Measurement of the angular correlation between the two gamma rays emitted in the radioactive decays of ^{60}Co with two NaI(Tl) scintillators

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Didactic purpose

Target

- Laboratory course for undergraduate students

Goals

- Understanding the interaction of photons with matter
- Operating and becoming familiar with scintillators
- Setting up an experiment to validate a theoretical model

Theoretical prediction

Most probable decay channel

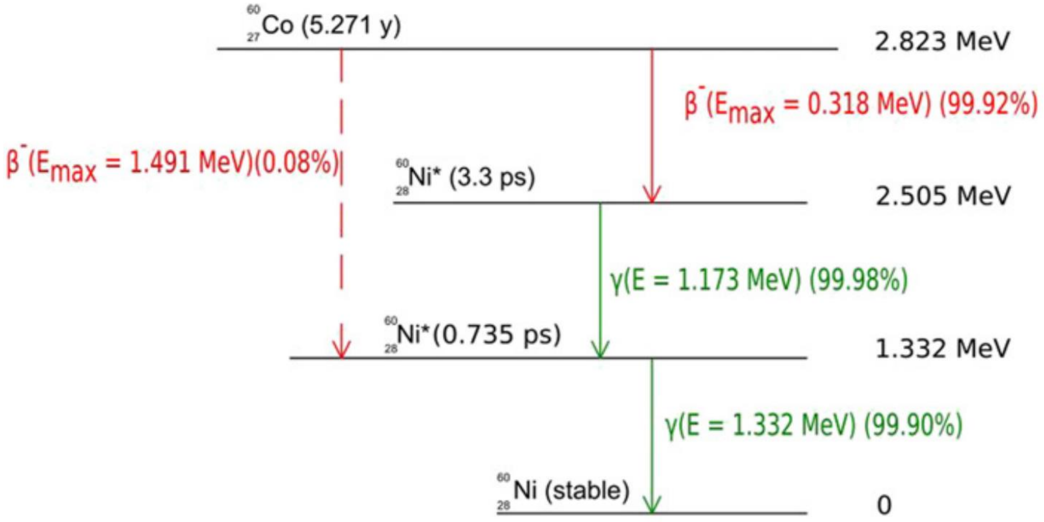
- $^{60}_{27}Co \rightarrow ^{60}_{28}Ni^{*} + e^{-} + \overline{\nu}_e \rightarrow$
  $^{60}_{28}Ni + e^{-} + \overline{\nu}_e + \gamma_1 + \gamma_2$

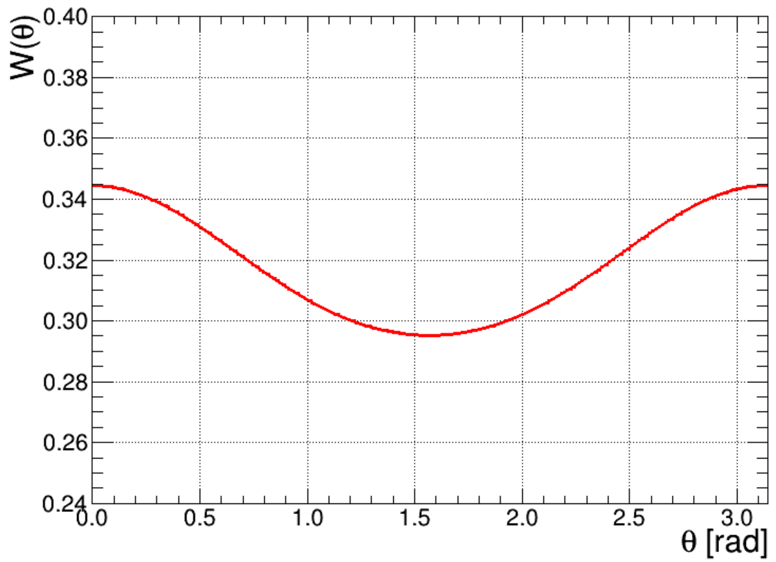
Lifetime of $^{60}_{28}Ni^{*}$ < ps

- γ_1 and γ_2 are emitted in coincidence

An angular correlation is expected between γ_1 and γ_2 (Hamilton, 1940)

- $W(\theta) \propto 1 + \frac{1}{8}cos^2\theta + \frac{1}{24}cos^4\theta$





Gamma-ray spectroscopy

The detection of γ rays is based on their interaction with matter

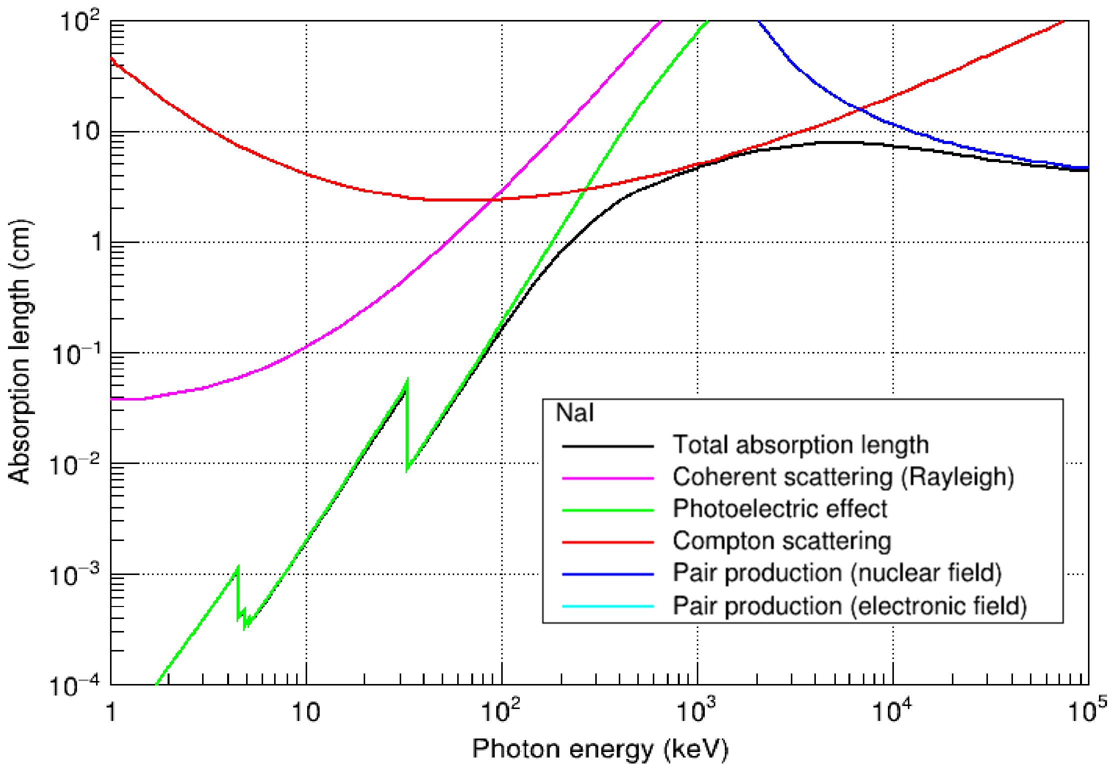
- **Photoelectric effect**
- **Compton scattering**
- **Pair production**

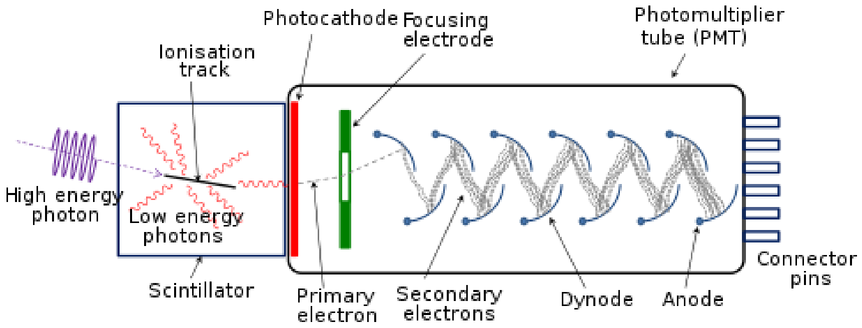
Properties of a γ-ray detector

- **Conversion medium for incident photons**
- **Conventional detectors for electrons produced in the γ-ray interaction**

Our experiment

- **NaI(Tl) scintillators equipped with PMTs**
- **Commonly available in laboratories for undergraduate physics students**





Experimental setup

^{60}Co disk source

- $A \approx 5\ kBq$
- $R = 0.5\ cm, L = 1\ mm$

2 NaI(Tl) scintillators coupled with PMTs

- S0: $R = 8.2\ cm, L = 8.2\ cm, Dist = 20.0\ cm$
- S1: $R = 5.8\ cm, L = 5.8\ cm, Dist = 14.1\ cm$

Digital oscilloscope

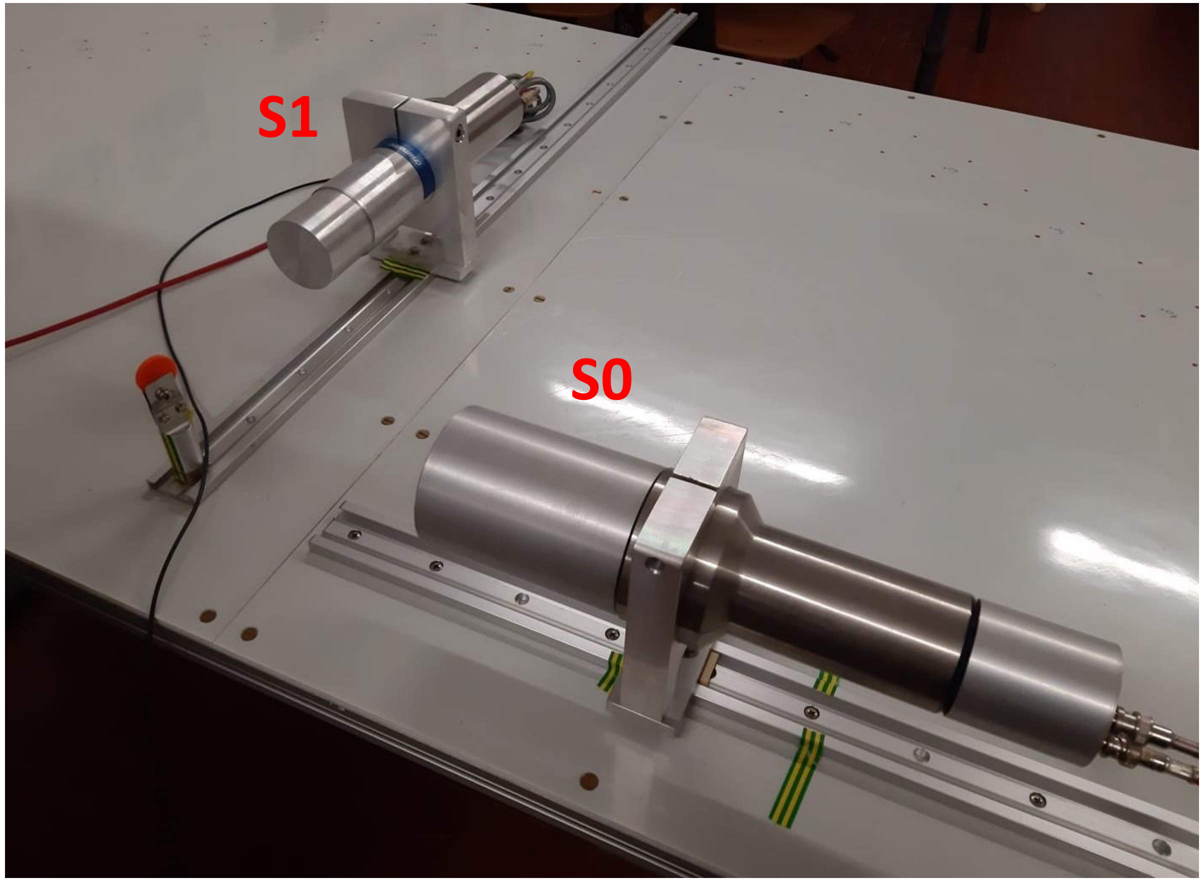
- Measurement of voltage signals and charge

NIM modules

- Fan-in/fan-out, Discriminator, Logic unit

2 rails

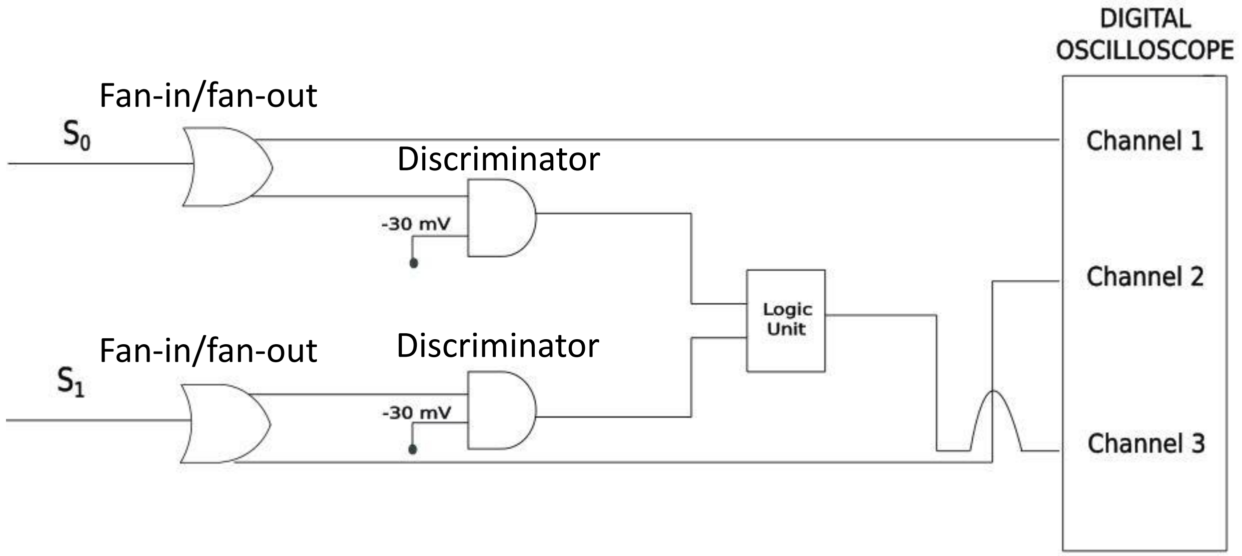
- A fixed rail for S0
- A mobile rail for S1



Trigger logic

Data acquisition

- **Channel 1: Signal from S0**
- **Channel 2: Signal from S1**
- **Channel 3: Trigger**

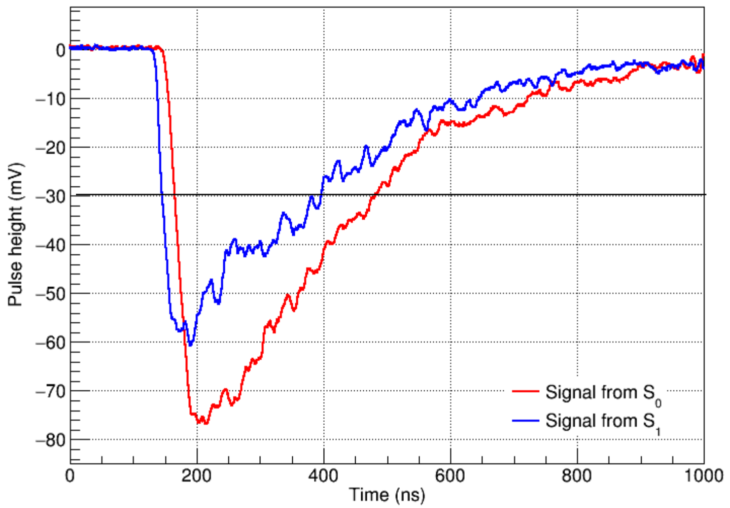


Trigger configurations

- **S0 v S1: energy calibration**
- **S0 & S1: correlation studies**

Pulse shape

- **Rise time:** $\tau_{RC} = 15\ ns$
- **Fall time:** $\tau_{sc} = 230\ ns$



Energy calibration

Goal

- **Conversion of charge signals into energy depositions in scintillators**

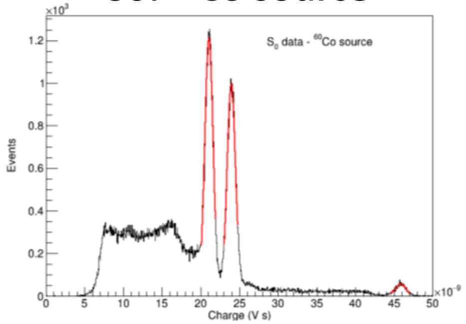
Calibration points

- **^{60}Co: 1.17 MeV, 1.33 MeV, 2.50 MeV**
- **^{137}Cs: 0.662 MeV**
- **Pedestal: null energy deposition (trigger on the other scintillator)**
- **Charge extracted through Gaussian fits to the full energy peaks**
- **Linear dependence is found**

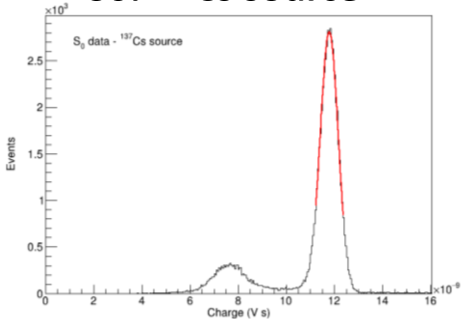
Energy resolution

- **S0: $\sigma_E/E \approx 2.5\,\%$ at 1 MeV**
- **S1: $\sigma_E/E \approx 5.0\,\%$ at 1 MeV**

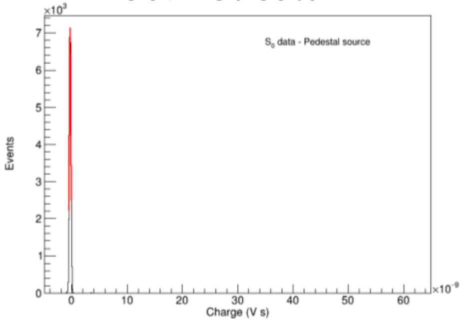
S0: ^{60}Co source



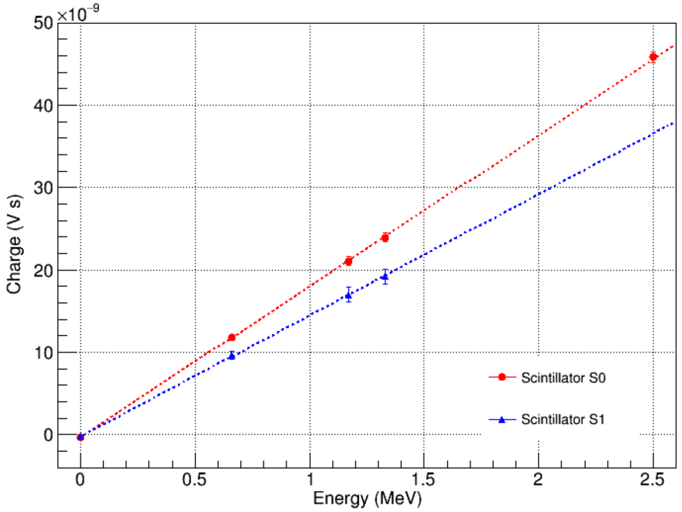
S0: ^{137}Cs source



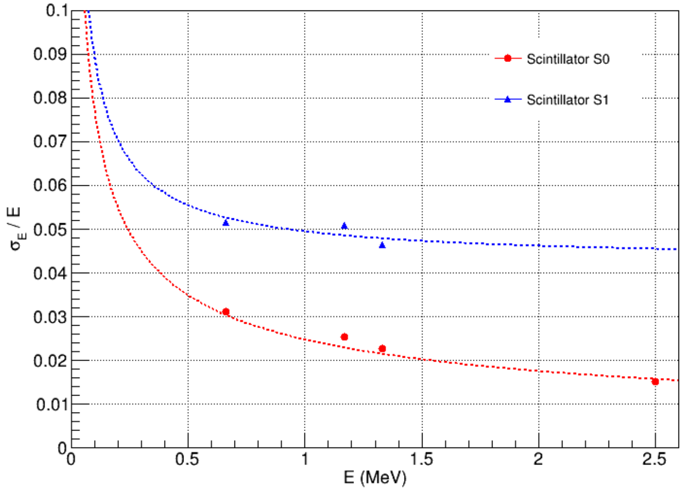
S0: Pedestal



Calibration curve



Energy resolution



Data analysis with ^{60}Co source

Event rates with ^{60}Co (S1&S2)

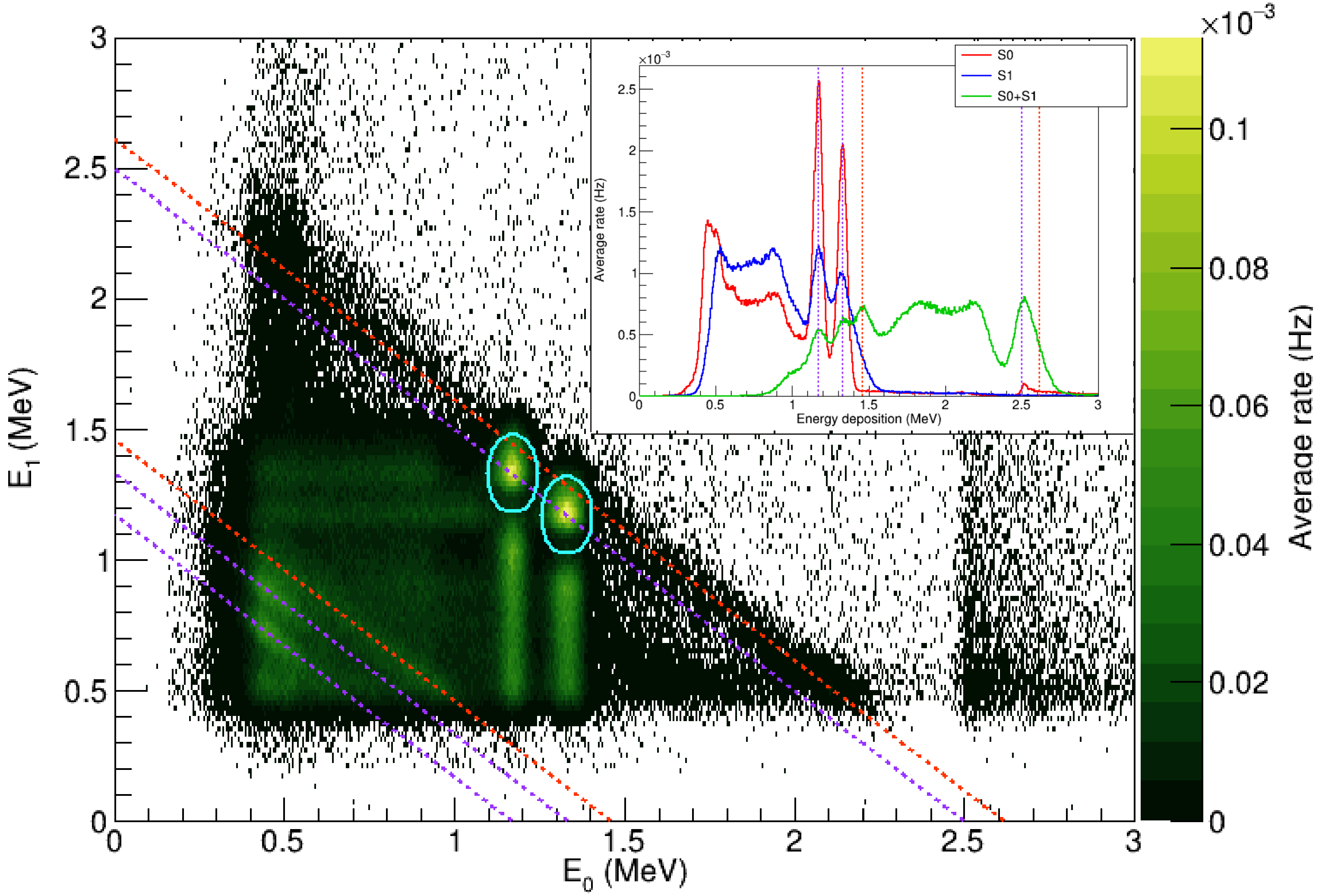
- Peaks at ^{60}Co photon energies: full energy deposition in S0 and S1
- Horizontal/vertical bands: full energy deposition only in S0 or S1
- Diagonal bands: scattered photons in S0/S1 reach S1/S0

Main background sources

- ^{40}K in windows of PMTs: 1.461 MeV
- ^{208}Tl in scintillators: 2.610 MeV
- Cosmic rays

Event selection

- $\left(\frac{E_0-1.17\ MeV}{0.075\ MeV}\right)^2+\left(\frac{E_0-1.33\ MeV}{0.150\ MeV}\right)^2<1$
- $\left(\frac{E_0-1.33\ MeV}{0.075\ MeV}\right)^2+\left(\frac{E_0-1.17\ MeV}{0.150\ MeV}\right)^2<1$



Data analysis without ^{60}Co source

Event rates without ^{60}Co (S1&S2)

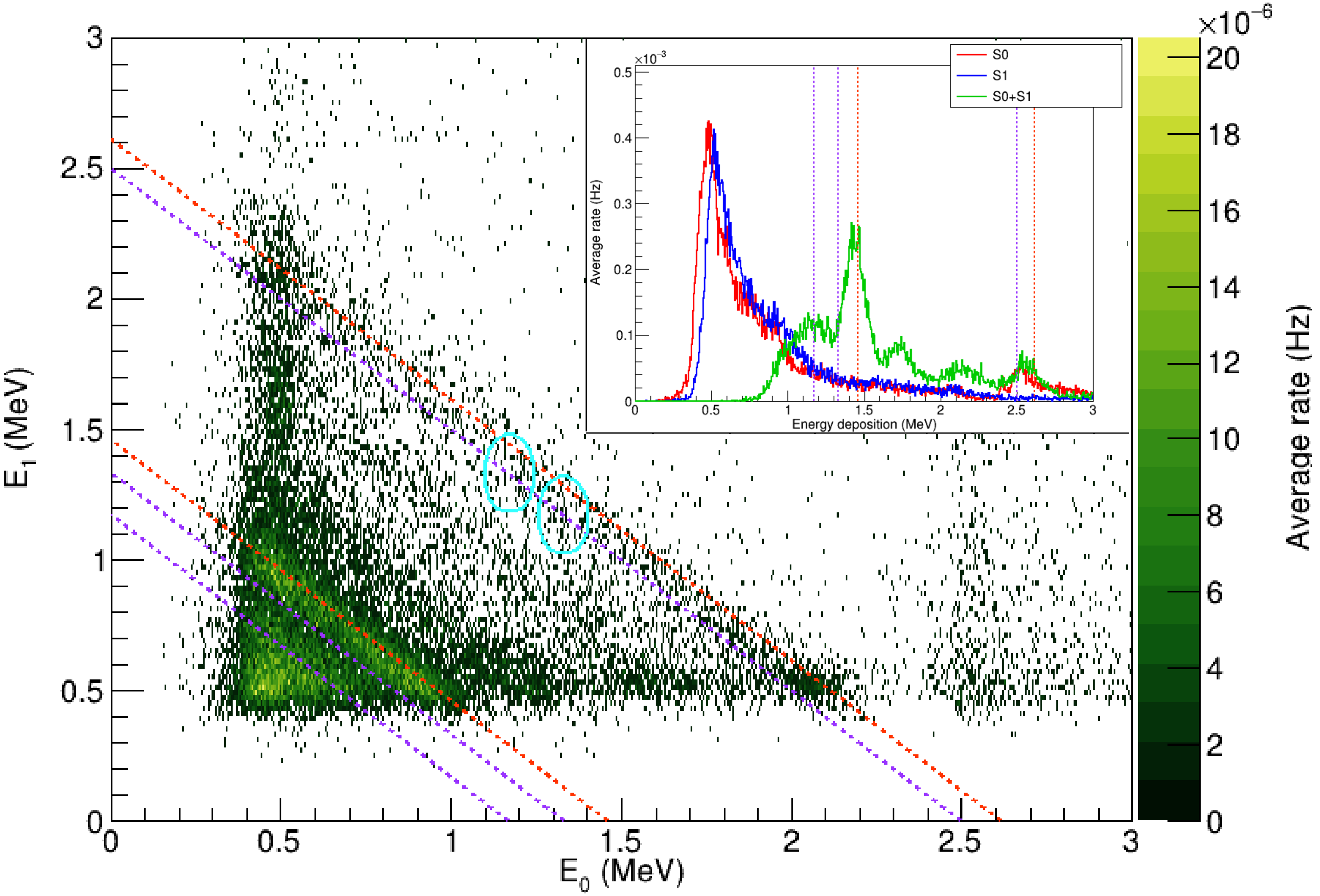
- **Peaks at ^{60}Co photon energies: disappear**
- **Horizontal/vertical bands: disappear**
- **Diagonal bands: background photons only**

Main background sources

- **^{40}K in windows of PMTs: 1.461 MeV**
- **^{208}Tl in scintillators: 2.610 MeV**
- **Cosmic rays**

Event selection

- $$\left(\frac{E_0-1.17\ MeV}{0.075\ MeV}\right)^2+\left(\frac{E_0-1.33\ MeV}{0.150\ MeV}\right)^2<1$$
- $$\left(\frac{E_0-1.33\ MeV}{0.075\ MeV}\right)^2+\left(\frac{E_0-1.17\ MeV}{0.150\ MeV}\right)^2<1$$



Results

Measurements

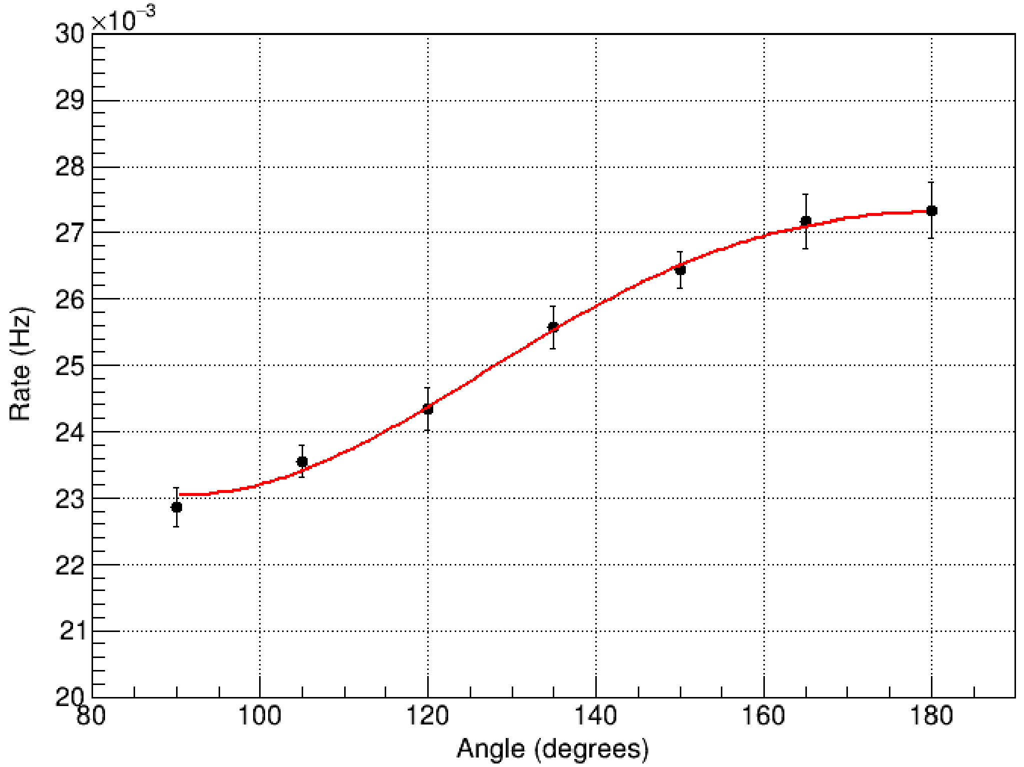
- Scan of [90°, 180°] with 15° steps
- Signal rates calculated as difference between rate with and without source

Fit model

- $r(\theta) = r_0\left(1 + a\cos^2\theta + b\cos^4\theta\right)$

Correlation parameters

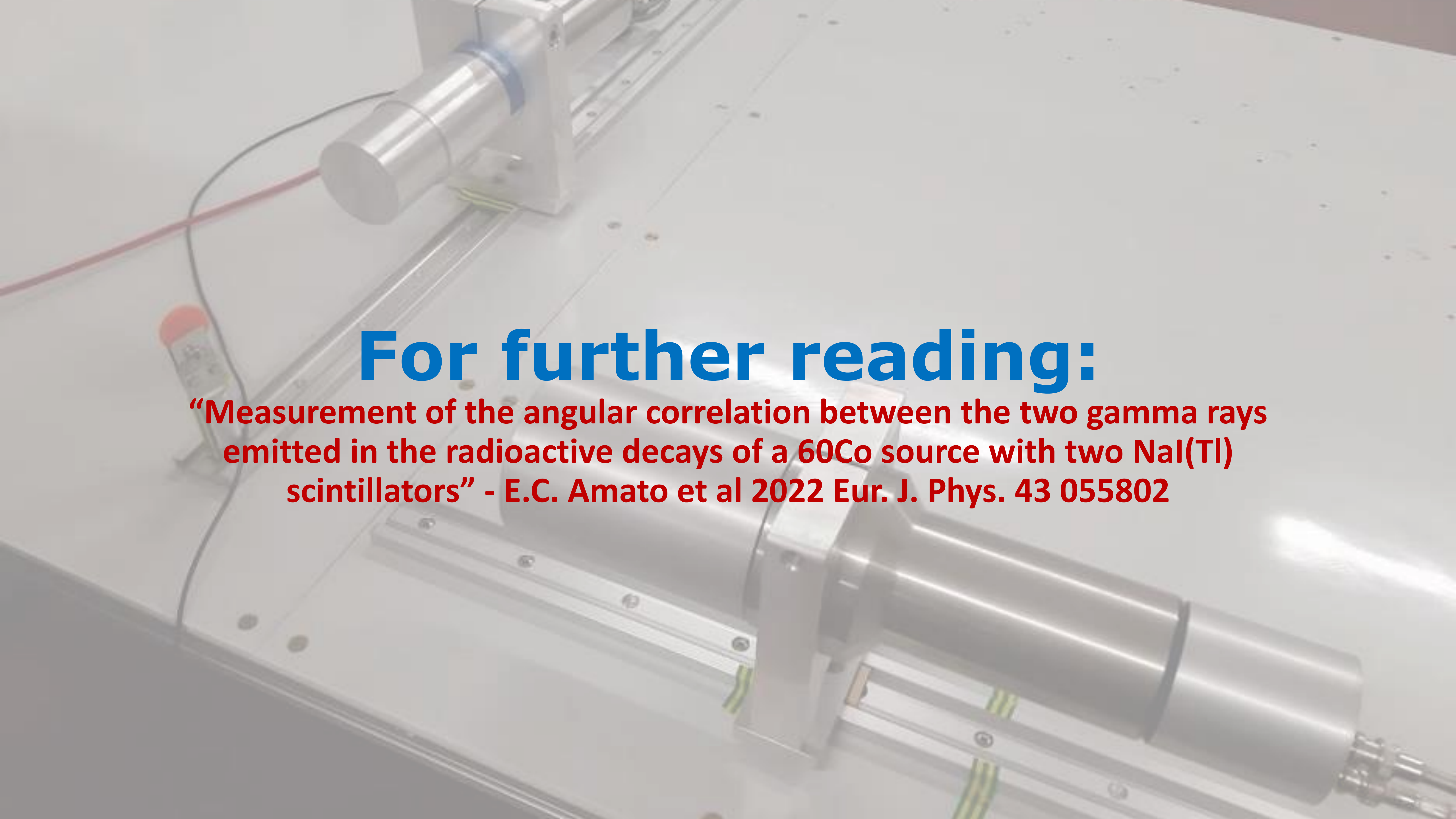
Fit parameters	Expected parameters
$a = 0.249 \pm 0.058$	a = 0.125
$b = -0.064 \pm 0.0588$	b = 0.0416



Compatibility within 2σ with expectations → … there is room for improvement!

Tips & tricks

1. Low activity source ⇒ Scintillators had to be close to the source ⇒ Large uncertainty on the opening angle (16°)
   - ✓Use of a higher activity source to keep scintillators farther from the source
2. Fixed disk-like source ⇒ The projected cross section of the source on the mobile scintillator changed with the rotation angle
   - ✓Use of a rotating source to compensate for the asymmetry
3. Statistics for signal rate limited by the size of the scintillators
   - ✓Use of larger scintillators (especially S1)



For further reading:

“Measurement of the angular correlation between the two gamma rays emitted in the radioactive decays of a 60Co source with two NaI(Tl) scintillators” - E.C. Amato et al 2022 Eur. J. Phys. 43 055802