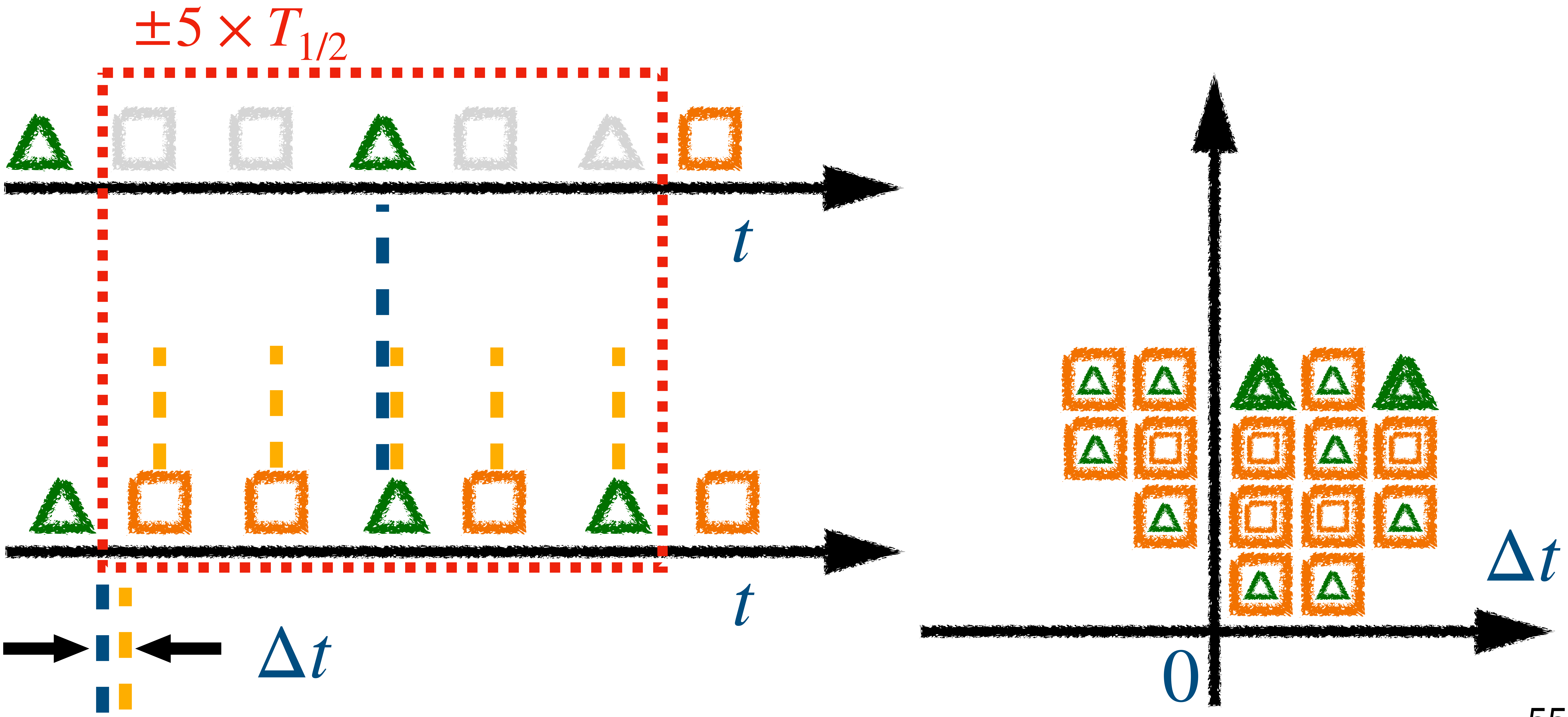
$^{226}Ra \rightarrow {}^{222}Rn$ Delayed Coincidence



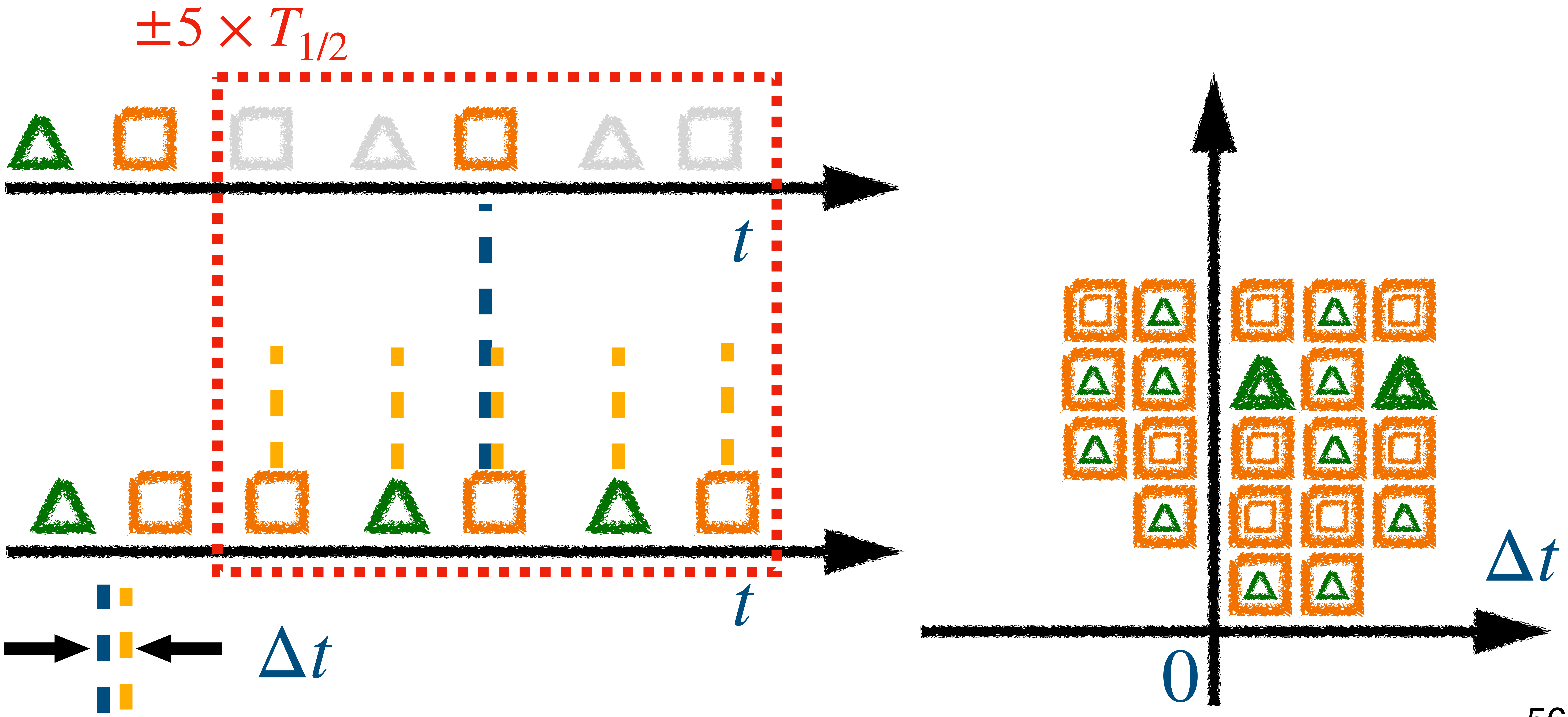
$^{226}Ra \rightarrow {}^{222}Rn$ Delayed Coincidence



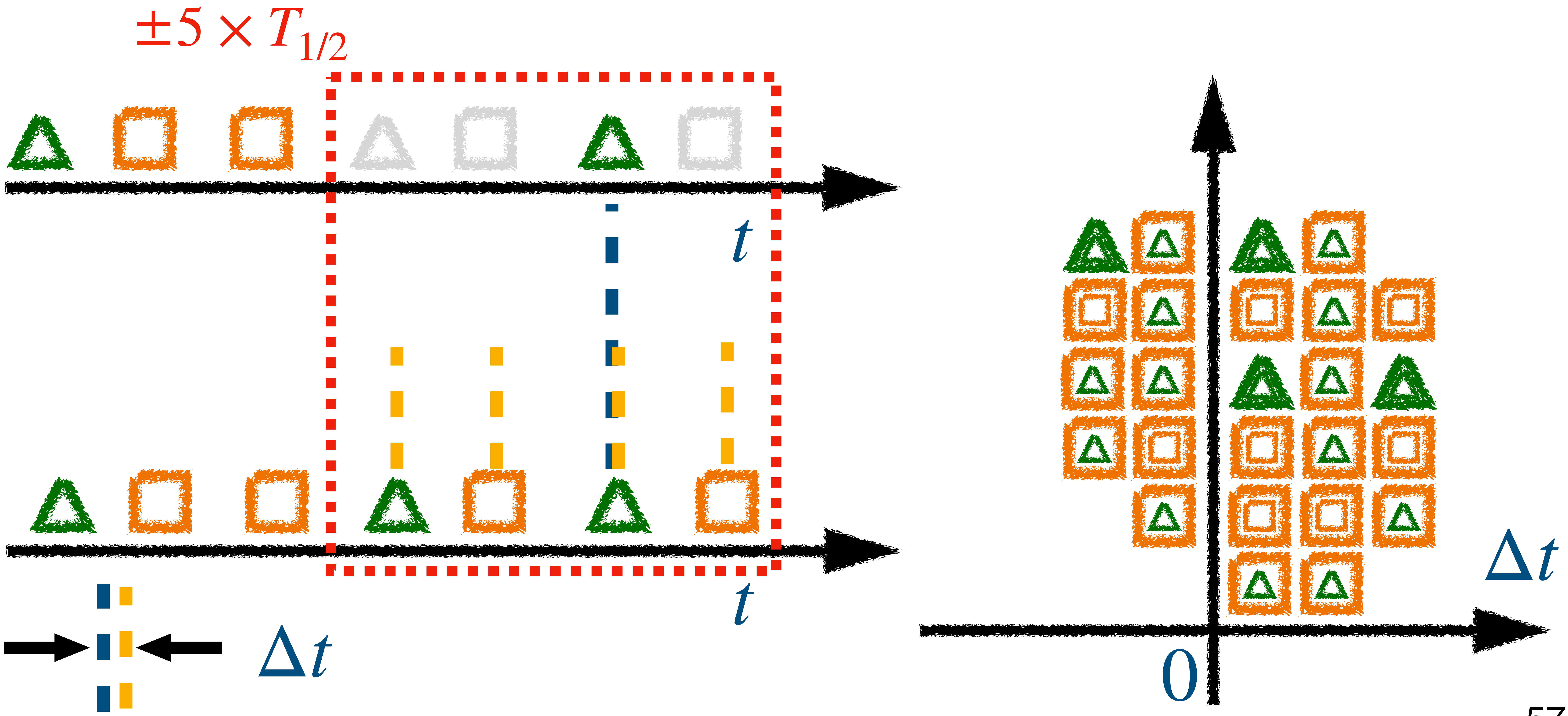
$^{226}\mathrm{Ra} \rightarrow {}^{222}\mathrm{Rn}$ Delayed Coincidence



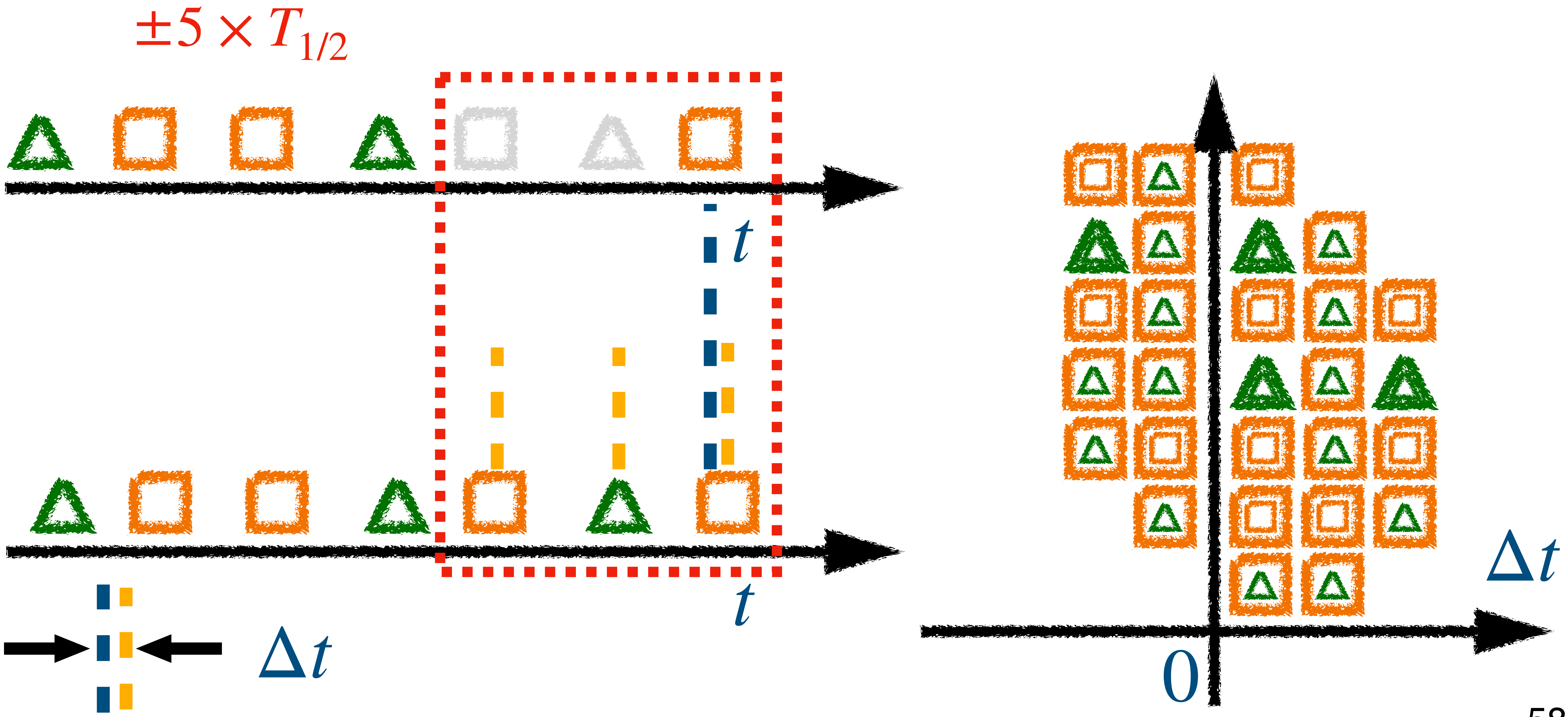
^{226}Ra $\rightarrow$ ^{222}Rn Delayed Coincidence



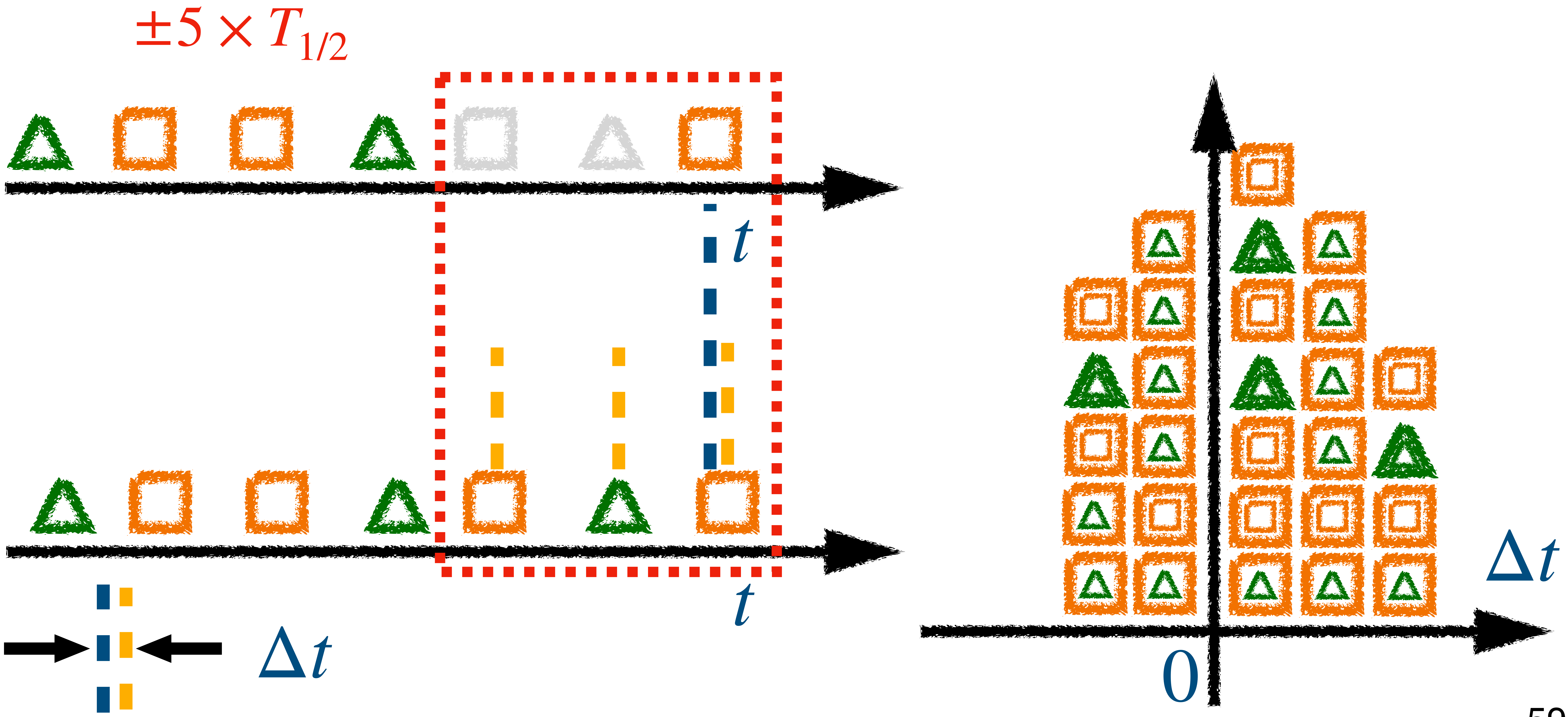
$^{226}Ra \rightarrow {}^{222}Rn$ Delayed Coincidence



^{226}Ra → ^{222}Rn Delayed Coincidence

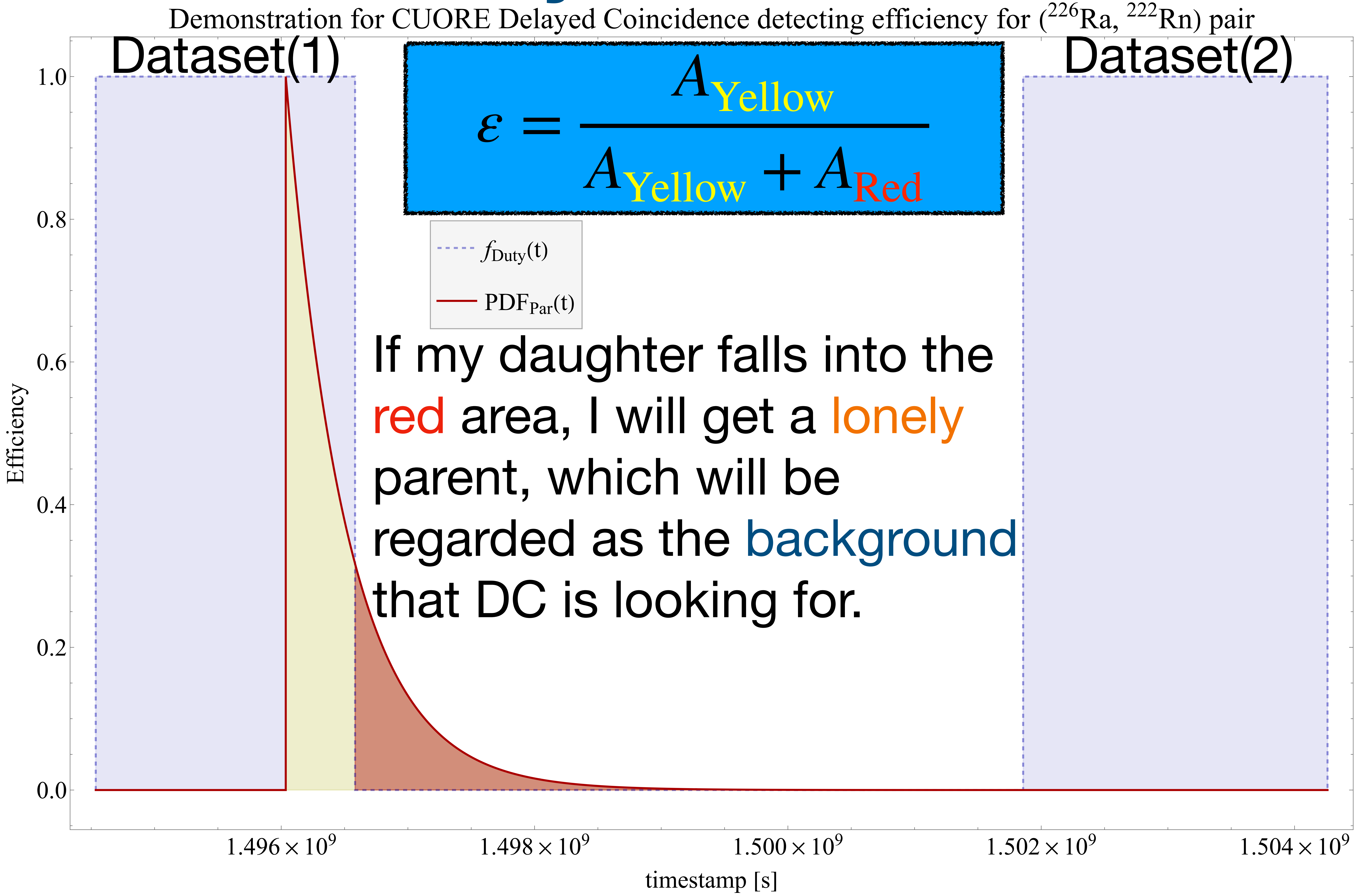


^{226}Ra → ^{222}Rn Delayed Coincidence



Delayed Coincidence pairing efficiency

$^{226}Ra \rightarrow {}^{222}Rn$ Delayed Coincidence

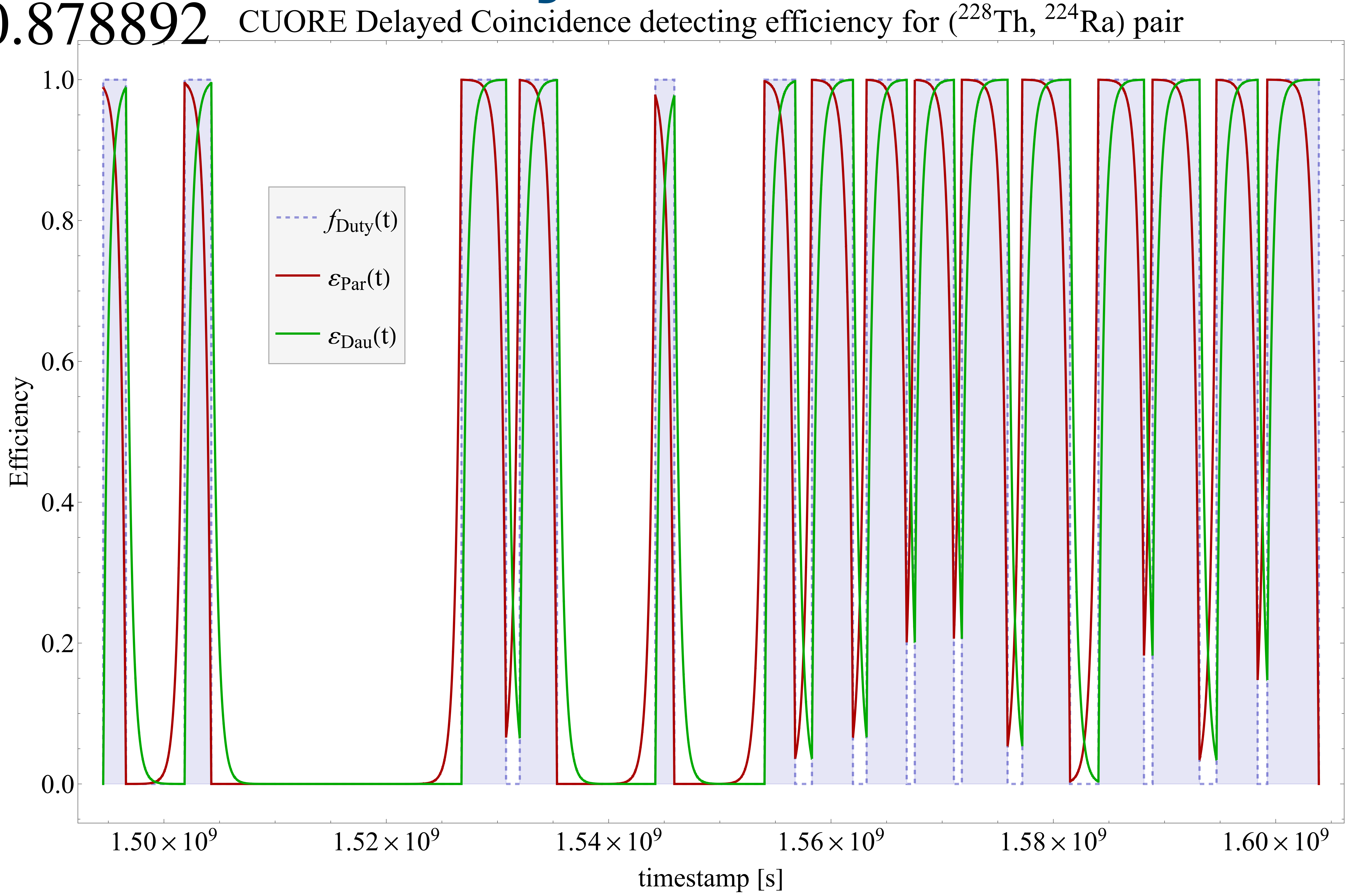


$$\varepsilon = \frac{A_{\text{Yellow}}}{A_{\text{Yellow}} + A_{\text{Red}}}$$

If my daughter falls into the red area, I will get a lonely parent, which will be regarded as the background that DC is looking for.

^{228}Th → ^{224}Ra **Delayed Coincidence**

$E[\varepsilon] = 0.878892$



Analysis of $^{212}\mathrm{Bi} \rightarrow {}^{208}\mathrm{Tl}$, $^{212}\mathrm{Pb} \rightarrow {}^{212}\mathrm{Bi}(\alpha)$ and, $^{228}\mathrm{Th} \rightarrow {}^{224}\mathrm{Ra}$ DC Summary

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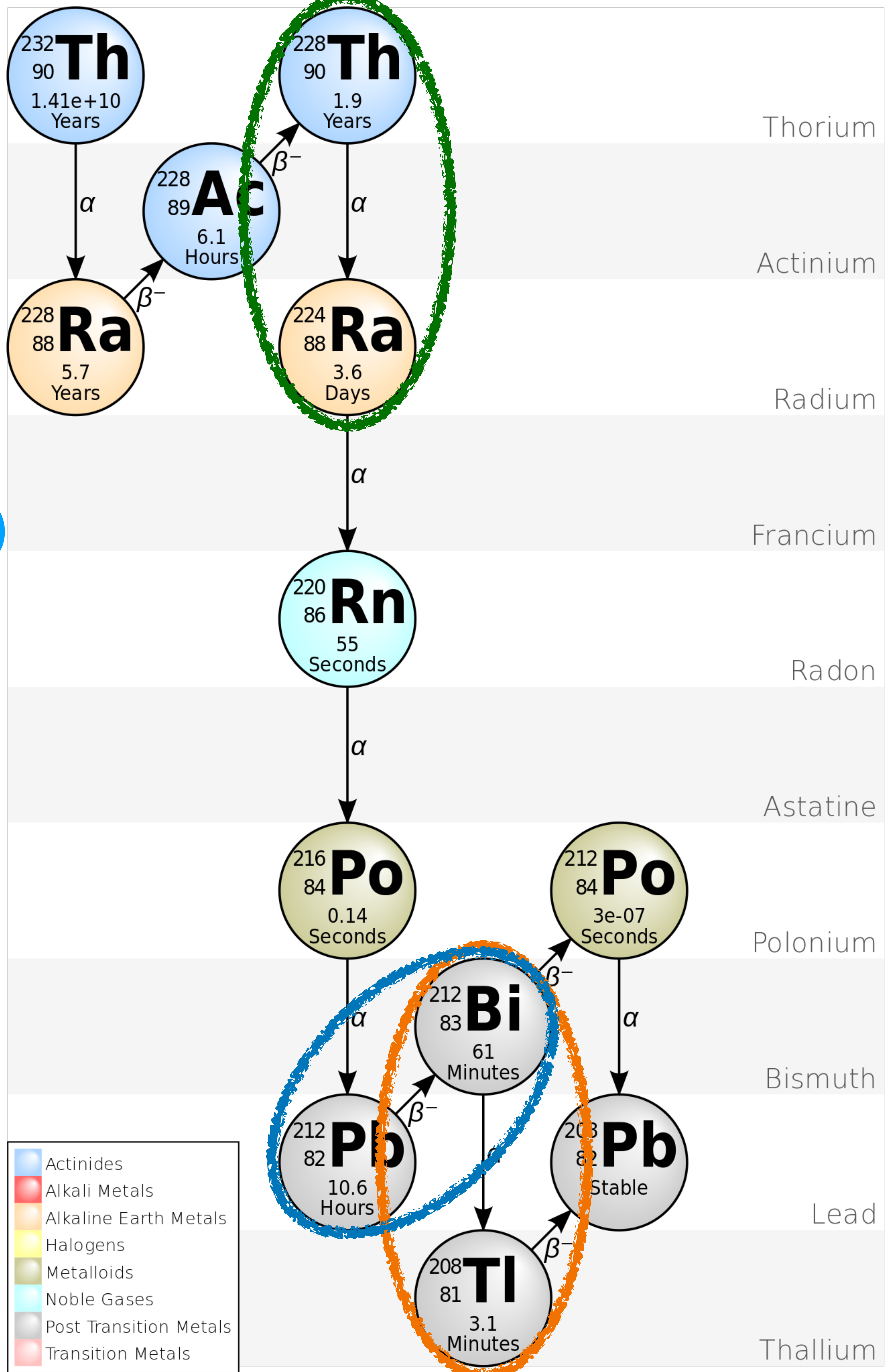
^{232}Th decay chain Delayed Coincidence

Decay Sub-Chain:

^{212}Bi → ^{208}Tl, ^{212}Pb → ^{212}Bi(α)

and, ^{228}Th → ^{224}Ra



^{232}Th decay chain Delayed Coincidence

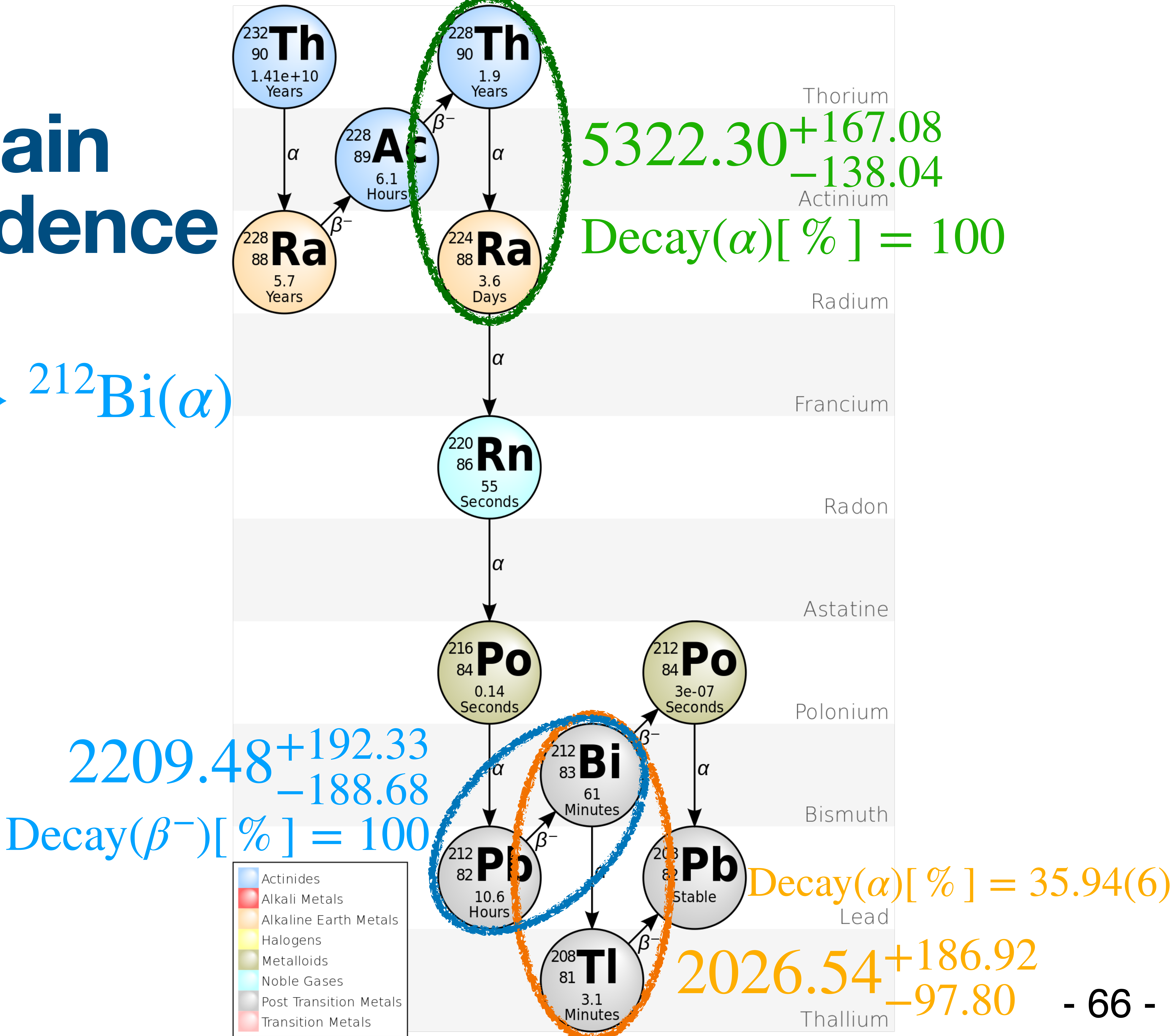
Decay Sub-Chain	Signature	Fitted N_0/ε	Signature	Fitted N_0/ε
^{212}Bi → ^{208}Tl	M1 → M1	$644.13^{+181.34}_{-85.89}$	M2 → M1	– – –
	M1 → M2	$441.87^{+22.93}_{-31.28}$	M2 → M2	– – –
	M1 → M3	$396.95^{+21.10}_{-25.79}$	M2 → M3	$51.07^{+8.83}_{-8.83}$
	M1 → M4	$241.70^{+22.85}_{-14.54}$	M2 → M4	$37.84^{+8.00}_{-7.24}$
	M1 → M5	$119.76^{+16.41}_{-9.85}$	M2 → M5	$22.07^{+6.78}_{-4.44}$
	M1 → M6	$57.50^{+8.76}_{-8.76}$	M2 → M6	– – –
	M1 → M7	$13.65^{+5.38}_{-3.04}$	M2 → M7	– – –
^{212}Pb → ^{212}Bi(α)	M1 → M1	$1879.5^{+178.0}_{-178.0}$	M2 → M1	$126.00^{+39.48}_{-33.41}$
	M1 → M2	$161.43^{+60.45}_{-52.02}$	M2 → M2	$42.55^{+9.70}_{-9.70}$
^{228}Th → ^{224}Ra	M1 → M1	$4629.8^{+150.2}_{-122.9}$	M2 → M1	$314.18^{+54.17}_{-39.72}$
	M1 → M2	$249.18^{+46.95}_{-46.95}$	M2 → M2	$129.14^{+14.73}_{-13.00}$
	^{212}Bi → ^{208}Tl	$2026.54^{+186.92}_{-97.80}$	^{212}Pb → ^{212}Bi(α)	$2209.48^{+192.33}_{-188.68}$
	^{228}Th → ^{224}Ra	$5322.30^{+167.08}_{-138.04}$		

^{232}Th decay chain
Delayed Coincidence

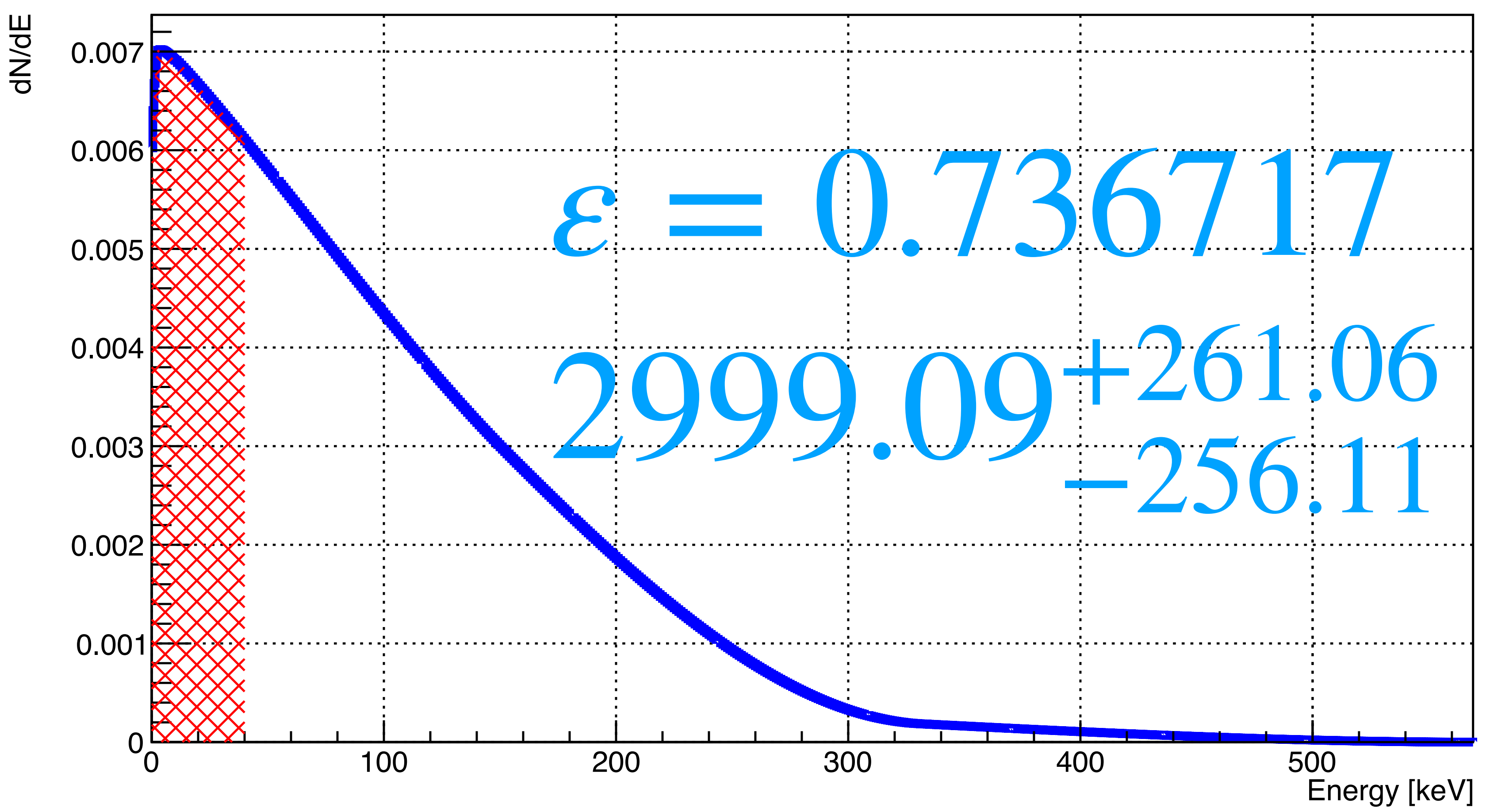
Decay Sub-Chain:

$^{212}\mathrm{Bi} \rightarrow {}^{208}\mathrm{Tl}$, $^{212}\mathrm{Pb} \rightarrow {}^{212}\mathrm{Bi}(\alpha)$

and, $^{228}\mathrm{Th} \rightarrow {}^{224}\mathrm{Ra}$

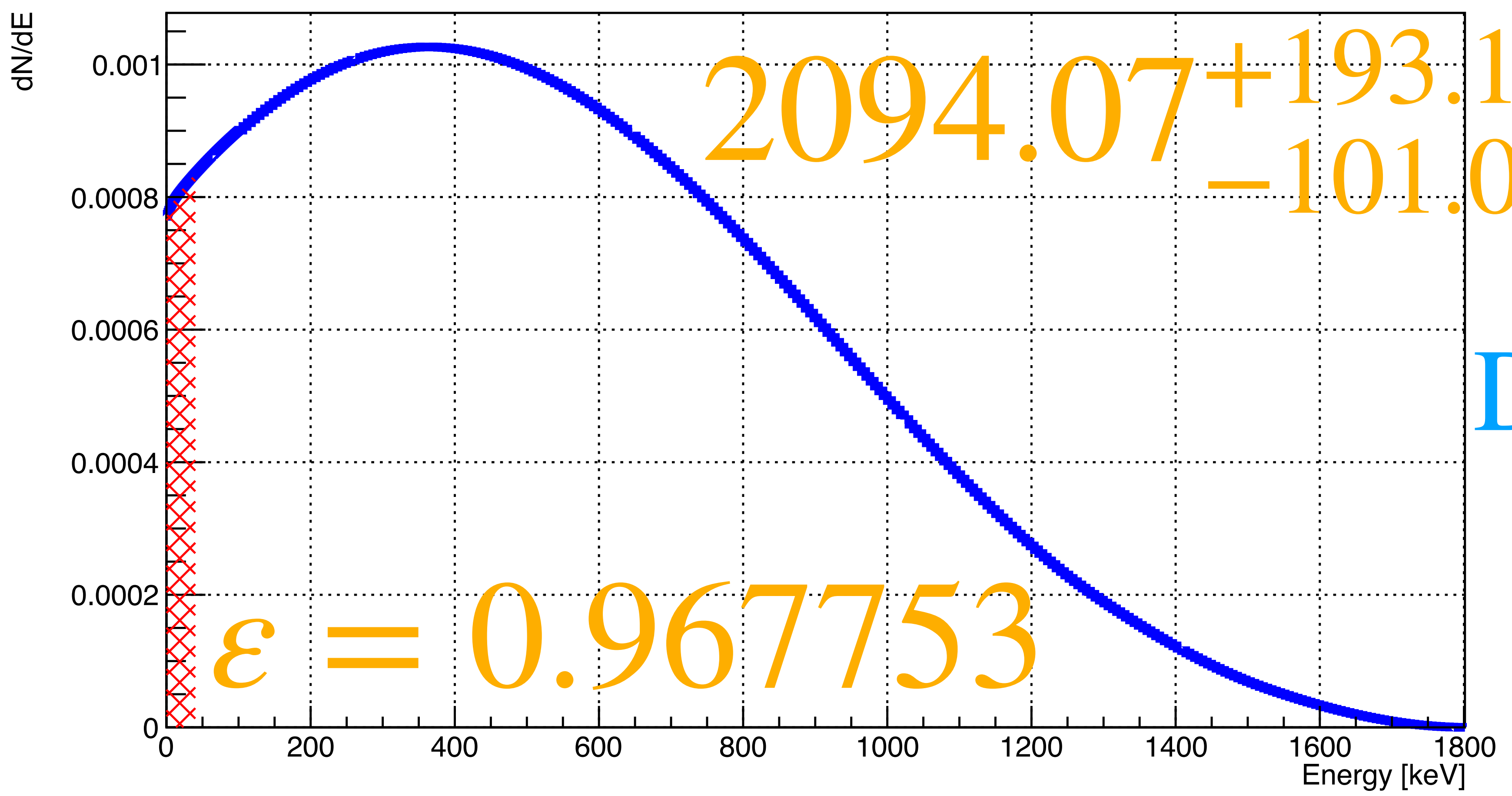


^{232}Th decay chain
Delayed Coincidence



$\varepsilon = 0.736717$

$2999.09^{+261.06}_{-256.11}$

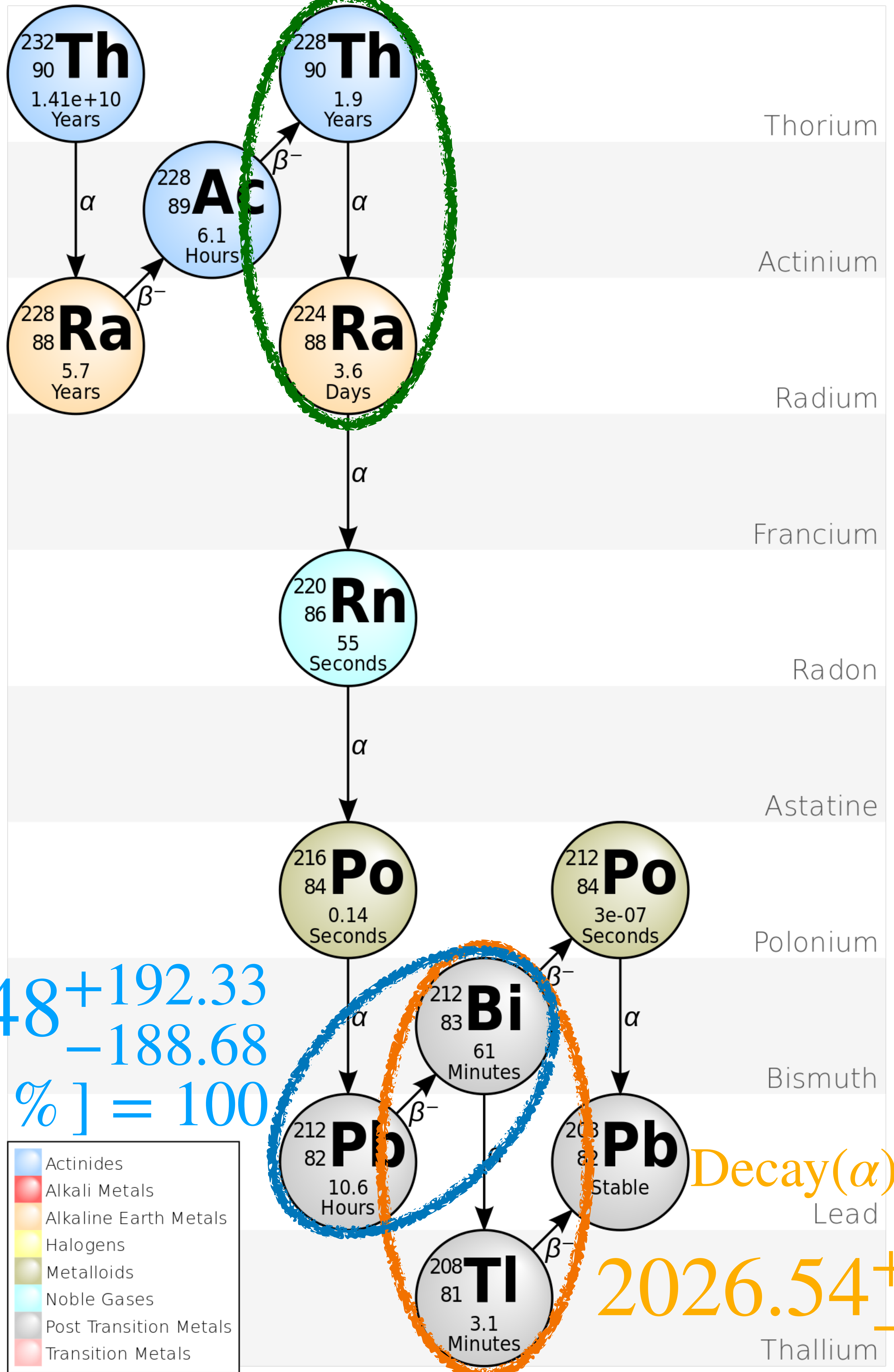


$2094.07^{+193.15}_{-101.06}$

$\varepsilon = 0.967753$

$2209.48^{+192.33}_{-188.68}$

$\mathrm{Decay}(\beta^-)[\,\%\,] = 100$



$\mathrm{Decay}(\alpha)[\,\%\,] = 35.94(6)$

$2026.54^{+186.92}_{-97.80}$

Thanks!

NvDEx-CUPID-China collaboration group 2023 annual meeting

Shihong Fu, 17 Dicembre, 2023