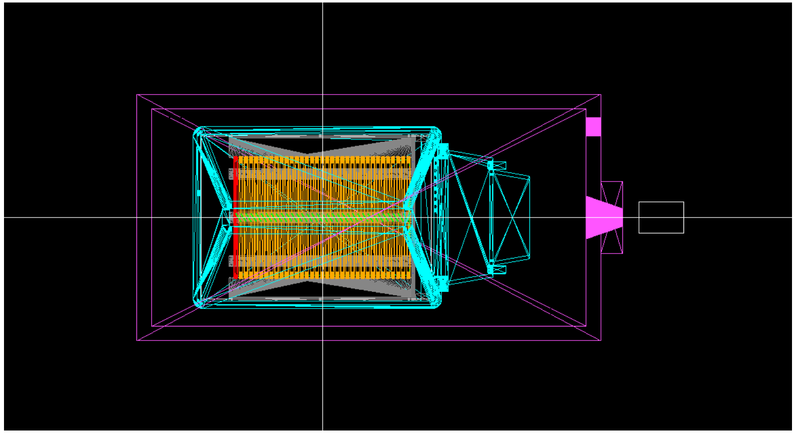
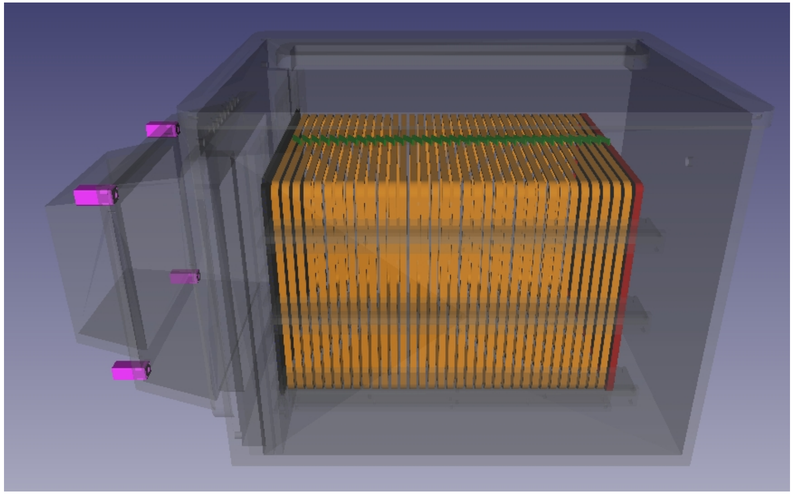
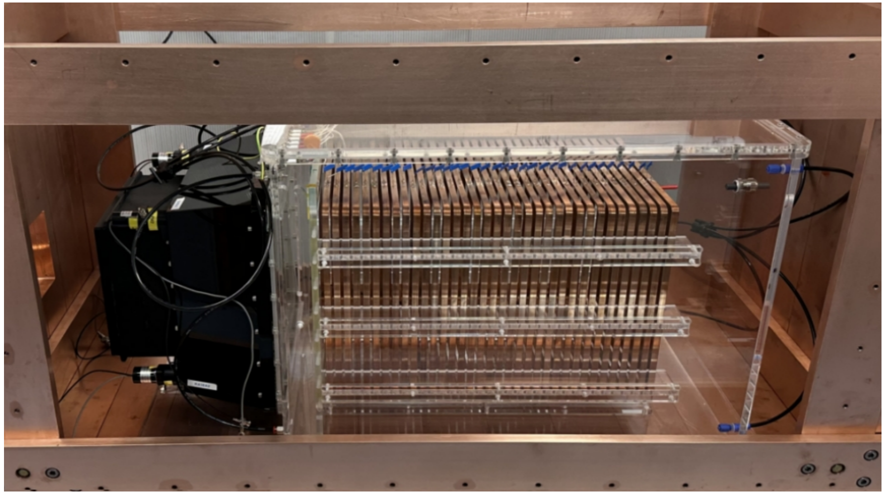
Analisi e confronto con il MC di Run 1, Run 2 e Run 3

LIME GEANT4 background simulation



- **Main LIME components** imported in GEANT4 from technical CAD design (acrylic vessel, field cage rings, field cage resistors, cathode, GEM foils, support structures), camera and camera lens as simple shapes in GEANT4
- Passive shielding implemented as simple boxes for optimization phase, then from final technical design

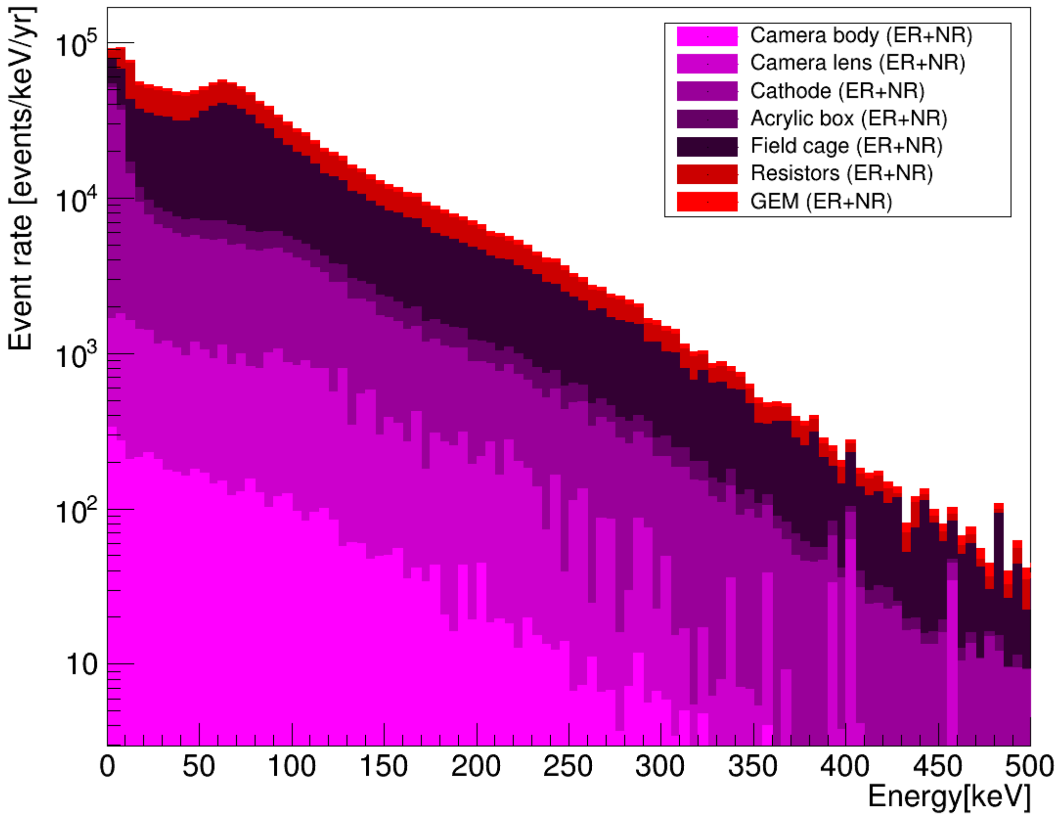




Background sources

- Internal background:
  - Intrinsic **radioactivity of LIME materials** (copper field cage rings, resistors, GEMs, copper cathode, acrylic vessel, camera body, camera lens)
    - Measured underground by the LNGS Special Techniques Division
  - **Radioactivity of shielding** materials (copper, lead)
    - From measurements of dismissed Cu and Pb bars from OPERA
  - **Radiogenic and cosmogenic neutrons** from shielding (negligible)
- External background:
  - **Environmental gammas and neutrons**
    - Goal: optimizing shielding to suppress external background below the internal one

Internal radioactivity



Mainly from ^{238}U and ^{232}Th chains

Source	Event rate [10^6 yr^{-1}]
Field cage	(3.57±0.01)
Resistors	(1.873±0.006)
Cathode	(1.095±0.001)
GEMs	(0.3891±0.0002)
Vessel	(0.268±0.001)
Camera lens	(0.151±0.004)
Camera body	(0.0242±0.0005)
TOTAL	**(7.34±0.01)**

LIME was not designed to minimize radioactivity → only main components were measured and simulated

Shielding material optimization

Copper or Lead?

- Simulated **radioactivity** (mainly ^{210}Pb) in two scenarios

	Shield	Isotope	Activity [Bq/kg]	ER [counts/yr]
1	5 cm Cu + 5 cm Pb	^{210}Bi	58	$(7.6 \pm 0.2) \times 10^4$
2	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

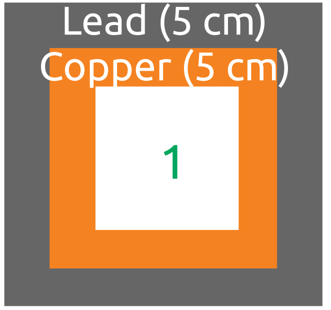
~10x difference

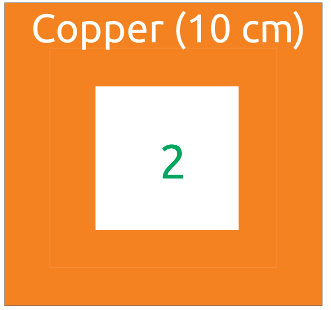
- Simulated **external** gammas and neutrons in the two scenarios:

  1 $1.29(5)\times10^6$ ev/yr 2 $4.76(8)\times10^6$ ev/yr **~3.5x difference**

- Larger neutron interaction cross section for Pb (10x)

  → distorted neutron-induced NR spectrum (in view of spectral measurement of neutron flux)

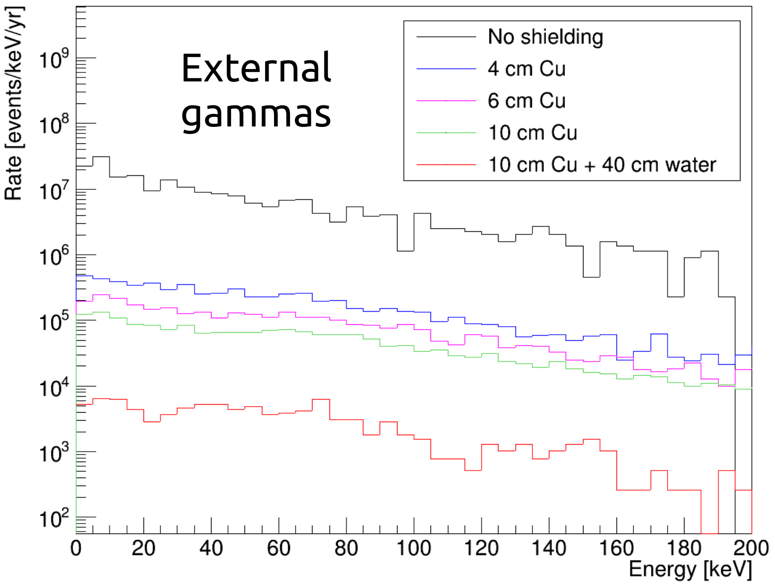




Shielding thickness

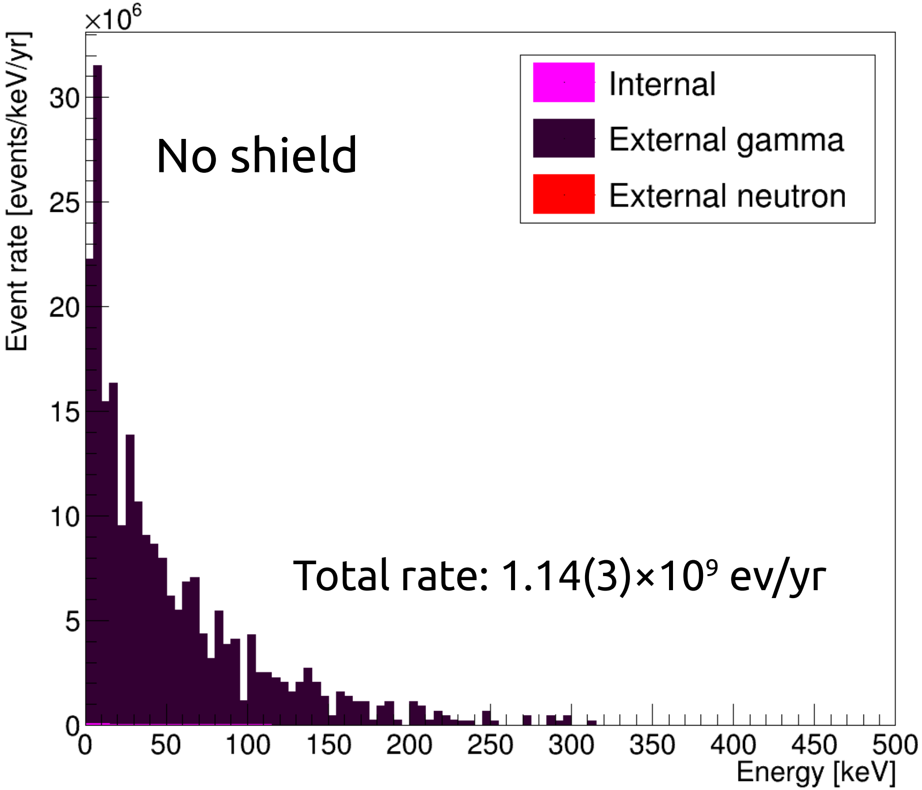
- A **staged approach** was planned to better characterize the shielding suppression capability
- **Final simulation** of external fluxes with 4 cm, 6 cm, 10 cm of Cu, 10 cm of Cu+40 cm of water in view of data taking

Shielding	Gamma background [10^6 ER yr^{-1}]	Neutron background [NR yr^{-1}]
Unshielded	(1140±30)	(1480±90)
4 cm Cu	(26.2±0.6)	(870±10)
6 cm Cu	(9.4±0.3)	(1000±30)
10 cm Cu	(1.96±0.04)	(930±20)
10 cm Cu + 40 cm H_2O	(0.5±0.2)	(2.0±0.2)

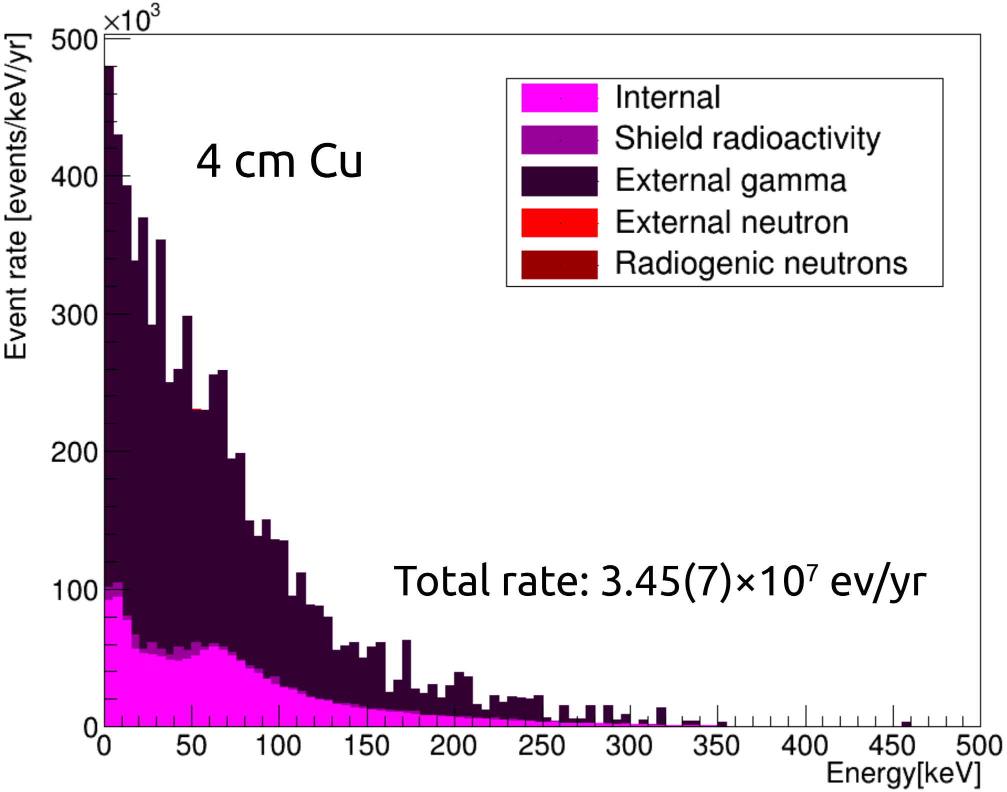


No shield → 4 cm Cu → 10 cm Cu → 10 cm Cu + 40 cm H_2O

Final simulation results

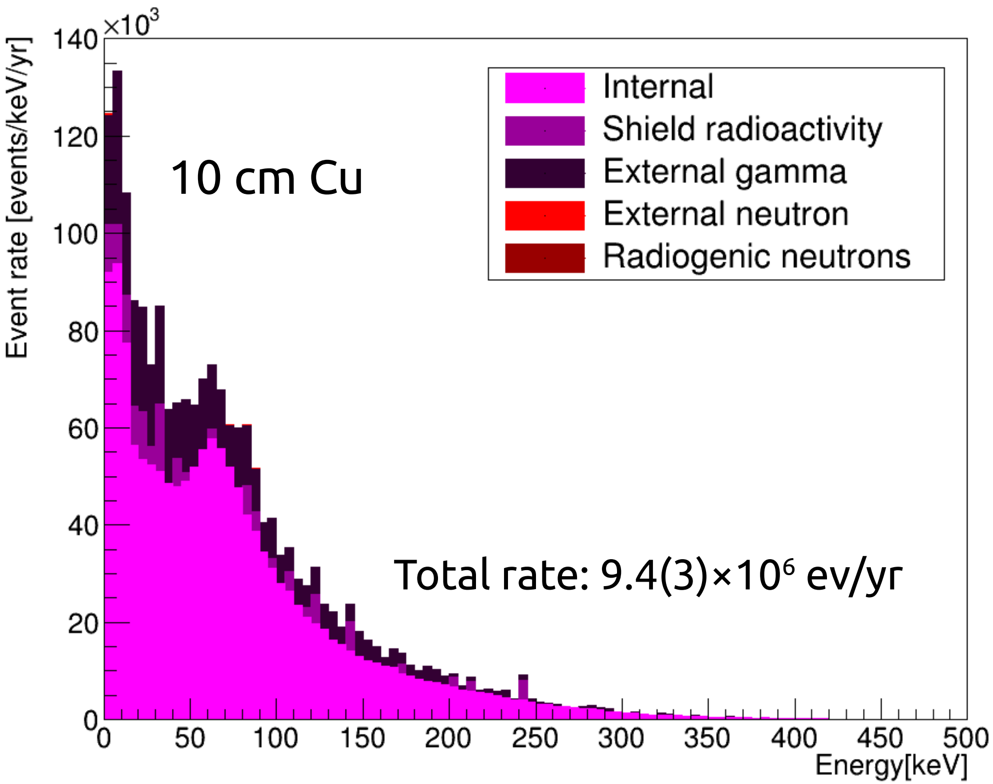


Completely dominated by external gammas
(internal is 0.6% of total)

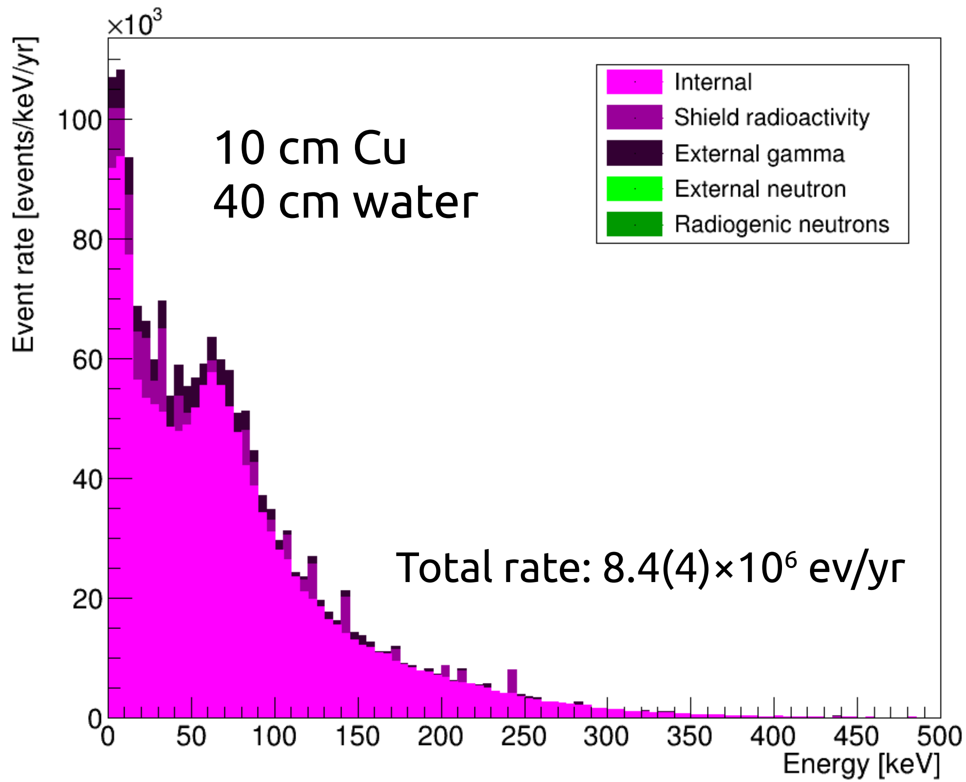


Starting to probe internal background
(internal is 20% of total)

Final simulation results



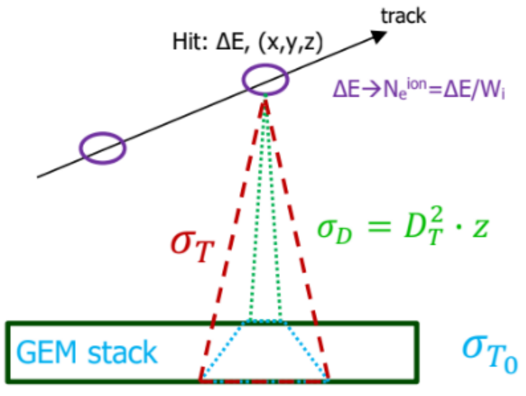
Internal background gives major contribution
(internal is 78% of total)

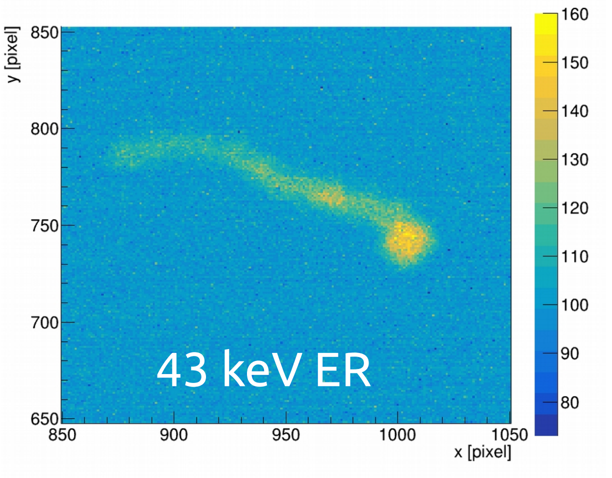


Largely dominated by internal background
(internal is 87% of total)

sCMOS image simulation

- **Energy → primary ionization electrons** (W value=46.2 eV)
- **Primary electron transport** (Gaussian **diffusion** of ionization electron cloud, $\sigma_{0T,0L}$ fitted to data, $\sigma_{T,L}$ simulated with Garfield++) $\sigma = \sqrt{\sigma^2_{0,T(L)} + \sigma^2_{T(L)} Z}$
- Electron **multiplication in GEM** stack + charge gain **saturation** on third GEM (simplified model)
- **Light emission** + optical effects + sCMOS sensor response
  - Projection on x-y plane + average n° counts per pixel (light emission, geometrical acceptance, sensor response, vignetting effect)
- Include effect of rolling shutter + add **sensor noise** (measured)
- Reconstructed the same way as real data





Only deposits <800 keV were digitized

Data taking program

Final data taking program based on MC results

Run 1 (no shield)

Dominated by external background,
expected background rate ~ 36 ev/s

Run 2 (4 cm Cu)

Start to probe internal background,
expected background rate ~ 1.1 ev/s

Run 3 (10 cm Cu) + AmBe

Mostly internal background,
expected background rate ~ 0.29 ev/s

Run 4 (10 cm Cu + 40 cm H_2O)

Dominated by internal background,
expected background rate ~ 0.27 ev/s

Background datasets

A subset of runs were analysed for MC comparison (good LY, stability, gas system operation)

Run 1 (no shield)
Oct 8 - Dec 6 2022

285665 images
~49 hr, Dec 2–6 2022
10 L/h flux

Run 2 (4 cm Cu)
Feb 15 - Mar 9 2023

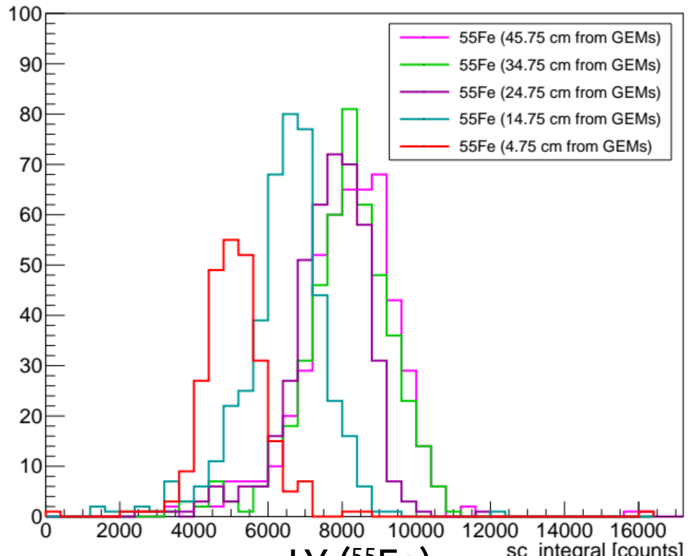
297992 images
~53 hr, Mar 6–9 2023
20 L/h flux

Run 3 (10 cm Cu)
May 5 - Nov 7 2023

171579 images
~53 hr, May 22–25 2023
20 L/h flux

^{55}Fe calibration and LY monitoring

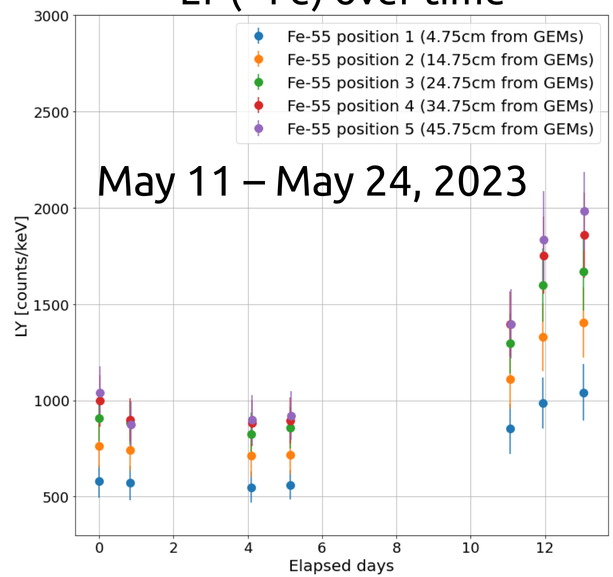
- 5.9 keV X-ray ^{55}Fe source on top face of LIME, pointing towards gas
- **Daily dataset** taken in 5 positions (only Run 2,3)



LY (^{55}Fe)

Standard candle for **energy calibration**

LY (^{55}Fe) over time

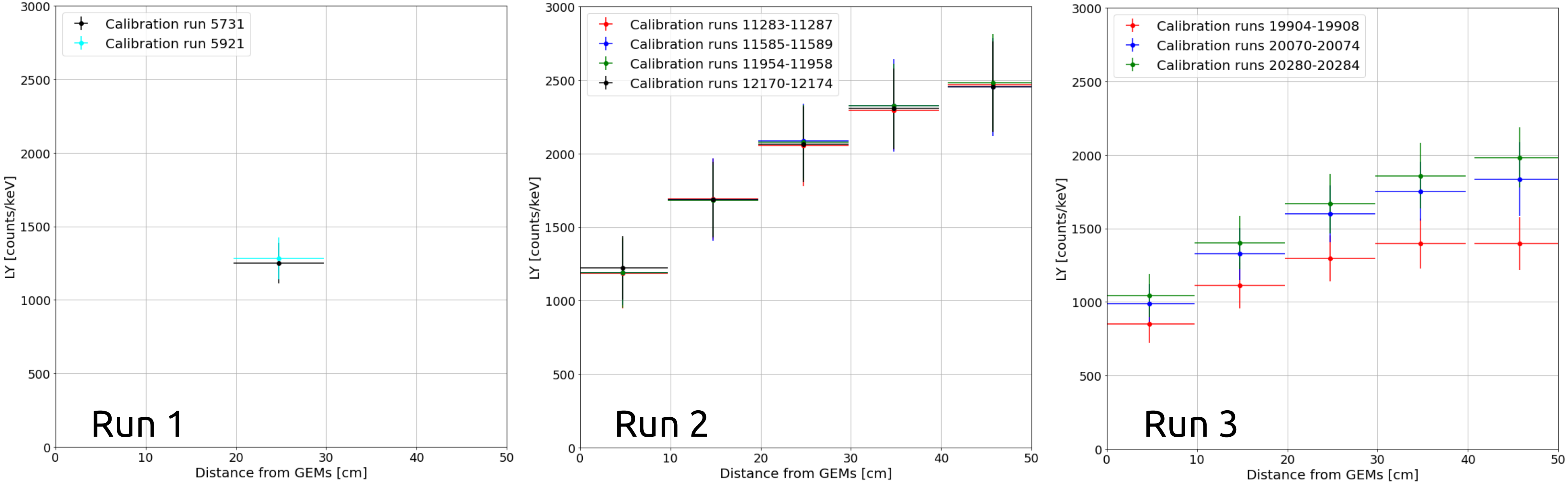


LY monitoring over time

Light yield and calibration (data)

- LY depends on Z (saturation) and on time (gas conditions) → randomly (uniform) extract Z, randomly (Gaussian) extract LY → **energy calibration**
- **Bootstrap sampling**: calibrate each track x1000, average and std. dev. bin by bin

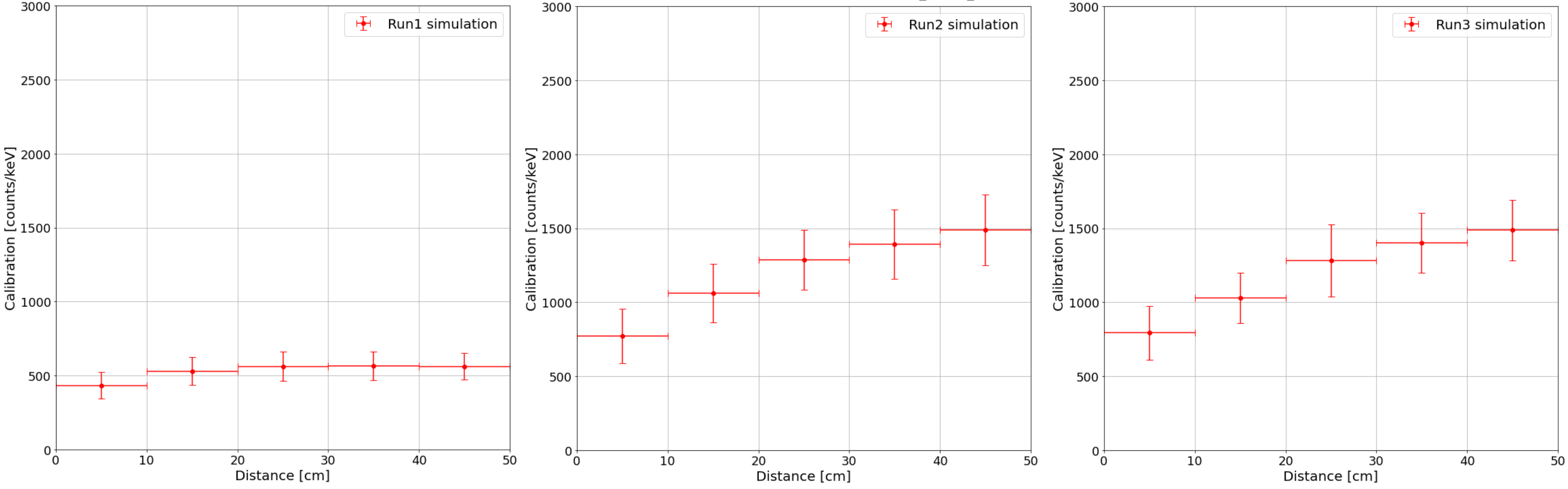
LY vs GEM distance [cm]



Light yield and calibration (MC)

- LY computed from MC sample of similar energy (between 2 and 10 keV)
- Same method as for data, but no dependence on LY variations over time
- Lower LY in MC than data (strongly depends on specific data taking conditions)

LY vs GEM distance [cm]



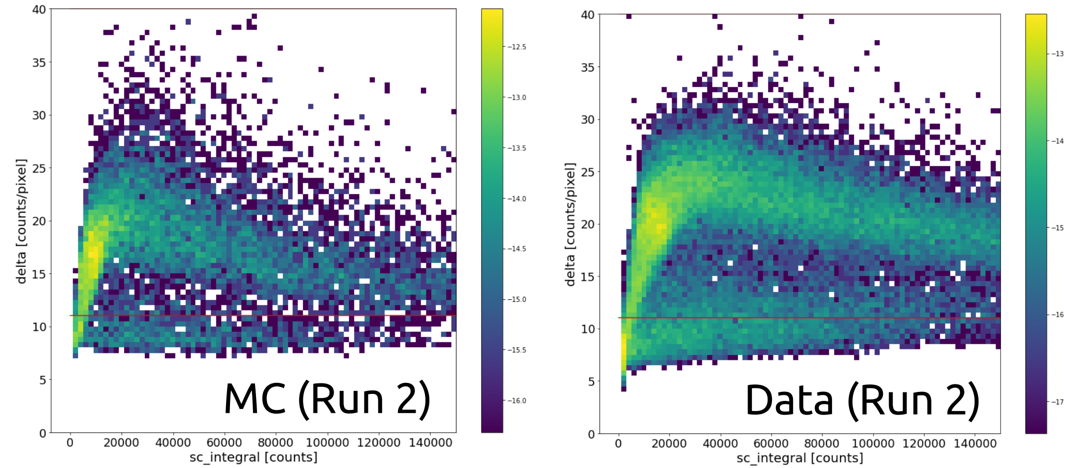
Track density (δ)

δ = light integral/n° of pixels
→ correlated to dE/dx

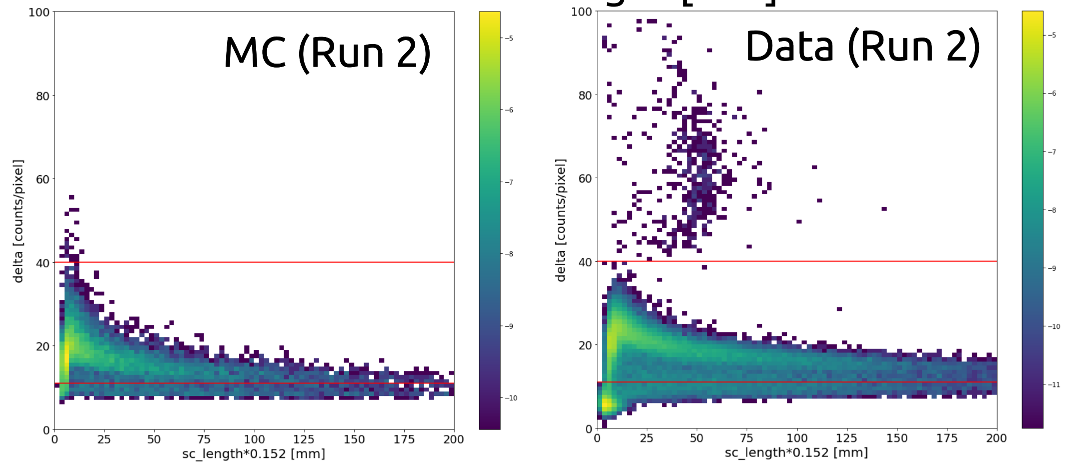
- Alpha particles have large dE/dx, few cm length
  → distinct population of large δ
- MIP-like events: low and constant dE/dx
  → constant δ band
- ERs have decreasing dE/dx with energy, asymptotically reaching the MIP band
  → upper δ band

Note: δ depends on the LY → if too low, MIPs are not reconstructed

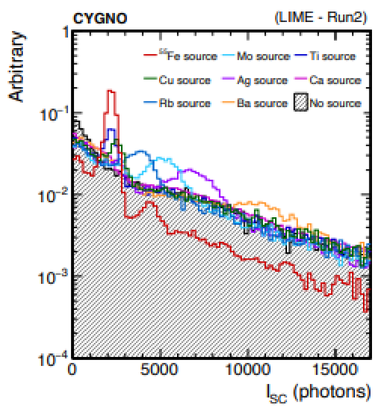
δ vs integral [counts]



δ vs track length [mm]

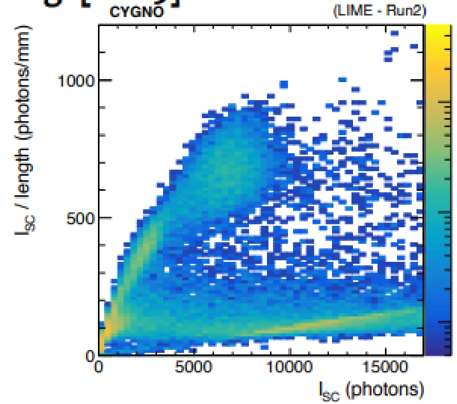


Track density (δ)

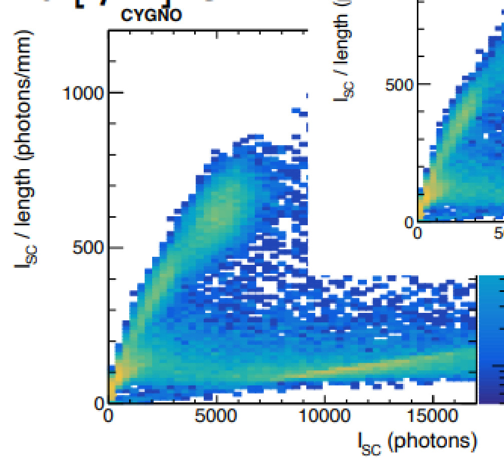


This proves that the ER band
is really ER-populated

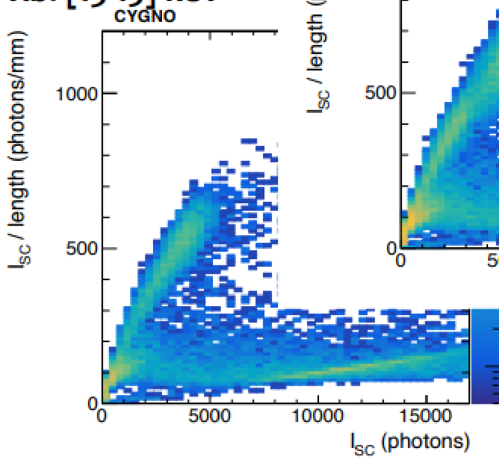
Ag: [22-25] keV



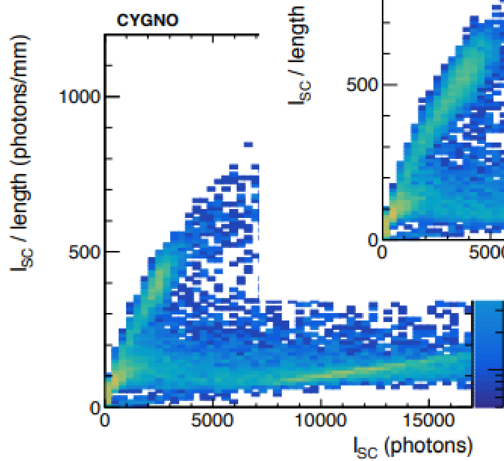
Mo: [17-20] keV



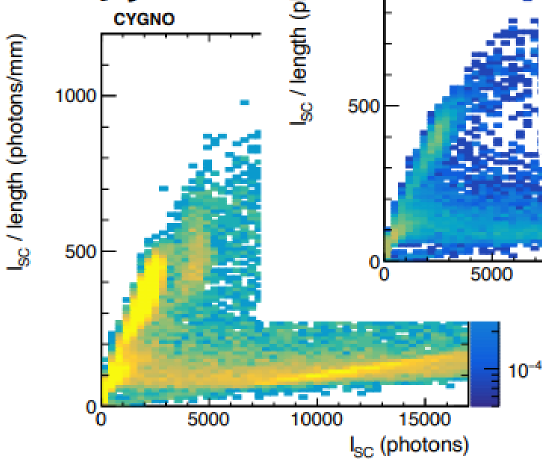
Rb: [13-15] keV



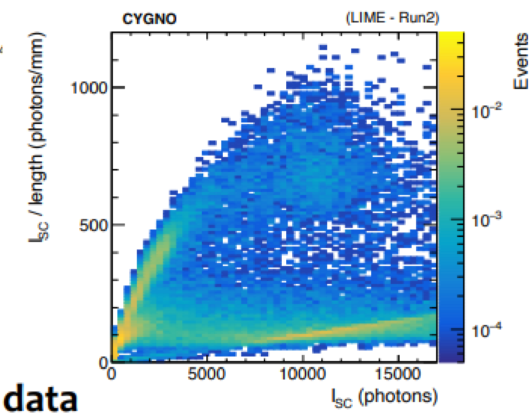
Cu: [8-9] keV



^{55}Fe: 5.9 keV

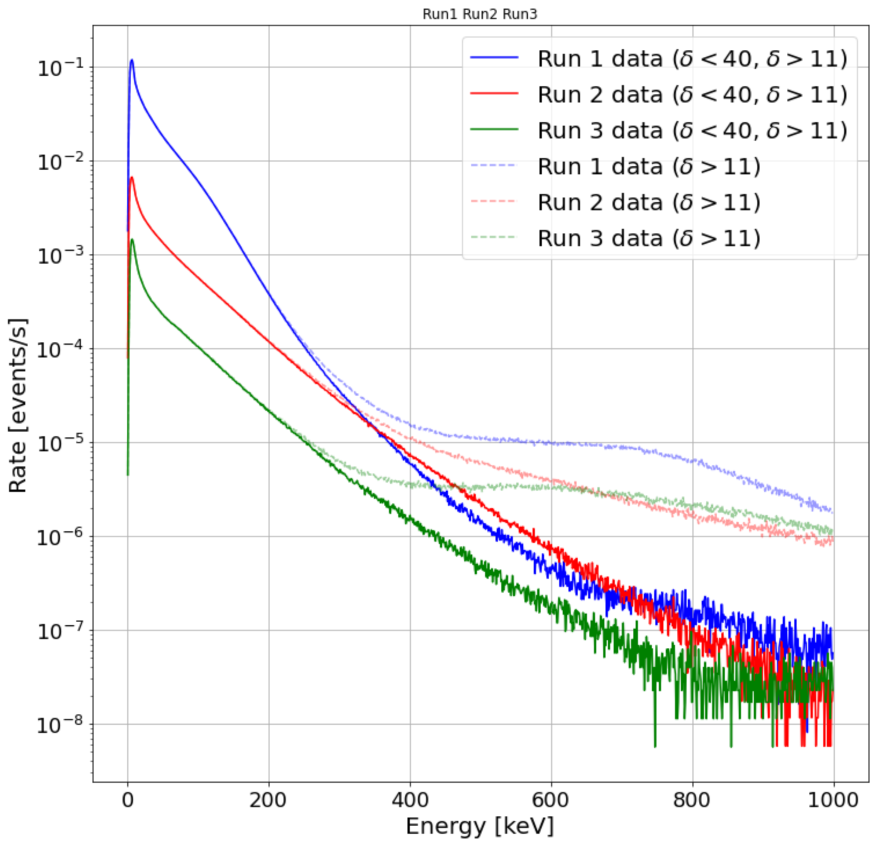


Ba: [32-37] keV



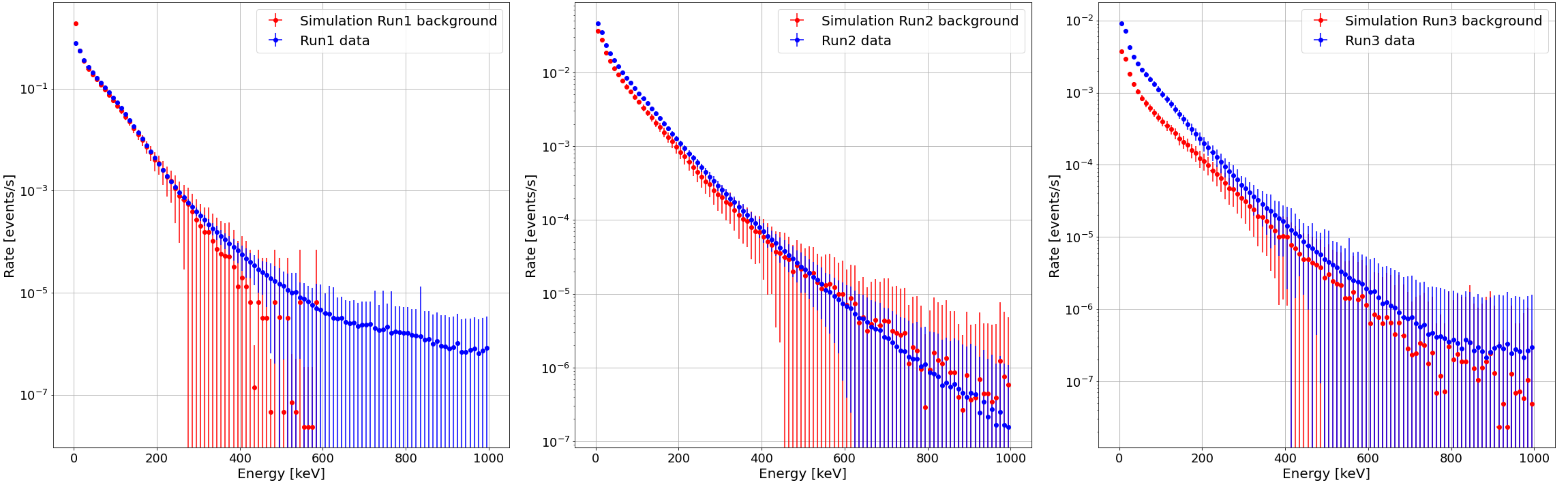
For the NR "band", need AmBe data

Energy spectra



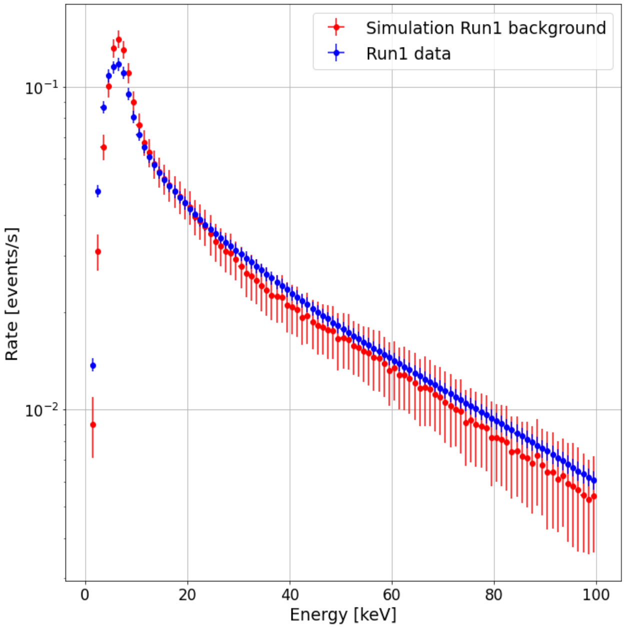
Selection cuts + energy calibration (^{55}Fe) + time normalization → energy spectra
Alpha population in all runs, saturated in energy, excluded with delta cut

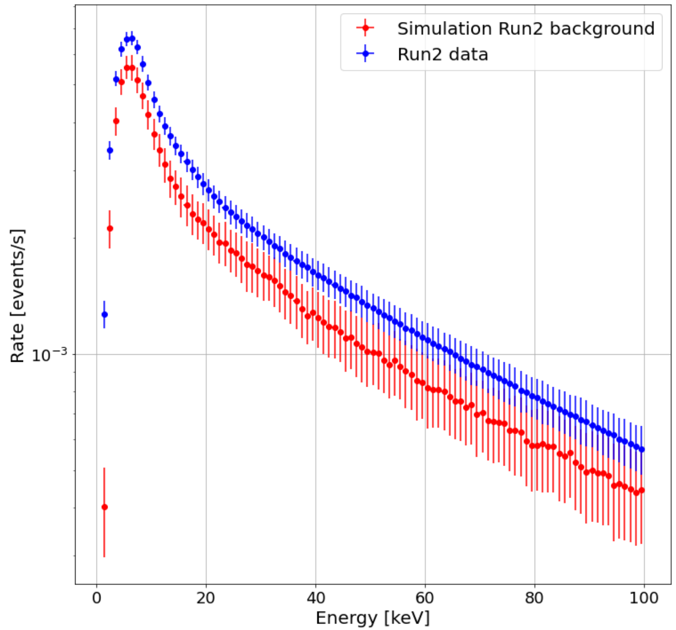
Results: Run1-2-3

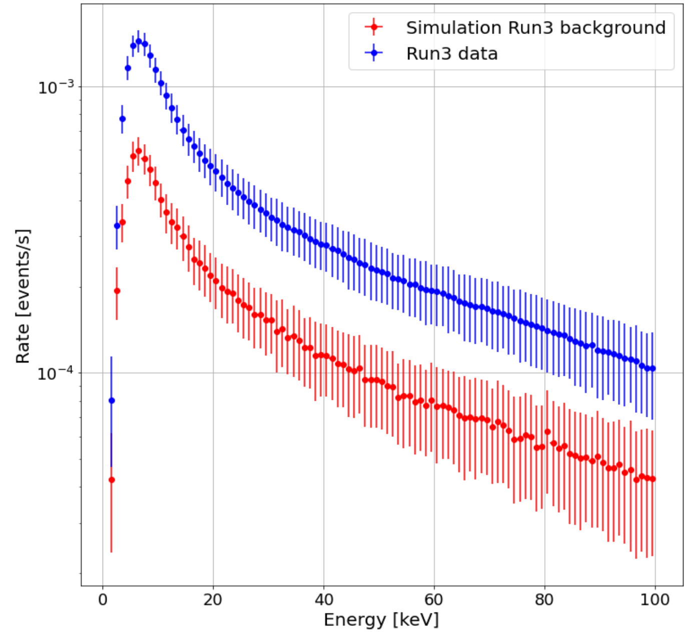


Having excluded alpha events, the spectra are consistent
Larger discrepancy is observed at low energy

Results: Run 1-2-3 (low energy)





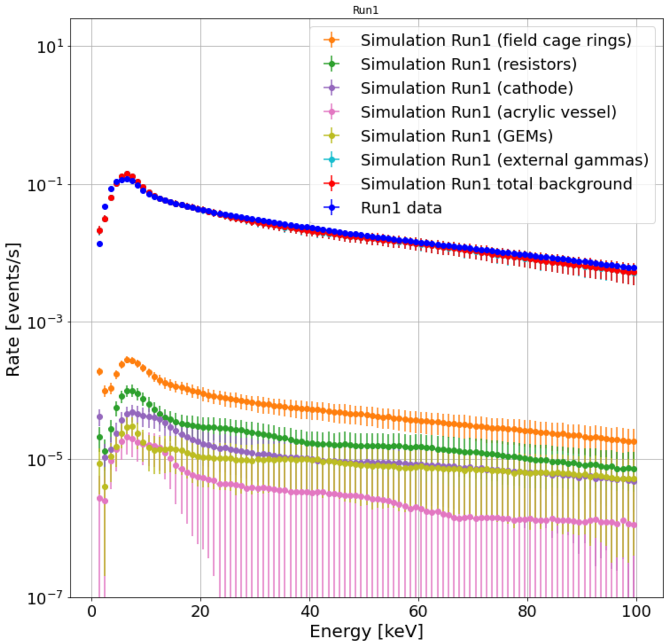


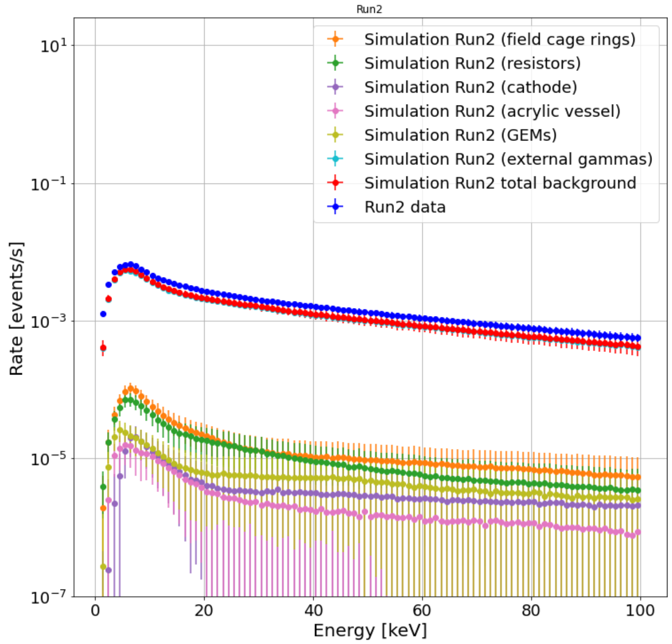
Run 1:
The consistency shows the capability of simulating external background

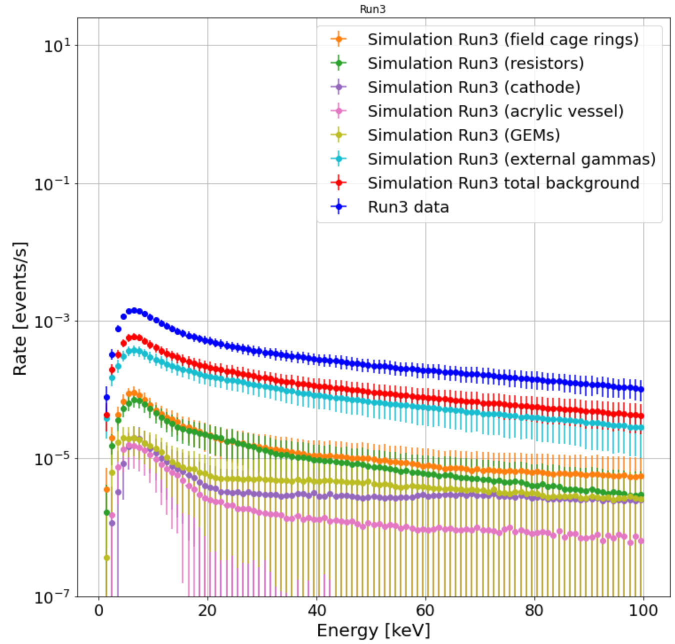
Run 2:
The simulation predicts a total rate 20% lower than data

Run 3:
Discrepancy increased to 60%

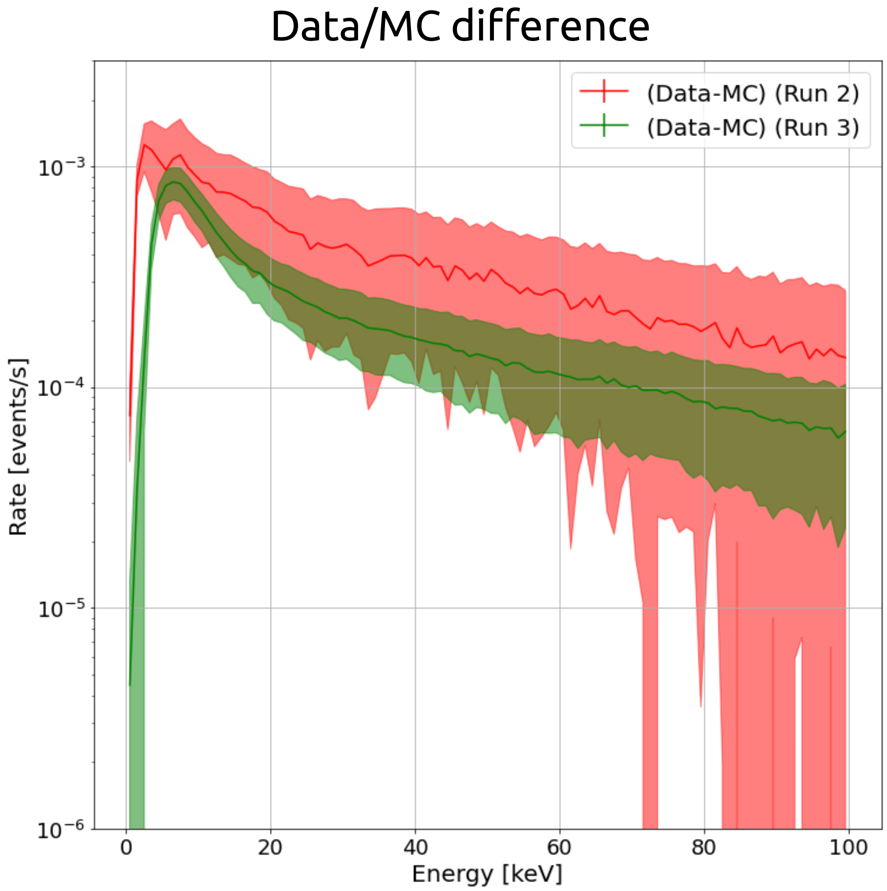
Results: Run 1-2-3 (MC components)







Data-MC difference



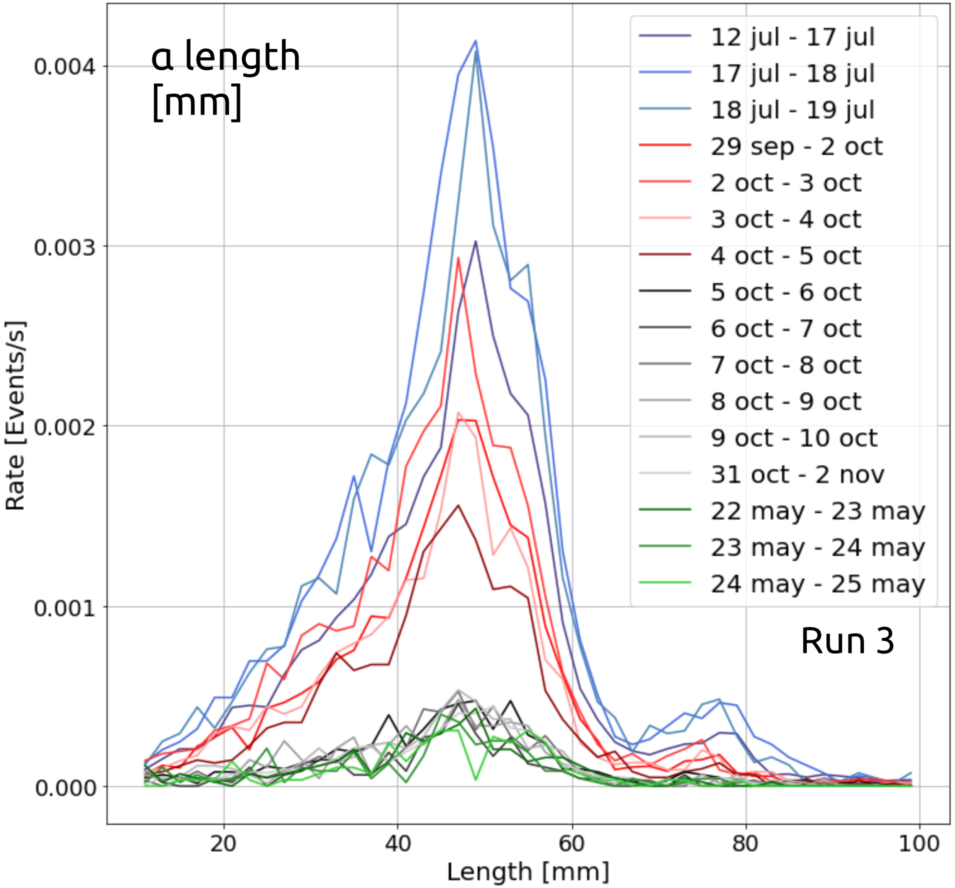
- Data-MC difference for Run 2 and Run 3 **is consistent** within the uncertainty

  → **internal** component (independent of shielding configuration)

- Total missing rate **O(10^{-2}) events/s**

Alpha events excess

- **Excess of α** events in all runs
  - Alphas from GEANT4 (not digitized) are not enough to explain the excess
- Energy measurement not feasible with ^{55}Fe calibration (charge gain saturation)
- **Length** distribution indicates peaks around 5.9 MeV, 6.6 MeV, 8.1 MeV peaks (close to ^{222}Rn)
- Radioactive contamination might also induce beta and gamma events, populating the **low energy region**
- The intensity of the peaks changes in time, probably related to variations in **radioactive contamination of the gas**

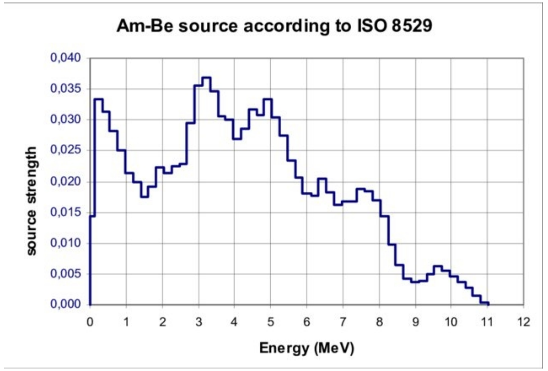


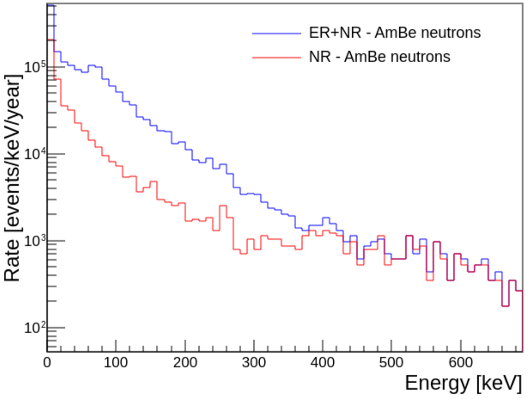
AmBe simulation

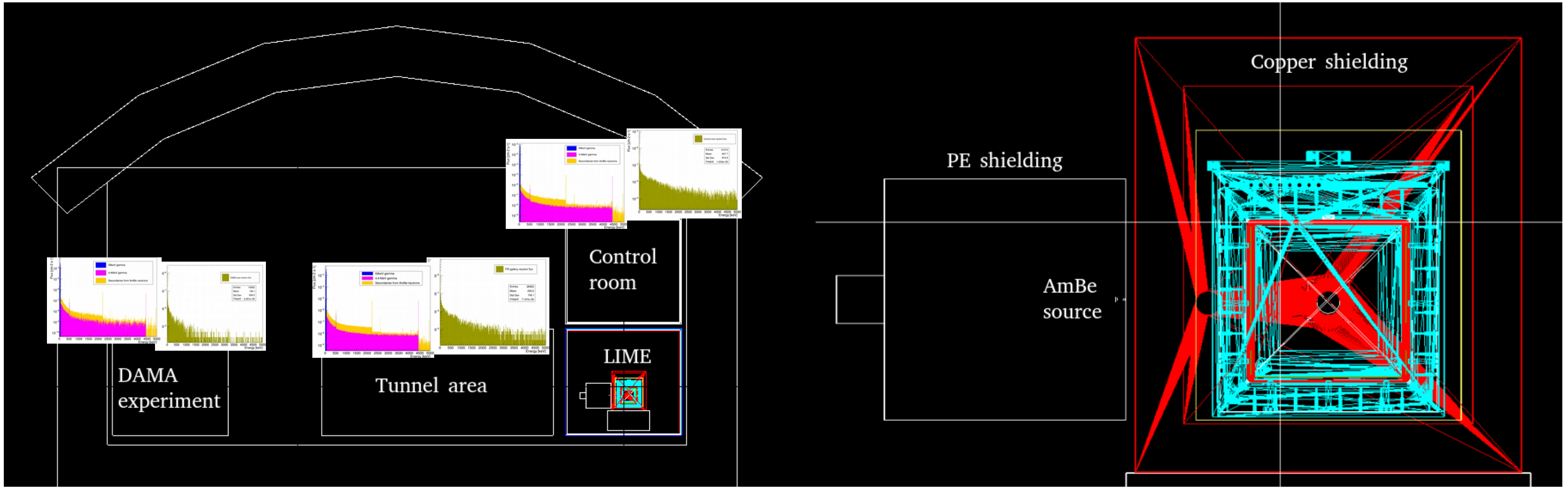
- AmBe neutrons*, 4.43 MeV gamma, 59 keV gamma isotropically emitted

$$\alpha +^{9} Be \longrightarrow n +^{12} C^{*}$$

- Neutron-induced events dominate over gamma, expected event rate (0.472 ± 0.004) ev/s (ER+NR), (0.146 ± 0.002) NR/s

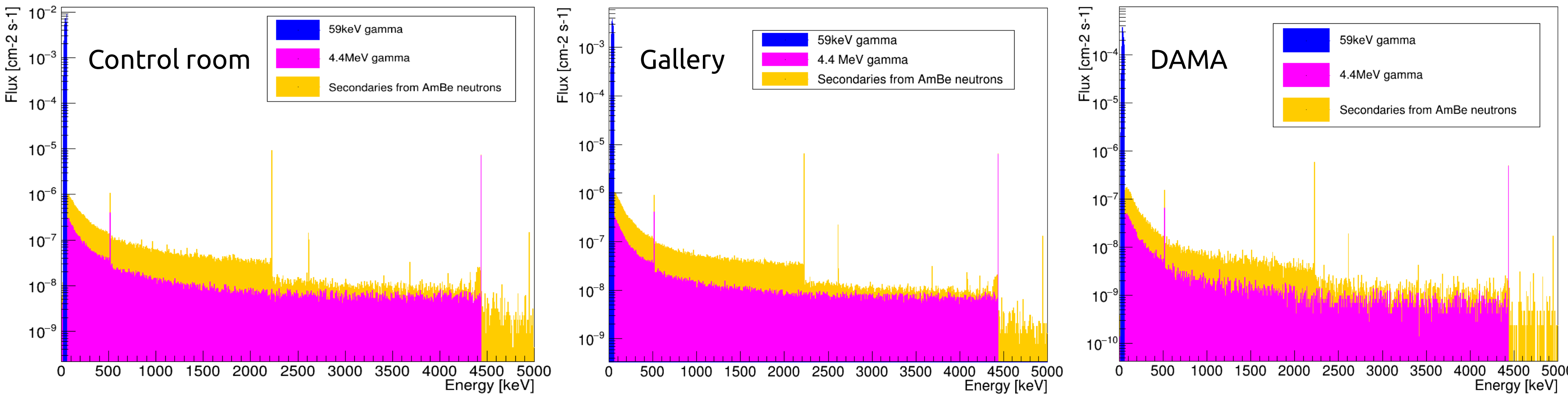






*ISO-8529 standard

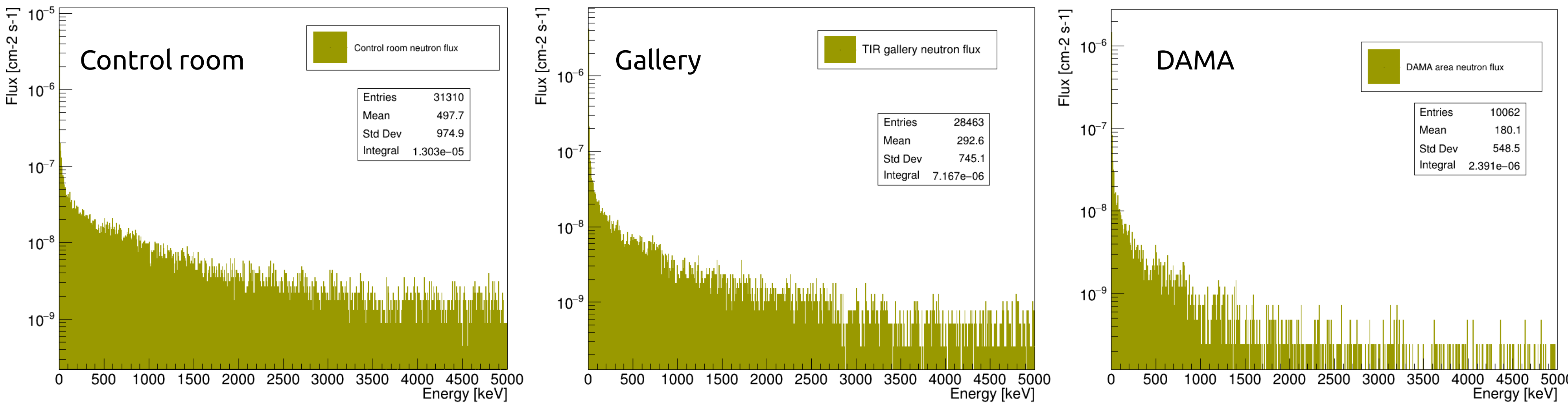
AmBe-induced fluxes



Source	Control room [cm^{-2} s^{-1}]	Gallery [cm^{-2} s^{-1}]	DAMA [cm^{-2} s^{-1}]
59 keV gammas	0.0429 ± 0.0004	0.0186 ± 0.0002	0.00162 ± 0.00006
4.43 MeV gammas	$(2.437 \pm 0.008) \times 10^{-5}$	$(2.471 \pm 0.006) \times 10^{-5}$	$(3.04 \pm 0.02) \times 10^{-6}$
Secondary gammas from neutrons	$(5.43 \pm 0.01) \times 10^{-5}$	$(4.71 \pm 0.01) \times 10^{-5}$	$(6.79 \pm 0.04) \times 10^{-6}$
Neutrons	$(1.303 \pm 0.007) \times 10^{-5}$	$(7.17 \pm 0.04) \times 10^{-6}$	$(2.39 \pm 0.02) \times 10^{-6}$

F. Di Giambattista

AmBe-induced fluxes



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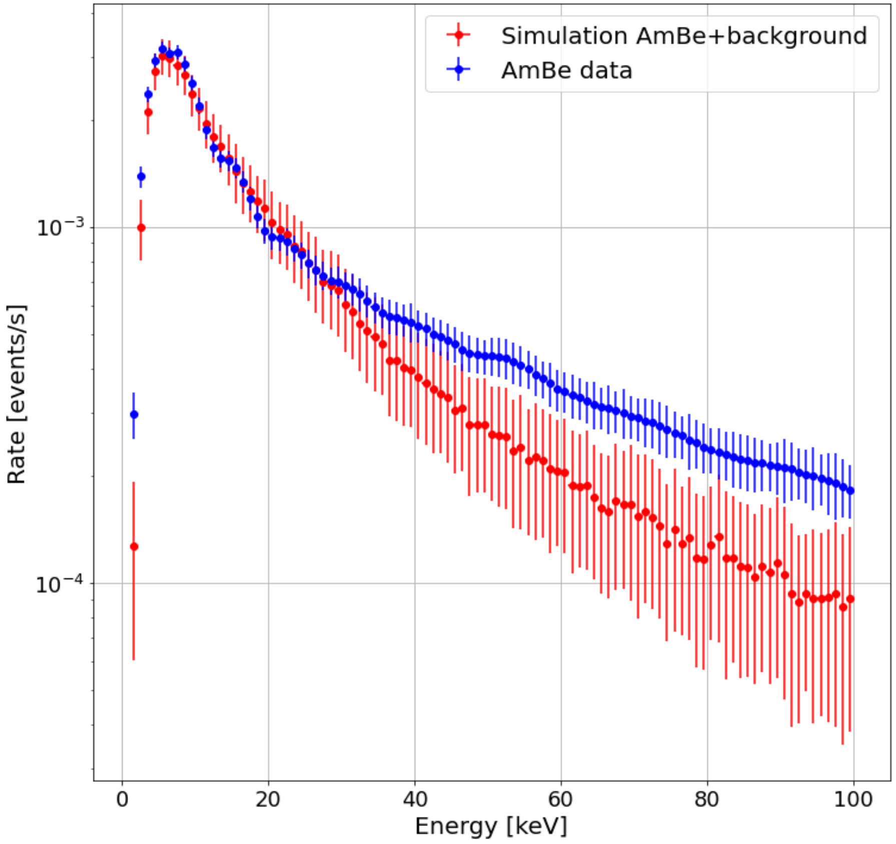
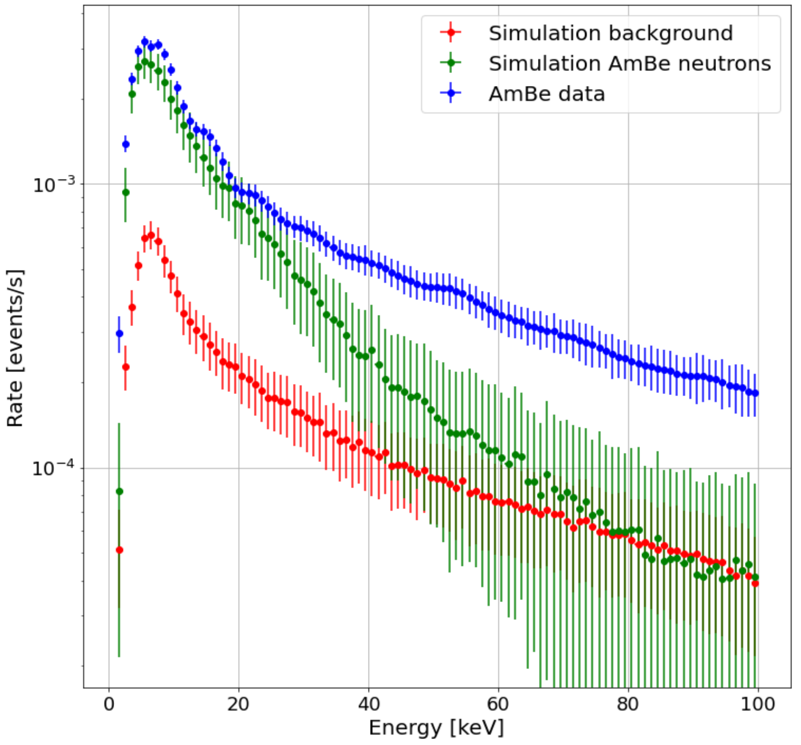
F. Di Giambattista

Results: AmBe



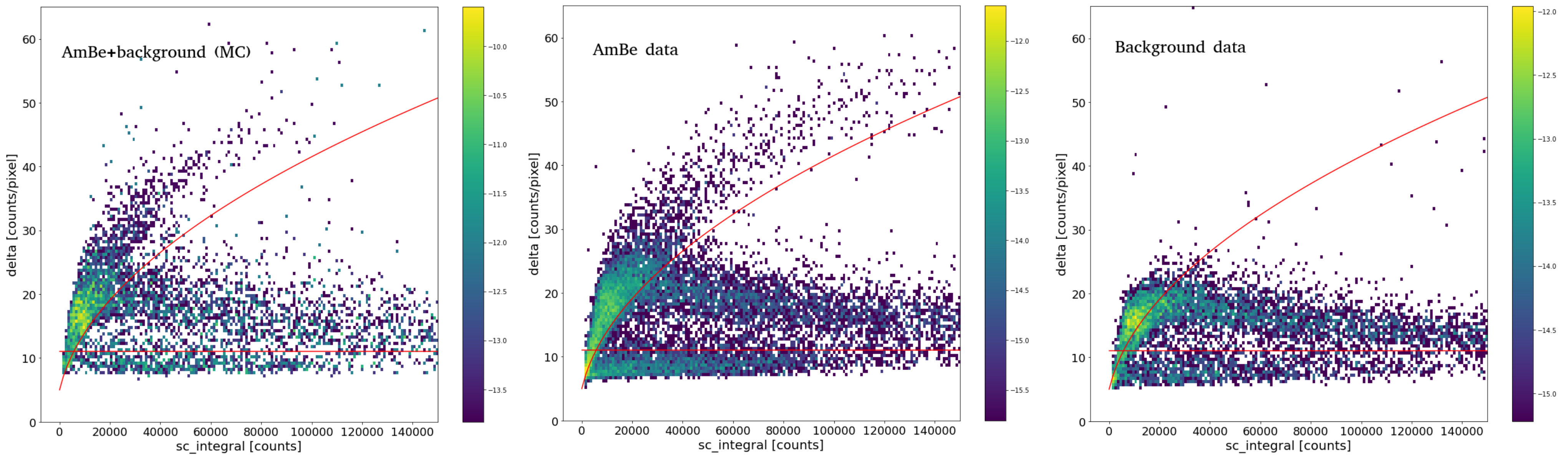
Further confirmation of missing component in the simulated background: when AmBe dominates (<30 keV), data/MC are consistent



AmBe-induced NRs

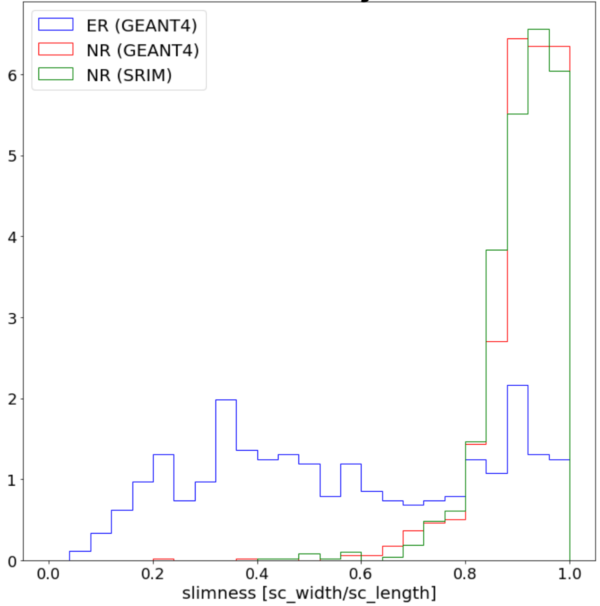
- Preliminary look at shape variables for ER/NR discrimination
- A clear high-density, low-energy population appears in AmBe data, consistent with AmBe neutron simulation → NRs

δ vs uncalibrated energy

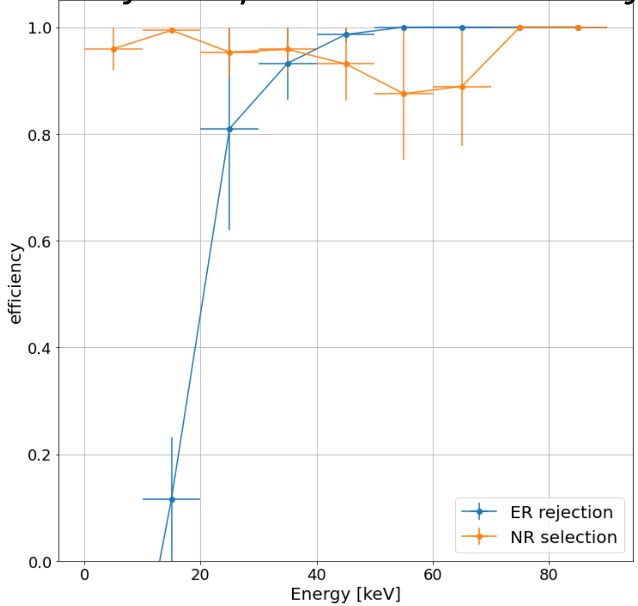


AmBe-induced NRs

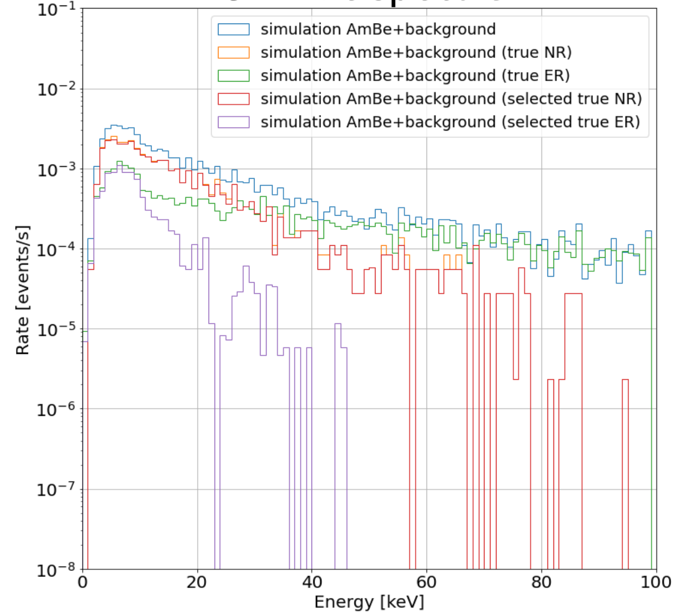
Track minor over major axis ratio



ER rejection/NR selection efficiency



MC AmBe spectrum



- Simple selection optimized on MC, cut on **track energy density** and **slimness** yields good **ER rejection** (>80% at 20 keV)
- Preliminary demonstration of feasibility of neutron flux measurement (Run 5)
- ML algorithm developments ongoing for ER/NR discrimination

Conclusions

- **LY variations** over time (dependent on pressure, humidity, gas contamination) strongly influence not only energy measurement, but also track reconstruction efficiency

    → stabilize LIME conditions (*achieved* in Run 4)

- Charge gain **saturation** has an important role in detection of dense tracks (low energy ERs, alpha)

    → extensive tests on GEM gain, drift field, transfer field (*ongoing)*

    → analysis development for correcting LY as a function of z *(ongoing)*

- Varying gas quality and **contamination** plays a major role

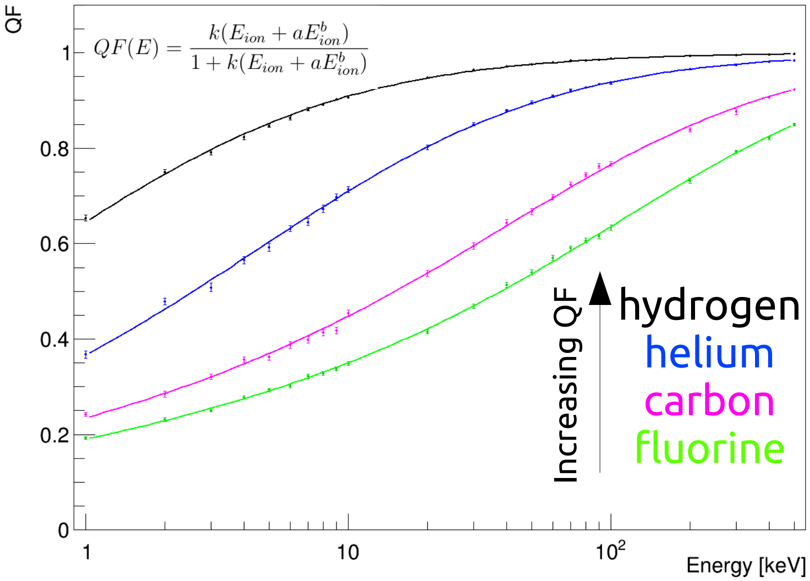
    → low radioactivity filters (*under test)*

- **AmBe data** show the feasibility of detecting and selecting NR events

    → further development of PID analysis (*ongoing)*, directionality studies

backup

Quenching factor



- NRs also undergo nuclear losses (invisible)→ **ionization quenching factor (QF)**

$$QF = \frac{E_{ioniz}}{E_r}$$

- **Assessing the QF** is fundamental for WIMP searches
- Determines the **visible shape** of the track → ER/NR discrimination, directionality, HT

- Energy threshold is different for each NR species → influence on minimum WIMP **mass sensitivity**

Energy threshold	1 keV_{ee}		0.5 keV_{ee}	
	$E_{r,thr}$ [keV_{nr}]	$m_{\chi,min}$ [GeV]	$E_{r,thr}$ [keV_{nr}]	$m_{\chi,min}$ [GeV]
Hydrogen	1.4	0.5	0.8	0.3
Helium	2.1	1.0	1.2	0.7
Carbon	3.1	1.9	1.8	1.4
Fluorine	3.8	2.5	2.2	1.9

3D track's ionization profiles

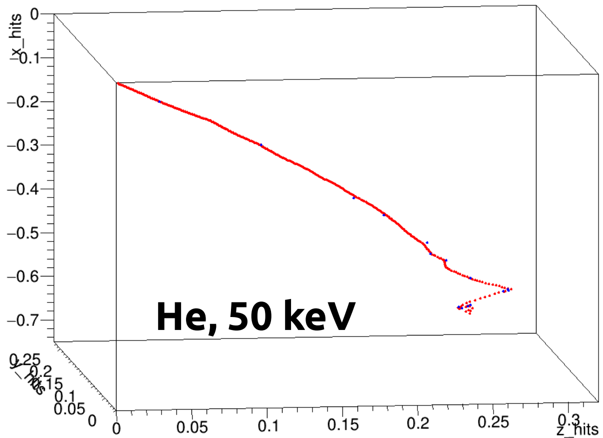
- Developed an algorithm to produce 3D NR tracks ionization profiles from SRIM

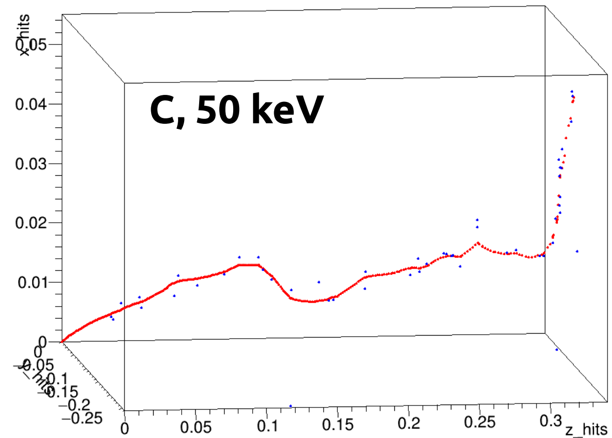
3D position as a function of E_r

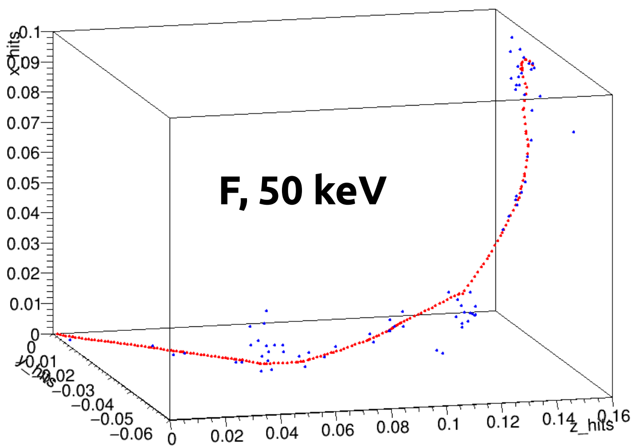
Generate NR cascades along path

Correct energy losses with QF

$$F(E) = \frac{d(E \times QF(E))}{dE}$$



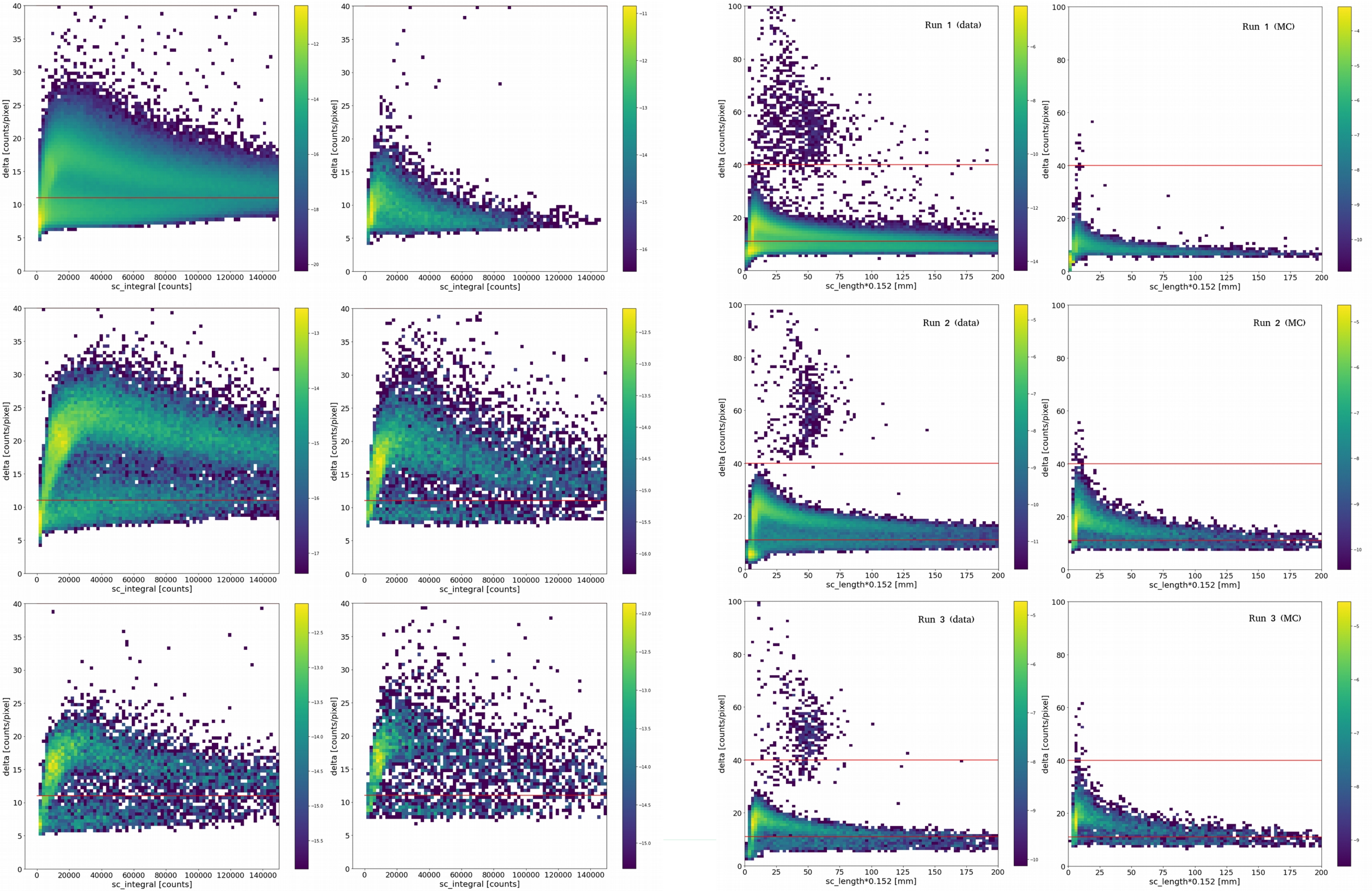




Output: energy hits ΔE(x,y,z)

- Developed for the Collaboration to carry out track shape studies
- Integrated in standard CYGNO simulation, as input for sCMOS images simulation

http://www.srim.org/index.htm


Run 1 (data)
Run 1 (MC)
Run 2 (data)
Run 2 (MC)
Run 3 (data)
Run 3 (MC)
delta [counts/pixel]
sc_integral [counts]
sc_length*0.152 [mm]