Reactor Antineutrino Experiments

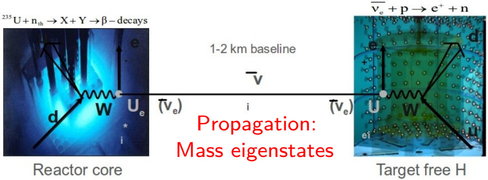
Double Chooz and RENO

Antoine Collin

Max-Planck-Institut für Kernphysik, Heidelberg

August 26, 2014

Neutrino Mixing



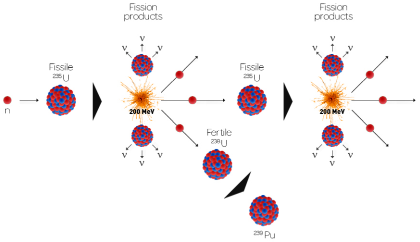
Interaction: flavours   Interaction: flavours

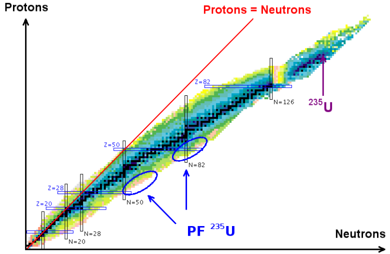
- Neutrino mixing and oscillations:

$$\begin{pmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \end{pmatrix} = \begin{pmatrix} 1 & & \\ & c_{23} & s_{23} \\ & -s_{23} & c_{23} \end{pmatrix} \begin{pmatrix} c_{13} & & e^{-i\delta} s_{13} \\ & 1 & \\ -e^{i\delta} s_{13} & & c_{13} \end{pmatrix} \begin{pmatrix} c_{12} & s_{12} & \\ -s_{12} & c_{12} & \\ & & 1 \end{pmatrix} \begin{pmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \end{pmatrix}$$

$\Delta m^2_{32} \simeq \Delta m^2_{31}$	$\lvert\Delta m^2_{31}\rvert \simeq 2.4 \cdot 10^{-3}\ eV^2$	$\Delta m^2_{21} \simeq 7.6 \cdot 10^{-5}\ eV^2$
$\sin^2 2\theta_{23} \simeq 1$	$\sin^2 2\theta_{13} \simeq 0.1$	$\sin^2 2\theta_{12} \simeq 0.8$
atmospheric ν	accelerator+reactor	solar ν

Reactor Antineutrinos



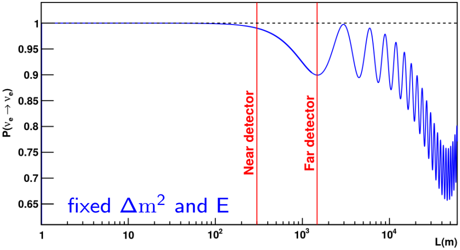


- Nuclear reactors rely on fission chain
- Fission products are neutron rich nuclei
- 1 fission $\rightarrow \sim 200\,\mathrm{MeV}$ and $6\,\bar{\nu}_e$
- Pure and intense source of $\bar{\nu}_e$ through β^- decays
- Energy up to $\sim 8\,\mathrm{MeV}$

Reactor Neutrino Oscillations

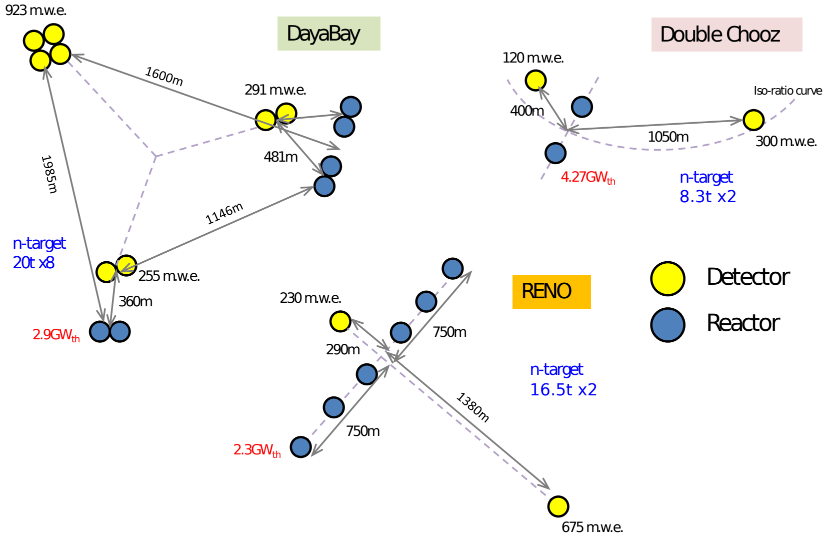
- Reactor $\bar{\nu}_e$ disappearance is directly related to θ_{13}

$$P(\bar{\nu}_e \to \bar{\nu}_e) \backsimeq 1 - \sin^2(2\theta_{13}) \ \sin^2\left(\frac{\Delta m^2_{31} L}{4E}\right)$$



- Clean measurement: insensitive to δ-CP phase value
- Chooz experiment (1999): yielded an upper limit
- Current generation of experiments: relative measurement with two identical detectors (or more) to reduce systematics

Sites of the Different Experiments



(T. Konno @Moriond, 2012)

Detection of Antineutrinos

- $\overline{\nu}_e$ are detected through inverse β decay:

$$\overline{\nu}_e + H^+ \rightarrow n + e^+$$

- Signal signature: time correlation
  - Prompt event: positron ionisation and annihilation

    $E(e^+) \simeq E(\bar{\nu}_e)$ - 0.8 MeV

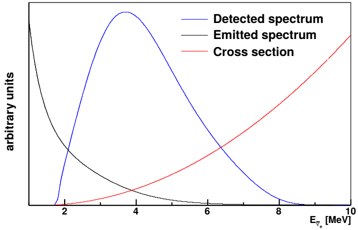
    very localized energy deposition
  - Delayed event: radiative neutron capture on Gd

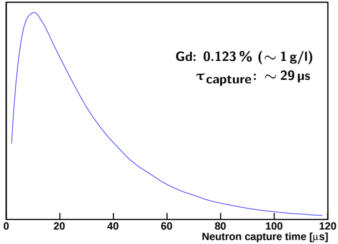
    γ cascade

    total energy $\sim$ 8 MeV

    time correlation of the order of a few tens of μs (depending on the Gd concentration)
  - Alternatively, delayed neutron capture on H ($\sim$ 2.2 MeV)

Detection of Antineutrinos





- $\overline{\nu}_e$ are detected through inverse β decay:

$$\overline{\nu}_e + H^+ \rightarrow n + e^+$$

- Signal signature: time correlation
  - Prompt event: positron ionisation and annihilation

    $E(e^+) \simeq E(\bar{\nu}_e)$ - 0.8 MeV

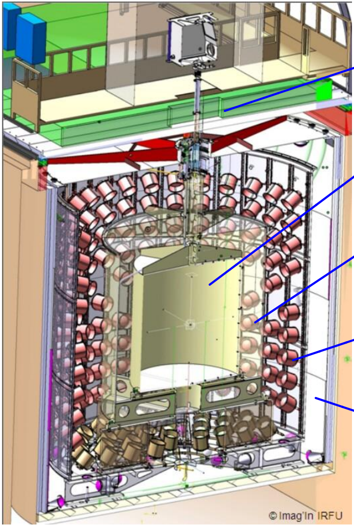
    very localized energy deposition
  - Delayed event: radiative neutron capture on Gd

    γ cascade

    total energy $\sim$ 8 MeV

    time correlation of the order of a few tens of µs (depending on the Gd concentration)
  - Alternatively, delayed neutron capture on H ($\sim$ 2.2 MeV)

Detectors: Double Chooz



Outer Veto : plastic scintillator strips

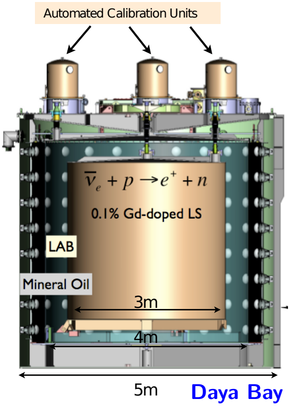
ν-Target: 10.3 m^3 liquid scintillator doped with 1 g/l of Gd in an acrylic vessel (8 mm)

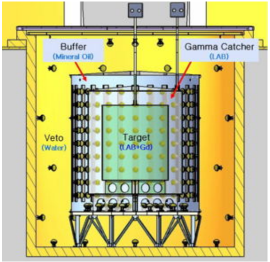
Gamma-catcher: ∼60 cm thick, 22.6 m^3 LS in an acrylic vessel (12 mm)

Buffer: ∼95 cm thick, 110 m^3 of mineral oil in a stainless steel vessel (3 mm) viewed by 390 PMTs (10 inches)

Inner Veto: 90 m^3 liquid scintillator in a steel vessel (10 mm) equipped with 78 PMTs (8 inches) + steel shielding

Detectors: Daya Bay and RENO Features





RENO

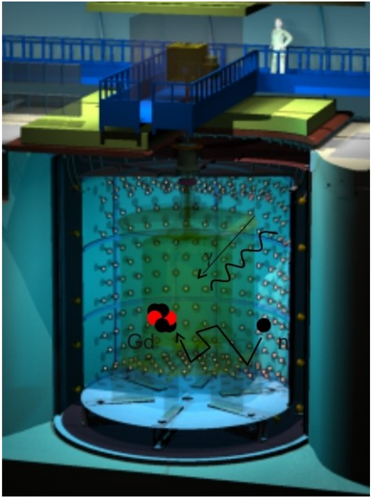
- $8 \times 20\,\text{t}$ detectors
- $\sim 50\,\text{cm}$ thick buffer
- no PMTs on top and bottom (reflective panels instead)
- muon veto: water pools

- $2 \times 16.5\,\text{t}$ detectors
- $\sim 70\,\text{cm}$ thick buffer
- muon veto: water

Accidental Background

Coincidence of two unrelated events

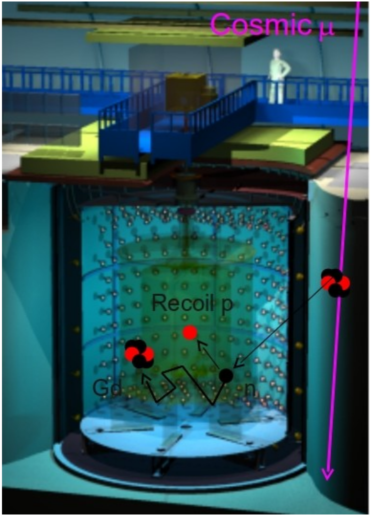
- Prompt signal: γ (natural radioactivity: materials, PMTs, rock, etc.)
- Delayed Signal: neutron capture (produced by cosmic muons, thermalised in the detector) or high energy γ



Correlated Backgrounds

Fast neutrons and stopping muons

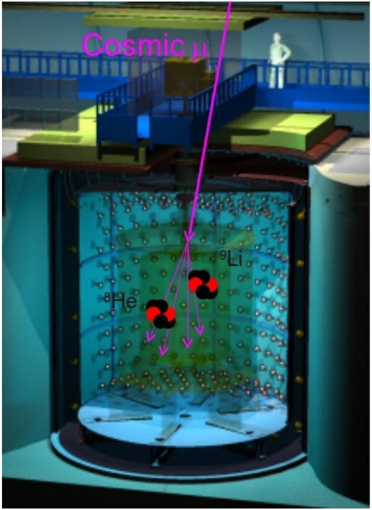
- Fast neutrons induced by reactions of spallation by muons on surrounding nuclei
  - Prompt signal: proton recoil due to neutron collision
  - Delayed signal: capture of the same neutron on gadolinium
- Muons decaying in the inner detector
  - Prompt signal: energy deposited along the muon track
  - Delayed signal: electron emitted by muon decay
- Multiple neutron captures



Correlated Backgrounds

Cosmogenic isotopes: ^{9}Li and ^{8}He

- $\beta - n$ emitters produced by reactions of spallation by muons on ^{12}C
- Lifetime of 178 and 119 ms respectively



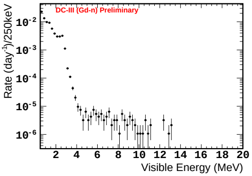
Double Chooz Latest Analysis and Results

Selection of Neutrino Candidates

- Muon veto
  - 1 ms after each muon
  - events in coincidence with Outer Veto and Inner Veto triggers are discarded
- Additional background rejection
  - "Light Noise": based on inhomogeneous charge and PMT hit times distributions
  - Stopping muons: based on poor position reconstruction
- Coincidence selection
  - Prompt event: [0.5; 20] MeV
  - Delayed event: [4; 10] MeV
  - Time coincidence: ΔT within [0.5; 150] μs
  - Prompt–delayed distance: $\Delta R < 1$ m
  - Multiplicity cut: no extra valid trigger within [-200; 600] μs from prompt

Backgrounds

Accidentals

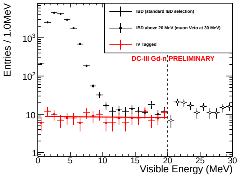


natural radioactivity

- 0.070 ± 0.003 /day
- DC-III / DC-II: **0.3**

prompt–delayed distance cut

Correlated events

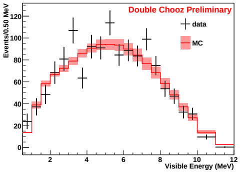


fast neutrons, stopping μ

- 0.60 ± 0.05 /day
- DC-III / DC-II: **0.5**

OV and IV vetoes + position reconstruction likelihood veto

Cosmogenics isotopes



β–n emitters (mainly ^{9}Li)

- $0.97^{+0.41}_{-0.16}$ /day
- DC-III / DC-II: **0.8**

$^{9}Li + ^{8}He$ likelihood veto

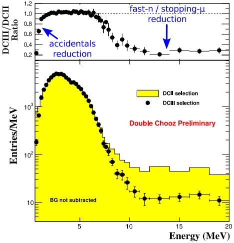
- Two reactor off measurement: 7 events observed when $12.9^{+3.1}_{-1.4}$ were expected
- $N_{BG}(\mathrm{OFF}) < \sum N_{BG}(\mathrm{ON})$ with compatibility of 9 % ($1.7\,\sigma$)
- constraint on possible unaccounted backgrounds

DC-II: 2012

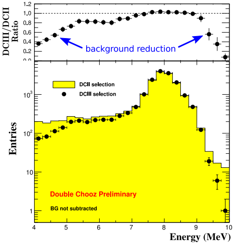
DC-III: 2014

New Analysis Improvements

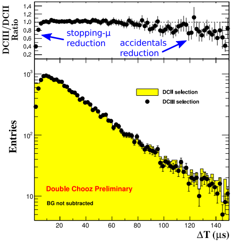
PROMPT ENERGY



DELAYED ENERGY



CORRELATION TIME



	DC-II (2012)	DC-III
ΔT_μ	LE: 1 ms, HE: 0.5 s	$>$ 1 ms
prompt energy	0.7 – 12.2 MeV	0.5 – 20 MeV
delayed energy	6 – 12 MeV	4 – 10 MeV
ΔT	2 – 100 μs	0.5 – 150 μs
ΔR	—	$<$ 1 m
isolation window	[−100, +400] μs	[−200, +600] μs

+ improved Light Noise rejection

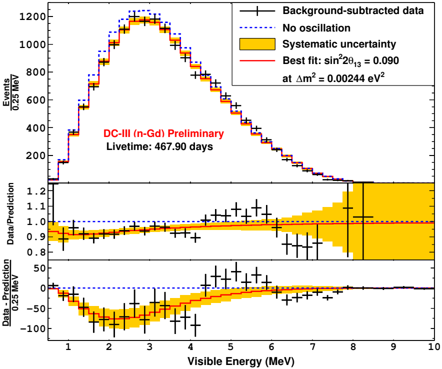
+ improved BG vetoes

- benefits from improved active background rejection
  - wide selection cuts ⇒ detection systematics reduction
  - increased S/B (15.6 → 22)

Summary of Uncertainties

Source		Uncertainty w.r.t. signal	
Statistics		0.8 %	
Reactor	Bugey4 measurement	1.4 %	1.7 %
	Fuel composition	0.8 %	
	Thermal power	0.5 %	
	Energy per fission	0.2 %	
	IBD cross-section	0.2 %	
	Baseline	< 0.1 %	
Detector	Vetoes	0.1 %	0.6 %
	IBD selection	0.2 %	
	Gd fraction	0.4 %	
	Spill in/out	0.3 %	
	Trigger efficiency	< 0.1 %	
	Target H	0.3 %	
Backgrounds	Accidental	< 0.1 %	$+1.1$ % / -0.4 %
	Fast neutron	0.1 %	
	$^{9}Li + ^{8}He$	$+1.1$ % / -0.4 %	

Rate + Shape θ_{13} measurement ("Gd Analysis")



- Other innovations compared to DC-II
  - range from 0.5–20 MeV (0.25 MeV bins)
  - measured ^{238}U spectrum in prediction
  - Δm^2 from MINOS 2013 (T2K confirmed)
  - extra bin from 2 reactor off measurement

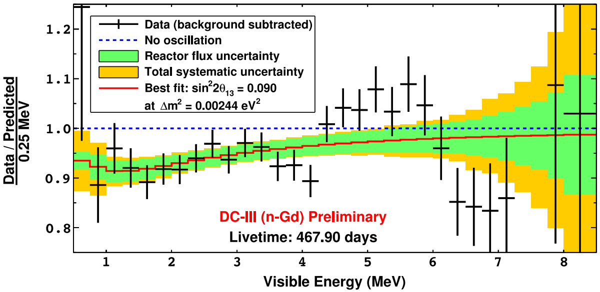
$$\sin^2(2\,\theta_{13}) = 0.090^{+0.032}_{-0.029}\ (\text{stat.}+\text{syst.})$$

arXiv:1406.7763

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

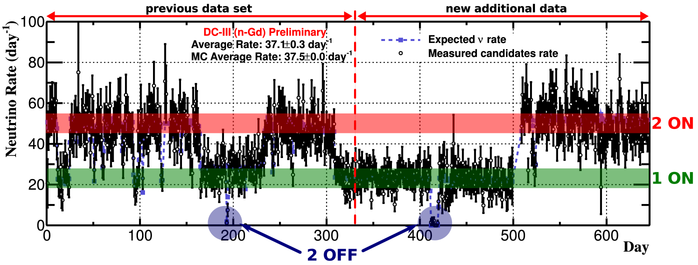
background rate after fit: $1.38 \pm 0.14\,\text{day}^{-1}$

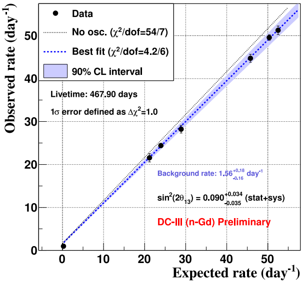
Excess in the Neutrino Spectrum at 5 MeV



- Spectral distortion above 4 MeV observed
- Several crosschecks have shown
  - θ_{13} measurement is not affected
  - energy scale at $E > 4$ MeV tested (e.g. n-^{12}C) and as cause disfavored
  - correlation with reactor power: unknown background disfavored

Reactor Rate Modulation Analysis (RRM)

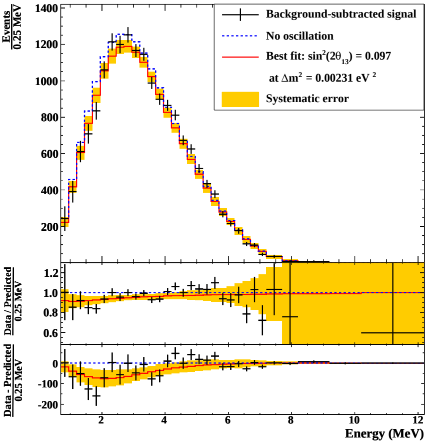




- Measure of θ_{13} (slope) and of the background rate (intercept) at the same time
  - background model independent θ_{13} analysis possible
  - unique to DC: additional reactor off data point
- Results:
  $\sin^2 2\theta_{13} = 0.090^{+0.034}_{-0.035}$ (stat+sys) and $B = 1.56^{+0.18}_{-0.16}$ day^{-1}
- Without background rate constraint:
  $\sin^2 2\theta_{13} = 0.060 \pm 0.039$ (stat+sys) and $B = 0.93^{+0.43}_{-0.36}$ day^{-1}

Rate + Shape θ_{13} measurement (“Hydrogen Analysis”)

Y. Abe et al., Phys. Lett. **B723** (2013) 66–70



- Identifying $\bar{\nu}_e$ by radiative neutron capture on H (and not Gd)
  - Different event sample
  - Different background contribution and systematics
- Using the whole volume filled with liquid scintillator – Gd-doped and un-doped – (target & γ-catcher)
  - Fiducial volume increased by a factor three
  - Increase of statistics
- Made possible by two factors:
  - θ_{13} is rather high
  - Background is lower than in our proposal

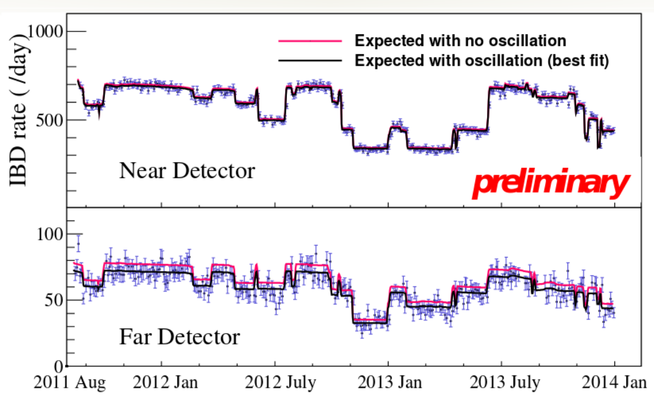
$$\sin^2(2\,\theta_{13}) = 0.097 \pm 0.048 \text{ (stat.+syst.)}$$

Publications of the Double Chooz collaboration: θ_{13} and beyond

- θ_{13} measurement ("Gd Analysis")
  - Indication for the disappearance of reactor electron antineutrinos in the Double Chooz experiment, Y. Abe *et al.*, Phys. Rev. Lett. 108 (2012) 131801
  - Reactor electron antineutrino disappearance in the Double Chooz experiment, Y. Abe *et al.*, Phys. Rev. D86 (2012) 052008
  - Improved measurement of the neutrino mixing angle θ_{13} with the Double Chooz detector, Y. Abe *et al.*, arXiv:1406.7763 (submitted to JHEP)
- Other θ_{13} measurement techniques
  - First Measurement of θ_{13} from Delayed Neutron Capture on Hydrogen in the Double Chooz Experiment, Y. Abe *et al.*, Phys. Lett. B723 (2013) 66-70
  - Background-independent measurement of θ_{13} in Double Chooz, Y. Abe *et al.*, Phys.Lett. B735 (2014) 51–56
- In site background measurement during reactor off-off periods
  - Direct Measurement of Backgrounds using Reactor-Off Data in Double Chooz, Y. Abe *et al.*, Phys. Rev. D87 (2013) 011102
- Beyond θ_{13}
  - First Test of Lorentz Violation with a Reactor-based Antineutrino Experiment, Y. Abe *et al.*, Phys. Rev. D86 (2012) 112009
  - Precision Muon Reconstruction in Double Chooz, Y. Abe *et al.*, arXiv:1405.6627 (submitted to NIM A)
  - Ortho-positronium observation in the Double Chooz Experiment, Y. Abe *et al.*, arXiv:1407.6913 (submitted to JHEP)

RENO Results

Latest RENO Release at Neutrino 2014: Daily IBD Rate



Latest RENO Release at Neutrino 2014: Rate only results

C data set (~800 days)

BKG: 2.2%

BKG: 7.2%

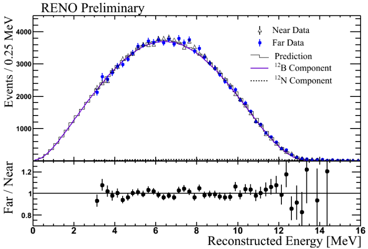
Near Live Rme = 761.11 days
#of IBD candidate = 433,196
#of background = 9499 (2.2 %)

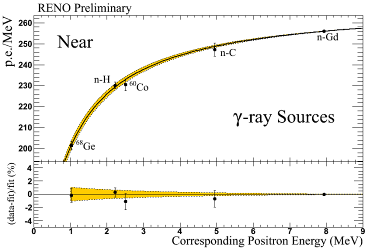
Far Live Rme = 794.72 days
#of IBD candidate = 50,750
#of background = 3672 (7.2 %)

Rate per day	Near	Far
IBD candidates	569.16	63.86
Accidentals	1.82 ± 0.11	0.36 ± 0.01
Fast neutrons	2.09 ± 0.06	0.44 ± 0.02
^{9}Li / ^{8}He	8.28 ± 0.66	1.85 ± 0.20
^{252}Cf contamination	0.28 ± 0.05	1.98 ± 0.27

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

Progress Report on Shape Analysis



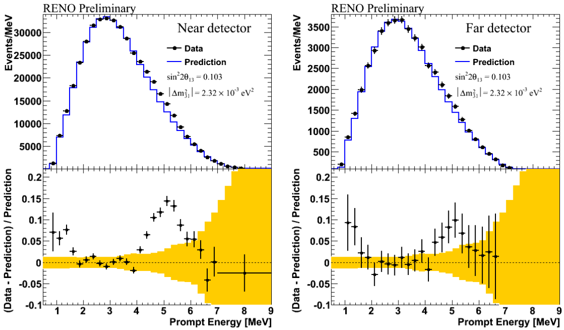


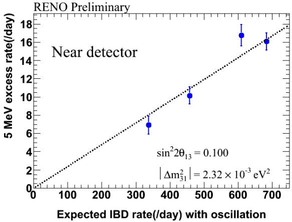
In progress

Stay tuned for Δm^2_{13} measurement

(courtesy of Soo-Bong Kim)

Excess in the Neutrino Spectrum at 5 MeV

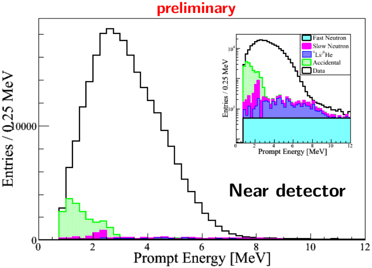


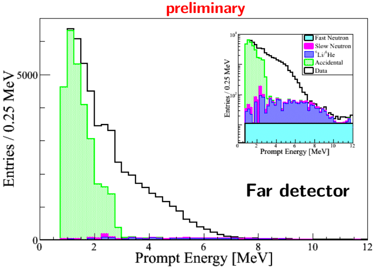


- Fraction of 5 MeV excess to expected flux (Mueller + Huber 2011)
  - Near: 2.314 ± 0.401 (experimental) ± 0.492 (expected shape error)
  - Far: 1.862 ± 0.708 (experimental) ± 0.486 (expected shape error)
- Excess follows the reactor power: not background related

(courtesy of Soo-Bong Kim)

"Hydrogen Analysis" Release at Neutrino 2014 (Rate only)





Rate per day	Near	Far
IBD candidates	646.05	144.47
Accidentals	40.87 ± 1.74	72.69 ± 0.83
Fast neutrons	5.63 ± 0.09	1.28 ± 0.10
^{9}Li / ^{8}He	7.24 ± 0.92	3.17 ± 0.35
Soft neutrons	6.42 ± 0.35	1.04 ± 0.47

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

Conclusion

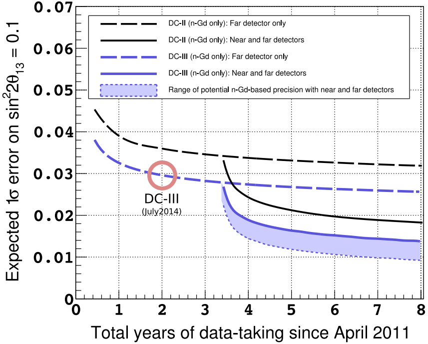
Summary

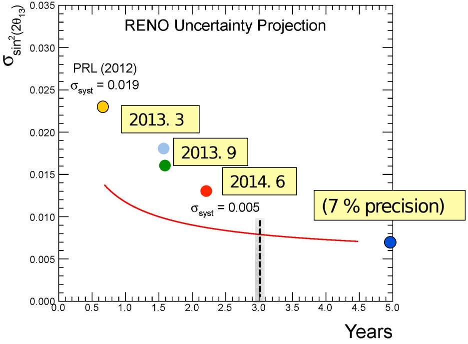
- New generation reactor antineutrino experiments gave a clear demonstration of the oscillation effect
- A precision measurement of θ_{13} is already reached
- Consistent results between
  - different experiments
  - different analysis methods
  - different neutrino samples (Gd/H)
- Latest results

Double Chooz R+S: $\sin^2(2\,\theta_{13}) = 0.090^{+0.032}_{-0.029}$ **arXiv:1406.7763**

RENO Rate only: $\sin^2(2\,\theta_{13}) = 0.101 \pm 0.013$ **Neutrino2014**

Future Sensitivities





- Double Chooz Near Detector will start data taking this fall
  - Aims for 10–15 % precision within three years
- RENO aims for 7 % precision with two more years

Schematic Summary of Current θ_{13} Results