# Les Rencontres de Physique

de la Vallée d'Aoste, La Thuile, Aosta Valley, Italy
February 26 - March 3, 2012

arXiv:1202.6181

# First Results from the Daya Bay Reactor Neutrino Experiment

Deb Mohapatra (Virginia Tech)
on behalf of the Daya Bay Collaboration

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# Outline

- Introduction
- Daya Bay experimental setup
- Preliminary detector performance
- Side by side comparison of first two detectors
- Sensitivity and systematics
- Summary

# The Neutrino Mixing Matrix

- The MNS matrix relates the mass eigenstates ($\nu_1, \nu_2, \nu_3$) to the flavor eigenstates ($\nu_e, \nu_\mu, \nu_\tau$)

$$\begin{pmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \end{pmatrix} = \begin{pmatrix} U_{e1} & U_{e2} & U_{e3} \\ U_{\mu 1} & U_{\mu 2} & U_{\mu 3} \\ U_{\tau 1} & U_{\tau 2} & U_{\tau 3} \end{pmatrix} \begin{pmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \end{pmatrix}$$

Last unknown matrix element

- It can be described by three 2D rotations

$$U_{MNS} = \underbrace{\begin{pmatrix} 1 & 0 & 0 \\ 0 & \cos\theta_{23} & \sin\theta_{23} \\ 0 & -\sin\theta_{23} & \cos\theta_{23} \end{pmatrix}}_{\text{Atmospheric}} \underbrace{\begin{pmatrix} \cos\theta_{13} & 0 & e^{-i\delta}\sin\theta_{13} \\ 0 & 1 & 0 \\ -e^{i\delta}\sin\theta_{13} & 0 & \cos\theta_{13} \end{pmatrix}}_{\text{Reactor}} \underbrace{\begin{pmatrix} \cos\theta_{12} & \sin\theta_{12} & 0 \\ -\sin\theta_{12} & \cos\theta_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix}}_{\text{Solar}} \underbrace{\begin{pmatrix} 1 & 0 & 0 \\ 0 & e^{i\alpha} & 0 \\ 0 & 0 & e^{i\beta} \end{pmatrix}}_{\text{Majorana Phases}}$$

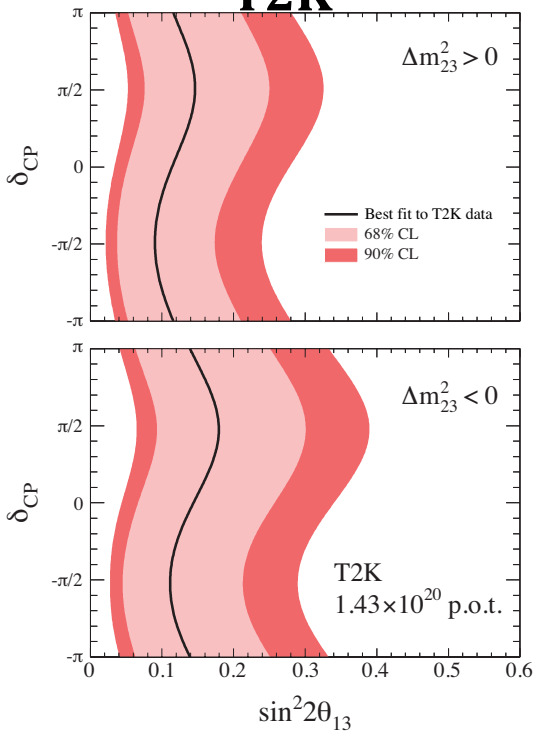
Measurement of the last unknown mixing angle is going to have a substantial impact on the future of neutrino physics.

# Recent Experimental Results (2011): $\theta_{13}$ may be large

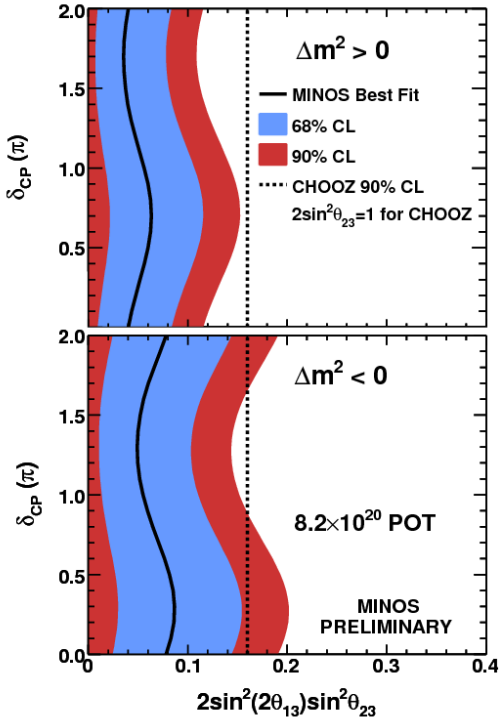
Accelerator based appearance expts

Reactor based disappearance expt

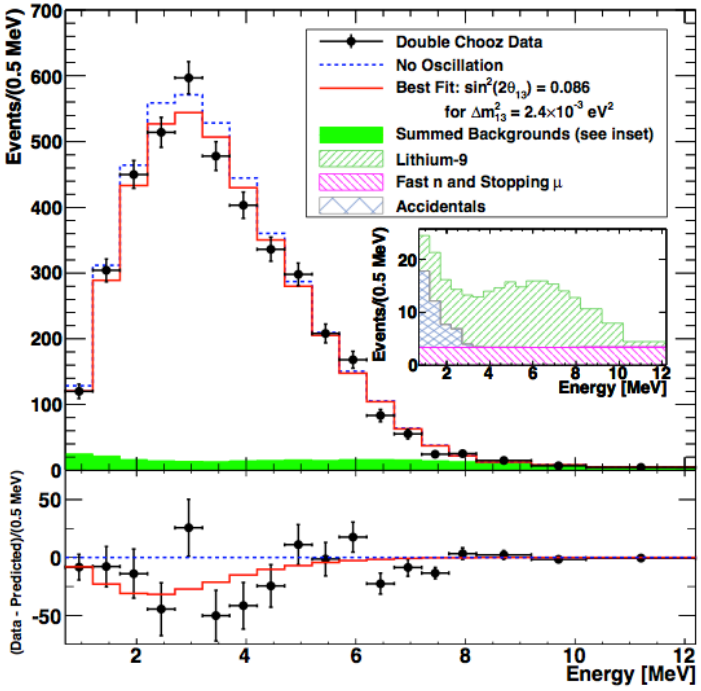
**T2K**




**MINOS**




**Double Chooz**




PRL 107, 041801 (2011)

**$0.03(0.04)<\sin^2 2\theta_{13}<0.28(0.34)$ at 90% CL**

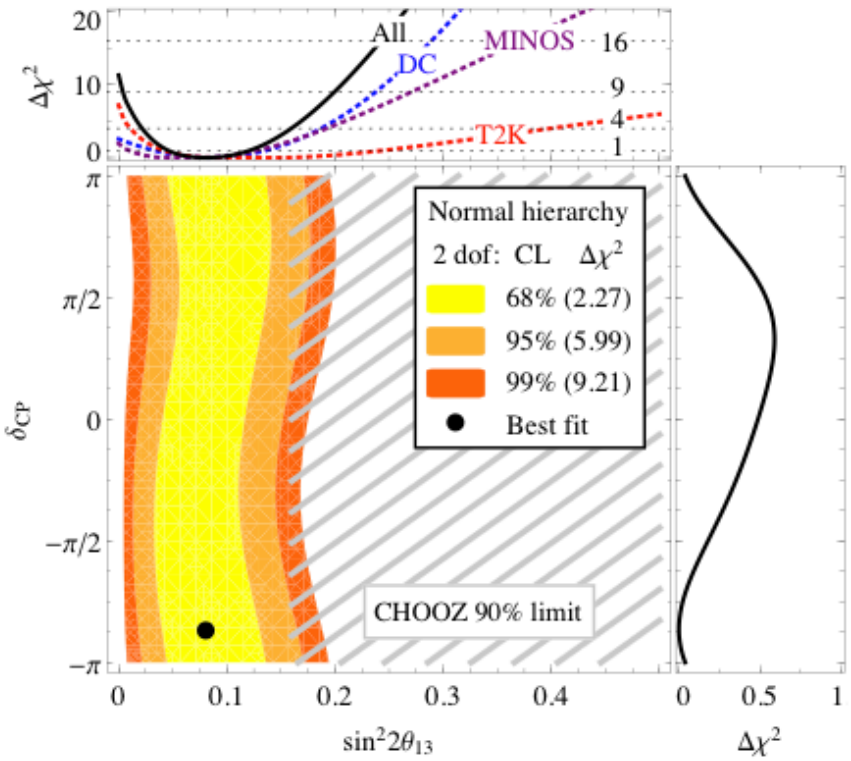
PRL107, 181802 (2011)

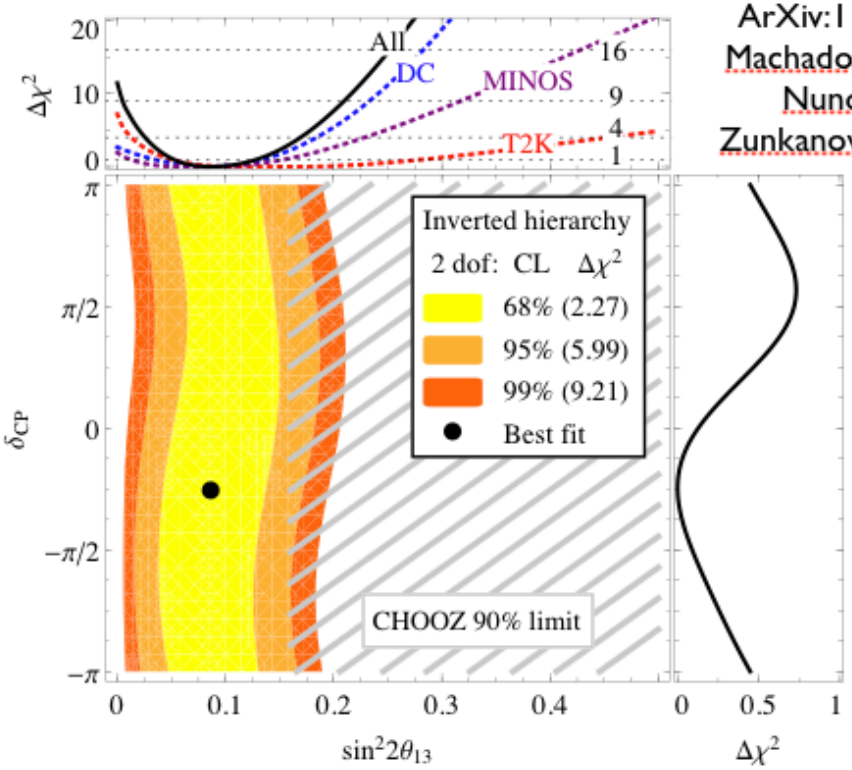
arXiv:1112.6353v2

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

**$(0.015<\sin^2 2\theta_{13}<0.16$ at 90% CL)**

# Combined Analysis



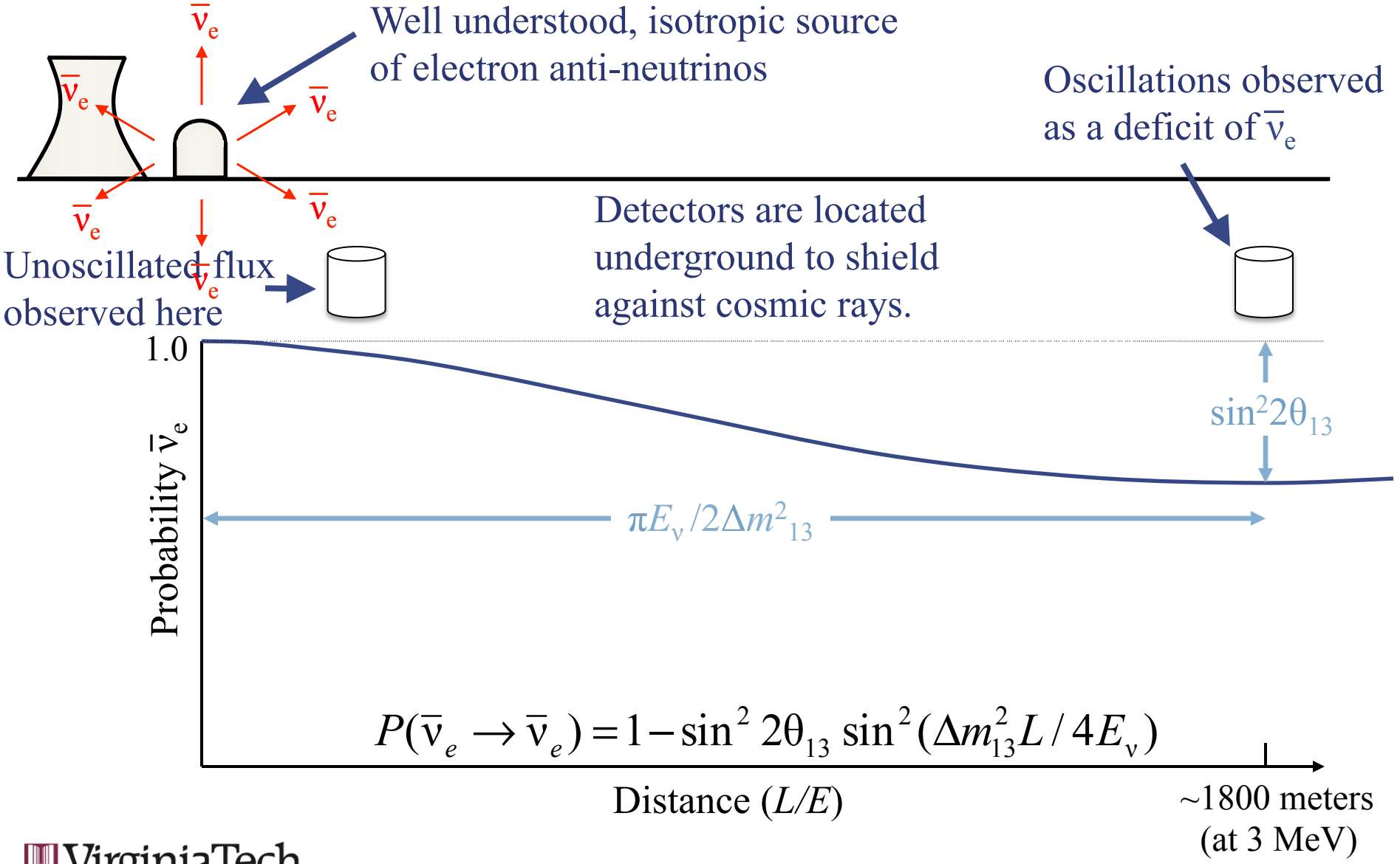




ArXiv:1111.3330, Machado, Minakata, Nunokawa, Zunkanovich Funcal

| $\text{Sin}^2 2\theta_{13}$ | Best Fit | 95% C.L. | $\text{Sin}^2 2\theta_{13}=0$ |
|---|---|---|---|
| Normal Hierarchy | 0.081 | 0.023-0.16 | 3.36 σ |
| Inverted Hierarchy | 0.087 | 0.027-0.17 | 3.36 σ |

Combined measurements exclude 0 at greater than 3 sigma.
But no single experiment has this sensitivity.

# Reactor Based $\theta_{13}$ Experiments

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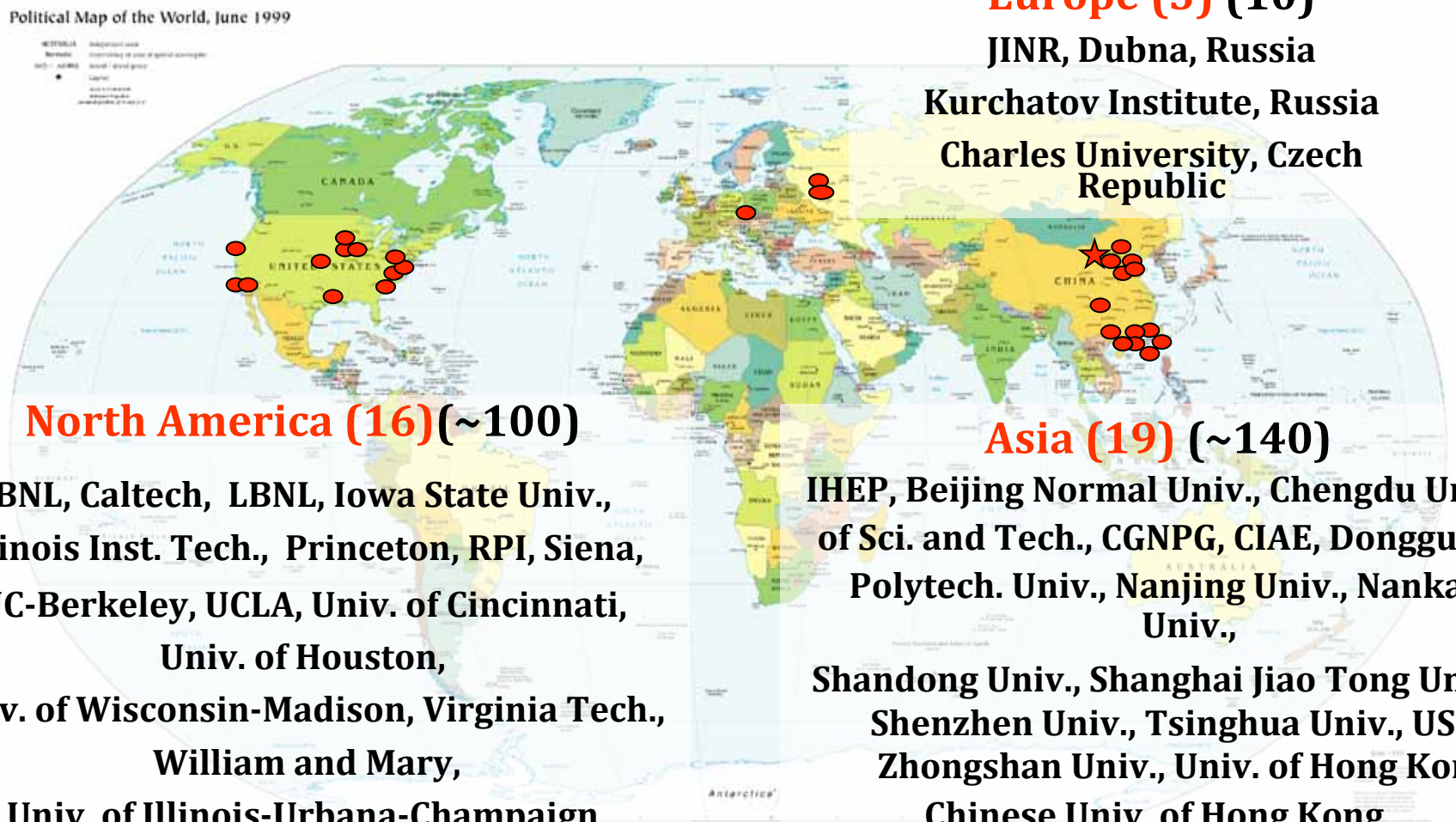
# The Daya Bay Collaboration




## Europe (3) (10)

**JINR, Dubna, Russia**

**Kurchatov Institute, Russia**

**Charles University, Czech Republic**

## North America (16)(~100)

**BNL, Caltech, LBNL, Iowa State Univ., Illinois Inst. Tech., Princeton, RPI, Siena, UC-Berkeley, UCLA, Univ. of Cincinnati, Univ. of Houston, Univ. of Wisconsin-Madison, Virginia Tech., William and Mary, Univ. of Illinois-Urbana-Champaign**

## Asia (19) (~140)

**IHEP, Beijing Normal Univ., Chengdu Univ. of Sci. and Tech., CGNPG, CIAE, Dongguan Polytech. Univ., Nanjing Univ., Nankai Univ., 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.**

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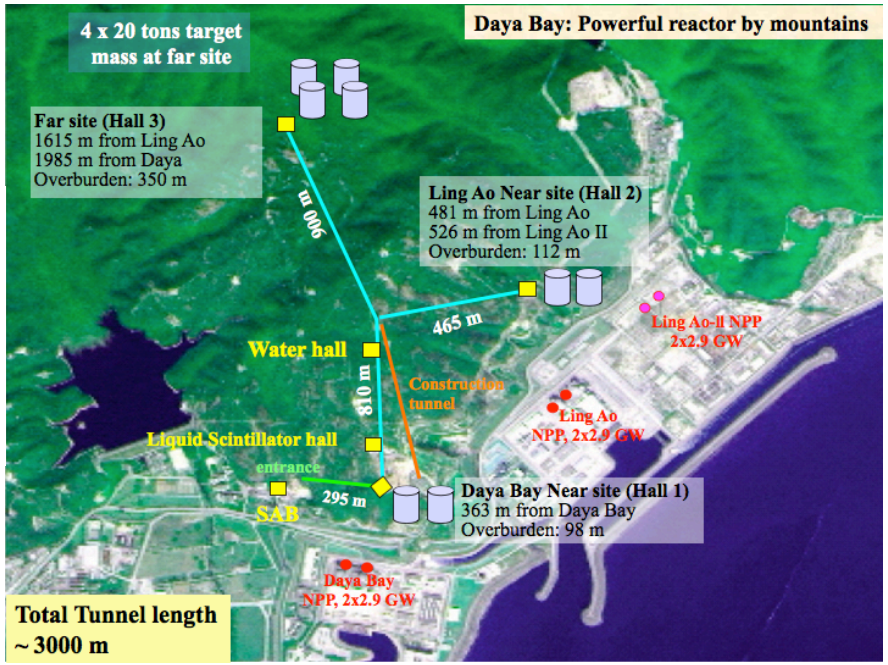
**~ 250 collaborators**

# Daya Bay Design Principle

- Identical near and far detectors cancel many systematic errors
- Multiple modules boost statistics while reducing systematic errors with multiple independent measurements
- Three zone detector design eliminates the need for spatial cuts which can introduce systematic uncertainties
- Shielding from cosmic rays and natural radioactivity reduces background rates
- Movable detectors allow possible cross calibration between near and far detectors to further reduce systematic errors.

## Experimental Layout

| | Overburden | D. B. | L. A. | L. A. II |
|---|---|---|---|---|
| EH1 | 280 | 360 | 860 | 1310 |
| EH2 | 300 | 1350 | 480 | 530 |
| EH3 | 880 | 1910 | 1540 | 1550 |
| | mwe | m | m | m |

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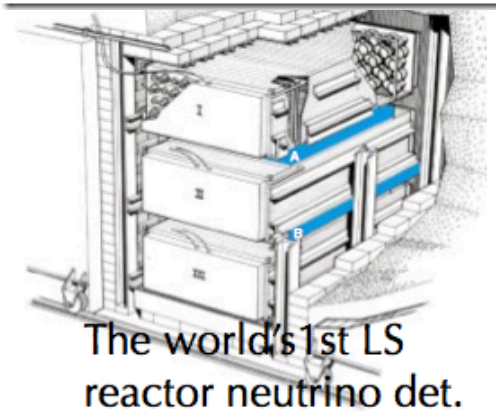
# Antineutrino Detection

Daya Bay: 0.1% Gd doped liquid scintillator as target

Savannah River Experiment

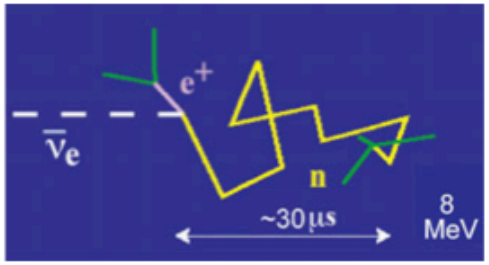
Reines *et al.*, Phys. Rev. **117**, 159 (1960)

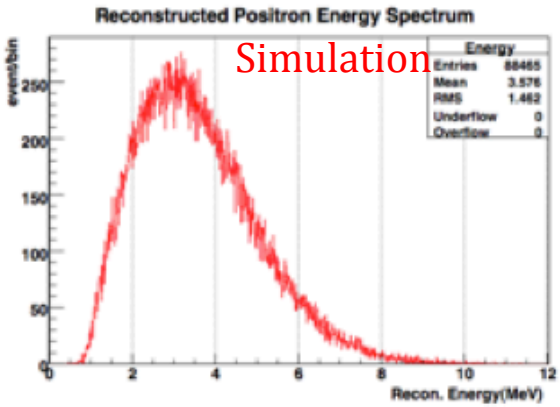


The world's1st LS reactor neutrino det.

$$\bar{\nu}_e + p \rightarrow e^+ + n \qquad (0.3\text{b}) \qquad n + p \rightarrow D + \gamma(2.2\,\text{MeV})$$

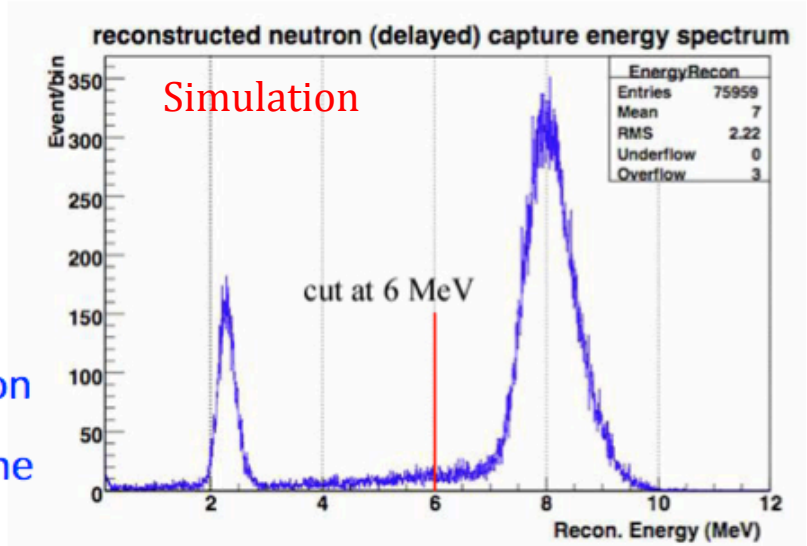
$$E_{\bar{\nu}_e} \approx E_{e^+} + m_n - m_p \qquad (\sim 49{,}000\text{b}) \qquad n + Gd \rightarrow Gd^* \rightarrow Gd + \gamma(\sim 8\,\text{MeV})$$



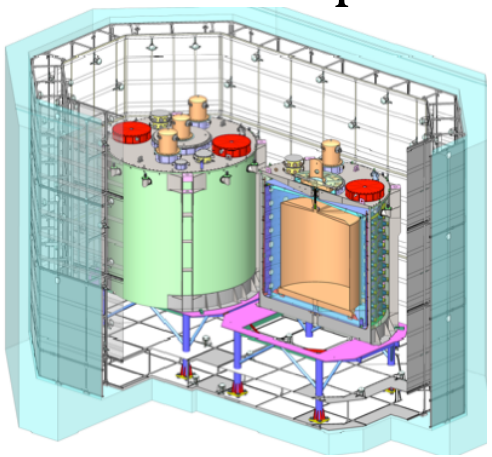

## Correlated Signals

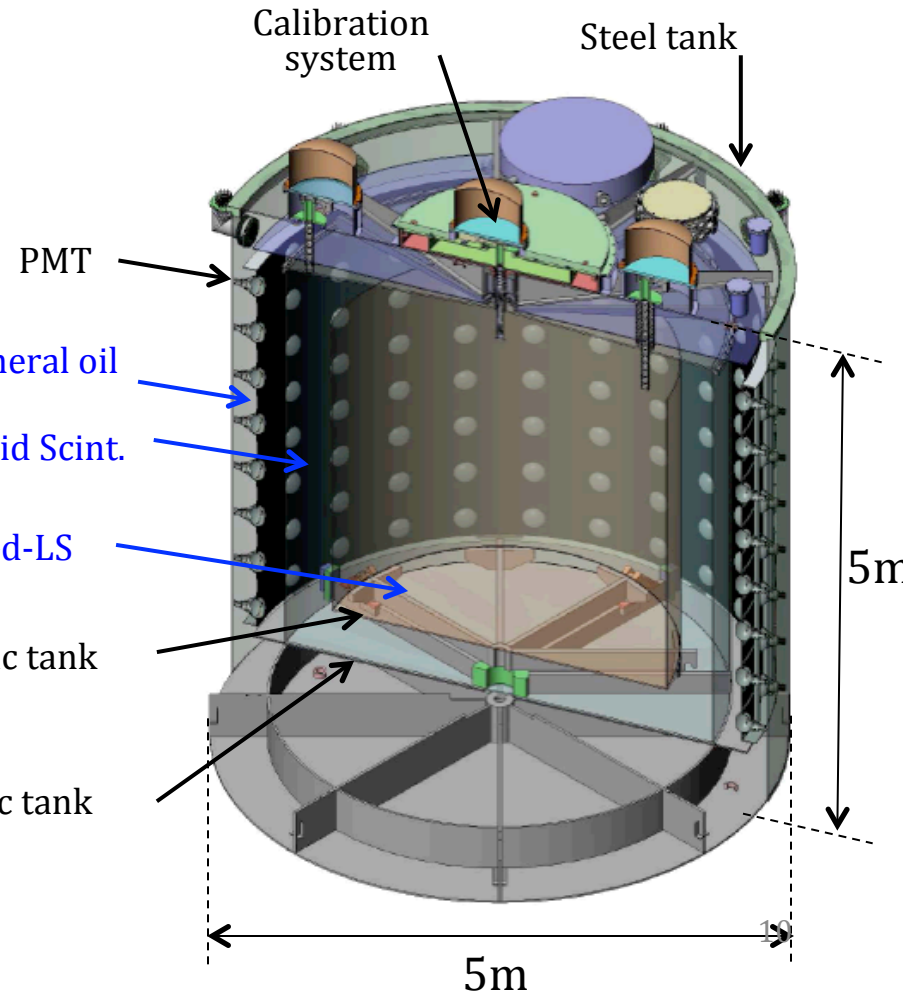
- background suppression
- well-defined target zone



# 8 Identical Antineutrino Detectors

- Three-zone cylindrical design
  - ✓ Target: 20 t (0.1% Gd based Liquid Scintillator)
  - ✓ Gamma catcher: 20 t LS
  - ✓ Buffer : 40 t (mineral oil)
  - ✓ Detector Mass ~ 110 ton
- 192 low-background 8” PMTs
- Reflectors at top and bottom
- ADs sit in a pool of water





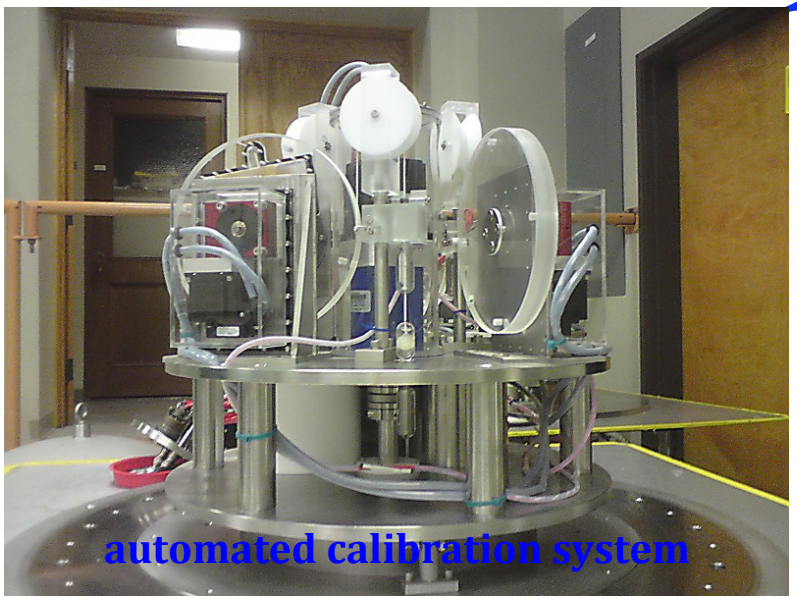
# AD Calibration System

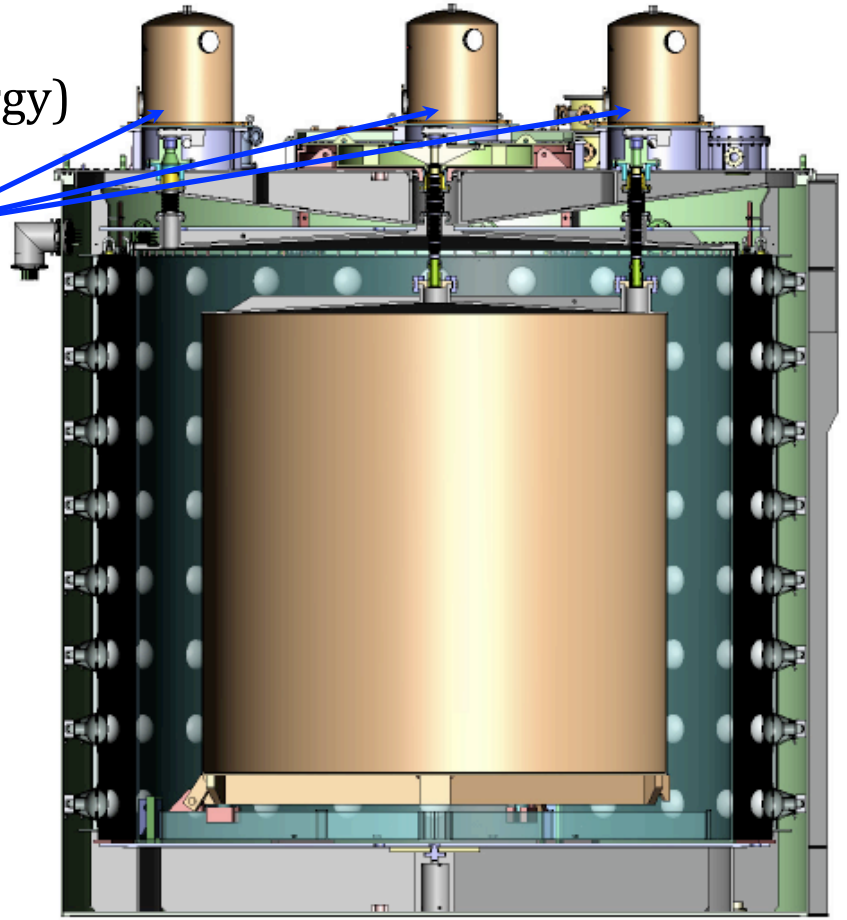
Automated calibration system
→ routine weekly deployment of sources

LED light sources
→ monitoring optical properties

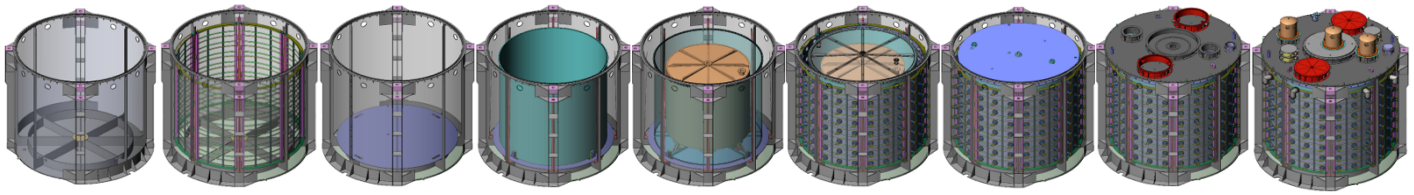
$e^+$ and n radioactive sources (=fixed energy)
→ energy calibration

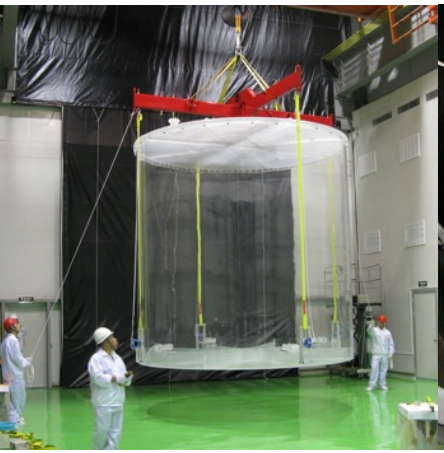
- $^{68}$Ge source
- Am-$^{13}$C + $^{60}$Co source
- LED diffuser ball

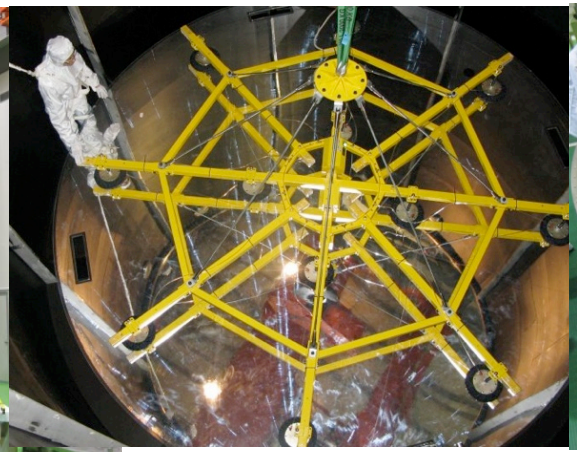


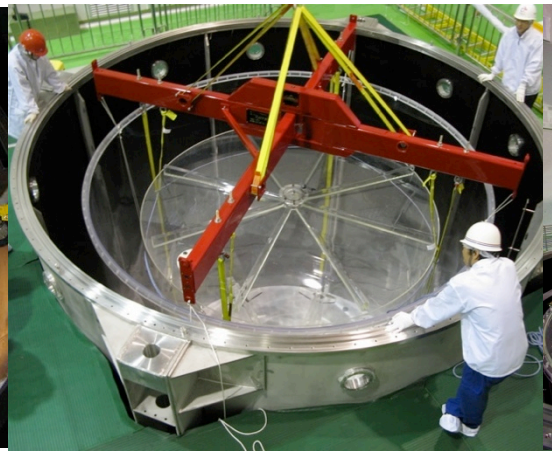



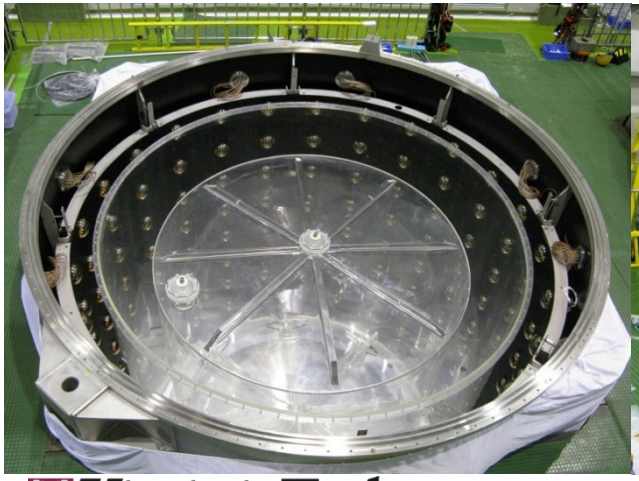
# Anti Detector Assembly

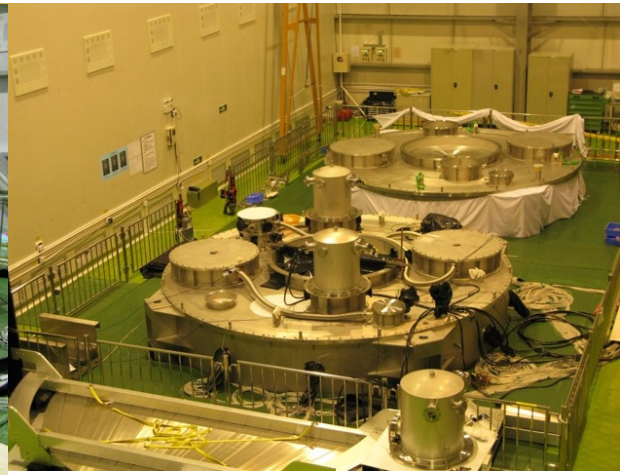




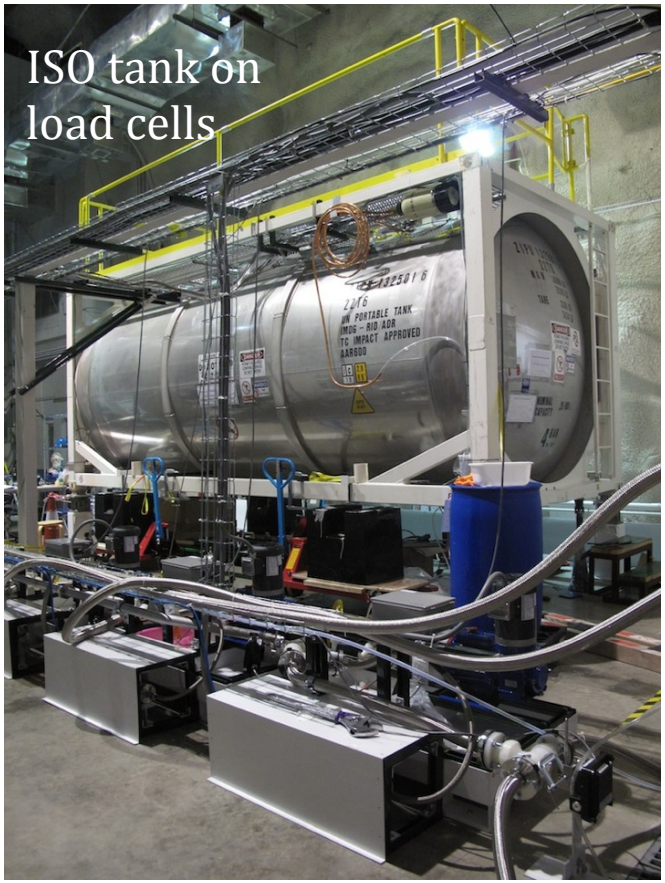


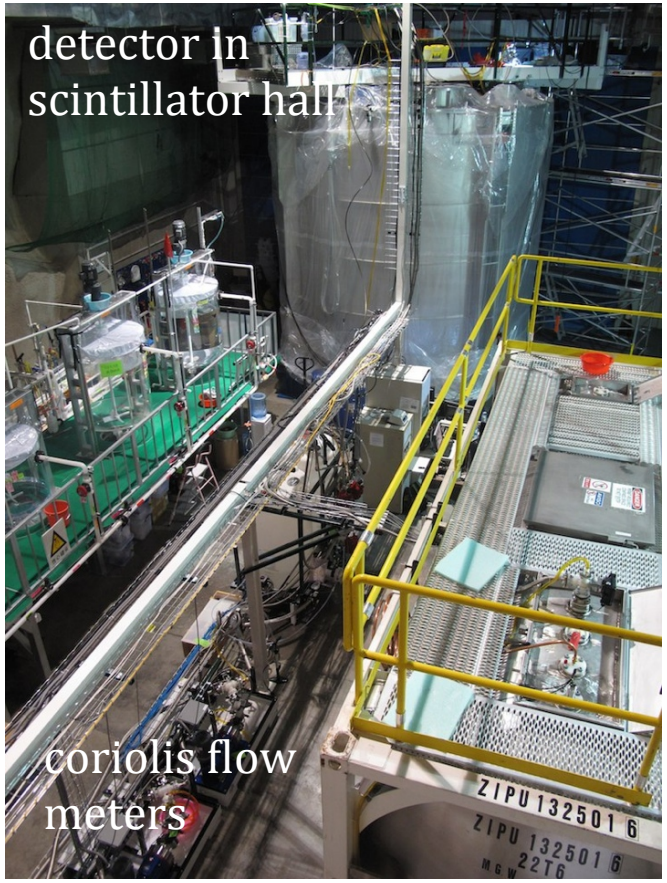


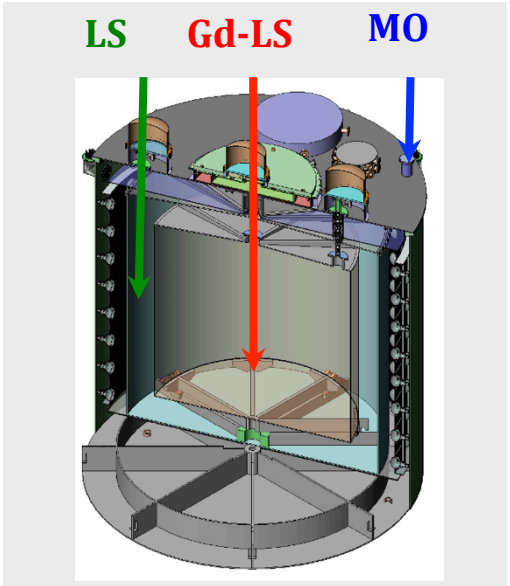


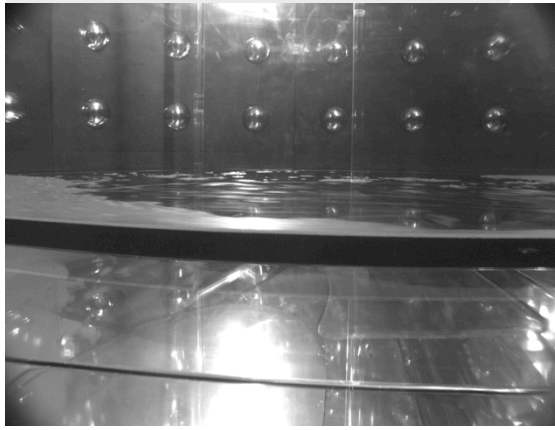


# Detector Filling and Target Mass Measurement



Target mass determination error ± 3kg out of 20,000 or <0.02%.

Detectors are filled from same reservoirs *"in-pairs"* within < 2 weeks.



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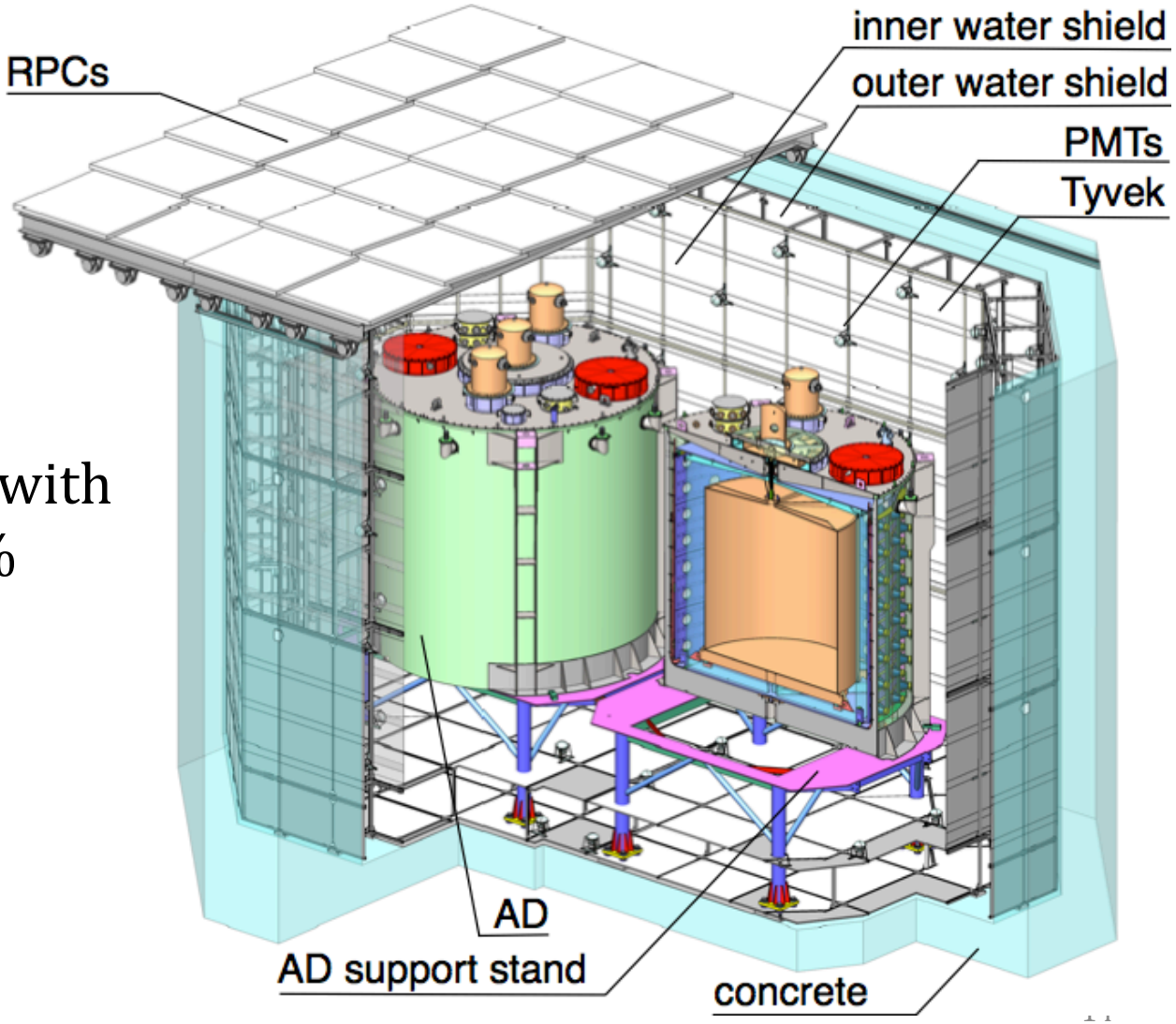
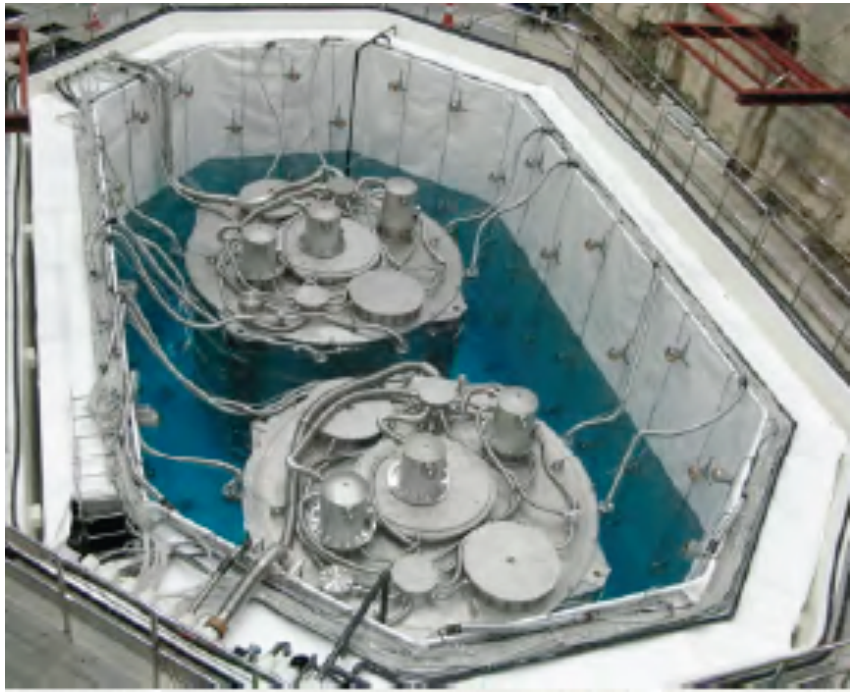
# The Muon Tagging System

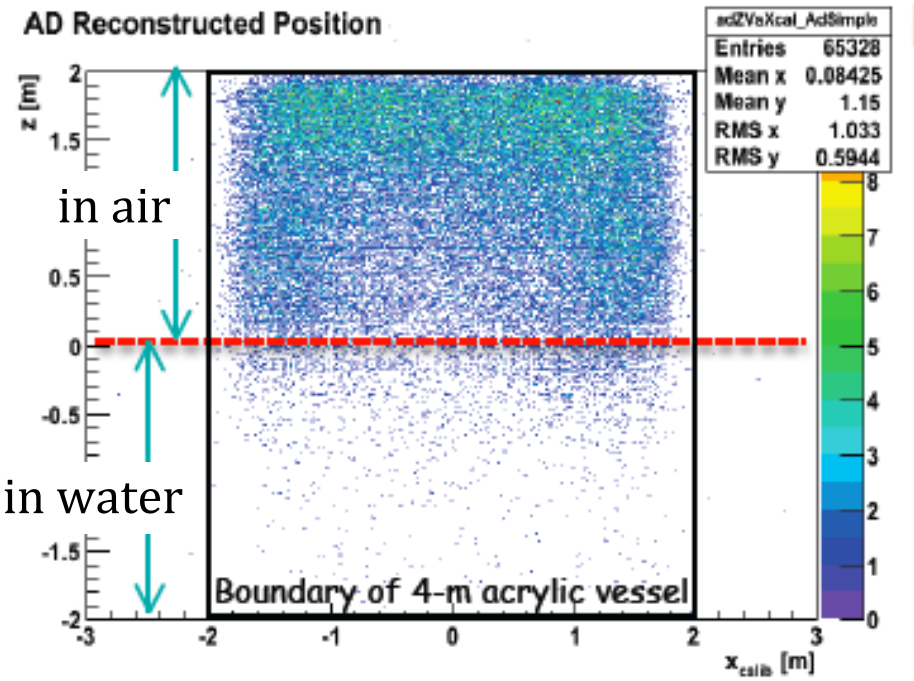
**Dual tagging systems: 2.5 meter thick two-section water shield and RPCs**




- Efficiency > 99.5% with uncertainty <0.25%

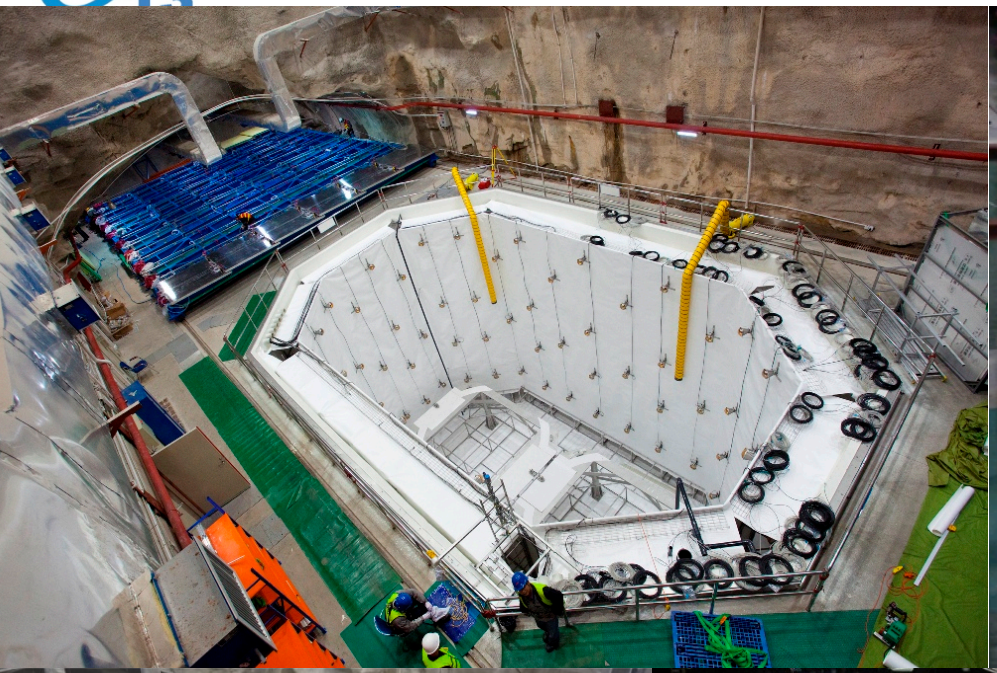
# Water Shield Suppresses the Radioactive background

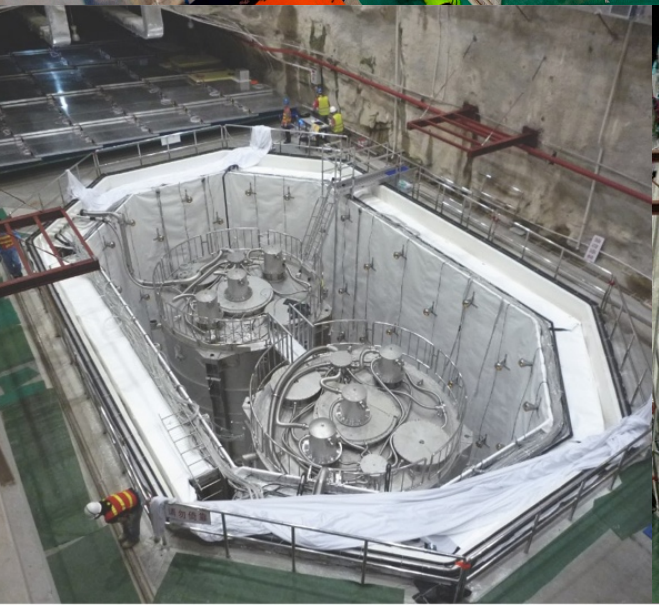


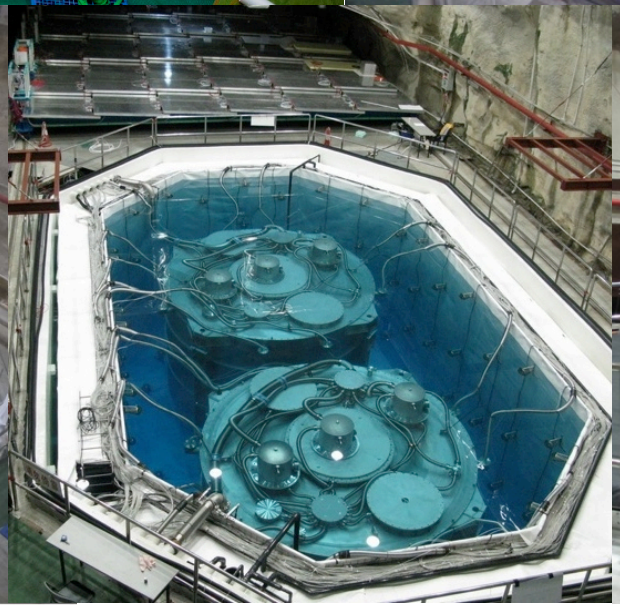



Singles events verses height in the partially filled pool show the suppression of radioactive backgrounds by water.

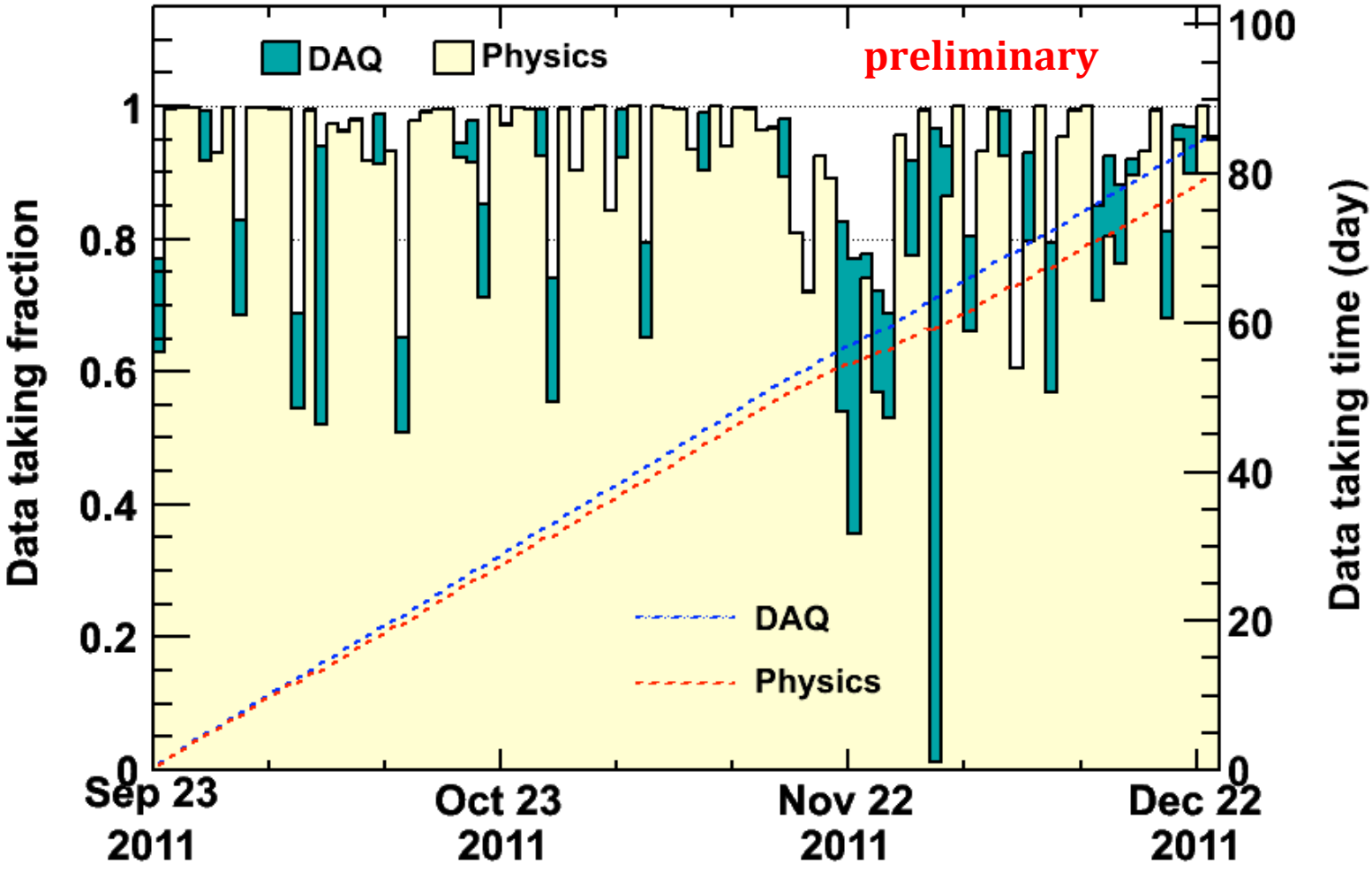
# Near Site Data Taking since August 2011





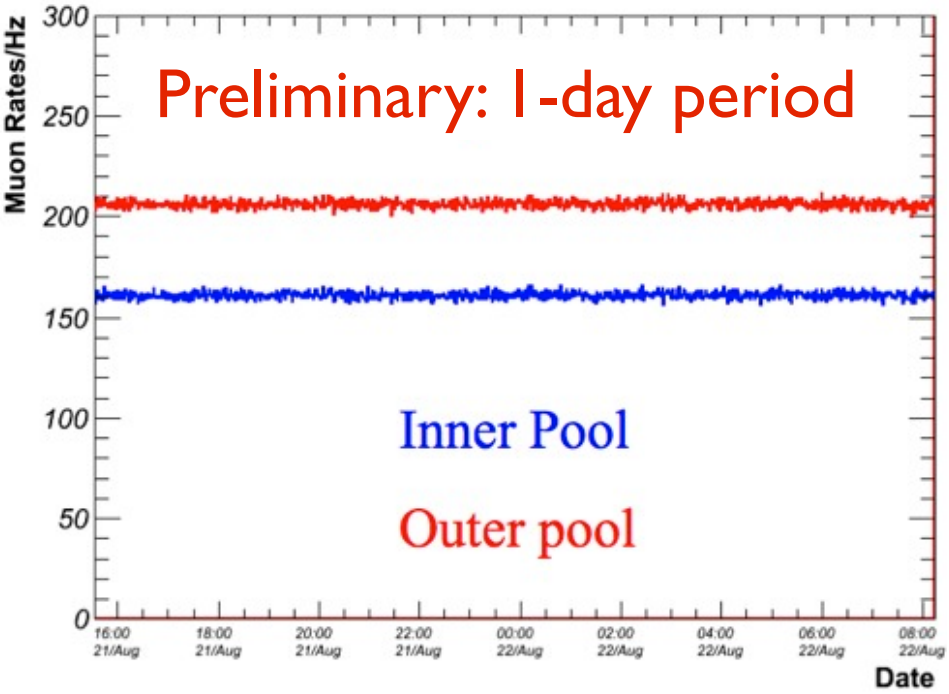


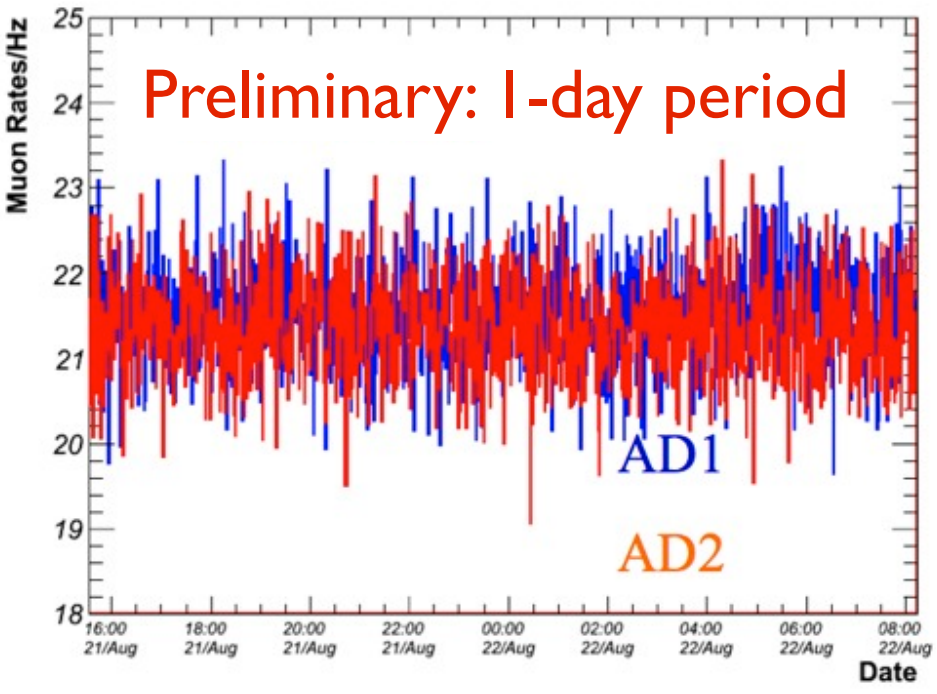
# Live Time of First Two Detectors




We have used this 3 months of data for side-by-side comparison of first two detectors.

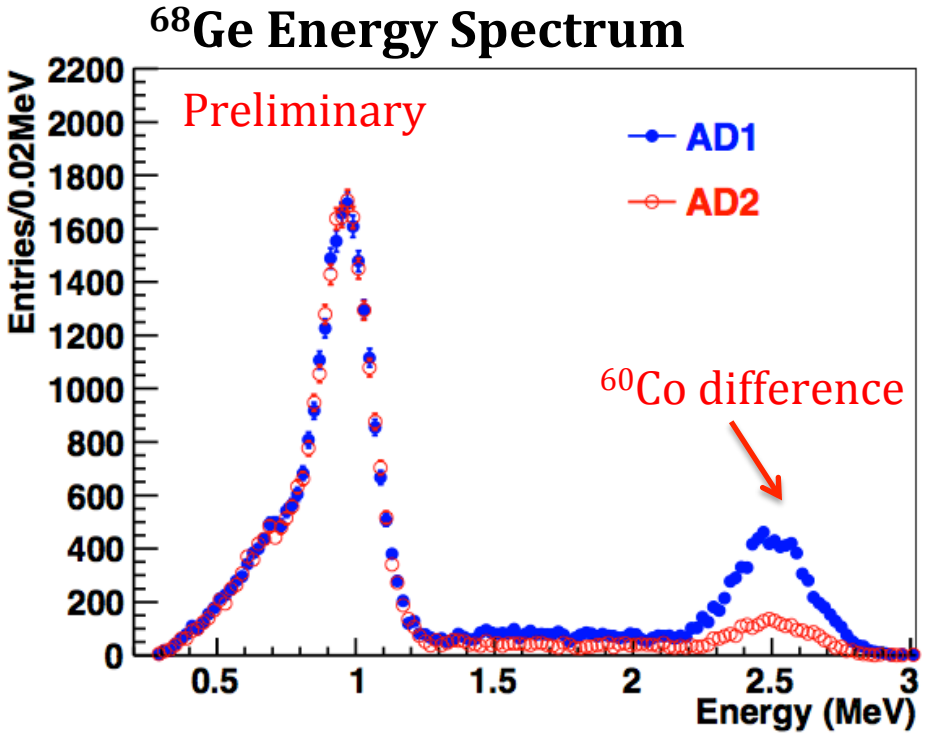
# Muon Rates at the Daya Bay Near Site

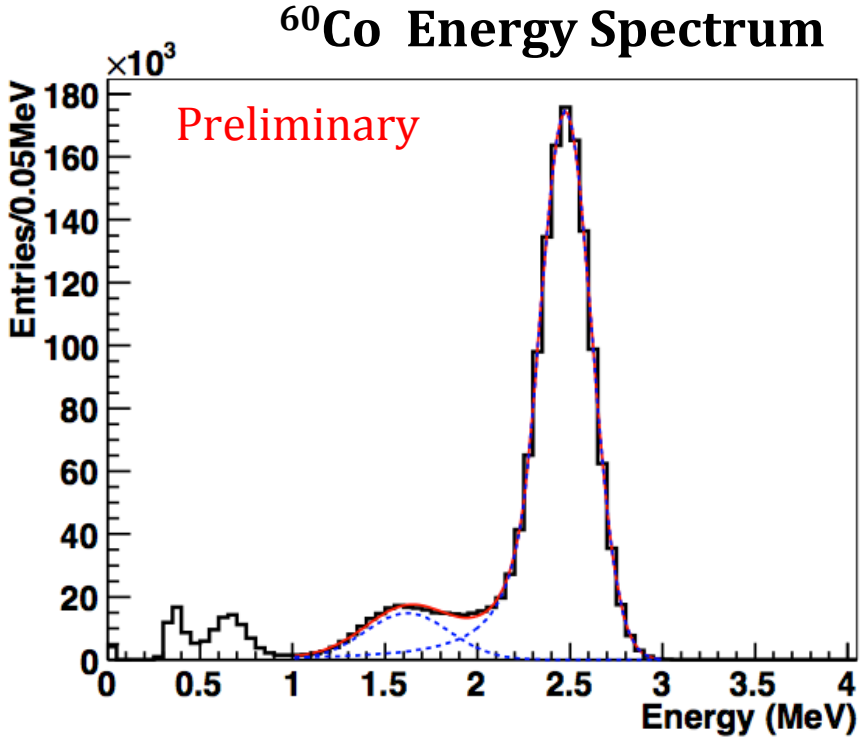



- Measured rates are consistent with expected ~20hz for each AD at the Daya Bay near site

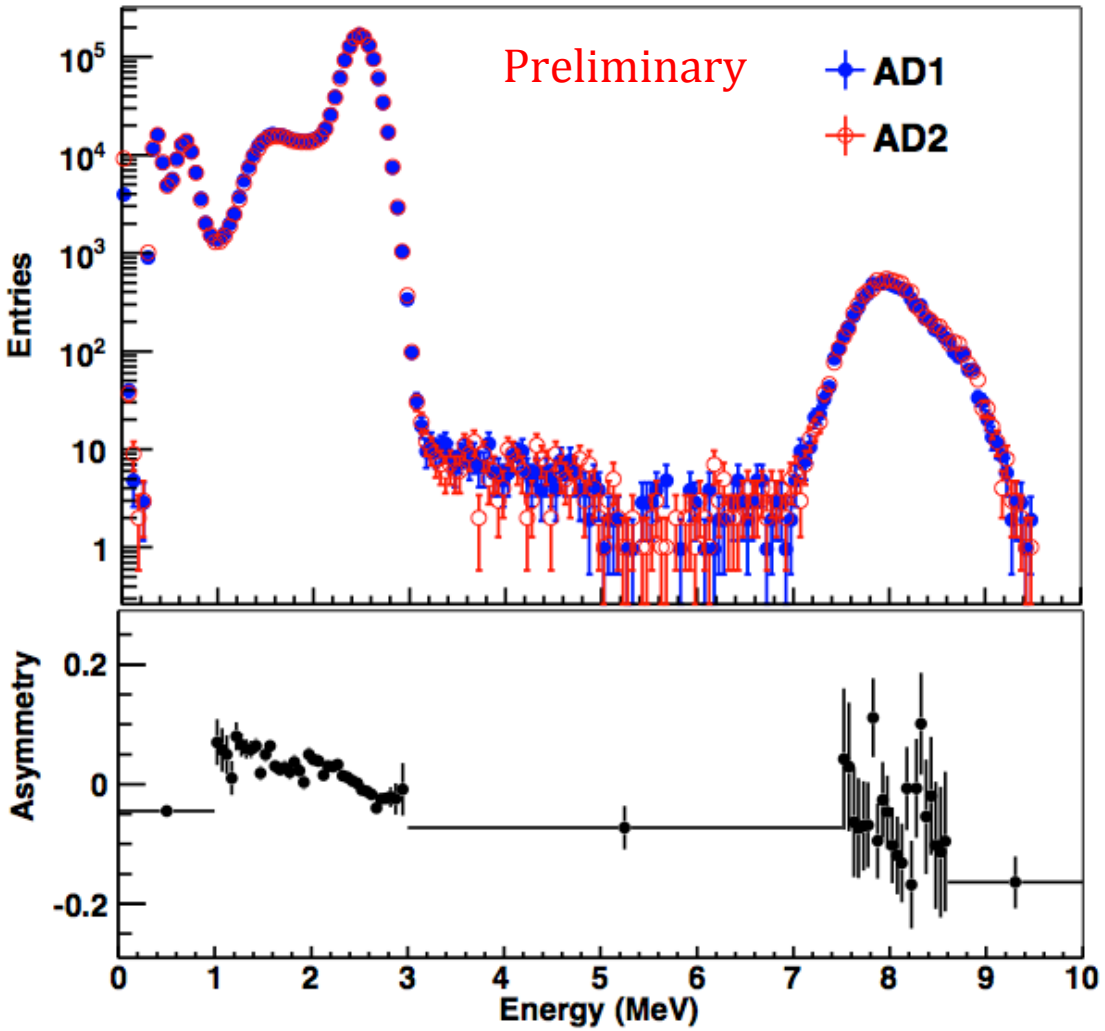
# Energy Response with Calibration Sources: $^{68}$Ge and $^{60}$Co




- Weekly automatic detector calibration
- Energy responses of the detectors are studied with $^{68}$Ge, $^{60}$Co and Am-$^{13}$C

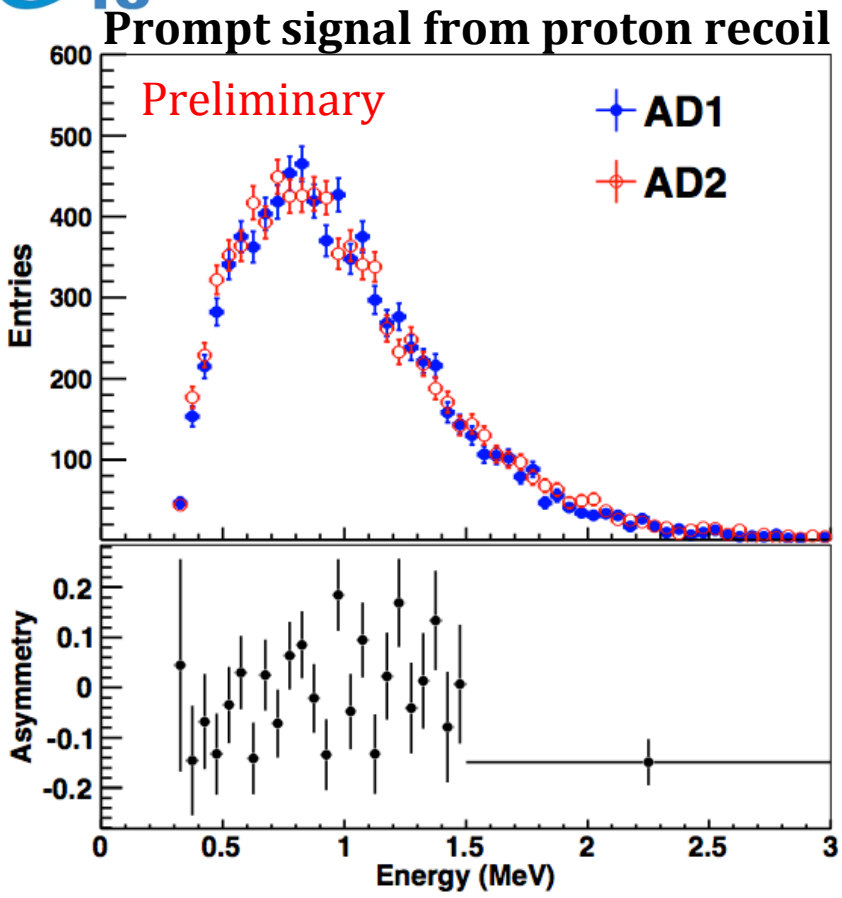
# Energy Spectrum with Am-$^{13}$C/ $^{60}$Co Source

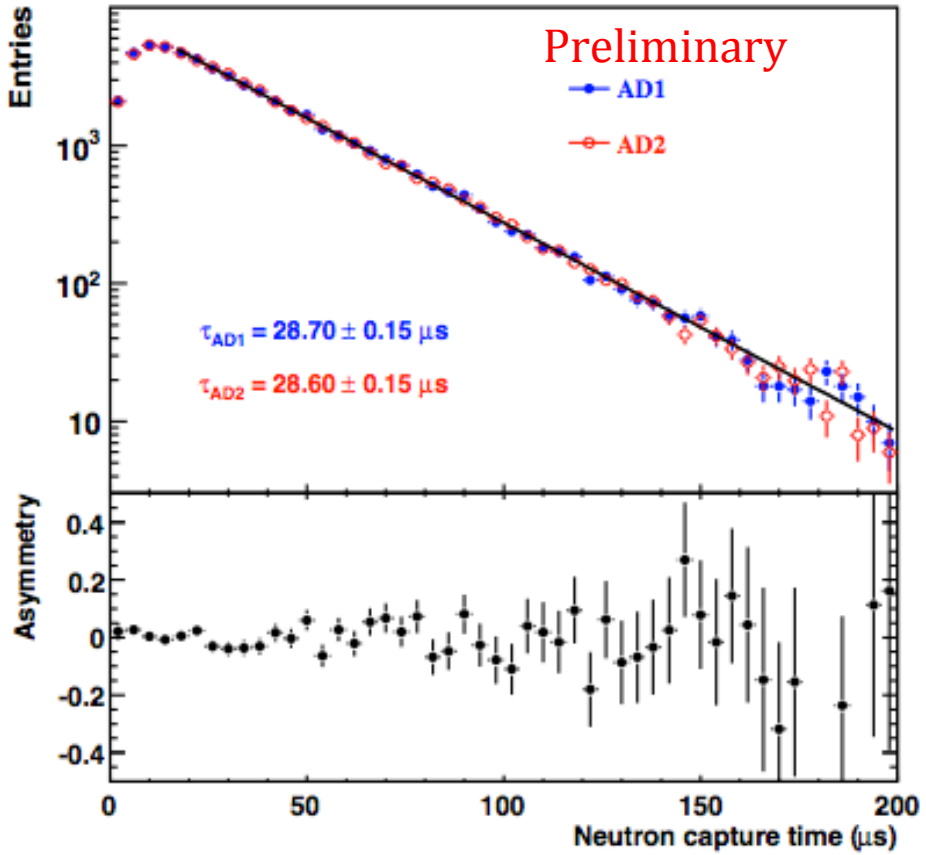



$$\text{Asymmetry} = \frac{N_{\text{AD1}} - N_{\text{AD2}}}{(N_{\text{AD1}} + N_{\text{AD2}})/2}$$

$N_{AD1,2}$ is the bin content for AD1 or 2

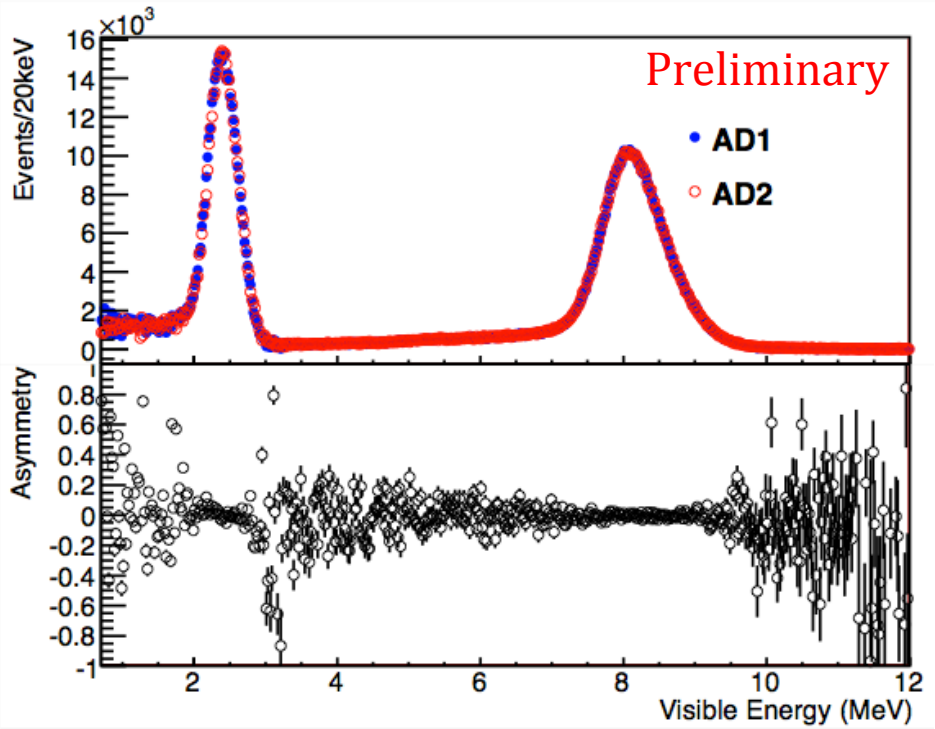
# Calibration with Am-$^{13}$C Source

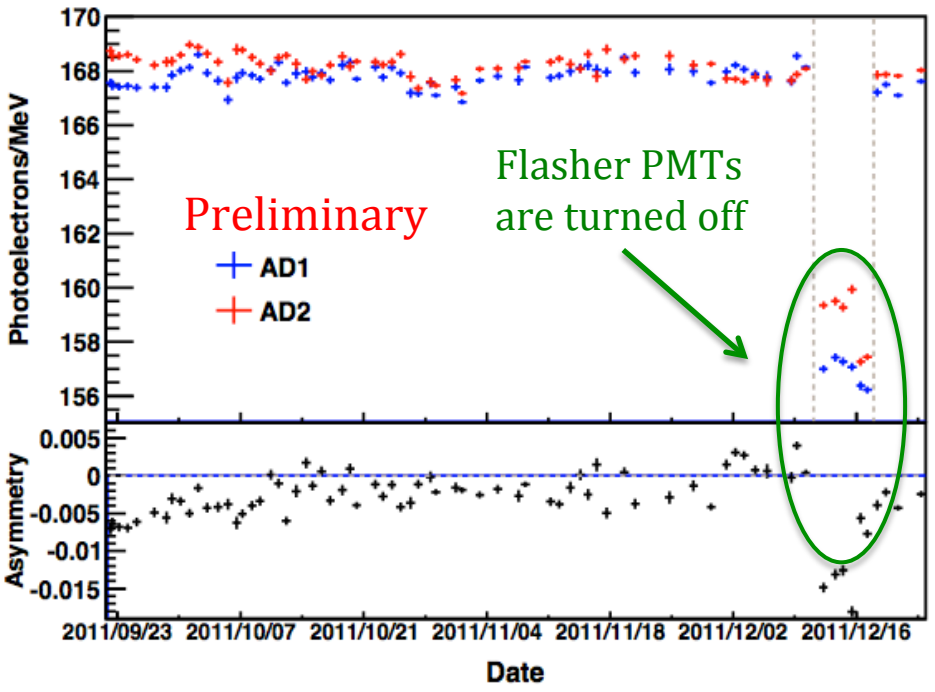



- Two ADs with similar energy responses (~0.5%)
- Consistent response in capture time measurements

# Spallation Neutron Energy Spectrum

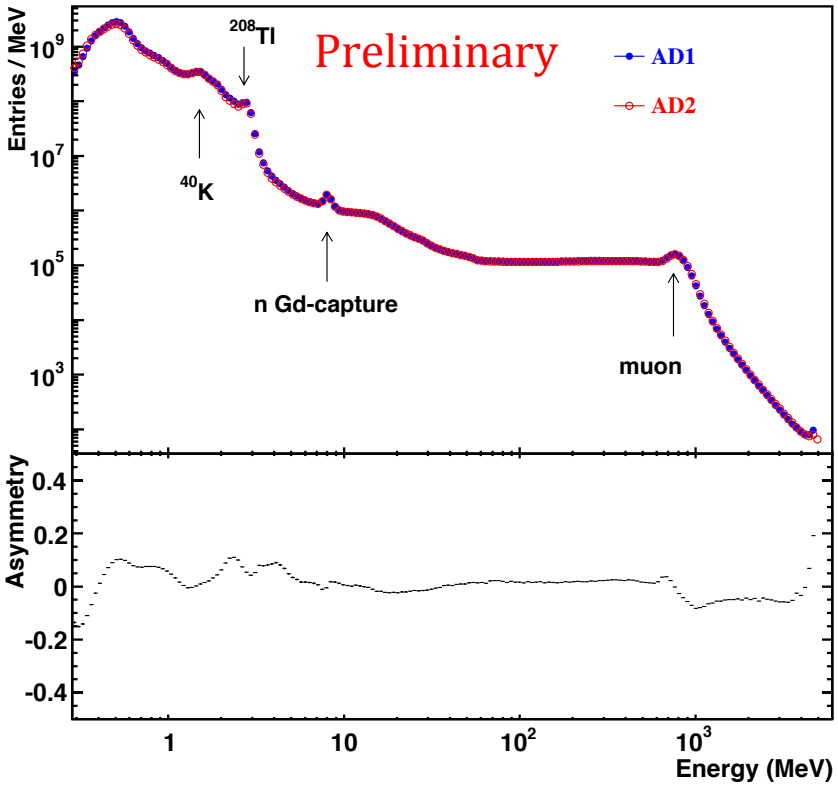


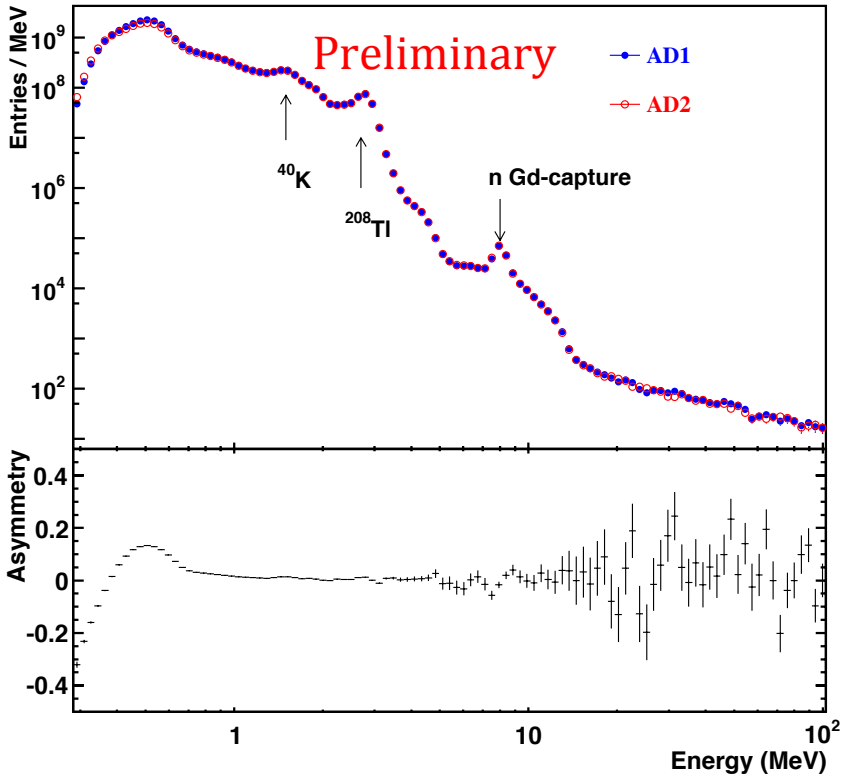

- Run-by-run calibration of detectors using spallation neutrons
  - ~168 p.e/MeV for AD1
  - ~169 p.e/MeV for AD2

# Energy Spectrum of AD Triggers

**Before Muon Veto**

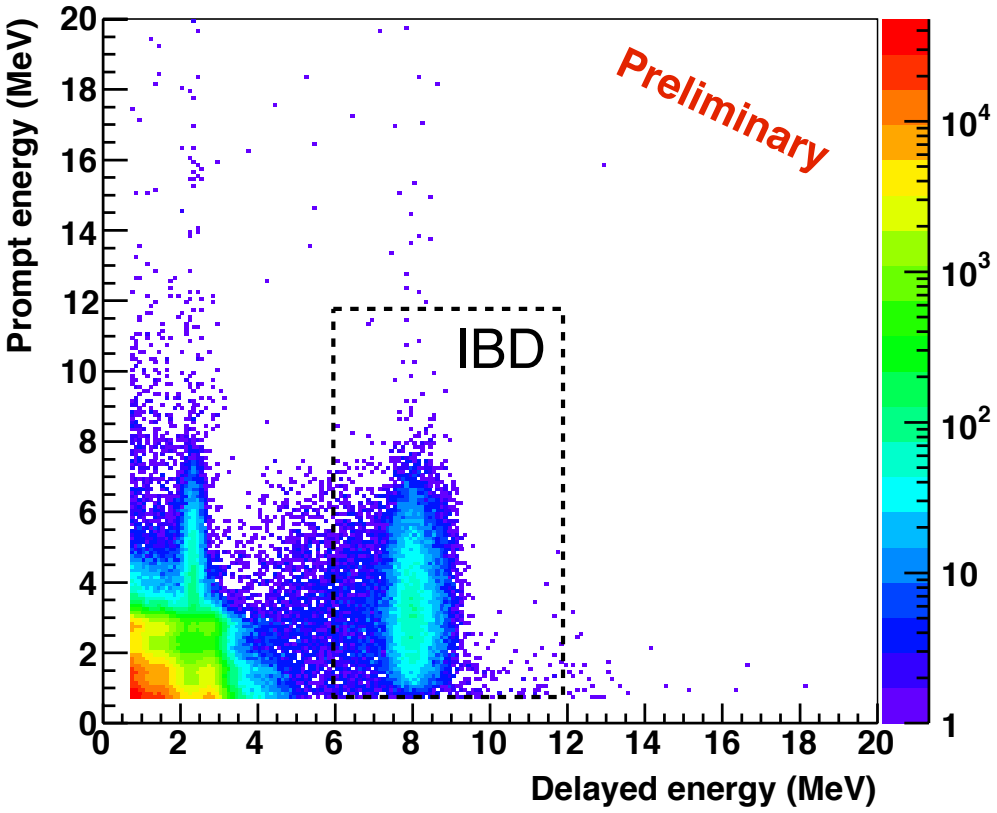



**After Muon Veto**

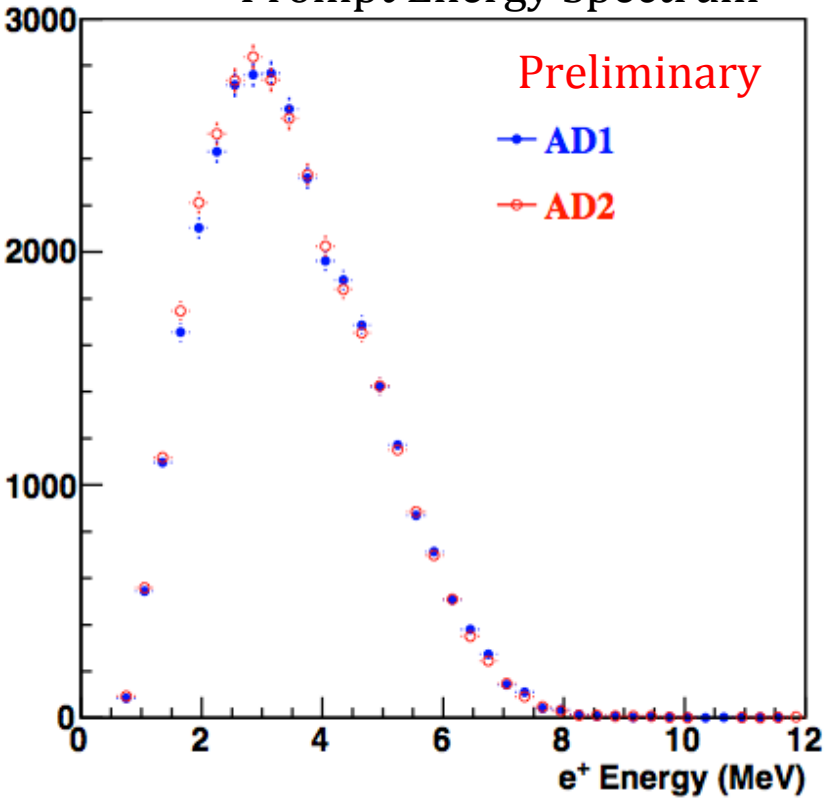



- The difference in AD1 and AD2 triggers is mostly due to nuisance triggers immediately following a Muon event.

# Selection of IBD Candidates

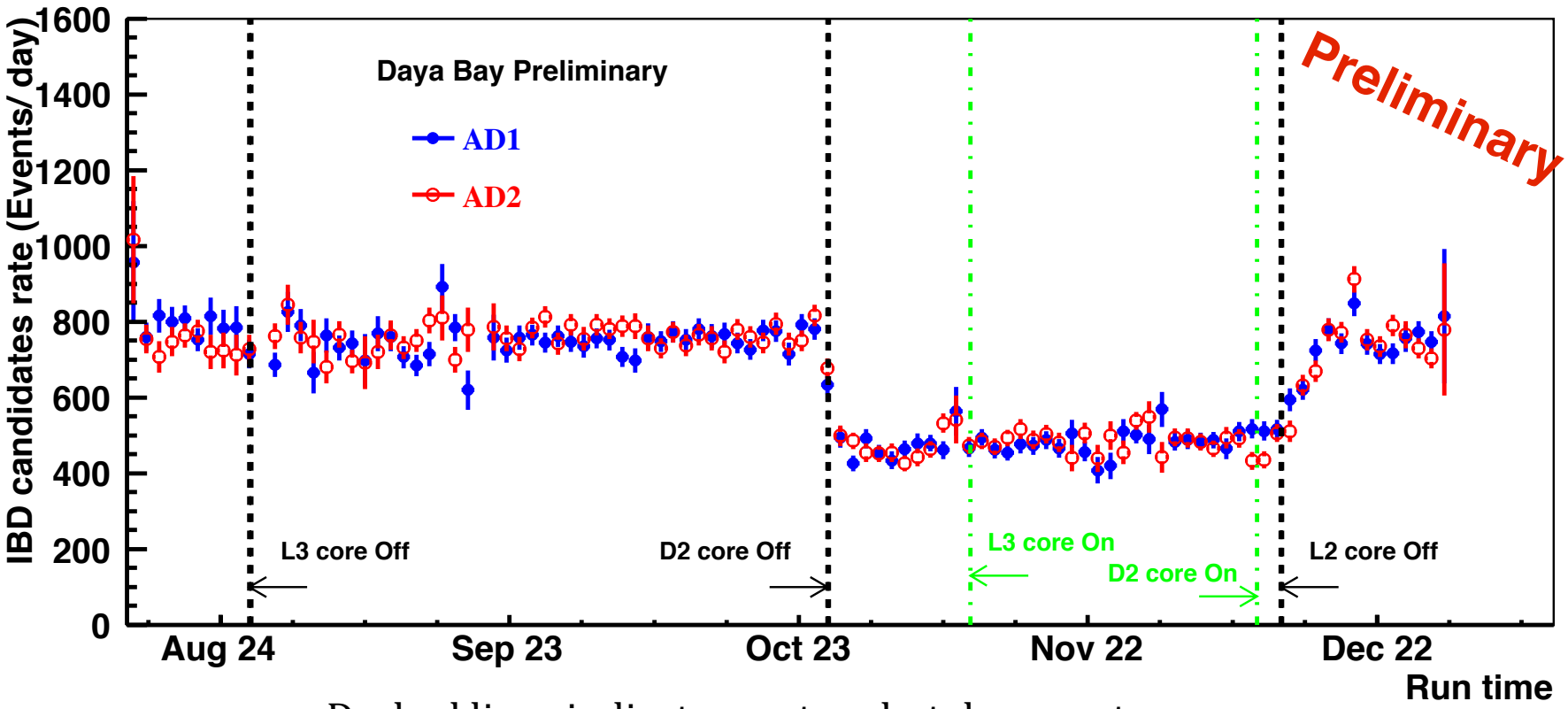



Prompt Energy Spectrum




With Flasher cut, Muon veto, Prompt Energy, Delayed Energy, Time correlation and Multiplicity cut

# IBD Candidate Rate




Dashed lines indicate reactor shut down or turn on.

Expected events (/day/detector)

| | DYB Site | LA Site | Far Site |
|---|---|---|---|
| IBD Evts | 840 | 760 | 90 |
| BKG Evts | <0.6% | <0.5% | <0.4% |

**Expected events with all cores ON**

VirginiaTech
Invent the Future

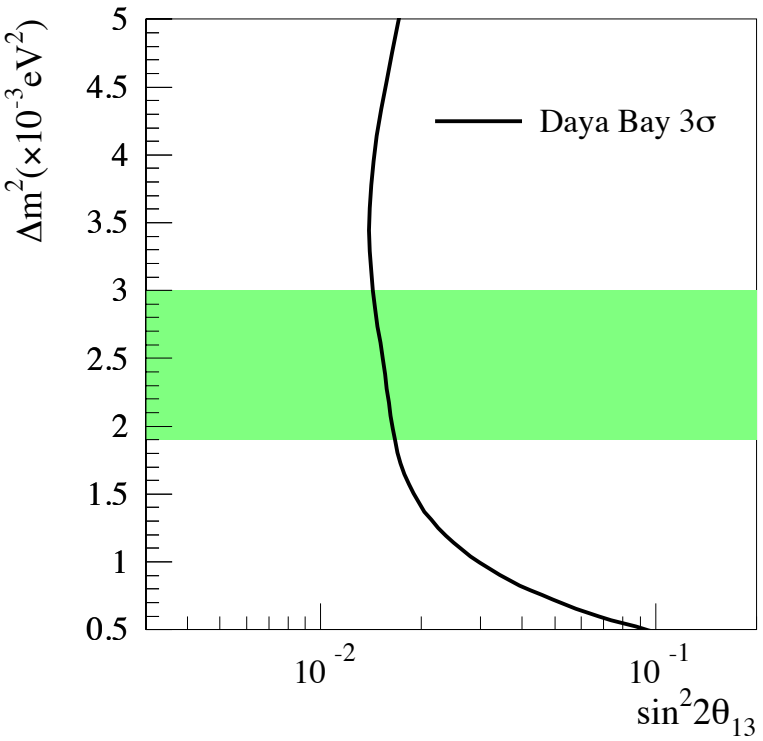
# Systematics

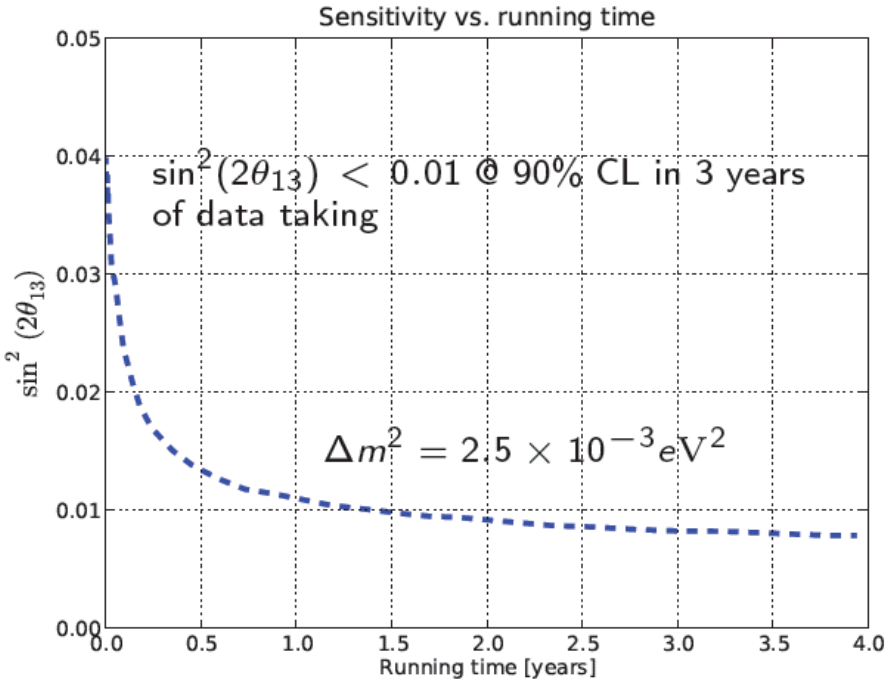
| Detector Uncertainty Sources | | Baseline | Design Goal | Preliminary Results |
|---|---|---|---|---|
| Number of protons | | **0.3%** | 0.1% | (relative) 0.02% |
| Detector Efficiency | Energy cut | **0.2%** | 0.1% | Understanding the 1st two |
| | H/Gd ratio | **0.1%** | 0.1% | Understanding the 1st two |
| | Time cut | 0.1% | 0.03% | Understanding the 1st two |
| | Neutron Multiplicity | 0.05% | 0.05% | Understanding the 1st two |
| | Trigger | 0.01% | 0.01% | Understanding the 1st two |
| | Live time | <0.01% | <0.01% | Understanding the 1st two |
| Total uncertainty | | 0.38% | 0.18% | Stay Tuned! |

Design Budget

Preliminary

# Summary



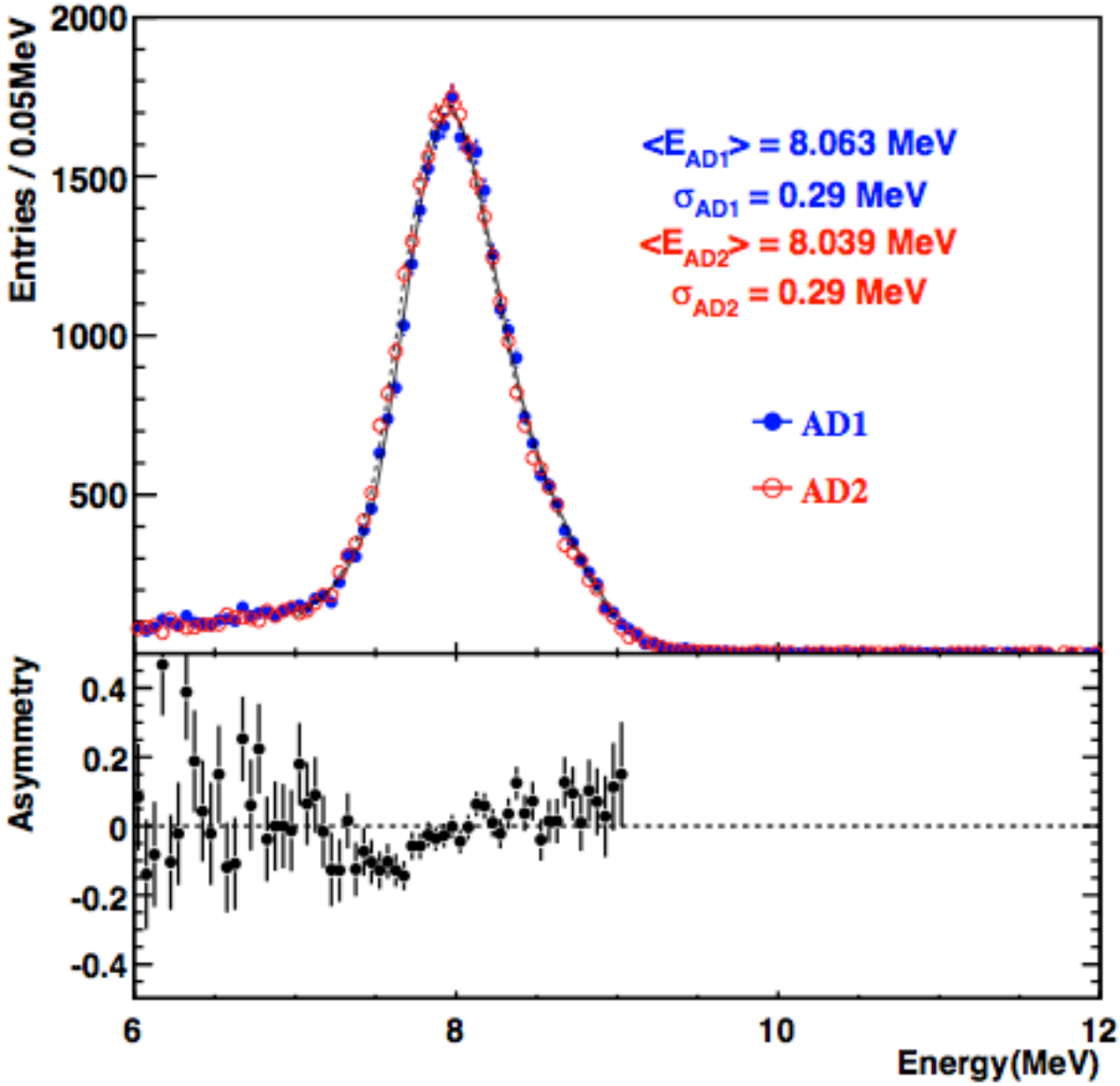

- We have demonstrated the identicalness of the first two detectors at Daya Bay near site
- With all 8 detectors running by summer 2012, Daya Bay is going to provide the most precise measurement of $\theta_{13}$.

# Backup Slides

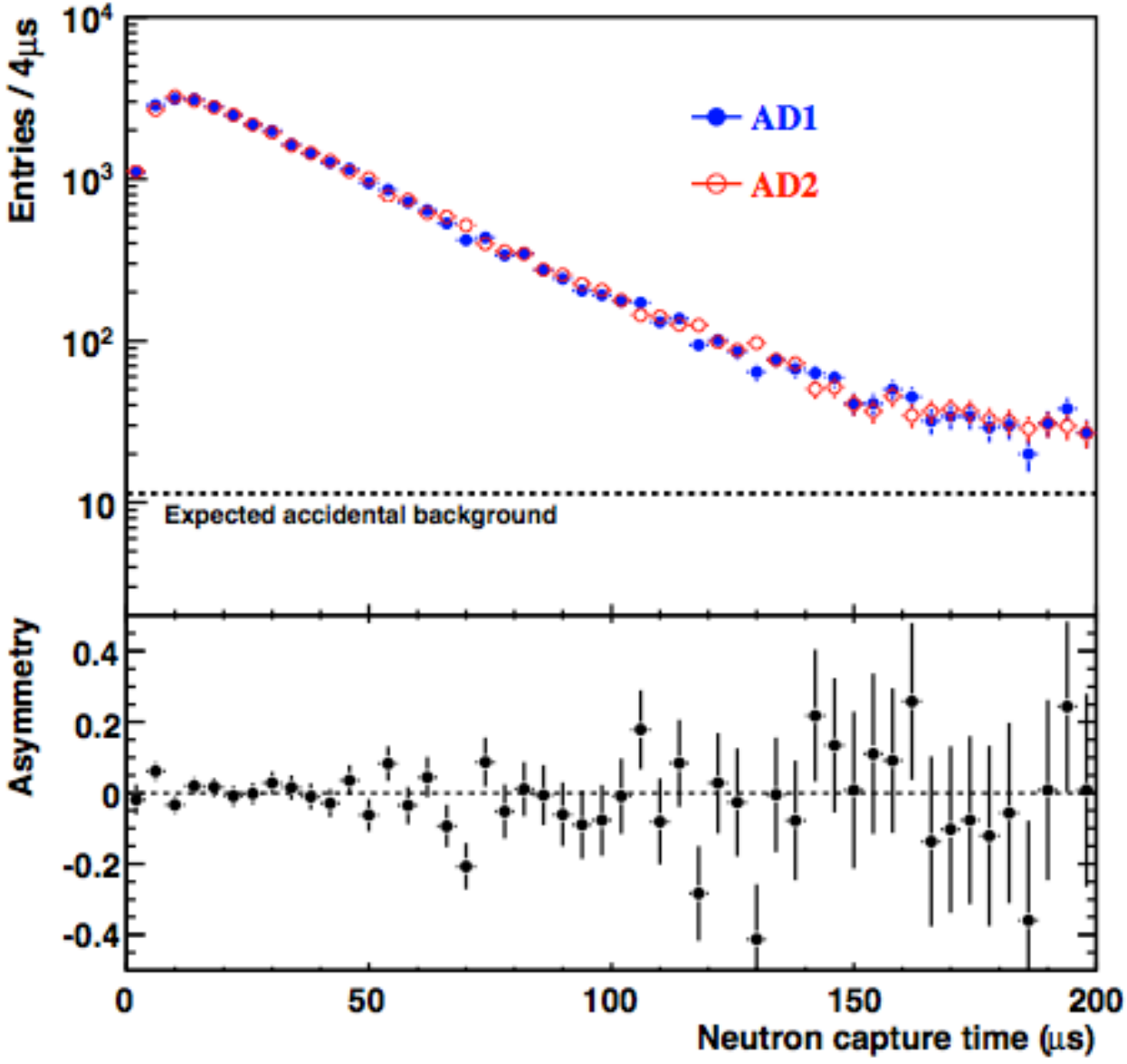
# IBD Selection Cut Details

- Flasher rejection: based on geometrical charge pattern
- Positron energy: 0.7 MeV < $E_{prompt}$ < 12.0 MeV
- Neutron energy: 6.0 MeV < $E_{delay}$ < 12.0 MeV
- Time coincidence: 1 μs < $\Delta t_{prompt,delayed}$ < 200 μs
- Muon veto:
  - Delayed signal is within 600 μs after water pool muon trigger
  - Delayed signal is within 1000 μs after AD muon trigger (AD energy deposit > 20 MeV)
  - Delayed signal is within 1 sec after AD muon with AD energy deposit > 2.5 GeV
- Multiplicity cut: No other >0.7 MeV trigger 200 μs before the prompt signal and 200 μs after the delayed signal

# Delayed Energy of IBD Candidates



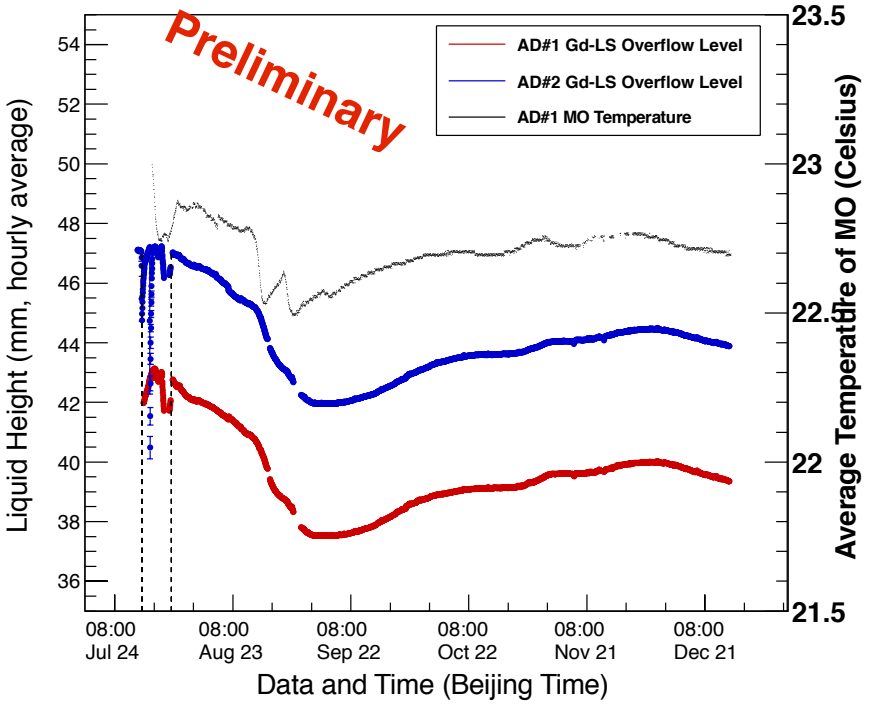
# IBD Neutron Capture Time

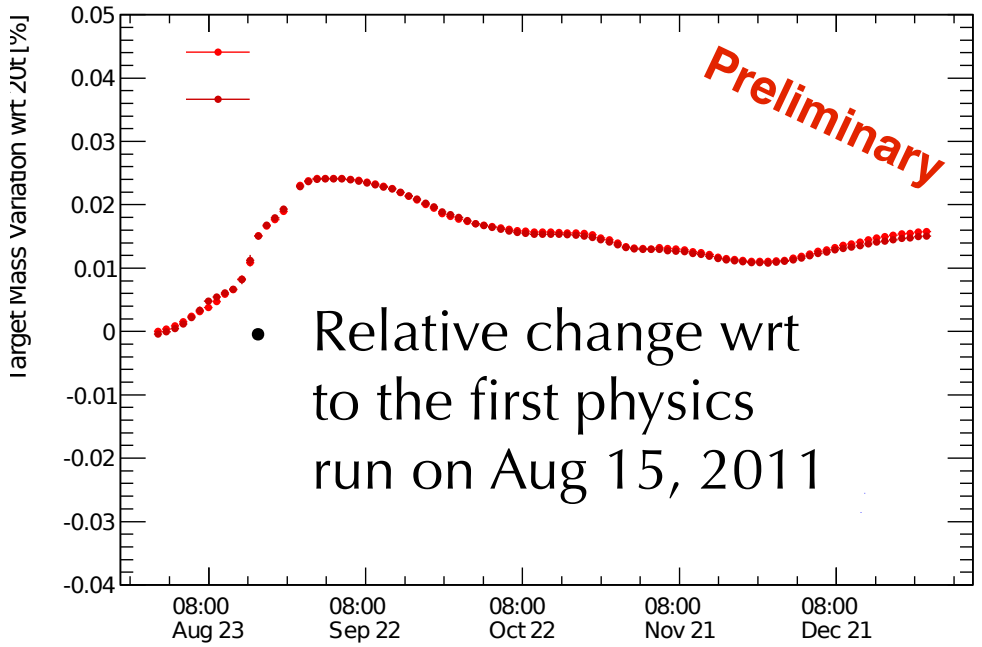


# Detector Related Uncertainty

| Source of uncertainty | Quantity |
|---|---|
| Mass measurement relative precision | 0.02% |
| Flasher cut | 0.01% |
| Efficiency of neutron energy cut | 0.11% |
| Efficiency of $e^+$ threshold cut | 0.01% |
| Efficiency of multiplicity cut | < 0.01% |
| Efficiency of capture time cuts | 0.01% |
| Relative precision on H/Gd ratio | <0.1% |
| Relative uncertainty of spill-in/out | 0.02% |
| Livetime precision | < 0.01% |
| Total detector-related uncertainty | 0.2% |

# Target Mass Variation




- Nominal target mass: 20 ton
- Target mass determination error ± 3kg out of 20,000 or <0.02%.