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The Double Chooz reactor antineutrino experiment: latest θ_{13} results

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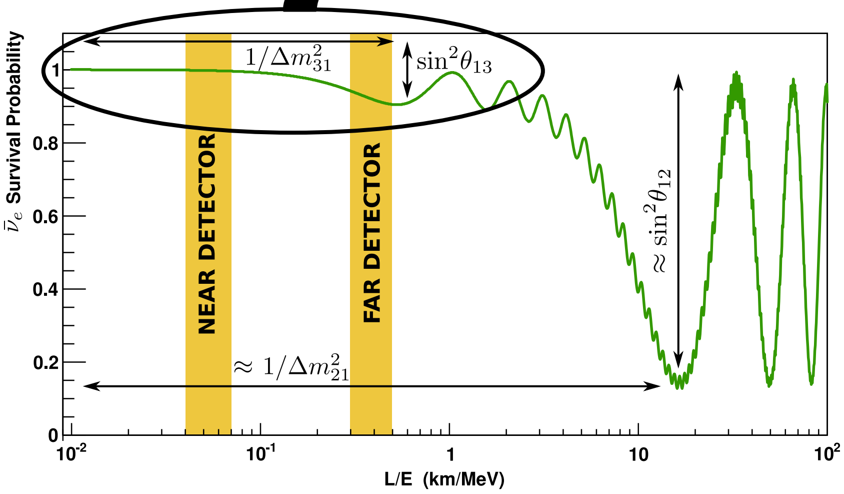
Outline

1. Double Chooz: motivations and experimental concept
2. Energy reconstruction, data selection and backgrounds (DC-III analysis with n-Gd)
3. Oscillation results
    a. Reactor rate modulation analysis
    b. Rate + shape analysis
    c. Spectrum distortion above 4 MeV
4. Near detector outlook and summary

1. Motivations & experimental concept

Reactor antineutrinos and θ_{13}

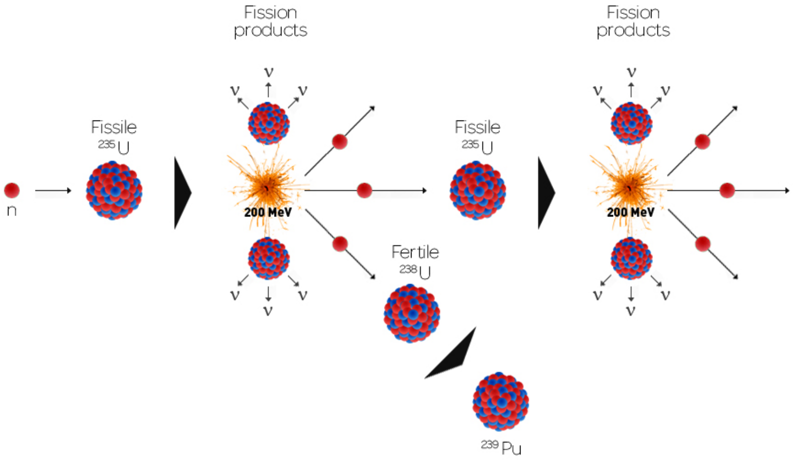


- Neutrino survival probability @ short baselines & in the MeV energy regime:

$$P_{\bar{\nu}_e \to \bar{\nu}_e} = \frac{\Phi^{\mathrm{osc}}_{\bar{\nu}_e}}{\Phi_{\bar{\nu}_e}} \approx 1 - \sin^2(2\theta_{13})\sin^2(1.27\frac{\Delta m^2_{31} L}{E})$$

- No degeneracy with any other parameters of the PMNS matrix: **robust measurement of θ_{13}**
- With a two identical detector experimental concept, cancellation of almost all detection systematics & source flux prediction systematics

- Nuclear reactors perfect neutrino sources for θ_{13} measurement:
  - Pure ν_e source from beta decay of fission products (no source related backgrounds)
  - Energies up to 8 MeV (disappearance measurement only)
  - Possible to place large detectors at O(1-2 km) baselines
  - Matter effects negligible at such distances
  - Very high flux ≈ 2×10^{20} ν_e s^{-1} GW^{-1}_{th}



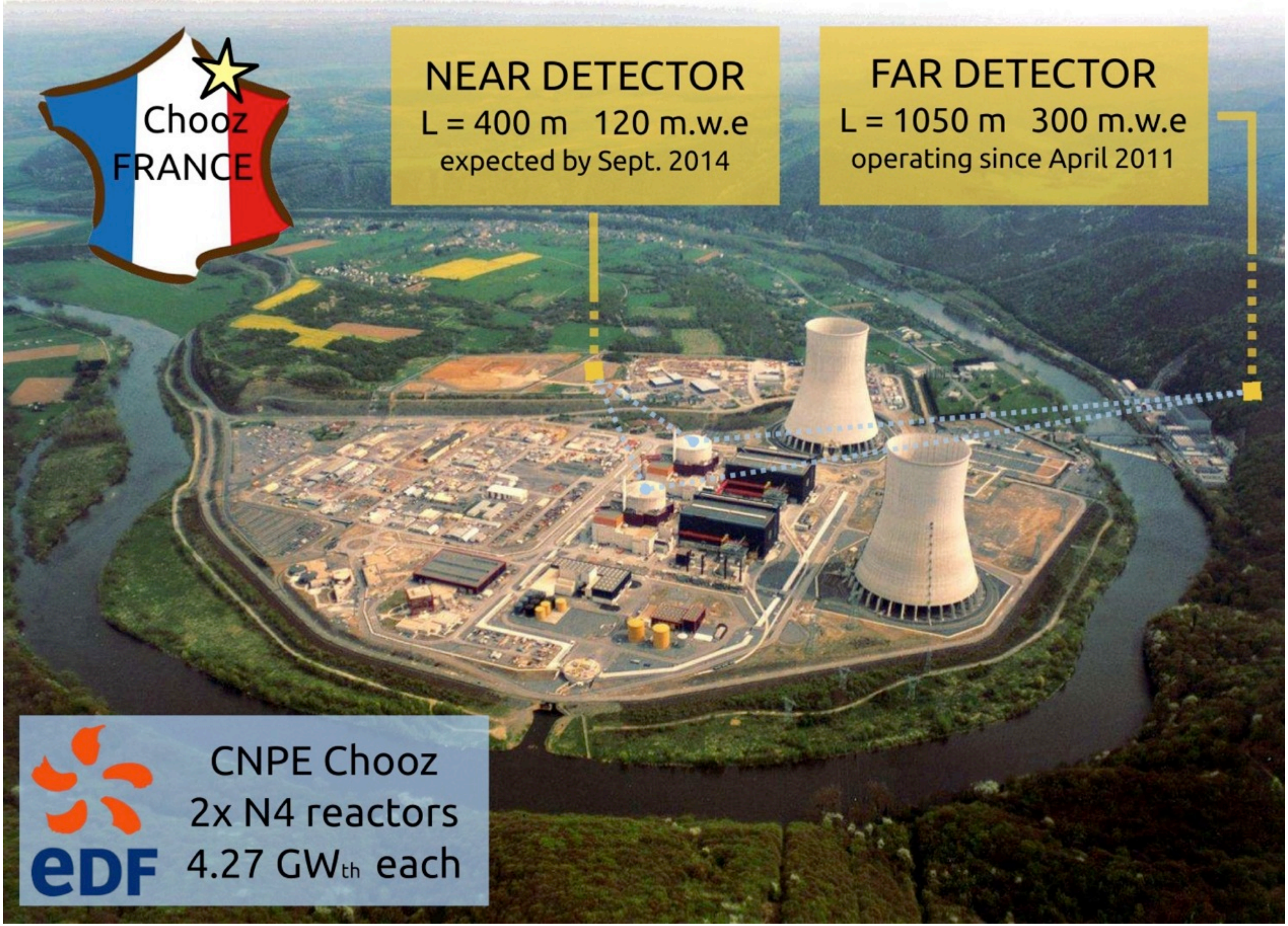
Double Chooz collaboration

BRAZIL	FRANCE	GERMANY	JAPAN	RUSSIA	SPAIN	USA
CBPF UNICAMP UFABC	APC CEA/DSM/IRFU: SPP, SPhN, SEDI, SIS, SENAC. CNRS/IN2P3: Subatech, IPHC.	EKU Tübingen MPIK Heidelberg RWTH Aachen TU München	Tohoku U. Tokyo Inst. Tech. Tokyo Metro. U. Niigata U. Kobe U. Tohoku Gakuin U. Hiroshima Inst. Tech.	INR RAS IPC RAS RRC Kurchatov	CIEMAT-Madrid	U. Alabama ANL U. Chicago Columbia U. UC Davis Drexel U. IIT KSU MIT U. Notre Dame U. Tennessee

150 scientists from 7 countries

Spokesperson: Hervé de Kerret (CNRS/IN2P3)
Project manager: Christian Veyssière (CEA Saclay)

Double Chooz experimental layout



NEAR DETECTOR
L = 400 m 120 m.w.e
expected by Sept. 2014

FAR DETECTOR
L = 1050 m 300 m.w.e
operating since April 2011

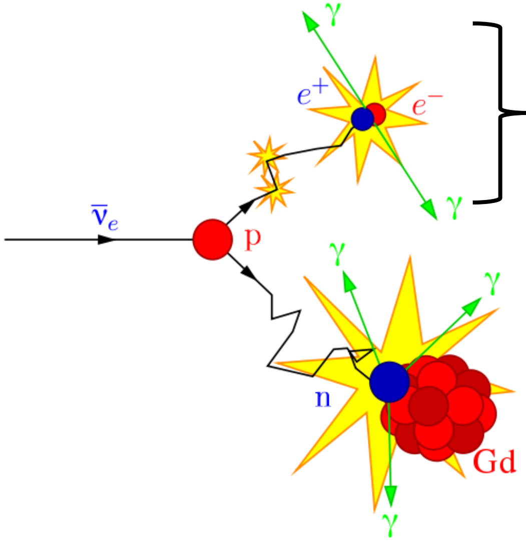
CNPE Chooz
2x N4 reactors
4.27 GW_{th} each

Detection of antineutrinos in Gd-doped LS

- Detection of antineutrinos through inverse beta decay (IBD):

$$\bar{\nu}_{\mathrm{e}} + \mathrm{p} \to \mathrm{n} + \mathrm{e}^{+}$$

- Experimental signature is a time-correlated prompt and delayed energy deposition:



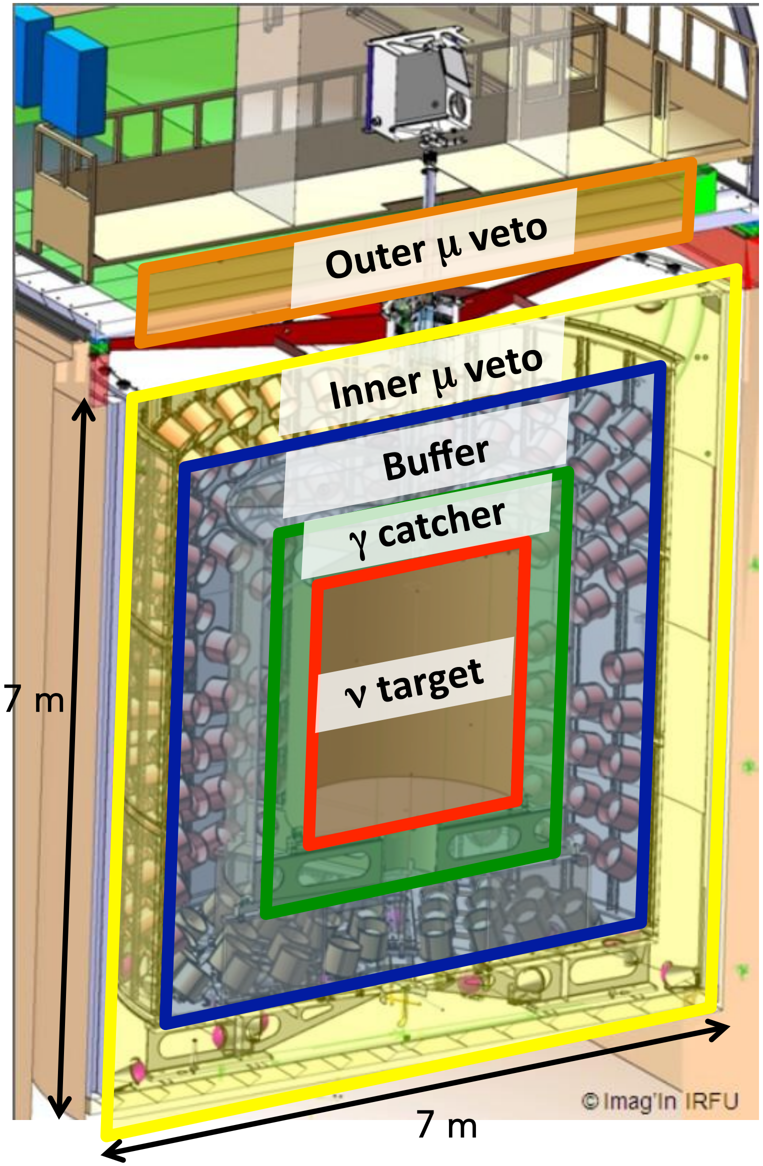
<u>Prompt</u> e^{+} energy deposition: ionization + e^{+}/e^{-} annihilation $E(e^{+}) \approx E(\nu_e) - 0.8$ MeV

<u>Delayed</u> energy deposition: 8 MeV (resp. 2.2 MeV) γ ray cascade from neutron capture on Gd (resp. H)

<u>Time correlation</u> between these two energy depositions ≈ neutron capture time (mostly driven by gadolinium content in the LS)

- Advantage of IBD detection in Gd-doped LS over other detection processes:
  - IBD cross-section 10-100 times higher than any other interaction processes
  - Time (and space)-correlation allows very efficient suppression of backgrounds
  - 8 MeV delayed energy deposition from neutron capture on Gd well above natural radioactivity

Double Chooz detectors



A concentric arrangement of cylindrical sub-detectors…

μ vetoes

- ○ Outer μ veto: plastic scintillator strips
- ○ Inner μ veto: 90 m^3 of LAB scintillator (50 cm thick) in a stainless steel tank equipped with 78 8' PMTs

Inner detector (IV)

- ○ Buffer volume: 100 m^3 of transparent mineral oil (105 cm thick) in a stainless steel tank, equipped with 390 low background 10' PMTs
- ○ γ catcher: 55 cm thick Gd-free LS (PXE) layer contained in a transparent acrylic vessel
- ○ ν target: 10 m^3 of Gd-doped LS (PXE + 1 g/L of Gd)

+ central chimney connected to all layers for calibration source insertion
+ fast readout electronics
+ laser system for PMT gain calibration
+ etc …

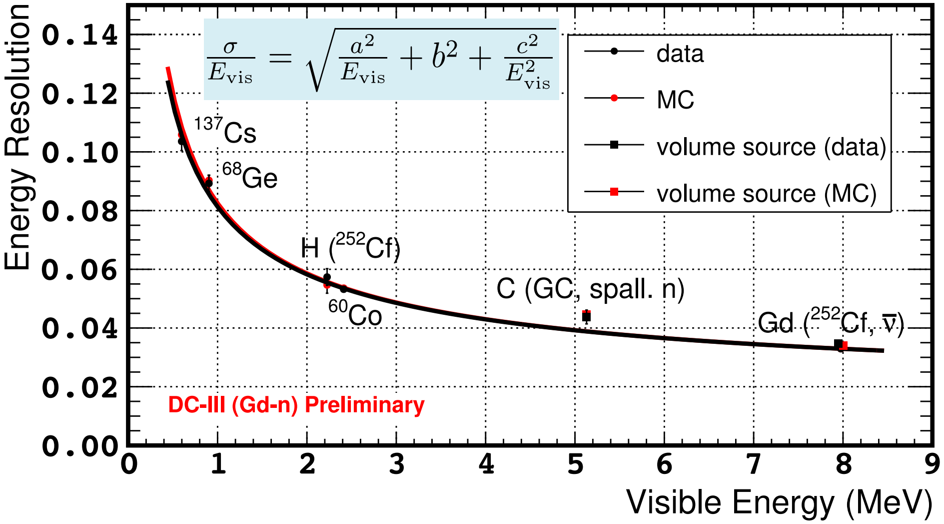
2. Energy reconstruction, data selection and backgrounds (DC-III analysis)

Energy reconstruction scheme

- Common to both data & MC:
  1. Charge to PE conversion for each channel: correction for gain non-linearity at low charges
  2. PE corrected for non-uniformity of the detector response: calculation of response map using spallation neutron capture on H for data, and IBD neutron capture for MC
  3. Absolute energy scale factor: from neutron capture of ^{252}Cf source deployed at the detector center

- Applied to data only: correction for gain and detector variations over the data taking period (stability calibration). Correction function estimated with Gd and H captures + α decays of ^{212}Po
- Applied to MC only: charge (modeling of readout electronics) and light (LS related) non-linearity corrections

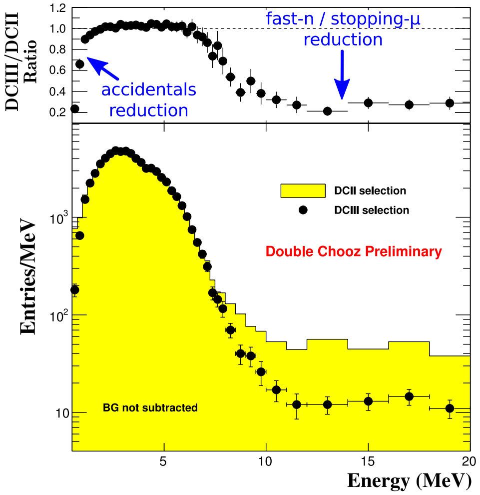
$$\mathrm{E_{vis}} = \mathrm{N^{m}_{pe}} \times \mathrm{f^{m}_{u}}(\rho, \mathrm{z}) \times \mathrm{f^{m}_{MeV}} \left(\times \mathrm{f^{data}_{s}}(\mathrm{t}) \right) \left(\times \mathrm{f^{MC}_{nl}} \right)$$



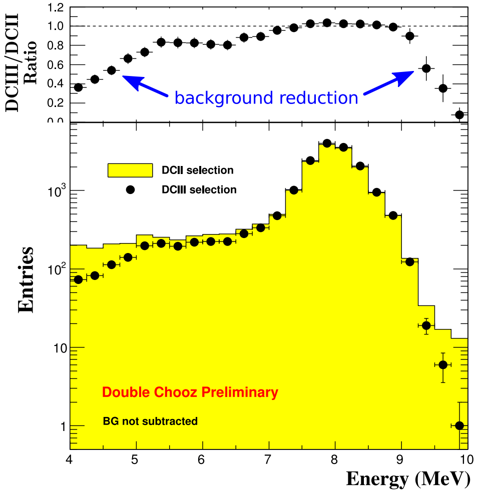
Very good data/MC agreement over the full energy range

Improved neutrino selection

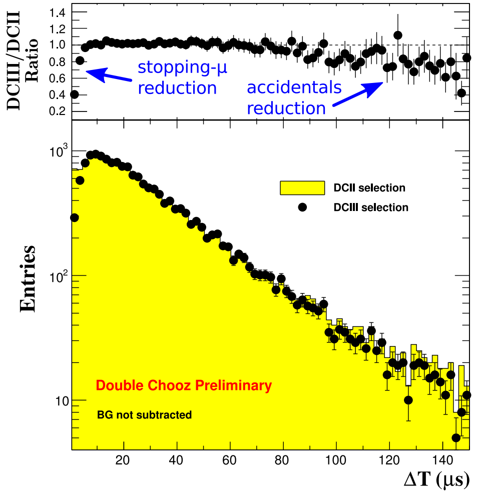
Prompt energy spectrum



Delayed energy spectrum



Correlation time distribution



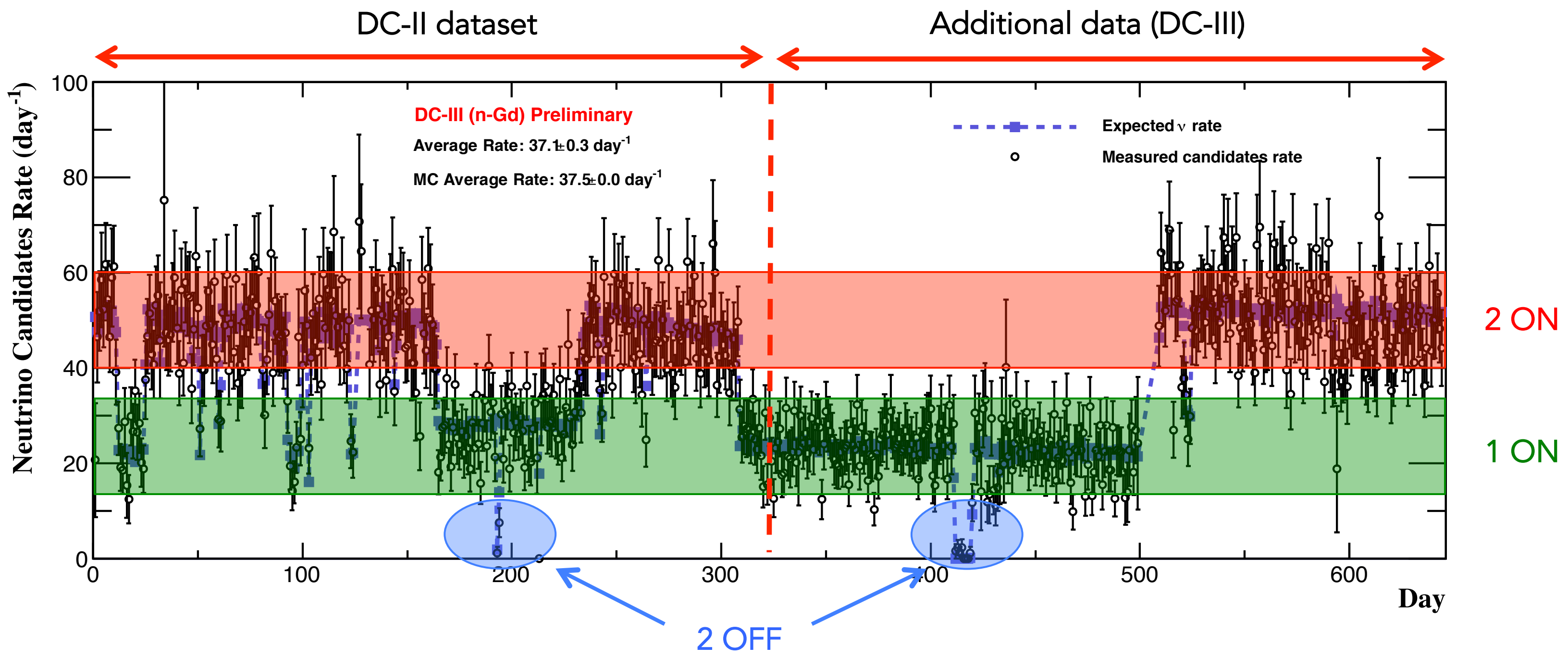
	DC-II (2012)	DC-III (2014)
ΔT_μ	LE: 1 ms; HE: 0.5 s	1 ms
E_{prompt}	[0.7 – 12.2] MeV	[0.5 – 20] MeV
$E_{delayed}$	[6 - 12] MeV	[4 - 12] MeV
ΔT	[2 - 100] μs	[0.5 - 150] μs
ΔR	-	< 1 m
Isolation window	[-100 - +400] μs	[-200 - +600] μs

→ Increased exposure
→ Better background characterization
→ Enhanced IBD efficiency + reduced detection systematics
→ Enhanced IBD efficiency
→ Accidental background suppression

+ improved light noise suppression
+ improved background vetoes: OV/IV vetoes, new ^{9}Li veto, new Fv veto

- Overall improvement in S/B wrt DC-II (15.6 → 22)
- Detection and residual background systematics lowered thanks to wider cuts

Neutrino candidates



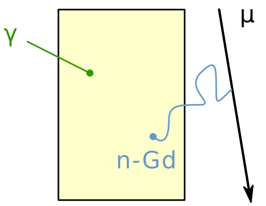
	Reactor ON	Reactor OFF
Live-time (days)	460.67 (April 2011 – Jan 2013)	7.24 (2011 & 2012)
Neutrino candidates	17351	7
Total prediction* (bck included)	18290^{+370}_{-330}	$12.9^{+3.1}_{-1.4}$

* Neutrino oscillation not included in the prediction

- IBD statistics enhanced by a factor 2 wrt to DC-II

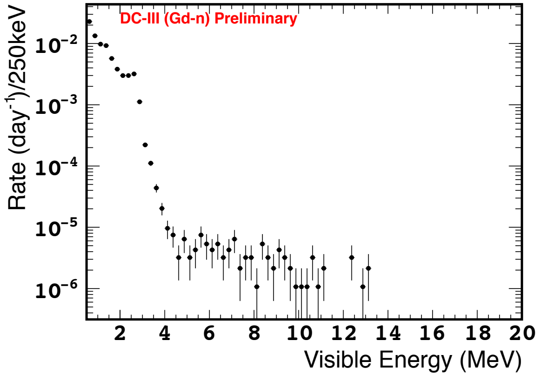
Background estimates with reactor ON data

Accidental coincidences



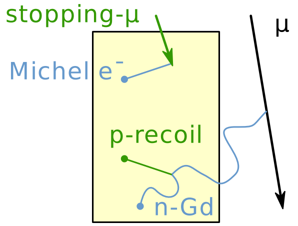
Natural radioactivity

- $R = 0.070 \pm 0.003\ d^{-1}$
- Measured by off-time coincidence window
- DC-III/DC-II = 0.27
- Further reduced thanks to (new) prompt-delayed distance cut



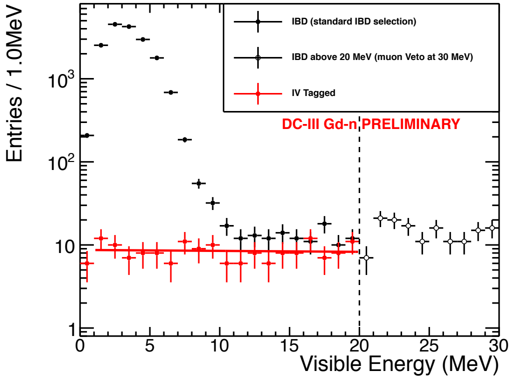
DC-II: 2012
DC-III: 2014

Correlated events

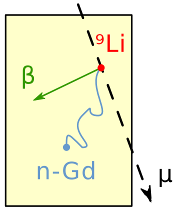


Fast neutrons & stopping μ

- $R = 0.604 \pm 0.051\ d^{-1}$
- Measured with IV-tagged IBD events
- DC-III/DC-II = 0.52
- Further reduced thanks to OV + IV vetos, and (new) Fv cut

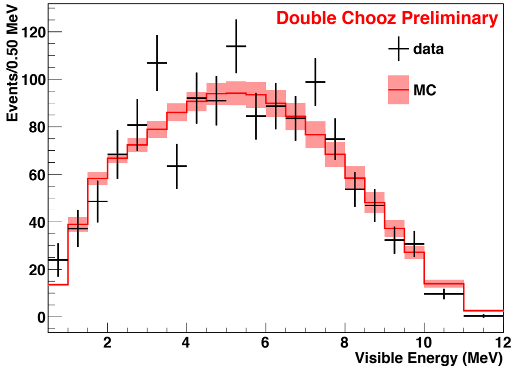


Cosmogenic isotopes



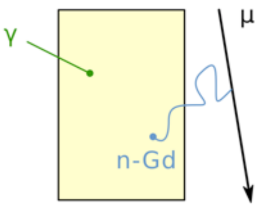
β-n emitters (^{9}Li & ^{8}He)

- $R = 0.97^{+0.41}_{-0.16}\ d^{-1}$
- Measured with distribution of ΔT_μ: time difference between μ and IBD-like prompt event
- DC-III/DC-II = 0.78
- Further reduced thanks to new ^{9}Li + ^{8}He veto



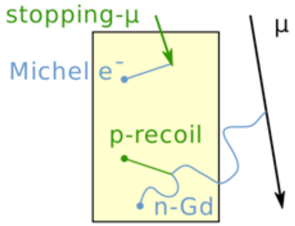
Measured background in reactor OFF data

Accidental coincidences



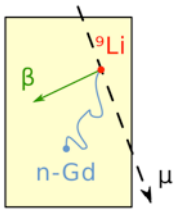
Natural radioactivity

Correlated events



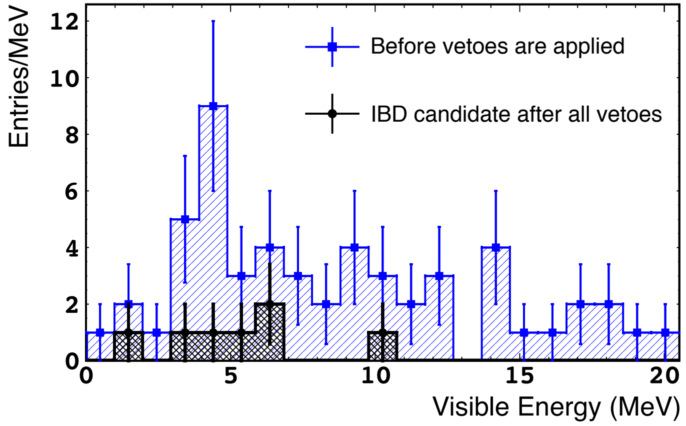
Fast neutrons & stopping μ

Cosmogenic isotopes



β-n emitters (^{9}Li & ^{8}He)

- 7.24 days of reactor OFF data taken in 2011 and 2012: unique opportunity to measure and study backgrounds in DC [Y. Abe et al. Phys. Rev. D **87**, 011102(R)]
- With new selection cuts (see next slide): $N^{IBD} = 7$ (54, before background vetoes)
- Expected number based on previous background estimates + residual reactor ν_e $N^{exp}= 12.9^{+3.1}_{-1.4}$
- Compatible at the 1.7 σ level (p-value = 9%)
- Reactor OFF data are used as an additional input in the different oscillations analyses



IBD prompt spectrum before and after background vetoes are applied

3. Oscillation results

Breakdown of normalization uncertainty

Uncertainties relative to total signal prediction

	Uncertainty (%)	DC-III/DC-II
Reactor flux	1.7	1.0
Detection efficiency	0.6	0.6 (- 40%)
9Li + 8He	+1.1 / -0.4	0.5 (- 50%)
Fast-n + stop. μ	0.1	0.2 (- 80 %)
Stat.	0.8	0.7 (- 30%)
Total	+2.3 / -2.0	0.8 (-20 %)

Uncertainty on accidental background negligible

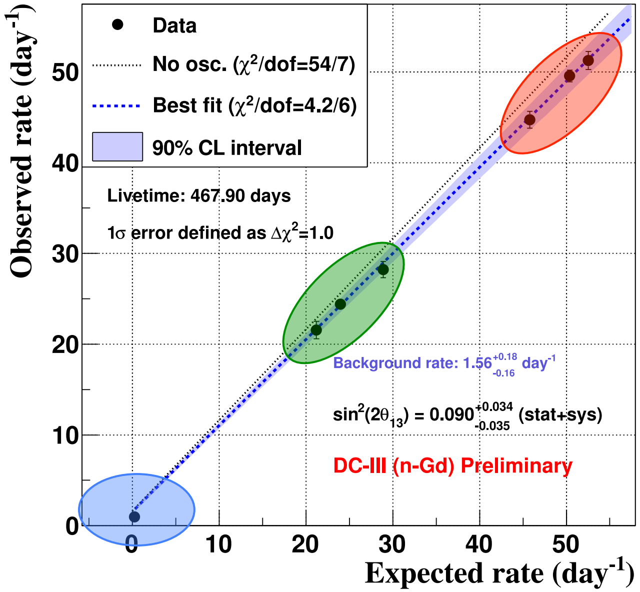
- All systematic uncertainties decreased by a factor of almost 2
- Not only background uncertainties were reduced, but also rates, thanks to improved neutrino selection cuts (see previous slides)
- Used as inputs into oscillation fits along with central values: better precision on θ_{13}

DC-III: reactor rate modulation analysis

- Same analysis as in [Y. Abe et al Phys.Lett. B735 (2014) 51-56]
- Background-model independent measure of θ_{13} using information brought by neutrino rates in different reactor power bins:

$$\mathrm{R}^{\mathrm{obs}} = \mathrm{B} + (1 - \sin^2(2\theta_{13})\alpha_{\mathrm{osc}})\mathrm{R}^{\nu}$$

- α_{osc} is $\sin^2(\Delta m^2 L/4E)$ averaged over neutrino spectrum
- Fit intercept (B) and slope ($\sin^2(2\theta_{13})$) either with or without background rate from OFF data
- χ^2 minimization in which, IBD efficiency, residual ν_e prediction and reactor flux prediction are systematics treated as nuisance parameters.



2 OFF 1 ON 2 ON

Results

- <u>Without bck rate from OFF data:</u>

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

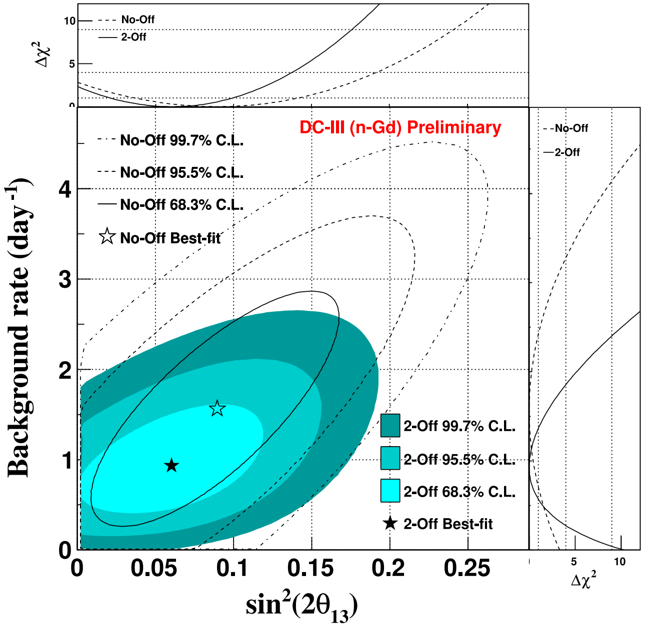
$B = 1.56^{+0.18}_{-0.16}$ d^{-1}

- <u>With bck rate from OFF data:</u>

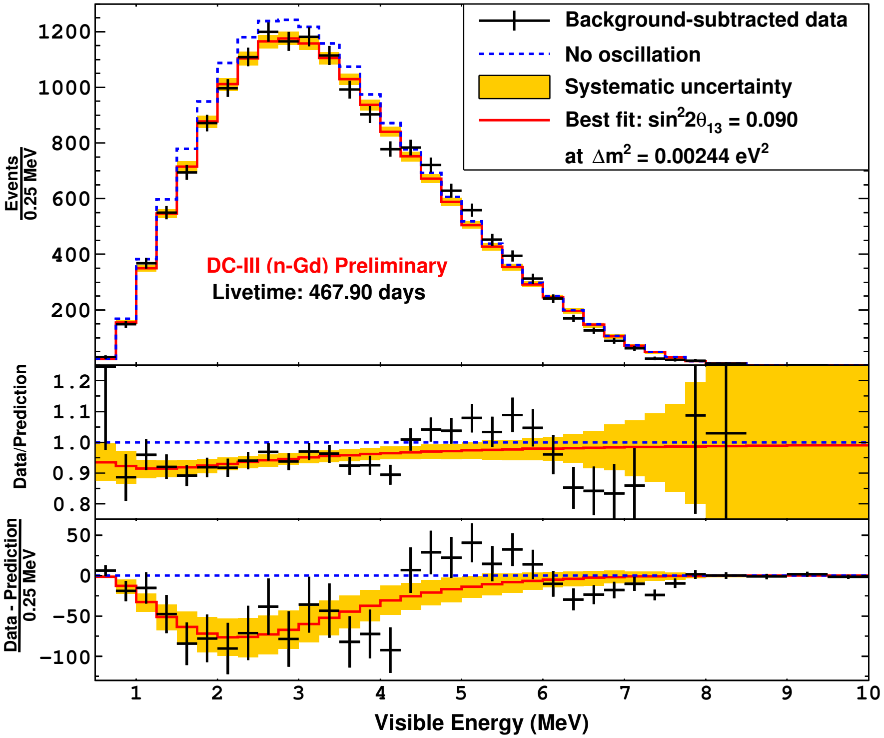
$\sin^2(2\theta_{13}) = 0.060 \pm 0.039$

$B = 0.93^{+0.43}_{-0.36}$ d^{-1}

[Y. Abe et al. arXiv:1406.7763]



DC-III: rate + spectrum shape analysis



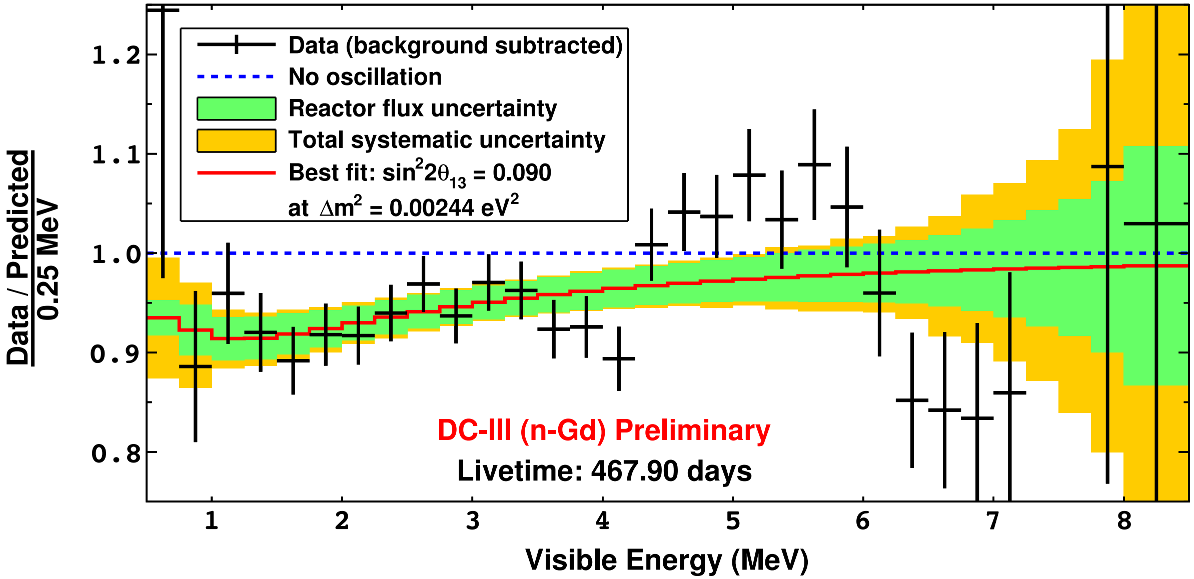
- Many improvements wrt DC-II analysis
  - Better treatment of energy scale
  - Range from 0.5 to 20 MeV (250 KeV energy bins)
  - Extra bin from 2-reactor OFF measurement
  - Δm^2 from 2013 Minos measurement (confirmed by T2K)
- χ^2 minimization with treatment of systematic uncertainties as nuisance parameters:
  - Background rates
  - Energy scale parameters
  - Δm^2
  - Residual neutrino rate in 2-reactor OFF data
- Rest of systematic uncertainties encoded into a covariance matrix (reactor, background shapes, and detection)

$\sin^2(2\theta_{13}) = 0.092^{+0.033}_{-0.029}$ (stat. + syst.)
$\chi^2_{min}/n_{dof} = 52.2/40$ (p-value = 9.4%)
Background rate after fit = 1.38 ± 0.14 d^{-1}

[Y. Abe et al. arXiv:1406.7763]

As a cross-check, rate only fit gives: $\sin^2(2\theta_{13}) = 0.090^{+0.036}_{-0.037}$ (stat. + syst.)

Spectrum distortion



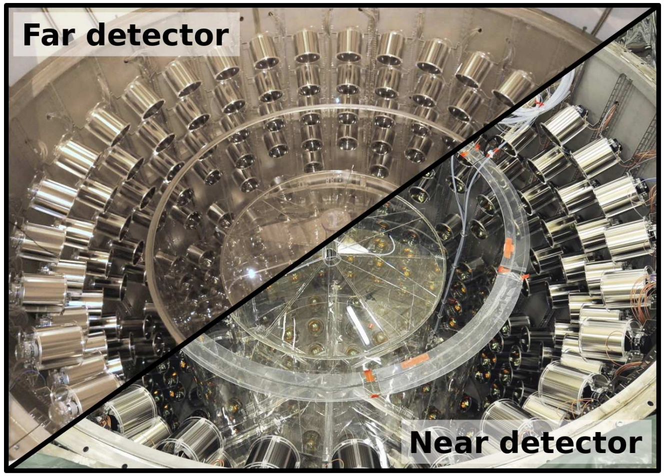
[Y. Abe et al. arXiv:1406.7763]

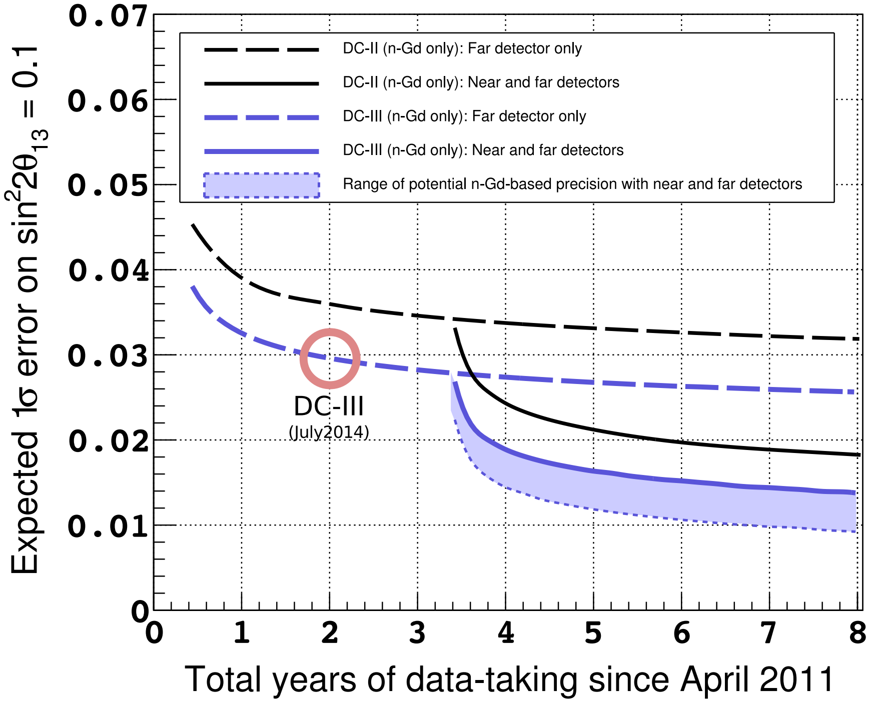
- Unexpected spectrum distortion observed above 4 MeV
- Many cross-checks have been done so far, and showed that:
  - θ_{13} measurement is not affected by the distortion: most of the θ_{13}-deficit is below 4 MeV + statistical power on θ_{13} measurement brought mostly by rate information, not spectrum distortion
  - Energy scale above 4 MeV seems ok (as showed by neutron capture peak on ^{12}C). Cross-checks still on-going though, because a < 1% bias in the energy scale modeling can cause migration of events between adjacent energy bins… (especially in the 4-8 MeV region where the spectrum steeply falls down)
  - Unknown background disfavored + excess/deficit in the 4 – 8 MeV region scale with reactor power
  - RRM fit in different energy bins disfavors a new background component, and rather favors an unaccounted reactor flux contribution.

4. Near detector outlook and summary

Near detector outlook

- Integration finished
- Sub-detector filling starts mid-september
- First neutrinos on October!





<u>Prospects on θ_{13} with ND</u>

- Cancellation of almost all reactor related uncertainties
- Background in the ND scaled wrt to FD using different μ flux
- Backgrounds and energy scales uncorrelated between FD and ND
- θ_{13} precision expected to improve as we accumulate background (stat. Limited)

1σ uncertainty within [0.015-0.010] after 3 years of data taking with ND+FD

Conclusion

- DC-III improvements:
  - Twice more statistics: 460.67 days
  - Improved energy reconstruction (non-linearity calibrated)
  - New selection cuts, active background rejection (IV,OV vetoes, etc): increased efficiencies, reduced systematics
  - Data-driven estimates of backgrounds, reduced systematics
  - θ_{13} analysis also uses information from 2-reactor OFF data: 7.24 days

- θ_{13} results:
  - R+S : $\sin^2(2\theta_{13}) = 0.092^{+0.033}_{-0.029}$ (stat. + syst.)
  - RRM: (w/o 2-reactor OFF data): $\sin^2(2\theta_{13}) = 0.090^{+0.034}_{-0.035}$
  - RRM: (with 2-reactor OFF data): $\sin^2(2\theta_{13}) = 0.060 \pm 0.039$

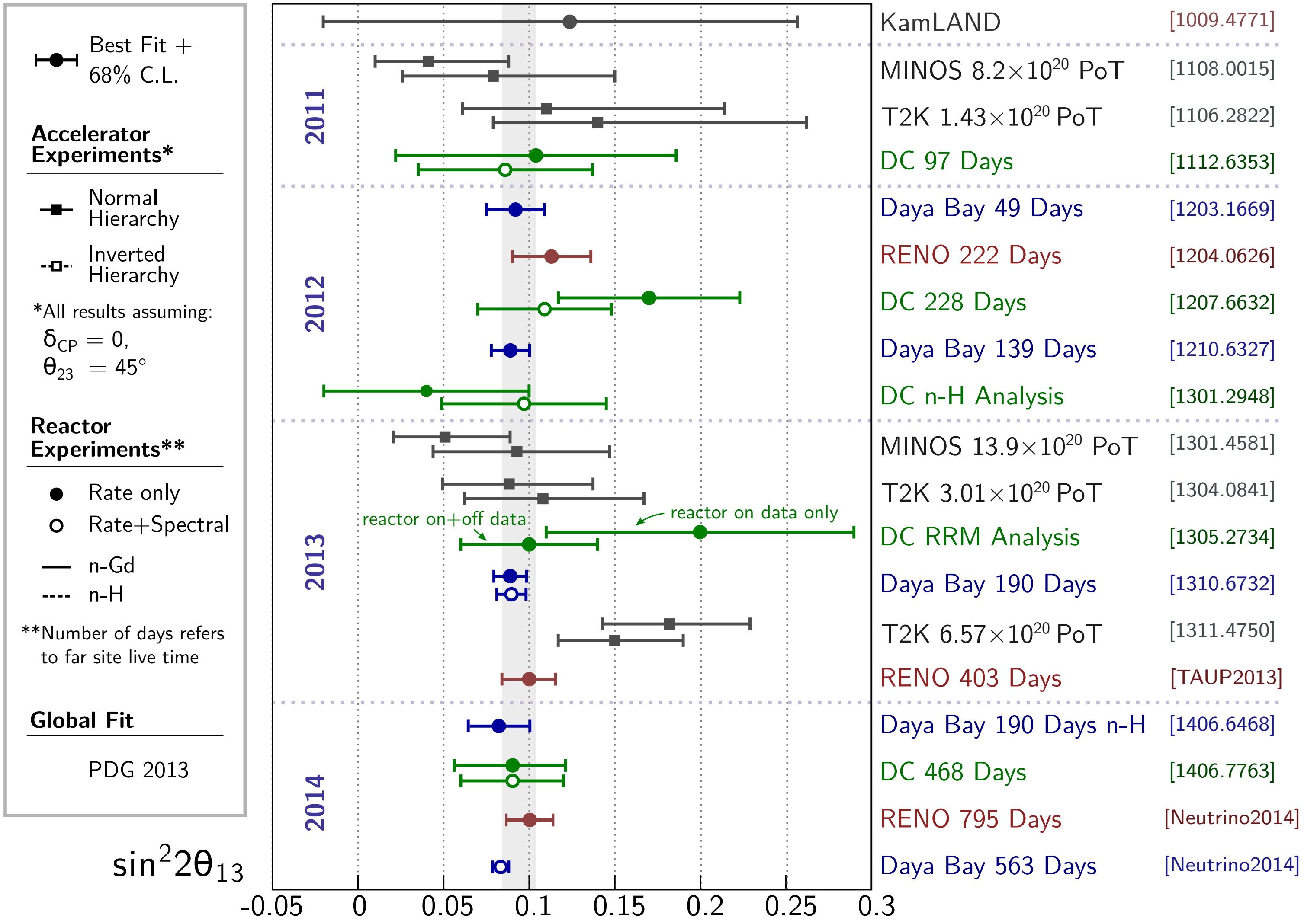
- Spectrum distortion observed between 4 - 8 MeV: unknown origin but unaccounted reactor flux component might be favored.
- ND ready by October:

< 0.015 1σ uncertainty on θ_{13} expected after 3 years of data taking

New DC paper on arxiv: 1406.7763 !!

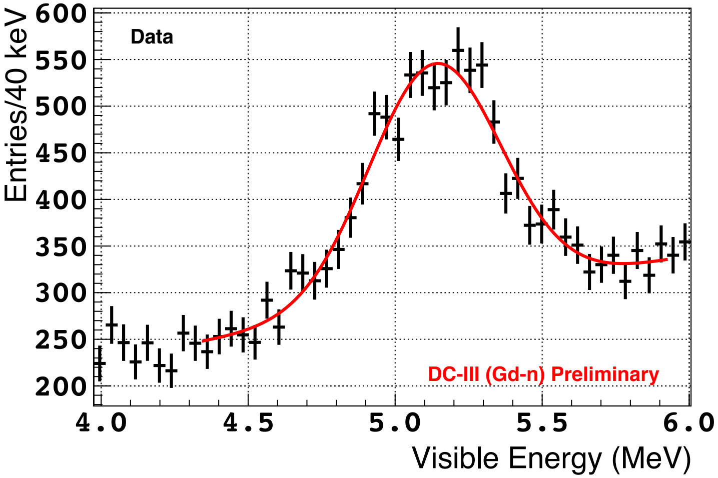
Backup slides

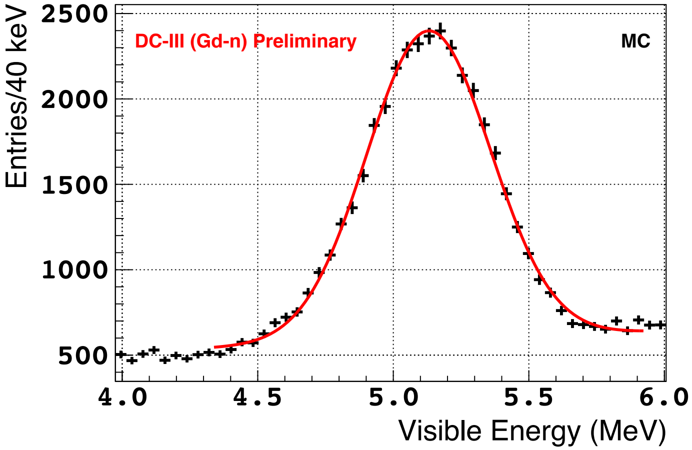
DC in the θ_{13} market…



Energy scale

- Neutron capture on ^{12}C in γ-catcher:

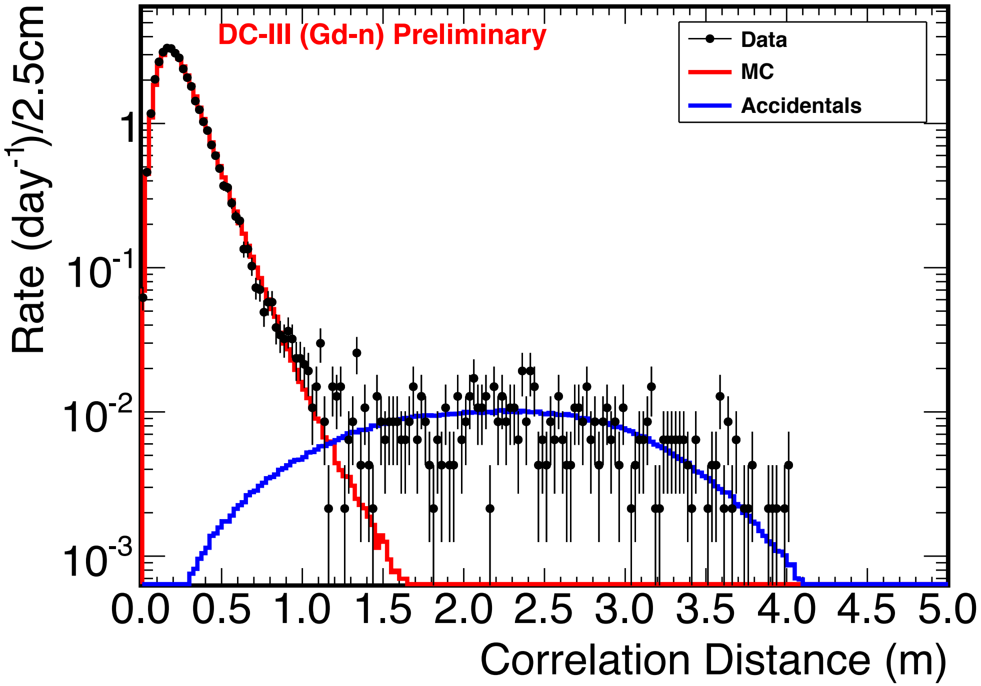




- Δ(data,MC) < 0.5%

Accidental background

- Correlation distance distribution:

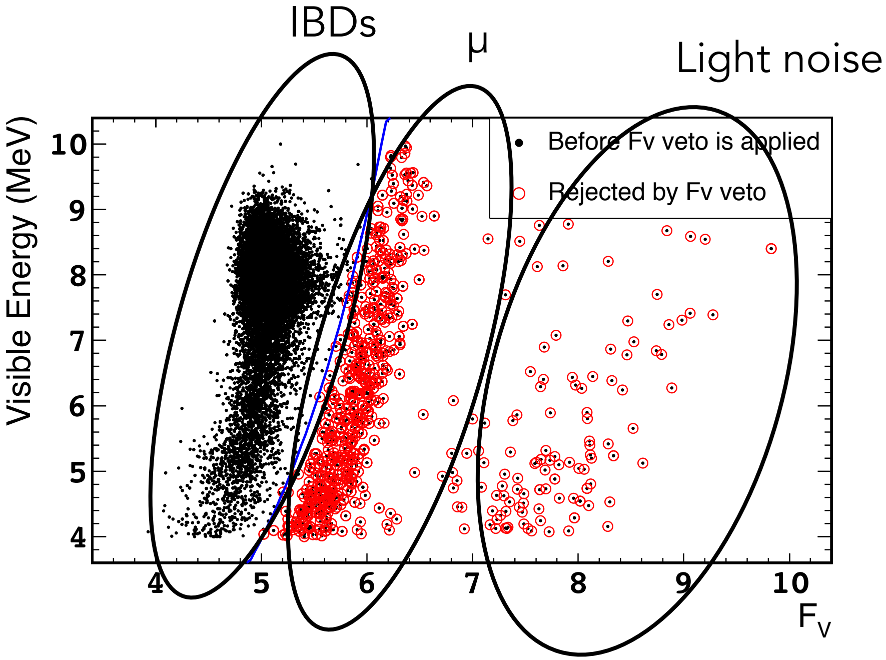


Vertex reconstruction: Fv cut

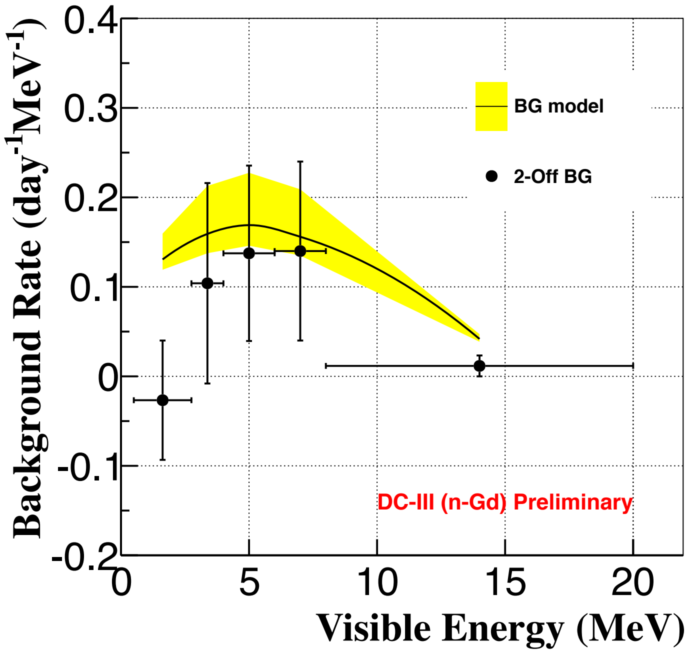
- Maximum likelihood algorithm using charge and time to reconstruct vertex position
- Assumption: **point-like energy deposition**

$$\mathcal{L}(\mathbf{X}) = \prod_{q_i=0} f_q(0;q'_i) \prod_{q_i>0} f_q(q_i;q'_i) f_t(t_i;t'_i,q'_i)$$

- f_q & f_t probabilities to measure charge and time given the model
- Fv = -ln(L(X))



2 reactor OFF data



- Agreement between background model (reactor ON data estimates) and measured 2-reactor OFF background.
- Compatibility between N_{BG}(OFF) and ΣN_{BG}(ON) is 9% (1.7σ)

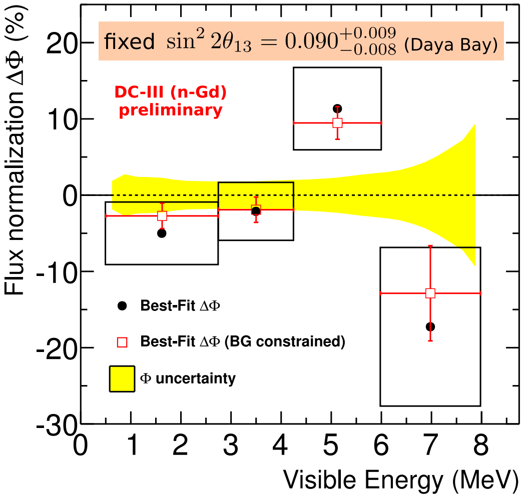
CEA FROM RESEARCH TO INDUSTRY

Testing spectral distortion with eRRM

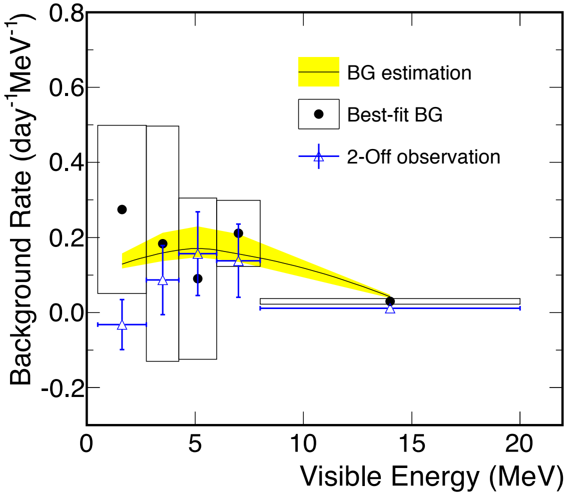
- **Reactor Rate modulation analysis in different energy bins:** fit the background rate and reactor flux normalization, using the $\sin^2(2\theta_{13})$ measured by Daya Bay

$$R^{obs} = \overset{\text{free}}{B} + (1 - \overset{\text{fixed}}{\sin^2(2\theta_{13})}\,\alpha_{osc})\overset{\text{free}}{R^{\nu}}$$

Flux normalization results



Background rate results



- Backgrounds compatible with both reactor ON and 2-reactor OFF estimates
- Discrepancy of reactor flux normalization with respect to predictions (3s in the [4.5 - 6 MeV] energy range)

Spectral distortion:
correlation to reactor power