Midas Ba-136 data analysis

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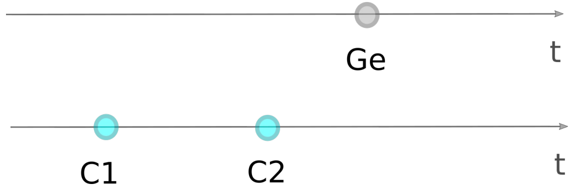
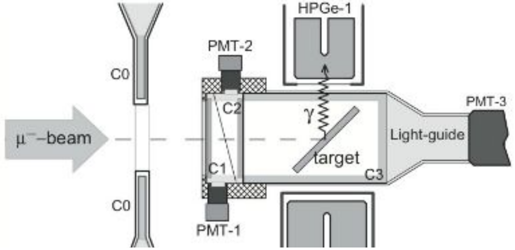
- i) Data cuts, datasets and selection
- ii) Data Cleaning & Quality plots: C# & Ge Counts & Rates (Hz)
- iii) Ba-136 line identification and spectra analysis

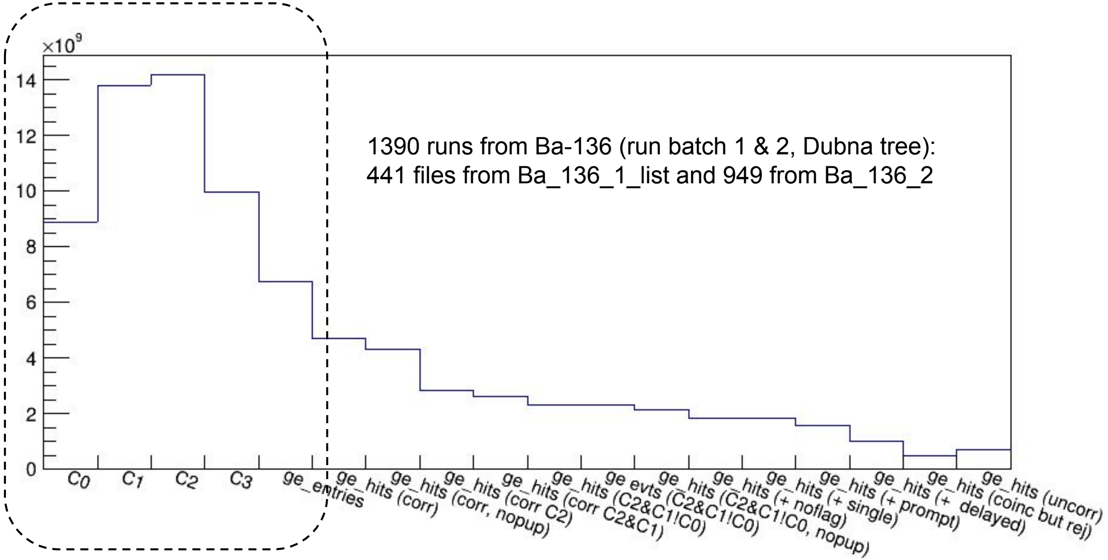
Data: 1390 runs from Ba-136 (run batch 1 & 2, Dubna tree)
441 files from Ba_136_1_list and 949 from Ba_136_2

Data cuts, datasets & selection

Events: C# hits (channel 1 to 4), Ge hits (ch 1-8, exc. ch 2 and 6)



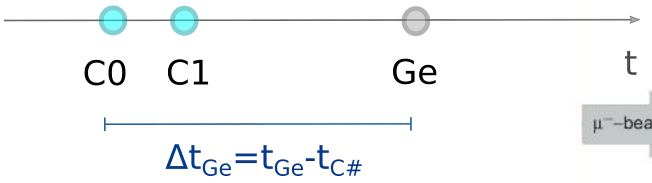


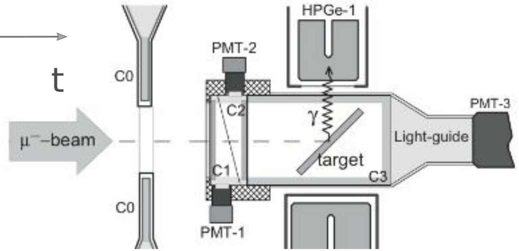


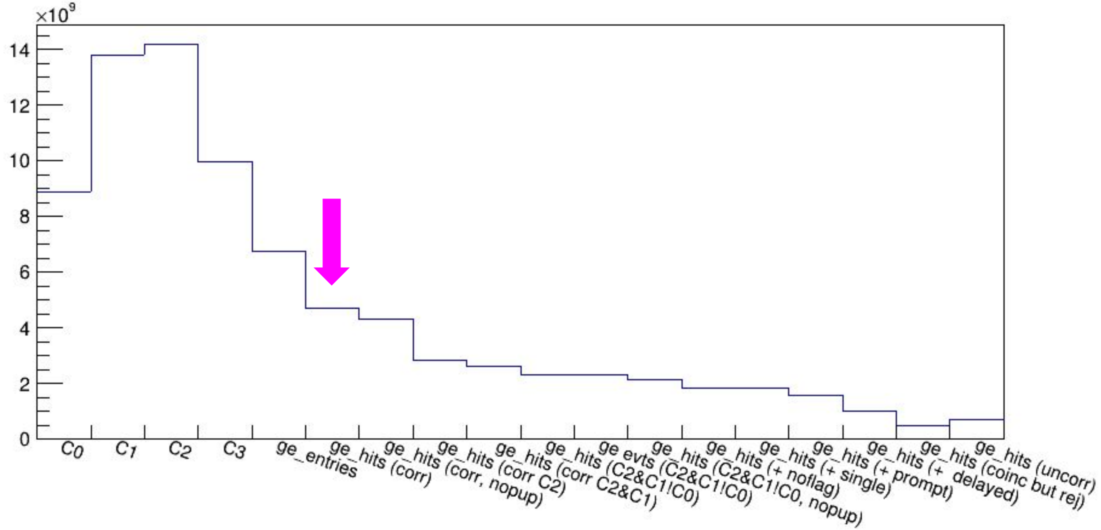
Data cuts, data types & selection

Events: C# hits (channel 1 to 4), Ge hits (ch 1-8, exc. ch 2 and 6)

- **Correlated:** Ge hit* close enough to a C# hit $W = -100 < \Delta t_{Ge} < 1440$ns.



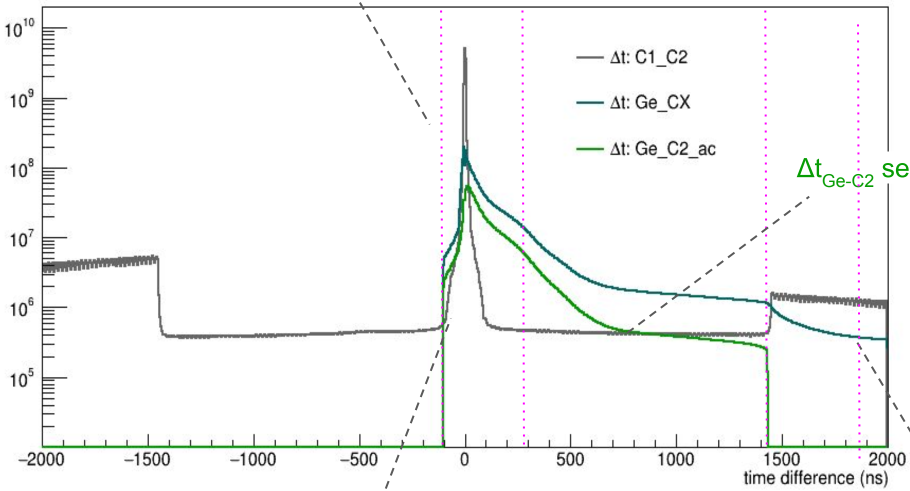




(*) Here Ge_2 and Ge_6 are excluded

ps: Time spectra & preliminary time window

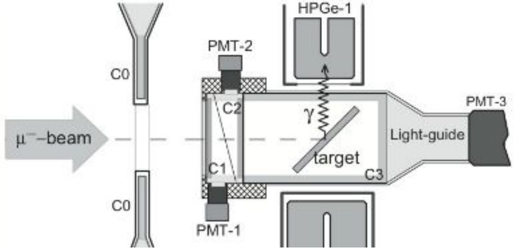
Preliminary time cuts: The objective is to optimize them, per channel!



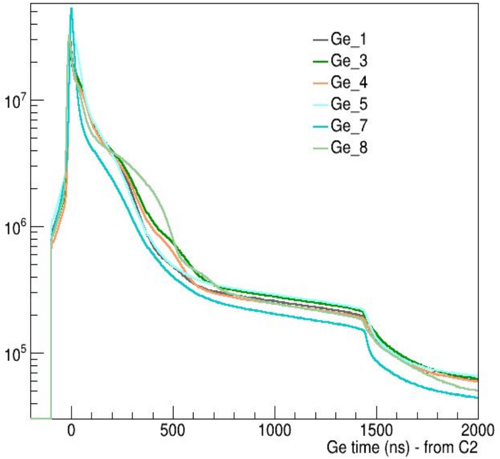
$\Delta t_{Ge\text{-}C2}$ selected events

Tail decay: Single muon selection?

$\Delta t_{Ge} = t_{Ge} - t_{C\#}$



$\Delta t_{Ge\text{-}C2}$ per Ge channel: Excluded Ge_2 and Ge_6



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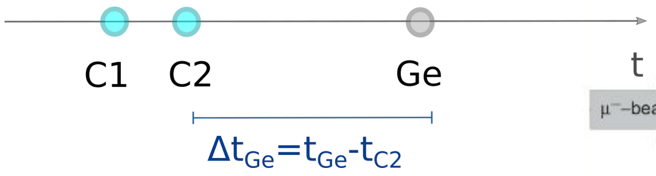
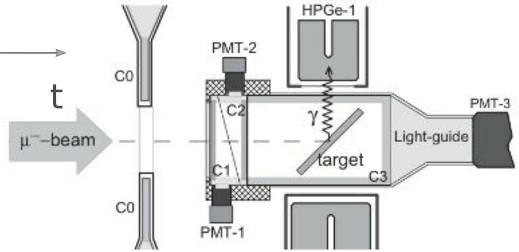
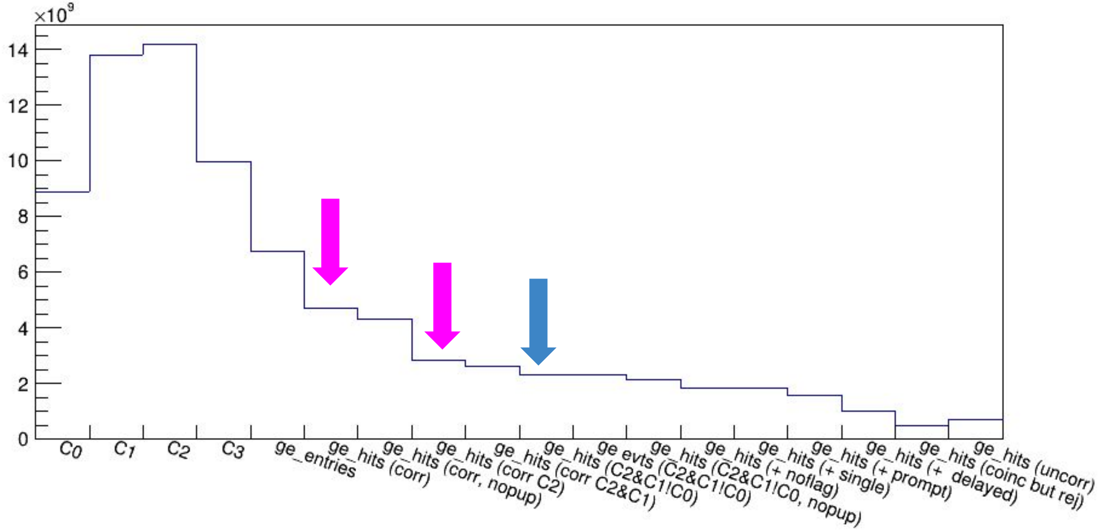
  - **Coincidence**: !C0 & C1 &C2: (!C3 not used, as it can be triggered by gammas)







Data cuts, data types & selection

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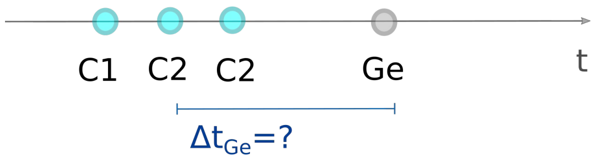
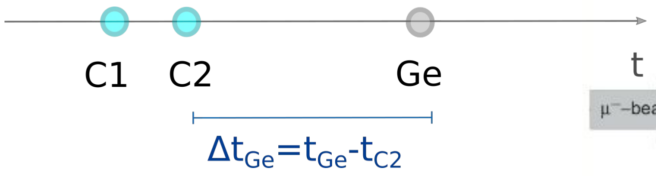
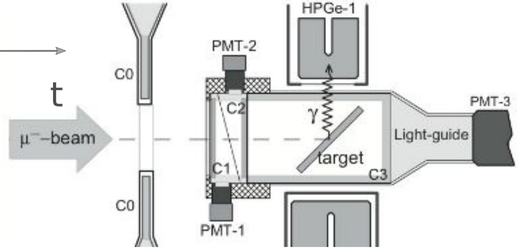
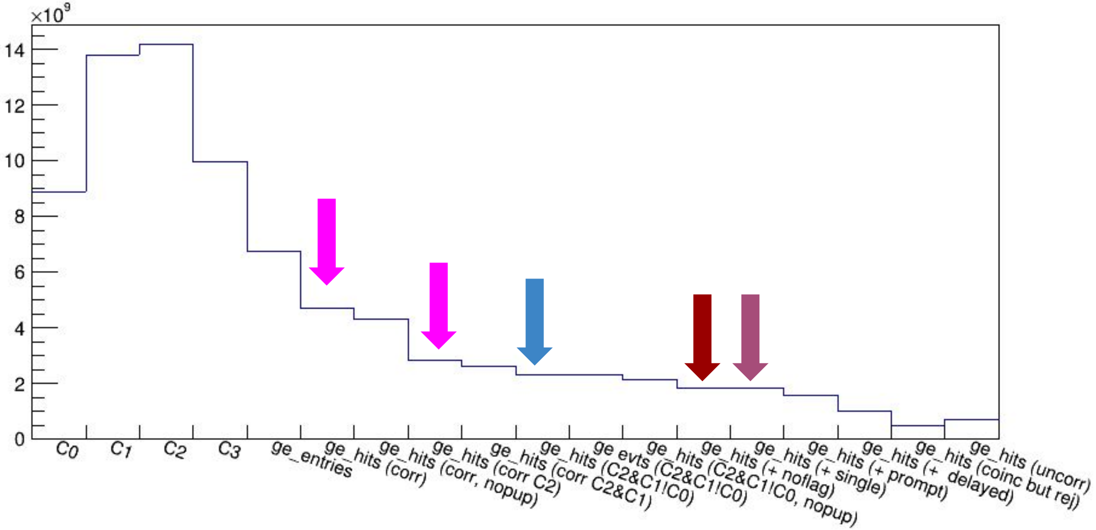
  - **Single muons:** we need a well defined Δt_{Ge}, we thus **reject "multiple muons in W"**, such as multiple C1-C1, C2-C2, hits (ps: dt is ~ 1400ns)









Data cuts, data types & selection

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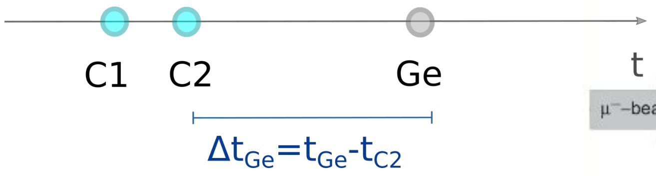
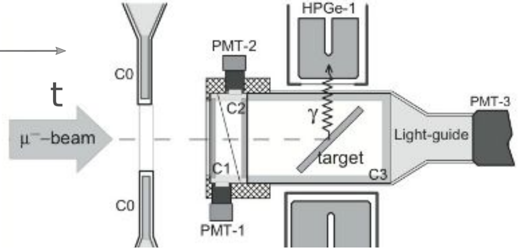
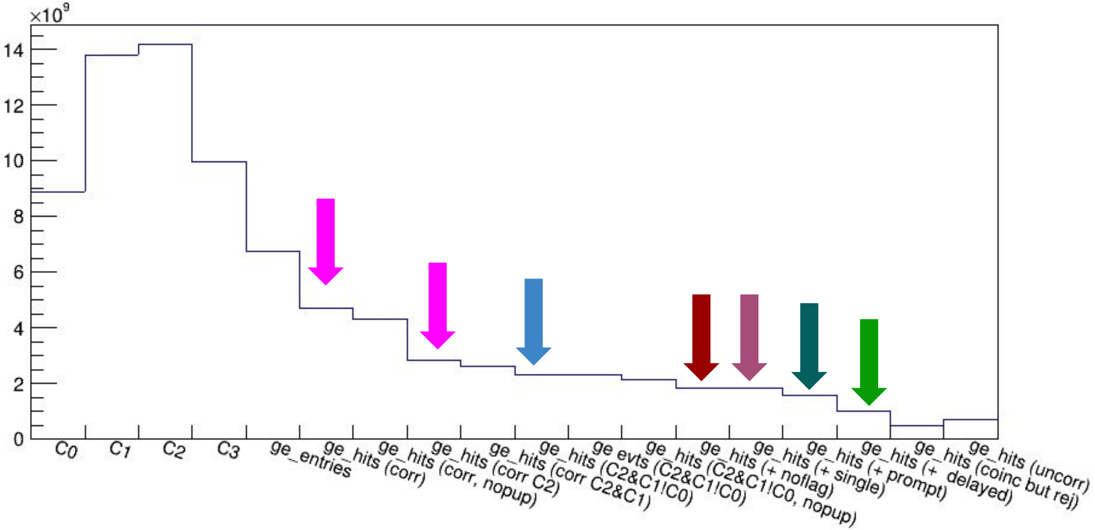
  - **Prompt** or **delayed**:

    $\Delta t_{Ge\text{-}C2} < 280$ ns or $280 < \Delta t_{Ge\text{-}C2} < 1440$ns.







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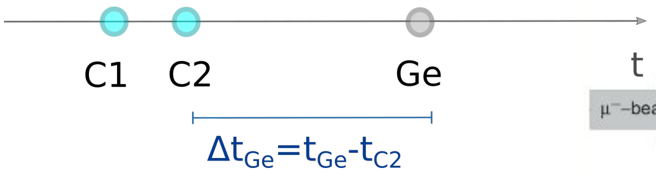
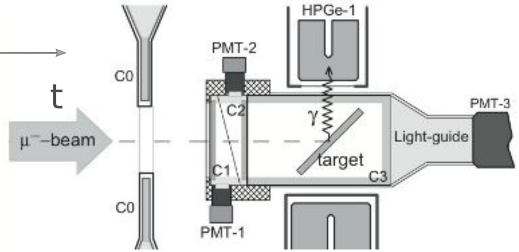
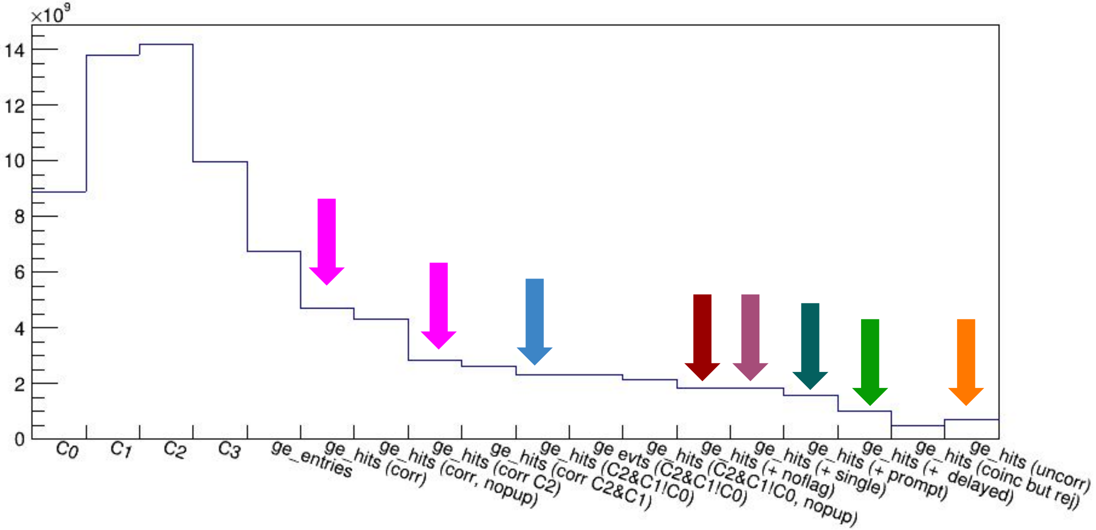
- **Uncorrelated**







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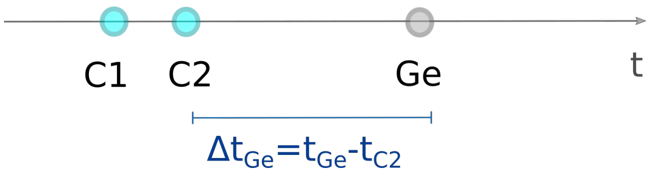
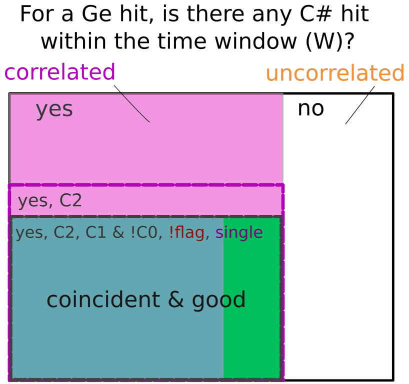
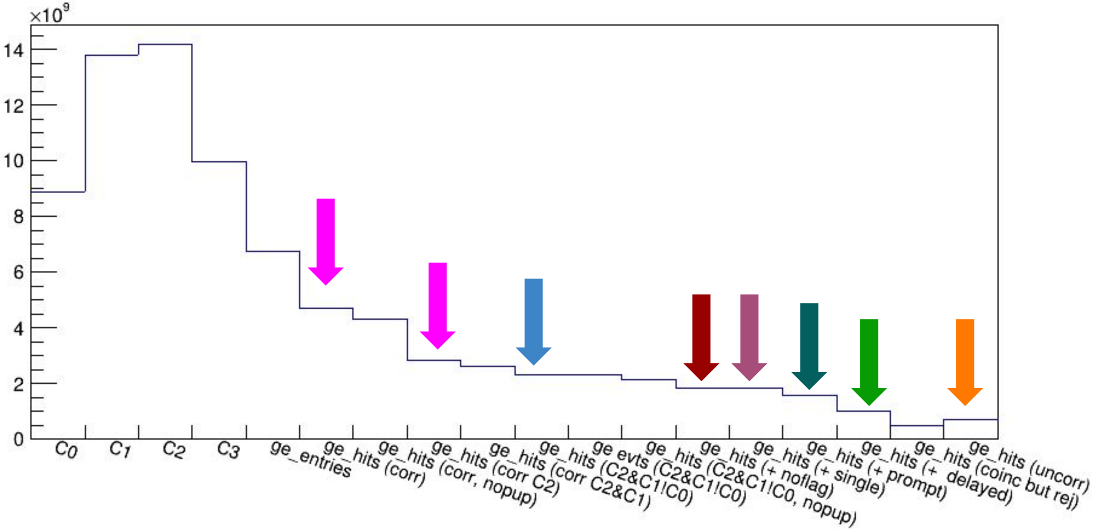
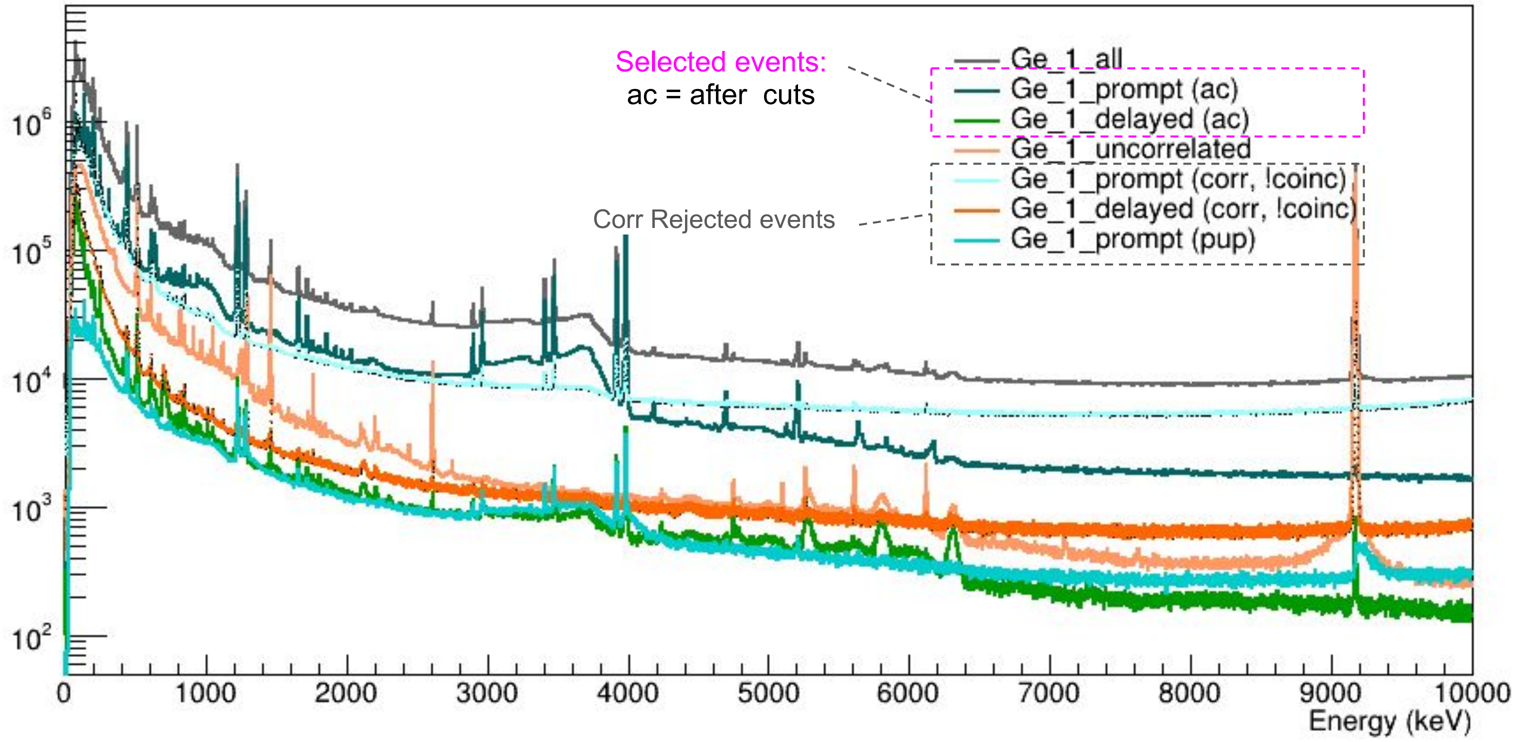




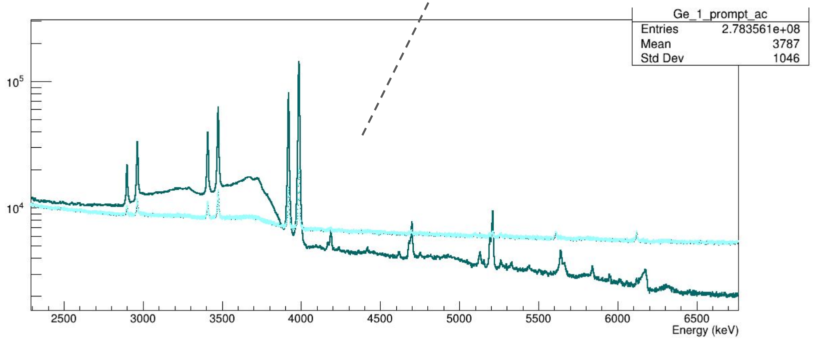


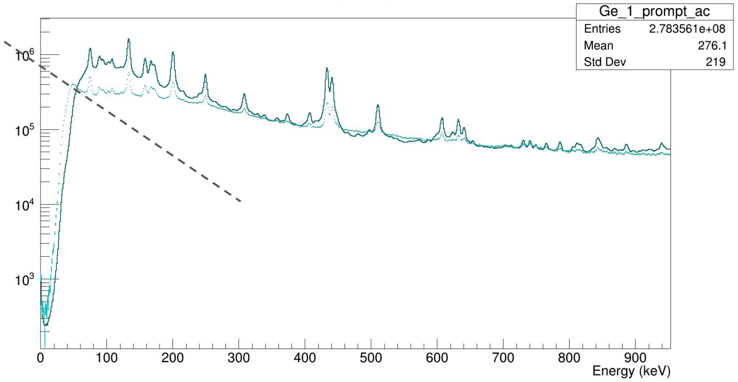
ps: Coinc but rej = coinc but flagged or multiple

Example of different data sets for Ge_1 (all Ba data)

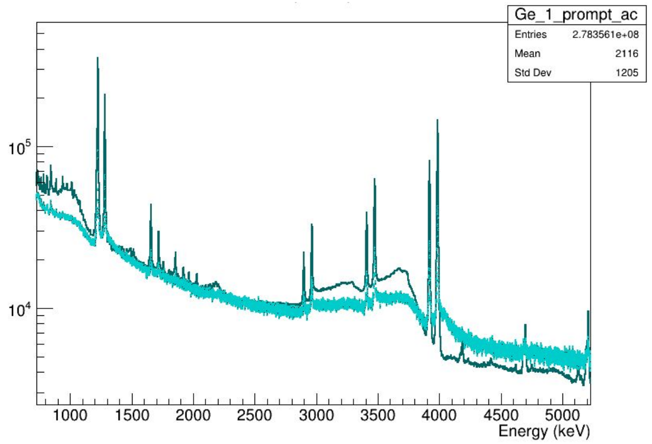


Investigation: Any special features in rejected events? Such as from muons that trigger C0 or pile up events?



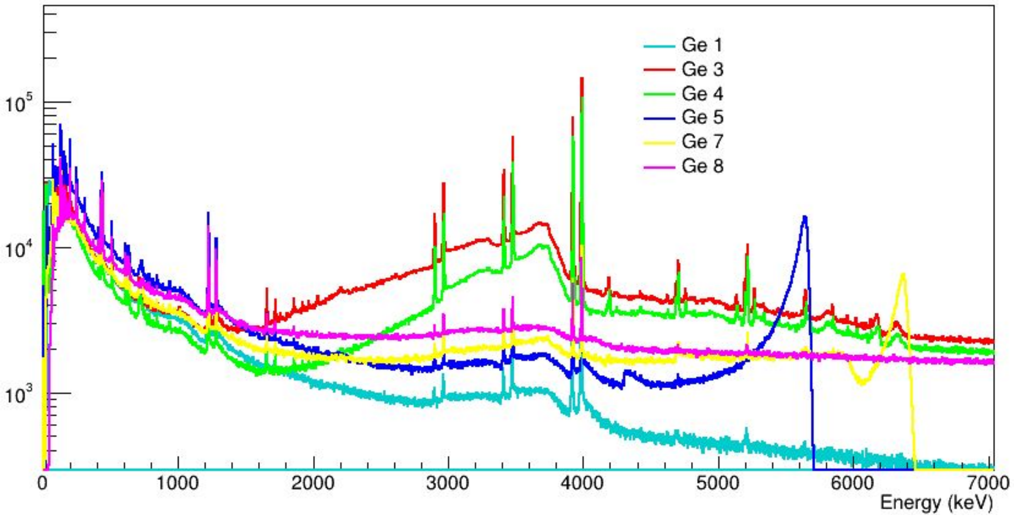


- **Prompt**
- **Prompt rejected** (due to coincidence or pile up cut)
- Or delayed vs delayed rejected

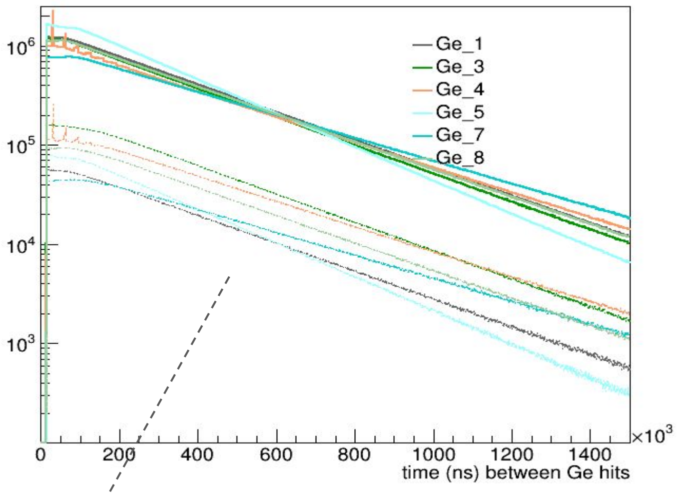


No special feature (like peaks that have higher intensity in the rejected data) is observed at a first look…

The shape of the pile up energy spectra vary for the different detectors, the time shape does not vary though



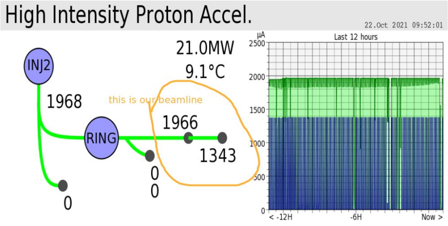
$\Delta t_{Ge\text{-}Ge}$ per channel: non-flagged (—), pile-up (---)



The "intensity" of pile-up changes for different Ge channels (as expected). The time distribution of pile-up events don't seem to be different.

Data Selection & Quality plots:
C# & Ge Counts & Rates (Hz)

1390 runs from Ba-136 (run batch 1 & 2, Dubna tree): 441 files from Ba_136_1_list and 949 from Ba_136_2



Expected:

Beam flux $\propto$ C# hits $\propto$ correlated Ge hits (all proportional, $\propto$)
uncorrelated Ge hits (constant, independent of the beam)

Data classification:

0) stable: beam has constant flux/current, C# hits, ge hits, uncorr events are ~ constant and $\propto$.

1) unstable beam: beam has dropped under average flux/current value, all C# hits and ge hits count rates drop accordingly, uncorrelated events may also drop a bit as there is some leakage of corr events into the uncorrelated window

Expected (and accepted)?

2) prompt/delayed ratio unstable: if the rate of prompt events decrease (or increase) the one of delayed events should follow the same pattern. (unless the time distribution of Ge hits changed somehow?)

3) uncorr events unstable: larger rate of uncorr event. (maybe due to electronic noise from LN2 fill? calibration mixed data?)

Unexpected (?)

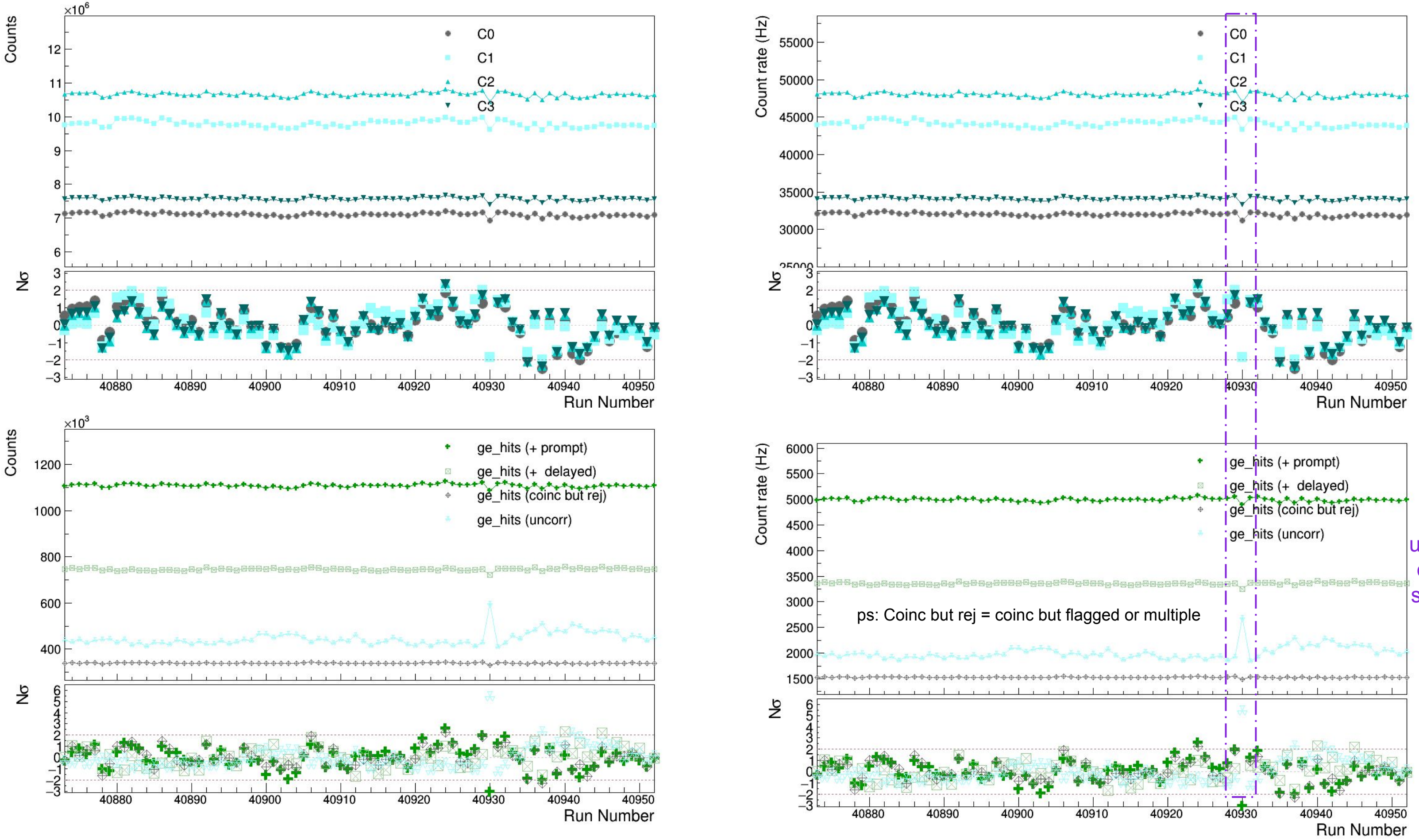
Data Quality plots:
Batch 1 of data (Ba_136_1)

Runs 40873-42523 (441 runs)

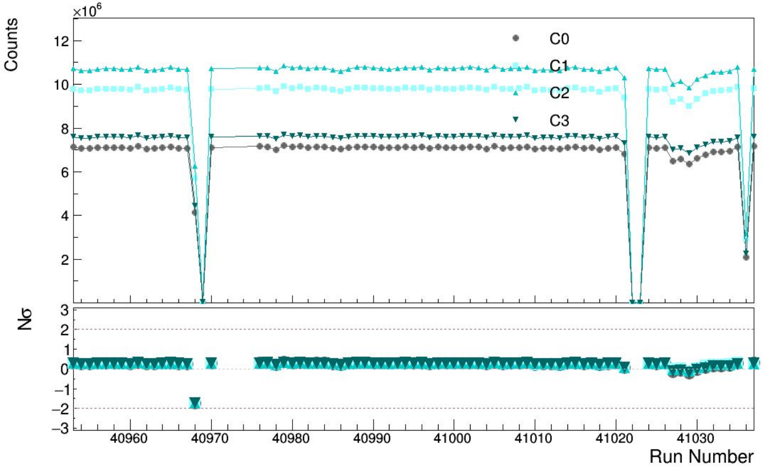
Counts & Rates (Hz)

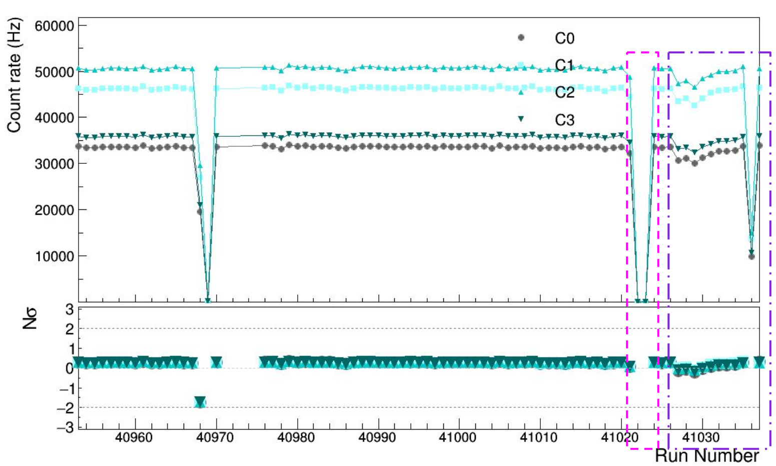
C#

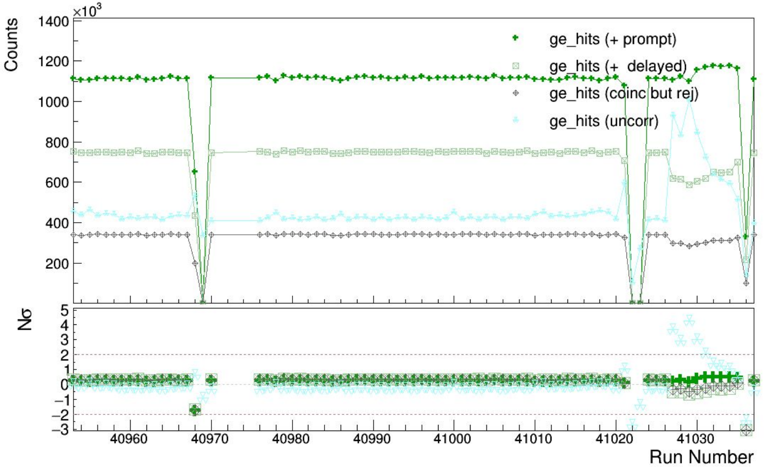
Ge



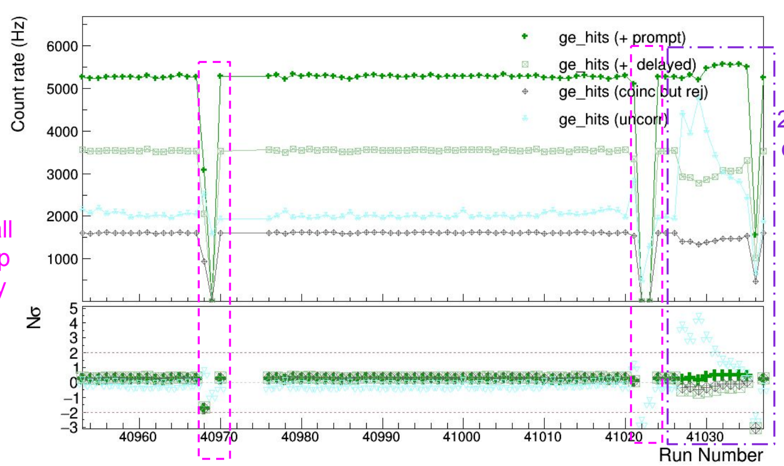
3) uncorr. unstable while others follow slight C# drop



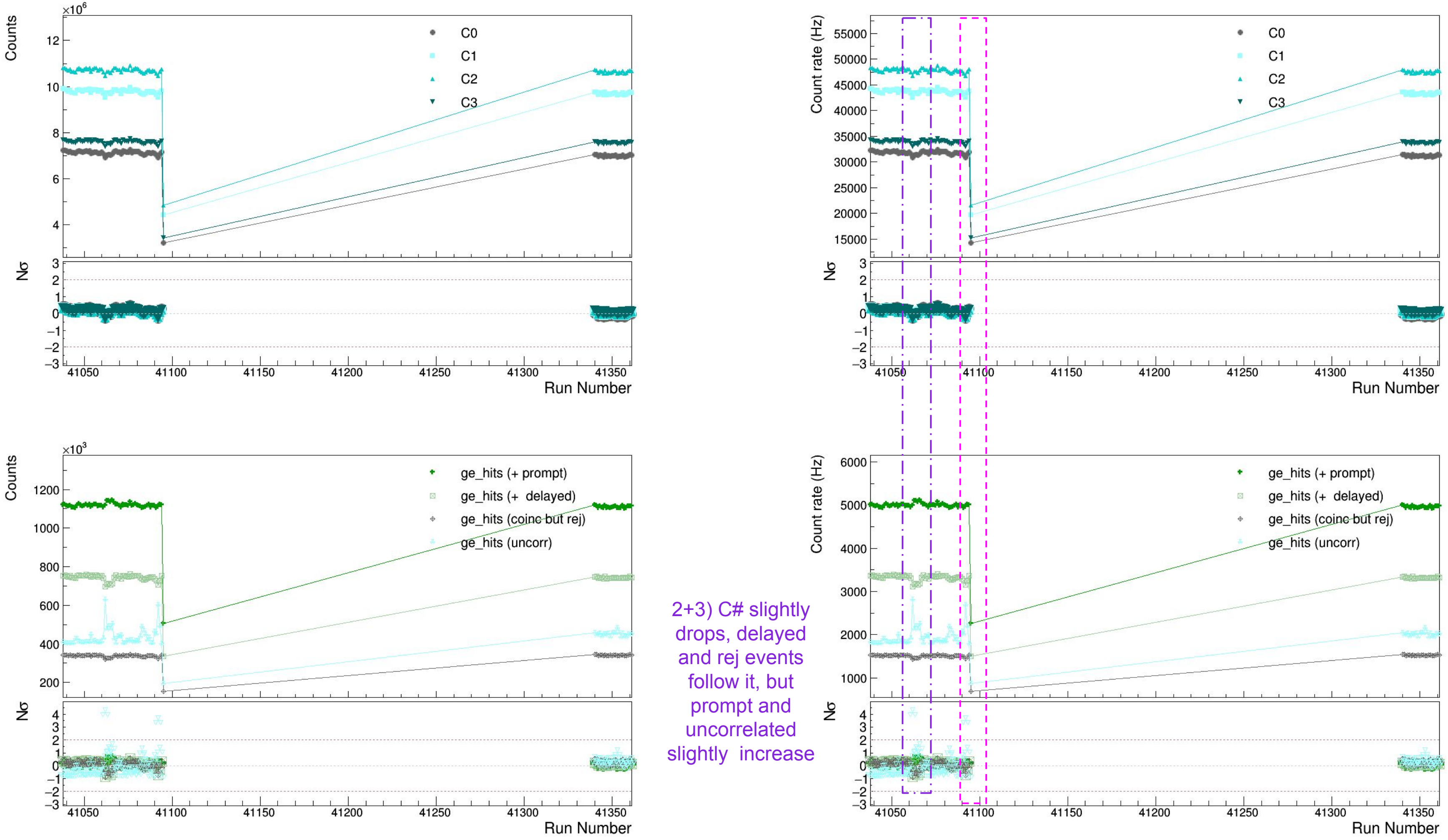




1) Beam is unstable: all counts drop accordingly



2+3) C# slightly drops, delayed and rej events follow it, but prompt and uncorrelated slightly increase



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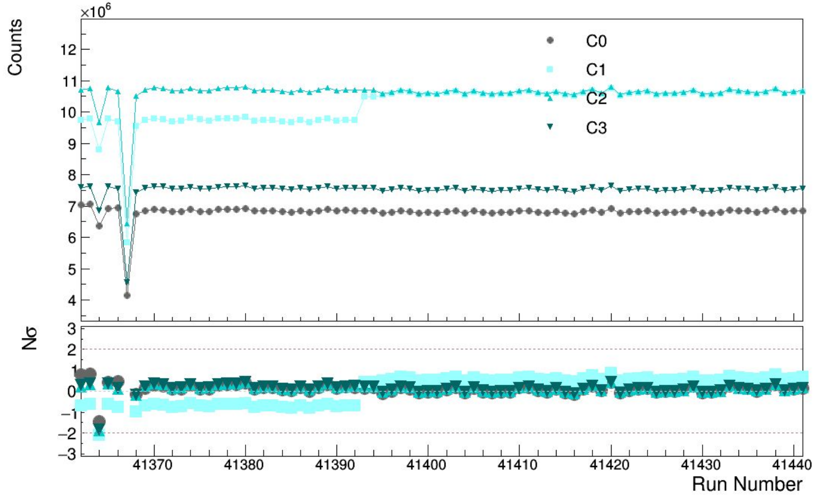

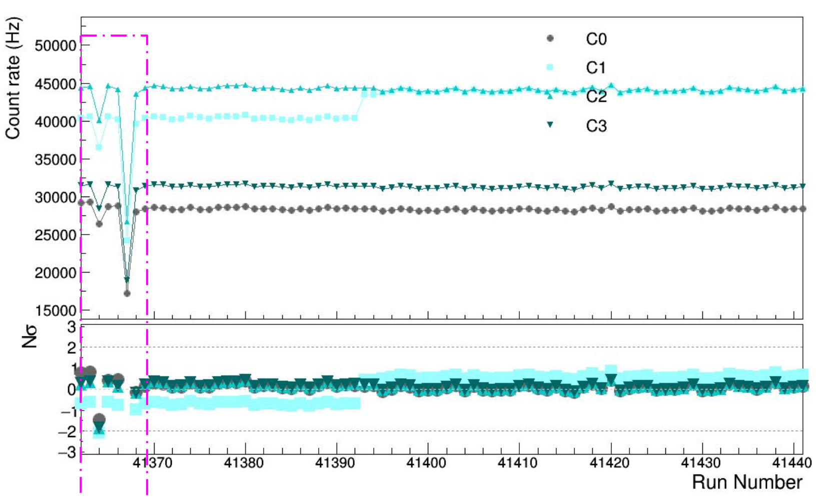

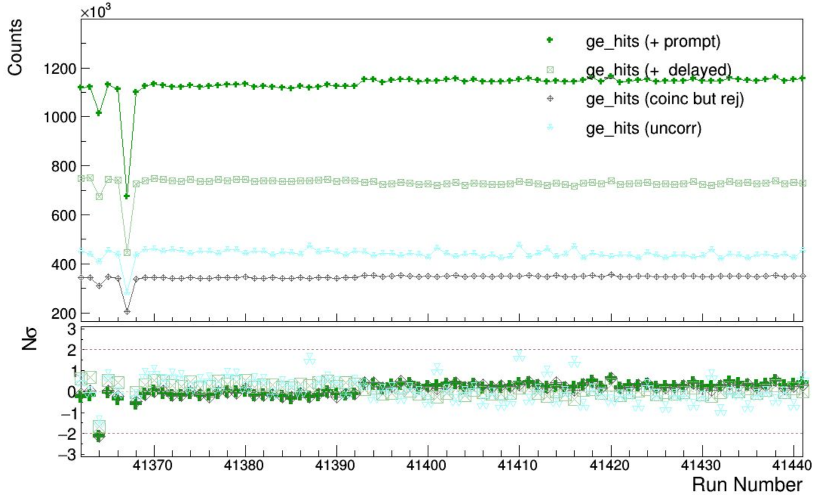

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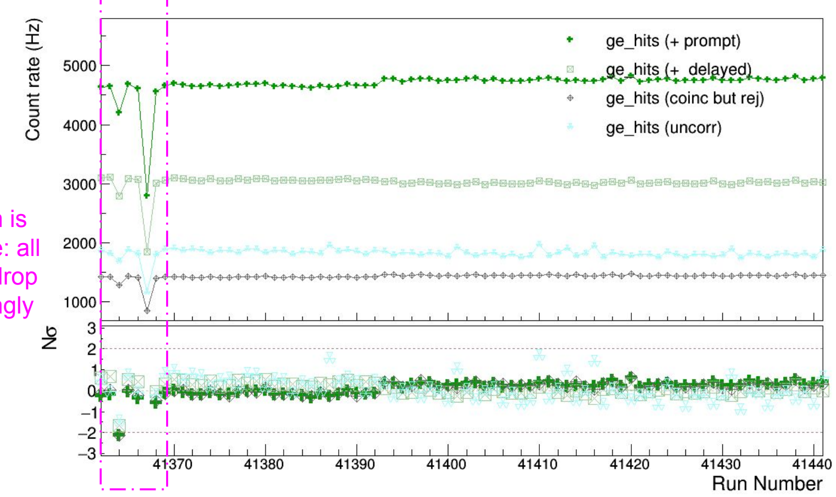
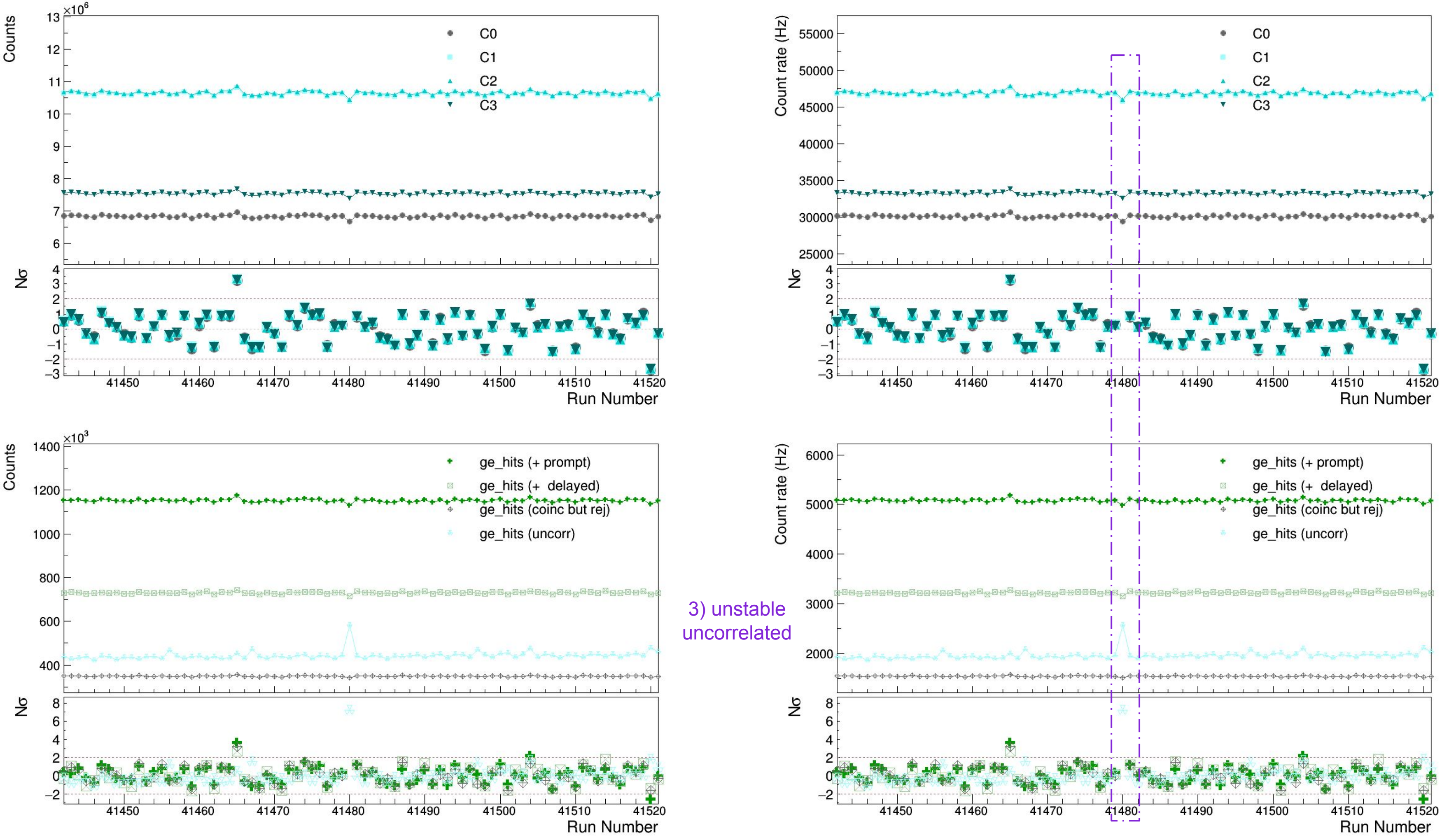
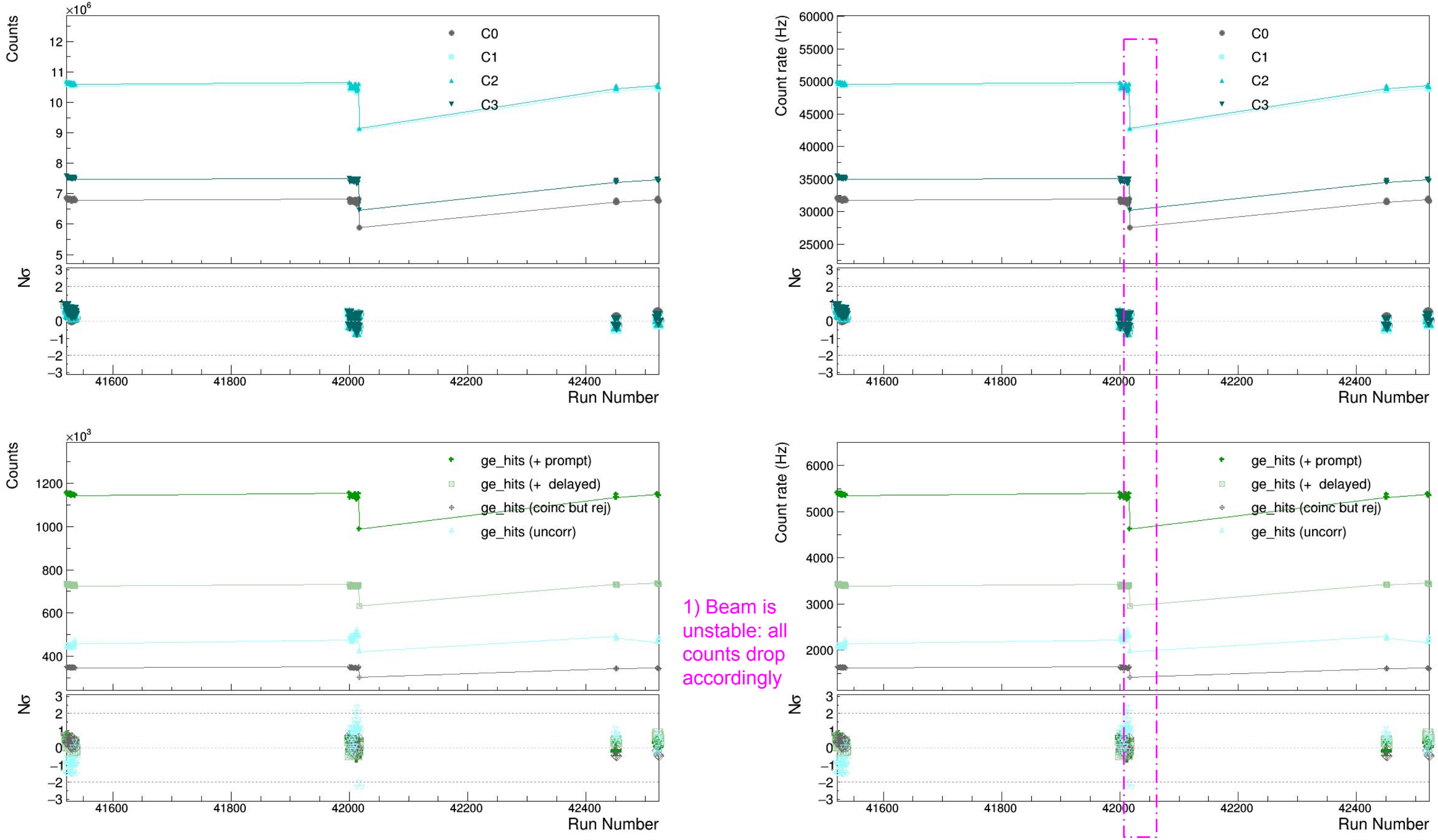




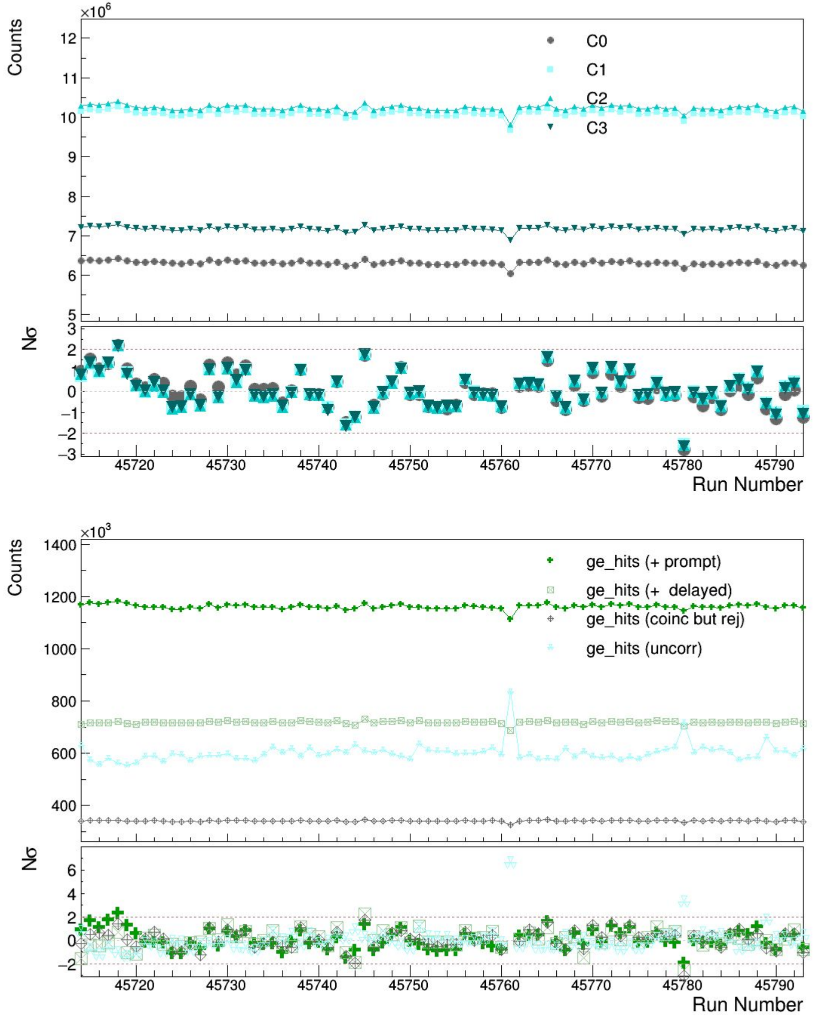
Counts
×10^6
C0
C1
C2
C3
Nσ
Run Number
Count rate (Hz)
ge_hits (+ prompt)
ge_hits (+ delayed)
ge_hits (coinc but rej)
ge_hits (uncorr)
×10^3
3) unstable uncorrelated



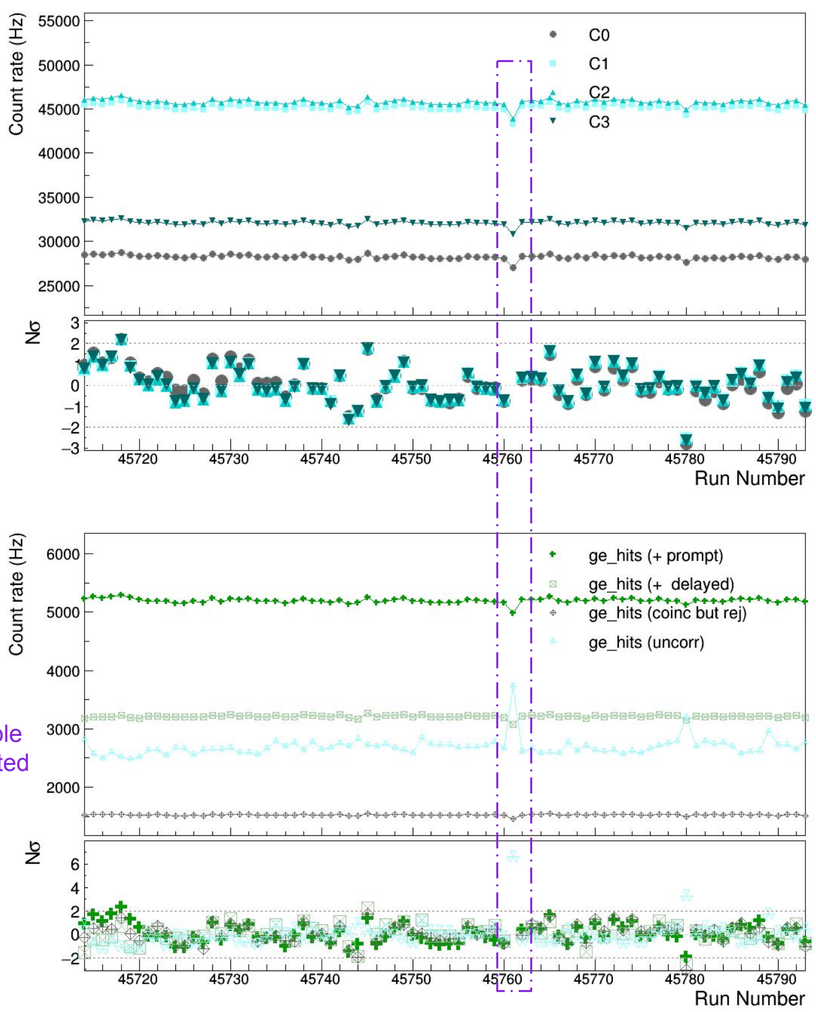
Counts
×10^6
C0
C1
C2
C3
Nσ
Run Number
Count rate (Hz)
ge_hits (+ prompt)
ge_hits (+ delayed)
ge_hits (coinc but rej)
ge_hits (uncorr)
×10^3
1) Beam is unstable: all counts drop accordingly

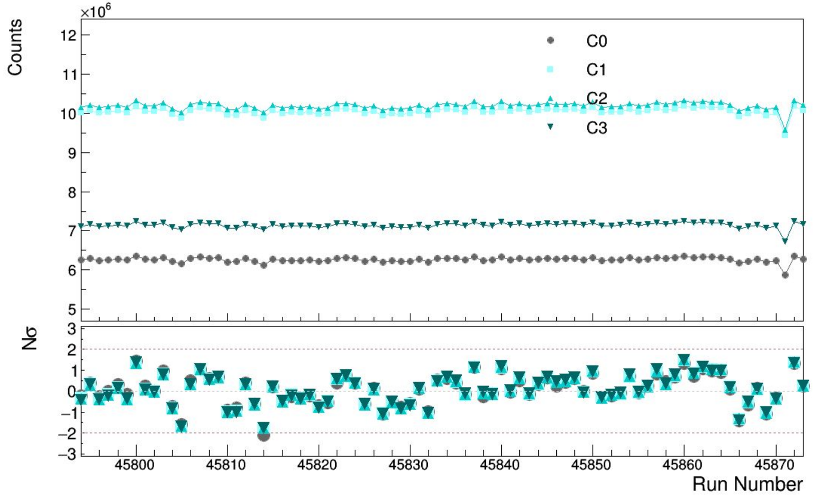
Data Quality plots:
Batch 2 of data (Ba_136_2)

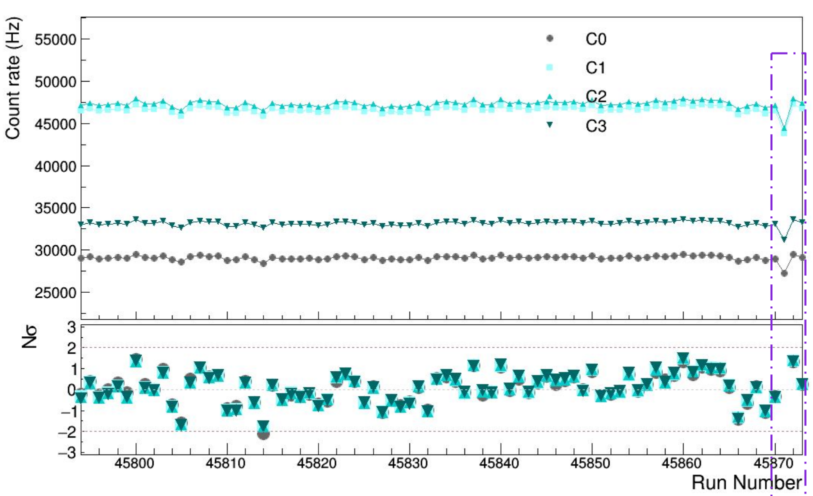
Runs 45714-46671 (949 runs)

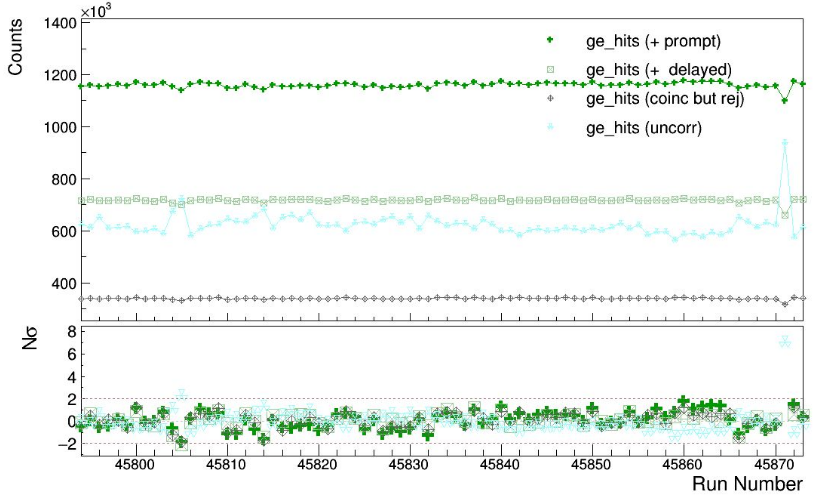


3) unstable uncorrelated









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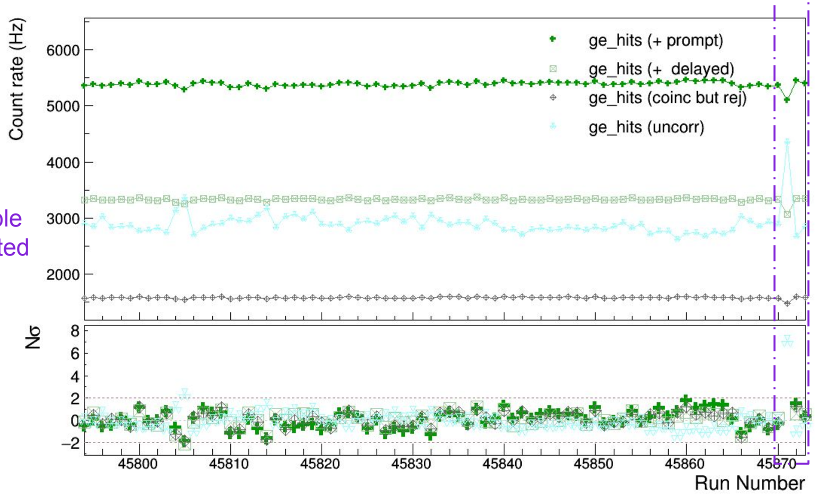
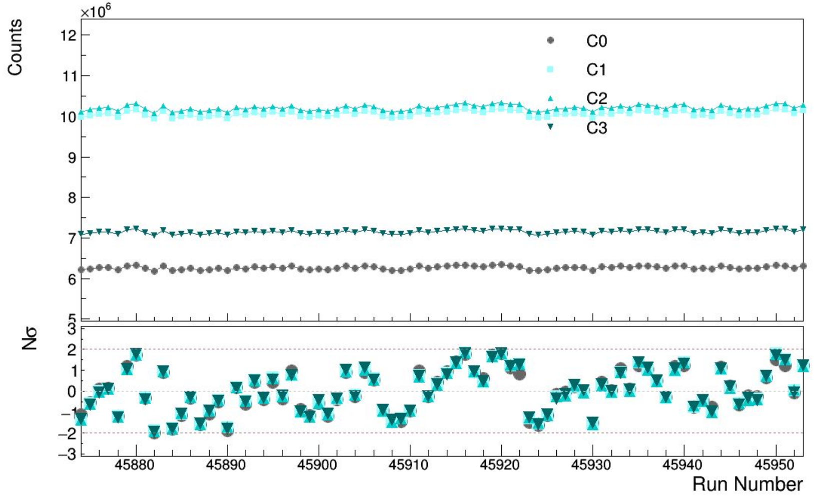
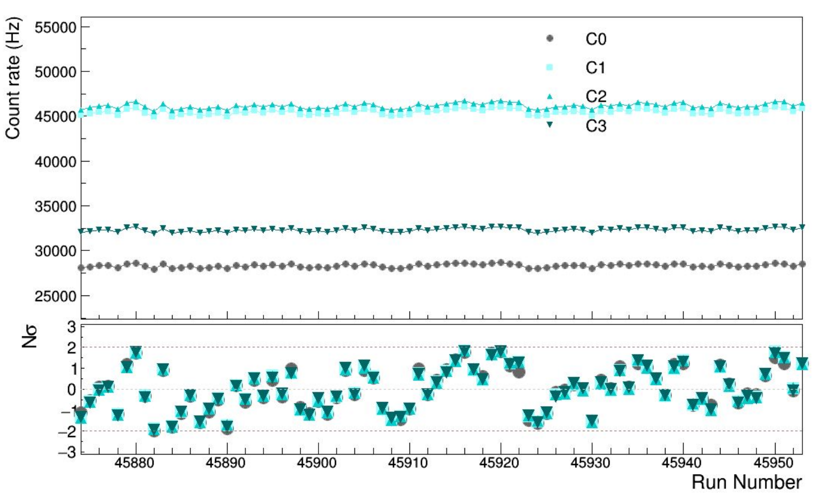
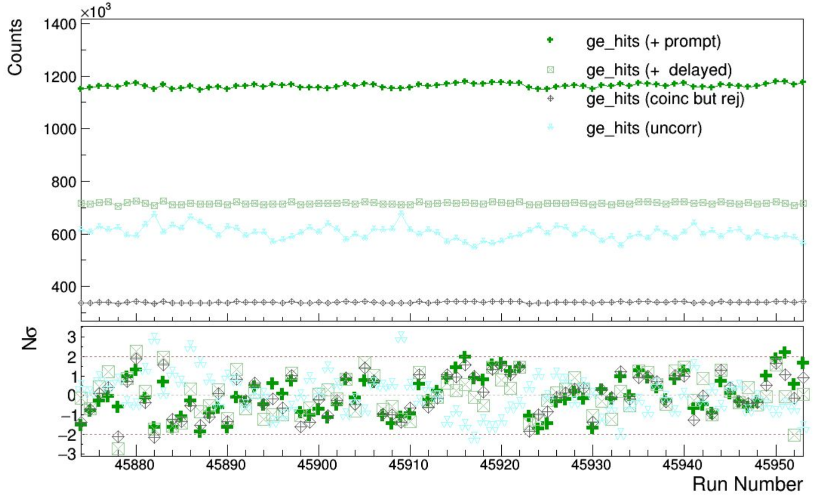




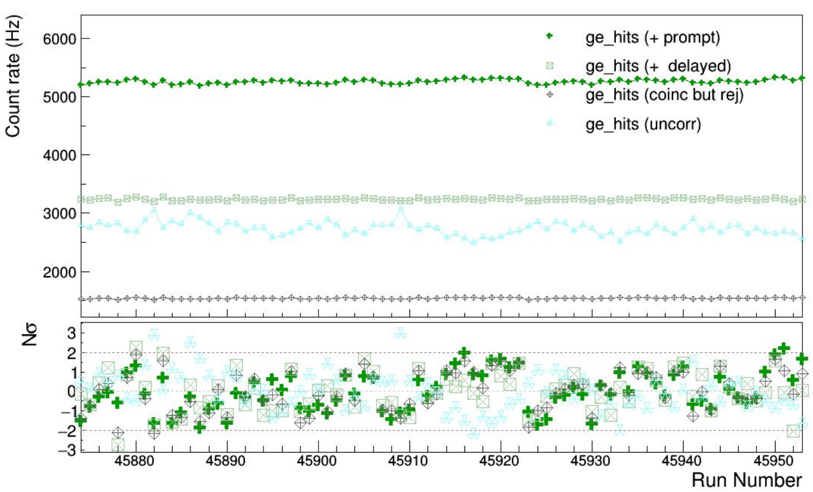
Counts
×10^6
C0
C1
C2
C3
Nσ
Run Number



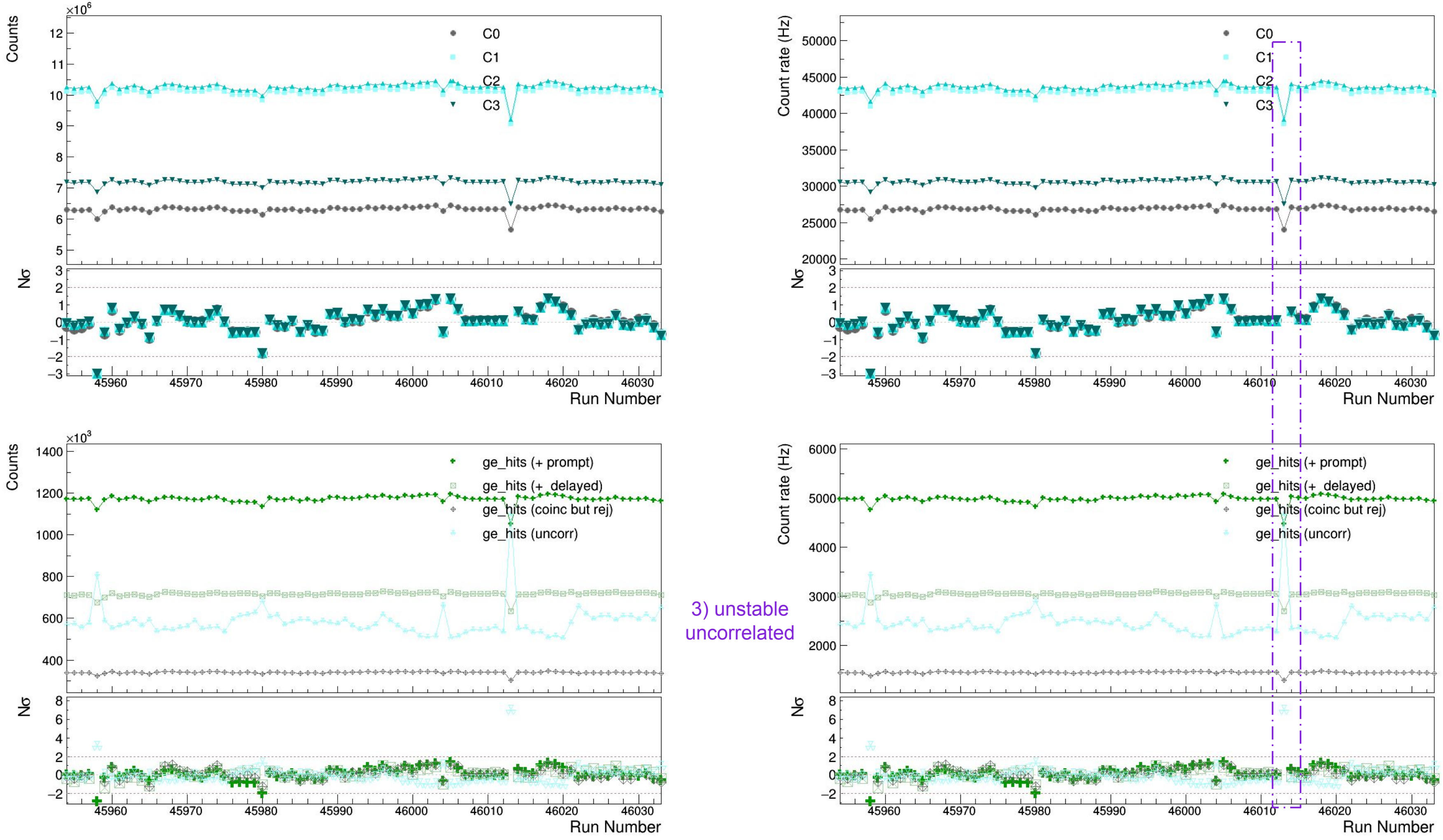
Count rate (Hz)
C0
C1
C2
C3
Nσ
Run Number



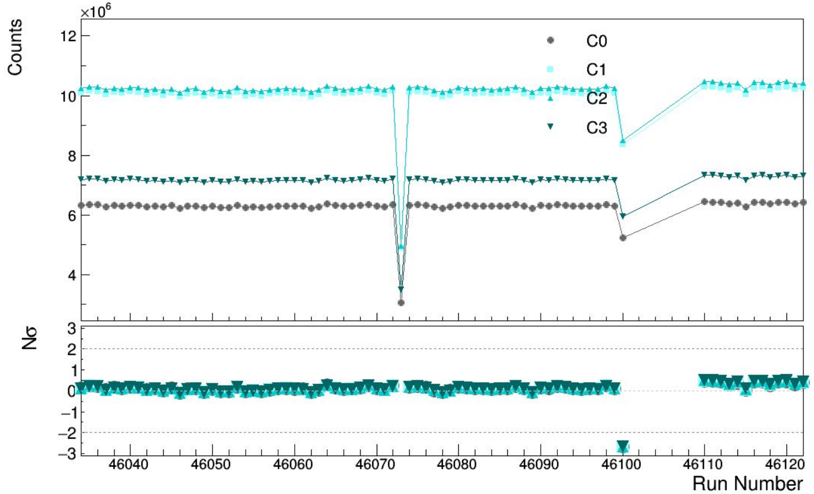
Counts
×10^3
ge_hits (+ prompt)
ge_hits (+ delayed)
ge_hits (coinc but rej)
ge_hits (uncorr)
Nσ
Run Number

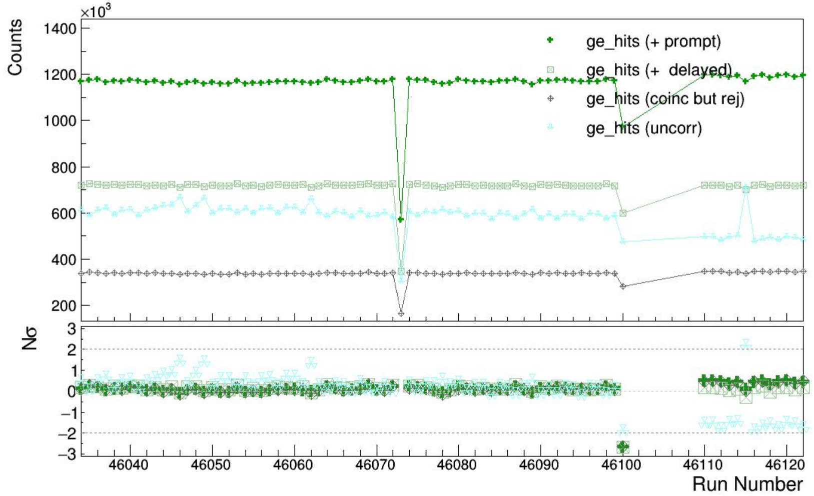


Count rate (Hz)
ge_hits (+ prompt)
ge_hits (+ delayed)
ge_hits (coinc but rej)
ge_hits (uncorr)
Nσ
Run Number

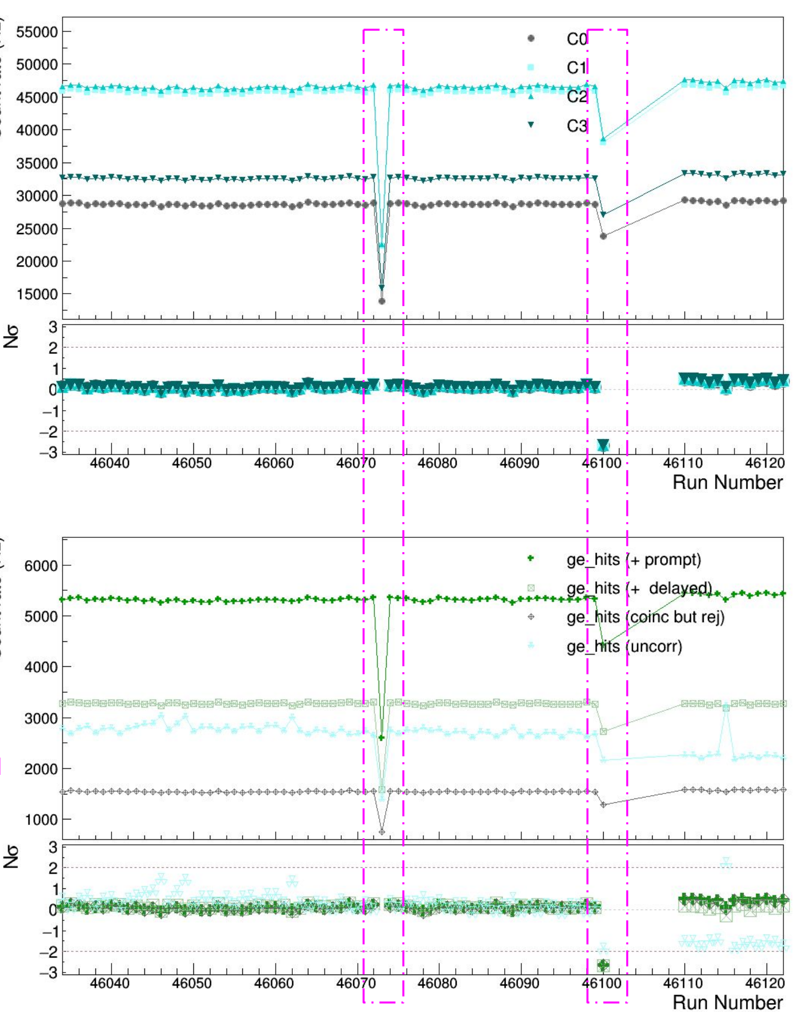


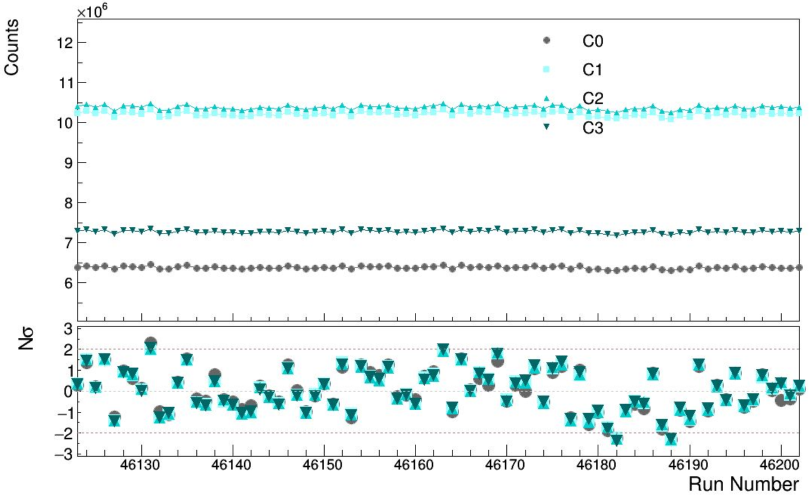
Counts
×10^6
C0
C1
C2
C3
Nσ
Run Number
Count rate (Hz)
ge_hits (+ prompt)
ge_hits (+_delayed)
ge_hits (coinc but rej)
ge_hits (uncorr)
×10^3
3) unstable
uncorrelated



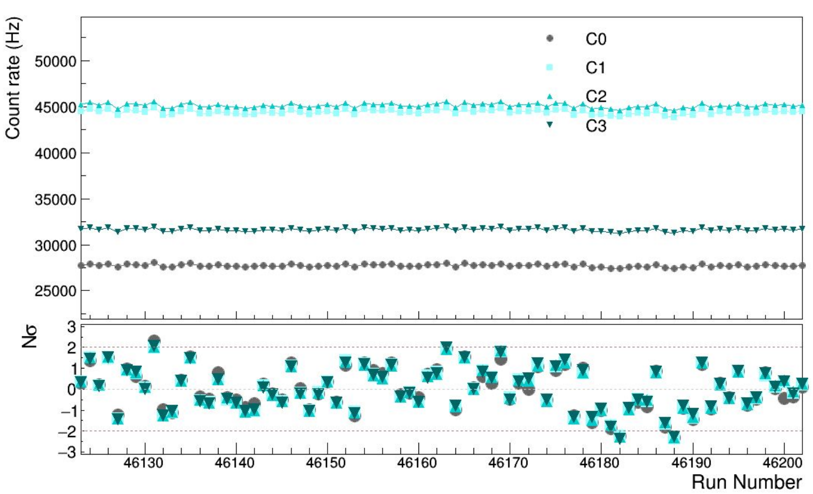


1) Beam is unstable: all counts drop accordingly

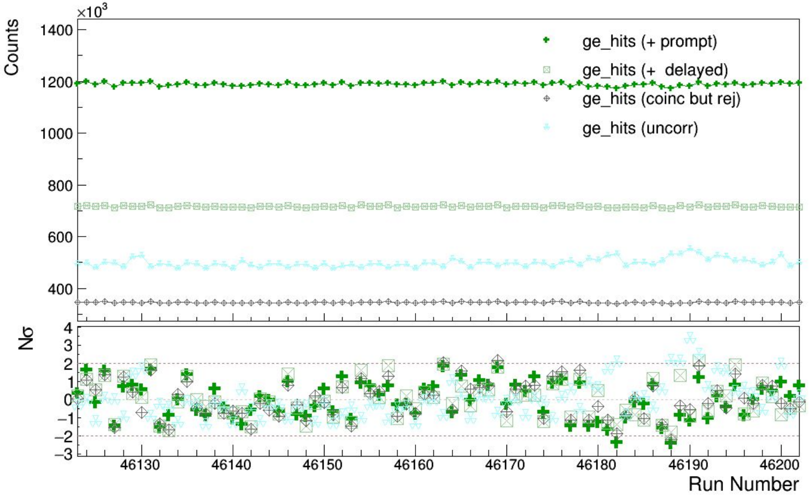




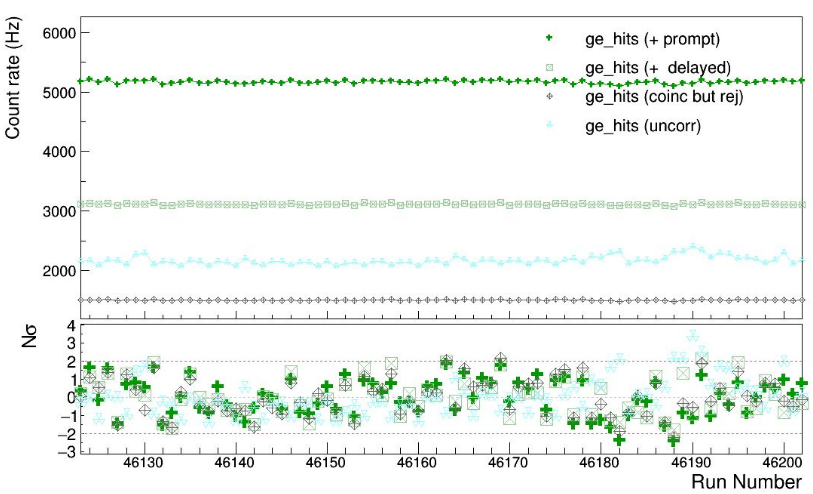
Counts
×10^6
C0
C1
C2
C3
Nσ
Run Number



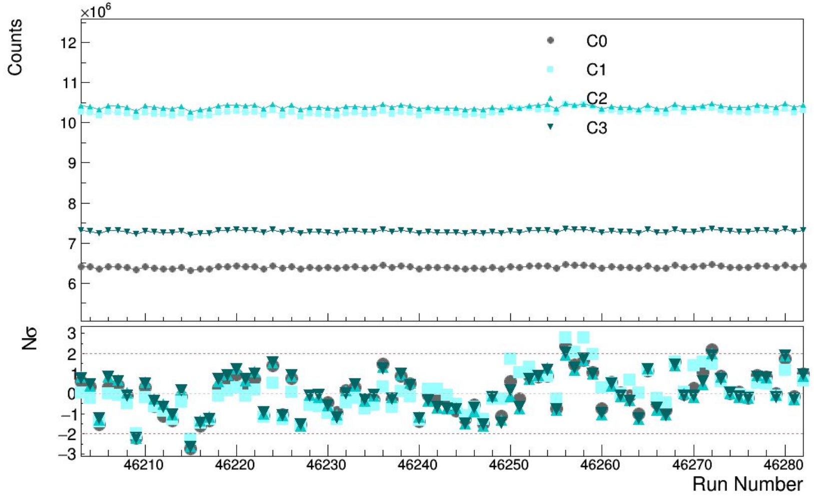
Count rate (Hz)
C0
C1
C2
C3
Nσ
Run Number

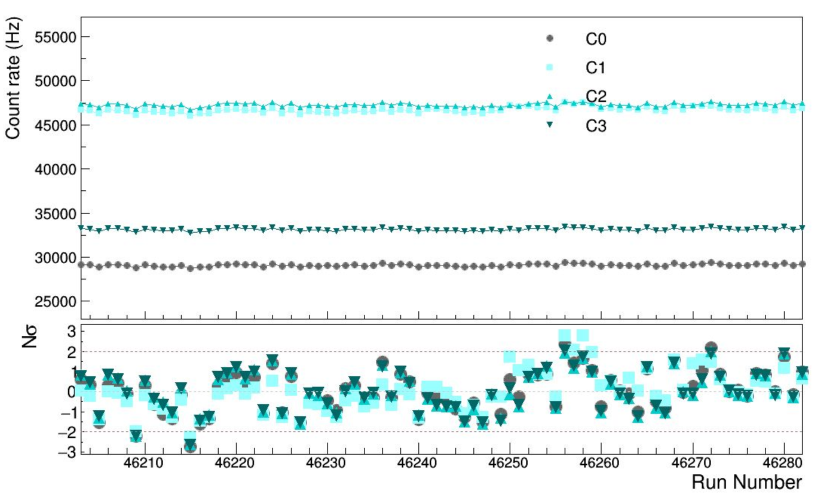


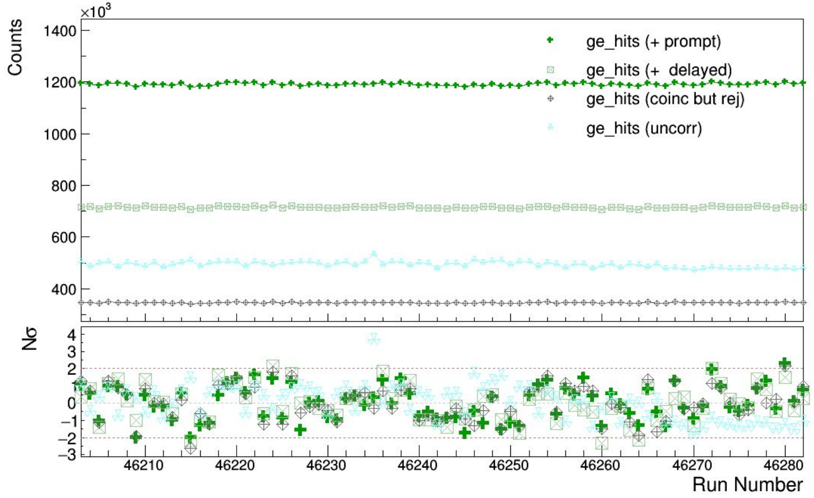
Counts
×10^3
ge_hits (+ prompt)
ge_hits (+ delayed)
ge_hits (coinc but rej)
ge_hits (uncorr)
Nσ
Run Number

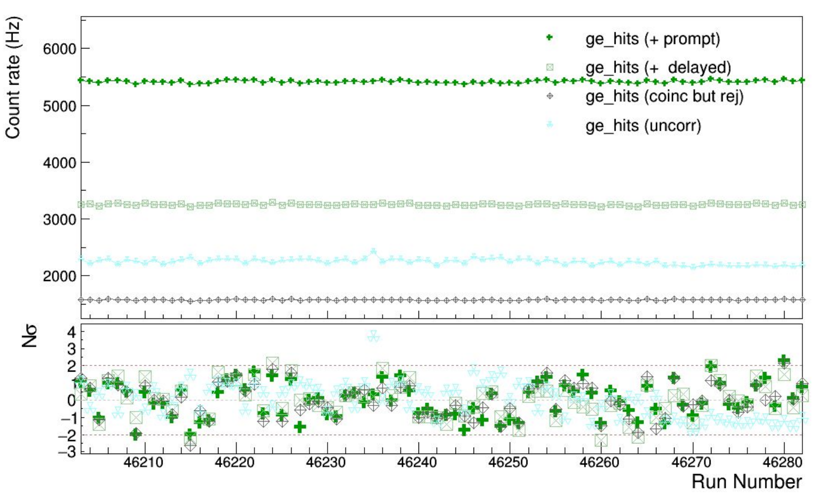


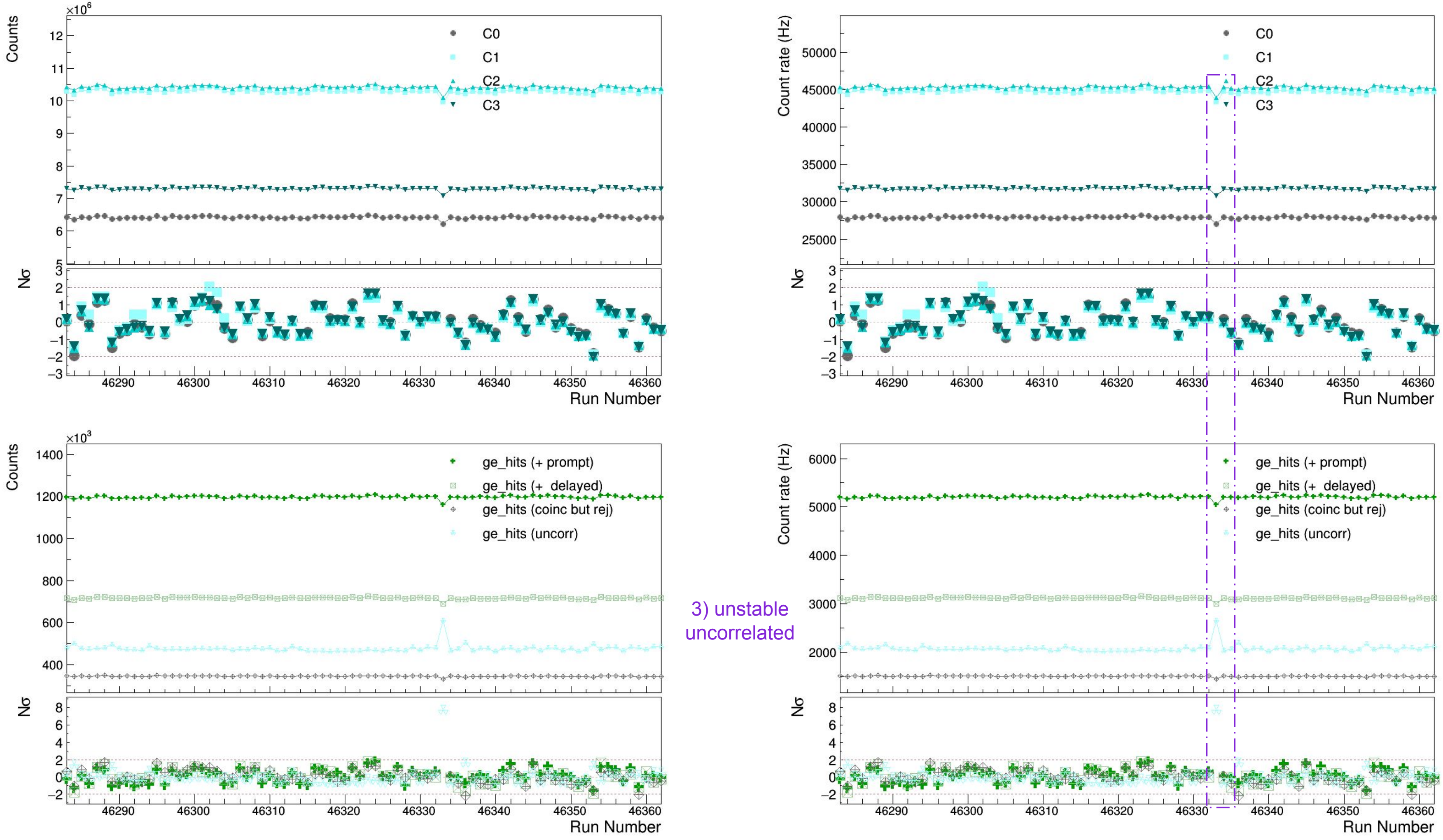
Count rate (Hz)
ge_hits (+ prompt)
ge_hits (+ delayed)
ge_hits (coinc but rej)
ge_hits (uncorr)
Nσ
Run Number

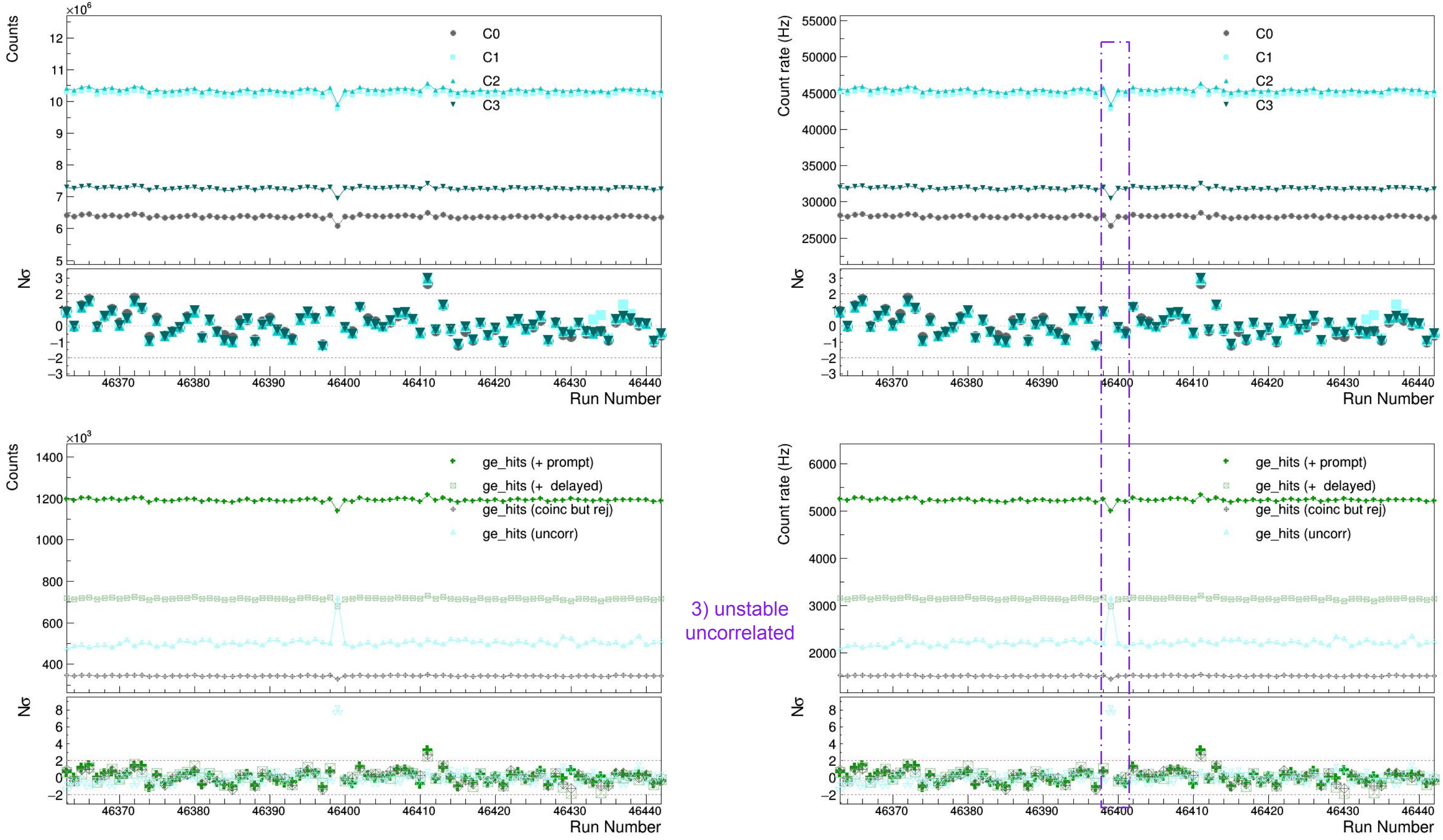

Counts
×10^6
C0
C1
C2
C3
Nσ
Run Number

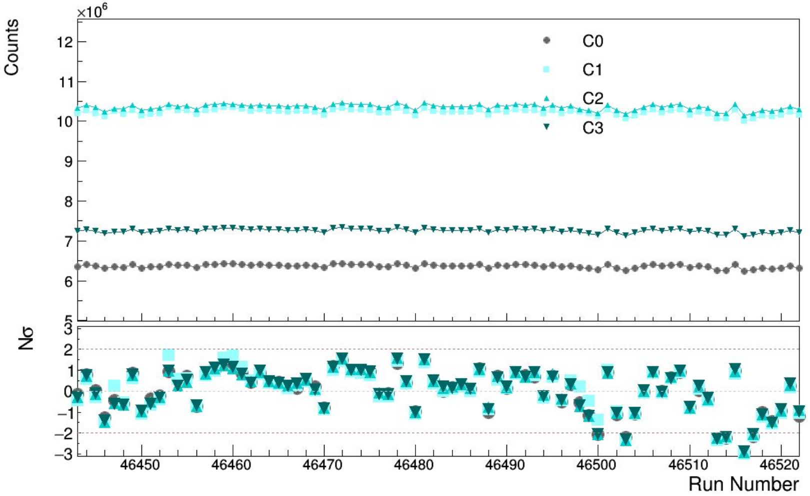

Count rate (Hz)
C0
C1
C2
C3
Nσ
Run Number


Counts
×10^3
ge_hits (+ prompt)
ge_hits (+ delayed)
ge_hits (coinc but rej)
ge_hits (uncorr)
Nσ
Run Number

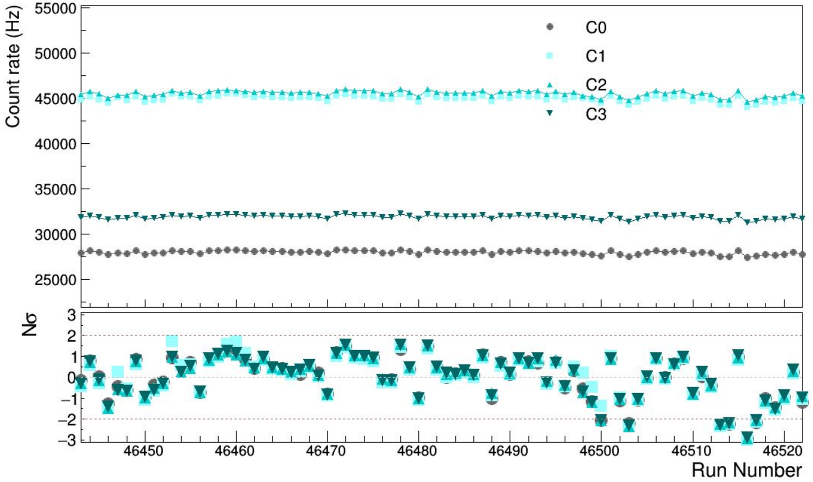

Count rate (Hz)
ge_hits (+ prompt)
ge_hits (+ delayed)
ge_hits (coinc but rej)
ge_hits (uncorr)
Nσ
Run Number


Counts
$\times10^6$
C0
C1
C2
C3
Nσ
Run Number
Count rate (Hz)
$\times10^3$
ge_hits (+ prompt)
ge_hits (+ delayed)
ge_hits (coinc but rej)
ge_hits (uncorr)
3) unstable
uncorrelated

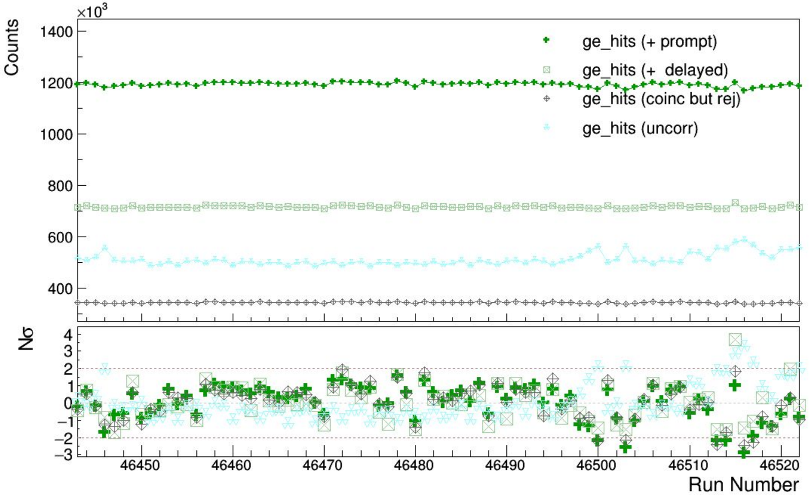

Counts
×10^6
C0
C1
C2
C3
Count rate (Hz)
Nσ
Run Number
×10^3
ge_hits (+ prompt)
ge_hits (+ delayed)
ge_hits (coinc but rej)
ge_hits (uncorr)
3) unstable
uncorrelated



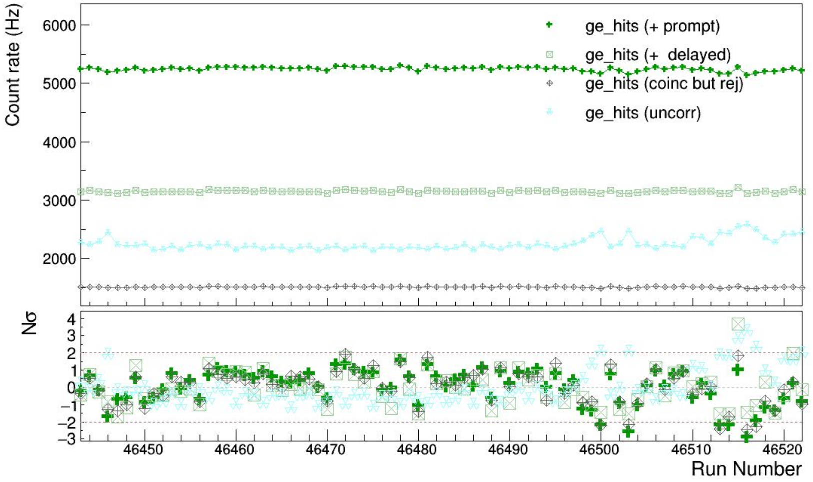
Counts
×10^6
C0
C1
C2
C3
Nσ
Run Number



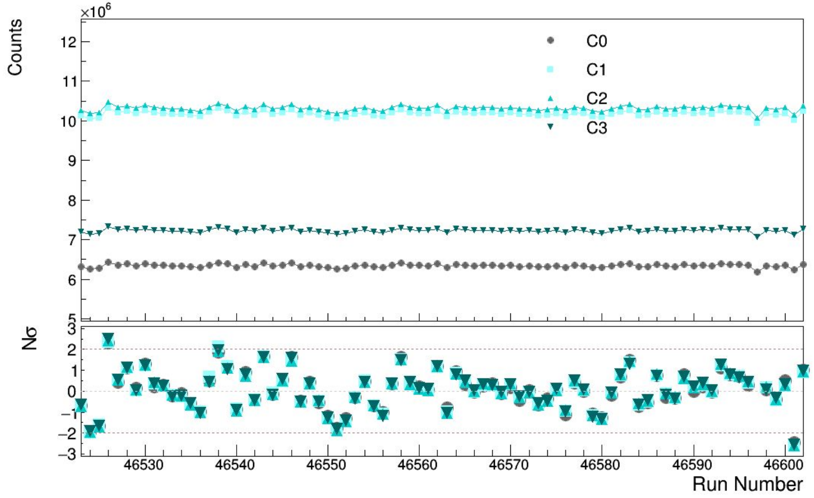
Count rate (Hz)
C0
C1
C2
C3
Nσ
Run Number



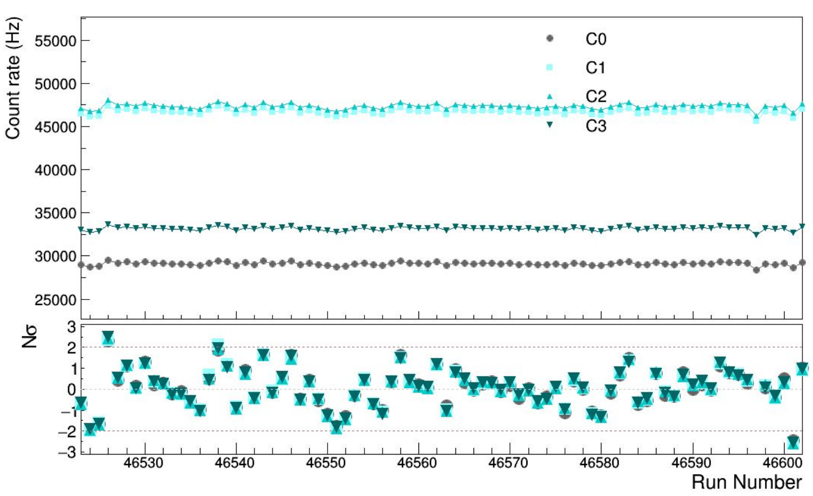
Counts
×10^3
ge_hits (+ prompt)
ge_hits (+ delayed)
ge_hits (coinc but rej)
ge_hits (uncorr)
Nσ
Run Number



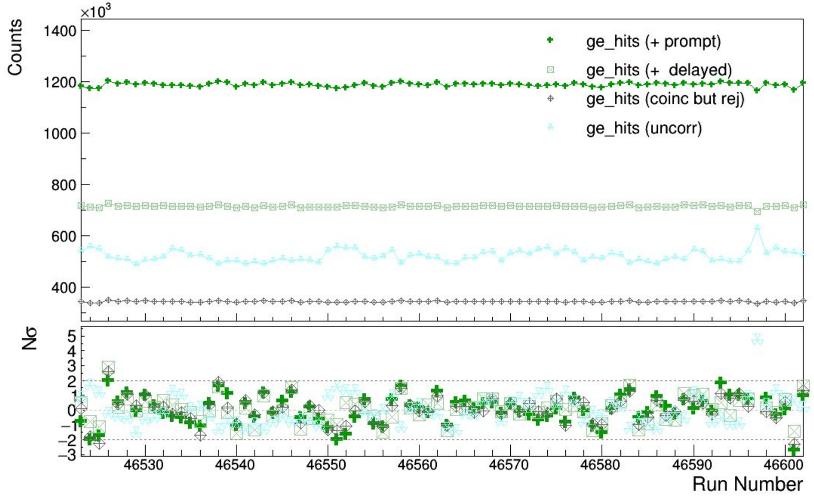
Count rate (Hz)
ge_hits (+ prompt)
ge_hits (+ delayed)
ge_hits (coinc but rej)
ge_hits (uncorr)
Nσ
Run Number



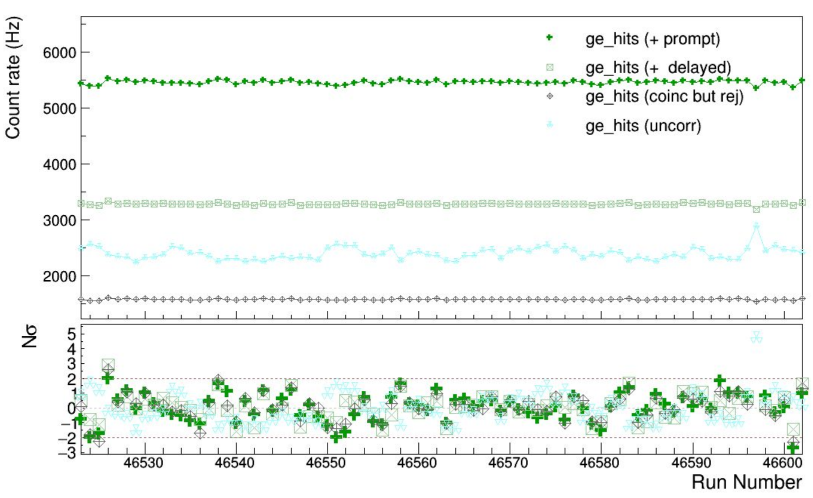
×10^6
Counts
C0
C1
C2
C3
Nσ
Run Number



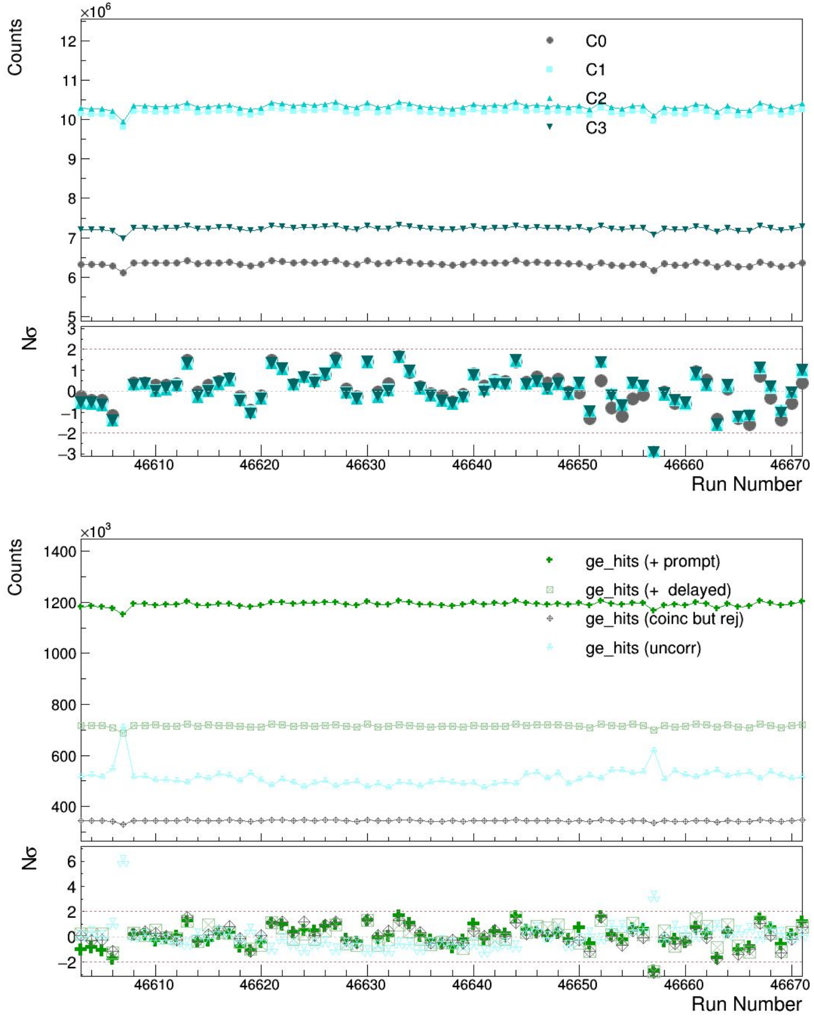
Count rate (Hz)
C0
C1
C2
C3
Nσ
Run Number



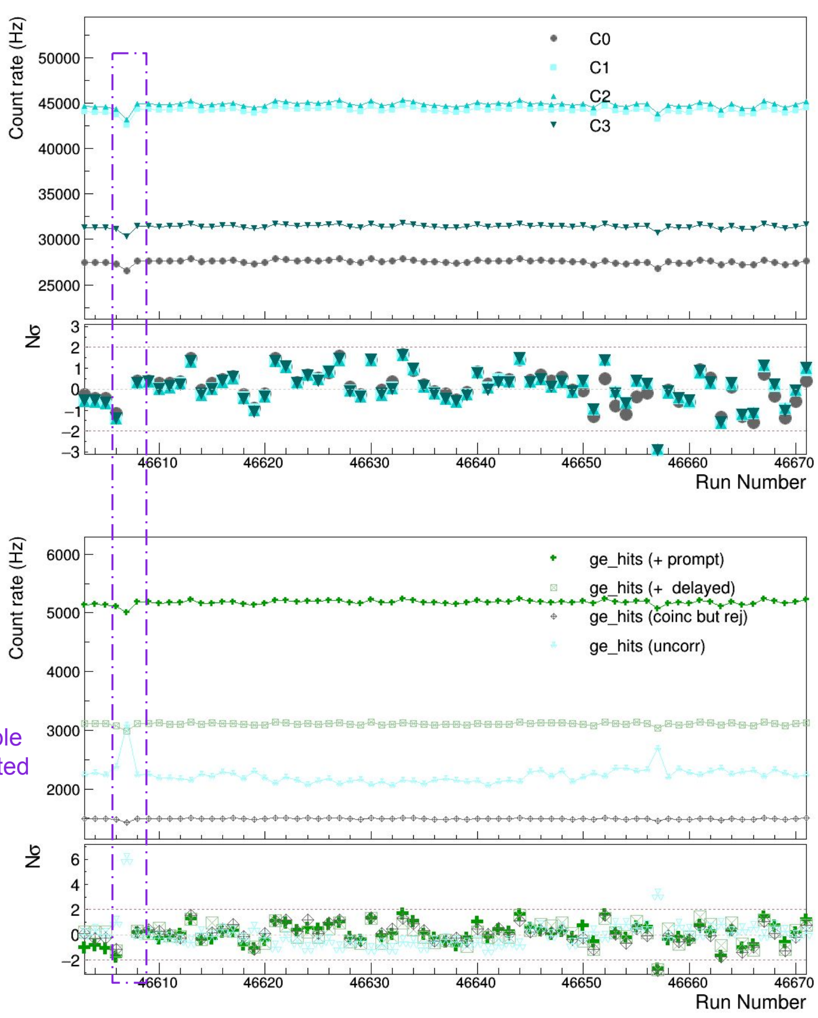
×10^3
Counts
ge_hits (+ prompt)
ge_hits (+ delayed)
ge_hits (coinc but rej)
ge_hits (uncorr)
Nσ
Run Number



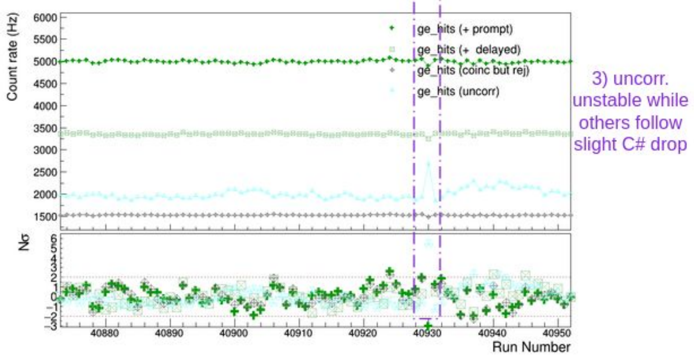
Count rate (Hz)
ge_hits (+ prompt)
ge_hits (+ delayed)
ge_hits (coinc but rej)
ge_hits (uncorr)
Nσ
Run Number

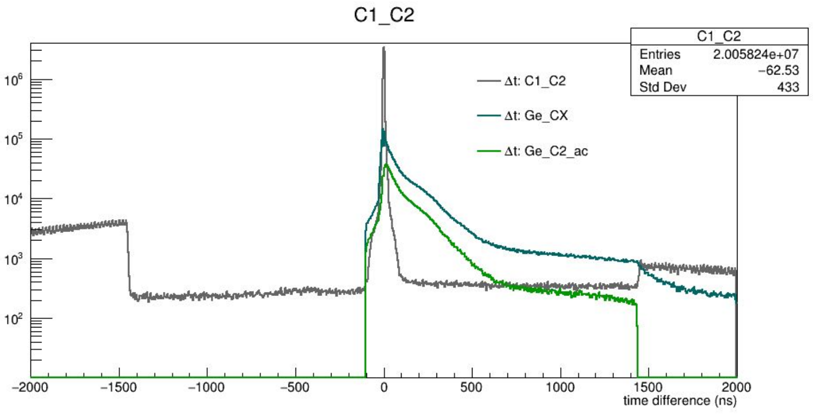


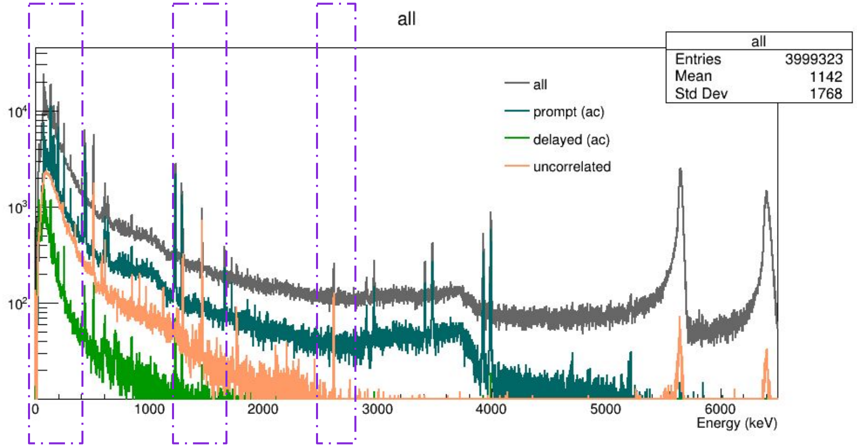
3) unstable uncorrelated



A close look at event type (3): unstable uncorrelated (run 40930)

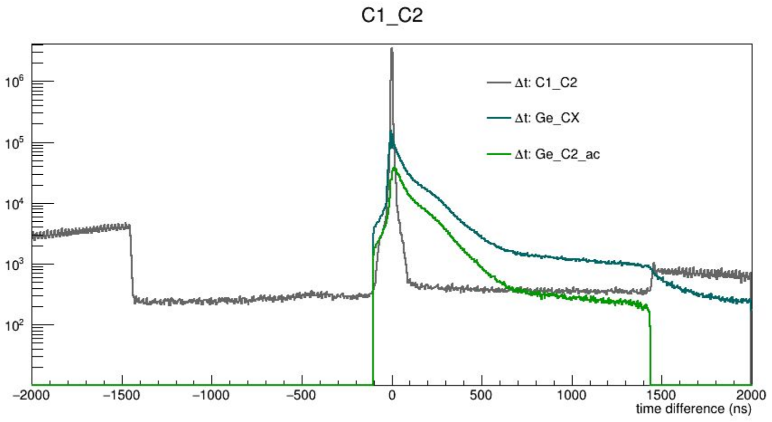


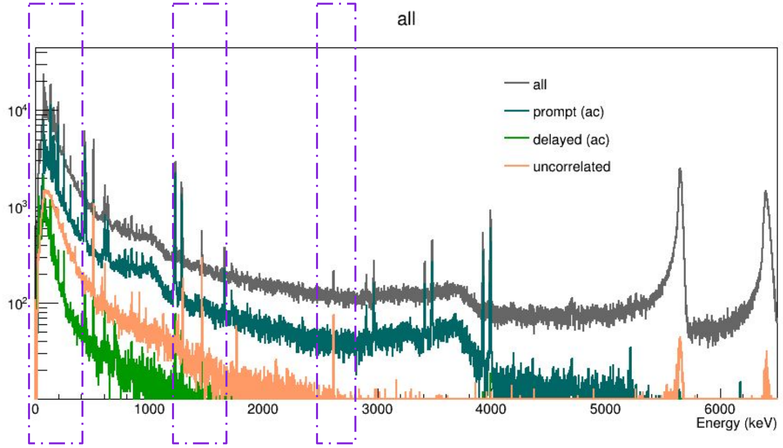




A close look at event type (3):
unstable uncorrelated (run 40930) vs. run 40931 (stable)

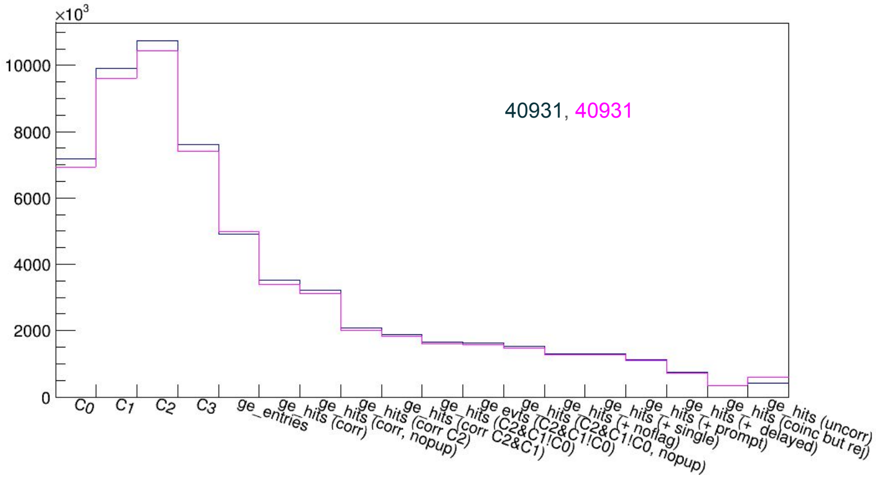
Time distributions look the same. Uncorrelated spectrum is higher in 40930, especially at the low energy and around the the Co-60, K-40, and Tl-208 lines

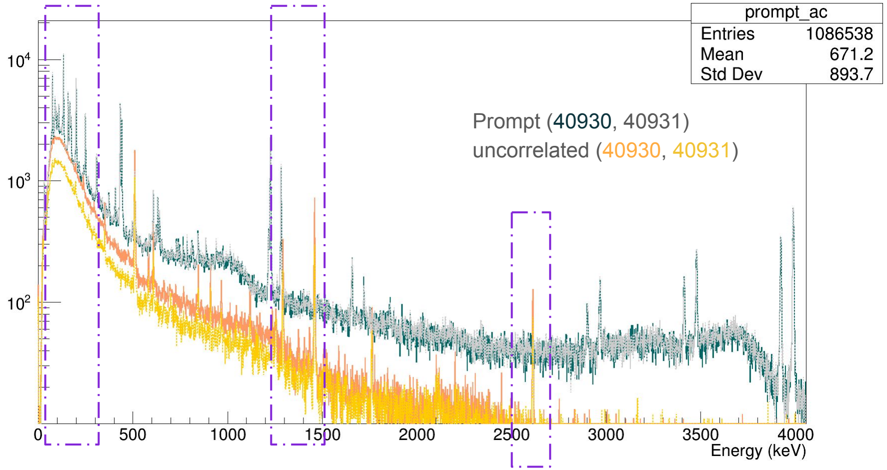




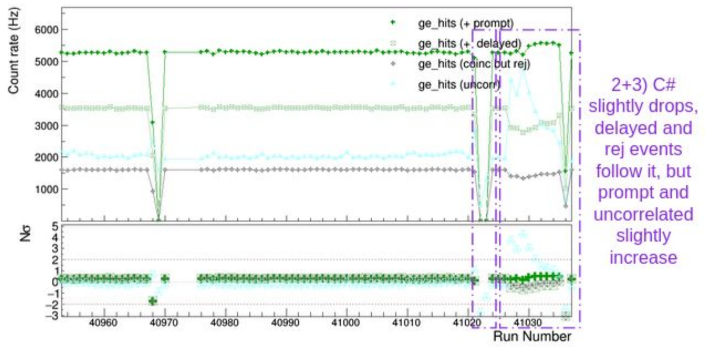
A close look at event type (3):
unstable uncorrelated (run 40930) vs. run 40931 (stable)

Prompt spectra look ~ same, all hits are slightly lower for run 40930, except for uncorr: its spectrum is clearly higher, especially at the low energy and around the Co-60, K-40, and Tl-208 lines

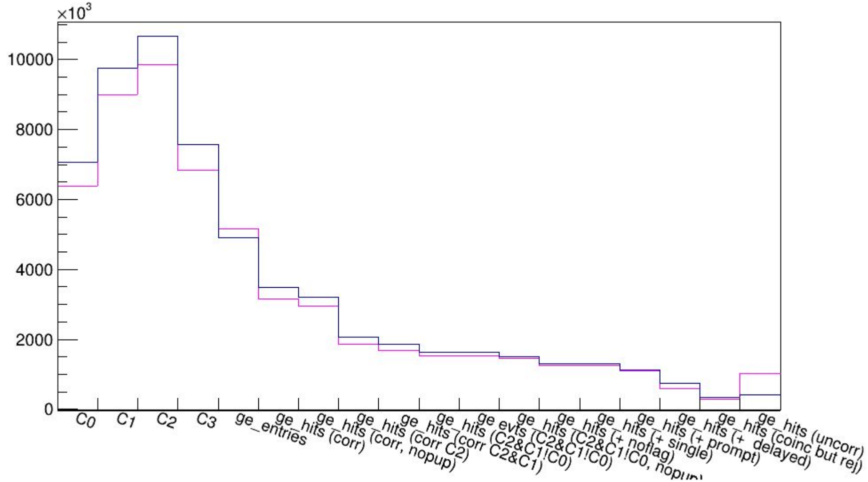


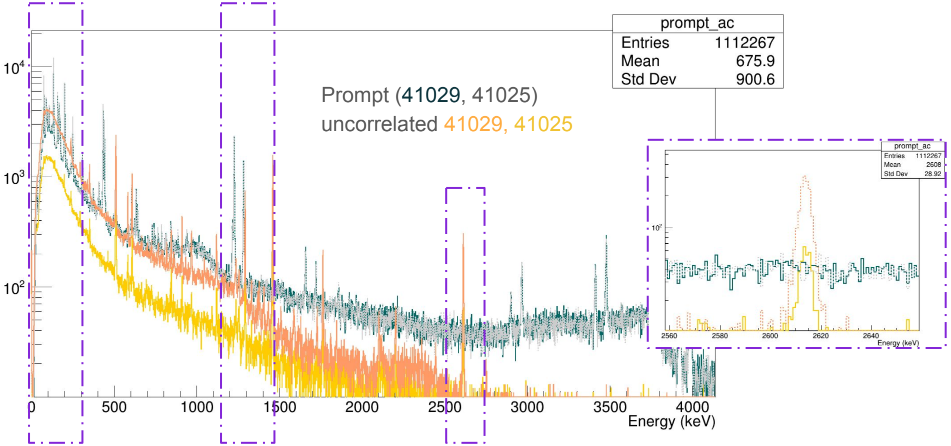


A close look at event type (2+3):
unstable uncorr & prompt increase
(run 41025 vs 41029)



Prompt spectra look ~ same, all hits are slightly lower for run 41029, except for uncorr: its spectrum is clearly higher, especially at the low energy and around the Co-60, K-40, and Tl-208 lines





Data Cleaning Summary

98% of the Ba-136 (selected) data is **stable**, especially during the second batch. The only significant unexpected event is **(3)**: There are ~ 20 runs in this category (for which uncorr rate >4σ above mean). This means ~ 1.4% of the selected data. There are also ~ 10 "unstable beam" runs (rate diff >3σ, ~0.7% of the data).

Data classification:

Accepted (98%):

0) stable: beam has constant flux/current, C# hits, ge hits, uncorr events are ~ constant and ∝.

Rejected (2%)

1) unstable beam: beam has dropped under average flux/current value, all C# hits and ge hits count rates drop accordingly, uncorrelated events may also drop a bit as there is some leakage of corr events into the uncorrelated window

2) prompt/delayed ratio unstable: if the rate of prompt events decrease (or increase) the one of delayed events should follow the same pattern. (unless the time distribution of Ge hits changed somehow?)

3) uncorr events unstable: larger rate of uncorr event. (maybe due to electronic noise from LN2 fill? calibration mixed data?)

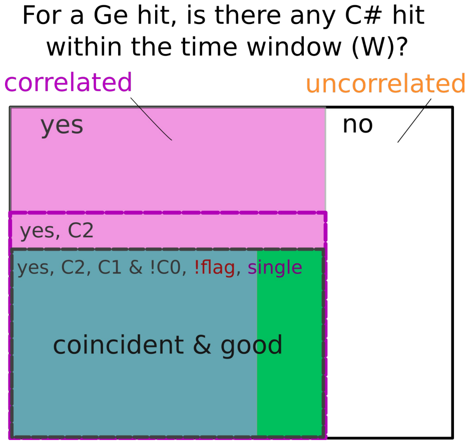
Excluded runs:

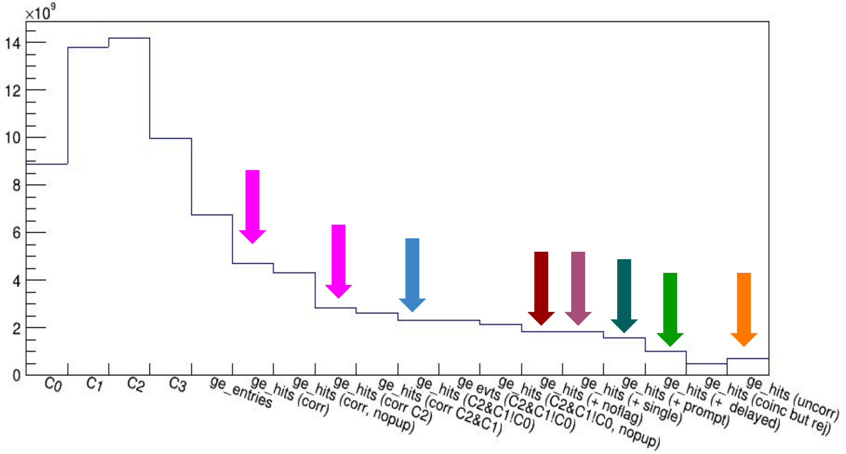
40930, 40968, 40969, 41022, 41023, 41027, 41028, 41029, 41030, 41031, 41032, 41033, 41034, 41035, 41036, 41062, 41095, 41367, 41480, 42017, 45761, 45871, 46013, 46073, 46100, 46333, 46399, 46597, 46607.

Total remaining: 1361/1390 runs (98%)

Conclusions and next steps

- Distribution of events seem to make sense: ~27% of the ge hits survive all the cuts (most of them are prompt). Correlation, coincidence cuts, & (!ch2, !ch6) have the largest impacts in the cuts.
- Pile up events do not seem to have any special features. Flag “8” (energy=0) needs to be understood (*).
- Ba-136 data is “clean” and ready to be analyzed (*)
- Next steps:
  - find potential “excitation” peaks
  - check their time decay (per channel).
  - Use this information to optimize time cuts.





Ba-136 line identification and spectra analysis

Data for the spectra: Runs 5714-46671 (949 runs) + beam off data (MuX processed hosts)

Line identification steps

- Identify possible processes and decays following OMC in Ba-136
  - Identify first “natural/uncorrelated” activity lines (for clean up) in the spectrum
  - Identify μX- rays, unstable isotopes and excitation lines
  - Check whether their time decays behaves as expected
  - Check whether the BR agree (for this step, folding with energy-dependent efficiency is needed)
- Do the same now for other Ba isotopes (Ba-137, Ba-138, ..)
  - Check agreement with Ba-nat data (for the lines that should increase in this dataset)

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Muon capture (μC) by $^{136}_{56}Ba$ and subsequent excitation*:

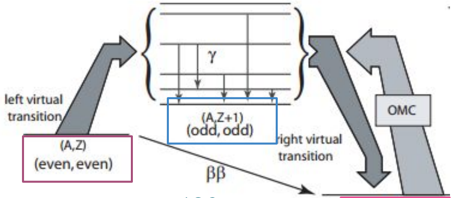
We aim to observe the gamma decays from the excitation state of the isotope Cs-136 that is formed following the muon capture by Ba-136

i) excited state:

$$\underline{^{136}_{55}Cs^*} \rightarrow {}^{136}_{55}Cs + \gamma$$

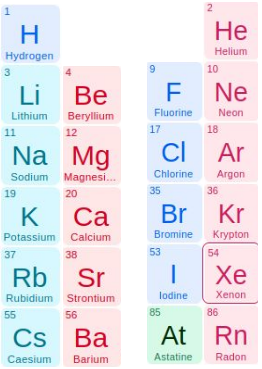
Excited state

$$^{136}_{56}Ba \xrightarrow{\mu C} {}^{136}_{55}Cs$$



$^{136}_{54}Xe$ $^{136}_{55}Cs$ $^{136}_{56}Ba$

$$\mu^- + (A, Z) \rightarrow \nu_\mu + (A, Z-1)^*$$



*Here shown simplified $\mu C\ : p + \mu \rightarrow n + \nu_\mu$

Muon capture (μC) by ${}^{136}_{56}Ba$ and subsequent excitation* and decays:

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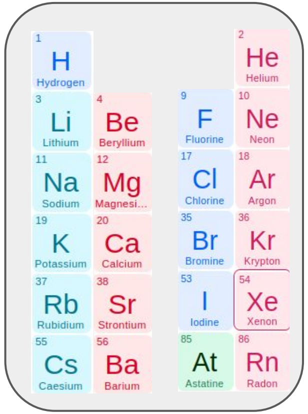


Due to the high E transfer, a concurrent process to the excitation (i) is the neutron emission (ii), which produces other daughter isotopes

i) excited state:

$$\boxed{{}^{136}_{55}Cs^* \rightarrow {}^{136}_{55}Cs + \gamma}$$

ii) n emission

${}^{136}_{56}Ba$	0n	d, τ	-1n	d, τ	-2n	d, τ	-3n	d, τ
$-1p + 1n\,(\mu C\; or\; eC)$	$\boxed{{}^{136}_{55}Cs}$	b^-, 13d	${}^{135(m)}_{55}Cs$	IT 53m	${}^{134(m)}_{55}Cs$	IT, 3h	${}^{133}_{55}Cs$	st

Click on the isotopes to see their decay database

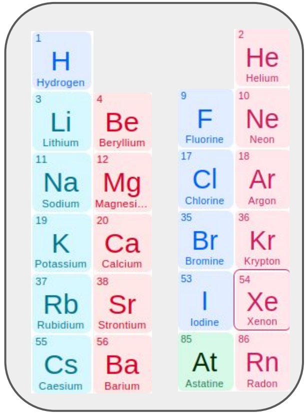
$\mu C\ : p + \mu \rightarrow n + \nu_\mu$

d, τ: decay modes with gamma emission and half-lifes <1y.

$eC\ : p + e \rightarrow n + \nu_e$

Muon capture (μC) by $^{136}_{56}Ba$ and subsequent excitation* and decays:

We aim to observe the gamma decays from the excitation state of the isotope Cs-136 that is formed following the muon capture by Ba-136



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$$^{136}_{55}Cs^* \to {}^{136}_{55}Cs + \gamma$$

ii) n emission

$^{136}_{56}Ba$	0n	d, τ	-1n	d, τ	-2n	d, τ	-3n	d, τ
$-1p + 1n\,(\mu C\ or\ eC)$	$^{136}_{55}Cs$	b^-, 13d	$^{135(m)}_{55}Cs$	IT 53m	$^{134(m)}_{55}Cs$	IT, 3h	$^{133}_{55}Cs$	st
$-2p + 2n\,(\mu C\ or\ eC)$	$^{136}_{54}Xe$	st	$^{135}_{54}Xe$ (Cs*)	IT, b^-, 15m-**9h**	$^{134}_{54}Xe$	st or IT,~ms	$^{133}_{54}Xe$	b^-, IT 2-5d

$$^{135}_{54}Xe \xrightarrow{b^-} {}^{135}_{55}Cs + \gamma \sim \quad {}^{135}_{55}Cs^* \to {}^{135}_{55}Cs + \gamma$$

ps: half-lives and BRs are however different

Gammas emitted in b^- decay of z-1 to z isotope has the same energies of the gammas emitted in the de-excitation of the z isotope

Click on the isotopes to see their decay database

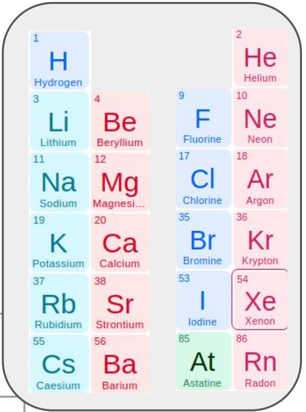
$$\mu C\ : p + \mu \to n + \nu_\mu$$

d, τ: decay modes with gamma emission and half-lifes <1y.

$$eC\ : p + e \to n + \nu_e$$

Muon capture (μC) by $^{136}_{56}Ba$ and subsequent excitation* and decays:

We aim to observe the gamma decays from the excitation state of the isotope Cs-136 that is formed following the muon capture by Ba-136



Due to the high E transfer, a concurrent process to the excitation (i) is the neutron emission (ii), which produces other daughter isotopes

i) excited state:

$$^{136}_{55}Cs^* \rightarrow \, ^{136}_{55}Cs + \gamma$$

ii) n emission

$^{136}_{56}Ba$	0n	d, τ	-1n	d, τ	-2n	d, τ	-3n	d, τ	-4n	d, τ
$-1p + 1n \, (\mu C \, or \, eC)$	$\boxed{^{136}_{55}Cs}$	b^-, 13d	$^{135(m)}_{55}Cs$	IT 53m	$^{134(m)}_{55}Cs$	IT, 3h	$^{133}_{55}Cs$	st	—	
$-2p + 2n \, (\mu C \, or \, eC)$	$\boxed{^{136}_{54}Xe}$	st	$^{135}_{54}Xe$ (Cs*)	IT, **b^-**, 15m-**9h**	$^{134}_{54}Xe$?	st or IT,~ms	$^{133}_{54}Xe$	b^-, IT 2-5d	$^{132(m)}_{54}Xe$	IT,~ms or st
	$\boxed{^{136(m)}_{53}I}$	b^-, ~50s	$^{135}_{53}I$	b^-, ~7h	$^{134(m)}_{53}I$?	IT, b^-, 4-53m	$^{133(m)}_{53}I$	b^-, ~7h	$^{132(m)}_{53}I$?	IT, or b^-, ~2h

α

b^- decay

Ps: isotopes marked in light color don't seem to be observed, isotopes marked with (?) seem to match some observed lines

Click on the isotopes to see their decay database

Also the possibility of α emission?

$$\mu C \; : p + \mu \rightarrow n + \nu_\mu$$

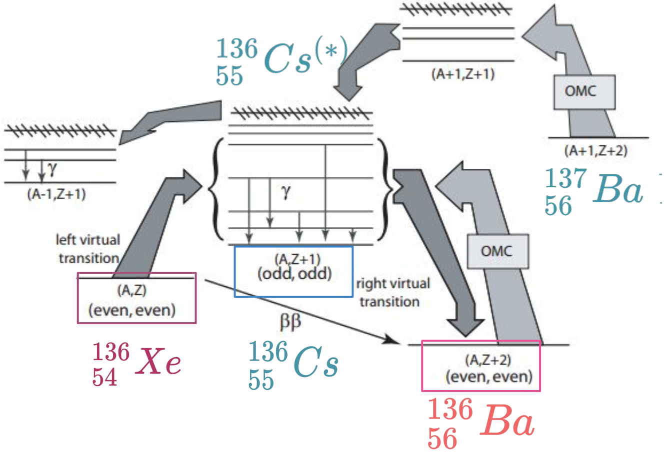
d, τ: decay modes with gamma emission and half-lifes <1y.

$$eC \; : p + e \rightarrow n + \nu_e$$

… but the target is not 100% Ba-136:

The neutron emission rate from other isotopes in the sample can be at the level of the searched excitation, so these need to be well understood.

Due to the high E transfer, a concurrent process to the excitation (i) is the neutron emission (ii), which produces other daughter isotopes



Ba isot	$_{enr}$Ba-136 (%)
138	**2.41**
137	**1.54**
136	95.27
135	0.74
134	0.04

$$^{137}_{56}Ba \xrightarrow{+\mu} {}^{137}_{55}Cs^{*} \rightarrow {}^{137}_{55}Cs + \gamma$$

$$^{137}_{56}Ba \xrightarrow{+\mu} {}^{137}_{55}Cs^{**} \xrightarrow{-n} {}^{136}_{55}Cs^{(*)}$$

ɣ from i) ~0:

Cs*-137 (suppressed)

Cs-137 (stable)

ɣ from ii) -n directly to Cs-136 or through de-exc.

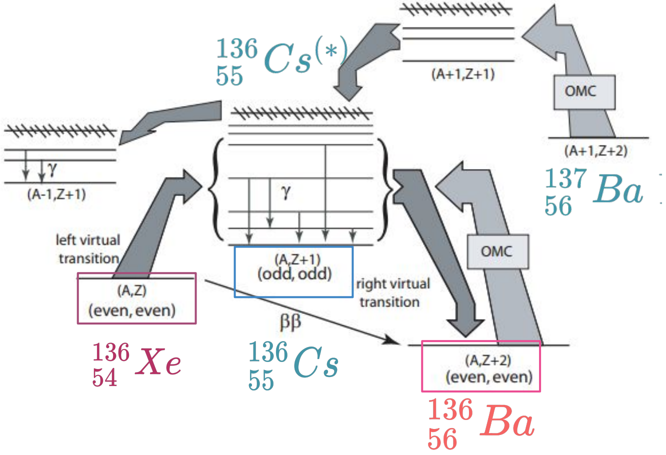
Cs*-136 (searched line)

Cs-136 (b^{-}, 13d) ps: Ba-136 is st

… but the target is not 100% Ba-136:

The neutron emission rate from other isotopes in the sample can be at the level of the searched excitation, so these need to be well understood.

Due to the high E transfer, a concurrent process to the excitation (i) is the neutron emission (ii), which produces other daughter isotopes



Ba isot	$_{enr}$Ba-136 (%)
138	**2.41**
137	**1.54**
136	95.27
135	0.74
134	0.04

$${}^{138}_{56}Ba \xrightarrow{+\mu} {}^{138}_{55}Cs^* \longrightarrow {}^{138}_{55}Cs + \gamma$$ *(suppressed)*

$${}^{138}_{56}Ba \xrightarrow{+\mu} {}^{138}_{55}Cs^{**} \xrightarrow{-n} {}^{137}_{55}Cs^{(*)} \rightarrow {}^{137}_{55}Cs + \gamma$$

$${}^{137}_{56}Ba \xrightarrow{+\mu} {}^{137}_{55}Cs^* \rightarrow {}^{137}_{55}Cs + \gamma$$ *(suppressed)*

$${}^{137}_{56}Ba \xrightarrow{+\mu} {}^{137}_{55}Cs^{**} \xrightarrow{-n} {}^{136}_{55}Cs^{(*)} \rightarrow {}^{136}_{55}Cs + \gamma$$

γ from de-excitation:

- ^{138}Cs* (suppressed, compared to -n)
- ^{137}Cs* (probable after -n)
- ^{136}Cs*(probable, searched line)

γ from unstable isotopes:

- ^{138}Cs (b$^-$, IT, 33m) -> Ba-138 (st) + γ
- ^{137}Cs (stable)
- ^{136}Cs (b$^-$, 13d) -> Ba-136 (st) + γ

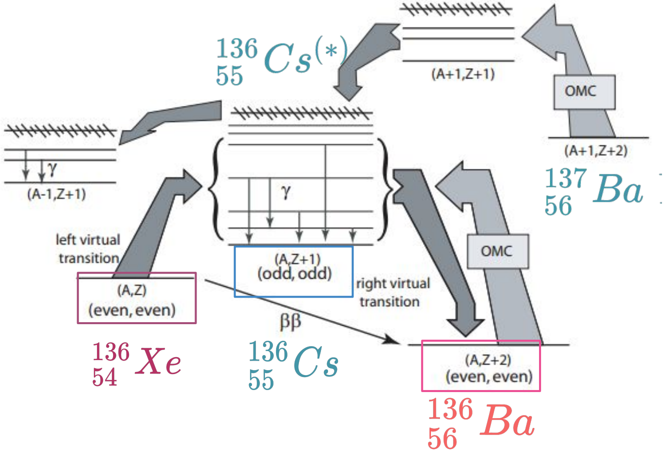
… but the target is not 100% Ba-136:

The neutron emission rate from other isotopes in the sample can be at the level of the searched excitation, so **these need to be well understood**.

Due to the high E transfer, a concurrent process to the excitation (i) is the neutron emission (ii), which produces other daughter isotopes

Additional measurement of Ba (natural)

Ba isot	$_{enr}$Ba-136 (%)	$_{nat}$Ba (%)
138	**2.41**	72
137	**1.54**	**11**
136	95.27	8
135	0.74	6.6
134	0.04	2.4



Main ɣ-lines from OMC by Barium:

$$^{138}_{56}Ba \xrightarrow{+\mu} {}^{138}_{55}Cs^* \longrightarrow {}^{138}_{55}Cs + \gamma$$ *(suppressed)*

$$^{138}_{56}Ba \xrightarrow{+\mu} {}^{138}_{55}Cs^{**} \xrightarrow{-n} {}^{137}_{55}Cs^{(*)} \longrightarrow {}^{137}_{55}Cs + \gamma$$

$$^{137}_{56}Ba \xrightarrow{+\mu} {}^{137}_{55}Cs^* \longrightarrow {}^{137}_{55}Cs + \gamma$$ *(suppressed)*

$$^{137}_{56}Ba \xrightarrow{+\mu} {}^{137}_{55}Cs^{**} \xrightarrow{-n} {}^{136}_{55}Cs^{(*)} \longrightarrow {}^{136}_{55}Cs + \gamma$$

3.5%

Cross population

i) $$^{136}_{56}Ba \xrightarrow{+\mu} {}^{136}_{55}Cs^* \longrightarrow {}^{136}_{55}Cs + \gamma$$ *i) searched line, less likely than n-emission*

ii) $$^{136}_{56}Ba \xrightarrow{+\mu} {}^{136}_{55}Cs^{**} \xrightarrow{-n} {}^{135}_{55}Cs^* \longrightarrow {}^{135}_{55}Cs + \gamma$$ ***(ii) well present in the spectrum***

$$^{135m}_{55}Cs \xrightarrow{53m} {}^{135}_{55}Cs + \gamma$$ ***well present in the spectrum***

$$^{136}_{55}Cs \xrightarrow{13d} {}^{136}_{56}Ba + \gamma$$ ***well present in the spectrum*** *(more clearly in beam off data)*

95.3%
(x27 larger)

ɣ from de-excitation:

- ^{138}Cs* : suppressed, compared to -n
- ^{137}Cs* : probable after -n, but low %
- ^{136}Cs* : probable + searched line
- ^{135}Cs*: probable

ɣ from unstable isotopes?:

- ^{138}Cs (b⁻, IT, 33m) -> Ba-138 (st) + ɣ : suppressed
- ^{137}Cs (stable) : 0
- ^{136}Cs (b⁻, 13d) -> Ba-136 (st) + ɣ : probable
- ^{135m}Cs (IT, 53m) : probable

The excited state is commonly present after neutron emission, and given that *-n* is much more frequent, we get much more ɣ's from ^{135}Cs* than from ^{136}Cs*

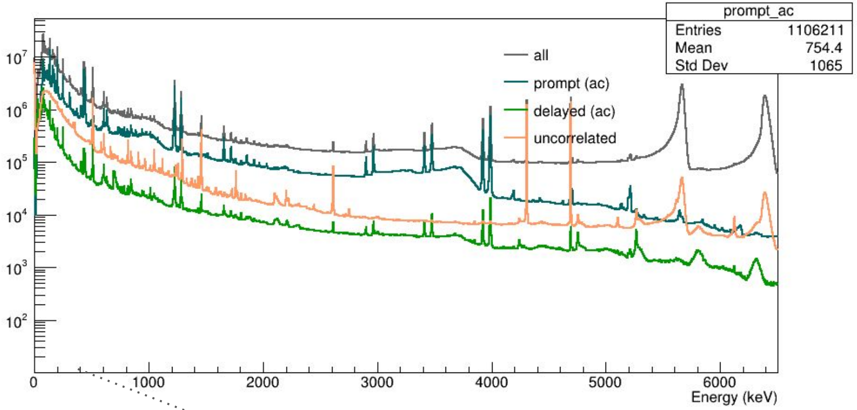
What to ideally expect in the spectra?

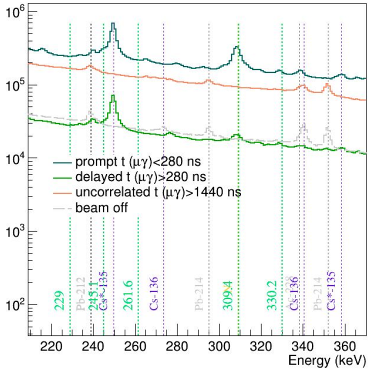
Prompt: μX-rays, from Ba-136

Delayed: ɣ's from de-excitations (mainly Cs*-136) and from short-lived beam-produced isotopes (or from the de-exc after n-emission, eg. Cs*-135)

Uncorrelated: ɣ's from natural radioactivity and beam-produced isotopes (Cs-136, Cs-135m, Cs-138)

Beam off data: more clear spectrum from natural radioactivity + slow decay of beam- produced middle-lived (15m-15d) isotopes.





What to ideally expect in the spectra?

Prompt: μX-rays, from Ba-136

Delayed: ɣ's from de-excitations (mainly Cs*-136) and from short-lived beam-produced isotopes (or from the de-exc after n-emission, eg. Cs*-135)

Uncorrelated: ɣ's from natural radioactivity and beam-produced isotopes (Cs-136, Cs-135m, Cs-138)

Beam off data: more clear spectrum from natural radioactivity + slow decay of beam- produced middle-lived (15m-15d) isotopes.

“Cross” leakage due to “time resolution”, especially in the low energy, and non-exact muon life-time

Also, muon life-time in Ba-136 is shorter?

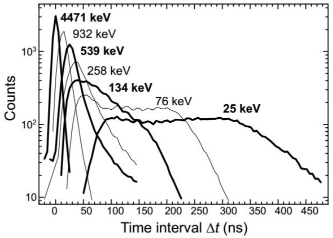
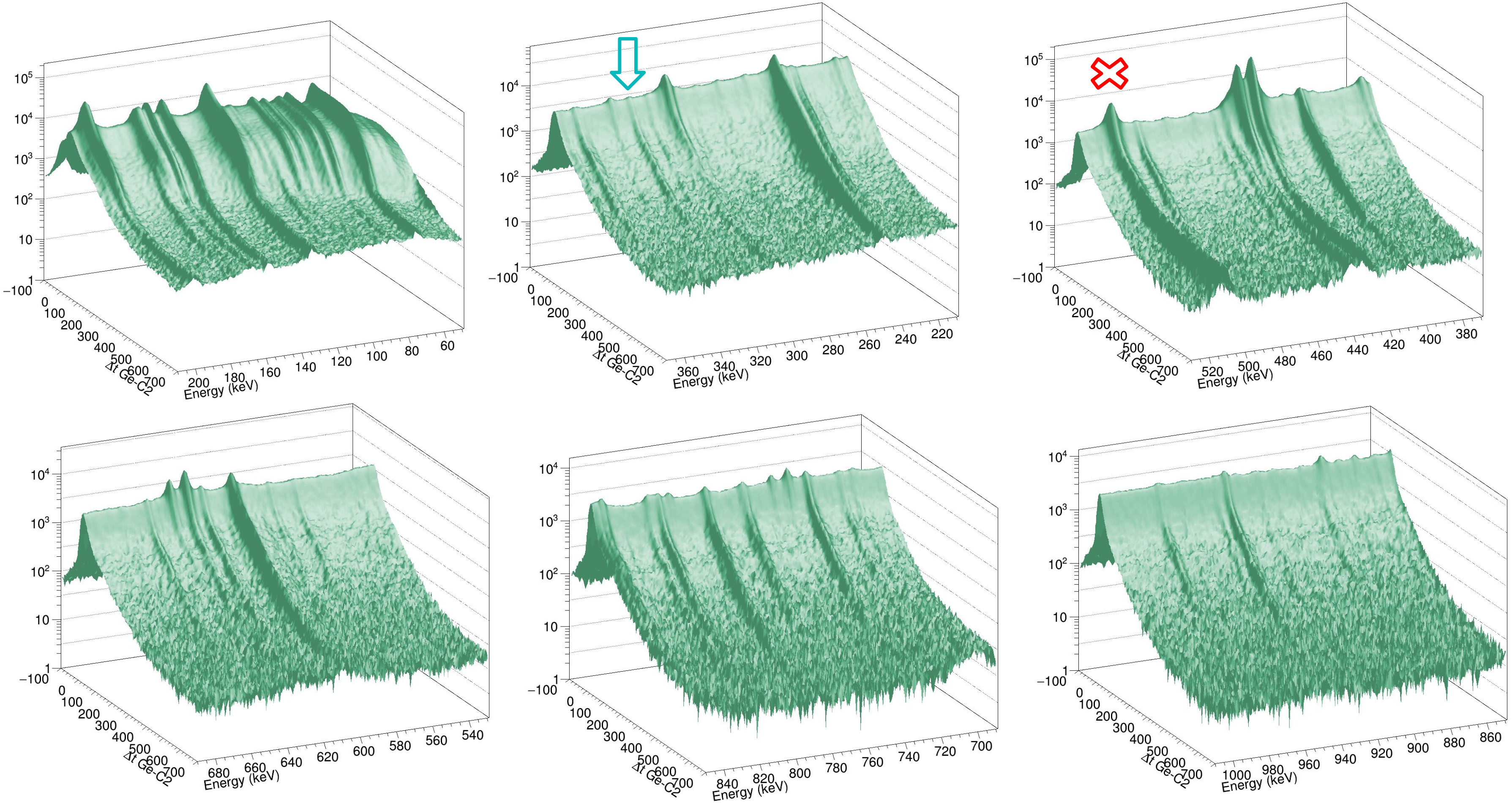


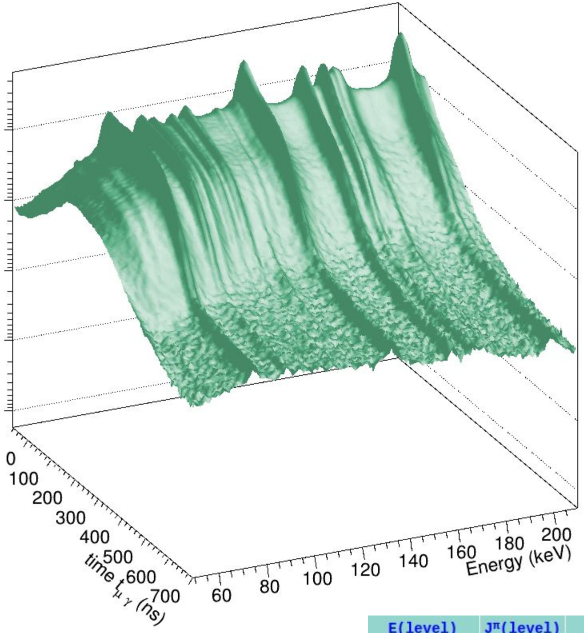
FIG. 8. Distribution of the instrumental delay Δt between the μ-stop and registration of prompt μX-rays of different energies measured with a big HPGe detector. Time resolution below 200 keV deteriorates due to slow charge collection near the surface edges of the Ge crystal.

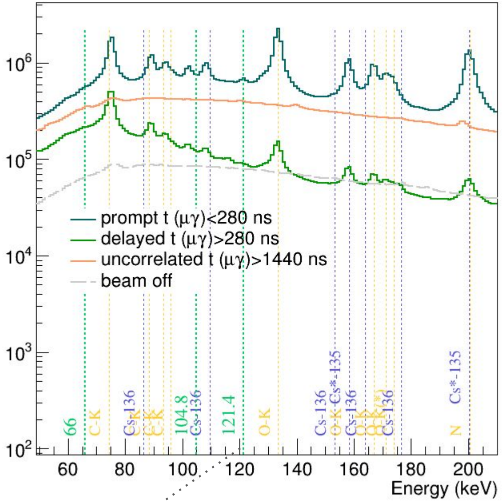
$$^{136}_{55}Cs^* \rightarrow {}^{136}_{55}Cs + \gamma$$

Looking for “excitation” candidates: delayed vs prompt (Ge3)



Analyzing spectra: Energy region 1 (50-210 KeV)





Prompt and delayed are very similar, especially because the time resolution of the detector is lower at low energies, so many prompt events leak into “delayed” and vice-versa. Many μX-rays from the K-shell of other materials (Carbon, Oxigen) are visible (C-K, O-K), as well as μX-rays from the N-shell of Ba (N). Cs*-135 lines (see table) overlap with other (O-K, N) x-rays. Cs-136 lines have low BR and are not visible.

E(level) (keV)	XREF	Jπ(level)	$T_{1/2}$(level)	E(γ) (keV)
0.0	ABCDE	7/2+	$2.3\times10^{+6}$ y 3 % β^- = 100	
249.767 4	A DE	5/2+	0.28 ns 8	249.770 4
408.026 5	A D			158.260 4 408.009 8
608.153 8	A D	5/2+		200.19 10 358.384 9 608.151 12

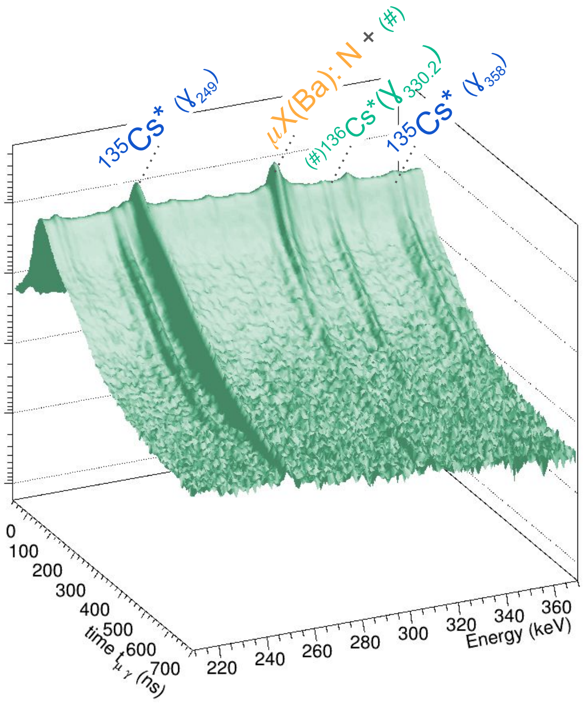
Gammas from ^{136}Cs (13.16 d 3)

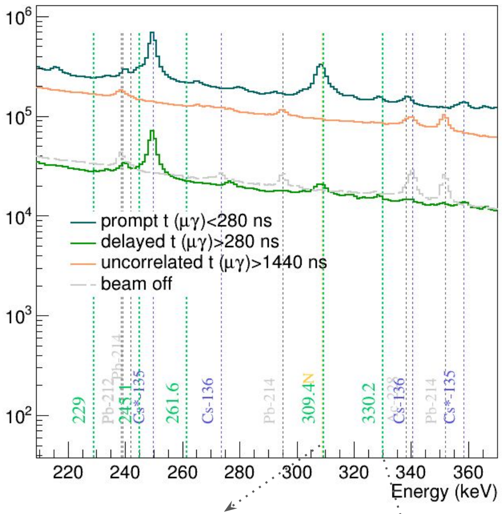
Eg (keV)	Ig (%)	Decay mode
66.881 17	4.79 20	b$^-$
86.36 3	5.18 20	b$^-$
109.681 7	0.21 3	b$^-$
153.246 4	5.75 18	b$^-$
163.920 2	3.39 12	b$^-$
166.576 6	0.37 4	b$^-$
176.602 4	10.0 4	b$^-$
187.285 6	0.36 4	b$^-$

E(level) (keV)	Jπ(level)	E(γ) (keV)	I(γ)
3520 5	1+		
3562.5 7	(13+)	635.0 5 1318.5 5	50 25 100 40
3684.0 7	(14+)	121.4 5 710.4 3	17 4 100 30

^{136}Cs* ($\gamma_{121.4keV}$) slightly appears, but 710 keV line is difficult to observe later.

Analyzing spectra: Energy region 2 (210-370 KeV)





E(level) (keV)	Jπ(level)	E(γ) (keV)	I(γ)
3520 *5*	1+		
3562.5 *7*	(13+)	635.0 *5* 1318.5 *5*	50 *25* 100 *40*
3684.0 *7*	(14+)	121.4 *5* 710.4 *3*	17 *4* 100 *30*
3929.1 *8*	(15+)	245.1 *3*	100
4086.7 *7*	(15-)	599.8 *5* 706.5 *5* 1113.2 *5*	100 *30* 11 *6* 56 *22*
4359.2 *9*	(16-)	979.1 *5*	100
4396.1 *8*	(16-)	309.4 *4* 1015.9 *5*	100 *50* 50 *25*

E(level) (keV)	Jπ(level)	$T_{1/2}$(level)	E(γ)	I(γ)
Band 2 - Sequence based on (12-). Configuration=$\pi g_{7/2}{}^{3}$				
2927.6 *7*	(12-)			
3257.8 *7*	(13-)		330.2 *3* 1013.7 *5*	100 *25* 100 *40*

Here, the μX-ray N line is less strong in the delayed spectrum (some remaining of it might be due to the ^{136}Cs* (Ɣ$_{309.4keV}$)). The ^{135}Cs* (Ɣ$_{249keV}$) line is clear in the prompt and delayed spectra (the 358keV one is visible but less clear, it has lower BR) . ^{136}Cs (Ɣ$_{273keV,}$ Ɣ$_{340keV}$) are visible, especially the latter with a higher BR and in the beam-off spectrum

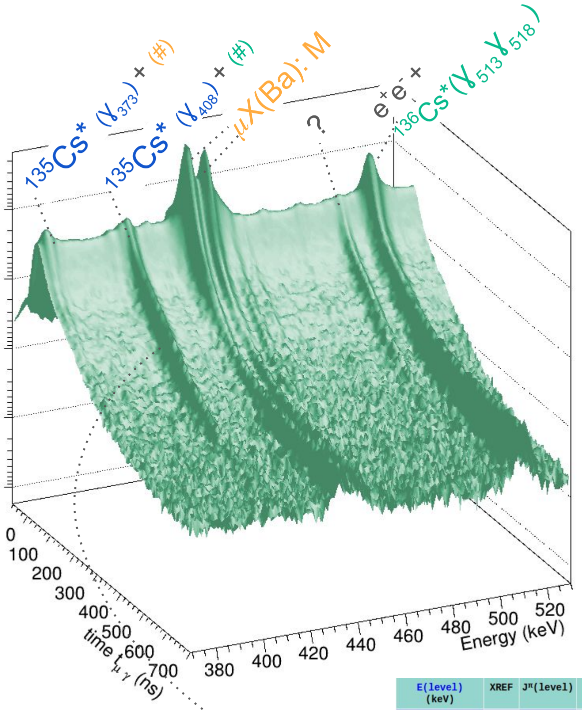
E(level) (keV)	Jπ(level)	E(γ) (keV)	I(γ)
0.0	7/2+		
249.767 *4*	5/2+	249.770 *4*	100
408.026 *5*		158.260 *4* 408.009 *8*	81 *3* 100 *3*
608.153 *8*	5/2+	200.19 *10* 358.384 *9* 608.151 *12*	0.40 *16* 7.6 *3* 100 *3*

Gammas from ^{136}Cs (13.16 d *3*)

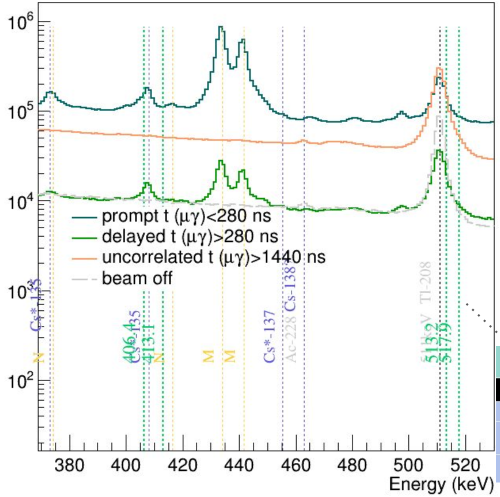
Eg (keV)	Ig (%)	Decay mode
233.5 *4*	0.080 *10*	b-
273.646 *8*	11.1 *4*	b-
302.9 *2*	0.030 *10*	b-
315.5 *5*	0.020 *18*	b-
319.911 *8*	0.50 *5*	b-
340.547 *8*	42.2 *13*	b-

Potential $^{(\#)}$ ^{136}Cs* (Ɣ$_{309.4,}$ Ɣ$_{330.2}$) lines: The 1015.9 and 1013.7 lines are observed as well.

Analyzing spectra: Energy region 3 (370 -530KeV)



Larger BR



E(level) (keV)	XREF	Jπ(level)	$T_{1/2}$(level)	E(γ) (keV)	I(γ)	M(γ)	Final Levels	
0.0	ABCDE	7/2+	$2.3\times10^{+6}$ y 3 % β⁻ = 100					
249.767 4	A DE	5/2+	0.28 ns 8	249.770 4	100	M1(+E2)	0.0	7/2+
408.026 5	A D			158.260 4 408.009 8	81 3 100 3		249.767 0.0	5/2+ 7/2+
608.153 8	A D	5/2+		200.19 10 358.384 9 608.151 12	0.40 16 7.6 3 100 3	 M1,E2 M1(+E2)	408.026 249.767 0.0	 5/2+ 7/2+
786.838 13	BCD	11/2+		786.836 13	100	E2	0.0	7/2+
981.396 19	A D			373.13 10 573.36 4 731.634 21	28 5 8.7 13 100 5		608.153 408.026 249.767	5/2+ 5/2+

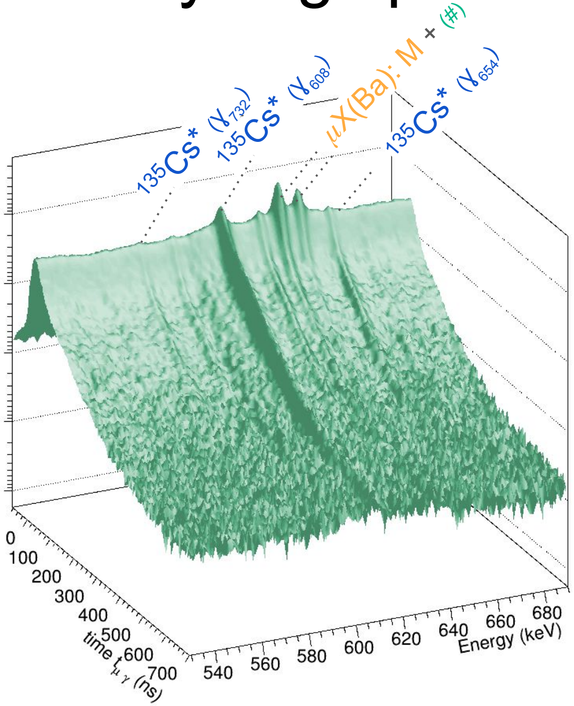
Here, the μX-ray M lines are quite clear. The ^{135}Cs* (ɣ$_{408keV}$) line is clear(¤), and overlaps with the ^{136}Cs* (ɣ$_{406.4}$) line. Unsure whether any accompanying lines of the latter are observed (ɣ$_{729.8}$, ɣ$_{261.6}$). There is some unknown line and the annihilation (e^+e^-) peak overlaps with other excitation lines ^{136}Cs*(ɣ$_{513}$ɣ$_{518}$). The 229 accompaigning the former is not observed.

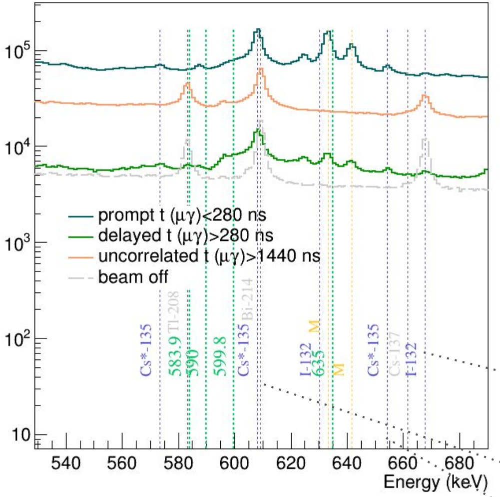
E(level) (keV)	Jπ(level)	$T_{1/2}$(level)	E(γ)	I(γ)
Band 2 - Sequence based on (12-). Configuration=π$g_{7/2}$				
2927.6 7	(12-)			
3257.8 7	(13-)		330.2 3 1013.7 5	100 25 100 40
3486.8 7	(14-)		229.0 4 513.2 4	100 25 100 30

E(level) (keV)	XREF	Jπ(level)	$T_{1/2}$(level)	E(γ) (keV)	I(γ)
0.0	A	5+	13.01 d 5 % β⁻ = 100		
104.8 3	A	4+		104.8	100
517.9 1	A D	8-	17.5 s 2 % IT > 0 % β⁻ = ?	413.1 3 517.9 1	0.072 100

(¤)its 158keV accompanying line was also clear, though it overlapped with O-K, and a line at at another Energy level, with lower BR is also observed ɣ$_{373keV}$)

Analyzing spectra: Energy region 4 (530-690 KeV)





Here, more μX-ray M lines are visible. One of them overlaps with the ^{136}Cs* (γ_{635}) line (it is unsure whether the 1318 accompanying line is observed). Again ^{135}Cs* (γ_{654}, γ_{608}) lines are clear (their high BR accompanying lines are also observed) as well as a bit of ^{135}Cs* (γ_{732}). Other ^{136}Cs* lines are not clearly observed to the overlap with other lines. ^{132}I (γ_{668}) is observed in the uncorr and beam off spectra (its accomp. Line at 772.6 is less clearly but also observed).

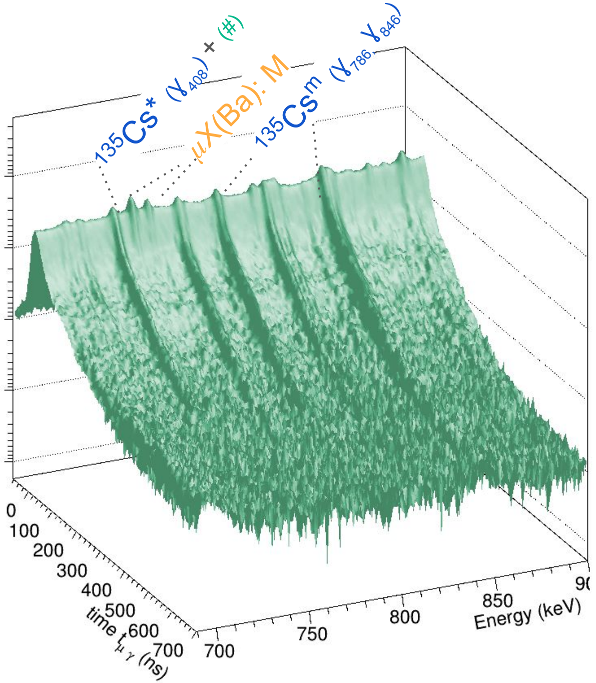
E(level) (keV)	XREF	Jπ(level)	E(γ) (keV)	I(γ)	Final Levels	
3520 5	B	1+				
3562.5 7	D	(13+)	635.0 5 1318.5 5	50 25 100 40	2927.6 2243.9	(12-) (12-)

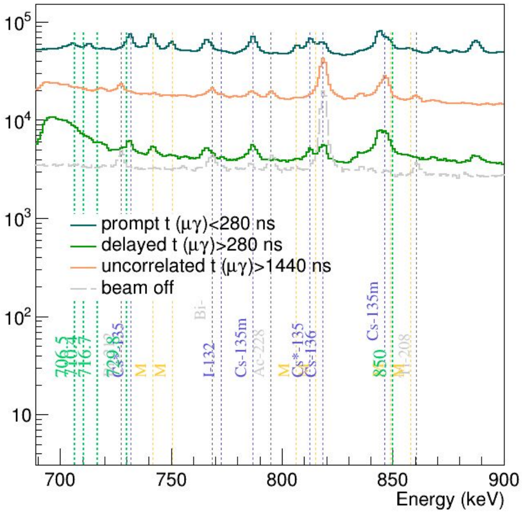
E(level) (keV)	XREF	Jπ(level)	E(γ) (keV)	I(γ)
0.0	ABCDE	7/2+		
249.767 4	A DE	5/2+	249.770 4	100
408.026 5	A D		158.260 4 408.009 8	81 3 100 3
608.153 8	A D	5/2+	200.19 10 358.384 9 608.151 12	0.40 16 7.6 3 100 3
786.838 13	BCD	11/2+	786.836 13	100
981.396 19	A D		373.13 10 573.36 4 731.634 21	28 5 8.7 13 100 5
1062.385 13	A D		454.2 2 654.296 23 812.635 22 1062.41 2	5.1 10 64 3 100 3 5.8 12

Gammas from ^{132}I (2.295 h 13)

Eg (keV)	Ig (%)	Decay mode
630.19 2	13.3 4	b-
642.2 4	<0.039	b-
650.5 2	2.57 20	b-
667.718 3	99	b-
669.8 2	4.6 6	b-
671.4 2	3.5 10	b-
684.4 2	0.08 4	b-
687.8 5	0.039 20	b-
706.4 7	~0.020	b-
727.0 3	2.2 6	b-
727.2 3	3.2 6	b-
728.4 2	1.6 4	b-
771.7	0.020 20	b-
772.60 1	75.6 13	b-

Analyzing spectra: Energy region 5 (690-900 KeV)





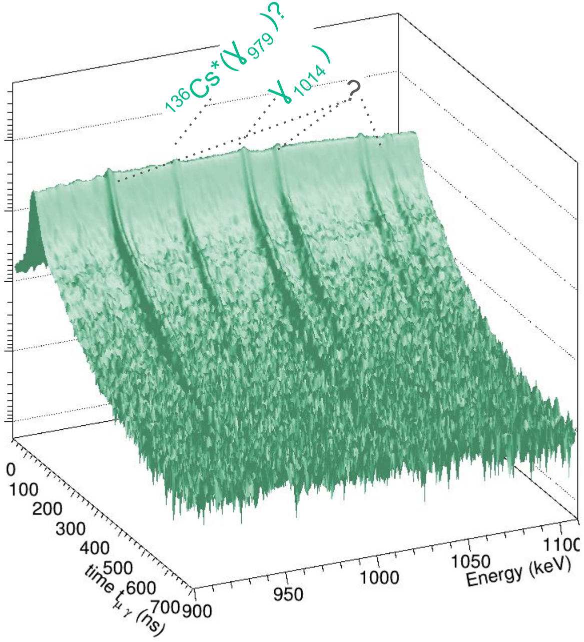
Here again, no clear excitation lines from ^{136}Cs* as all of them overlap with other lines (or with the neutron production in Ge).... Again we see a few lines from ^{135}Cs* and now also ^{135}Cs^{m}

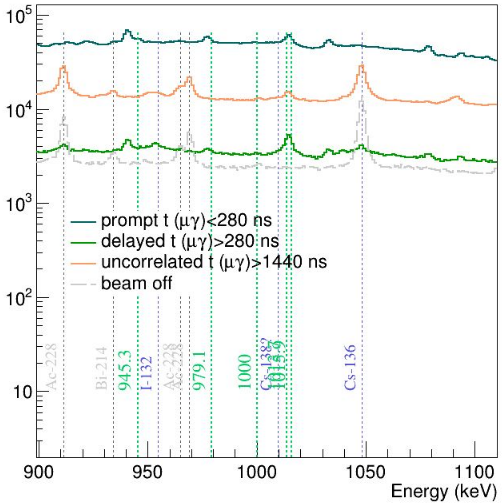
E(level) (keV)	J^π(level)	$T_{1/2}$(level)	E(γ)	I(γ)	M(γ)	Final Levels	
Band 1 - Sequence based on (11-). Configuration=$\pi d_{5/2}$~#$\pi g_{7/2}{}^4$~#$\nu h_{11/2}{}^{-1}$							
1982.3 *6*	(11-)						
2243.9 *6*	(12-)		261.6 *2*	100		1982.3	(11-)
2973.7 *7*	(13-)		729.8 *3*	100		2243.9	(12-)

Gammas from ^{135m}Cs (53 m 2)

Eg (keV)	Ig (%)	Decay mode
786.836 *13*	100	IT
846.1	95.9	IT

Analyzing spectra: Energy region 6 (900-1100 KeV)



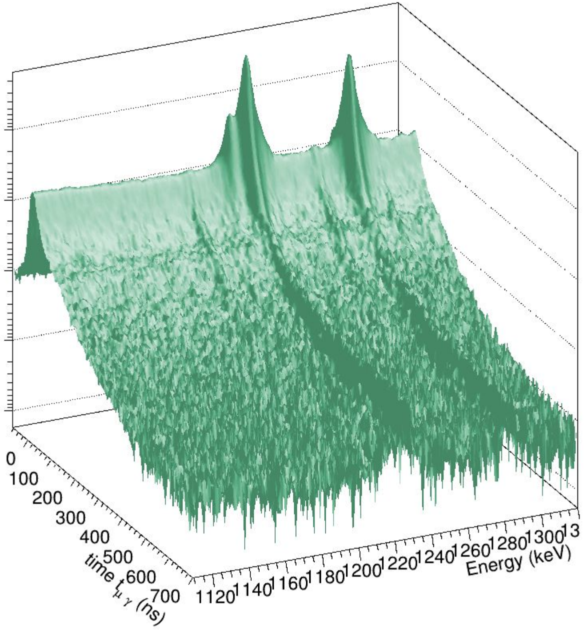


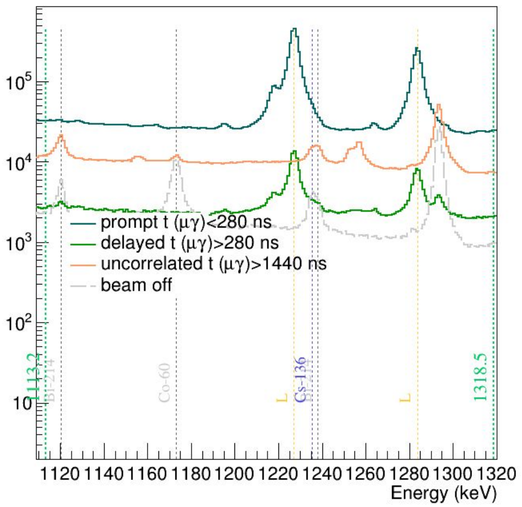
^{136}Cs* lines: The 1015.9 and 1013.7 lines overlap and their previous $\gamma_{309.4}$, $\gamma_{330.2}$ lines: were observed. γ_{979} line is either slightly shifted or not present

E(level) (keV)	Jπ(level)	$T_{1/2}$(level)	E(γ)	I(γ)
Band 2 - Sequence based on (12-). Configuration=$\pi g_{7/2}^{3}$				
2927.6 7	(12-)			
3257.8 7	(13-)		330.2 3 1013.7 5	100 25 100 40

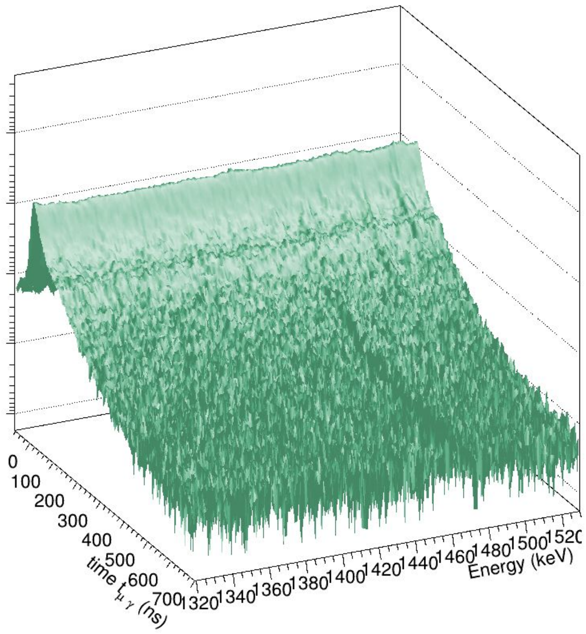
E(level) (keV)	Jπ(level)	E(γ) (keV)	I(γ)
3520 5	1+		
3562.5 7	(13+)	635.0 5 1318.5 5	50 25 100 40
3684.0 7	(14+)	121.4 5 710.4 3	17 4 100 30
3929.1 8	(15+)	245.1 3	100
4086.7 7	(15-)	599.8 5 706.5 5 1113.2 5	100 30 11 6 56 22
4359.2 9	(16-)	979.1 5	100
4396.1 8	(16-)	309.4 4 1015.9 5	100 50 50 25

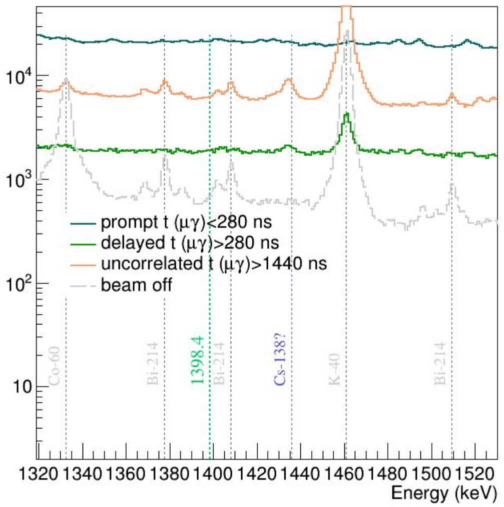
Analyzing spectra: Energy region 7 (1110-1320 KeV)



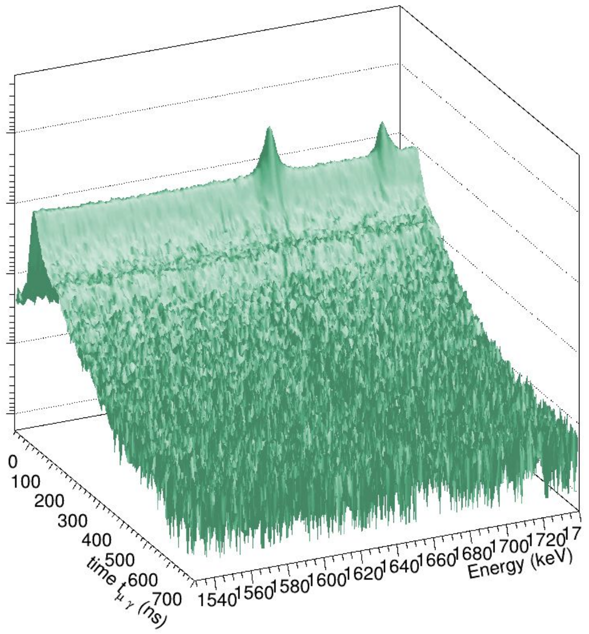


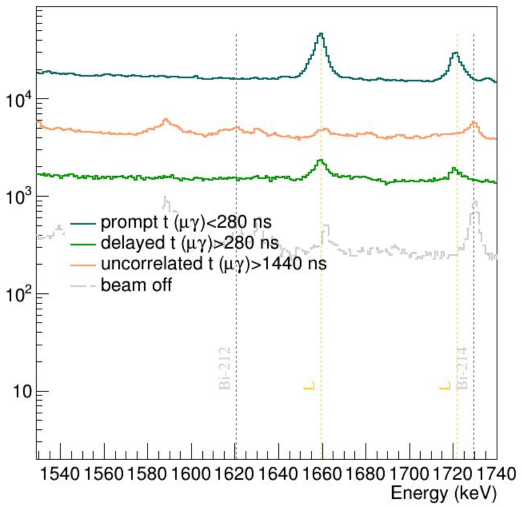
Analyzing spectra: Energy region 8 (1320-1530 KeV)



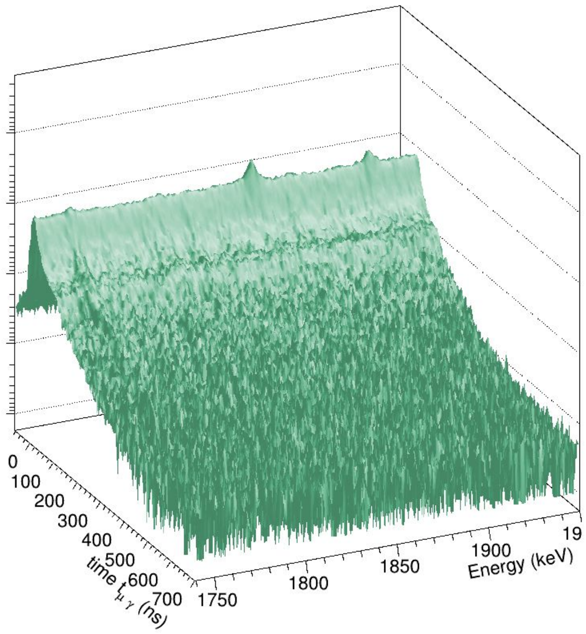


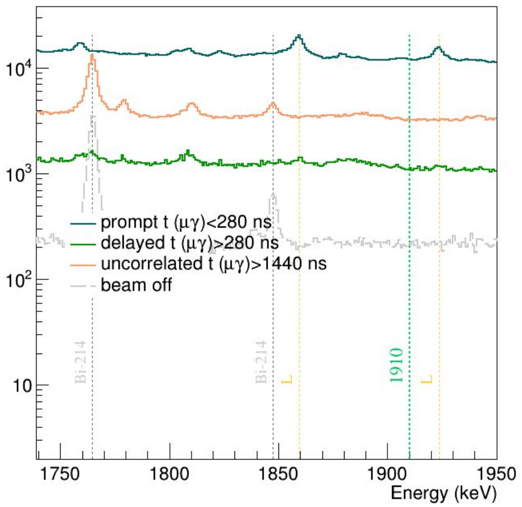
Analyzing spectra: Energy region 9 (1530-1740 KeV)



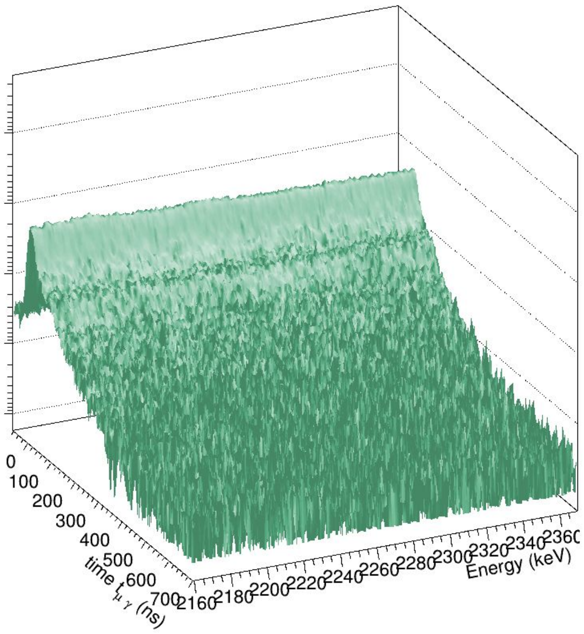


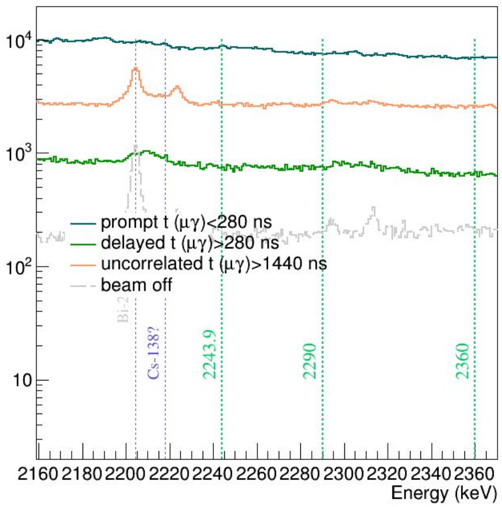
Analyzing spectra: Energy region 10 (1740-1950 KeV)



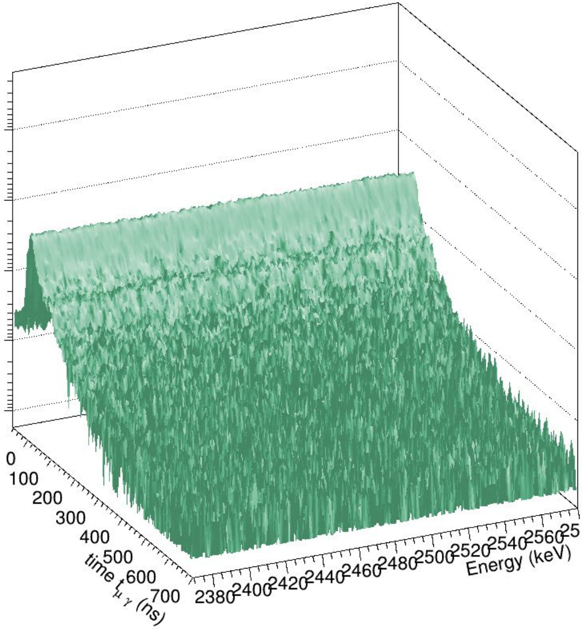


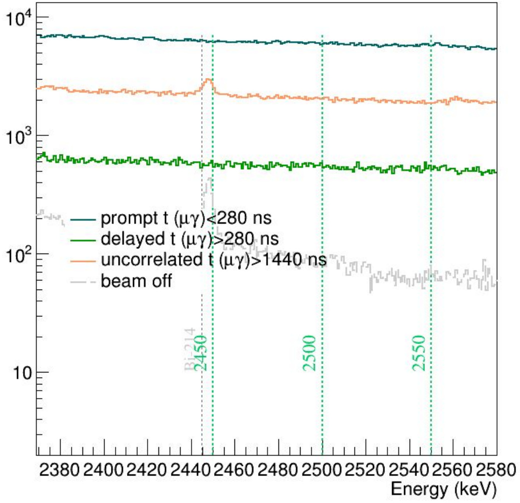
Analyzing spectra: Energy region 11 (2160-2370 KeV)



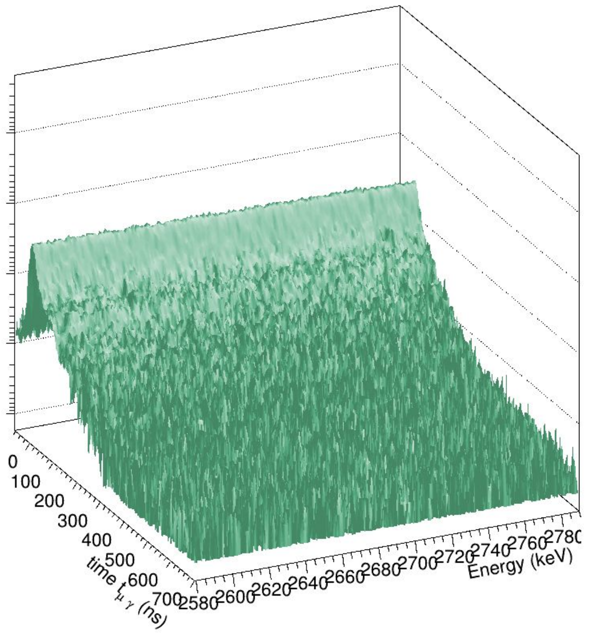


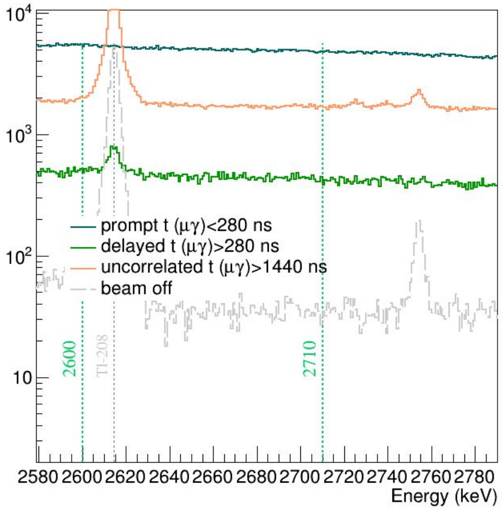
Analyzing spectra: Energy region 12 (2370-2580 KeV)



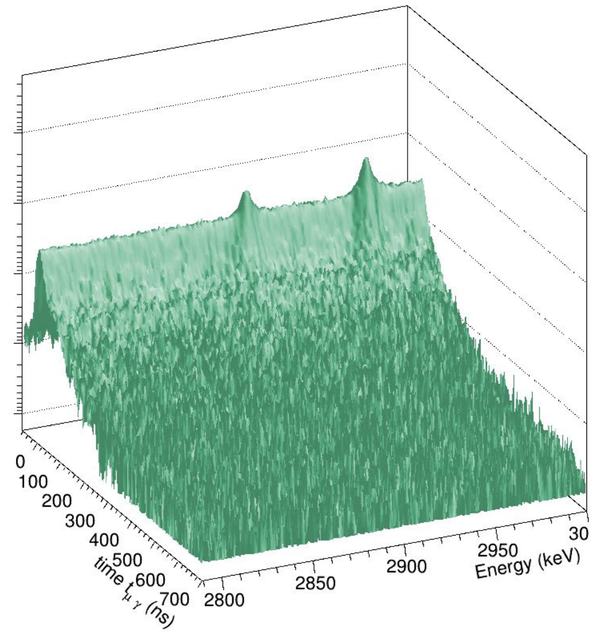


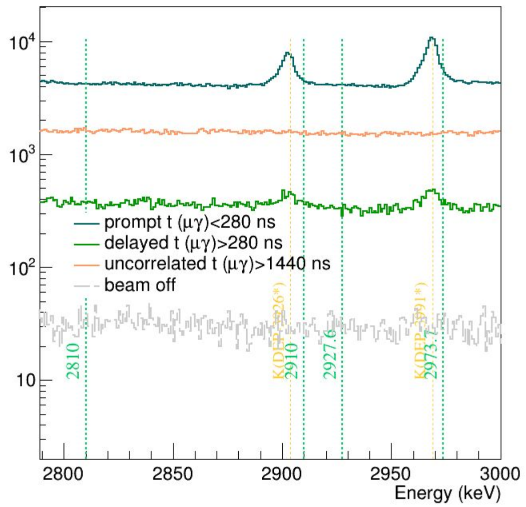
Analyzing spectra: Energy region 13 (2580-2790 KeV)



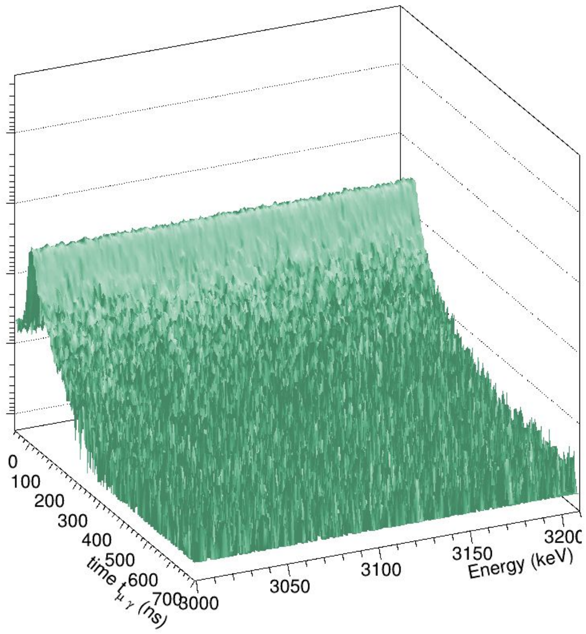


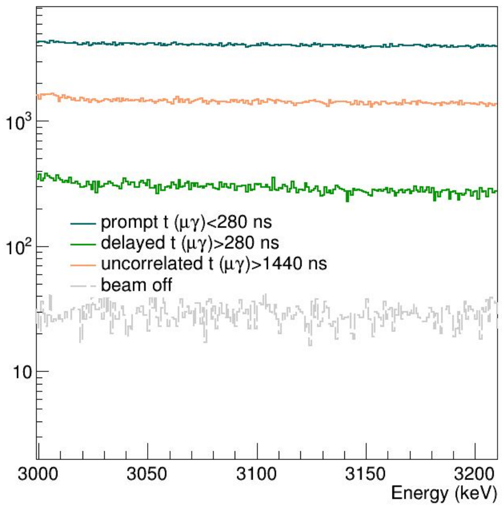
Analyzing spectra: Energy region 14 (2790-3000 KeV)



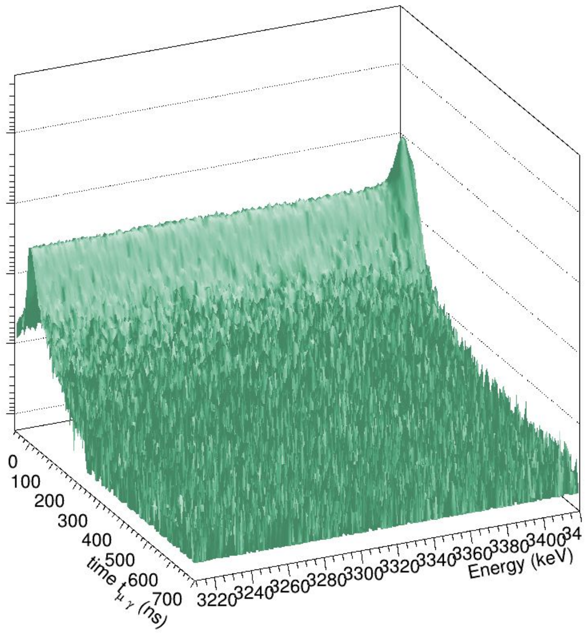


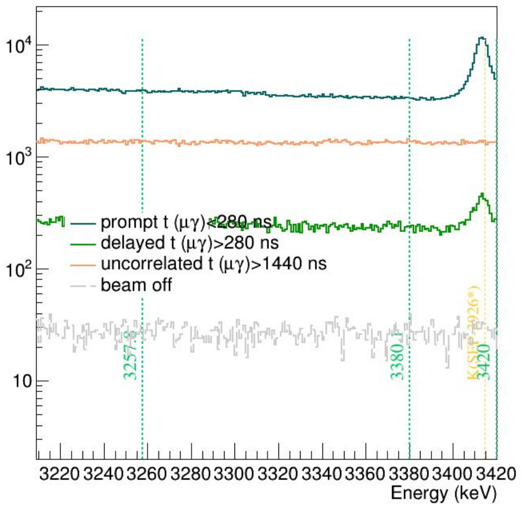
Analyzing spectra: Energy region



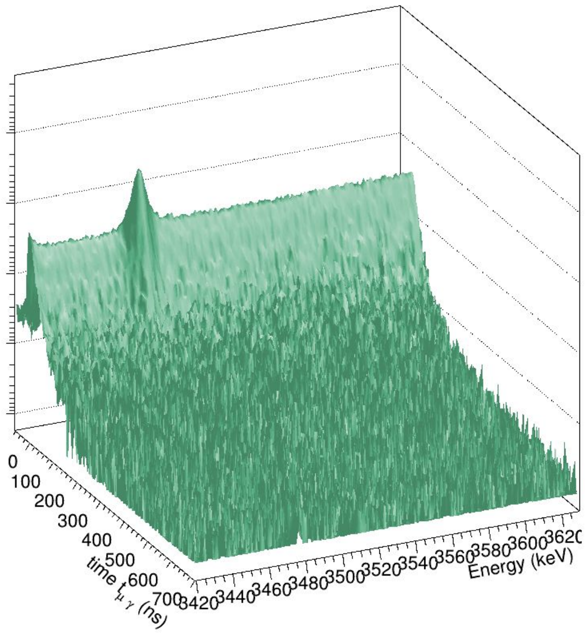


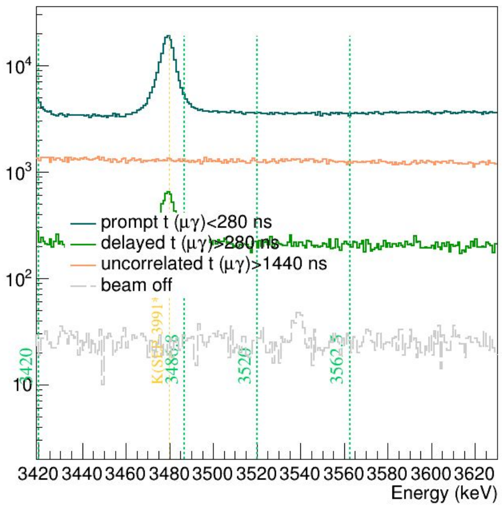
Analyzing spectra: Energy region



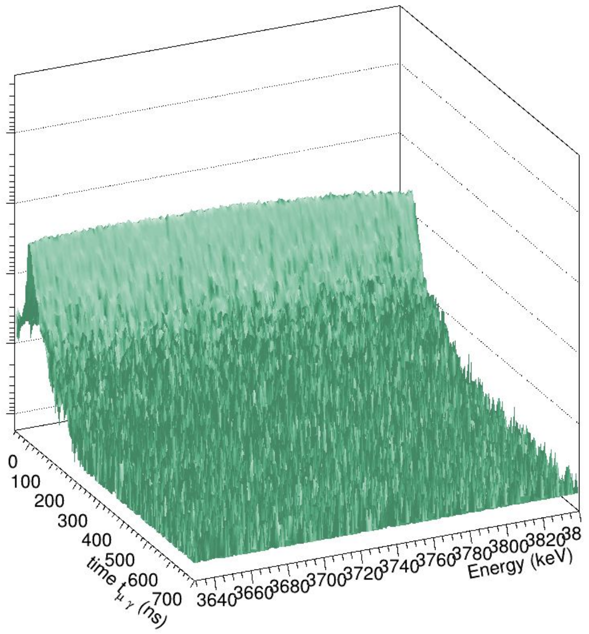


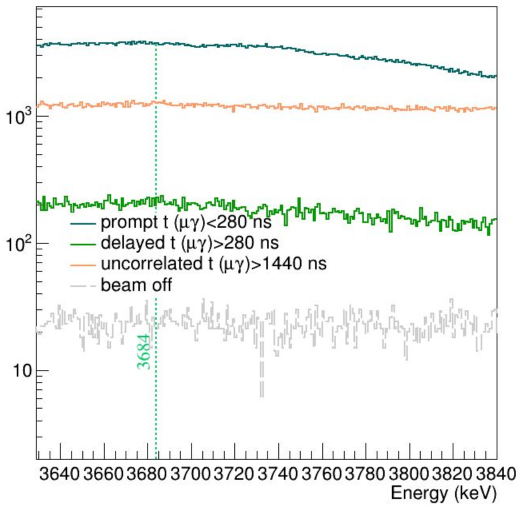
Analyzing spectra: Energy region



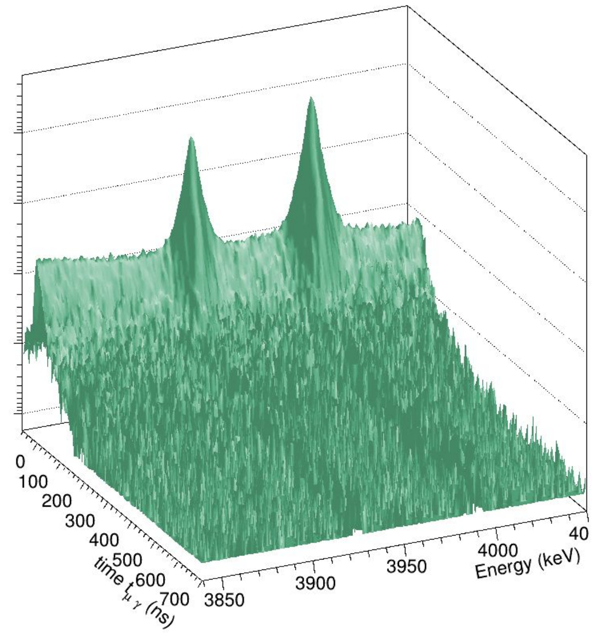


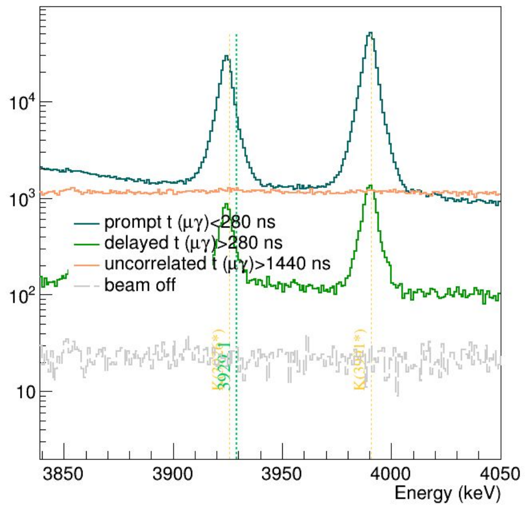
Analyzing spectra: Energy region





Analyzing spectra: Energy region





In summary, very few lines are “well” identified for Ba-136

(at least for Ge 3, but will it get much better for other channels?)

E(level) (keV)	XREF	Jπ(level)	E(γ) (keV)	I(γ)	Final Levels	
0.0	A	5+				
104.8 3	A	4+	104.8	100	0.0	5+
517.9 1	A D	8-	413.1 3 517.9 1	0.072 100	104.8 0.0	4+ 5+
583.9 5	D	9-	66.0 5	100	517.9	8-
590 5	B	1+				
850 5	B	1+				
1000 5	B	(2-)				
1910 5	B	1+				
1982.3 6	D	(11-)	1398.4 3	100	583.9	9-
2010 5	B	1+				
2243.9 6	D	(12-)	261.6 2	100	1982.3	(11-)
2290 5	B	1+				
2360 5	B	1+				
2450 5	B	1+				
2500 5	B	1+				
2550 5	B	1+				
2600 5	B	1+				
2710 5	B	1+				
2810 5	B	1+				
2910 5	B	1+				
2927.6 7	D	(12-)	945.3 4	100	1982.3	(11-)
2973.7 7	D	(13-)	729.8 3	100	2243.9	(12-)
3257.8 7	D	(13-)	330.2 3 1013.7 5	100 25 100 40	2927.6 2243.9	(12-) (12-)
3380.1 7	D	(14-)	406.4 3	100	2973.7	(13-)
3420 5	B	1+				
3486.8 7	D	(14-)	229.0 4 513.2 4	100 25 100 30	3257.8 2973.7	(13-) (13-)

The excited state is commonly present after neutron emission, and given that *-n* is much more frequent, we get much more ɣ’s from ^{135}Cs* than from ^{136}Cs* . I guess this is usually the case (?) like the marked lines in the ^{76}Se-spectrum (which are from ^{75}As*, not from ^{76}As*.) Q: how did the ^{76}As* lines look like in the spectrum?

E(level) (keV)	XREF	Jπ(level)	E(γ) (keV)	I(γ)	Final Levels	
3520 5	B	1+				
3562.5 7	D	(13+)	635.0 5 1318.5 5	50 25 100 40	2927.6 2243.9	(12-) (12-)
3684.0 7	D	(14+)	121.4 5 710.4 3	17 4 100 30	3562.5 2973.7	(13+) (13-)
3929.1 8	D	(15+)	245.1 3	100	3684.0	(14+)
4086.7 7	D	(15-)	599.8 5 706.5 5 1113.2 5	100 30 11 6 56 22	3486.8 3380.1 2973.7	(14-) (14-) (13-)
4359.2 9	D	(16-)	979.1 5	100	3380.1	(14-)
4396.1 8	D	(16-)	309.4 4 1015.9 5	100 50 50 25	4086.7 3380.1	(15-) (14-)
4645.8 9	D		716.7 4	100	3929.1	(15+)
13380	B	0+				

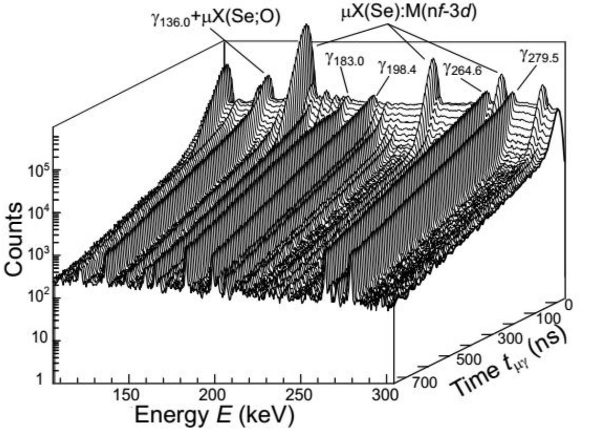


FIG. 5. (E,t) distribution of the correlated events measured with the ^{76}Se target.

Back up

A few questions……

Regarding OMC4DBD

- How did the ^{76}As* lines look like in the spectrum? How was their significance defined?
- Were OMC rates ever implemented in QRPA models? By how much did they improve (or what would be the precision required for the OMC partial rate such that this information could improve these models?) Are limits also useful? -> Answer from J.Suhonen in the CM: First, one needs to do the calculation for the OMC - the input values here can largely vary (by a factor a few hundred percent) and still yield relevant input for the QRPA models.
- Does the excitation level matter in the calculation? or calculating rates to any levels helps? Answer: The probability of reaching different excitation levels vary, and their ratios are often found in the literature (yet, I guess this is one of the parameters we want to find?)

General:

- Do neutron emissions delay signal? Or are they prompt
- Given the better resolution of a few Ge channels, are our results useful to updating μX databases?
- Are muon lifetimes known for all isotopes or do our results contribute to these values?

E(level) (keV)	XREF	Jπ(level)	E(γ) (keV)	I(γ)	Final Levels	
3520 5	B	1+				
3562.5 7	D	(13+)	635.0 5 1318.5 5	50 25 100 40	2927.6 2243.9	(12-) (12-)
3684.0 7	D	(14+)	121.4 5 710.4 3	17 4 100 30	3562.5 2973.7	(13+) (13-)
3929.1 8	D	(15+)	245.1 3	100	3684.0	(14+)
4086.7 7	D	(15-)	599.8 5 706.5 5 1113.2 5	100 30 11 6 56 22	3486.8 3380.1 2973.7	(14-) (14-) (13-)
4359.2 9	D	(16-)	979.1 5	100	3380.1	(14-)
4396.1 8	D	(16-)	309.4 4 1015.9 5	100 50 50 25	4086.7 3380.1	(15-) (14-)
4645.8 9	D		716.7 4	100	3929.1	(15+)
13380	B	0+				

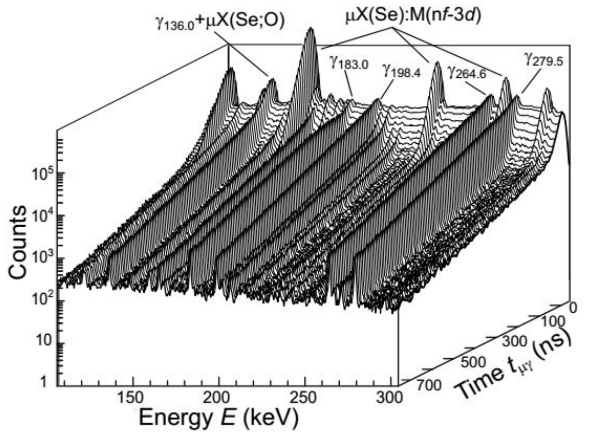


FIG. 5. (E,t) distribution of the correlated events measured with the ^{76}Se target.