First Pan-African Astro-Particle and Collider Physics Workshop

# STUDY OF MUON INDUCED BACKGROUND IN DOUBLE CHOOZ NEUTRINO OSCILLATION EXPERIMENT

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Paris, 22 March 2021

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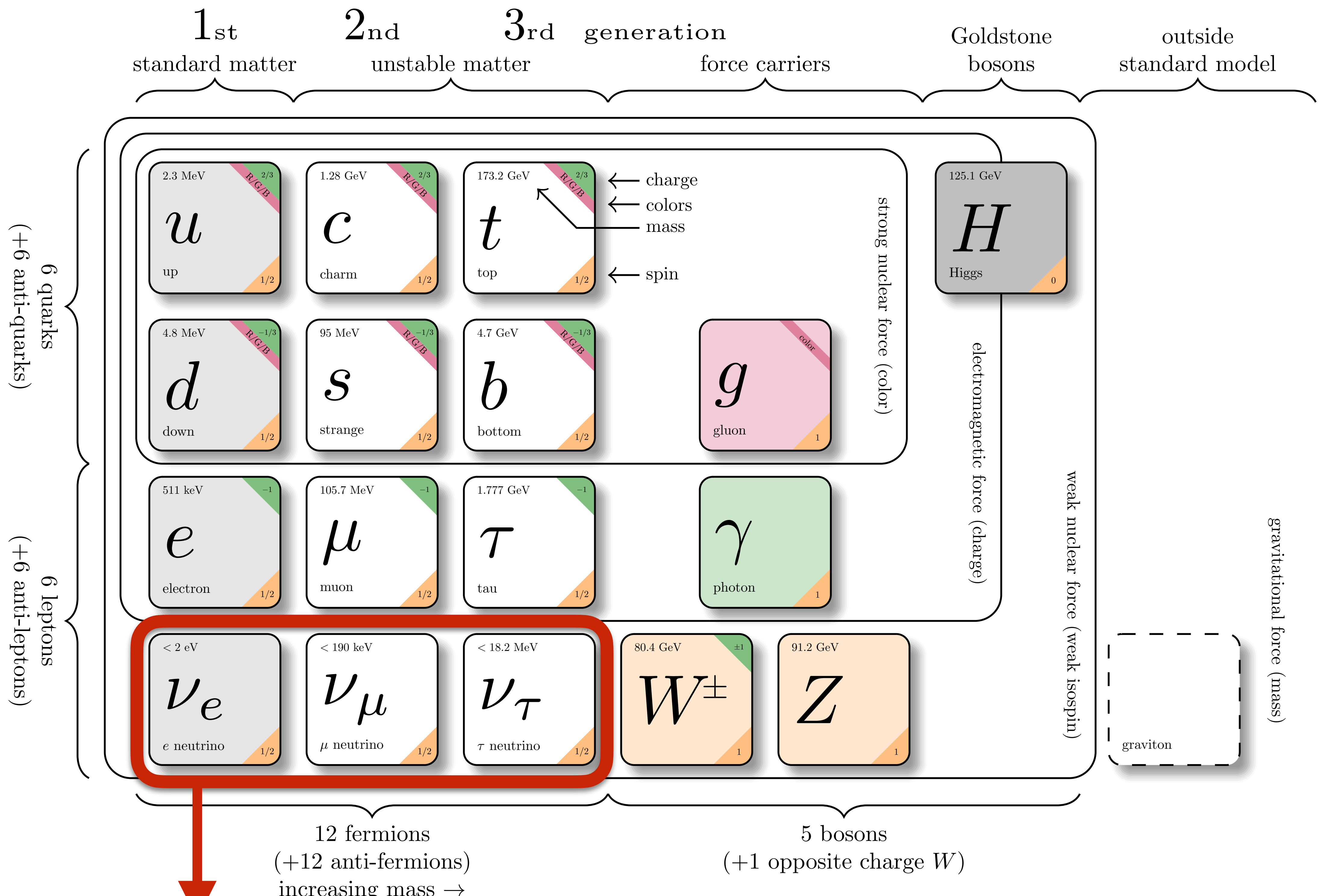
# NEUTRINOS IN THE STANDARD MODEL

# NEUTRINOS IN THE STANDARD MODEL




## 3 NEUTRINO FLAVORS

Neutrinos flux from the sun is lower that predictions of solar standard model (SSM).

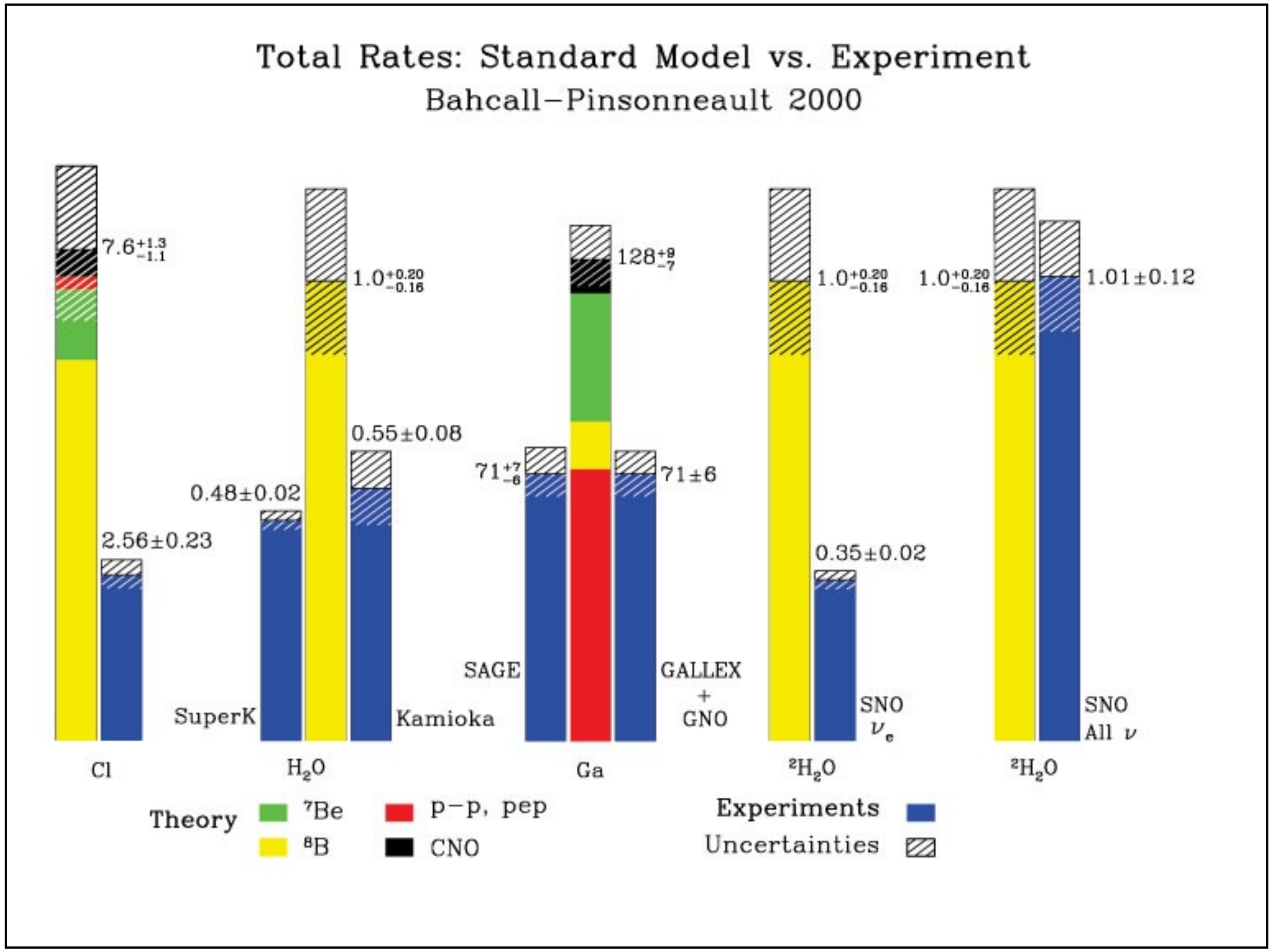
## SNO EXPERIMENT

$$\Phi_e = 1.76^{\pm 0.45(syst)}_{\pm 0.48(stat)} \times 10^6 cm^2 s^{-1}$$

$$\Phi_{\mu,\tau} = 3.41^{\pm 0.48(syst)}_{\pm 0.45(stat)} \times 10^6 cm^2 s^{-1}$$

## SSM PREDICTION

$$\Phi_{SSM} = 5.05^{+1.01}_{-0.81} \times 10^6 \quad cm^{-2} s^{-1}$$




$$\Phi_e + \Phi_{\mu,\tau} \simeq \Phi_{SSM}$$ → **neutrinos oscillate !**

- Mass eigenstates and flavours eigenstates are linked by a matrix

$$\begin{pmatrix}\nu_e\\ \nu_\mu\\ \nu_\tau\end{pmatrix} = V^{\mathrm{PMNS}}\begin{pmatrix}\nu_1\\ \nu_2\\ \nu_3\end{pmatrix}$$

$$V = \underbrace{\begin{bmatrix}1 & 0 & 0\\ 0 & c_{23} & s_{23}\\ 0 & -s_{23} & c_{23}\end{bmatrix}}_{\text{Atmospheric}} \underbrace{\begin{bmatrix}c_{13} & 0 & s_{13}e^{-i\delta}\\ 0 & 1 & 0\\ -s_{13}e^{i\delta} & 0 & c_{13}\end{bmatrix}}_{\text{Reactor}} \underbrace{\begin{bmatrix}c_{12} & s_{12} & 0\\ -s_{12} & c_{12} & 0\\ 0 & 0 & 1\end{bmatrix}}_{\text{solar}} \underbrace{\begin{bmatrix}e^{i\alpha_1/2} & 0 & 0\\ 0 & e^{i\alpha_2/2} & 0\\ 0 & 0 & 1\end{bmatrix}}_{\text{Majorana}}$$

$C_{ij} = \cos\theta_{ij}$ and $S_{ij} = \sin\theta_{ij}$

**4+2 parameters**

3 mixing angles
1 CP violation phase CP
2 Majorana phases

- **Oscillation probability**

$$P_{\alpha\to\beta} = |\langle\nu_\beta(t)|\nu_\alpha\rangle|^2 = \left|\sum_i U^*_{\alpha i}U_{\beta i}e^{-im_i^2 L/2E}\right|^2.$$

- **In two flavours case**

$$P_{\alpha\to\beta,\alpha\neq\beta} = \sin^2(2\theta)\sin^2\left(1.27\frac{\Delta m^2 L}{E}\frac{[\mathrm{eV}^2]\,[\mathrm{km}]}{[\mathrm{GeV}]}\right)$$ where $\Delta m^2 = m_i^2 - m_j^2$

# DOUBLE CHOOZ EXPERIMENT


**Near detector**
Distance: ~400 m
Overburden: ~120 m.w.e. flat

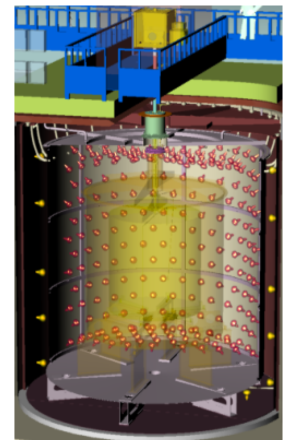
**2 PWR reactors**
$P_{th}$=4.25 GW each

**Far detector**
Distance: ~1050 m
Overburden: ~300 m.w.e. hill

**Probability of disparition:** $$P(\bar{\nu}_e \rightarrow \bar{\nu}_e) \simeq 1 - \sin^2(2\theta_{13})\sin^2\left(1.27\frac{\Delta m^2_{32}(\mathrm{eV}^2)L(\mathrm{m})}{E(\mathrm{MeV})}\right)$$

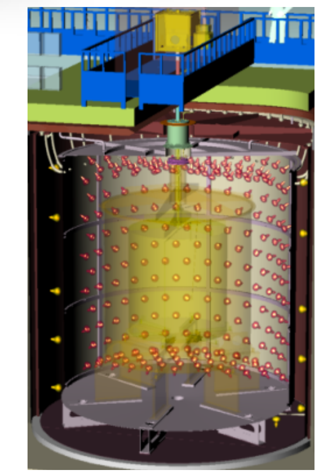
**Chooz Nuclear plant**
**2 réacteurs de 4.25 $GW_{th}$ each**

$\bar{\nu}_e$ → **Flux total**

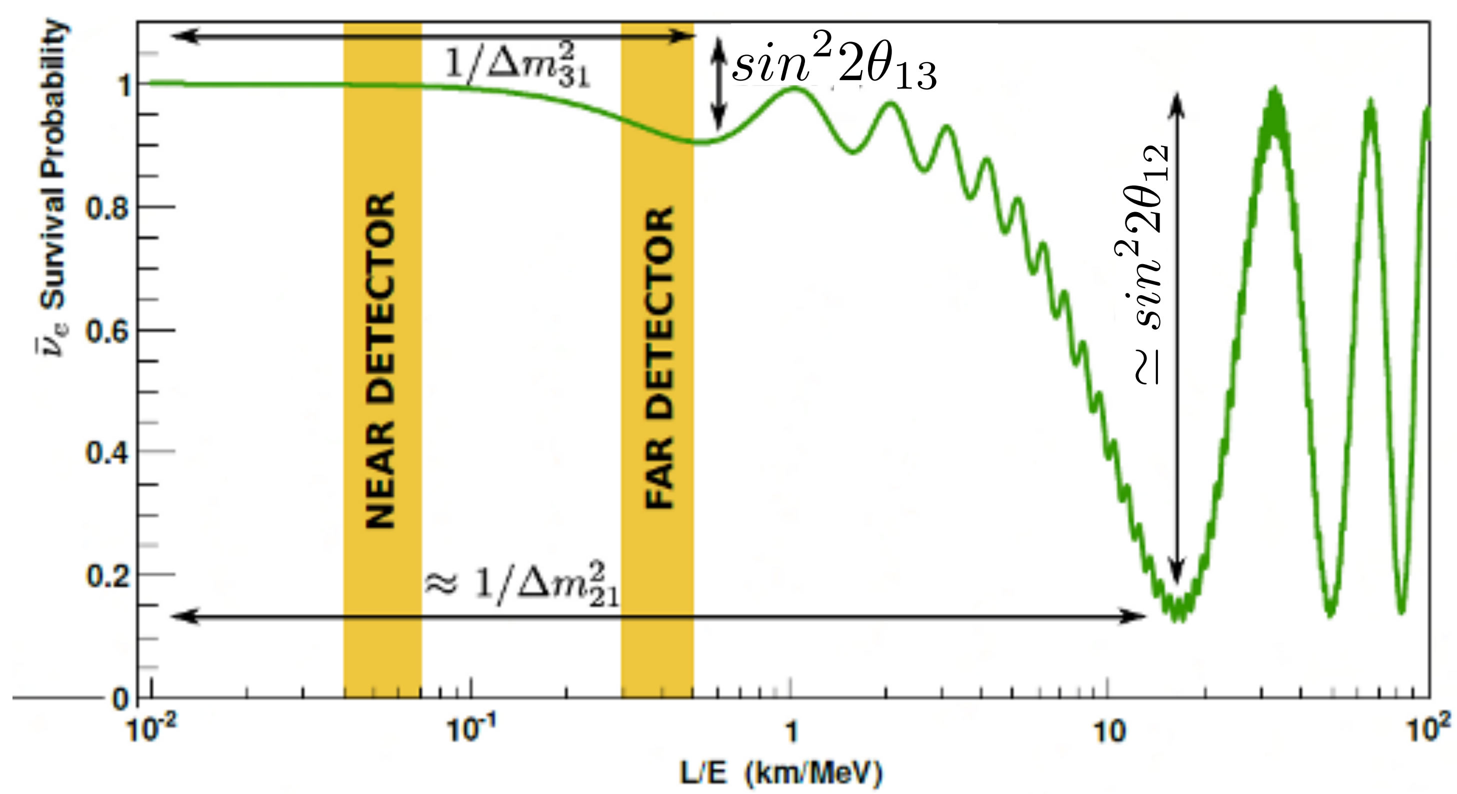


**Near detector**
**400 m**

$\bar{\nu}_{e,\mu,\tau}$ → **Flux oscillé**

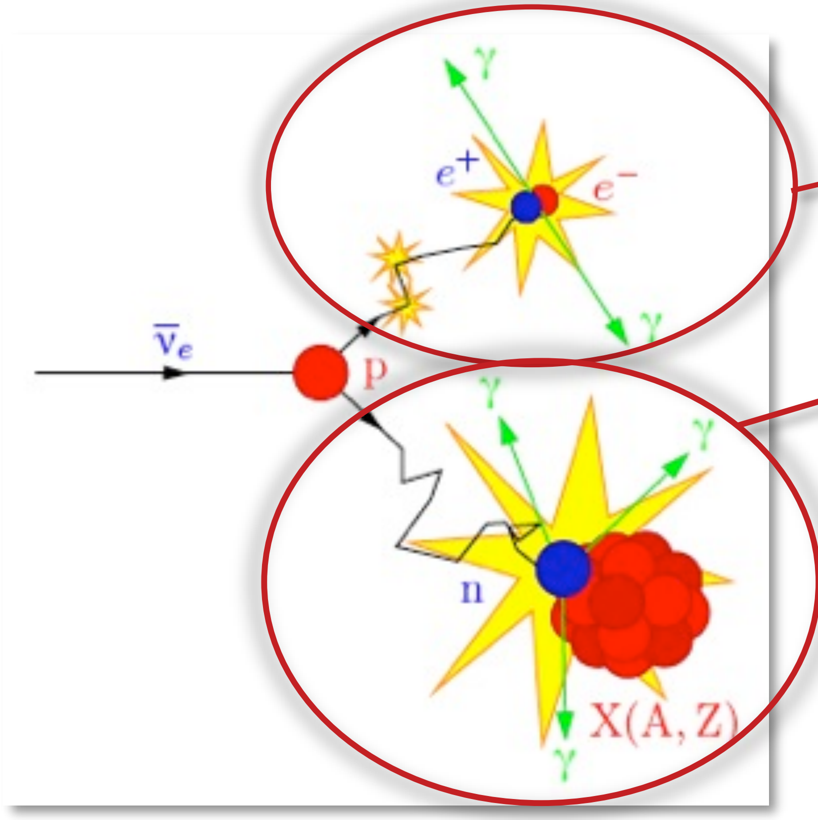


**Far detector**
**1050 m**



Inverse Beta Decay (IBD):
(Threshold à 1.8 MeV)

$$\overline{\nu_e} + p \rightarrow e^+ + n$$



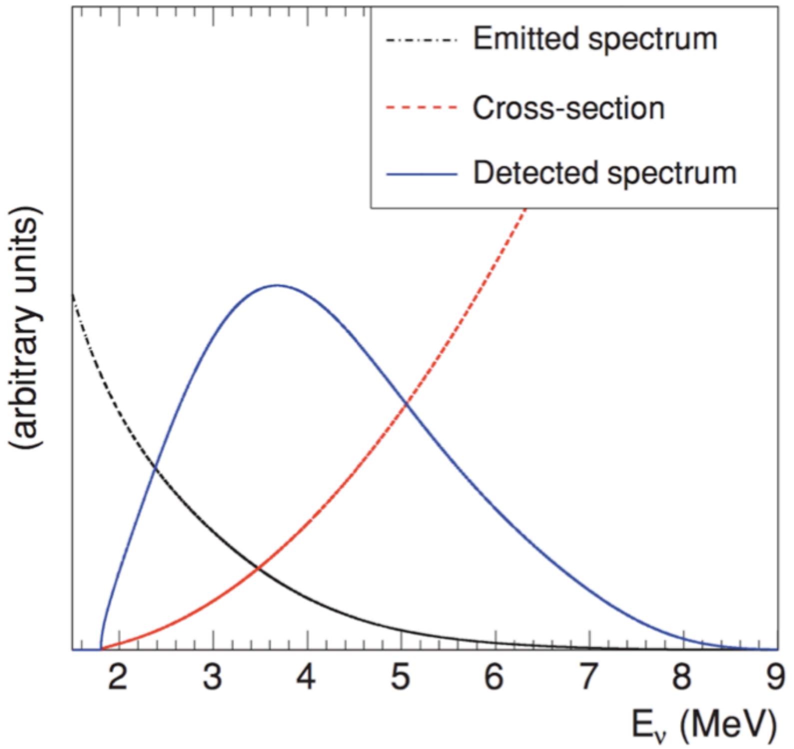

Prompt signal - Positron ionization+Annihilation

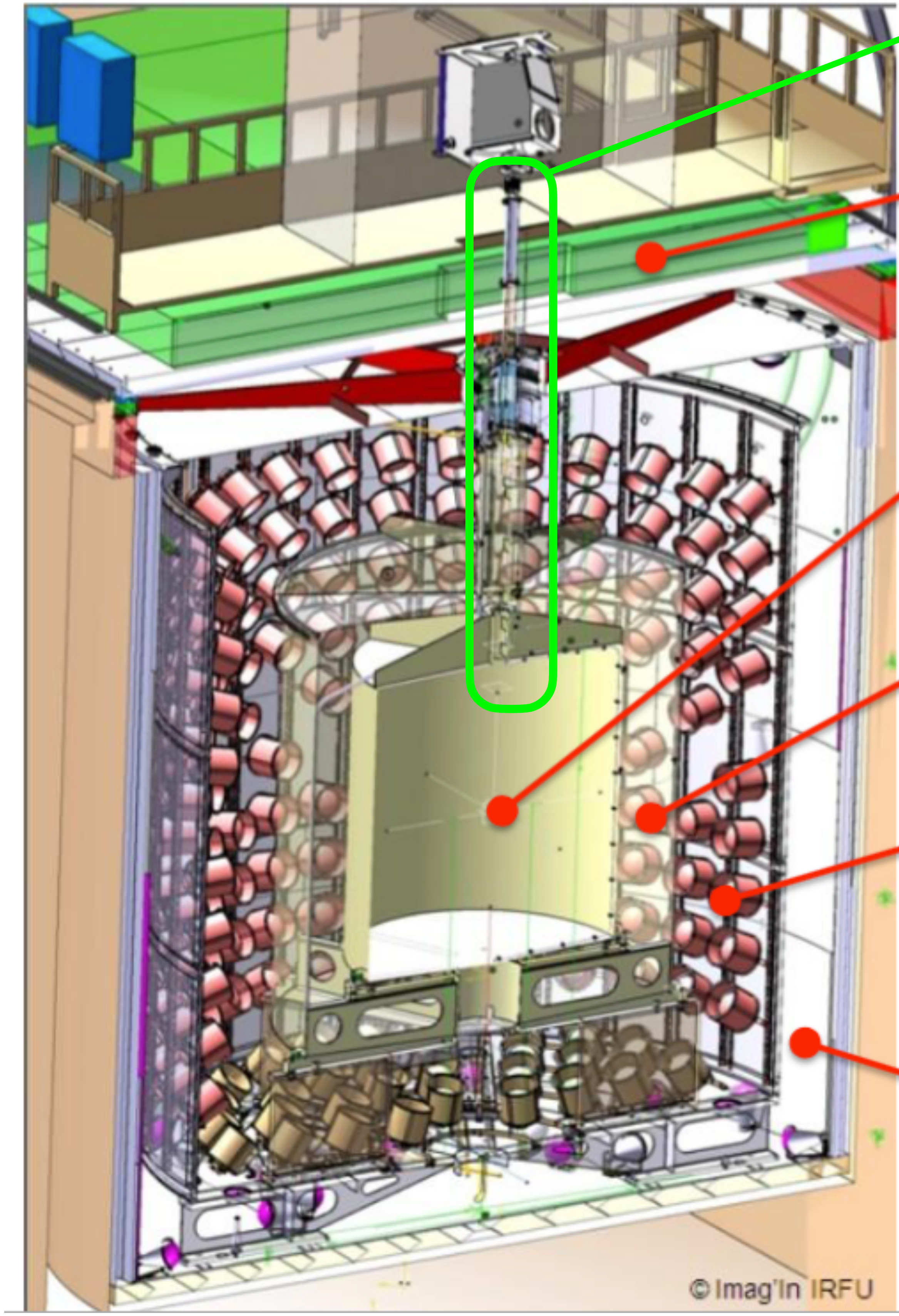
Delayed signal - capture of neutron by Gd (~ 8MeV)
Or H (2.2 MeV)

Δt ~ 30 μs for neutron capture on Gd
~ 200 μs for neutron capture on H

IBD selection

| | | |
|---|---|---|
| Delayed energy. | : | **1.3 < Evis < 3 MeV(H) or 4 < Evis<10 MeV (Gd)** |
| Dist correlation. | : | **Dr < 1 m** |
| Time correlation | : | **0.5 < Dt< 800 μs (H) or 0.5 < Dt< 150 μs (Gd)** |






**The Chimney**

**Outer Veto (OV):**
Plastic scintillator strips

**Inner Detector**

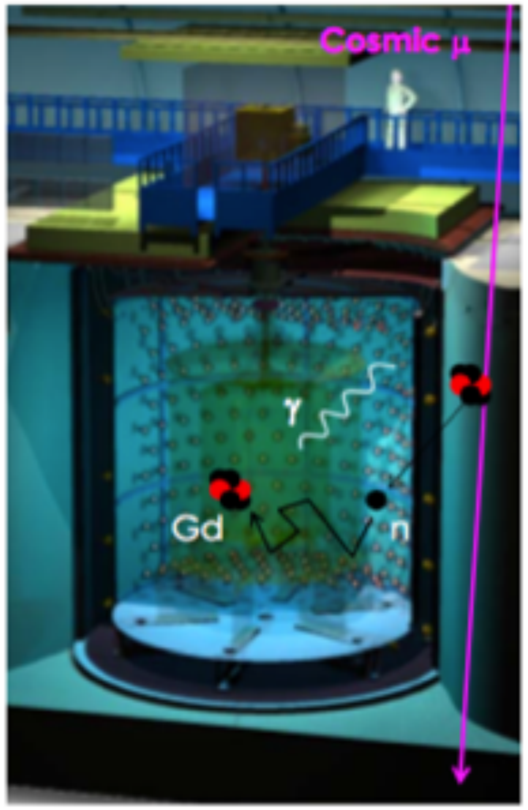
**ν-target (NT):**
- Gd loaded liquid scintillator ($10m^3$)

**γ-catcher (GC):**
- Liquid scintillator ($22m^3$)

**Buffer:**
- Mineral oil ($110m^3$)
- 390 10-inch PMT

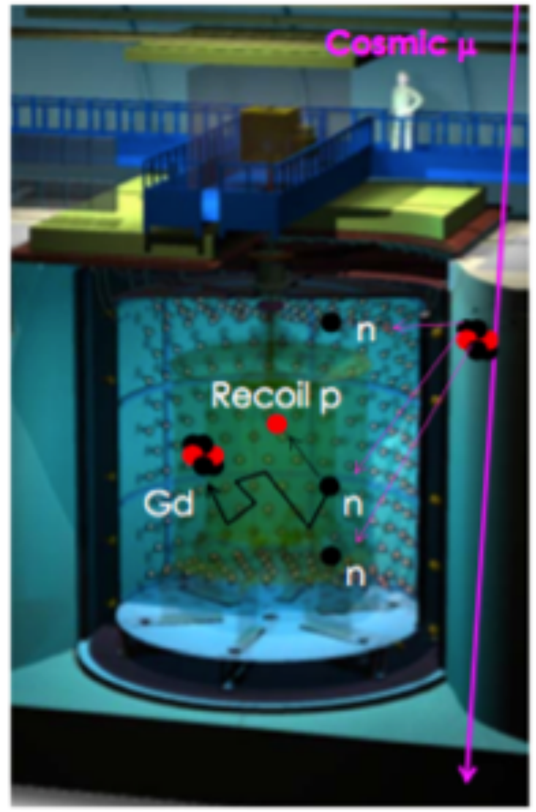
**Inner Veto (IV):**
- Liquid scintillator ($90m^3$)
- 78 8-inch PMT

## Accidental BG

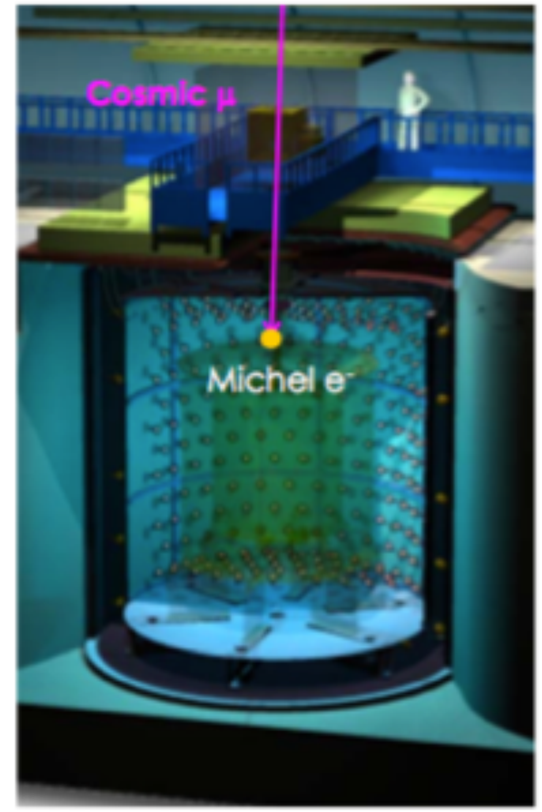



## Correlated BG

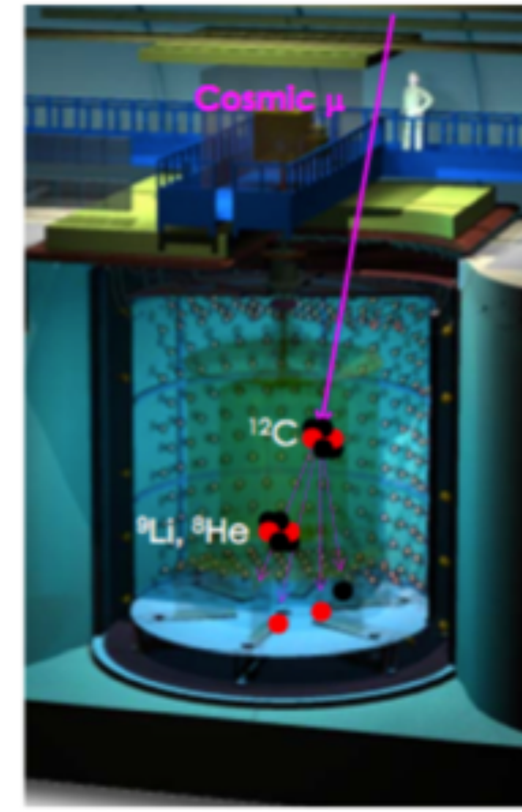
### Fast neutrons




### Stopping μ




### Cosmogenics




| | Accidental BG | Fast neutrons | Stopping μ | Cosmogenics |
|---|---|---|---|---|
| **Prompt** | Radioactivity from materials, PMTs, surrounding rock ($^{208}$Tl). | Neutrons from cosmic μ spallation gives recoil protons (low energy). | Cosmic μ entering from the chimney. | Electrons from $^{9}$Li/$^{8}$He β + n decays. |
| **Delay** | Neutrons from cosmic μ spallation captured on Gd/H, or γ like prompt fake signal in case of H analysis. | Neutrons from cosmic μ spallation captured on Gd/H, or γ like prompt fake signal in case of H analysis. | Michel electrons. | Neutrons from $^{9}$Li/$^{8}$He β + n decays captured on Gd/H. |

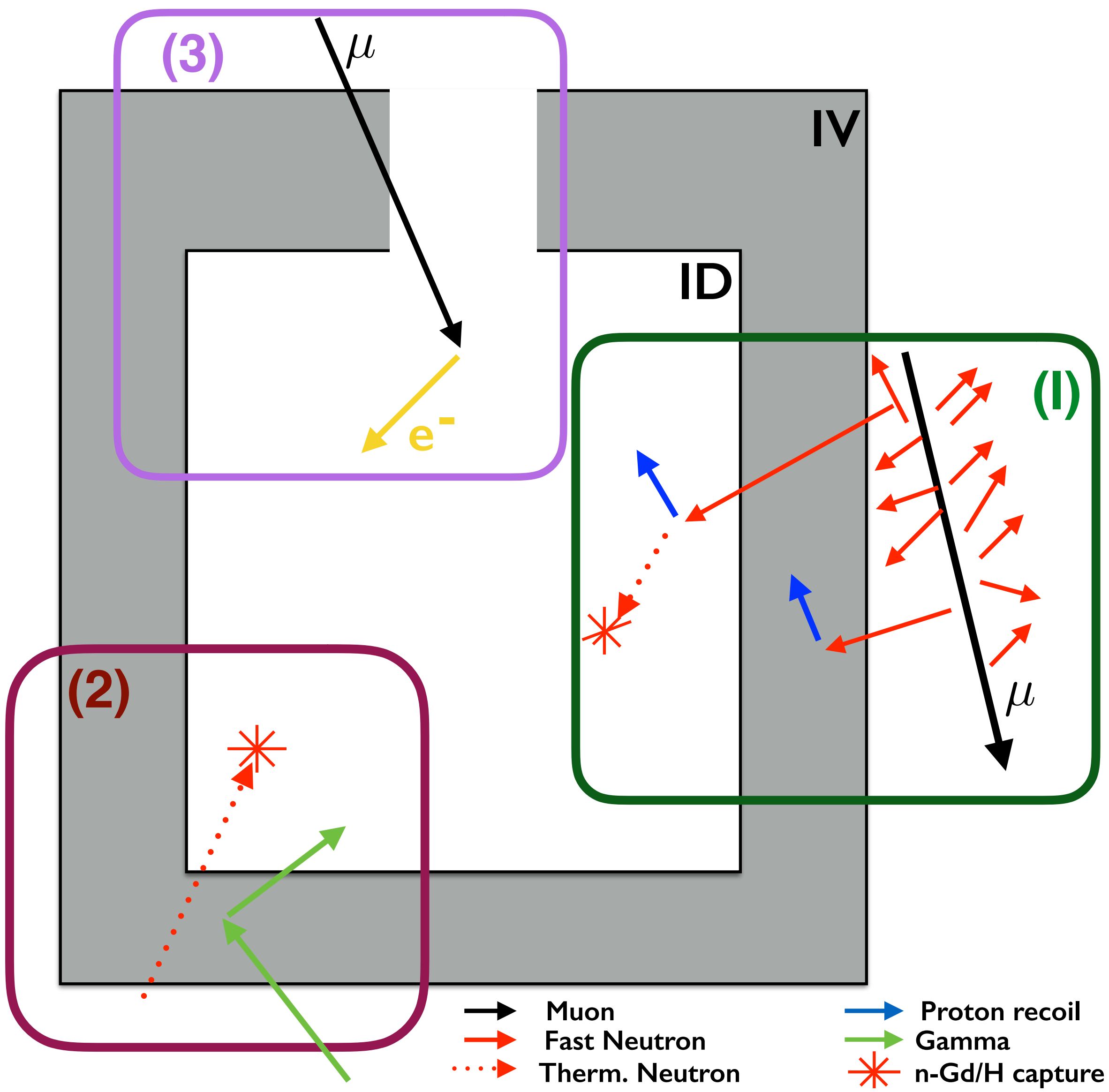
**Double Chooz has developed dedicated techniques for identifying and studying these backgrounds.**

**The identified background noise is removed from the final selection of IBDs for the final fit.**

**However, since the cuts are never 100% effecient, we must estimate the level of background remaining in the final sample of IBDs to constrain the final fit and therefore improve the precision of the measurement of $\theta_{13}$**

# FAST NEUTRONS

# IVT: Background identification by means of l'Inner Veto




## 1. FAST NEUTRONS (FN)

-Created by interactions of muons with the surrounding rocks.

-Enter the l'IV and diffuse on protons

-Le recul du proton et la capture du neutron imitent le signal

## 2. GAMMA GAMMA (γ-γ) EVENEMENTS

-Uncorrelated coincidence between a natural radioactivity gamma and a neutron capture.

## 3. STOPPING MUONS (SM)

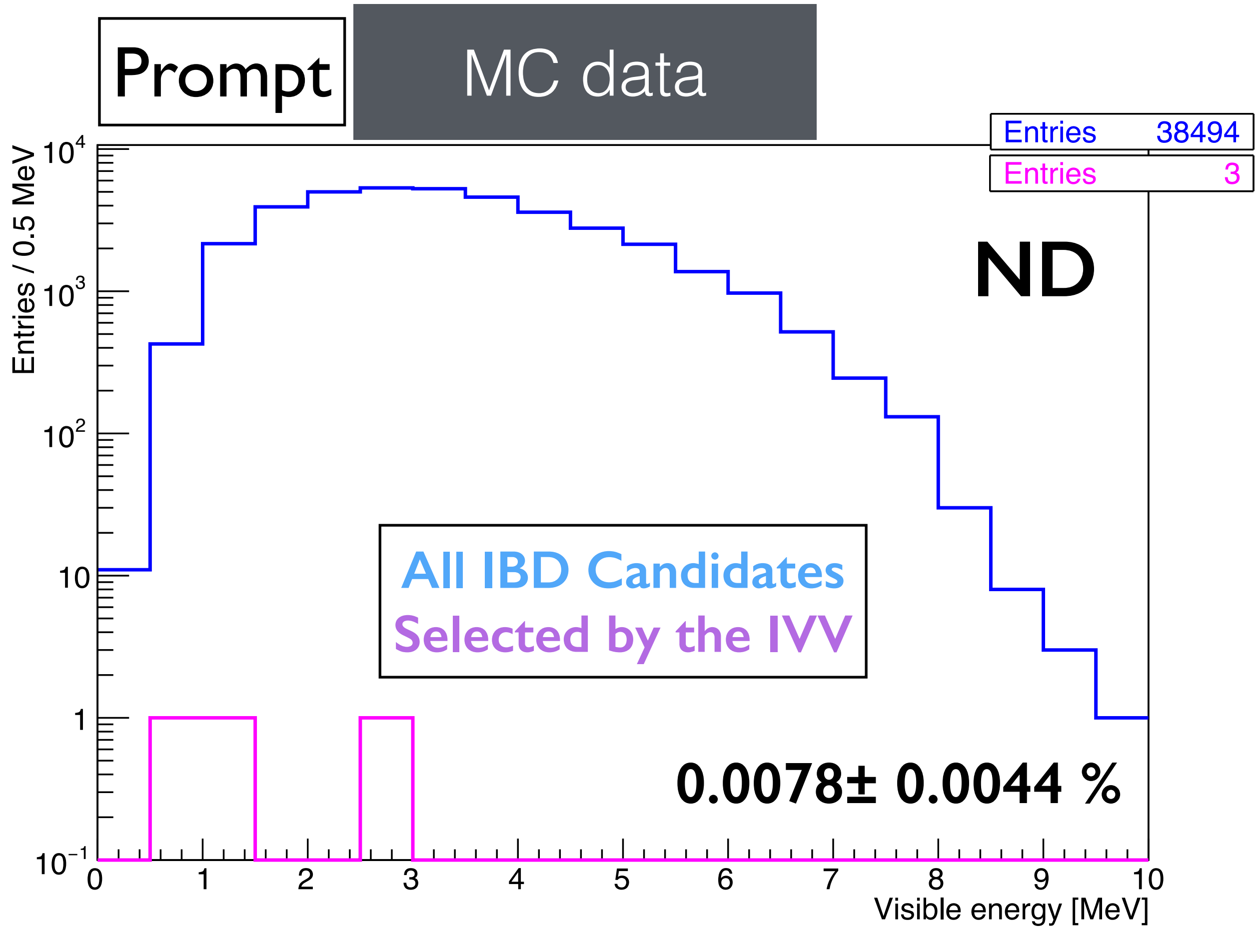
-Can deposit energy in the Inner Veto

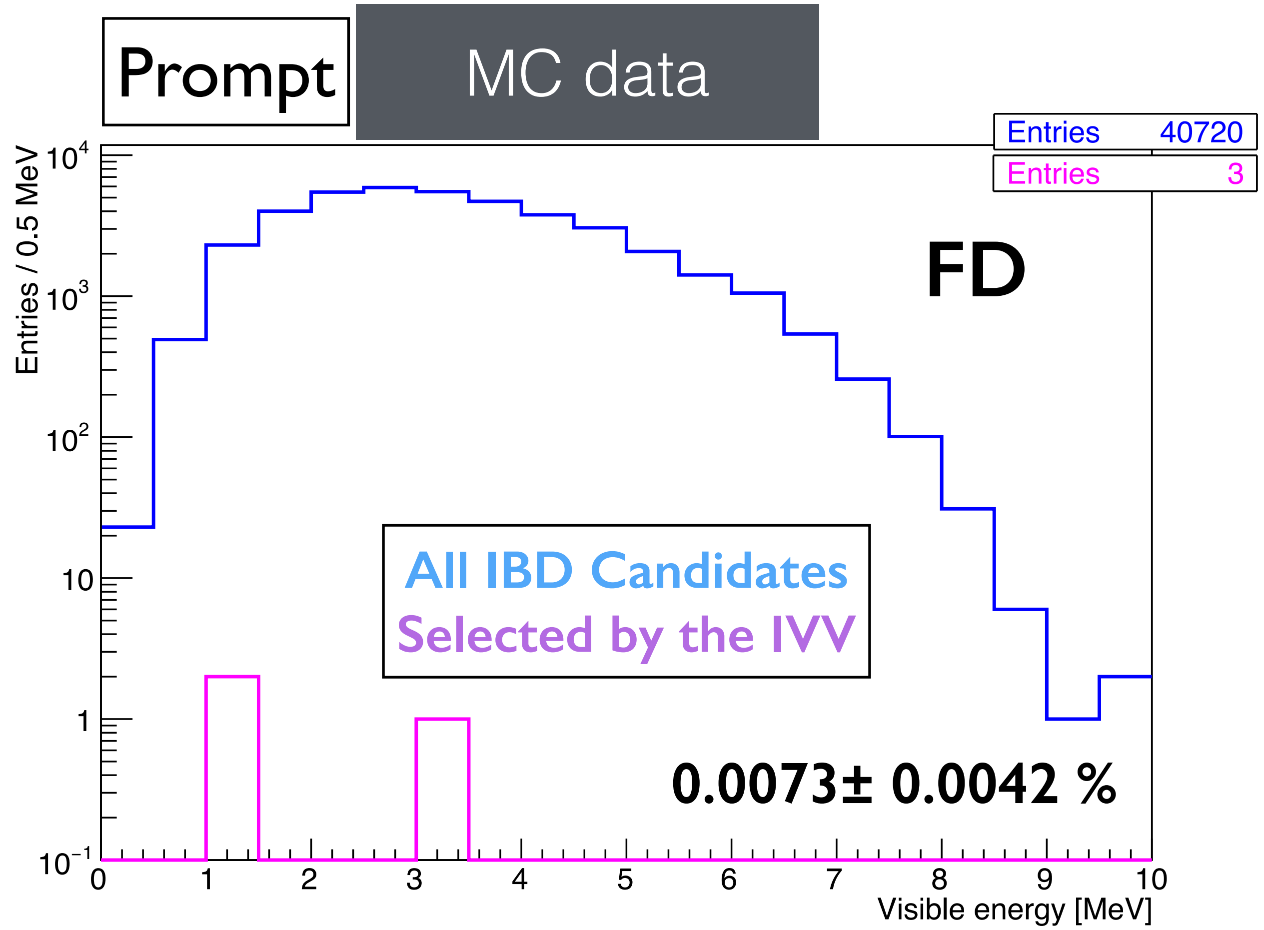
-Stop and decay in the detector

-The stopping energy and the Michel électrons michel mimic the IBD signals.

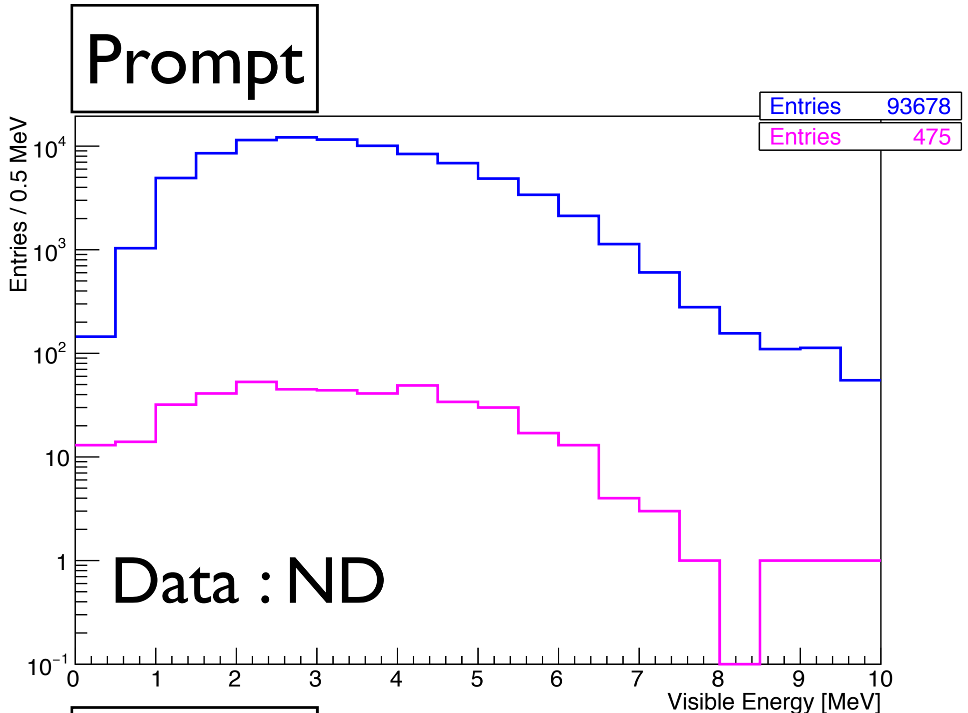
**IVT CUTS**: Events whose prompt signal satisfy these conditions are tagged as background.

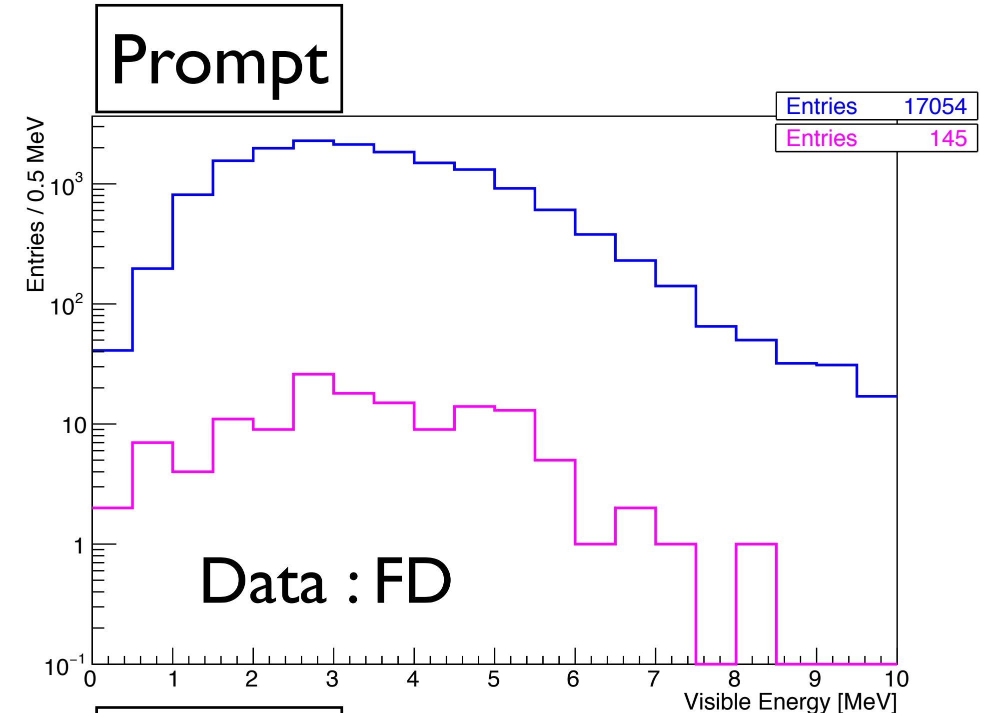
| Cuts | ND & FD-II |
|---|---|
| #PMT IV | nPMT > 1 |
| DR (ID-IV) | < 3.7 m |
| Dt (ID-IV) | [-40;70] ns |
| Charge | > 300 DUQ |



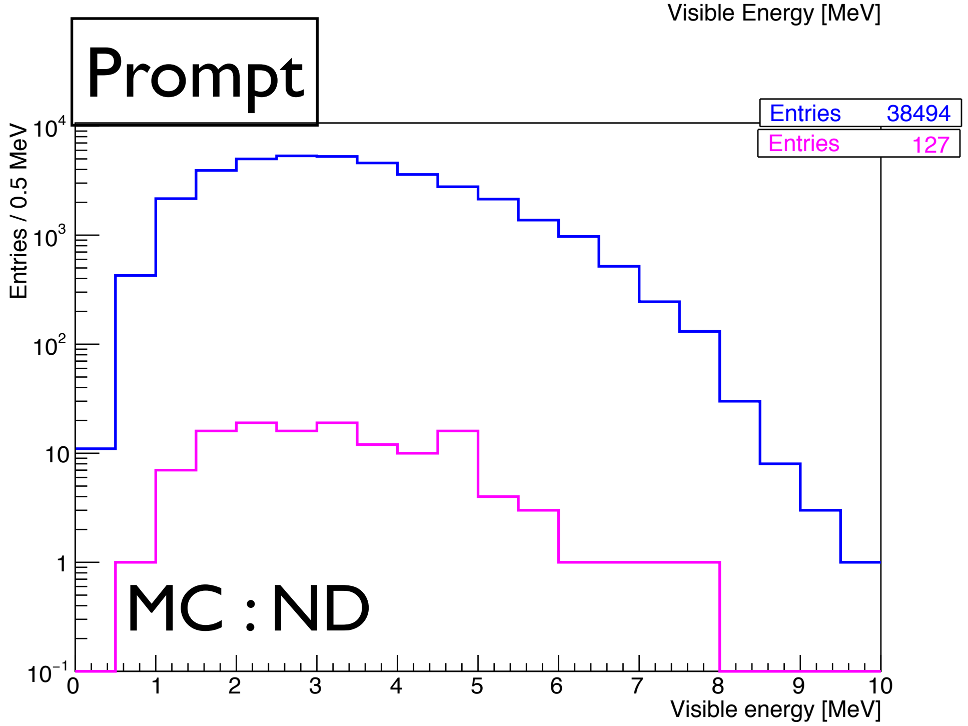



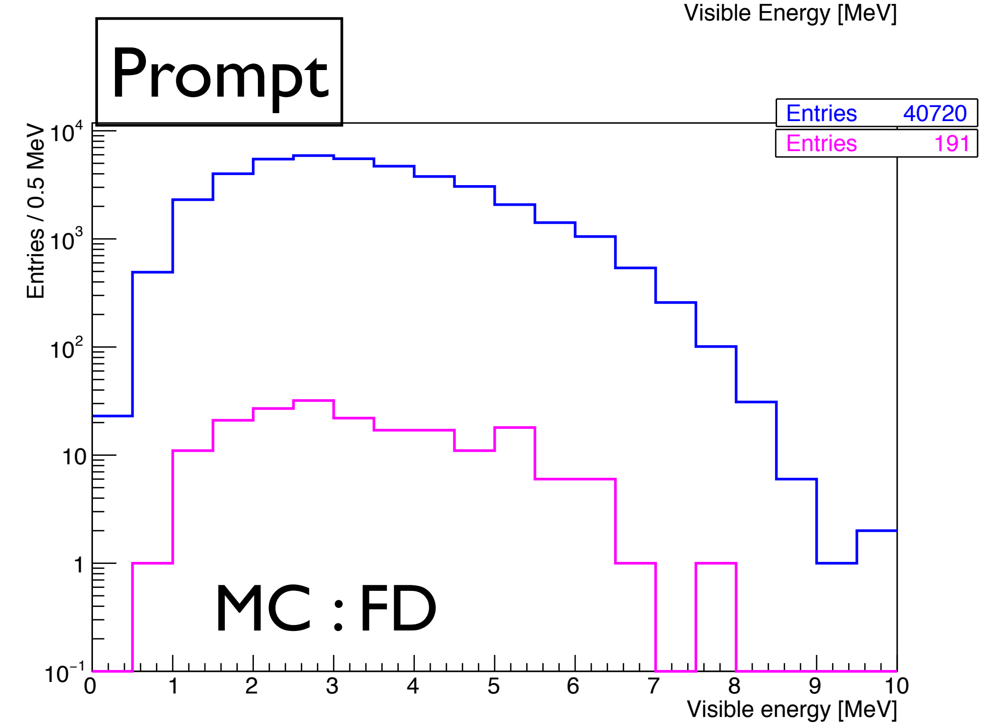
## IVT retardé appliqué sur la sélection Gd a servi à valider le MC utilisé



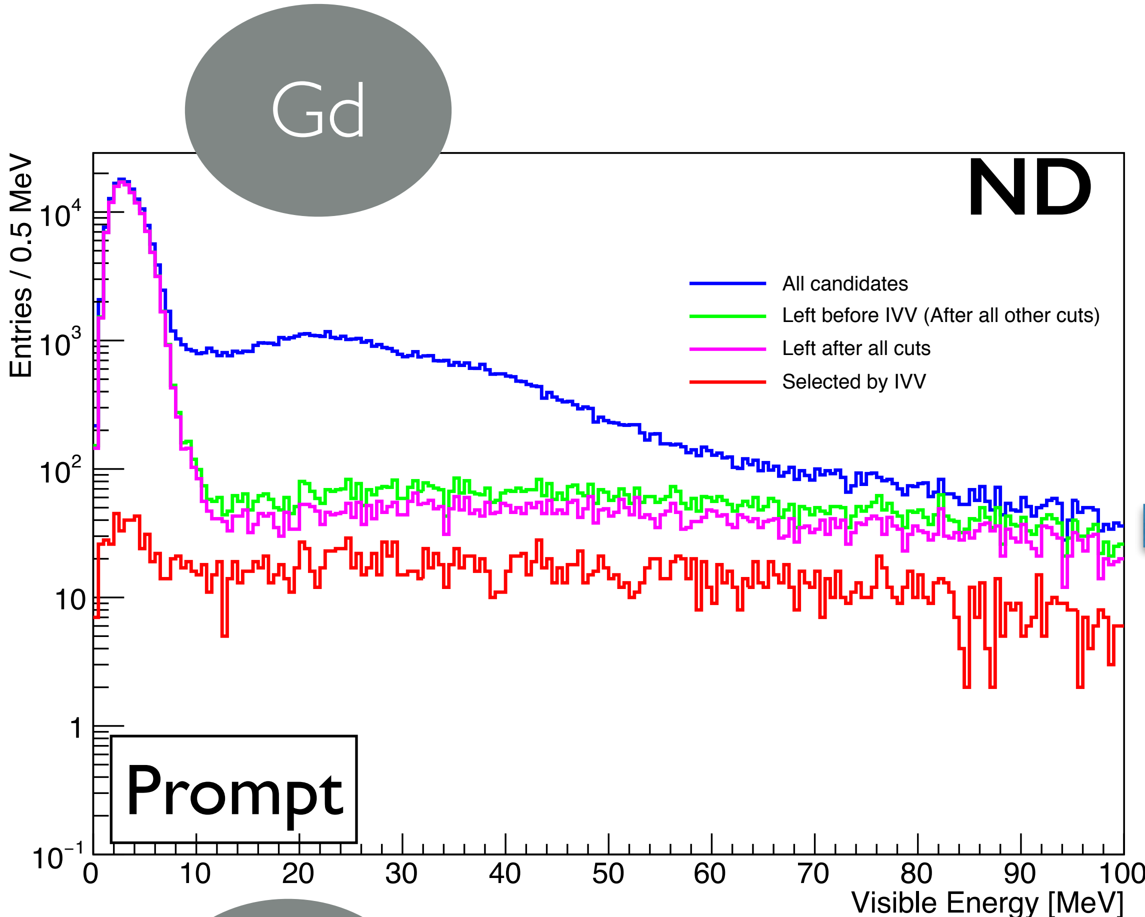



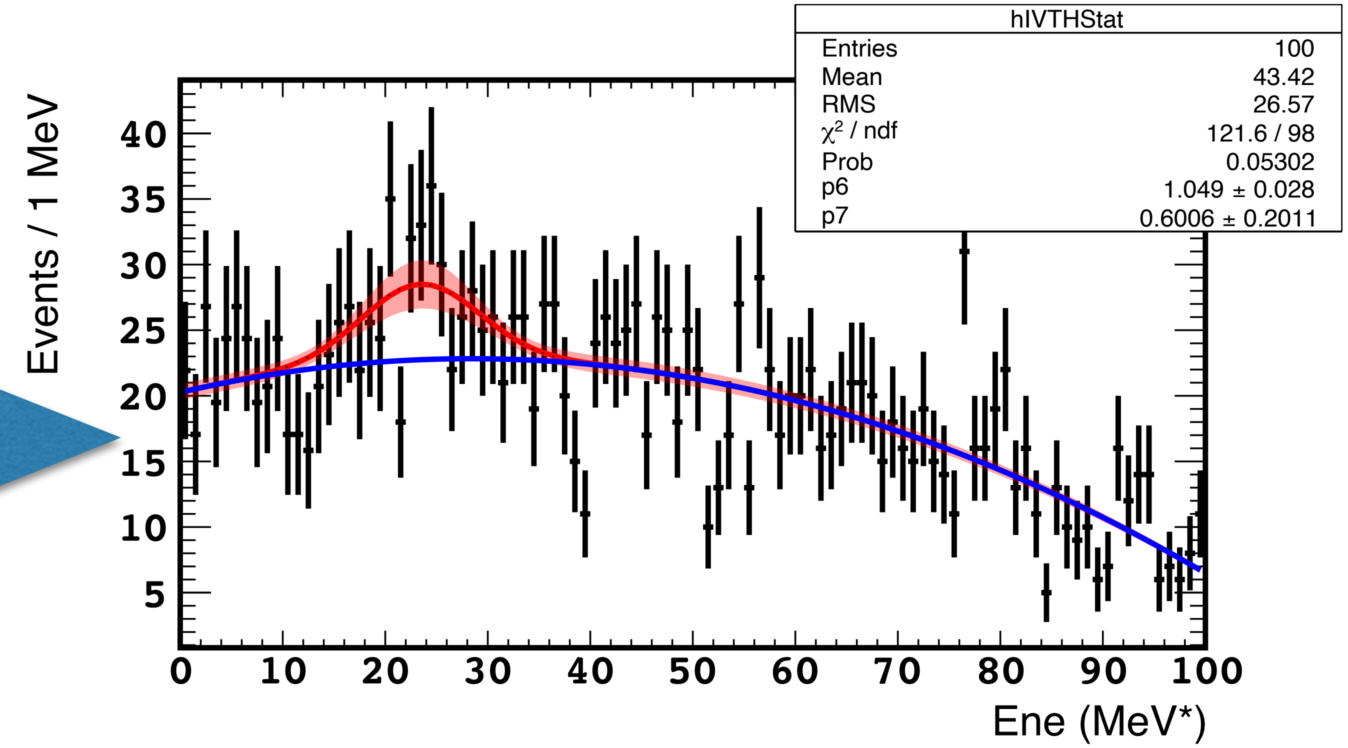

**All IBD candidates**
**Selected by IVV**

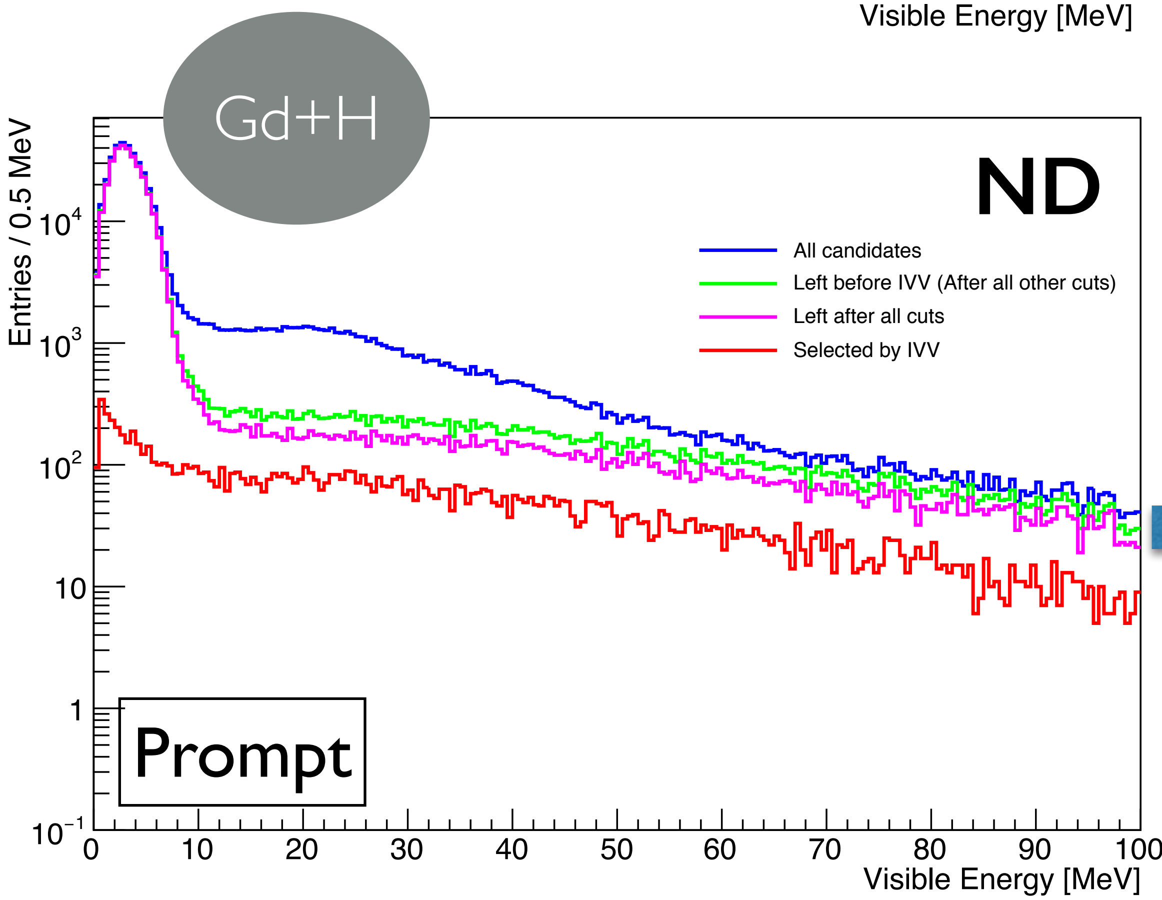


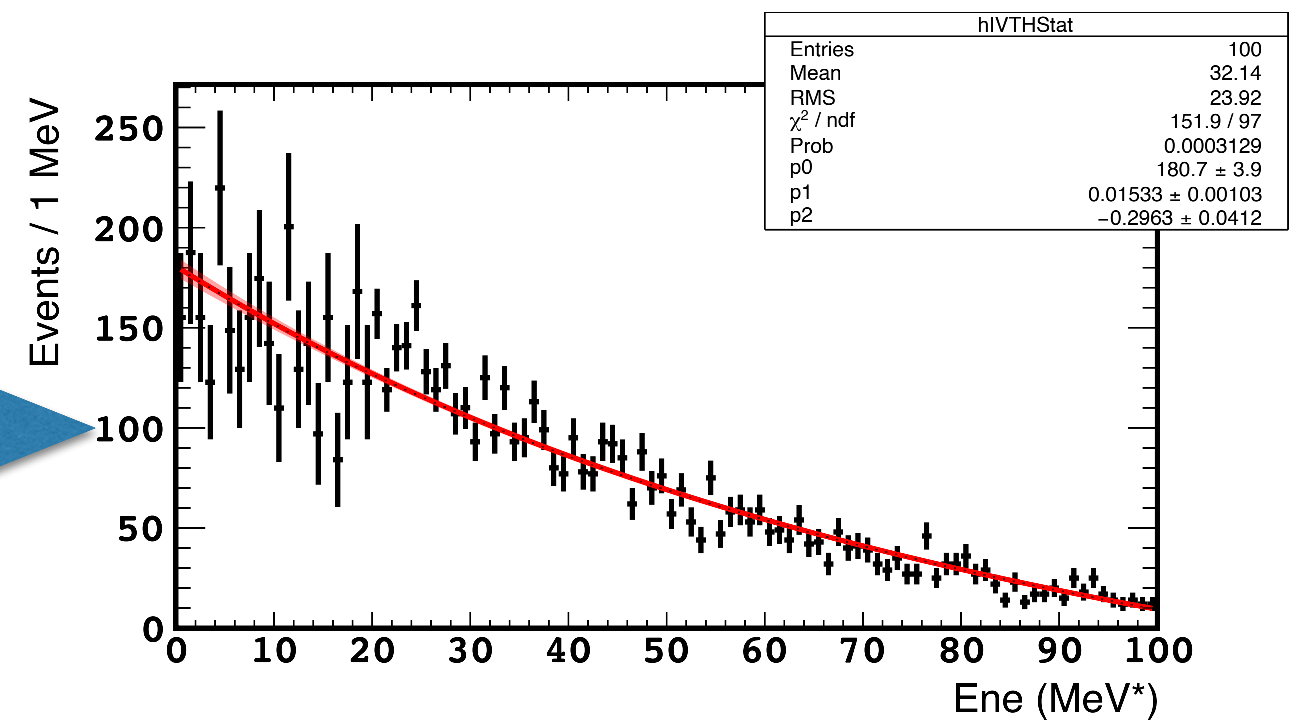




| Detector | $\bar{\varepsilon}_{D-IVV}$ (Monte Carlo) | $\bar{\varepsilon}_{D-IVV}$ (Data) |
|---|---|---|
| ND | 0.33±0.03 % | 0.50±0.02 % |
| FD | 0.47±0.03 % | 0.85±0.07 % |


Gd
ND
All candidates
Left before IVV (After all other cuts)
Left after all cuts
Selected by IVV
Prompt
Entries / 0.5 MeV
Visible Energy [MeV]

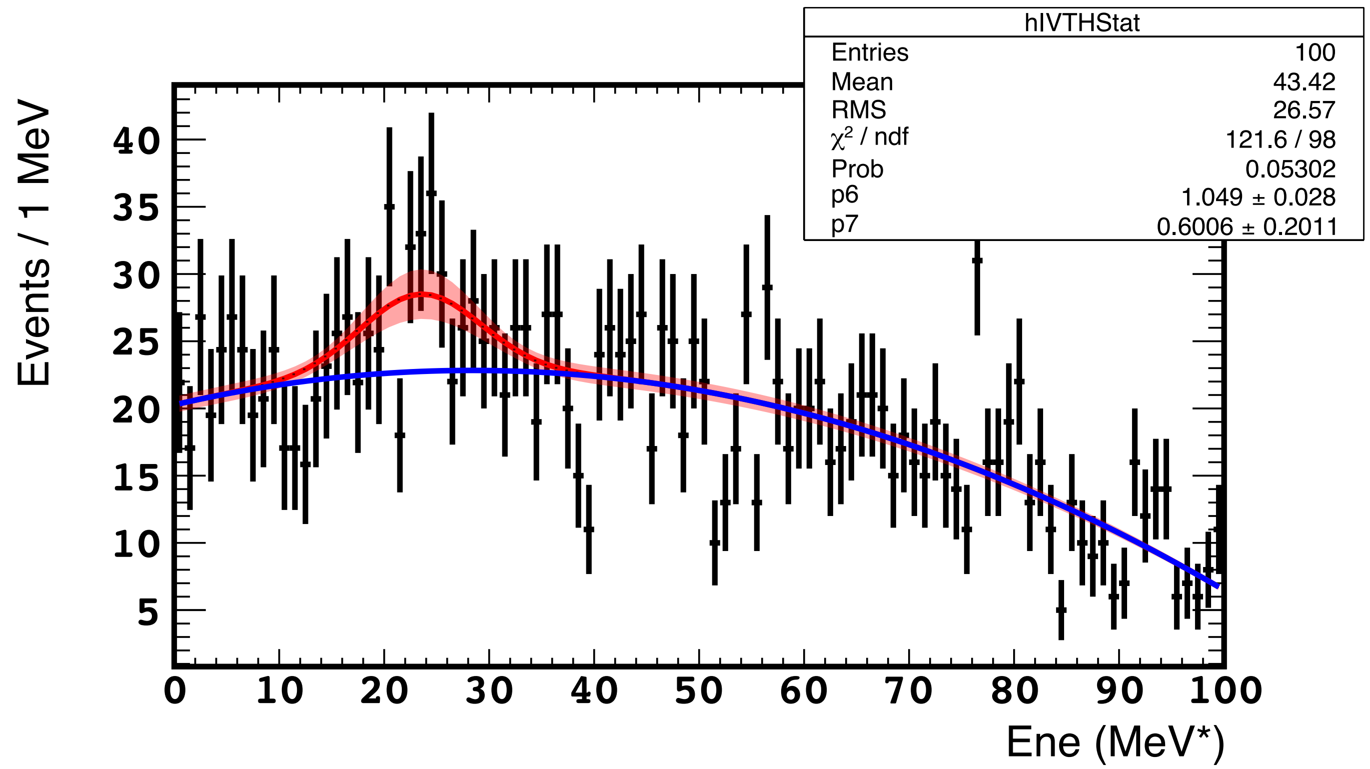

hIVTHStat
Entries 100
Mean 43.42
RMS 26.57
$\chi^2$ / ndf 121.6 / 98
Prob 0.05302
p6 1.049 ± 0.028
p7 0.6006 ± 0.2011
Events / 1 MeV
Ene (MeV*)


Gd+H
ND
All candidates
Left before IVV (After all other cuts)
Left after all cuts
Selected by IVV
Prompt
Entries / 0.5 MeV
Visible Energy [MeV]


hIVTHStat
Entries 100
Mean 32.14
RMS 23.92
$\chi^2$ / ndf 151.9 / 97
Prob 0.0003129
p0 180.7 ± 3.9
p1 0.01533 ± 0.00103
p2 −0.2963 ± 0.0412
Events / 1 MeV
Ene (MeV*)

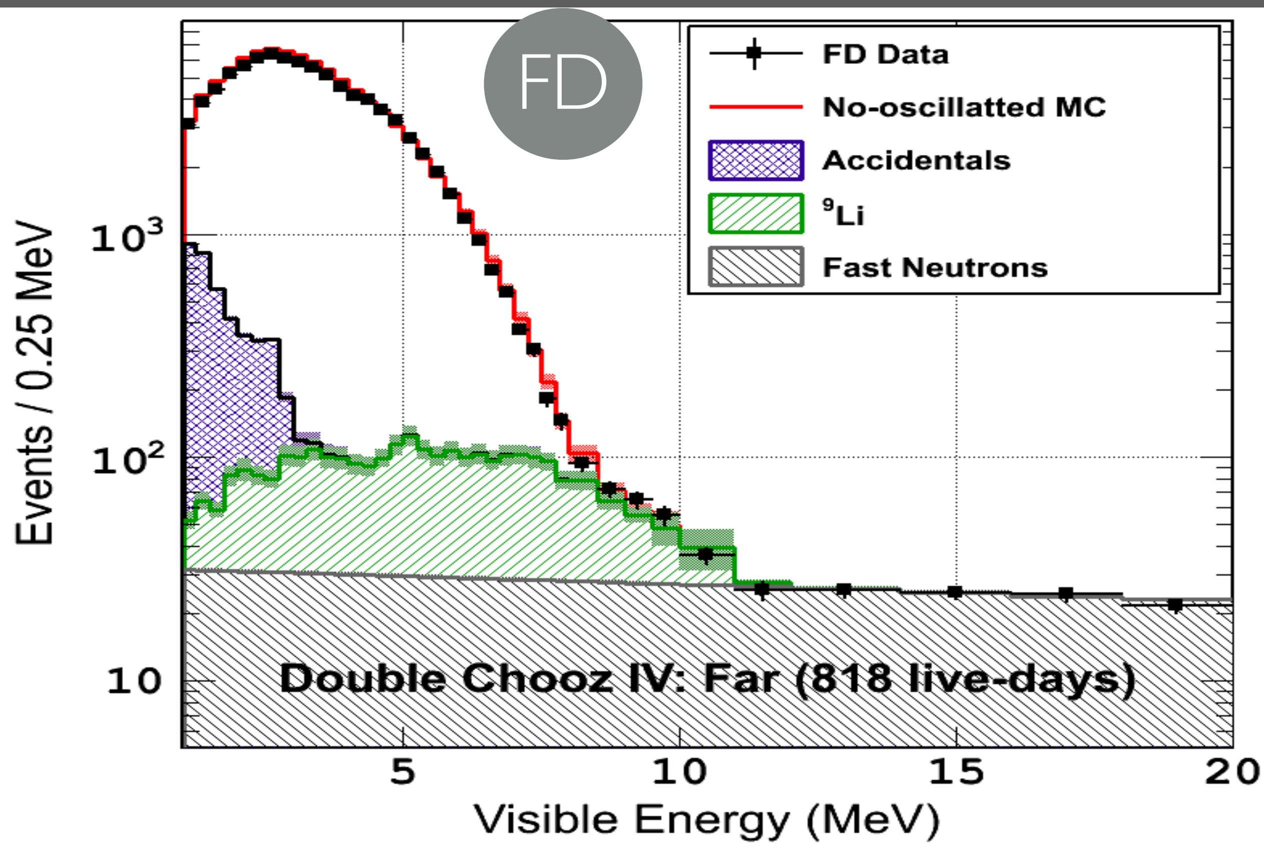
## To measure the rates

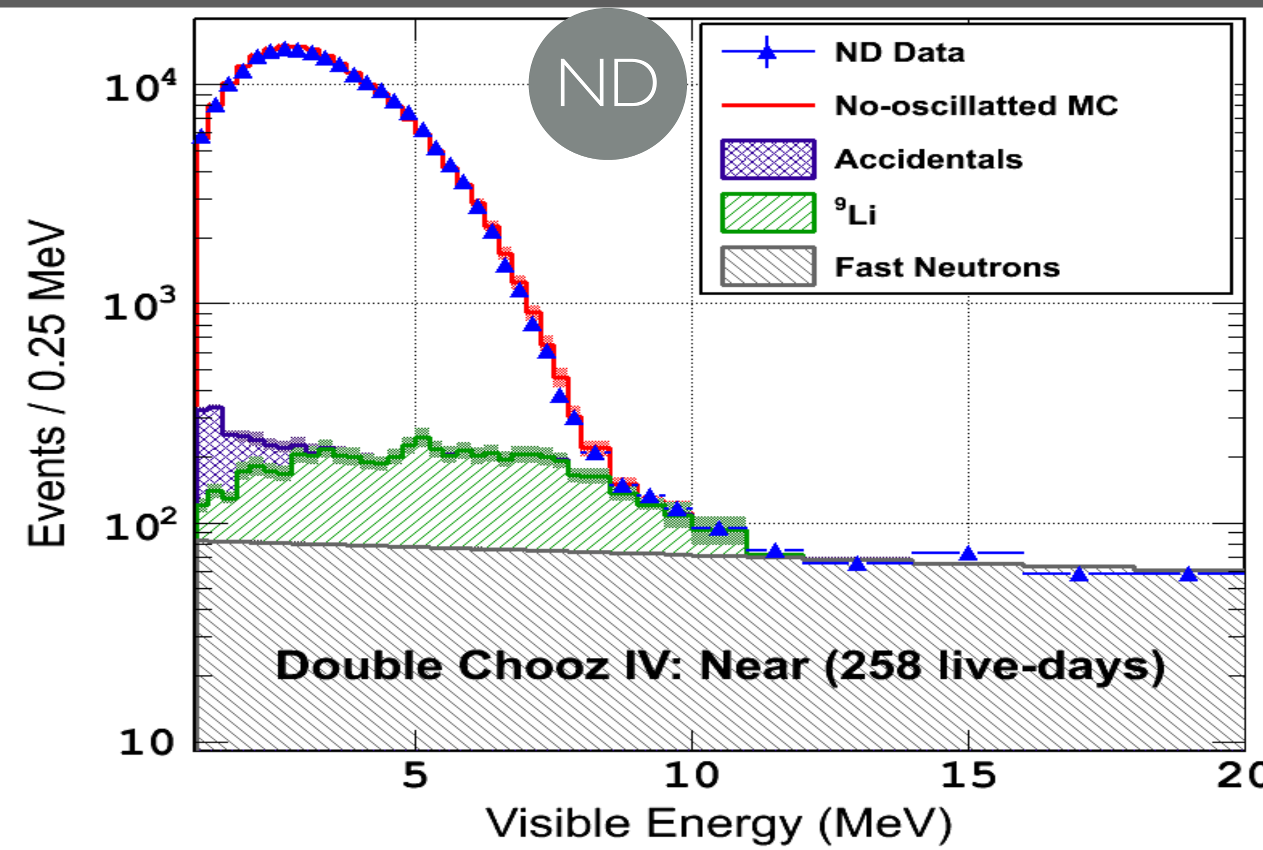
- We consider there are only fast neutrons beyond 20 MeV.
- We calculate our cut efficiency IVV in this region [20;100] MeV

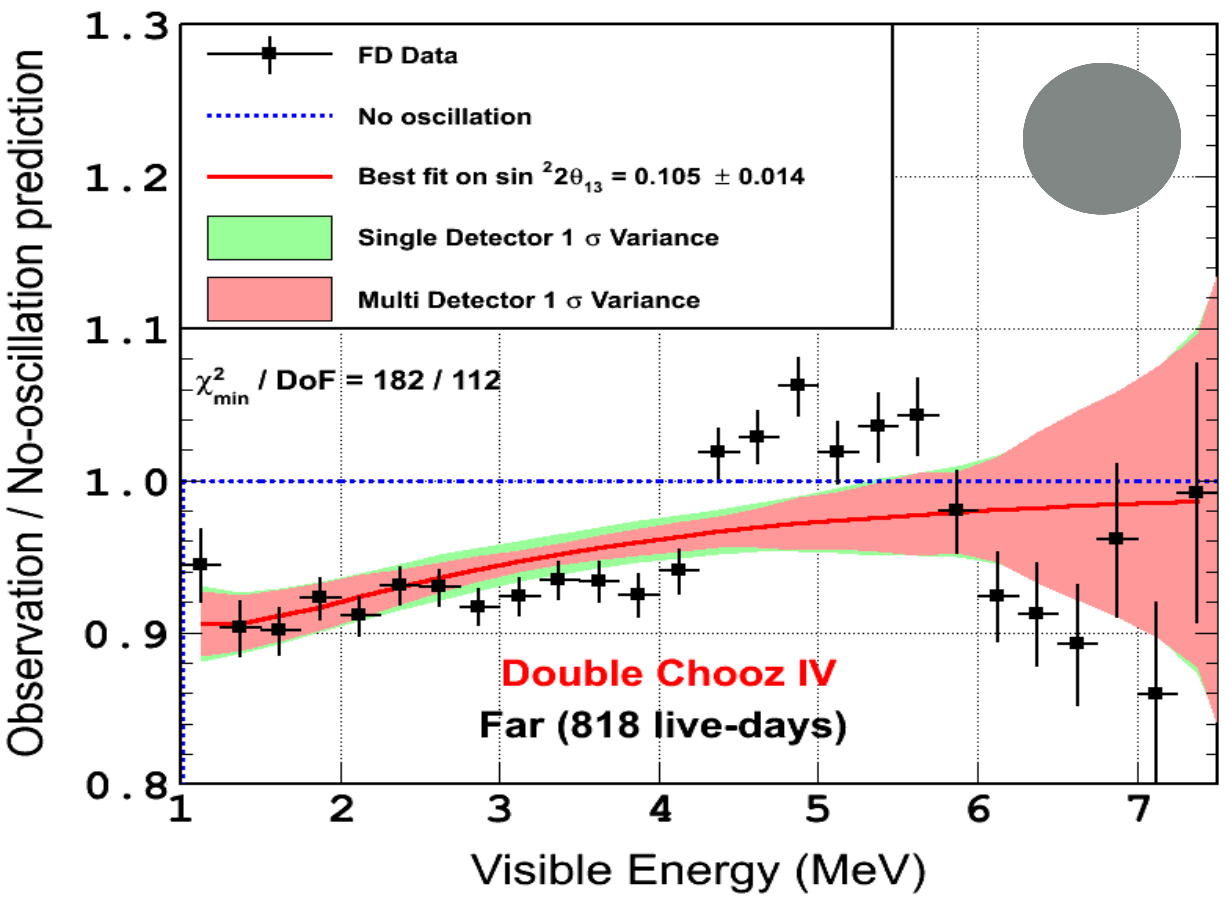



- This allows an estimation of the remaining rate **(per day)** in the final fit region i.e [0;20] MeV

| Detector | Gd selection | Gd+H selection |
|---|---|---|
| ND | 3.42 ± 0.23 | 20.77 ± 0.43 |
| FD | 0.586 ± 0.06 | 2.54 ± 0.10 |




$$\sin^2(2\theta_{13}) = 0.105 \pm 0.014$$

Rate / day of fast neutrons

| | | |
|---|---|---|
| Output | 2.50 ± 0.05 | 20.85 ± 0.31 |
| Input | 2.54 ± 0.10 | 20.77 ± 0.43 |

## SUMMARY

- ☑ (IVV) tagging of fast neutrons set by me is the official Double Chooz .

- ☑ Spectrum of events selected by l'IVV allowed fast neutrons remaining rate, which serves as input to the final fit.

- ☑ Analysis updated for each data release and still valid..