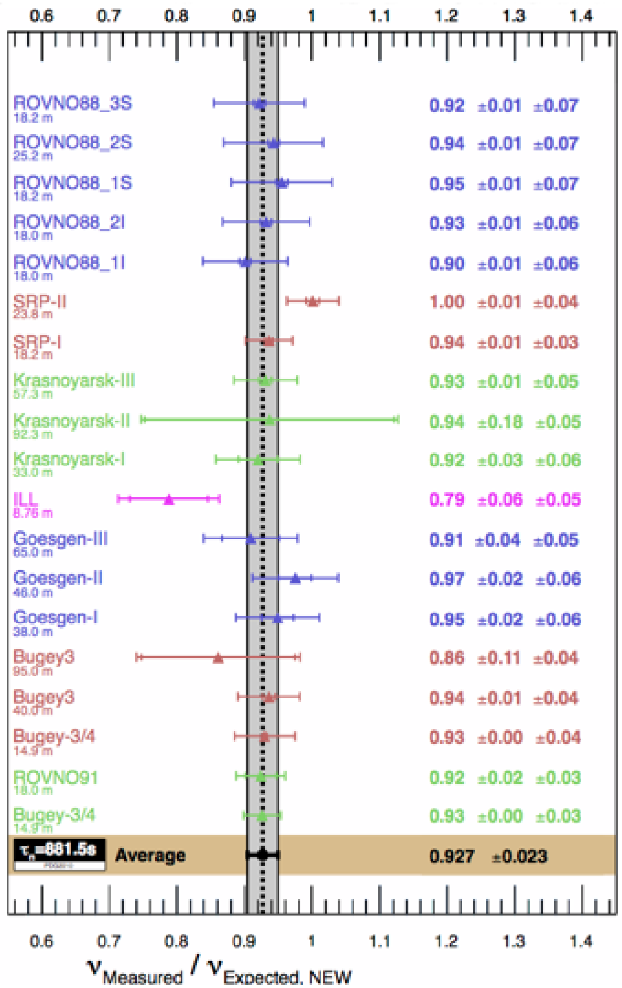
Search for Sterile Neutrino at NEOS Experiment

2017.07.21
13th Rencontres du Vietnam

Hyunsoo Kim
Sejong University

on behalf of NEOS Collaboration

Reactor Antineutrino Anomaly (RAA)

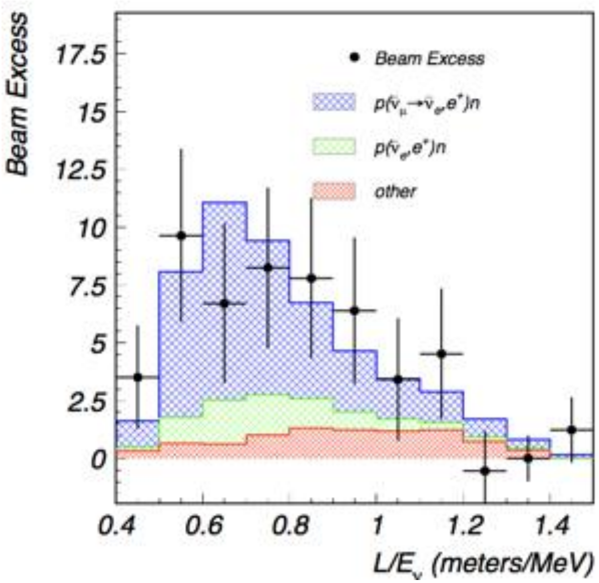


arXiv:1204.5379

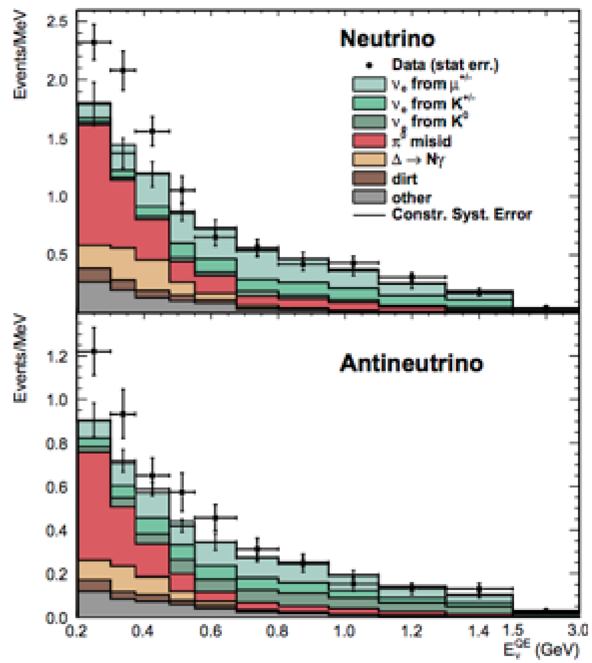
Short baseline reactor neutrino experiments

- Measured/Prediction=0.927±0.023

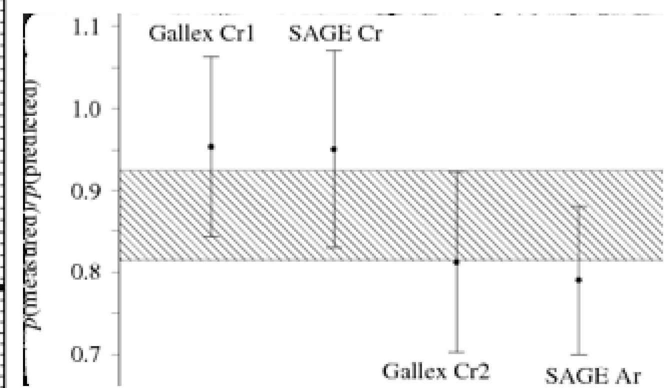
Other Anomalies/Conflicts



PRD 64 (2001) 112007



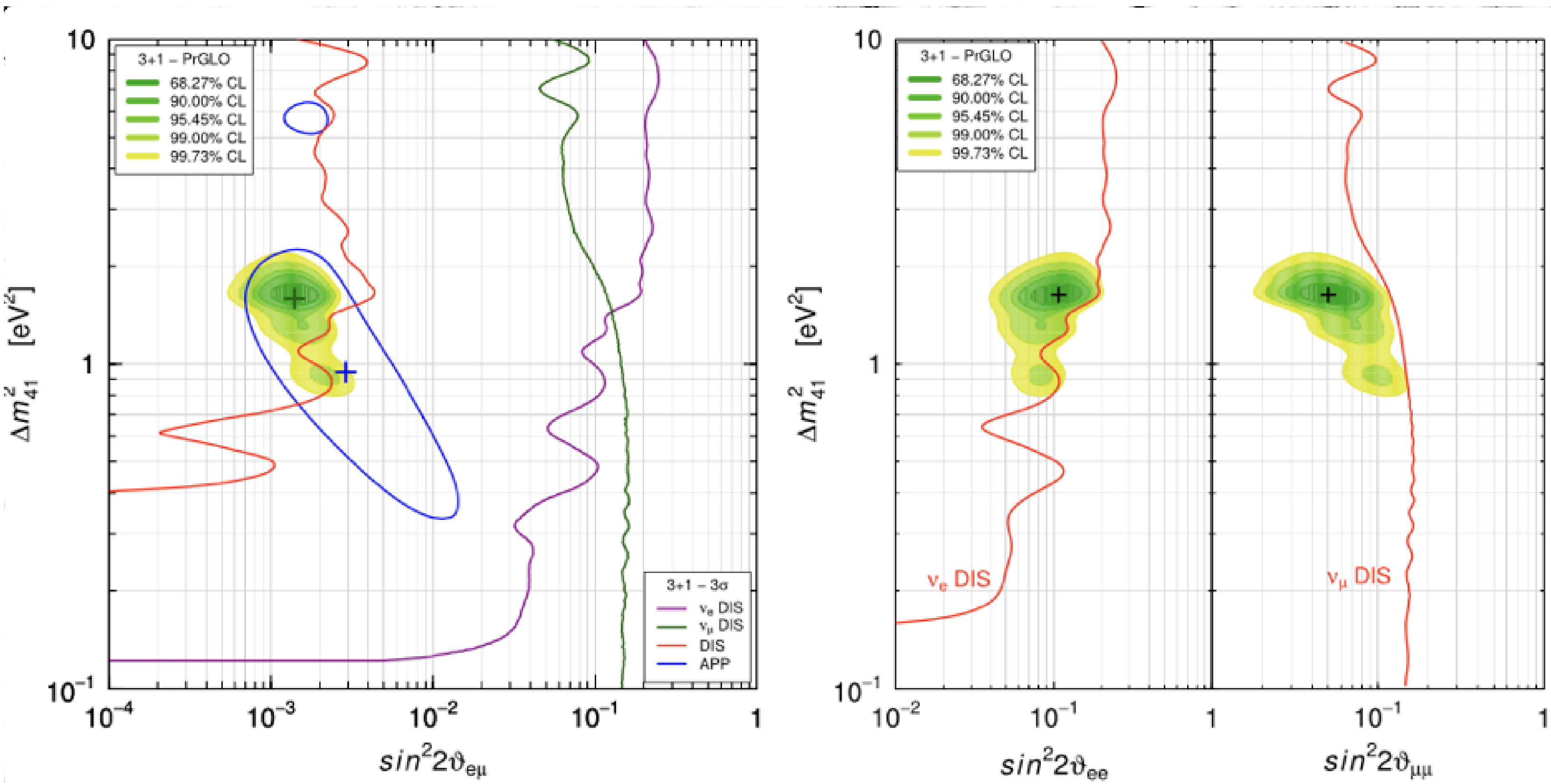
PRL 110 (2013) 161801



PRC 80 (2009) 015807

- LSND: $\bar{\nu}\mu \to \bar{\nu}e$ appearance event excess with $\Delta m^2 > 0.2$ eV^2 ($>3\sigma$)
- MiniBooNE: ν mode disfavors / $\bar{\nu}$ mode consistent with LSND result $\Delta m^2 \sim 1$ eV^2
- GALLEX / SAGE: 2.9σ deficit from expected
- KARMEN, MINOS, IceCube, … : negative results

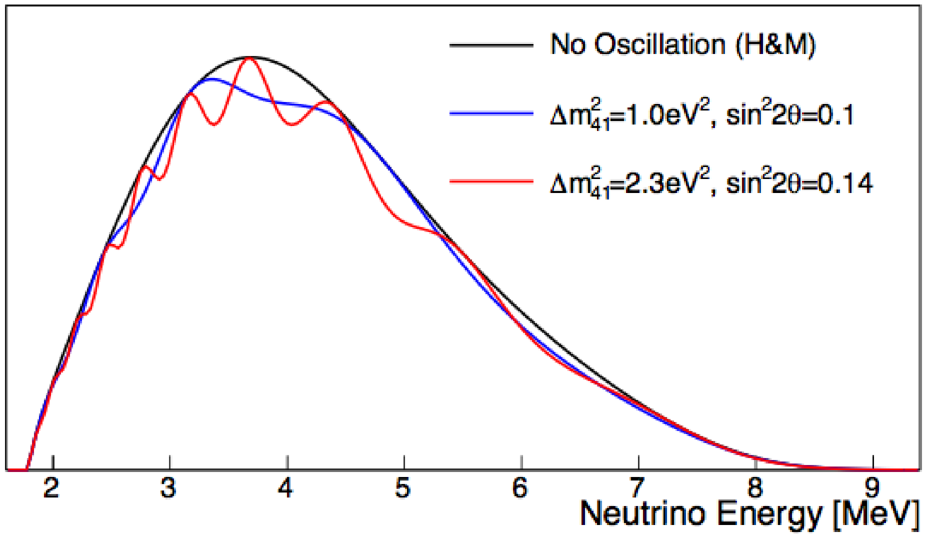
Combined Results: (3+1)-ν

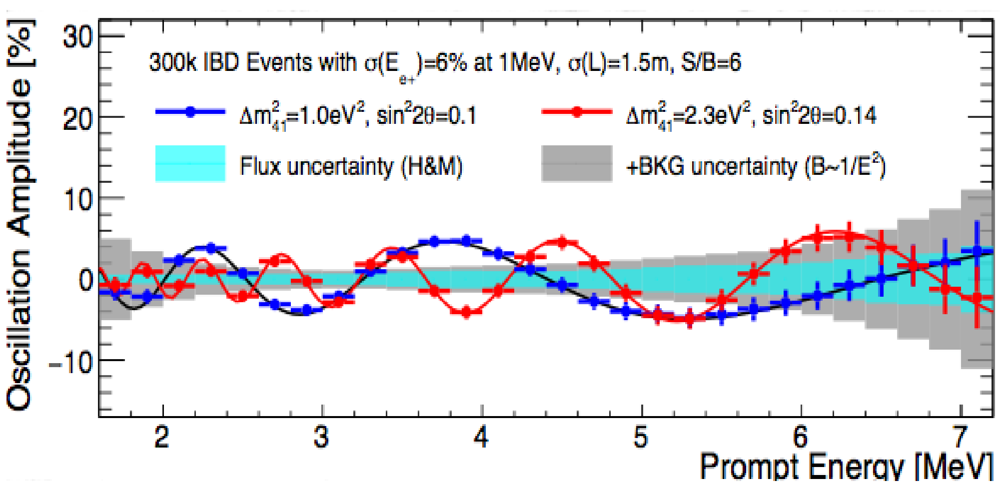


Gariazzo *et al.*, JPG 43 (2016) 033001

All seem to point toward ~1 eV sterile neutrino

(3+1)ν and SBL Oscillation





$$P(\bar{\nu}_e \rightarrow \bar{\nu}_e) \approx \mathbf{1} - \sin^2 \mathbf{2\theta_{14}} \sin^2\left(\mathbf{1.27}\frac{\Delta m^2 L}{E_\nu}\left[\frac{eV^2 \cdot m}{MeV}\right]\right)$$

Oscillation pattern washes out in the measured prompt energy spectrum

- Baseline (L): reactor/detector size
- Energy (E_ν): Energy loss/resolution
- Systematic errors
- Backgrounds

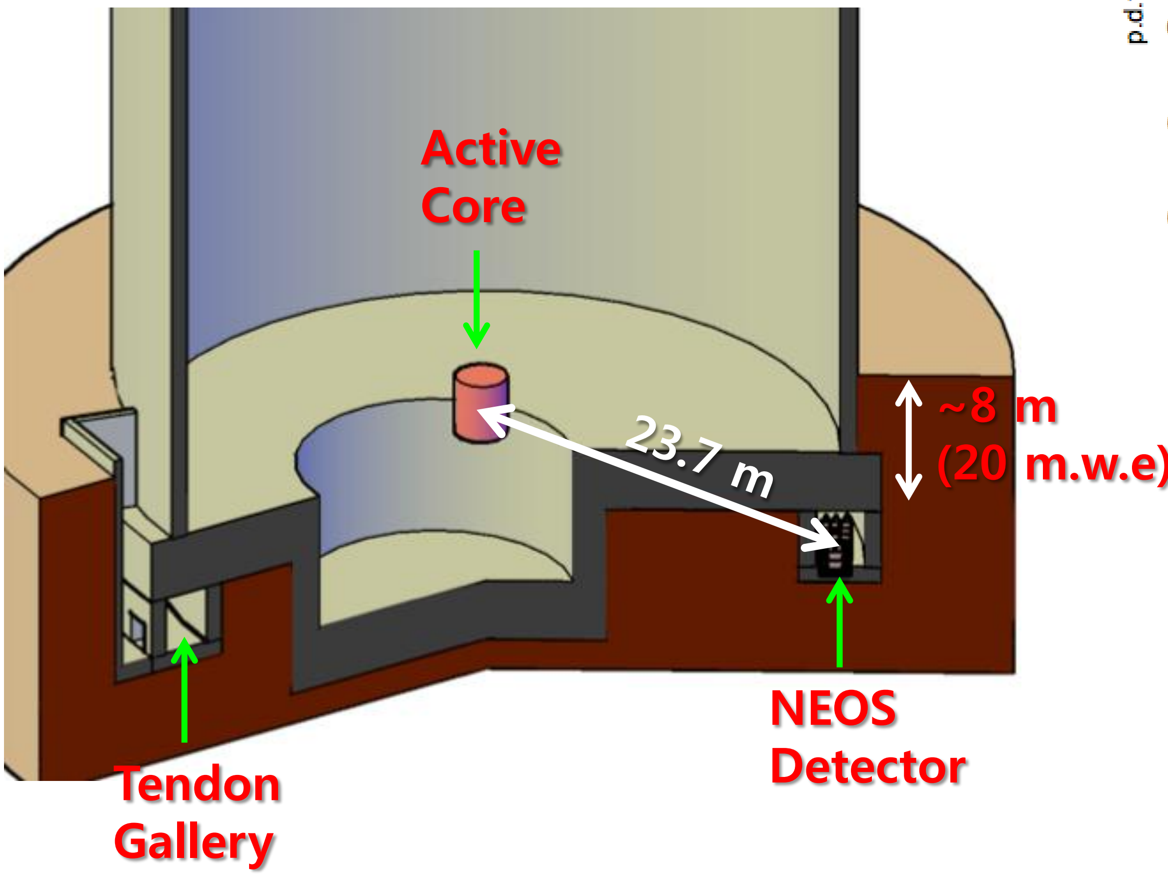
NEOS Collaboration

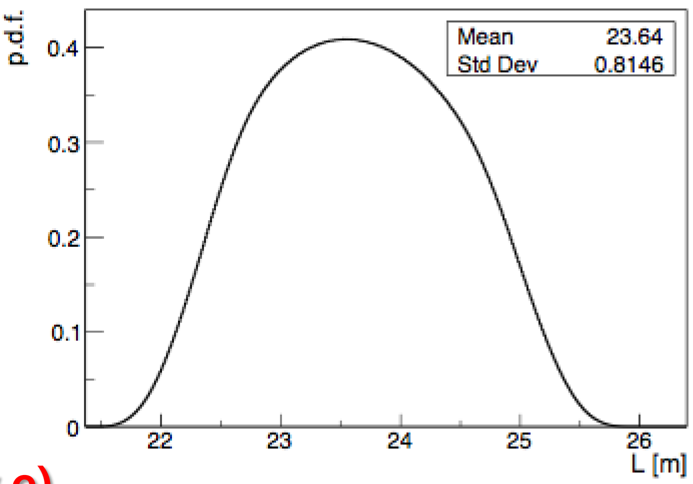
- **N**eutrino **E**xperiment for **O**scillation at **S**hort baseline
- 20 Researchers from 8 institutes in Korea
  - Chonnam National University
  - Chung-Ang University
  - Institute for Basic Science (IBS)
  - Korea Research Institute of Standard and Science (KRISS)
  - Korea Atomic Energy Research Institutes (KAERI)
  - Kyungpook National University
  - Sejong University
  - University of Science and Technology
- Project launched in 2012
- Data taking from Aug. 2015 to May 2016

Experimental Site

- Reactor Unit 5 at Hanbit Nuclear Power Plant in Yeonggwang, Korea
- Same NPP for RENO Experiment.

Detector Location

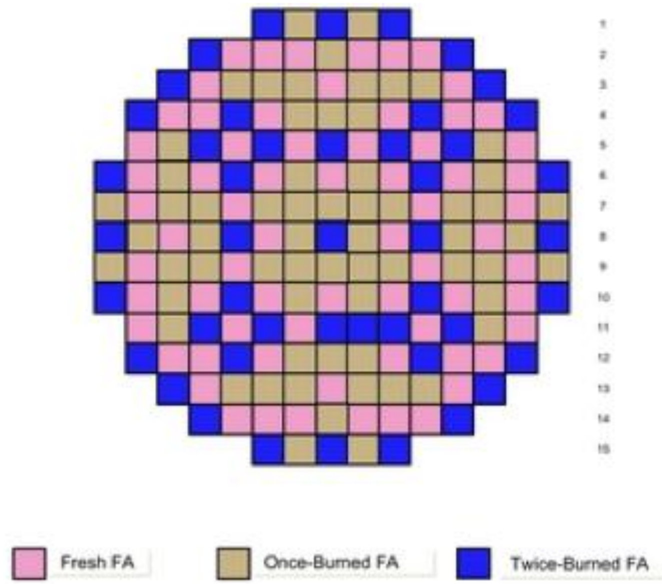


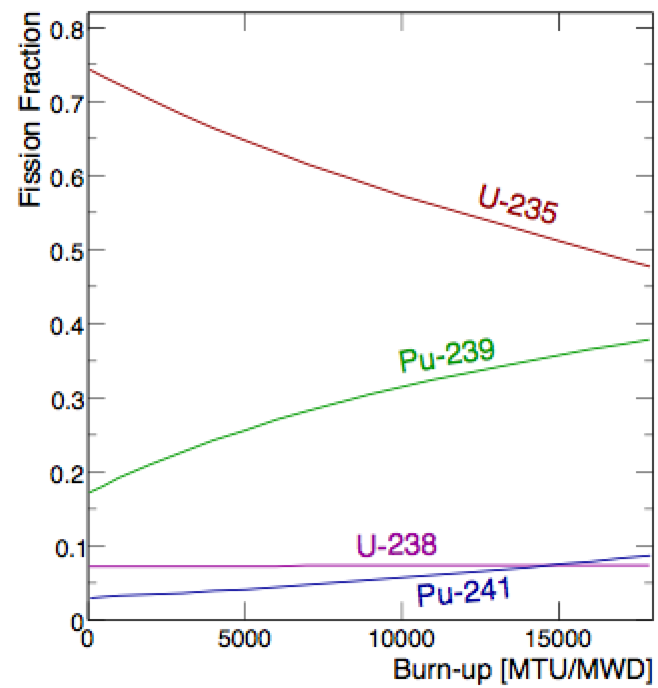


Neutrino flight distance profile

- Neutrinos uniformly generated in cylindrical core
- IBD interaction $\propto 1/L^2$

Neutrino Source

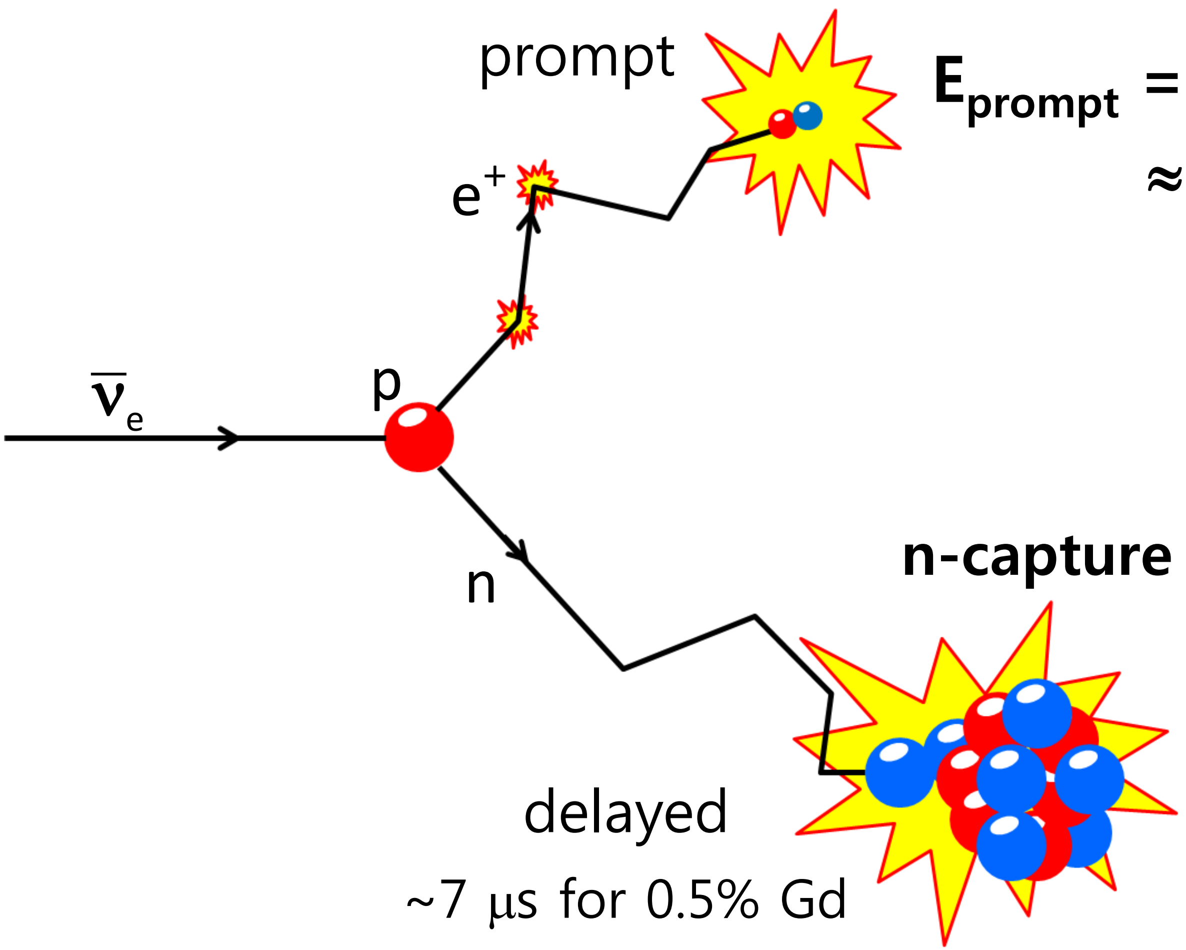




- Thermal Output: 2.8 GW_{th}
- Low enriched (4.65%) Uranium-235
- Refueling by swapping 1/3 of fuel rods for each burn-up cycle (~1.5 years)
- Active core size: 3.1 m (diameter), 3.8 m (height)

Neutrino Detection

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



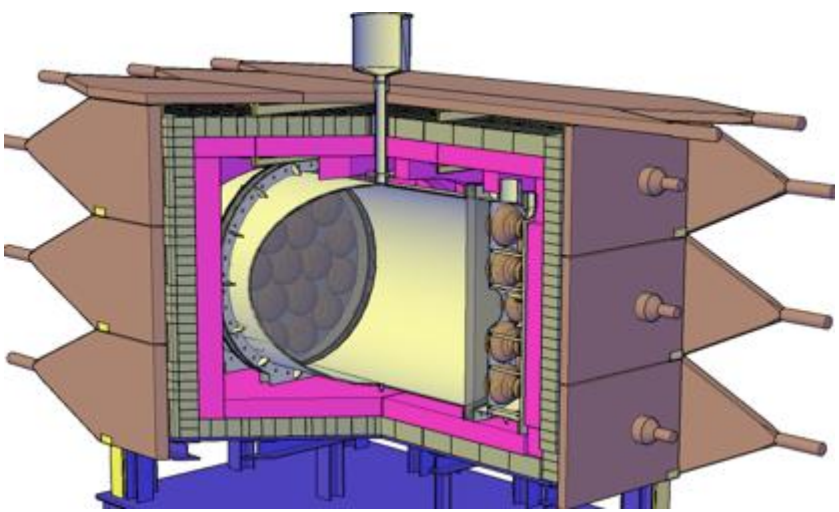
$\mathbf{E_{prompt} = KE_{e+} + 1.02\ MeV}$

$\mathbf{\approx E_{\nu} - 0.78\ MeV}$

n-capture by nuclei (H, Gd)

NEOS Detector

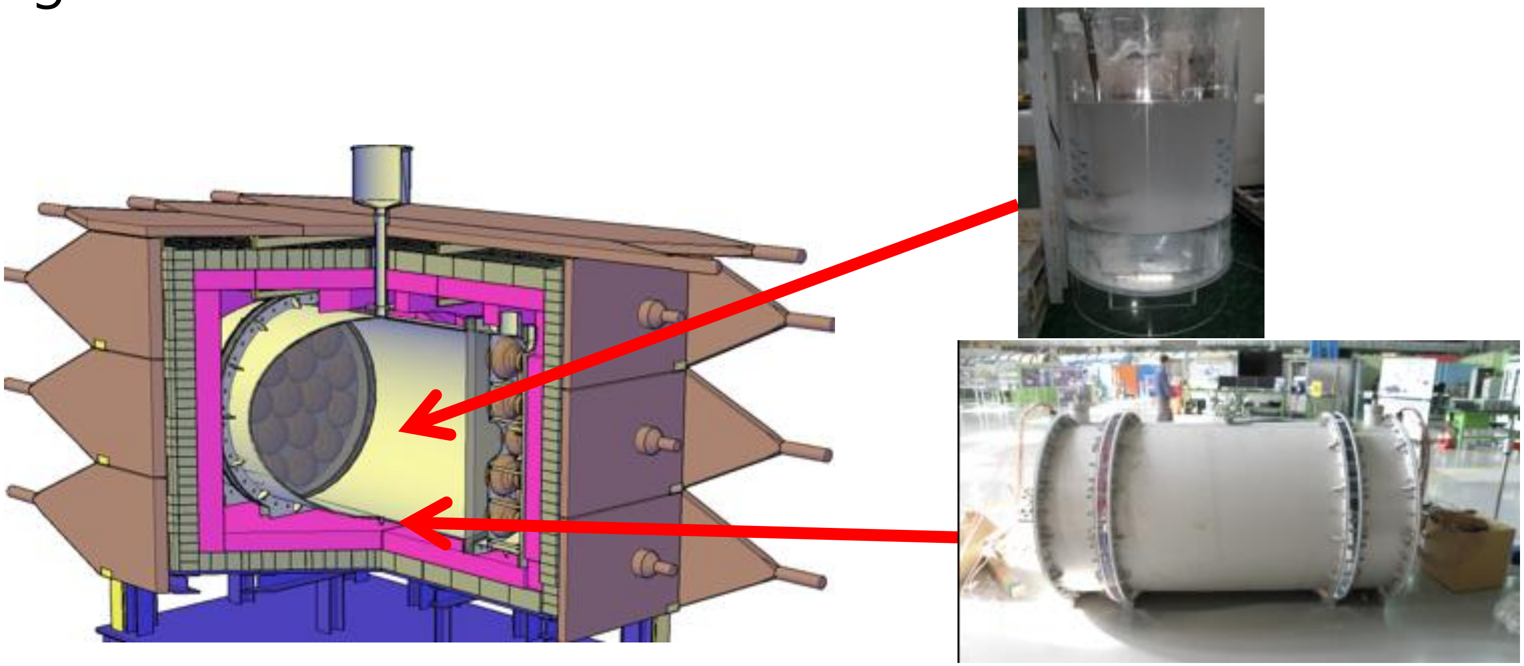
- Detector size determined by the available space in the tendon gallery [4 m(h) x 3 m(w)]
- Simple construction
  - Homogeneous liquid scintillator target with no gamma catcher and limited buffer coverage.



NEOS Detector

Homogeneous Liquid Scintillator Target

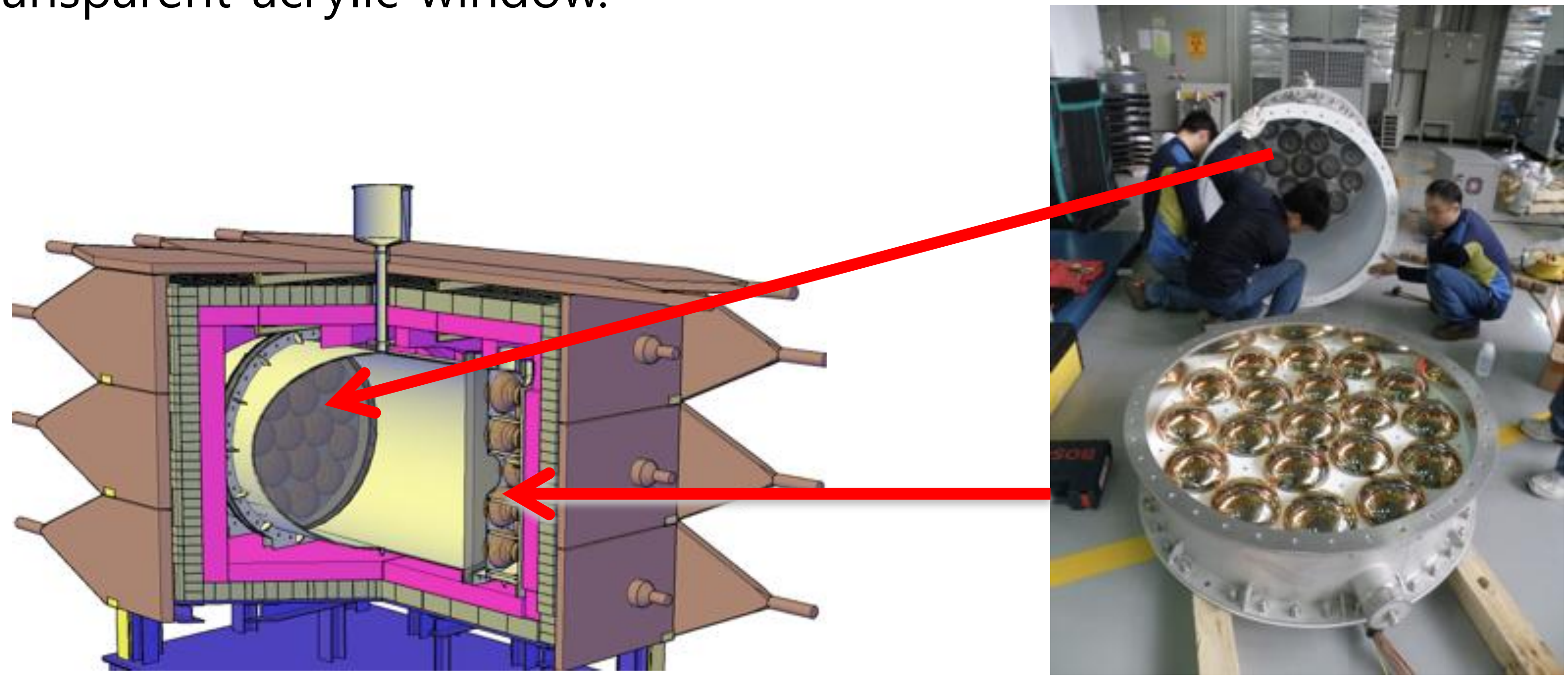
- ~1000 L in volume [1.2 m (L)/0.5 m (R)]
- LAB+DIN based LS (Ultima Gold-F) (9:1)
    - improve pulse shape discrimination over LAB only
- 0.5% Gd for high neutron capture efficiency
- Target vessel lined with teflon



NEOS Detector

PMTs

- 19 8-inch PMTs on each side of target
- PMTs are installed in buffer tanks filled with mineral oil
- Separated from target by a 6 cm thick transparent acrylic window.



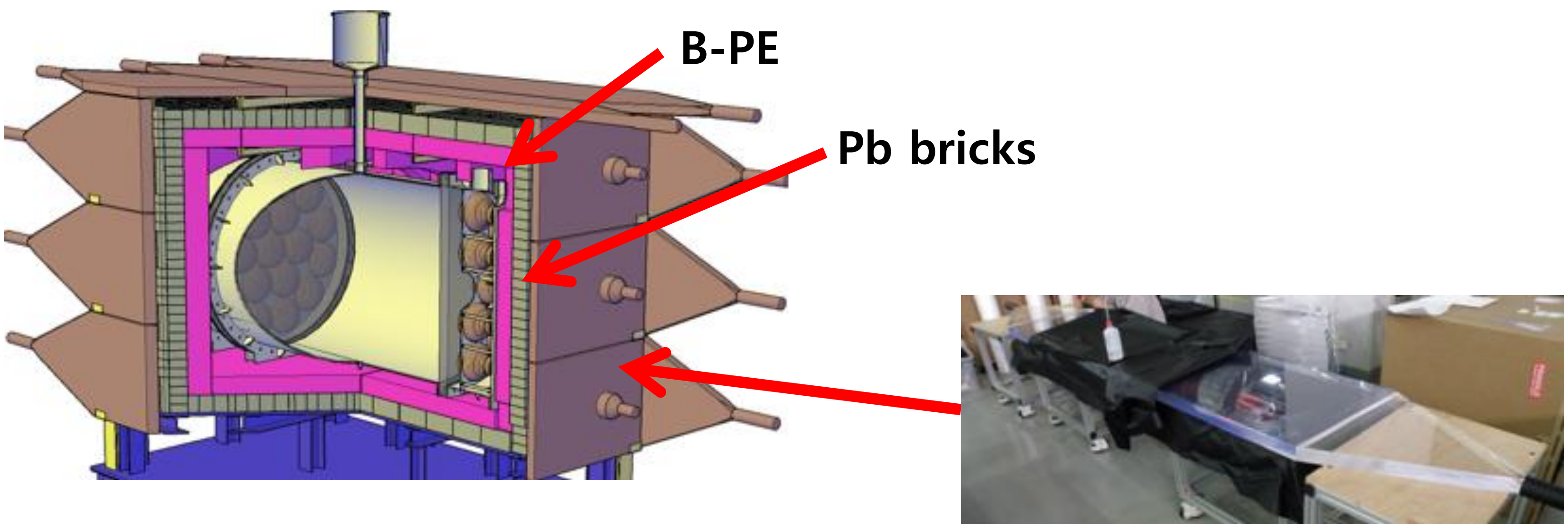
NEOS Detector

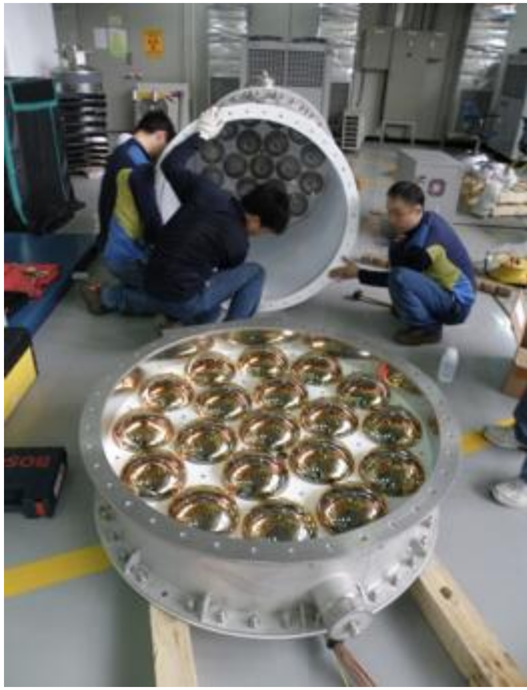
Shieldings

- 10 cm thick borated polyethylene (B-PE) for neutrons
- 10 cm thick Pb against external gammas

Muon Veto

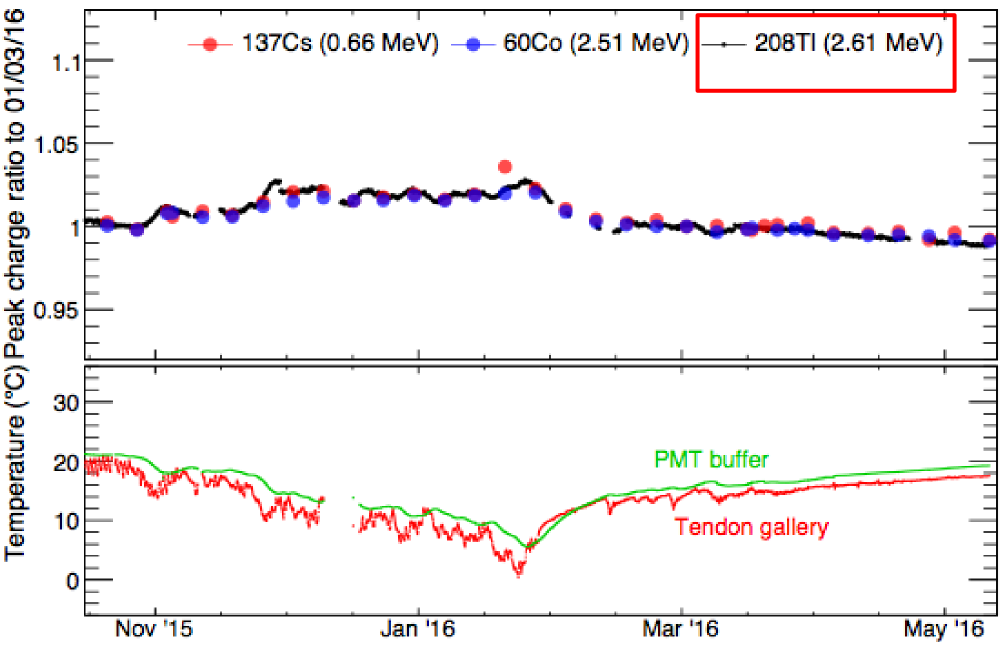
- Plastic scintillators covering top and sides.

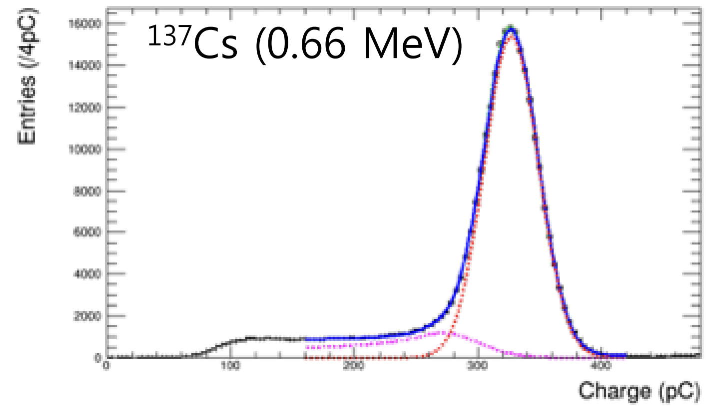


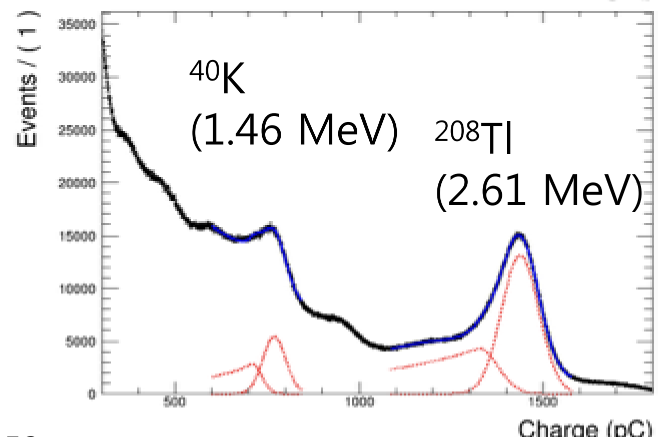





Calibration

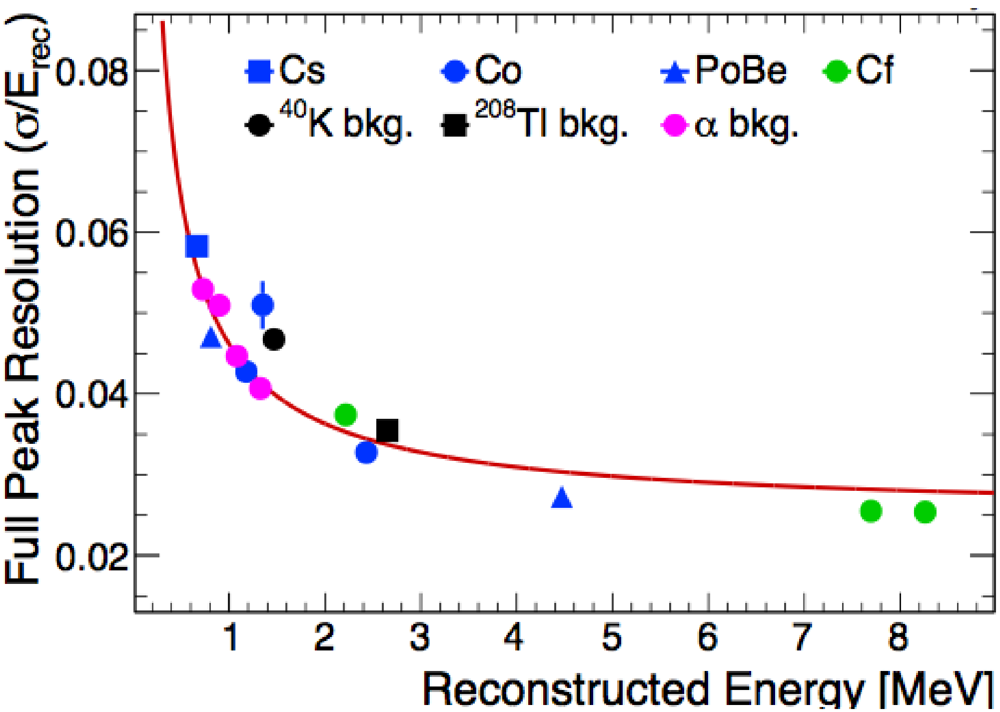


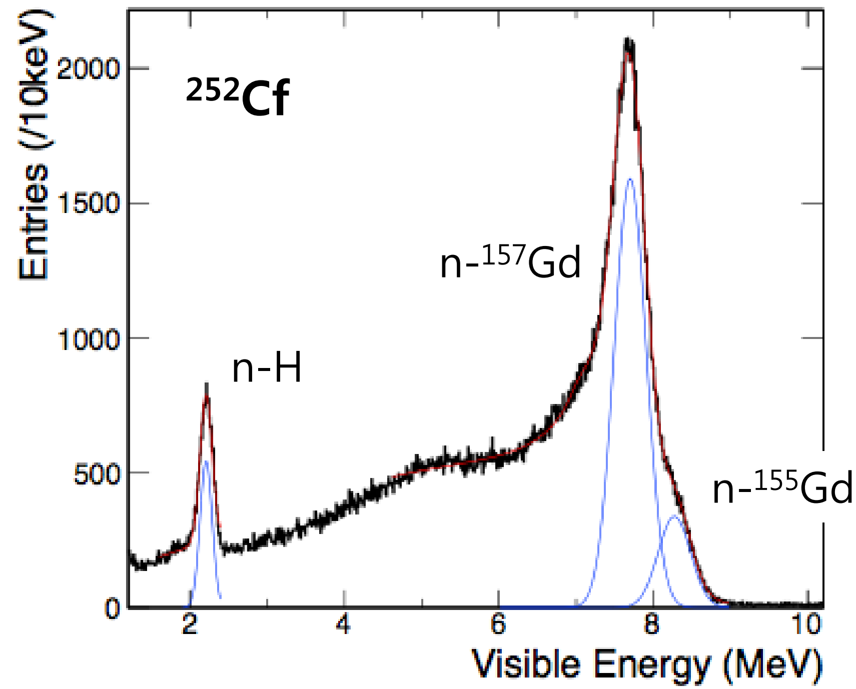




- Weekly calibration with point source
  - ✓ ^{137}Cs (γ:0.66 MeV), ^{60}Co (γ: 1.17/1.33 MeV), ^{252}Cf (n: 8 MeV from n-capture), PoBe (n, γ: 4.4 MeV)
- Internal/external backgrounds (continuous volume source)
  - ✓ ^{40}K (γ:1.46 MeV), ^{208}Tl (γ:2.6 MeV), ^{230}Th chain (α, β, γ)

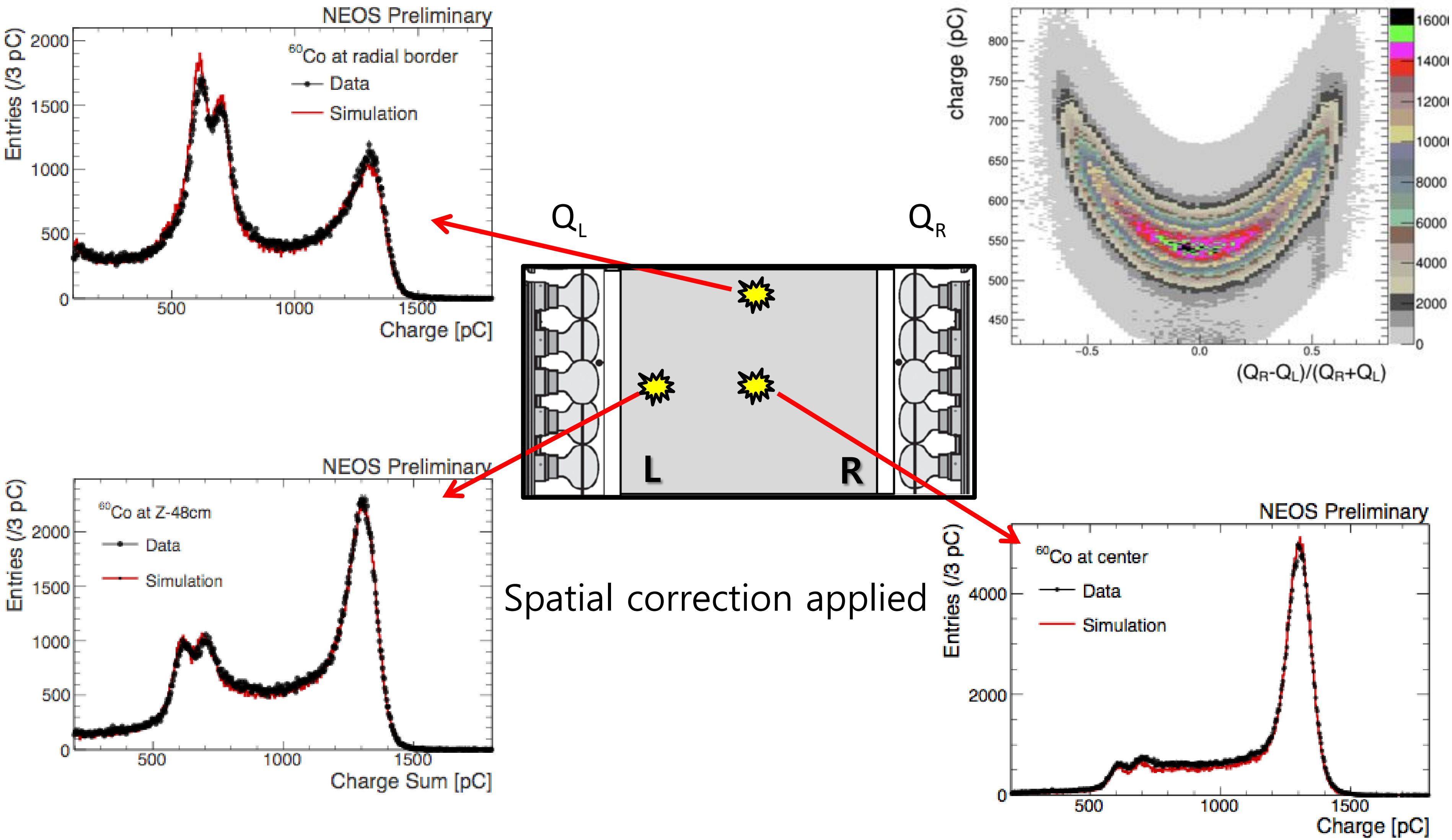
Energy Resolution





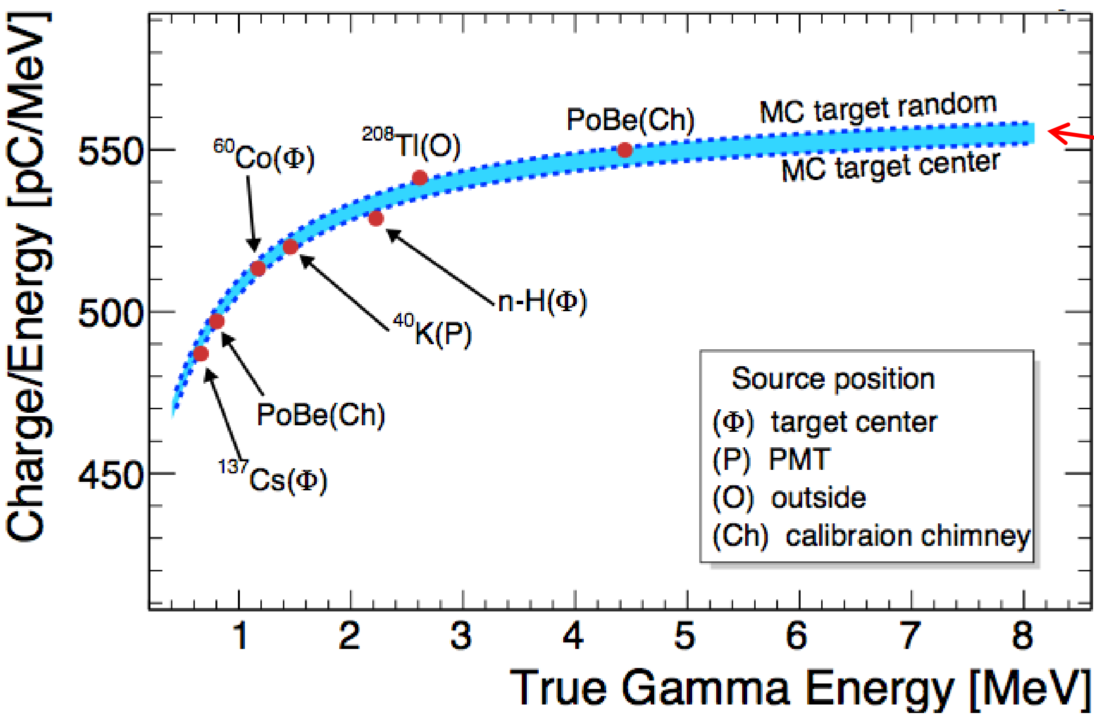
σ/E=5% for a full peak at 1 MeV

Non-Uniform Response



Spatial correction applied

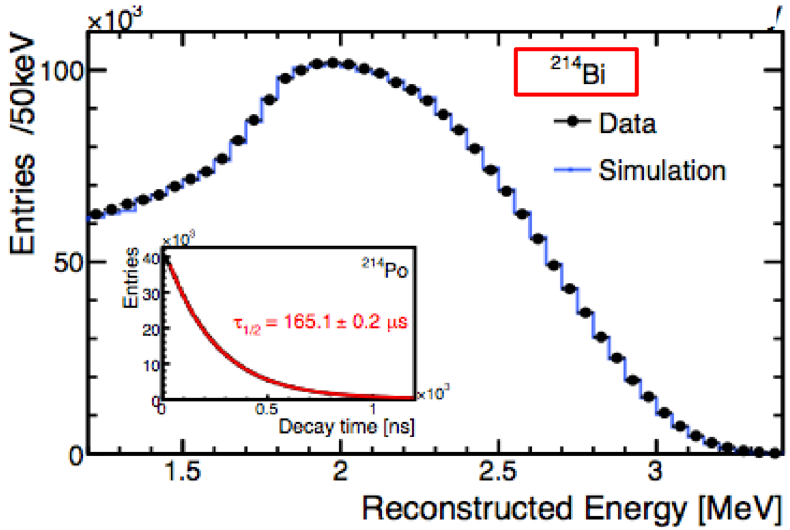
Charge-to-Energy Conversion

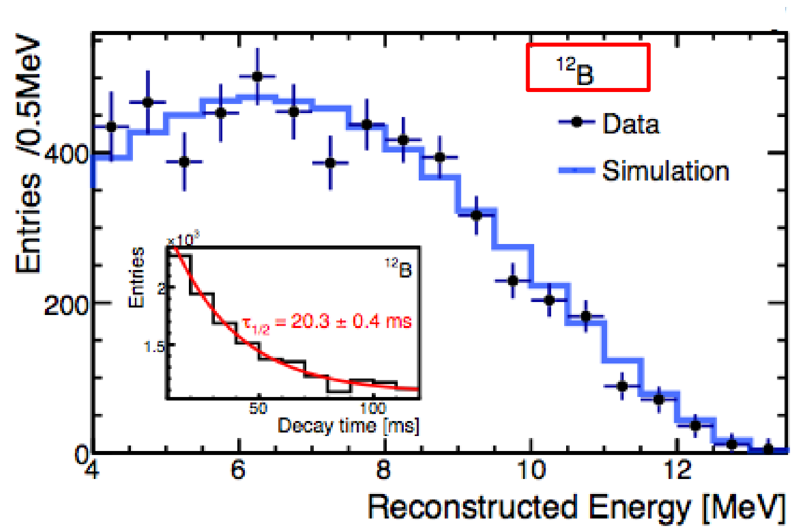


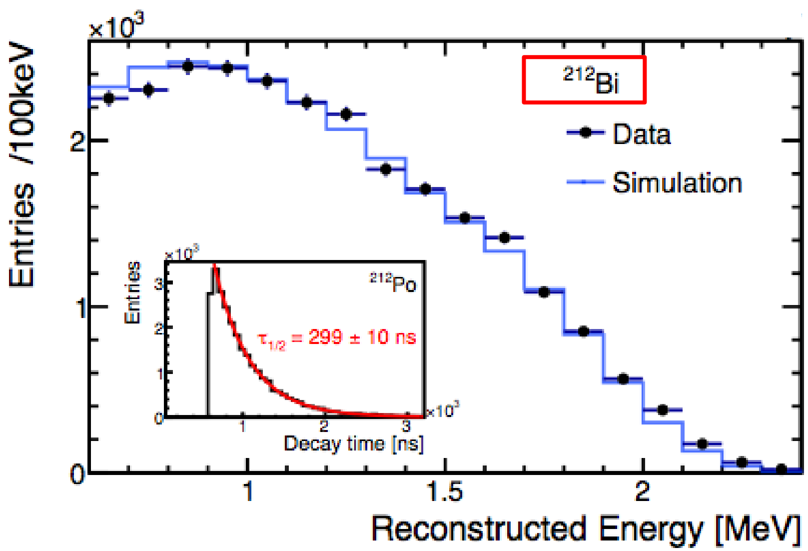
$$\frac{Q}{E_\gamma} = (p_0 + p_1 E_\gamma)(1 + p_2 e^{-p_3\sqrt{E_\gamma}})$$

- Signal quenched at low energy
- Cerenkov light important at higher energy

β-decay Events and Simulation

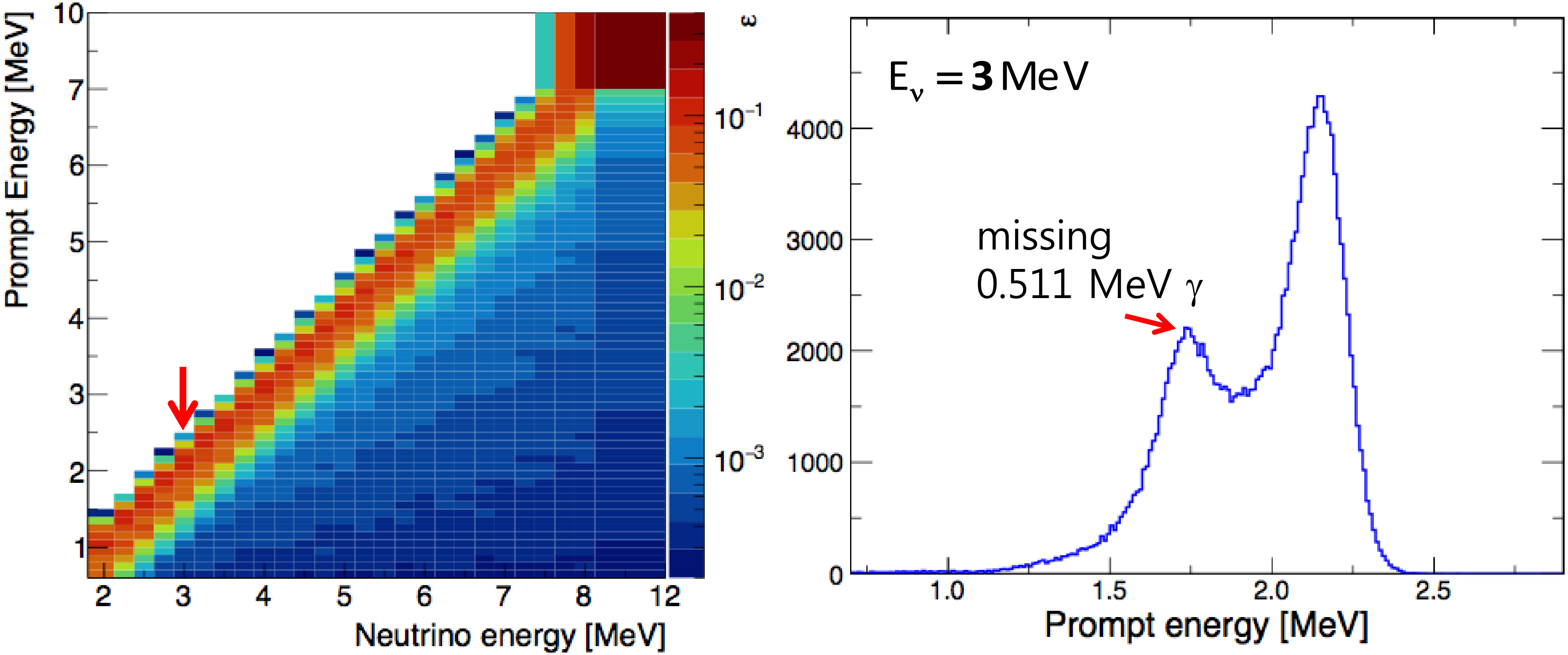






- Geant4 based full MC simulation including trigger simulation
- Excellent agreement with data

Neutrino Energy Response (MC)



Energy loss due to escaping γ

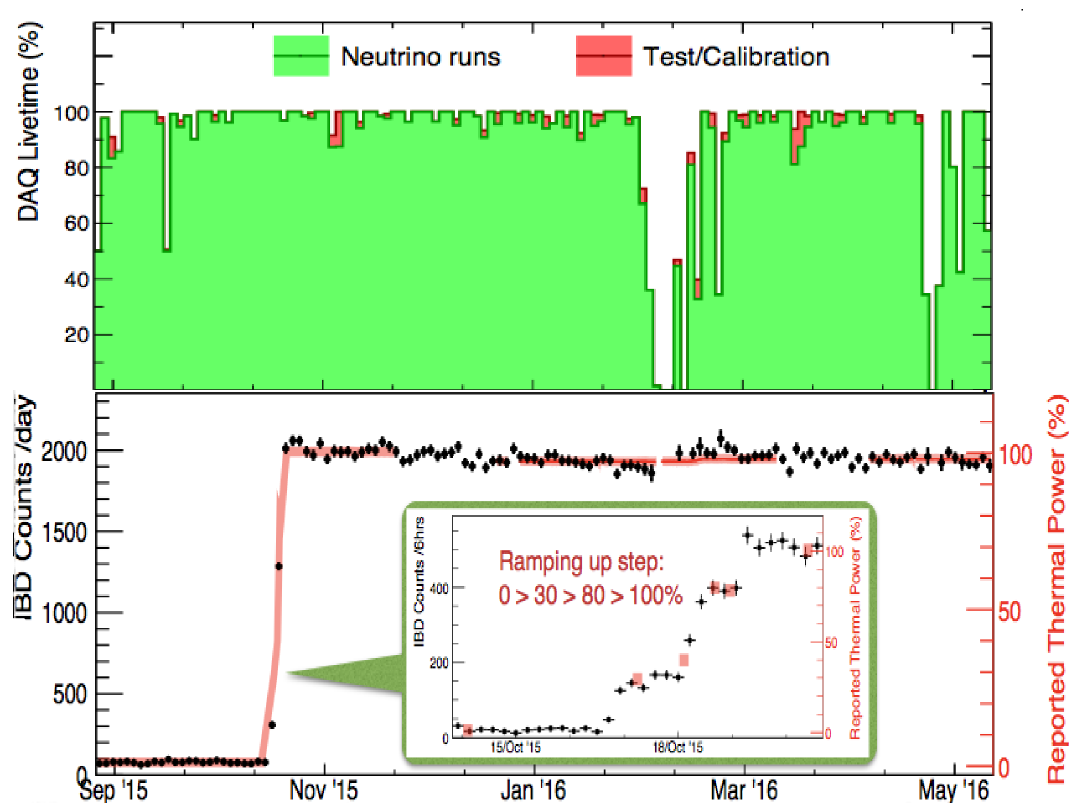
IBD Candidate Event Rate

Data taking period: Aug. 2015 - May 2016

- Data taking was terminated due to a scheduled maintenance of the tendon gallery (once every 5 years)
- Reactor-on: 180 days
- Reactor-off: 46 days
- DAQ over 90% efficient

IBD Candidates

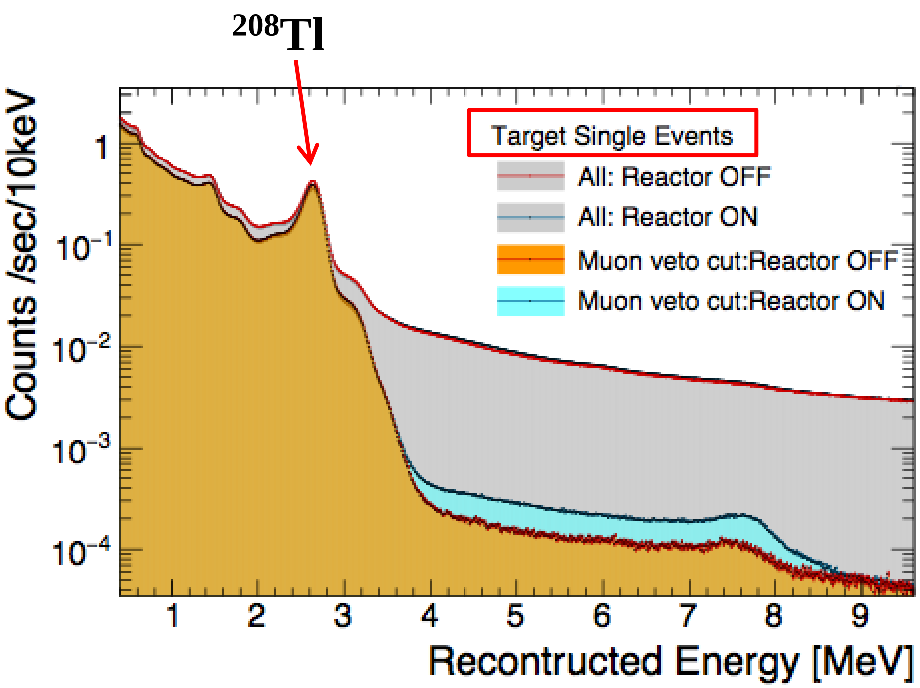
- Reactor-on: 2000/day
- Reactor-off: 80/day



Single Event and Muon Veto

Events before prompt-delayed event pairing

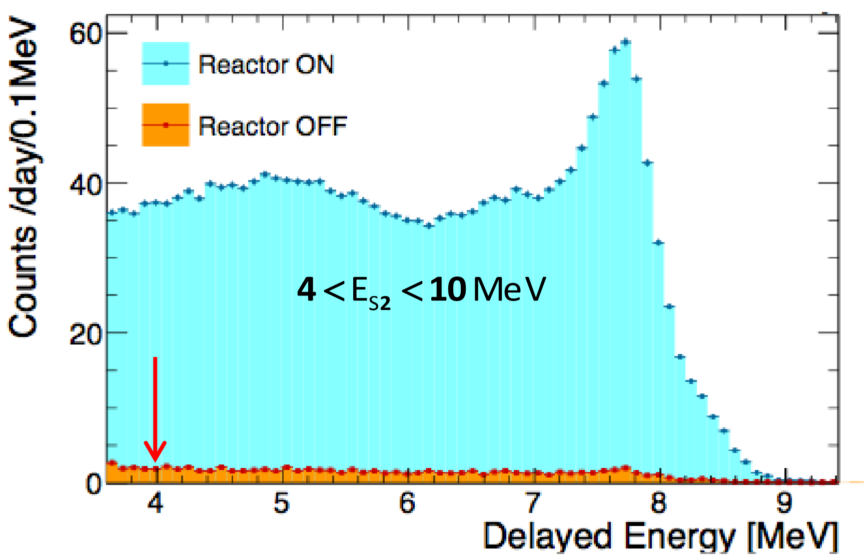
- Muon veto: discards any events within 150 μs after a muon event.
- a peak at 2.6 MeV due to ^{208}Tl
- Reactor-on and off difference after veto is due to IBD pairs

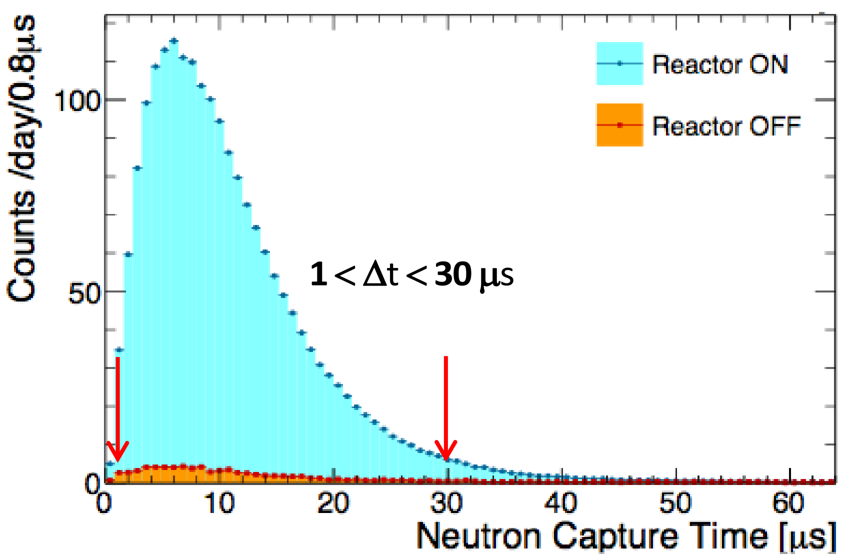


IBD Reconstruction

- Prompt event: 1 < E < 10 MeV
- Delayed event: 4 < E < 10 MeV
- Delayed coincidence: 1 < Δt < 30 μs

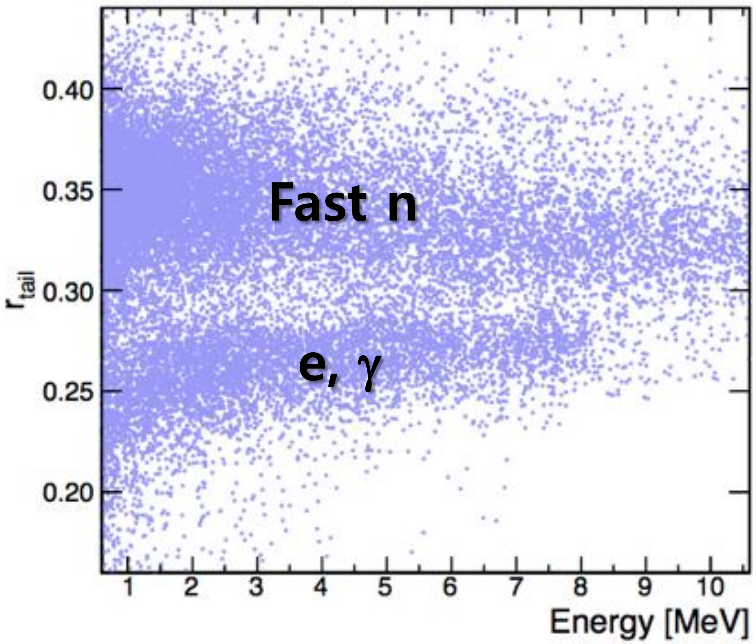
- Multiplicity veto: no event before 30, after 150 μs from the prompt/delayed pair.

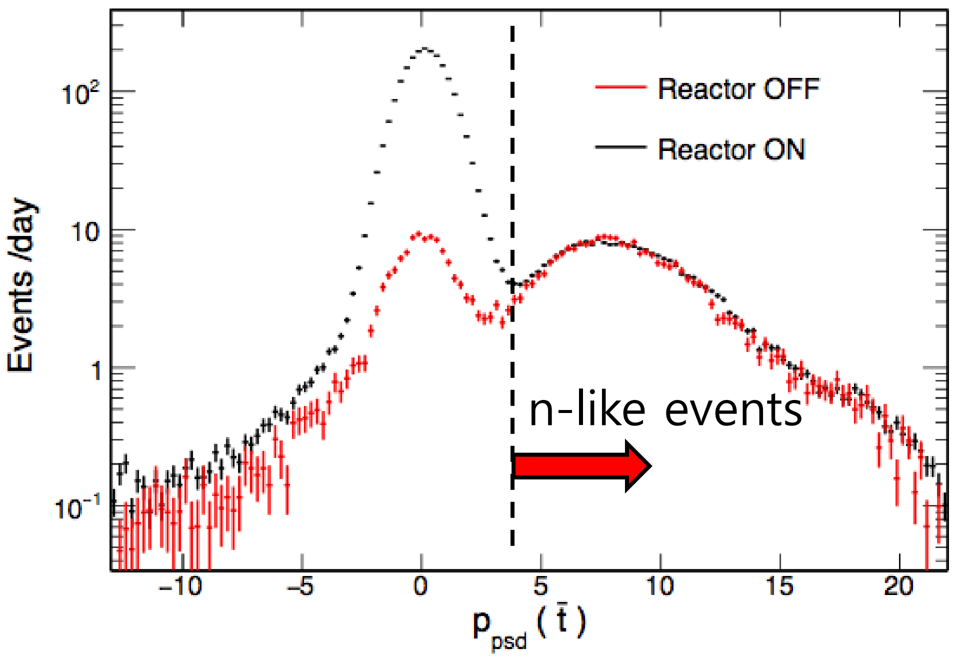




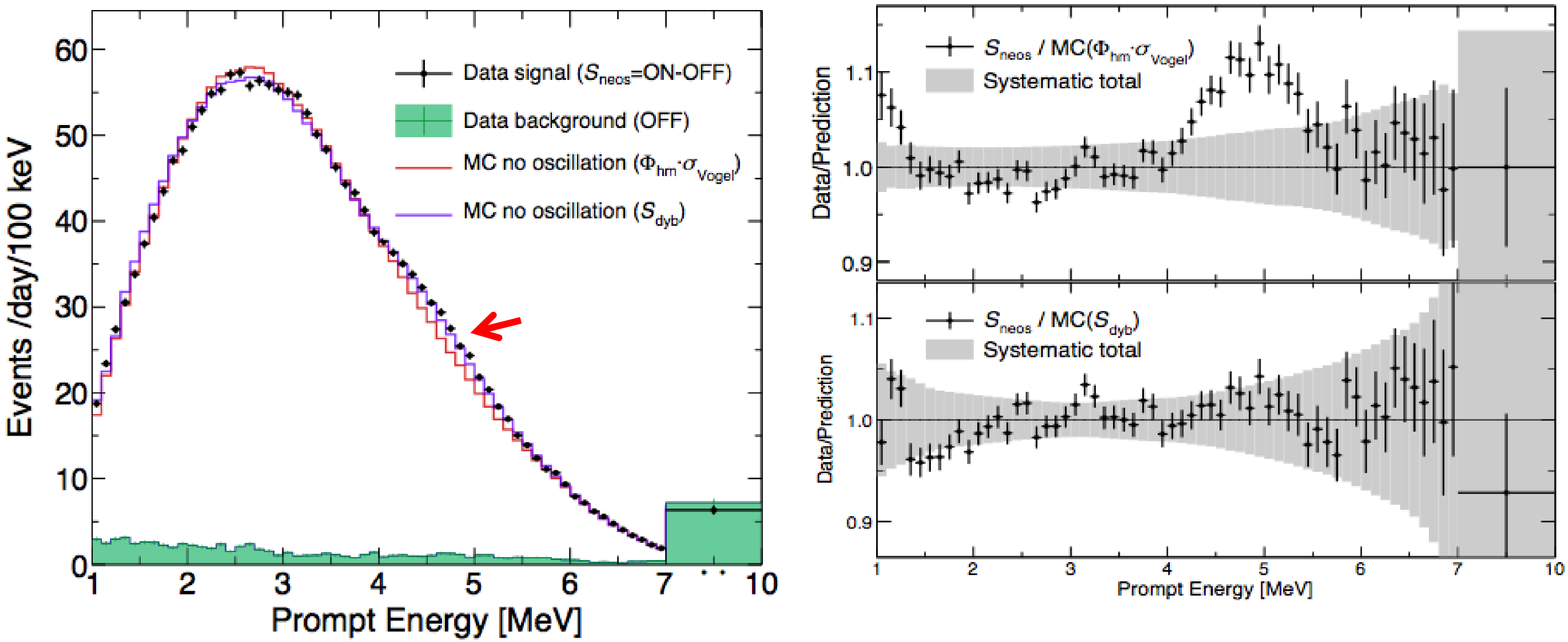
Pulse Shape Discrimination

- Fast neutron scattering events have relatively slowly decaying pulse.
- Background is reduced by more than 70%.
- γ-like event acceptance is 99.9%.





Prompt Energy Spectrum



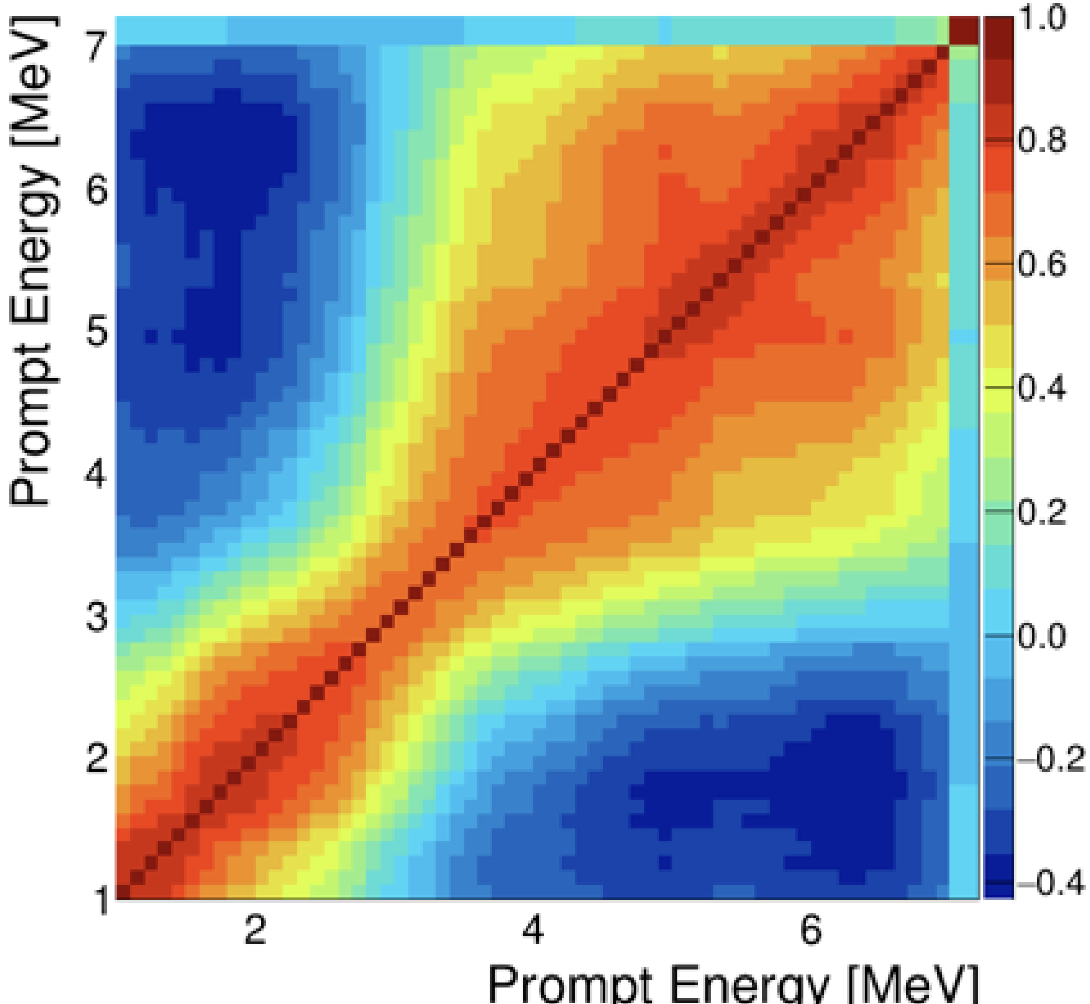
- S/N ~ 23
- vs H-M: 5 MeV bump, not so practical to do the oscillation analysis
- vs Daya Bay: bump not totally disappeared, fission fraction difference
- Systematic uncertainties for the shape analysis:
  reference spectrum > energy recon. >> backgrounds, etc.

χ^2 Construction

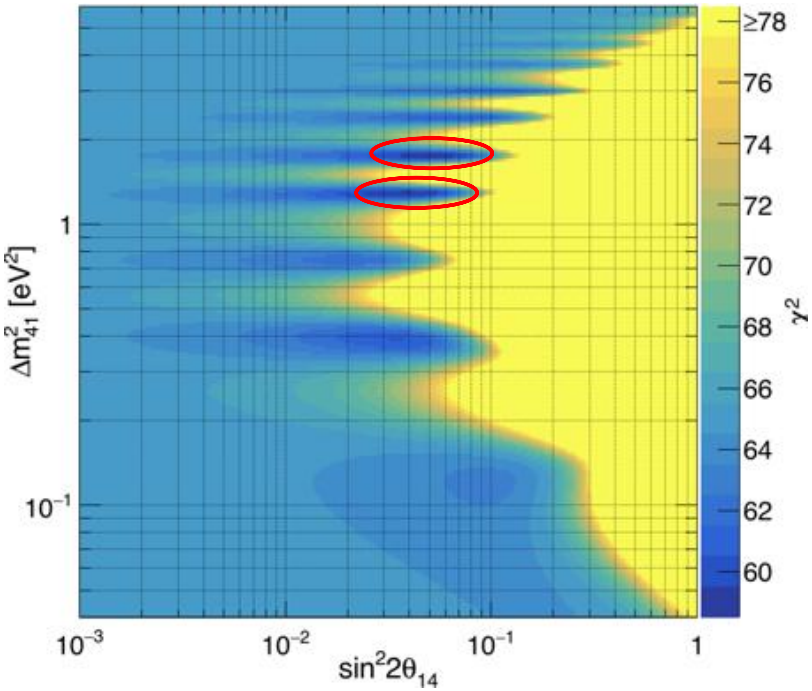
$$\chi^2 = (N_i^{on} - (t_{on}/t_{off})N_i^{off} - T_i)V_{ij}^{-1}(N_j^{on} - (t_{on}/t_{off})N_j^{off} - T_j)$$

- N_i^{on} : Number of events in the i^{th} energy bin in reactor on period
- N_i^{off} : Number of events in the i^{th} bin in reactor-off period
- t_{on}/t_{off}: time period of reactor on/off
- $T_i = T_i(\Delta m^2, \sin^2 2\theta)$: expected spectrum for each oscillation parameter set generated from model spectrum and convoluted with the detector response (Daya Bay spectrum used)
- V_{ij}: covariance matrix including statistical/systematic uncertainties and their correlation between energy bins

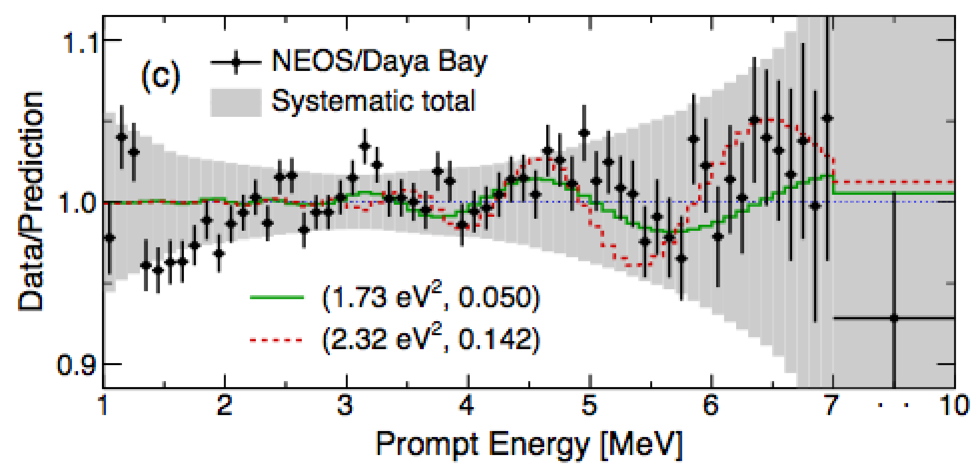
Covariance Matrix



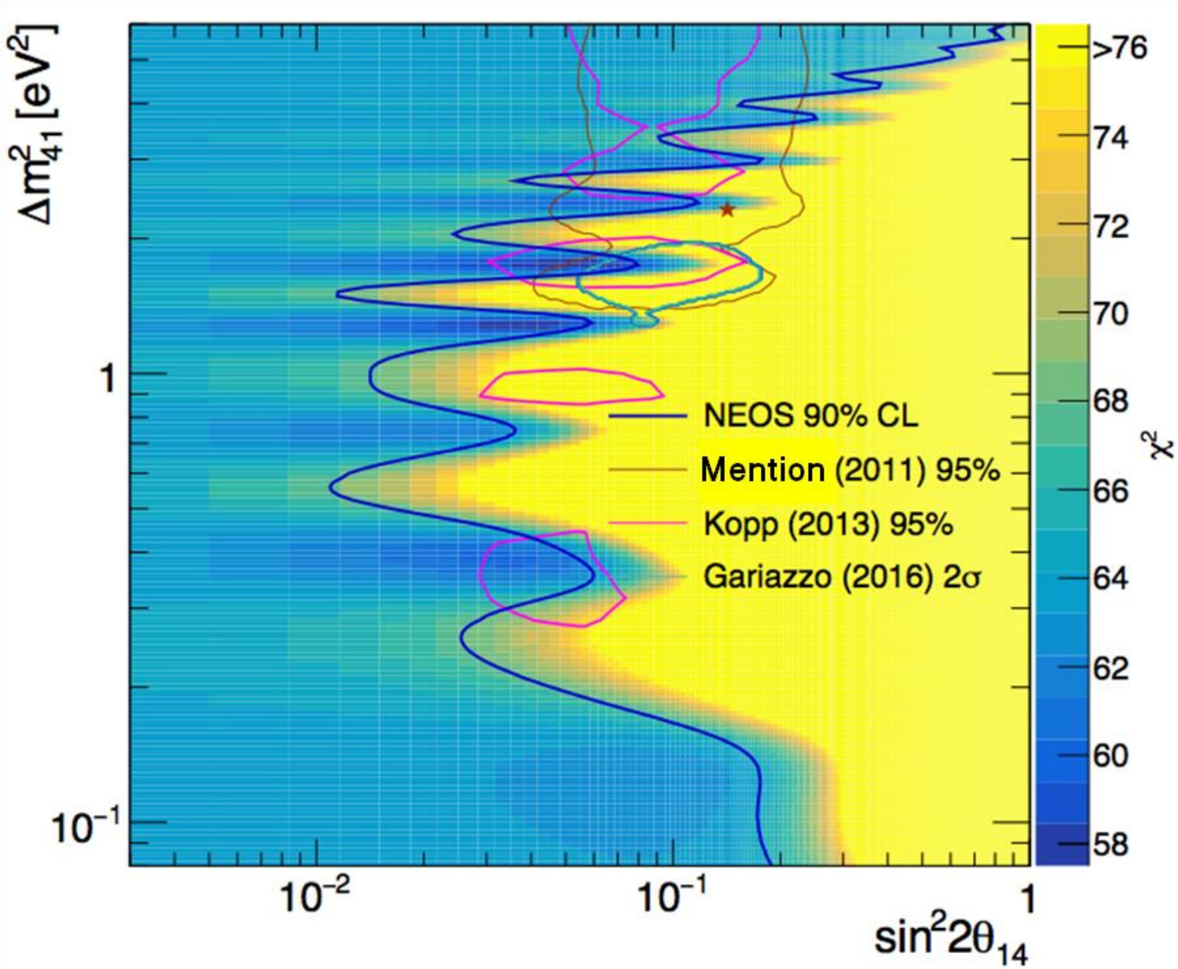
Oscillation



- χ^2 minima at
  $(\sin^2 2\theta, \Delta m^2) = (0.04, 1.3\ \text{eV}^2)$
  $(0.05, 1.73\ \text{eV}^2)$
  with $\Delta\chi^2 = \chi^2_{3\nu} - \chi^2_{4\nu} = 6.5$.
- p-value ~ 22%
- No strong sign of 3+1 active-to-sterile ν oscillation.



Limits



Phys. Rev. Lett. 118, 121802 (2017)

Future Works

- "NEOS2" is in proposal stages
  - To install at a newly planned powerplant site.
    - New reactors would have ~4 GW_{th} (Hanbit~2.8 GW_{th})
    - We are writing a LoI for a dedicated space for various neutrino experiments.
  - Measuring one burn-up cycle at Hanbit NPP should help to understand the spectrum in details
- We are investigating a possible collaboration with DANSS.

Summary

- We examined neutrino spectrum shape at ~24 m from a reactor.
- No strong evidence for oscillation from 3+1 neutrino ($\Delta m^2 \sim 1$ eV^2) mixing.
  - Best fits to ($\sin^2 2\theta$, Δm^2)=(0.04, 1.3 eV^2)/(0.05, 1.73 eV^2)
  - RAA optimum is highly disfavored.