From neutrons to neutrinos and back again

*Pablo FM (DIPC), a **Gd**Child*

*2025/04/23 – The **Gd**Father is reborn*

Outlook

In the beginning there was gadolinium and neutrons…

- The gadolinium R&D era
  - When I didn't know
  - When I learned
- Neutron thermalization and acceleration of research
- Looking forward and beyond

… And then, there is no end (a "popurrí")

- Let's gadiate all detectors! (or closer to Gd-efficient)
- Atmospheric neutrinos
- Combined (neutrino oscillation) analyses for the bigger picture

The Gd R&D era

[Submitted on 26 Sep 2003]

GADZOOKS! Antineutrino Spectroscopy with Large Water Cerenkov Detectors

John F. Beacom, Mark R. Vagins

Thanks to the commitment of the Super-Kamiokande collaboration a long and fruitful R&D period started with the **EGADS** prototype

It was already crucial for the UAM to become the first Spanish SK (and then HK) member in 2008

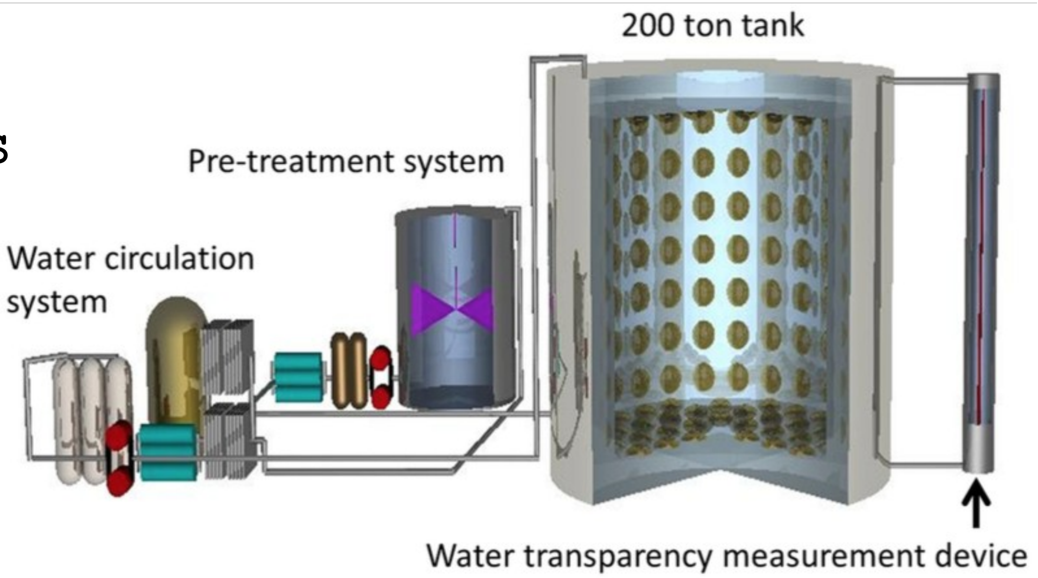
But it was a bit too early for me...


Former
miner

Nevertheless, thanks to **EGADS** and the SuperK-Gd project, I could start my research very soon almost 15 years ago

At it was like being at home, huge green mountains and mines, only learning much more

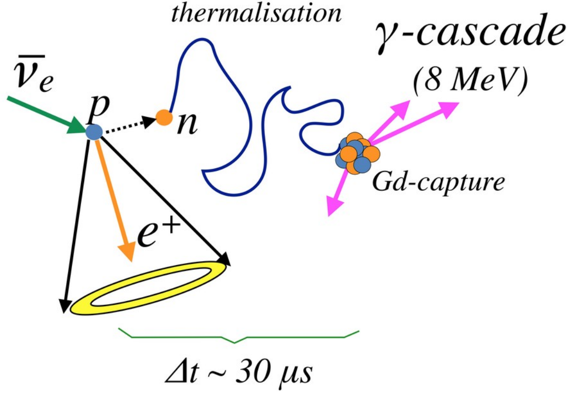
The next 3 summers we pre-calibrated the EGADS/HK PMTs and installed EGADS (with a SK LINAC festival in the middle)

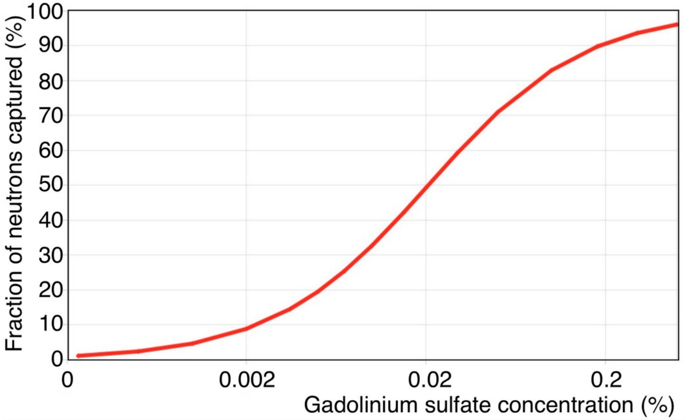


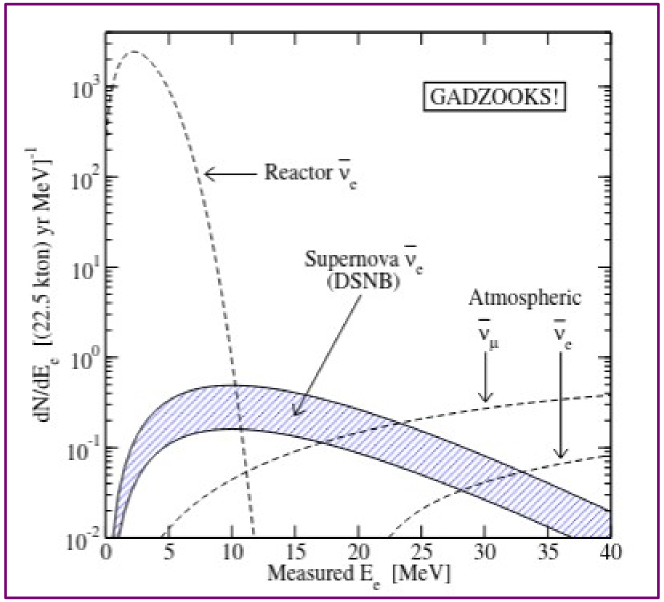
...and a bit of rust-cleaning again

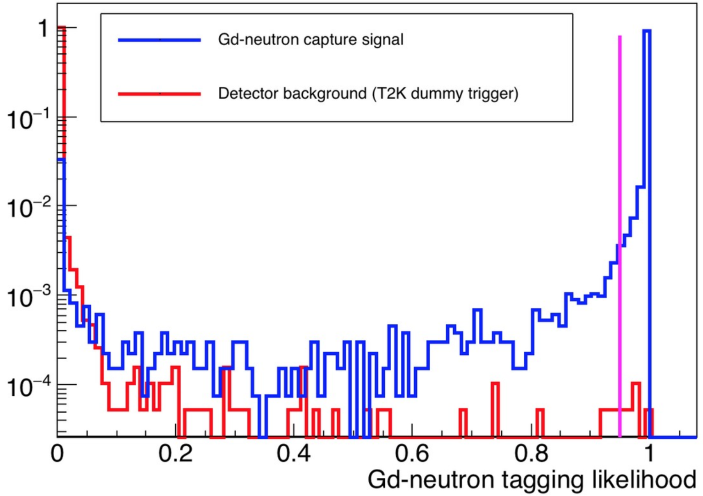
And started to analize one of the biggest threats of Gd, having too many radioactive impurities

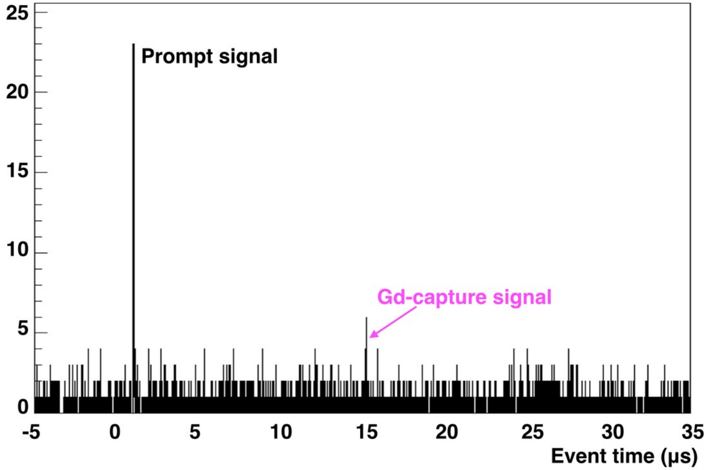
- Radioactive measurement (Ge detector) of a lot of Gd batches
- Estimate backgrounds for solar and reactor neutrinos and, of course, the Diffuse Supernova Neutrino Bakcground (DSNB)











Isotope	Natural Abundance (%)	Cross-section (barn)	De-excitation energy (MeV)
152Gd	0.20	1050	6.25
154Gd	2.18	85.0	6.44
155Gd	**14.80**	**60700**	**8.54**
156Gd	20.47	1.71	6.36
157Gd	**15.65**	**254000**	**7.94**
158Gd	24.84	2.01	5.94
160Gd	21.86	0.765	5.64

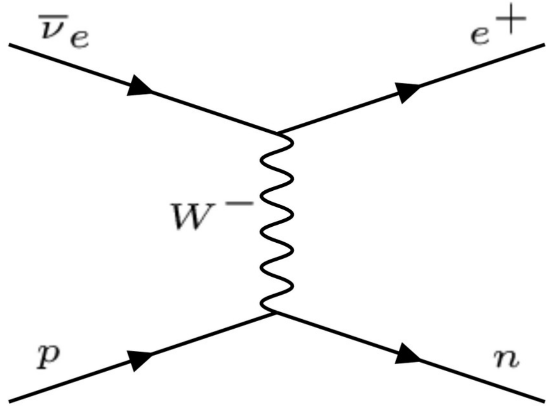
$$n +^{X} Gd \rightarrow^{X+1} Gd^{*} \rightarrow^{X+1} Gd + \gamma s$$

It’s a great moment to thank the support from everyone in SK and all they taught me, especially Mark as the one coordinating and leading every Gd-aspect.

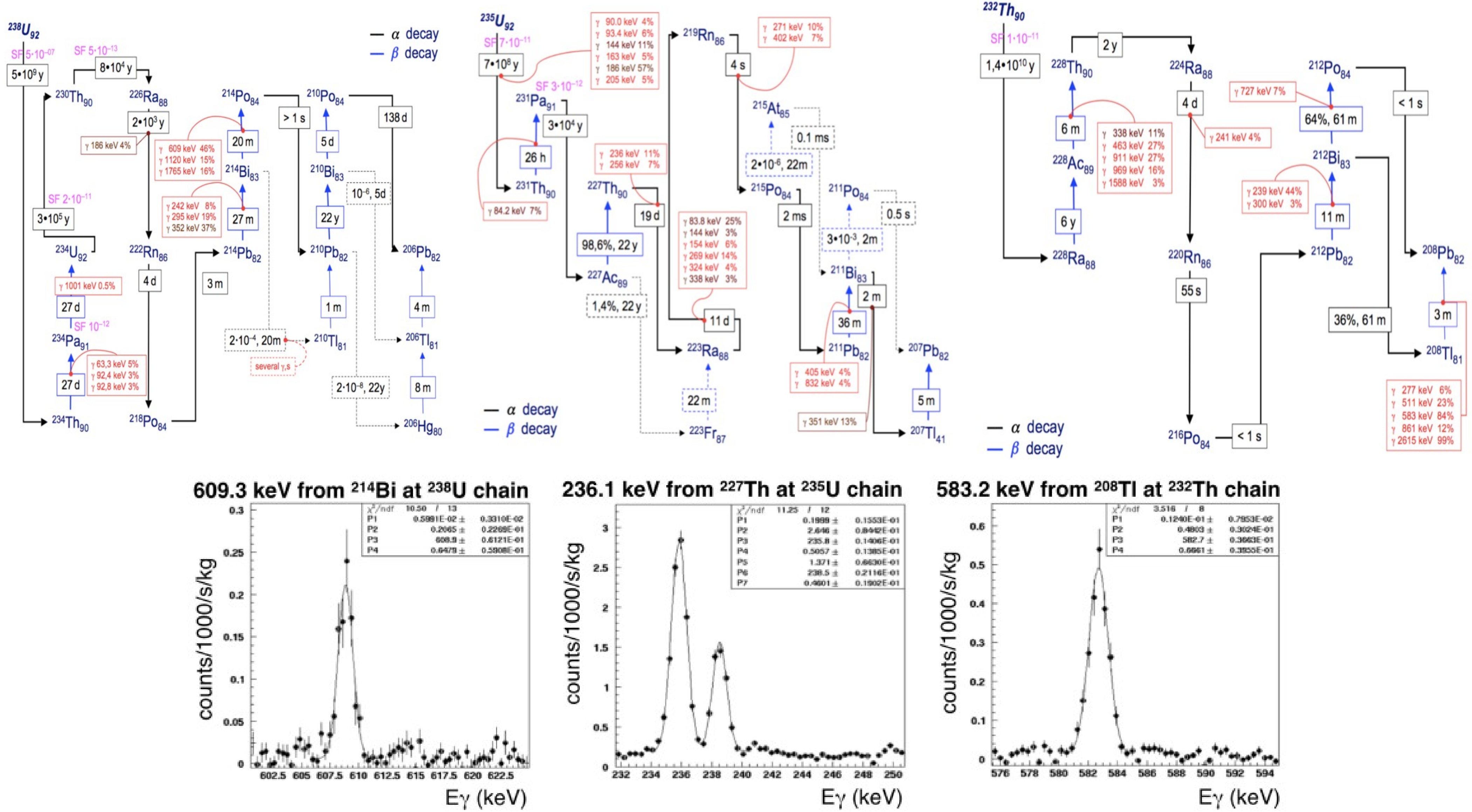
Finally, I started to understand the physics and what neutrinos were about, and was able to start my PhD in SuperK-Gd.

Low Energy Physics of SuperK-Gd

- Below ~70 MeV, inverse beta decay dominates the antineutrino cross-section
- Neutron-tagging provides a very clean way to separate neutrinos and (most of) spallation background from small antineutrino signals



- One of the worries was that there might be too many neutrons, mainly coming from radioactivity
- The other one is that Gd was too "dirty" to be compatible with ultrapure water and O(MeV) neutrino physics
- ... or the effect of Gd in light transmittance of water



$^{238}U_{92}$
$^{235}U_{92}$
$^{232}Th_{90}$
α decay
β decay
609.3 keV from ^{214}Bi at ^{238}U chain
236.1 keV from ^{227}Th at ^{235}U chain
583.2 keV from ^{208}Tl at ^{232}Th chain
counts/1000/s/kg
Eγ (keV)

^{238}U Spontaneous Fission

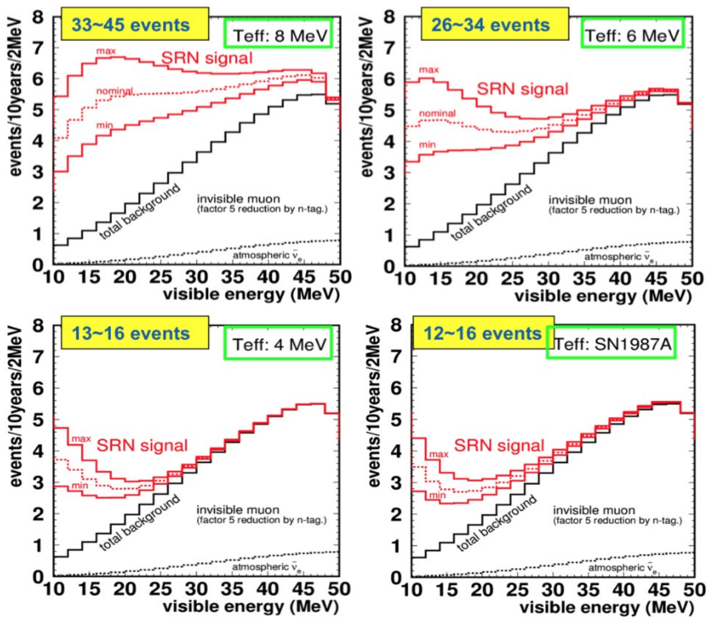
what

When the nucleus splits, gammas and neutrons are emmited. In the case that an energetic enough (MeV) gamma and a single neutron could match the IBD signal.

$$N_{SF}(1\gamma + 1\,Gd\text{-}tagged\ n) = 21.75\left(e^{-\frac{E_{min}}{1.4}} - e^{-\frac{E_{max}}{1.4}}\right)\frac{1}{day \cdot SKFV}$$

impact

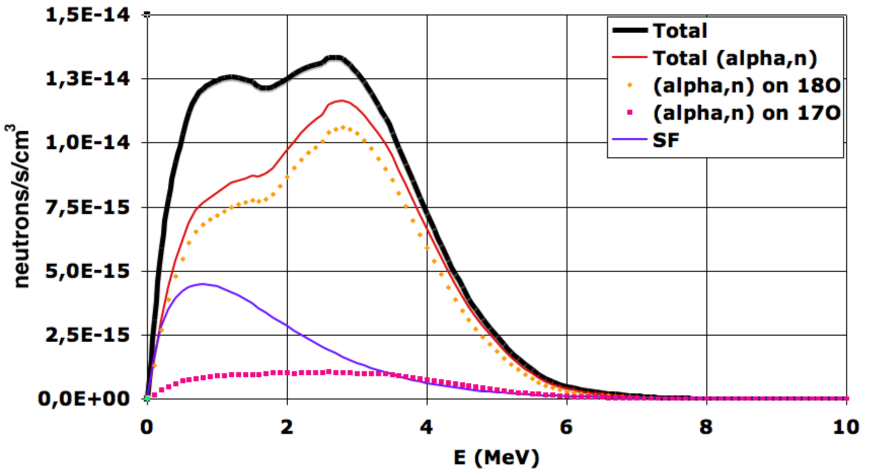
This was/is one of the main new backgrounds for the **DSNB** searches, which put very rigid limits to the contamination from this chain.



Radioactivity-Induced Neutron Production

what

Neutrons produced due to the radioactive contamination is large, there will be many neutron captures with no prompt signal.
They could be mistaken for neutrino signals or even saturate the detector



impact

This is the largest radioactive background source, all chains contribute largely to it.

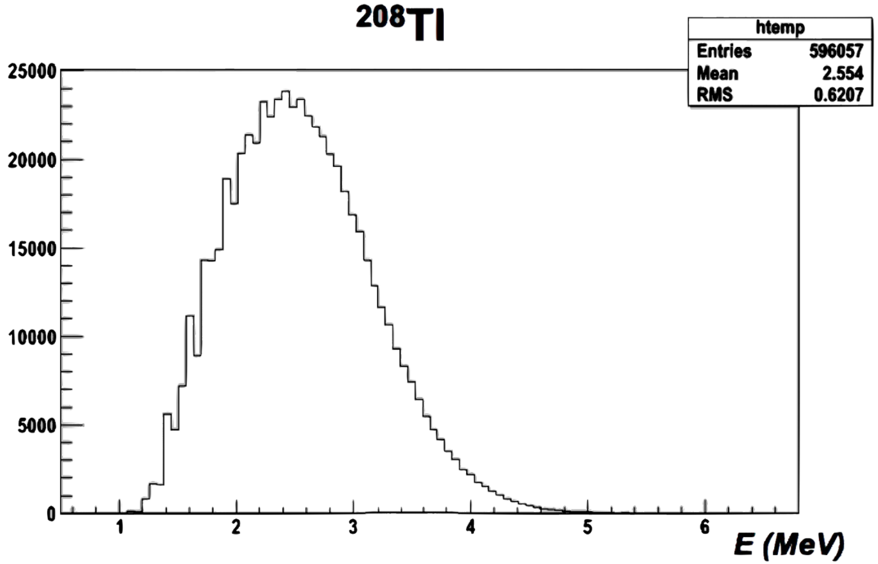
Therefore it impacts **solar** neutrinos (because of the gammas from the capture) and, to a lesser extent, antineutrinos (**reactor and DSNB**) due to accidental coincidences.

Additionally, they impact the ability to detect very low-enery antineutrinos from **pre-supernova** stages

β-Rays from Radioactivity

what

The main contributions are from the ^{208}Tl (Q_β = 5.00 MeV), ^{212}Bi (Q_β = 2.25 MeV) and ^{214}Bi (Q_β = 3.27 MeV) isotopes, those with higher Q_β-value of the three radioactive chains.



impact

This backgroun largely affects the lower energy bins of **solar** neutrinos.

But could also contribute significantly to **reactor** antineutrinos due to accidental coincidences.

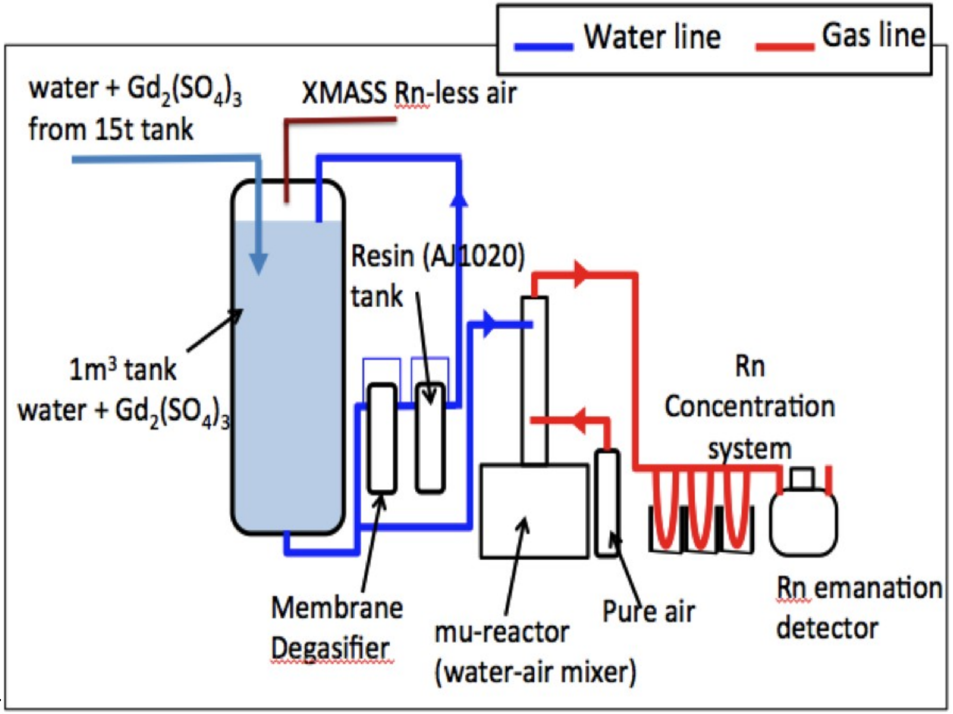
Low Energy Physics of SuperK-Gd

With that we could set the requirements on the cleanness of gadolinium (R&D cleaning programs) or at least set our physics goals.

[Submitted on 13 Sep 2022]

Development of Ultra-pure Gadolinium Sulfate for the Super-Kamiokande Gadolinium Project

K. Hosokawa, M. Ikeda, T. Okada, H. Sekiya, P. Fernandez, L. Labarga, I. Bandac, J. Perez, S. Ito, M. Harada, Y. Koshio, M. D. Thiesse, L. F. Thompson, P. R. Scovell, E. Meehan, K. Ichimura, Y. Kishimoto, Y. Nakajima, M. R. Vagins, H. Ito, Y. Takaku, Y. Tanaka, Y. Yamaguchi



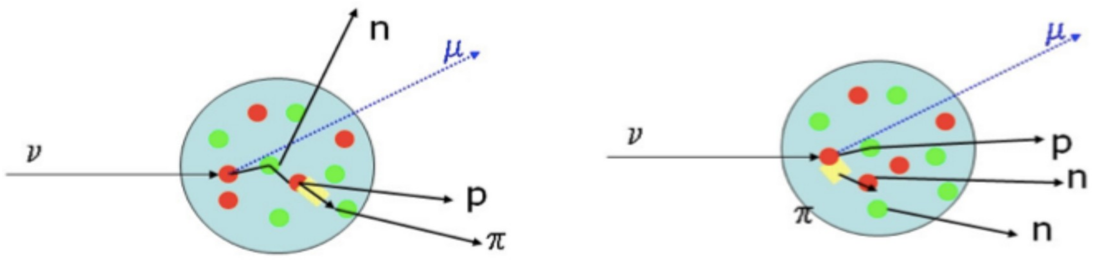
Radium-removal system

That's way too many things/backgrounds to take into account, let's move to higher energies.

High(er) Energy Physics of SuperK-Gd

What opportunities could neutrons bring to mainly atmospheric, but also accelerator neutrinos

- Varied interaction modes and with oxygen nuclei make that separating neutrinos from antineutrinos is not precise but statistical

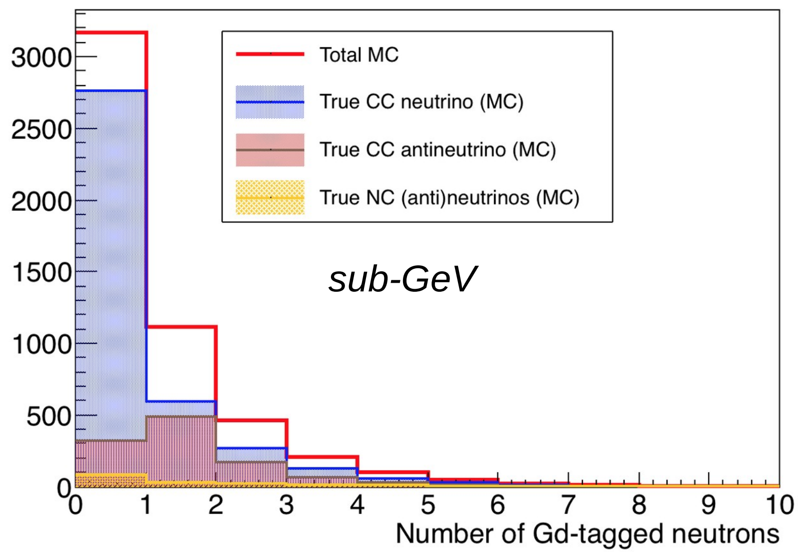


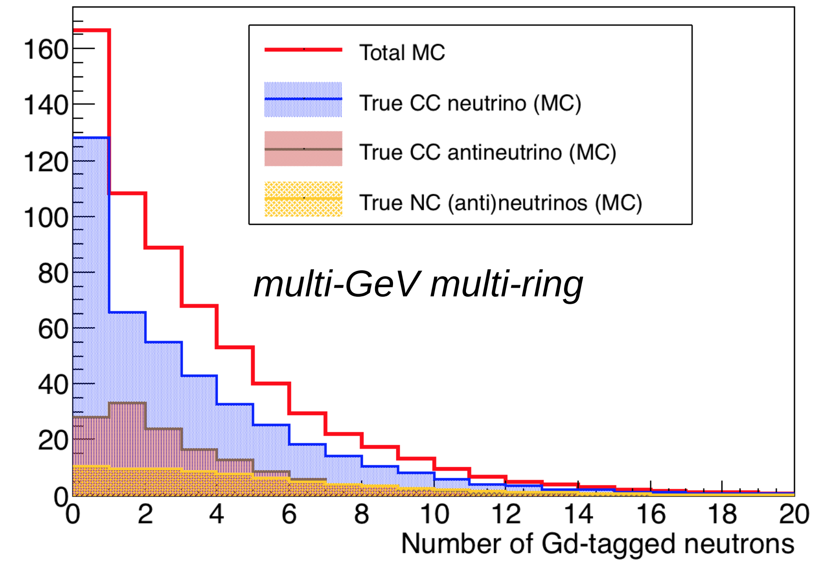
High(er) Energy Physics of SuperK-Gd

- Still, we studied the potential of neutrons beyond that
  - Neutrino-antineutrino separation
  - Classification of charged and neutral currents
  - Neutron-corrected neutrino energy reconstruction
- All of them rely on the same principle: The amount of neutrons knocked-out encloses in a “diffuse way” information of the neutrino interactions that is washed out by nuclear media and secondary interactions

Neutrino-Antineutrino

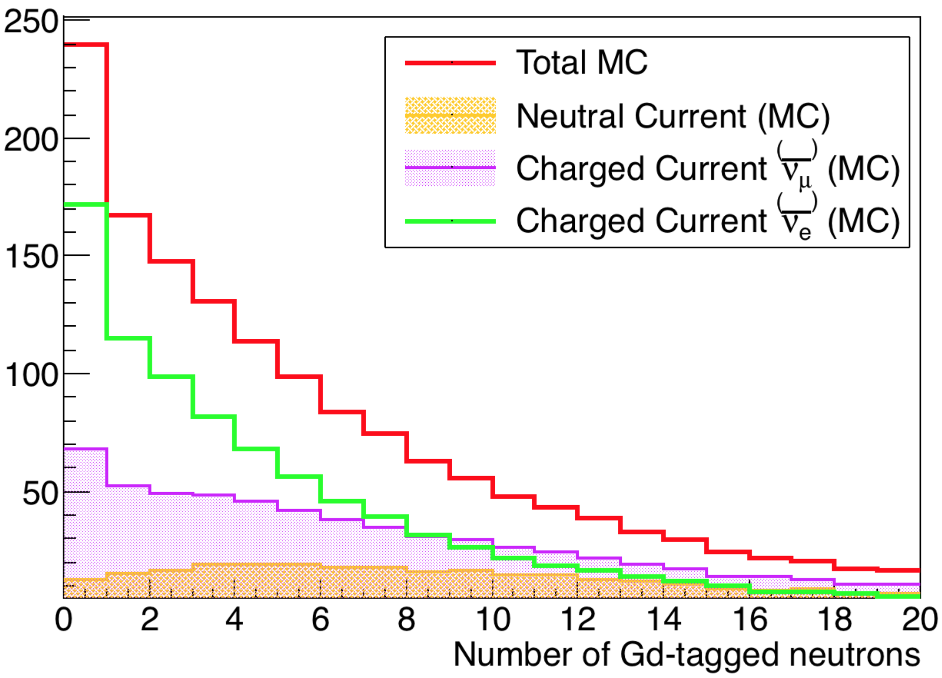
Interaction	Name
$\nu + N \to l + P$ $\overline{\nu} + P \to \bar{l} + N$	CCQE
$\nu + P \to l + P + \pi^+$ $\overline{\nu} + N \to \bar{l} + N + \pi^-$ $\nu + N \to l + P + \pi^0$ $\overline{\nu} + P \to \bar{l} + N + \pi^0$ $\nu + N \to l + N + \pi^+$ $\overline{\nu} + P \to \bar{l} + P + \pi^-$	CC1π (from Δ resonance)
$\nu + O^{16} \to l + O^{16} + \pi^+$ $\overline{\nu} + O^{16} \to \bar{l} + O^{16} + \pi^-$	CC1π
$\nu + N/P \to l + N/P + \text{multi}\pi$ $\overline{\nu} + N/P \to \bar{l} + N/P + \text{multi}\pi$	CCmultiπ
$\nu + N \to l + P + \eta^0$ $\overline{\nu} + P \to \bar{l} + N + \eta^0$	CC1η (from Δ resonance)
$\nu + N \to l + \Lambda + \kappa^0$ $\overline{\nu} + P \to \bar{l} + \Lambda + \kappa^0$	CC1κ (from Δ resonance)
$\nu + N/P \to l + N/P + \text{mesons}$ $\overline{\nu} + N/P \to \bar{l} + N/P + \text{mesons}$	CC deep inelastic (JET set)





NC-CC classification

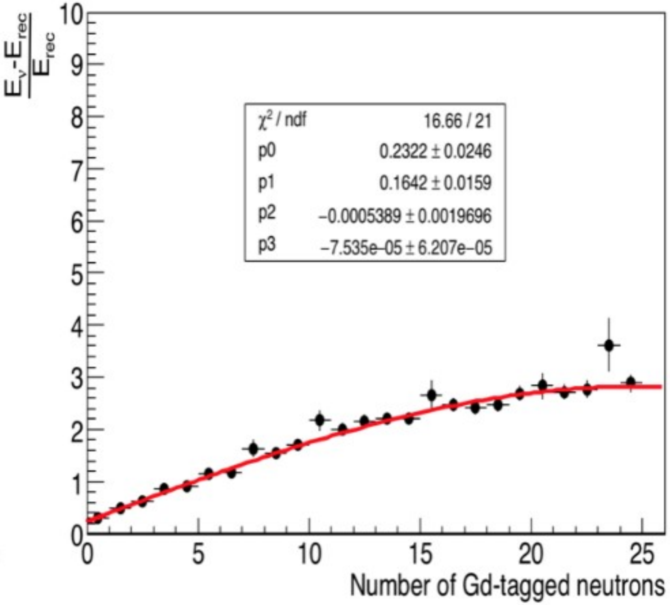
Neutrinos interacting via neutral current interactions leave a larger fraction energy in the target nucleus than those interacting charged current. This makes the typical neutron production of NC events larger than CC ones.

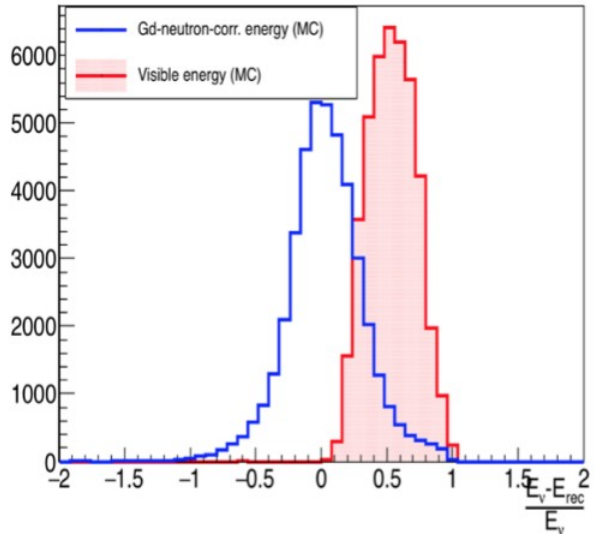


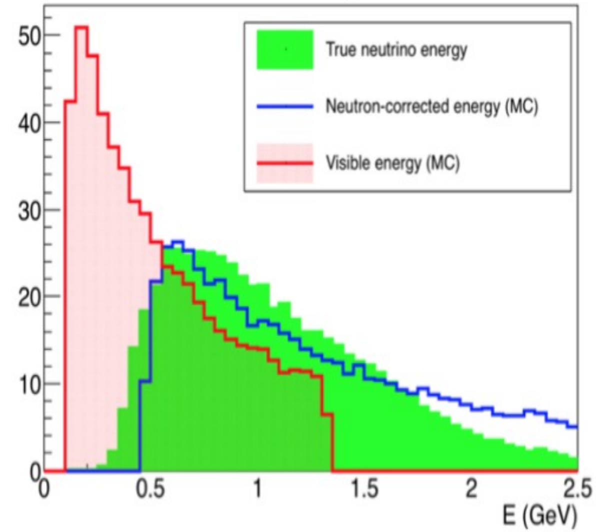
Neutron-corrected energy reconstruction

Upon event classification, the differences in neutron mutplicities are impacted by the amount of neutrino energy transferred to hadrons. This complements the visible energy reconstruction of charged leptons.

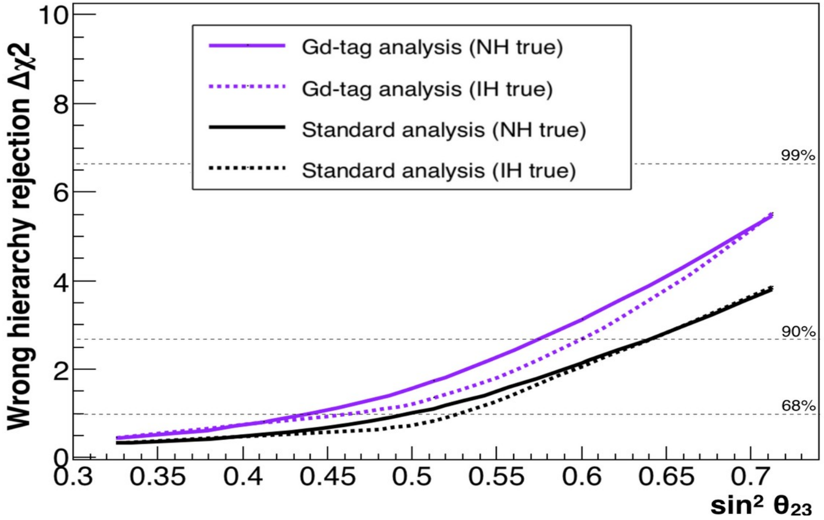
$$E_{rec}^{Gd} = E_{vis}(1 + f(\text{Gd-neutrons}))$$

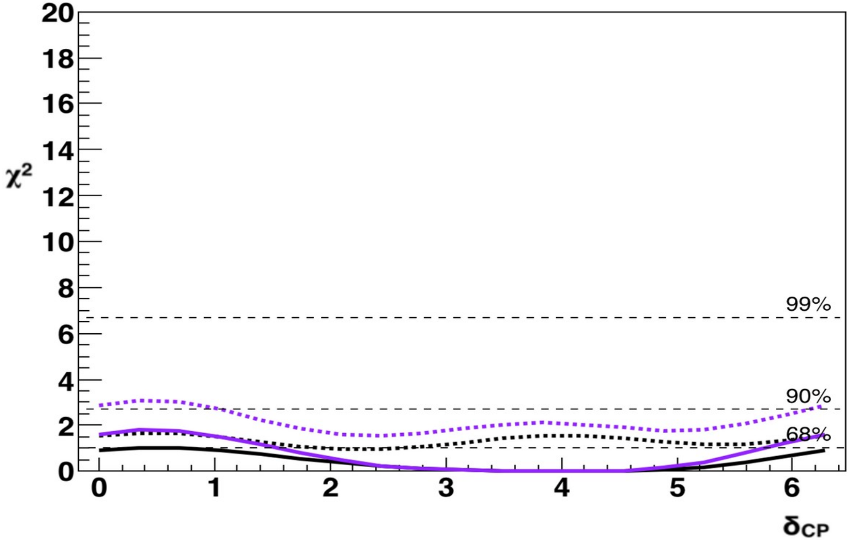




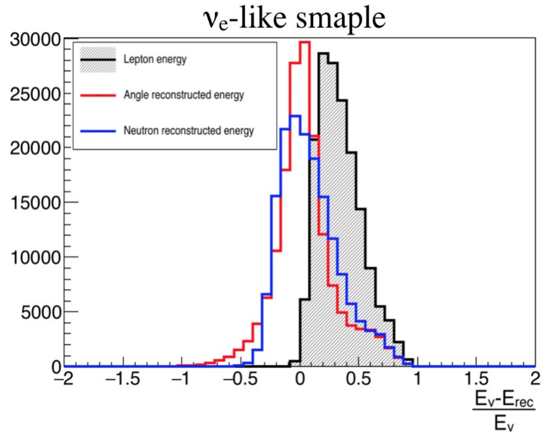


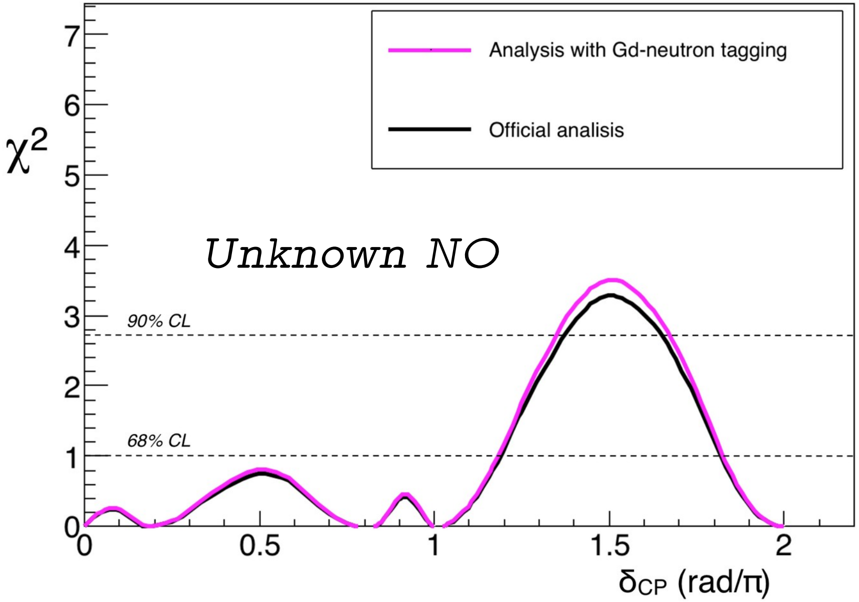
Atmospheric neutrinos





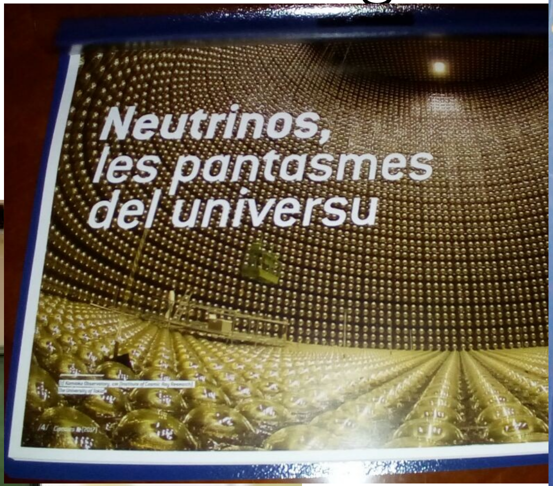
T2K neutrinos

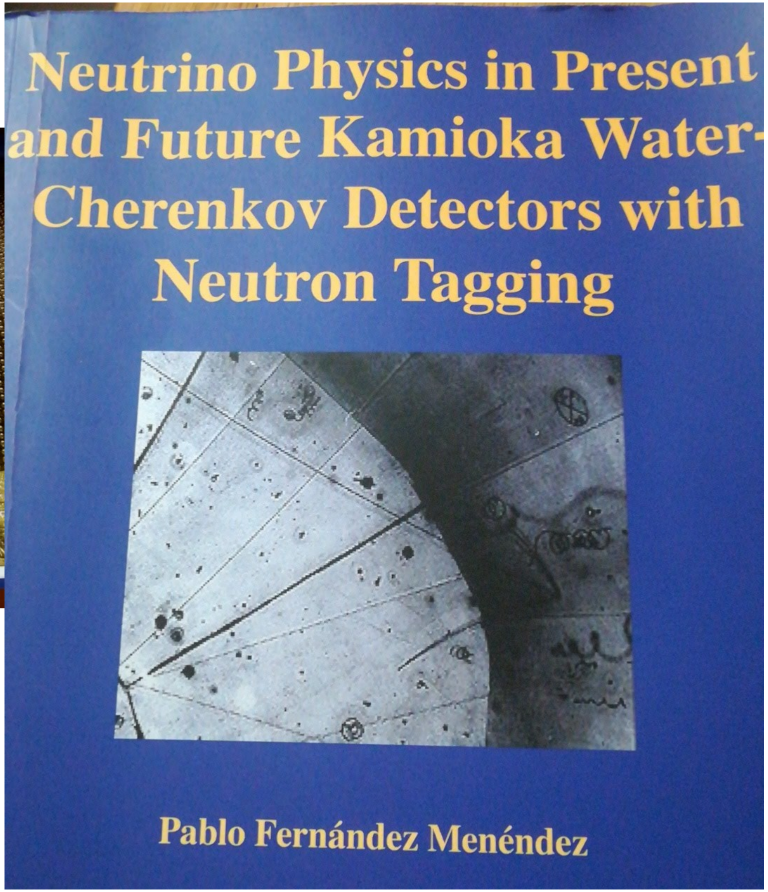




Concluding my first Gd-path

And Mark (and Roger) came all the way to Spain to hear me saying all this once again





A brief saying of my current whereabouts

“Gadiating” the next-generation, HK

Gadolinium (and everything that comes with it) is expensive, so something else has to be done to tag neutrons in Hyper-Kamiokande

- Take advantage of HK superior PMTs and machine-learning to improve neutron tagging on hydrogen

New Approaches of first selection for Neutron Tagging in Hyper-Kamiokande

Sergio Luis Suárez Gómez[a,*] **and Pablo Fernández Menéndez**[b,c]

a Department of Mathematics, University of Oviedo, C/ Leopoldo Calvo Sotelo 18, Oviedo, Spain

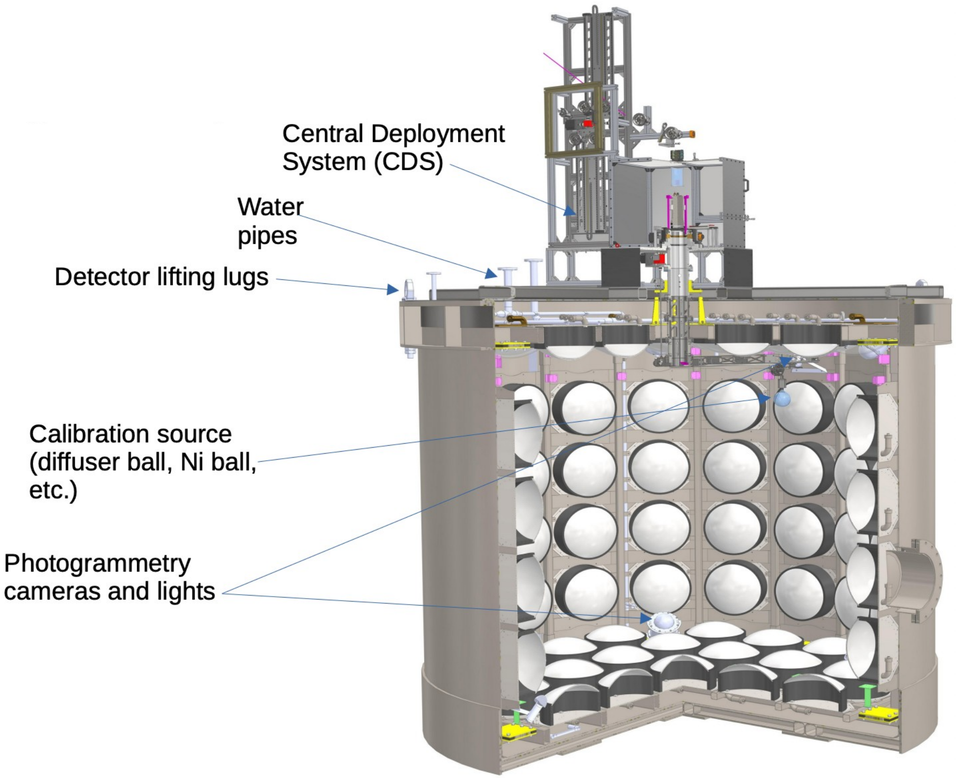
b University of Liverpool, Department of Physics, Liverpool, United Kingdom

From 58% to 82% selection efficiency at the same false positive rate of previous methods

“Gadiating” the next-generation, WCTE&IWCD

WCTE is another small Gd-based prototype installed at CERN

- Ideal detector to study the neutron production of different beam particles ($e^{\pm}$, $\mu^{\pm}$, $\pi^{\pm}$, and p) from 200 MeV/c to 1.2 GeV/c
- Improve the impact of neutrons for accelerator and atmospheric neutrinos

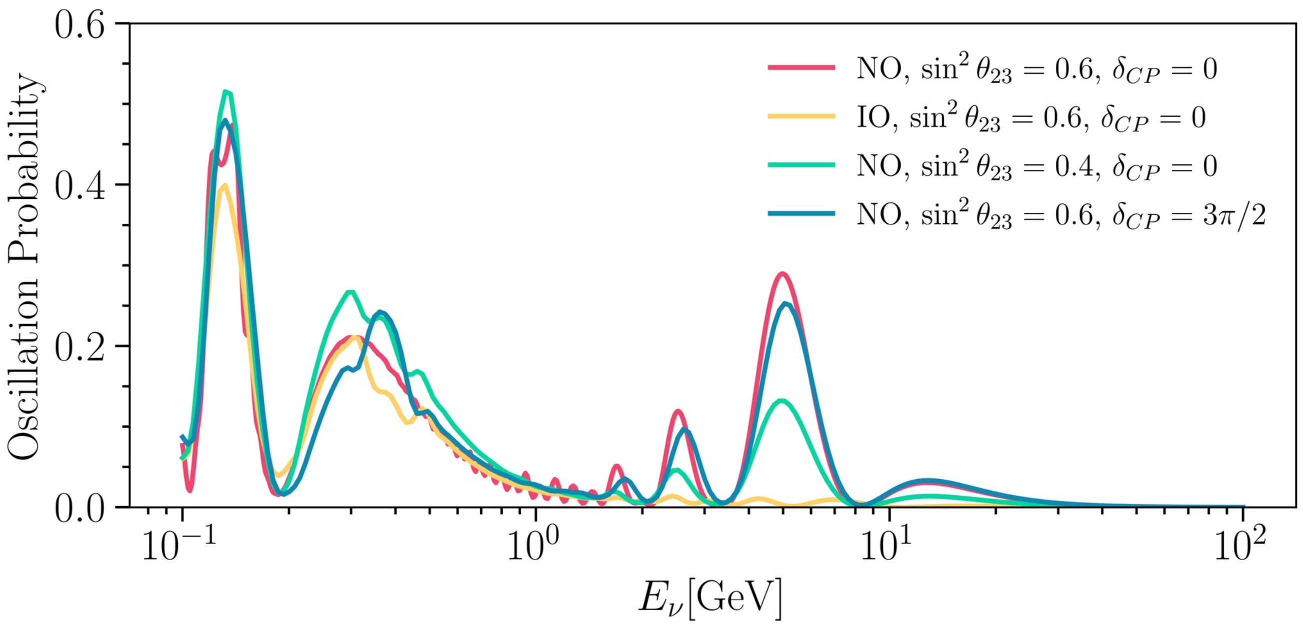


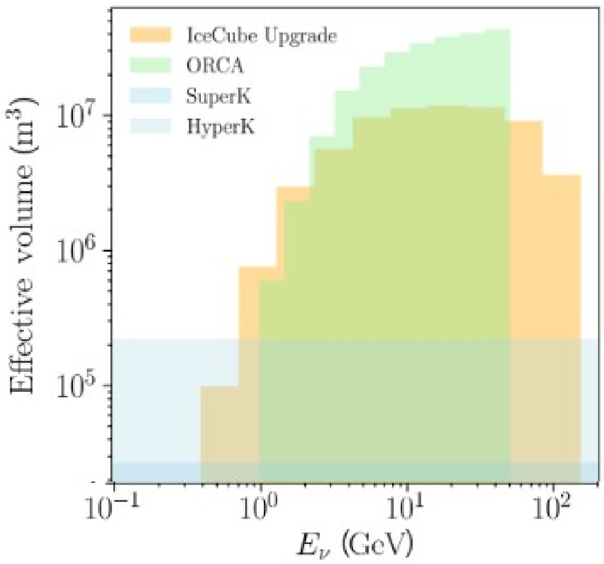
Followed and complemented by IWCD?

Combined Oscillation Analyses

- There have been two major strategies combining the neutrino experimental data to improve the precision of the oscillation parameters
  - Solar and reactor for θ_{12} and Δm^2_{21}
  - Atmospheric and long-baseline (and reactor) θ_{23}, Δm^2_{31}, δ_{CP} and the ordering
- The latter are the most critical as those parameters are the most uncertain
- But there are issues:
  - Pheno.: not enough detail (especially for SK)
  - Exp./official: not all datasets are included
  - Both: very CPU demanding (oscillations, fits, systematics)

Focusing on atmospherics





$\nu\mu \to \nu e$ oscillation probabilities of **atmospheric neutrinos** illustrating the effects of different for cos θzen $= -0.85$

Combined Oscillation Analyses

Working towards a comprehensive solution:

- Closed eyes to make an SK simulation using only public information
  - Which is being improved further thanks to the latest SK MC release
  - And can be used for many other things

[Submitted on 21 Mar 2025]

Probing the general axion-nucleon interaction in water Cherenkov experiments

Mael Cavan-Piton, Diego Guadagnoli, Axel Iohner, Pablo Fernandez-Menendez, Ludovico Vittorio

Atmospheric Neutrino Monte Carlo Simulations

Fernández, Pablo (Contact person) [1, 2];
Argüelles-Delgado, Carlos (Project member) [3];
Jin, Miaochen (Project member) [3]; Iván, Martínez-Soler (Project member) [3]

Hide affiliations

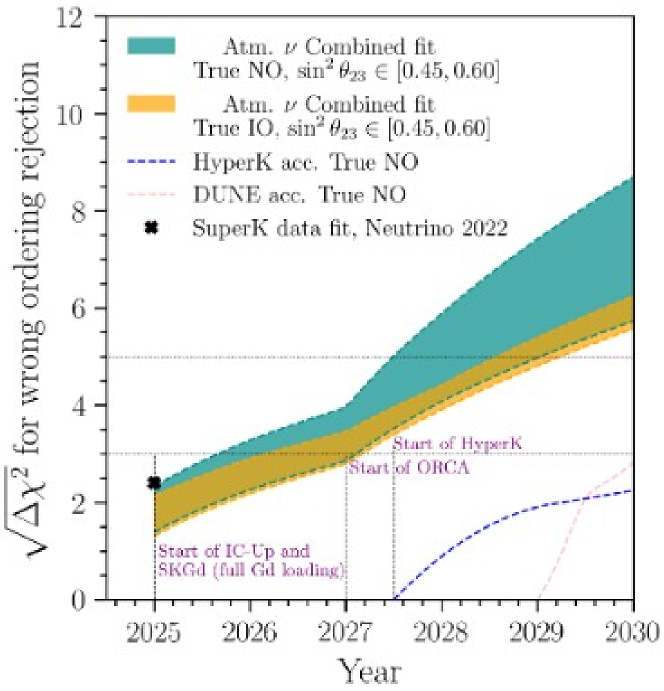
1. Donostia International Physics Center
2. University of Liverpool
3. Harvard University

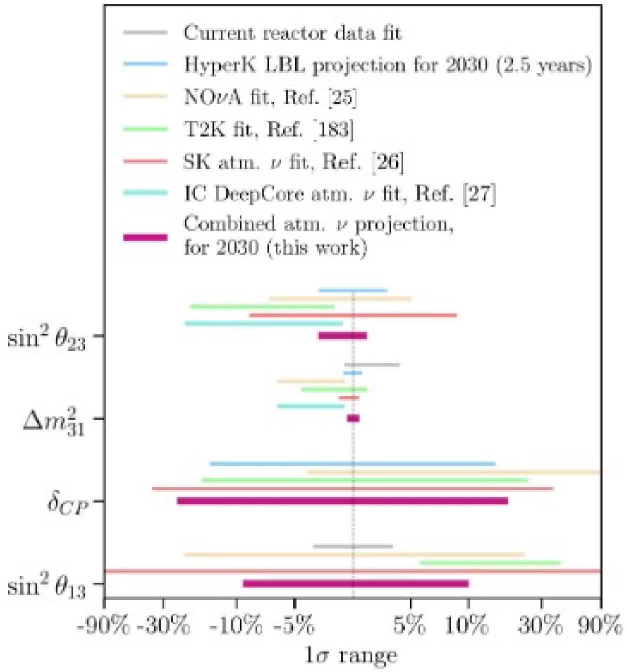
We provide the MC simlation files of atmospheric neutrinos for the following experiments in HDF5 (https://www.hdfgroup.org/solutions/hdf5/) format.

- **IceCube-Upgrade:** Copied from publibly available simulation from the [IceCube Collaboration](https://icecube.wisc.edu/data-releases/2020/04/icecube-upgrade-neutrino-monte-carlo-simulation/) converted into .hdf5 format for completeness.
- **ORCA:** Projected simulation based on IceCube-Upgrade's upgrade Monte Carlo applying reported detector response.
- **SuperK:** Simulation of fully-contained (FC) events with no neutron tagging covering the first 3 phases of the experiment. It can be used as simulation for Hyper-Kamiokande scaling the weights accordingly (x8.3).
- **SuperK with neutron tagging on Gadolinium:** Simulation of fully-contained (FC) events with neutron tagging on gadolinium (80% efficiency) assuming the SuperK detector is loaded with Gd at the goal concentration of 0.1%.
- **SuperK with neutron tagging on Hydrogen:** Simulation of fully-contained (FC) events with neutron tagging on hydrogen (~24% efficiency) for phases 4 and 5 of SuperK and also used as HyperK's simulation file scaling the weights accordingly (x8.3).

Combined Oscillation Analyses

- How the sensitivty to the “atmospheric” parameters will look like adding all atmospheric ν data





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Measuring Oscillations with a Million Atmospheric Neutrinos

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C. A. Argüelles[1,*], P. Fernández[2,3,†], I. Martínez-Soler[1,‡], and M. Jin (靳淼辰)[1,§]

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Phys. Rev. X **13**, 041055 –
Published 20 December, 2023

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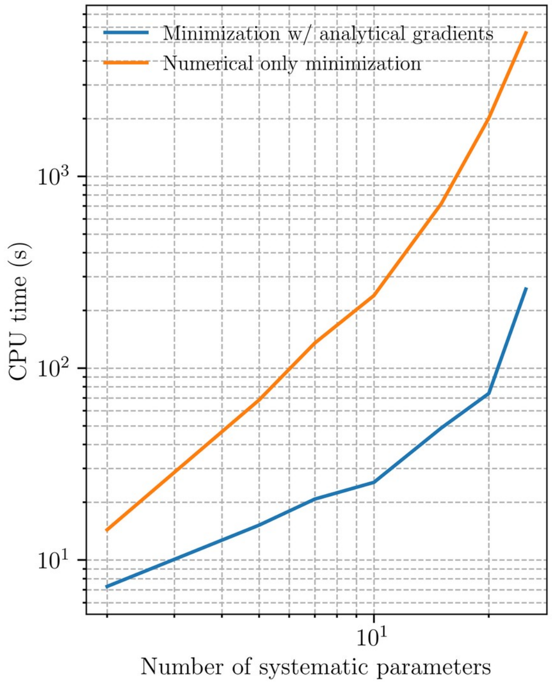
To be followed very soon by a combined fit to the data…

Combined Oscillation Analyses

- Improving the fit methodology …ongoing…
  - For a frequentist/profiling approach, one working thing is to compute analytically the derivative w.r.t. the systematic errors
  - For marginalizing, you also get similar improvements by using more sophisticated intagration methods that rely in derivatives



Combined Oscillation Analyses

- It means you will need the derivatives of the oscillation probabilities
- Rather complicated to do "analytically", but it's an opportunity
  - Improve computation time of oscillation probabilities
  - They bring new insights for the oscillation effects (see soon to be published HK sensitivity paper)

...but that's ongoing and maybe for another time...

CHICOS: Neutrino Oscillation Probabilities using Caley-Hamilton and Hamiltonian Invariants

Neutrino Oscillations, Hamiltonian Invariants and Tangent Spaces

Hamiltonian Monte Carlo for Bayesian Inference at High-Energy Physics Statistical Analyses

Summary

- For me, it opened the huge and exciting field of neutrino physics research
- But adding gadolinium in water-Cherenkov detectors brought loads of original research paths, developments and new ideas, and will continue to do so for many years

Congratulations and thank you, Mark!

Thank you very much for the invitation and for everything