Latest results from the Double Chooz experiment

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On Behalf of the Double Chooz Collaboration

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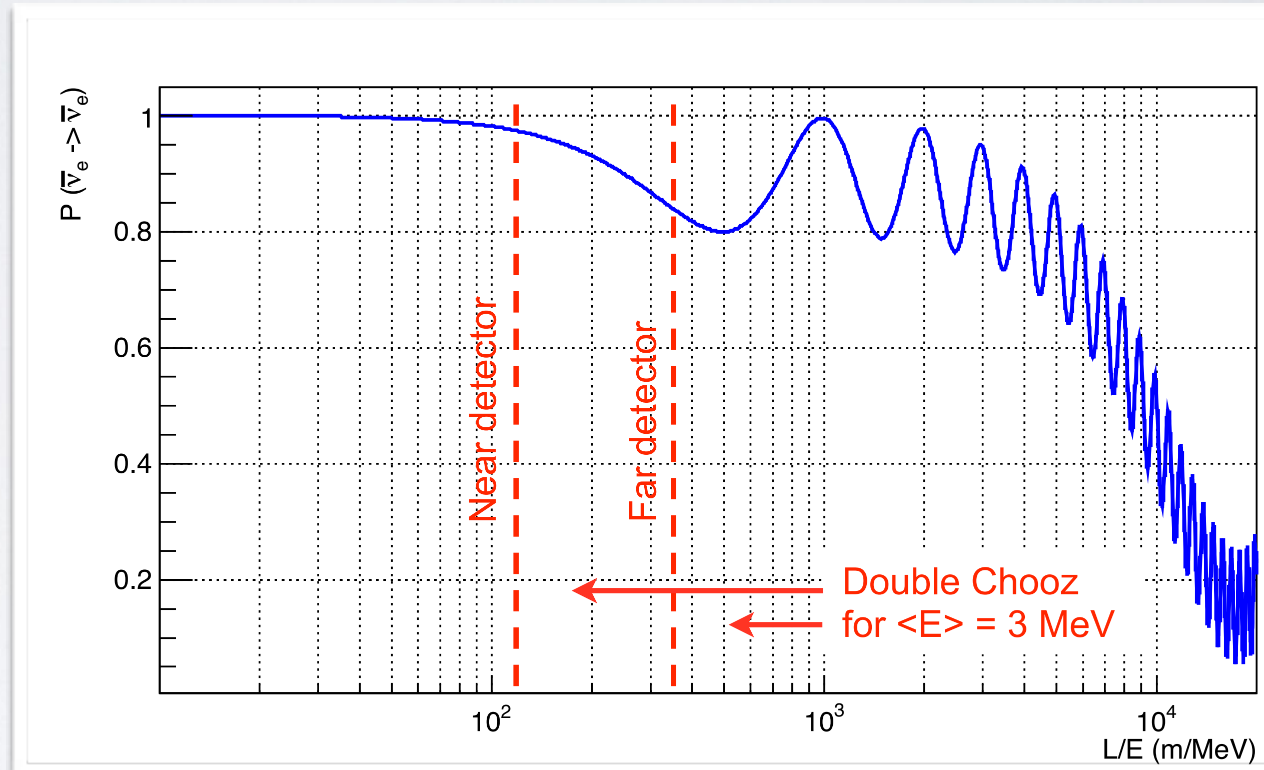
INTRODUCTION

- Reactor oscillation experiments aim at the measurement of θ_{13} through the observation of $\overline{\nu}_e \rightarrow \overline{\nu}_e$ transition according to the oscillation probability:

$$P(\bar{\nu}_e \rightarrow \bar{\nu}_e) \simeq 1 - \sin^2(2\theta_{13}) \sin^2\left(\frac{\Delta m^2_{32} L}{4E}\right)$$

- The use of two detectors allows to measure the flux before and after the oscillation to cancel out the associated systematics.



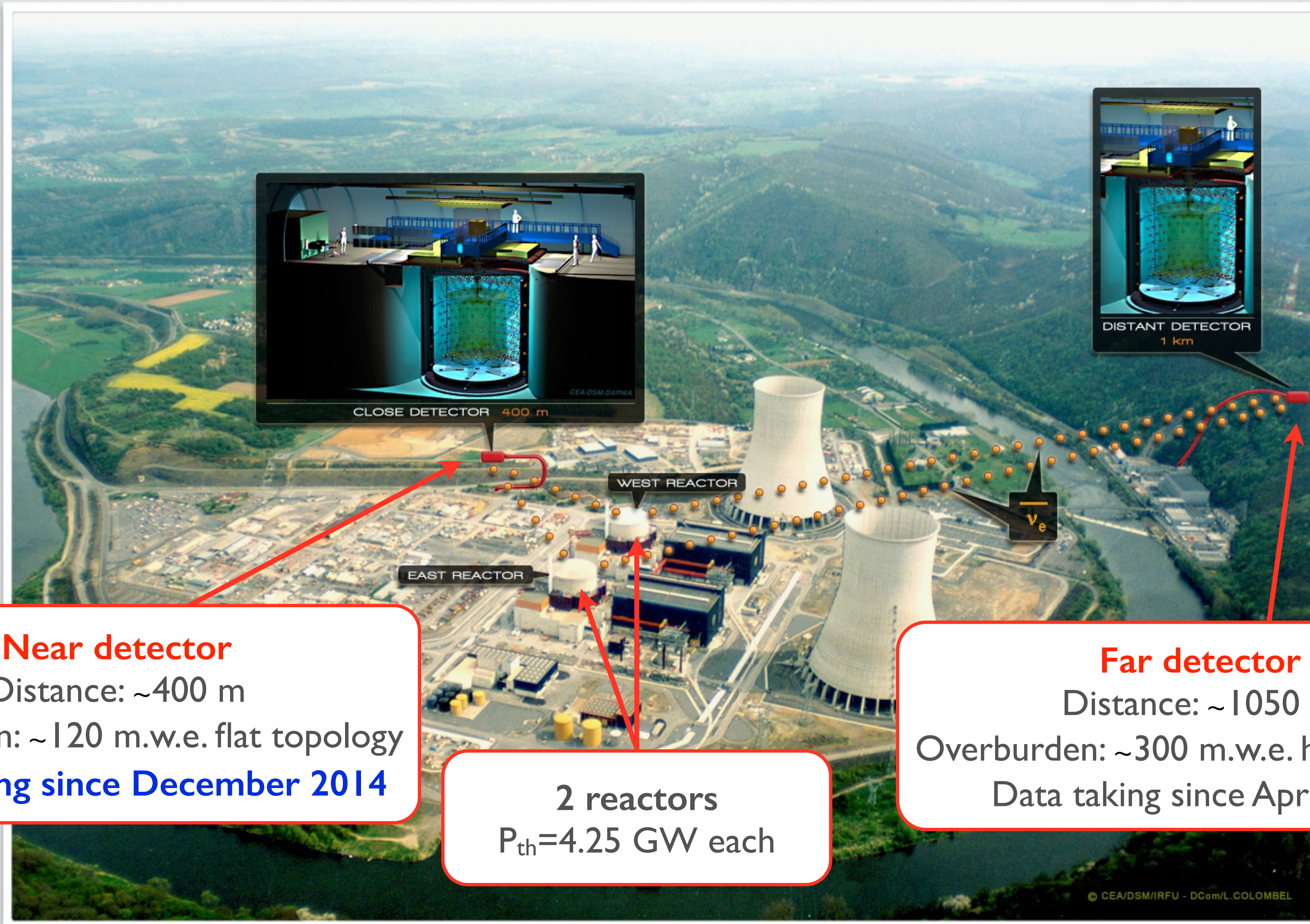
$\Delta m^2_{12}=7\times10^{-5}$ eV^2 $\sin^2(2\theta_{13})=0.2$

$\Delta m^2_{23}=2.5\times10^{-3}$ eV^2 $\cos^2(\theta_{12})=0.7$

- The advantages of this measurement with respect to long baseline oscillation experiments is a ***clean measurement*** of θ_{13} since:

  1. It is a disappearance experiment, therefore insensitive to the value of the δ-CP phase.
  2. It has a short baseline (order of 1 km) and it is therefore insensitive to matter effects.
  3. The dependence on Δm^2_{21} is very weak : O ($\Delta m^2_{21}/\Delta m^2_{31}$).

Double Chooz OVERVIEW

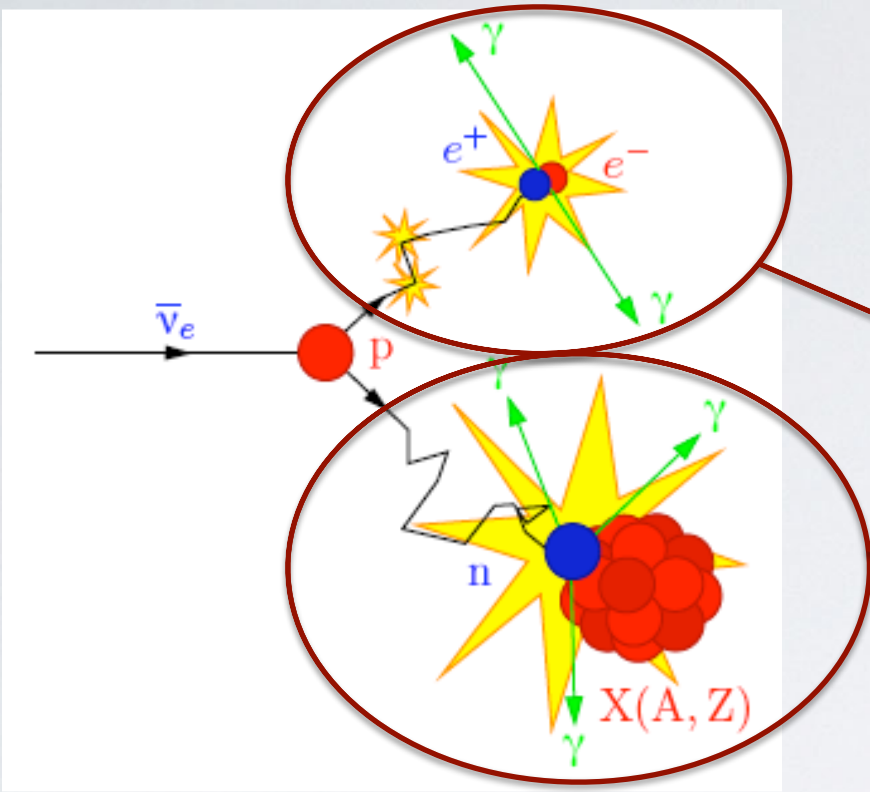


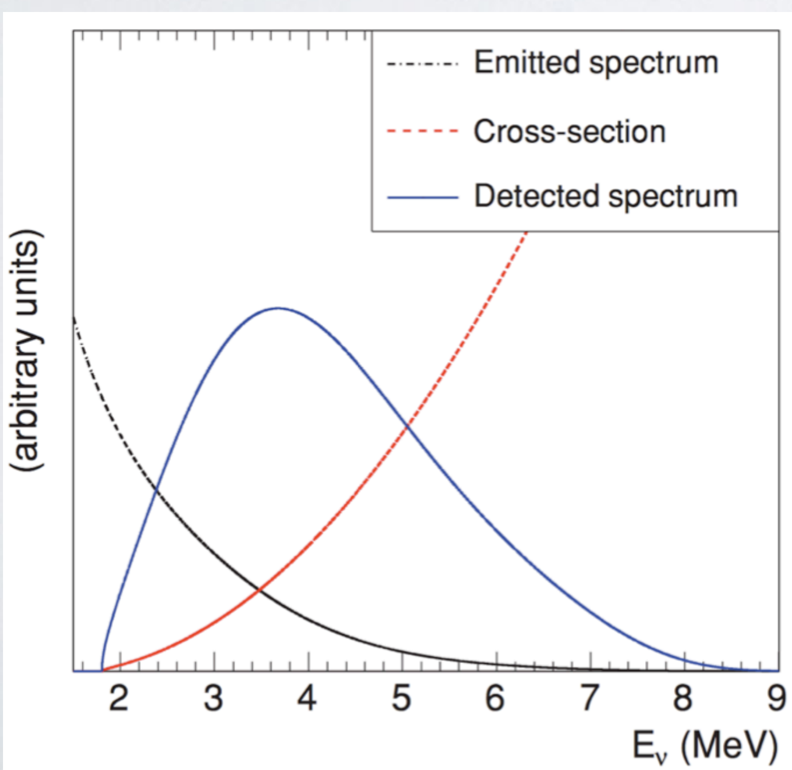
Near detector
Distance: ~400 m
Overburden: ~120 m.w.e. flat topology
Data taking since December 2014

2 reactors
P_{th}=4.25 GW each

Far detector
Distance: ~1050 m
Overburden: ~300 m.w.e. hill topology
Data taking since April 2011

NEUTRINO DETECTION





- Neutrinos are observed via Inverse Beta Decay (IBD):

$$\boxed{\bar{\nu}_e + p \rightarrow e^+ + n}$$

- The signal signature is given by a **twofold coincidence**:

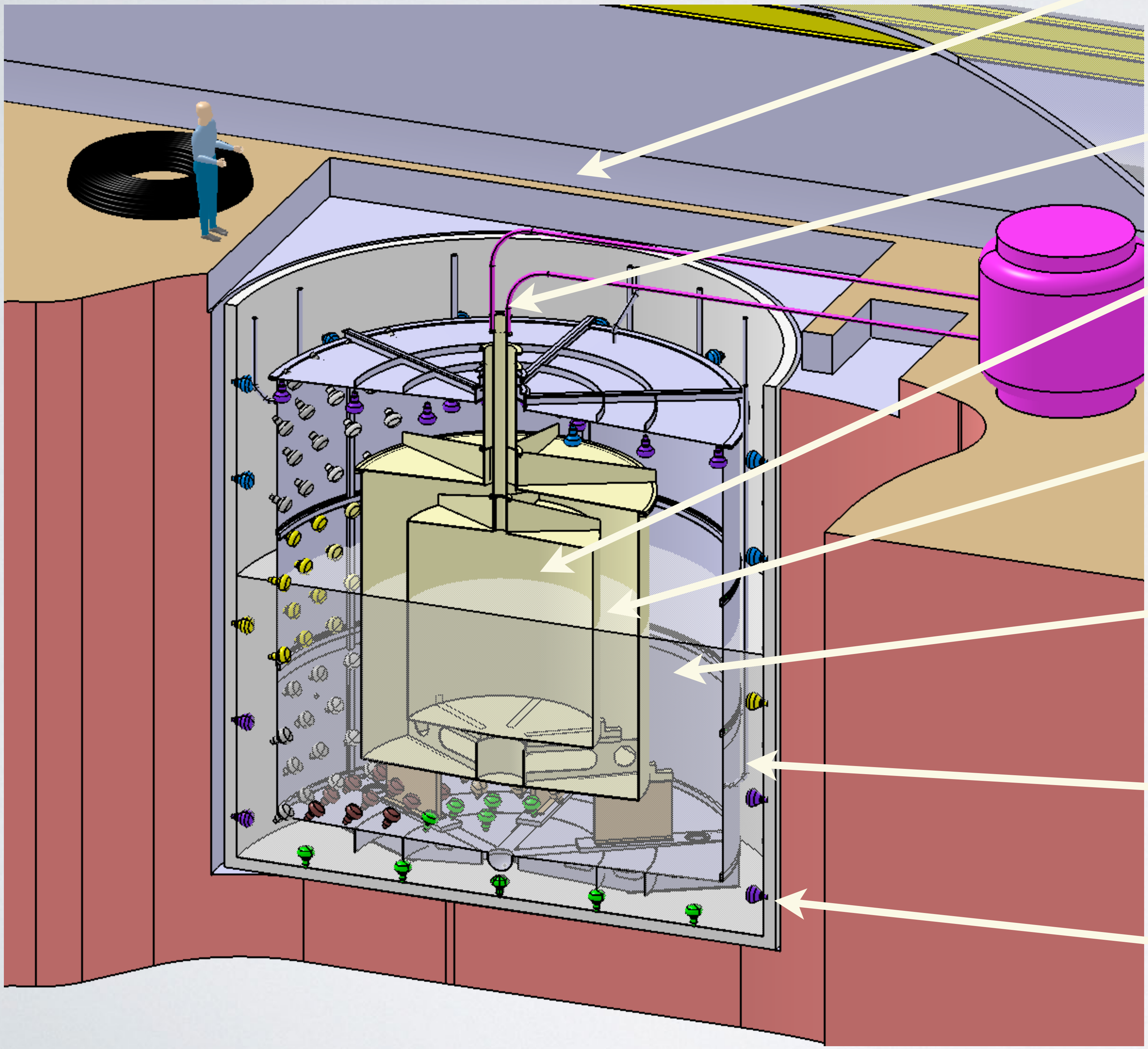
1. Prompt photons from e^+ ionisation and annihilation (1-8 MeV).
2. Delayed photons from n capture on Gadolinium (~8 MeV) or H (2.2 MeV).
3. Time correlation: Δt ~30 μs for Gd and Δt ~200 μs for H.
4. Space correlation (< 1m).

- The energy spectrum is a convolution of flux and cross section (threshold at 1.8 MeV).
- The prompt energy is related to $\bar{\nu}_e$ energy:

$$\boxed{E_{prompt}=E_\nu-T_n-0.8\ \text{MeV}}$$

- The survival probability depends on E_ν therefore we have a measurement of θ_{13} using rate and spectral deformation.

DETECTOR DESIGN



Outer Veto: plastic scintillator strips

Chimney: deployment of radioactive source for calibration in the ν-Target and γ-Catcher.

ν-Target: 10.3 m^3 scintillator (PXE based) doped with 1g/l of Gd in an acrylic vessel (8 mm)

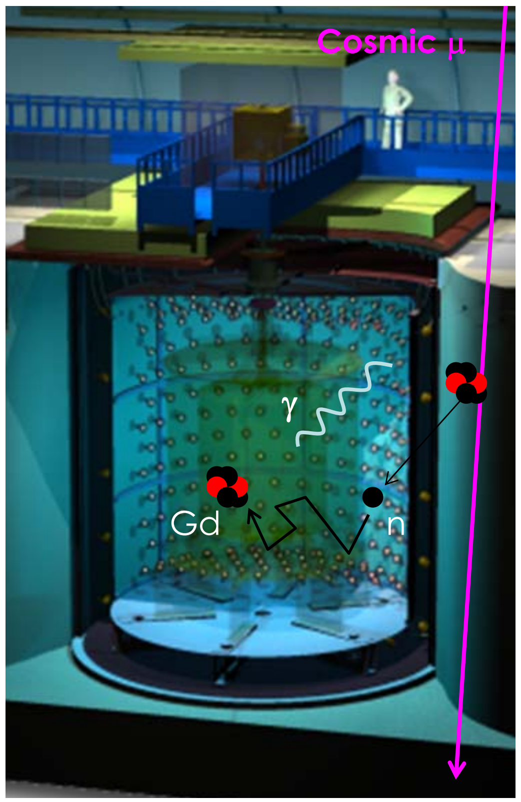
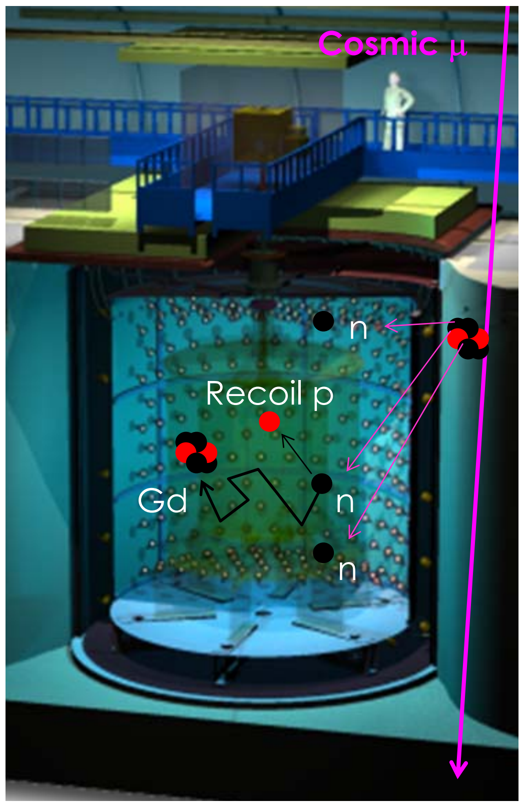
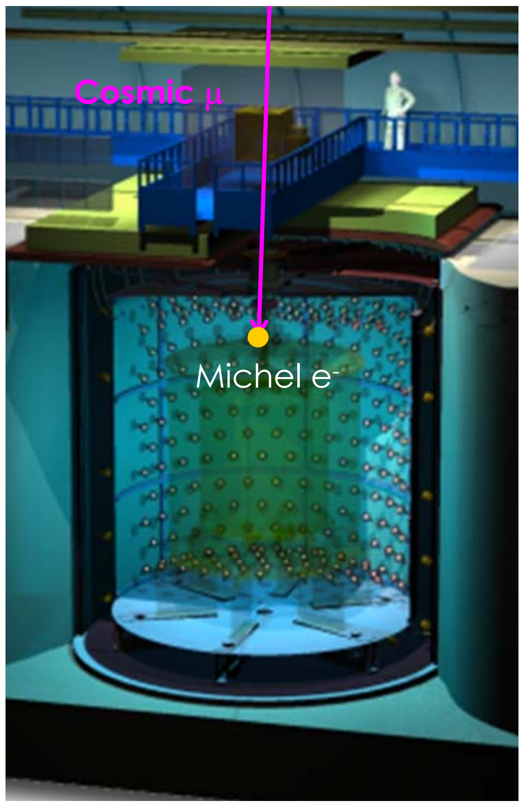
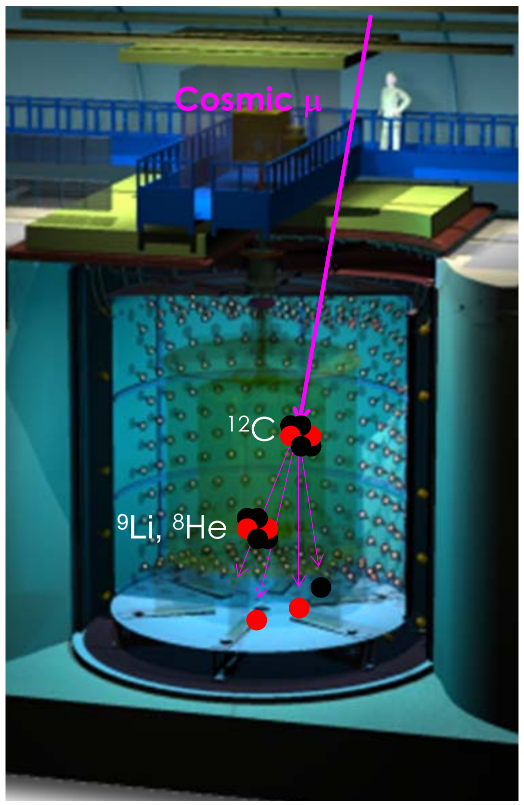
γ-Catcher: 22.5 m^3 scintillator (PXE based) in an acrylic vessel (12 mm)

Buffer: 100 m^3 of mineral oil in a stainless steel vessel (3 mm) viewed by 390 PMTs (10 inches)

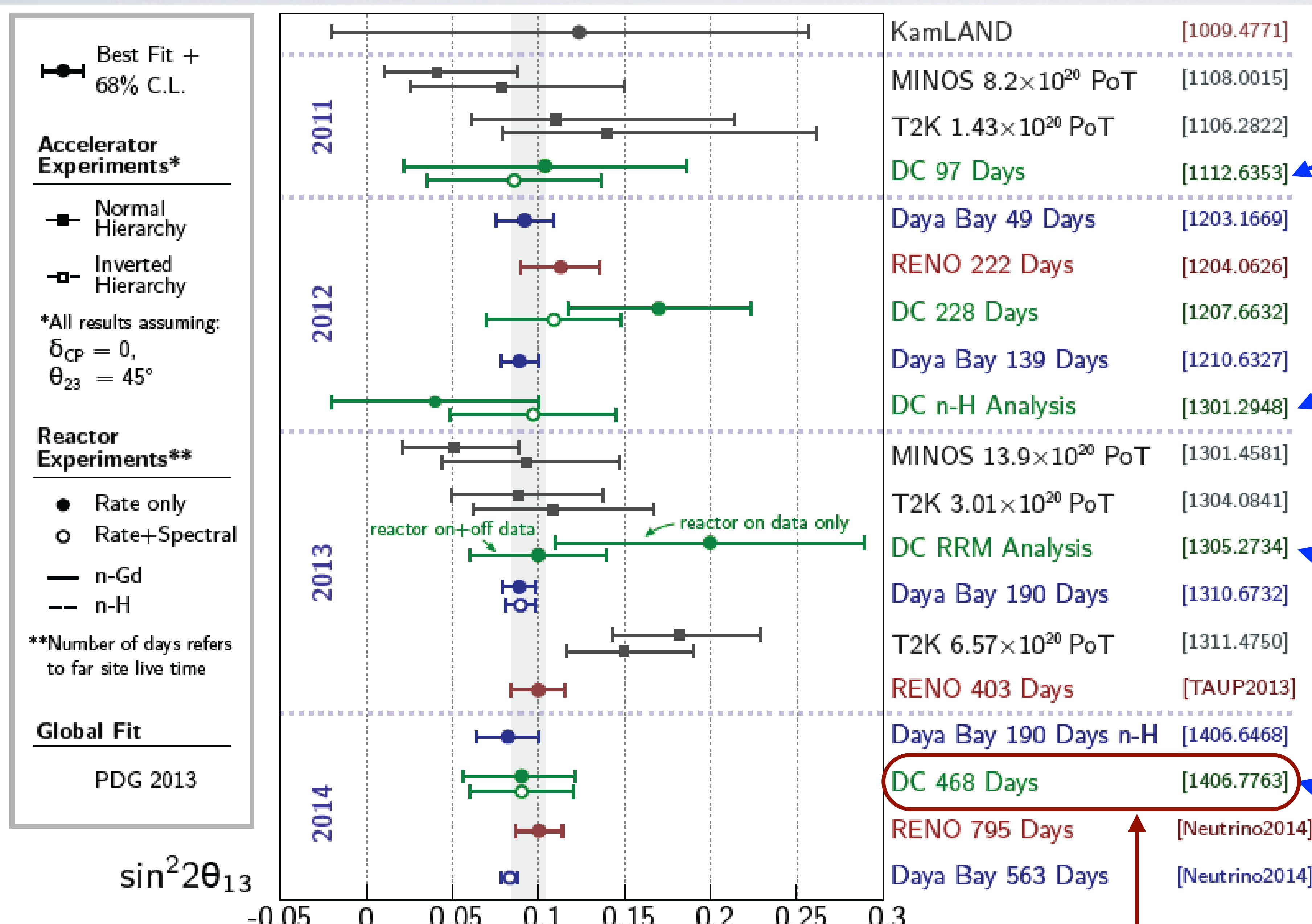
Inner Veto: 90 m^3 of scintillator (LAB based) in a steel vessel (10 mm) equipped with 78 PMTs (8 inches)

Shielding: about 250 t steel shielding (150 mm) (FD) / 1 m water (ND)

BACKGROUND

	Accidental BG	Correlated 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 MILESTONES



First indication of non-zero θ_{13} and rate+shape analysis

Phys.Rev.Lett. 108 (2012) 131801

First n-H capture analysis

Phys.Lett. B723 (2013) 66-70

First (and only) Reactor Rate Modulation (RRM) analysis

Phys.Lett. B735 (2014) 51-56

First publication on "5 MeV excess"

JHEP 1410 (2014) 86

In this talk I will present the results of the so called Gd-III publication.

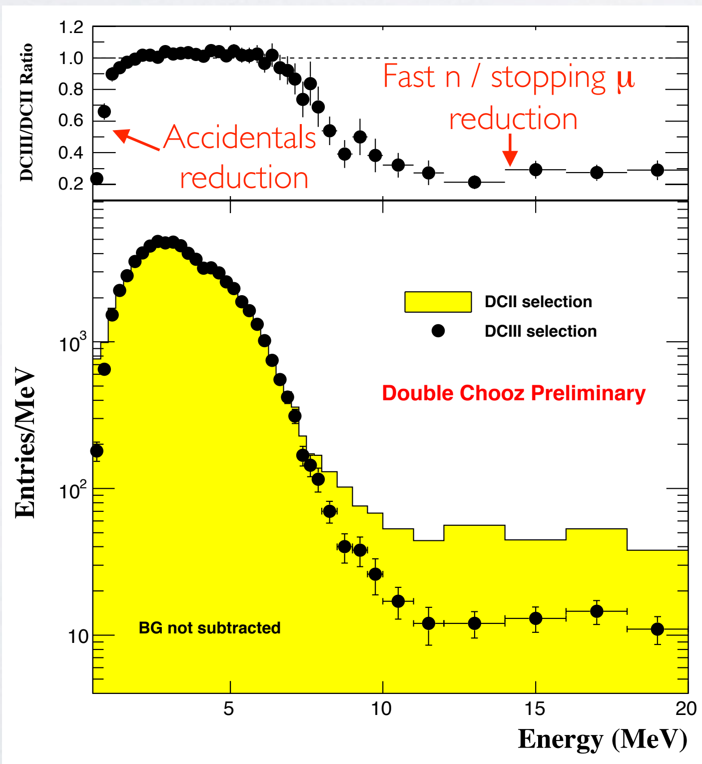
EVENTS SELECTION

Veto on single triggers → Neutrino candidates selection

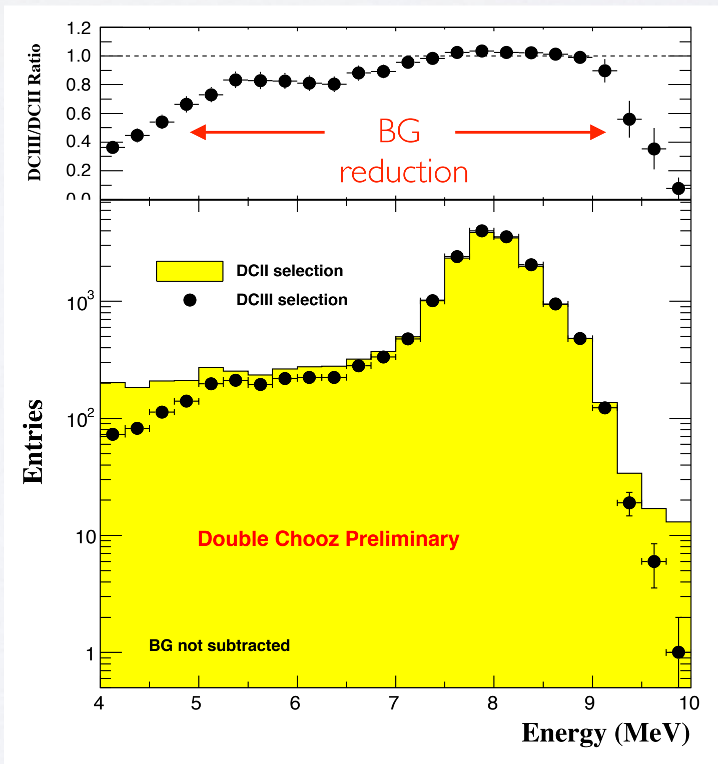
Muon veto	No triggers in 1 ms after muon
OV	No coincidence with OV
Li veto	Likelihood trained on ^{12}B for 50% rejection and dead time < 0.5%
IV	Cut on charge, multiplicity and space/time coincidence to reject fast neutrons and accidentals
“FV”	Point like characterization of the event (reject stopping muons)
Light noise	Rejection base on PMTs charge/time distribution

Prompt Energy	0.5 - 20 MeV
Delayed Energy	4 -10 MeV
Δt	0.5 - 150 μs
ΔR	< 1 m
Isolation window (prompt)	[-200, +600] μs

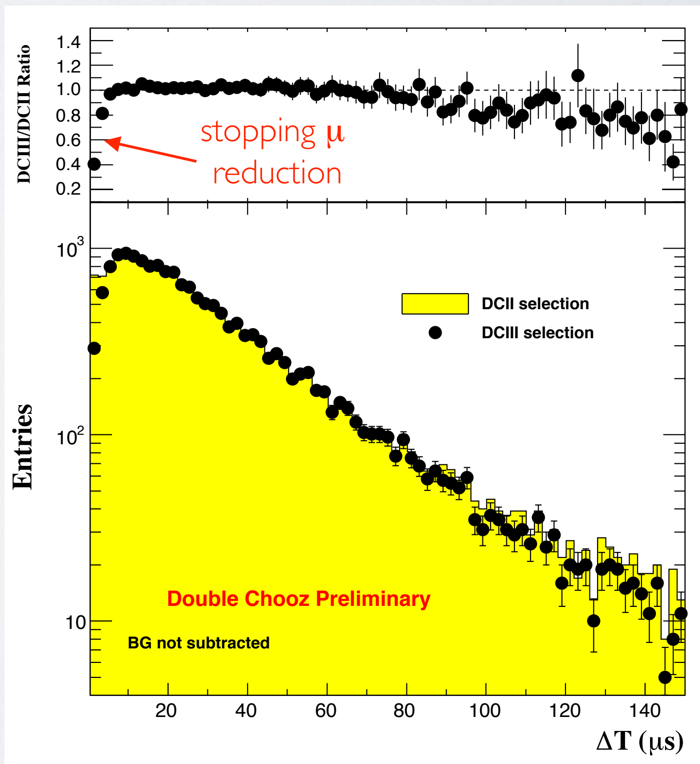
Prompt energy



Delayed energy



Time correlation



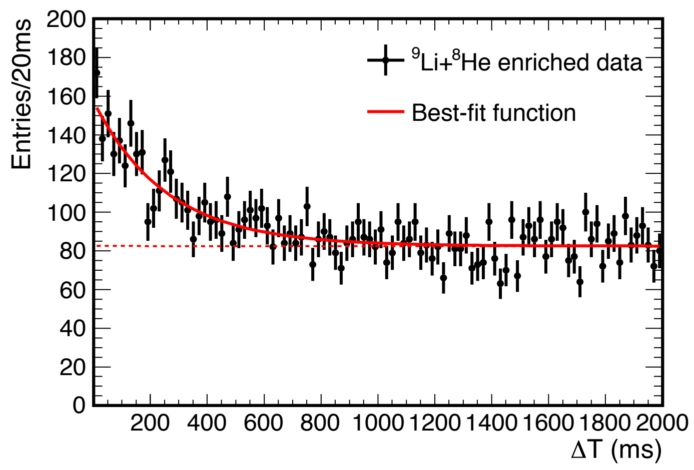
Gd-III/Gd-II: more signal and less BG

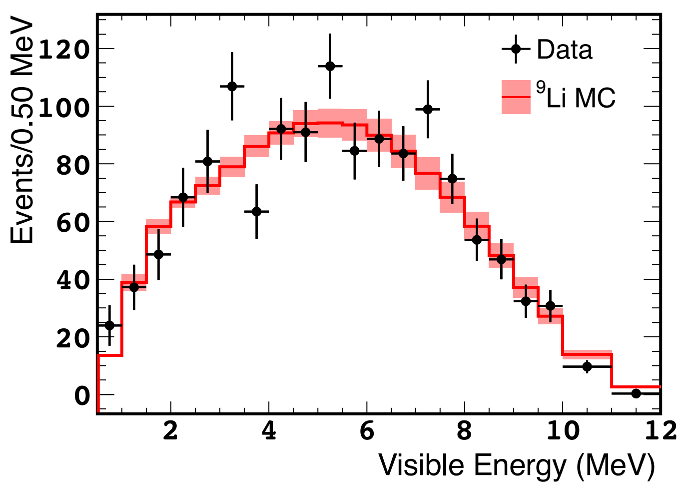
BACKGROUND ESTIMATE

Cosmogenics

The cosmogenic (mainly ^{9}Li) β + n emitter background was estimated using rate and shape information.

$0.97^{+0.41}_{-0.16}$ events/day

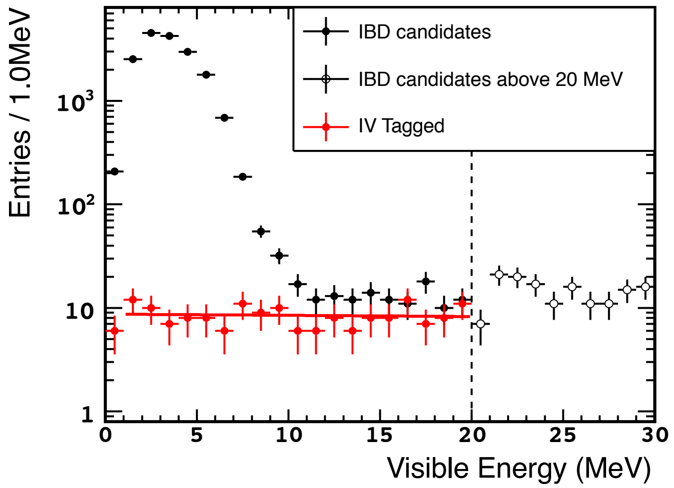




Fast neutrons and cosmic μ

The fast neutrons and stopping μ shape was estimated using the IV tag whereas the rate was computed looking at the 20 - 30 MeV energy region.

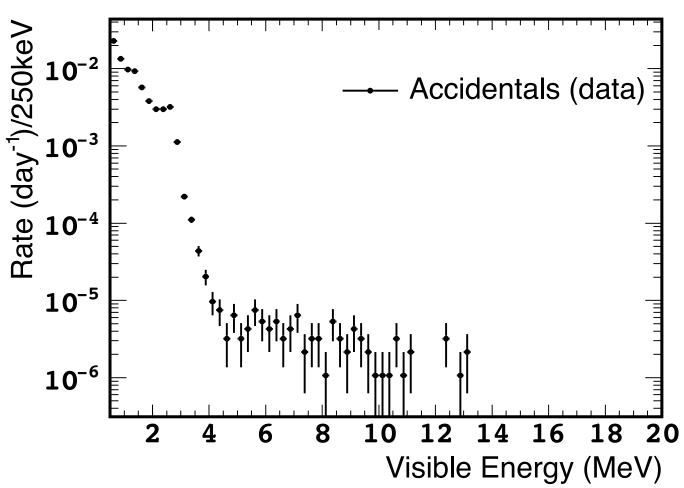
0.604 ± 0.051 events/day



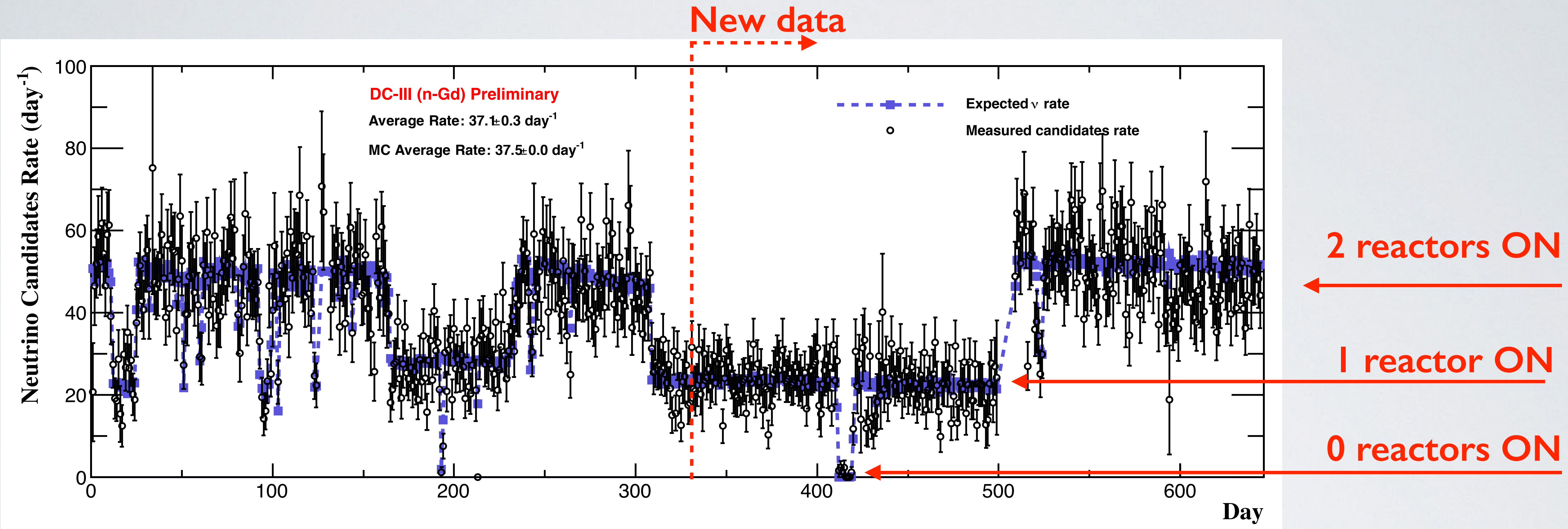
Accidentals

The accidental background was evaluated using off-time coincidence window (1 s after the IBD signal).

0.070 ± 0.003 events/day



NEUTRINO CANDIDATES



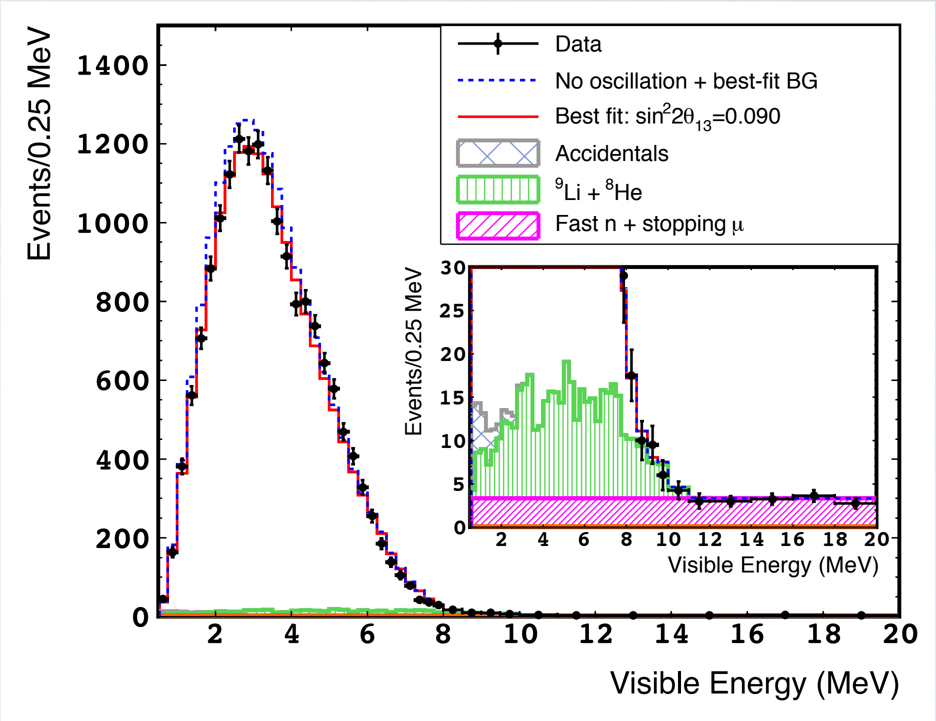
- Data from April 2011 till June 2013.
- Live time of 467.9 days (previously 227.9 days) out of which 7.5 days of two reactors OFF data.
- **Doubled statistics** with 17358 neutrino candidates (previously 8249 candidates).
- **Reduction of the uncertainty** by **~20%** from 2.7% to +2.3%/-2.0% still dominated by the 1.7% error on the reactor flux.

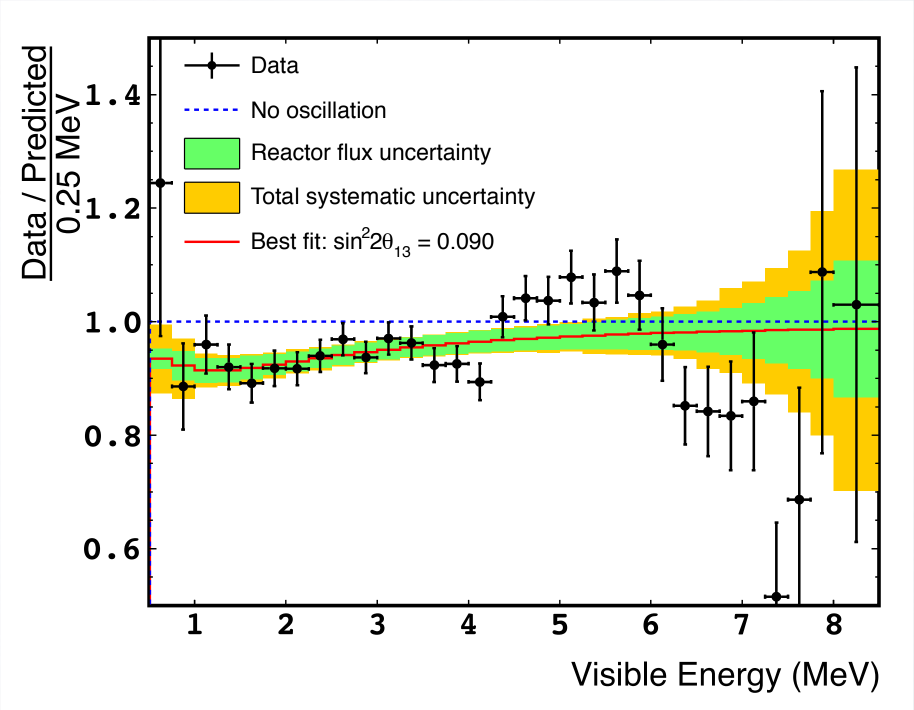
	Reactor On	Reactor Off
Live-time (days)	460.67	7.24
IBD Candidates	17351	7
Reactor $\bar{\nu}_e$	17530 ± 320	1.57 ± 0.47
Cosomogenic ^{9}Li/^{8}He	447^{+189}_{-74}	$7.0^{+3.0}_{-1.2}$
Fast-n and stop-μ	278 ± 23	3.83 ± 0.64
Accidental BG	32.3 ± 1.2	0.508 ± 0.019
Total Prediction	18290^{+370}_{-330}	$12.9^{+3.1}_{-1.4}$

RATE + SHAPE ANALYSIS

- The rate and shape information were used in the fit for the θ_{13} measurement.
- "5 MeV excess" under investigation but with negligible impact on the θ_{13} measurement.
- The **major improvements** with respect to previous analyses are:
  1. Finer binning (more statistics) and larger energy range (0.5 - 20 MeV)
  2. Data driven background shape.
  3. Reactor off-off included as extra bin.

$$\sin^2 2\theta_{13} = 0.092^{+0.033}_{-0.029} \qquad \chi^2_{\mathrm{min}}/d.o.f. = 52.2/40$$





RRM

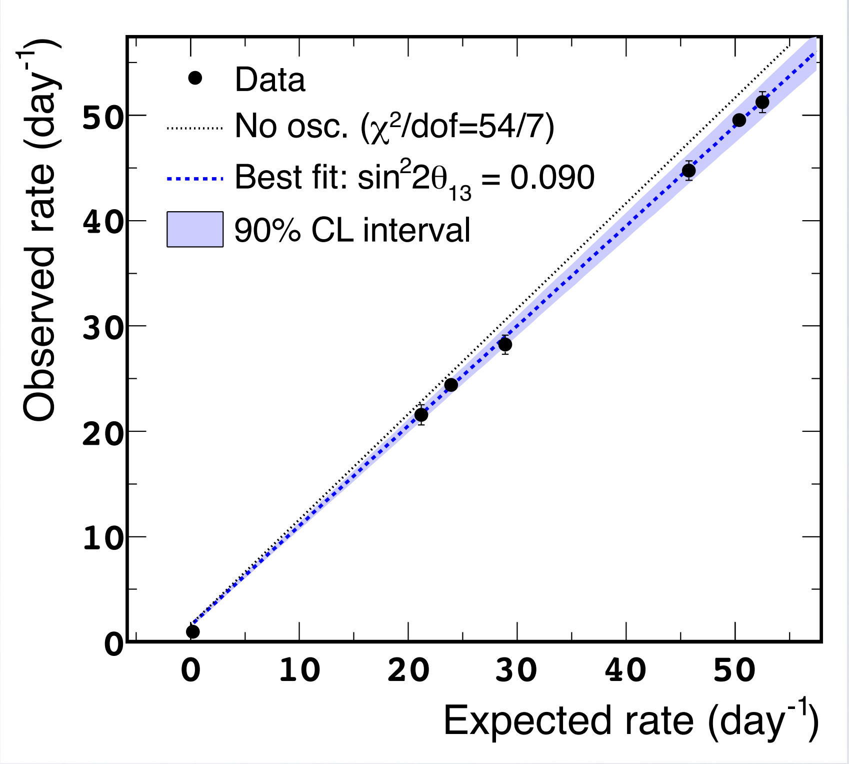
- The Reactor Rate Modulation consists in comparing the observed IBD rate with the expected one for different reactor power conditions.
- The **advantage** of such a measurement is the possibility to **estimate θ_{13} without any constraint on the background** knowledge.
- The results clearly show that reactor off-off data have a strong impact on the achievable θ_{13} precision.

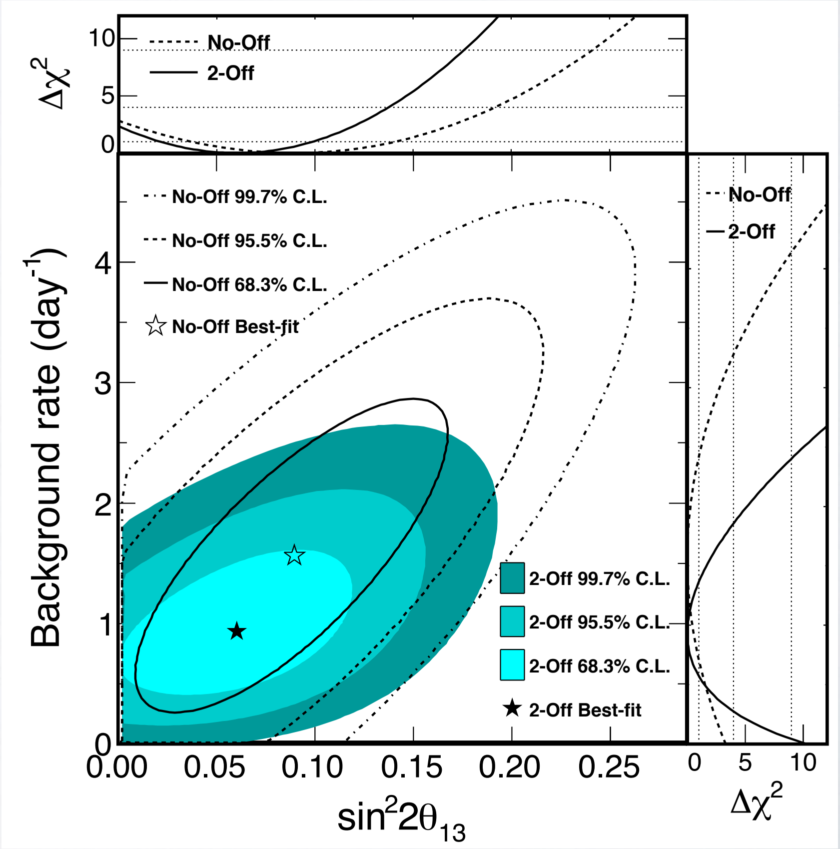
Best fit no off-off (free BG)	BG rate
$\sin^2 2\theta_{13} = 0.089 \pm 0.052$	$1.56 \pm 0.86\,\mathrm{events/day}$

Best fit with off-off (free BG)	BG rate
$\sin^2 2\theta_{13} = 0.060 \pm 0.039$	$0.93^{+0.43}_{-0.36}\,\mathrm{events/day}$

- The same measurement can be carried out constraining the total background rate and the result is in excellent agreement with the one obtained with the rate+shape fit.

Best fit (BG constrained)	BG rate	BG expected
$\sin^2 2\theta_{13} = 0.090^{+0.034}_{-0.035}$	$1.56^{+0.18}_{-0.16}\,\mathrm{events/day}$	$1.64^{+0.41}_{-0.17}\,\mathrm{events/day}$



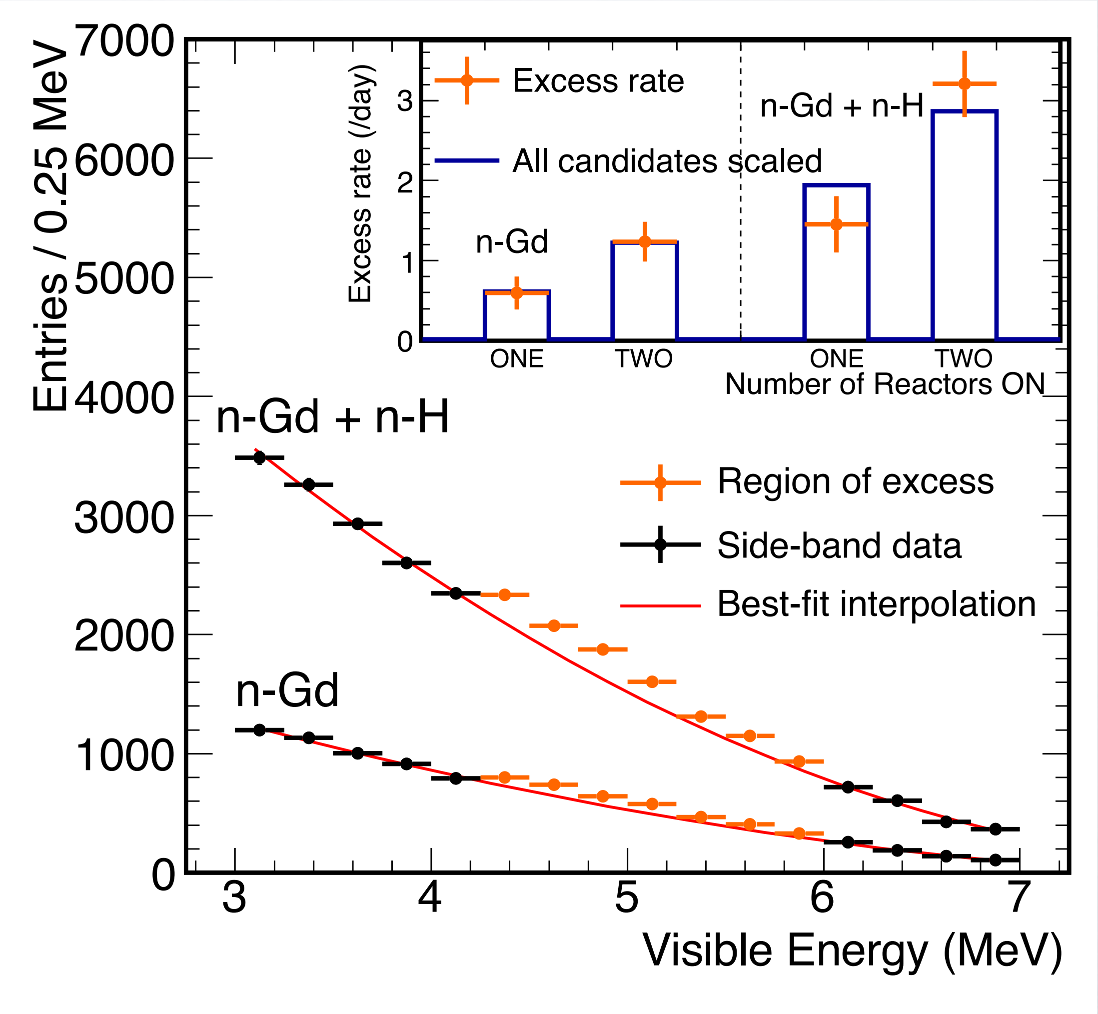


5 MeV EXCESS

- The excess of events at 5 MeV was deeply studied and it seems consistent with **unaccounted neutrinos from reactor**.

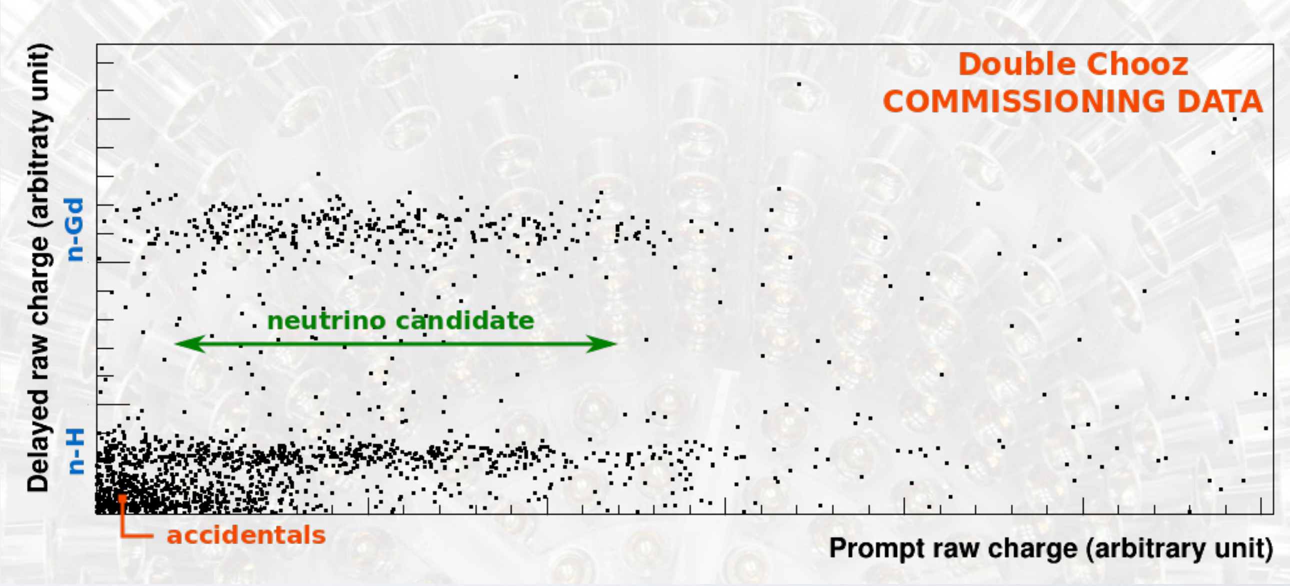
- Given the results of RRM and the tests with addition artificial excess around 5 MeV, **no impact** was seen **on θ_{13}** measurement.

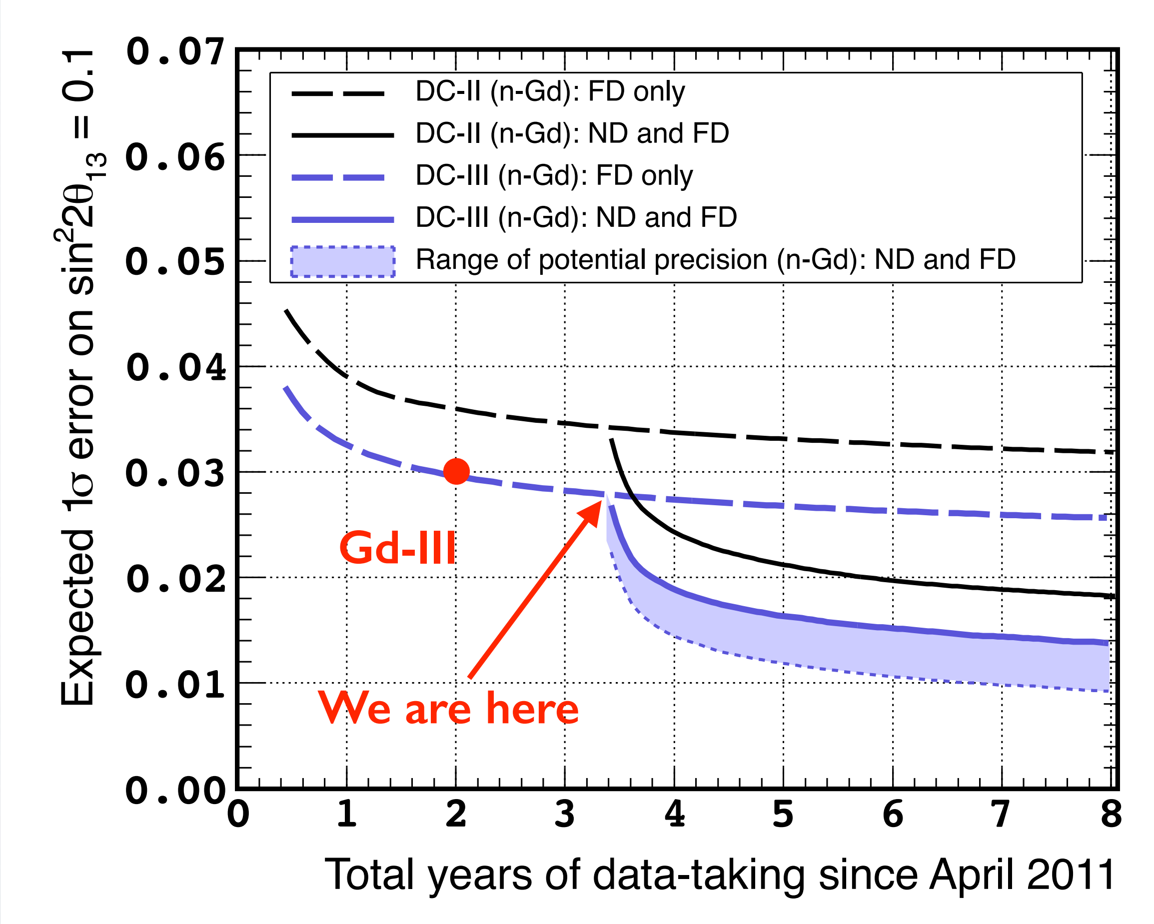
- The **strong correlation** of the excess with the **reactor power** points indeed towards an unaccounted component of the reactor flux and **disfavors** the possibility of an **unaccounted background component**.

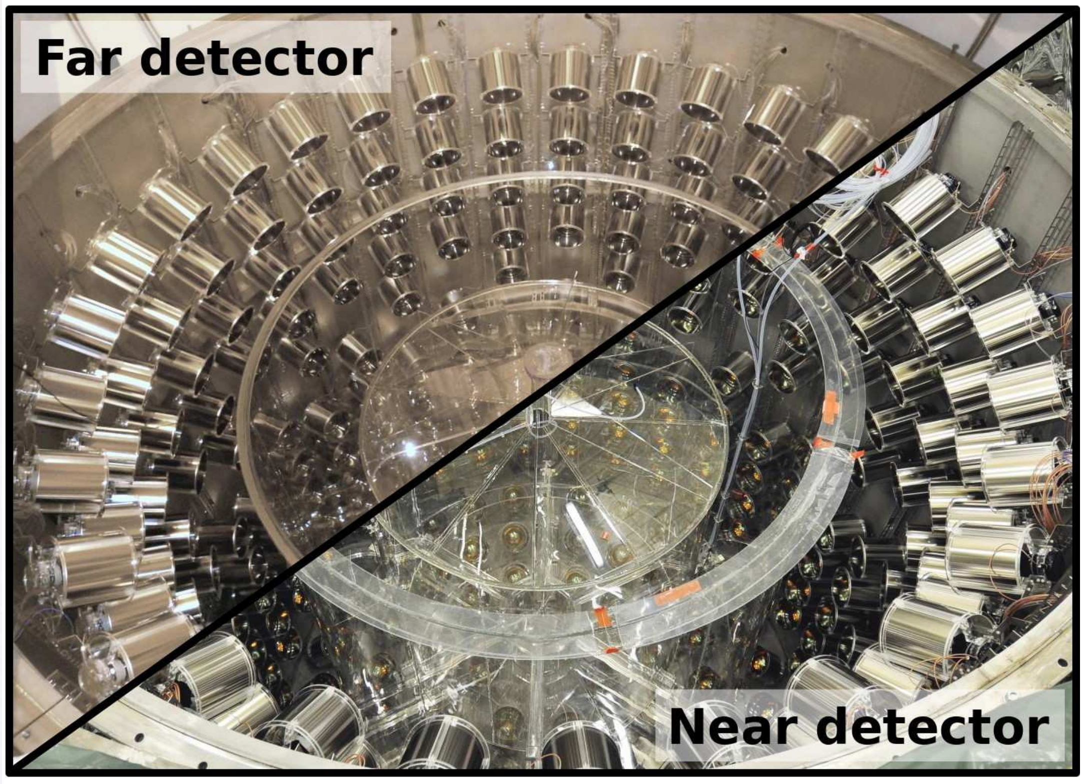


NEAR DETECTOR

- 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 $\sigma \sim 0.01$**.

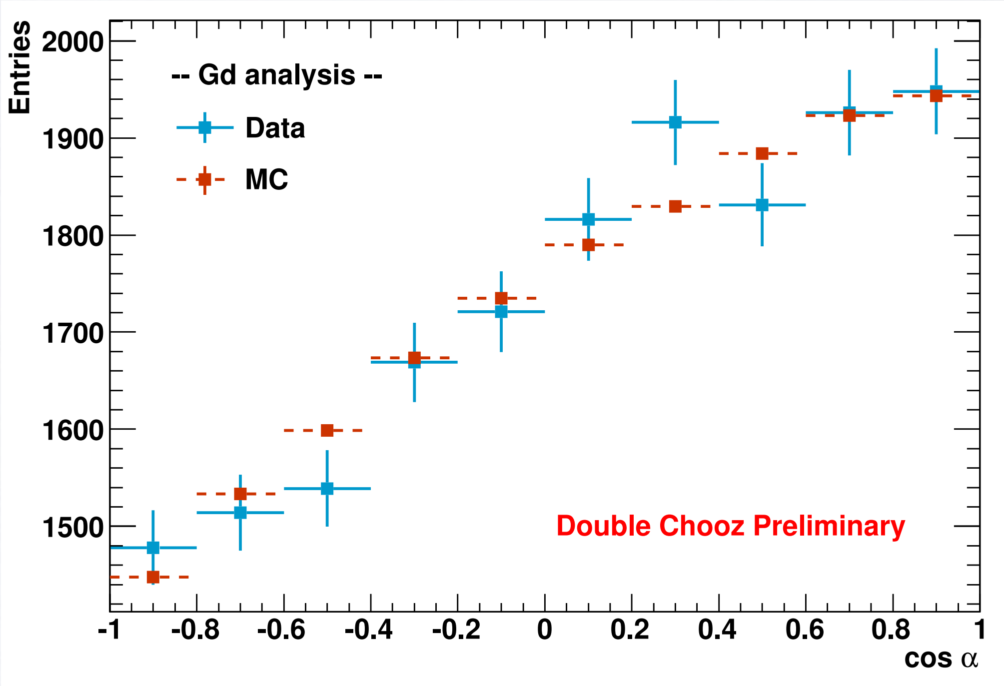






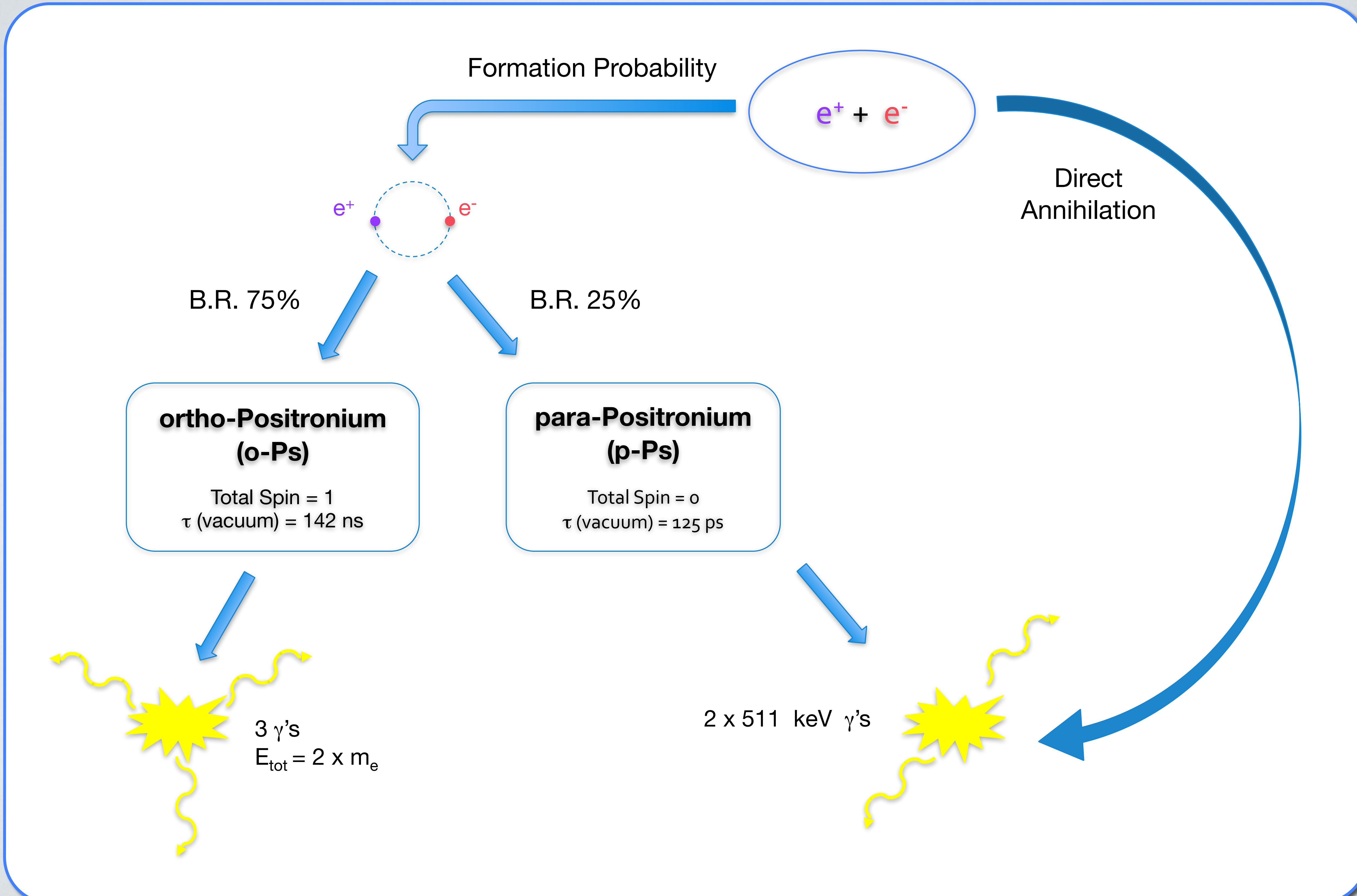
ADDITIONAL PHYSICS

- Besides the search of θ_{13} Double Chooz has performed additional physics measurements namely:
  - Lorentz violation searches (**Phys.Rev. D86 (2012) 112009**).
  - Sterile neutrino search (paper in preparation).
  - Neutrino directionality studies (paper in preparation).
  - Ortho-positronium observation (**JHEP 1410 (2014) 32**).

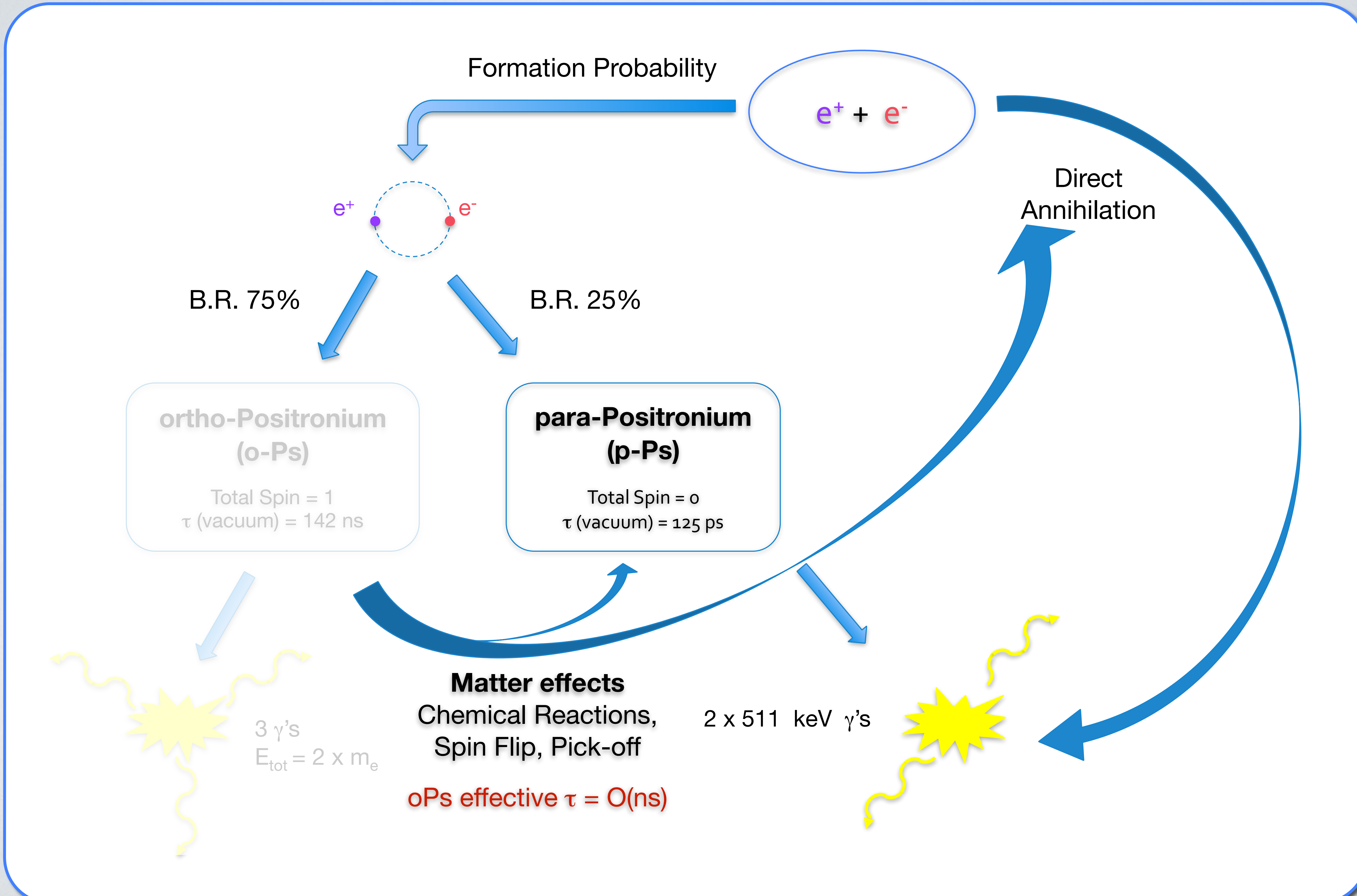


Possible e^+/e^- discrimination, interesting for background rejection in $\overline{\nu}_e$ physics, in particular when looking at particular sources such as a core-collapse supernovae, geo-neutrinos or for nuclear reactor monitoring.

o-Ps OBSERVATION

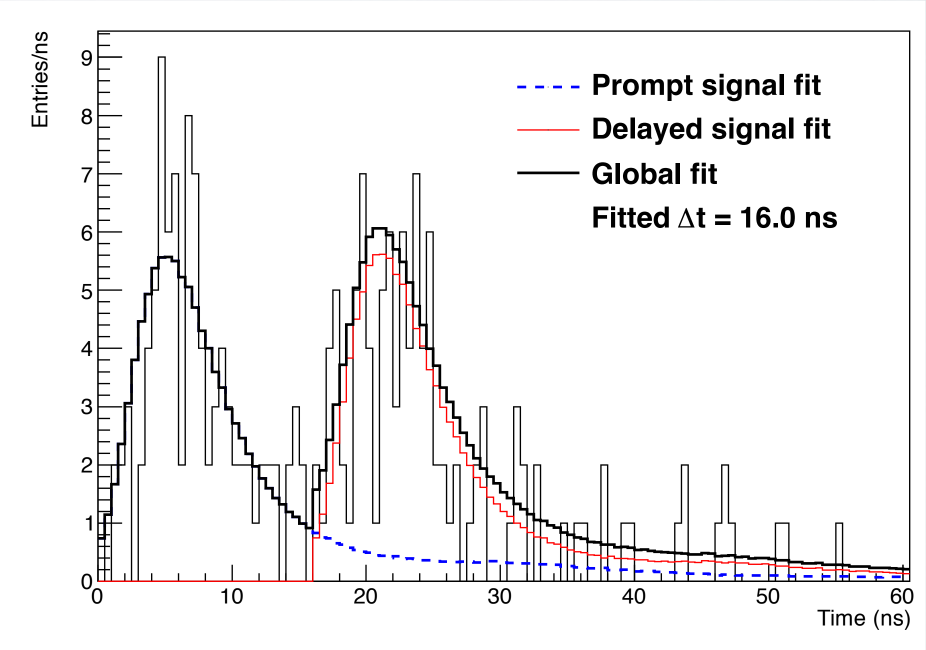


o-Ps OBSERVATION



o-Ps OBSERVATION

- The e^+ light emission (pulse shape) is distorted by the delay between ionization and annihilation according to the o-Ps lifetime.

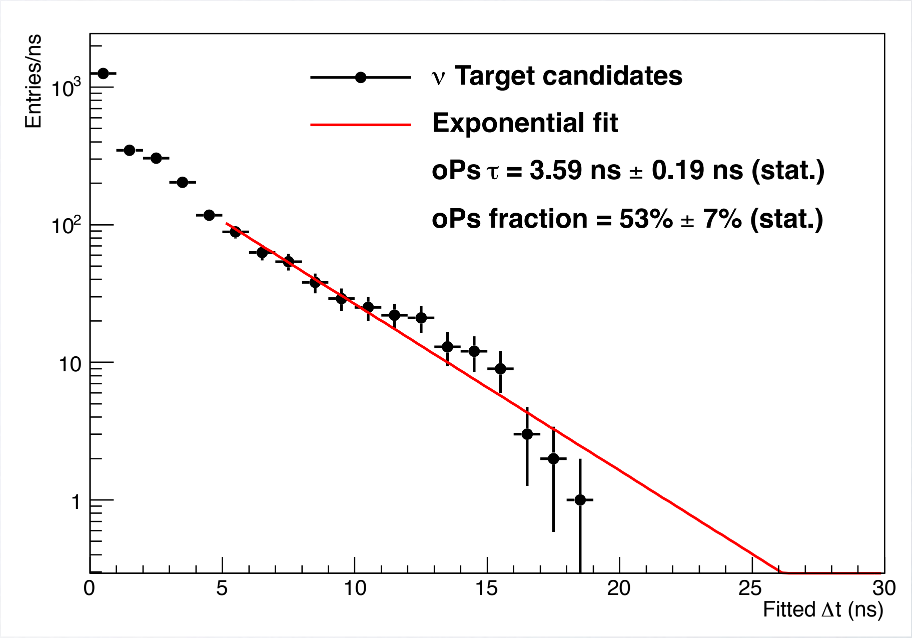


- The pulse shape distortion can be used to discriminate between e^+ and e^-.

- The pulse shapes of **single events** can be fitted with reference ones (from calibration sources) to estimate the o-Ps lifetime.

- The global Δt distribution can be fitted to estimate o-Ps fraction and lifetime and the results are in agreement with dedicated measurements using PALS (Positron Annihilation Lifetime Spectroscopy) on the Target and Gamma Catcher scintillators.

^{60}Co as reference



	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.)

CONCLUSIONS

- Double Chooz has measured the mixing angle θ_{13} both with n-H and n-Gd capture.
- The latest measurement based on rate + shape is $\sin^2(2\theta_{13})=0.090^{+0.033}_{-0.029}$ (Gd-III publication **JHEP 1410 (2014) 86**).
- The unique feature of Double Chooz of reactor off data allowed to well understand the background and reduce the related uncertainty.
- The near detector has just started data taking: **results with two detectors soon!**
- Additional background reductions expected with new analyses including pulse shape exploitation: **H-III publication expected soon** will already use it.
- An error of 0.01 is within reach in 3 years of data taking.

THE COLLABORATION

- **France:**

  CEA/IRFU SPP & SPhN & SEDI & SIS & SENAC Saclay, APC Paris, Subatech Nantes, IPHC Strasbourg

- **Germany:**

  MPIK Heidelberg, TU München, EKU Tübingen, RWTH Aachen

- **Japan:**

  Tohoku U., Niigata U., Tokyo Metropolitan U., Tokyo Inst.Tech., Kobe U., Tohoku Gakuin U., Hiroshima I Inst.Tech.

Russia:

RAS, Kurchatov Institute (Moscow)

Spain:

CIEMAT Madrid

- **USA:**

  Alabama, ANL, Chicago, Columbia, Drexel, Kansas State, MIT, Notre Dame, Tennessee, IIT, U.C. Davis, Virginia Tech

- **Brazil:**

  CBPF, UNICAMP, UFABC