First Measurement of θ_{13} from Delayed Neutron Capture on Hydrogen in Double Chooz

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-- On behalf of the Double Chooz Collaboration --

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"New Directions in Neutrino Physics"

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Outline

- Brief θ_{13} synopsis
- The Double Chooz Experiment
- $\bar{\nu}_e$ Detection via n-capture on H and Gd
- θ_{13} from n-H analysis
- Summary and Conclusions

A Brief Synopsis of θ_{13}

Neutrino oscillations are parameterized by the PMNS matrix, **U**:

$$\begin{pmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \end{pmatrix} = \begin{pmatrix} c_{12} & s_{12} & 0 \\ -s_{12} & c_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix} \begin{pmatrix} 1 & 0 & 0 \\ 0 & c_{23} & s_{23} \\ 0 & -s_{23} & c_{23} \end{pmatrix} \boxed{\begin{pmatrix} c_{13} & 0 & s_{13}e^{-i\delta} \\ 0 & 1 & 0 \\ -s_{13}e^{i\delta} & 0c_{13} & \end{pmatrix}} \begin{pmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \end{pmatrix}$$

flavor eigenstates | solar - θ_{12} | atmospheric - θ_{23} | reactor - θ_{13} | mass eigenstates

where $c_{ij} = \cos\theta_{ij}$ and $s_{ij} = \sin\theta_{ij}$

Oscillation probability:

$$P(\bar{\nu}_\alpha \rightarrow \bar{\nu}_\beta) = \delta_{\alpha\beta} - 4\sum_{i>j} \mathrm{Re}(U^*_{\alpha i}U_{\beta i}U_{\alpha j}U^*_{\beta j})\,\sin^2(\Delta_{ij}) - 2\sum_{i>j} \mathrm{Im}(U^*_{\alpha i}U_{\beta i}U_{\alpha j}U^*_{\beta j})\,\sin(2\Delta_{ij})$$

where $\Delta_{ij} = \dfrac{\Delta m^2_{ij} L}{4E_\nu}$ and $\Delta m^2_{ij} \equiv m^2_j - m^2_i$

θ_{12} and Δm^2_{12} -> Probed with Solar + KamLAND data

θ_{23} and Δm^2_{23} -> Probed with SuperK, K2K and MINOS data

θ_{13} -> *As of Nov. 2011, weak indication of $\theta_{13} \neq 0$ from Chooz, MINOS and T2K*

A Brief Synopsis of θ_{13}

In 2012, the question of whether or not $\theta_{13} \neq 0$ had finally been answered by three reactor experiments…

Double Chooz: $\sin^2(2\theta_{13}) = 0.086 \pm 0.051$

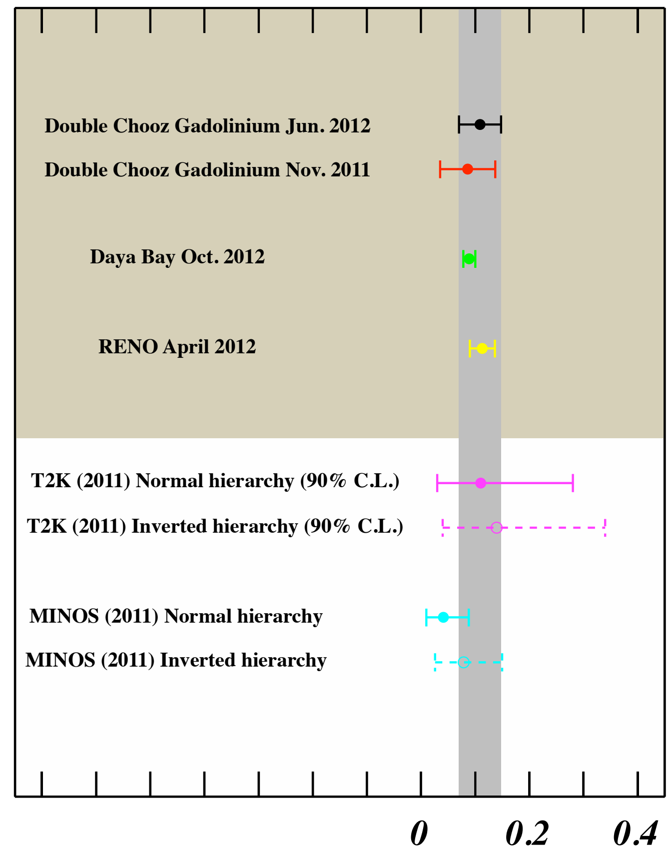
Daya Bay: $\sin^2(2\theta_{13}) = 0.092 \pm 0.017$

RENO: $\sin^2(2\theta_{13}) = 0.113 \pm 0.023$

Double Chooz: $\sin^2(2\theta_{13}) = 0.109 \pm 0.039$

Daya Bay: $\sin^2(2\theta_{13}) = 0.089 \pm 0.011$

$\sin^2(2\theta_{13})$ measurements at 68% C. L.



For the next couple years:

More precise θ_{13} = Improved search for CP-violation, mass hierarchy…

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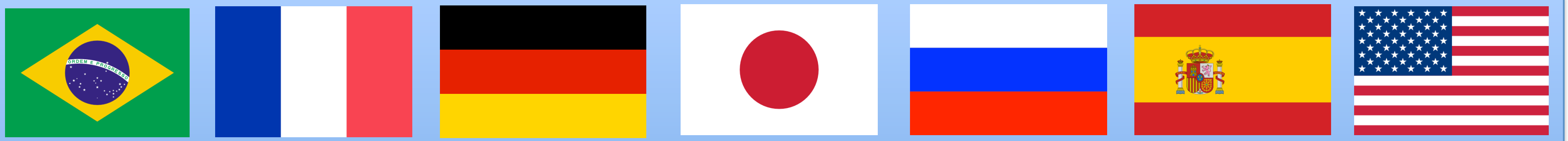
The Double Chooz Experiment

Spokesperson:
Herve de Kerret
(IN2P3)

Project Manager:
Christian Veyssière
(CEA-Saclay)

Website:
www.doublechooz.org



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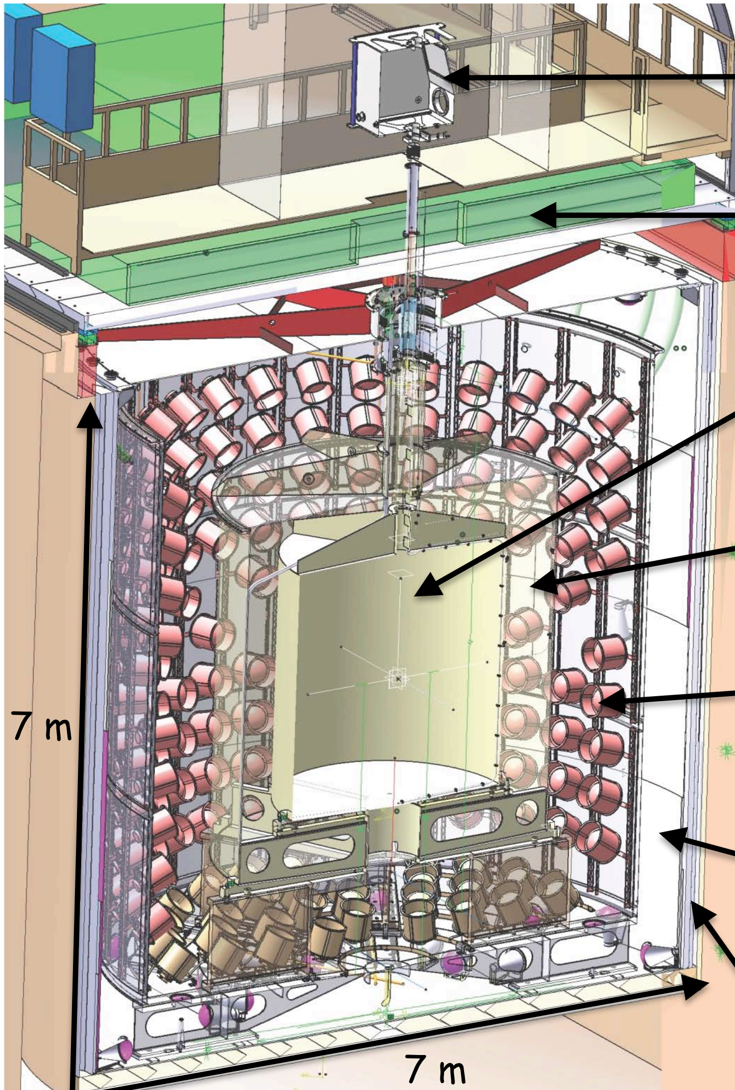
The Double Chooz Experiment



Glove-box and Calibration systems

Outer Veto:
Scintillator strip-based muon tracking system

$\bar{\nu}_e$ Target:
10.3 m^3 LS doped with 1 g/l Gd inside an 8mm-thick Acrylic vessel

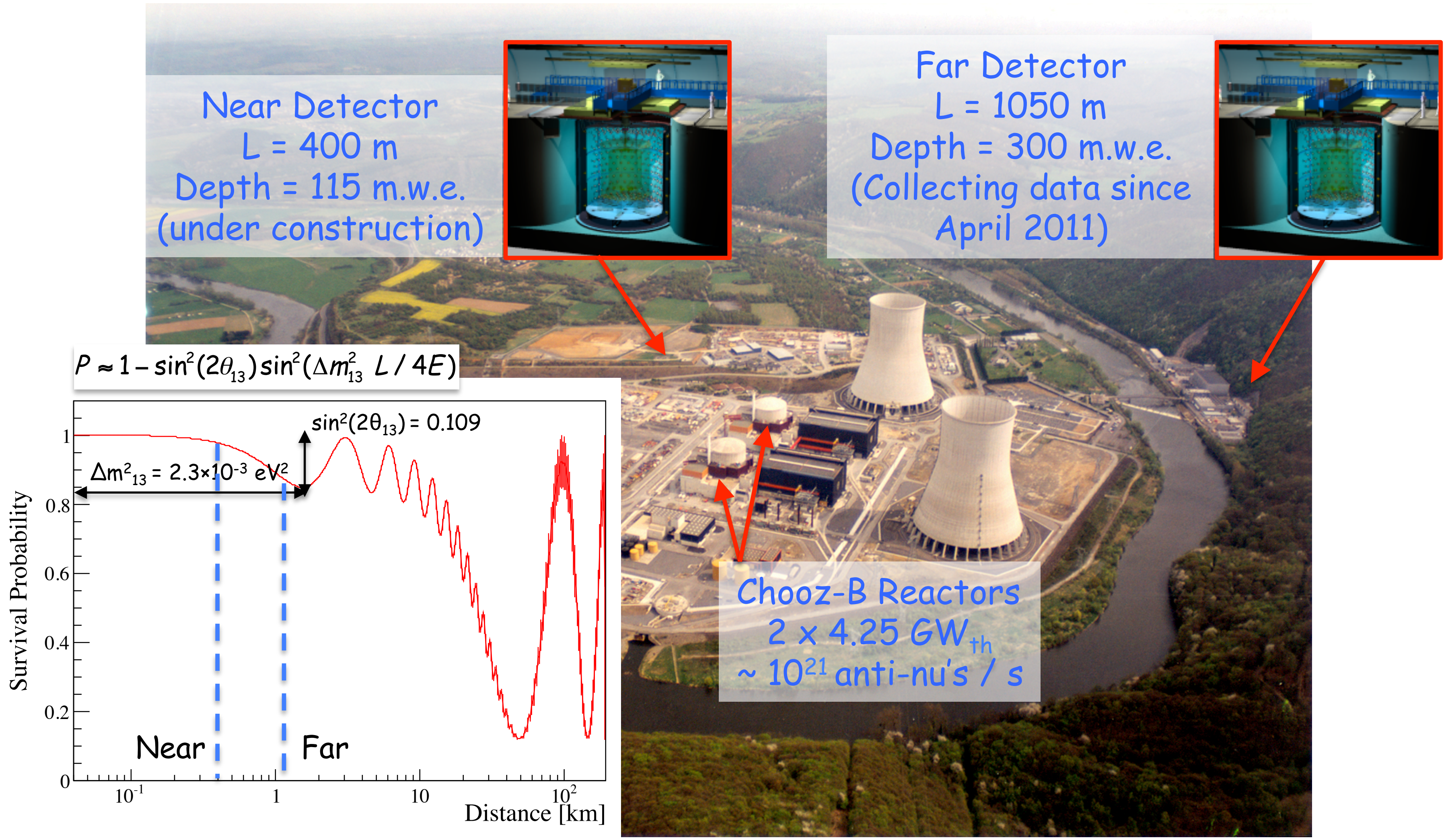
Gamma Catcher:
22.6 m^3 LS (undoped) inside an 8mm-thick Acrylic vessel

Buffer:
114.2 m^3 mineral oil inside a 3mm-thick stainless steel tank which holds 390 10-inch PMTs

Inner Veto (IV):
80 m^3 LS (undoped) inside of a 10mm-thick stainless steel tank which holds 78 8-inch PMTs

Steel Shield:
15cm-thick and demagnetized

The Double Chooz Experiment



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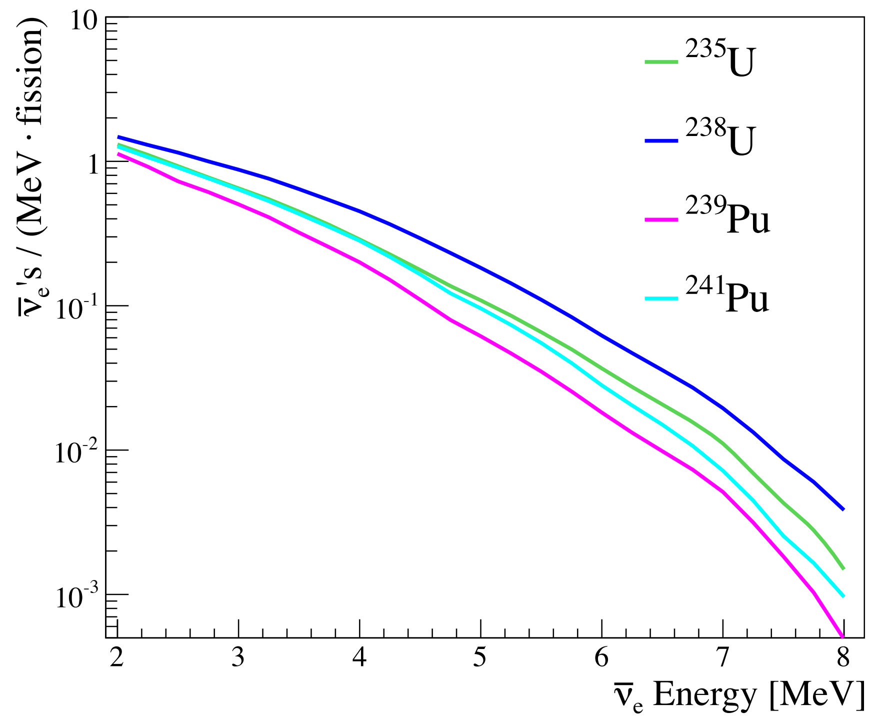
$\bar{\nu}_e$ Detection Using Neutron Capture

$\bar{\nu}_e$ Flux Source:

Data from T. A. Mueller et al., arXiv:1101.2663v3



β-decays from neutron-rich fission products in nuclear reactors

~ 200 MeV / fission

~ 6 anti-nu's / fission

~ 2 x 10^{20} anti-nu's / GW_{th}

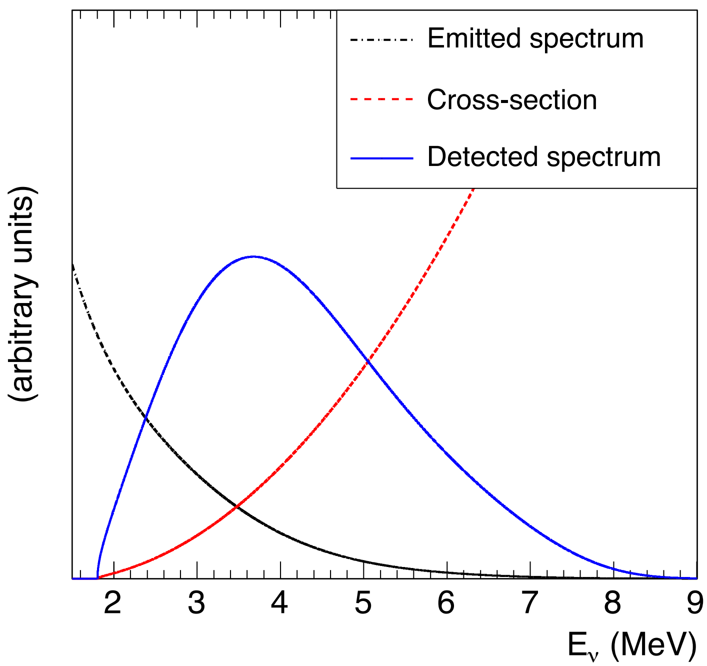
To calculate fission rates:

Double Chooz uses reactor simulations (MURE and DRAGON) in combination with an anchor point from Bugey4 to minimize systematic uncertainty

$\bar{\nu}_e$ Detection Using Neutron Capture

$\bar{\nu}_e$ Detector Signal:

T. A. Mueller et al., arXiv:1101.2663v3



Inverse β-decay reaction

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

Threshold E_ν = 1.806 MeV

Prompt γ's from e^+ annihilation -> 1 – 12 MeV

$$E_{vis} = E_\nu - (M_n - M_p + m_e)$$

Delayed γ's from n-capture on H or Gd

n-H capture: Δt ~ 200 μs, E ~ 2.2 MeV

n-Gd capture: Δt ~ 30 μs, E ~ 8 MeV

In the Gd-LS target, about 95% of n-captures occur on Gd

$\bar{\nu}_e$ Detection Using Neutron Capture

Why use n-H capture to search for θ_{13}?

- n-H capture occurs in a 3 times larger volume in Double Chooz

  $10.3\ m^3 + 22.6\ m^3 = 32.9\ m^3$ -> this means **2 times more statistics** available to extract θ_{13}

- Data sets are statistically different and have somewhat different systematic uncertainties

  Possible to perform an independent cross-check of n-Gd θ_{13} results

- Proof of principle! May be useful for other reactor experiments

  Squeezing every bit of useful information out of other experiments could improve θ_{13} results

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θ_{13} from n-H Analysis

IBD Candidate Selection:

Data from 240.1 days live time
(exposure of 113.1 GW-ton-years)

Reduce Muon Backgrounds:
$\Delta t_\mu > 1$ ms

Prompt Event:
$0.7\ \mathrm{MeV} < E_{prompt} < 12.2\ \mathrm{MeV}$
(trigger efficiency ~100% $E_{vis} > 0.7$ MeV)

Delayed Event:
$1.5\ \mathrm{MeV} < E_{delay} < 3.0\ \mathrm{MeV}$

Time and Space Coincidence:
$10\ \mu\mathrm{s} < \Delta t < 600\ \mu\mathrm{s}$
$\Delta r < 90$ cm

Multiplicity cuts:
Reduce fast neutrons

Light Noise Cuts:
Reduce backgrounds from flashing PMT bases

IBD selection yields a total of 36284 ± 520 events which include backgrounds from:

- Accidental coincidences
- Fast neutrons (from muons in rock)
- Long-lived cosmogenic isotopes (mostly ^{9}Li)
- Remaining light noise

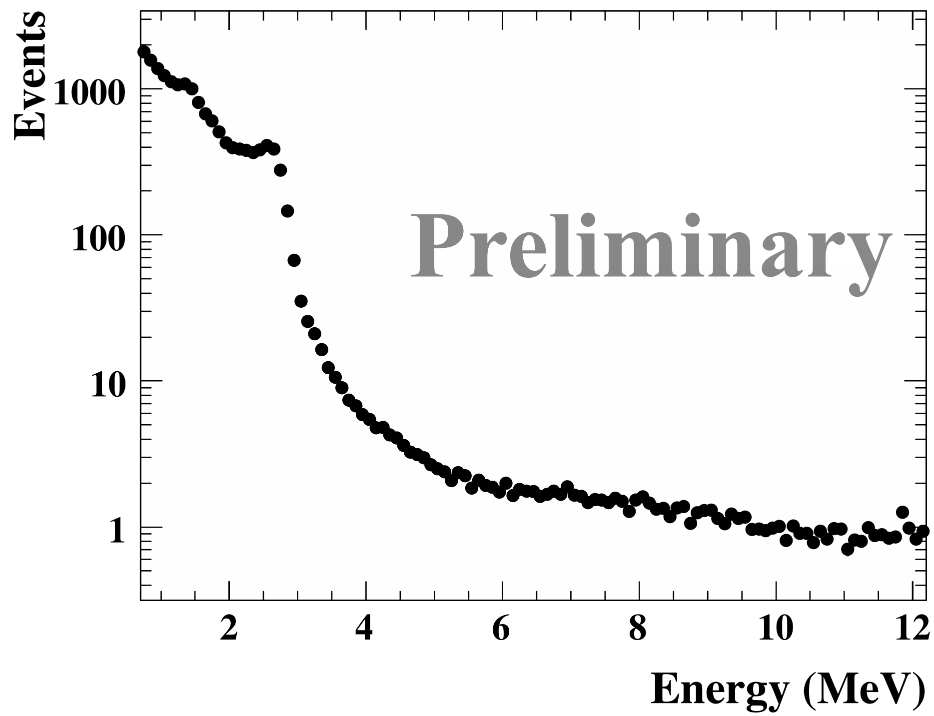
θ_{13} from n-H Analysis

IBD Backgrounds:

Accidental Coincidences:

Association of γ's from natural radioactivity with a neutron-like event

Estimated with many off-time sampling windows for high statistics:
73.45 ± 0.16 events/day



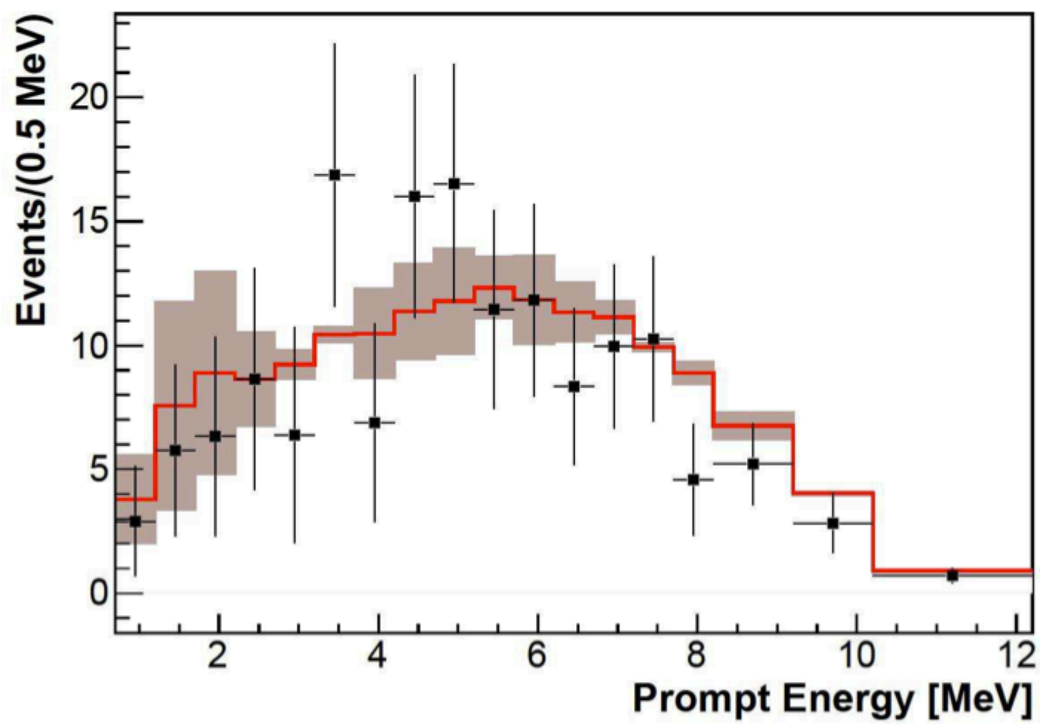
θ_{13} from n-H Analysis

IBD Backgrounds:

Cosmogenic Isotopes (^9Li) :

^9Li lifetime = 257 ms
β-decay + neutron emission

Estimated by time-correlation with muons and a fit to ^9Li lifetime:
2.84 ± 1.15 events/day



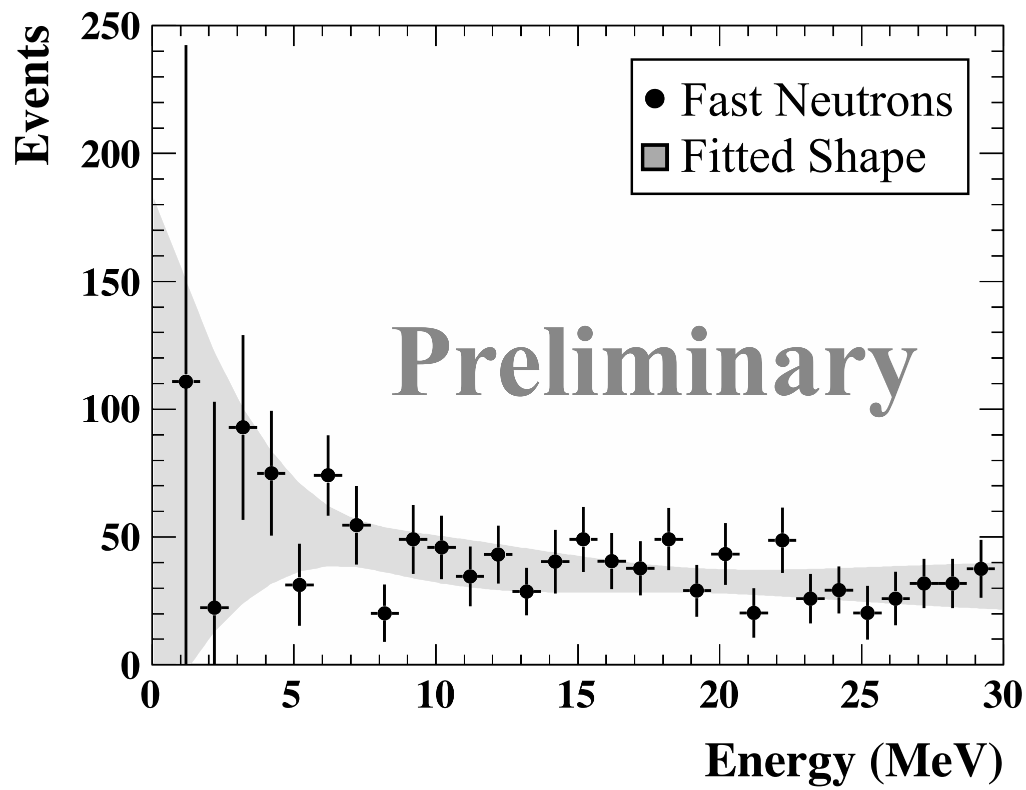
θ_{13} from n-H Analysis

IBD Backgrounds:

Fast Neutrons:

Fast neutron recoils off proton (prompt) and later captures (delay)

Estimated from fast neutron spectrum obtained from IV-ID tagging:
2.50 ± 0.47 events/day



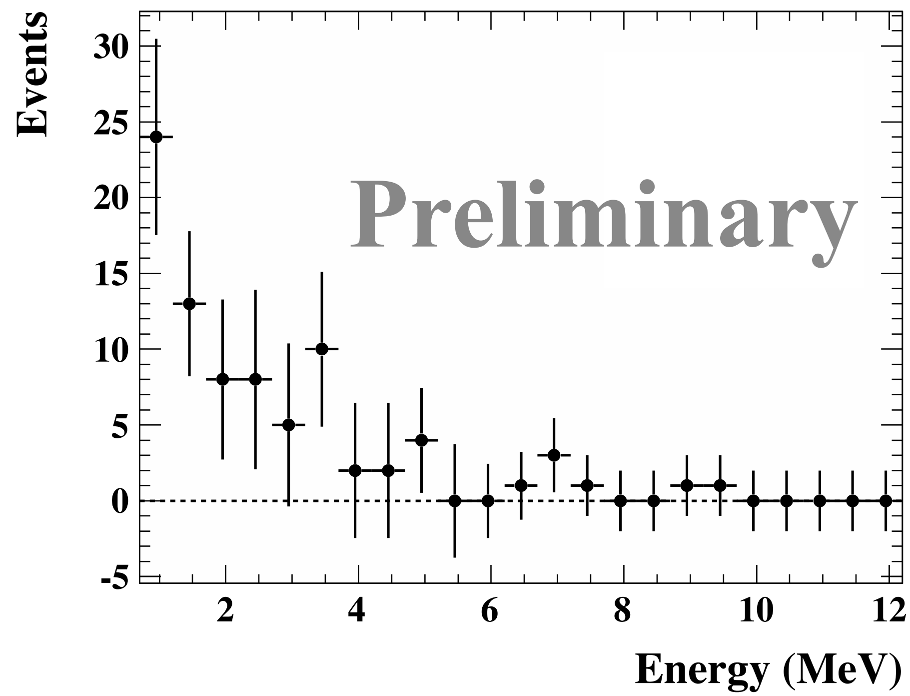
θ_{13} from n-H Analysis

IBD Backgrounds:

Light Noise:

Spontaneous flash of PMT base forming two consecutive triggers

Estimated with a volume cut on reconstructed vertex:
0.32 ± 0.07 events/day



θ_{13} from n-H Analysis

IBD Background Summary:

	Gd Analysis Rate (events / day)	H Analysis Rate (events / day)
Accidentals	0.261 ± 0.002	73.45 ± 0.16
Cosmogenics (^{9}Li)	1.25 ± 0.54	2.84 ± 1.15
Fast Neutrons	0.67 ± 0.20	2.50 ± 0.47
Light Noise	N/A	0.32 ± 0.07
BG Total	2.18 ± 0.58	79.11 ± 1.25
IBD Candidate Total	36.2 ± 0.4	151.1 ± 0.8

less statistics, larger S/B

more statistics, smaller S/B

θ_{13} from n-H Analysis

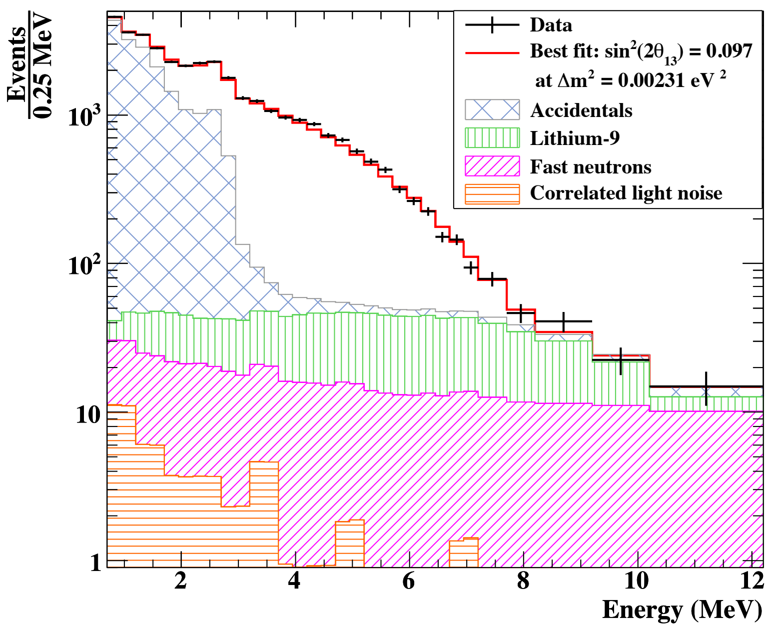
Normalization Uncertainties Relative to Predicted Signal:

Source	Uncertainty [%]
Reactor Flux	1.8
Statistics	1.1
Accidentals	0.2
Cosmogenics (^{9}Li)	1.6
Fast Neutrons	0.6
Light Noise	0.1
Energy Scale	0.3
Detection Efficiency	1.6

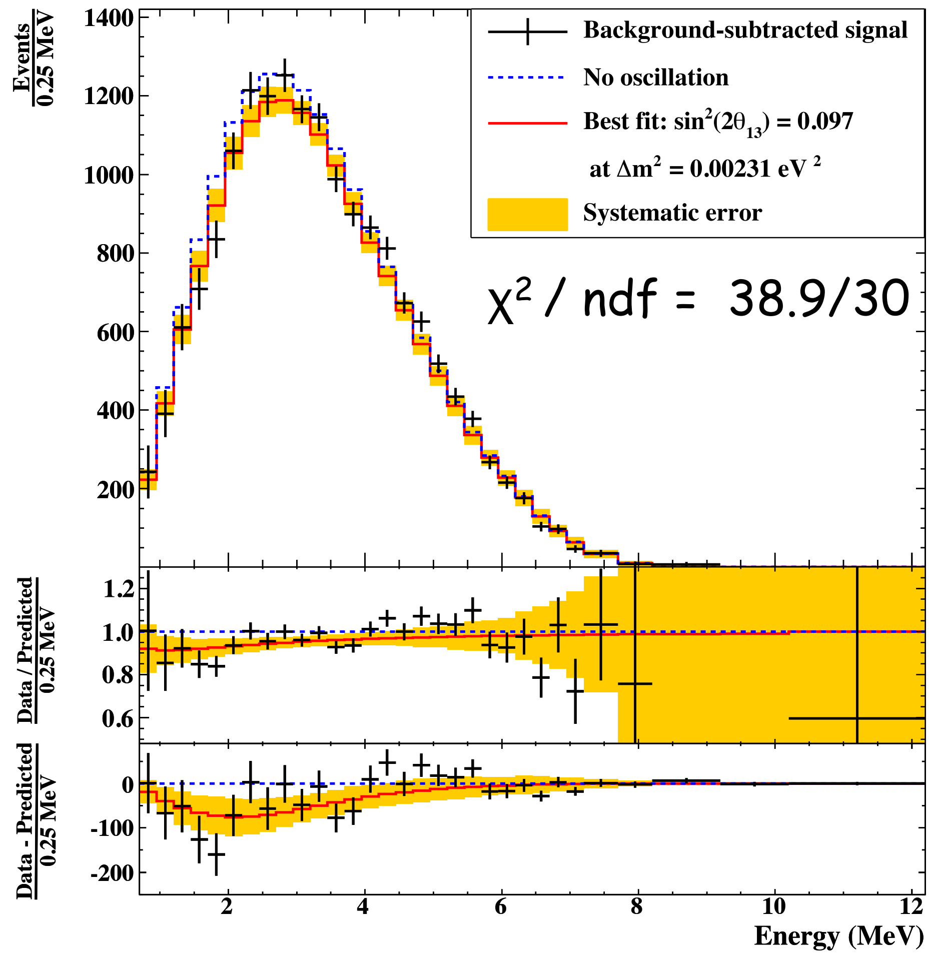
Reactor simulation + Bugey4 result minimize uncertainty on reactor anti-nu flux prediction

Includes IBD selection efficiency and fraction of n-H captures - obtained from ^{252}Cf neutron source calibrations

θ_{13} from n-H Analysis



Background subtracted data with fit



Rate + Shape:

$\sin^2(2\theta_{13}) = 0.097 \pm 0.048$

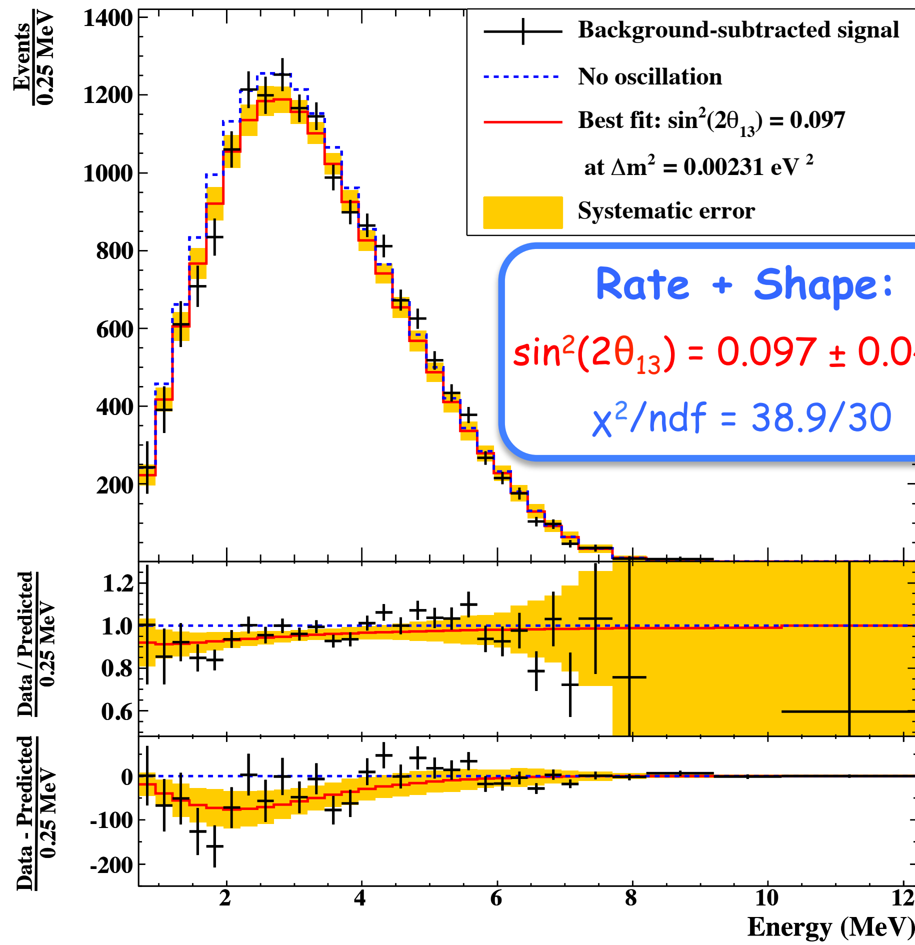
$\alpha_E = 0.993 \pm 0.007$

^{9}Li Rate = 3.90 ± 0.61 events/day

FN Rate = 2.57 ± 0.35 events/day

$\Delta m^2_{31} = (2.31 \pm 0.12)\times10^{-3}\ \mathrm{eV}^2$

θ_{13} from n-H Analysis

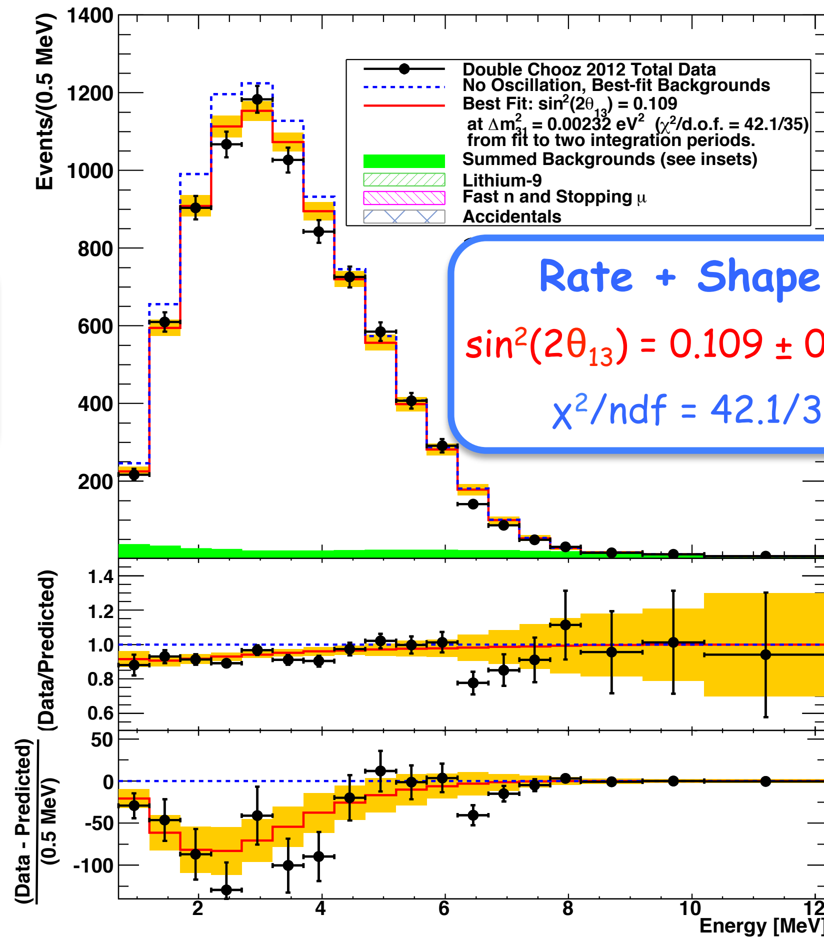


Rate + Shape:

$\sin^2(2\theta_{13}) = 0.097 \pm 0.048$

$\chi^2/ndf = 38.9/30$

Hydrogen Best Fit



Rate + Shape:

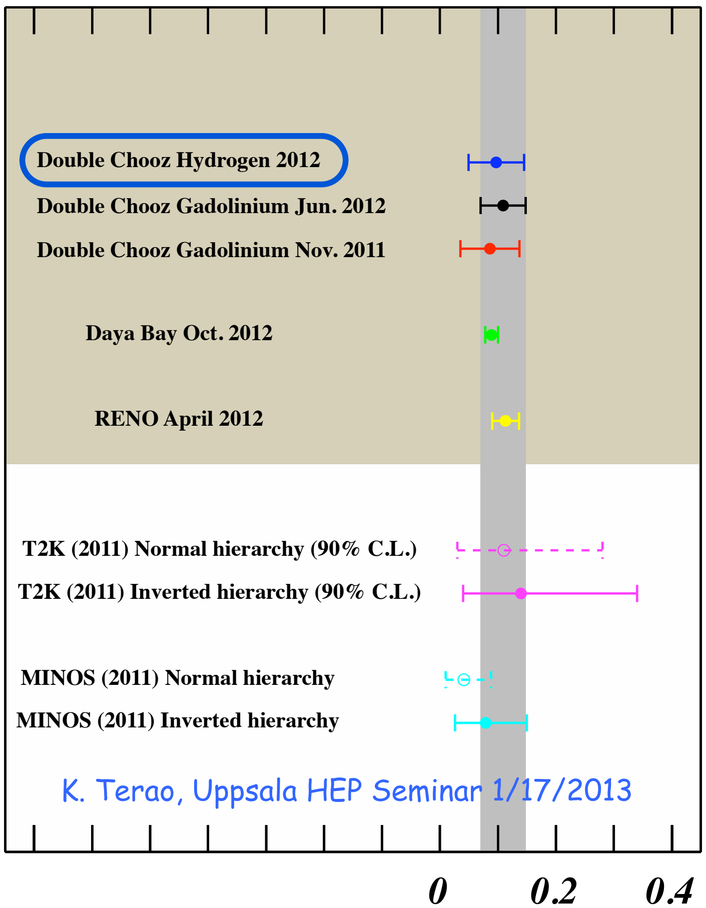
$\sin^2(2\theta_{13}) = 0.109 \pm 0.039$

$\chi^2/ndf = 42.1/35$

Gadolinium Best Fit

θ_{13} from n-H Analysis

$\sin^2(2\theta_{13})$ measurements at 68% C. L.



First-ever θ_{13} measurement from n-capture on H (arXiv:1301.2948v1)

Rate + Shape:

$\sin^2(2\theta_{13}) = 0.097 \pm 0.034(\text{stat}) \pm 0.034(\text{syst})$

Excludes no-oscillation hypothesis at 2.0σ

Latest θ_{13} measurement from n-capture on Gd (Phys. Rev. D 86, 052008)

Rate + Shape:

$\sin^2(2\theta_{13}) = 0.109 \pm 0.030(\text{stat}) \pm 0.025(\text{syst})$

Excludes no-oscillation hypothesis at 2.9σ

Two distinct measurements are in good agreement!

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Summary and Conclusion

- Low background levels in Double Chooz have allowed the first measurement of $\sin^2(2\theta_{13})$ using n-capture on Hydrogen!
- Provides cross-check for Gd analysis using a different data set
- H results are in good agreement with Gd results
- Just to reflect back -> Gd-doped LS bought us an extra ~1σ rejection of the no-oscillation hypothesis

Summary and Conclusion

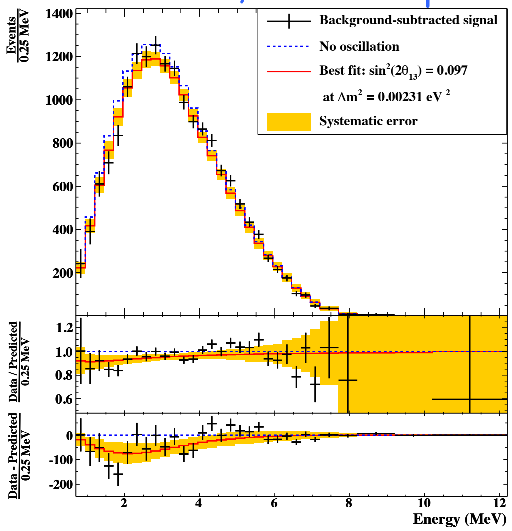
- H and Gd analyses are still ongoing -> updated results soon!
- Near detector data will reduce the systematic uncertainty contribution from the reactor flux

Future Work:

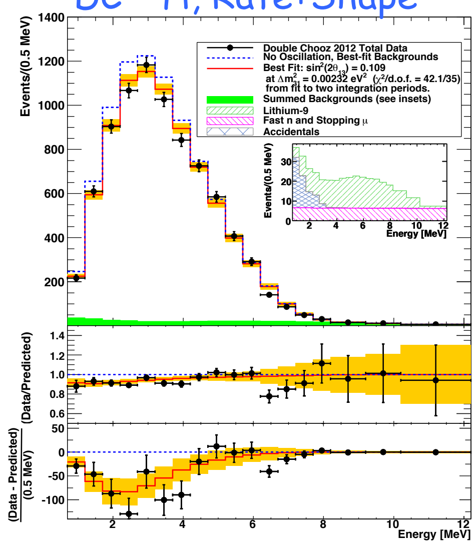
More statistics + improved understanding of systematic uncertainties
= possibility to combine n-H and n-Gd results!

Just for thought…

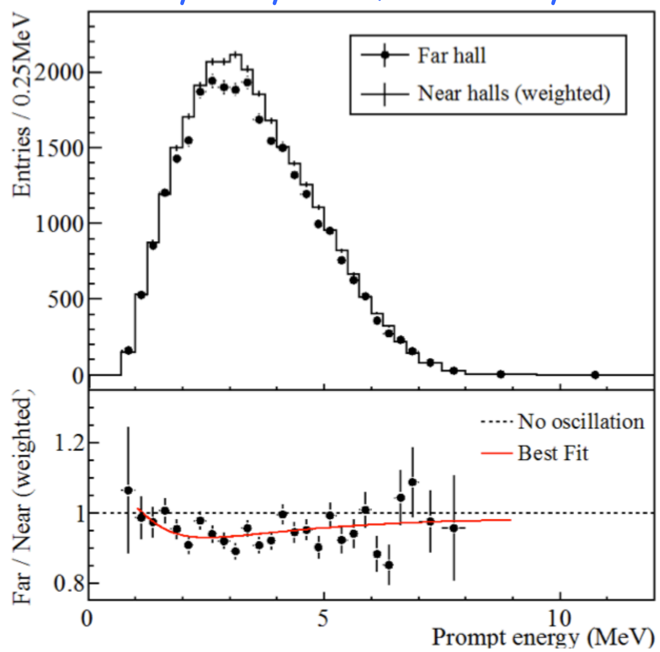
DC – Gd, Rate+Shape



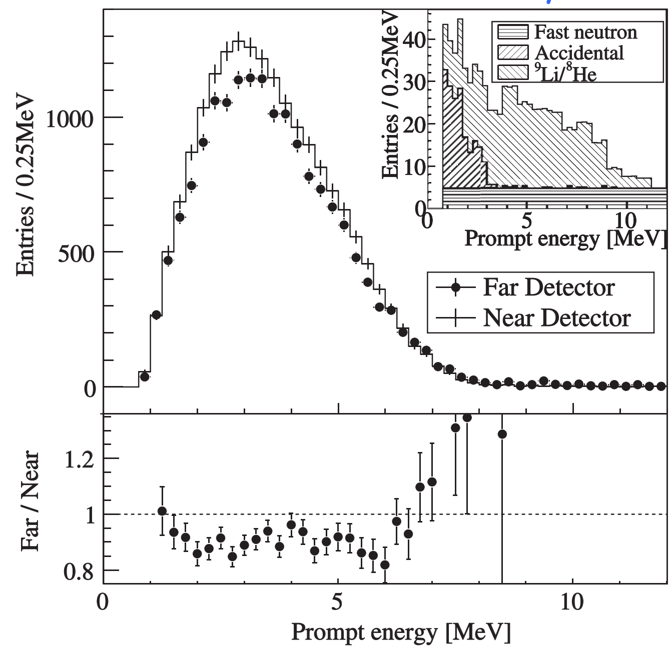
DC – H, Rate+Shape



Daya Bay – Gd, Rate Only



RENO – Gd, Rate Only



θ_{13} depends on the rate *and shape* information!

So far, only Double Chooz has performed rate + shape analyses

Backup Stuff

Reactor Calculations

$$N^{exp}_{\bar{\nu}_e}(E,t) = \sum_{R=1,2}^{Reactors} \frac{N_p\,\epsilon}{4\pi L^2} \times \frac{P^{th}_R(t)}{\langle E_f\rangle_R(t)} \times \langle\sigma_f\rangle_R(E,t)$$

Mean energy per fission

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

Fission values used

Isotope	$\langle E_f\rangle_k$ (MeV)	$\langle\alpha_k\rangle$
^{235}U	201.92±0.46	0.496±0.016
^{239}Pu	209.99±0.60	0.351±0.013
^{238}U	205.52±0.96	0.087±0.006
^{241}Pu	213.60±0.65	0.066±0.007

Mean cross-section per fission

$$\langle\sigma_f\rangle = \langle\sigma_f\rangle^{Bugey} + \sum_k (\alpha^{DC}_k(t) - \alpha^{Bugey}_k(t))\,\langle\sigma_f\rangle_k$$

Mean cross-section per fission isotope

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

Summary of uncertainties

Source	Normalization Only	Uncertainty [%]
P_{th}	yes	0.5
$\langle\sigma_f\rangle^{Bugey}$	yes	1.4
$S_k(E)\sigma_{IBD}(E^{true}_\nu)$	no	0.2
$\langle E_f\rangle$	no	0.2
L_R	yes	<0.1
α^R_k	no	0.9
Total		1.8

Fitting Procedure

Rate + Shape analysis with χ^2 minimization:

$$\chi^2 = \sum_{i,j} (N_i - N_i^{pred})(M_{ij})^{-1}(N_j - N_j^{pred})^T$$
$$+ \sum_{b}^{FN,{}^9Li} \frac{(P_b)^2}{\sigma_b^2} + \frac{(\alpha_E - 1)^2}{\sigma_{\alpha_E}^2}$$
$$+ \frac{(\Delta m_{31}^2 - (\Delta m_{31}^2)_{\mathrm{MINOS}})^2}{\sigma_{\mathrm{MINOS}}^2}$$

Pull terms used to constrain FN, ^{9}Li, energy scale and Δm^2_{31}

M_{ij} = covariance matrices

- Signal covariance matrix
- Detector covariance matrix
- Statistical covariance matrix
- Background covariance matrix