Neutron and Gamma Tagging in Plastic Scintillators

Asa Nehm (they/them)

MPA Summer School 2023

On behalf of Antoine Laudrain,
Sebastian Ritter, Claudia Delogu

DEEP UNDERGROUND NEUTRINO EXPERIMENT

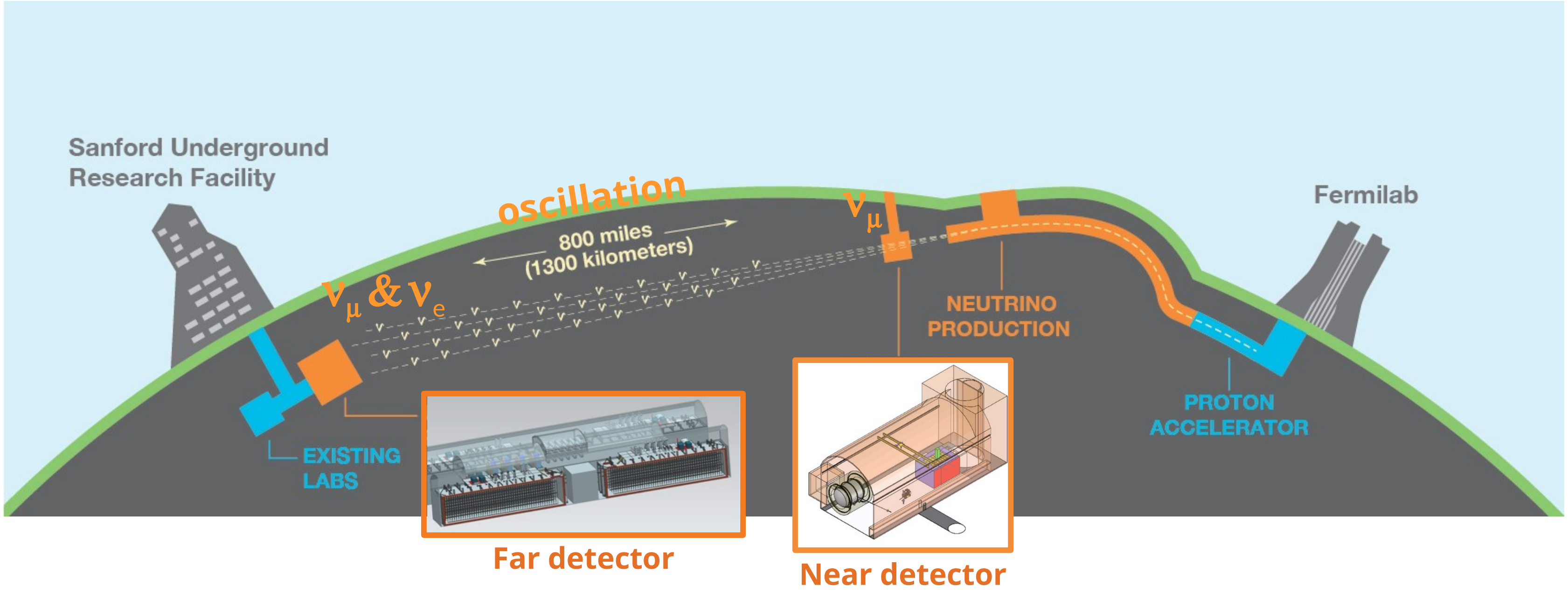
PRISMA+ DETECTOR LAB

JOHANNES GUTENBERG UNIVERSITÄT MAINZ

DUNE – Deep Underground Neutrino Experiment

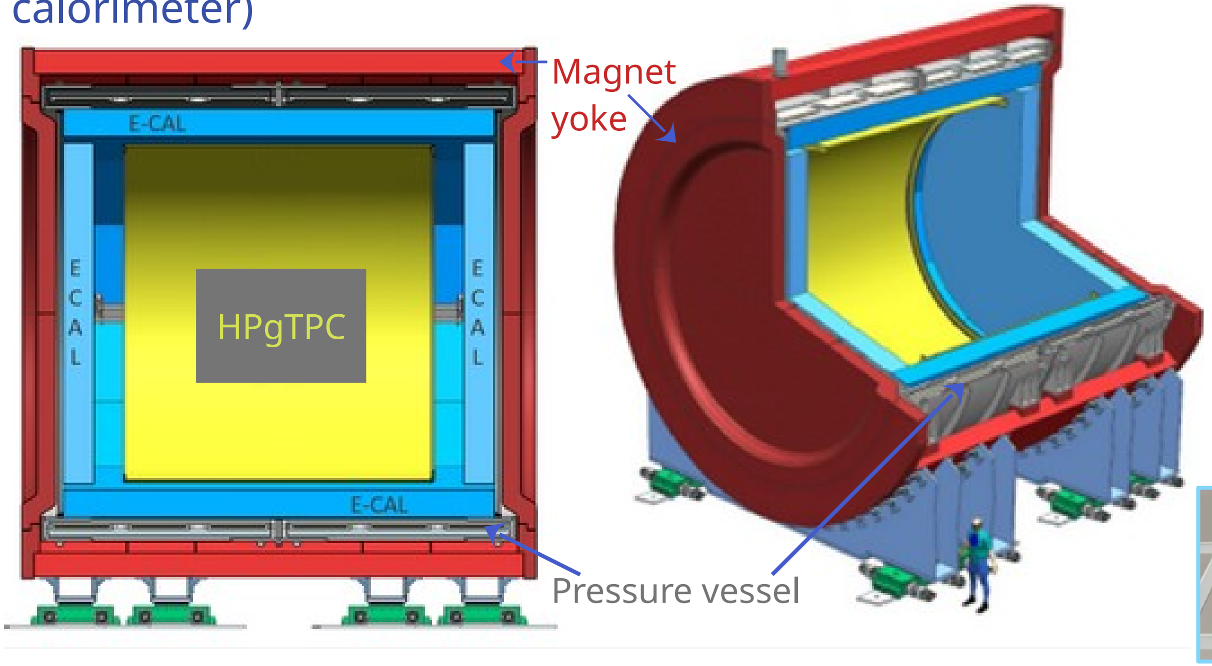
Next generation long baseline neutrino experiment based at Fermilab, USA

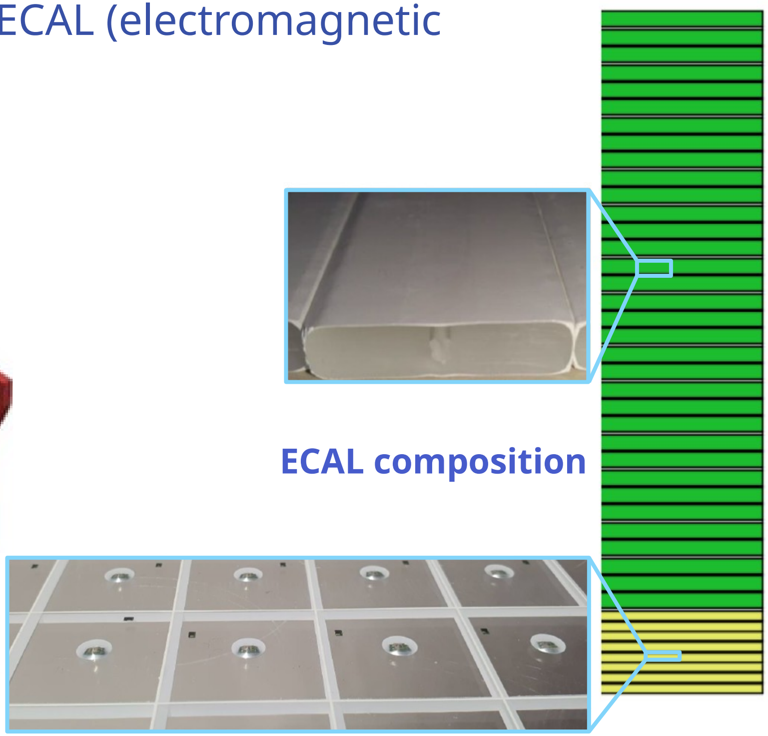
- Origin of matter (CP violation), unification of forces (proton decay), black hole formation (SN neutrinos)



Motivation for PID in ECAL of gaseous argon near detector of DUNE

- High pressure gas TPC (HPgTPC) can't detect neutral particles, but a calorimeter can
- Need to identify which neutral particle was detected in the ECAL (electromagnetic calorimeter)

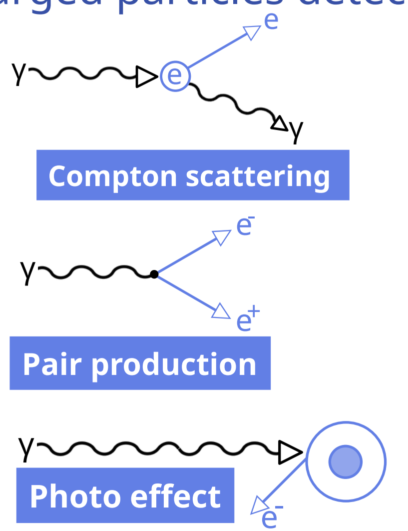


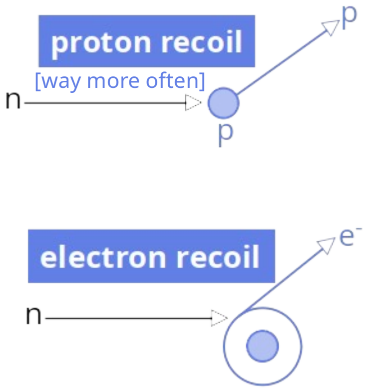


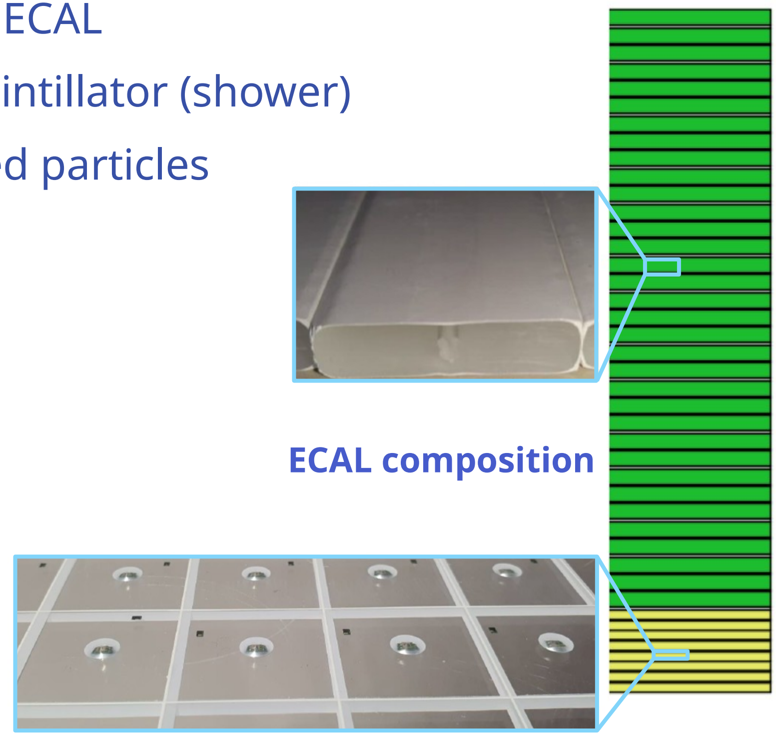
ECAL composition

Motivation for PID in ECAL of gaseous argon near detector of DUNE

- High pressure gas TPC (HPgTPC) can't detect neutral particles, but a calorimeter can
- Need to identify which neutral particle was detected in the ECAL
  - Charged particles produce light while losing energy in scintillator (shower)
  - Uncharged particles detected via interaction with charged particles

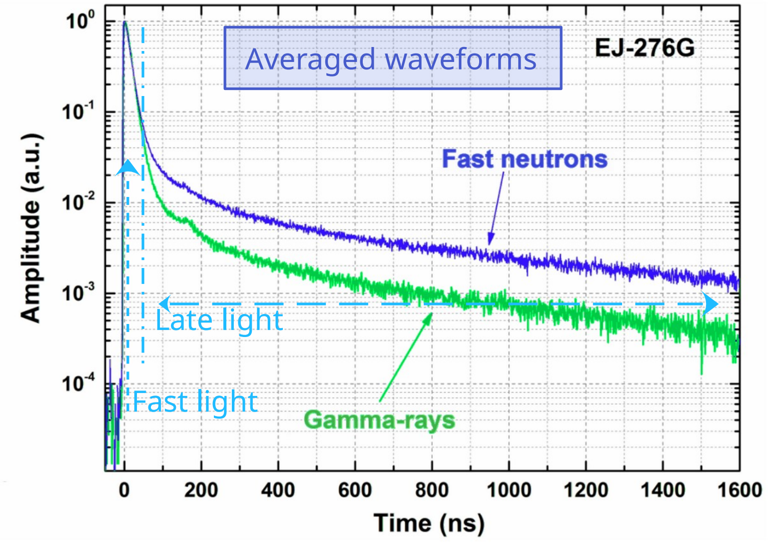






Introduction to Pulse Shape Discrimination (PSD)

- Certain scintillators have different intrinsic responses to neutron and gamma excitation → most prominent in delayed response (late light signals)
- Neutron scattering → proton recoil → proton signal

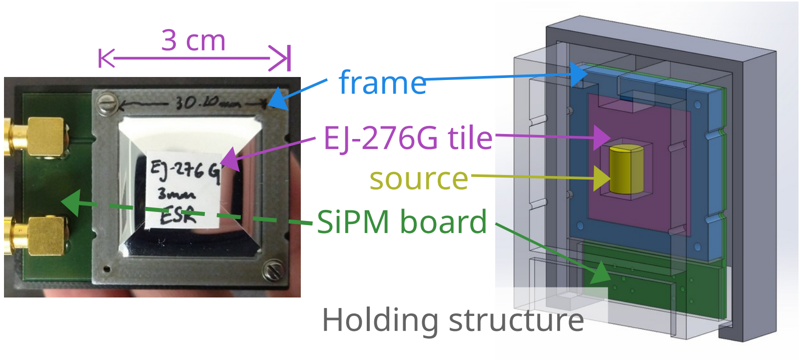


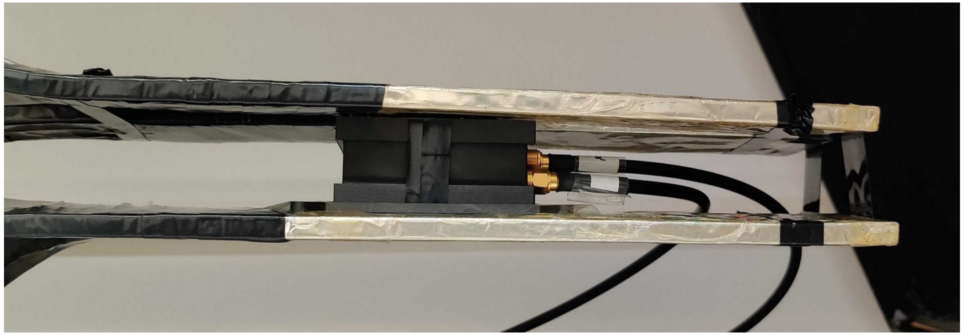
M. Grodzicka-Kobylka et al.

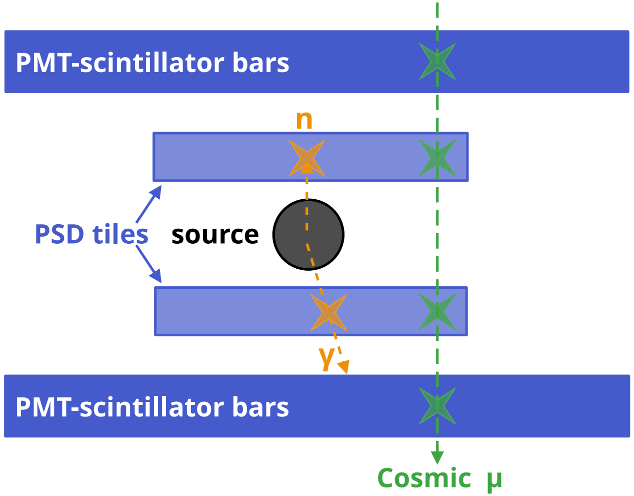
particle	Medium decay constant		Long decay constant			
Gamma	13±1 ns	84%	110±10 ns	7%	800±80 ns	9%
Neutron	14±1 ns	62%	95±10 ns	13%	800±80 ns	25%

The PSD-setup

- AmBe source emits gammas and neutrons
- Source is surrounded by 2 PSD scintillator tiles (EJ-276G) read out by SiPMs
  - Measure neutron in one tile and gamma in other in coincidence
- Cosmic muon veto above and below



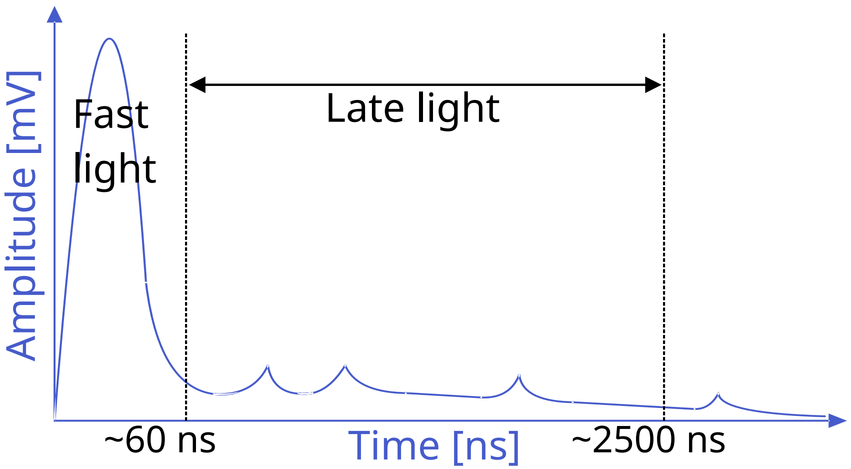




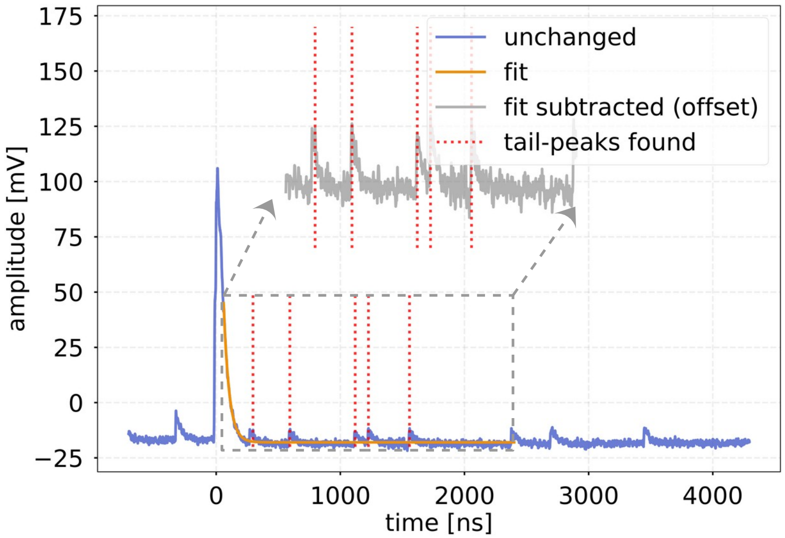
Data-taking

- Taking data with oscilloscope
- Information about time and amplitude of all peaks per event
- Compare fast component with long component light output

The expected waveform



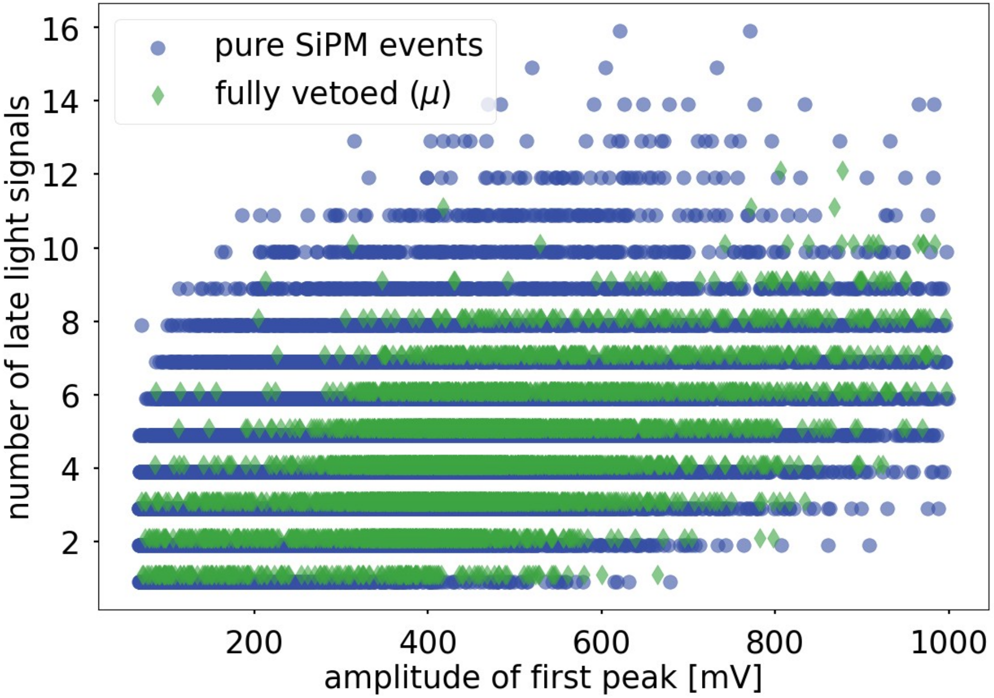
Example of a waveform

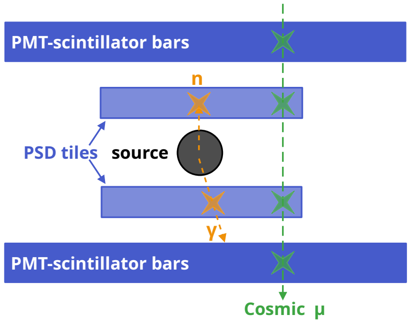


Tagging idea

Build a neutron – gamma discriminant

- Number of late light signals per event vs. amplitude of first peak

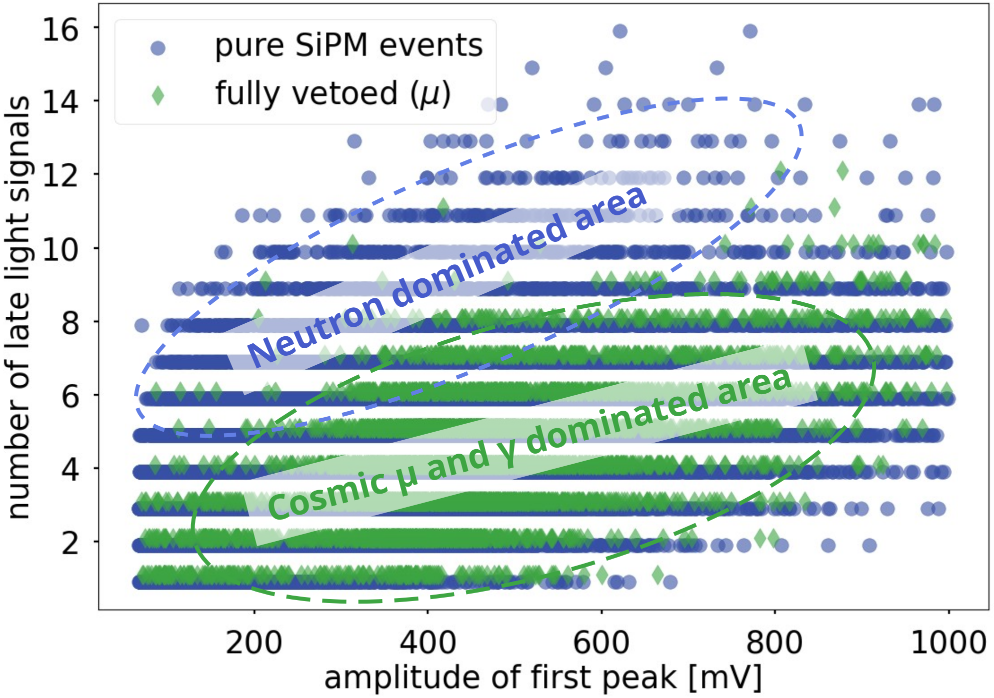


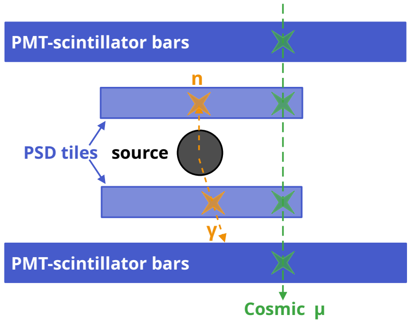


Tagging idea

Build a neutron – gamma discriminant

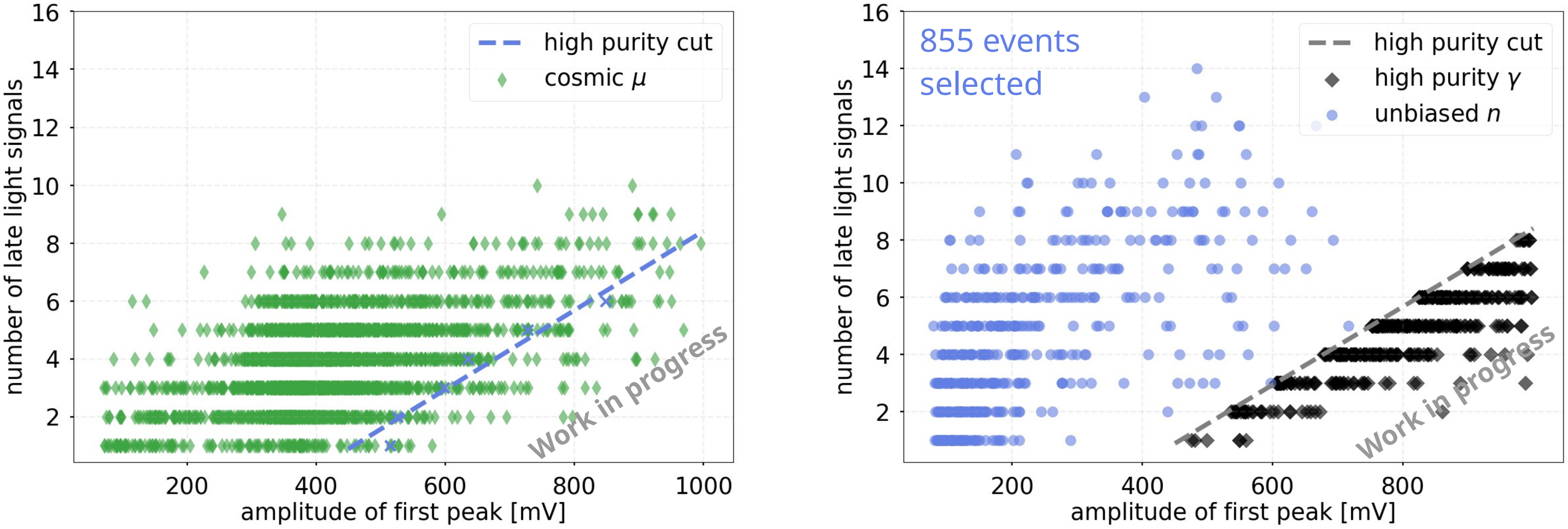
- Number of late light signals per event vs. amplitude of first peak





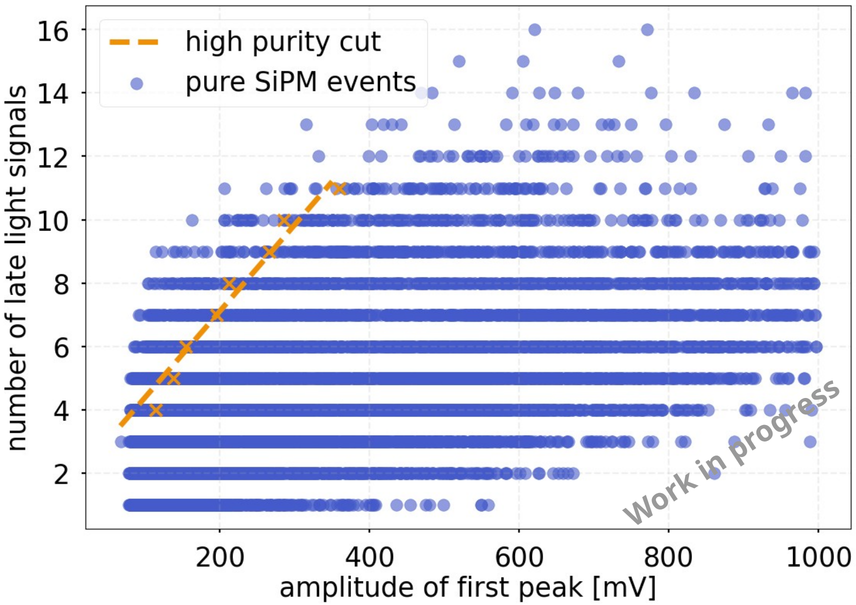
High purity γ / cosmic μ cut

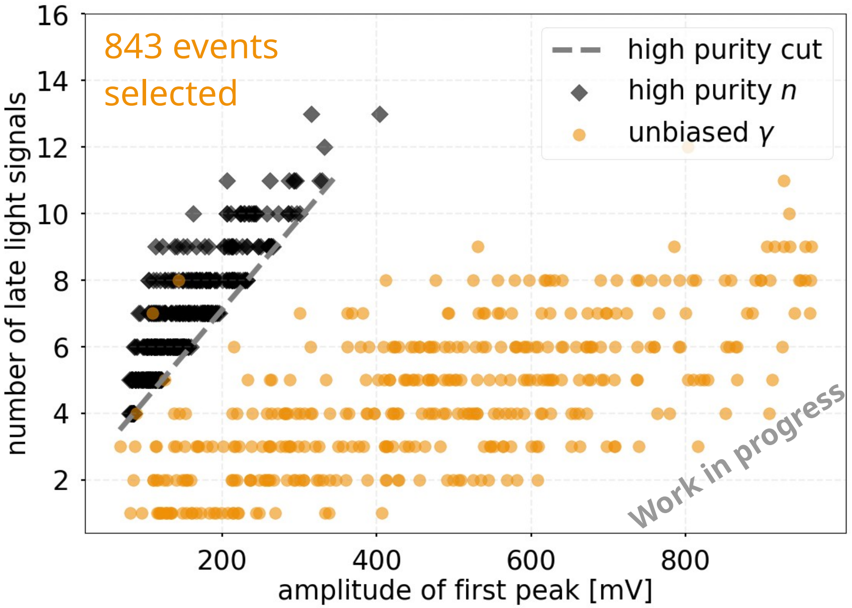
- Select cosmic muon events for neutron separation
- Step 1) determine high purity gamma cut
- Step 2) select events below cut as high purity gamma sample and corresponding events from other tile as **unbiased neutron sample**



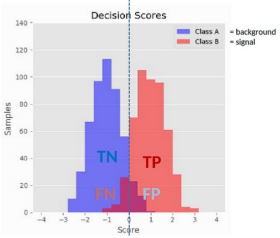
High purity neutron cut

- Step 1) determine high purity neutron cut
- Step 2) select events above cut as high purity neutron sample and corresponding events from other tile as **unbiased gamma sample**

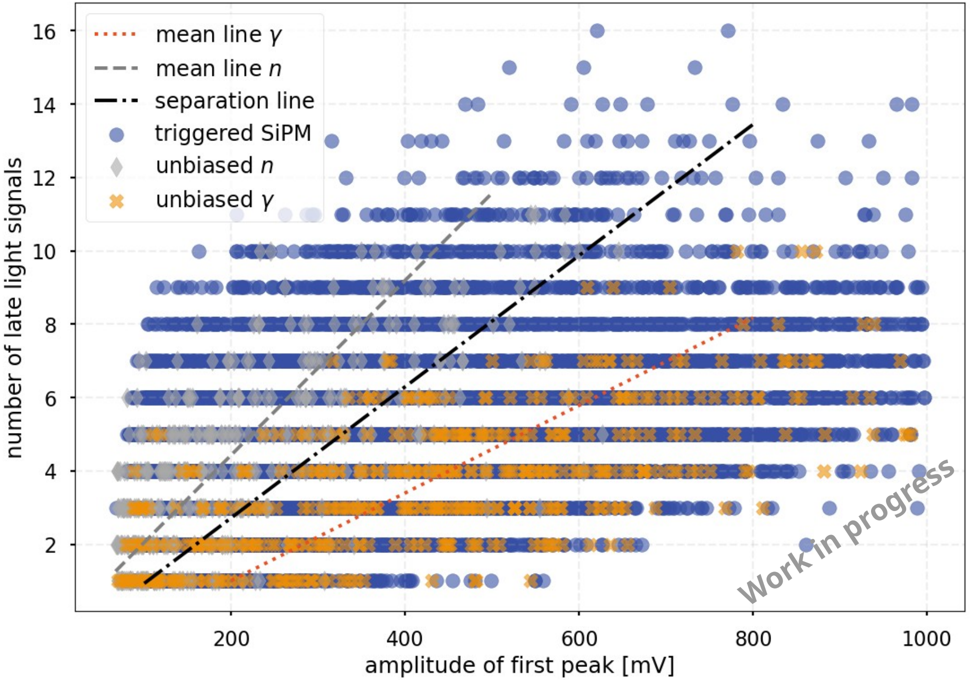


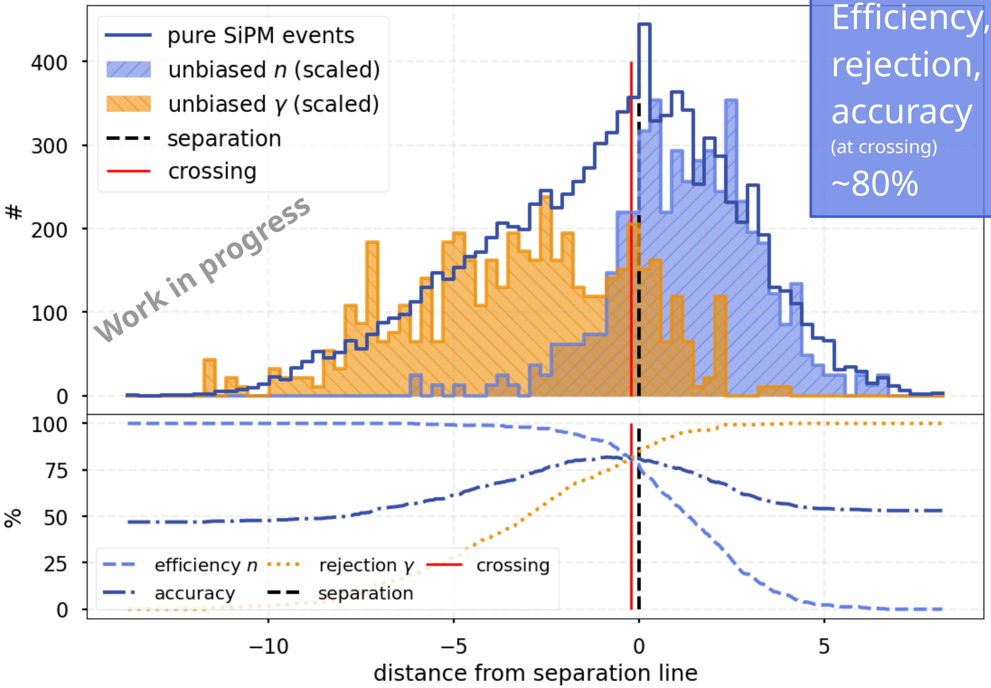


Evaluating separation power



- Calculate mean lines of unbiased distributions and take mean of those for separation of neutrons and gammas
- Calculate distance for every event from the separation line



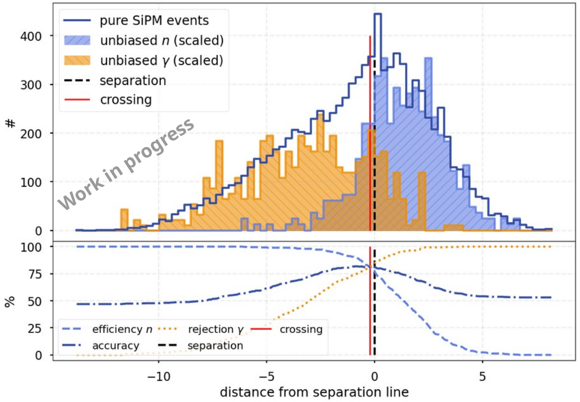


Efficiency, rejection, accuracy
(at crossing)
~80%

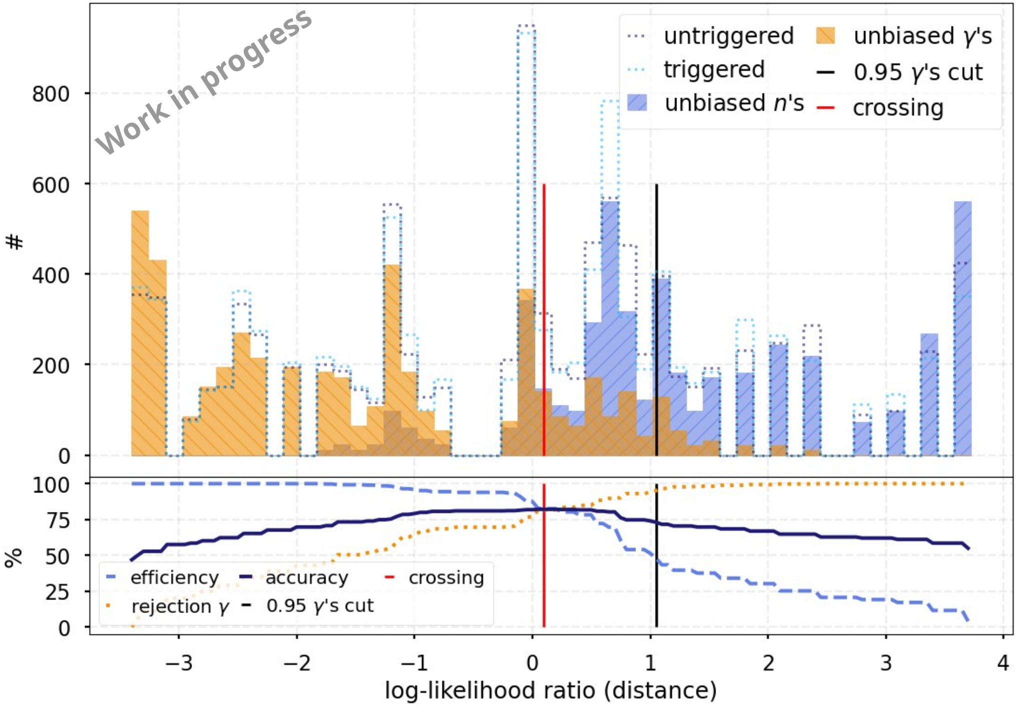
Evaluating separation power

Calculate log-likelihood ratio from distance histogram

- log(event in bin of n-histogram) – log(event in bin of γ-histogram)



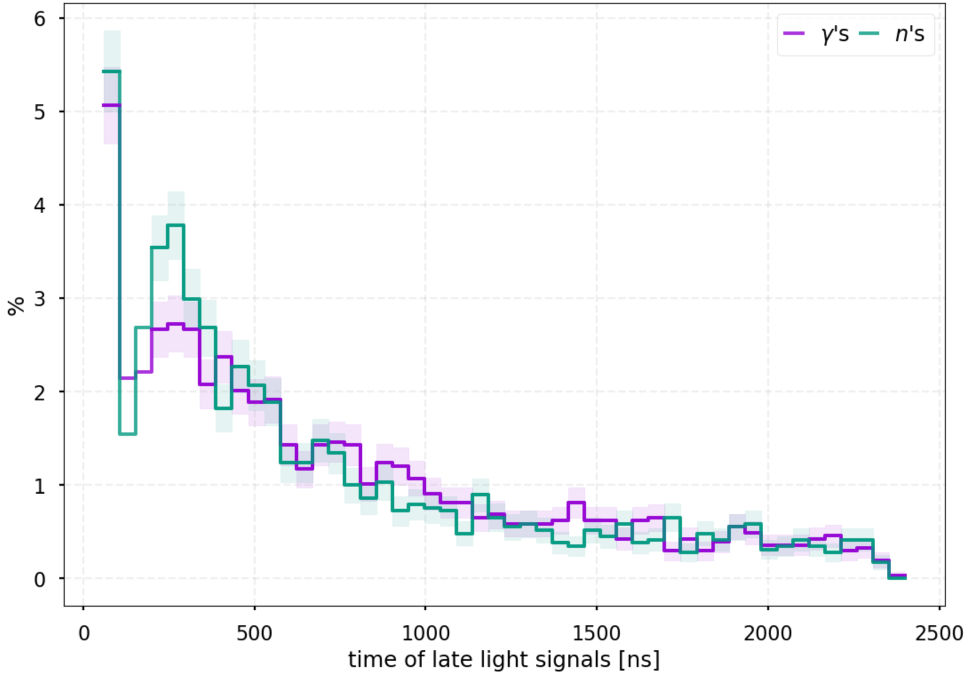
Efficiency, rejection, accuracy ~80% (at crossing)

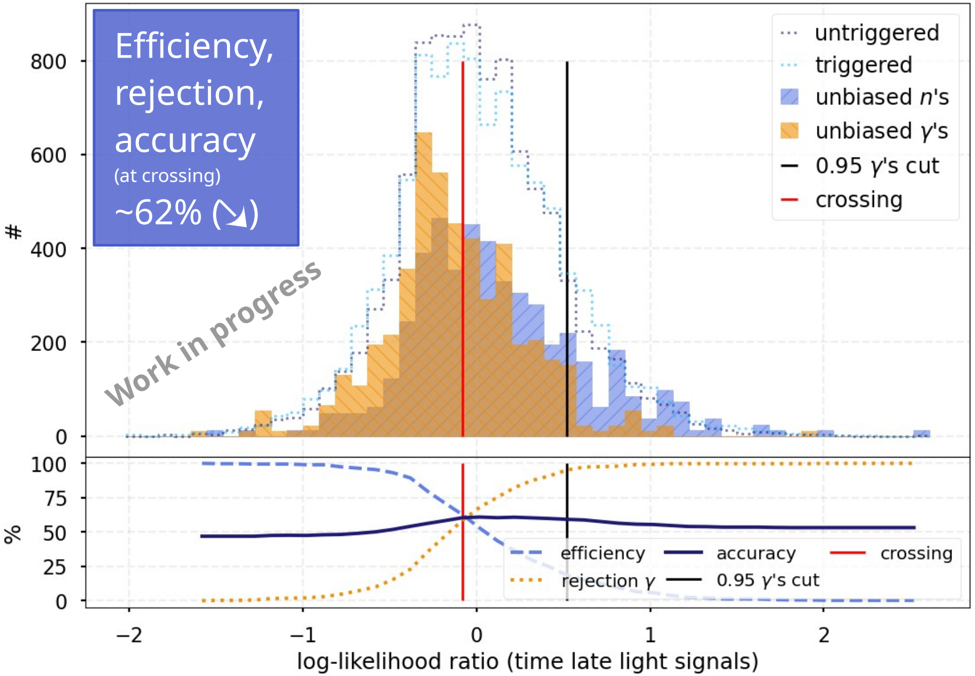


Efficiency ~76%
Rejection ~81%
Accuracy ~78%
(at crossing)

Use time information of late light

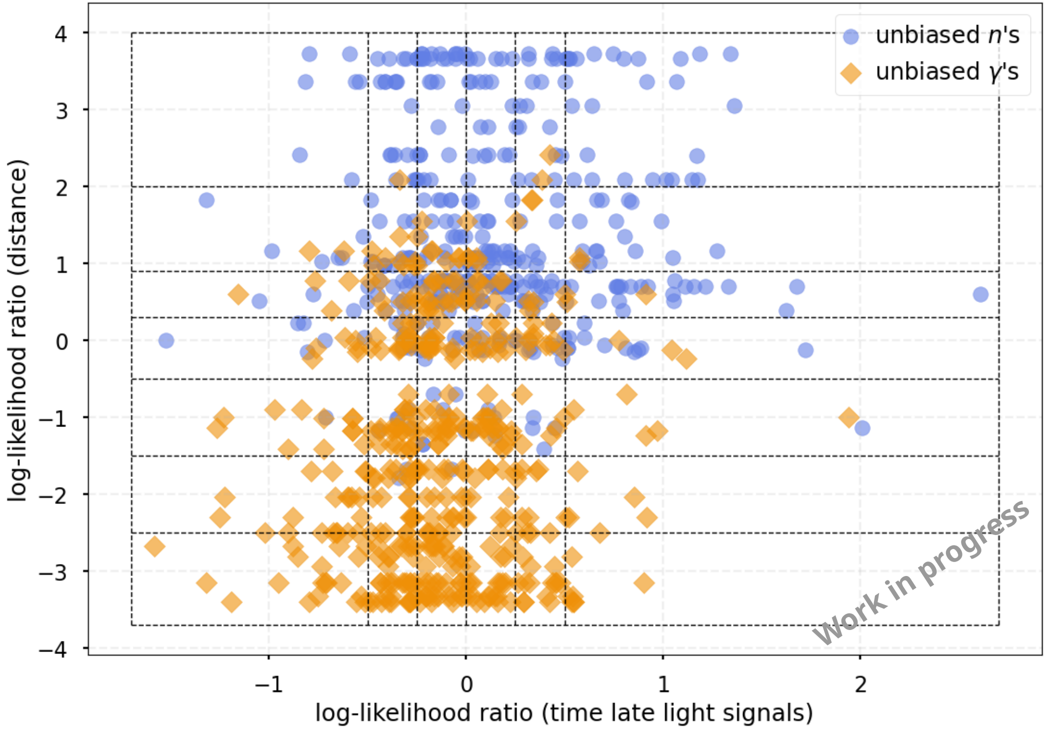
- Determine histogram of times of late light signals as probability distribution
- Calculate log-likelihood ratios of either being a neutron or a gamma from histogram





Combine distance and times

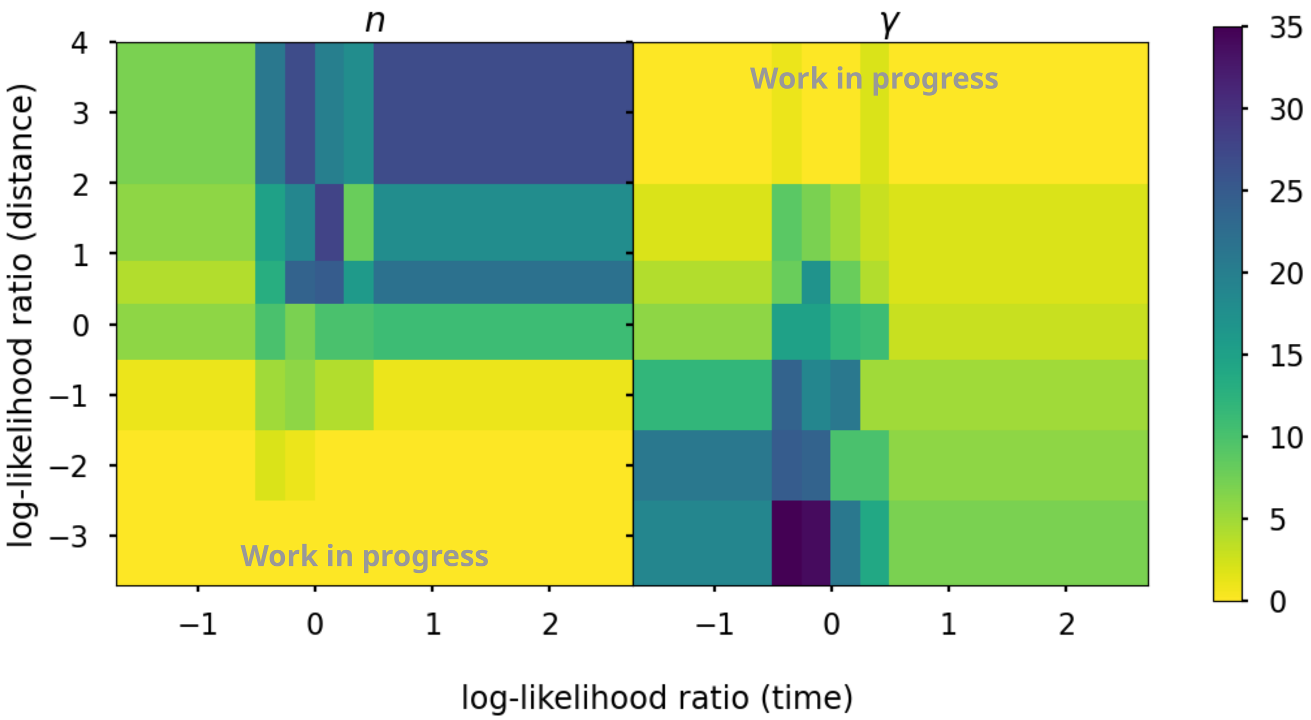
- Scatter plot of both log-likelihood ratios
- Determine (by hand) 2d histogram bin edges



Combine distance and times

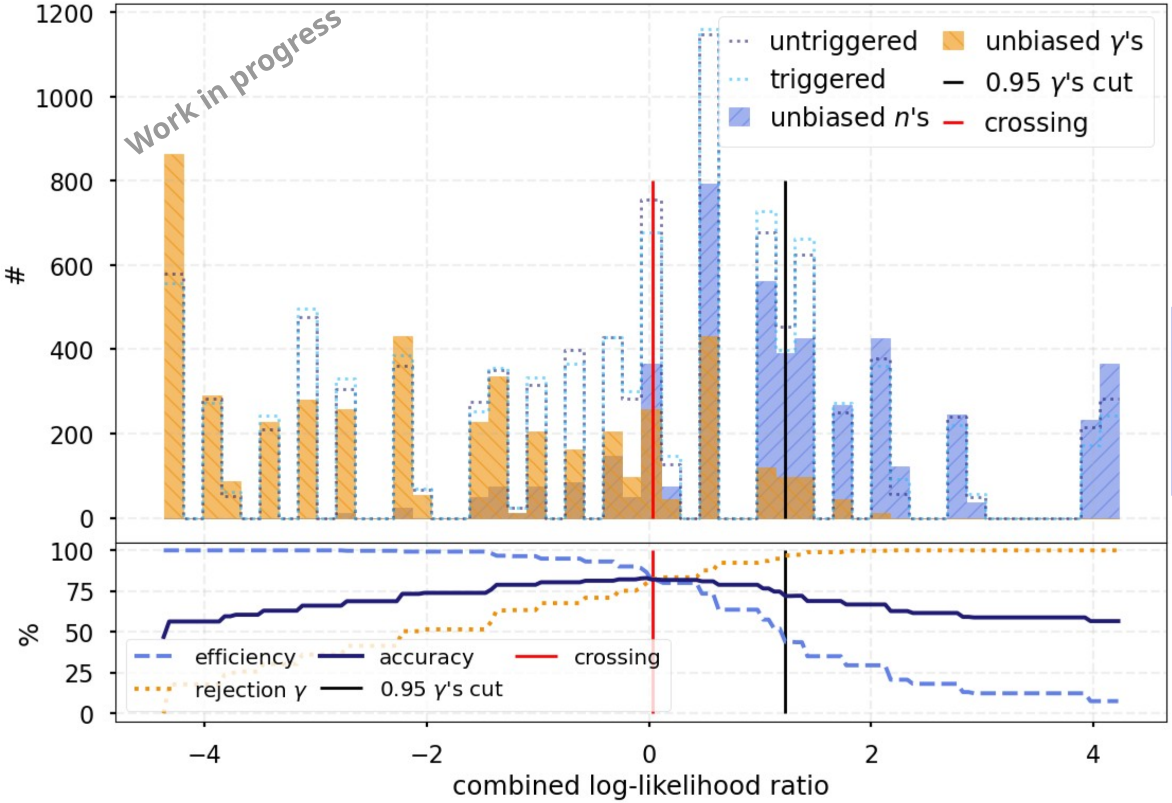
Calculate 2d histogram of unbiased neutron and gamma distributions

- Use as probability distributions for event being neutron or gamma



Combine distance and times

Calculate log-likelihood ratio of an event being a neutron or a gamma



Efficiency ~85%
Rejection ~79%
Accuracy ~83%
(at crossing)

Distance from separation line
- efficiency, rejection, accuracy ~80%

Log-likelihood ratio distance
- Efficiency ~76%
- Rejection ~81%
- Accuracy ~78%

Log-likelihood ratio time
- efficiency, rejection, accuracy ~62%

Summary and Outlook

- Developed a successful setup for neutron and gamma tagging / separation
- Tested several methods for separating the neutron and gamma distributions
  - Number of late light signals vs. amplitude of first peak
  - Time of late light signals
- Outlook
  - New data with new oscilloscope (improves data quality and makes peak finding easier)
  - Try out bigger SiPMs for expected better separation
  - Compare with standard methods
  - Prepare publication

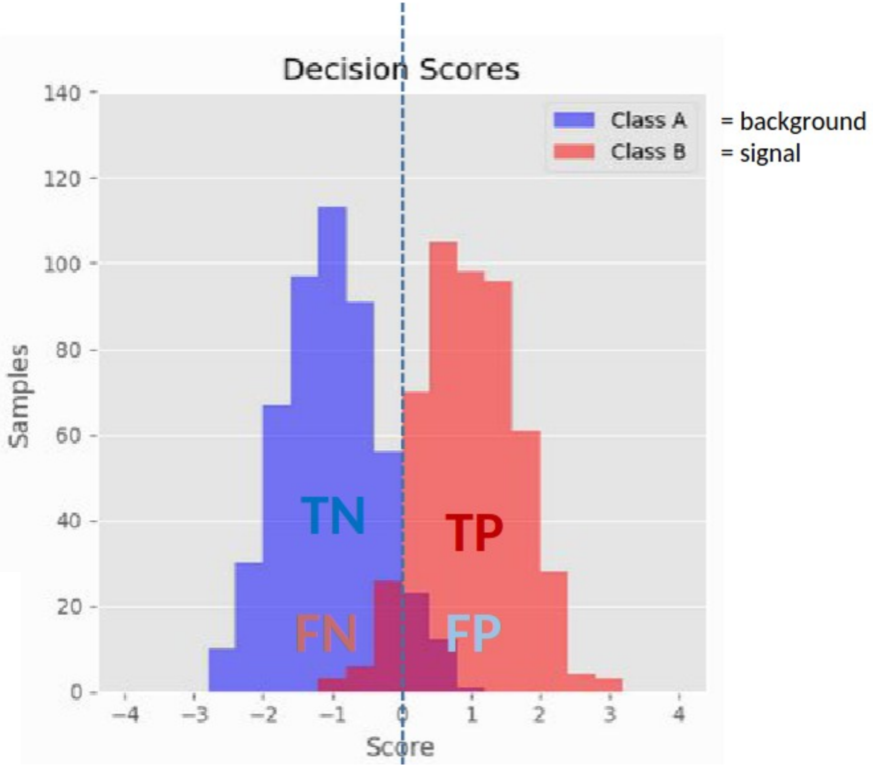
Thank you for your attention!

Backup

- Definition efficiency, accuracy
- SiPM, PMT
- Coincidence of gammas and neutrons for the new setup

Efficiency, Purity, Accuracy

- Efficiency
  - TP / (TP + FN)
- Purity
  - TP / (TP + FP)
- Accuracy
  - (TP + TN) / (TP + FP + TN + FN)



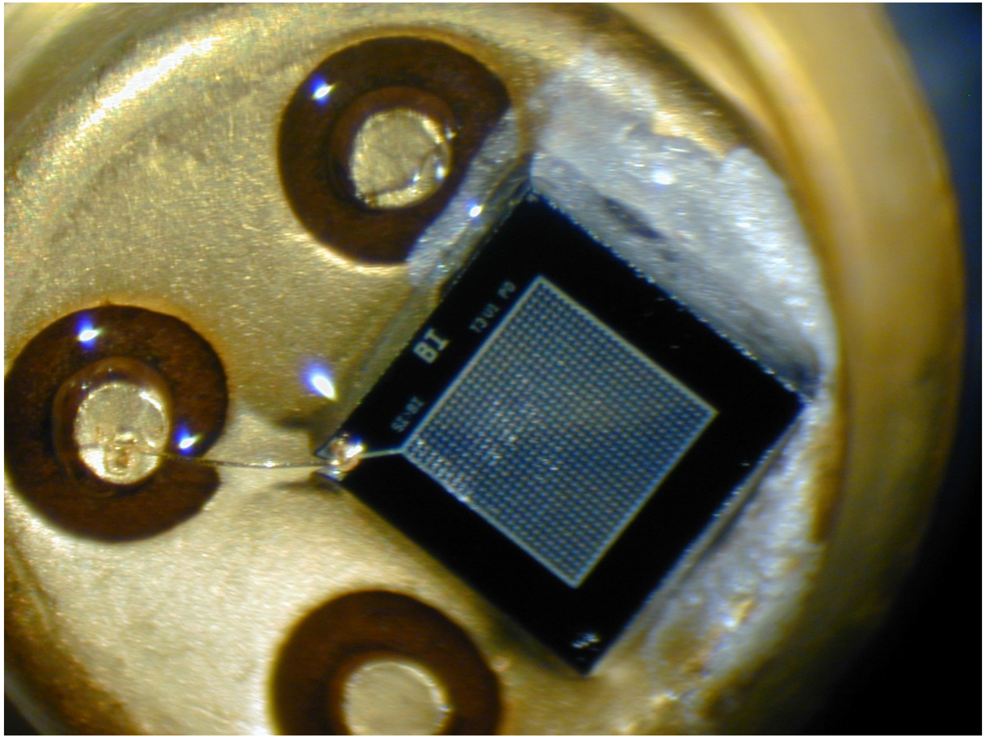
Key quantities:
- True positives (TP)
- False positives (FP)
- False negatives (FN)
- True negatives (TN)

Log-likelihood ratio times (example)

```python
def hist_distribution(hist_n, hist_g, bins, times_peaks, number):
    #get bin(s) of time-peak(s)
    middle_points = np.array([np.mean([bins[i], bins[i + 1]]) for i in range(len(bins) - 1)]);

    if int(number) == 1:
        bins_peaks = np.argmin(np.abs(times_peaks - middle_points));
    else:
        bins_peaks = analysis.bin_selection(middle_points, times_peaks);

    #sum bin height(s) for all time-peaks
    sum_gammas = 0.;
    sum_neutrons = 0.;
    if int(number) == 1:
        sum_gammas = np.log(hist_g[bins_peaks] + 0.001); # + 0.001 to avoid log(0) = inf
        sum_neutrons = np.log(hist_n[bins_peaks] + 0.001);
    else:
        for i in range(int(number)):
            sum_gammas = sum_gammas + np.log(hist_g[bins_peaks[i]] + 0.001);
            sum_neutrons = sum_neutrons + np.log(hist_n[bins_peaks[i]] + 0.001);

    #calculate ratio from both hypotheses
    ratio = sum_neutrons - sum_gammas;

    return ratio;
```

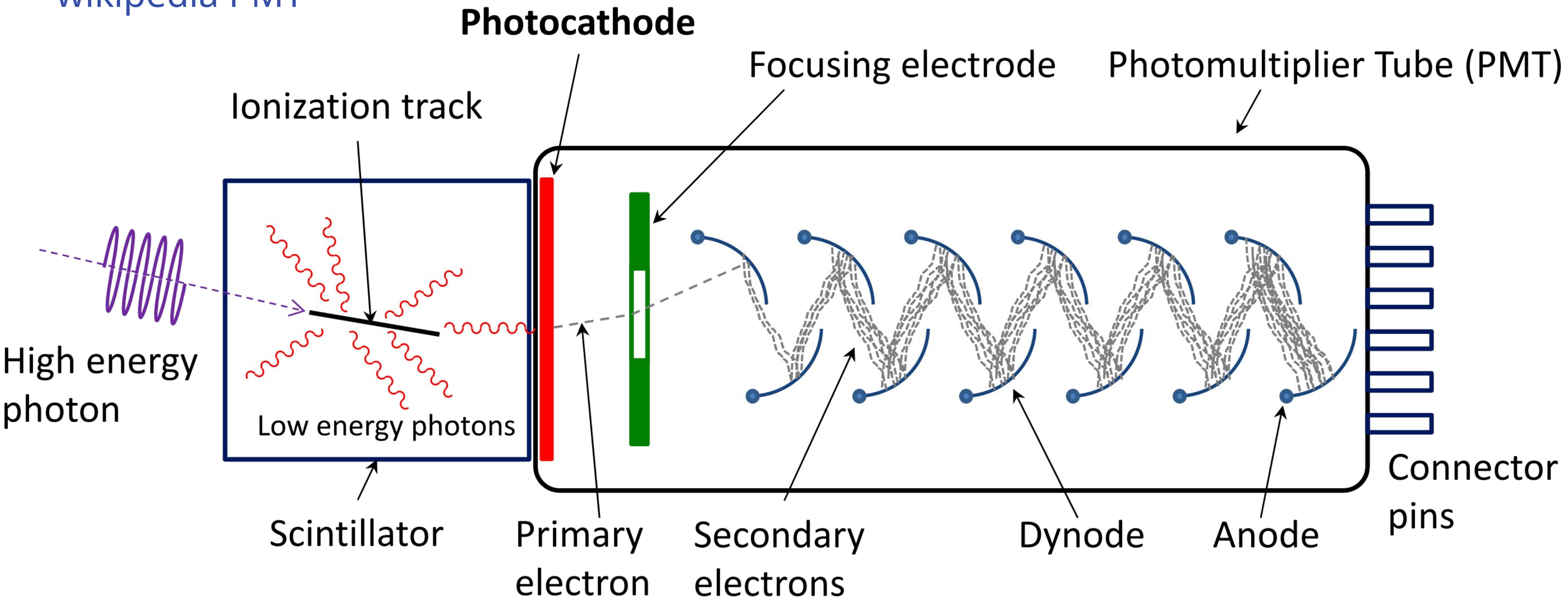
SiPM (Silicon Photo Multiplier)

wikipedia SiPM



PMT (Photo Multiplier Tube)

wikipedia PMT



Coincidence of gammas and neutrons

- Detailed summary of AmBe decay characteristics on next three slides
- Short summary:
  - α from Am ‘triggers’ decay of Be that gives the neutron
    - Am decay contains low-energy γ (not detectable)
  - Two main decay modes of Be
    - n + γ: 4.4 MeV gamma from Carbon decay occurs about 60% of the time
      - Both independently isotropic in space (without correlation)
    - n

What 12C excited state do we reach?

- Total: ~ 600 mb
- 1ES: ~ 325 mb
- ~ 55%

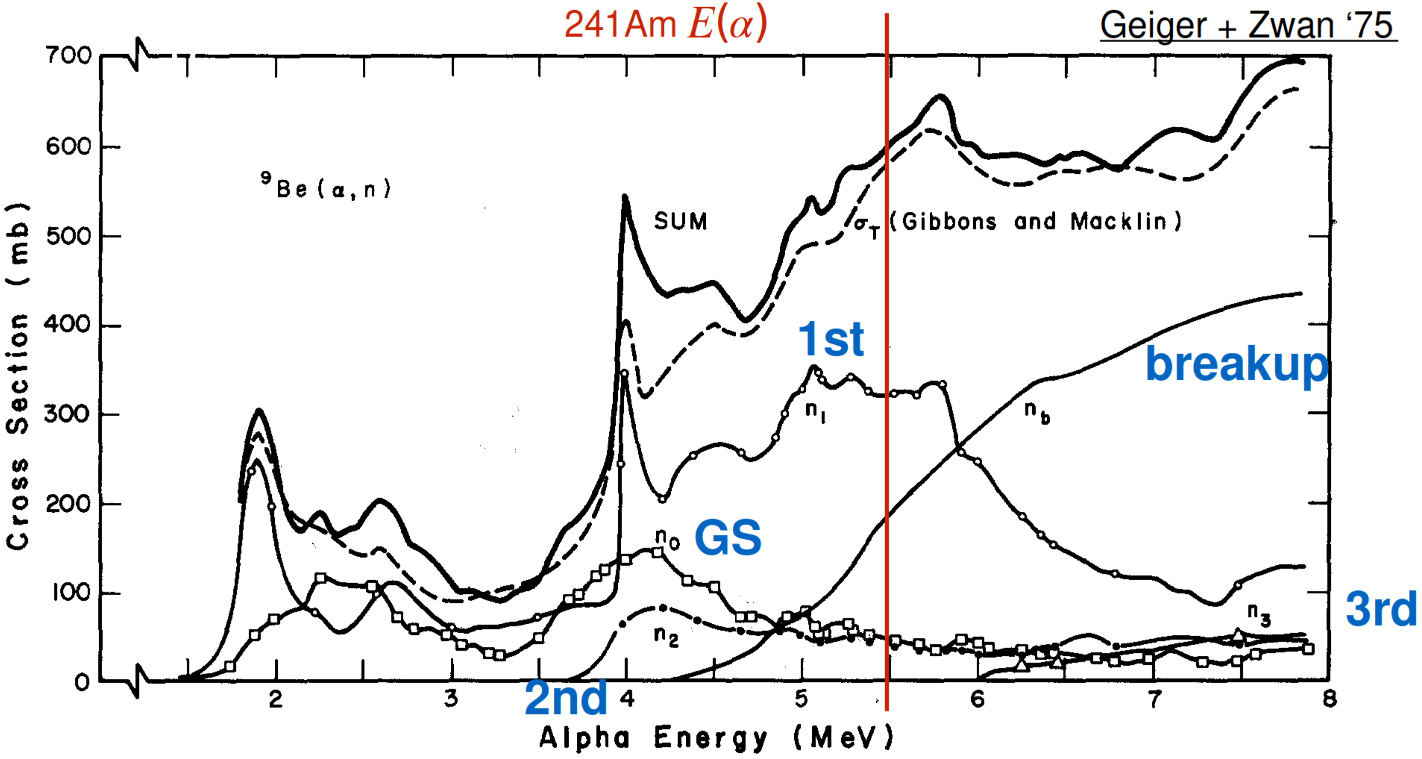


Fig. 1. Evaluated neutron production cross sections for the individual neutron groups n_0 to n_3 and for the break-up neutrons n_b. Their sum is compared to the measurement by Gibbons and Macklin[4]). The points in the curves indicate where angular distributions are available.

How often do we have the 4.4 MeV gamma?

- [Croft’89]

Table 1

A summary of $R = S_\gamma / S_n$ values drawn from the literature for various $^9Be(\alpha, n)$ sources. R is the ratio of the number of 4438 keV γ-rays to the number of neutrons produced in the source as a result of α-reactions on ^9Be

	(α, n) source	Form	R-value	Gamma detector	Year	Ref.
1	$^{210}Po/Be$	Not stated	0.62 ±0.12	estimation	1950	[17]
2	$^{210}Po/Be$	Thin Be target	0.60 ±0.06	NaI(Tl)	1954	[18]
3	RaD/Be	$RaBr_2-Be$	0.69 ±0.14	1 in. × 1 in. NaI(Tl)	1956	[19]
4	$^{239}Pu/Be$	$PuBe_{13}$	0.544 ± 0.04	NaI(Tl)	1968	[7]
5	$^{239}Pu/Be$	Not stated	1.8 ±0.3 Total γ to total n	$1\frac{1}{2}$ in. × $1\frac{1}{2}$ in. stilbene crystal with PSD	1968	[20]
6	$^{239}Pu/Be$	$PuBe_{13}$	0.59 ±0.06	calculation	1968	[21]
	$^{241}Am/Be$	$AmBe_{13}$	0.59 ±0.06	calculation		
7	$^{239}Pu/Be$	$PuBe_{13}$	0.71 ±0.11	5 in. × 4 in. NaI(Tl)	1970	[8]
	$^{241}Am/Be$	$AmBe_{13}$	0.75 ±0.11	5 in. × 4 in. NaI(Tl)		
8	$^{241}Am/Be$	AmO_2-Be	0.558 ± 0.031	3 in. × 3 in. NaI(Tl)	1986	[9]
9	$^{241}Am/Be$	AmO_2-Be	0.591 ± 0.015	101 cm^3 HPGe	1988	this work
			0.566 ± 0.057	calculation		

Gamma spectrum

[Mowlavi, Koohi-Fayegh'04]

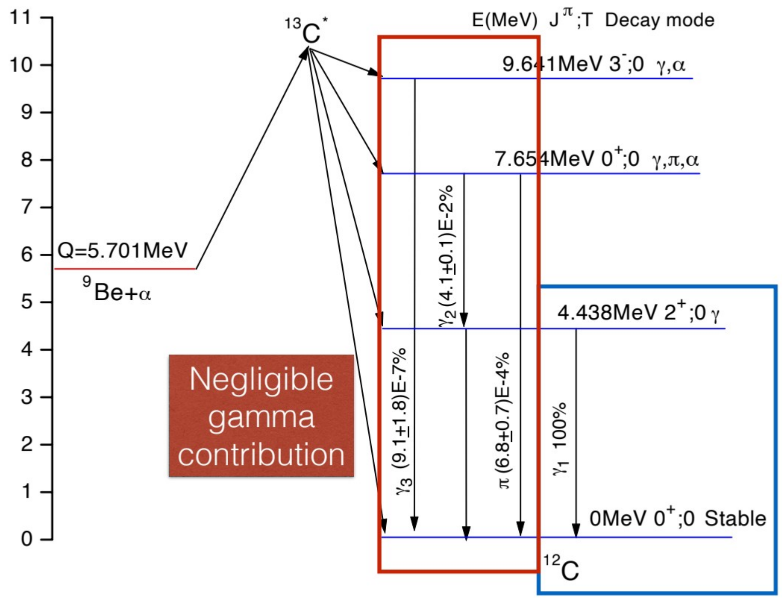


Fig. 1. Energy level diagram for ^{12}C indicating the electromagnetic transition.

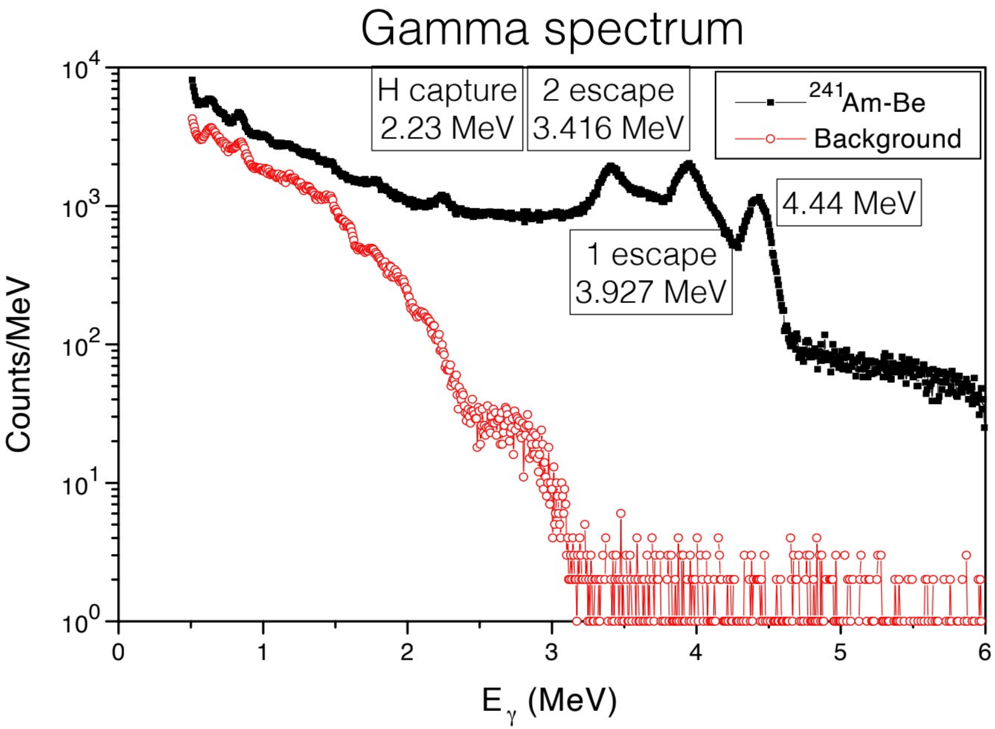


Fig. 2. ^{241}Am–^{9}Be source and background pulse height γ-ray spectra measured with a 2″ × 2″ NaI(Tl) detector.