Status of data/MC comparison for LIME underground

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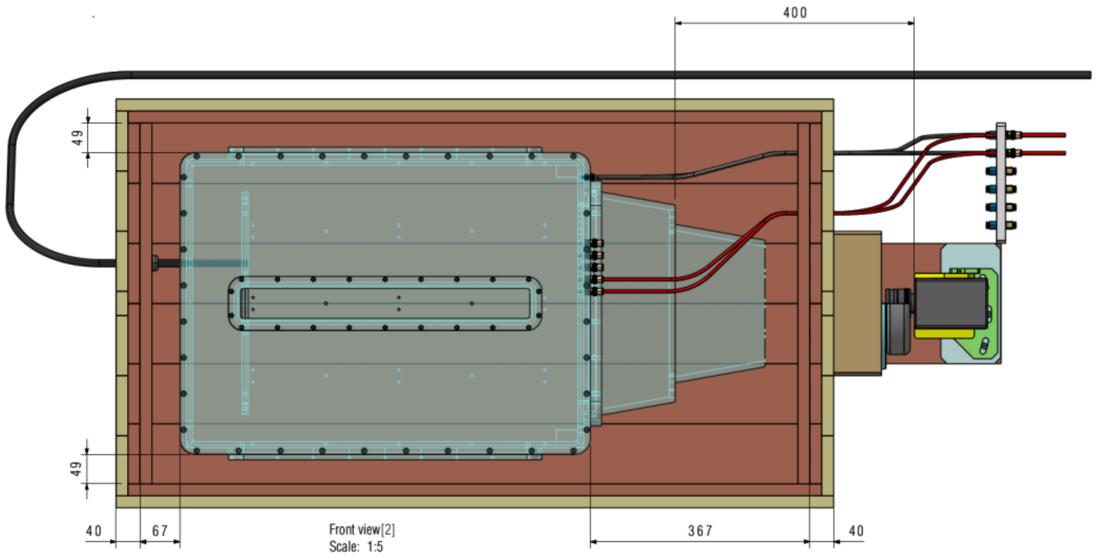
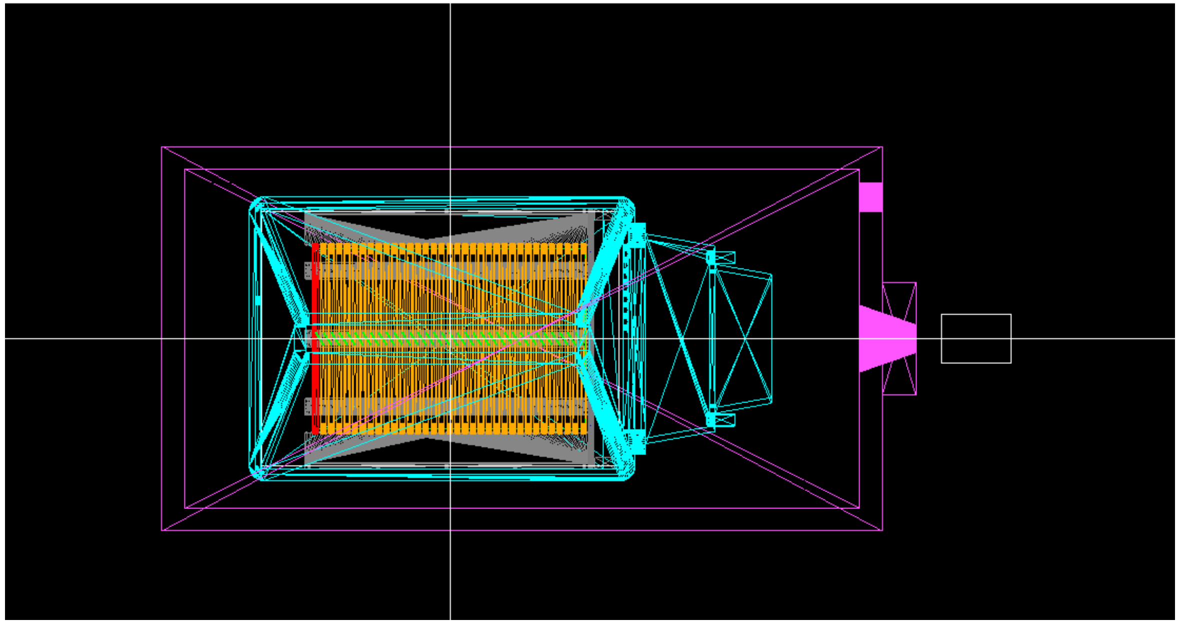
CYGNO Analysis Meeting 29/02/24

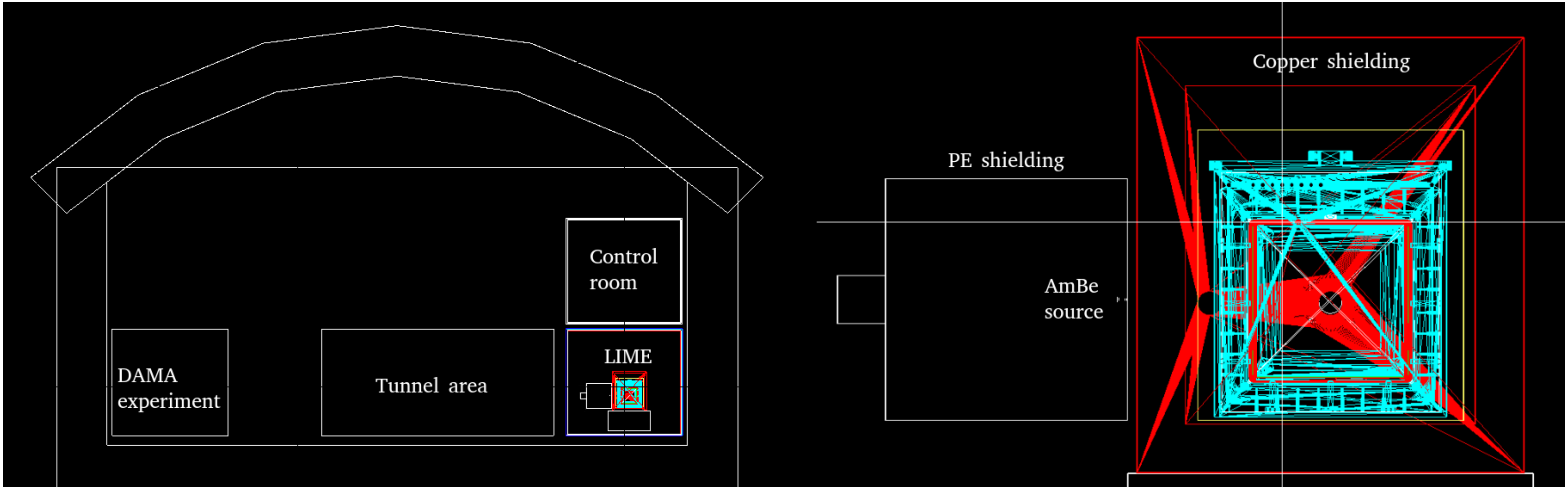
LIME simulation

- Geometry setup in GEANT4: **field cage rings, resistors, cathode, gem foils, acrylic vessel, camera body, camera lens,** PMTs, internal support structures
- **Shielding**: first implemented as simple boxes for the initial material/thickness optimization, then implemented in CAD (copper, 4-6-10cm)





LIME simulation



For the AmBe setup simulation also the rock hall (1.5m thick), PE base below LIME and PE shielding around AmBe source also implemented (and the 10cm Cu shielding)

GEANT4 simulation of background

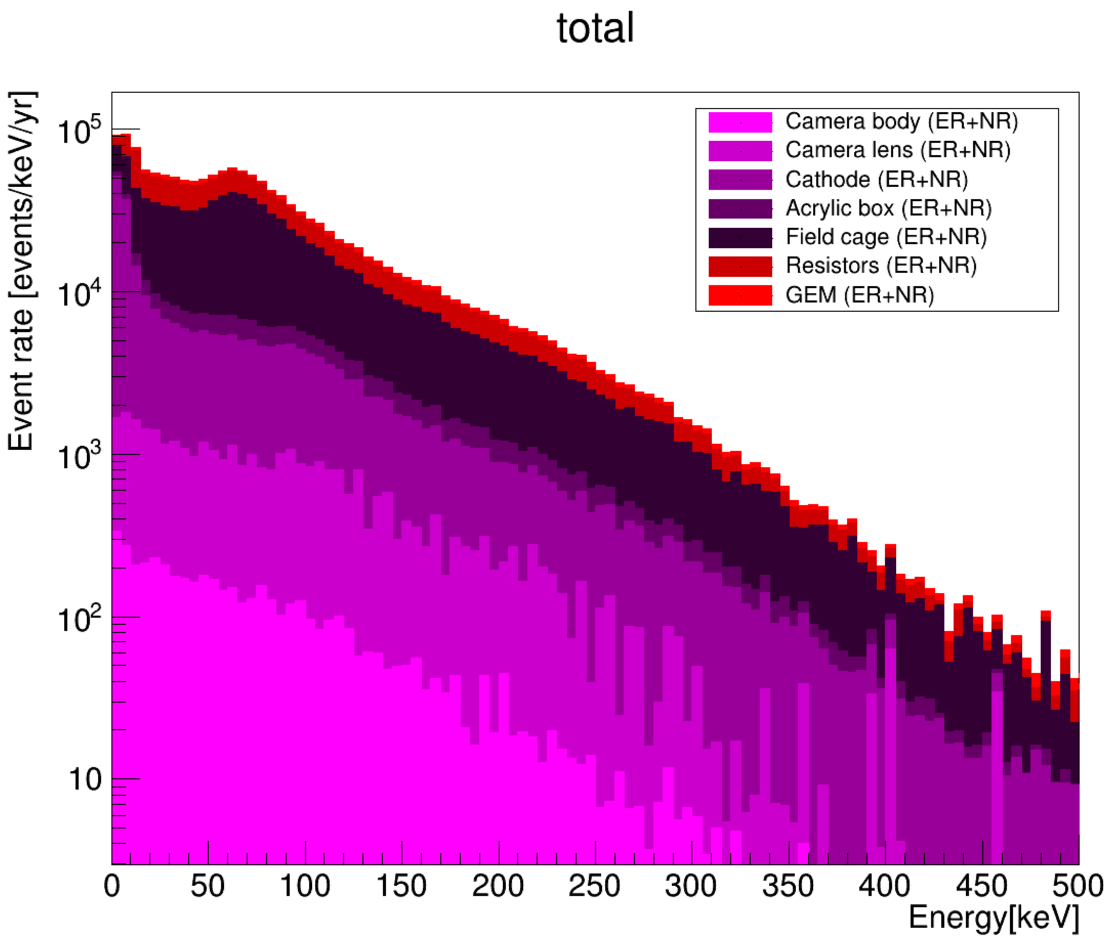
- External sources:
  - Environmental gammas
  - Environmental neutrons
    - Neutron-induced background is 100-1000 times less than external gammas-induced one
- Internal sources:
  - Radioactivity: shielding, GEM foils, acrylic vessel, cathode, field cage rings, resistors, camera, lens
  - Radiogenic and cosmogenic neutrons produced in the shielding
    - 95% of internal background comes from GEM foils, acrylic vessel, cathode, field cage rings and resistors

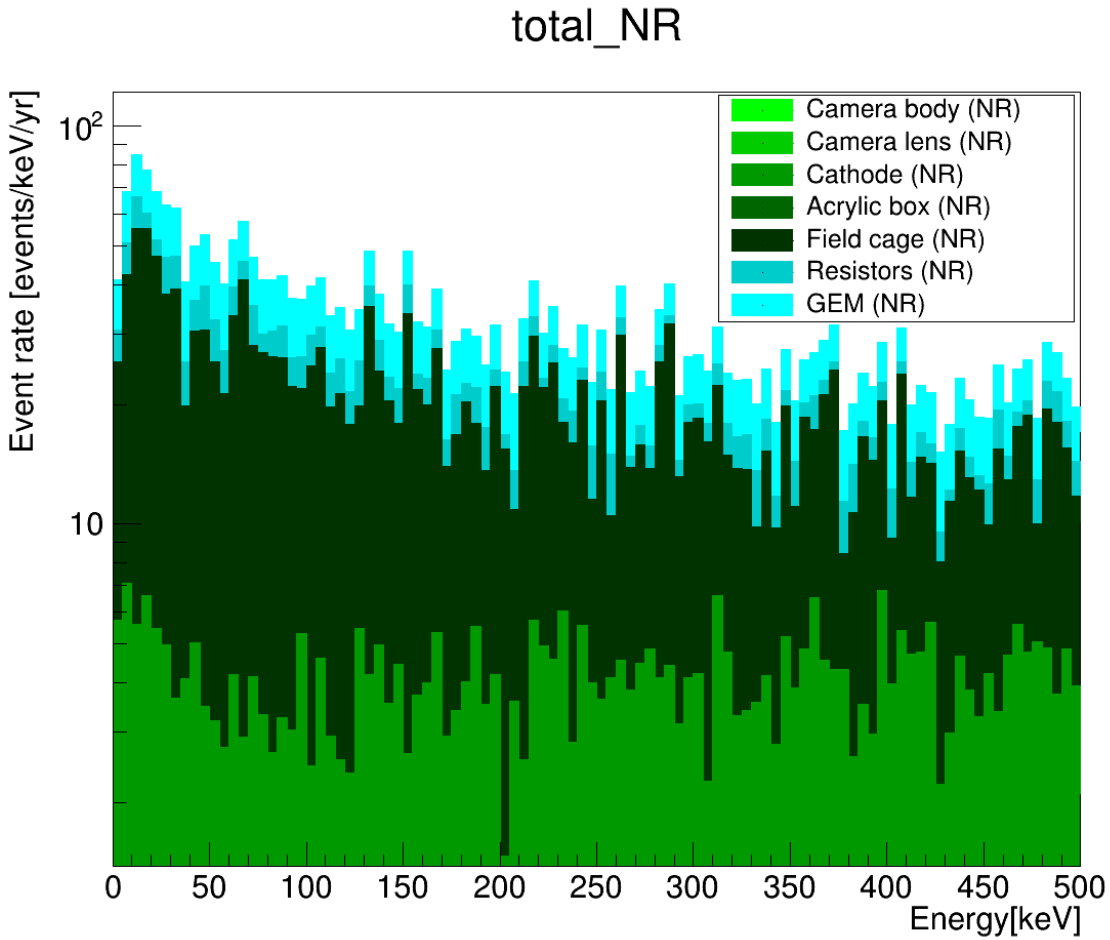
- **Digitized and reconstructed**: external gammas, GEM foils, acrylic vessel, cathode, field cage rings and resistors
  - Excluded, to be included in next simulations (CYGNO_04?): external neutrons, radiogenic and cosmogenic neutrons, camera and camera lens (precise materials and geometry to be implemented), PMTs, shielding radioactivity

Measured radioactivity

Isotope	Activity [mBq/kg]						
	Field rings	Resistors	GEM	PMMA	Camera body	Camera lens	PMT
^{234}Th	< 210	$(20 \pm 2) \times 10^3$	163 ± 65	< 3.5	3290 ± 940	4200 ± 1400	40 ± 10
^{234m}Pa	< 77	$(22 \pm 7) \times 10^3$	163 ± 65	< 3.5	3290 ± 940	4200 ± 1400	< 61
^{226}Ra	< 1.3	2160 ± 160	32 ± 16	< 3.5	850 ± 50	1920 ± 90	15 ± 1
^{210}Pb	< 13	$(592 \pm 70) \times 10^3$	32 ± 16	< 3.5	850 ± 50	1920 ± 90	
^{228}Ra	< 1.1	3500 ± 320	< 30.9	< 5	990 ± 90	360 ± 40	11 ± 1
^{228}Th	< 1.3	3360 ± 320	< 15.6	< 4.5	990 ± 50	365 ± 28	12 ± 1
^{235}U	< 1.6	330 ± 60	< 15.8	-	190 ± 50	145 ± 37	1.3 ± 0.5
^{40}K	< 6	< 1780	< 358	< 35	890 ± 140	$(52 \pm 5) \times 10^3$	1200 ± 300
^{137}Cs	< 0.47	< 74	< 8.13	-	42 ± 14	< 27	< 0.52
^{60}Co	< 0.57	< 7.7	< 7.48	-	< 5.6	< 46	-
^{58}Co	0.9 ± 0.3	< 3.1	-	-	-	-	-
^{54}Mn	< 0.43	< 3.3	-	-	-	-	-
^{138}La	-	-	-	-	-	2430 ± 190	-

GEANT4 simulation: internal radioactivity

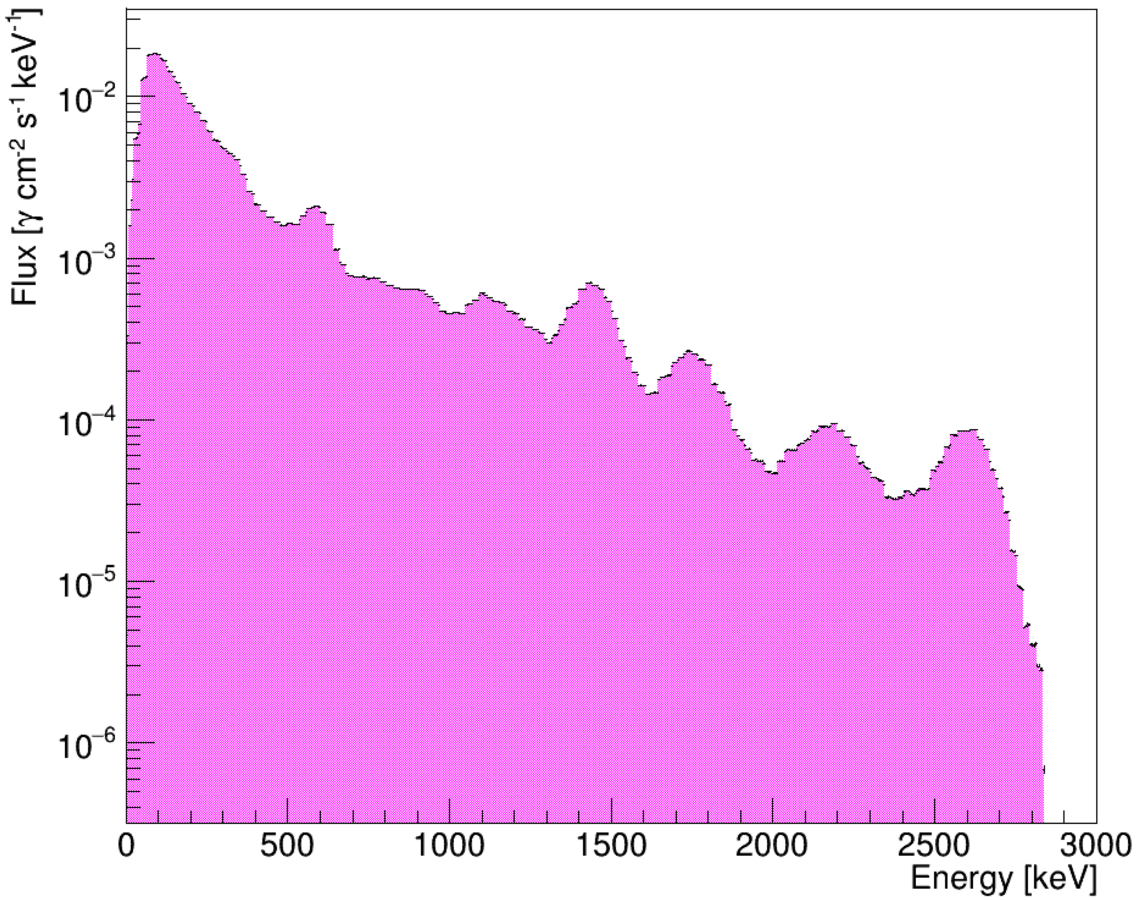


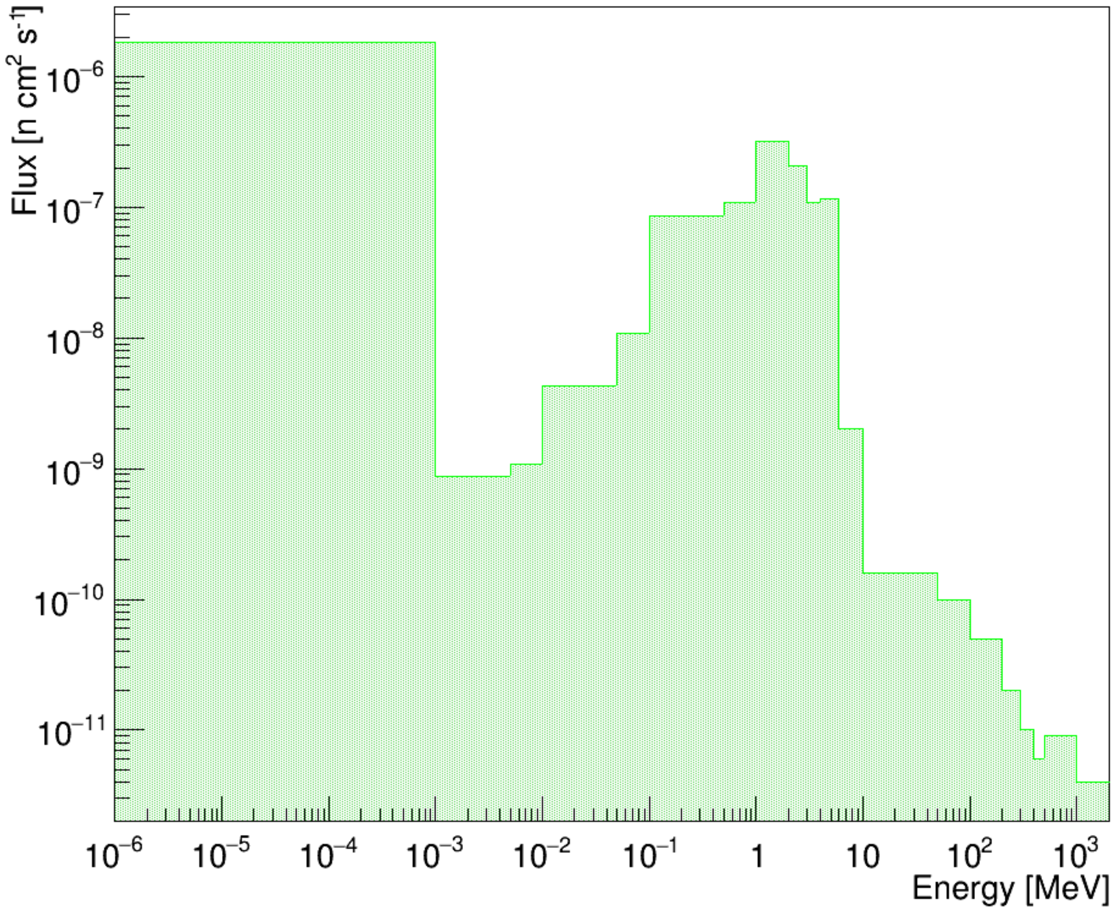


GEANT4 simulation: internal radioactivity

Energy range [keV]	ER+NR [10^5 counts/yr]	NR [counts/yr]
Camera body		
0-1 keV	0.0043 ± 0.0007	0
1-20 keV	0.048 ± 0.002	0
20-50 keV	0.057 ± 0.003	0
50-3000 keV	0.137 ± 0.003	0
Camera lens		
0-1 keV	0.020 ± 0.005	0
1-20 keV	0.26 ± 0.02	0
20-50 keV	0.30 ± 0.02	0
50-3000 keV	0.95 ± 0.03	0
Cathode		
0-1 keV	0.264 ± 0.002	3 ± 2
1-20 keV	5.059 ± 0.009	120 ± 10
20-50 keV	1.573 ± 0.005	130 ± 10
50-3000 keV	4.322 ± 0.008	22100 ± 200
Acrylic vessel		
0-1 keV	0.039 ± 0.001	0
1-20 keV	0.495 ± 0.004	0
20-50 keV	0.522 ± 0.005	0
50-3000 keV	1.662 ± 0.008	0
Field cage rings		
0-1 keV	0.33 ± 0.01	1.5 ± 0.5
1-20 keV	5.03 ± 0.04	770 ± 90
20-50 keV	7.53 ± 0.05	890 ± 90
50-3000 keV	23.13 ± 0.09	22700 ± 400
Resistors		
0-1 keV	0.160 ± 0.009	2 ± 1
1-20 keV	3.80 ± 0.04	150 ± 20
20-50 keV	4.41 ± 0.03	210 ± 20
50-3000 keV	10.52 ± 0.04	6590 ± 80
GEMs		
0-1 keV	0.0499 ± 0.0003	3.7 ± 0.3
1-20 keV	0.655 ± 0.001	319 ± 3
20-50 keV	0.825 ± 0.001	457 ± 4
50-3000 keV	2.411 ± 0.002	24600 ± 30
Total		
0-1 keV	0.87 ± 0.01	10 ± 2
1-20 keV	15.35 ± 0.06	1360 ± 90
20-50 keV	14.95 ± 0.06	1690 ± 90
50-3000 keV	43.1 ± 0.1	76000 ± 450

GEANT4 simulation: external fluxes





GEANT4 simulation: external sources

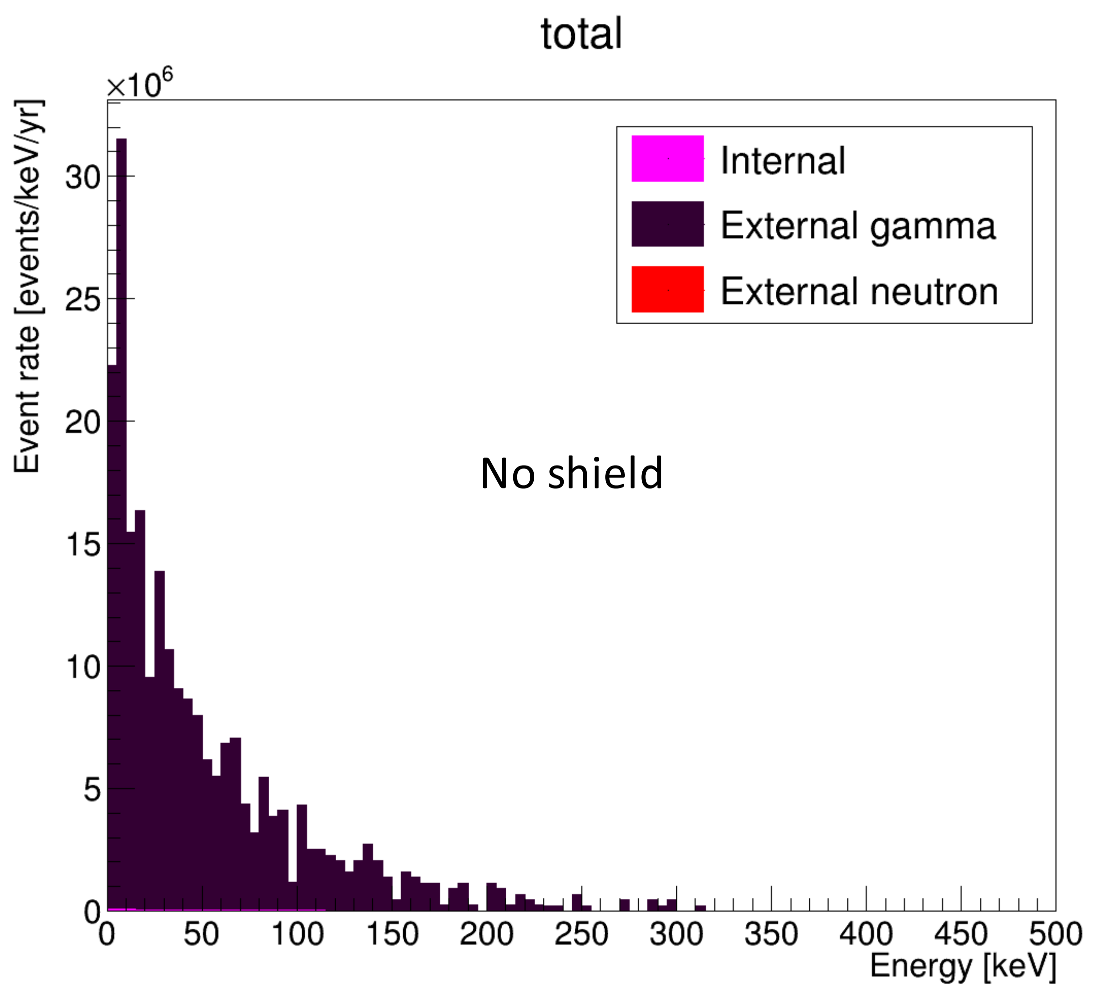
Unshielded	Gammas	Neutrons	
Energy range [keV]	ER [10^6 counts/yr]	ER+NR [counts/yr]	NR [counts/yr]
0-1 keV	25 ± 5	2800 ± 100	370 ± 40
1-20 keV	410 ± 20	480 ± 50	350 ± 40
20-50 keV	300 ± 20	390 ± 40	220 ± 30
50-3000 keV	430 ± 20	1430 ± 900	910 ± 70

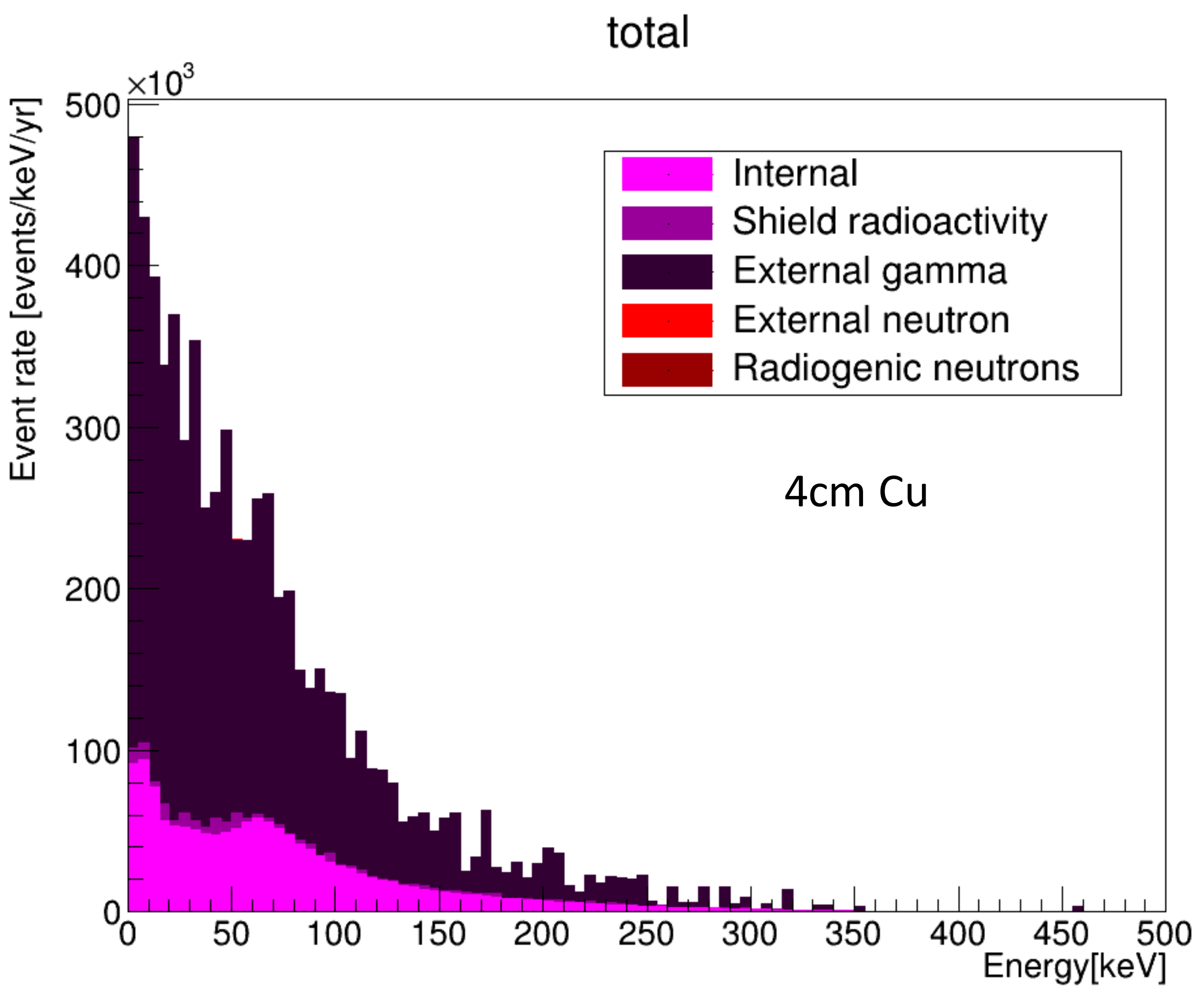
Shield	Isotope	Activity [Bq/kg]	ER [counts/yr]
5 cm Cu + 5 cm Pb	^{210}Bi	58	$(7.6 \pm 0.2) \times 10^4$
4 cm Cu (inner)	^{210}Bi	7	$(5.1 \pm 0.3) \times 10^5$
	^{207}Bi	0.61×10^{-3}	$(2.22 \pm 0.01) \times 10^4$
	^{108m}Ag	0.25×10^{-3}	64 ± 3
6 cm Cu (outer)	^{210}Bi	7	$(4 \pm 4) \times 10^3$
	^{207}Bi	0.61×10^{-3}	$(3.11 \pm 0.05) \times 10^3$
	^{108m}Ag	0.25×10^{-3}	0

4 cm of Cu	Gammas	Neutrons	
Energy range [keV]	ER [10^6 counts/yr]	ER+NR [counts/yr]	NR [counts/yr]
0-1 keV	0.38 ± 0.08	2180 ± 20	167 ± 6
1-20 keV	6.2 ± 0.3	1310 ± 20	409 ± 9
20-50 keV	7.5 ± 0.3	1350 ± 20	173 ± 6
50-3000 keV	12.9 ± 0.4	3330 ± 30	285 ± 8
10 cm of Cu	Gammas	Neutrons	
Energy range [keV]	ER [10^6 counts/yr]	ER+NR [counts/yr]	NR [counts/yr]
0-1 keV	0.025 ± 0.005	1970 ± 40	210 ± 10
1-20 keV	0.47 ± 0.02	1360 ± 30	550 ± 20
20-50 keV	0.5 ± 0.02	1270 ± 30	200 ± 10
50-3000 keV	0.99 ± 0.03	2930 ± 50	180 ± 10

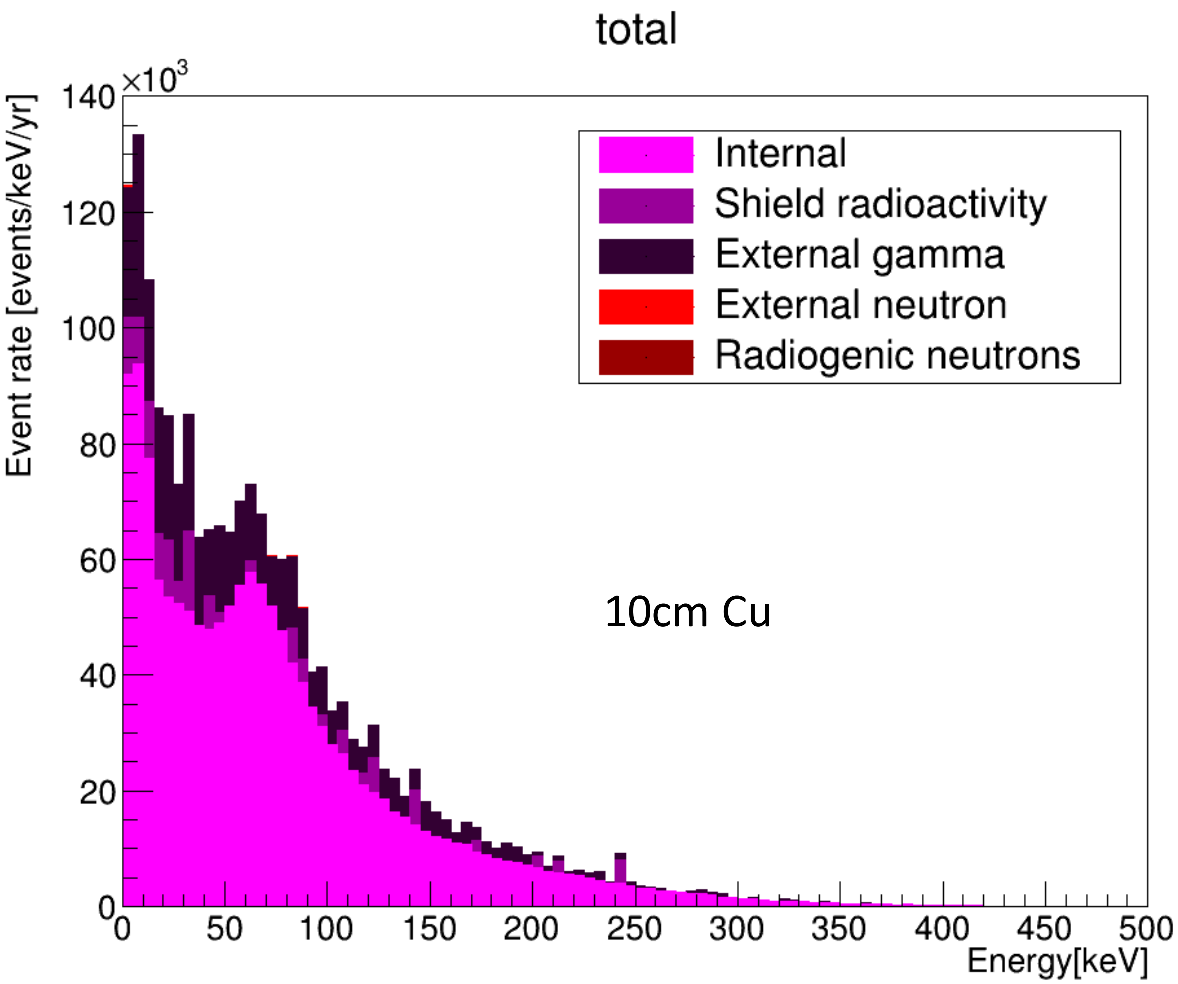
10 cm Cu + 40 cm H_2O	Gammas	Neutrons	
Energy range [keV]	ER [10^6 counts/yr]	ER+NR [counts/yr]	NR [counts/yr]
0-1 keV	0.004 ± 0.002	1.5 ± 0.2	0.35 ± 0.08
1-20 keV	0.11 ± 0.01	5.1 ± 0.4	1.0 ± 0.1
20-50 keV	0.13 ± 0.01	4.5 ± 0.4	0.39 ± 0.08
50-3000 keV	0.27 ± 0.2	11.6 ± 0.7	0.6 ± 0.1

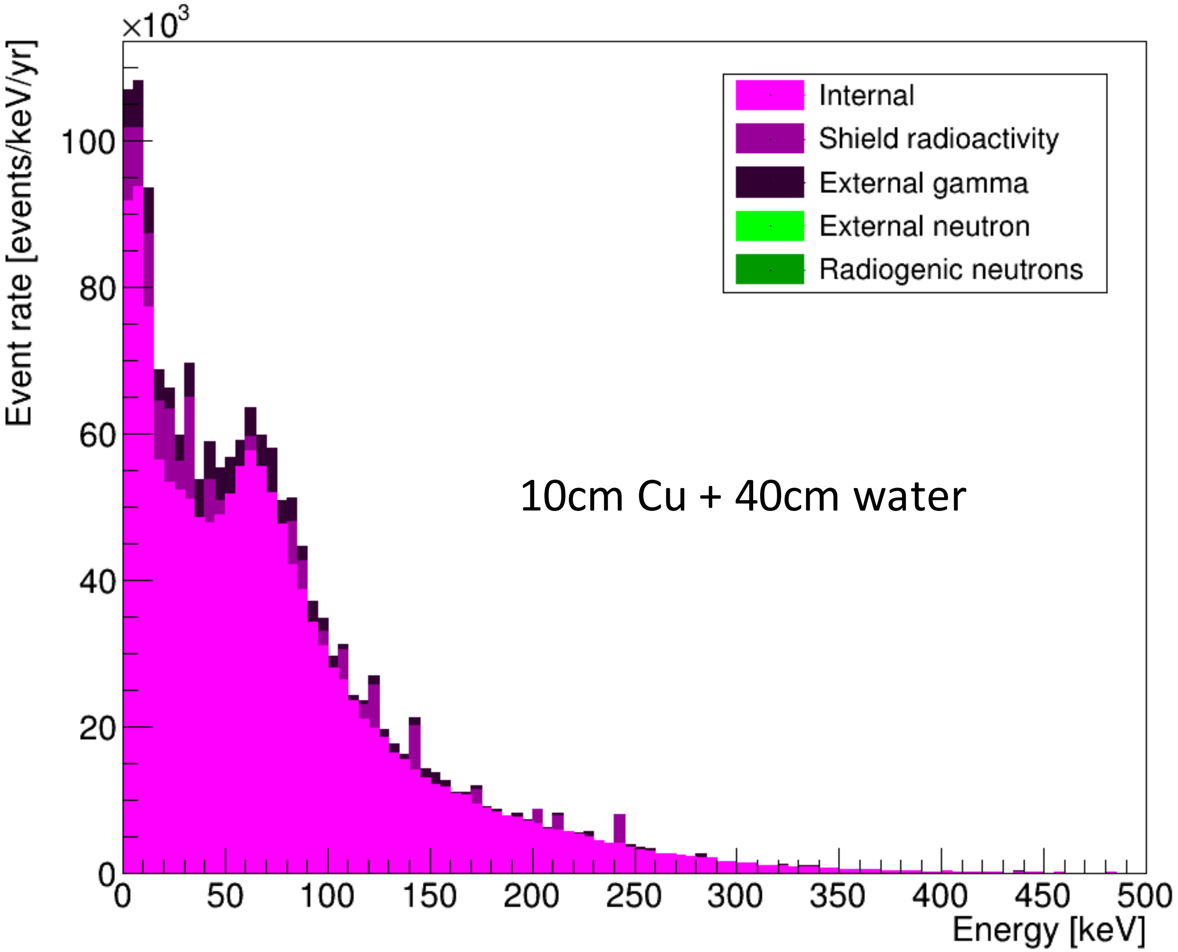
GEANT4 simulation: total background





GEANT4 simulation: total background





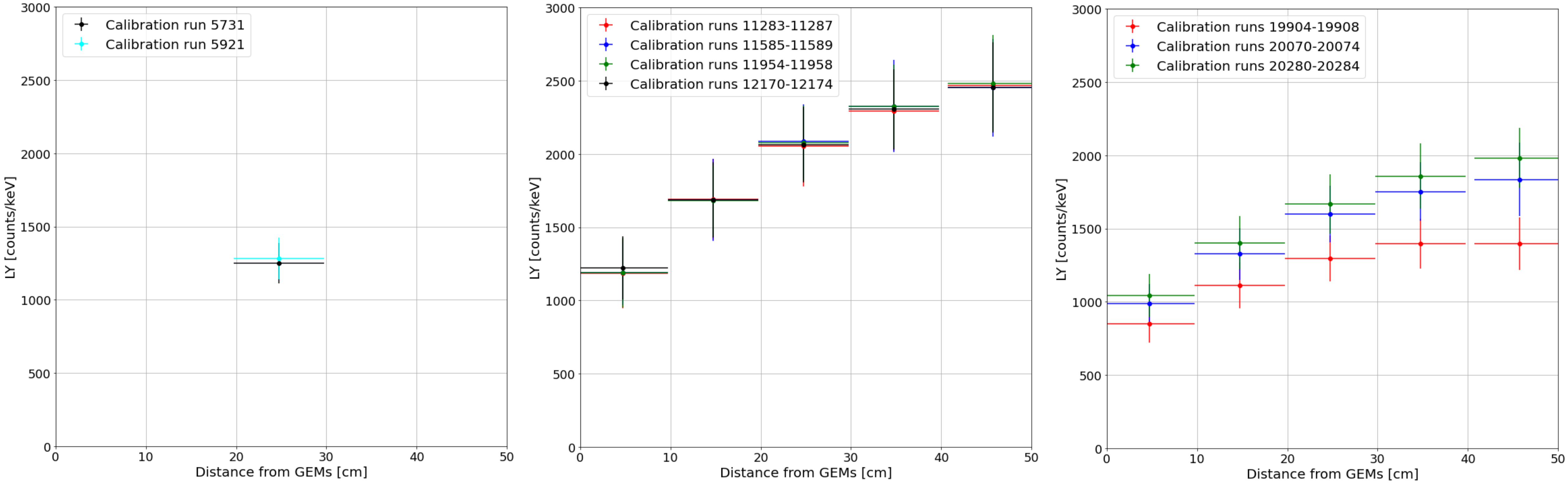
Datasets

- **Data**:
  - Run 1: 5922-6744 (285665 images, 49 hours) - 420 Vgem, 10 L/h
    - 2 calibration runs (no scan in z)
  - Run 2: 11288-12191 (297992 images, 53 hours) - 440 Vgem, 20 L/h
    - 4 calibration sets (daily calibrations)
  - Run 3: 19908-20415 (171579 images, 53 hours) - 440 Vgem, 20 L/h
    - 3 calibration sets (daily calibrations)

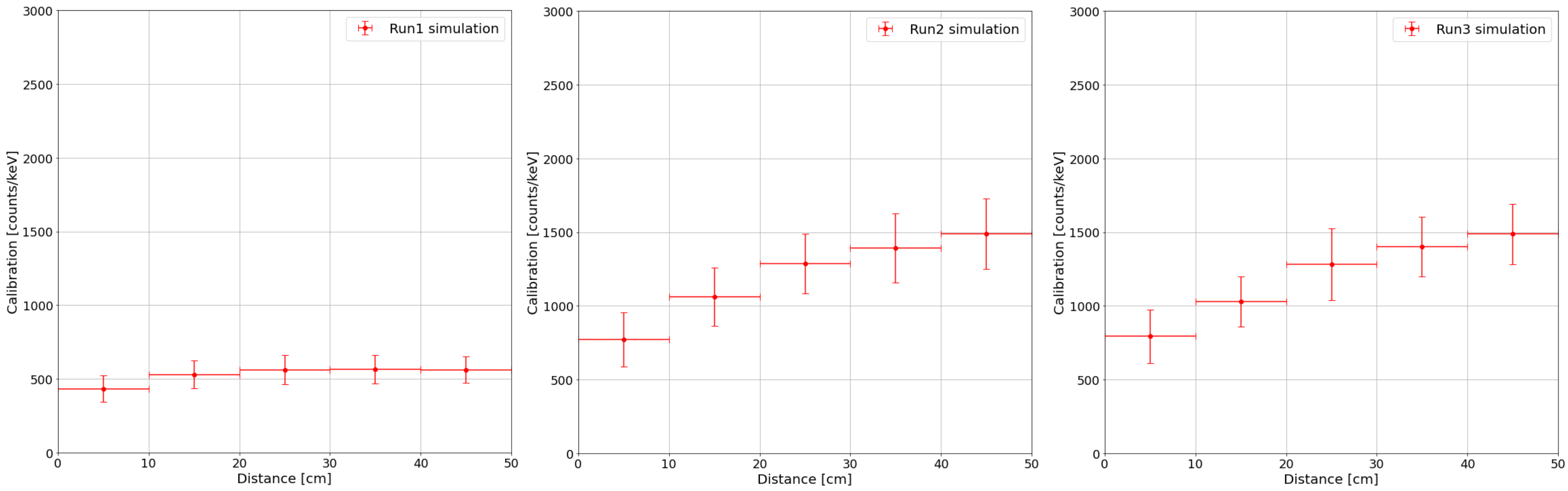
- **MC simulation**:
  - Internal radioactivity: 120 hours equivalent time
  - External gammas:
    - Run 1: 1 hour equivalent time
    - Run 2: 16 hours equivalent time
    - Run 3: 48 hours equivalent time

  - Only digitized energy deposits above 800 keV
  - Set of pedestals from the corresponding runs randomly extracted and added as noise
  - Exposure time of the camera included

Light yield (calibration) - data



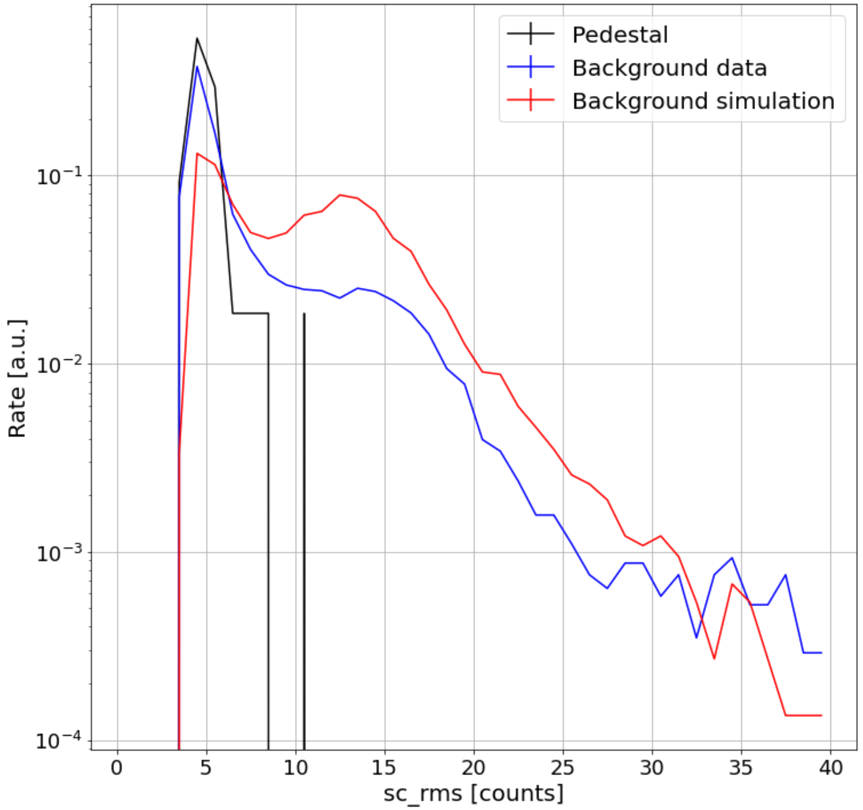
Light yield (calibration) - MC

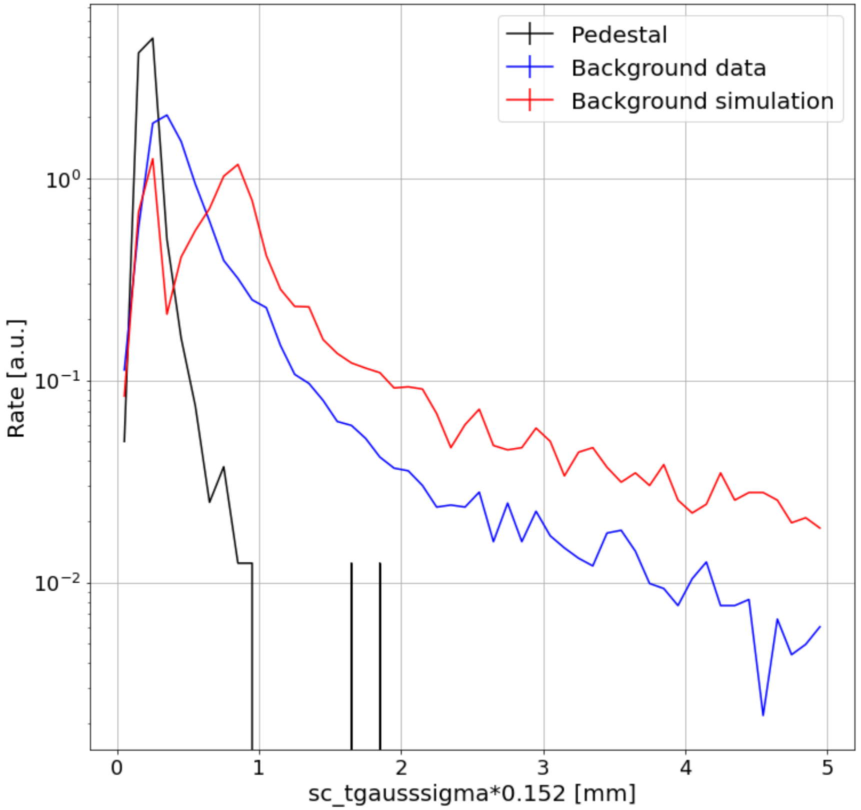


MC events between 2 and 10 keV (around iron energy), divided in 5 bins along distance z from the GEMs
Gaussian fit of sc_integral/MC_energy (MC_energy=true deposited energy, after cut of camera exposure)

Selection cuts

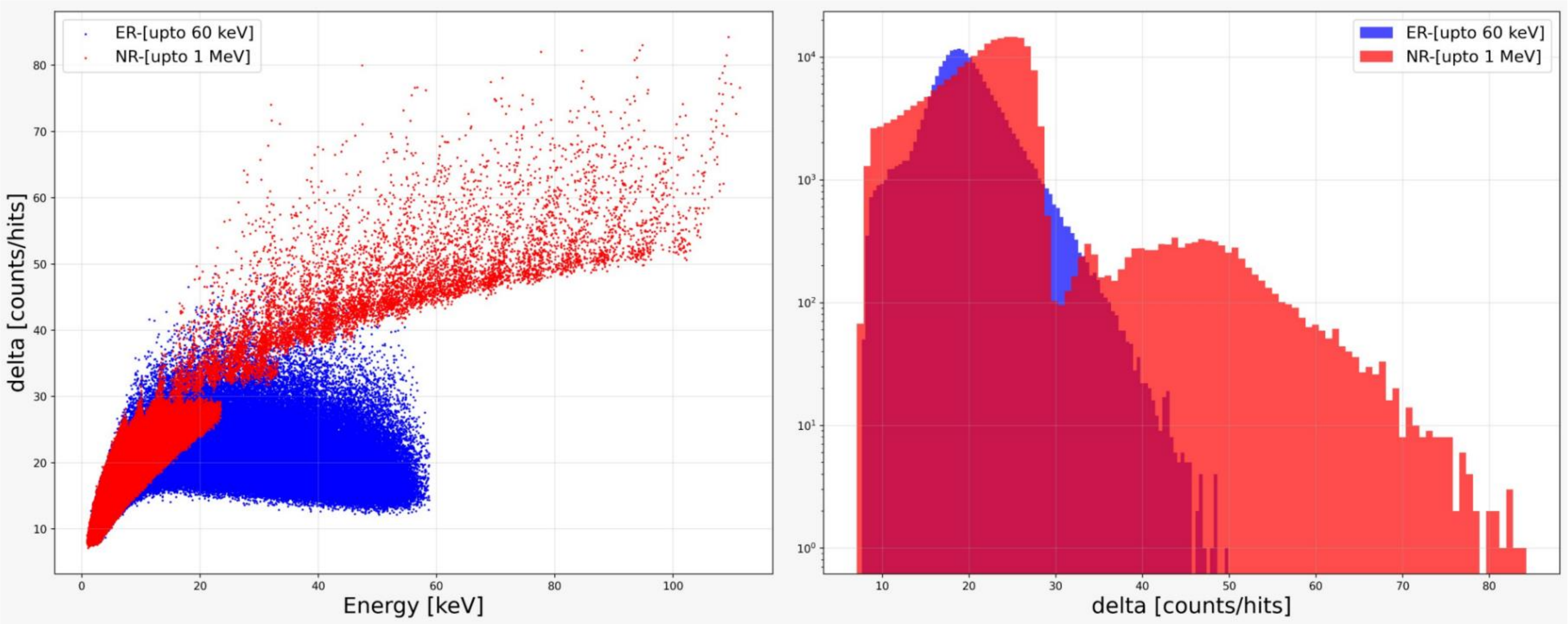
Fiducial cut: sc_xmin>400 && sc_ymin>400 && sc_ymax<1900 && sc_xmax<1900 (selects a centered square)
Fake cut: sc_rms>6 && sc_tgausssigma*0.152>0.5 mm





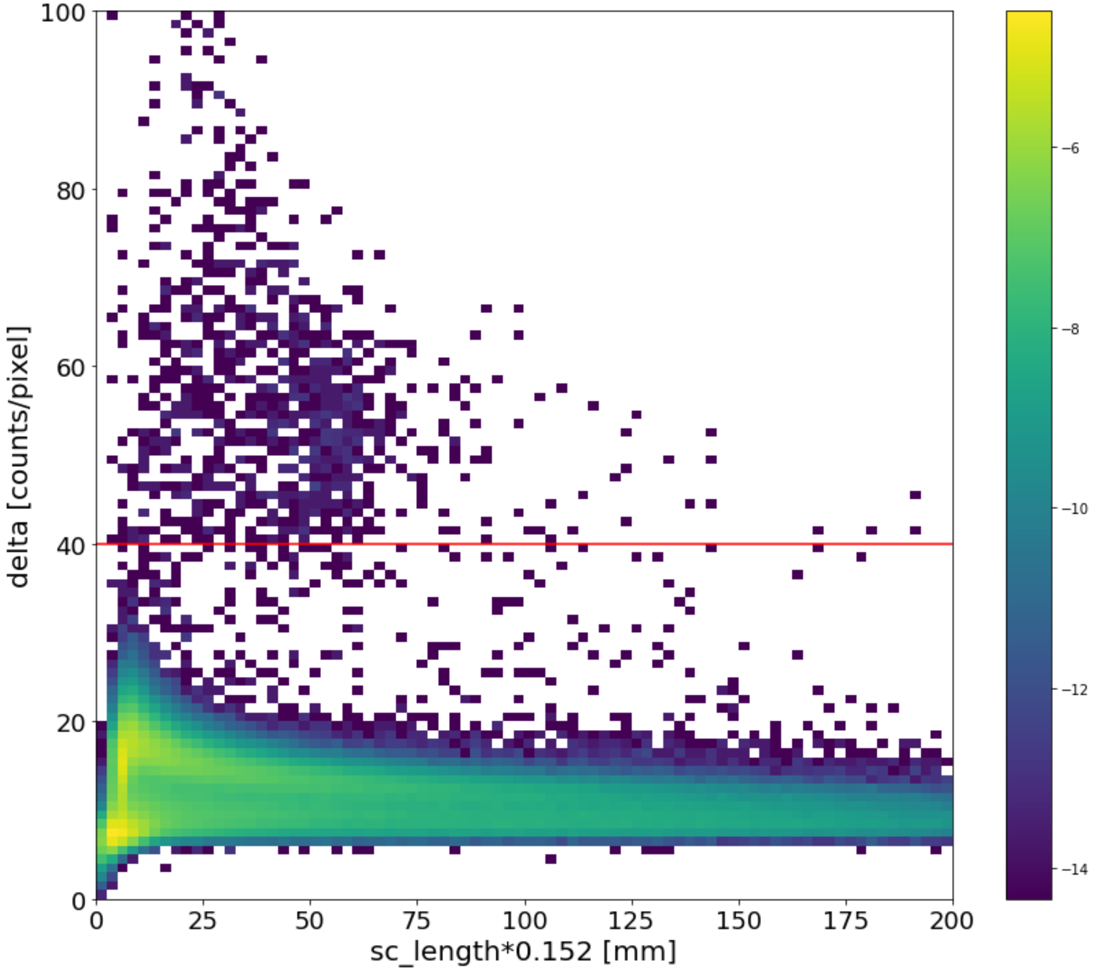
- Excludes 98.7% of pedestal tracks
- Selects 18.9% of data, 71.9% of MC events
- There is a difference in data/MC changing these shape variables
- No tracks above 800 keV are included in MC

Selection cuts - alphas

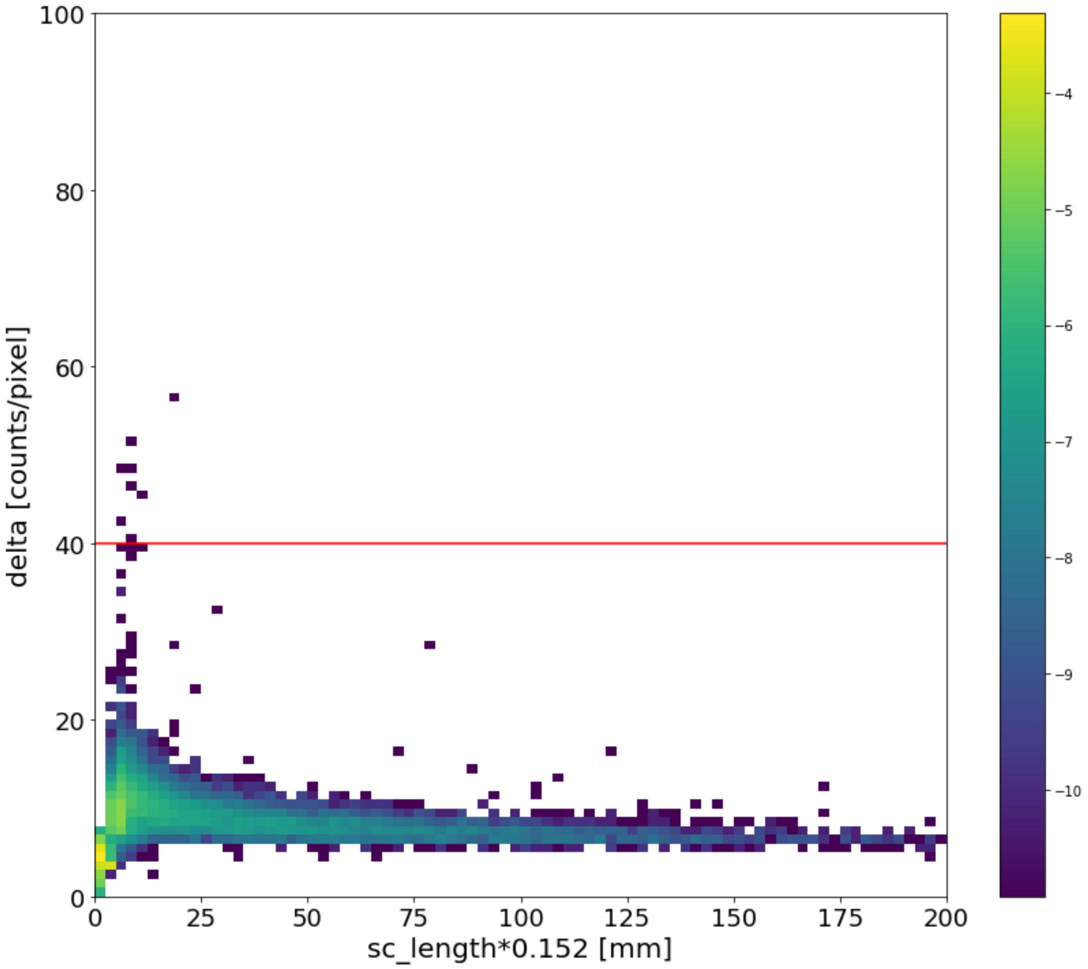


Plot by Atul Prajapati

Selection cuts - alphas (Run 1)

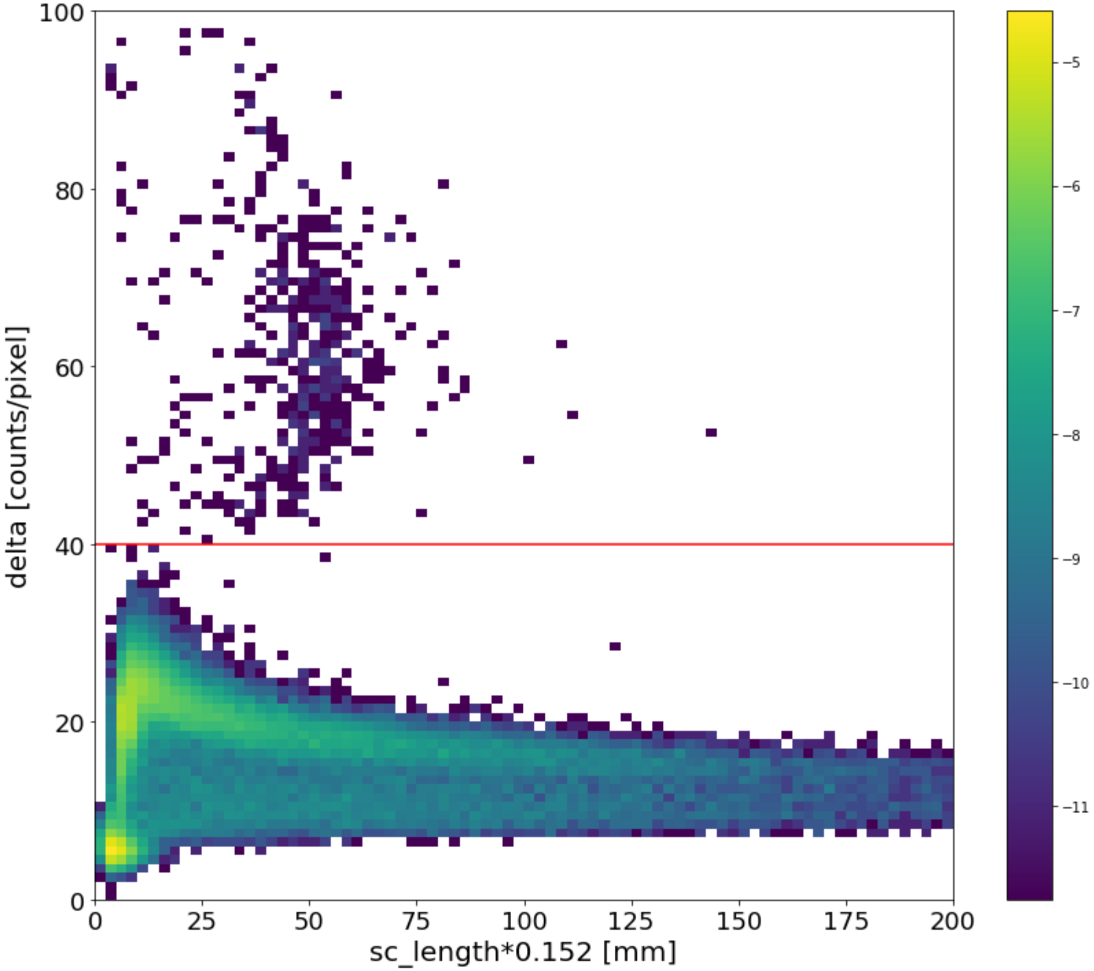


data

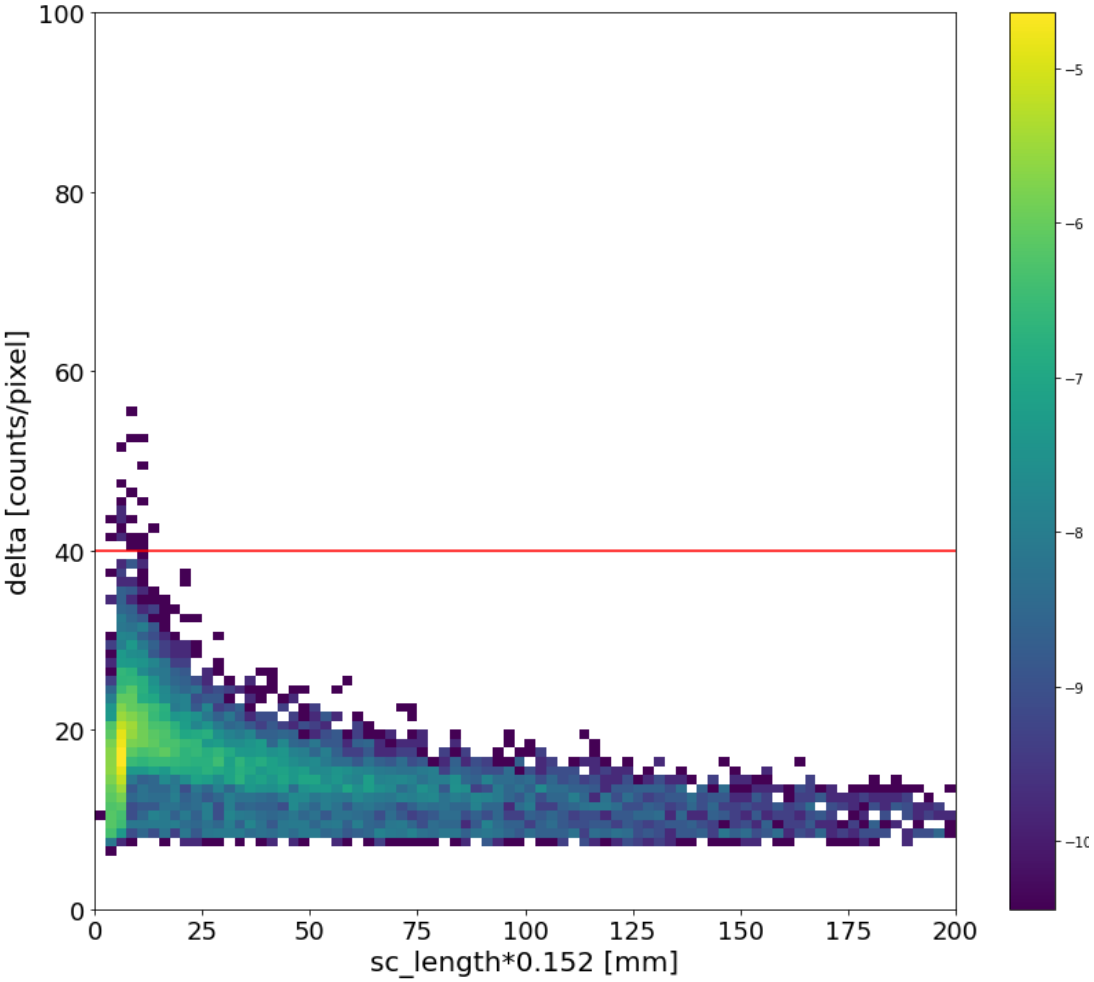


MC

Selection cuts - alphas (Run 2)

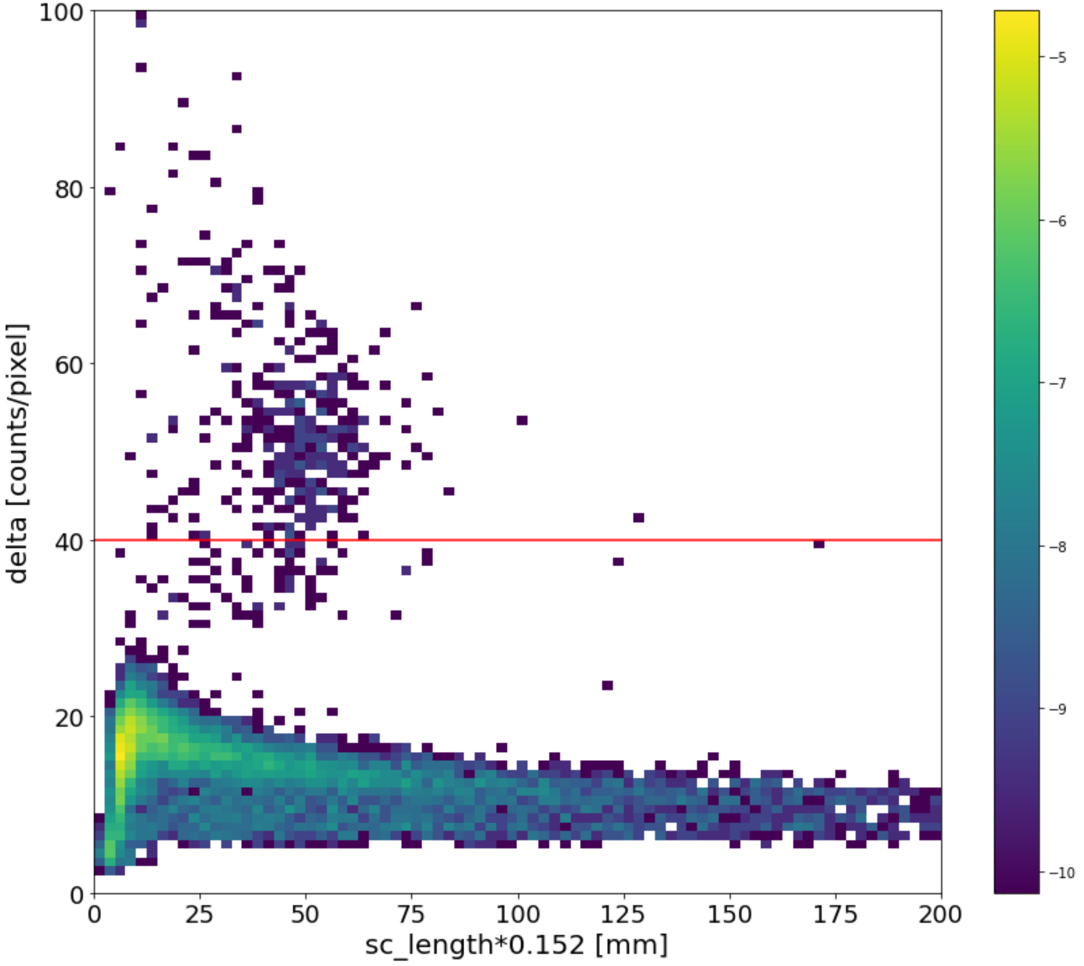


data

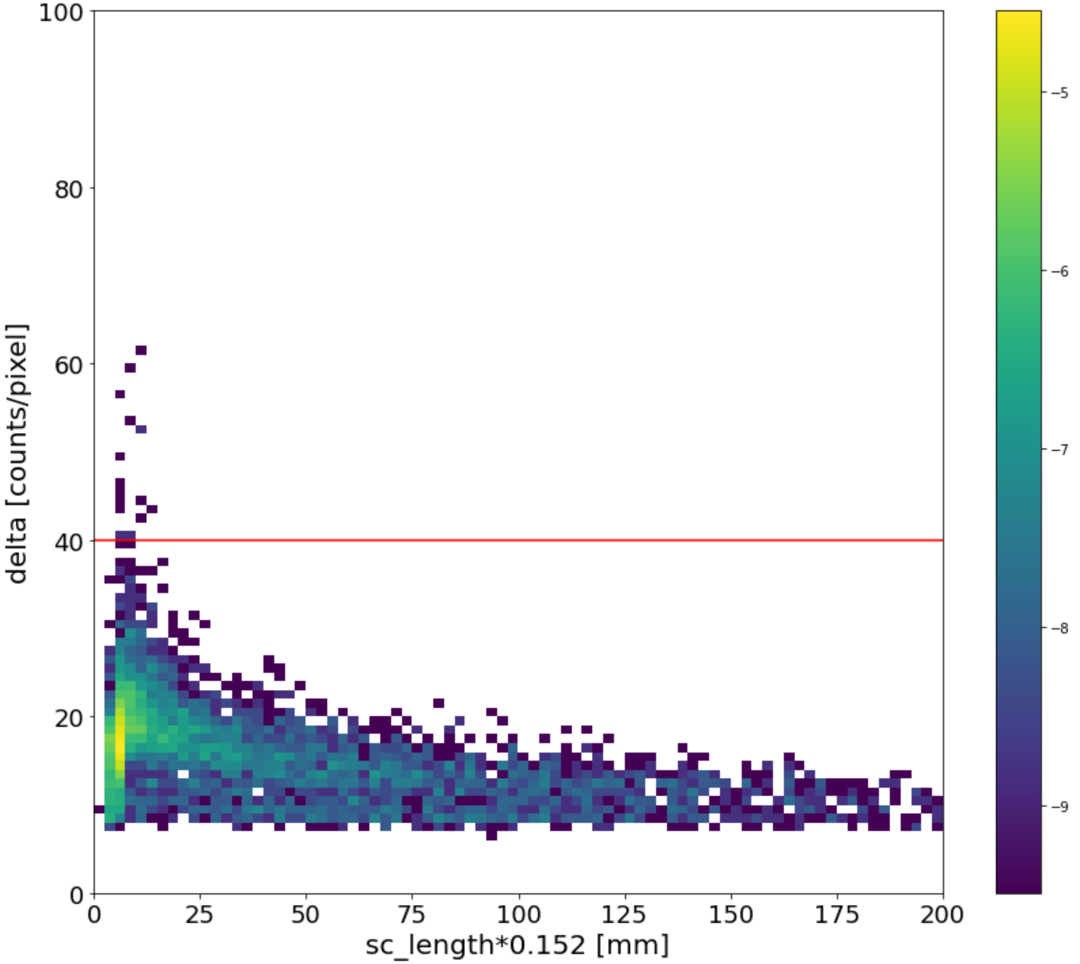


MC

Selection cuts - alphas (Run 3)

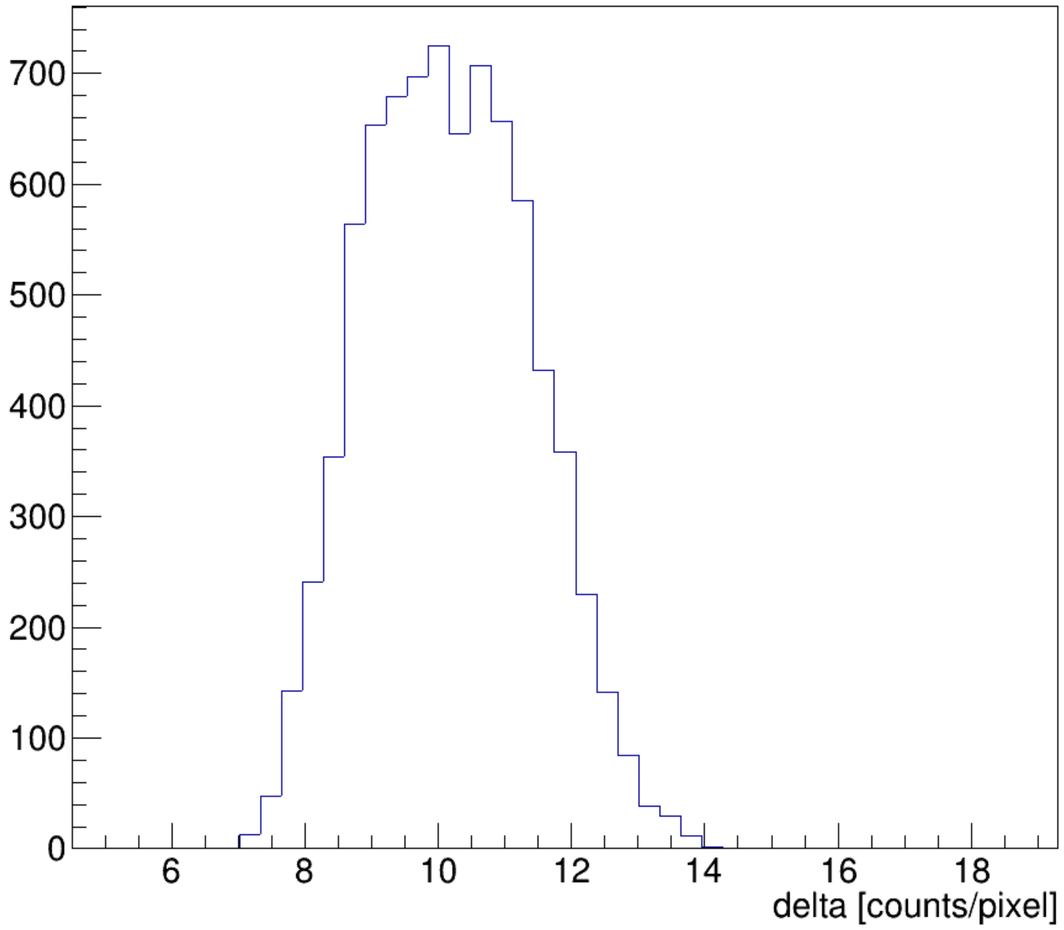


data



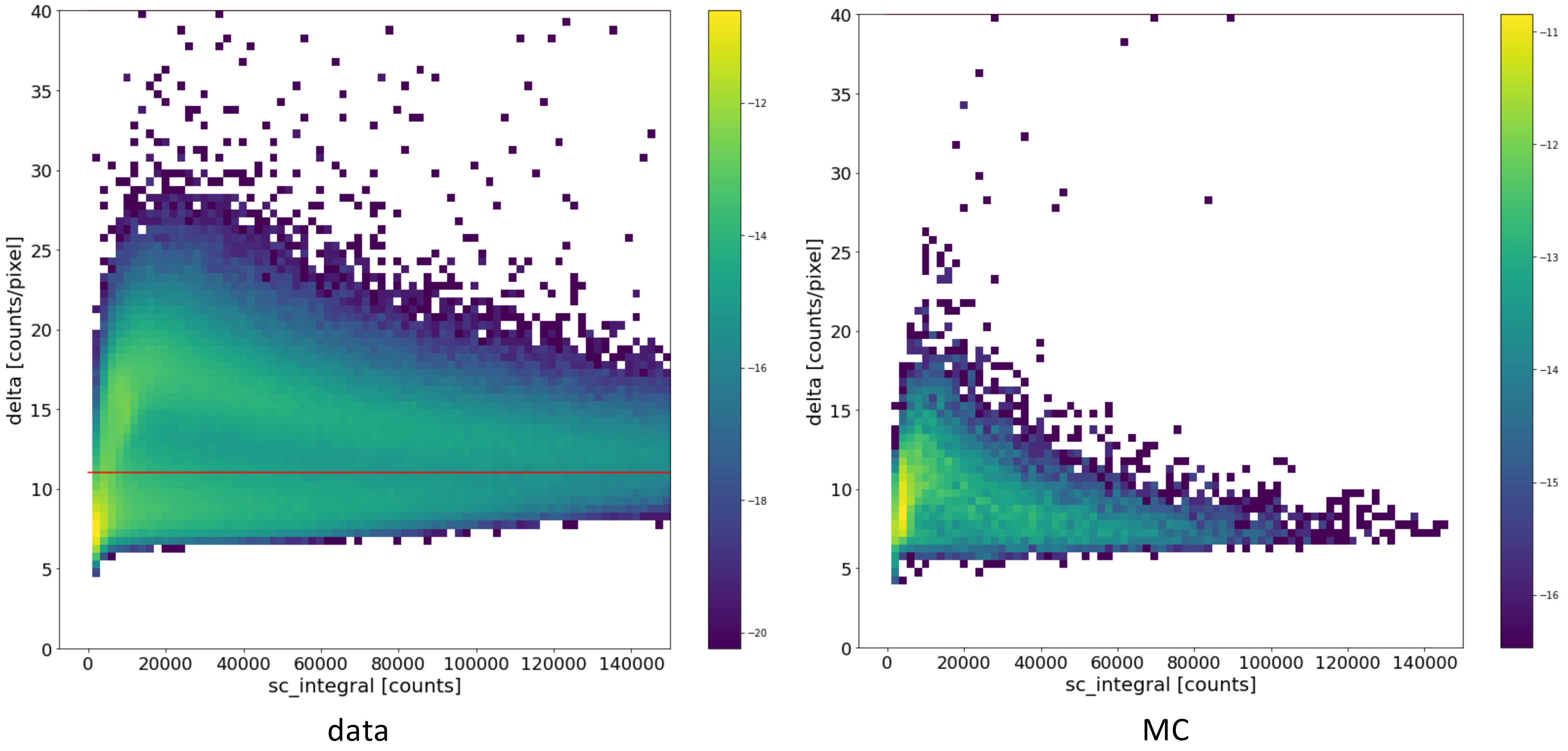
MC

Selection cuts - high energy electrons

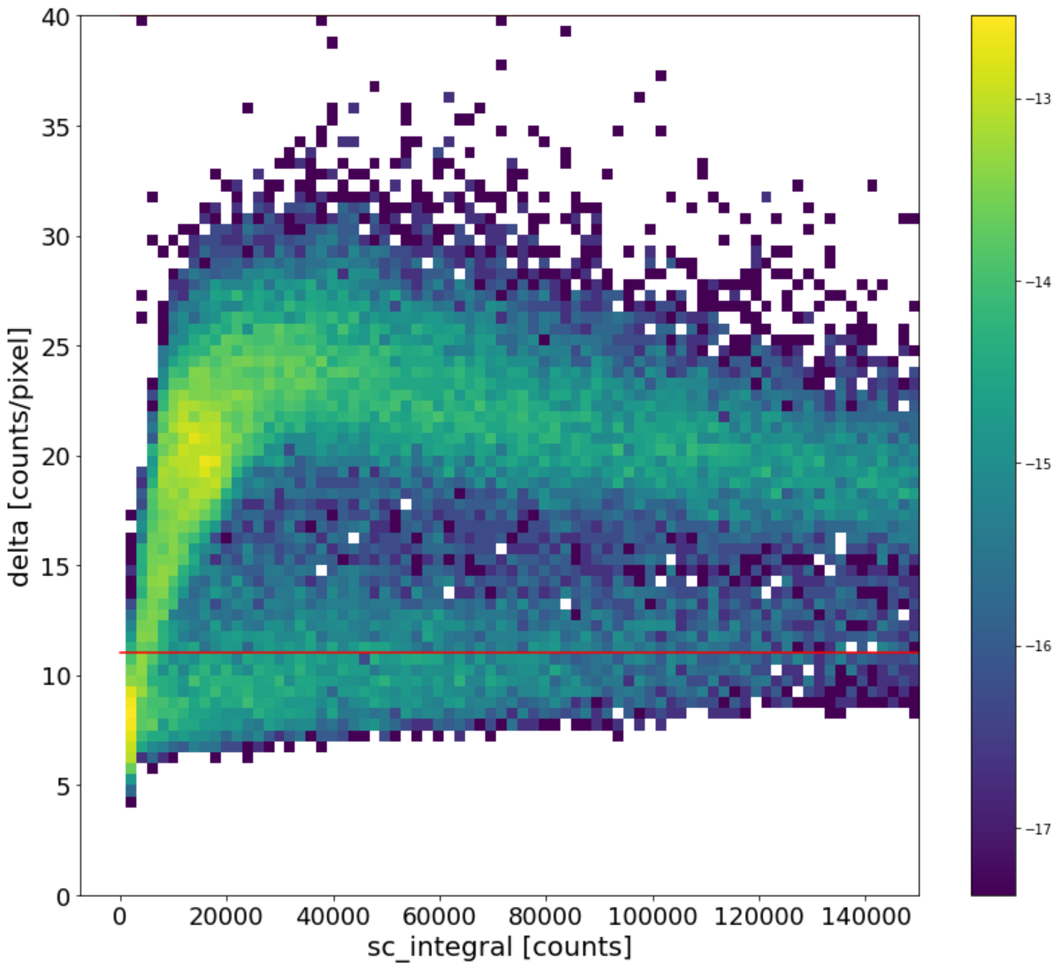


- High energy electrons have low stopping power, hence very low density (delta=sc_integral/sc_nhits)
- Eu152 data, with selection sc_length>1900 and barycenter in the center of the image (high energy tracks passing the whole volume from top to bottom), show a delta around 10
- This corresponds to tracks with E>120 keV
- High energy ERs have a low delta, while low energy (below 60 keV) are above delta=12
- Notice that energy deposits below 800 keV by high energy electrons (also with E>800 keV) are expected both in data and MC
- The reconstruction of these faint tracks strongly depend on the LY

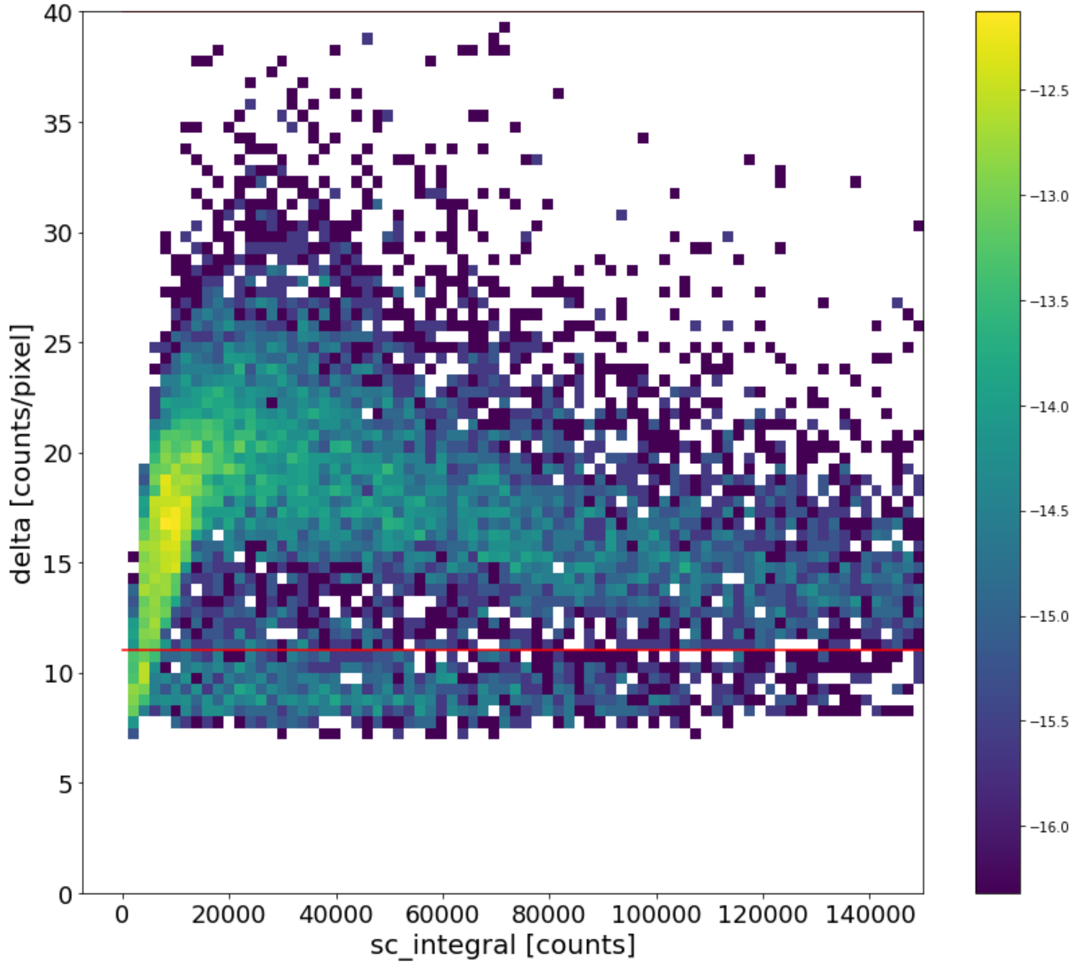
Selection cuts – high energy electrons (Run 1)



Selection cuts – high energy electrons (Run 2)

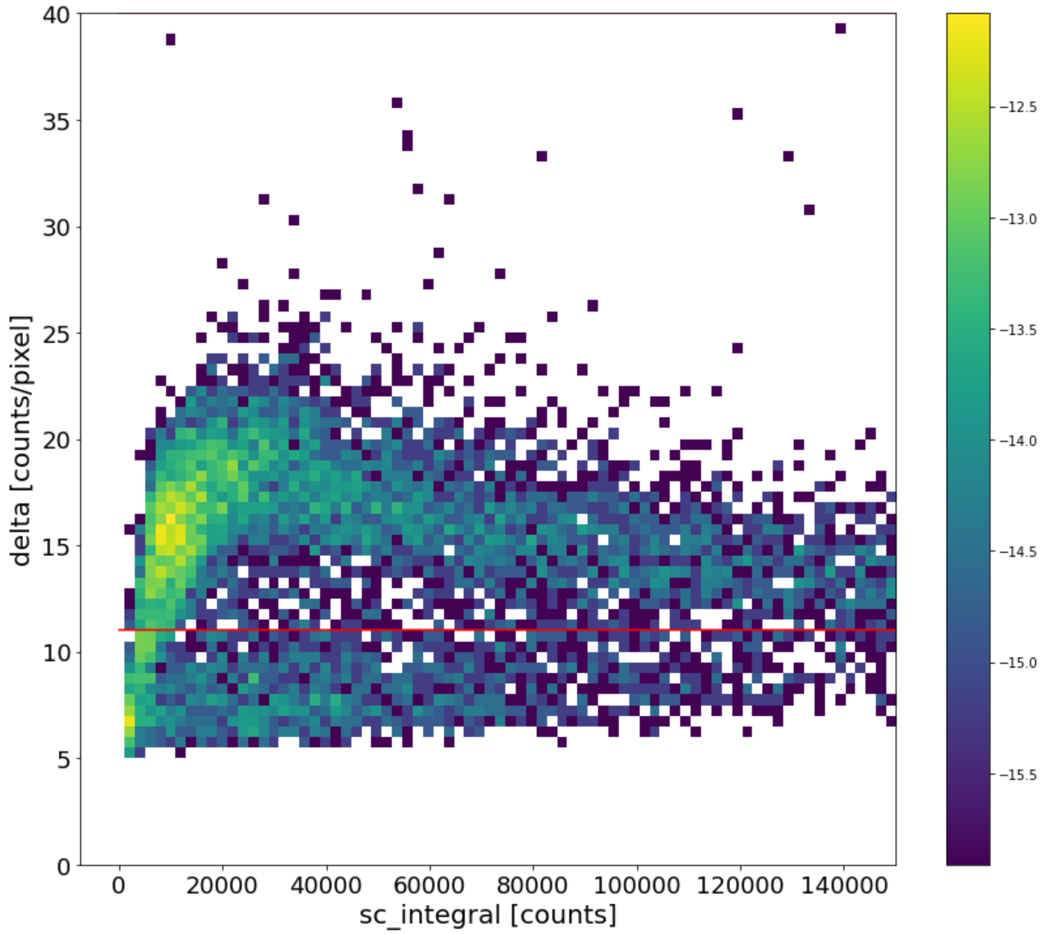


data

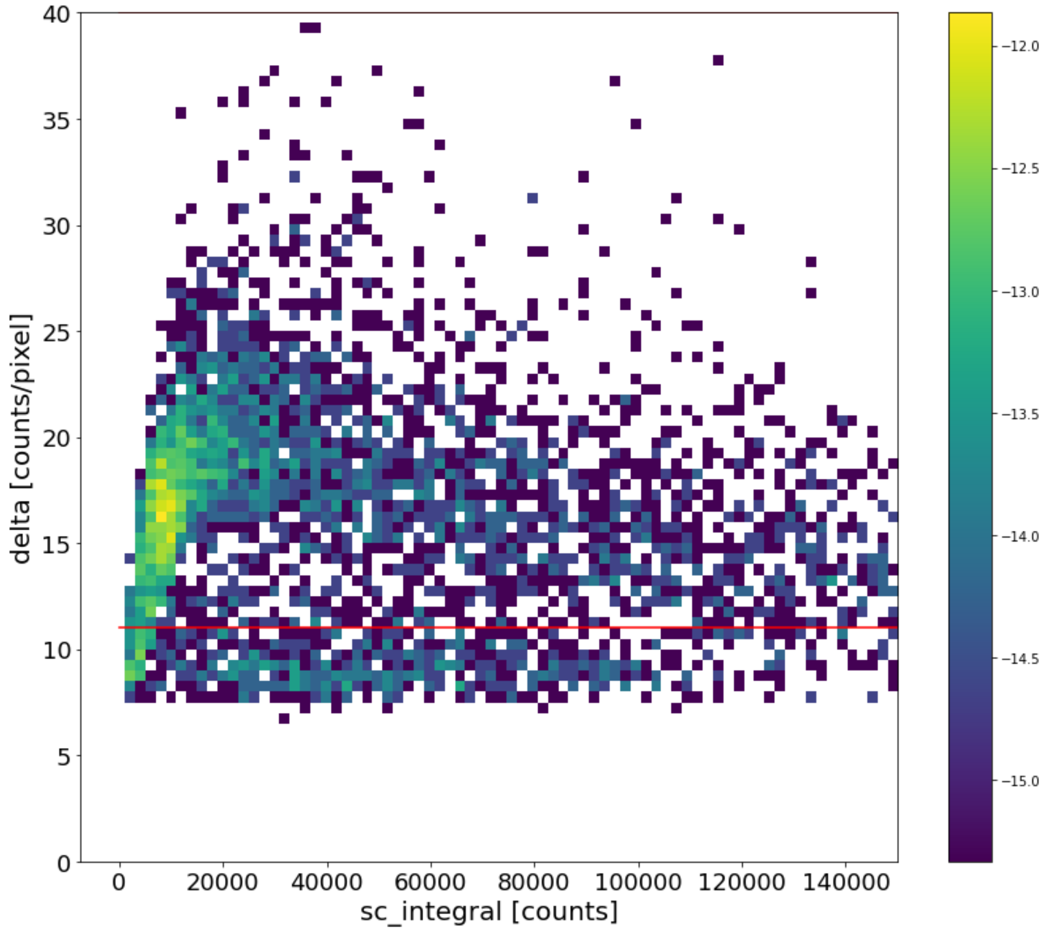


MC

Selection cuts – high energy electrons (Run 3)

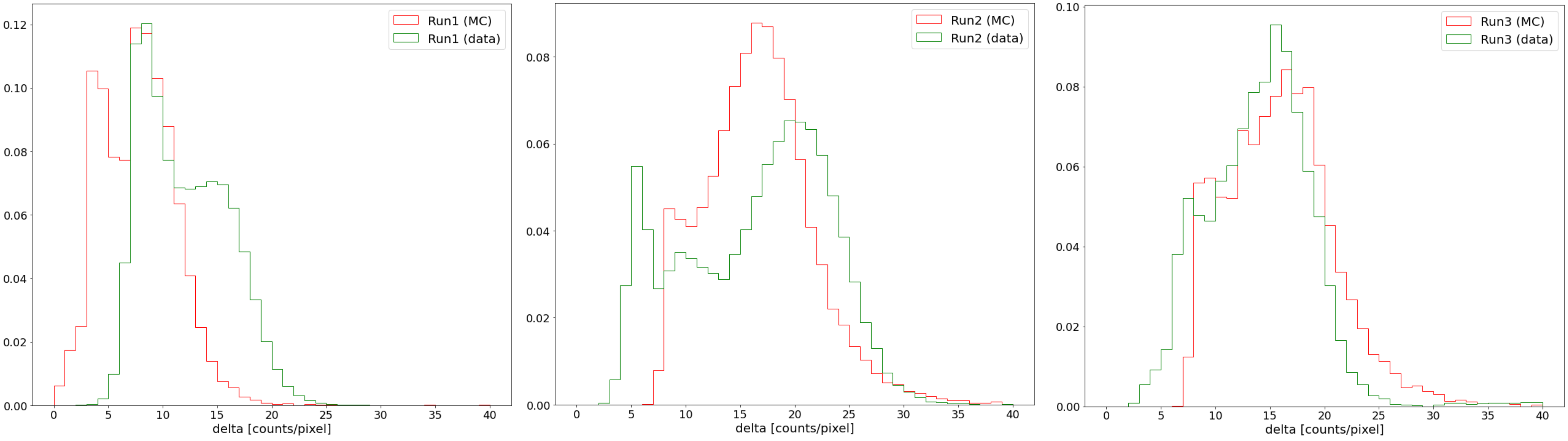


data



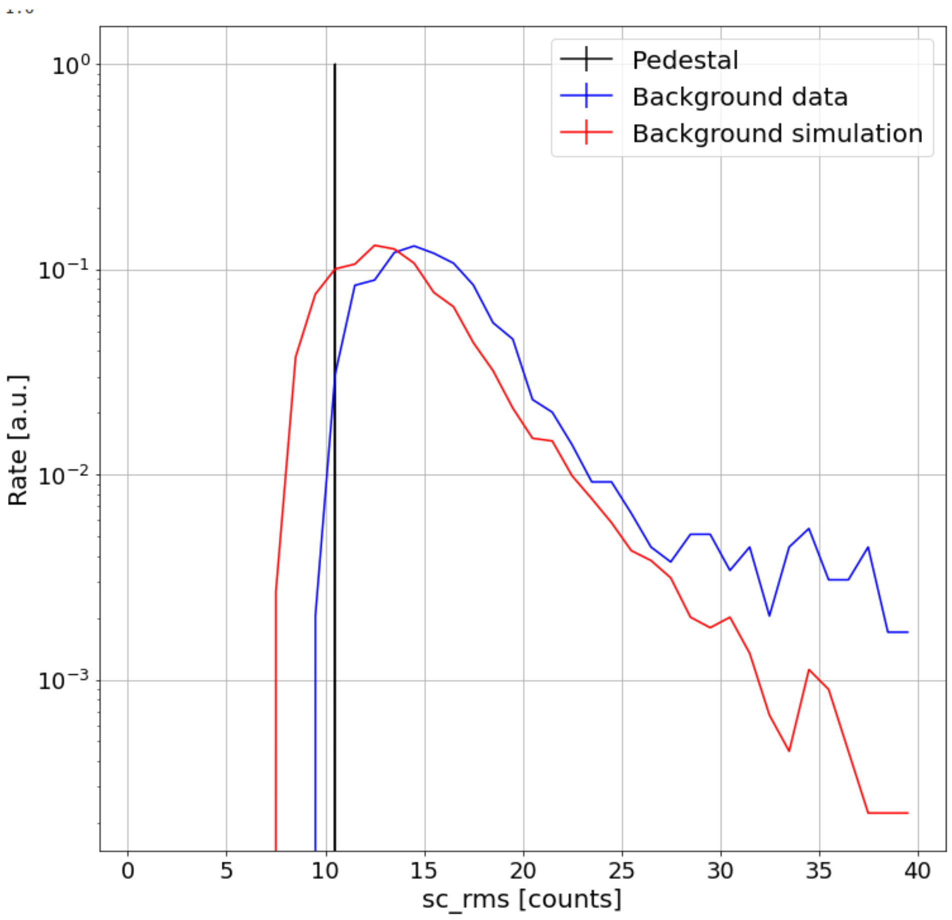
MC

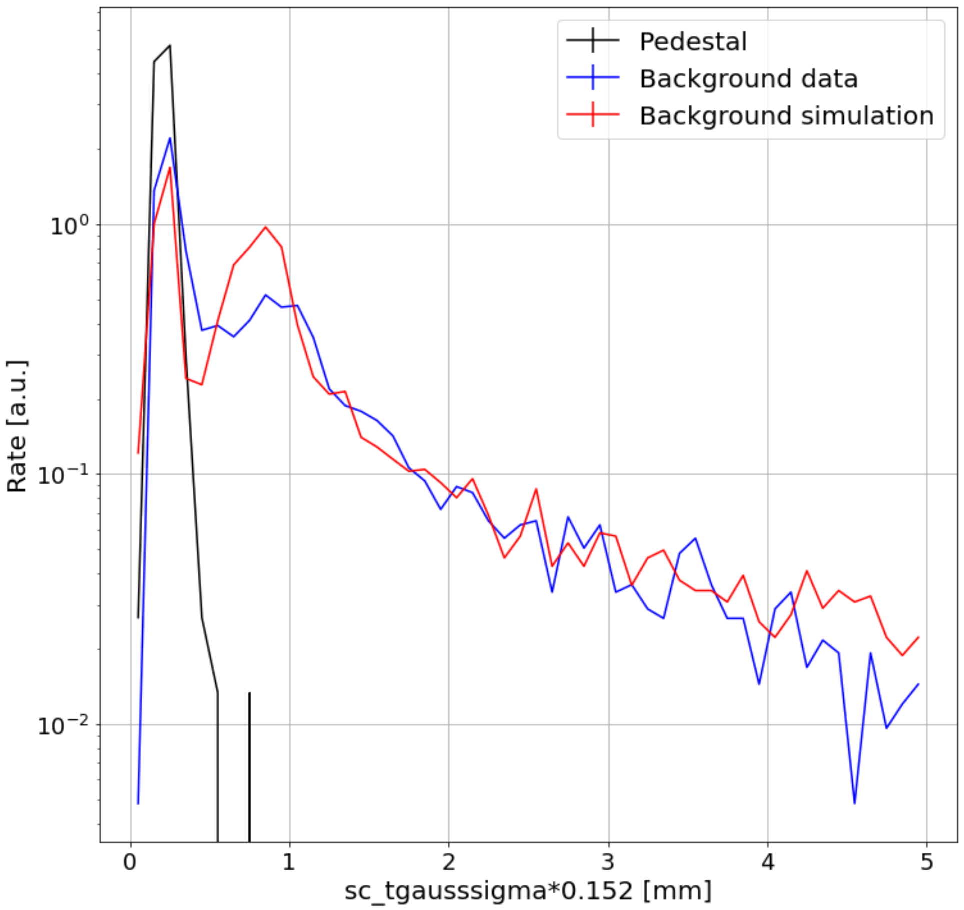
Selection cuts – high energy electrons



Tracks are then also selected with delta>11 and delta<40

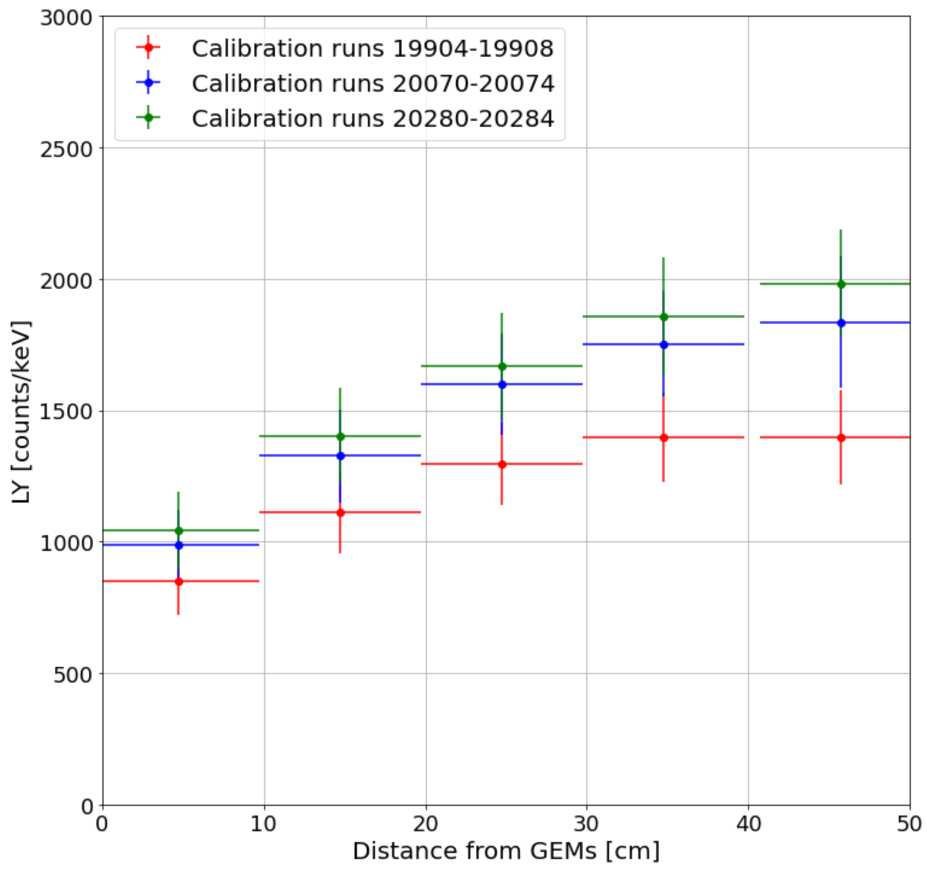
Fake selection after delta cut





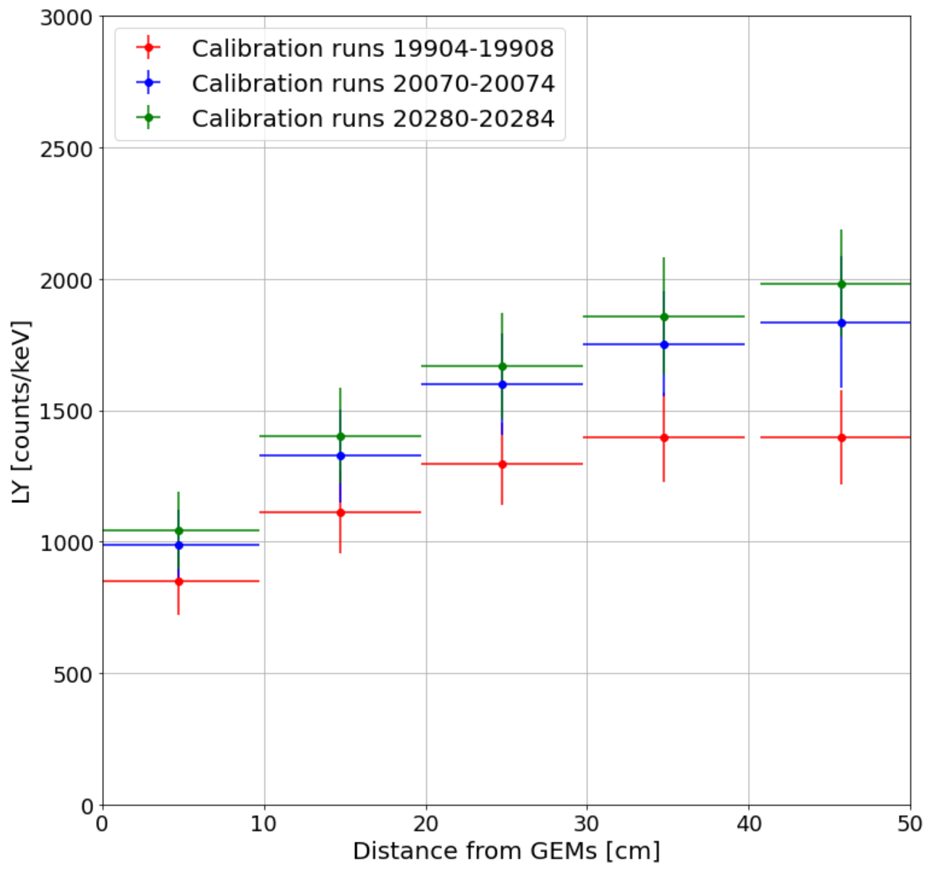
- Excludes 99.7% of pedestal events
- Selects 52.7% of data, and 67.3% of MC events

Energy calibration (data)



- LY depends on z position and on time period (it's highly variable)
- Z position of each event is unknown, so this variability must be included, enlarging the systematic uncertainty
- For **each track** in a given dataset (Run 1, Run 2, Run 3)
  - Select the iron-55 calibration dataset closest in time
    - (A calibration set corresponds to one of the colored *set of points*)
  - Randomly extract position along z, and therefore choose the corresponding point (with a mean LY and std dev fitted with a gaussian on iron peak)
  - Randomly extract LY from a gaussian, and use that value to calibrate
  - Store the obtained energy in a histogram

Energy calibration (data)



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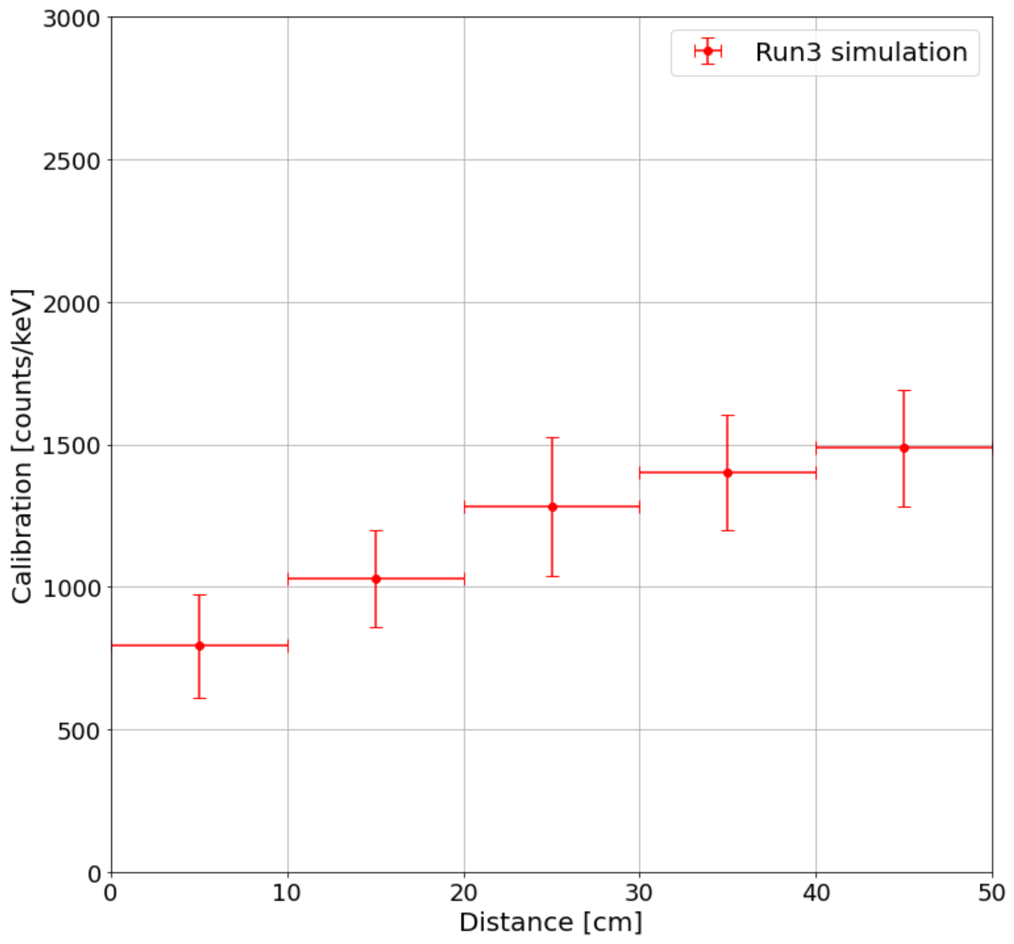
  - Randomly extract position along z, and therefore choose the corresponding point (with a mean LY and std dev fitted with a gaussian on iron peak)
  - Randomly extract LY from a gaussian, and use that value to calibrate
  - Store the obtained energy in a histogram

This is repeated N=1000 times (for each dataset, N histograms)

The mean (over the N histograms) of the content of each bin is set as the mean of each bin of the final spectrum
The standard deviation (over the N histograms) is set as an uncertainty of each bin of the final spectrum (+ other errors)

Energy calibration (MC)



- From the MC, select all the tracks between 2 keV and 10 keV (close to iron energy)
- The z position is divided in 5 bins
- The LY is computed as the ratio between the sc_integral and the real energy deposition (known from GEANT4)
- Same procedure is applied (but only one set of LY for each dataset, NO TIME dependence is simulated)

Time normalization (dead time)

- MC spectra are normalized from the equivalent time of the corresponding GEANT4 simulation
- Data are normalized from the total live time of each run (difference in the timestamp of start and end of run)
- Dead time correction is applied to data (DAQ is not in the MC)
- First estimate of the dead time done by Stefano Piacentini, assuming it is linear with the number of PMT waveforms

$$\tau = T_{cam} + N_{wf} \cdot t_{wf}$$

$$r_{meas} = \frac{k}{T_{run}} \qquad r_{true} = \frac{k+m}{T_{run}}$$

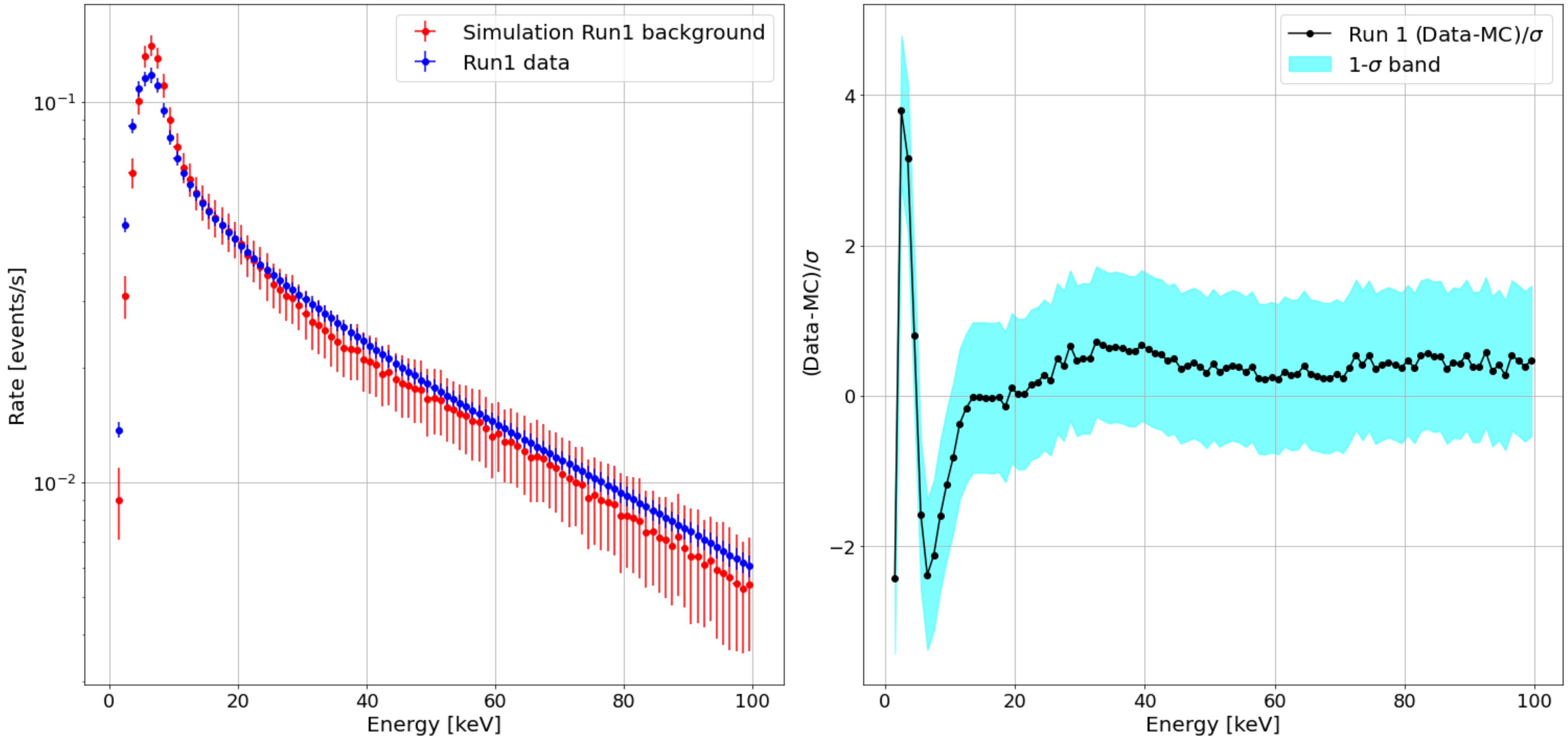
$$r_{true} = \left(1 + \frac{m}{k}\right) r_{meas} = D r_{meas}$$

$$k = R_{true} T_{window} \qquad m = R_{true} \tau$$

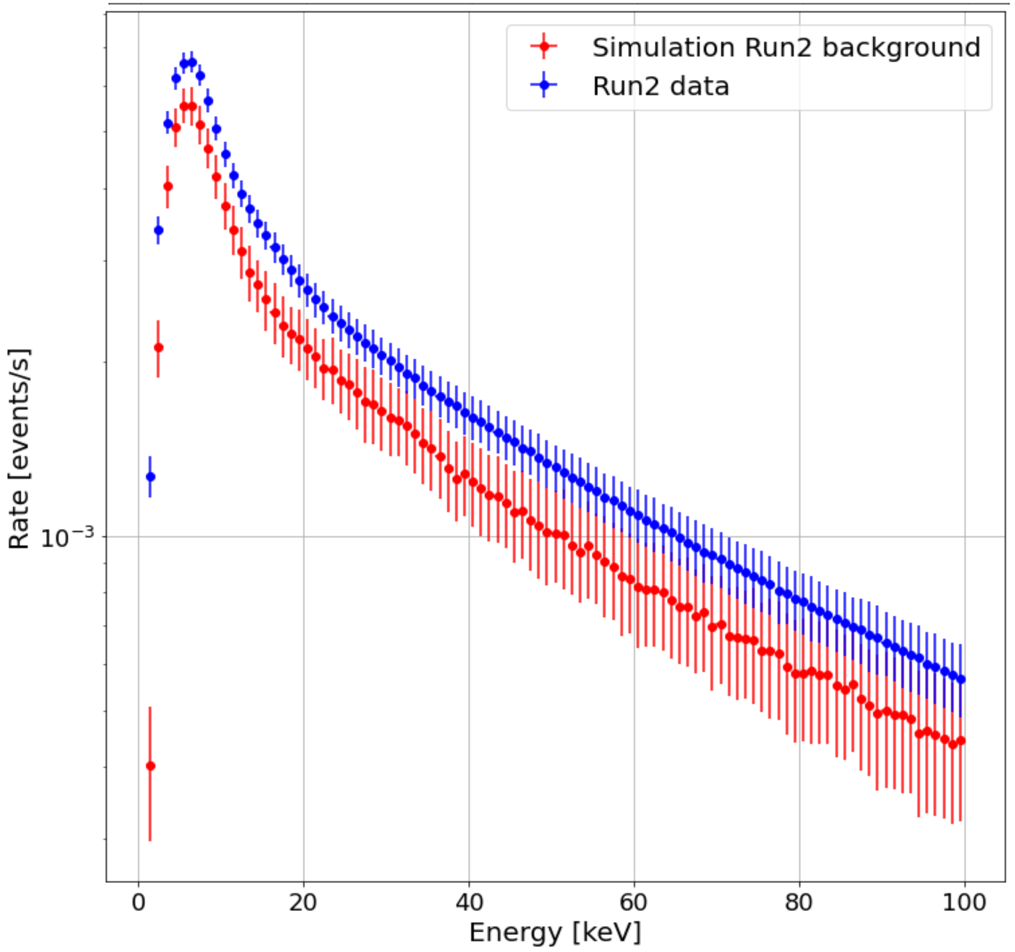
$$D = 1 + \frac{m}{k} = 1 + \frac{T_{cam} + R_{PMT} \cdot T_{window} \cdot t_{wf}}{T_{window}}$$

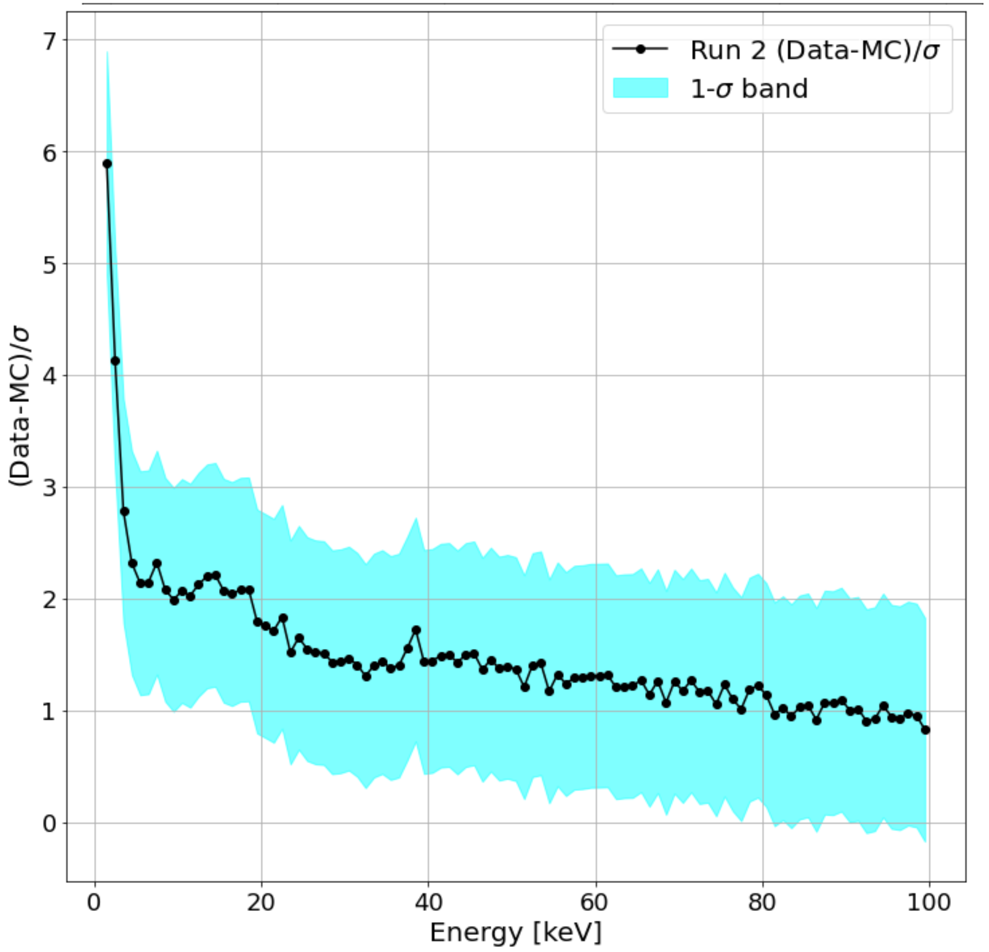
Phase	R_{PMT} [Hz]	D
Run 1	30	1.42 ± 0.06
Run 2	3.5	1.104 ± 0.009
Run 3	1.6	1.081 ± 0.007

Energy spectra data/MC (Run 1)

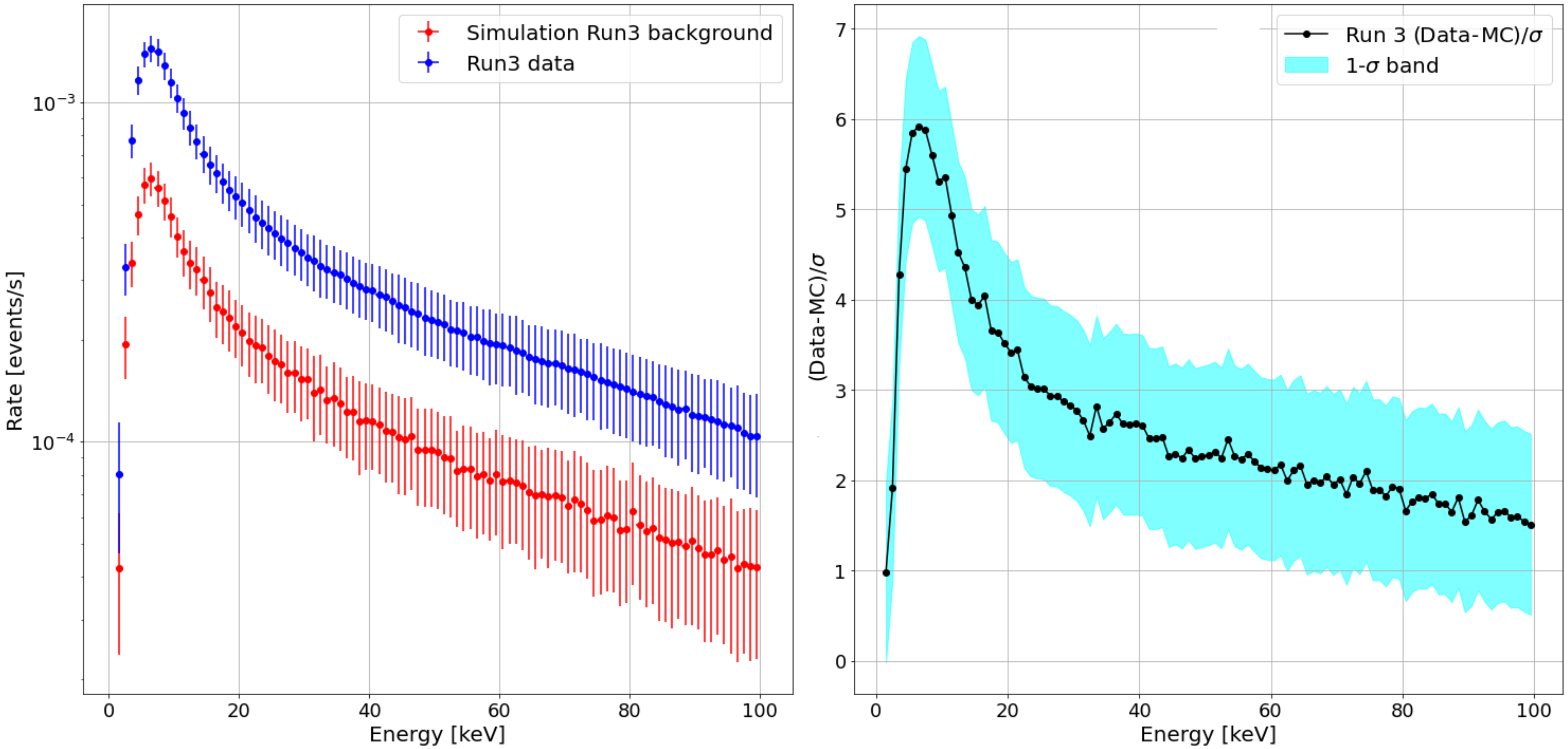


Energy spectra data/MC (Run 2)

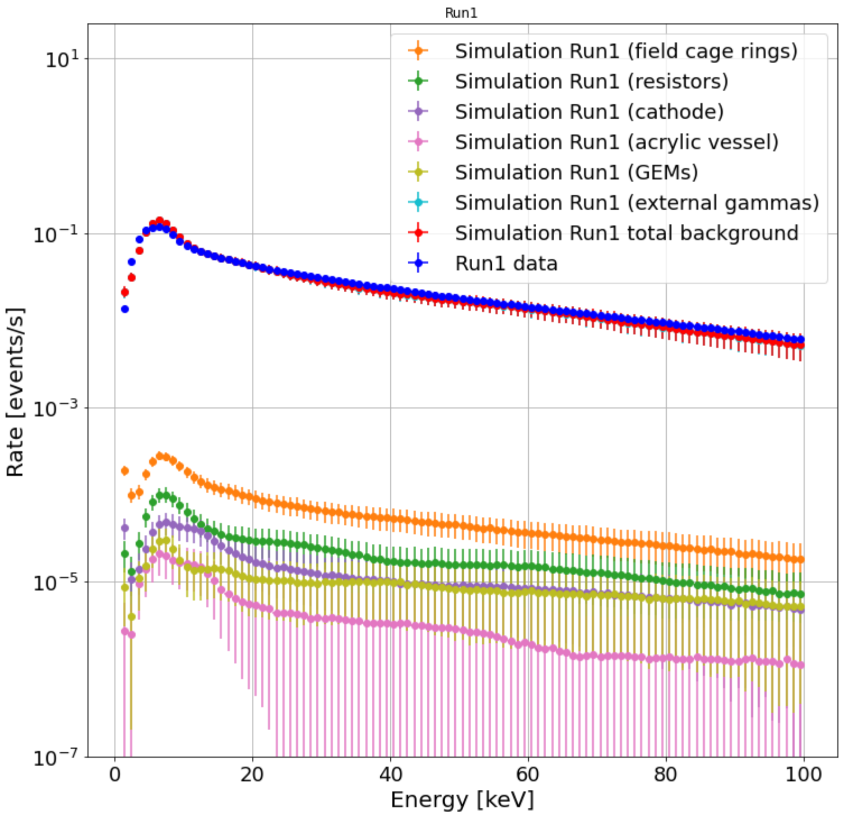


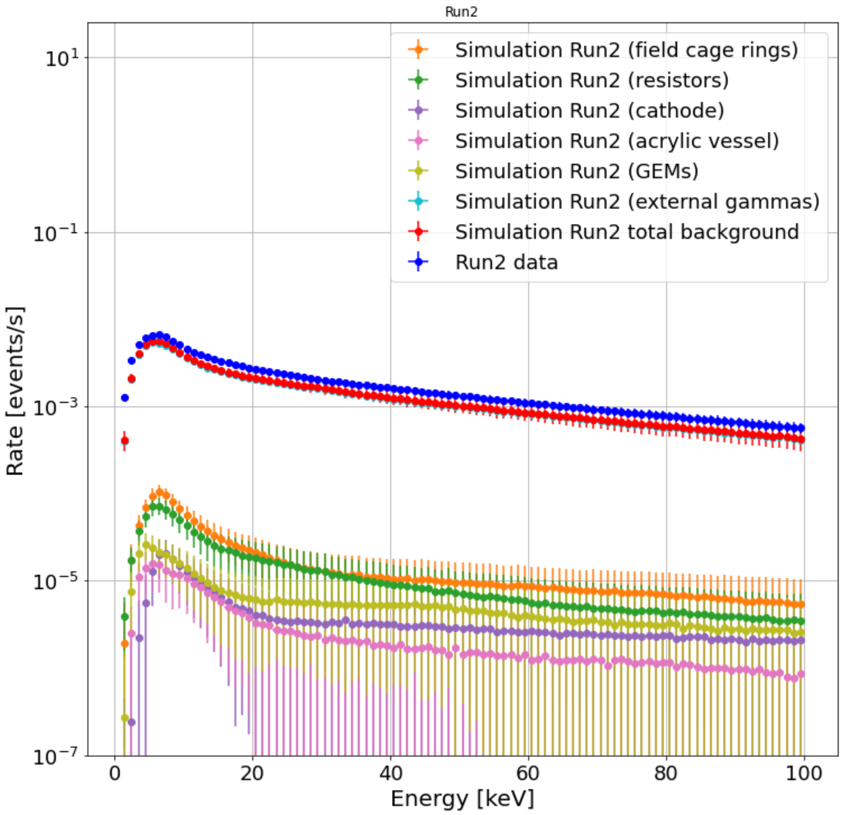


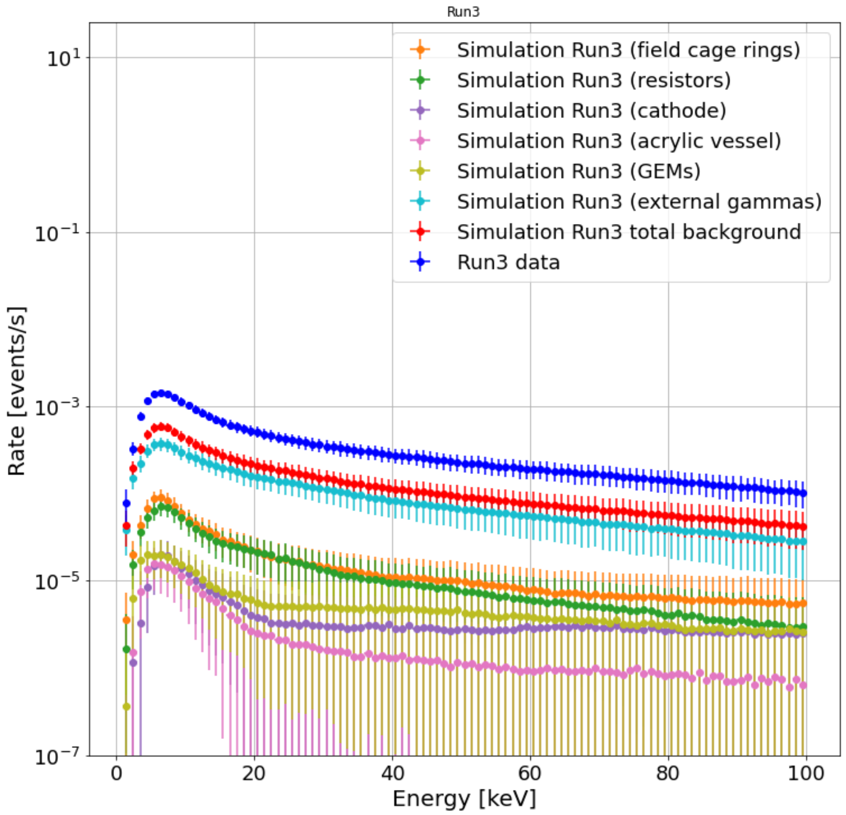
Energy spectra data/MC (Run 3)



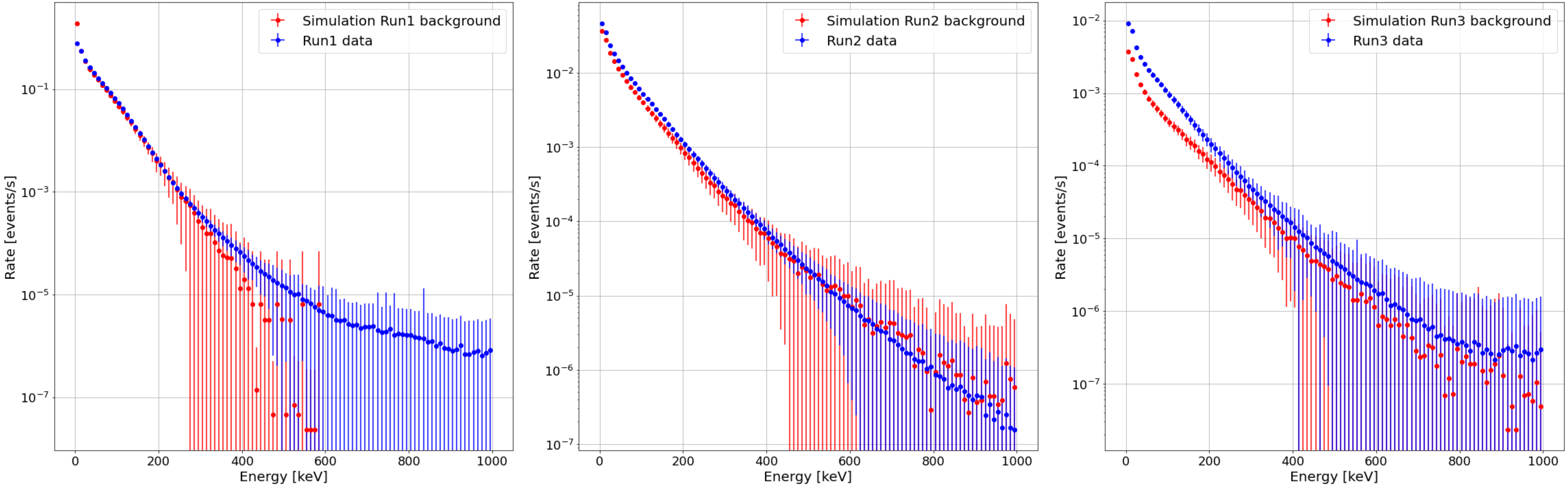
Energy spectra data/MC (separate components)



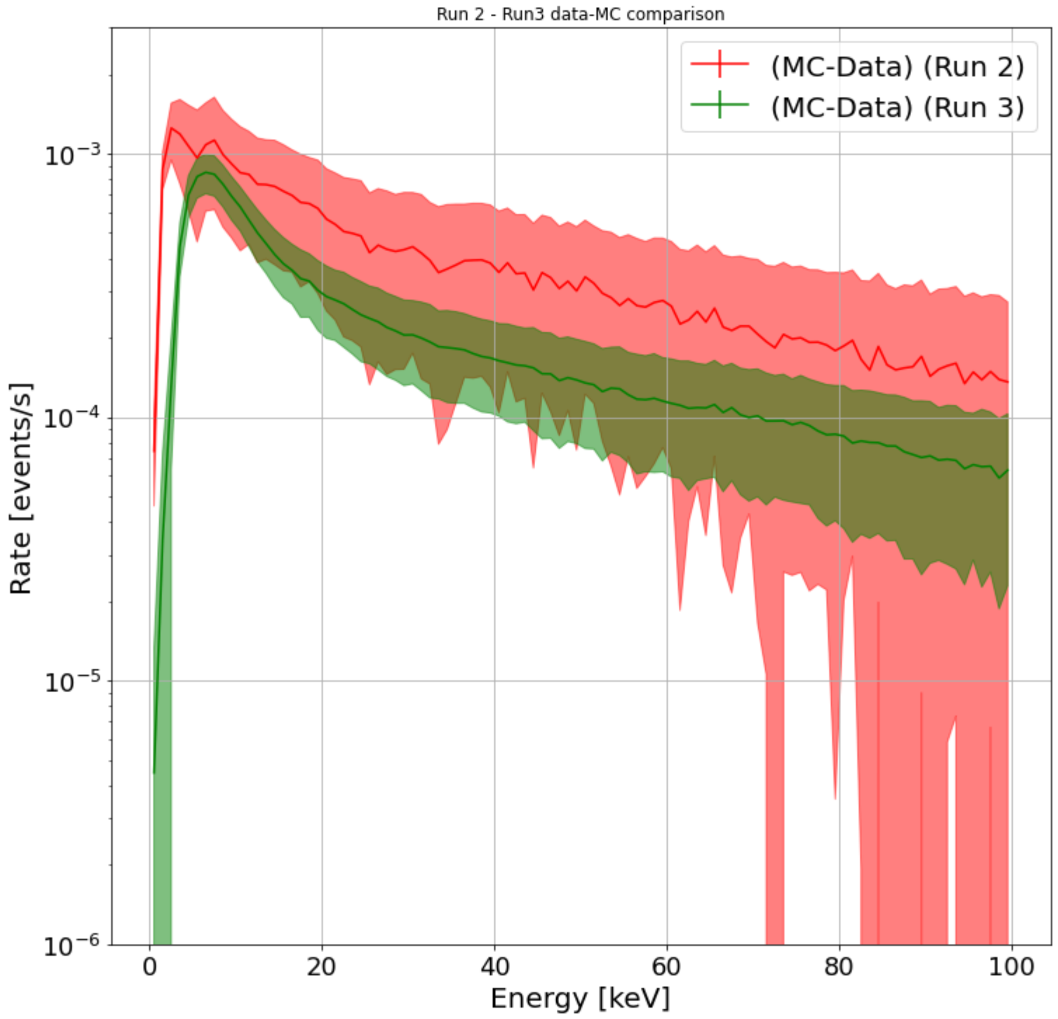


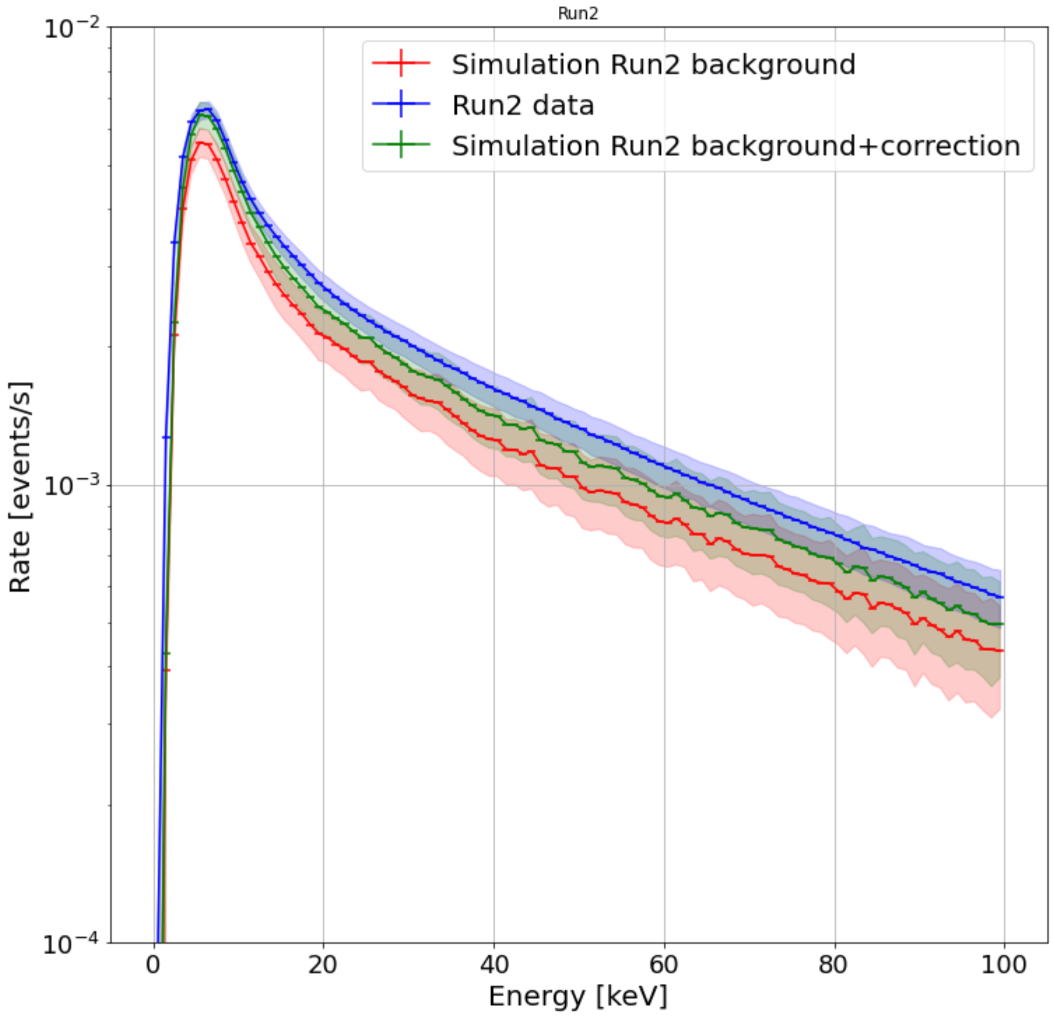


Energy spectra data/MC (up to 1 MeV)

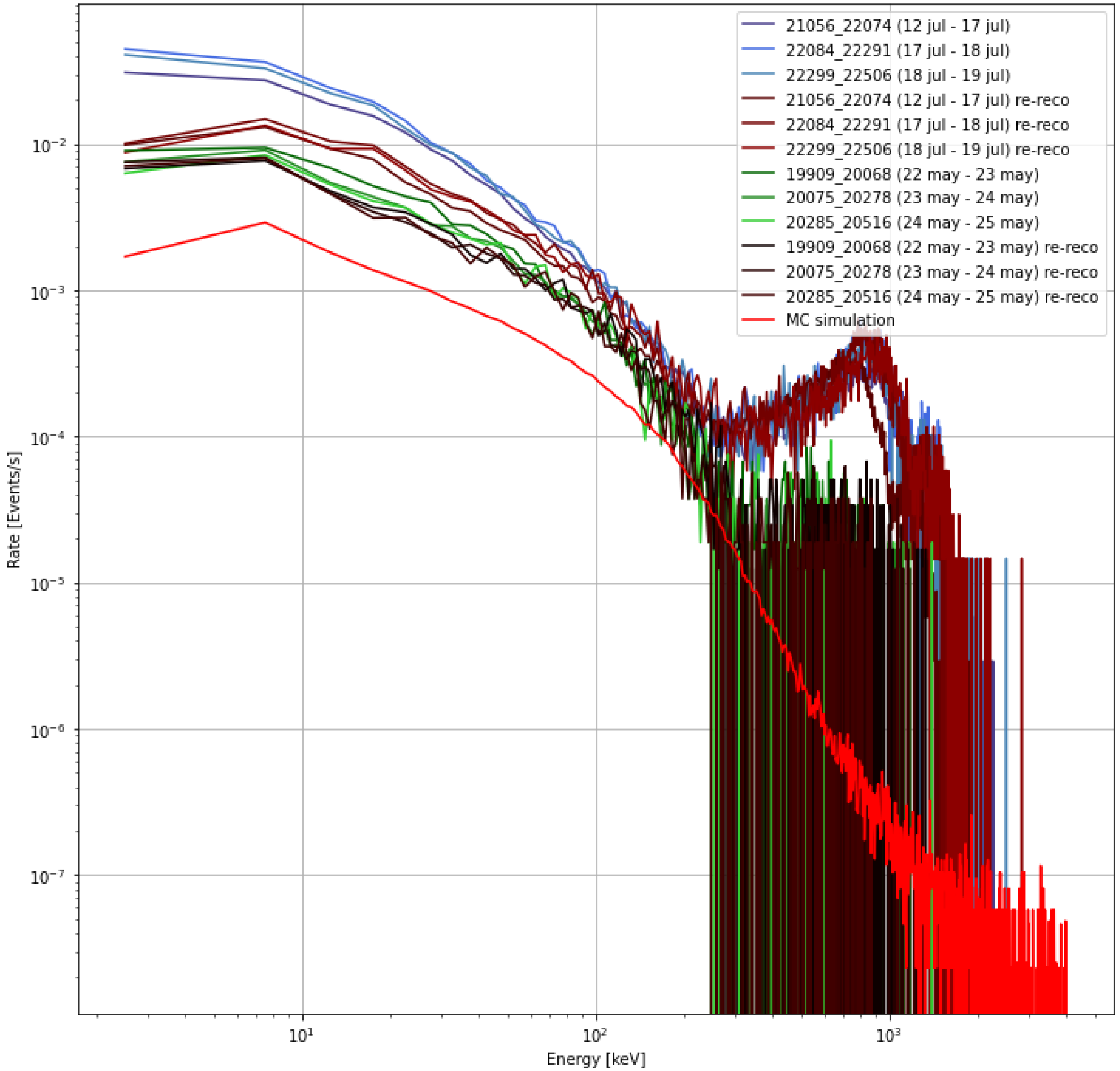


Data-MC difference (Run 2 vs Run 3)





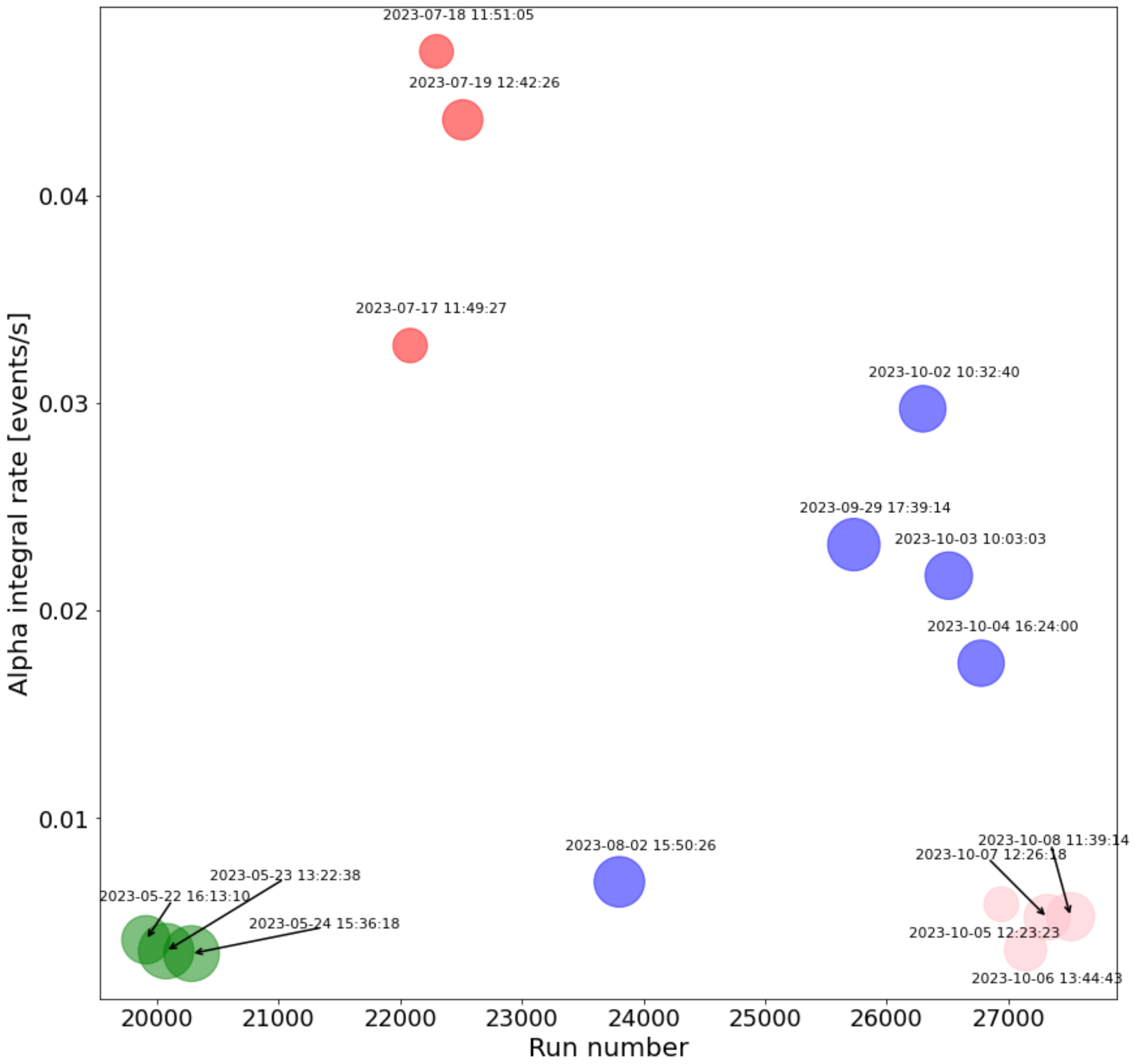
High and low energy excess



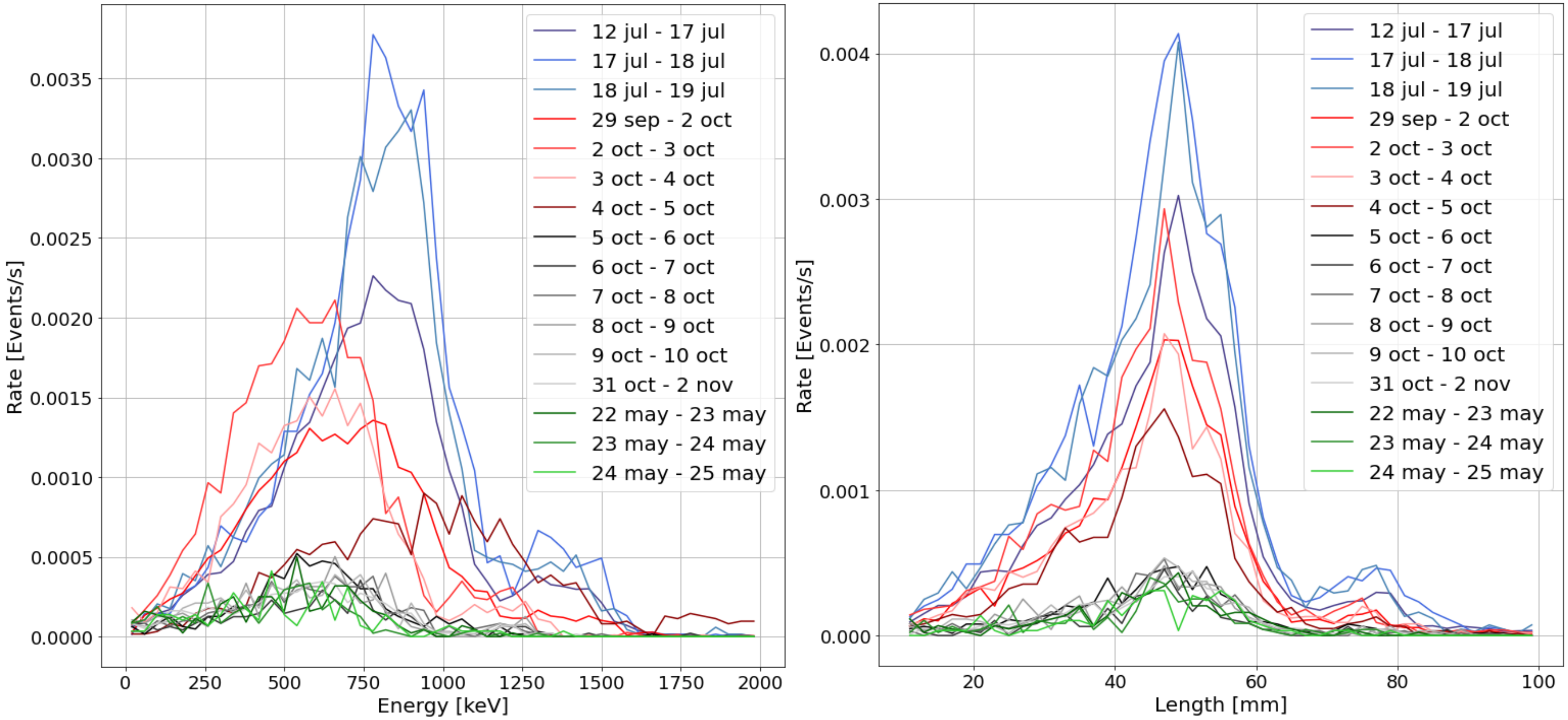
- The excess at low energy (<100 keV) in Run 3 is correlated to an excess at high energy (300-1000 keV)
- High energy excess is events with high density (delta>40), i.e. alpha particles
- They should not be at hundreds of keV
    - Not completely contained
    - **Saturated**

Alpha rate vs gas condition

- Rate of alpha events (delta>40) is correlated to the gas system conditions
- Lowest rate in may (no recirculation, no filter)
- Each color represents a different filter
- The size of the circle is proportional to the measured LY
- After AmBe measurement (blue circle at low alpha rate) there were interventions on the gas system
- This suggests that there is a radioactive contamination of the gas, which increases both the rate at high and low energy
- The gas radioactivity was not simulated (it was not known, and not expected – not at this level)



Alpha energy



5.9MeV, 6.6MeV,8.1MeV - Might be consistent with radon-222 contamination of O(0.1-1) Bq/m3

Data/MC event rates

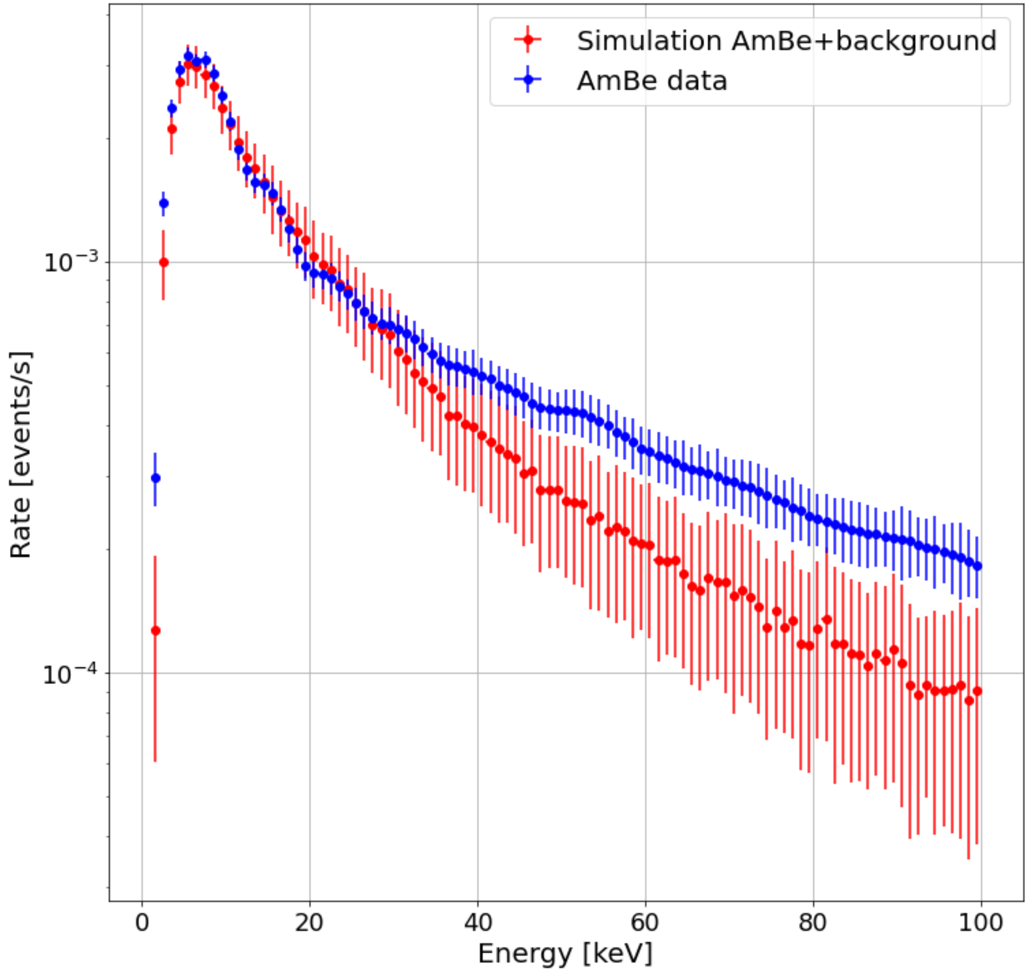
Phase	Energy range [keV]	MC [events/s]	Data [events/s]
Run 1	0-1	0.31 ± 0.01	0.0018 ± 0.0001
	1-20	1.36 ± 0.03	1.31 ± 0.01
	20-50	0.78 ± 0.02	0.833 ± 0.007
	>50	0.70 ± 0.02	0.771 ± 0.005
	>1	2.84 ± 0.04	2.93 ± 0.02
Run 2	0-1	0 ± 10^{-5}	$(8 \pm 3) \times 10^{-5}$
	1-20	0.064 ± 0.001	0.080 ± 0.001
	20-50	0.044 ± 0.001	0.0561 ± 0.0008
	>50	0.061 ± 0.001	0.0805 ± 0.0009
	>1	0.170 ± 0.002	0.218 ± 0.002
Run 3	0-1	0 ± 0	$(2 \pm 1) \times 10^{-5}$
	1-20	0.0066 ± 0.0002	0.0167 ± 0.0004
	20-50	0.0041 ± 0.0002	0.0103 ± 0.0003
	>50	0.0065 ± 0.0002	0.0158 ± 0.0004
	>1	0.0173 ± 0.0004	0.0429 ± 0.0007

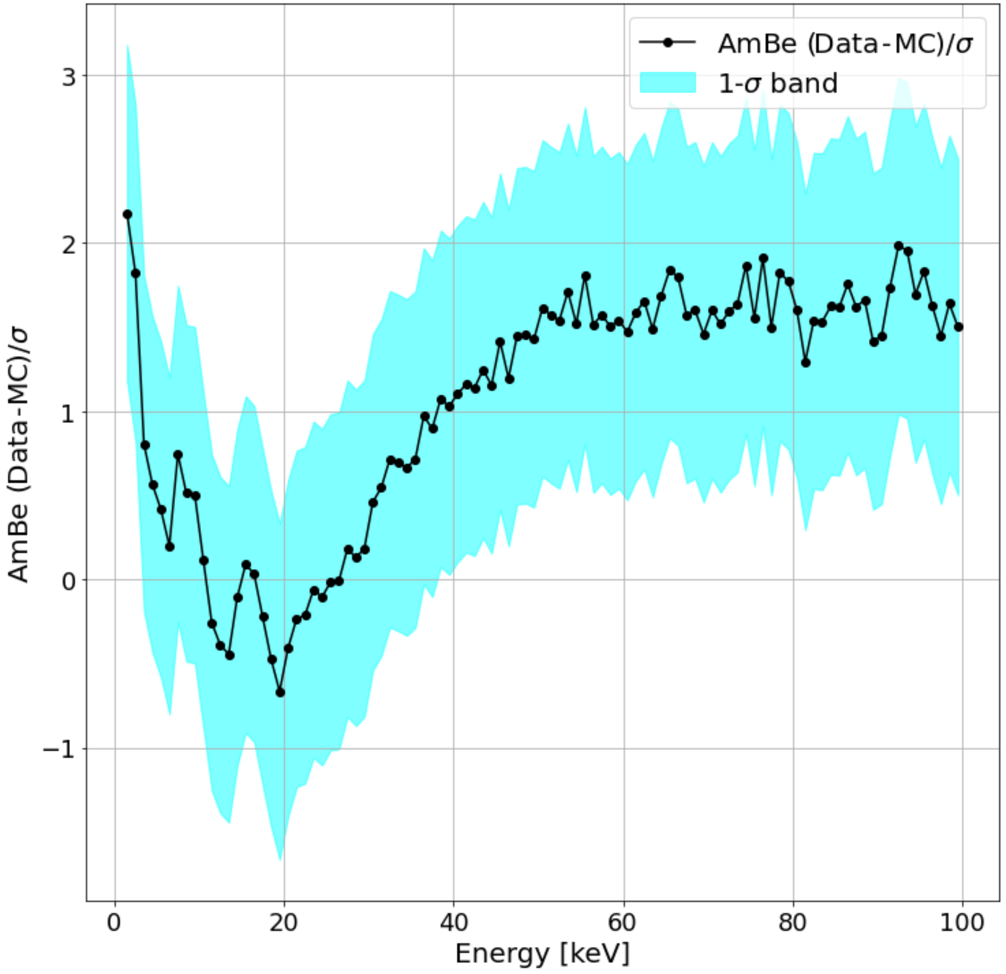
Run 1 is consistent

Run 2 is predicted 22% lower

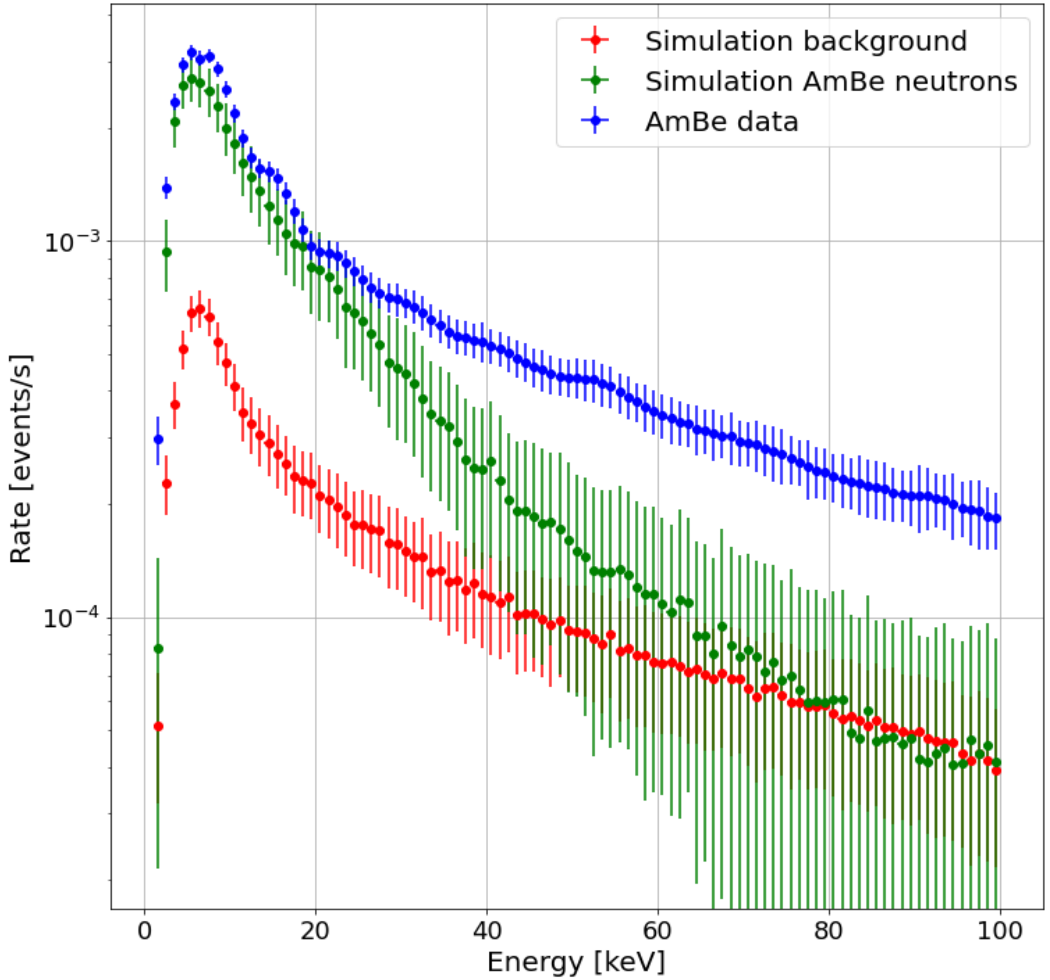
Run 3 is predicted 60% lower

AmBe energy spectra



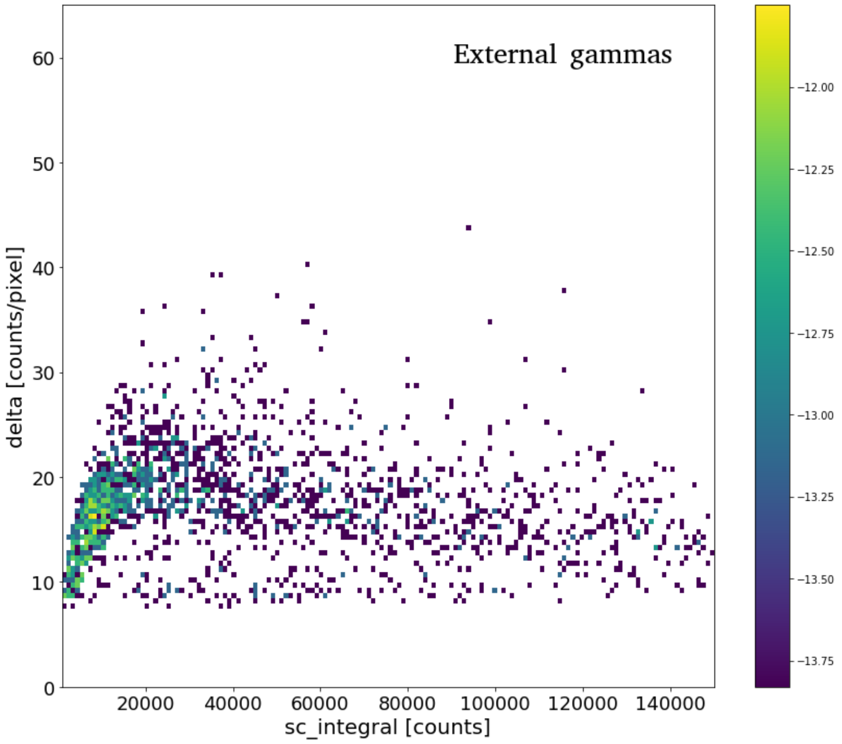


AmBe energy spectra

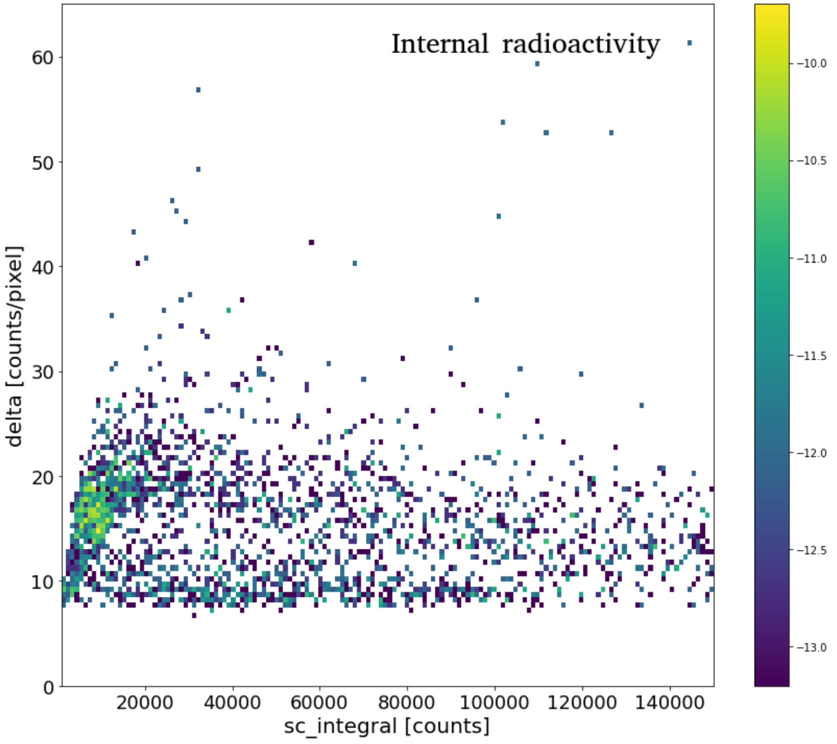


	Energy range [keV]	MC [events/s]	Data [events/s]
AmBe	0-1	0 ± 0	$(1 \pm 1) \times 10^{-5}$
	1-20	0.037 ± 0.001	0.0366 ± 0.0005
	20-50	0.0157 ± 0.0008	0.0189 ± 0.0003
	>50	0.0125 ± 0.0006	0.0248 ± 0.0004
	>1	0.066 ± 0.002	0.0803 ± 0.0007

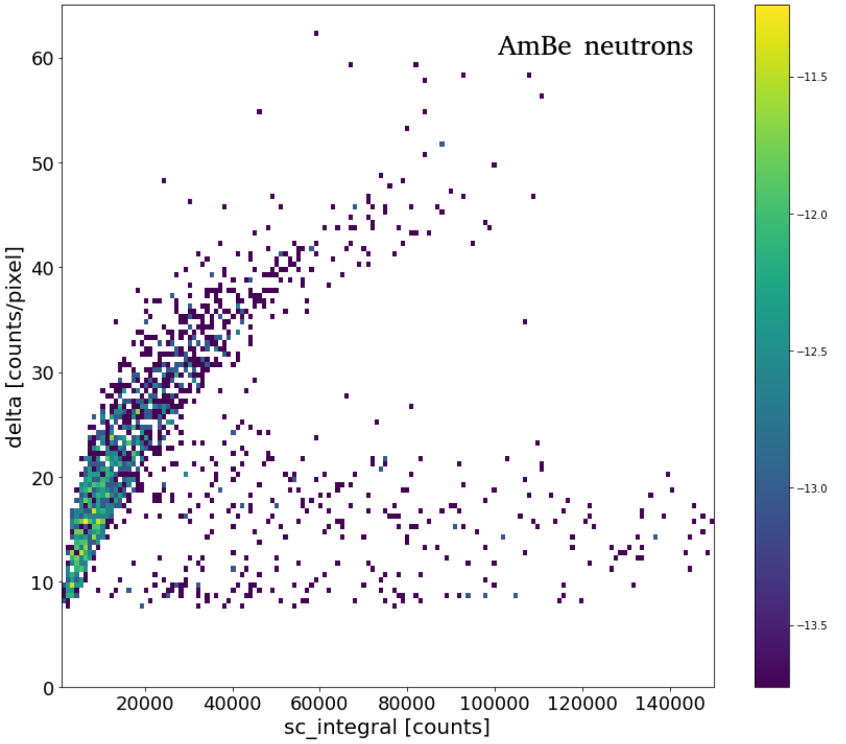
Delta vs integral (MC)



Mainly low energy ERs (<100 keV)



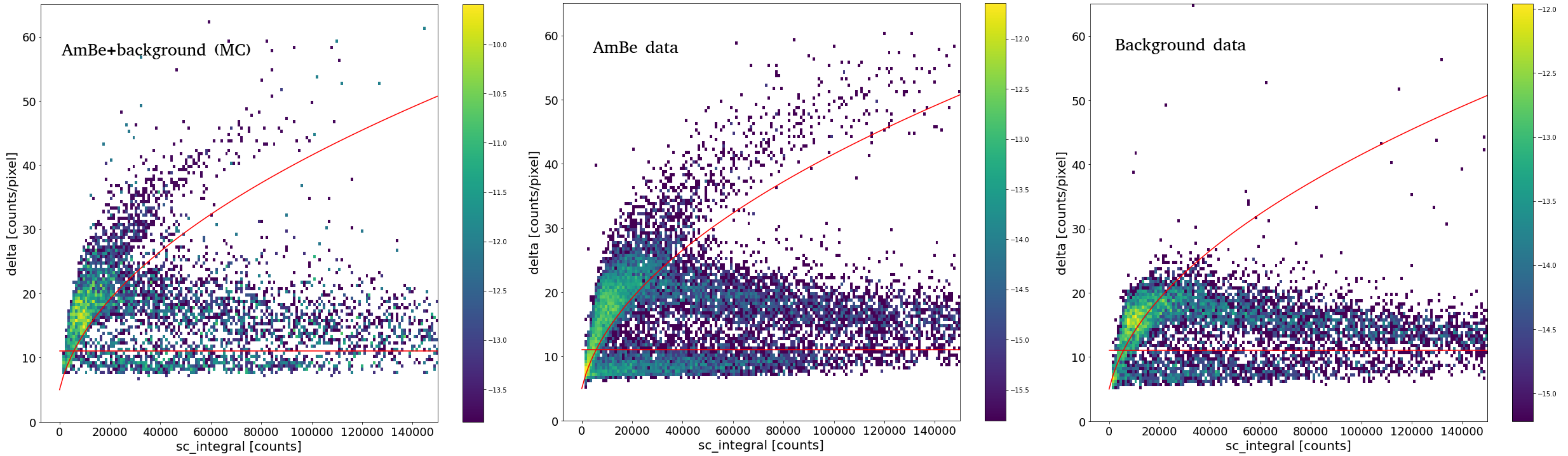
Low energy ERs, high energy ERs (low band), alpha fragments



Mainly low energy NRs

Delta vs integral (data)

Same delta bands in data and MC; NR band absent in background data



To select NRs, cut delta<sqrt(a+b*sc_integral) (on top of delta<11 cut) with a=25, b=0.017

NR cut efficiency and rejection power