Scintillator Characterization with MANGO

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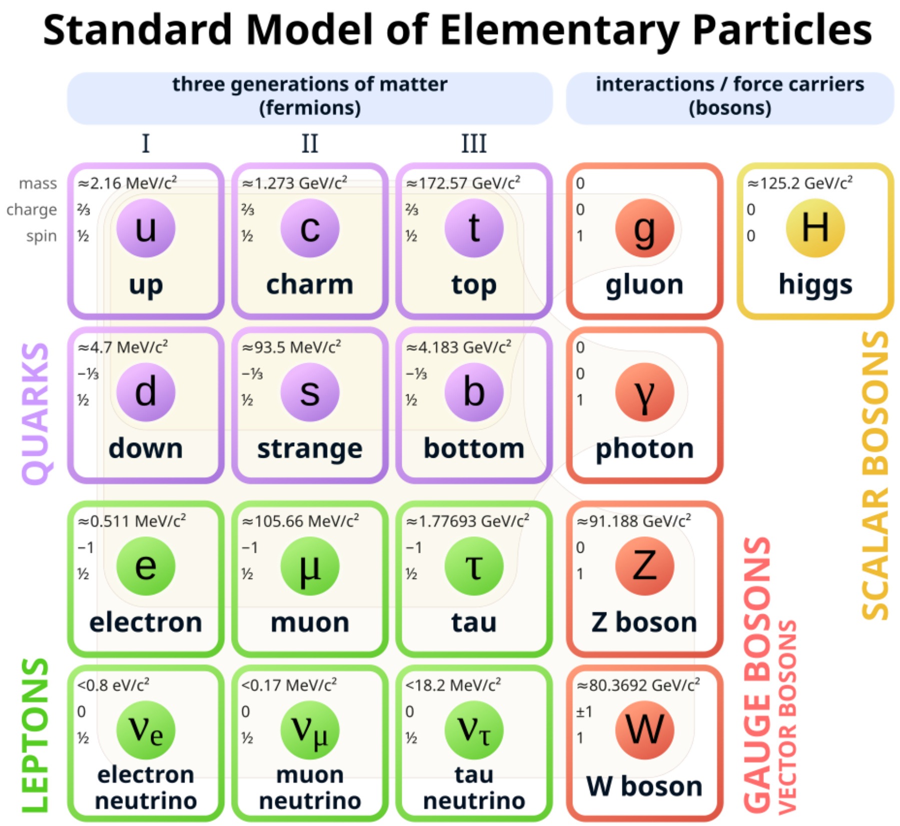
INTRODUCTION - NEUTRINOS

- First predicted by Pauli from continouity of the beta decay electron spectrum
- Discovered in 1965 in the Cowan–Reines neutrino experiment (inverse beta decay)
- Known to be massive from neutrino oscillations



Wikipedia, File:Standard Model of Elementary Particles.svg, Author CUSH

OPEN QUESTIONS IN NEUTRINO PHYSICS

- What is the absolute mass of the neutrino?
- What is the ordering of the neutrino masses?
- Are neutrinos their own anti-particle?
- Are there sterile neutrinos?
- Is there CP violation in the leptonic sector?
- If yes, can it explain the matter-antimatter asymmetry?

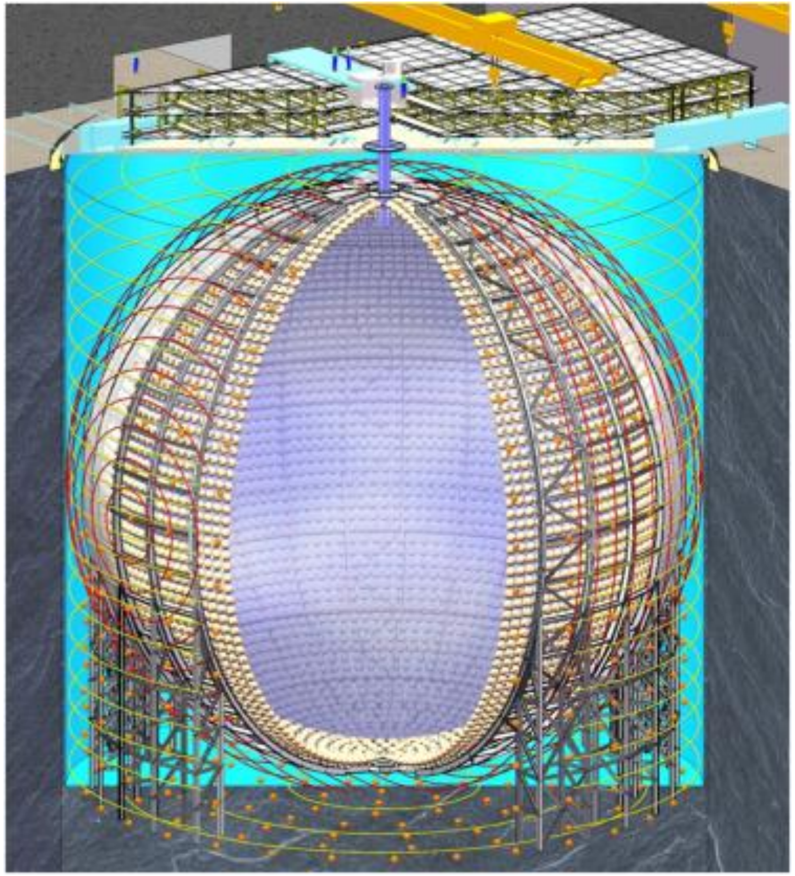
THE JUNO DETECTOR

- Multi purpose neutrino detector
- 20 kt of liquid scintillator
- Inverse beta decay reaction of reactor neutrinos:

$$\bar{\nu}_e + p \rightarrow e^+ + n$$

- Main goal: determine neutrino mass ordering
- Variety of other physics program

→ see in multiple papers on JUNO



Cedric Cerna. (2020). The Jiangmen Underground Neutrino Observatory (JUNO). Nuclear Instruments and Methods in Physics Research Section A: Accelerators, Spectrometers, Detectors and Associated Equipment, Volume 958

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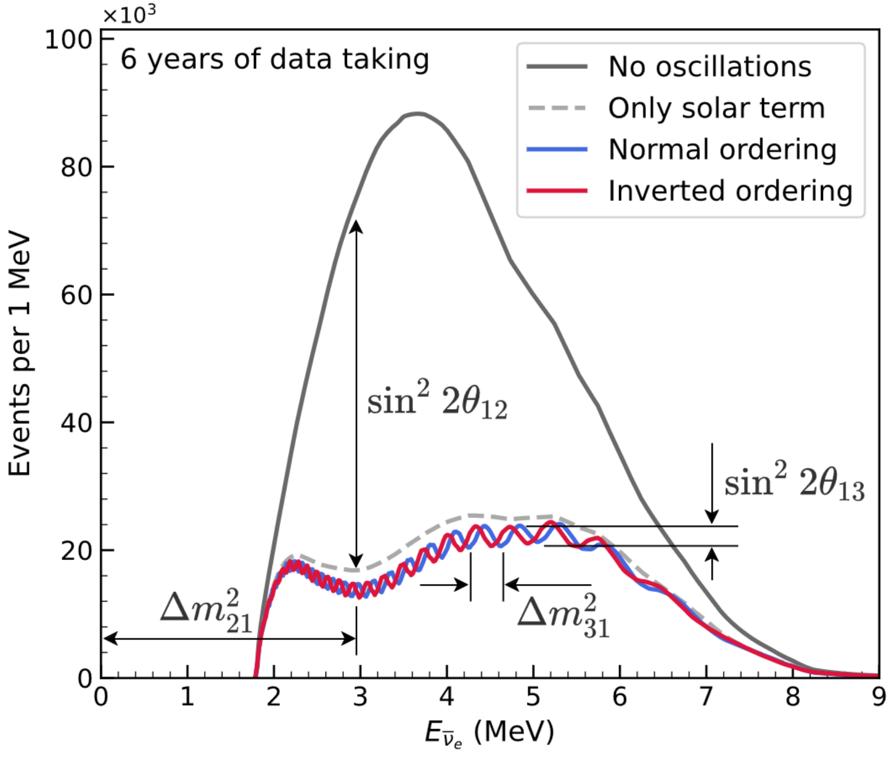
NEUTRINO MASS ORDERING WITH JUNO

Survival probability of electron antineutrinos:

$$P(\bar{\nu}_e \rightarrow \bar{\nu}_e) =$$
$$1 - \sin^2(2\theta_{12})c_{13}^4 \sin^2 \frac{\Delta m_{21}^2 L}{4E} - \sin^2(2\theta_{13}) \left[c_{12}^2 \sin^2 \frac{\Delta m_{31}^2 L}{4E} + s_{12}^2 \sin^2 \frac{\Delta m_{32}^2 L}{4E} \right]$$

Sensitive to neutrino mass ordering

→ Measure rate of electron antineutrinos in Juno detector to observe the difference
→ Very high energy resolution required (see figure on the right)
→ Very precise calibration of energy scale required

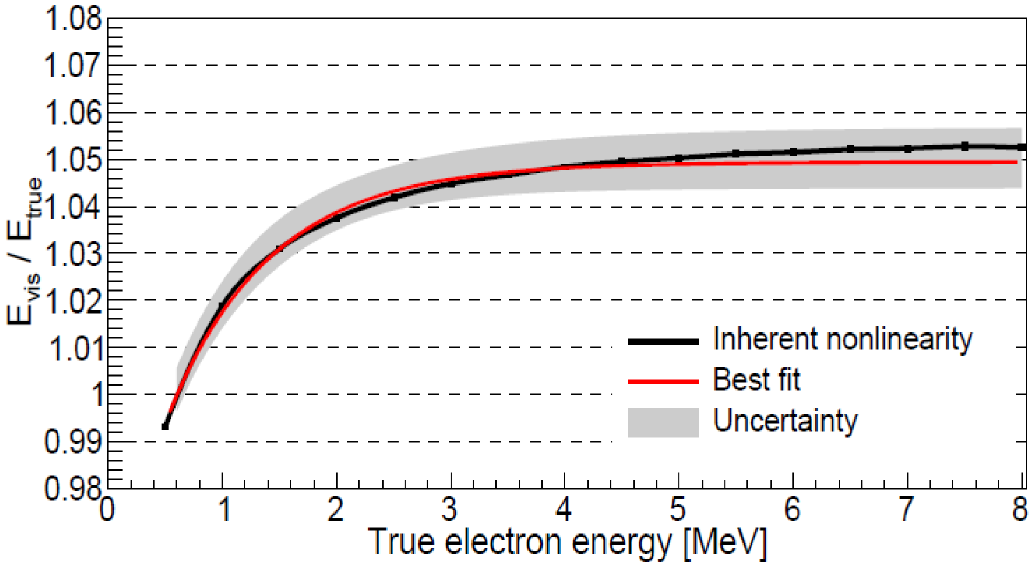


JUNO Collaboration. Sub-percent precision measurement of neutrino oscillation parameters with JUNO. *Chinese Physics C*, 46(12):123001, 12 2022

SCINTILLATOR ENERGY RESPONSE

- In theory: Birks law relates light yield to energy of the particle:
  - $$\frac{dL}{dr} = \frac{S\,\frac{\mathrm{d}E}{\mathrm{d}r}}{1 + kB\,\frac{\mathrm{d}E}{\mathrm{d}r}}$$
  - Largest non-linearity at small energies
  - Nearly linear for high energies
- In practice:
  - Birks constant kB dependent on particle and scintillator
  - Semi empiric formula

→ Should be checked → MANGO



Abusleme, Angel, et al. "Calibration strategy of the JUNO experiment." *Journal of high energy physics* 2021.3 (2021): 1-33.

OBJECTIVES OF MANGO

- MANGO: **M**ainz **A**dvanced **N**eutron **G**amma **O**bservatory
- Investigate liquid scintillator response to high energy particles
- Investigation of pulse-shape discrimination capability of neutrons and gammas
- Measure quenching factors in liquid scintillator from neutron induced recoil protons and pulse shape of protons

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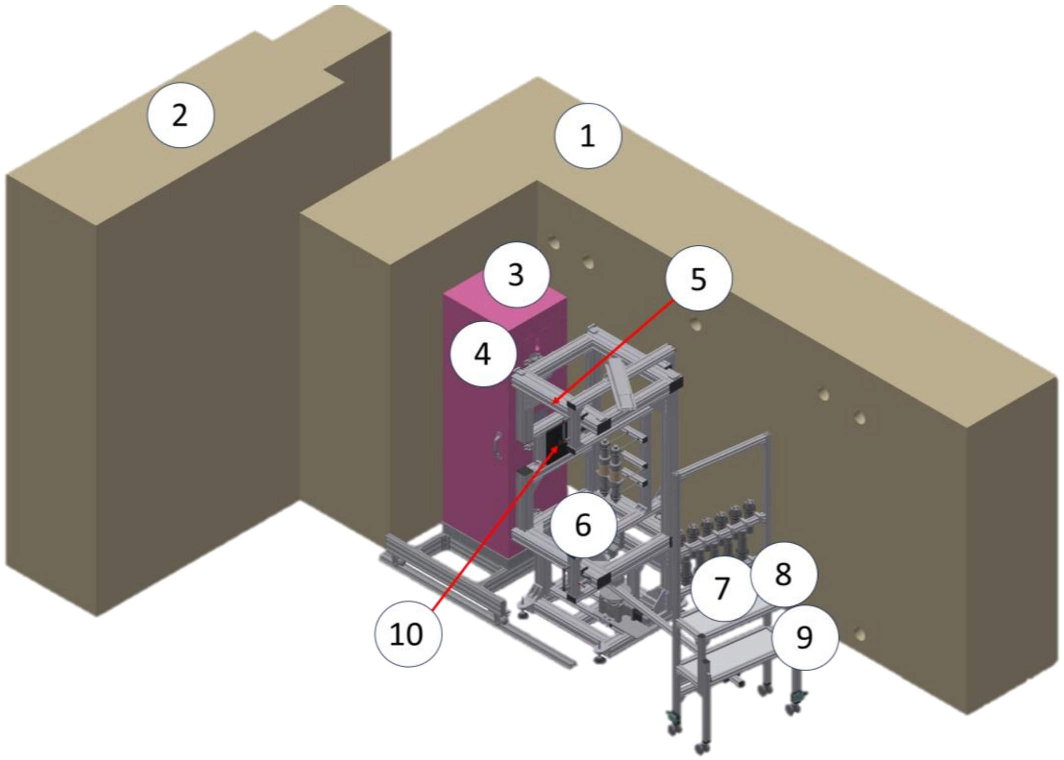
EXPERIMENTAL SETUP

- Two operation modes:
 neutron mode and gamma mode
- DD neutron generator produces 2.45 MeV neutrons at a flux of 1×10^8 n/s
- Neutron-gamma converter produces gammas from capture on Nickel (in gamma mode)
- Liquid scintillator test target with PMT readout
- Movable secondary detector array with neutron and gamma detectors (plastic and LBC)



1. Concrete bunker
2. Bunker door
3. DD-neutron generator, E_n = 2.45 MeV
4. Borated PE shielding of neutron generator
5. Neutron-gamma converter (nickel), E_γ = 9 MeV
6. Scintillator test cell, surrounded by PMTs
7. Lanthanum BromoChloride gamma detectors
8. Plastic scintillator neutron detectors
9. Movable detector frame
10. Lead collimator for gammas

SCINTILLATOR ANALYSIS

Observables:

- Energy deposition in target (test scintillator surrounded by PMTs)
- Hit time in target
- Hit time in secondary detector
- Energy deposition in secondary detector
- Scattering angle

Neutron mode	Gamma mode
Time difference of > 23 ns between target and secondary detector	Time difference of < 2 ns between target and secondary detector
Energy deposition in target determined based on time of flight	Energy deposition in target and secondary detector should sum up to 9 MeV
Energy deposition in target determined based on scattering angle	Energy deposition in target determined based on Compton scattering angle
Consistency check of energy deposition observed in target	

MANGO AND JUNO

- Take JUNO scintillator sample to Mainz (less than 2l)

→ Calibration of scintillator independent of systematic uncertainties of the JUNO detector

- Production of single electrons at high energies by Compton scattering

→ Observe non-linearities in their energy deposition

- Cross check of Legnaro measurements for pulse shape discrimination

→ Valuable for DSNB studies

- Measure quenching factors of recoil protons up to 2.45 MeV

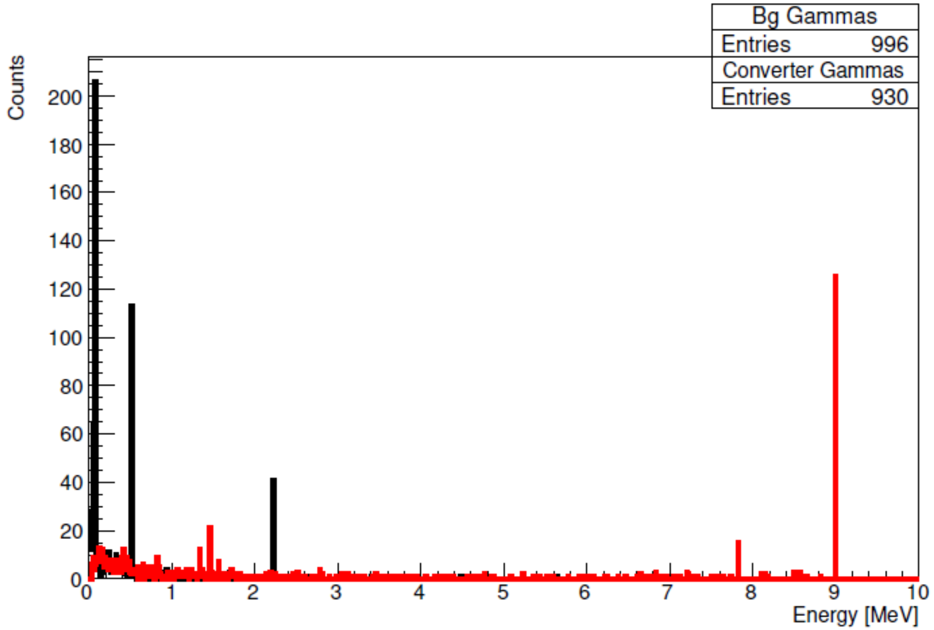
CHARACTERIZATION OF THE SETUP

- Measurement of the incoming gamma spectrum
- Energy calibration of secondary detectors
- Time resolution of the secondary detectors
- Characterization of the target PMTs: timing and gain
- Determination of secondary detector position

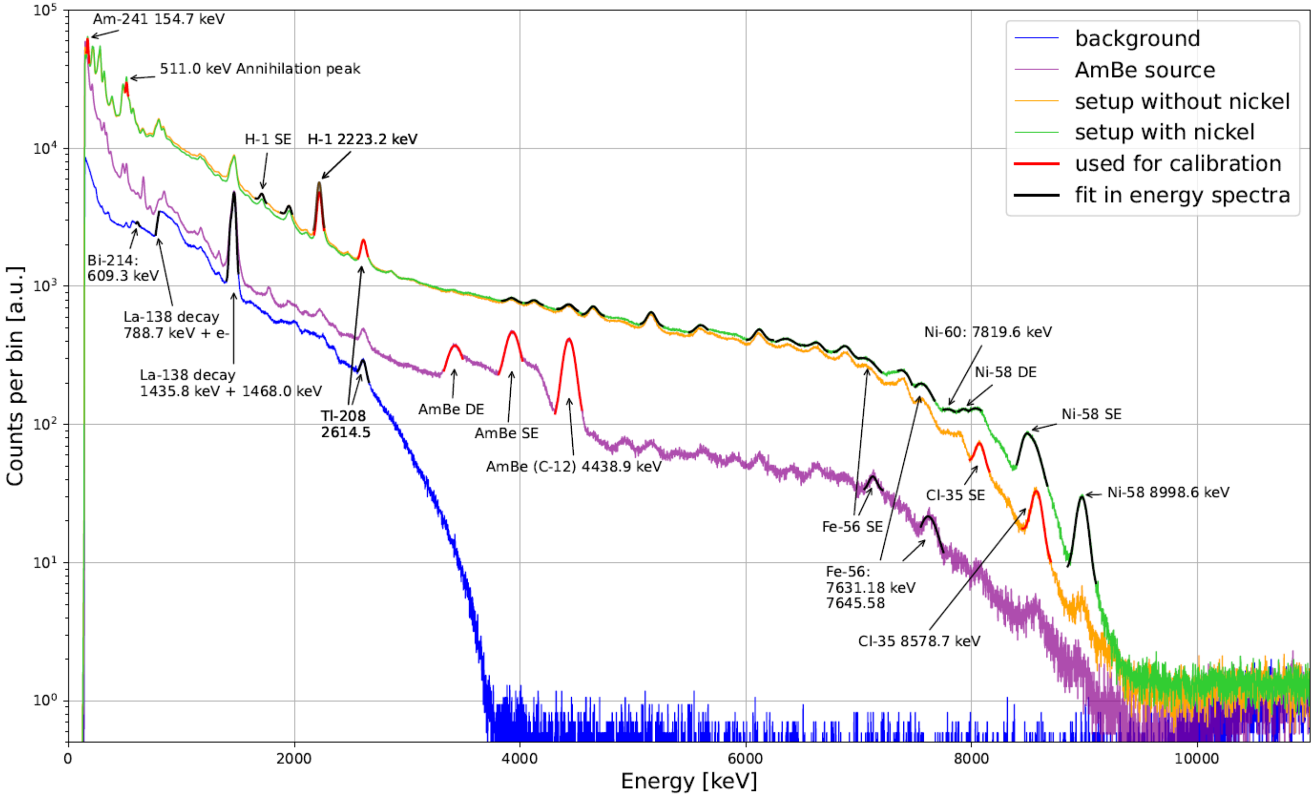
→ Combine for systemeatic uncertainty of the experiment

INCOMING GAMMA SPECTRUM

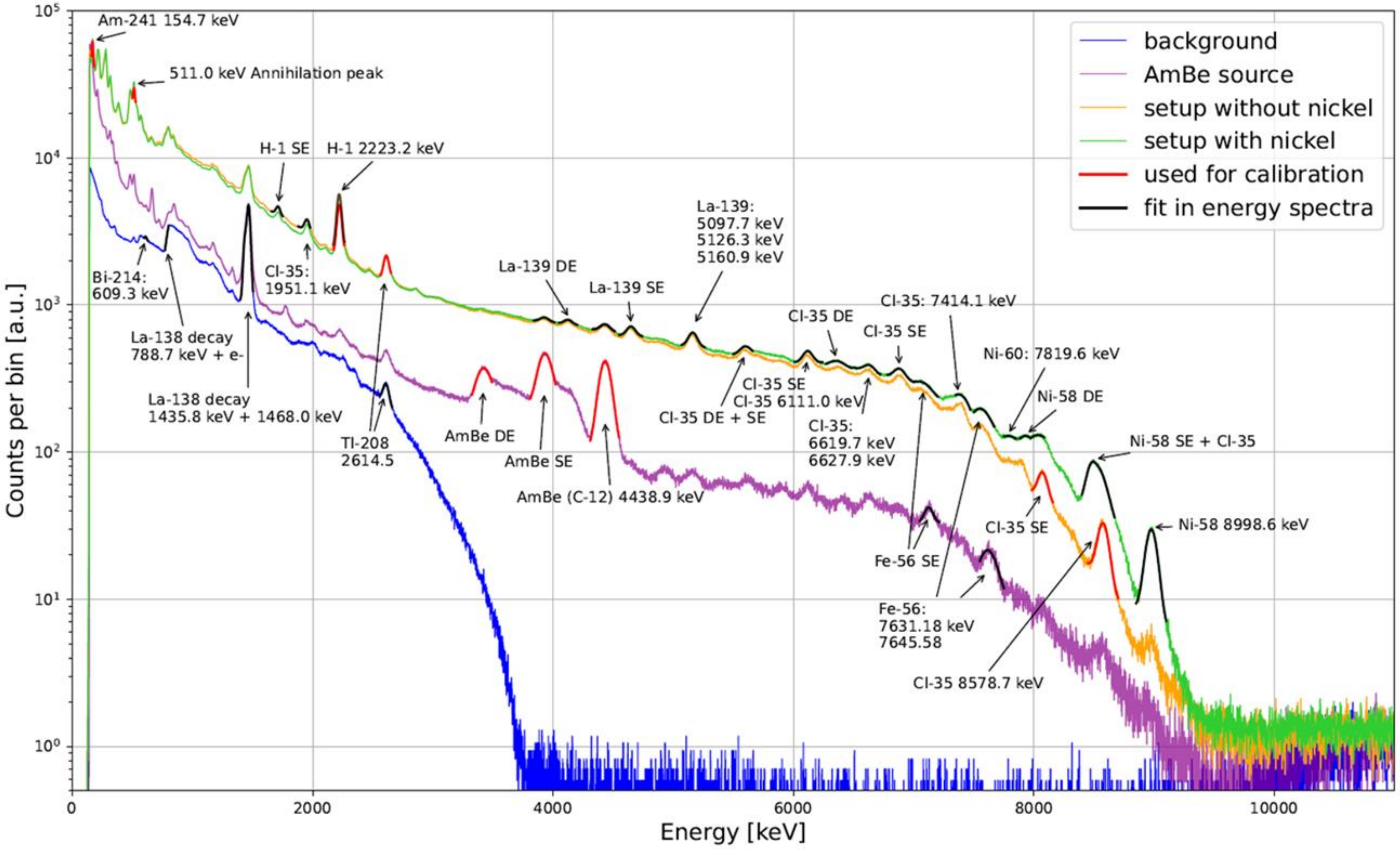
Monte-Carlo simulation of the gammas reaching the target



So far: only measurement with AmBe neutron source and different hardware possible



INCOMING GAMMA SPECTRUM



What we learned

Observed neutron capture on the detector material

→ (hopefully) removed by taking coincidences with target and sufficient shielding

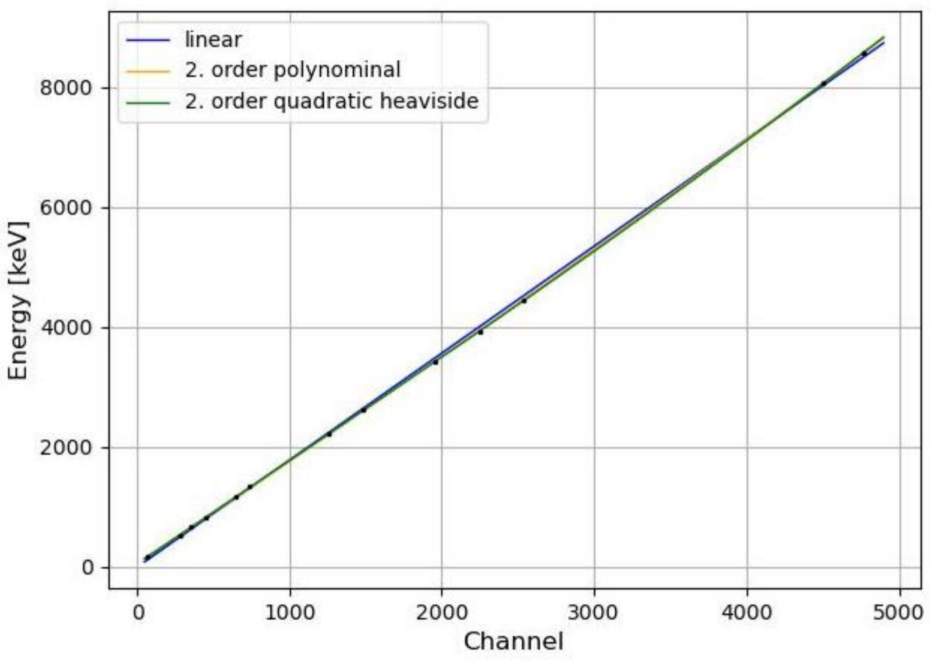
Non linear energy response of setup

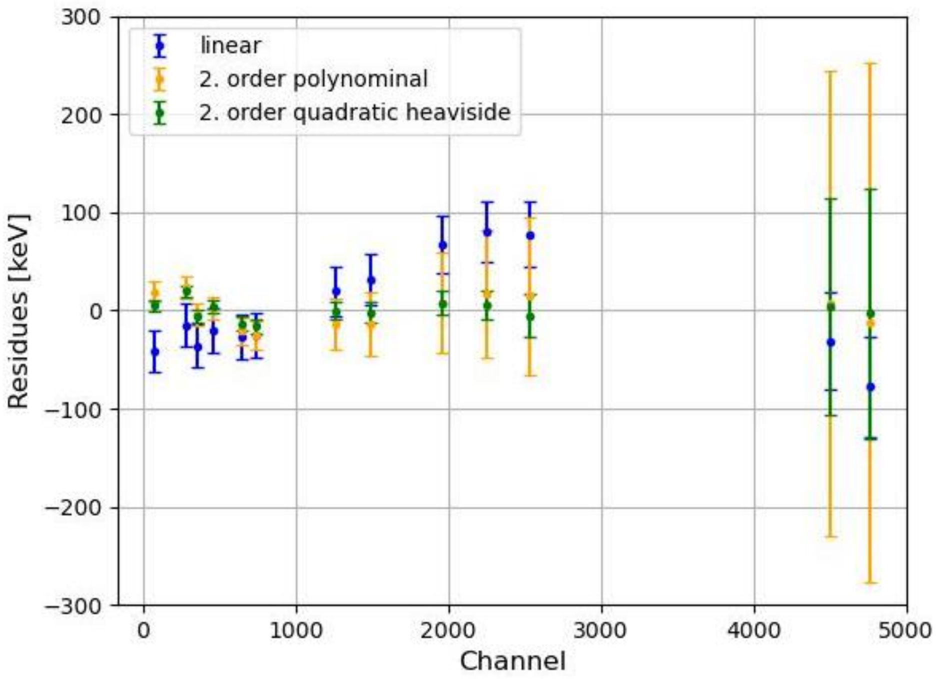
→ Possibly from non-linear detector

→ See next slide

GAMMA DETECTOR CALIBRATION

→ Use internal lines of the spectrum for more precise calibration



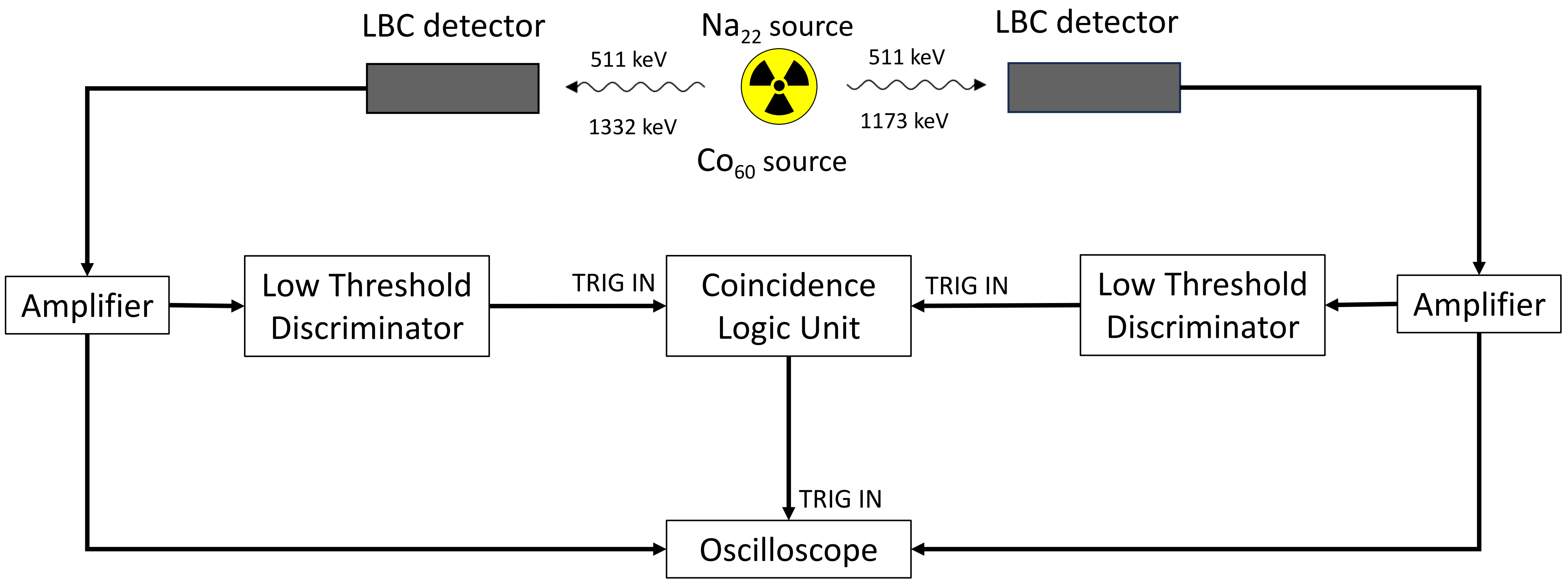


Linear calibration: $E = a + b \cdot \text{ch}$

2. order polyonminal: $E = a + b \cdot \text{ch} + c \cdot \text{ch}^2$

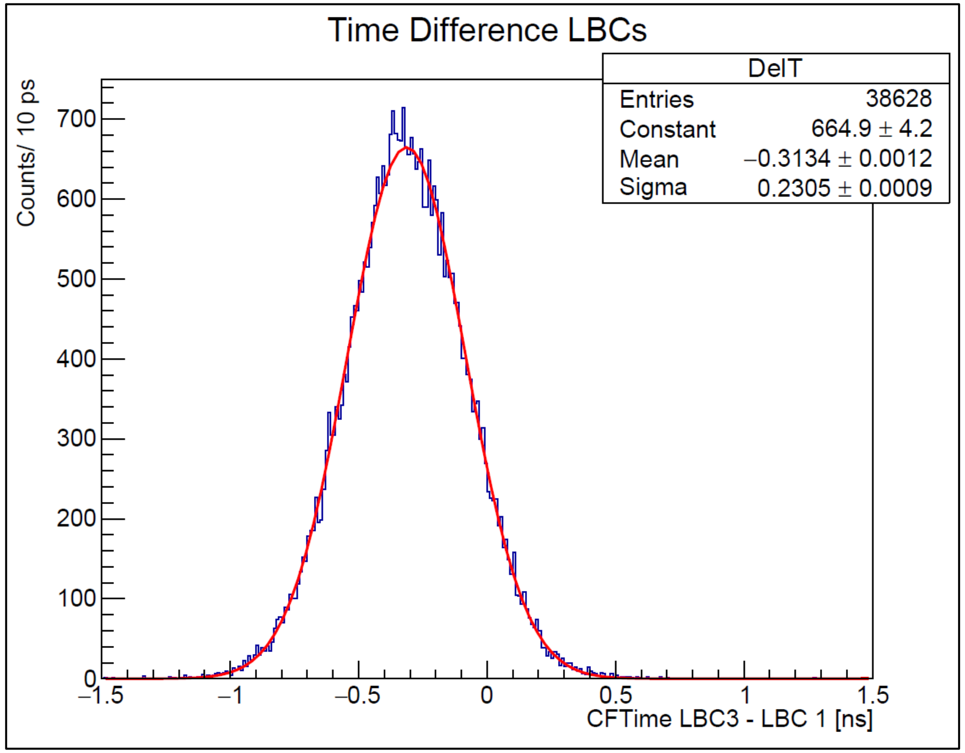
2. order quadratic heaviside: $E = a + b \cdot \text{ch} + c \cdot (\text{ch} - d)^2 \cdot \text{H}(\text{ch} - d)$

TIME RESOLUTION OF GAMMA DETECTORS



FIRST RESULTS OF TIMING MEASURMENTS

Combined time resolution of two detectors



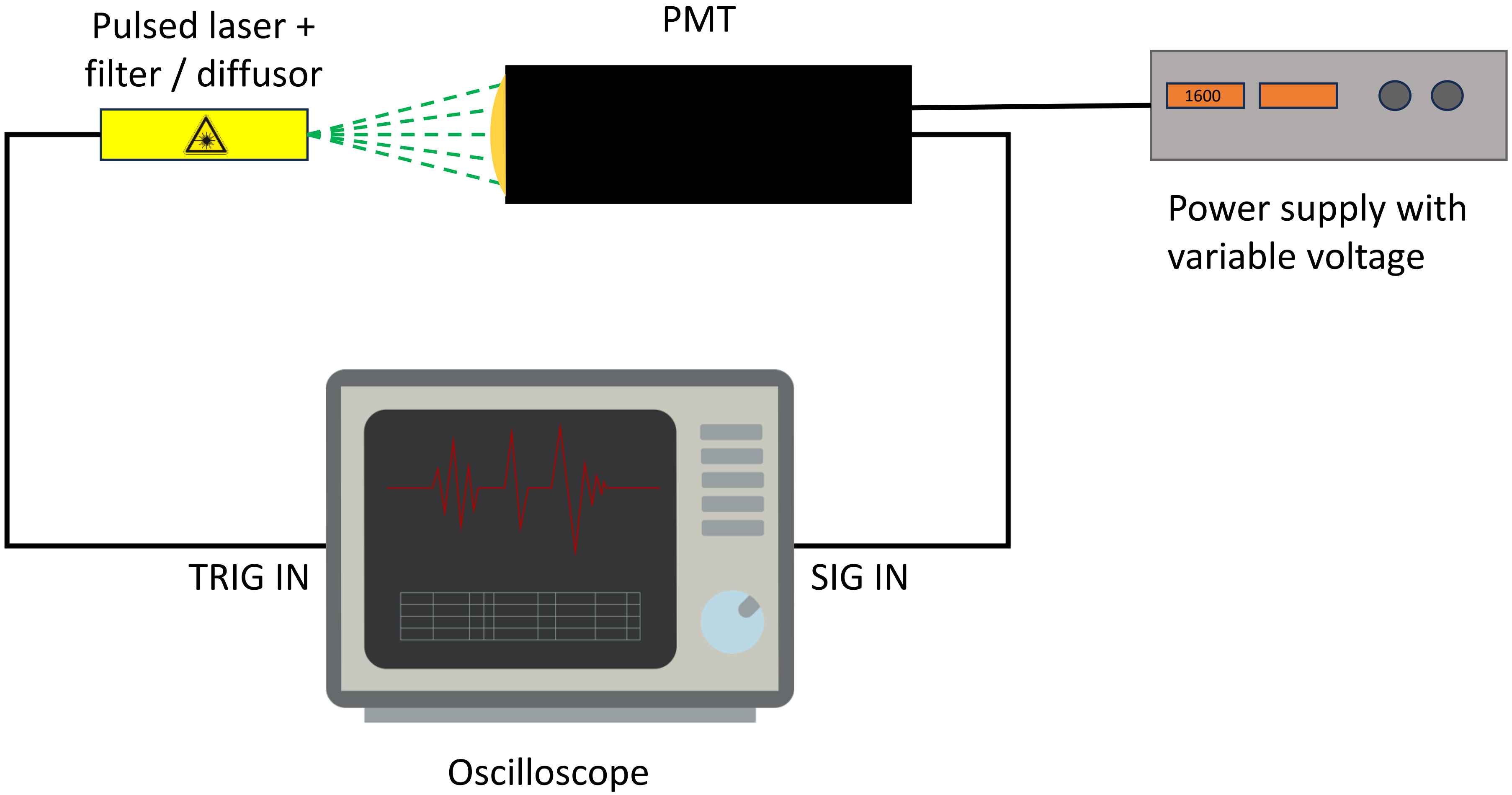
- Measurements with all combinations of three (or four) different detectors
- Cross check/ averaging with fourth detector possible

→ Isolate time response of individual detectors

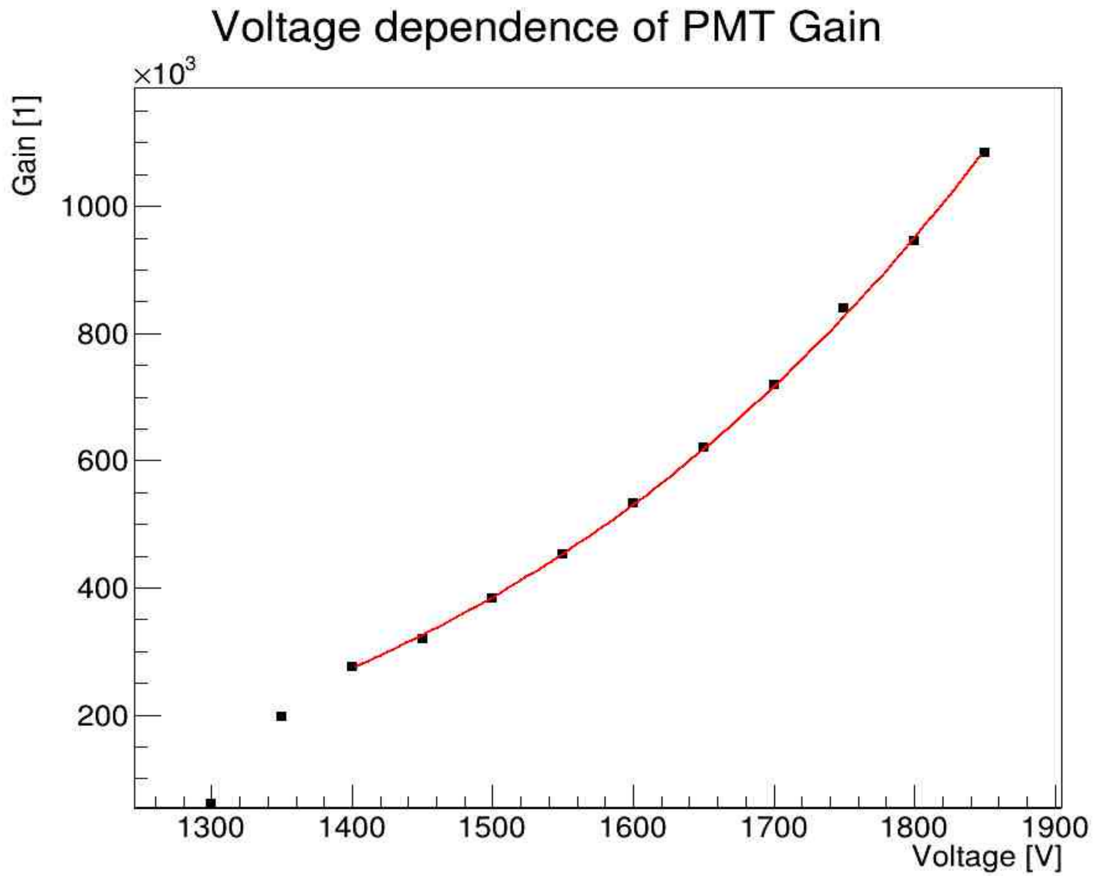
- Investigate energy dependence by using both Na_{22} and Co_{60}
- Preliminary results at 1000 V voltage with Na_{22}

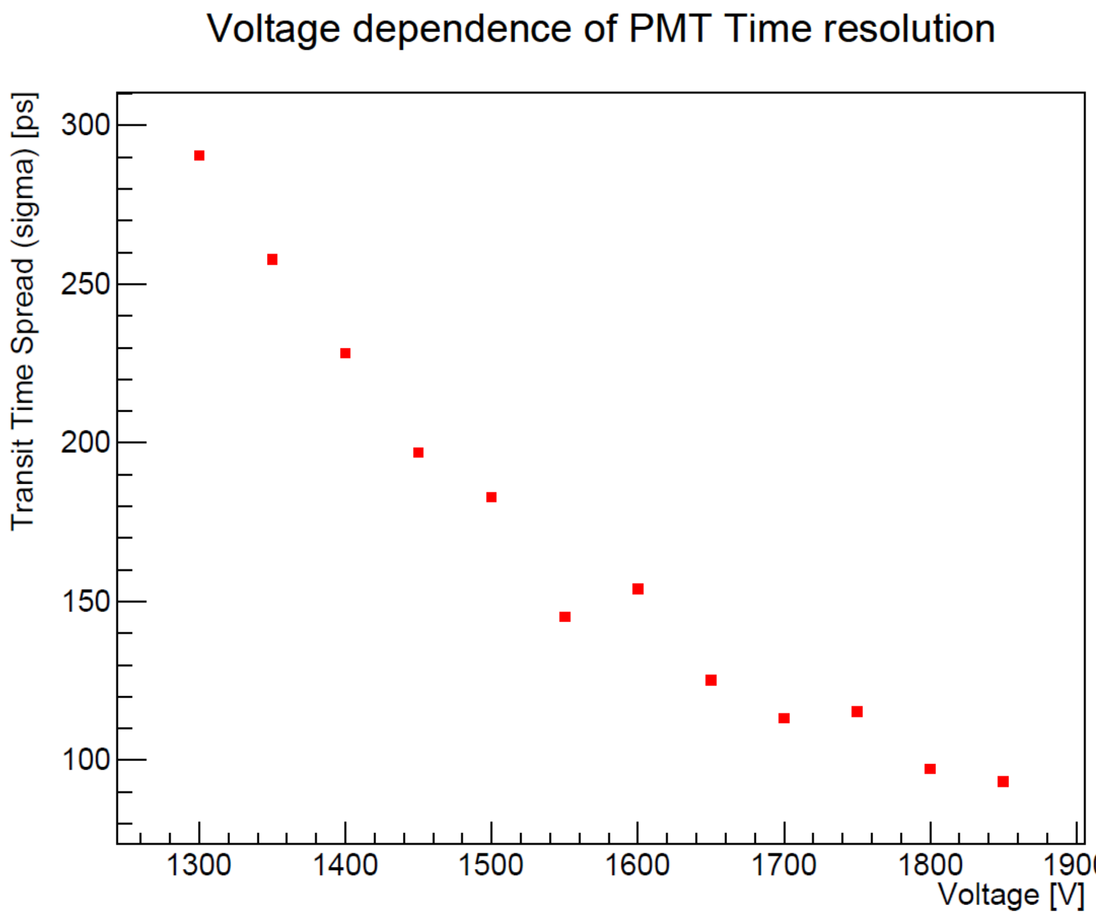
	Sigma [ps]	FWHM [ps]
LBC 1	154	363
LBC 2	167	394
LBC 3	172	405
LBC 4	148	347

PMT CHARACTERIZATION



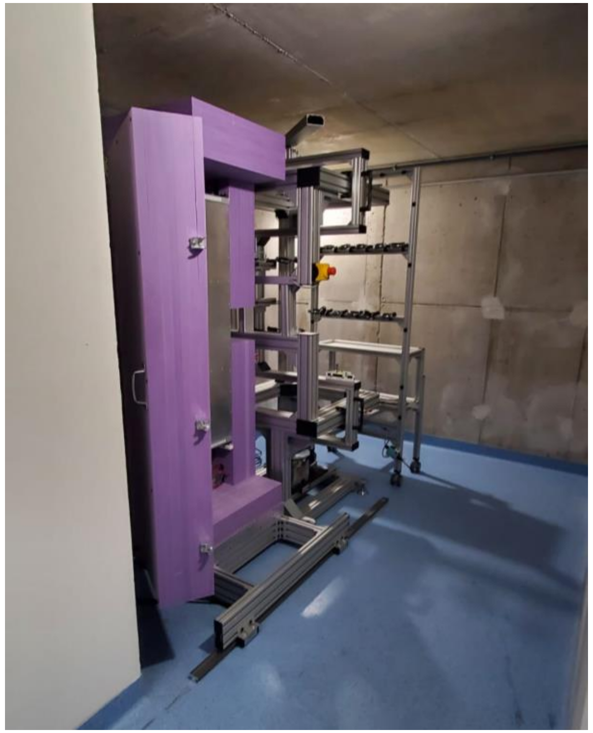
PMT GAIN AND TIMING DETERMINATION

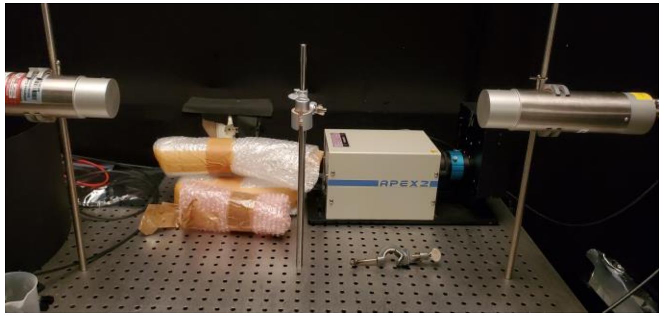


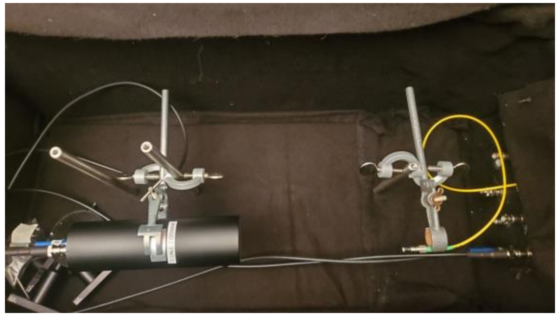


CURRENT STATUS

- Characterization (timing and energy response) of gamma detectors and PMTs ongoing
- Setup to characterize neutron detectors yet to be deviced
- Installation of neutron generator and mechanical components ongoing
- DAQ software and analysis framework to be written next year
- Expect data taking end of 2025/ beginning 2026







SUMMARY

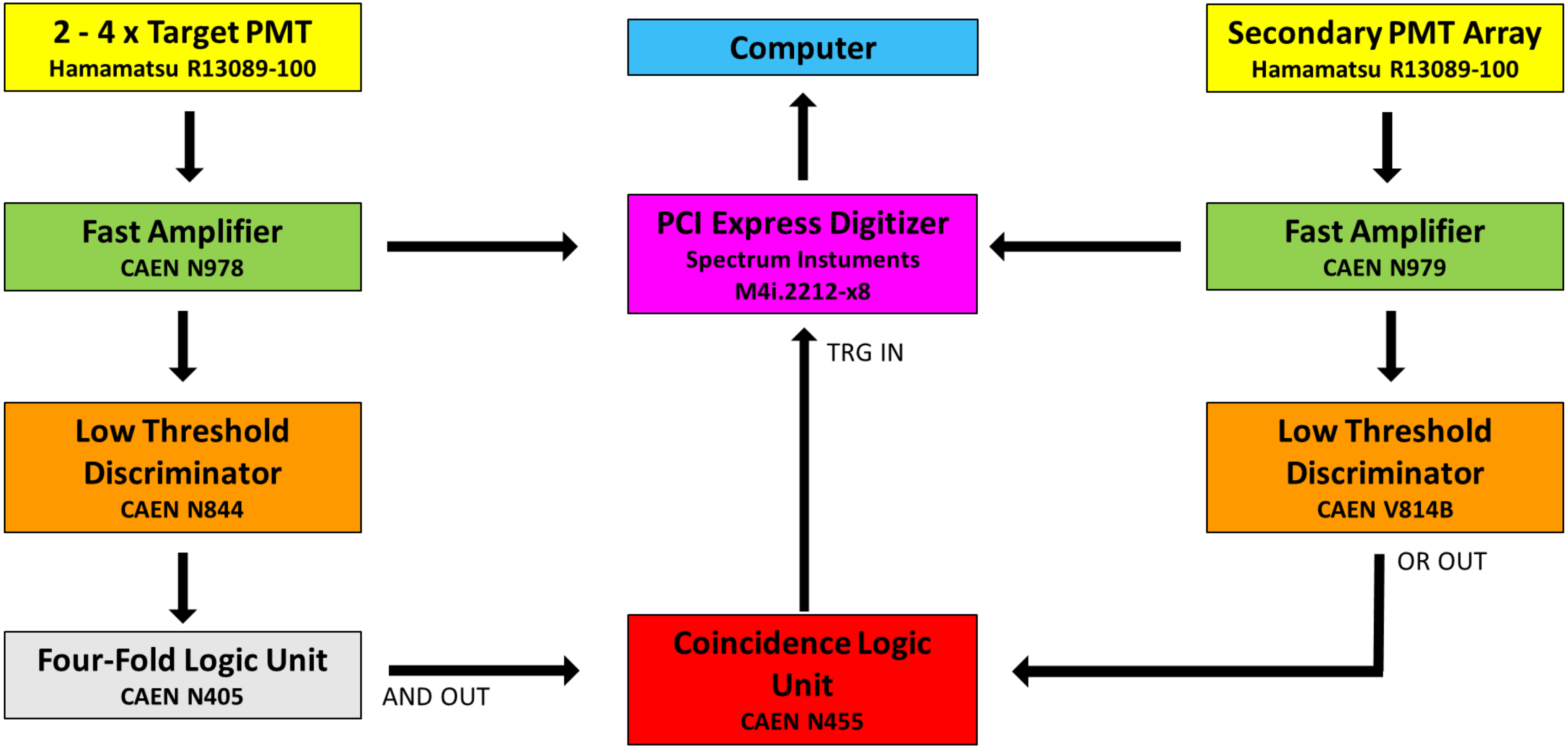
- MANGO: Setup for liquid scintillator characterization
- Neutron and gamma irradiation of test target
- 2.45 MeV neutrons and 9 MeV gammas
- Detection and analysis of scattered particles in secondary array

➢ Perfect for calibration of scintillator in the energy region of reactor neutrinos

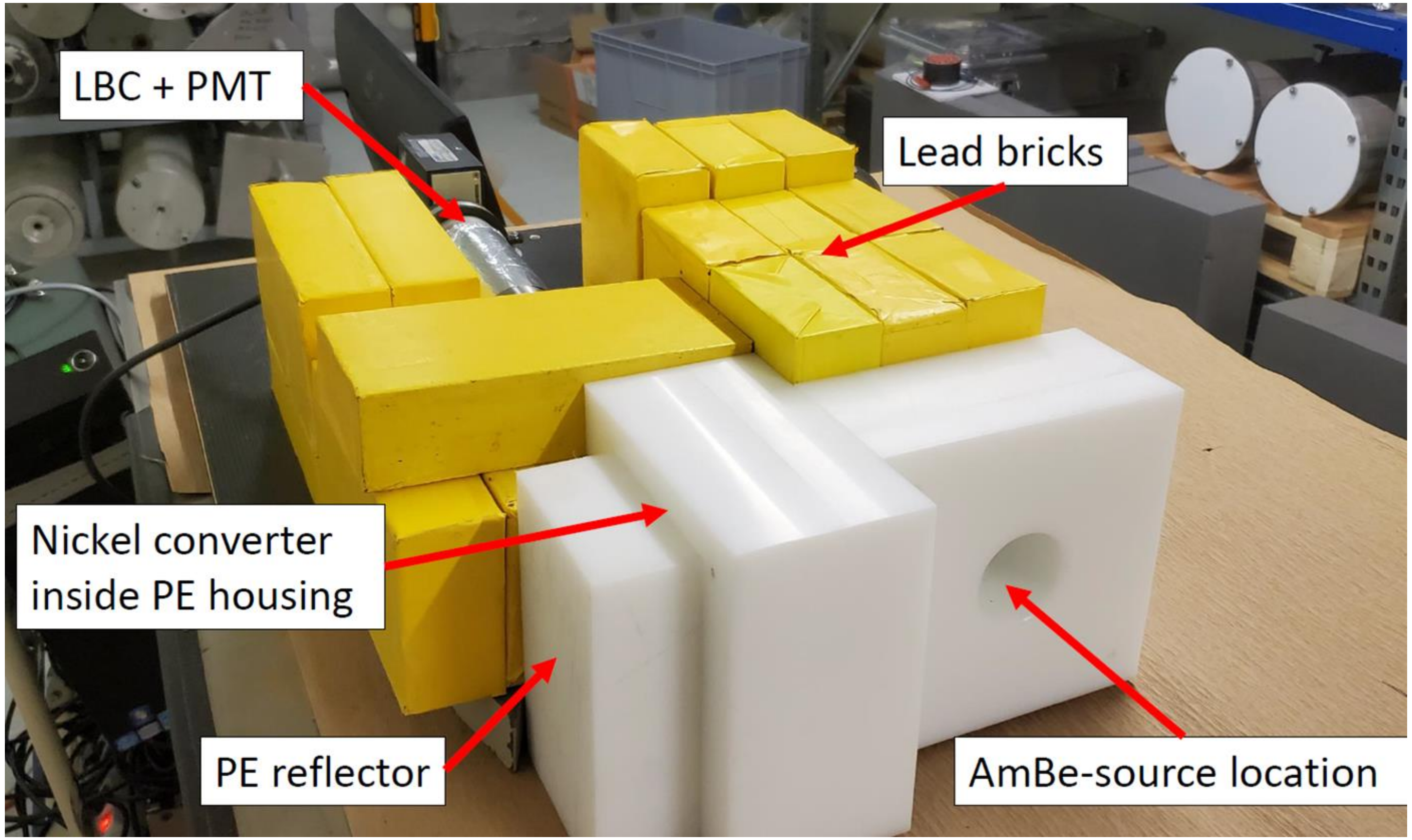
Thank you for the attention!

BACKUP SLIDES

DATA AQUISITION SYSTEM OF MANGO



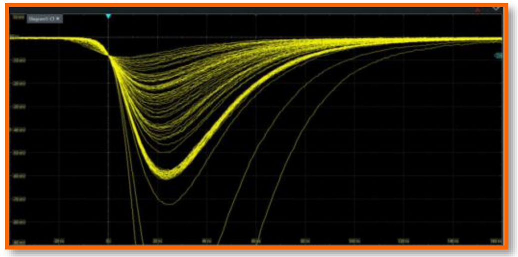
TEST SETUP FOR THE NEUTRON-GAMMA CONVERTER

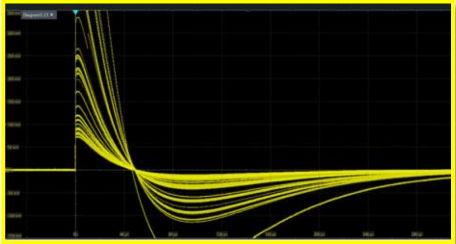


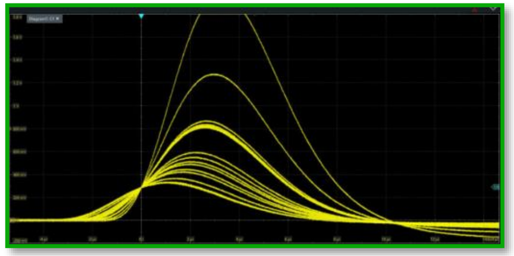
HARDWARE CONFIGURATION OF CONVERTER TEST SETUP

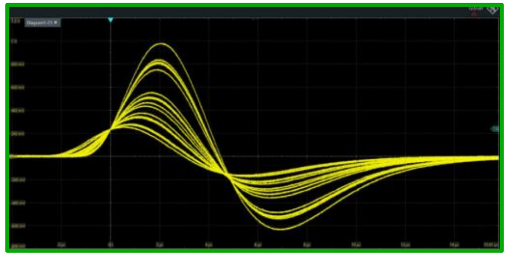
LBC Scionix 51B51/2M-LBC → **PMT** Hamamatsu R13089-100 → **Pre-Amp** Canberra 2007 → **Shaper** Ortec 672 → **Multi-Channel-Analyzer** Fast ComTec MCA-3FADC

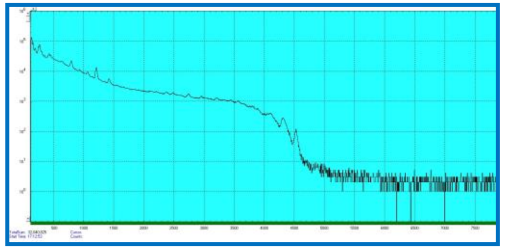
https://www.berkeleynucleonics.com/lanthanum-bromochloride











25

COMPARISON OF DETECTOR MATERIALS

	$LaBr_3(Ce)$	LBC	$CeBr_3$	LYSO
1/e decay time [ns]	16	35	18	36
Energy resolution [% at 662 keV]	3	3	4	8
Light yield [photons/keV]	63	70	60	35
Full absorption fraction (2" crystal) [%]	30.7	29.6	28.0	44.8
Density [g/cm^3]	5.08	4.9	5.23	7.2
Hygroscopic	yes	yes	yes	no