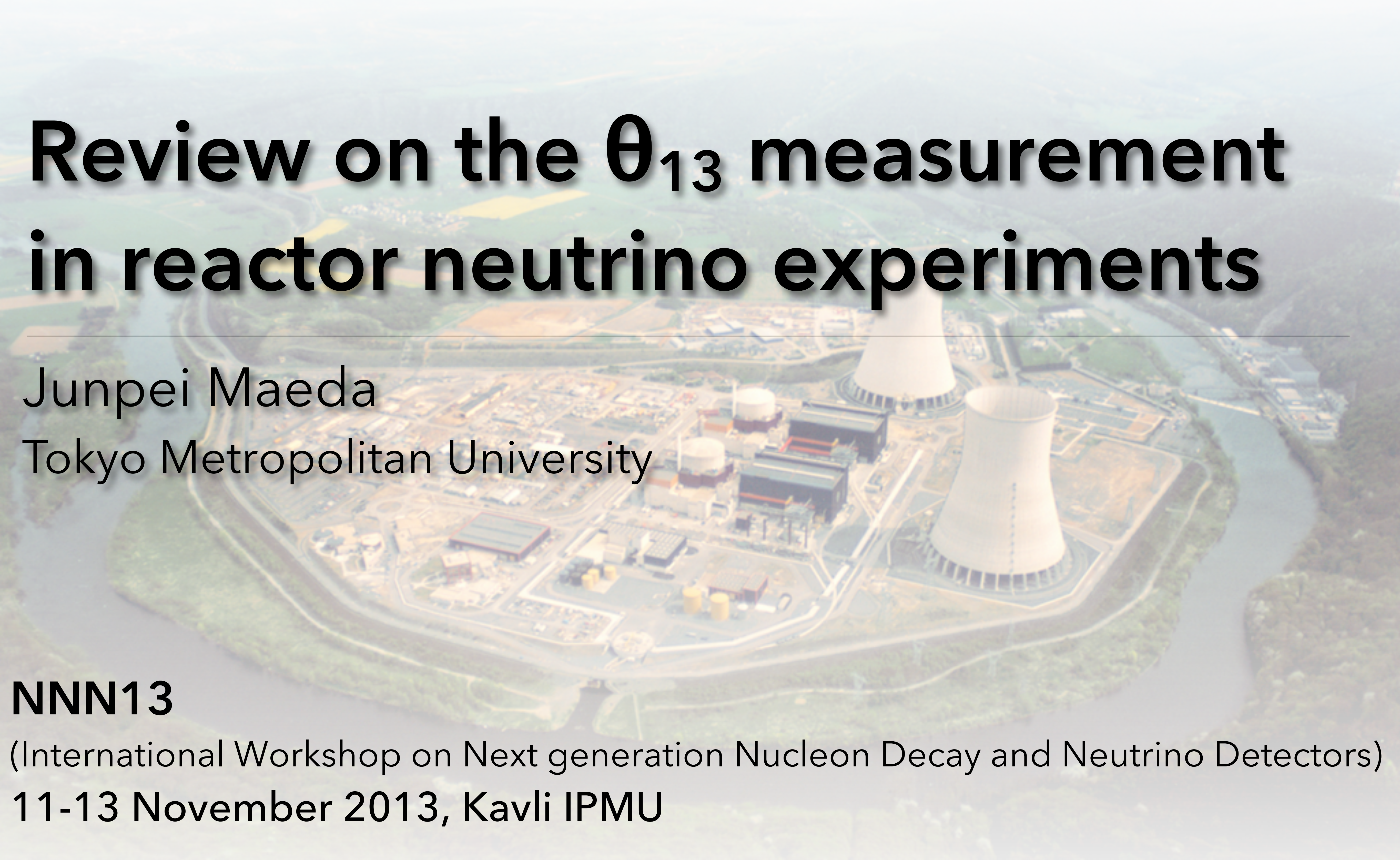


Review on the θ_{13} measurement in reactor neutrino experiments

Junpei Maeda
Tokyo Metropolitan University

NNN13
(International Workshop on Next generation Nucleon Decay and Neutrino Detectors)
11-13 November 2013, Kavli IPMU

Contents

- General introduction to reactor θ_{13} measurements
  - Neutrino Oscillation and reactor neutrinos
  - Concept of reactor neutrino experiments
  - Detection principle
  - Main backgrounds

- Experimental setup and results of ongoing experiments
  - Double Chooz
  - Daya Bay
  - RENO

- Summary

Introduction to reactor θ_{13} measurements

Neutrino Oscillation

Neutrino oscillation occurs as a consequence of non-zero mass and mixing of mass eigenstates and flavor eigenstates as:

$(*)\ c_{ij} = cos\theta_{ij},\ s_{ij} = sin\theta_{ij}$

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

θ_{23} : $P(\nu_\mu \rightarrow \nu_\mu)$ by Atoms. ν and ν beam

θ_{13}: $P(\nu_e \rightarrow \nu_e)$ by Reactor ν
θ_{13} & δ: $P(\nu_\mu \rightarrow \nu_e)$ by ν beam

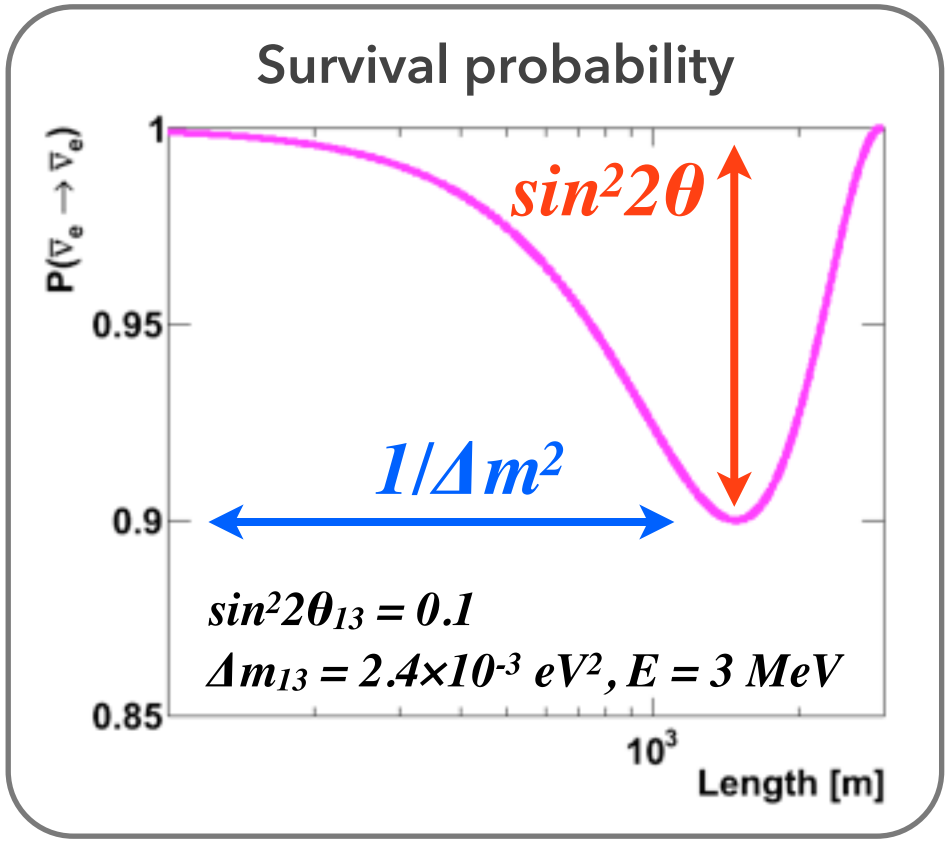
θ_{12} : $P(\nu_e \rightarrow \nu_e)$ by Reactor and solar ν

Neutrino oscillation parameters:

- three mixing angles: θ_{12}, θ_{23}, θ_{13}
- two mass difference scales: Δm^2_{12}, Δm^2_{23}
- one phase δ → CP violation in ν-sector

Neutrino oscillation in two flavor scheme:

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

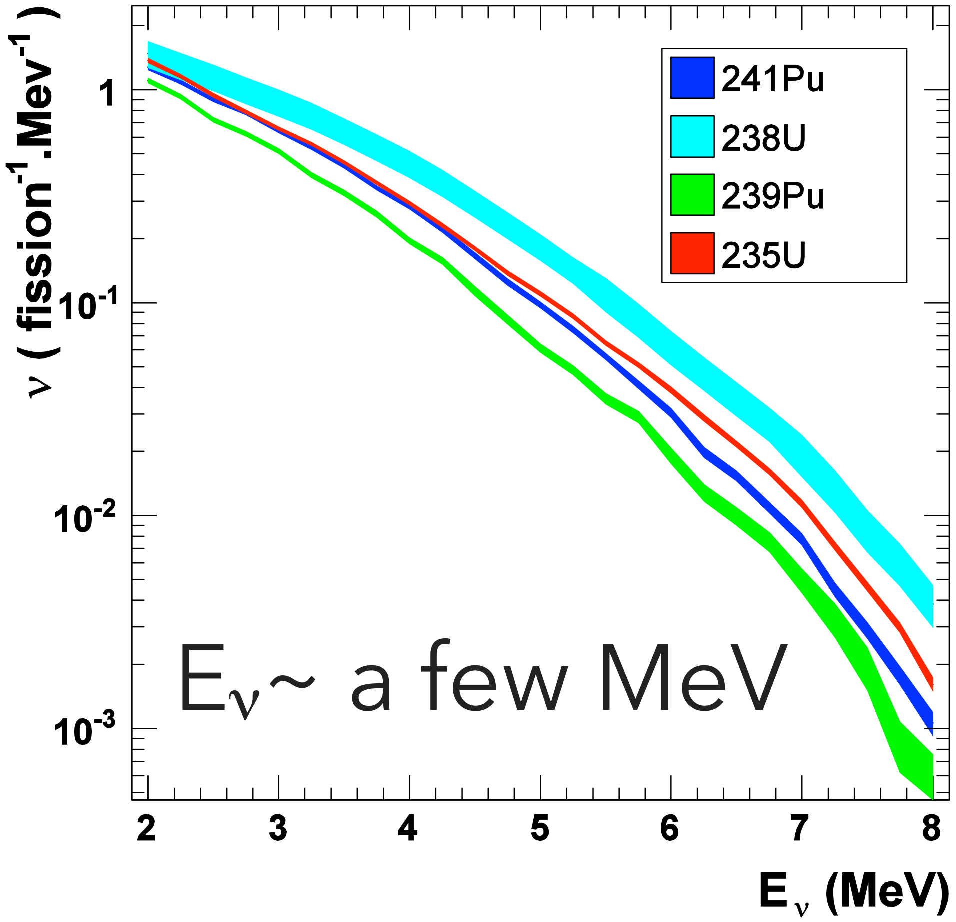


θ_{13} is the gateway to leptonic CP violation δ.

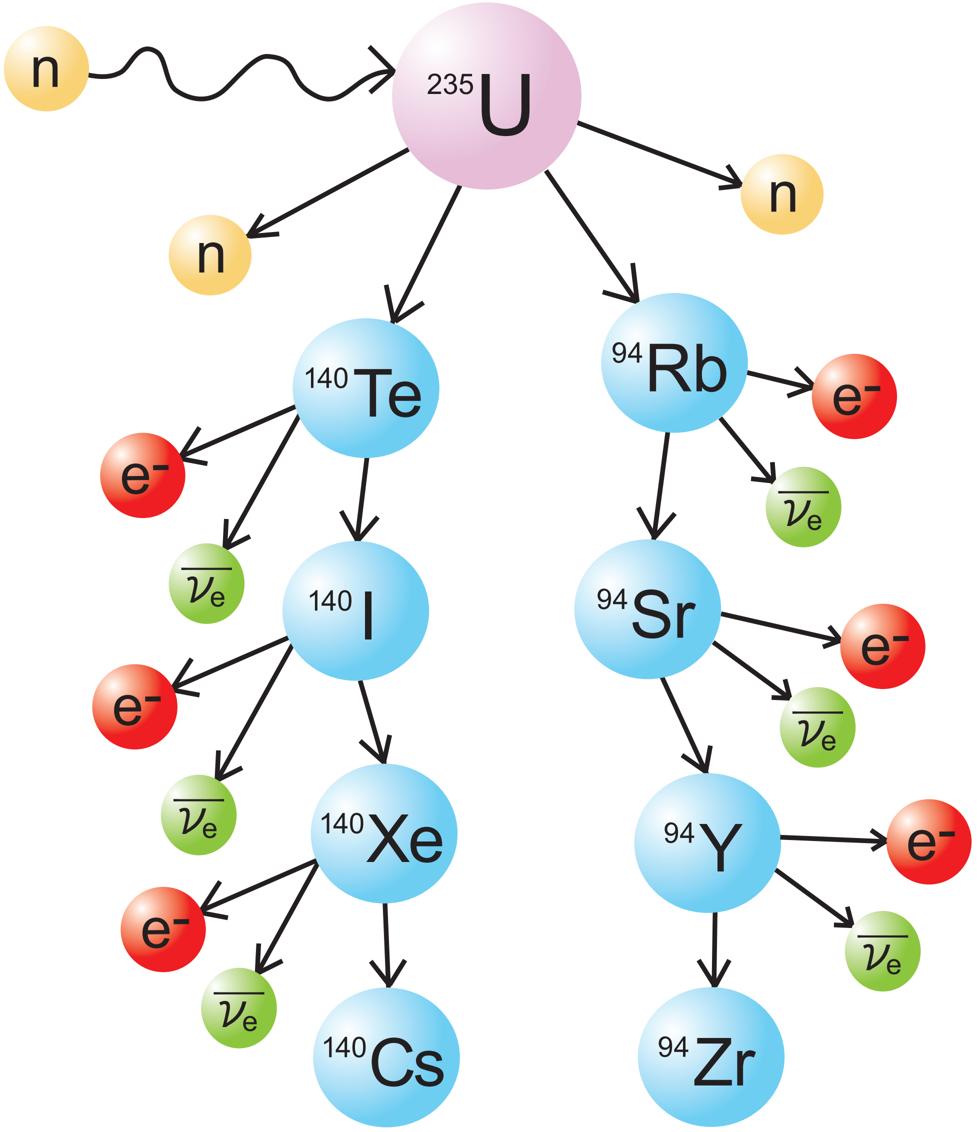
Why reactors?

- Electron antineutrinos emitted through decays of fission products of ^{235}U, ^{238}U, ^{239}Pu, and ^{241}Pu.
  - ~6 $\overline{\nu}_e$s/fission, ~200 MeV/fission
    → 2×10^{20} $\overline{\nu}_e$/s @ 1GW$_{th}$

Reactors are powerful and "free" sources of low-energy (isotropic) neutrinos.



E_ν~ a few MeV



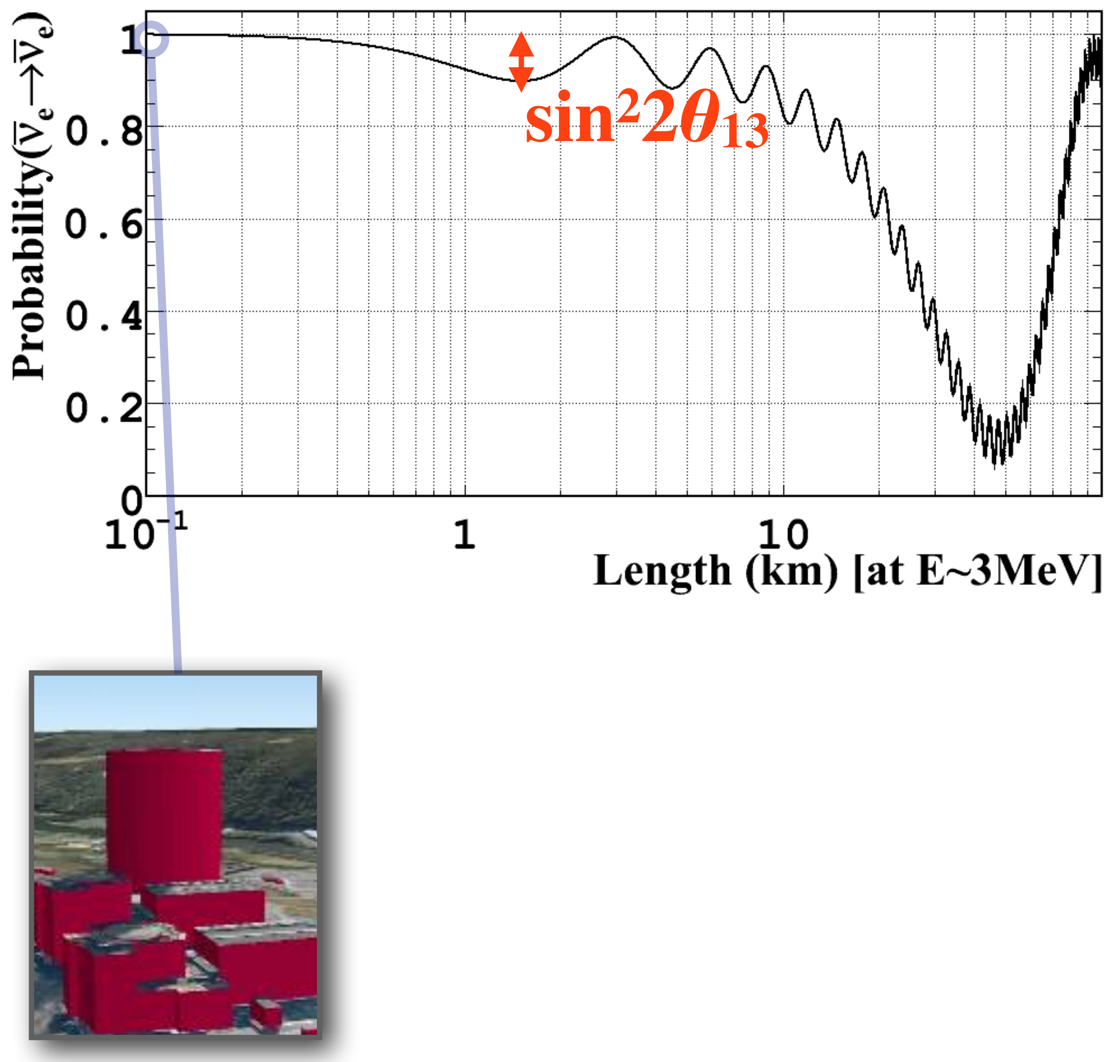
(example)

Th. A. Mueller *et al.*, Phys. Rev. C83 (2011) 054615
P. Huber, Phys. Rev. C84 (2011) 024617

Principle of reactor-θ_{13} measurements

Features of reactor neutrino experiment to measure θ_{13}:

Survival probability of $\bar{\nu}_e$



Reactor
power plant

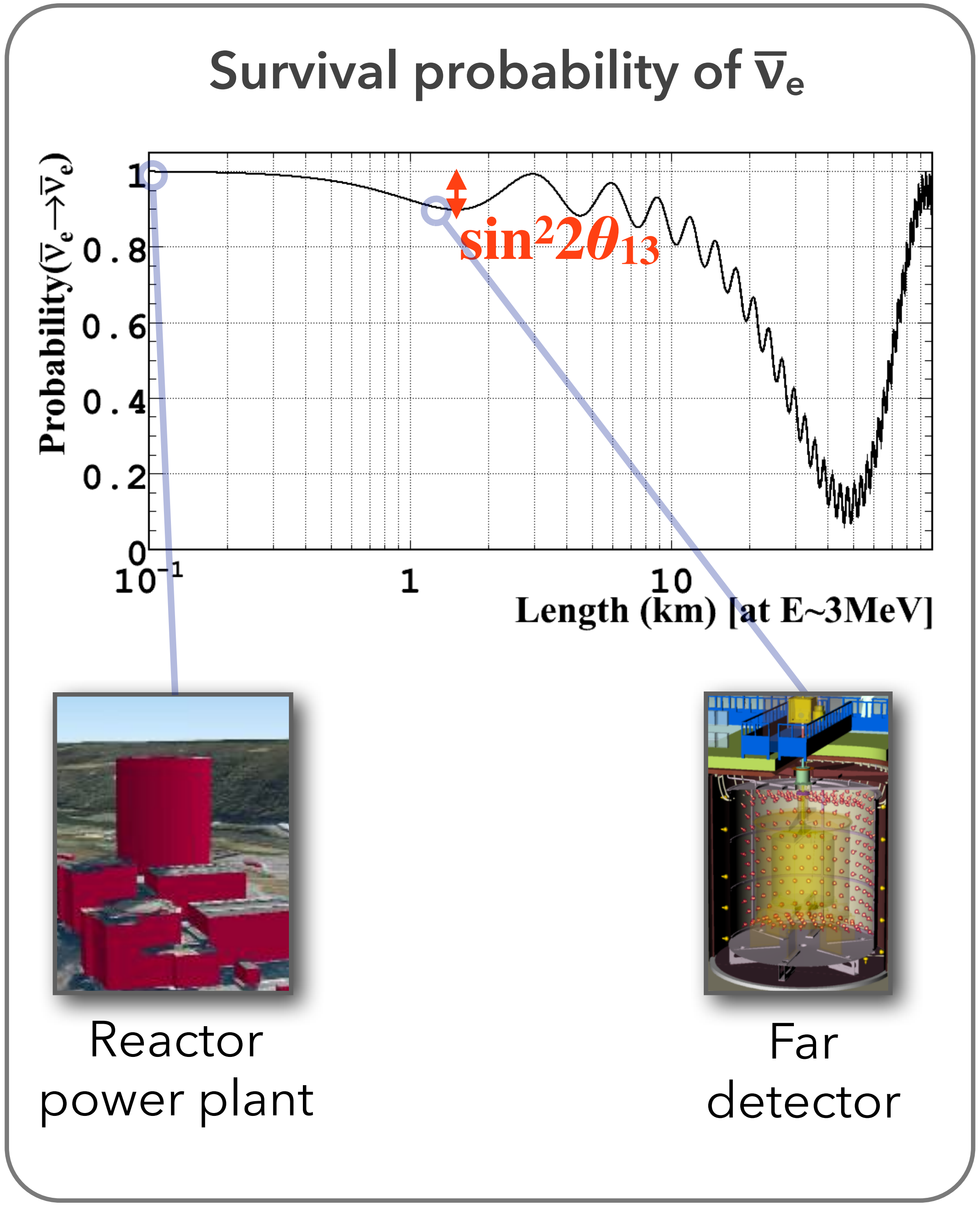
- Direct measurement of θ_{13} with a $\bar{\nu}_e$ disappearance at ~1km baseline.

$$P(\bar{\nu}_e \to \bar{\nu}_e) = 1 - \boxed{\sin^2 2\theta_{13}} \sin^2\left(\frac{\Delta m^2_{31} L}{4E}\right) + O(10^{-3})$$

- Reactor is a free and rich $\bar{\nu}_e$ source. Flux expectation within 2% error.

Principle of reactor-θ_{13} measurements

Features of reactor neutrino experiment to measure θ_{13}:



Survival probability of $\overline{\nu}_e$

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- The reactor neutrinos are detected by a well-designed detector.
- Rate is predictable from the distance, target mass, and IBD cross sections.

Principle of reactor-θ_{13} measurements

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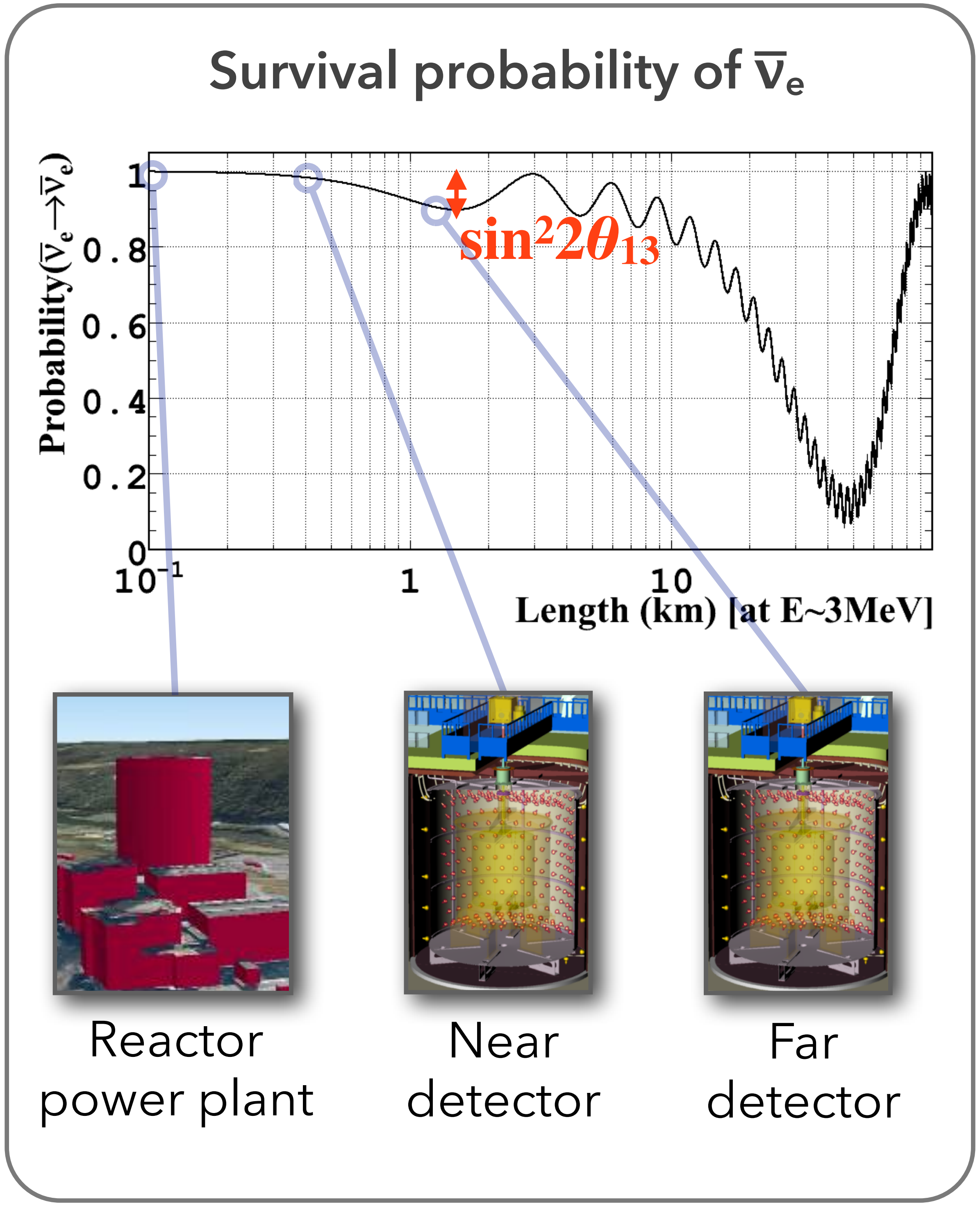

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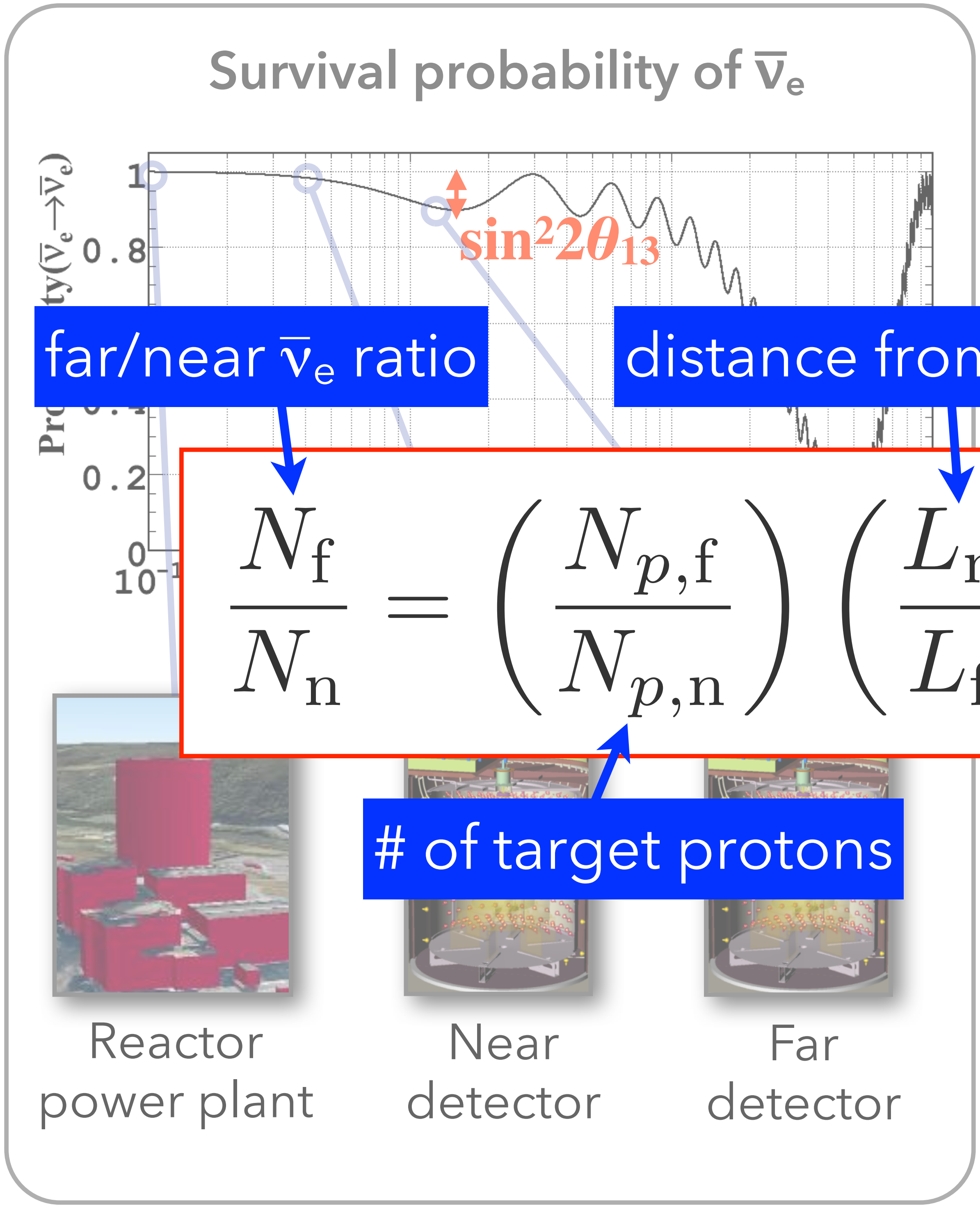
- Systematic uncertainties are further reduced by two identical detectors.

Principle of reactor-θ_{13} measurements

Features of reactor neutrino experiment to measure θ_{13}:



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- Reactor is a free and rich $\bar{\nu}_e$ source.
- r.
- cted
- I from the distance, target mass, and IBD cross sections.
- Systematic uncertainties are further reduced by two identical detectors.

far/near $\bar{\nu}_e$ ratio

distance from reactor

oscillation deficit

$$\frac{N_\mathrm{f}}{N_\mathrm{n}} = \left(\frac{N_{p,\mathrm{f}}}{N_{p,\mathrm{n}}}\right)\left(\frac{L_\mathrm{n}}{L_\mathrm{f}}\right)^2\left(\frac{\epsilon_\mathrm{f}}{\epsilon_\mathrm{n}}\right)\left[\frac{P_\mathrm{sur}(E, L_\mathrm{f})}{P_\mathrm{sur}(E, L_\mathrm{n})}\right]$$

# of target protons

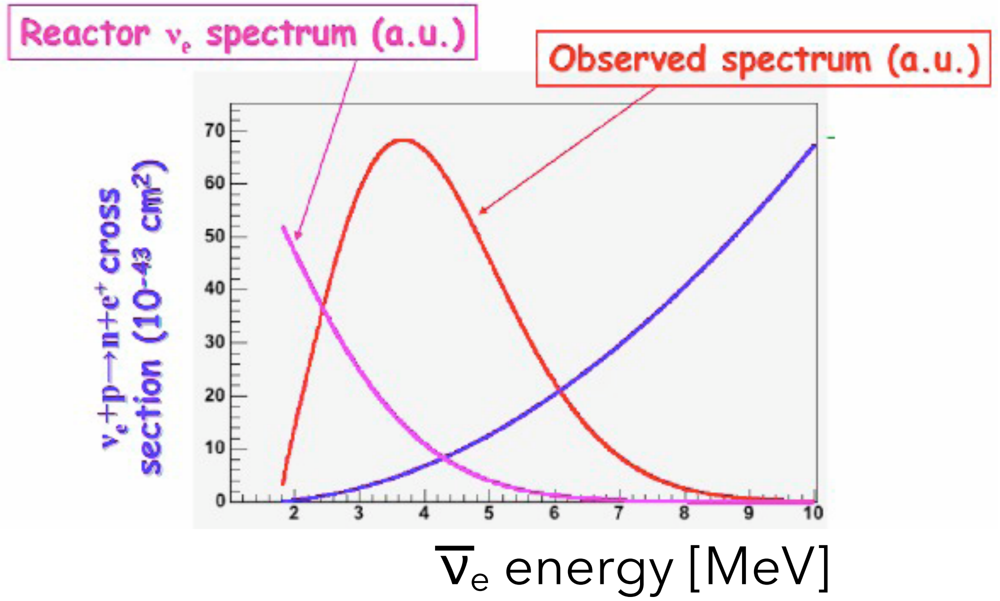
detection efficiency

Detection principle of reactor neutrinos

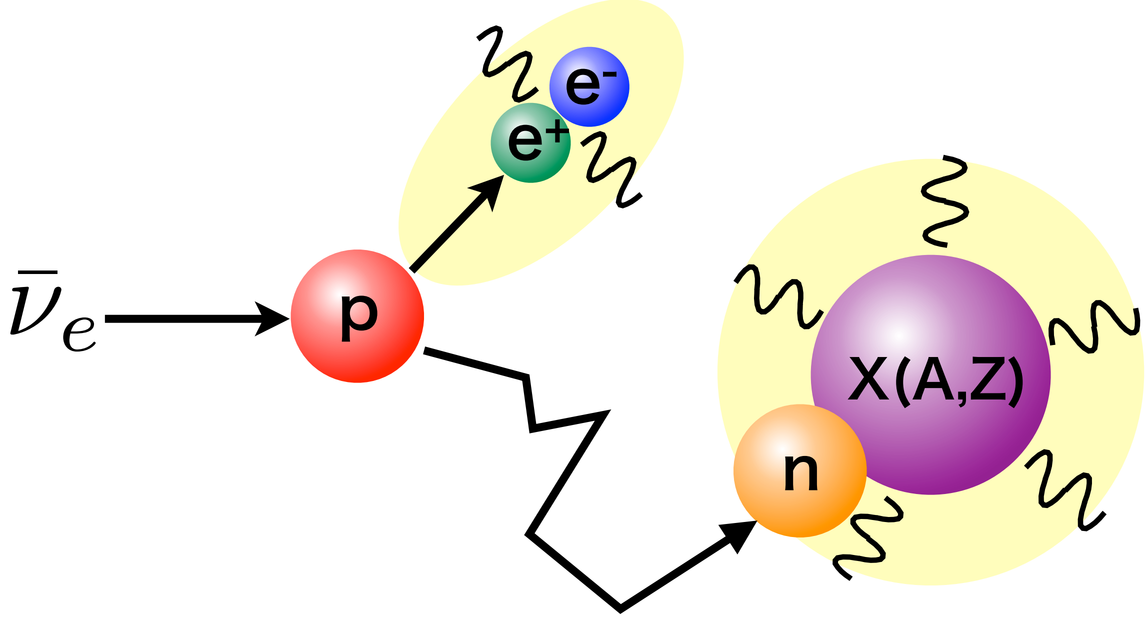
Inverse Beta Decay (IBD) reaction:

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

(*) Energy threshold = 1.8 MeV
$\sigma \sim 10^{-43}$ cm^2



Delayed coincidence technique:



(1) Prompt signal from e$^+$ ionization and annihilation (1~8 MeV).

(2) Delayed signal from neutron capture on nucleon (~8 MeV for Gd).

(3) Time coincidence of those (τ~30μsec for Gd).

In the IBD process, prompt energy is related to neutrino energy:

$$E_{vis} = E(kin)_{e^+} + 2m_e \simeq E_{\bar{\nu}_e} - (M_n - M_p) + m_e \simeq E_{\bar{\nu}_e} - 0.782\,\mathrm{MeV}$$

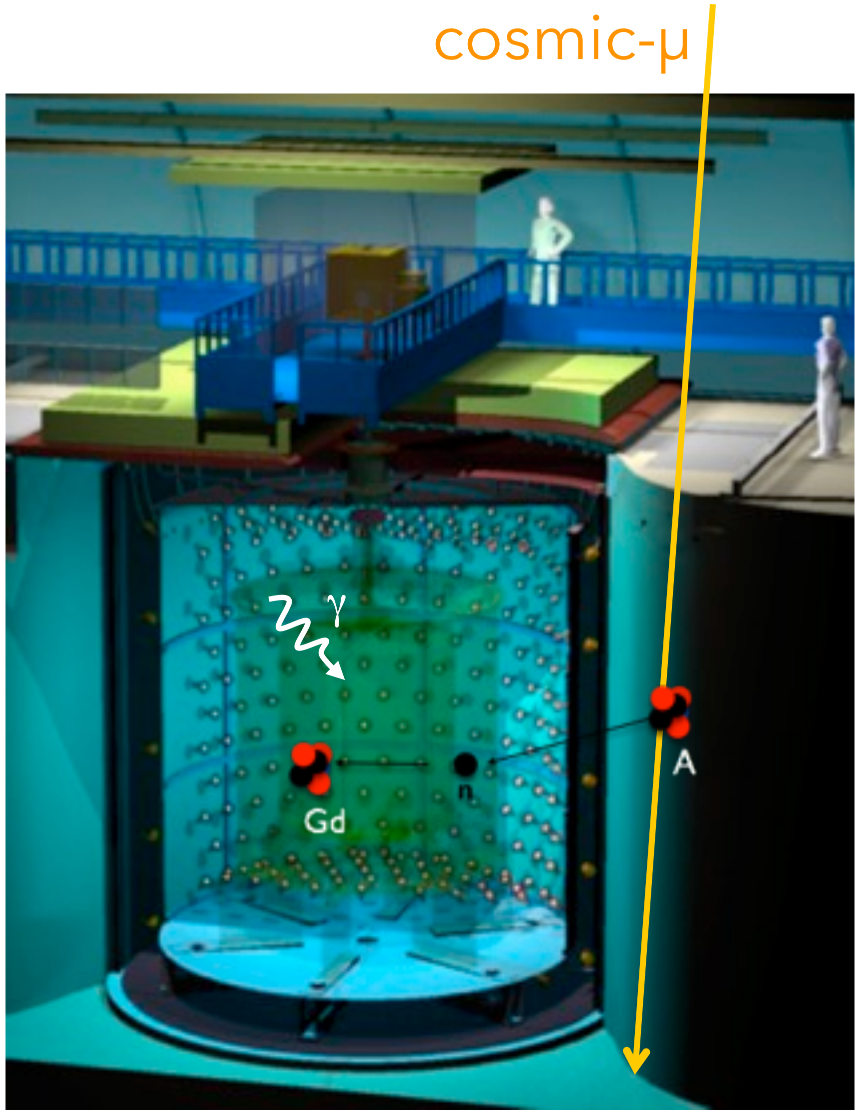
→ Spectral shape of the prompt signal gives us further information.

Main backgrounds

Accidental bkg.

Accidental coincidences

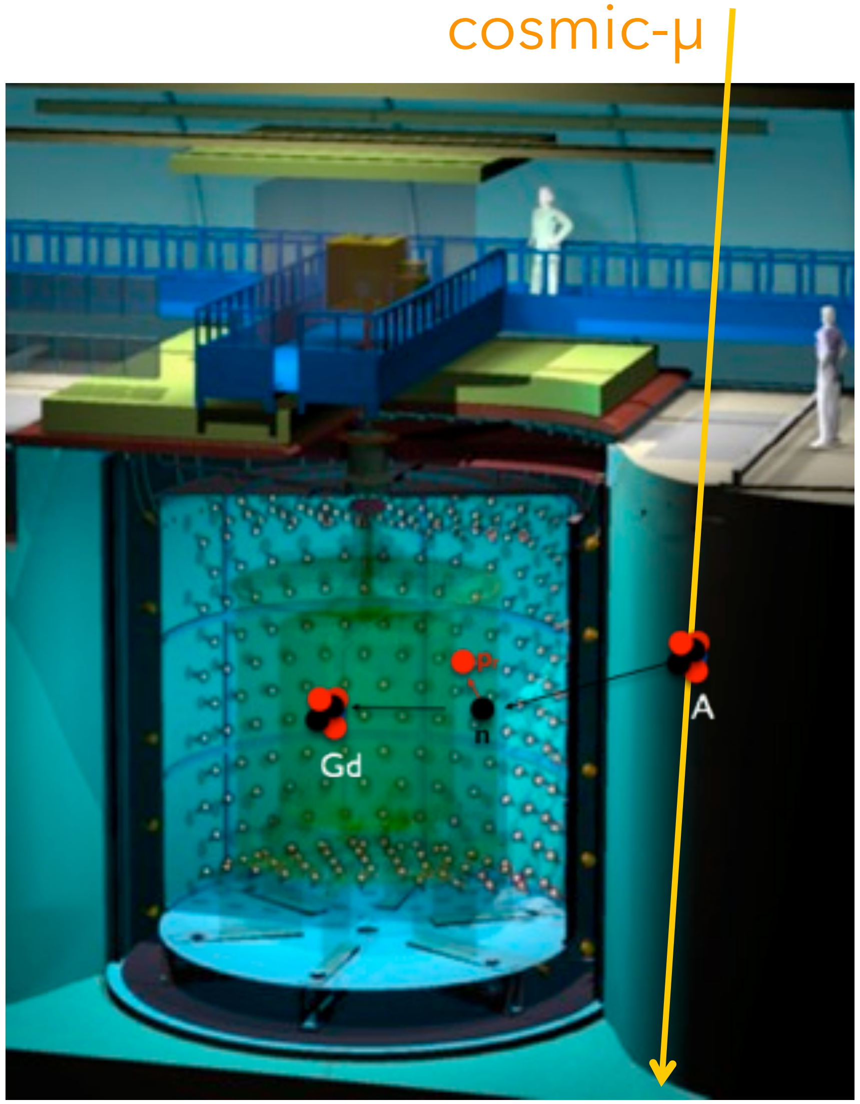
Prompt: gammas from radioactivity materials, rock...
Delayed: neutrons from cosmic-muons



Correlated bkg.

muon-induced fast-neutrons and stopping muons

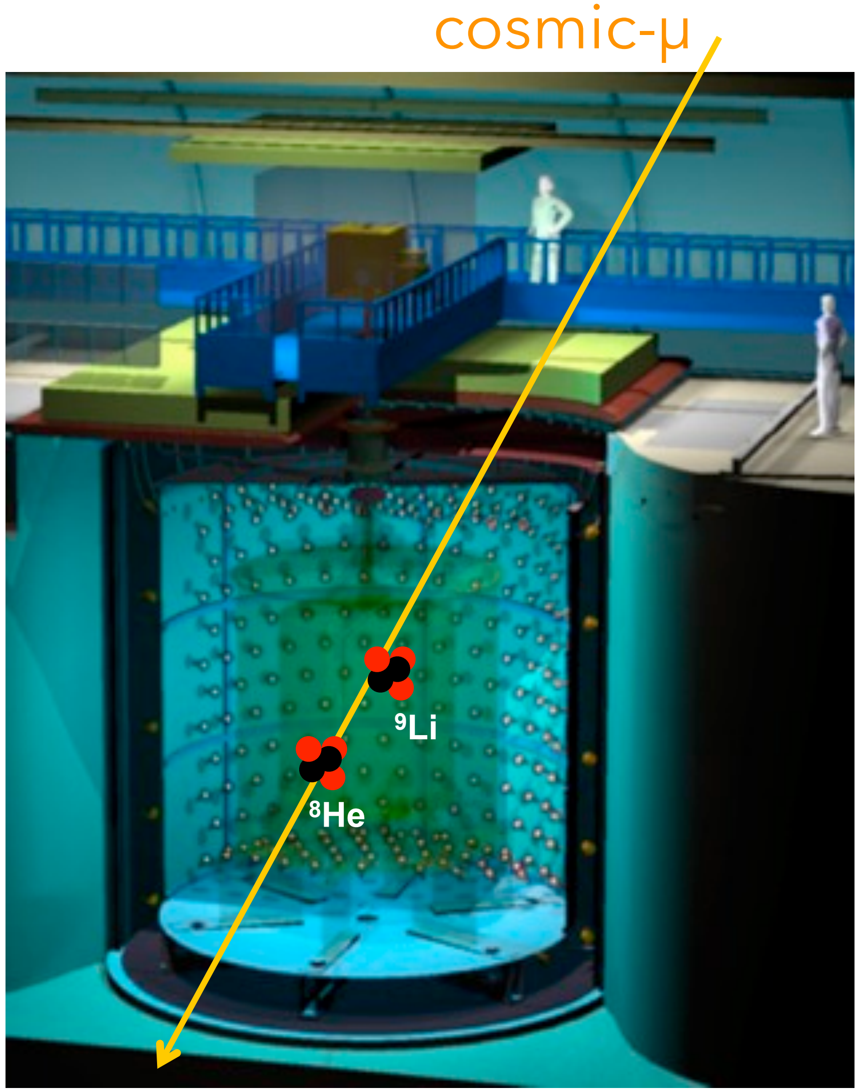
Prompt: recoil proton from neutron scattering or muon track
Delayed: neutron capture or Michel-electrons



Cosmogenic bkg.

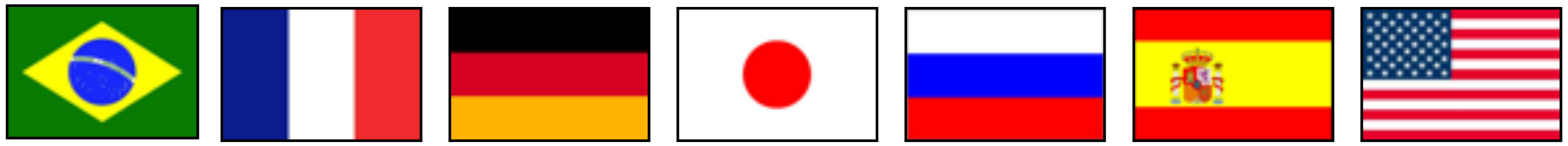
muon-induced spallation βn emitters (^{9}Li etc.)

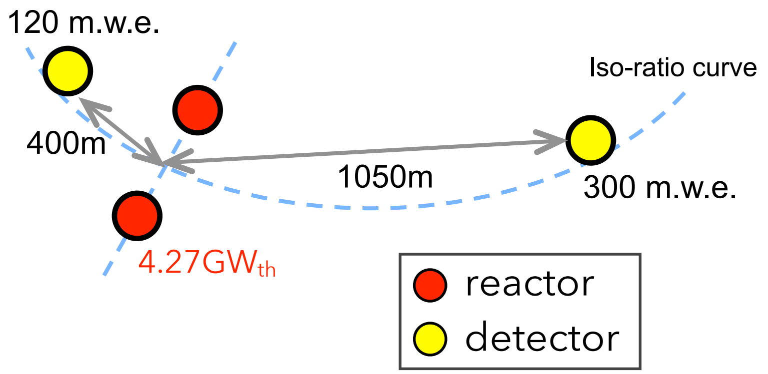
Prompt: electron
Delayed: neutron capture



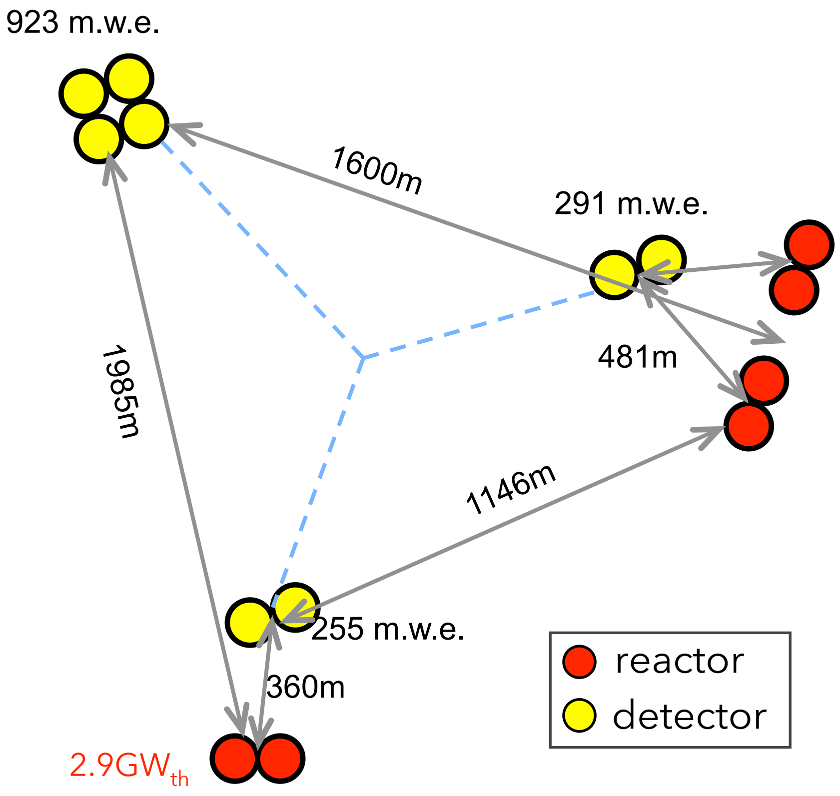
Ongoing reactor-θ_{13} experiments

Double Chooz (France)

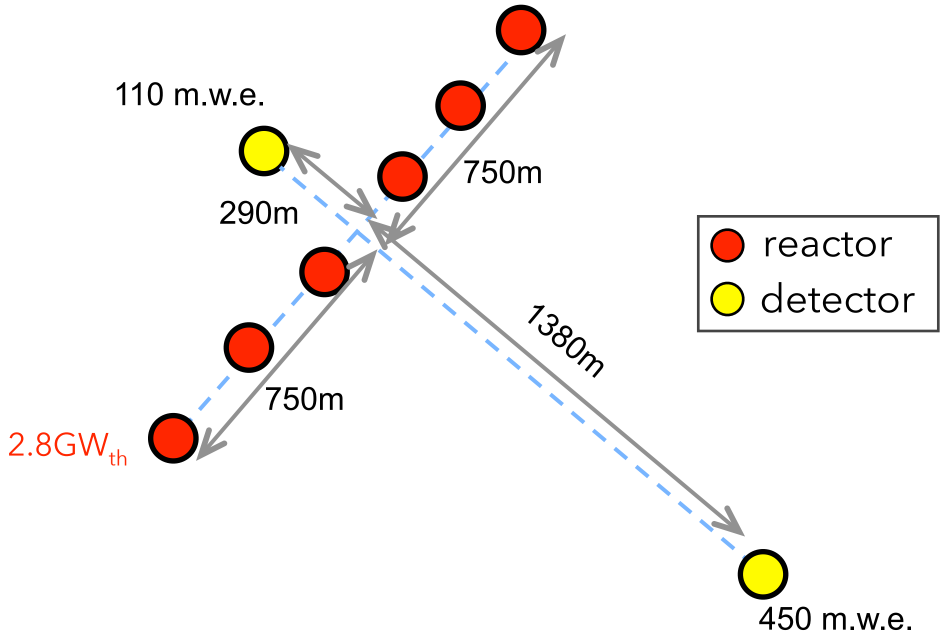




Daya Bay (China)



RENO (Korea)



Double Chooz

Experimental layout

Reactor

EDF
Electricité de France

Two reactor cores
4.27 GW$_{th}$ for each core

Near detector

<L> ~400 m
~120 m.w.e.
450 ν/day

Under construction

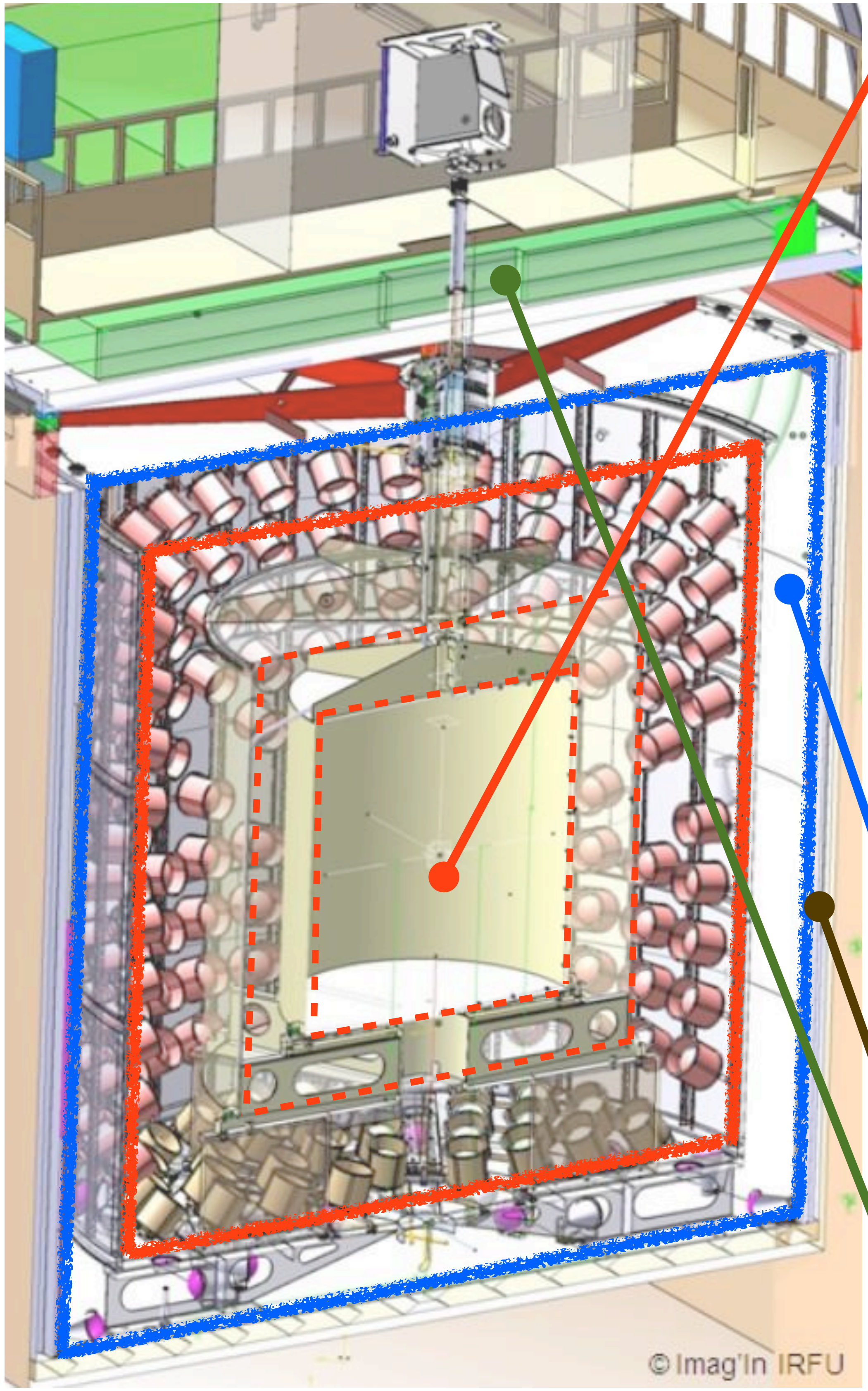
Far detector

<L> ~1050 m
~300 m.w.e.
65 ν/day

Operating since Apr. 2011

Far only operation: Measure the mixing angle θ_{13} by comparing observed neutrino candidates at the Far detector with prediction.

Double Chooz detector


© Imag'In IRFU

Inner Detector (ID) - three cylindrical layers

ν-target region:

- Gd-loaded (1 g/l) liquid scintillator (10.3 m^3)
- Target of neutrino interaction

------------ Transparent acrylic vessel ------------

γ-catcher region:

- 22.3 m^3 liquid scintillator
- Measure γ's escaped from ν-target region

------------ Transparent acrylic vessel ------------

Buffer region:

- 110 m^3 mineral oil & 390 low-BG 10″ PMTs
- Reduce environmental γ & neutron BG

Inner veto (IV)

- Liquid scintillator & 78 8″ PMTs in steel tank
- Identify cosmic μ & reduce environmental γ

Shielding

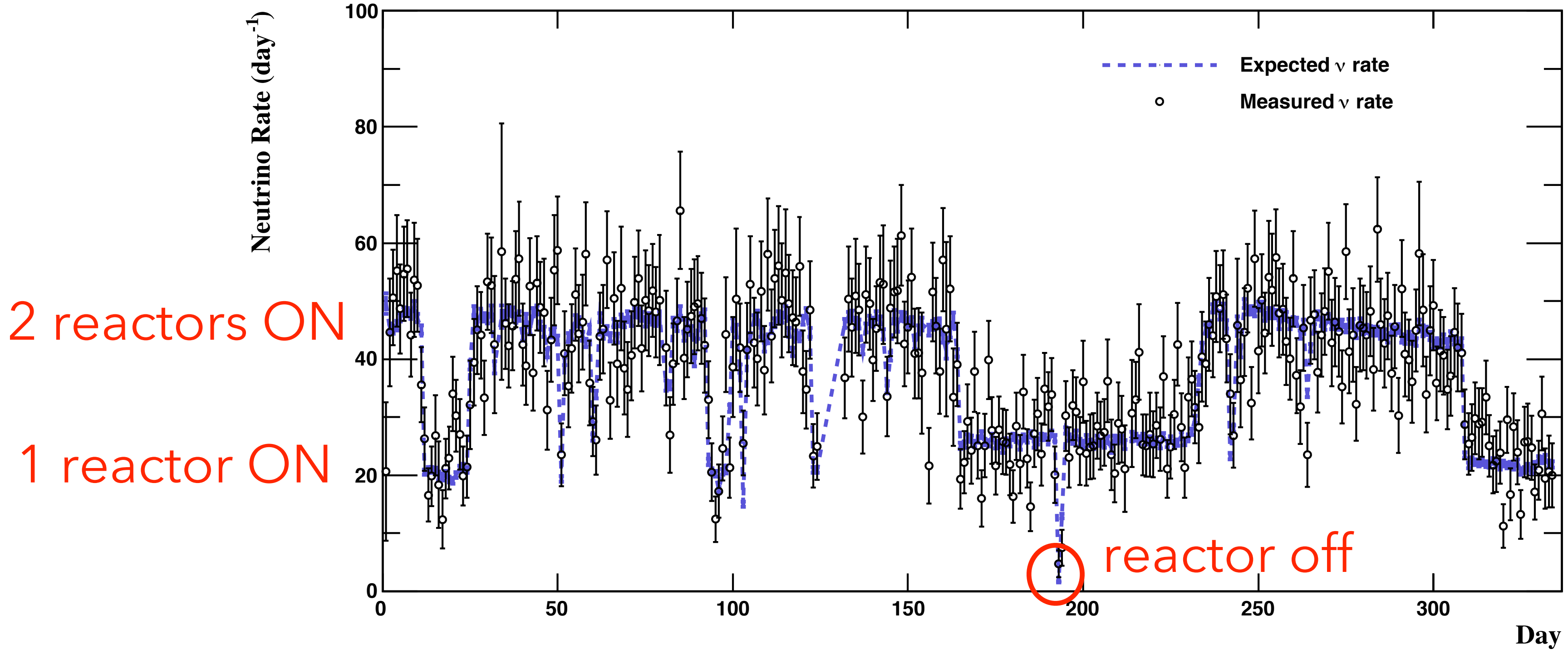
- 15 cm thickness of steel shielding

Outer veto (OV)

- Plastic scint. strip + WLS fiber + MAPMT
- Identify cosmic μ

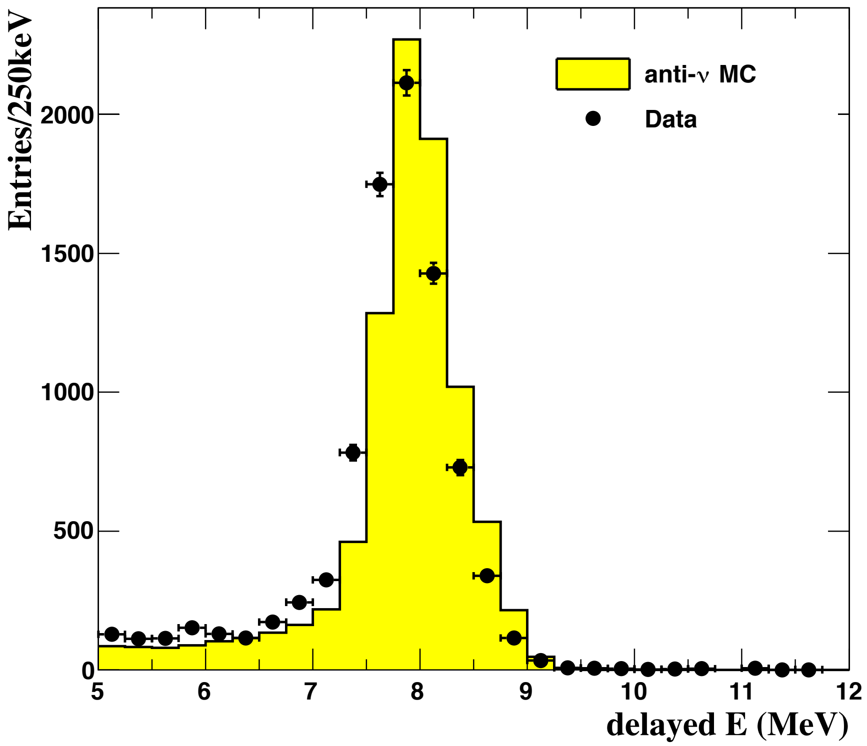
IBD Candidates

Gd analysis (Live time=227.93 days, Candidates=8249)

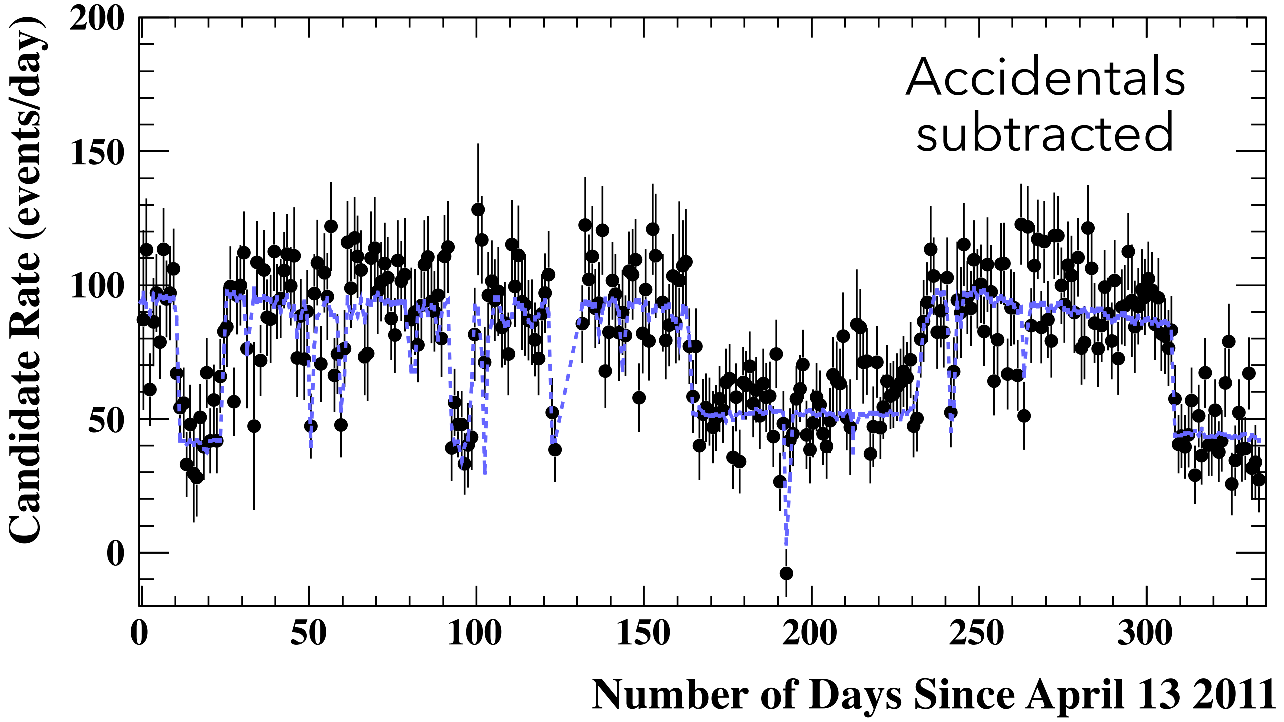

2 reactors ON

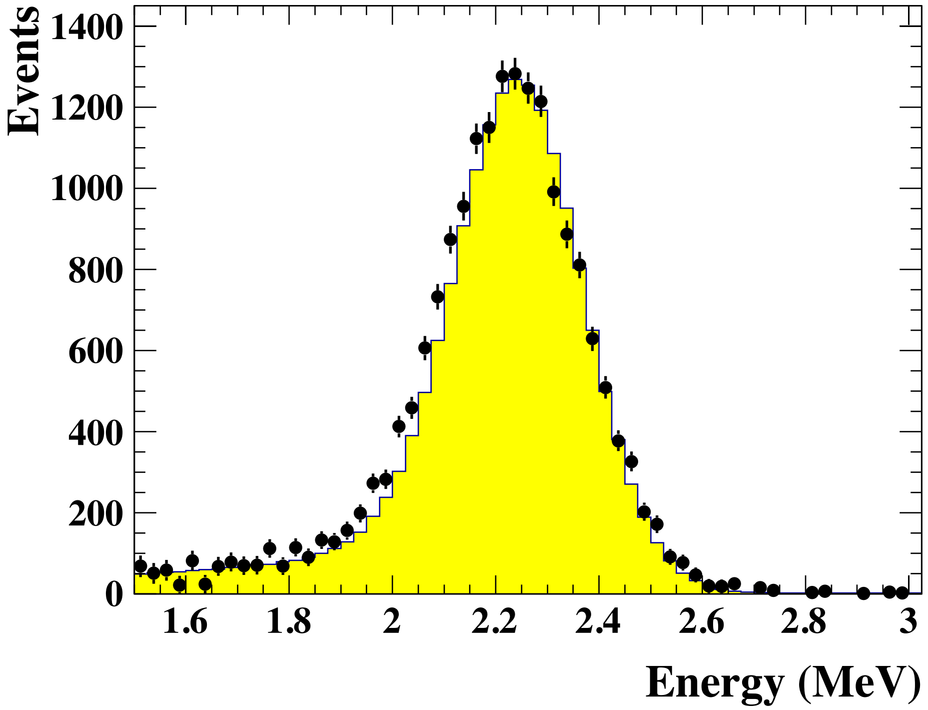
1 reactor ON

reactor off



H analysis (Live time=240.1 days, Candidates=36284)

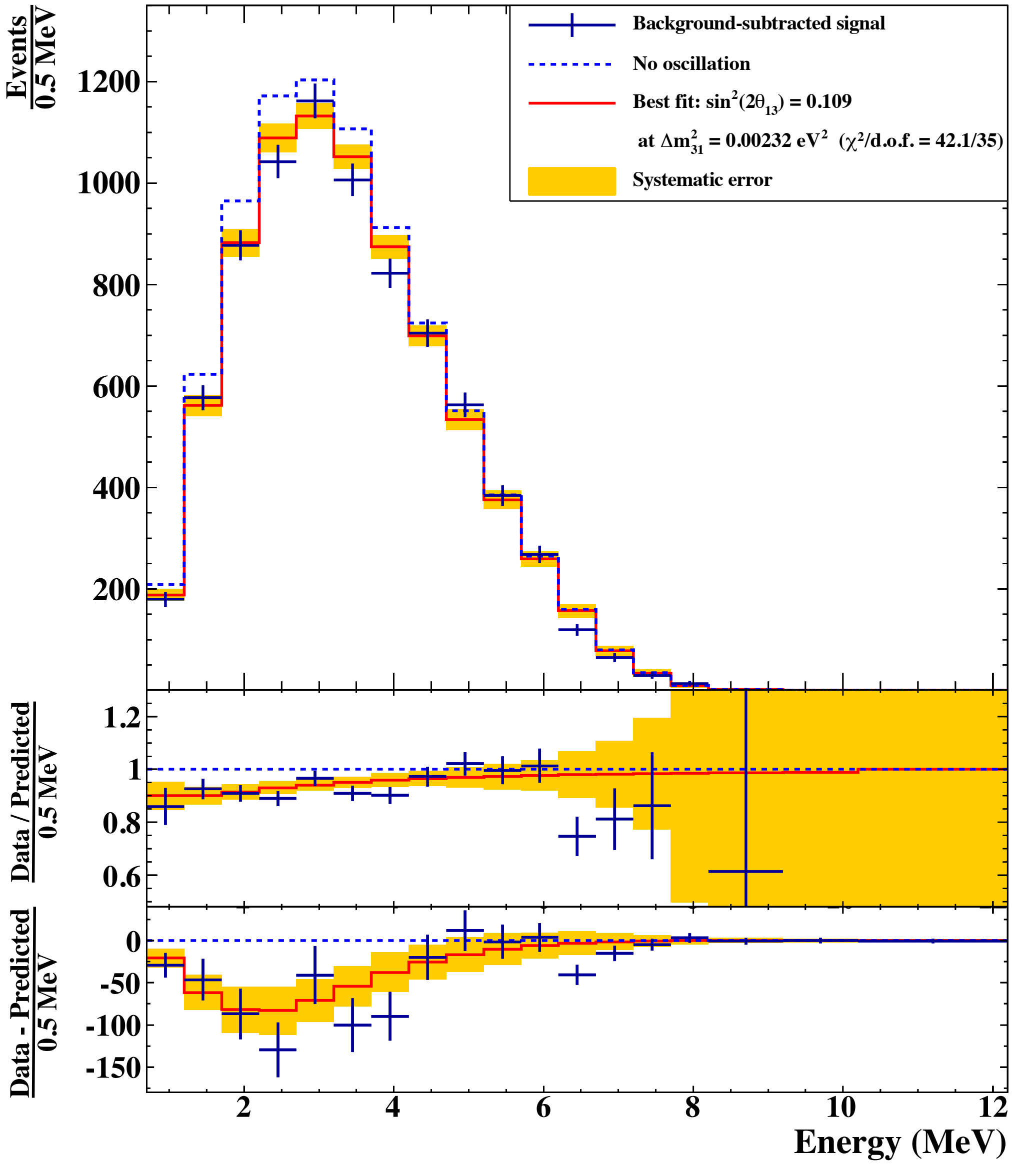

Accidentals subtracted



Rate + Shape results

Gd analysis, June 2012

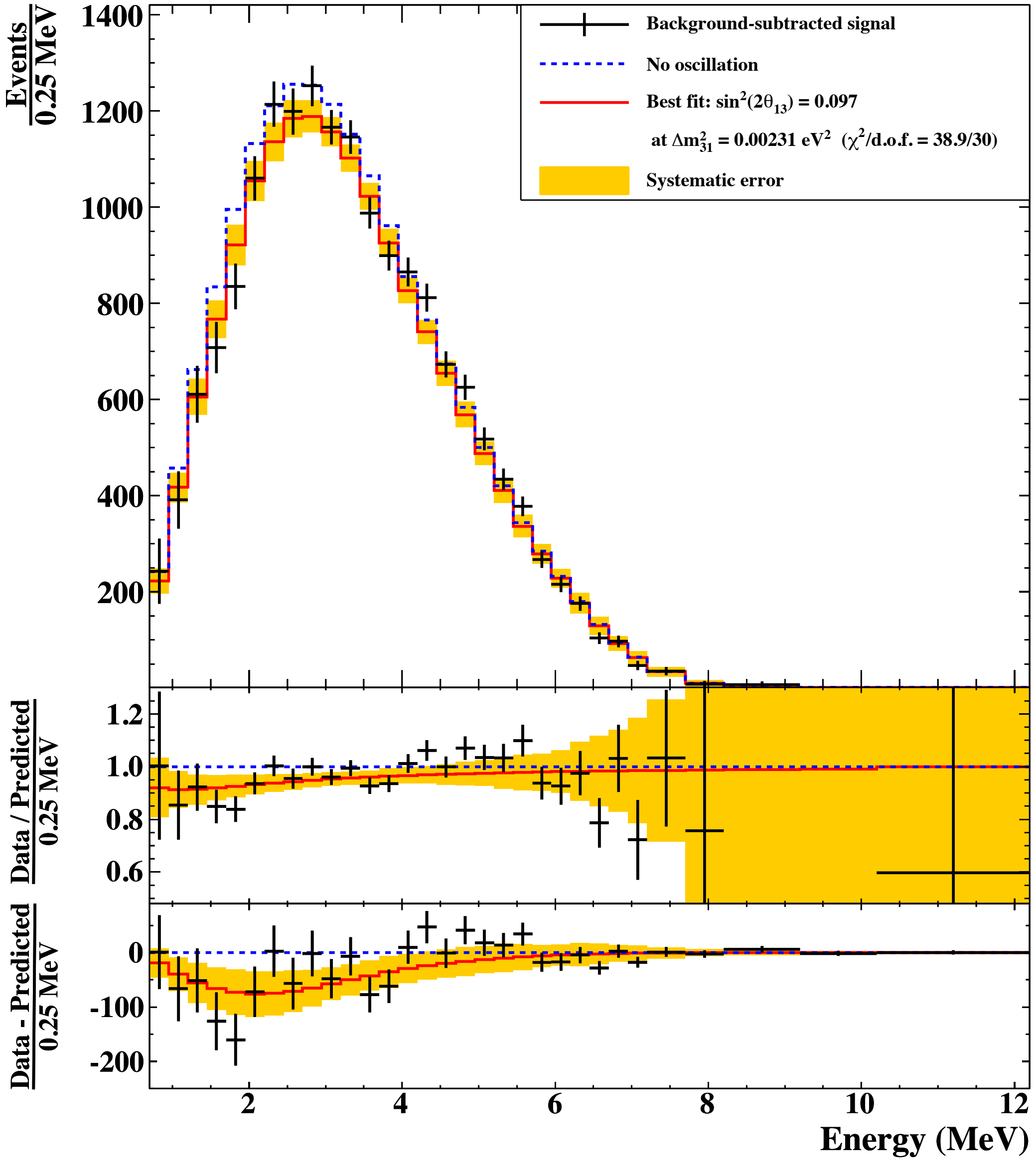
Phys. Rev. D 86 (2012)



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

H analysis, December 2012

Phys. Lett. B 723 (2013)



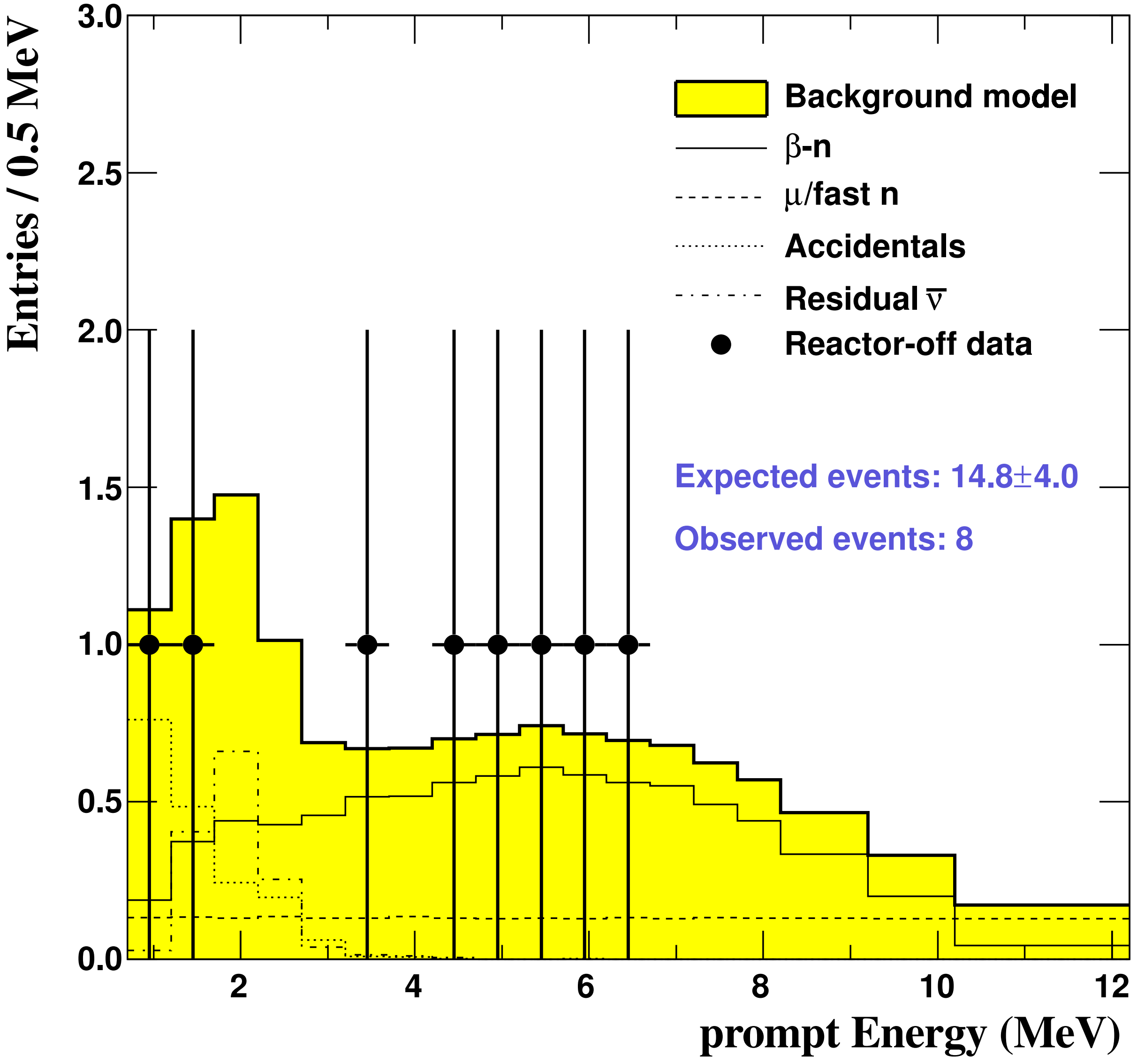
$\sin^2 2\theta_{13} = 0.097 \pm 0.048$

The combined result of Gd & H: $\sin^2 2\theta_{13} = 0.109 \pm 0.035$ (preliminary)

Reactor off background measurements

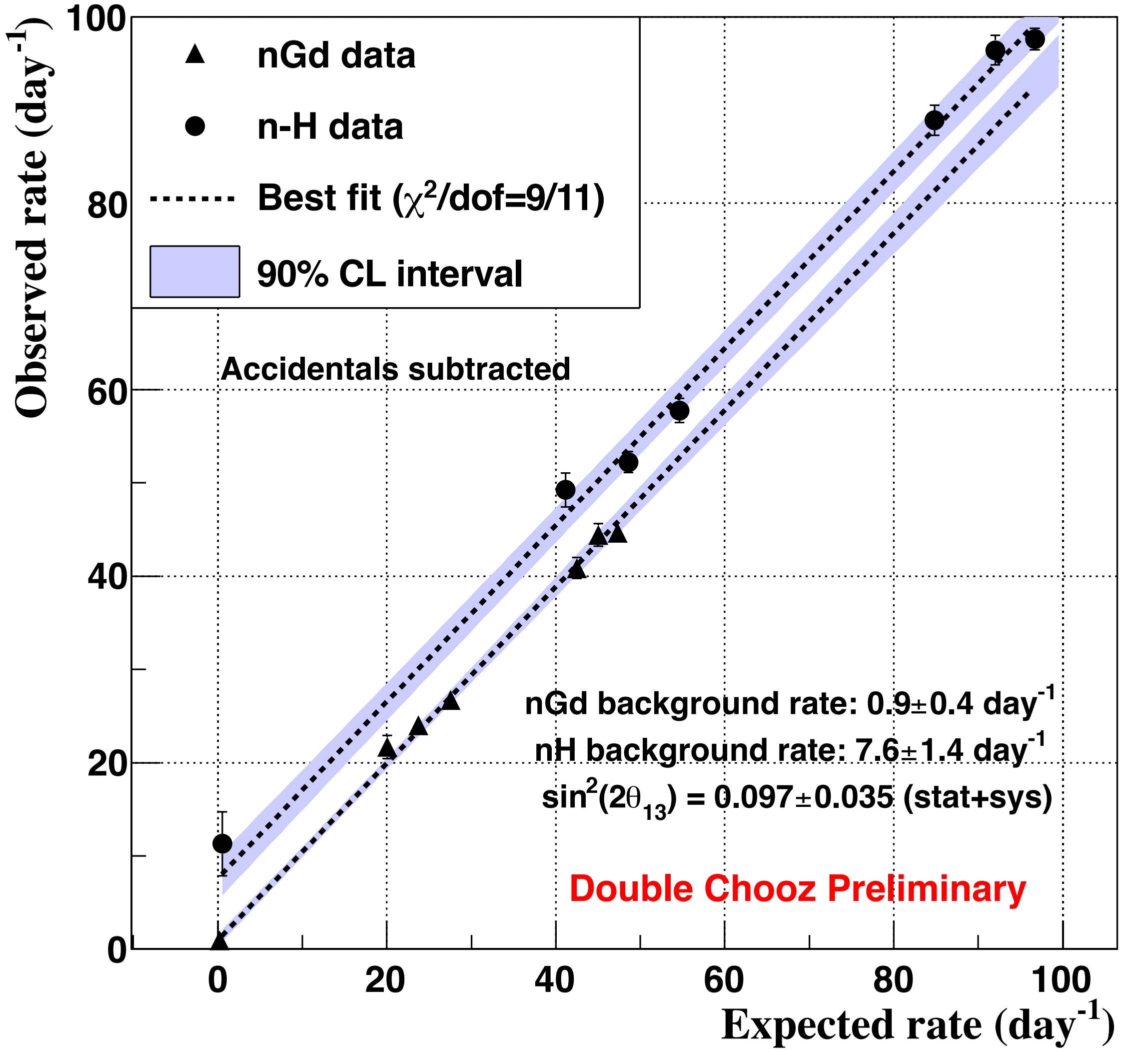
Phys. Rev. D 87 (2013) 011102(R)

- 7.5 days of data with both reactors off
  → pure background data
- Unique Double Chooz capability
- Same selection than for Gd analysis
- Rate consistent with predictions
  - Observed: 1.0±0.4 [/day]
  - Predicted: 2.0±0.6 [/day]
- New constraint for oscillation fit



Reactor rate modulation (RRM) analysis

- Rate-only background-independent analysis
  - Observed vs expected $\overline{\nu}_e$ rate using different reactor power
  - Fit provides $\sin^2 2\theta_{13}$ and the total background rate
- No background model assumed
- includes the reactors-off background measurement



Gd+H combined result:

$\sin^2 2\theta_{13} = 0.097 \pm 0.035$ (preliminary)

in agreement (~same precision) with R+S results

Prospects from Double Chooz

- Currently finishing new improved analysis including...
  - Statistics (> 2x)
  - Optimized selection to enhance S/B
  - Reduced systematics
- Near + Far detector analysis (mid. 2014)
  - Reactor flux uncertainty almost cancels
  - Projected final precision: ~10%

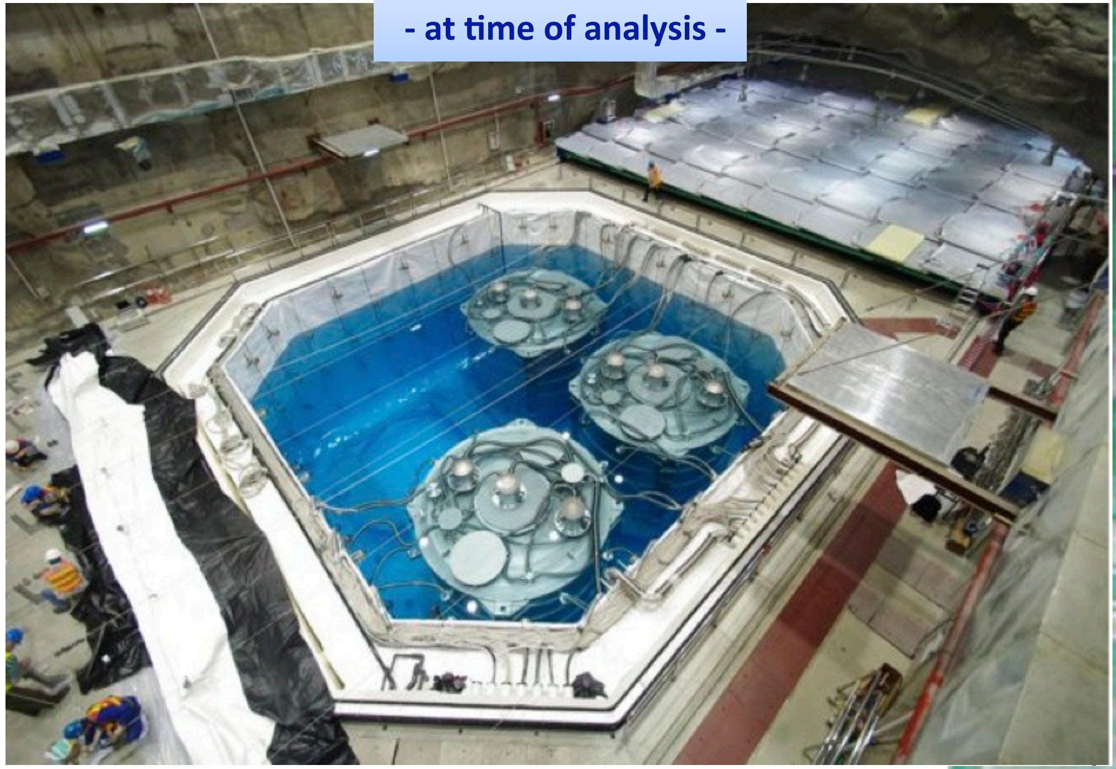
May 2013

Daya Bay

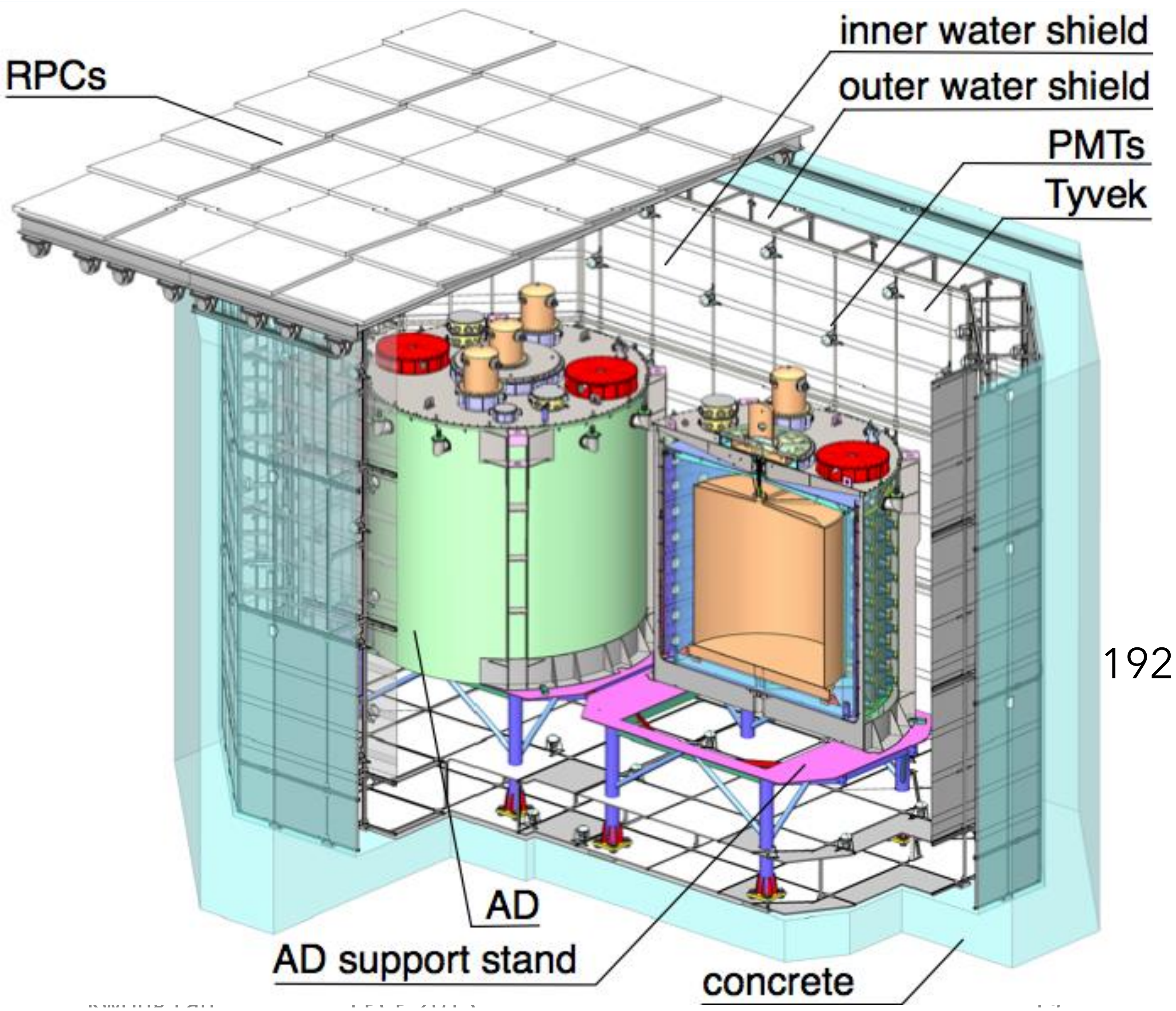
Experimental layout

- 8 detectors in 2 near and 1 far site
  - results shown here use data collected with 6/8 detectors

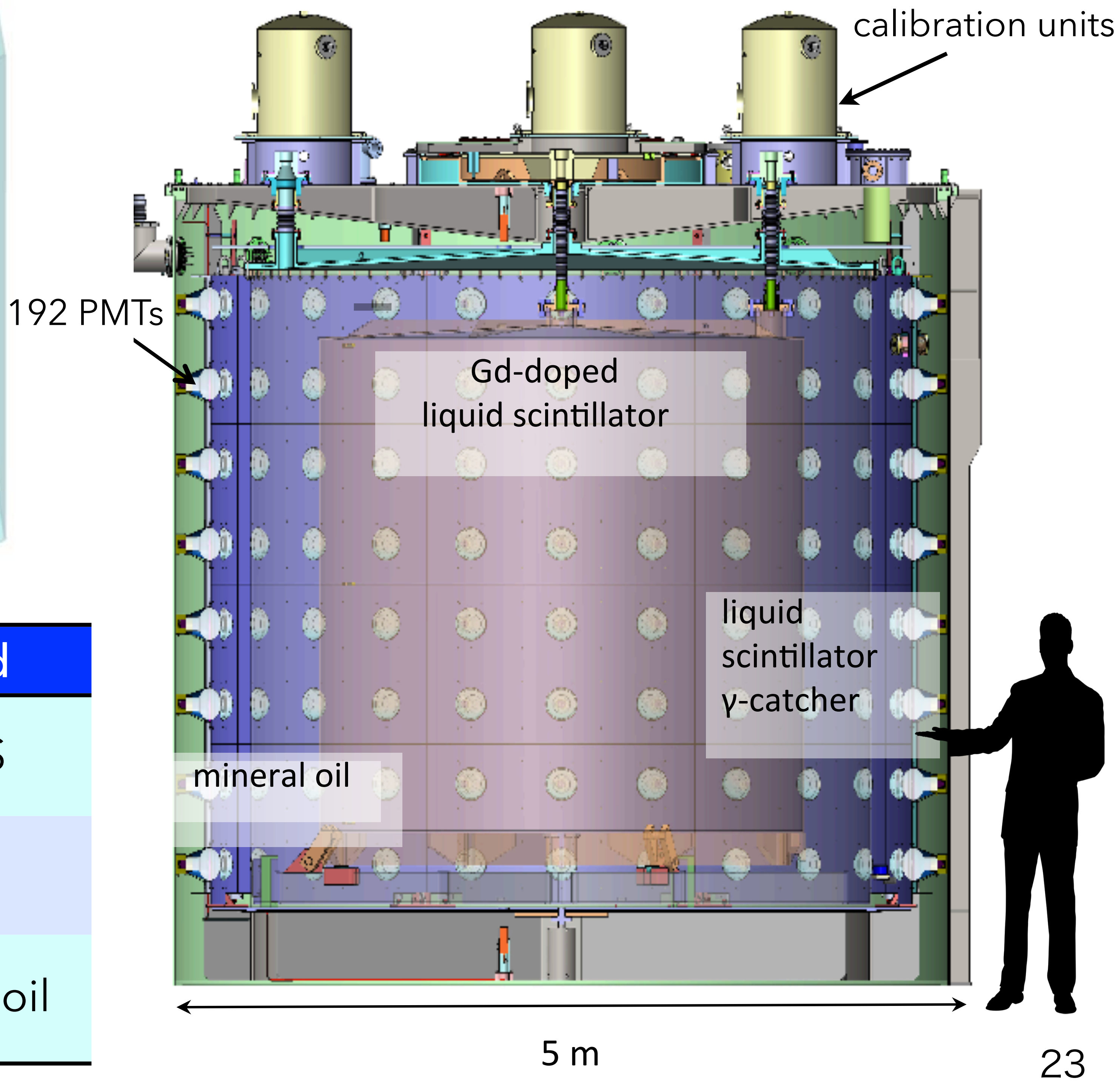
EH3 (Far Hall)
- at time of analysis -



The Daya Bay detector



- Antineutrino detectors are surrounded by two-section water shield and RPCs.



Zone	Mass	Liquid
Inner acrylic vessel (neutrino-target)	20 t	Gd-LS
Outer acrylic vessel (γ-catcher)	20 t	LS
Stainless steel vessel (Radiation shielding)	40 t	Mineral oil

Daya Bay status

Two detector comparison [1202.6181]

- 90 days of data, Daya Bay near only
- NIM A 685 (2012) 78-97

First oscillation analysis [1203.1669]

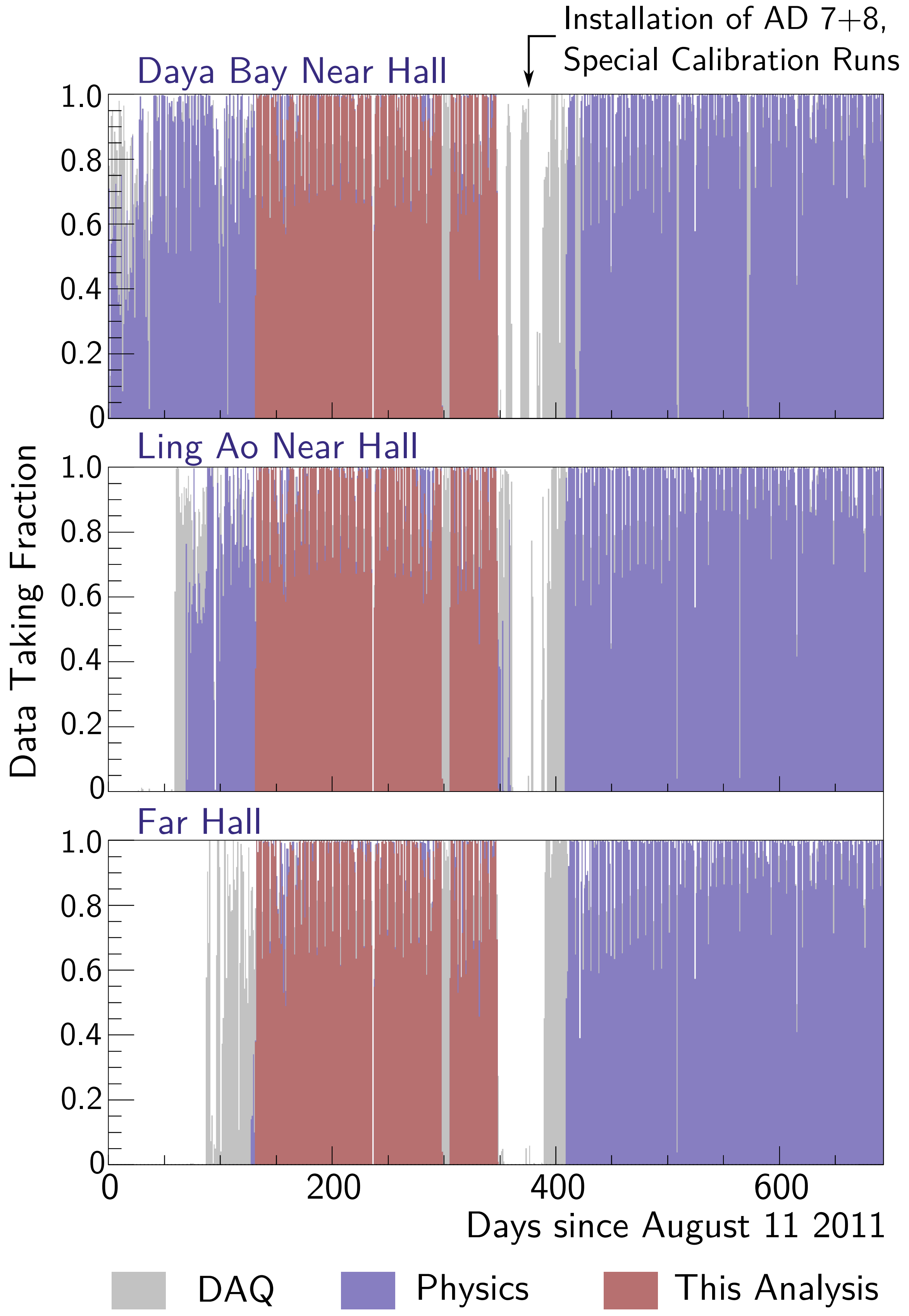
- 55 days of data, 6 ADs near+far
- PRL 108 (2012) 171803

Improved oscillation analysis [1210.6327]

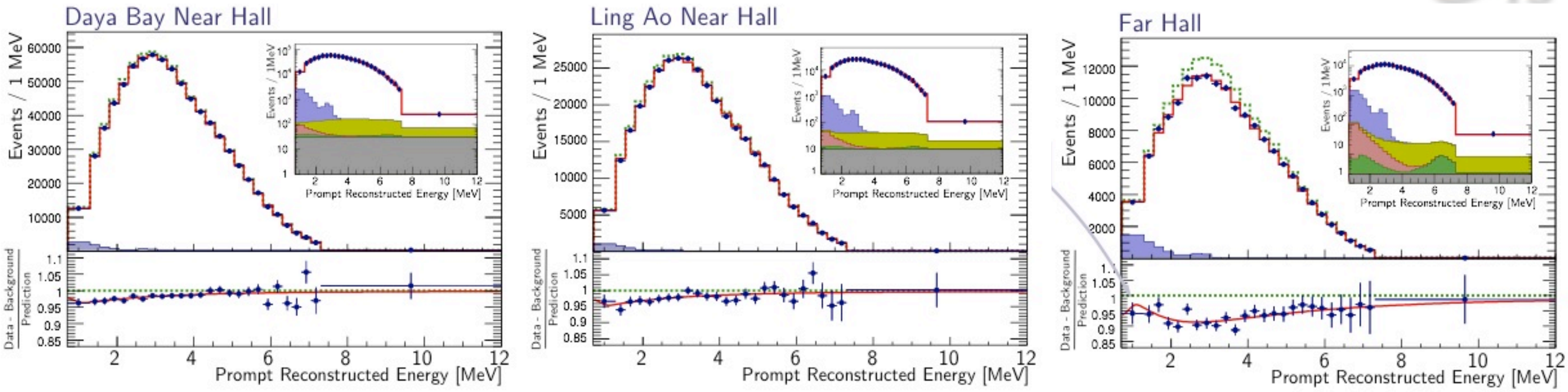
- 139 days of data, 6 ADs near+far
- CP C 37 (2013) 011001

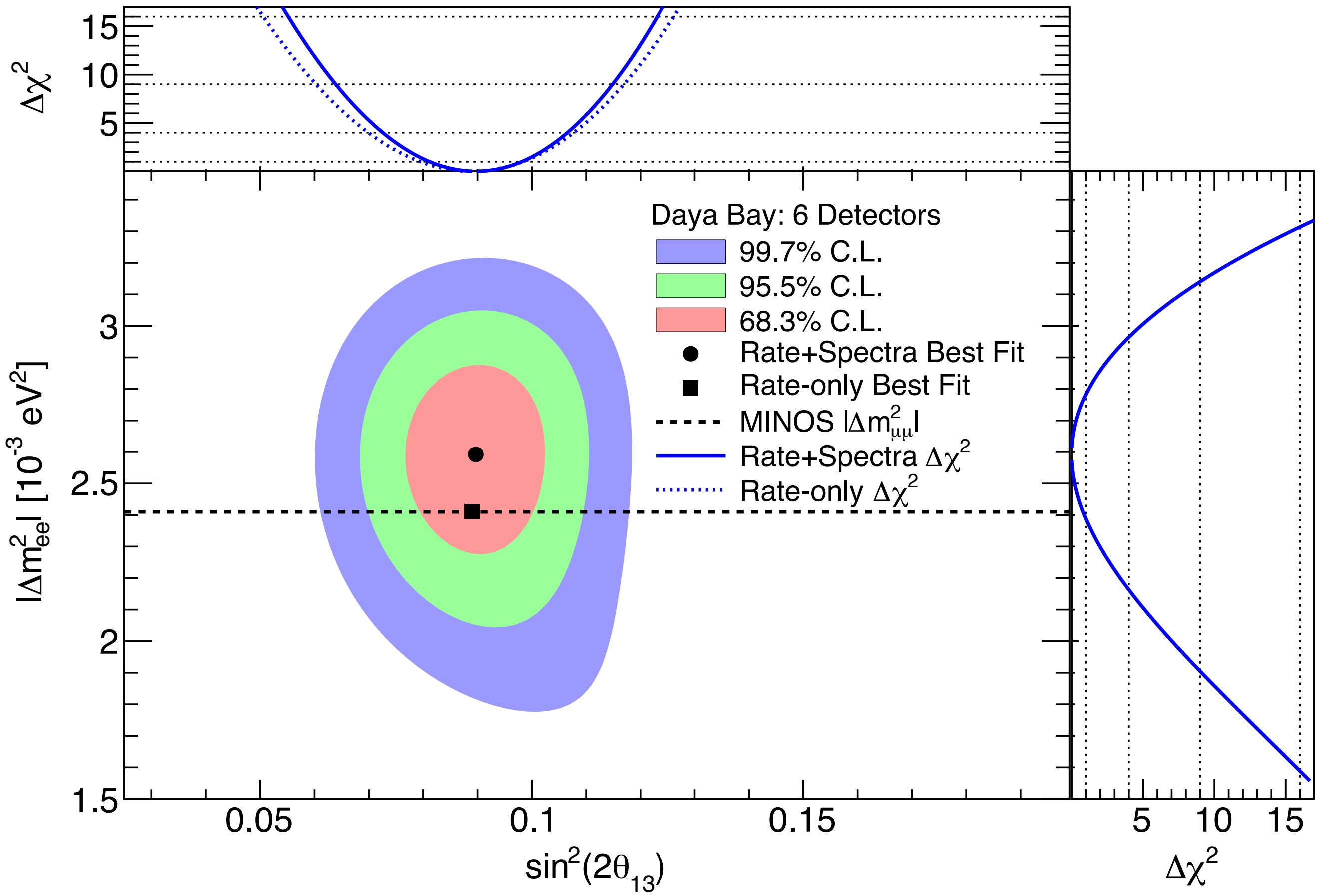
Spectral analysis [1310.6732]

- 217 days complete 6 AD period
- 55 % more statistics than CPC result



The newest result [arXiv:1310.6732]





$\sin^2 2\theta_{13} = 0.090^{+0.008}_{-0.009}$

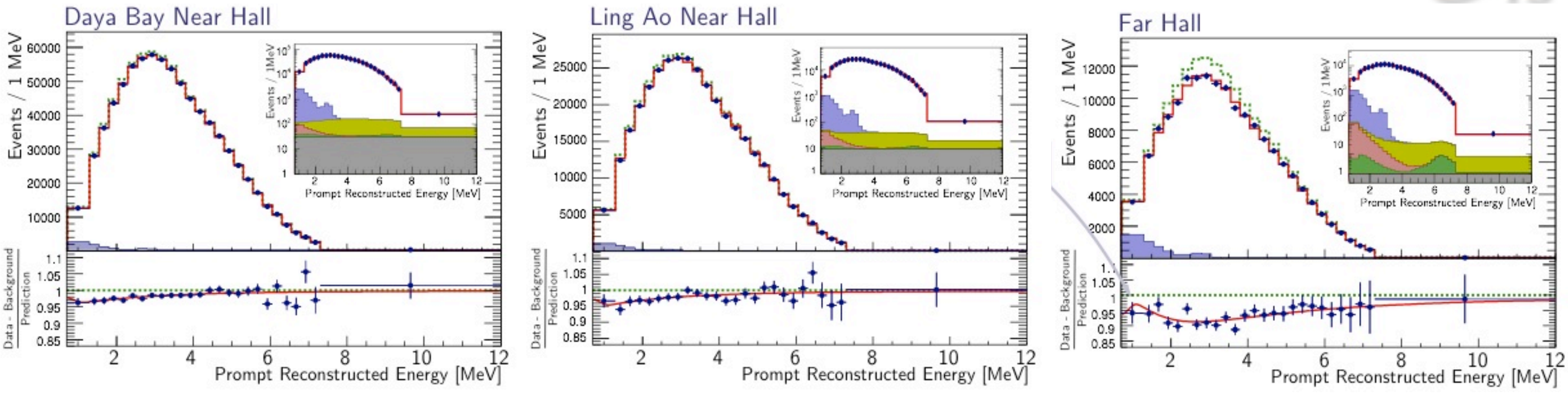
$|\Delta m^2_{ee}| = 2.59^{+0.19}_{-0.20} \times 10^{-3}\ \mathrm{eV}^2$

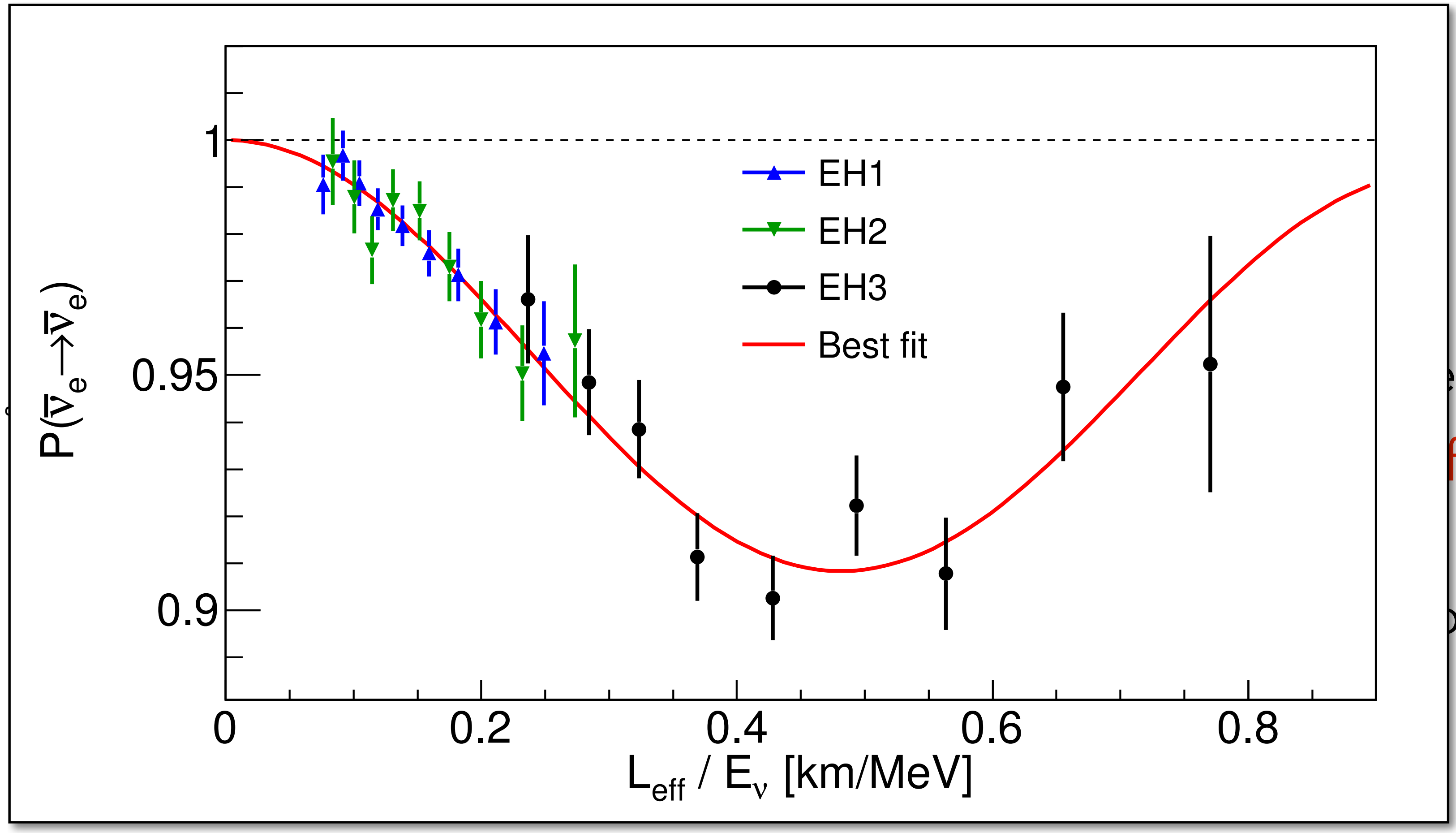
(world's first measurement in this channel)

$\chi^2/N_{DoF} = 162.7/153$

The result strongly confirms of oscillation-interpretation of observed ν_e deficit.

The newest result [arXiv:1310.6732]





$_{13} = 0.090^{+0.008}_{-0.009}$

$| = 2.59^{+0.19}_{-0.20} \times 10^{-3}$ eV^2

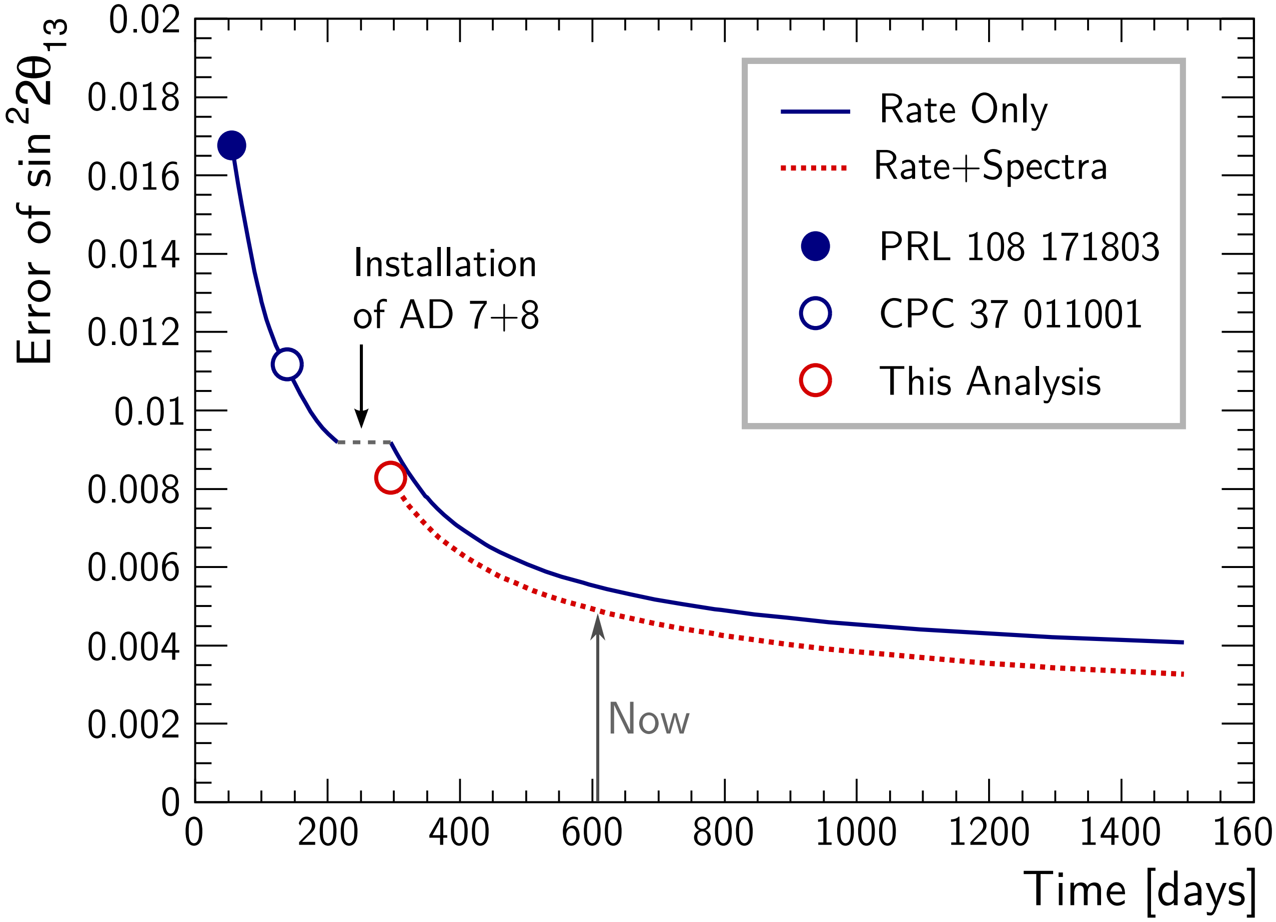
first measurement in this channel)

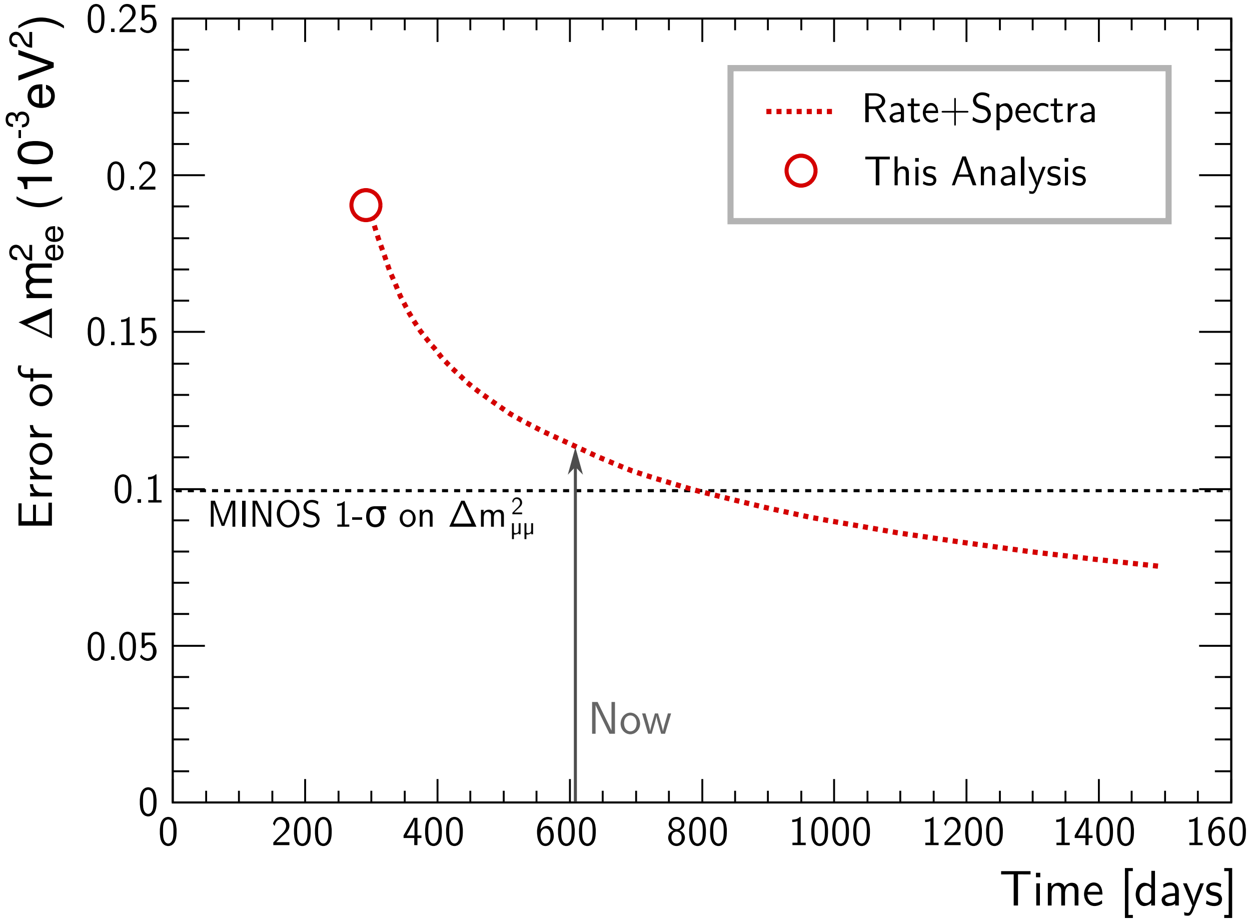
$_F = 162.7/153$

The result strongly confirms of oscillation-interpretation of observed ν_e deficit.

Prospects from Daya Bay

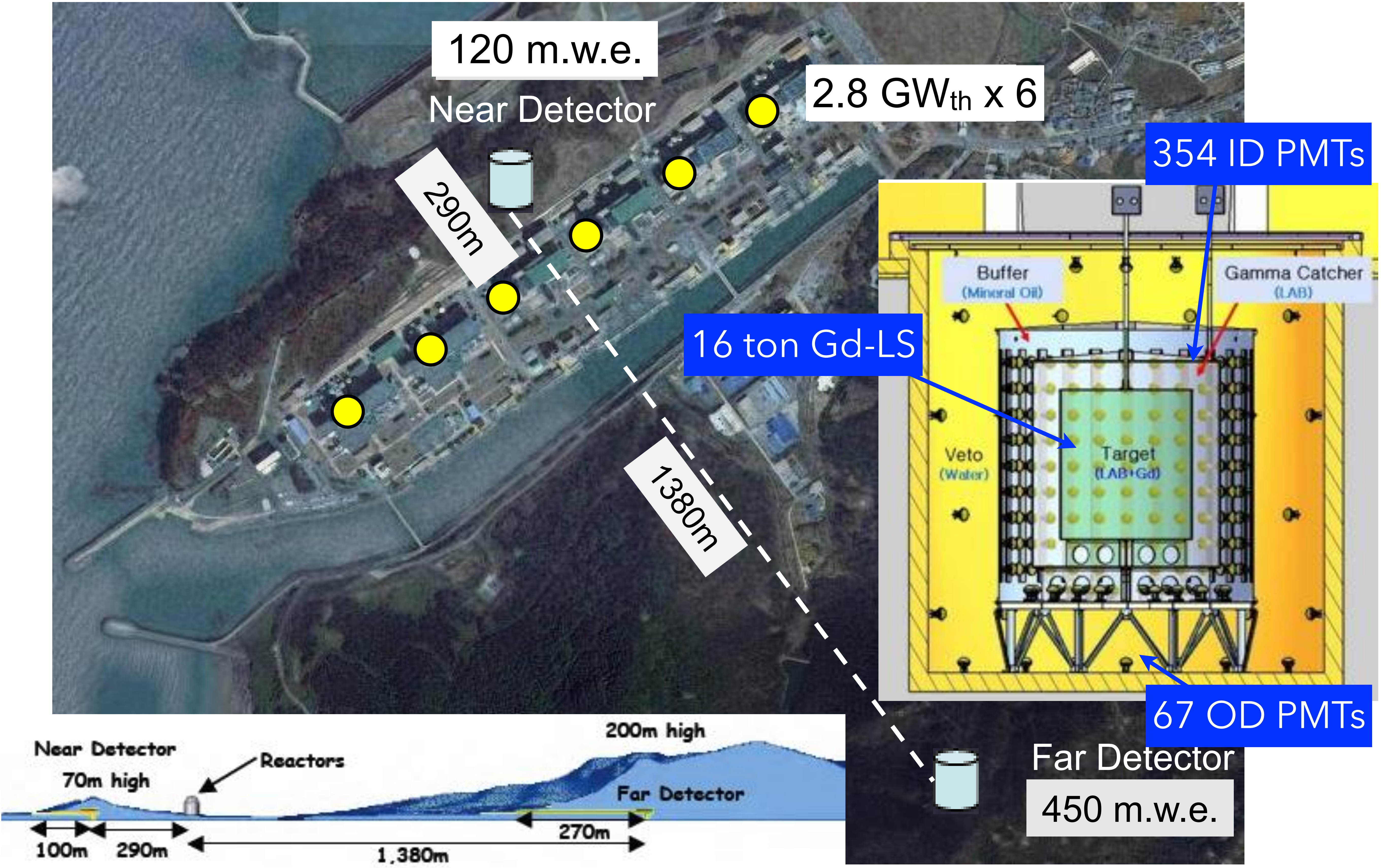
- increased the precision in oscillation parameters
  - constrains non-standard oscillation models
  - improves the reach of next-generation experiments
  - Absolute reactor neutrino spectrum flux and shape measurement
    - probe reactor models and explore reactor antineutrino anomaly





RENO

Experimental layout



120 m.w.e.

Near Detector

2.8 GW_{th} x 6

354 ID PMTs

16 ton Gd-LS

67 OD PMTs

Far Detector

450 m.w.e.

Data taking & analysis status

- Data taking began on Aug. 1, 2011 with both near and far detectors.

A (220 days): first θ_{13} result

$\sin^2 2\theta_{13} = 0.113 \pm 0.013(\text{stat}) \pm 0.019(\text{syst})$

PRL 108 (2012) 191802

B (403 days): improved θ_{13} result

$\sin^2 2\theta_{13} = 0.100 \pm 0.010(\text{stat}) \pm 0.015(\text{syst})$

NuTel2013

B' (403 days): updated result

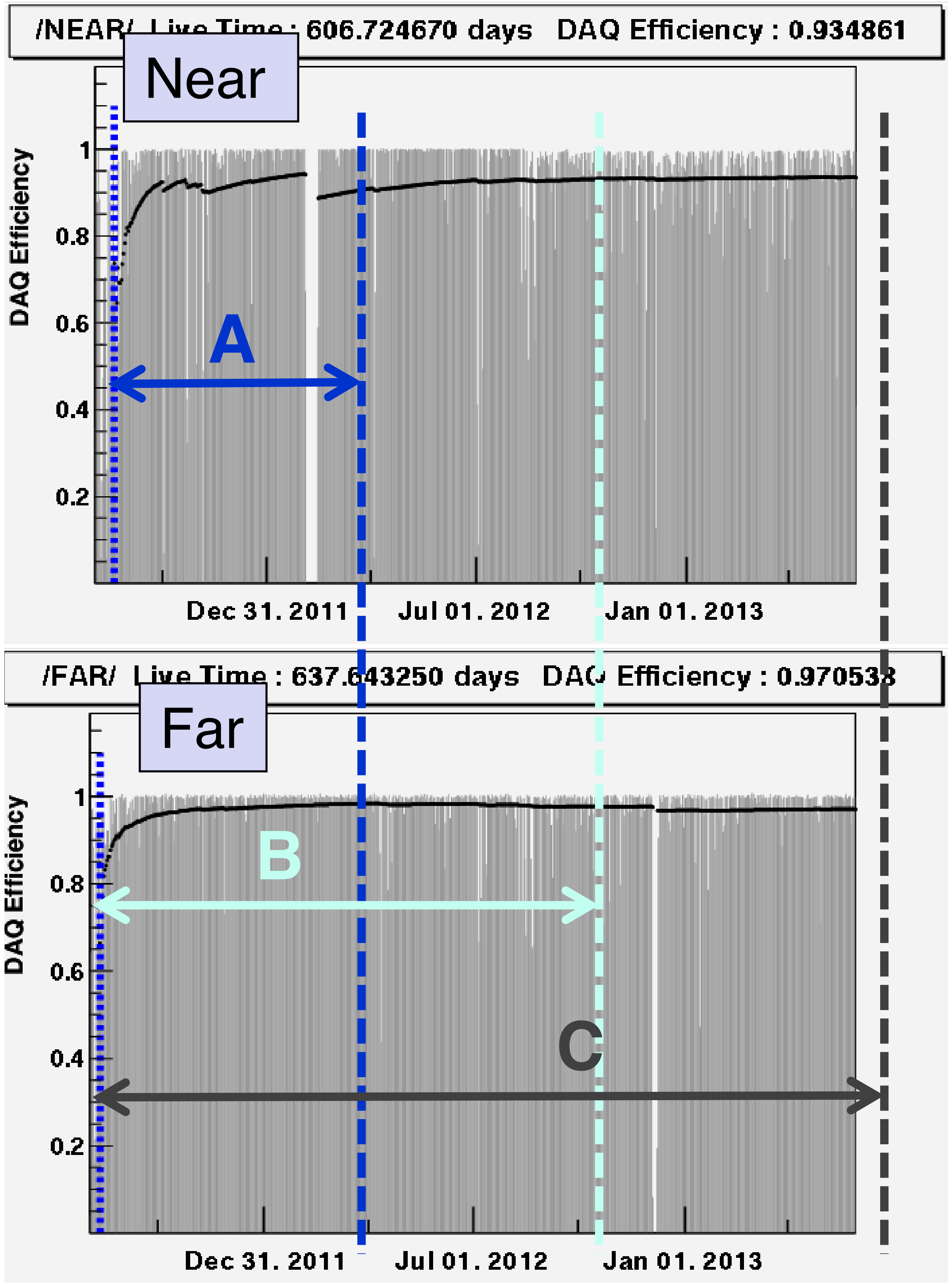
$\sin^2 2\theta_{13} = 0.100 \pm 0.010(\text{stat}) \pm 0.012(\text{syst})$

WIN2013

C (~700 days): rate+shape analysis

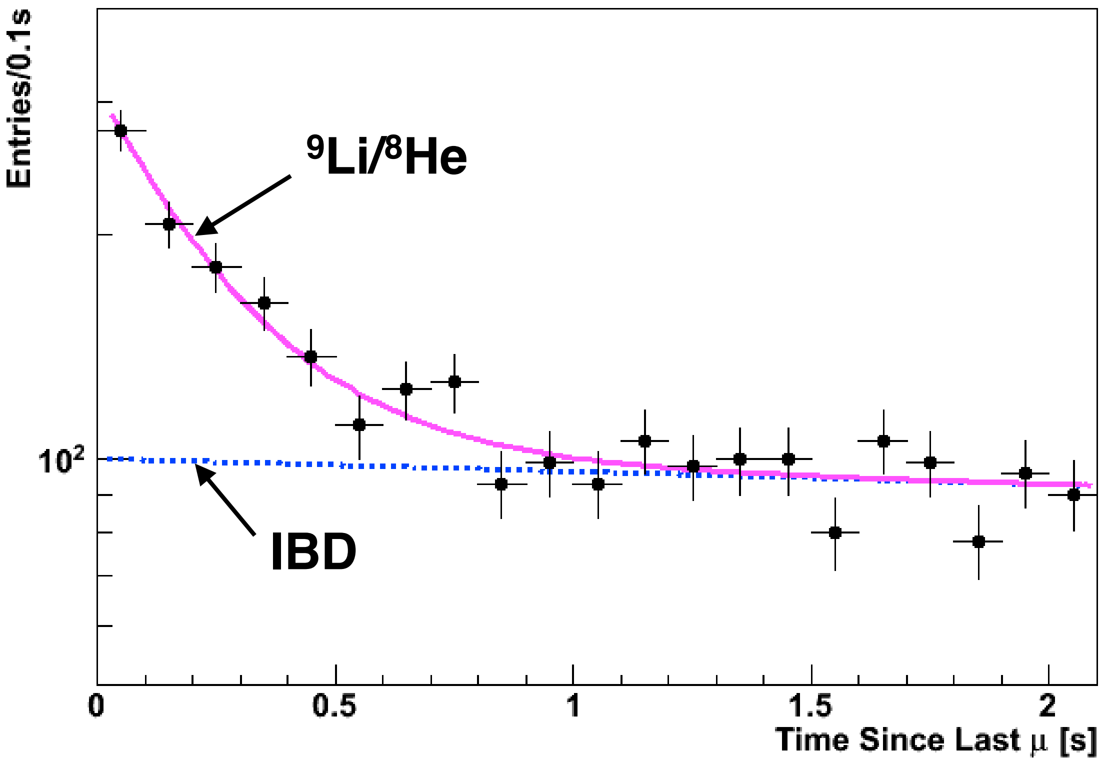
in progress

Absolute reactor neutrino flux measurement in progress [reactor anomaly & sterile neutrinos]

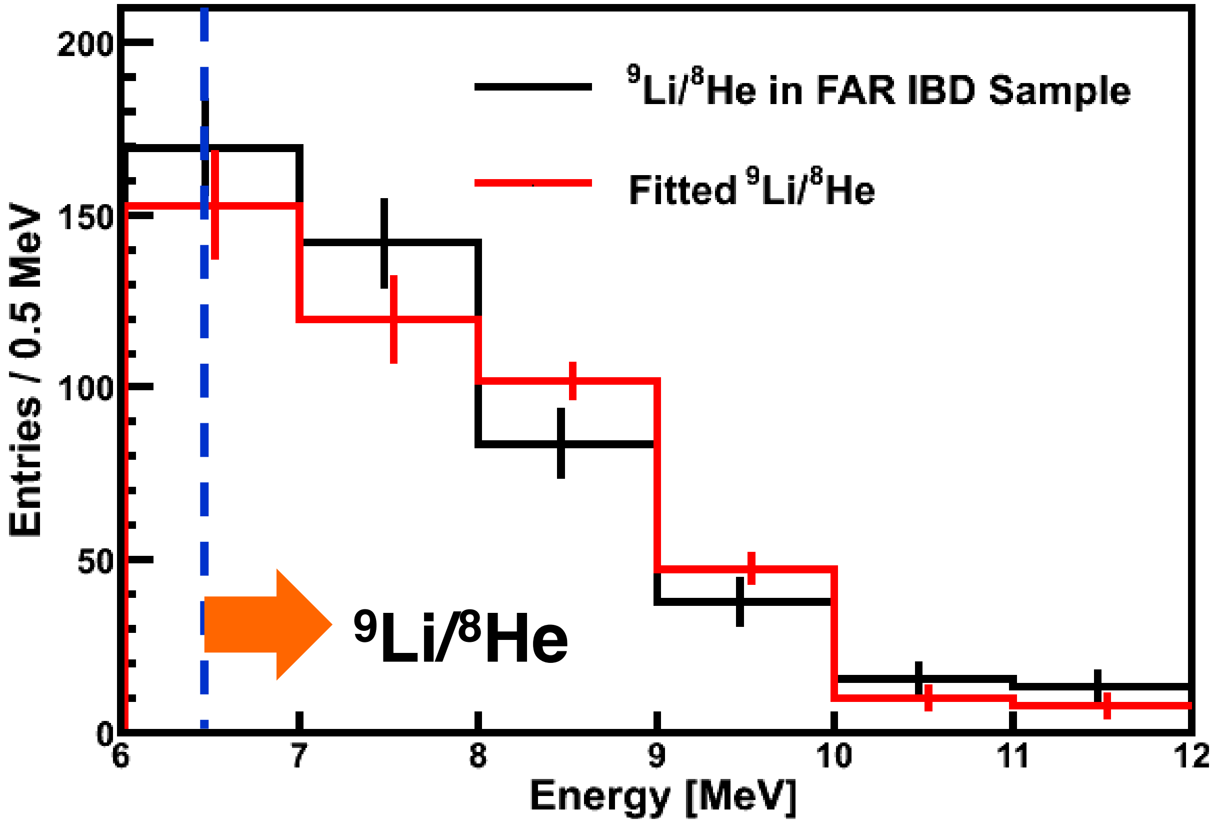


improved ^{9}Li/^{8}He background estimation

- ^{9}Li/^{8}He background estimation has been improved at WIN2013.
  - fit range: 8 MeV → 6.5 MeV
  - increased statistics of BG sample



Fitted shape from bkg. sample matches well within the ^{9}Li/^{8}He shape contained in IBD sample.



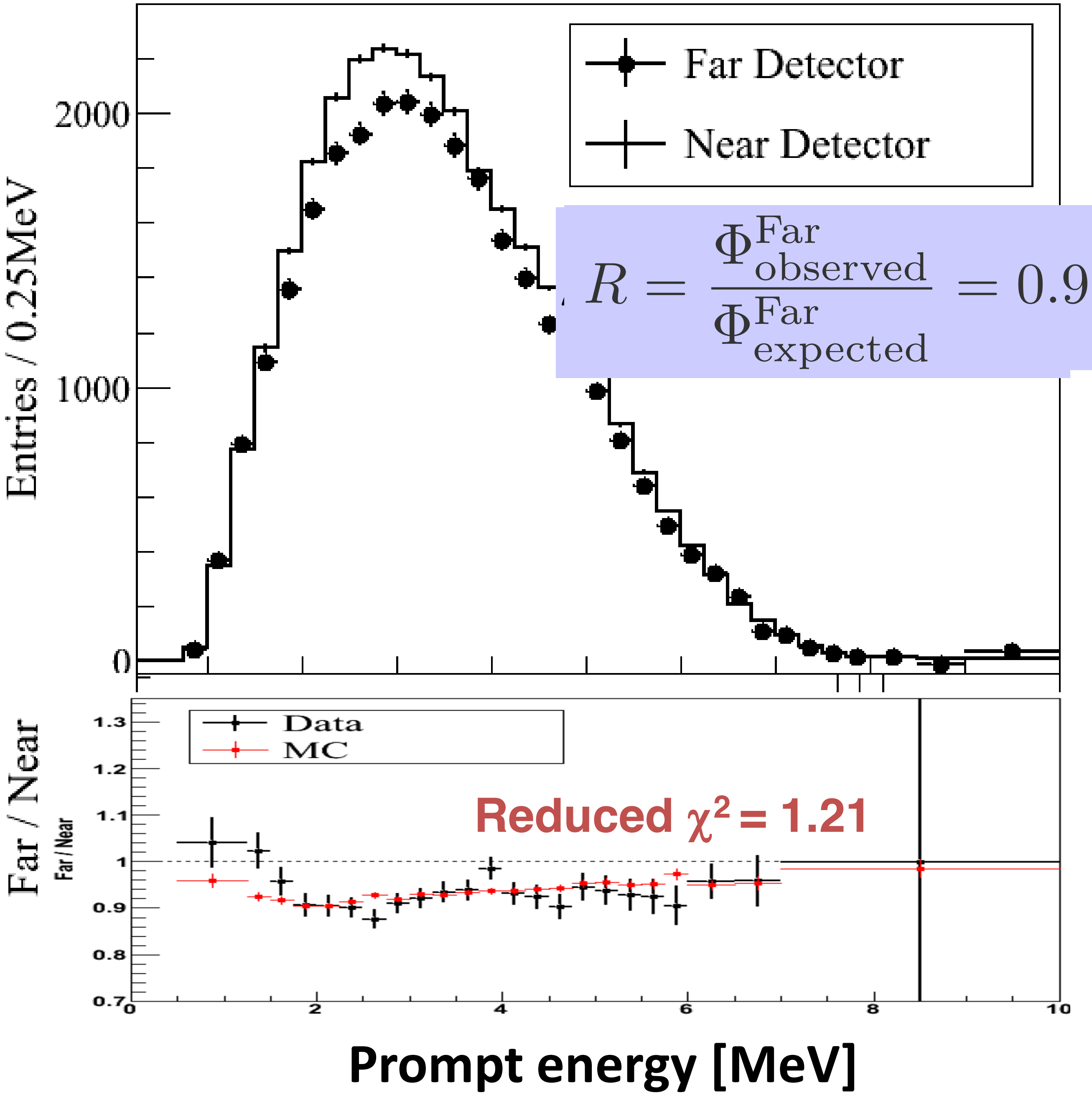
Far

3.61±0.11(stat.)±0.59(sys.) /day
→3.55±0.11(stat.)±0.44(sys.) /day

Near

13.73±0.22(stat.)±2.12(sys.) /day
→13.97±0.22(stat.)±1.52(sys.) /day

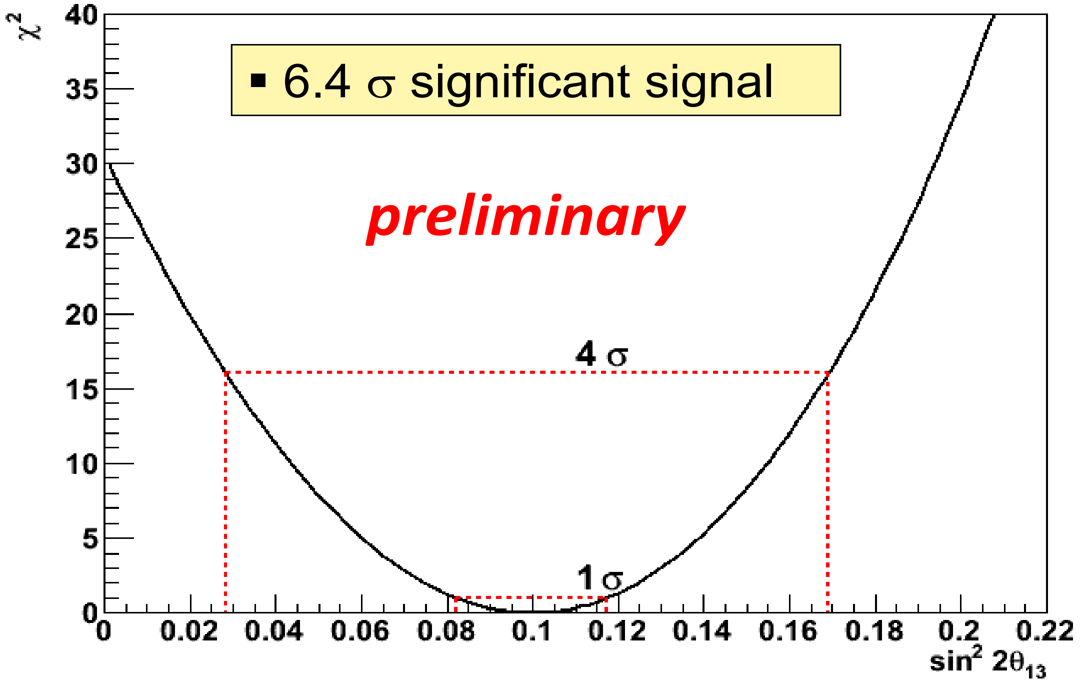
Newest result



preliminary

$$R = \frac{\Phi^{\text{Far}}_{\text{observed}}}{\Phi^{\text{Far}}_{\text{expected}}} = 0.929 \pm 0.006(\text{stat}) \pm 0.007(\text{sys})$$

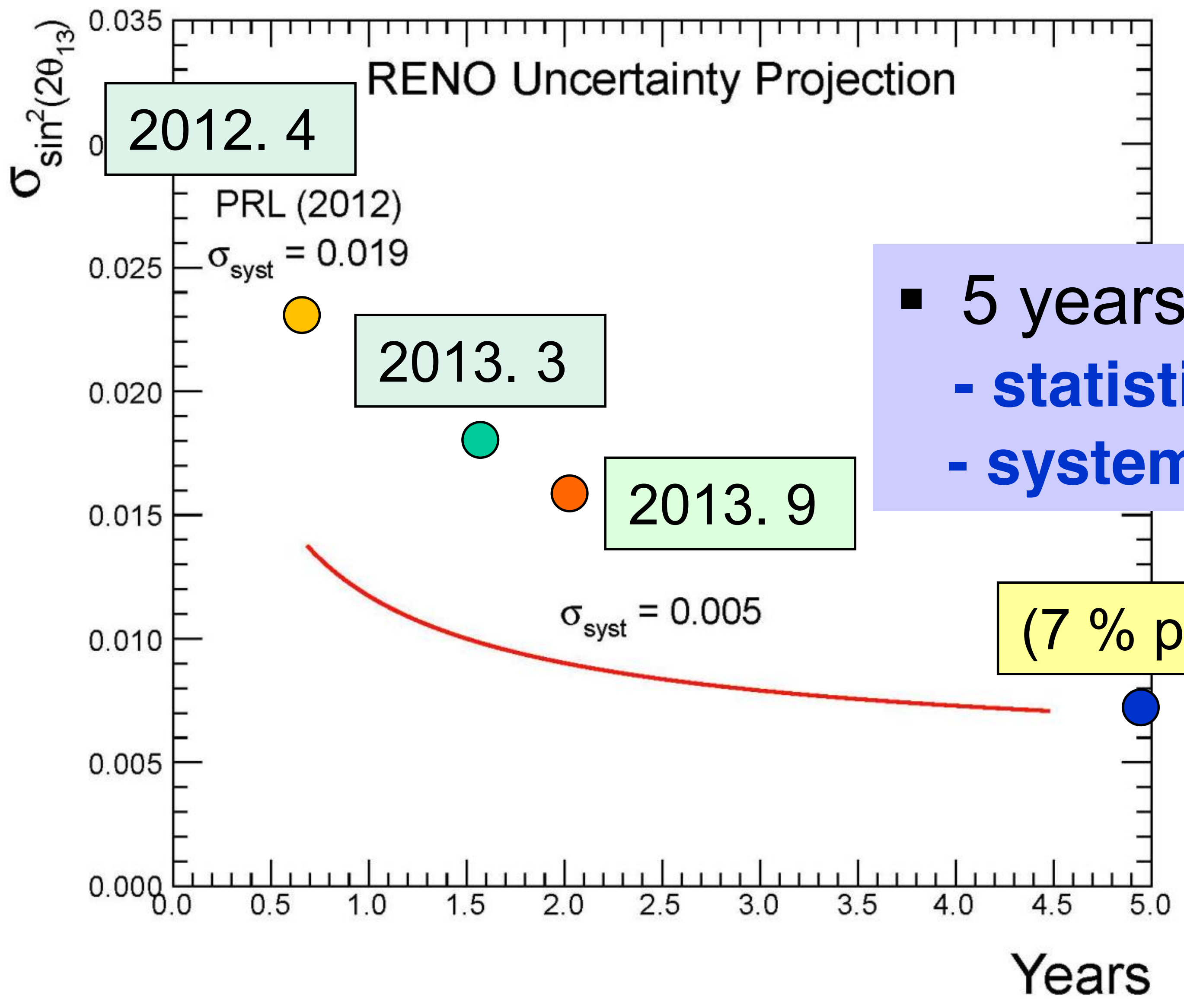
- A clear deficit in rate (~7%)
- Consistent with the neutrino oscillation in the spectral distortion



$\sin^2 2\theta_{13} = 0.100 \pm 0.010(\text{stat.}) \pm 0.012(\text{syst.})$

For more details, see H. Seo's talk @ WIN2013

Prospects from RENO



by H. Seo @ WIN2013

- 5 years of data : ±0.007 (7% precision)
  - **- statistical error : ±0.010 → ±0.005**
  - **- systematic error : ±0.012 → ±0.005**

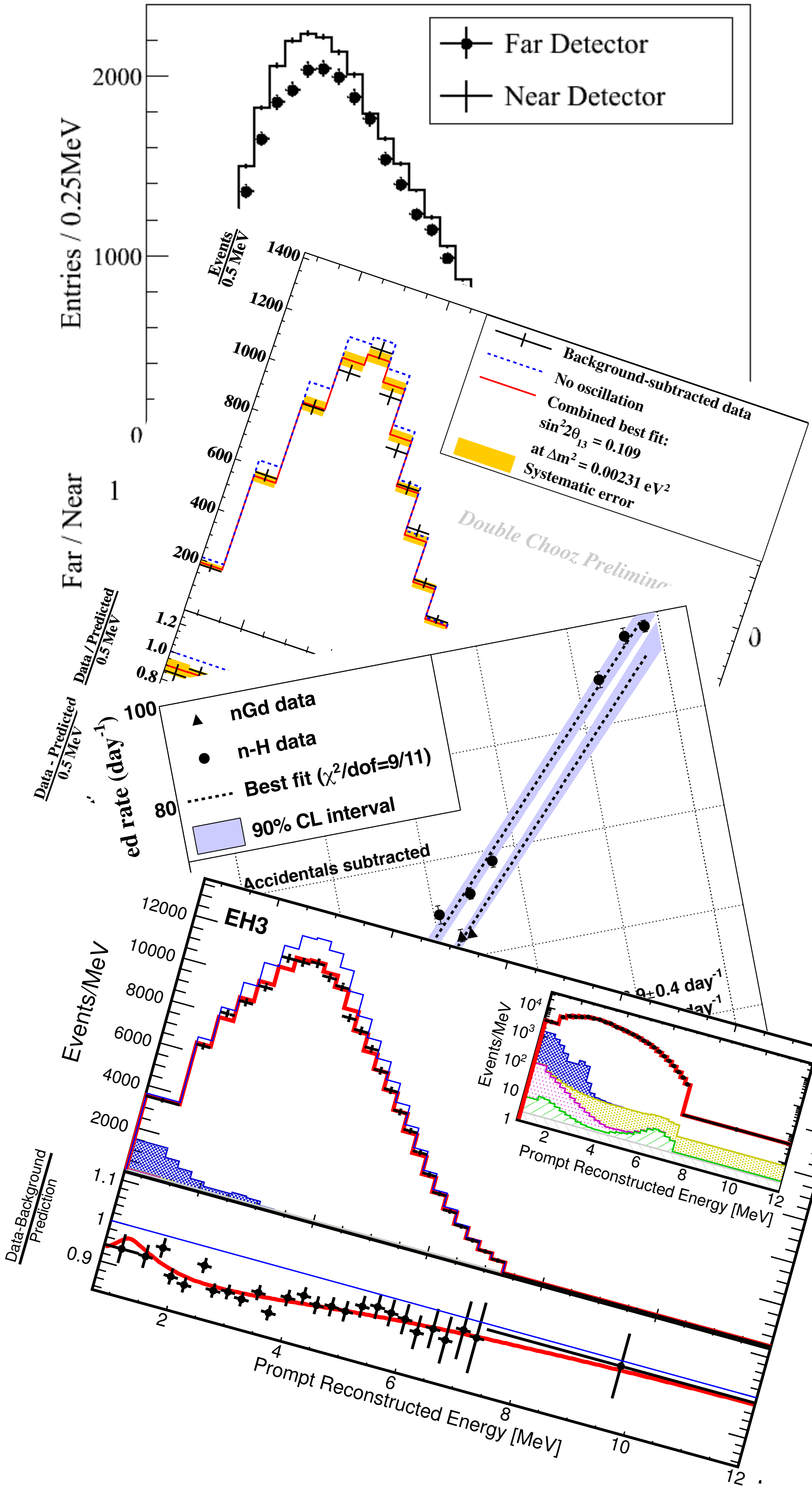
- already collected ~700 live days of reactor neutrino data
  - new θ_{13} result with improved energy calibration and bkg. estimation
  - direct measurement of Δm^2_{31}
  - precise measurement of reactor neutrino flux and spectrum

Summary

Summary

- **Double Chooz** [EPS-HEP2013]
  - Rate+Shape (Gd+H): $\sin^2 2\theta_{13}=0.109\pm0.035$
  - RRM (Gd+H): $\sin^2 2\theta_{13}=0.097\pm0.035$
- **Daya Bay** [NuFact2013]
  - Rate+Shape (Gd): $\sin^2 2\theta_{13}=0.090^{+0.009}_{-0.008}$
- **RENO** [WIN2013]
  - Rate (Gd): $\sin^2 2\theta_{13}=0.100\pm0.016$

- Three experiments are in good agreement.
- Reactor experiments have measured θ_{13} to a precision better than other mixing angles.
- Continuation of current measurements will help CP violation measurements in future accelerator experiments.



backup slides

Comparison between three experiments

The detector setup and analysis strategy is similar between three experiments.

Experiment	**Double Chooz**	**Daya Bay**	**RENO**
# of reactors (total power)	2 (9.4 GW)	3 (17.4 GW)	6 (16.8 GW)
Reactor configuration	2	3	6 inline
Detector configuration	1 near + 1 far	2 near + 1 far	1 near + 1 far
Baseline [m]	(400, 1050)	(364, 480, 1912)	(290, 1380)
Overburden [m.w.e.]	(120, 300)	(280, 300, 880)	(120, 450)
Target mass [ton]	(8.3, 8.3)	(40, 40, 80)	(16, 16)
Detector geometry	Cylindrical detector (Gd-LS, γ-catcher, buffer)		
Outer shield	0.5m of LS & 0.15 m of steel	2.5m water	1.5m of water
Muon veto system	LS & Scinti-Strip	Water Cerenkov & RPC	Water Cerenkov
Designed sensitivity (90% C.L.)	~0.03	~0.01	~0.02

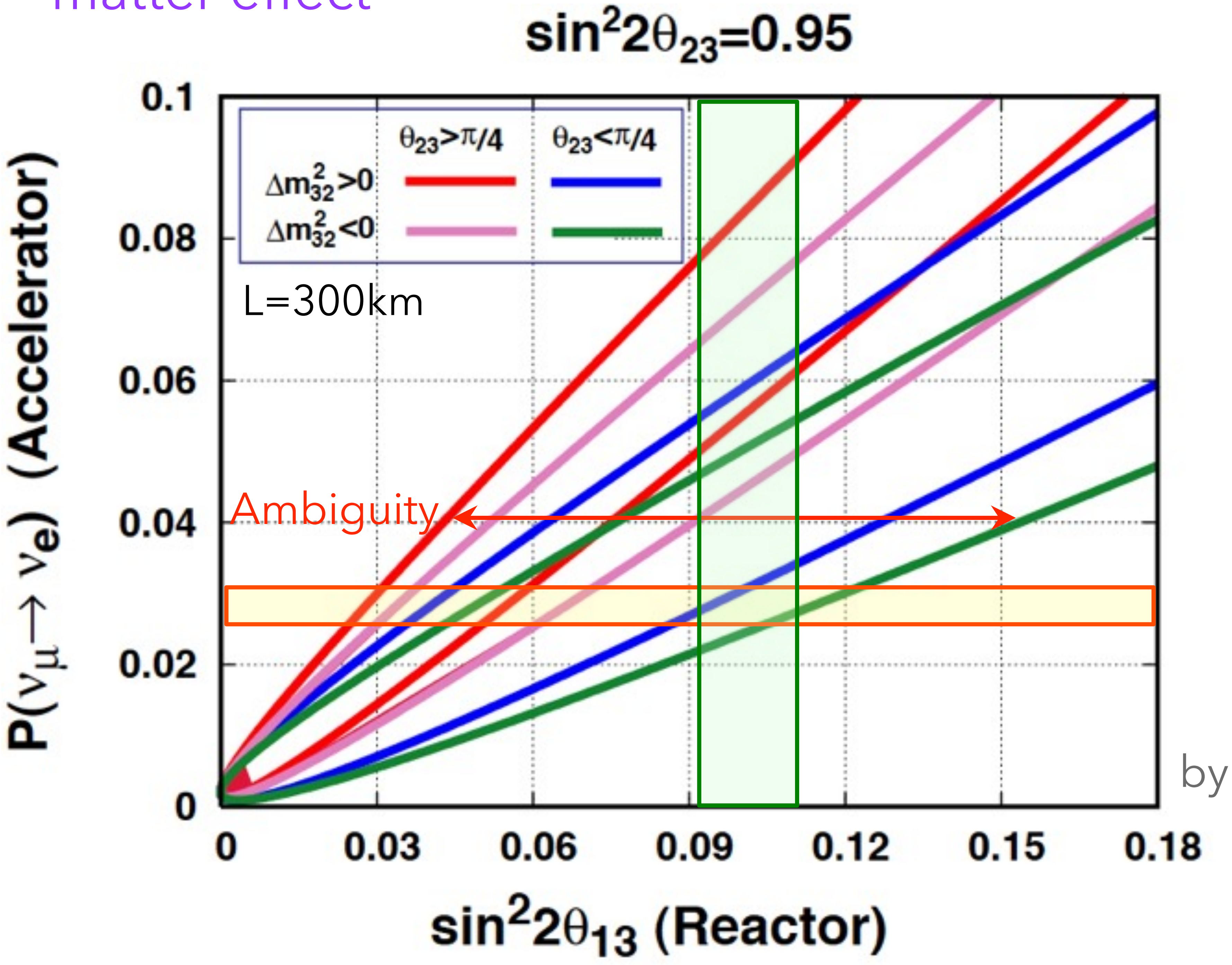
Complementarity with accelerator experiments

θ_{23} degeneracy

$$P_{AC}(\nu_\mu \to \nu_e) = \frac{\boxed{0.50 \pm 0.11}}{(\boxed{1 \mp 0.00017L\ [\mathrm{km}]})^2} \sin^2 2\theta_{13} \boxed{\pm 0.045 \sin 2\theta_{13} \sin \delta}$$

matter effect

δ dependence

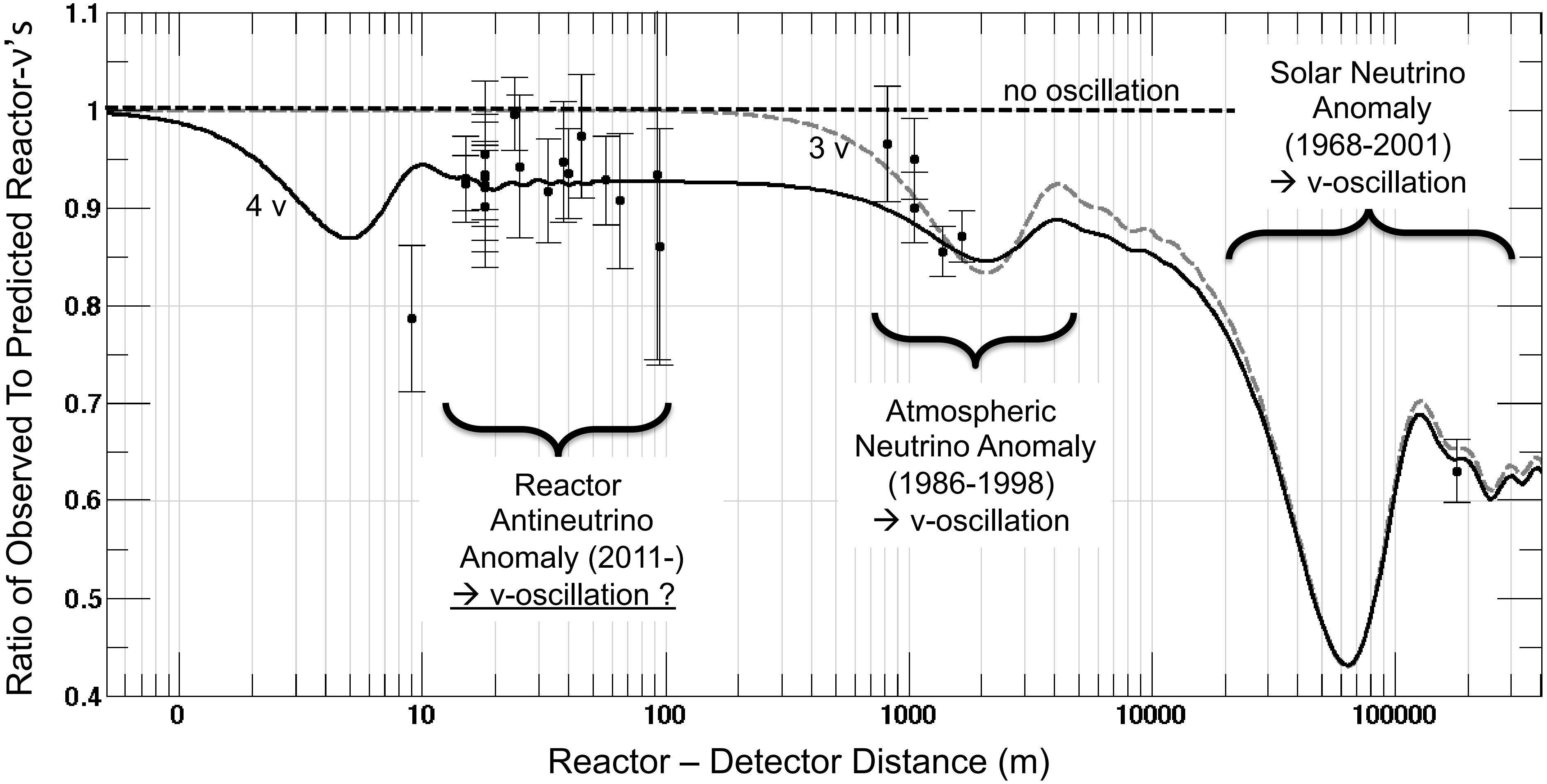


by O. Yasuda

Reactor anomaly

- Reevaluation of reactor $\overline{\nu}_e$ spectra and flux
  - Th. A. Mueller et al., Phys. Rev. C83 (2011) 054615
- Reanalysis of past reactor experiments
  - G. Mention et al., Phys. Rev. D83 (2011) 073006
  - Reactor anomaly 3σ (new physics??)
- Revisited with known θ_{13}
  - C. Zhang et al., arXiv:1303.0900 [nucl-ex]
  - New world average ~1.4σ lower than unity.

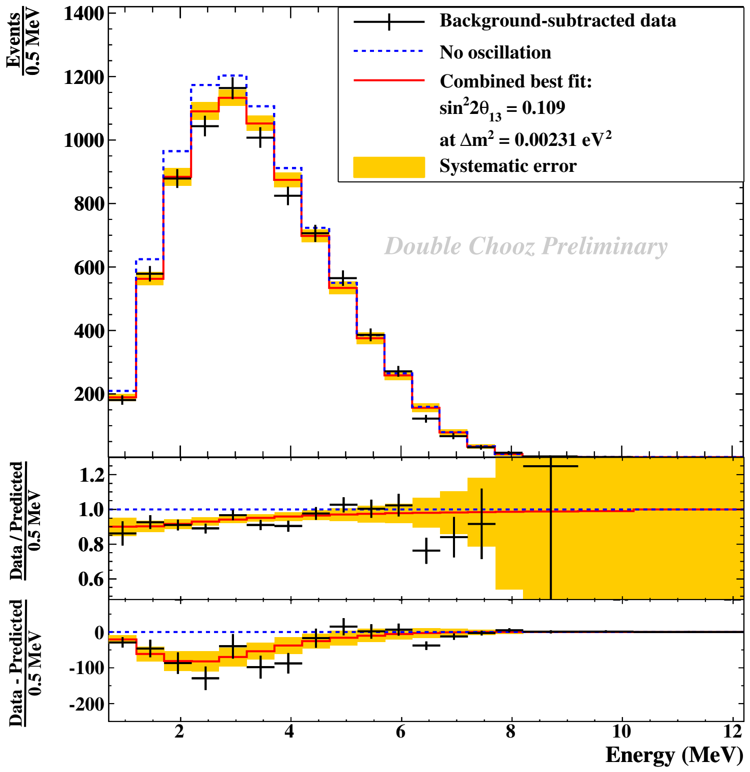
TPC-Paris2012 by Th. Lasserre



Results of three experiments

Double Chooz

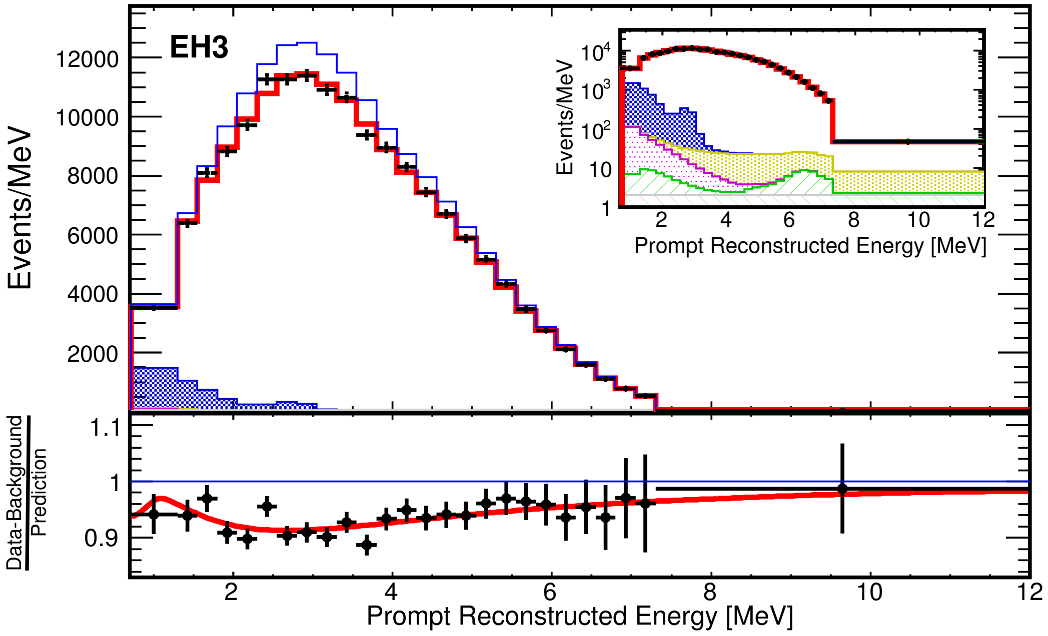
(R+S, Gd+H, EPS-HEP2013)



$\sin^2 2\theta_{13} = 0.109 \pm 0.035$

Daya Bay

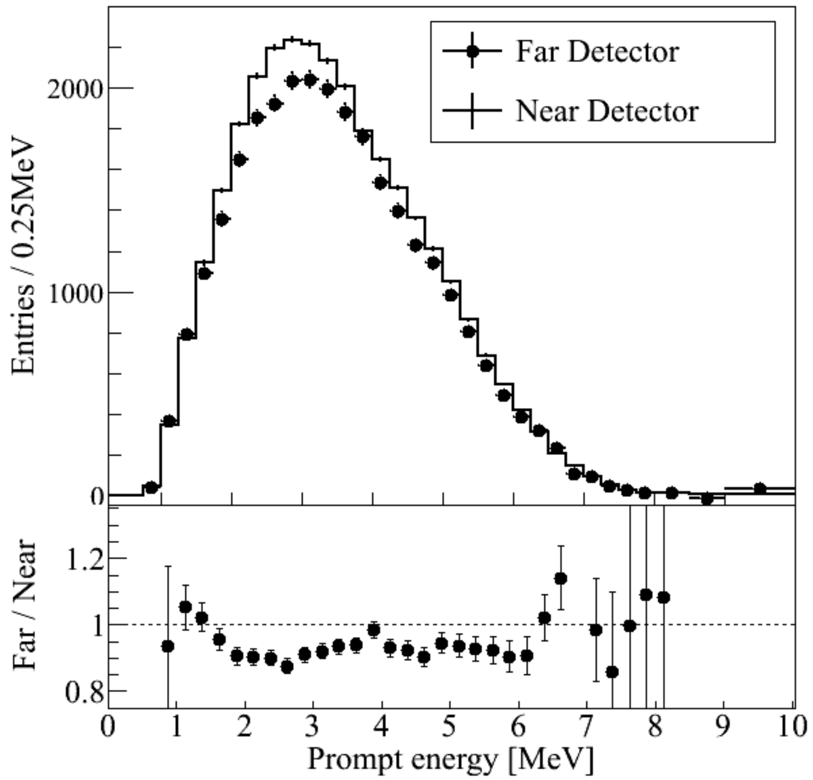
(R+S, NuFact2013)



$\sin^2 2\theta_{13} = 0.090^{+0.009}_{-0.008}$

RENO

(Rate only, WIN2013)



$\sin^2 2\theta_{13} = 0.100 \pm 0.016$

- θ_{13} has been measured precisely. (<10% precision)
  - c.f. θ_{23} error is ~13%.

Comparison between θ_{13} measurements

modified from DayaBay's talk in NuFact 2013

●— Best Fit + 68% C.L.

Accelerator Experiments*

■— Normal Hierarchy

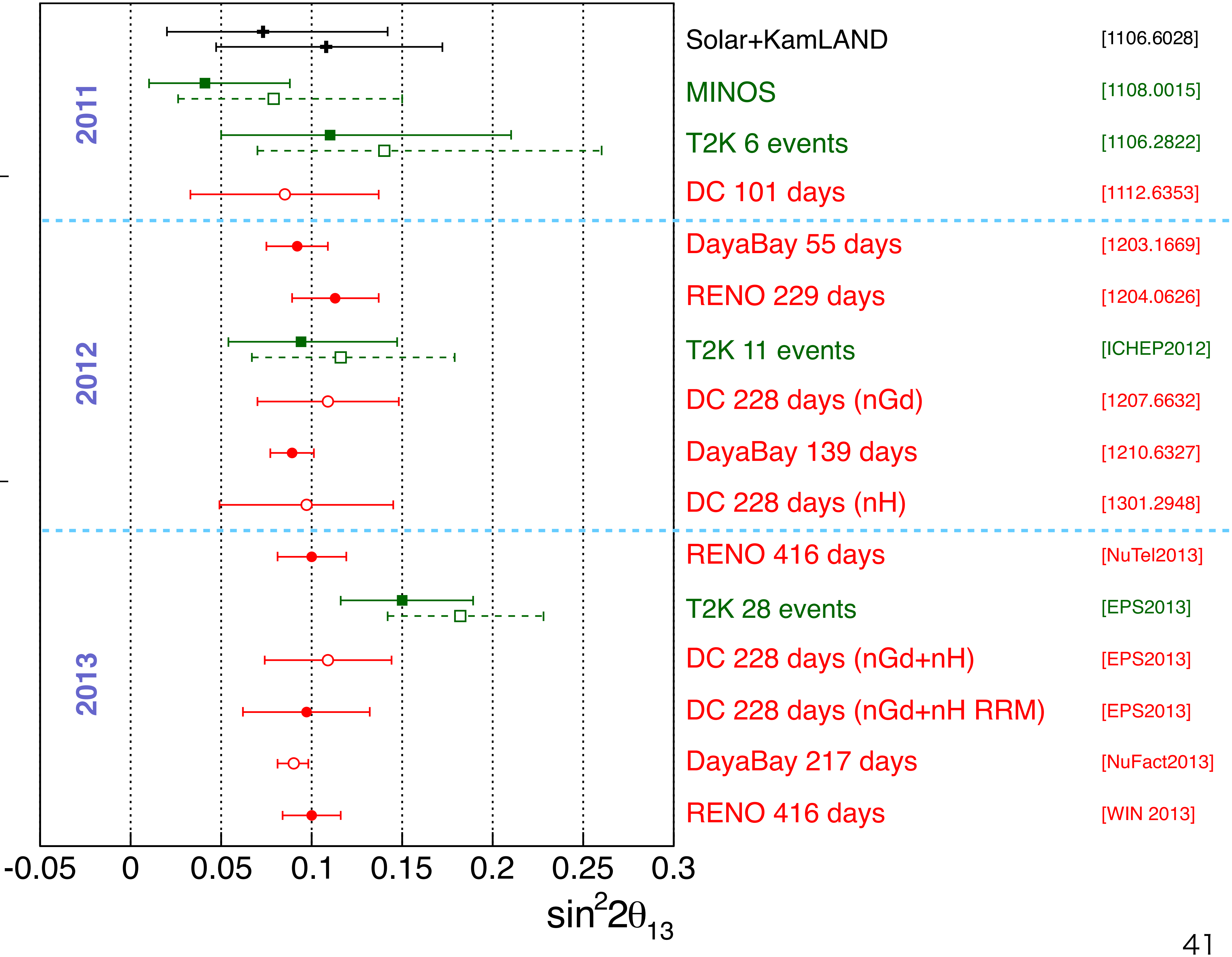
□- - Inverted Hierarchy

*All results assuming: $\delta_{CP}=0$, $\theta_{23}=45°$

Reactor Experiments

● Rate only

○ Rate+Shape



Backup slides for Double Chooz

Double Chooz collaboration

Brazil

CBPF
UNICAMP
UFABC

France

APC
CEA/DSM/IRFU:
- SPP
- SPhN
- SEDI
- SIS
- SENAC

CNRS/IN2P3:
- Subatech
- IPHC

Germany

EKU Tübingen
MPIK Heidelberg
RWTH Aachen
TU München
U. Hamburg

Japan

Tohoku U.
Tokyo Inst. Tech.
Tokyo Metro. U.
Niigata U.
Kobe U.
Tohoku Gakuin U.
Hiroshima Inst. Tech.

Russia

INR RAS
IPC RAS
RRC Kurchatov

Spain

CIEMAT-Madrid

USA

U. Alabama
ANL
U. Chicago
Columbia U.
UCDavis
Drexel U.
IIT
KSU
LLNL
MIT
U. Notre Dame
U. Tennessee

Spokesperson:
H. de Kerret (IN2P3)

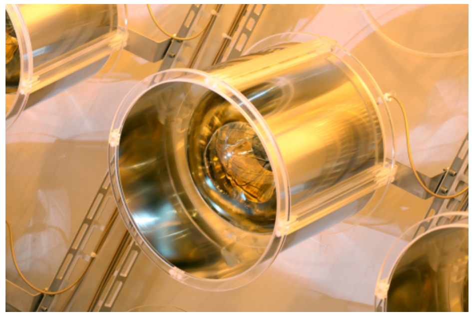
Project Manager:
Ch. Veyssière (CEA-Saclay)

Web Site:
www.doublechooz.org/

~150 scientists from 7 countries

Double Chooz Electronics

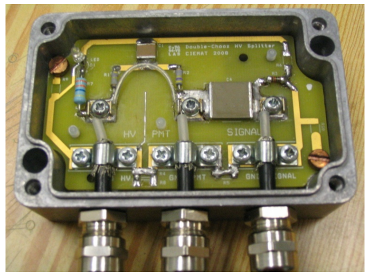
Photo-multiplier tubes
ID : 390 PMTs (R7081MOD)
IV : 78 PMTs (R1408)



HV

Signal

HV/sig. splitter
Custom (by CIEMAT)

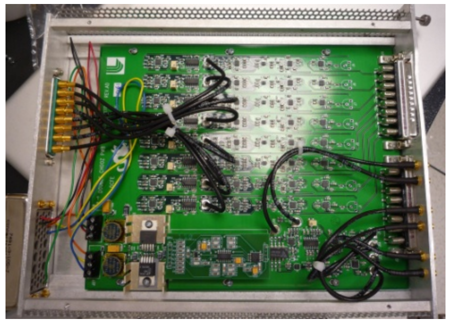


HV

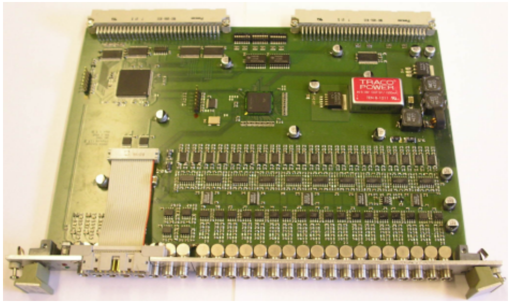
HV supply
SY1527LC & A1535P (CAEN)

Signal

Front-end electronics
Custom (by Drexel Univ. & LLNL)



Trigger & clock
Custom (by RWTH-Aachen)

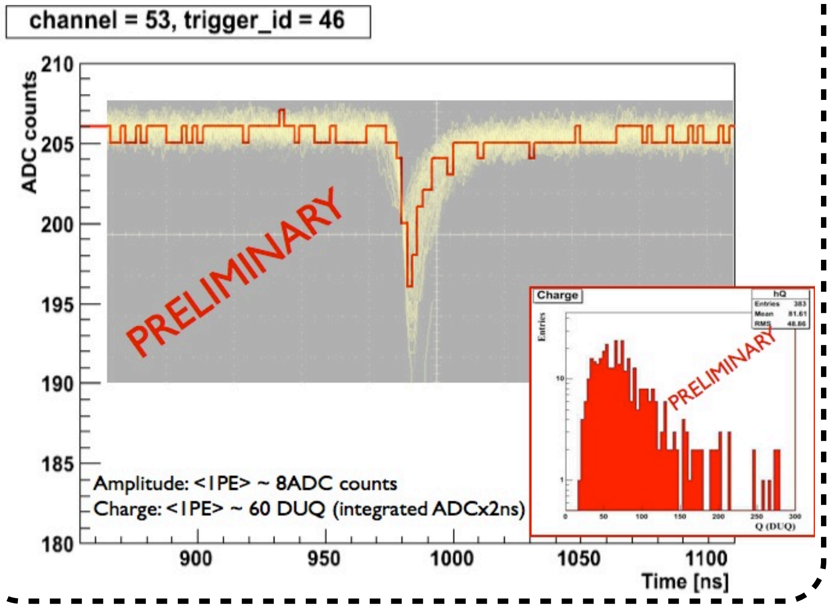


Trigger pattern
& clock (T=16 ns)

ν-FADC VX1721 (by CAEN & APC)
μ-FADC Custom (by CBPF)

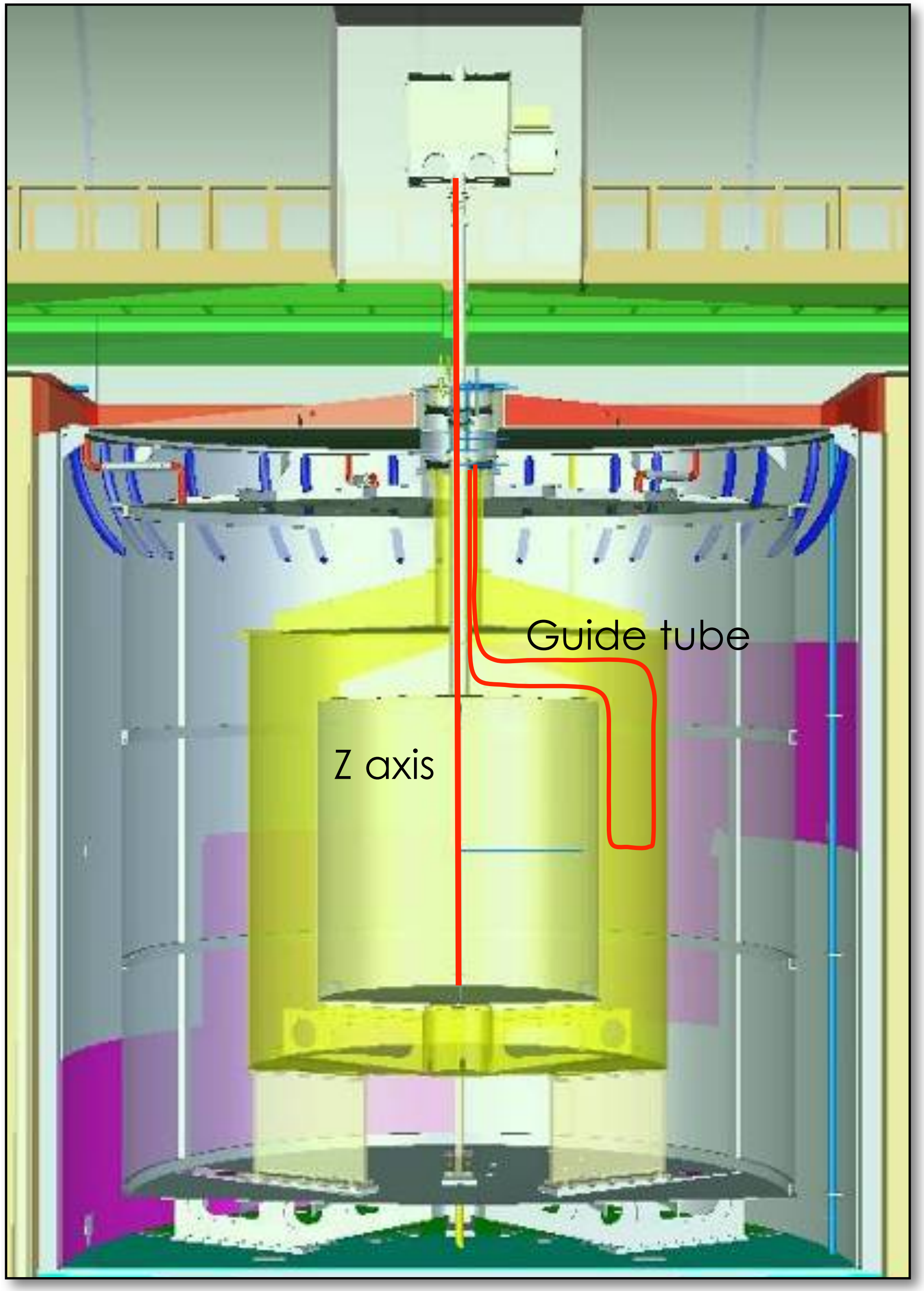
ν-DAQ
MVME3100 (by Emerson)
implemented in Ada

Flash-ADC signal example



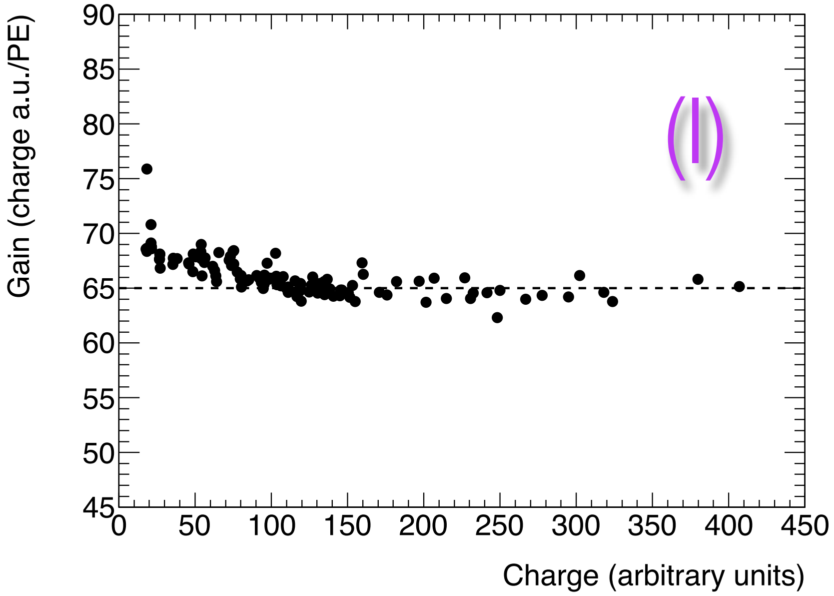
Calibration

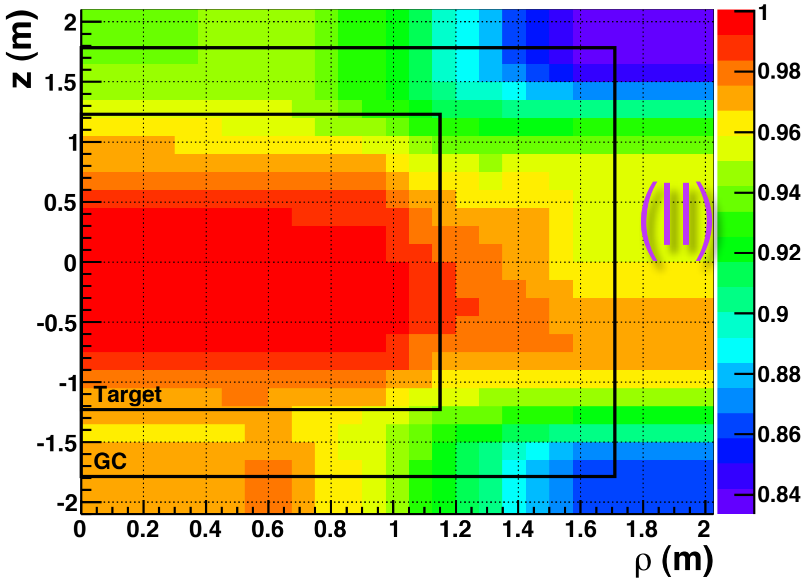
- Light injection in ID and IV:
  - monitor stability of readout (timing & gain) and scintillator
- Radioactive sources:
  - Sources deployed in Z-axis in target and guide tube in GC
  - ^{137}Cs, ^{68}Ge, ^{60}Co, ^{252}Cf for E-scale and neutron detection efficiency
- Spallation neutrons generated by cosmic-rays

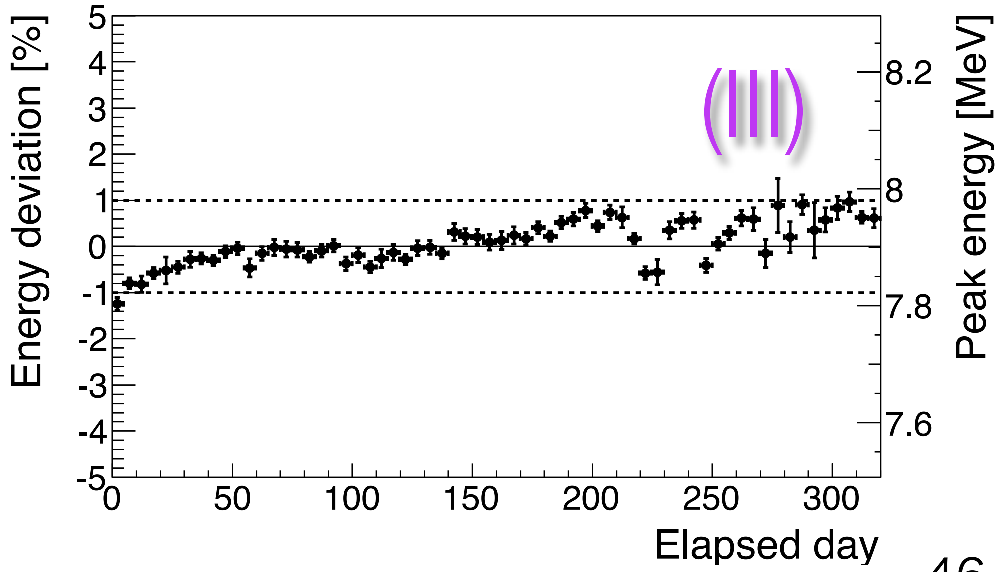


Energy reconstruction

- Charge to PE (I)
  - Gain nonlinearity correction
- Detector nonuniformity correction (II)
  - Response maps of cosmogenic neutron captures on H across volume
- Time instability correction (III)
  - Using cosmogenic neutron captures on Gd peak variation
- Absolute MeV scale (PE/MeV)
  - H capture peak from ^{252}Cf at center of target







Neutrino selection

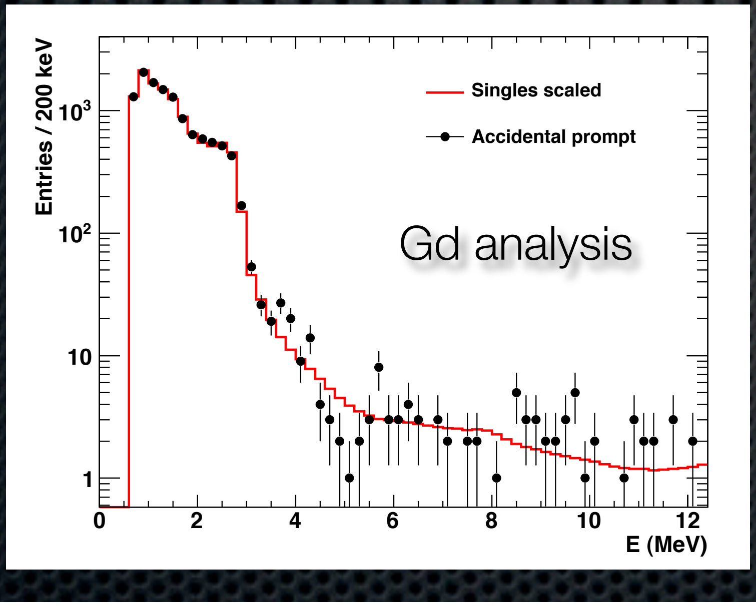
	Gd analysis	H analysis
Muon veto	$\Delta t > 1$ ms	
Light noise rejection	$Q_{max}/Q_{tot} < 0.09$ (0.055) & RMS(T_{start}) < 40 ns	
E_{prompt}	0.7-12.2 MeV	
$E_{delayed}$	6.0-12.0 MeV	1.5-3.0 MeV
ΔT	2-100 μs	10-600 μs
Δd	—	< 0.9 m
Multiplicity	No additional triggers around signal	
OV veto	No OV hit coincident with prompt	—
Showering muon veto	Δt_{μ} ($E_{\mu} > 600$ MeV) > 0.5 s	—

Background estimation

by I. Gil Bottera @ PACT-IFT workshop

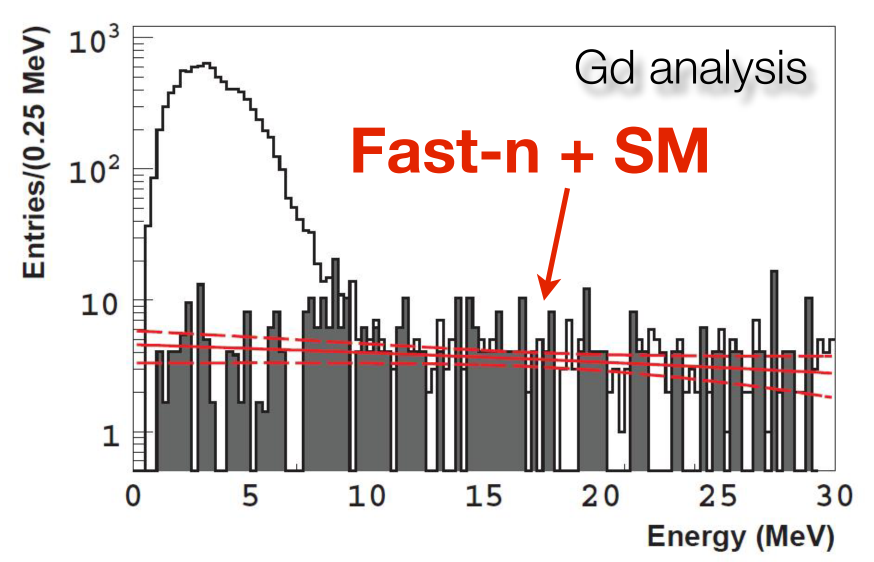
Accidentals:

- Stable along data taking period
- Determined by off-time window
  - Gd: 0.261 ± 0.002 evts/day
  - H: 73.5 ± 0.2 evts/day
- Rate and shape: data-driven



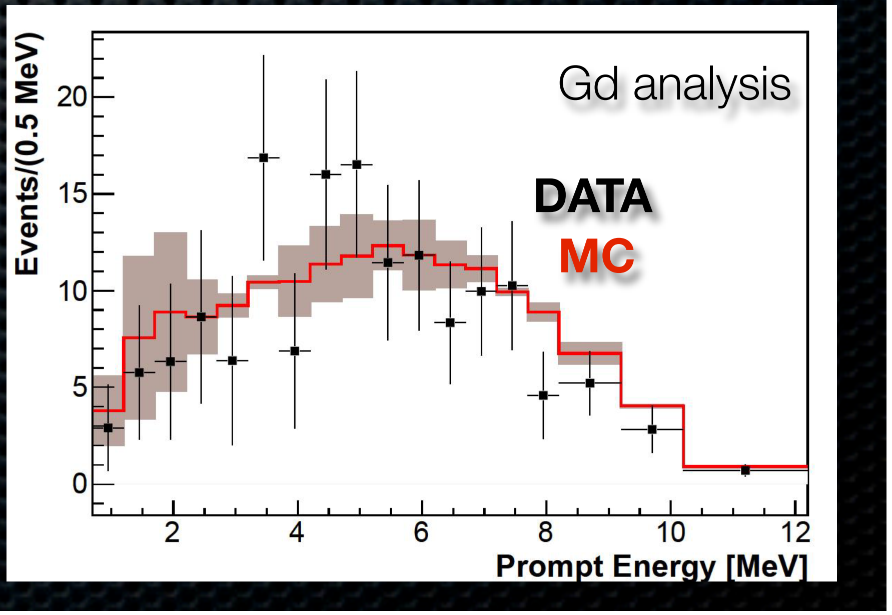
Fast-n and stopping μ's:

- Prompt energy extended up to 30 MeV
- Rate: IV-tagged events
  - Gd: 0.67 ± 0.20 evts/day
  - H: 2.5 ± 0.5 evts/day
- Shape: from fit to tagged events



Cosmogenic background:

- ^{9}Li rate from Δt between showering muon and prompt event
  - Gd: 1.25 ± 0.54 evts/day
  - H: 2.8 ± 1.2 evts/day
- Energy spectrum from MC (poorly known)



Reactor neutrino flux prediction

by I. Gil Bottera @ PACT-IFT workshop

Dominant source of systematic errors in DC phase-I

Expected neutrino flux

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

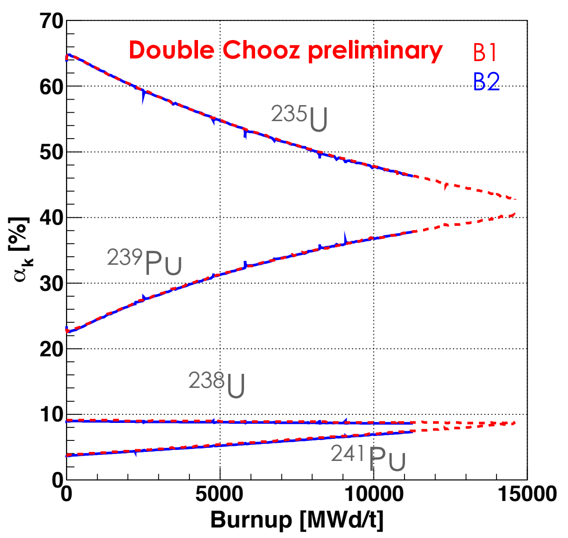
- ε = detection efficiency
- N_p = number of protons in fiducial volume
- L = distance between reactor and far detector
- $P_{th}(t)$ = thermal power of reactor

Average energy per fission:

$$\langle E_f \rangle = \sum_k \alpha_k(t) \langle E_k \rangle$$ (from EdF & simulations)

$\alpha_k(t)$ = **fractional fission rate** of k isotope

k = ^{235}U, ^{238}U, ^{239}Pu, ^{241}Pu

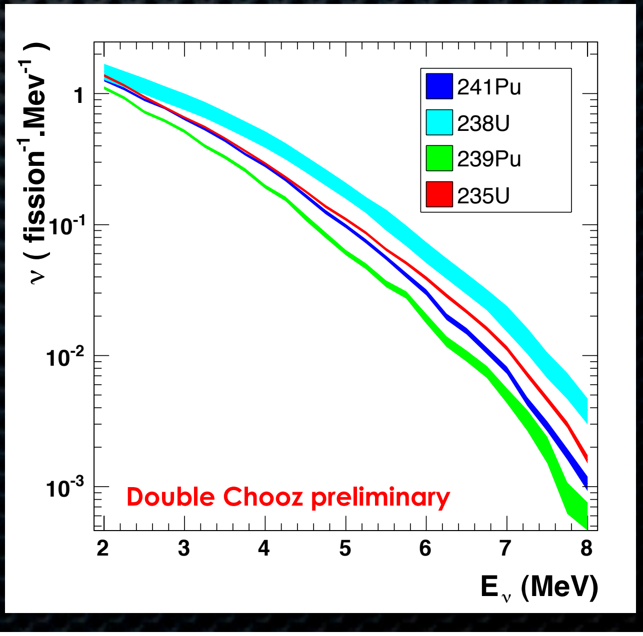


Average cross section per fission:

→ anchored to Bugey4 measurement at L=15m

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

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



Summary of background events

	Gd analysis	H analysis
Livetime (days)	227.93	240.1
IBD candidates	8249	36284
Neutrino prediction (no-osc)	8439.6	17690
Cosmogenic isotopes	284.9	680
Correlated Fast-n + SM	152.7	600
Accidentals	59.5	17630
Light noise	—	80
Total prediction	8936.7	36680

Uncertainties

- Normalisation uncertainties (relative to signal):

	Gd analysis	H analysis
Statistical error	1.1%	1.1%
Reactor antineutrino flux	1.7%	1.7%
Efficiency	1.0%	1.6%
^{9}Li rate	1.4%	1.6%
Correlated Fast-n + SM rate	0.5%	0.6%
Accidental rate	<0.1%	0.2%
Light noise	—	0.1%
Total	2.7%	3.1%

- Spectrum shape uncertainties:
  - Reactor anti-ν_e spectrum
  - Energy scale
  - Background spectrum (^{9}Li and Fast neutron+SM)

Predicted neutrino spectrum

$$N_i = \frac{\epsilon N_p}{4\pi}\sum_R \frac{1}{L_R^2}\frac{P_{th}^R}{\langle E_f\rangle_R}\left(\boxed{\frac{\langle\sigma_f\rangle_R}{\sum_k \alpha_k^R\langle\sigma_f\rangle_k}}\sum_k \alpha_k^R\langle\sigma_f\rangle_k^i\right)$$

Bugey4 “anchor”: $\langle\sigma_f\rangle_R = \langle\sigma_f\rangle_{\mathrm{Bugey}} + \sum_k(\alpha_k - \alpha_k^{\mathrm{Bugey}})\langle\sigma_f\rangle_k$

scales predicted $\langle\sigma_f\rangle$ to match $\langle\sigma_f\rangle$ at L=15m,
removing sensitivity to $\Delta m^2 \sim 1\,\mathrm{eV}^2$ oscillations.

R = {Reactor 1, Reactor 2}
k = {^{235}U, ^{238}U, ^{239}Pu, ^{241}Pu}

ϵ = detection efficiency
N_p = number of protons in fiducial volume
L_R = distance between Rth reactor and far detector
P_{th}^R = thermal power of Rth reactor (time-dependent)
$\langle E_f\rangle_R$ = mean energy per fission in Rth reactor (time-dependent)
$\langle\sigma_f\rangle_R$ = mean cross section per fission in Rth reactor (time-dependent)
α_k^R = fission fraction for kth isotope in Rth reactor (time-dependent)
$\langle\sigma_f\rangle_k$ = mean cross section per fission of kth isotope
$\langle\sigma_f\rangle_k^i$ = mean cross section per fission of kth isotope in ith energy bin

χ^2 definition for combined Gd+H fit

$$
\begin{aligned}
\chi^2 = & \sum_{i,j}^{B} (N_i^{\mathrm{obs}} - N_i^{\mathrm{pred}}) M_{ij}^{-1} (N_j^{\mathrm{obs}} - N_j^{\mathrm{pred}}) \\
& + \frac{(\Delta m^2 - \Delta m^2_{\mathrm{MINOS}})^2}{\sigma^2_{\mathrm{MINOS}}} \\
& + \left[\begin{array}{cccccc} \alpha_{\mathrm{Li}}^{\mathrm{Gd}} - 1 & \alpha_{\mathrm{fn}}^{\mathrm{Gd}} - 1 & \alpha_{E}^{\mathrm{Gd}} - 1 & \alpha_{\mathrm{Li}}^{\mathrm{H}} - 1 & \alpha_{\mathrm{fn}}^{\mathrm{H}} - 1 & \alpha_{E}^{\mathrm{H}} - 1 \end{array} \right] \\
& \times \left[\begin{array}{cccccc}
(\sigma_{\mathrm{Li}}^{\mathrm{Gd}})^2 & 0 & 0 & \rho_{\mathrm{Li}} \sigma_{\mathrm{Li}}^{\mathrm{Gd}} \sigma_{\mathrm{Li}}^{\mathrm{H}} & 0 & 0 \\
0 & (\sigma_{\mathrm{fn}}^{\mathrm{Gd}})^2 & 0 & 0 & \rho_{\mathrm{fn}} \sigma_{\mathrm{fn}}^{\mathrm{Gd}} \sigma_{\mathrm{fn}}^{\mathrm{H}} & 0 \\
0 & 0 & (\sigma_{E}^{\mathrm{Gd}})^2 & 0 & 0 & \rho_{E} \sigma_{E}^{\mathrm{Gd}} \sigma_{E}^{\mathrm{H}} \\
\rho_{\mathrm{Li}} \sigma_{\mathrm{Li}}^{\mathrm{H}} \sigma_{\mathrm{Li}}^{\mathrm{Gd}} & 0 & 0 & (\sigma_{\mathrm{Li}}^{\mathrm{H}})^2 & 0 & 0 \\
0 & \rho_{\mathrm{fn}} \sigma_{\mathrm{fn}}^{\mathrm{H}} \sigma_{\mathrm{fn}}^{\mathrm{Gd}} & 0 & 0 & (\sigma_{\mathrm{fn}}^{\mathrm{H}})^2 & 0 \\
0 & 0 & \rho_{E} \sigma_{E}^{\mathrm{H}} \sigma_{E}^{\mathrm{Gd}} & 0 & 0 & (\sigma_{E}^{\mathrm{H}})^2
\end{array} \right]^{-1} \\
& \times \left[\begin{array}{cccccc} \alpha_{\mathrm{Li}}^{\mathrm{Gd}} - 1 & \alpha_{\mathrm{fn}}^{\mathrm{Gd}} - 1 & \alpha_{E}^{\mathrm{Gd}} - 1 & \alpha_{\mathrm{Li}}^{\mathrm{H}} - 1 & \alpha_{\mathrm{fn}}^{\mathrm{H}} - 1 & \alpha_{E}^{\mathrm{H}} - 1 \end{array} \right]^{T} \\
& + \left[\begin{array}{cc} \alpha_{\mathrm{Li}}^{\mathrm{Gd}} R_{\mathrm{Li}}^{\mathrm{Gd,pred}} + \alpha_{\mathrm{fn}}^{\mathrm{Gd}} R_{\mathrm{fn}}^{\mathrm{Gd,pred}} - R_{\mathrm{off}}^{\mathrm{Gd}} & \alpha_{\mathrm{Li}}^{\mathrm{H}} R_{\mathrm{Li}}^{\mathrm{H,pred}} + \alpha_{\mathrm{fn}}^{\mathrm{H}} R_{\mathrm{fn}}^{\mathrm{H,pred}} - R_{\mathrm{off}}^{\mathrm{H}} \end{array} \right] \\
& \times \left[\begin{array}{cc} (\sigma_{\mathrm{off}})^2 & \rho_{\mathrm{off}} \sigma_{\mathrm{off}}^{\mathrm{Gd}} \sigma_{\mathrm{off}}^{\mathrm{H}} \\ \rho_{\mathrm{off}} \sigma_{\mathrm{off}}^{\mathrm{H}} \sigma_{\mathrm{off}}^{\mathrm{Gd}} & (\sigma_{\mathrm{off}}^{\mathrm{H}})^2 \end{array} \right]^{-1} \times \left[\begin{array}{c} \alpha_{\mathrm{Li}}^{\mathrm{Gd}} R_{\mathrm{Li}}^{\mathrm{Gd,pred}} + \alpha_{\mathrm{fn}}^{\mathrm{Gd}} R_{\mathrm{fn}}^{\mathrm{Gd,pred}} - R_{\mathrm{off}}^{\mathrm{Gd}} \\ \alpha_{\mathrm{Li}}^{\mathrm{H}} R_{\mathrm{Li}}^{\mathrm{H,pred}} + \alpha_{\mathrm{fn}}^{\mathrm{H}} R_{\mathrm{fn}}^{\mathrm{H,pred}} - R_{\mathrm{off}}^{\mathrm{H}} \end{array} \right]
\end{aligned}
$$

Inner product with covariance matrix,
as defined on previous slide

Mass splitting pull term

Correlated pull terms on
background rates and energy scale

Reactor-off rate constraints

χ^2 definition for individual Gd and H fits

$$\chi^2_{\mathrm{Rate+Shape}} = \sum_{i,j}^{B} (N_i^{\mathrm{obs}} - N_i^{\mathrm{pred}}) M_{ij}^{-1} (N_j^{\mathrm{obs}} - N_j^{\mathrm{pred}})^T$$

$$+ \frac{(\alpha_{\mathrm{Li}} - 1)^2}{\sigma^2_{\mathrm{Li}}} + \frac{(\alpha_{\mathrm{FNSM}} - 1)^2}{\sigma^2_{\mathrm{FNSM}}} + \frac{(\alpha_E - 1)^2}{\sigma^2_E}$$

$$+ \frac{(\Delta m^2 - \Delta m^2_{\mathrm{MINOS}})^2}{\sigma^2_{\mathrm{MINOS}}}$$

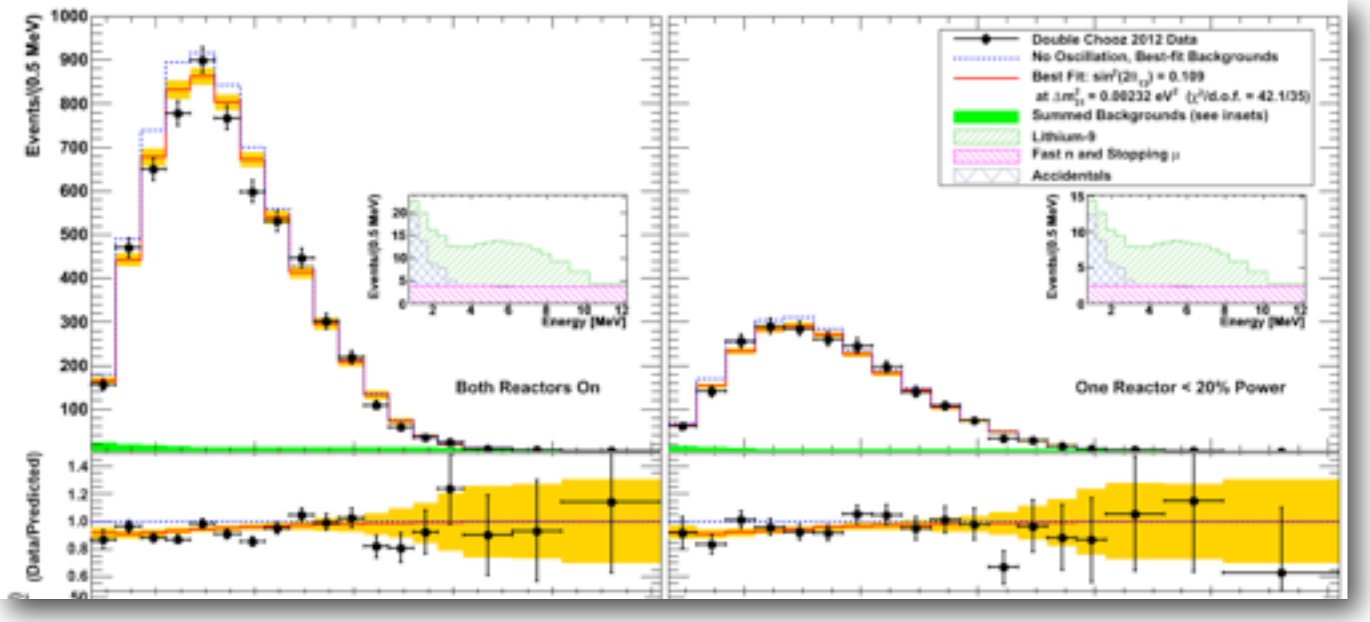
with covariant matrix:

$$M = M_{\mathrm{stat}} + M_{\mathrm{reactor}} + M_{\mathrm{acc}} + M_{\mathrm{corr\ LN}} + M_{\mathrm{Li\ shape}} + M_{\mathrm{FNSM\ shape}}$$

Some results from Double Chooz

θ_{13} analysis (Gd capture)

Phys.Rev.D86 (2012) 052008.

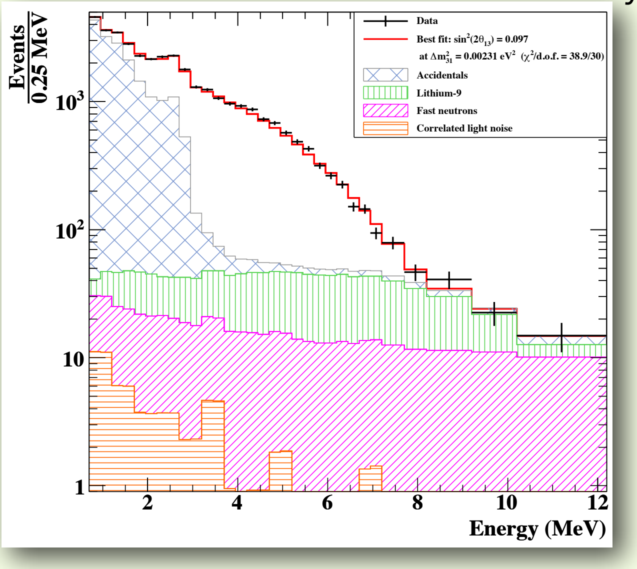


$\sin^2 2\theta_{13} = 0.109 \pm 0.030 \pm 0.025$

θ_{13} on Hydrogen capture

Independent signal $n+p \rightarrow d+\gamma$ (2.2 MeV)

Phys.Lett.B 723 (2013) 66-70.

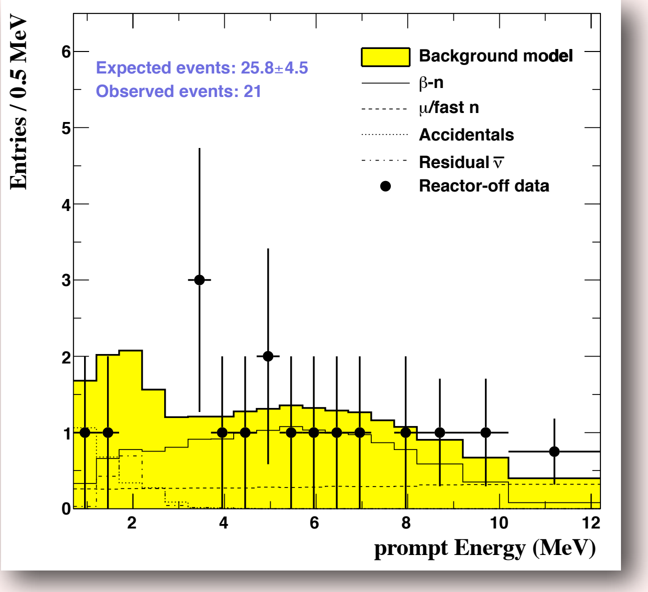


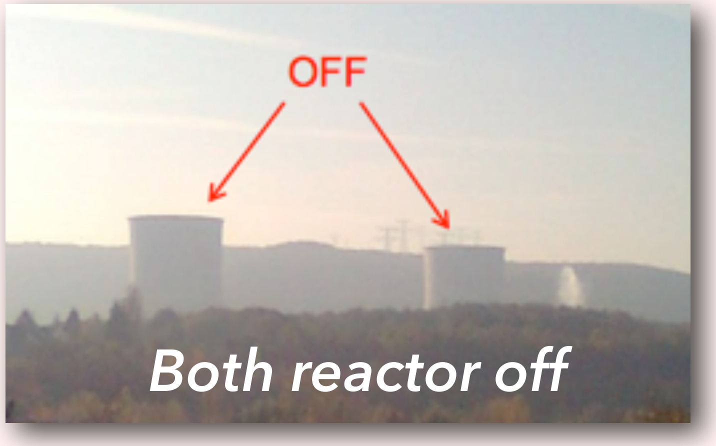
$\sin^2 2\theta_{13} = 0.097 \pm 0.034 \pm 0.034$

Reactor Off-Off analysis

Unique opportunity for DC

Phys.Rev.D87 (2013) 011102.

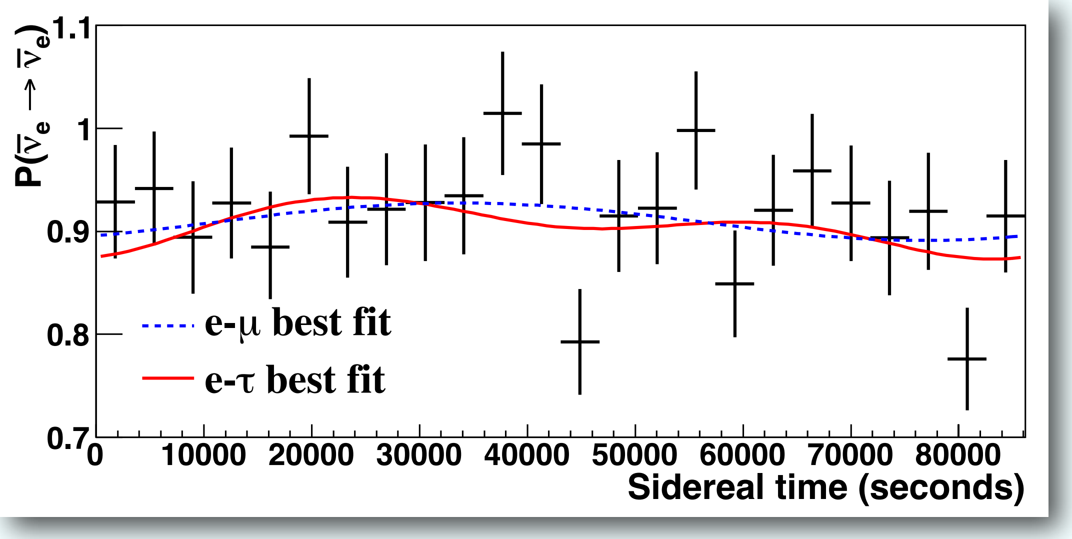




Lorentz violation

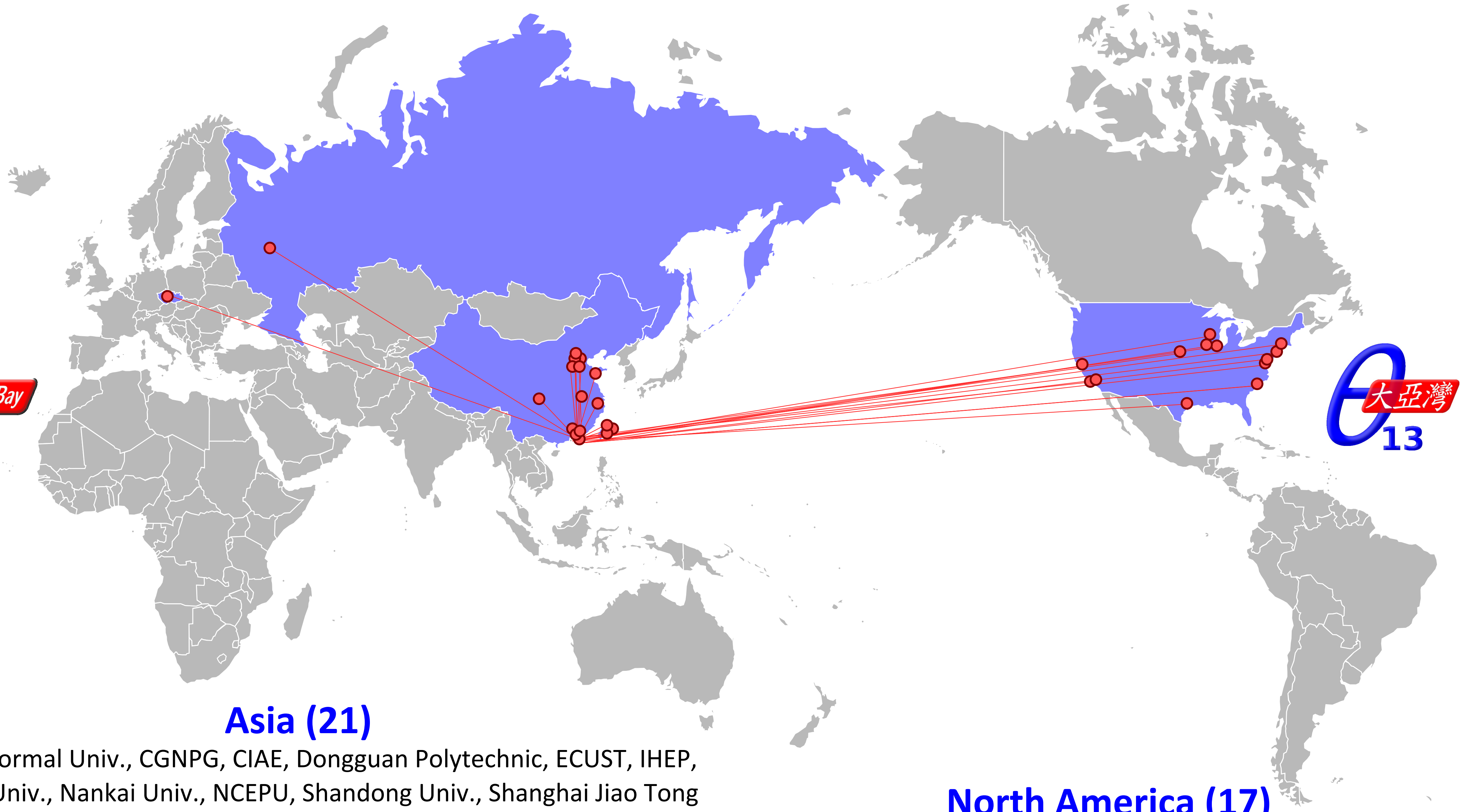
First test with reactor neutrinos

Phys.Rev.D86 (2012) 112009.



backup slides for Daya Bay

❖ The Daya Bay Collaboration:



Asia (21)

Beijing Normal Univ., CGNPG, CIAE, Dongguan Polytechnic, ECUST, IHEP, Nanjing Univ., Nankai Univ., NCEPU, Shandong Univ., Shanghai Jiao Tong Univ., Shenzhen Univ., Tsinghua Univ., USTC, Xian Jiaotong Univ., Zhongshan Univ.,
Chinese Univ. of Hong Kong, Univ. of Hong Kong,
National Chiao Tung Univ., National Taiwan Univ., National United Univ.

Europe (2)

Charles University, JINR Dubna

North America (17)

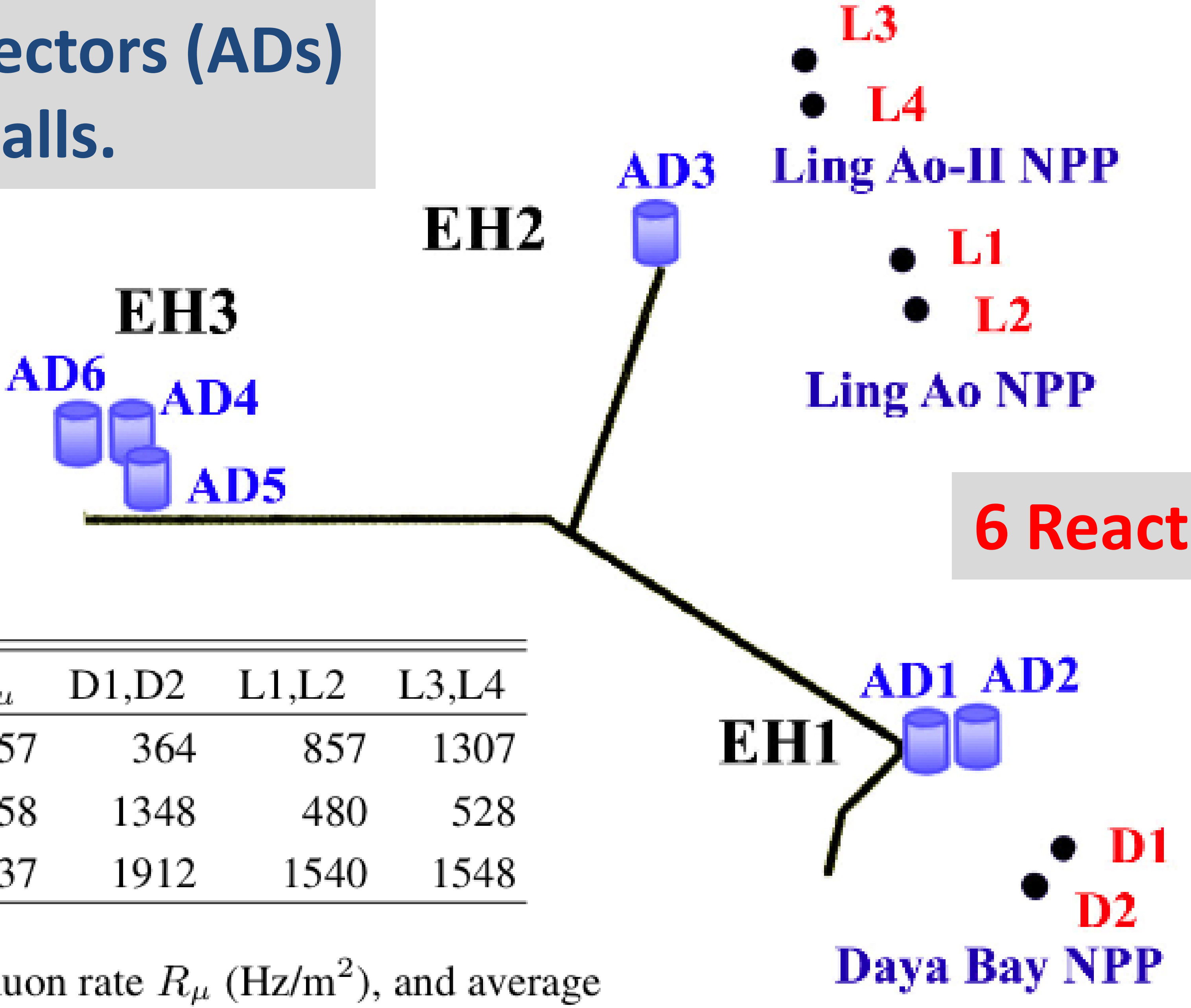
Brookhaven Natl Lab, CalTech, Illinois Institute of Technology, Iowa State, Lawrence Berkeley Natl Lab, Princeton, Rensselaer Polytechnic, Siena College, UC Berkeley, UCLA, Univ. of Cincinnati, Univ. of Houston, UIUC, Univ. of Wisconsin, Virginia Tech, William & Mary, Yale

~230 Collaborators

Experimental Layout

by K. Lau @ FPCP2013

6 Antineutrino Detectors (ADs) in 3 underground halls.



6 Reactor Cores

	Overburden	R_μ	E_μ	D1,D2	L1,L2	L3,L4
EH1	280	1.27	57	364	857	1307
EH2	300	0.95	58	1348	480	528
EH3	880	0.056	137	1912	1540	1548

TABLE I. Overburden (m.w.e), muon rate R_μ (Hz/m^2), and average muon energy E_μ (GeV) of the three EHs, and the distances (m) to the reactor pairs.

Experiment survey

by K. Lau @ FPCP2013

Negligible reactor flux uncertainty (<0.02%) from precise survey.

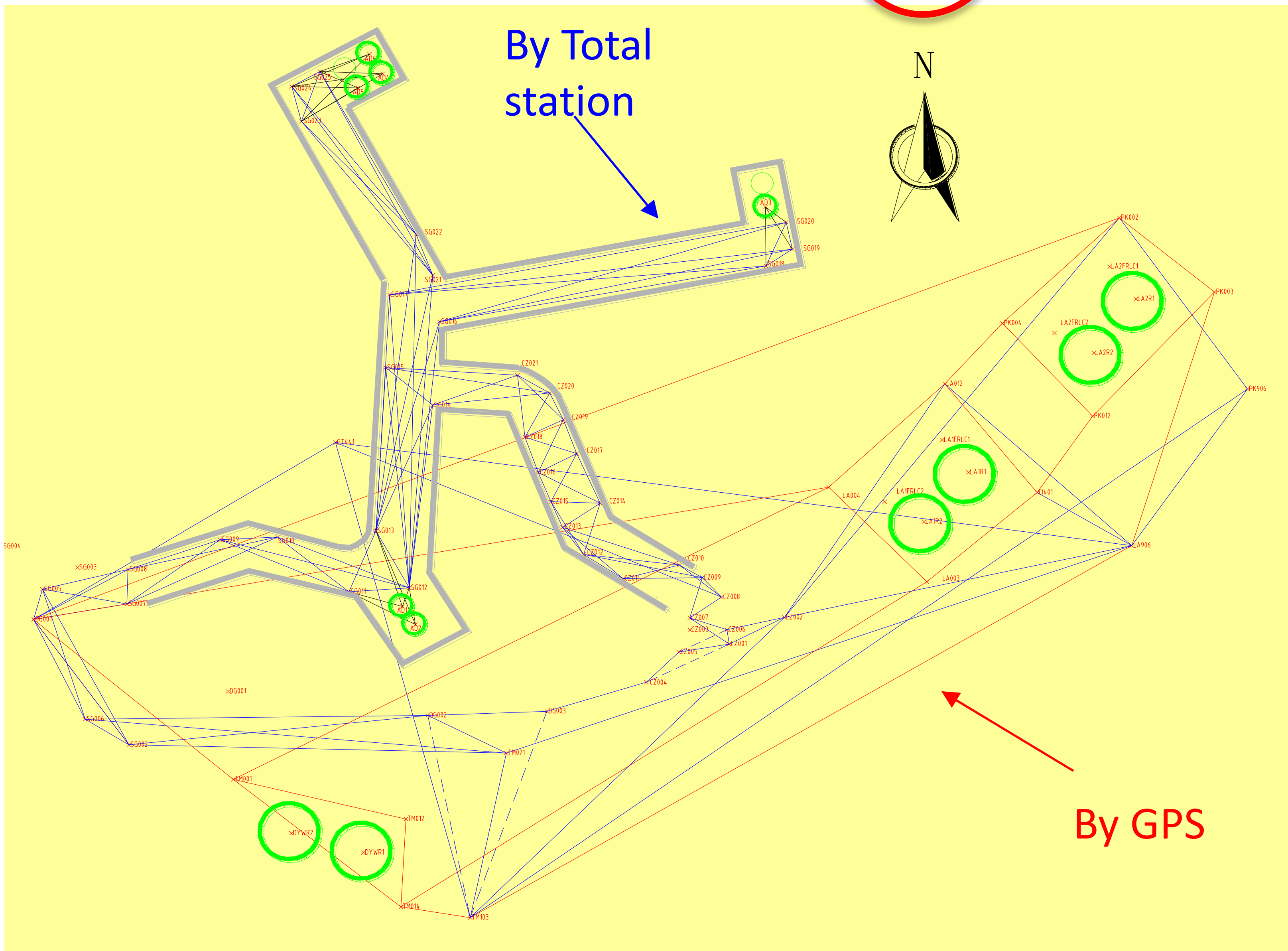
$$\frac{N_{\mathrm{f}}}{N_{\mathrm{n}}} = \left(\frac{N_{\mathrm{p,f}}}{N_{\mathrm{p,n}}}\right)\left(\frac{L_{\mathrm{n}}}{L_{\mathrm{f}}}\right)^2\left(\frac{\epsilon_{\mathrm{f}}}{\epsilon_{\mathrm{n}}}\right)\left[\frac{P_{\mathrm{sur}}(E,L_{\mathrm{f}})}{P_{\mathrm{sur}}(E,L_{\mathrm{n}})}\right]$$

Detailed Survey:

- GPS above ground
- Total Station underground
- Final precision: 28mm

Validation:

- Three independent calculations
- Cross-check survey
- Consistent with reactor plant and design plans



By Total station

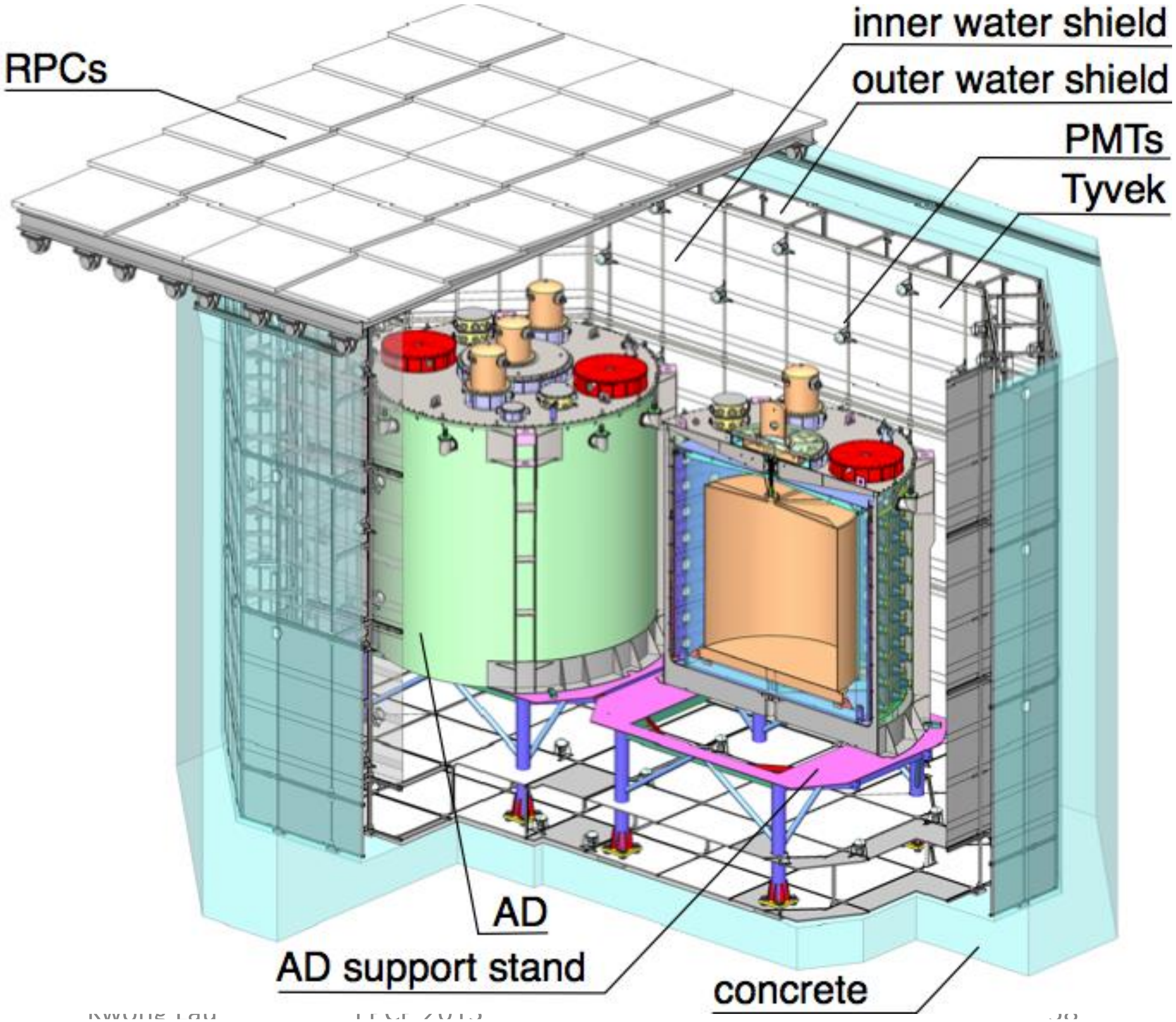
By GPS

Muon tagging system

by K. Lau @ FPCP2013

Dual tagging systems: 2.5 meter thick two-section water shield and RPCs

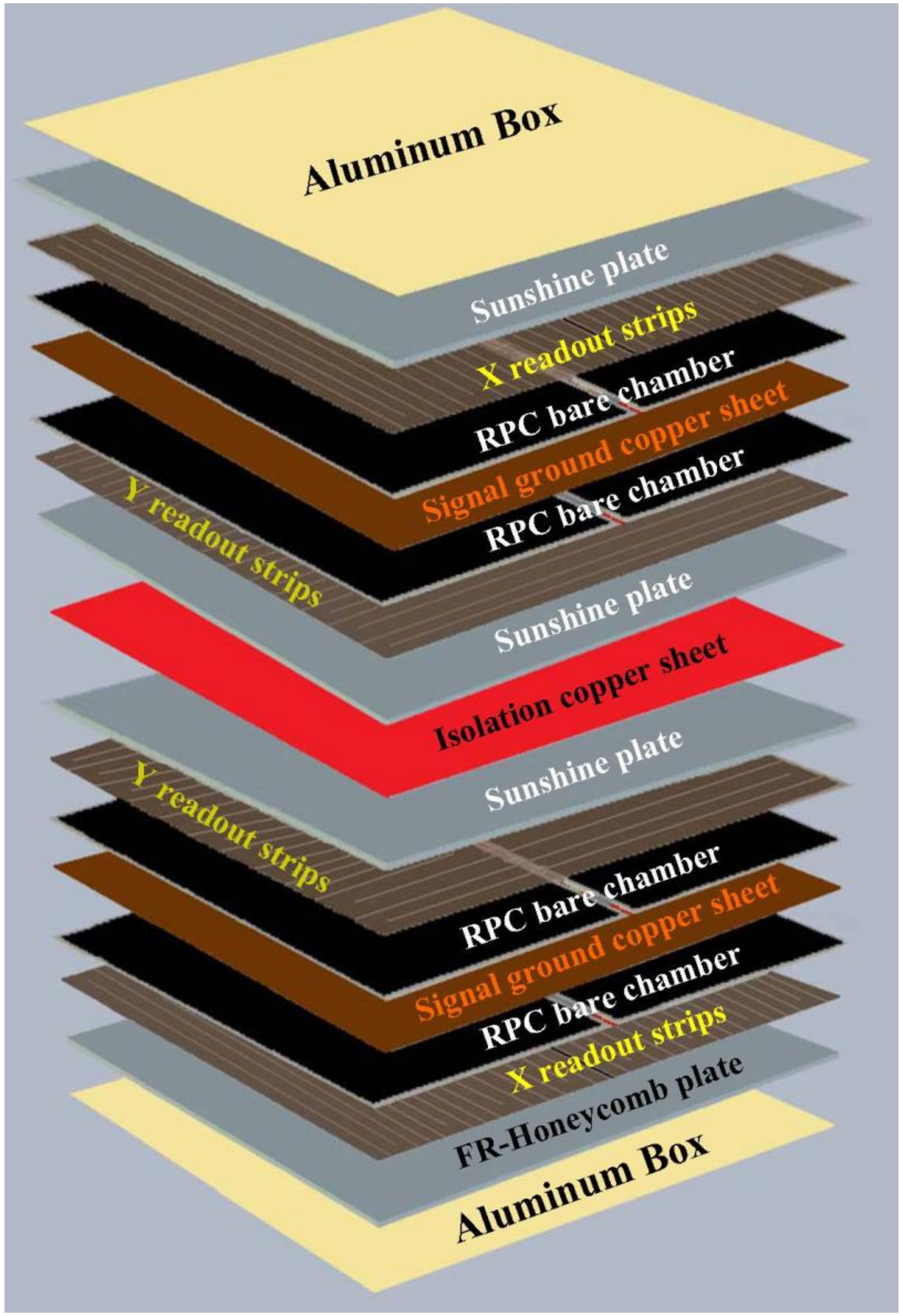
- Outer layer of water veto (on sides and bottom) is 1m thick, inner layer >1.5m. Water extends 2.5m above ADs
  - 288 8” PMTs in each near hall
  - 384 8” PMTs in Far Hall
- 4-layer RPC modules above pool
  - 54 modules in each near hall
  - 81 modules in Far Hall
- Goal efficiency: > 99.5% with uncertainty <0.25%



Daya Bay RPC modules

- 2m x 2m @ 1 module
- 4 layers of bare RPCs, each with 1 readout plane, inside an Al box
- 2X and 2Y 25-cm wide strips per module
- The spatial resolution is about 8 cm per coordinate.
- 54 modules each in EH1 and EH2, and 81 in EH3.
- The RPCs are triggered by having 3 out of 4 ayers hit per module.
- The muon detection efficiency based on RPCs alone is >95%.

by K. Lau @ FPCP2013



Trigger performance

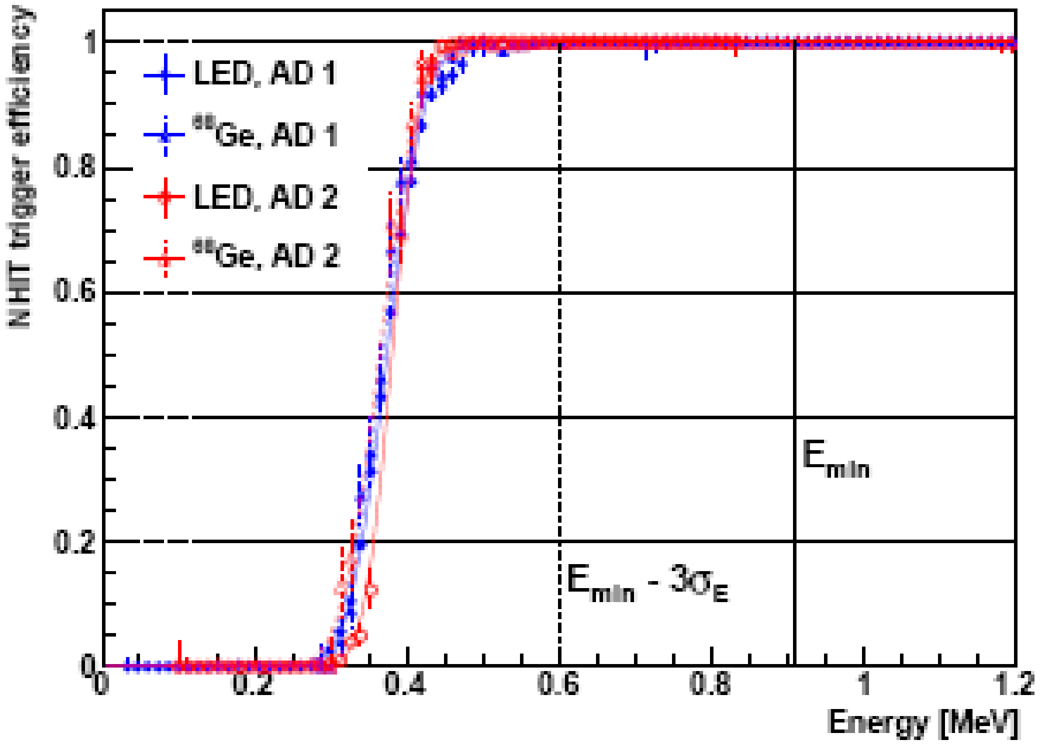
by K. Lau @ FPCP2013

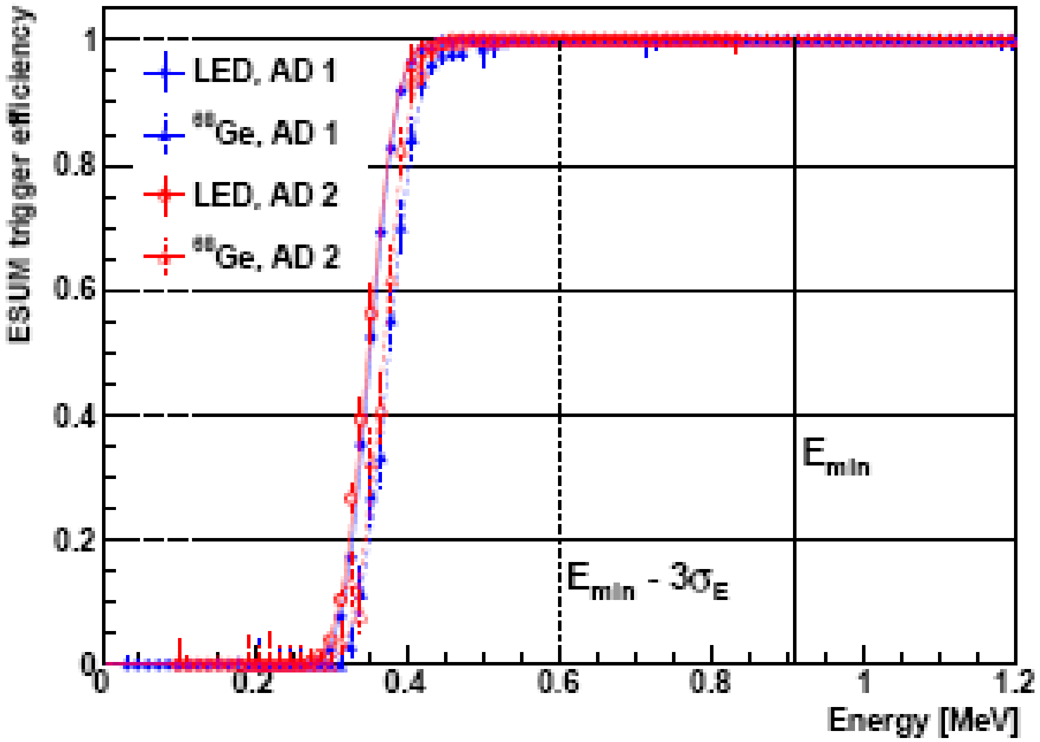
Trigger thresholds

- AD: >45 PMTs (digital trigger)
  >0.4 MeV (analog trigger)
- Inner Water Veto: >6 PMTs
- Outer Water Veto: >7 PMTs
- RPC: 3/4 layers in a module

Trigger efficiency

- No measureable inefficiency >0.7 MeV
- Minimum energy expected for prompt antineutrino signal is ~0.9 MeV.

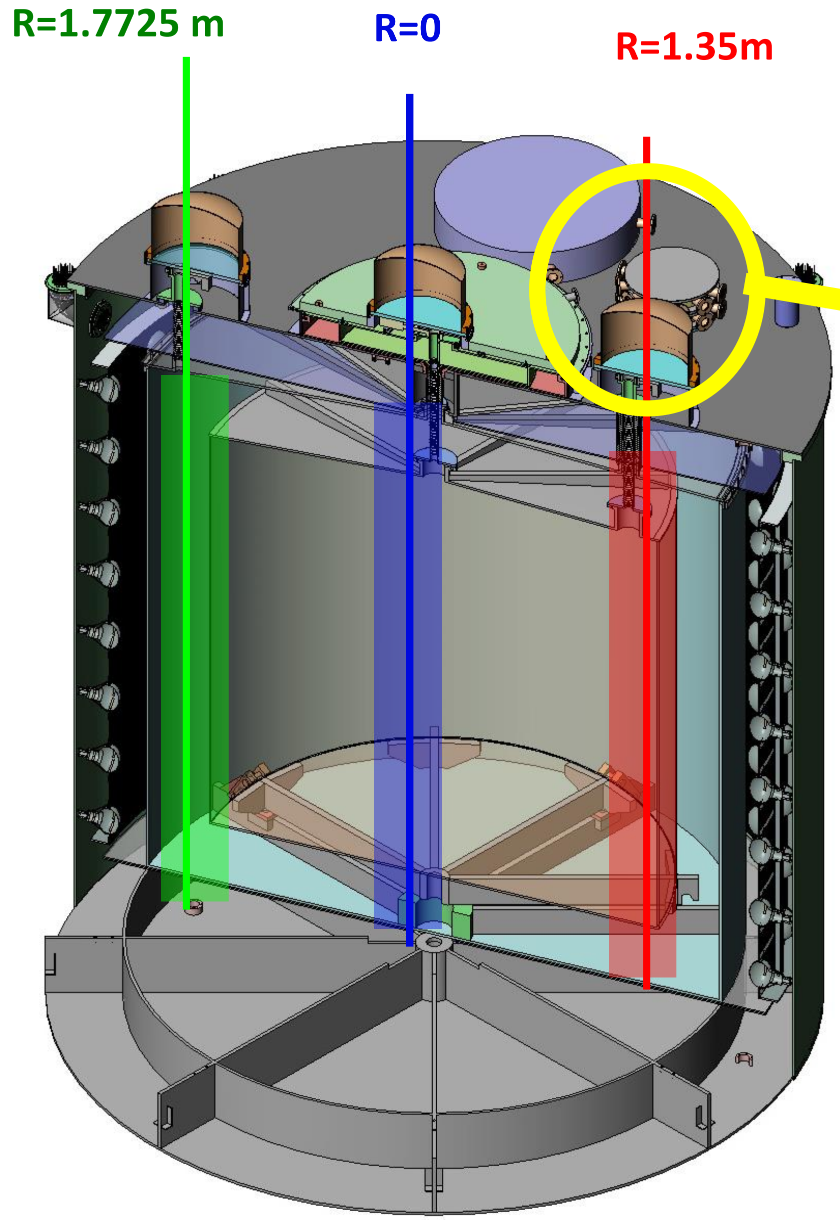




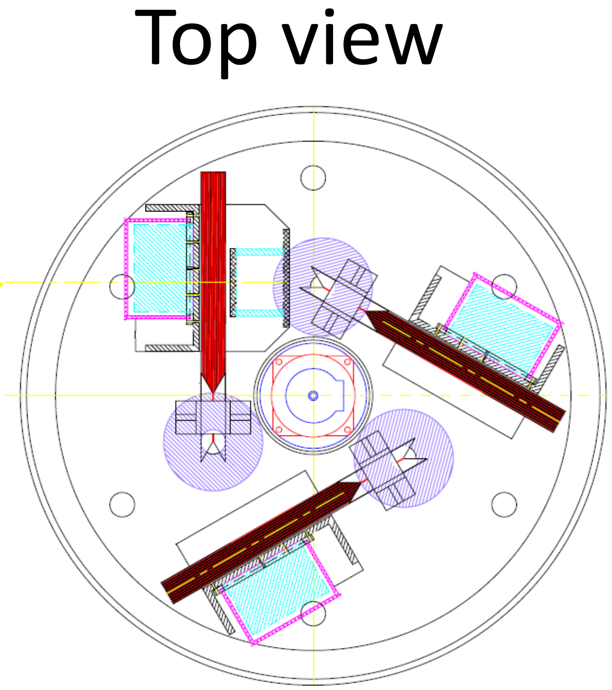
Automated Calibration System

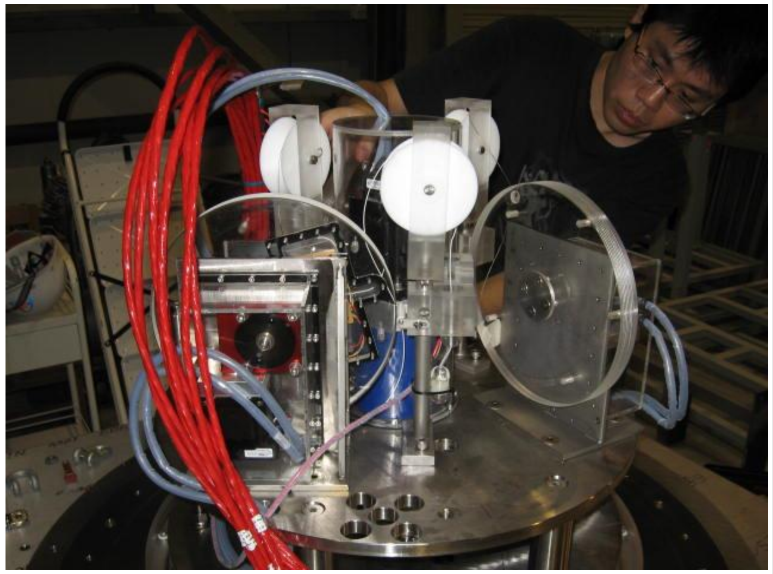
by K. Lau @ FPCP2013

3 Automated calibration 'robots' (ACUs) on each detector



Three axes: center, edge of target, middle of gamma catcher





3 sources for each z axis on a turntable (position accuracy < 5 mm):

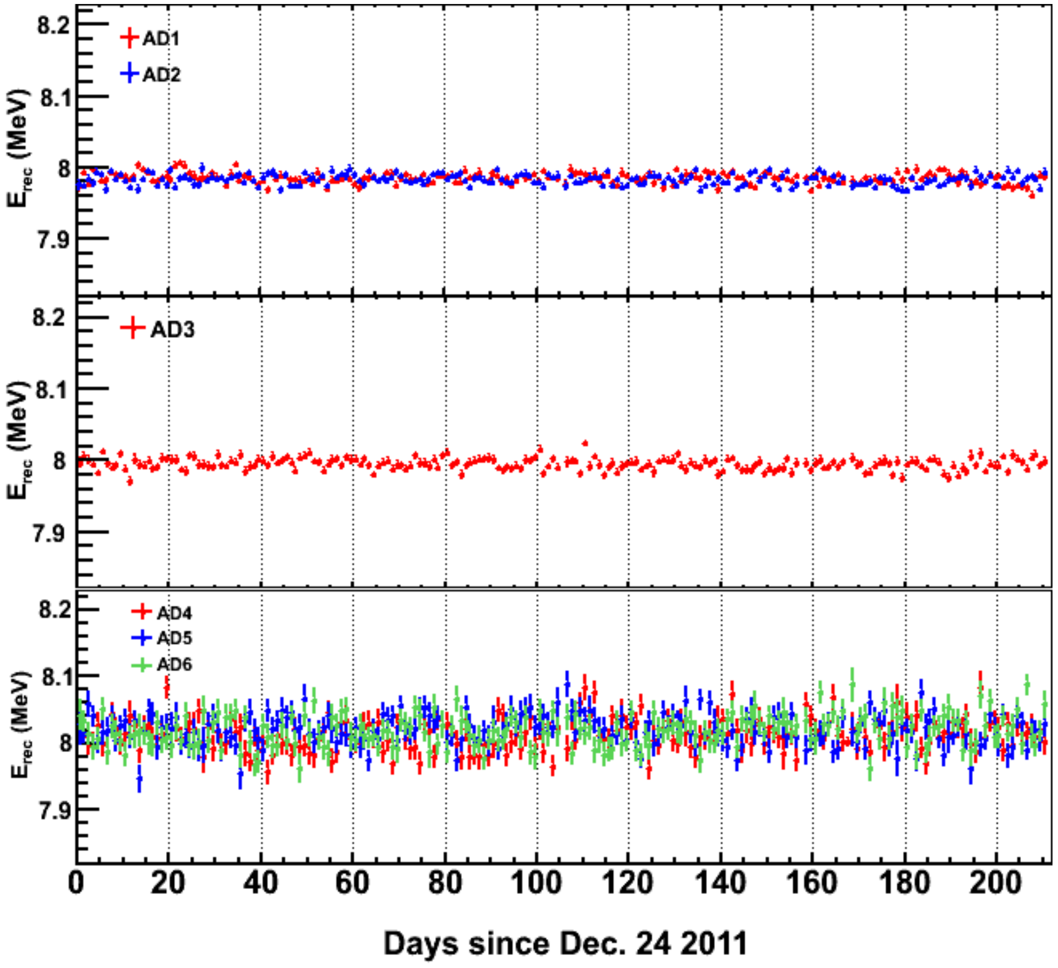
- 10 Hz ^{68}Ge (0 KE e^+ = 2×0.511 MeV γ's)
- 0.5 Hz ^{241}Am-^{13}C neutron source (3.5 MeV n without γ) + 100 Hz ^{60}Co gamma source (1.173+1.332 MeV γ)
- LED diffuser ball (500 Hz) for T_0 and gain

Ingredient #1: Calibration

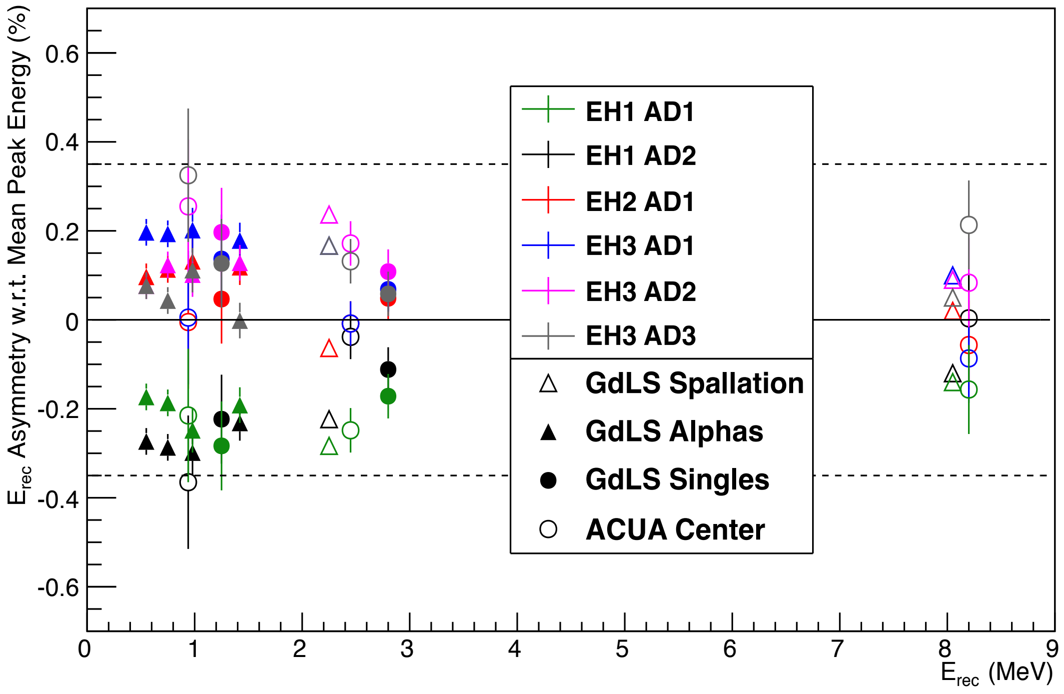
- One key is achieving a stable and consistent energy response between detectors:

After calibration, achieve energy response that is **stable to ~0.1%** in all detectors, with a **total relative uncertainty of 0.35%** between detectors.

Spallation *n*Gd capture peak vs. time (after calibration)



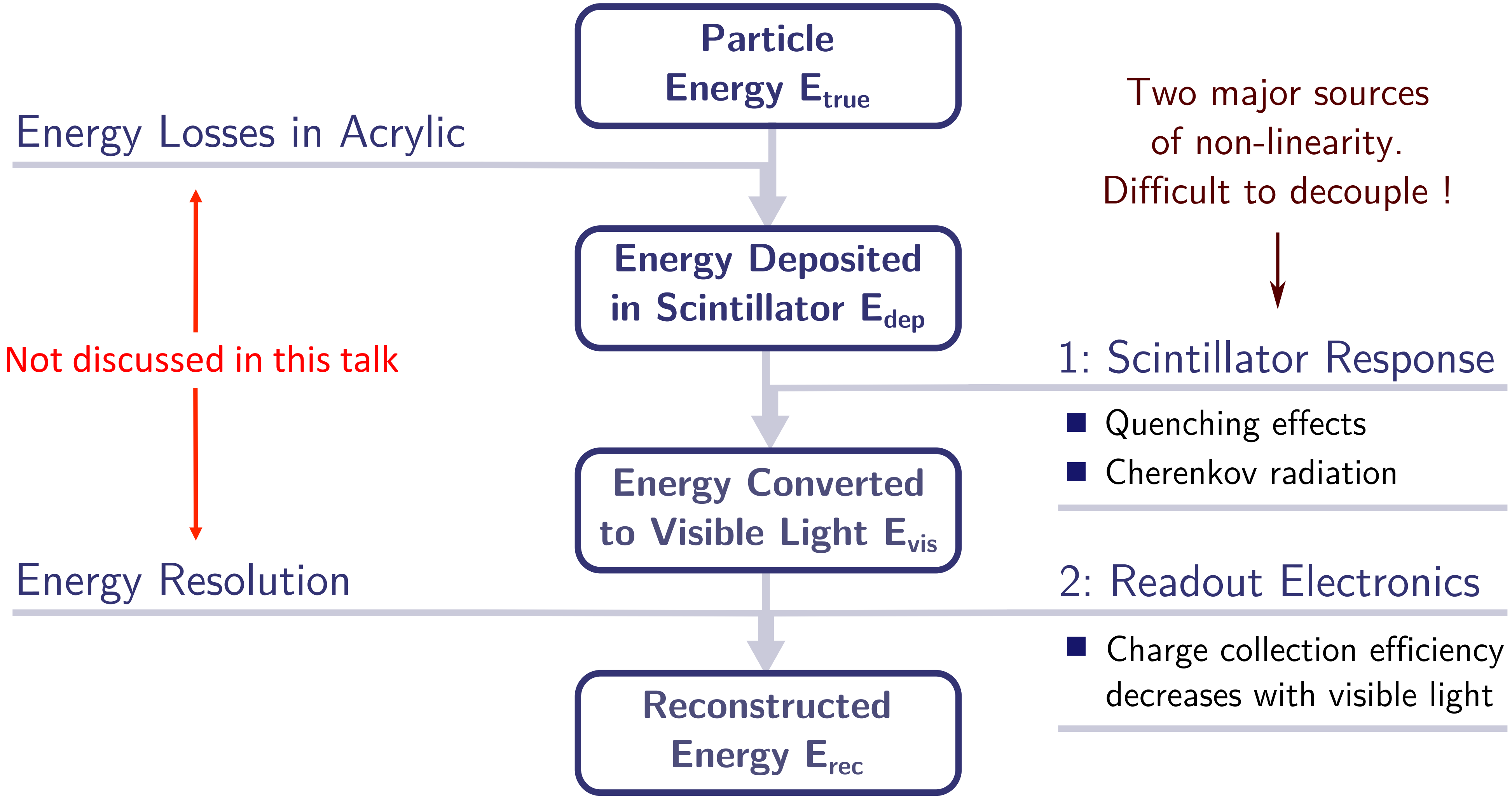
Relative energy peaks in all detectors (after calibration)



After initial reconstruction, position non-uniformity is also corrected for

Ingredient #2: Energy Response Model

- Also need to relate reconstructed kinetic energy E_{rec} to true energy E_{true}:



Particle Energy E_{true}

Energy Losses in Acrylic

Energy Deposited in Scintillator E_{dep}

Not discussed in this talk

Energy Converted to Visible Light E_{vis}

Energy Resolution

Reconstructed Energy E_{rec}

Two major sources of non-linearity. Difficult to decouple !

1: Scintillator Response
- Quenching effects
- Cherenkov radiation

2: Readout Electronics
- Charge collection efficiency decreases with visible light

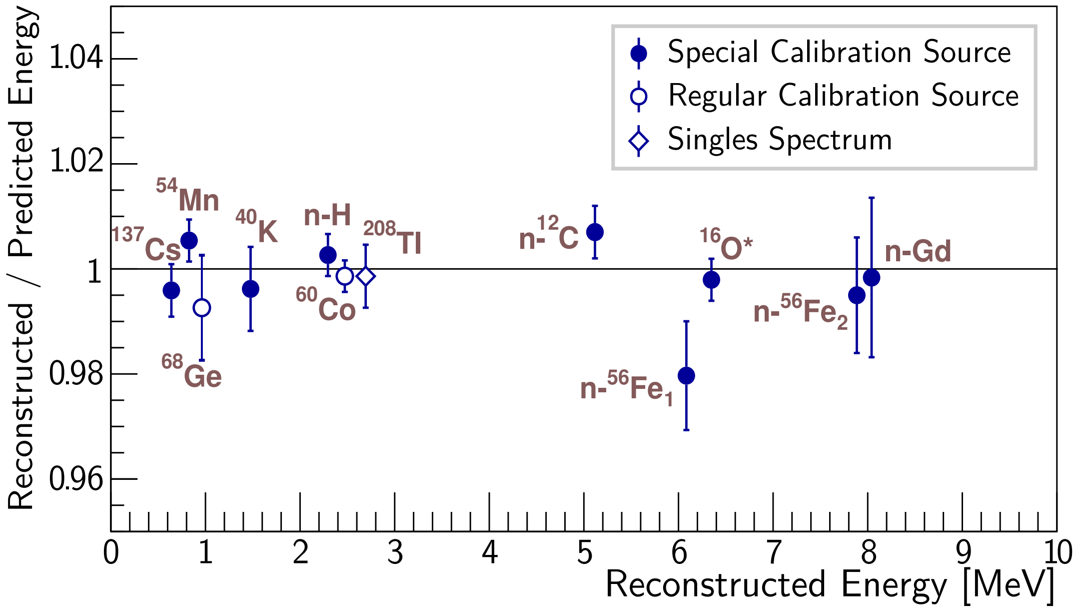
✓ **Minimal impact on oscillation measurement**

✓ **Crucial for measurement of reactor spectra (in progress)**

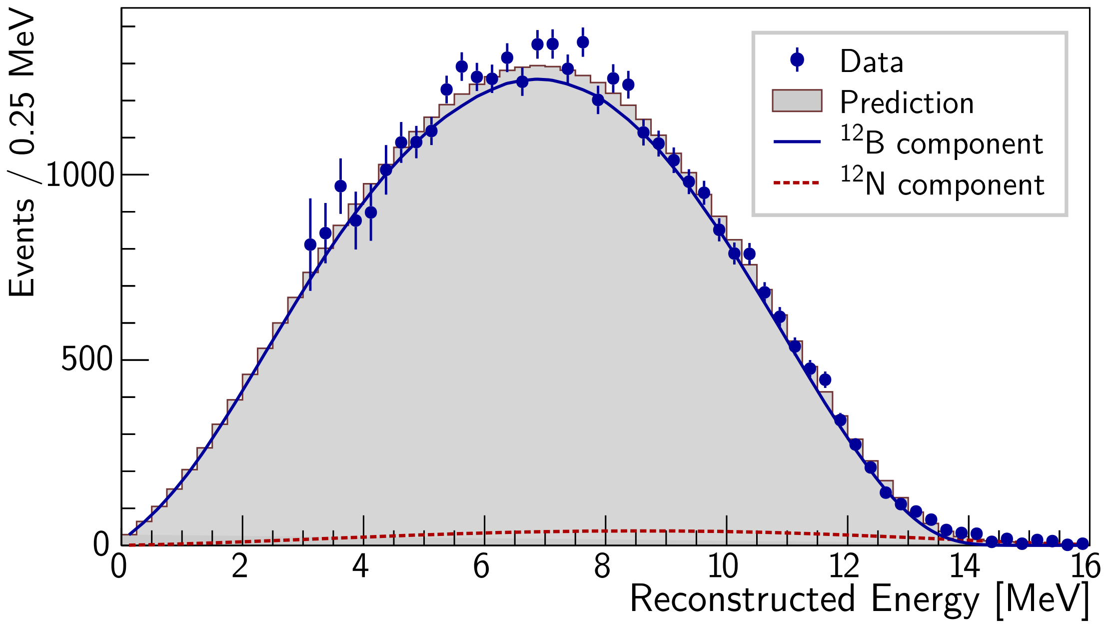
Ingredient #2: Non-Linearity Response Model

- Model is constrained using monoenergetic gamma lines from various sources and continuous spectrum from ^{12}B produced by muon spallation inside the scintillator:

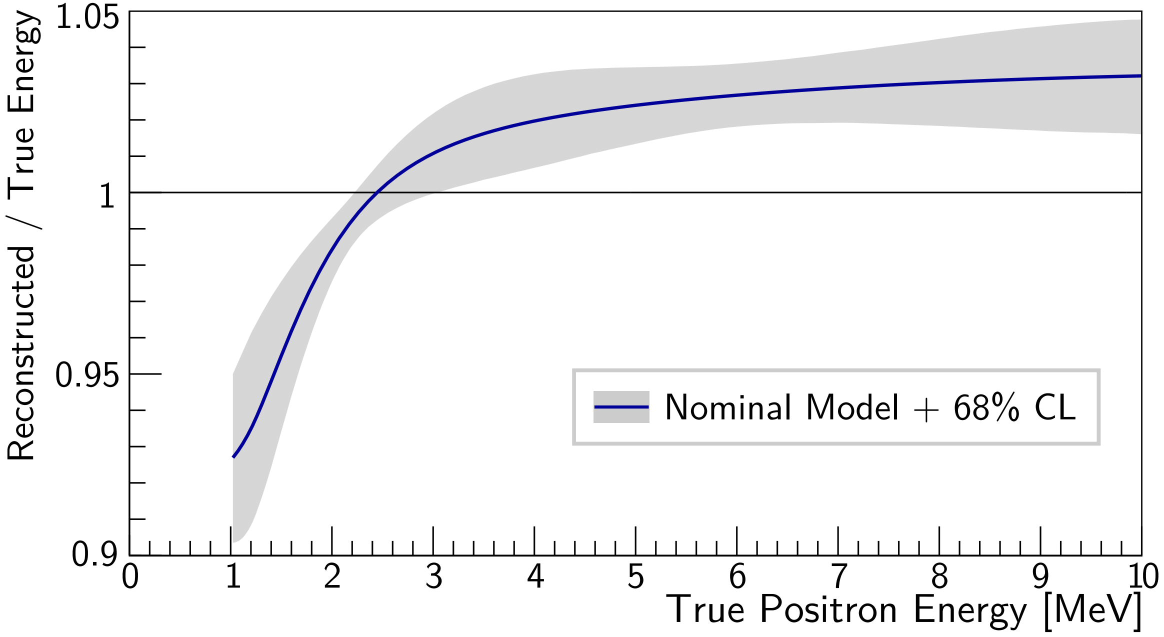
Gamma Ray Energy Peaks



^{12}B Beta-Decay Spectrum



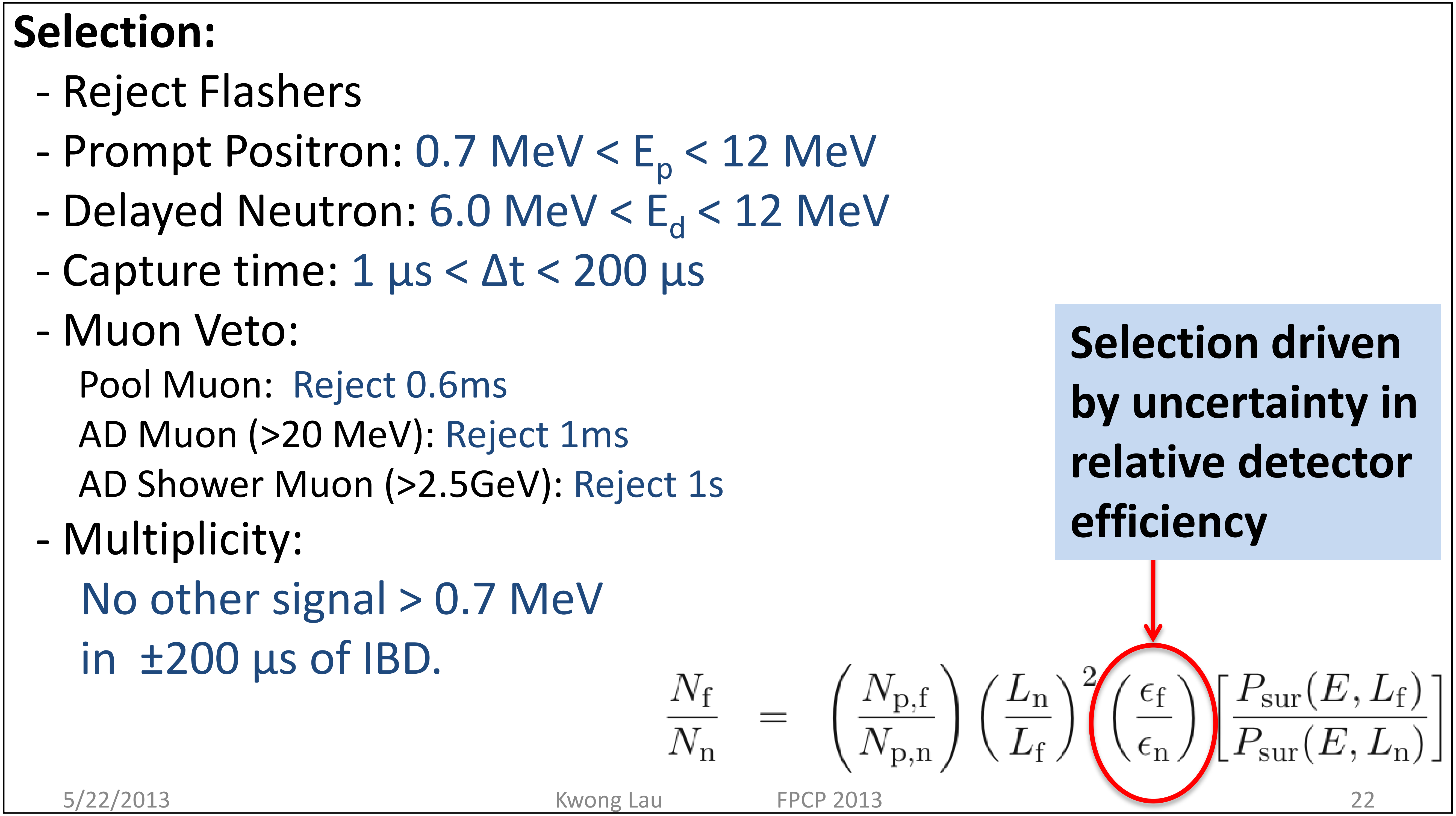
Positron Energy Response Model



Final positron energy non-linearity response

Event selection criteria

by K. Lau @ FPCP2013



Selection:

- Reject Flashers
- Prompt Positron: 0.7 MeV < E_p < 12 MeV
- Delayed Neutron: 6.0 MeV < E_d < 12 MeV
- Capture time: 1 μs < Δt < 200 μs
- Muon Veto:
  - Pool Muon: Reject 0.6ms
  - AD Muon (>20 MeV): Reject 1ms
  - AD Shower Muon (>2.5GeV): Reject 1s
- Multiplicity:
  - No other signal > 0.7 MeV in ±200 μs of IBD.

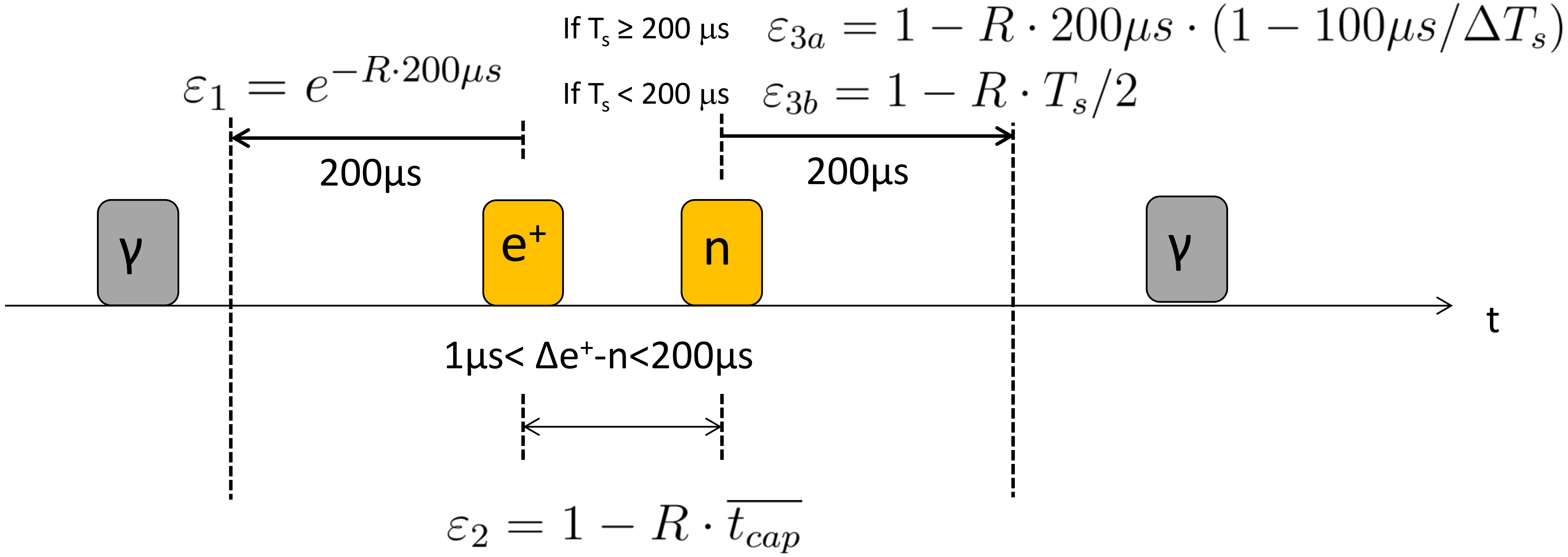
Selection driven by uncertainty in relative detector efficiency

$$\frac{N_\mathrm{f}}{N_\mathrm{n}} = \left(\frac{N_\mathrm{p,f}}{N_\mathrm{p,n}}\right)\left(\frac{L_\mathrm{n}}{L_\mathrm{f}}\right)^2\left(\frac{\epsilon_\mathrm{f}}{\epsilon_\mathrm{n}}\right)\left[\frac{P_\mathrm{sur}(E, L_\mathrm{f})}{P_\mathrm{sur}(E, L_\mathrm{n})}\right]$$

Multiplicity cut

by K. Lau @ FPCP2013

- Ensure exactly one prompt-delayed coincidence



$$\varepsilon_1 = e^{-R \cdot 200\mu s}$$

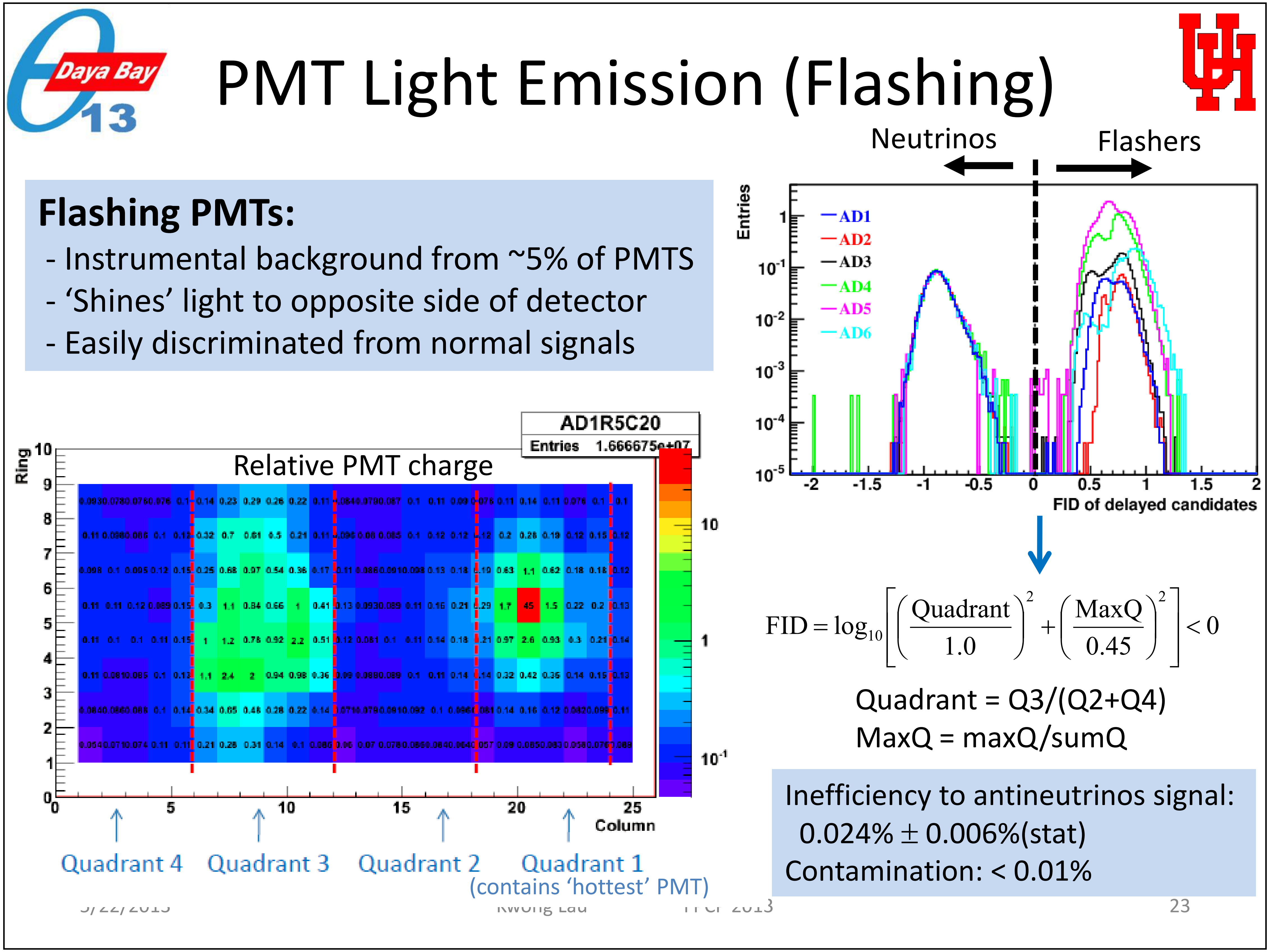
If $T_s \geq 200\ \mu s$ $\varepsilon_{3a} = 1 - R \cdot 200\mu s \cdot (1 - 100\mu s / \Delta T_s)$

If $T_s < 200\ \mu s$ $\varepsilon_{3b} = 1 - R \cdot T_s / 2$

$$\varepsilon_2 = 1 - R \cdot \overline{t_{cap}}$$

Uncorrelated background and IBD signals result in ambiguous prompt, delayed signals.

-> Reject all IBD with >2 triggers above 0.7 MeV in -200μs to +200μs.
Introduces ~2.5% IBD inefficiency, with negligible uncertainty



PMT Light Emission (Flashing)

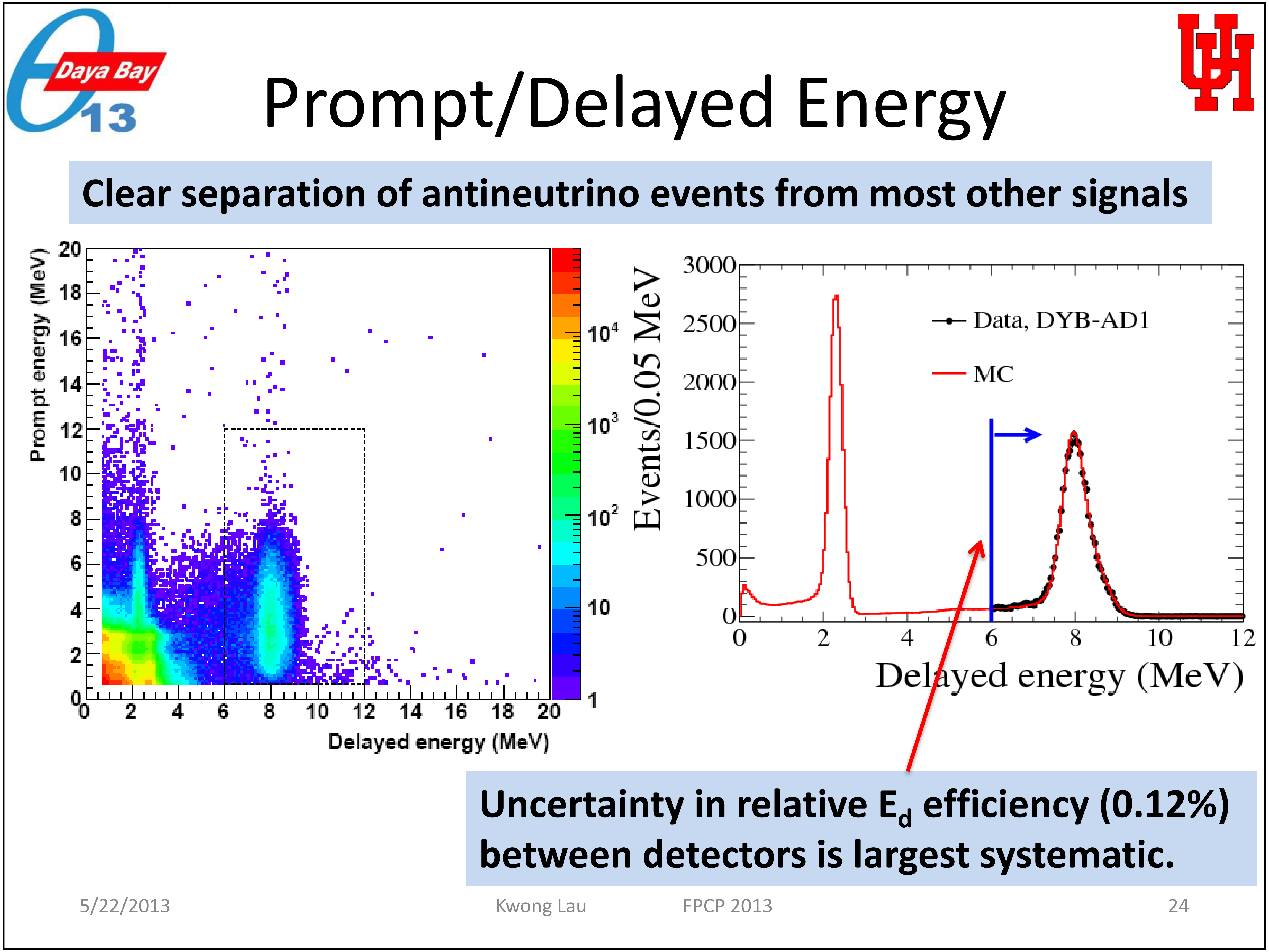
Flashing PMTs:
- Instrumental background from ~5% of PMTS
- ‘Shines’ light to opposite side of detector
- Easily discriminated from normal signals

Quadrant 4 Quadrant 3 Quadrant 2 Quadrant 1
(contains ‘hottest’ PMT)

$$\mathrm{FID} = \log_{10}\left[\left(\frac{\mathrm{Quadrant}}{1.0}\right)^2 + \left(\frac{\mathrm{MaxQ}}{0.45}\right)^2\right] < 0$$

Quadrant = Q3/(Q2+Q4)
MaxQ = maxQ/sumQ

Inefficiency to antineutrinos signal:
$0.024\% \pm 0.006\%$(stat)
Contamination: < 0.01%



Prompt/Delayed Energy

Clear separation of antineutrino events from most other signals

Uncertainty in relative E_d efficiency (0.12%) between detectors is largest systematic.

5/22/2013 Kwong Lau FPCP 2013 24

Reactor flux expectation

by K. Lau @ FPCP2013

- Antineutrino flux is estimated for each reactor core.

Flux estimated using:

$$S(E_\nu) = \frac{W_{th}}{\sum_i (f_i/F) e_i} \sum_i^{istopes} (f_i/F) S_i(E_\nu)$$

Reactor operators provide:

- Thermal power data: W_{th}
- Relative isotope fission fractions: f_i

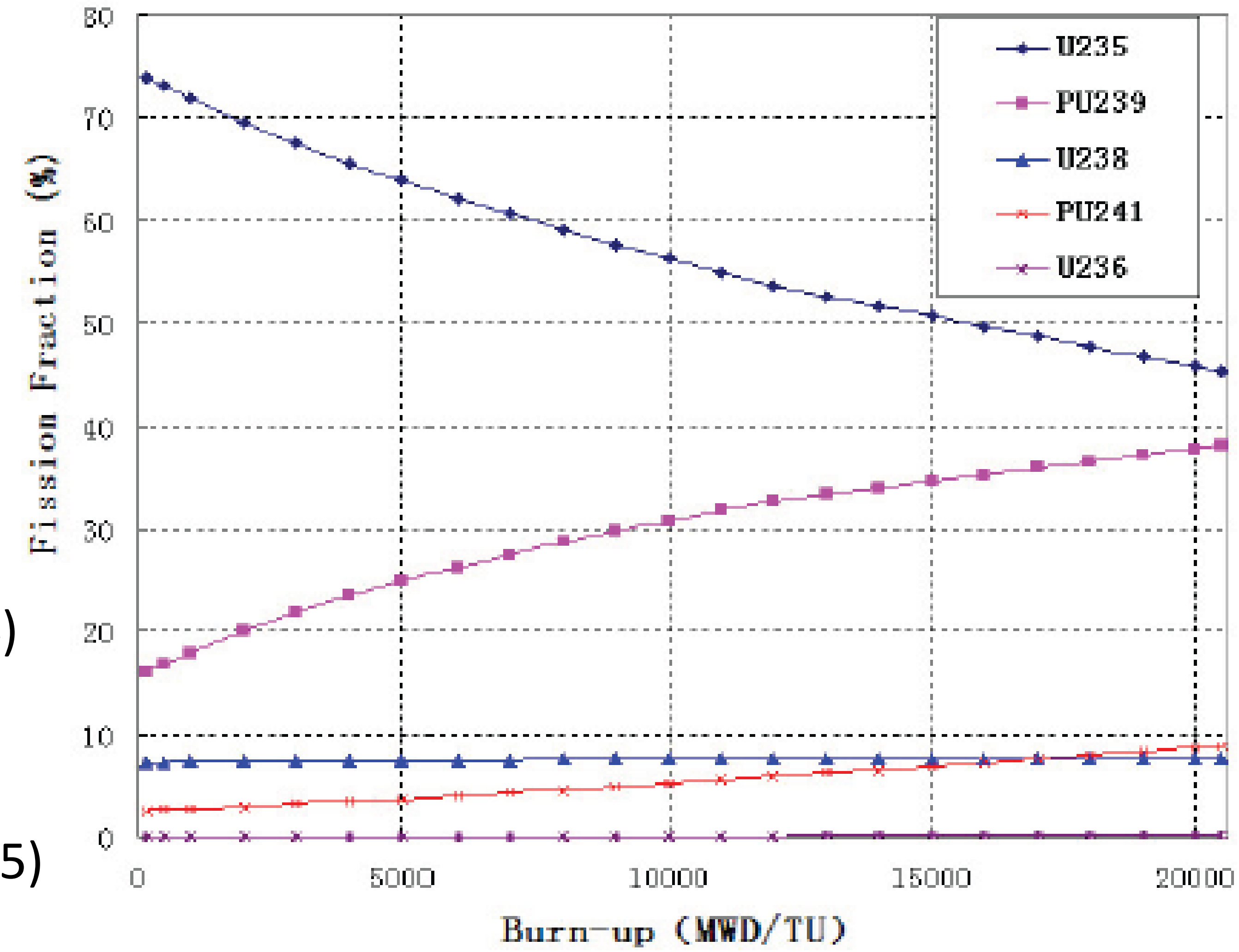
Energy released per fission: e_i

V. Kopekin et al., Phys. Atom. Nucl. 67, 1892 (2004)

Antineutrino spectra per fission: $S_i(E_\nu)$

K. Schreckenbach et al., Phys. Lett. B160, 325 (1985)
A. A. Hahn et al., Phys. Lett. B218, 365 (1989)
P. Vogel et al., Phys. Rev. C24, 1543 (1981)
T. Mueller et al., Phys. Rev. C83, 054615 (2011)
P. Huber, Phys. Rev. C84, 024617 (2011)

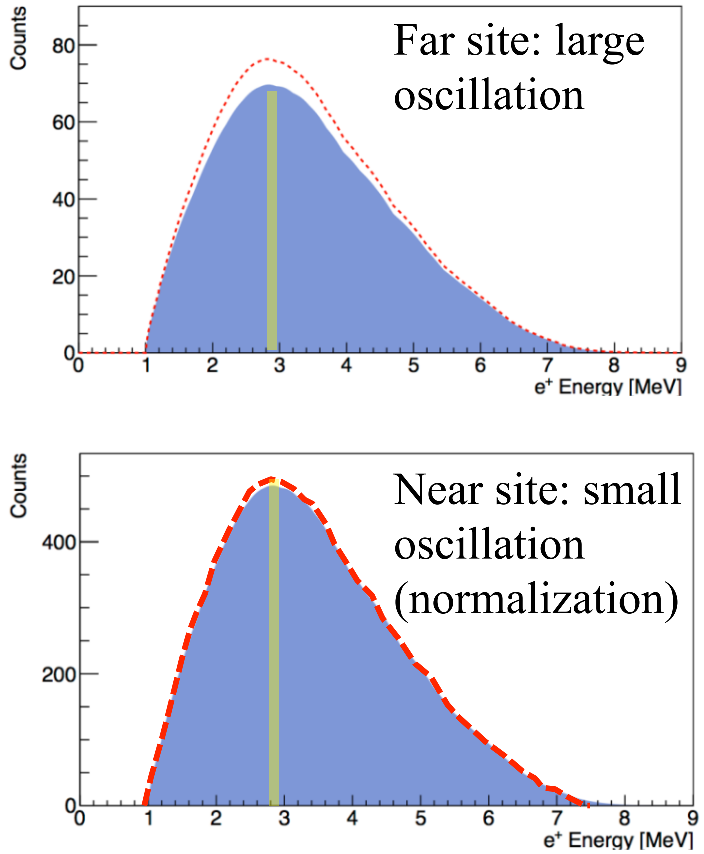
Isotope fission rates vs. reactor burnup



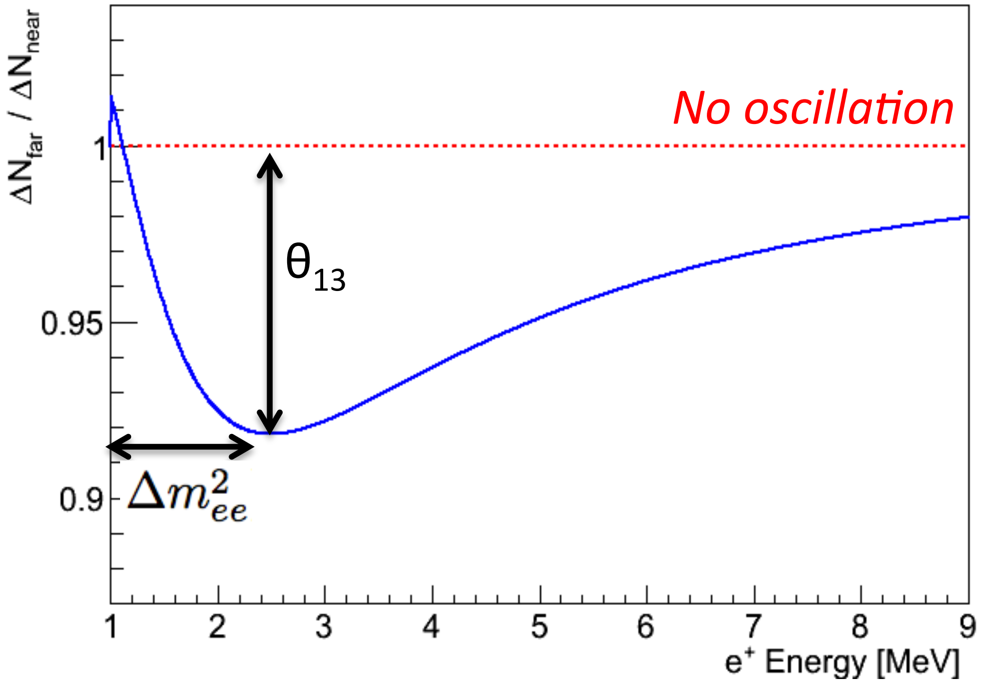
Flux model has negligible impact on far vs. near oscillation measurement

Doing a Spectral Measurement

- With a spectral measurement can measure the mass splitting:



Compare each energy



But require good understanding of the detectors' energy response!

- Which mass splitting do we measure? Define an effective mass splitting Δm^2_{ee} :

$$P_{\bar{\nu}_e \to \bar{\nu}_e} = 1 - \sin^2 2\theta_{13} \sin^2\left(\Delta m^2_{ee} \frac{L}{4E}\right) - \sin^2 2\theta_{12} \cos^4\theta_{13} \sin^2\left(\Delta m^2_{21} \frac{L}{4E}\right)$$

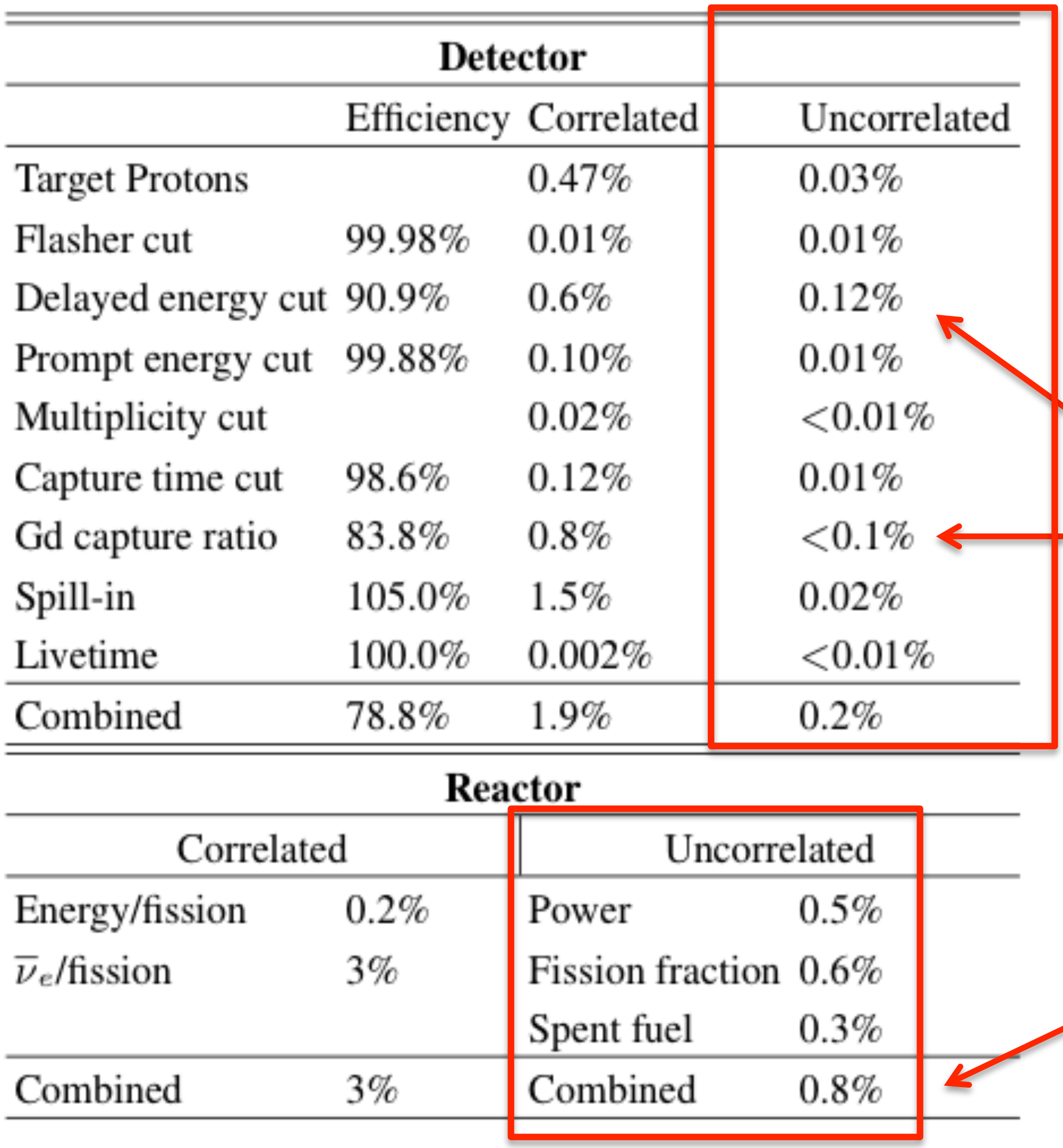
$$\sin^2(\Delta m^2_{ee} \tfrac{L}{4E}) \equiv \cos^2\theta_{12} \sin^2(\Delta m^2_{31} \tfrac{L}{4E}) + \sin^2\theta_{12} \sin^2(\Delta m^2_{32} \tfrac{L}{4E})$$

so that: $|\Delta m^2_{ee}| \simeq |\Delta m^2_{32}| \pm 5.21 \times 10^{-5} \mathrm{eV}^2$

+: Normal Hierarchy
−: Inverted Hierarchy

Systematic uncertainties

by J. Pedro Ochoa @ WIN2013



	Detector		
	Efficiency	Correlated	Uncorrelated
Target Protons		0.47%	0.03%
Flasher cut	99.98%	0.01%	0.01%
Delayed energy cut	90.9%	0.6%	0.12%
Prompt energy cut	99.88%	0.10%	0.01%
Multiplicity cut		0.02%	<0.01%
Capture time cut	98.6%	0.12%	0.01%
Gd capture ratio	83.8%	0.8%	<0.1%
Spill-in	105.0%	1.5%	0.02%
Livetime	100.0%	0.002%	<0.01%
Combined	78.8%	1.9%	0.2%

Reactor			
Correlated		Uncorrelated	
Energy/fission	0.2%	Power	0.5%
$\overline{\nu}_e$/fission	3%	Fission fraction	0.6%
		Spent fuel	0.3%
Combined	3%	Combined	0.8%

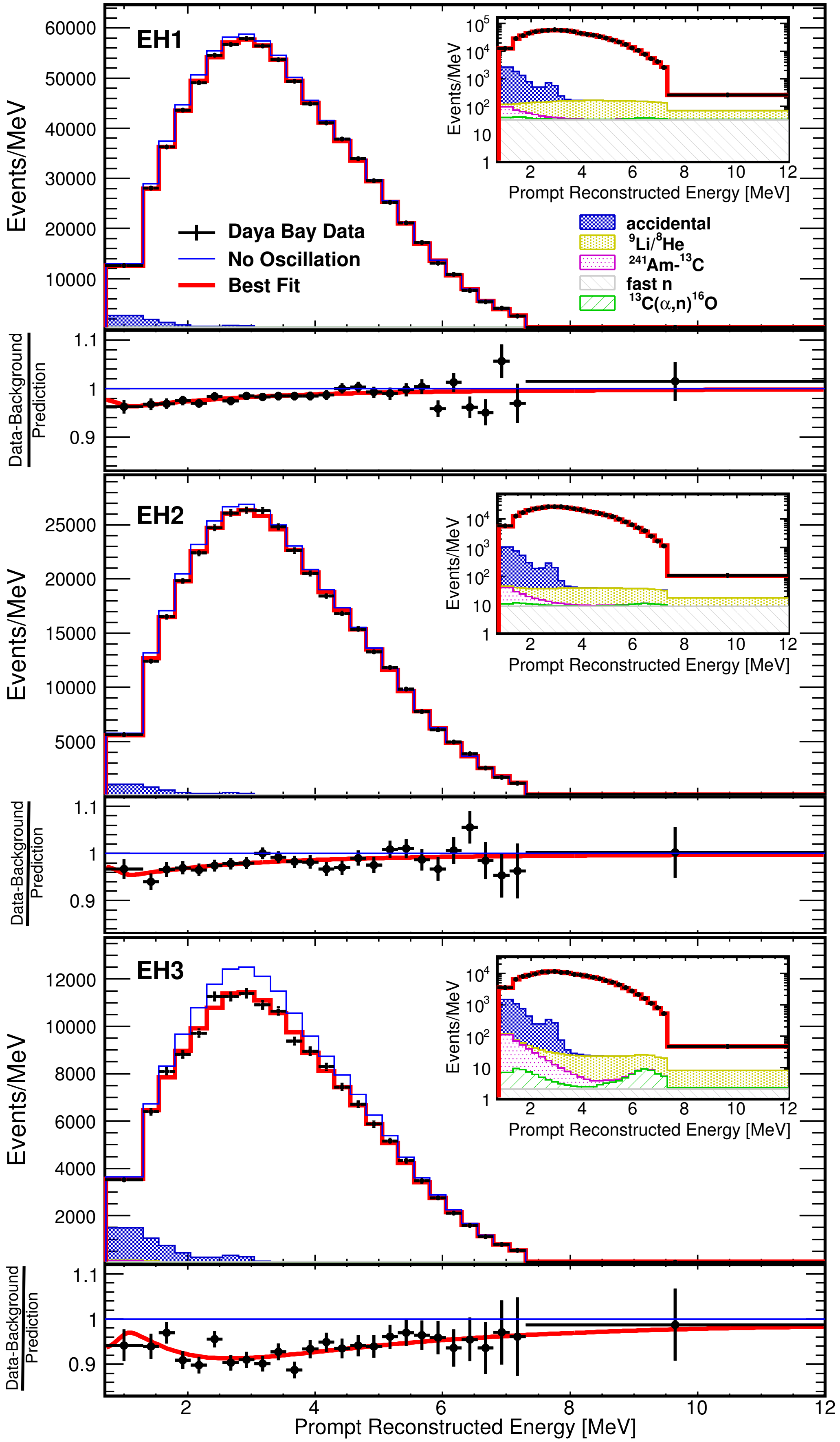
For near/far oscillation, only uncorrelated uncertainties play a significant role

Largest systematics are smaller than far site statistics (~0.5%)

Influence of uncorrelated reactor systematics reduced by far vs. near measurement.

- Statistic uncertainties contribute 73 % (65%) to total uncertainty in $\sin^2 2\theta_{13}$ ($|\Delta m^2_{ee}|$)
- Major systematics:
  - θ_{13}: reactor model, relative+absolute energy, and relative efficiencies
  - $|\Delta m^2_{ee}|$: Relative energy model, relative efficiencies, and backgrounds

Prompt positron spectra



High statistics and good S/N is obtained.

←EH1 (near)

←EH2 (near)

←EH3 (far)

The best fit

$$\sin^2 2\theta_{13} = 0.090^{+0.008}_{-0.009}$$

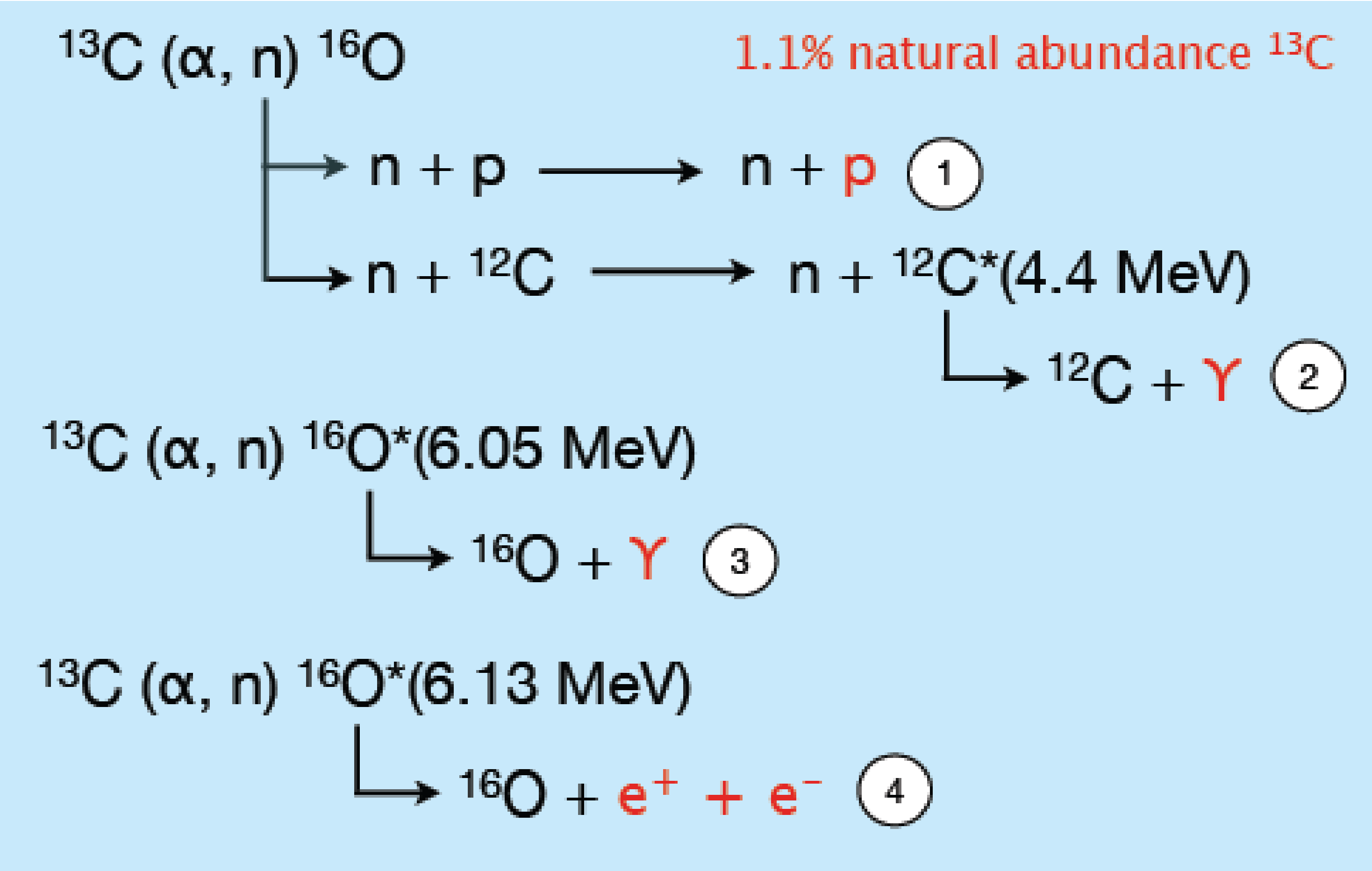
$$|\Delta m^2_{ee}| = (2.59^{+0.19}_{-0.20}) \times 10^{-3}\ \mathrm{eV}^2$$

$$\chi^2/ndf = 163/153$$

from arXiv:1310.6732 [hep-ex]

$^{13}C(\alpha, n)^{16}O$ backgrounds

by K. Lau @ FPCP2013



$^{13}C\ (\alpha, n)\ ^{16}O$

1.1% natural abundance ^{13}C

$\hookrightarrow n + p \longrightarrow n + p$ ①

$\hookrightarrow n + {}^{12}C \longrightarrow n + {}^{12}C^*(4.4\ MeV)$

$\hookrightarrow {}^{12}C + \gamma$ ②

$^{13}C\ (\alpha, n)\ ^{16}O^*(6.05\ MeV)$

$\hookrightarrow {}^{16}O + \gamma$ ③

$^{13}C\ (\alpha, n)\ ^{16}O^*(6.13\ MeV)$

$\hookrightarrow {}^{16}O + e^+ + e^-$ ④

Example alpha rate in AD1	^{238}U	^{232}Th	^{235}U	^{210}Po
Bq	0.05	1.2	1.4	10

Potential alpha source:

^{238}U, ^{232}Th, ^{235}U, ^{210}Po:

Each of them are measured in-situ:

U&Th: cascading decay of

Bi(or Rn) – Po – Pb

^{210}Po: spectrum fitting

Combining (α,n) cross-section, correlated background rate is determined.

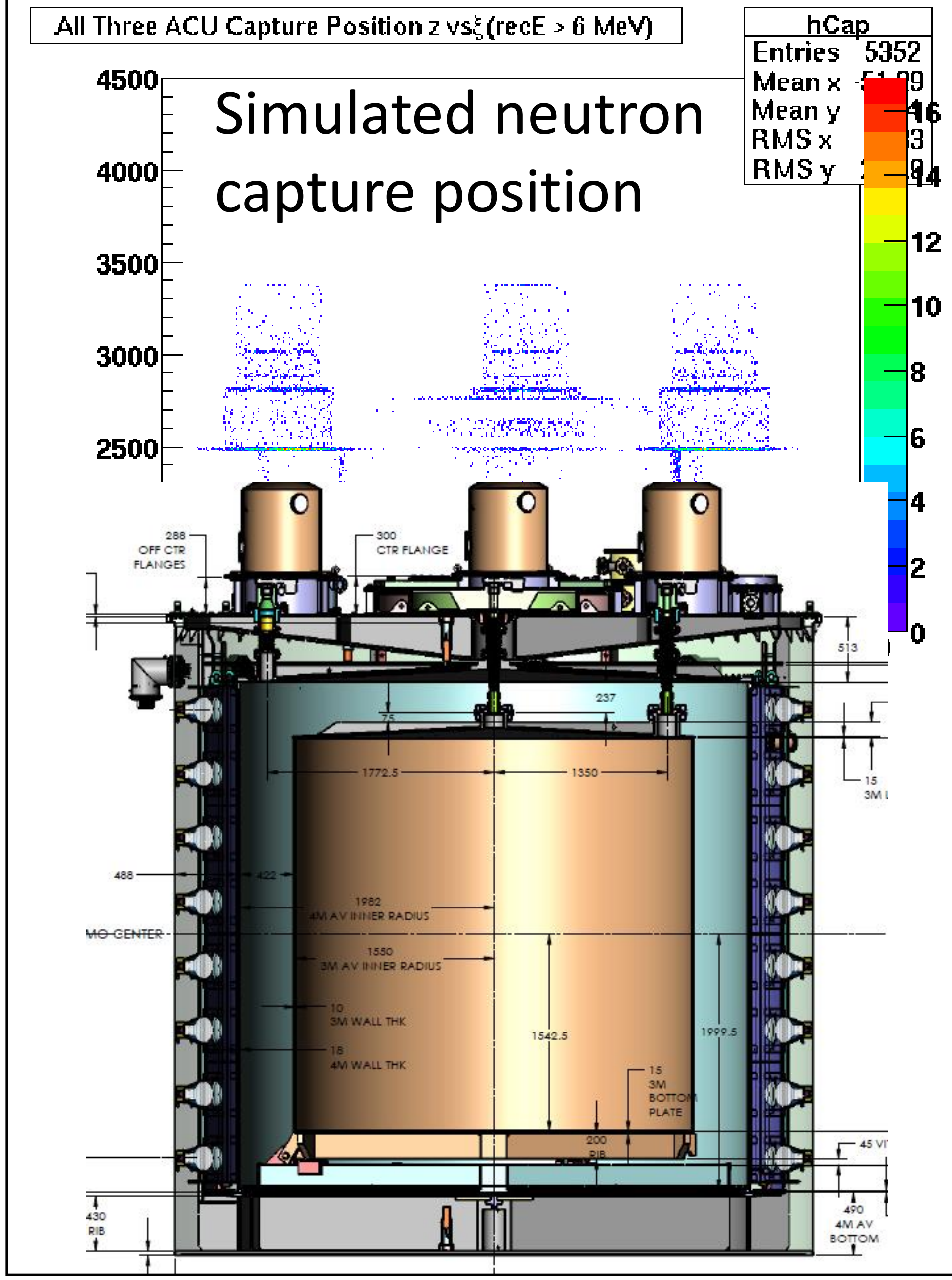
Near Site: 0.04+-0.02 per day, B/S $(0.006\pm0.004)\%$

Far Site: 0.03+-0.02 per day, B/S $(0.04\pm0.02)\%$

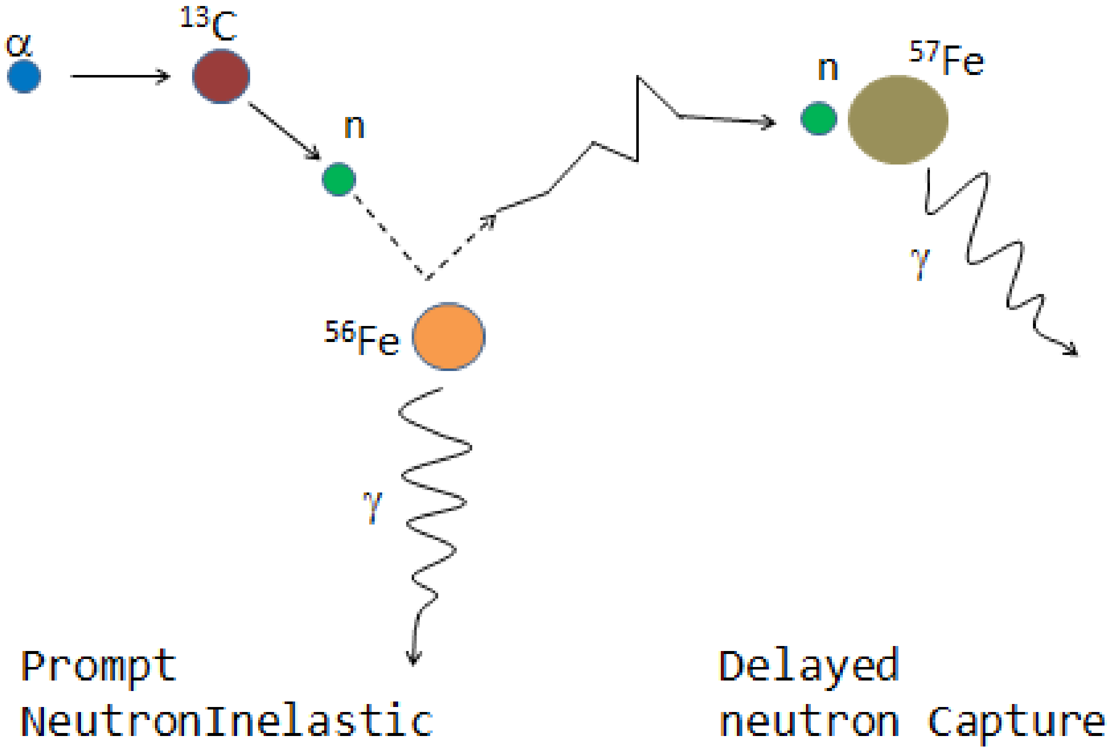
^{241}Am-^{13}C neutron backgrounds

by K. Lau @ FPCP2013

Weak (0.5Hz) neutron source in ACU can mimic IBD via inelastic scattering and capture on iron.



Simulated neutron capture position

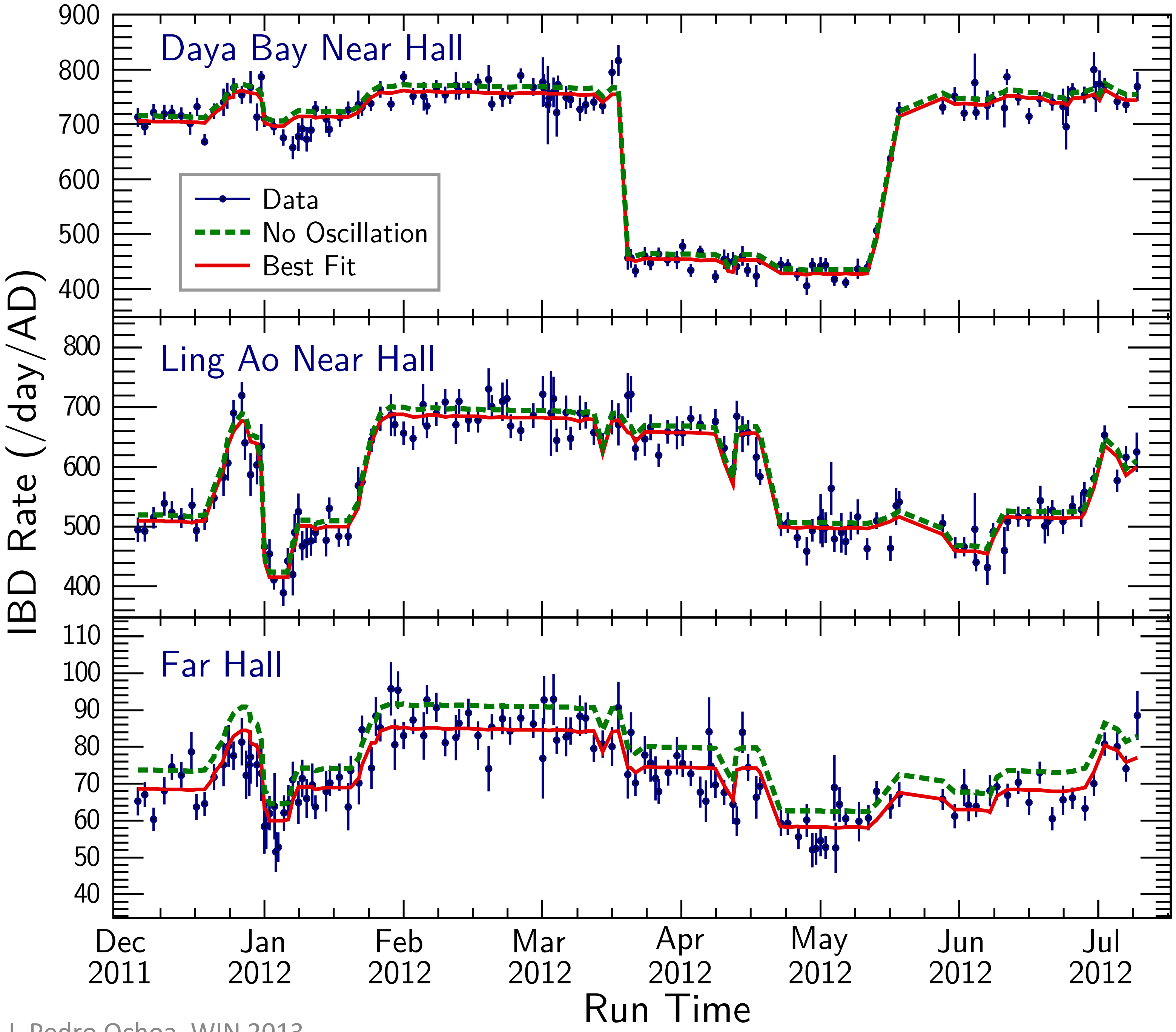


Constrain far site B/S to 0.3 ± 0.3%:

- Measure uncorrelated gamma rays from ACU in data
- Estimate ratio of correlated/uncorrelated rate using simulation
- Assume 100% uncertainty from simulation

Antineutrino Rates vs. Time

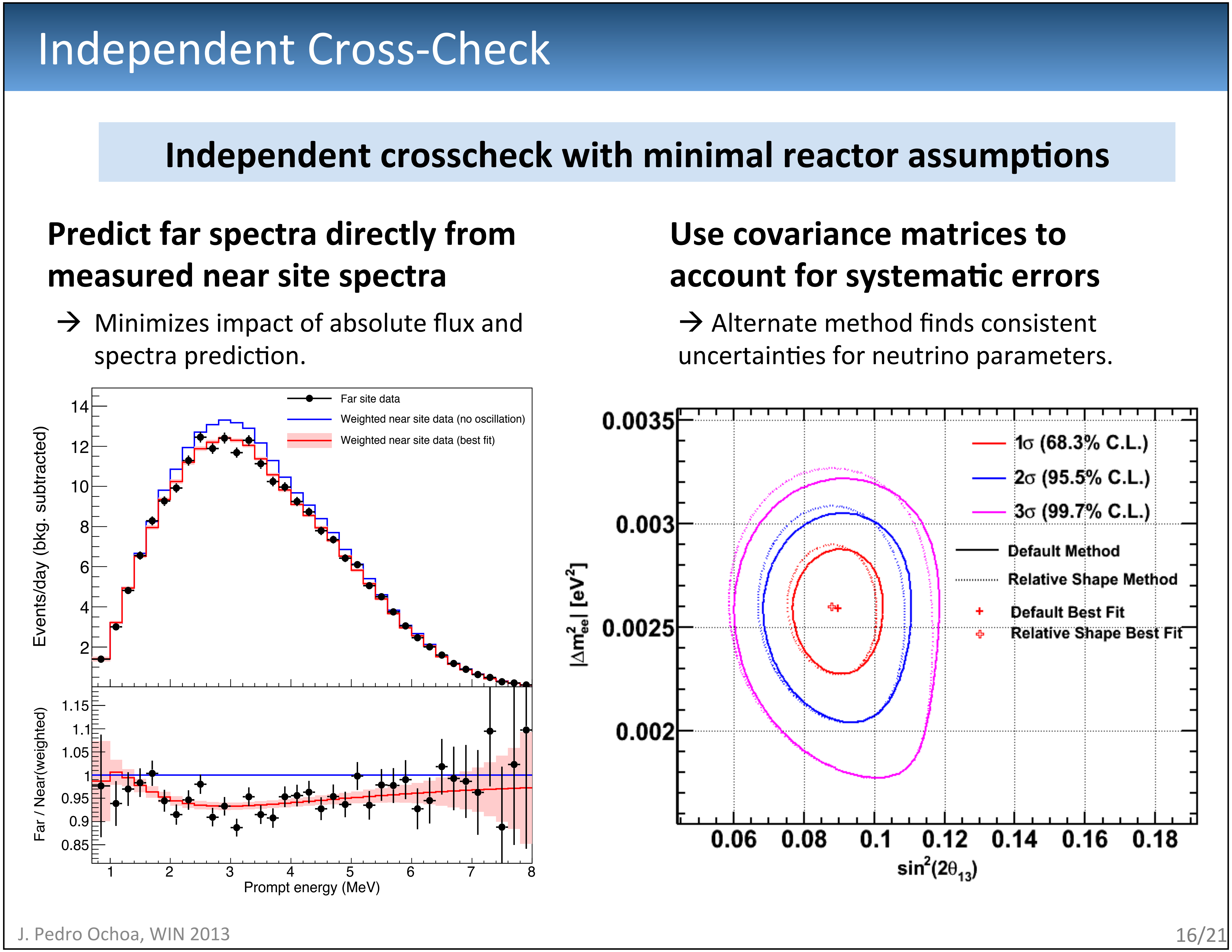
- For main analysis we simultaneously fit all detectors <u>using reactor model</u>, with the absolute normalization as a free parameter:



Note:

- Normalization is determined by fit to data. It is within a few percent of expectations.
- Paper on absolute reactor neutrino flux and shape is in preparation

Detected rate strongly correlated with reactor flux expectations



Independent Cross-Check

Independent crosscheck with minimal reactor assumptions

Predict far spectra directly from measured near site spectra

→ Minimizes impact of absolute flux and spectra prediction.

Use covariance matrices to account for systematic errors

→ Alternate method finds consistent uncertainties for neutrino parameters.

backup slides for RENO

RENO Collaboration

(12 institutions and 40 physicists)

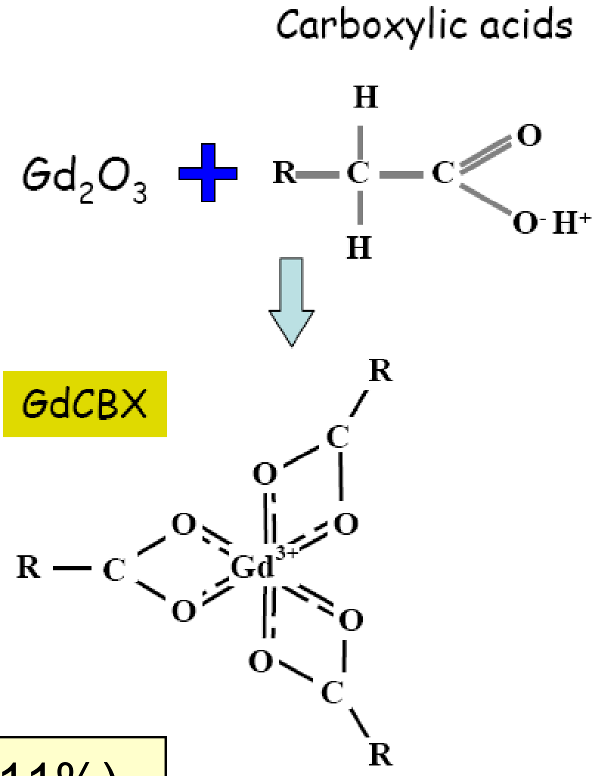
- Chonbuk National University
- Chonnam National University
- Chung-Ang University
- Dongshin University
- Gyeongsang National University
- Kyungpook National University
- Pusan National University
- Sejong University
- Seokyeong University
- Seoul National University
- Seoyeong University
- Sungkyunkwan University

- Total cost : $10M
- Start of project : 2006
- The first experiment running with both near & far detectors from Aug. 2011

Yonggwang reactor

→ Hanbit reactor (new name)

Gd Loaded Liquid Scintillator

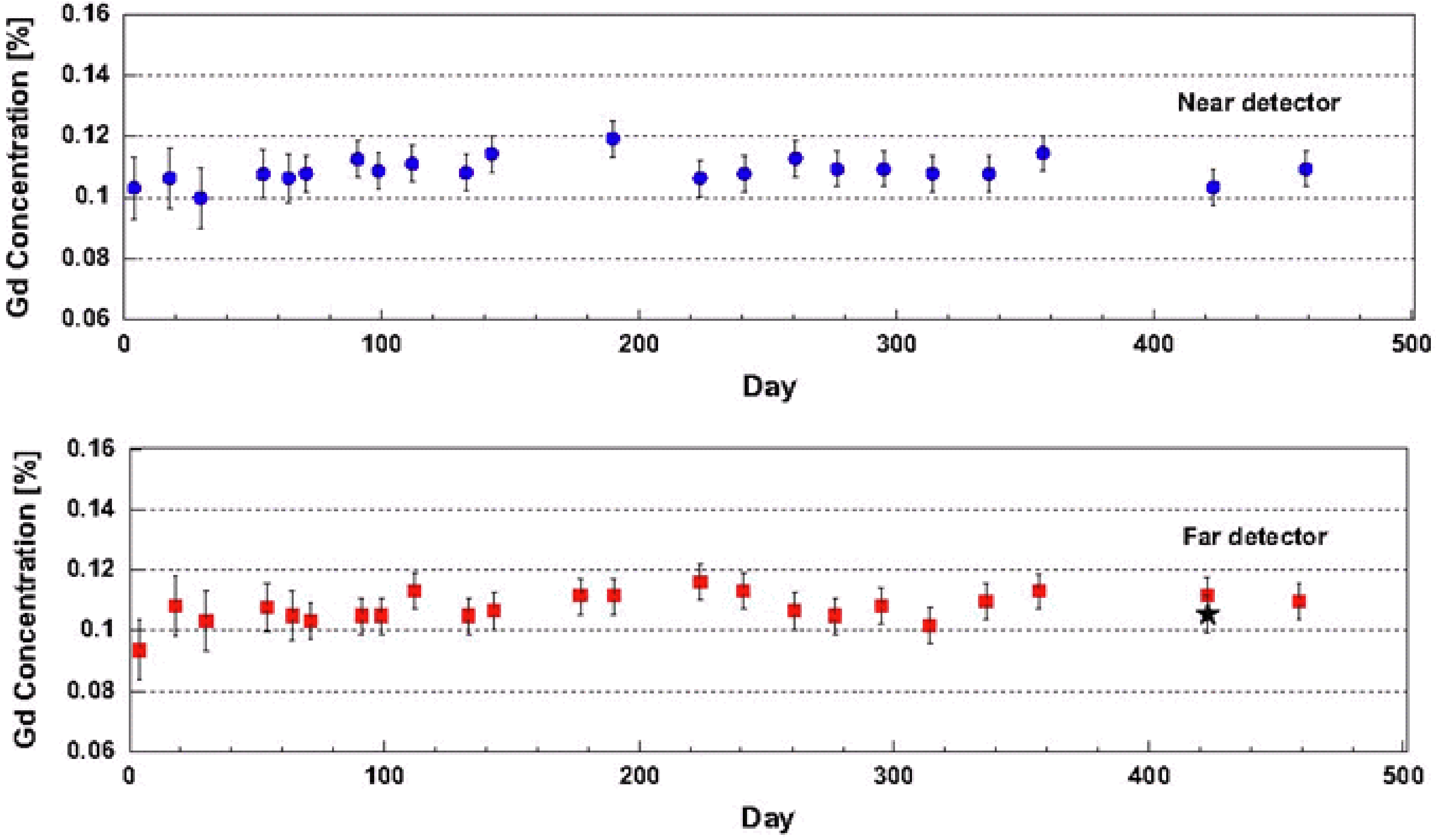


❑ Recipe of Liquid Scintillator

Solvent & Flour	WLS	Gd−compound
LAB	PPO + Bis−MSB	0.1% Gd + $(TMHA)^3$

❑ Steady properties of Gd-LS

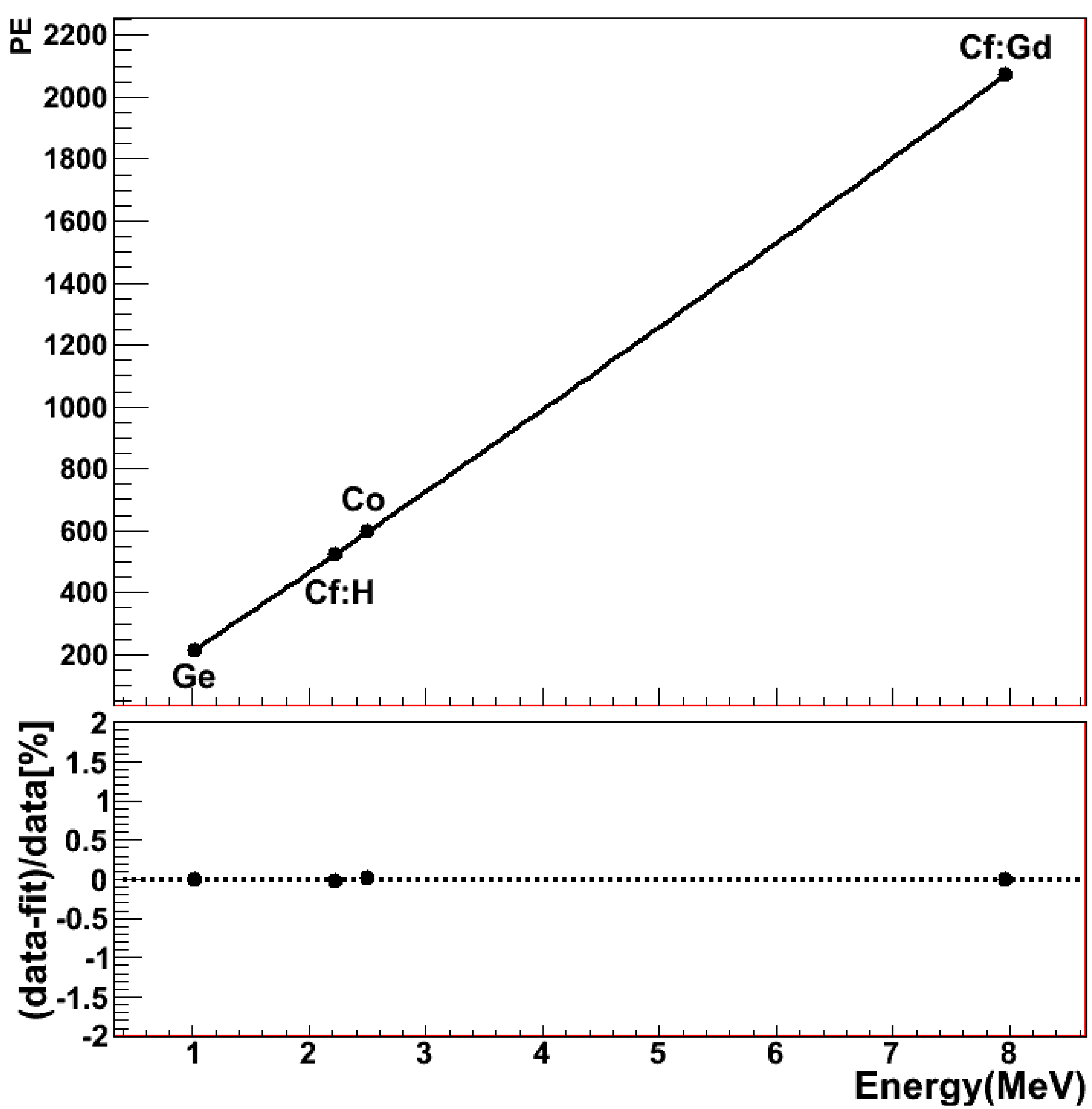
- Stable light yield (~250 pe/MeV) , transparency & Gd concentration (0.11%)



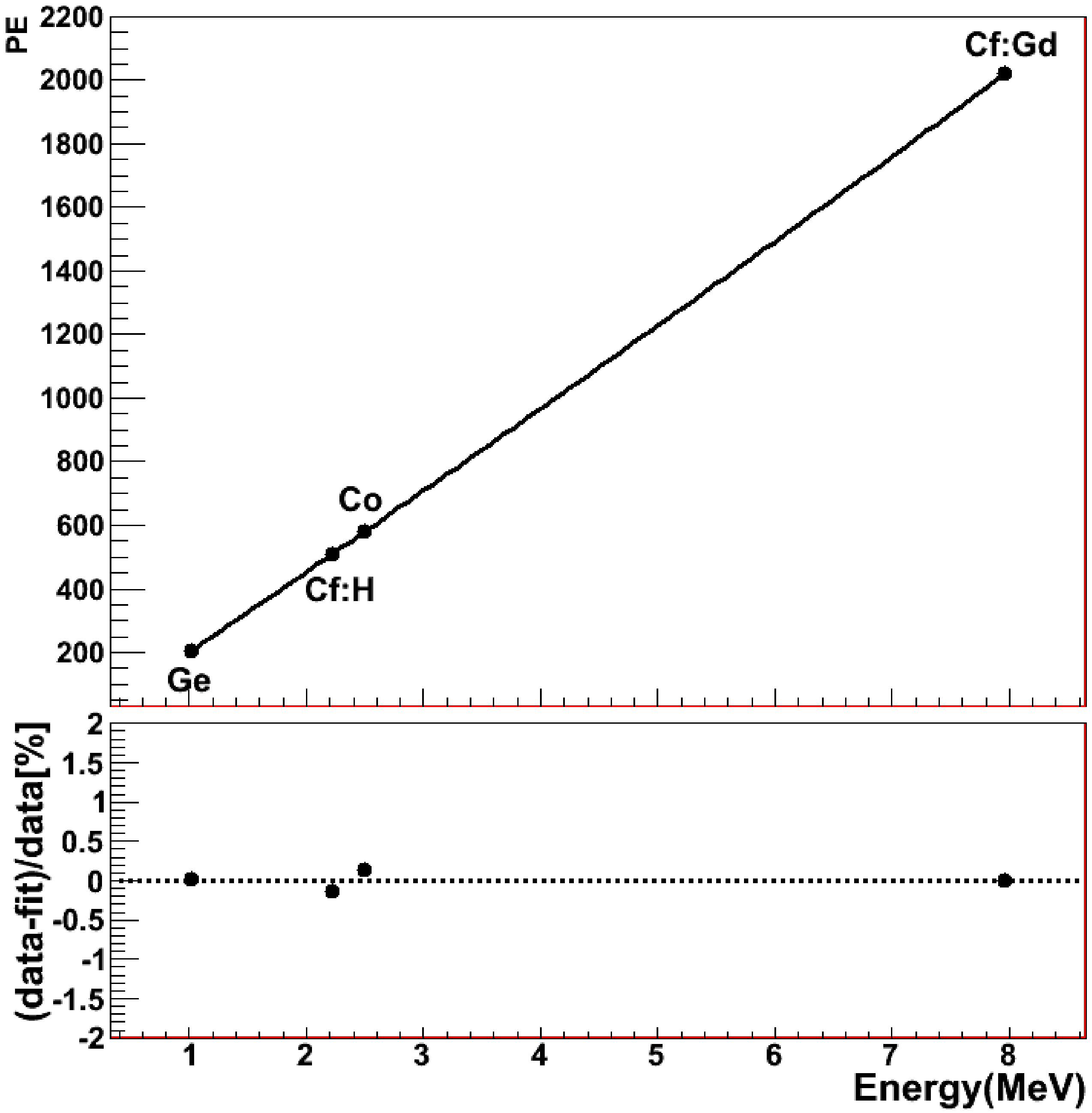
NIM A, 707, 45-53 (2013. 4. 11)

Energy calibration

by H. Seo @ WIN2013



Far Detector

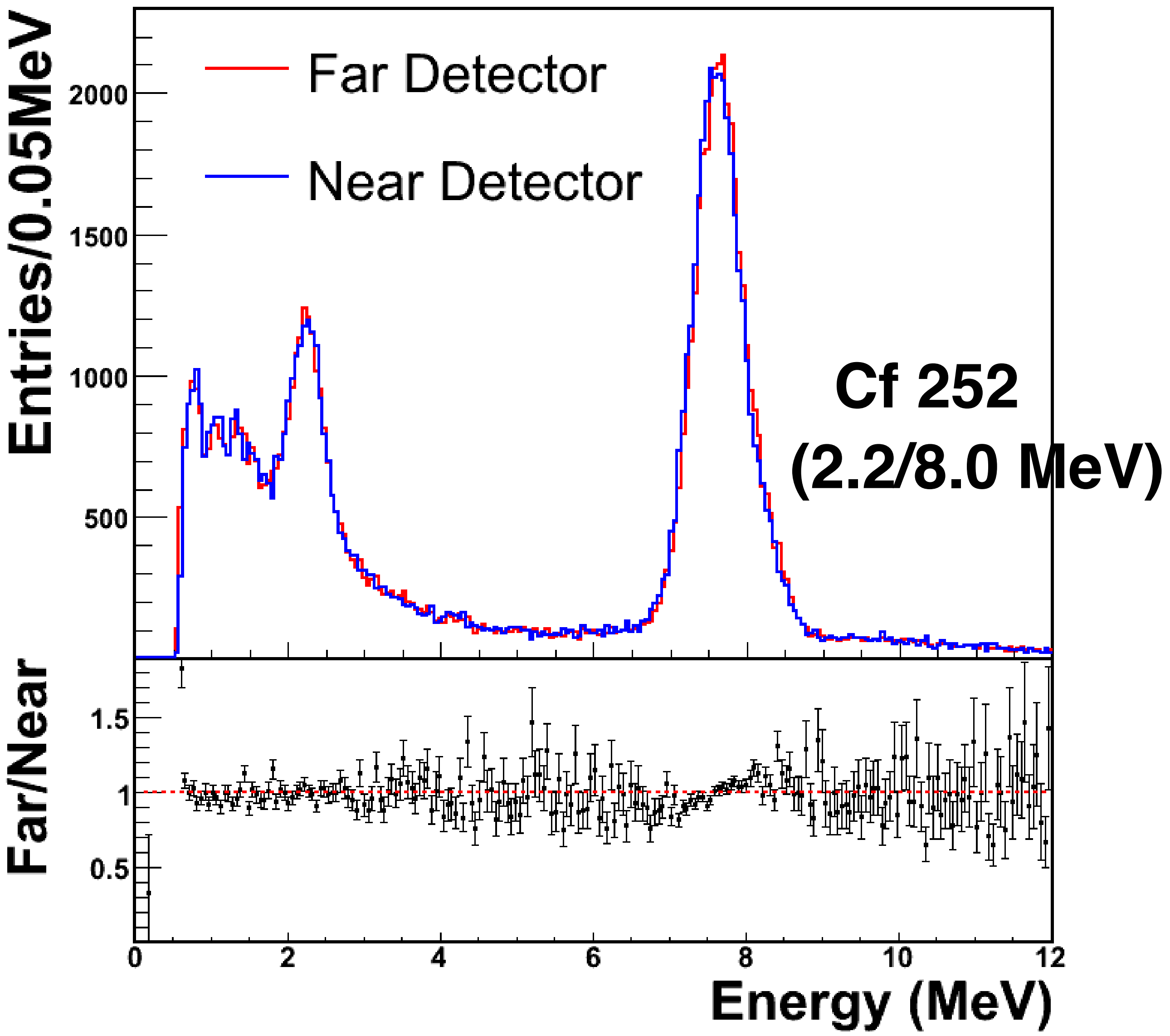


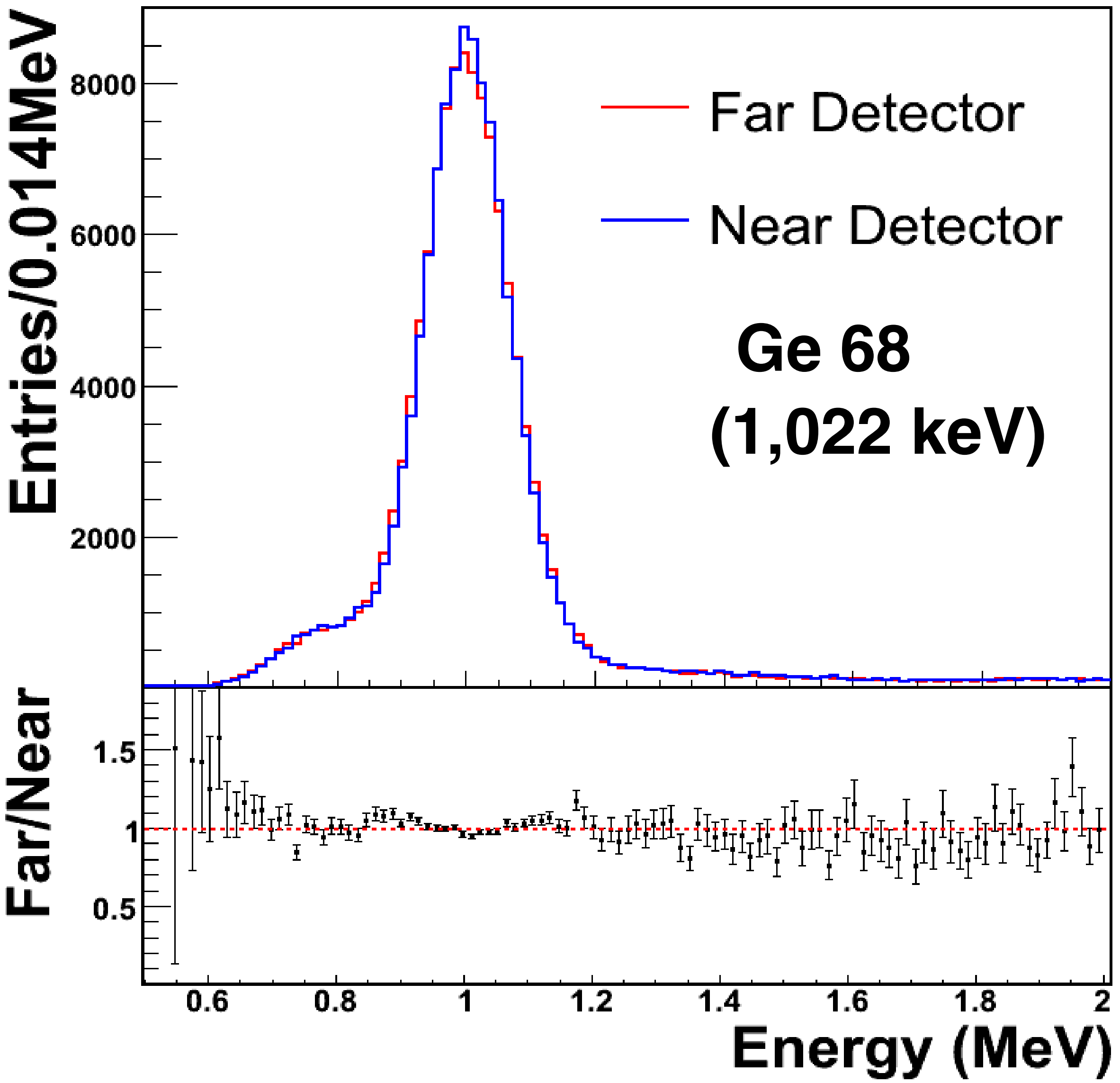
Near Detector

Fitting accuracy: 0.1%

Energy calibration

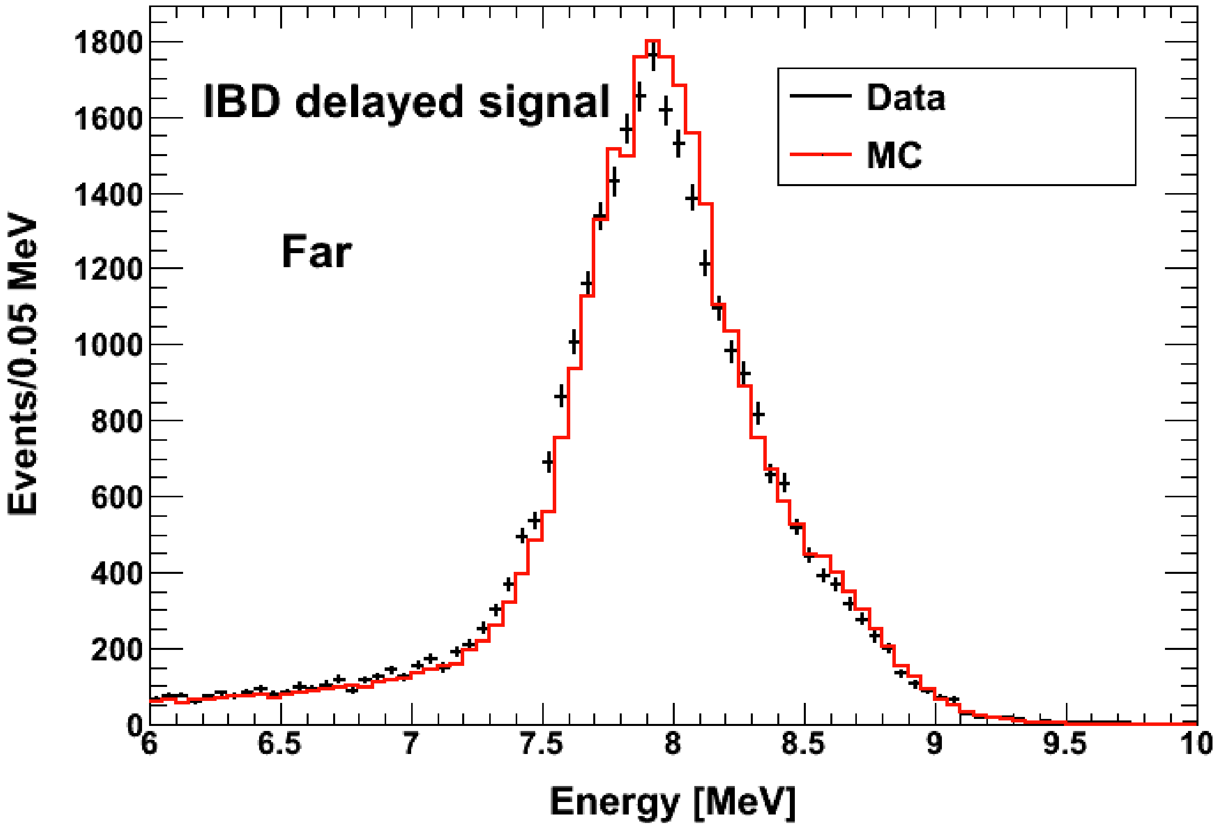
by H. Seo @ WIN2013

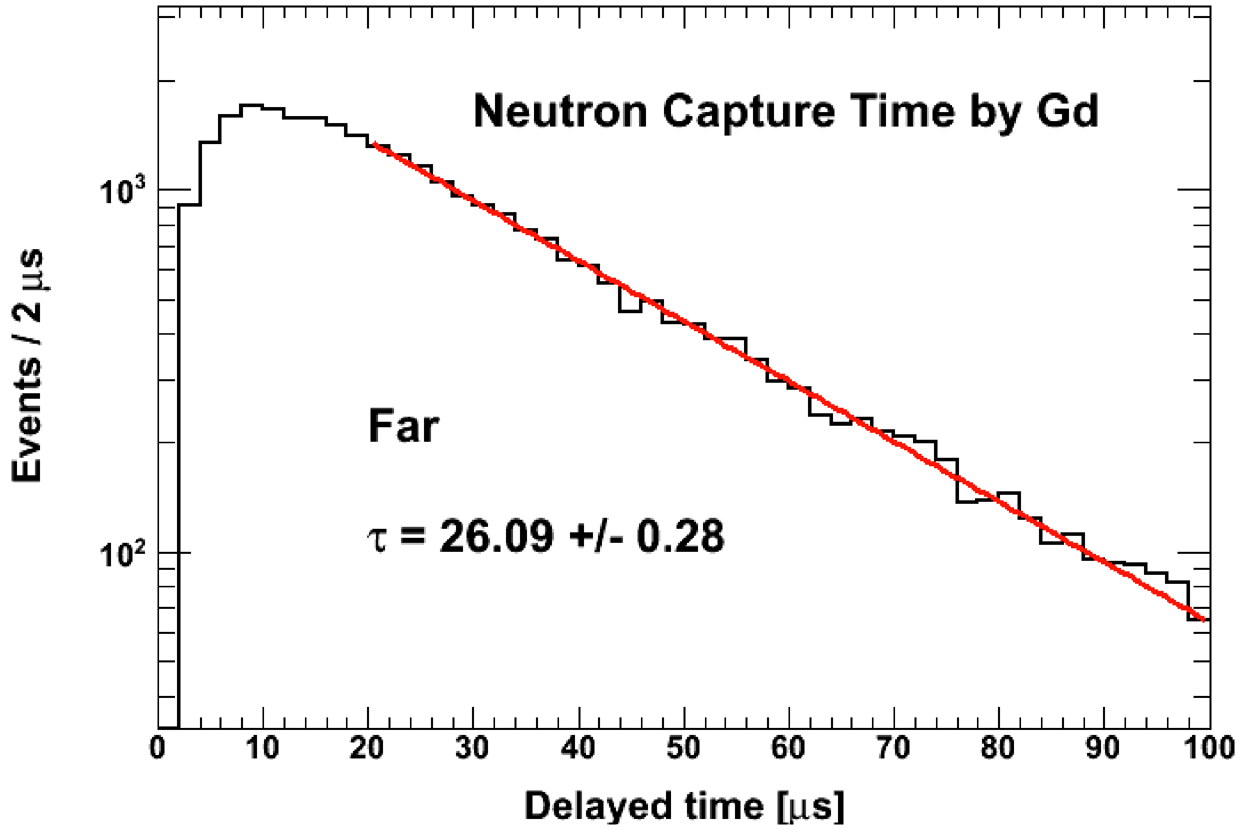


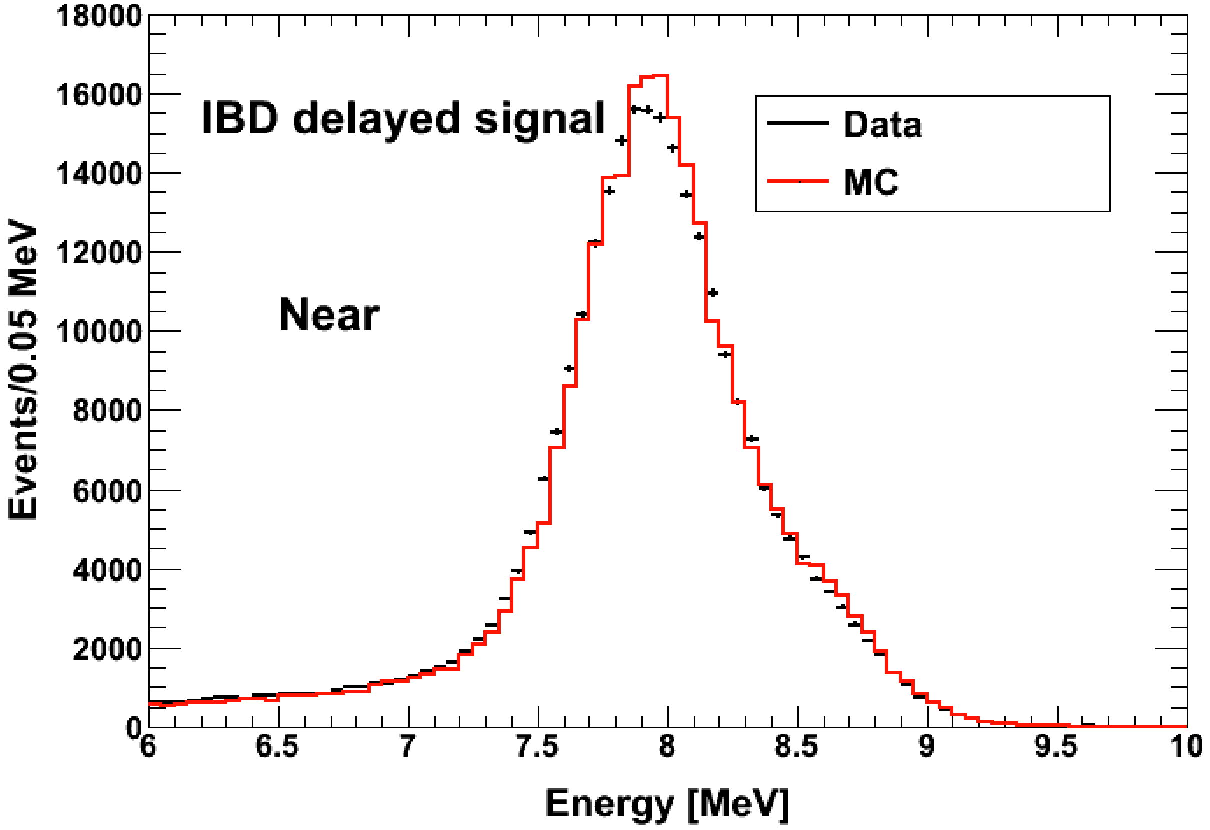


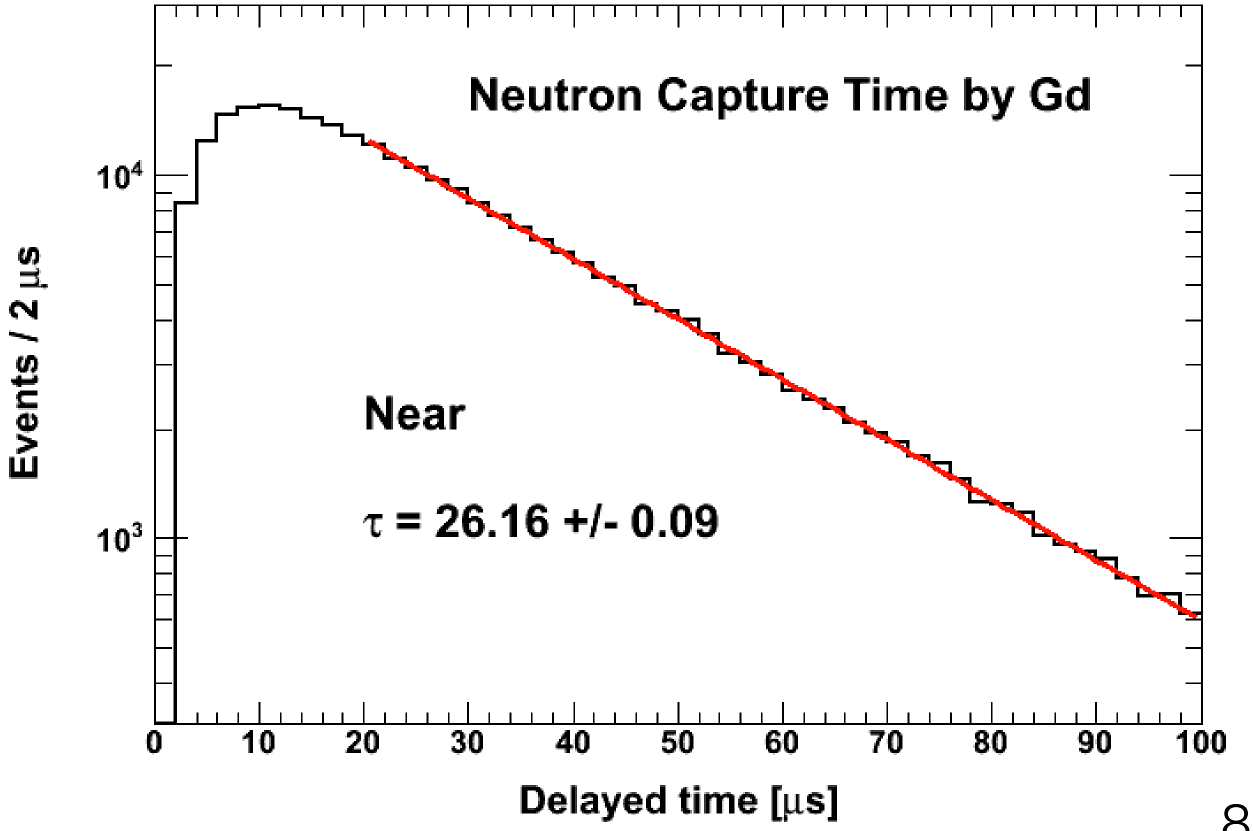
Neutron capture by Gd

by H. Seo @ WIN2013





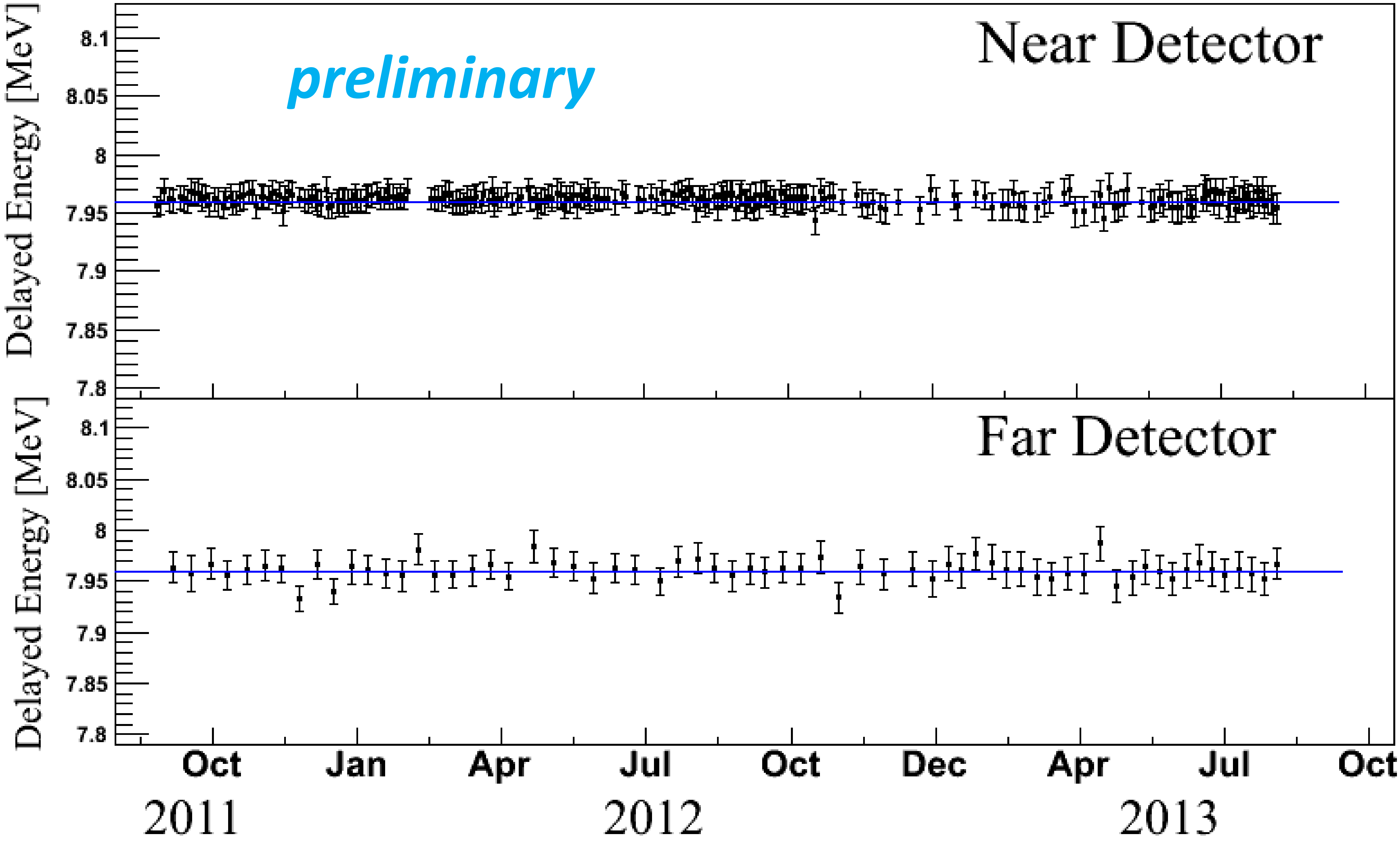




Detector stability of E-scale

by H. Seo @ WIN2013

IBD candidte's delayed signals (neutron capture by Gd)

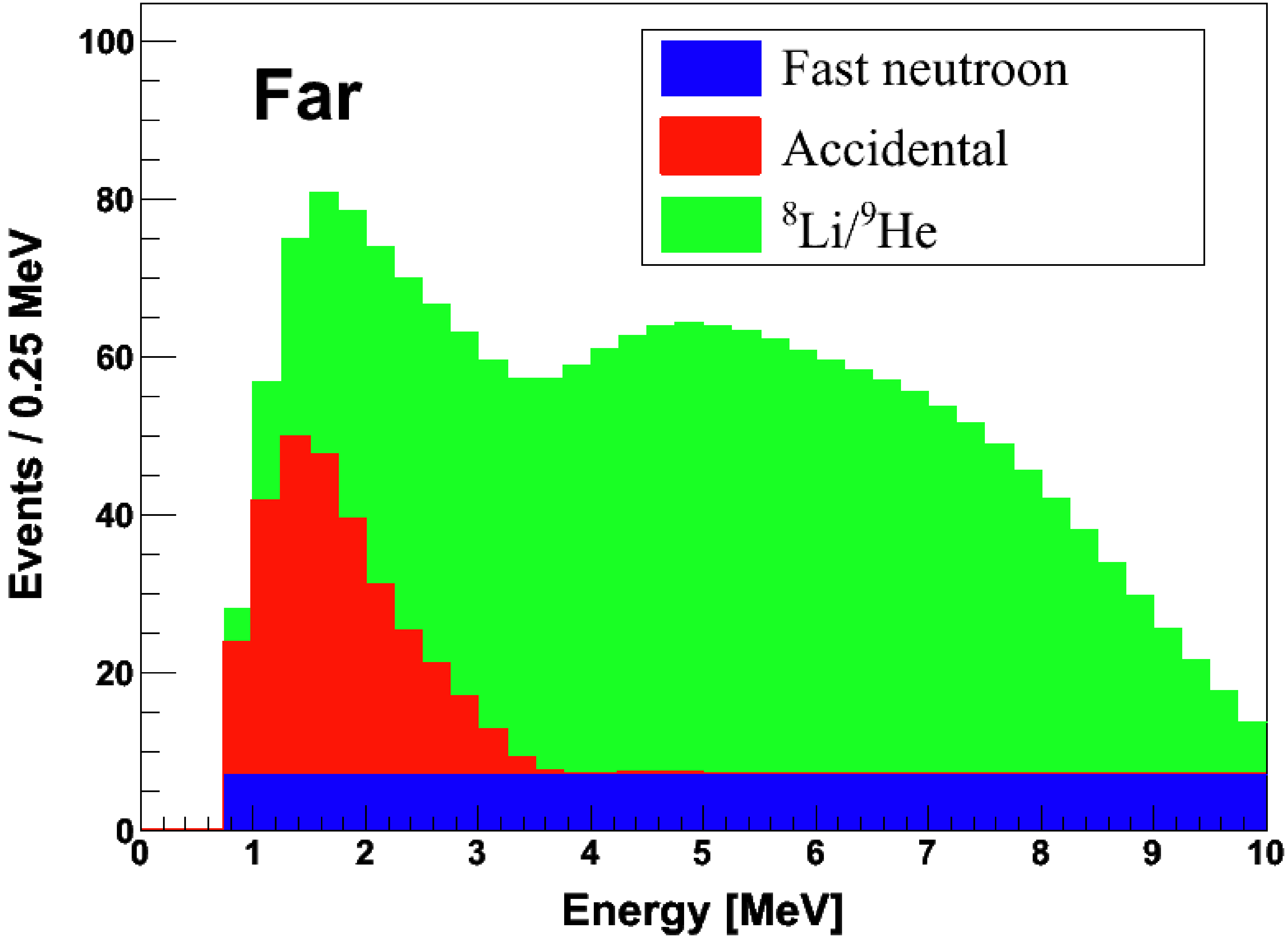


Background spectra

by H. Seo @ WIN2013

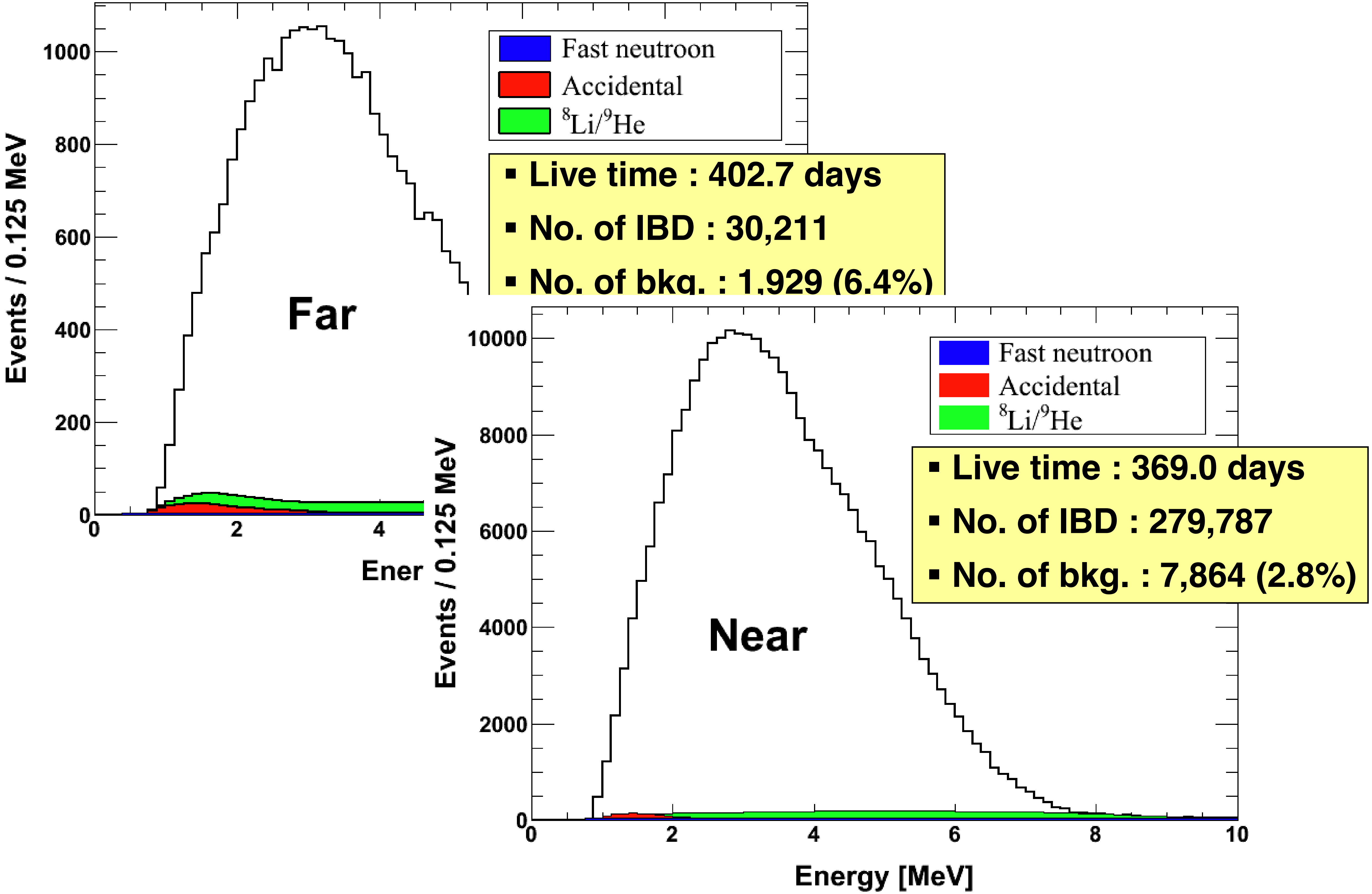
- Background shapes and rates are well understood

- Total backgrounds : 6.4% at Far
  2.8% at Near



Measured spectra of IBD prompt signal

by H. Seo @ WIN2013



- **Live time : 402.7 days**
- **No. of IBD : 30,211**
- **No. of bkg. : 1,929 (6.4%)**

- **Live time : 369.0 days**
- **No. of IBD : 279,787**
- **No. of bkg. : 7,864 (2.8%)**

Summary of final data sample

by H. Seo @ WIN2013

Detector	Near	Far
Selected events	279787	30211
Total background rate [day^{-1}]	21.17±1.81	4.80±0.46
IBD rate after bkg. subtraction [day^{-1}]	737.00±2.31	70.22±0.64
DAQ live time [days]	369.03	402.69
Detection efficiency	62.0±0.014 %	71.4±0.014 %
Accidental rate [day^{-1}]	3.61±0.05	0.60±0.03
9Li/8He rate [day^{-1}]	13.97±1.54	3.55±0.45
Fast neutron rate [day^{-1}]	3.59±0.95	0.65±0.10

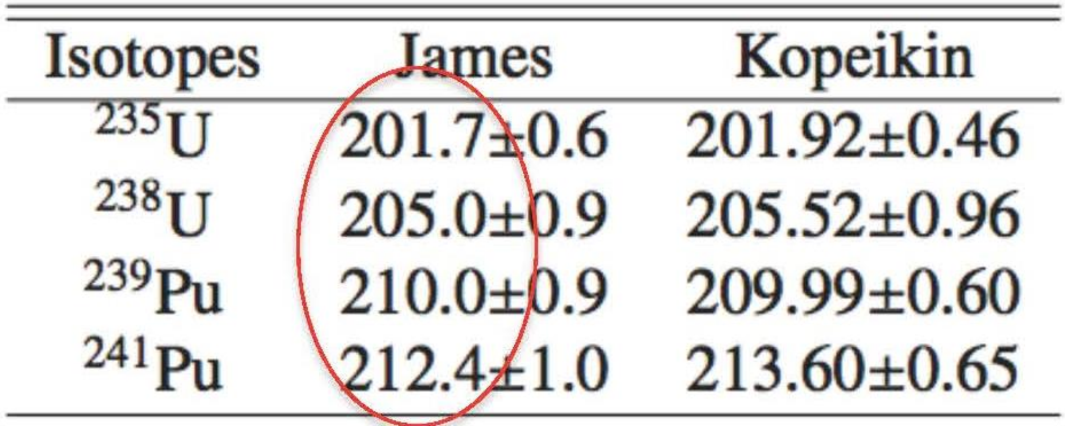
(Prompt energy < 10 MeV)

Expected Reactor Antineutrino Fluxes

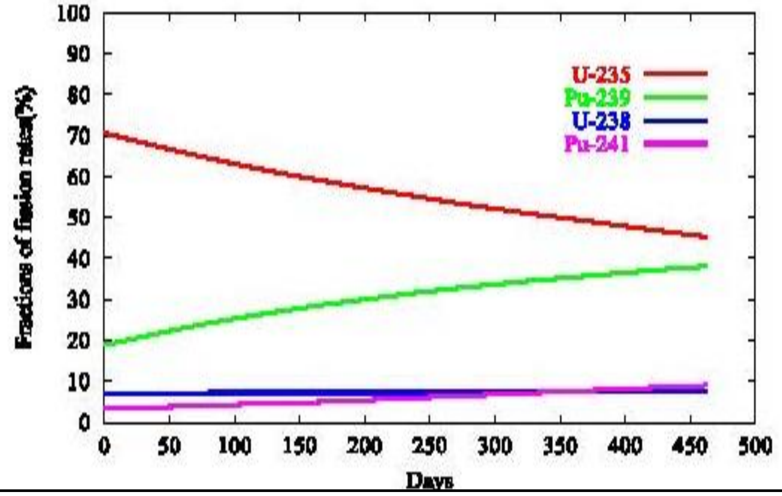
- Reactor neutrino flux

$$\Phi(E_\nu) = \frac{P_{th}}{\sum_i^{isotopes} f_i \cdot E_i} \sum_i^{isotopes} f_i \cdot \phi_i(E_\nu)$$

- P_{th} : Reactor thermal power provided by the YG nuclear power plant
- f_i : Fission fraction of each isotope determined by reactor core simulation of Westinghouse ANC
- $\phi_i(E_\nu)$: Neutrino spectrum of each fission isotope
  [* P. Huber, Phys. Rev. C84, 024617 (2011)
  T. Mueller *et al*., Phys. Rev. C83, 054615 (2011)]
- E_i : Energy released per fission
  [* V. Kopeikin *et al*., Phys. Atom. Nucl. 67, 1982 (2004)]



Isotopes	James	Kopeikin
^{235}U	201.7±0.6	201.92±0.46
^{238}U	205.0±0.9	205.52±0.96
^{239}Pu	210.0±0.9	209.99±0.60
^{241}Pu	212.4±1.0	213.60±0.65

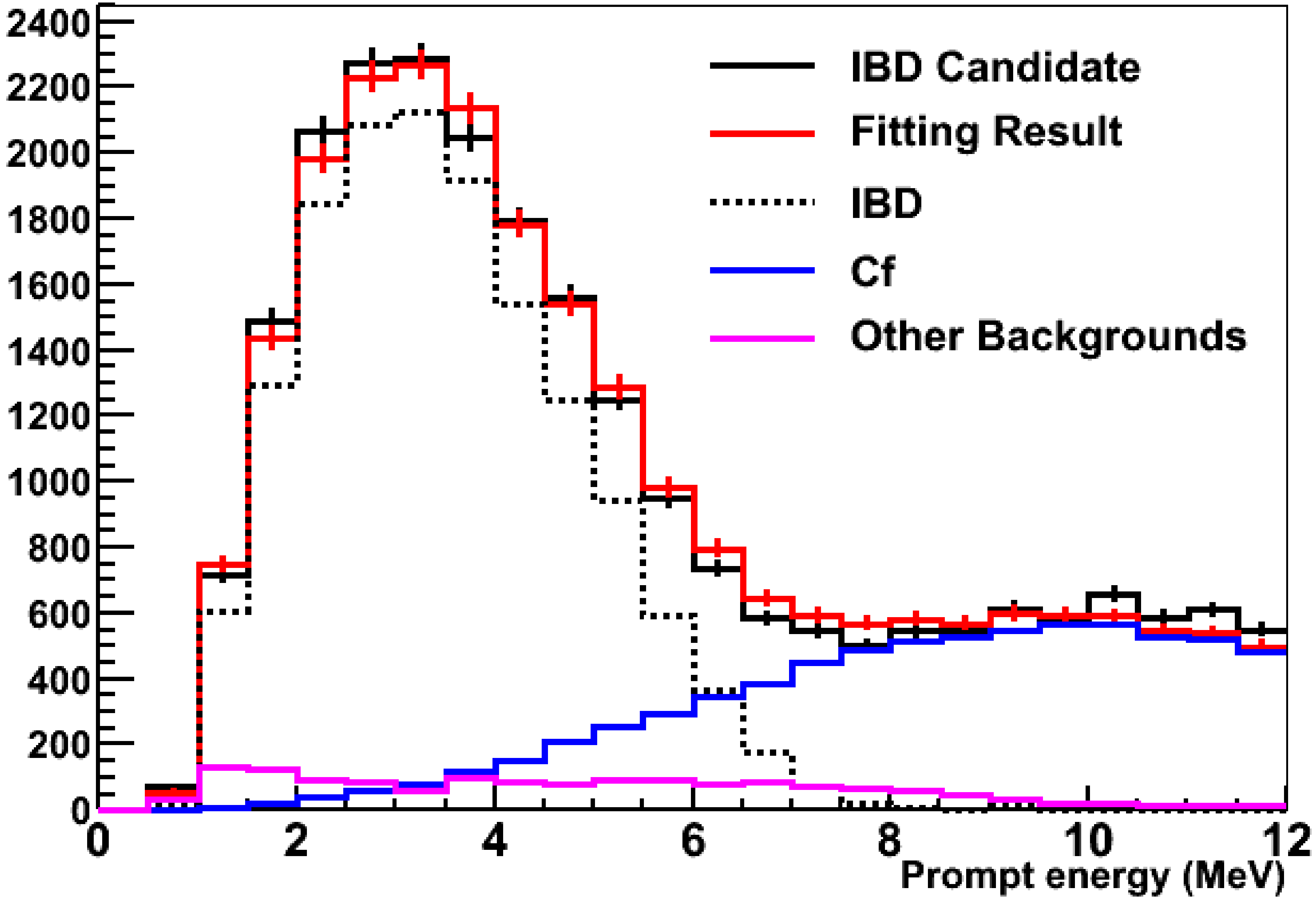


Spectrum of ^{252}Cf contaminated data

by H. Seo @ WIN2013

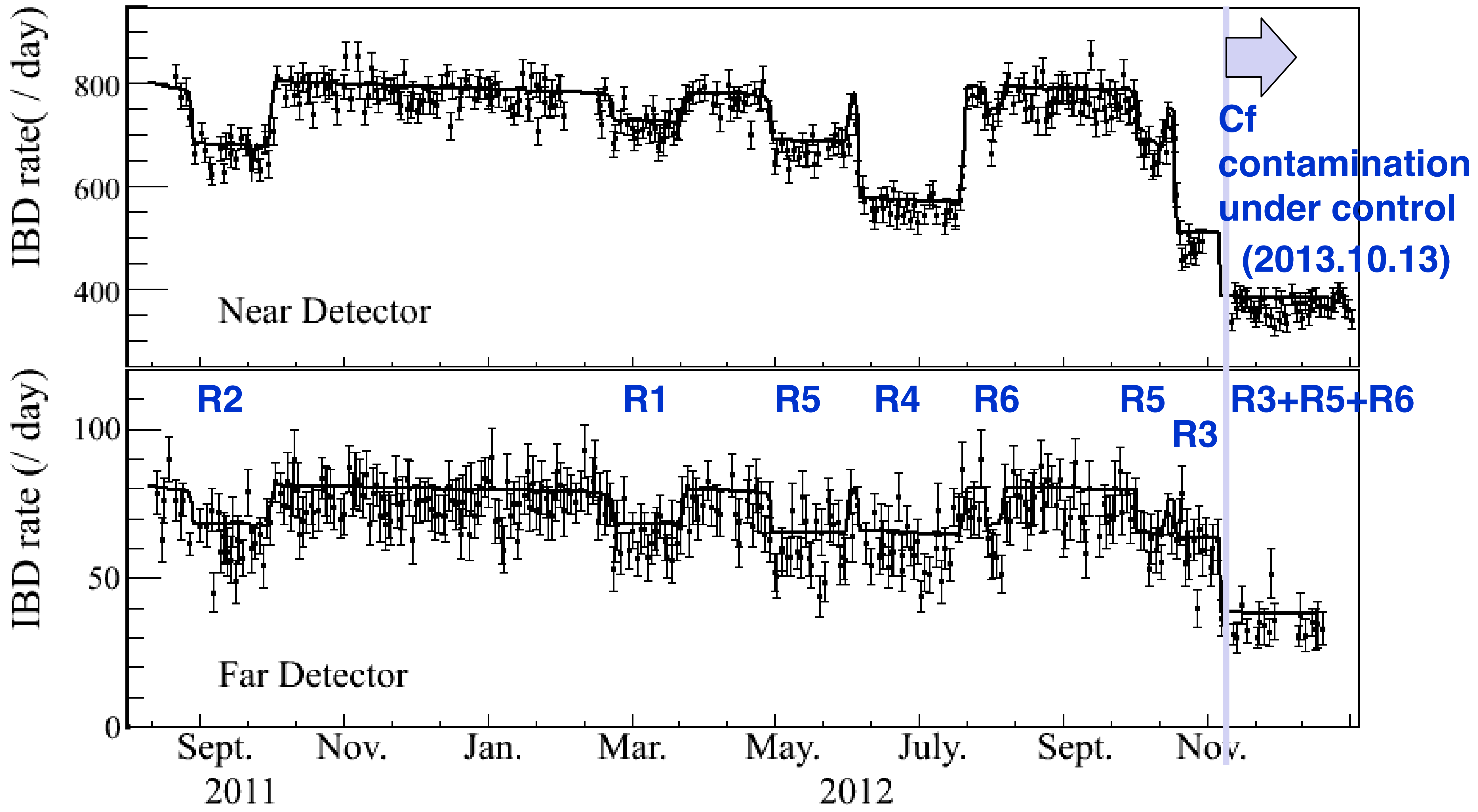
IBD (/day) : 54.5094 +- 0.489393
Cf (/day): 26.2655 +- 0.361229

13th Oct. 2012 ~ 25th July. 2013



Observed daily IBD rate

by H. Seo @ WIN2013

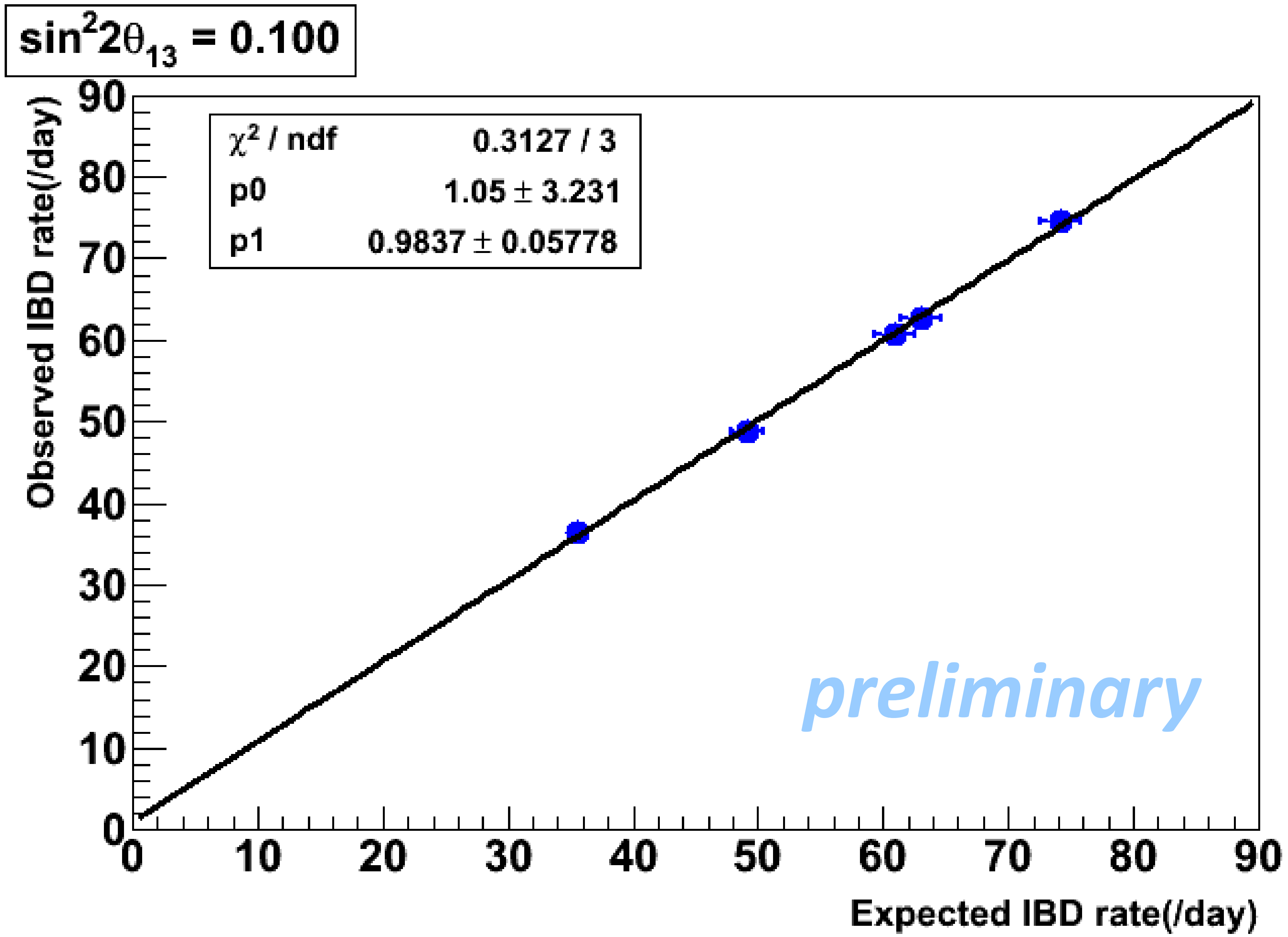


Cf contamination under control (2013.10.13)

R2 R1 R5 R4 R6 R5 R3 R3+R5+R6

Observed vs Expected IBD rate

by H. Seo @ WIN2013



- A good agreement between observed and expected rates with oscillation hypothesis
- Correct background subtraction