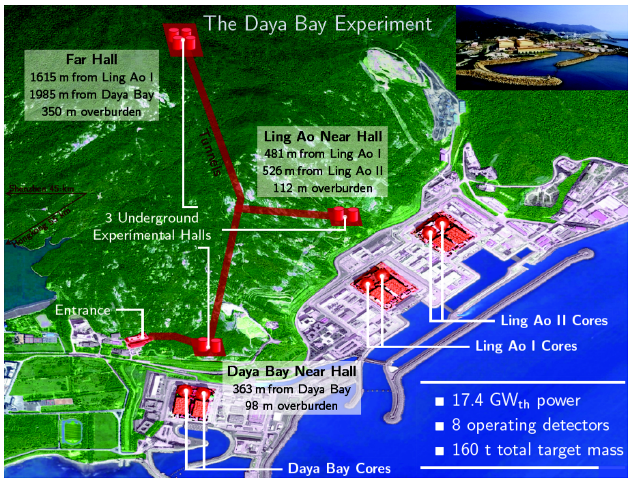
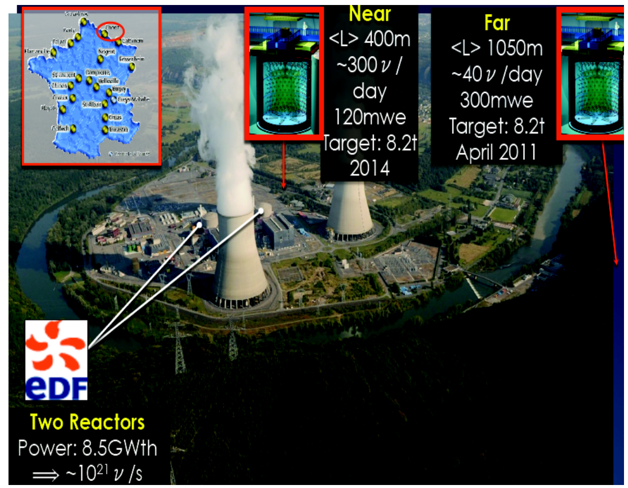
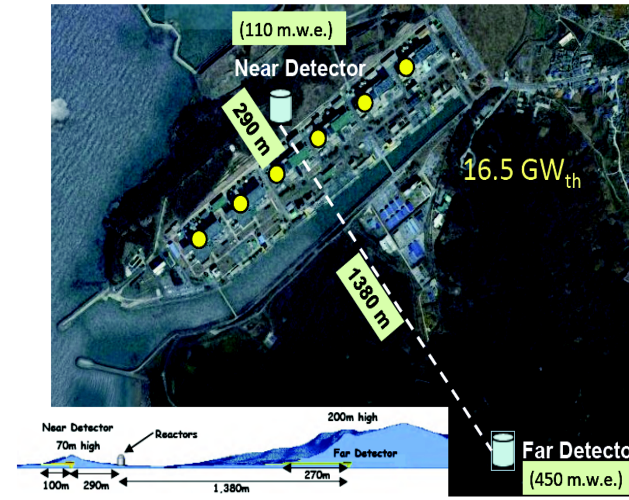
Reactor Neutrino Experiments



Daya Bay

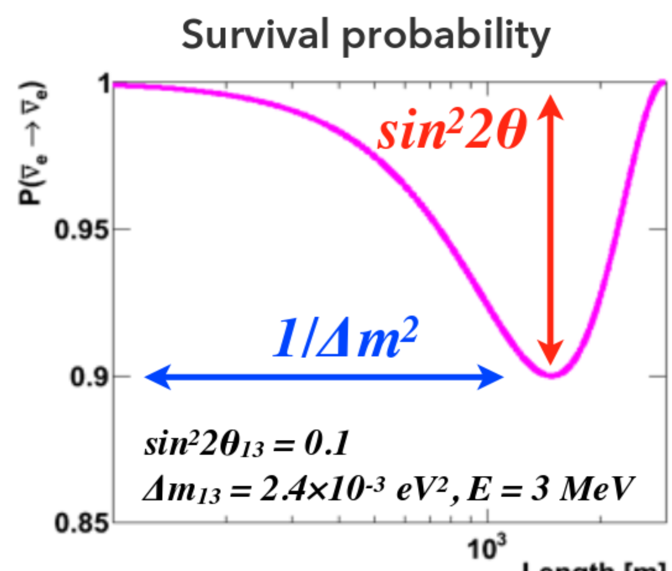


Double Chooz



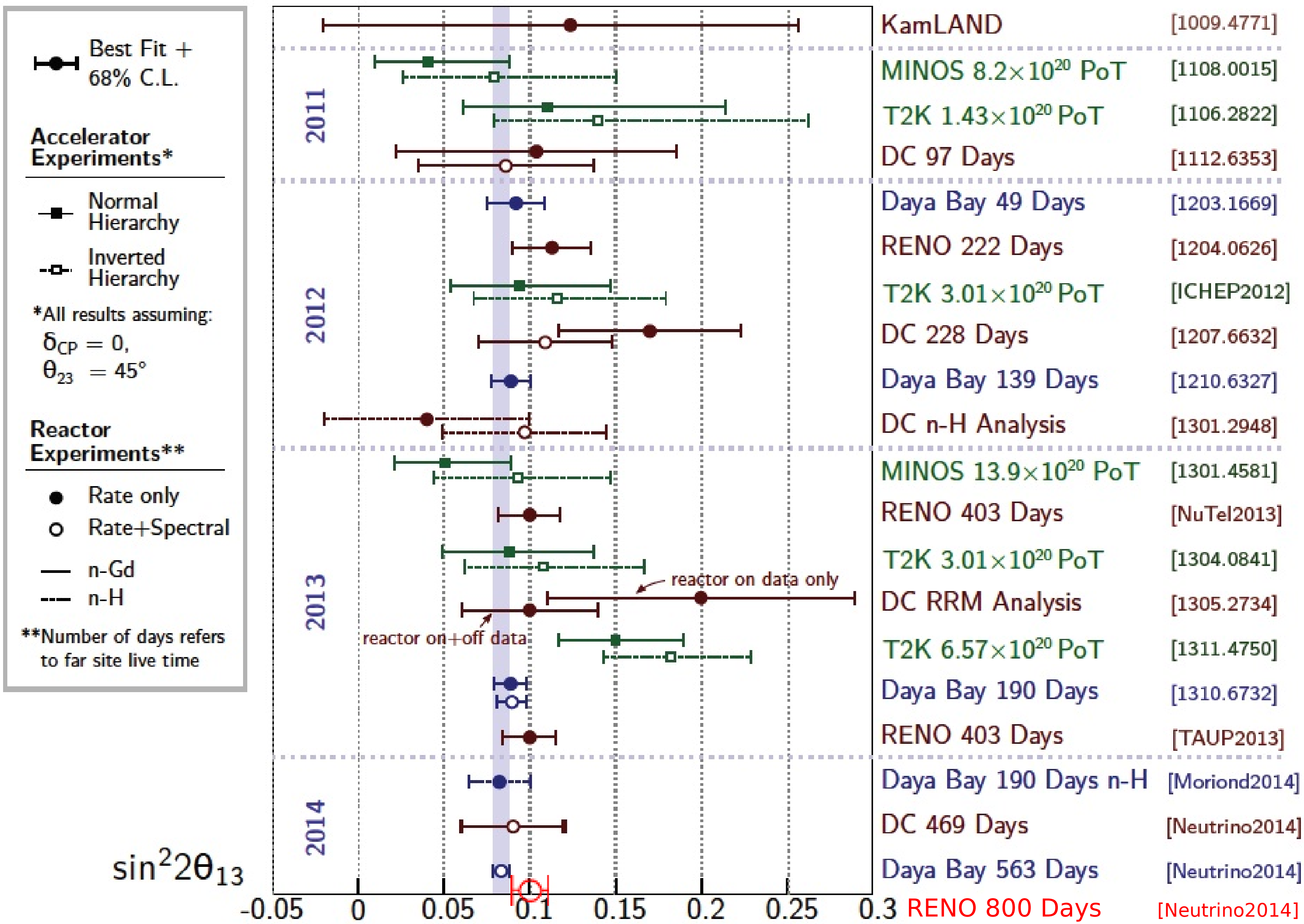
RENO

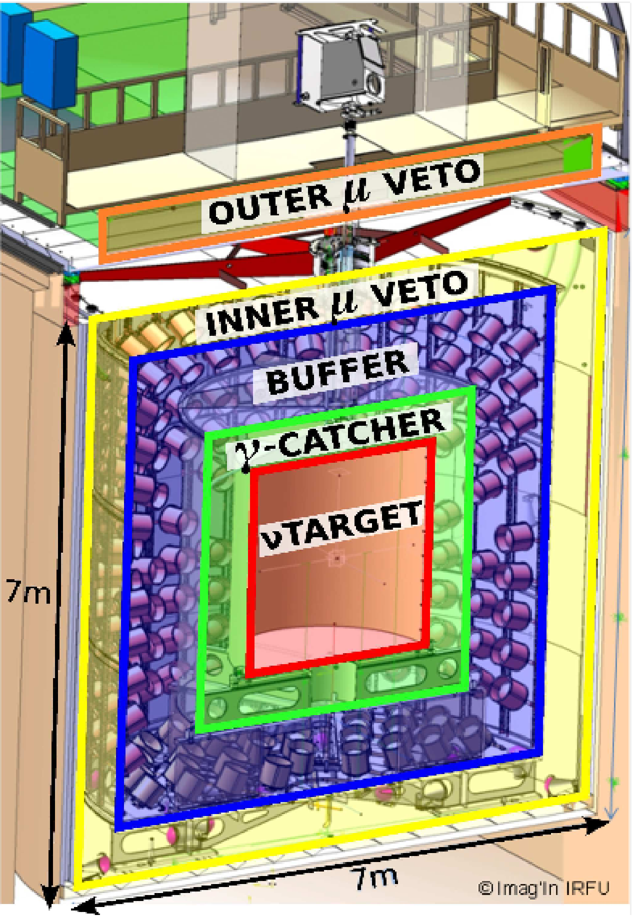
$$P(\nu_\alpha \to \nu_\alpha) = 1 - \sin^2 2\theta \sin^2\left(\frac{1.27 \times \Delta m^2\ [\text{eV}^2] \times L\ [\text{m}]}{E\ [\text{MeV}]}\right)$$

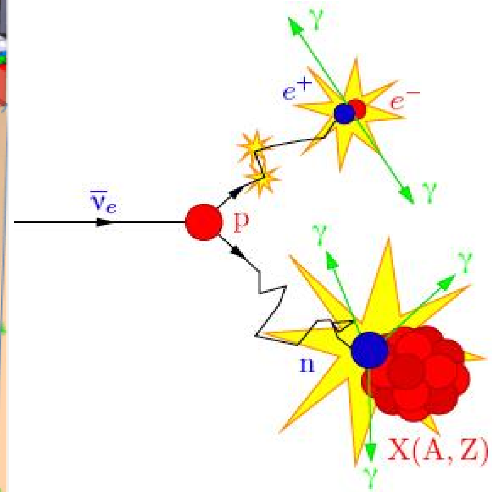


Jaime Dawson, SUSY2014

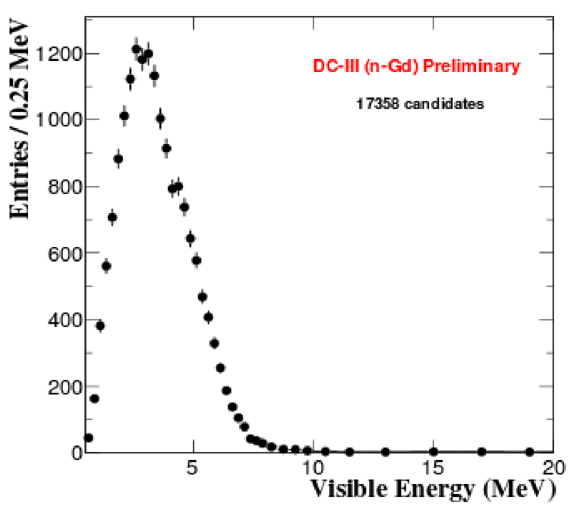
Timeline of Results

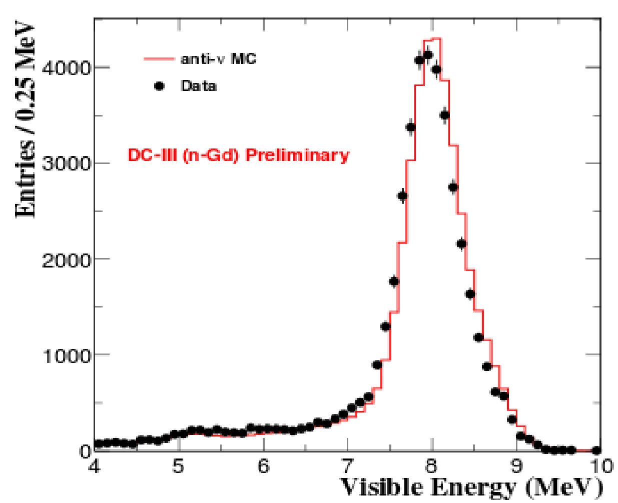


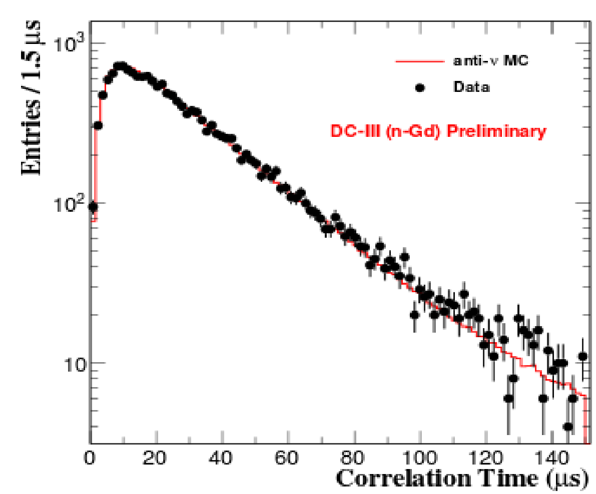


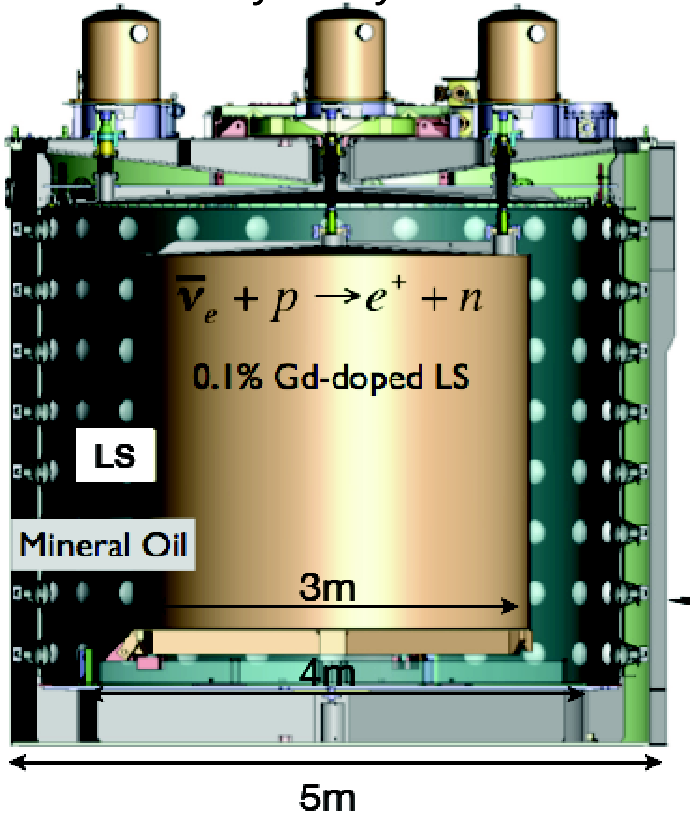
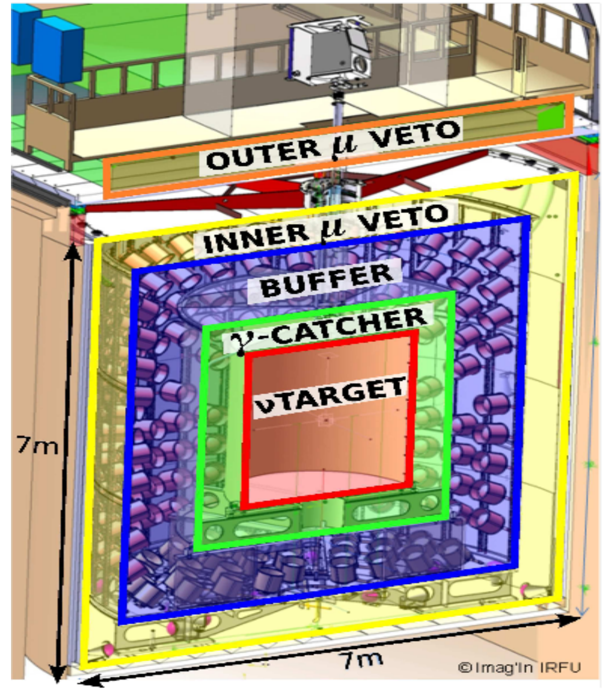
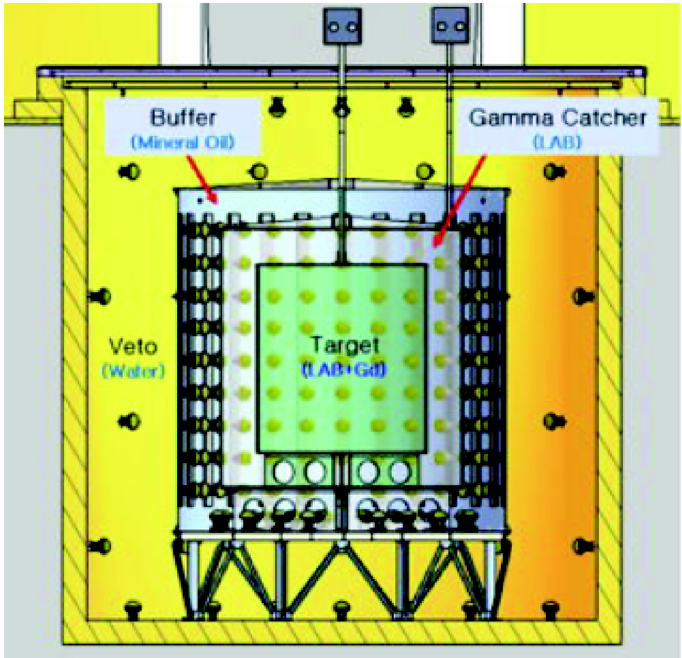


- Detect anti-neutrinos via inverse beta decay
  - $\bar{\nu} + p \rightarrow n + e^+$
- In Gd-loaded scintillator
  - Prompt e^+ signal 1-8MeV
  - Prompt e^+ e^- annihilation(2 x 511 keV)
- $E_{vis} = E_{\nu} - (M_n - M_p) + m_e$
  - Delayed neutron capture on
- Gd ~30 μs ~ 8 MeV (>80%)
- H ~200 μs 2.2 MeV





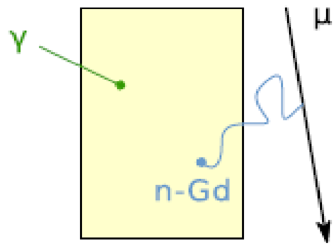


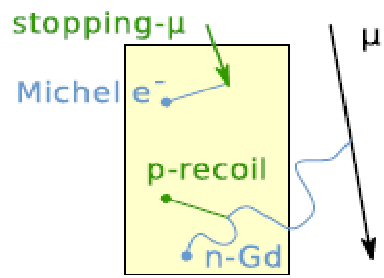
Daya Bay	Double Chooz	RENO
		

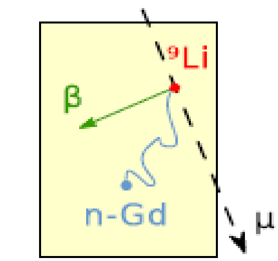
Daya Bay	Double Chooz	RENO
Near: 4* 20 ton GD-LS	8.3 ton*	16.5 ton
Far: 4 * 20 ton	8.3 ton	16.5 ton
621 live days	460 live days	794 live days
Max Reactor Power 17GWth	8.5 GWth	16.5 GWth
Detected neutrinos 150k (far)	17351	0.1M
1M (near)	* near detector In preparation	1M

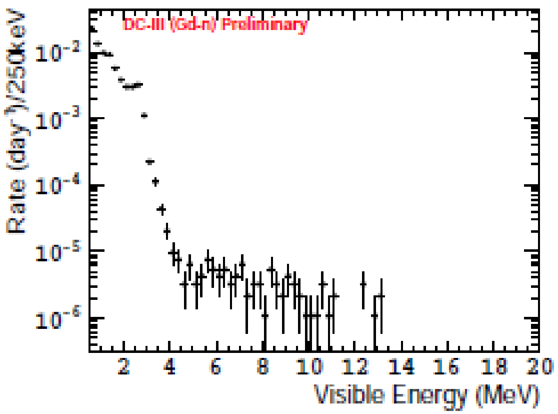
Backgrounds

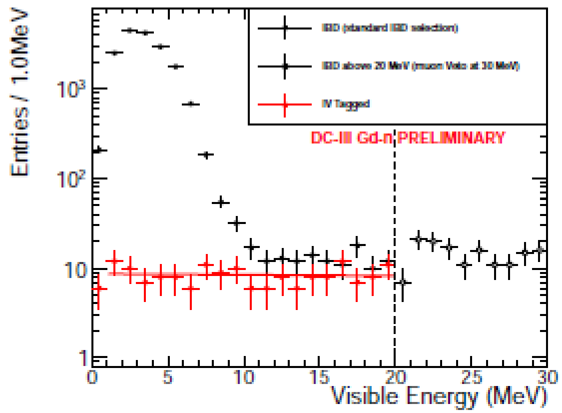
Accidental	Correlated	Cosmogenic

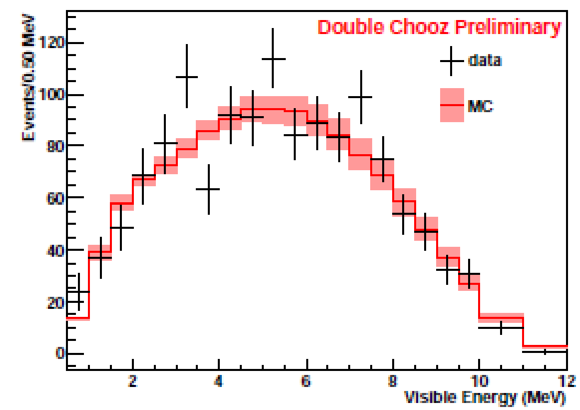








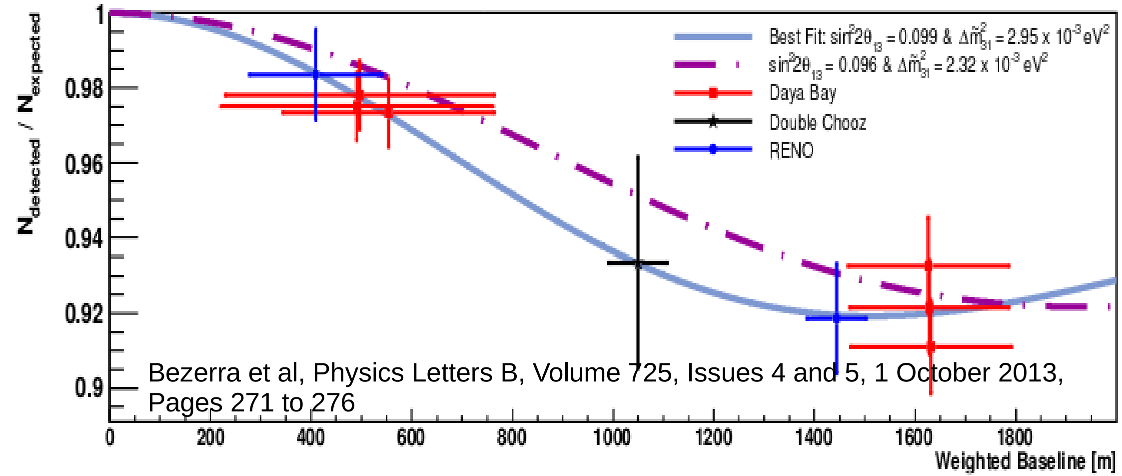




Background rates /day	Accidental	Correlated	Cosmogenic	Additional Sources
DC FAR:	0.07 +/- 0.003	0.6 +/- 0.05	0.97 +0.41 -0.16	
RENO FAR:	0.36 +/- 0.01	0.44 +/- 0.02	1.85 +/- 0.20	1.98 +/- 0.27
NEAR:	1.82 +/- 0.11	2.09 +/- 0.06	8.28 +/- 0.66	0.28 +/- 0.05
DayaBay				
NEAR: AD1:	8.62 +/- 0.09	0.78 +/- 0.12	2.8 +/- 1.5	0.2 +/- 0.09
AD2:	8.76 +/- 0.09			0.21 +/- 0.09
AD3:	6.43 +/- 0.07	0.54 +/- 0.19	1.7 +/-0.9	0.18 +/- 0.08
AD8:	6.86 +/- 0.07			0.22 +/- 0.10
FAR: AD4:	1.07 +/- 0.01	0.05 +/- 0.01	0.27 +/- 0.14	0.06 +/- 0.03
AD5:	0.94 +/- 0.01			0.04 +/- 0.02
AD6:	0.94 +/- 0.01			0.04 +/- 0.02
AD7:	1.26 +/- 0.01			0.07 +/- 0.02

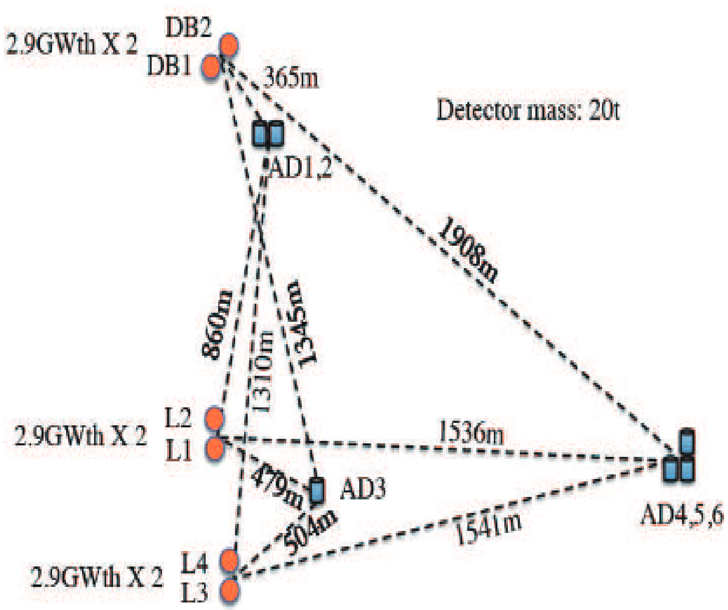
Different Baselines & Configurations

$$P_{\bar{\nu}_e \rightarrow \bar{\nu}_e} \approx 1 - \sin^2(2\theta_{13}) \sin^2\left(1.27 \frac{\Delta m^2_{31} L}{E}\right)$$

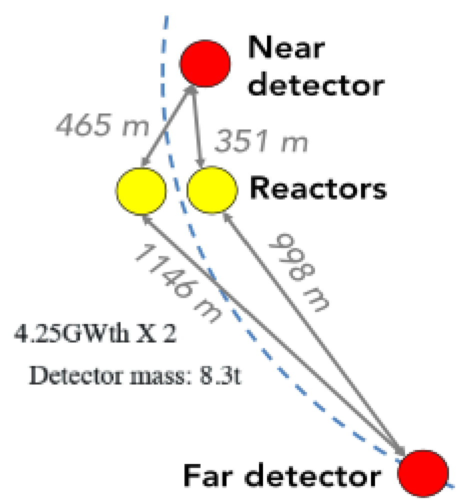


Bezerra et al, Physics Letters B, Volume 725, Issues 4 and 5, 1 October 2013, Pages 271 to 276

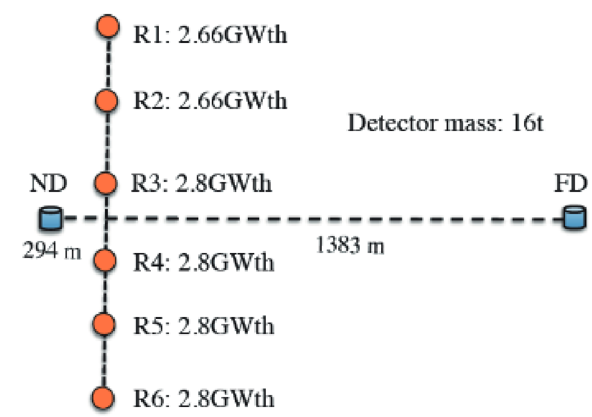
Daya Bay



Double Chooz



RENO

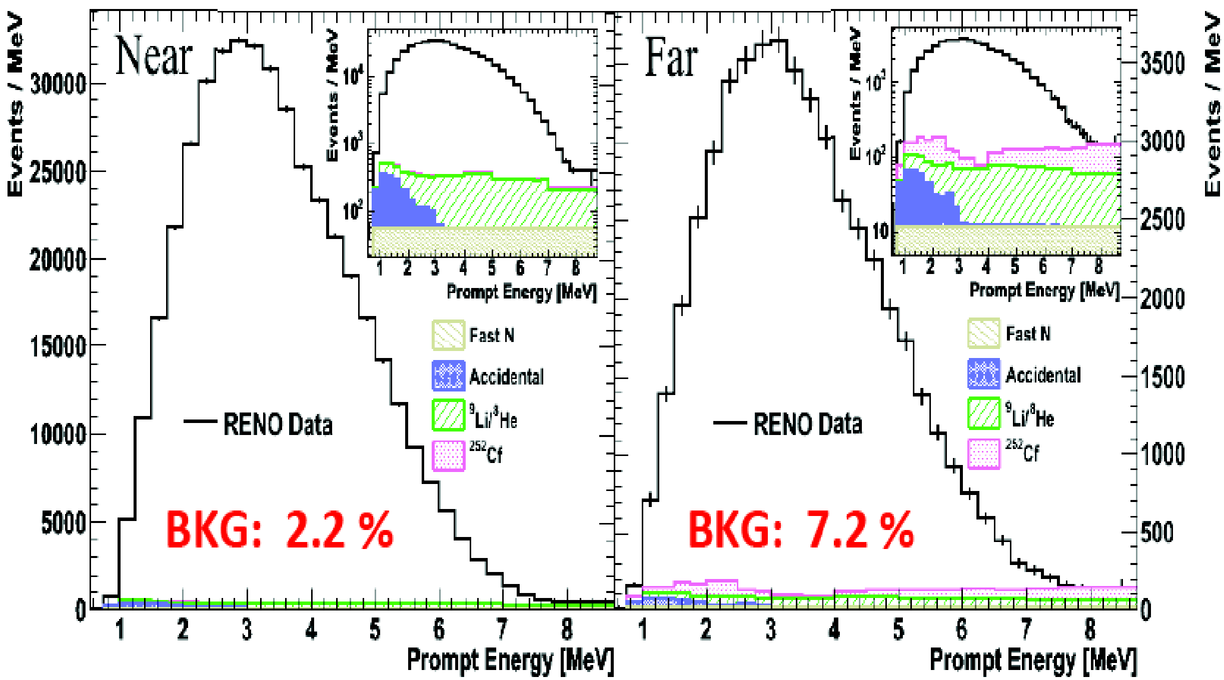


How to obtain θ_{13}

Method		Model Background	Measure Background (Reactor Off)	Δm^2_{ee}
Rate	Gd sample	Estimate all components	Useful as cross check	Using different baselines measure Δm^2_{ee} too!
	H sample			
Rate & Shape	Gd sample	Estimate & Constrain	Estimate & Constrain	Using L/E measure Δm^2_{ee}
	H sample			
Reactor Rate Modulation	Gd sample	Independent/ improve precision	Improve precision	
	H sample			

Rate Results from RENO at Neutrino2014

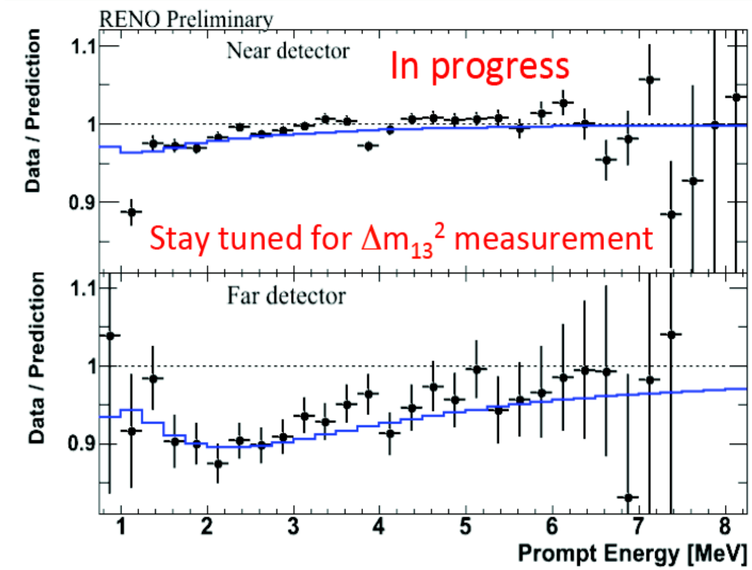
C data set (~800 days)



Near Live time = 761.11 days
# of IBD candidate = 433,196
# of background = 9499 (2.2 %)

Far Live time = 794.72 days
# of IBD candidate = 50,750
# of background = 3672 (7.2 %)

Shape analysis in progress

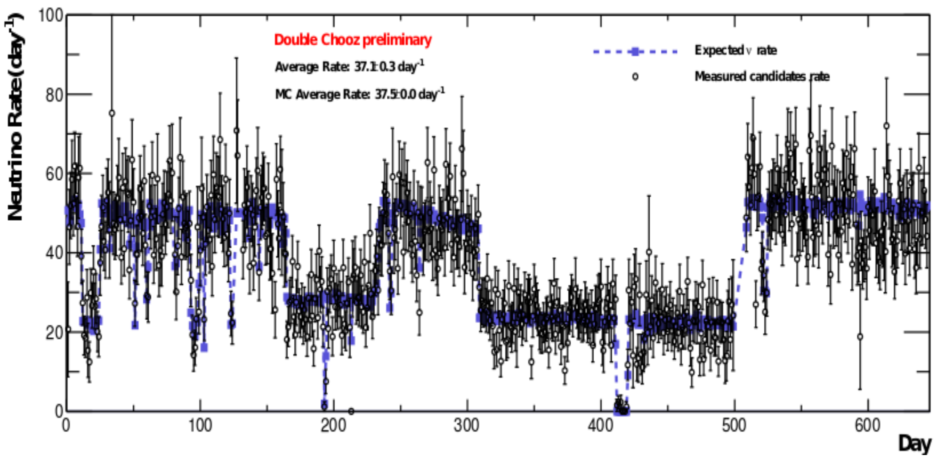


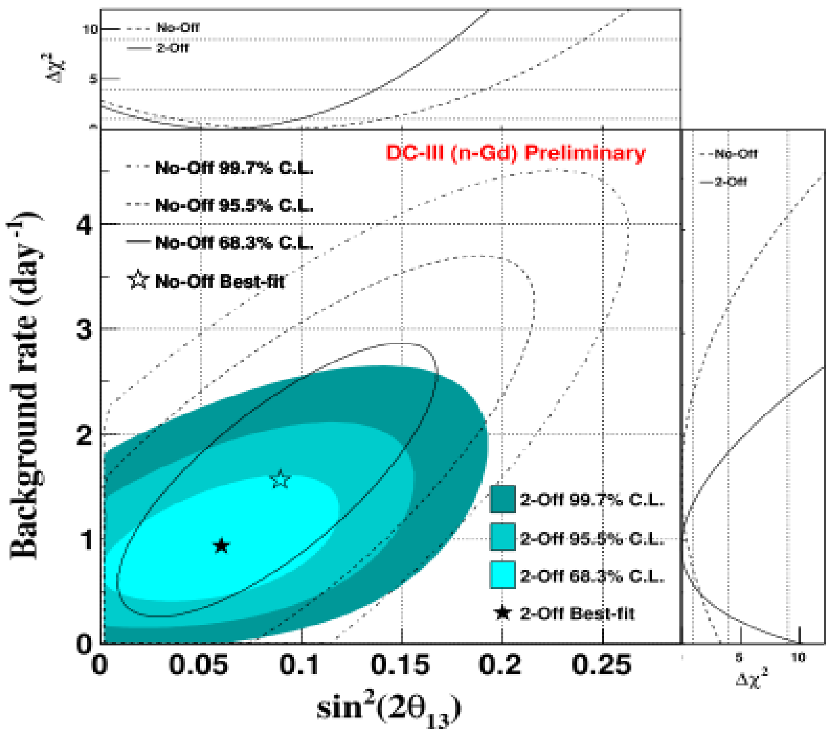
Preliminary result

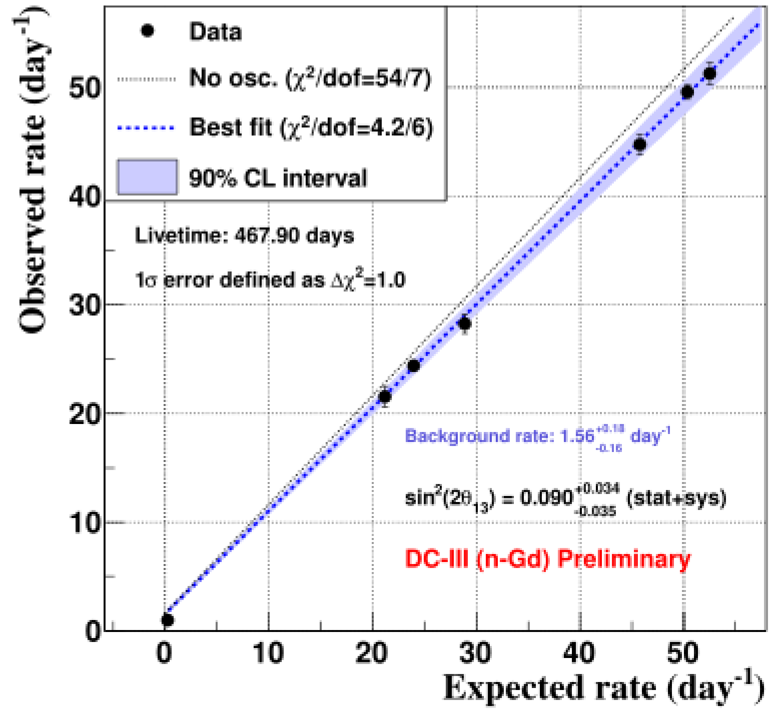
C data set (~800 days)

$$\sin^2(2\theta_{13}) = 0.101 \pm 0.008\ (\text{stat.}) \pm 0.010\ (\text{sys.})$$

Reactor Rate Modulation







Measure θ_{13} and background

Background model independent

With Reactor Off

$$\sin^2 2\theta_{13} = 0.060 \pm 0.039 \text{ (stat+sys)}$$

$$B = 0.93^{+0.43}_{-0.36} \text{ day}^{-1}$$

And include background model

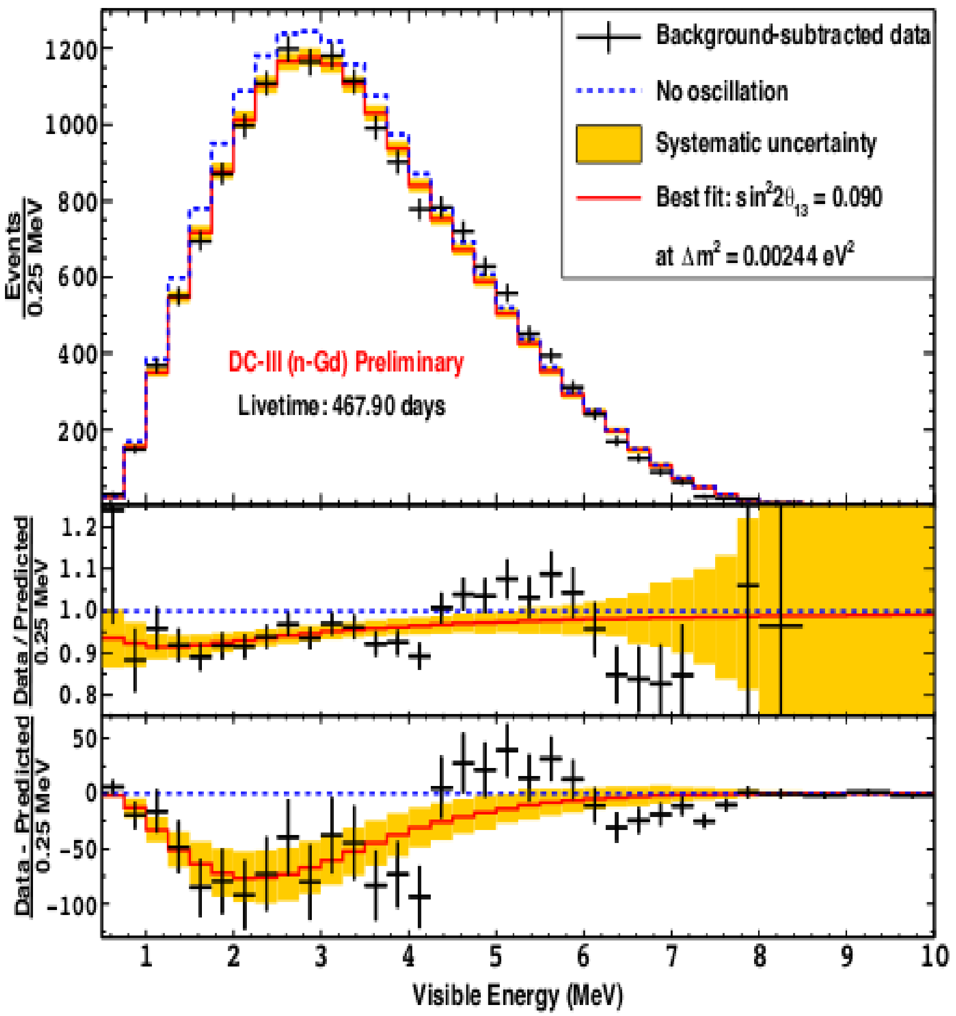
$$\sin^2 2\theta_{13} = 0.090^{+0.034}_{-0.035} \text{ (stat+sys)}$$

$$B = 1.56^{+0.18}_{-0.16} \text{ day}^{-1}$$

arXiv:1406.7763

Rate & Shape from Double Chooz

arXiv:1406.7763



Includes 7 days of reactor off!

$\sin^2 2\theta_{13} = 0.090^{+0.032}_{-0.029}$ (stat+sys)

$\chi^2_{min}/\text{dof} = 52.2/40$ (p = 9.4 %)

BG rate after fit: 1.38 ± 0.14 day^{-1}

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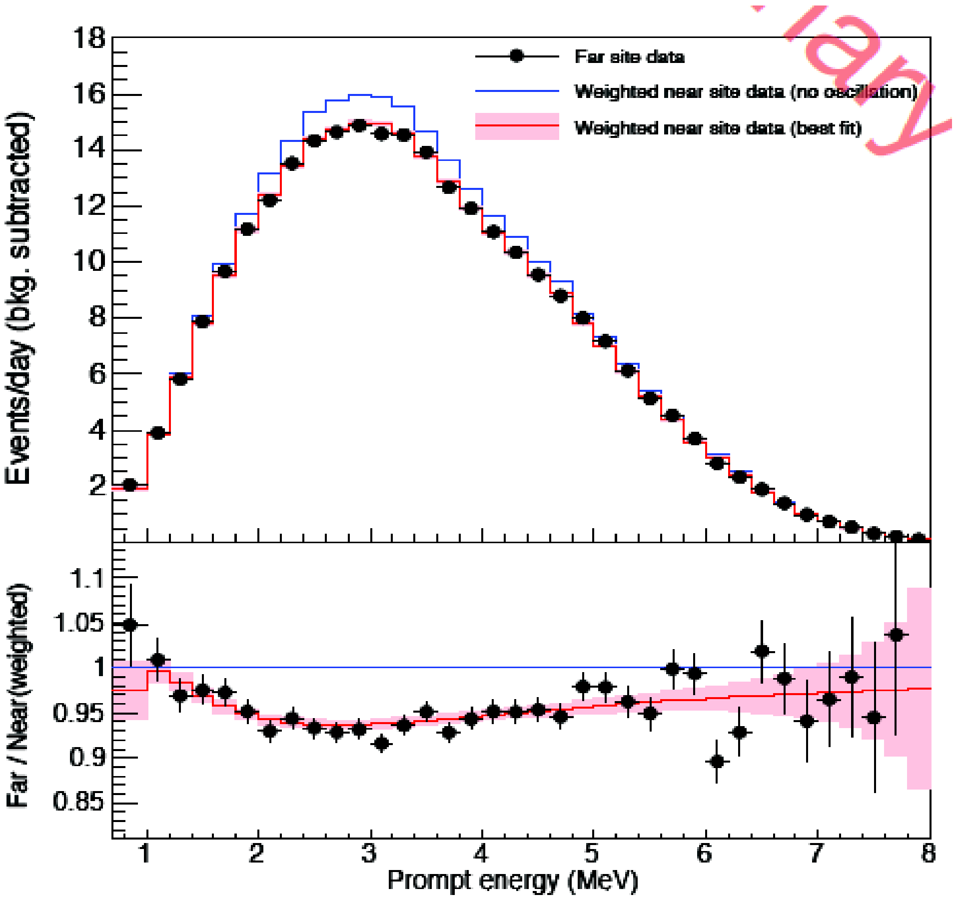
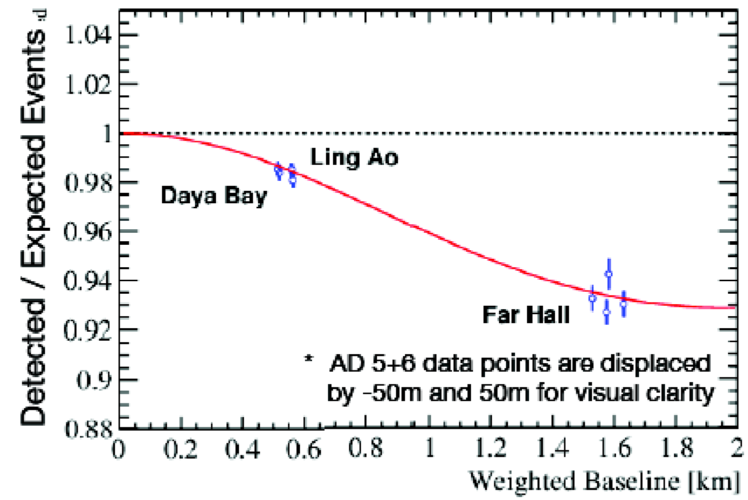
Rate & Shape & Δm^2_{ee} from Daya Bay at Neutrino2014

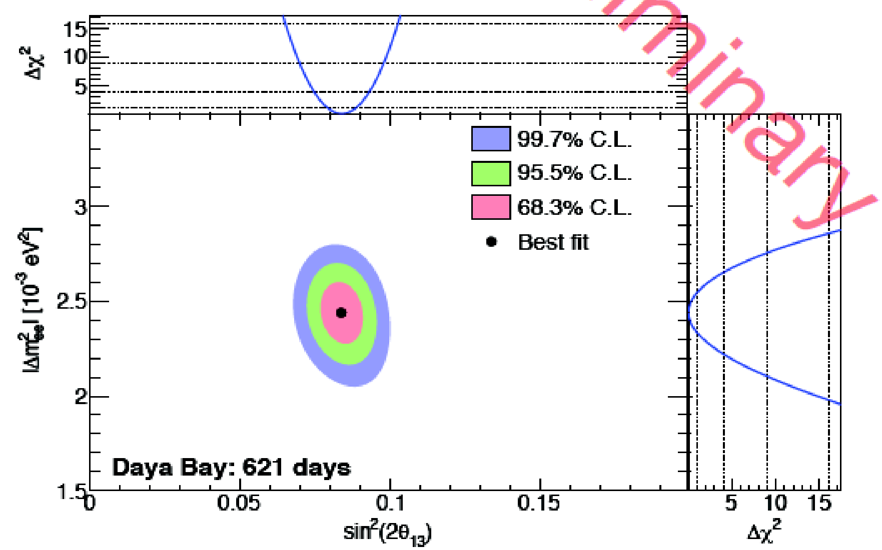


$$\sin^2 2\theta_{13} = 0.084^{+0.005}_{-0.005}$$

$$|\Delta m^2_{ee}| = 2.44^{+0.10}_{-0.11} \times 10^{-3}\mathrm{eV}^2$$

$$\chi^2/NDF = 134.7/146$$





	Normal MH Δm^2_{32} [10^{-3}eV^2]	Inverted MH Δm^2_{32} [10^{-3}eV^2]
From Daya Bay Δm^2_{ee}	$2.39^{+0.10}_{-0.11}$	$-2.49^{+0.10}_{-0.11}$
From MINOS $\Delta m^2_{\mu\mu}$	$2.37^{+0.09}_{-0.09}$	$-2.41^{+0.11}_{-0.09}$

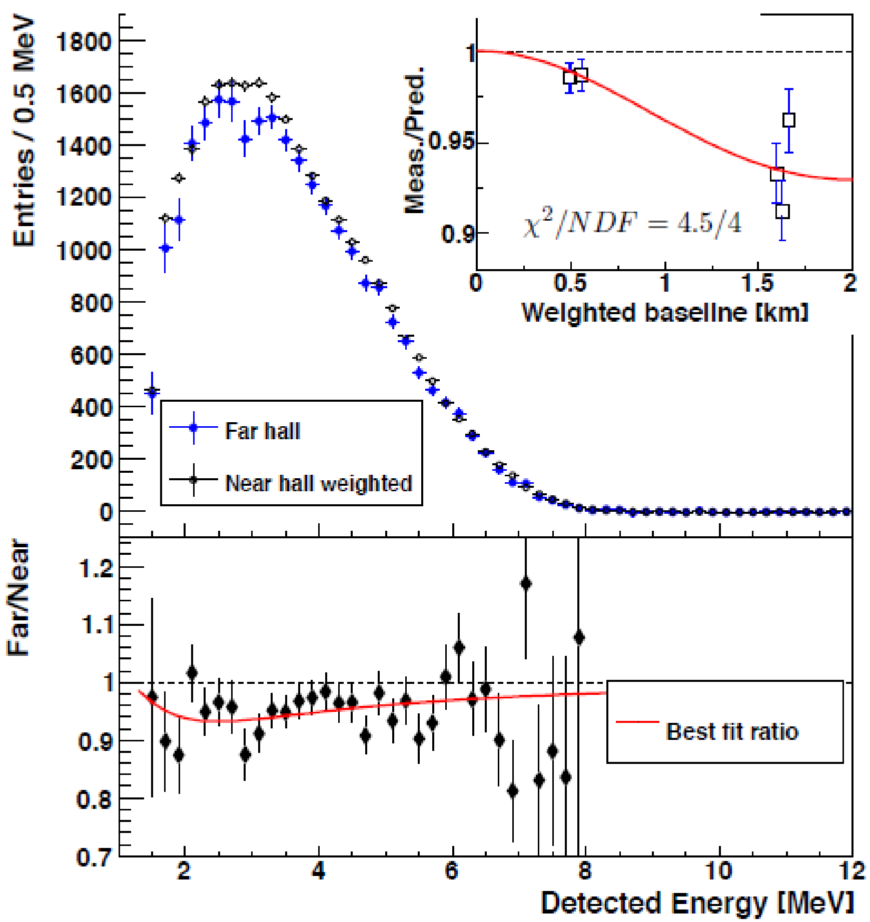
A. Radovic, DPF 2013

Hydrogen Analysis

First analysis Double Chooz Jan 2013

Recent rate-only results from Daya Bay and RENO

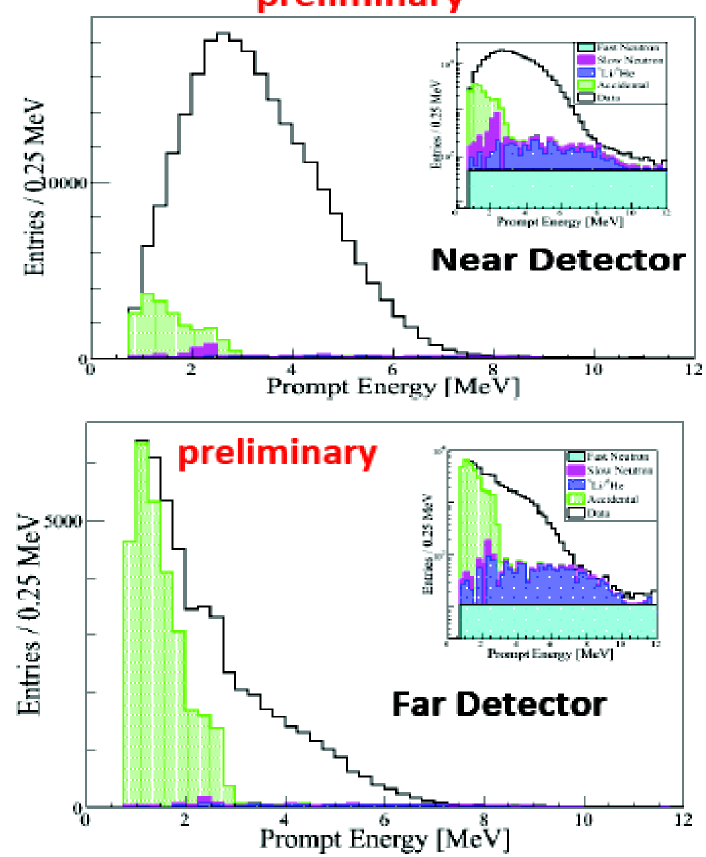
$\sin^2 2\theta_{13} = 0.083 \pm 0.018$



Daya Bay (arXiv: 1406.6468)

$\sin^2(2\theta_{13}) = 0.095 \pm 0.015$ (stat.) ± 0.025 (sys.)

preliminary



RENO (Neutrino2014)

$Sin^2 2\theta_{13}$ Summary

- Agreement
  - between all 3 experiments
  - different analysis methods
  - different neutrino samples (Gd/H)
- Clear demonstration of neutrino oscillation effect
- Precision measurements achieved (6%!)

Daya Bay:	0.084 ± 0.005
RENO:	0.101 ± 0.013
Double Chooz:	0.09 ± 0.03

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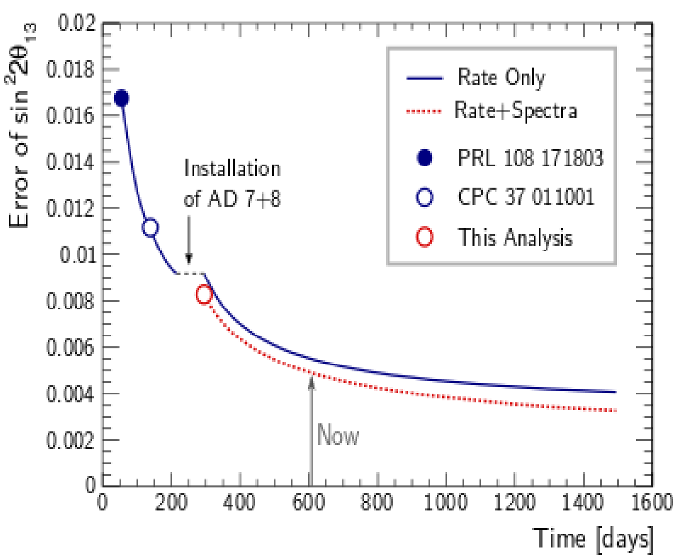
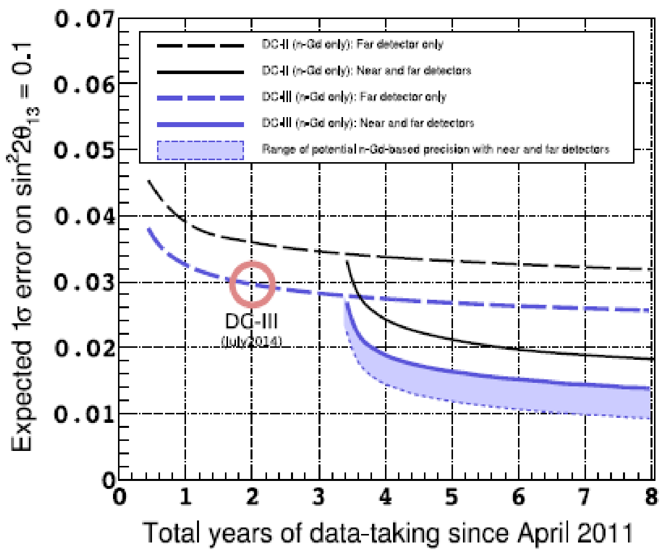
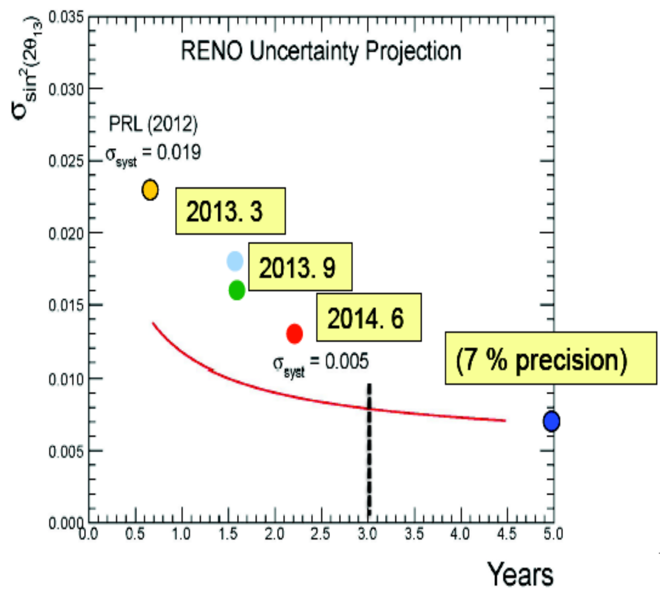
Future

- Daya Bay aims to measure both θ_{13} and Δm^2_{ee} for 3% by 2017
- Double Chooz runs with near detector (Sept/Oct)

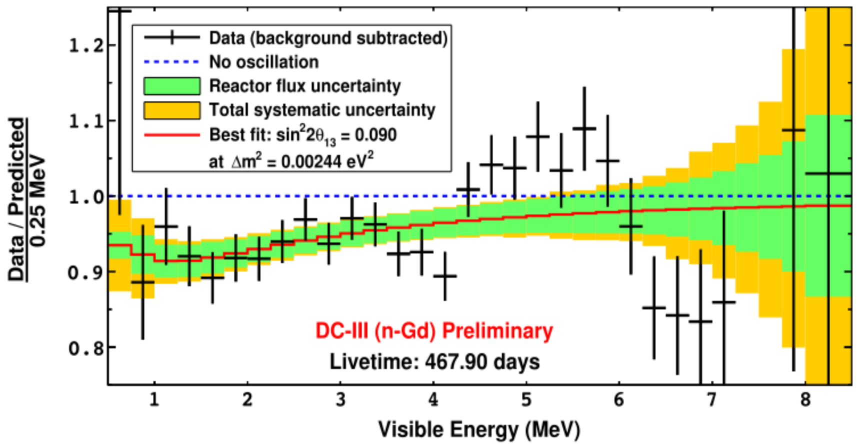
  Aims for 10-15% precision within 3 years
- RENO aims for 7% precision with 2 more years







Reactor Spectrum

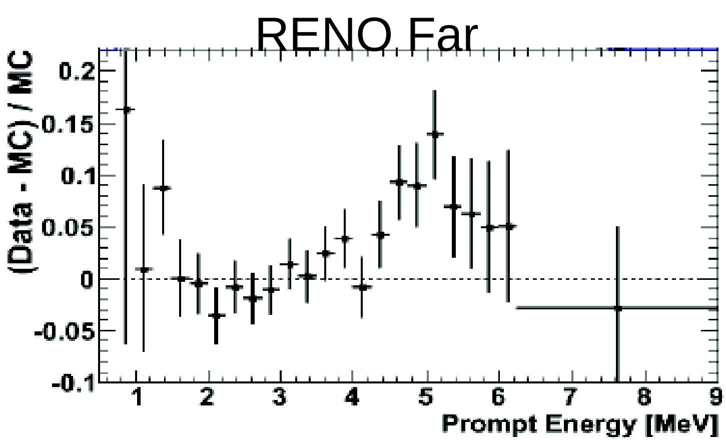


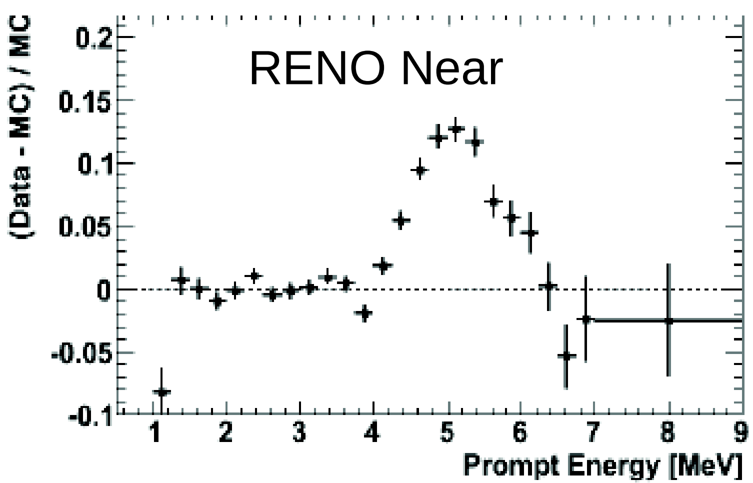
Spectral distortion observed in DC Far spectrum (arXiv:1406.7763 & Neutrino2014)

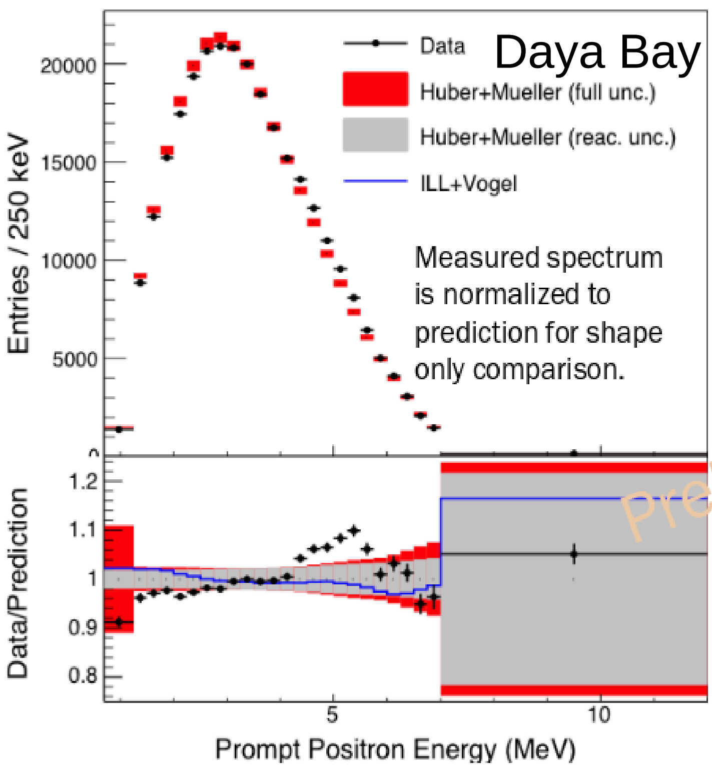
Observed by RENO in Near & Far detectors (Neutrino2014)

Confirmed by Daya Bay (ICHEP2014)

Possible explanation from reactor predictions: arXiv: 1407.1281

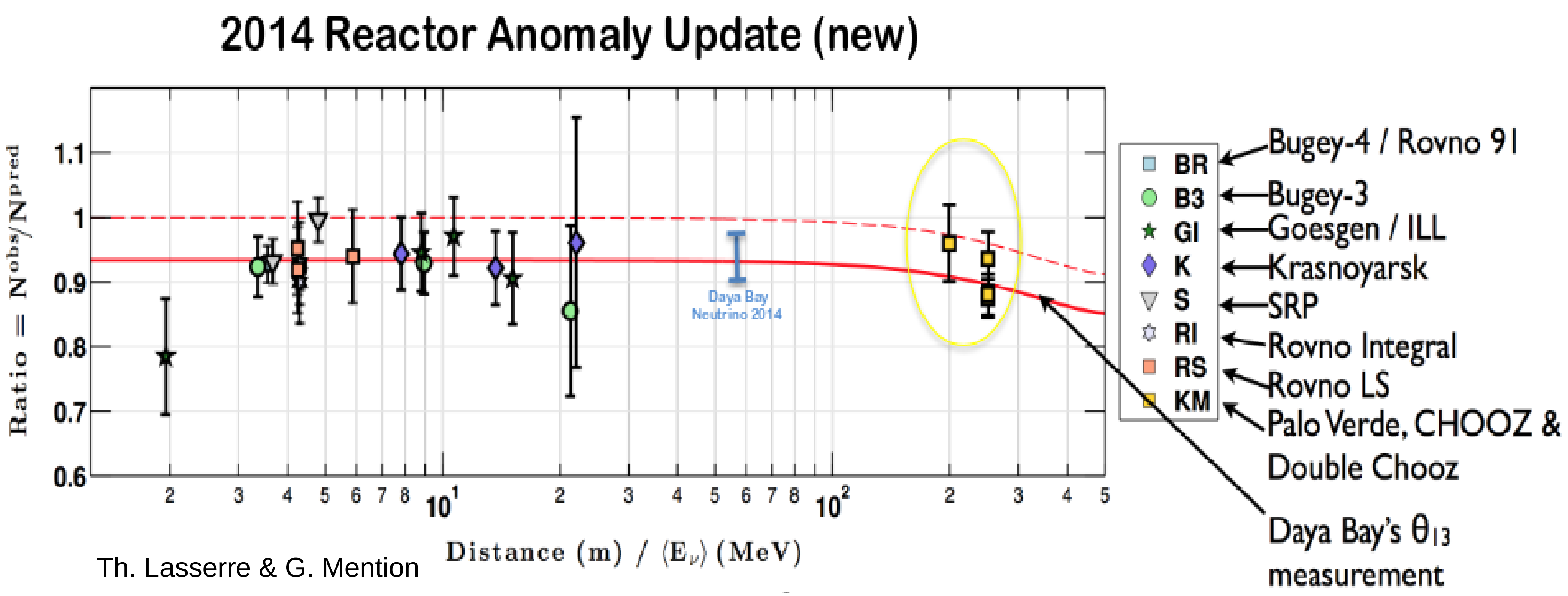






Reactor Flux

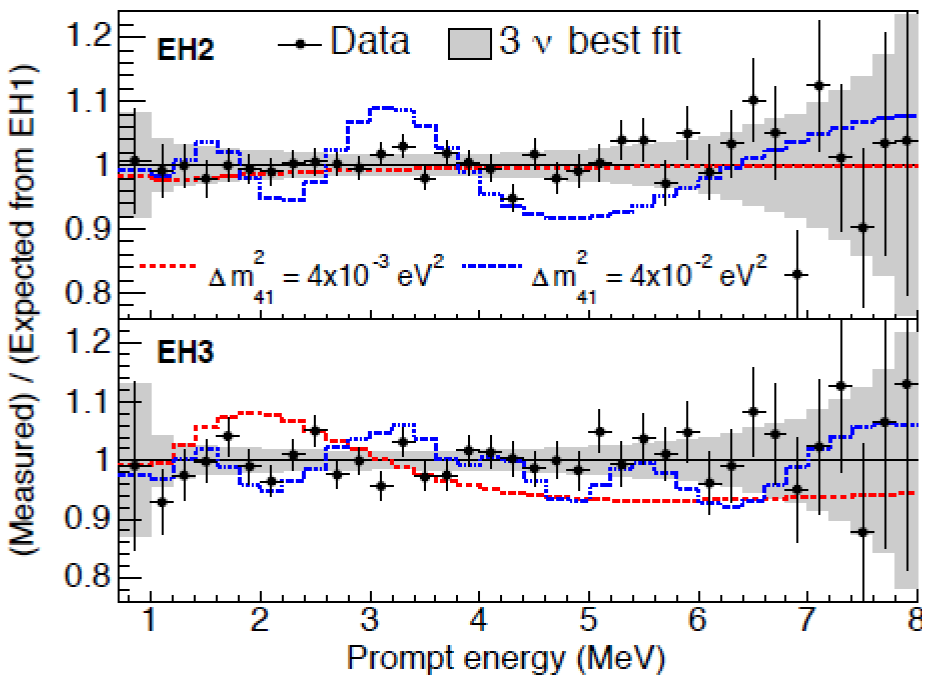
- Comparing measured to predicted flux
- Latest results from Daya Bay (Neutrino2014) – consistent with all previous short baseline experiments



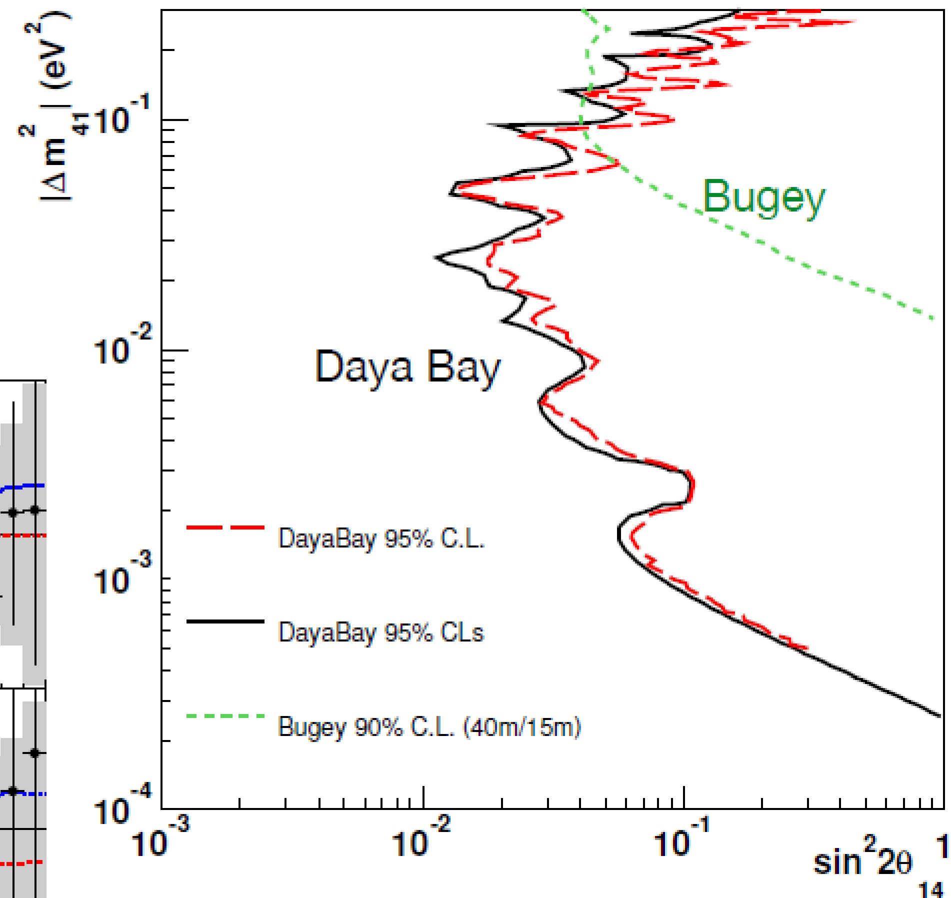
Th. Lasserre & G. Mention

Sterile Neutrino Searches

- Results from Daya Bay (Neutrino2014)
- Baselines: EH1 (~350m), EH2 (~500m), EH3 (~1600m)
- Search for additional spectral distortions in EH2/EH1 and EH3/EH1



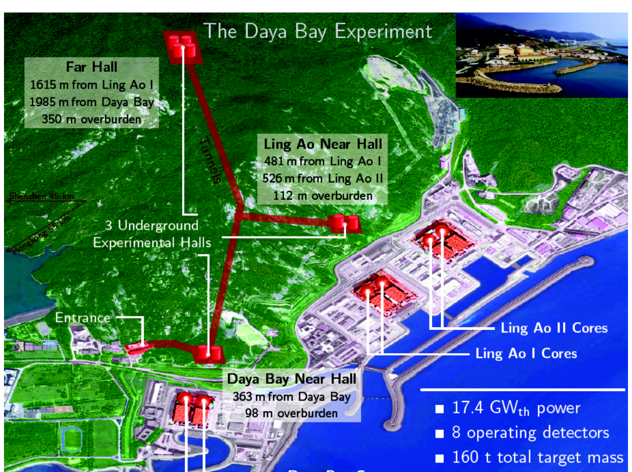
dashed curves assumes $\sin^2 2\theta_{14} = 0.1$

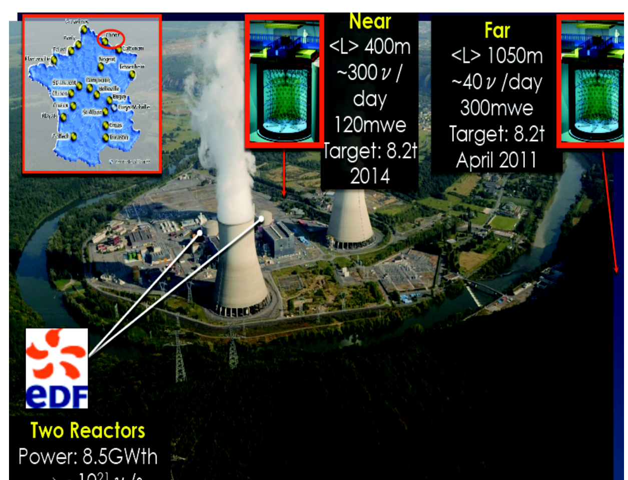


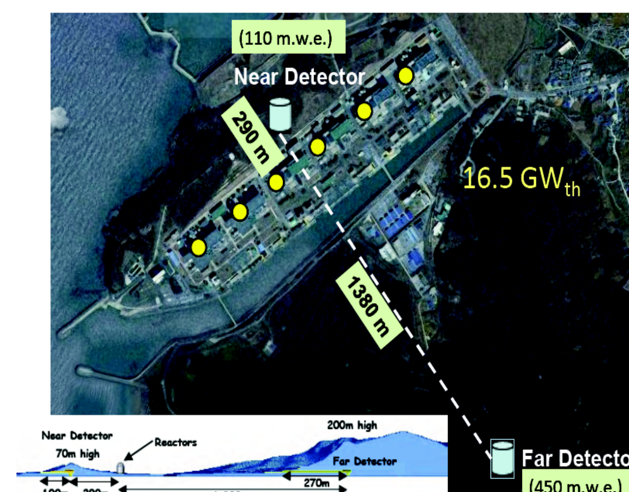
$$P(\bar{\nu}_e \to \bar{\nu}_e) \simeq 1 - \cos^4\theta_{14}\sin^2 2\theta_{13}\sin^2\left(\frac{\Delta m^2_{ee}L}{4E_\nu}\right) - \sin^2 2\theta_{14}\sin^2\left(\frac{\Delta m^2_{41}L}{4E_\nu}\right)$$

Conclusion

- Impressive results from Reactor experiments
- Agreement between experiments and different methods
- Precision measurements on θ_{13} and Δm^2_{ee}
- Limits on sterile neutrinos
- Reactor Predictions: Flux and Spectrum







DC 3rd publication

Parameter	Input C.V.	Input Error	Output C.V.	Output Error
E-scale a'	-0.027	0.006	-0.026	$+0.006, -0.005$
E-scale b'	1.012	0.008	1.011	$+0.004, -0.007$
E-scale c'	-0.0001	0.0006	-0.0006	$+0.0006, -0.0005$
FN+SM rate (d^{-1})	0.60	0.05	0.56	0.04
Li+He rate (d^{-1})	0.97	$+0.41, -0.16$	0.80	$+0.15, -0.13$
Accidentals rate (d^{-1})	0.0701	0.0054	0.0708	0.0053
Residual $\bar{\nu}_e$	1.57	0.47	1.49	0.47
Δm^2 (10^{-3} eV^2)	2.44	$+0.09, -0.10$	2.44	$+0.09, -0.10$
$\sin^2 2\theta_{13}$	—	—	0.090	$+0.033, -0.028$
χ^2/d.o.f.	—	—	51.4/40	—

BG	rate (day^{-1})	shape	energy range	S/BG (%)	δ (BG) (%)	suppression (wrt Gd-II)
^{9}Li+^{8}He	**$0.97^{+0.41}_{-0.16}$**	data (Li+He tag)	[0,12]MeV	2.61	**0.78**	1.3
fast-n stopped-μ	**0.60 ± 0.05^{stat}**	data (IV tag)	[0,20]MeV	1.62	0.13	1.9
accidental	0.070 ± 0.005^{syst}	data (off-time)	<3MeV	0.19	0.01	3.7
^{12}B	<0.003@68CL	neglected	[0,13]MeV	-	-	>7.0
BiPo	<0.1	neglected	<2MeV	-	-	same

Reactor Prediction

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

N_p - number of target protons
ε - detector efficiency
L - distance reactor-detector

$\langle E_f \rangle$ - Mean energy per fission

$$\langle E_f \rangle = \sum_k \alpha_k(t) \langle E_f \rangle_k$$

$\sigma_{IBD}(E)$ – Inverse Beta Decay cross-section
$\langle \sigma_f \rangle$ - Mean cross-section per fission

$$\langle \sigma_f \rangle_k = \int_0^\infty dE\, S_k(E)\, \sigma_{IBD}(E)$$

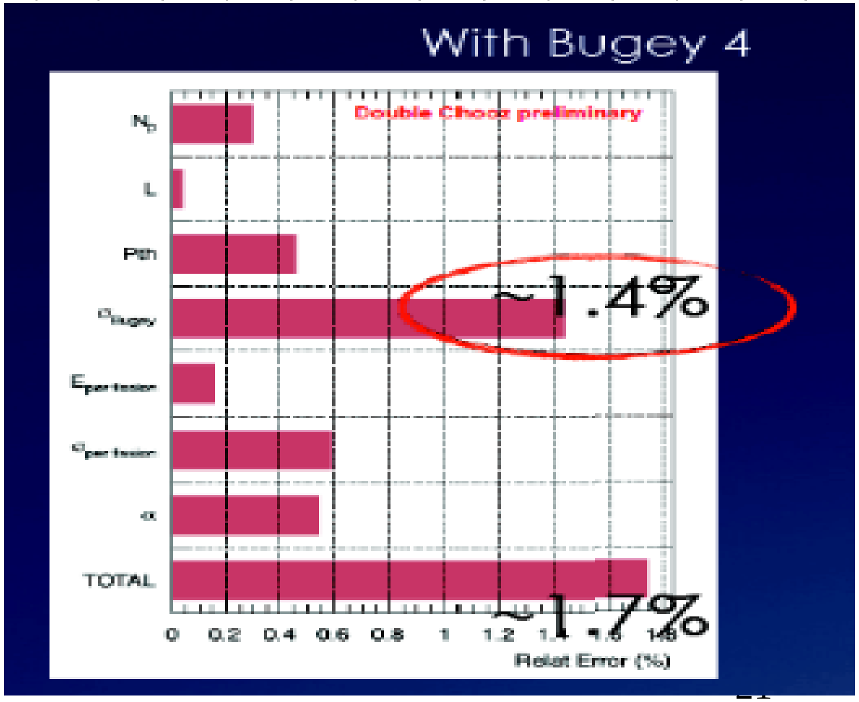
$$\langle \sigma_f \rangle = \langle \sigma_f \rangle^{Bugey} + \sum_k \left(\alpha_k^{DC}(t) - \alpha_k^{Bugey}(t) \right) \langle \sigma_f \rangle_k$$

$P_{th}(t)$ - Thermal Power – monitored by EDF

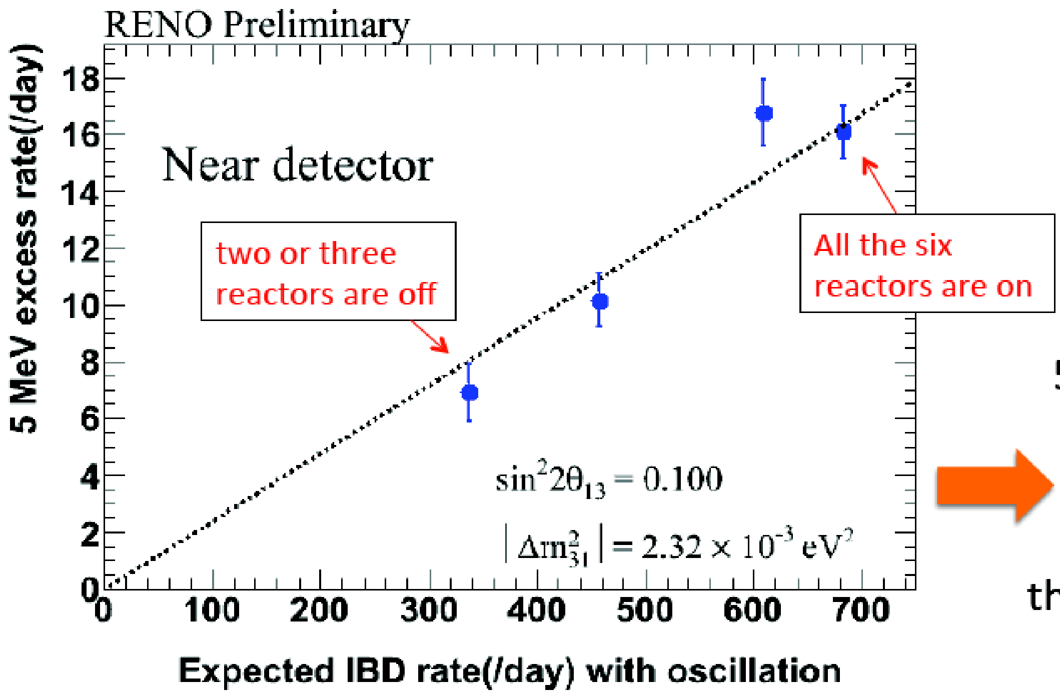
Isotopic content of core:
k= ^{235}U, ^{238}U, ^{239}Pu, ^{241}Pu
α_k - fractional fission rate
Full core simulation MURE
EDF inputs: initial fuel loading, geometry etc

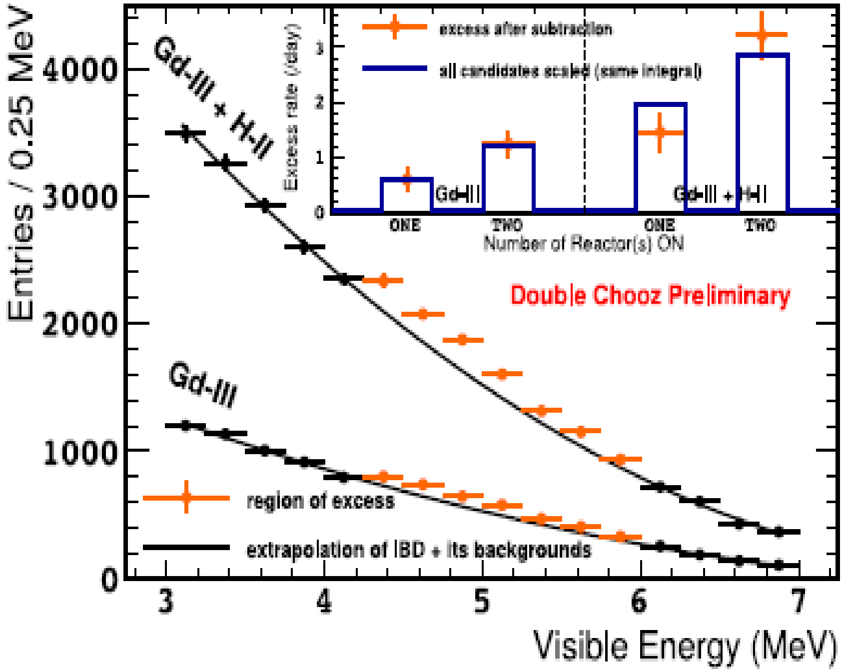
$S_k(E)$ – reference anti-neutrino spectra

Use Bugey-4 as reference and account for different core composition. Suppresses uncertainty on $S_k(E)$.



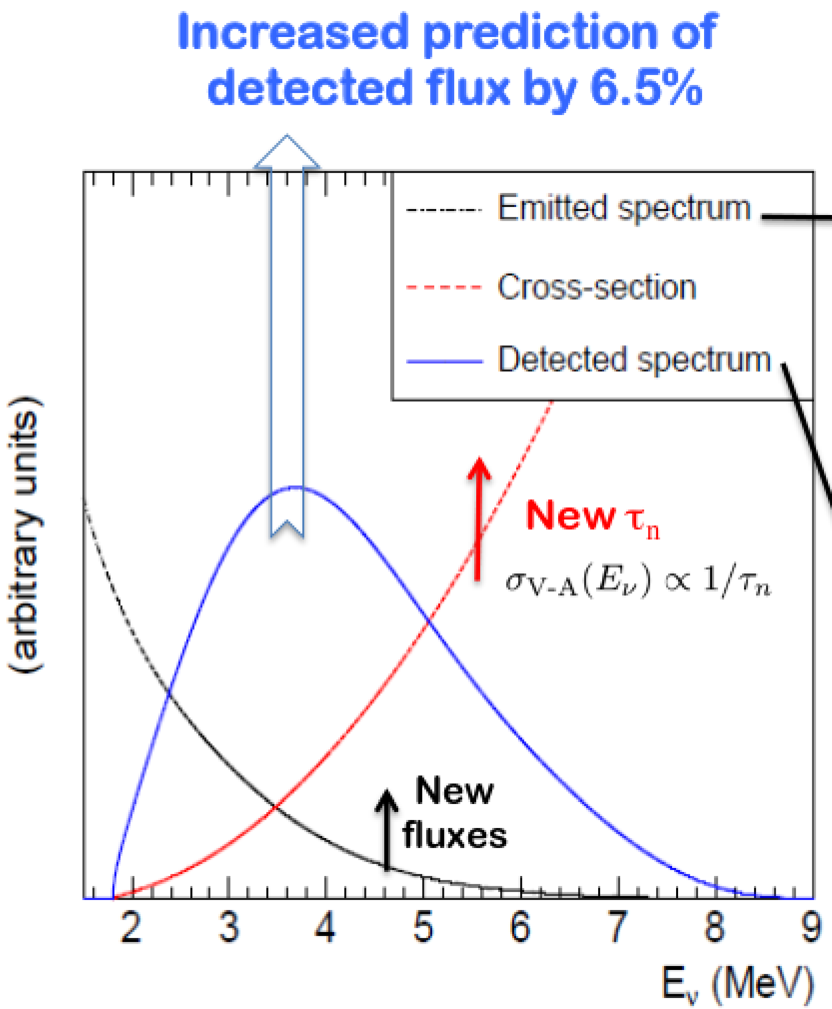
Feature in Spectrum





5 MeV excess has a clear correlation with reactor thermal power !

Reactor Anomaly I



i) **Neutrino Emission:**

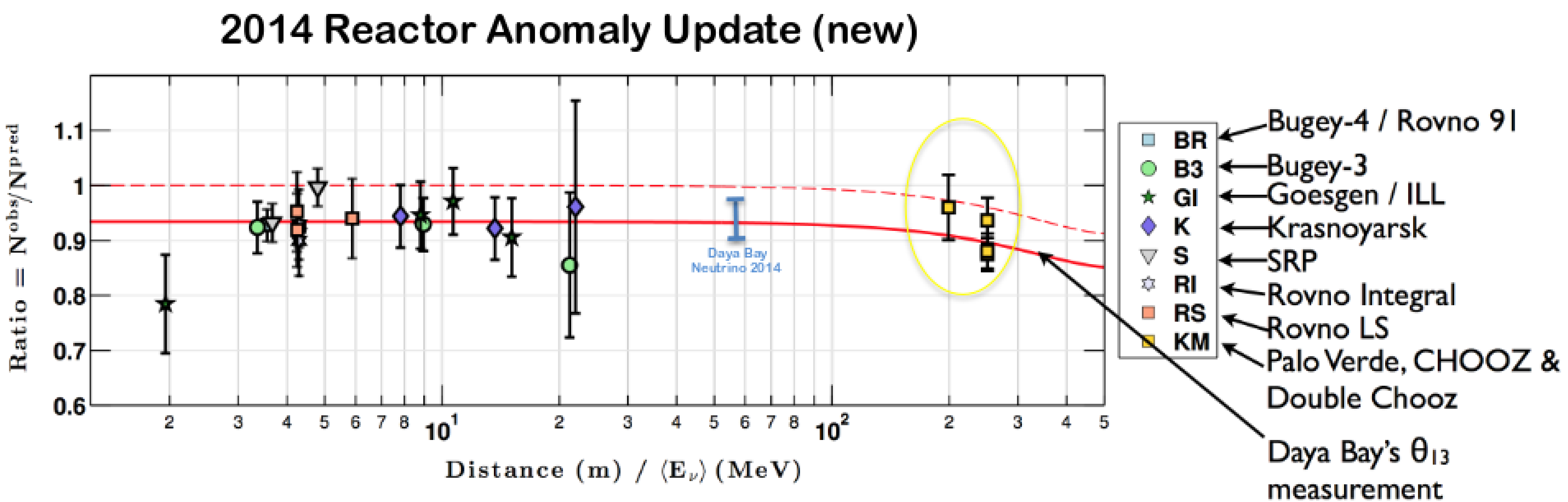
- **Improved reactor neutrino spectra → +3.5%**
- **Accounting for long-lived isotopes in reactors → +1%**

ii) **Neutrino Detection:**

- **Reevaluation of σ_{IBD} → +1.5% (evolution of the neutron life time)**
- **Reanalysis of all SBL experiments**

T. Lasserre

Reactor Anomaly II



- All known nuclear corrections to β - ν spectra
- Refined treatment of experimental correlations
- Latest updated neutron mean life (τ_n = 881.5 s)
- Corrects for a statistical bias (1% shift)
- km-scale baselines (Chooz, DC, PV)
  - correcting for θ_{13} deficit from Daya Bay's measured value
- 2014 result: μ = 0.938 ± 0.023, 2.7σ deviation from unity