NEOS Detector

for Measuring Energy of Reactor Neutrinos

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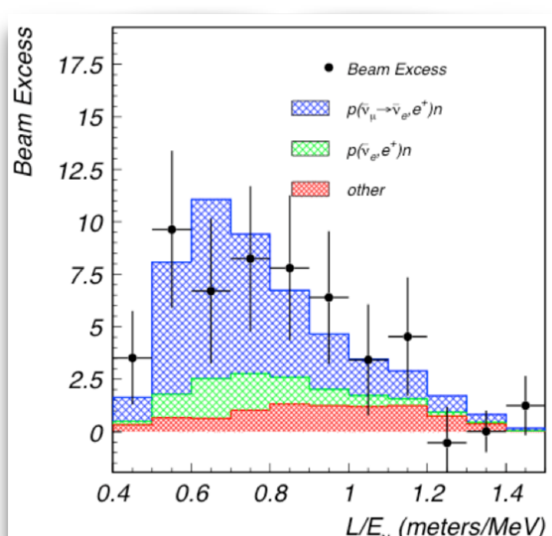
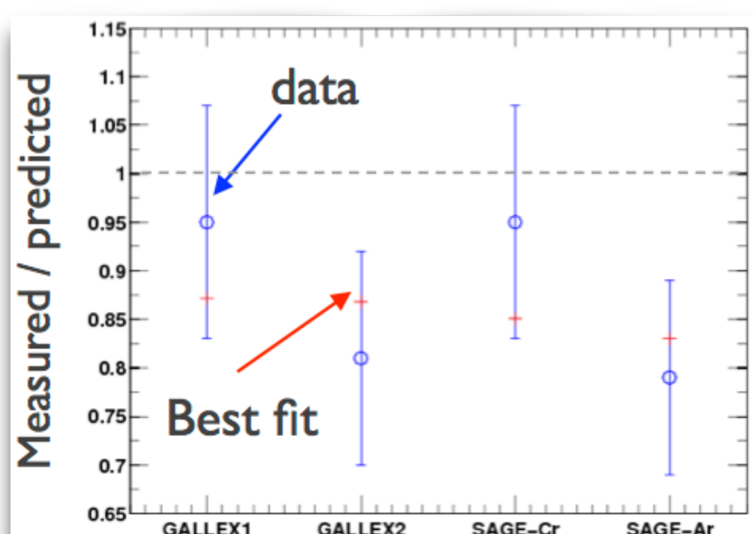
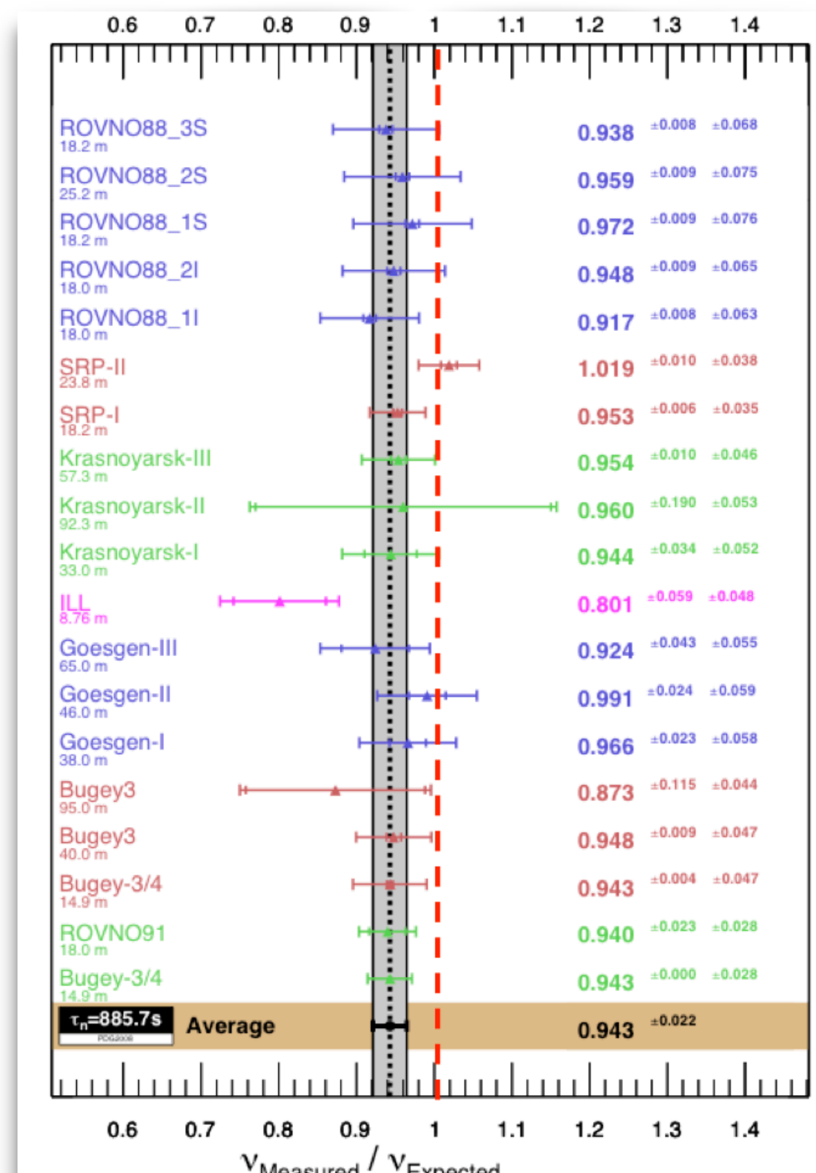
Contents

Neutrino Anomalies and 3+1 Framework

- **There are some neutrino anomalies, which cannot be explained with 3ν oscillation.**
- **Those anomalies can be explained with 3+1ν framework assuming a light sterile neutrino.**
- **NEOS: Neutrino Experiment for Oscillation at Short baseline**
- **NEOS is a reactor neutrino experiment at short baseline to search for sterile neutrino in the 3+1ν framework.**







Reactor Anti-neutrino Measurement

- **Neutrino source: β-decay in the reactor core**

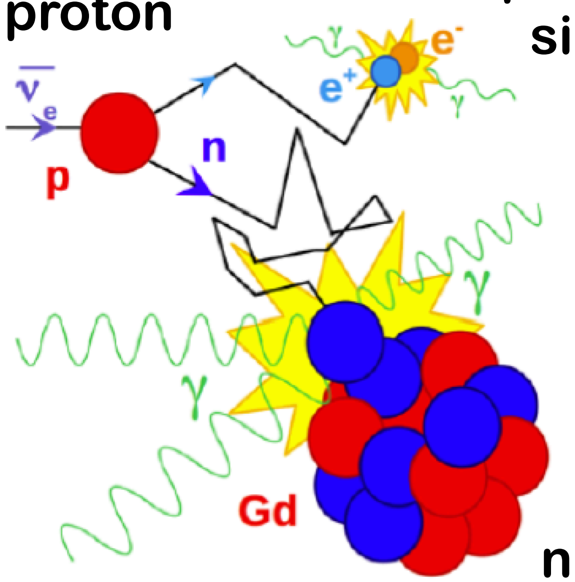
$$n \rightarrow p + e^- + \bar{\nu}_e \quad \text{(beta decay)}$$

- **Neutrino detection: inverse beta decay (IBD) in the active target**

$$\bar{\nu}_e + p \rightarrow e^+ + n \quad \text{(IBD)}$$

- **IBD in the Gd loaded liquid scintillator (Gd-LS)**

IBD with a proton



positron signal → **prompt signal (S1)**
e^+ energy deposition + e^+/e^- annihilation

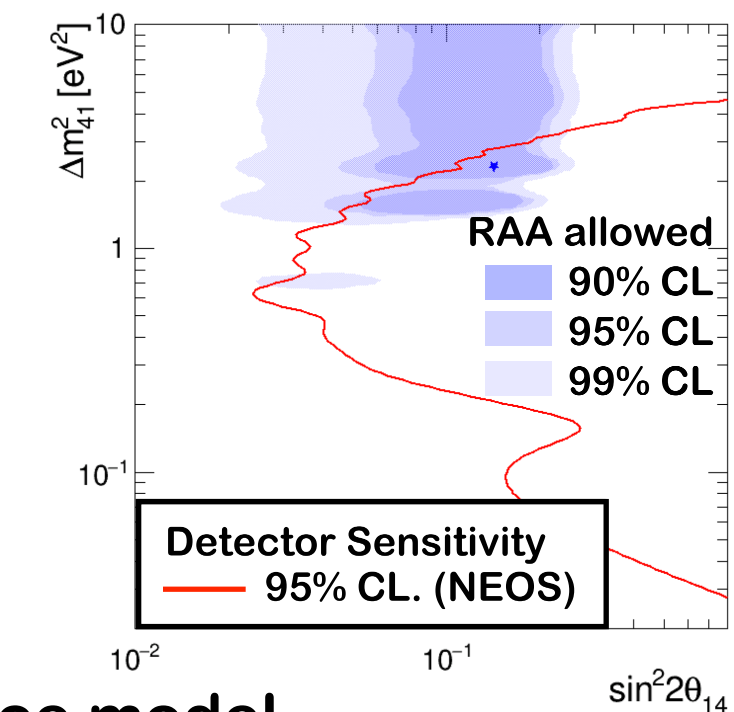
IBD pairing (coincidence)

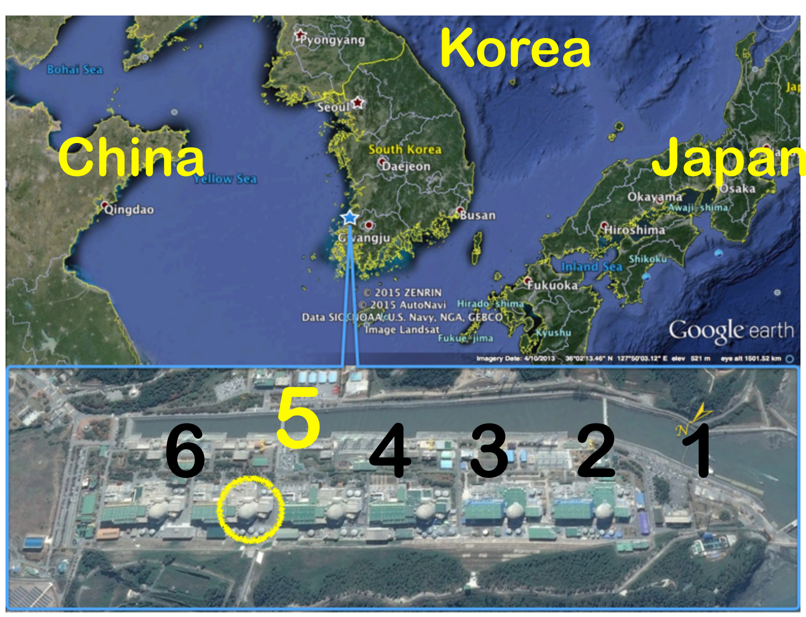
※ In Gd-LS, there are time coincidence between signals by positron and neutron from IBD interaction.

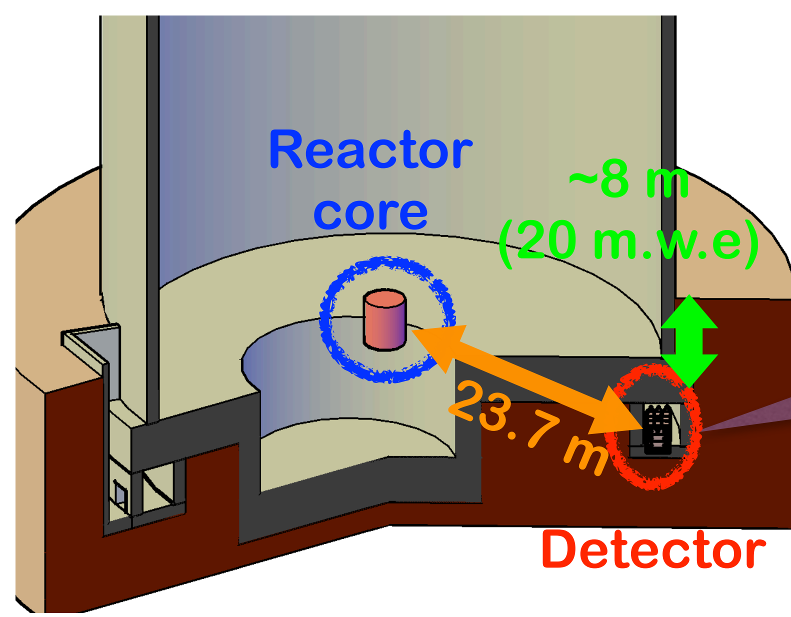
neutron capture signal → **delayed signal (S2)**
neutron capture on Gd ($\Sigma E_\gamma \approx 8$ MeV)

Experimental Site

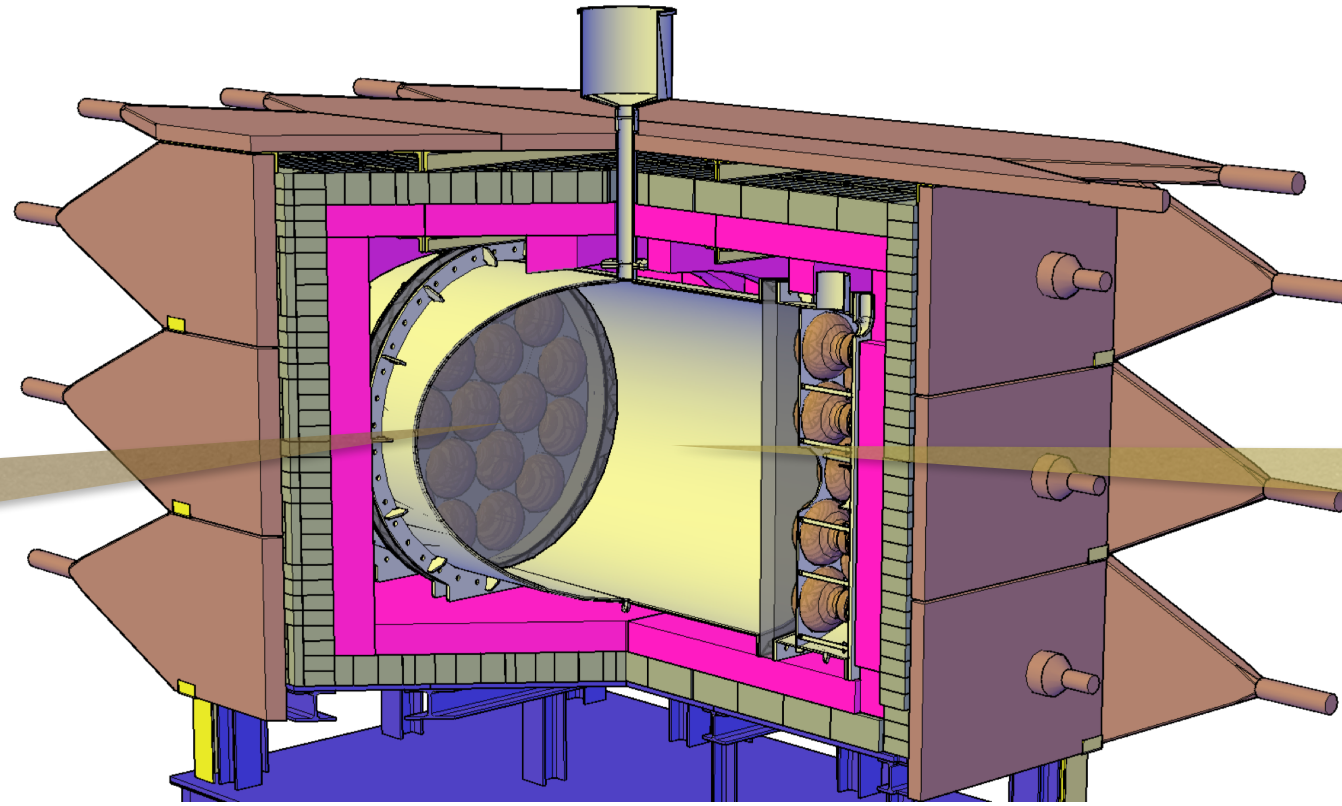
- **Reactor Unit 5 in Hanbit Nuclear Power Plant, Younggwang, Korea**
  - **2.8 GW_{th} commercial reactor**
  - **Core size: 3.1-m diameter and 3.8-m height**
  - **Low enriched uranium fuel (4.6% ^{235}U)**
- **Detector in tendon gallery**
  - **23.7-m baseline and 20-m.w.e overburden**
  - **Most sensitive range is ~eV sterile neutrinos**
  - **Single detector**
    - **Understanding detector response and reference model**







NEOS Detector



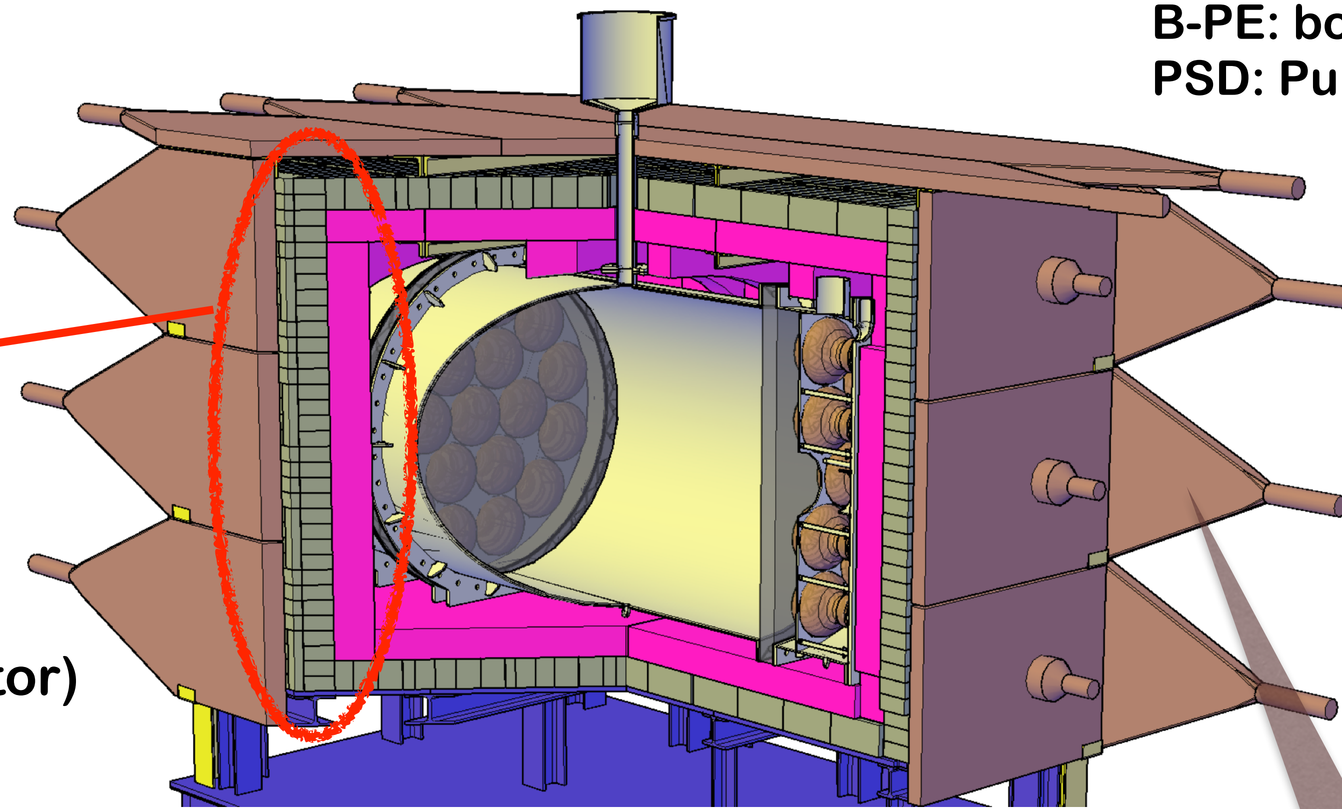
- Photomultiplier tubes (PMTs)
  - Two buffer tanks filled with mineral oil at both side of the target tank
  - Acrylic windows b/w target and buffers
  - 19 R5912 (8 inch) PMTs are installed in each buffer tank.

- Active target
  - Homogeneous liquid scintillator (LS)
  - 1008-L volume: (R, H) = (51.5, 121) cm
  - IBD in 0.5% Gd-LS
    - coincidence time = 7~8 μs
  - Mixed LS: LAB- and DIN-based LS (9:1)

LAB: Linear Alkyl Benzene
DIN: Di-isopropylnaphthalene

NEOS Detector

B-PE: borated polyethylene
PSD: Pulse shape discrimination



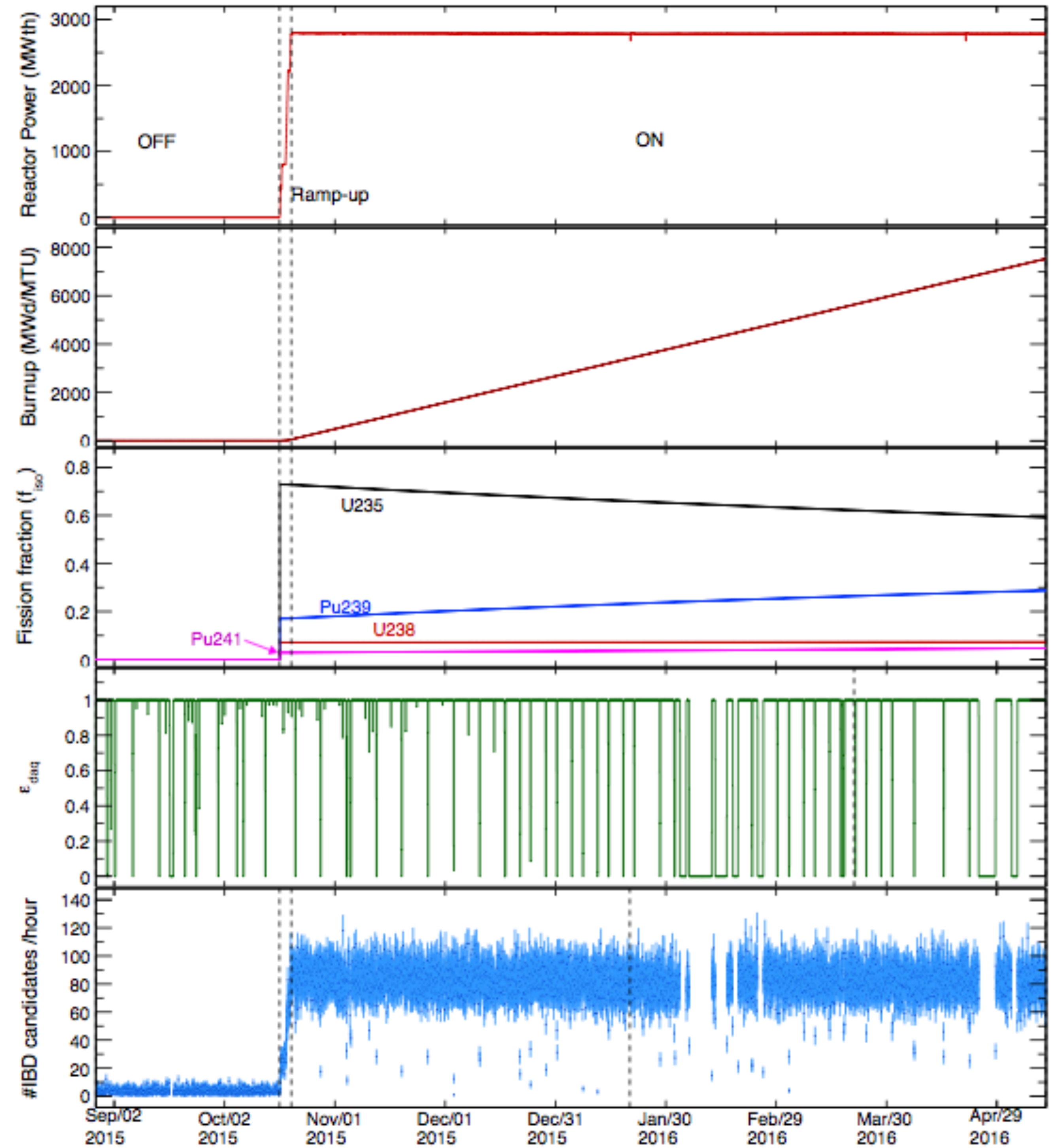
- **Shieldings**
  - **10-cm B-PE (n)**
  - **10-cm Pb (γ)**
  - **Muon detectors (Plastic scintillator)**

- **DAQ systems**
  - **500 MS/s Flash ADC for target**
  - **Recording waveforms for PSD**
  - **62.5 MS/s ADC for muon detectors**

- **Muon detectors for veto**
  - **15 plastic scintillators with PMTs except bottom side**

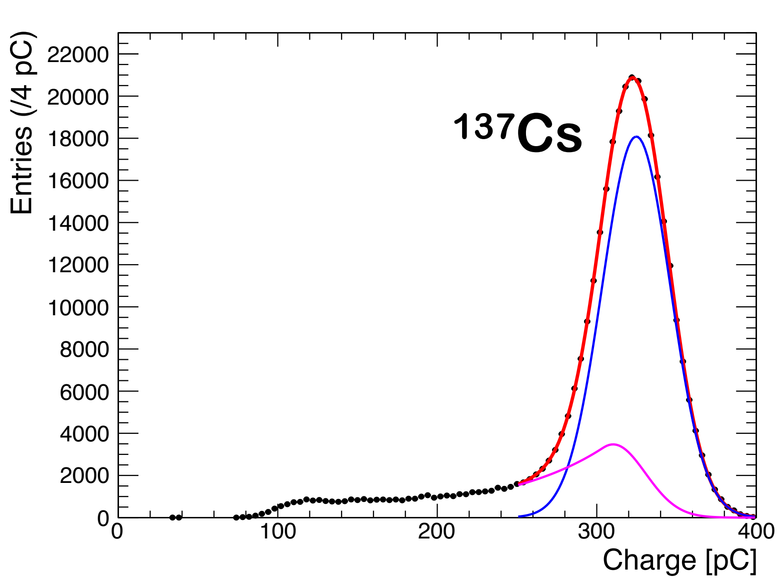
Detector Operation

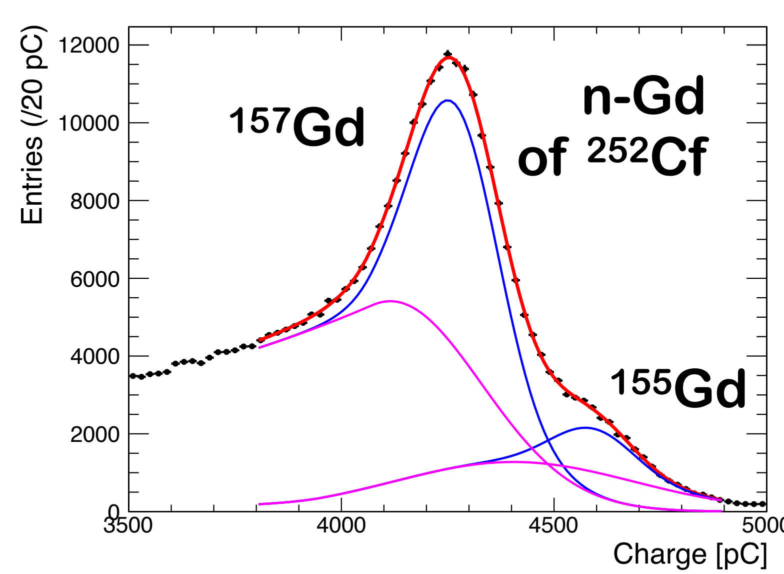
- **Installation and operation**
  - **Install in Jul. 2015**
  - **Data was taken from Aug. 2015.**
  - **Reactor-on data: 180 days (1977 /day)**
  - **Reactor-off data: 46 days (85 /day)**
- **~90% DAQ efficiency**
  - **Calibration runs**
  - **Checking trigger condition**
  - **Power outage**
- **Data taking is over in May 2016 due to regular maintenance of the tendon.**

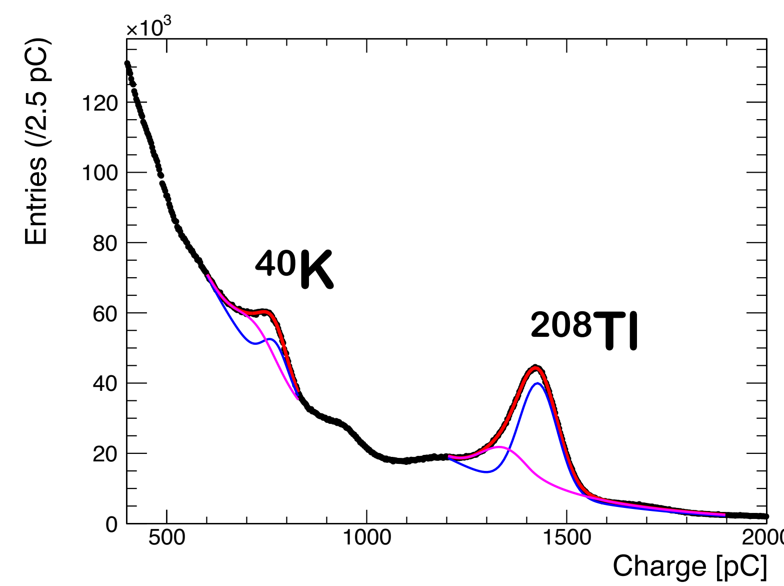


Calibration Campaign

- **Source calibration**
  - **Once a week with point sources**
    - **^{137}Cs (0.66-MeV γ), ^{60}Co (1.17/1.33-MeV γ), PoBe (0.8/4.4-MeV γ / n), ^{252}Cf (n; n-H 2.2-MeV γ, n-Gd 8-MeV γs)**
- **Internal/external background**
  - **Continuous and volume source**
    - **^{40}K (1.46-MeV γ) in PMT glass, ^{208}Tl (2.61-MeV γ) in B-PE**
    - **Radon in LS (α / β)**
- **They are also used for position and time dependence corrections**

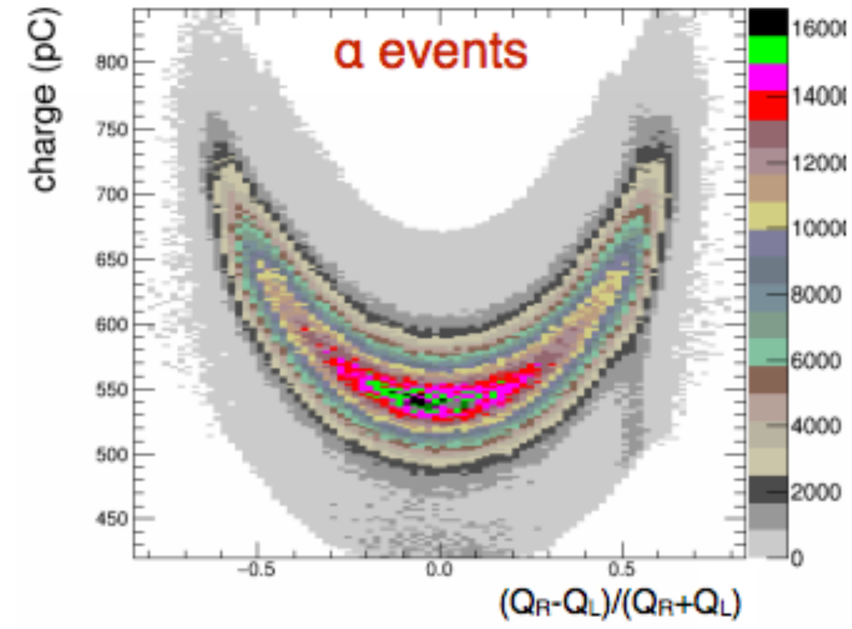


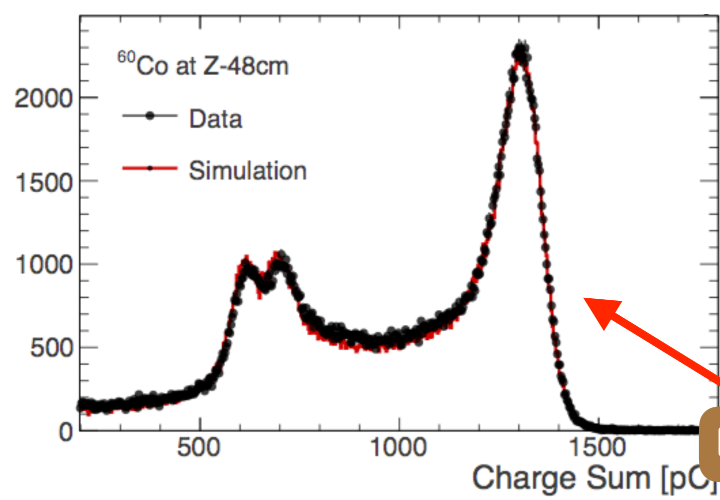


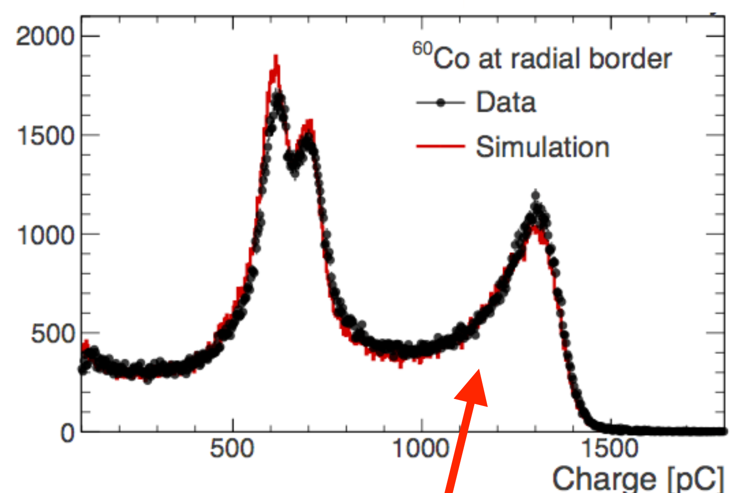


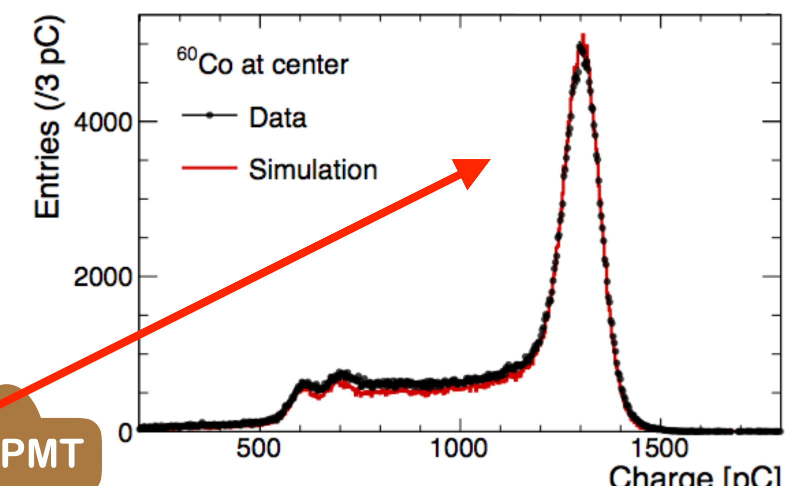
Detector Response and Simulation

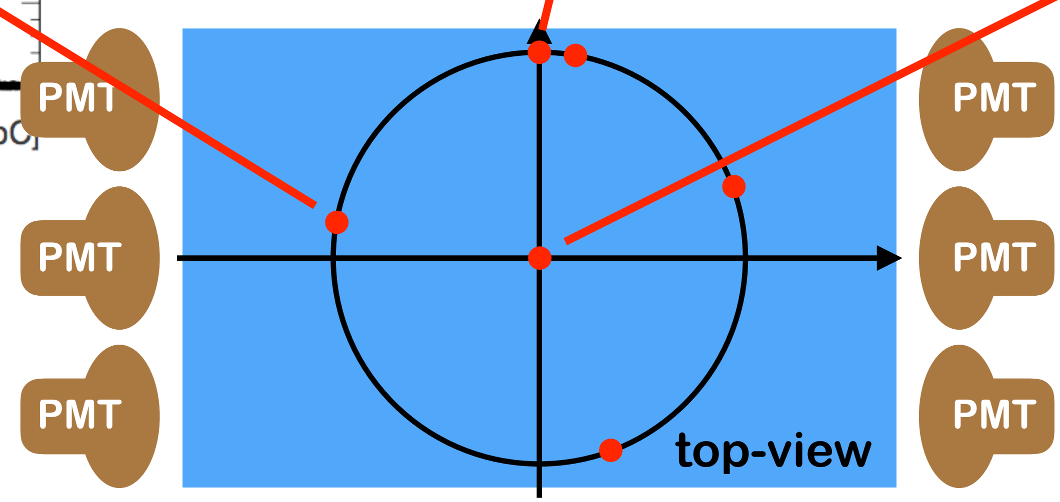
- **Non-uniform response & escaping γ**
  - **Detector response depends on position**
  - **There are lots of escaping γ due to the detector size**
  - **MC is tuned for several positions and works good.**





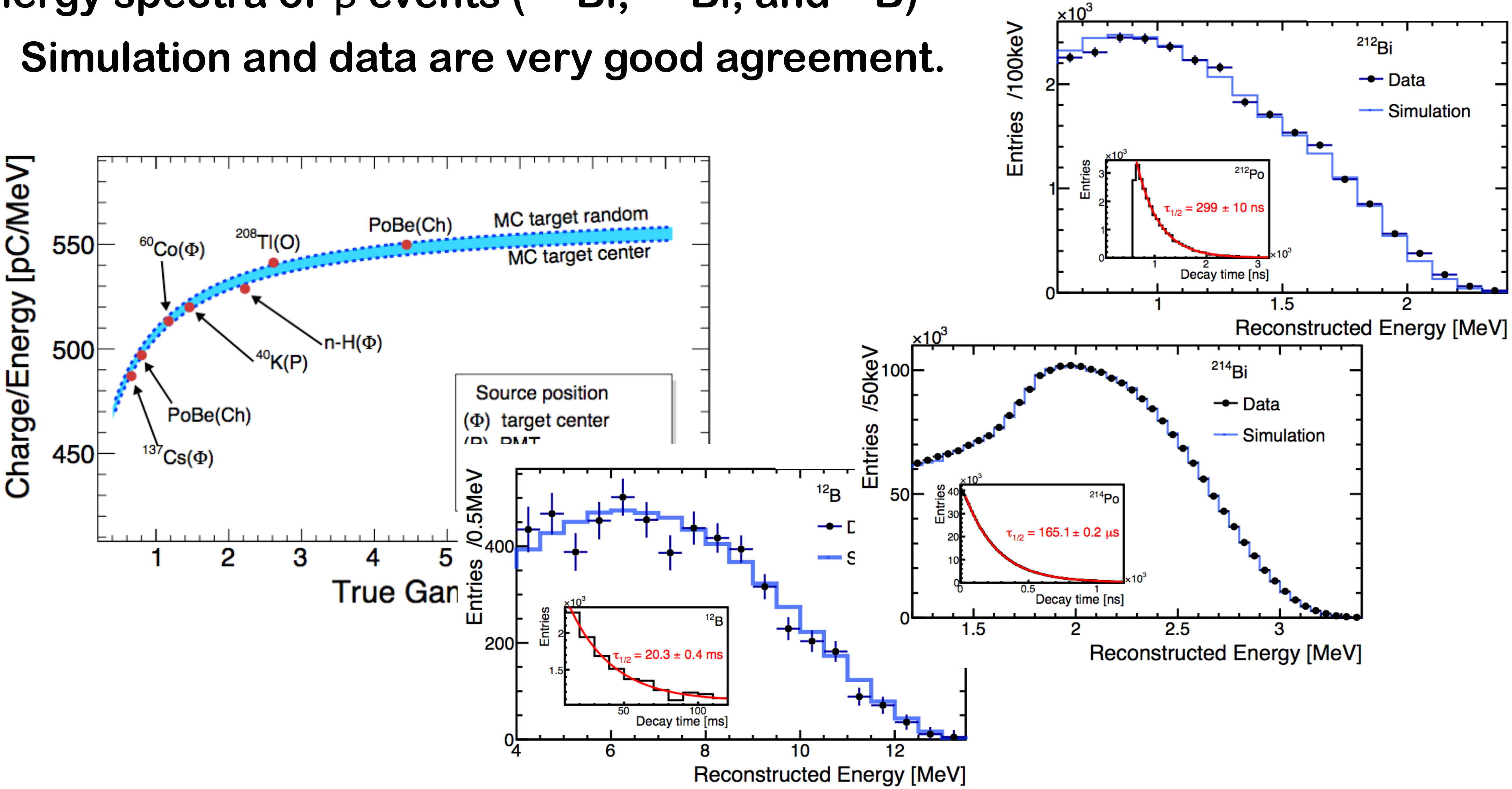






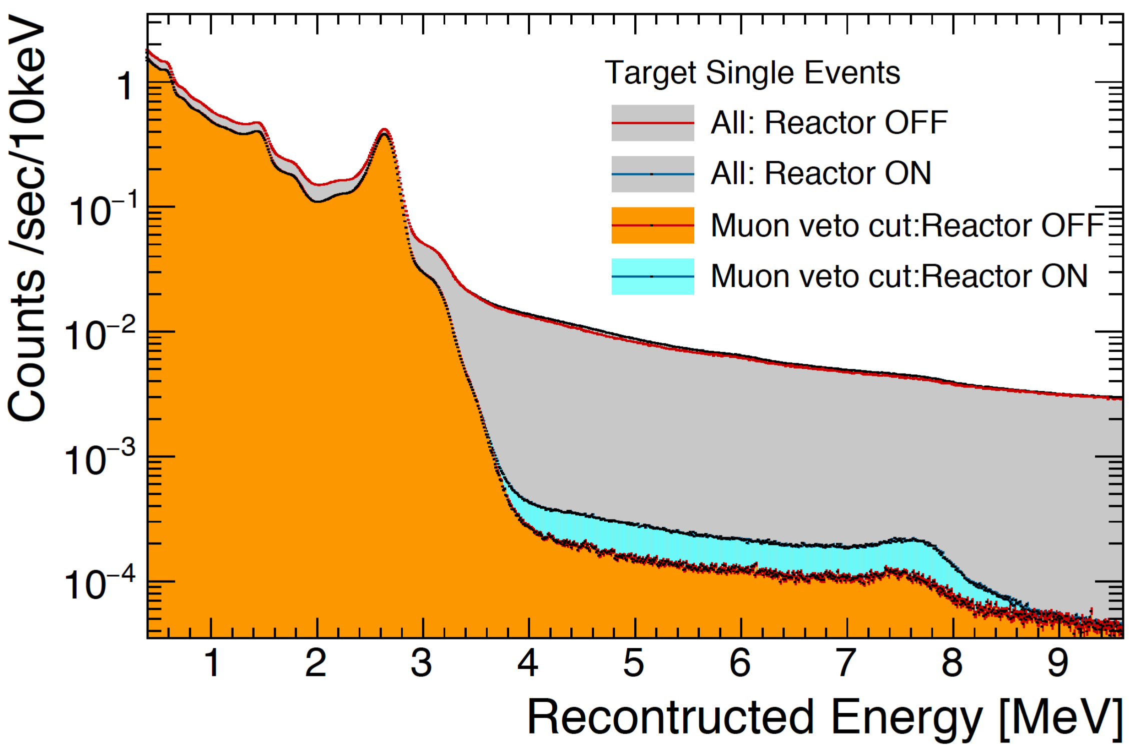
Detector Response and Simulation

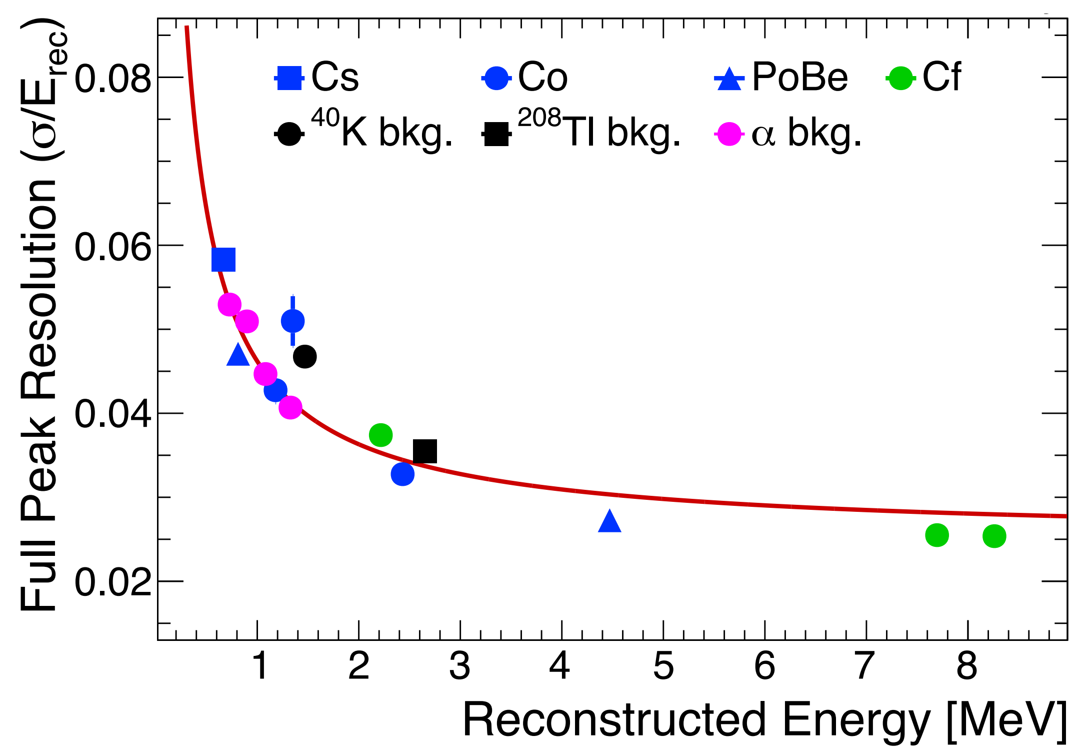
- **Charge to energy conversion**
  - **Only single γ sources are used for conversion**
  - **Non-linearity due to quenching and Cherenkov effect**
- **Energy spectra of β events (^{212}Bi, ^{214}Bi, and ^{12}B)**
  - **Simulation and data are very good agreement.**



Single Events Reconstruction

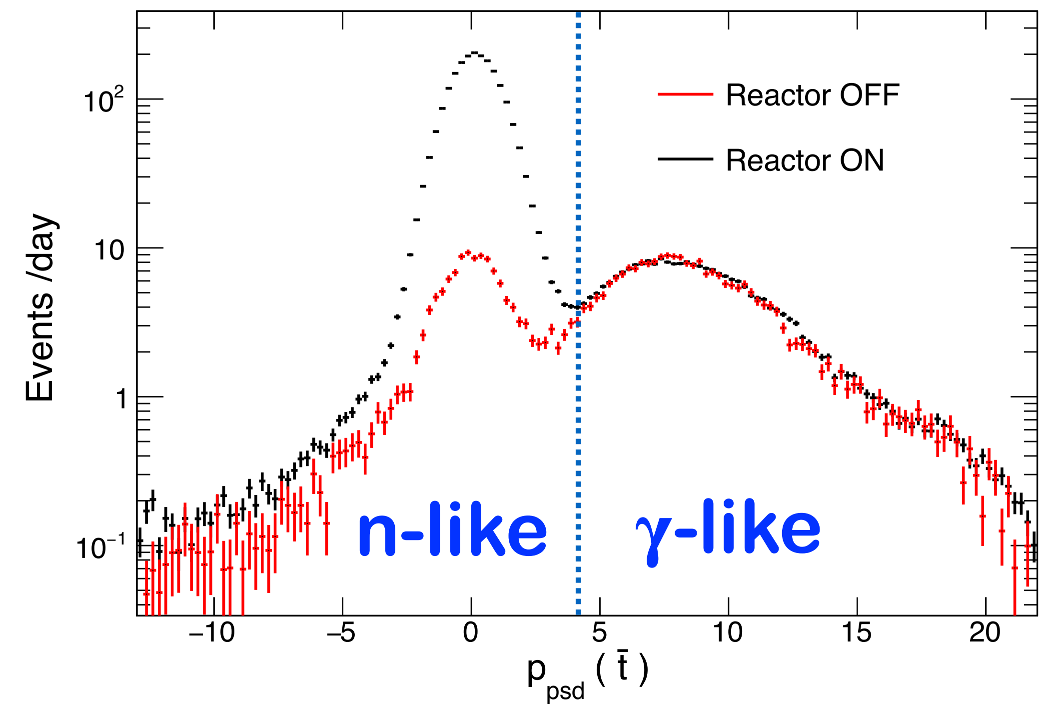
- **Energy spectrum of reconstructed events**
  - **Energy is reconstructed via charge to energy conversion function including non-linearity.**
  - **Selection: E_{recon} > 0.6 MeV**
- **Energy resolution for full peak**
  - **~4.8% at 1 MeV**

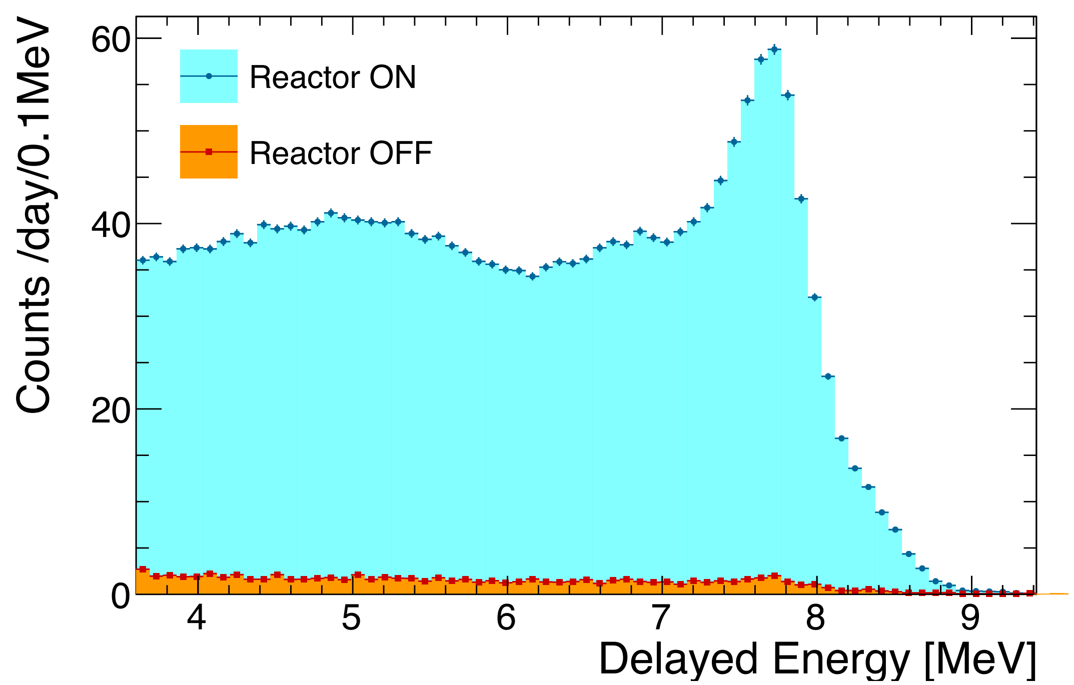


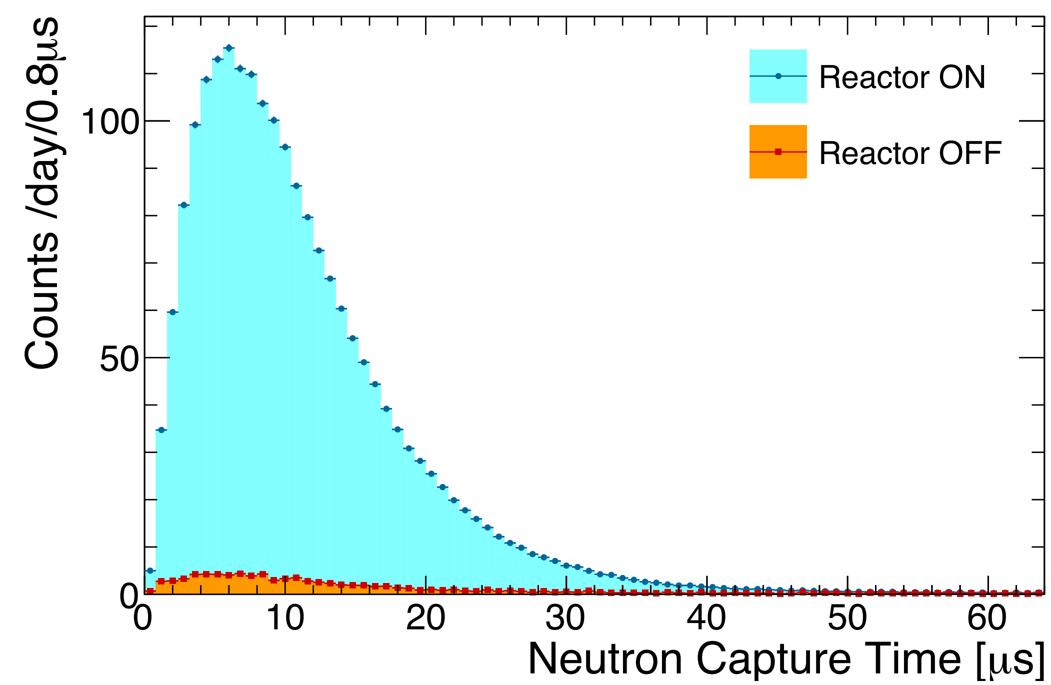


IBD Criteria - Events Selection

- **Criteria for delayed events**
  - **Energy range: 4-10 MeV**
  - **Time coincidence: 1-30 μs**
- **Multiplicity cut: No event before (after) 30 (150) μs from IBD pair**
- **PSD: Use Q_{tail}/Q_{tot} as PSD parameter**
  - **More than 70% of background is reduced via PSD.**
- **Muon veto window: 150 μs**

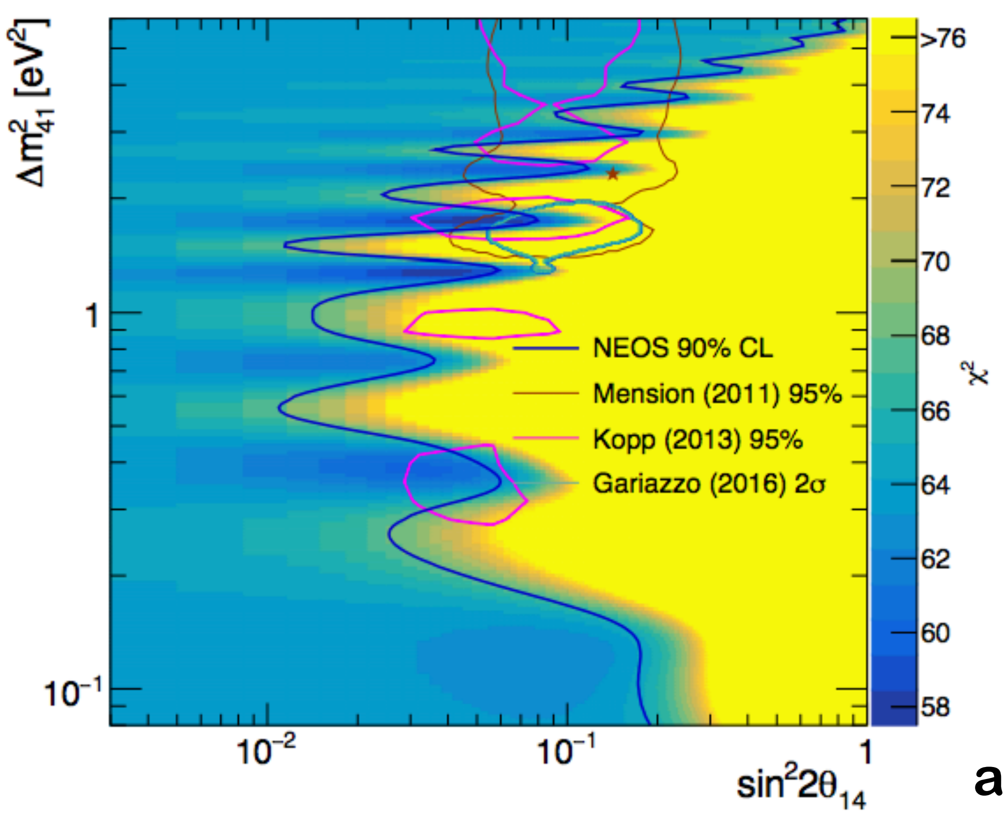


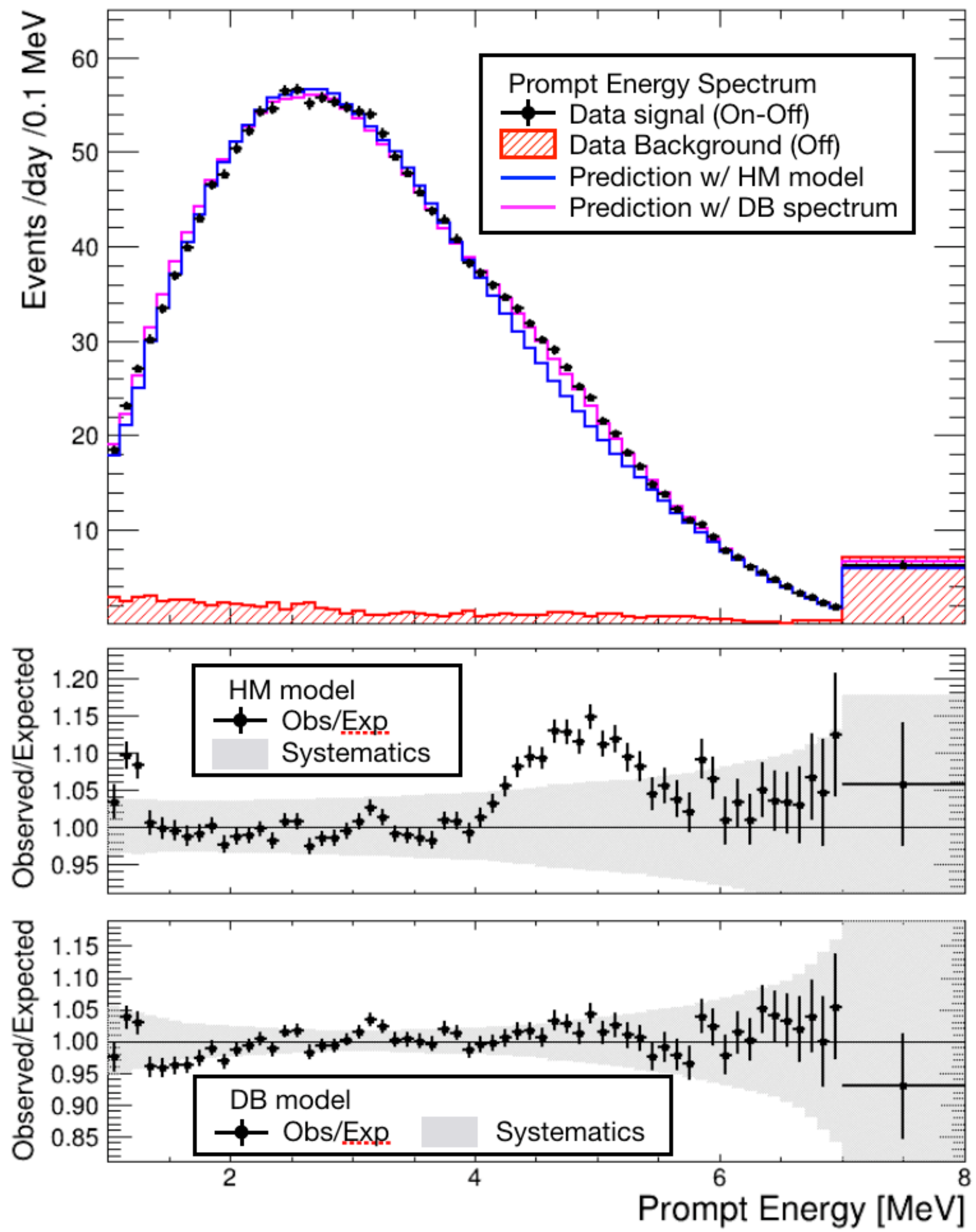




Spectrum and Limits

- **Prompt energy spectrum**
  - **Number of IBD candidates in reactor-on period = 1977 /day**
  - **Signal to background ratio = ~22**
- **Exclusion limit curve**
  - **There is no strong evidence of light sterile neutrino with 3+1 hypothesis.**





arXiv: 1610.05134 / PRL 118, 121802 (2017)

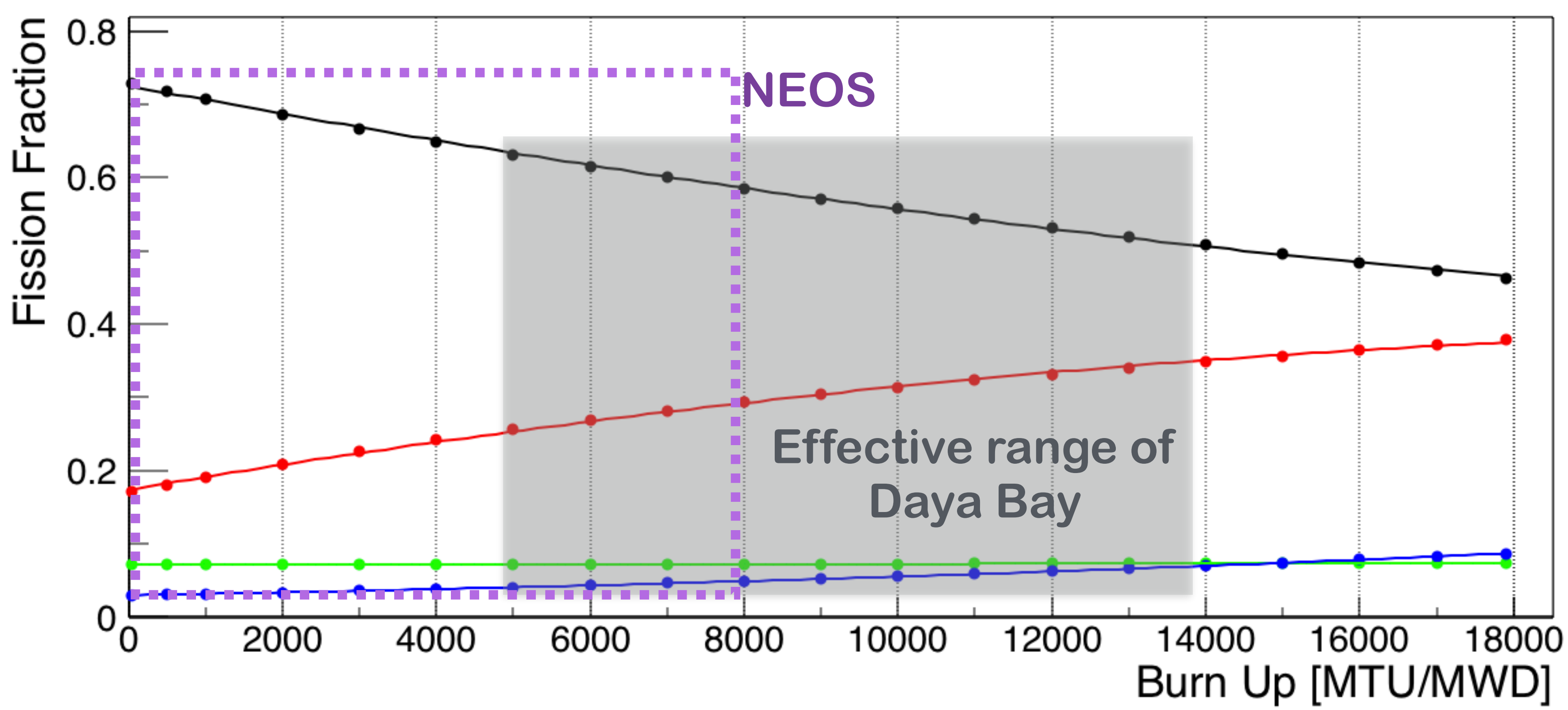
Summary

- **Data was taken for eight months, and data taking is over due to maintenance of the tendon gallery.**
- **Detector performance is pretty good.**
  - **Energy resolution is 4.8% at 1 MeV.**
  - **PSD reduces more than 70% of background**
  - **Signal to background ratio is 22.**
- **There is no strong evidence of light sterile neutrino.**
  - **Exclusion limit curve**

And …

Plan of NEOS Phase-2

- **The measurement is planned to resume, and data will be taken at least one full cycle of 500 days.**
  - **Reactor neutrino spectrum**
  - **Flux evolution in fission fraction**
    ⇨ **Similar uncertainty with Daya Bay thanks to larger changes in fission fraction**
- **Background will be measured in both overhaul periods before and after the full cycle.**



Backup

Neutrino Anomalies and 3+1 Framework

- **LSND and MiniBooNE**
  - Electron anti-neutrino appearance experiment
    ⇨ There are excess of neutrino appearance.
- **GALLEX and SAGE (gallium anomaly)**
  - For calibration, electron anti-neutrino disappearance is measured.
    ⇨ There are deficit of survived neutrinos.
- **Reactor antineutrino anomaly (RAA)**
  - Re-analysis with past short baseline reactor experiments
  - Predicted number of electron anti-neutrinos from reactor is increased due to update of flux. ⇨ Measured to predicted ratio = 0.94 ± 0.02.
- **3+1 framework**
  - three active neutrinos and a sterile neutrino
  - It can explain excess or deficit of anomalies.
- **According to analysis of the anomalies in the 3 + 1 framework, Δm_{41}^2 is expected to be large (~ eV^2 scale).**

Reactor Anti-neutrino Measurement

- **Neutrino energy spectrum at detector**

$$S(E_{\bar{\nu}_e}) = \sigma_{\text{IBD}}(E_{\bar{\nu}_e}) \sum_k f_k \Phi_k(E_{\bar{\nu}_e})$$

IBD cross section
calculated by P. Vogel (thin line)

Fission fraction of isotopes

Neutrino flux from reactor
P. Huber and Th. A. Mueller's model (HM model, color lines)

- **Predicted number of IBD in energy bin i**

$$N_i^{\text{predicted}}(L) = \frac{N_p \epsilon_i}{4\pi L^2} \frac{P_{\text{th}}}{\sum_k f_k E_k} \int_i S(E_{\nu_e}) P(E_{\nu_e}, L) \, dE_{\nu_e}$$

Detector part — **Number of fissions** — **Survival probability**

- **Survival probability of electron antineutrino in leading order**

$$P_{\bar{\nu}_e \to \bar{\nu}_e}(E_\nu,\ L;\ \theta_{1j},\ \Delta m_{j1}) = 1 - \sin^2 2\theta_{1j}\ \sin^2\left(1.27 \frac{\Delta m_{j1}^2 L}{E_\nu}\right)$$

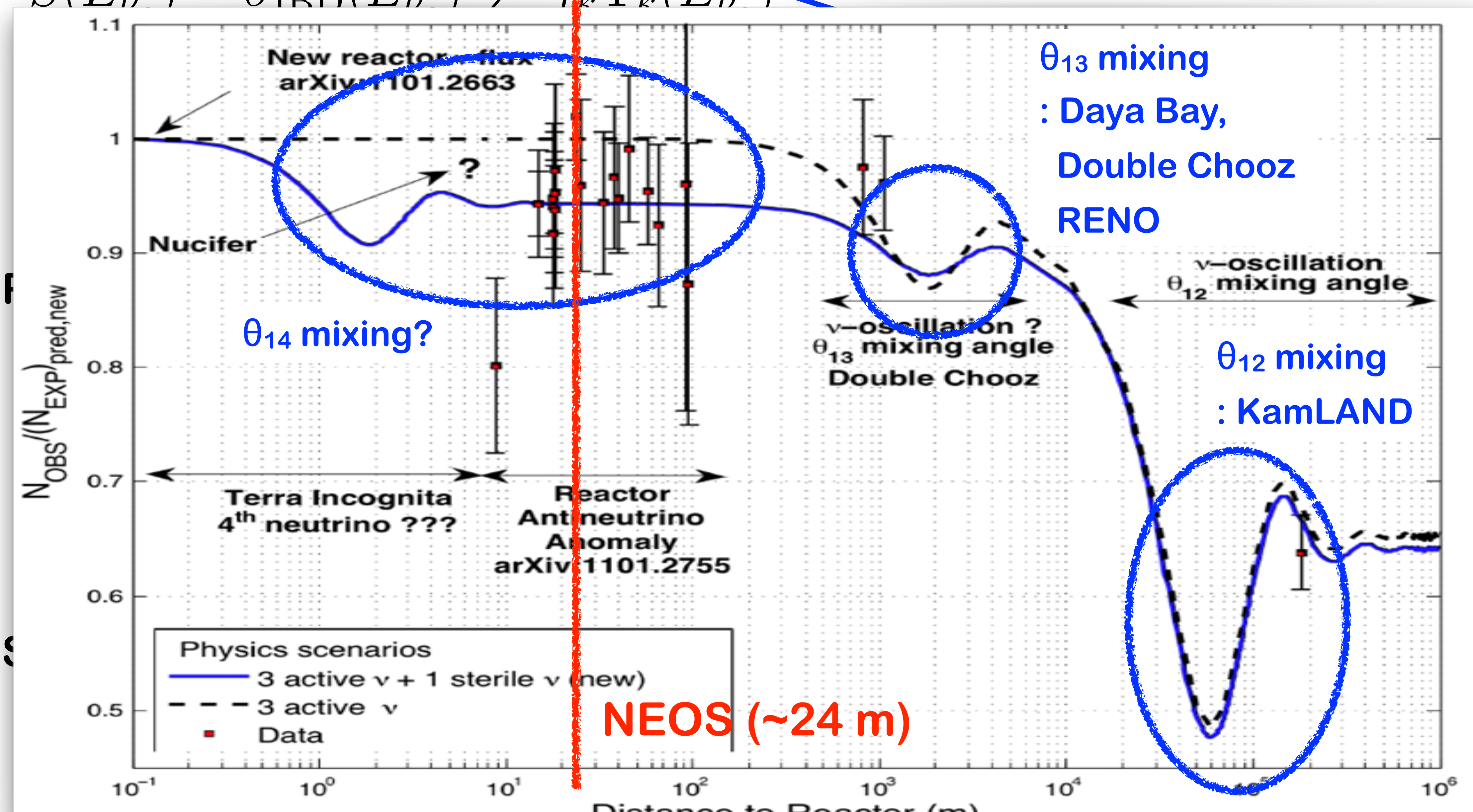
Reactor Anti-neutrino Measurement

- **Neutrino energy spectrum at detector**

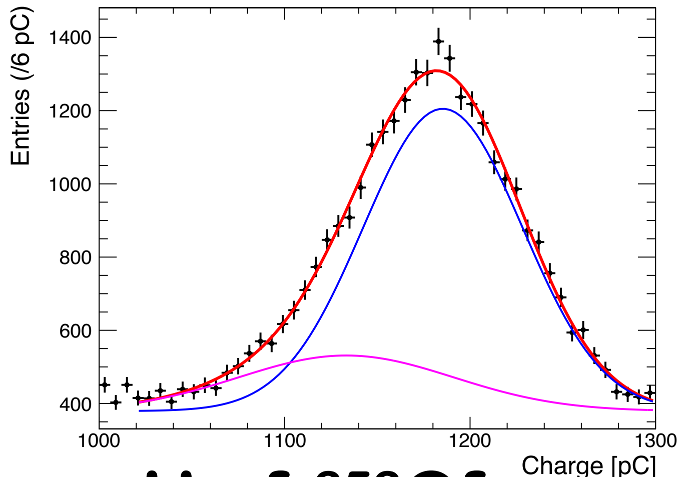
$$S(E_{\bar{\nu}}) = \sigma_{\mathrm{IBD}}(E_{\bar{\nu}}) \sum f_k \Phi_k(E_{\bar{\nu}})$$

del

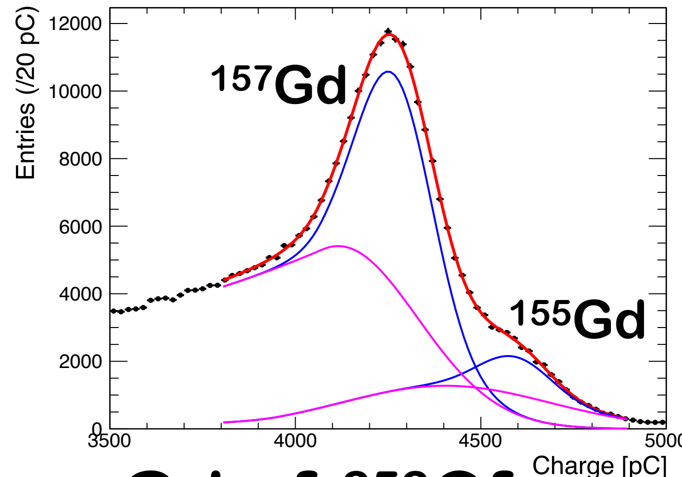
- F
- S



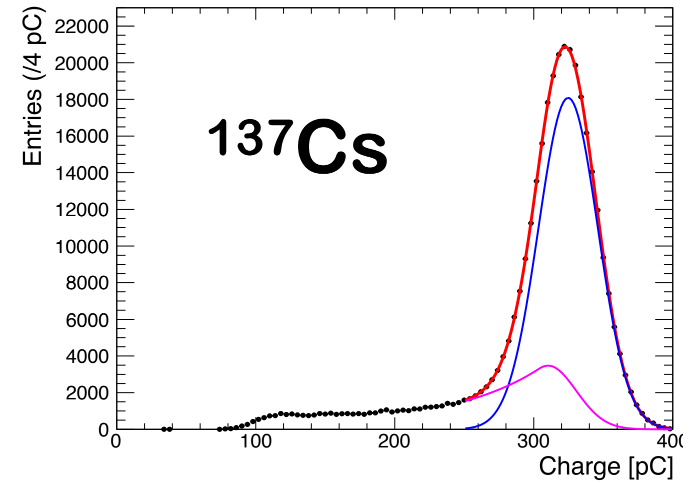
Calibration w/ Point Source

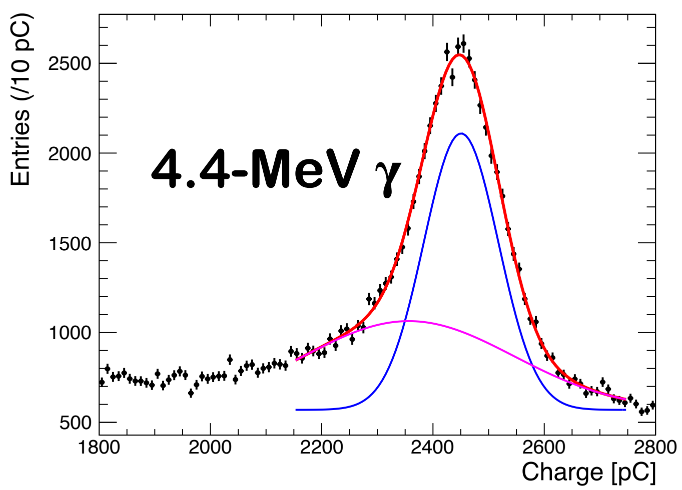


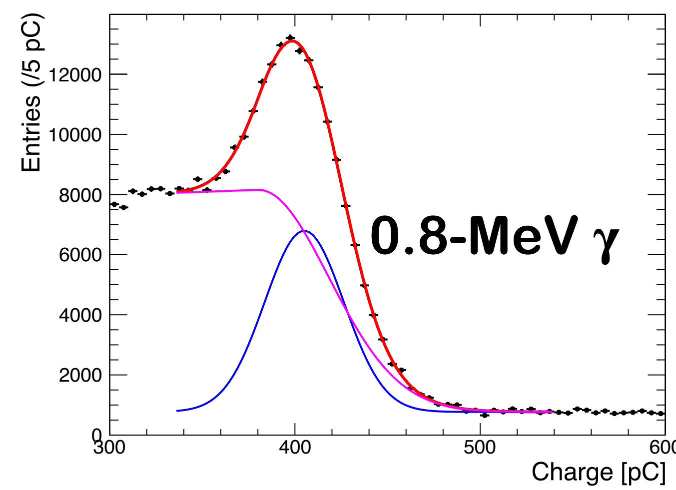
n-H of ^{252}Cf

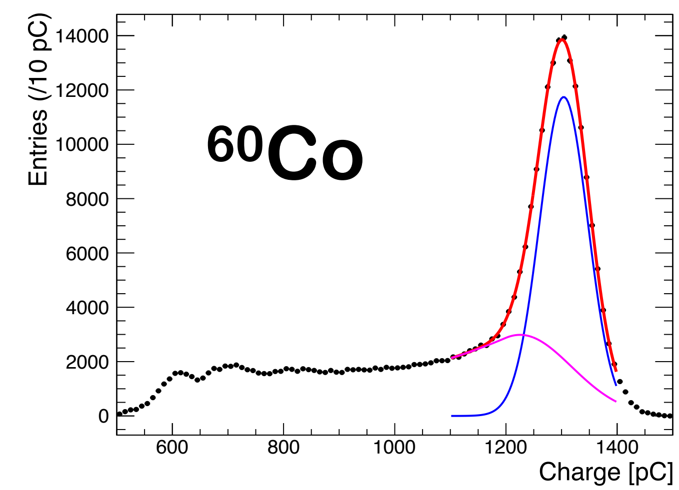


n-Gd of ^{252}Cf









Po-Be

Response and Corrections

Vertex dependency

- Charge sum of event occurring near PMTs has a larger value than that of center.

Charge asymmetry A_z

- A_z is defined for vertex correction.

$$A_z \equiv \frac{Q^{\text{un}}_{\text{sum,R}} - Q^{\text{un}}_{\text{sum,L}}}{Q^{\text{un}}_{\text{sum,R}} + Q^{\text{un}}_{\text{sum,L}}}$$

Fitting function and correction function

- fitting function: 4th order polynomial

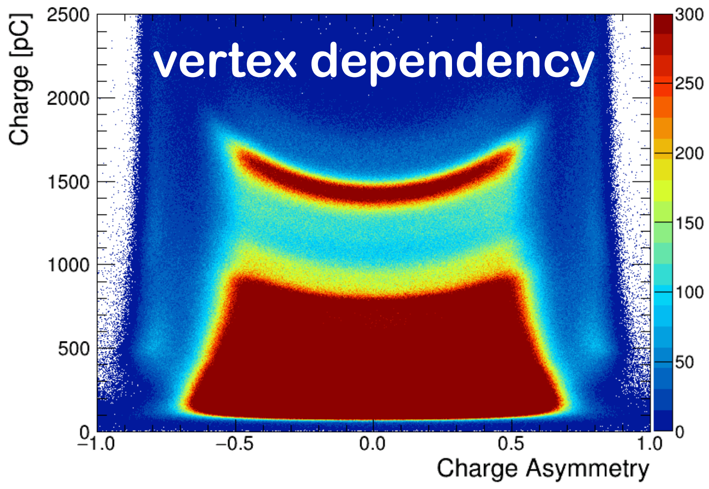
$$f_{\text{asym}}(A_z) = \sum_{i=0}^{4} p_i A_z^i$$

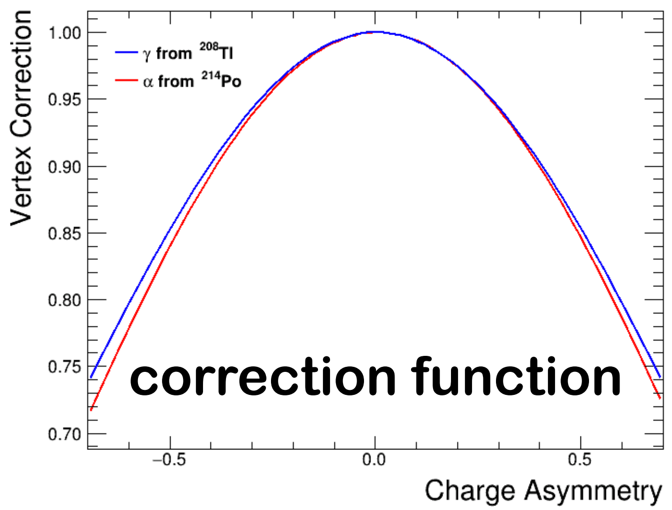
- correction function

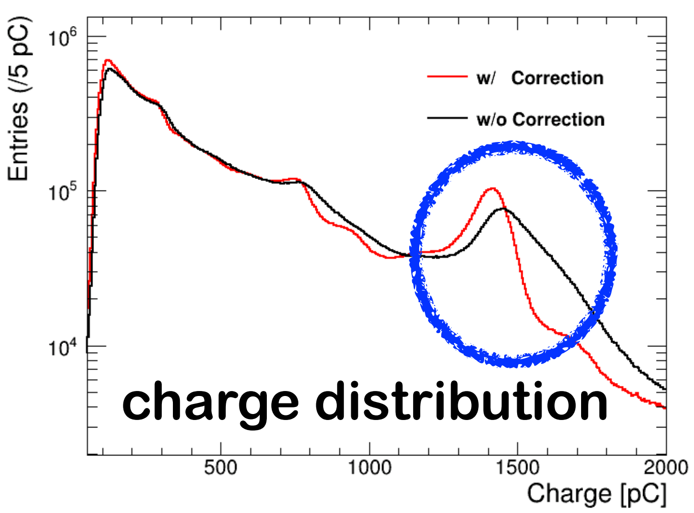
$$c_{\text{vertex}}(A_z) = \frac{f_{\text{asym}}(0)}{f_{\text{asym}}(A_z)}$$

Corrected charge sum

$$Q_{\text{sum}}(t_{\text{trg}}) = c_{\text{vertex}}(A_z) \cdot Q^{\text{un}}_{\text{sum}}(t_{arg})$$





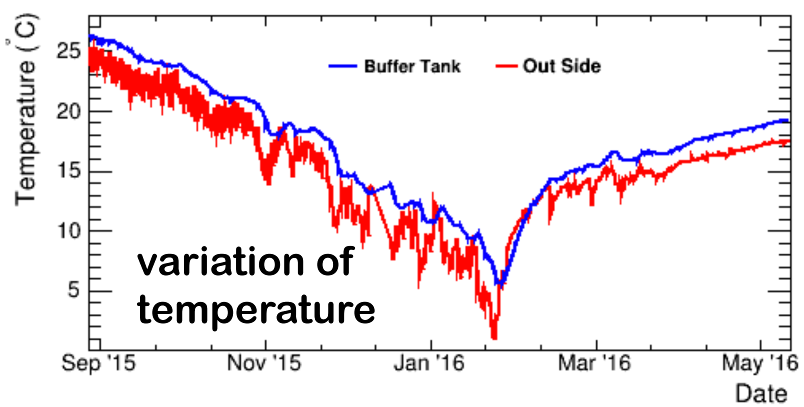


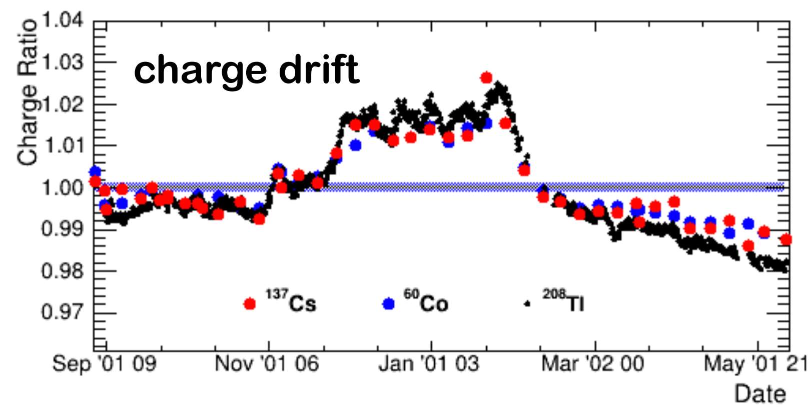
Response and Corrections

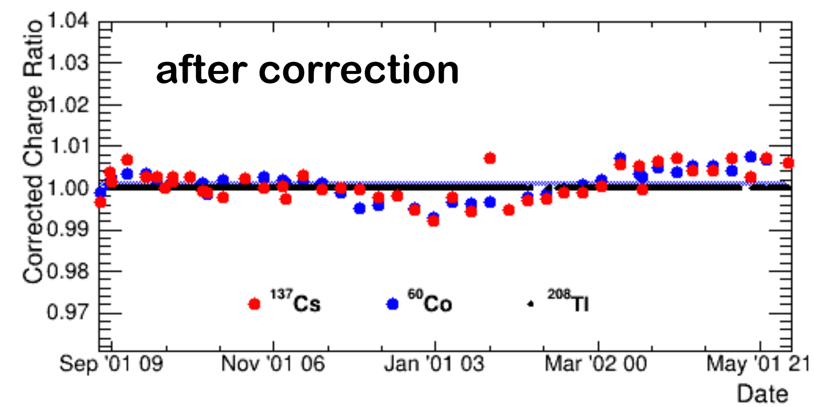
Correction for charge drift

- There are charge drift due to variation of temperature.

  ⇨ It can be corrected with gamma from ^{208}Tl







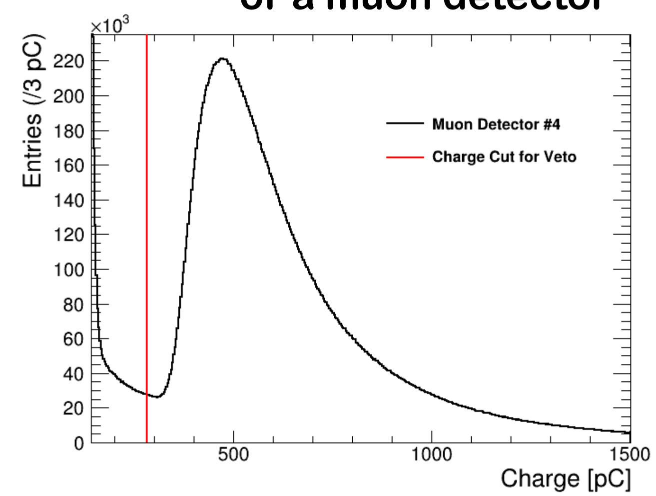
Muon event selection for veto

- If it is judged that it is a muon event, all the events for a certain time are vetoed

Muon cuts

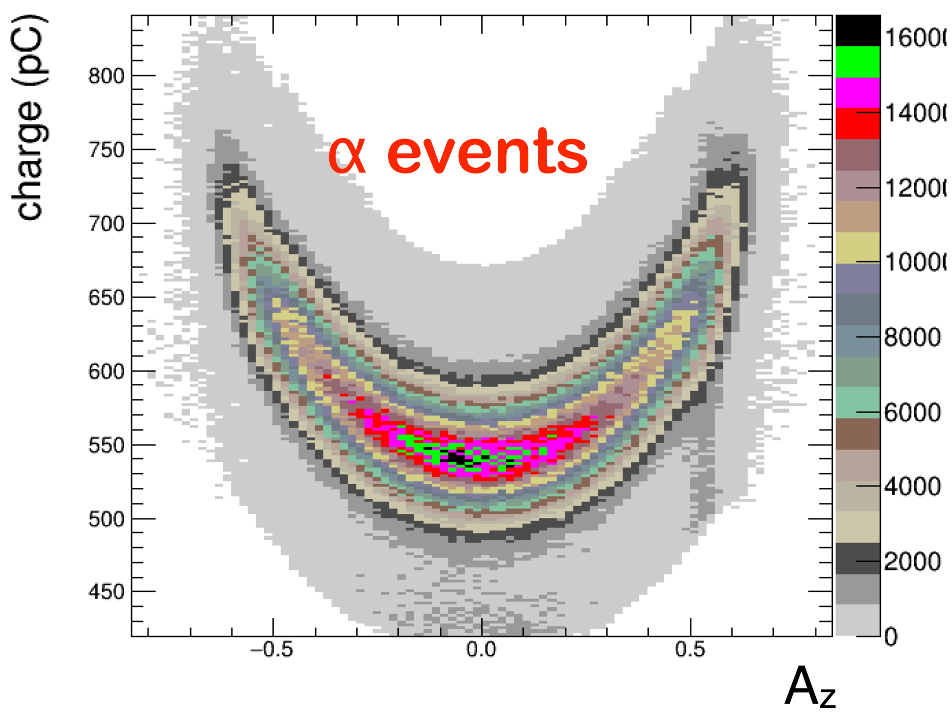
detector #	cut (pC)	detector #	cut (pC)	detector #	cut (pC)
1	297	6	281	11	453
2	297	7	297	12	453
3	297	8	297	13	453
4	281	9	297	14	453
5	266	10	453	15	453

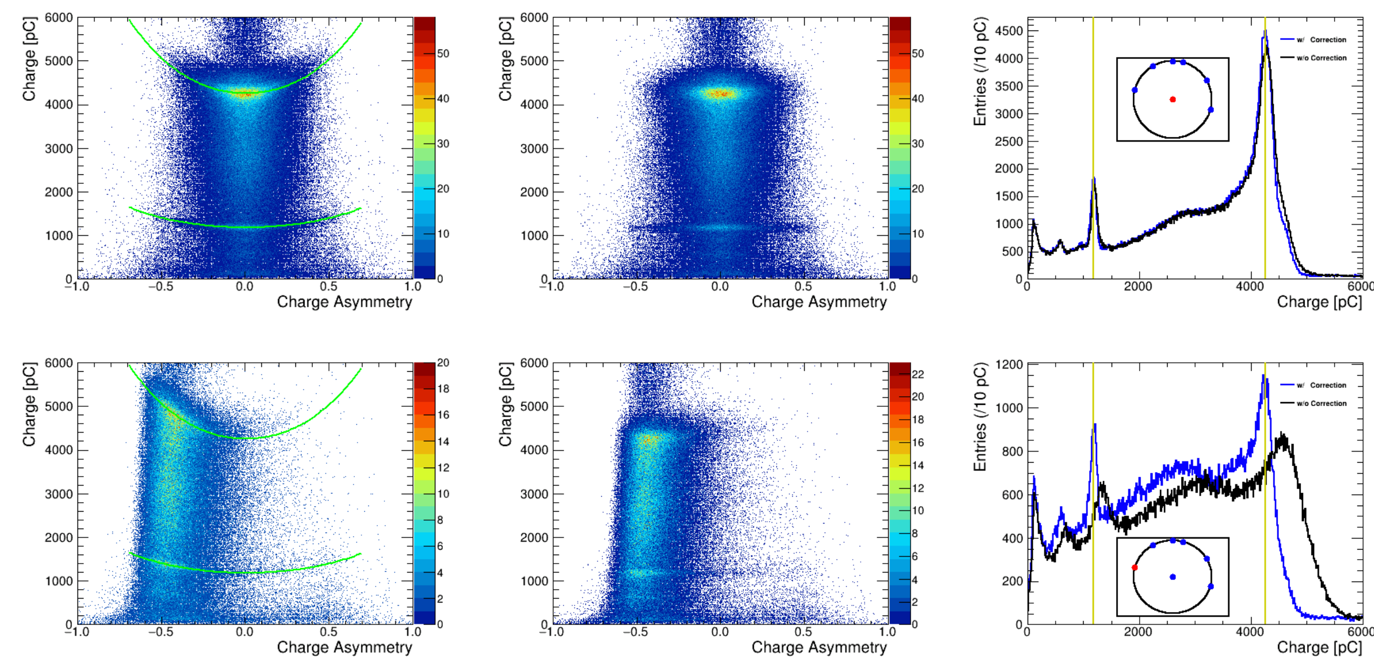
charge distribution of a muon detector

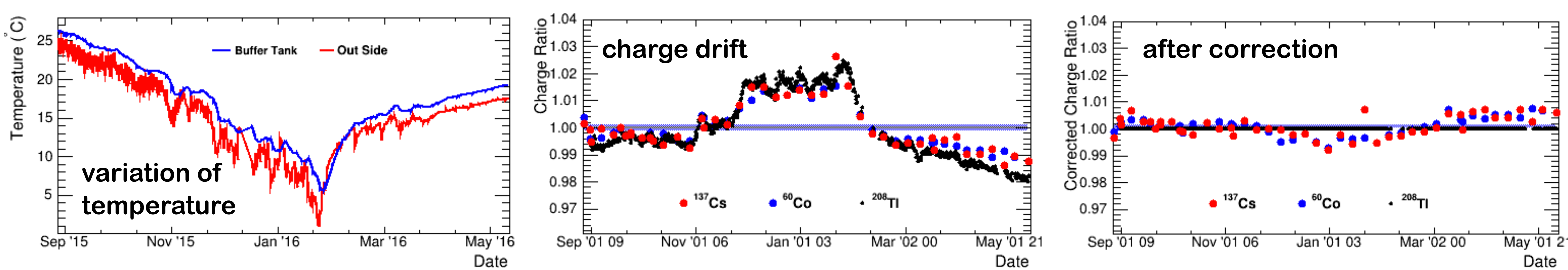


Response and Corrections

- **Non-uniform response**
  - **α events from radon in LS are used for correction**
- **Charge drift in time is corrected with γ events from ^{208}Tl**

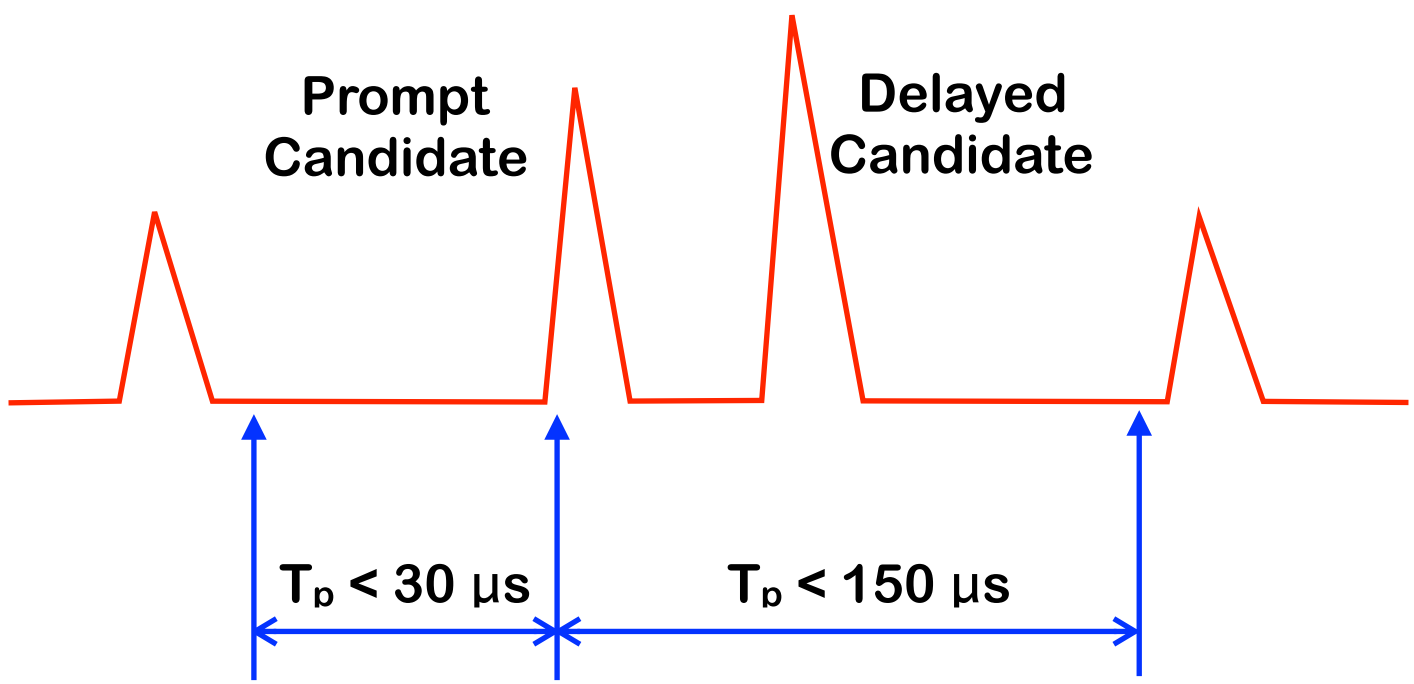






Multiplicity Cut

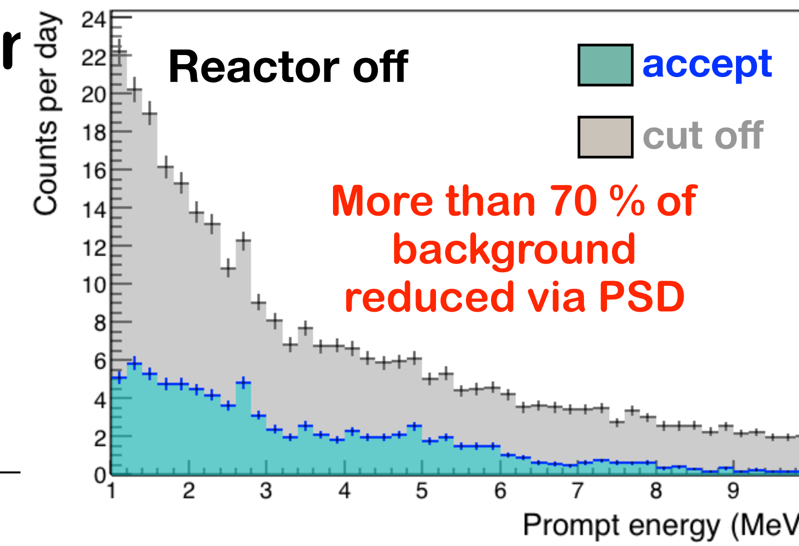
- **Multiplicity cut**
  - **For reducing backgrounds due to multiple neutrons**
  - **No event in time window, [T_p - 30 μs, T_p + 150 μs]**

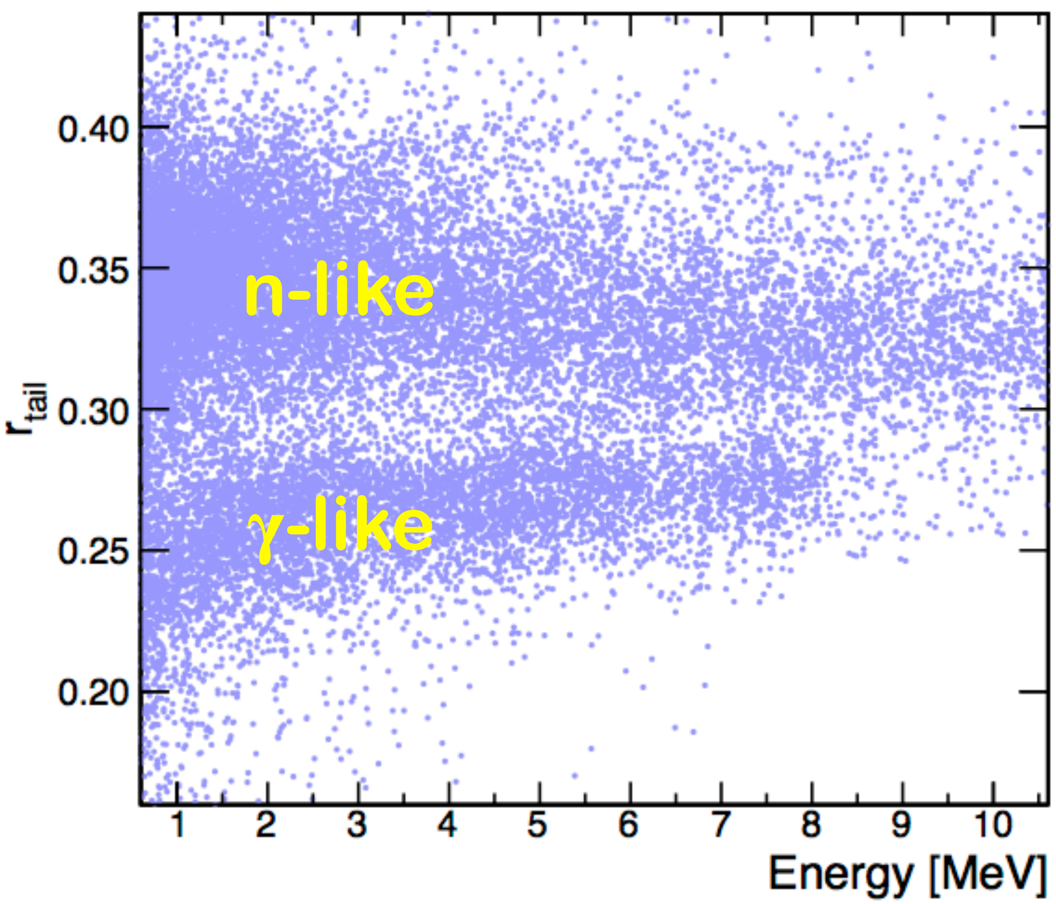


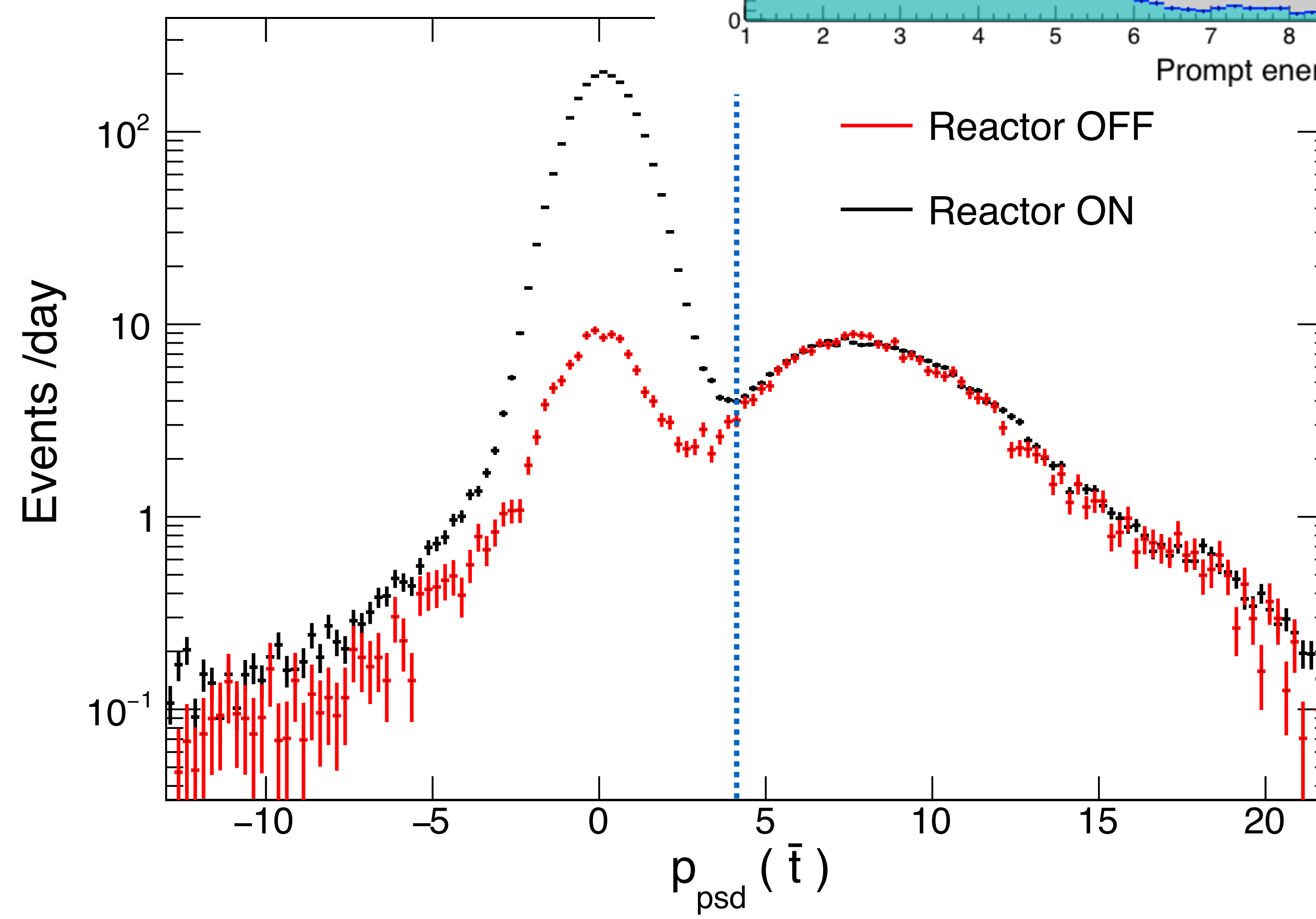
T_p: prompt event time
T_v: muon event time

Pulse Shape Discrimination

- **Pulse shape discrimination (PSD)**
  - **For reducing backgrounds due to fast neutror**
  - **Accepting 99.9% γ-like events**
  - **More than 70% of background is reduced.**
  - **Mixed LS (LAB + DIN)**

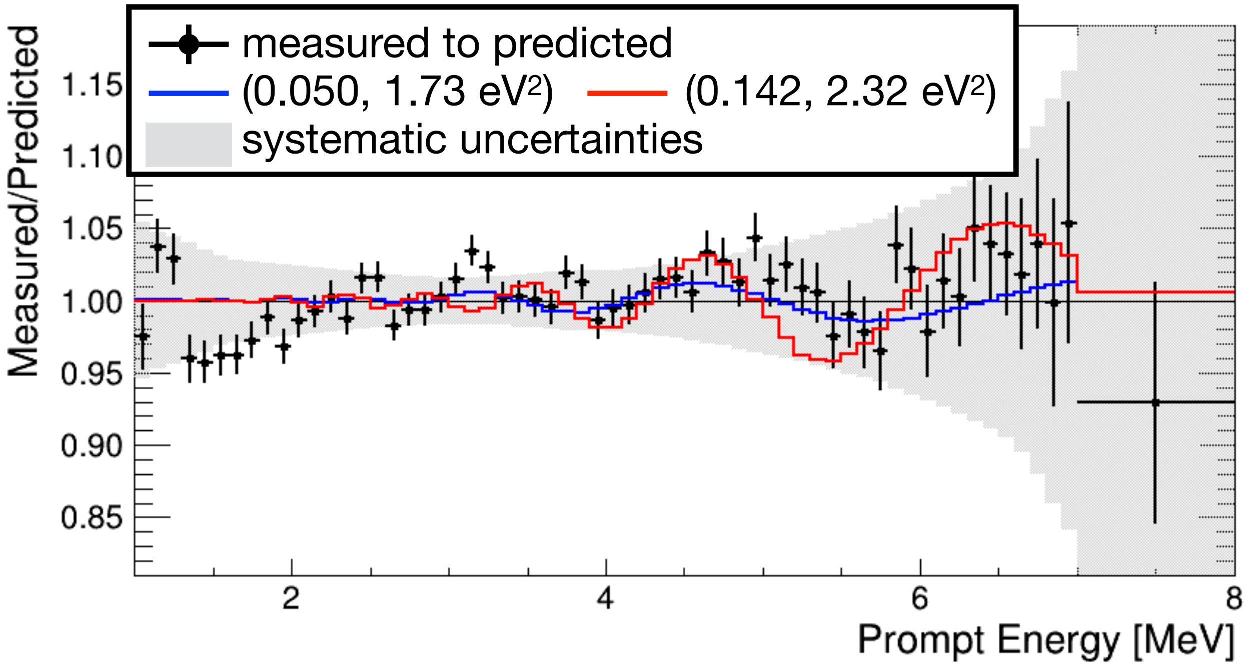






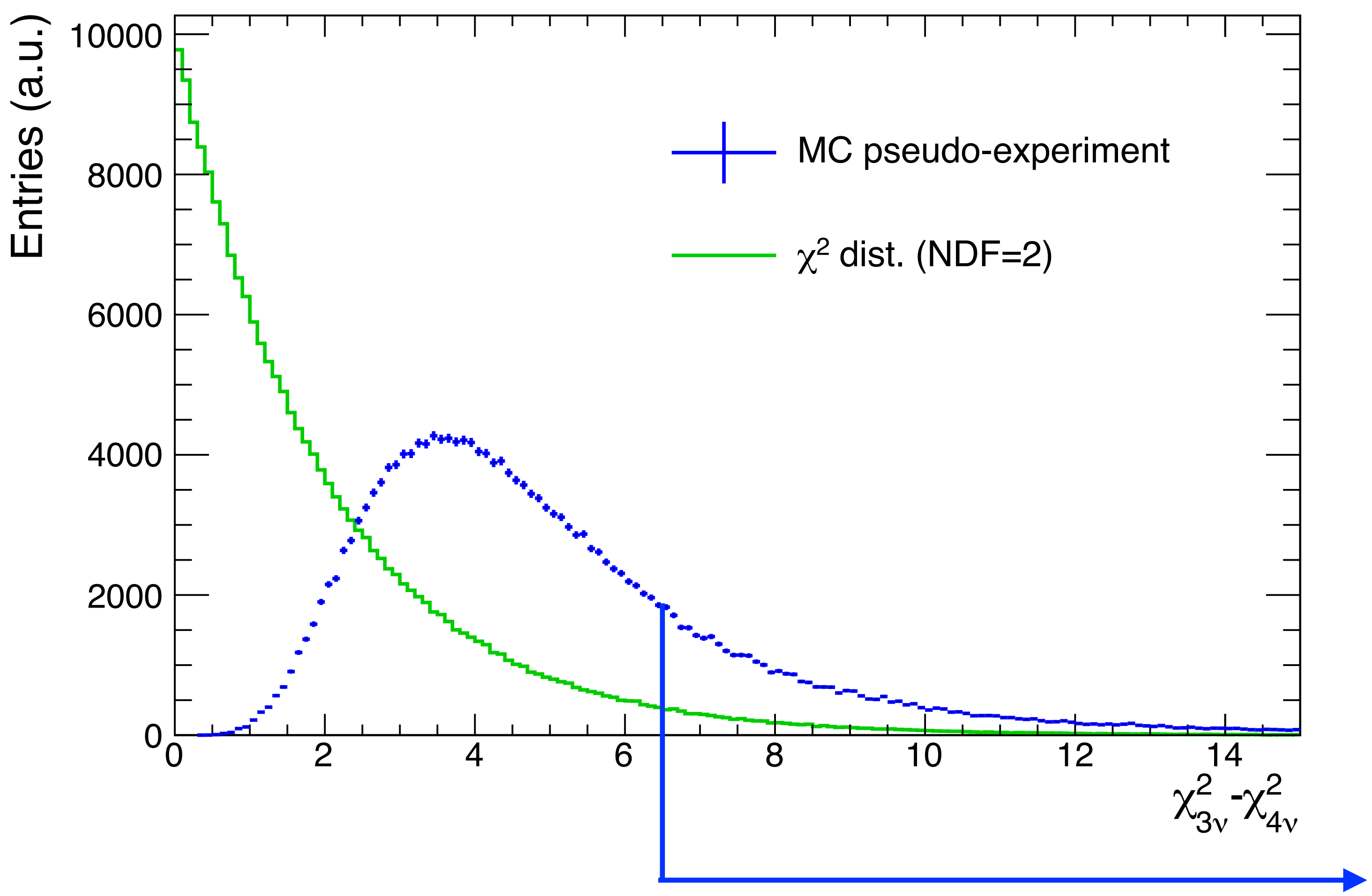
Oscillation Analysis

- Comparison with HM model
  - 5-MeV excess ⇨ Not suitable for oscillation analysis
- Comparison with Daya Bay
  - Different fission fraction ⇨ Correction with HM
  - Generally in an agreement
  - Oscillation analysis with spectral shape only
    ⇨ high dependence on reference spectrum
- χ^2 minimum (best fit) with 3+1ν hypothesis
  - $\chi^2_{4\nu}$/NDF = 57.5/59 at ($\sin^2 2\theta_{14}$, Δm_{41}^2) = (0.05, 1.73 eV^2)
- χ^2 with 3ν hypothesis
  - $\chi^2_{3\nu}$/NDF = 64.0/61
  - $\Delta\chi^2 = \chi^2_{3\nu} - \chi^2_{4\nu} = 6.5$



Significance Test

- **Significance test**
  - **0.3M sets of pseudo-experiments for significance test**
  - **There is no strong evidence of light sterile neutrino with 3+1 hypothesis.**



$\Delta\chi^2$ = 6.5 from data
⇨ p-value ~ 22% with $\Delta\chi^2$ distribution by MC

Flux Evolution in Fission Fraction