Novel „PSD“ techniques in the context of Double Chooz

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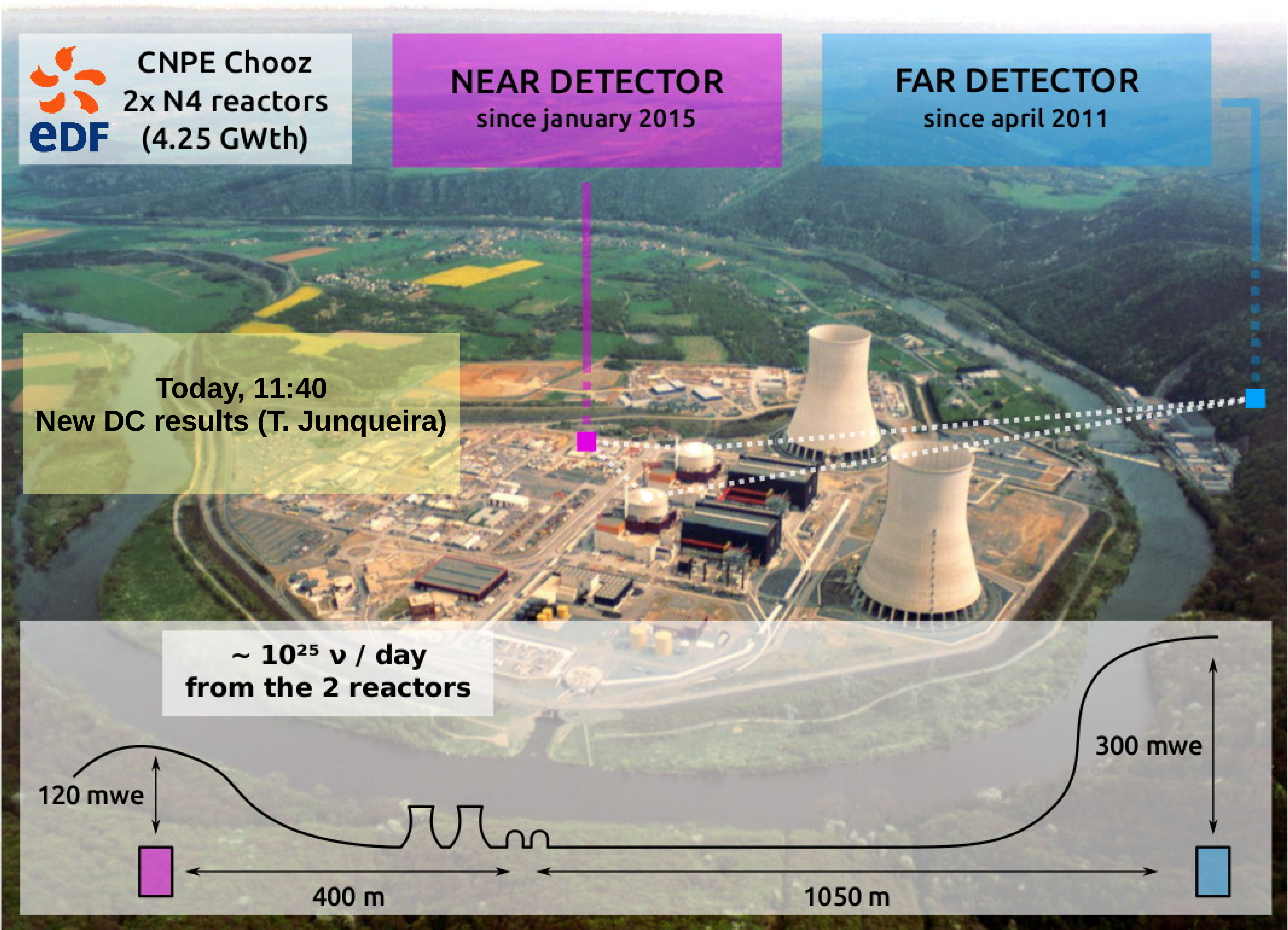
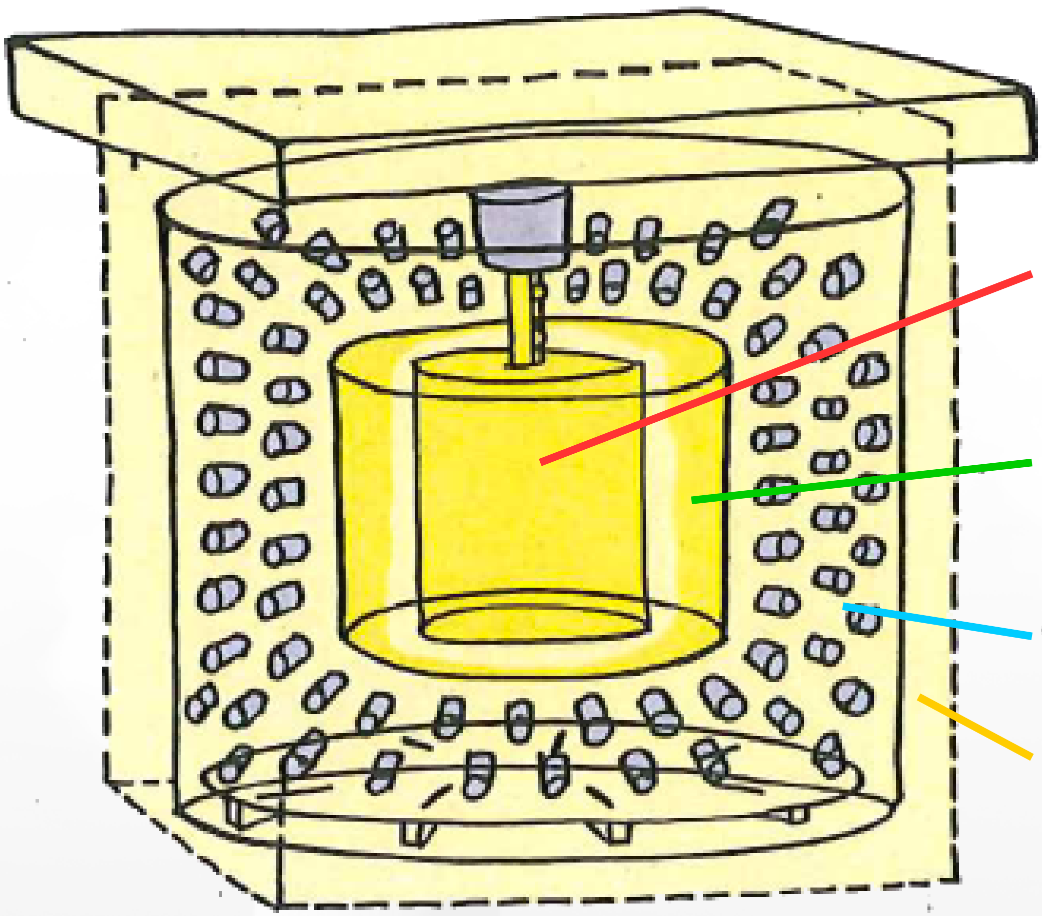
GDR meeting, LPNHE, 21/11/2017

Overview

- Introduction
- Motivation
- Comparison of PSD techniques
- Particle identification
- Conclusions


CNPE Chooz
2x N4 reactors
(4.25 GWth)
NEAR DETECTOR
since january 2015
FAR DETECTOR
since april 2011
Today, 11:40
New DC results (T. Junqueira)
~ 10^{25} ν / day
from the 2 reactors
120 mwe
300 mwe
400 m
1050 m

Liquid scintillator antineutrino detector



Design of modern LANDs:

Target: Gd-doped LS volume for neutrino detection

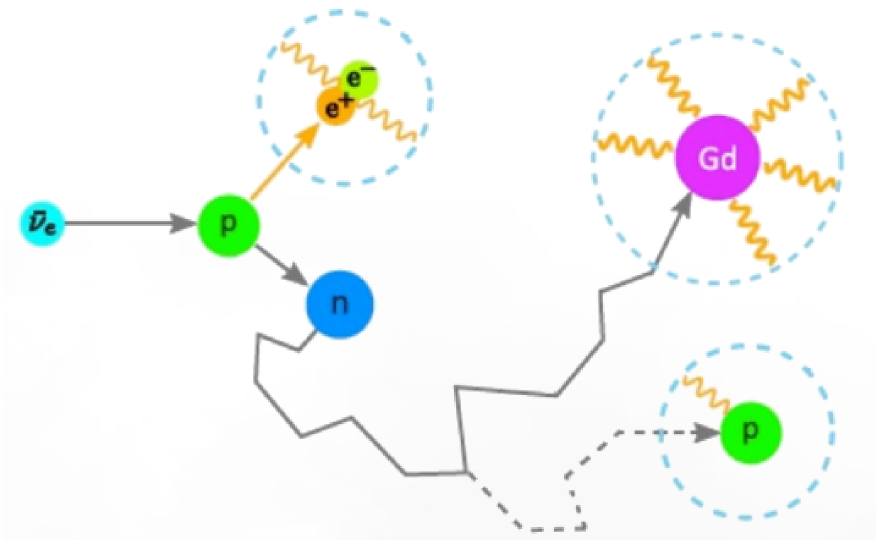
Gamma Catcher: unloaded LS for energy reconstruction

Buffer: transparent mineral oil

Inner Veto: surrounding LS for muon rejection

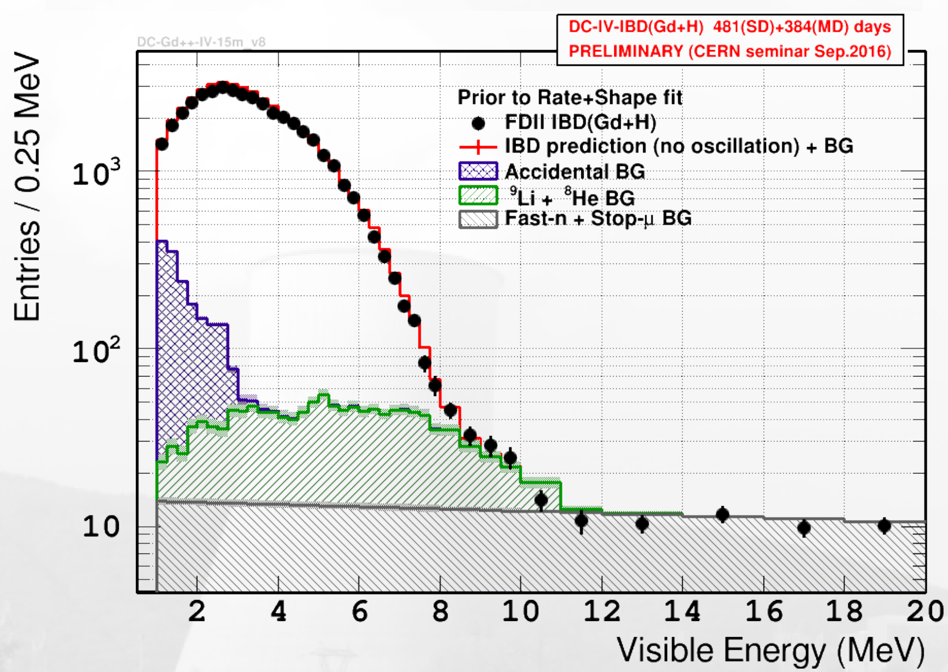
In the end, all we see is just light...

Identifying antineutrinos



IBD as antineutrino detection reaction: $\boldsymbol{\nu} + \mathbf{p} \longrightarrow \mathbf{e}^{+} + \mathbf{n}$

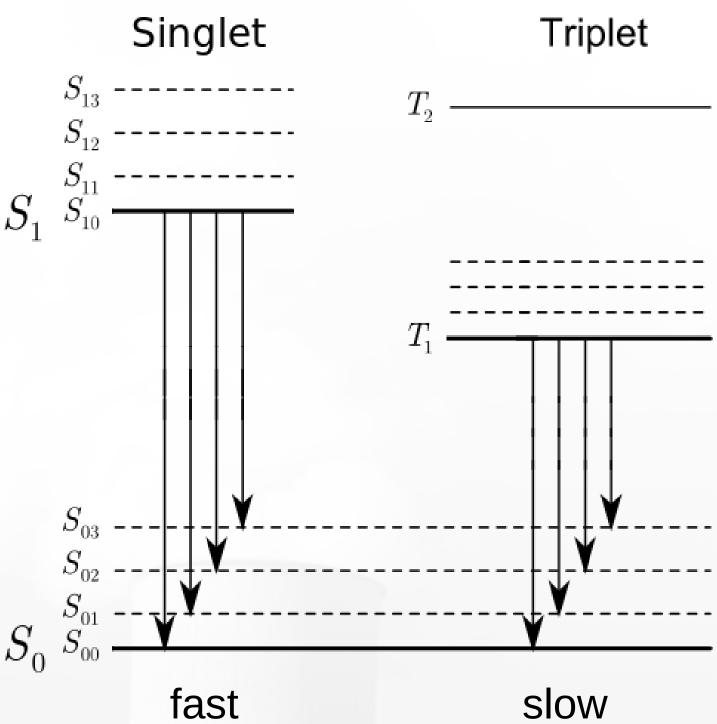
Muon veto and coincidence signature rejects most of the background



Remaining background has to be treated statistically

What about scintillation pulse shapes?

Scintillation waveforms depend on particle



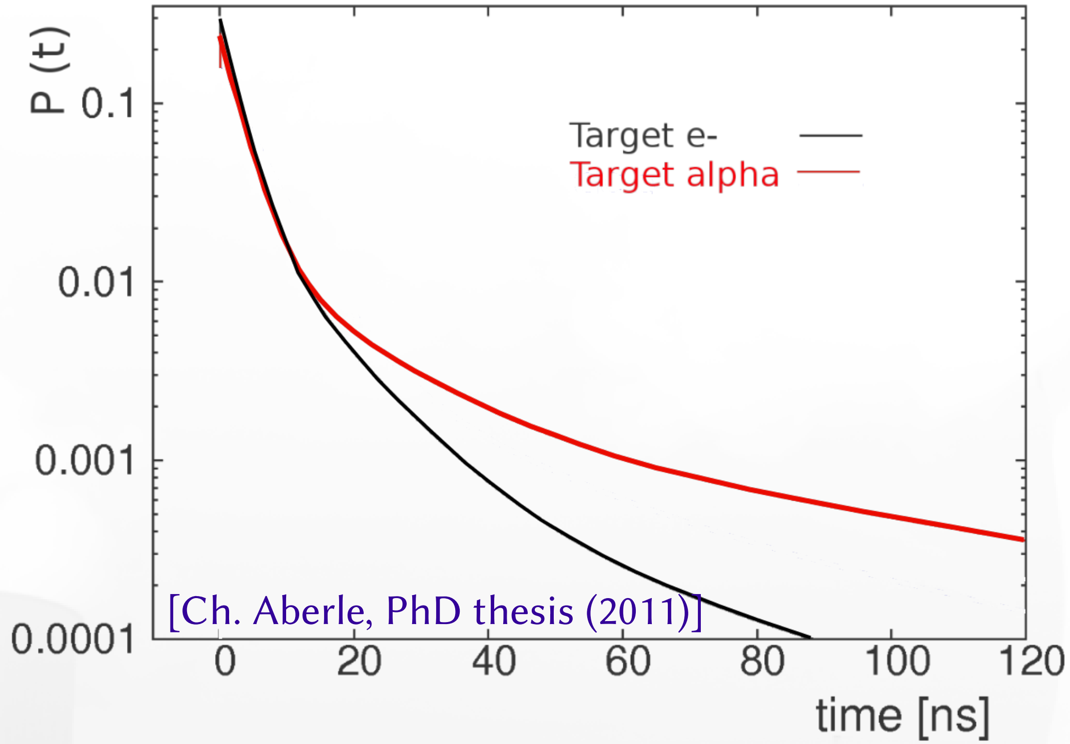
Different energy deposition mechanisms ⟨dE/dx⟩

Different ratios of excited singlet and triplet states

Different scintillation decay time profiles

What about scintillation pulse shapes?

Scintillation waveforms depend on particle

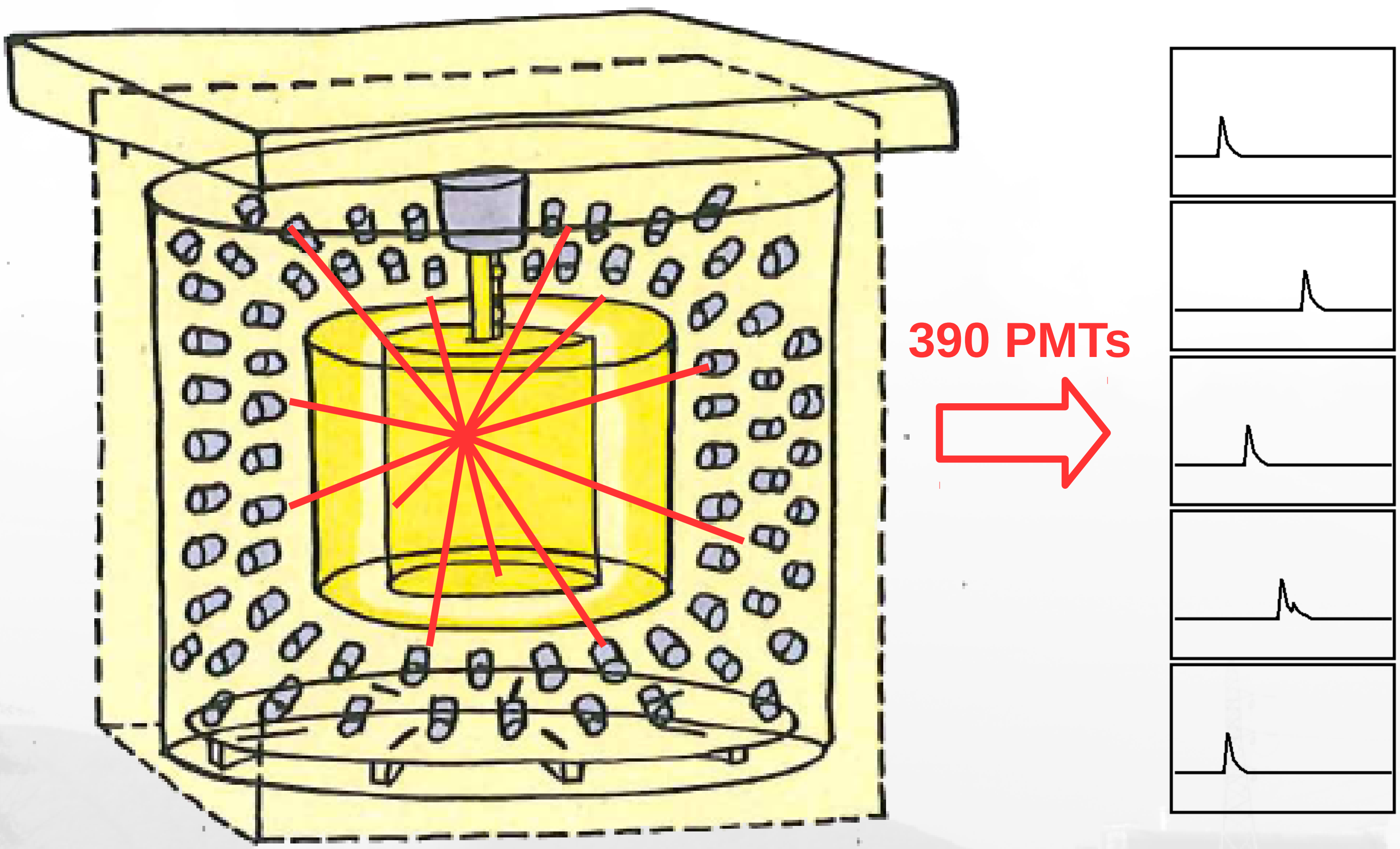


[Ch. Aberle, PhD thesis (2011)]

Can we exploit this in a large detector?

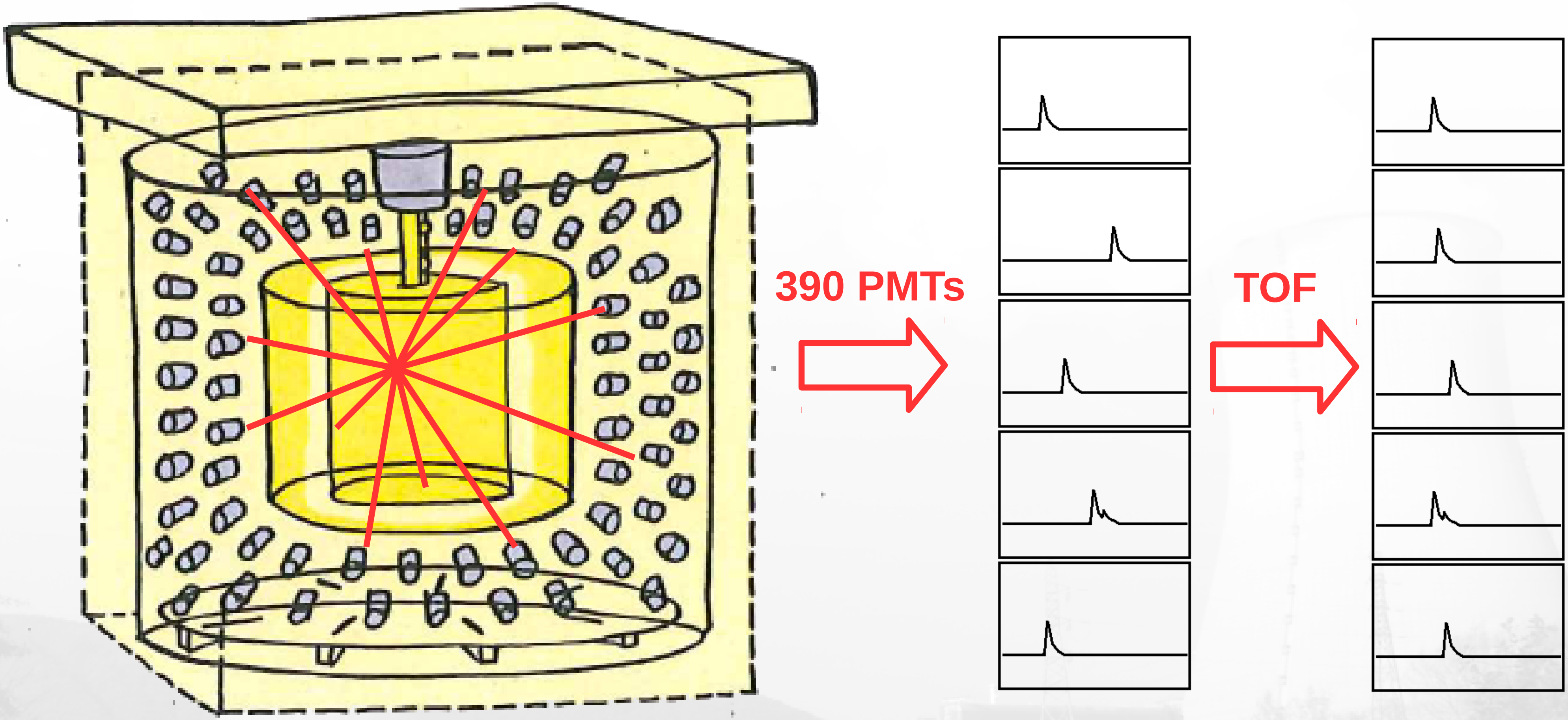
What about scintillation pulse shapes?

The scintillation waveform, as seen by the detector, is obtained by taking the 390 PMT signals



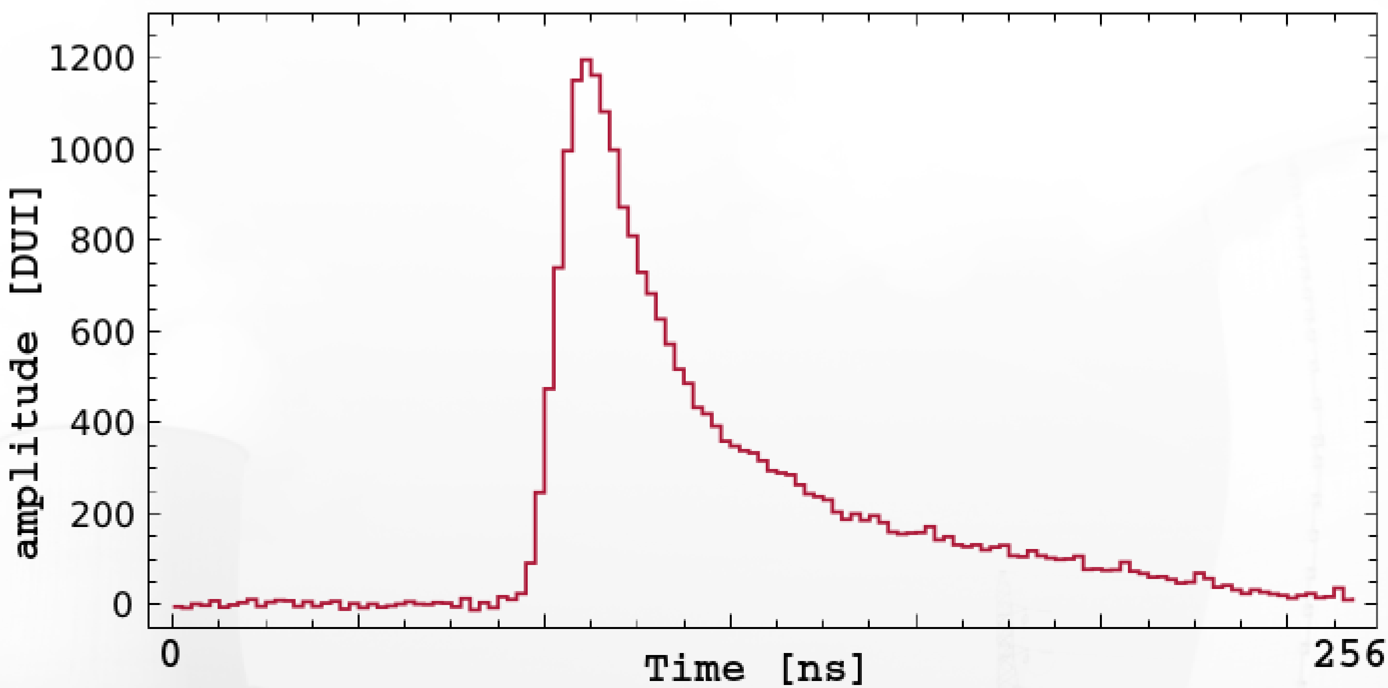
What about scintillation pulse shapes?

The scintillation waveform, as seen by the detector, is obtained by taking the 390 PMT signals, correcting them for the photon time of flight in the LS, and adding them up.



What about scintillation pulse shapes?

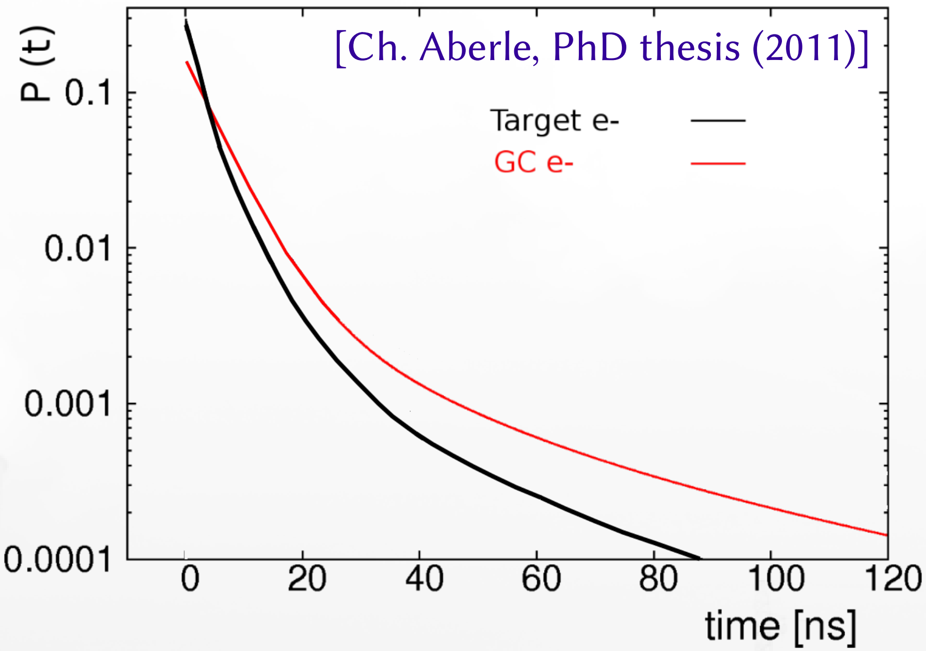
The scintillation waveform, as seen by the detector, is obtained by taking the 390 PMT signals, correcting them for the photon time of flight in the LS, and adding them up. The result looks more or less like this:



Testing PSD methods

<u>Test:</u> separation of Gamma Catcher and Target volumes

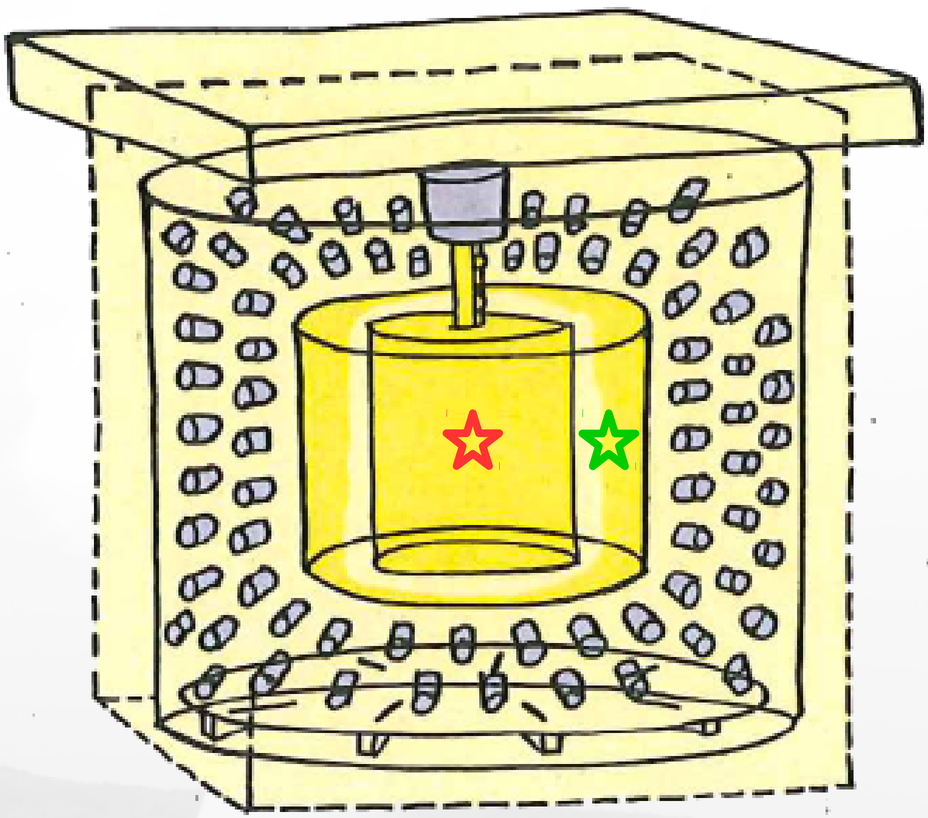
Since the two scintillators have different chemical compositions, they also have rather different pulse shapes



Can we still see differences in a large detector?

What about scintillation pulse shapes?

We tested different established techniques for separation of events in Target and Gamma Catcher volumes (different chemical composition)



Use calibration source in **Target** and **Gamma Catcher** centers

What about scintillation pulse shapes?

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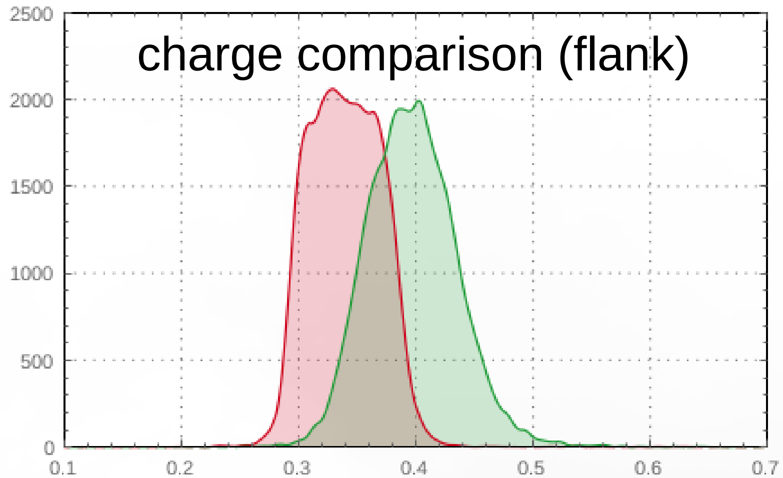
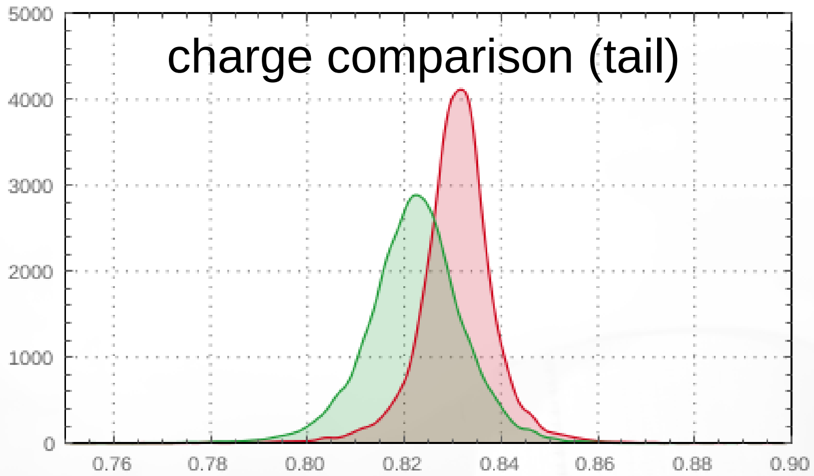
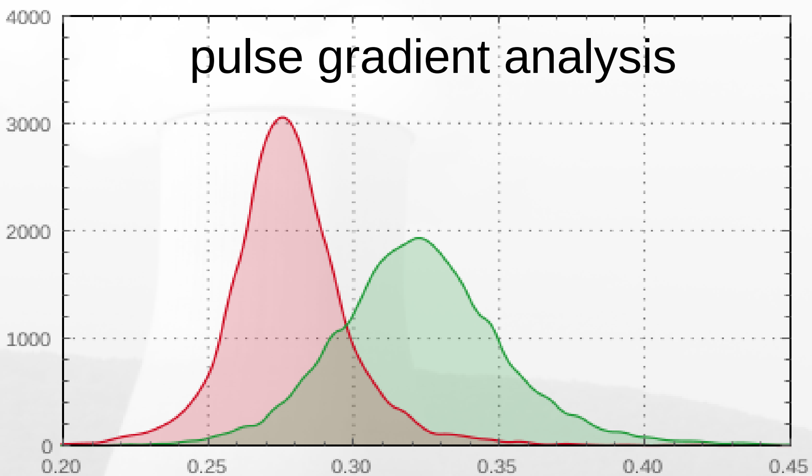
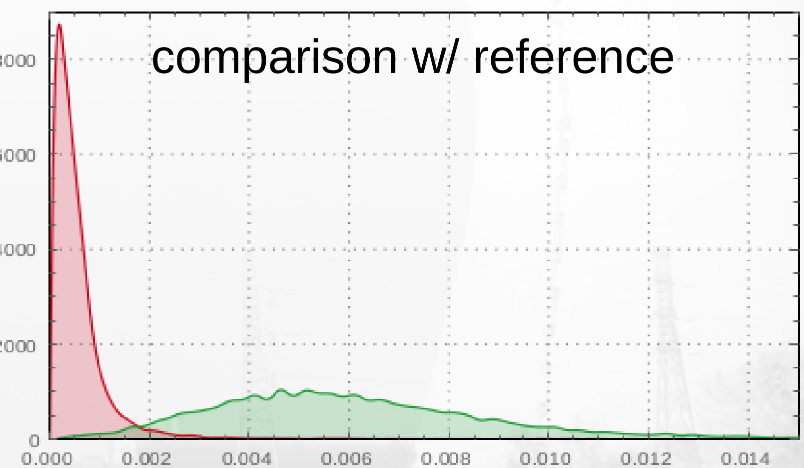


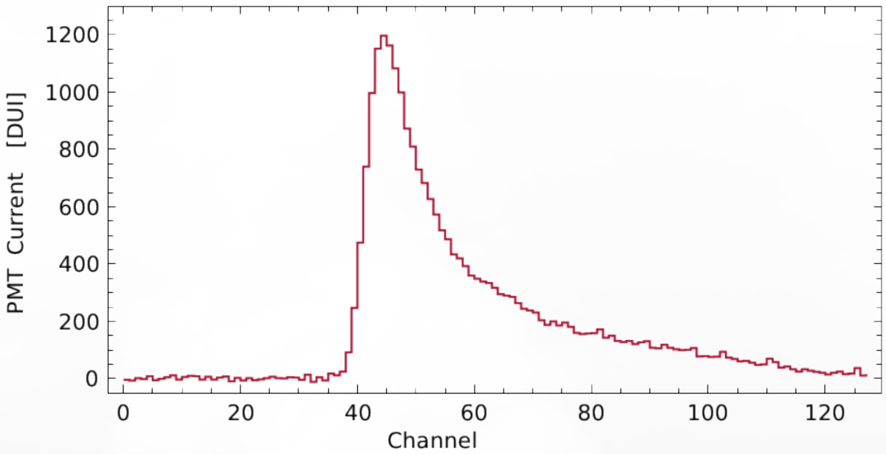


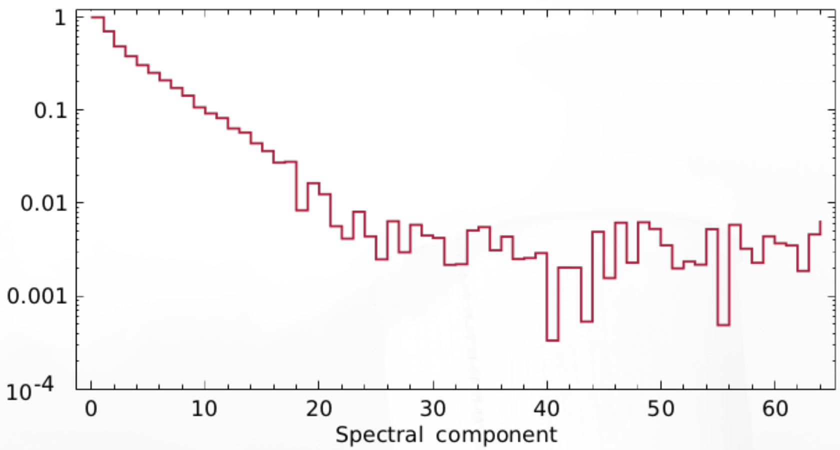




What about scintillation ~~pulse shapes~~ power spectra?

A new approach: look at the Fourier power spectra of the waveforms



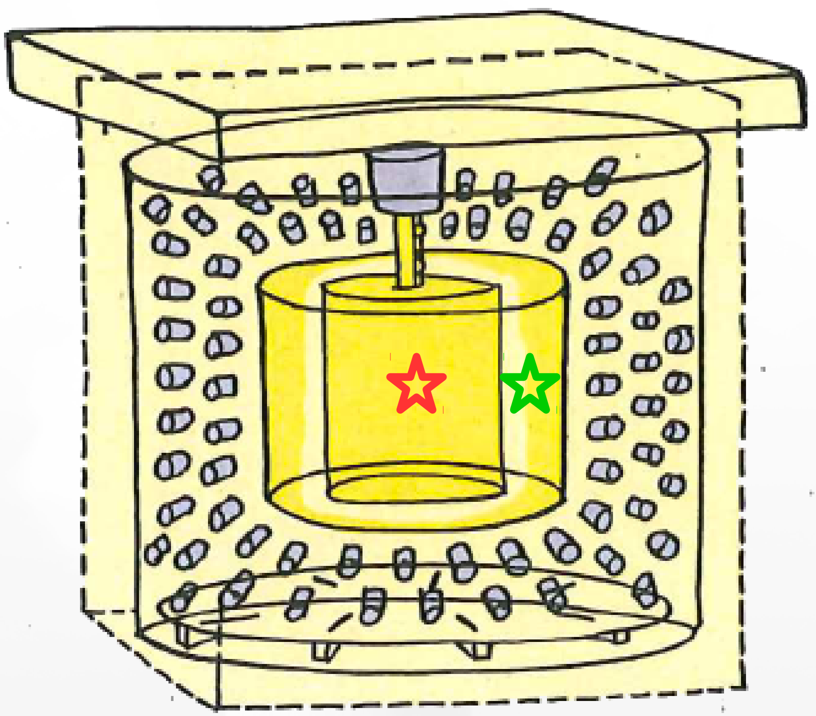


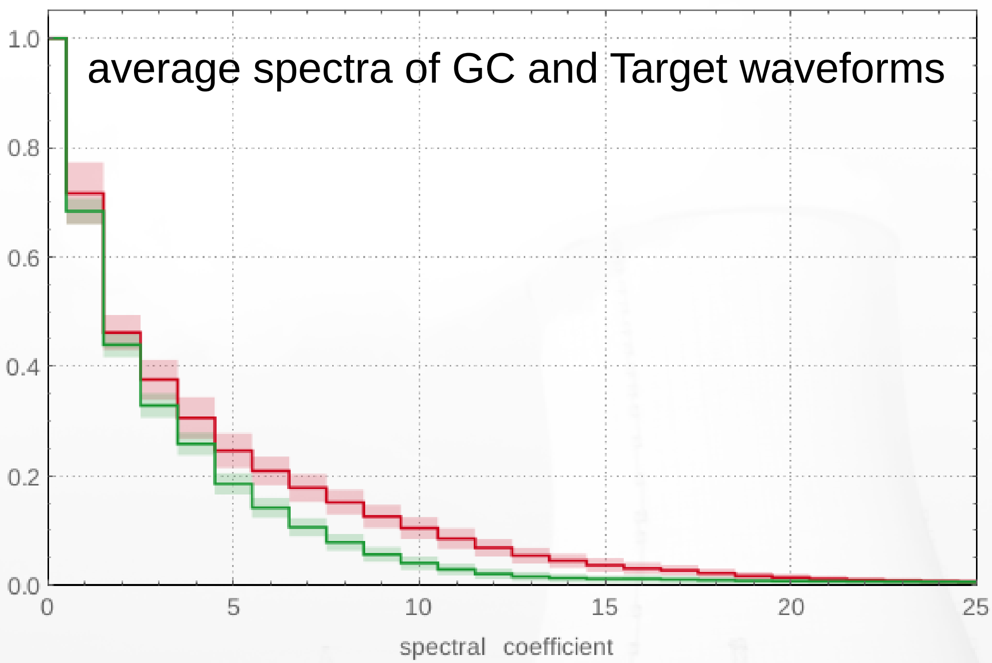
$$\mathscr{F}_j\{p(t)\} = \sum_{j=0}^{k-1} p(t)\, e^{-2\pi i\, j\omega_j/k} \qquad s_j := \left|\mathscr{F}_j\{p(t)\}\right|$$

Power spectrum can reveal characteristics that are hidden in the time domain

What about scintillation ~~pulse shapes~~ power spectra?

Indeed, spectra of the Target and the GC look quite different:





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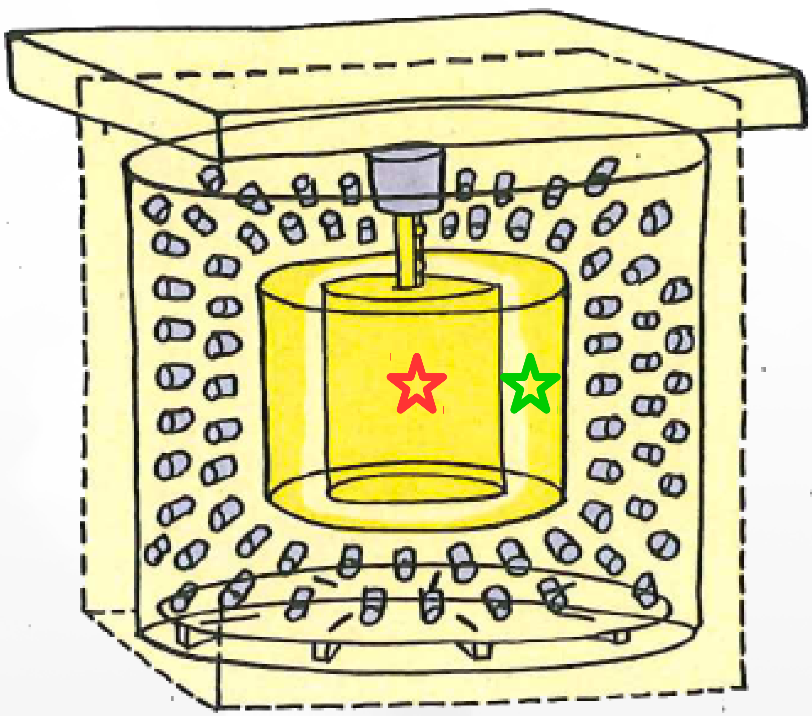
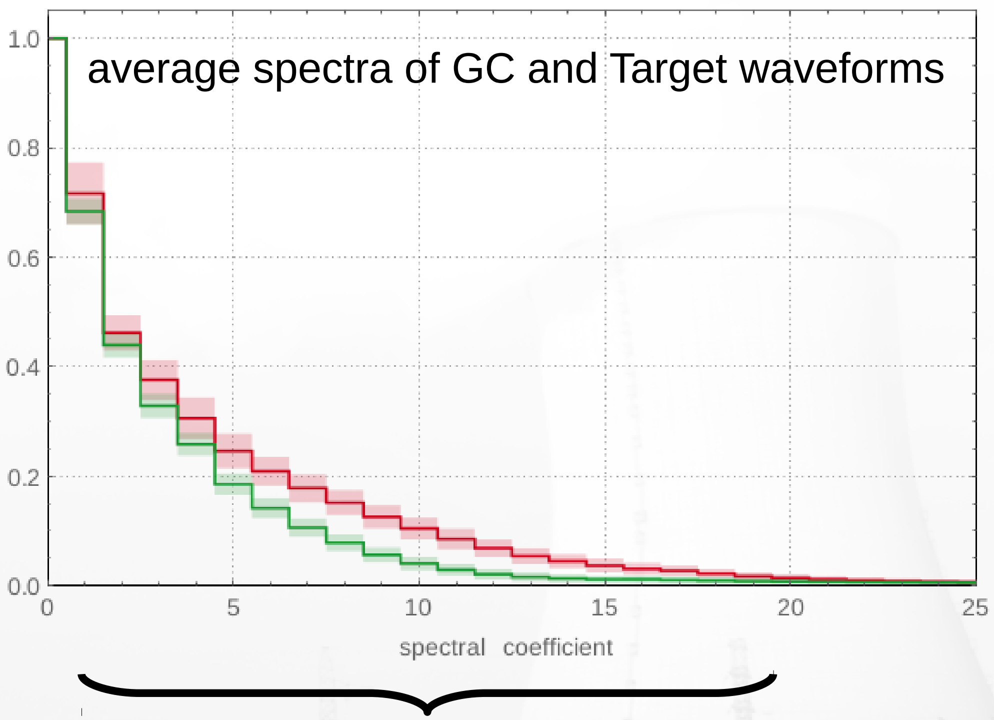
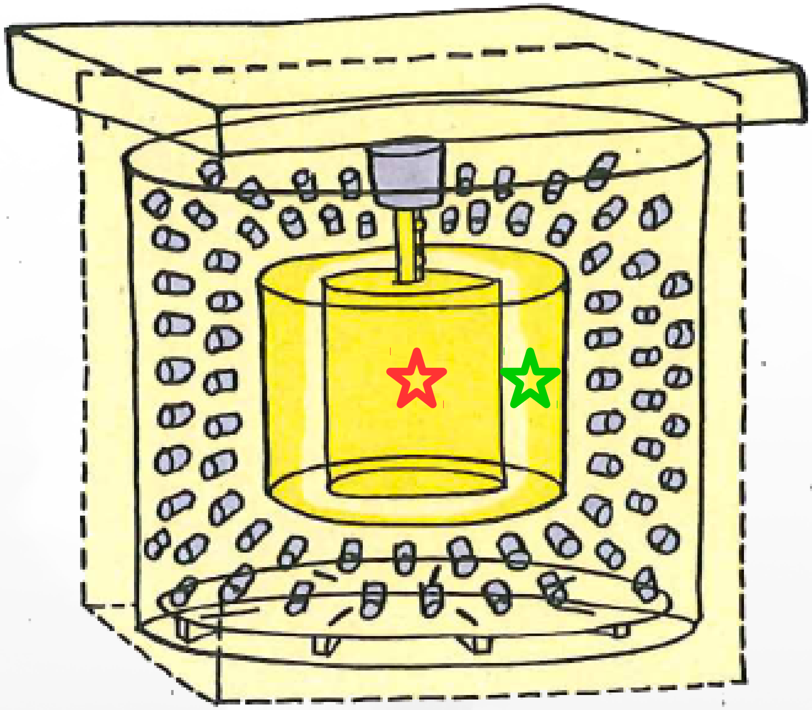


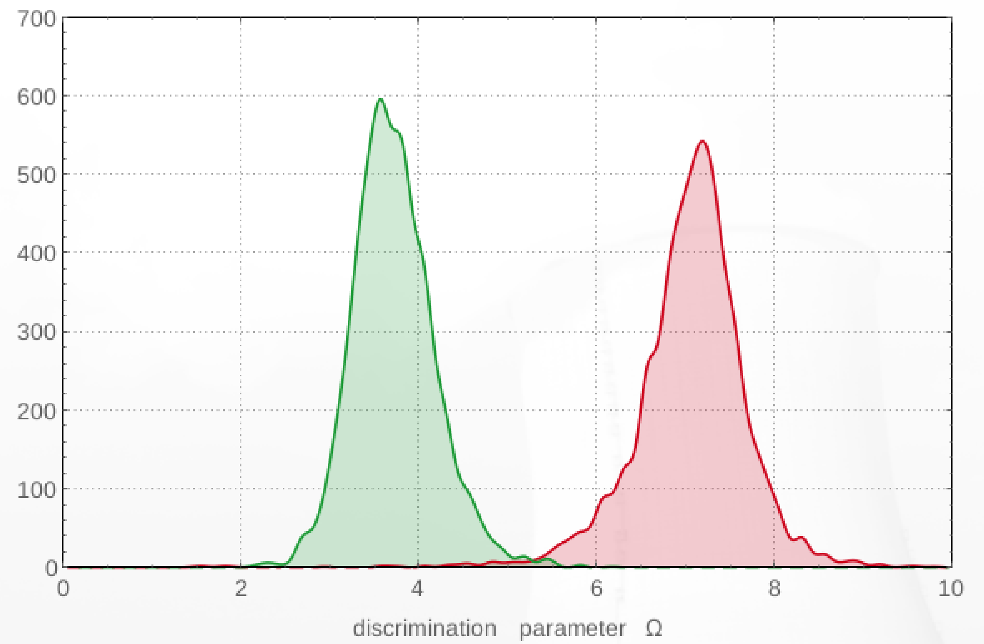


Build classifier from the spectral coefficients: $\Omega := \sum_{j=1}^{n} w_j \left|\mathcal{F}_j\{p(t)\}\right|$

Spectral Shape Discrimination (SSD)

Performance of the new Ω classifier for GC/Target separation:





- Nearly no overlap in distributions ⟶ clean separation
- Spectrum-based classifier surpasses all other tested methods

Spectral Shape Discrimination (SSD)

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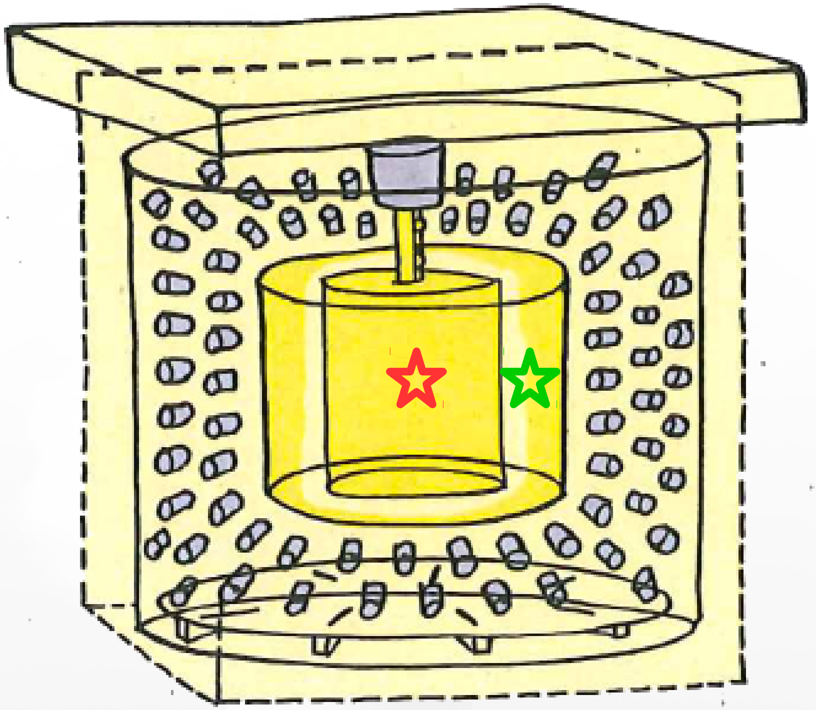
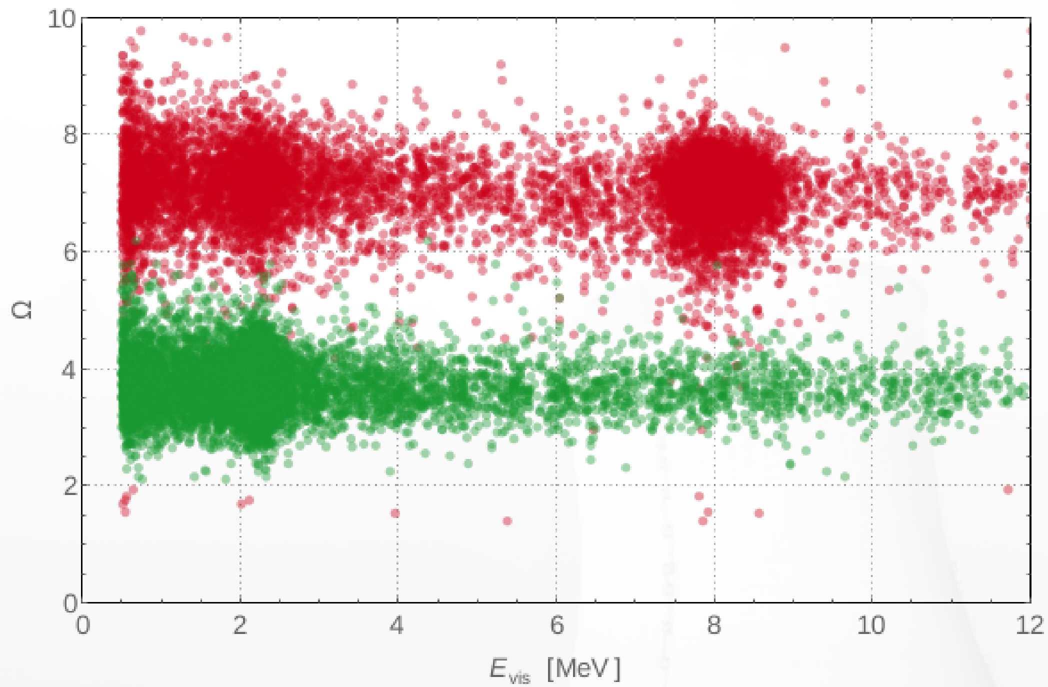
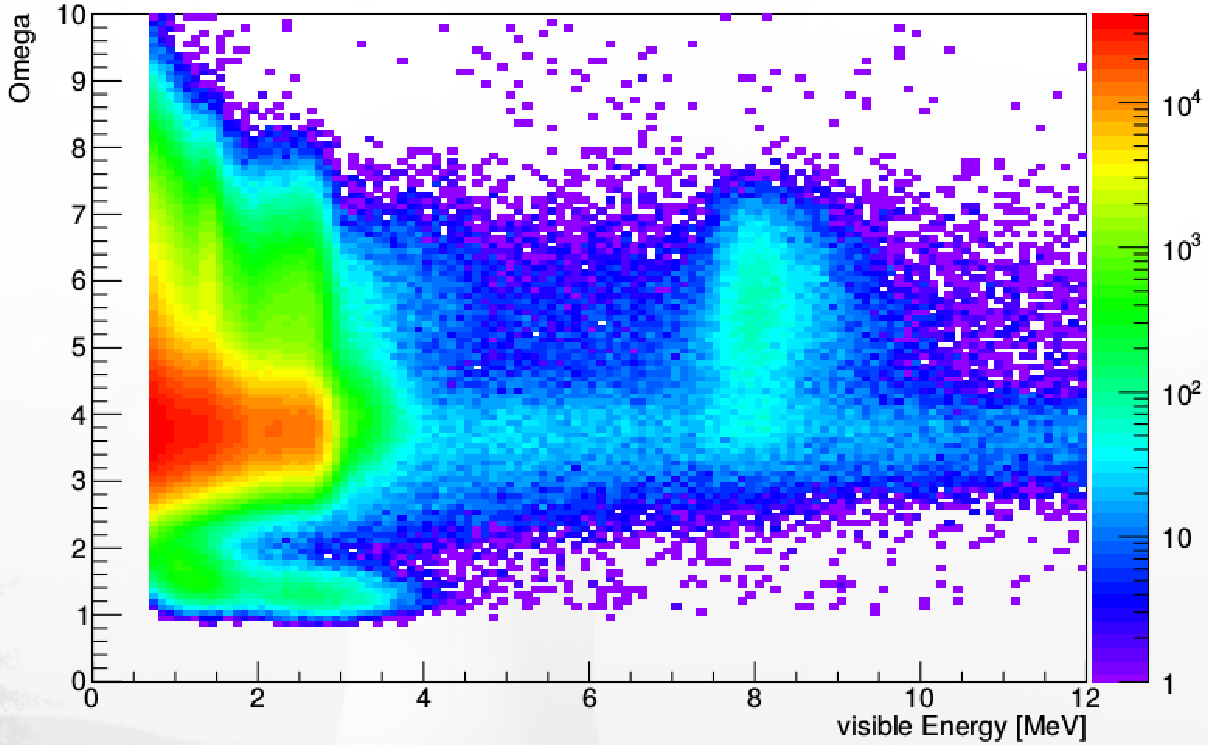




- Nearly no energy dependence (horizontal bands)
- n-Gd nicely visible and in Target-band only

Spectral Shape Discrimination (SSD)

Now turn it around: look at singles events in the detctor (whole volume)



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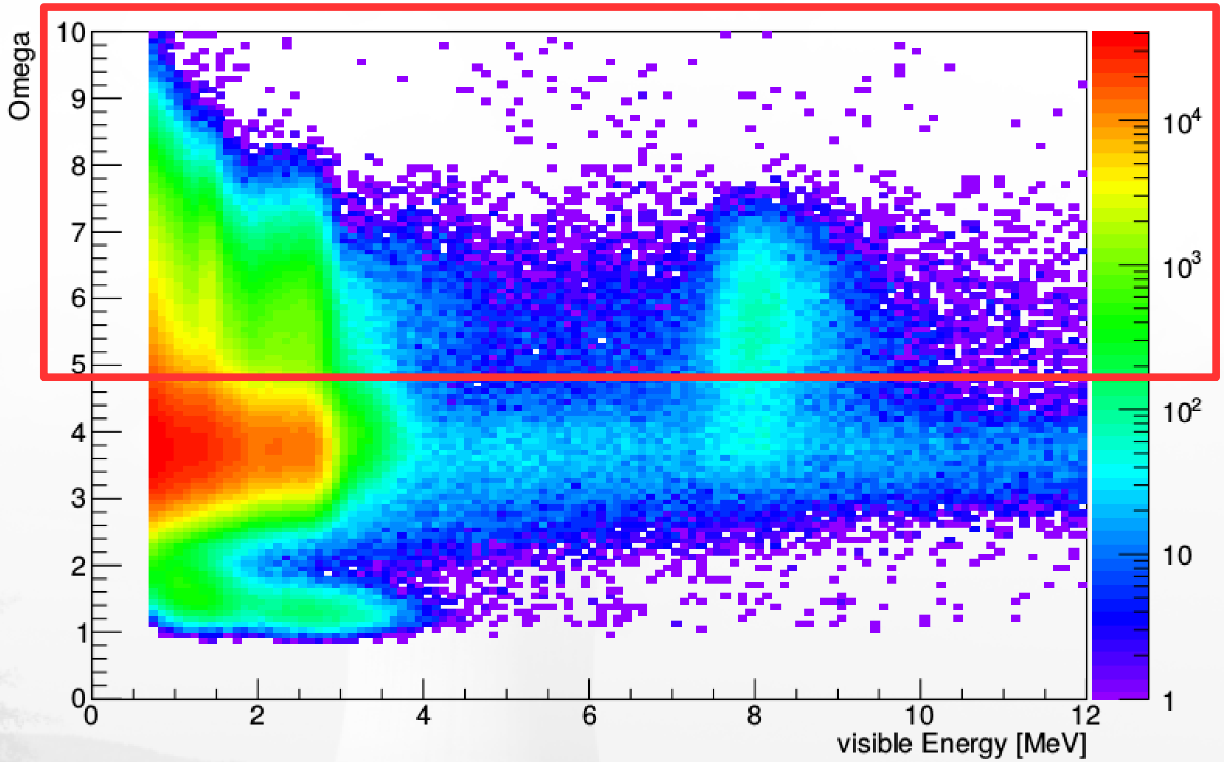

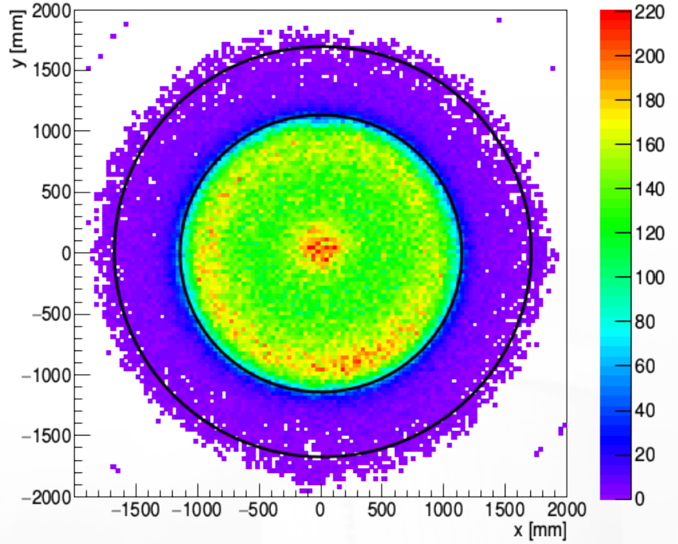

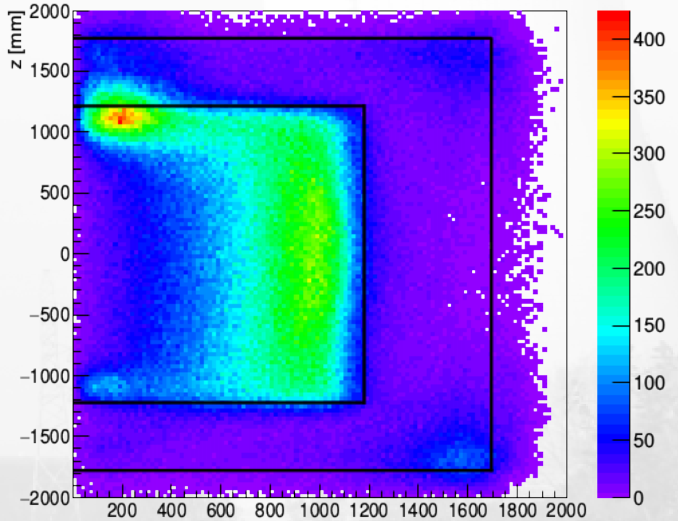

With just a cut on Ω we can cleanly select detector volumes

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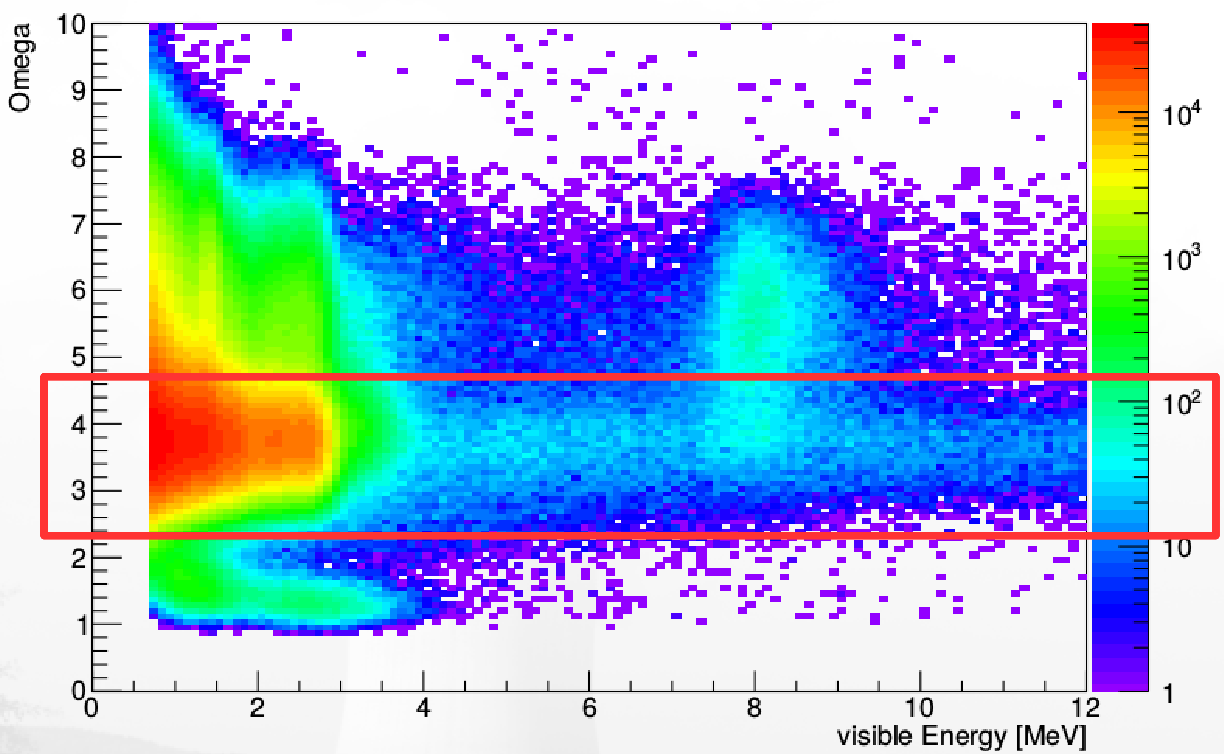

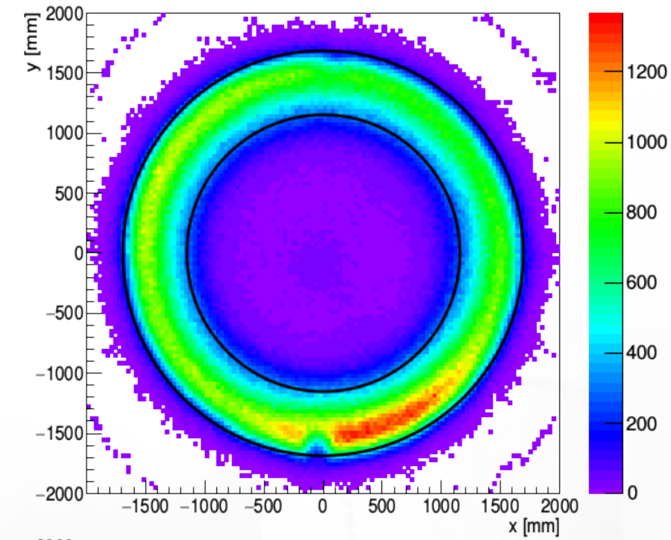

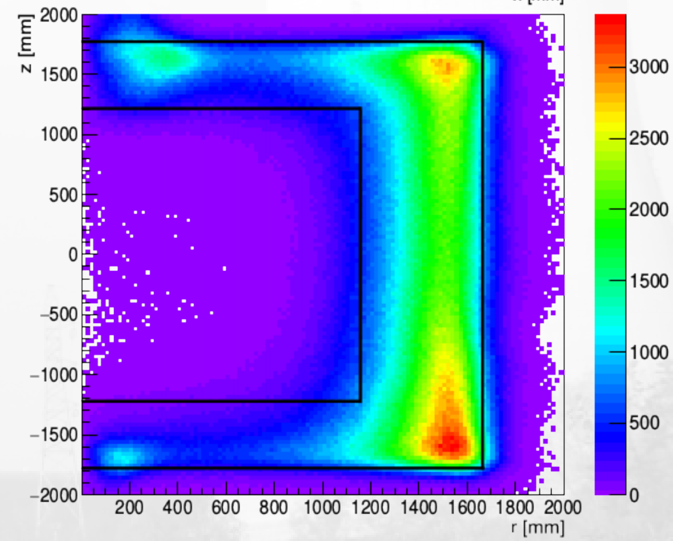

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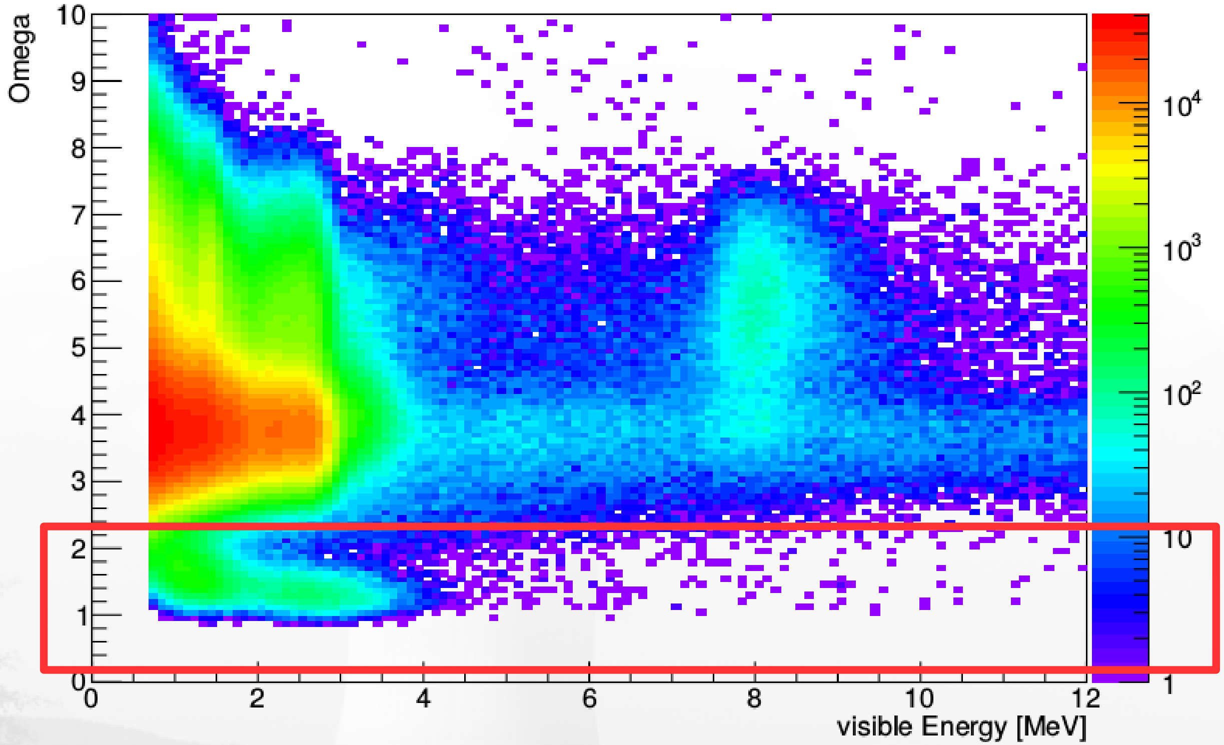

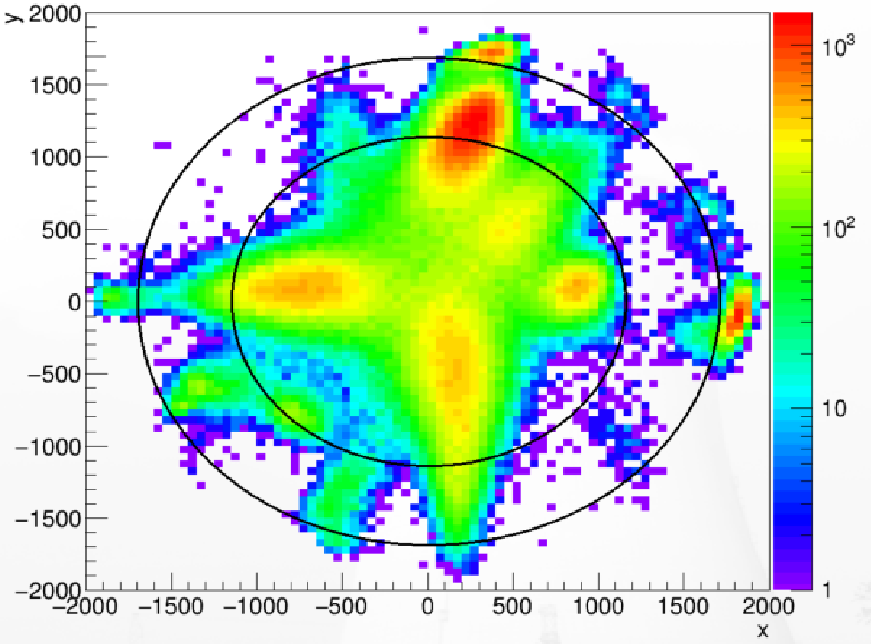

With just a cut on Ω we can cleanly select detector volumes and light noise!

Spectral Shape Discrimination (SSD)

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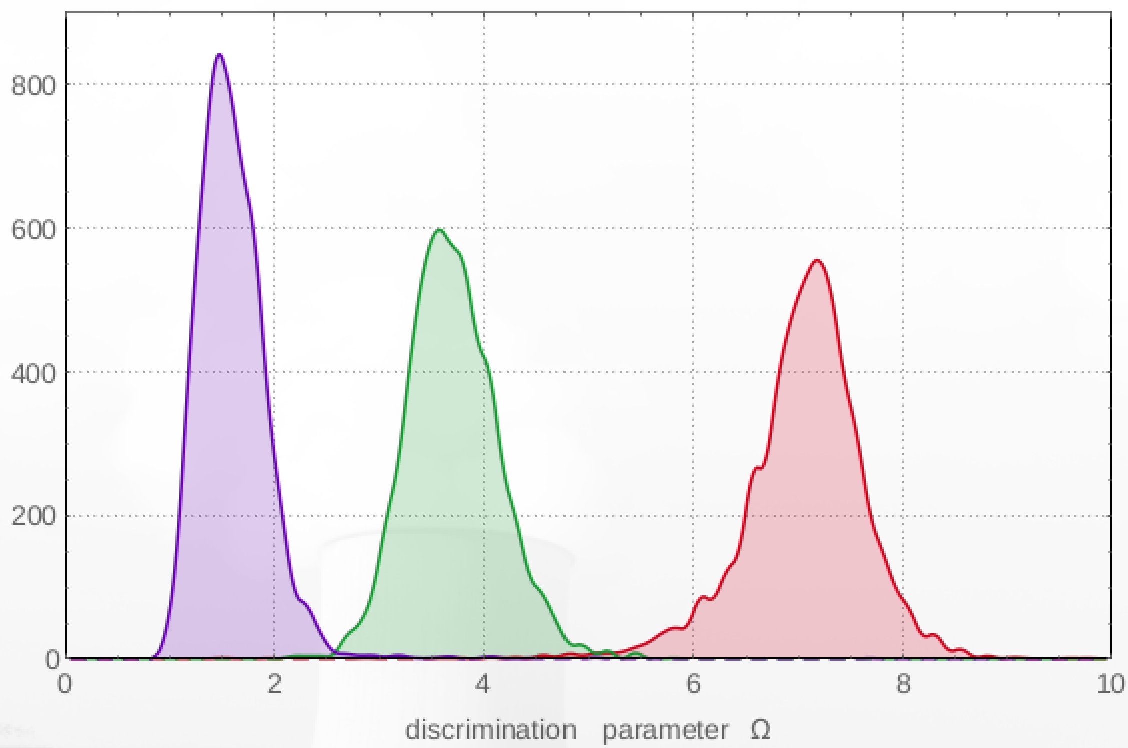
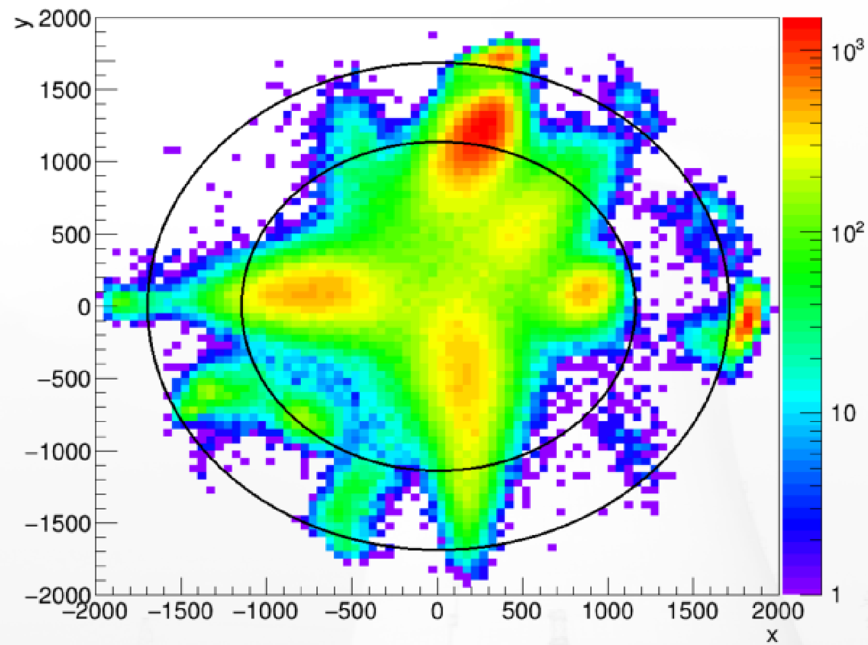




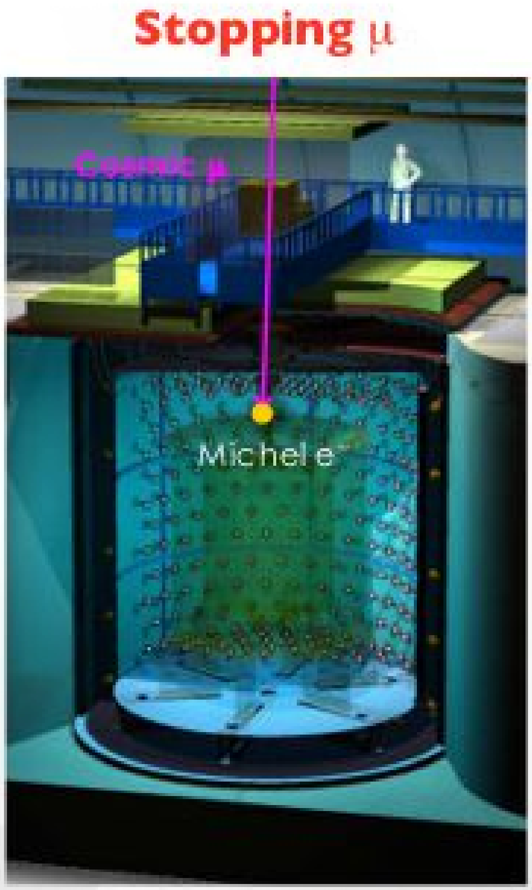
SSD can also reject „light noise" events with nearly 100% efficiency!

First results

- The new SSD passed the first test!
- Remarkable performance for GC/Target separation
- Use on singles data: genuine effect of PS
- Potential application: Efficient light noise rejection
- Can we use this technique for particle identification?

The curious case of stopping muons

Look at stopping muon background in the detector



- Stopping muons can enter through the chimney without being detected by the Inner Veto
- Muon gives prompt signal, decay electron gives delayed signal → correlated BG
- Scintillation light is partly blinded in the chimney region

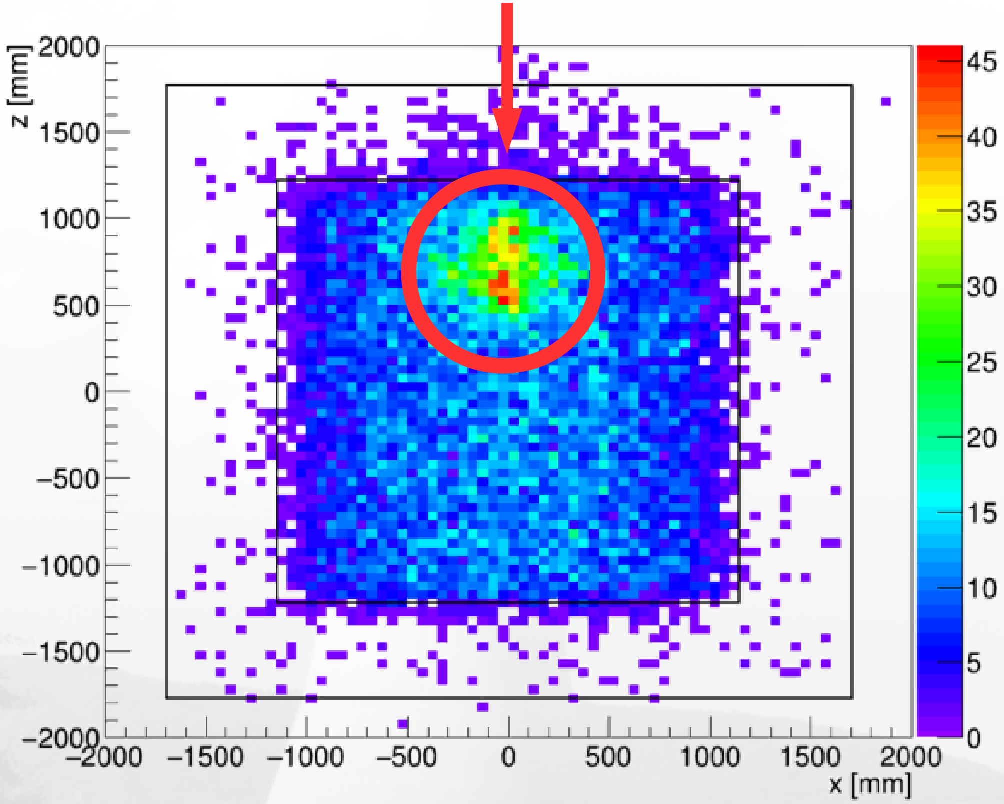
  → distorted pulse shape

  → biased vertex reconstruction

Stopping muon identification

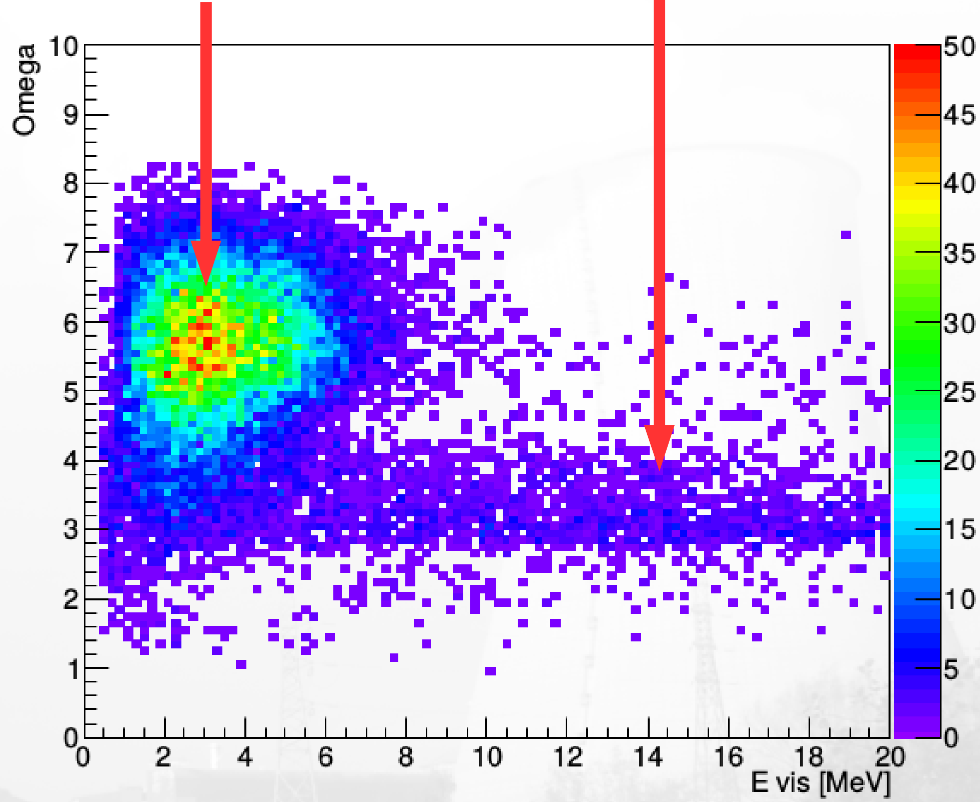
- An (unofficial) IBD sample contaminated with stopping muons

Erroneous vertex reconstruction of SM events causes this population in the Target



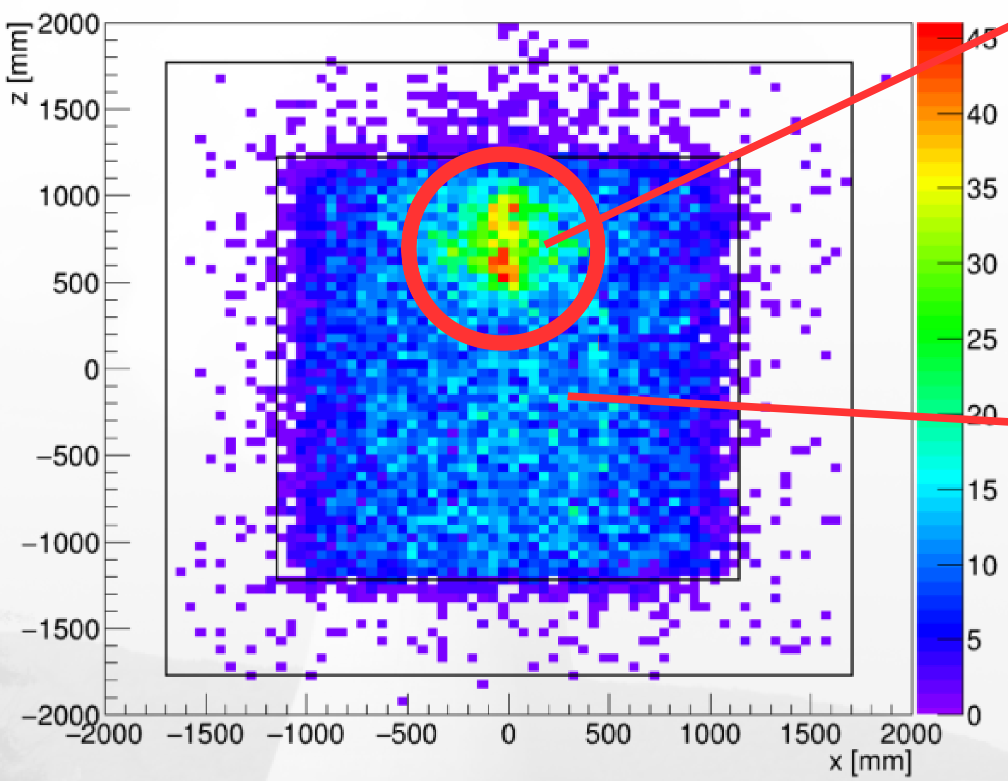
This band has GC-like values and is not expected in the Target

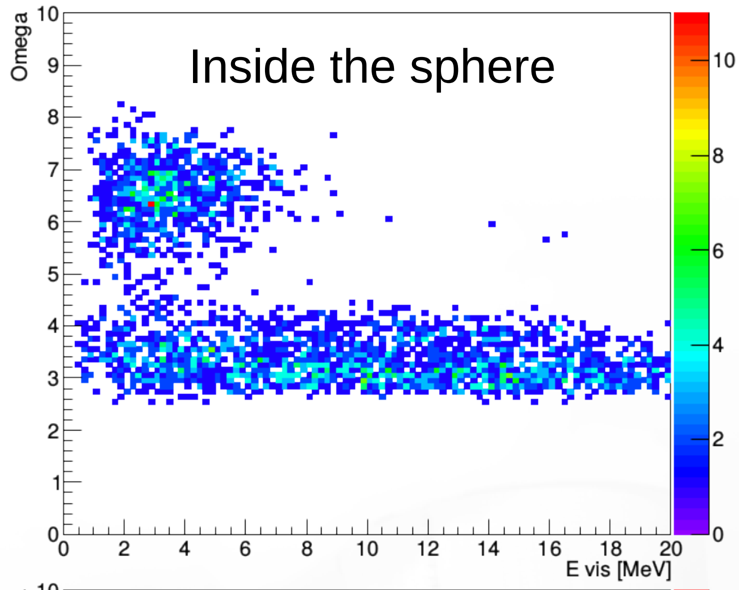
This is expected (IBD)

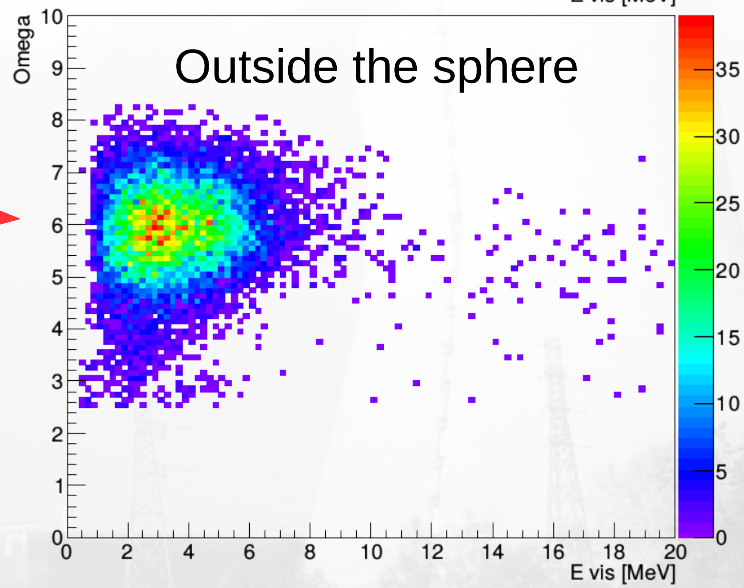


Stopping muon identification

- Look at discriminator values inside and outside the sphere
- „GC-band“ vanishes outside the sphere

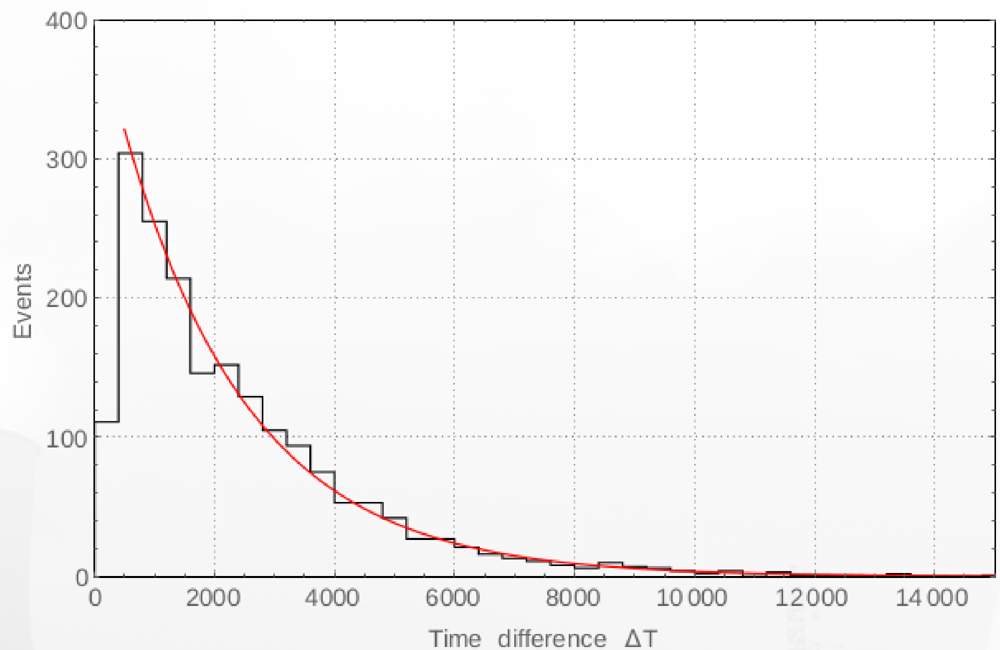






Stopping muon identification

- We can select stopping muons with a vertex cut and a cut on Ω
- Time difference between prompt and delayed event is proof of stopping muon events:



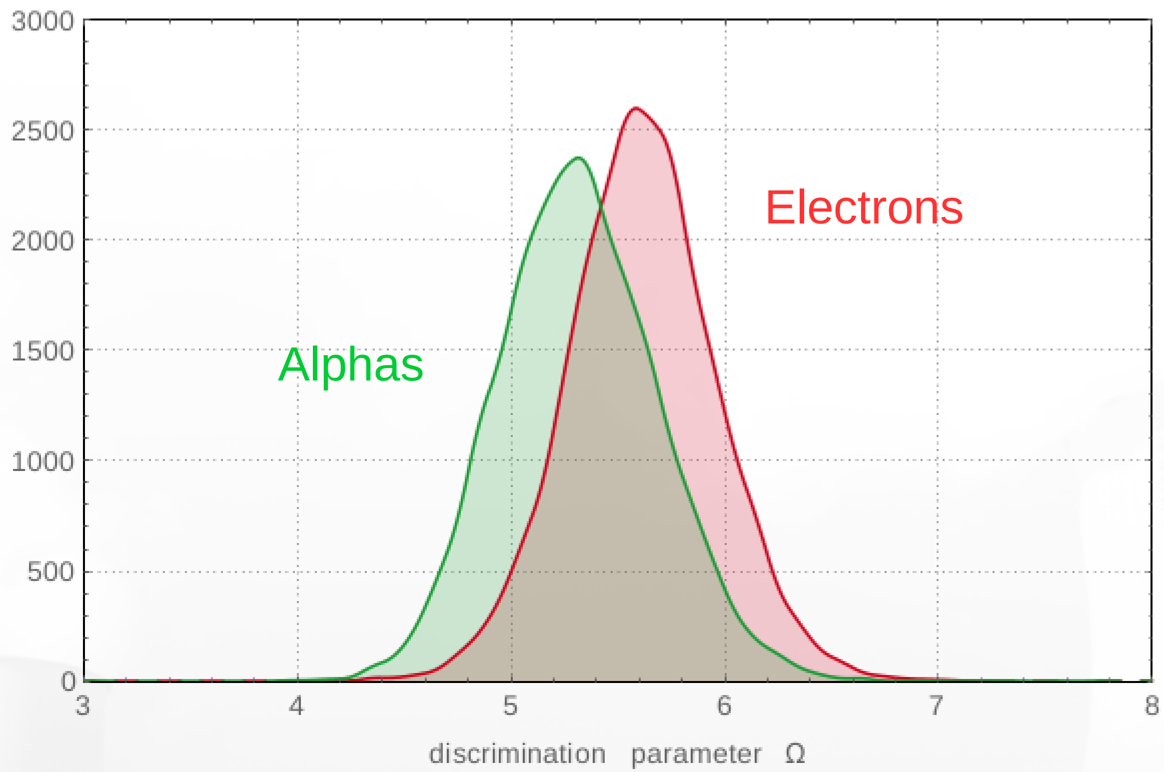
$$\Delta T = 2.120 \pm 0.052\ \mu s \qquad (\tau_\mu = 2.197\ \mu s)$$

The big question is: Is further particle identification possible?

An efficient waveform-based particle identification could help significantly to reject backgrounds!

Further particle identification

Alphas and electrons (from a sample of Bi-Po events):



Definitely some sensitivity, but not enough for discrimination

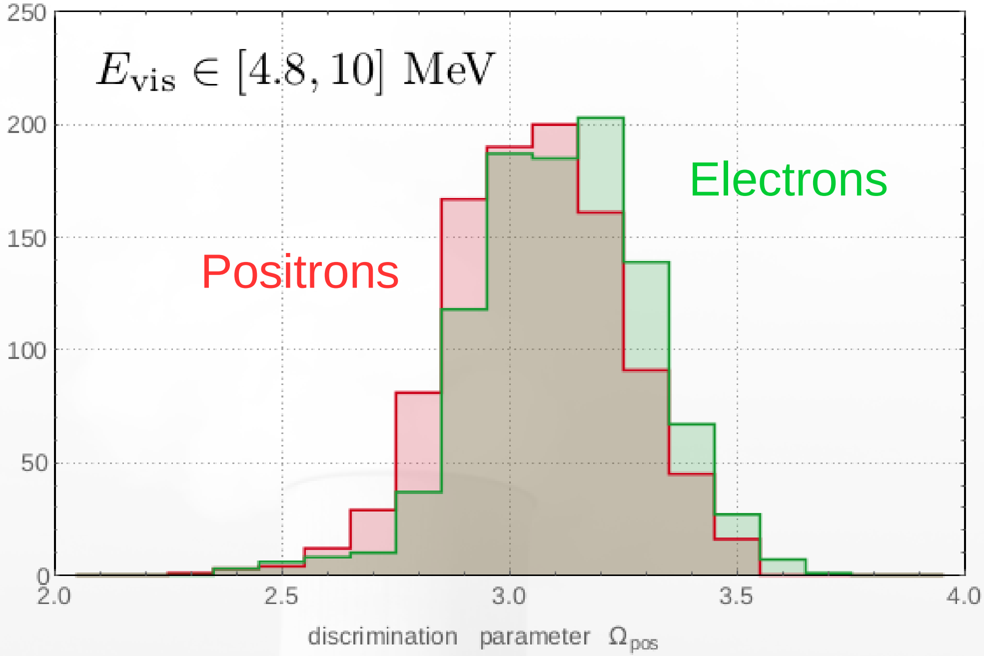
Outlook

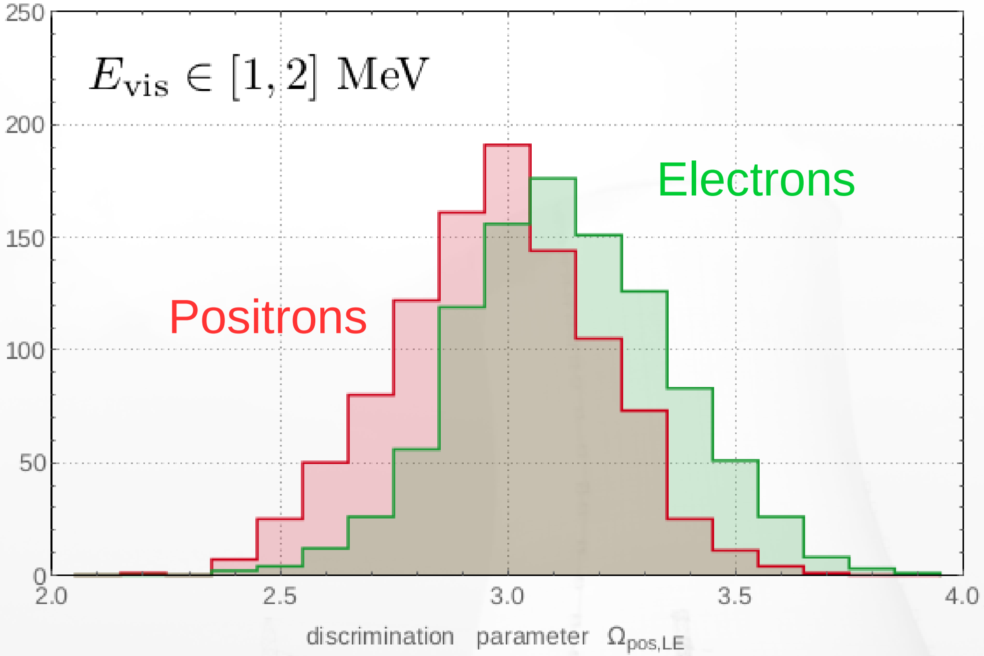
- Double Chooz was never optimized
  - Stochastic fluctuations of photon hit times
  - Stochastic fluctuation of PMT response
  - Additive noise due to electronics
  - Quantization noise introduced by digitization
  - Limited readout window truncates pulses
  - etc...

These effects might be reduced or eliminated with an advanced reconstruction of the photon hits $\longrightarrow$ under development!

Further particle identification

- Or electrons and positrons (due to the annihilation gammas)?
- IBD sample positrons vs. samples of electrons





Again, some sensitivity, but not enough for discrimination

The big question is: Is further particle identification possible?

The answer: maybe...

Further particle identification

Sensitivity is proof that particle information is present in the pulses

- Double Chooz was never designed or optimized for PSD
  - Despite this, SSD achieved remarkable results
  - Performance could be even better in other experiments / new detectors
  - Further improvements are expected with advancements in analysis
- Results were obtained with a simple classifier
  - We have the whole Fourier power spectrum at our disposal
  - Nonlinear classifier or advanced methods could exploit the spectrum better
  - Phase information not used yet

Conclusion

- Spectral Shape Discrimination is a new approach for waveform-based event identification and superior to other established methods that were tested
- Achieved remarkable results in a detector that was not even optimized for pulse shape discrimination:
  - GC/Target identification, light noise rejection, stopping muon identification, and sensitivity to electrons/alphas and electrons/positrons
- Improvements expected with advanced analysis methods and pre-processing of waveforms