Pulse Shape studies in the Double Chooz experiment

JRJC 2013 - Neutrino Physics session

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Anti-ν_e disappearance in reactor experiments

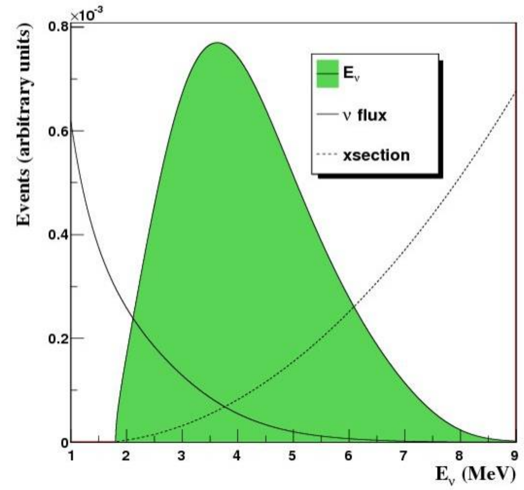
The ν_e (anti-ν_e) survival probability has 2 factors coming into play at different L/E values. By exploring the medium baseline (L/E ≈ 0.5 Km/MeV) one have access to the θ_{13} value (middle term of the PMNS matrix).

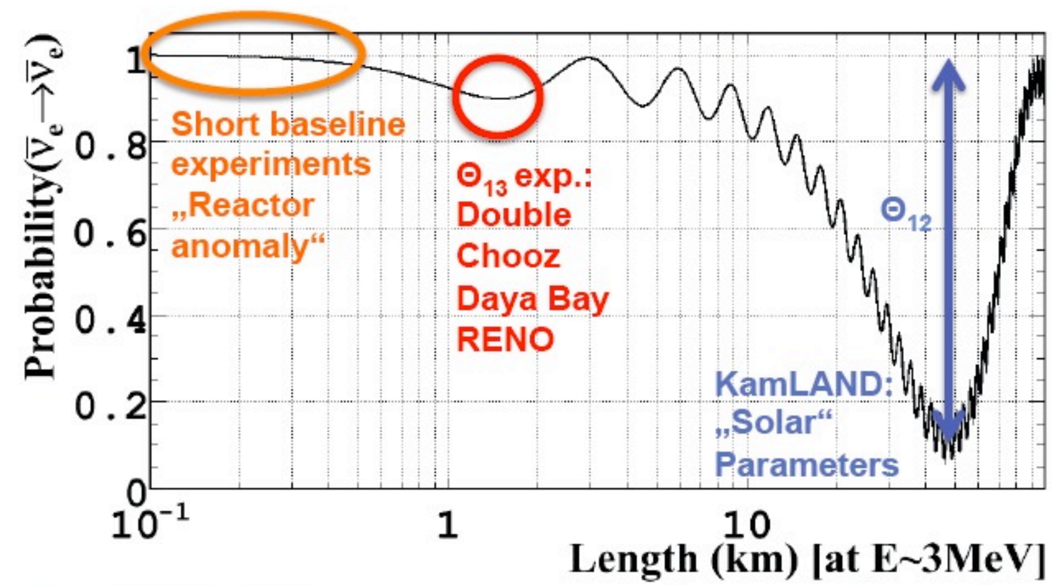
$$U=\begin{pmatrix}1&0&0\\0&c_{23}&s_{23}\\0&-s_{23}&c_{23}\end{pmatrix}\begin{pmatrix}c_{13}&0&s_{13}e^{-i\delta}\\0&1&0\\-s_{13}e^{i\delta}&0&c_{13}\end{pmatrix}\begin{pmatrix}c_{12}&s_{12}&0\\-s_{12}&c_{12}&0\\0&0&1\end{pmatrix}$$

$$P_{ee}\approx 1-\sin^2 2\theta_{13}\sin^2\left(\frac{\Delta m_{13}^2 L}{4E_\nu}\right)-\cos^4\theta_{13}\sin^2 2\theta_{12}\sin^2\left(\frac{\Delta m_{21}^2 L}{4E_\nu}\right)$$

Reactor neutrinos:

- Good flux (1 GWth = $2\cdot 10^{20}$ ν/s)
- Well known flux (error of the few %)
- Pure source of anti-ν_e (no contamin.)
- Energy of few MeV (<E> ≈ 3 MeV)





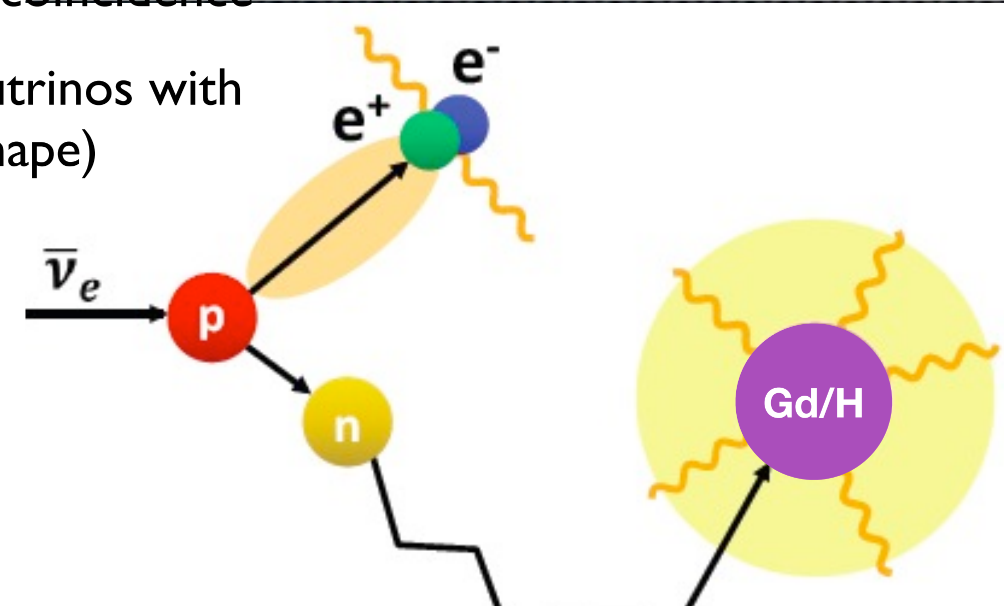
Reactor neutrinos experiments

Detection principles: **Inverse β decay** (IBD) ⇒ Prompt-Delayed coincidence

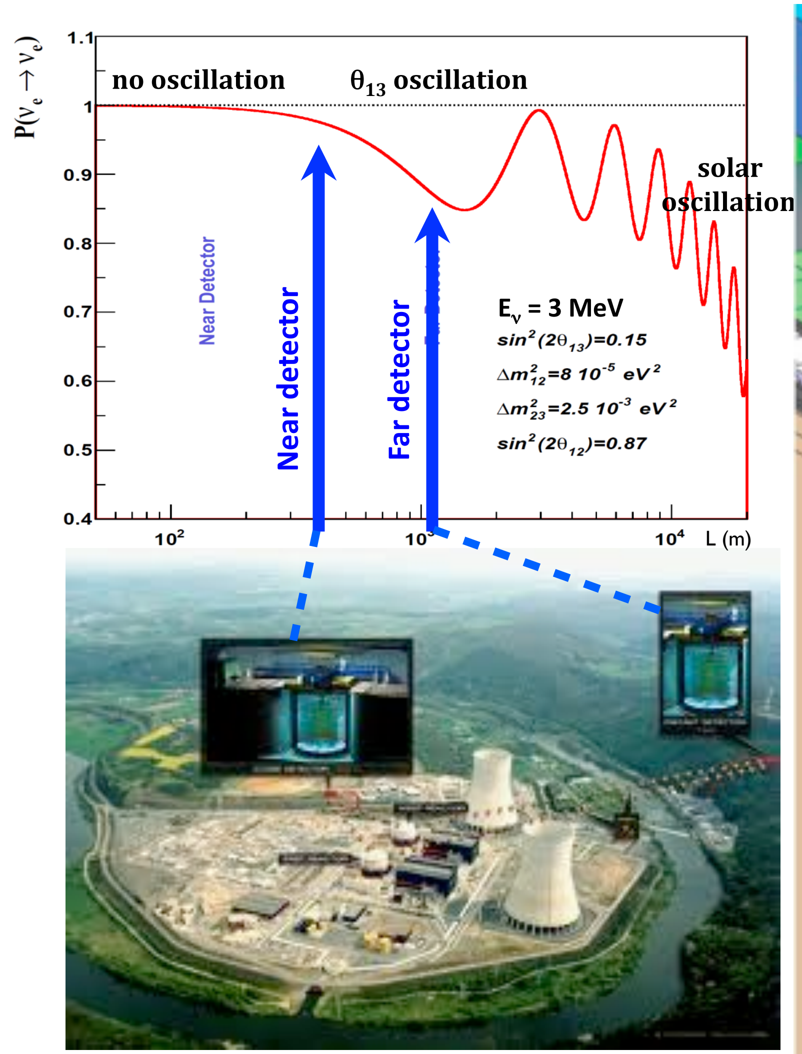
Disappearance experiment: Compare the number of interacting neutrinos with the expected one, globally (rate analysis) or per energy bin (rate+shape)

IBD signature:

- **Prompt signal** e+ ionization + annihilation → γs (1-8 MeV)
- **Separation time** n thermalization → Δt (~30 μs for Gd)
- **Delayed signal** n capture → γs (~8 MeV on Gd)



The Double Chooz experiment



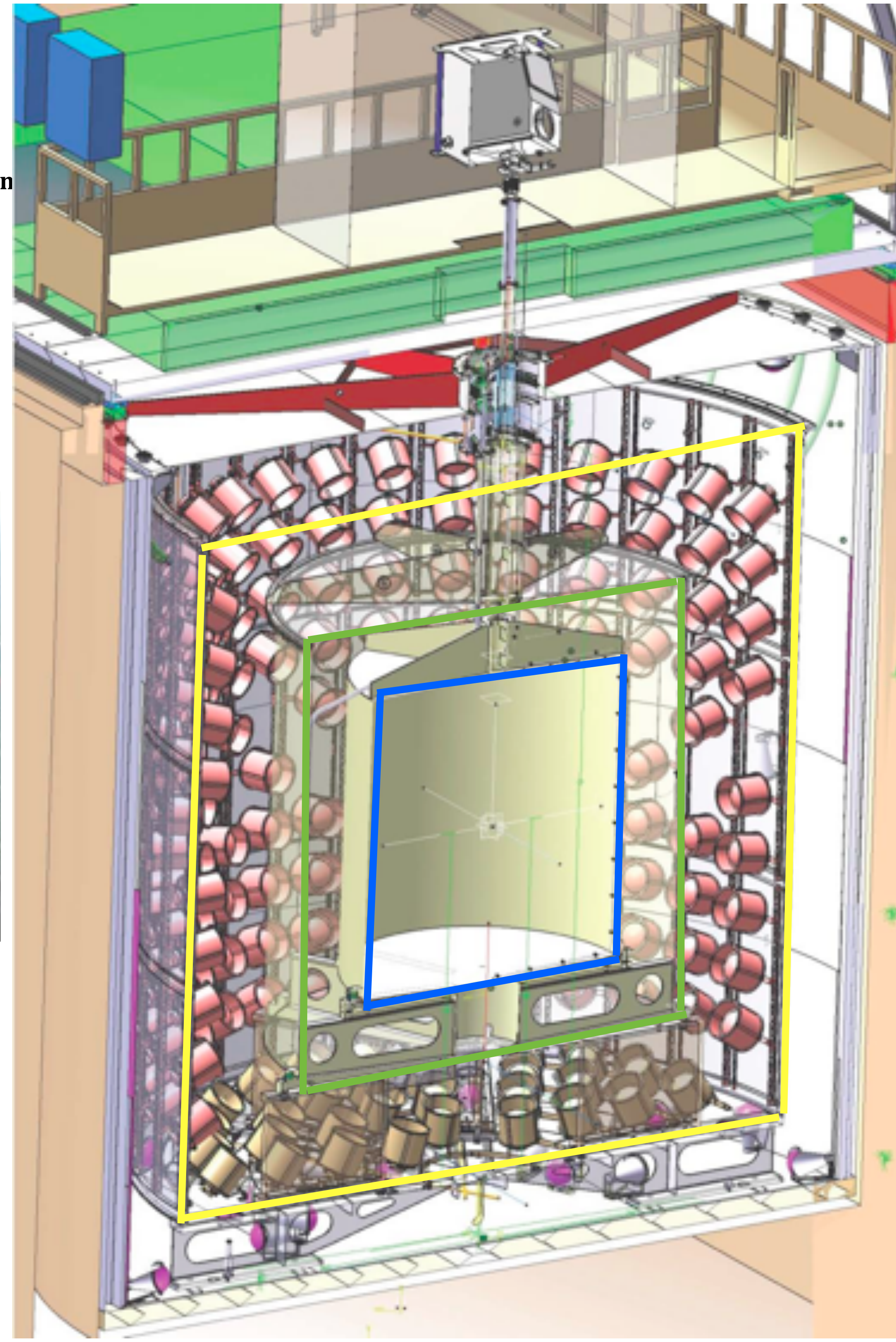
Detection strategy

Far detector only (*4/2011-5/2014*):

- Flux deficit and spectral distortion measured

Two identical detectors (*5/2014*):

- Flux uncertainty cancellation



Inner detector

Inner Target:

8 tons Gd doped scintillator in acrylic vessel.

Gd: large n-capture cross-section and high γs energy

Gamma Catcher:

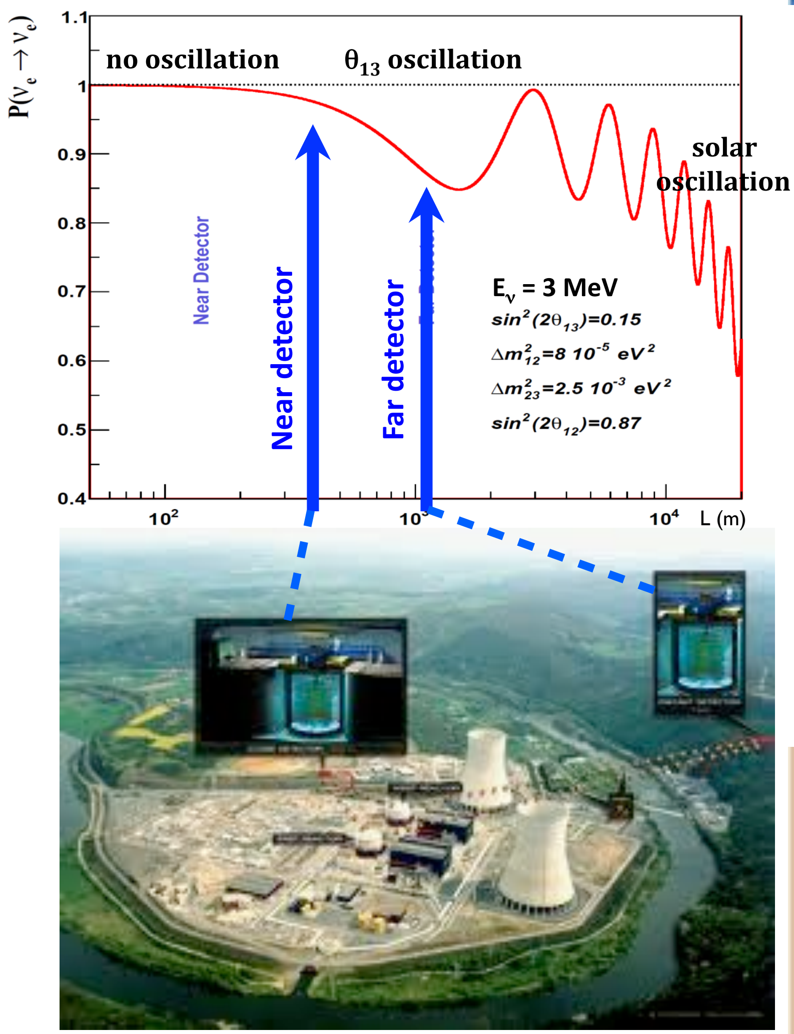
12 tons un-doped scintillator in acrylic vessel.

Detect γs escaping the IT.

Buffer:

80 tons non scintillating mineral oil and 390 10" PMTs in stainless steel vessel.

The Double Chooz experiment



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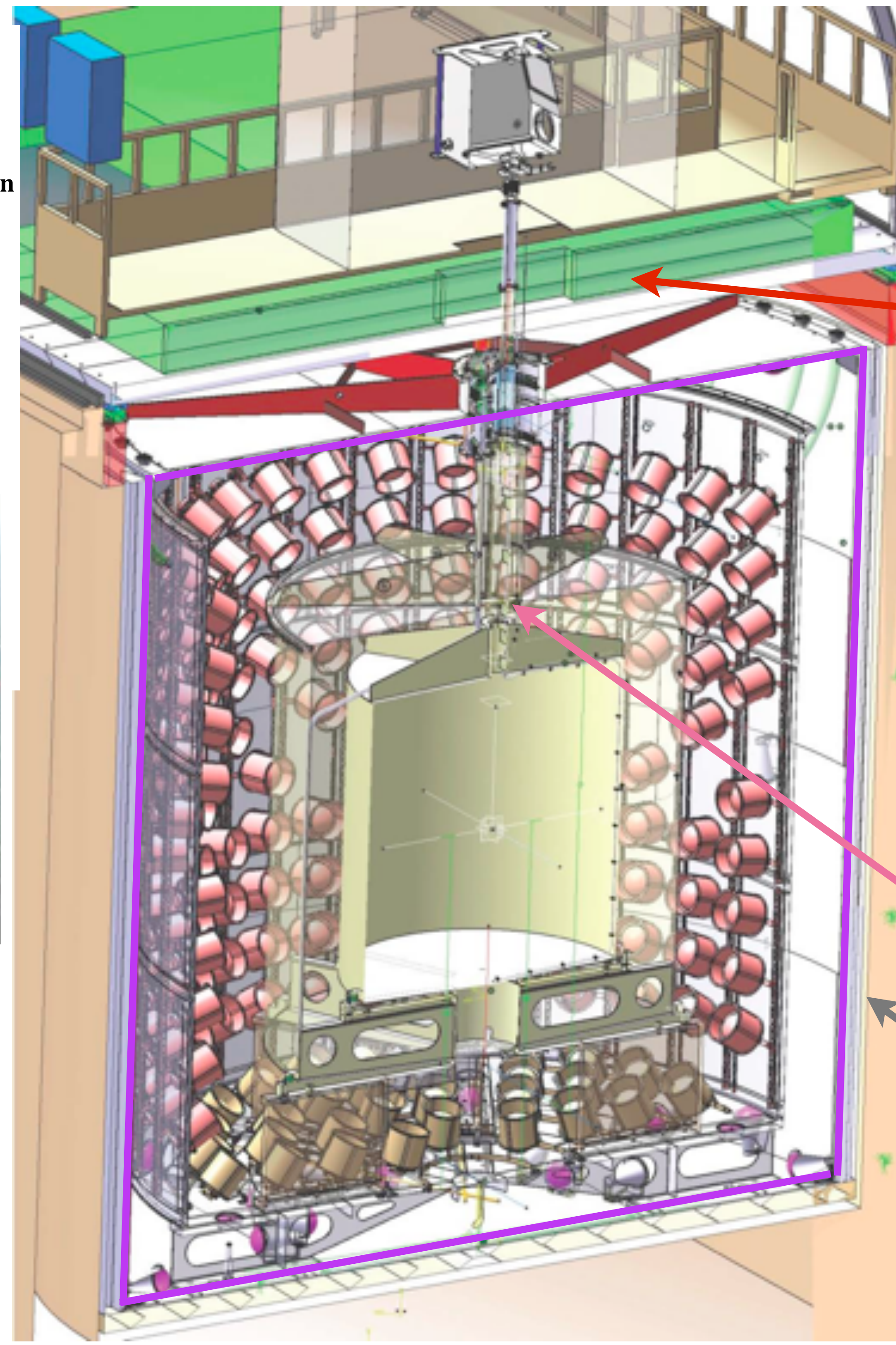


Other tools

Outer Veto:
Array of plastic scintillator strips (13m x 7m). Vetoes cosmic μs.

Inner Veto:
70 tons un-doped liquid scintillator and 78 10" PMTs in stainless steel vessel. Cosmic μs veto and spallation neutrons shielding.

Chimney

Target shielding:
15cm steel external shielding

Rock shielding:
300/120 MWE rock overburden for far/near detector

Double Chooz signal selection and background

Criteria to identify a neutrino event:

- Prompt-delayed time coincidence
  (0.5 μs < Δt < 150 μs)
- Energy selection in Prompt & Delayed signals
- Selections on Outer Veto & Inner Veto signals

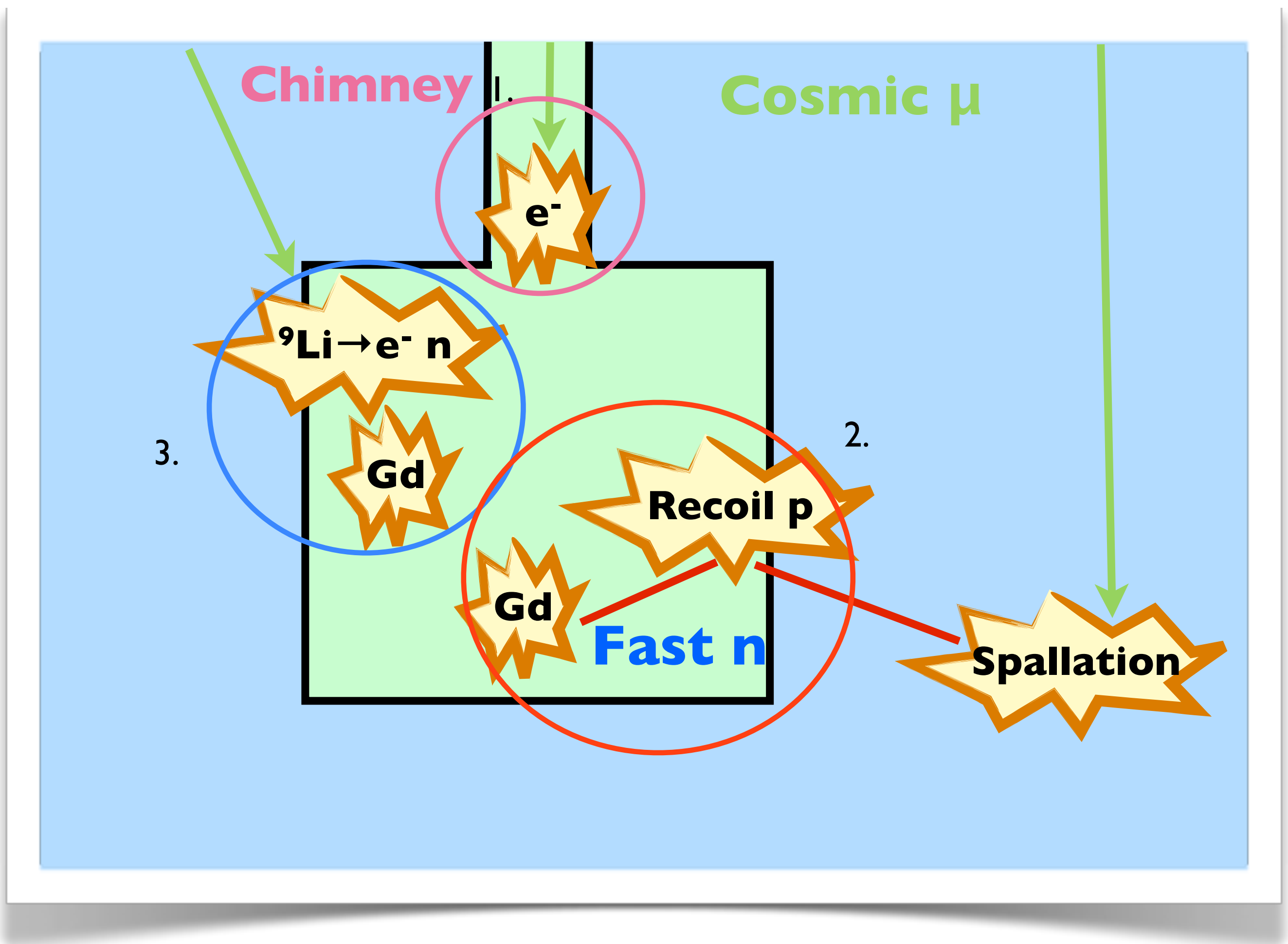
Remaining backgrounds:

Accidental coincidences between radioactivity γs and spallation neutrons captures.

Correlated, i.e. physics events simulating the IBD e^+- n coincidence (scheme)

1. **Stopping μ** (in the chimney)
2. **Fast neutron** (isotropic)
3. **Cosmogenic β-n** (isotropic)

Correlated bkg scheme

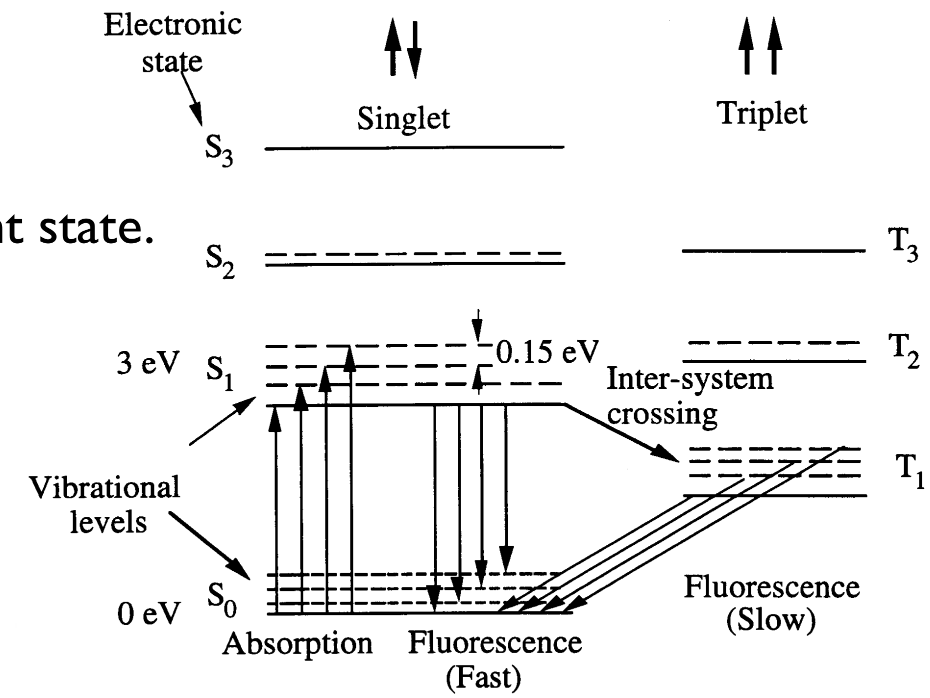


Fast neutrons (and possibly stopping μ) **can be selected with the Pulse Shape Discrimination (PSD)** using the difference in the Pulse Shape between positrons and protons (muons).

Organic scintillators and pulse shape discrimination (PSD)

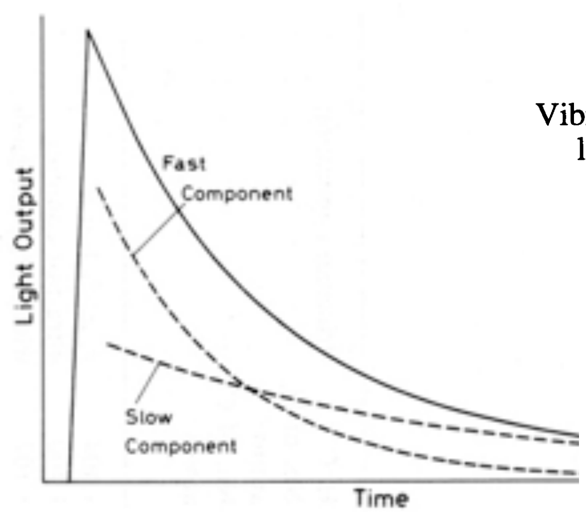
Organic scintillator's behavior:

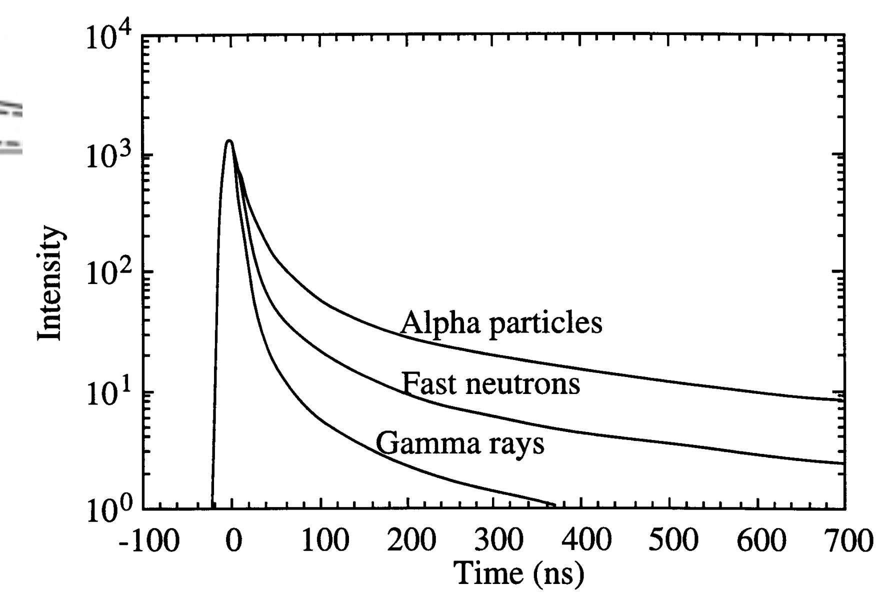
1. Incident radiation populates vibrational states of S1 level.
2. Non radiative transfer of energy from vibrational states to fluorescent state.
3. Decay of fluorescent state: direct (fast) or via triplet state (slow).



The global waveform profile of the scintillation light (Pulse Shape) reflects the scintillation process:

- Initial rise (τ_1)
- Two components fall (fast τ_2, slow τ_3).





Excited state population depends on dE/dx: **higher slow component (τ_3) for heavy particles** (protons, alphas, ions) than for light particles (electrons, positrons, photons).

The **Pulse Shape Discrimination** (PSD) aims to **disentangle α and protons from e^+, e^- and γs** by using this difference.

My analysis in Double Chooz: PSD on the correlated background.

Not trivial: PXE+PPO (DC scintillator) has shorter $\tau_{2,3}$ than LAB or PC.

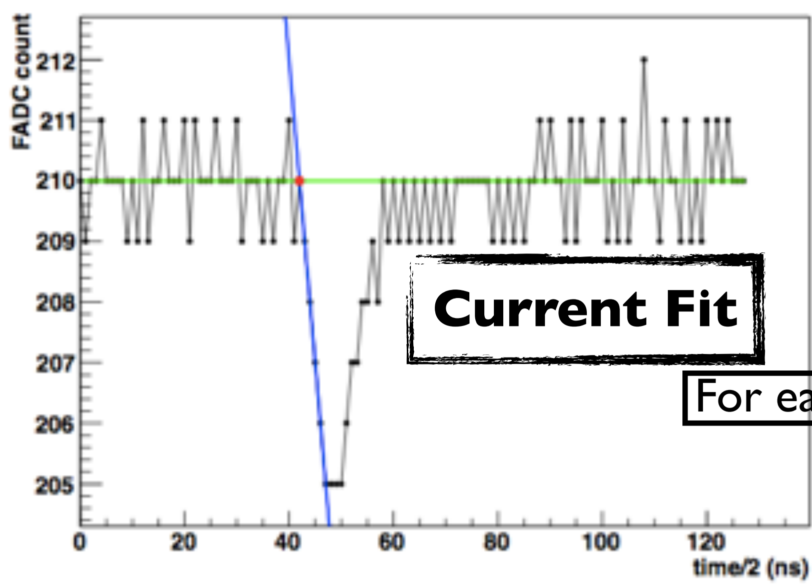
Scintillator	τ_1 [ns]	τ_2 [ns]	τ_3 [ns]
PC + 1.5 g/l PPO	3.57	17.6	59.9
PXE + 1.5 g/l PPO	3.16	7.70	34.0
LAB + 1.5 g/l PPO	7.46	22.3	115.0

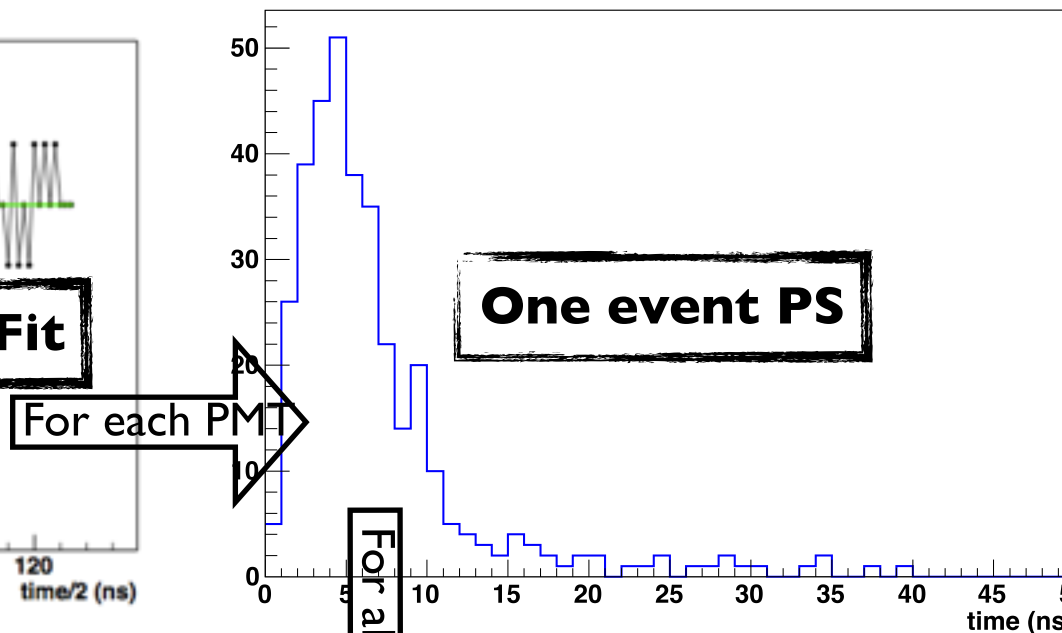
Pulse Shape construction in Double Chooz

<u>For this analysis</u> **Pulse Shape** (PS) = **Time distribution of PMTs light pulses** corrected for the TOF (single event).

Pulse Shape construction:

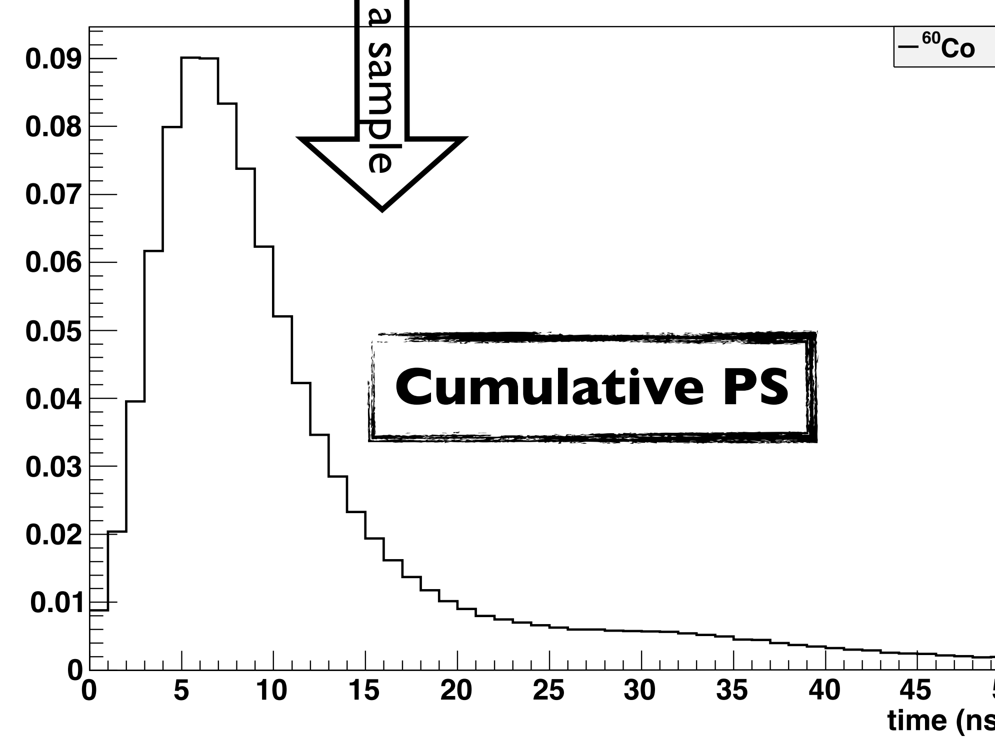
- Each pulse is fitted to get a starting time
- Times are corrected for the TOF and the PMT transit time
- Times are combined together in a global light profile





This Pulse Shape is sensitive to:

- Particle nature (α, p vs e^+, e^-, γ)
- Reconstructed vertex (TOF correction)



Cumulative PS (sum of all PSs) of a sample = high statistics representation of the mean PS behavior.

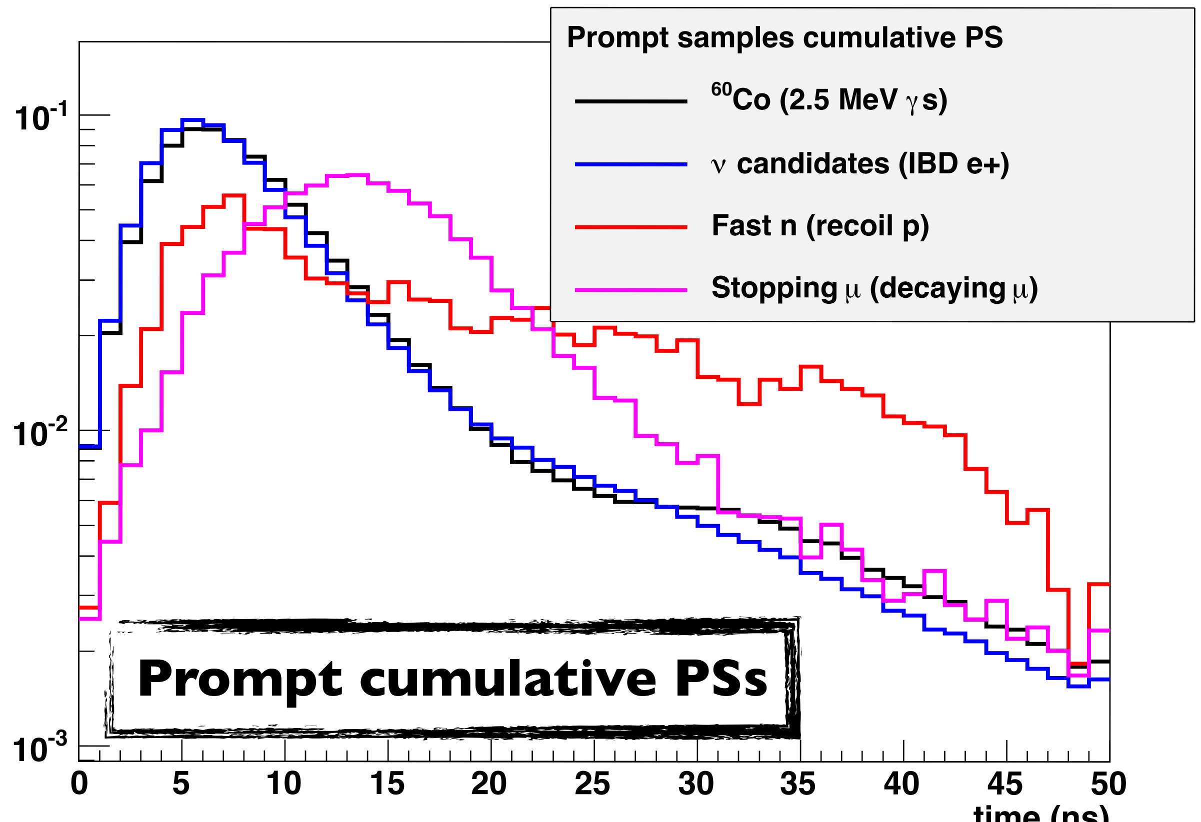
By comparing cumulative PSs of different samples we can look for differences (differences → discrimination?)

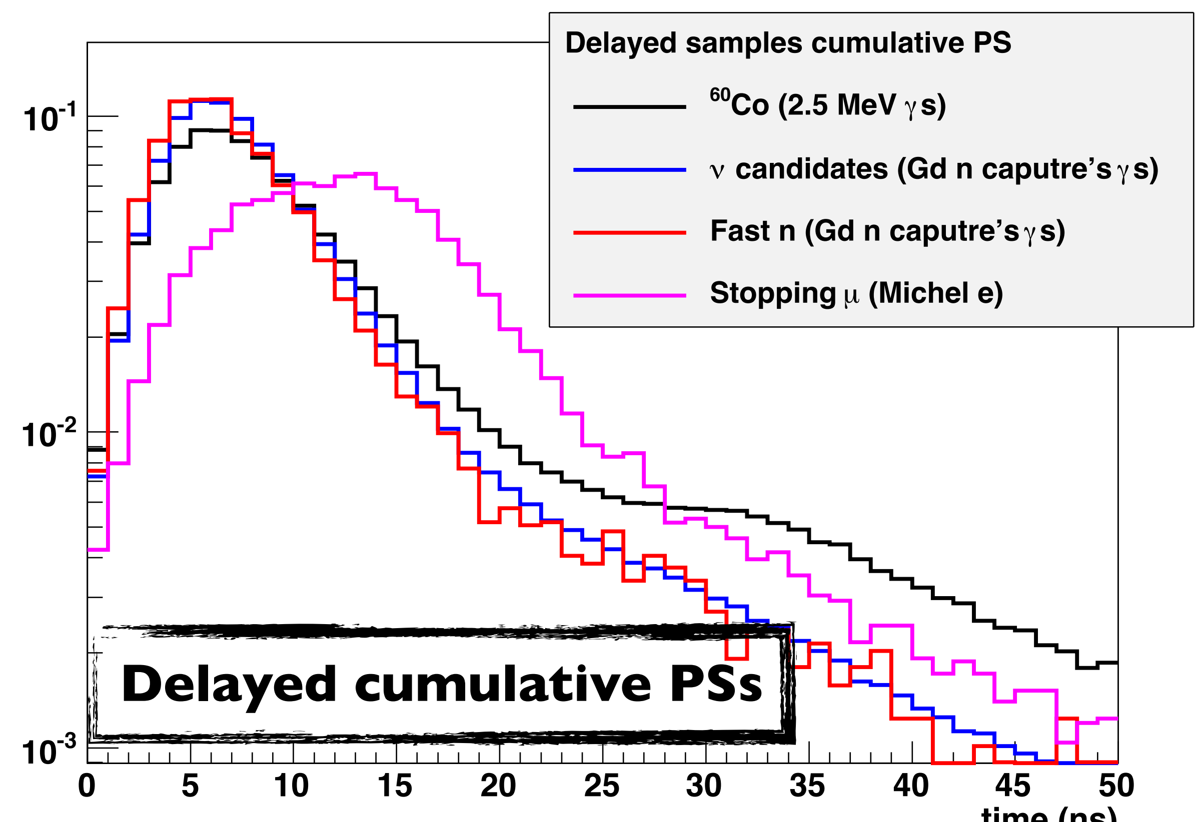
Pulse Shape distributions

We study a cumulative Pulse Shape of a Stopping Muons and Fast Neutrons samples. By using the Outer Veto (OV) trigger and considering that Stopping Muons have short Prompt-Delayed Δt, we select these <u>raw</u> samples:

Neutrinos	OV not triggered	(prompt = e^+, delayed = Gd γs)
« Stopping μ »	OV triggered & Δt < 10μs	(prompt = μ, delayed = Michel electron)
« Fast neutrons »	OV triggered & Δt > 10μs	(prompt = recoil p, delayed = Gd γs)
^{60}Co	Calibration source run (2.5 MeV γs) added in both prompt and delayed	

- Recoil protons i.e. **« Fast Neutrons » prompt have a different PS** than e+ and ^{60}Co (expected).
- **« Stopping μ » have a different PS both on prompt and on delayed** (unexpected, vertex).



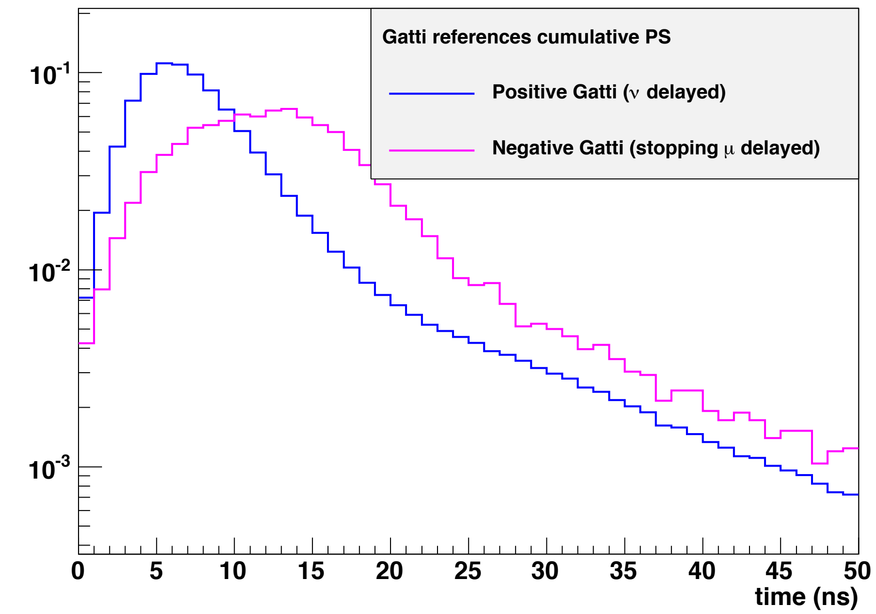


We use this differences to **discriminate Stopping Muons** (Fast Neutrons) **in the neutrino sample.**

Stopping Muons separation via Gatti method

The **Gatti method** *[Nuclear Electronics, vol .2, pp. 265-276, IAEA Wien (1962)]* is designed to perform PSD:

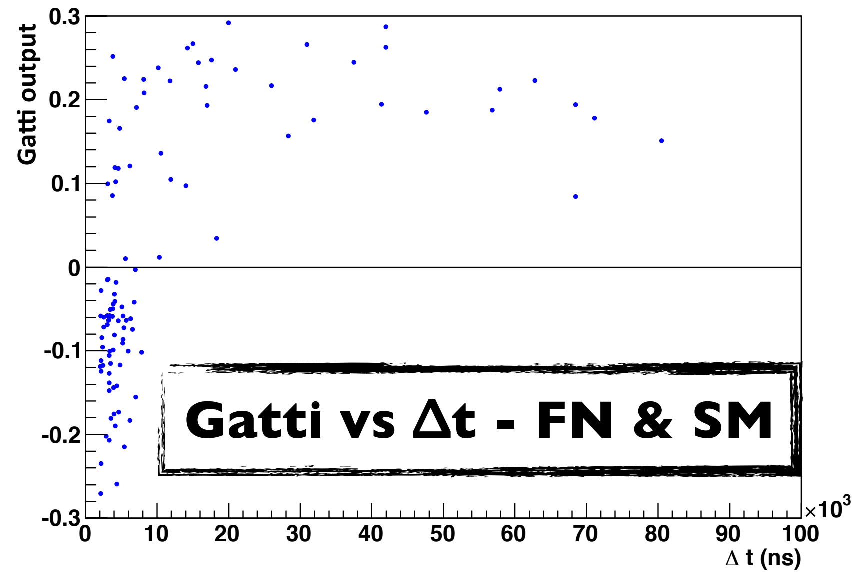
- Given 2 reference PSs α and β, we build a bin per bin weight $P_i = \frac{(\overline{\alpha_i} - \overline{\beta_i})}{(\overline{\alpha_i} + \overline{\beta_i})}$ (α_i and β_i = pulses in a t_i bin)
- Given a PS S (bin content S_i), the Gatti discrimination parameter is $\mathbf{G_s = \Sigma_i P_i S_i}$ (positive α-like event, negative β-like)

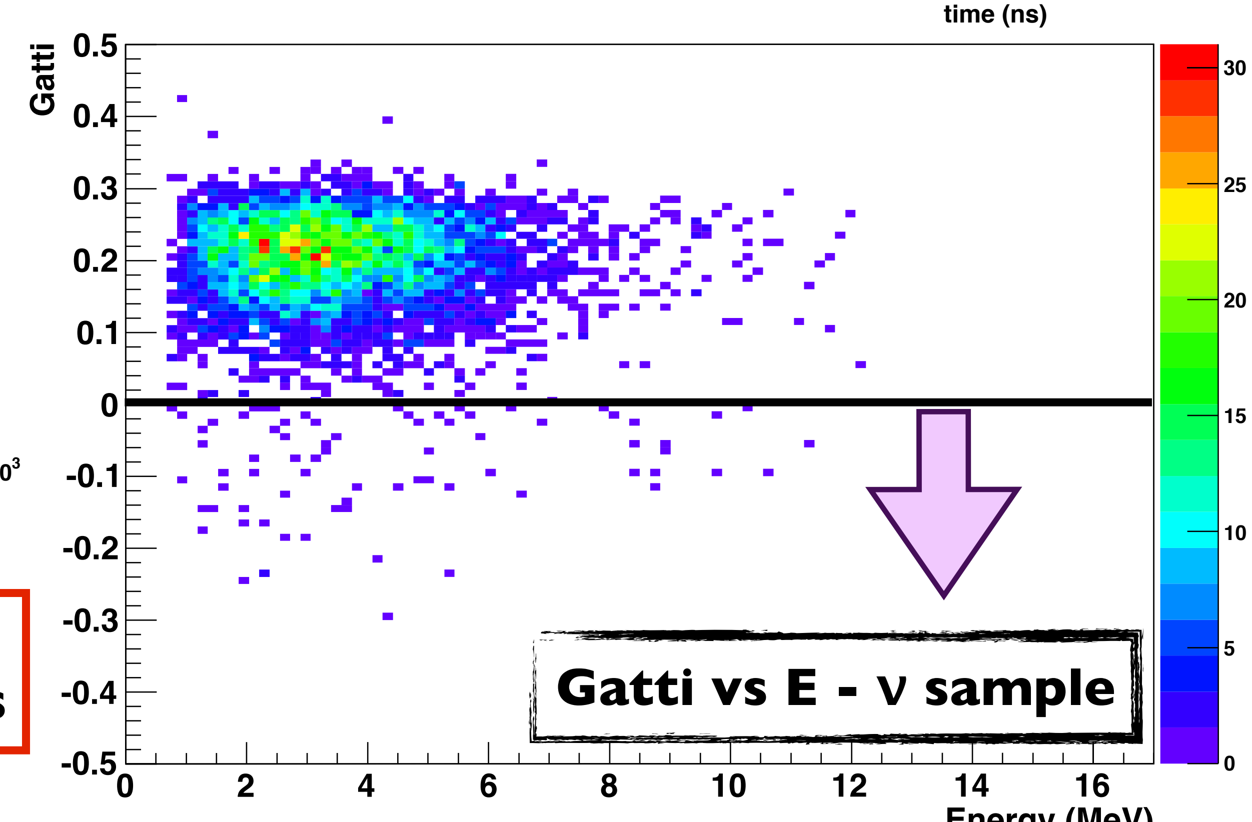


We use the Gatti method to separate Stopping μs. References:

- Neutrino Delayed cumulative Pulse Shape (G > 0)
- "Stoping Muon" Delayed cumulative PS (G < 0)

The Gatti analysis applied to "Stoping Muons" and "Fast Neutrons" separate the two populations.



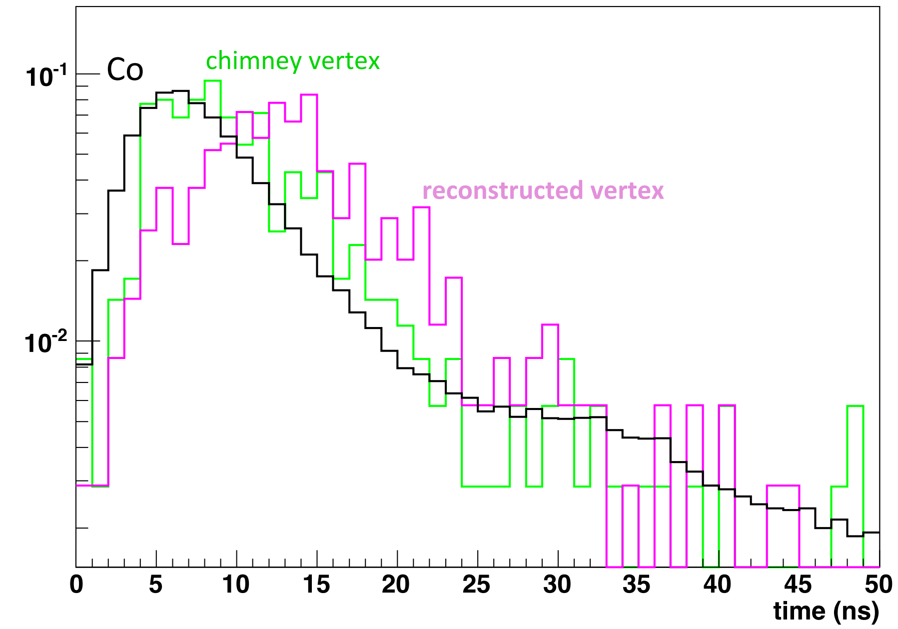


The Gatti analysis applied to <u>all Neutrino sample</u> **selects** some events with a negative Gatti, i.e. as **Sopping Muons**

Vertex position correction using Pulse Shape

Stopping Muons' Pulse Shape is due to vertices reconstructed in the target while they must be in the chimney.

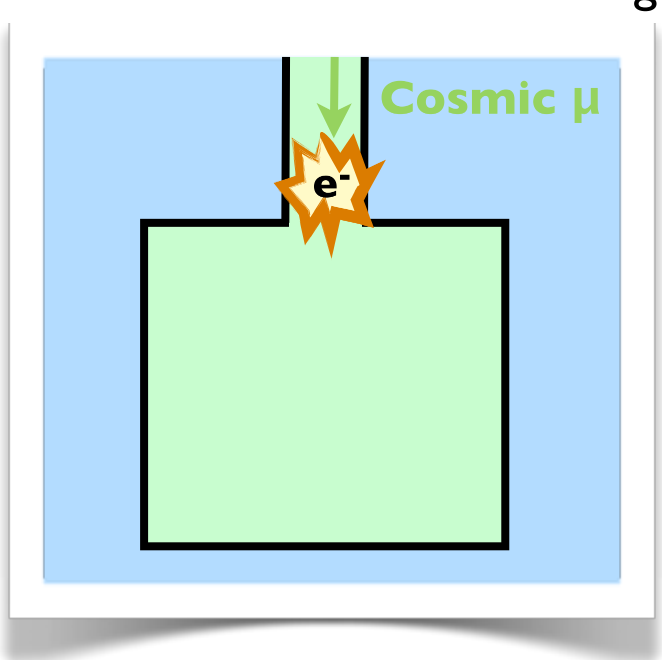
Re-computing the Pulse Shape using a vertex inside the chimney, Stopping Muons (Gatti < 0) generally have a Pulse Shape more similar to the ^{60}Co cumulative PS.

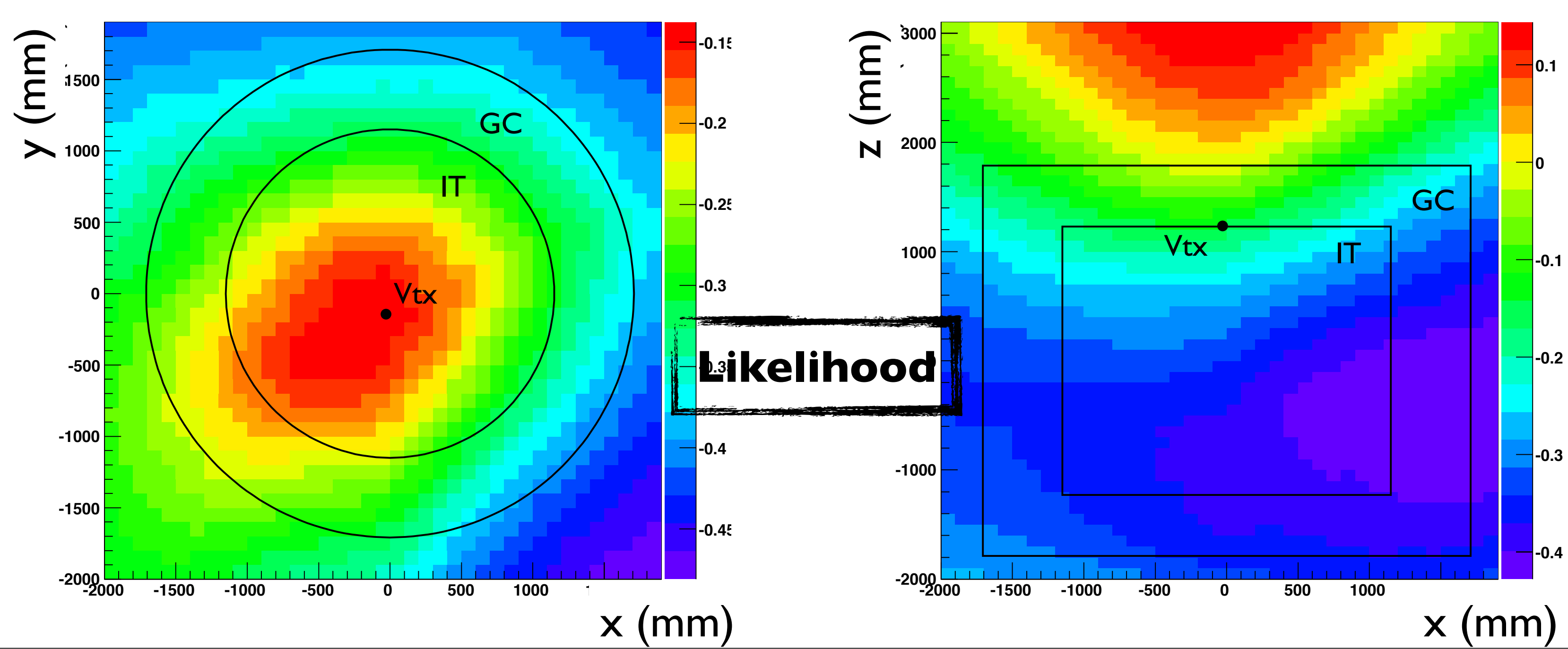


Approach extension: scan the whole detector volume, re-compute the Pulse Shape for each vertex position and search the best agreement with the the ^{60}Co reference using a likelihood approach.

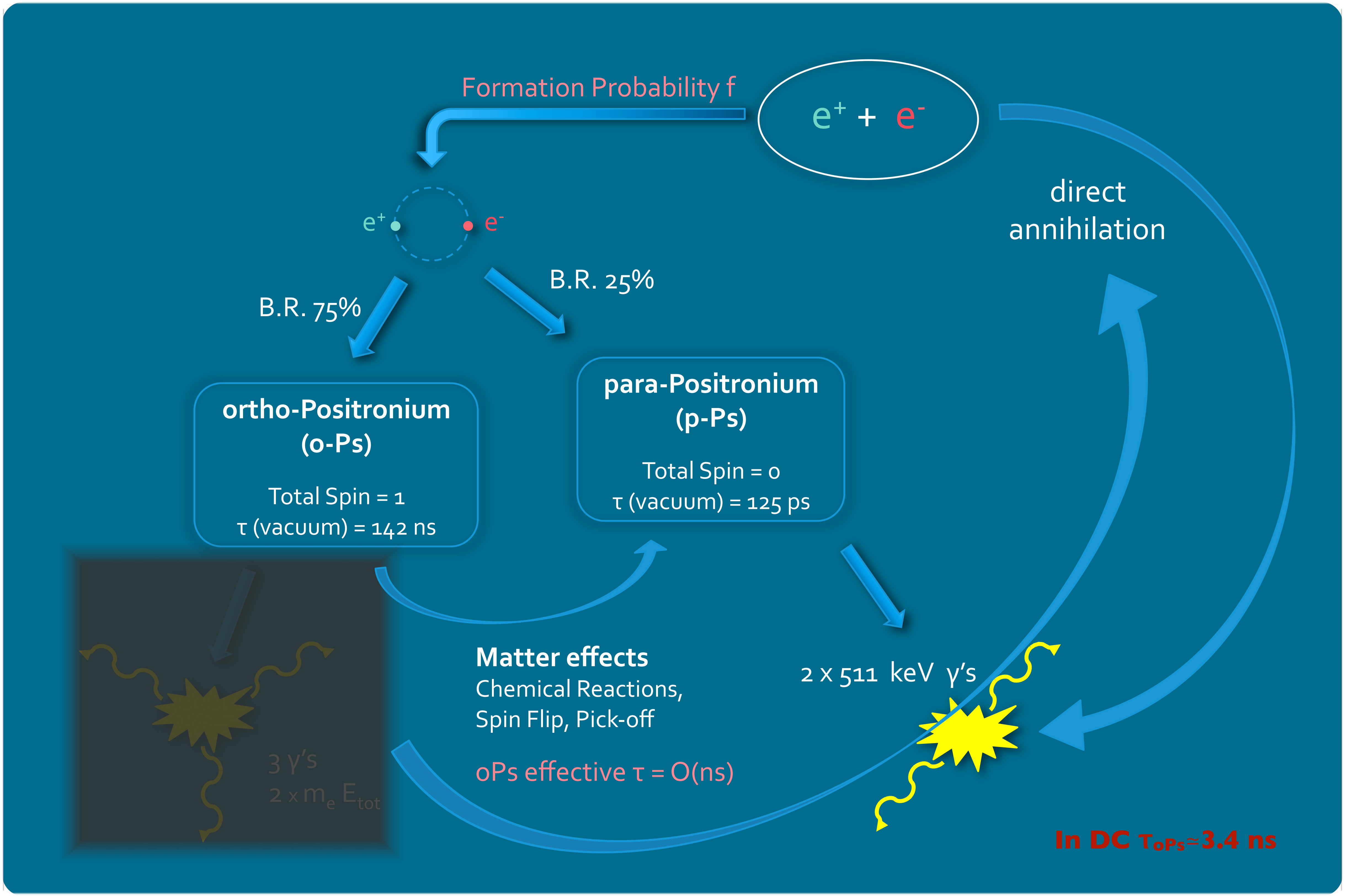
Position of maximum likelihood = **new alternative vertex**.

For most (≳70%) of the Stopping Muons (Gatti < 0) this new vertex is in the chimney. By changing the vertex with the new one and re-running the Gatti analysis, the new Gatti value is positive.





Ortho-Positronium formation



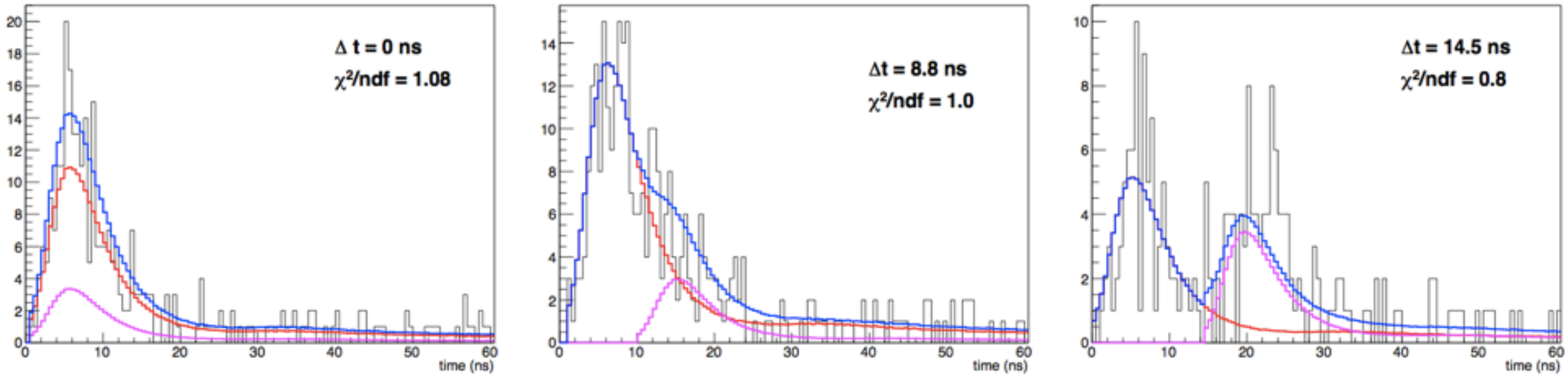
Possibility of o-Ps signature in Double Chooz

DC neutrinos' prompt event = e^+ ionization followed by e^+e^- annihilation (2 · 511 KeV γs).

In case of oPs formation, the time between the two signals can be enough to be seen in the single event's PS with the DC time resolution (≲2ns).

We developed a fit which searches for a double bump structure in the single event PS. Using the ^{60}Co cumulative PS, we build a reference with two signals (normalized as 1MeV for the 2^{nd}, remaining energy for the 1^{st}) separated by a Δt. The fitted Δt value gives the oPs lifetime for that event.

— 1^{st} bump, — 2^{nd} bump, — Total PS, Fit and Chi-square with MINUIT.



Applying the fit to all the neutrino sample we obtained a Δt distribution. The **formation probability and a time of life** extracted from the Δt distribution are **in agreement with the expected values** for the DC scintilators.

Conclusions

- **Double Chooz**, a liquid scintillator reactor anti-neutrino disappearance experiment, studies the oscillation parameter θ_{13} by measuring a deficit in the flux of neutrinos coming from the Chooz nuclear plant.

  $\mathbf{\sin^2(2\theta_{13}) = 1.109 \pm 0.039}$ (Phys. Rev. D 86, 052008 - 2012)

- Double Chooz detects neutrinos' IBDs by looking for a Prompt-Delayed signal. Correlated background from cosmic muons interacting in the detector simulates the IBD signal.

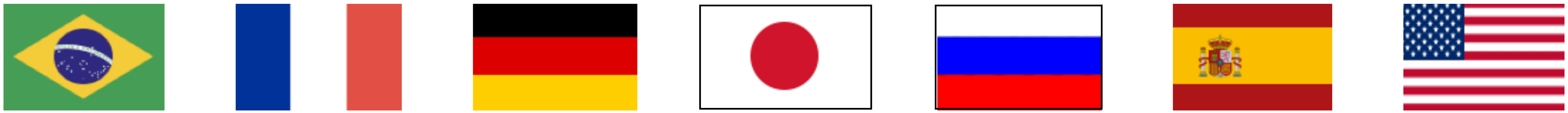
- The **Pulse Shape Discrimination** (PSD), a technique specific for scintillators relying on the PMT pulses time profile (Pulse shapes), aims to disentangle some backgrounds from the signal, for example using a Gatti analysis.

- My work in Double Chooz mostly consisted in implementing a PSD analysis. Up to now, I have been able to **disentangle the Stopping Muons**' background and I'm working on a Fast Neutron separation.

- The **ortho-Positronium** (oPs) can be exploited as a method to **separate e^+ and e^-** events using the distortion in the Pulse Shape induced by the oPs formation.

- We developed a technique (fit) to look at the oPs formation in DC for the first time. With this fit, we **measured a formation probability and a mean lifetime** in agreement with the ones expected for the Double Chooz scintillators.

Thank you for you attention



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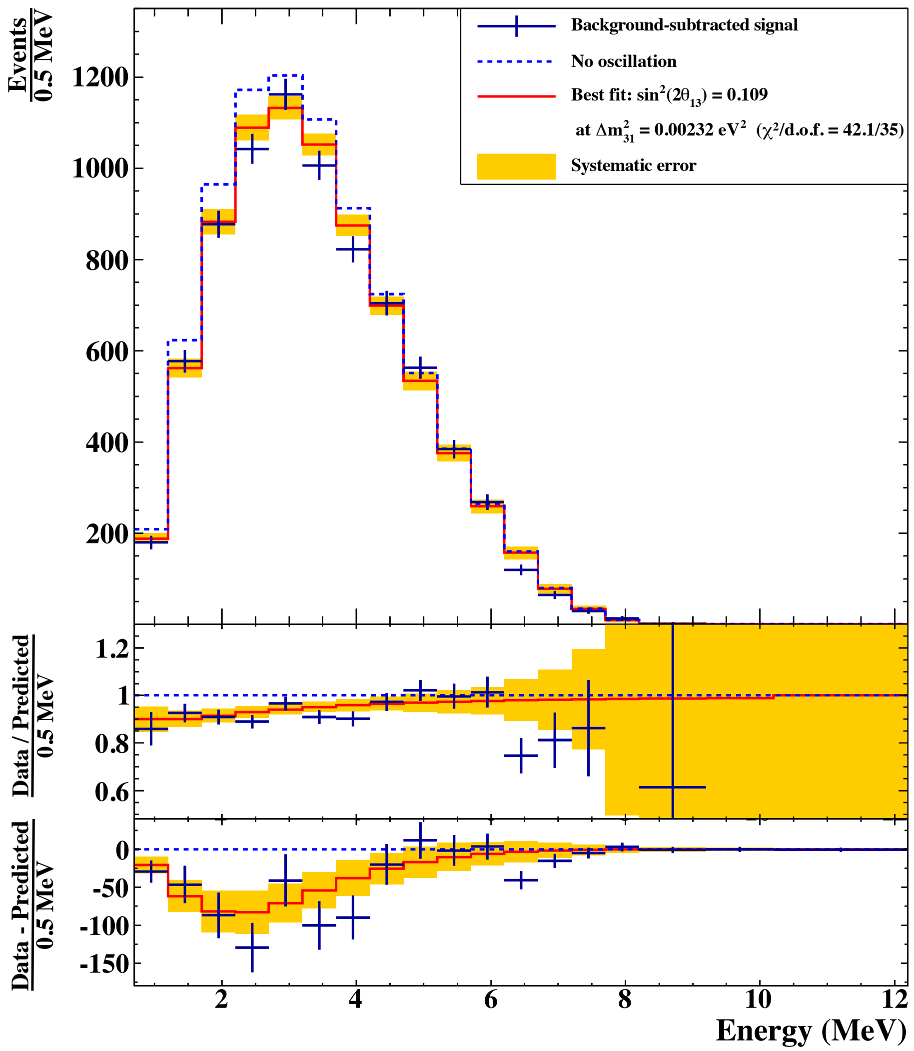
Backup



Scintillator	Composition
Target (10.3 m)	80 $\%_{vol}$ n-dodecane (99.1 %)
	20 $\%_{vol}$ o-PXE (ortho-Phenylxylylethane) (99.2 %)
	4.5 g/l Gd-$(thd)_3$ (Gd(III)-tris-(2,2,6,6-tetramethyl-heptane-3,5-dionate)) (sublimed)
	0.5 $\%_{wt.}$ Oxolane (tetrahydrofuran, THF, > 99.9 %)
	7 g/l PPO (2,5-Diphenyloxazole, neutrino grade)
	20 mg/l bis-MSB (4-bis-(2-Methylstyryl)benzene)
GC (22.5 m^3)	66 $\%_{vol}$ Mineral oil (Shell Ondina 909)
	30 $\%_{vol}$ n-dodecane
	4 $\%_{vol}$ o-PXE (ortho-Phenylxylylethane)
	2 g/l PPO (2,5-Diphenyloxazole)
	20 mg/l bis-MSB (4-bis-(2-Methylstyryl)benzene)
Buffer (100 m^3)	53 $\%_{vol}$ Mineral oil (Shell Ondina 917)
	47 $\%_{vol}$ n-paraffins (Cobersol C 70)
Inner Veto (90 m^3)	50 $\%_{vol}$ Linear Alkyl Benzene (LAB)
	47 $\%_{vol}$ n-paraffins (Cobersol C 70)
	2 g/l PPO (2,5-Diphenyloxazole)
	20 mg/l bis-MSB (4-bis-(2-Methylstyryl)benzene)

Muon event:
- Total charge in IV > 30000 DUQ
- Energy in ID > 20 MeV

Valid trigger:
- Not a muon
- Δt w.r.t last muon > 1000 μs
- E > 0.4 MeV

Light Noise Rejection:
- MQ/TQ < 0.12
- Qdiff < 30000 DUQ
- RMS(Tstart) < 36 or RMS(Q) < 464 - 8*RMS(Tstart)

Prompt energy window:
- 0.5 < E < 20 MeV

OV veto (prompt):
- (if good OV) candidates whose prompt signal is coincident with an OV trigger (fCoincidentOVTrigger == true) are rejected

IV veto (prompt):
- IV PMT multiplicity >= 2
- Total charge in IV > 400 DUQ
- ID-IV space coincidence: Δd < 3.7 m
- ID-IV time coincidence (ID - IV): -110 < Δt < -10 nsec

Li-9 reduction (prompt)
- Li-9 likelihood < 0.4

Gd Analysis

Multiplicity:
- No valid triggers allowed in the 200 μs preceding the prompt candidate
- Only one trigger (the delayed) in the time window from 0.5 μs to 600 μs following the prompt
- Delayed energy window: 4 < E < 10 MeV

Coincidence (prompt and delayed):
- Space coincidence: ΔR < 100 cm
- Time coincidence: 0.5 μs < Δt < 150 μs

FV veto (delayed):
- E > 0.068 * exp(FuncV(time likelihoood)/1.23)