Sterile Neutrino Search at the NEOS Experiment

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NEOS Collaboration

September 26, 2017
NUFACT 2017 @ Uppsala University

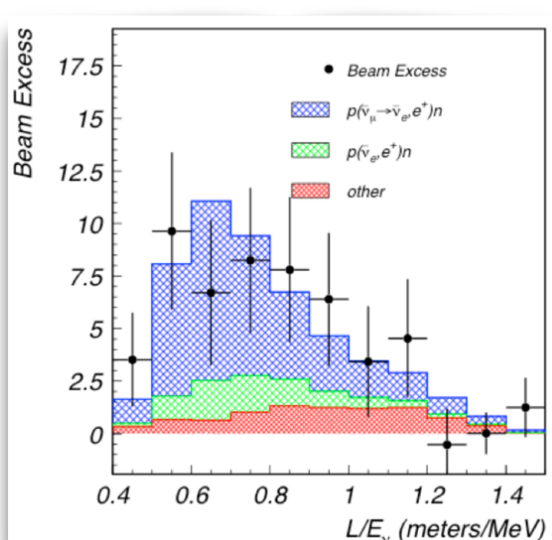
Contents

NEOS Collaboration

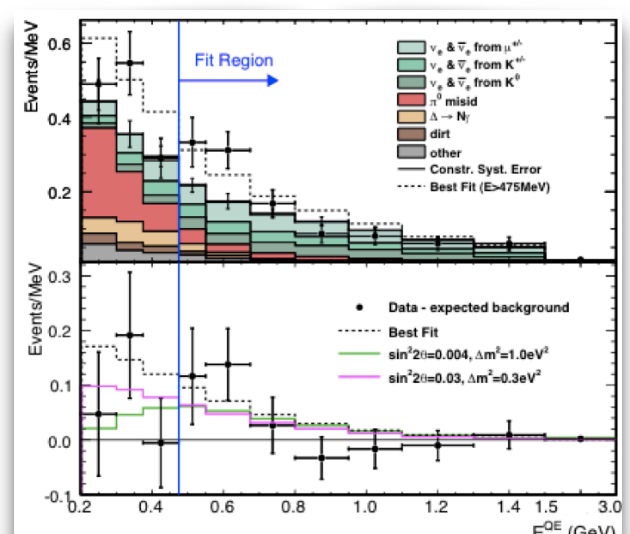
- **NEOS: Neutrino Experiment for Oscillation at Short baseline**
- **NEOS Collaboration: 19 collaborators at 6 institutes**
  - **Chung-Ang University**
  - **Institute for Basic Science**
  - **Jeonnam National University**
  - **Korea Atomic Energy Research Institute**
  - **Kyungpook National University**
  - **Sejong University**

Neutrino Anomalies and 3+1 Framework

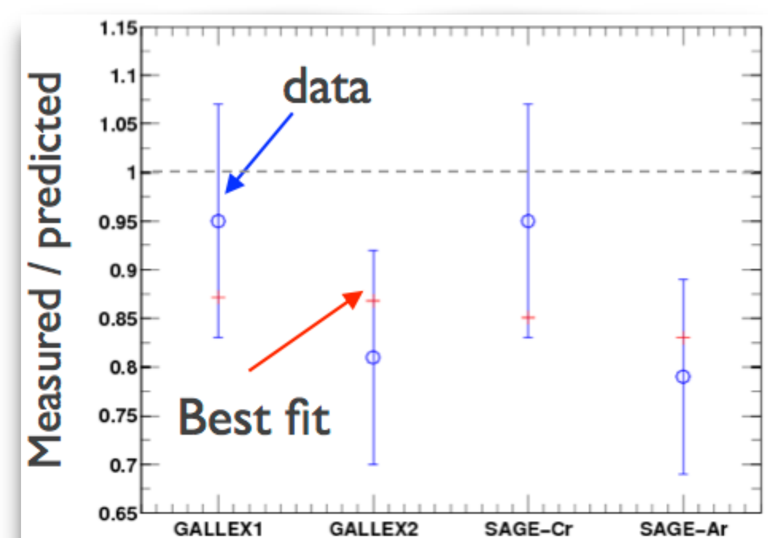
- **LSND and MiniBooNE**
  - **- $\nu_\mu \longrightarrow \nu_e$ appearance experiment**
    - **⇨ There are excess of neutrino appearance.**
- **GALLEX and SAGE (gallium anomaly)**
  - **- For calibration, $\nu_e \longrightarrow \nu_e$ disappearance is measured.**
    - **⇨ There are deficit of survived neutrinos.**



LSND



MiniBooNE

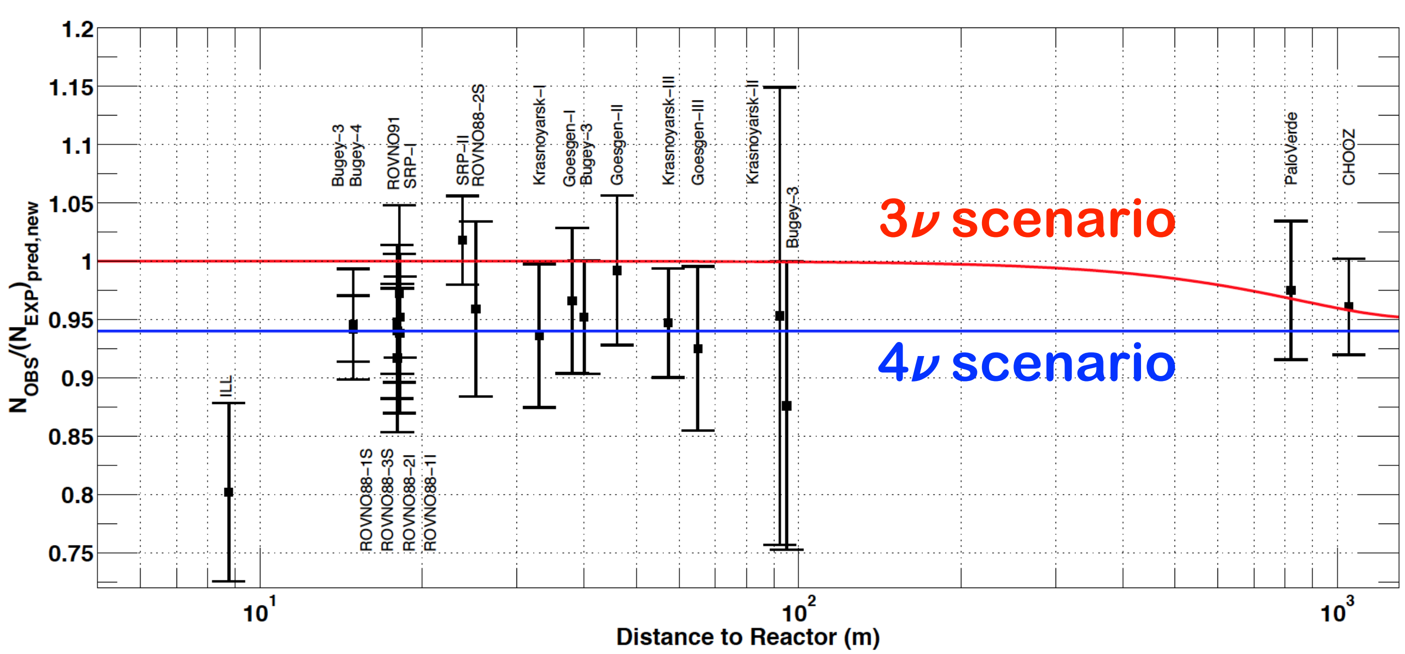


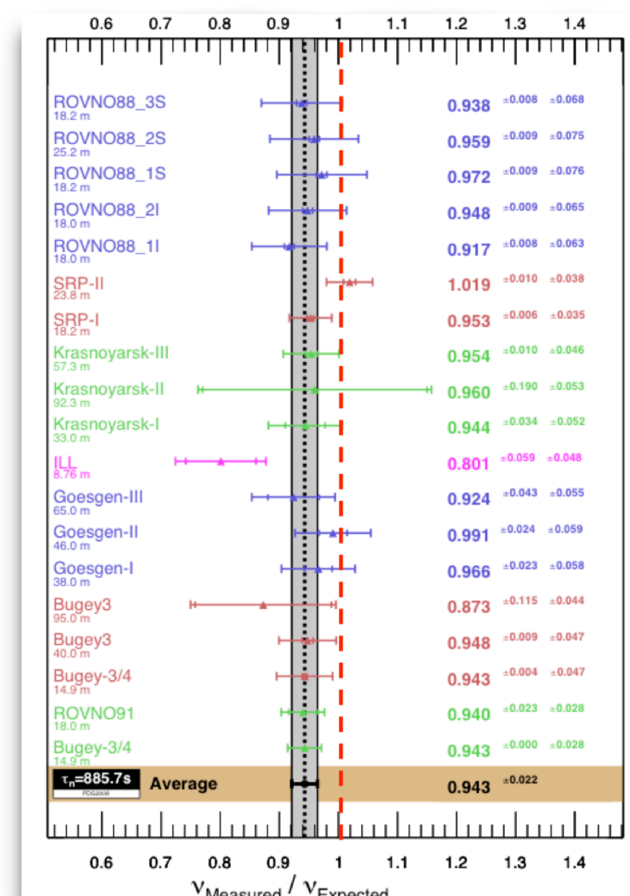
Gallium anomaly

Neutrino Anomalies and 3+1 Framework

- **Reactor antineutrino anomaly (RAA)**
  - **Short baseline reactor experiments ($\nu_e \longrightarrow \nu_e$ disappearance)**
  - **Predicted number is increased due to update of flux.**

  ⇨ **Measured to predicted ratio = 0.94 ± 0.02.**

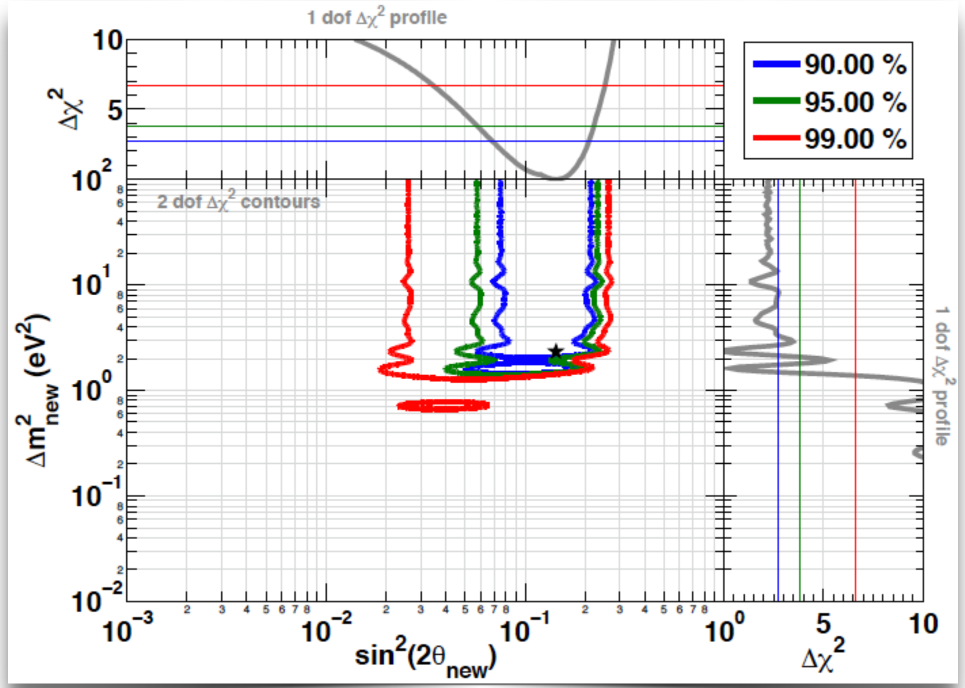




Neutrino Anomalies and 3+1 Framework

- **Anomalies cannot be explained with 3-ν oscillation.**
- **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).**

- **NEOS:**
  - **- Reactor neutrino experiment at short baseline.**
  - **- To search for sterile neutrino in the 3+1 framework**



RAA (combined result)

Reactor Neutrino Experiment

- **Beta decay in the reactor core: neutrino source**

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

- **Inverse beta decay (IBD) in the detector: neutrino detection**

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

- **Neutrino energy spectrum at detector**

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

Neutrino flux from reactor

P. Huber and Th. A. Mueller's model

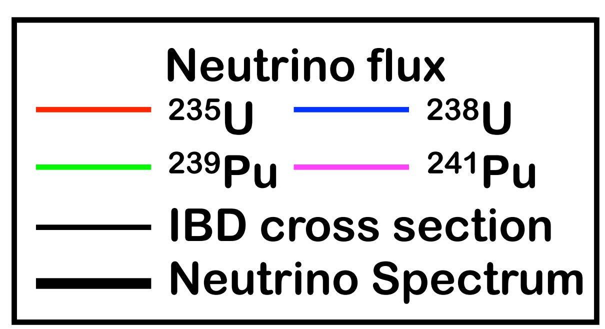
(HM model, color lines)

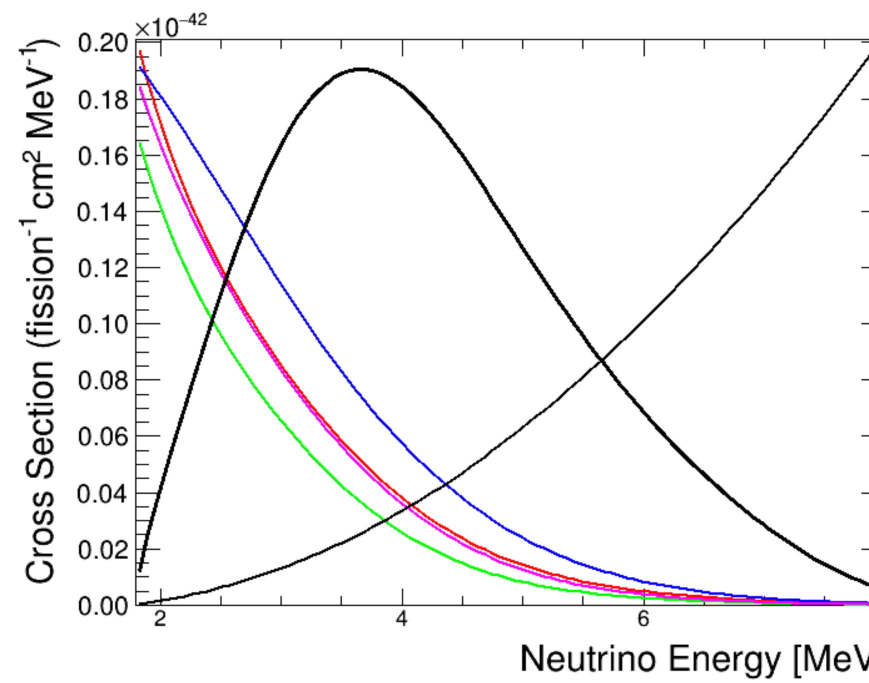
IBD cross section

calculated by P. Vogel (thin line)

Fission fraction

of isotopes



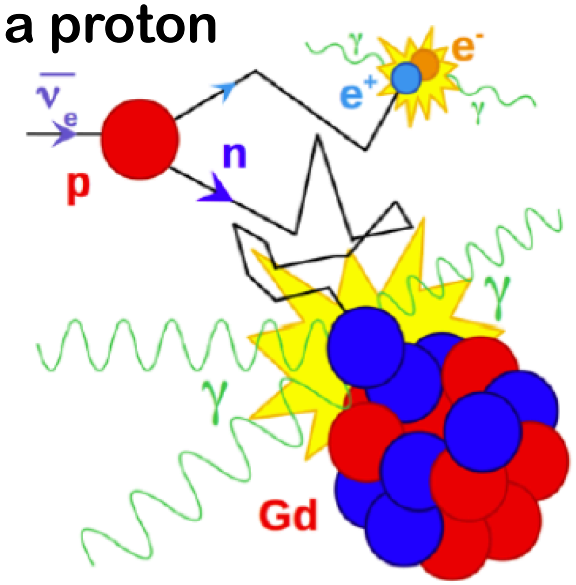


Reactor Neutrino Experiment

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

IBD with a proton

positron signal



neutron capture signal

prompt signal (S1)

e^+ energy deposition + e^+/e^- annihilation

IBD pairing

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

delayed signal (S2)

neutron capture on Gd ($\Sigma E_\gamma \approx 8$ MeV)

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

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

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

Reactor Neutrino Experiment

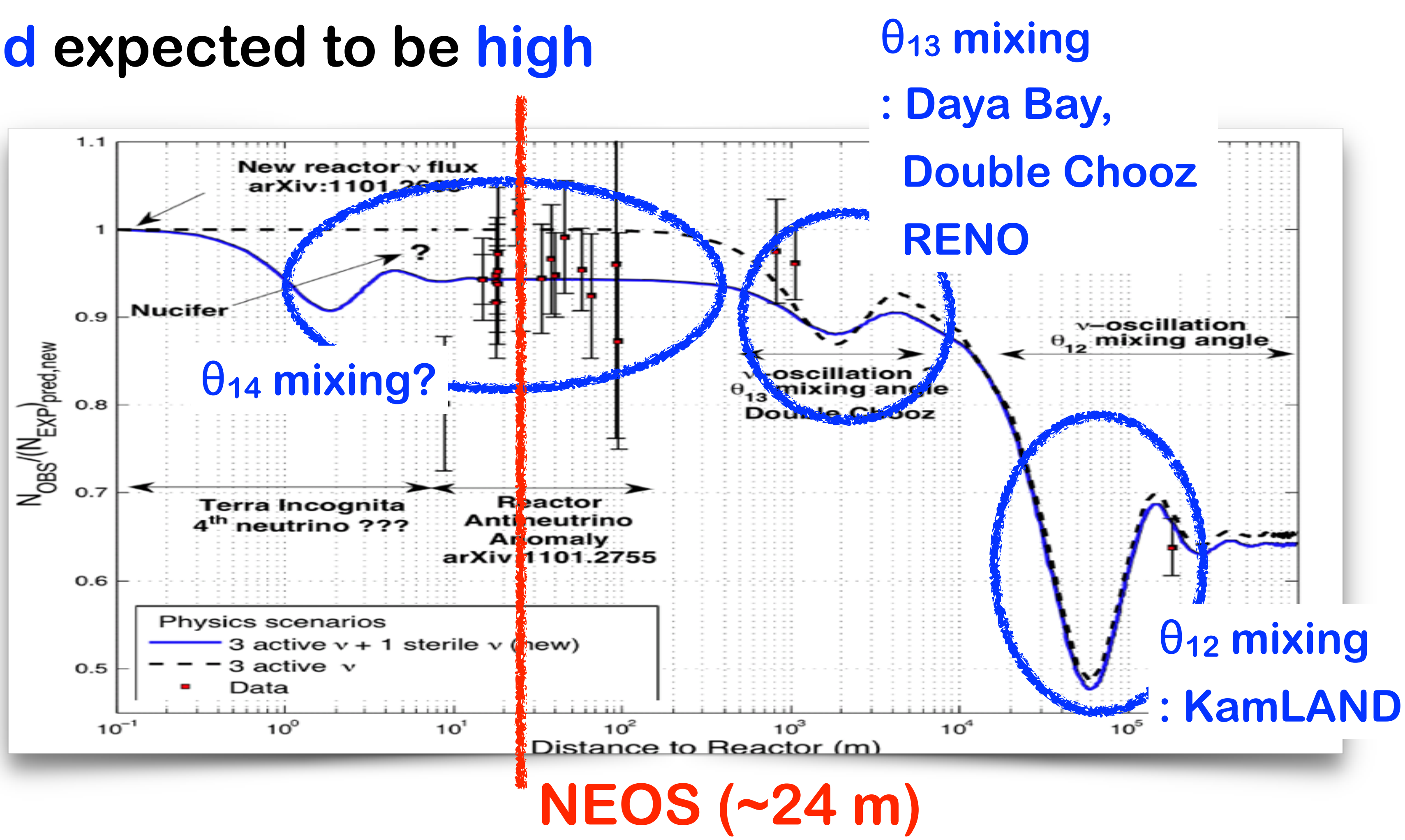
- **Survival probability of electron antineutrino in leading order**

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

- MeV-scale neutrino energy and eV^2-scale Δm_{41}^2

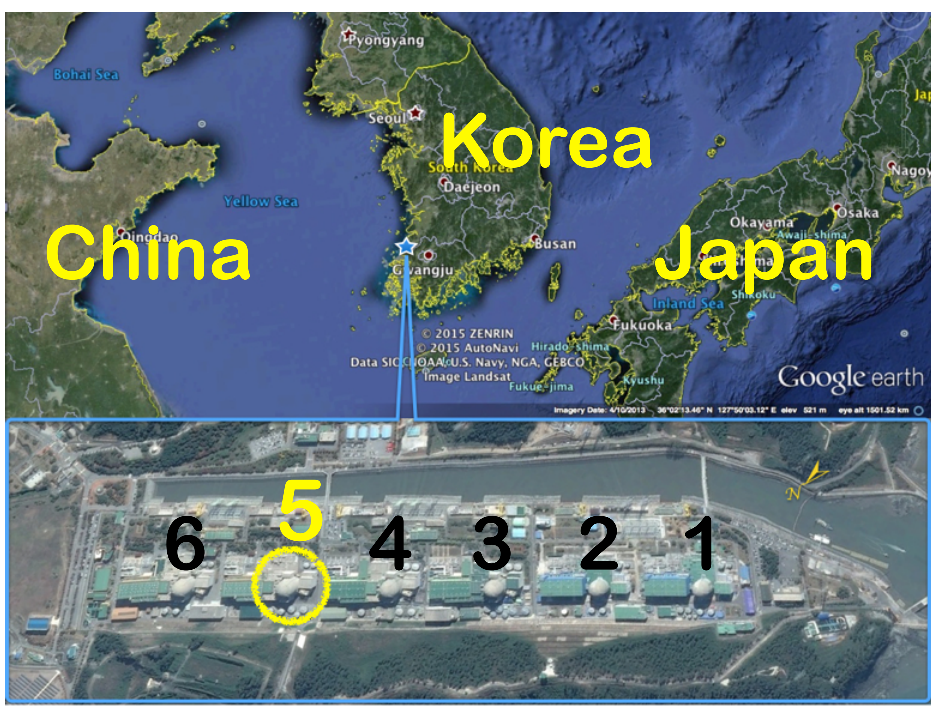
⇨ Short baseline experiment (several to tens meters)

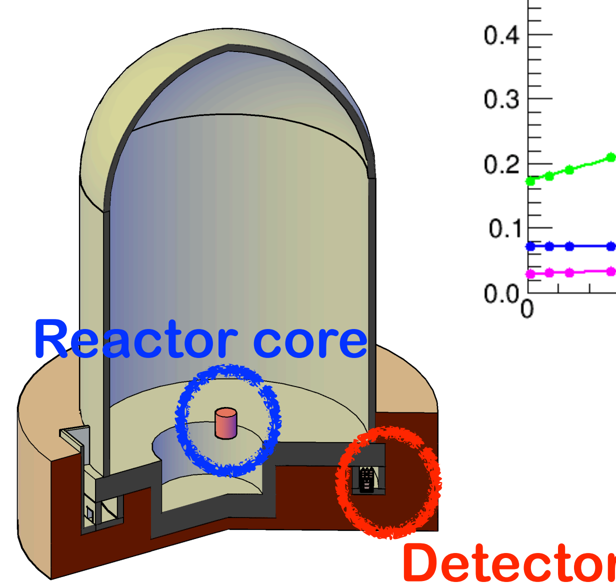
⇨ Background expected to be high

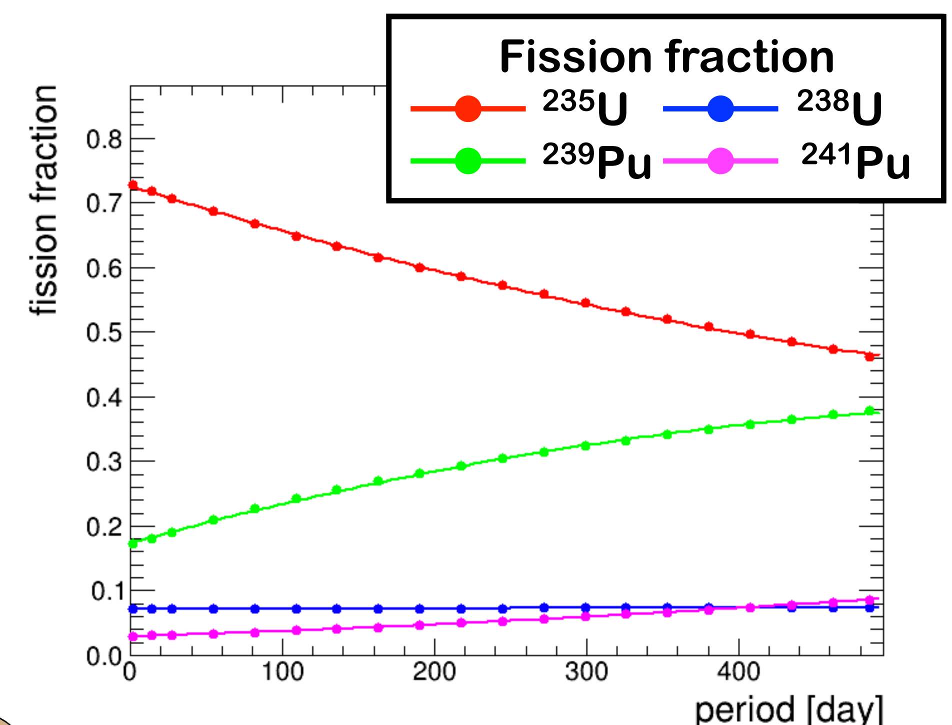


Experimental Site

- **Hanbit Nuclear Power Plant (NPP) in 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)**
  - **Refuel: change 1/3 of fuel rods for each burn-up cycle**

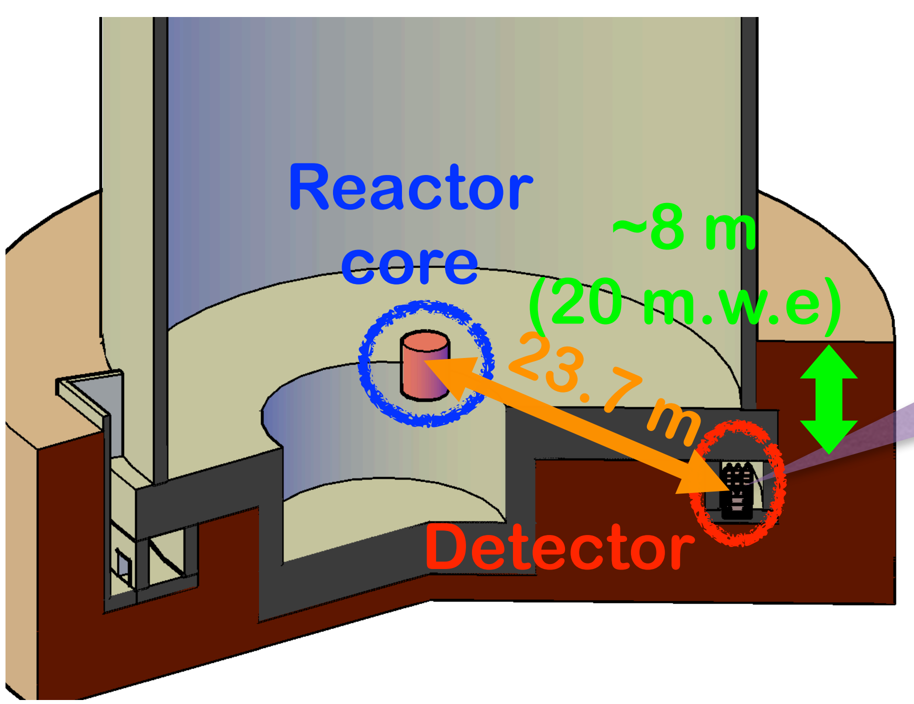


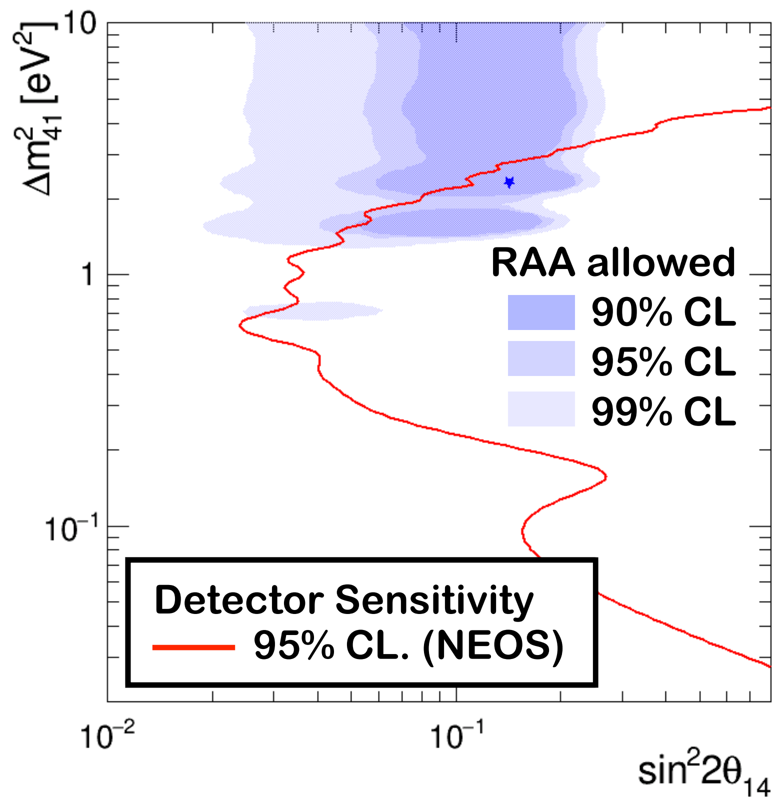




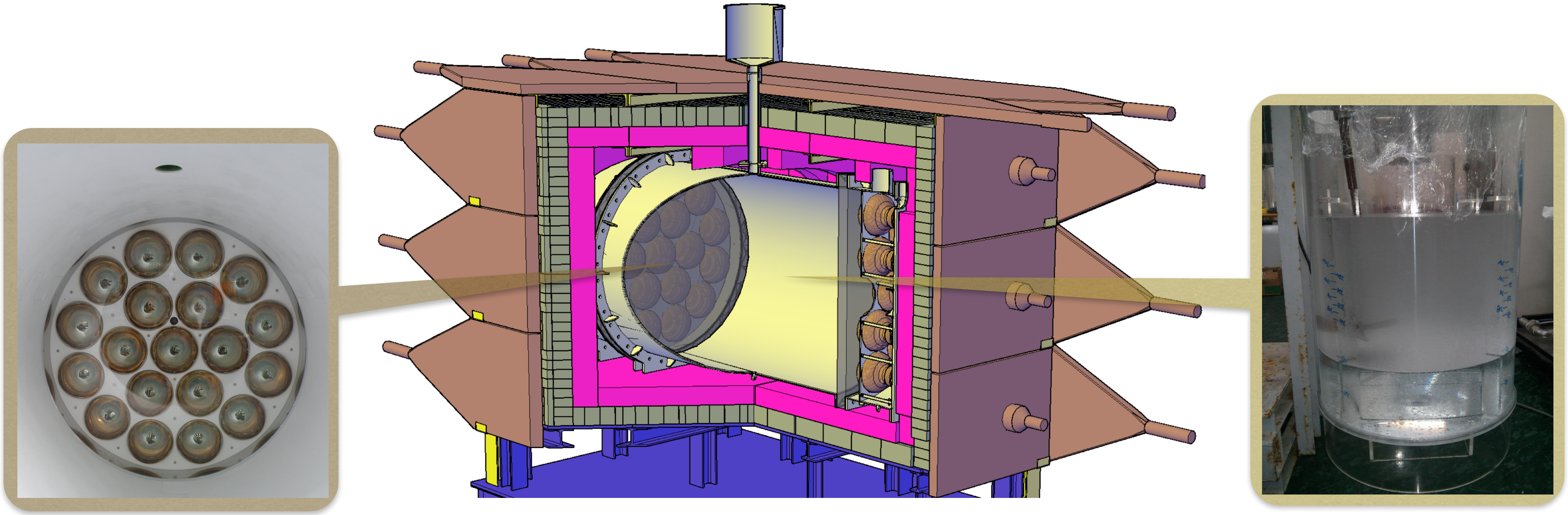
Experimental Site

- **Detector in tendon gallery of Reactor Unit 5**
  - **23.7-m baseline and 20-m.w.e overburden**
- **Detector sensitivity**
  - **Most sensitive range for ~eV sterile neutrinos**
- **Single detector**
  - **Understanding detector response**
  - **Reference model**





NEOS Detector

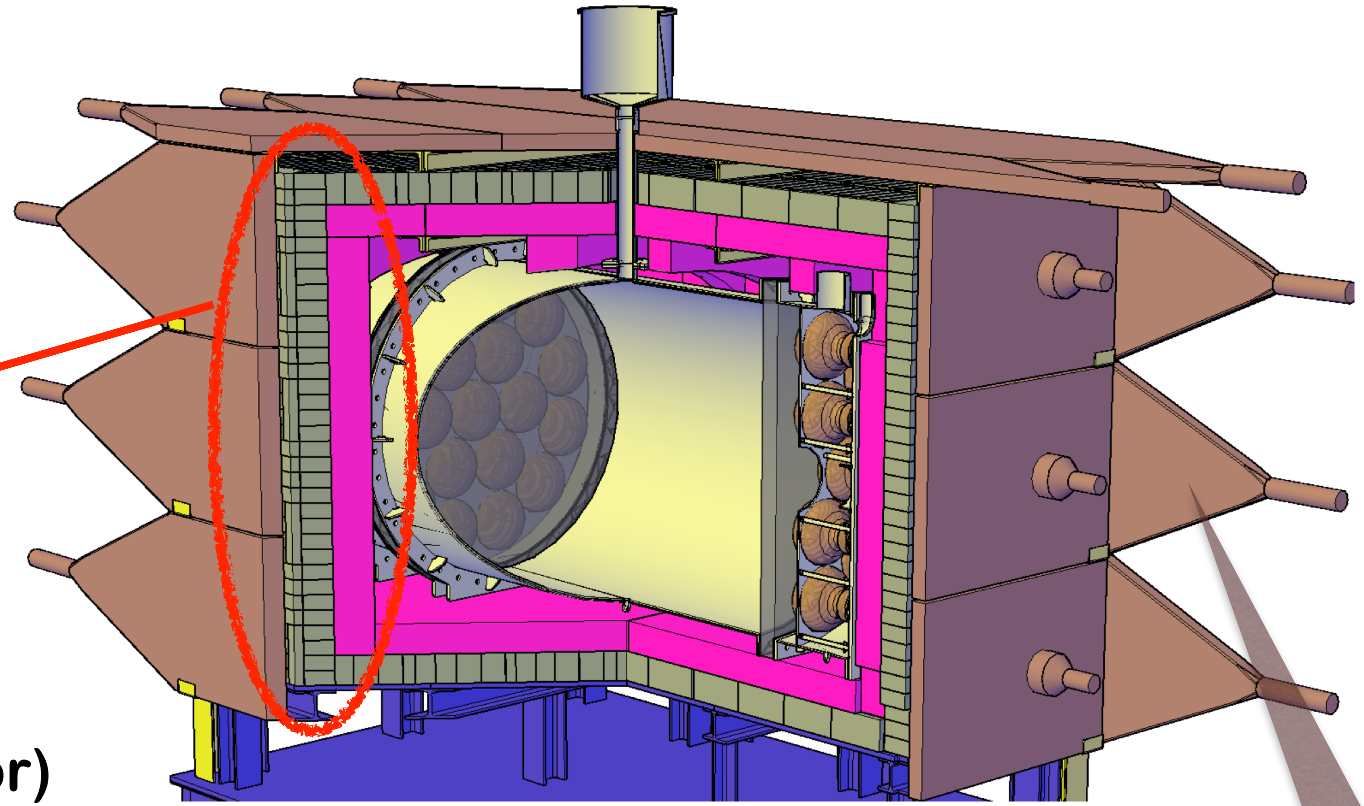


- **Photomultiplier tubes (PMTs)**
  - **Two buffer tanks filled with mineral oil at both side of the target tank**
  - **Acrylic windows b/w target and buffers**
  - **19 R5912 (8 inch) PMTs are installed in each buffer tank.**

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

LAB: Linear Alkyl Benzene
DIN: Di-isopropylnaphthalene
PSD: Pulse Shape Discrimination

NEOS Detector

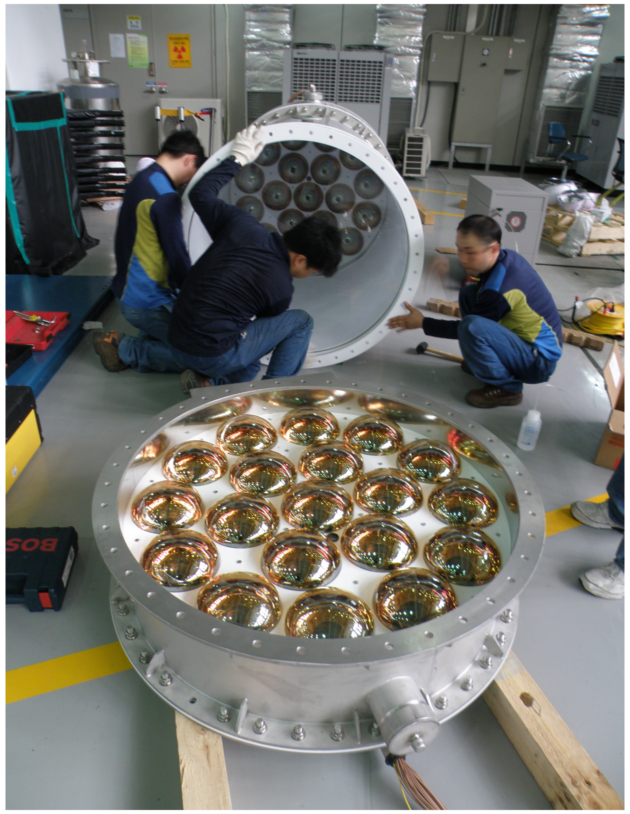


- **Shieldings**
  - **10-cm B-PE (n)**
  - **10-cm Pb (γ)**
  - **Muon detectors (Plastic scintillator)**

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

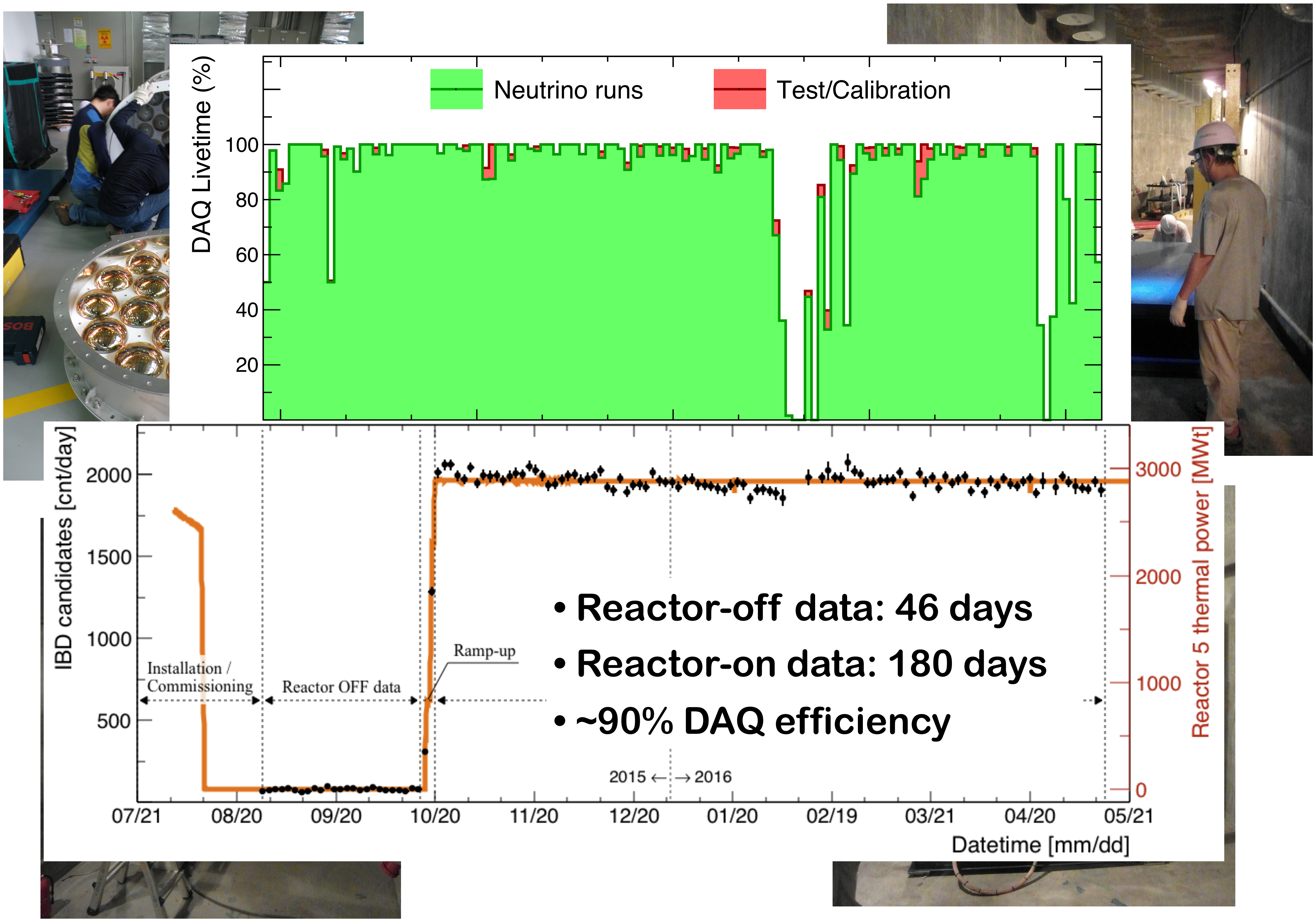
- **Muon detectors for veto**
  - **15 plastic scintillators with PMTs except bottom side**

Construction and Operation





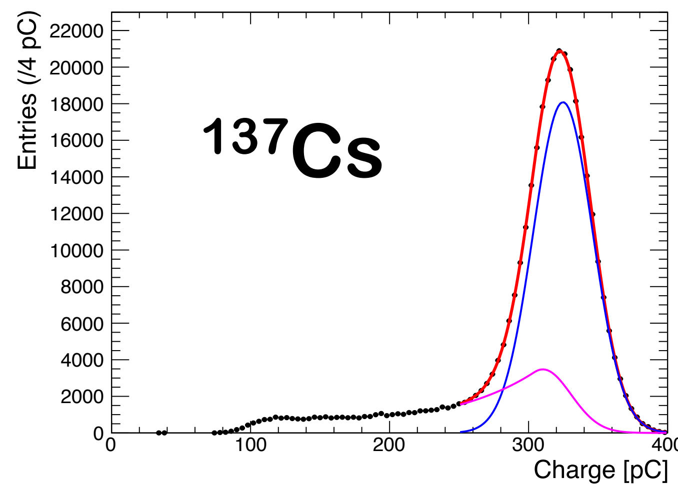
Construction and Operation

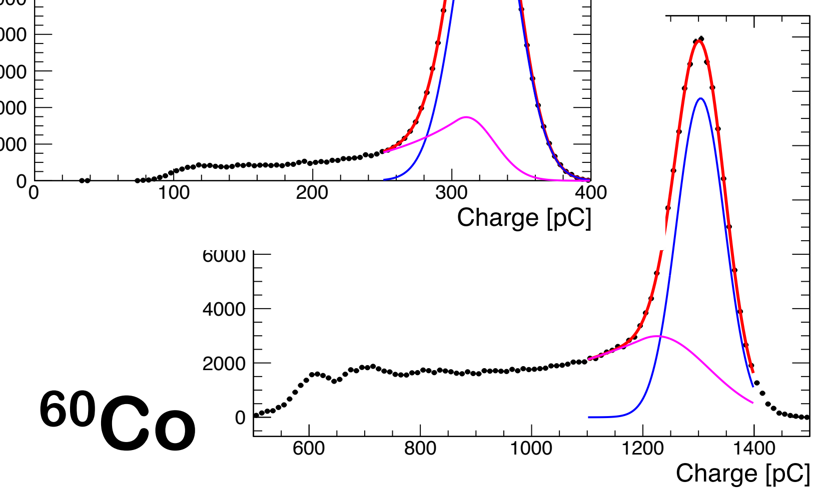


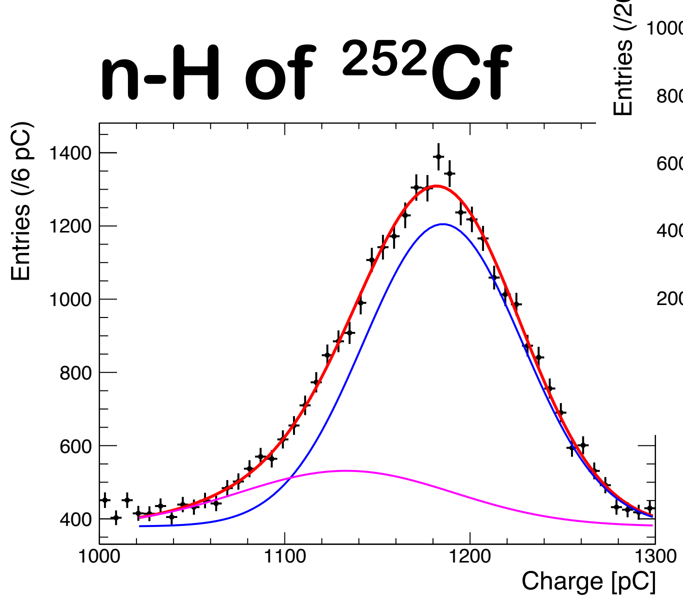
- **Reactor-off data: 46 days**
- **Reactor-on data: 180 days**
- **~90% DAQ efficiency**

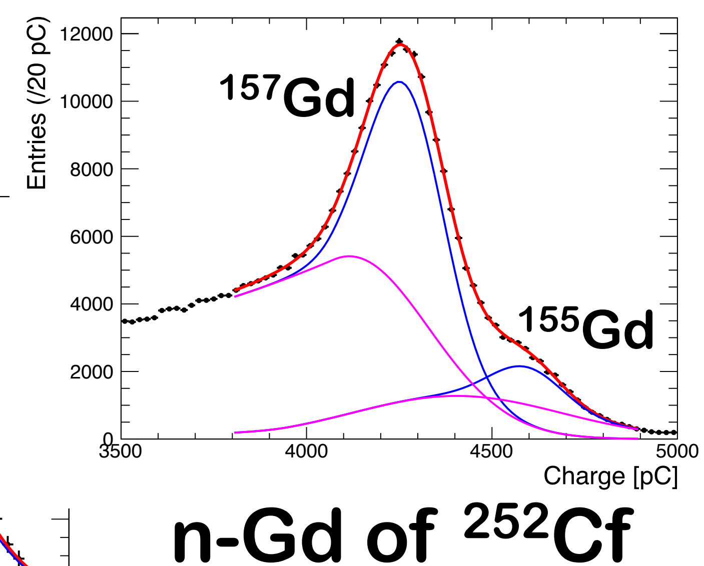
Calibration

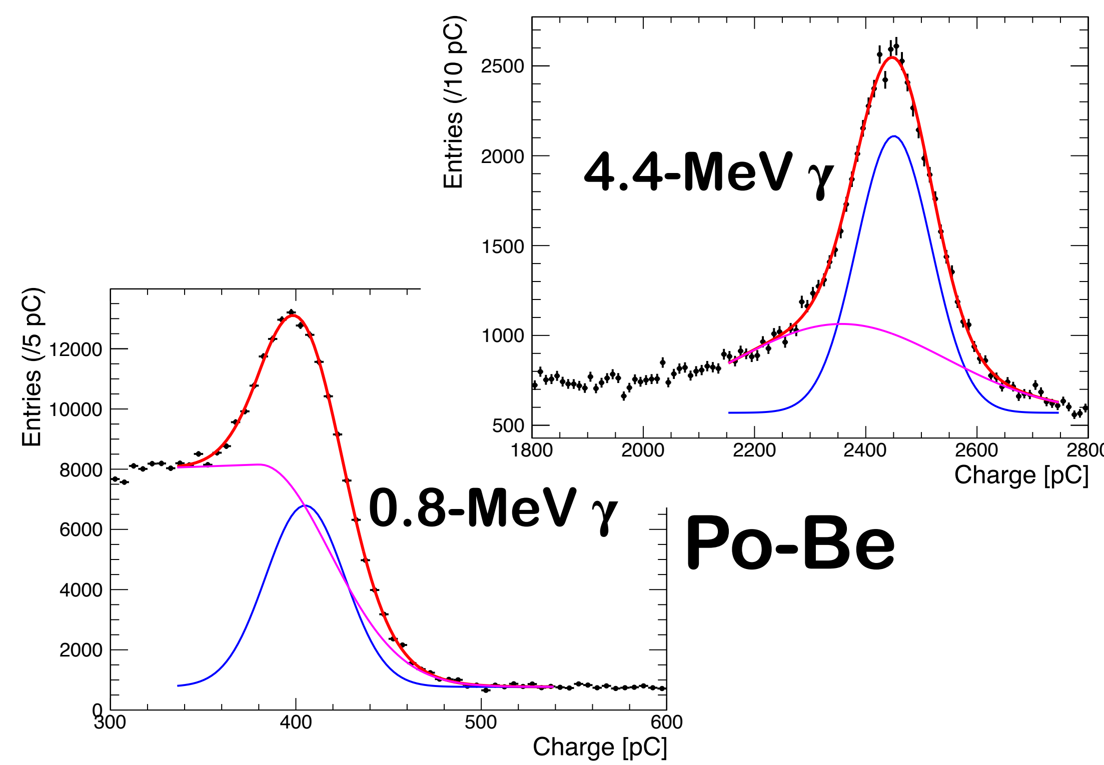
- **Source calibration**
  - **Once a week with point sources**
    - **^{137}Cs: 0.66-MeV γ, ^{60}Co: 1.17/1.33-MeV γ**
    - **^{252}Cf: neutron source**
      - **⇨ 2.2-MeV γ from n-H capture**
      - **⇨ γs (8 MeV) from n-Gd capture**
    - **Po-Be: neutron and 0.8-/4.4-MeV γ**





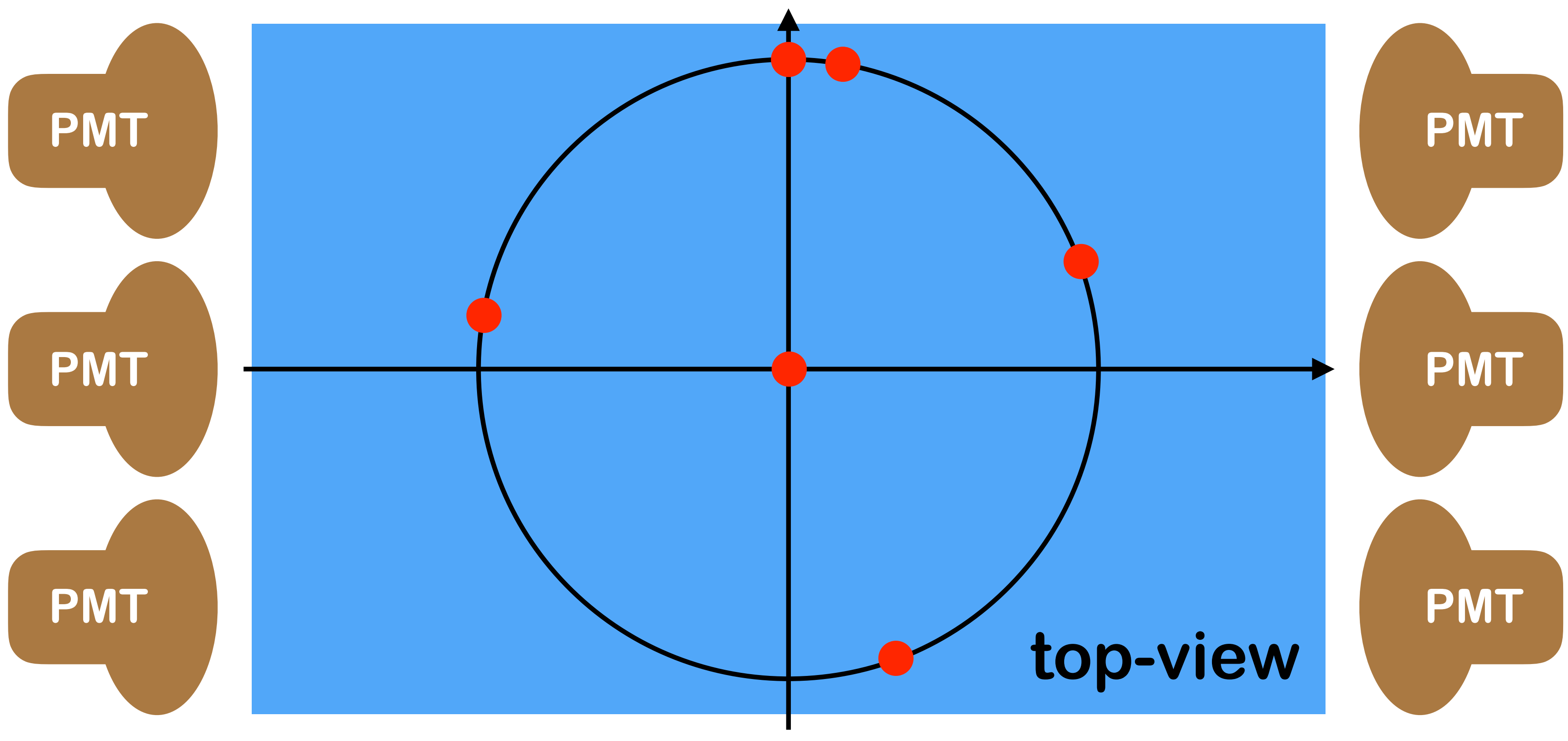






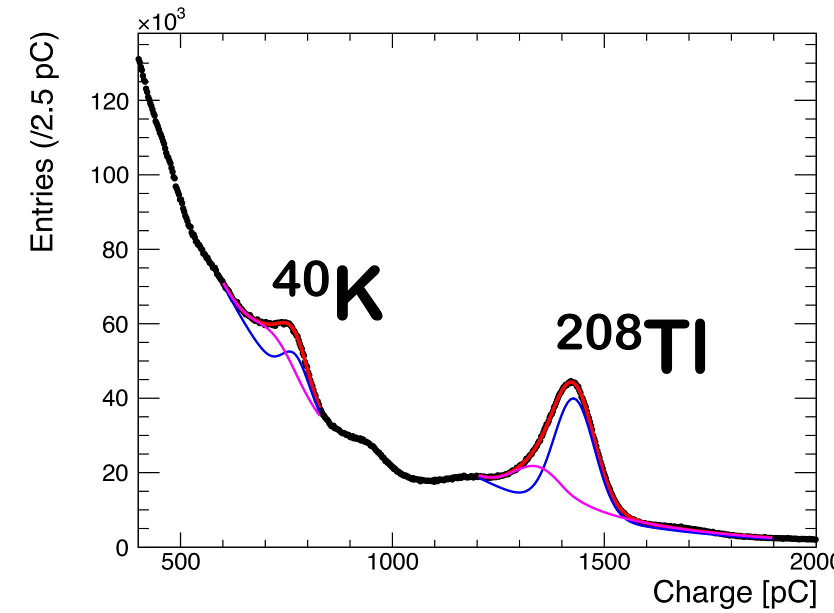
Calibration

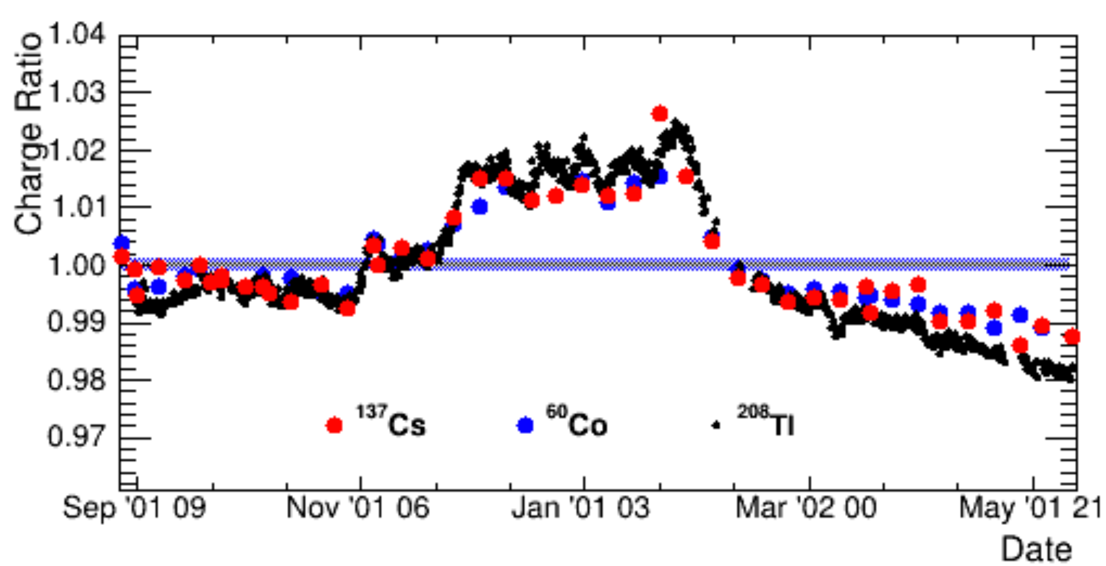
- **3D calibration**
  - **^{137}Cs, ^{60}Co, and ^{252}Cf at various positions**
  - **Position dependence**
  - **escaping γs from target**
  - **used for MC tuning**

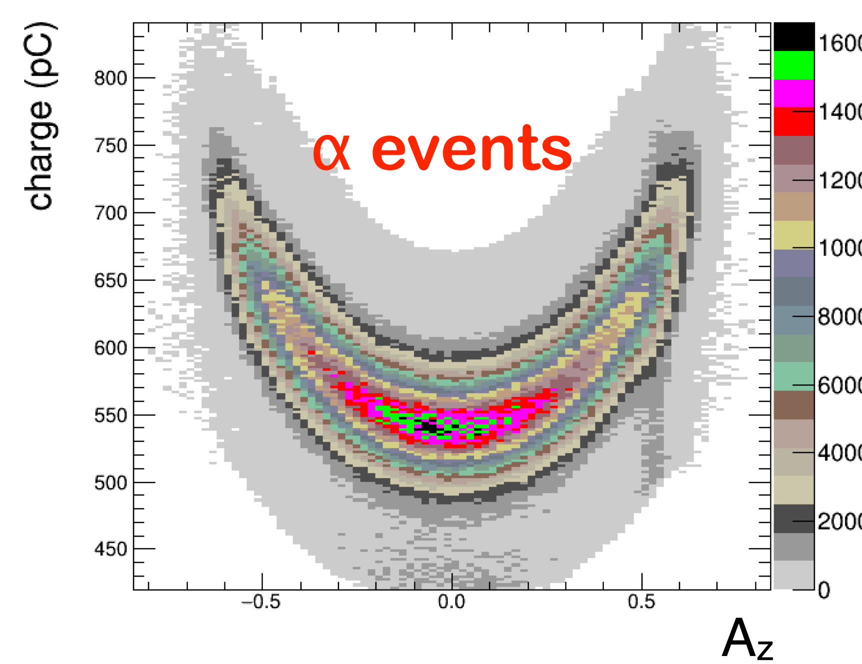


Calibration

- **Internal/external background**
  - **Continuous and volume source**
    - **^{40}K in PMT glass: 1.46-MeV γ**
    - **^{208}Tl in B-PE: 2.61-MeV γ**
      - **Correction for time dependence**
    - **Radon in LS: α-/β-decay**
      - **α: Correction for position dependence**
      - **β: Validation of MC tuning**

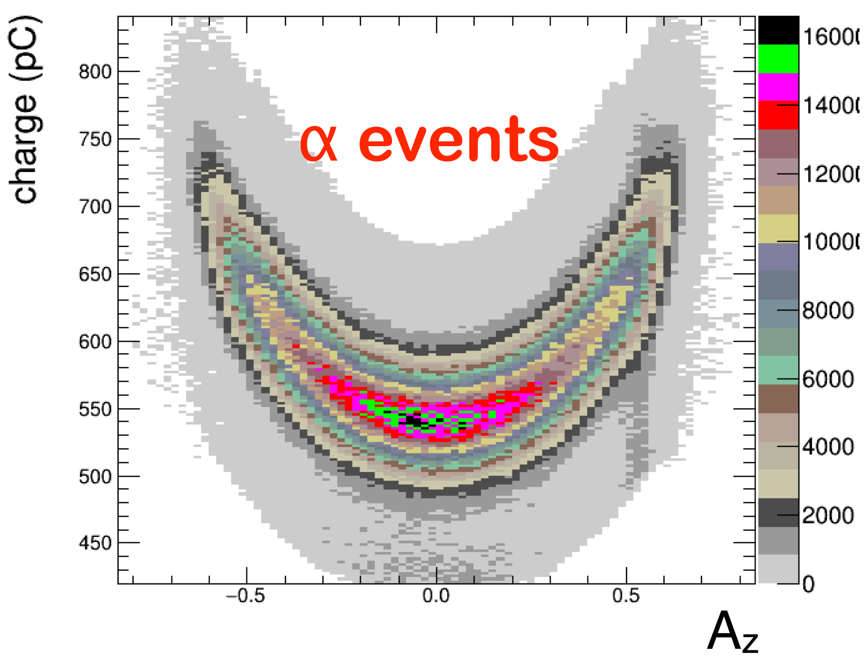


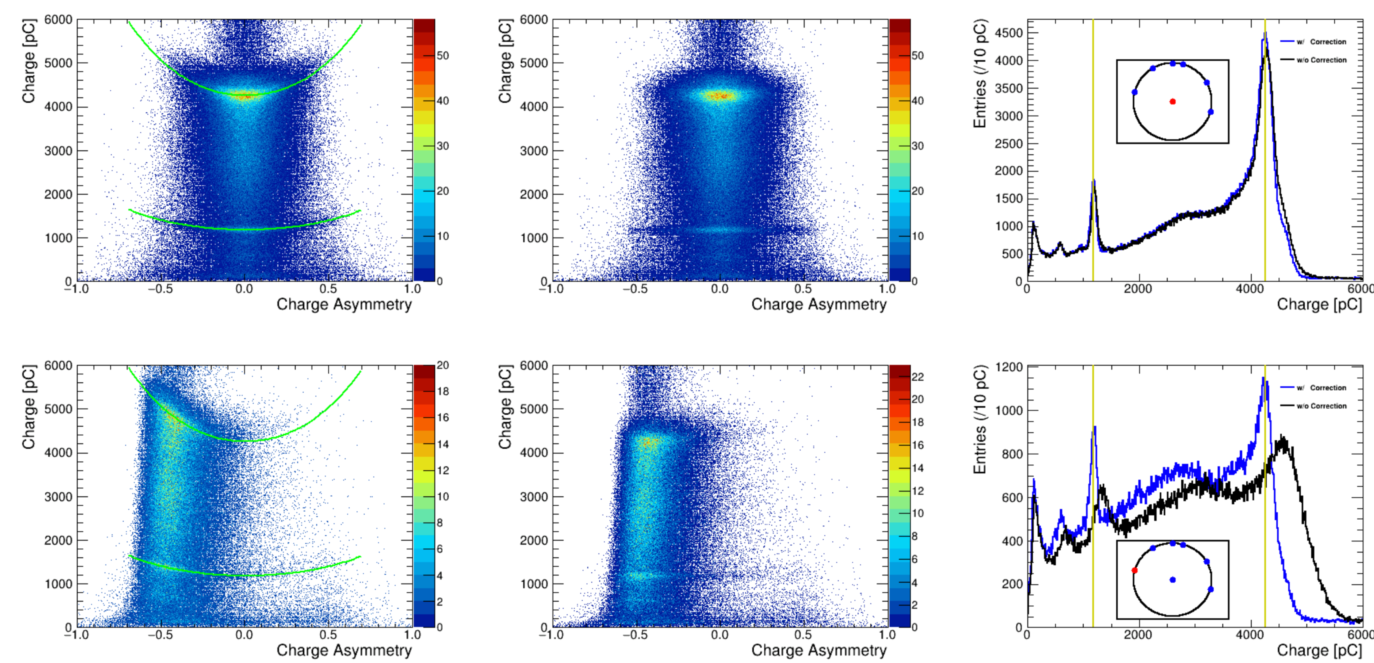




Response and Simulation

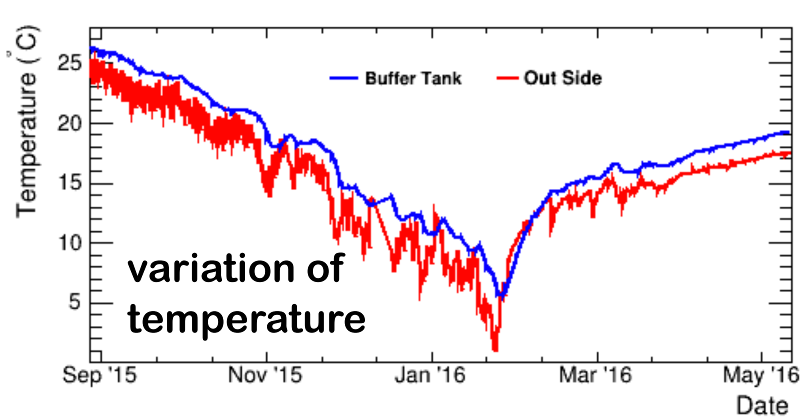
- **Correction for position with α**
  - **α source is uniformly distributed throughout LS**

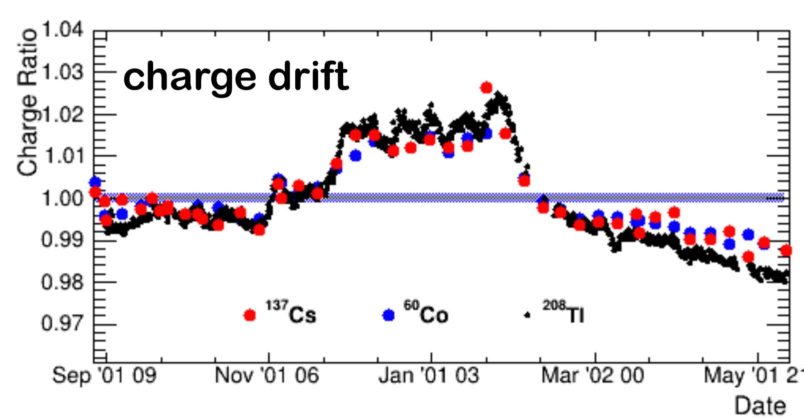


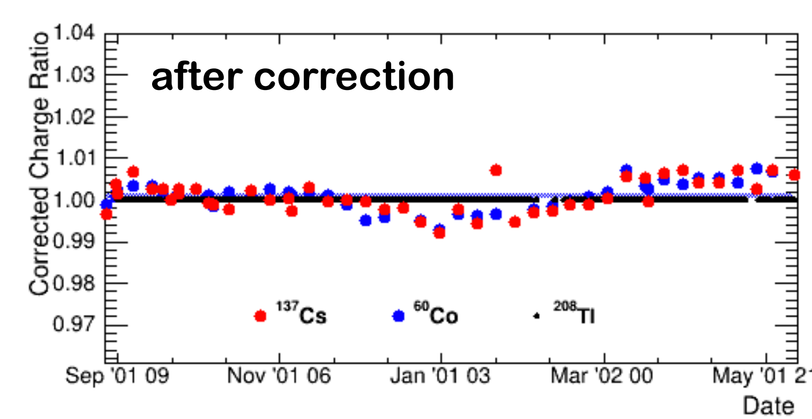


3D calibration with ^{252}Cf

- **Correction for time with γ from ^{208}Tl**

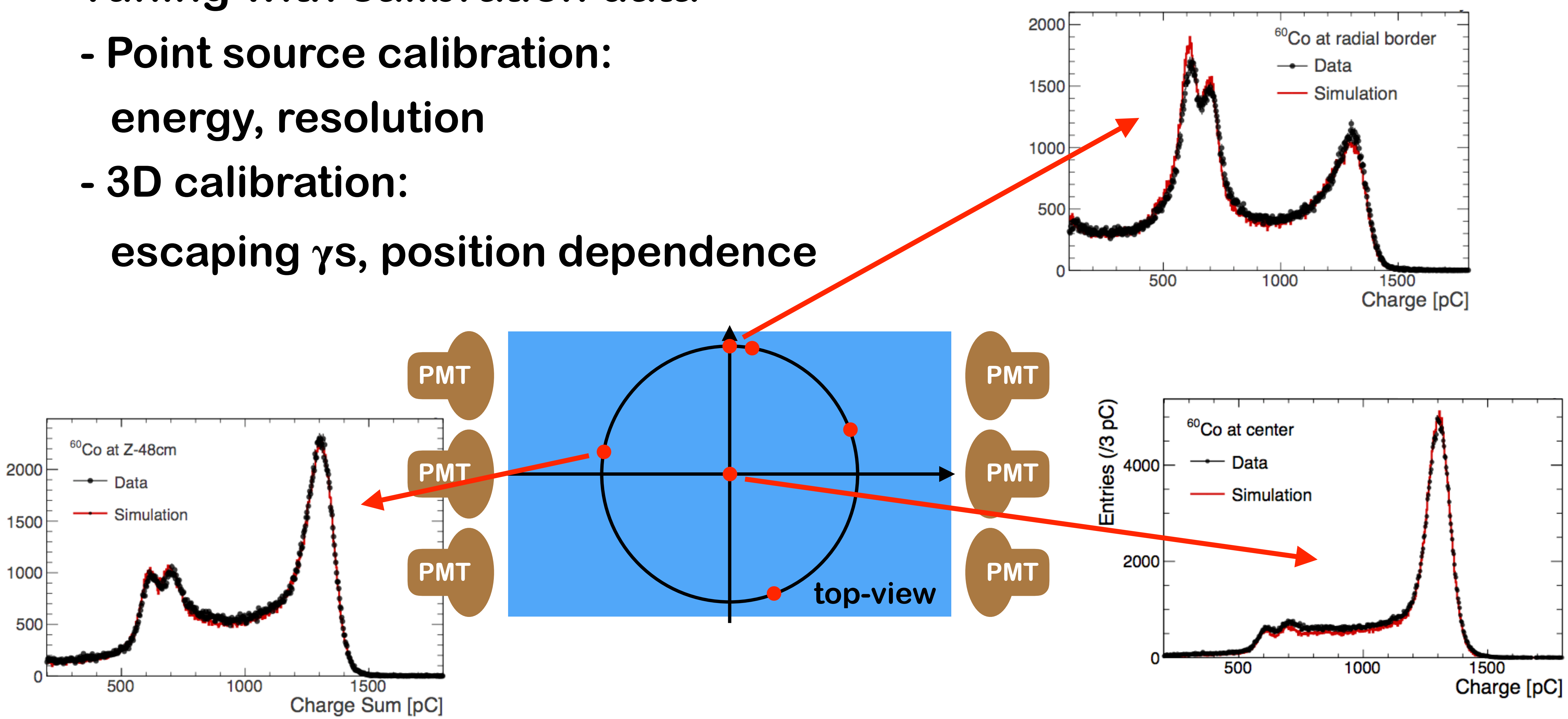






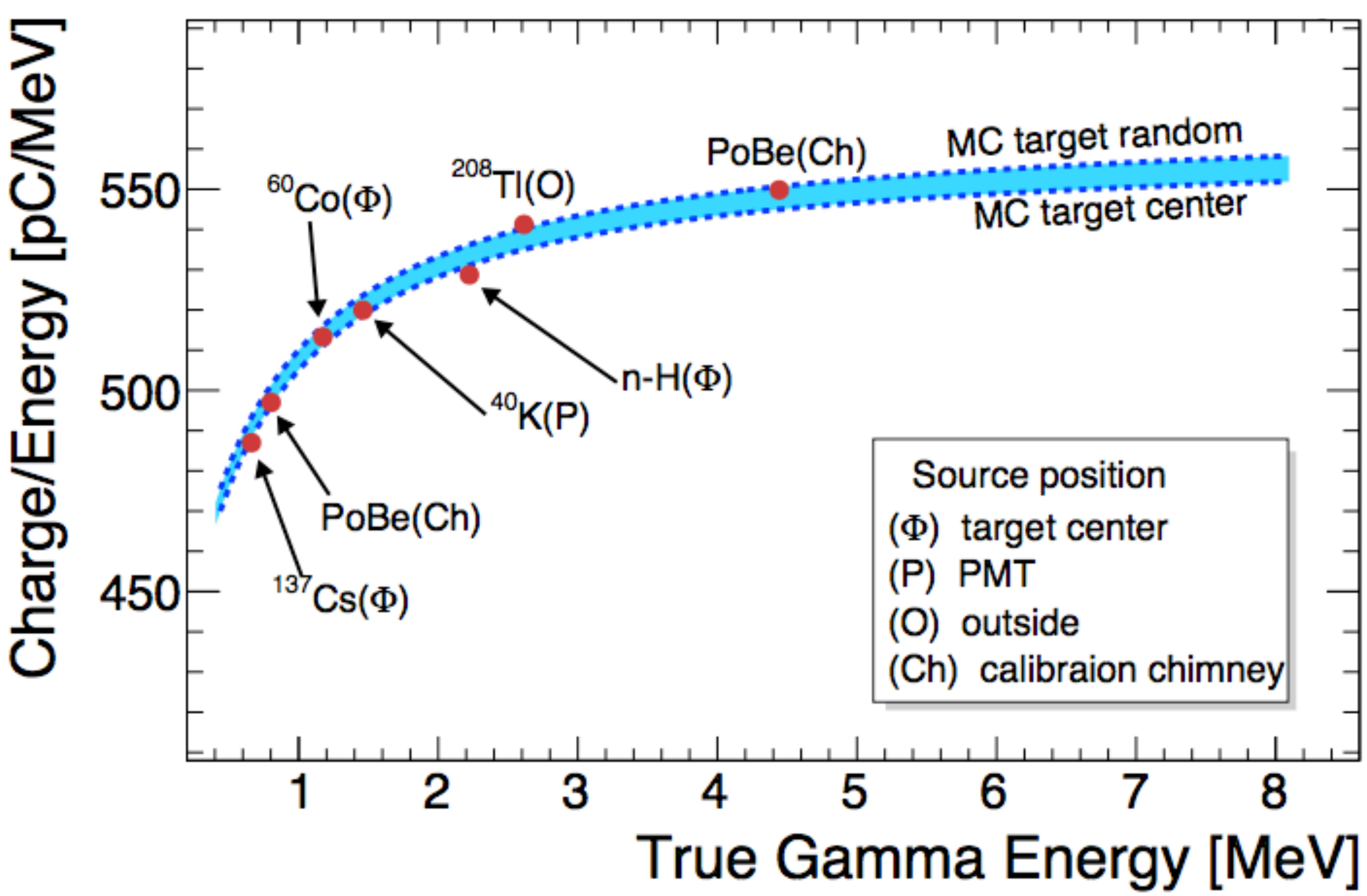
Response and Simulation

- **MC Simulation based on GEANT4**
  - **LS optical properties, PMT properties**
  - **Full simulation including electronics simulation**
- **Tuning with calibration data**
  - **Point source calibration: energy, resolution**
  - **3D calibration: escaping γs, position dependence**



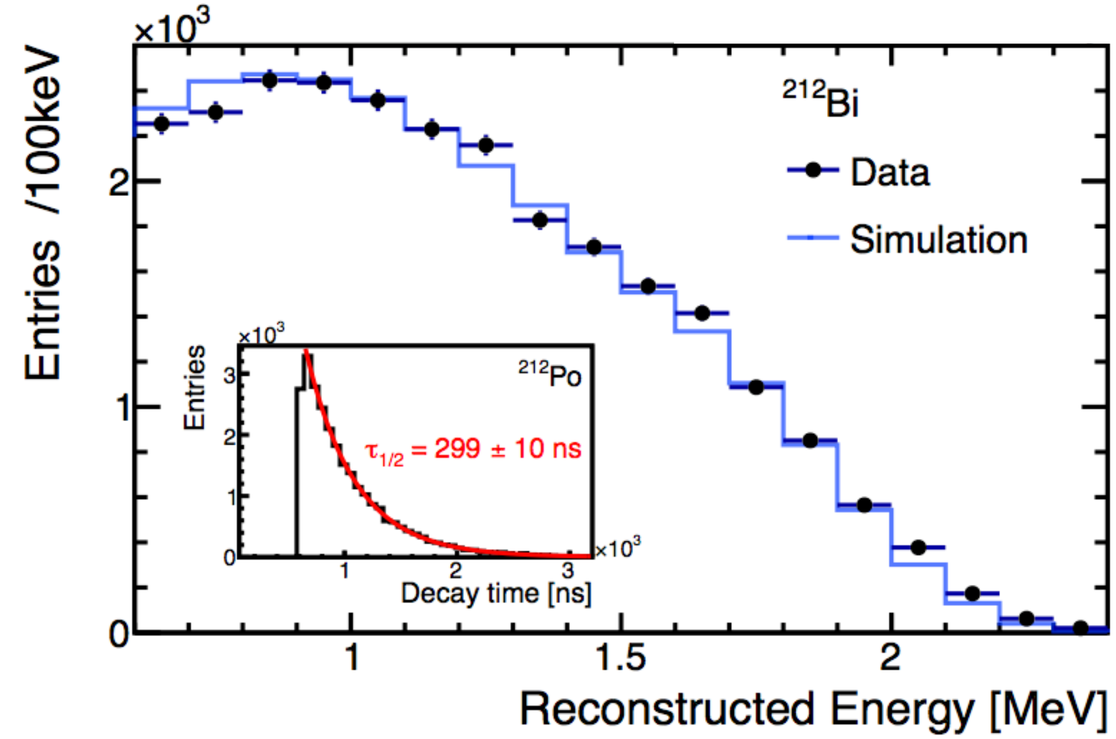
Response and Simulation

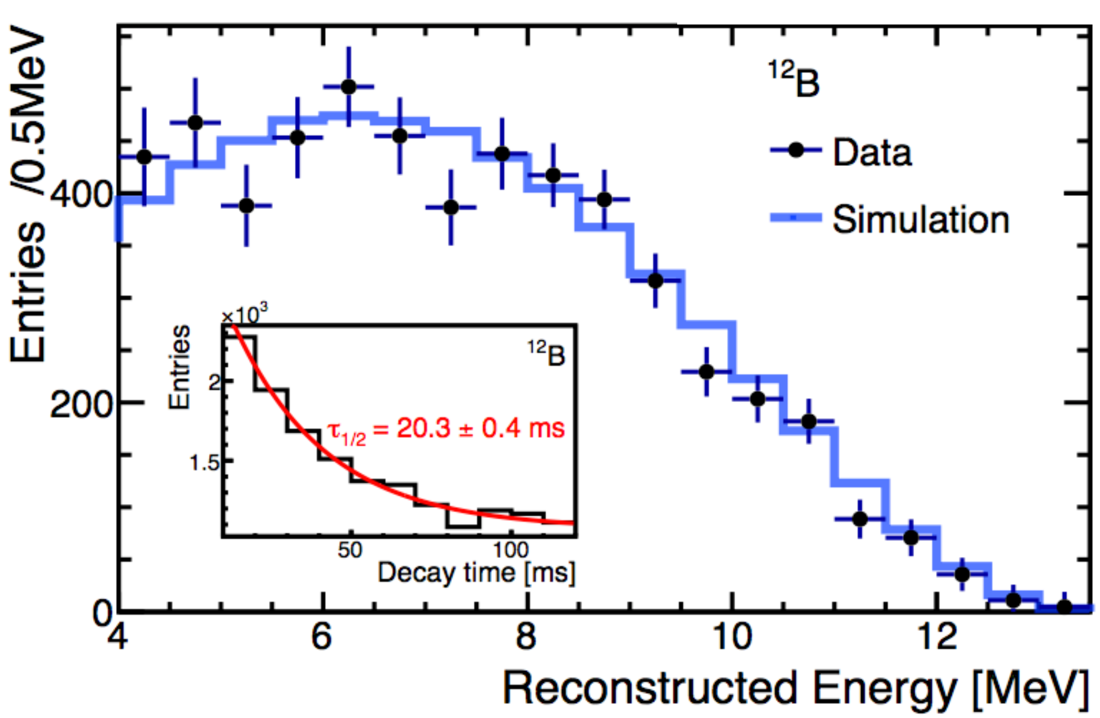
- **Charge to energy conversion**
  - **Only single γ sources are used for conversion.**
  - **Non-linearity due to quenching and Cherenkov effect**
    - **Energy is quenched at low energy**
    - **Cherenkov effect is dominant at higher energy.**

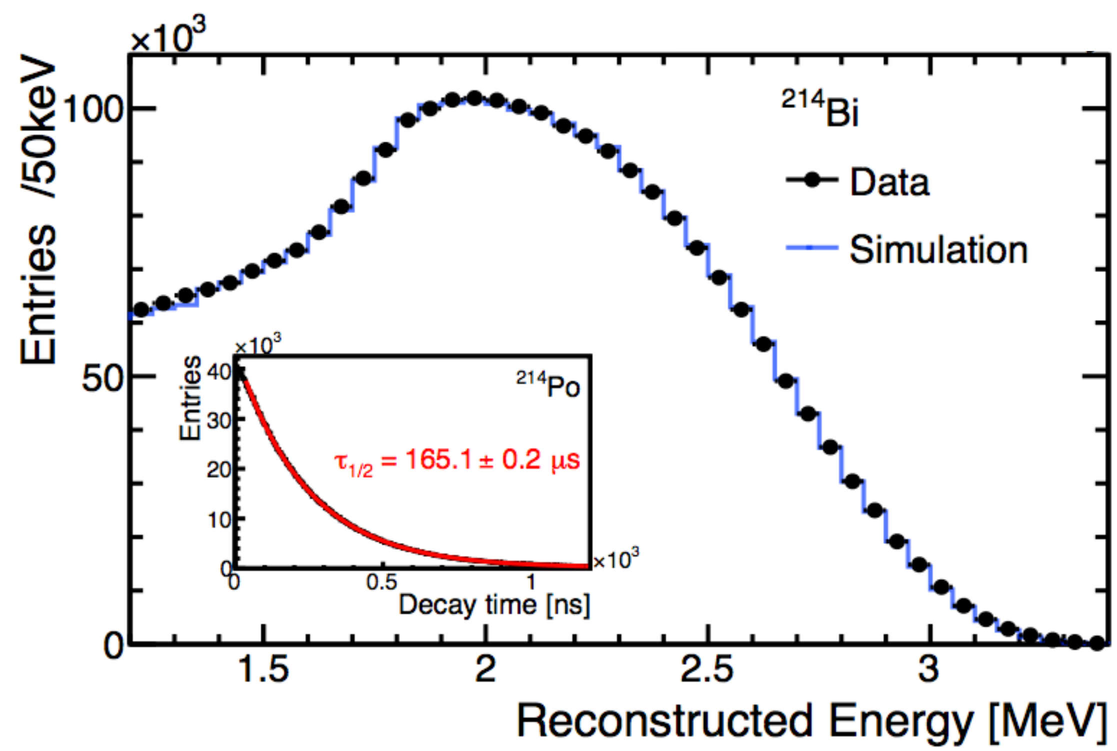


Response and Simulation

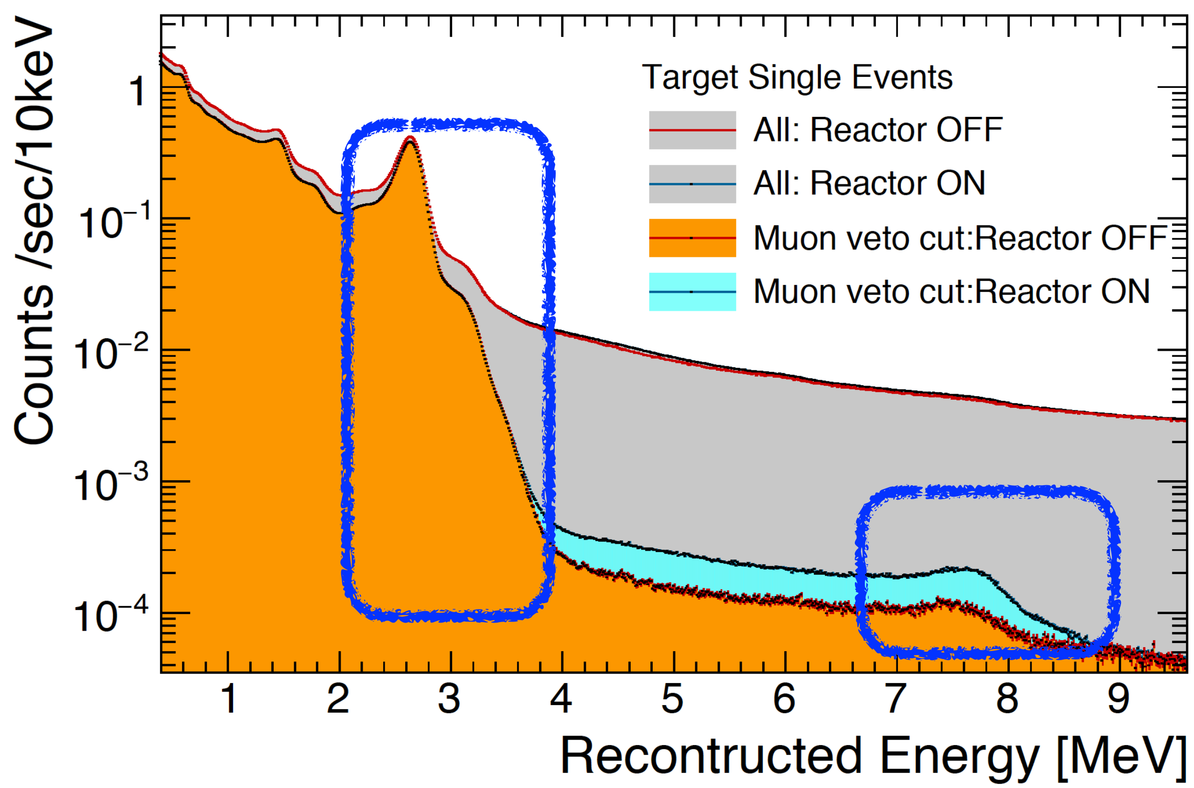
- **Energy spectra of β-decay**
  - **- ^{212}Bi, ^{214}Bi, and ^{12}B**
  - **- Uniform distribution throughout LS**
- **Simulation and data are in good agreement.**





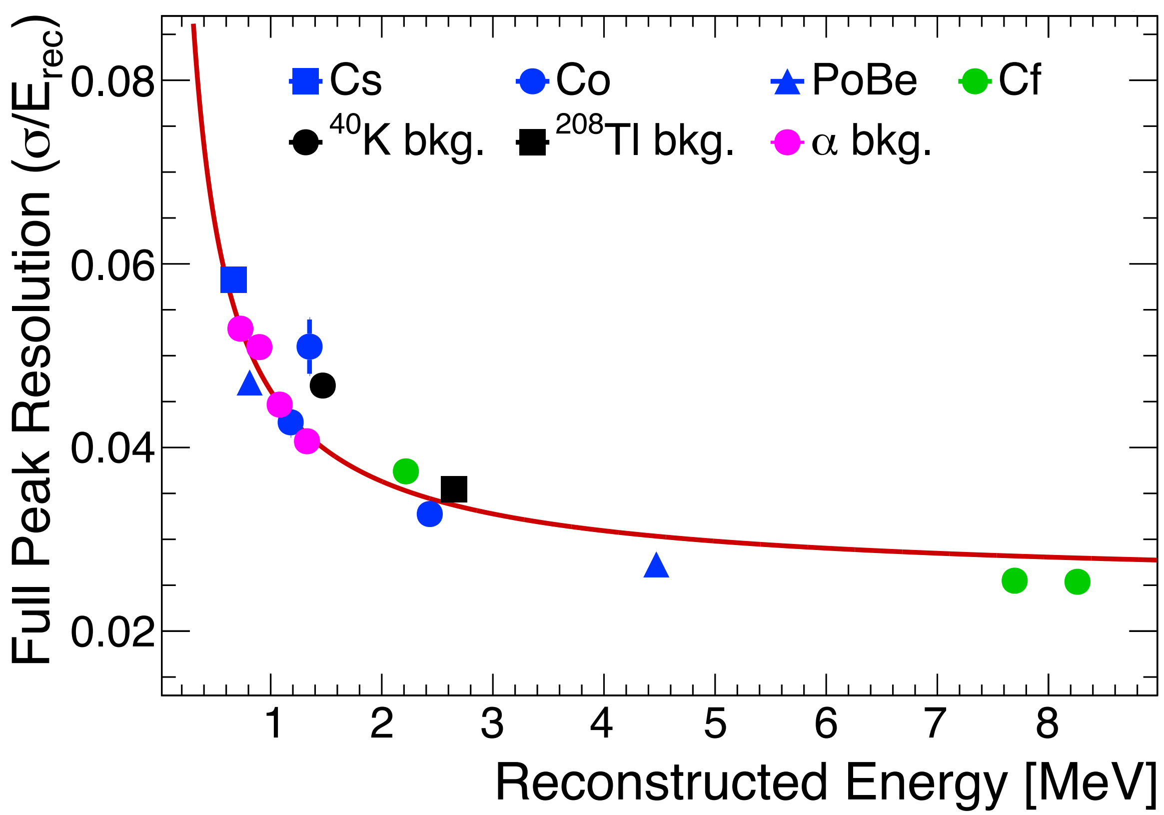


Single Event Reconstruction



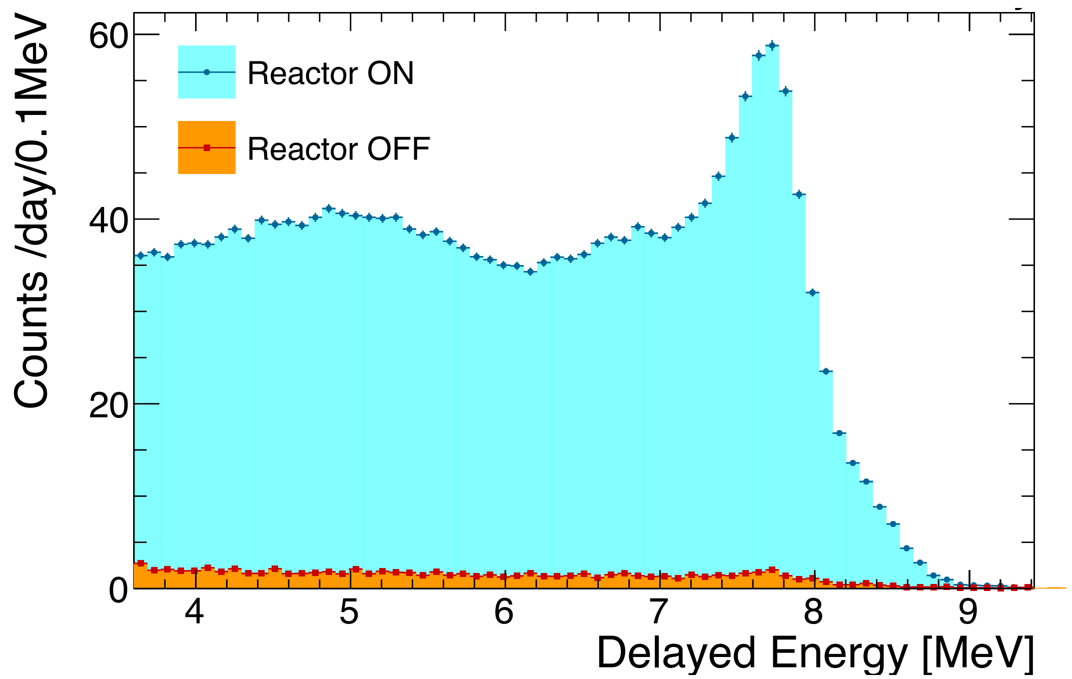
- **Energy distribution**
  - **- Selection: E_s > 0.6 MeV**
  - **- 2.61-MeV γ from ^{208}Tl**
  - **- n-Gd capture signals at 8 MeV**

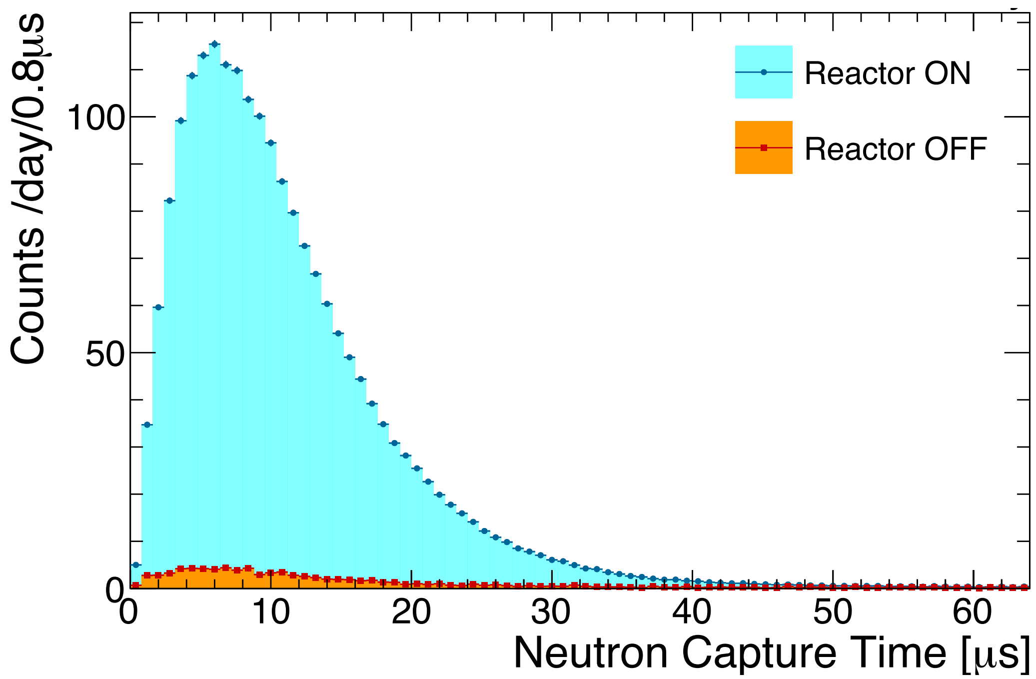
- **Energy resolution for full peak**
  - **- ~4.8% at 1 MeV**



IBD Candidate

- **Criteria for delayed events**
  - **Energy range: 4-10 MeV**
    - **Signal due to n-Gd capture (ΣE_γ ~ 8 MeV)**
    - **Escaping γs ⇨ lower the lower bound**
    - **γ events from ^{208}Tl can affect near 4 MeV.**
  - **Time coincidence: 1-30 μs**
    - **Capture time is 7-8 μs in 0.5% Gd-LS**

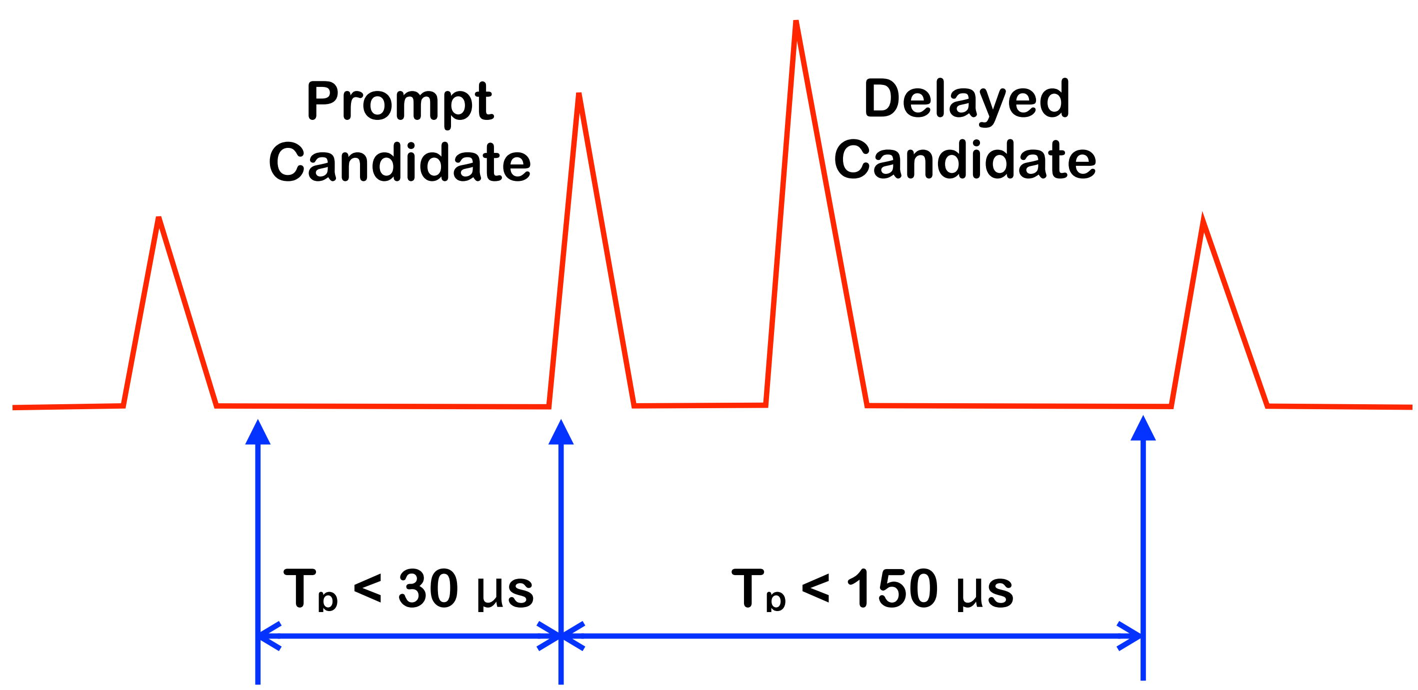




IBD Candidate

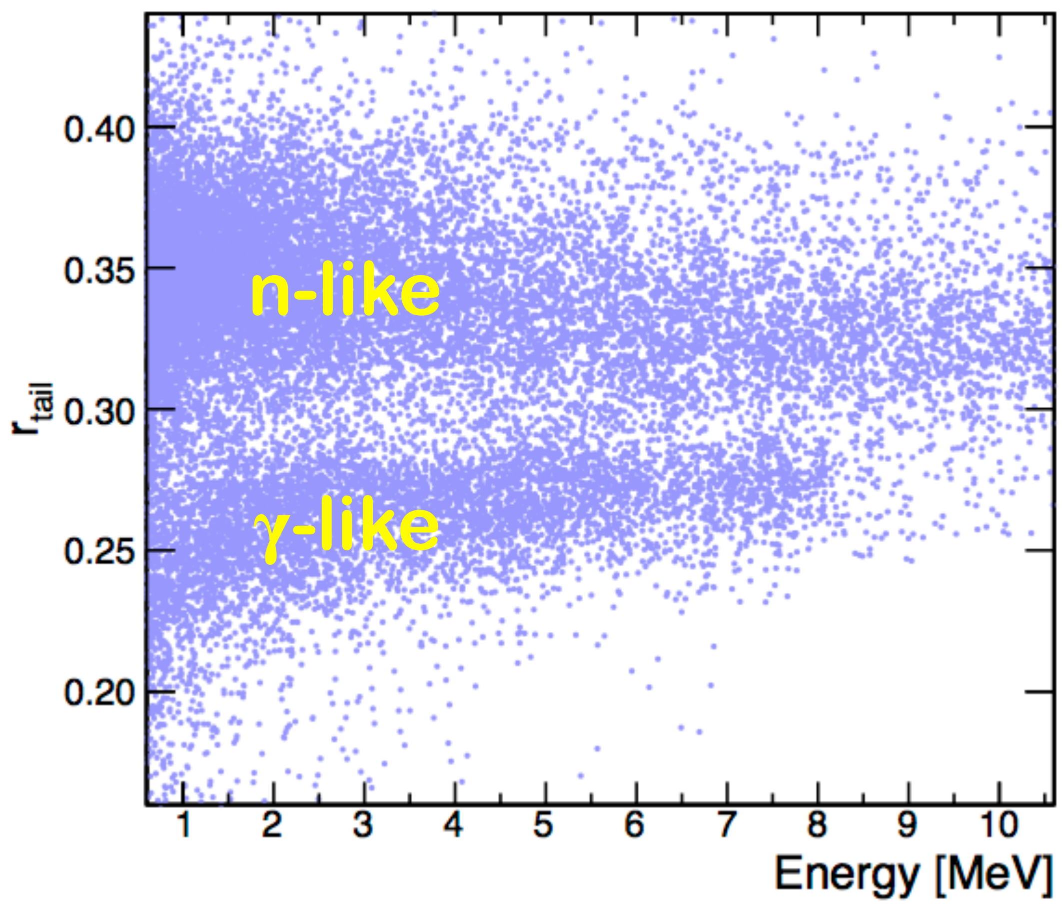
- **Multiplicity cut**
  - **For reducing backgrounds due to multiple neutrons**
  - **No event in time window, [T_p - 30 μs, T_p + 150 μs]**
- **Muon veto**
  - **All events are vetoed in time window, [T_v, T_v + 150 μs]**

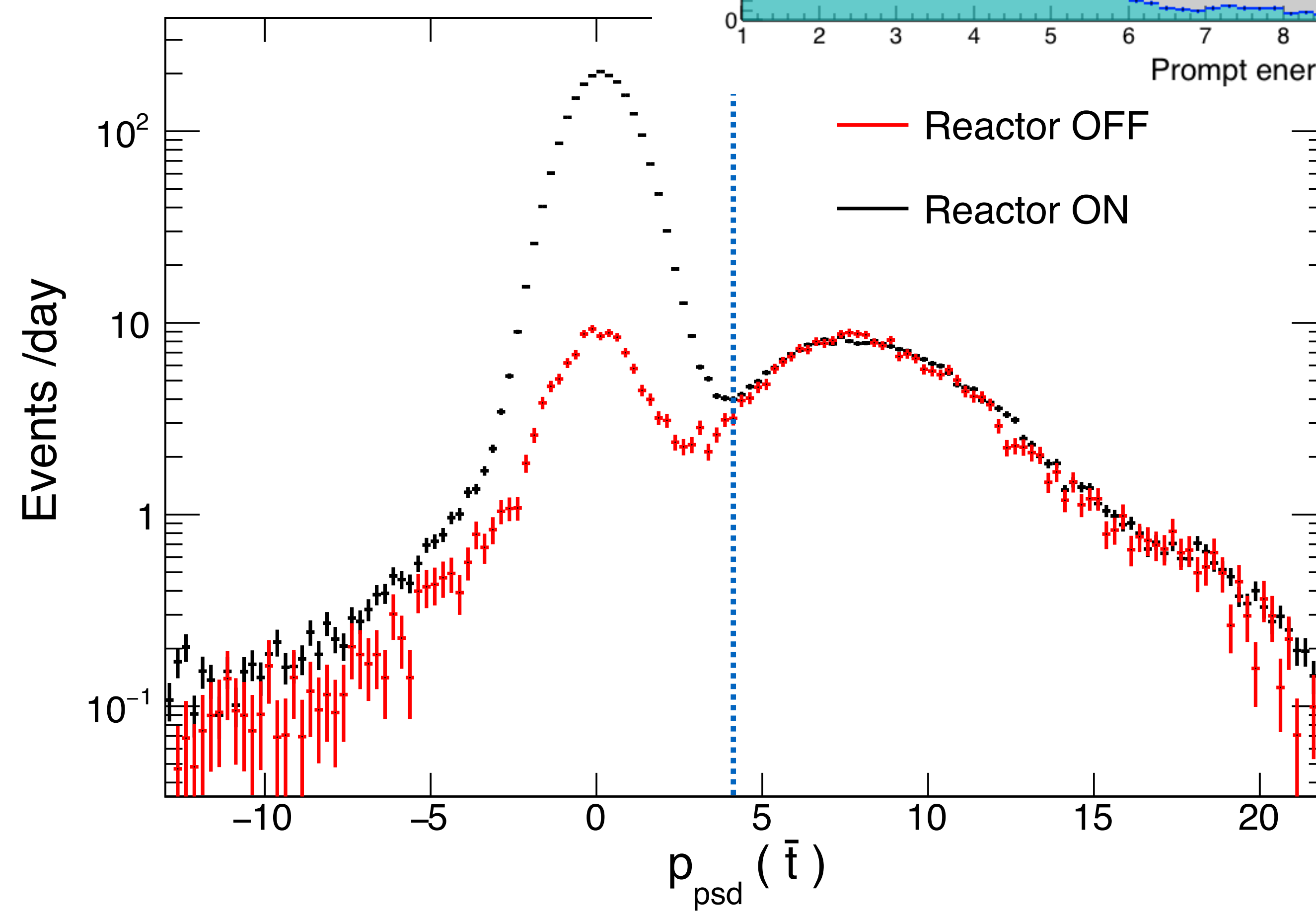
T_p: prompt event time
T_v: muon event time

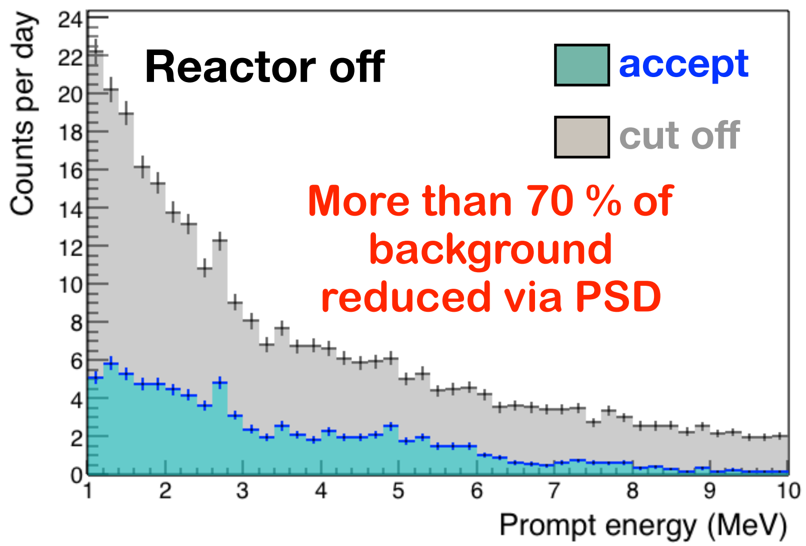


IBD Candidate

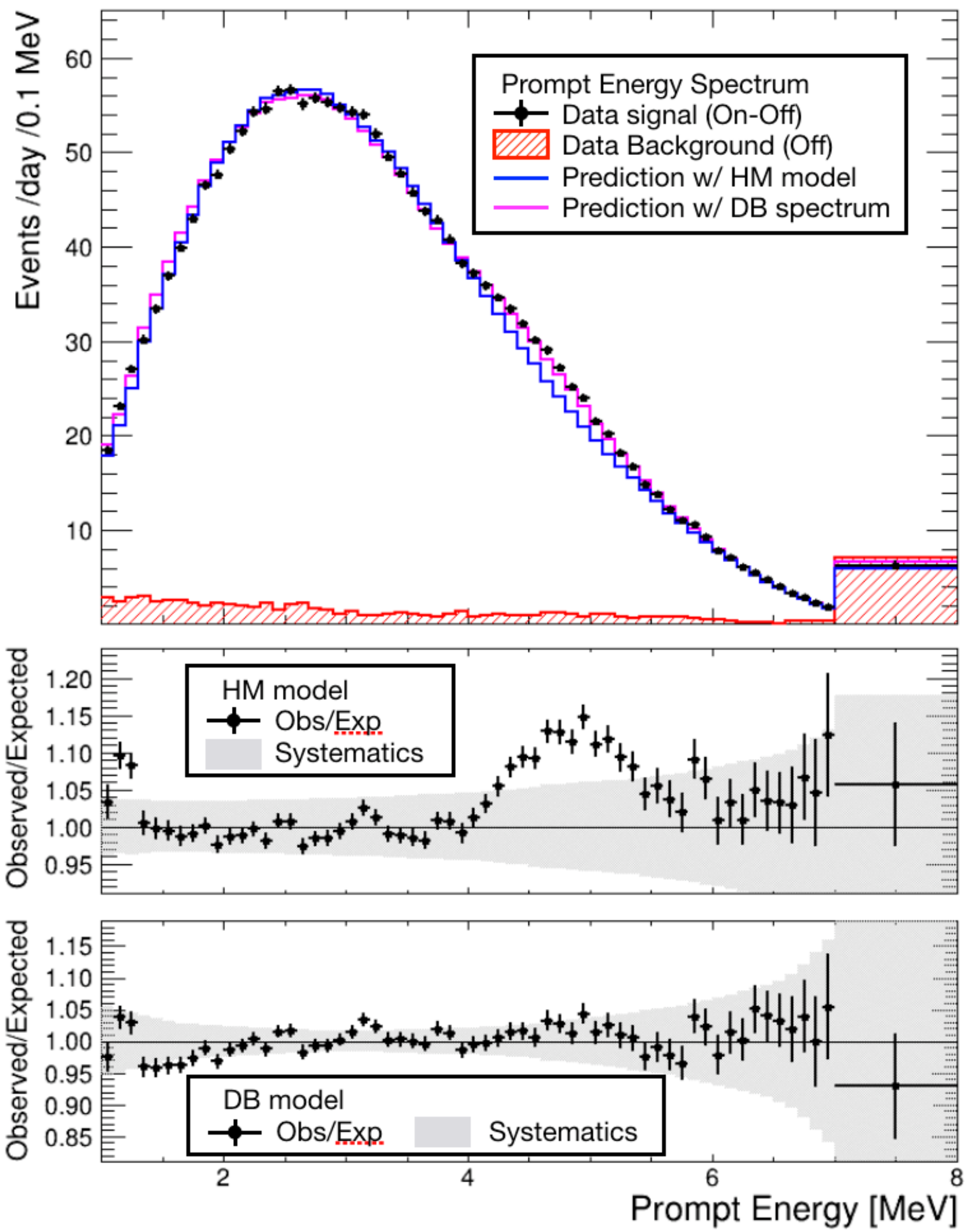
- **Pulse shape discrimination (PSD)**
  - **For reducing backgrounds due to fast neutrons**
  - **Accepting 99.9% γ-like events**
  - **More than 70% of background is reduced.**







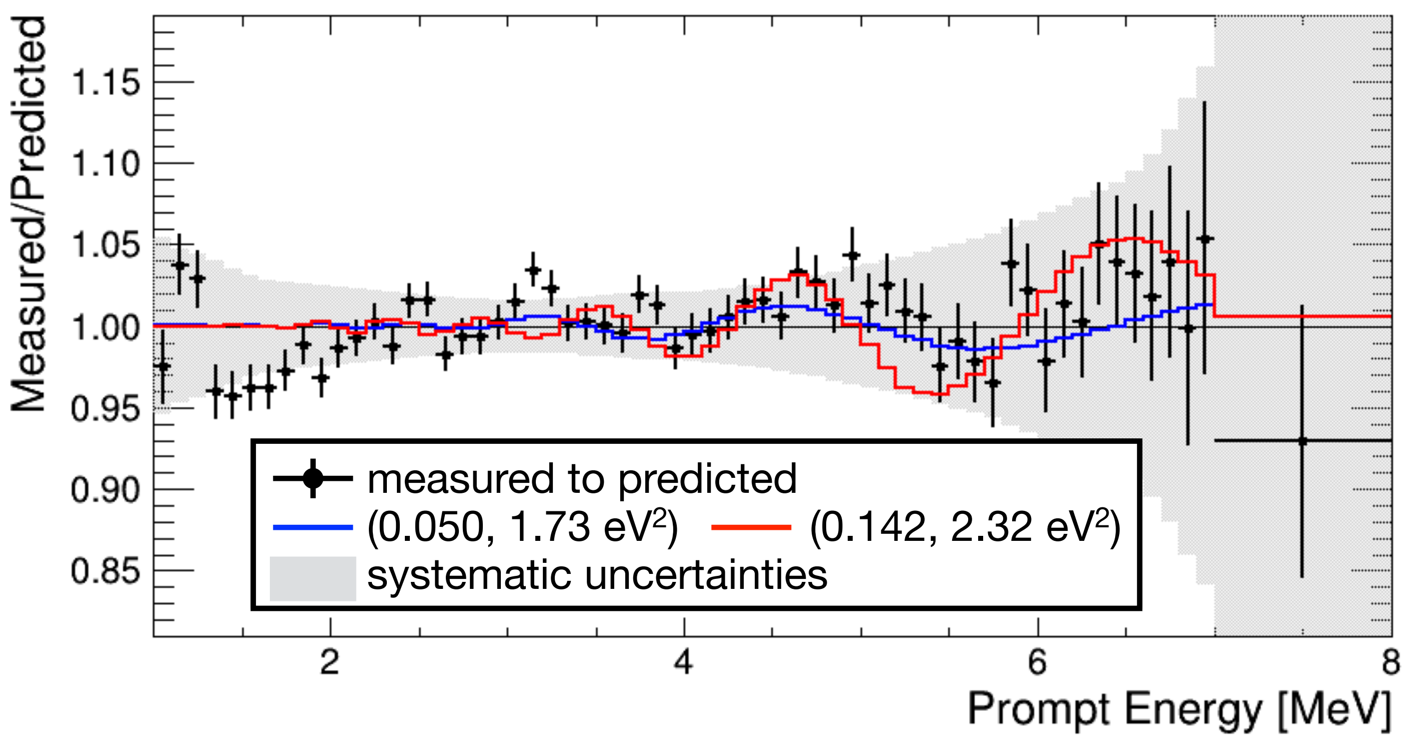
Prompt energy spectrum

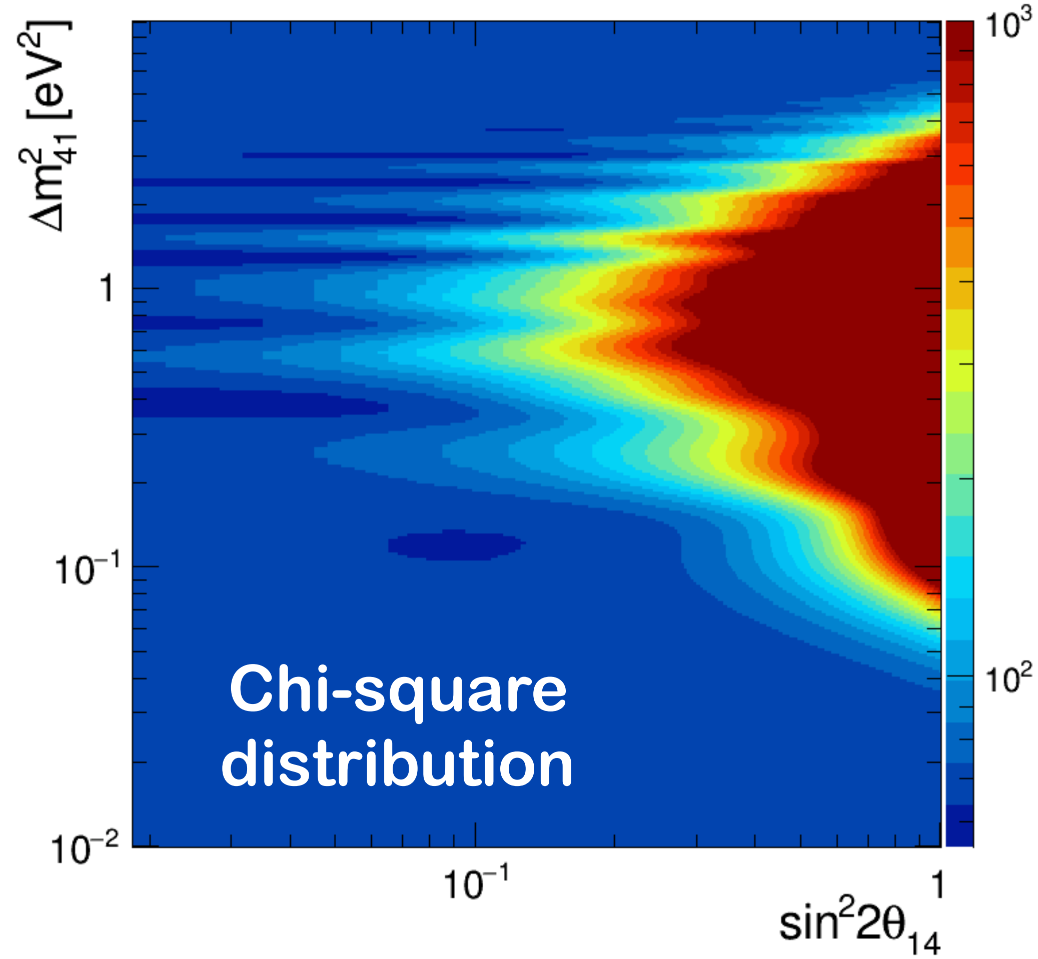


- S/B ratio ~ 22
  - Reactor-on: ~2000 /day
  - Reactor-off: ~85 /day
- Comparison with HM model
  - 5-MeV excess
    - ⇨ Not suitable for oscillation analysis
- Comparison with Daya Bay
  - Different fission fraction
    - ⇨ Correction with HM
  - Generally in an agreement
  - Oscillation analysis
    - Spectral shape analysis: High dependence on reference spectrum

Chi-square Distribution

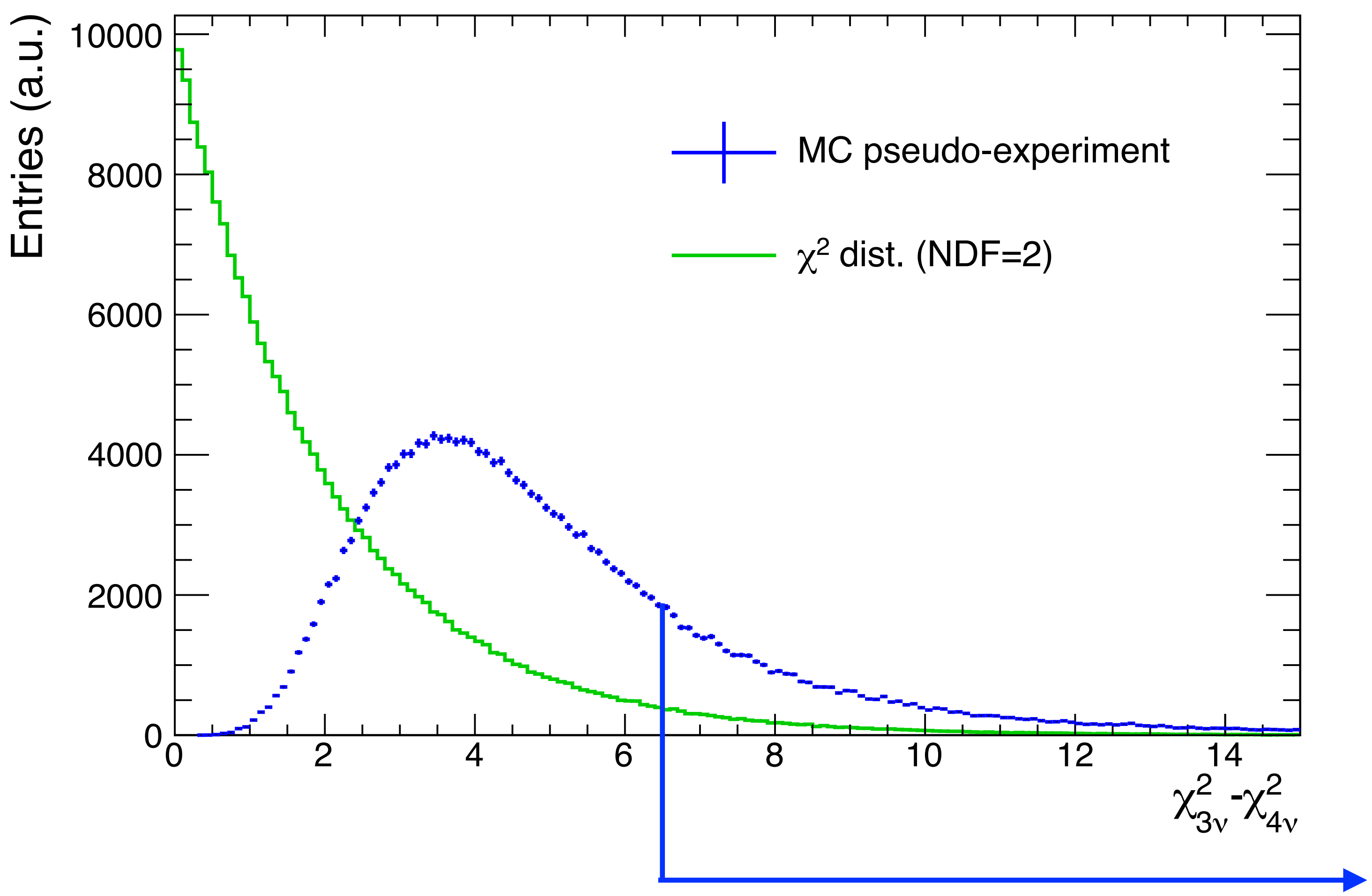
- **χ^2 minimum (best fit) with 3+1ν hypothesis**
  - **$\chi^2_{4\nu}$/NDF = 57.5/59**
  - **at ($\sin^2 2\theta_{14}$, Δm_{41}^2) = (0.05, 1.73 eV^2)**
- **χ^2 with 3ν hypothesis**
  - **$\chi^2_{3\nu}$/NDF = 64.0/61**
  - **$\Delta\chi^2 = \chi^2_{3\nu} - \chi^2_{4\nu} = 6.5$**





Significance Test

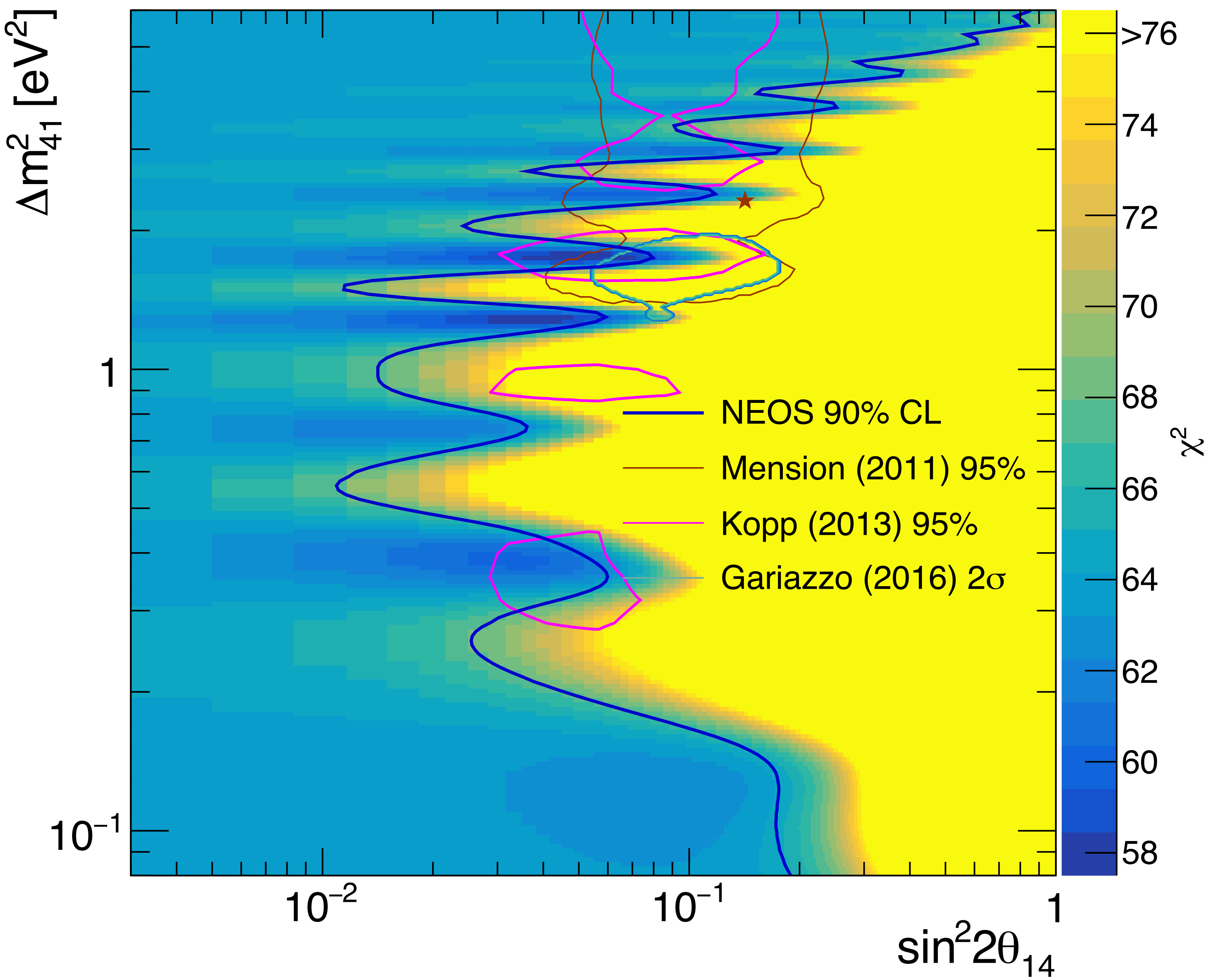
- **Significance test**
  - **0.3M sets of pseudo-experiments for significance test**
  - **There is no strong evidence of light sterile neutrino with 3+1 hypothesis.**



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

Significance Test and Exclusion Limits

- **Exclusion limits: Raster scan with χ^2 distribution**



arXiv: 1610.05134 / PRL 118, 121802 (2017)

Conclusion

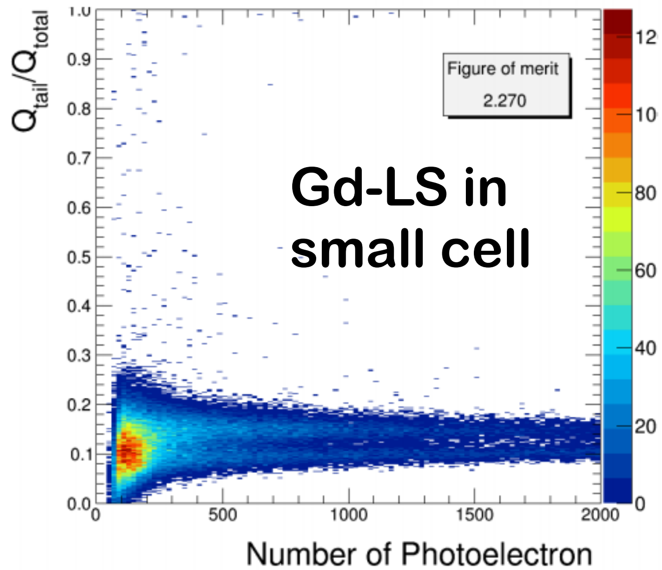
- **Physics Goal of NEOS**
  - **Sterile neutrinos search beyond Standard Model**
  - **Short distance behavior of reactor neutrino**
- **Detector Performance**
  - **PSD reduces more than 70% of background.**
  - **Energy resolution is about 4.8% at 1 MeV.**
  - **Signal to background ratio is about 22.**
- **Spectrum is compared with two models**
  - **5 MeV excess is confirmed at short baseline for the first time.**
  - **There is no strong evidence of light sterile neutrino with 3+1 hypothesis.**
  - **Best fit of Reactor Antineutrino Anomaly is disfavored.**

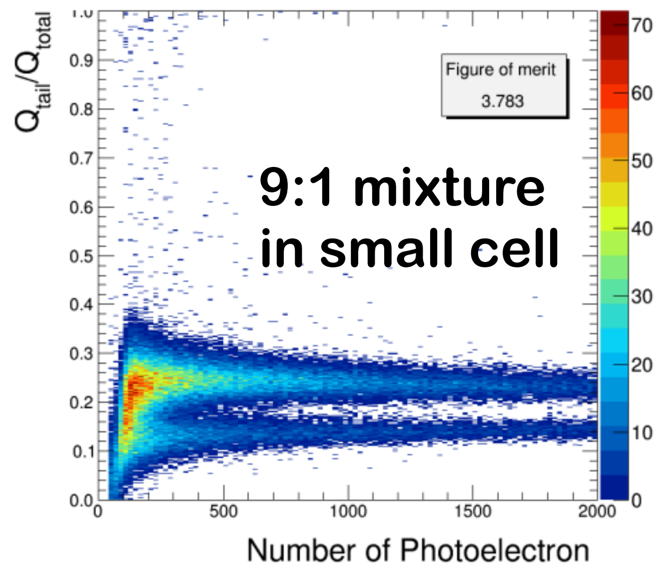
Thank you

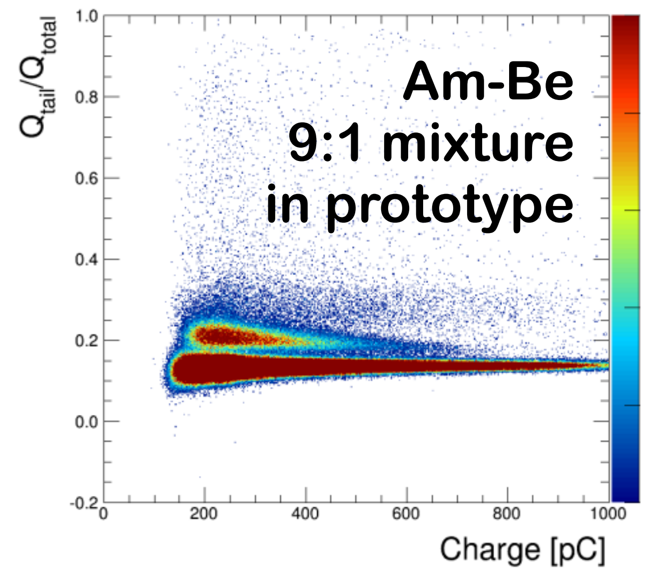
Backup

NEOS Detector: PSD improvement

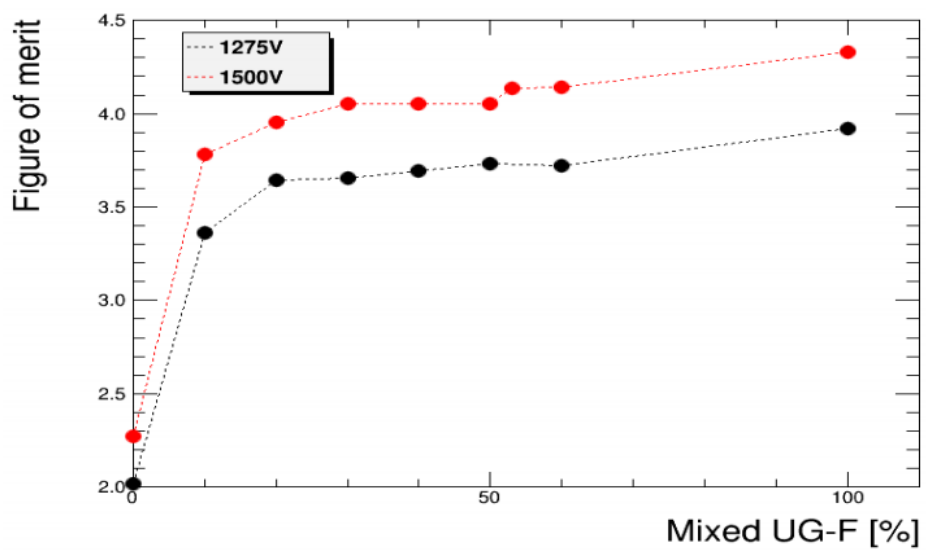
PSD tests

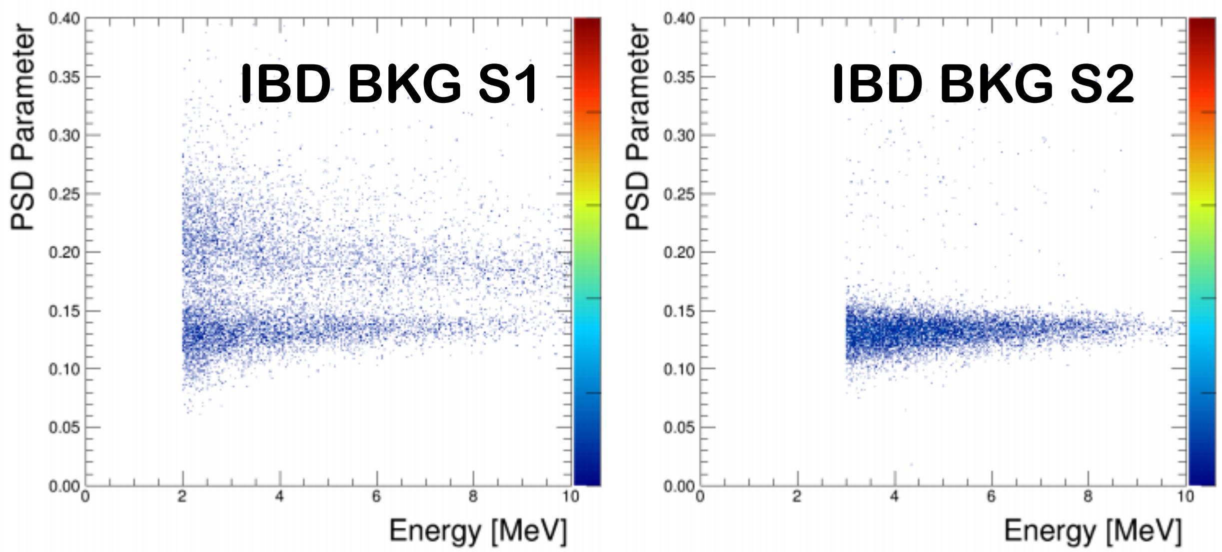






Optimization of fraction





9:1 mixture in prototype

Charge and Time from Waveform

Energy measurement by NEOS detector

- The detector is a calorimeter.
- Signals from PMTs are recorded in waveforms.
- Charge and time are obtained from the waveforms.

Charge Q and FADC value F

- FADC value: height of waveform
- Charge: integration (summation) of waveform

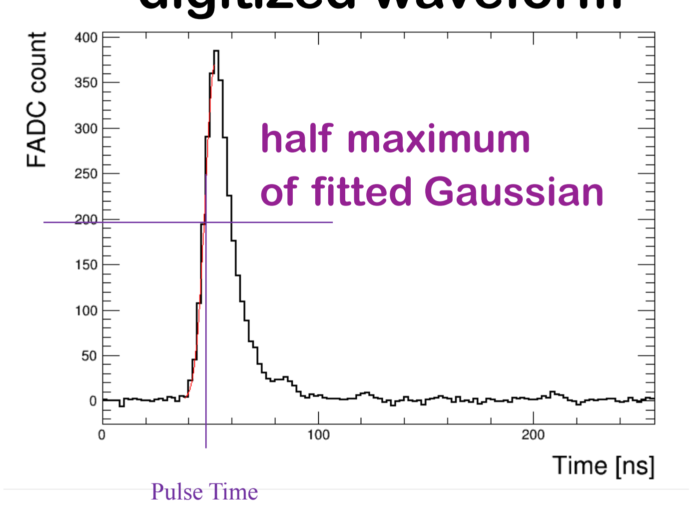
$$Q = \int \frac{V}{R_{terminal}} dt = 0.024 \sum_{i=sbin}^{bin} F_i \quad \Rightarrow \quad Q \approx 0.024 \left(\sum_{i=sbin}^{bin} F_i - (ebin - sbin + 1) F_{pedestal} \right)$$

subtract pedestal

Definition of some information

- Q_{tot} : charge of waveform with whole range
- F_{max} : Maximum of FADC value in Waveform
- F_{maxx}: time bin at F = F_{max}
- t_{pulse} : time at half maximum of fitted Gaussian
- t_{trg} : triggered time of events

digitized waveform



Corrections: Vertex dependency

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.

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

Fitting function and correction function

- fitting function: 4^{th} order polynomial

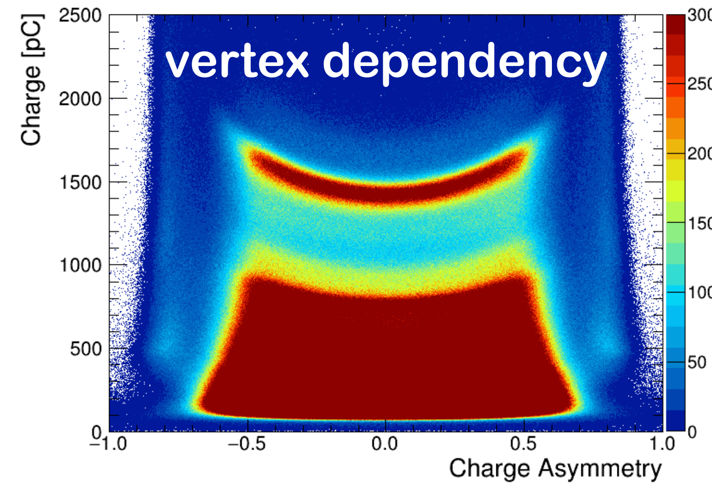
$$f_{\mathrm{asym}}(A_z) = \sum_{i=0}^{4} p_i A_z^i$$

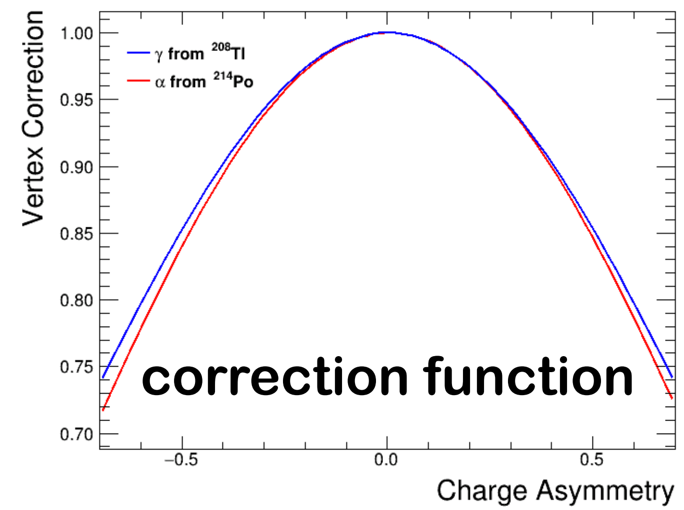
- correction function

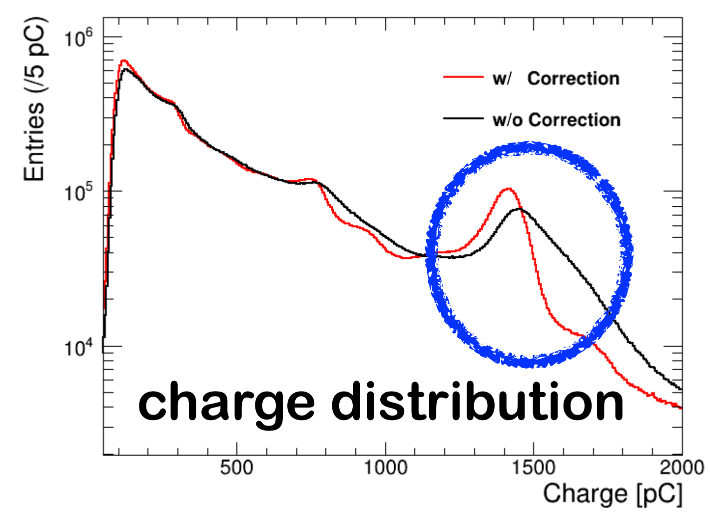
$$c_{\mathrm{vertex}}(A_z) = \frac{f_{\mathrm{asym}}(0)}{f_{\mathrm{asym}}(A_z)}$$

Corrected charge sum

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





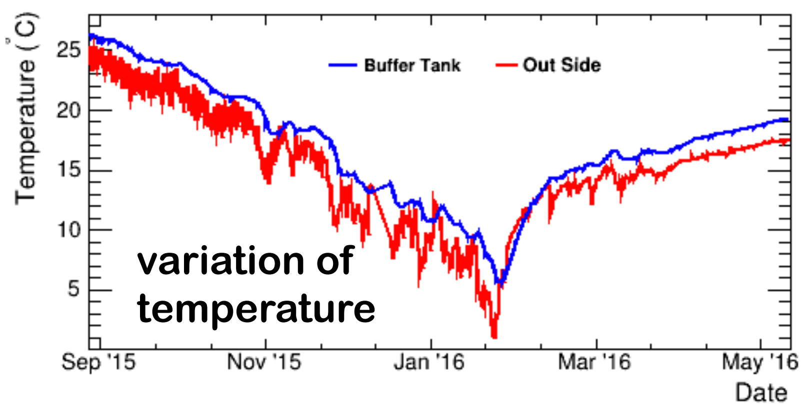


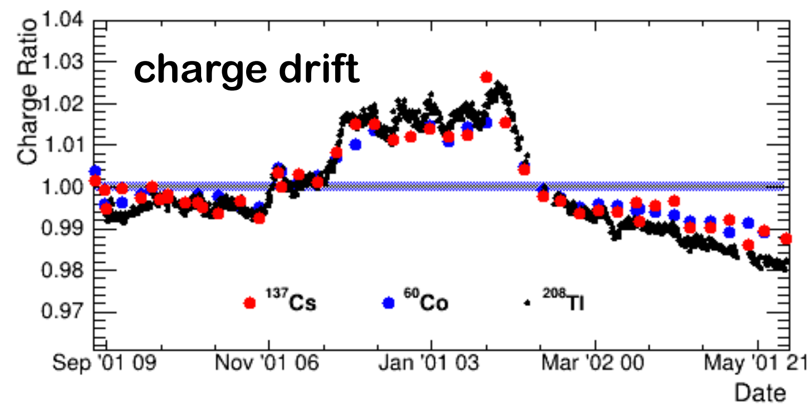
Charge Drift and Muon Selection

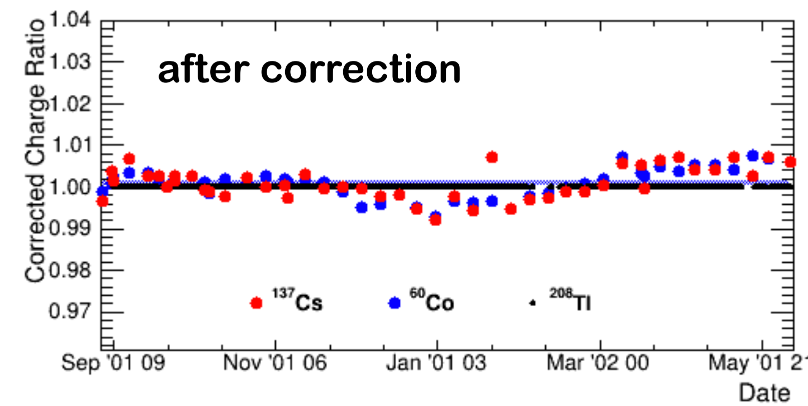
Correction for charge drift

- There are charge drift due to variation of temperature.

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







Muon event selection for veto

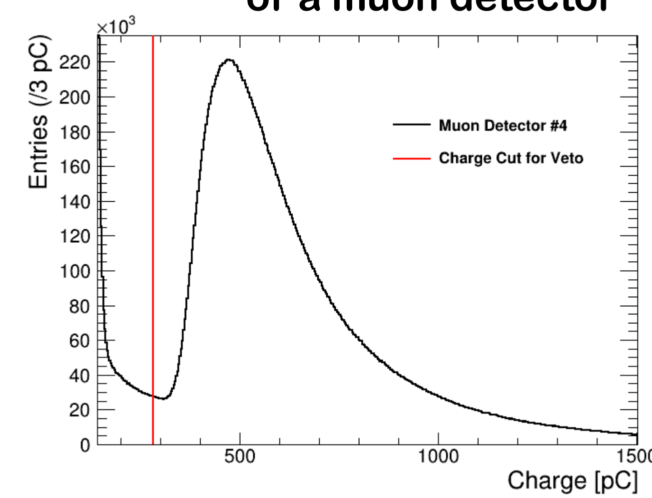
- If it is judged that it is a muon event,

  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



Escaping Gammas

Detector response matrix

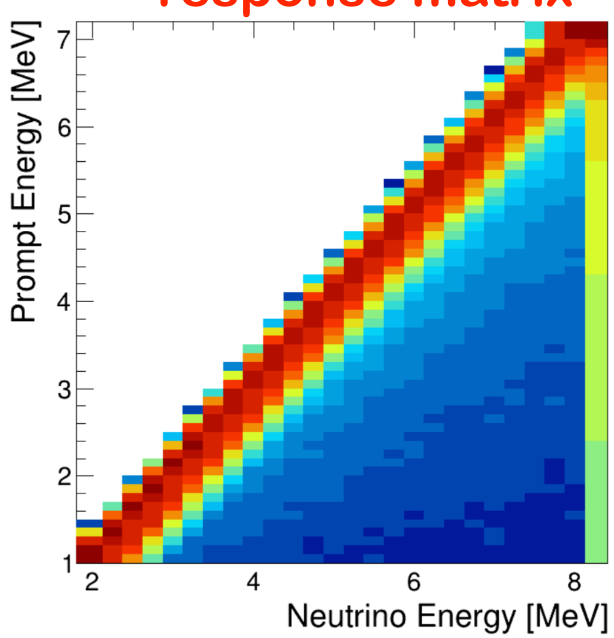
- It has effects of resolution and escaped gamma
- It can be obtained by detector simulation

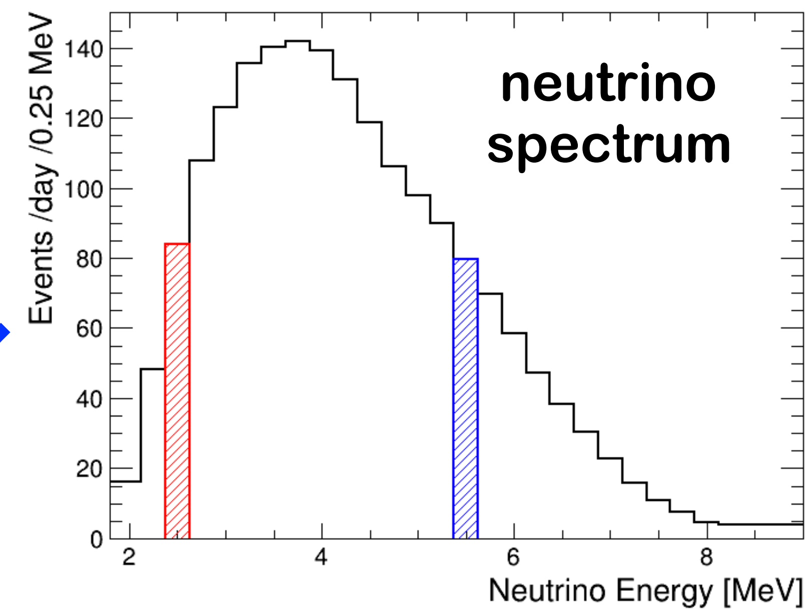
$$N^i_{exp} = \sum_k D^{ik} S^k_{model}$$

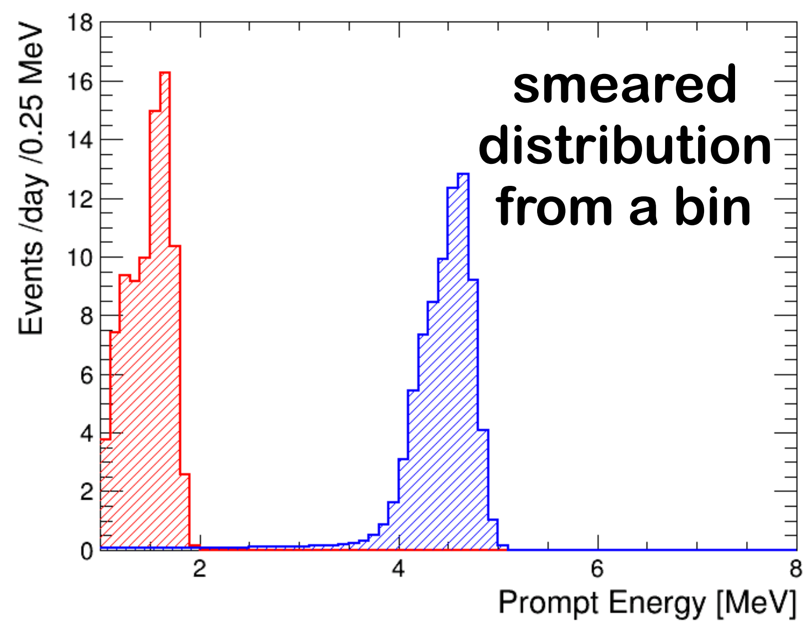
expected number of i^{th} bin

flux of j^{th} bin

response matrix

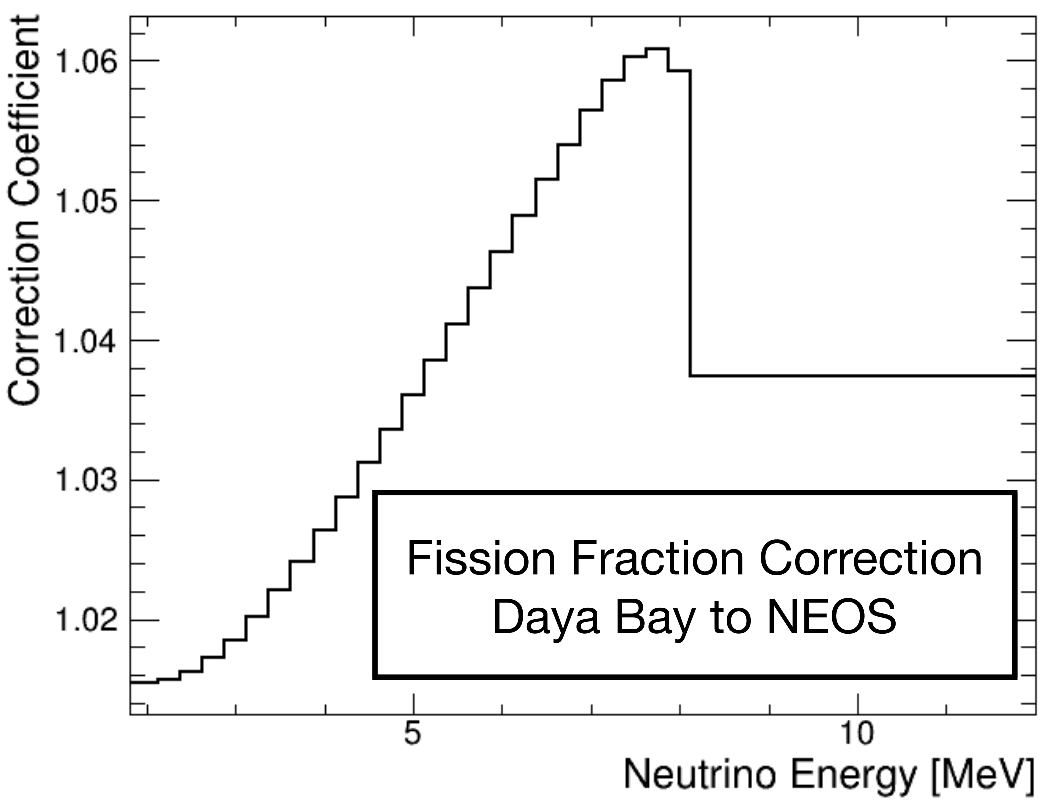


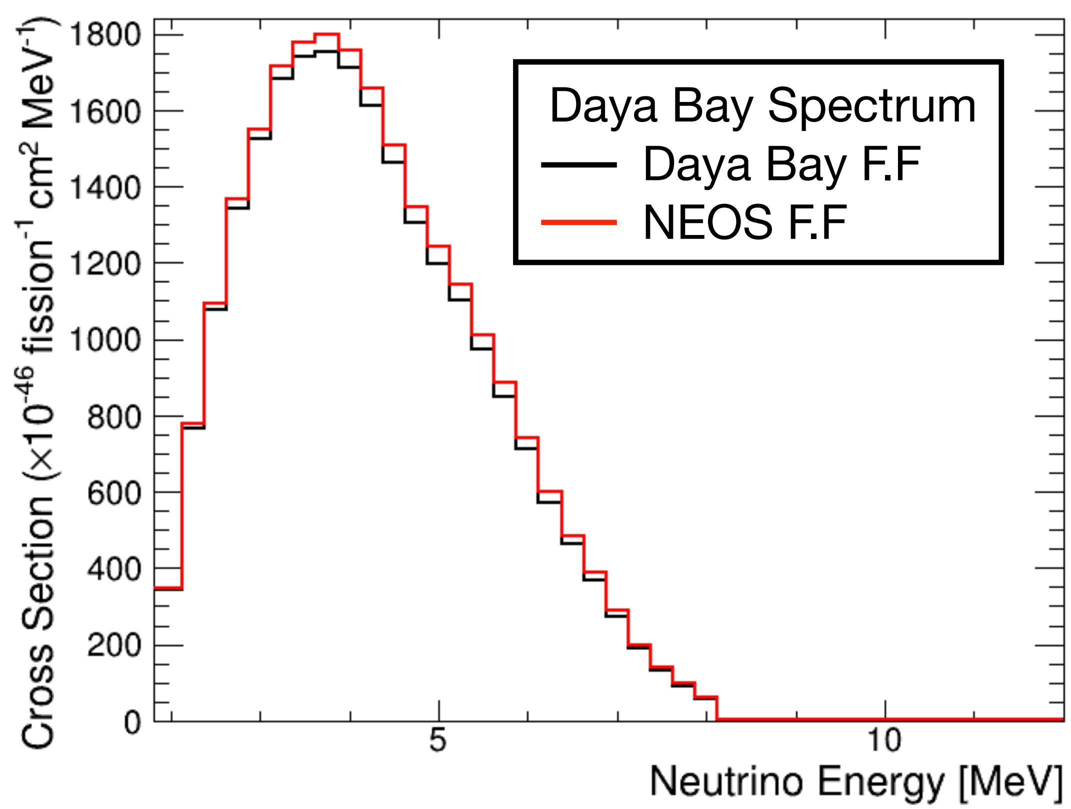




Detector Sensitivity

Fission fraction correction





$$c_{\mathrm{ff}}^{i} = \frac{\sum_k f_k^{\mathrm{NEOS}} \int^{i} \Phi_k(E_{\bar{\nu}_e})\,\sigma(E_{\bar{\nu}_e})\,dE_{\bar{\nu}_e}}{\sum_k f_k^{\mathrm{DB}} \int^{i} \Phi_k(E_{\bar{\nu}_e})\,\sigma(E_{\bar{\nu}_e})\,dE_{\bar{\nu}_e}}$$

HM flux model

Vogel
IBD cross section

Systematic Uncertainties: Flux Model

Propagation of covariance matrix

- Daya Bay provides uncertainty of the flux as the form of a covariance matrix.
- Covariance for analysis is propagated from the covariance of Daya Bay.

$$M^{ij}_{flux} = \sum_{k,l} D^{ik} \frac{V^{kl}_{DB}}{S^k_{DB} S^l_{DB}} D^{jl}$$

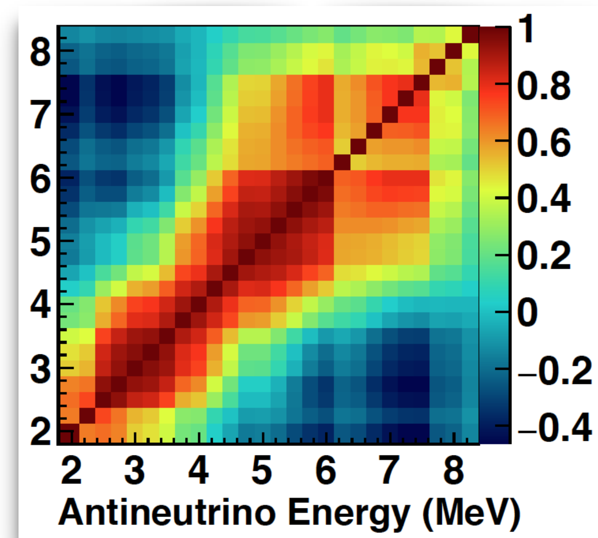
- Correlation matrix

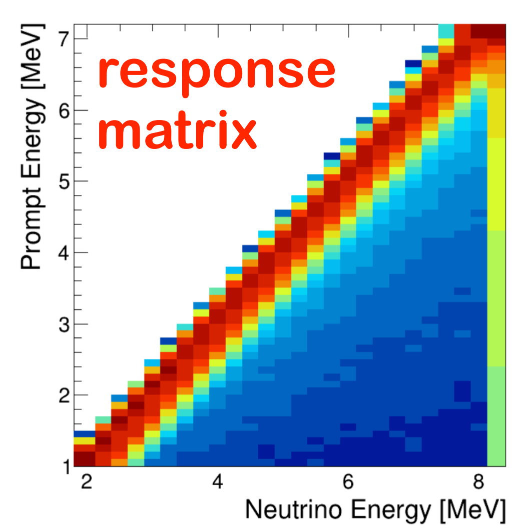
$$\rho^{ij}_{DB} = \frac{V^{ij}_{DB}}{\sqrt{V^{ii}_{DB} V^{jj}_{DB}}}, \quad \rho^{ij}_{flux} = \frac{M^{ij}_{flux}}{\sqrt{M^{ii}_{flux} M^{jj}_{flux}}}$$

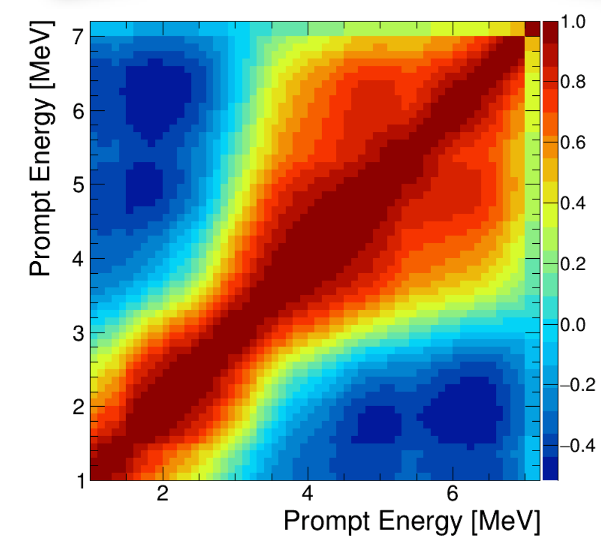
correlation matrix of absolute flux measured by DB

propagated correlation matrix with detector response matrix

correlation matrix of DB







propagated correlation matrix

Systematic Uncertainties: Energy Scale

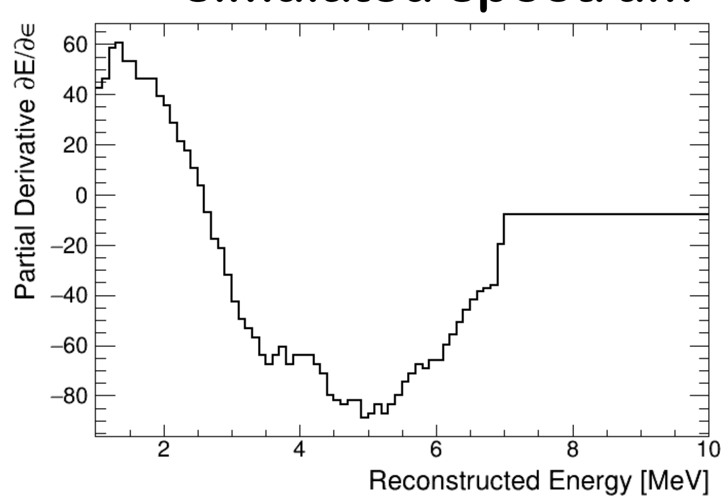
Derivative of template for scale factor ε

- Energy scales of the simulated data and the measured data can be different.
- Systematic uncertainties due to energy scale differences should be considered.

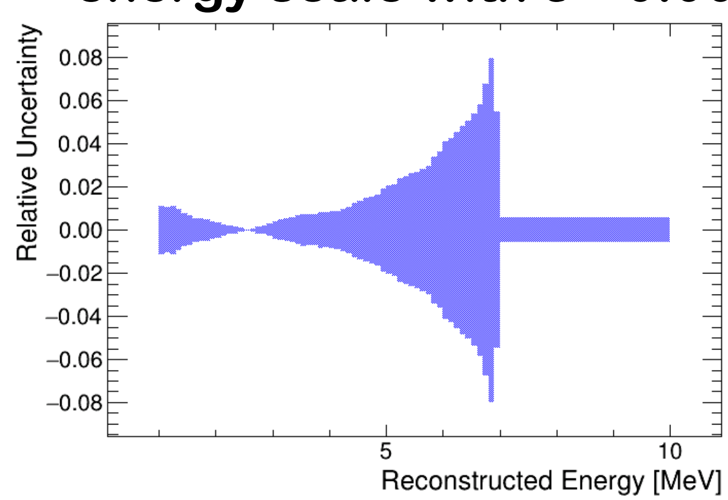
$$N_{\rm exp}\big|_{E\to(1+\sigma_\epsilon)E} \approx N_{\rm exp} + \sigma_\epsilon \frac{\partial N_{\rm exp}}{\partial \epsilon}\bigg|_{\epsilon=0}$$

$$\text{where} \quad \frac{\partial N_{\rm exp}}{\partial \epsilon}\bigg|_{\epsilon=0} = \frac{f_N(E(1+\Delta\epsilon)) - f_N(E(1-\Delta\epsilon))}{2\Delta\epsilon}$$

derivative of simulated spectrum



systematic uncertainty of energy scale with ε = 0.005



Covariance Matrix and Chi-square Distribution

Covariance matrix

- Covariance method is used for analysis
- All uncertainties must be expressed in the form of a covariance matrix.

$$M^{ij} = M^{ij}_{\mathrm{stat,on}} + M^{ij}_{\mathrm{stat,off}} + M^{ij}_{\mathrm{norm}} + M^{ij}_{\epsilon} + M^{ij}_{\mathrm{bkg}} + M^{ij}_{\mathrm{flux}}$$

statistical uncertainty of reactor-on period

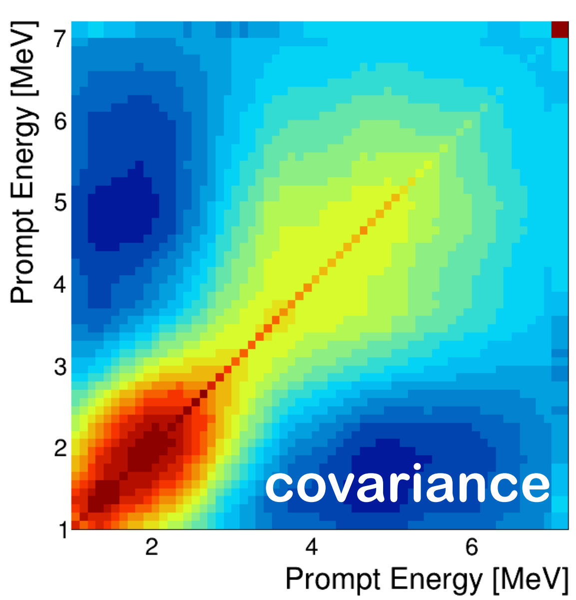
statistical uncertainty of reactor-off period

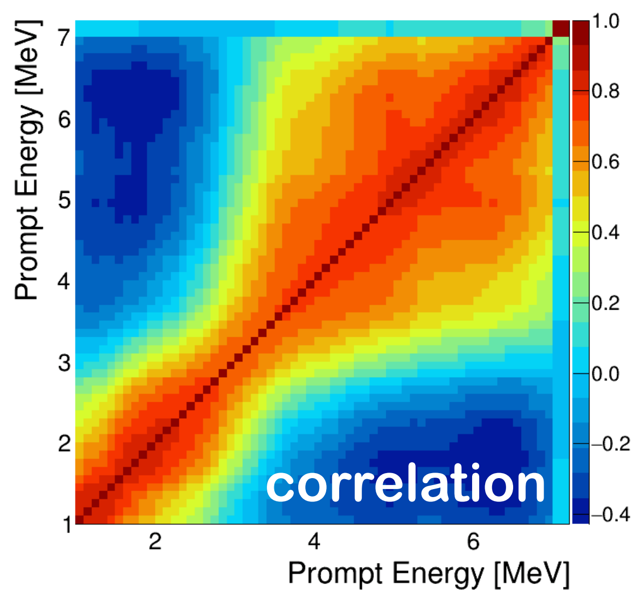
overall normalization (shape-only analysis)

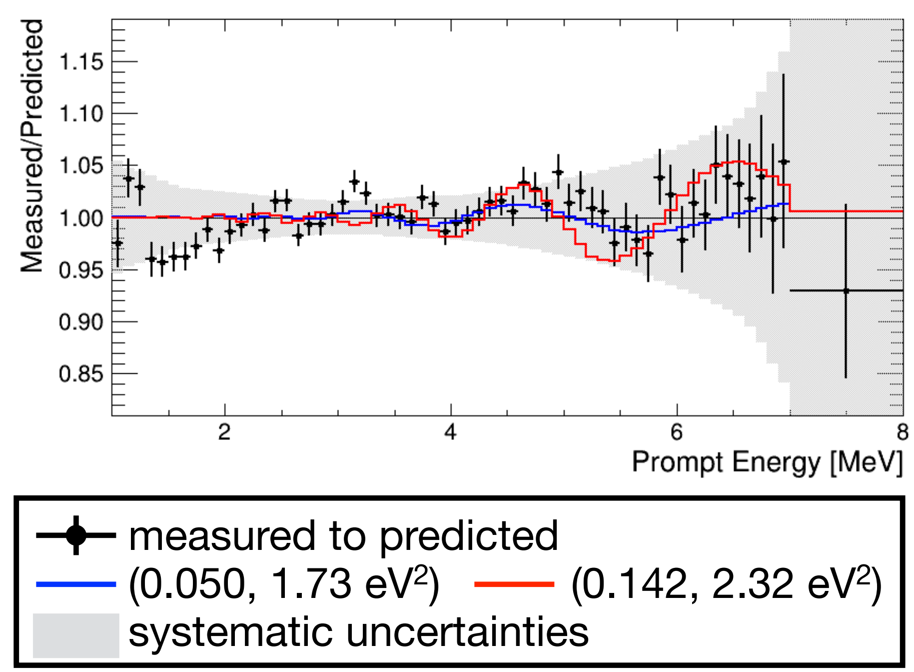
systematic uncertainty of energy scale

background normalization

uncertainty propagated from flux model







Covariance Matrix and Chi-square Distribution

Chi-square formula

- **Covariance method**
- **Shape-only analysis**

$$\chi^2 = \sum_{i,j} \left(N^i_{\rm obs} - N^i_{\rm exp}\right) \left[M^{ij}\right]^{-1} \left(N^j_{\rm obs} - N^j_{\rm exp}\right)$$

$$\text{where} \quad N^i_{\rm obs} = N^i_{\rm on} - (t_{\rm on}/t_{\rm off}) N^i_{\rm off}$$
$$N^i_{\rm exp} = N^i_{\rm exp}(\sin\theta_{14},\ \Delta m^2_{41})$$

Hypothesis	χ^2/NDF	$\sin^2 2\theta_{14}$	Δm_{41}^2 [eV^2]
3ν	64.0/61	0	0
4ν (best)	57.5/59	0.05	1.73
RAA (best)	69.4/59	0.142	2.32

$\Delta\chi^2 = 6.5$