COMPARISON OF SIMULATIONS AND DATA FROM SMALL HIGH VOLTAGE SINGLE CRYSTAL DETECTORS FOR DARK MATTER SEARCHES

Final Examination

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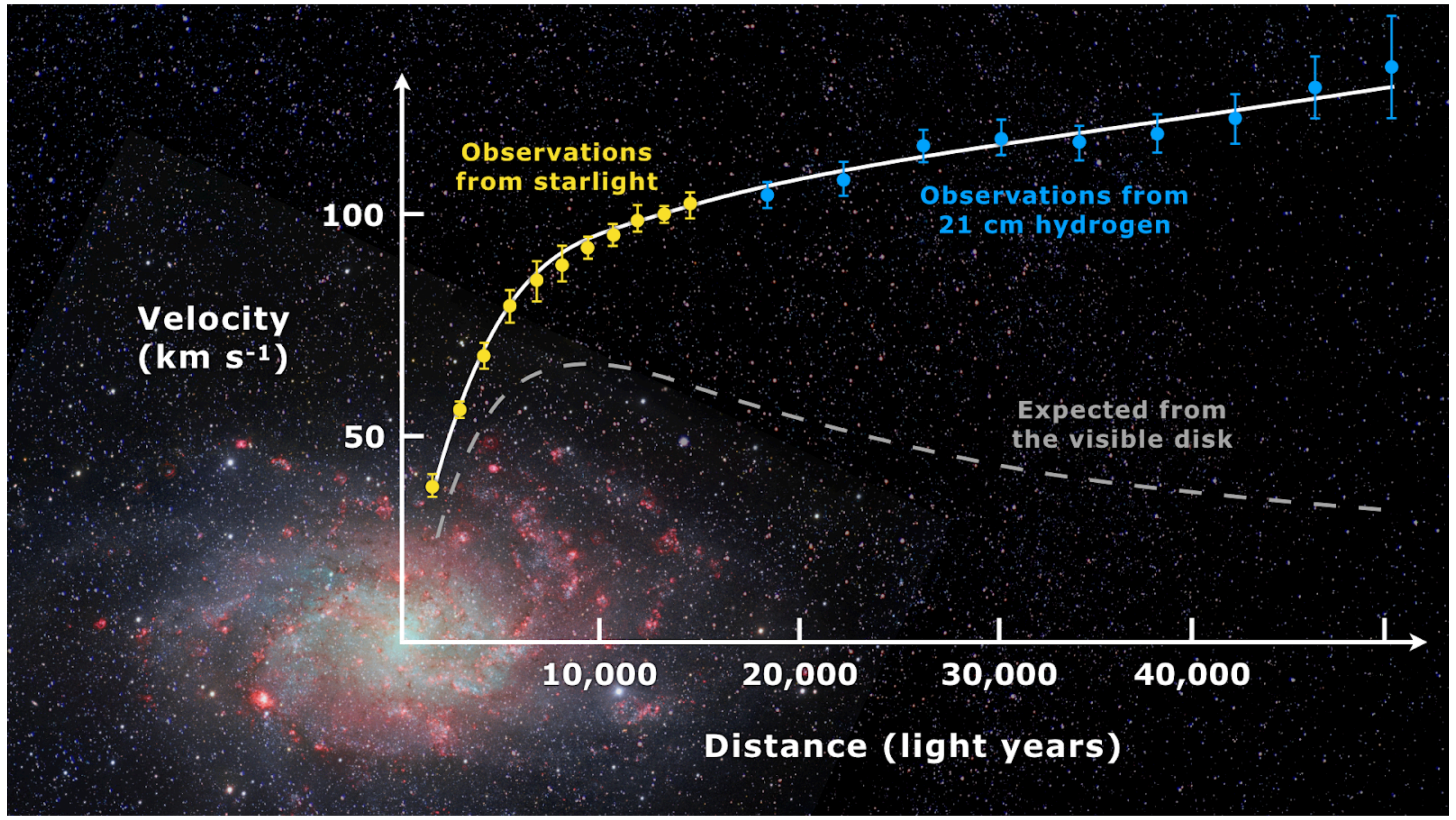
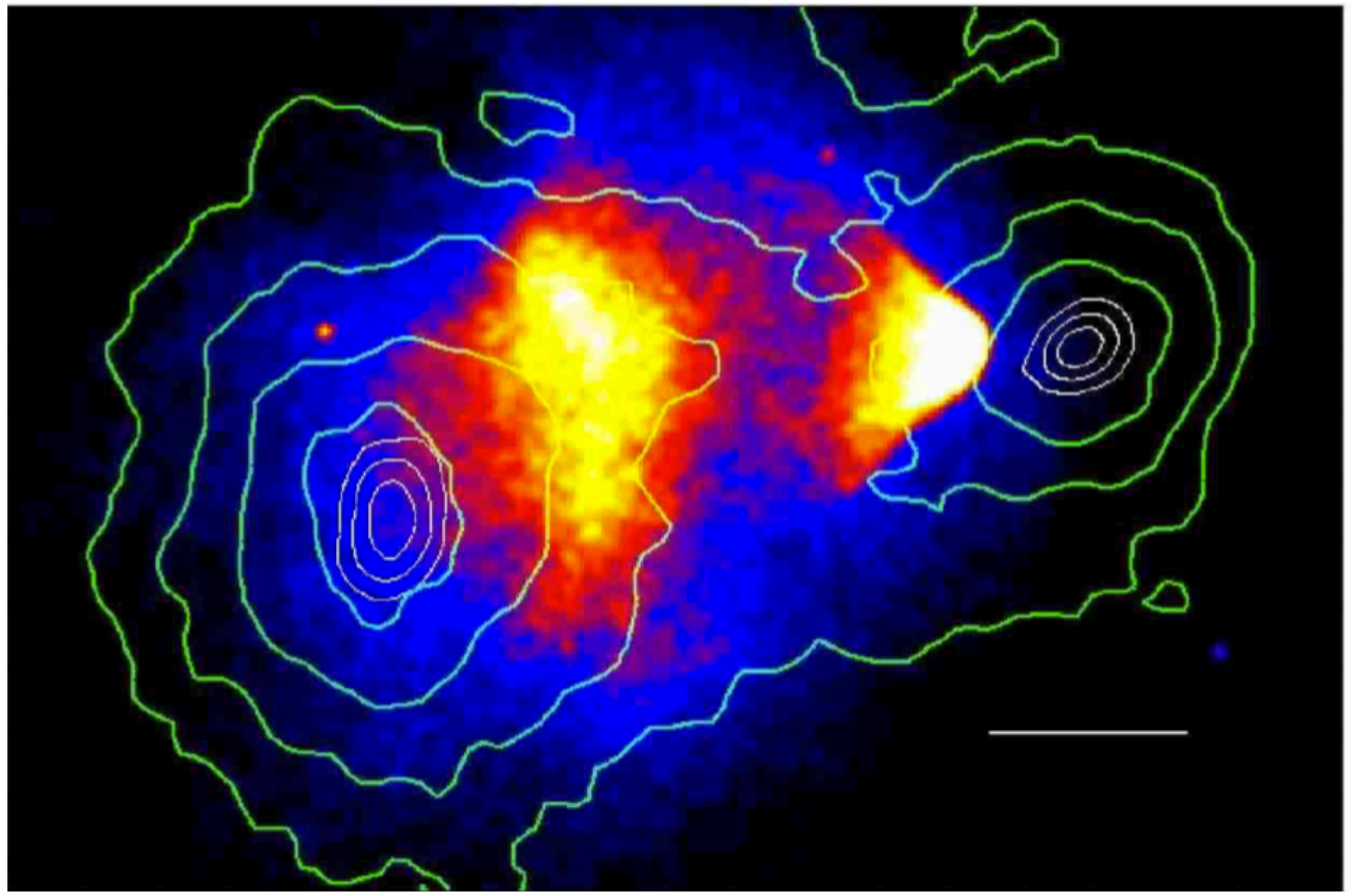
Outline

- Introduction and Motivation
- Detectors
- HVeV Experiment
- HVeV Simulation
- Data and Simulation Comparison
- Conclusions

Introduction and Motivation | Dark Matter Evidence

Numerous observations indicate that the universe mostly consists of unseen massive particles that have no electromagnetic interactions





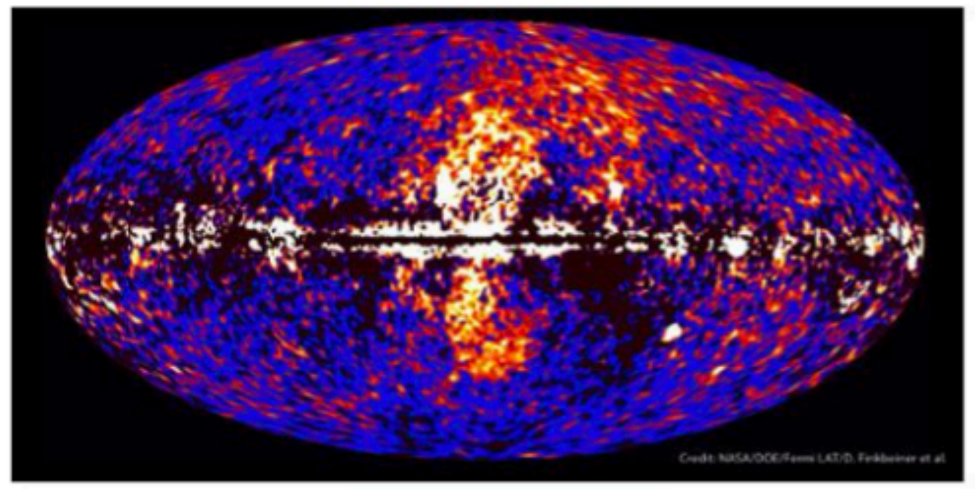
Galaxy Rotation Curves:
Most of the visible mass of the galaxies is concentrated in the center. We would expect rotation velocity to decrease as we get further from the center. This is not consistent with observation.

Bullet Cluster:
Two galaxy clusters collided. We expect most of the matter in the yellow region where we get the x-rays. This is not consistent with the gravitational lensing map (green curves). This suggests that dark matter most likely consists of minimally interacting particles.

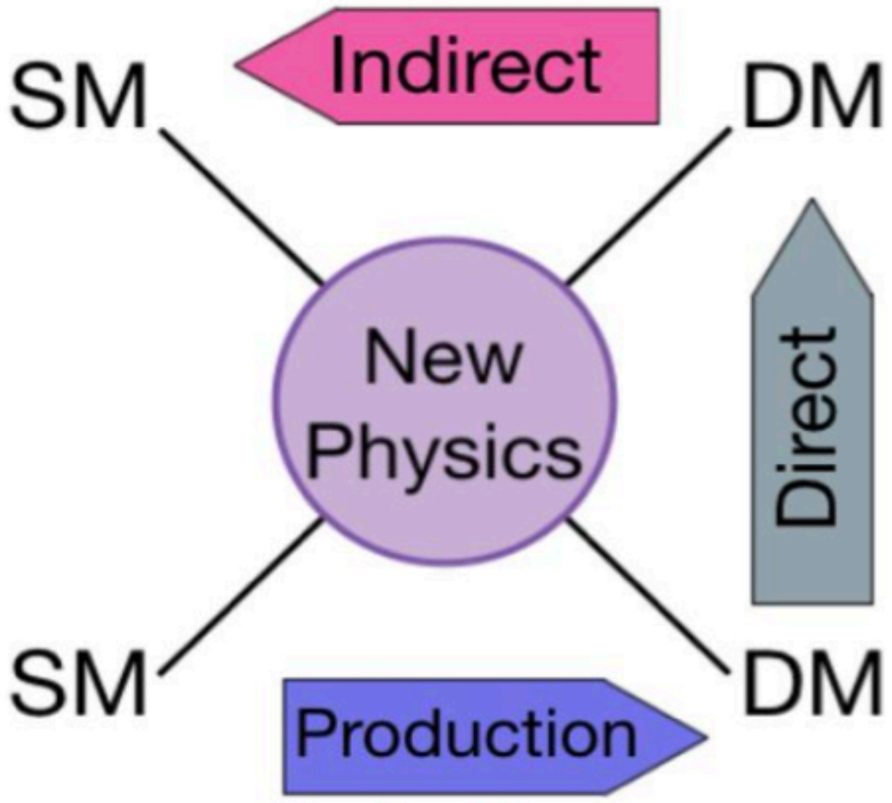
Particle solution does a nice job of explaining the data. Dark matter particles should be:

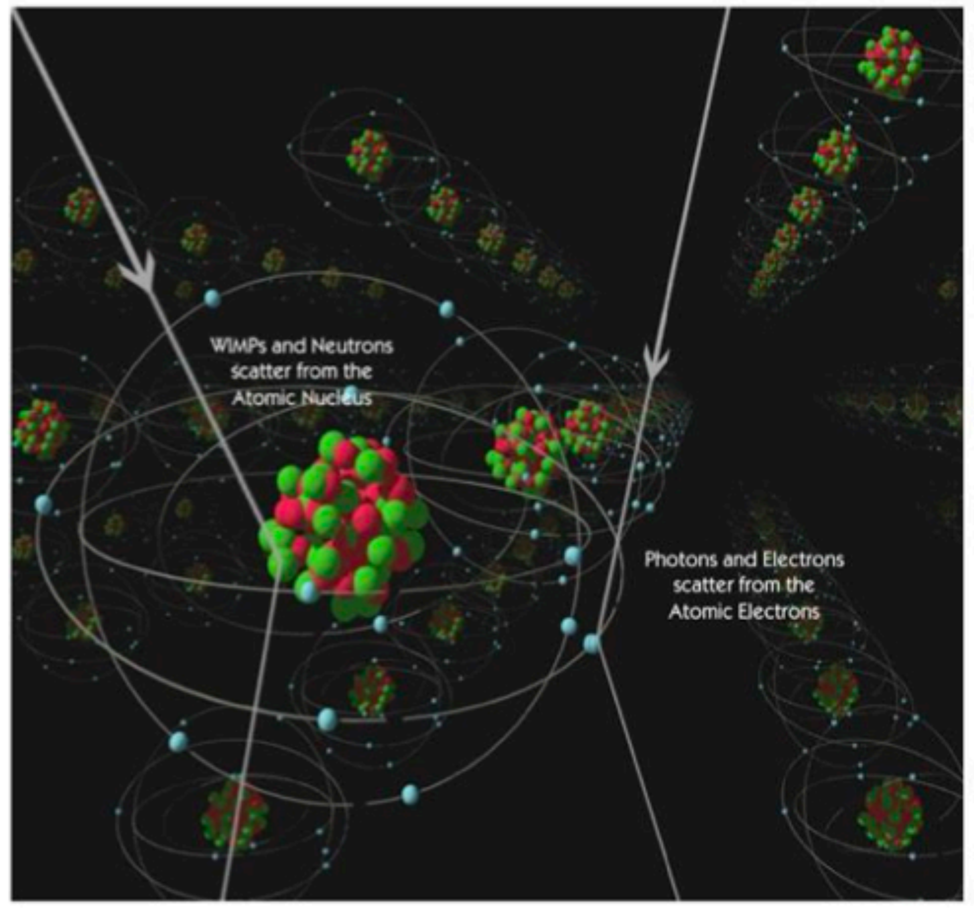
- Massive
- Neutral and minimally interacting
- Stable (very long lifetime)
- Non-relativistic

Multiple possible observation techniques

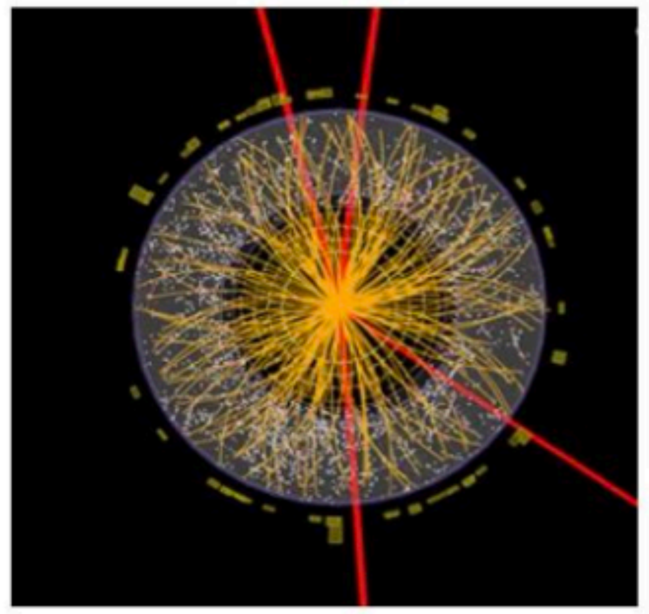


Cosmological Observation





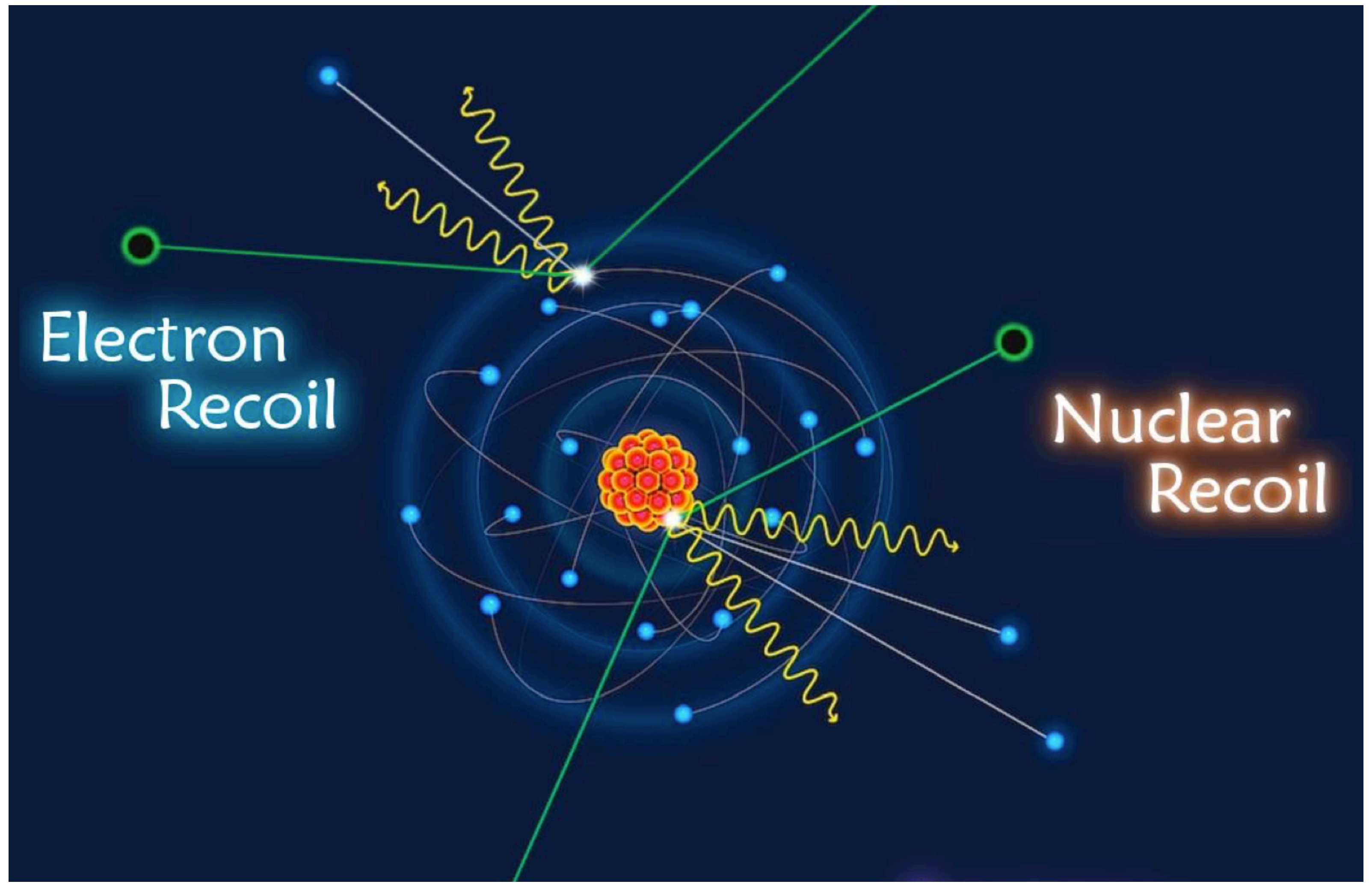
Direct Detection:
SuperCDMS HVeV



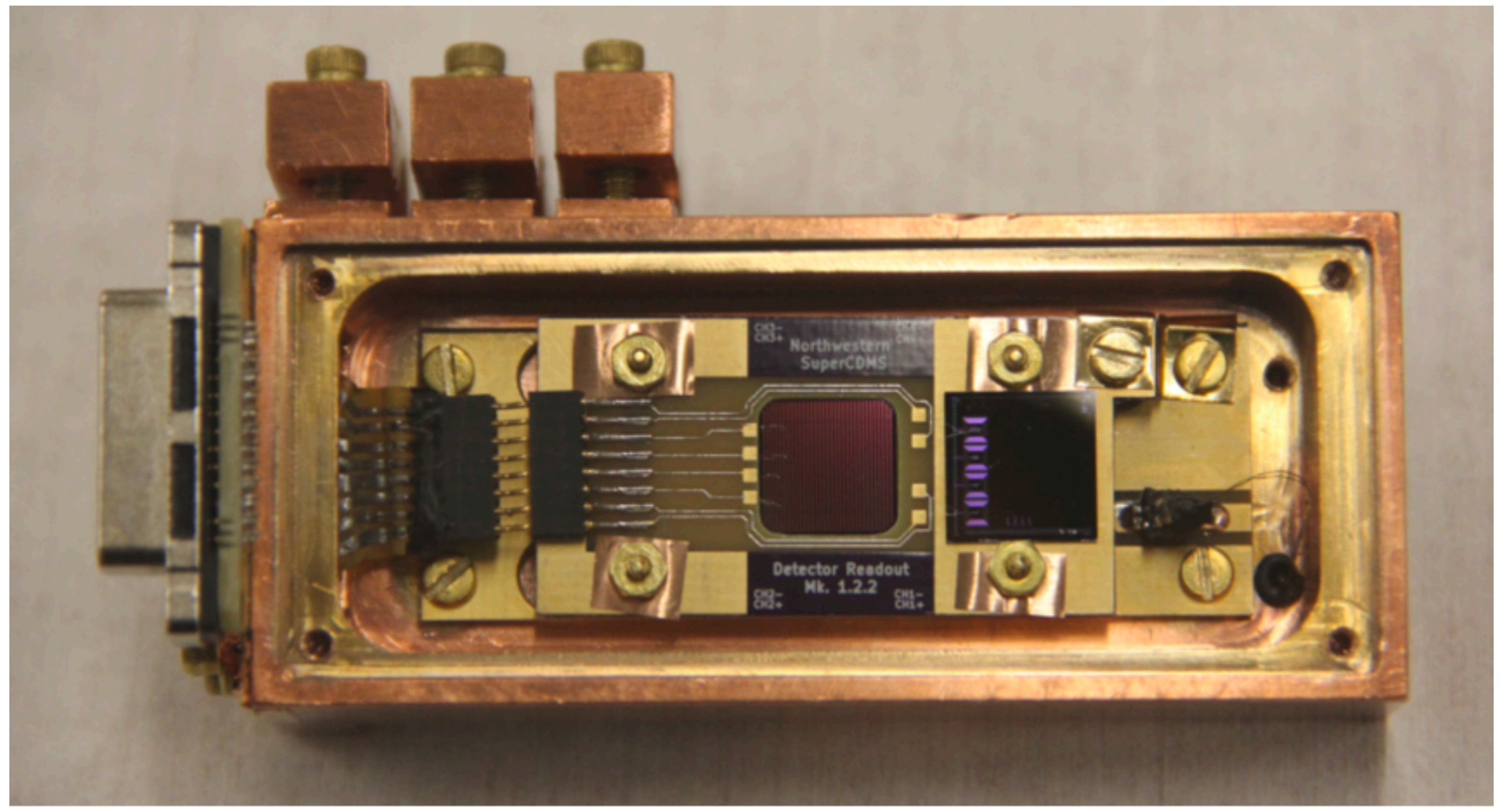
Collider Physics

Introduction and Motivation I SuperCDMS and Dark Matter Detection

- Theories predict that dark matter and normal matter interact with each other (rarely) through nuclear recoil and/or electron recoil at eV to KeV energy scales
- If we make very sensitive detectors, we might be able to observe these interactions experimentally
- Combined semiconductor and superconductor technologies are promising avenues for detecting very low-energy interactions
- SuperCDMS experiment uses these technologies to build multiple complementary detectors for its dark matter search
- In this thesis, we focus on small high-resolution phonon detectors that are called HVeV detectors



HVeV Detector



Introduction and Motivation | Quick Introduction to this Thesis

- This thesis is about understanding one of the next generation of dark matter detectors, which are small, high-energy resolution devices called HVeV (for "High Voltage eV resolution")
- We learned a lot from the CDMS experiment at Soudan, and now we have new detectors which are more powerful
- However, with more sophistication requires more understanding to get out better science results
- There will be two parts:
  - The detector design, experiment and data (which was done before I joined, and is a combination R&D and physics search)
  - The simulations and comparison to data (which is my part)
- We next turn to why we are focusing on the detectors used in this dissertation

Introduction and Motivation | HVeV Program

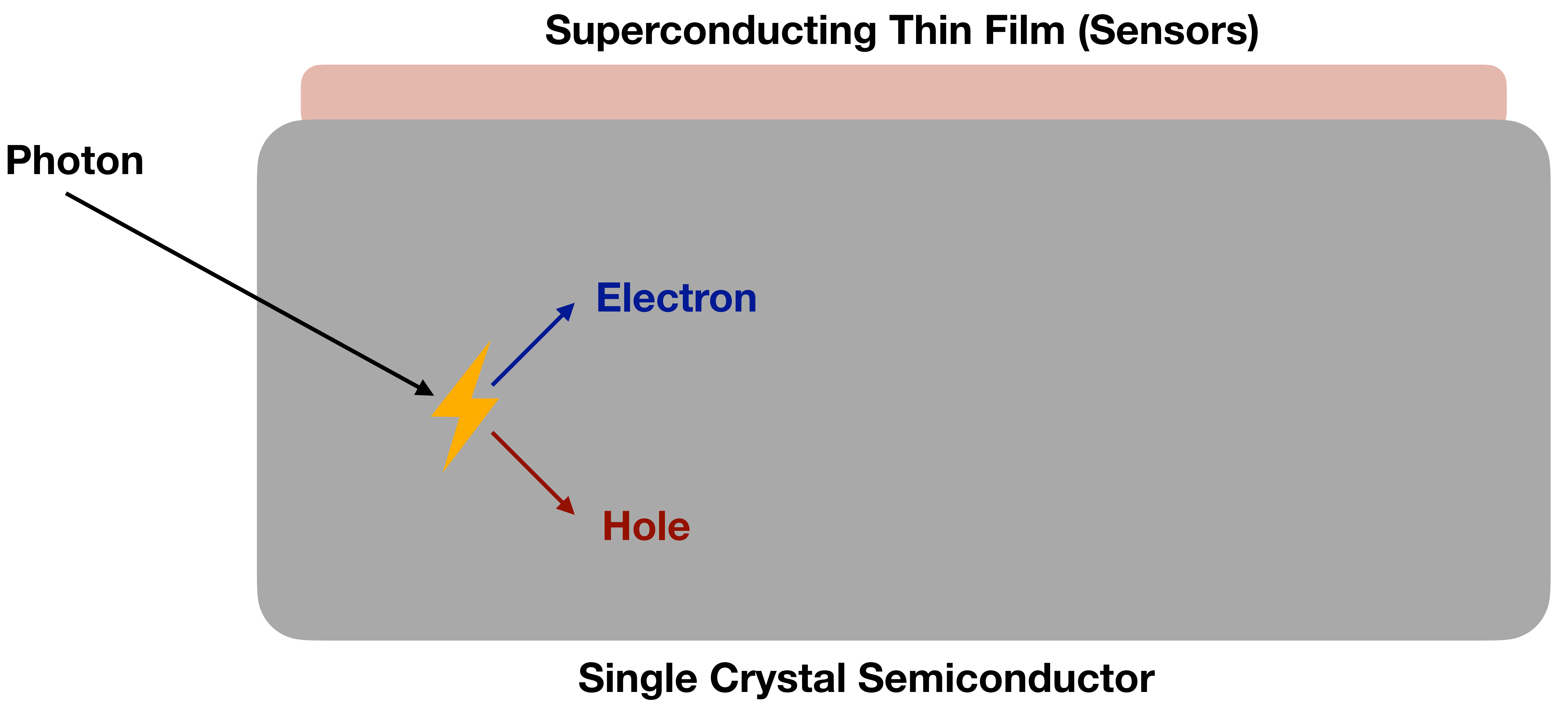
- HVeV detectors are very **small** and they are operated under **high-voltage** bias
- **Why small?**
  - It is easier to understand
- **Why high-voltage?**
  - We can go to very low thresholds under high voltage. (Will talk about this mechanism more later)

- **Main Achievements/Objectives of the HVeV Program:**
  - Using such a low threshold, this program has been able to expand the sensitivity reach for lower dark matter masses (from 0.5 to 10 MeV/c^2) with above-ground runs
  - HVeV detectors also provide a great opportunity to run tests in preparation for the real experiment with much bigger detectors

- The goal of this thesis is to compare the simulation of HVeV detectors with well-understood photon interactions from **laser data** to:
  - Understand the physics of the detectors using simulations
  - Validate and improve the simulation
  - Use the simulation to obtain otherwise inaccessible information about the experiment which can suggest new ways to improve the detectors and/or analyze the data we get from them

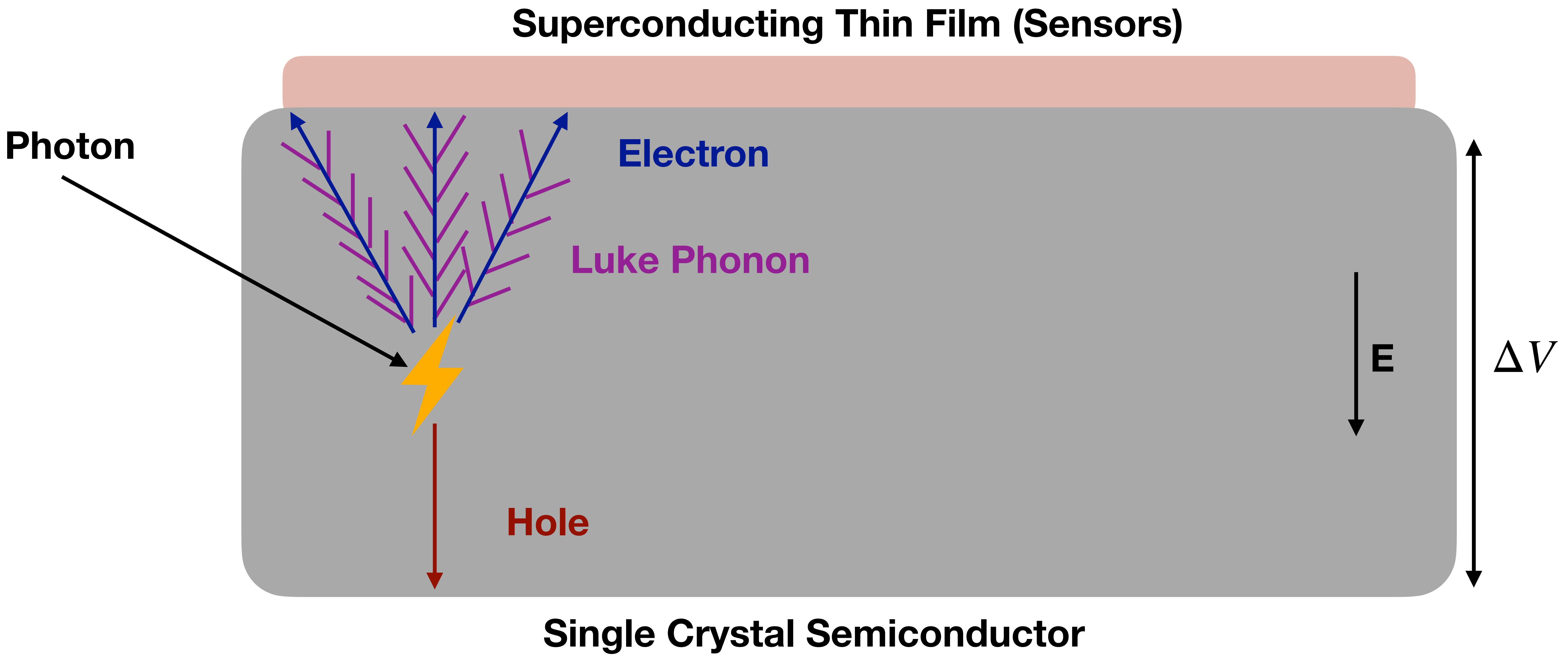
- We will talk about:
  - Detectors
  - HVeV Experiment
  - HVeV Simulation
  - Data and Simulation Comparison
  - Conclusions

Detectors | Photons Create Electron-Hole Pairs



Photons hitting the crystal (Si) can send an electron in the valence band to the conduction band and make an unoccupied valence state called a hole

Detectors | Applying Voltage and Luke Phonons

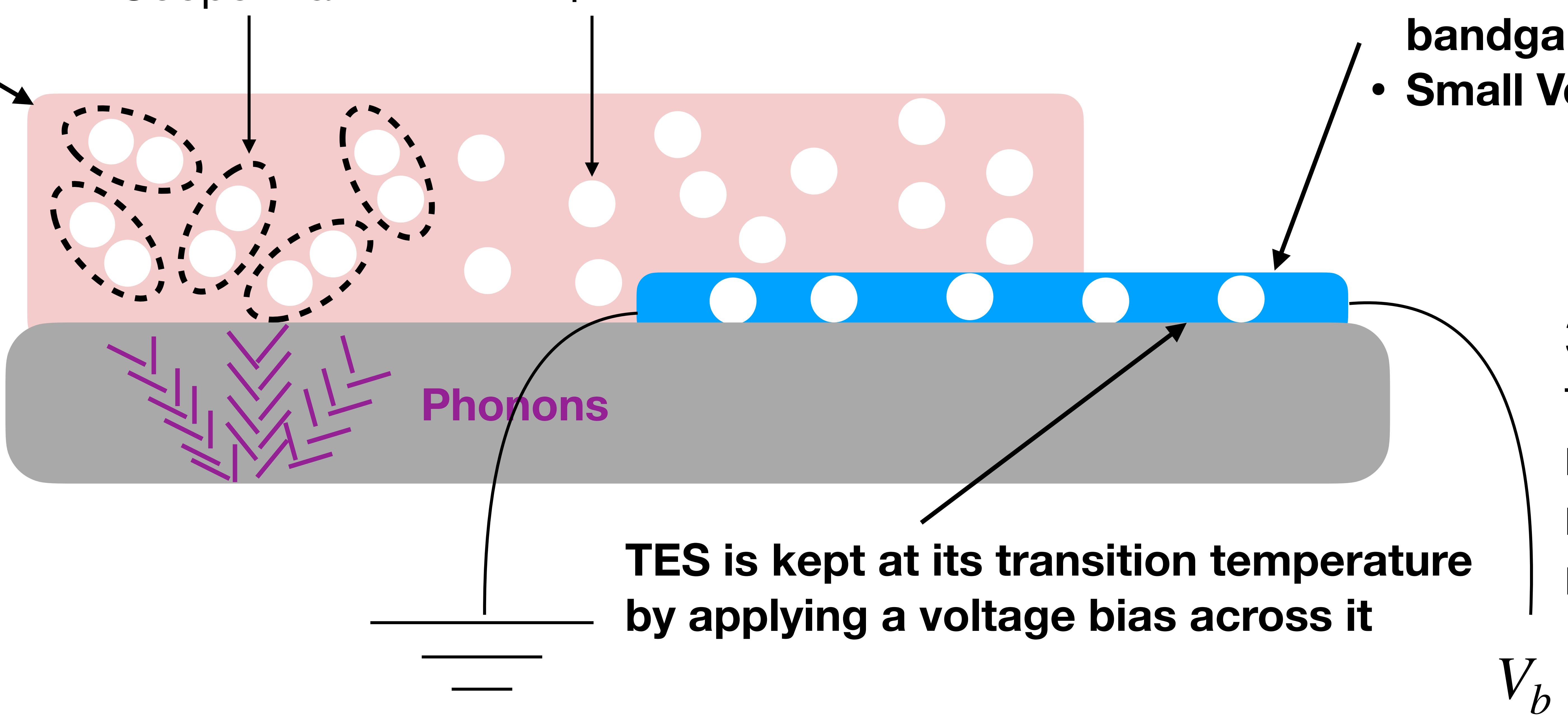


- Electrons and holes will travel under the voltage bias and pick up more energy, bang into the lattice which creates more phonons called Luke phonons. This is why we have a large voltage. More voltage, more Luke phonons
- Electrons travel along valleys (minimum energy potentials) while Holes go straight in the opposite direction
- Phonons bounce until they are eventually absorbed by the superconductor
- The total phonon energy measured by the sensor gives us an estimate of the energy deposited

Detectors I Superconducting Sensors (QETs)

First Superconductor (Al):
- **Large superconducting bandgap energy**
- **Large Volume**

Second Superconductor (TES) :
- **Small superconducting bandgap energy**
- **Small Volume**

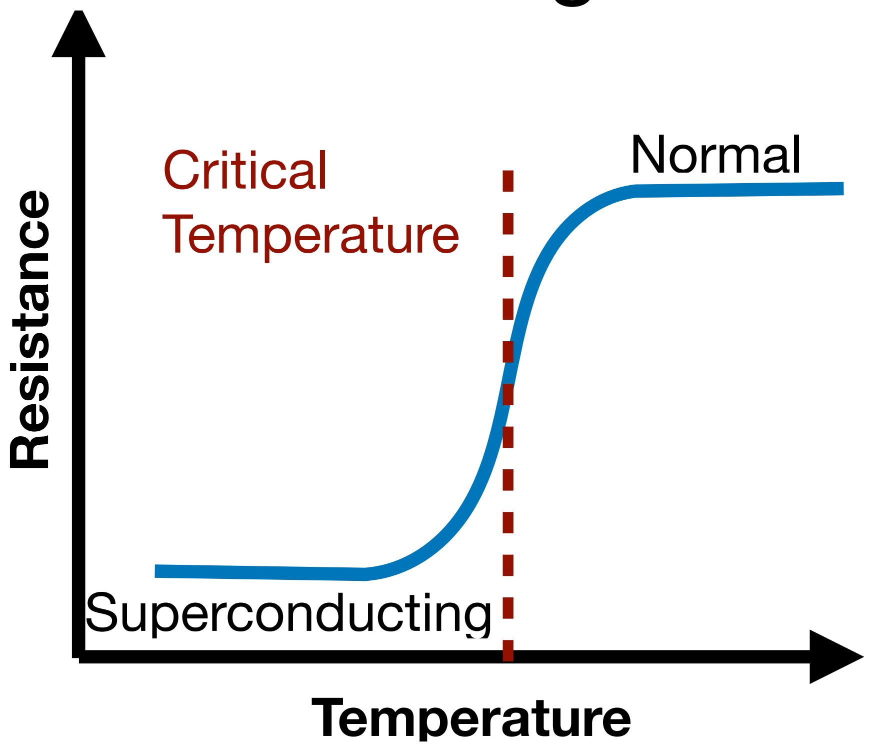


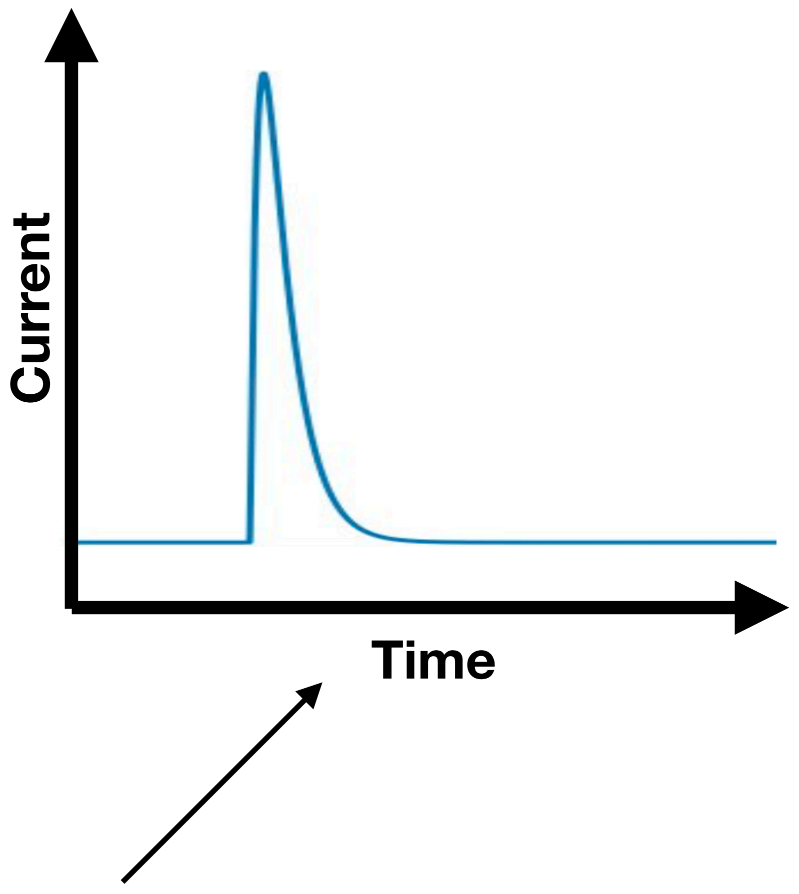
1. Phonons generated from the interaction will get absorbed by the Al, break Cooper pairs and produce quasi-particles

TES is kept at its transition temperature by applying a voltage bias across it

3. Small changes in the temperature of TES will result in a big change in its resistance, which we can measure from the current

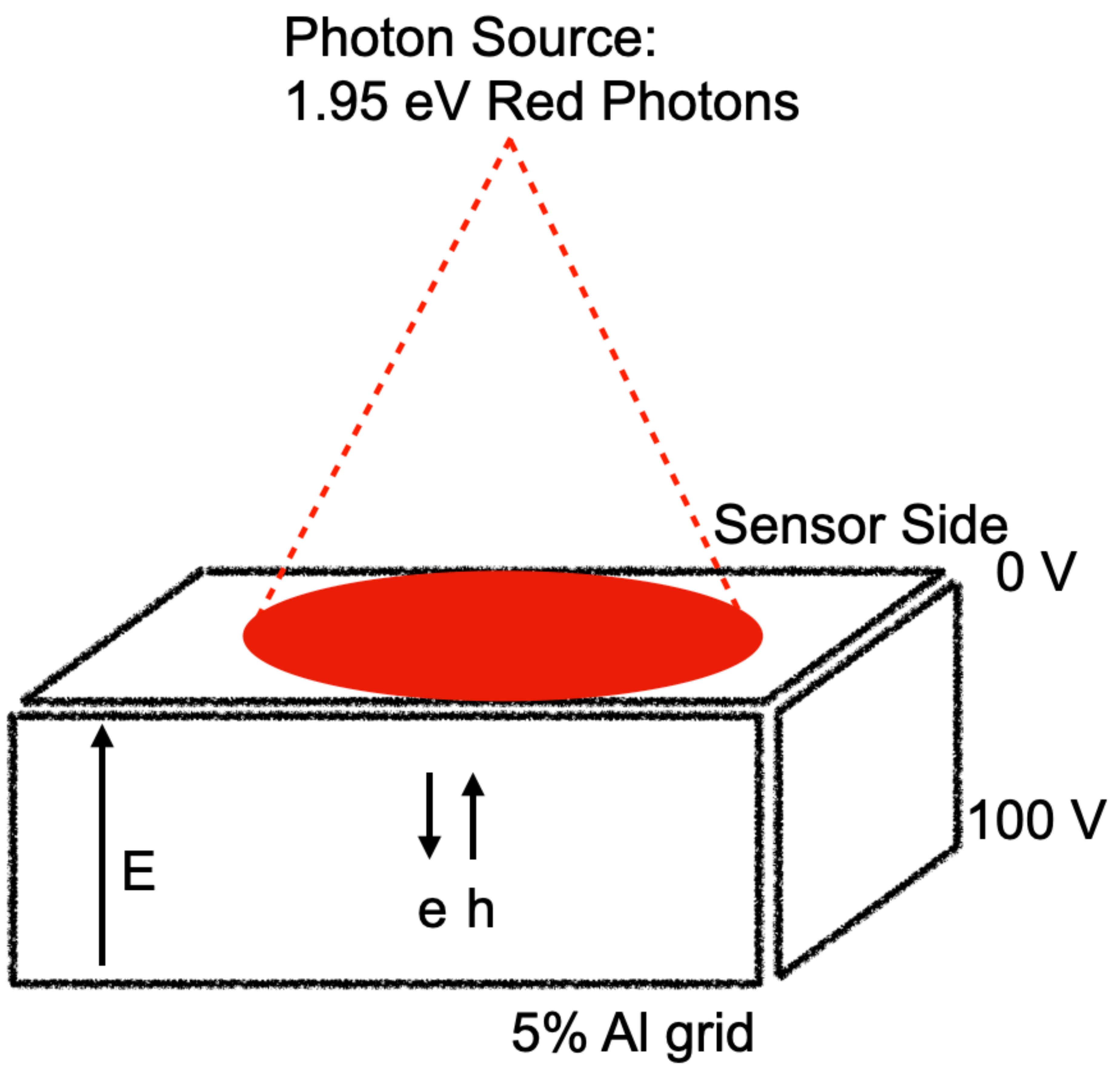
2. The quasi-particles will travel to the TES and transfer their heat to the TES which is at the edge of superconductivity





Measured TES Pulse

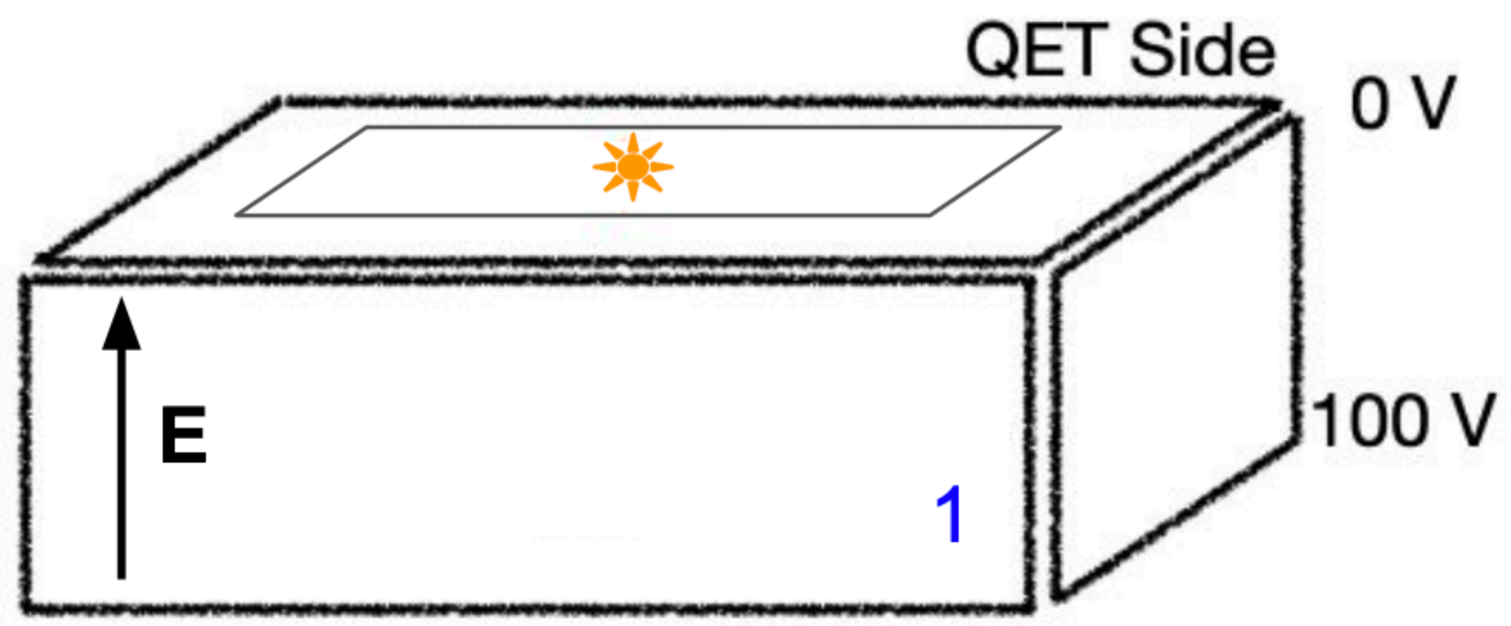
Detector | Photon Interactions with the Detector



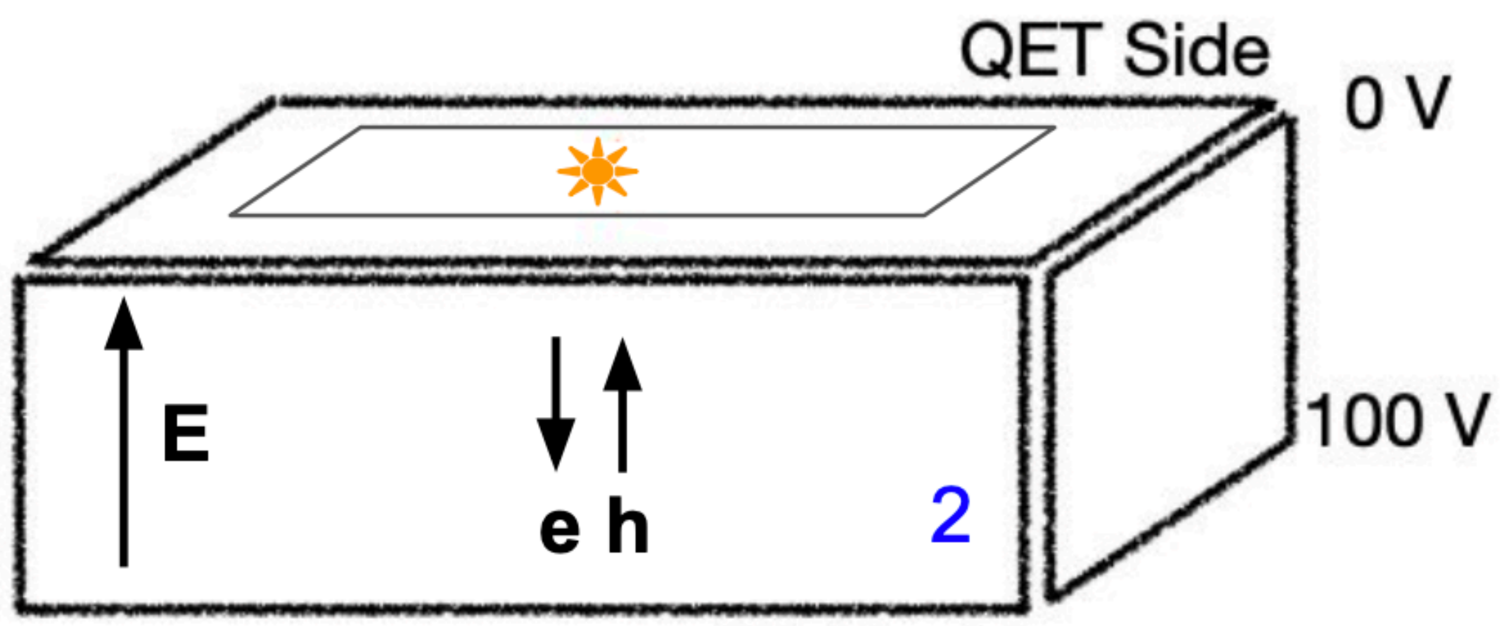
- In our experiment, the top surface of the detector is bombarded with 1.95 eV photons from a laser
- We will now look into the detector response to the photon interaction starting with a simplifying case and then adding complexity

Detector | Collected Phonon Energy: 1 Photon

There are two possible outcomes:



Collected Phonon E = 1.95 eV
Probability = 50%



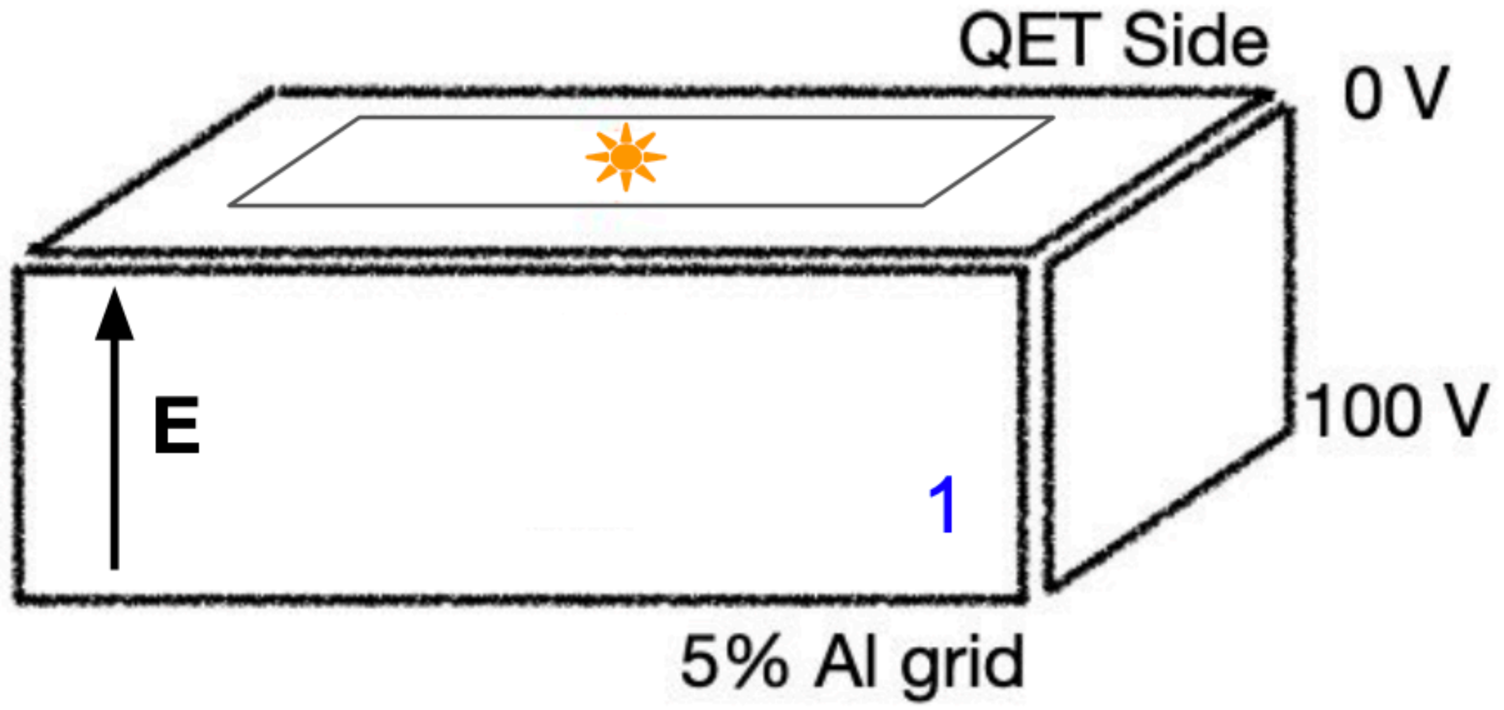
Collected Phonon E = 101.95 eV
Probability = 50%

One photon hits the middle of the top surface of the detector and **the generated eh pair recombines or is trapped at the surface immediately.**
Collected Phonon E:
- Initial Photon Energy = 1.95 eV
- Luke Amplification = 0 e * 100 V =0 eV
- **Collected Phonon E = 1.95 eV**
- ~50% probability

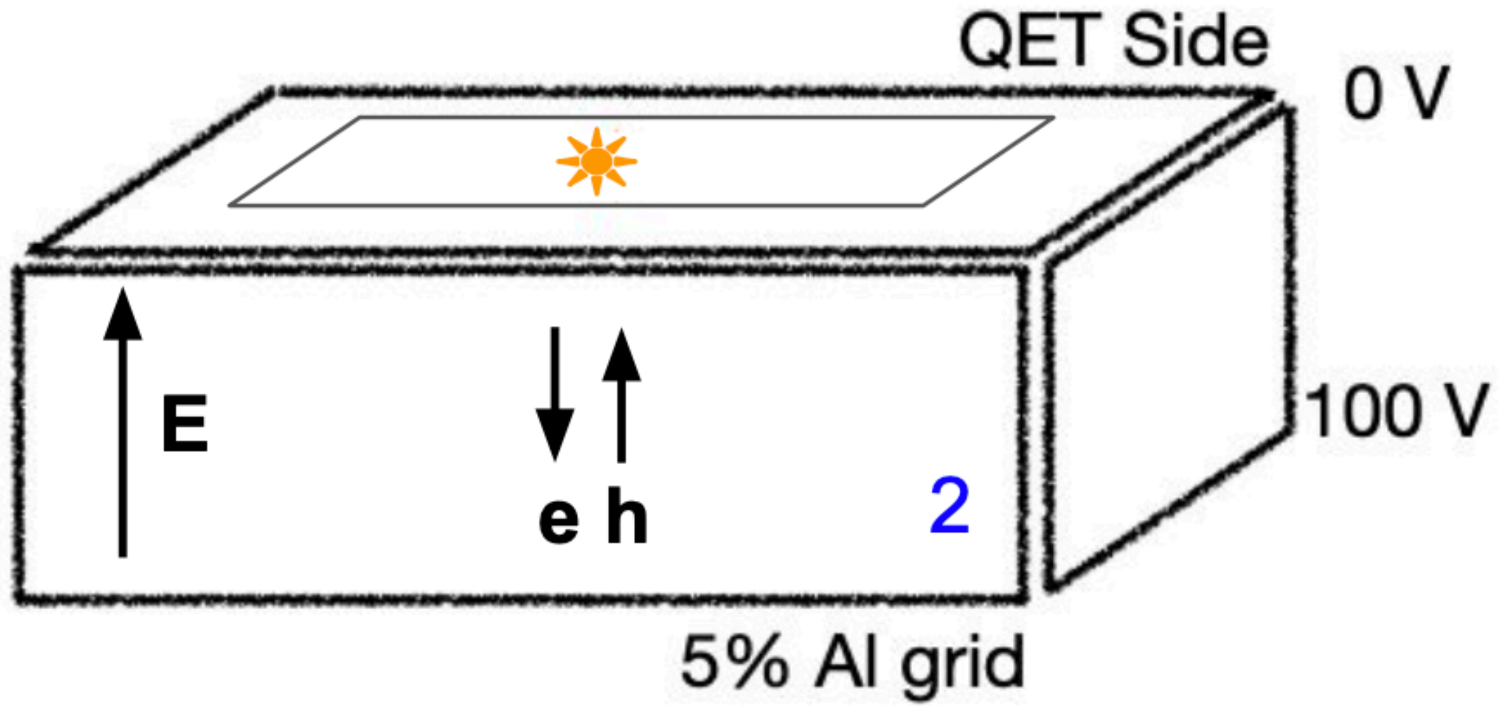
One photon hits the middle of the top surface of the detector and generates **one eh pair that goes through full Luke amplification**.
Collected Phonon E:
- Initial Photon Energy = 1.95 eV
- Luke Amplification = 1 e * 100 V =100 eV
- **Collected Phonon E = 101.95 eV**
- ~50% probability

Detector | Collected Phonon Energy: 1 Photon

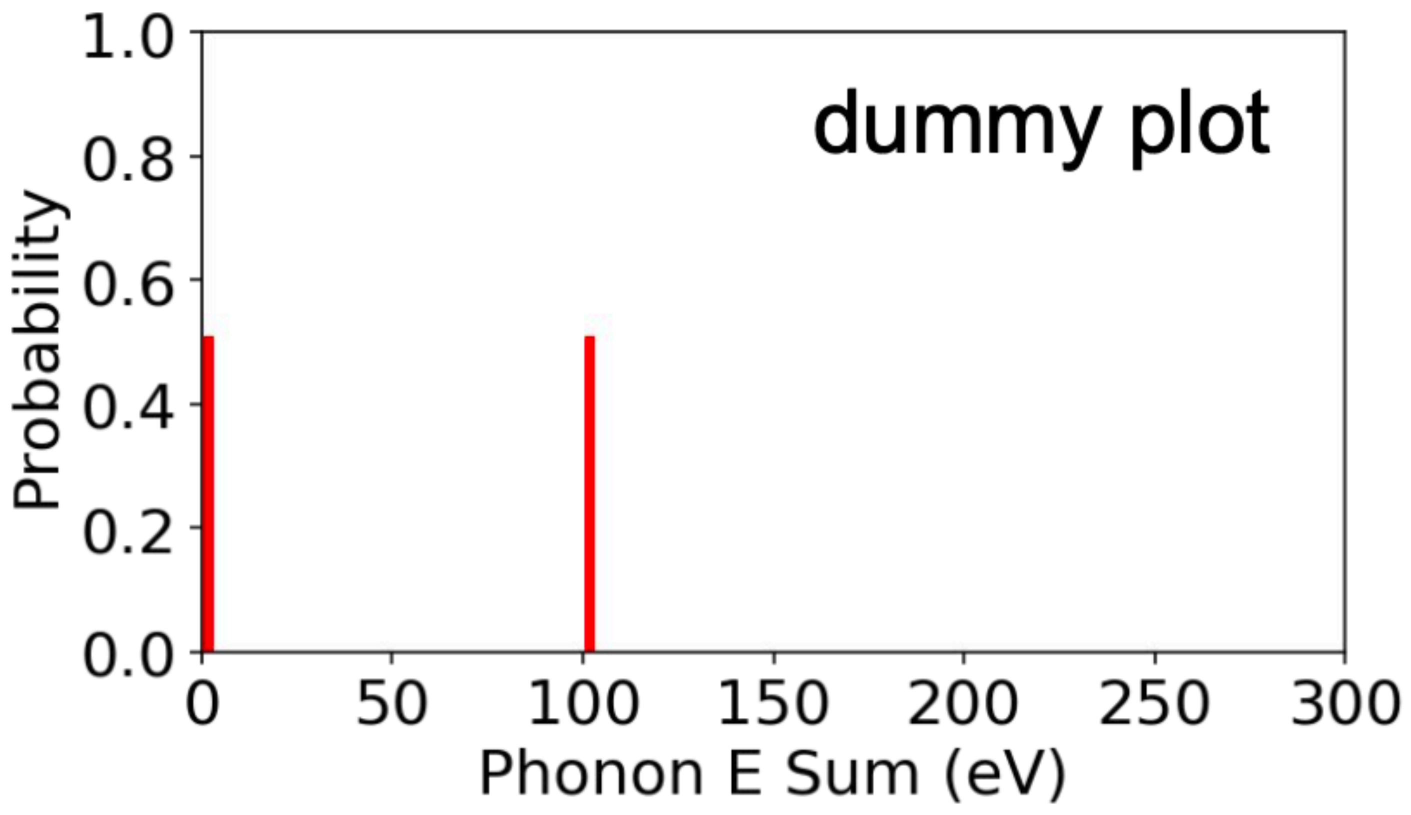
There are two possible outcomes:



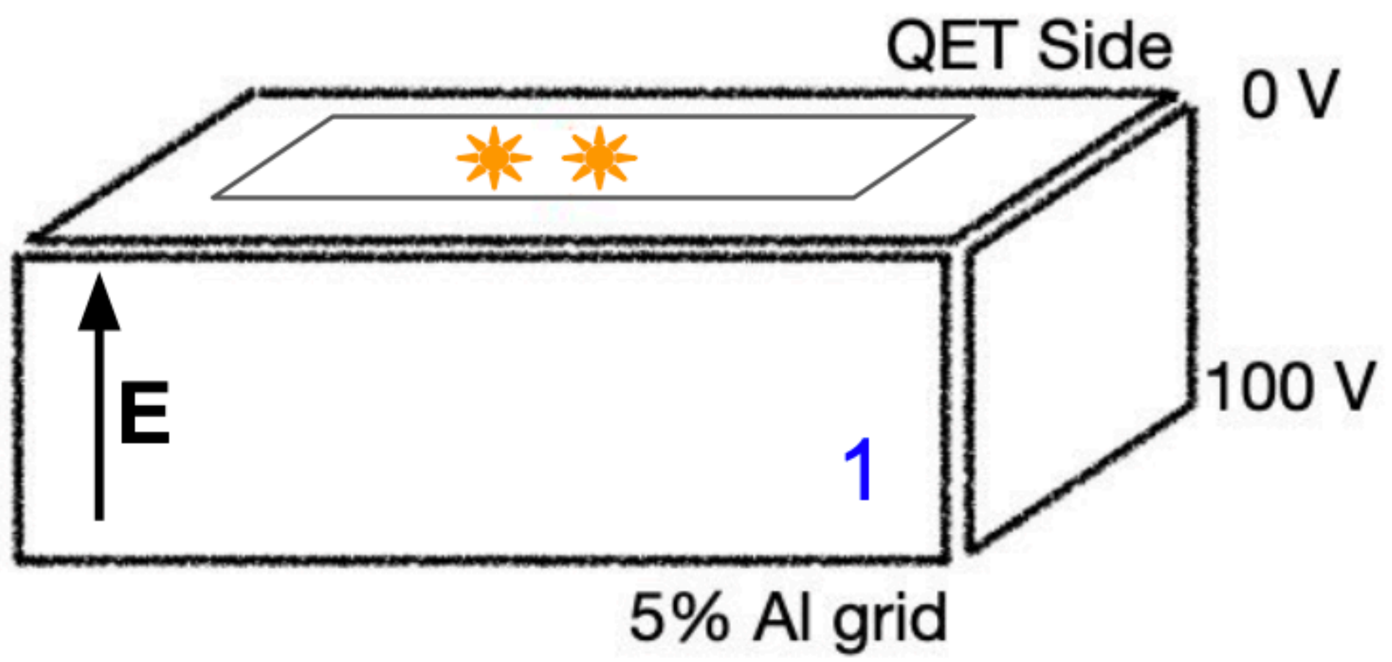
Collected Phonon E = 1.95 eV
Probability = 50%



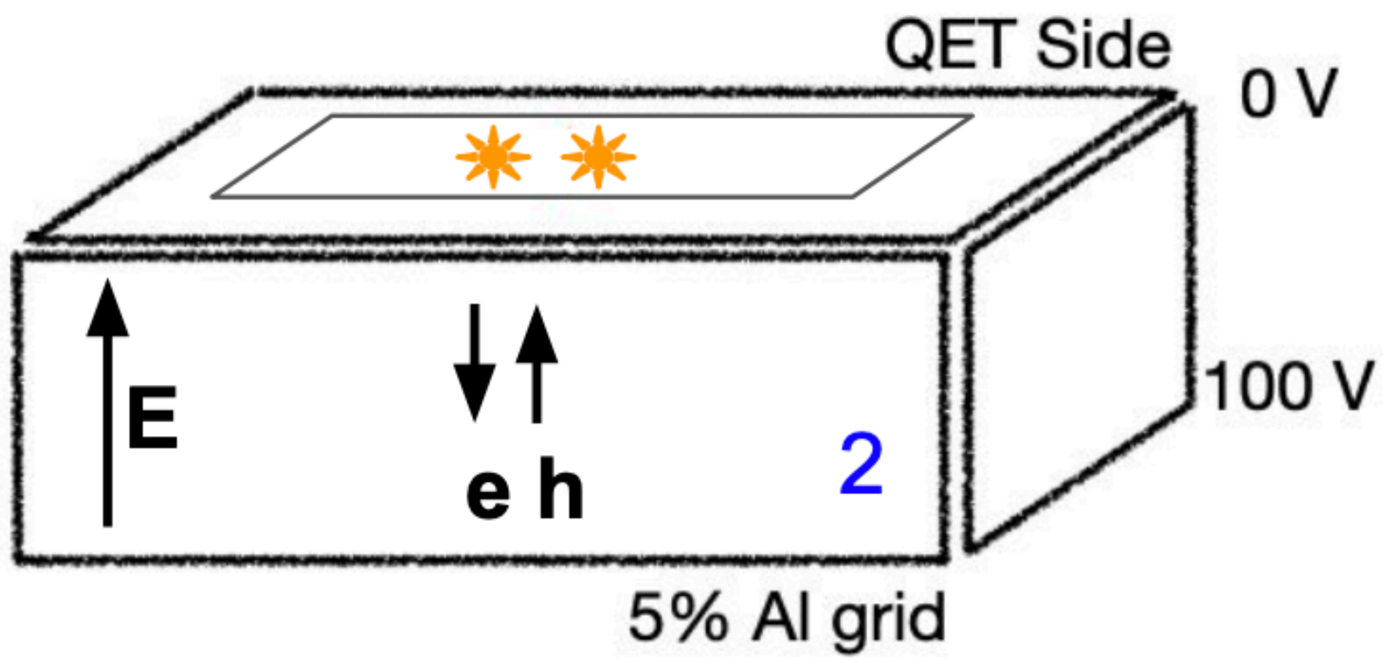
Collected Phonon E = 101.95 eV
Probability = 50%



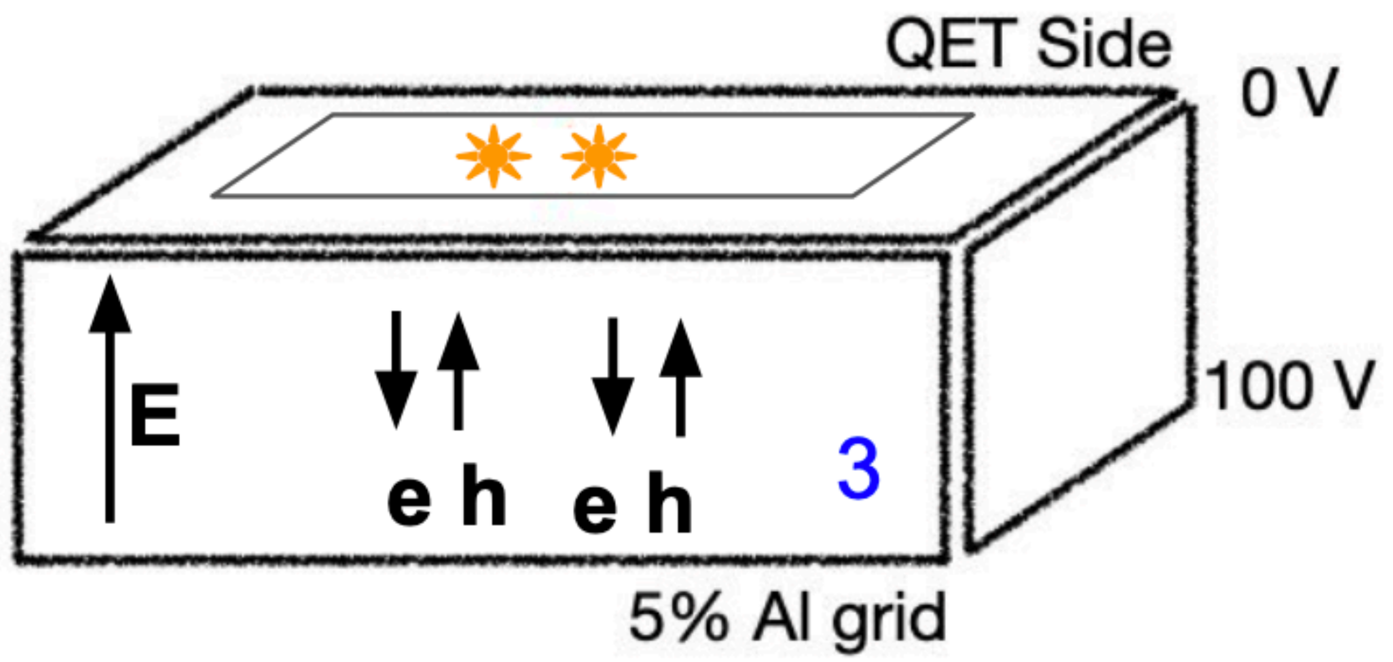
Detectorl Collected Phonon Energy: 2 Photons



Collected Phonon E = 3.9 eV
Probability = ~25%



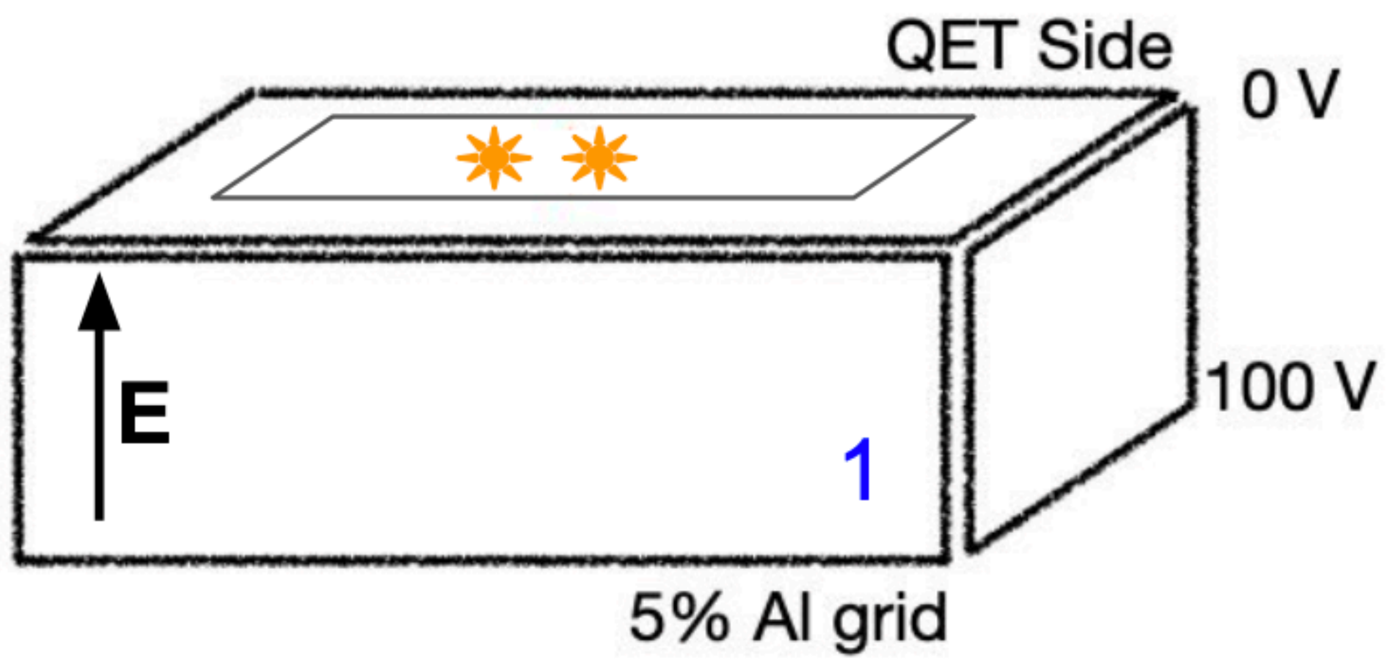
Collected Phonon E = 103.9 eV
Probability = ~50%



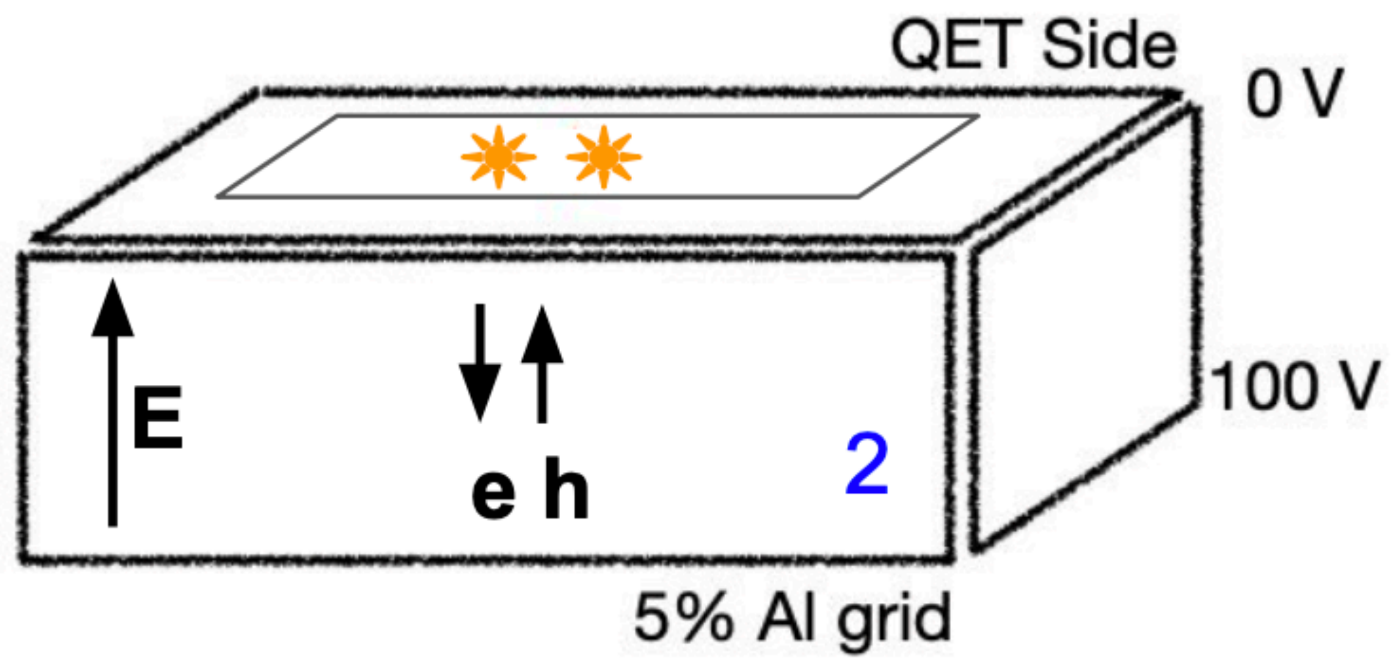
Collected Phonon E = 203.9 eV
Probability = ~25%

E= N*1.95 + M*100
N: Number of Photons;
M: Number of ehs fully amplified;
M<=N

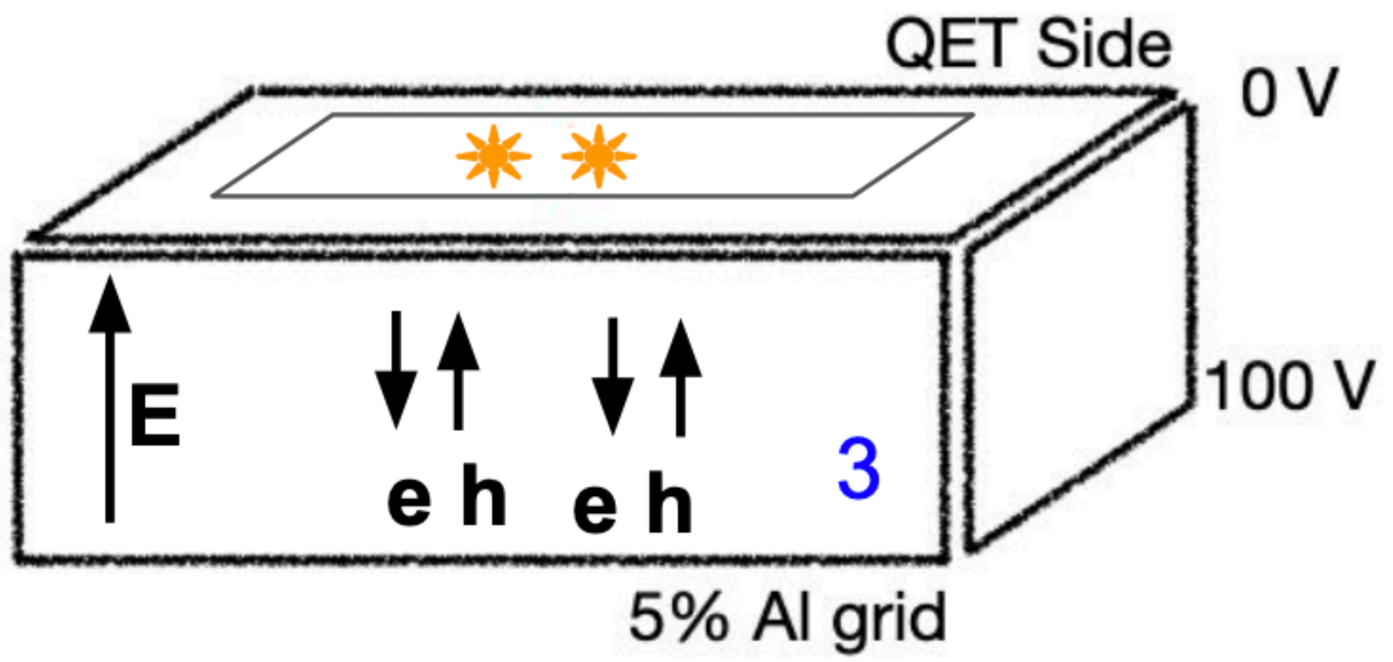
DetectorI Collected Phonon Energy: 2 Photons



Collected Phonon E = 3.9 eV
Probability = ~25%



Collected Phonon E = 103.9 eV
Probability = ~50%



Collected Phonon E = 203.9 eV
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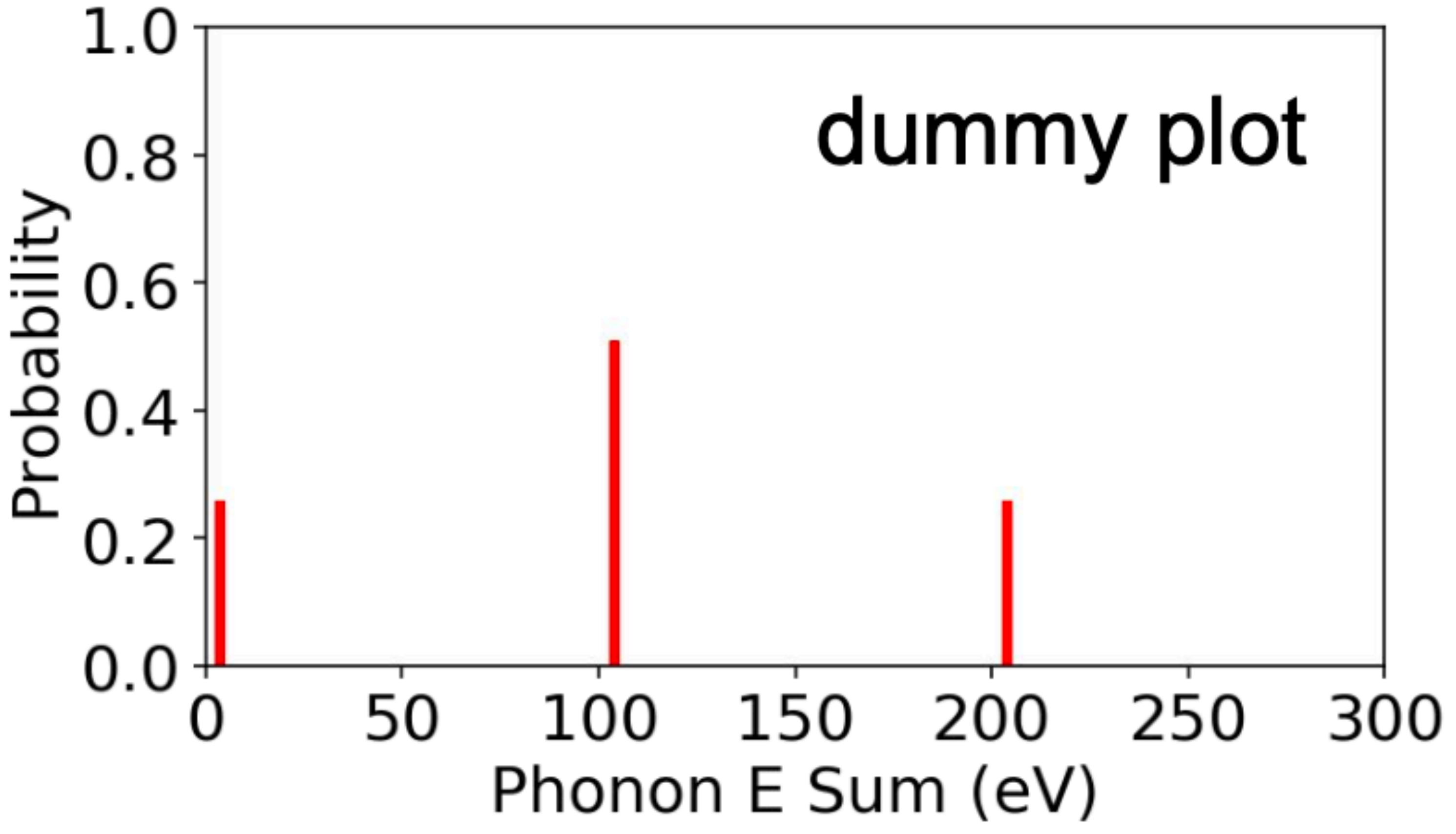
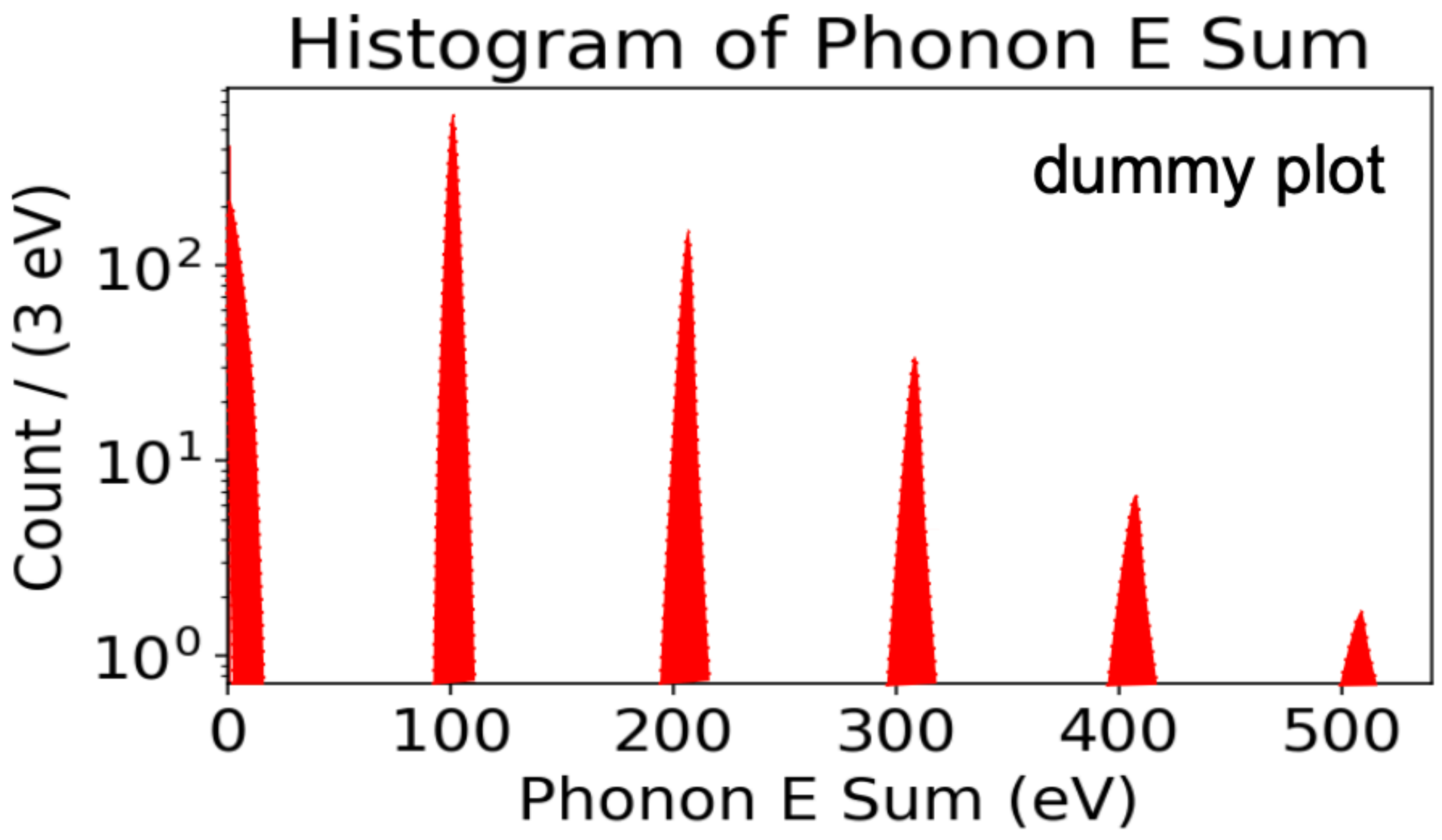


Detector | Larger Number of Photons and Detector Resolution Effects

- Now let's assume we have 1500 laser shots
- Each shot has N photons hitting the detector, where N follows a Poisson distribution with Lambda = 1
- The RHS plot is a dummy plot of what we would expect for those 1500 laser shots considering different combinations of N and M and some detector resolution effects

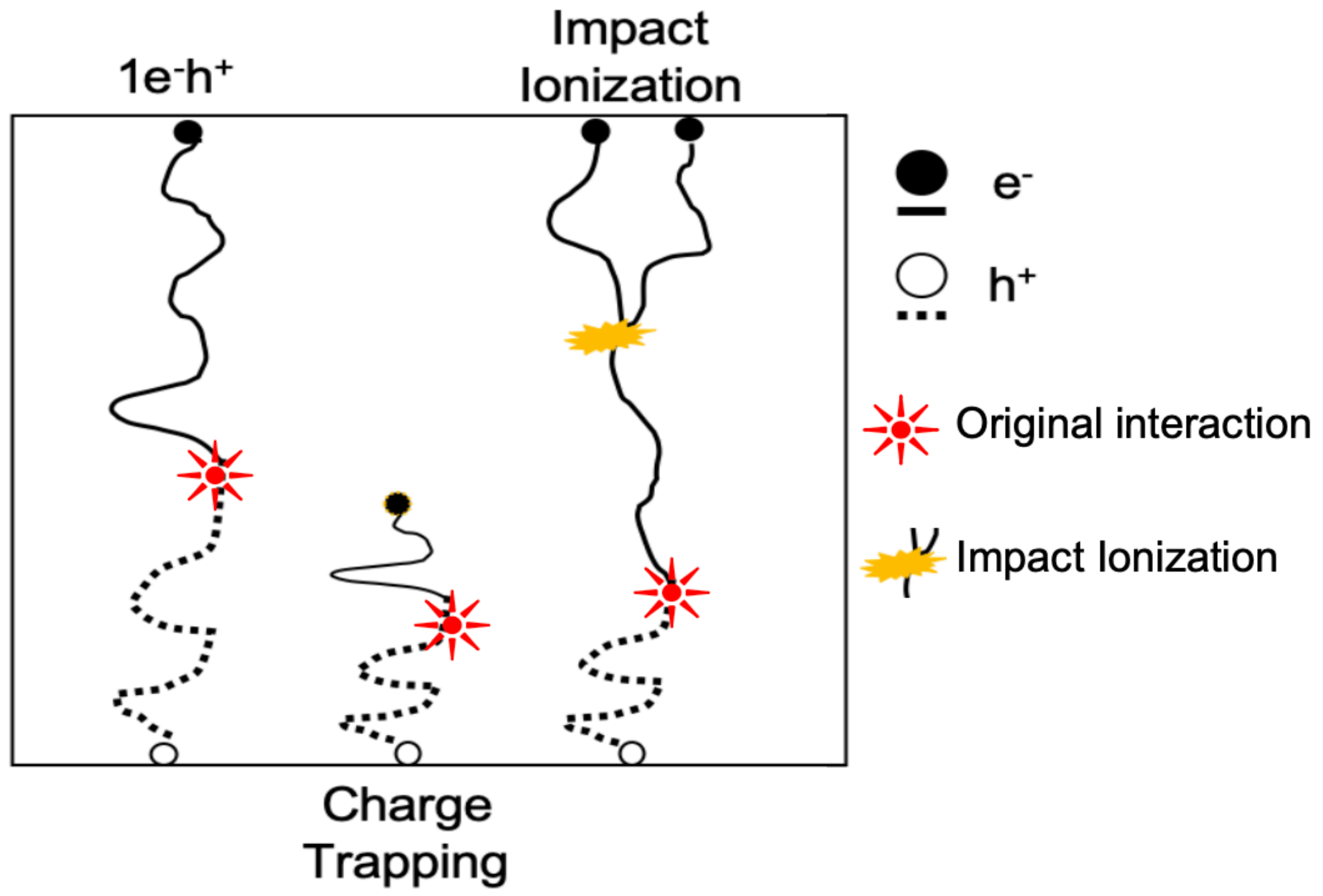


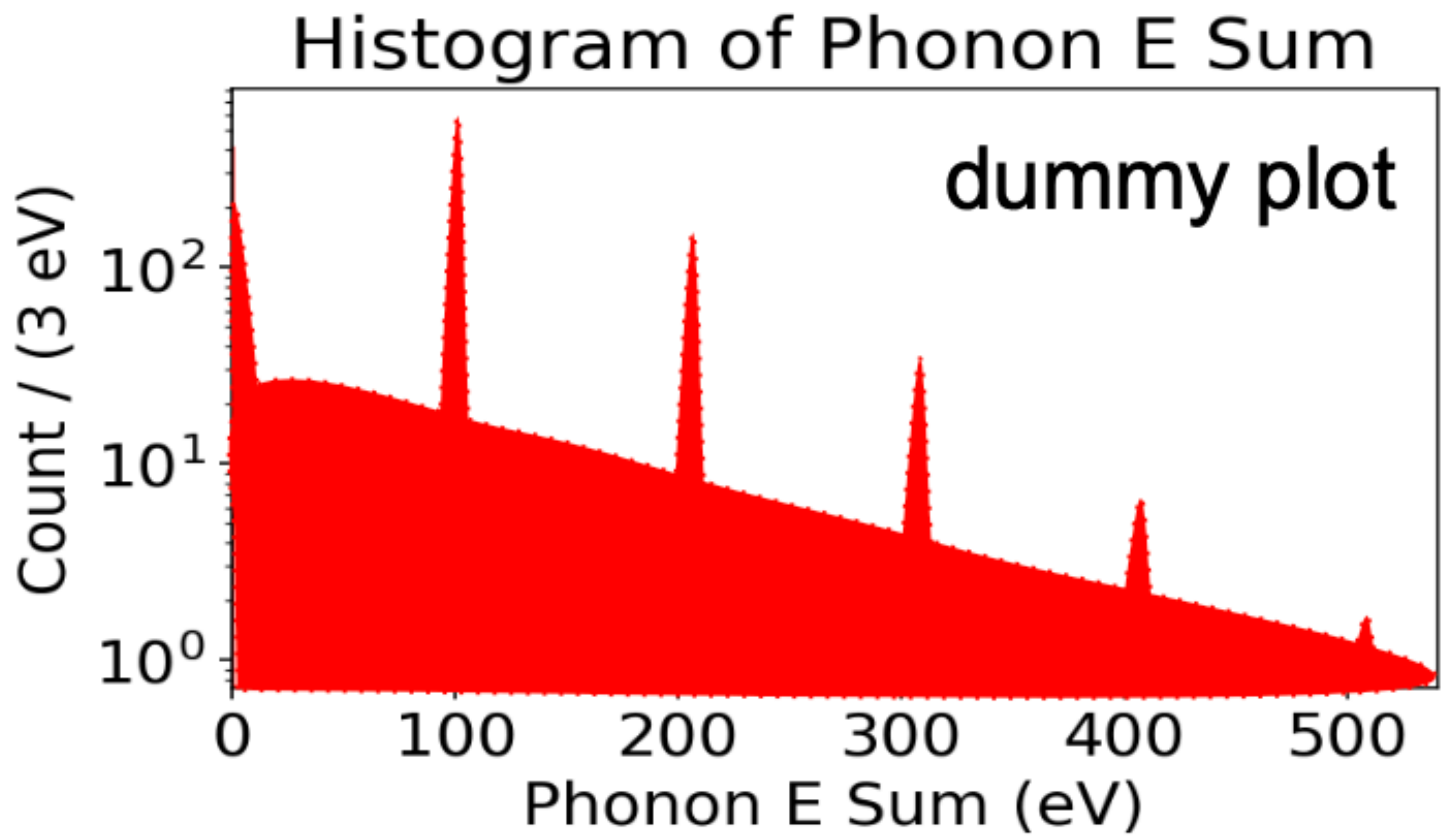
In reality, our crystals are have impurities and we don't get full energy collection all the time.

Charges traveling through the crystal can:

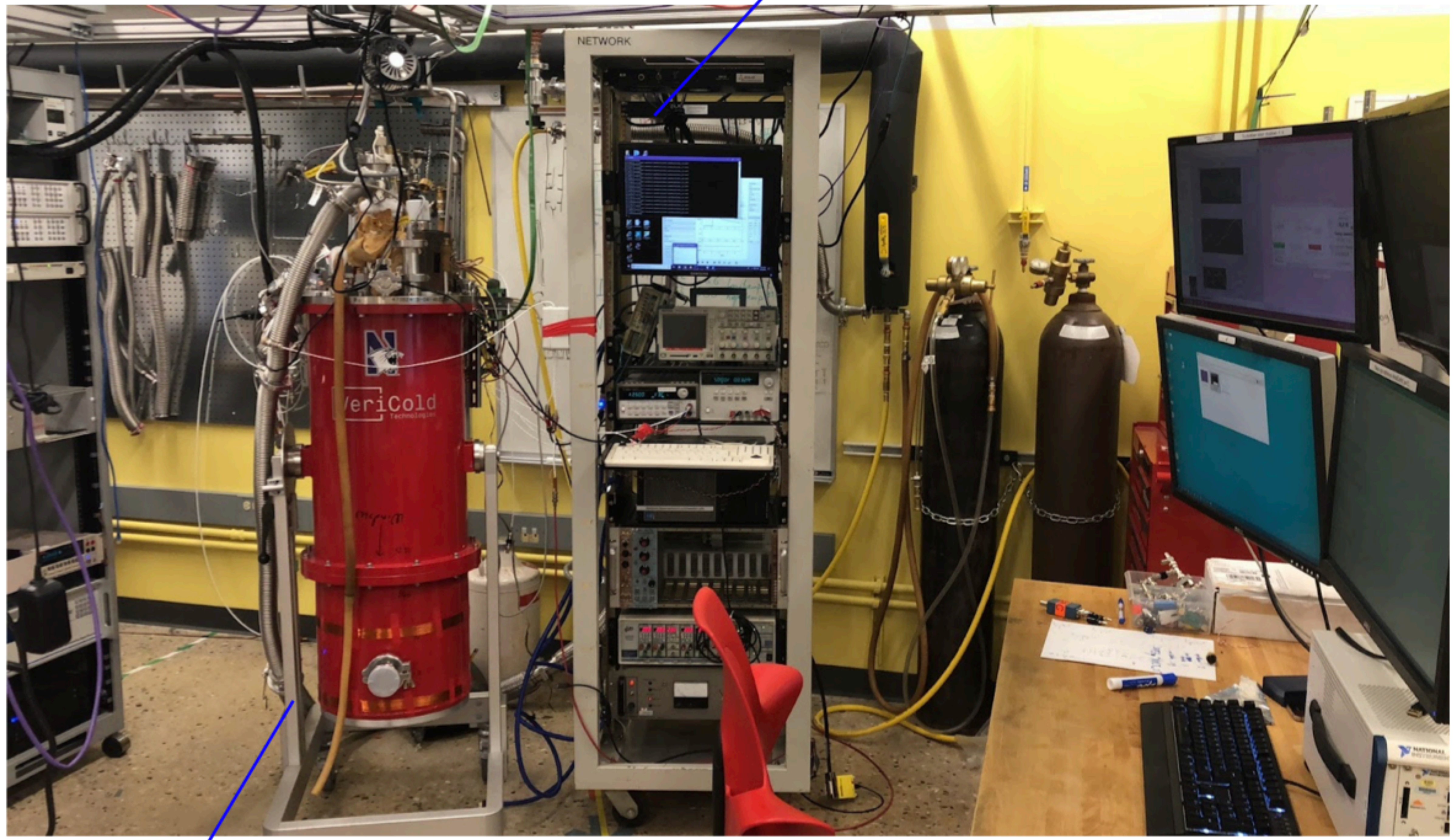
- Get trapped in defects so we lose some of the phonon energy
- Liberate additional charges that are stuck in overcharged impurity regions. These charges are accelerated, creating additional phonons

These processes will lead to partial energy collection which will show up as a background in between the peaks of the spectrum. The amount of each depends on the quality of the crystal used.



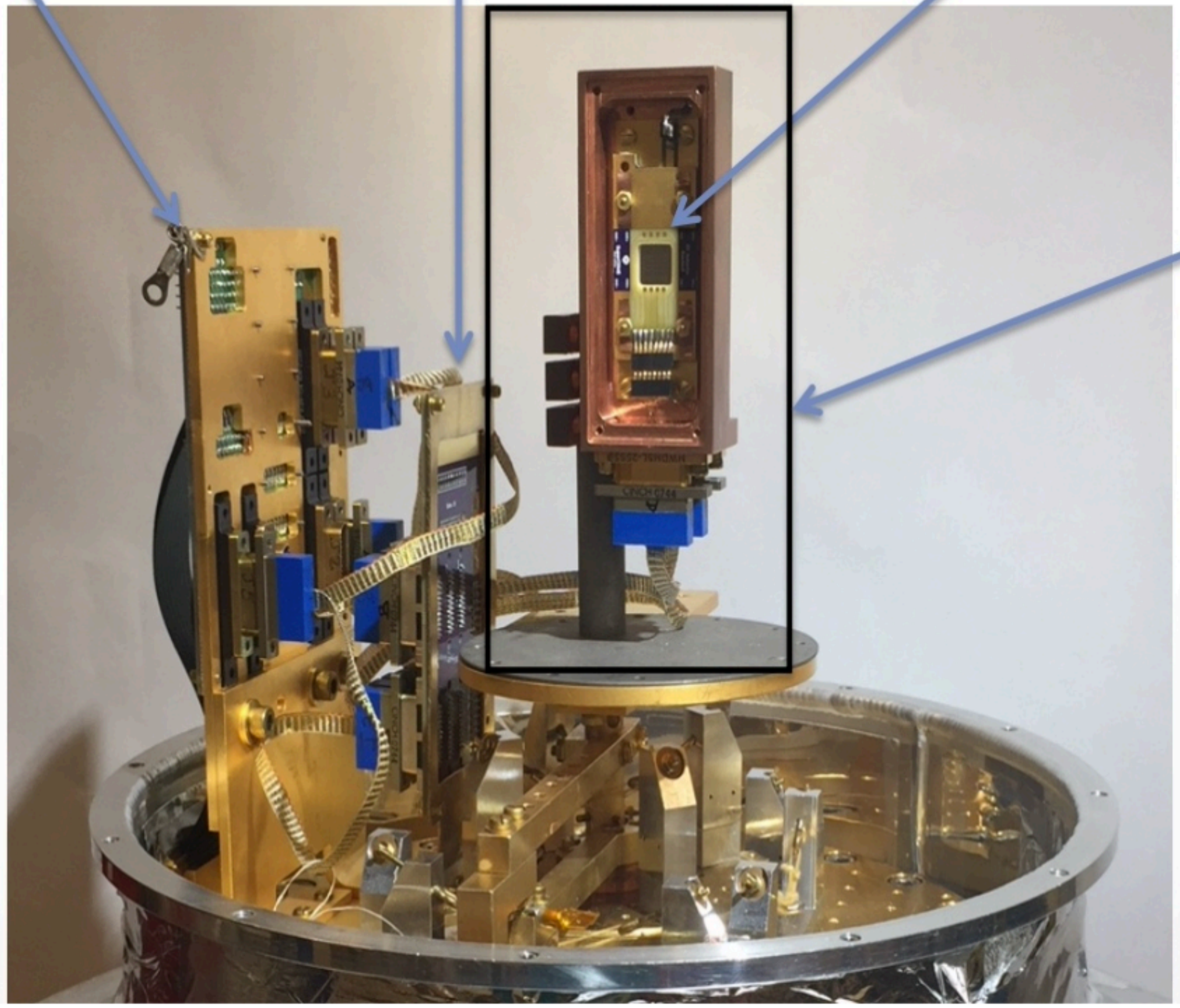


HVeV Experiment I NEXUS Facility and Experimental Setup

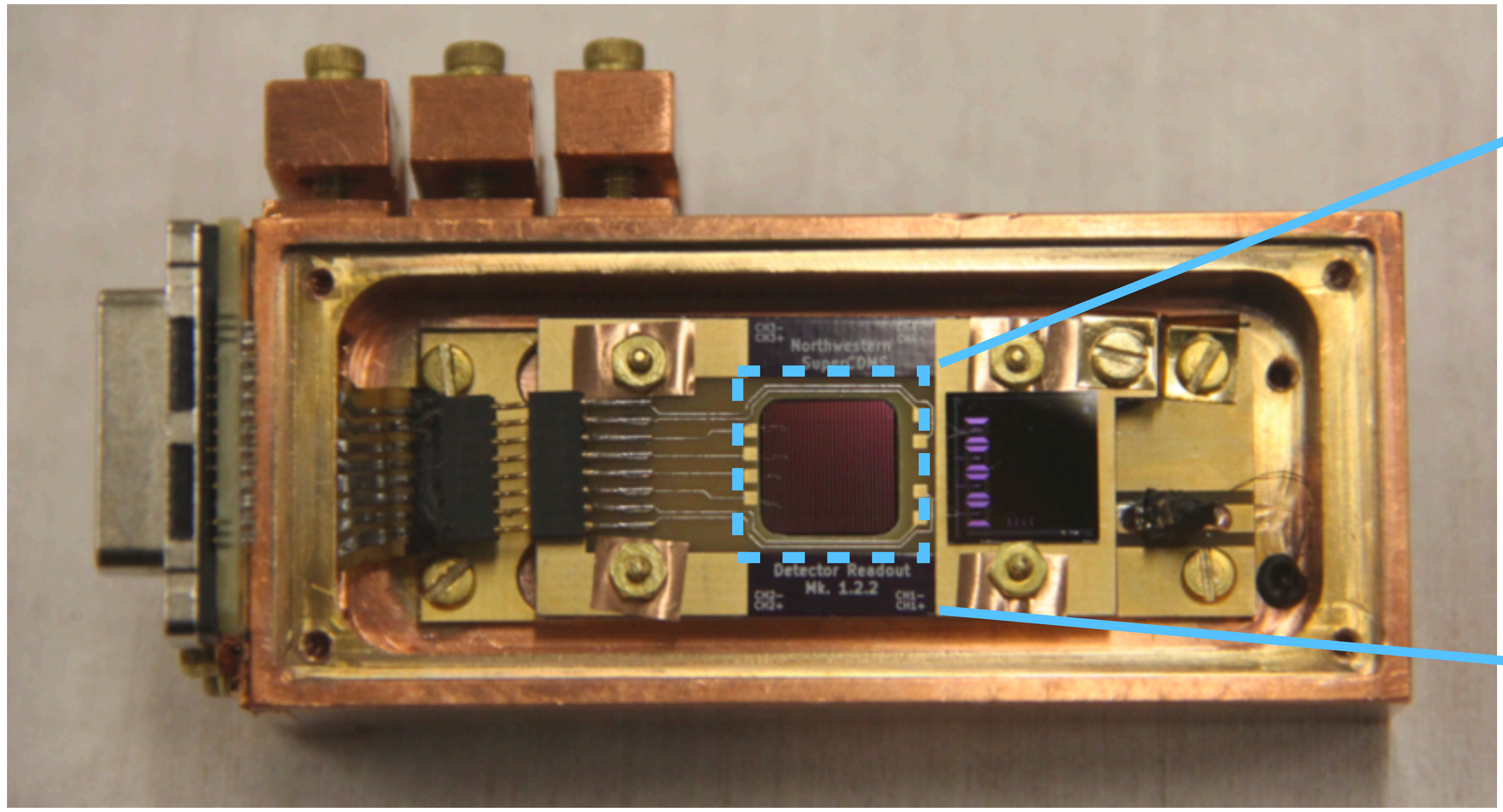


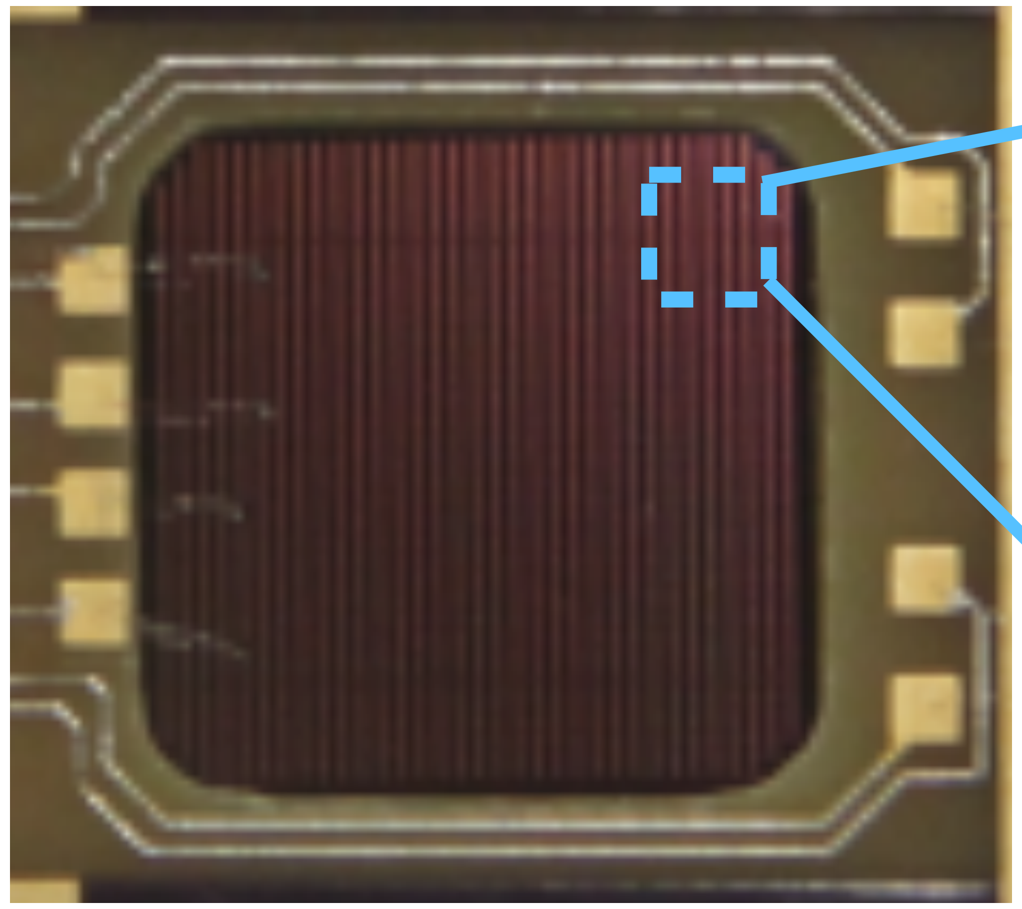
Lab Setup

Vericold ADR Fridge (The detector is here)

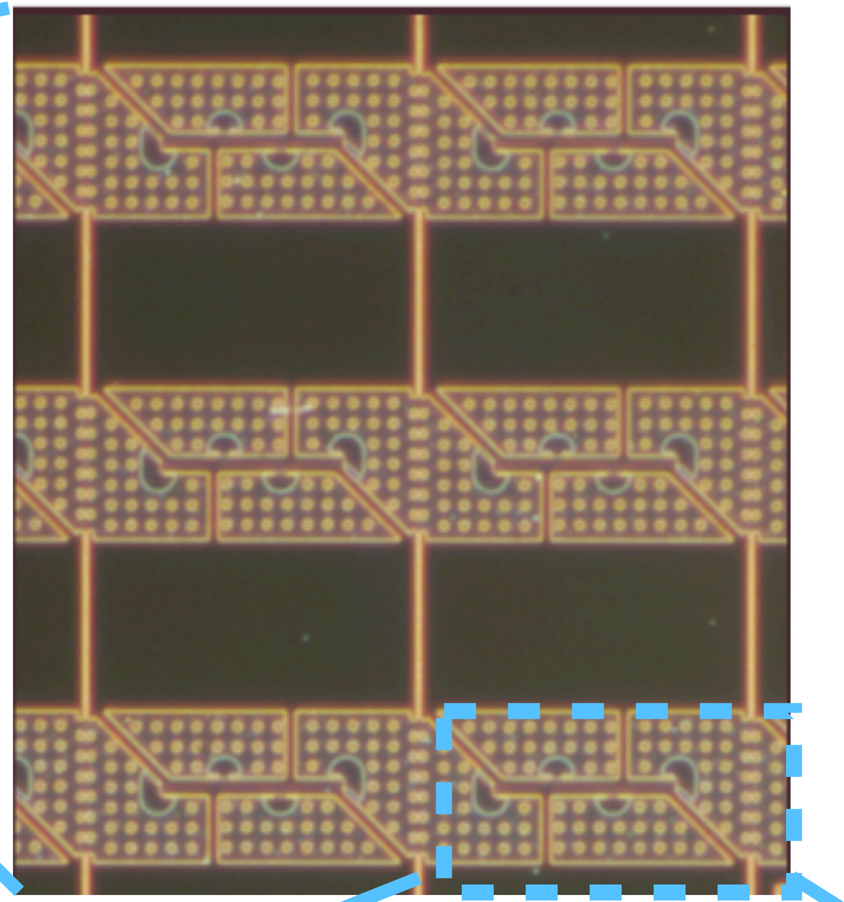


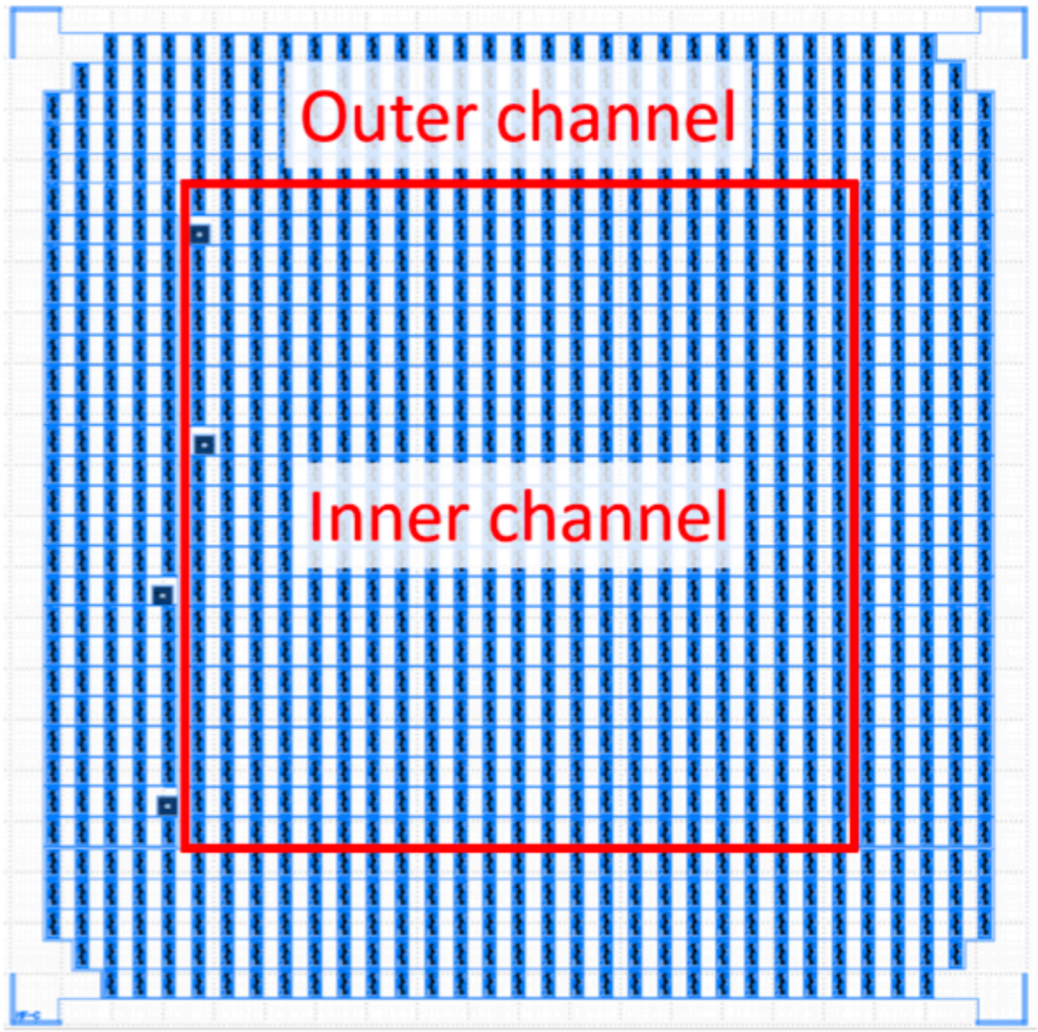
HVeV Experiment | Detector Mask and Geometry

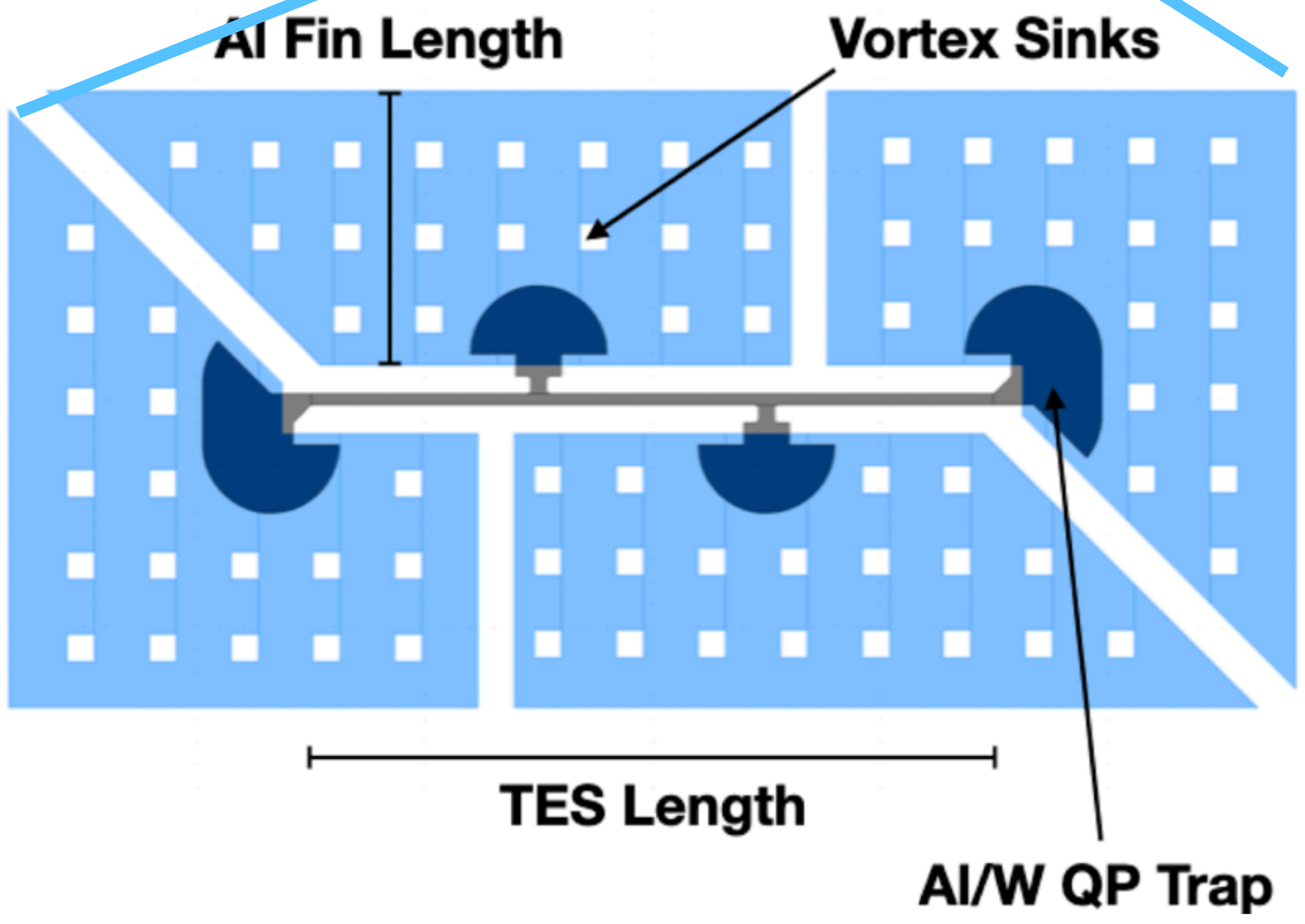




Rotated by 90 degrees





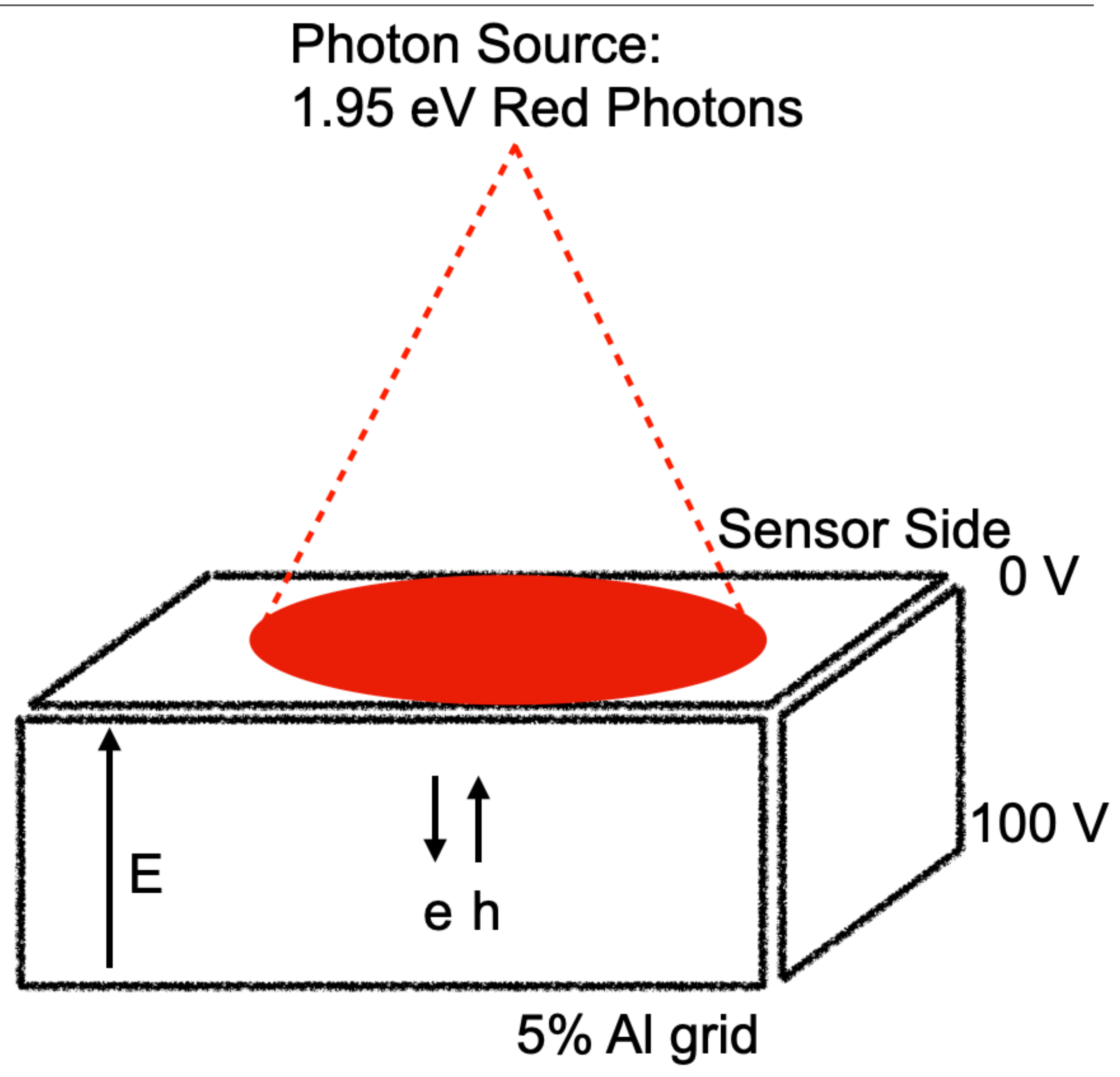


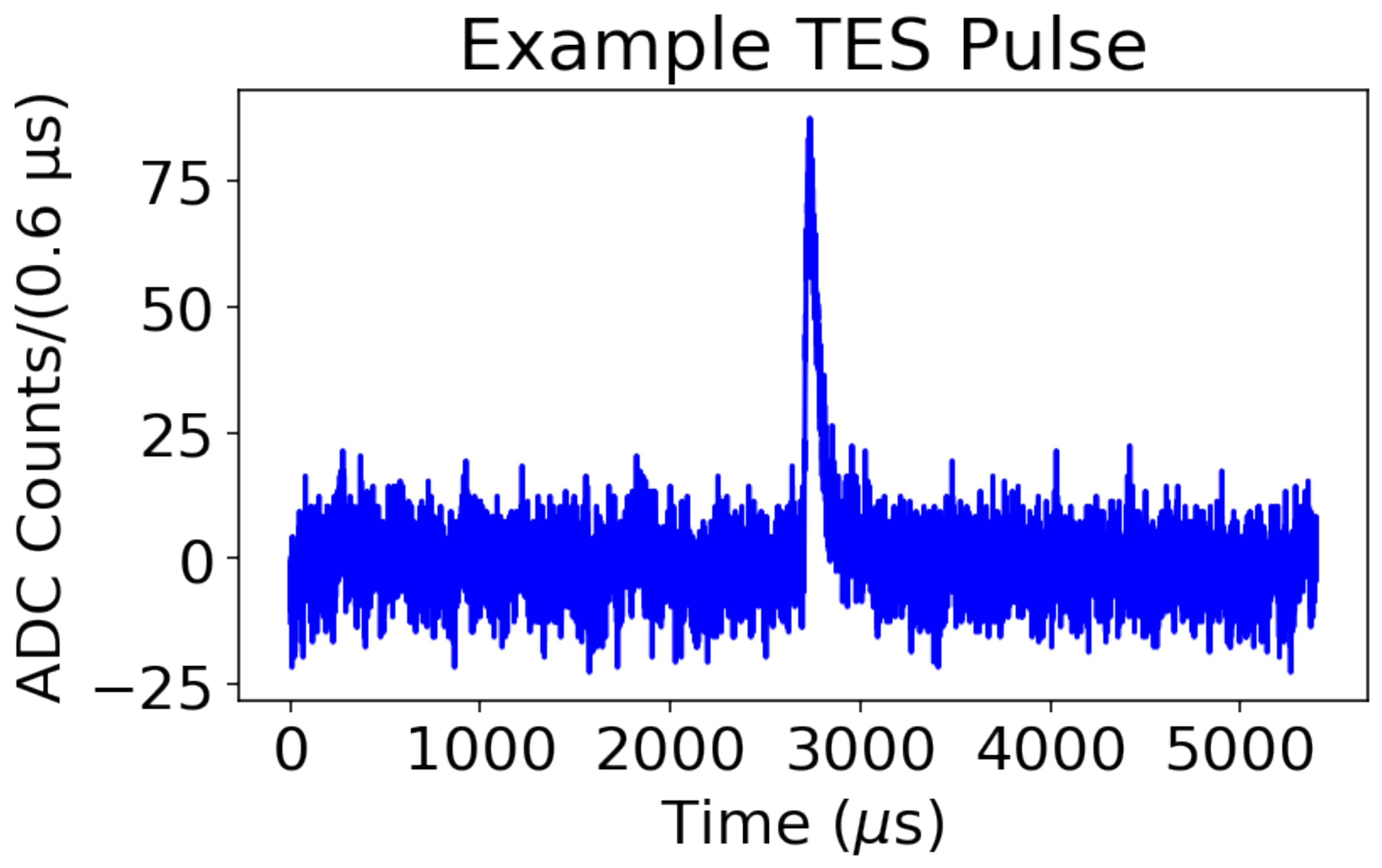
- Si HVeV mounted in the copper holder
- 10×10×4 mm silicon chip with a total mass of 0.93 g
- Two QET channels, with a critical temperature of 65 mK
- Channel 1 is 23 x 22 which is 506 QETs
- Channel 2 has 538 QETs

HVeV Experiment I Laser Calibration Experiment

In this thesis we will focus on the Laser calibration runs:

- The laser shoots 1.95 eV photons to the top surface of the detector. Visual spot of R=2.5 mm
- Si band gap is 1.1 eV so 1.95 eV photons can only liberate one eh pair. This makes the calibration data easier to understand
- The number of photons hitting the detector at the same time follows a near-Poisson distribution with Lambda~1
- The detector is biased at 100 V
- The penetration depth of the photons to the crystal is ~5.3 um and falls exponentially
- An example measured TES pulse along with the electronics noise is shown on the right
- Standard algorithm converts the pulse into an energy measurement



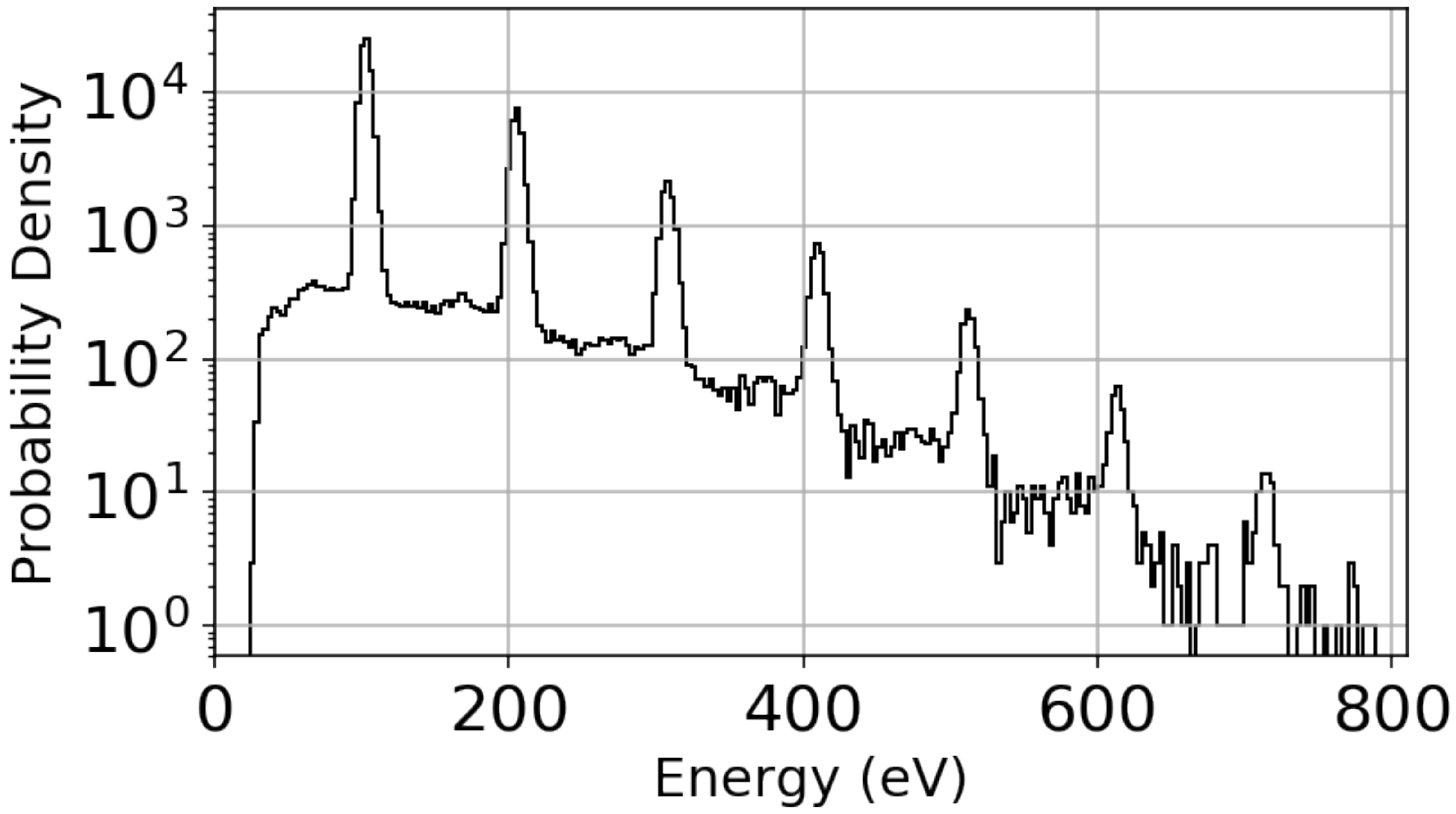


HVeV Experiment I Results, Main Features and Goals

Laser data shows a number of these effects:

- The number of photons hitting the detector follows a near-Poisson distribution with Lambda~1
- As expected, we see the Gaussian peaks with roughly flat background between the peaks caused by impurities in the crystal (Charge Trapping and Impact Ionization)
- RMS of the first eh pair peak ~ 3 eV

Collected Phonon Energy Spectrum at 100 V

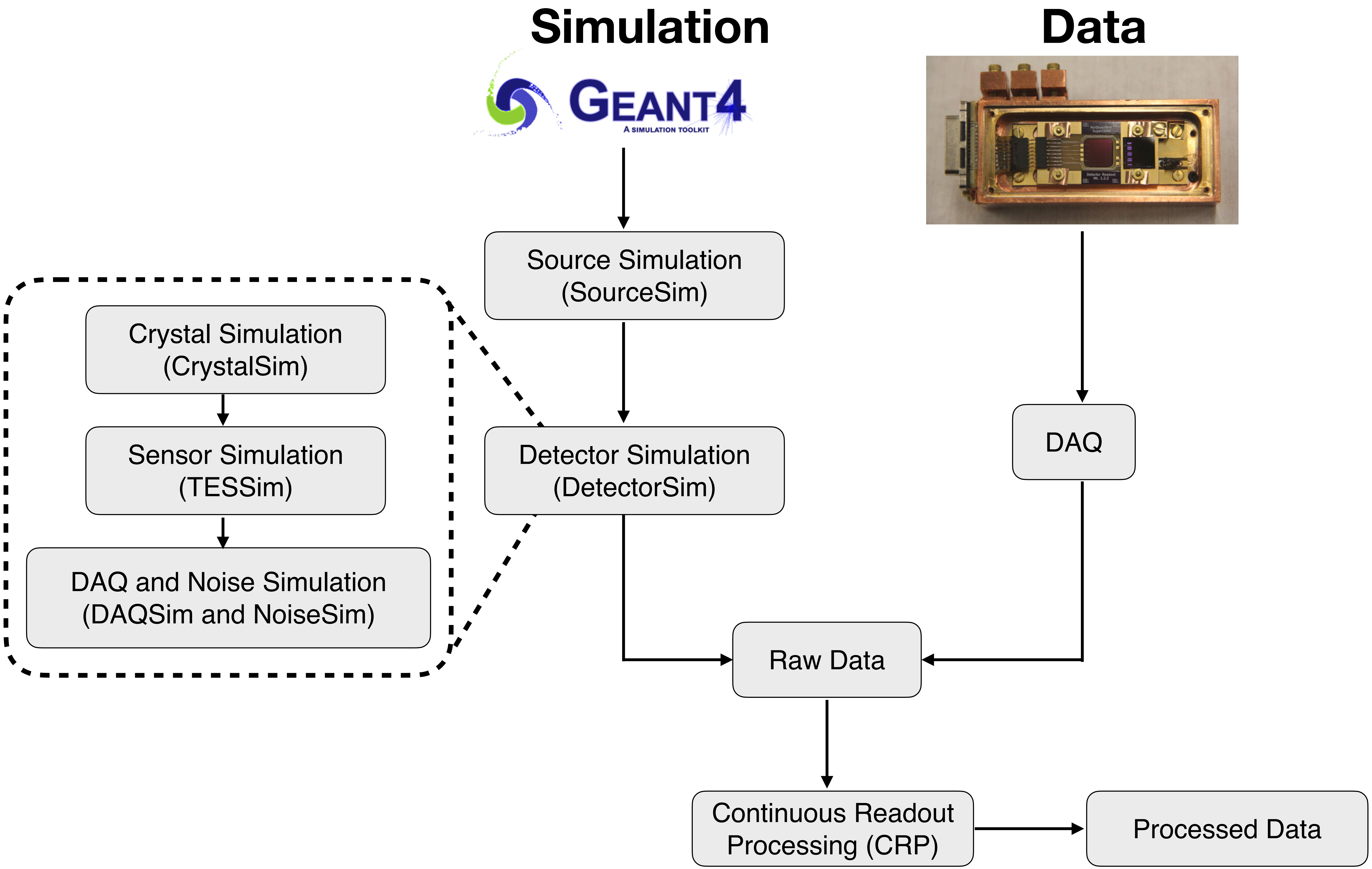


The goal of the simulation is to understand and reproduce these features:

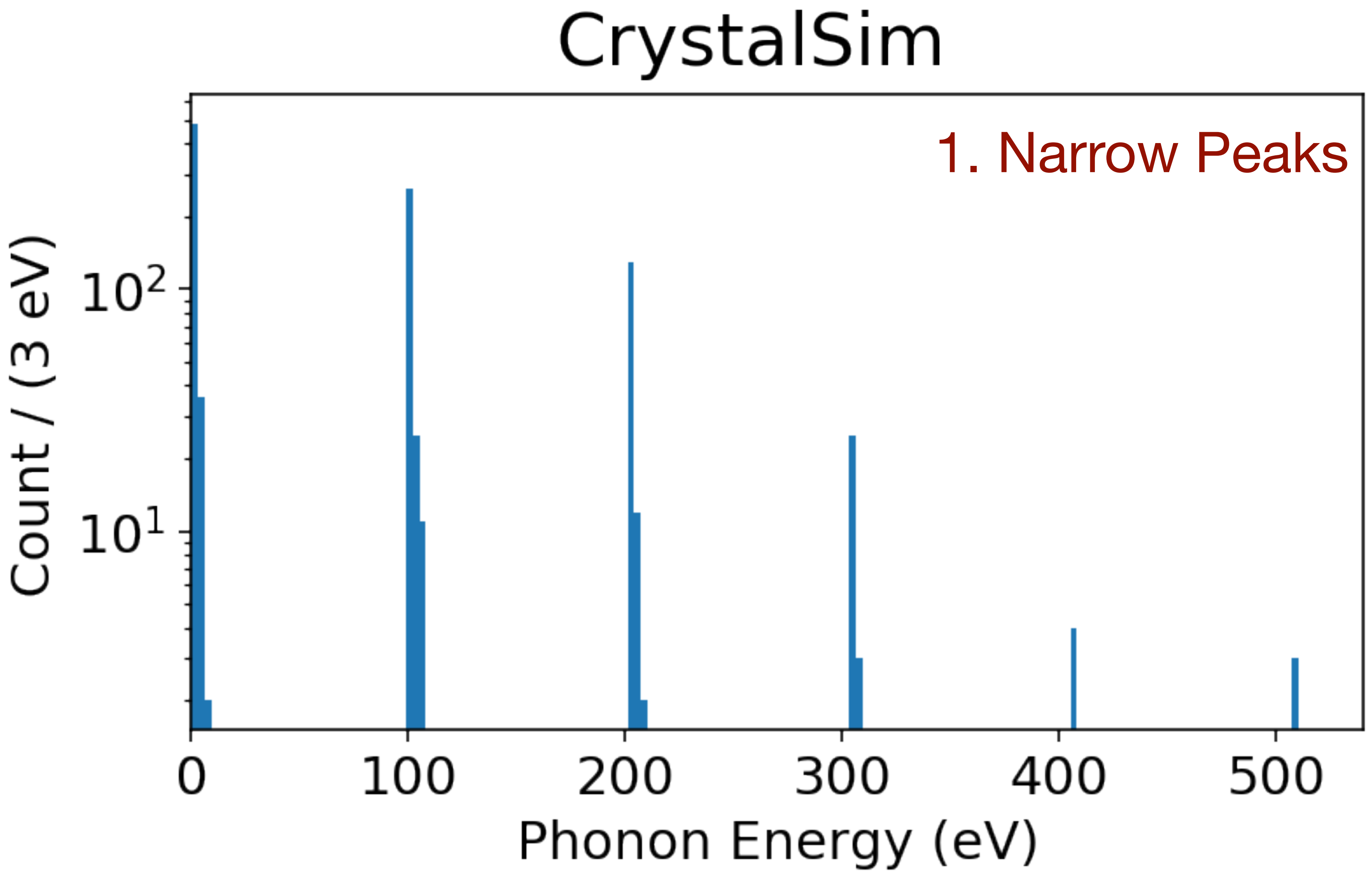
- **Location of the peaks**
- **RMS of the peaks (Which can hopefully tell us about the detector resolution)**
- **Understand the events between them to understand the purity of the crystal**

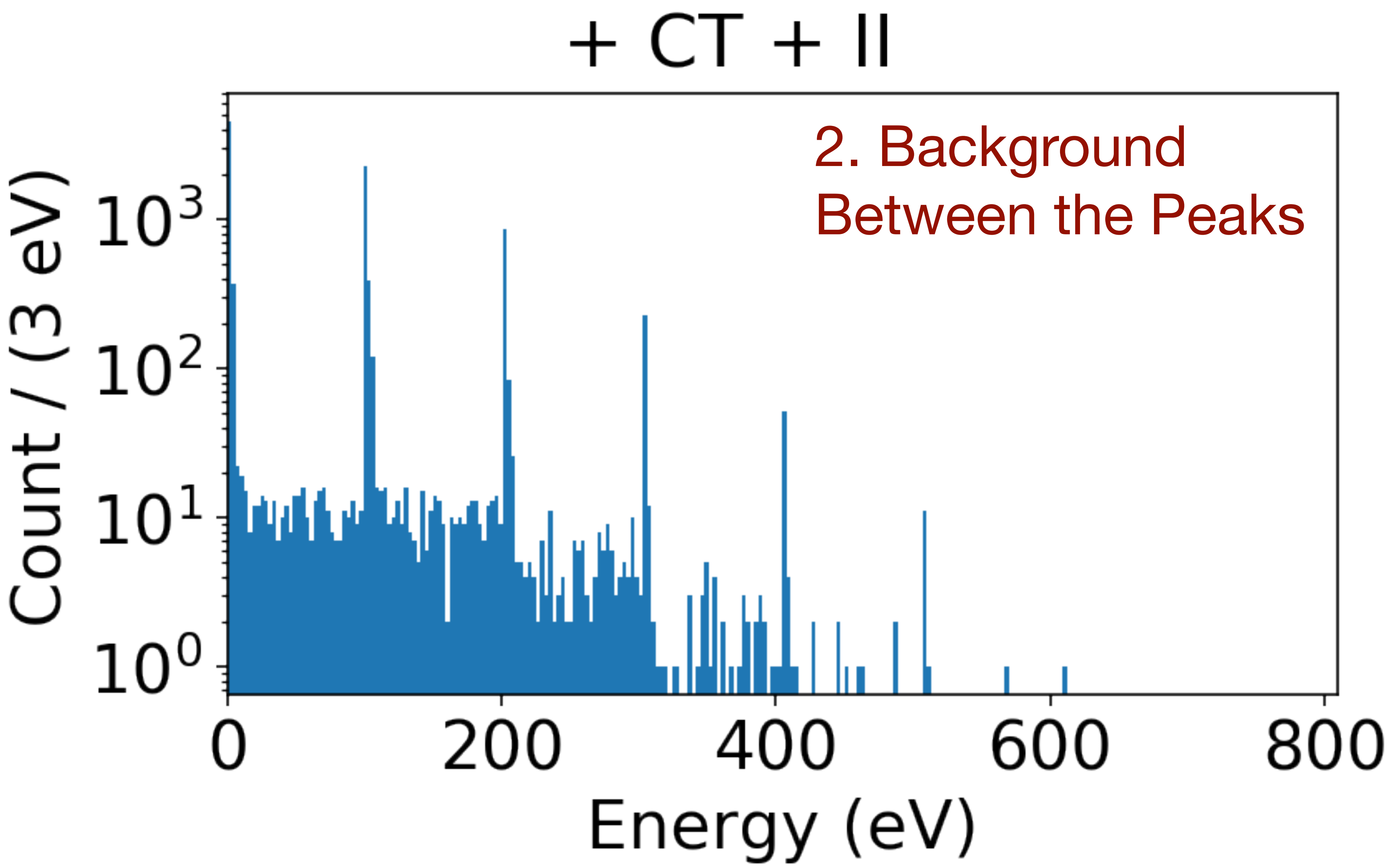
If we can build up the understanding event by event we might be able to identify poorly measured events and reject them from our dark matter searches.

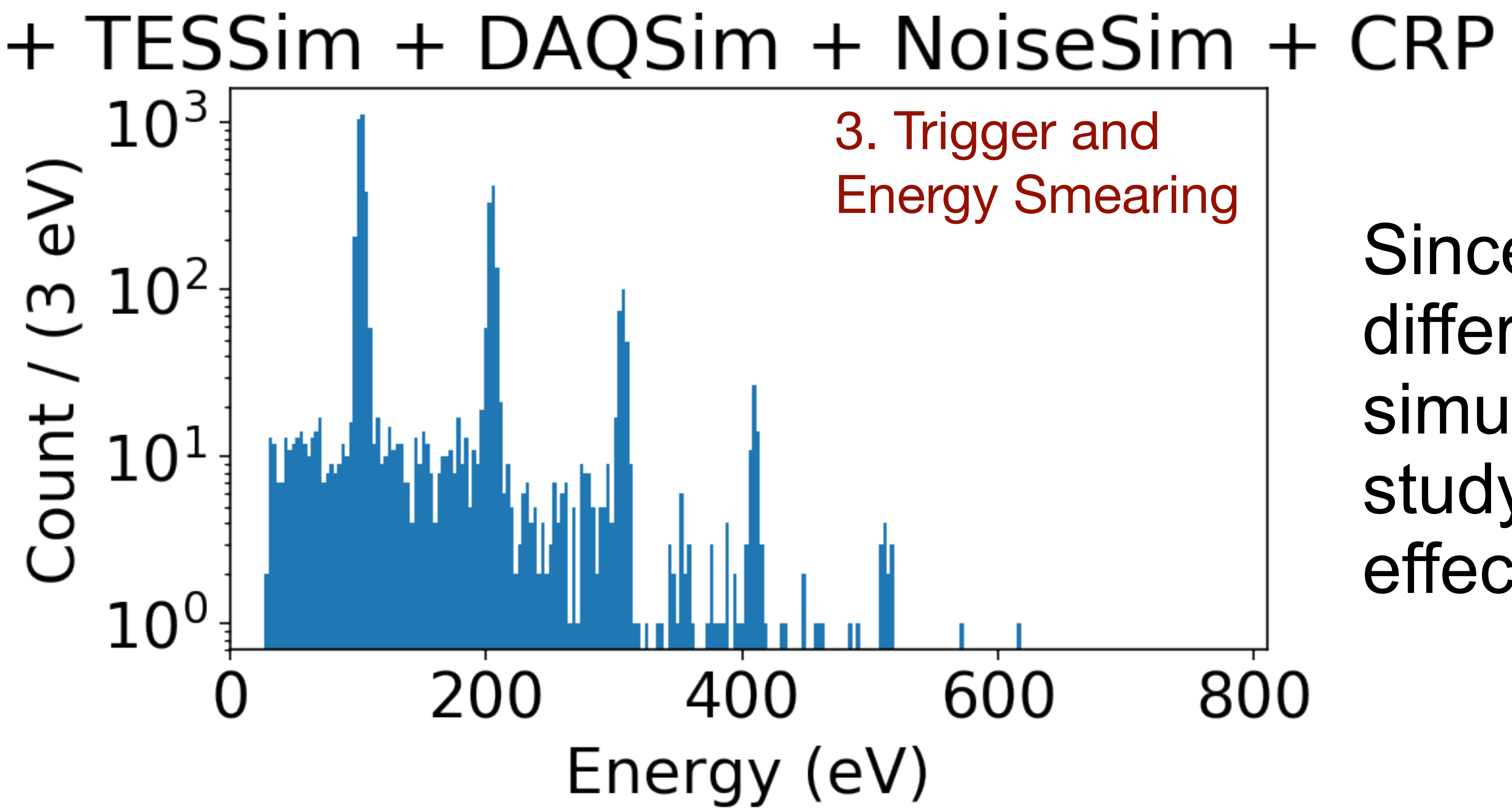
HVeV Simulation | Overview of the Full Simulation



HVeV Simulation | Overview of Simulation Steps for a Poisson Laser

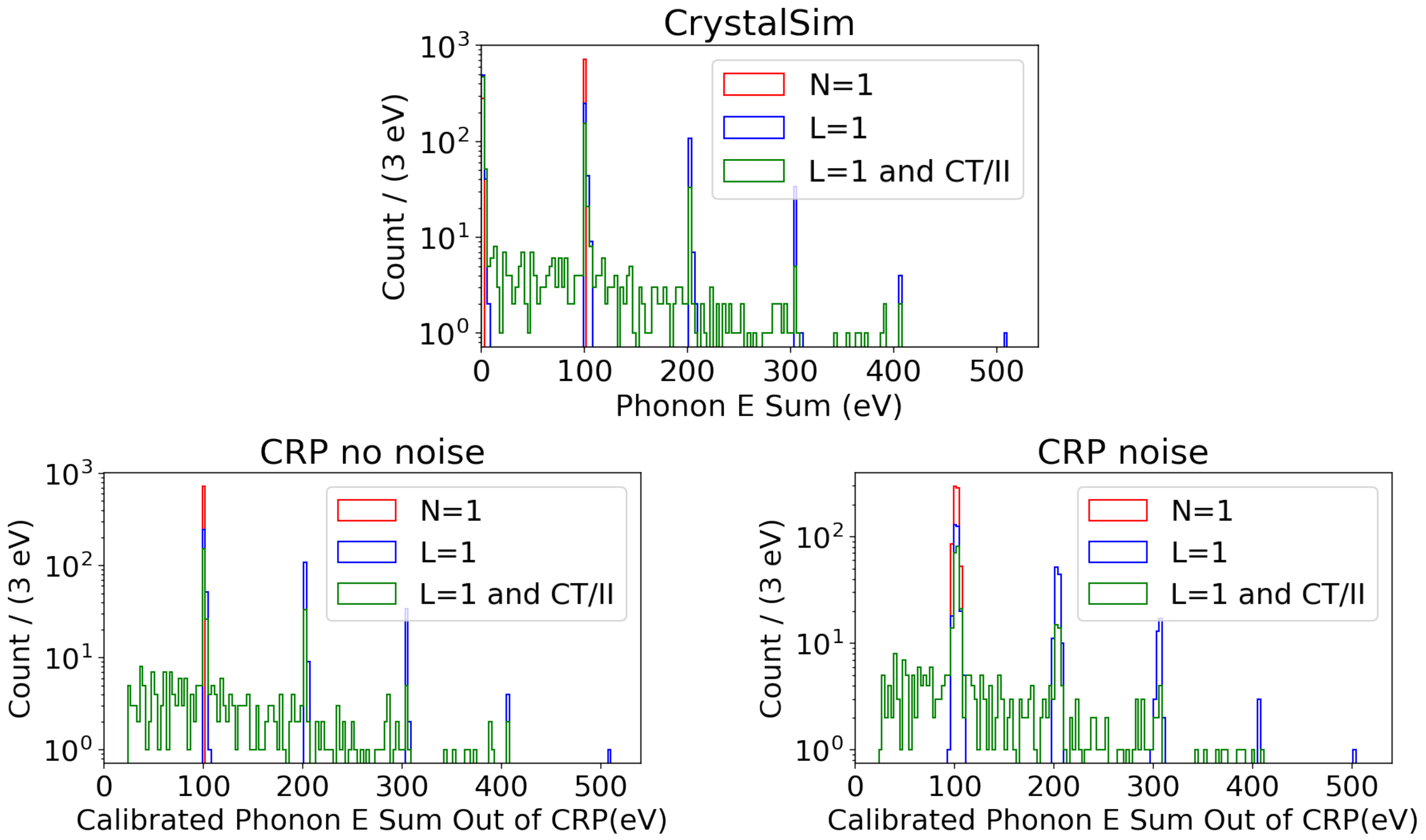




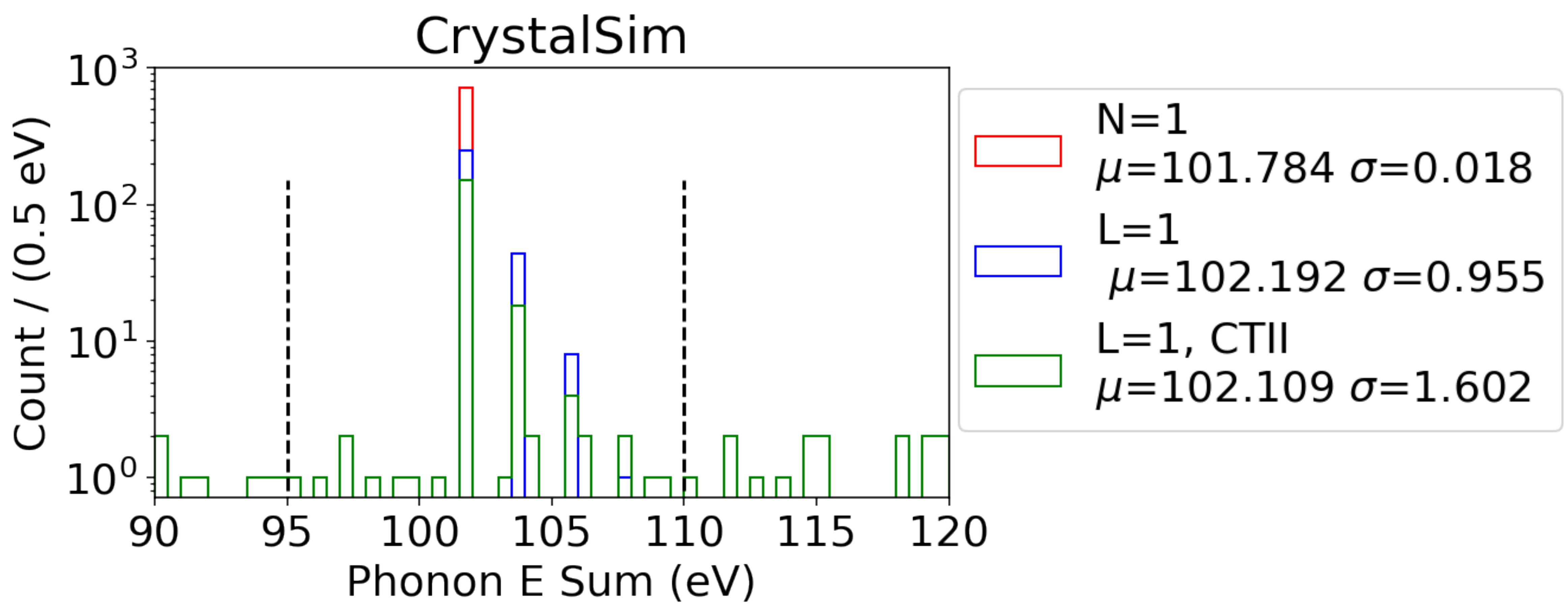


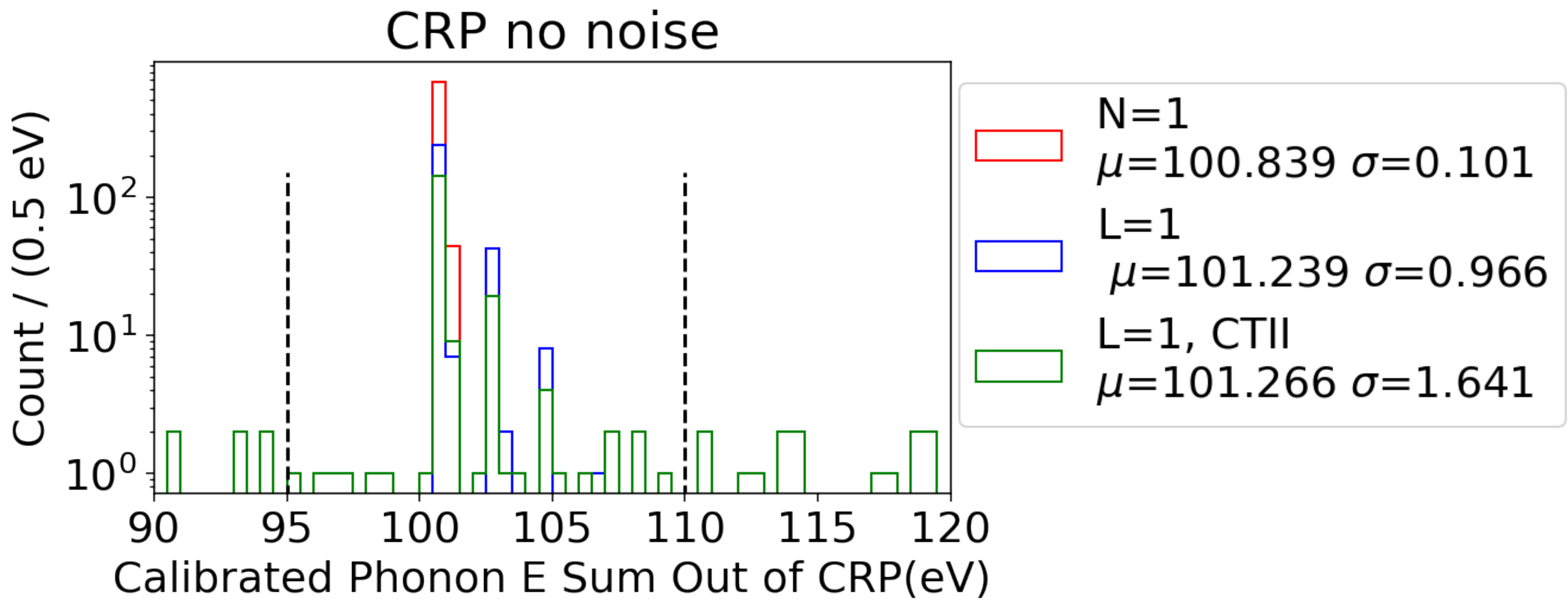
Since we can turn on/off different effects in the simulation, we can use it to study the contribution of each effect to the resolution

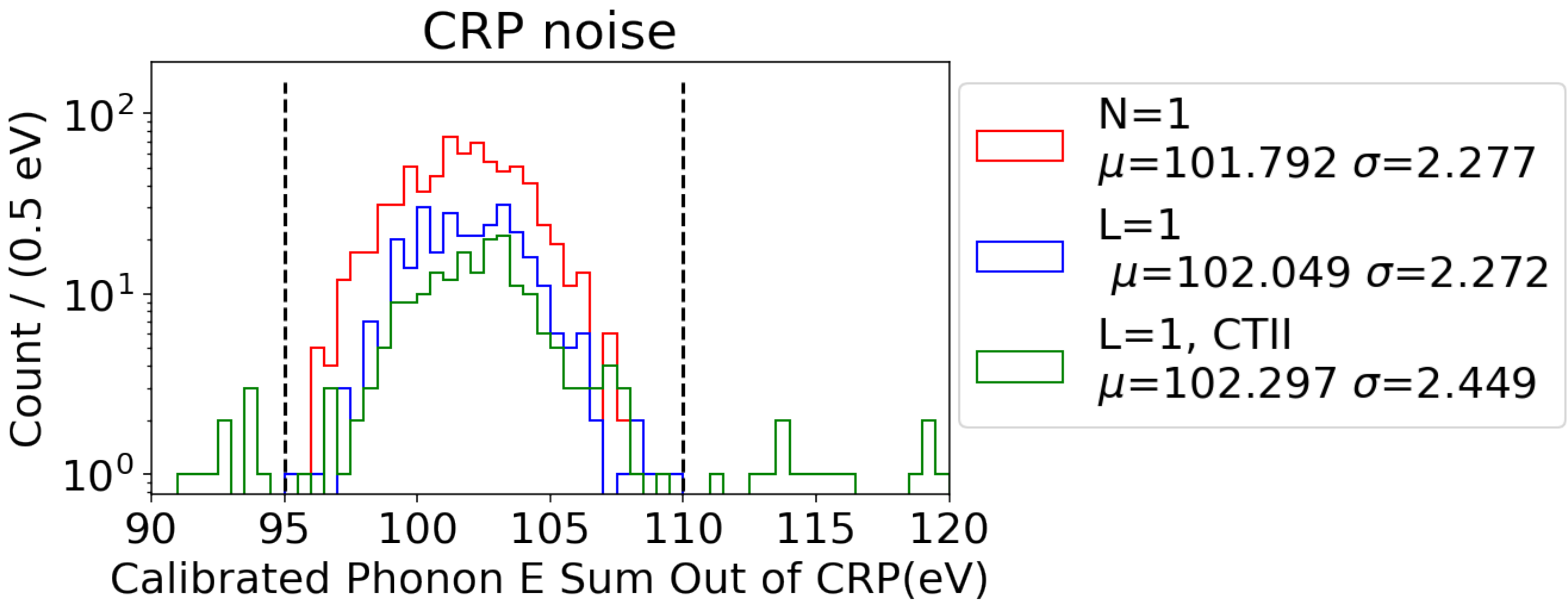
HVeV Simulation | Samples for Resolution Study



HVeV Simulation | Resolution: RMS of the First Peak







HVeV Simulation | Calculating the Resolution Due to Different Effects

	N=1	L=1	L=1 and CTII
CrystalSim	0.018	0.955	1.602
+TESSim	0.019	0.954	1.321
+CRP	0.101	0.966	1.641
+Noise	2.277	2.272	**2.449**

	Resolution
CrystalSim	0.018
TESSim	0.006
CRP	0.099
Noise	2.274
Laser	0.955
CTII	1.286
Total	**2.783**

- LHS shows the resolution after adding each effect to the simulation
- We assumed resolution due to each effect adds in quadrature. RHS is the calculated resolution due to each effect
- Colors show how we calculated the contribution of each effect. For example:
  - TESSim Resolution = sqrt((0.019)^2 - (0.018)^2)
- Total is the sum of all contributions in quadrature. Will discuss on the next page

HVeV Simulation I Calculating the Resolution Due to Different Effects

	N=1	L=1	L=1 and CTII
CrystalSim	0.018	0.955	1.602
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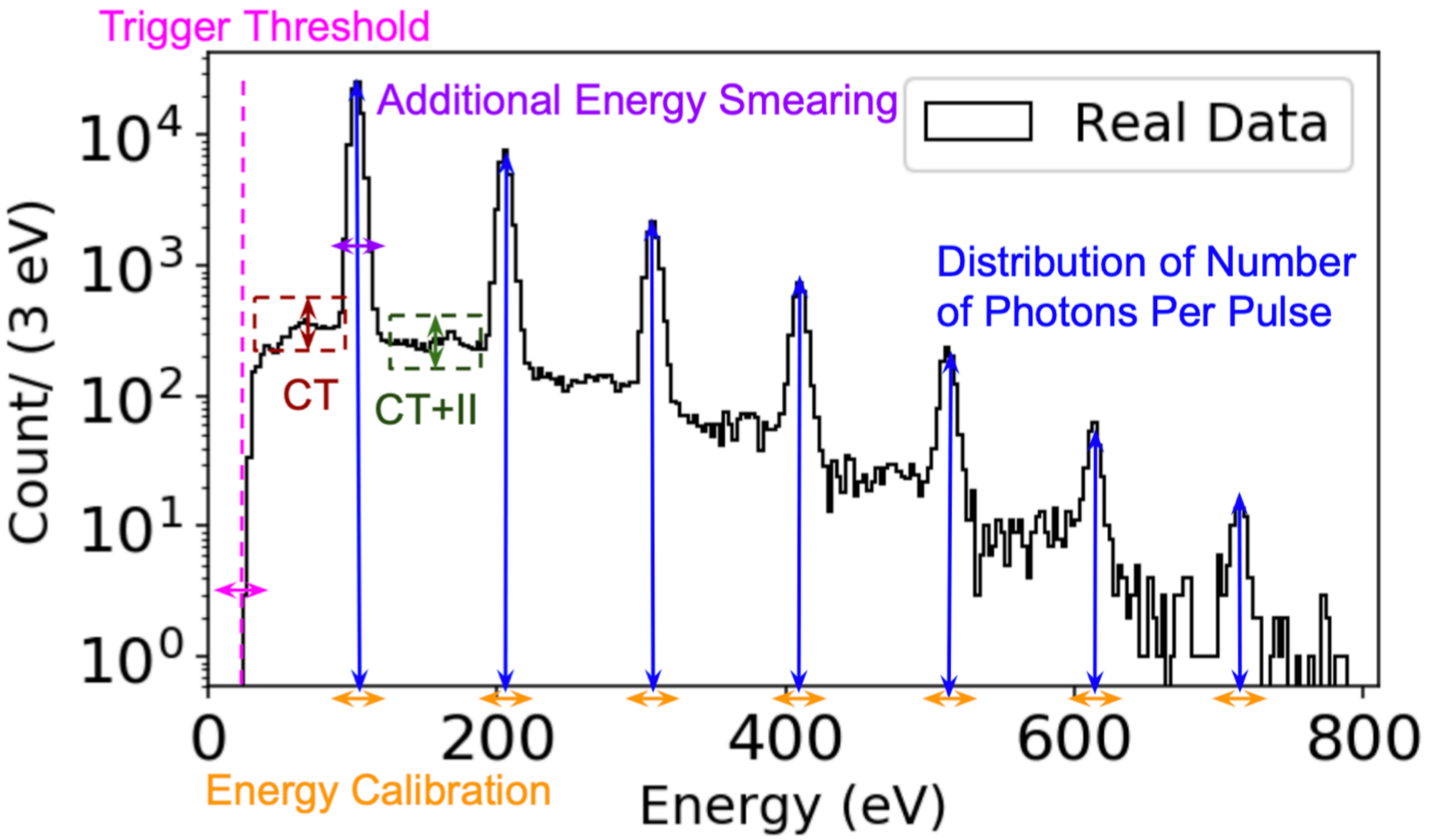
	Resolution
CrystalSim	0.018
TESSim	0.006
CRP	0.099
Noise	2.274
Laser	0.955
CTII	1.286
Total	**2.783**

- Noise has the biggest contribution to the resolution. CTII and Laser have the next two biggest contributions
- If we add all effects in quadrature, we will get a total resolution of **2.783 eV** which is higher than **2.449 eV**.
- The fact that the simulation shows an RMS that is smaller than in the data suggests that there are some missing events in the simulation which are beyond the studies in this thesis

HVeV Simulation | Simulation Parameters



Charge trapping (CT) and impact ionization (II) are controlled with the mean free path parameters which are the probabilistic distance that charges can travel before encountering an impurity region

HVeV Simulation | Overview of Simulation Steps to Reproduce Data

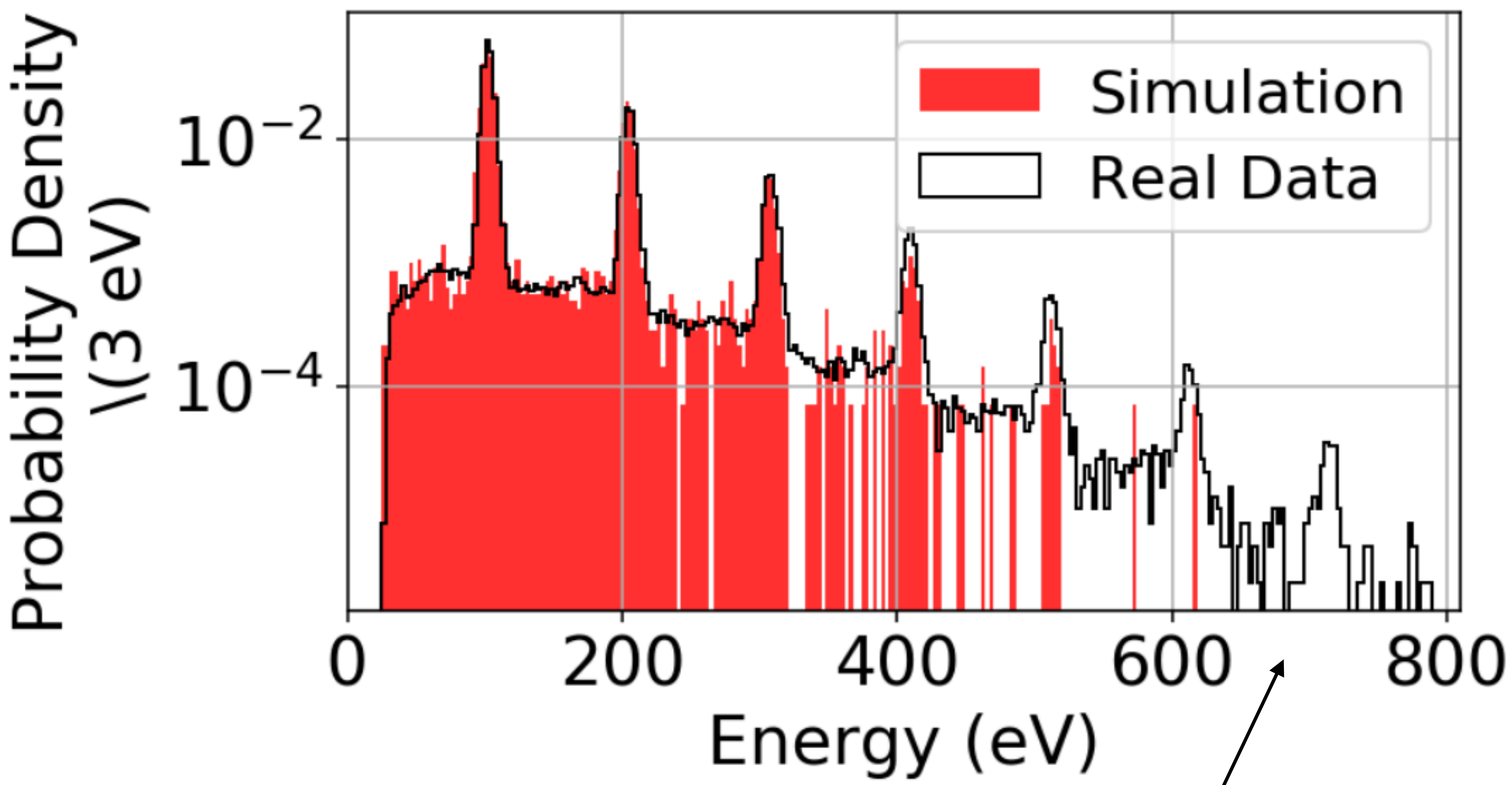
- We will see that simulation of a Poisson laser out of the box with the optimized CT and II parameters does not reproduce the spectrum accurately. So we are going to do some tuning that we will explain in more detail later.
- Here is a quick overview:
  - Custom Laser with a configurable distribution of the number of photons hitting the detector at the same time
  - We also need to add Additional Energy Smearing to our simulated data because the simulation is not reproducing the same resolution as the data

- Outline of what's coming next:
  - Poisson Laser
  - Custom Laser
  - Parameter Tuning
  - Final Data and Simulation Comparison
  - Conclusions

HVeV Simulation I Poisson Laser

How did we make this plot?

1. Simulated a laser that emits Photons based on a Poisson distribution with Lambda = 1
2. Found the optimized CT and II values for a Poisson laser (CT = 260 mm and II = 2700 mm)
3. Ran simulated data through DAQSim and CRP and selected a trigger threshold that produces similar turn-on curve to data
4. Calibrated the energy using the following functional form:
   Energy = a*A_OF*(1+b*A_OF) where A_OF is the estimated energy directly from evaluation of the pulse (Details in the thesis)
5. Added additional energy smearing to get the resolution right (Will describe later)

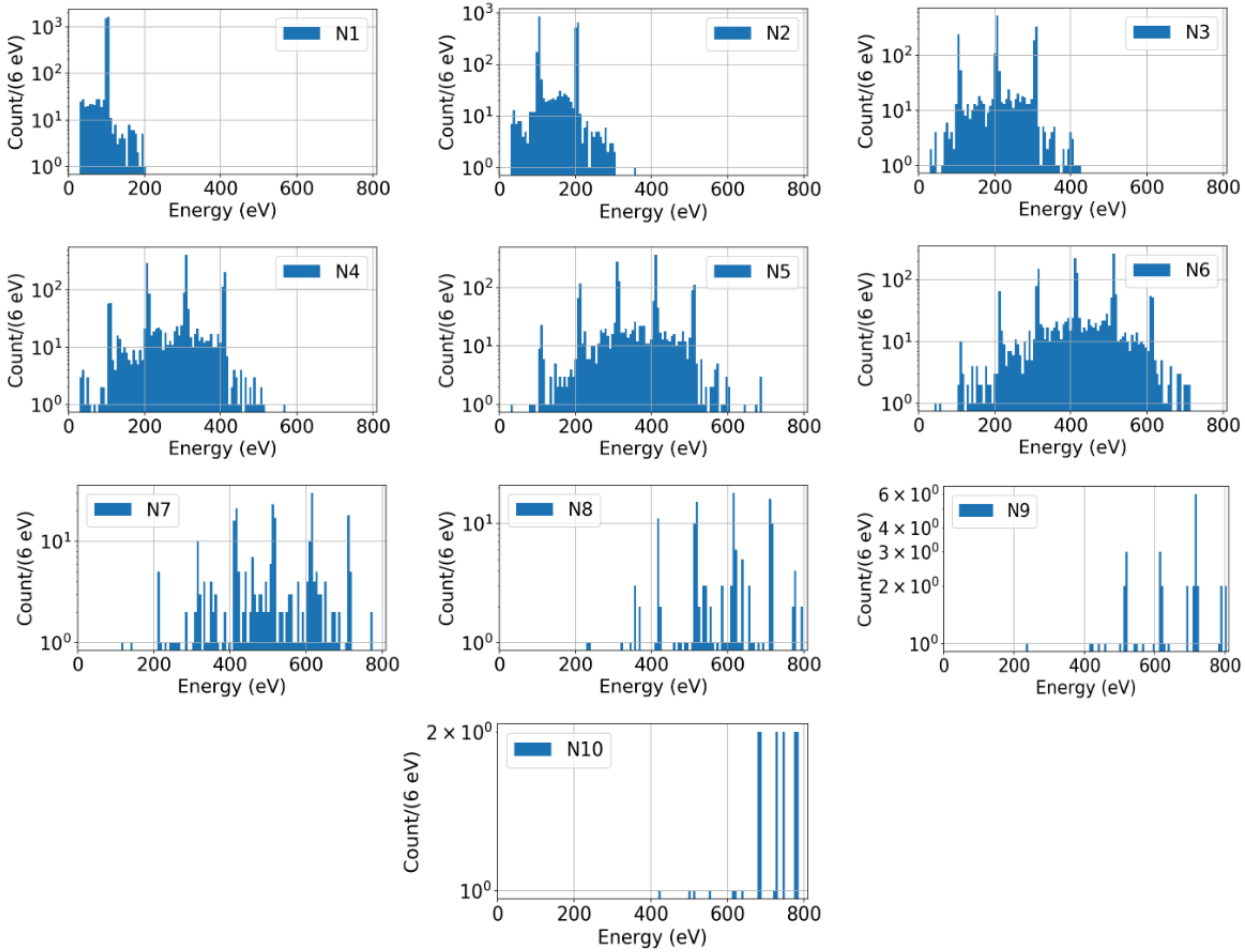


Too few events in the higher energy peaks

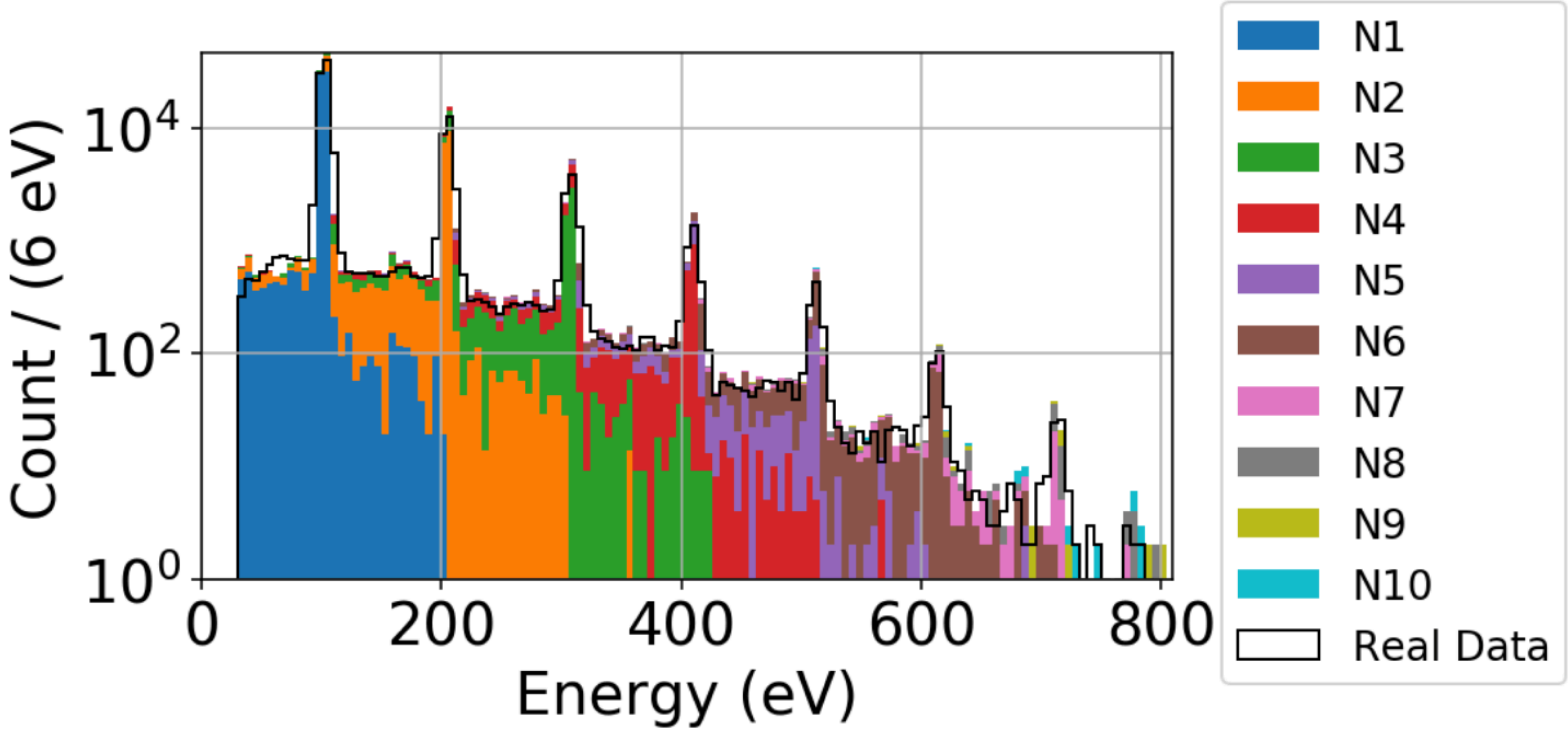
Since the Poisson laser simulation does not reproduce all the main features of the spectrum, we will not show the details of each step. We will simulate a custom laser where we make samples with different number of photons hitting the detector then we weigh our samples to get the best match between simulation and data. We will show the details of each step for the custom laser.

HVeV Simulation | Custom Laser

Simulate samples with N = 1 through N = 10 (running through all stages including CRP)

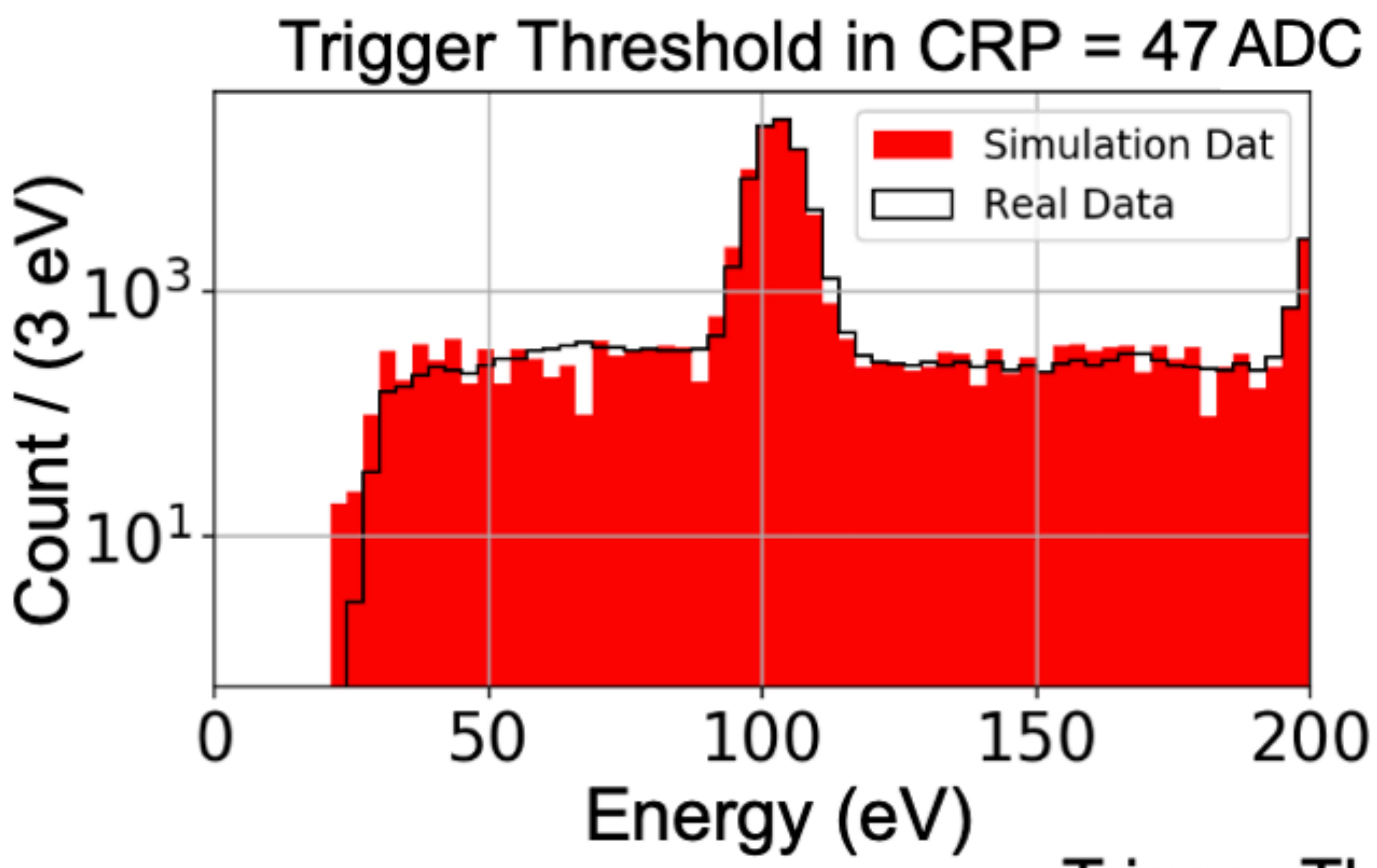


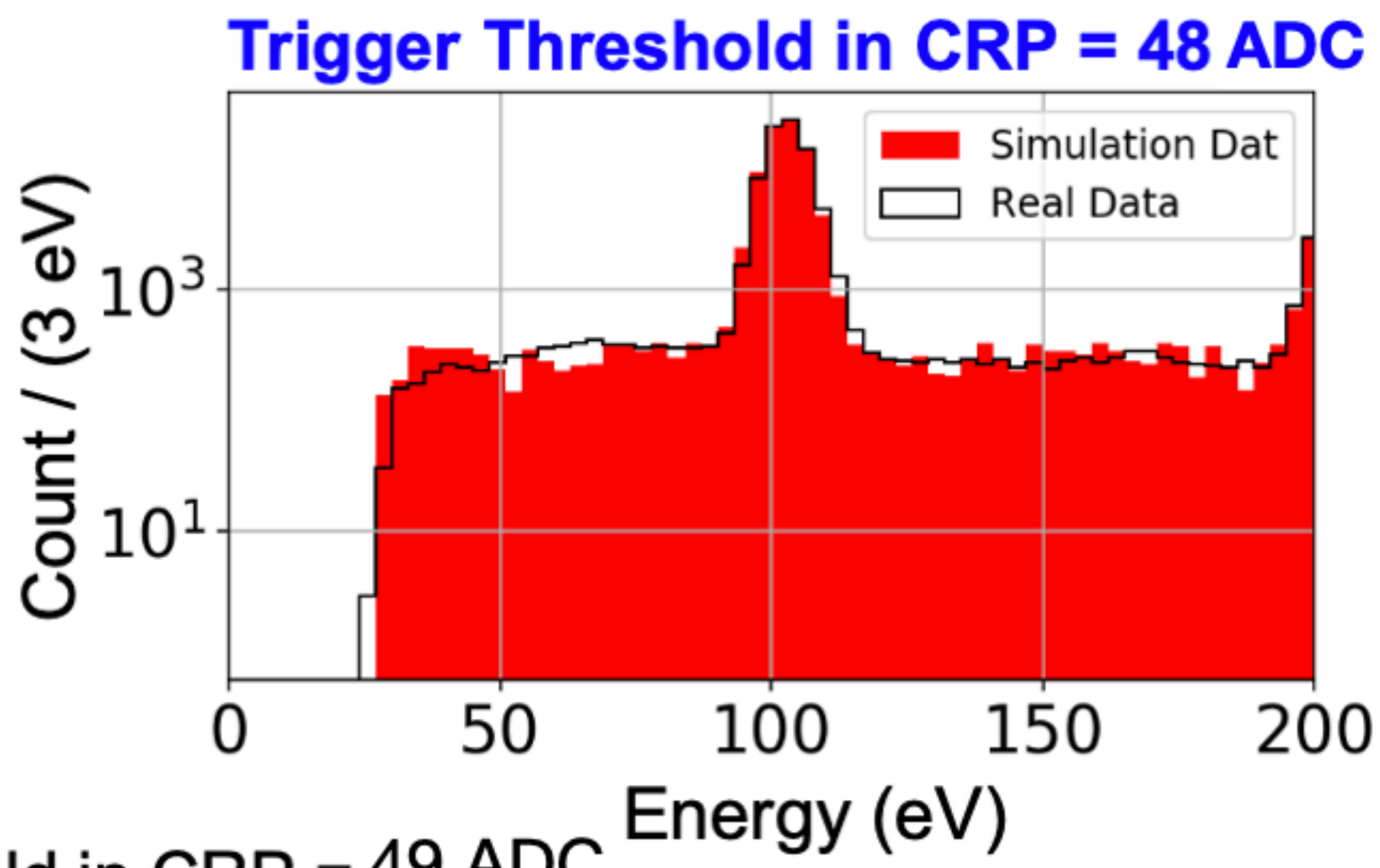
HVeV Simulation | Parameter Tuning : Weights

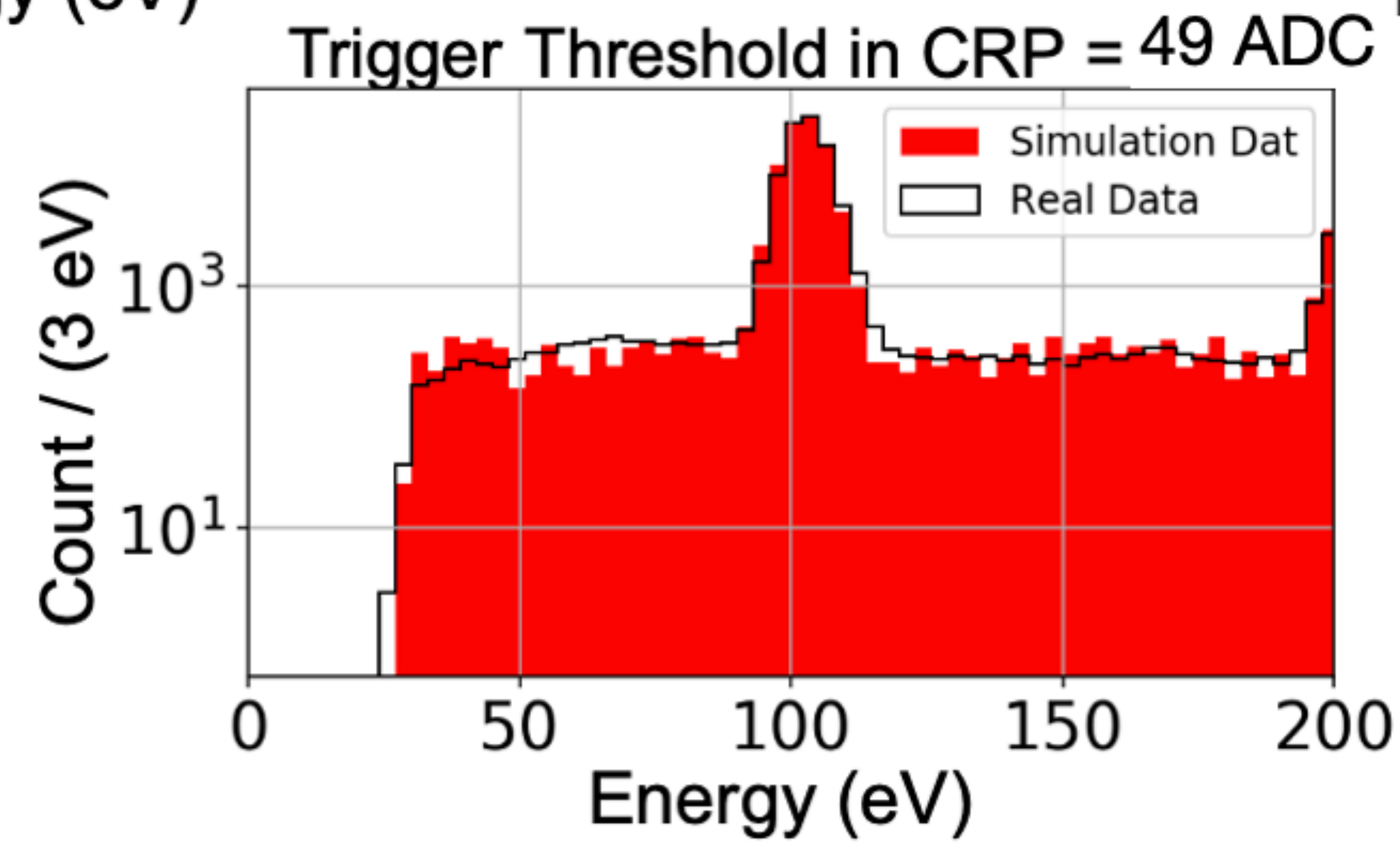


- This figure shows an example of what things look like when we combine the samples after running through all the steps, with the final CT+II values, the final trigger threshold, but before the additional energy smearing
- Note that the simulated samples are scaled to match the data
- Now we will show how we pick the trigger threshold

HVeV Simulation | Parameter Tuning : Trigger

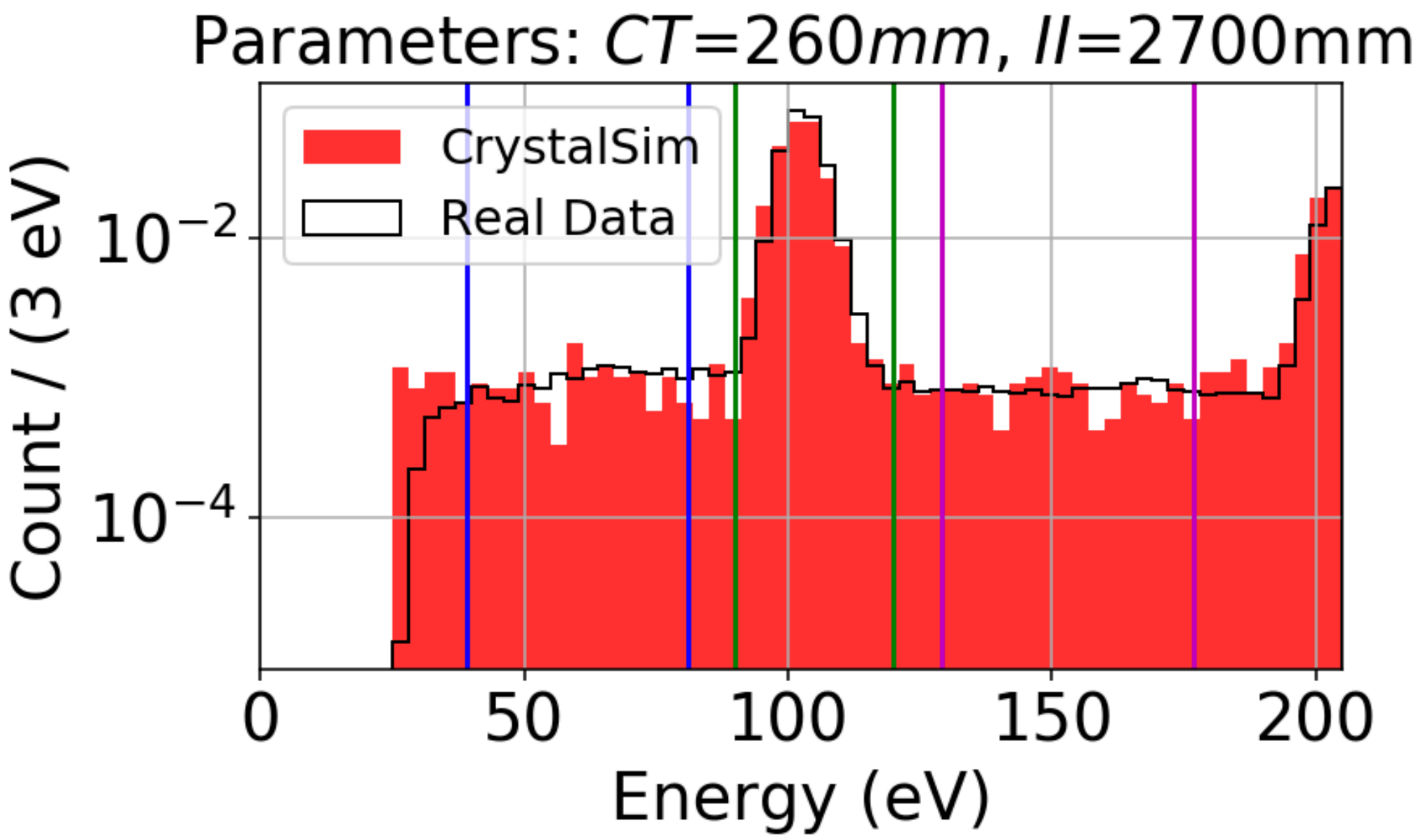






This figures include additional energy smearing
(Will explain later)

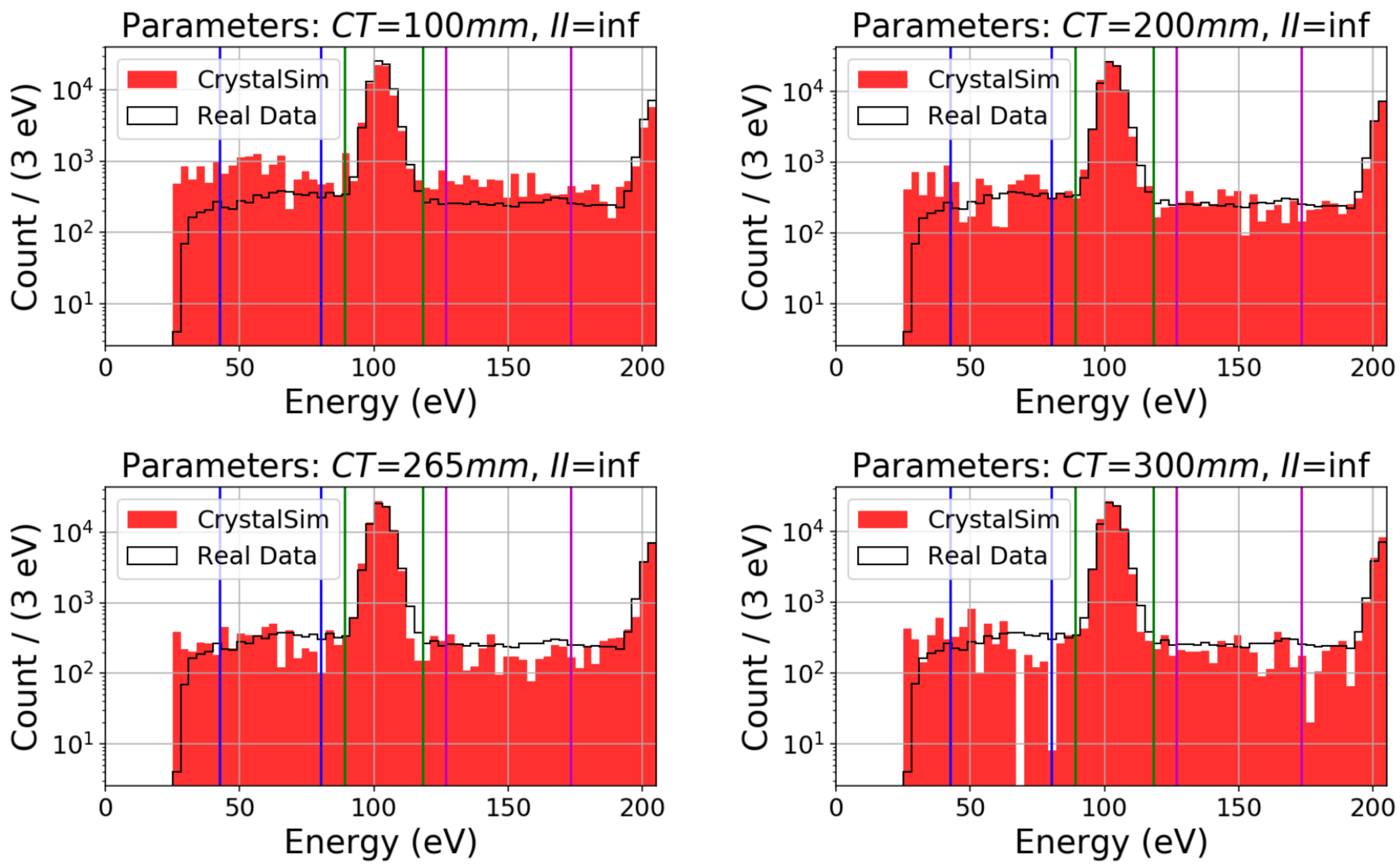
HVeV Simulation | Parameter Tuning : CT and II

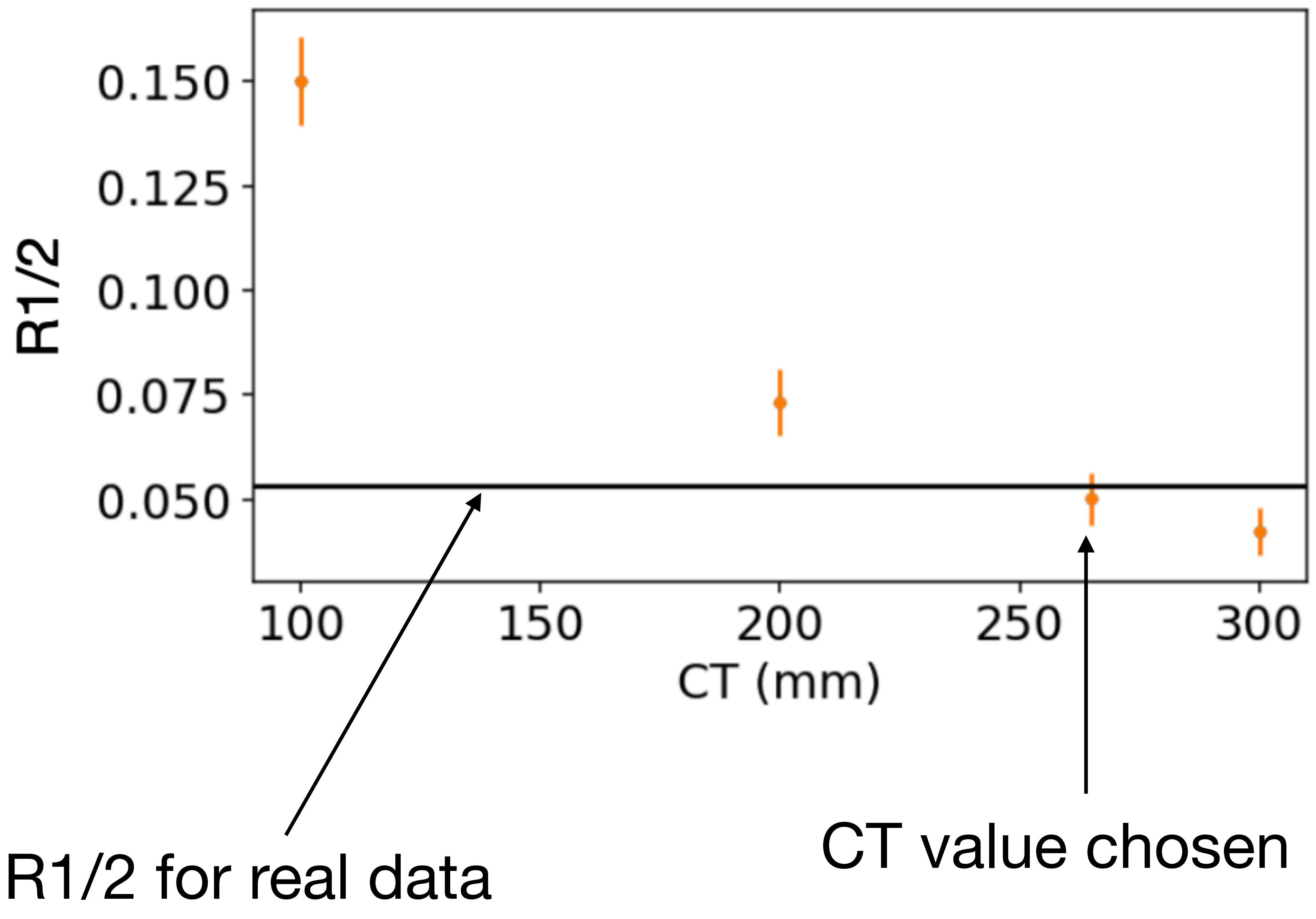


- We simulate samples with different CT and II Mean Free Path Values and compare the simulation to data to find the best match
- We pick three energy regions, shown in blue, green and purple, and compare data and simulation counts by defining the following parameters:

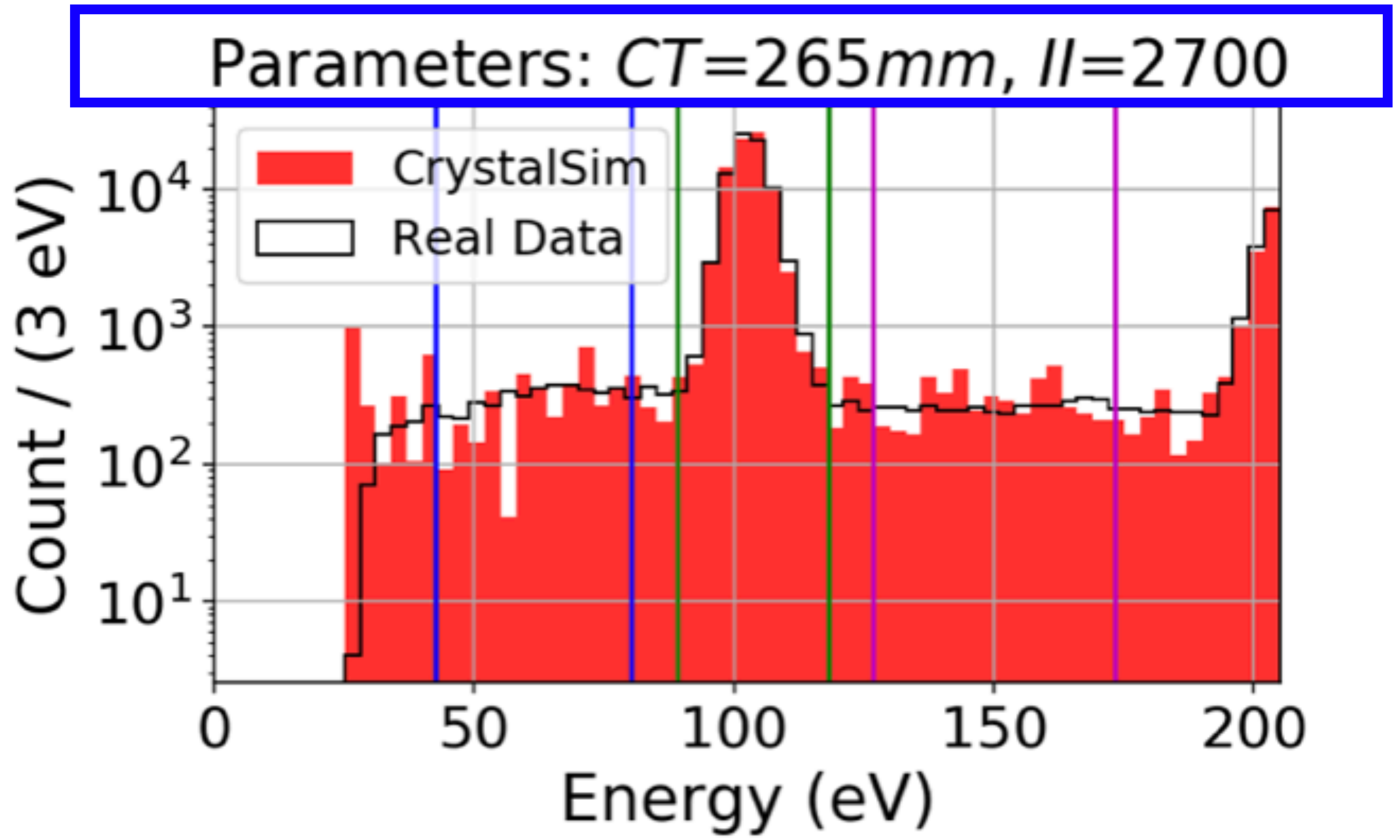
R1/2 = Blue/Green
R3/2 = Magenta/Green

HVeV Simulation | Parameter Tuning : CT



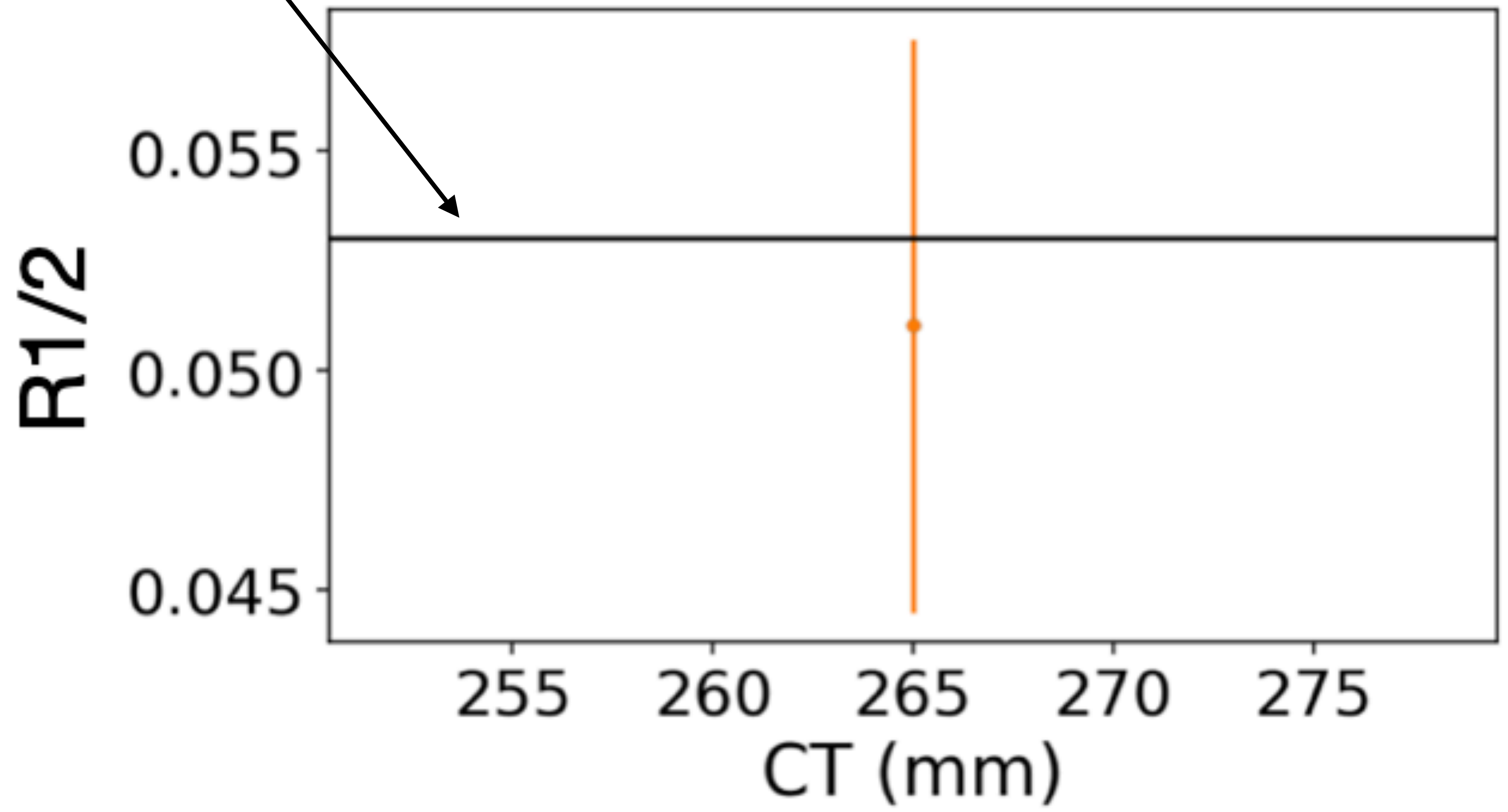


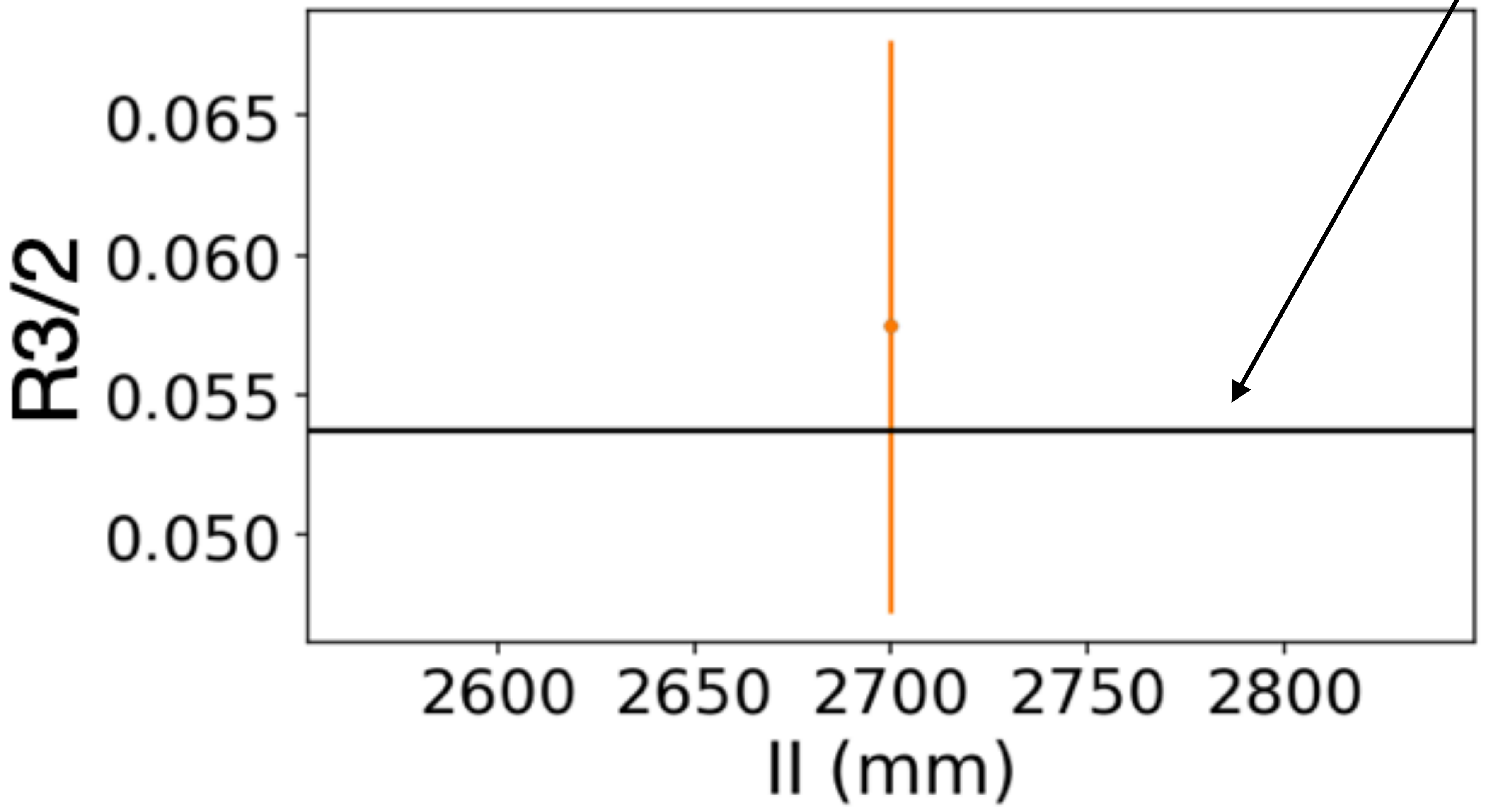
HVeV Simulation | Parameter Tuning : Adding II and Final CT and II



R1/2 for real data

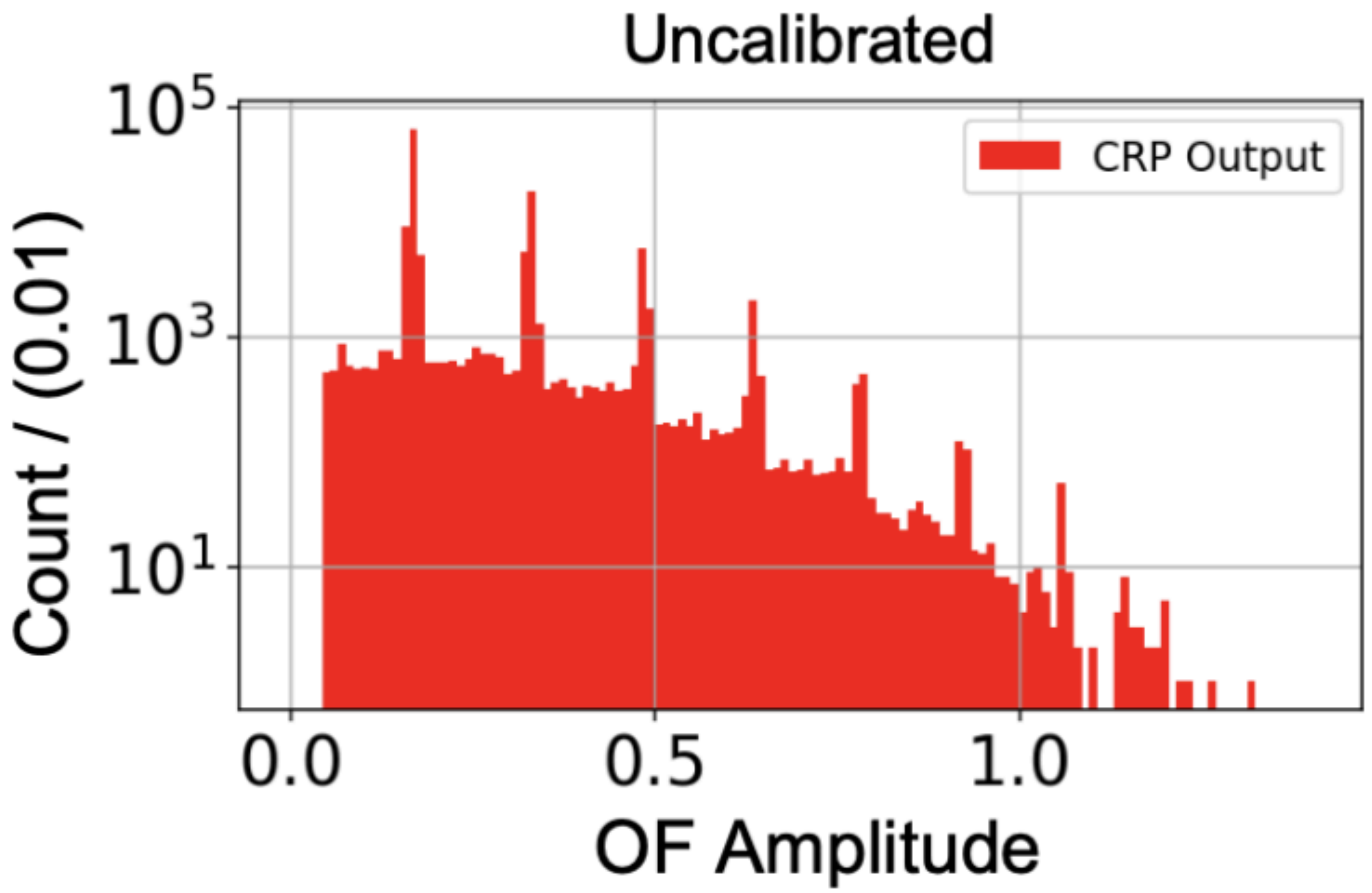
R3/2 for real data

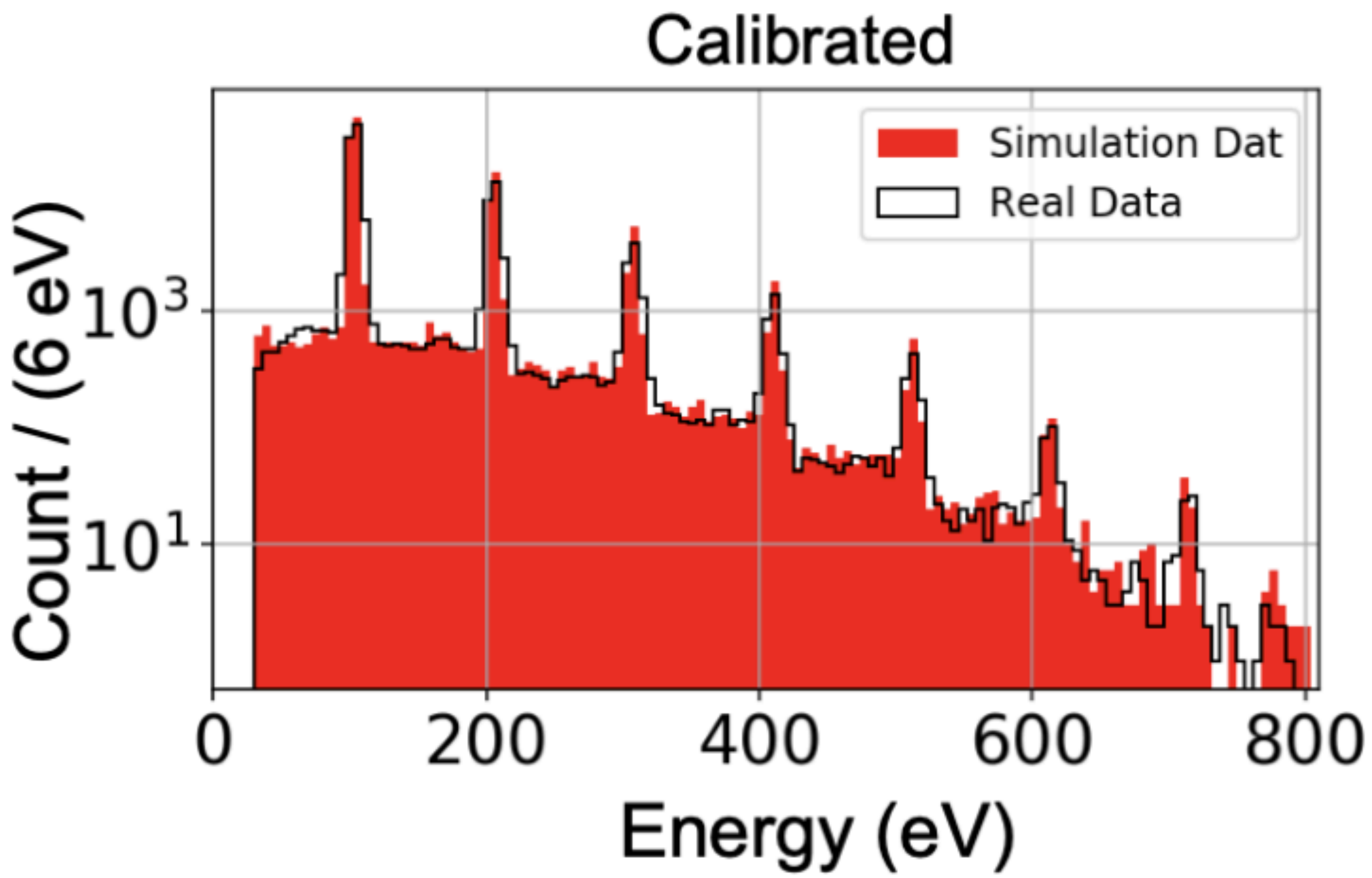


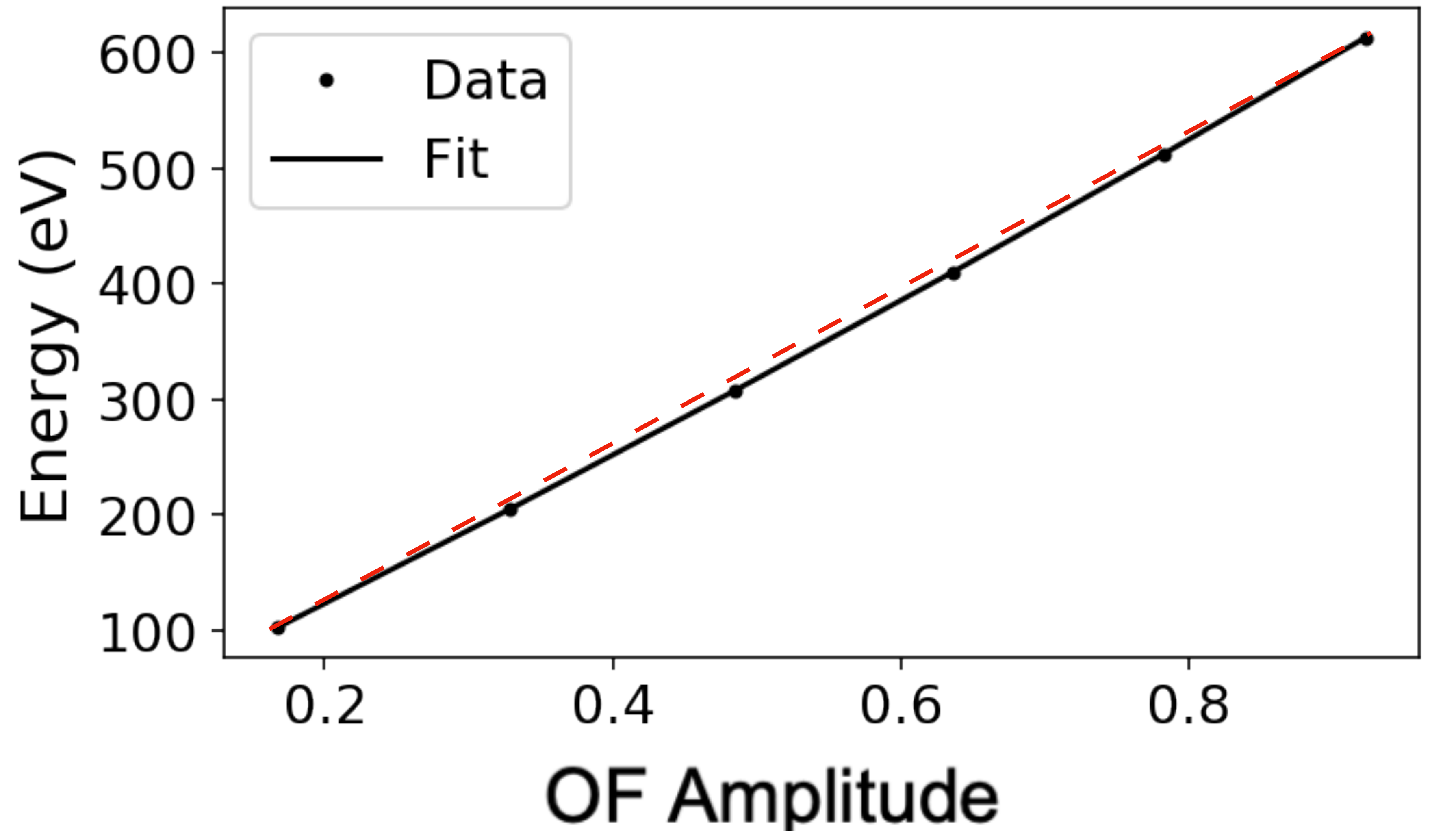


The combination of parameter choices reproduce both values within statistics

HVeV Simulation | Parameter Tuning : Calibration







Red dashed-line shows a straight line

Calibration Function:

Energy = a*A_OF*(1+b*A_OF)

[Same as HVeV Real Data]

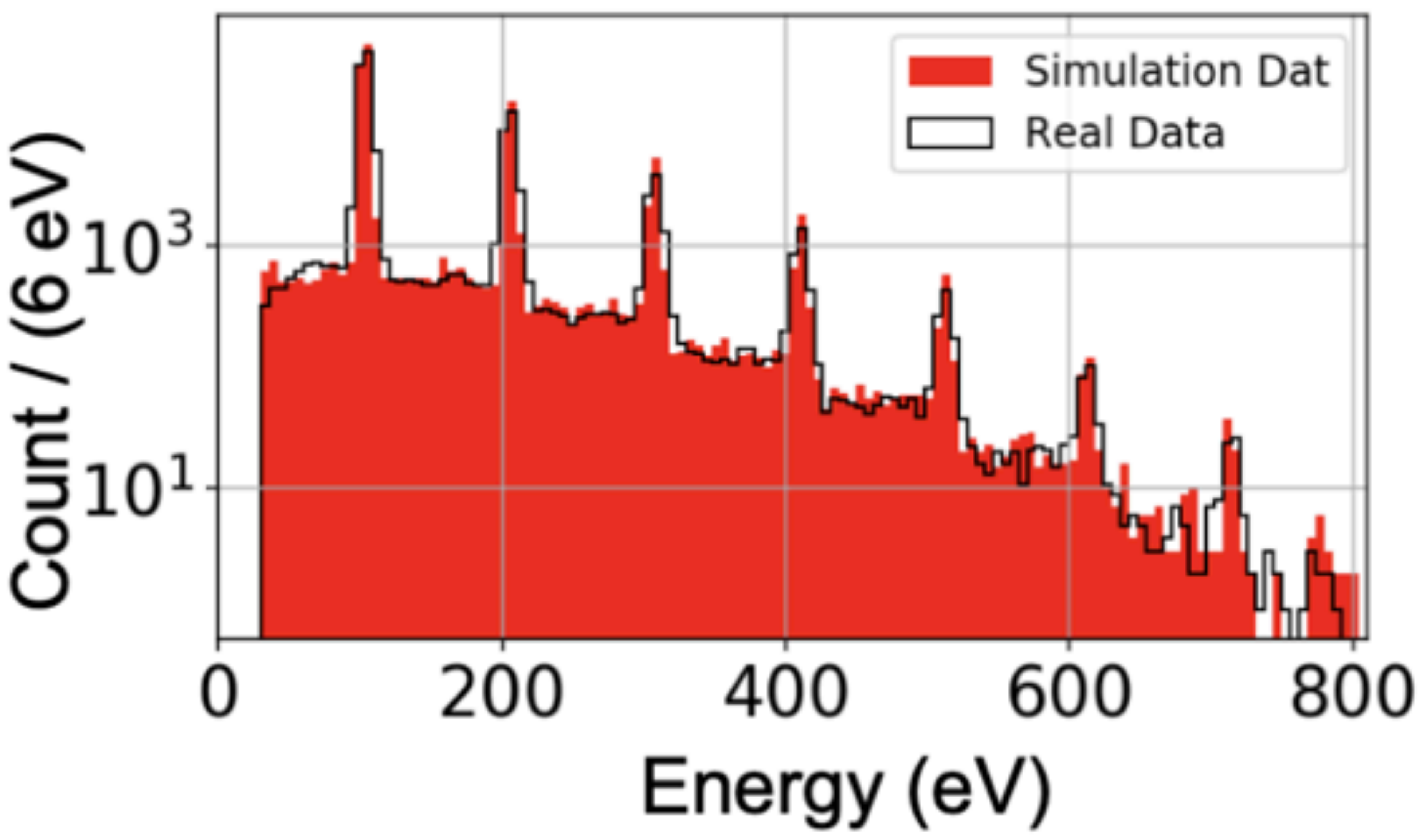
Constants:

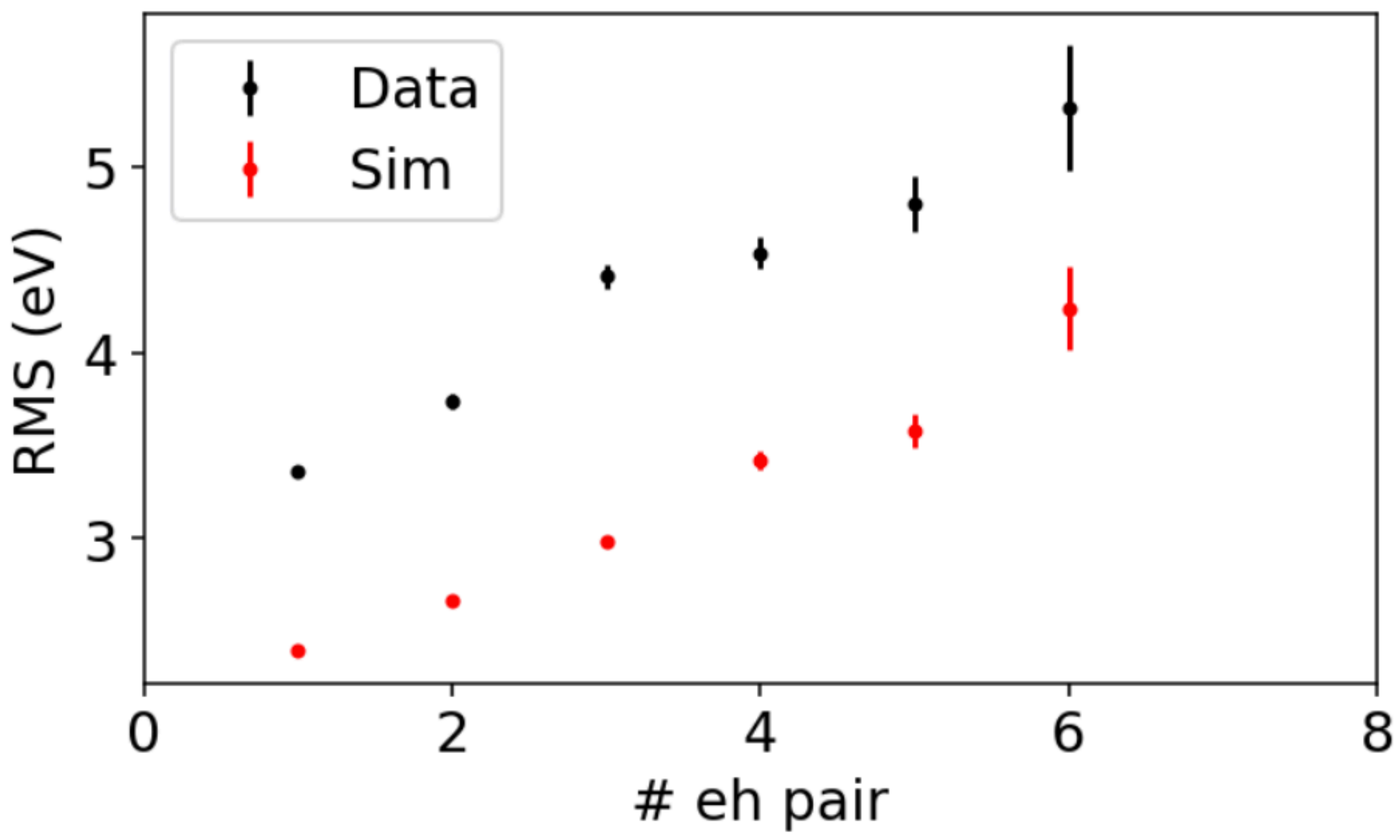
a = 601

b = 0.115

Peaks are at the right place but the RMS of the peaks in simulation are smaller than the data

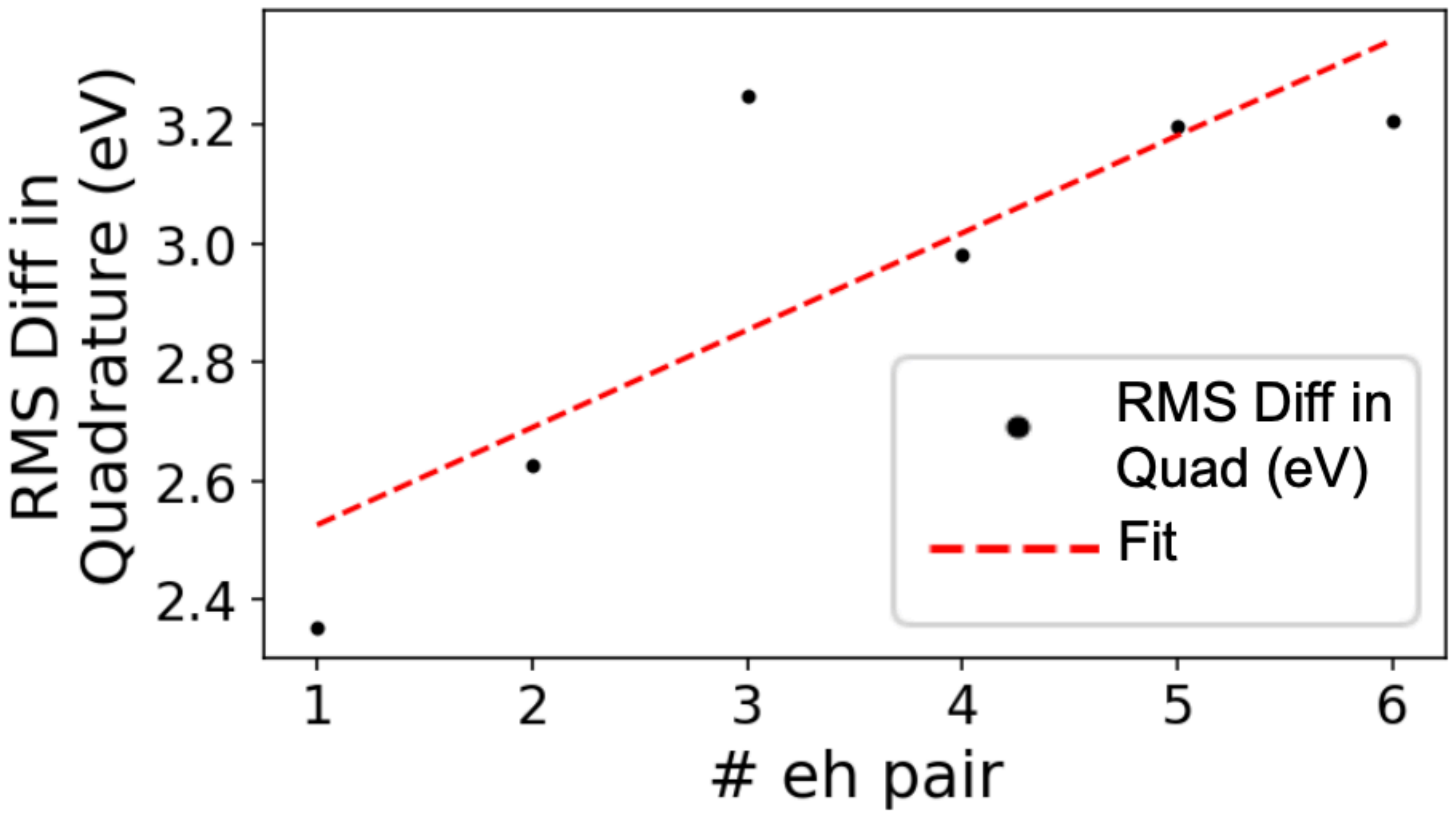
HVeV Simulation | Adding Additional Energy Smearing

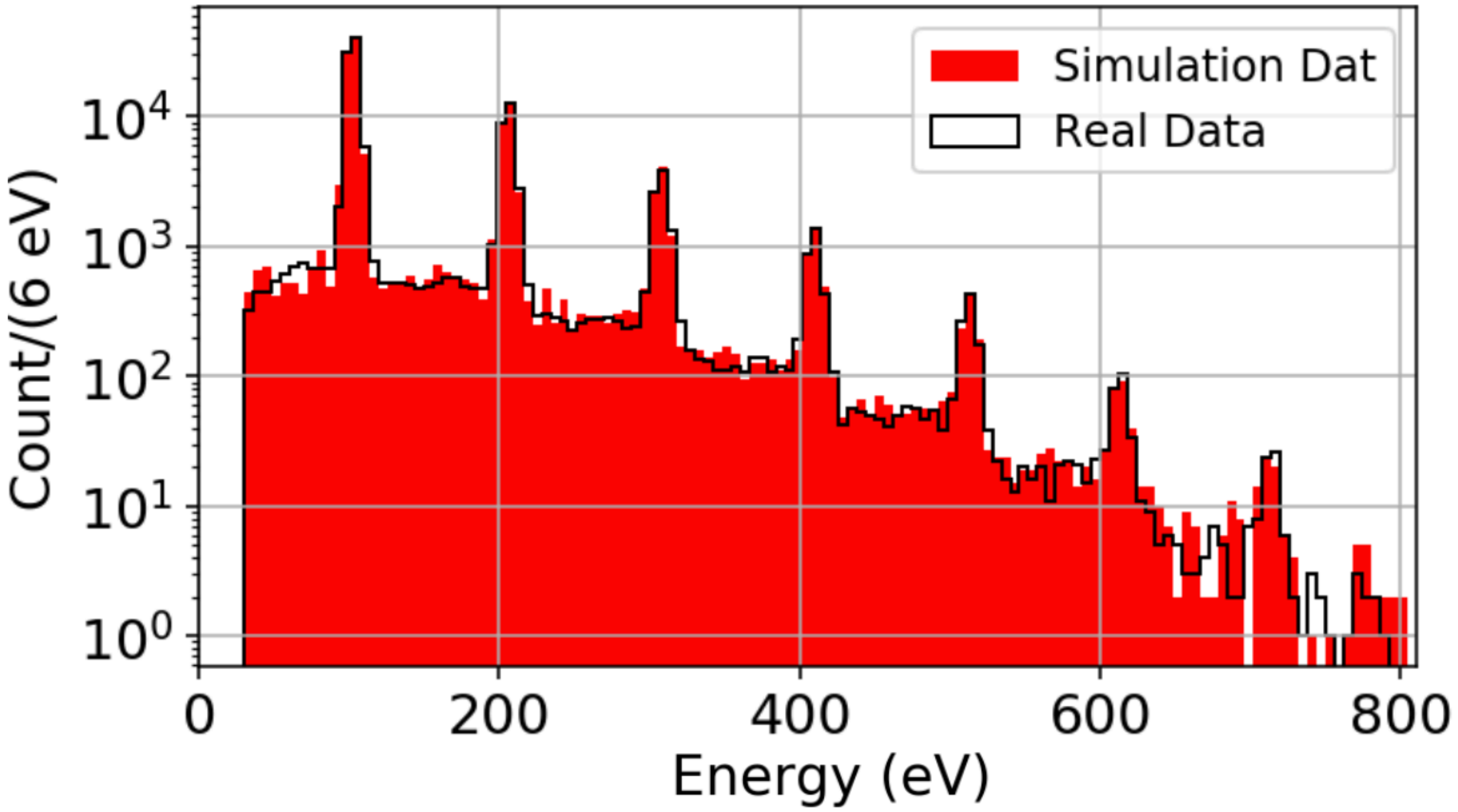




- Sample weights and calibration look reasonable but resolution is off
- Next: Add additional energy smearing to take into account the fact that the RMS of the peaks is smaller in simulation than data

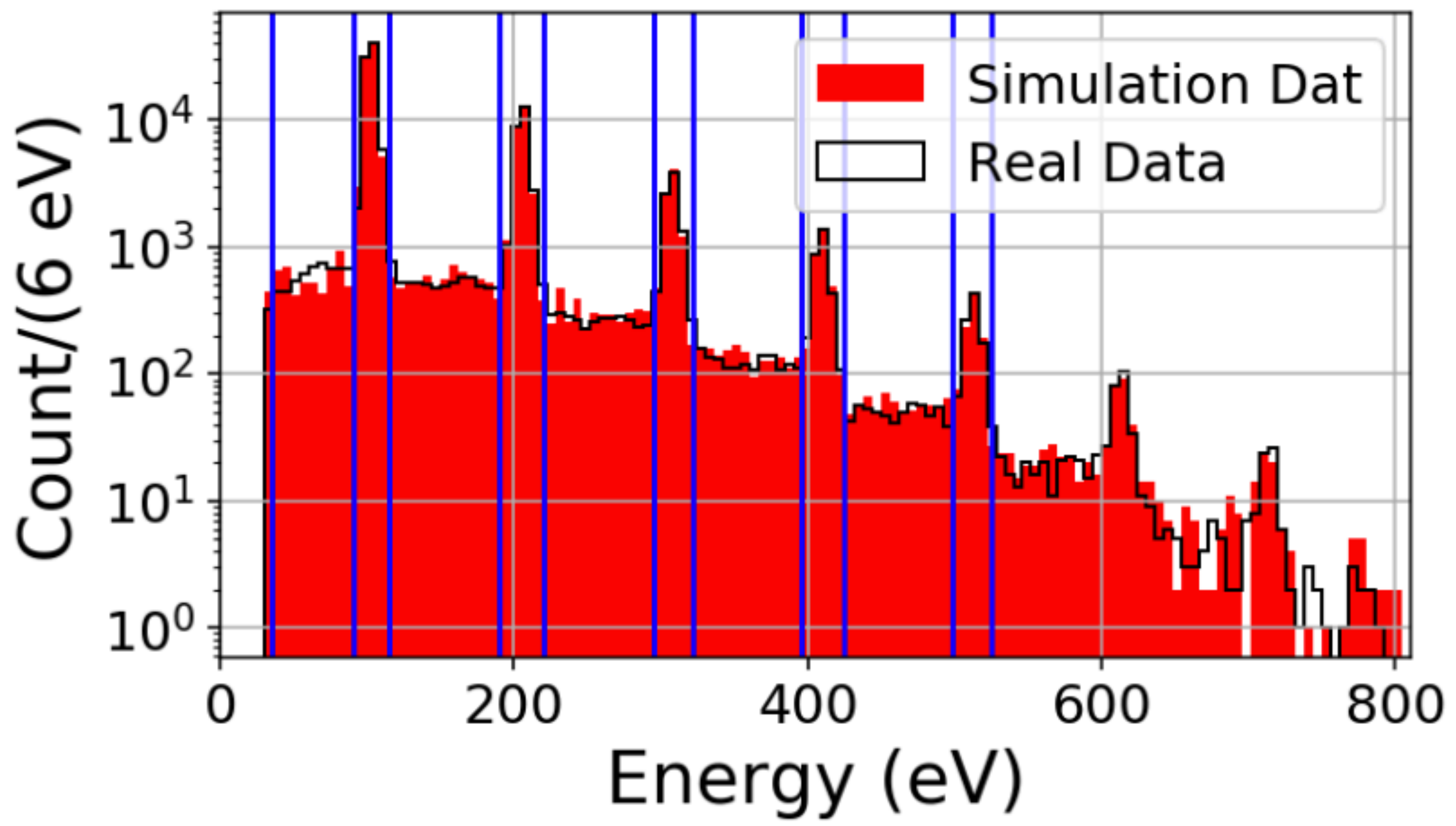
HVeV Simulation | Adding Additional Energy Smearing

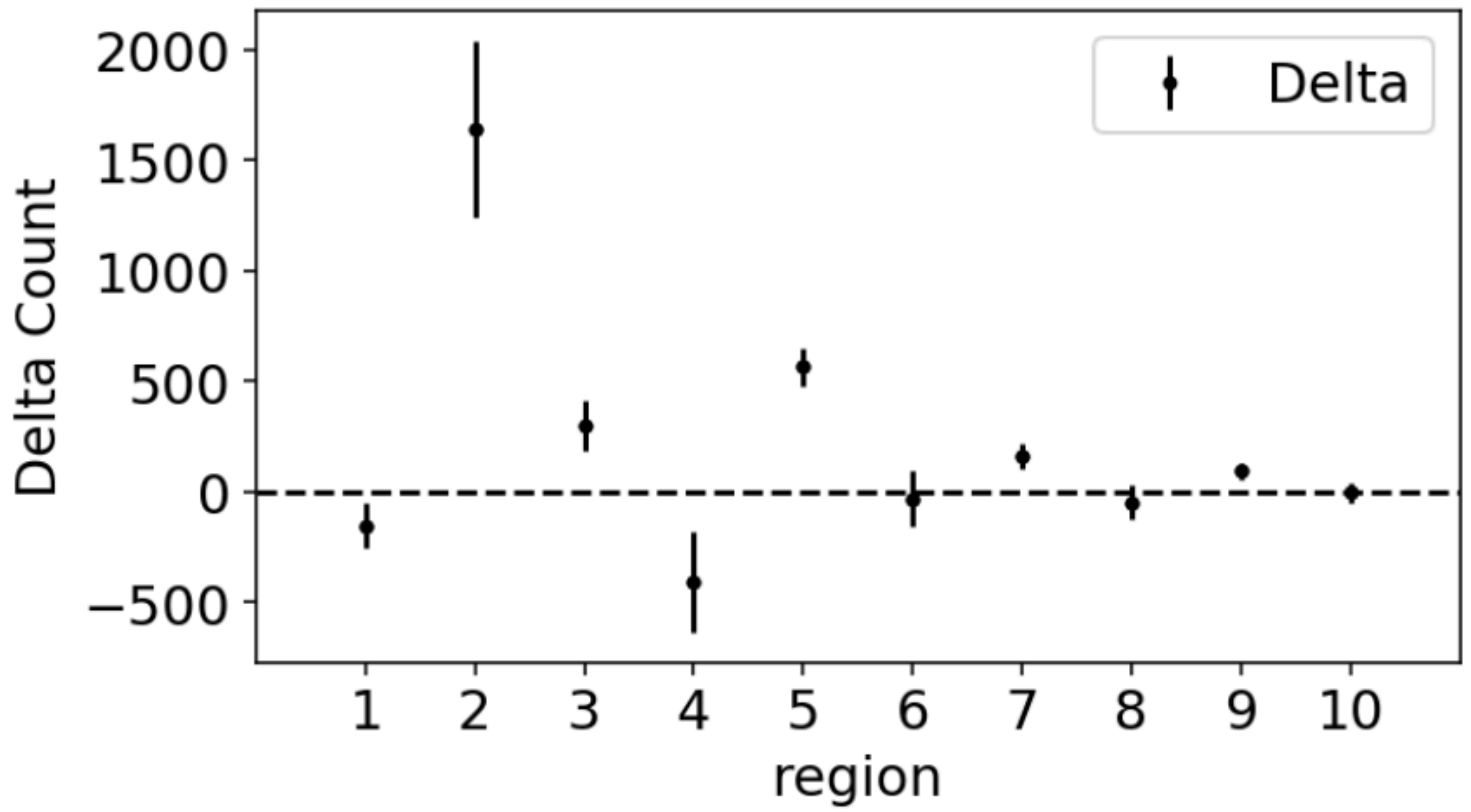


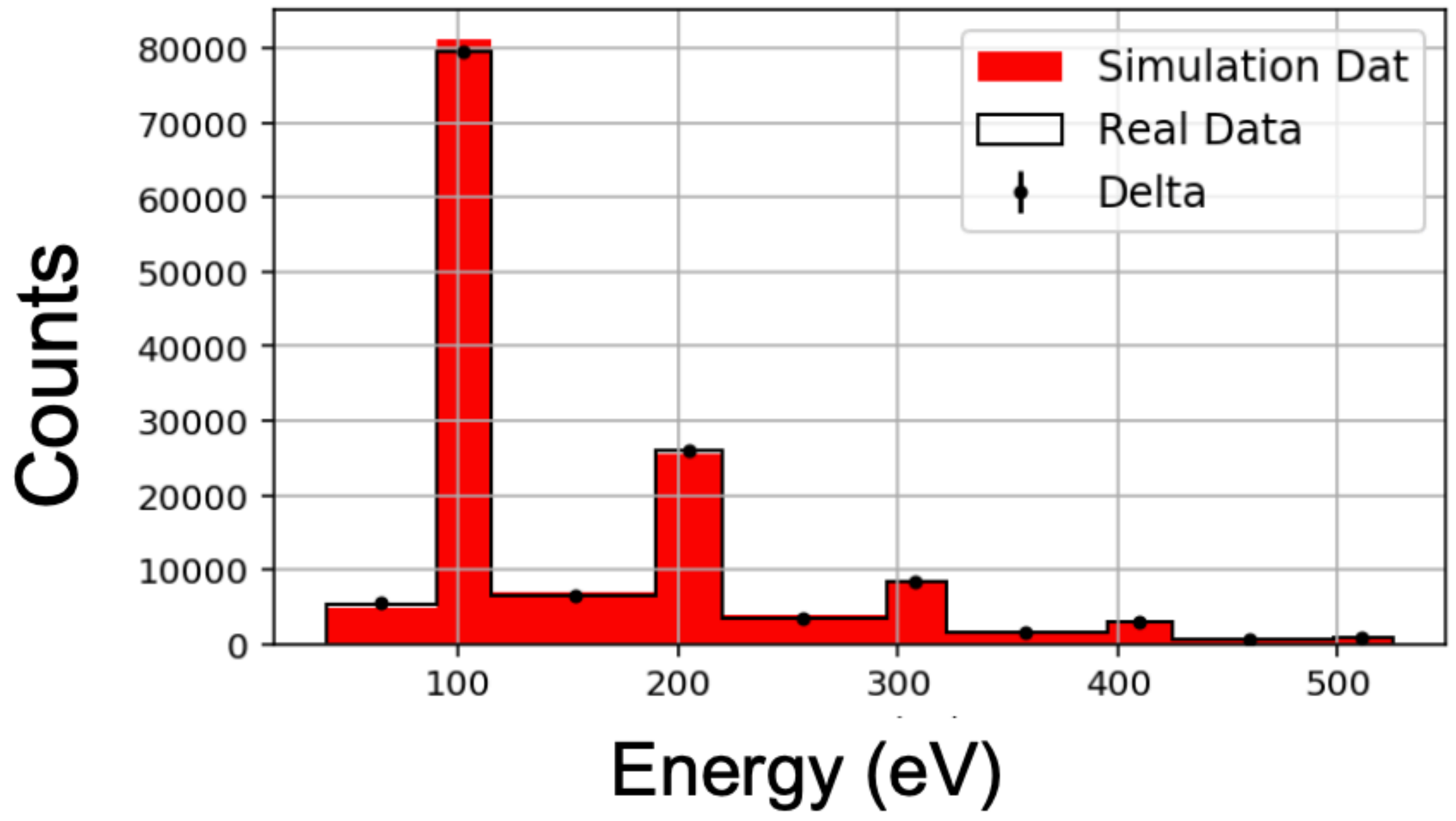


- Full simulation does not give a good match between data and simulation
- If we calculate the difference in quadrature between data and simulation resolution, we see that it scales with energy which suggests there is a missing effect in the simulation that rises with energy
- We add Gaussian smearing that has an RMS that increases linearly with energy. This is done by hand, at the analysis level
  - Additional Smearing = (gaussian with mu=0 and sigma = 1) * (0.0016* energy + 2.36)
- The right figure shows a good agreement between the simulation and data after adding additional energy smearing

Data and Simulation Comparison I Custom Histograms



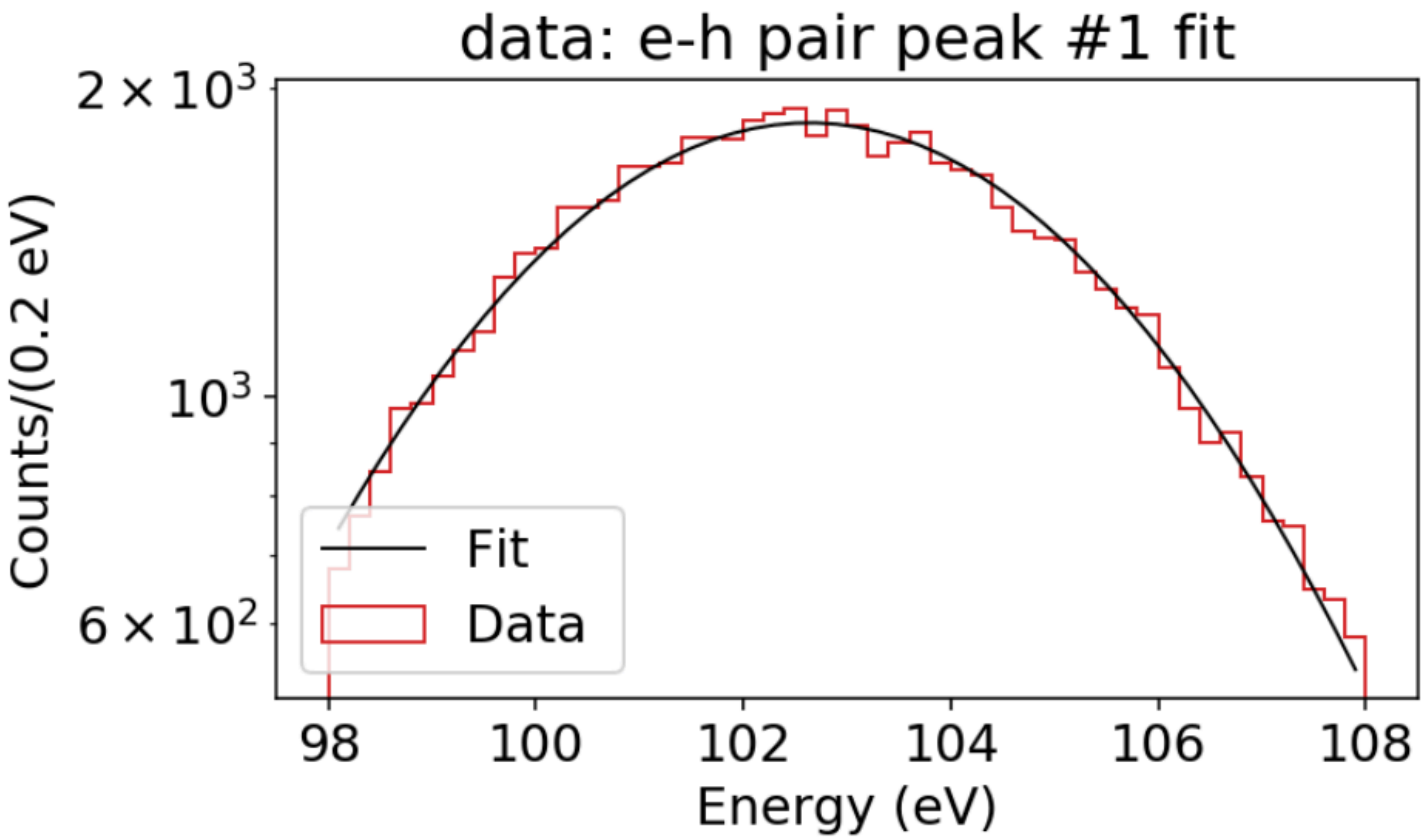




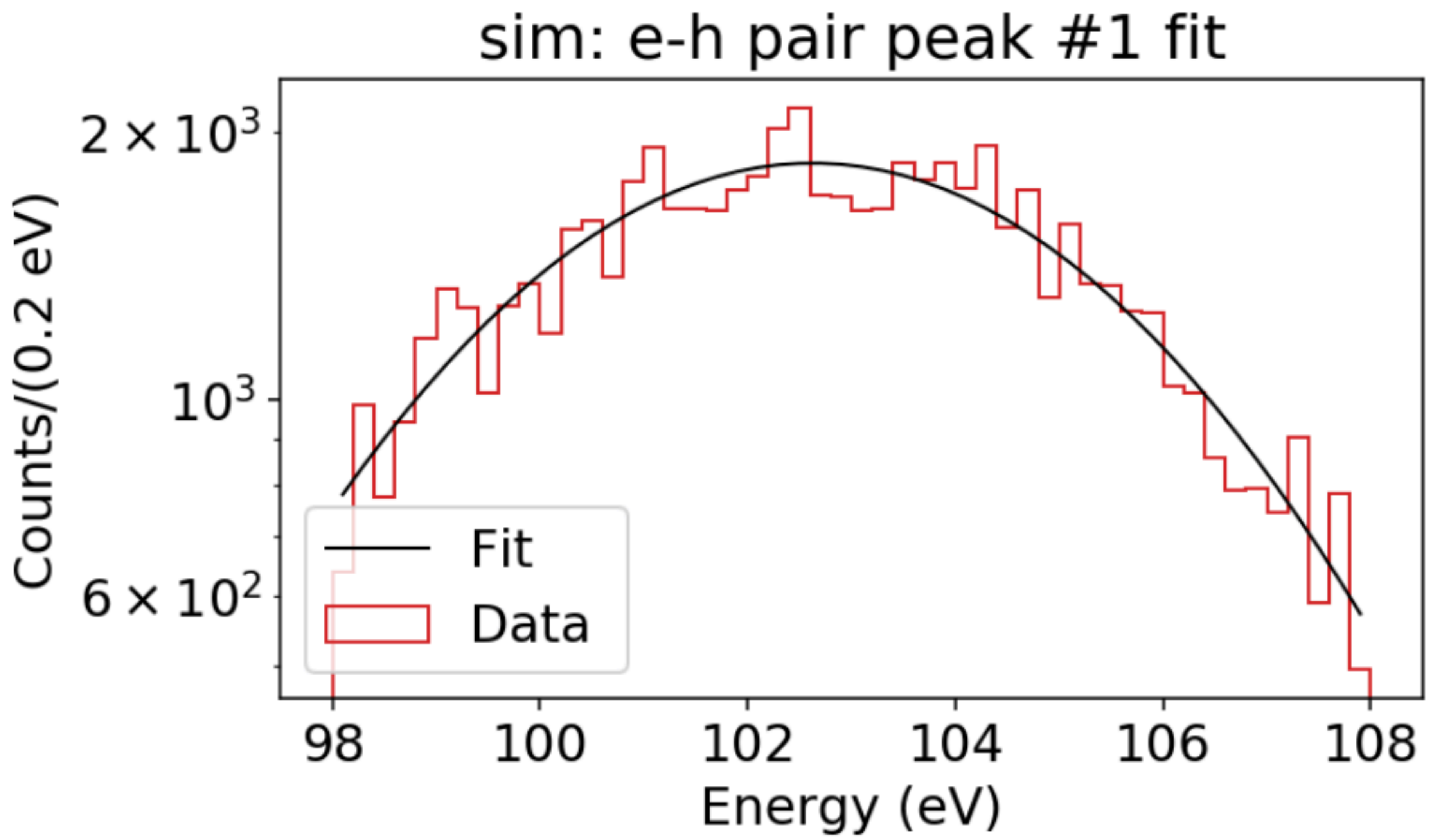
We see good agreement with the possible exception that another iteration of the number of events in the custom laser simulation might have helped

Data and Simulation Comparison | Gaussian Fits

- We can also compare simulation and data by fitting the peaks to gaussian function
- Here is an example for the first peak:

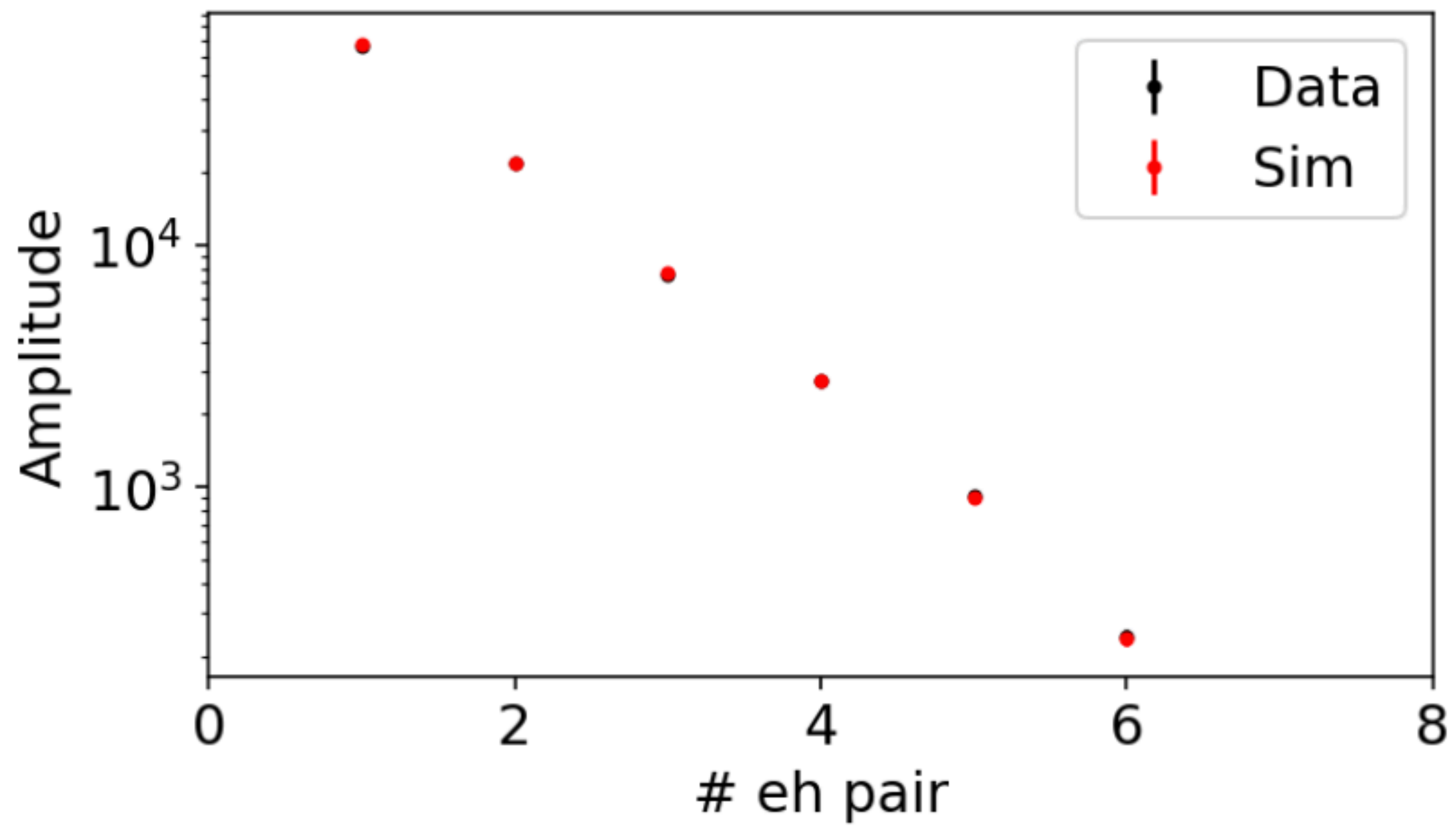


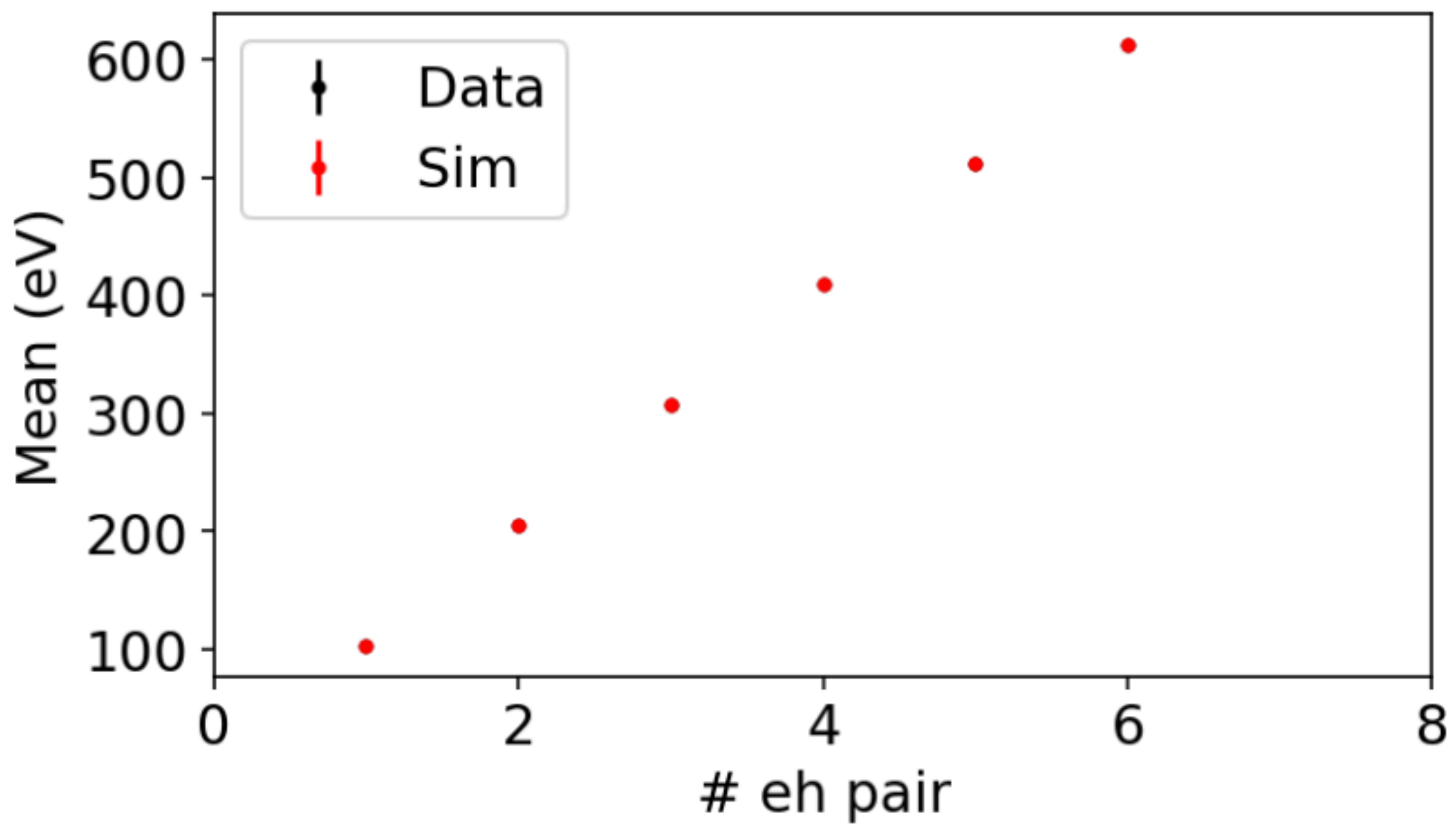
Amp = 66962 +- 258
Mean = 102.635 +- 0.018
RMS = 3.358 +-0.022

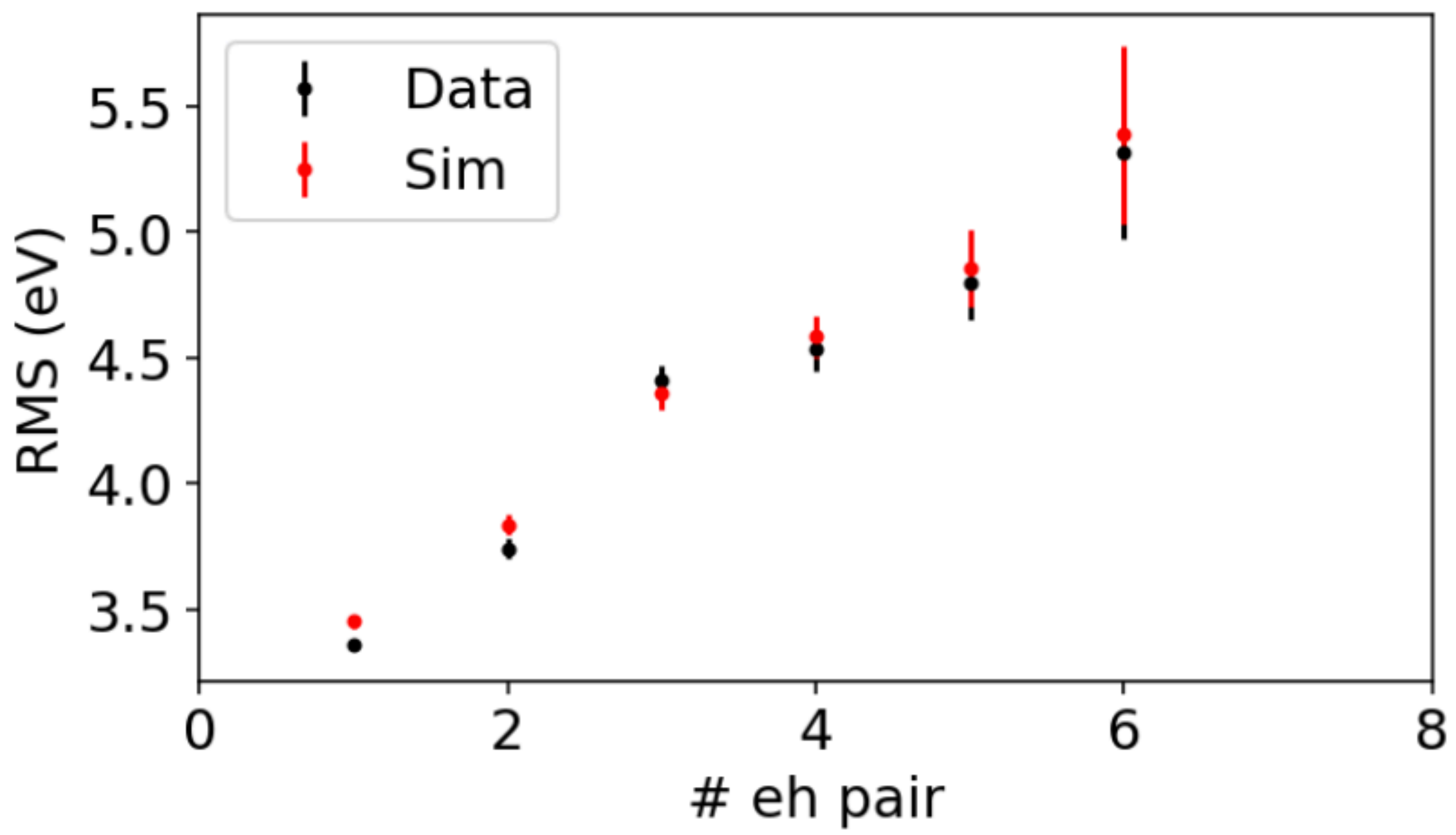


Amp = 67797 +- 260
Mean = 102.624 +- 0.018
RMS = 3.450 +-0.024

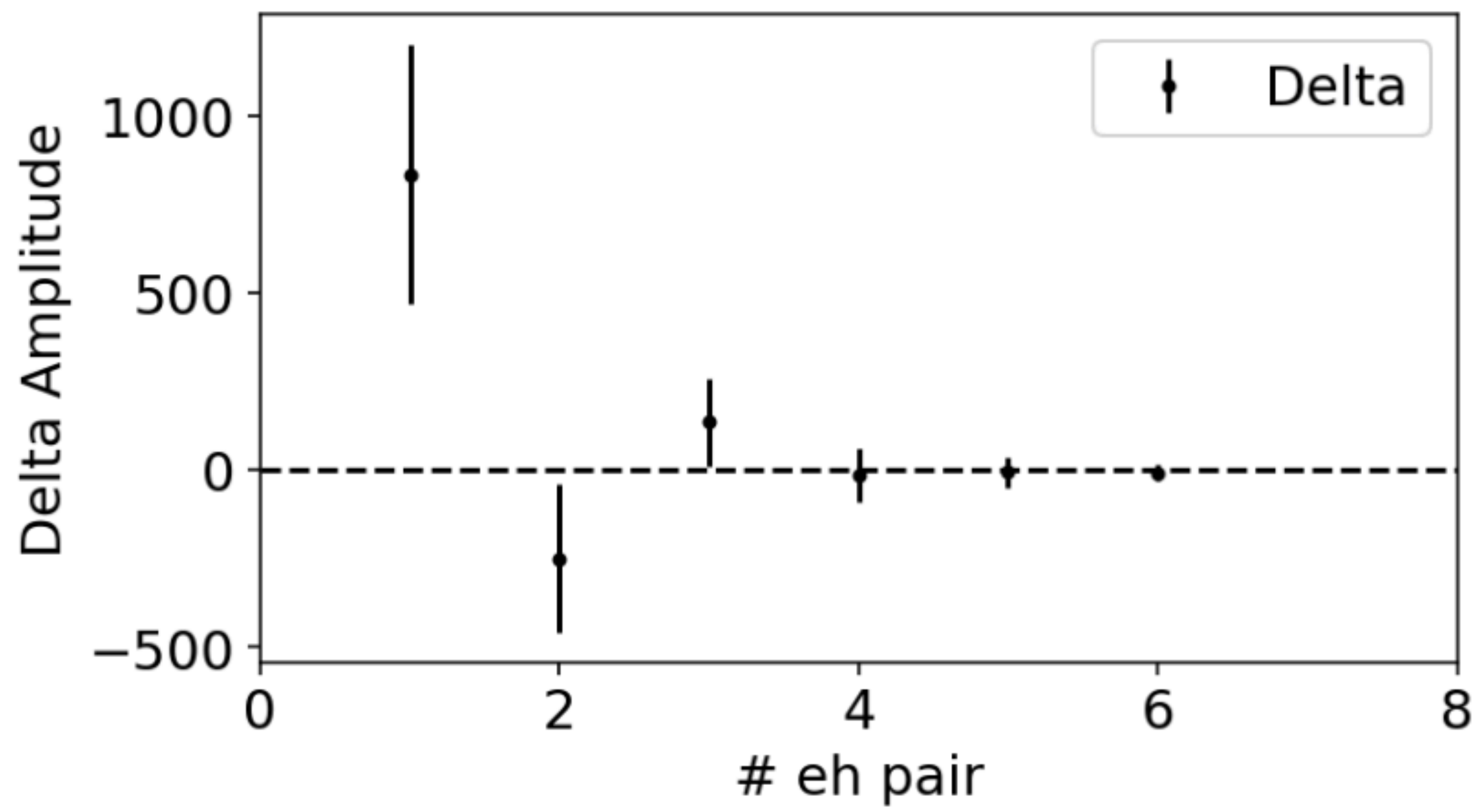
Data and Simulation Comparison | Calculated Fit Parameters

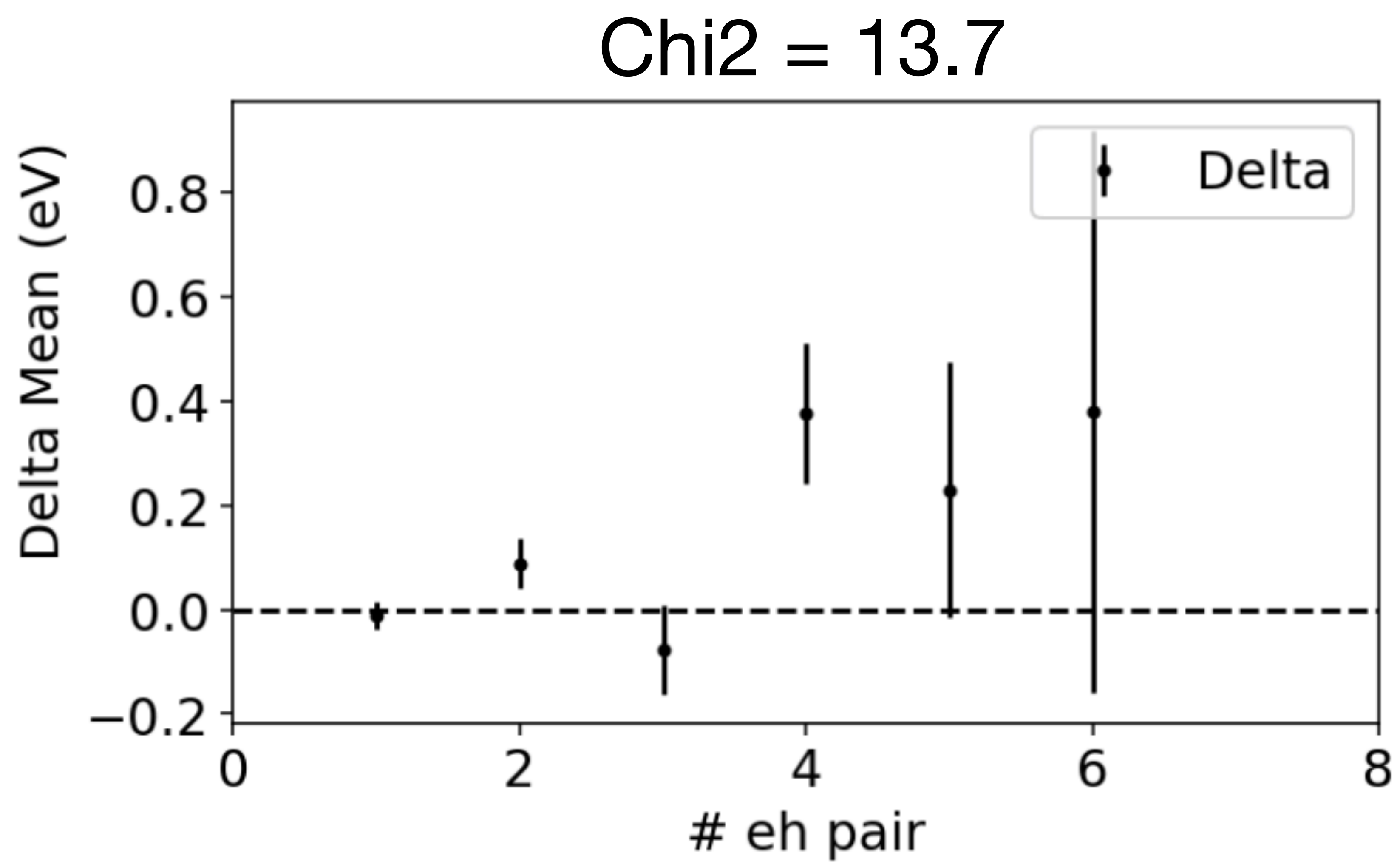


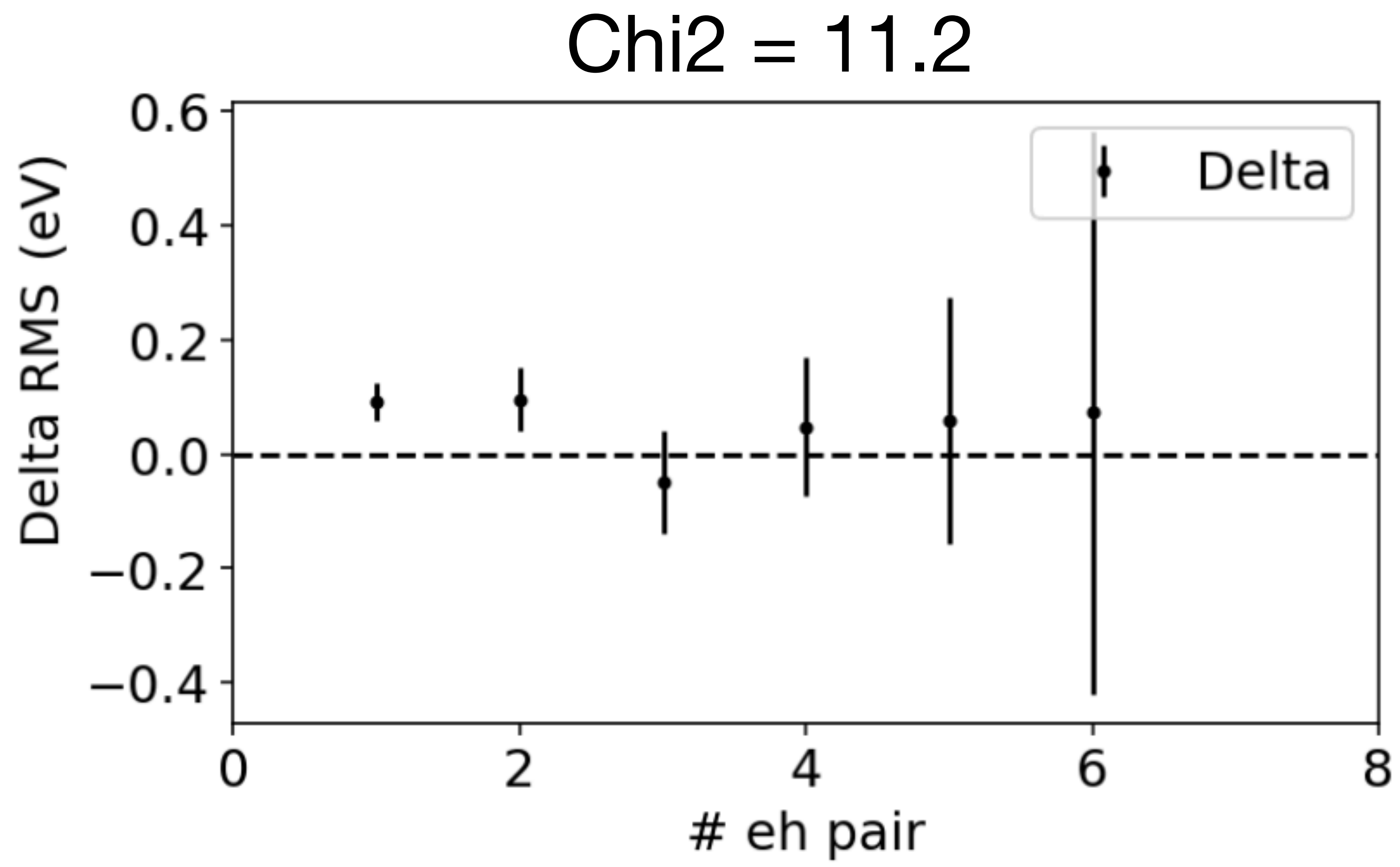




Data and Simulation Comparison | Calculated Fit Parameters Diff







This shows that a combination of the standard SuperCDMS simulation and additional tools can produce simulated data that matches with data with no discernible trend

Summary and Future Directions

Summary:

- Simulation of a Poisson laser gives us a nice starting point but we showed that we need more sophisticated tools to get a good match between simulation and data:
  - To get a better match at high energies, we need a custom laser where we can tune the distribution of the number of photons hitting the detector at the same time
  - Since the resolution of the simulation data is systematically less than real data and scales with energy, we need to add Gaussian smearing that has an RMS that increases linearly with energy
- We could measure the CT and II parameter values that produce background levels that match with data
- Using simulation and additional tools, we got a good match between the simulation and data

Future Directions:

- Understand and simulate the missing effects that contribute to the resolution
- Simulation of eV photons instead of direct energy deposits
- Conduct an optimized simulation-based dark matter search

Conclusions

- SuperCDMS effectively uses combined semiconductor and superconductor technologies to be one of the most sensitive dark matter search experiments, but the sensitivity of the next-generation experiment is limited by the lack of understanding of the physics of the detectors
- In this work, we focused on using the full simulation of HVeV detectors and their response in laser experiment:
  - We have verified that our data is well-described by the photons liberating a single electron-hole pair in a silicon crystal, and the Luke amplification and phonon collection methods using sensors work as expected
  - Using simulations, we estimated the relative importance of different effects which show that electronic noise, crystal impurities, and multiple photons from the laser have the biggest contribution to the energy measurement resolution
  - Our results show that a Poisson laser does not accurately describe the data at high energies and there is a missing effect in the simulation which rises with energy
- With this work completed, the next generation of researchers are well-prepared to simulate the dark matter interactions with the detectors and conduct an optimized simulation-based dark matter search which might be the missing ingredient for making a major discovery

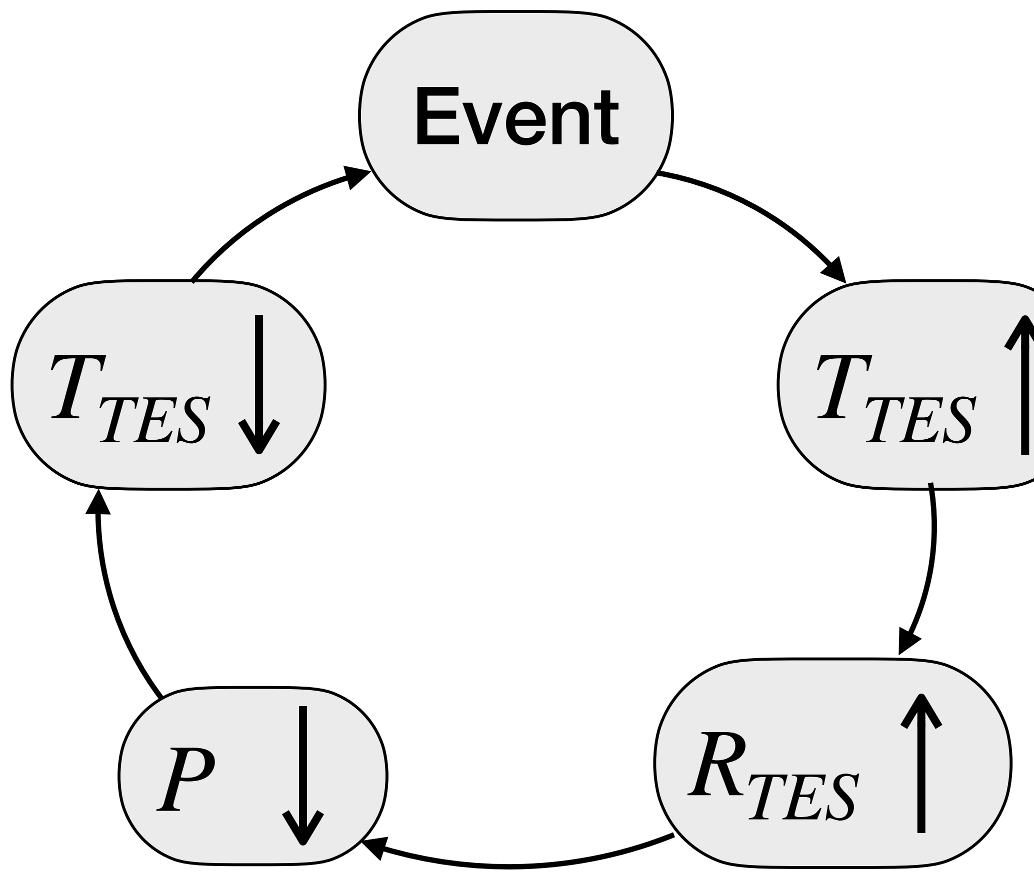
Supplementary Materials

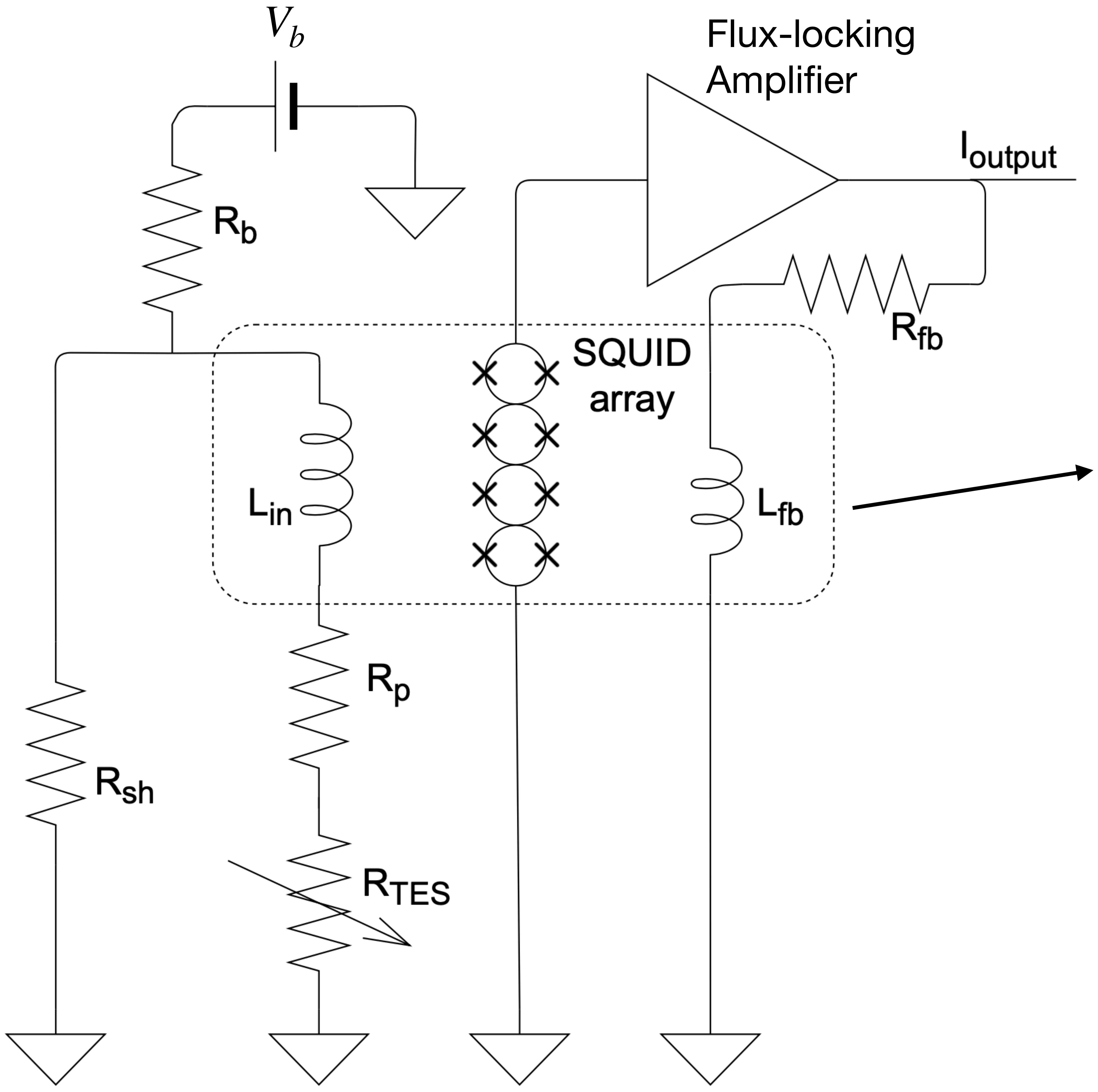
Detectors | Detector Readout Electronics

Electrothermal Feedback

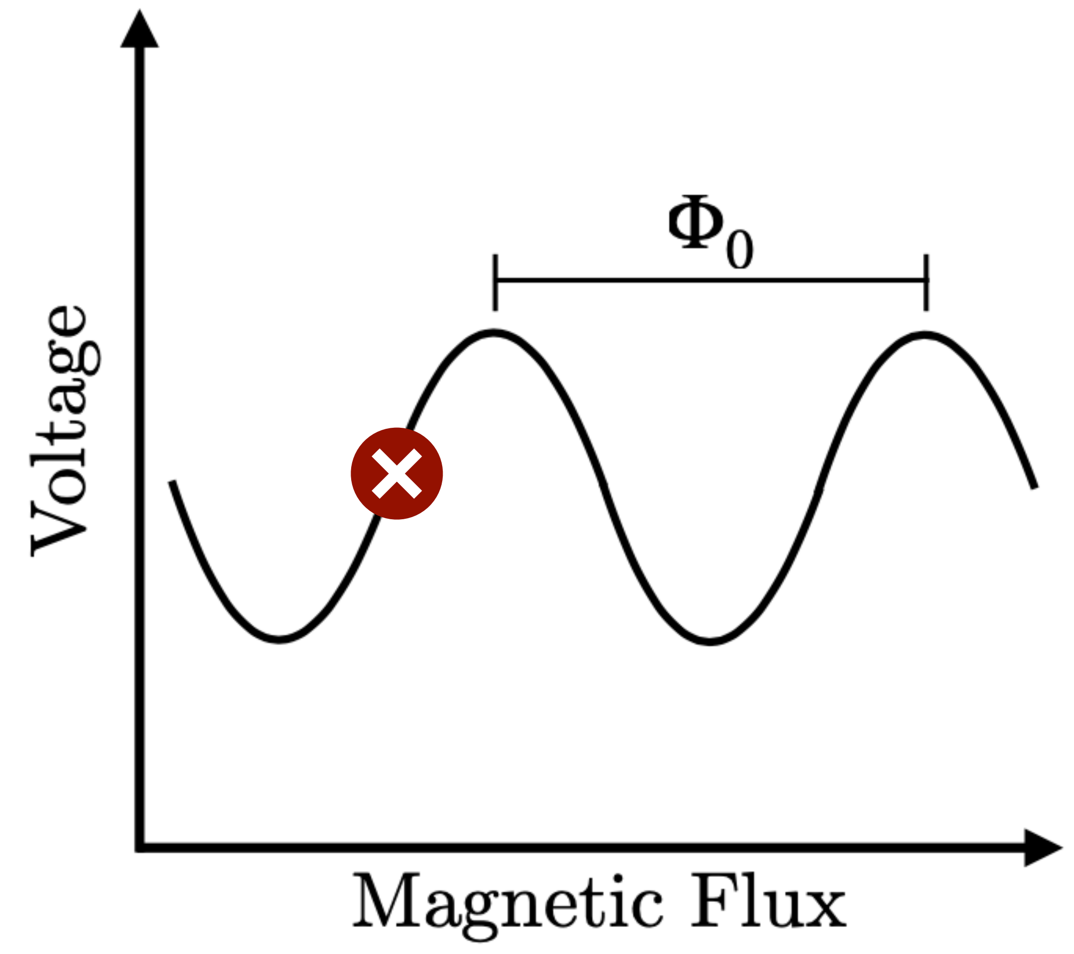
$$P = K(T_{TES}^5 - T_b^5)$$

$$P = V_b^2 / R_{TES}$$



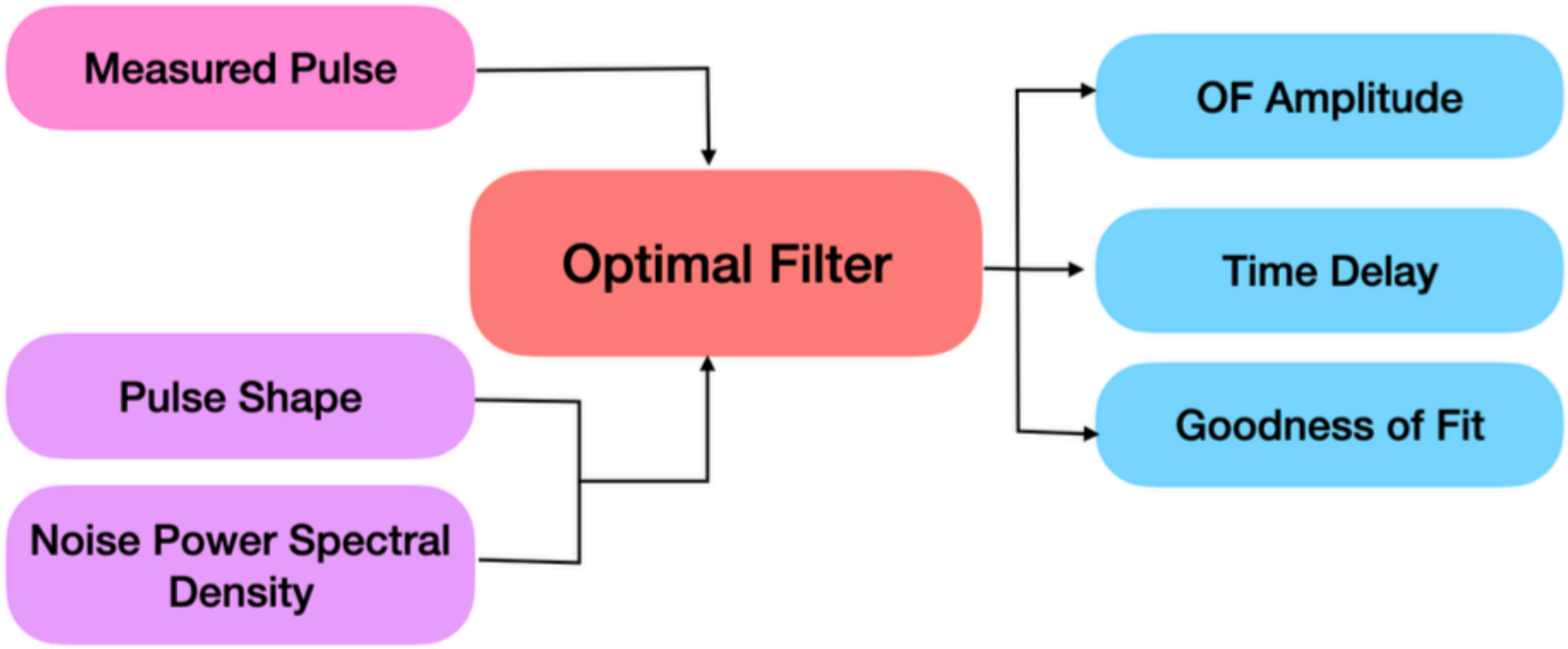


Flux-locking Feedback



$$L_{in} + L_{fb} = Const.$$

Optimal Filter



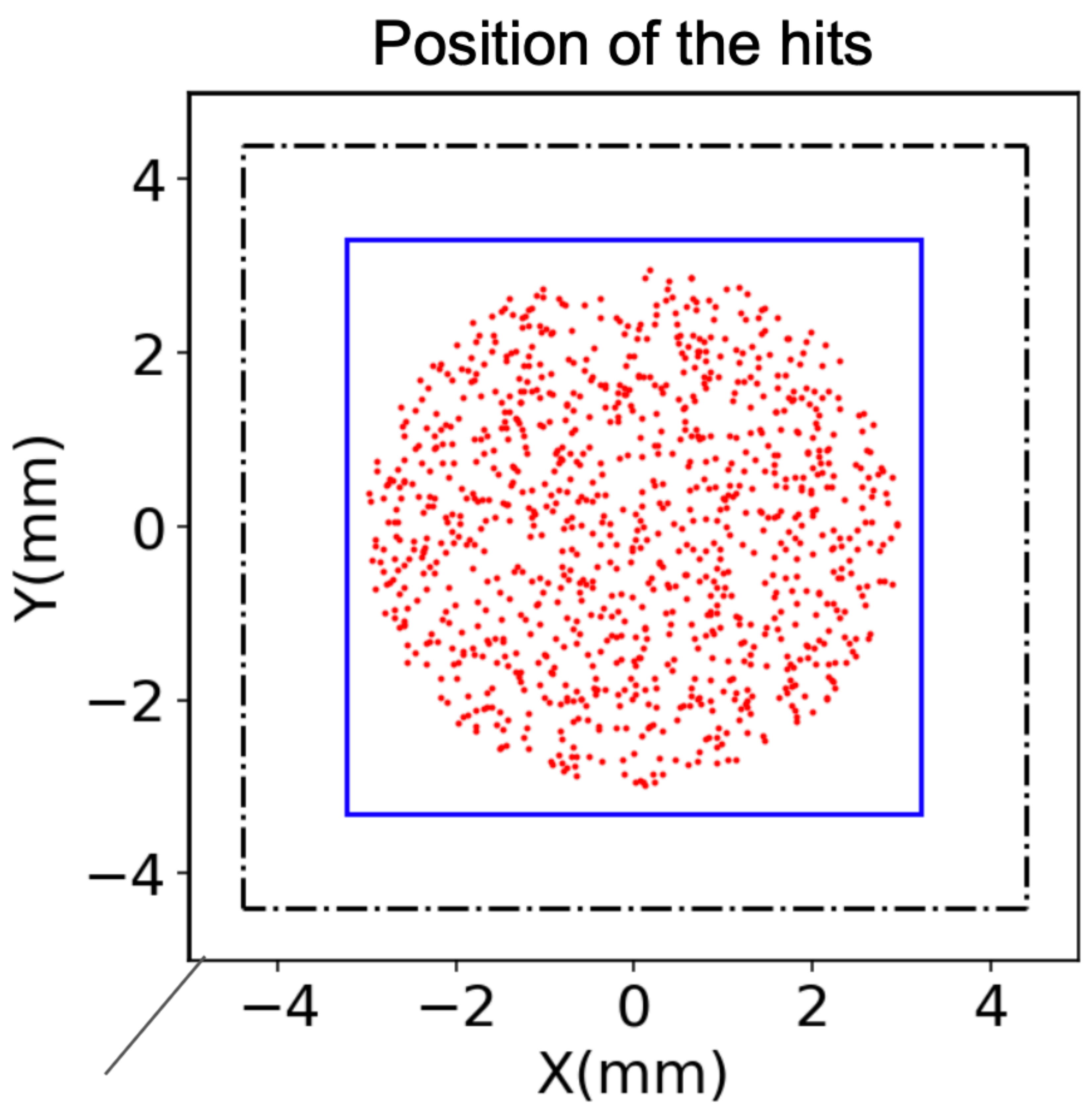
$$\chi^2(\nu; a) = \sum_{\nu} \frac{|S(\nu) - aA(\nu)|^2}{J(\nu)}$$

$$a = \sum_{\nu} \phi(\nu) S(\nu), \qquad \phi(\nu) = \frac{A^*(\nu)/J(\nu)}{\sum_{\nu'} A(\nu')A^*(\nu')/J(\nu')}$$

$$a = \sum_{t} \phi(t) S(t), \qquad \phi(t) = \mathscr{F}^{-1}\left(\frac{A^*(\nu)/J(\nu)}{\sum_{\nu'} A(\nu')A^*(\nu')/J(\nu')}\right)$$

HVeV Simulation | SourceSim

-



Top surface of the detector