Underground Measurements of the $^{16}O(p,\gamma)^{17}F$ Reaction at LUNA

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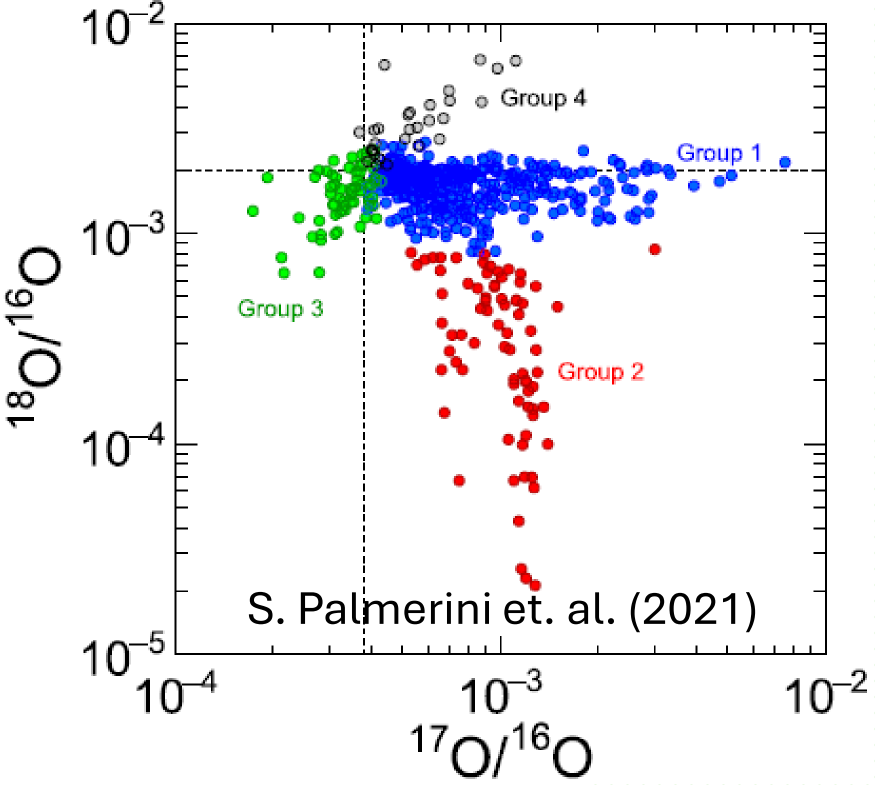
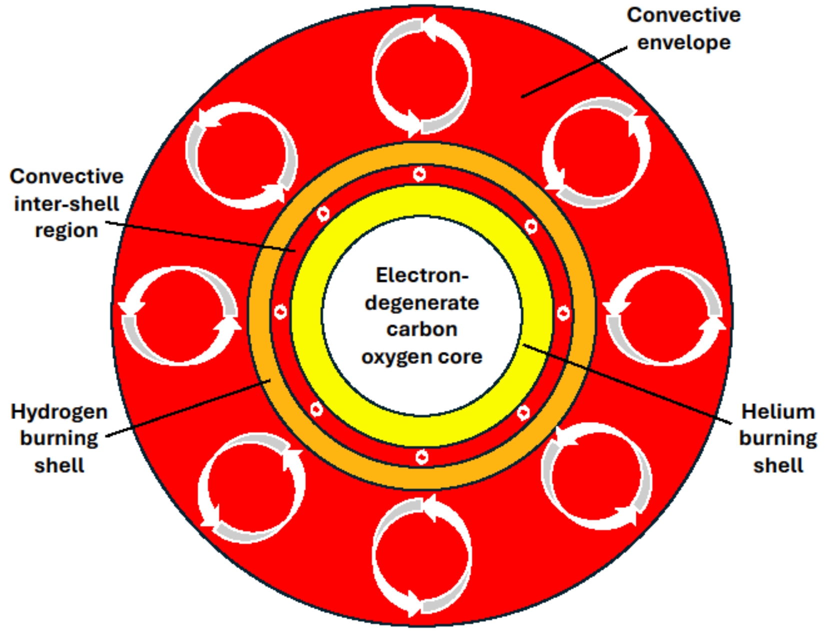
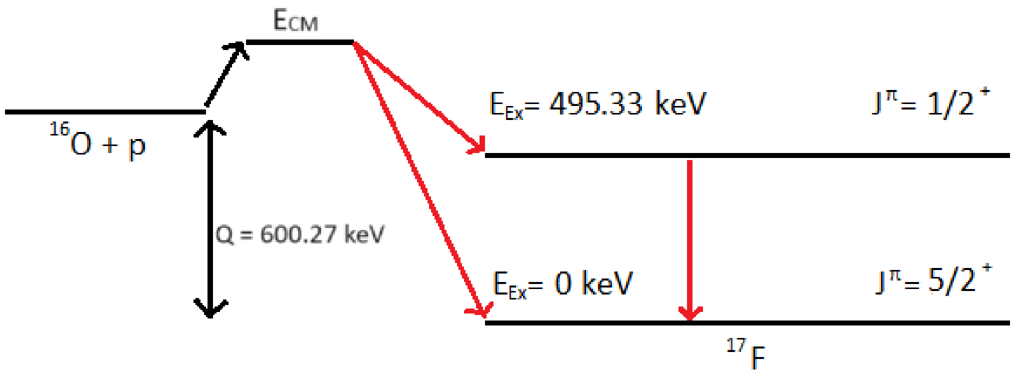
AGB Stars - Pre-Solar Grains and Hot Bottom Burning

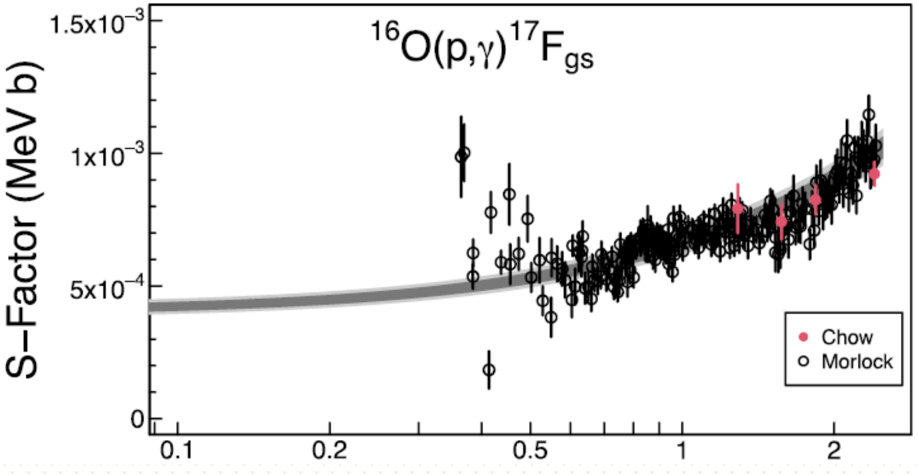
- **Group 2** pre-solar grains are predicted to have originated in **AGB** stars
- With the current $^{16}O(p,\gamma)^{17}F$ rate standard stellar models struggle to account for the observed $^{17}O/^{16}O$ ratios
- **Hot Bottom Burning** is a suggested additional mixing mechanism. Its success depends sensitively on the $^{16}O(p,\gamma)^{17}F$ rate



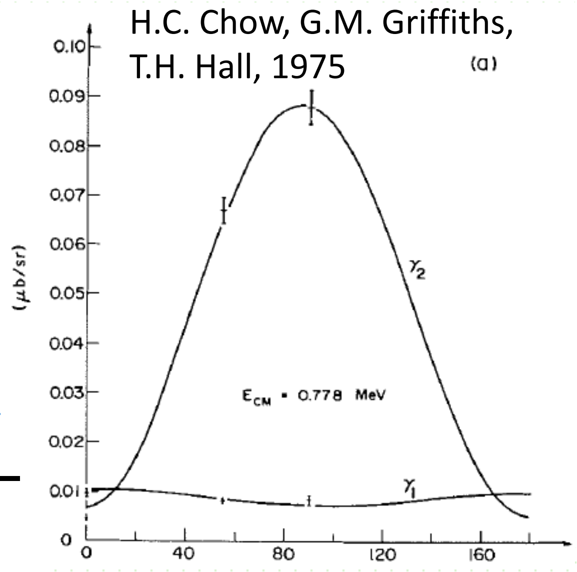


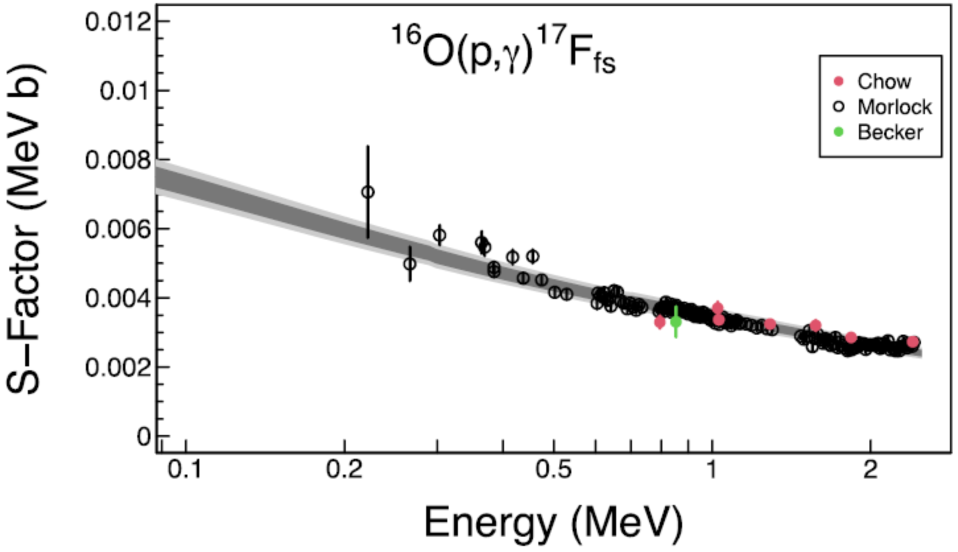
State of the Art

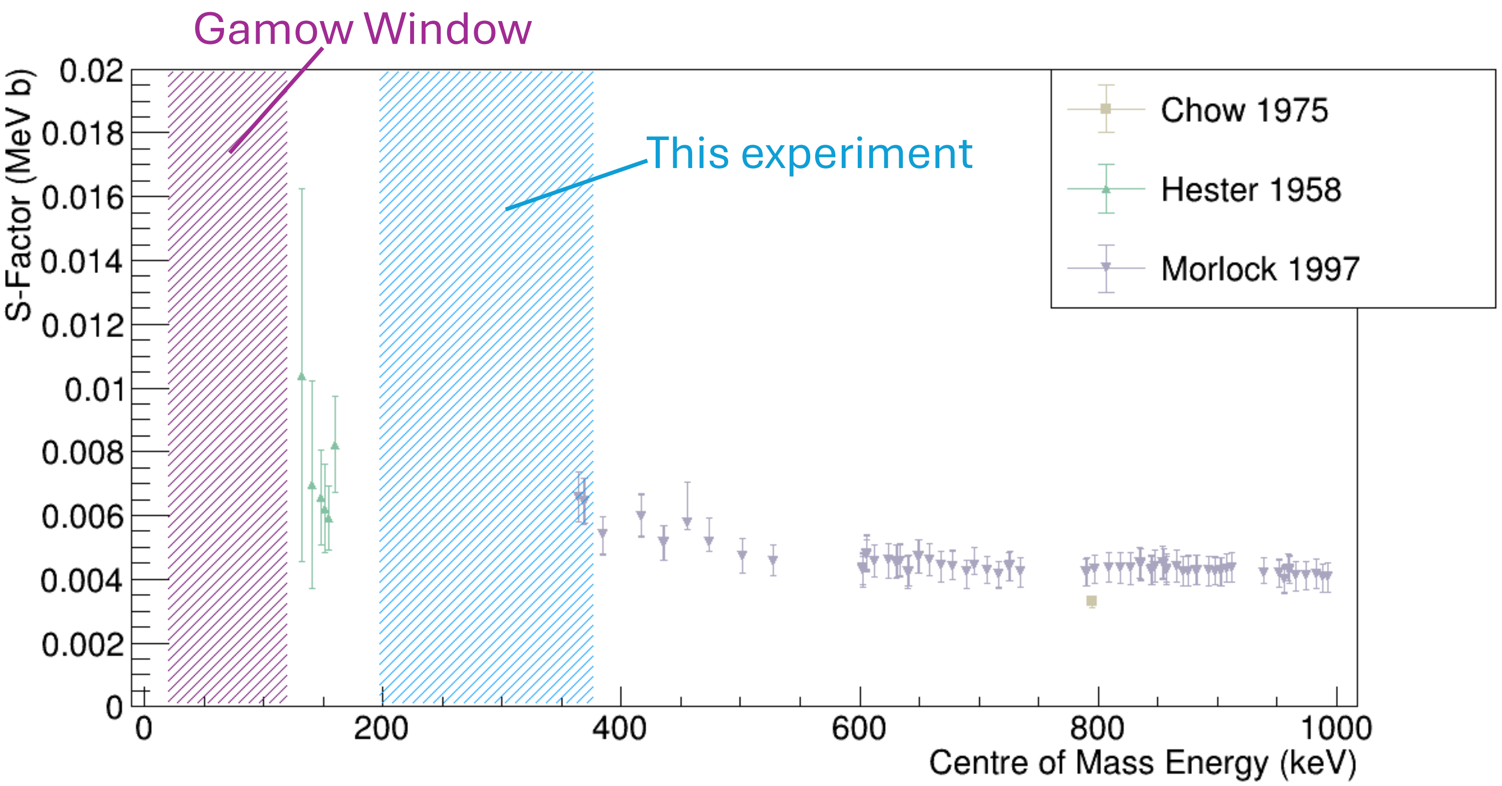




C. Iliadis, V. Palanivelrajan, RS de Souza, 2022







Prompt Gamma Method

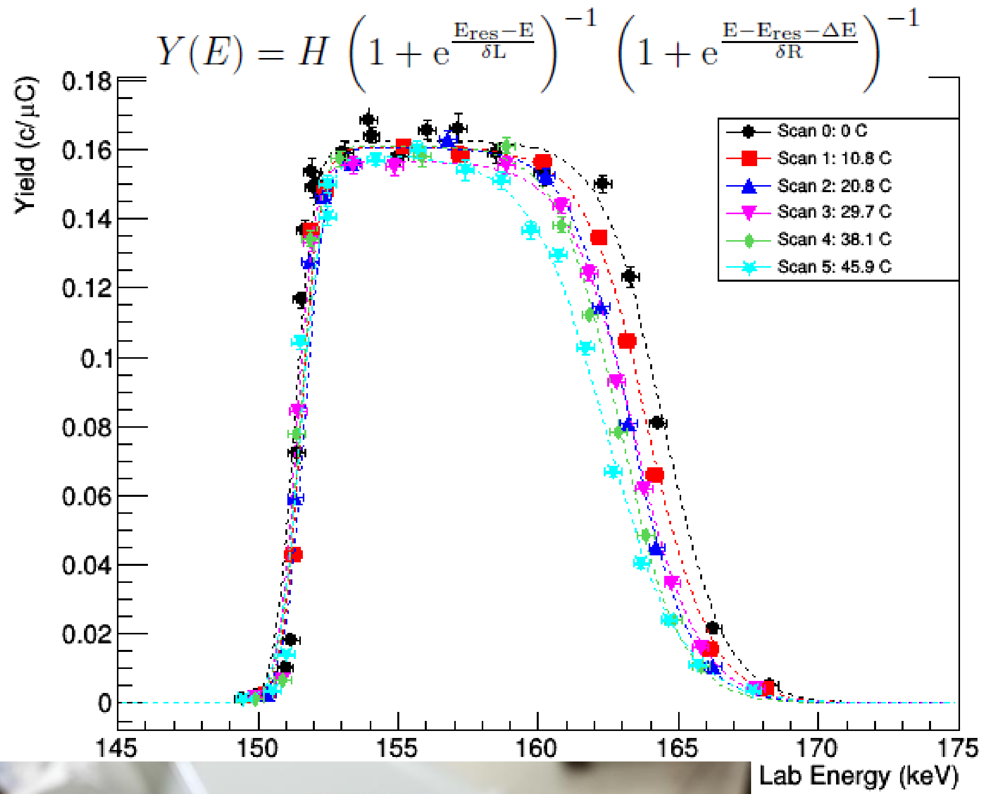
- Directly measure the **gamma rays** from the $^{16}O(p,\gamma)^{17}F$ reaction
- Measure **DC->0** and **DC->495** transitions separately
- Sensitive to **angular distribution** effects
- Low efficiency, high resolution detectors

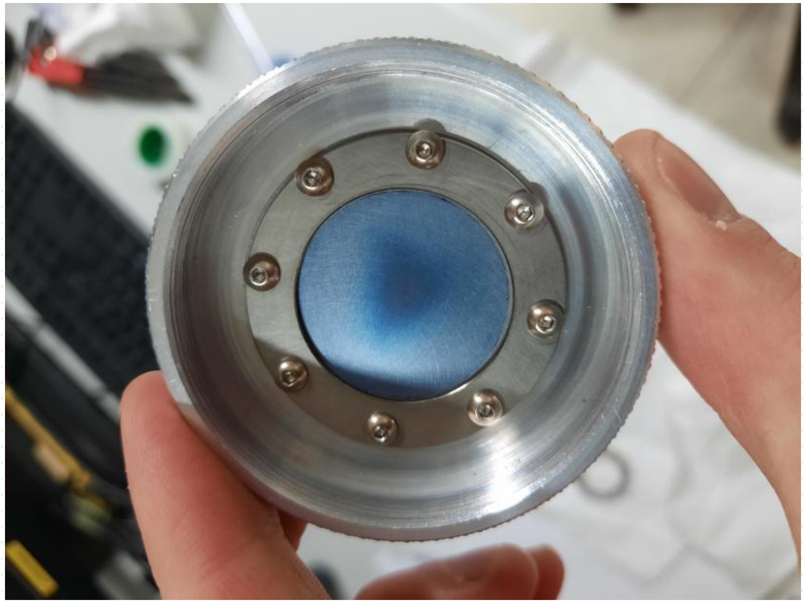
Activation Method

- Measure the **decay** of the daughter nucleus $\mathbf{^{17}F}$
- Measure the **total cross section**, insensitive to individual transitions
- **No angular distribution** effects
- High efficiency, low resolution detectors

Targets

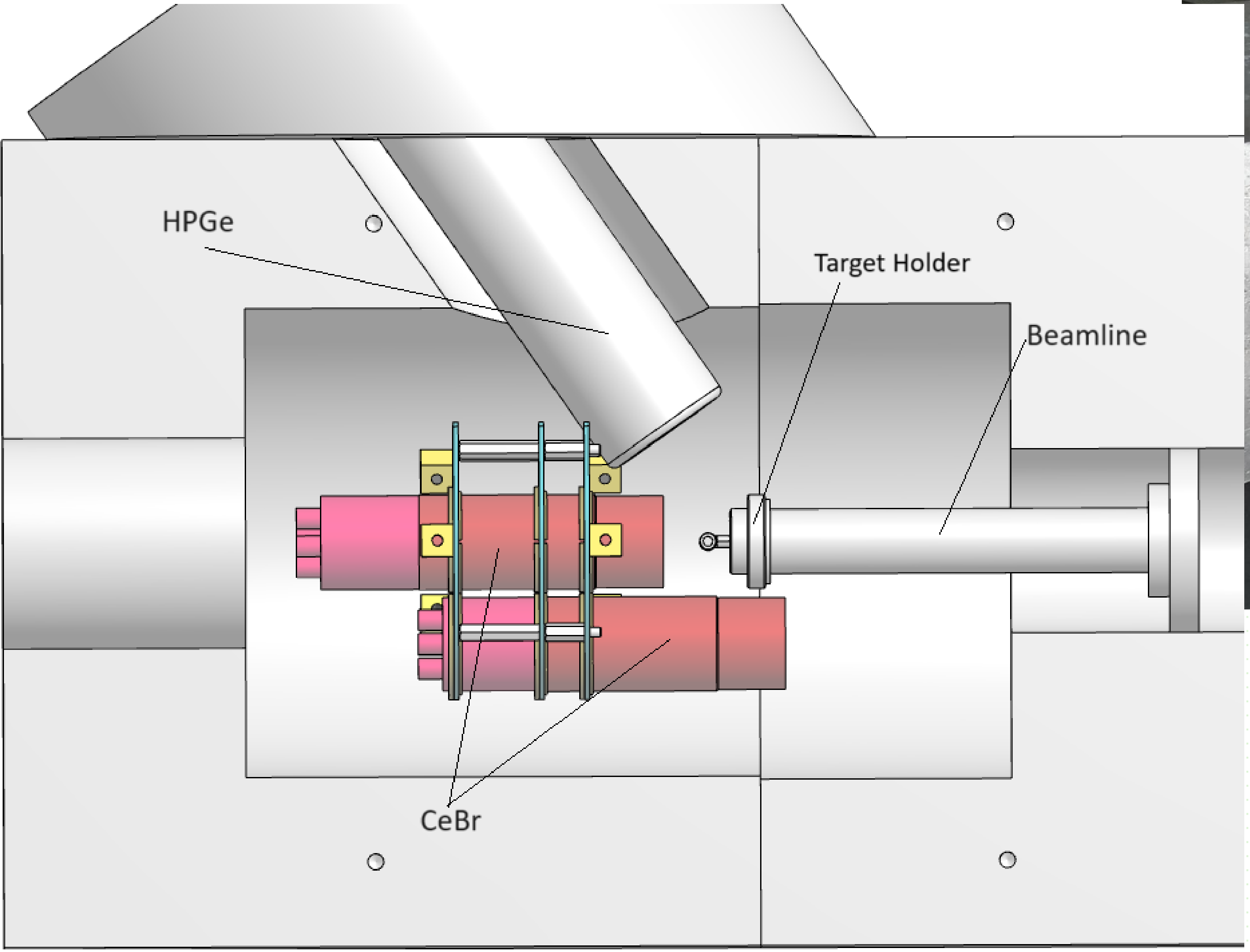
- Solid $\mathbf{Ta_2O_5}$ targets
- Mostly created by **anodic oxidation** of tantalum backings in water
- Two created by **reactive sputtering**
- Different levels of enrichment in $\mathbf{^{18}O}$
- Analysis by Nuclear Resonant Reaction Analysis (**NRRA**) on the E_p=151 keV resonance of $^{18}O(p,\gamma)^{19}F$

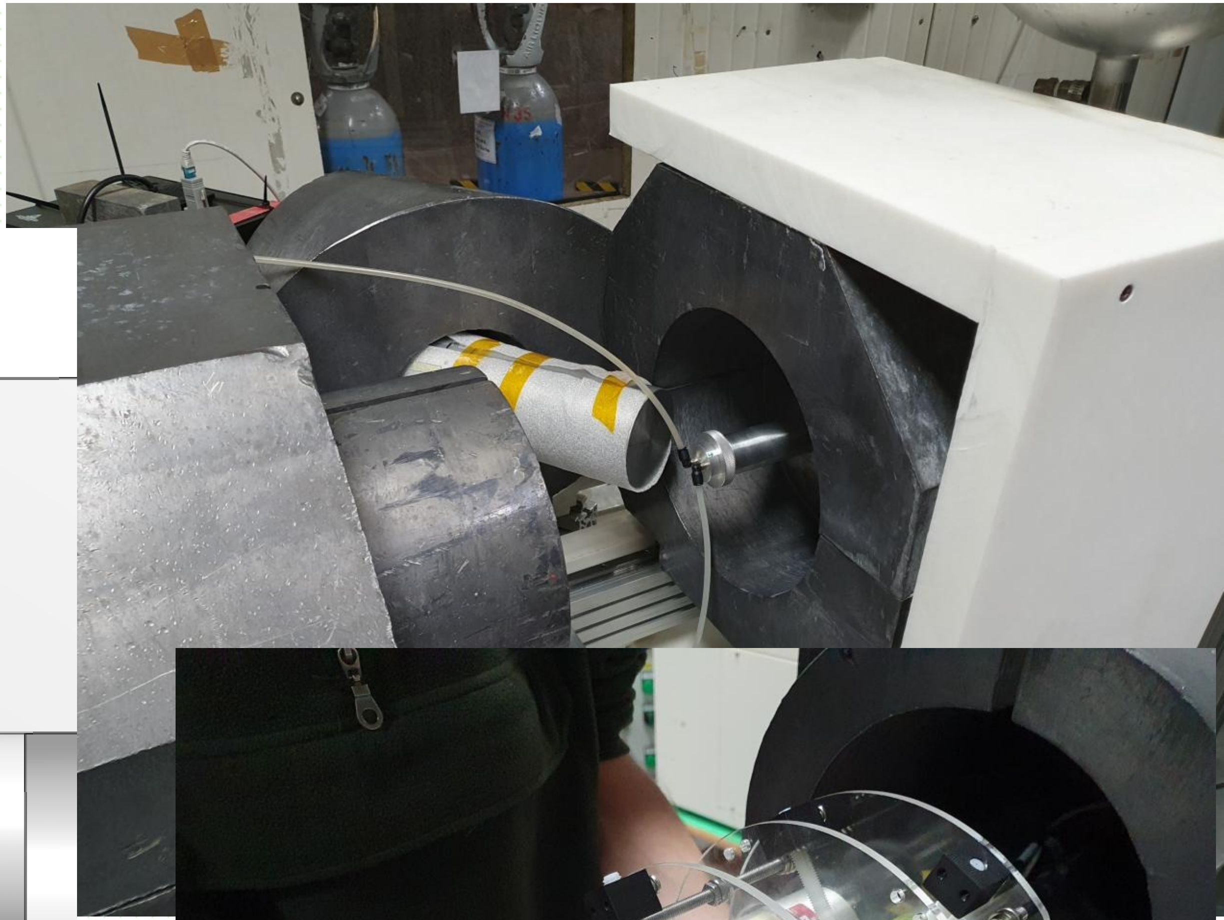


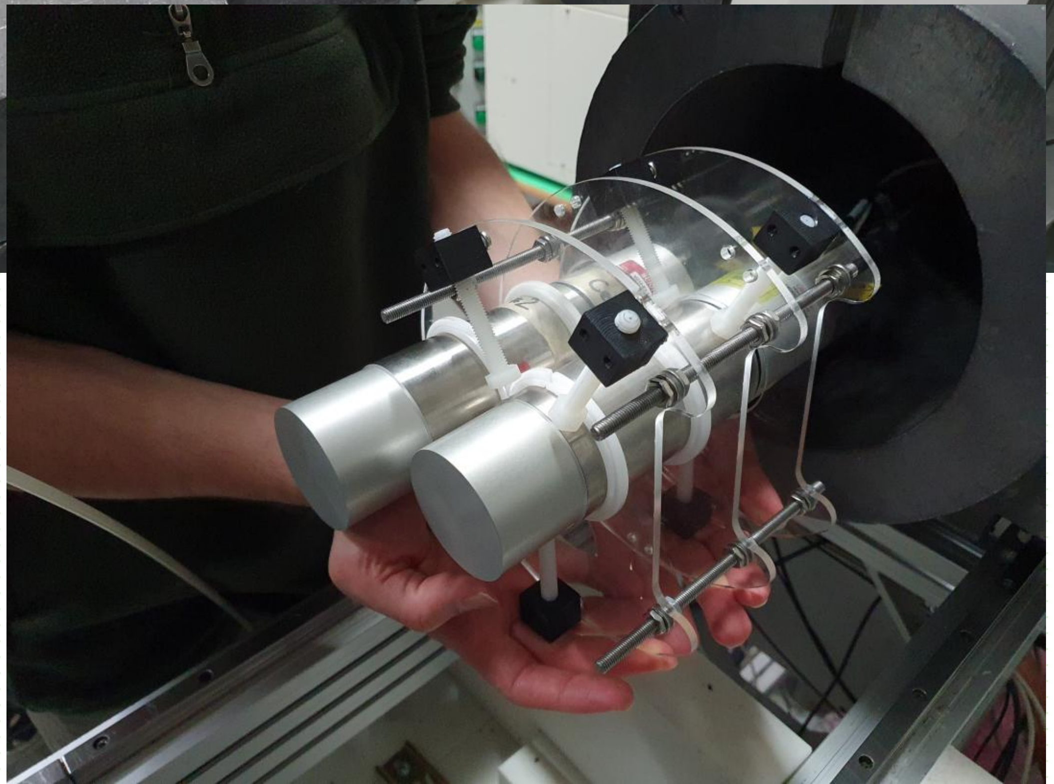


See recent paper for details: Recent Results and Future Perspectives with Solid Targets at LUNA (Frontiers, 2024)

Prompt Gamma Ray Setup

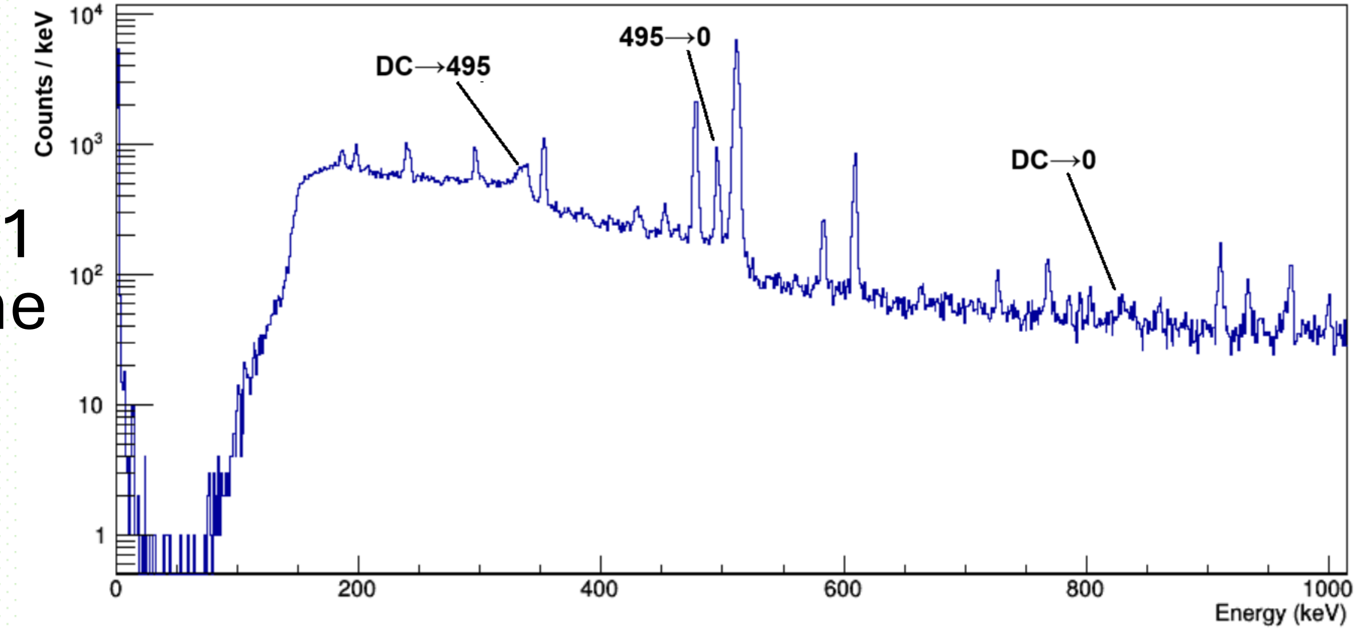






Reaction Peak Areas

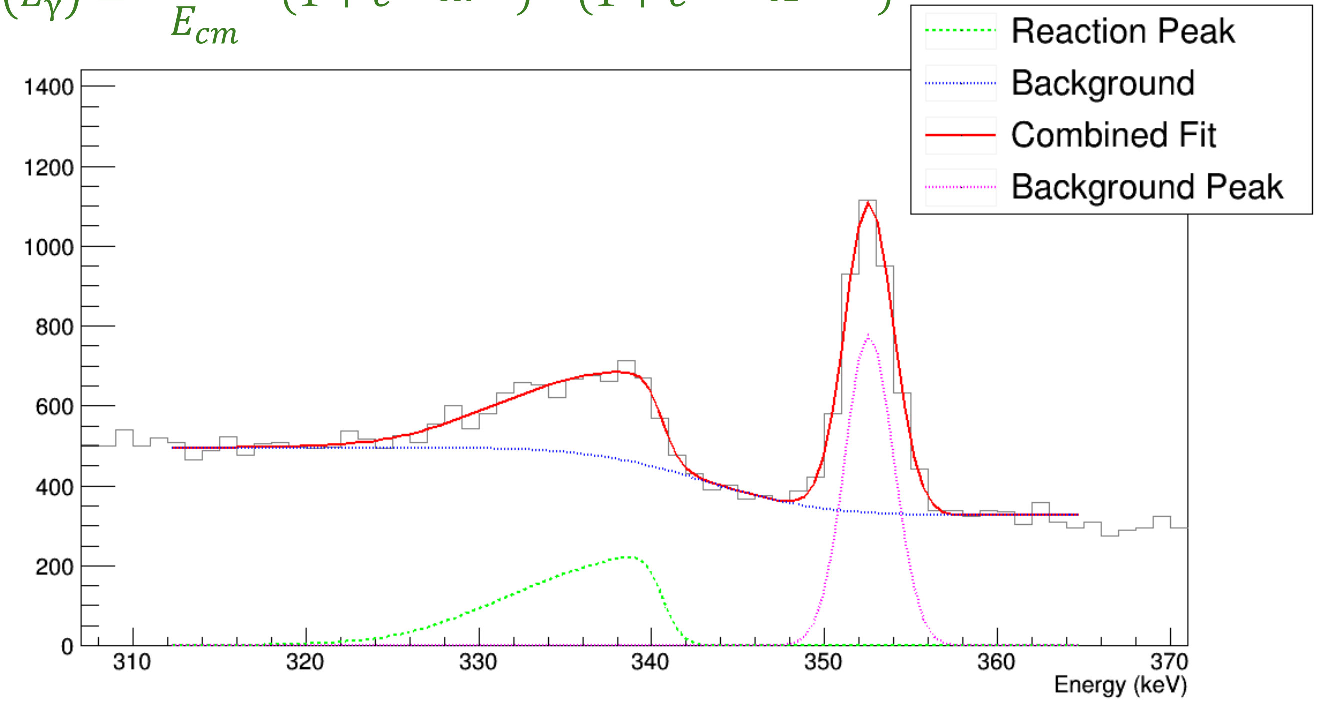
- DC->495 peaks are all below the 511 keV positron annihilation peak. In the lowest energy runs they are on the **Compton edge of the annihilation peak**



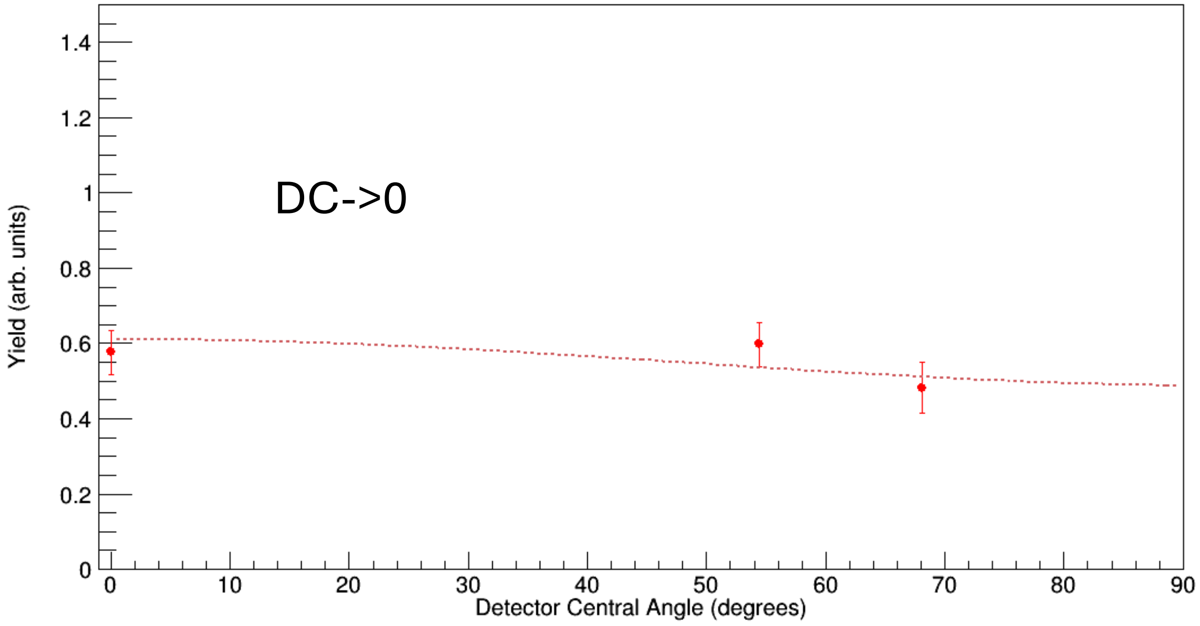
- For higher energies and all DC->0 peaks we can assume a **linear background**

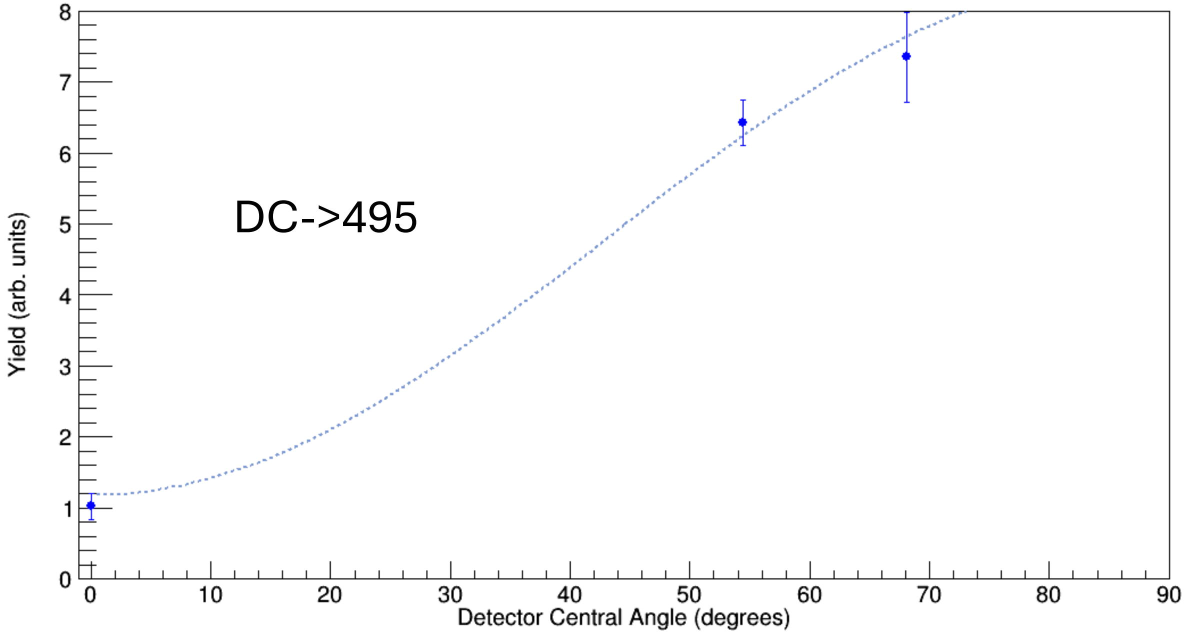
- For peaks on the Compton edge the background was fit with an **error function** - the Compton edge shape does not depend strongly on beam energy

$$f(E_\gamma) = \frac{Ae^{-2\pi\eta}}{E_{cm}}\left(1+e^{\frac{E_{fit}-E_\gamma}{\delta R}}\right)^{-1}\left(1+e^{\frac{E_\gamma-E_{fit}-\Delta E}{\delta L}}\right)^{-1}$$



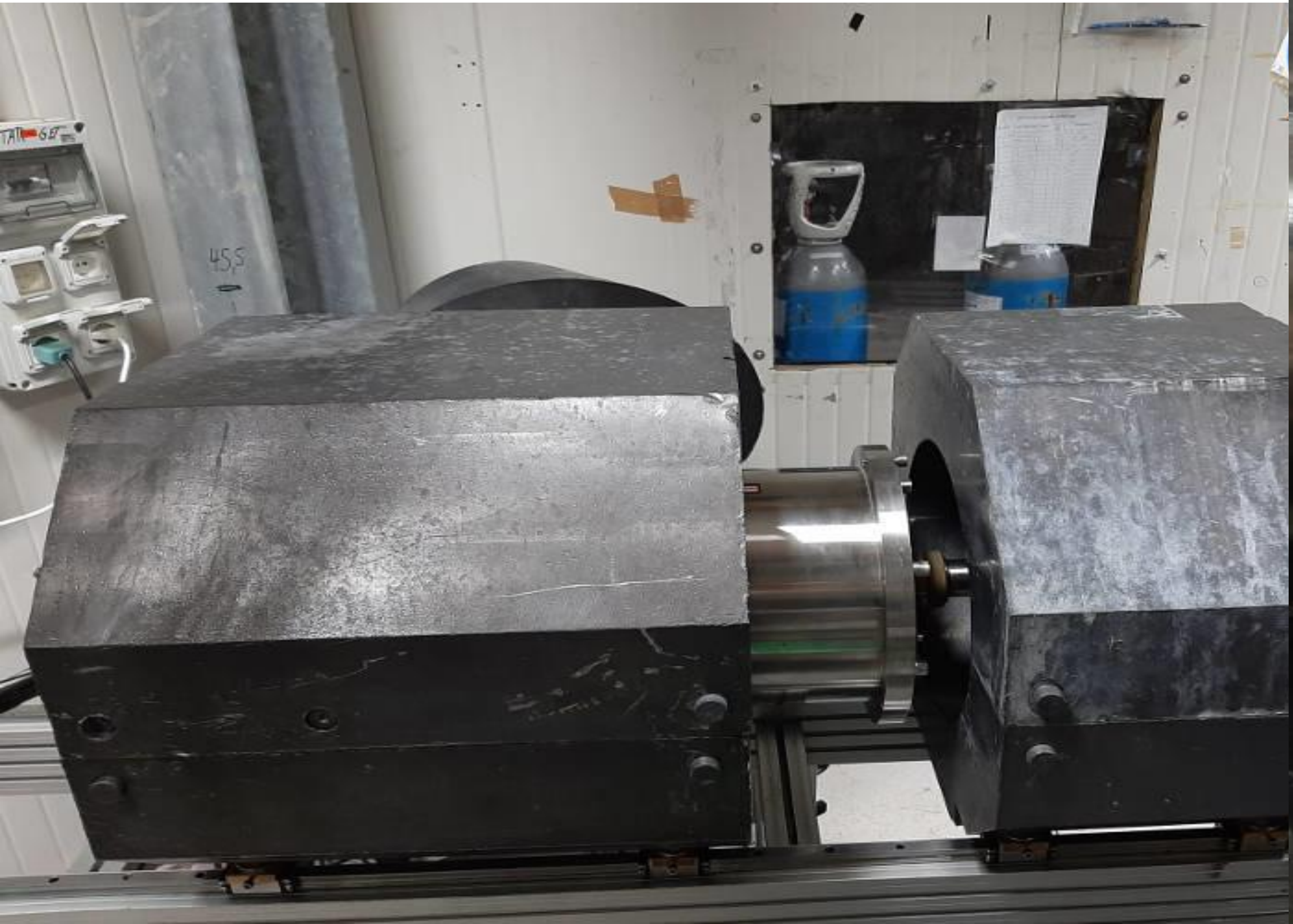
Measured Angular Distributions





- 3 detectors is not enough to independently determine the angular distributions
- Instead, the yields (after correcting for efficiency, summing, and target effects) were compared to the **extrapolated distributions**
- Found **good agreement** with the extrapolated distributions

Activation Setup



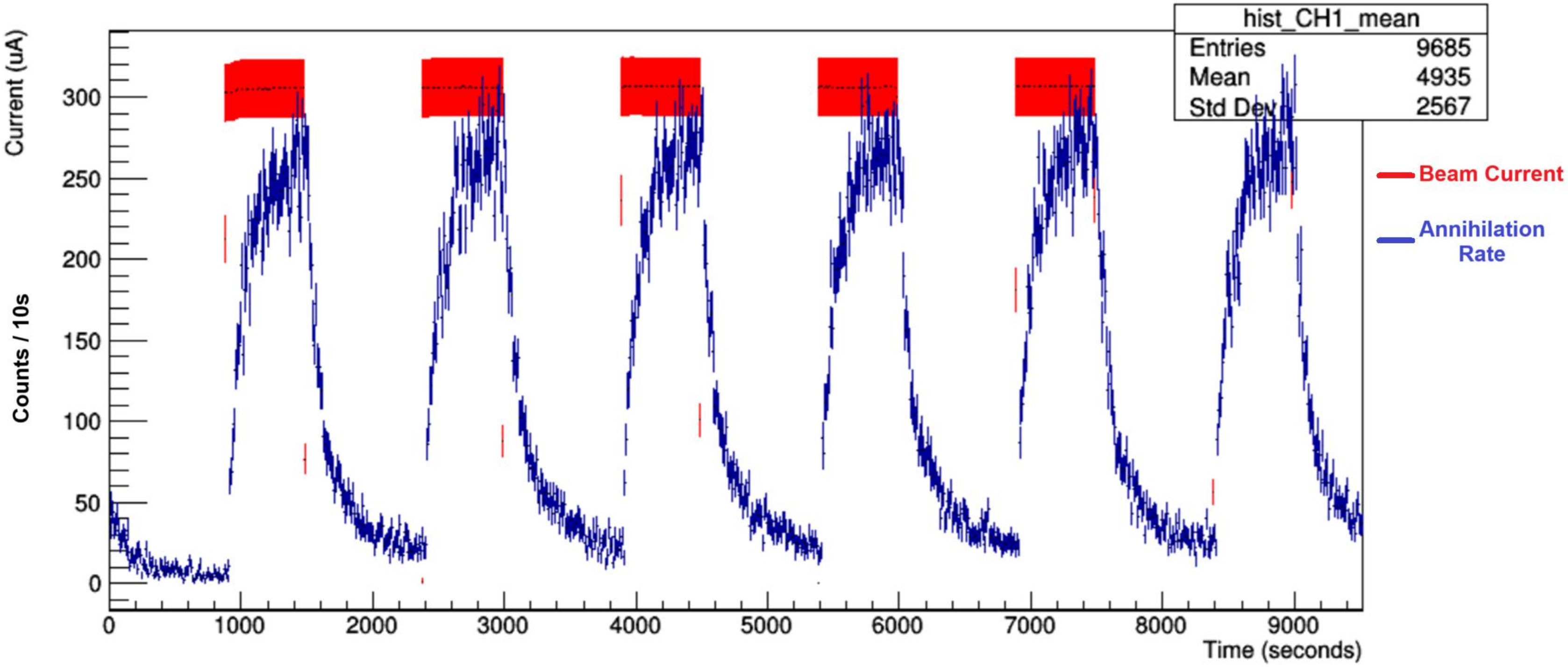
$^{16}O(p,\gamma)^{17}F$ by the In Situ Activation Method at LUNA

- Positrons from the **β^+** emitters (^{17}F in this case) annihilate in the target to produce **two 511 keV gamma rays at 180º**

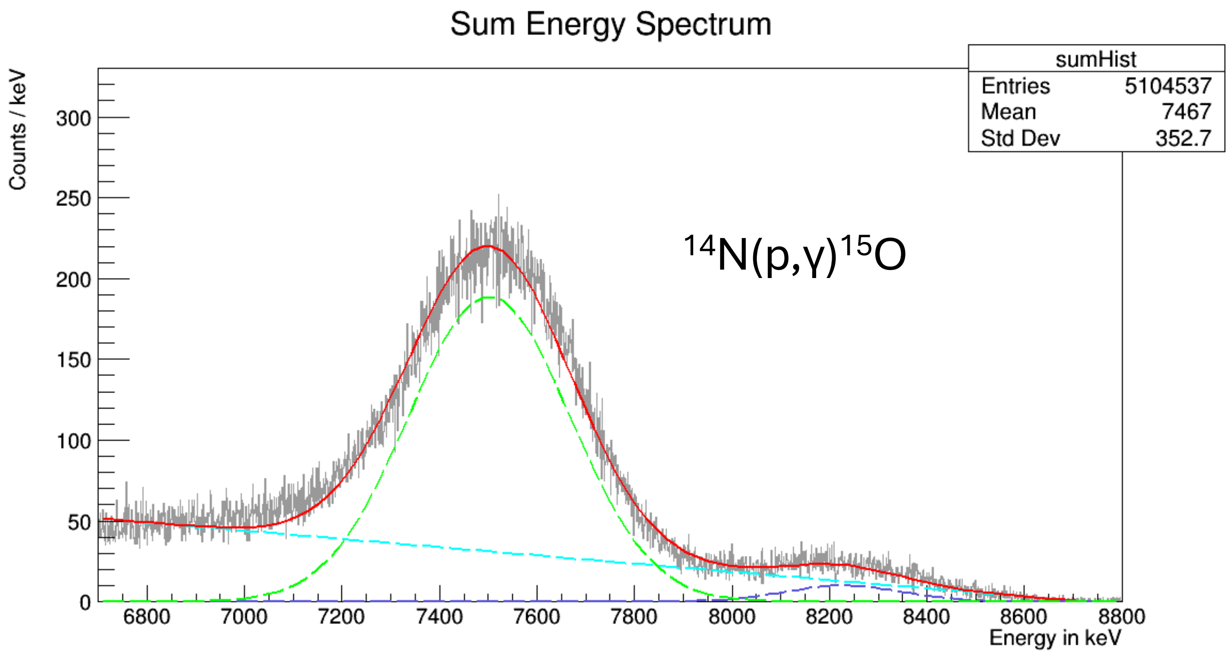
- Counting only **back-to-back coincidence** events eliminates almost all background

- **^{17}F** β^+ decays with a half-life of **64.4 s**

- Major contaminants:
  - **^{15}O** from $^{14}N(p,\gamma)^{15}O$: half-life = **122.3 s**
  - **^{13}N** from $^{12}C(p,\gamma)^{13}N$: half-life = **598.0 s**

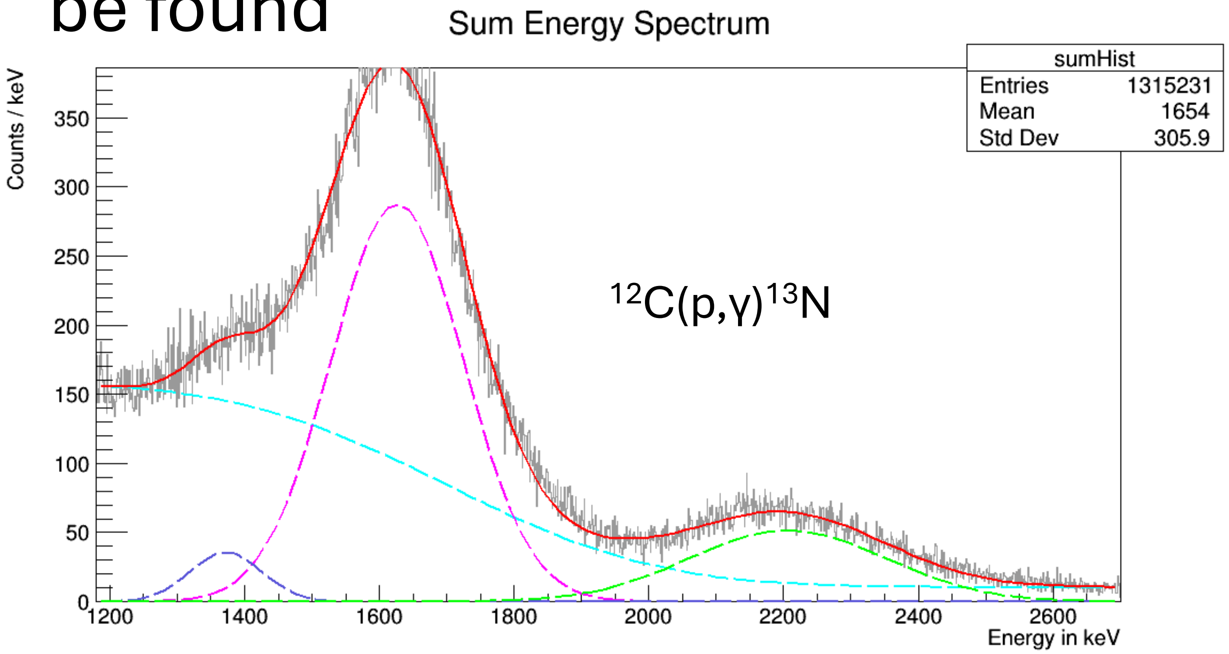


Constraining the Contaminants



- The BGO can act as a **single high efficiency detector** by summing the signals across all 6 crystals

- From the **sum spectra**, constraints on the major contaminants could be found



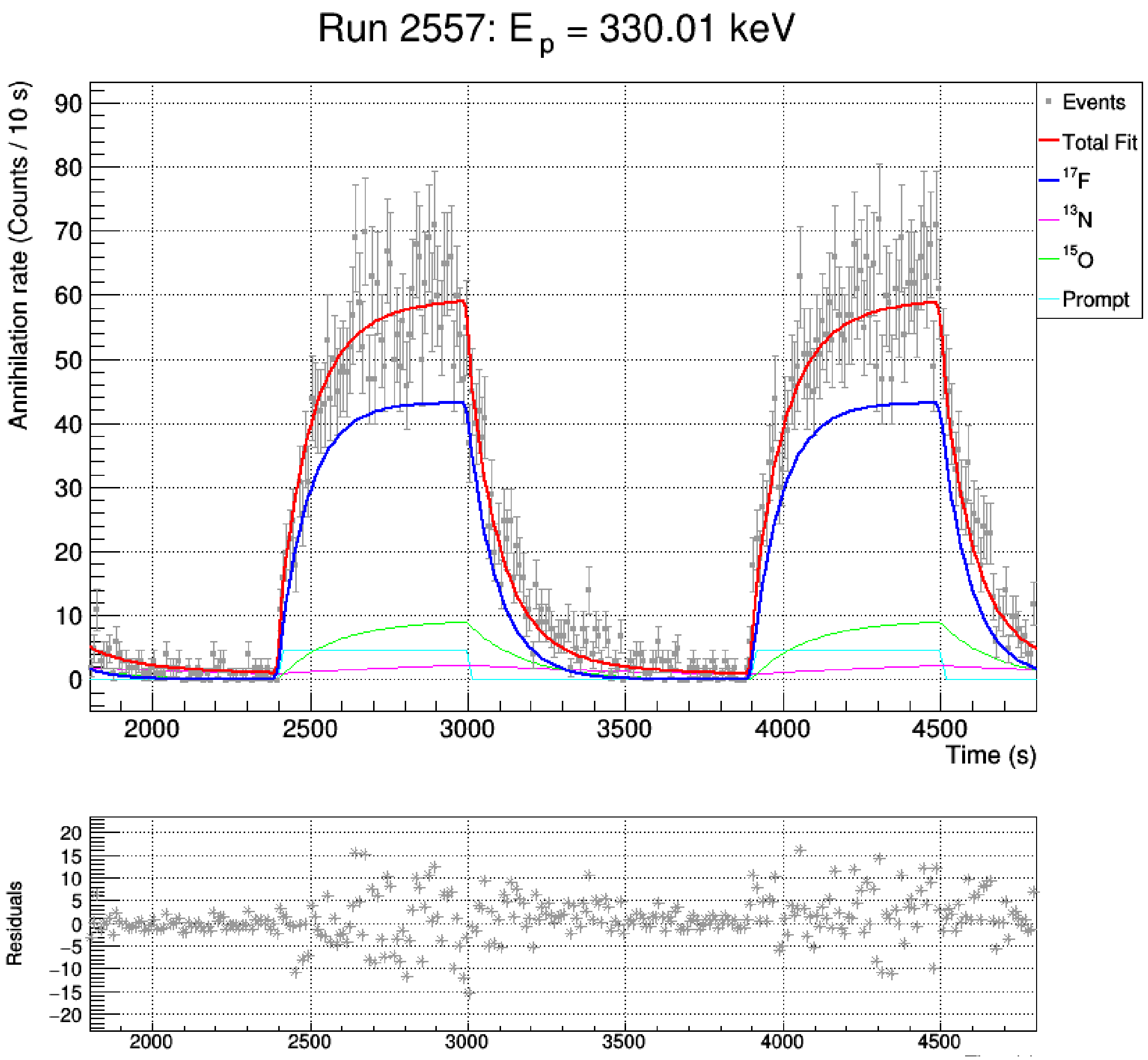
- **Contaminant yields** were found by fitting the sum spectrum peaks from the two reactions $^{12}C(p,\gamma)^{13}N$ and $^{14}N(p,\gamma)^{15}O$

Production and Decay Fitting

- The annihilation rate spectra were fitted with the following differential equation:

$$\frac{dN}{dt} = KI(t) + \sum_i Y_i I(t) - \lambda_i N_i(t)$$

- ***t*** is **time**
- ***N_i*** is the **number of nuclei** of species *i*
- ***Y_i*** is the **yield** of species *i*
- ***λ_i*** is the **decay constant** of species *i*
- ***I(t)*** is the **beam current**
- ***K*** is the contribution from **prompt gamma rays**



Bayesian Fitting with MCMC

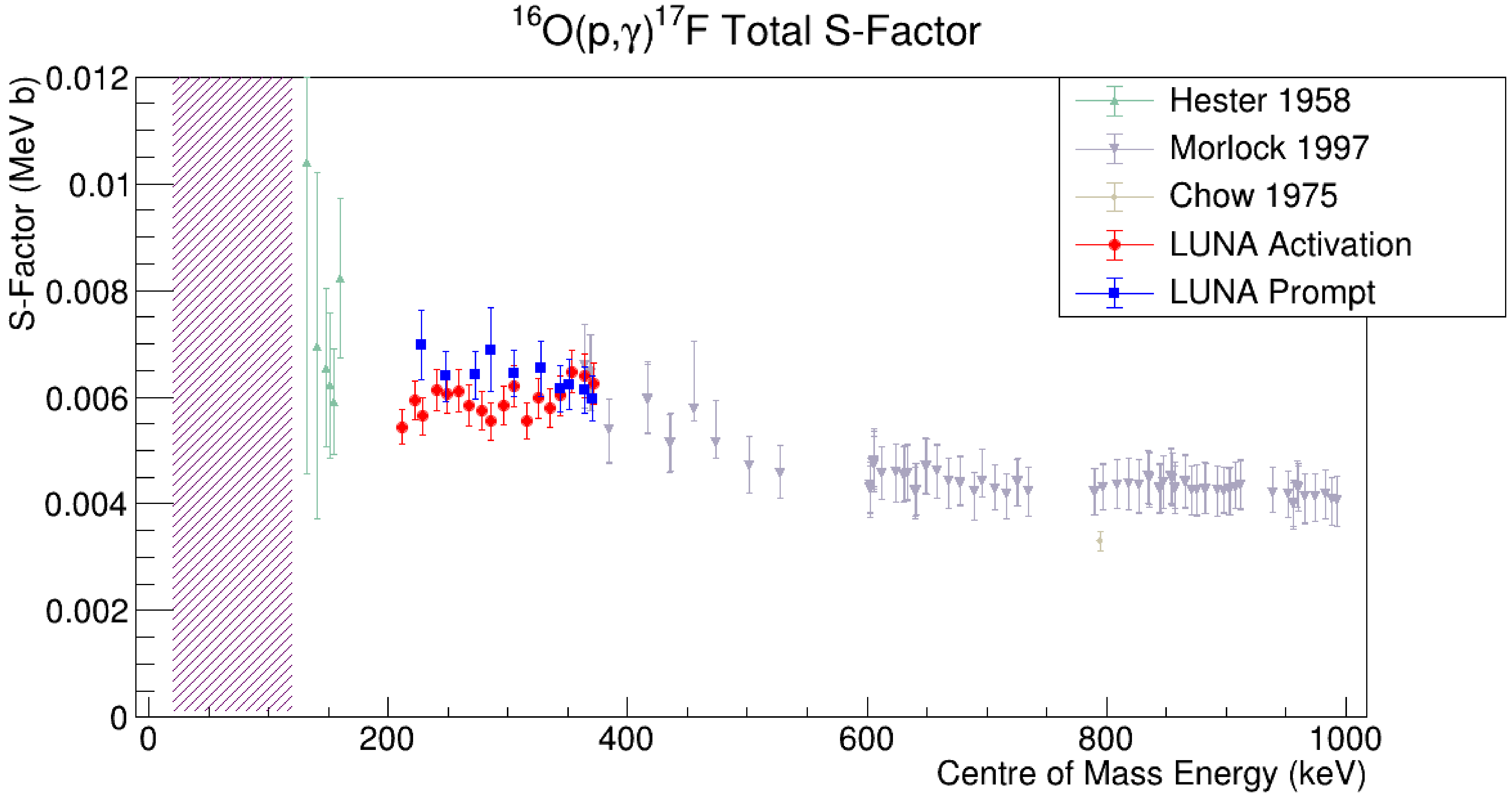
- Fits using **MINUIT** often hit parameter limits – **unreliable uncertainties**

- Fits were re-done using **Markov Chain Monte Carlo** (MCMC) to perform a **maximum log-likelihood** fit:

$$\ln(L) = \sum_i y_i \ln(\mu_i) - \mu_i$$

where y_i is the counts in time bin i, and μ_i is the model value at time bin i

- Contaminant constraints were implemented as **gaussian priors**



$^{16}O(p,\gamma)^{17}F$ Total S-Factor
S-Factor (MeV b)
0.012
0.01
0.008
0.006
0.004
0.002
0
0
200
400
600
800
1000
Centre of Mass Energy (keV)
Hester 1958
Morlock 1997
Chow 1975
LUNA Activation
LUNA Prompt

THANK YOU!

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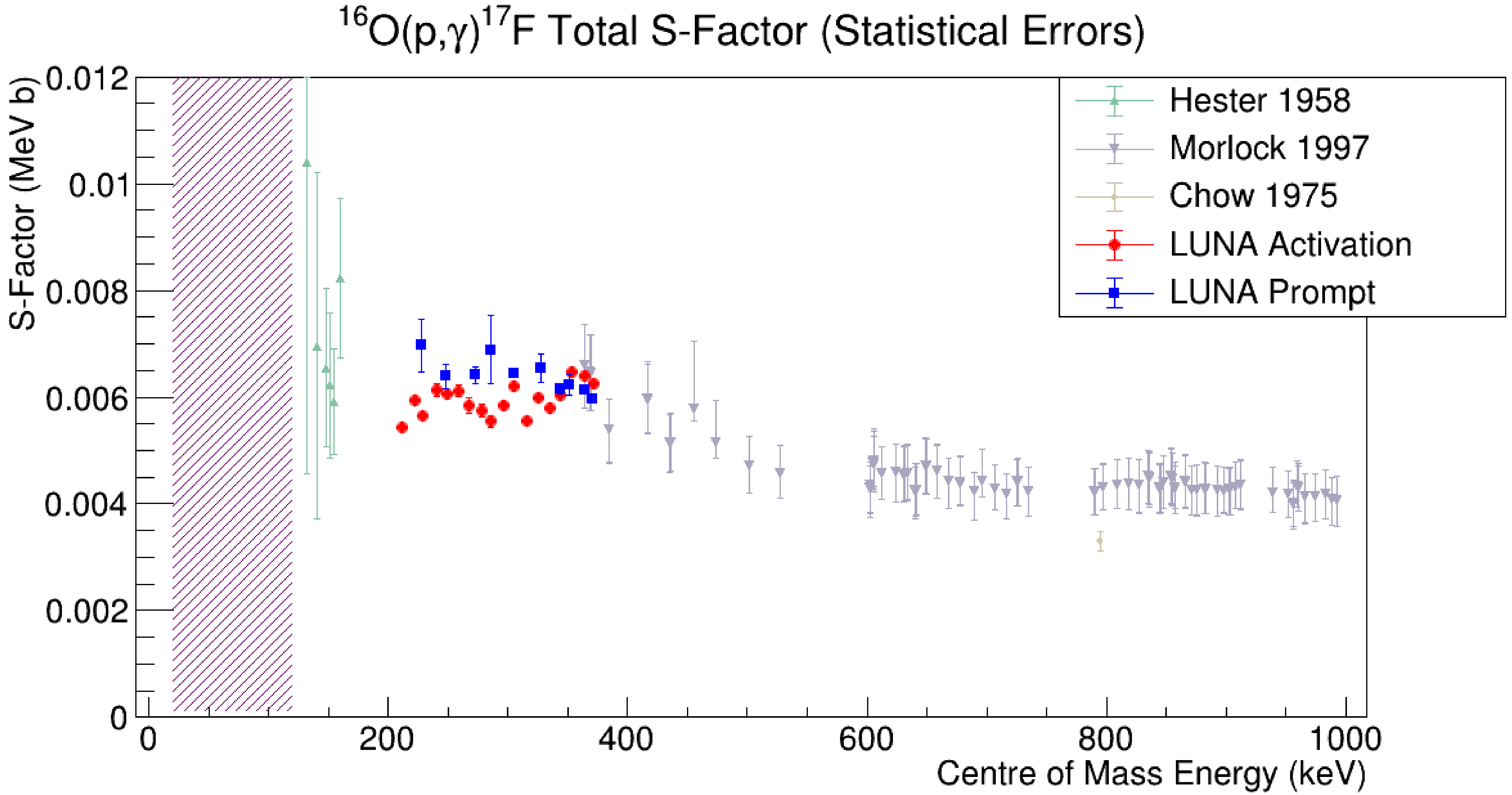
Thanks for listening!

Extra Slides



$^{16}O(p,\gamma)^{17}F$ Total S-Factor (Statistical Errors)
S-Factor (MeV b)
Centre of Mass Energy (keV)
0.012
0.01
0.008
0.006
0.004
0.002
0
0
200
400
600
800
1000
Hester 1958
Morlock 1997
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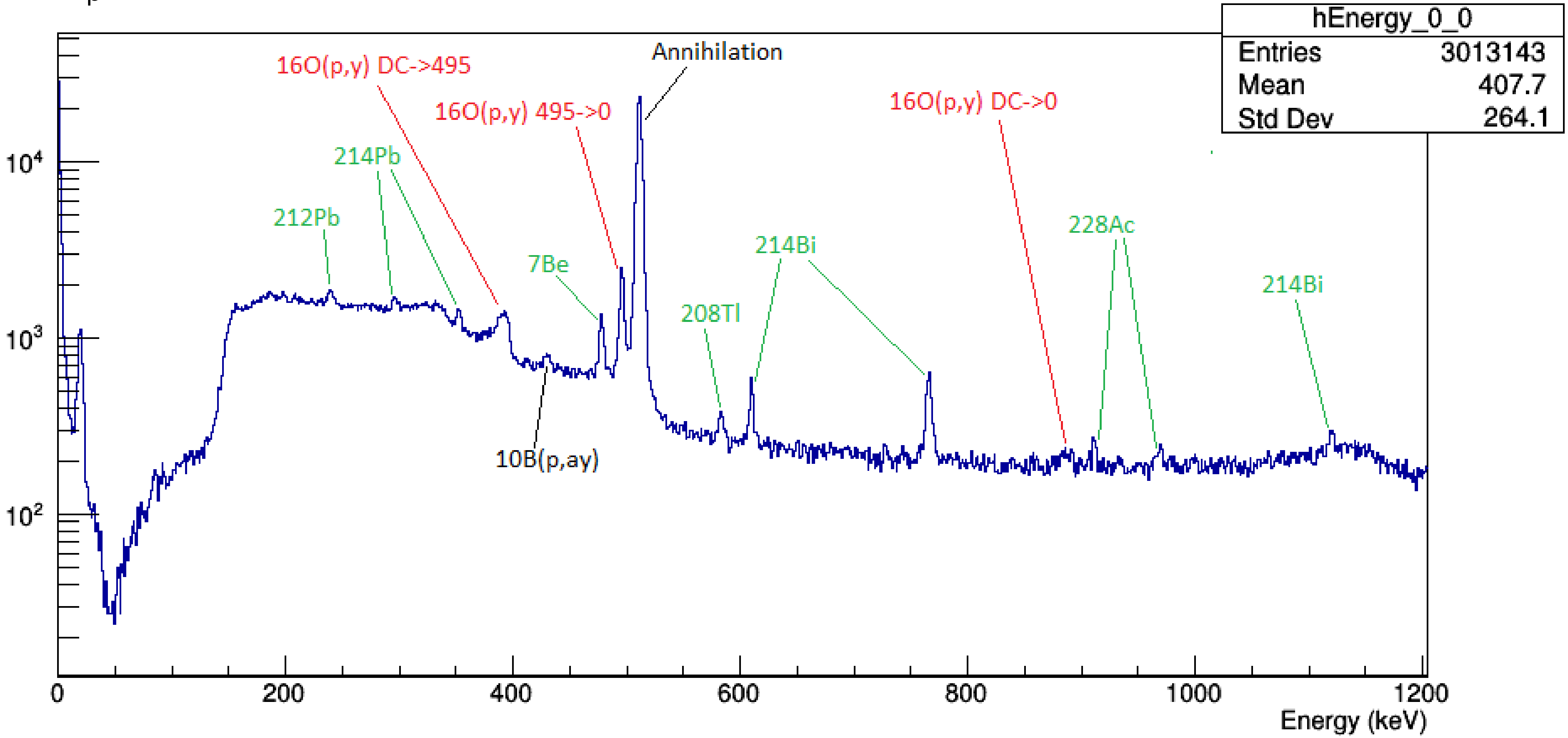
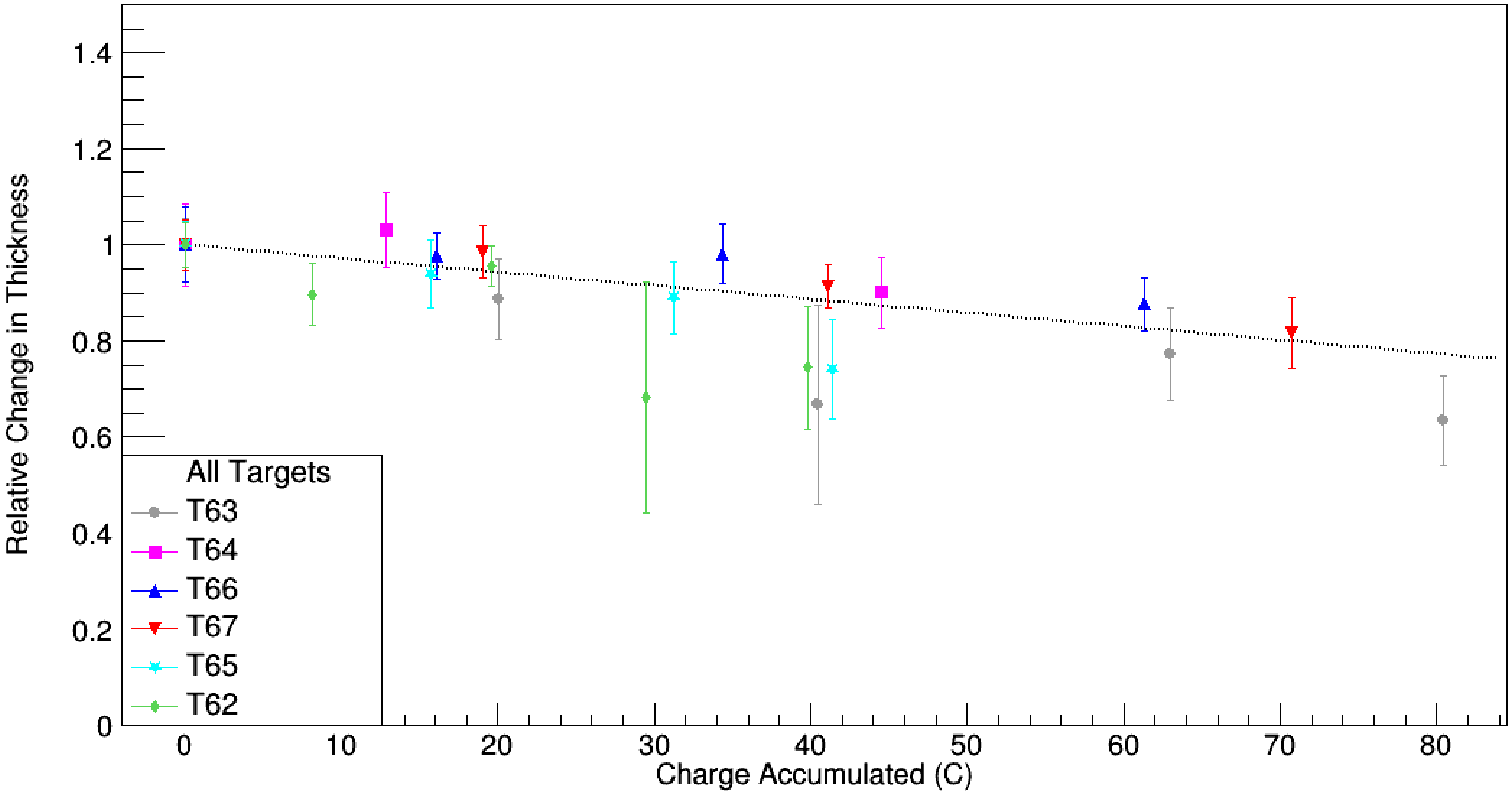
LUNA Activation
LUNA Prompt

Typical Spectrum (HPGe)

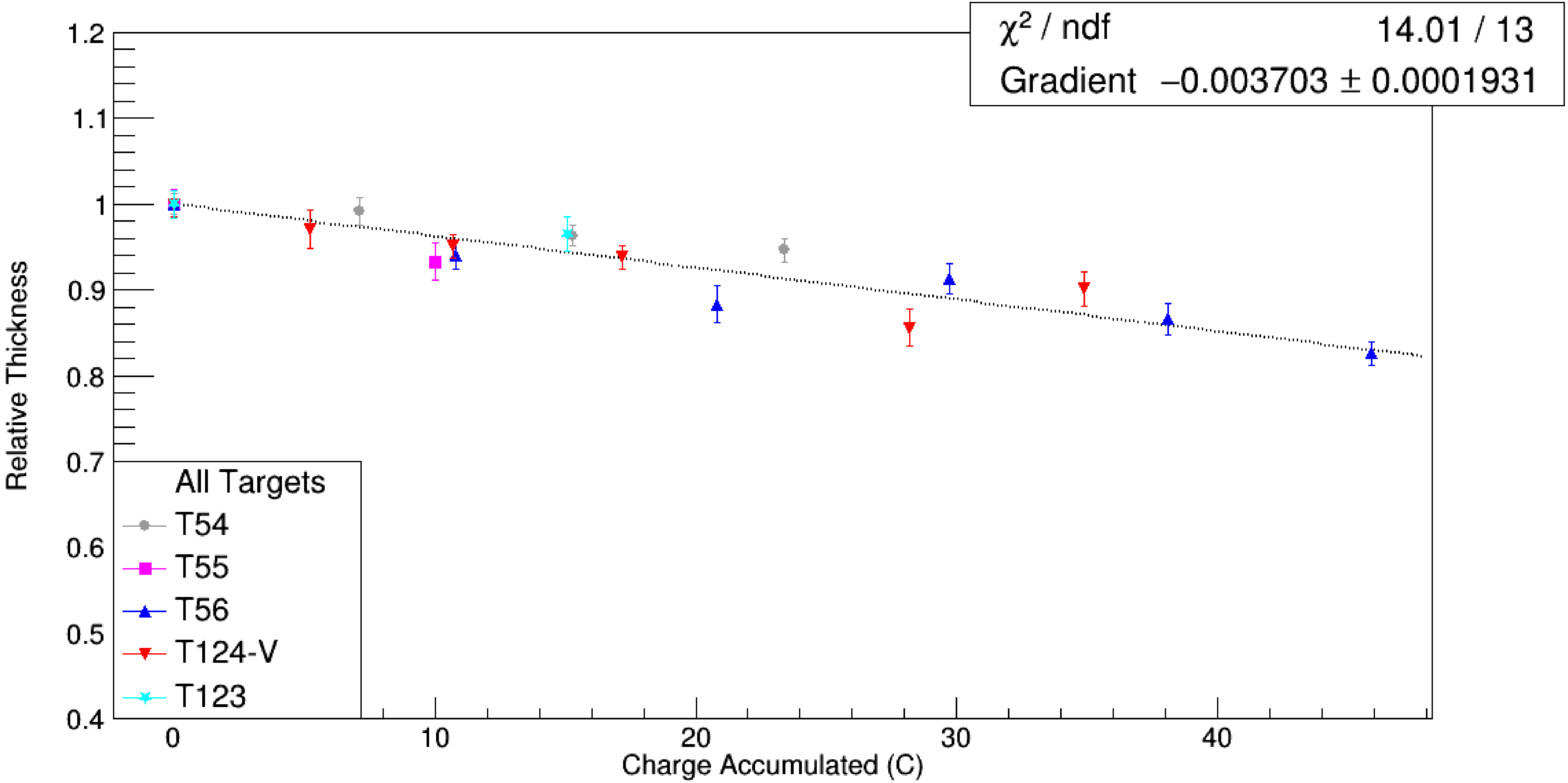
E_p = 310 keV



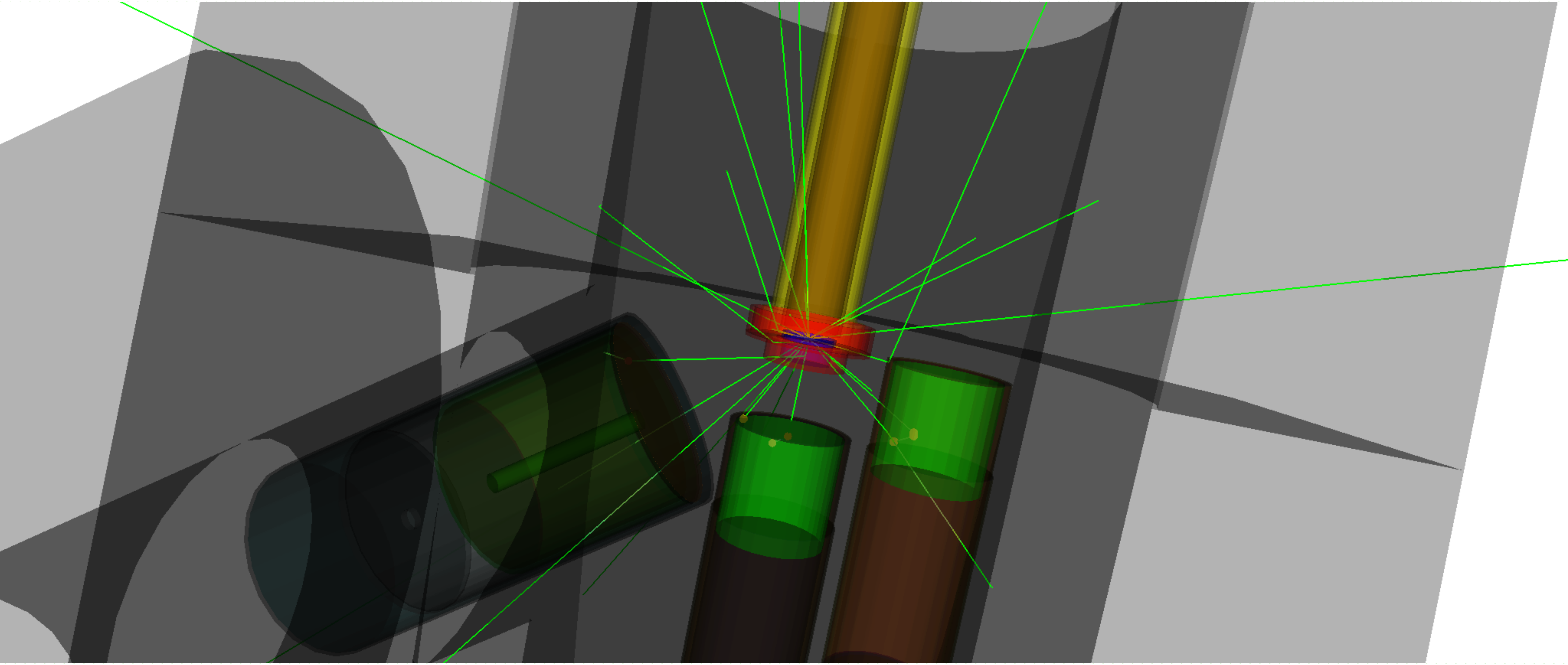
Prompt Gamma Ray Target Degradation



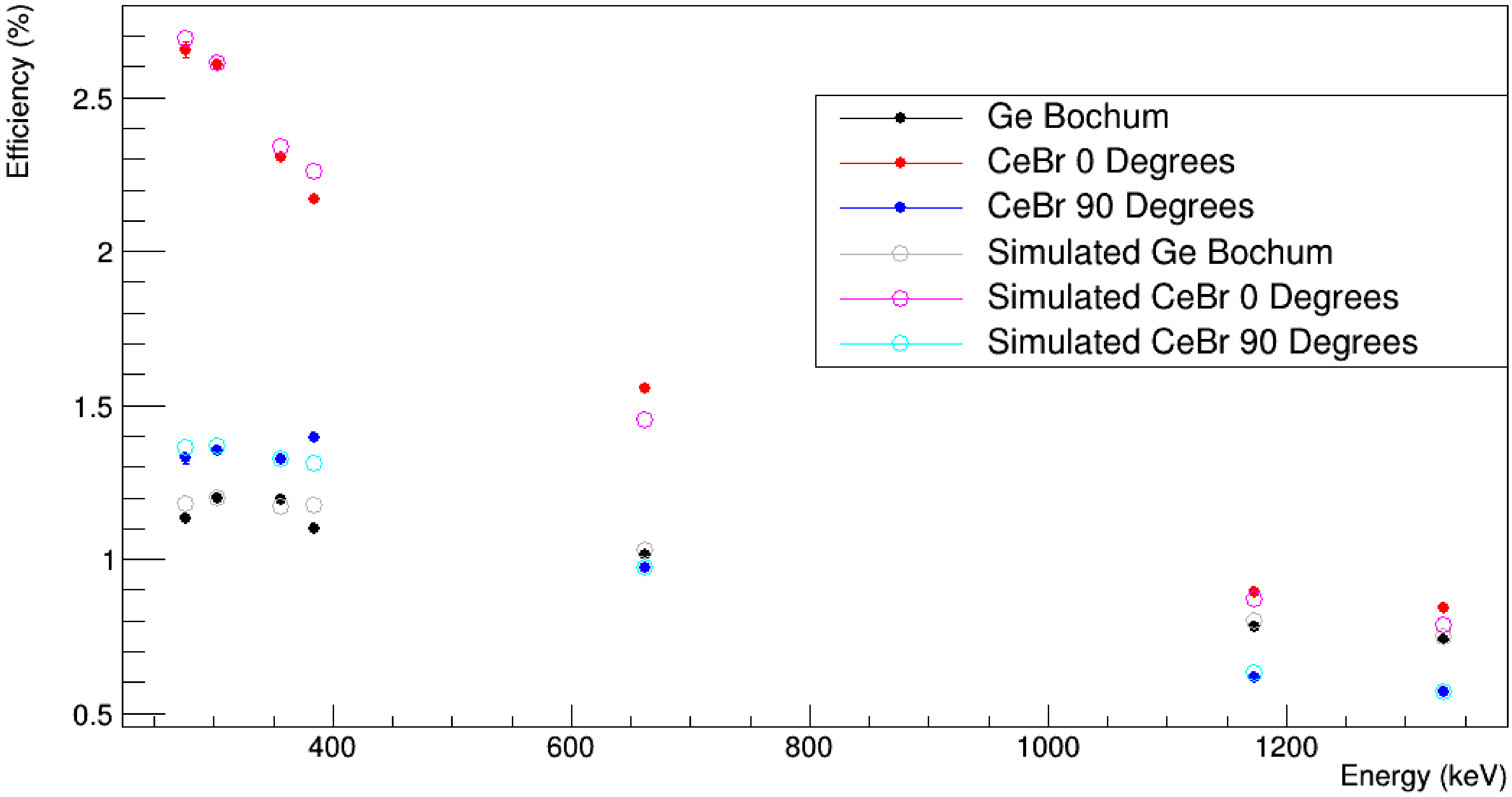
Activation Target Degradation



Prompt Gamma Ray Simulated geometry



Prompt Gamma Ray Simulated Efficiency



Efficiency Summing Corrections

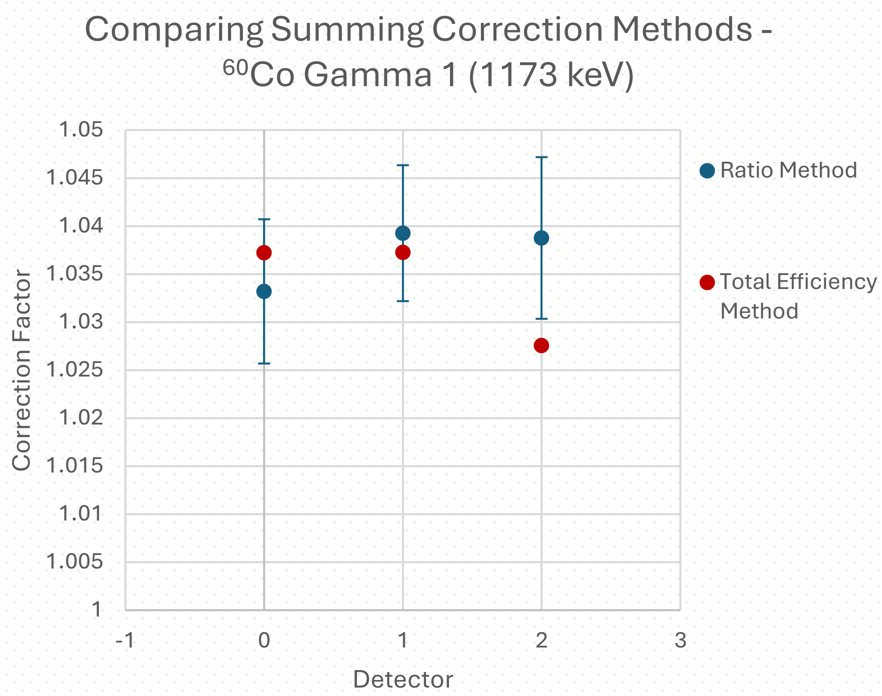
- Simulated efficiency measurements with ^{137}Cs, ^{60}Co and ^{133}Ba sources

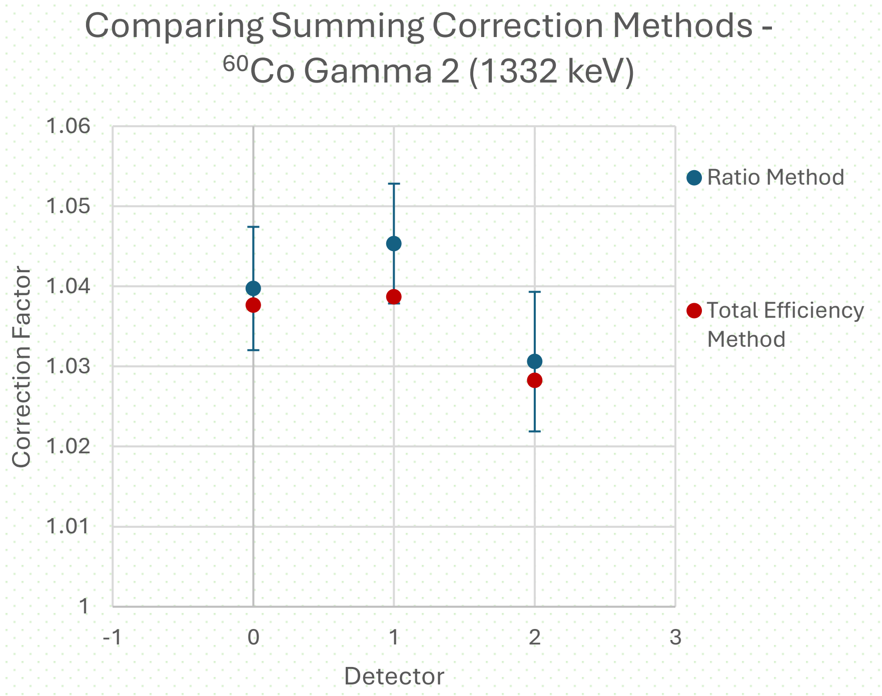
- Simulated runs with the individual gammas emitted separately

- Summing correction factor equals the ratio of the two yields

- Also calculated analytically using the total efficiency from the separate gamma sims (^{60}Co only)

$$C_{TCS} = \frac{n_1}{n_1'} = \frac{1}{1 - \epsilon_{T2}}$$



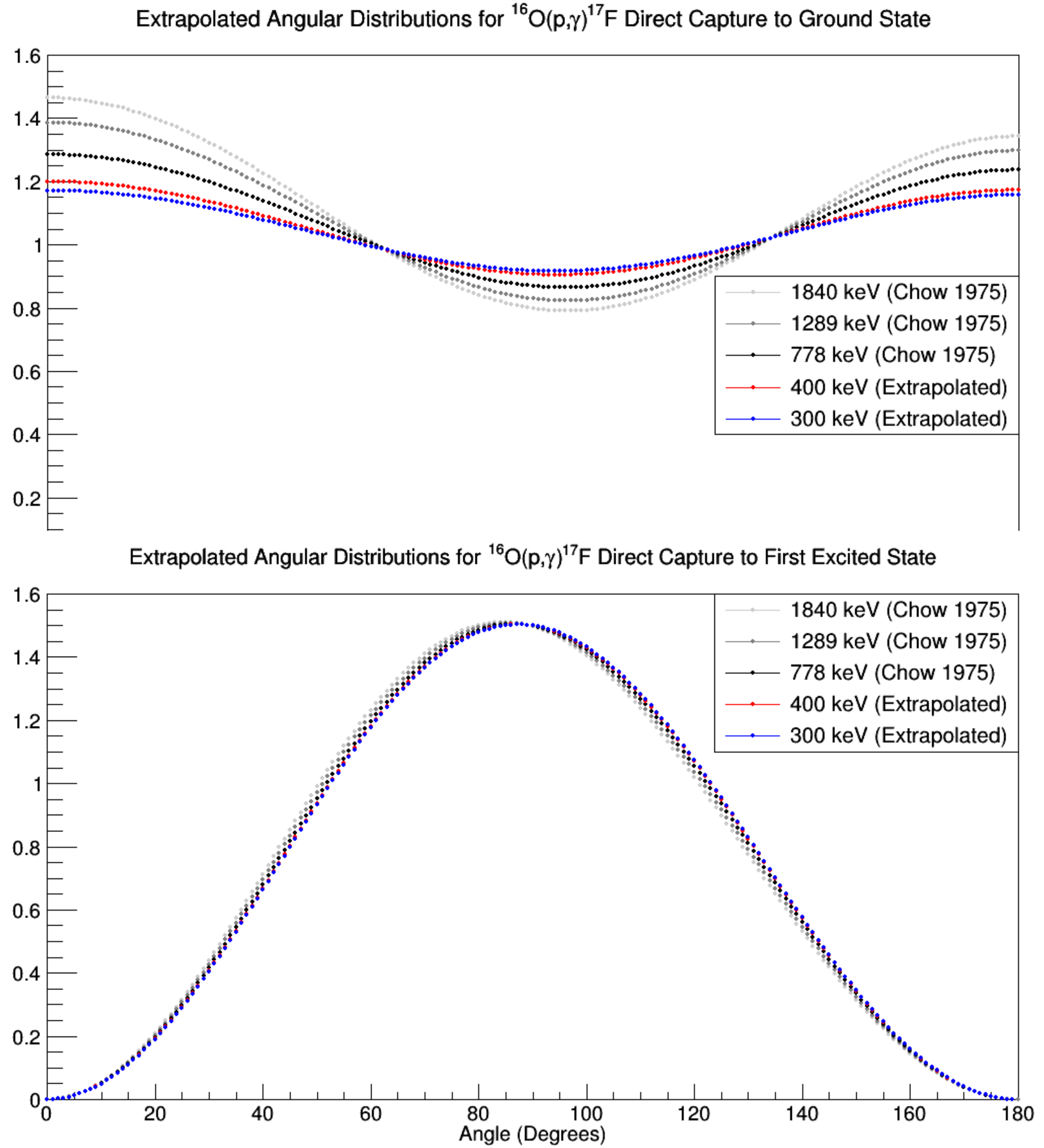


Angular Distribution

- The two primary gammas have an **intrinsic non-isotropic** angular distribution. We **extrapolated** from measurements made in the 1970s to our energies
- The distributions are described by the sum of **Legendre polynomials**, up to order 3 for DC->0 and order 4 for DC->495:

$$W(\theta) = \sum_{n=0}^{N} A_{\mathrm{n}} P_{\mathrm{n}}(cos\theta)$$

Legendre Order	DC→0 Coefficient	DC→495 Coefficient
0	1	1
1	0.02632	0.05856
2	0.18635	-0.99931
3	-0.01258	-0.05842
4		-0.0006

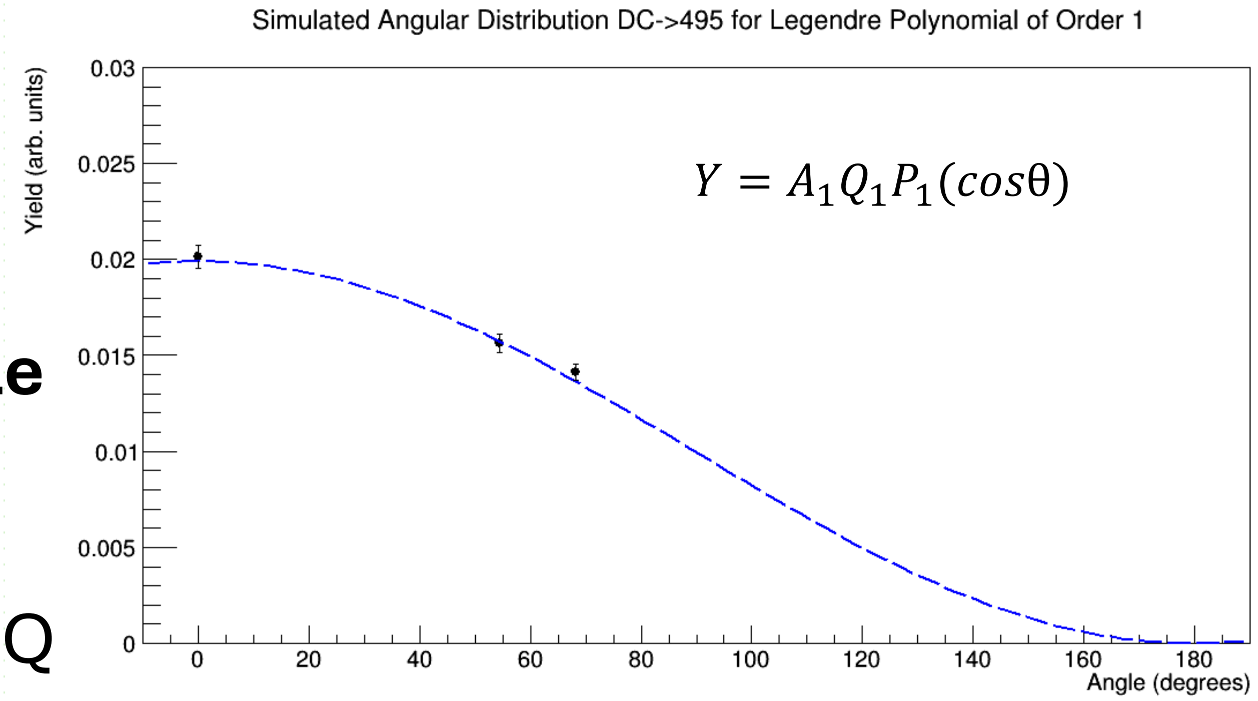


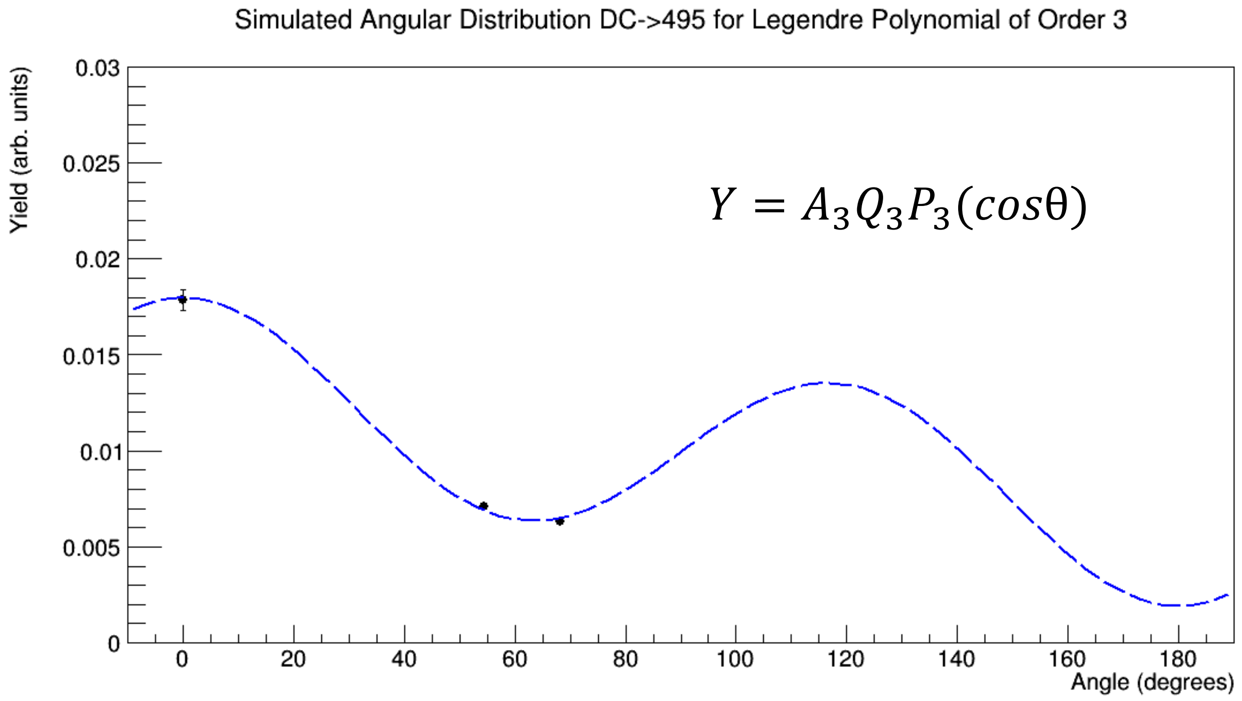
Attenuation Factors

- Our detectors were quite close to the target holder (~ 1 - 5 cm), so subtended quite a **large solid angle**
- Can fully account for this by introducing an **attenuation factor** Q into the angular distribution equation (Rose 1953):

$$W(\theta) = \sum_{n=0}^{N} A_n \, Q_n \, P_n(cos\theta)$$

- The Qs can be calculated analytically for single detectors, or found from simulations





Reaction Summing Corrections

- Simulated $^{16}O(p,\gamma)^{17}F$ reaction with extrapolated angular distribution

- Simulated runs with the individual gamma rays emitted separately, also with extrapolated angular distribution

- Summing correction factor equals the ratio of the two yields

Gamma	GeBochum C_{TCS}	CeBr0 C_{TCS}	CeBr90 C_{TCS}
DC→495	1.036 ± 0.002	1.040 ± 0.018	1.032 ± 0.001
495→0	1.033 ± 0.012		
DC→0	0.876 ± 0.001	0.890 ± 0.086	0.819 ± 0.008

Gamma	GeBochum C_{TCS}
DC→495	1.064 ± 0.001
495→0	1.064 ± 0.001
DC→0	0.775 ± 0.003

Extrapolated Legendre Coefficients