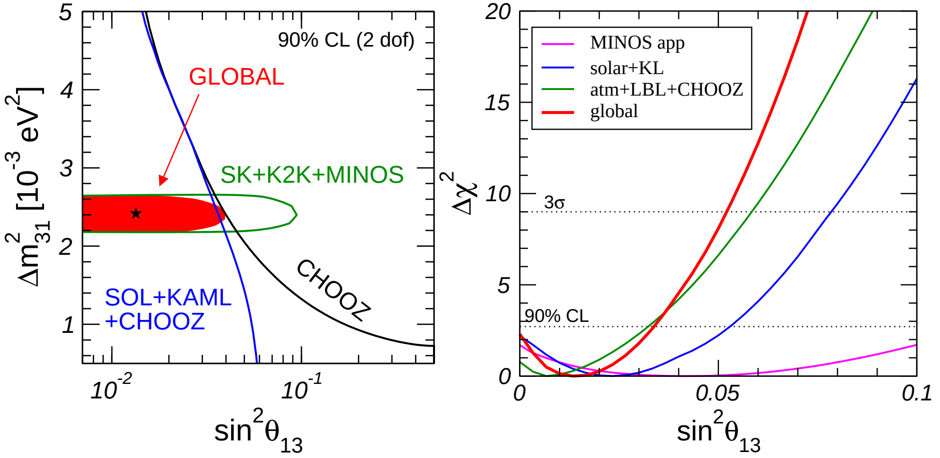
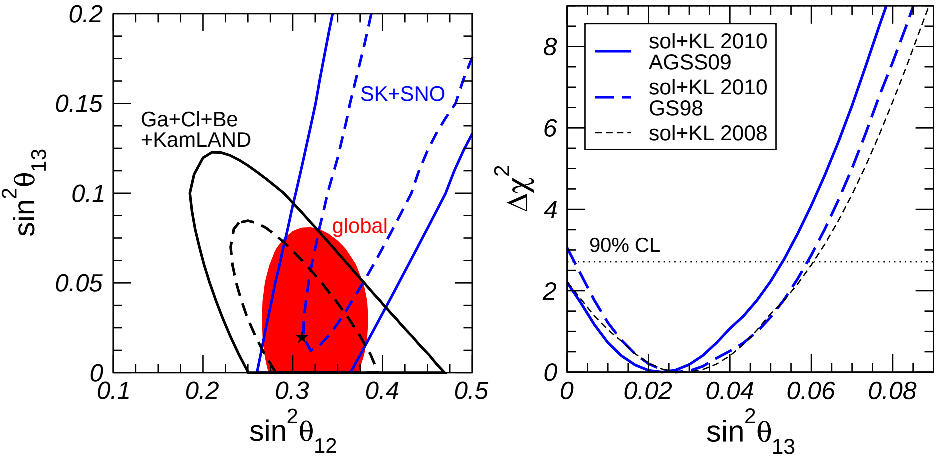
Present status of θ_{13}



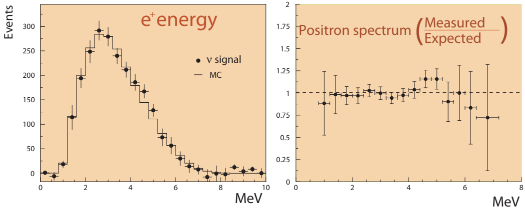
$$\begin{aligned} \sin^2\theta_{13} &\leq 0.034 \quad (0.053) \\ \sin^2 2\theta_{13} &\leq 0.13 \quad (0.20) \qquad 90\%\ (3\sigma)\ \text{CL}. \\ \theta_{13} &\leq 10.6^\circ \quad (13.3^\circ) \end{aligned}$$

Solar neutrinos prefer $\theta_{13} \neq 0$

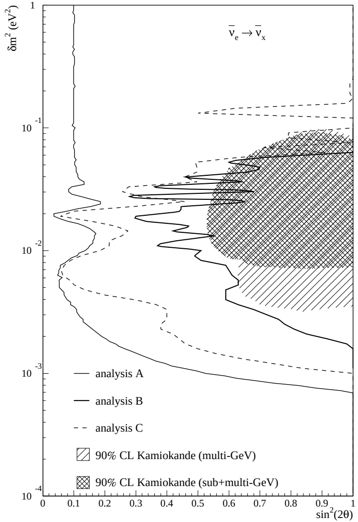


Reactor and Accelerator experiments don't see any signal

Reactors: CHOOZ (1998)

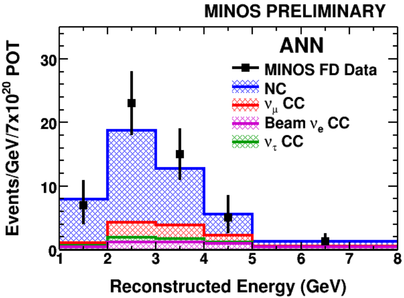


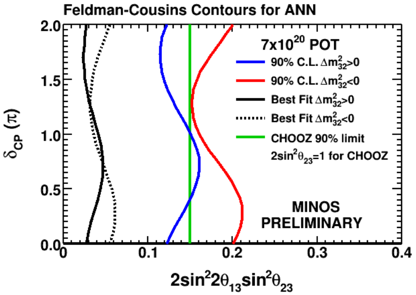
$$R = 1.01 \pm 2.8\%(\mathrm{stat}) \pm 2.7\%(\mathrm{syst})\,.$$



Reactor and Accelerator experiments don't see any signal

Accelerators: Minos (2010)



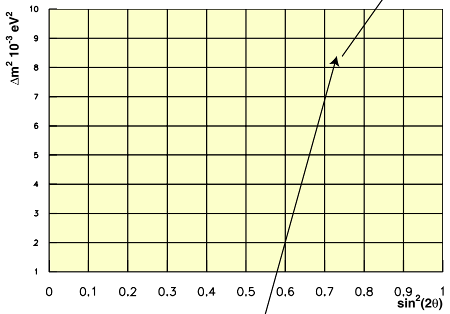


Events: 54

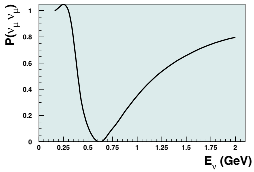
Backgrounds: $49.1 \pm 7(\mathrm{stat}) \pm 2.7(\mathrm{syst})$

How to build the signal/exclusion plot

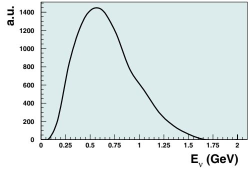
Grid in the $\sin^2 2\theta, \Delta m^2$ plane



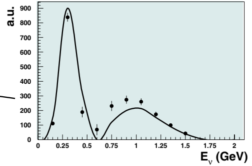
Every $\sin^2 2\theta$, Δm^2 cell defines $P_{\nu_\mu \nu_\mu}$



That modulates the non-oscillated predicted spectrum



The prediction is compared to the data



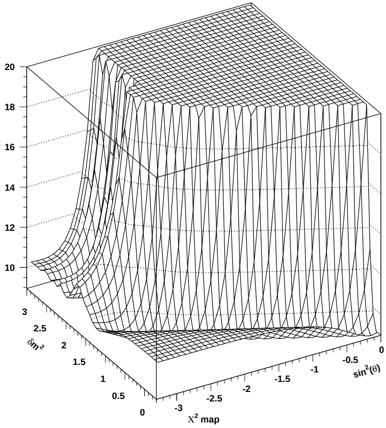
Fill the grid with the χ^2

How to build the signal/exclusion plot (II)

- The minimum of the χ^2 distribution is the best fit
- The region at a given confidence level (CL) is defined by the contour at a given $\Delta\chi^2$ from the minimum.
- The CL is computed from the probability distribution of a χ^2 at two degrees of freedom $(\sin^2 2\theta, \Delta m^2)$

Question: Why $\Delta\chi^2$ and not χ^2?
Hint: Why two degrees of freedom?

A more formal approach in G.Feldman and R.Cousins, Phys.Rev.D57:3873-3889,1998

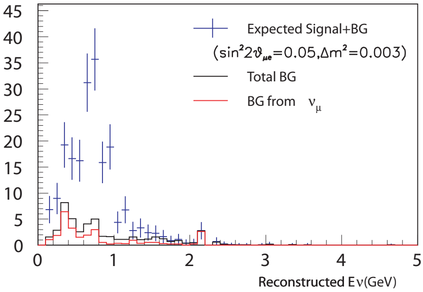


θ_{13} at reactors

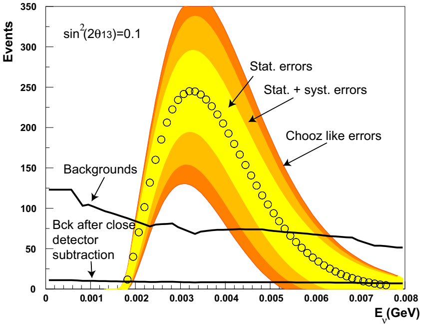
$$1 - P_{\bar\nu_e\bar\nu_e} \simeq \sin^2 2\theta_{13} \sin^2(\Delta m^2_{31} L/4E) + (\Delta m^2_{21}/\Delta m^2_{31})^2 (\Delta m^2_{31} L/4E)^2 \cos^4\theta_{13} \sin^2 2\theta_{12}$$

- $P_{\bar e \bar e}$ and θ_{13}, directly connected, no controbution by $\delta_{\rm CP}$ e $\mathrm{sign}(\Delta m^2_{23})$.
- No way to measure CP violation and mass hierarchy
- Complementary to the accelerators.
- Disappearance experiments: systematic errors dominate.

T2K appearance signal in 5 years, from hep-ex/0106019



Double Chooz FAR-Near difference in 5 years, from hep-ex/0606025



Reactor Experiments

CHOOZ result

$$R = 1.01 \pm 2.8\%(\text{stat}) \pm 2.7\%(\text{syst})\,.$$

Goal:

- Improve by a factor 5, at least, the statistical error (25 times more neutrinos)
  - Bigger detectors (CHOOZ was 5 ton fiducial)
  - More stable in time (CHOOZ took data for 8761.7 h, then stopped because liquid scintillator degraded thanks to the gadolinium.)
- Improve systematic errors by a factor 5 at least:
  - Add a close detector
  - Design a detector optimized to a better background reduction and a better control of systematics.

Neutrinos from nuclear reactors

Nuclear reactors are a very intense source of $\overline{\nu}_e$ from β decays of the fission fragments.

Every fission reaction emits about 200 MeV of energy and 6 $\overline{\nu}_e$.

$$\Downarrow$$

Flux $\sim 2 \cdot 10^{20}\ \overline{\nu}_e\ s^{-1}\ \mathrm{GWatt}^{-1}$, isotropic, $\langle E(\overline{\nu}_e)\rangle \simeq 0.5\, MeV$.

Oscillation experiments look for $\overline{\nu}_e$ disappearance at different baselines:

- $L = \mathcal{O}(1\mathrm{km}) \quad \Rightarrow$ atmospheric regime: Double Chooz, RENO, Daya Bay.
- $L = \mathcal{O}(200\mathrm{km}) \quad \Rightarrow$ solar regime: Kamland

Neutrino flux

See Bemporad, Gratta, Vogel Rev.Mod.Phys.74:297,2002

Detect absolute number of neutrino interaction and distortions of their spectrum

prompt positron signal, energy range.

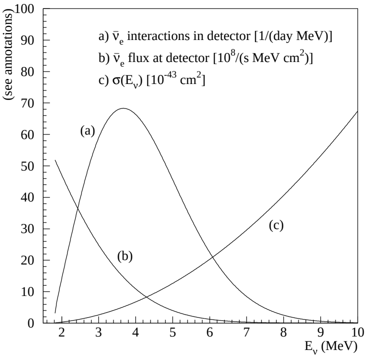
$\overline{\nu_e} p \rightarrow e^+ n$

$$n + p \underset{\tau \simeq 186\ \mu s}{\longrightarrow} d + \gamma(2.2\ MeV)$$

delayed correlated photon.

To determine neutrino flux:

1. **Measure of the reactor thermal power**
2. **Determination of the neutrino spectrum**
3. **Definition of the experimental observable: positron momentum spectrum.**

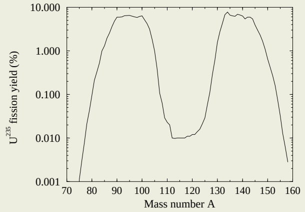


Thermal power of the reactor

The leading reaction is ^{235}U fission:

$$^{235}U + n \rightarrow X_1 + X_2 + 2n$$

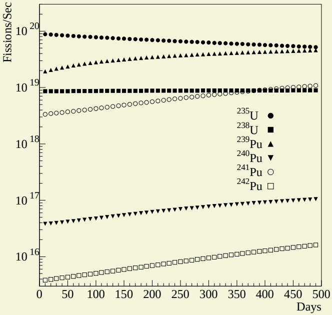
The lightest fragment have on average $A \simeq 94$, the heavier: $A \simeq 140$. Stable nuclei with $A = 94$, 140 are $_{40}Zr^{94}$ e $_{58}Ce^{140}$. ^{235}U has 98 protons and 142 neutrons $\Rightarrow$ to reach the stability, on average it needs 6 neutron β decays $\Rightarrow$ 6 $\overline{\nu}_e$.



The interaction process $\overline{\nu}_e + p \rightarrow n + e^+$ has a threshold of $\sim 1.8\,MeV \Rightarrow$ only $\sim 25\%$ of neutrinos can be detected.

All the neutrinos from low Q-value processes, as nuclear fuel stored in the reactors and radioactivity induced in the nuclear plant structures, don't produce detectable neutrinos.

The fuel composition of the reactor core changes with the time, it's under monitor (reactor power depends from its composition).



From fission rate to the $\overline{\nu}_e$spectrum

The $\overline{\nu}_e$spectrum of three of the four principal fission nuclei: (^{235}U, ^{239}Pu, ^{241}Pu), has been derived by measuring the electron spectrum. The fourth: ^{238}U, has been computed from nuclear models, as well all the processes in the decay chain. Systematic error: $\sim 1\%$.

From $\overline{\nu}_e$to positrons

$\overline{\nu}_e + p \rightarrow n + e^+$ cross section:

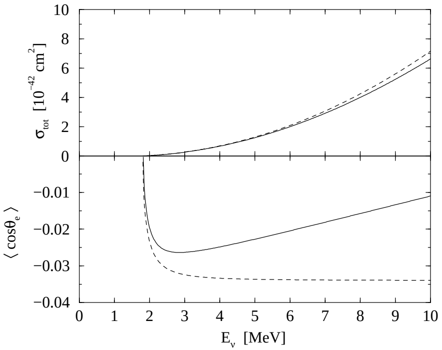
$$\sigma_{tot}^{(0)} = \sigma_0 \, (f^2 + 3g^2) \, E_e^{(0)} p_e^{(0)} = 0.0952 \left(\frac{E_e^{(0)} p_e^{(0)}}{1 \ \mathrm{MeV}^2} \right) \times 10^{-42} \ \mathrm{cm}^2 \quad (1)$$

$E_e^{(0)} = E_\nu - (M_n - M_p)$: positron energy (neglecting neutron recoil, marginal effect) $p_e^{(0)}$ momentum,

$f = 1, g = 1.26$ vector and axial coupling constants

$$\sigma_0 = \frac{G_F^2 \cos^2 \theta_C}{\pi} (1 + \Delta_{inner}^R) \ , \qquad (2)$$

radiative corrections: $\Delta_{inner}^R \simeq 0.024$.

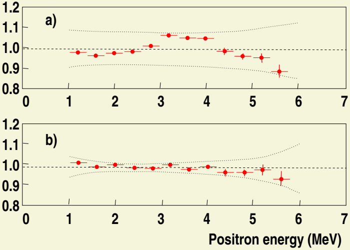


Solid lines: predictions at$\mathcal{O}(1/M_n)$, dashed $\mathcal{O}(1)$.

Data/prediction agreement

Experiment Bugey 3 (years 80', now considered a non oscillation experiment): expected and measured $\overline{\nu}_e$spectrum.

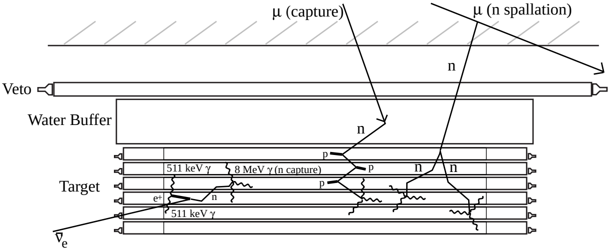
Curve b) is the most updated prediction.



Systematic errors summary (from `hep-ph/0107277`) Origin and magnitude of systematic errors in PALO VERDE and CHOOZ. Note that the two experiments offer different breakdowns of their systematics. For simplicity we do not show the systematics for the PALO VERDE ON-OFF analysis. The PALO VERDE results are from the analysis of the full data set (Boehm *et al.* 2001).

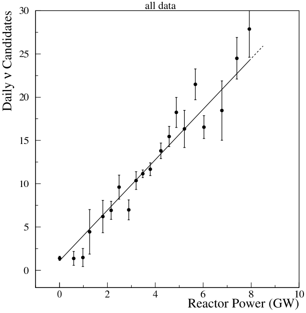
Systematic	CHOOZ (%)	P.V. (%)
$\sigma(\overline{\nu}_e + p \rightarrow n + e^+)$	1.9	-
Number of p in target	0.8	-
W_{th}	0.7	-
Energy abs. per fission	0.6	-
Total rate prediction	2.3	2.1
e^+ trigger eff.	-	2.0
n trigger eff.	-	2.1
$\overline{\nu}_e$selection cuts	-	2.1
$(1-\epsilon_1)B_{pn}$ estimate	-	3.3
Total $\overline{\nu}_e$efficiency	1.5	4.9
Total	2.7	5.3

Experimental backgrounds



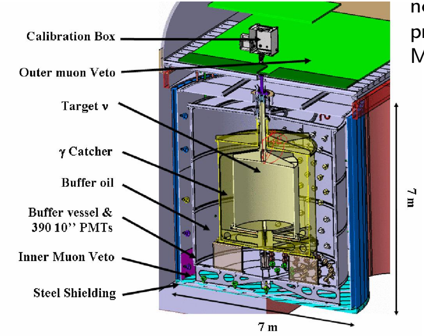
Two main categories:

- Accidental backgrounds from the random superposition of a “positron-like" and “neutron-like" signals. Directly estimated from the measured rates of the two processes.
- Backgrounds from neutrons induced by cosmic rays. They can be measured only if the reactor is off (impossible to pay to have a reactor shutdown).



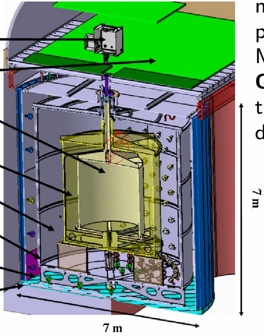
Chooz counting rate as function of the reactors power.

Design of a reactor neutrino detector



Inner detector Liquid scintillator doped with Gadolinium (0.1%) in a acrylic vessel. Gadolinium increases neutron capture cross section, reducing capture time from $\sim 170\,\mu$s to $\sim 27\,\mu$s $\Rightarrow$ with a reduction of not-correlated noise. Furthermore it increases the energy of the γs produced by the neutron capture, from ~ 2 MeV to ~ 8 MeV.

Design of a reactor neutrino detector



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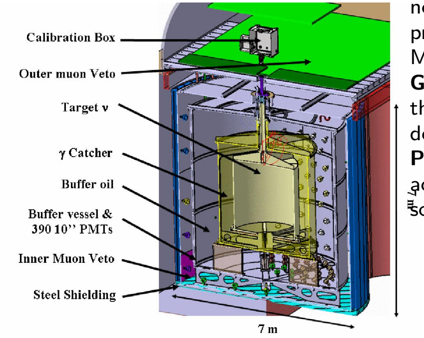
Gamma catcher: Not doped liquid scintillator to capture the γs emitted by the neutron capture. It allows a better definition of the fiducial volume.

Design of a reactor neutrino detector



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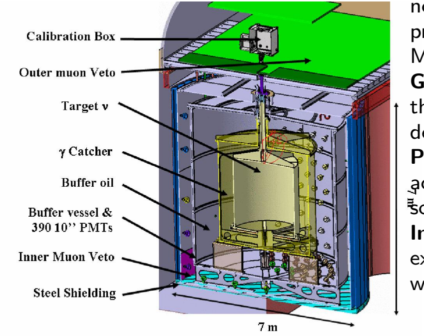
Design of a reactor neutrino detector



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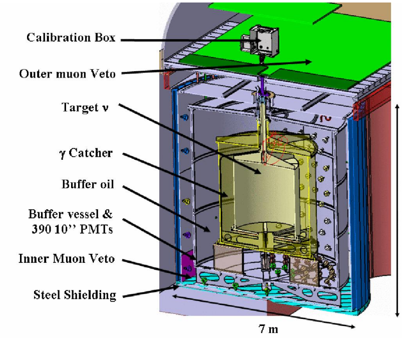
Inner veto: To shield against Comptons induced by external radioactivity and by crossing muons. Equipped with phototubes.

Design of a reactor neutrino detector



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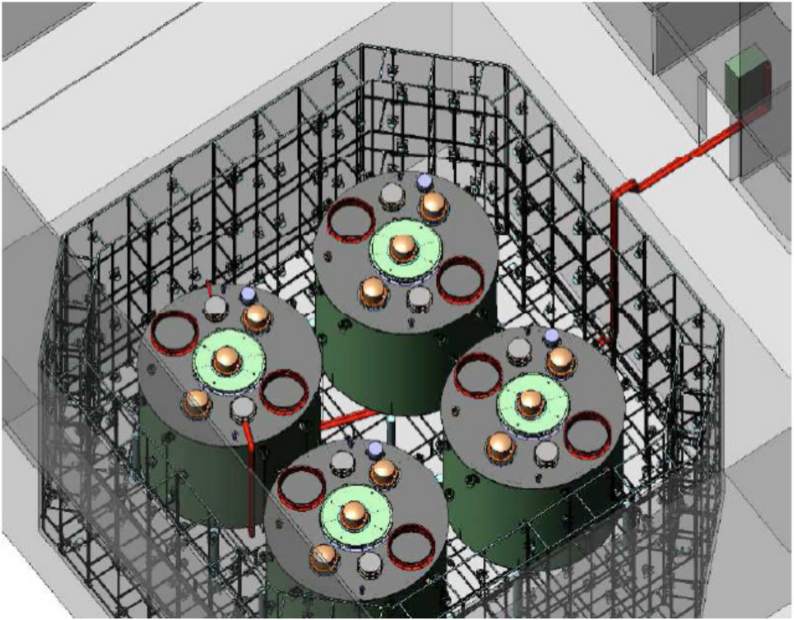
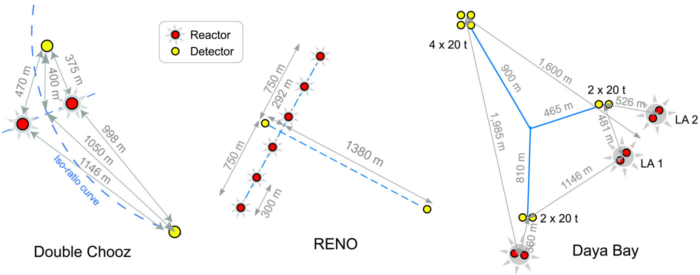
Outer veto: To veto crossing muons. It is required a minimum 100 m.w.e depth to keep dead times below 25%. Some ions produced by μs: ^{8}He and ^{9}Li, withd decaying times of 119 ms and 174 ms cannot be vetoed anyway.



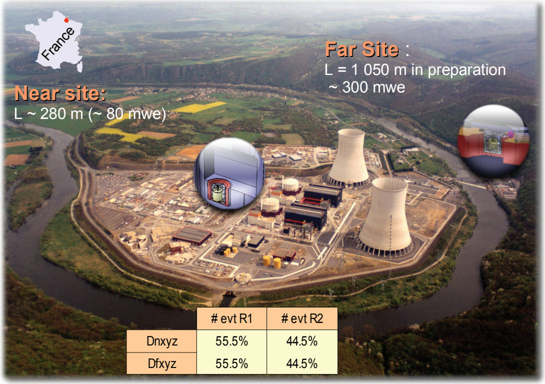
The three players

Setup	P_{Th} [GW]	L [m]	m_{Det} [t]	Events/year	Backgrounds/day
Daya Bay	17.4	1700	80	$10 \cdot 10^4$	0.4
Double Chooz	8.6	1050	8.3	$1.5 \cdot 10^4$	3.6
RENO	16.4	1400	15.4	$3 \cdot 10^4$	2.6



Double Chooz

Talk by J. Dawson



	# evt R1	# evt R2
Dnxyz	55.5%	44.5%
Dfxyz	55.5%	44.5%

2 cores – 1 site – 8.5 GW_{th}

1 near position, 1 far

- target: 2 x 8.3 t

Civil engineering

- 1 near lab ~ Depth 40 m, Ø 6 m
- 1 available lab

Statistics (including ε)

- far: ~ 40 evts/day
- near: ~ 460 evts/day

Systematics

- reactor : ~ 0.2%
- detector : ~ 0.5%

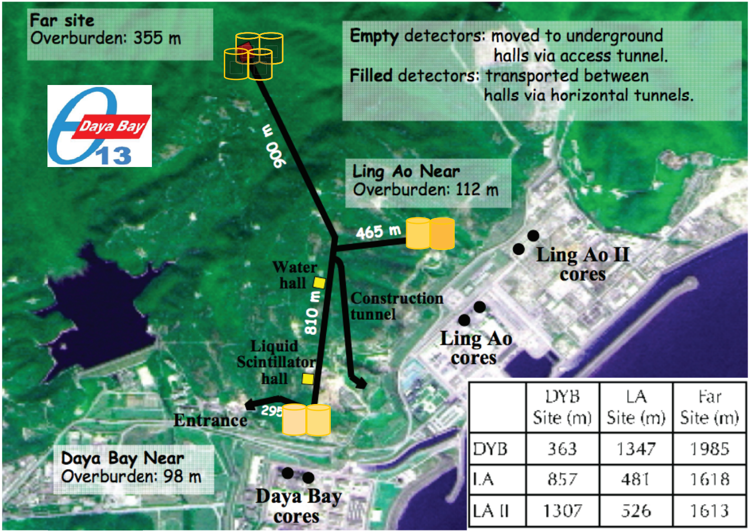
Backgrounds

- σ_{b2b} at far site: ~ 1%
- σ_{b2b} at near site: ~ 0.5%

Planning

1. Far detector only
   - Sensitivity (1.5 ans) ~ 0.06
2. Far + Near sites
   - available from 2010
   - Sensitivity (3 years) ~ 0.025

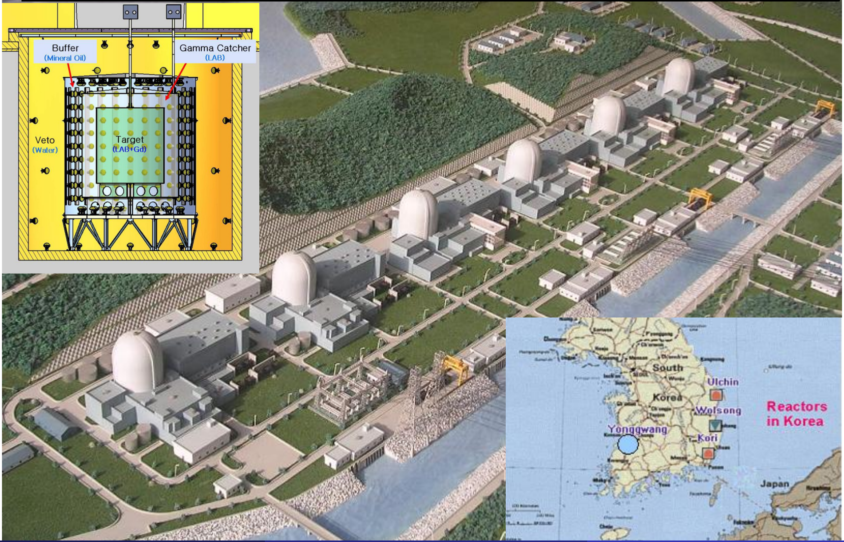
Daya Bay



	DYB Site (m)	LA Site (m)	Far Site (m)
DYB	363	1347	1985
LA	857	481	1618
LA II	1307	526	1613

RENO

	Location	Thermal Power	Distances Near/Far (m)	Depth (mwe)	Target Mass (tons)	Cost
RENO	Korea	17.3 GW	290/1380	120/450	16/16 ton	~10M$



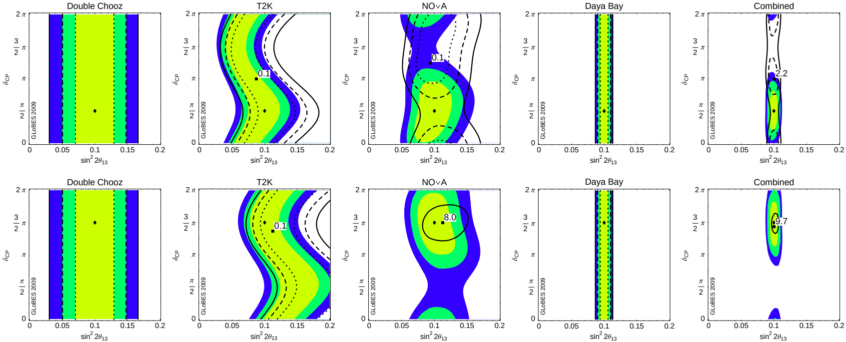
Reactors systematic business

G. Mention, T. Lasserre and D. Motta, arXiv:0704.0498 [hep-ex].

Error Description	**CHOOZ**	**Double Chooz**		**Daya Bay**		
					No R&D	**R&D**
	Absolute	**Absolute**	**Relative**	**Absolute**	**Relative**	**Relative**
Reactor						
Production cross section	1.90 %	1.90 %		1.90 %		
Core powers	0.70 %	2.00 %		2.00 %		
Energy per fission	0.60 %	0.50 %		0.50 %		
Solid angle/Bary. displct.			0.07 %		0.08 %	0.08 %
Detector						
Detection cross section	0.30 %	0.10 %		0.10 %		
Target mass	0.30 %	0.20 %	0.20 %	0.20 %	0.20 %	0.02 %
Fiducial volume	0.20 %					
Target free H fraction	0.80 %	0.50 %		?	0.20 %	0.10 %
Dead time (electronics)	0.25 %					
Analysis (paticle id.)						
e^+ escape (D)	0.10 %					
e^+ capture (C)						
e^+ identification cut (E)	0.80 %	0.10 %	0.10 %			
n escape (D)	0.10 %					
n capture (% Gd) (C)	0.85 %	0.30 %	0.30 %	0.10 %	0.10 %	0.10 %
n identification cut (E)	0.40 %	0.20 %	0.20 %	0.20 %	0.20 %	0.10 %
$\overline{\nu}_e$time cut (T)	0.40 %	0.10 %	0.10 %	0.10 %	0.10 %	0.03 %
$\overline{\nu}_e$distance cut (D)	0.30 %					
unicity (n multiplicity)	0.50 %				0.05 %	0.05 %
Total	**2.72 %**	**2.88 %**	**0.44 %**	**2.82 %**	**0.39 %**	**0.20 %**

Reactors vs Accelerators: 2018

Fit at $\sin^2 2\theta_{13}$=0.1 (1,2,3 σ)



What to compare

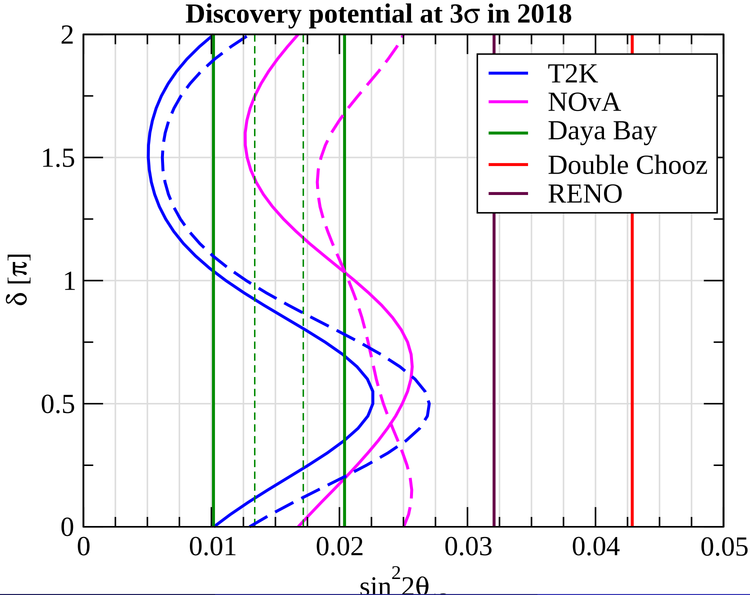
Sensitivity: The highest value of a parameter (say θ_{13}) that can be excluded at a given CL in absense of a signal.
True value $= 0$; fit value $\neq 0$.

Discovery potential: The smallest value of a parameter that can be provide a signal that can't be fitted with a null value at a given CL.
True value $\neq 0$; fit value $= 0$.

Probability of discovery: The probability that a given true value of θ_{13} produces a not null result at a given CL

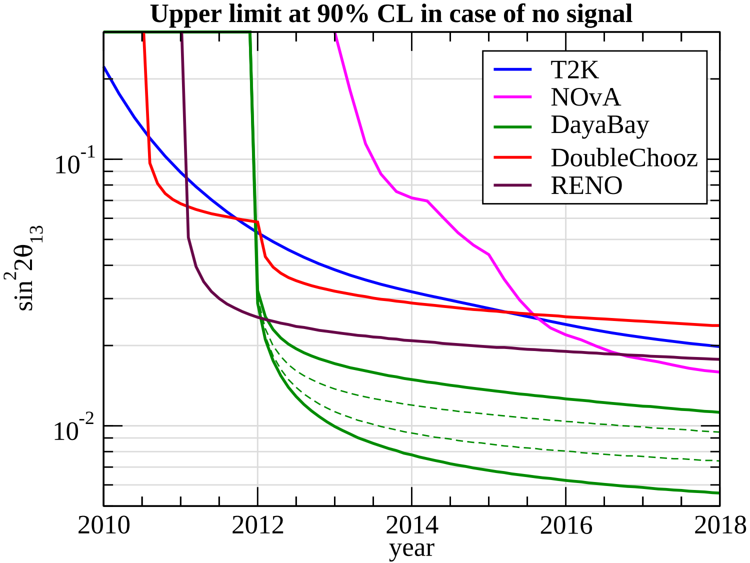
Discovery potential at 3 σ: 2018

From M.M. and T. Schwetz, arXiv:1003:5800



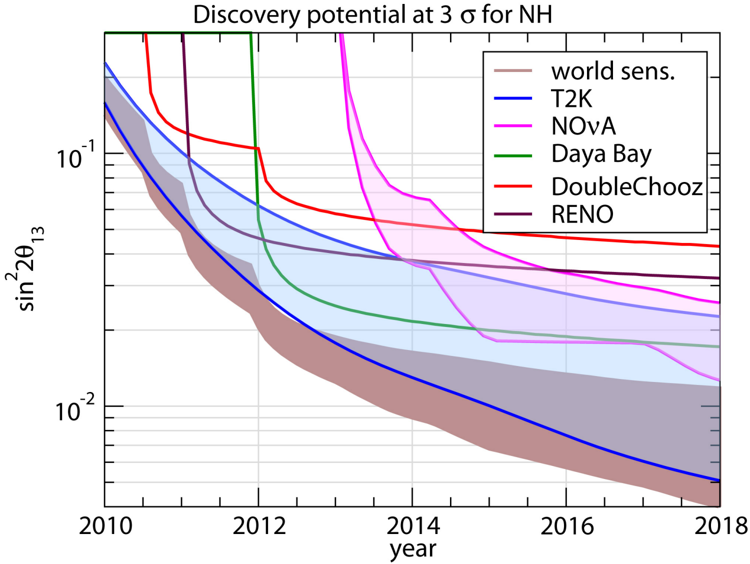
Sensitivity time evolution

From M.M. and T. Schwetz, arXiv:1003:5800



Discovery Potential: time evolution

From M.M. and T. Schwetz, arXiv:1003:5800



Probability of excluding $\theta_{13} = 0$ (3σ)