EXCESS2022 Workshop

February 16th, 2022

Measurement of low-energy Compton scattering with a DAMIC-M skipper CCD

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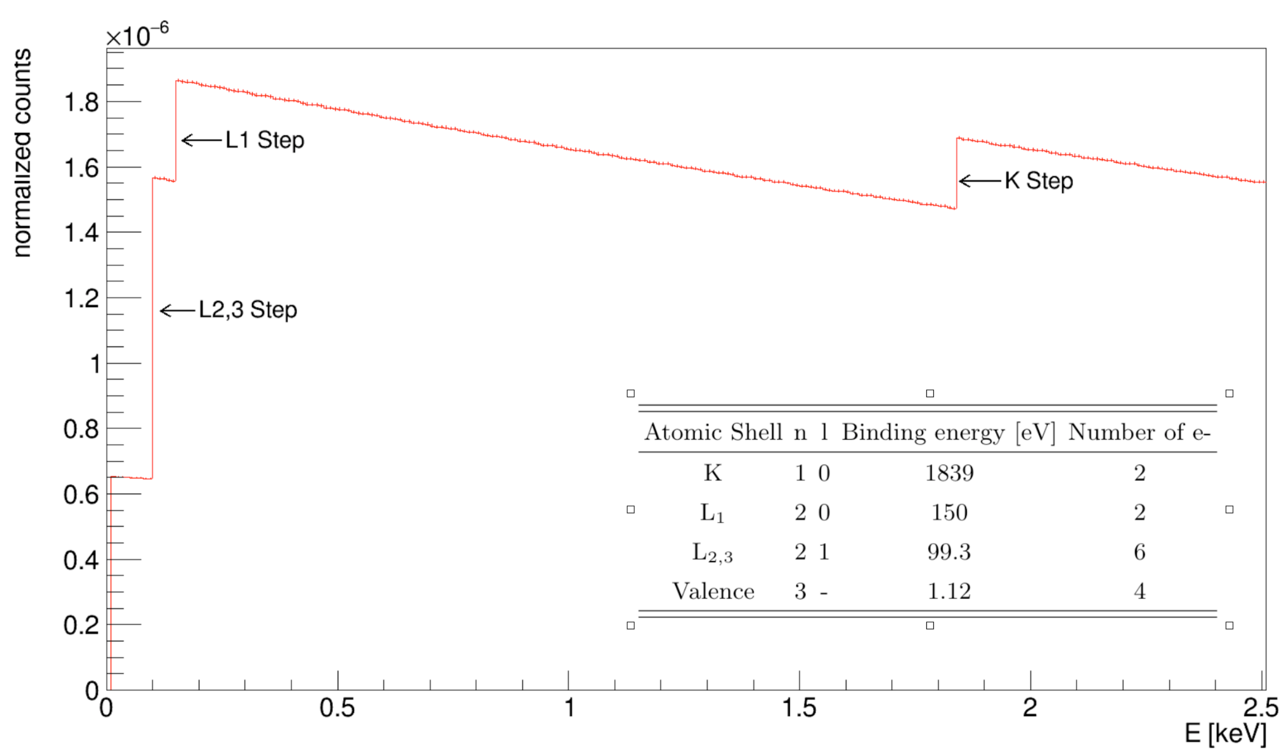
for the DAMIC-M Collaboration

- Motivation
- Review of previous measurements
- Experimental setup
- Data analysis
- Results and outlook

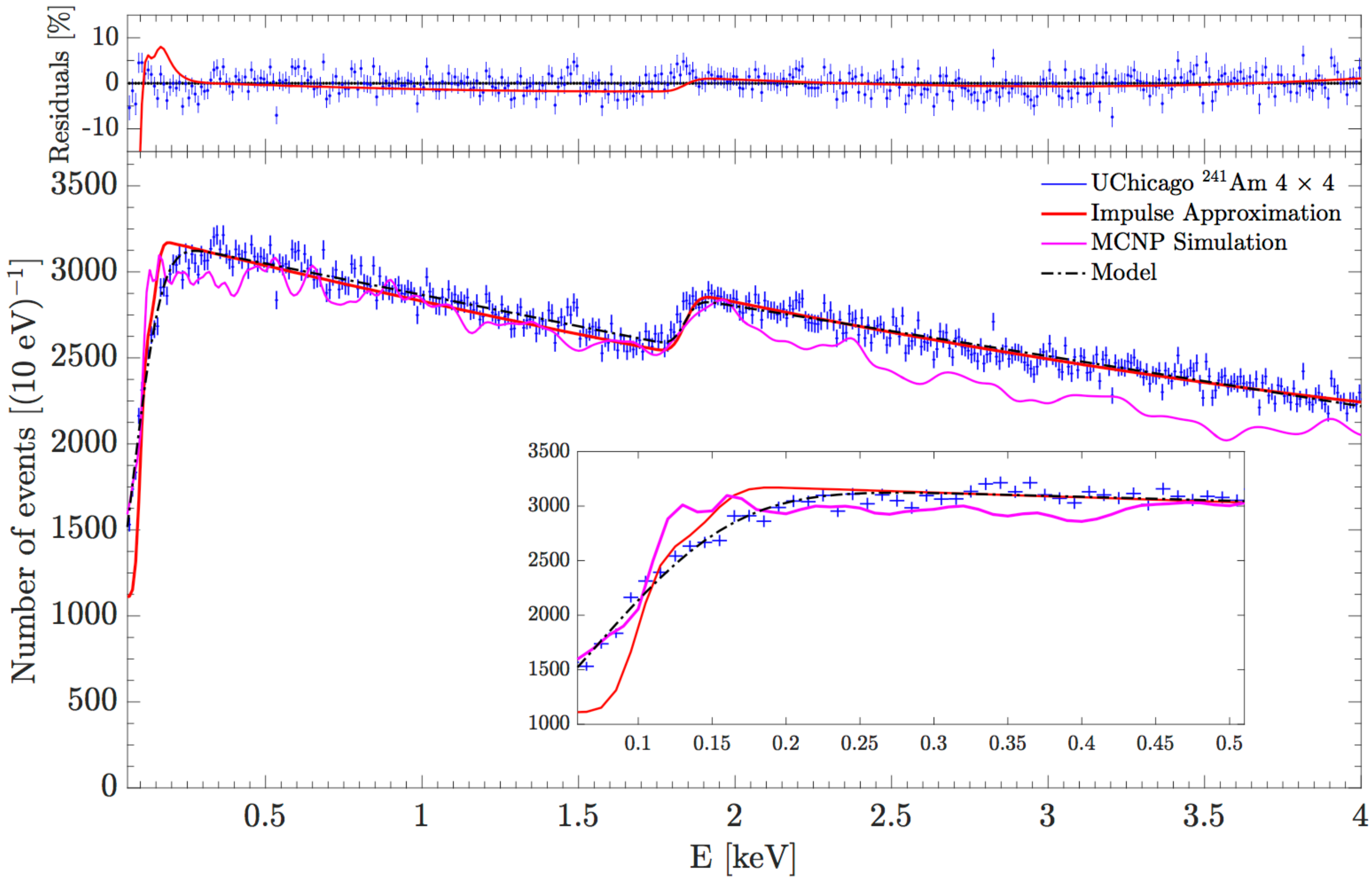
Why Compton scattering?

- Provide detector calibration relevant for DM searches with the new generation of experiments featuring few eV thresholds
- Unique because produces low-energy electrons in the bulk of the detector, vs a low-energy beta source which makes only surface events
- Compton induced events may be a substantial contribution to the background at very low energy: validation of Monte Carlo simulations (e.g. Geant4) employed to build background models is essential. An EXCESS may just be a background component not properly simulated.
- Probe our understanding of scattering with electrons bound in semiconductors, relevant also for DM-electron scattering
- Theoretical calculations for Compton scattering involve approximations (e.g. the Relativistic Impulse Approximation, RIA) that may not be valid at recoil energies of few eV. Measurements at these low energies will be essential to guide improvements in the theory (which we can then implement in our Monte Carlo simulations)
- The lowest threshold measurement published so far (K. Ramanathan et al, Phys. Rev. D 96, 042002 (2017)) observed a noticeable deviation from the prediction of the RIA model



<u>A new measurement with lower threshold is required</u>

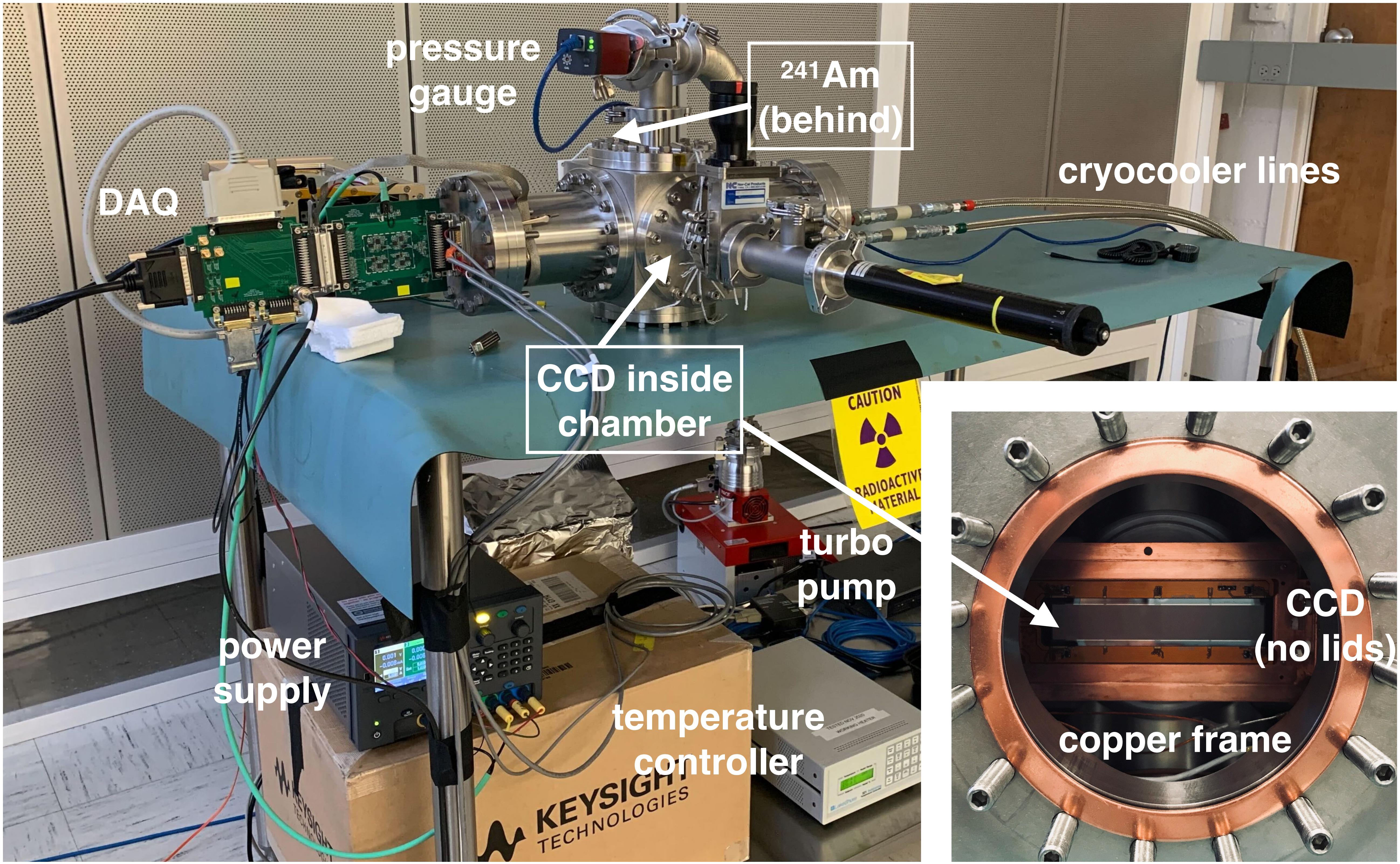
Previous Results



K. Ramanathan et al, Phys. Rev. D 96, 042002 (2017)

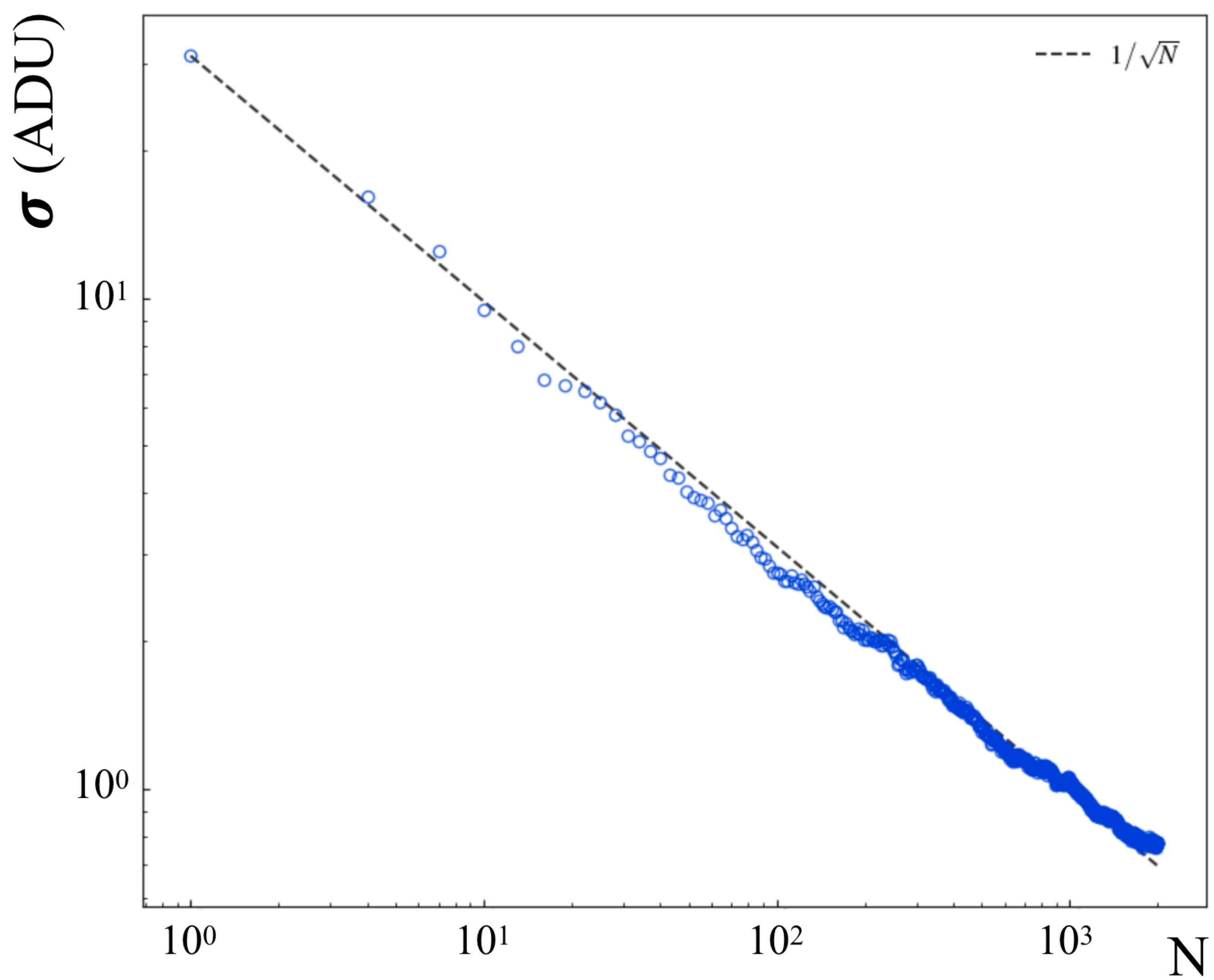
- Significant differences between data and the predictions of Impulse Approximation/MCNP simulation; the spectrum shape softening around L-shell energies cannot be explained by experimental resolution
- Plateau below $L_{2,3}$ shell (99 eV) not observed, at the limit of experimental resolution

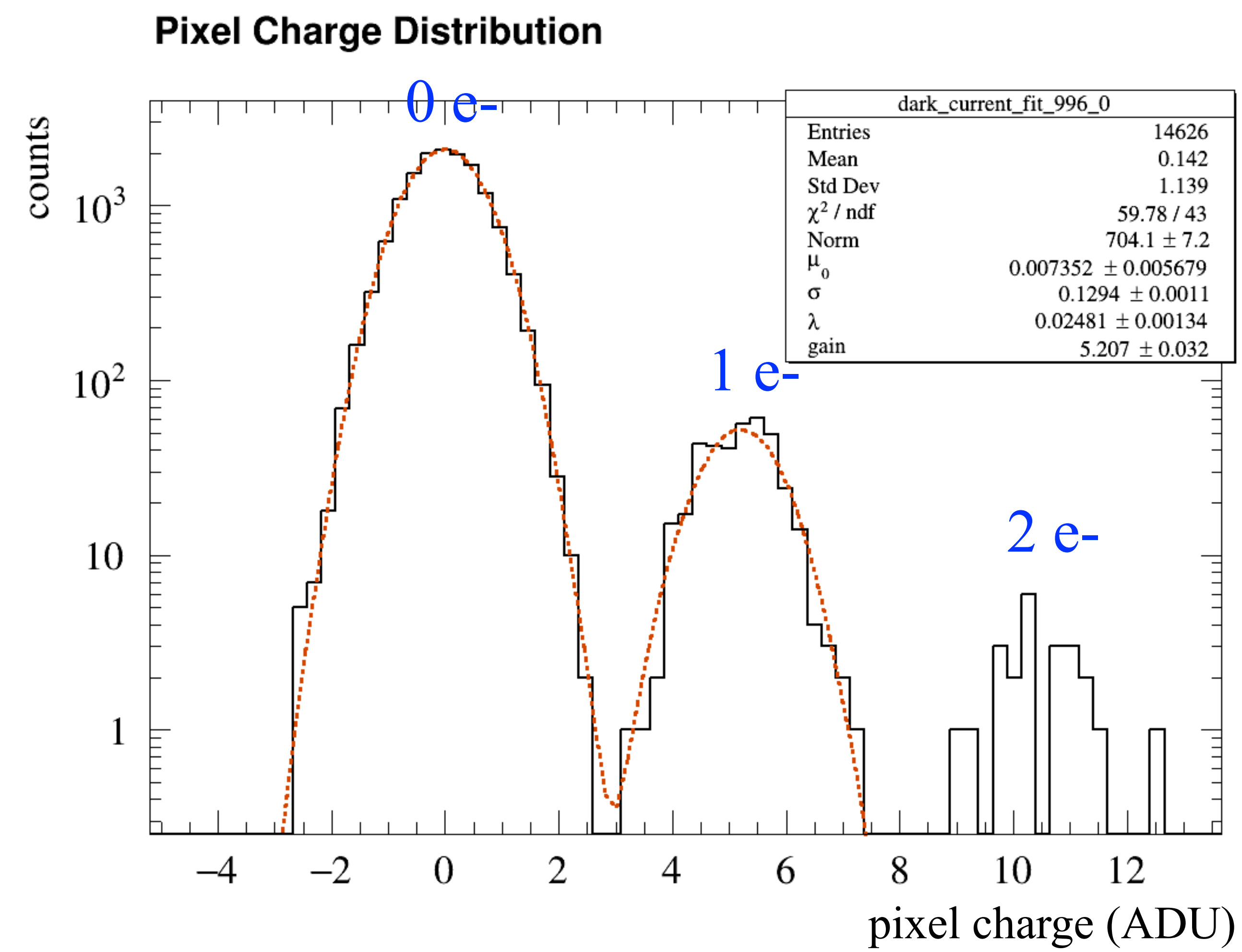
New setup with a DAMIC-M Skipper CCD



Skipper CCD with single electron resolution

- The measurement was performed with a prototype DAMIC-M 1k x 6k CCD (15 μm x 15 μm pixel size), 675 μm thick
- The CCD has Skipper readout: N multiple non destructive charge measurements reduce the pixel readout noise by sqrt(N)





- Single-electron resolution allows counting of individual electrons
- Caveat: readout time is much larger than in a standard CCD (proportional to N)

Data Taking

- A significant statistics is required for an accurate measurement at low energy (>10^6 events). This requires an optimization of CCD readout parameters and the ^{241}Am activity, to ensure that data collection is completed in a reasonable time and the images are not too crowded (pileup of clusters may distort the energy spectrum).

- We found good data taking conditions with binned images (4x4) and N=64 providing a resolution of 0.7 e-
  (binning sums the charge of 4x4 pixels before readout reducing the readout time by 16)

$$\sigma_E^2 = (\sigma_e x 3.74\ \mathrm{eV})^2 + (3.74\ \mathrm{eV})\ F\ E$$

The experimental resolution increases by only 7% the expected resolution from the Fano factor at the L shell energy

- Data set:

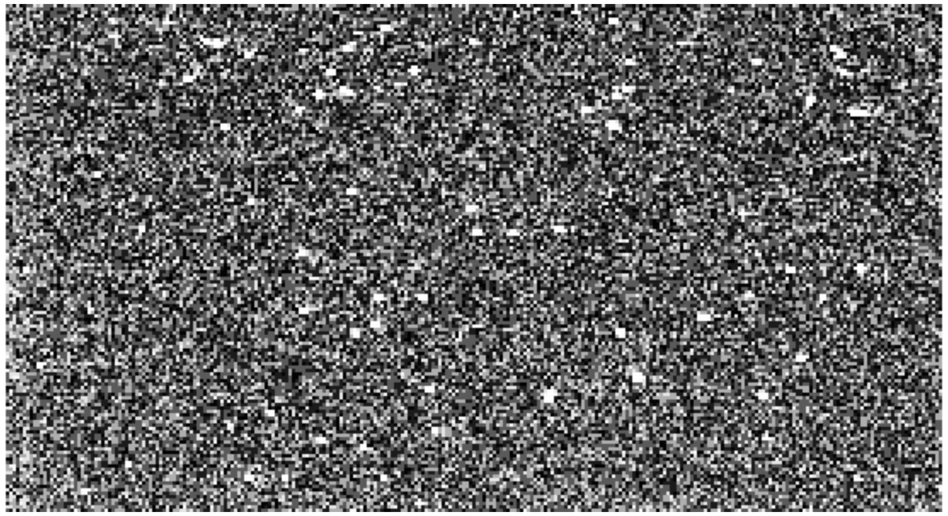
  4x4 binning with ^{241}Am, N=64,
  84.4 days total exposure

  4x4 binning background (no source),
  similar exposure

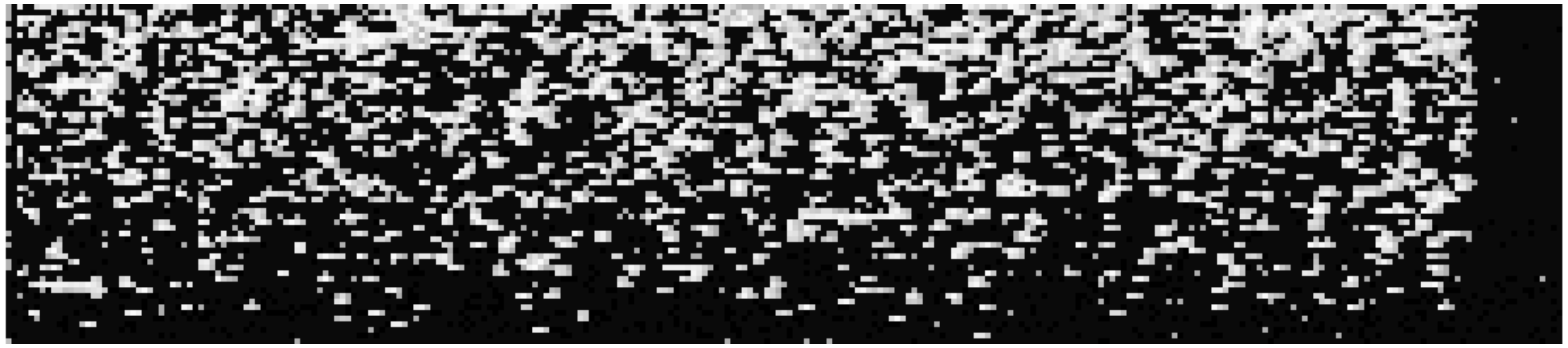
Also for monitoring and calibration we took periodically

no binning, full image

4x16 binning, N=2000 image

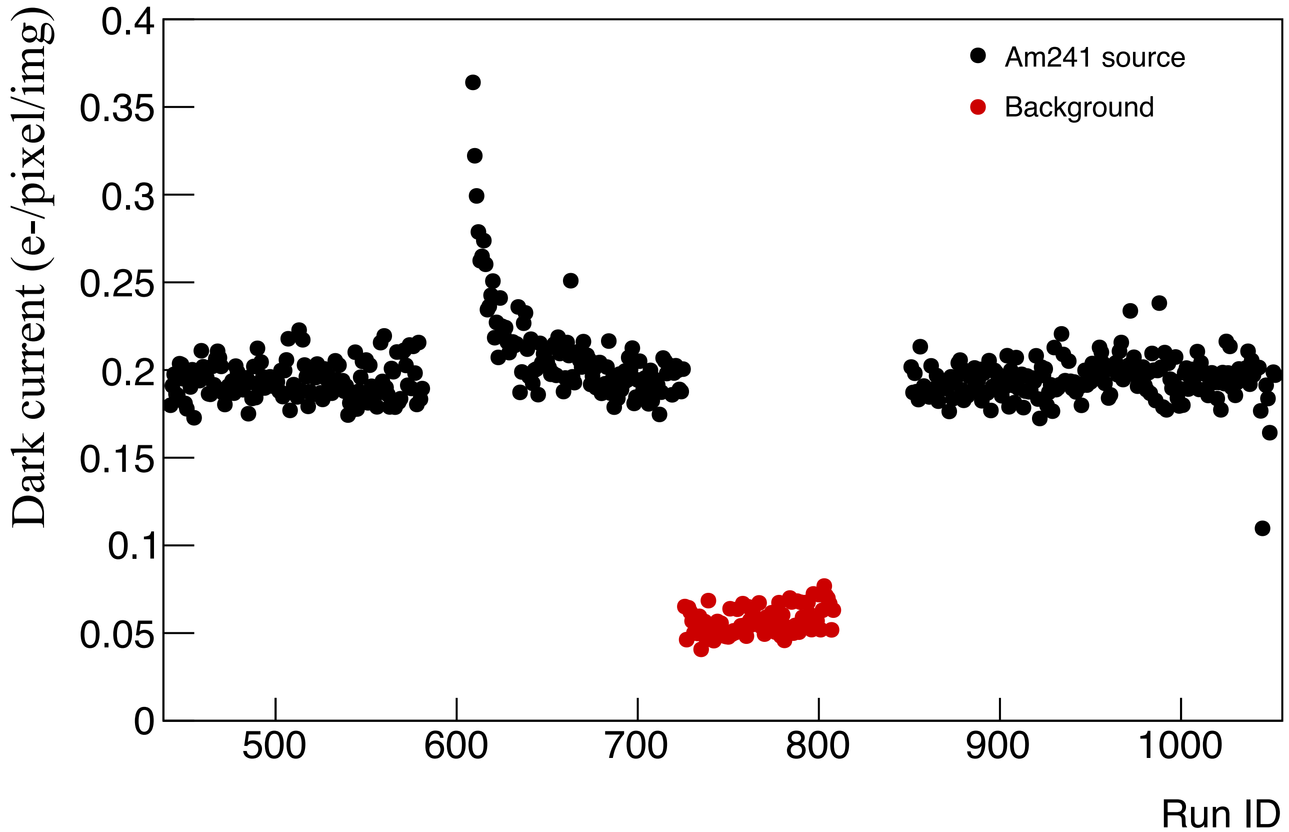


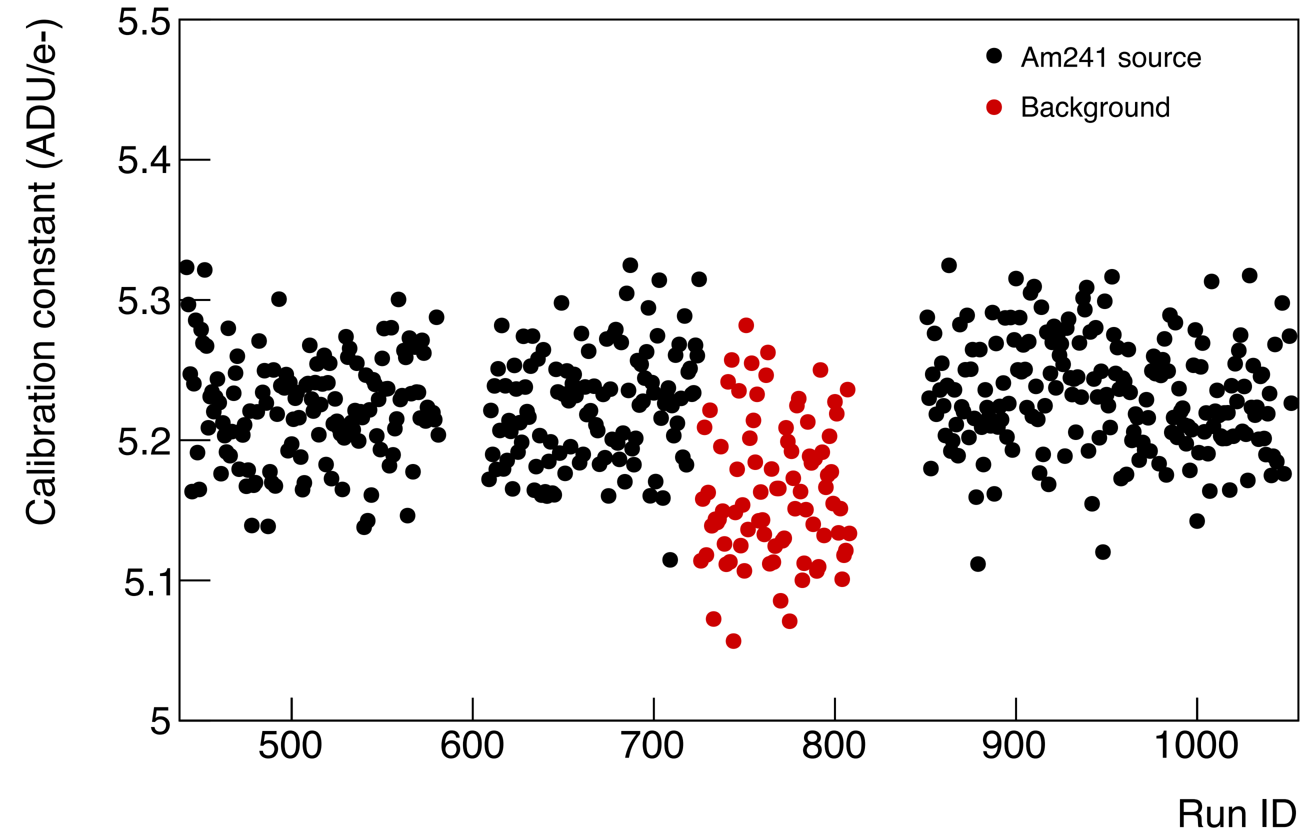
4x4 N=64

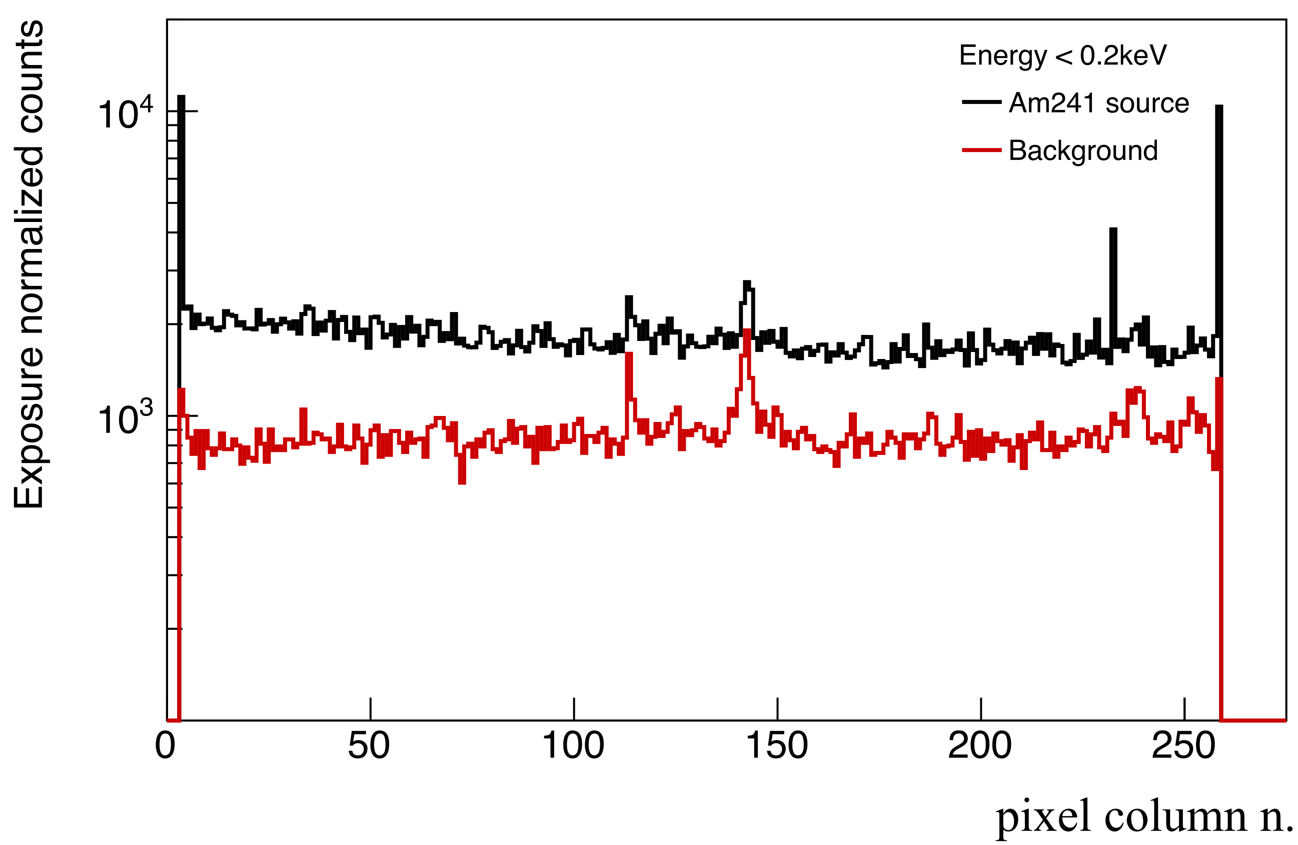


16x4 N=2000

Data Quality



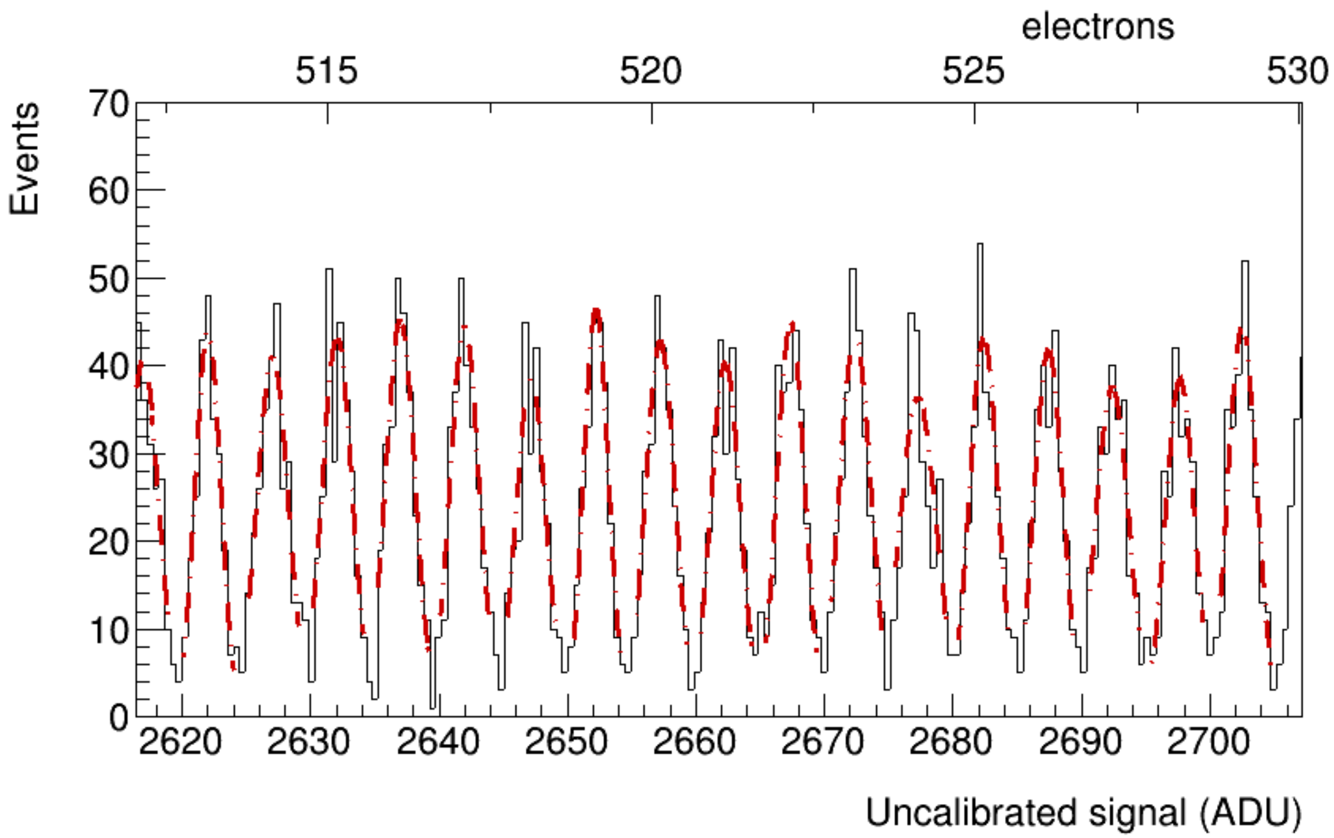


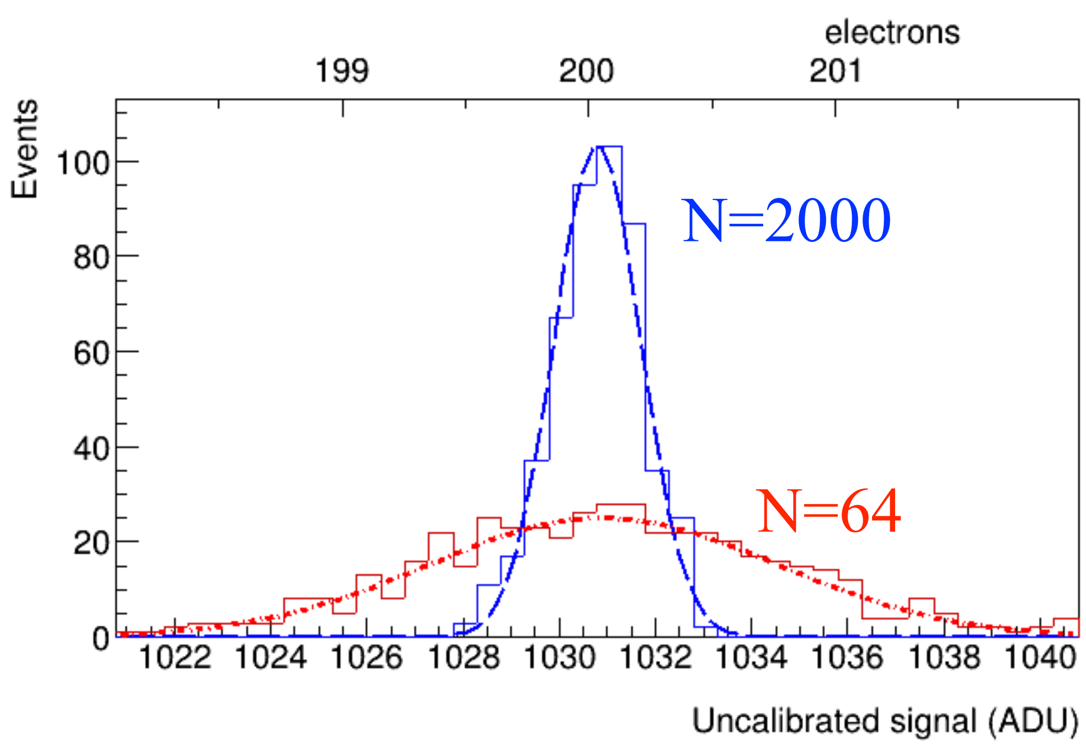


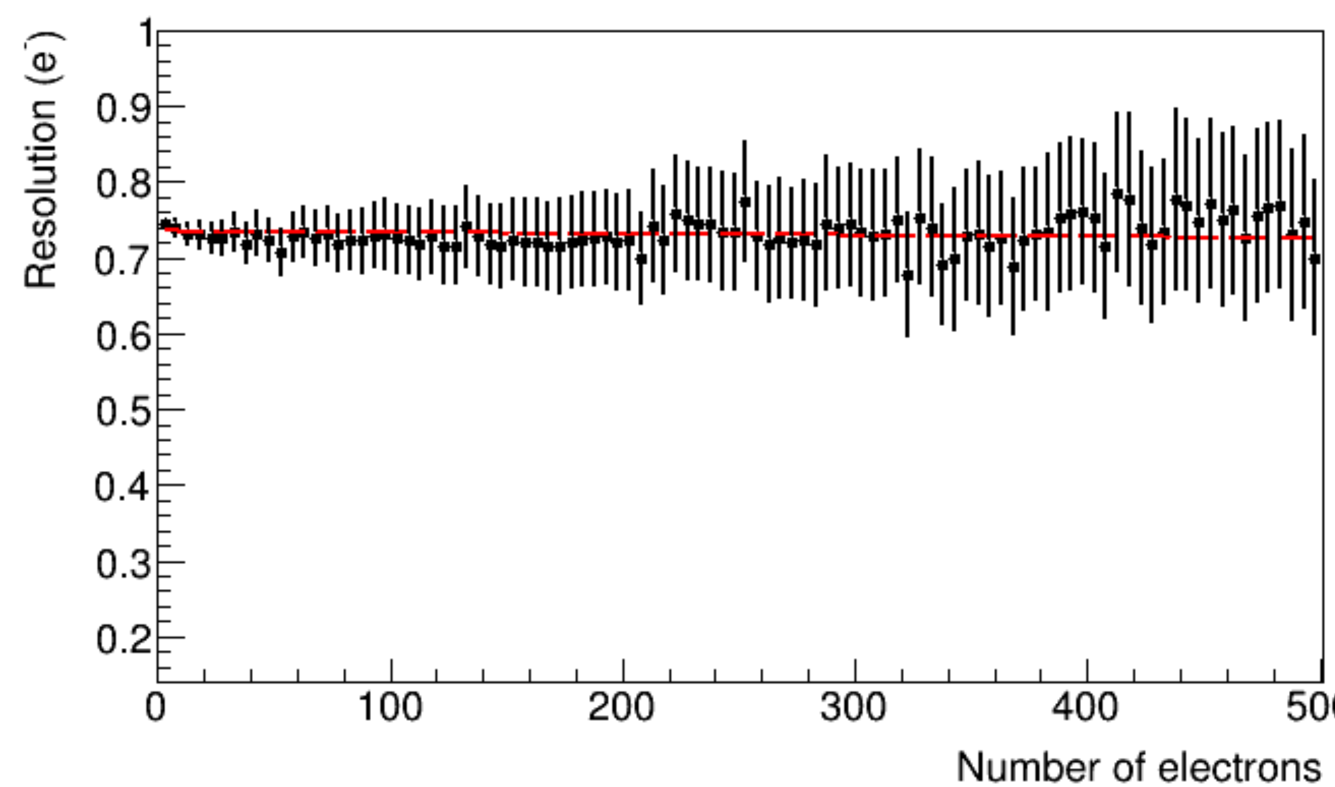
- Data quality was constantly monitored during data taking: stability of baselines, calibration constant fitted from single electron spectra, resolution, dark current, etc. The system operated with excellent stability
- Data selection included rejection of noisy images and masking of "hot" columns/pixels

Calibration

- Single electron resolution provides a powerful (and simple) way to calibrate the pixel charge (measured in ADU) in units of electrons: value in ADU corresponding to the position of the n-peak
- We found a linearity better than few ‰ up to to the K shell energy
- We also measured the resolution: select a peak in the high resolution (N=2000) data and then calculate the charge using only 64 of the 2000 (this also check the linearity of the N=64 data)

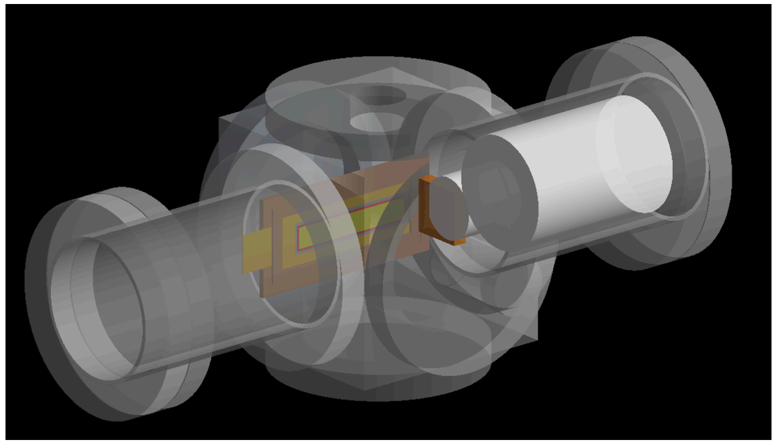


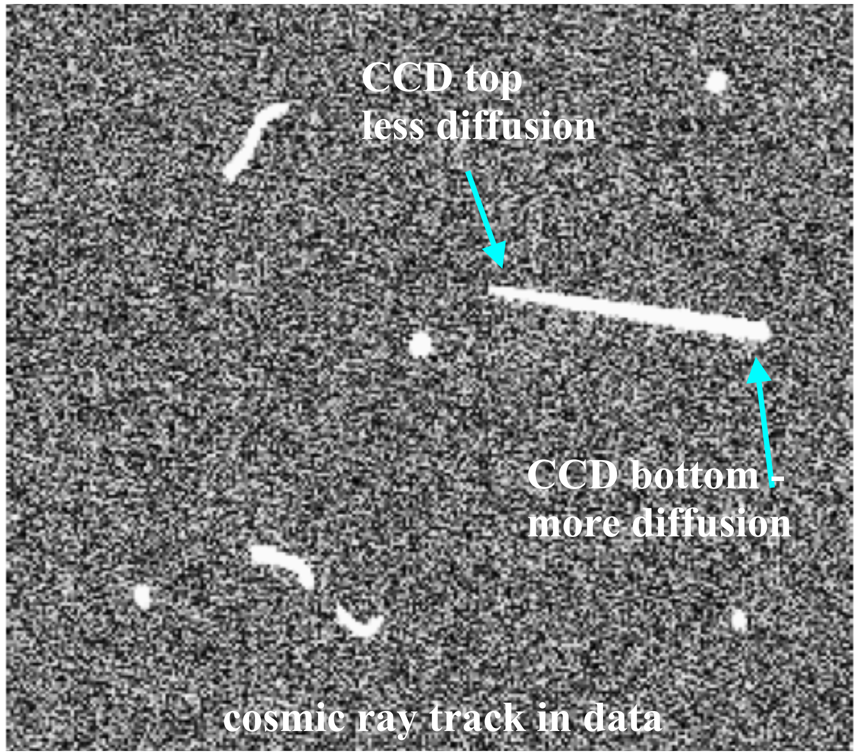




NOTE: the experimental resolution is constant

Simulations





- A full Geant4 simulation of the experiment was performed (several low-energy physics lists were tested)

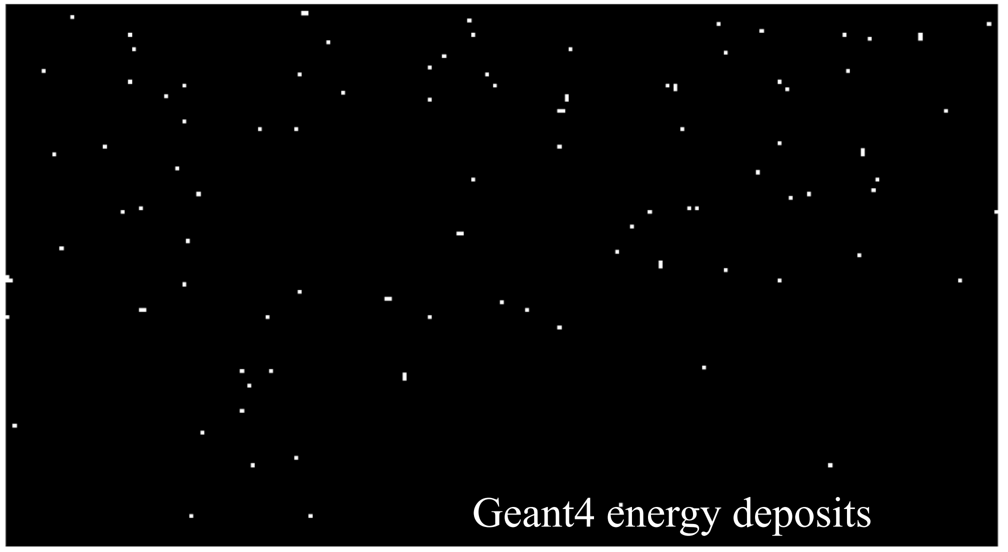
- Realistic simulated images were constructed from Geant4 energy deposits:

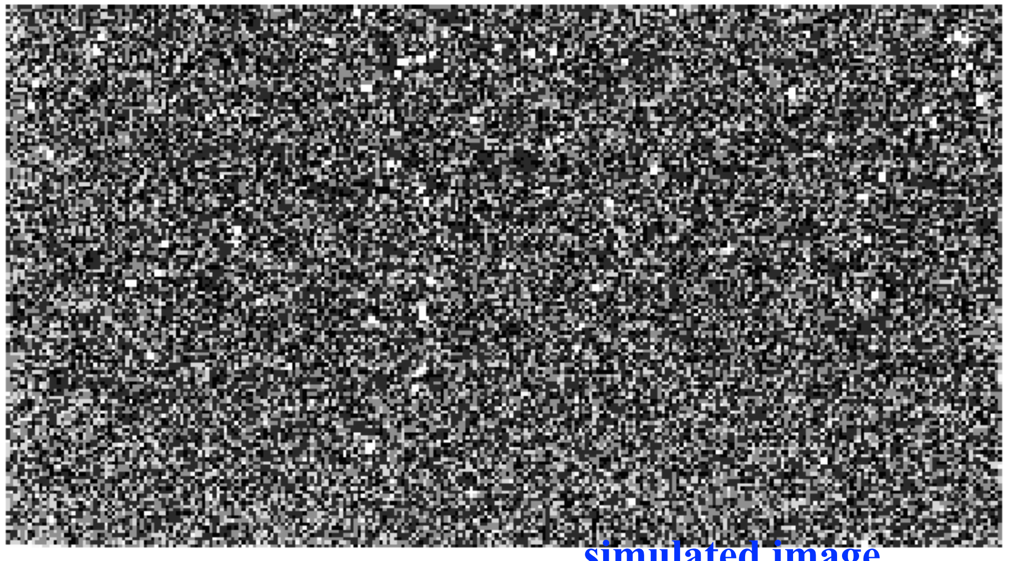
  - The Fano factor is applied to the energy deposit and energy is converted to electrons

  - electrons are diffused in the bulk silicon of the CCD towards the pixel array (diffusion parameters as measured with cosmic rays)

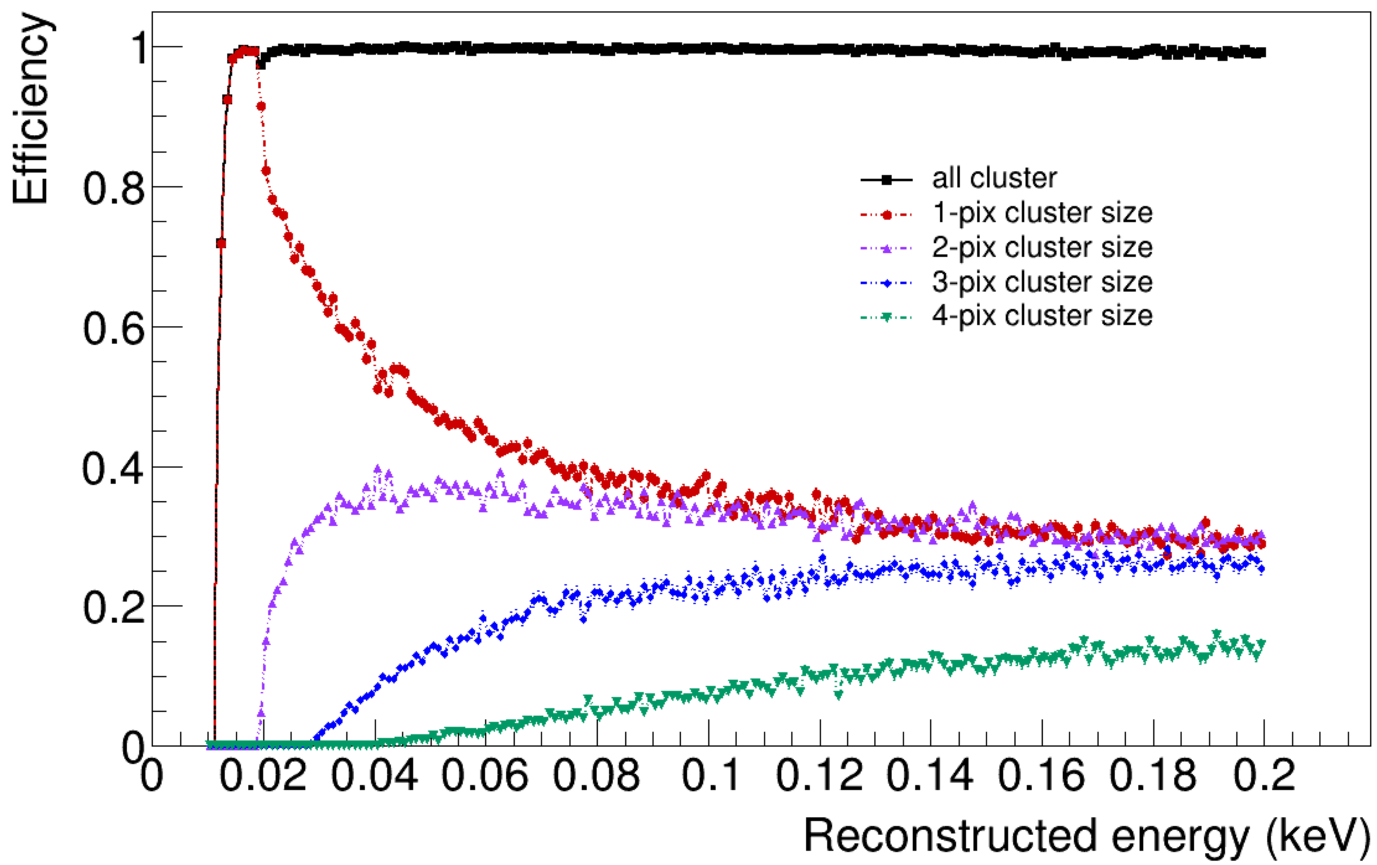
  - charges are assigned to pixels in the array

  - the simulated clusters are pasted in data background images for an accurate reproduction of experimental effects (pixel readout noise, hot pixels/columns, overlap with cosmic ray/radioactive background tracks, dark current) essential for the understanding of backgrounds at the lowest energy



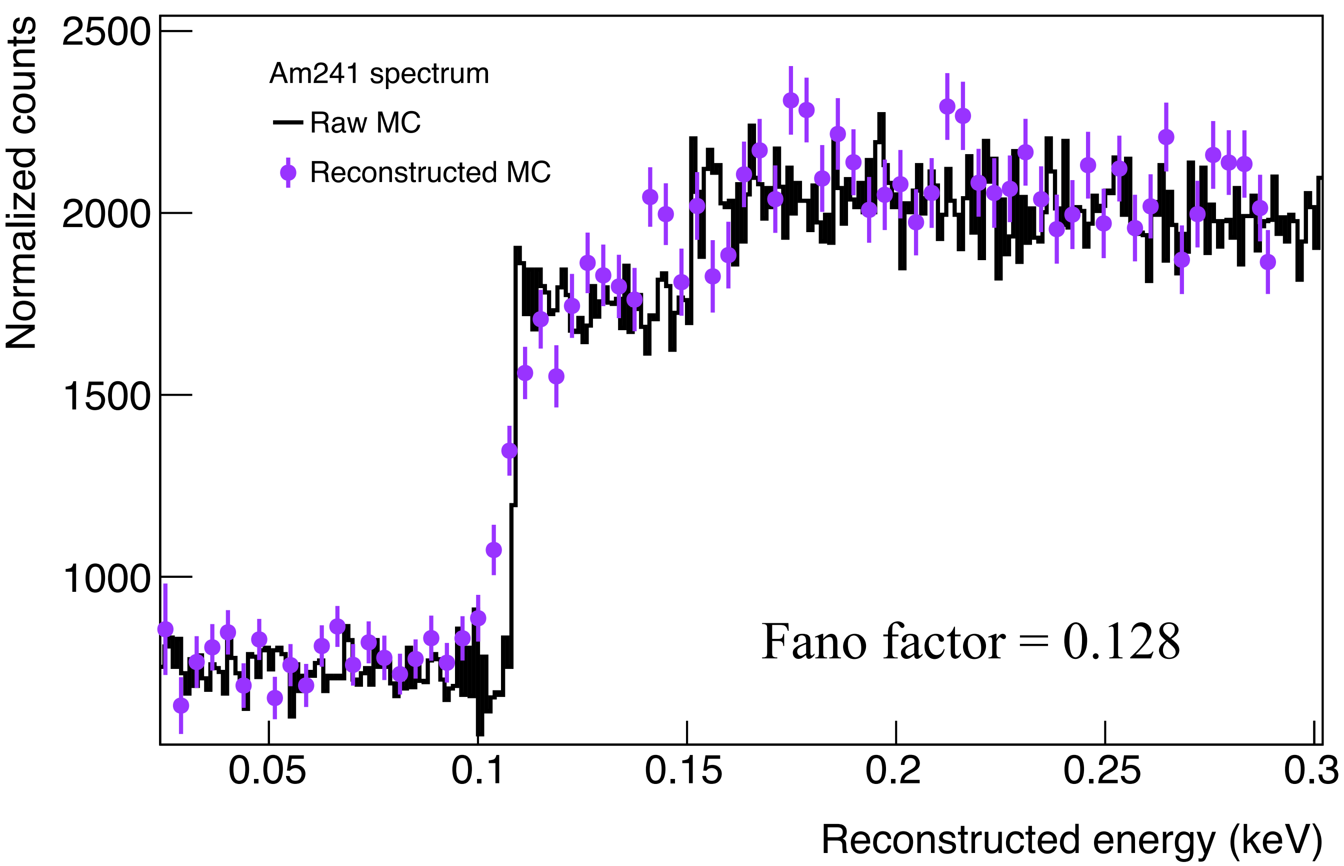


Simulations



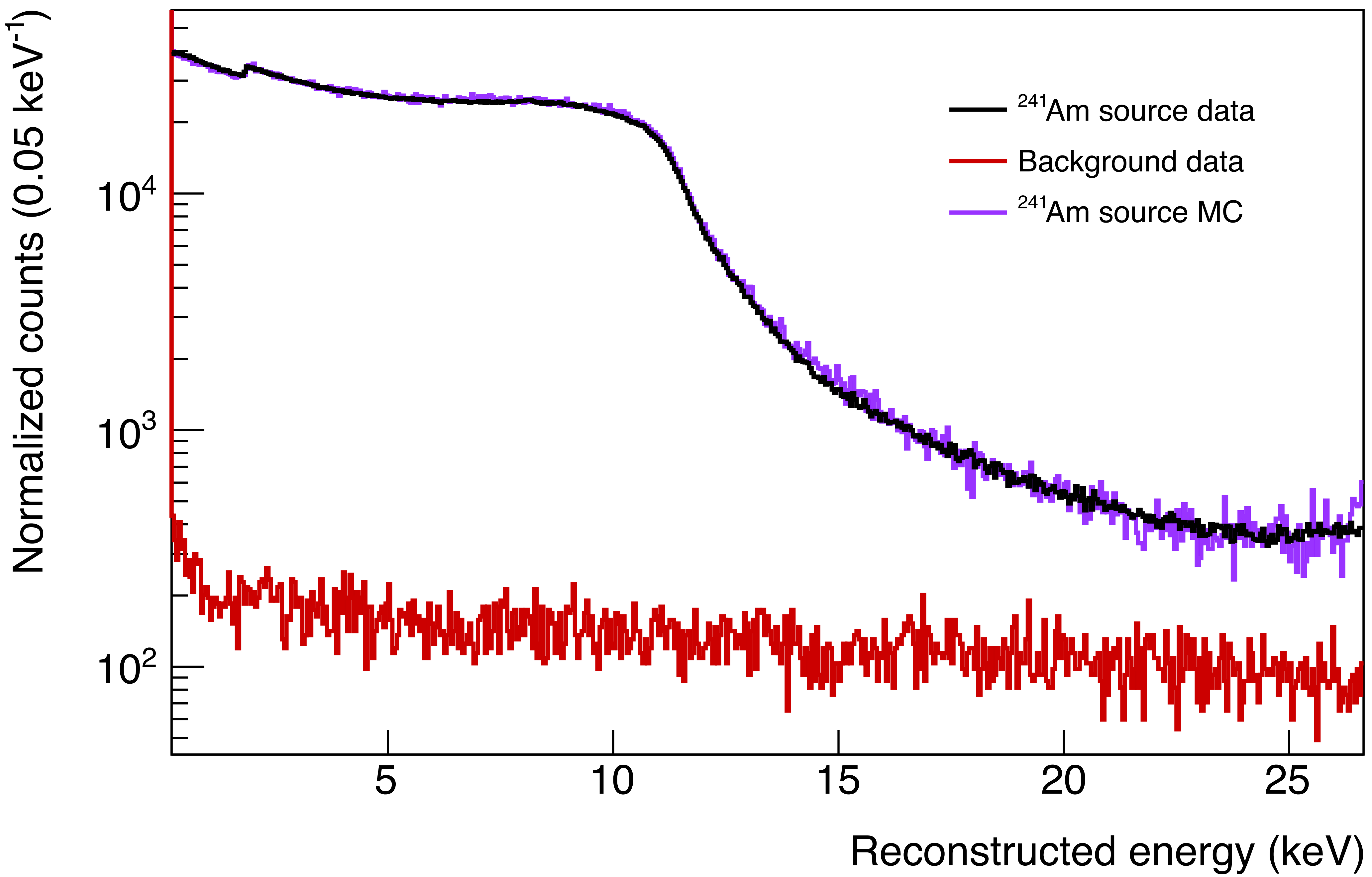
- The simulated images are then processed with the same cluster reconstruction and analysis chain as the data.
- The reconstruction efficiency estimated from MC pasted images is 100% down to 15 eV

- We accurately reconstruct the simulated Compton spectrum reproducing the expected features at the lowest energy (Geant4 implements the RIA model)



(Energy calculated assuming $\varepsilon_{eh} = 3.74$ eV/e-)

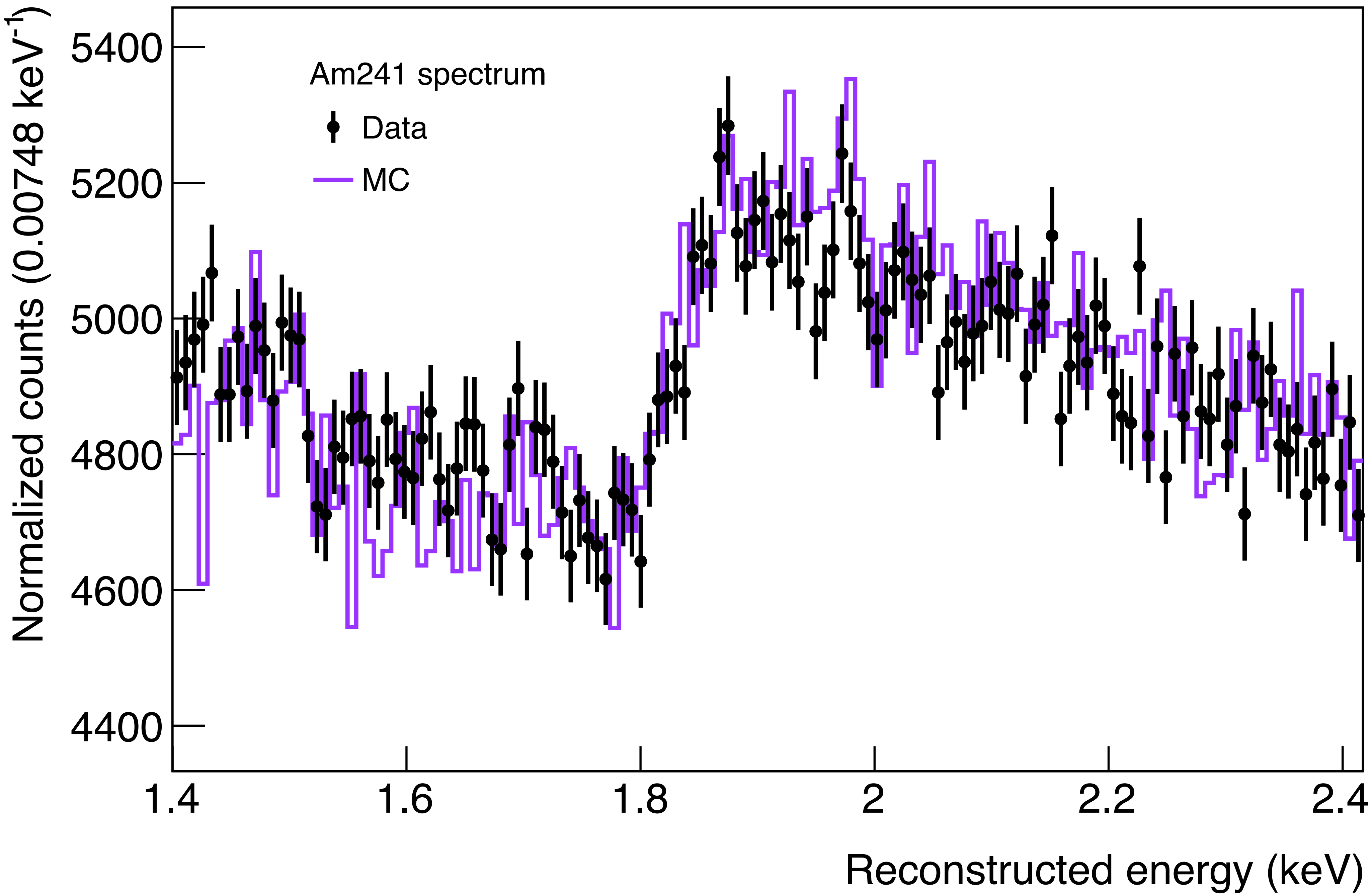
Results in the keV energy range



The measured spectrum at high energy accurately matches the Monte Carlo expectations (data shown up to Compton edge, at higher energy the electronics saturate)

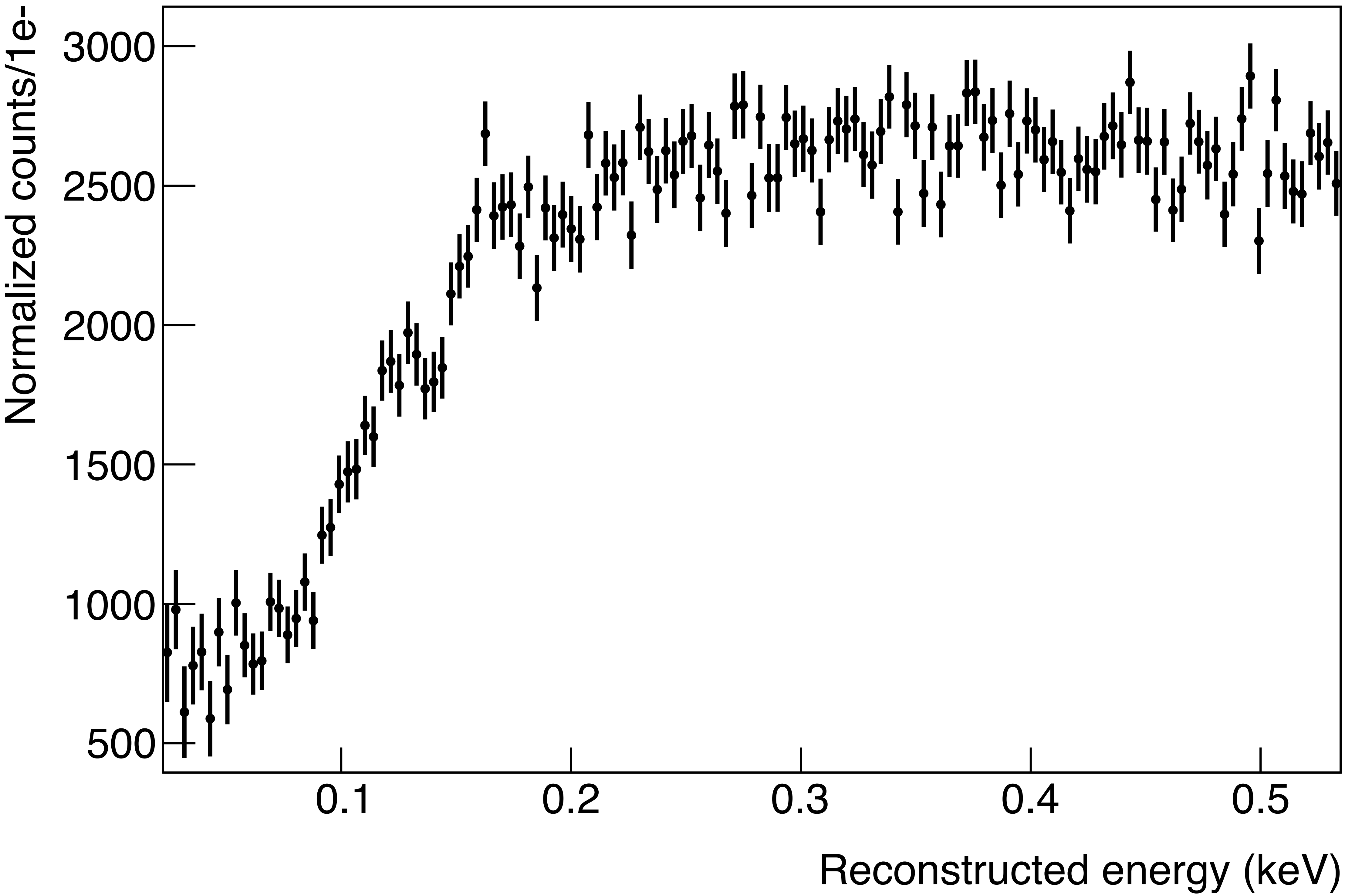
The final spectrum is obtained after background subtraction

Results in the keV energy range



There is also excellent agreement in the K-shell region. Note how the MC reproduces the position of the step indicating an accurate energy calibration (and a value of ε_{eh} close to the nominal 3.74 eV/e-)

Results at the L-shell down to 20 eV (6 e-)



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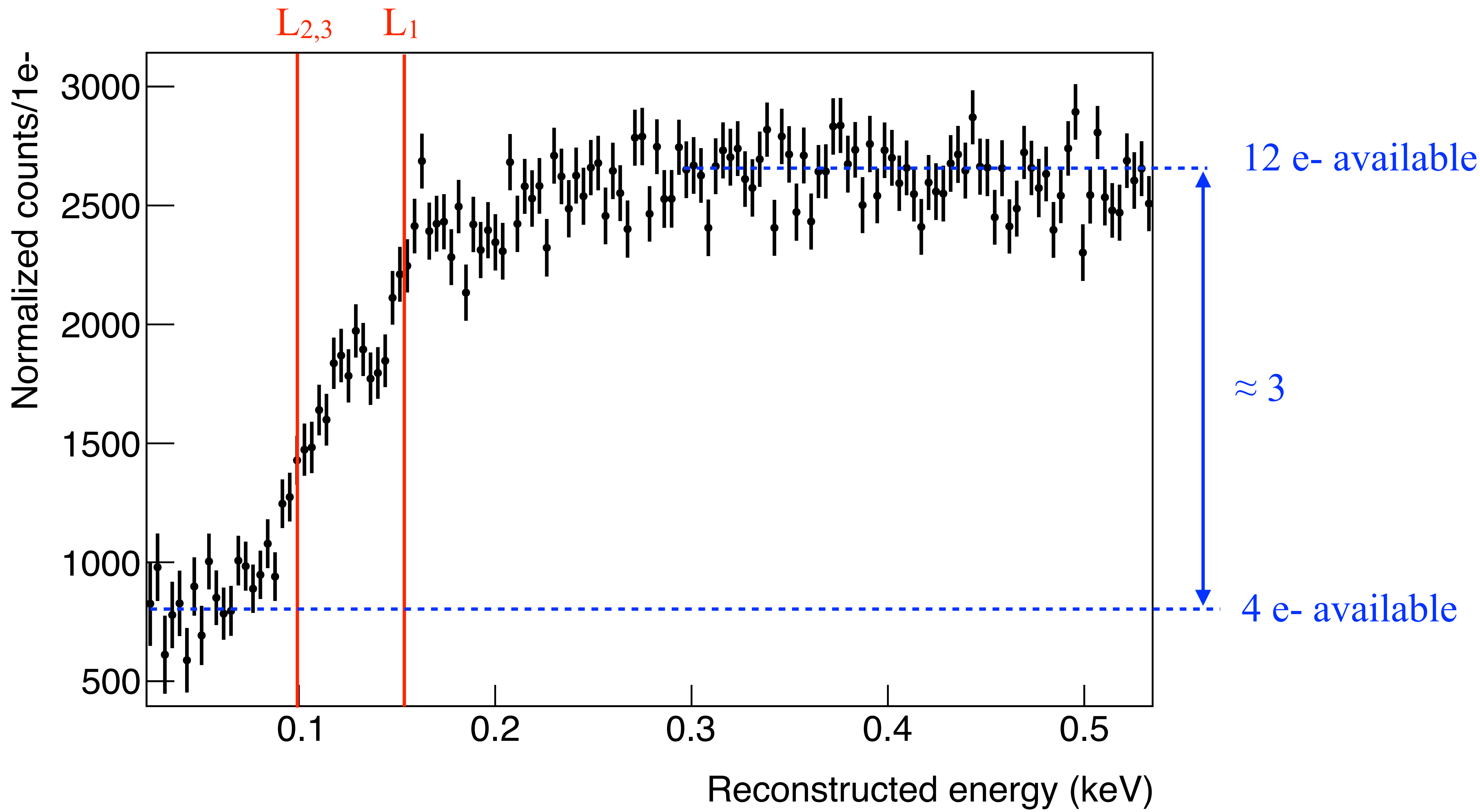
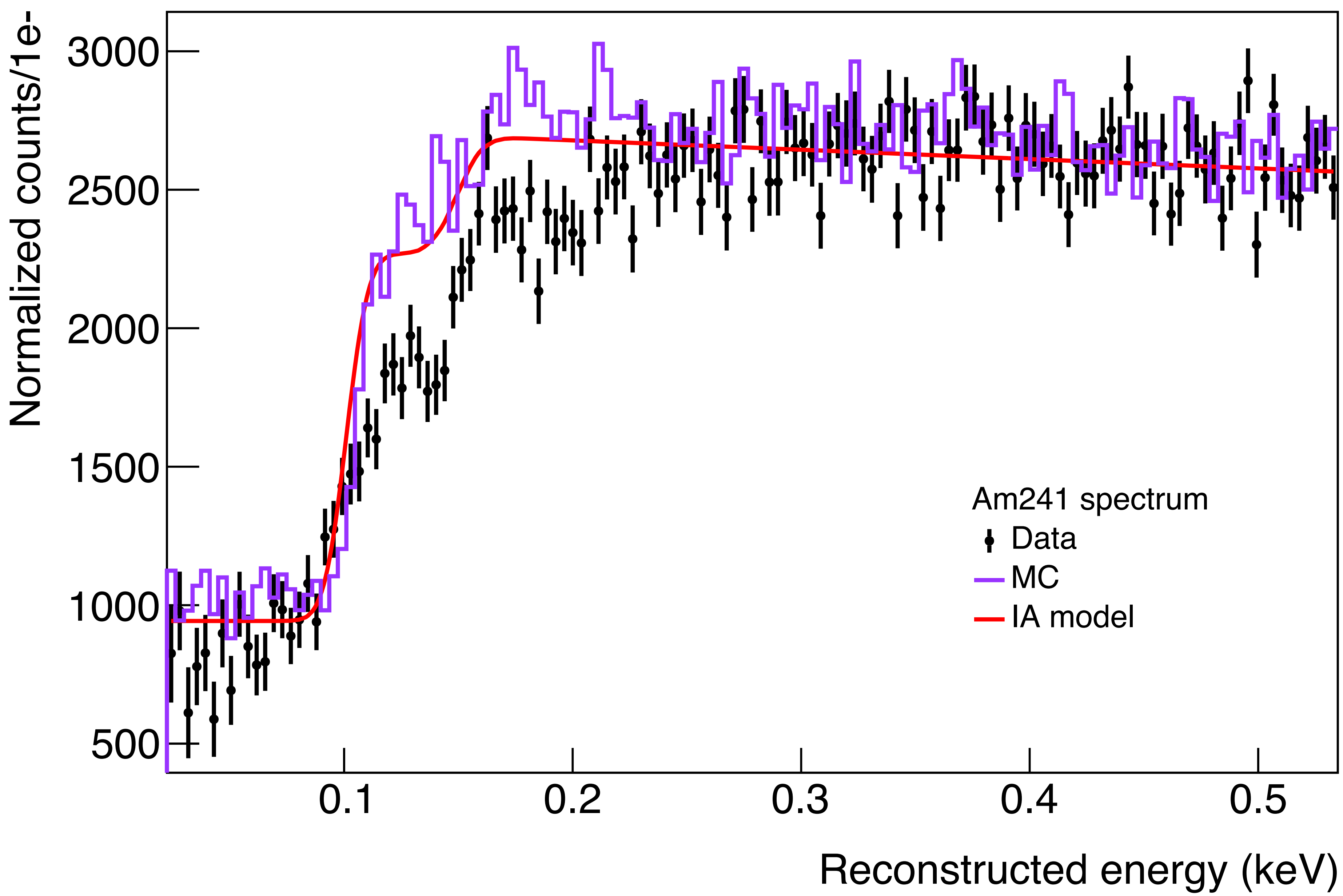


The plateau below the L-edge is clearly observed; the ratio of the rates below/above the L shell energies matches well the expectations (ratio of n. electrons available for scattering)

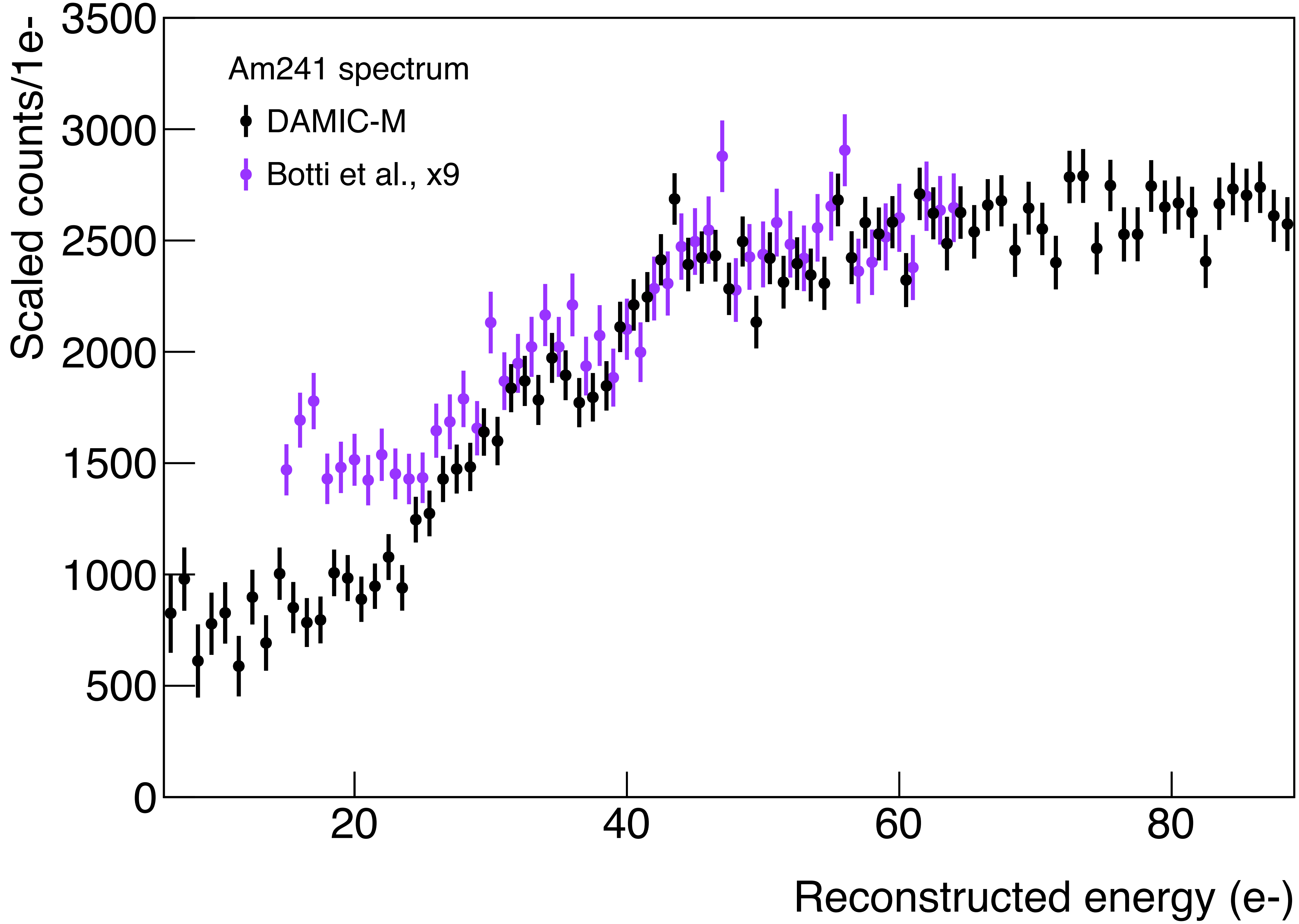
More data necessary to clarify features between L_1 and $L_{2,3}$ energies (plateau? softening of edges)

Results at the L-shell down to 20 eV (6 e-)



The plateau below the L-step is clearly observed; the reduction from the K-shell level matches well the expectations (ratio of n. electrons available for scattering)

The Geant4 Monte Carlo (RIA model) does not reproduce the data in the region of the L step (confirms observations in Ramanathan et al. 2017)



Botti et al. (arXiv:2202.03924) compatible with this measurement, apart at the lowest energy (< 25 e-) where they fail to reproduce the expected step (likely due to background as explicitly stated in Botti et al. paper)

Outlook

- We have performed an accurate measurement of the Compton-scattering energy spectrum in silicon CCDs down to ≈20 eV (6 electrons), significantly improving on published results both in terms of resolution and threshold. Relevant for this workshop:

  - below the L steps (< 100 eV) the measured rate of Compton scattering follows the theoretical expectations. This is good news in terms of reliability of MC estimation of Compton-scattering backgrounds down to 20 eV.

  - there are notable differences in the L step energy range between data and MC; opportunity to test theories of Compton scattering beyond the RIA model and update the MC

- An accurate measurement of the spectrum in the L_1 to $L_{2,3}$ energy range will require higher statistics. We have plans to perform this measurement with an improved setup

- This measurement makes us confident on the prospects for the upcoming nuclear recoil ionization measurement with a photoneutron source with the same setup