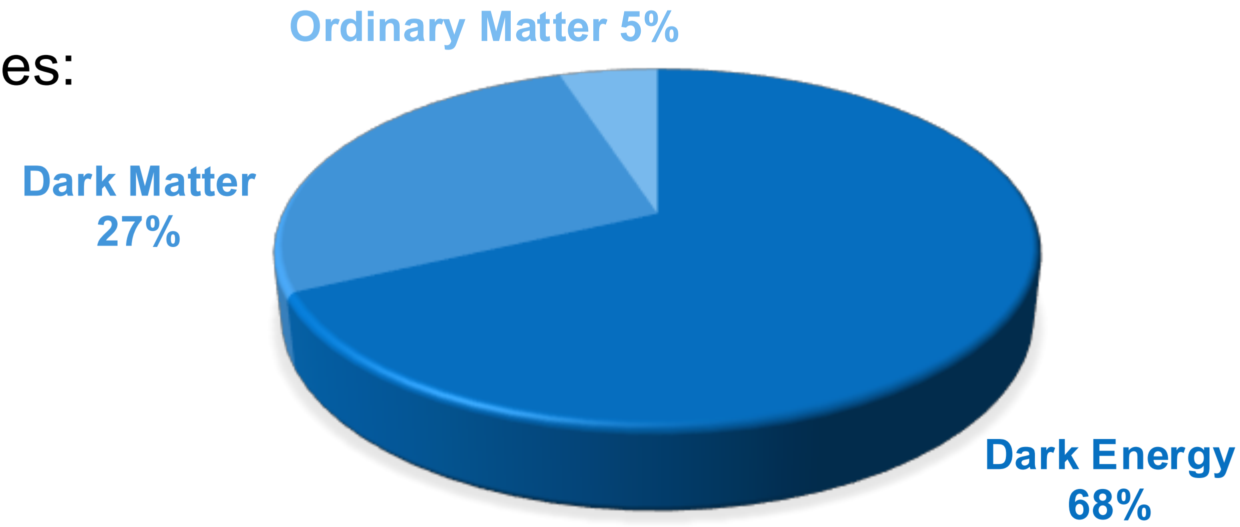
STUDY OF MUON-INDUCED NEUTRONS IN XENONnT

Veronica Beligotti – 30/10/2025
INFN | Università di Bologna

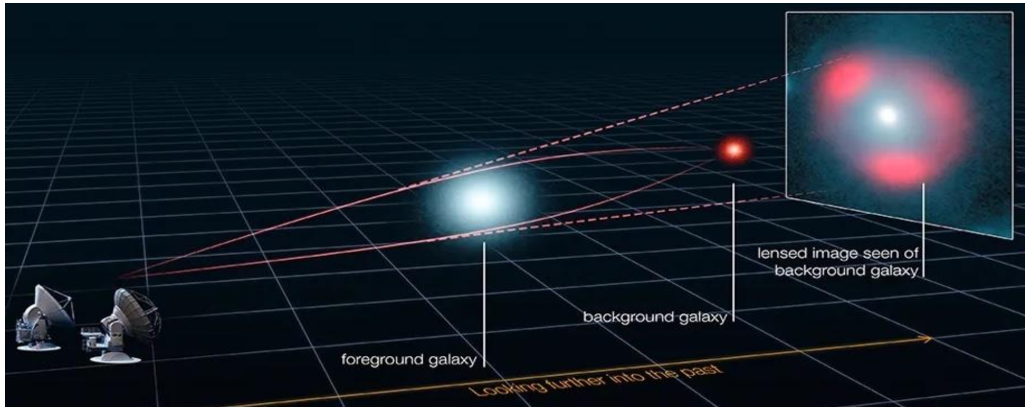
DARK MATTER

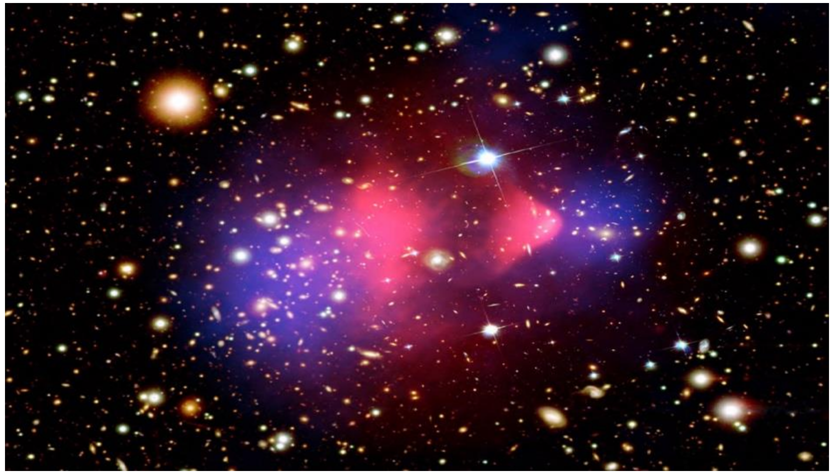


Several astrophysical and cosmological evidences:

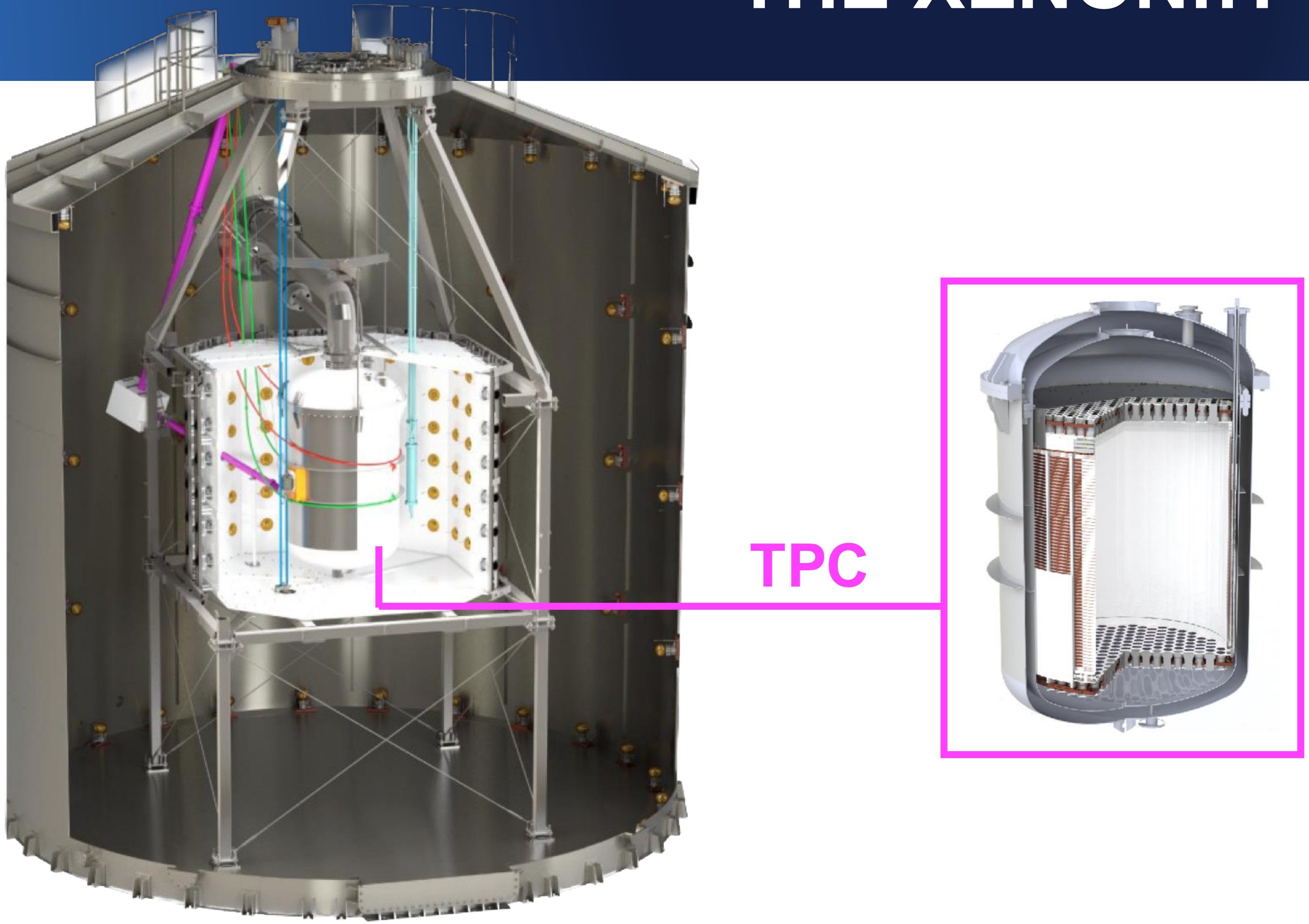
- Galaxy rotation curves
- Gravitational lensing
- Bullet cluster
- CMB anisotropies
- Large-scale structure

Among the most promising candidates are **WIMPs** (Weakly Interacting Massive Particles), characterized by gravitational and weak interactions.





THE XENONnT EXPERIMENT



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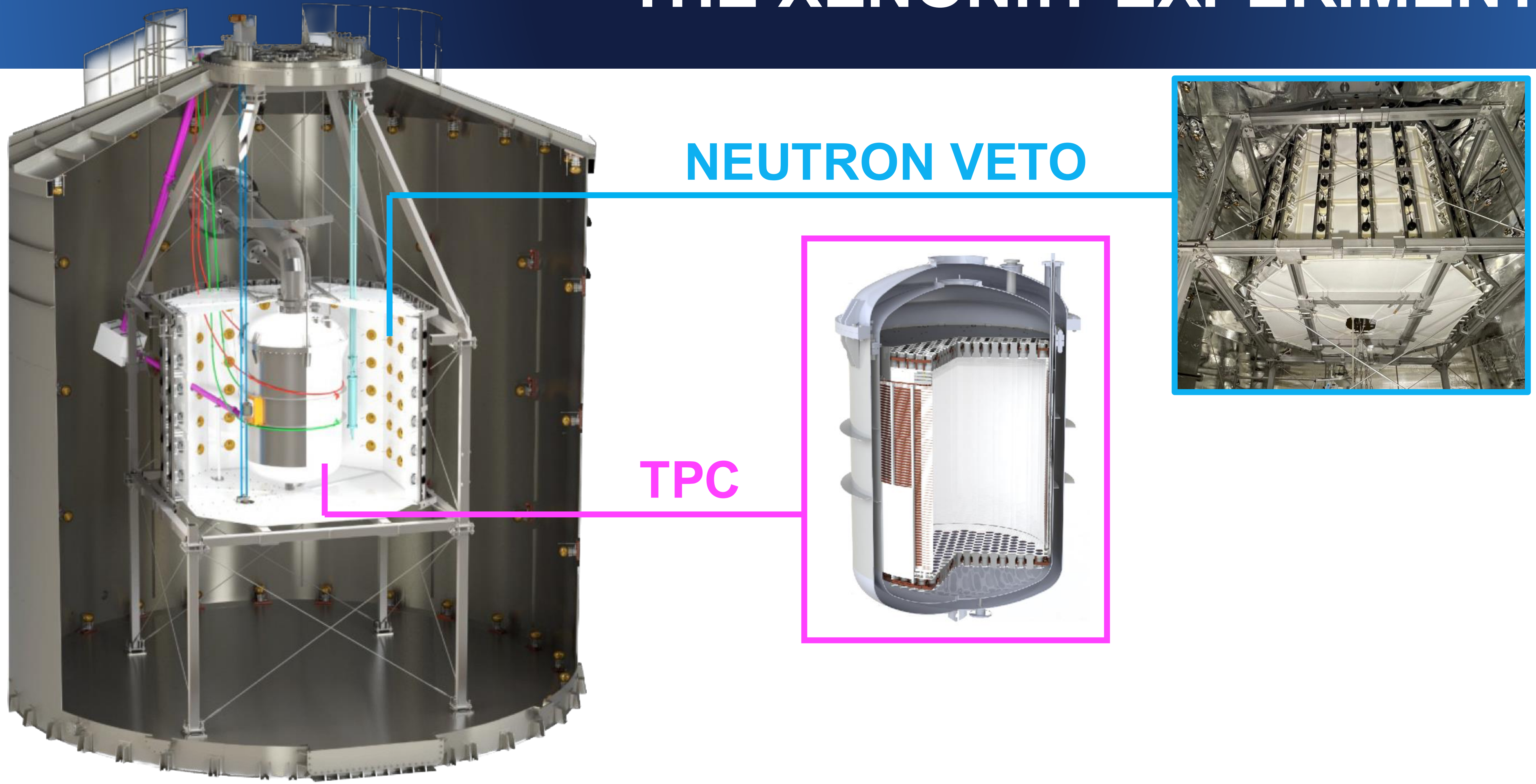
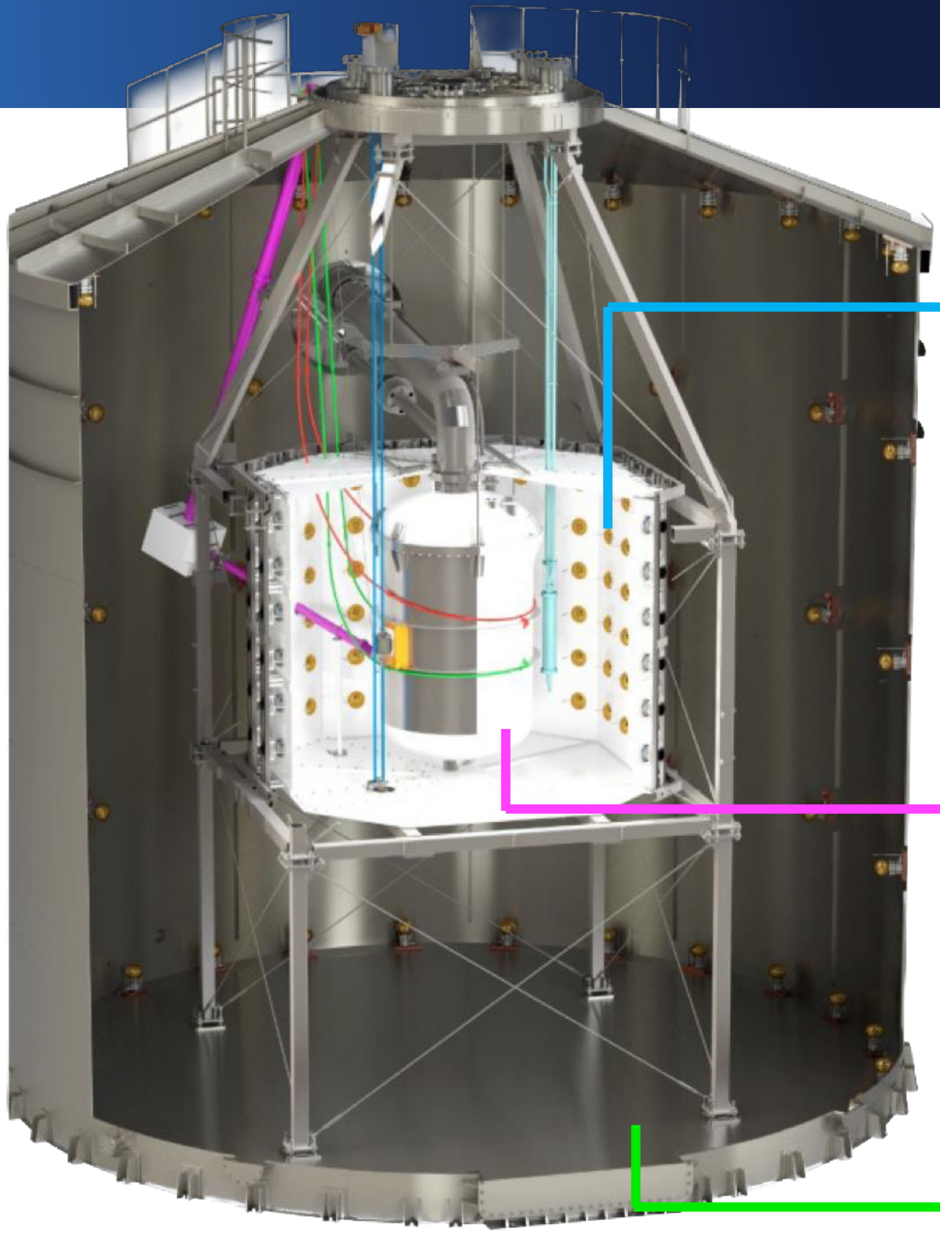


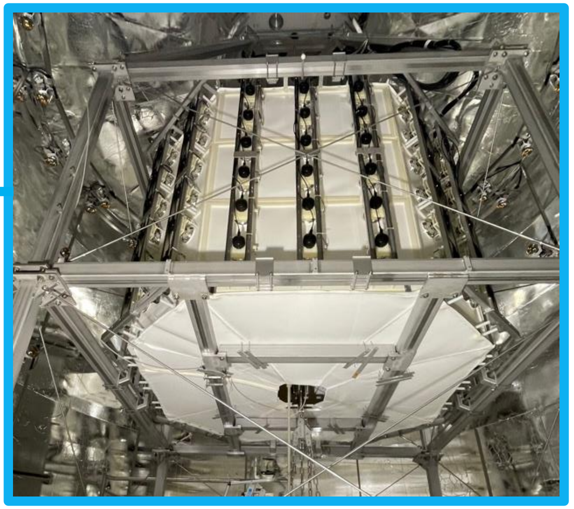
NEUTRON VETO

TPC

THE XENONnT EXPERIMENT

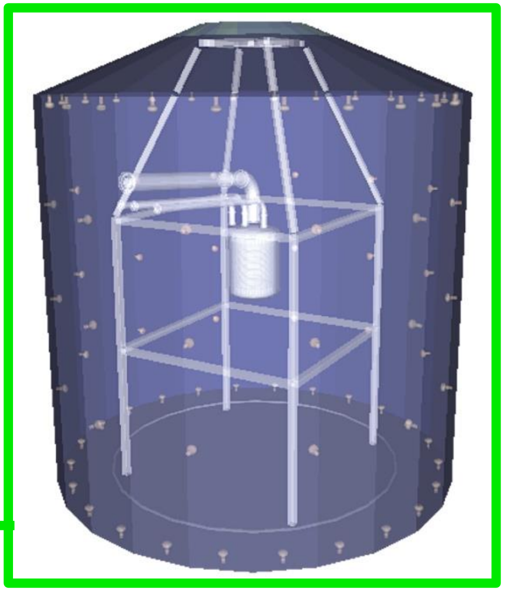


NEUTRON VETO



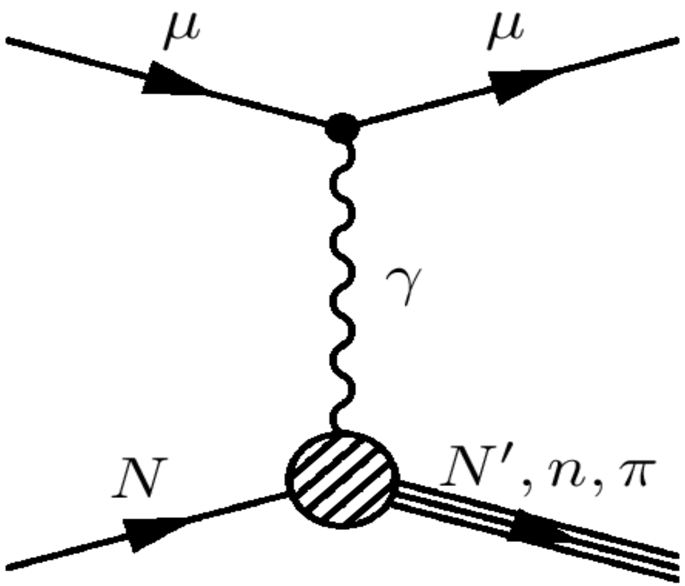
TPC

MUON VETO



MUON-INDUCED NEUTRONS

Muon-induced neutrons represent a source of background, producing **signals** in the TPC **identical** to those expected from **WIMPs**.



Muons can generate neutrons through two mechanisms:

- **Indirectly** (from electromagnetic and hadron showers)
- **Directly** (spallation, nuclear μ^-captures…)

For this analysis, **muon** events provide the **trigger** after which all the signals registered by the **Neutron Veto** are analysed looking for **neutron capture events**.

Then the neutron-capture **time constant** (τ) and the **neutron yield** (n/μ) are calculated.

MUON-INDUCED NEUTRONS

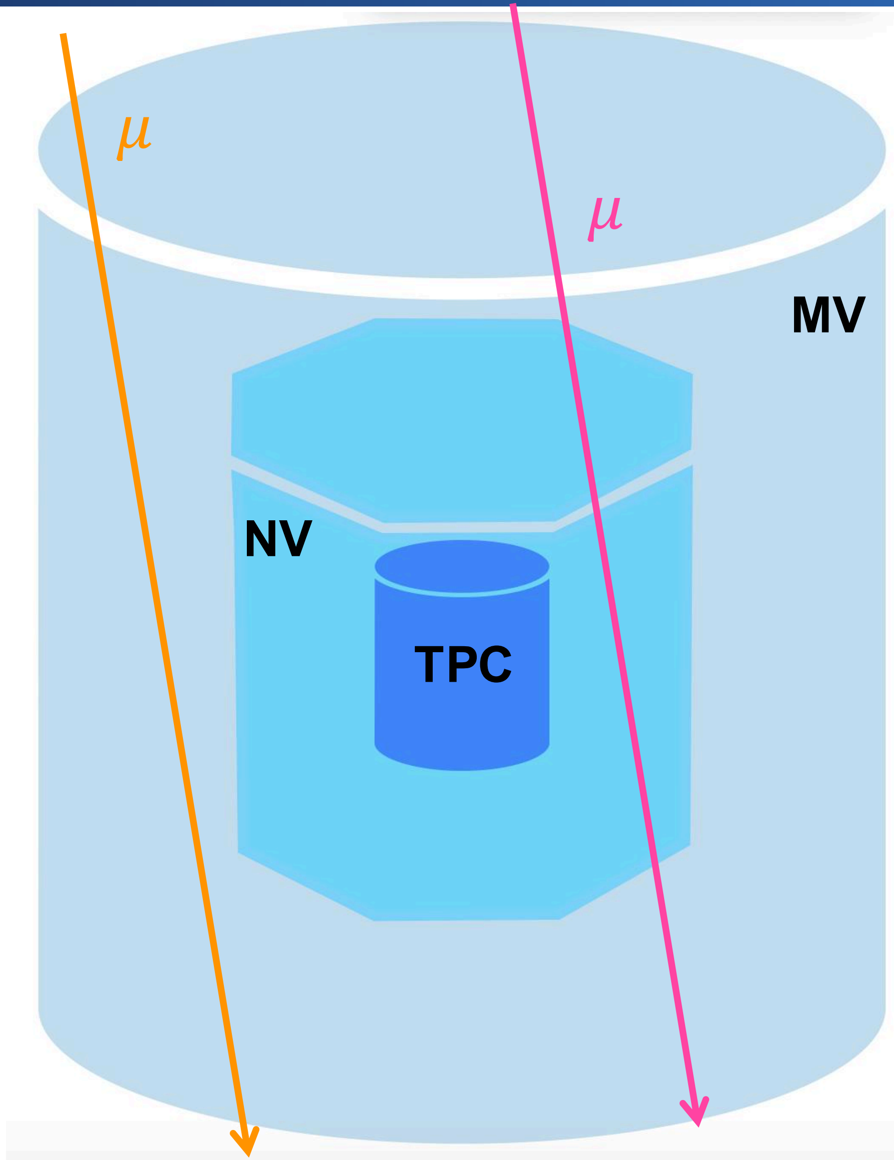
Muons crossing **at least one** of the **veto** systems are identified. They are then divided into:

- Muons detected by the MV that do not enter the NV (**MV only**)
- Muons passing through both veto systems (**MV and NV**), from which comes the majority of the neutrons detected

After the Muon event, **neutron signals** are searched in the **Neutron Veto only**.

The analysis was carried out on:

- **SR1** data with **demineralized** water
- **SR2** data when the water was doped with **Gadolinium sulphate salt**.



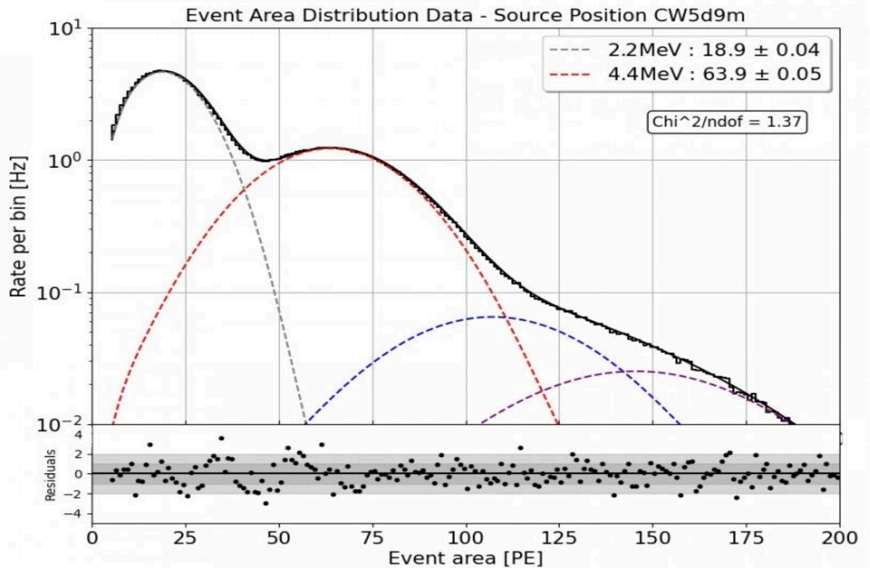
NEUTRON CAPTURE EVENTS

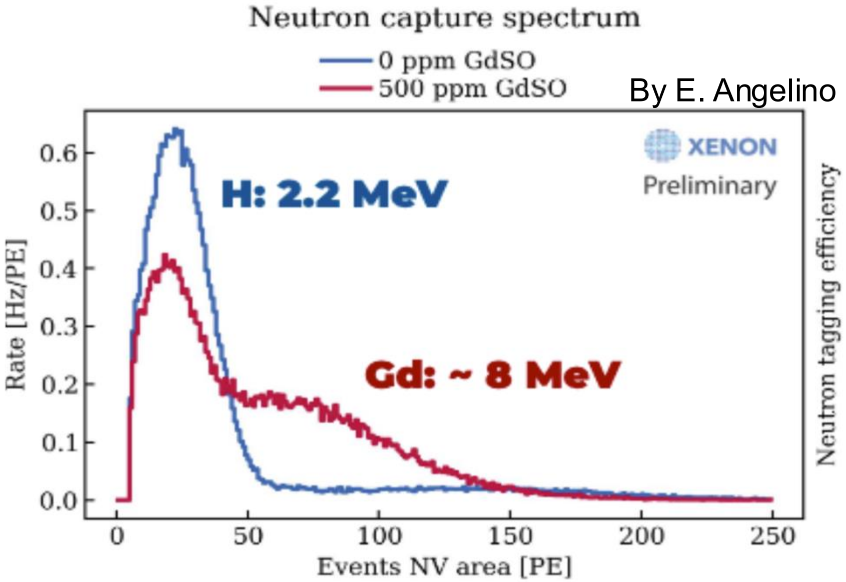
To calculate the **muon-induced neutron rate**, once the primary muon event is identified, a time window of **[–1, 1] ms** is opened and all events recorded by the NV are collected.

Among these events, those compatible with **neutron captures** are then selected, specifically:

Capture events in **demineralized water**:
- Multiplicity ≥ 5 PMTs
- Area: **[10, 60]** PE

Capture events in **Gd-doped water**:
- Multiplicity ≥ 5 PMTs
- Area: **[10, 150]** PE





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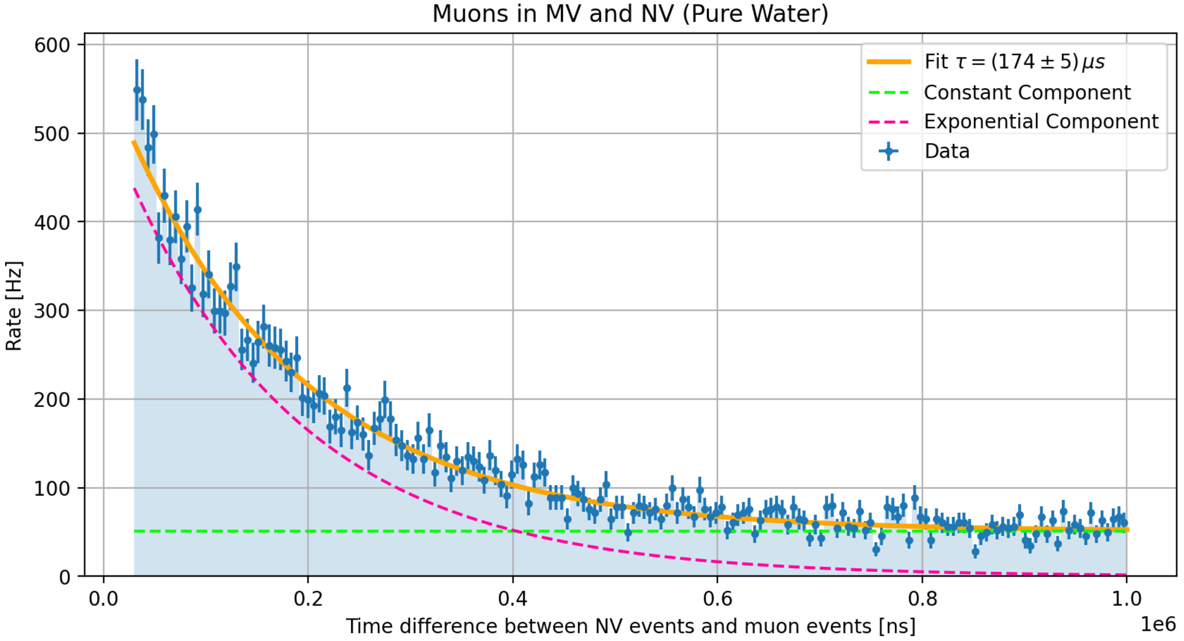
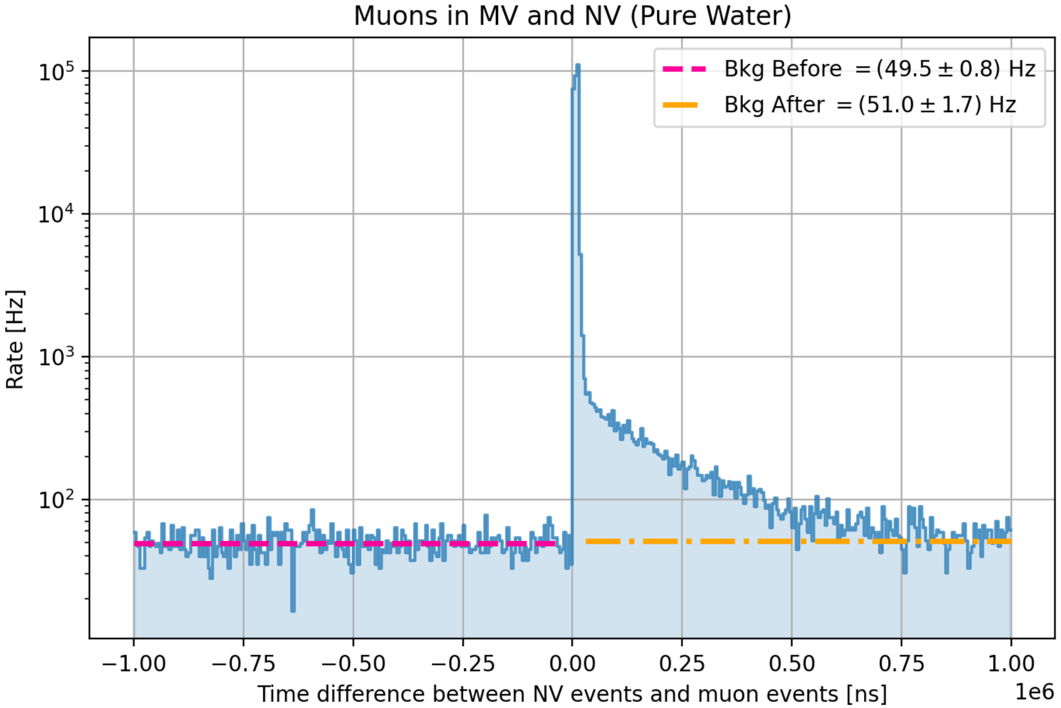
MUONS IN MV AND NV – PURE WATER

Demineralized water [0.03, 1] ms



Pure Water	Results
Tau	(174 ± 5) μs
N° muons	85574
Neutrons yield per muon	0.076 ± 0.002

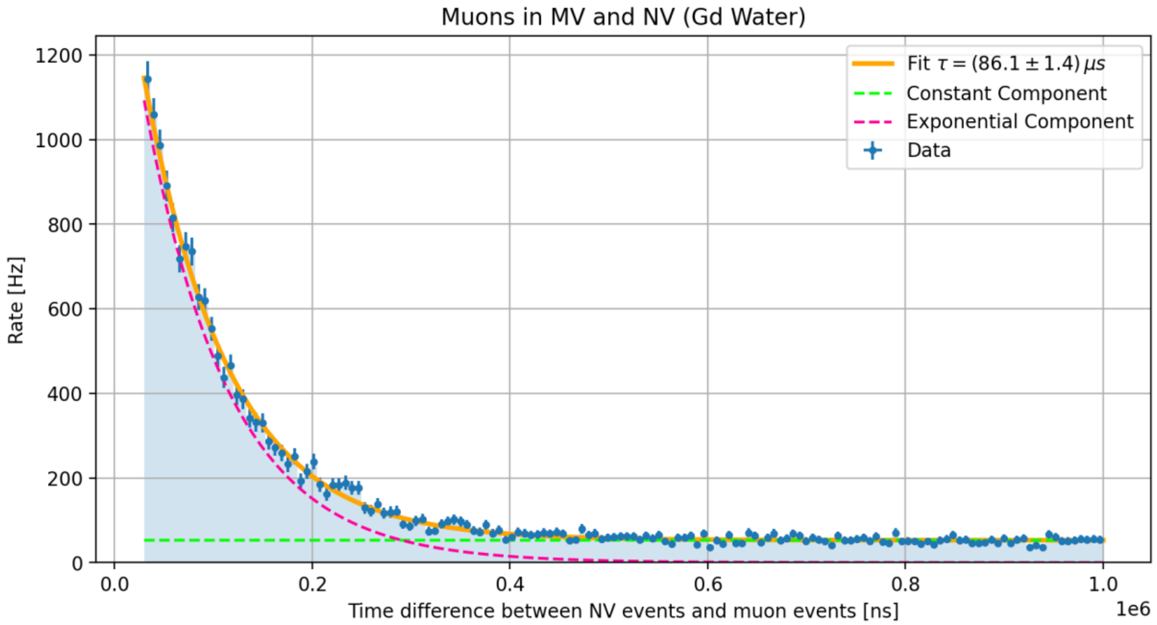
Background Analysis



	Before [-1, 0] ms	After [0.03, 1] ms
Rate Background	(49.6 ± 0.8) Hz	(51.0 ± 1.7) Hz

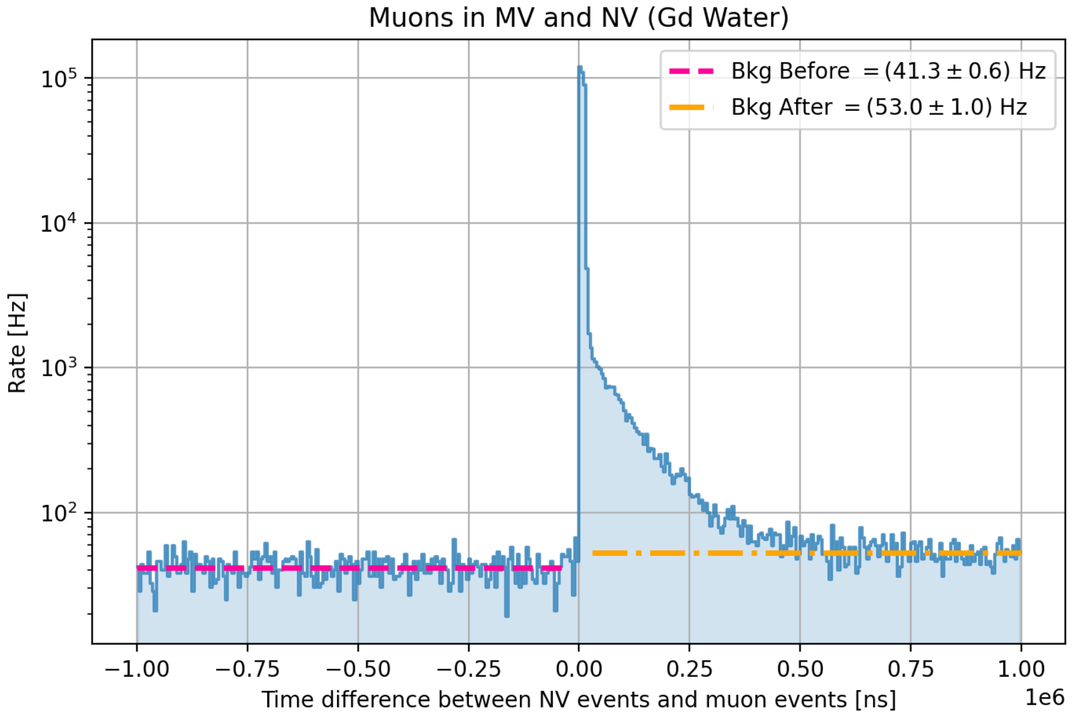
MUONS IN MV AND NV – Gd DOPED

Gadolinium [0.03, 1] ms



Gd Water	Results
Tau	$(86 \pm 1.4)\ \mu s$
N° muons	104877
Neutrons yield per muon	0.094 ± 0.001

Background Analysis



	Before [-1, 0] ms	After [0.03, 1] ms
Rate Background	(41.3 ± 0.6) Hz	(53.0 ± 1.0) Hz

PRELIMINARY RESULTS

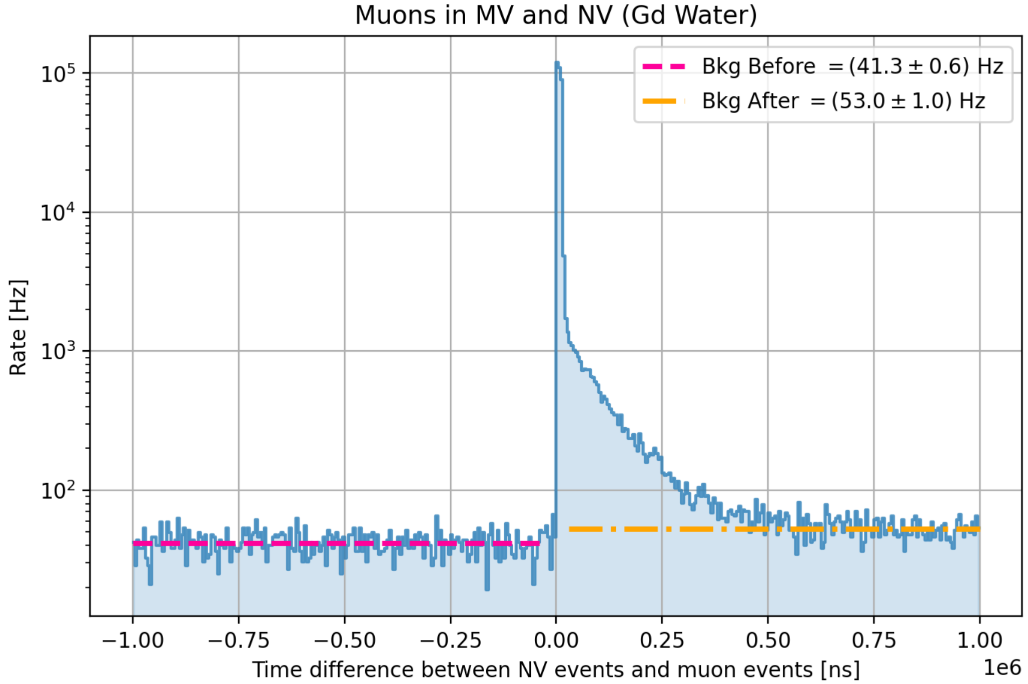
Comparing the results obtained with **pure water** and after **Gadolinium doping**, an increase has been observed especially in the **neutrons yield per muon** detected by **both** MV and NV.

In **Gadolinium data**, a **background mismatch** before and after the neutron capture events has also been observed.

	Pure Water	**Gadolinium**
Tau	~ 177 μs	~ 85 μs
n yield per μ (MV & NV)	~ 0.076	~ 0.094

Background Analysis – Gd Water

- Area: [10,150] PE



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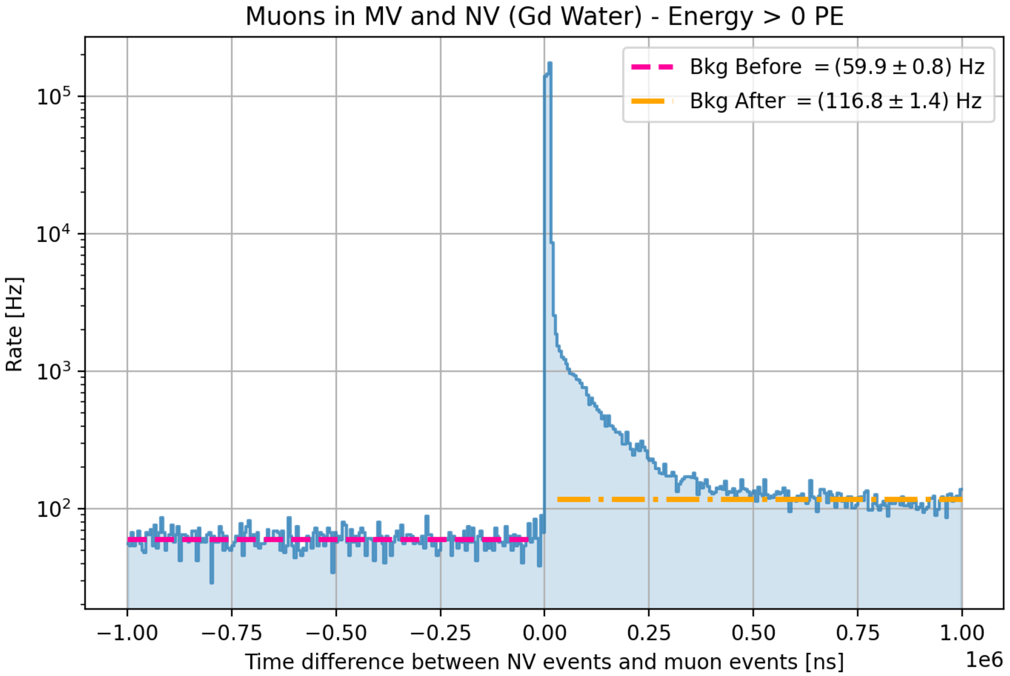
- ~~Area: [10,150] PE~~



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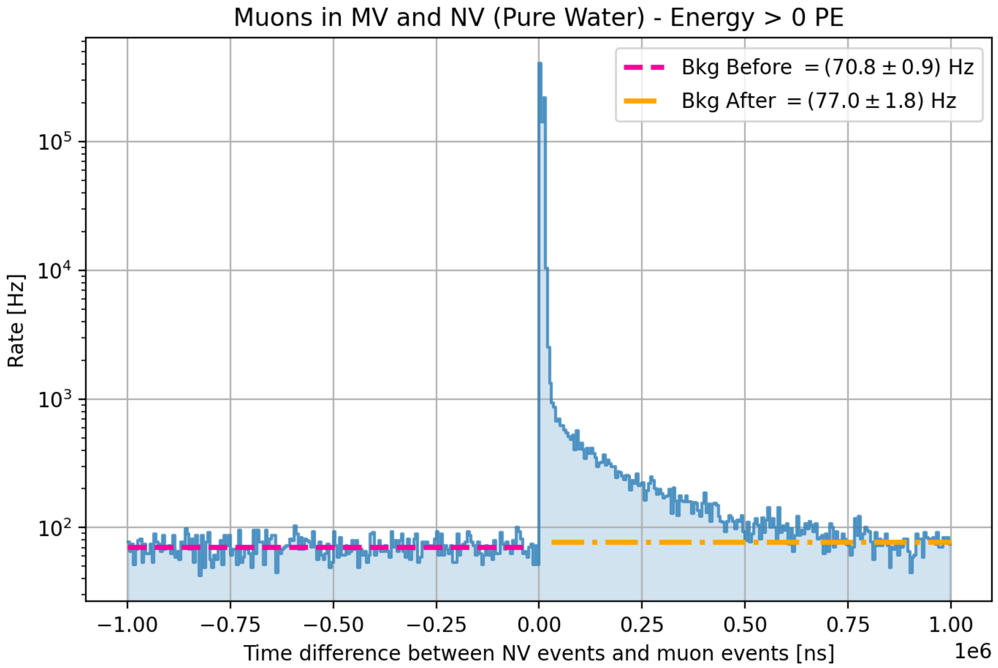
	Pure Water	Gadolinium
Tau	~ 177 μs	~ 85 μs
n yield per μ (MV & NV)	~ 0.076	~ 0.094

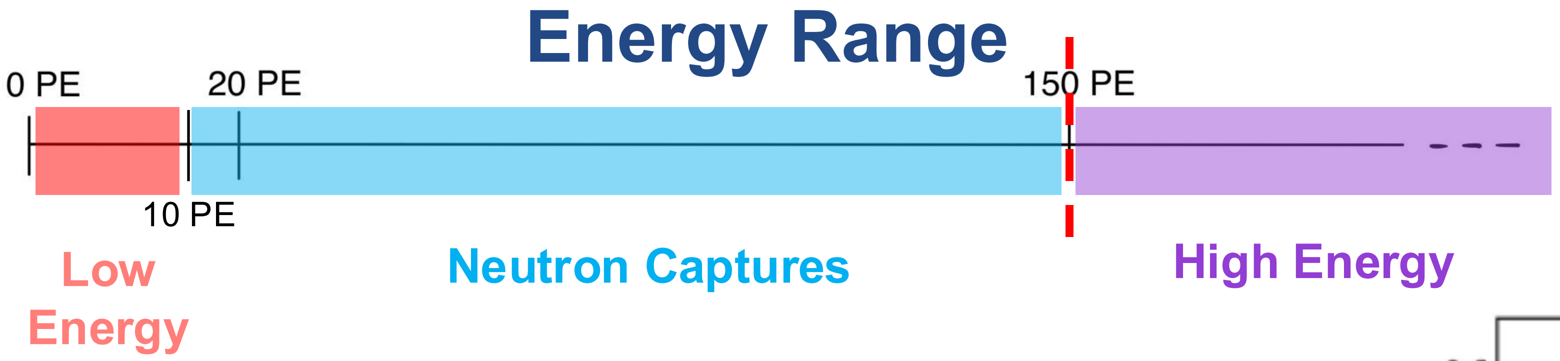
Background Analysis – Pure Water

- ~~Area: [10,60] PE~~



BACKGROUND ANALYSIS

To investigate the problem, the **background accordance** was recalculated selecting events in specific **energy ranges**.



Energy Range

0 PE

20 PE

150 PE

10 PE

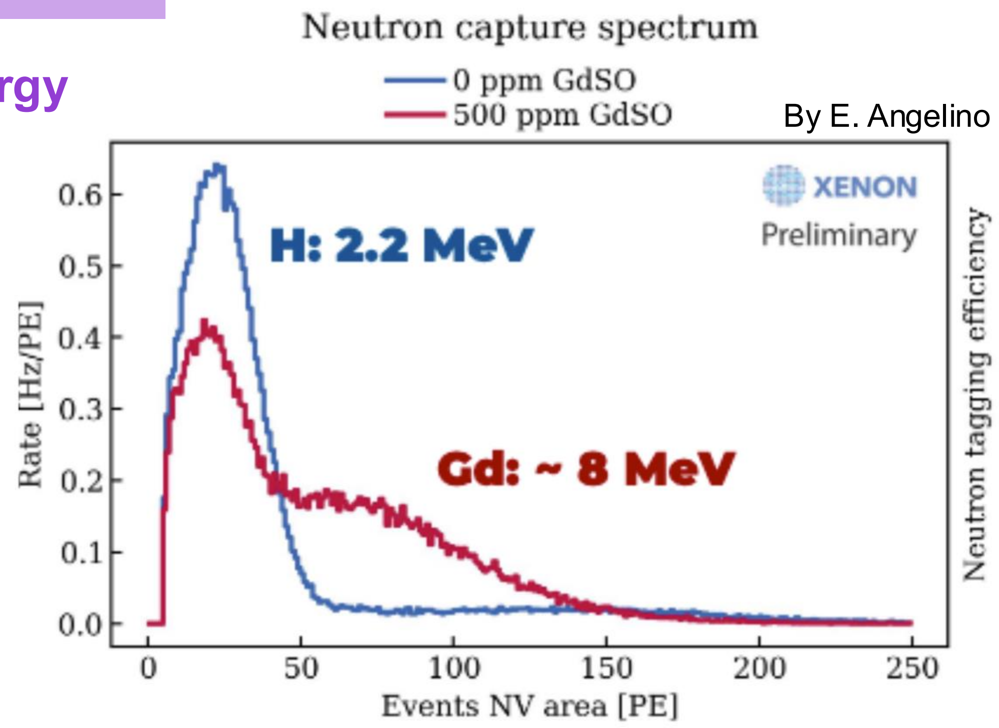
Low Energy

Neutron Captures

High Energy

The energy range selected were:

- **> 0 PE** (Low Energy + Neutron captures)
- **> 10 PE** (Neutron captures)
- **> 20 PE**



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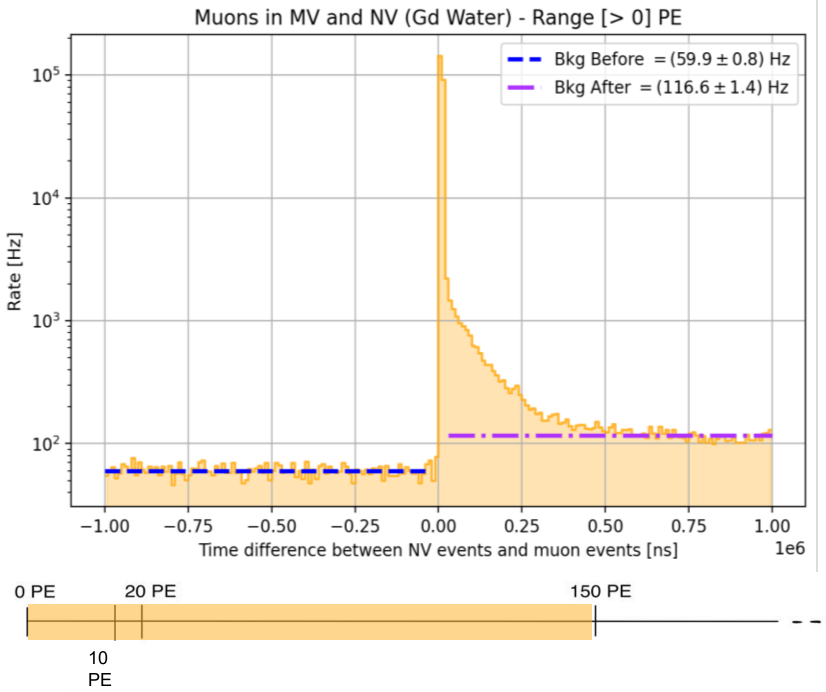
BACKGROUND ANALYSIS

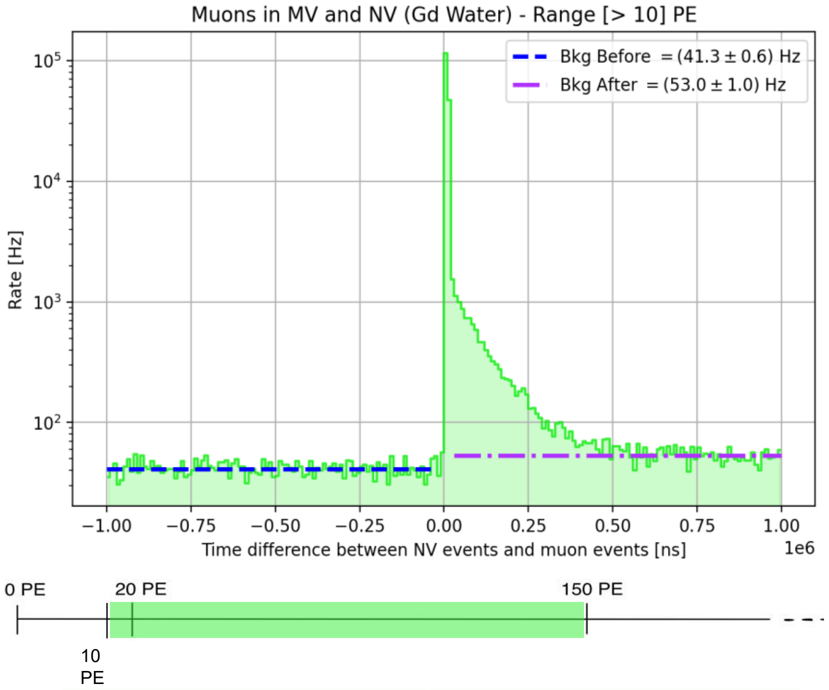
Analysing the specific energy range the background mismatch appears to be due to **low energy** events in the **[0, 20] PE range**.

> 0 PE



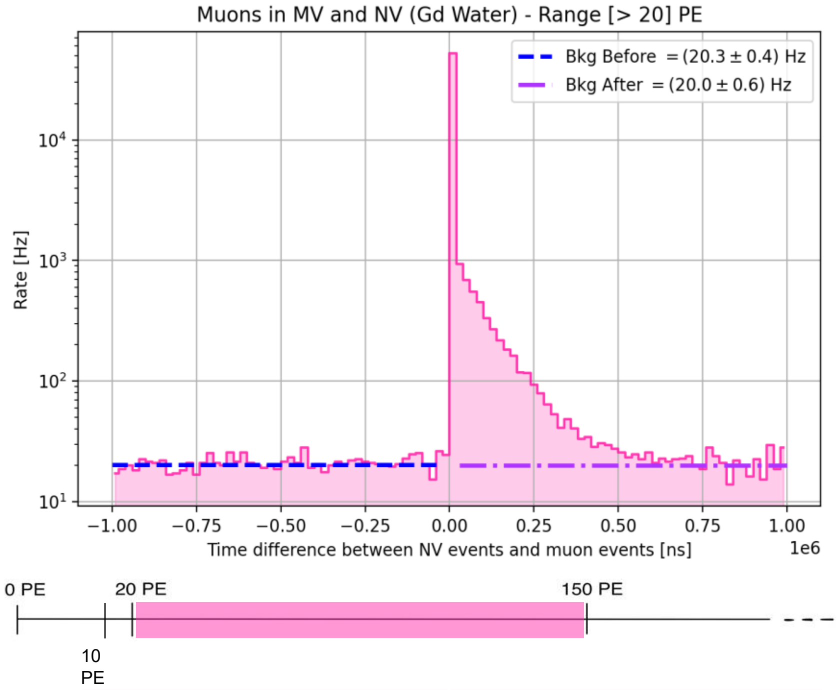
Before [-1, 0] ms	After [0.03, 1] ms
(59.9 ± 0.8) Hz	(111.6 ± 1.4) Hz

> 10 PE



Before [-1, 0] ms	After [0.03, 1] ms
(41.3 ± 0.6) Hz	(53.0 ± 1.0) Hz

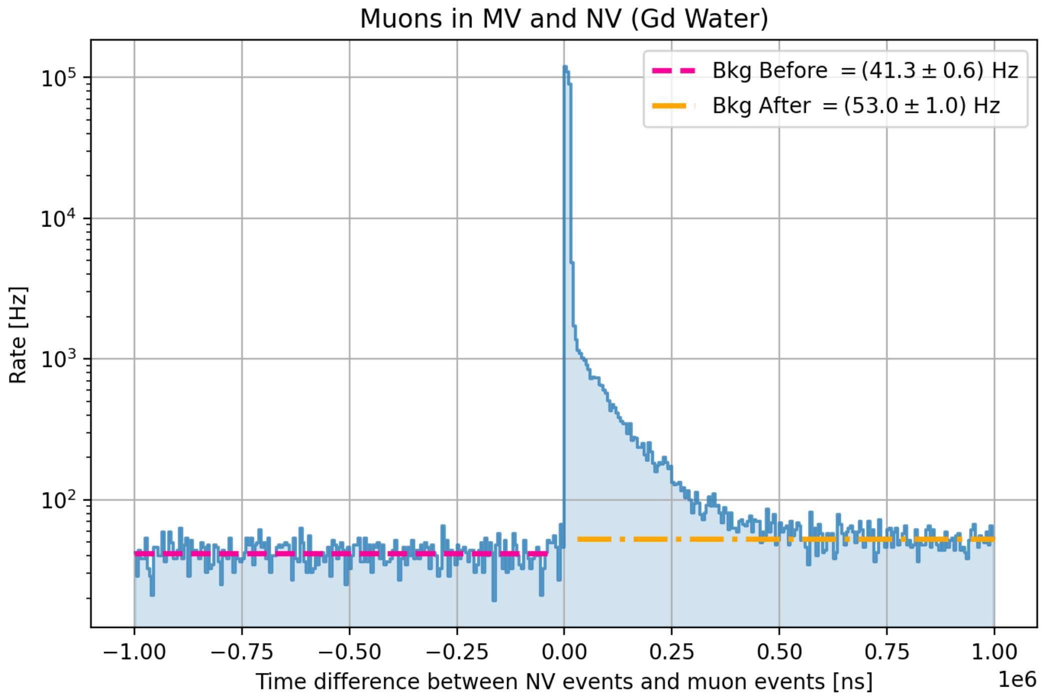
> 20 PE

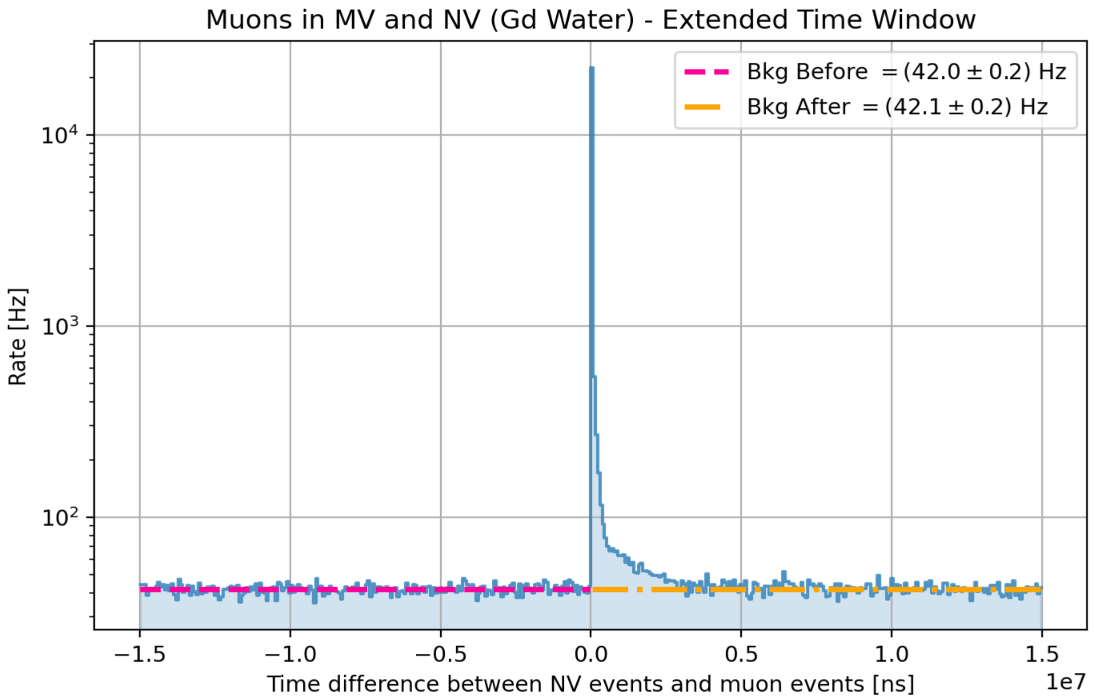


Before [-1, 0] ms	After [0.03, 1] ms
(20.3 ± 0.4) Hz	(20.0 ± 0.6) Hz

EXTENDED TIME WINDOW

Expanding the time window clearly reveals the presence of a **secondary effect** with an **exponential decay** at **longer timescale**.



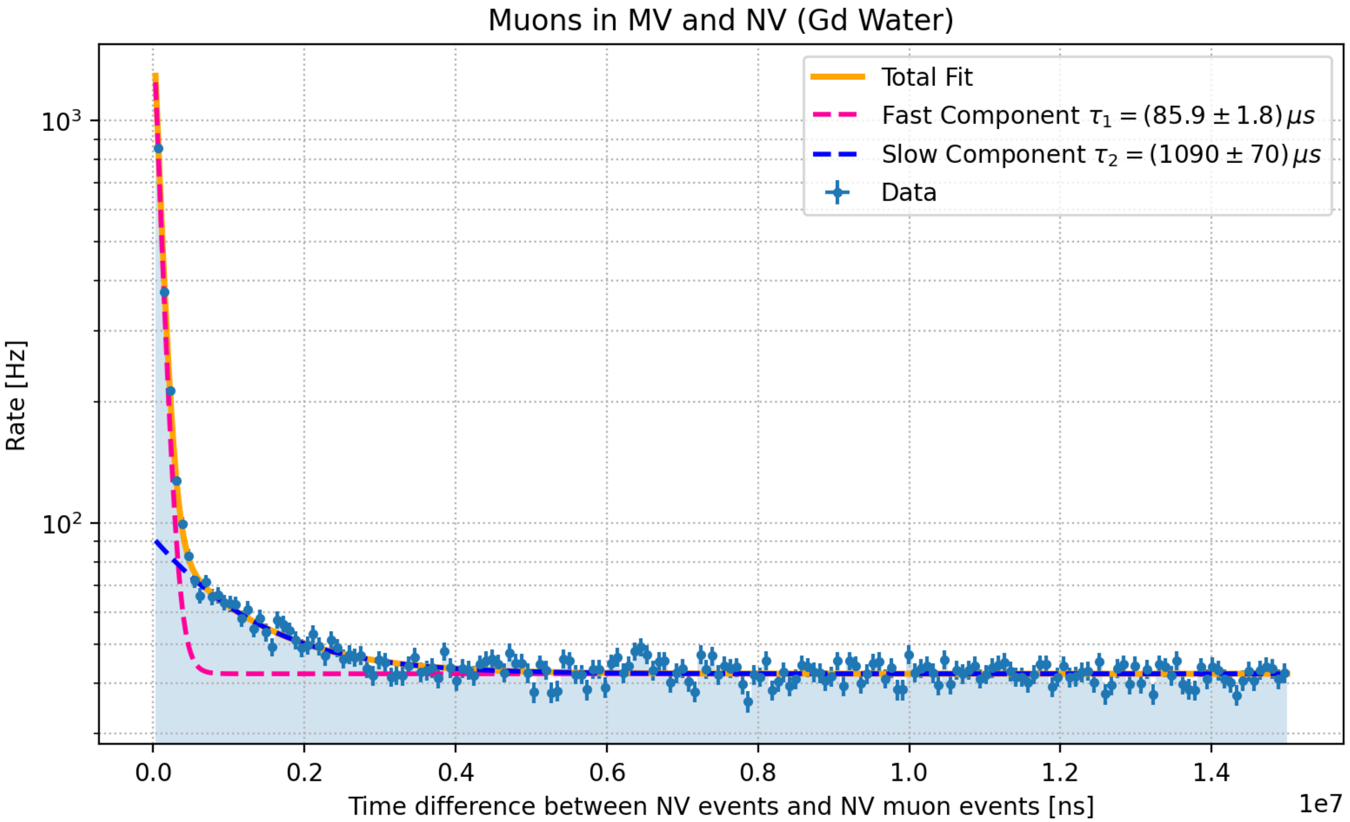


	Before [-1, 0] ms	After [0.03, 1] ms
Rate Background	(41.3 ± 0.6) Hz	(53.0 ± 1.0) Hz

	Before [-15, 0] ms	After [0.03, 15] ms
Rate Background	(42.0 ± 0.2) Hz	(42.1 ± 0.2) Hz

DOUBLE EXPONENTIAL FIT

The analysis was repeated, **extending** the data-acquisition time window to **[–15,15] ms** and performing a fit with a **double-exponential function**.



$$f(x) = A + Be^{\frac{-t}{\tau_1}} + Ce^{\frac{-t}{\tau_2}}$$

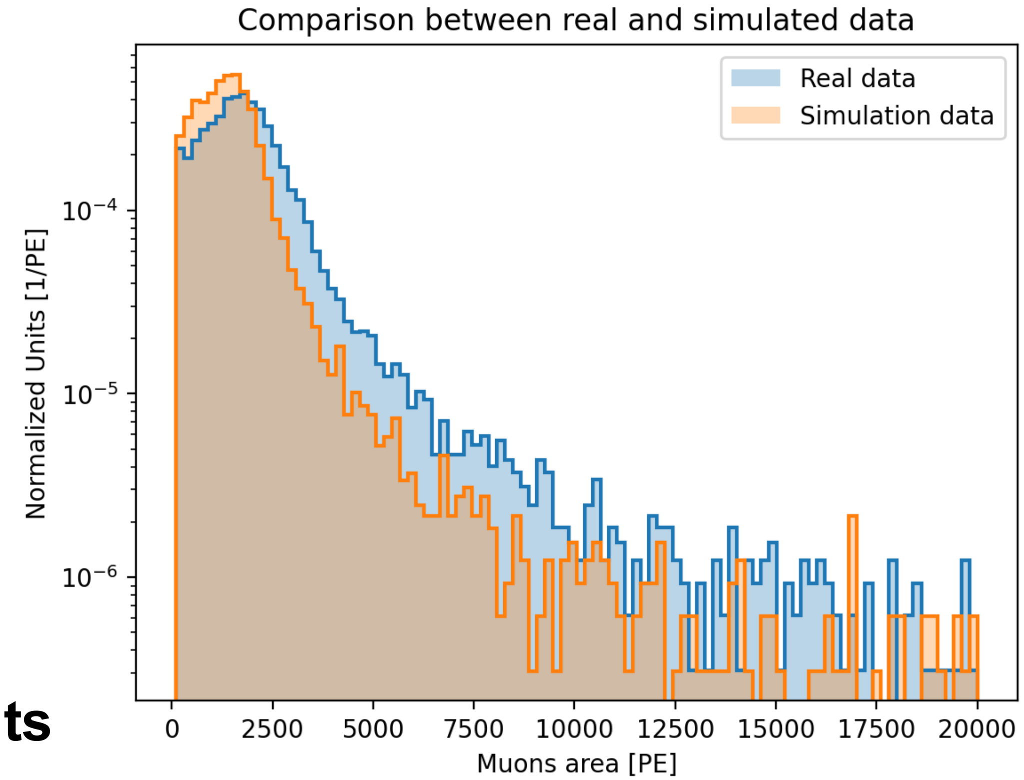
Gd Water	Results
Tau_1	$(85.9 \pm 1.8)\ \mu s$
Tau_2	$(1093 \pm 73)\ \mu s$
N° muons	96032
Neutrons yield per muon	0.103 ± 0.002

SIMULATIONS MUON VETO

To reproduce the analysis employing Monte Carlo data, a **preliminary framework** for a future Muon Veto **Hitlet Simulator** has been developed.

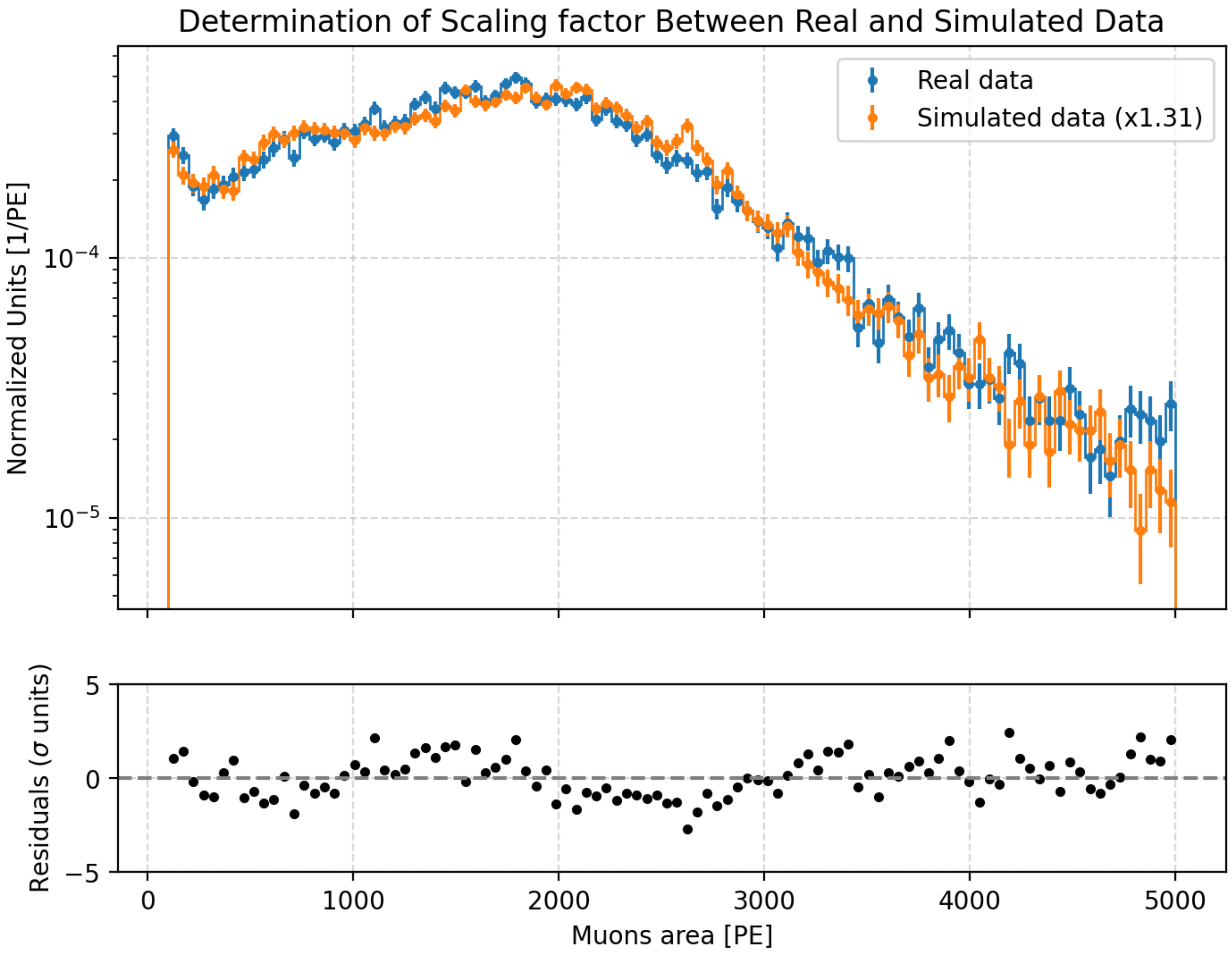
Framework

- ~ **30k muons** generated
- Selection of photons detected by MV PMTs
- PMT **quantum efficiency** was applied to determine the binomial **detection probability**
- **PE conversion**: Gaussian distribution (μ = 1 PE, σ = 0.5)
- Application of **trigger conditions** and **analysis cuts**



Applying this framework the final simulated **area spectrum** was obtained.

SIMULATIONS MUON VETO



This discrepancy is likely due to the several **simplifications** introduced.

To enable a consistent comparison, a global scale factor was introduced: **effective Collection Efficiency (eCE)**

eCE account for both **CE effects** and possible **mismodelling** of the MV optical properties in Geant4.

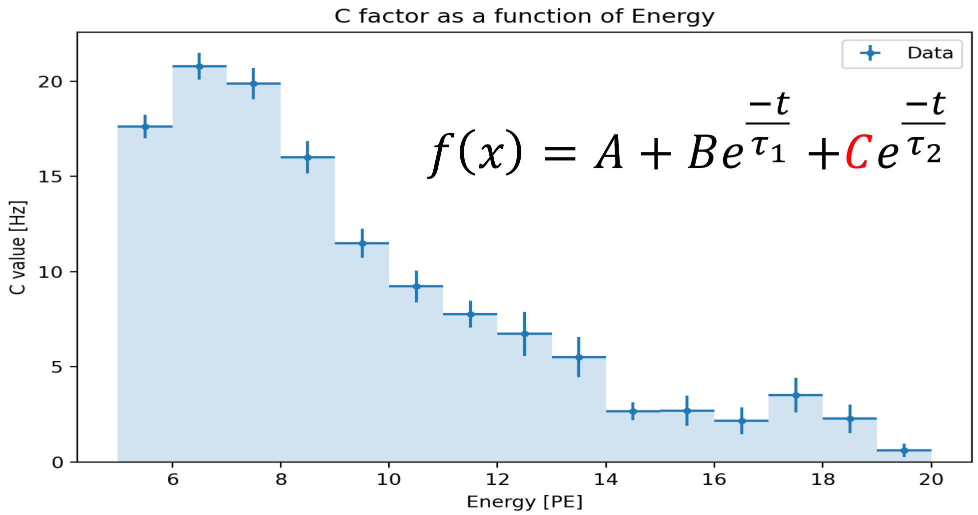
Optimal eCE factor: **1.31**

CONCLUSIONS

- ★ We measured the the **neutron yield** in water after a muon event.
- ★ **Monte Carlo simulations** are now under **development** to compare these results with MC predictions.

	Pure Water	Gd (double exponential fit)
Tau (n capture)	~ 177 μs	~ 85 μs
n yield per μ (MV & NV)	~ 0.076	~ 0.103

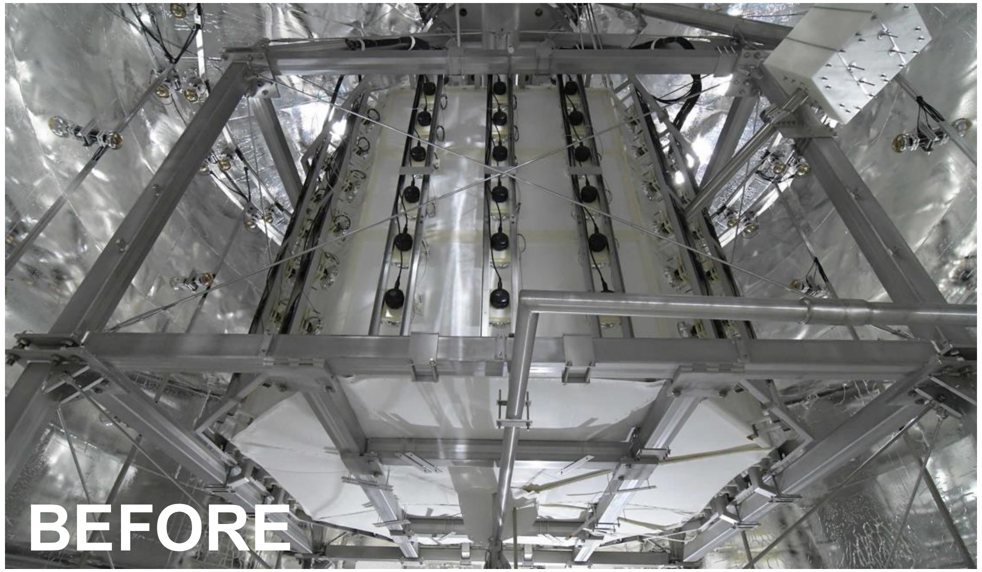
- ★ From the double exponential fit results, it is evident that during **neutron-capture processes** in Gd doped water a **second phenomenon develops** characterized by:
  - Energy in the **[0,20] PE** range, with a peak around **7 PE**
  - Decay time $\boldsymbol{\tau \approx 1}$ **ms**

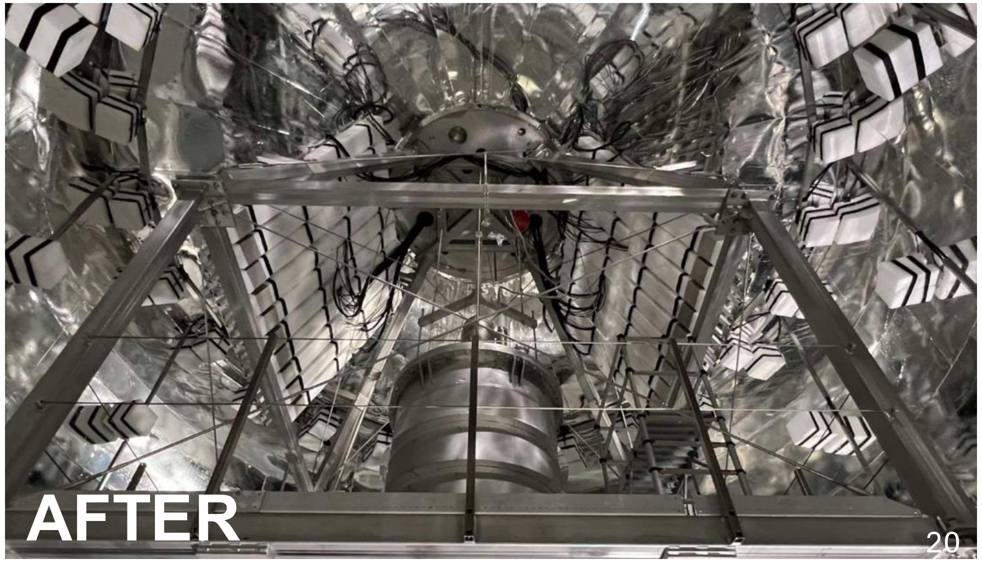


- ★ This could be a Gd “**fluorescence**” induced by the high energy of the cosmic muons.

⟶ To be investigated further.

INFN INTERNSHIP AT LNGS



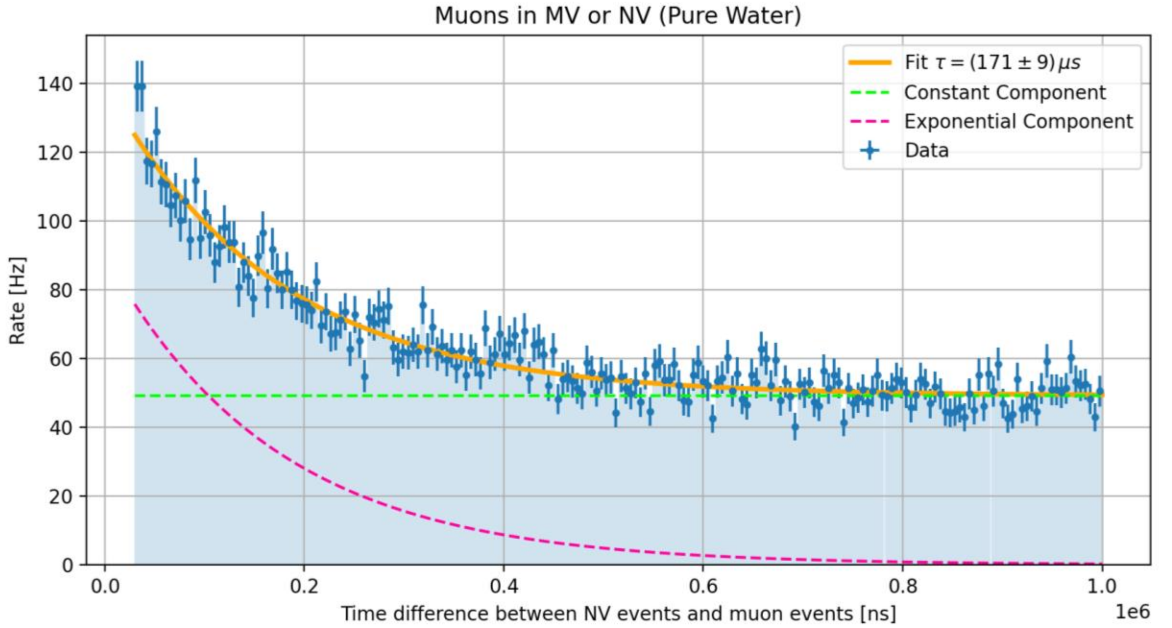


Thank you for your attention!

BACKUP

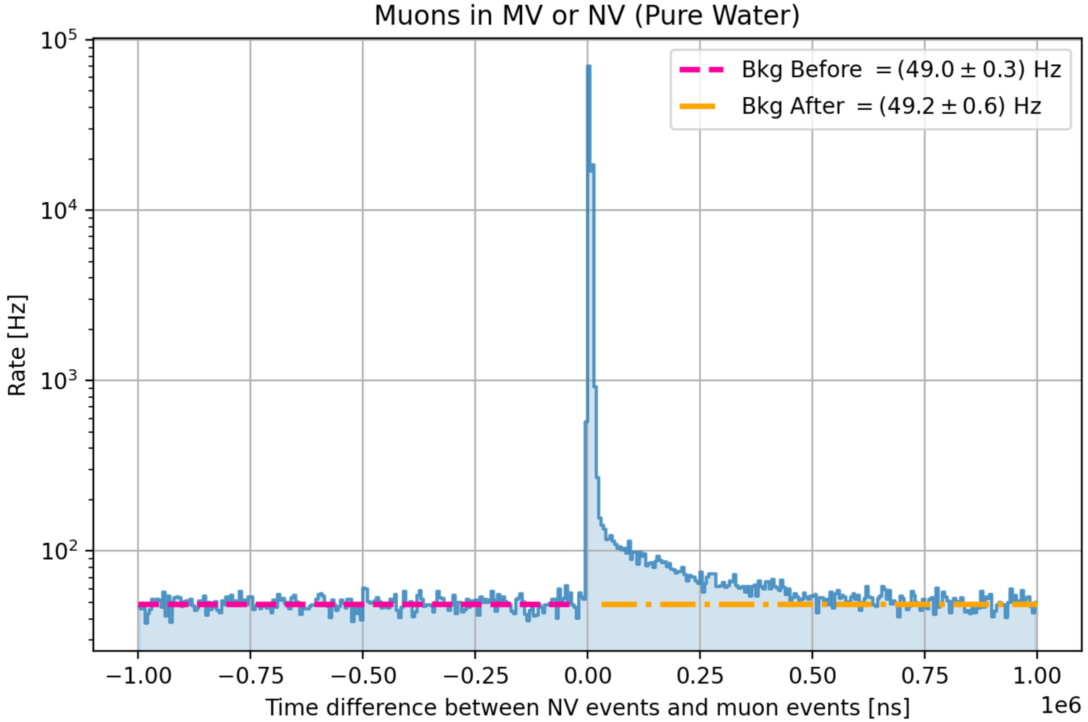
ALL MUONS – PURE WATER

Demineralized water [0.03, 1] ms



Pure Water	Results
Tau	$(171 \pm 9)\ \mu s$
N° muons	518622
Neutrons yield per muon	0.0129 ± 0.0005

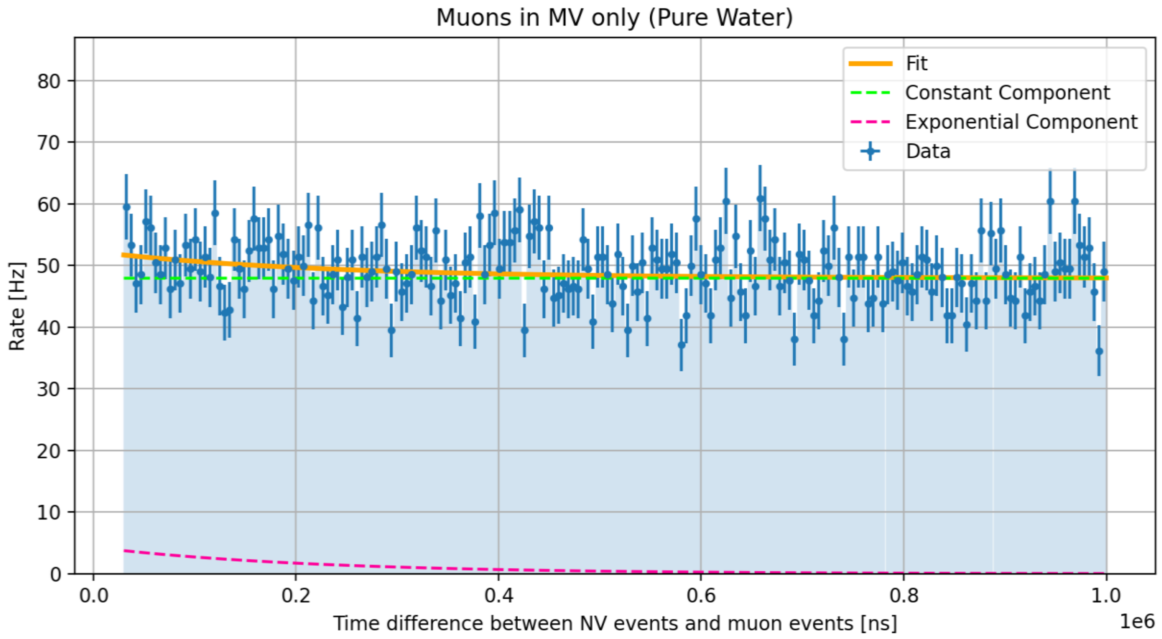
Background Analysis



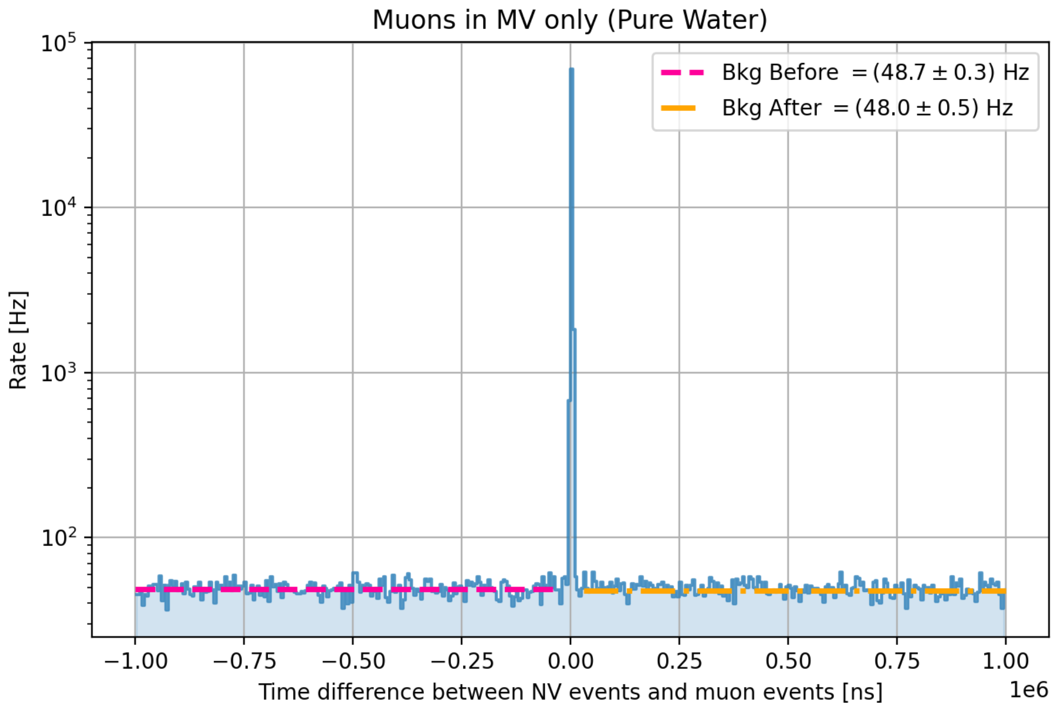
	Before [-1, 0] ms	After [0.03, 1] ms
Rate Background	(49.0 ± 0.3) Hz	(49.2 ± 0.6) Hz

MUONS IN MV ONLY – PURE WATER

Demineralized water [0.03, 1] ms



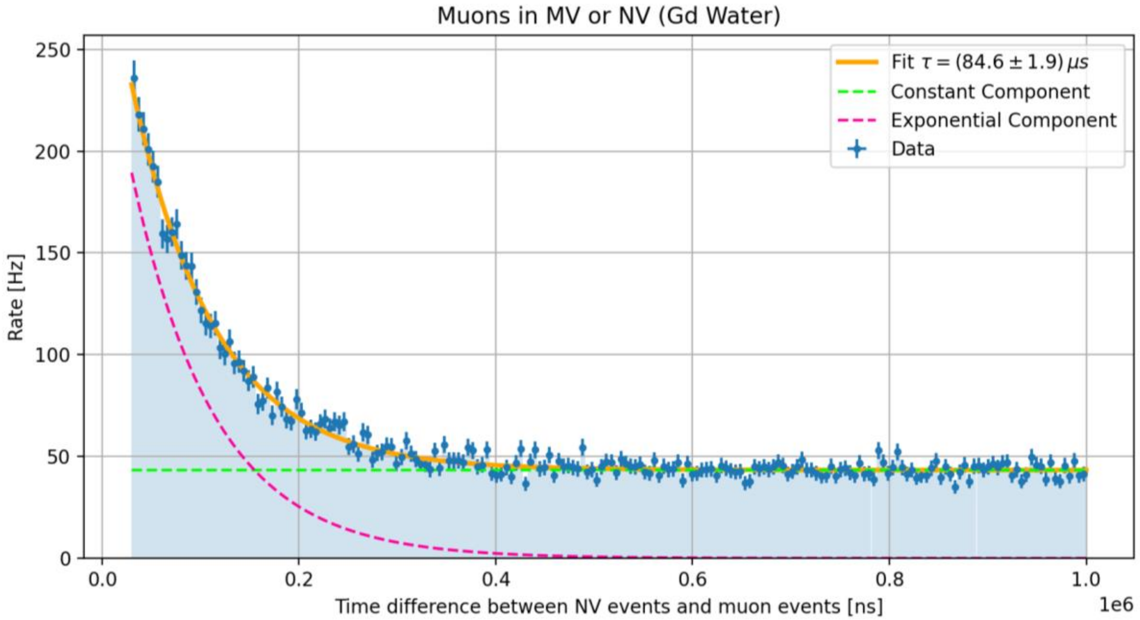
Background Analysis



	Before [-1, 0] ms	After [0.03, 1] ms
Rate Background	(48.7 ± 0.3) Hz	(48.0 ± 0.5) Hz

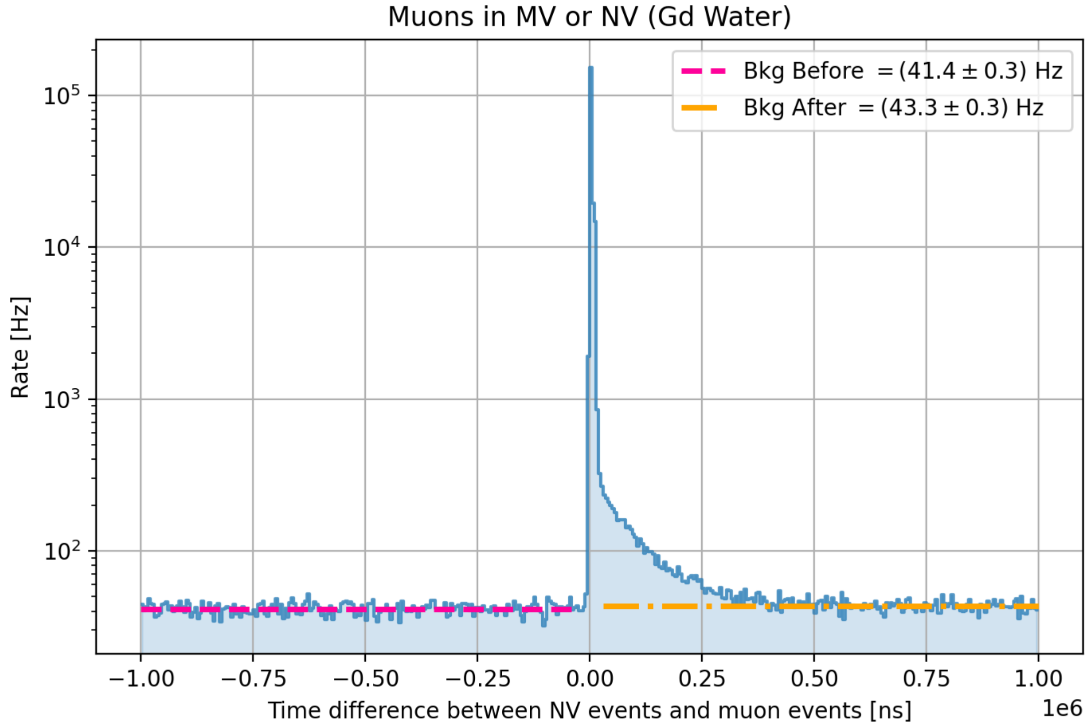
ALL MUONS – Gd DOPED

Gadolinium [0.03, 1] ms



Gd Water	Results
Tau	$(84.6 \pm 1.9)\ \mu s$
N° muons	643085
Neutrons yield per muon	0.0160 ± 0.0003

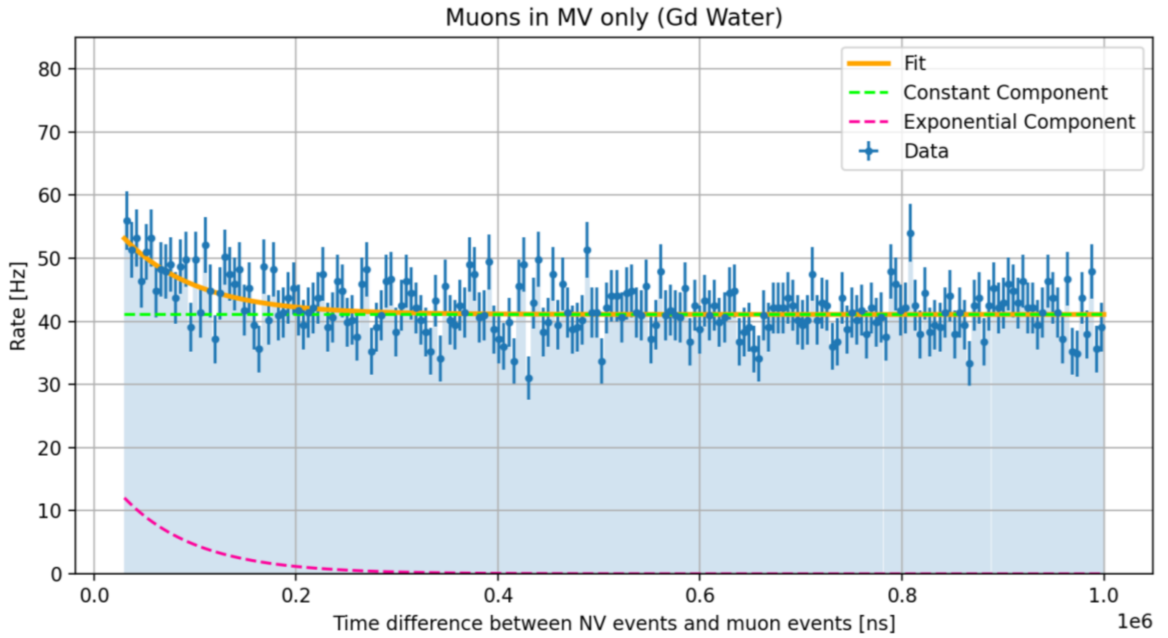
Background Analysis



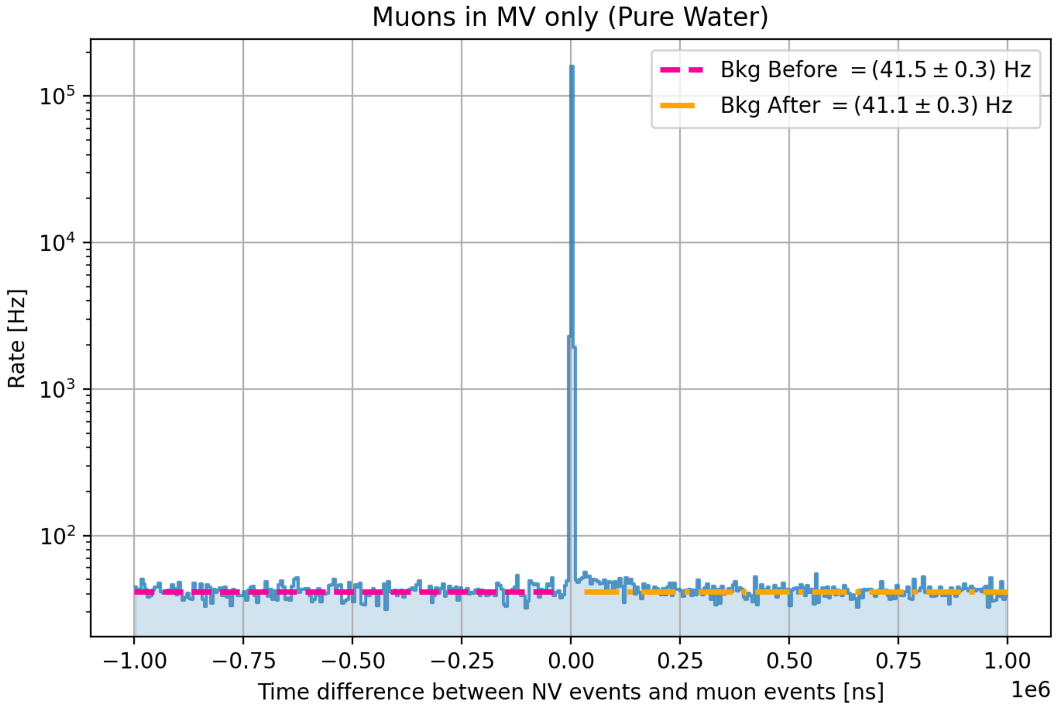
	Before [-1, 0] ms	After [0.03, 1] ms
Rate Background	(41.4 ± 0.3) Hz	(43.3 ± 0.3) Hz

MUONS IN MV ONLY – Gd DOPED

Gadolinium [0.03, 1] ms



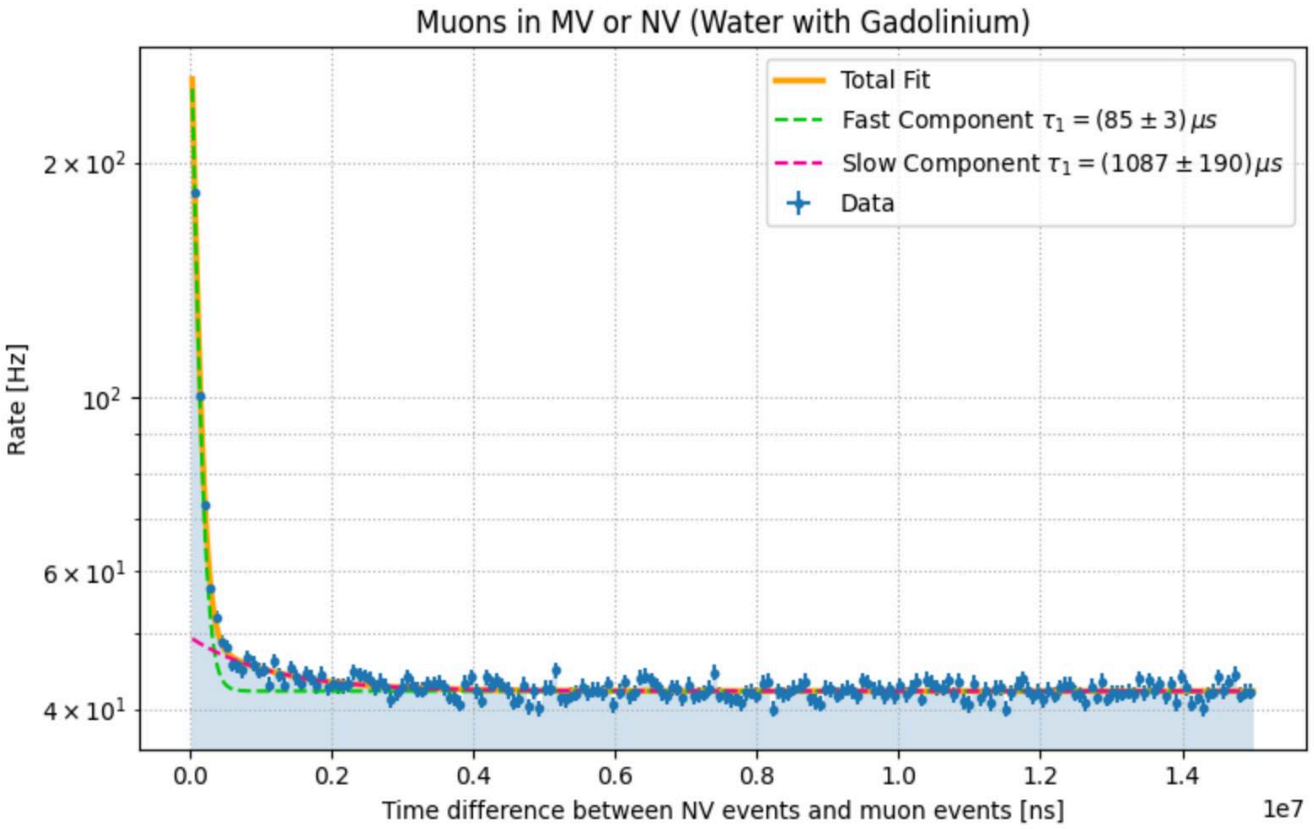
Background Analysis



	Before [-1, 0] ms	After [0.03, 1] ms
Rate Background	(41.5 ± 0.3) Hz	(41.1 ± 0.3) Hz

DOUBLE EXPONENTIAL FIT – ALL MUONS

The analysis was repeated, **extending** the data-acquisition time window to **[–15,15] ms** and performing a fit with a **double-exponential function**.

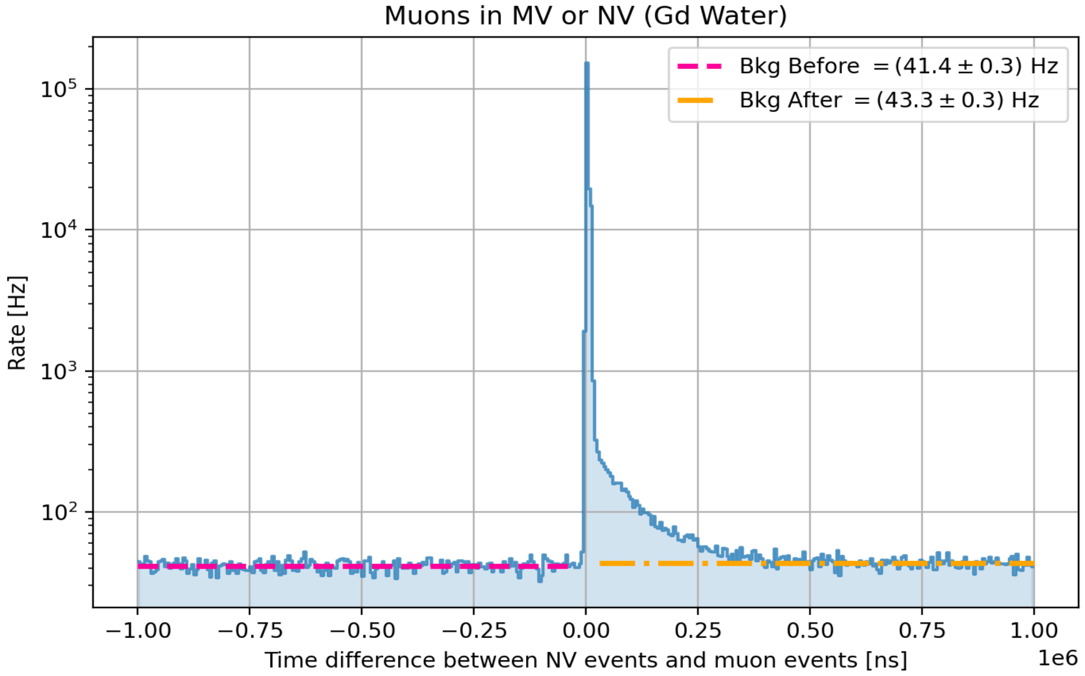


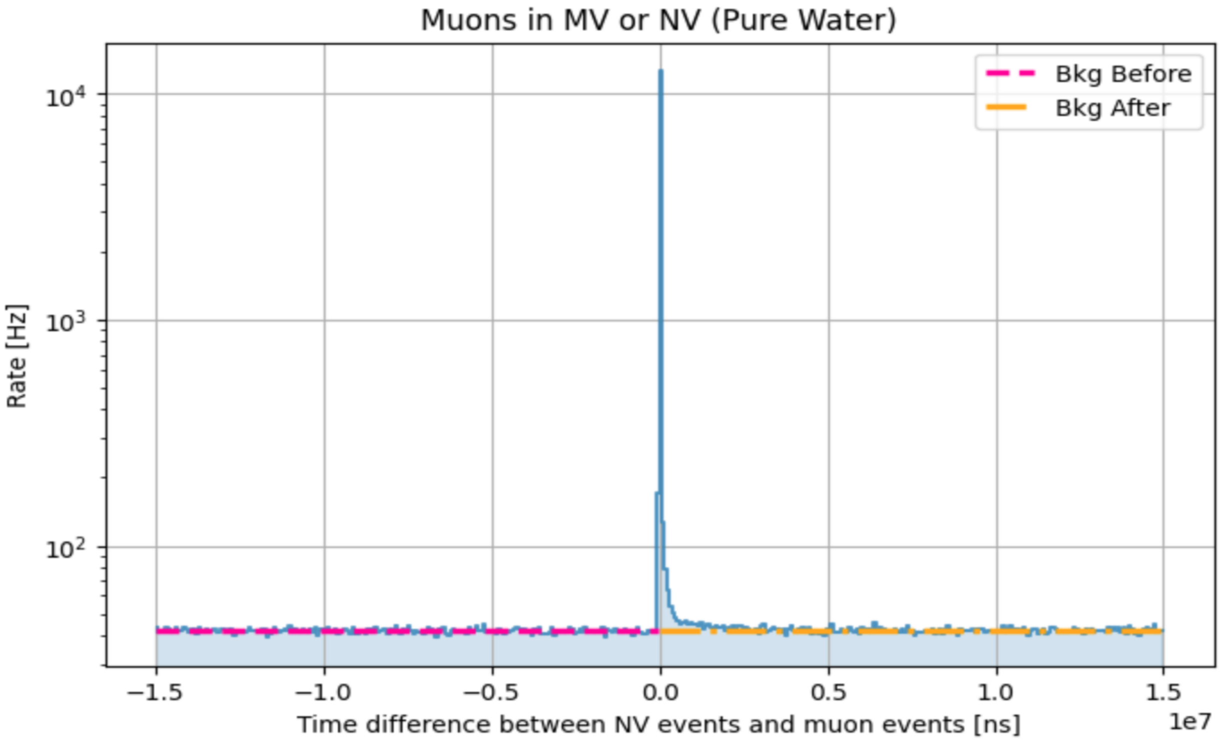
$$f(x) = A + Be^{\frac{-t}{\tau_1}} + Ce^{\frac{-t}{\tau_2}}$$

Gd Water	Results
Tau_1	$(85 \pm 3)\ \mu s$
Tau_2	$(1087 \pm 190)\ \mu s$
N° muons	590518
Neutrons yield per muon	0.0176 ± 0.0004

EXTENDED TIME WINDOW – ALL MUONS

Expanding the time window clearly reveals the presence of a **secondary effect** with an **exponential decay** at **longer timescale**.





	Before [-1, 0] ms	After [0.03, 1] ms
Rate Background	(41.4 ± 0.3) Hz	(43.3 ± 0.3) Hz

	Before [-15, 0] ms	After [0.03, 15] ms
Rate Background	(42.04 ± 0.07) Hz	(42.15 ± 0.08) Hz