Double Chooz Achievements

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on behalf of the Double Chooz Collaboration

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Topics:
Measuring θ_{13} with Reactor Antineutrinos
Double Chooz Experiment
Double Chooz Results

Neutrino Flavor Transitions

Given the massive neutrinos, there is no known symmetry which would imply that the neutrino flavor eigenstates (states of the weak interaction) are the same with the neutrino mass eigenstates (states of the free particle Hamiltonian).

$$|\nu_\alpha\rangle = \sum U_{\alpha i} |\nu_i\rangle$$

$$U_{\alpha i} = \begin{pmatrix} 1 & & \\ & c_{23} & s_{23} \\ & -s_{23} & c_{23} \end{pmatrix} \begin{pmatrix} c_{13} & & s_{13} e^{-i\delta} \\ & 1 & \\ -s_{13} e^{i\delta} & & c_{13} \end{pmatrix} \begin{pmatrix} c_{12} & s_{12} & \\ -s_{12} & c_{12} & \\ & & 1 \end{pmatrix} *$$

where $c_{ij}=\cos\Theta_{ij}$, $s_{ij}=\sin\Theta_{ij}$ and δ is the CPV phase and $-\pi \le \delta \le \pi$

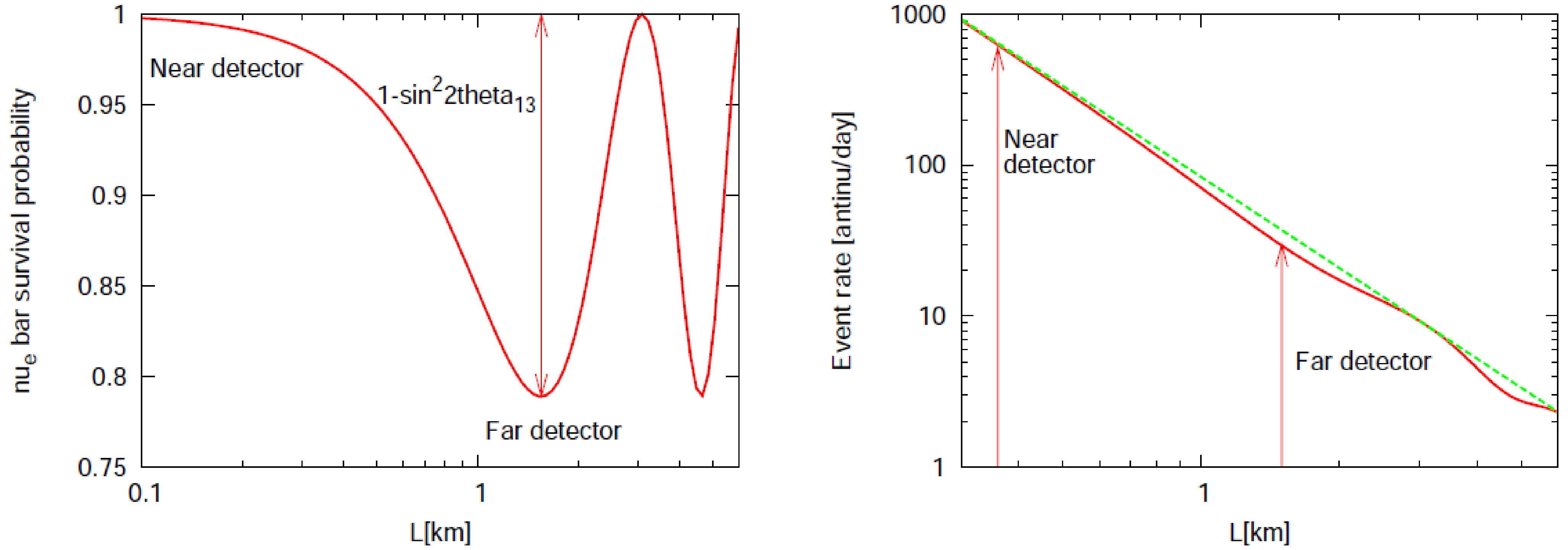
* for Majorana neutrinos, there are additional CPV phases.

Oscillation parameters: 3 mixing angles, 2 Δm^2 differences, 1 CPV phase.

Need sizeable Θ_{13} for access to δ CPV phase.

Antineutrino Oscillations at Short Distances

$$P(\overline{\nu}_e \rightarrow \overline{\nu}_e) = 1 - \sin^2(2\theta_{13}) \cdot \sin^2\left(\frac{1.27 \cdot \Delta m^2_{31}[eV^2] \cdot L[m]}{E[MeV]}\right)$$

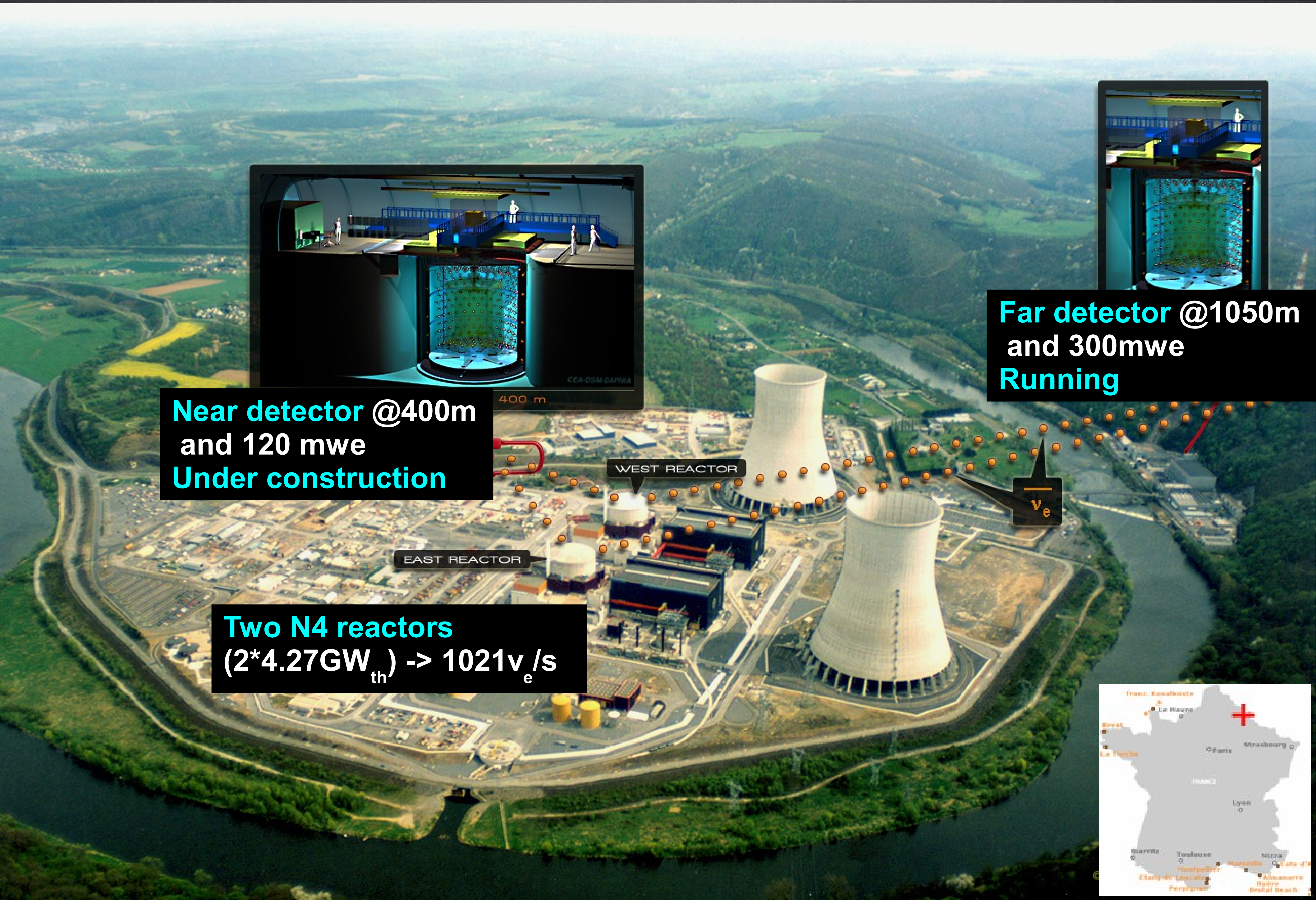


«Pure» θ13 measurement: free of CPV and mass hierarchy dependence.

Flux and spectrum are compared with the no oscillation hypothesis.

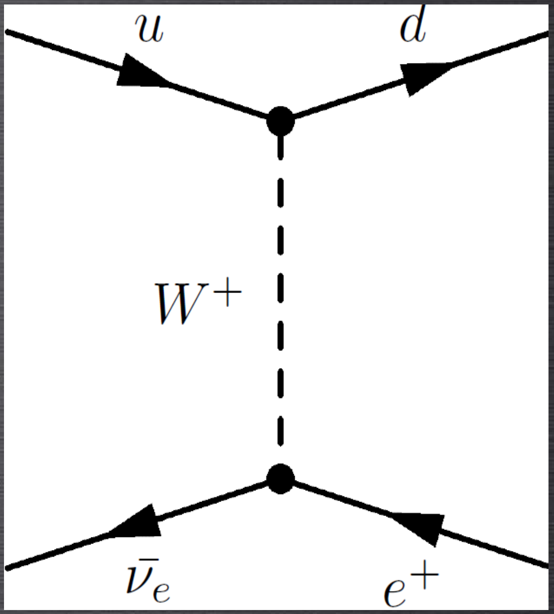
Identical detectors: cancellation of the source induced uncertainties.

(Double) Chooz Site



Reactor Antineutrinos and Their Detection

$\bar{\nu}_e$ from fission products (^{235}U, ^{238}U, ^{239}Pu, ^{241}Pu):
→ well-understood source.
Pure, intense and completely isotropic ν_e flux.
<E>~3MeV, detection via inverse beta decay in liquid scintillator:



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

Prompt event: dE/dx of e^+ and e^+e^- annihilation: E_p=1-8 MeV
Delayed event: nuclear capture: E_d= 8MeV (Gd)

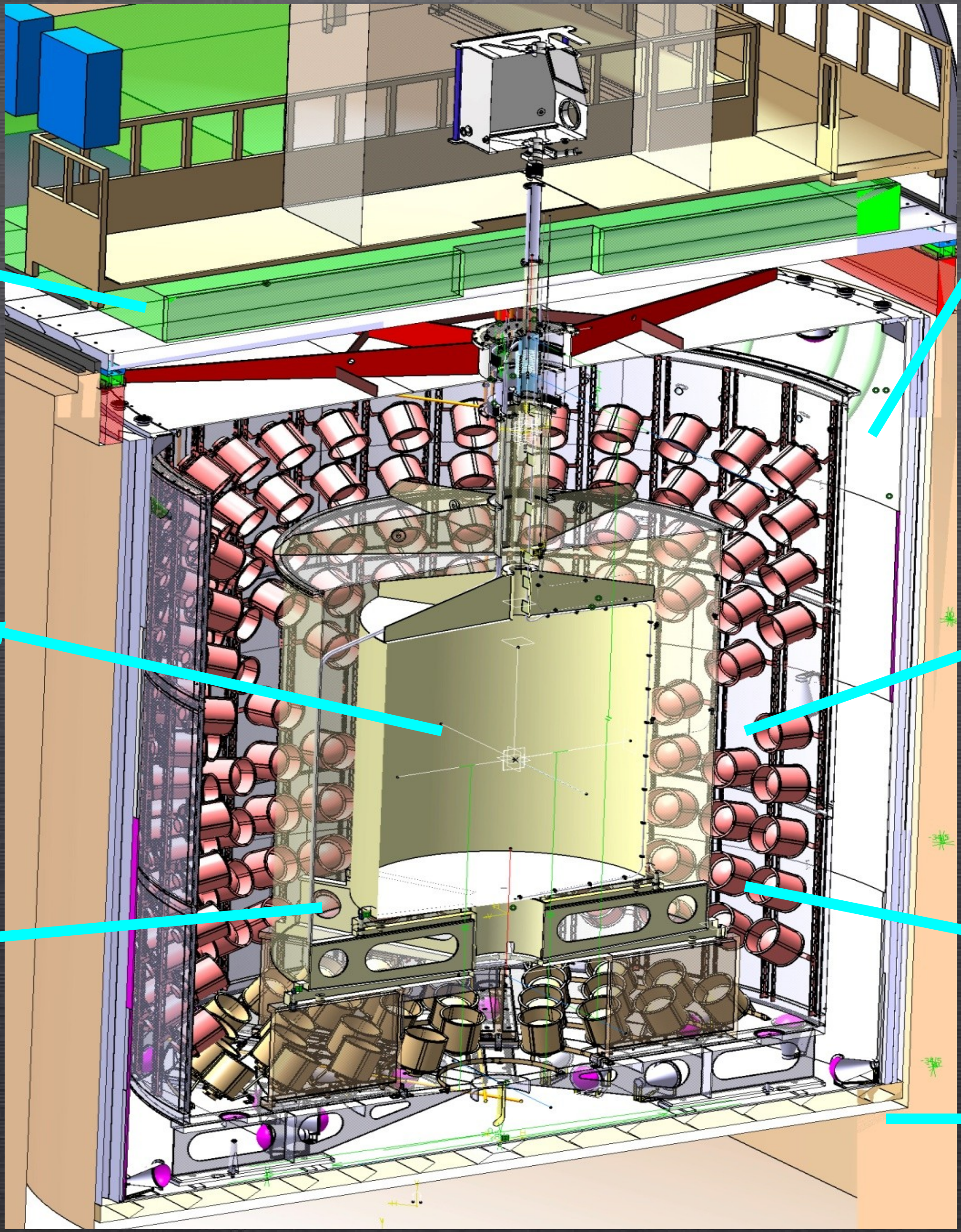
Space (1m) and time (30µs) correlation between prompt and delayed events
→ powerful background rejection.
Antineutrino energy can be directly measured: $E_p = E_\nu - 0.8$MeV
No background from other neutrino species.
Protons abundant in liquid scintillator.
Low energy threshold (1.8MeV).

Double Chooz Detector

Outer Muon Veto (plastic scintillator planes) tags near passing muons

Target, ν_e **interaction volume,** acrylic vessel 10.1m³ Gd doped LS

Gamma Catcher ν_e **interaction extra-volume,** acrylic vessel 22.6m³ LS



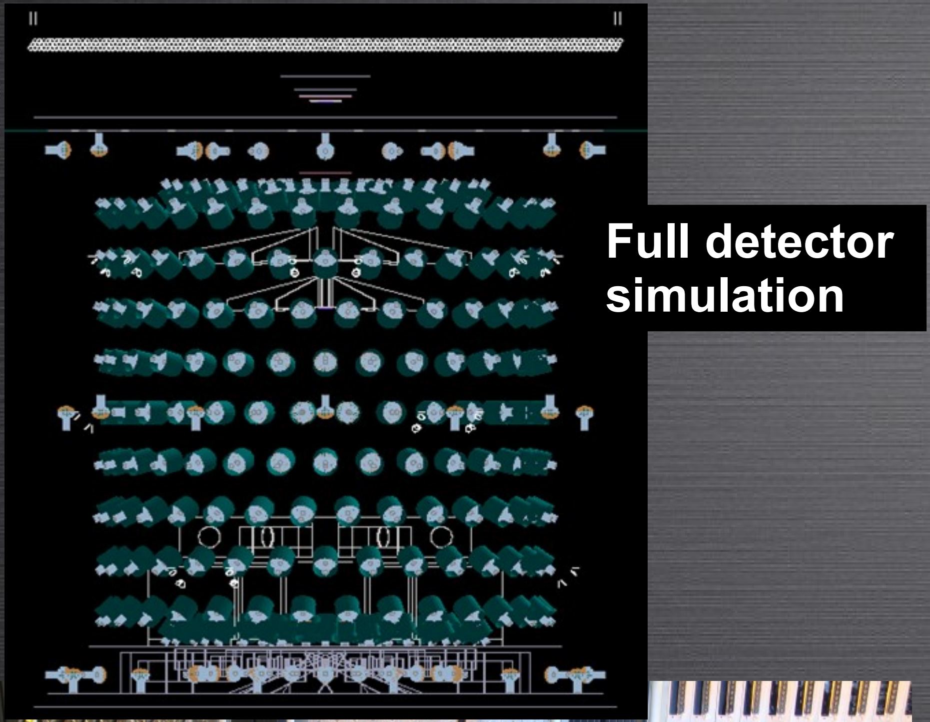
Muon Inner Veto, tags traversing muons and fast-n, stainless steel vessel 80m³ LS, 78 PMT (8inch)

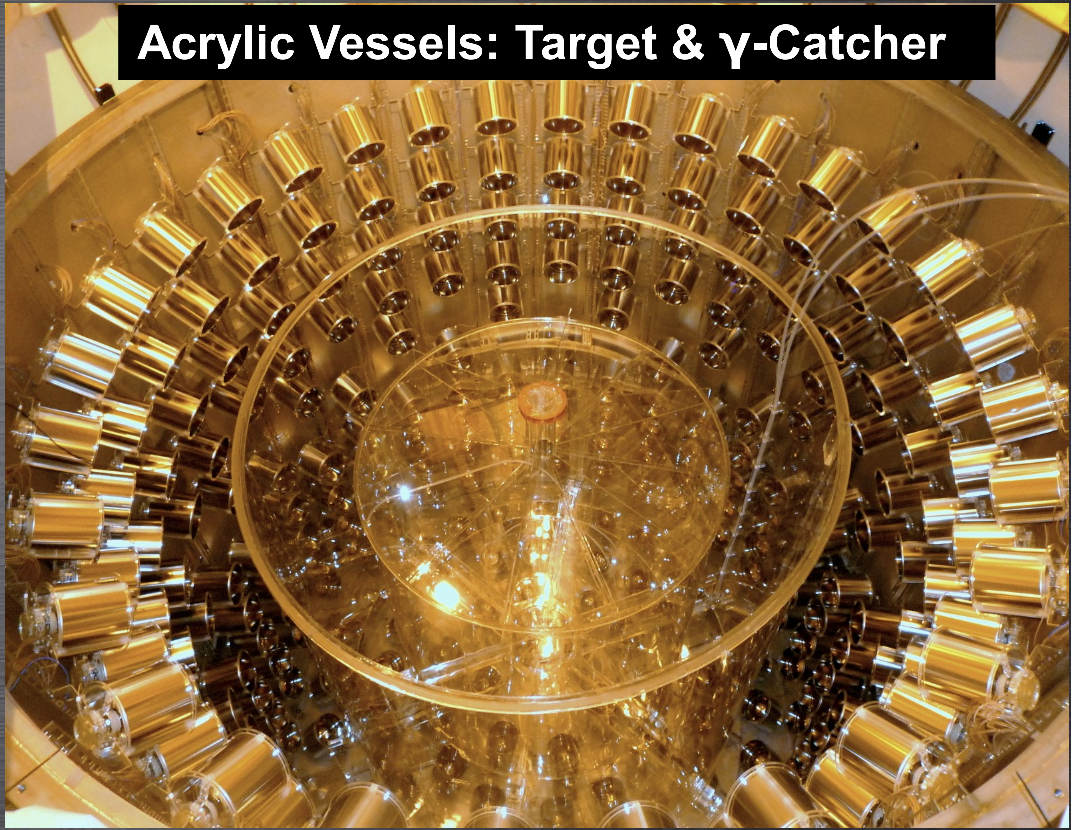
Buffer, isolates the Target from PMTs reducing background, stainless steel vessel 114.2m³ mineral oil

390 PMT (10 inch)

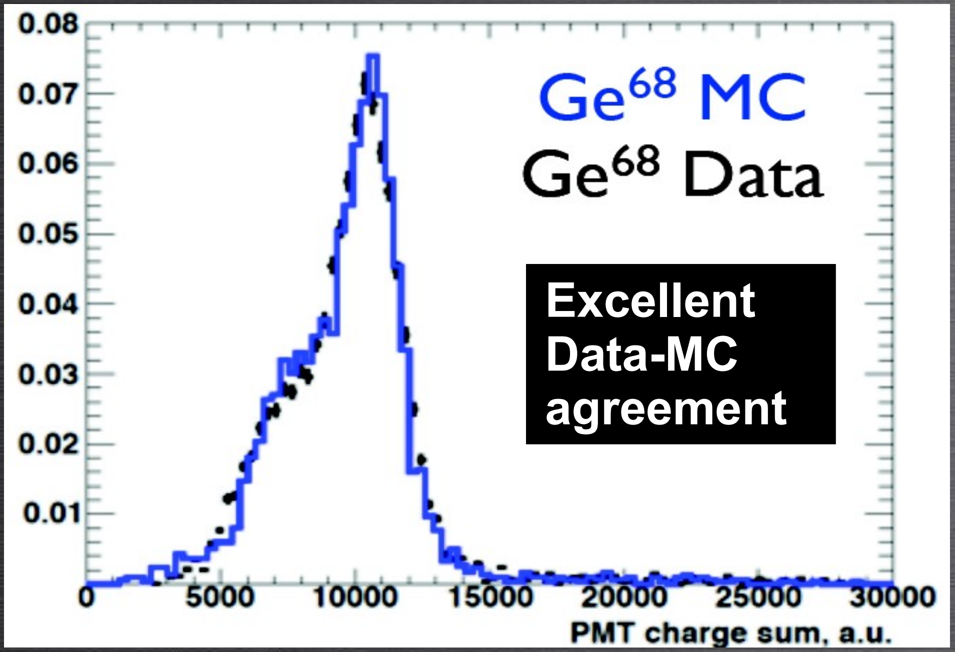
Shielding, reduces radioactivity from the rock, steel 17cm

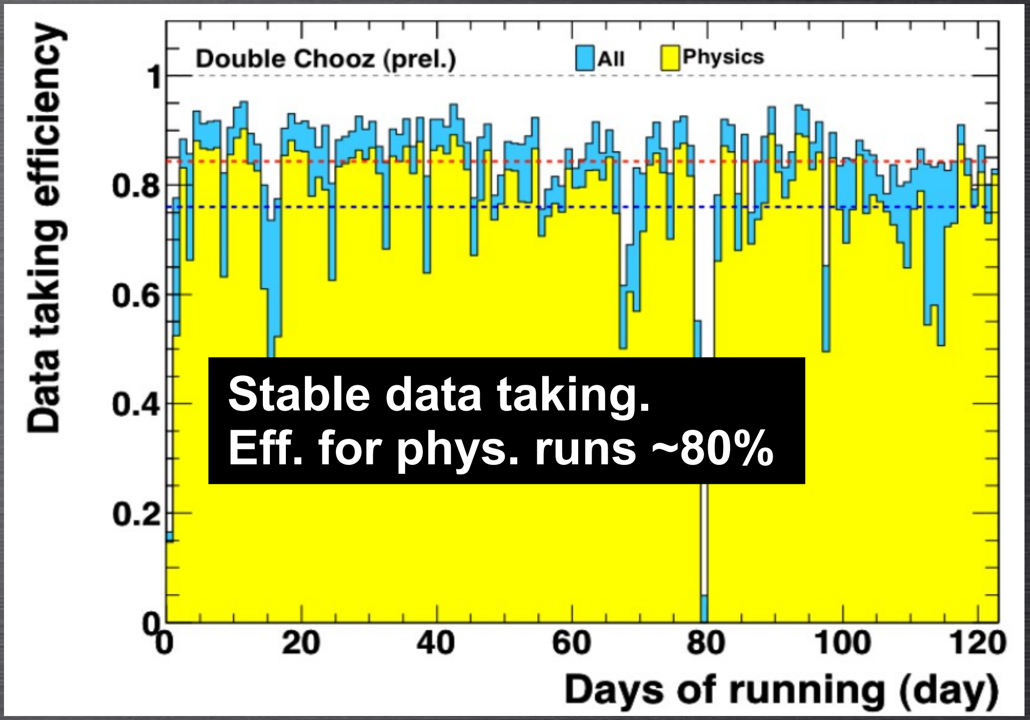
Far Detector Outlook

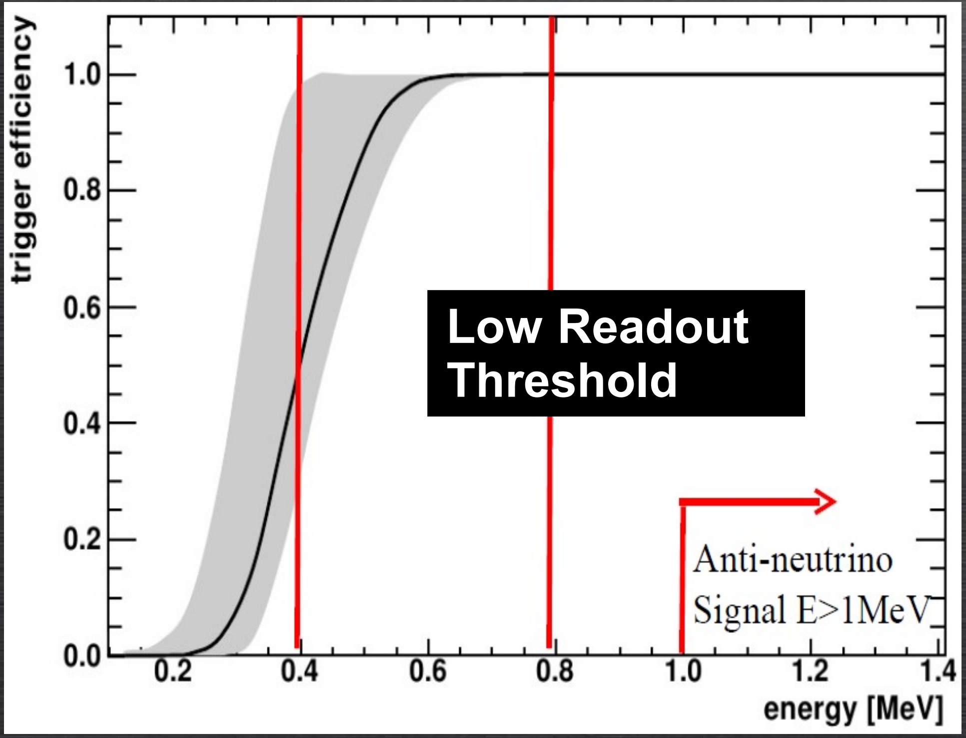


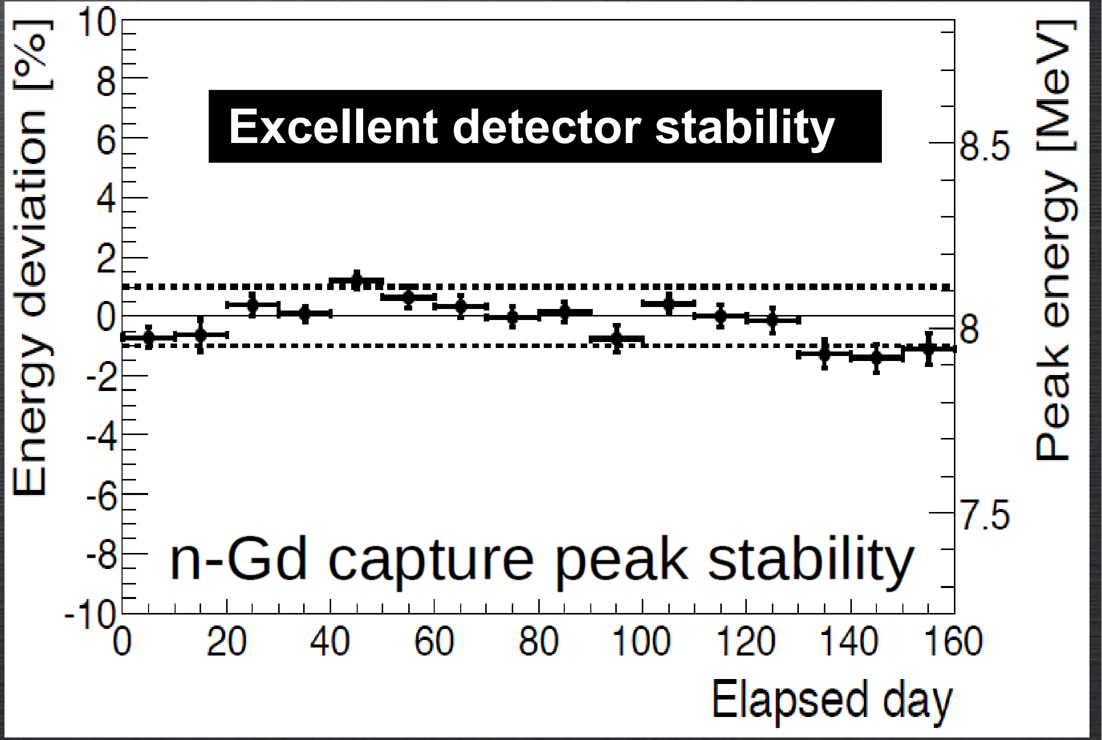


Far Detector Performance

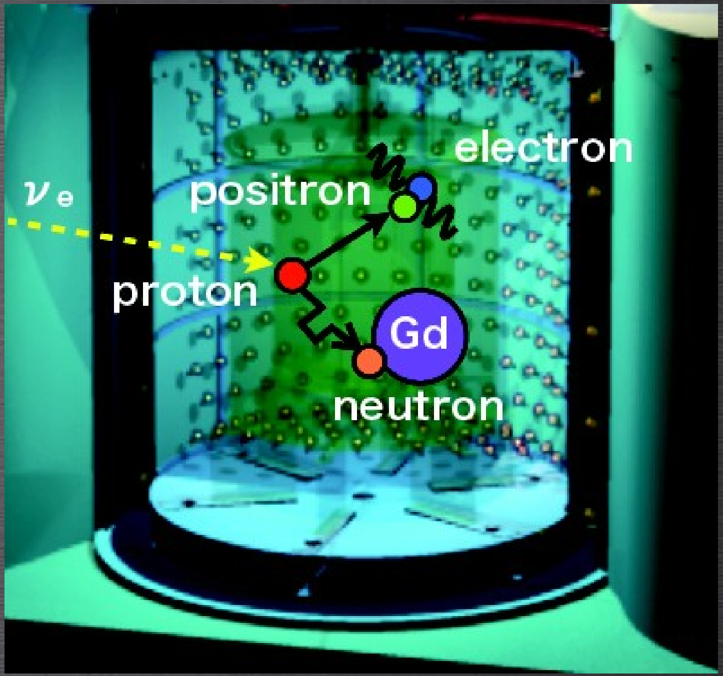








Neutrino Candidates Selection



Prompt event: Energy between 0.7 and 12 MeV.

Delayed signal: Energy between 6 and 12 MeV.

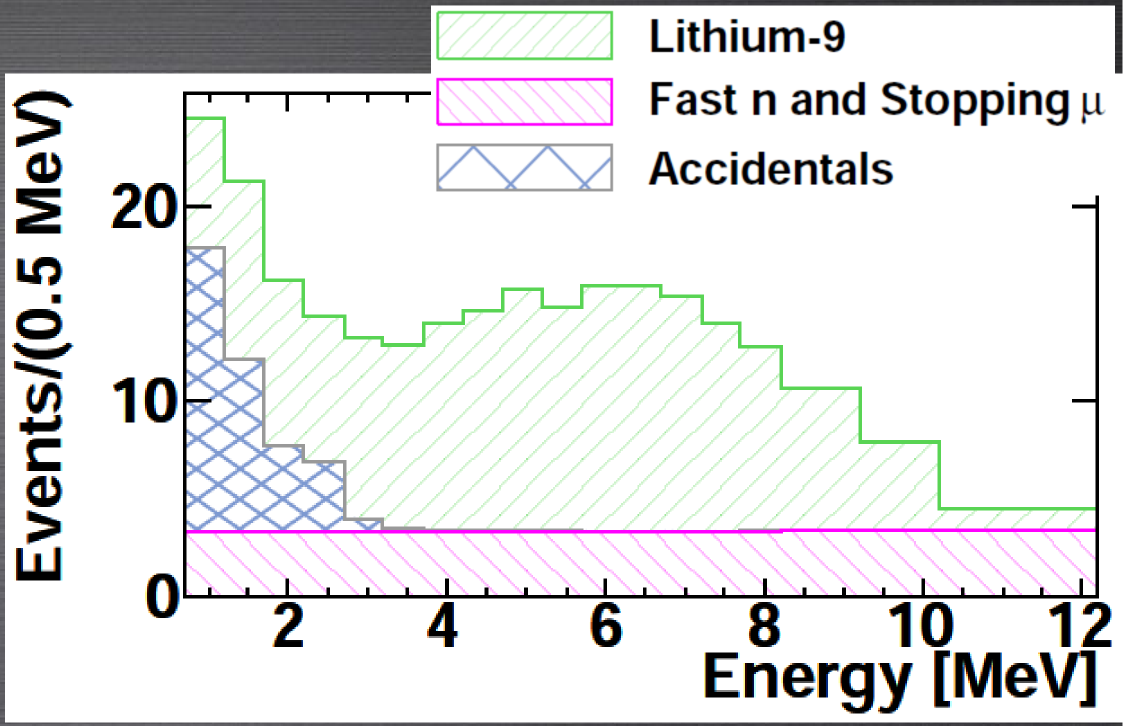
Coincidence time window: 2 to 100 μs.

Muon Veto: Discard all trigg. at 1ms after a muon.

Multiplicity:
No trigger with energy >500keV between prompt and delayed.
No trigger 100μs before or 400μs after the prompt.

PMT spontaneous light emission rejection cuts (14 ID PMT switched OFF).
Ensure light approx. homogeneously spread across (use ratio Qmax/Qtotal).
Ensure light arrives at approx. the same time (use RMS of hit-time per PMT).

Background Estimation

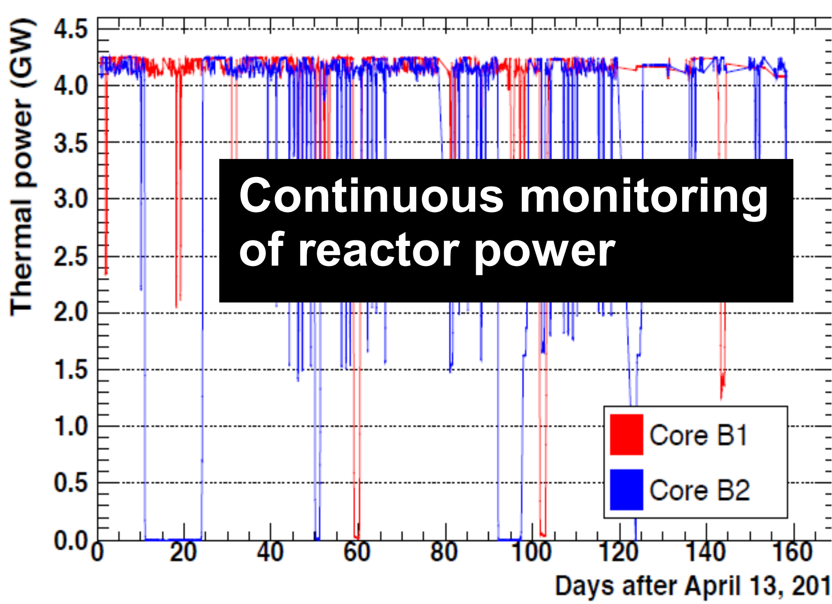


Accidentals: 0.332±0.03 ev/d
Environmental γ + n capture
Estimated with:
off-time window (1,100)ms.

Correlated - Fast neutrons: 0.8±0.4 ev/d
Recoil p + n capture
Estimated with: off-energy window (12,30) MeV.

Correlated – cosmogenic: 2.3±1.2 ev/d
n + β decay (9Li→8Be + n + e-)
Estimated with: time correlation with showering muons of the selected neutrino candidates.

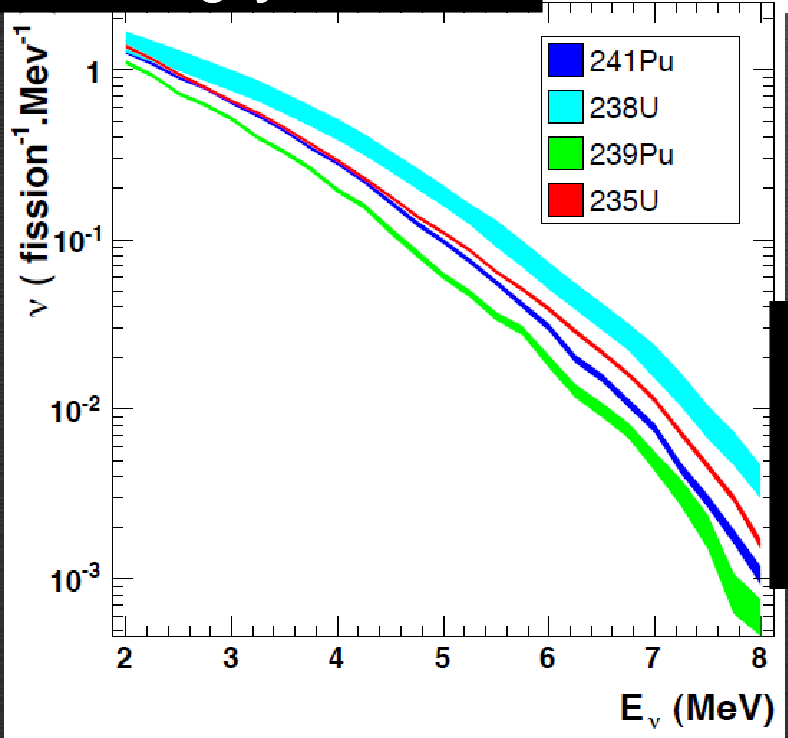
Neutrino Flux Prediction



Without Near Detector we have to use the predicted neutrino rate for oscillation analysis:

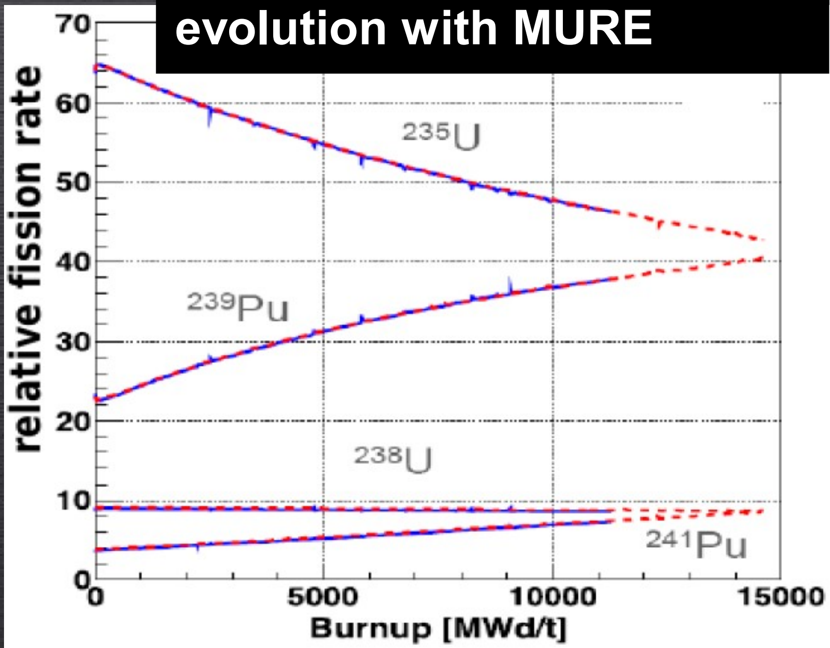
$$N_{\nu}^{\exp}(E,t) = \frac{N_p \varepsilon}{4\pi L^2} \times \frac{P_{th}(t)}{\langle E_f \rangle} \times \langle \sigma_f \rangle$$

mean cross section per fission normalized with Bugey4 data

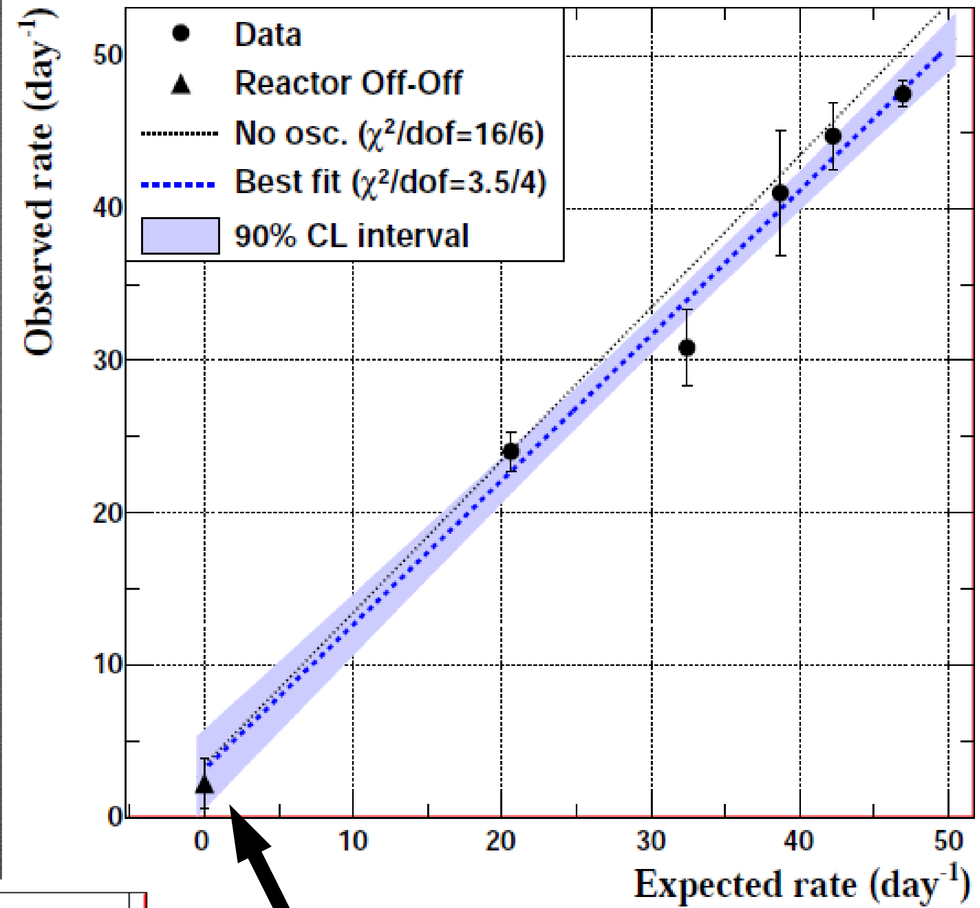


Reference spectra:
Th.A.Mueller et al., Phys.Rev.C83(2011)
P.Huber, Phys.Rev.C84(2011)

detailed simulation of core evolution with MURE

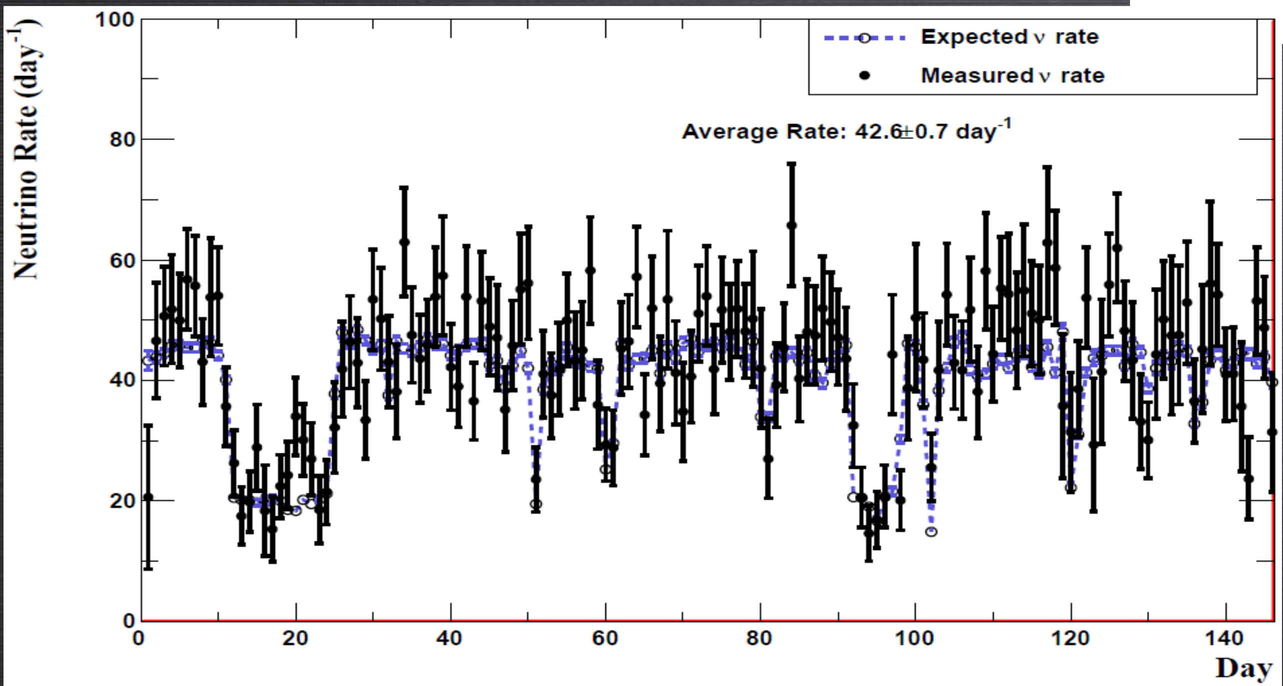


IBD Candidates Rate



Good correspondence to reactor power history → low background level in detector

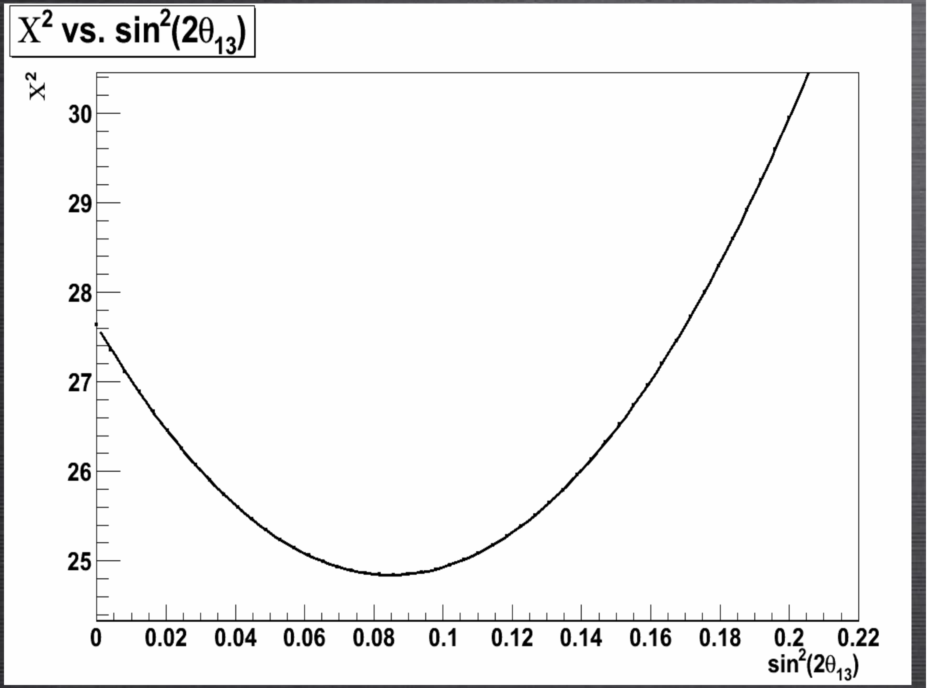
Background from fit: 3.2±1.3/d

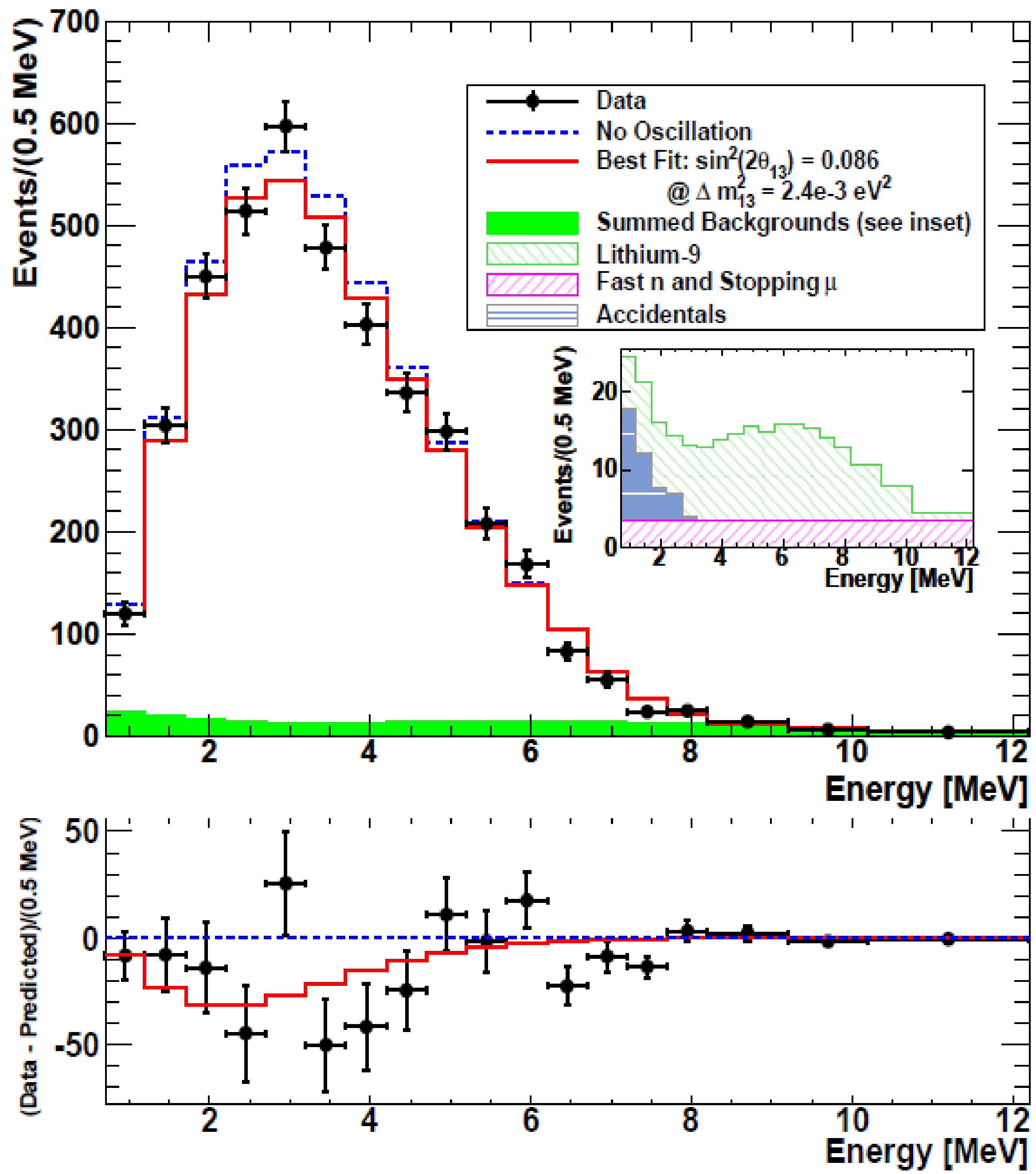


Reactor OFF-OFF: unique opportunity to validate background estimation.

2 candidates found in ~24h (following high energetic muons -> ^{9}Li like events) **consistent with background estimation.**

Rate+Shape Fit

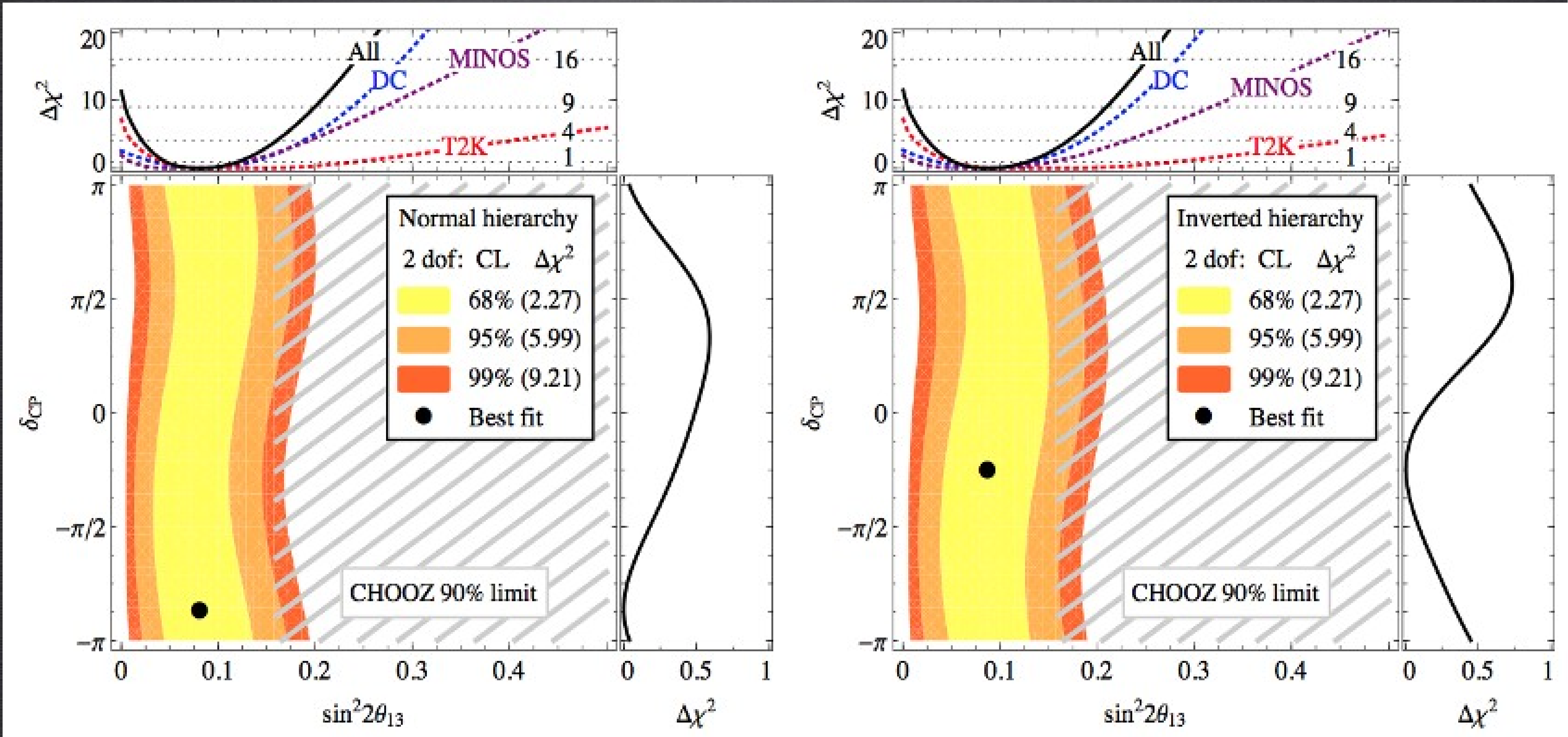




$\sin^2(2\Theta_{13}) = 0.086 \pm 0.041$ (stat.) ± 0.030 (syst.)

no-oscillation hypothesis excluded at 94.6% CL

Θ_{13} From a Global Analysis: MINOS, T2K, DoubleChooz, Daya Bay, RENO (arXiv:1111.3330v4, update 04/28/2012)

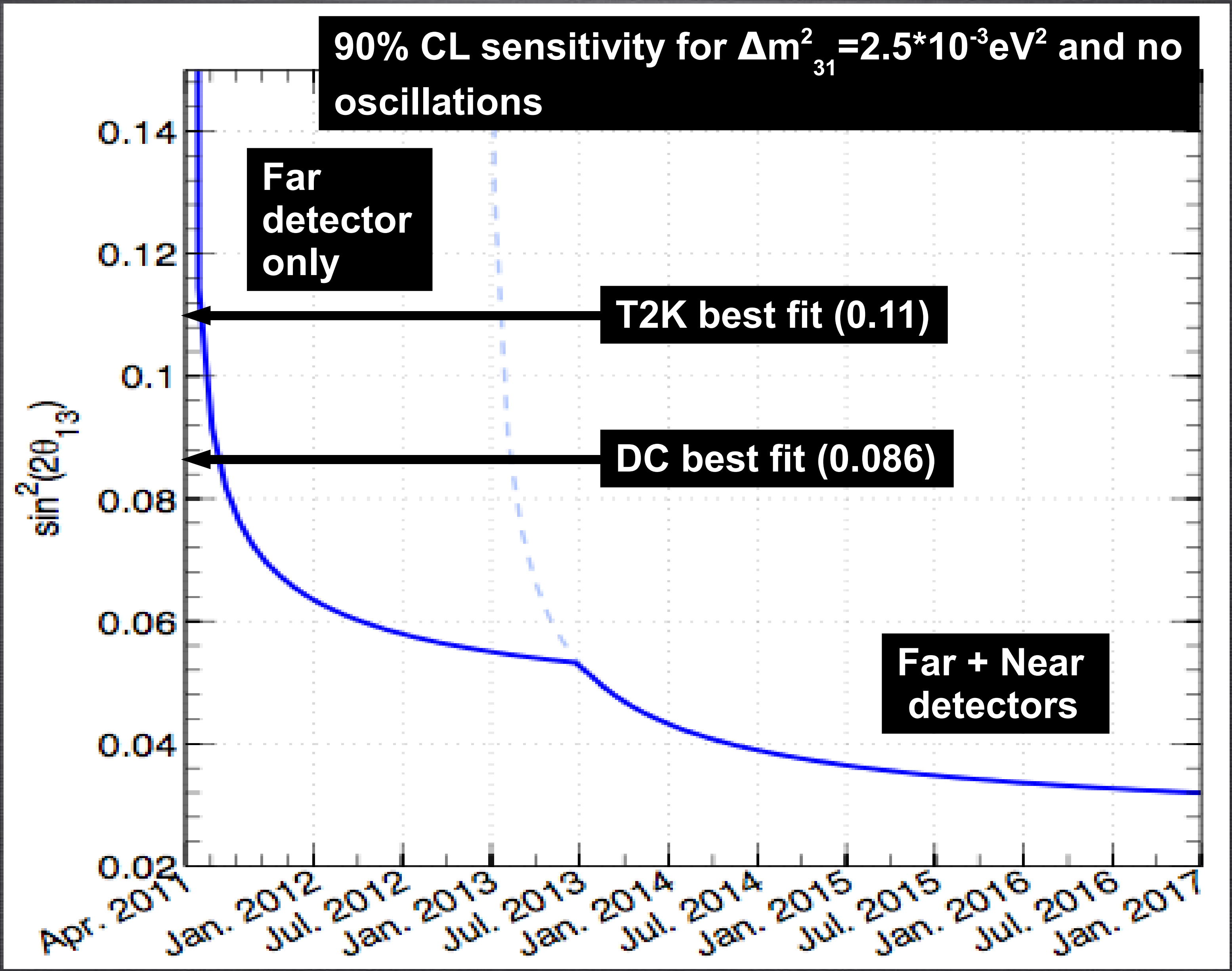


$0.026(0.03) < \sin^2 2\theta_{13} < 0.15(0.16)$ at 95%CL. Best fit: $\sin^2 2\theta_{13} = 0.083\ (0.086)$ for normal (inverted) hierarchy.

$\Theta_{13}=0$ is excluded at 3.5σ CL, for any mass hierarchy.

Looking Further:
Near Detector Progress

Looking Further: The Double Chooz Measurement



Discovery at 3σ if $\sin^2(2\Theta_{13}) > 0.05$

Outlook

Physics runs taken with Far detector since April 2011, and continuing ...
→ First oscillation result presented in: Y. Abe et al PRL 108, 131801, (2012).

Promising analysis improvements underway with two times more statistics already available → New result to be released very soon.

Near detector will start to take data in 2014. → Precise oscillation measurement.

BKP: Effect of the 'Reactor Anomaly'

In Double Chooz we used the experimental cross section per fission of Bugey-4 (with a correction from burn-up) as CHOOZ done. This method give results independent of either new physics at very short distance or mis-prediction of the neutrino flux.

BKP: Summary of Uncertainties

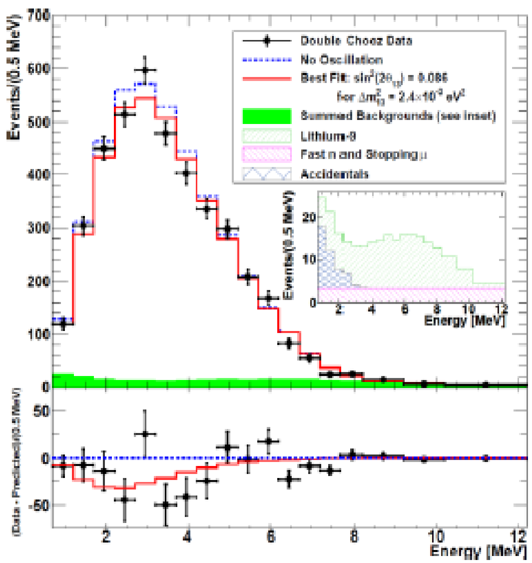
Source		Uncertainty w.r.t signal	
Statistics		1.6%	
Reactor	Bugey4 measurement	1.4%	1.8%
	Fuel composition	0.9%	
	Thermal power	0.5%	
	Reference spectra	0.5%	
	Energy per fission	0.2%	
	IBD cross section	0.2%	
	Baseline	0.2%	
Detector	Energy response	1.7%	2.1%
	E_{delay} containment	0.6%	
	Gd fraction	0.6%	
	Δt_{e+n}	0.5%	
	Spill in/out	0.4%	
	Trigger efficiency	0.4%	
	Target H	0.3%	
Background	Accidental	< 0.1%	3.0%
	Fast neutron	0.9%	
	^{9}Li	2.8%	

BKP: The Three (Neutrino) Musketeers

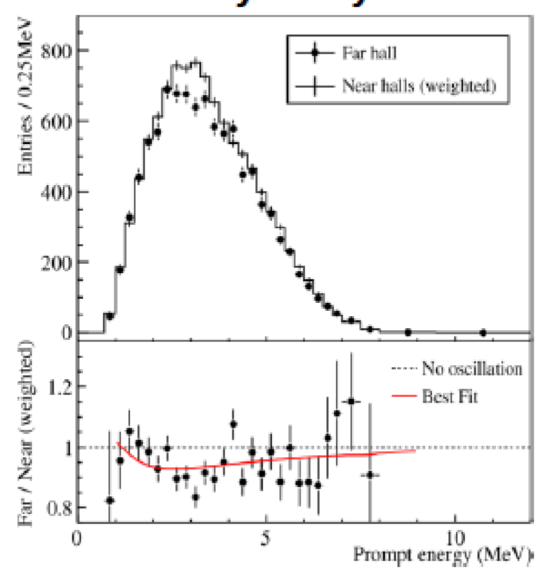
- **DC:** $\sin^2(2\theta_{13}) = 0.086 \pm 0.041(\text{stat.}) \pm 0.030(\text{syst.})$
  (rate + shape)
- **Daya-Bay:** $\sin^2(2\theta_{13}) = 0.092 \pm 0.016(\text{stat.}) \pm 0.005(\text{syst.})$
  (rate only)
- **Reno:** $\sin^2(2\theta_{13}) = 0.103 \pm 0.013(\text{stat.}) \pm$ ~~0.011~~ 0.019 (syst.)
  (rate only)

	N_{det}	V_{det}	Reactors
DC	2	8.3	2*4.25 GW_{th}
Daya-Bay	6	20	6*2.9 GW_{th}
Reno	2	16	6*2.8GW_{th}

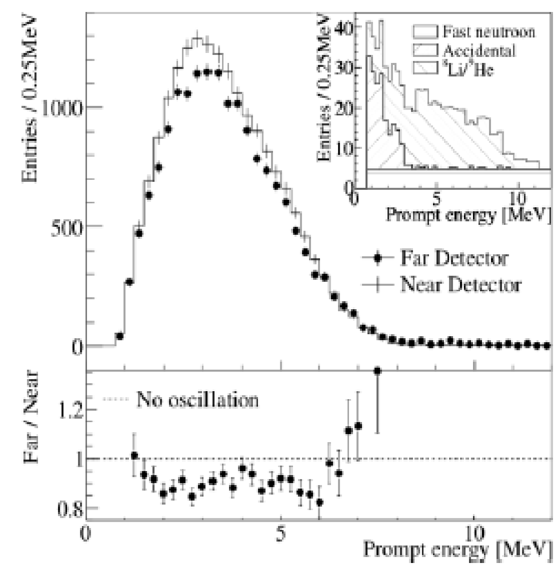
DC



Daya-Bay



Reno



Measured energy spectrum of the prompt signals from the reactor neutrinos in the far detector(s) compared with the no-oscillation prediction (Reno/Daya-Bay → Near detector(s), DC → Simulated rate)