The Double Chooz experiment
Directionality studies and latest results

December 8 –AAP 2015 / Virginia Tech

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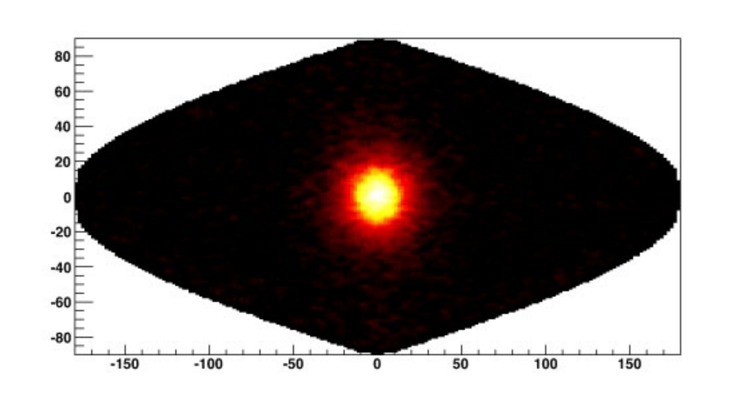
IPHC

Neutrino directionality –General aspect

Neutrino directionality is an interesting information in a various number of fields :

- ν astronomy → SN early detection
- ν from reactors → Power plant location and activities
- Geo ν → origin determination (crust, mantle)
- For everyone → background rejection

How to determinate the ν direction :



- Elastic scattering : $\nu_e + e^- \rightarrow \nu_e + e^-$
  - Good directionality information
  - Background
  - SK, SNO, Borexino, ...

- Inverse Beta Decay (IBD) : $\bar{\nu}_e + p \rightarrow e^+ + n$
  - Hard to obtain information on direction
  - Clean signature
  - Double Chooz, DB, Reno, ...

The Double Chooz experiment

Aim of the Double Chooz experiment → Measurement of θ_{13} through the observation of $\bar{\nu}_e \rightarrow \bar{\nu}_e$ transition according to the oscillation probability :

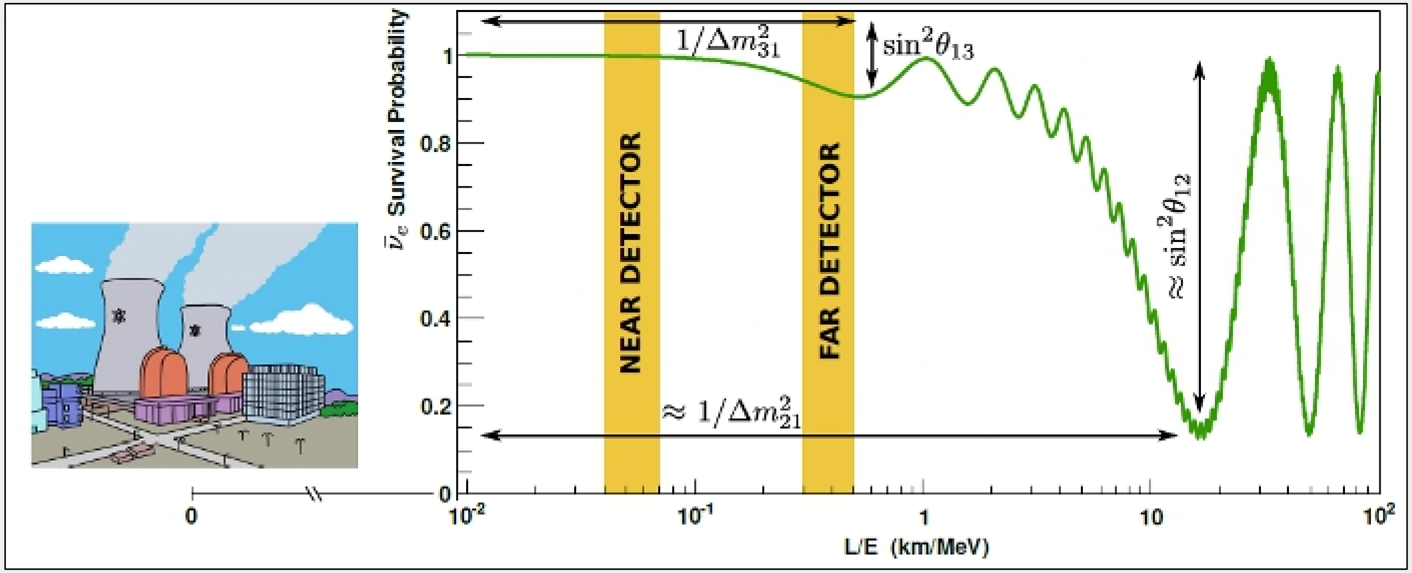
$$\boxed{P_{\bar{\nu}_e \rightarrow \bar{\nu}_e} = 1 - \sin^2(2\theta_{13}) \sin^2\left(\frac{\Delta m^2_{31} \mathrm{L}}{4\ \mathrm{E}}\right) + O(10^{-3}) \quad \text{for L/E} \lesssim 1}$$

Reactors : Pure $\bar{\nu}_e$, low energy, high intensity (10^{21} $\bar{\nu}_e$/s)

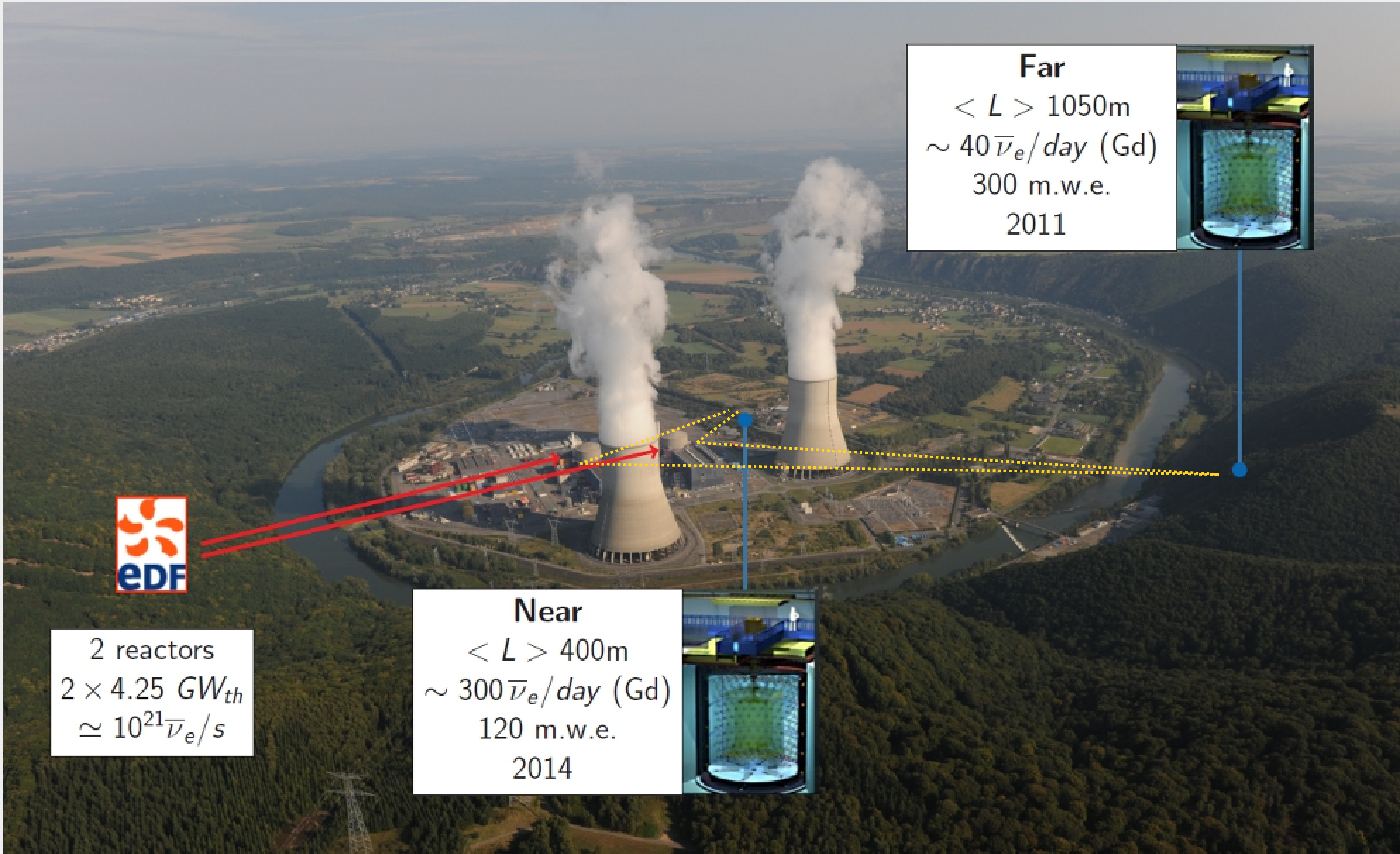
→ Short baseline, no matter effect

2 identical detectors : Cancel flux & efficiency uncertainties

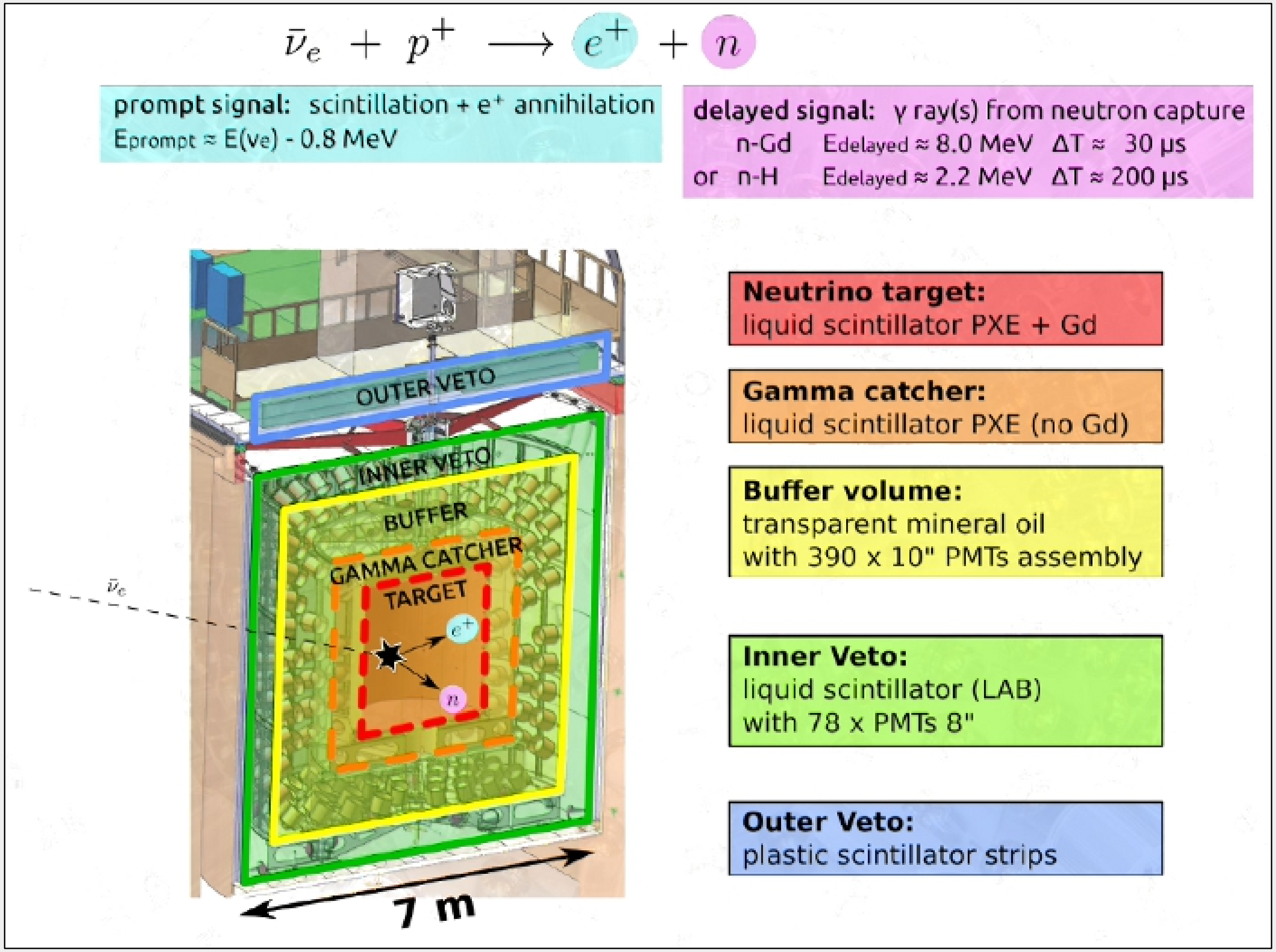
→ Unoscillated flux @ Near, disappearance around the first minimum @ Far



Power plant @ Chooz (France)



Neutrino detection in Double Chooz



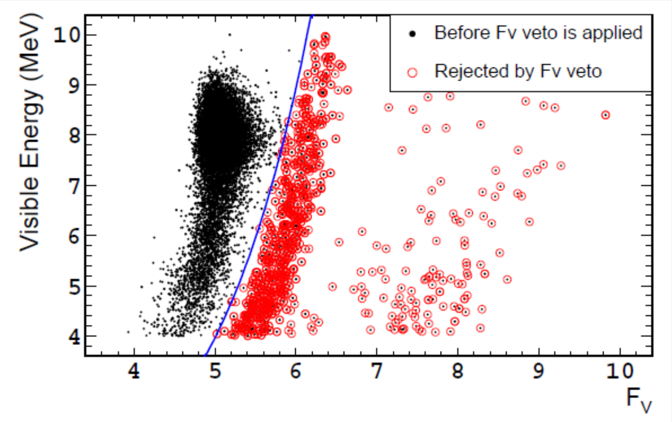
IBD threshold → 1.8 MeV

Shielding → @ Far : 150mm of steel / @ Near : 1m of water

Candidates selection in Double Chooz

Veto on single triggers :

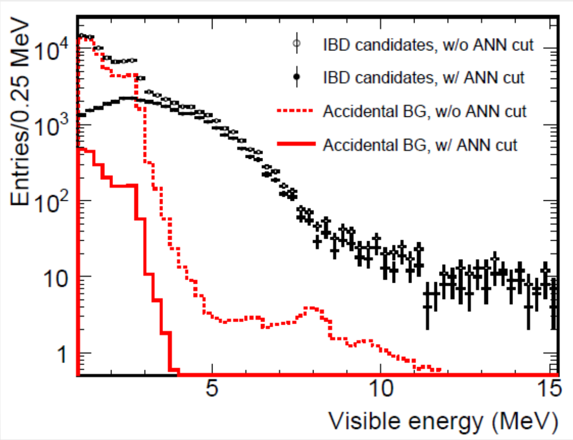
- Muon veto → no triggers 1ms after a muon (1.25 ms for H)
- OV → No coincidence with the Outer Veto
- Li+He veto → Likelihood trained on ^{12}B : 50% rejection and deadtime < 0.5%
- IV → Cut on charge, multiplicity and space/time coincidence (fast n, stopped μ, γ scattering)
- FV → stopped μ spontaneous light emission
- MPS → Stopping muon (H only)
- “Light noise” → rejection based on PMTs charge/time distribution



Neutrino candidates selection :

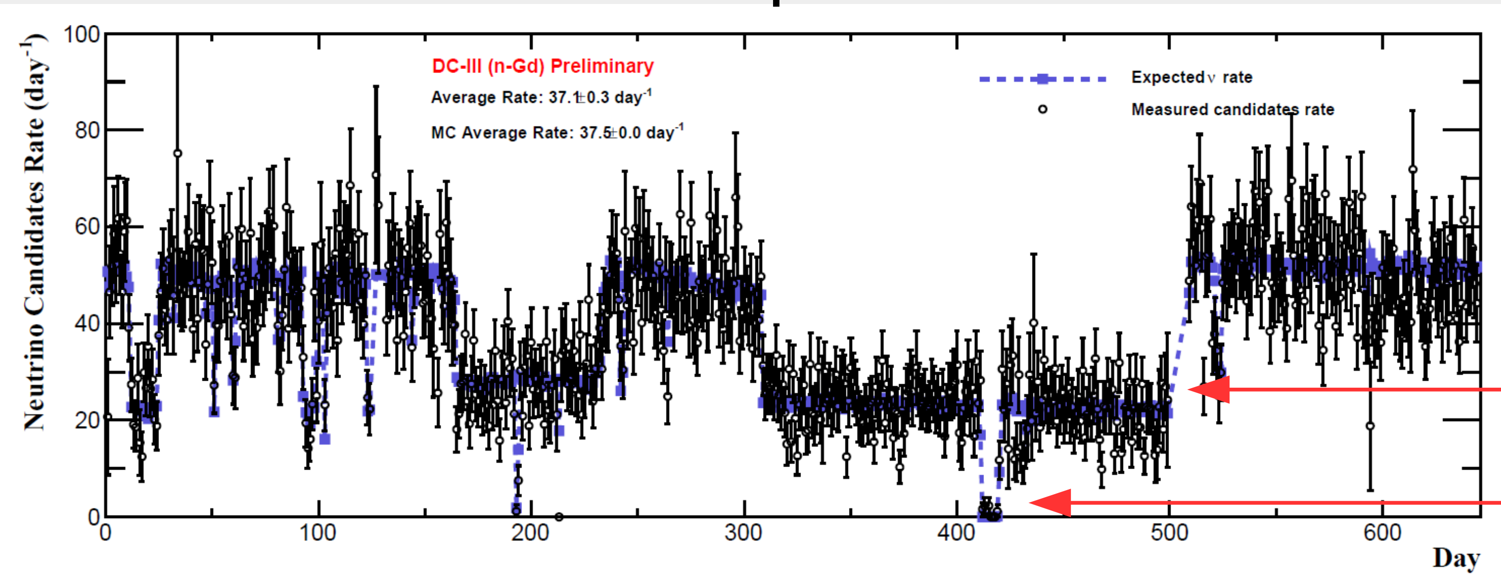
	Gd	H
- Prompt energy	0.5 – 20 MeV	1 – 20 MeV (H)
- Delayed energy	4 – 10 MeV	1.3 – 3 MeV (H)
- Δt	0.5 – 150 μs	0.5 – 800 μs
- ΔR (distance “p - d”)	< 1 m	< 1.2 m
- Isolation window (prompt)	(-200, +600) μs	(-800, +900) μs

- ANN cut → Multivariate tool using Δt, ΔR and $E_{dalayed}$ to reject random coincidences (H-only)



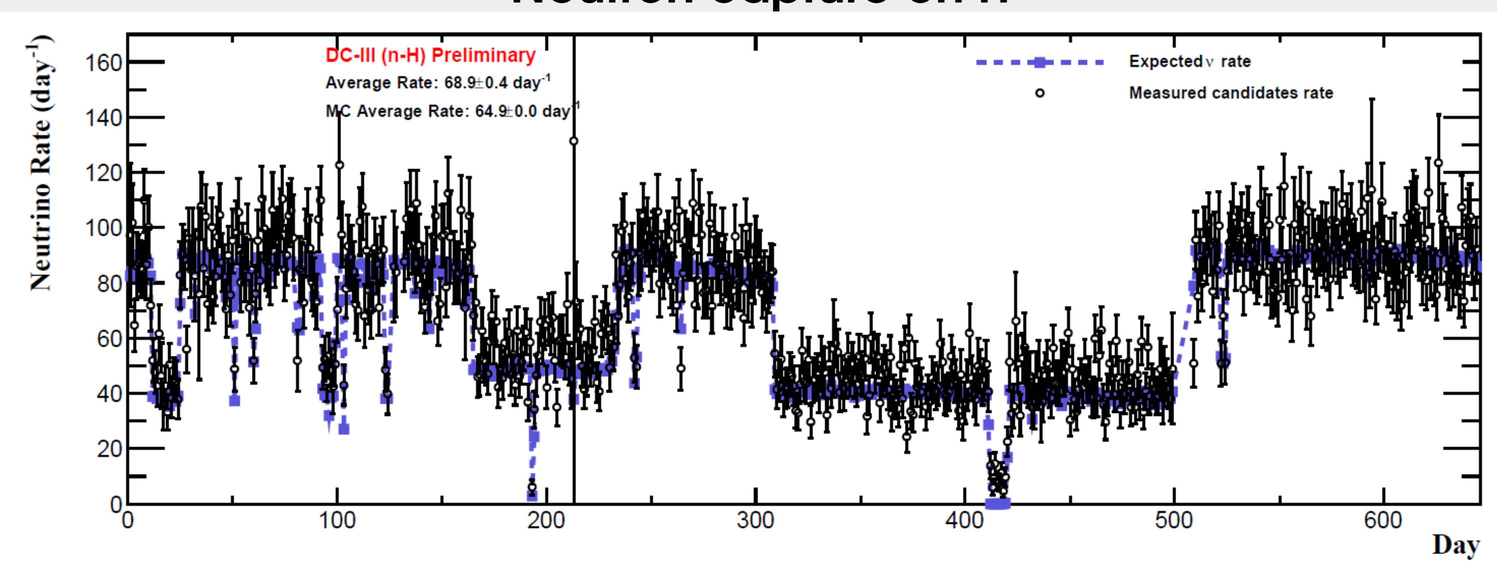
Double Chooz event rate monitoring

Neutron capture on Gd



2 reactors ON
(~ 60 %)
1 reactor ON
(~ 40 %)
0 reactor ON
(~7,15 days)

Neutron capture on H

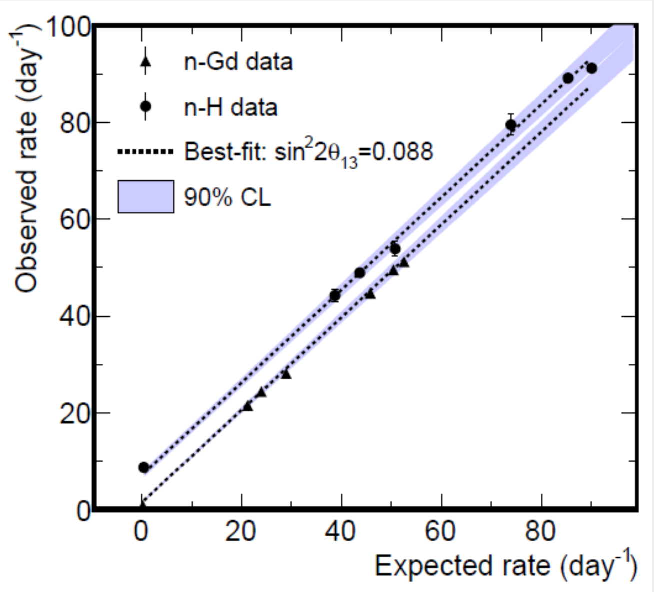


Reactor Rate Modulation (RRM)

- Comparison of observed vs. Expected IBD rates at different powers

- Fit of $\sin^2 2\theta_{13}$ **and** total background rate (B) :

$$\boxed{R^{obs} = \mathbf{B} + \left(1 - \sin^2 2\theta_{13} \left\langle \sin^2 \frac{1.27 \Delta m^2 L}{E_\nu} \right\rangle\right) R^{exp,\, no\ osc}}$$

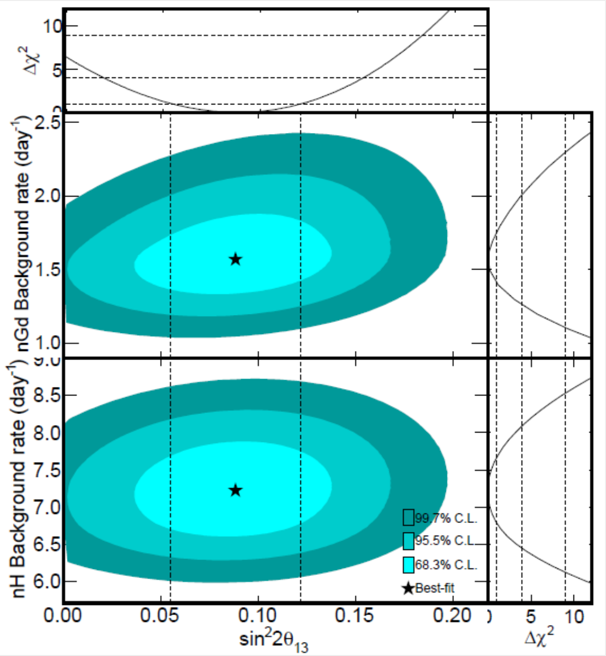


- Constrain with a priori background model
  → increase $\sin^2 2\theta_{13}$ precision

- Very good agreement between Gd and H data :

$$\sin^2 2\theta_{13} = 0.090 \pm 0.033$$

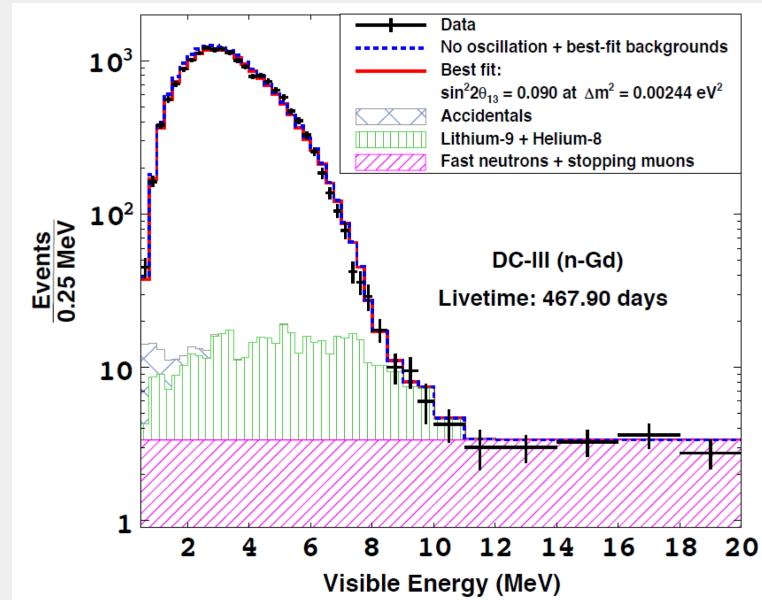
H only: $\sin^2 2\theta_{13} = 0.098^{+0.038}_{-0.039}$, Gd only: $\sin^2 2\theta_{13} = 0.090^{+0.034}_{-0.035}$
Correlations between Gd and H have minimal impact. This result assumes no correlation.

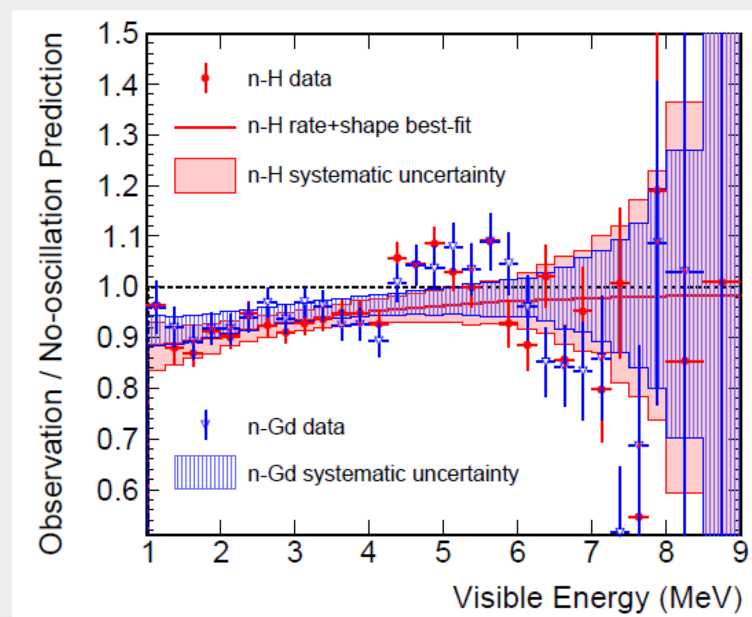


Rate + Shape fit

- The rate and the shape information were used in the fit for θ_{13} measurement

- The major improvements with respect to previous analyses are :
  - Finer binning (more statistics)
  - Larger energy range (0,5 – 20 MeV)
    → more precision on the background
  - Data driven background shape
  - Reactor off-off data included as a separate term in the χ^2 (low stat → rate only)





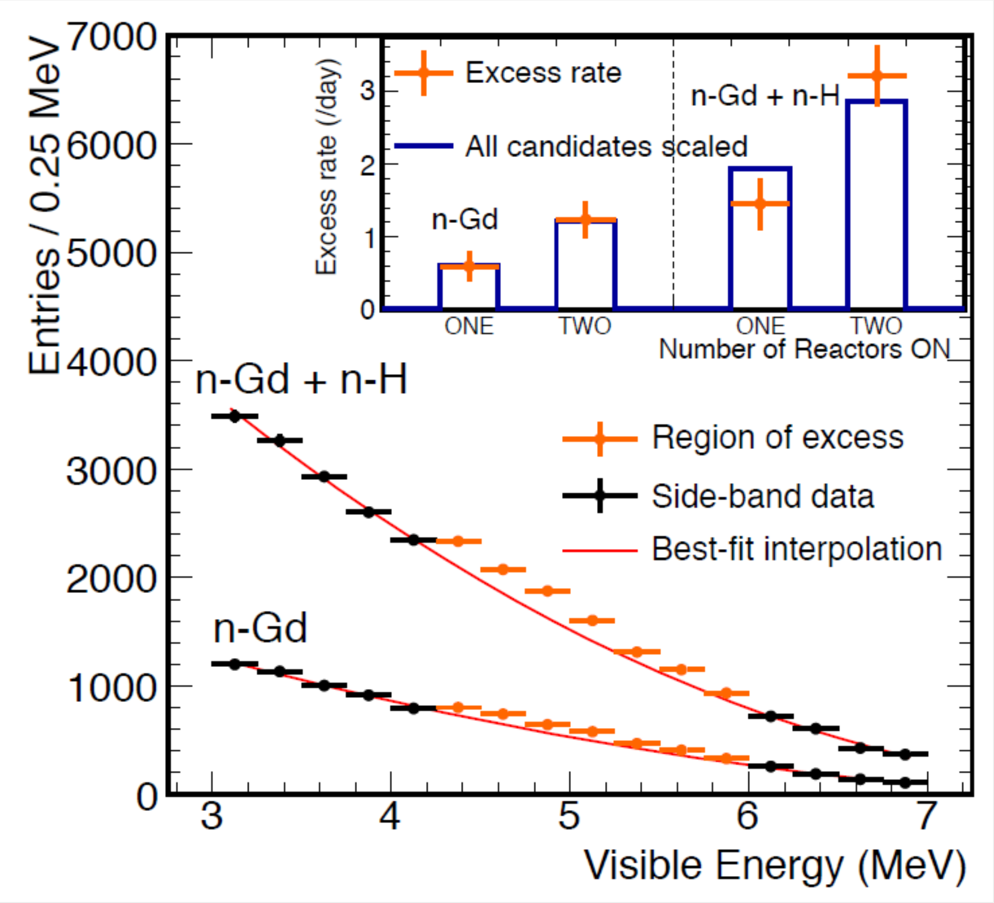
Results:

On Gd	On H
$\sin^2 2\theta_{13} = 0.090^{+0.032}_{-0.029}$	$\sin^2 2\theta_{13} = 0.124^{+0.030}_{-0.039}$
arXiv:1406.7763 (hep-ex)	**arXiv:1510.08937 (hep-ex)**

Excess @ 5 MeV

- Given the results of RRM + the tests with addition artificial excess around 5 MeV :
  → **no impact** seen **on θ_{13}** measurement

- The strong correlation of the excess with the reactor power :
  → **points** indeed towards an **unaccounted component of the reactor flux**.
  → **disfavors** the possibility of an **unaccounted background component**.



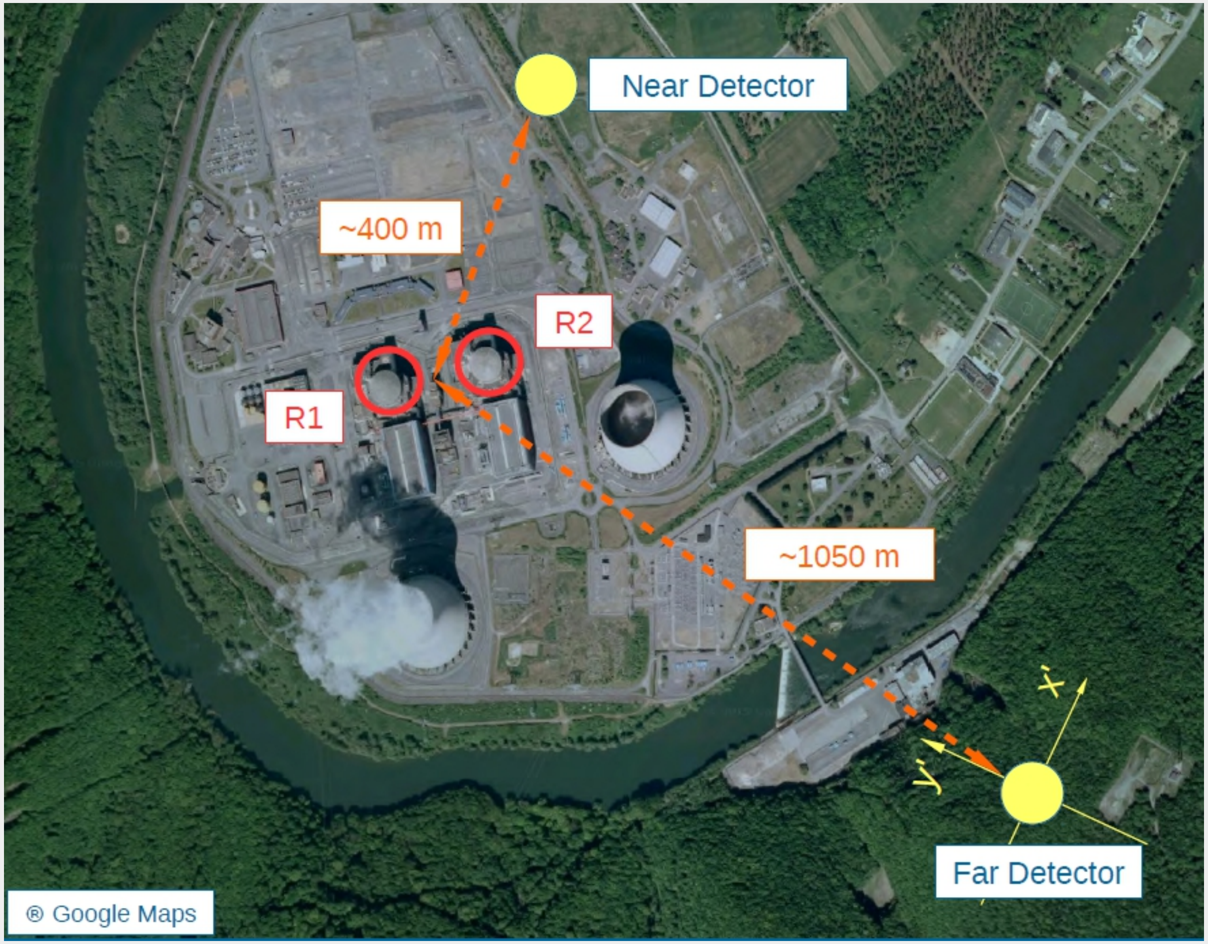
Directionality with IBD

- Double Chooz is not the best tool to measure neutrino directionality, but It has some assets to test the precision of the method :

- $\bar{\nu}_e$ origin is known (reactors)

- Different reactor configurations :
  → ON-ON and ON-OFF

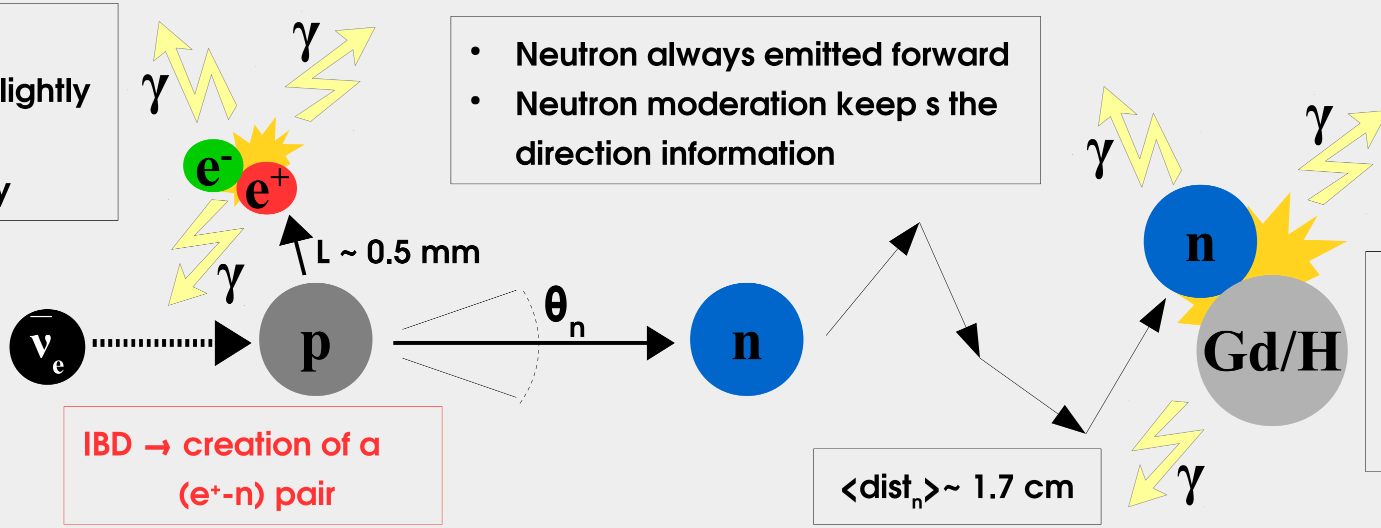
- 2 samples for cross-checks :
  → n-Gd and n-H captures



Neutrino detection in Double Chooz

Prompt signal :

- Positron emitted slightly backward
- Energy ∝ ν energy



Delayed signal :

- Neutron capture on Gd or H
- Energy 8 or 2.2 MeV

- From CHOOZ experiment, the average positron displacement is ~ 0.5 mm :
  → e⁺ vertex assumed to be the $\bar{\nu}_e$ vertex

- Correlation between the $\bar{\nu}_e$ and the emitted neutron direction :

Emission angle

$$\boxed{\cos(\theta_n)_{max} = \frac{\sqrt{2E_{\bar{\nu}_e}\Delta - (\Delta^2 - m_e^2)}}{E_{\bar{\nu}_e}}}$$

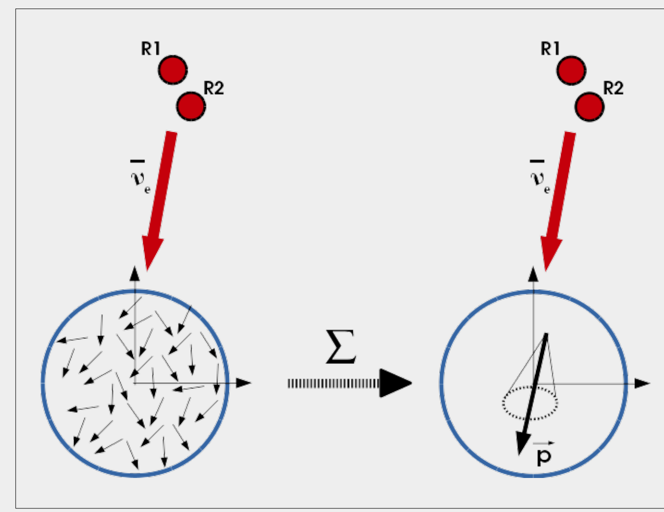
($\Delta = M_n - M_p$)

Scattering angle

$$\boxed{\langle \cos(\theta_n) \rangle = \frac{2}{3A}}$$

(A → atomic number)

Phys. Rev. D 60 (1999) 033007
Phys. Rev. D 61 (2001) 012001



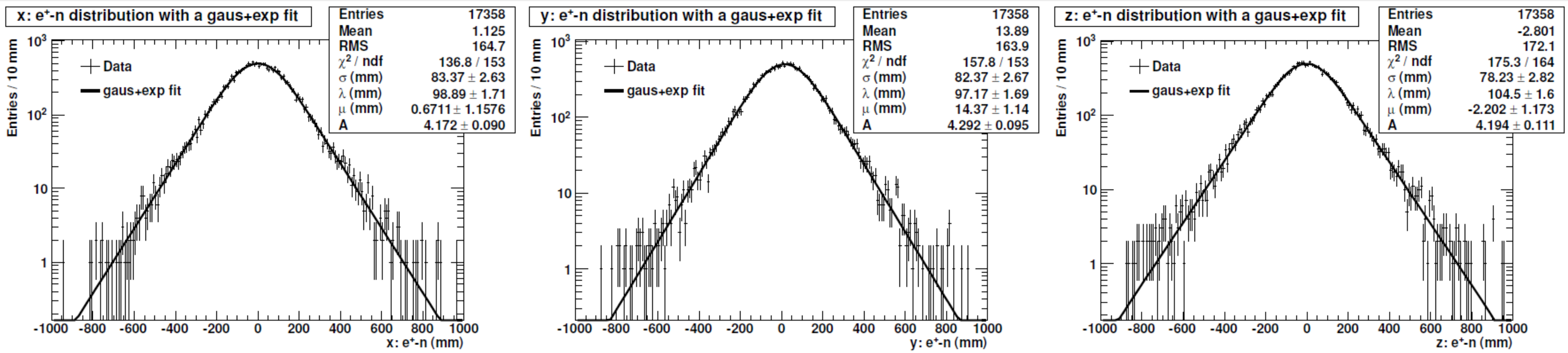
Double Chooz spatial resolution : ~ 15 cm
→ mean information is extracted

Results on Gadolinium

- **Mean neutron displacement :**

17358 neutrino candidates

Romain Roncin PhD Thesis



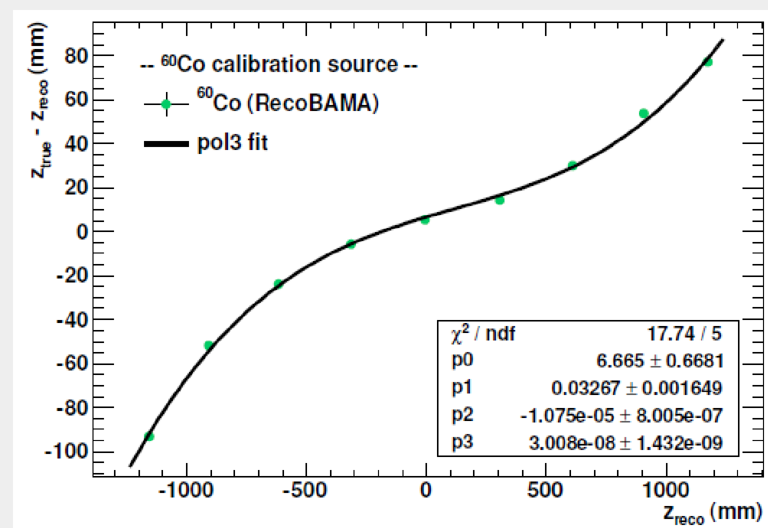
Δx = 0.67 ± 1.16 mm **Δy = 14.37 ± 1.14 mm** **Δz = -2.20 ± 1.17 mm**

(expected → the y-axis almost pointing the reactors) **(Δz > 0 expected !)**

$$l_{\text{Data}} = \sqrt{\mu_x^2 + \mu_y^2 + \mu_z^2} = 14.55 \pm 1.14 \text{ mm}$$

$$l_{\text{MC}} = 14.27 \pm 0.11 \text{ mm}$$

- A dedicated studie has addressed the Δz issue :
  - → reconstruction effect (MC/data)
  - → position and energy depend (calibration sources)
- But the sources :
  - - are not deployed in all detector positions
  - - have limited energy range
- No Impact on θ_{13}
- New study using cosmogenics will come soon!



Results on Gadolinium

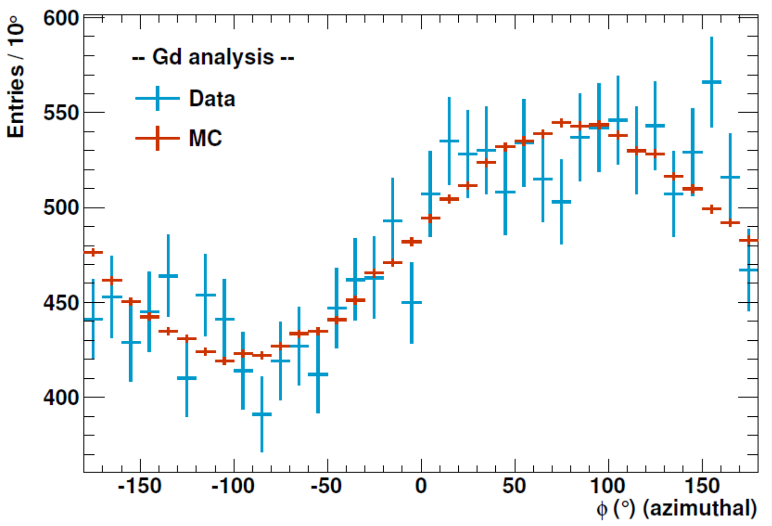
- Final result on Gd :

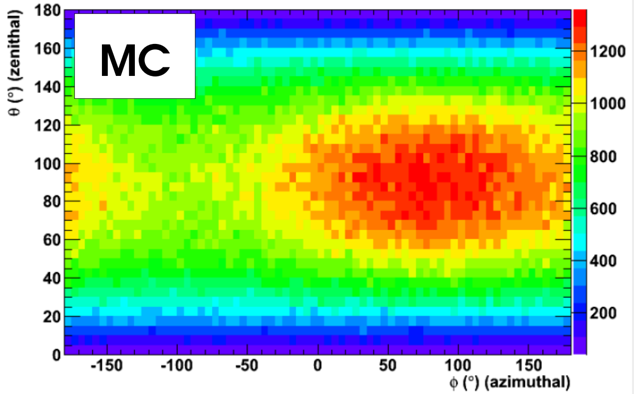
Gd analysis	ϕ (°)	θ (°)	δ (°)
Data	85.8	98.1	7.0
MC	84.0	89.6	0.7

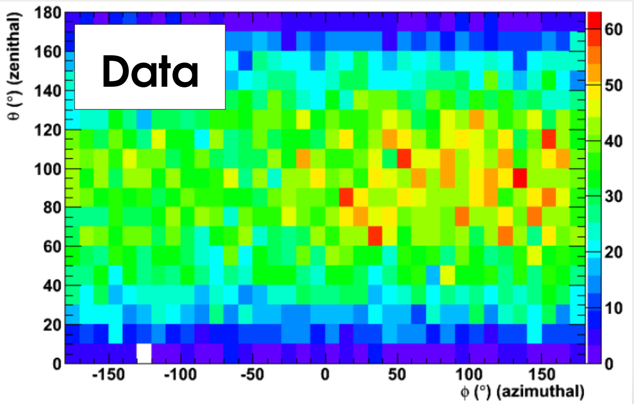
- Analysis of 1-reactor OFF data :

B1 off	Events	ϕ (°)	θ (°)	δ (°)
Gd analysis	1432	86.3°	109.8°	26.1°
H analysis	1142	81.0°	101.7°	26.4°

B2 off	Events	ϕ (°)	θ (°)	δ (°)
Gd analysis	3464	95.2°	95.7°	13.5°
H analysis	2620	73.2°	94.6°	15.3°







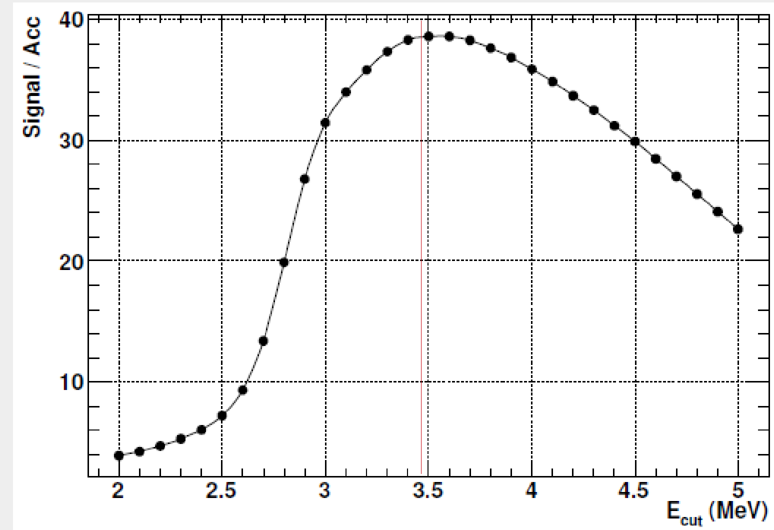
The reactors are 6° apart for far detector :

→ Compatible with the results

→ Need more statistics

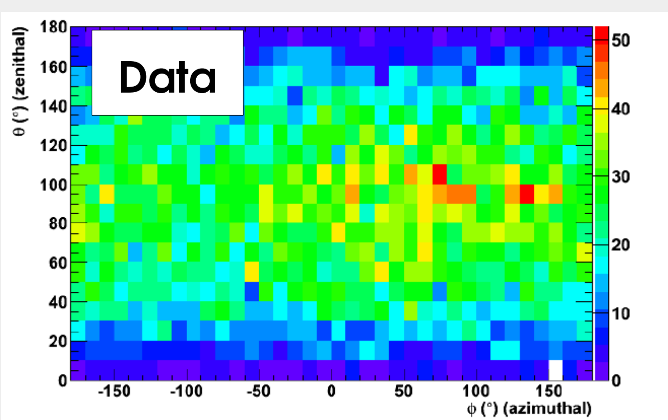
Results on hydrogen

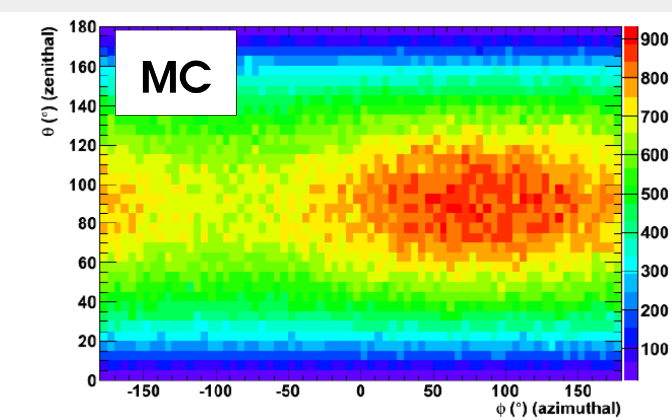
- **n-H candidates selection :**
  - H analysis was not finalized at the time of this study
  - Accidental background dominate at low energy :
    - → additional cut on E_{prompt} (>3.5MeV)
    - → selection of a purer sample
  - ΔT and ΔR correlated with the directionality measurement :
  - → cuts not implemented for the selection

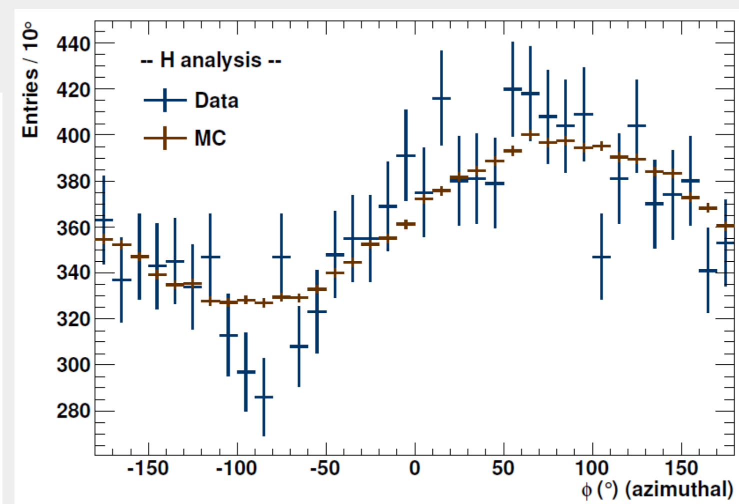


- **Final result on H :**

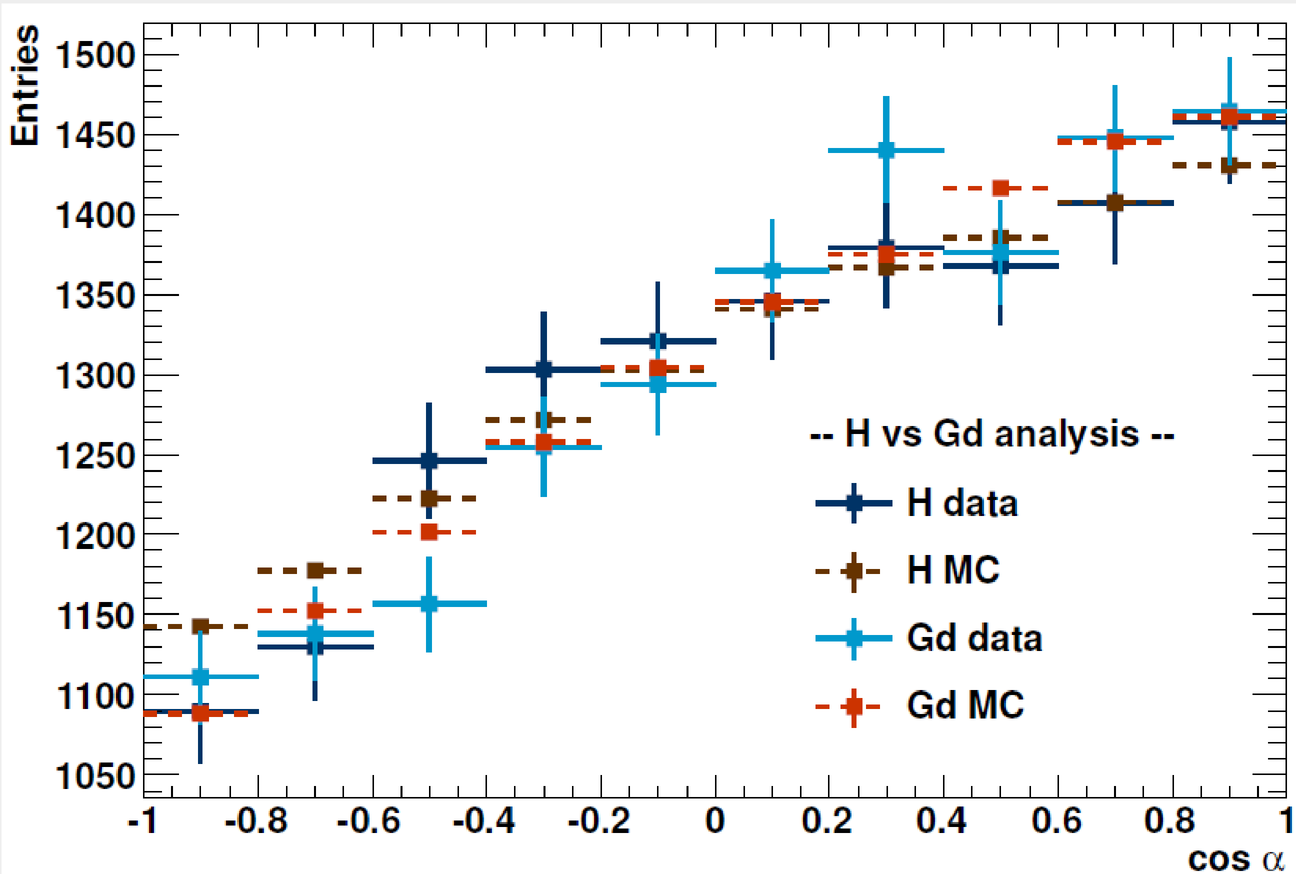
H analysis	ϕ (°)	θ (°)	δ (°)
Data	73.0	88.5	8.9
MC	84.4	87.3	1.1

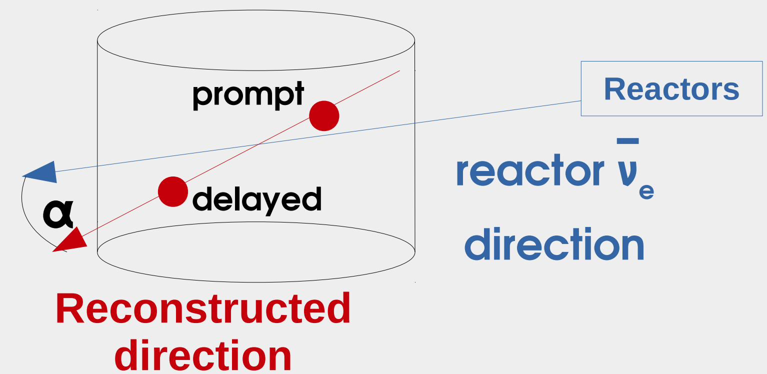






Results comparison

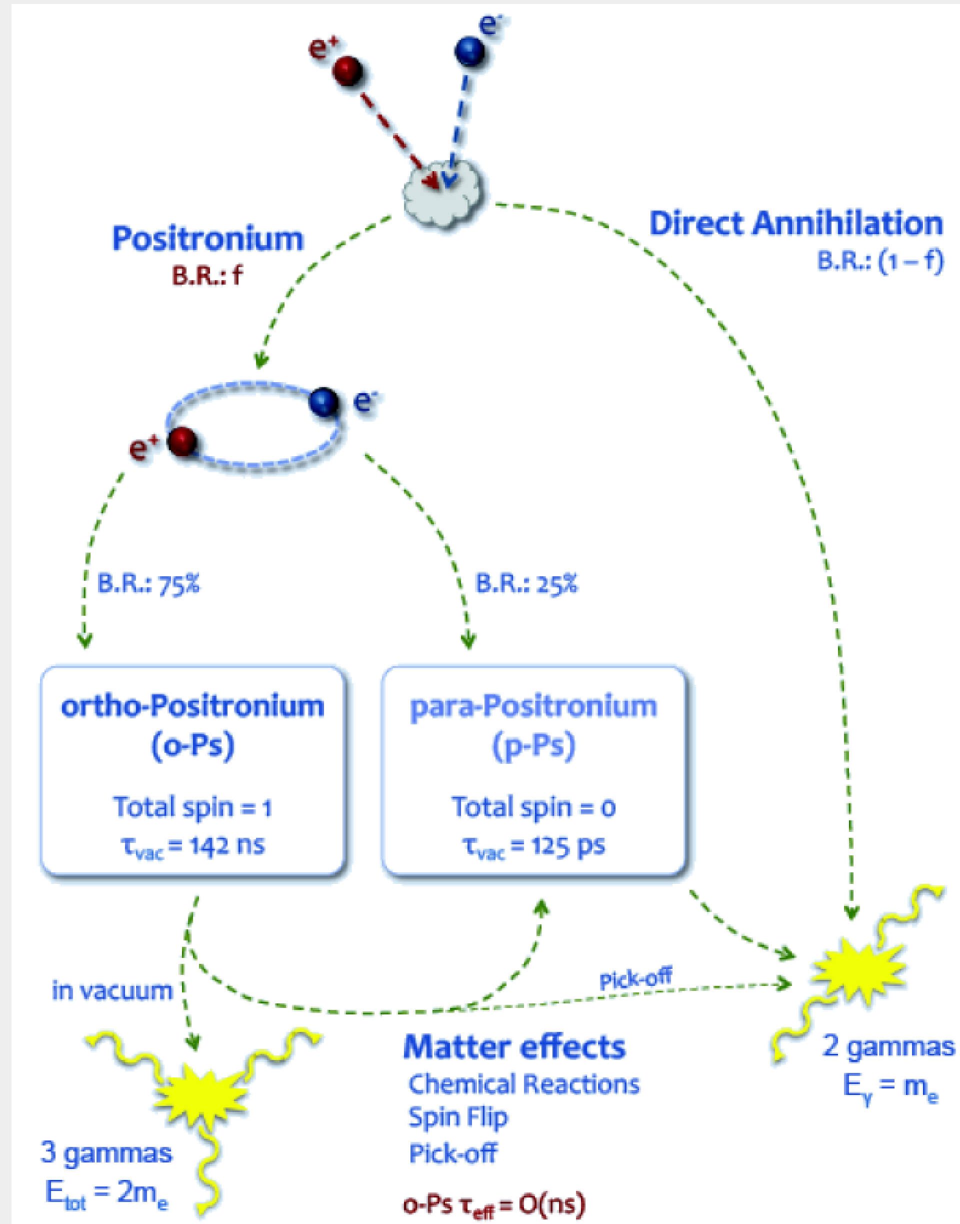




→ Very good agreement between n-Gd, n-H and respective MC results

o-Ps in Double Chooz

- **Electron/Positron :**
  - Direct annihilation
  - Metastable bound state
    → Positronium
- **2 possible congurations :**
  - para-Positronium (p-Ps / BR : 25%, spin 0)
  - ortho-Positronium (o-Ps / BR : 75%, spin 1)
- **Matter effects :**
  - Reduce o-Ps lifetime to a few ns



__**Positron identication :**__

- 2 contributions in prompt signal :

→ o-Ps state observation via detection of 2γs of 511keV each after the ionization signal

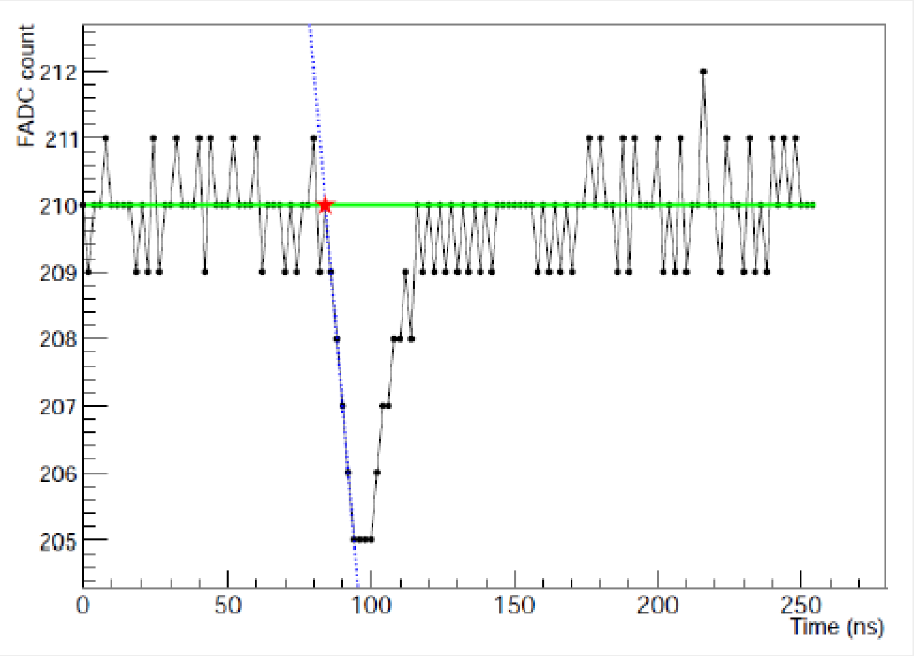
__**Why :**__

Select pure sample of νe. ($^{9}Li \rightarrow ^{8}Be + n + e^{-}$)

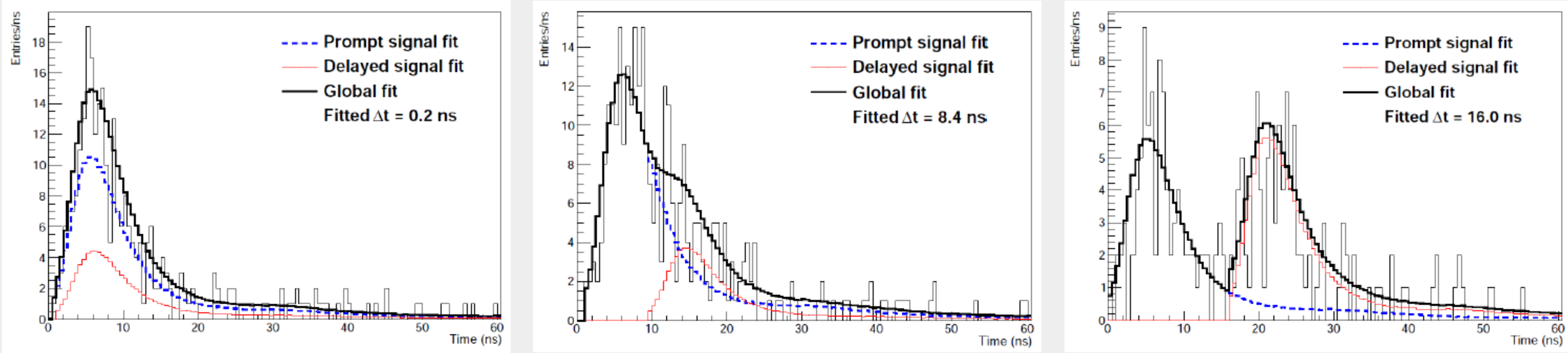
Scintillator	o-Ps formation fraction	o-Ps lifetime
Target	47.6 ± 1.3 %	3.42 ± 0.03 ns
Gamma Catcher	45.6 ± 1.3 %	3.45 ± 0.03 ns

o-Ps in Double Chooz

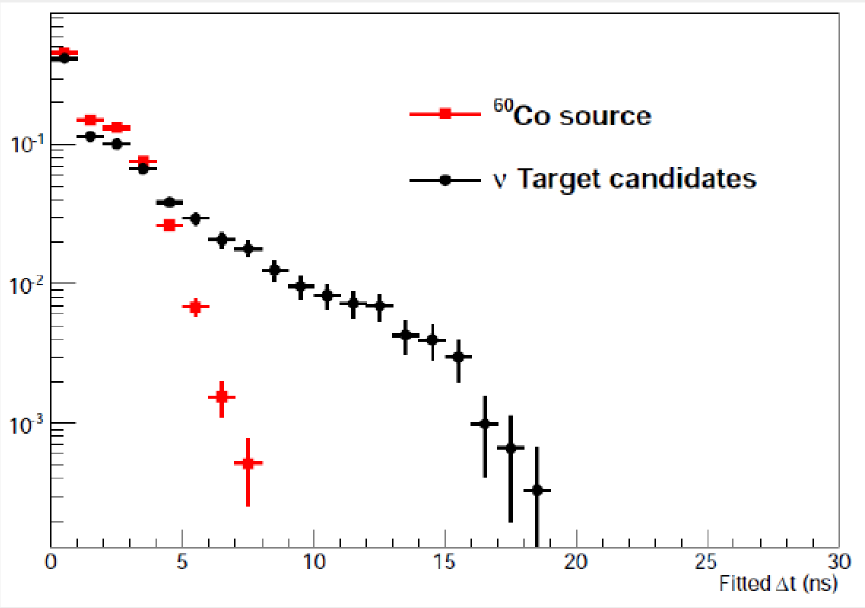
<u>Pulse Shape (PS) :</u>
→ Time distribution of PMT signals

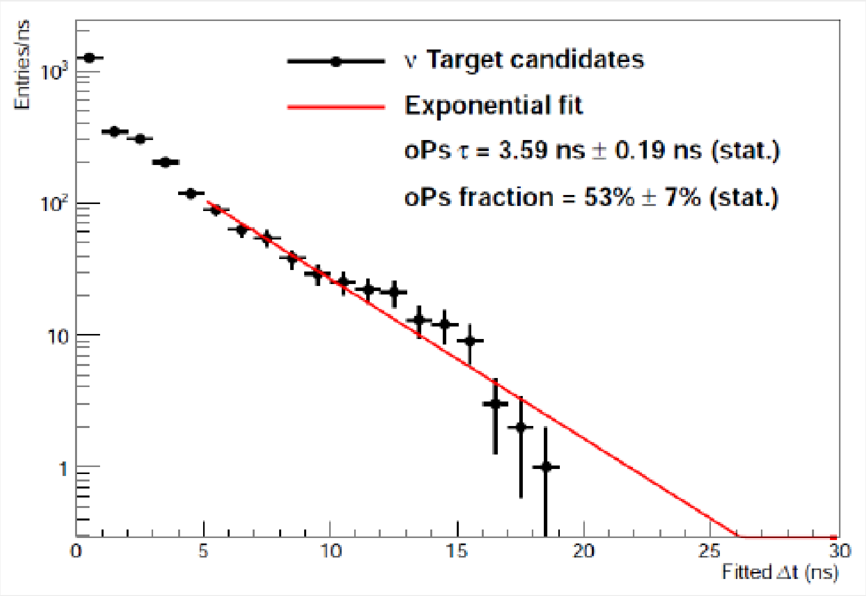


Second peak : annihilation
→ 2 x 511 keV



o-Ps in Double Chooz





- Energy cuts applied : (1.2 MeV → 3 MeV)
  - under 1.2 MeV : first peak too small
  - over 3 MeV : second peak masked by the first peak tail
- Cobalt distribution "large"

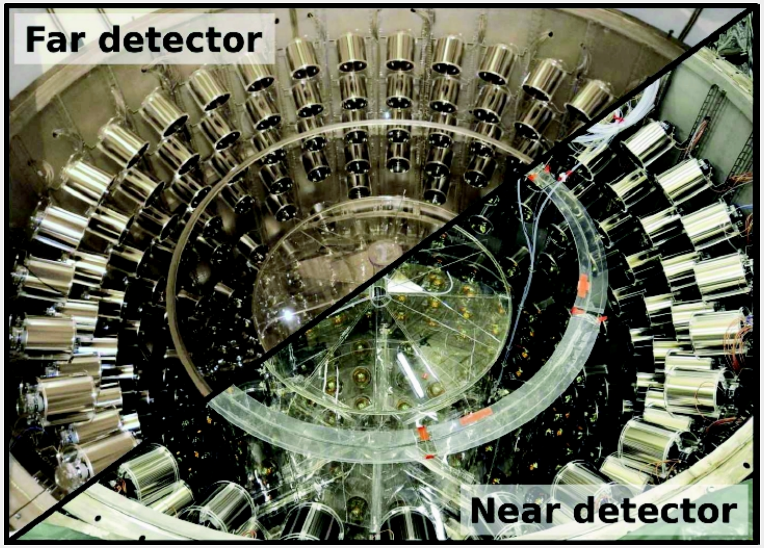
→ But effect clearly visible for Δt > 5 ns

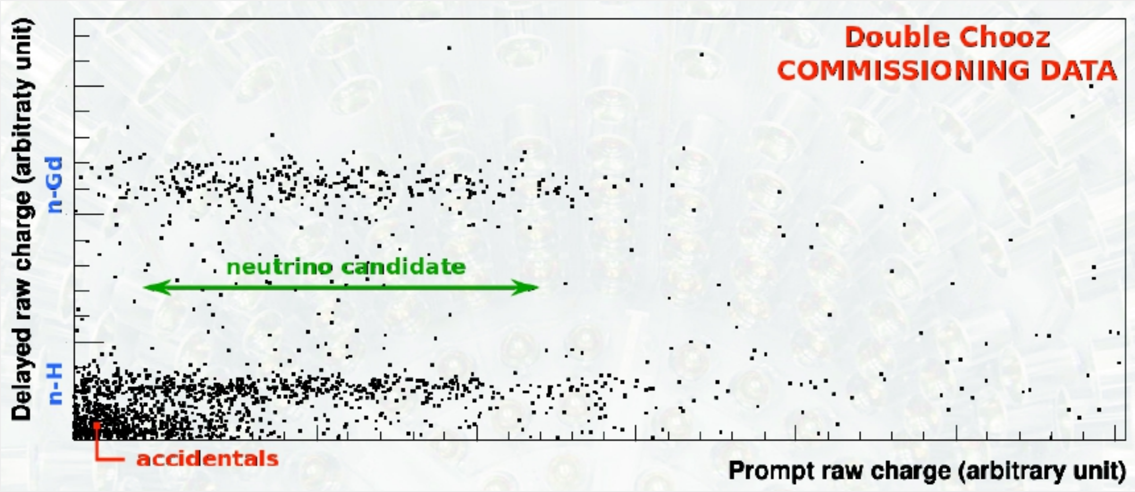
	o-Ps formation fraction error [%]	o-Ps lifetime error [ns]
Measurements with dedicated setup	47.6 ± 1.3	3.42 ± 0.03
DC (II publication) results	44 ± 5 (stat.) ± 12 (sys.)	3.68 ± 0.15 (stat.) ± 0.17 (sys.)

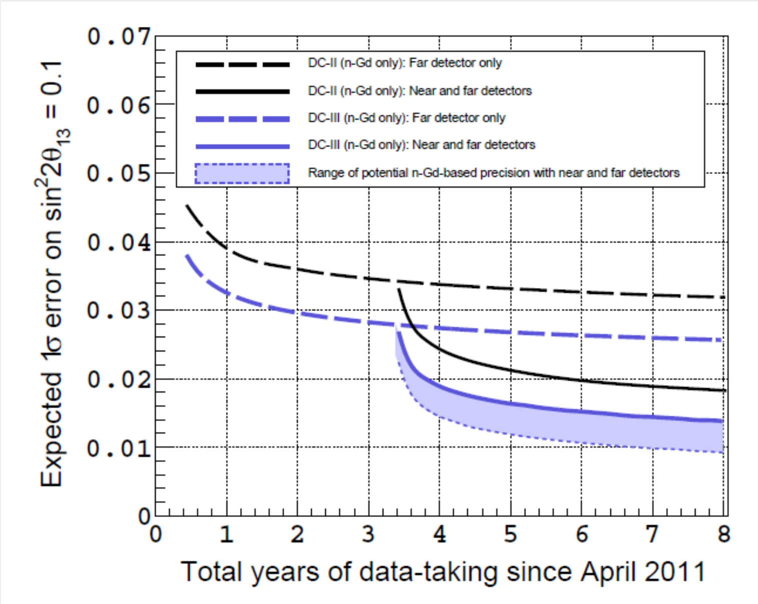
Ortho-positronium observation in the Double Chooz Experiment (JHEP10(2014)032)

Characterization of positronium properties in doped liquid scintillators (Phys. Rev. C - 2013 - NuToPs ANR)

Future with Near+Far data







- The near detector commissioning ended in December 2014 and the data taking has started.
- The projected sensitivity shows an error on $\sin^2 2\theta_{13}$ of 0.015 in 3 years.
- Further analysis improvements will make possible a reduction to the level of $\sigma \sim 0.01$.
- Really interesting for directionality studies
  - → more stat.
  - → better sensitivity to distinguish each reactor

Conclusion

θ_{13} measurement :

- Rate + Shape measurement with neutron capture on Gd and H.
- RRM analysis with neutron capture on Gd and H.

→ Multiple cross-checks

- New data taking since December 2014 with Near + Far configuration !

Neutrino directionality :

- Capability to measure neutrino source direction by the inverse β decay process
- The mean "neutrino wind" direction has been obtained using IBD candidates with neutron capture on Gd and H.
- sensitivity to each reactor has been observed, but need more stat.

→ Analysis using near detector data coming soon !

Double Chooz collaboration

Brazil
CBPF
UNICAMP
UFABC

France
APC
CEA/DSM/IRFU:
SPP, SPhN
SEDI, SIS
SENAC
CNRS/IN2P3:
Subatech
IPHC

Germany
EKU
Tübingen
MPIK
Heidelberg
RWTH
Aachen
TU München

Japan
Tohoku U.
Tokyo Inst. Tech.
Tokyo Metro. U.
Niigata U.
Kobe U.
Tohoku Gakuin U.
Hiroshima Inst.
Tech.

Russia
INR RAS
IPC RAS
RRC
Kurchatov

Spain
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USA
U. Alabama
ANL,U.
Chicago
Columbia U.
UC Davis
Drexel U.
IIT, KSU, MIT,
U. Notre Dame
U. Tennessee
Virginia Tech

Thank you !