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Title: Temperature and dopant concentration effects on proton light quenching in rare-earth inorganic scintillators

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Los Alamos NATIONAL LABORATORY

Temperature and dopant concentration effects on proton light quenching in rare-earth inorganic scintillators

Tatiana Nathaly Espinoza

Master Thesis Defense – June 15th 2023

Advisor: Professor Adam A. Hecht

LANL mentors: David Walter, PhD; Kurtis D. Bartlett, PhD; Caleb Roecker, PhD

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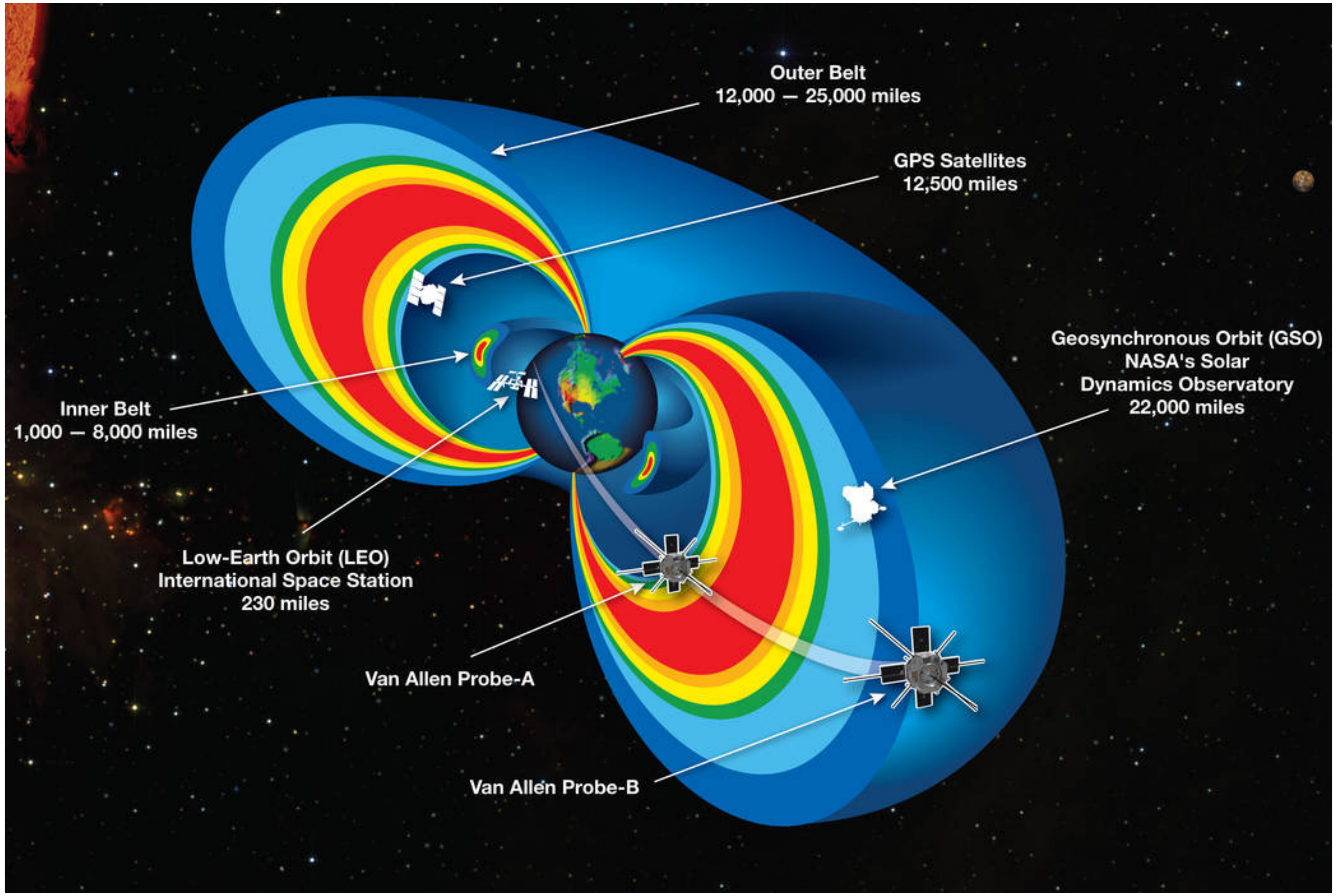
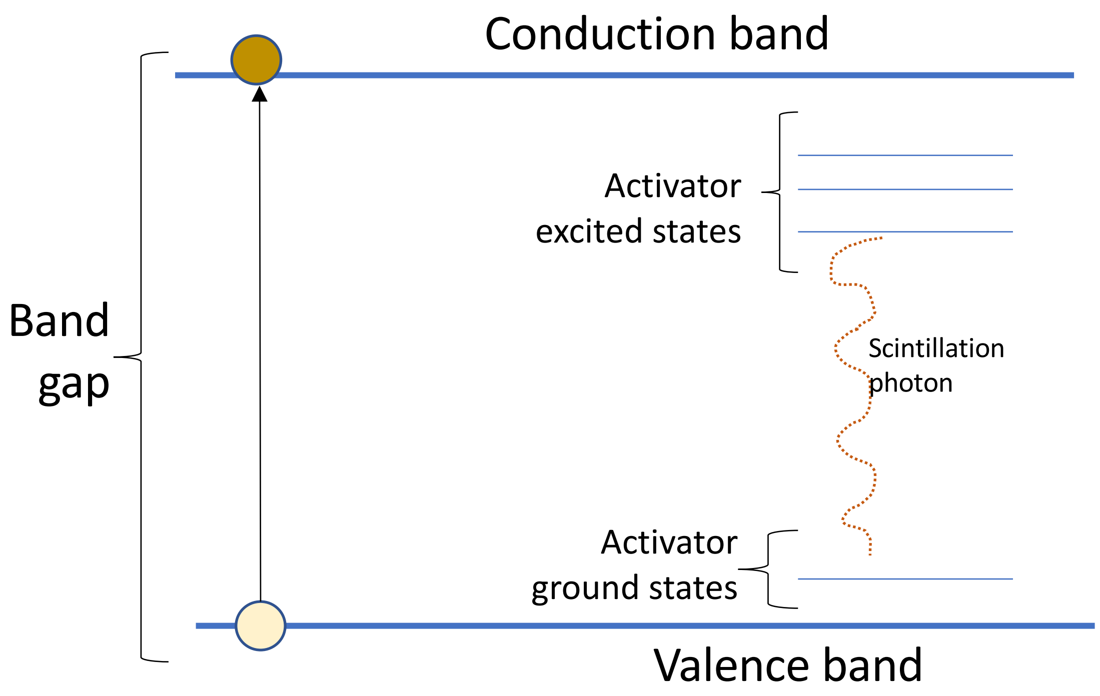
Radiation detectors for space applications

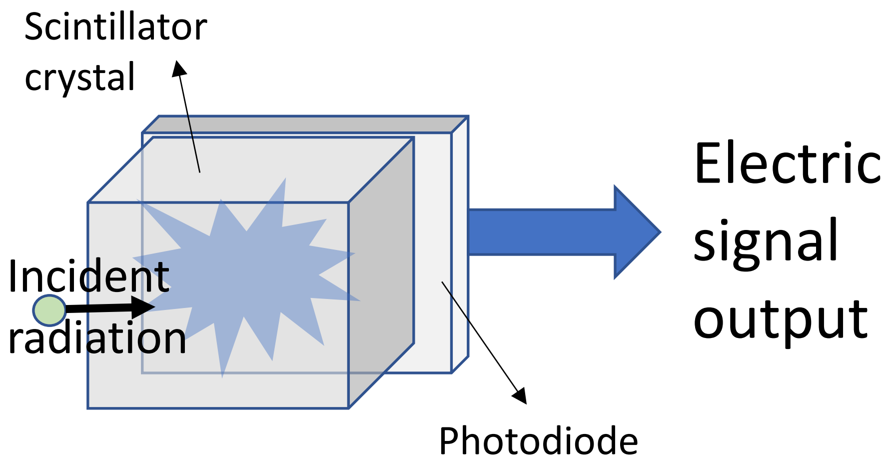


- Detection of energetic charged particles (ECP) in space from:
  - Trapped energetic electrons and protons
  - Galactic and solar cosmic rays
- Detectors in satellites are exposed to large energy range of charged particles fluxes and temperature fluctuations.
- Reduction of size, weight and power is important for payloads.
- Scintillators detectors are a good choice for reduction of SWaP.

Scintillation process in inorganic crystals

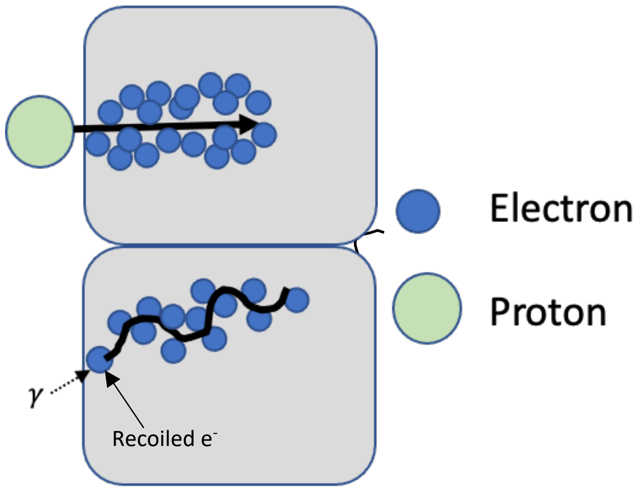
- Discrete energy bands available based on crystal lattice.
- Photons are emitted when electrons in excited atoms de-excite to ground state.
- For pure crystals, photons may have too much energy to emit energy in the visible range.
- Cerium, thallium and other elements are used to create impurities sites in the lattice, that increase the likelihood of photons to be emitted in the visible range.





Quenching

- Non-proportional scintillation light output between incident gamma and incident light charged particle of the same energy.
- Quenching can be related to the stopping power of a material which is energy dependent, incident radiation dependent and material dependent.
- Found in literature as the α/β ratio and typically presented in calibrated units to 662 keV Cs137 gamma peak.



$$-\frac{dE}{dx} = \frac{4\pi e^2 z^2}{m_0 v^2} NB$$

$$B \stackrel{\text{def}}{=} Z[ln\frac{2m_0 v^2}{I} - \ln(1 - \frac{v^2}{c^2}) - \frac{v^2}{c^2}]$$

v	= primary particle’s velocity
ze	= primary particle’s charge,
N	= number density
Z	= atomic number of the absorber atom
m_0	= electron rest mass
e	= electronic charge
I	= avg excitation and ionization potential of absorber

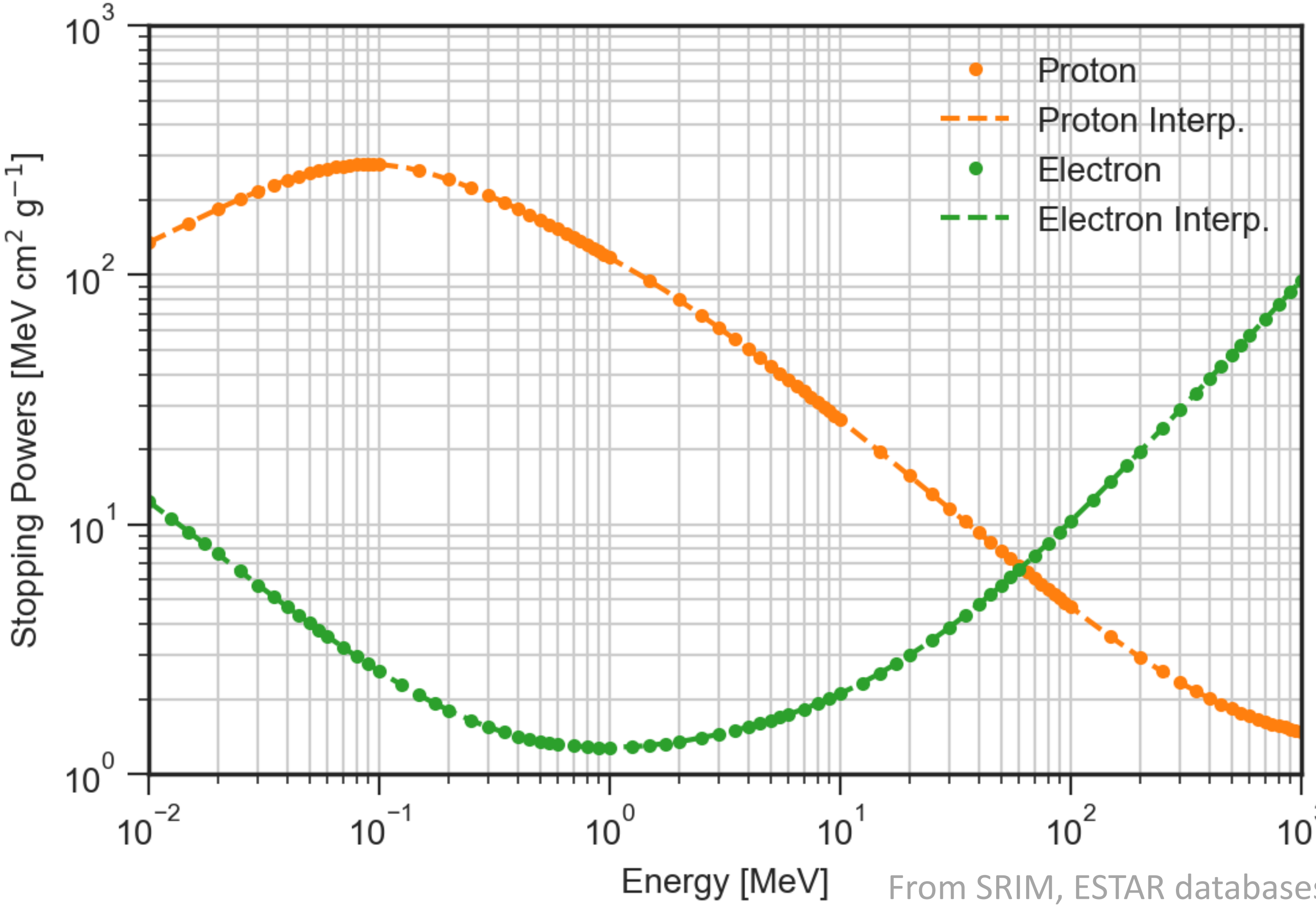
Parameterizing quenching

$$^{*}\ \frac{dL}{dx} = \frac{S\frac{dE}{dx}}{1 + kB\frac{dE}{dx}}$$

dL/dx = Light yield
S = Scintillation constant
kB = Birks factor
dE/dx = Stopping power

$$^{*}\ Q_i(E) = \frac{L_i(E)}{L_e(E)} = \frac{\int_0^E \frac{dE}{1+kB(\frac{dE}{dr})_i}}{\int_0^E \frac{dE}{1+kB(\frac{dE}{dr})_e}}.$$

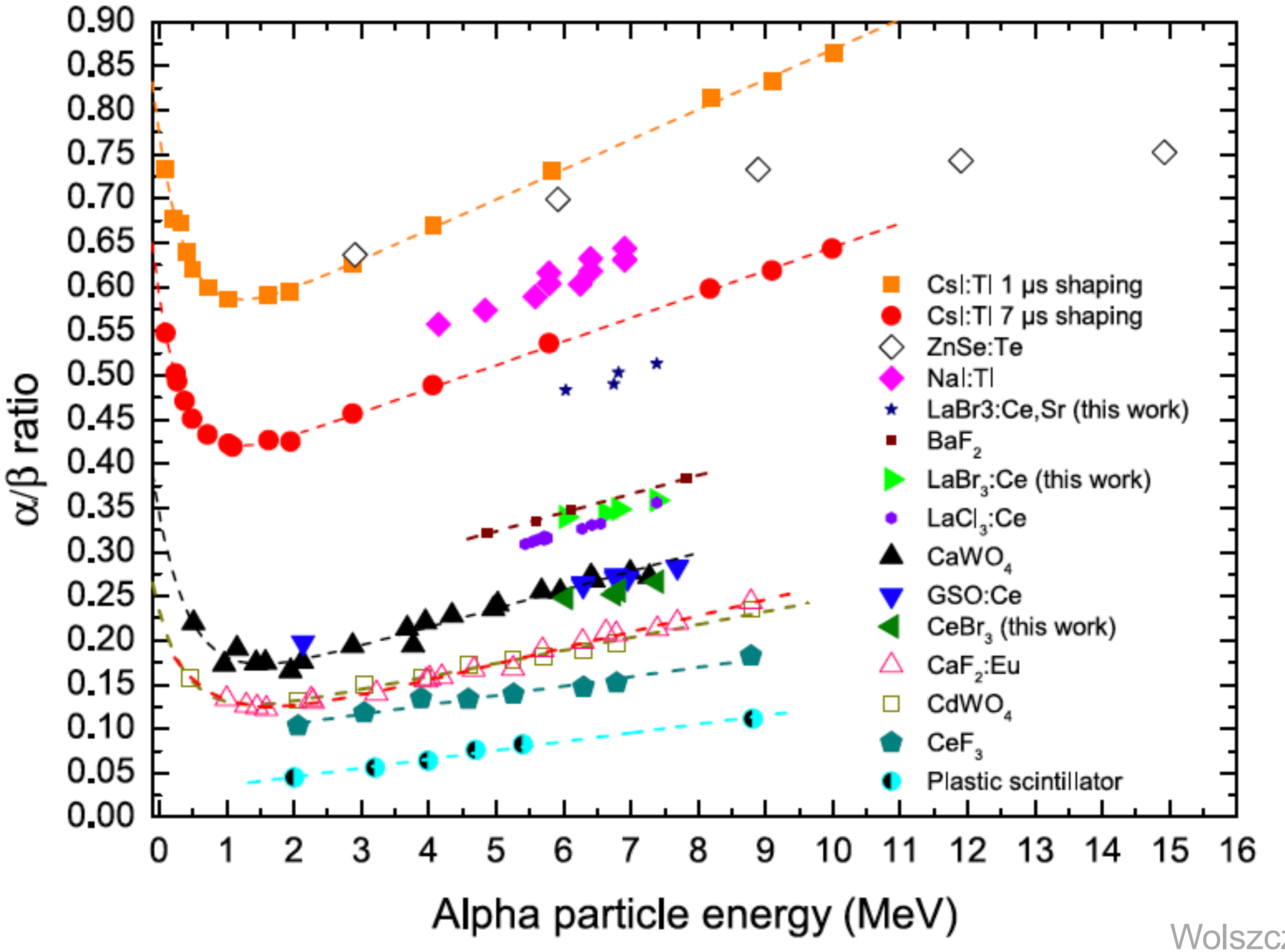
$Q_i(E)$ = Quenching factor
$L_i(E)/L_e(E)$ = light output of ion vs e^-



From SRIM, ESTAR databases

* Tretyak, V.I. "Semi-empirical calculation of quenching factors for ions in scintillators". 2009.

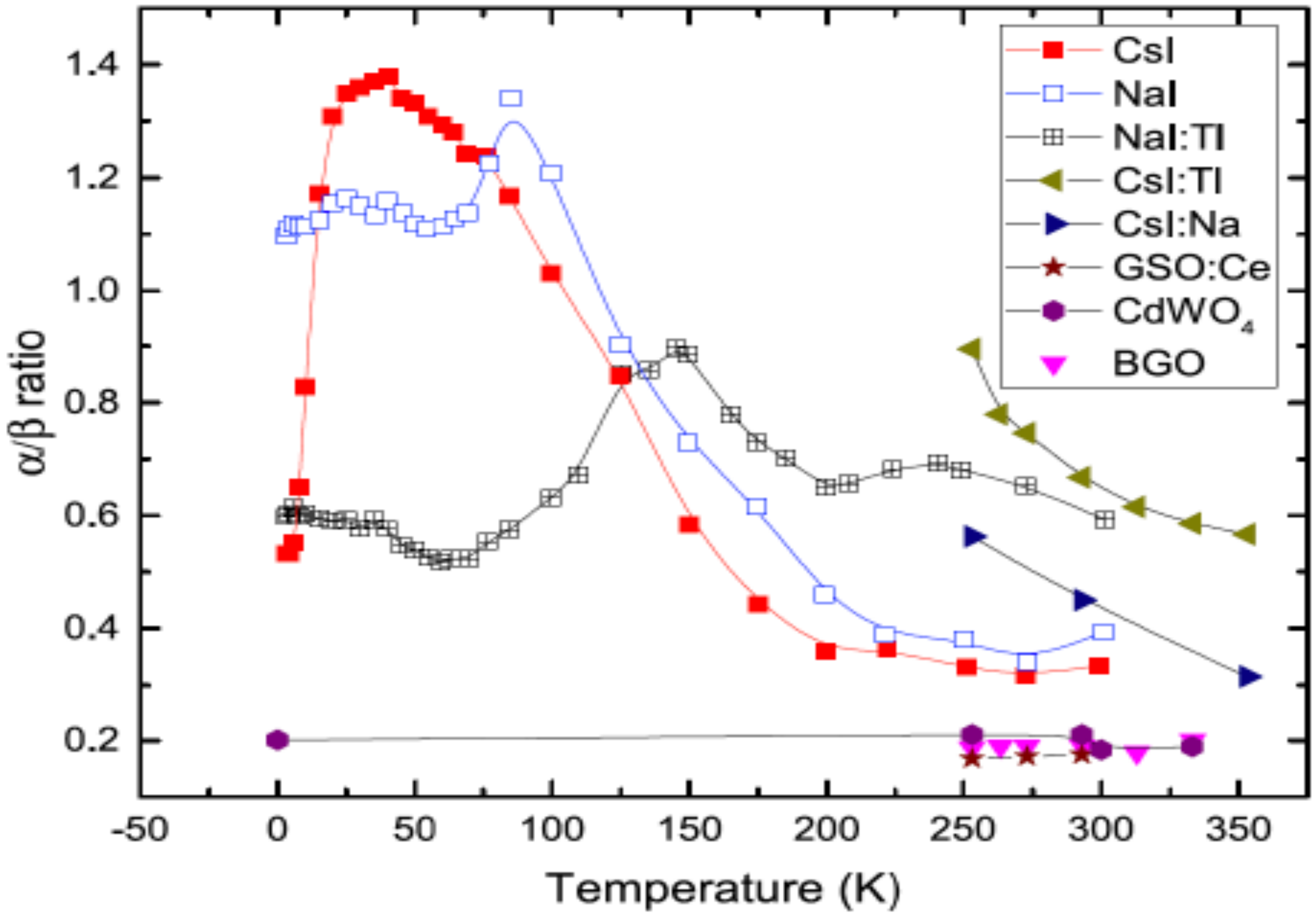
Factors that influence quenching



- α (helium) / β (electron) ratio describes nonlinear effects in scintillators (quenching)
- Systematic effects:
  - Scintillator type
  - Energy
  - Temperature
  - Dopant concentration
  - Electronics
  - Others

Wolszczak W. and P. Dorenbos. “Nonproportionality response of scintillators to alpha particle excitation”. 2017.

Temperature effects on quenching is material dependent



- Different material exhibit different effects as temperature changes
- The pattern of the effect is material dependent and therefore cannot be generalized to all scintillators

W. Wolszczak and P. Dorenbos. *IEEE Transactions on Nuclear Science*, vol. 64, no. 6, pp. 1580-1591, June 2017, doi: 10.1109/TNS.2017.2699327.

Experiment goal

- To measure rare earth inorganic scintillators' light output quenching from incident protons at a specific energy range under different systematic effects (i.e., temperature and dopant variations)

Rare earth inorganic scintillators

- Characteristics: fast decay (YSO), high light output yield (GAGG), non-hygroscopic, reduced size, weight and power
- Manufactured by Advatech UK

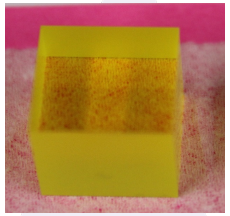
GAGG ($Gd_3Al_2Ga_3O_{12}$:Ce)

Three types:

High Yield [<150 ns, 60 photons/keV]

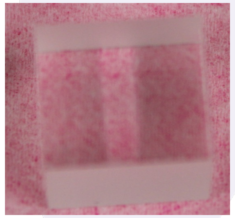
Standard [<90 ns, 50 photons/keV]

Fast Decay [<50 ns, 40 photons/keV]



YSO (Y_2SiO_5:Ce)

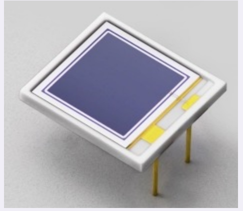
[50-70 ns, 10 photons/keV]



Other types such as NaI

[from Advatech: ~230 ns, ~38 photons/keV, **hygroscopic**]

- Si PIN photodiode: quantum efficiency matches max emission wavelength, good energy resolution



Hamamatsu photodiodes
S3590: 08 and 18

Schematic of detector

NIA Pixie digitizer: Takes in signal from preamp and convolves the input signal with a trapezoidal filter:

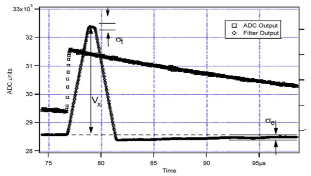
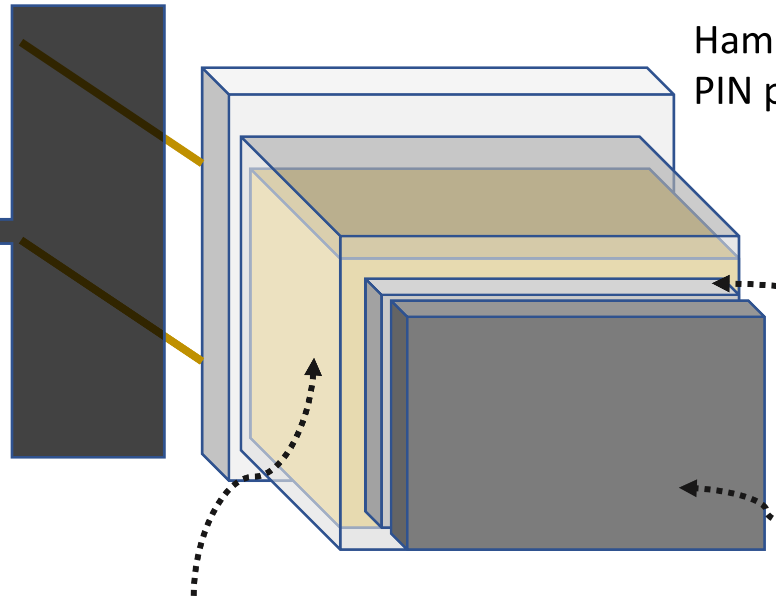


Figure 11-4: A γ-ray event displayed over a longer time period to show baseline noise and the effect of preamplifier decay time.

Laptop:
Collects .csv files with counts and bin numbers, data processing

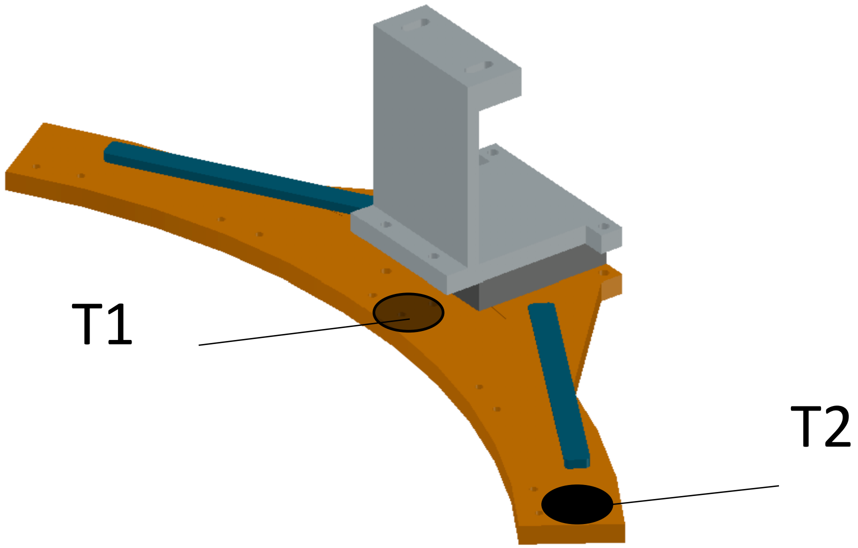
CAEN A1422 Pre-amplifier
Decay time:
27 μs
Sensitivity
400 mV/MeV

NIM power supply biased at 80 V to each detector

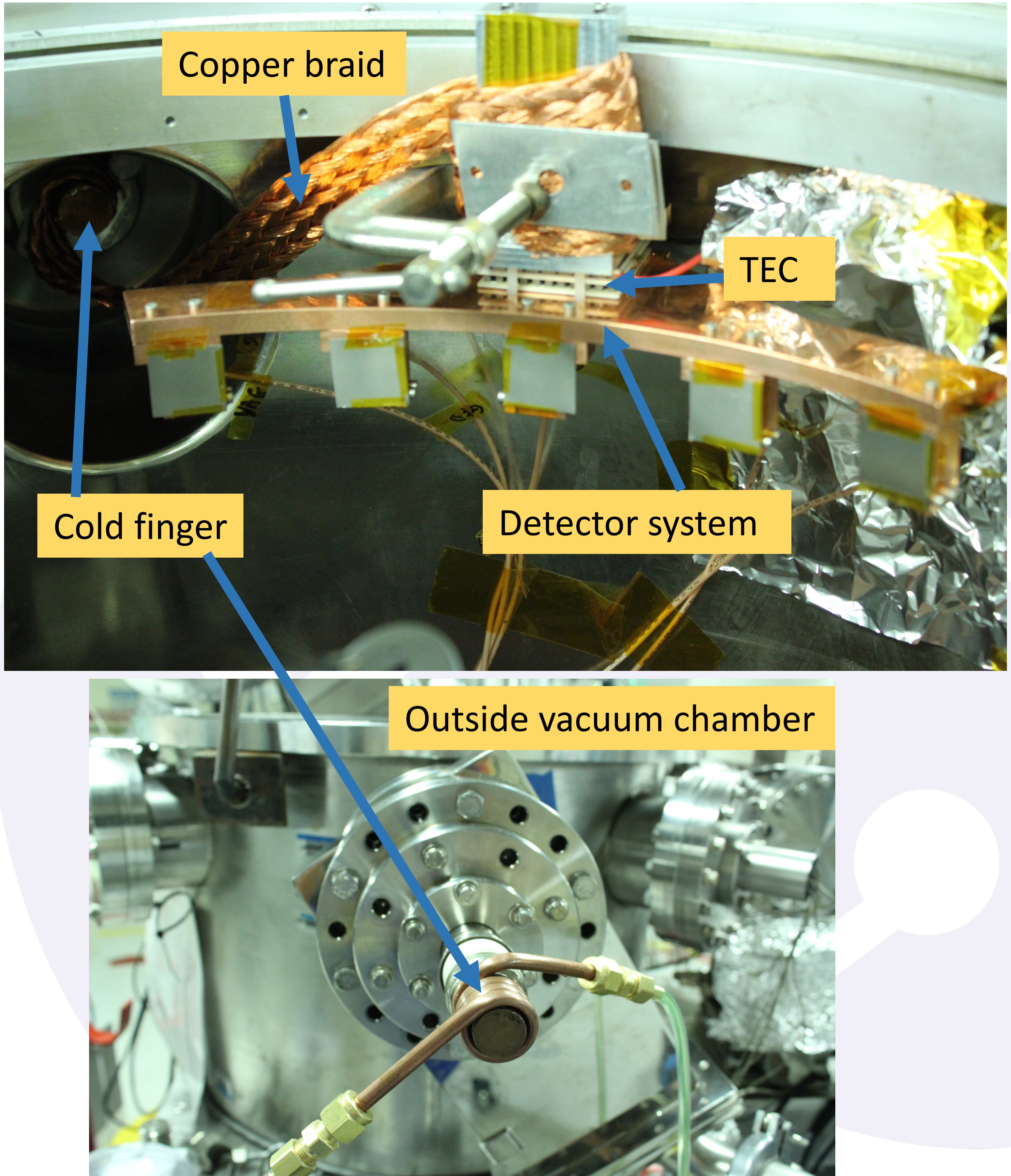


Temperature control

- TEC and two thermistors (T1 and T2)
- Temperature controller TC-XX-PR-59 and software from manufacturer

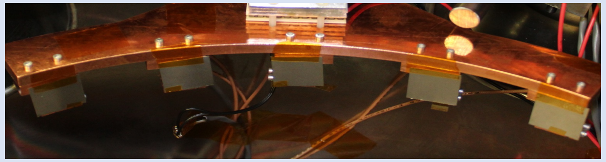


- Not optimal temperature stability



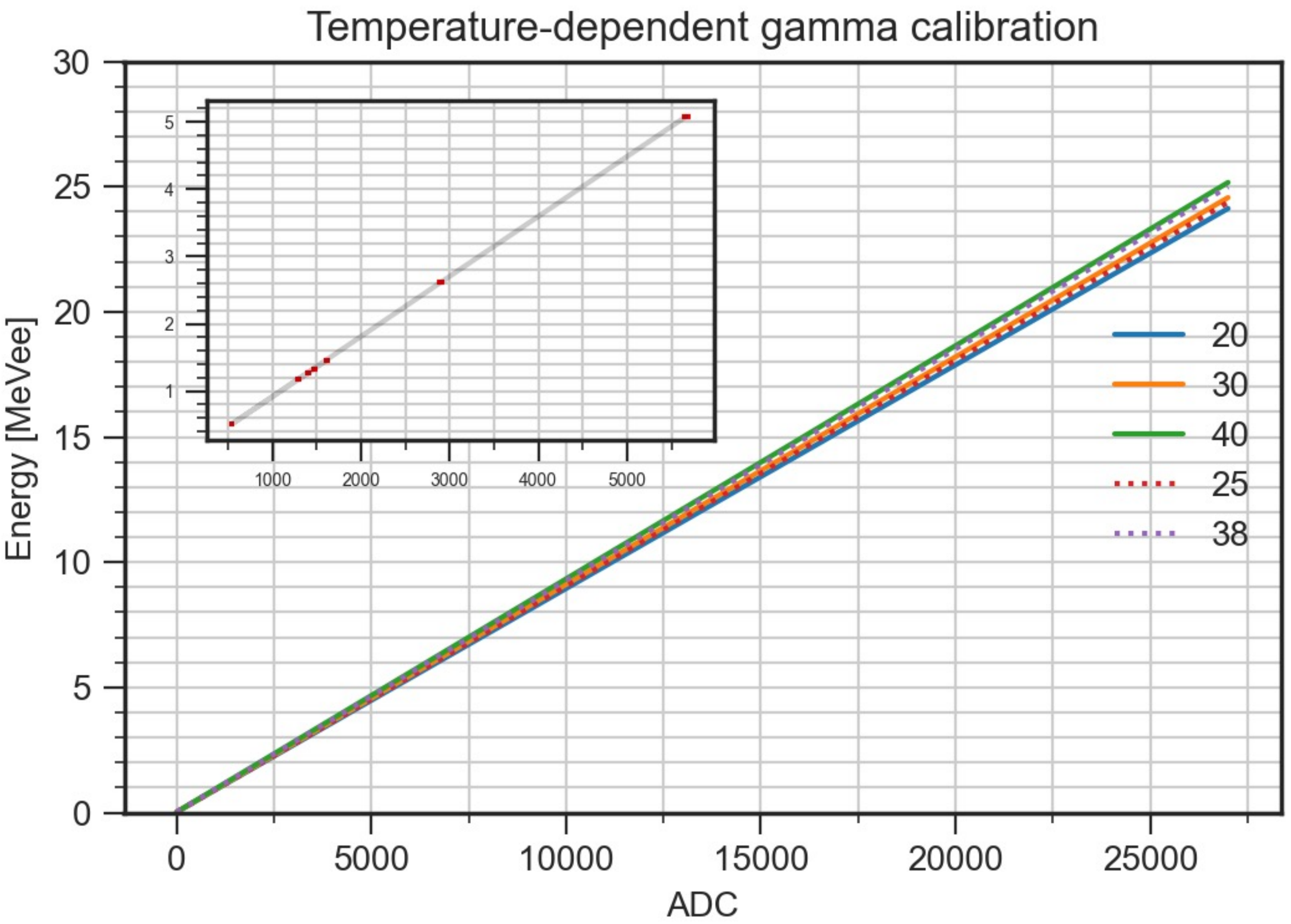
Energy calibration

Tenney temperature chamber



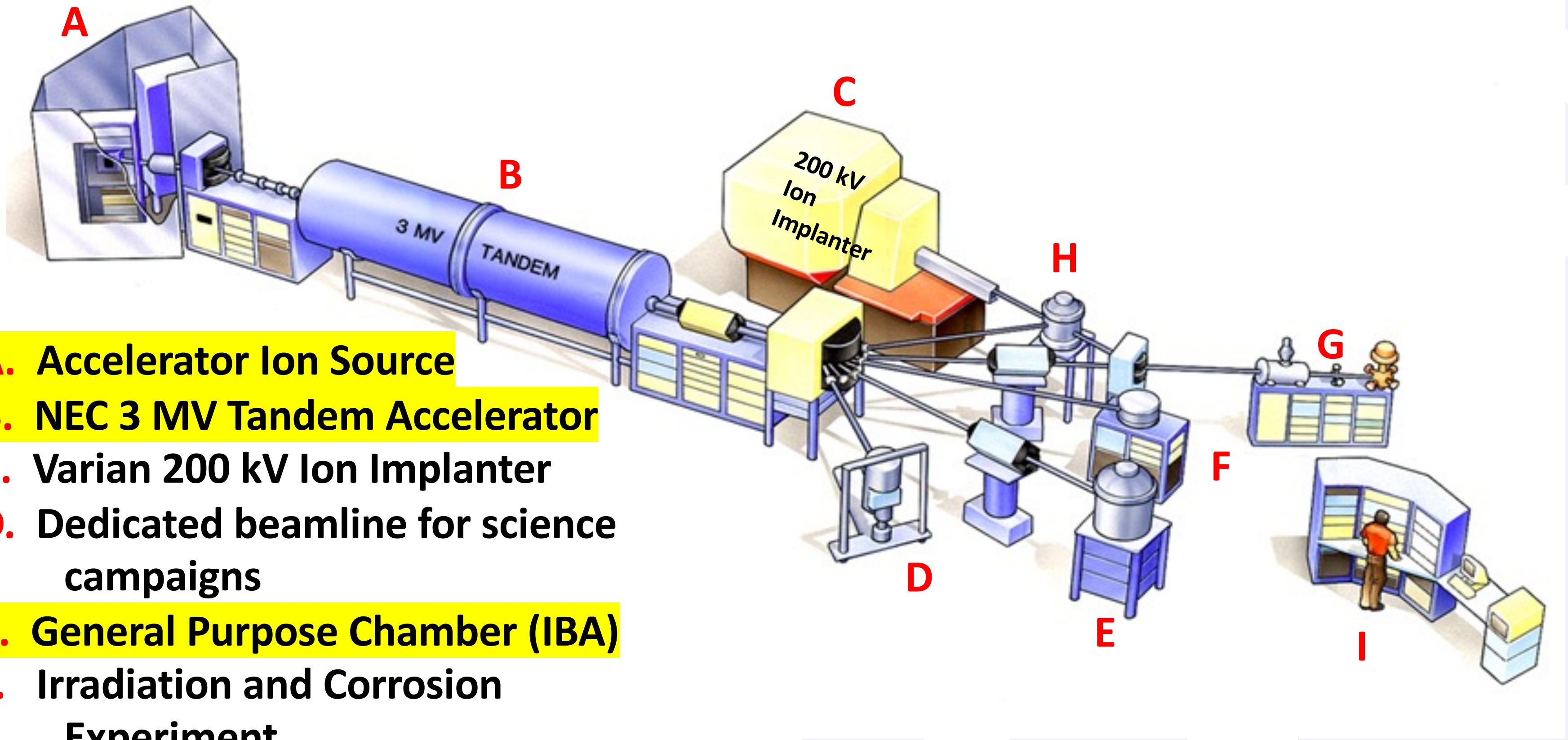
Gamma source

Source Name	Energy (MeV)	Spectral feature measured
^{22}Na	0.511	Annihilation peak
^{60}Co	1.173	Photopeak
^{22}Na	1.275	Photopeak
^{60}Co	1.333	Photopeak
^{40}K	1.460	Photopeak
^{228}Th	2.614	Photopeak
^{16}O	5.078	Double escape peak



Ion Beam Materials Laboratory (IBML)

- 3MV Pelletron tandem accelerator allows the production of energy tunable protons with small energy spread *

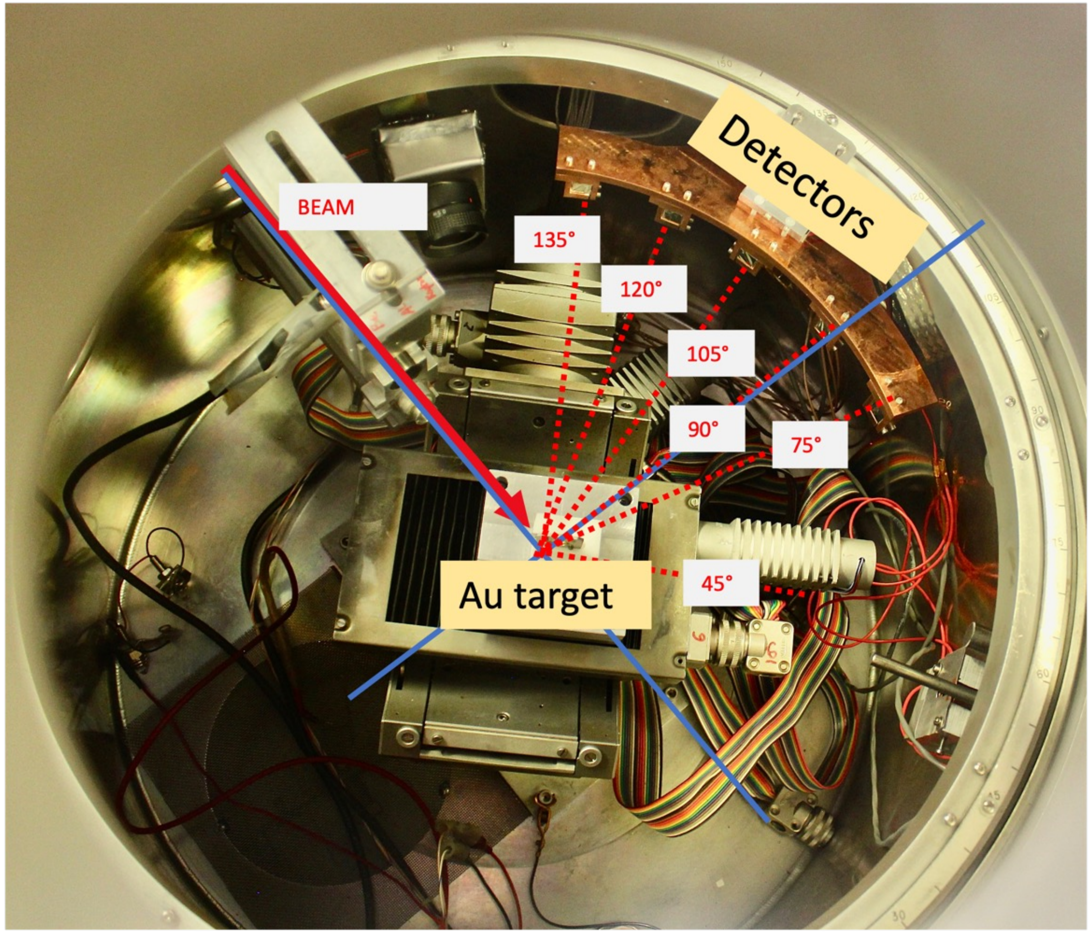


A. Accelerator Ion Source
B. NEC 3 MV Tandem Accelerator
C. Varian 200 kV Ion Implanter
D. Dedicated beamline for science campaigns
E. General Purpose Chamber (IBA)
F. Irradiation and Corrosion Experiment
G. Radiolysis and In-situ Characterization
H. Dual Beam Joint Chamber
I. Tandem Control Console

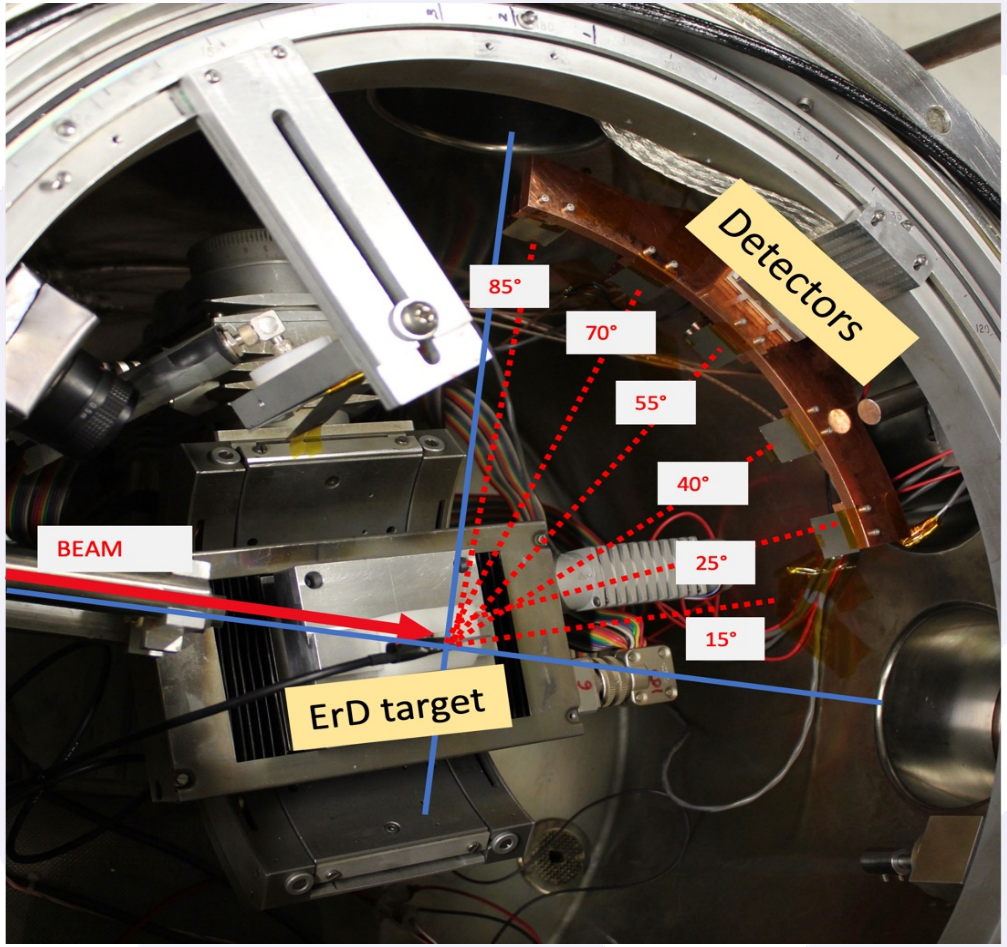
* Wang, Y.Q. "Production of high energy and low flux protons using $^{2}D(^{3}He,p)^{4}He$ for space detector calibrations". 2014.

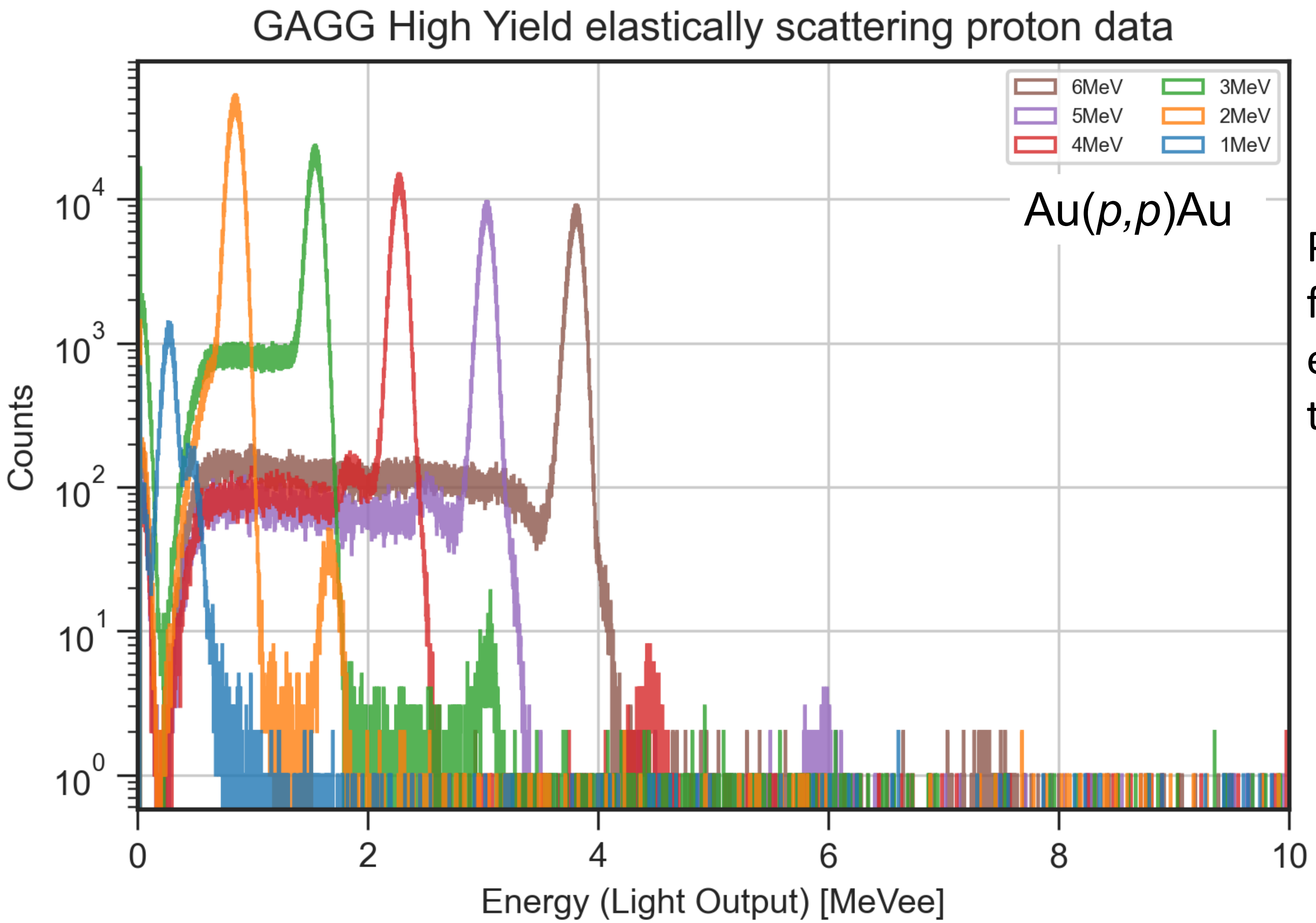
Energy ranges of interest

Elastic scattering off a thin Au target
1.0 MeV < E_p < 6.0 MeV

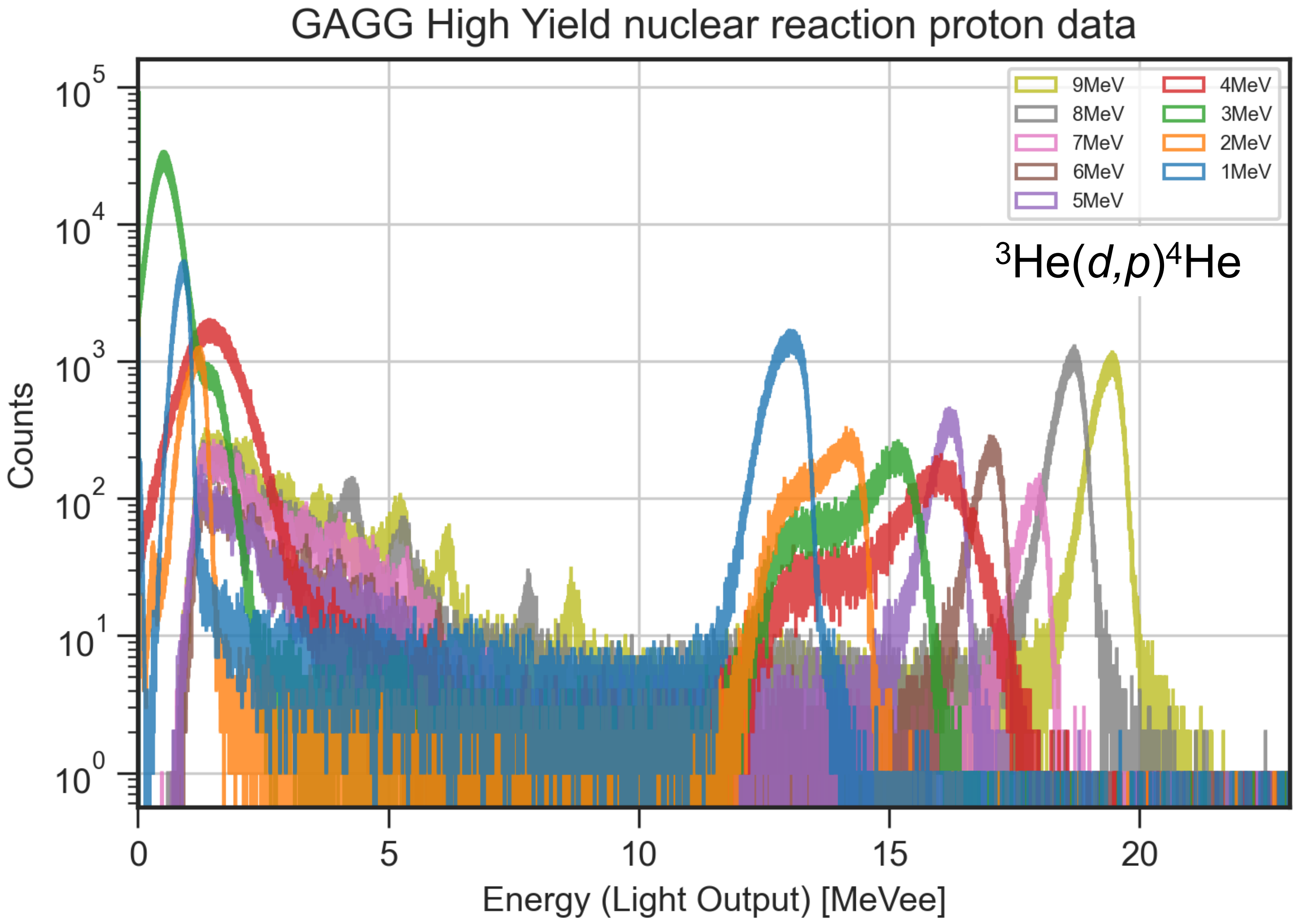


Nuclear reaction off ErD_2 target [$^3He(d,p)^4He$]
15.0 MeV < E_p< 25.0 MeV

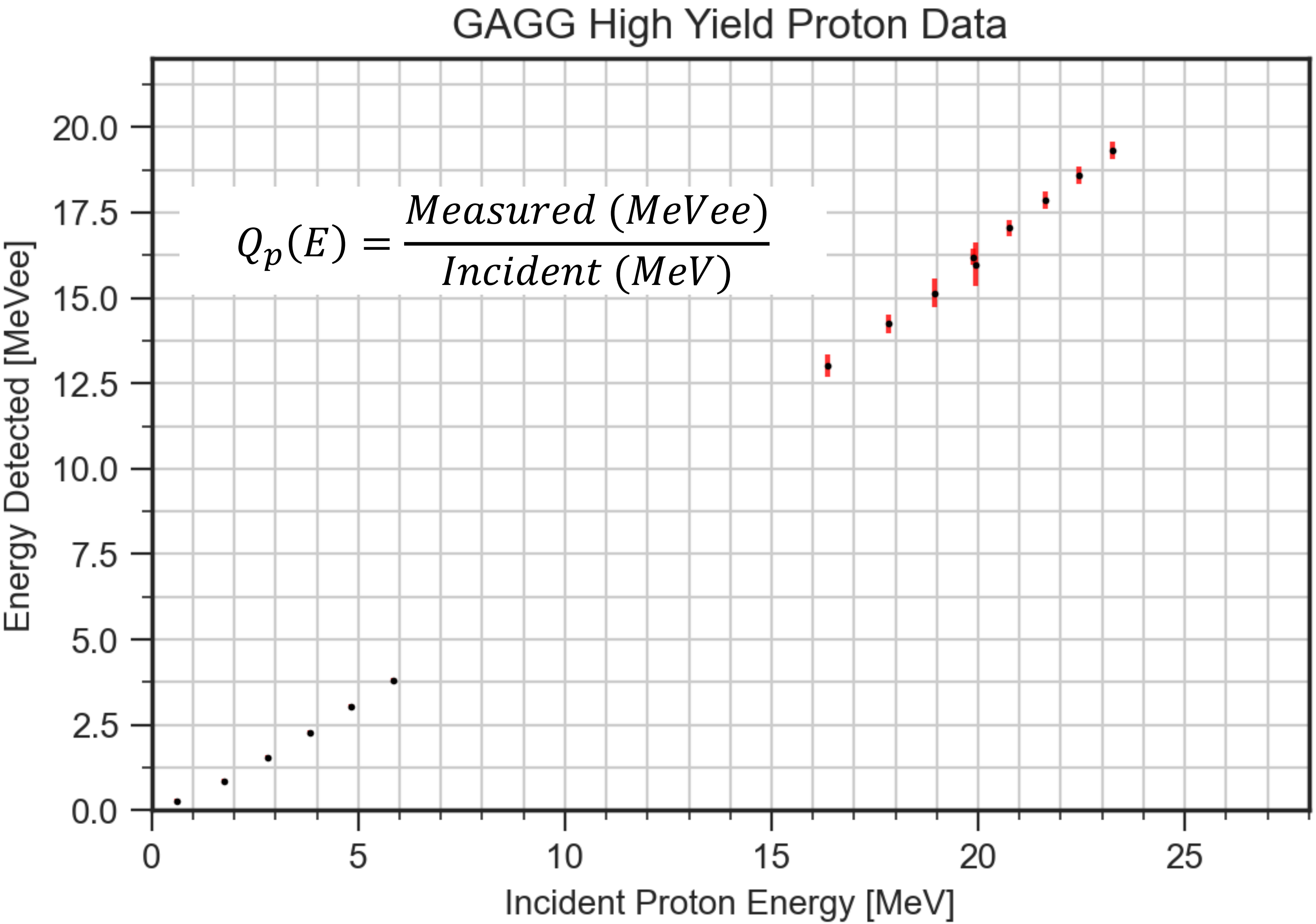




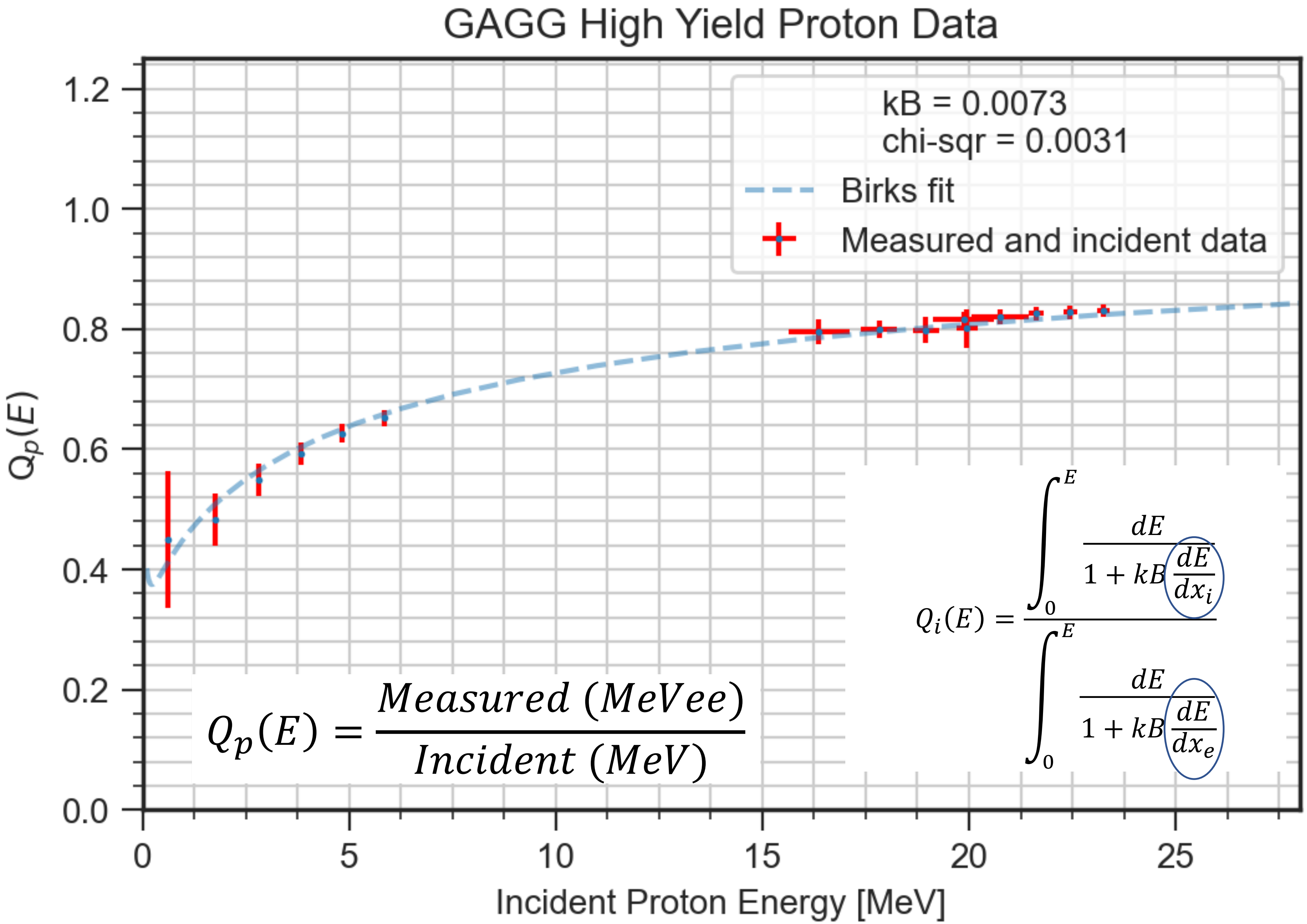
Proton energy spectra from different p^+ beam energies impinging on Au target.



Proton energy spectra from protons produced from different ^3He beam energies impinging on ErD_2 target.



$$Q_p(E) = \frac{Measured\ (MeVee)}{Incident\ (MeV)}$$

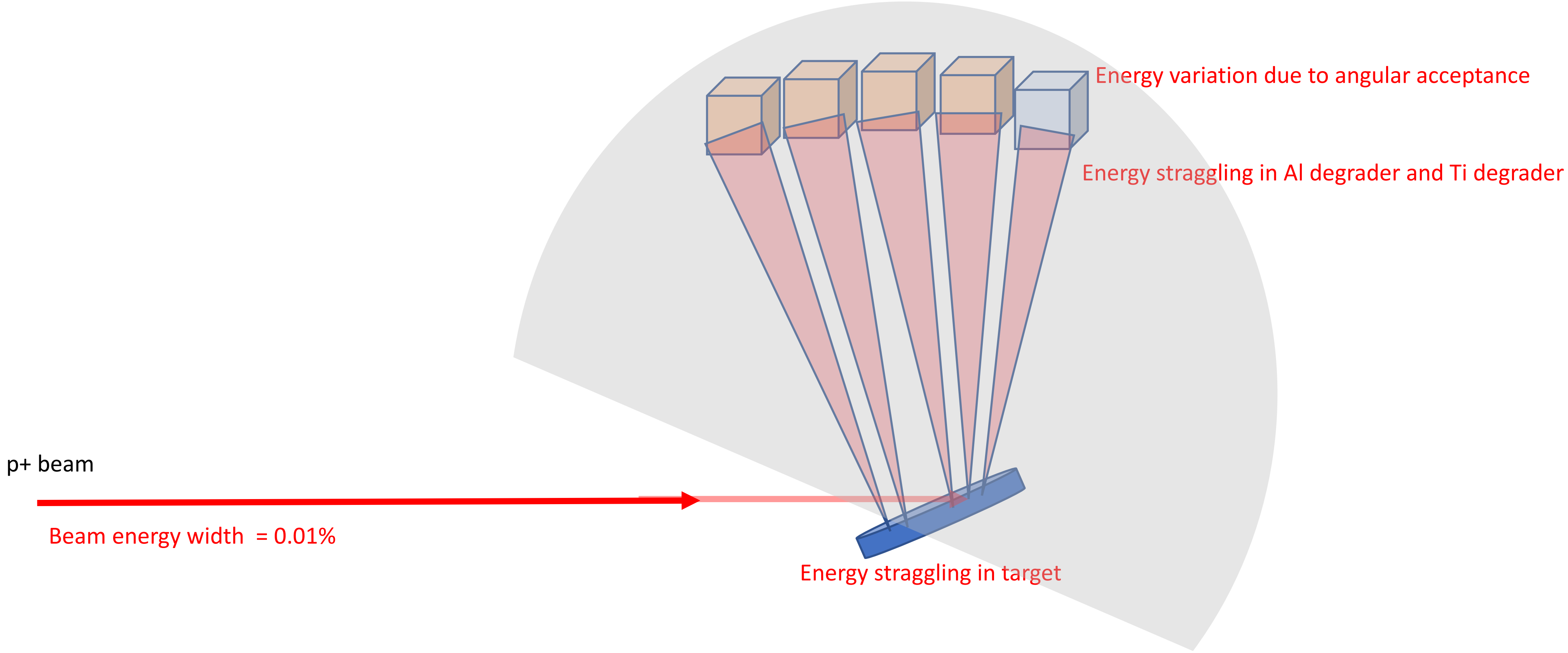


$$Q_p(E) = \frac{Measured\ (MeVee)}{Incident\ (MeV)}$$

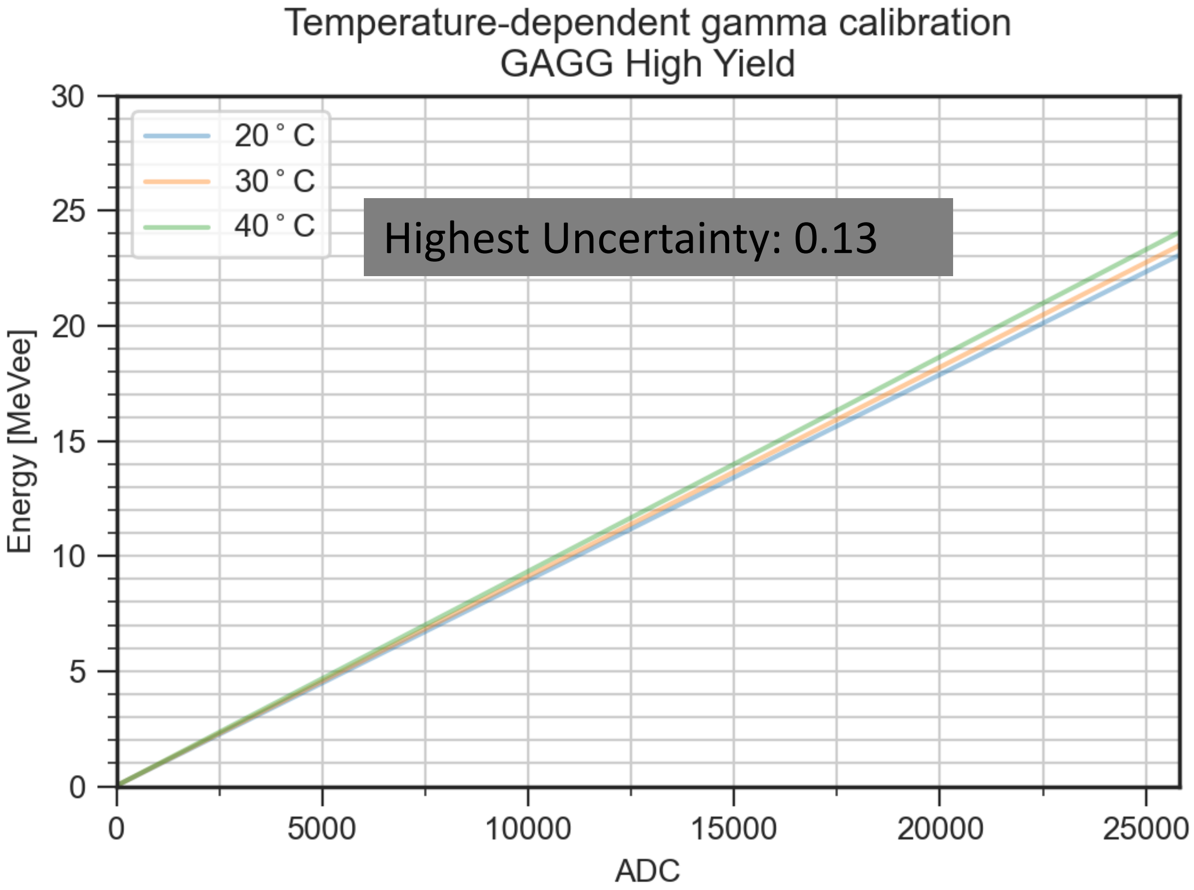
$$Q_i(E) = \frac{\int_0^E \frac{dE}{1 + kB\frac{dE}{dx_i}}}{\int_0^E \frac{dE}{1 + kB\frac{dE}{dx_e}}}$$

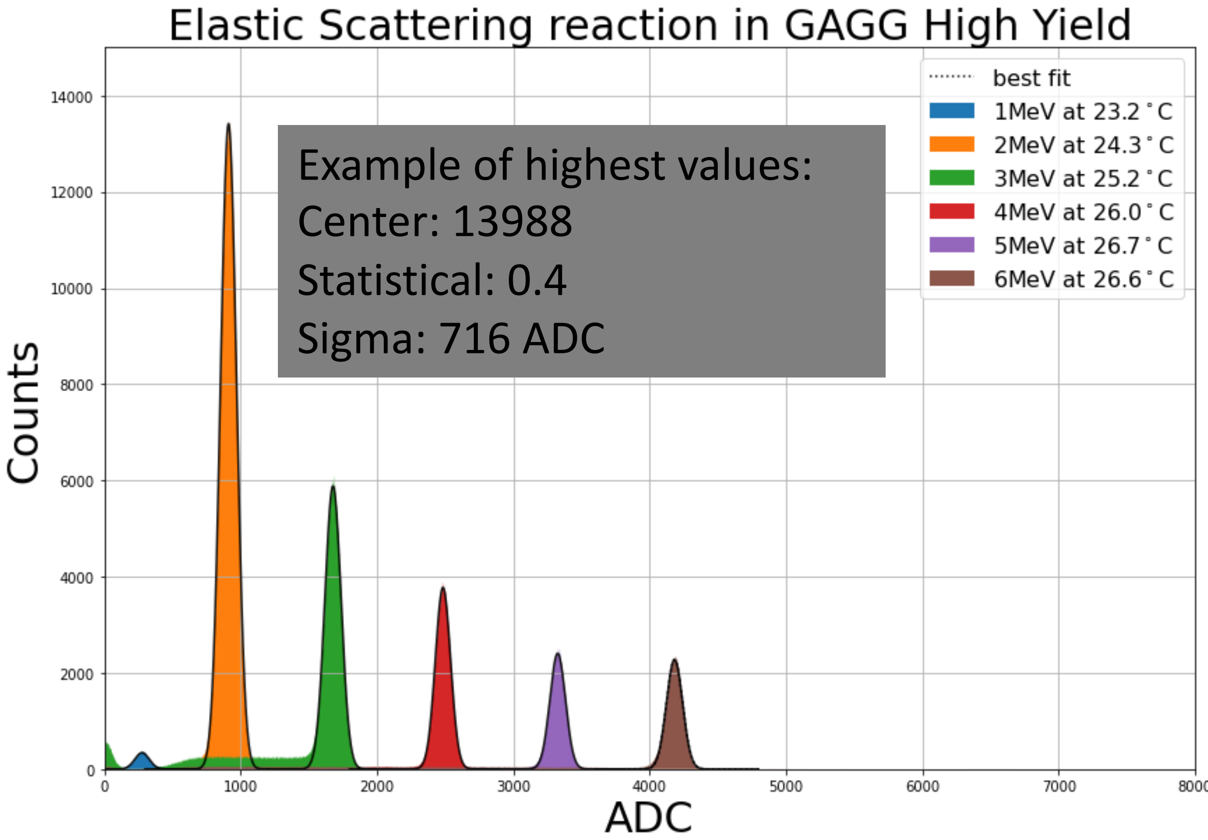
The fitting routine allows the extraction of the kB parameter which can be used for describing quenching for other incident charged particles (e.g., alphas).

Determination of uncertainty for incident energy

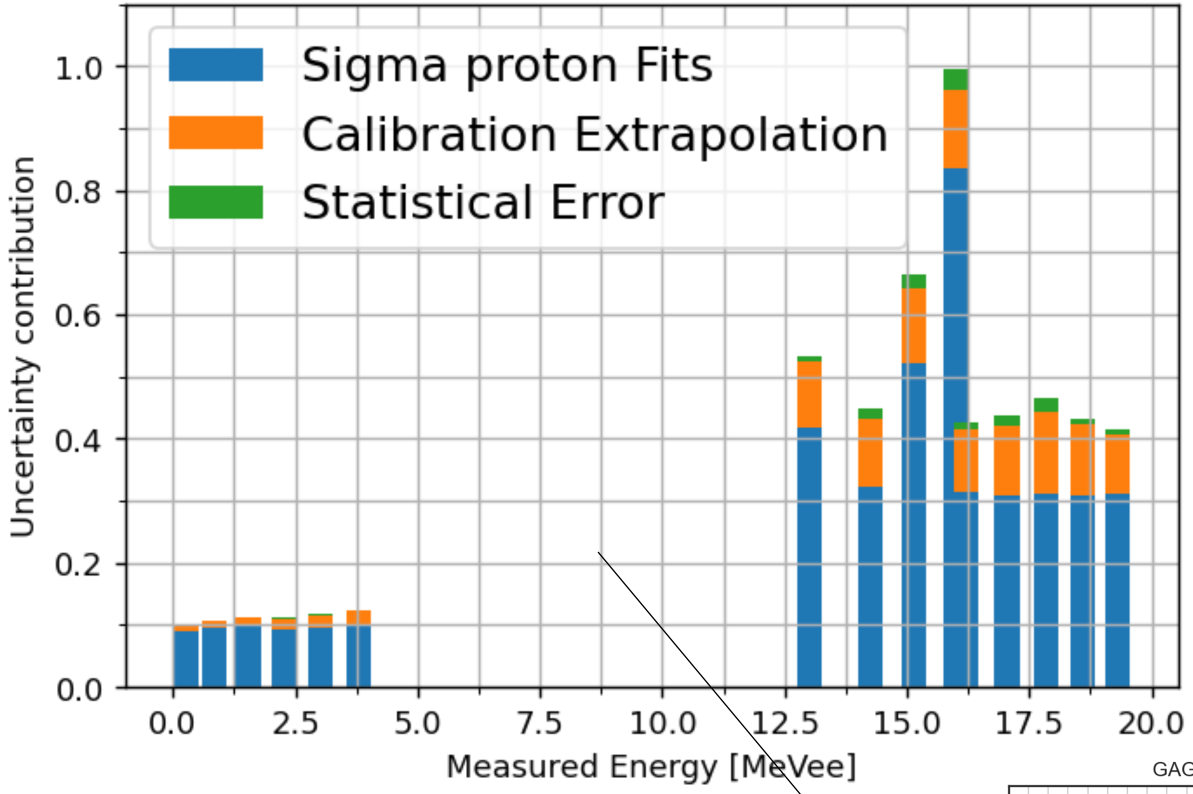


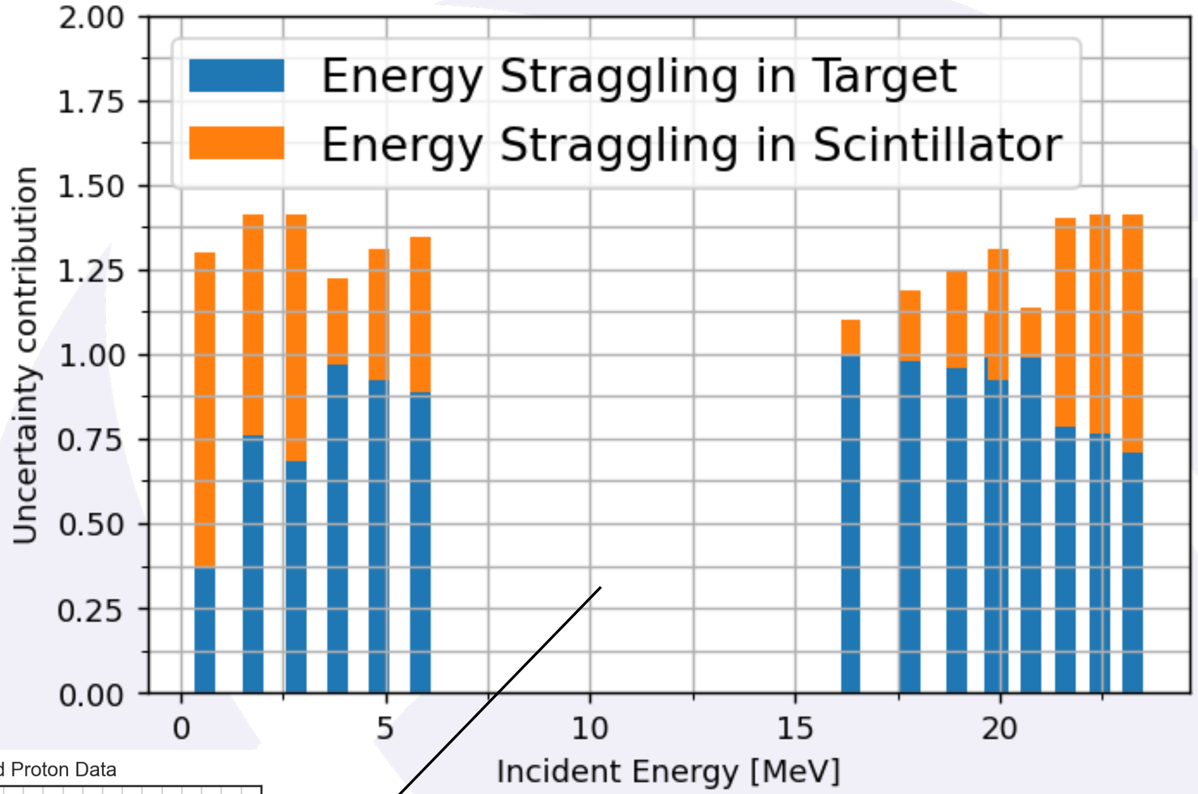
Determination of uncertainty for measured energy

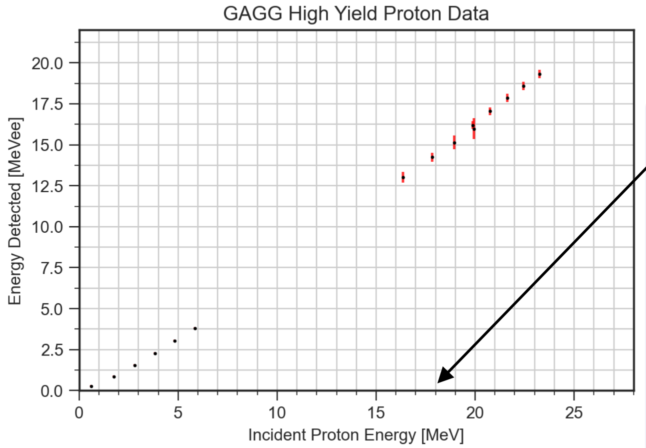




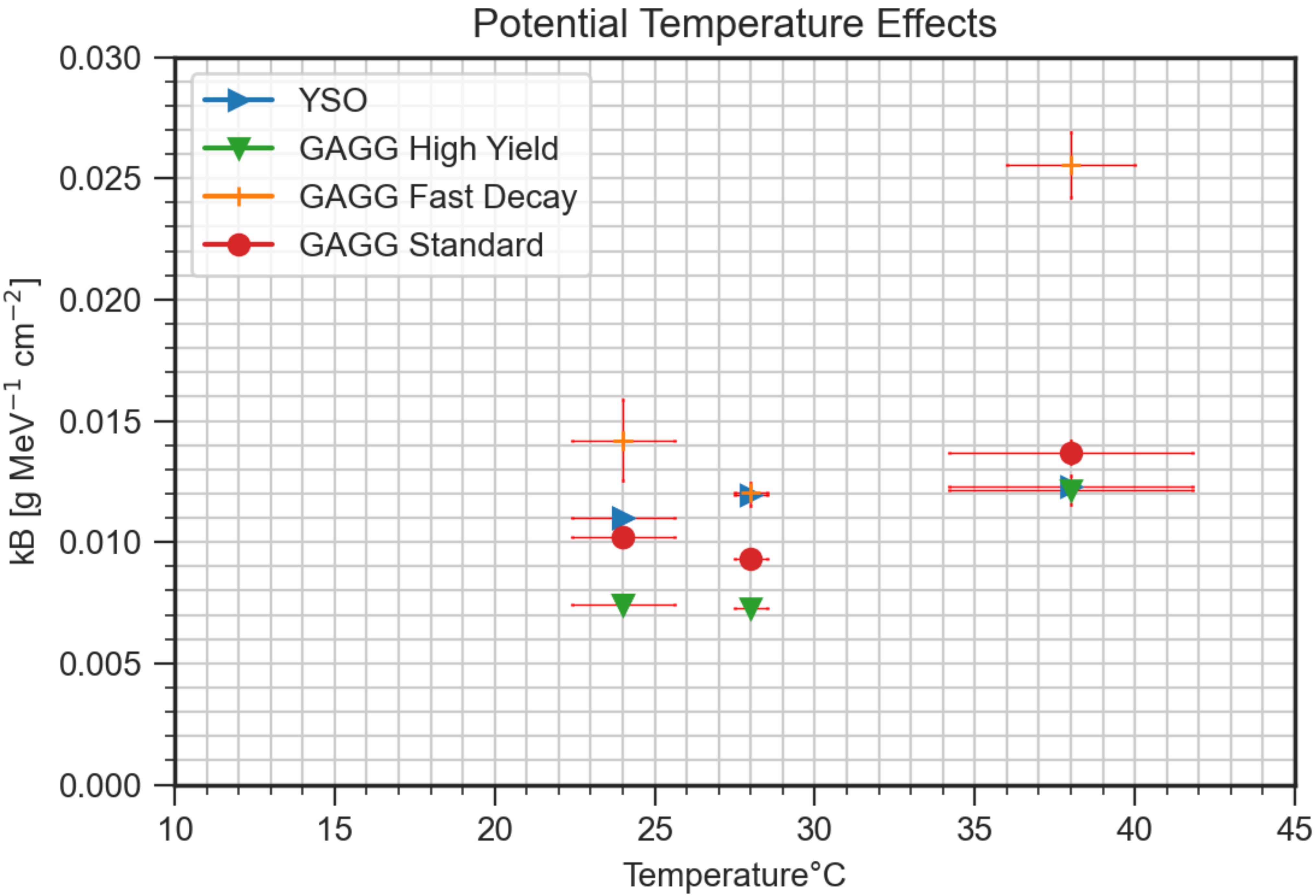
Determination of uncertainty contribution for final propagation



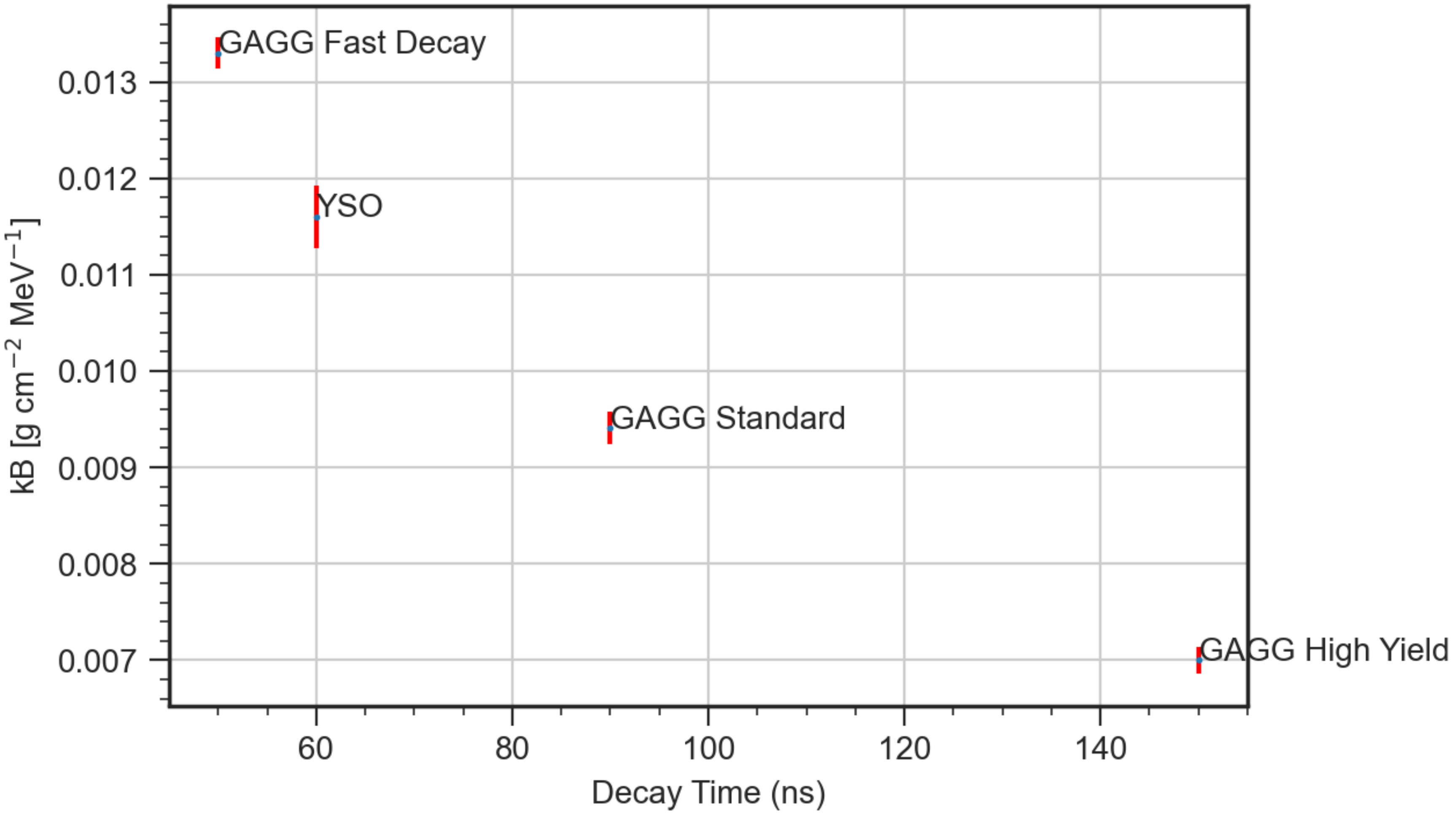




$$\frac{\sigma_Q}{Q} = \left(\left(\frac{\sigma_{M(E)}}{M(E)} \right)^2 + \left(\frac{\sigma_{I(E)}}{I(E)} \right)^2 - 2 \frac{\sigma_{M(E)I(E)}}{M(E)I(E)} \right)^{0.5},$$


Potential Temperature Effects
YSO
GAGG High Yield
GAGG Fast Decay
GAGG Standard
kB [g MeV^{-1} cm^{-2}]
0.030
0.025
0.020
0.015
0.010
0.005
0.000
10
15
20
25
30
35
40
45
Temperature°C

Results



Detector:	GAGG Fast Decay	GAGG Standard	GAGG High Yield	YSO
decayTime:	50	90	150	60
kB_parameter:	0.01205	0.00933	0.00729	0.01197
error:	0.00024	0.000225	0.000156	0.000449

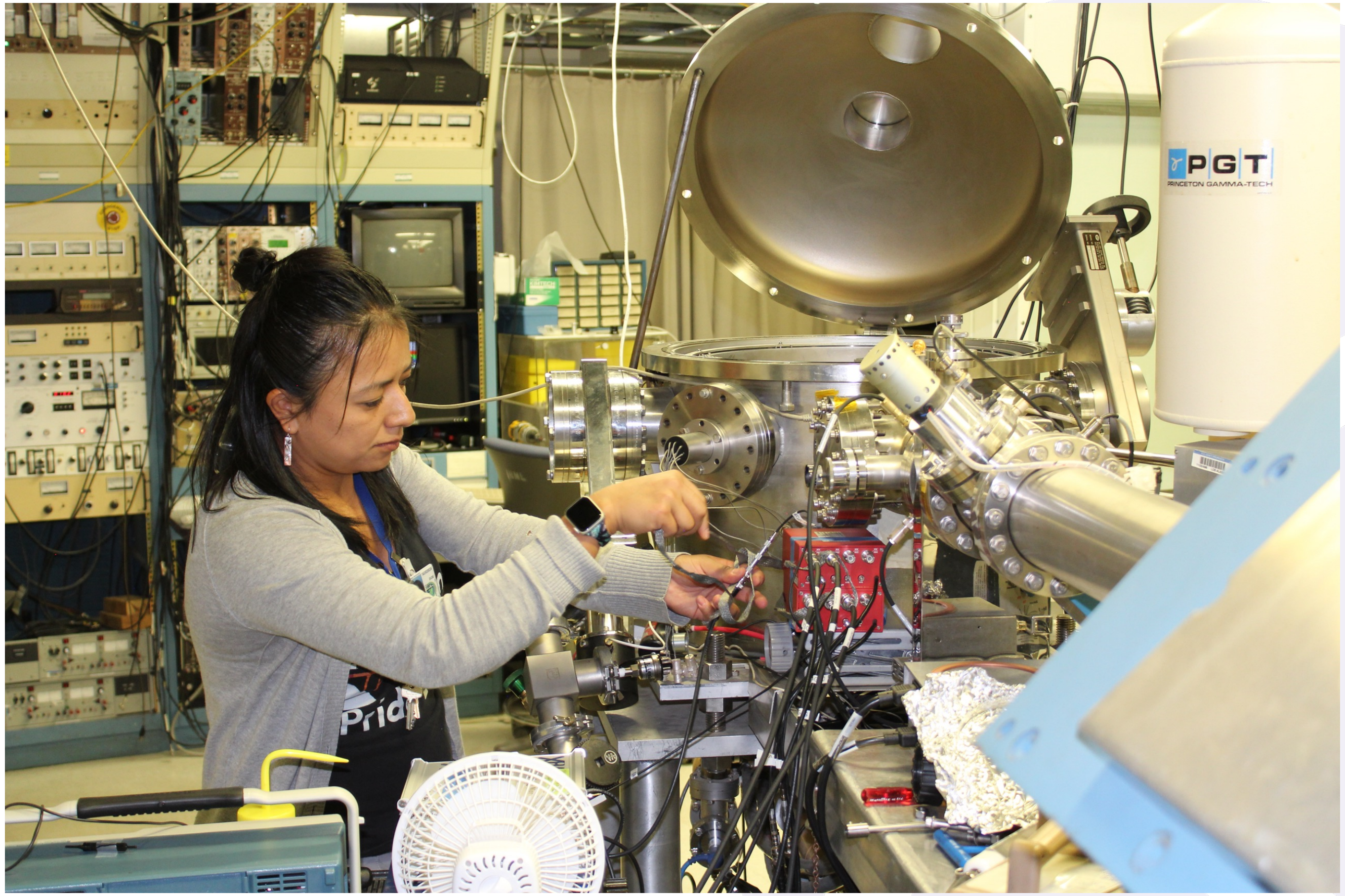
Conclusions

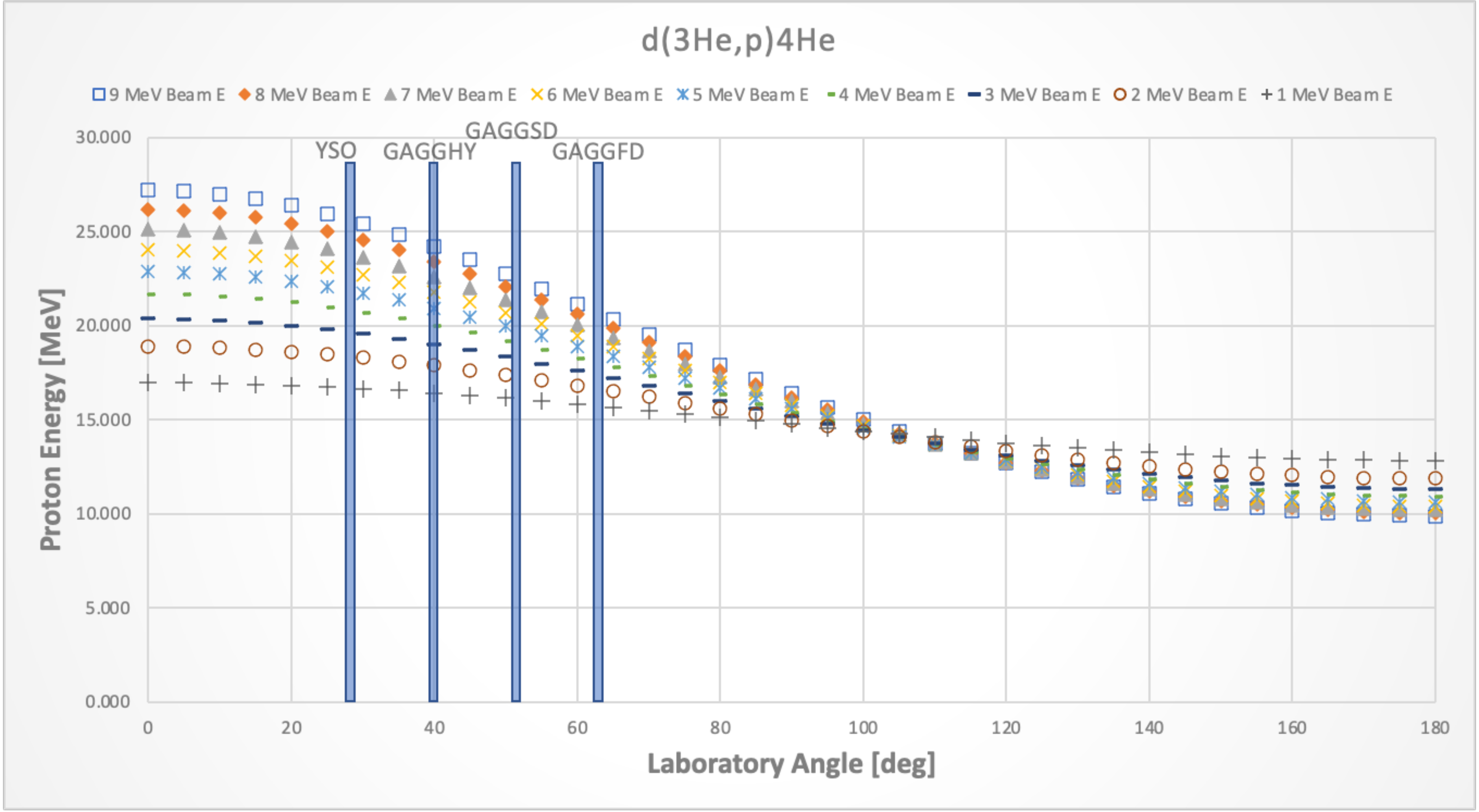
- Rare-earth inorganic scintillators have characteristics that offer optimal detection qualities for space applications as long a quenching is considered.
- Incident proton and electron response was measured in four different rare-earth inorganic scintillators of interest.
- We observed:
  A temperature effect on quenching for GAGG type detectors.
  A dopant concentration/decay time effect on quenching for GAGG detectors.
- Extracting the Birks' factor for future detectors will improve the analysis of data.

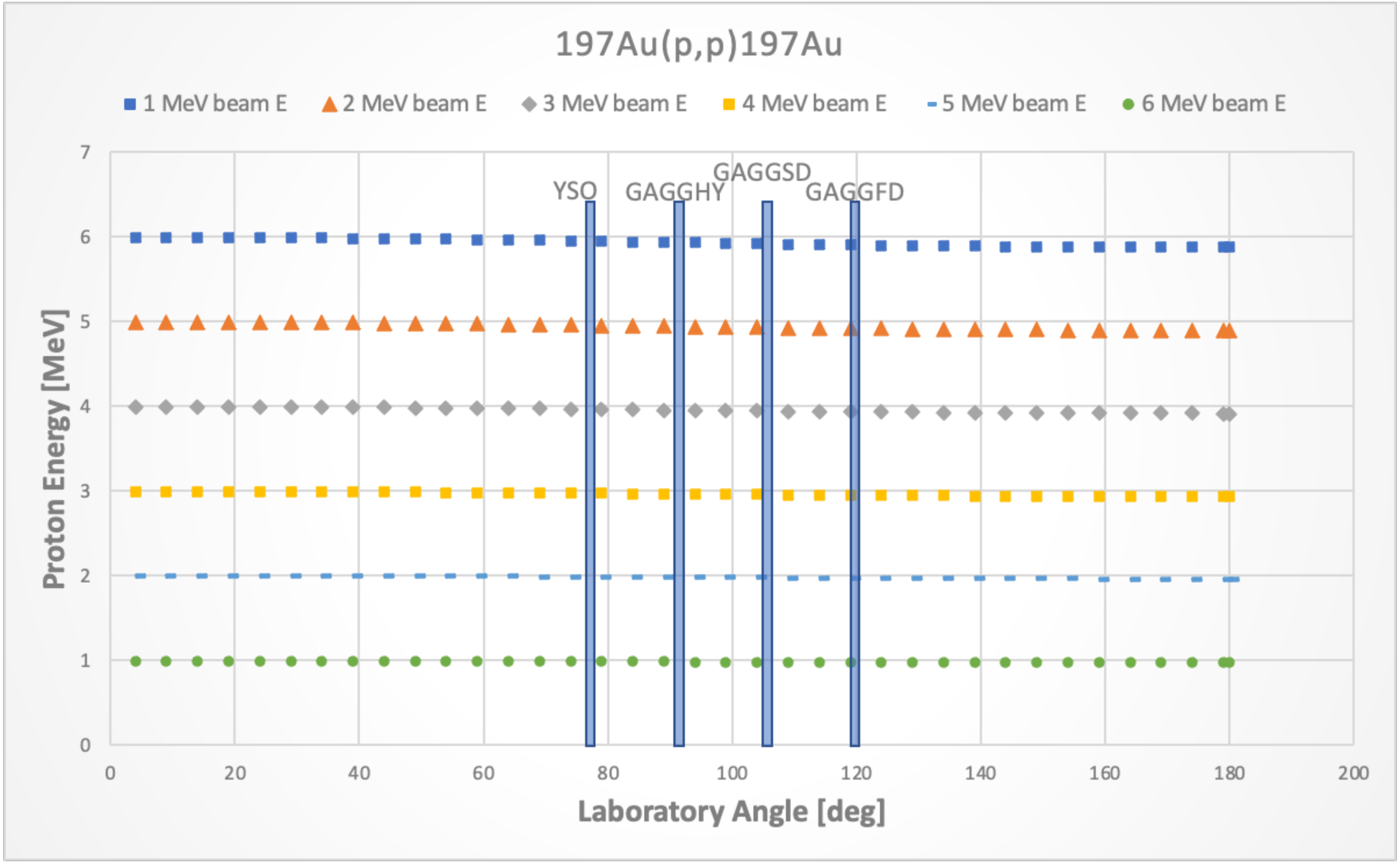
Desired future work

- This measurement could be repeated to compare samples between manufacturers.
- Measurements of how radiation damage changes this parameter over time would be interesting.
- An improved temperature controller system for the chamber can be developed.

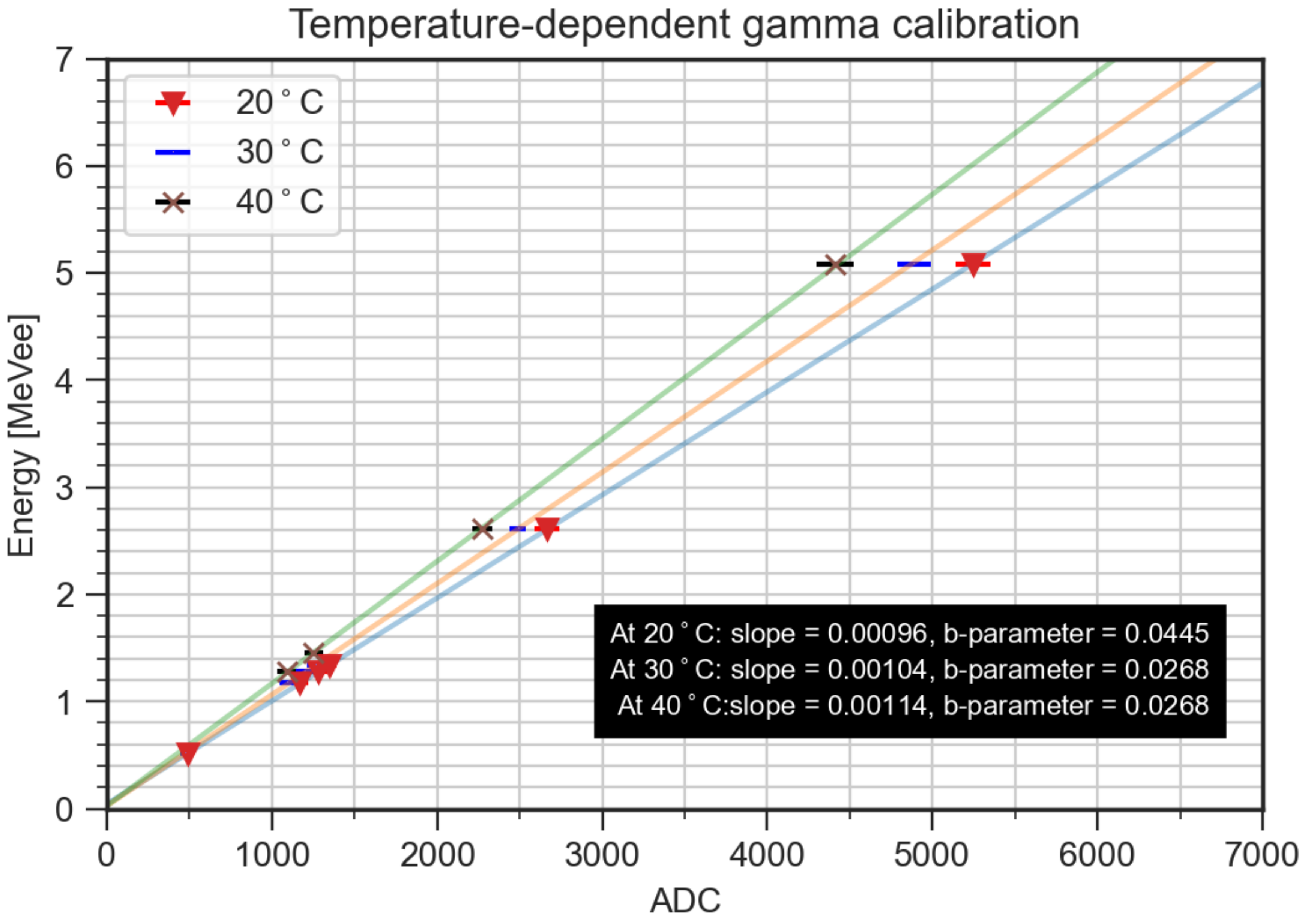
Thanks!



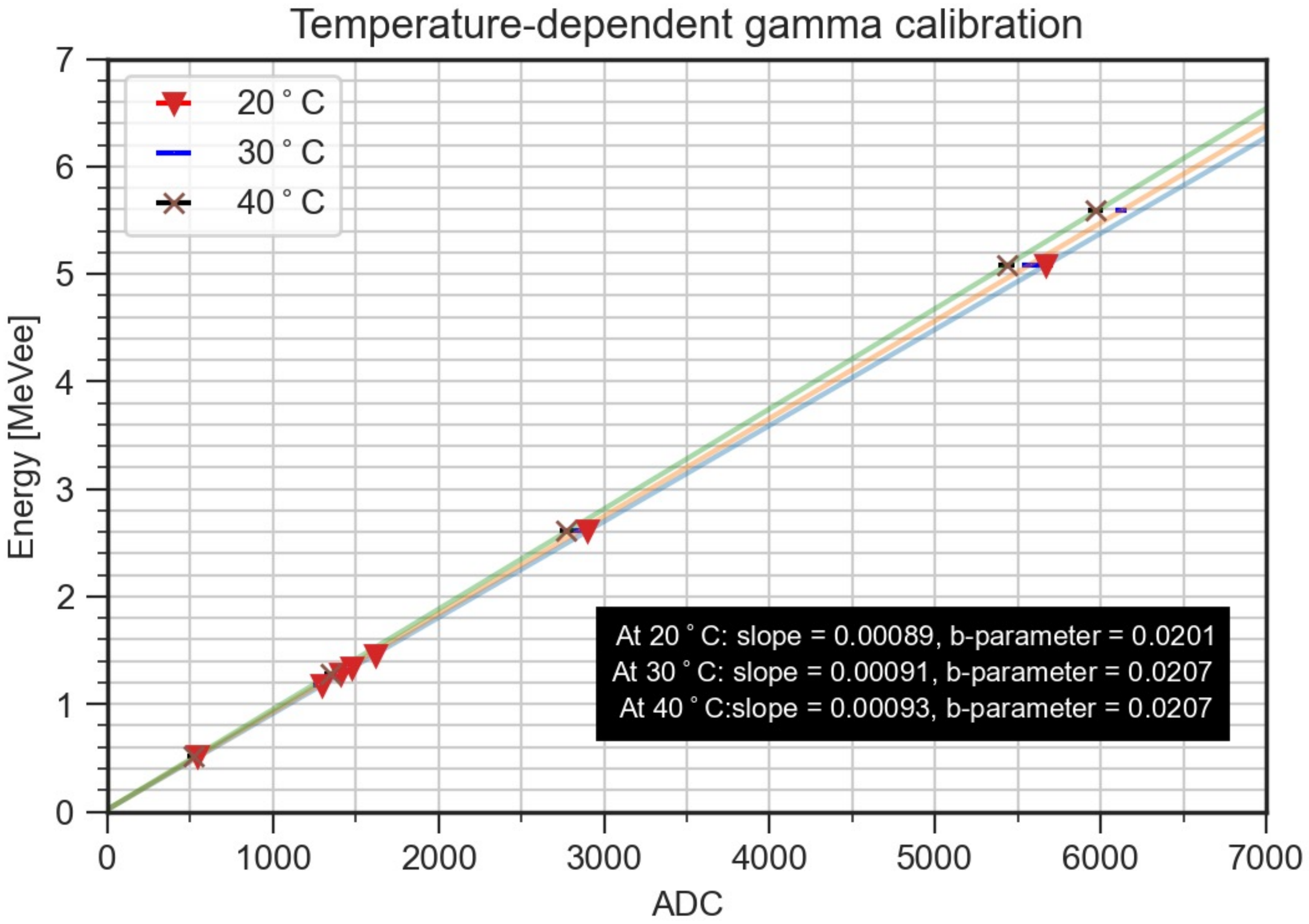

d(3He,p)4He
9 MeV Beam E
8 MeV Beam E
7 MeV Beam E
6 MeV Beam E
5 MeV Beam E
4 MeV Beam E
3 MeV Beam E
2 MeV Beam E
1 MeV Beam E
YSO
GAGGHY
GAGGSD
GAGGFD
Proton Energy [MeV]
30.000
25.000
20.000
15.000
10.000
5.000
0.000
0
20
40
60
80
100
120
140
160
180
Laboratory Angle [deg]



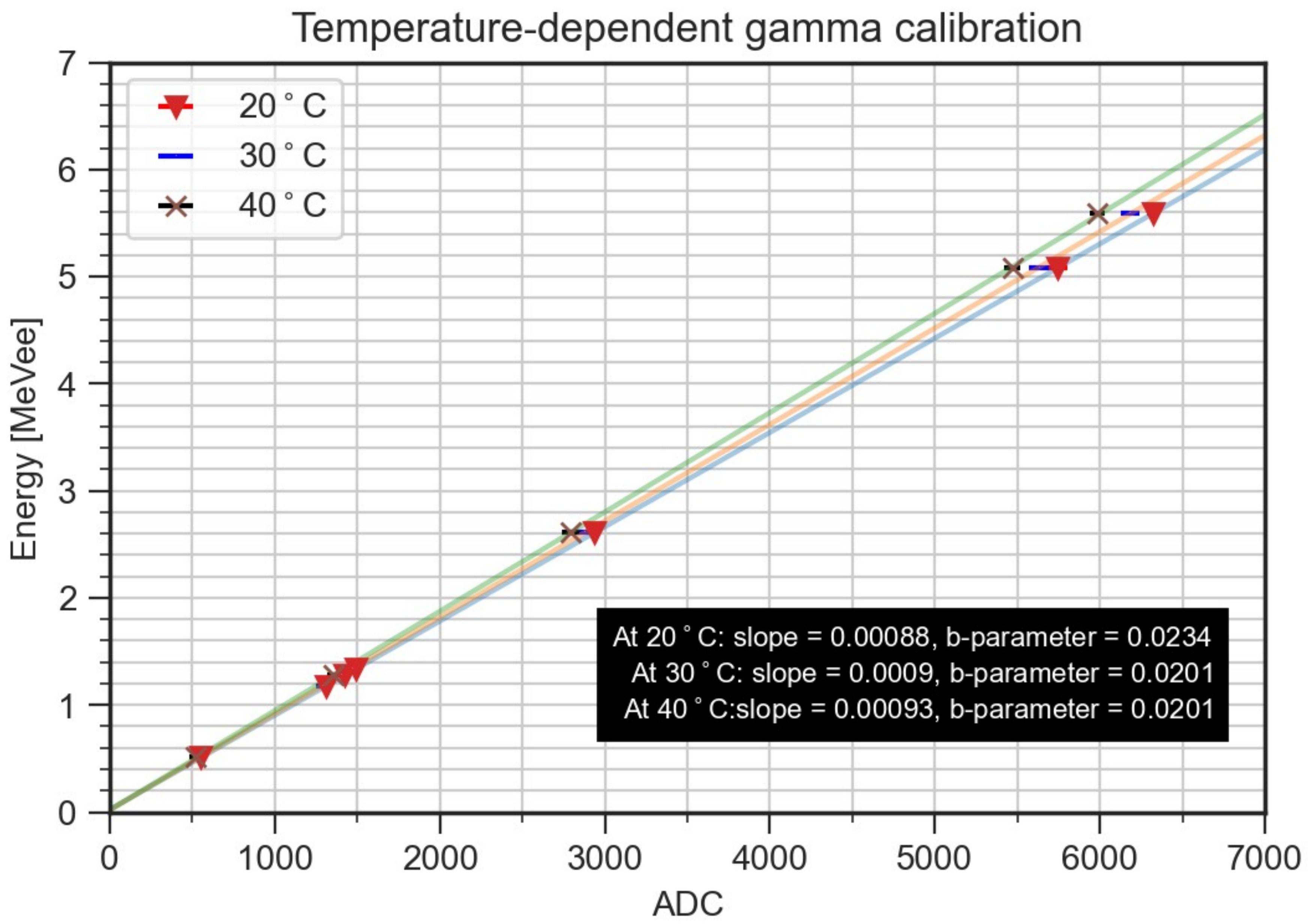
197Au(p,p)197Au
1 MeV beam E
2 MeV beam E
3 MeV beam E
4 MeV beam E
5 MeV beam E
6 MeV beam E
YSO
GAGGHY
GAGGSD
GAGGFD
Proton Energy [MeV]
Laboratory Angle [deg]
0
1
2
3
4
5
6
7
0
20
40
60
80
100
120
140
160
180
200



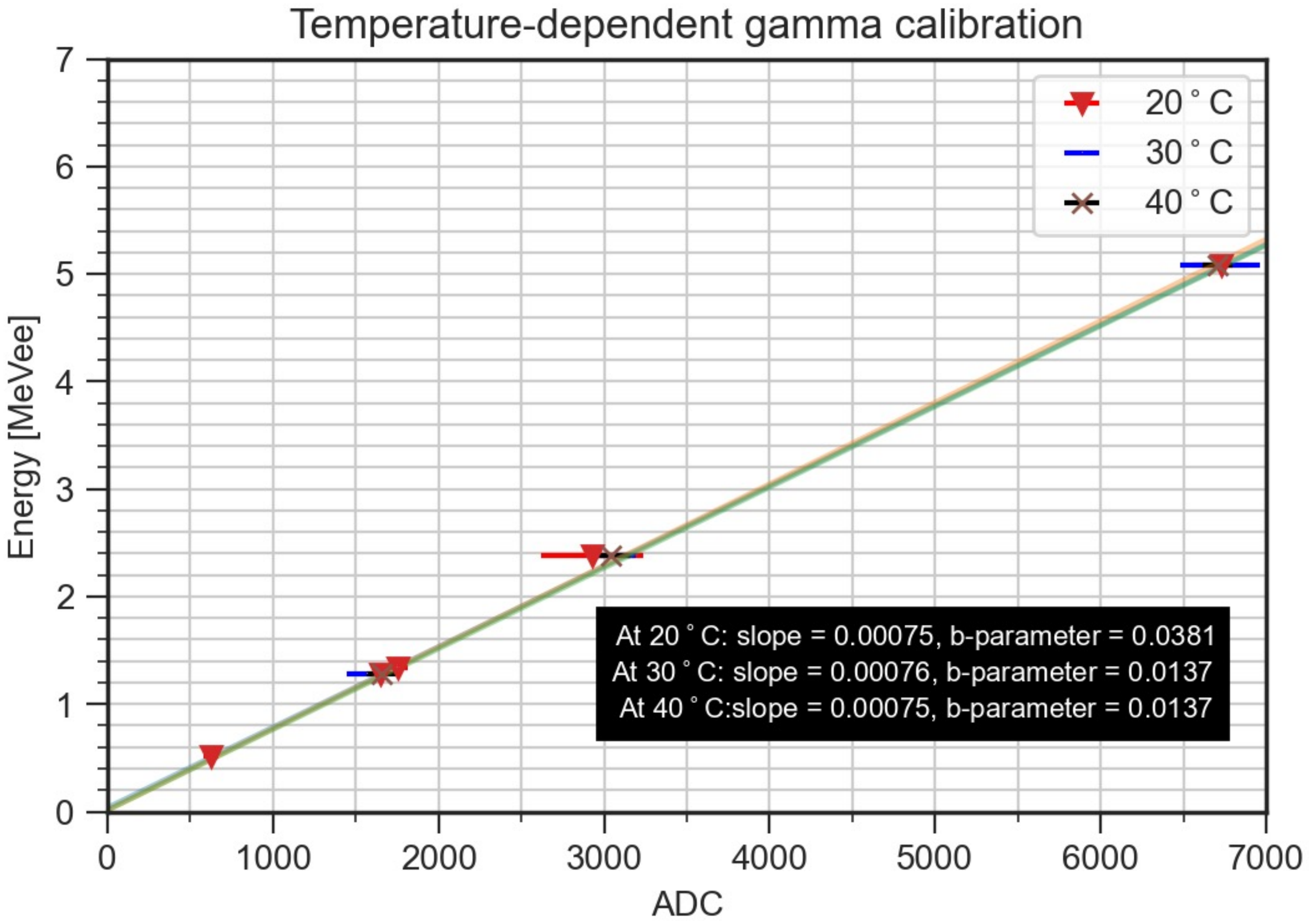
GAGG Fast Decay



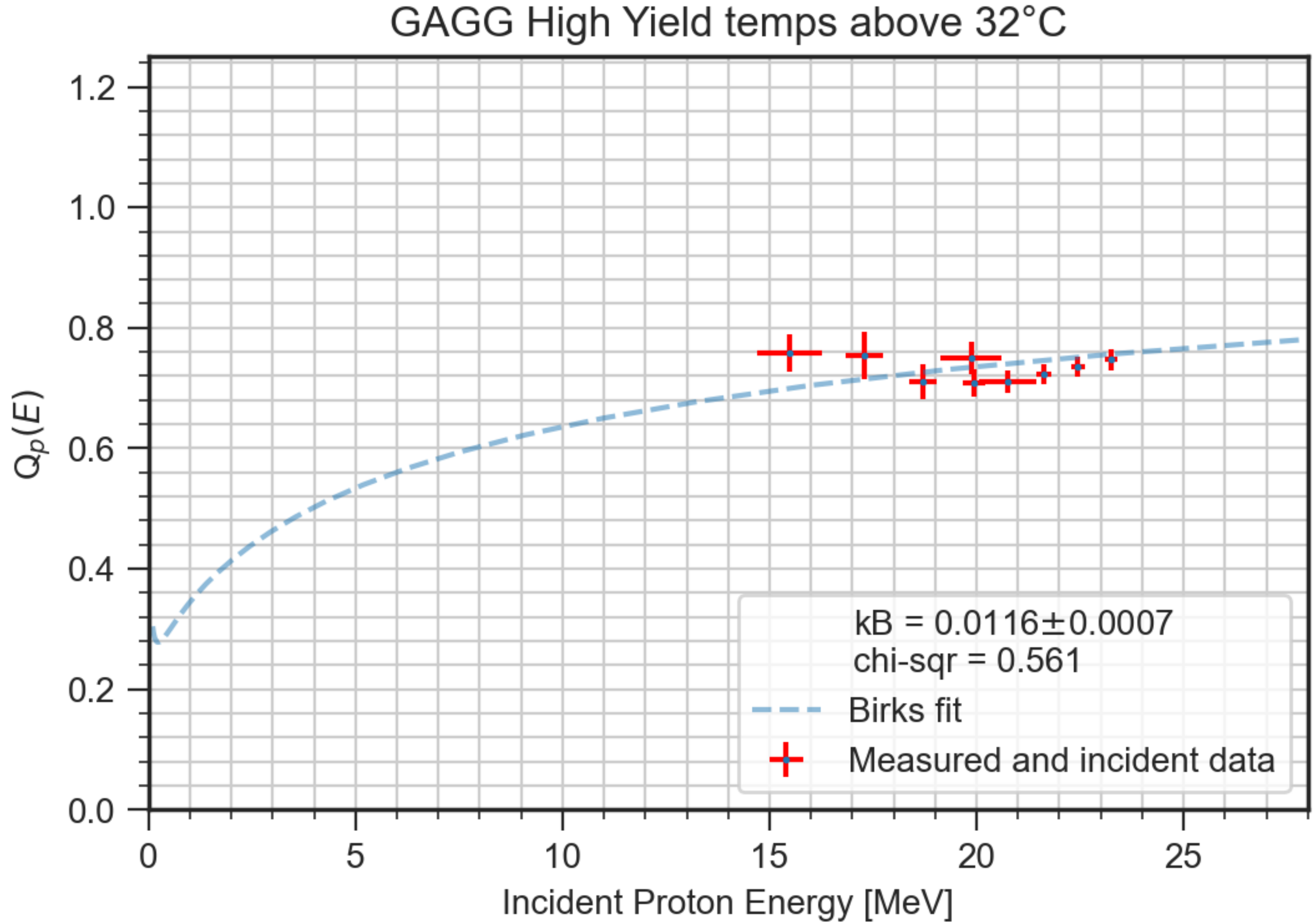
GAGG Fast Decay

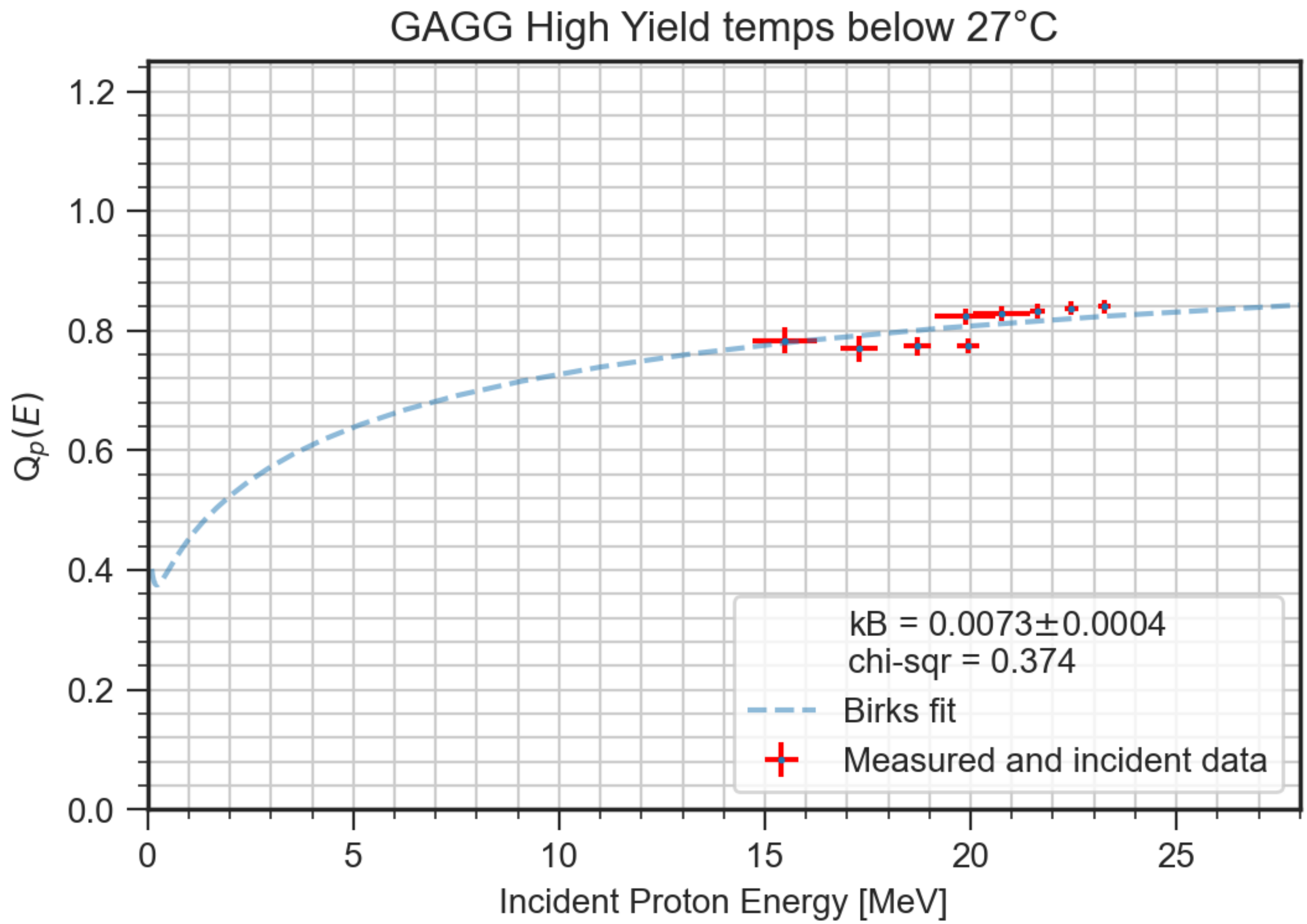


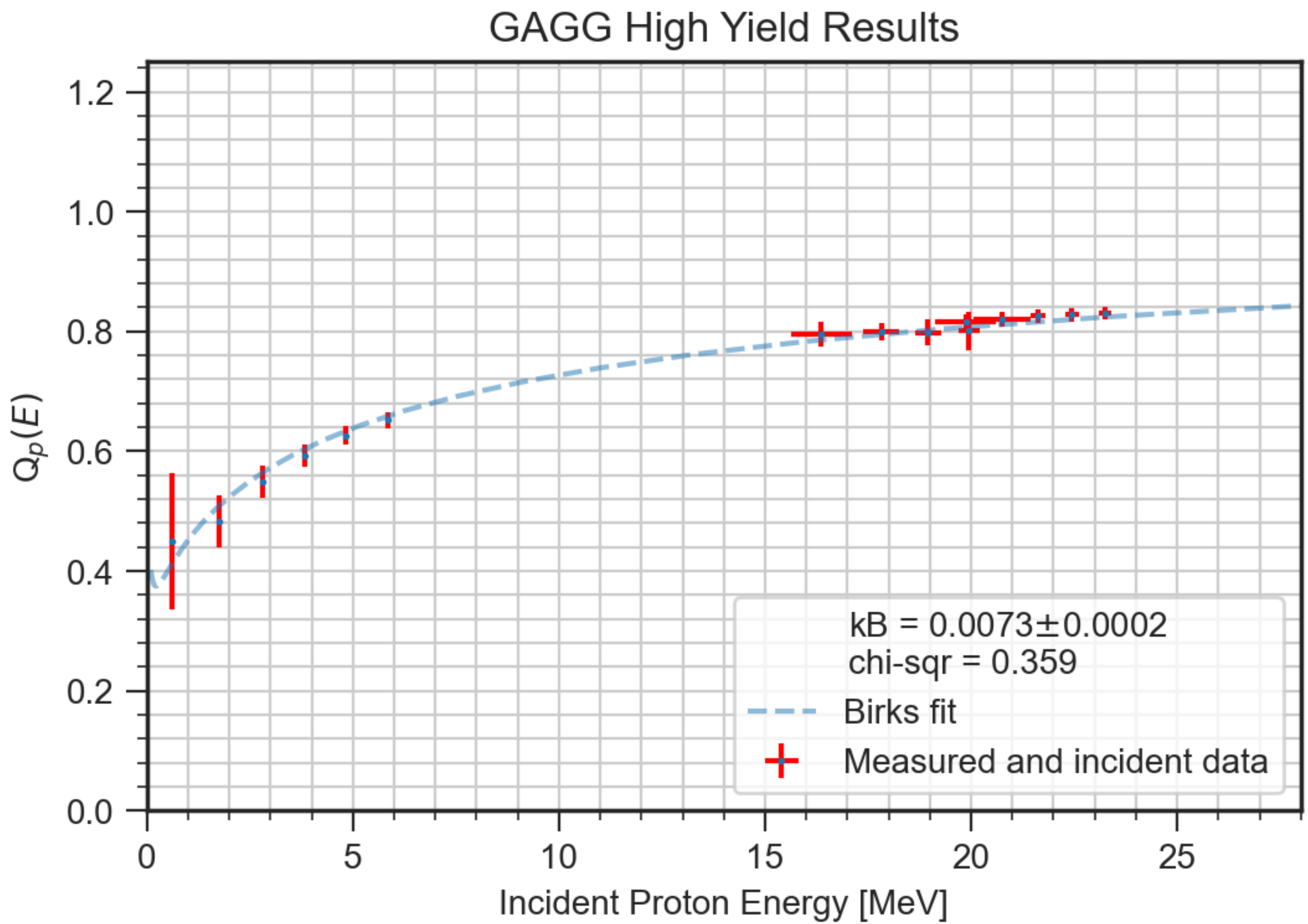
GAGG Standard


Temperature-dependent gamma calibration
Energy [MeVee]
ADC
0
1000
2000
3000
4000
5000
6000
7000
0
1
2
3
4
5
6
7
20 ° C
30 ° C
40 ° C
At 20 ° C: slope = 0.00075, b-parameter = 0.0381
At 30 ° C: slope = 0.00076, b-parameter = 0.0137
At 40 ° C:slope = 0.00075, b-parameter = 0.0137

YSO


GAGG High Yield temps above 32°C
kB = 0.0116±0.0007
chi-sqr = 0.561
Birks fit
Measured and incident data
$Q_p(E)$
Incident Proton Energy [MeV]
0.0
0.2
0.4
0.6
0.8
1.0
1.2
0
5
10
15
20
25


GAGG High Yield temps below 27°C
1.2
1.0
0.8
0.6
0.4
0.2
0.0
$Q_p(E)$
0
5
10
15
20
25
Incident Proton Energy [MeV]
kB = 0.0073±0.0004
chi-sqr = 0.374
Birks fit
Measured and incident data


GAGG High Yield Results
$Q_p(E)$
Incident Proton Energy [MeV]
kB = 0.0073±0.0002
chi-sqr = 0.359
Birks fit
Measured and incident data
0.0
0.2
0.4
0.6
0.8
1.0
1.2
0
5
10
15
20
25