La Thuile, 23 February-1st March 2014

Double Chooz and recent results

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on behalf of the
Double Chooz Collaboration

Outlook

1. Experiment overview.

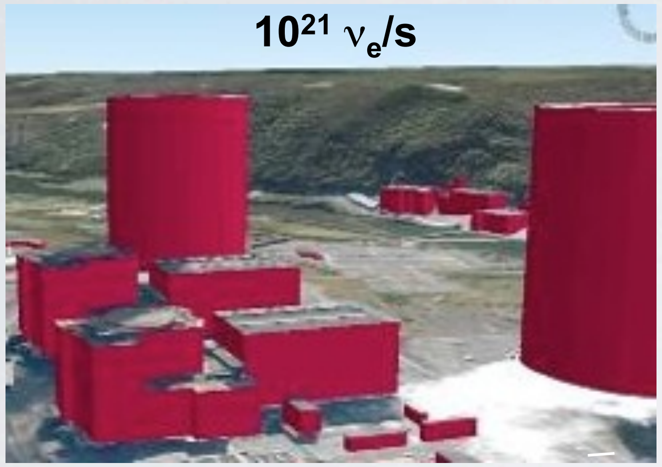
2. Double Chooz results:
    - Measurement of θ_{13} from neutron capture on Gadolinium and Hydrogen.
    - Reactor-off background measurement.

3. Latest results:
    - Reactor Rate Modulation Analysis.
    - Ortho-Positronium observation in on event-by-event basis.

Experimental concept and neutrinos mixing at reactors

Disappearance probability:

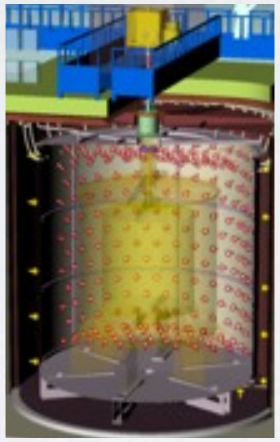
$$P(\bar{\nu}_e \to \bar{\nu}_e) \simeq 1 - \sin^2(2\theta_{13})\sin^2\left(1.27\frac{\Delta m^2_{32}(\mathrm{eV}^2)L(\mathrm{m})}{E(\mathrm{MeV})}\right)$$



Chooz Nuclear Power Station
2 cores of 4.27 GW_{th} each

$\bar{\nu}_e$

Total flux

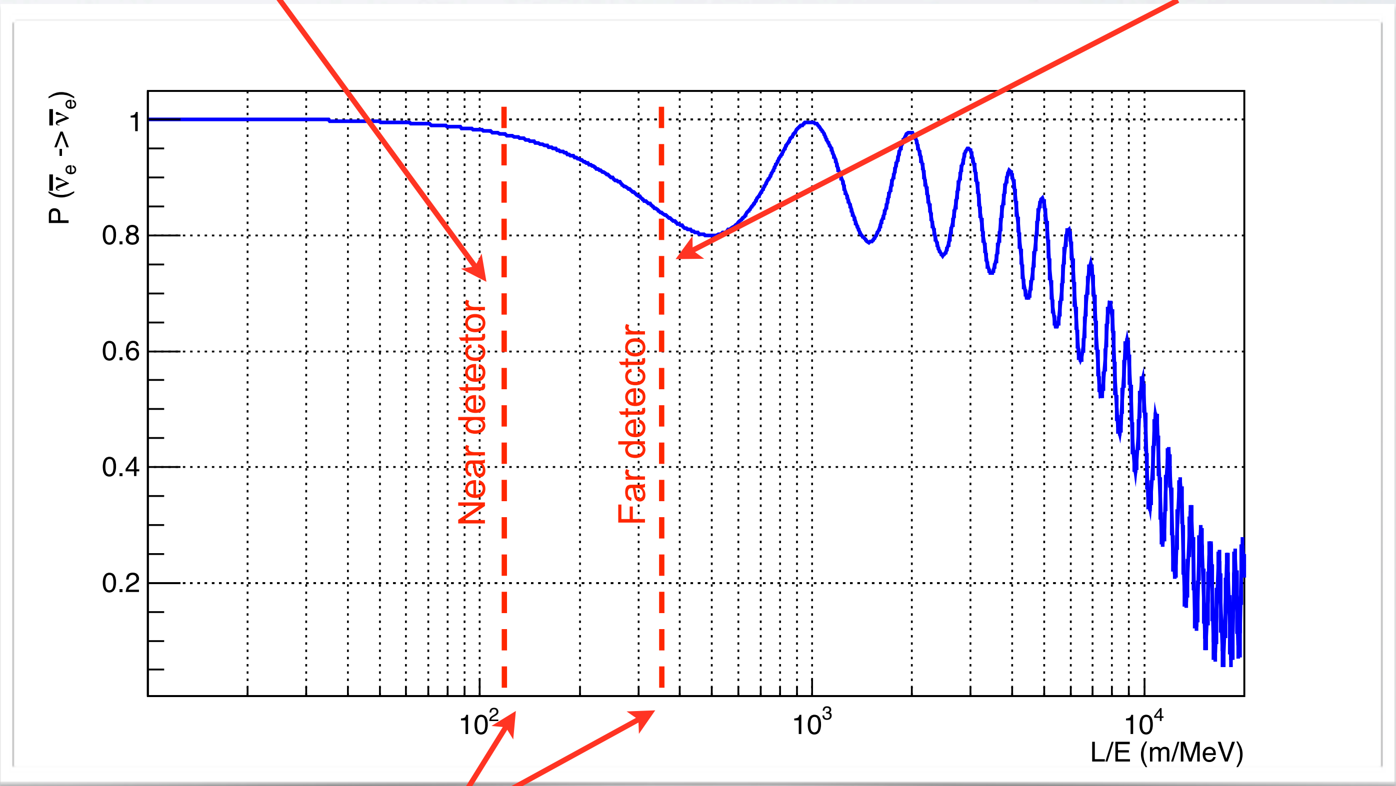


Near detector
400 m

$\bar{\nu}_{e,\mu,\tau}$

Oscillated flux

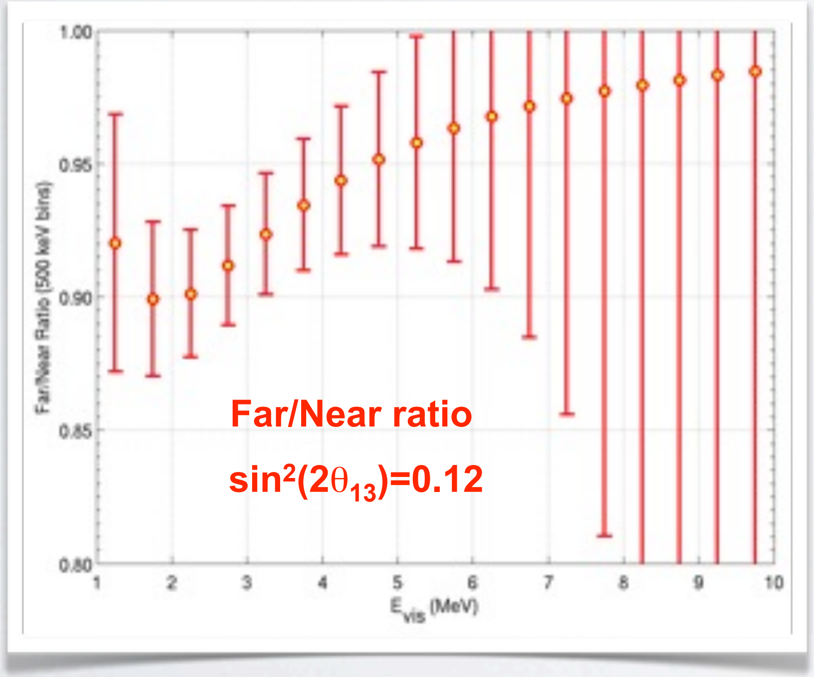
Far detector
1050 m



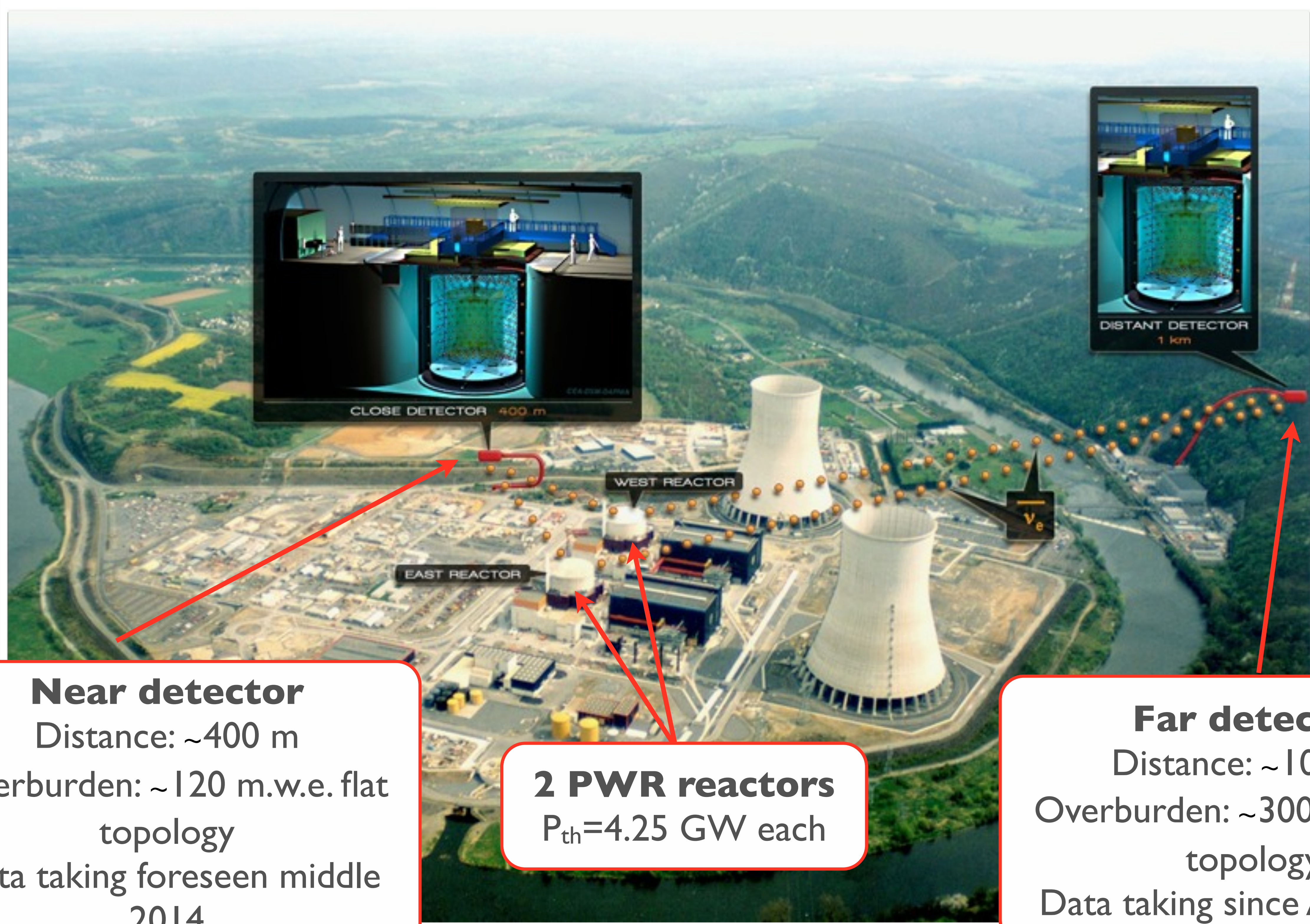
For <E> = 3 MeV

$\Delta m^2_{12}=7\times10^{-5}$ eV^2	$\sin^2(2\theta_{13})=0.2$
$\Delta m^2_{23}=2.5\times10^{-3}$ eV^2	$\cos^2(\theta_{12})=0.7$

Prompt energy spectra comparison



Double Chooz overview



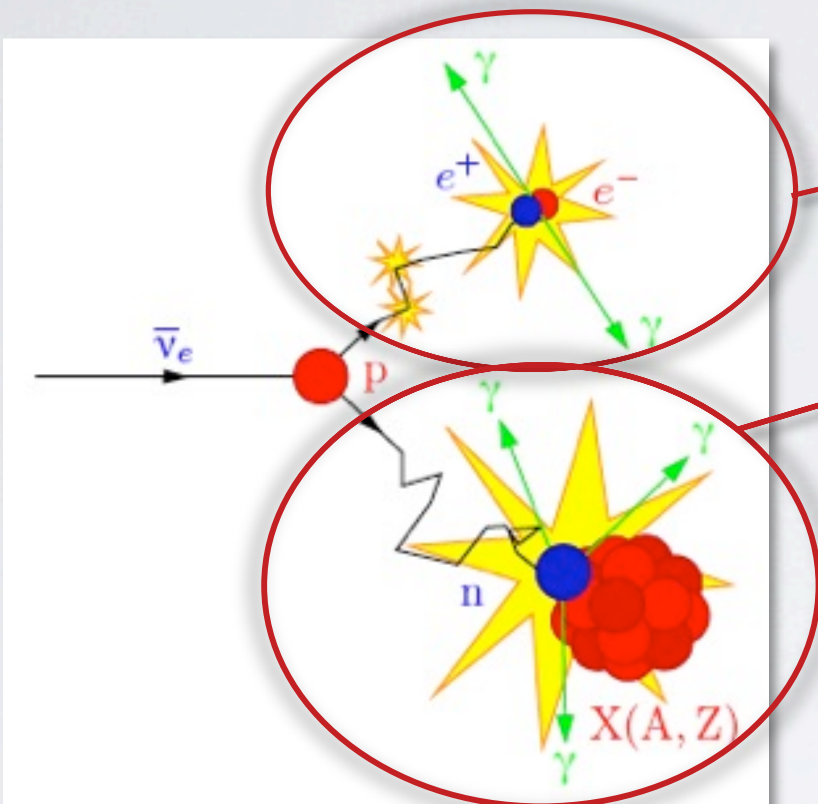
Near detector
Distance: ~400 m
Overburden: ~120 m.w.e. flat topology
Data taking foreseen middle 2014

2 PWR reactors
P_{th}=4.25 GW each

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

Detection of electron anti-neutrinos

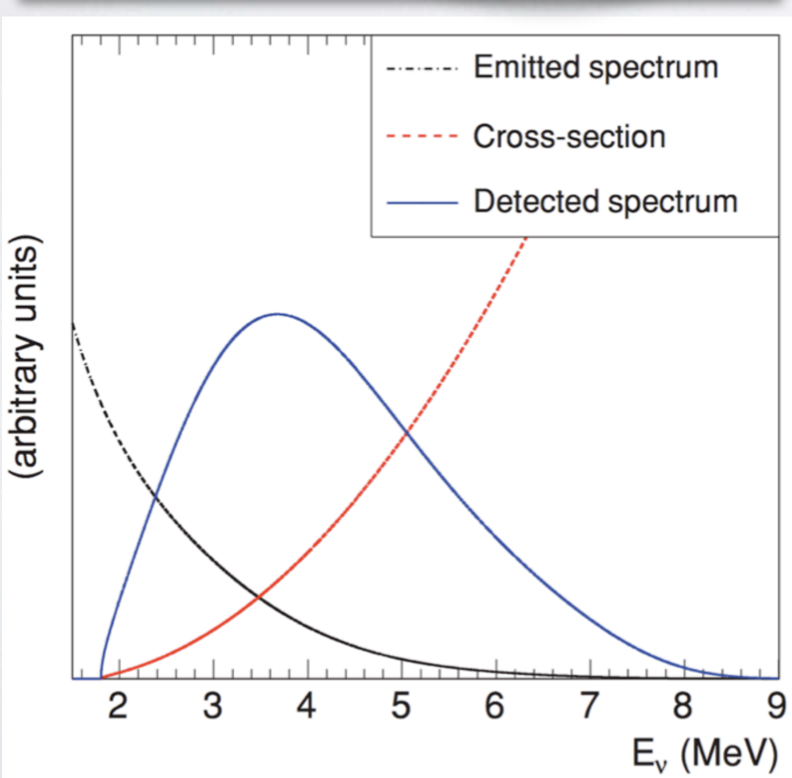
Inverse Beta Decay
(threshold at 1.8 MeV)



Prompt Signal - Positron ionization+Annihilation

Delayed Signal - n absorption on Gd (~ 8MeV) or on H (2.2 MeV)

Δt ~ 30 μs for n-absorption on Gd
~ 200 μs for n-absorption on H



Two-fold coincidence: strong background suppression

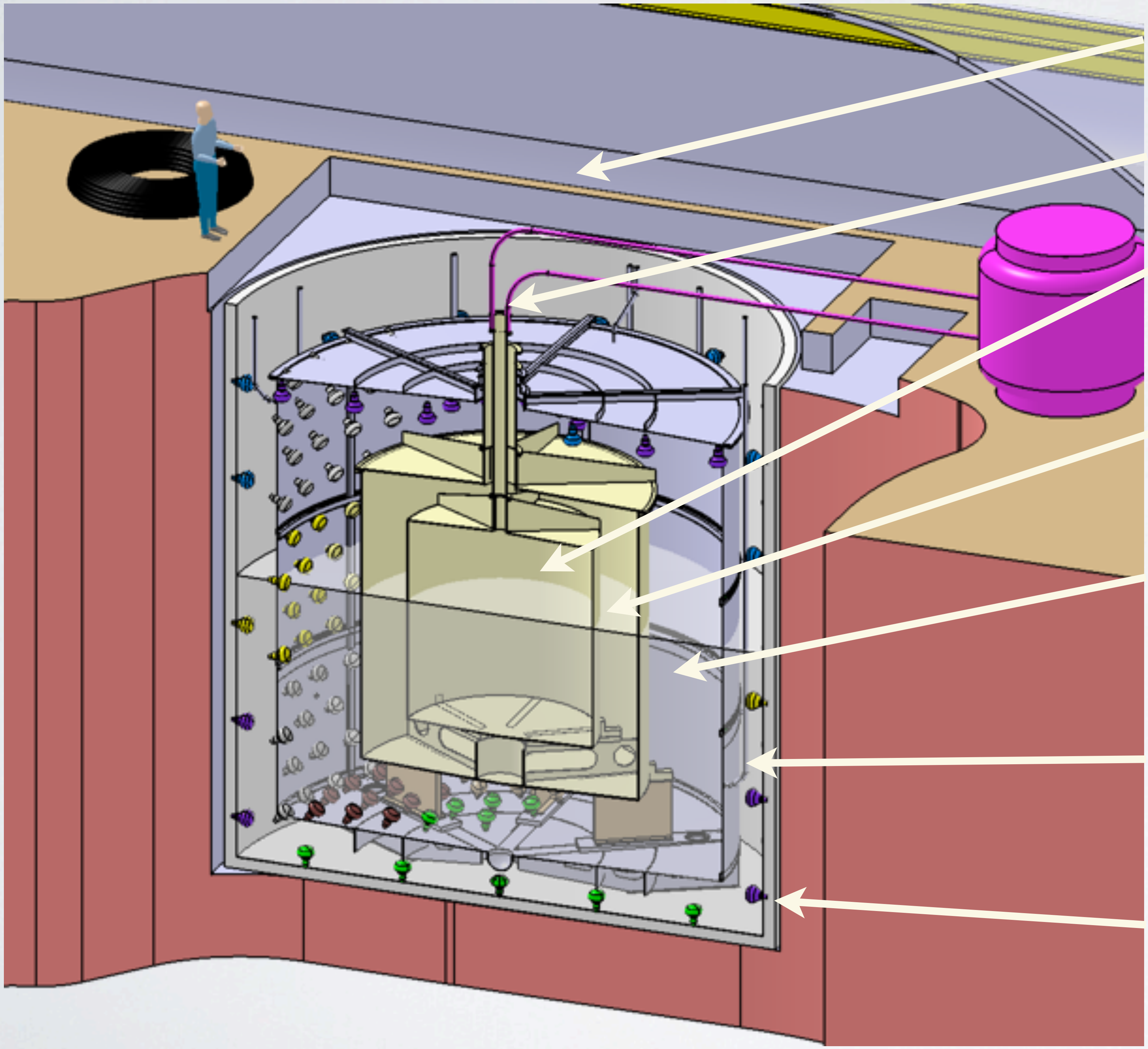
The prompt energy is related to $\overline{\nu}_e$ energy:

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

The survival probability depends on E_ν

⇒ 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 compound in an acrylic vessel (8 mm)

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

Buffer: 110 m^3 of mineral oil in a stainless steel vessel (3 mm) viewed by 390 PMTs (10 inches)

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

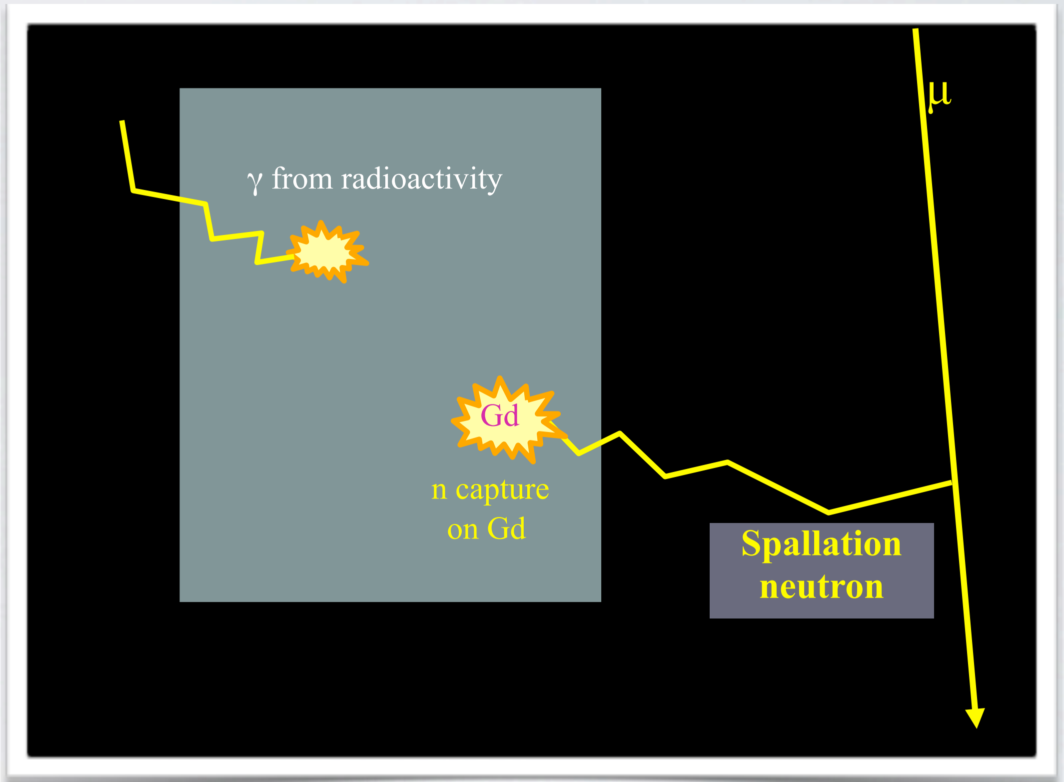
Shielding: about 250t steel shielding (150 mm)

Background

- There are two different types of background: accidental and correlated.

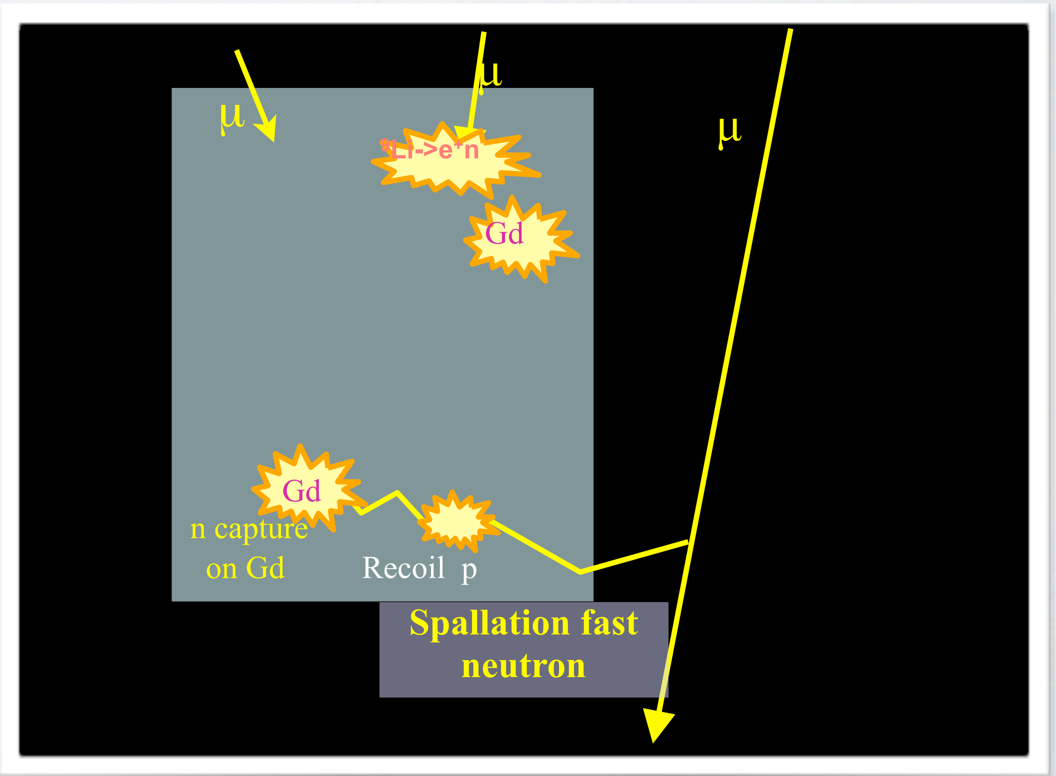
Accidental BG

- e^+-like signal: radioactivity from materials, PMTs, surrounding rock (^{208}Tl).
- delayed signal: n from cosmic μ spallation, thermalised in detector and captured on Gd.



Correlated BG

- Fast n (by cosmic μ) gives recoil protons (low energy) and are captured on Gd.
- Stopping μ.
- Long-lived (^{9}Li, ^{8}He) β-n decaying isotopes induced by μ.



Neutrino selection

Two channels are used for neutrino detection:

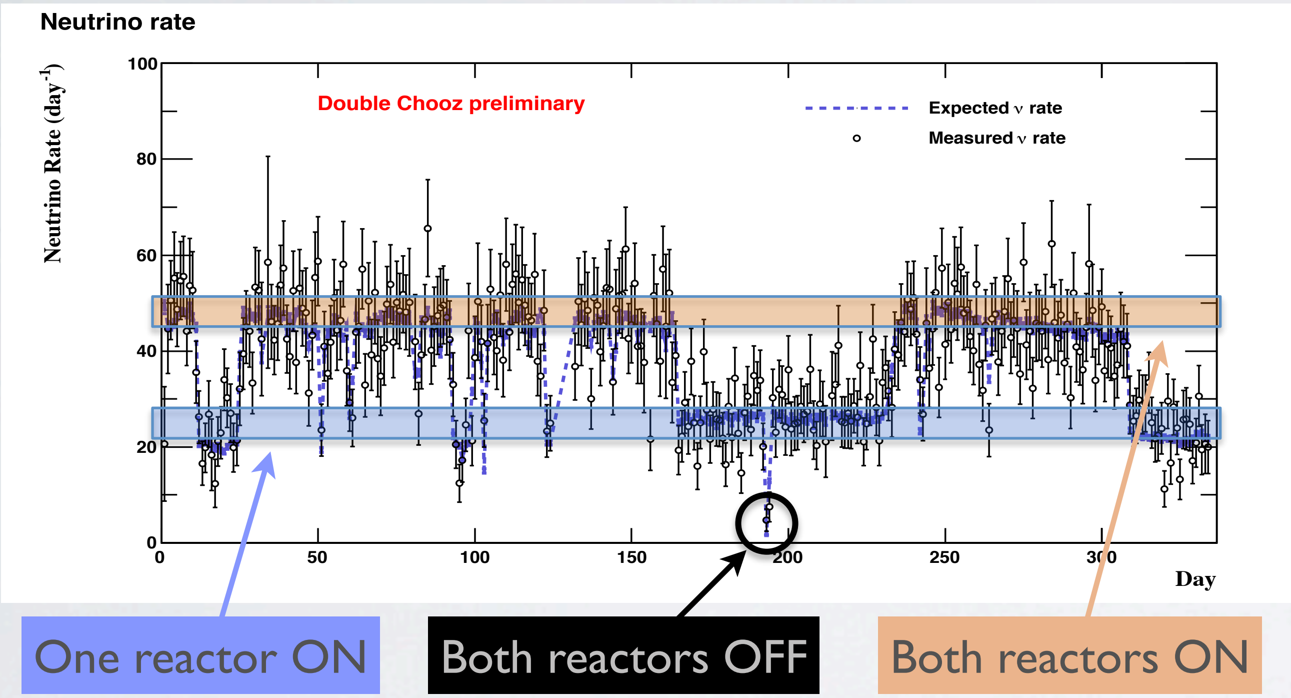
Gd-capture
- High cross-section for n-capture
- Capture time: 30 μs
- n-capture released energy: 8 MeV (low background)

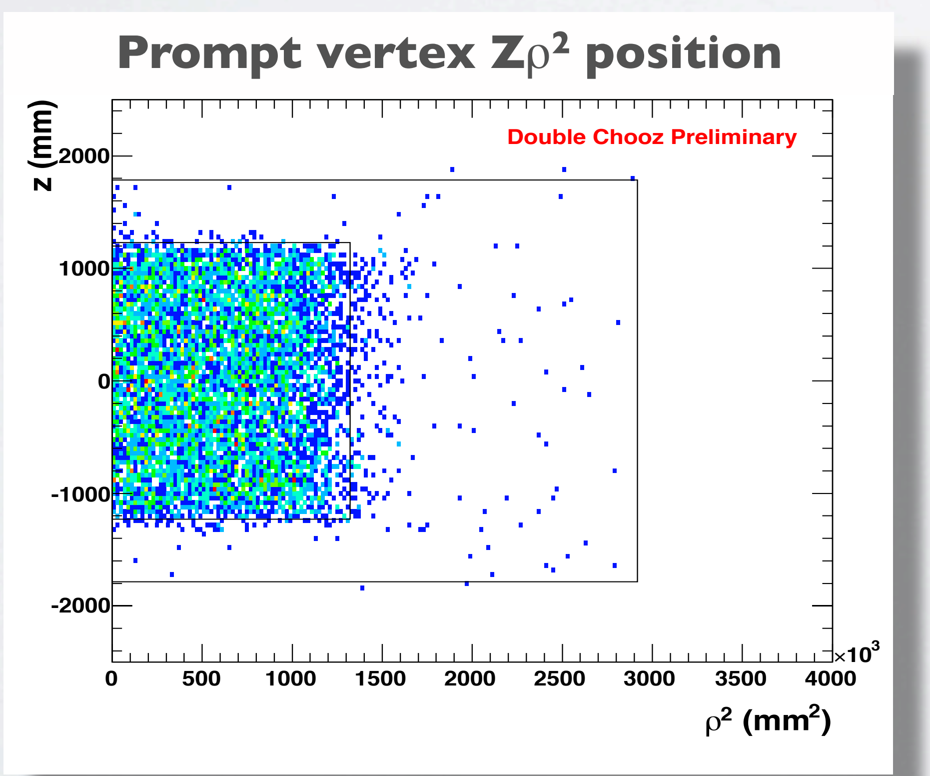
H-capture
- High statistics (target and γ-catcher)
- Capture time: 200 μs
- n-capture released energy: 2.2 MeV

Cut	Gd capture	H capture
Muon veto	no triggers in 1 ms after a muon	
Light noise rejection		
E(prompt)	0.7-12.2 MeV	
E(delayed)	6-12 MeV	1.5-3 MeV
Δt (time)	2-100 μs	10-600 μs
Δd (distance)	--	<0.9 m
Multiplicity	no extra events around signal	
Showering muon veto	Δt_μ (E_μ >600 MeV)>500 ms	--
No coincidence with OV signal		

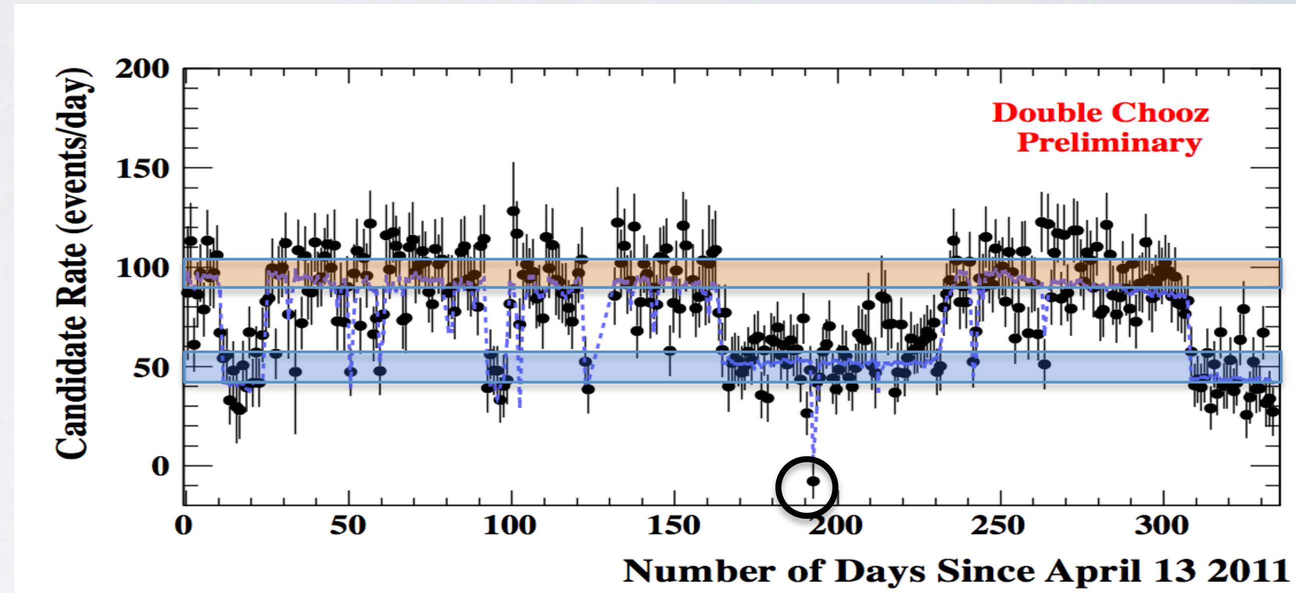
Neutrino candidates

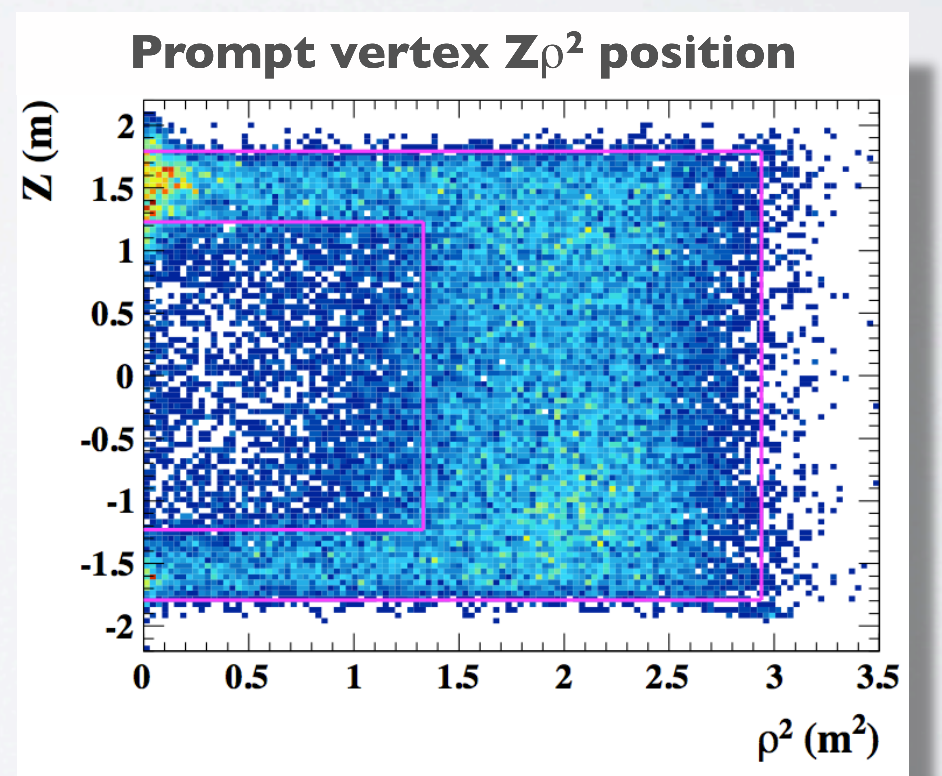
Gd-capture





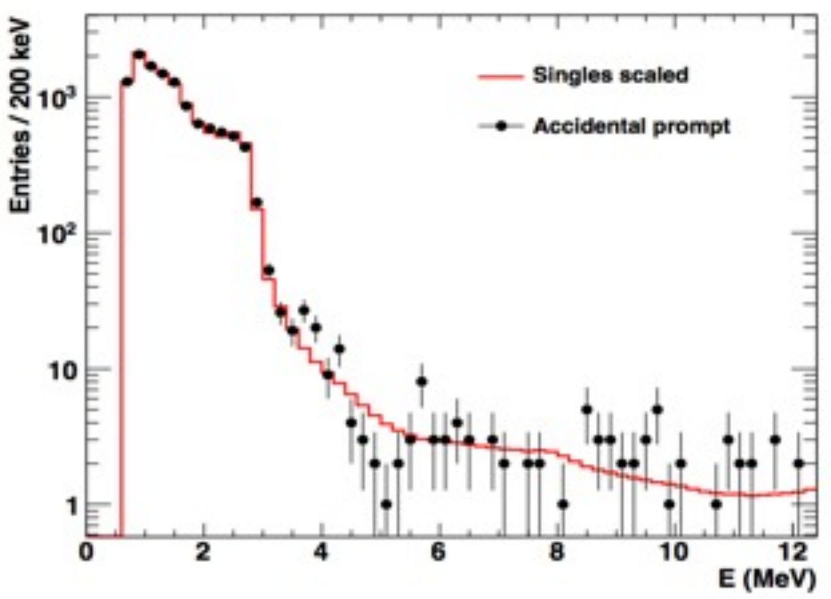
H-capture





Backgrounds

Gd-capture (Signal/Noise~16) **H-capture (Signal/Noise~1)**

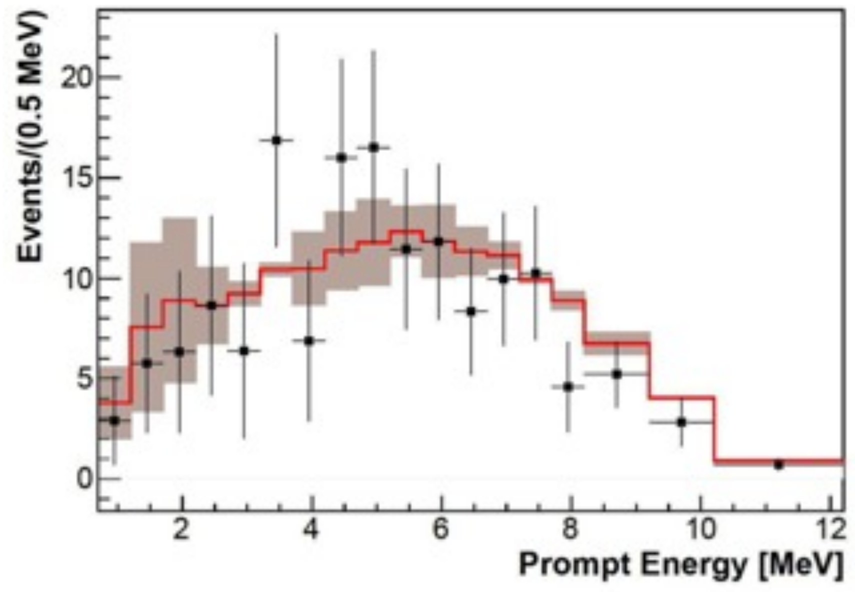


<u>Accidentals</u>

Radioactivity+n absorption

-Determined by off-time window
-Stable along data taking period

Rate Gd: 0.261±0.002 events/day
Rate H: 73.5±0.2 events/day

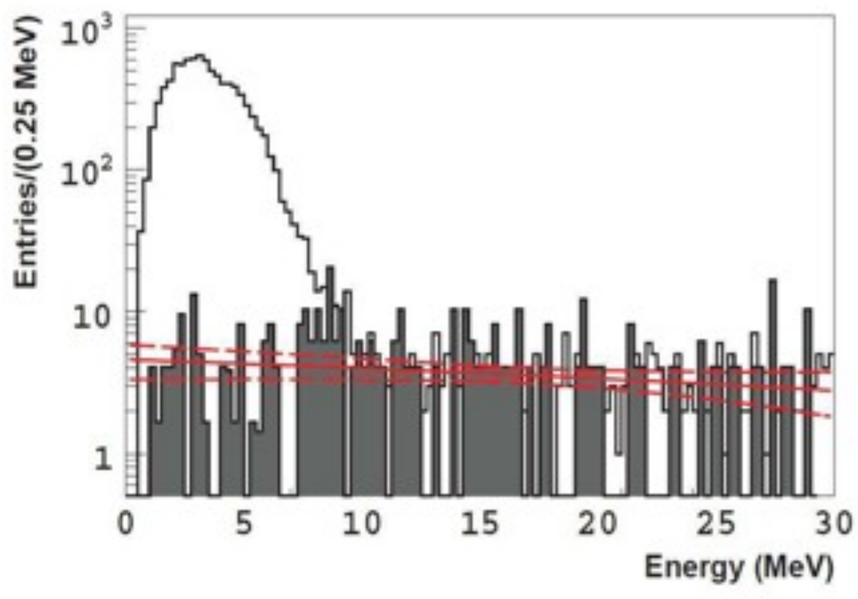


<u>Cosmogenic Background (^{8}He & ^{9}Li)</u>

β+n absorption

-^{9}Li rate from Δt between showering muon and prompt event.

Rate Gd: 1.25±0.54 events/day
Rate H: 2.8±1.2 events/day



<u>Fast n/Stopping μ</u>

p-recoil +n-absorption/
μ+Michel e^-

-Prompt energy extended up to 30 MeV.

Rate Gd: 0.67±0.20 events/day
Rate H: 2.5±0.5 events/day

Neutrino candidates: rate uncertainties

	Gd capture	H capture
Predicted neutrino candidates (no oscillation)+ Background	8936.8	36680
Selected neutrino candidates	8249 (228 days)	36284 (240 days)

Signal and background normalization uncertainties relative to the predicted signal

Gd capture

Source	Uncertainty [%]
Reactor Flux	1.67%
Detector Response	0.32%
Statistics	1.06%
Efficiency	0.95%
Cosmogenic Isotope Background	1.38%
FN/SM	0.51%
Accidental Background	0.01%
Total	2.66%

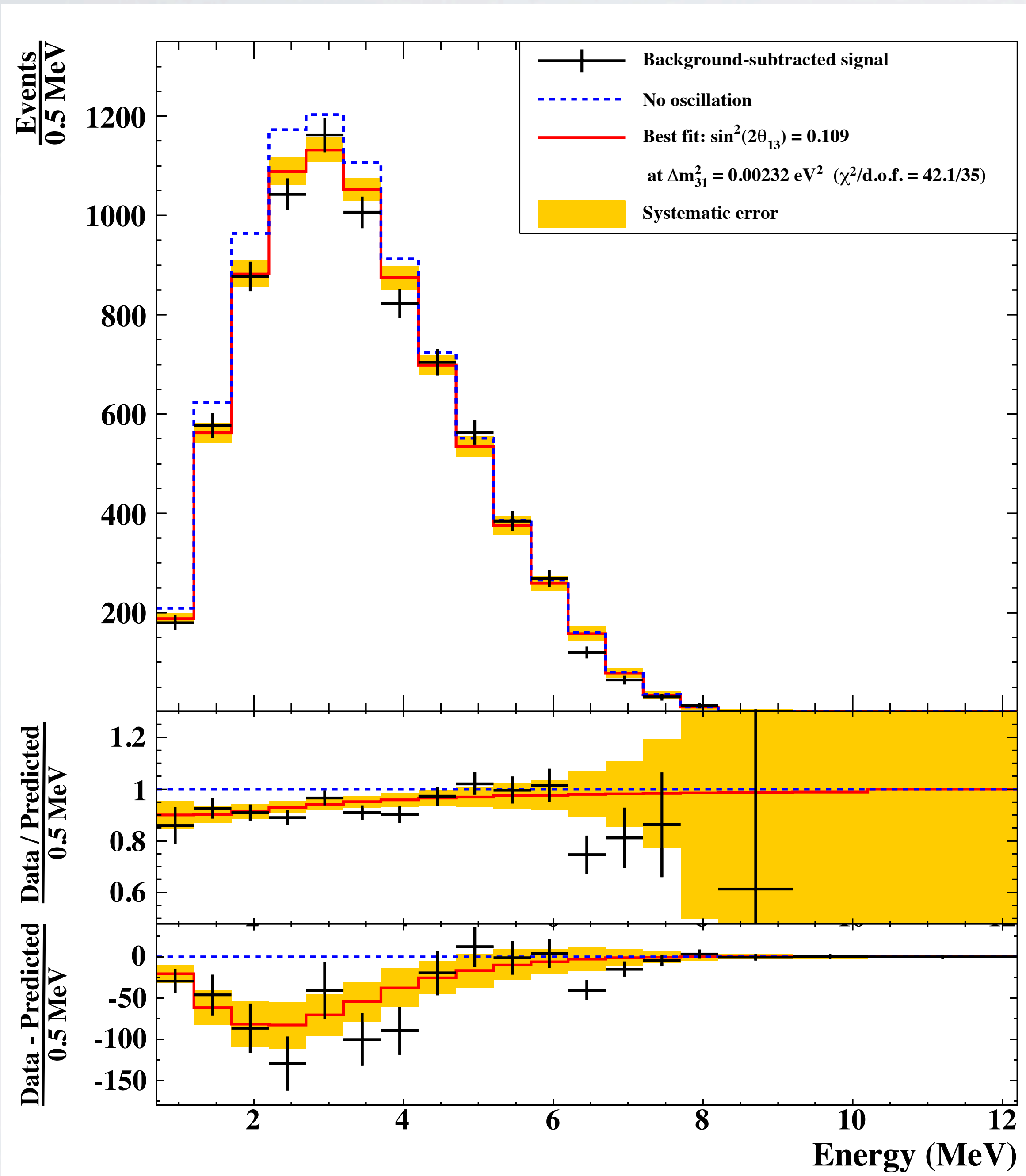
H capture

Source	Uncertainty [%]
Reactor flux	1.8
Statistics	1.1
Accidental background	0.2
Cosmogenic isotope background	1.6
Fast neutrons	0.6
Light noise	0.1
Energy scale	0.3
Efficiency	1.6
Total	3.1

θ_{13} measurement: Rate+Shape analysis

Gd capture

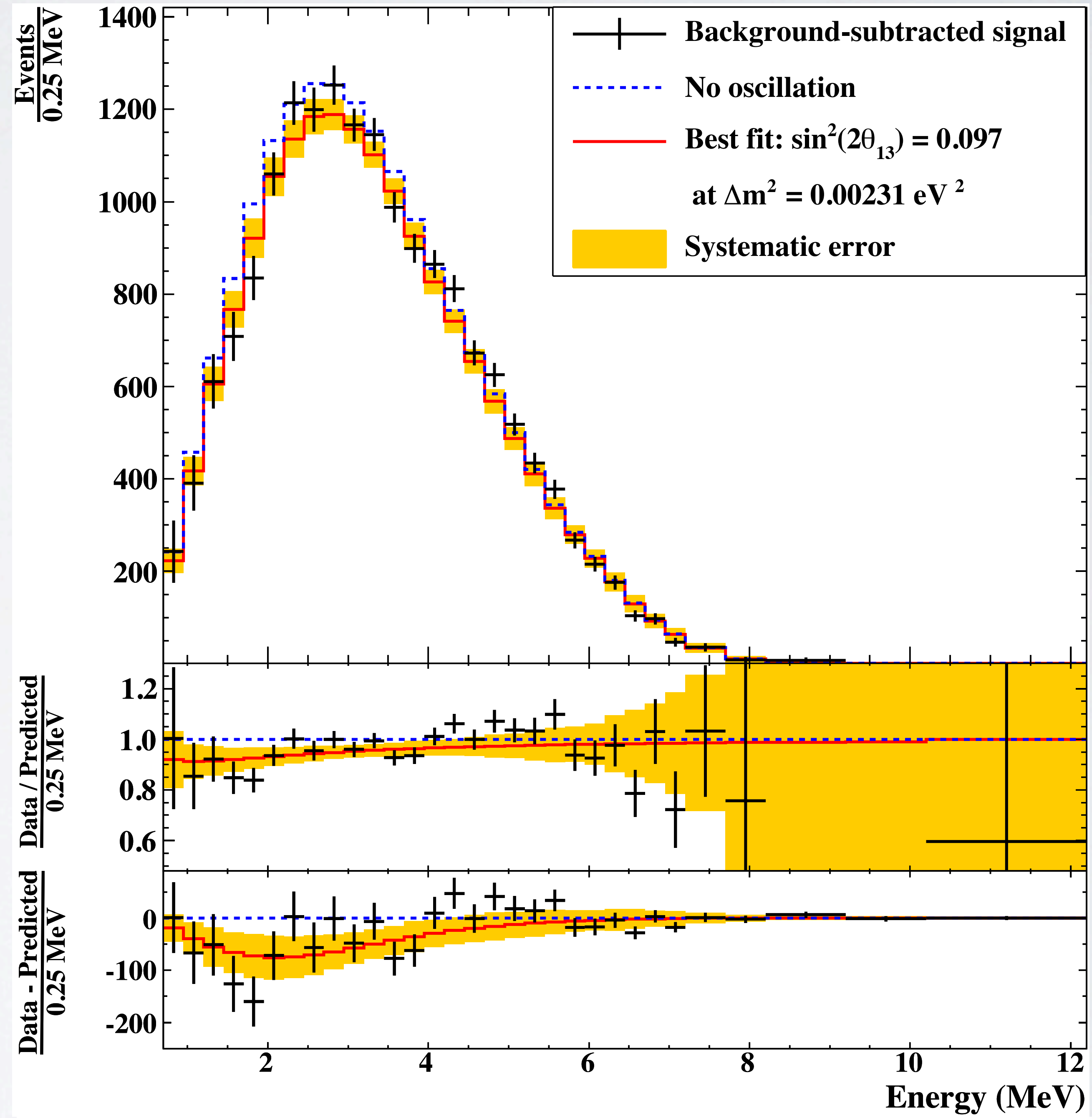
Phys. Rev. D86 (2012) 052008



$\sin^2 2\theta_{13} = 0.109 \pm 0.030$ (stat) ± 0.025 (syst)

H capture

Phys. Lett. B723 (2013) 66-70



$\sin^2 2\theta_{13} = 0.097 \pm 0.034$ (stat) ± 0.034 (syst)

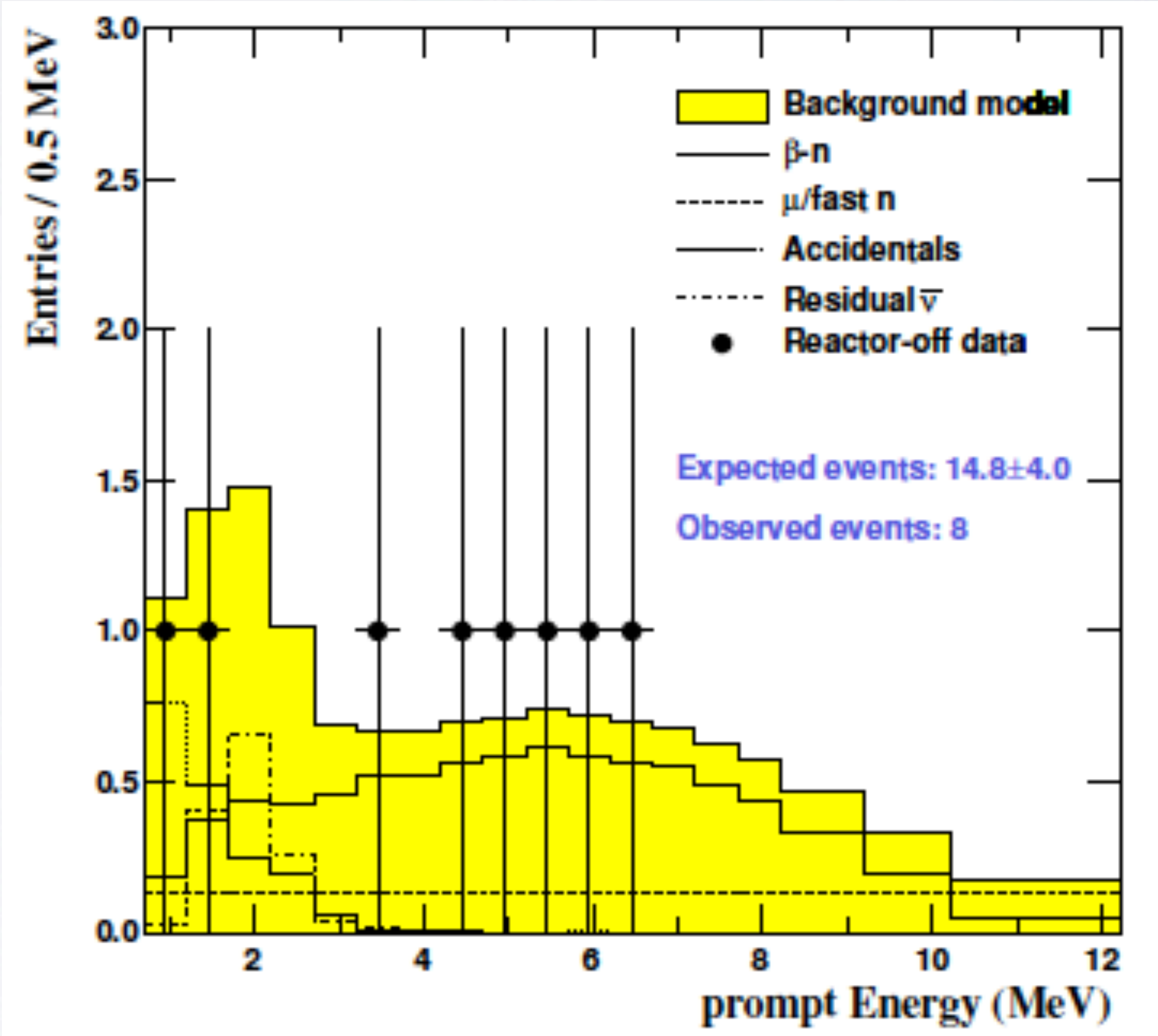
Combining Gd and H analysis: **$\sin^2(2\theta_{13})=0.109\pm0.035$**

Data with both reactors off

Double Chooz registered 7.53 days of data with both reactors off.

- Unique Double Chooz capability.
- Rate consistent with predictions.
- New constraints for oscillation fits.

Phys. Rev. D87 (2013) 011102

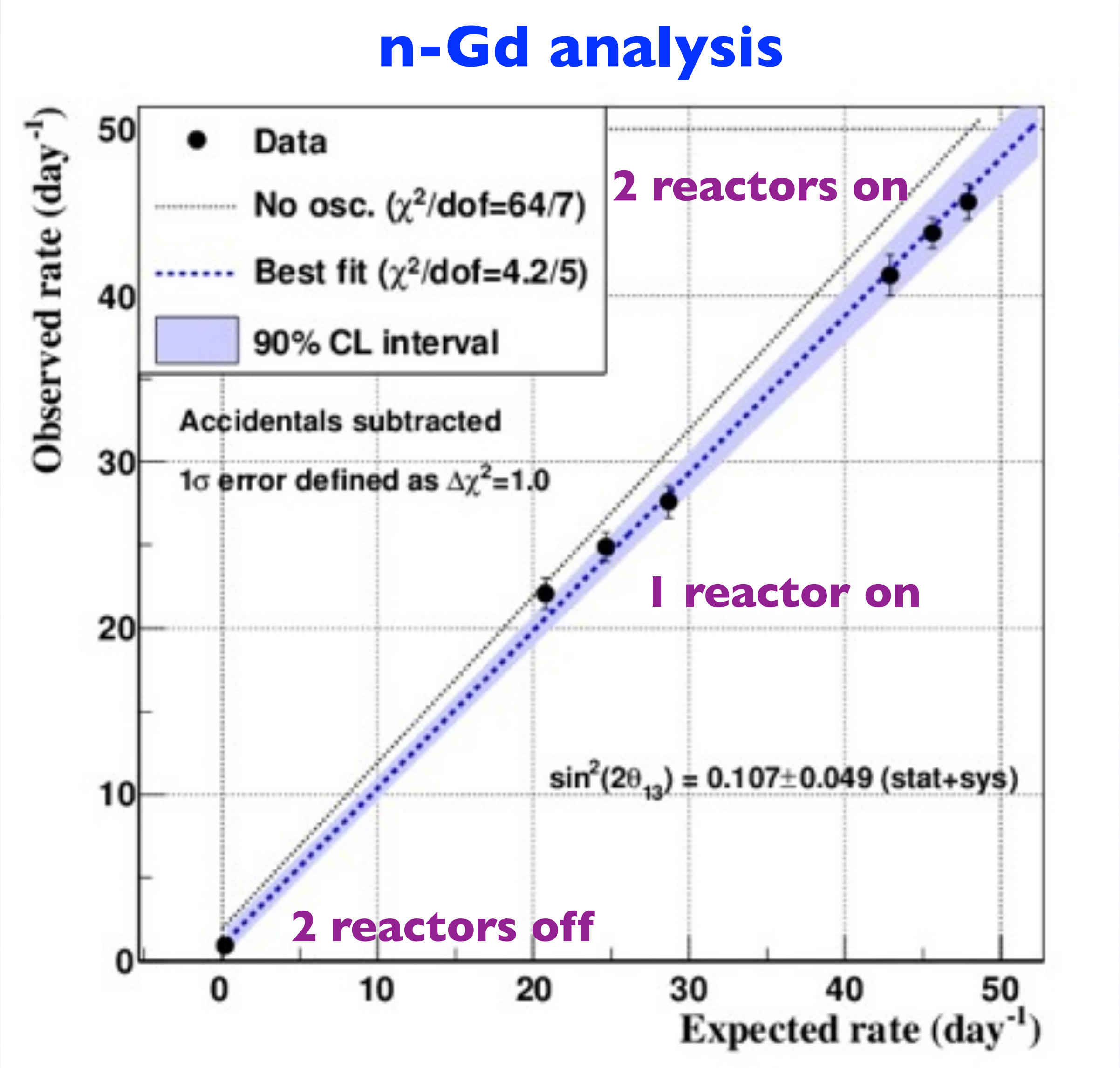


Gd analysis:
Measured background rate: 1.0±0.4 events/day
Expected background rate: 2.2±0.6 events/day
(with residual $\bar{\nu}_e$ subtracted)

H analysis:
Measured background rate: 10.8±3.4 events/day
Expected background rate: 5.3±1.3 events/day
(with residual $\bar{\nu}_e$ and accidental subtracted)

Reactor Rate Modulation (RRM) Analysis

arXiv:1401.5981

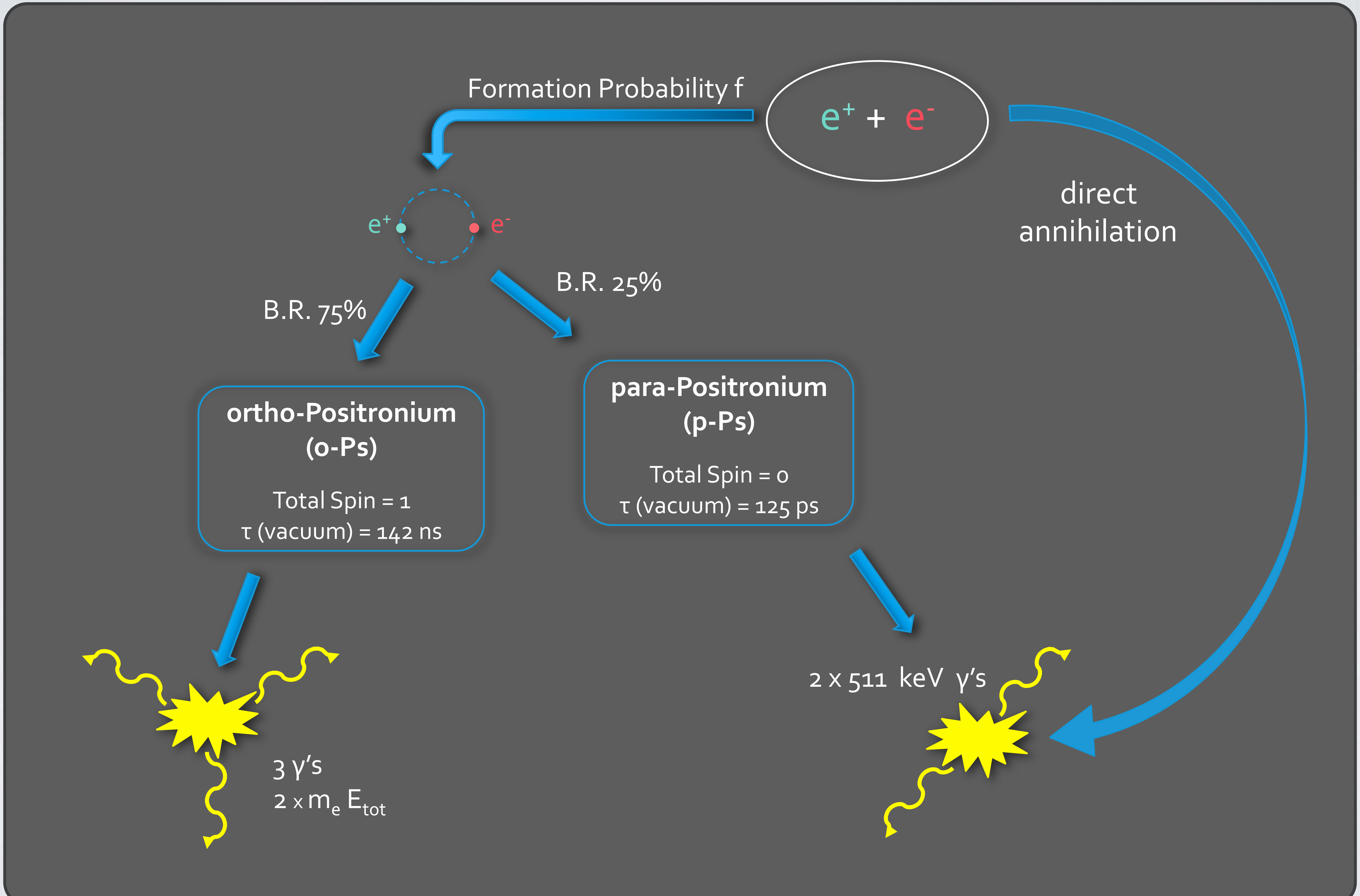


- Rate-only background independent analysis:
  - Observed vs expected $\overline{\nu}_e$ candidates rate at different reactor power.
  - Fit provides $\sin^2(2\theta_{13})$ and the total background rate.
- No background model assumed.
- background reactor-off measurement included.

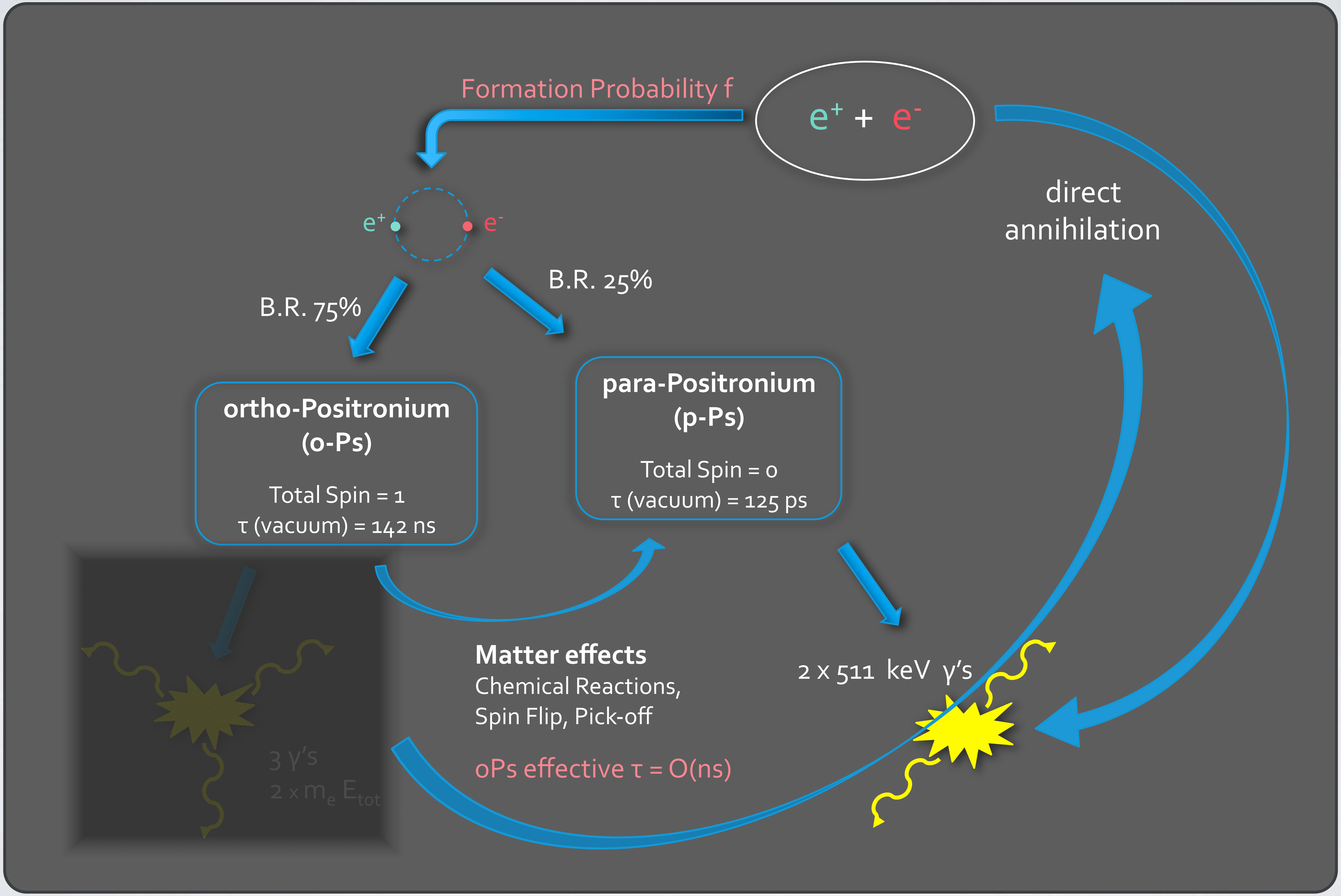
- RRM combined fit using n-Gd and n-H $\overline{\nu}_e$ candidates:

$\sin^2(2\theta_{13})$=0.102±0.028(stat.)±0.033(syst.)

Positronium formation



Positronium formation



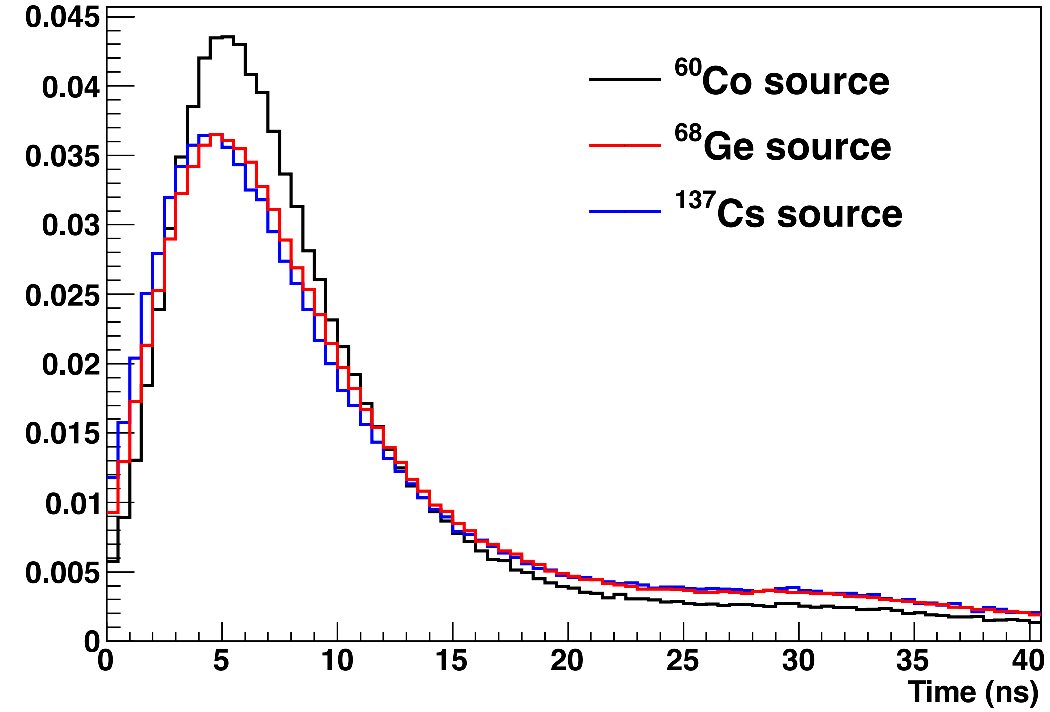
ortho-Positronium observation in DC

- The o-Ps lifetime has been measured with a dedicated setup in DC liquids, it is about 3.4 ns.
- The time between the 2 processes i.e. e^+ ionization signal and the two 511 keV γ-rays emission is no longer negligible which permit to distinguish them.
- We developed an algorithm to select the events in which o-Ps was formed, based on the presence of a double bump signature on the Pulse Shape (PS) distribution.

- The PS of one event is made of the distribution of the arrival time of the pulses recorded by each PMT (around 300 pulses per event).
- The PS of neutrino events is similar to that of radioactive sources (^{60}Co or ^{137}Cs), even if an energy dependence is noticeable.

PS distribution for radioactive sources in the center of the target

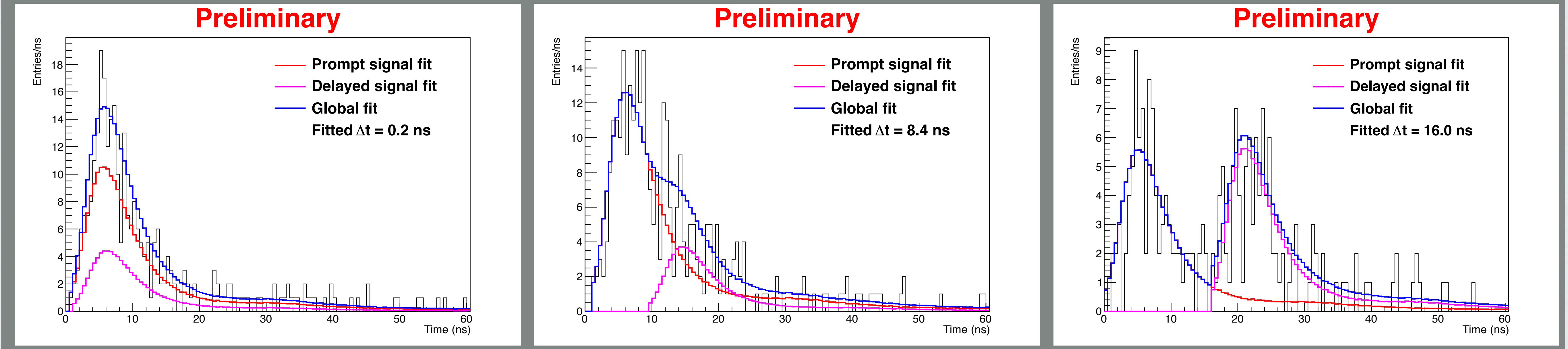
Preliminary



ortho-Postronium tagging algorithm in DC

- We assume that each signal has a PS as the one obtained for Co (Cs) events that we use as reference.
- A fit function is built with the combination of 2 reference PS separated by a delay Δt.
- The fit is meaningful for energy range 1.2-3 MeV (at high energy, the 2nd signal is hidden by the tail of the 1st one).

o-Ps fit examples on neutrino events (Gd analysis)

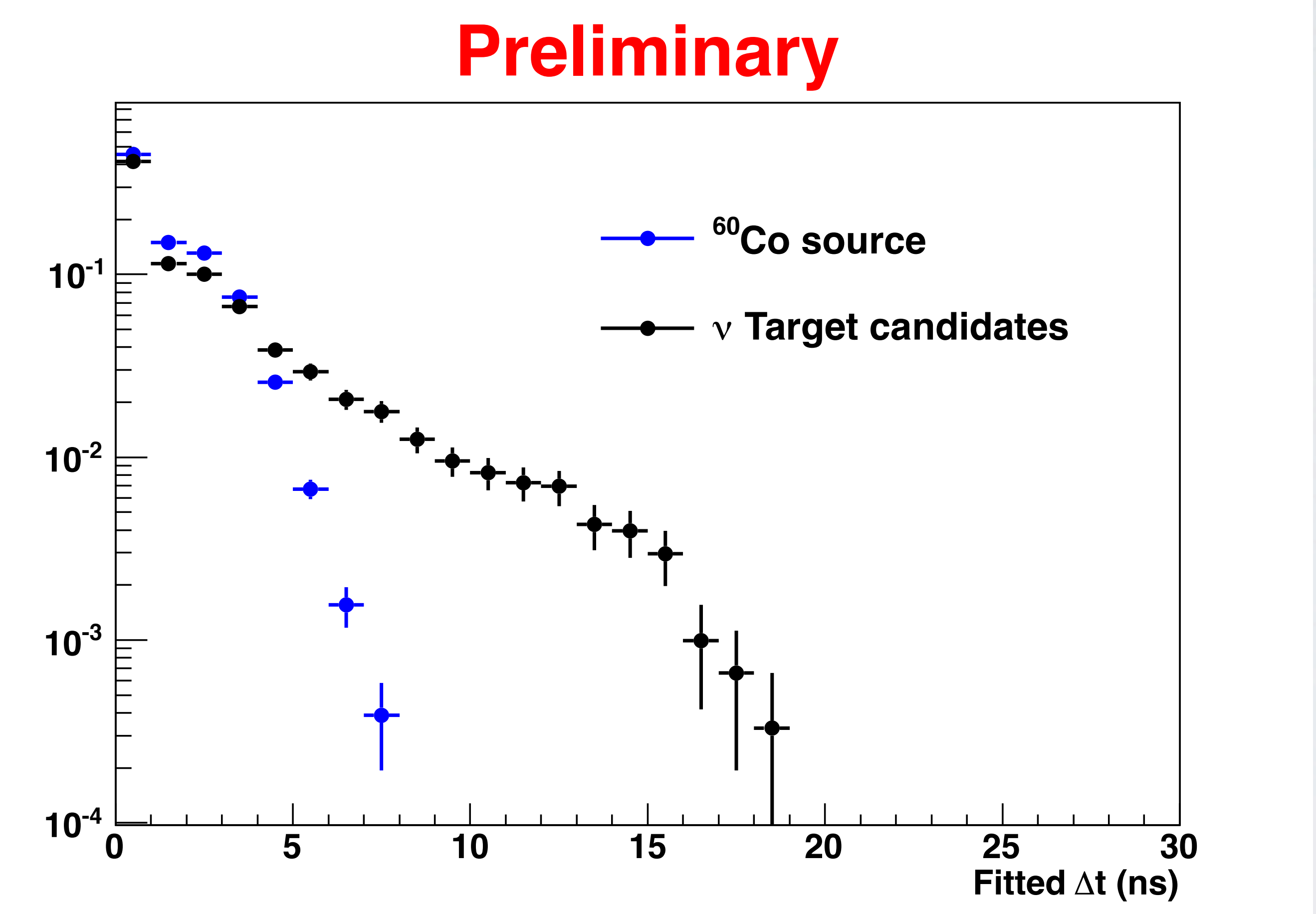


ortho-Postronium observation

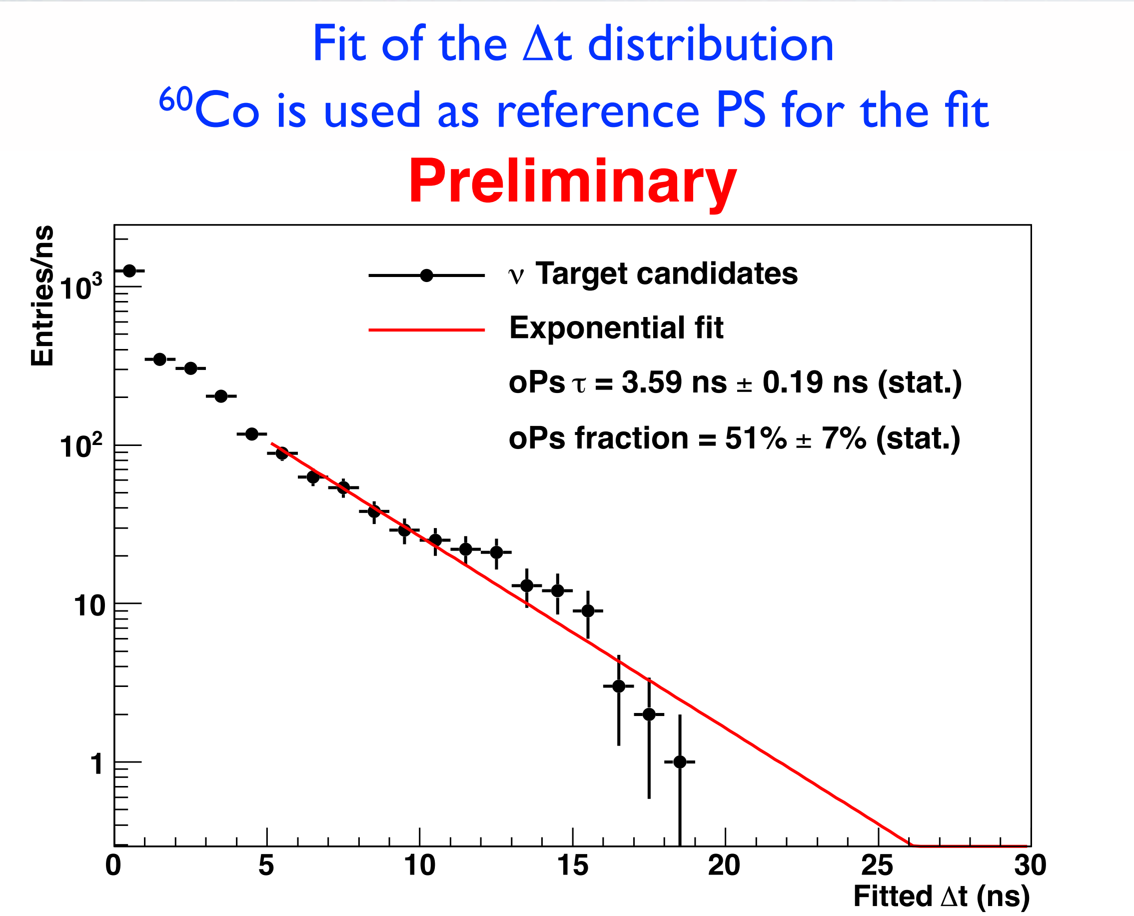
- Comparing Co Δt distribution (where no o-Ps is expected) with neutrino distribution, we observe a clear excess of events at large Δt.

- The lifetime and the o-Ps production fraction are estimated fitting the Δt distribution with an exponential function.

Δt distribution determined by the fit



ortho-Positronium measurement



- Taking into account the energy dependence on the PS and the low energy events selection (1.2-3 MeV), the final values are computed as the average between Co and Cs as reference PS for the fit.

	oPs fraction(%)	**oPs lifetime (ns)**
Measured with DC using ^{60}Co and ^{137}Cs ref. PS with all syst.	42 ± 5(stat.) ± 12 (sys.)	3.68 ± 0.15(stat.) ± 0.17(sys.)
Measured with the dedicated setup NuToPs	47.6 ± 1.3	3.42 ± 0.03

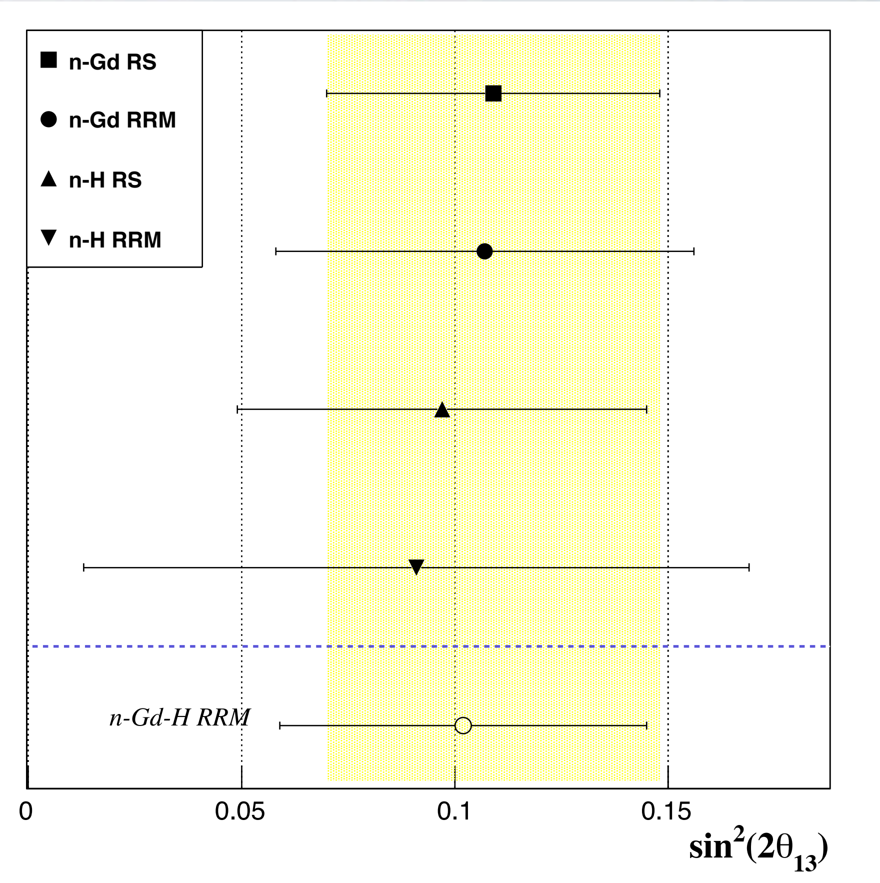
- The results are in good agreement with the expectations.
- First observation of the o-Ps on an event-by-event basis in a reactor experiment.
- The detection of the o-Ps is an additional handle for background reduction in anti-neutrino interaction experiments.

Summary/Conclusions

- **Only with Far Detector:**
  - Double Chooz provided independent measurements of θ_{13} (Gd and H n-capture).
  - Results on θ_{13} are achieved combining Gd and H analysis:

    $$\sin^2(2\theta_{13})=0.109\pm0.035$$

  - Background-model-independent measurement of θ_{13} (Reactor Rate Modulation).



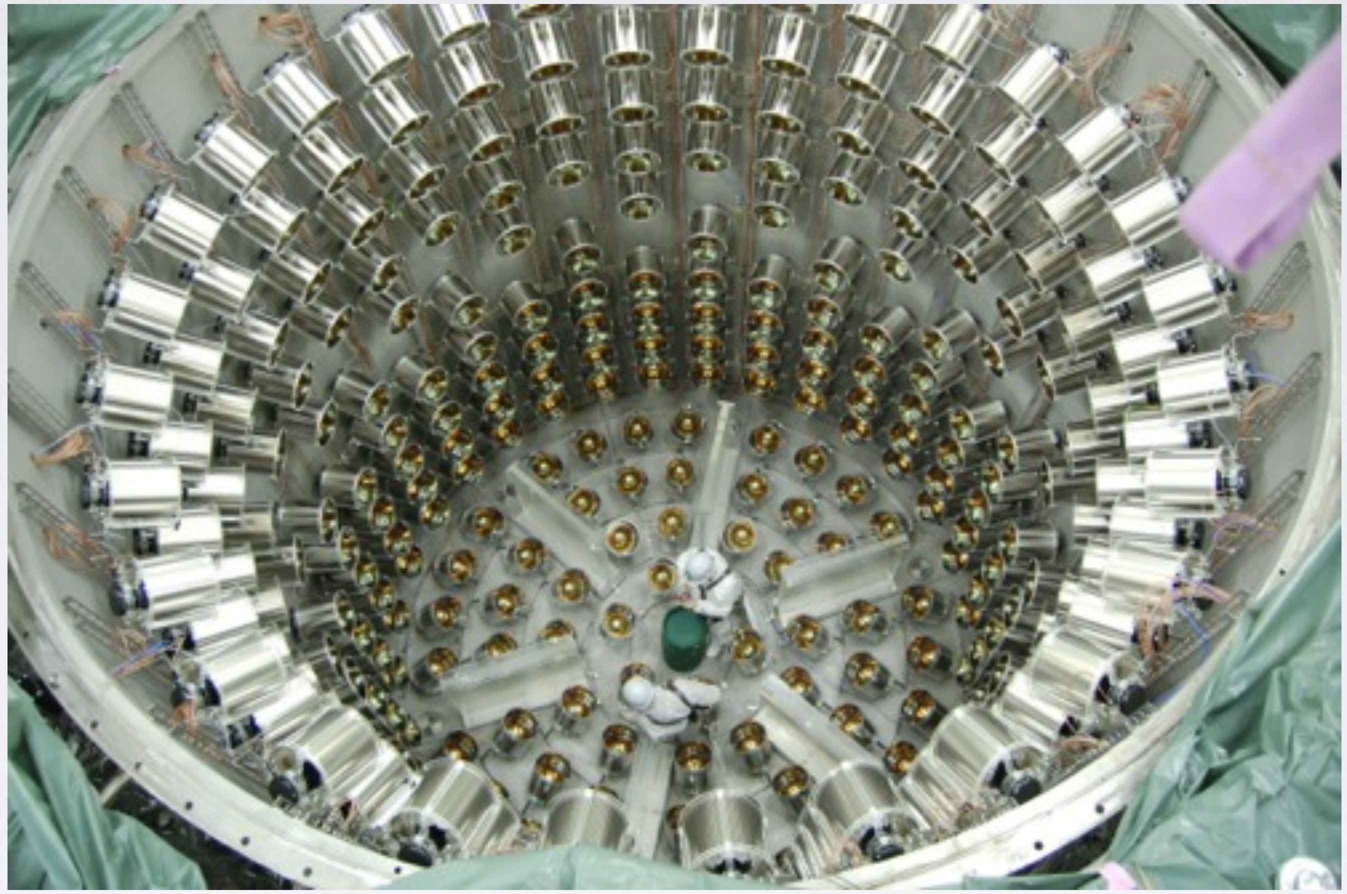
- **The Near Detector is under construction:**
  - The start of data taking is foreseen middle of 2014.
  - With two detectors, the final precision will be about 10%.

- **Double Chooz collaboration has performed physics beyond θ_{13}:**
  - Background studies (reactor off-off) *(PRD 87, 011102(R), 2013)*
  - Lorentz violation *(PRD 86, 112009, 2012)*
  - Neutrino directionality
  - Ortho-Positronium observation

Interesting for background rejection in $\bar{\nu}_e$ physics, in particular when looking at particular sources such as a core-collapse supernovae, geo-neutrinos or for nuclear reactor monitoring.

Summary/Conclusions and Collaboration

Near Detector -December 2013



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
- U. Hamburg

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- Tokyo Metro. U.
- Niigata U.
- Kobe U.
- Tohoku Gakuin U.
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- IIT
- KSU
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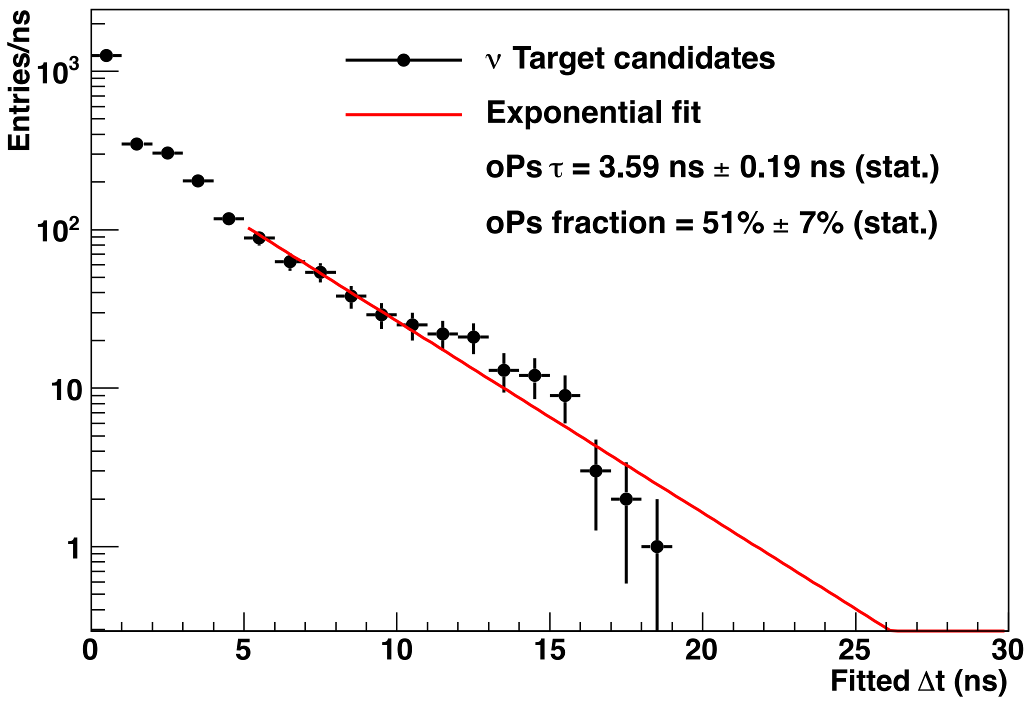
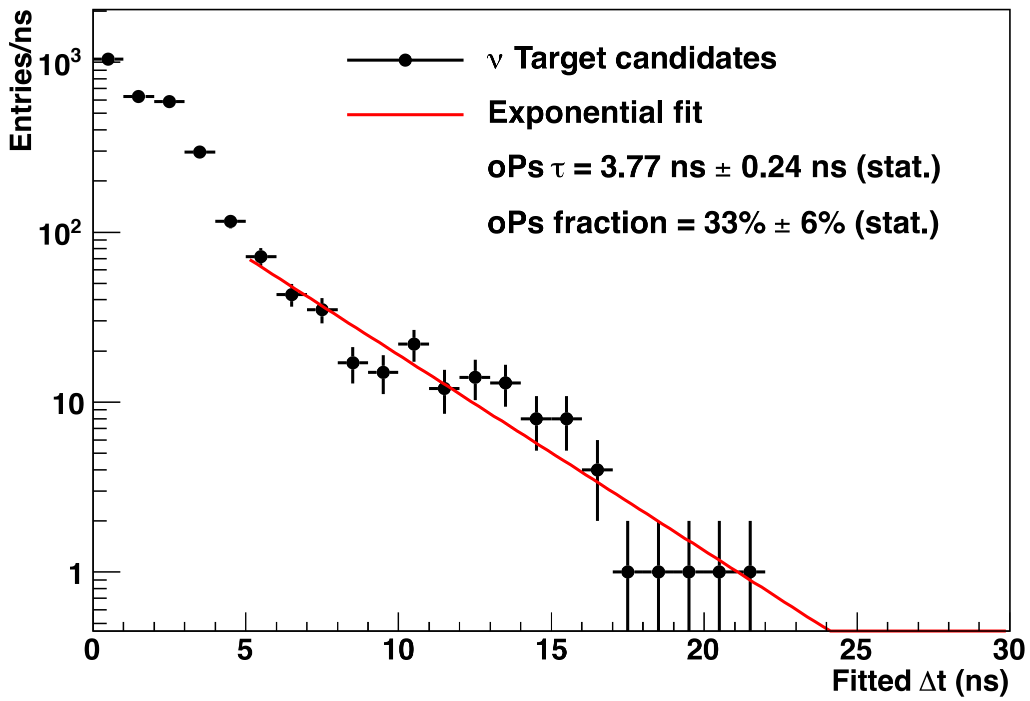
- MIT
- U. Notre Dame
- U. Tennessee

ortho-Positronium measurement

Fit of the Δt distribution
^{60}Co is used as reference PS for the fit
Preliminary



Fit of the Δt distribution
^{137}Cs is used as reference PS for the fit
Preliminary



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