Measurement of $\sin^2 2\theta_{13}$ with Reactor Electron-Antineutrino Disappearance

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College of William and Mary

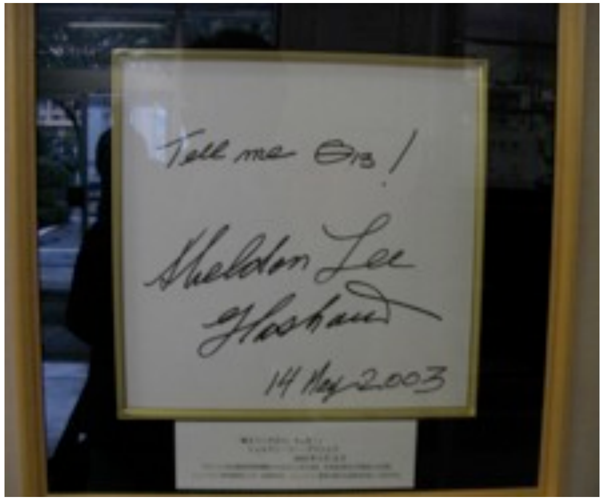
PHENO12, Pittsburgh

- *A brief review of theta13 in PMNS*
- *Daya Bay made a 5-sigma discovery*
- *Other current generation reactor neutrino experiments*
- *Summary*

Our Field Had a Breakthrough in March 2012

$$
\begin{aligned}
U_{PMNS} &= \begin{pmatrix} 1 & 0 & 0 \\ 0 & \cos\theta_{23} & \sin\theta_{23} \\ 0 & -\sin\theta_{23} & \cos\theta_{23} \end{pmatrix} \begin{pmatrix} \cos\theta_{13} & 0 & e^{-i\delta_{CP}}\sin\theta_{13} \\ 0 & 1 & 0 \\ -e^{i\delta_{CP}}\sin\theta_{13} & 0 & \cos\theta_{13} \end{pmatrix} \begin{pmatrix} \cos\theta_{12} & \sin\theta_{12} & 0 \\ -\sin\theta_{12} & \cos\theta_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix} \\
&= (V_{\alpha i})
\end{aligned}
$$

$$P_{\nu_\alpha \to \nu_\beta} = 1 - 4\sum_{i<j} |V_{\alpha j}|^2 |V_{\beta i}|^2 \sin^2 \frac{\Delta m^2_{ji} L}{4E}$$



Tell me θ_{13}!

Sheldon Lee Glashow

14 May 2003

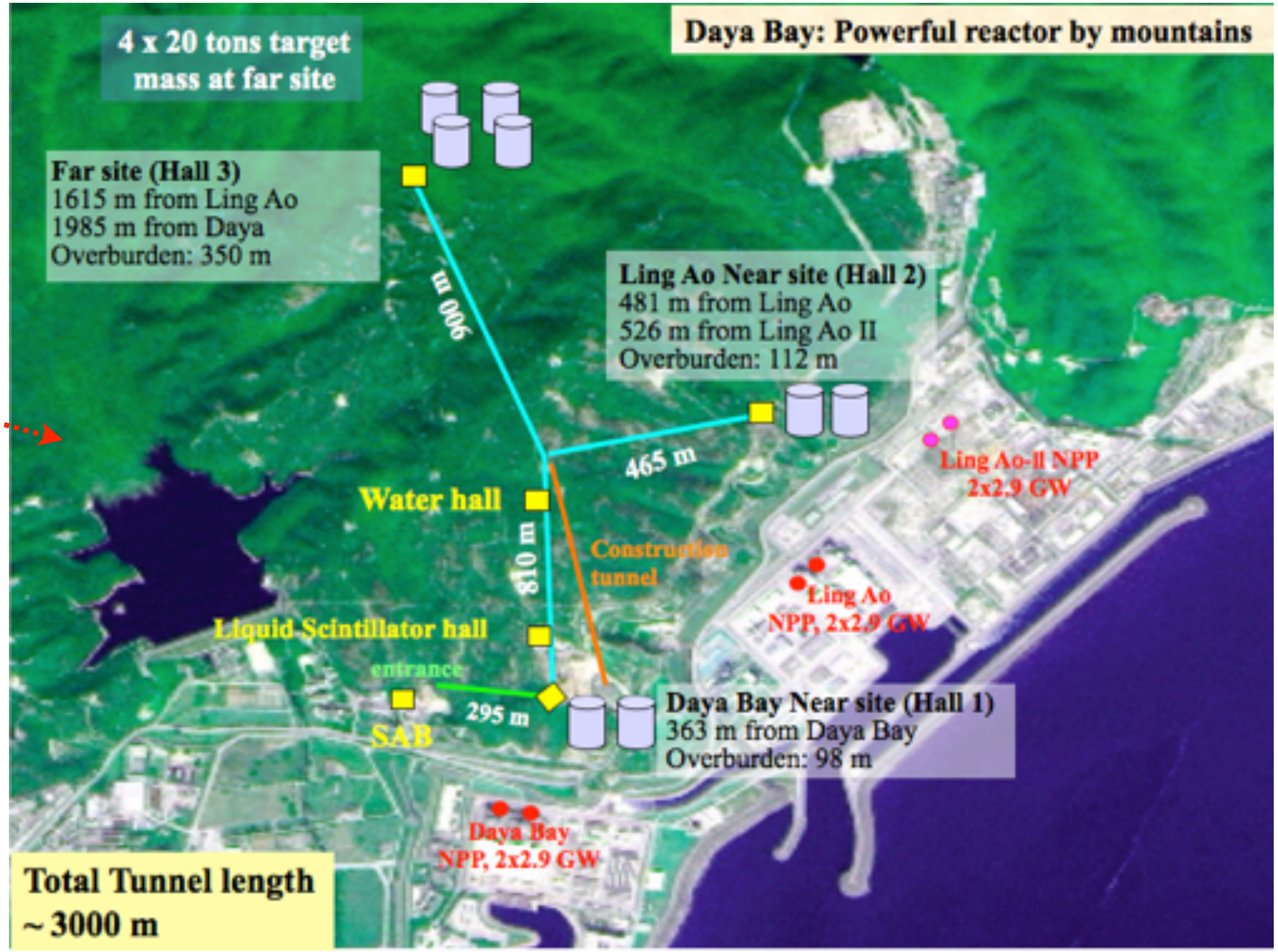
- There are two ways to measure θ_{13}
  - Appearance experiments $\nu_\mu \rightarrow \nu_e$ depends on 3 unknown parameters θ_{13}, δ_{CP} and mass hierarchy (and θ_{23} octant):
    - Summer 2011, T2K published $\sin^2 2\theta_{13} > 0$ with ~2.5-sigma significance. MINOS had consistent results
  - Short-baseline reactor experiments depends on 2 unknown parameters θ_{13} and mass hierarchy, with mass hierarchy has little effect:
    - Before 2011, Chooz was what we had: $\sin^2 2\theta_{13} < 0.17$ @ 90% confidence level
    - Right before Xmas 2011, Double Chooz showed an indication $\sin^2 2\theta_{13} > 0$
- On March 8, 2012, Daya Bay announced $\sin^2 2\theta_{13} > 0$ with >5-sigma significance for the first time. In April 2012, RENO announced their consistent measurement.

The Daya Bay Reactor Neutrino Experiment

To reach ~0.01 in $\sin^2 2\theta_{13}$

@ the Daya Bay Plant, China

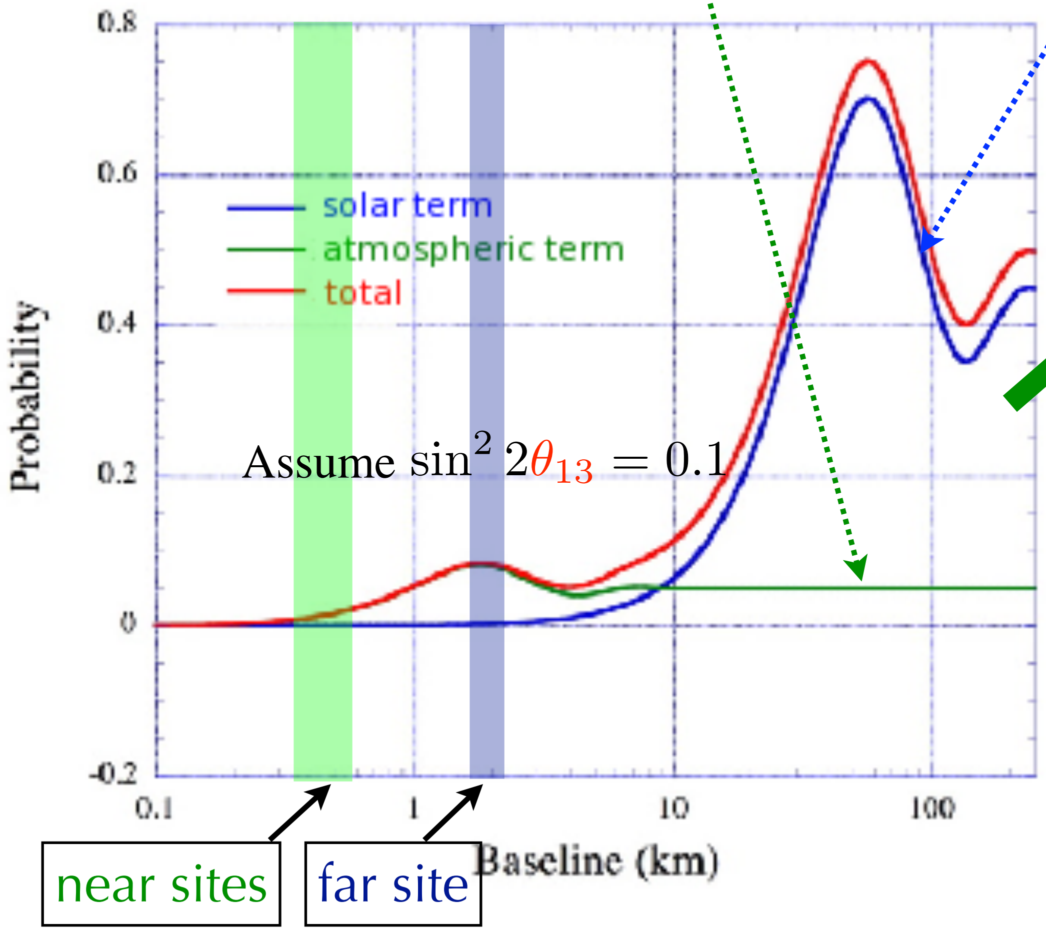
$$\frac{N_f}{N_n} = \frac{N_{\mathrm{proton},f}}{N_{\mathrm{proton},n}} \frac{\epsilon_f}{\epsilon_n} \left(\frac{L_n}{L_f}\right)^2 \frac{P_{sur}(\sin^2 2\theta_{13}, L_f, E)}{P_{sur}(\sin^2 2\theta_{13}, L_n, E)}$$



- 2 near-sites + 1 far-site
- 8 functionally **"identical"** 20 t antineutrino detectors
- Near-far flux uncertainty **cancellation**: a factor of ~20 suppression

Oscillation Maximum: Daya Bay Baseline Choices

$$P_{\bar{\nu}_e \to \bar{\nu}_x} = \sin^2 2\theta_{13} \sin^2\left(\frac{\Delta m^2_{31} L}{4E}\right) + \cos^4 \theta_{13} \sin^2 2\theta_{12} \sin^2\left(\frac{\Delta m^2_{21} L}{4E}\right)$$



Assume $\sin^2 2\theta_{13} = 0.1$

Baselines (m) (rough numbers)

	DYB Site	LA Site	Far Site
DYB	364	1348	1912
LA	857	480	1540
LA II	1307	528	1548

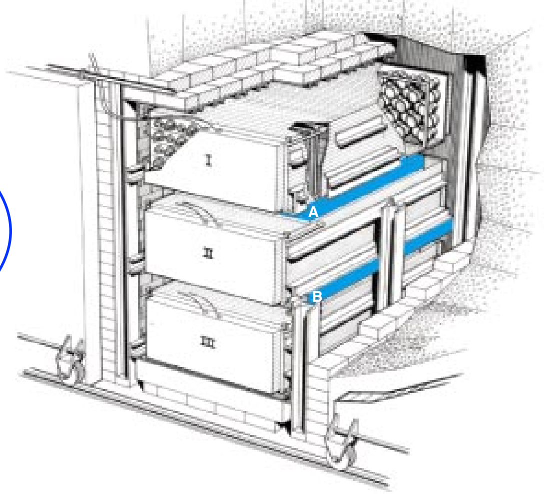
Expected events (when designed)

	DYB Site	LA Site	Far Site
IBD Evts (/det/day)	840	760	90
BKG Evts (/det/day)	<0.6%	<0.5%	<0.4%

The Well Known Time Correlation Detection Technique

Daya Bay: 0.1% Gd doped liquid scintillator as target

In 1956, Savannah River Detector used Cd

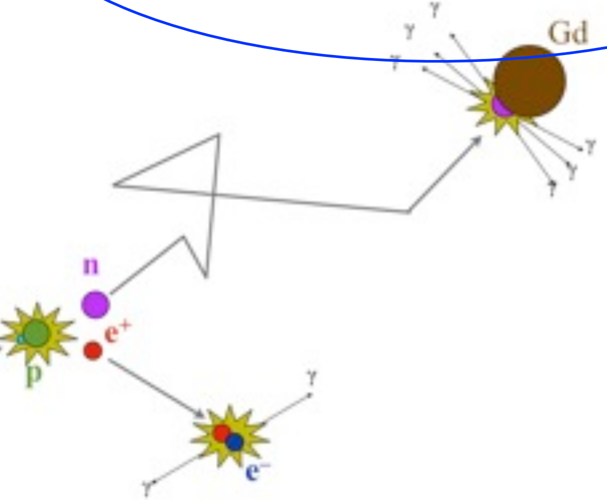


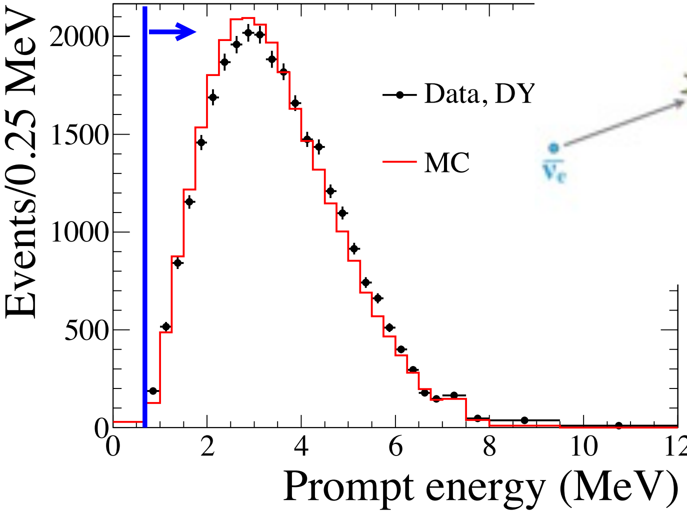
$$\bar{\nu}_e + p \rightarrow e^+ + n$$

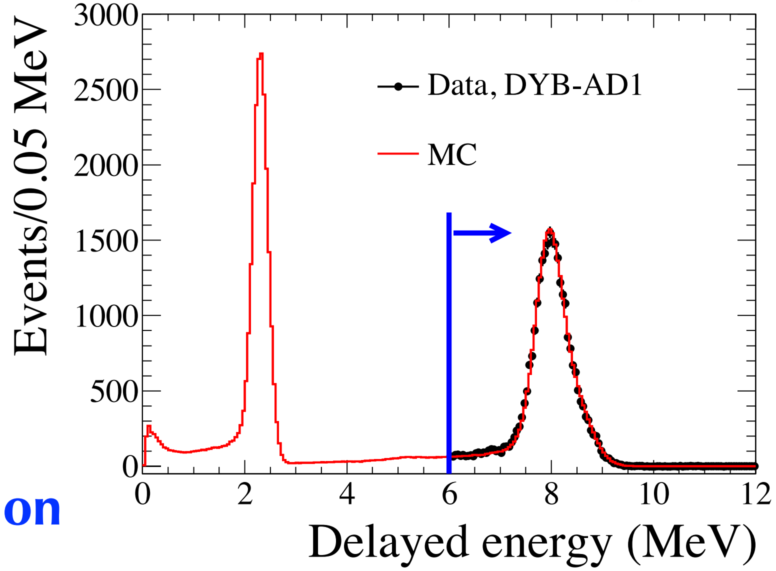
0.3b: $n + p \rightarrow D + \gamma(2.2\,\mathrm{MeV})$

~49,000b: $n + Gd \rightarrow Gd^* \rightarrow Gd + \gamma(\sim 8\,\mathrm{MeV})$

$$E_{\bar{\nu}_e} \approx E_{e^+} + m_n - m_p$$



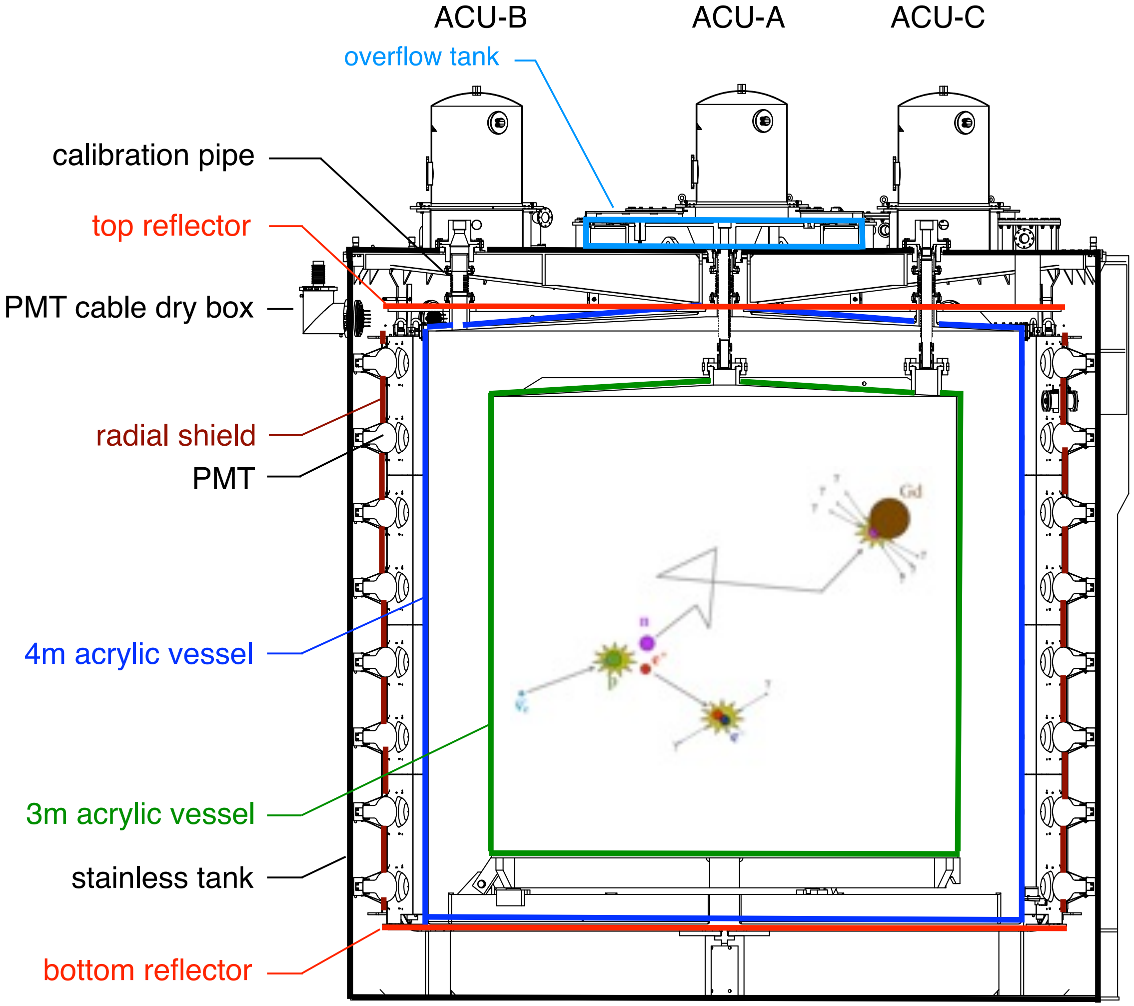




Correlated Signals

- **Background suppression**
- **Well-defined target zone**

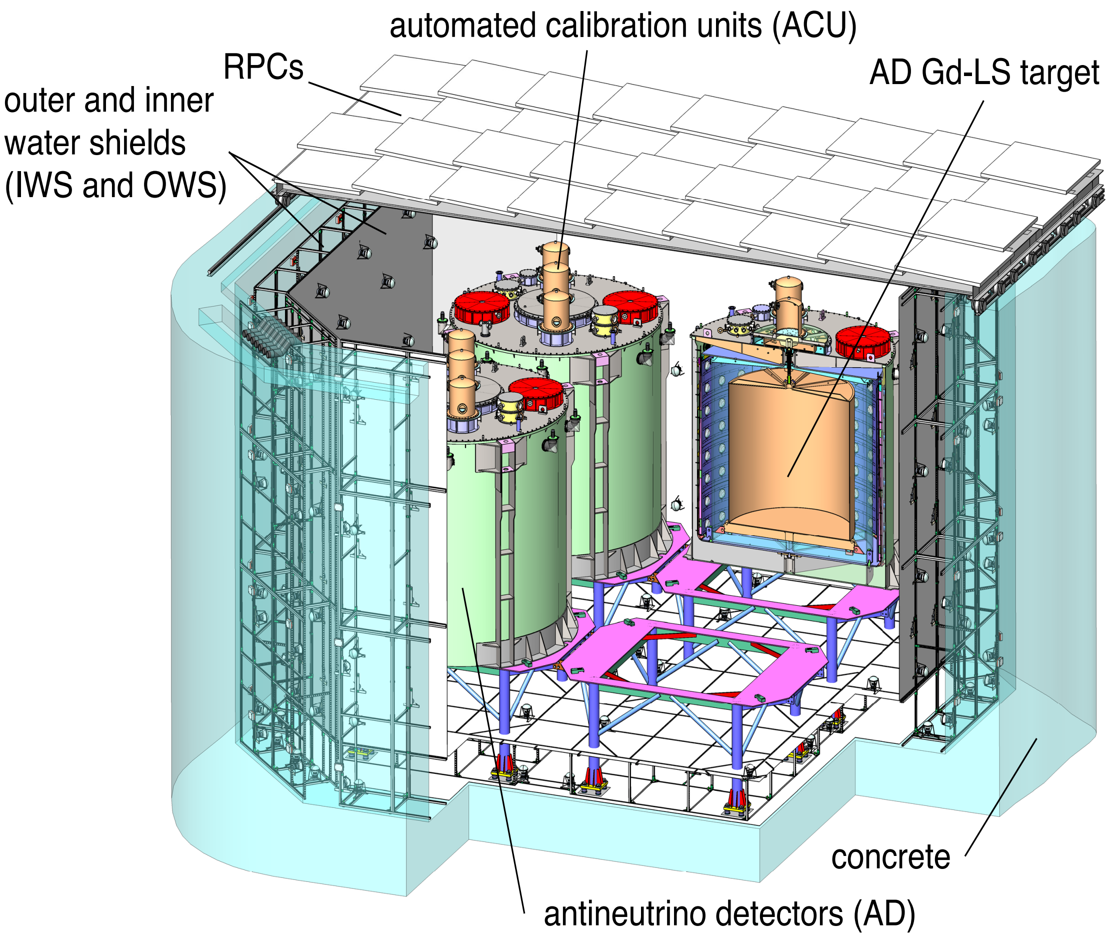
A 3-Zone Antineutrino Detector via Inverse Beta Decay



- **Well-defined target zone**
- **Well-controlled detection uncertainty**

- The inner most zone of 0.1% doped Gd-LS as target, LS as gamma catcher and mineral oil to shield radiative backgrounds
  - **Well-defined target mass: Measured during filling and monitored during data taking to 0.02%**
- 192 PMTs+ top/bottom reflectors to sufficient and uniform photon collection
- Automatic Calibration Units in both Gd-LS and LS zones
  - To calibrate PMTs and detector energy scales key to select IBD events
  - With data and other calibration means: **Prompt energy cut uncertainty negligible 0.01%; Delayed energy cut relative uncertainty 0.12%**

Muon Veto System to Reduce Background



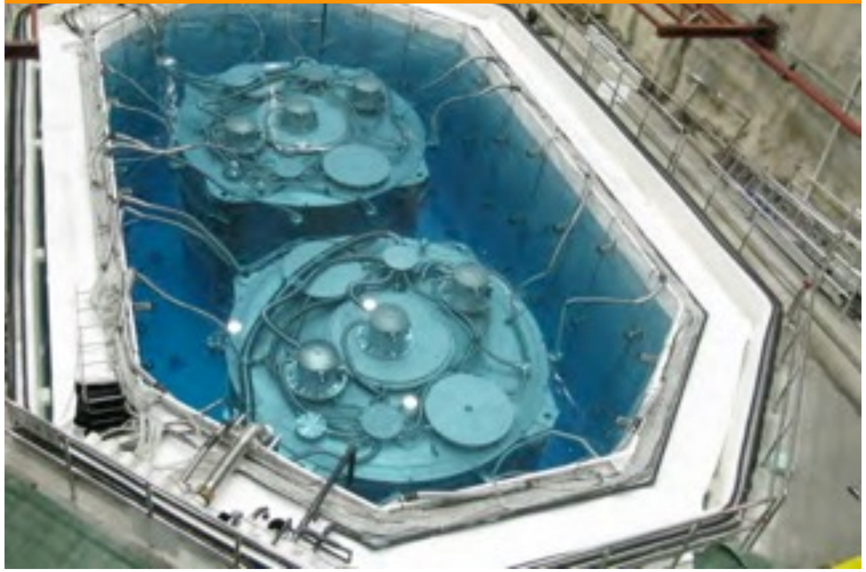
- ADs are submerged in water Cherenkov/RPC veto
  - Water Cherenkov has light isolated inner and outer parts
  - 4 layers of RPC on top
- Negative impact of cosmic ray muons
  - Live time loss
  - Muon induced backgrounds
    - Long-lived cosmogenic isotopes that have IBD like signals: ^{8}He/^{9}Li
    - Spallation neutrons
      - Fast neutrons in Gd-LS
      - Accidentals when combined with radioactive backgrounds

	DYB Site	LA Site	Far Site
Depth (m)	98	112	350
AD μ Rate (Hz)	~20	~15	~5

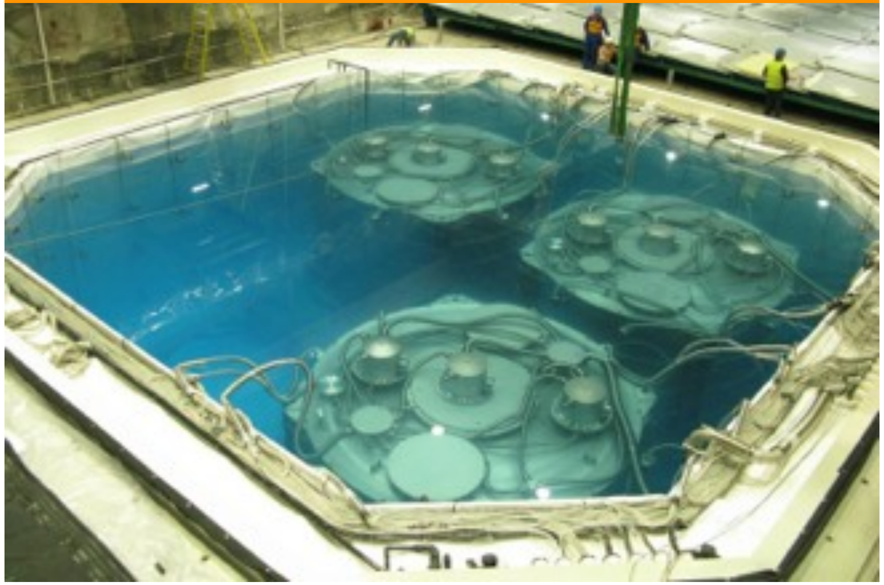
All Three Sites Physics Ready in Dec 2011

Nesting a detector into muon pool

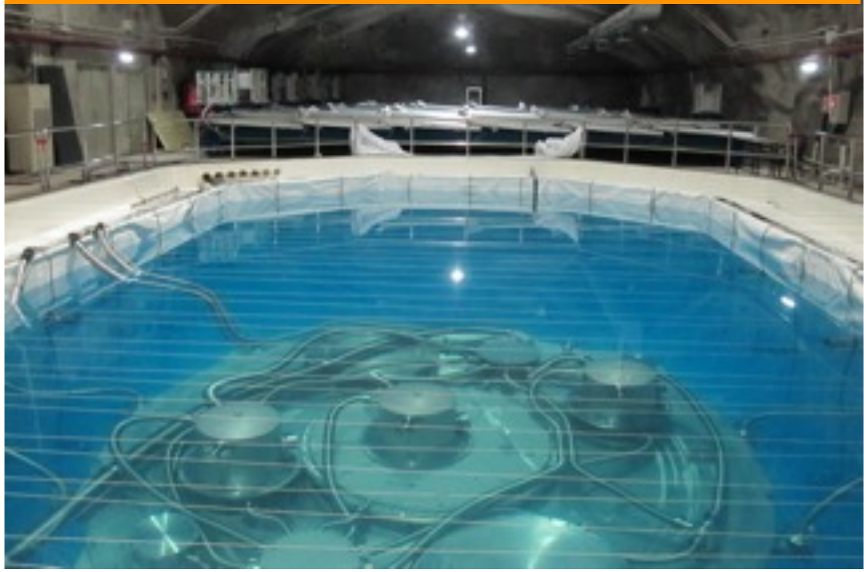
Aug 2011, Daya Bay site data taking



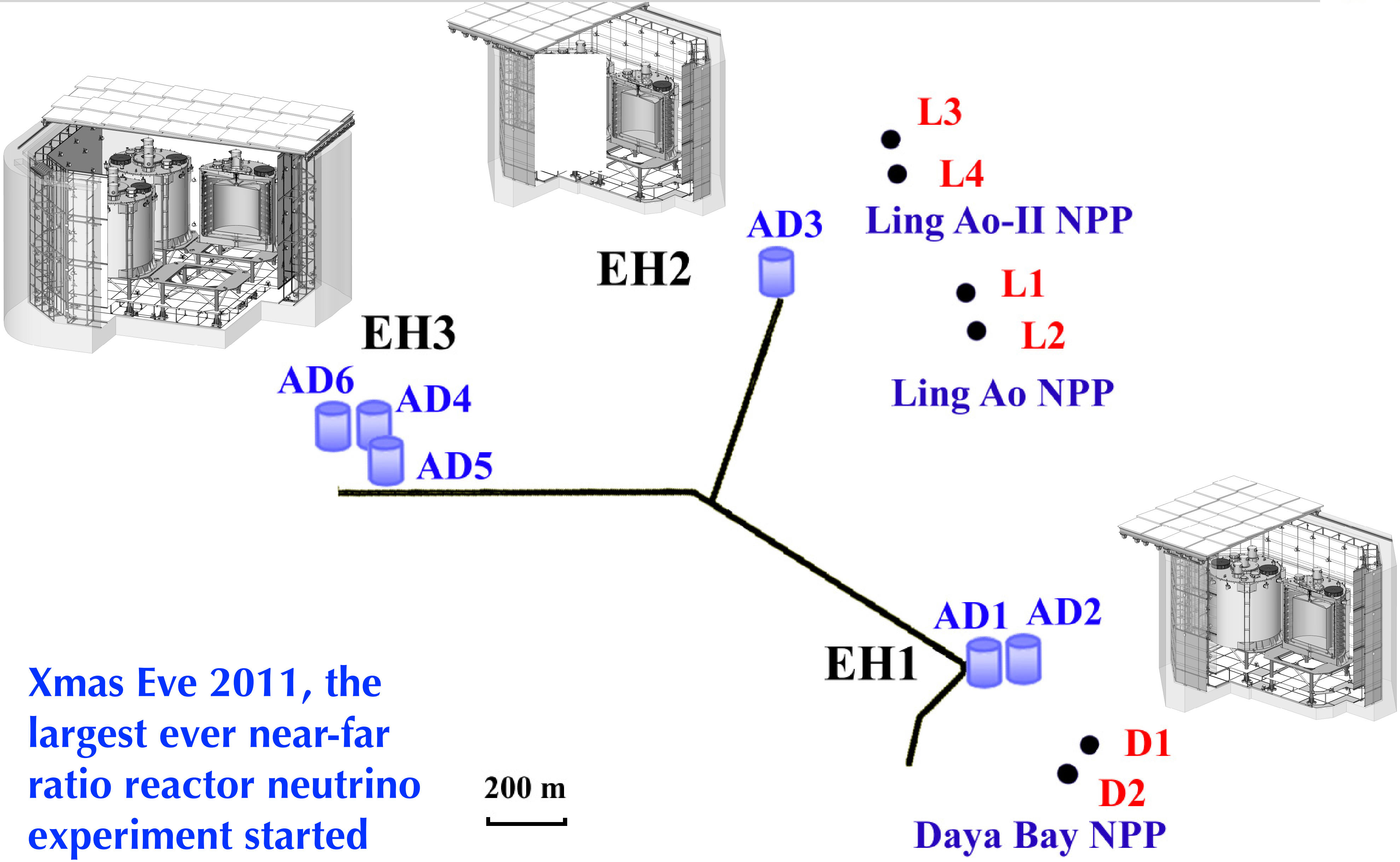
Dec 2011, far site data taking



Nov 2011, Lingao site data taking

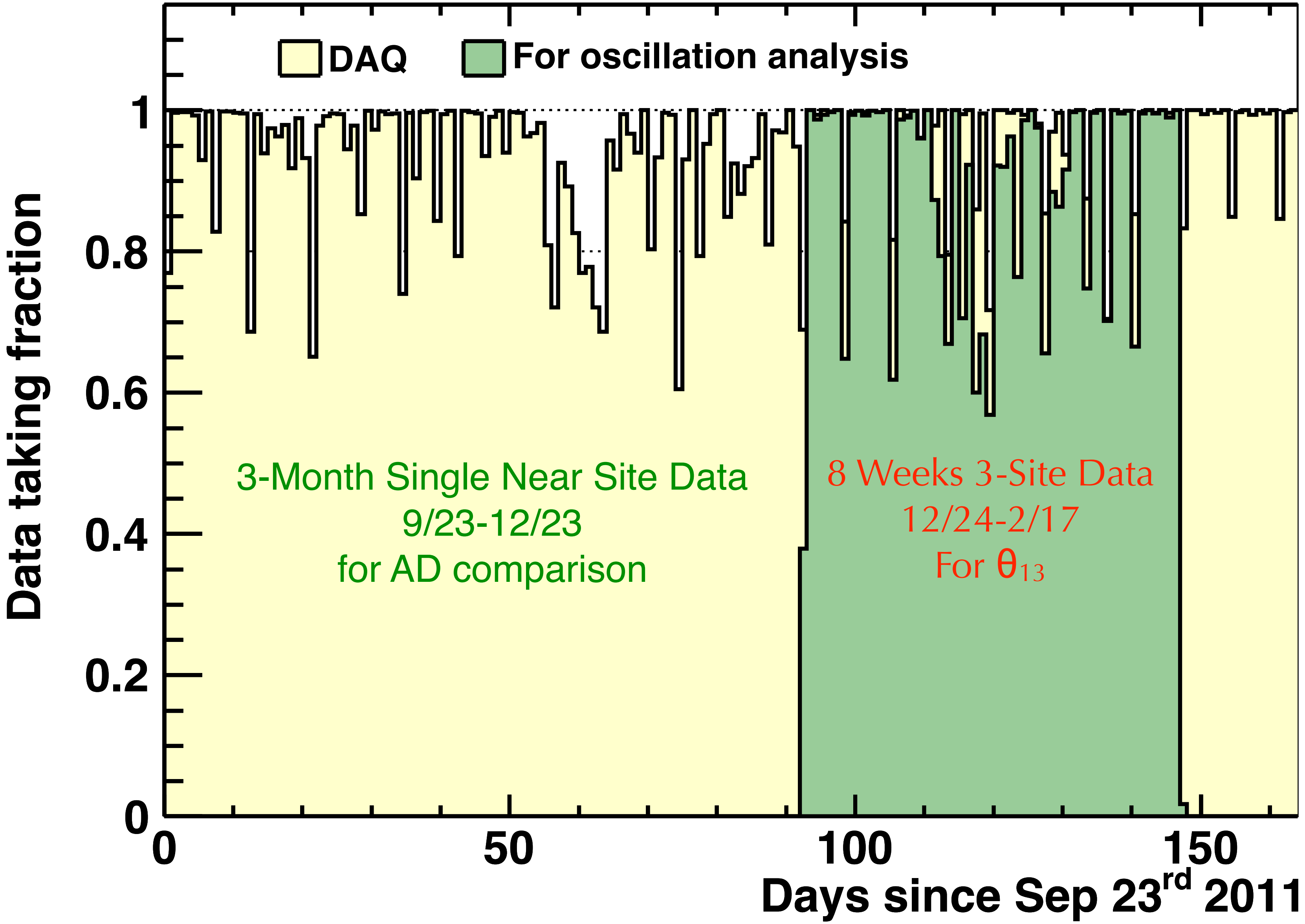


In the Xmas Eve of 2011 at Daya Bay

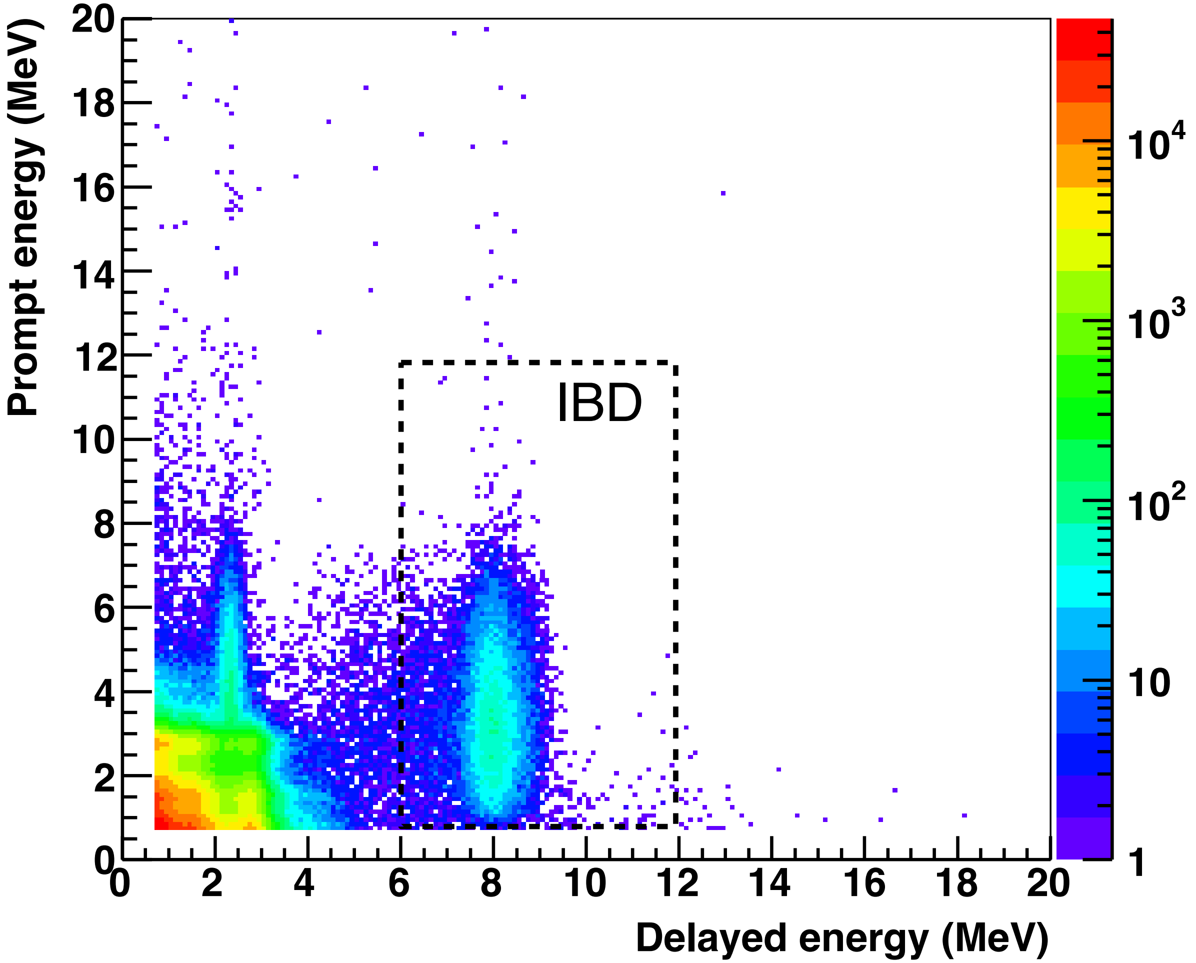


Xmas Eve 2011, the largest ever near-far ratio reactor neutrino experiment started

Data Taking and Detector Livetime



Time Correlation to Pick Out IBD Events



✓ IBD event selection efficiency can be calculated precisely from collected data. Uncertainty ~0.02%

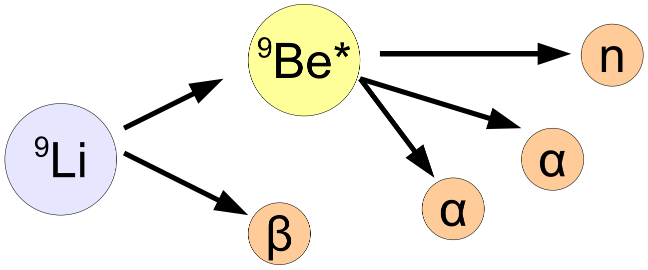
✓ Apply IBD rules to estimate backgrounds

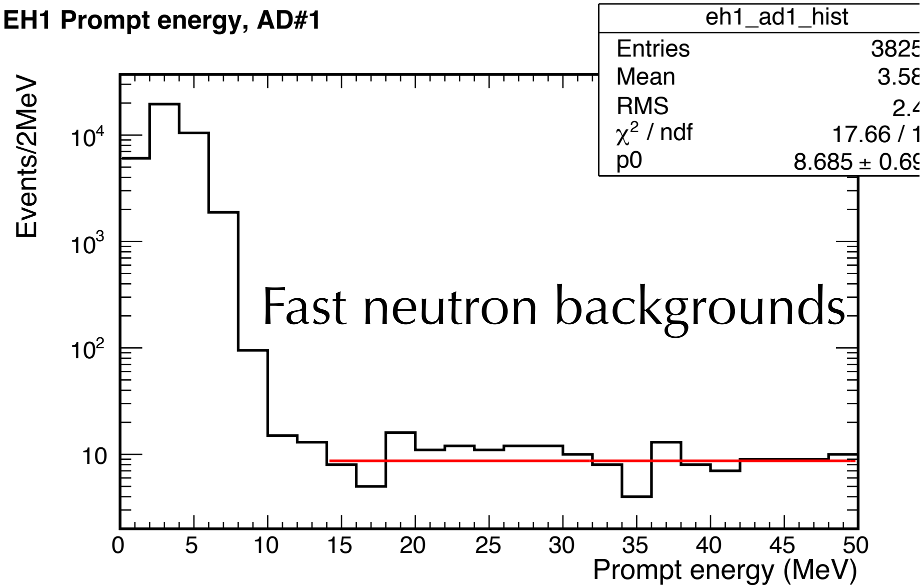
1. First apply noise cuts to clean up the data
2. Muon veto to get rid of cosmogenic products
3. Select inverse beta decay events
   - Prompt energy cut: (0.7, 12) MeV. Uncertainty negligible
   - **Delayed energy cut: (6, 12) MeV. Uncertainty 0.12%**
   - **Time correlation (Multiplicity)** cut to select IBD signal pairs, including backgrounds

Daya Bay Accidental and Correlated Backgrounds

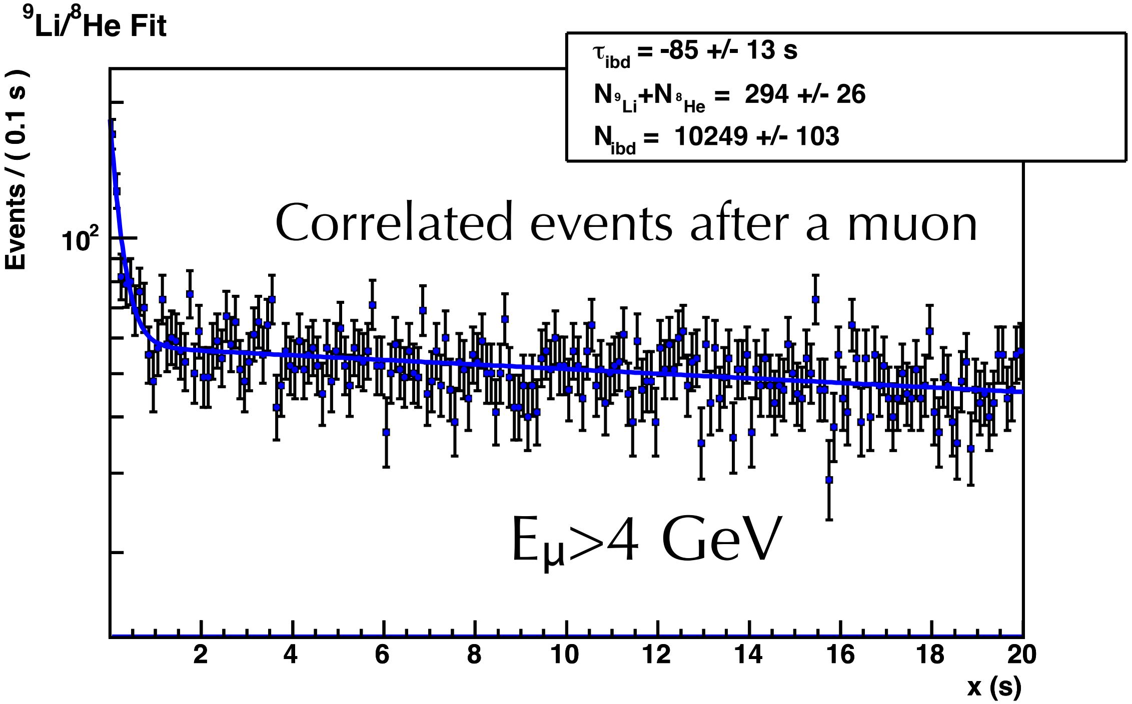
- **Accidental backgrounds** can be calculated accurately: Prompt and delayed signals follow Poisson distributions ⇒ background rate: ~8-10/day near sites; ~3/day far site
- **Correlated backgrounds:**
  - Neutron calibration source caused backgrounds: ~0.2/day
  - Cosmogenic backgrounds $^{9}Li/^{8}He$:
    ~2-3/day at near sites; ~0.2/day at far site
  - Fast neutron backgrounds:
    ~0.7-0.8/day at near sites; ~0.04/day at far site
  - Radiative alpha decays caused backgrounds ($^{13}C(\alpha,n)^{16}O$): ~0.03-0.04/day

β-n decay:
- Prompt: β-decay
- Delayed: neutron capture





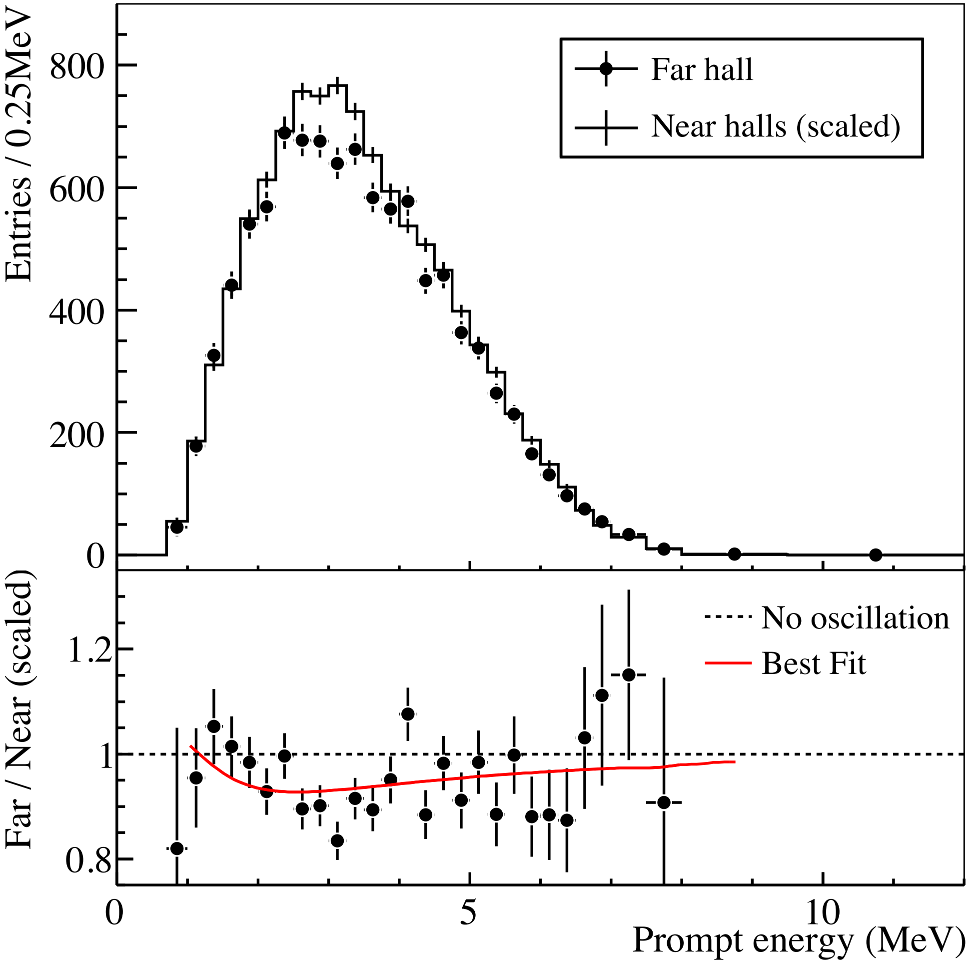
Fast neutron backgrounds

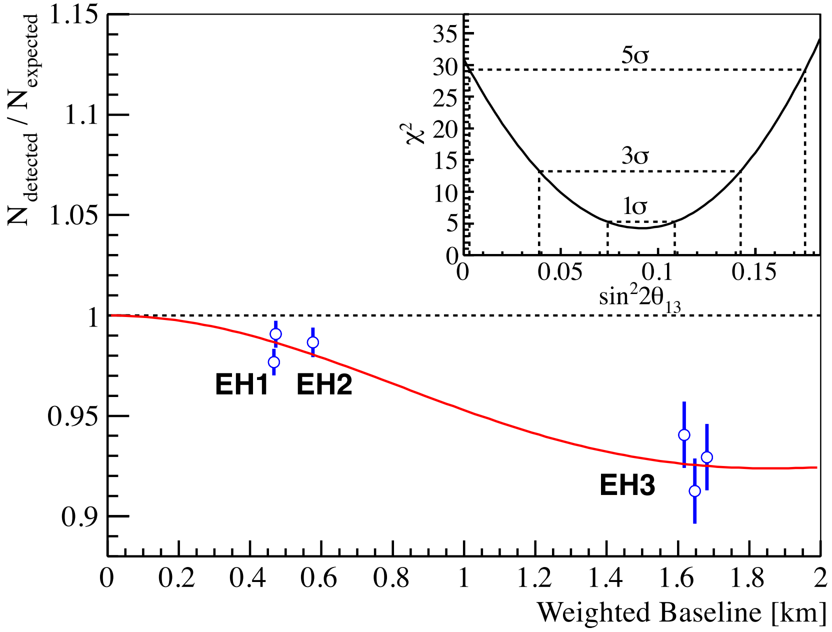


Correlated events after a muon

$E_\mu > 4$ GeV

The m_3 Component of the Electron Flavor Neutrino





$$\chi^2 = \sum_{d=1}^{6} \frac{\left[M_d - T_d\left(1+\varepsilon+\sum_r \omega_r^d \alpha_r + \varepsilon_d\right) + \eta_d\right]^2}{M_d + B_d} + \sum_r \frac{\alpha_r^2}{\sigma_r^2} + \sum_{d=1}^{6}\left(\frac{\varepsilon_d^2}{\sigma_d^2} + \frac{\eta_d^2}{\sigma_B^2}\right),$$

Rate analysis with free normalization gives a 5-sigma measurement:
$\sin^2 2\theta_{13}=0.092 \pm 0.016(\mathrm{stat}) \pm 0.005(\mathrm{sys})$

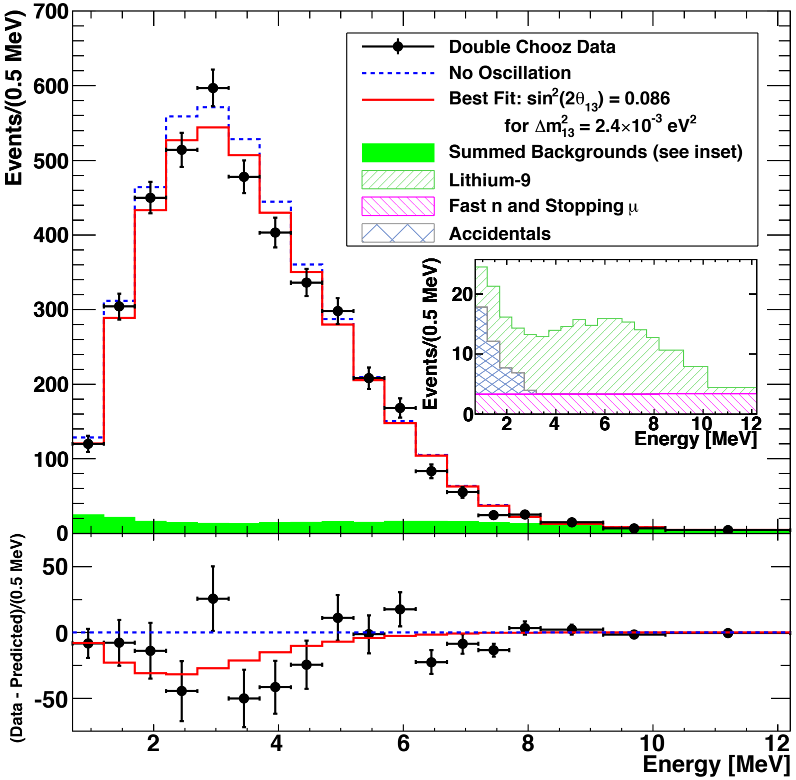
The Double Chooz Indication

from Camillo

Near detector
Distance: ~400 m
Overburden: ~120 m.w.e. flat topology

Reactor power 2 x 4.7 GW/th

Far detector
Distance: ~1050 m
Overburden: ~300 m.w.e. hill topology

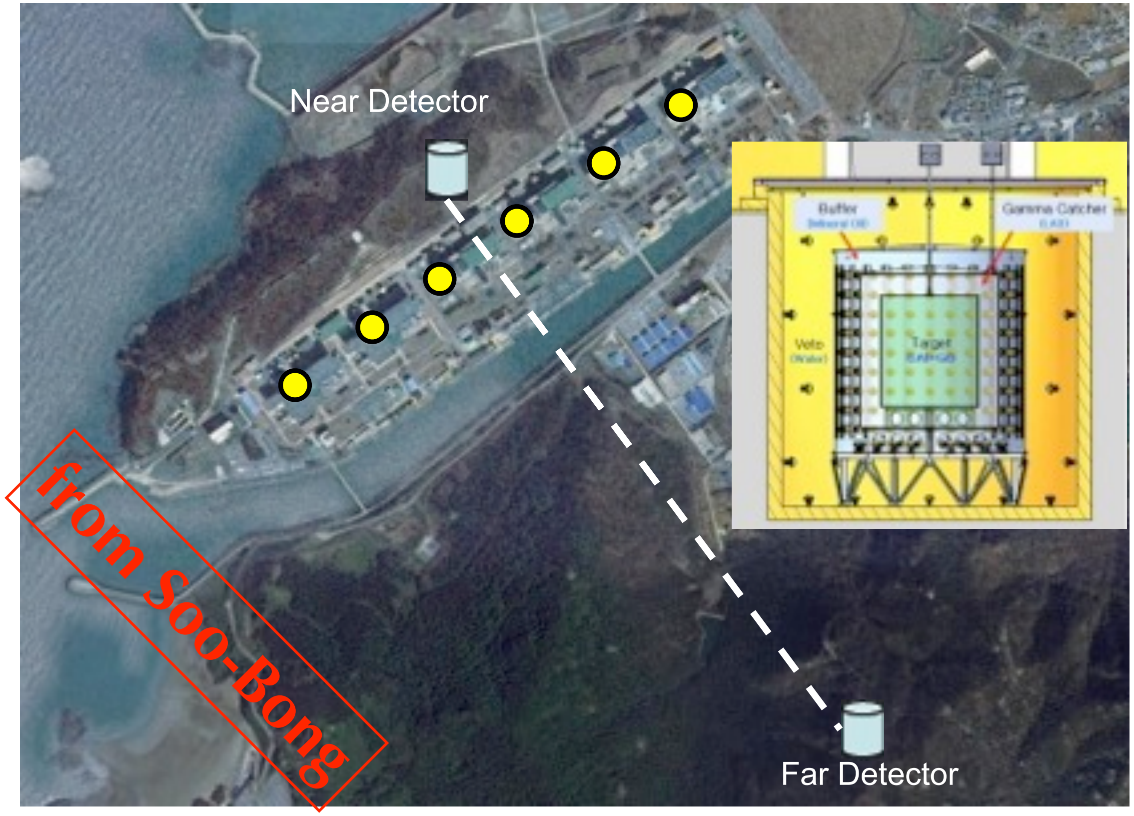


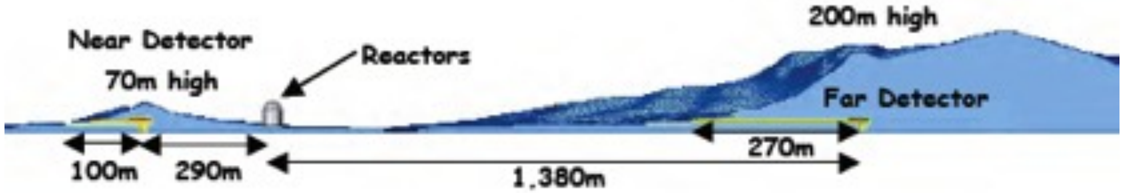
PRL108, 131801(2012) arXiv:1112.6353v1

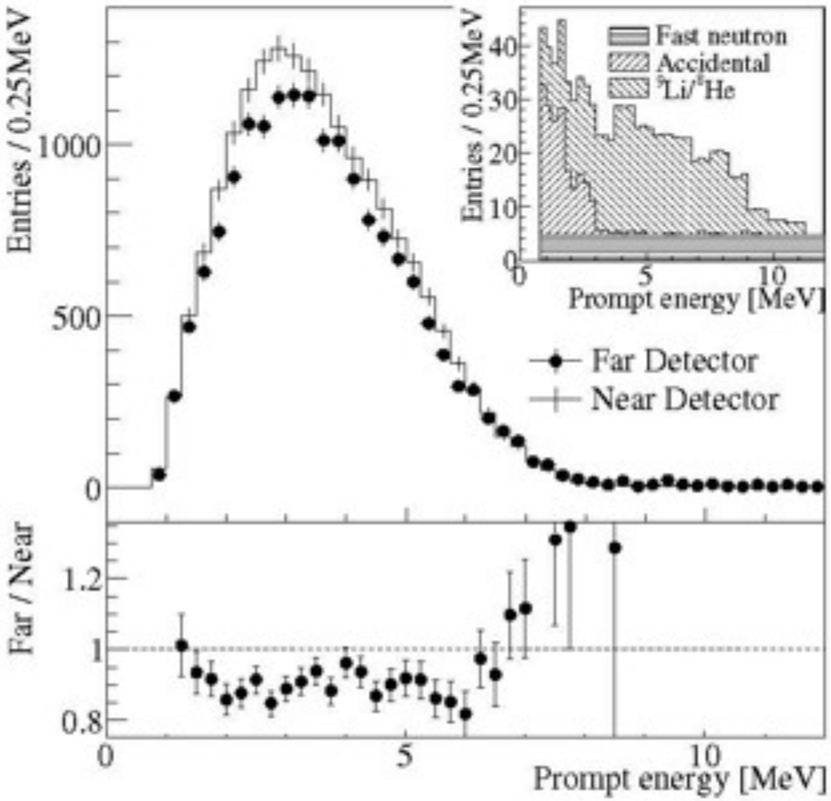
$\sin^2 2\theta_{13}=0.086\pm0.041(\text{stat})\pm0.030(\text{sys})$

- The common strategy: near-far cancellation
  - Far site is the previous Chooz site; Near site will take data Spring 2013
- The first new generation reactor experiment started data taking (far site only)
- Single site oscillation analysis: flux normalization is from an early short-baseline reactor experiment Bugey4

The RENO Measurement in South Korea







- Same strategy; Similar detector design; Similar Analysis; Consistent result

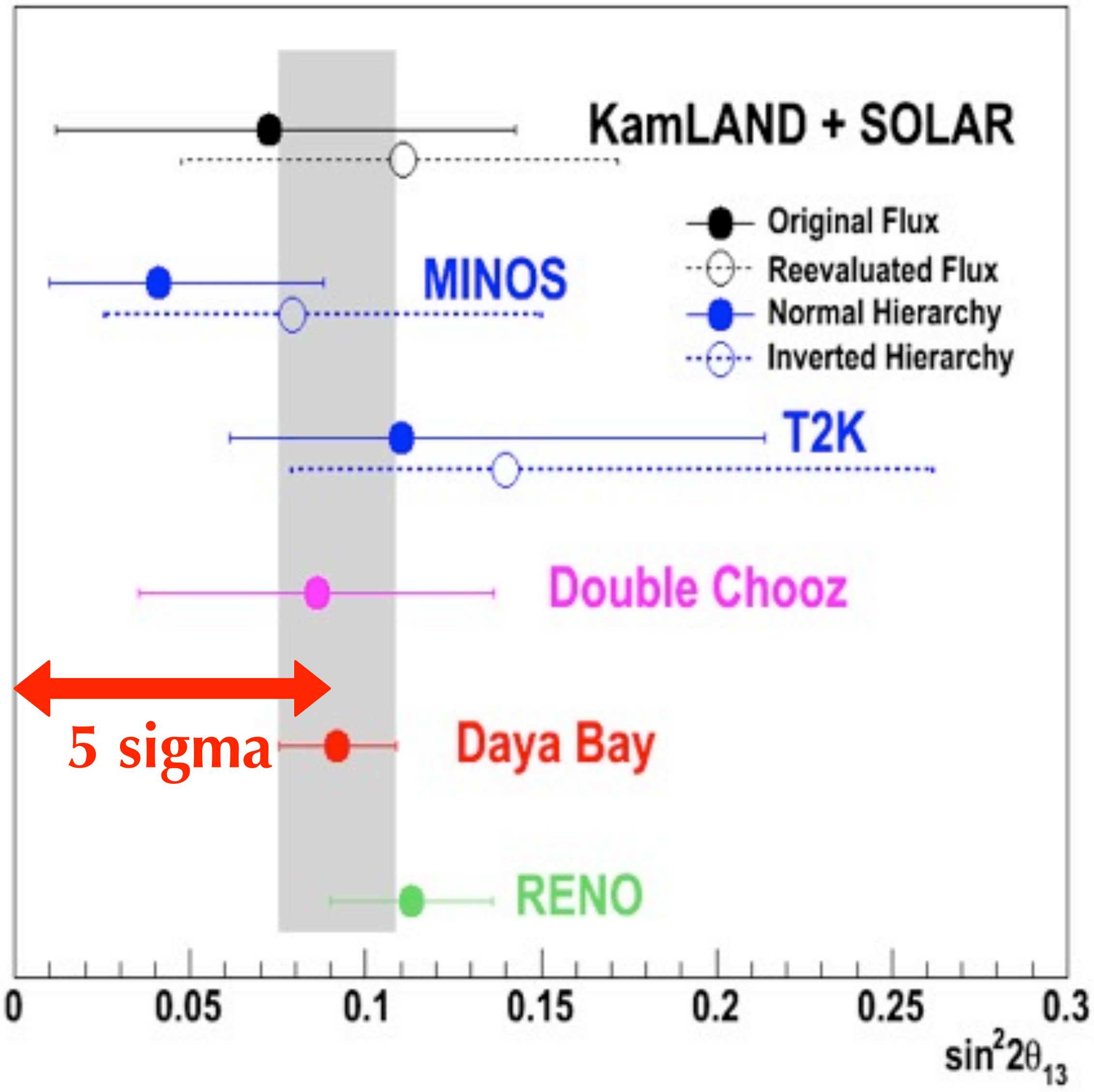
$$\sin^2 2\theta_{13} = 0.113 \pm 0.013(stat.) \pm 0.019(syst.)$$

arXiv:1204.0626v2

A Personal View of Current Reactor Neutrino Experiments

Experiment	Daya Bay	RENO	Double Chooz
Thermal Power	**2.9GWx6**	2.8GWx6	4.7GWx2
Far Site Baseline	**1.54-1.91 km**	1.38-1.52 km	**1.05km**
Target Mass (far site)	**4x~20t (3 commissioned)**	~16.5t	~8.6t
Far Site Event Rate (based on calendar days)	**~63/day/detector**	**~75/day**	~43/day
Far Site Background Rate	**~3.5/day/detector (Accidental dominated)**	~4.2/day (^{8}He/^{9}Li dominated)	**~3.5/day (^{8}He/^{9}Li dominated)**
Energy Scale Calibration	Automatic+Manual (spectrum not yet ready)	Via Glove Boxes (spectrum not yet ready)	**Via Glove Boxes (spectrum ready)**
Energy Resolution	~7.5%/$\sqrt{E}$	**~5.9%/$\sqrt{E}$**	~6.5%/$\sqrt{E}$
Shape Analysis	Not Yet	Not Yet	**Yes (with global Δm^2_{31})**
Absolute Reactor Flux	Not Yet (norm free)	Not Yet (2.5% on the obtained free norm)	Yes (allow a 1.8% uncertainty on Bugey4)

We Tell You θ_{13} Now --- What's Next?

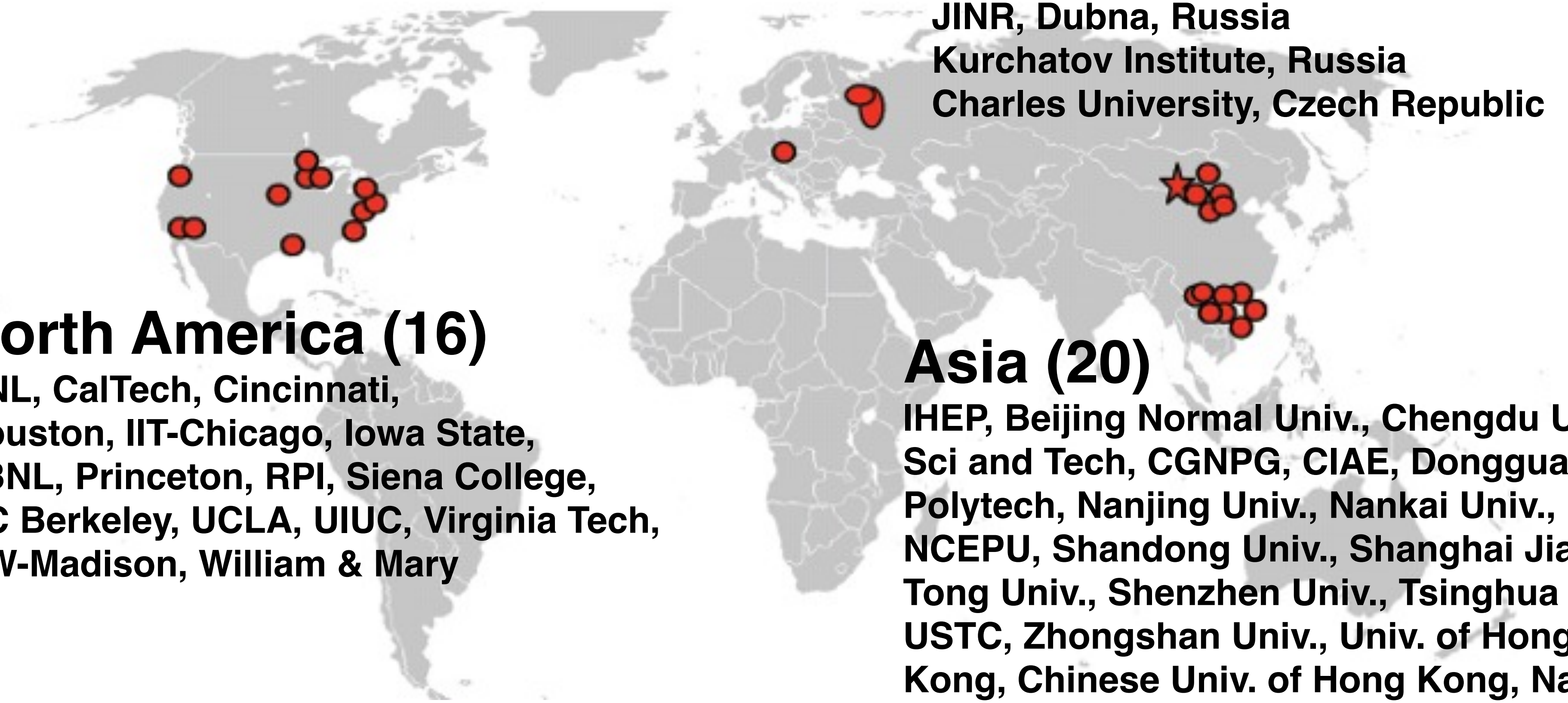


$\sin^2 2\theta_{13} = 0.092 \pm 0.016(\text{stat}) \pm 0.005(\text{syst})$

- ➡ **Daya Bay has discovered non-zero θ_{13} with 5-sigma significance**
  - There were indications from T2K, MINOS and Double Chooz. The discovery is confirmed by RENO.
  - Right techniques + dedicated people made job easier
- ➡ Daya Bay will do shape analysis
- ➡ Daya Bay will finish all 8 ADs in Summer 2012 and will deliver a more precise measurement.
  - Personal Speculation: <5% uncertainty in $\sin^2 2\theta_{13}$ in 2 years
- ➡ The gate to CP phase in PMNS is now open; The job of resolving the mass hierarchy and θ_{23} degeneracy made easier

The Daya Bay Collaboration

An International Effort



Europe (3)

JINR, Dubna, Russia
Kurchatov Institute, Russia
Charles University, Czech Republic

North America (16)

BNL, CalTech, Cincinnati, Houston, IIT-Chicago, Iowa State, LBNL, Princeton, RPI, Siena College, UC Berkeley, UCLA, UIUC, Virginia Tech, UW-Madison, William & Mary

Asia (20)

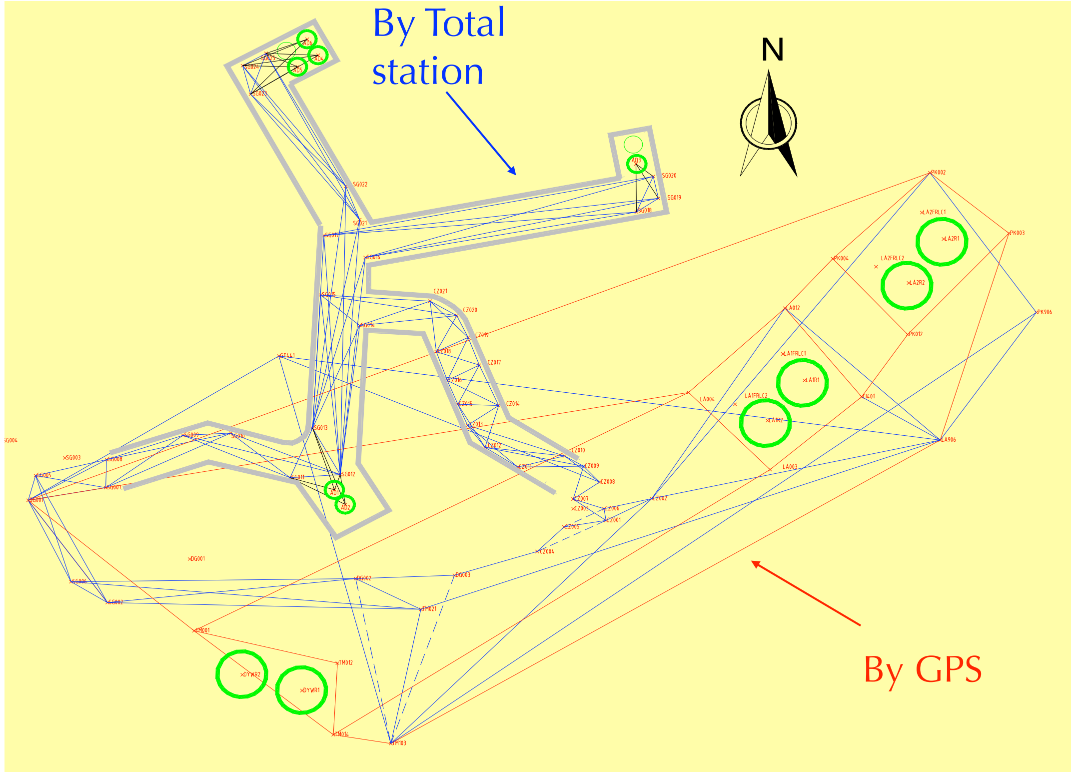
IHEP, Beijing Normal Univ., Chengdu Univ. of Sci and Tech, CGNPG, CIAE, Dongguan Polytech, Nanjing Univ., Nankai Univ., NCEPU, Shandong Univ., Shanghai Jiao Tong Univ., Shenzhen Univ., Tsinghua Univ., USTC, Zhongshan Univ., Univ. of Hong Kong, Chinese Univ. of Hong Kong, National Taiwan Univ., National Chiao Tung Univ., National United Univ.

228 active collaborators

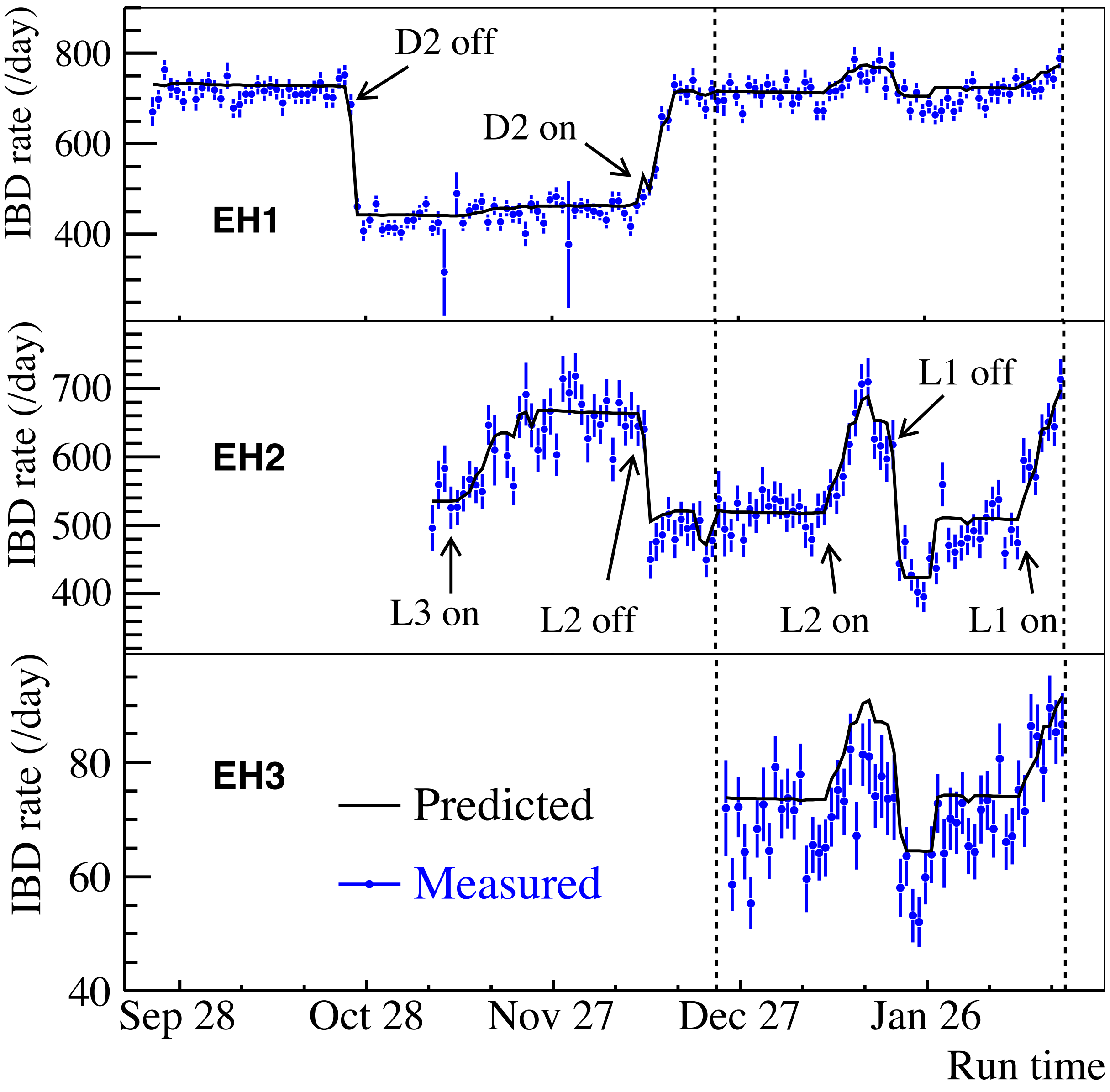
Further Information

Baselines

- Various measurements: GPS, Total Station, laser tracker, level instruments, …
- Compared with design values, and NPP coordinates
- Data processing by three independent software
- Final baseline uncertainty is 28 mm
- Uncertainty of the fission center from reactor simulation:
  - **2 cm horizontally**
  - **20 cm vertically**
- The combined baseline
- error is 35mm,
- corresponding to a
- negligible reactor flux
- uncertainty (<0.02%)



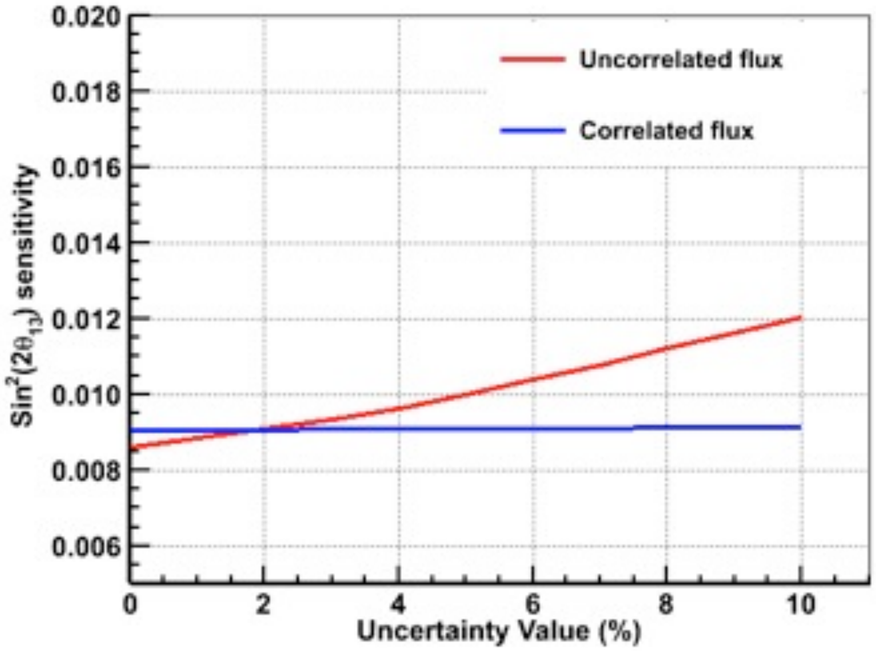
IBD Rates and Reactor On/Off Correlation



- We collected 10,416 antineutrino events at the far site during the synchronized 3-site running period:
  - The detector comparison paper arXiv:1202.6181 covers the period before Xmas
  - Turning points were when reactors were refueled or maintained
- Counting all the events, backgrounds and systematic factors, we see ......

The Impact of Reactor Flux

- Recent calculations show that reactor flux is larger than ILL by ~3%.
  - T. A. Mueller et al., PRC 83, 054615
  - P. Huber, PRC84, 024617
- Correlated uncertainty (common to all reactors)
  - Come from ILL spectrum normalization (1.9%), energy release per fission(0.3%), and IBD cross section (0.2%).
  - Cancel out by near-far detectors
- Uncorrelated uncertainty
  - Dominated by power measurement (0.6%) and isotope fraction (0.5%)
  - Mostly cancelled, only 5% residual for the final systematic error of Daya Bay



A larger correlated flux uncertainty has no impact on Daya Bay sensitivity.

Uncorrelated flux uncertainty most cancelled

Neutrino Flux Calculation

Neutrino Flux

$$S(E_\nu) = \sum_{i}^{istopes} f_i S_i(E_\nu)$$

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

$$W_{th} = \sum_i f_i e_i \;, \qquad F = \sum_i f_i$$

E_ν : Neutrino energy

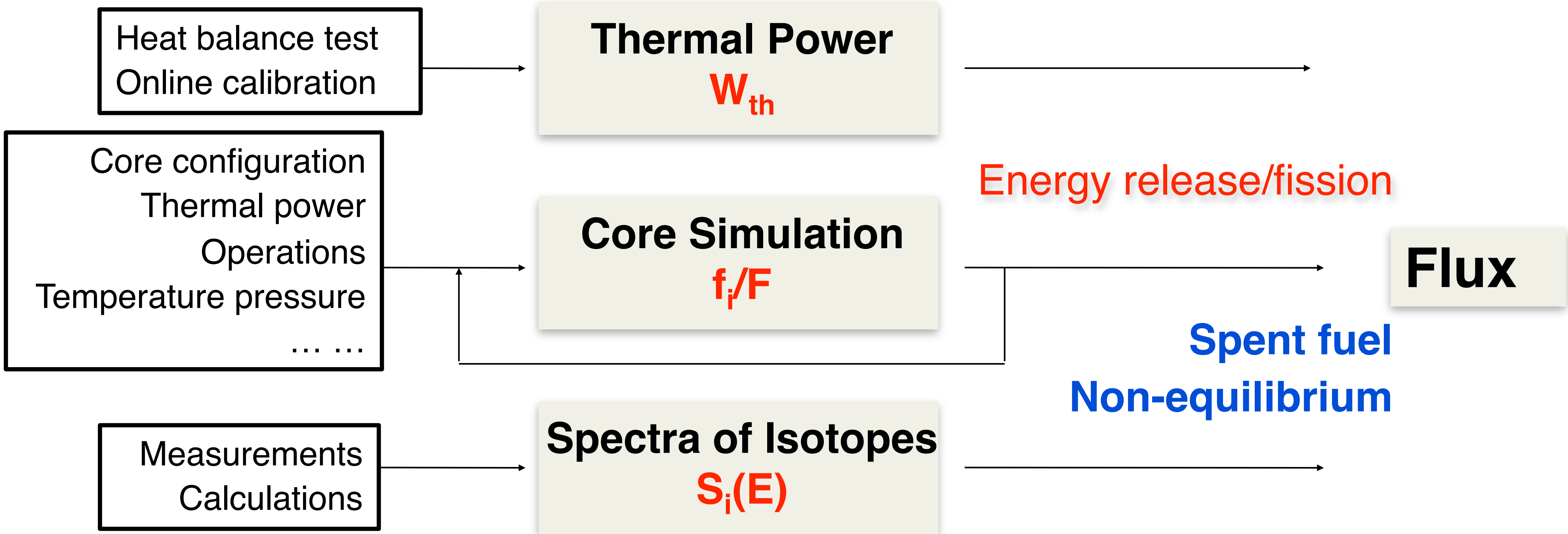
f_i : Fission rate of isotope i

$S_i(E_\nu)$: Neutrino energy spectra/f

(f_i/F): Fission fractions

W_{th} : Reactor thermal power

e_i : Energy release per fission



Heat balance test
Online calibration

Thermal Power
W_{th}

Core configuration
Thermal power
Operations
Temperature pressure
… …

Core Simulation
f_i/F

Energy release/fission

Flux

Spent fuel
Non-equilibrium

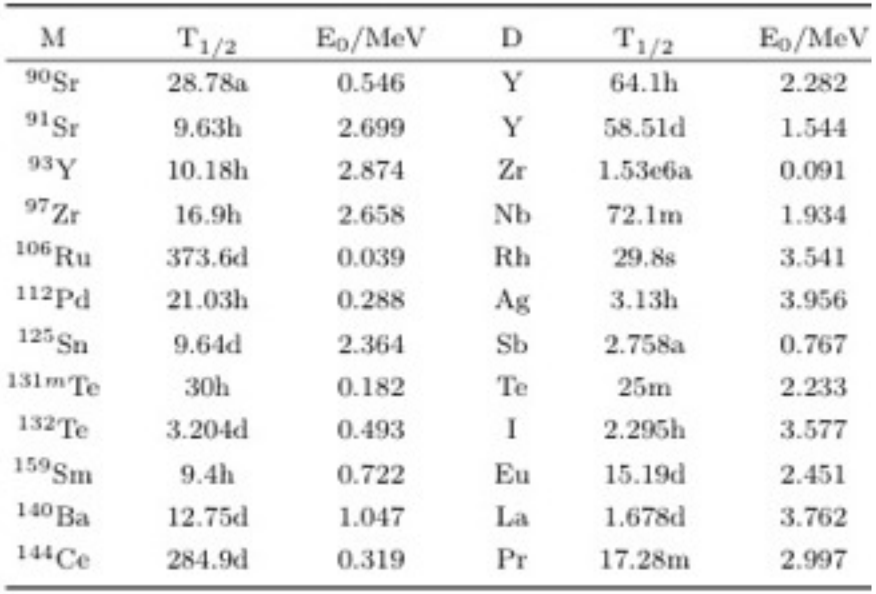
Measurements
Calculations

Spectra of Isotopes
S_i(E)

Spent Fuel

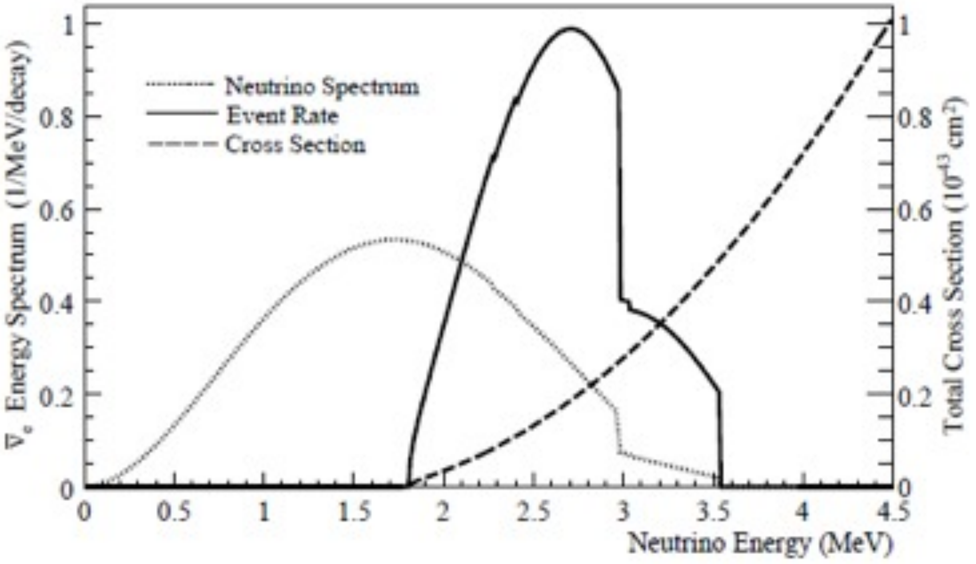
- Spent fuel stored temporarily adjacent to the core, could be up to 10 years.
- Similar to non-equilibrium contributions, long-lived fragments in spent fuel will emit neutrinos continuously.

Isotopes with E_ν >1.8 MeV and $T_{1/2}$ > 10 h.



M	$T_{1/2}$	E_0/MeV	D	$T_{1/2}$	E_0/MeV
^{90}Sr	28.78a	0.546	Y	64.1h	2.282
^{91}Sr	9.63h	2.699	Y	58.51d	1.544
^{93}Y	10.18h	2.874	Zr	1.53e6a	0.091
^{97}Zr	16.9h	2.658	Nb	72.1m	1.934
^{106}Ru	373.6d	0.039	Rh	29.8s	3.541
^{112}Pd	21.03h	0.288	Ag	3.13h	3.956
^{125}Sn	9.64d	2.364	Sb	2.758a	0.767
^{131m}Te	30h	0.182	Te	25m	2.233
^{132}Te	3.204d	0.493	I	2.295h	3.577
^{159}Sm	9.4h	0.722	Eu	15.19d	2.451
^{140}Ba	12.75d	1.047	La	1.678d	3.762
^{144}Ce	284.9d	0.319	Pr	17.28m	2.997

Spent fuel antineutrino spectrum, mainly contributes 1.8 -3.5 MeV, the ratio to reactor antineutrino is ~ 0.3%.



BONUS: Transportation of Our Detectors

Pull All Signals and Backgrounds Together

	AD1	AD2	AD3	AD4	AD5	AD6
IBD candidates	28935	28975	22466	3528	3436	3452
DAQ live time (day)	49.5530		49.4971	48.9473		
Muon veto time (day)	8.7418	8.9109	7.0389	0.8785	0.8800	0.8952
$\epsilon_\mu \cdot \epsilon_m$	0.8019	0.7989	0.8363	0.9547	0.9543	0.9538
Accidentals (/day)	9.82±0.06	9.88±0.06	7.67±0.05	3.29 ±0.03	3.33 ± 0.03	3.12 ±0.03
Fast neutron (/day)	0.84±0.28	0.84±0.28	0.74±0.44	0.04±0.04	0.04±0.04	0.04±0.04
^{9}Li/^{8}He (/day)	3.1±1.6		1.8±1.1	0.16±0.11		
Am-C correlated (/day)	0.2±0.2					
^{13}C(α, n)^{16}O background (/day)	0.04±0.02	0.04±0.02	0.035±0.02	0.03±0.02	0.03±0.02	0.03±0.02
IBD rate (/day)	714.17±4.58	717.86± 4.60	532.29±3.82	71.78 ± 1.29	69.80±1.28	70.39±1.28

- At this point, we have two choices to extract the oscillation information
  - Using near site data to predict the far site expectation
  - Form a chi-square with the prediction based on reactor flux as initial input to extract both the oscillation parameter and the correction parameters which include the ones to the initial reactor flux
- We have both approaches but our official result is based on the chi-square approach.

Daya Bay Systematic Uncertainty Summary

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%

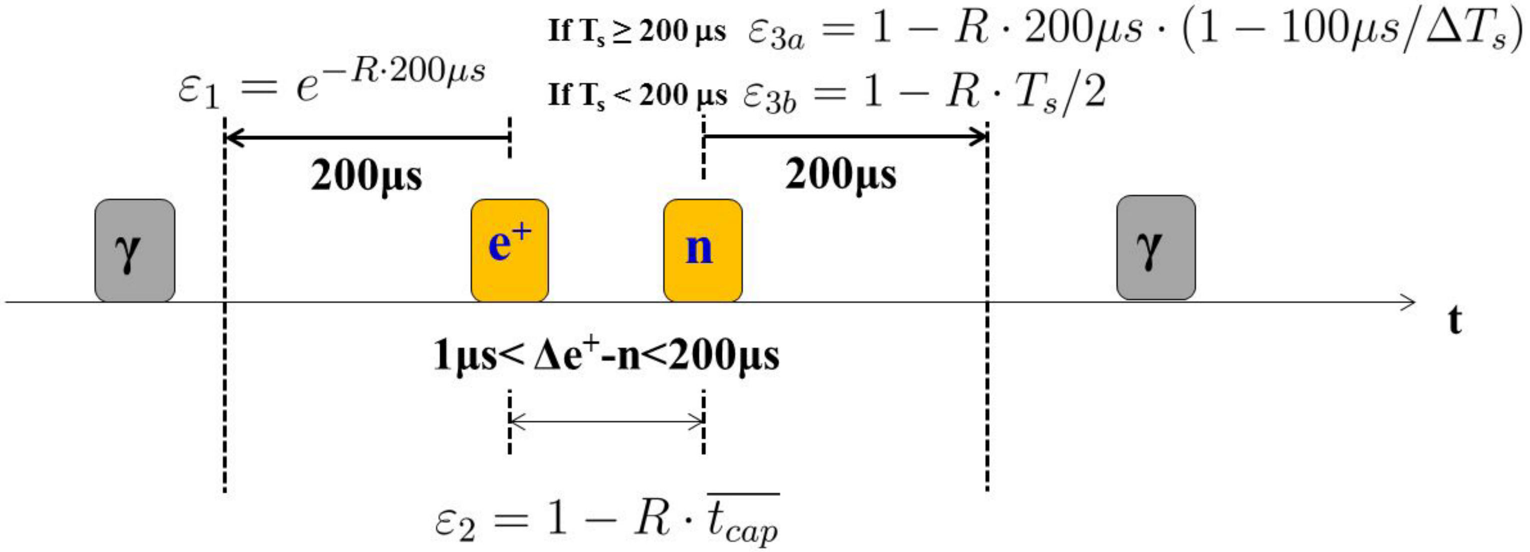
Reactor			
Correlated		Uncorrelated	
Energy/fission	0.2%	Power	0.5%
$\overline{\nu}_e$/fission	3%	Fission fraction	0.6%
		Spent fuel	0.3%
Combined	3%	Combined	0.8%

From CDR (hep-ex/0701029)

Detector Uncertainty Sources		Baseline	Design Goal
Number of protons		0.3%	0.1%
Detector Efficiency	Energy cut	0.2%	0.1%
	H/Gd ratio	0.1%	0.1%
	Time cut	0.1%	0.03%
	Neutron Multiplicity	0.05%	0.05%
	Trigger	0.01%	0.01%
	Live time	<0.01%	<0.01%
Total uncertainty		0.38%	0.18%

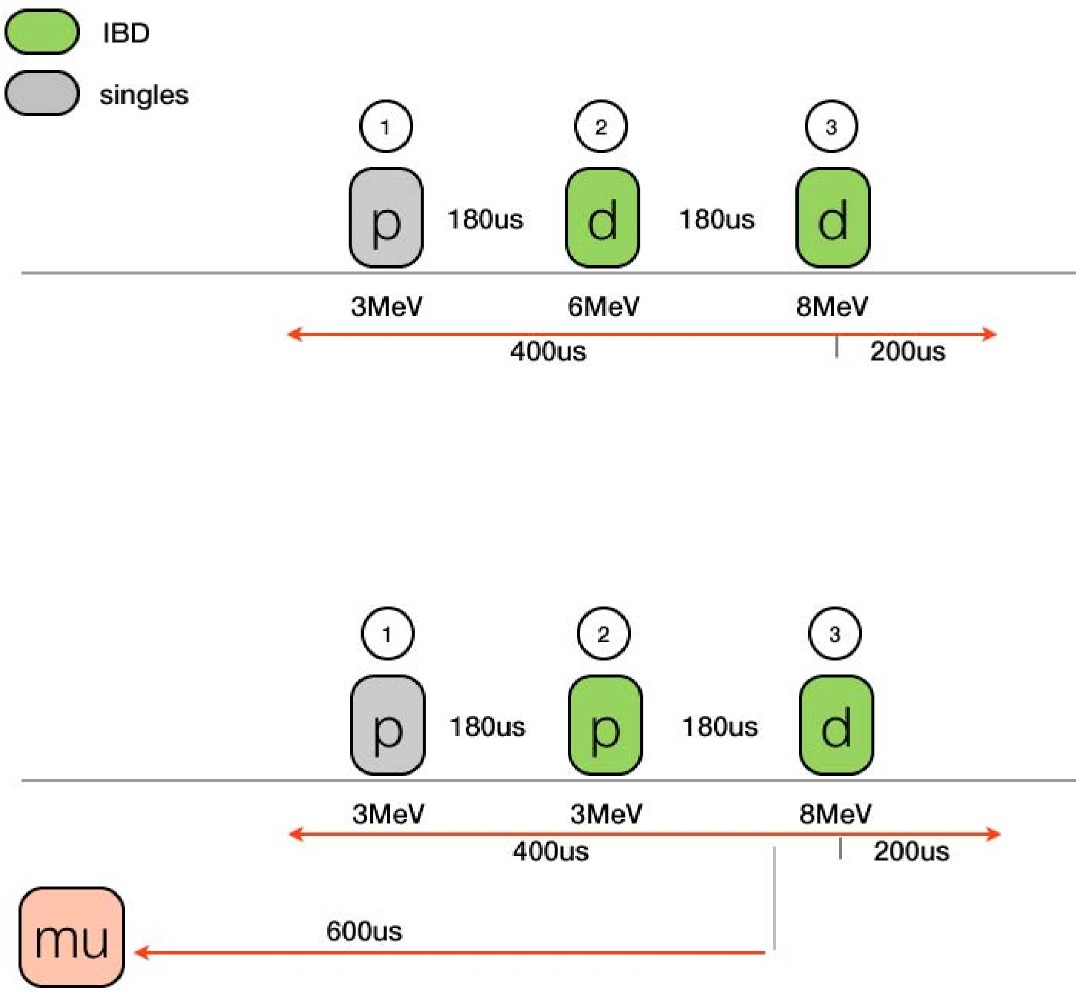
CDR Design Budget

Time Correlation Cut to Pick Out IBD Events



- IBD pair selection rules:
  - Identify the delayed signal
  - No other delayed like signal within 200μs after the delayed one
  - Time span of the delayed and prompt signal is between 1μs and 200μs
  - No other prompt signal within 200μs window before the prompt one
- The selection efficiency can be calculated precisely: $\varepsilon_{IBD} = \varepsilon_1\ \varepsilon_2\ \varepsilon_3$
  - $R = R_{prompt}$ is the prompt like single event trigger rate
  - The time correlation guarantees low background and little dependence on the detector MC to understand the detection efficiency

Alternative IBD Selection Method (Decoupled Multiplicity Cut)

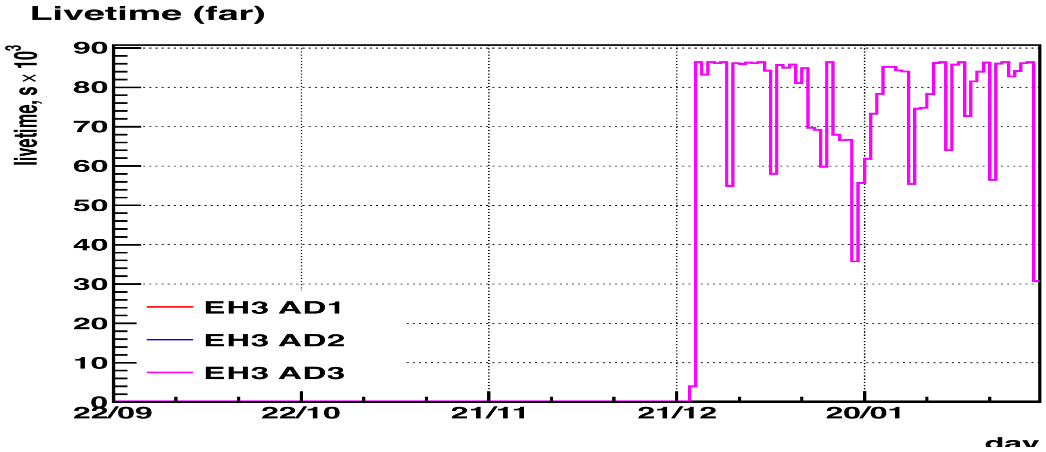


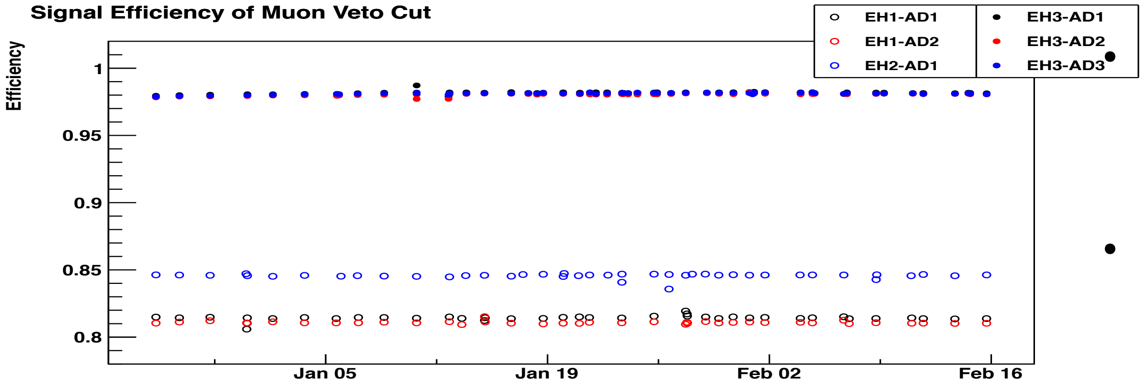
- A set of simple rules:
  - Identify the delayed signal
  - No other delayed like signal within 200μs after the delayed one
  - In the fixed 200μs window before the delayed one, there is only one prompt signal.
  - No other prompt signal within 400μs window before the delayed one
- The selection efficiency is then: $Poisson(0, R_{prompt} \cdot 400\mu s) \cdot Poisson(0, -R_{delay} \cdot 200\mu s)$

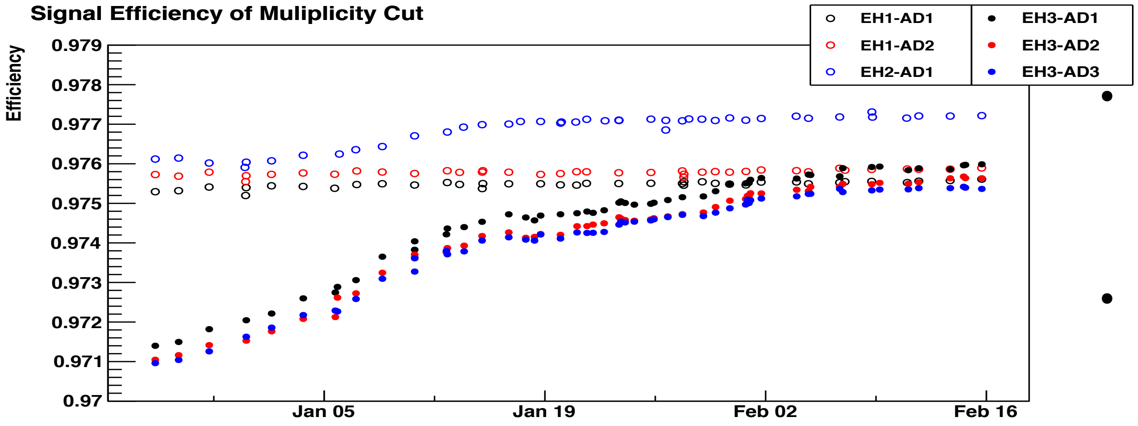
➡ Singles rates are the key to correlation analysis

  ➡ Livetime and background estimation will follow naturally

How to Predict Expected IBDs (as initial inputs)?



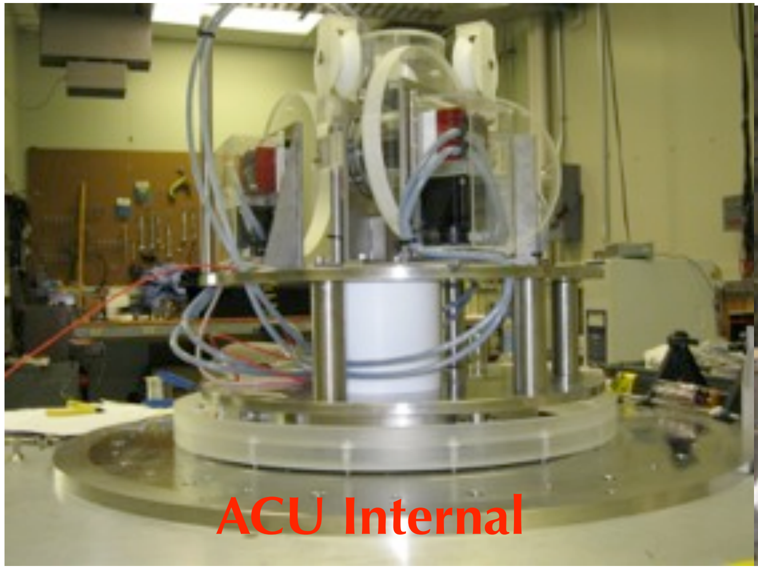


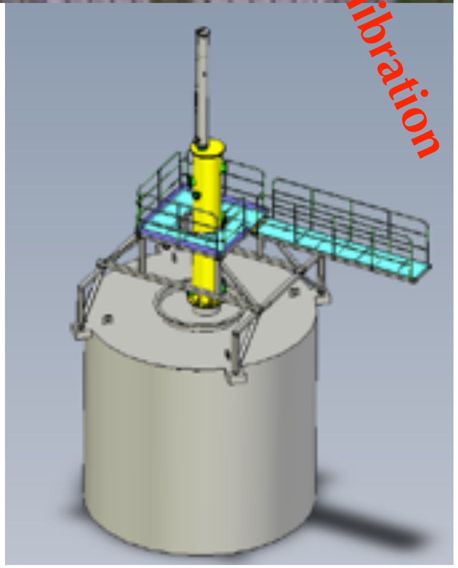


- Reactor flux as a function of time
  - Sufficient information from the power plant
  - Two independent approaches were carried out
  - A factor ~20 suppression on the flux uncertainty due to the near-far cancellation
- Target mass
  - Little variation wrt time, ~10^{-4}, as pool temperature has been stable
- Gd capture ratio and spill-in/out correction
  - Based on MC. Correlated between detectors
- Prompt and delayed signal energy cut efficiency
  - Comparing MC and data
- Livetime, muon veto efficiency, IBD selection efficiency as function of time.

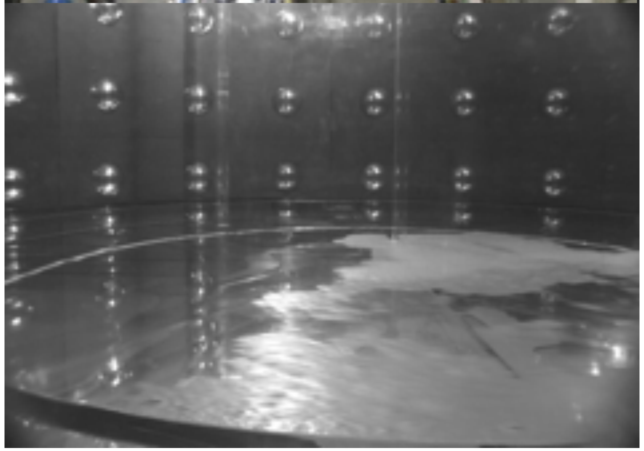
The Calibration Systems

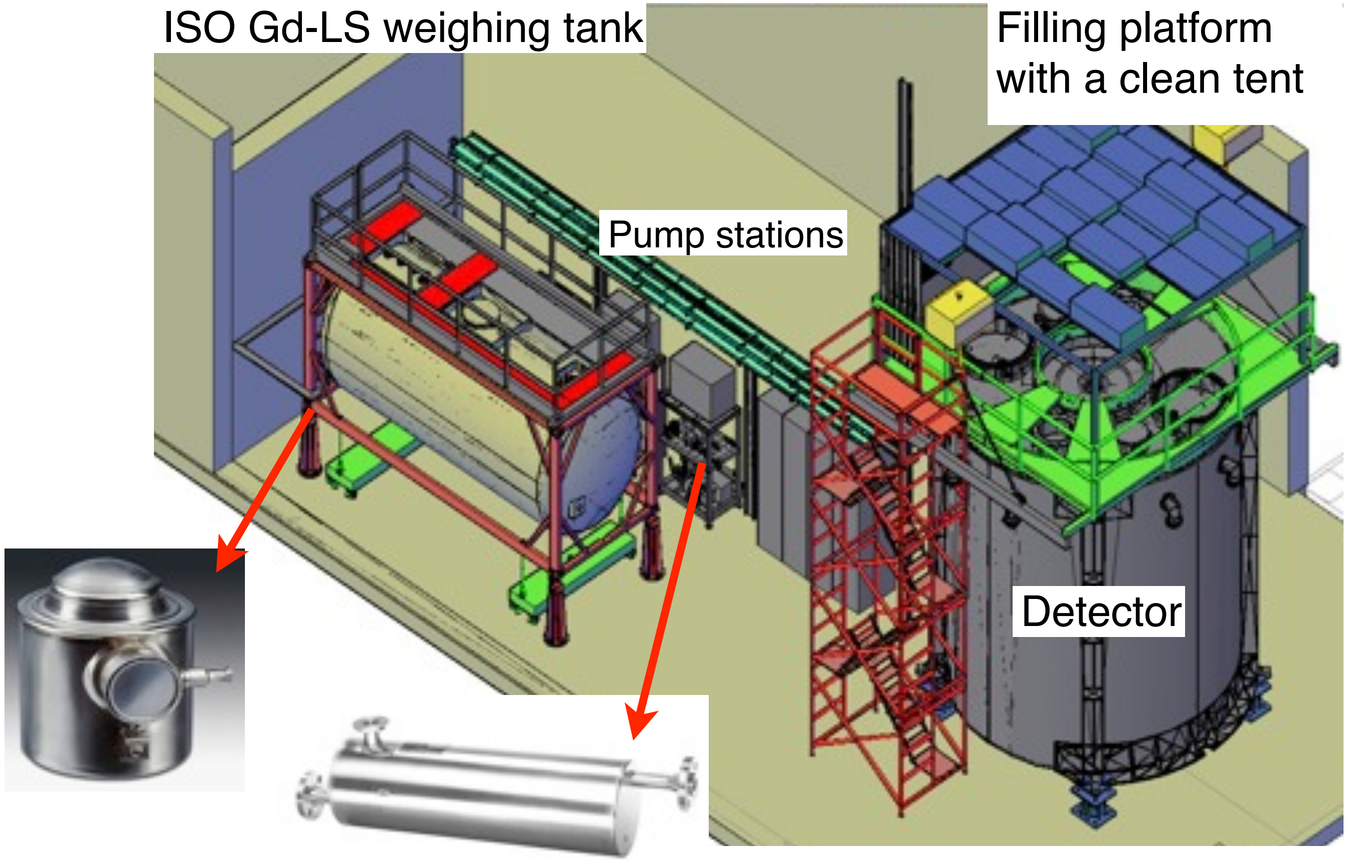
- The calibration system designed to reach 1%~2% uncertainty in energy scale
  - To reach 0.2% uncertainty in neutron capture cut
  - 3 automated calibration units on each AD
    - Two for the Gd-LS volume and one for the LS
    - Sources: ^{68}Ge(e^+) ~100Hz, 20Hz ^{60}Co (~2.5 MeV)+ 0.5Hz ^{241}Am-^{13}C(n), and a LED diffuser ball
  - Manual calibration system (under construction) to further understand detector energy responses





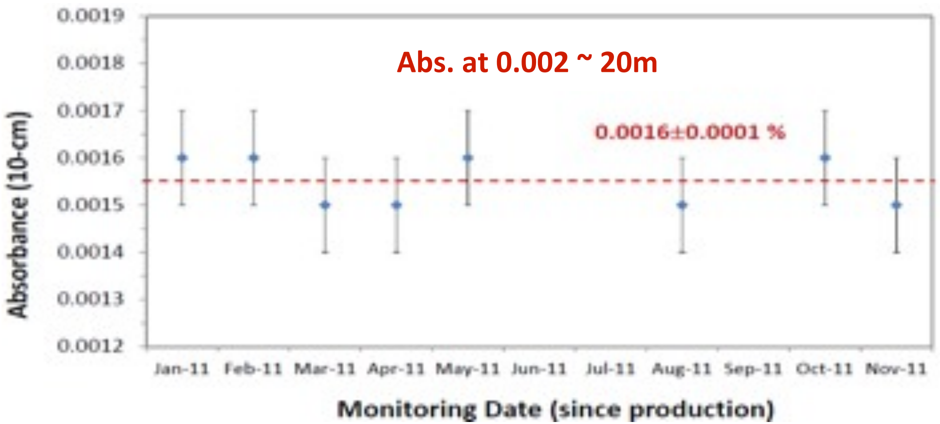
Detector Filling (Identicalness and Target Mass Control)

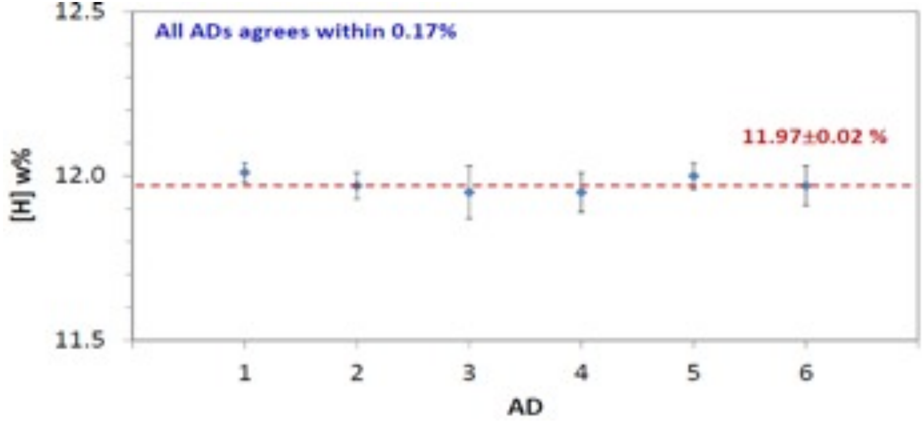


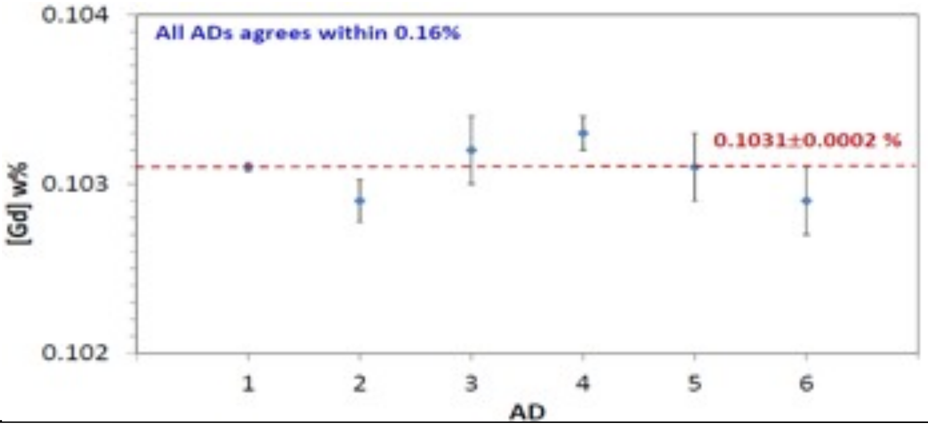


- Doped and un-doped liquid scintillators are filled from their own common reservoirs which have been produced
  - Gd-LS drawn from the ~40t ISO tank and LS from a 200t pool
- A pair of ADs are filled within ~2 weeks: identical liquids
- Load cells and flow meters to measure the target mass (relative uncertainty is <0.02% in lab tests)

Liquid QA/QC and 6 AD Comparison

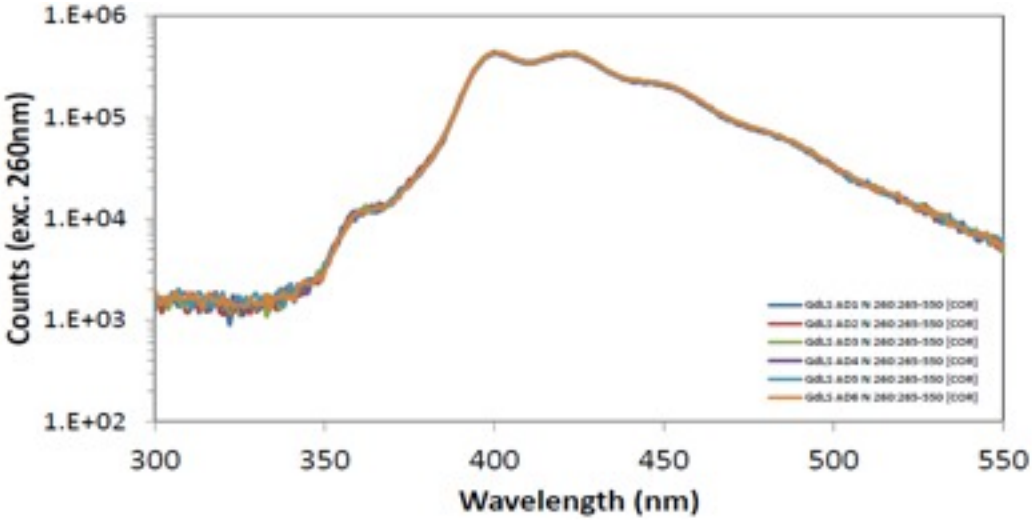




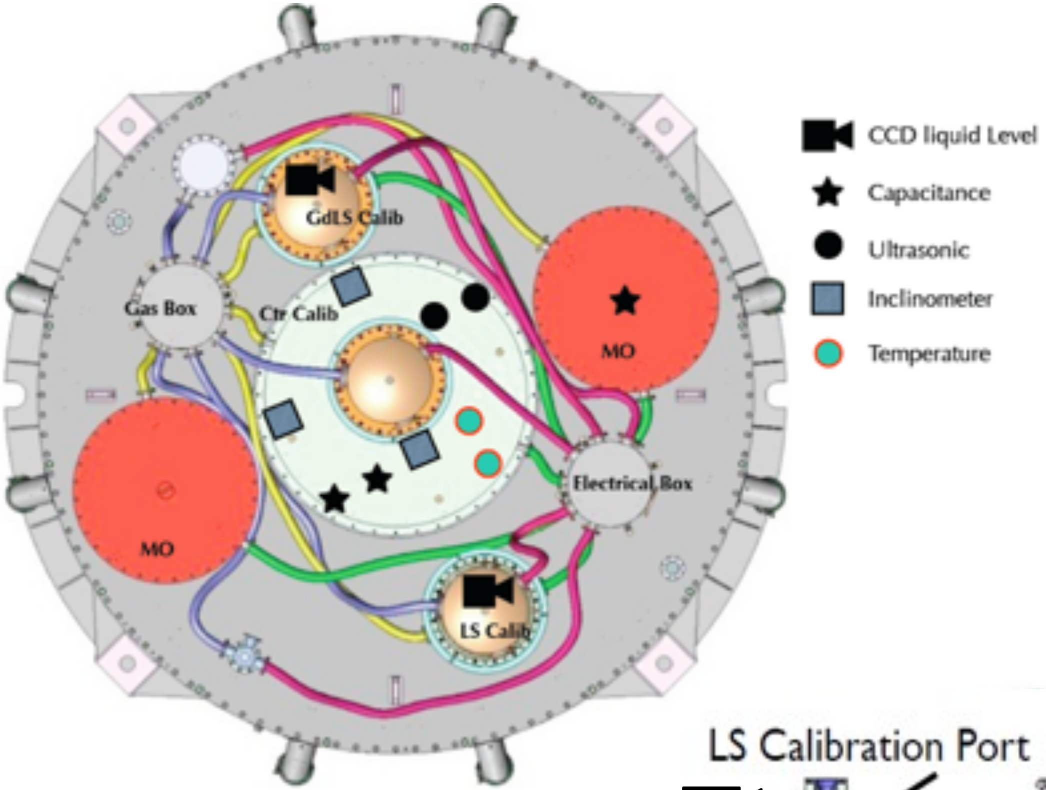


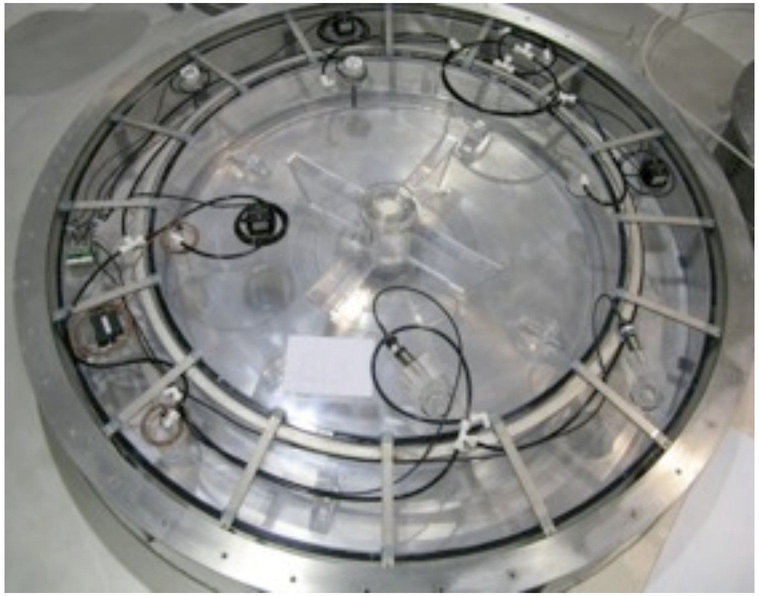
- Liquids are monitored since production (1-yr)
- Liquids before and after filling are taken
- Between 6 ADs:
  - [Gd] agrees within 0.16% (ICP-MS and XRF)
  - [H] agrees within 0.17% (Combustion analysis)
  - [Gd-LS] $\lambda_{ave.}$ >20m and no change (10-cm and 1-m auto-attn. system)
  - Light-yield emission agrees within 1% (fluorescence)

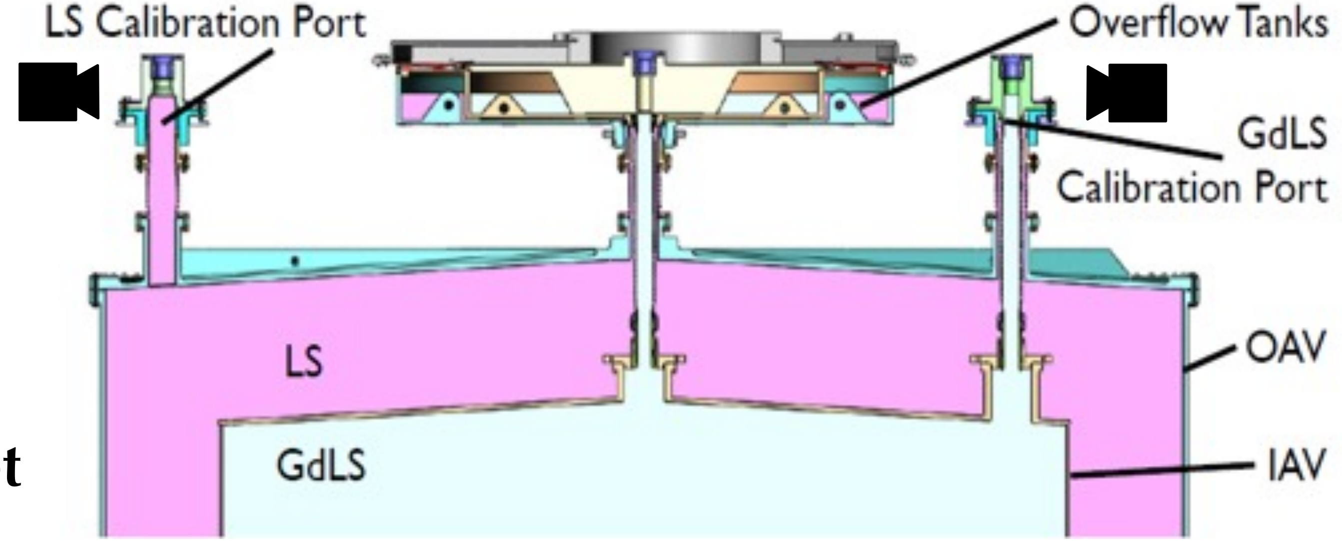
❖Note: Chemical QA is only a cross check. Uncertainties are evaluated w/ data also.



The Monitoring of Target Mass during Data Taking

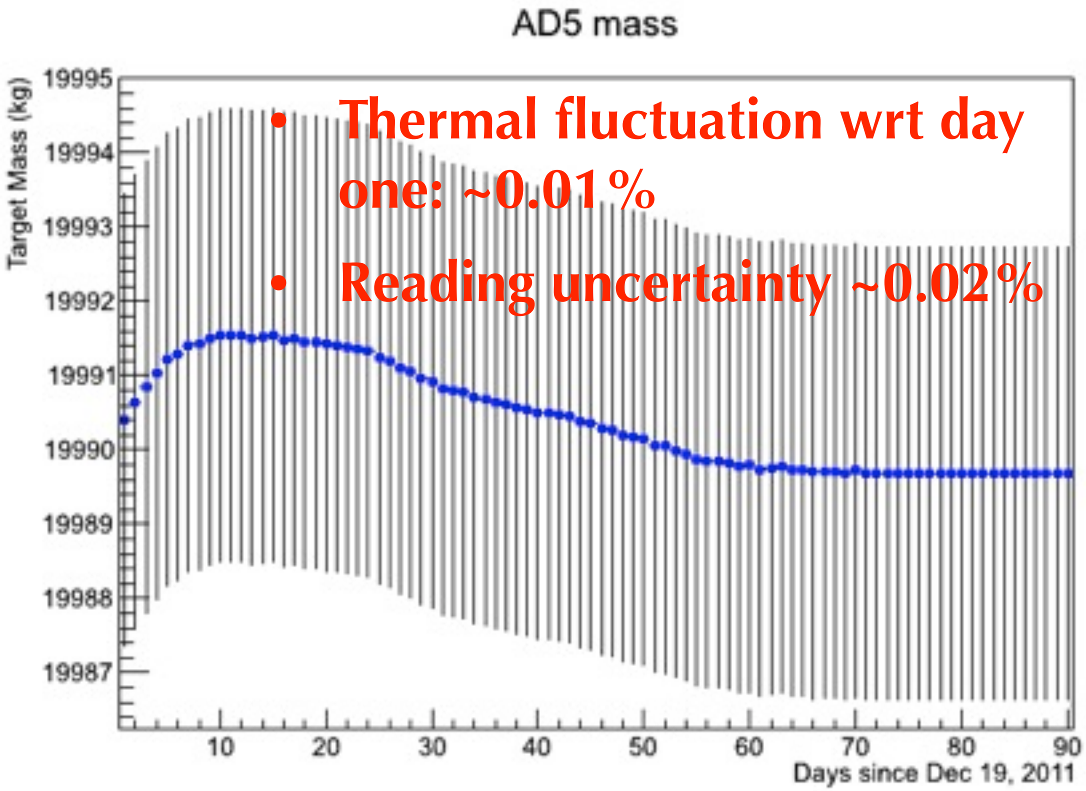




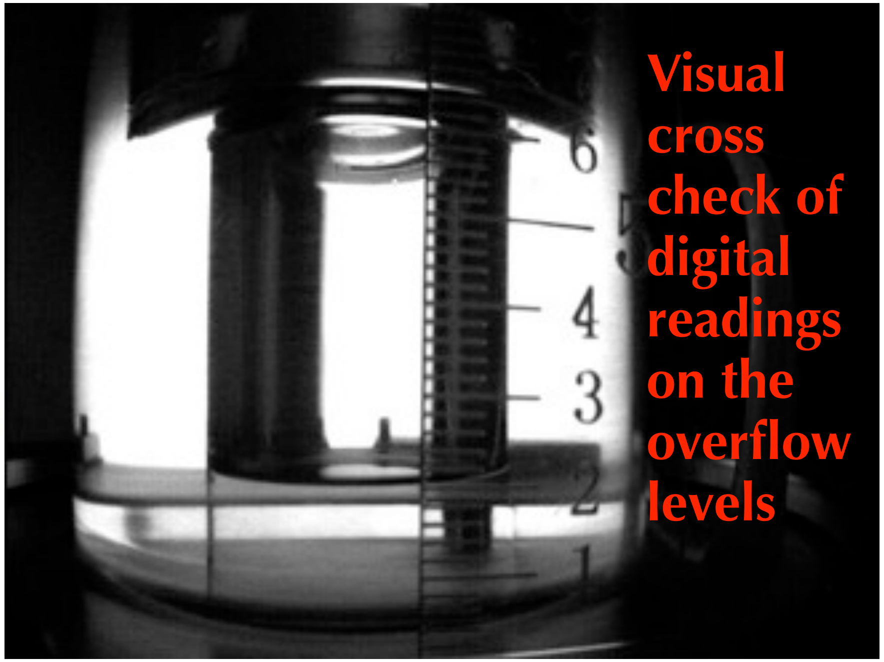


Overflow liquid level monitoring <1mm, which corresponds to **<1kg target**

Target Proton Variation during Data Taking



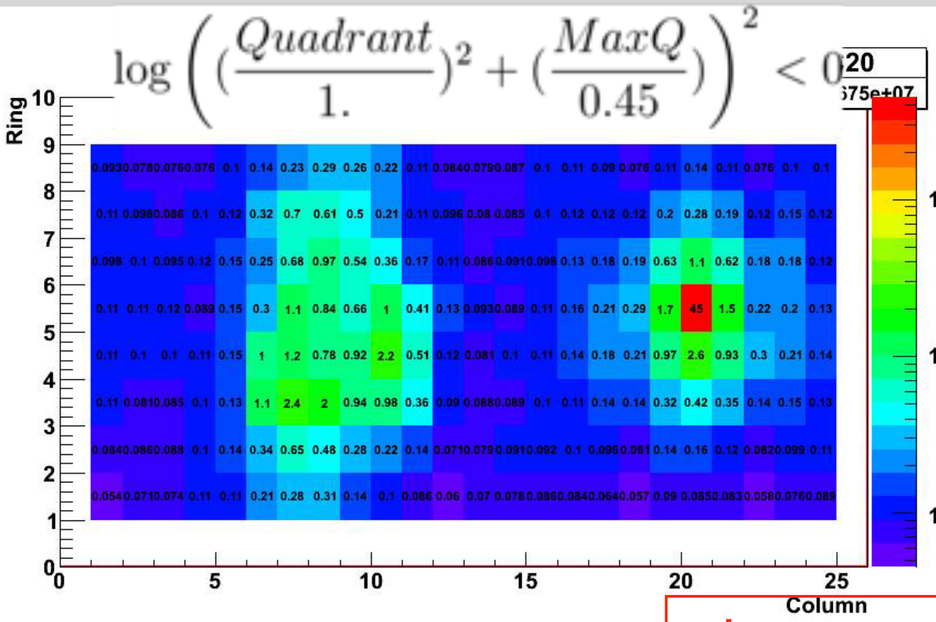
- Thermal fluctuation wrt day one: ~0.01%
- Reading uncertainty ~0.02%



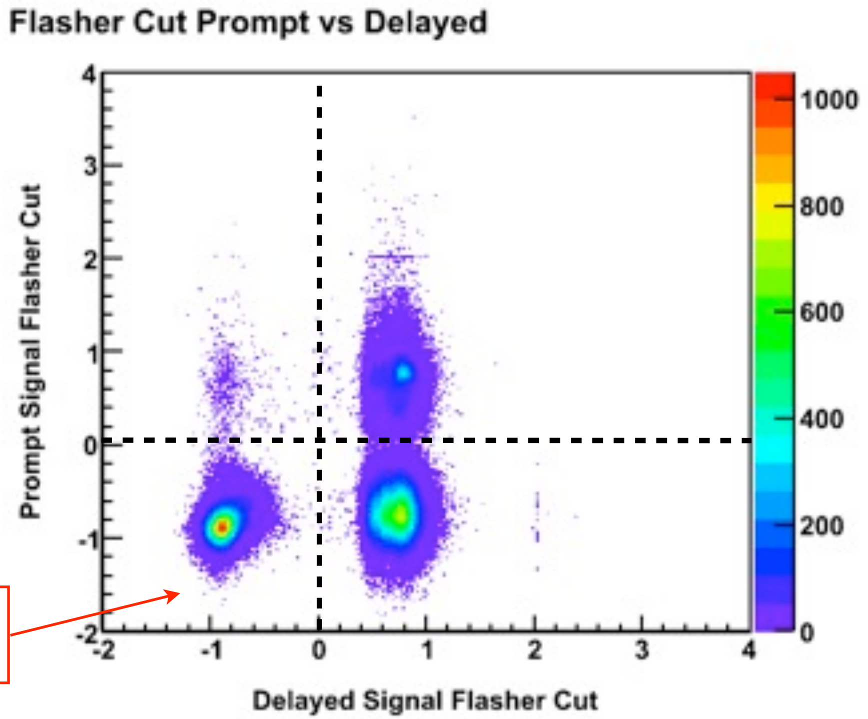
Visual cross check of digital readings on the overflow levels

- Measuring target mass is straightforward
  - Total filled liquid: accurately weighed by load cells under the ISO tank
  - The amount overflow tanks: monitored by redundant sensors
- Total protons in Gd-LS are one of the deciding factors for the expected events. Our study shows that relative uncertainty on the total target mass can be controlled to 0.02% level. H/C ratio becomes the dominant factor at this point.

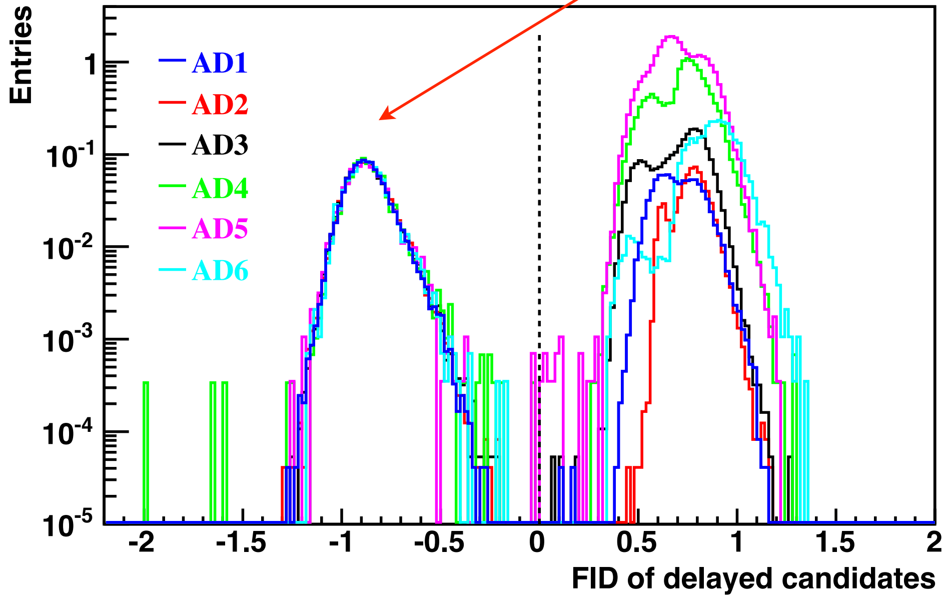
Flashers, bleep Flashers



$$\log\left(\left(\frac{Quadrant}{1.}\right)^2+\left(\frac{MaxQ}{0.45}\right)\right)^2 < 0$$

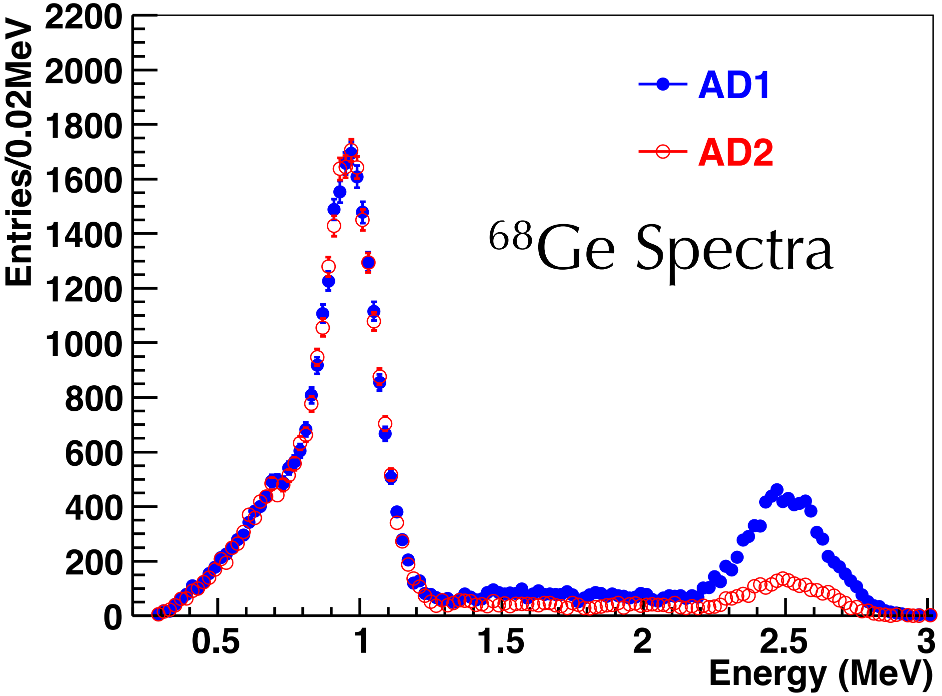


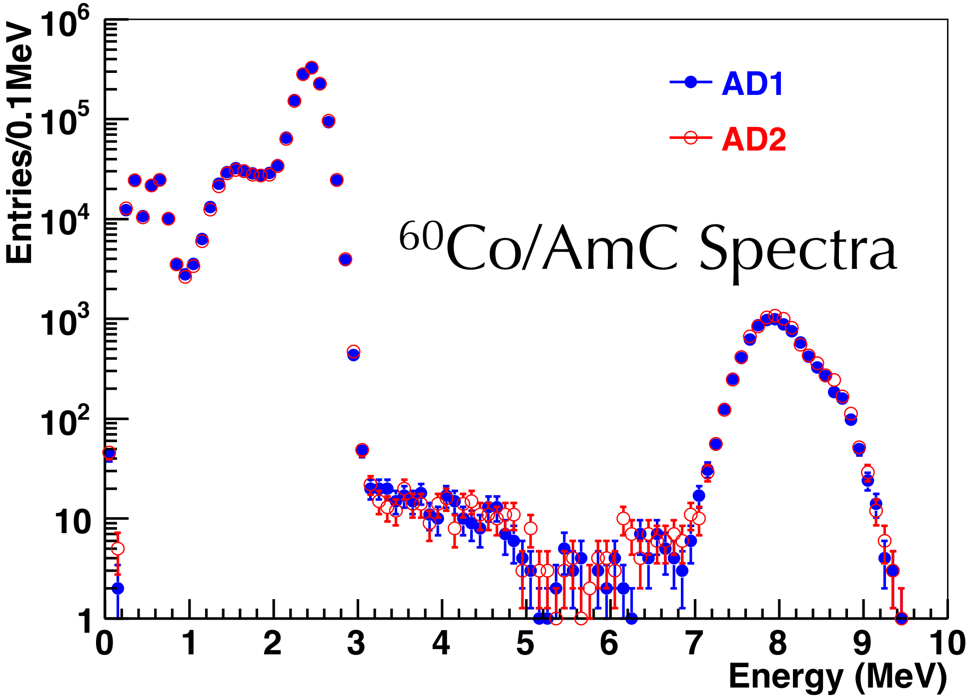
Physics Evts



- Based on the charge spacial features, we form a very effective flasher identifier
  - Multiple cuts based on both charge pattern and temporal features cross check each other
- Flasher identifier is confirmed in hardware tests
- Cut inefficiency ~0.02% and uncertainty is evaluated to be 0.01%
- Contamination negligible, ~10^{-4}

Energy Responses with Calibration Sources



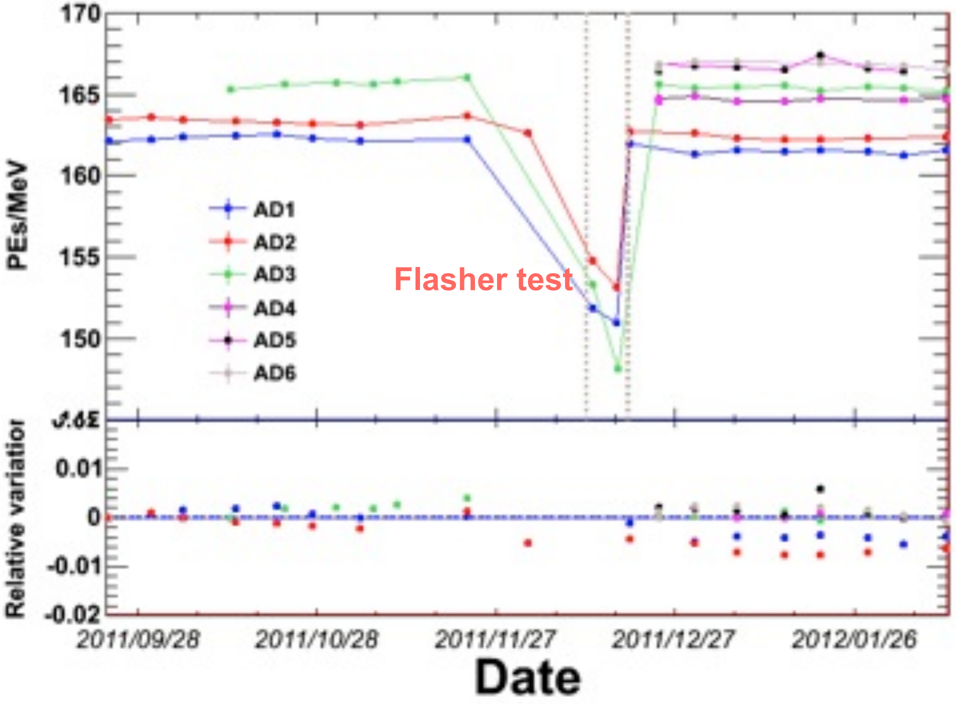


- Weekly automatic calibration. Using AD1&2 as examples
- ^{60}Co 2.506 MeV peak at the center of the detector sets the energy scale
  - Geometrical effect corrected using reconstructed vertexes

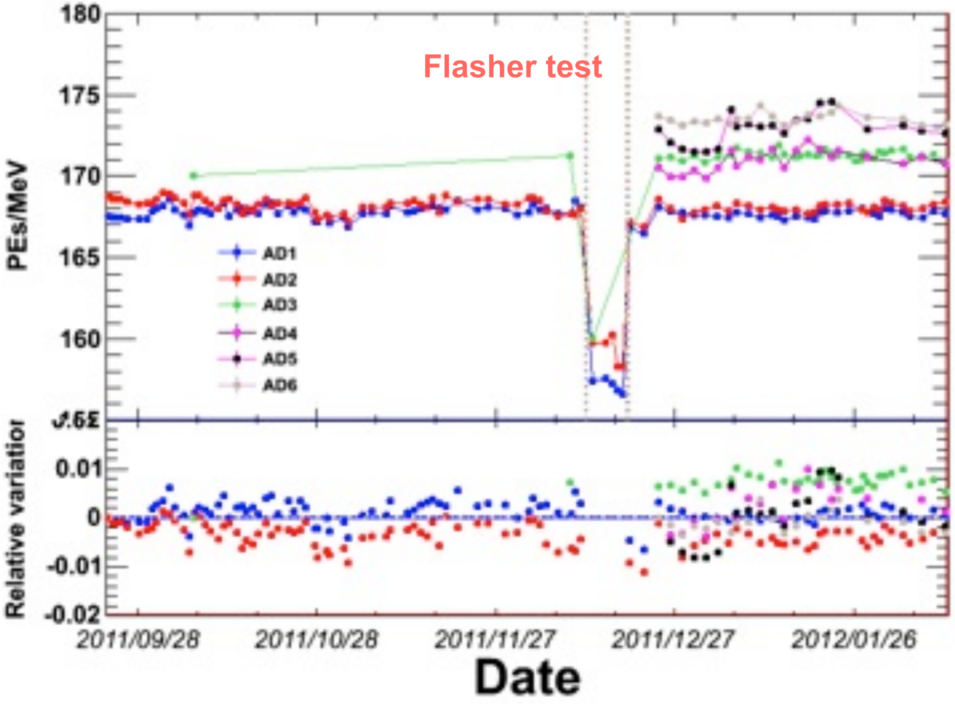
Energy Scale Stability

6 ADs from ^{60}Co at center

(this is our primary method)



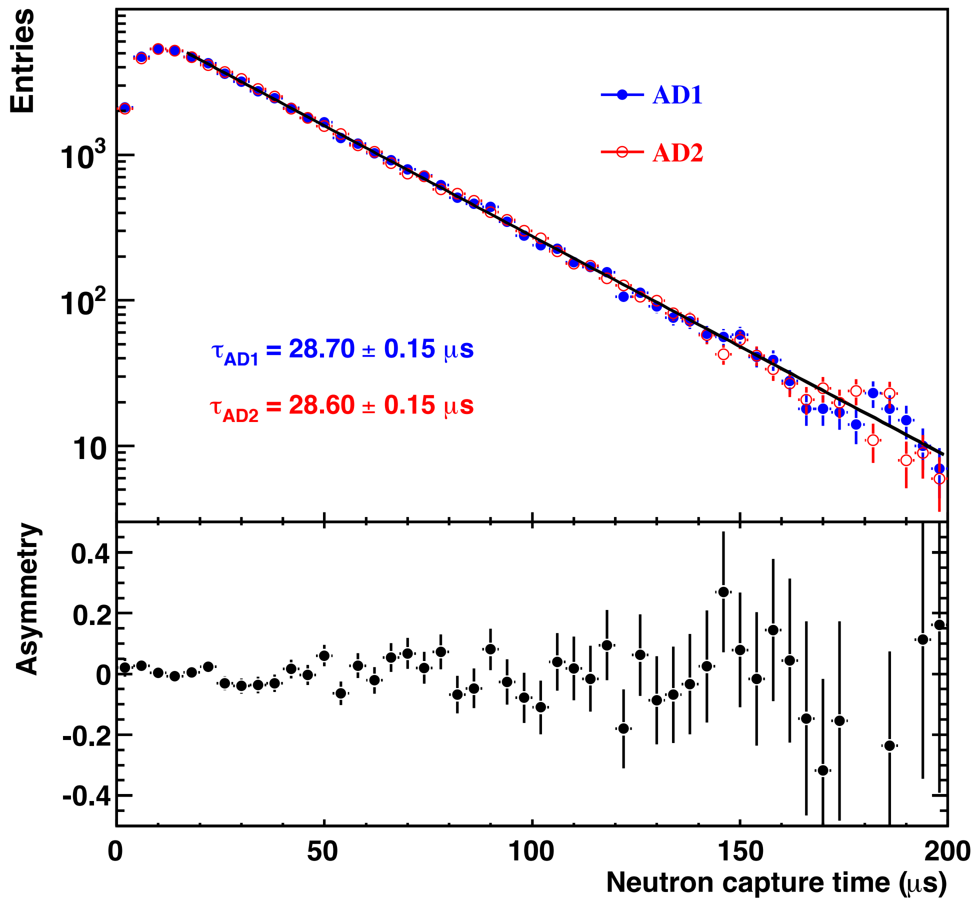
6 ADs from spallation neutron



- From data of ^{60}Co source at detector center
- The gap is the special flasher test during Dec 13 - Dec19

- Based on the spallation neutron data in each detector
- Others same as the ^{60}Co source data

Neutron Capture Time using Am-^{13}C Sources (H/Gd Ratio)



- Capture time measurements and comparisons can tell us the uncertainty of the neutron capture ratios on H and Gd and the "identicalness" of the two detectors

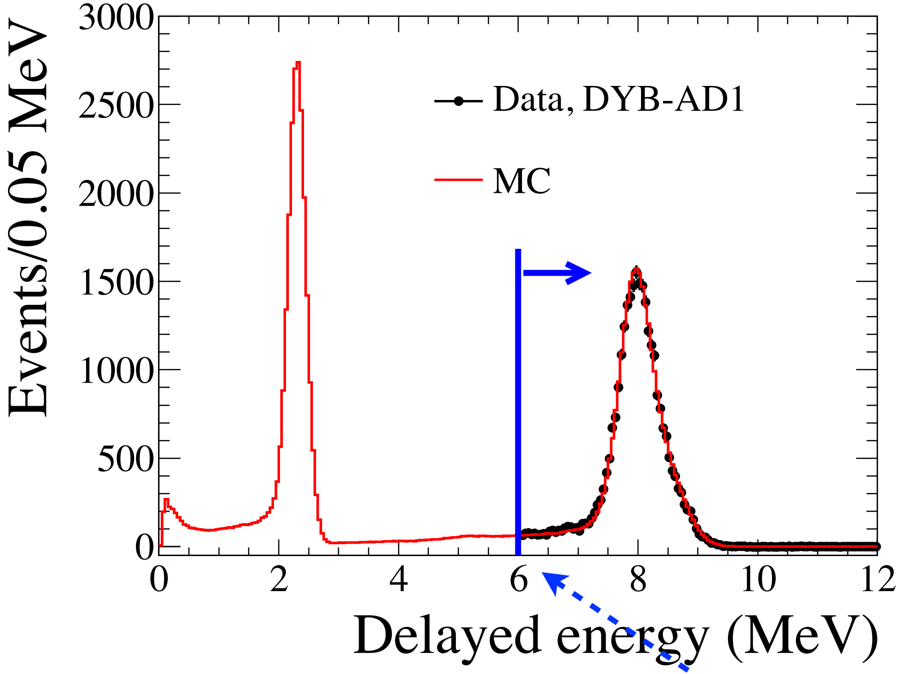
✓ Our detectors are "identical" in H/Gd capture ratio. Critical for total event normalization

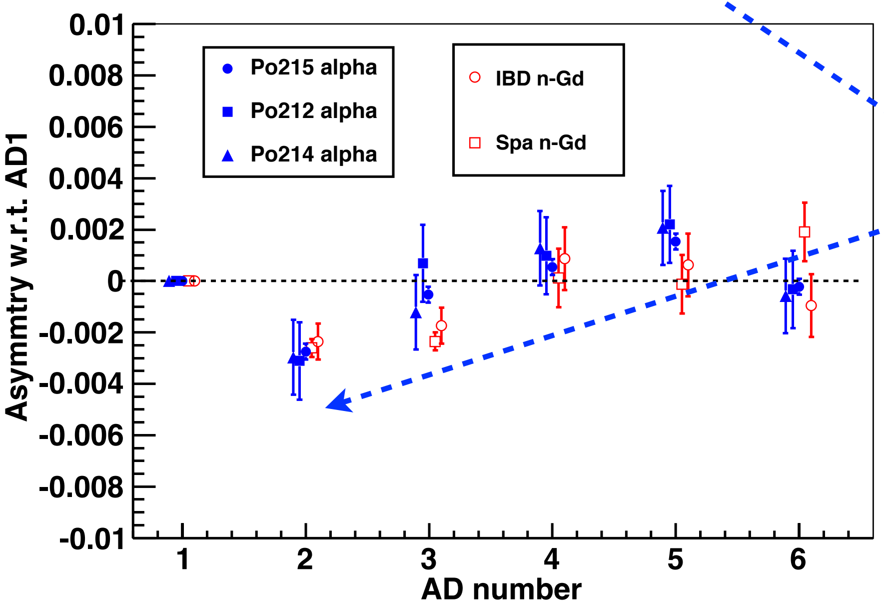
Recall Poisson distribution (useful later):

$$P(n, \lambda) = \frac{\lambda^n e^{-\lambda}}{n!}$$

Separation follows an exponential distribution

The nGd Capture Related Efficiencies and Uncertainties



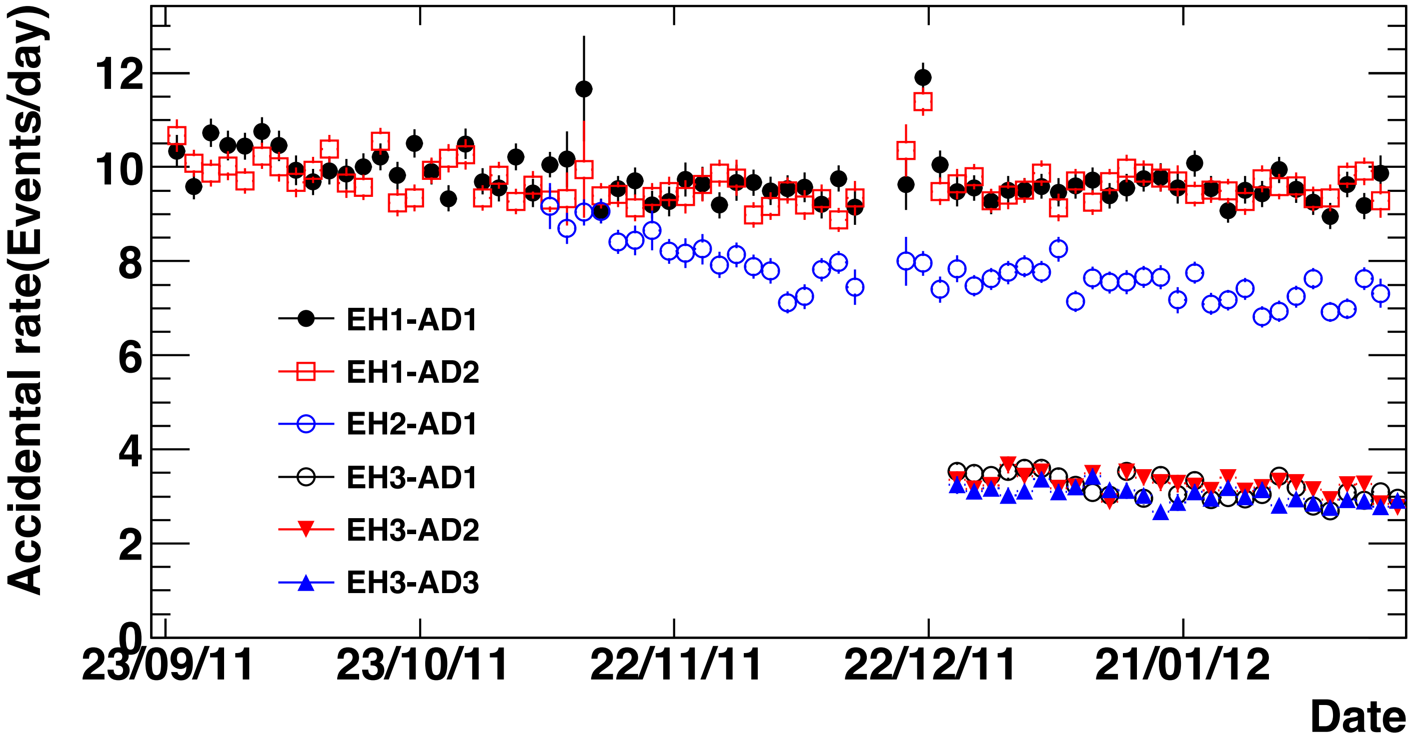


- The nGd capture related efficiencies are
  - nGd capture fraction: 83.8% based on MC. Major part correlated among all detectors. Uncorrelated part is evaluated using capture time <0.1%
  - Spill-in/out correction: 1.05 based on MC. Major part correlated among all detectors. Uncorrelated part is caused by the acrylic <0.02%
  - Capture time cut: 98.6% evaluated based on MC. Major part is correlated. Uncorrelated part is <0.01%
  - **Delayed 6 MeV energy cut**: 90.9% based on MC. Major part correlated among all detectors. Uncorrected part evaluated by comparing the energy scales of all detectors. A 0.5% energy scale uncertainty is observed which causes 0.12% relative cut efficiency uncertainty

Accidental Backgrounds: the Largest

- To form an IBD candidate, a delayed and prompt signal pair is needed and their separation in time is less than 200μs. If the two signals are not correlated in time but brought together by chance ⇒ accidental backgrounds

- It can be calculated accurately: *Prompt and delayed signals follow Poisson distributions ⇒ background rate*
  - $Rate_{acc} = Rate_{delayed} \cdot (1\text{-}Poisson(0, Rate_{prompt} \cdot 199\mu s))$
  - ~8-10 events/day/detector at near sites; ~3 events/day/detector at far site



^{9}Li/^{8}He Backgrounds: the 2nd Largest Backgrounds

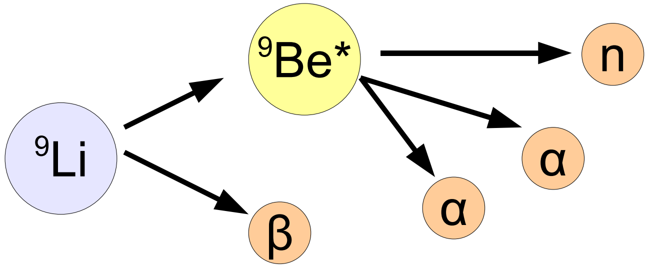
Muon interactions in liquids produce radioactive isotopes. ^{9}Li and ^{8}He are long-lived β,n emitters that can fake the IBD signature.

^{9}Li: $\tau_{1/2}$ = 178 ms, Q = 13. 6 MeV

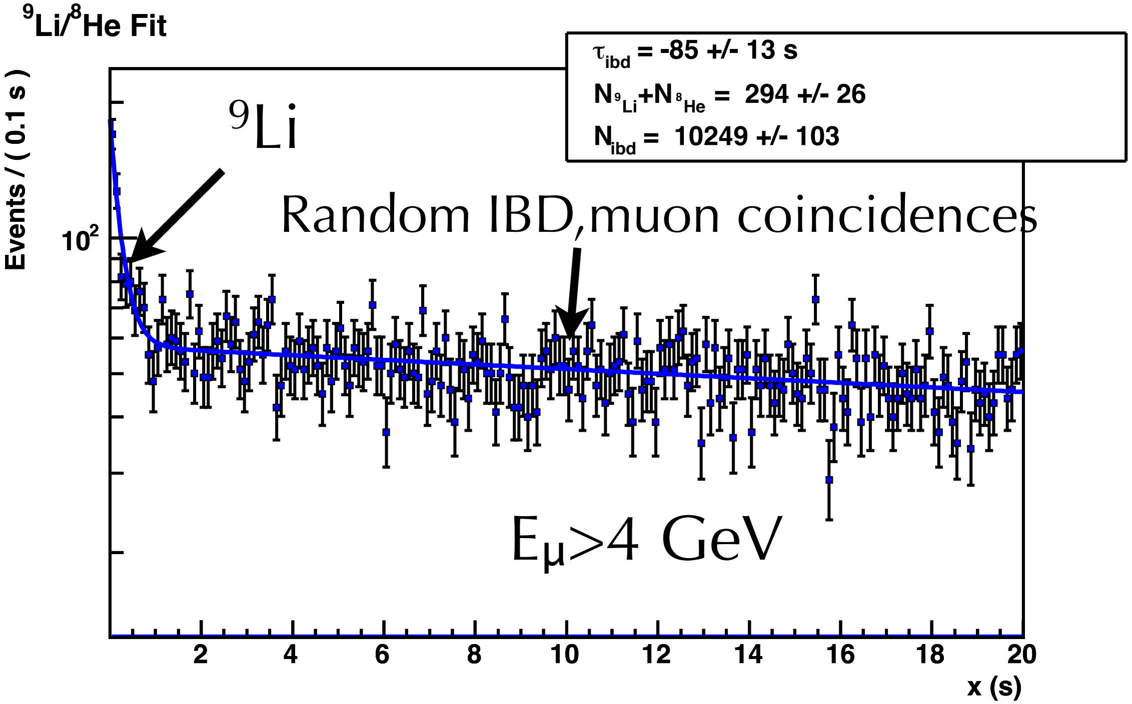
^{8}He: $\tau_{1/2}$ = 119 ms, Q = 10.6 MeV

β-n decay:

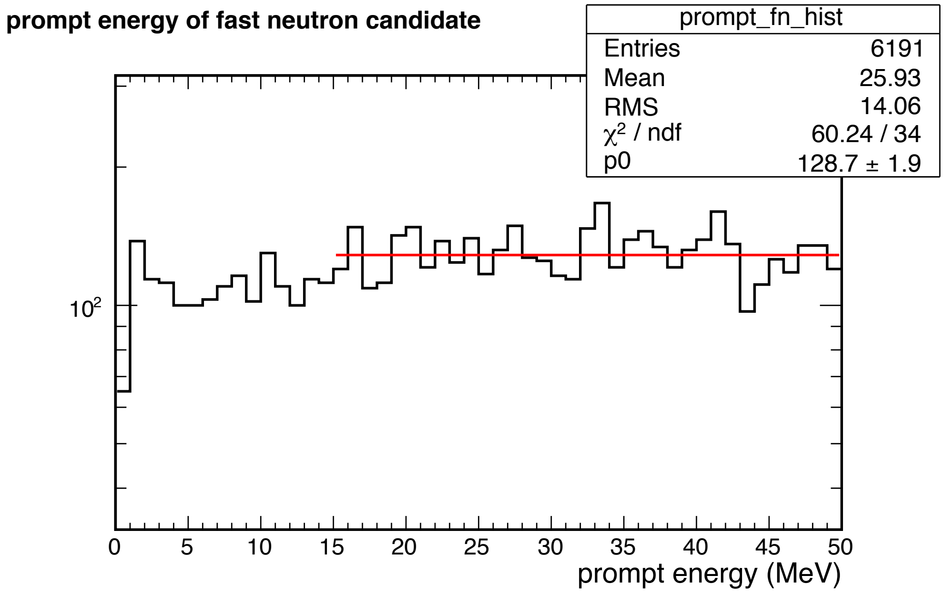
- Prompt: β-decay
- Delayed: neutron capture

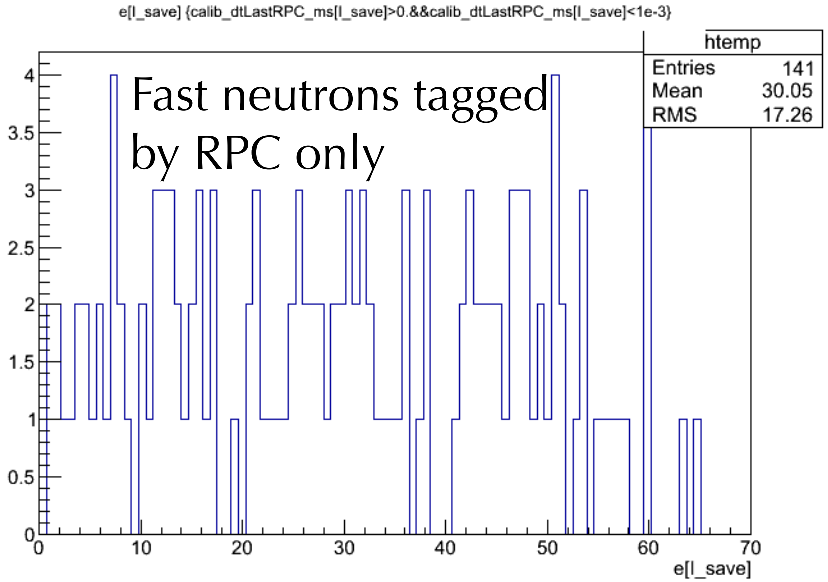


- In the time correlated events after muons, there are both IBDs and such cosmogenic isotopes.
- Use a mixed lifetime exponential decay formula to fit different components to extract ^{9}Li/^{8}He background numbers
- For near sites, around 2-3 ^{9}Li/^{8}He backgrounds per AD per day; for far site, only at the level around 0.16/AD/day
  - Uncertainties are from statistics and the strategy of selecting muons responsible for the isotopes

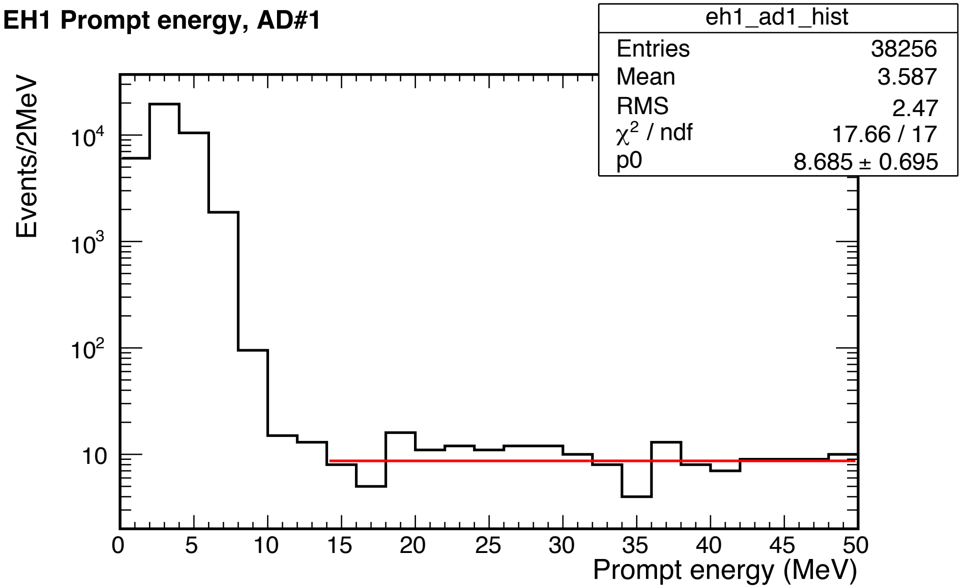


Fast Neutron Backgrounds: the 3rd Largest One



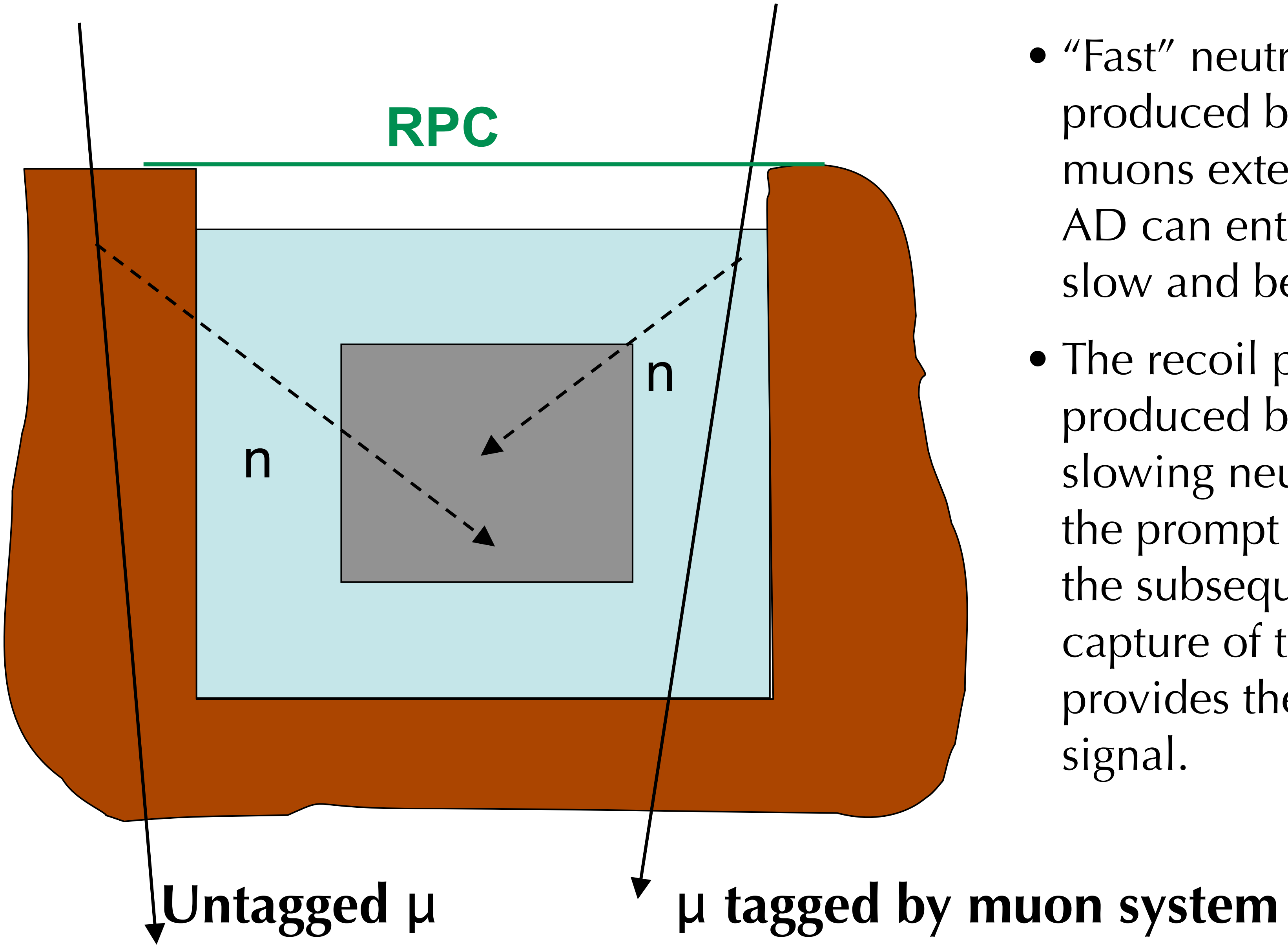


Fast neutrons tagged by RPC only



- Estimate fast neutron contribution by extrapolating from prompt energy distribution (15-50) MeV.
  - Check validity of extrapolation by tagging fast neutrons using the water pool and RPCs.
- Near sites: 0.7~0.8/day; Far: 0.04/day

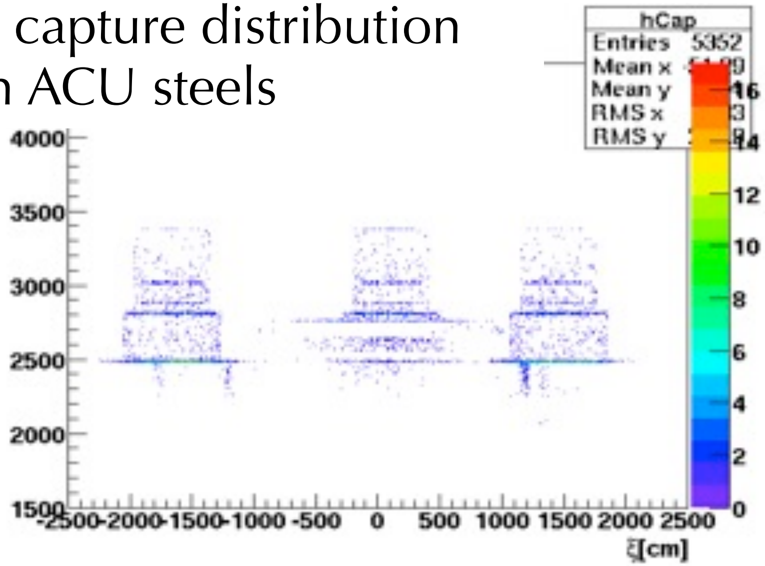
Fast Neutron Faking IBD: the 3rd Largest Background



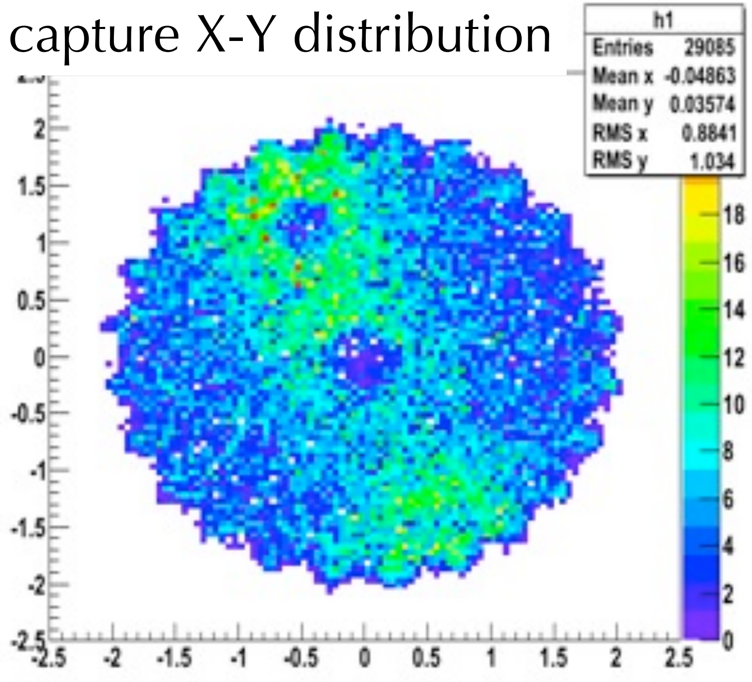
- "Fast" neutrons produced by cosmic muons external to the AD can enter the AD, slow and be captured.
- The recoil proton(s) produced by the slowing neutron fakes the prompt signal and the subsequent capture of the neutron provides the delayed signal.

Calibration Source Backgrounds (Am-^{13}C): Small

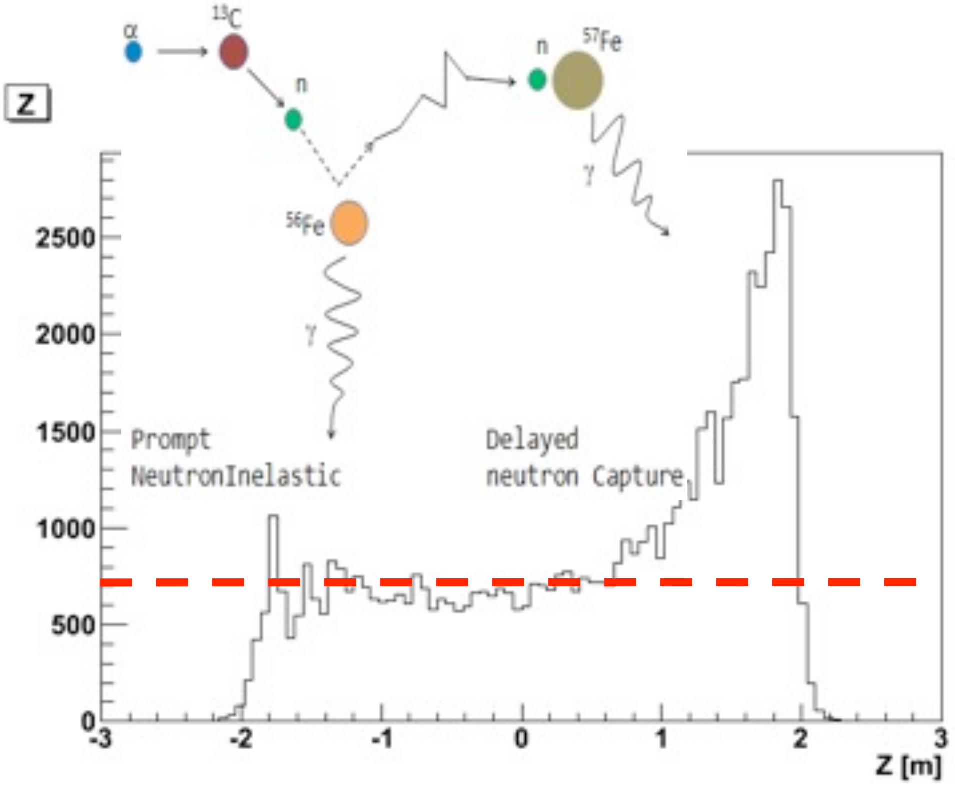
n capture distribution in ACU steels



n capture X-Y distribution



- ~0.5 Hz ^{241}Am^{13}C source produces single neutrons via ^{13}C(α,n)^{16}O.
- Neutrons from sources parked in ACUs on top of AD interact to produce fake (prompt,delayed) pair.
- Measured single neutron background due to AmC ~ 230±40 /module: 0.2+/-0.2 /AD/day



Backgrounds of $^{13}C(\alpha,n)^{16}O$: Smallest

Potential α sources:

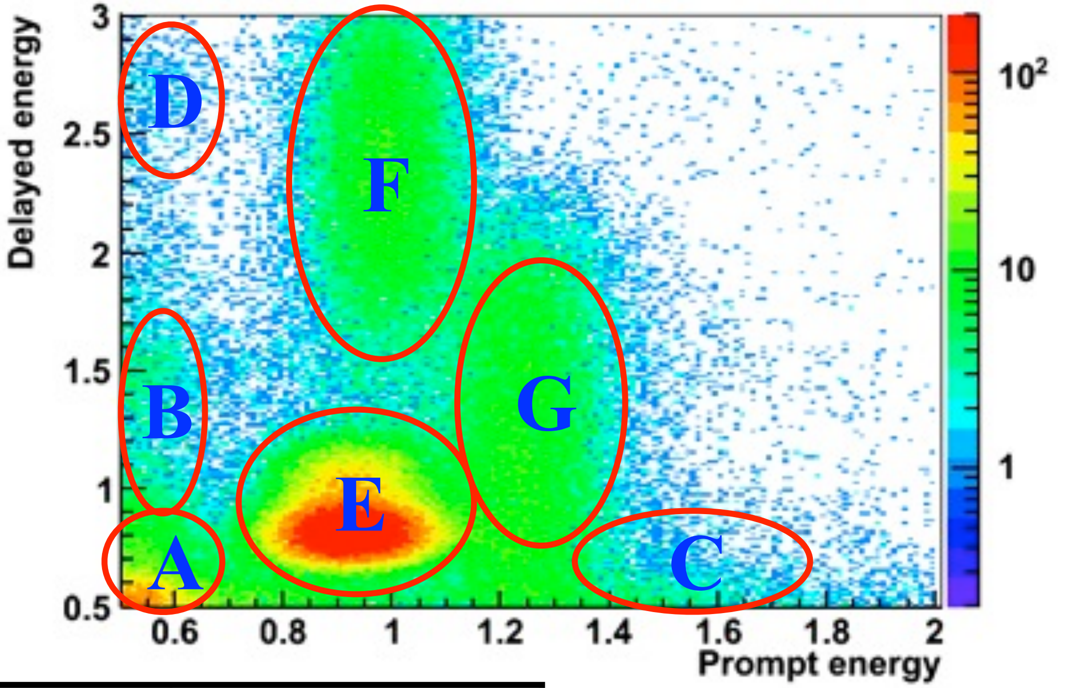
^{238}U, ^{232}Th, ^{227}Ac, ^{210}Po

Good understanding on time coincidence events at low energies

B/S at near site: (0.007+-0.003)%

B/S at far site: (0.05+-0.02)%

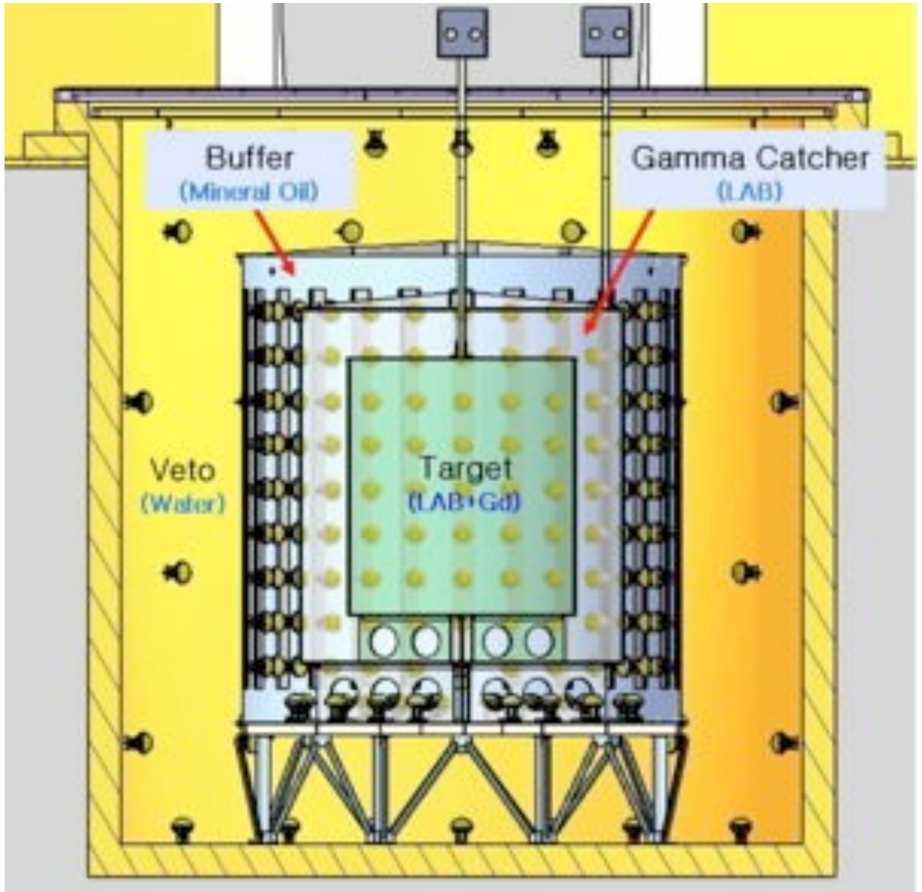
Uncertainty: 50%



	Components	Total α Rate	Background Rate
Region A	Acc. Coincidence of ^{210}Po&^{210}Po	^{210}Po: 10Hz at DYB 8Hz at LA 6Hz at Far	0.02/day at DYB 0.015/day at LA 0.01/day at Far
Region B	Acc. Coincidence of ^{210}Po&^{40}K		
Region C	Acc. Coincidence of ^{40}K&^{210}Po		
Region D	Acc. Coincidence of ^{208}Tl&^{210}Po		
Region E	Cascade decay in ^{227}Ac chain	1.4 Bq	0.01/day
Region F	Cascade decay in ^{238}U chain	0.07Bq	0.001/day
Region G	Cascade decay in ^{232}Th chain	1.2Bq	0.01/day

RENO Detector

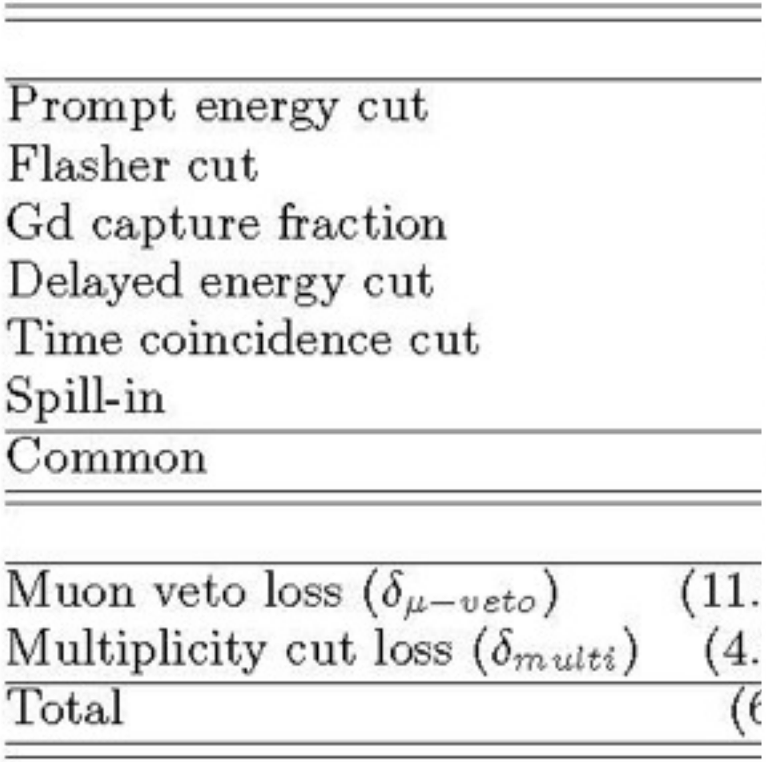
RENO from Soo-Bong



- 354 ID +67 OD 10” PMTs
- Target : 16.5 ton Gd-LS, R=1.4m, H=3.2m
- Gamma Catcher : 30 ton LS, R=2.0m, H=4.4m
- Buffer : 65 ton mineral oil, R=2.7m, H=5.8m
- Veto : 350 ton water, R=4.2m, H=8.8m

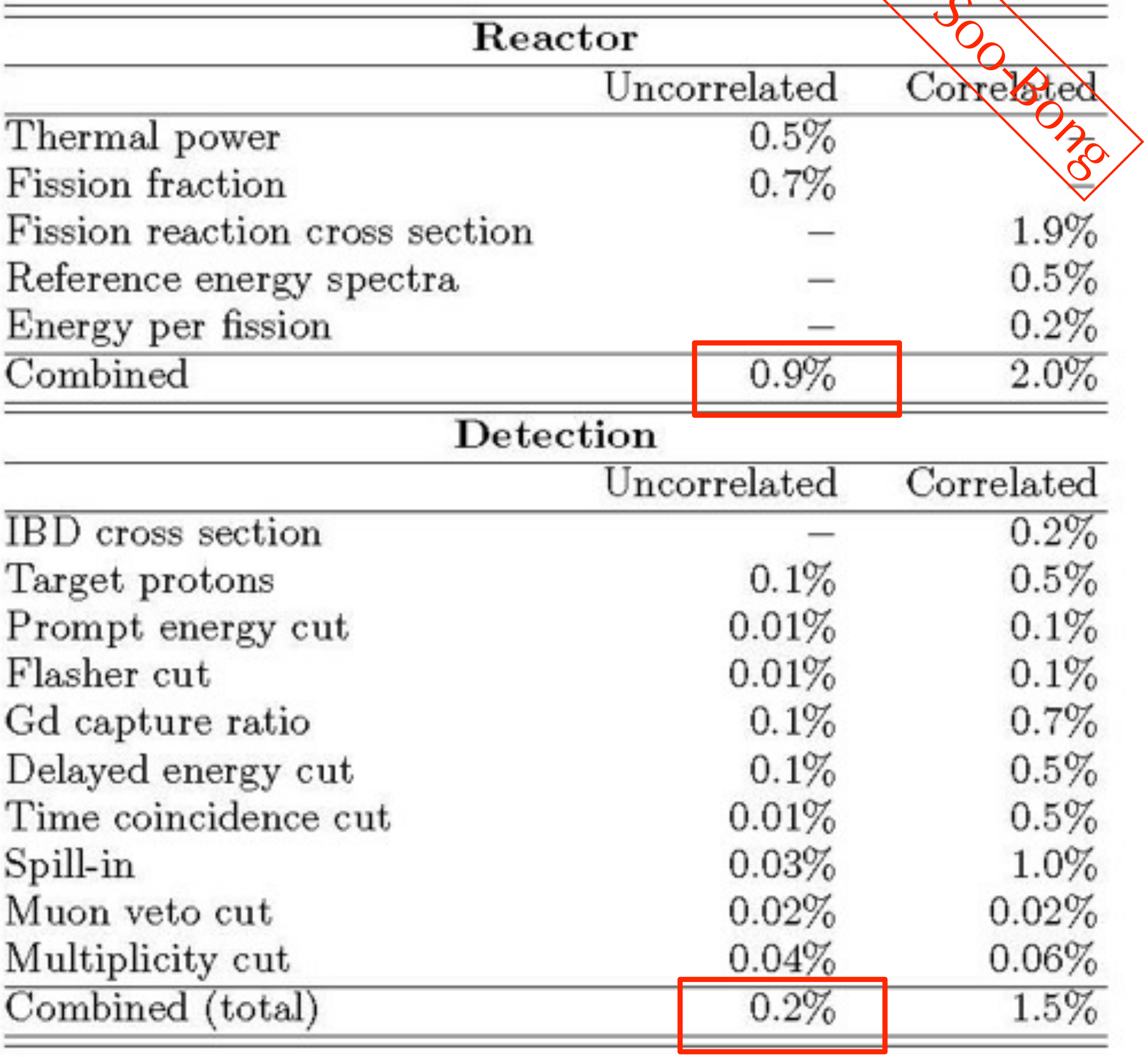
Efficiency & Systematic Uncertainties

RENO from Soo-Bong



Prompt energy cut
Flasher cut
Gd capture fraction
Delayed energy cut
Time coincidence cut
Spill-in
Common

Muon veto loss ($\delta_{\mu-veto}$)	(11.
Multiplicity cut loss (δ_{multi})	(4.
Total	(



Reactor		
	Uncorrelated	Correlated
Thermal power	0.5%	
Fission fraction	0.7%	
Fission reaction cross section	–	1.9%
Reference energy spectra	–	0.5%
Energy per fission	–	0.2%
Combined	0.9%	2.0%

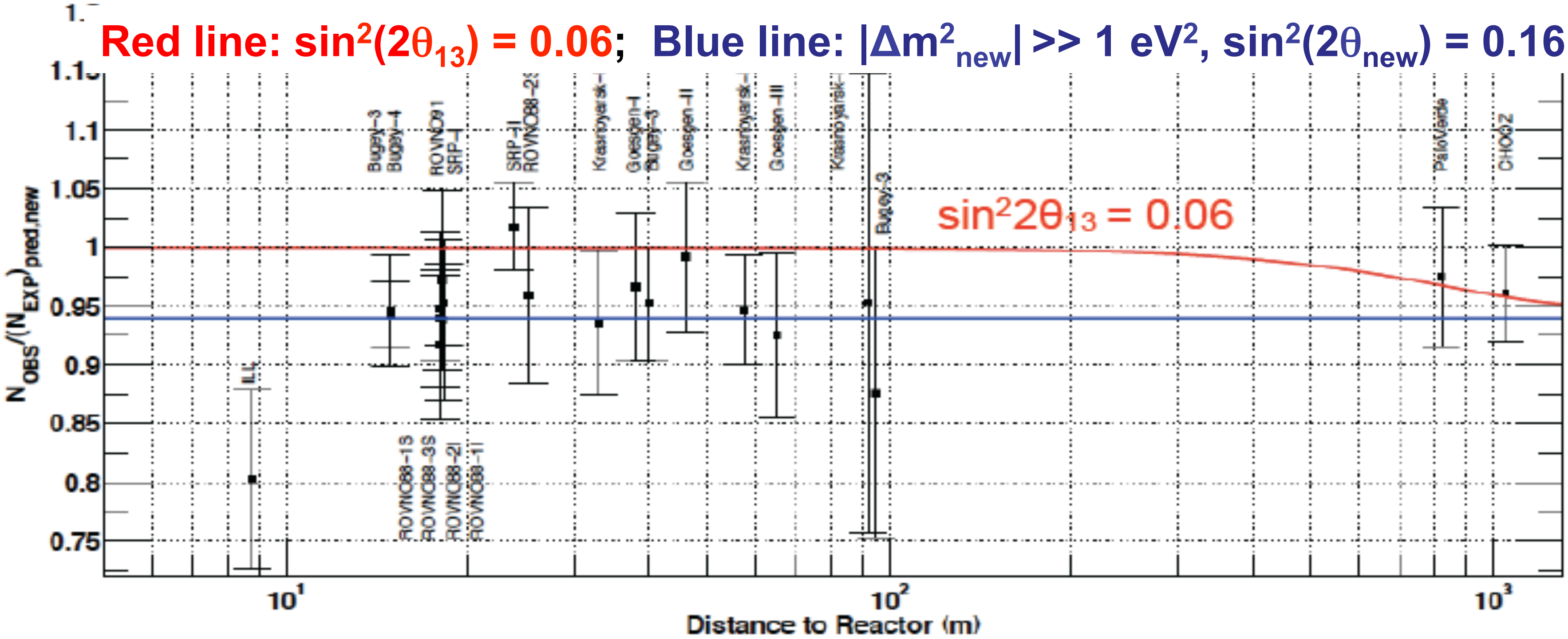
Detection		
	Uncorrelated	Correlated
IBD cross section	–	0.2%
Target protons	0.1%	0.5%
Prompt energy cut	0.01%	0.1%
Flasher cut	0.01%	0.1%
Gd capture ratio	0.1%	0.7%
Delayed energy cut	0.1%	0.5%
Time coincidence cut	0.01%	0.5%
Spill-in	0.03%	1.0%
Muon veto cut	0.02%	0.02%
Multiplicity cut	0.04%	0.06%
Combined (total)	0.2%	1.5%

Reactor Antineutrino Anomaly

from Camillo

The flux is now higher by 6%
All reactor neutrino experiment are below

arXiv:1101.2755v4



Red line: $\sin^2(2\theta_{13}) = 0.06$; Blue line: $|\Delta m^2_{new}| >> 1\ eV^2$, $\sin^2(2\theta_{new}) = 0.16$

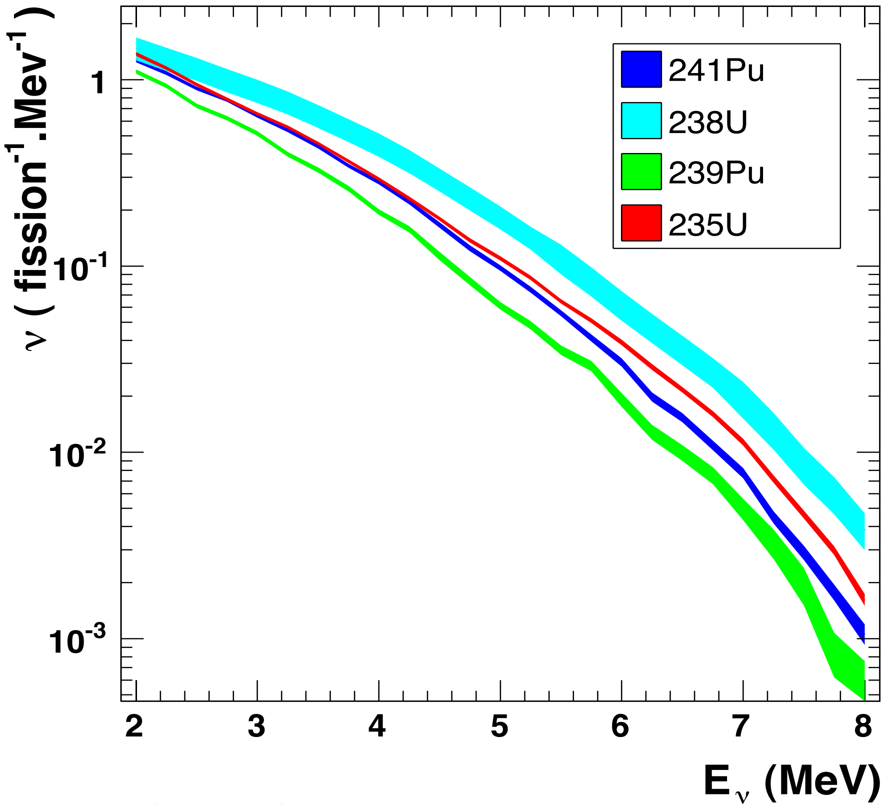
- Use accurate experimental mean value at short distances as an absolute normalization.
- Includes all interpretations of the anomaly.

Reference spectra + Bugey exp.

from Camillo

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

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



Includes latest neutron life time τ_n = 881.4 s, PDG2011

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

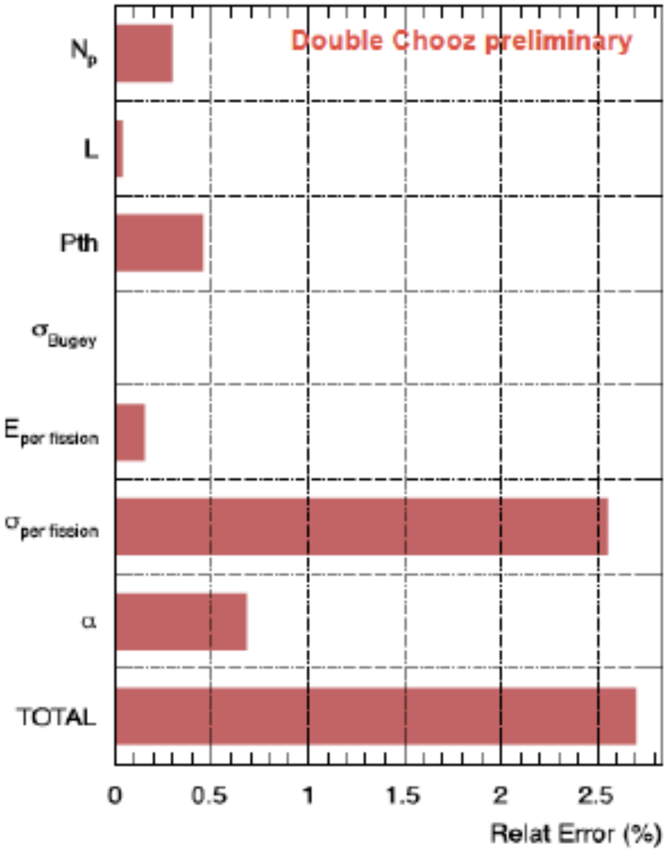
+

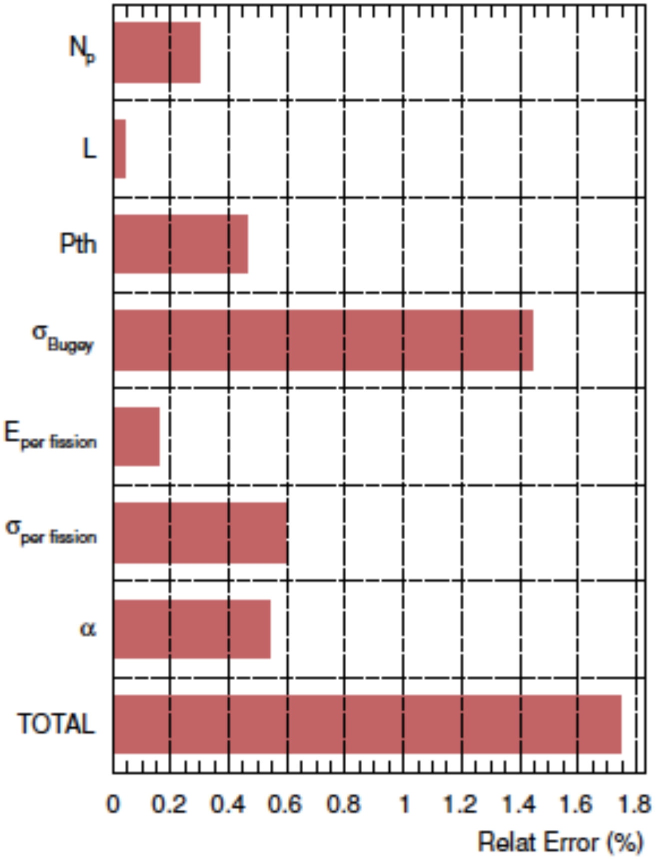
Use as normalization the experimental data from Bugey 4

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

from Camillo

Errors of Reactor Predictions





Without Anchor: 2.70% error

With Anchor: 1.74% error

1.74% total error
(only relevant for 1-detector experiment, Chooz error = 2%)

- Bugey4 measurement suppresses sensitivity to reference spectra uncertainties
- Accurate reactor simulation (MURE) keeps uncertainty on fission rates low