NEOS-II Status Report

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On behalf of the NEOS collaboration

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IAEA

Center for Underground Physics ibs

❑ NEOS-II Goals & Achievements:

1. understanding of reactor neutrino **anomalies** → finalizing the analysis
2. Search for **sterile neutrinos** → close to the preliminary result

❑ Challenges:

1. **Decrease of light yield** during data-taking
2. **Small group** consisting of only domestic institutions

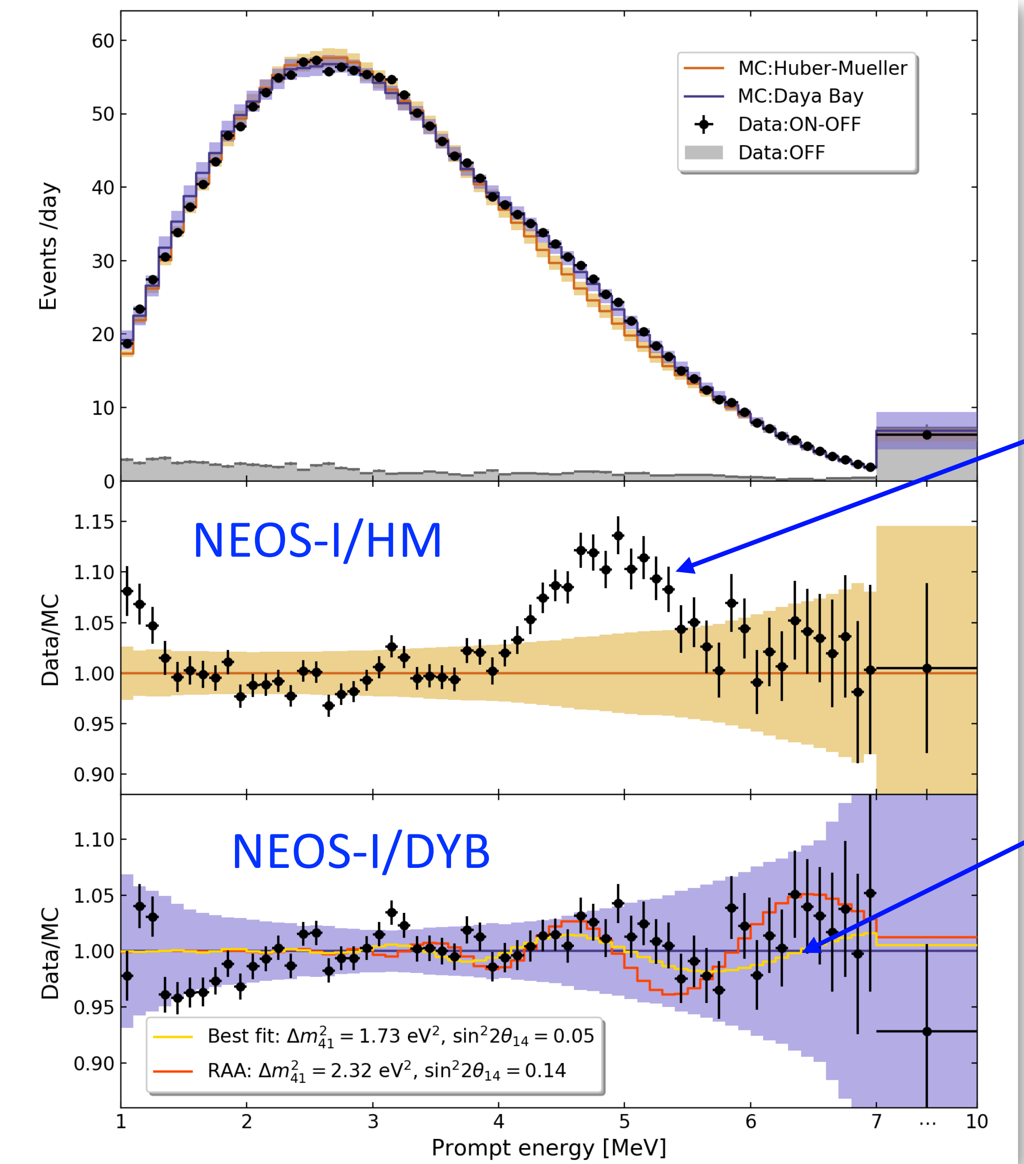
❑ Opportunities:

1. NEOS-II detector has one of the **best energy resolutions** among VSBL exp.
2. High statistics (commercial reactor)
3. Low background (good overburden: ~20 mwe)
4. Excellent PSD: **S/B = 29**
5. **Full Fuel cycle** data
6. Beyond NEOS-II?

NEOS-I Results in 2017

NEOS 180 (46) days reactor-on(off)data

- 1977 (85) IBD/day during on (off) period; S/B ~ 22



PRL 118, 121802 (2017)

"5 MeV excess" observation

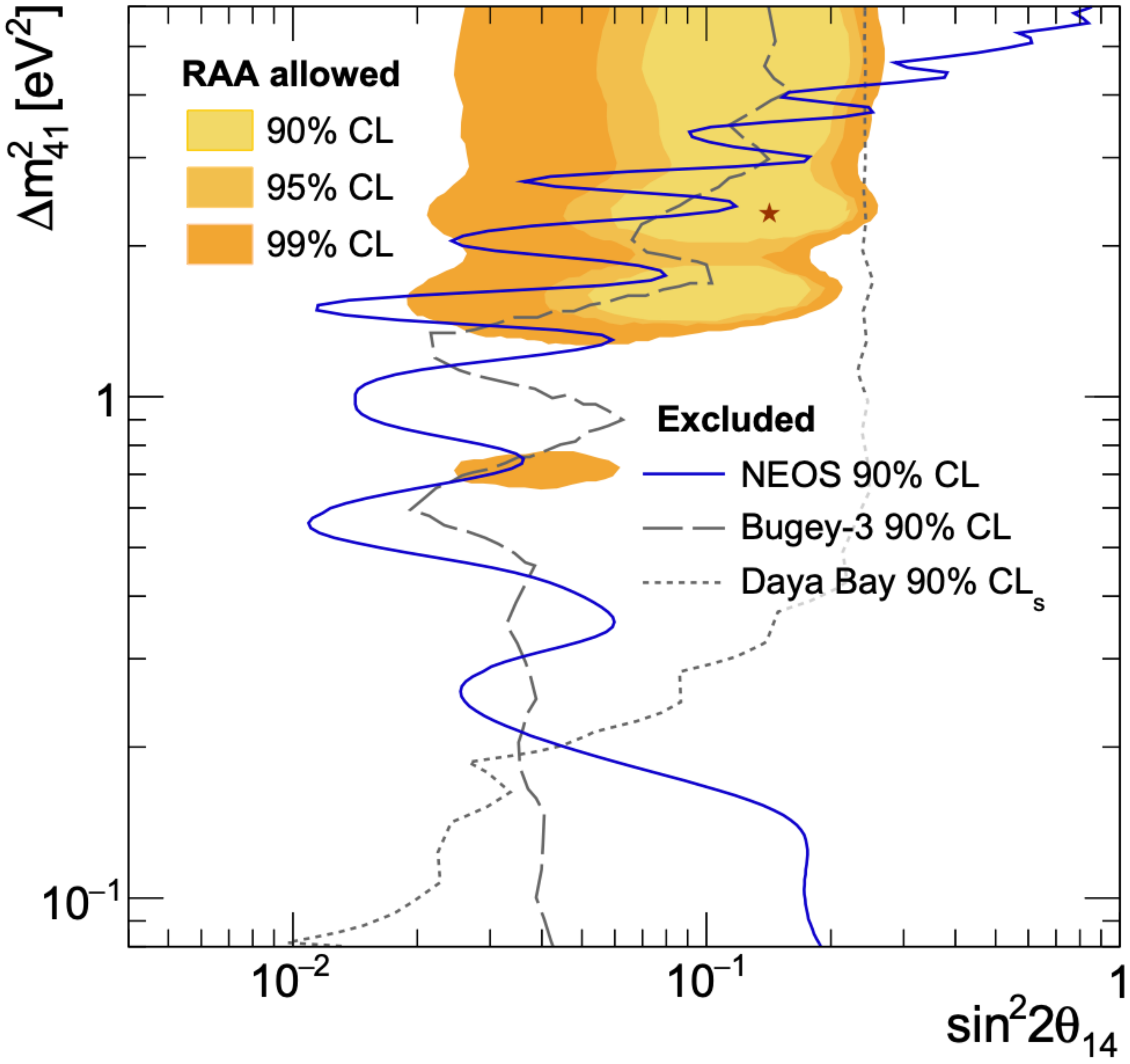
NEOS best fit values:

(1.73 eV^2, 0.05), (1.30 eV^2, 0.04)
with $\chi^2(3\nu) - \chi^2(4\nu) = 6.5$
p-value = 0.22

→ No strong evidence of active-to-sterile neutrino oscillation

NEOS-I Results in 2017

NEOS 180 (46) days reactor-on(off)data



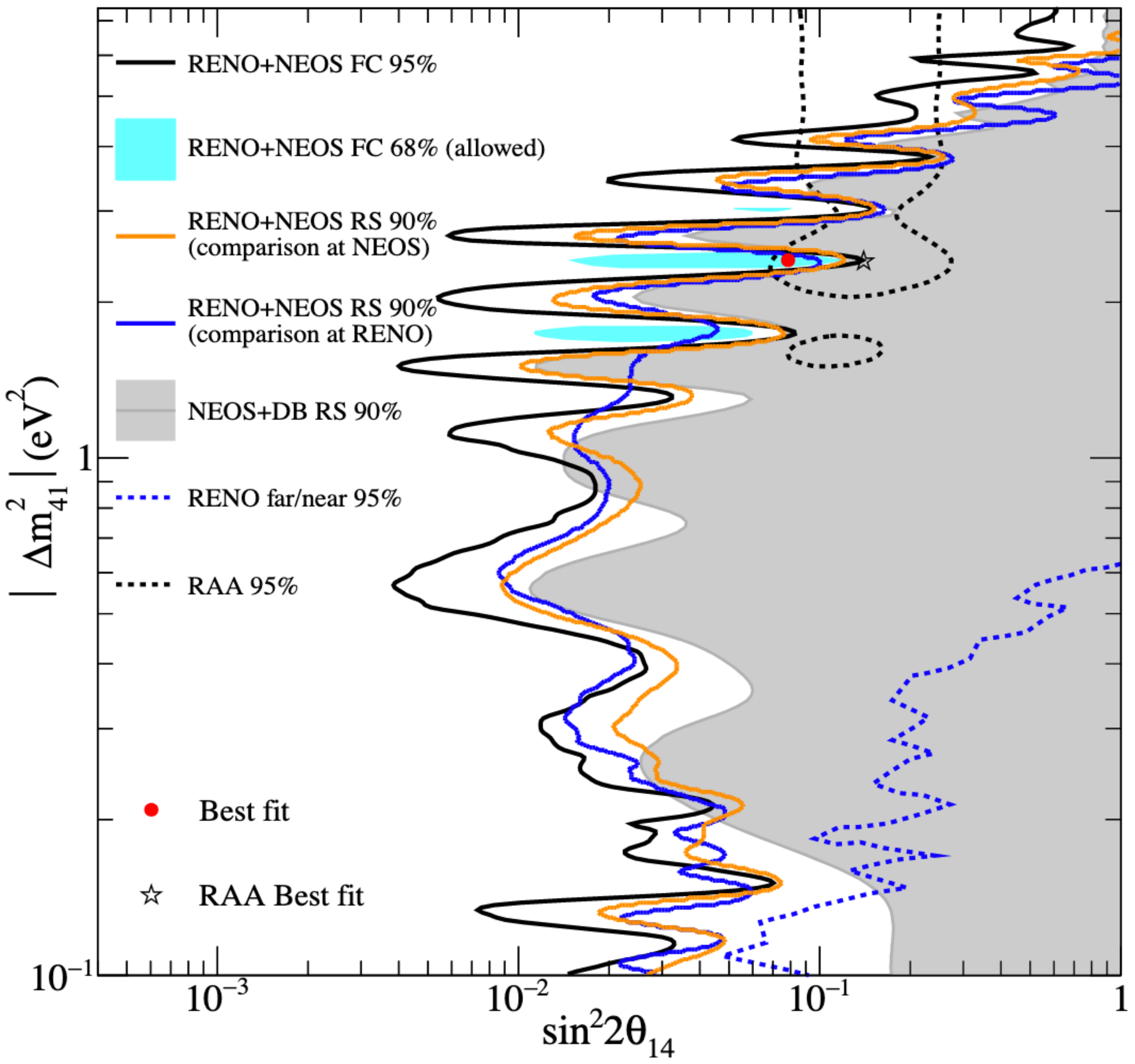
PRL 118, 121802 (2017)

- RAA best fit is excluded at ~4 σ.
- Limited by "systematic" uncertainty (model, energy scale).

** Daya Bay data was used as a reference model (3ν osc.).

NEOS-I + RENO Results in 2022

NEOS-I & RENO Joint Analysis



Phys. Rev. D 105, L111101 (2022)]

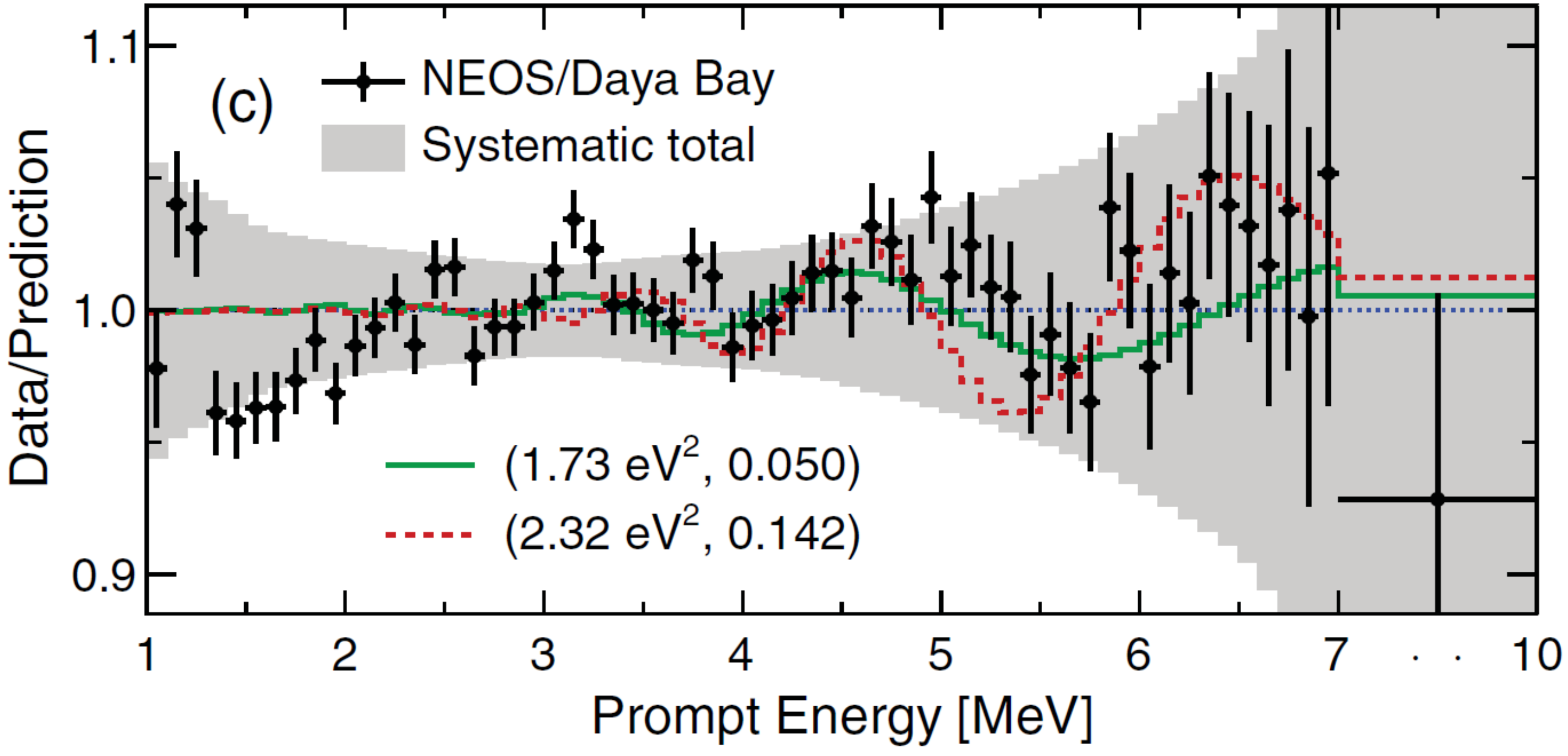
→ The NEOS-I & RENO result is improved compared to the NEOS-I & DYB result.

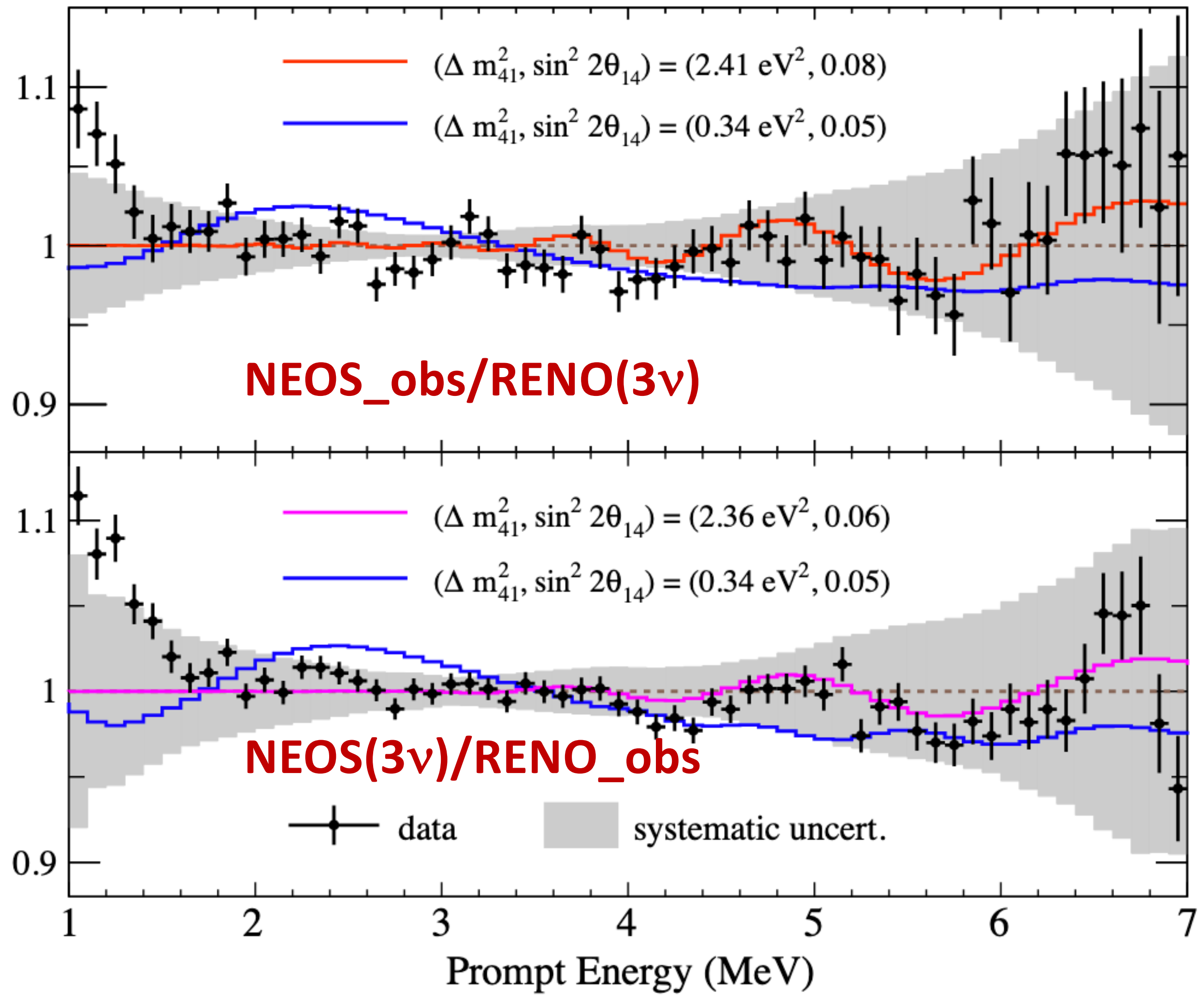
- The best fit falls in RAA 95% allowed region.

➢ NEOS+RENO best fit: (2.41 eV^2, 0.08) with $\chi^2(3\nu) - \chi^2(4\nu) = 8.4$, p-value = 8.2%

** RENO data was used as a reference model (3ν osc.).

Sterile ν oscillation feature or not ???





- NEOS best fits: (1.73 eV^2, 0.05), (1.30 eV^2, 0.04) with $\chi^2(3\nu) - \chi^2(4\nu) = 6.5$, p-value = 22%

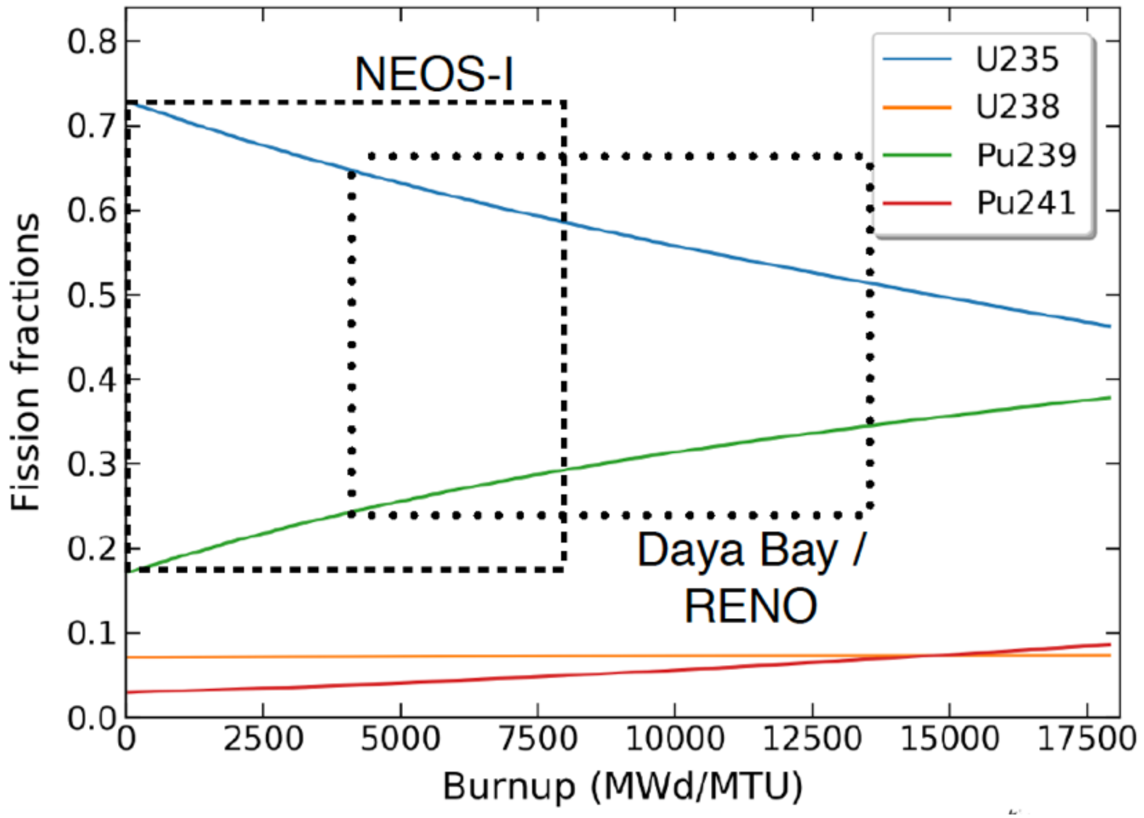
- A. Sonzogni et al. @ AAP2018:
This feature is due to ^{99}Nb, ^{143}La, ^{92}Y, ^{99}Zr.

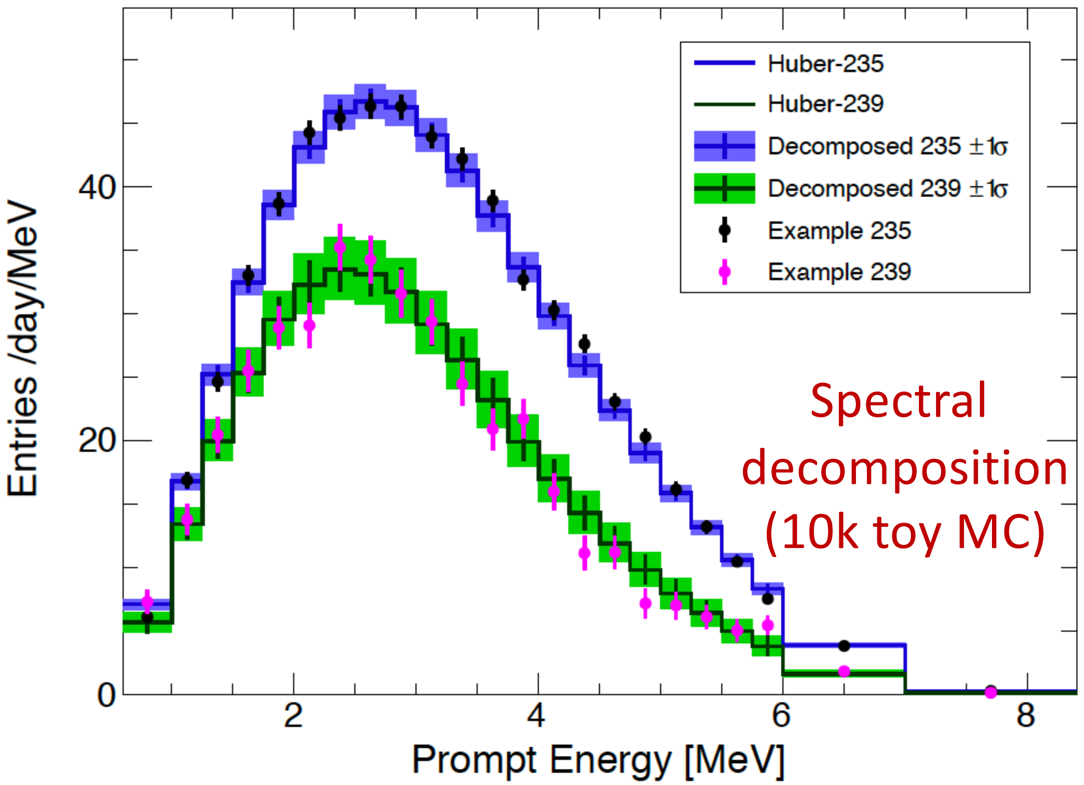
- NEOS+RENO best fit: (2.41 eV^2, 0.08) with $\chi^2(3\nu) - \chi^2(4\nu) = 8.4$, p-value = 8.2%

If Sonzogni et al are correct, we should observe the same feature in NEOS-II, PROSPECT, STEREO data.

NEOS-II (Sept. 2018 – Oct. 2020)

- Refurbished detector from NEOS-I.
- Took ~388 live days of data (full fuel cycle) + 2 OFF periods (45+67 days)
- Time evolution of reactor ν flux/shape; spectral decomposition
- Rate+Shape analysis on (3+1)ν oscillation





Spectral decomposition (10k toy MC)

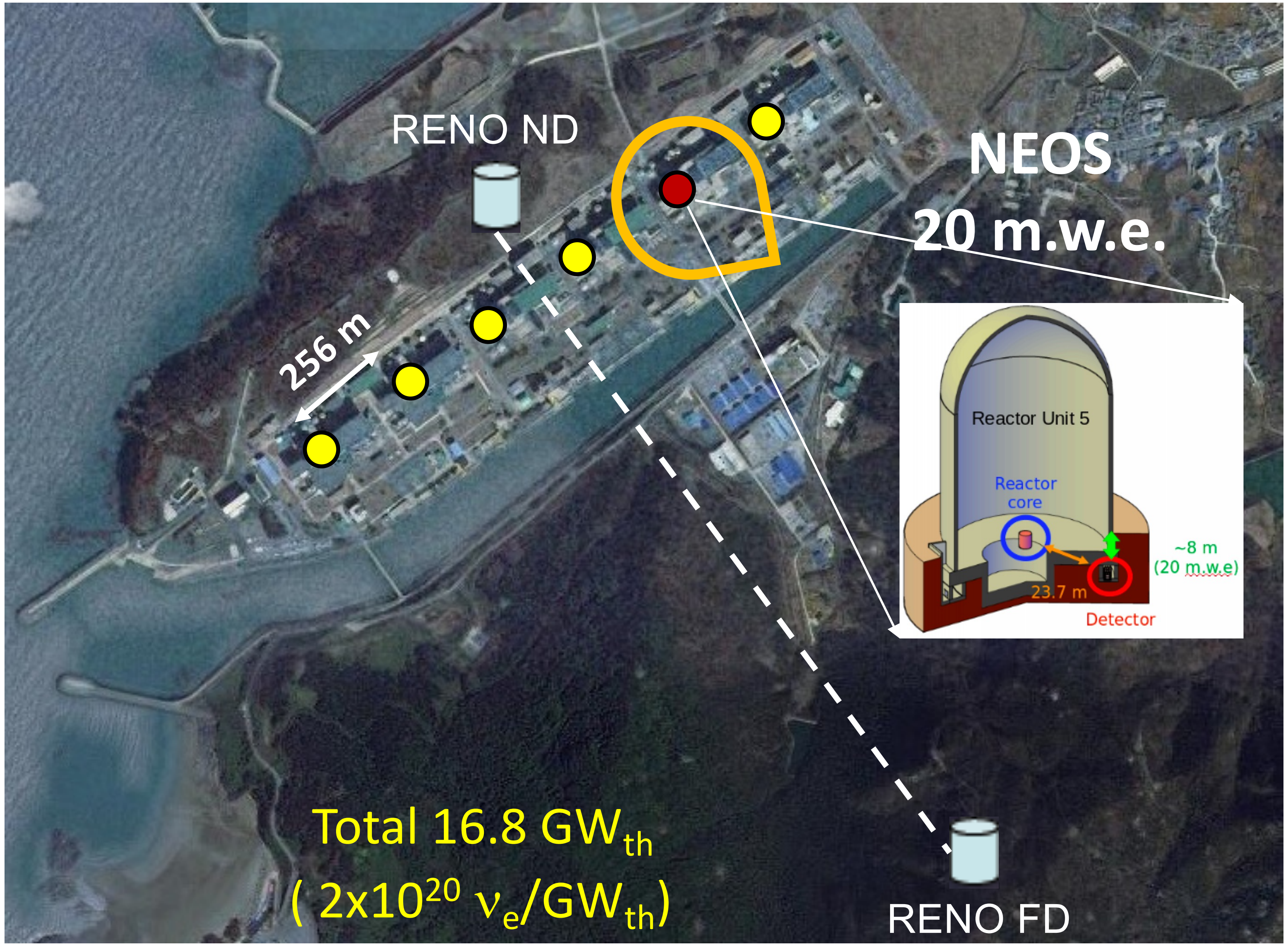
NEOS-II Collaboration

Currently, total **20** members from **7** institutions

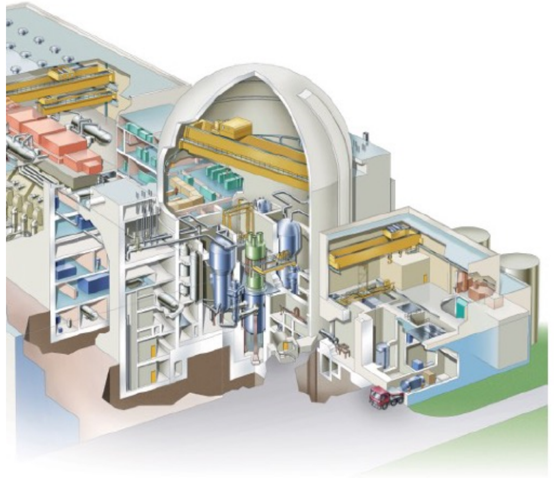
- ❑ Chung-Ang University (CAU)
- ❑ Institute for Basic Science (IBS)
- ❑ Korea Atomic Energy Research Institute (KAERI)
- ❑ Kyungpook National University (KNU)
- ❑ Korea University (KU)
- ❑ Sejong University (SJU)
- ❑ Sungkyunkwan University (SKKU)

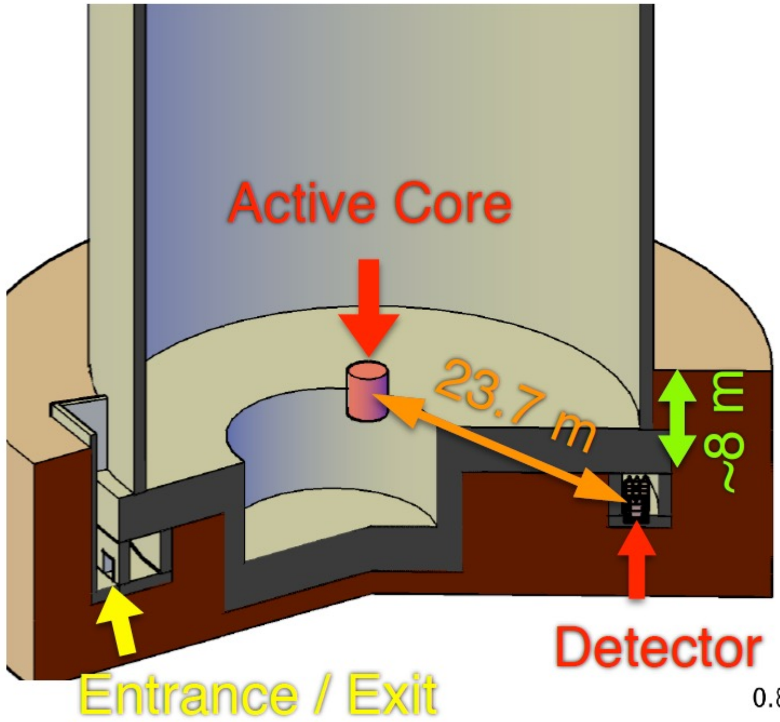
NEOS Site

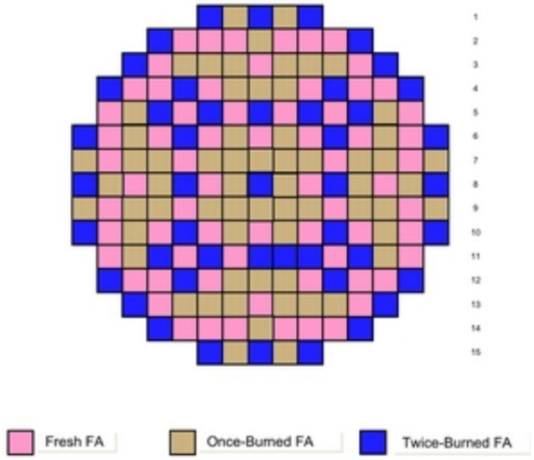

RUSSIA
CHINA
HAMGYŎNG BUK-DO
HAMGYŎNGNAM-DO
P'YŎNG-ANBUK-DO
P'YŎNG-AN NAM-DO
HWANGHAE-DO
KANGWON-DO
KYŎNGGI-DO
38°
KOREA
YongGwang
CH'UNG CH'ŎNG BUK-DO
CH'UNG CH'ŎNG NAM-DO
KYŎNGSANG BUK-DO
CHŎLLA BUK-DO
KYŎNGSANG NAM-DO
CHŎLLA NAM-DO
CHEJU-DO
KOREA STRAIT
JAPAN


RENO ND
NEOS
20 m.w.e.
256 m
Reactor Unit 5
Reactor core
~8 m
(20 m.w.e)
23.7 m
Detector
Total 16.8 GW_{th}
($2x10^{20}$ ν_e/GW_{th})
RENO FD

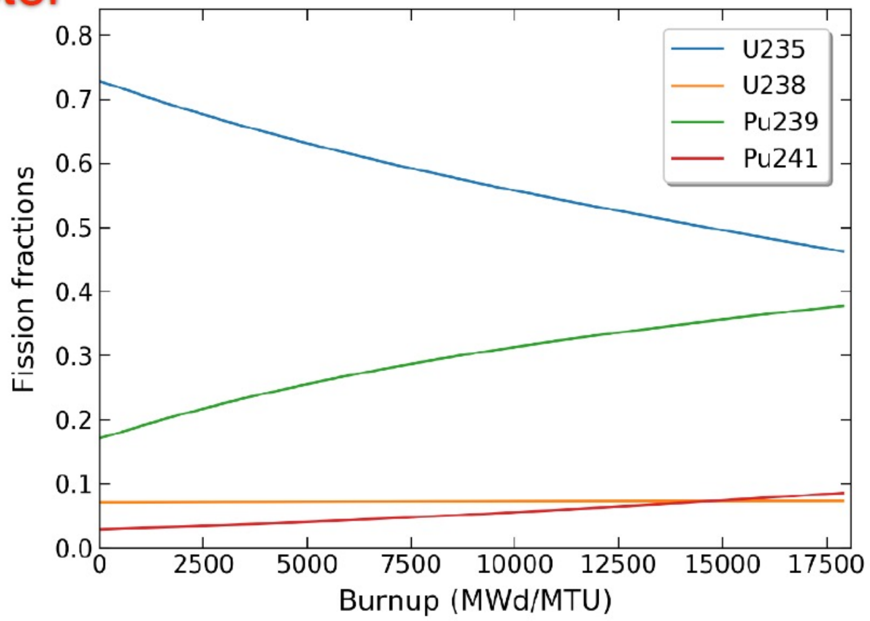
Hanbit-5 reactor and tendon gallery





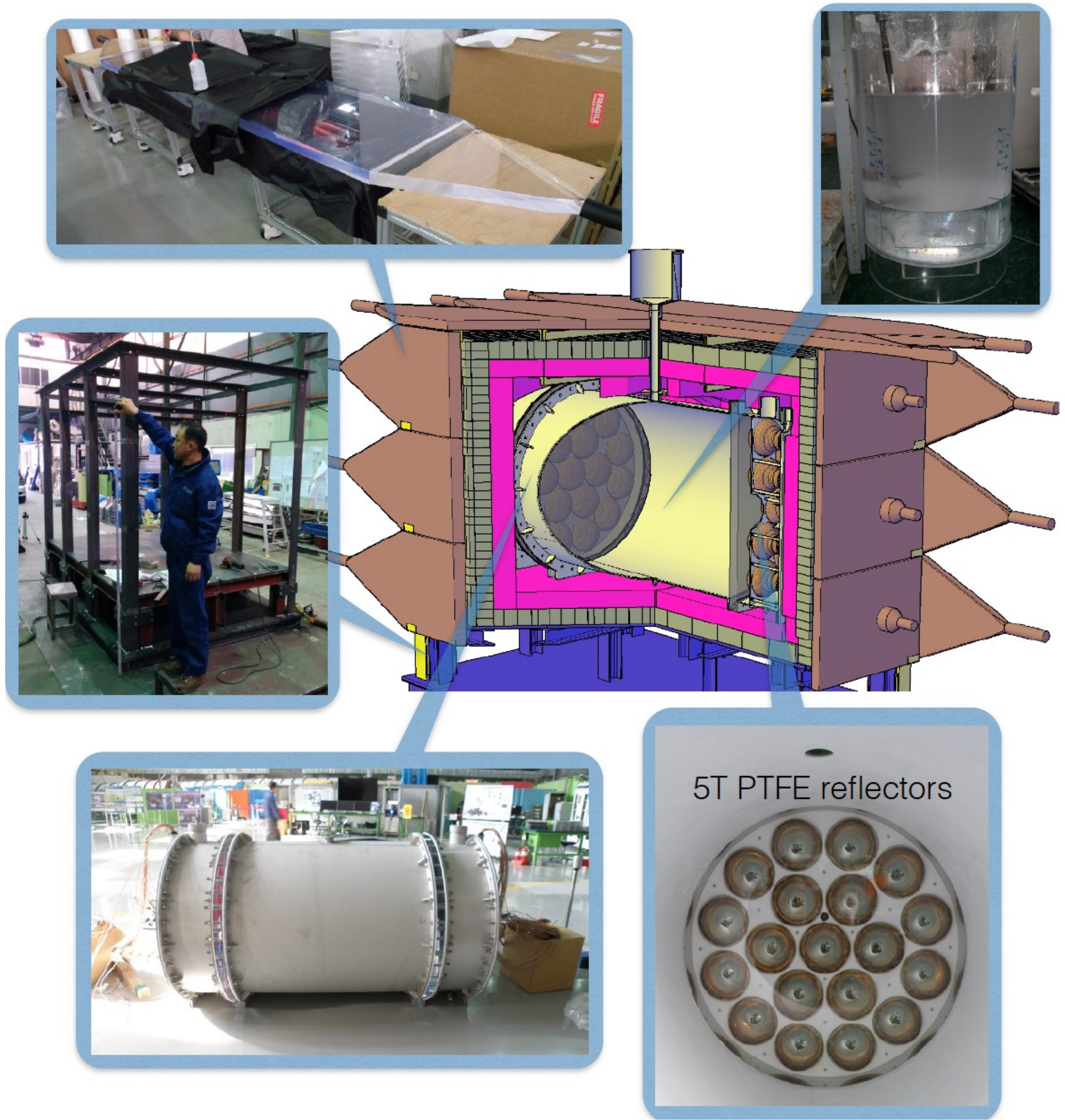


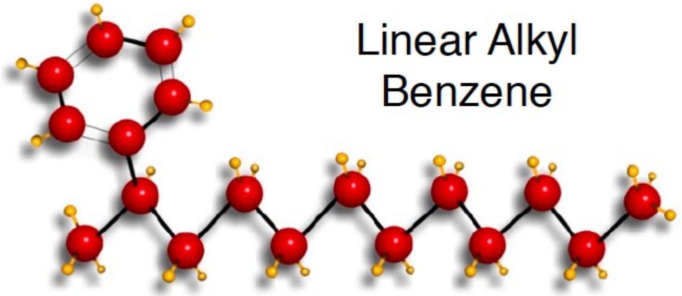
- Thermal power: 2.8 GW
- Active core size: Φ 3.1 m, H 3.8 m
- LEU fuel: ~4.x% U-235 enrichment
- Distance between neighboring cores: 256 m
- L = 23.7 m
- Overburden > 20 m.w.e.



NEOS Detector

➢ NEOS-II detector is refurbished from NEOS-I, almost identical.





* Homogeneous LS target
  - 1008 L volume
    (R 51.5, L 121) cm
  - LAB+UG-F (9:1)
  - 0.5% Gd loaded for high neutron capture efficiency
  - 38 8″ PMT in mineral oil buffer

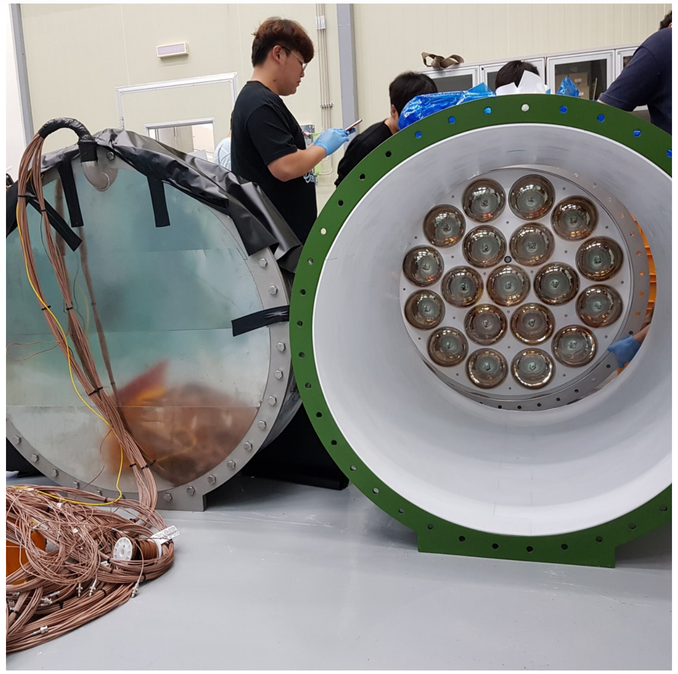
3% PPO
0.03% bis-MSB

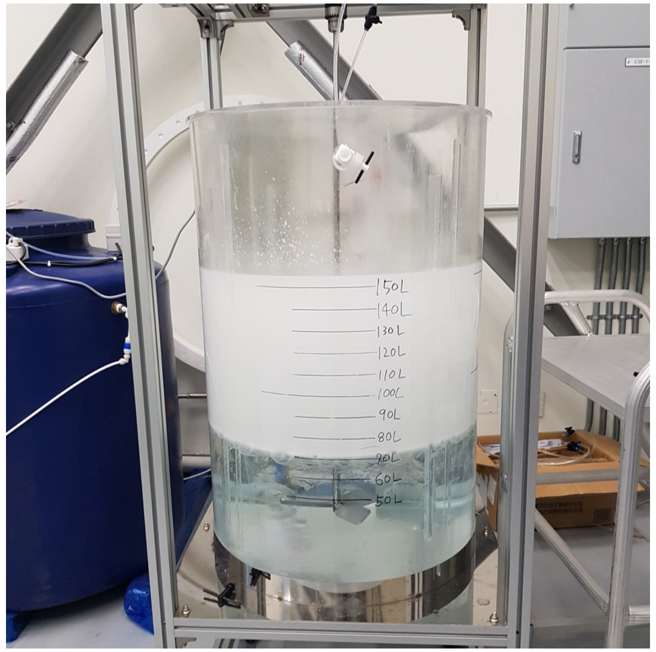
* Shieldings
  - 10 cm B-PE (n), 10 cm Pb (γ)
  - active muon counter
* Data AcQuisition
  - 500 MS/s FADC (waveform)
  - 62.5 MS/s ADC (μ veto)
* Source calibration through chimney

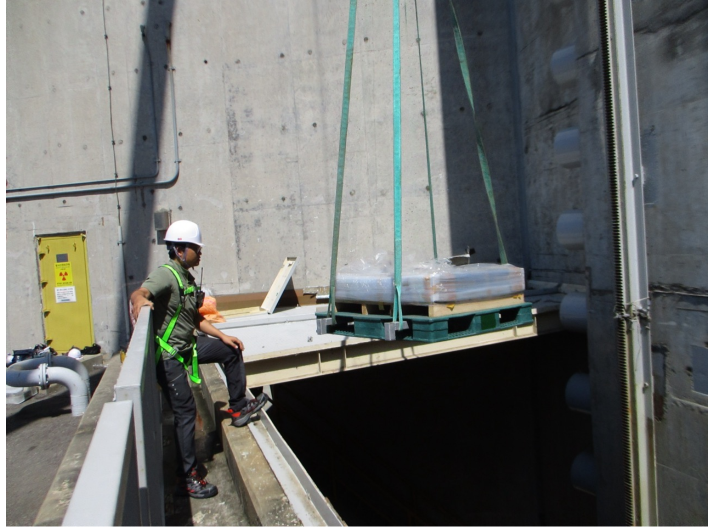
* Newly produced Gd-LS w/ the same recipe

* 9/15 muon counters are newly prepared.

NEOS-II Preparation (July~Sept. 2018)



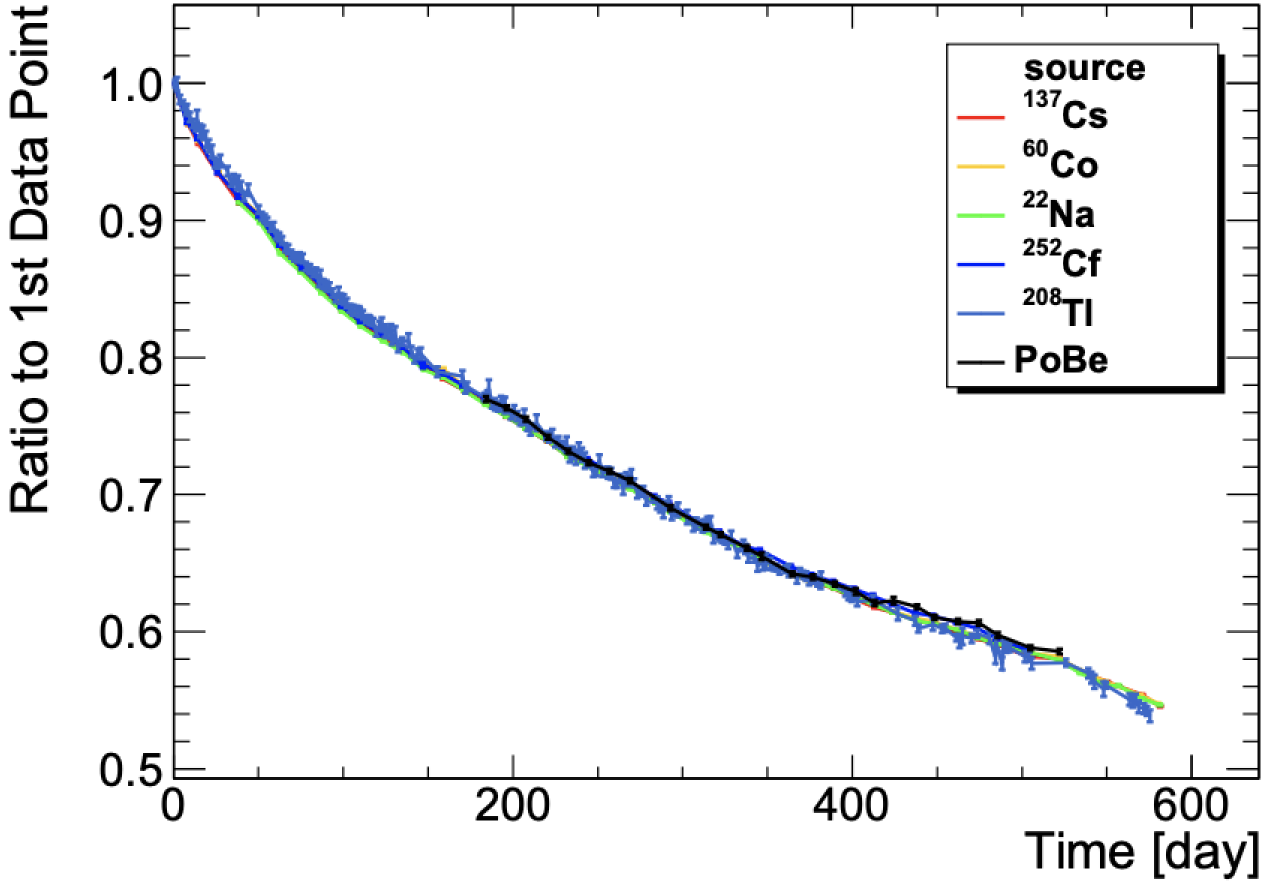


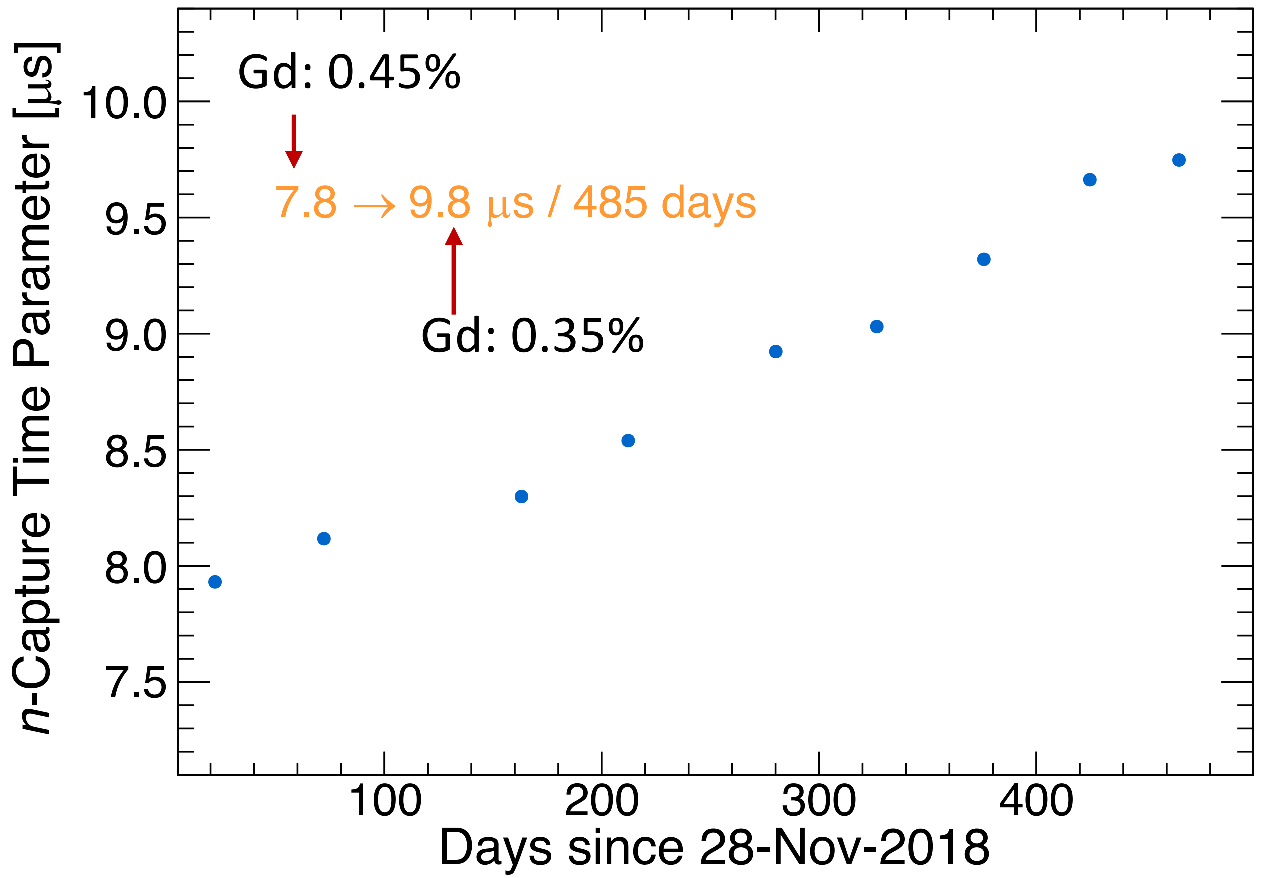



2018. Sept.

Challenge

➢ Continuous decrease of light yield during data-taking





➢ ~46% decrease is observed at end of data-taking

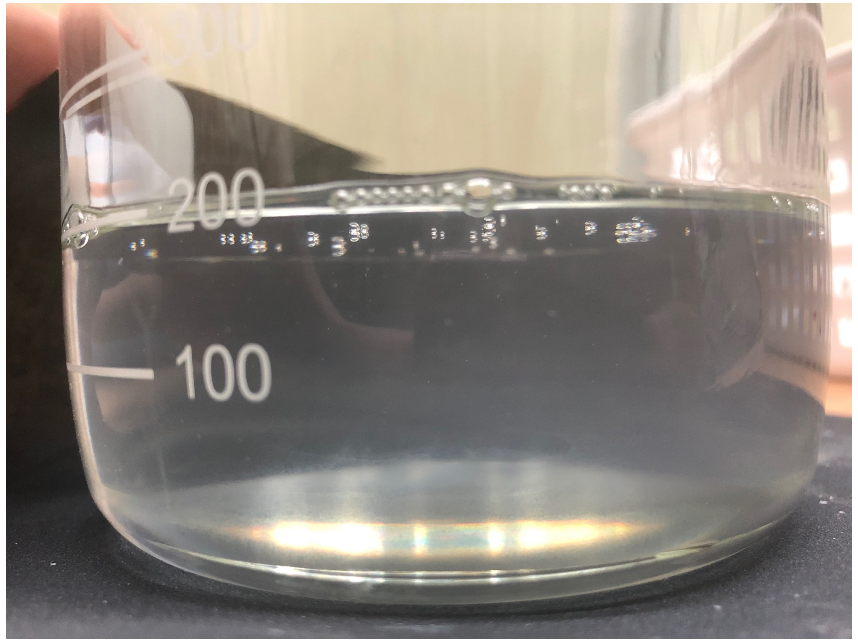
➢ Light yield decrease is independent on energy.

➢ Delayed time increase is observed, too.

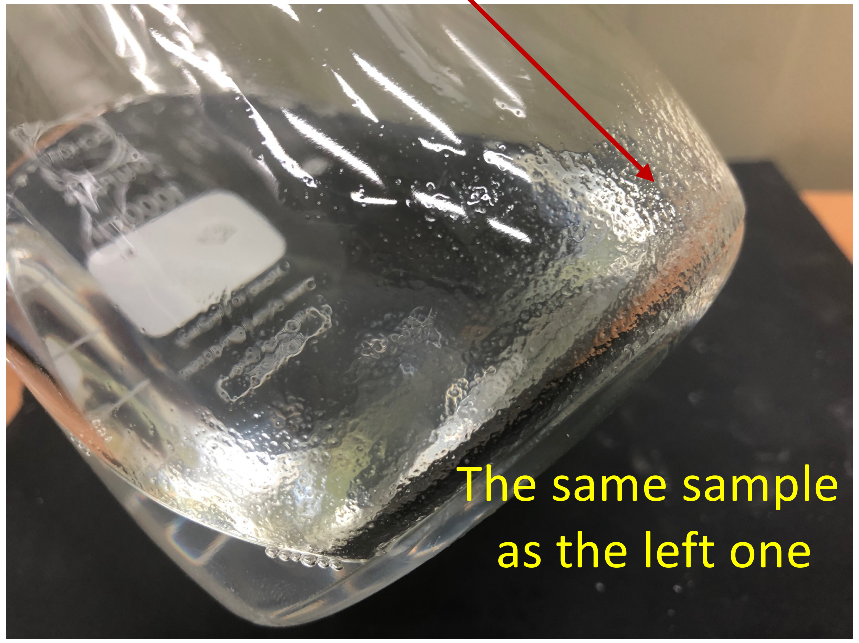
GdLS Sample from Target in 2019

* Precipitation was observed at the wall and bottom.

* Precipitation contains Gd compound.



Sample taken in 2019.03.05



❑ Possible causes of LY decrease:

→ Inflow of humidity/oxygen to GdLS??

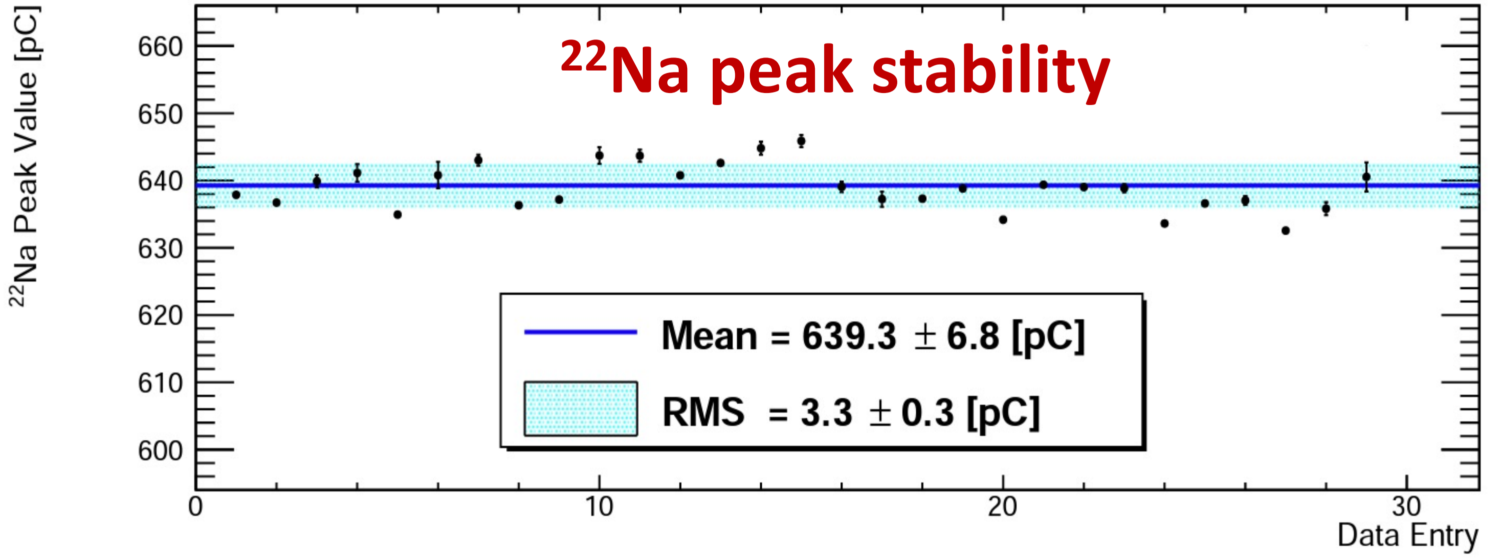
→ High concentration of Gd??

Coping w/ LY Decrease

1. Charge (pe) correction

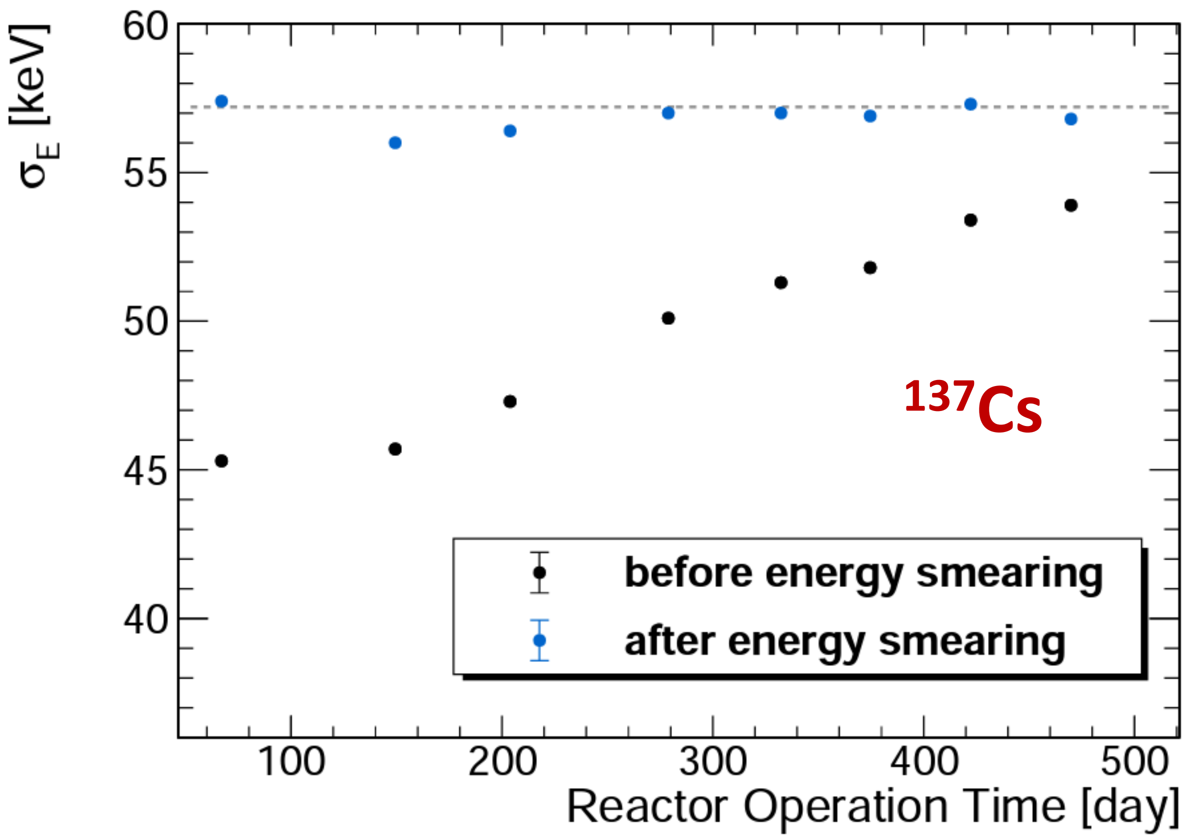
→ Reference: ^{208}Tl peak in data

→ This is always done regardless of LY decrease.



2. Energy resolution correction

→ Corrected to the worst energy resolution (7.3%)

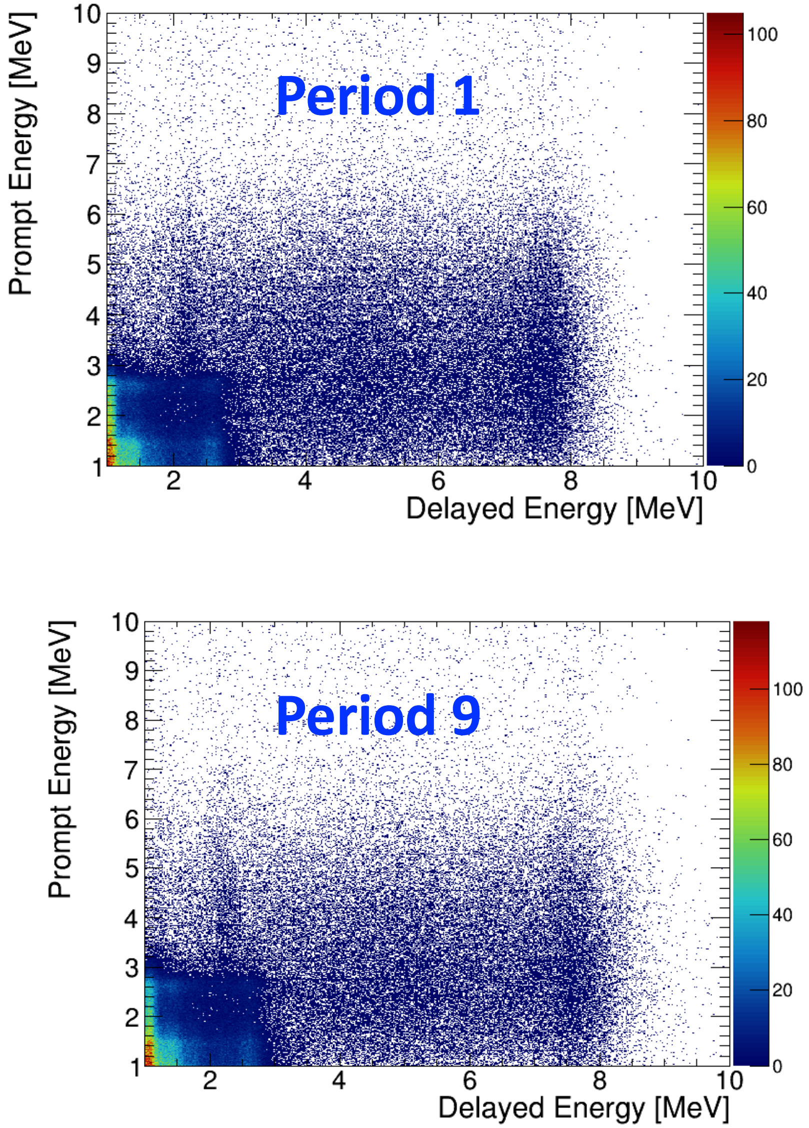


3. Change IBD selection cut values

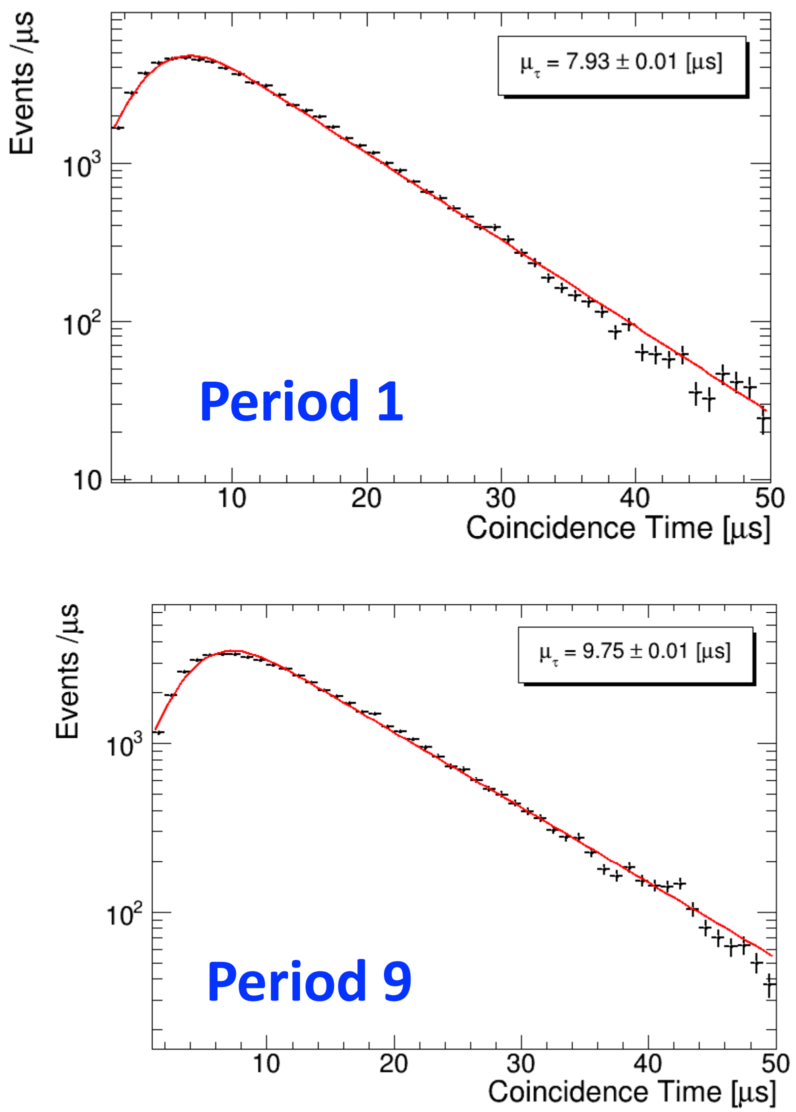
→ To keep the same detection efficiency

NEOS-II Initial & Latest Data Sets

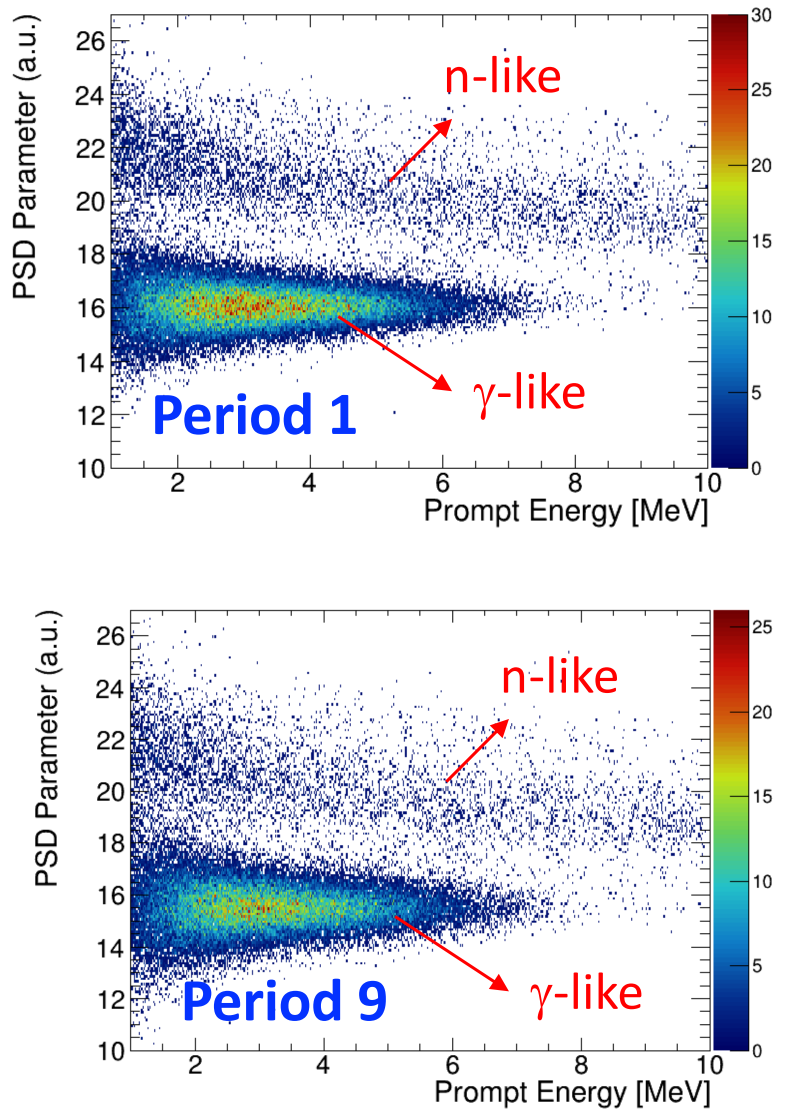
- ❑ Prompt Vs. Delayed Energy



- ❑ Delayed Time



- ❑ Pulse Shape Discrimination

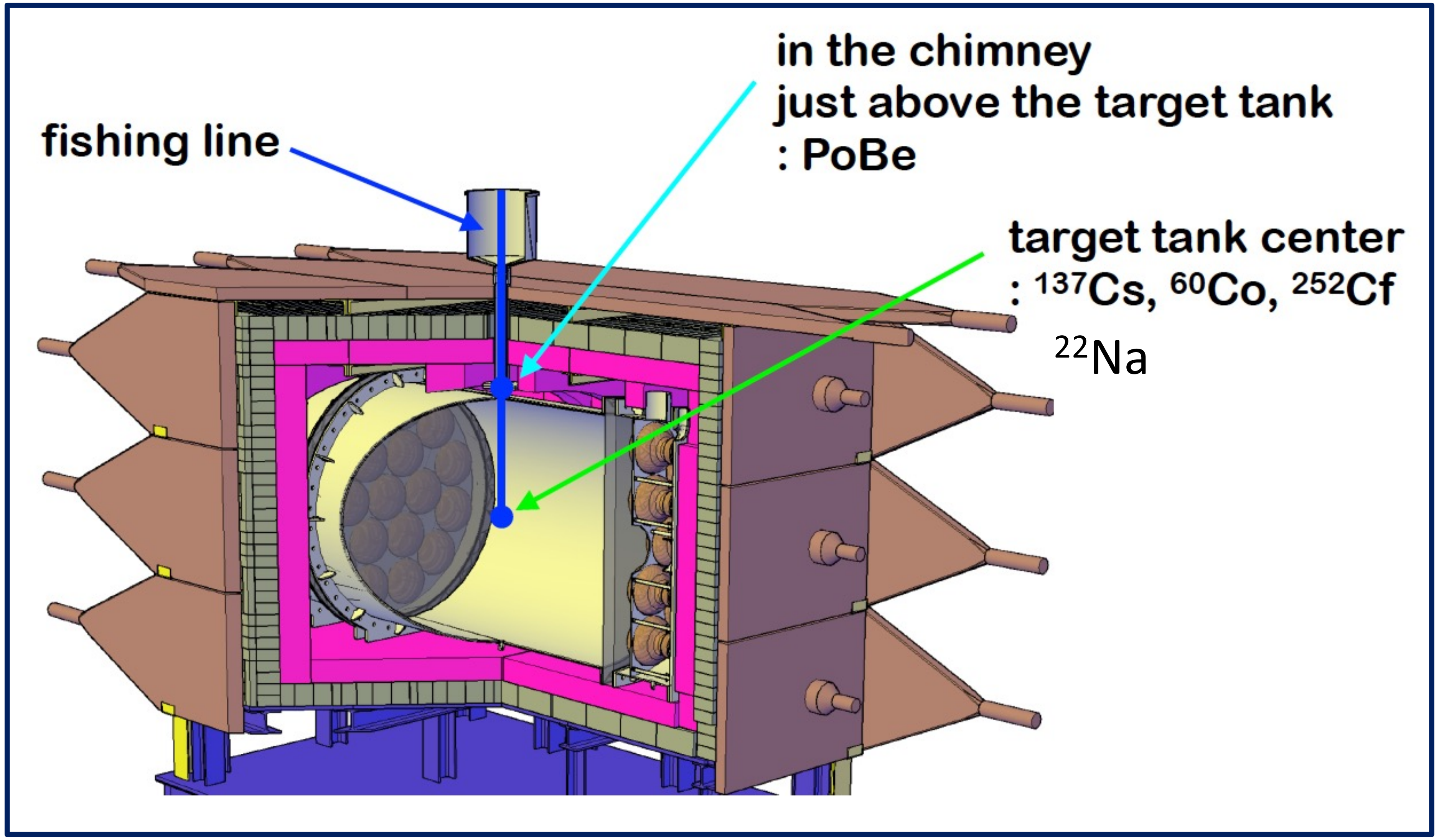


→ The latest data set (Period 9) looks fine!

Except for ΔT increase &
worse E resolution

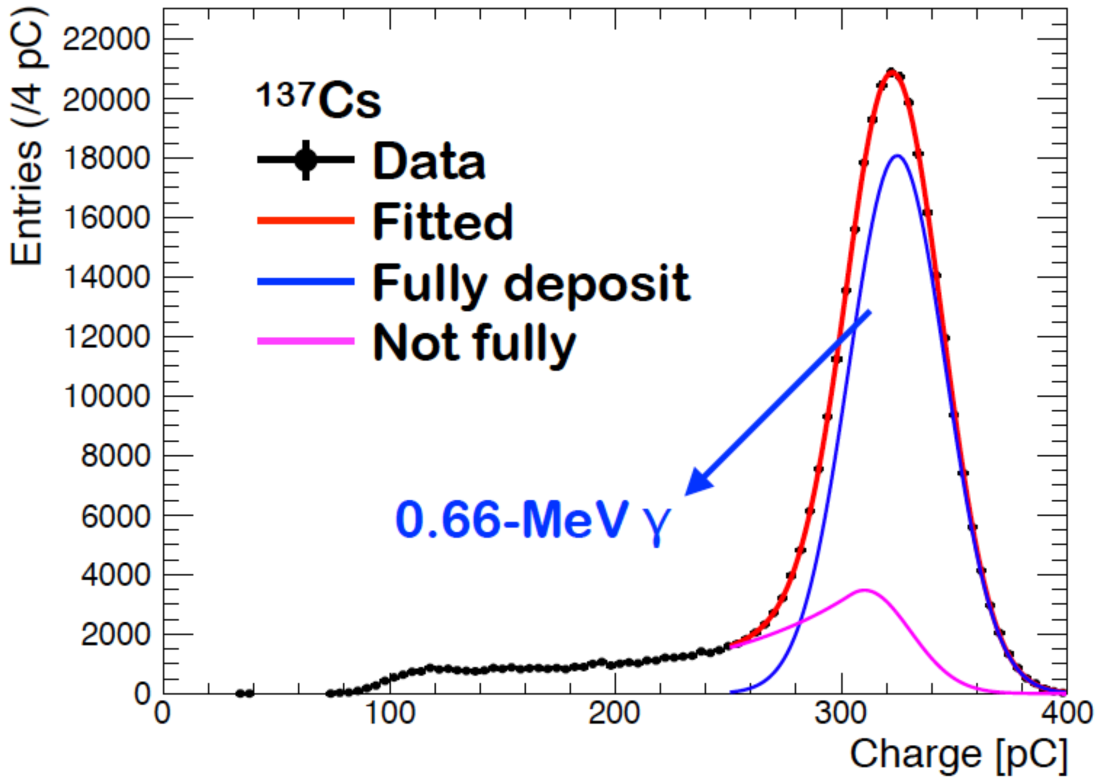
Energy Calibration (I)

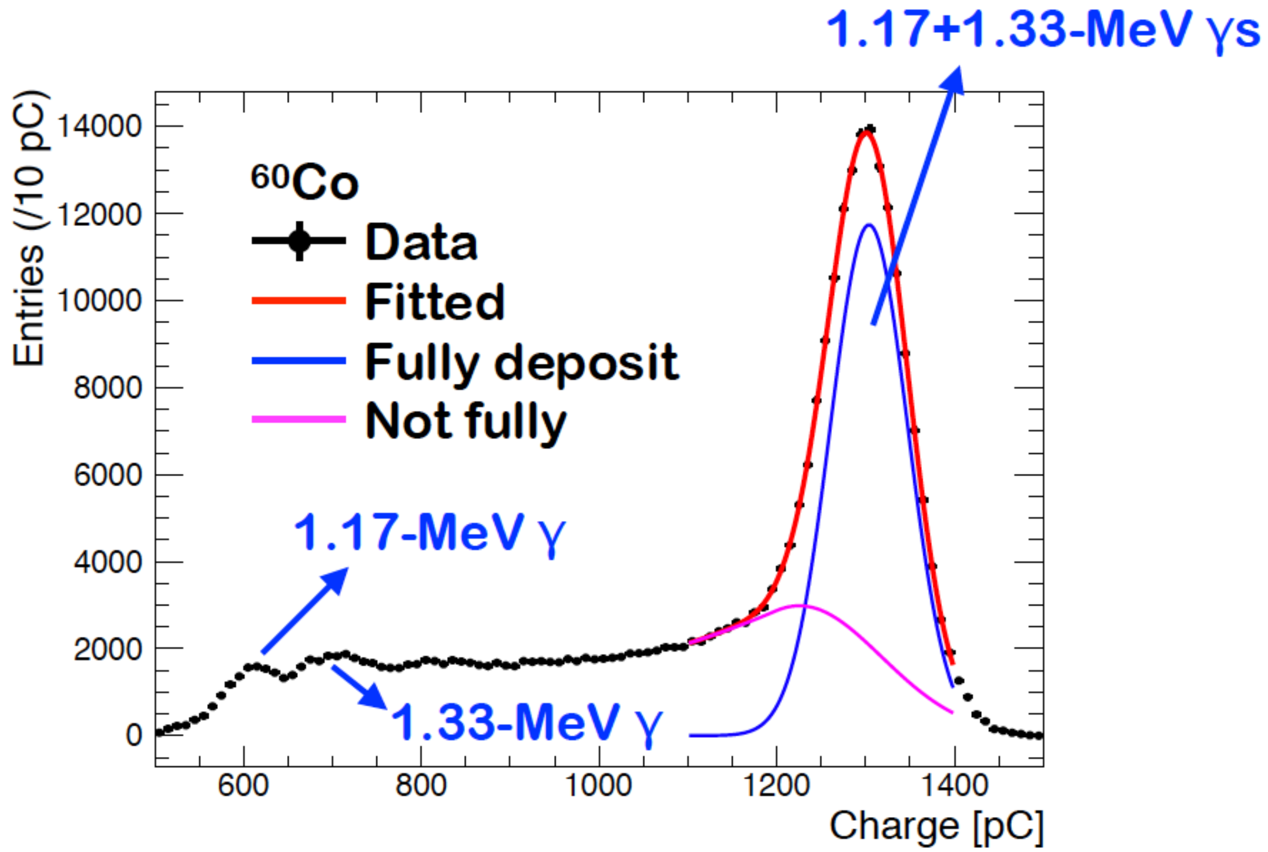
Bi-weekly taking of source data at target center



- ^{137}Cs: 0.66 MeV γ
- ^{22}Na: 2.297 MeV γ
  (2x0.511+1.275) MeV
- ^{60}Co: 2.505 MeV γ
  (1.173+1.332) MeV
- ^{252}Cf: n-H (2.2MeV γ)
  n-Gd (~8 MeV γs)
- PoBe: 0.8/4.44 MeV γ + n

Energy Calibration (II)

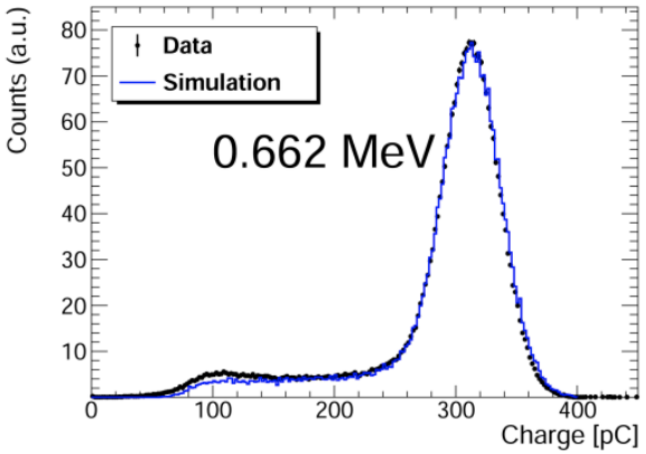




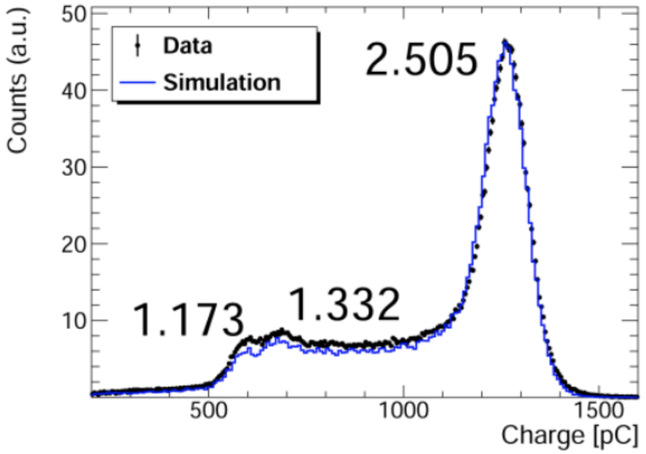
- Fully deposited γ events are modeled by a Gaussian.
- Not fully deposited γ events are fitted by a Crystal ball.

(There are many escaping γs due to the small size of the detector.)

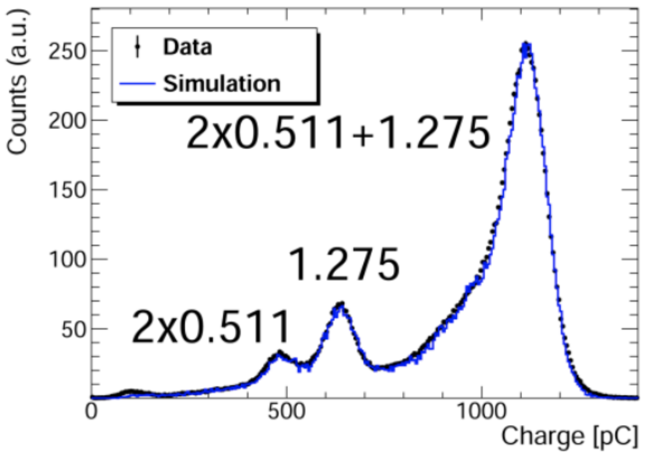
Source Data & MC



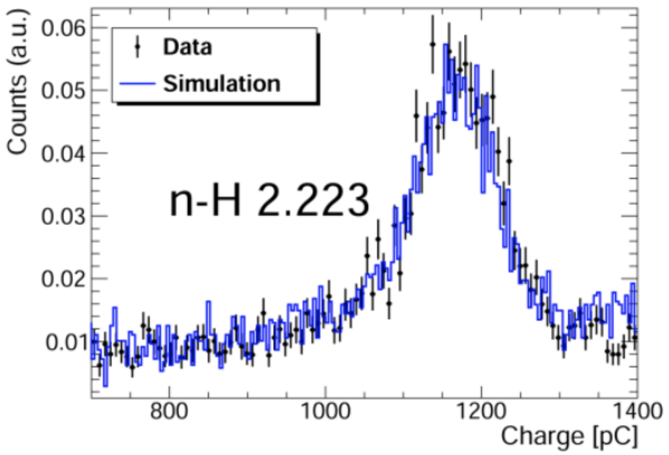
^{137}Cs



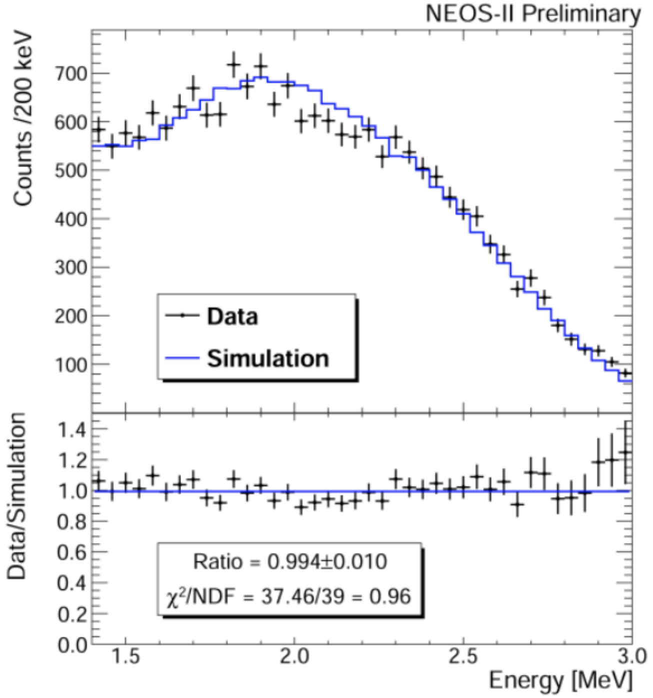
^{60}Co



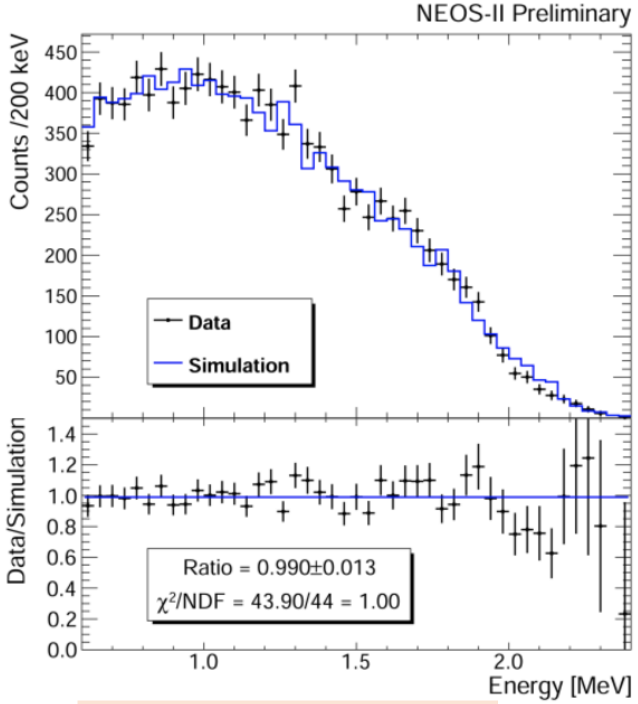
^{22}Na



n-H



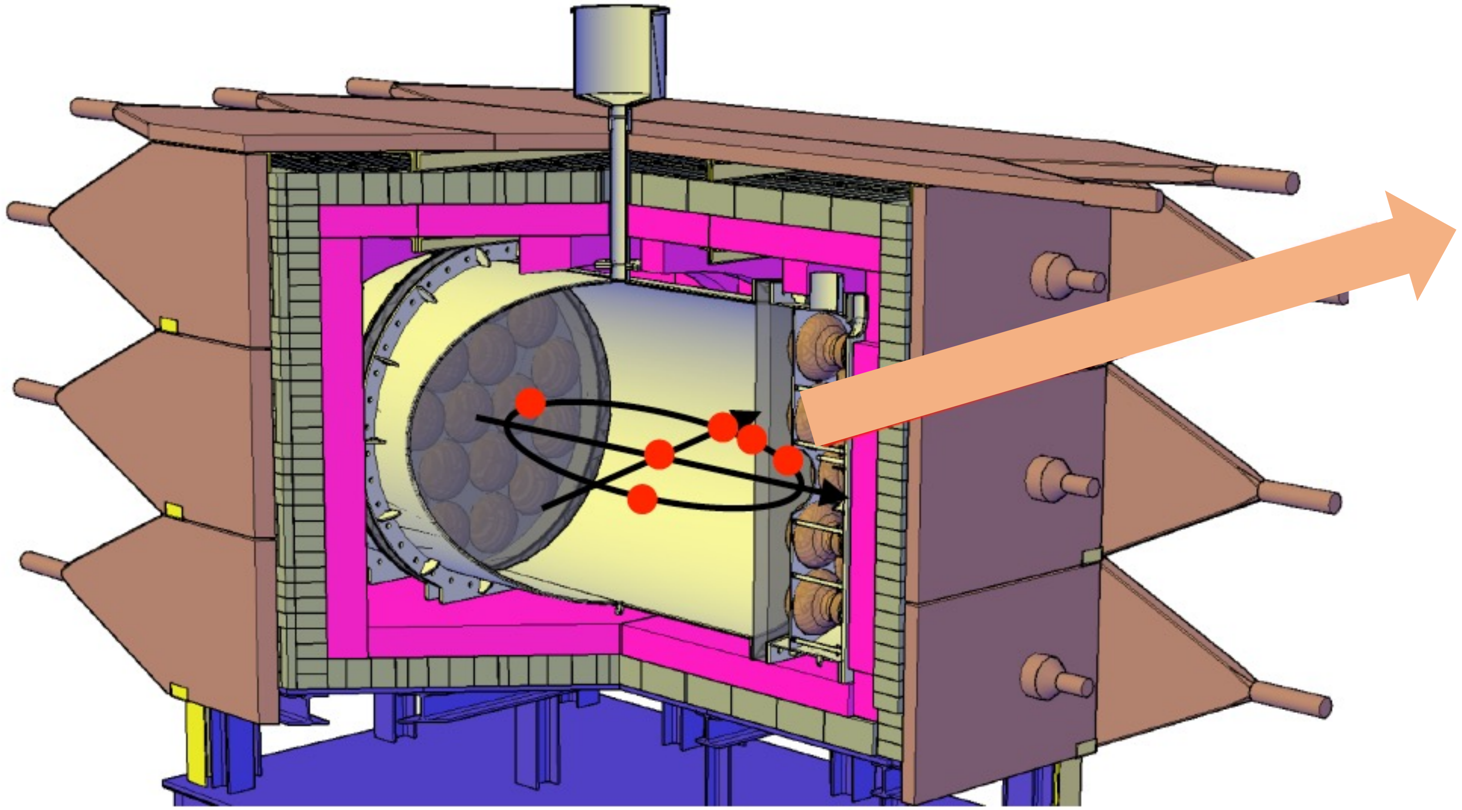
$^{214}Bi \rightarrow {}^{214}Po$

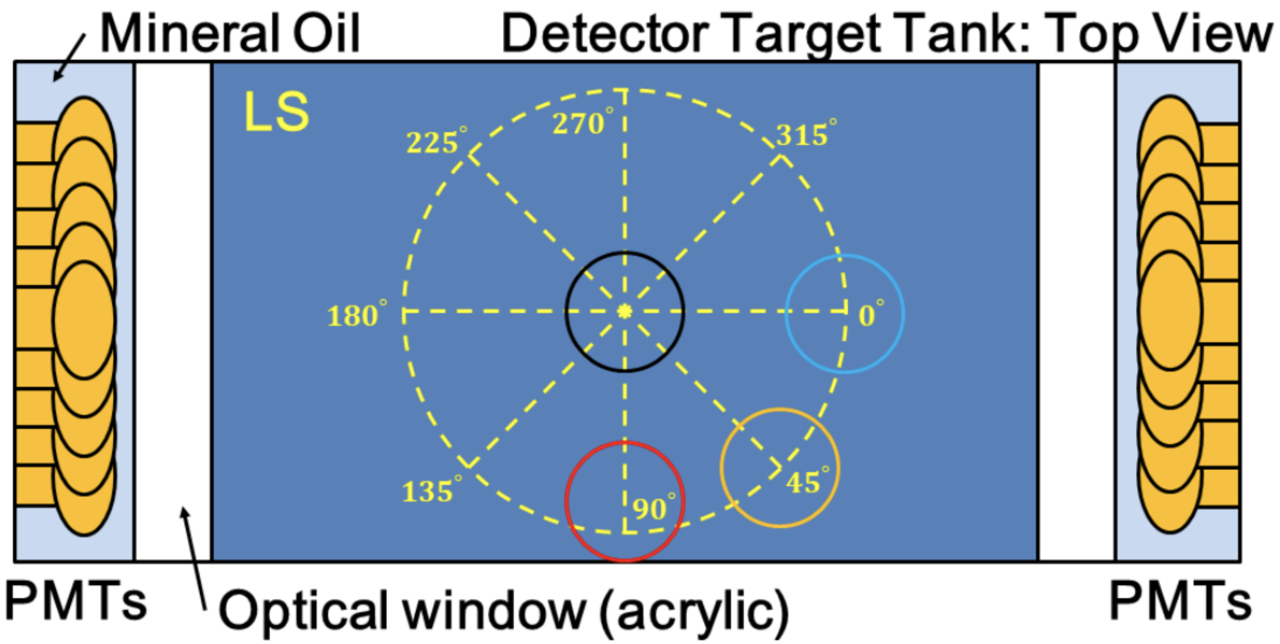


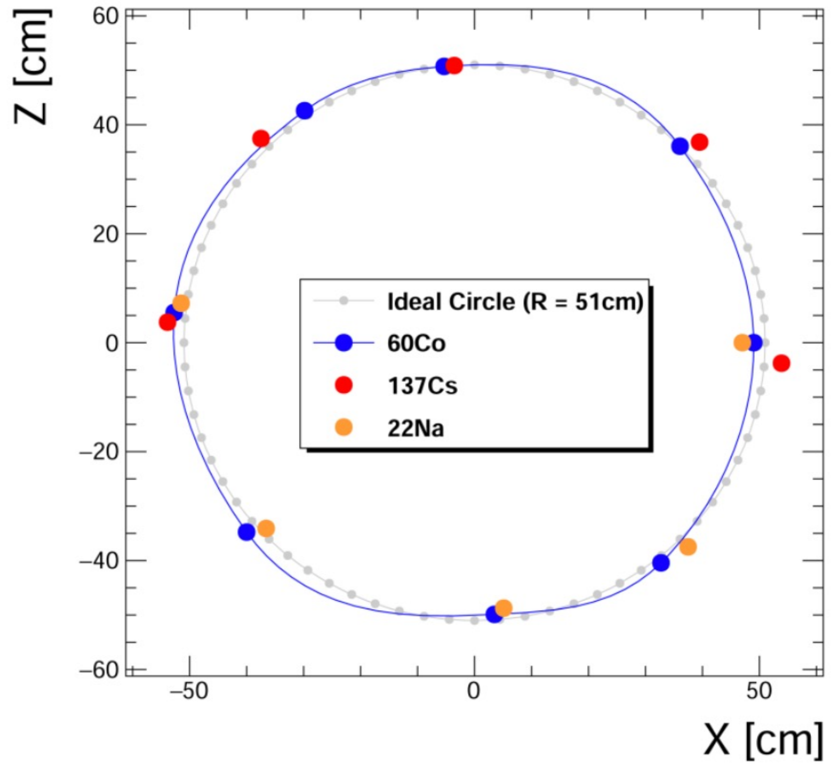
$^{212}Bi \rightarrow {}^{212}Po$

- Source Data & MC match very well!

2-D Calibration

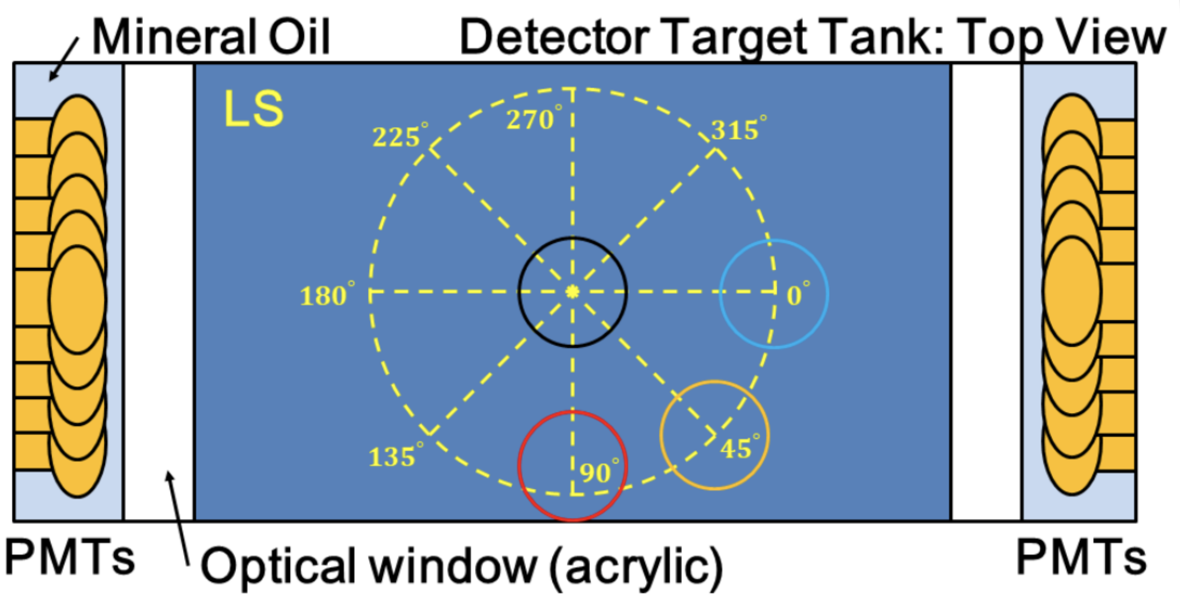




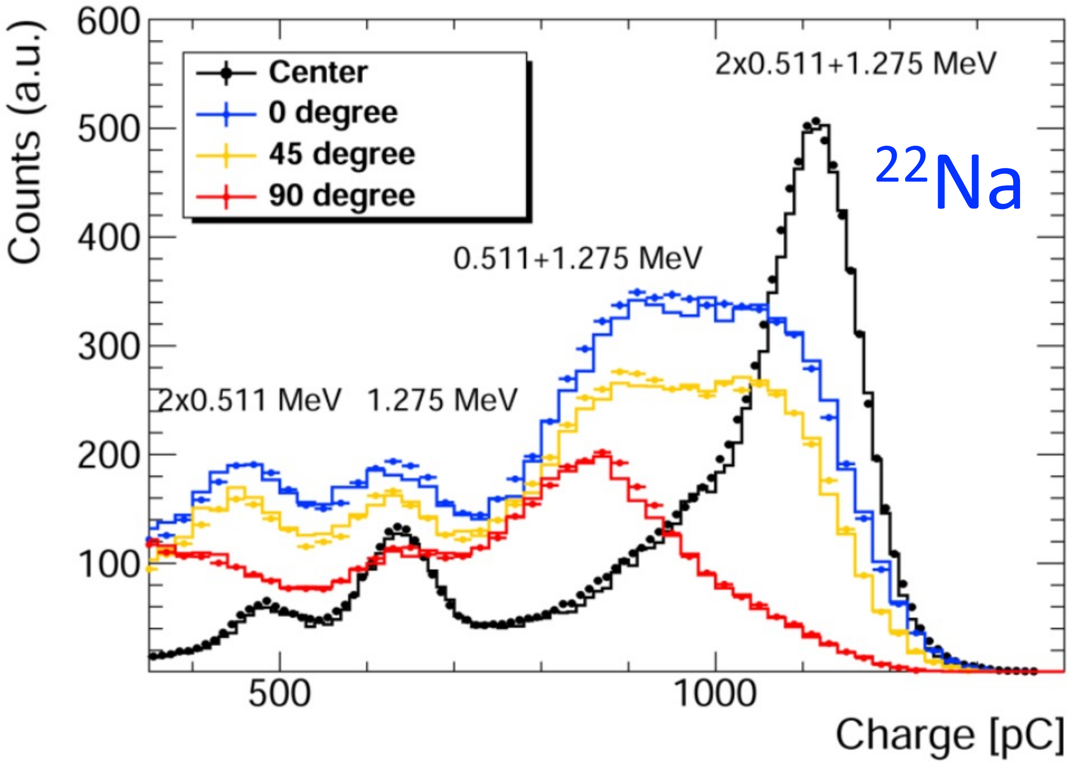


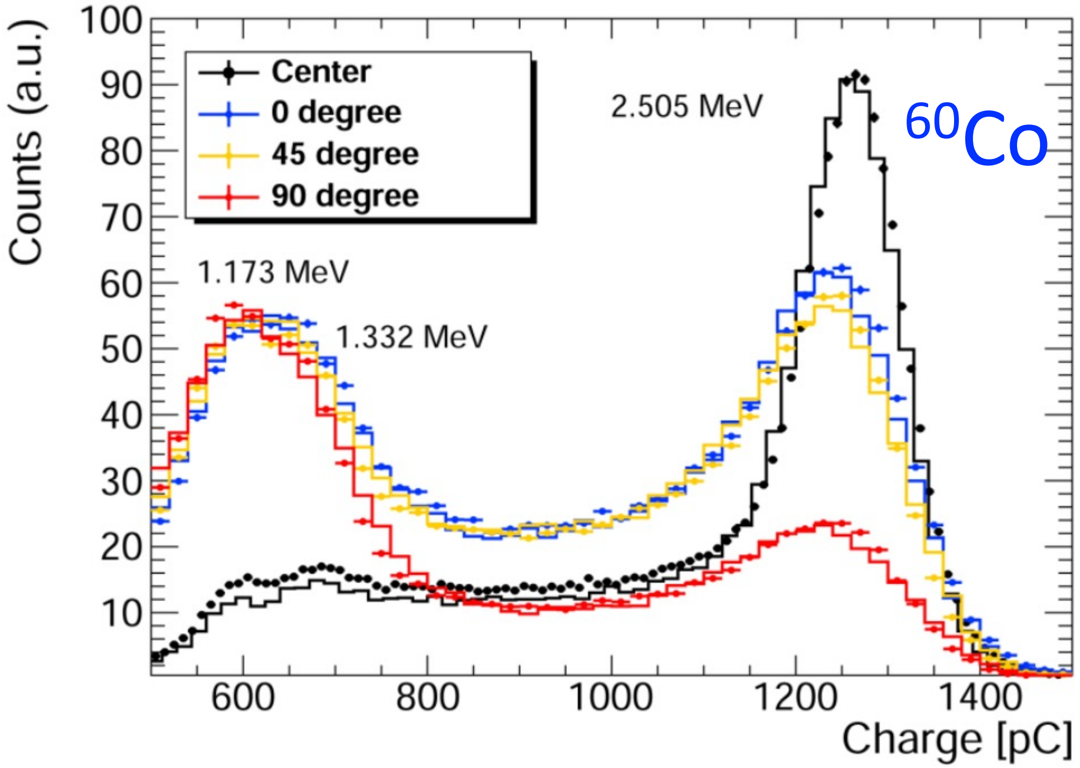
- ❑ 2-D calibration data was taken only once.

2-D Calibration

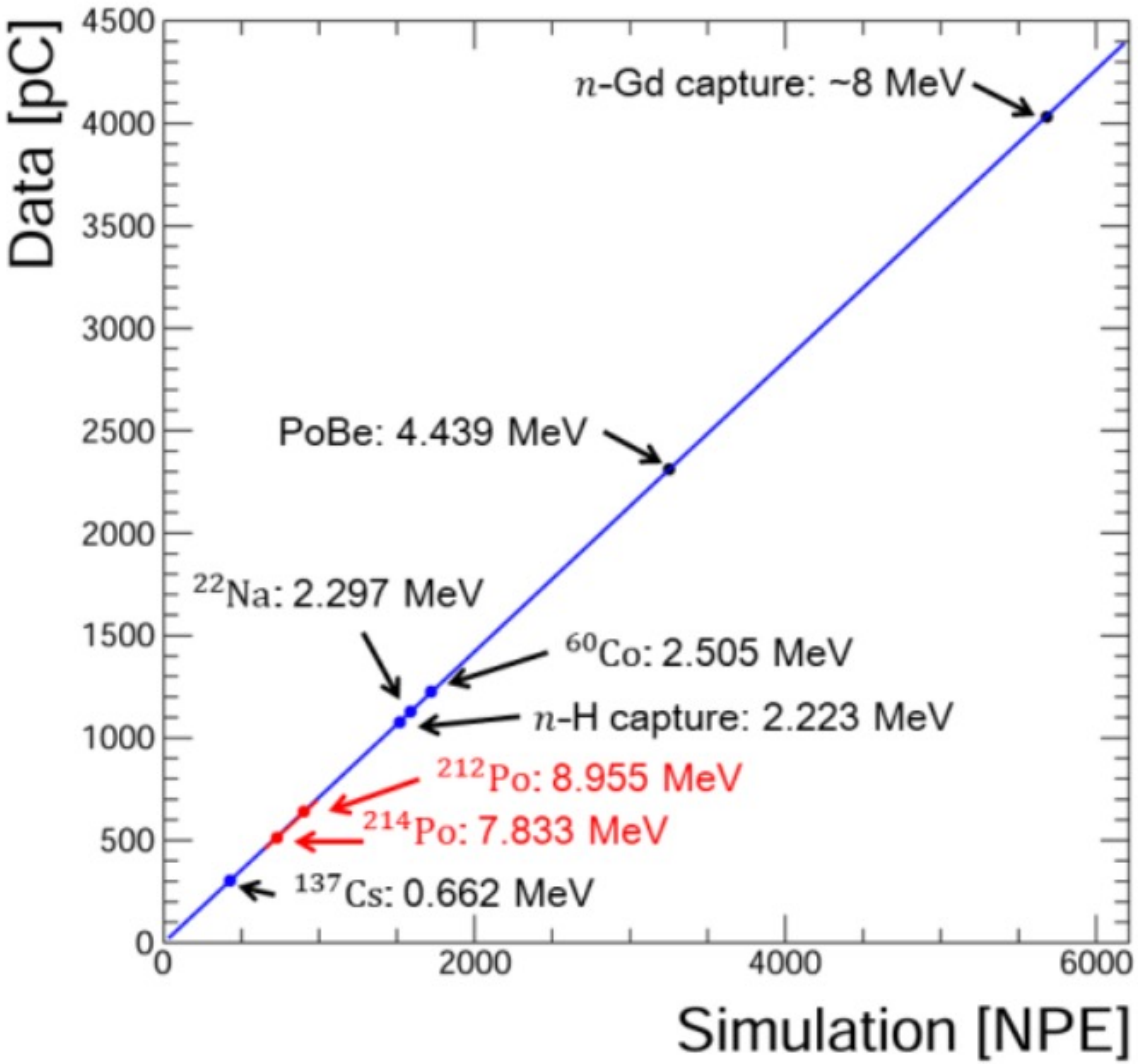


❑ Data and MC match well, including escaping γs.





Source Data Vs. MC



❑ Linearity between data and simulation for calibration sources

Note: all data points have participated in the fitting.

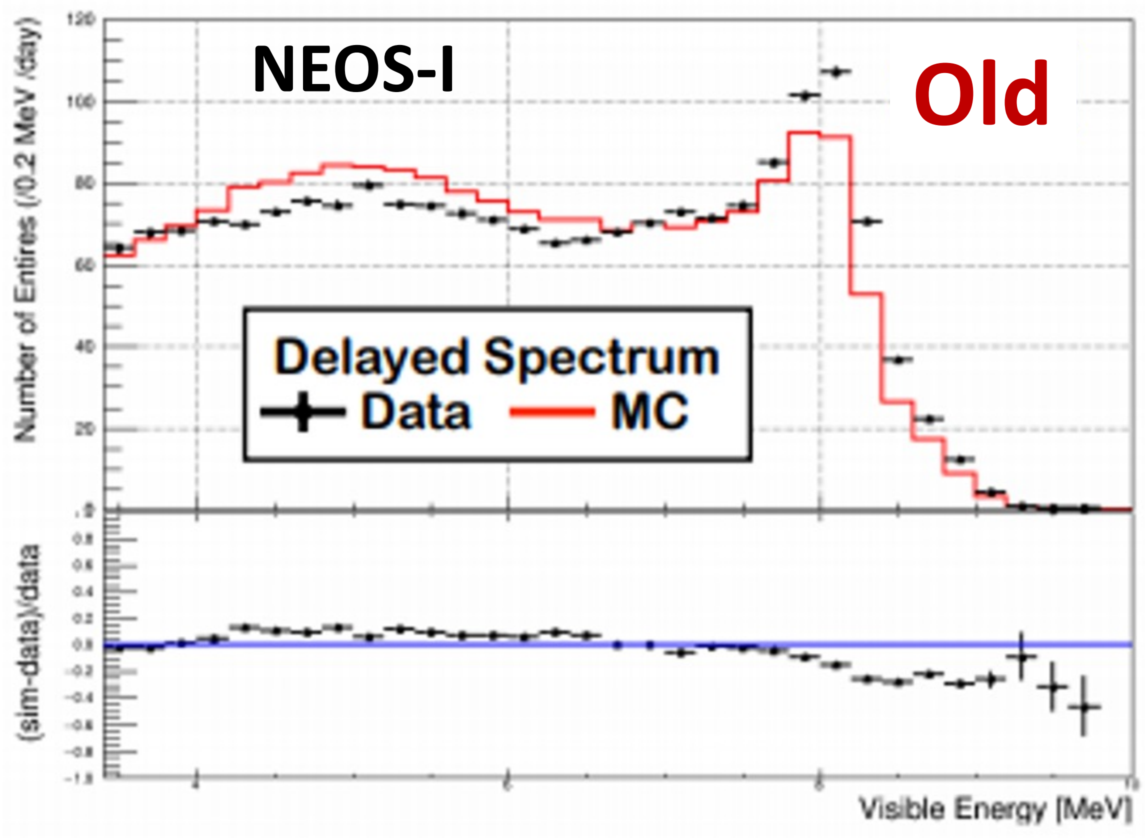
NEOS-II MC Improvement

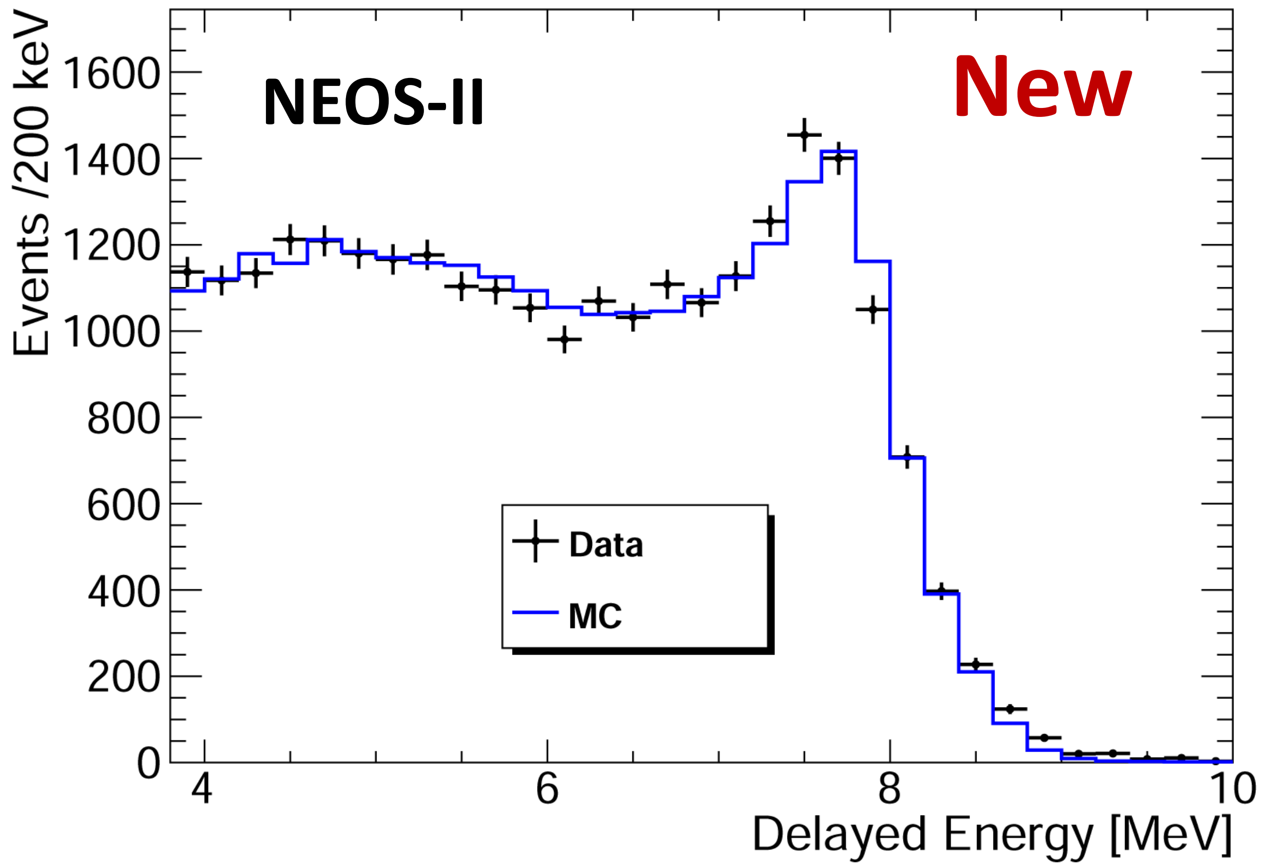
- NEOS simulation is based on Geant4.
  → full simulation including electronics simulation
- An update was made for NEOS-II.

- n-Gd MC update:
  GLG4Sim → new model (by Okayama Univ.)

ANNRI-Gd model

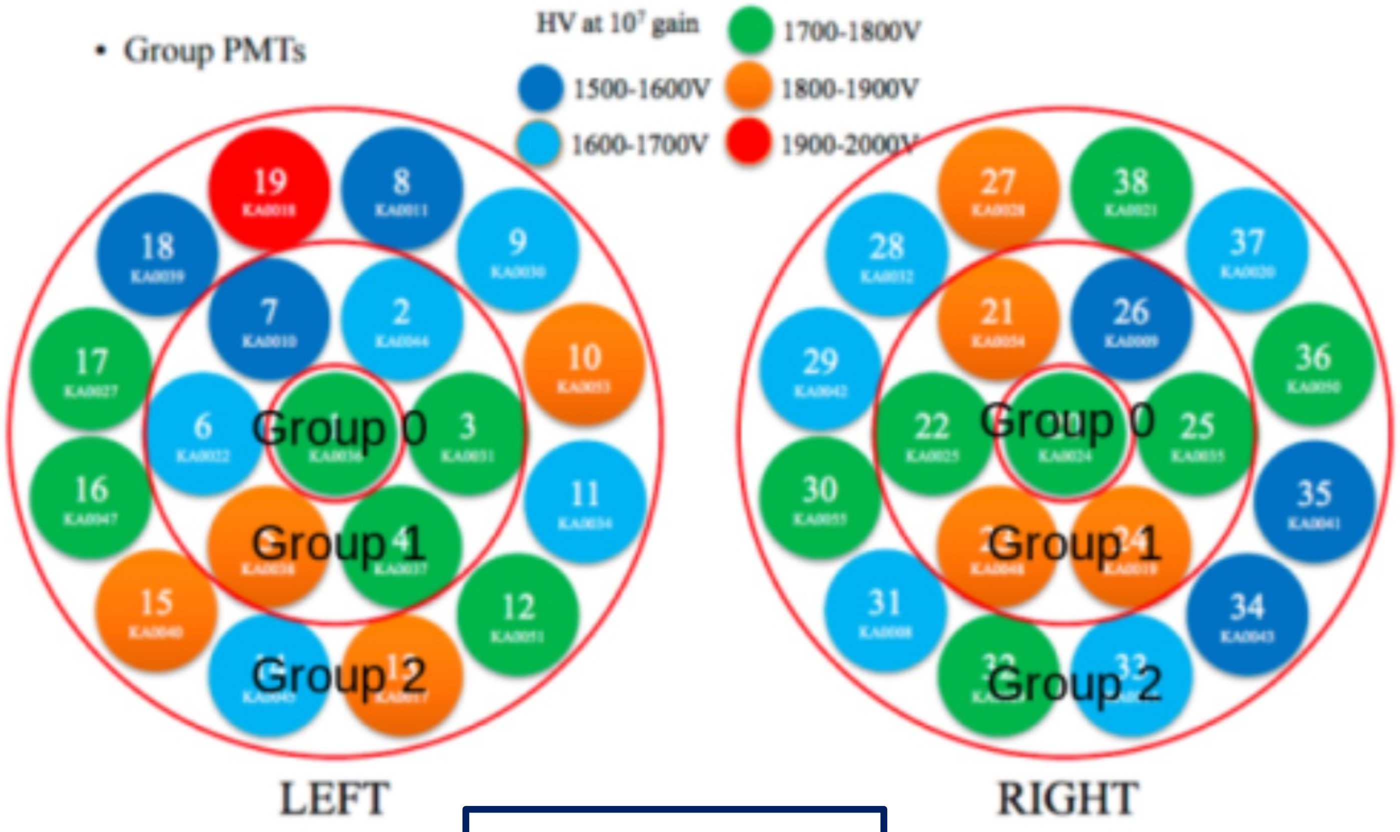
PTEP 2019, 023D01





PMT Charge Correction

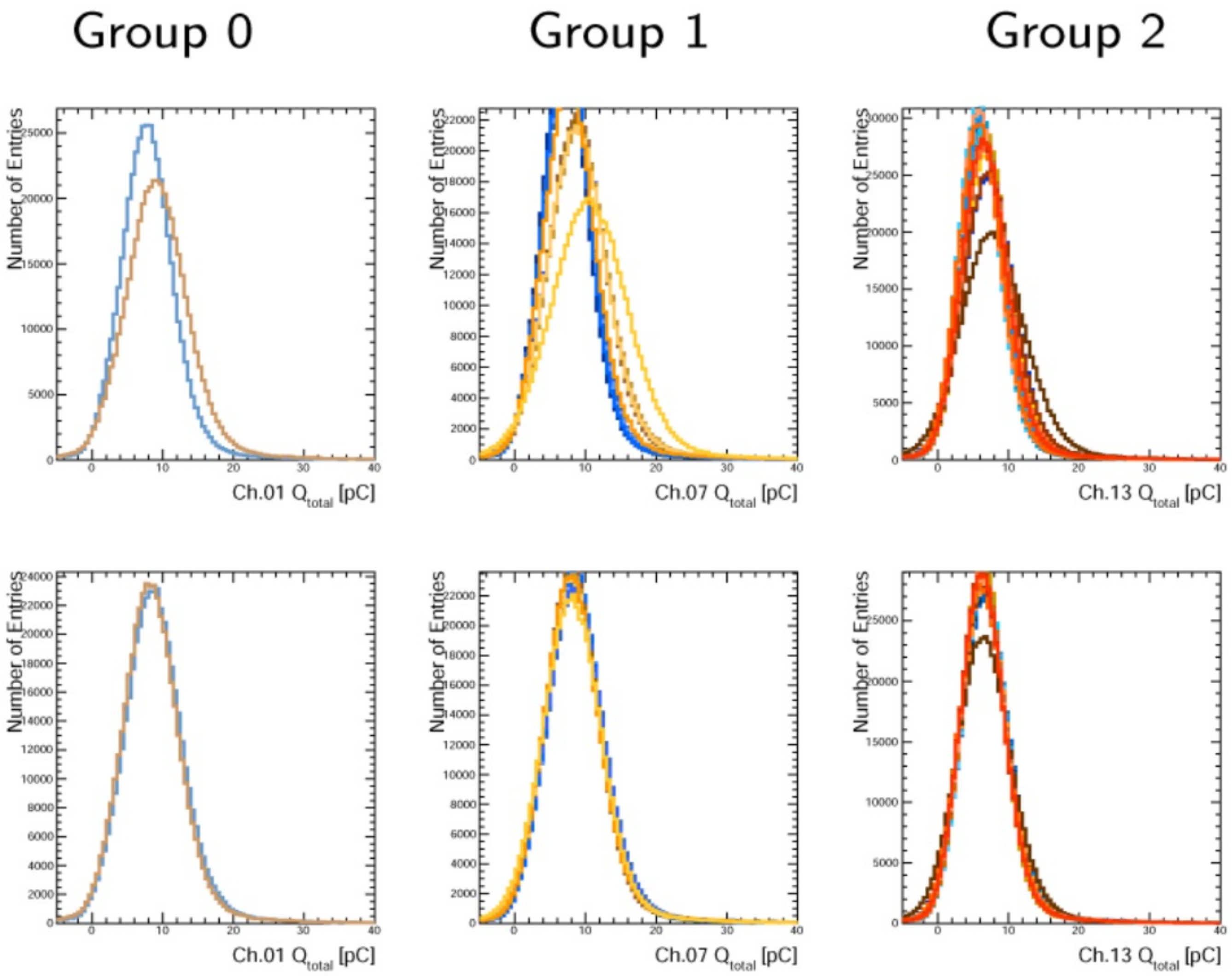
To correct PMT gain differences & its drift over time



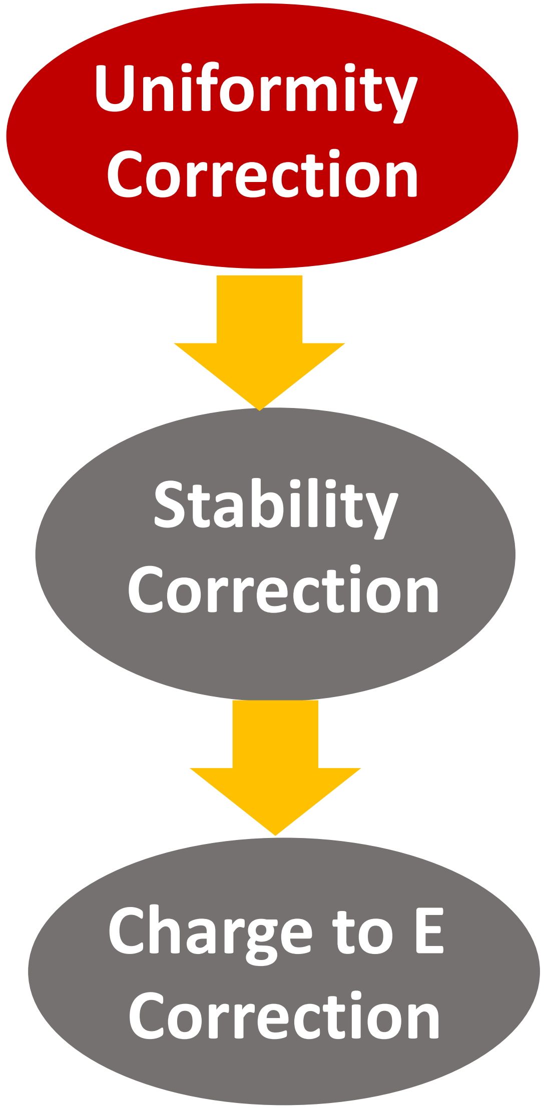
$$C_i = \frac{< Q >_j}{\overline{Q_i}},$$

where $< Q >_j$ is the averaged charge value in group j, and Q_i is the mean charge value for i th PMT.

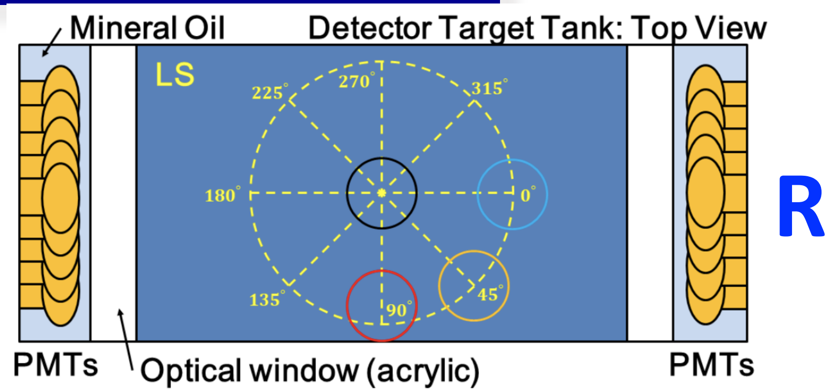
^{60}Co source data at the center position



Energy Reconstruction (I)

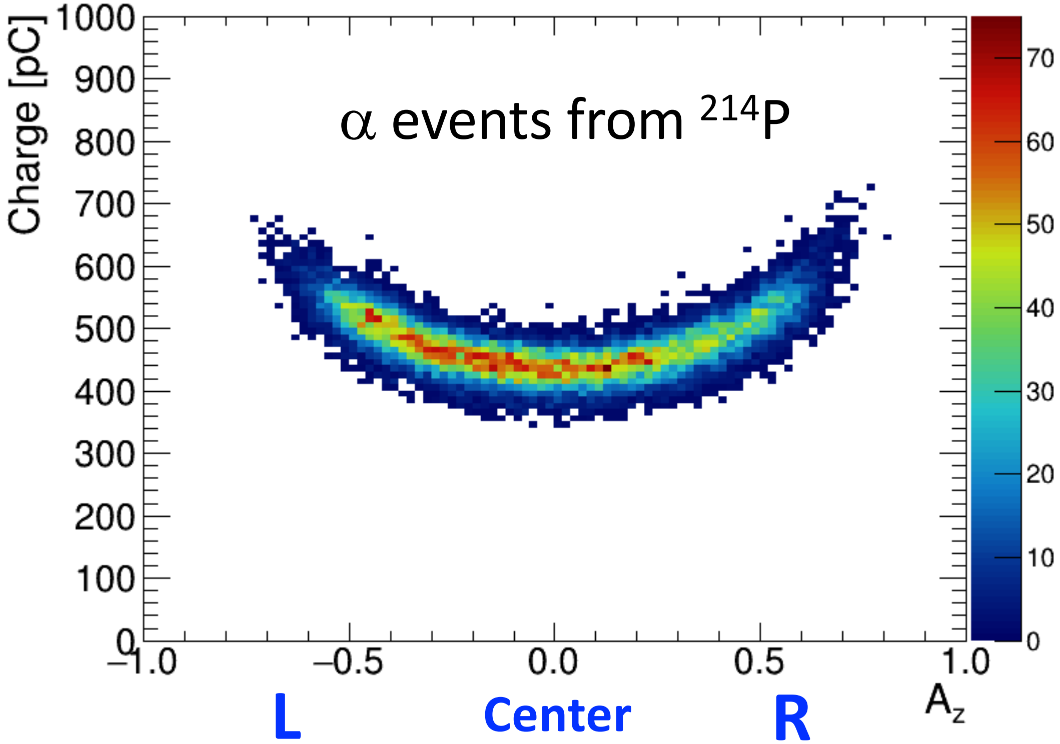


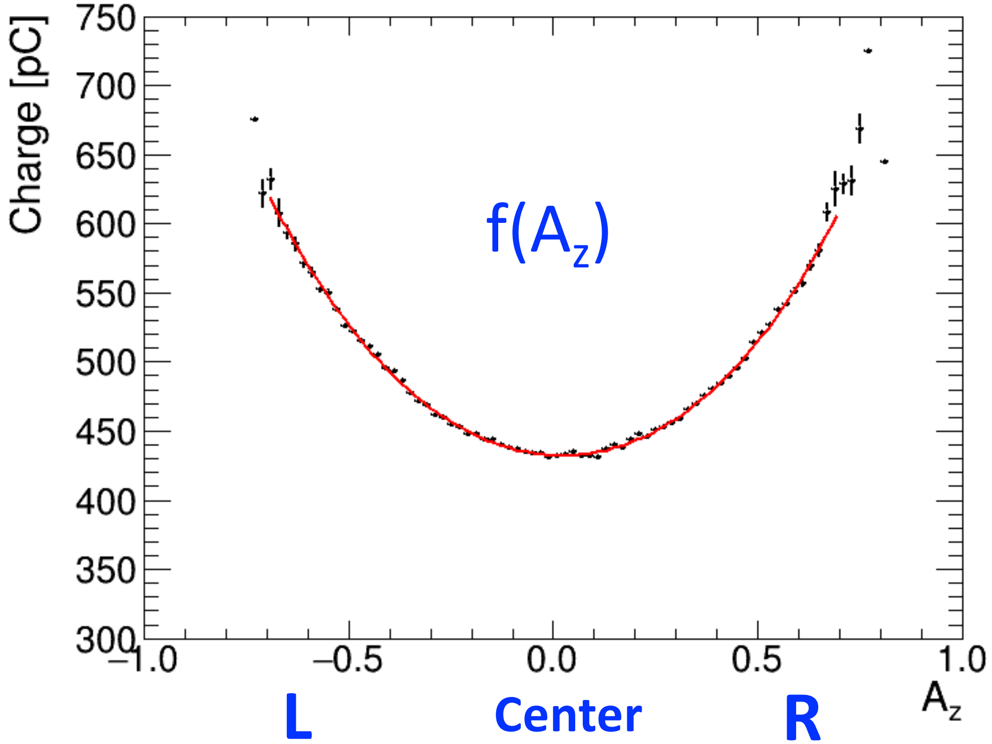
$$Q = S(t) \cdot U(A_z) \cdot \sum_{i}^{38} q_i$$



The charge has a position dependence along the cylindrical axis.

$$U(A_z) = \frac{f(0)}{f(A_z)}, \qquad \text{where } A_z = \frac{Q_r - Q_l}{Q_r + Q_l}$$

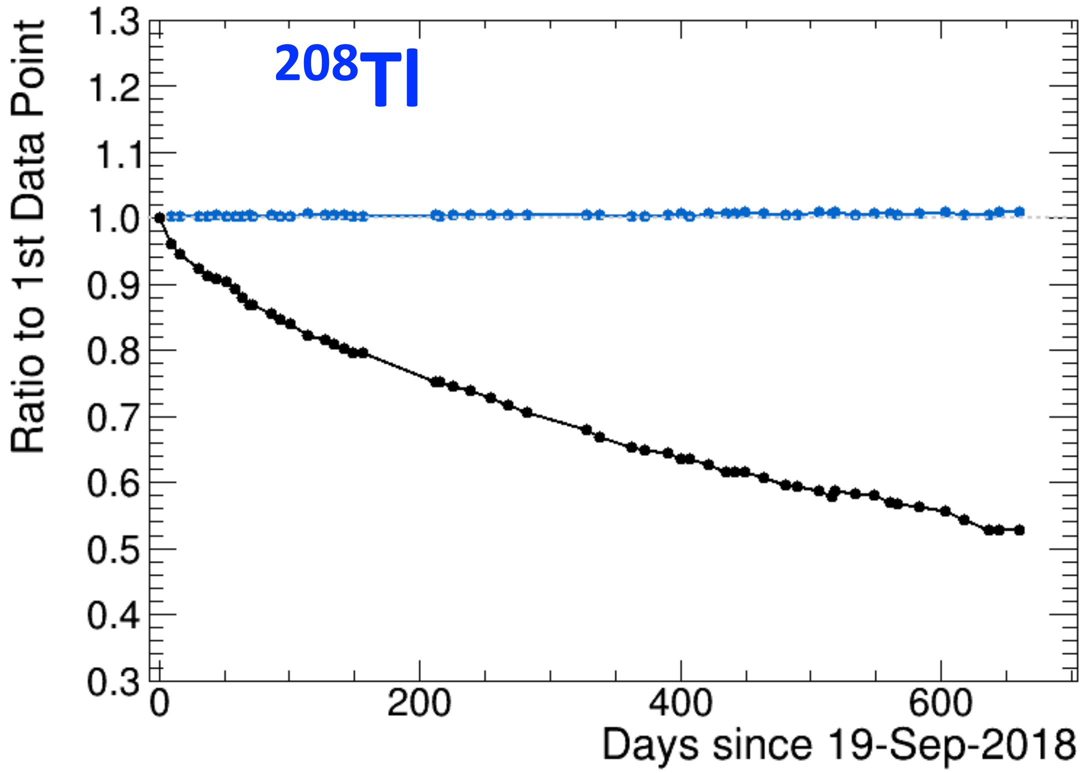


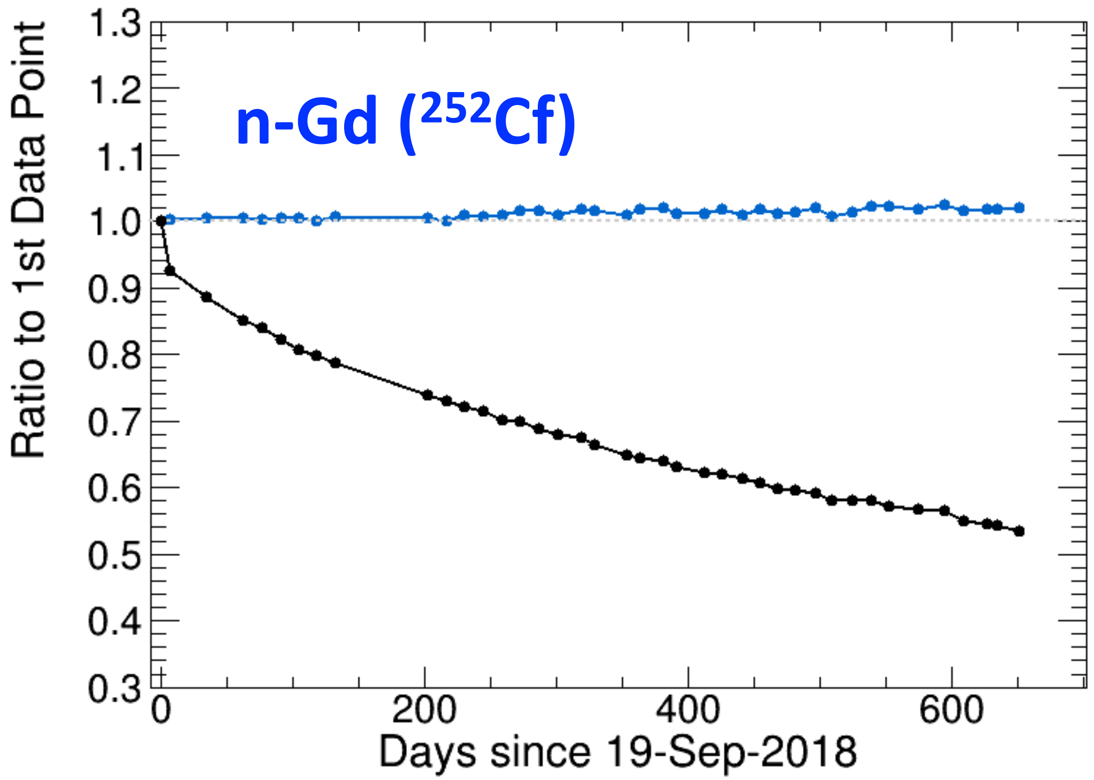


Energy Reconstruction (II)

$$Q = S(t) \cdot U(A_z) \cdot \sum_{i}^{38} q_i \qquad S(t) = \frac{Q(^{208}\mathrm{Tl}, 0)}{Q(^{208}\mathrm{Tl}, t)}$$

- ^{208}Tl is used as a reference for the stability correction.



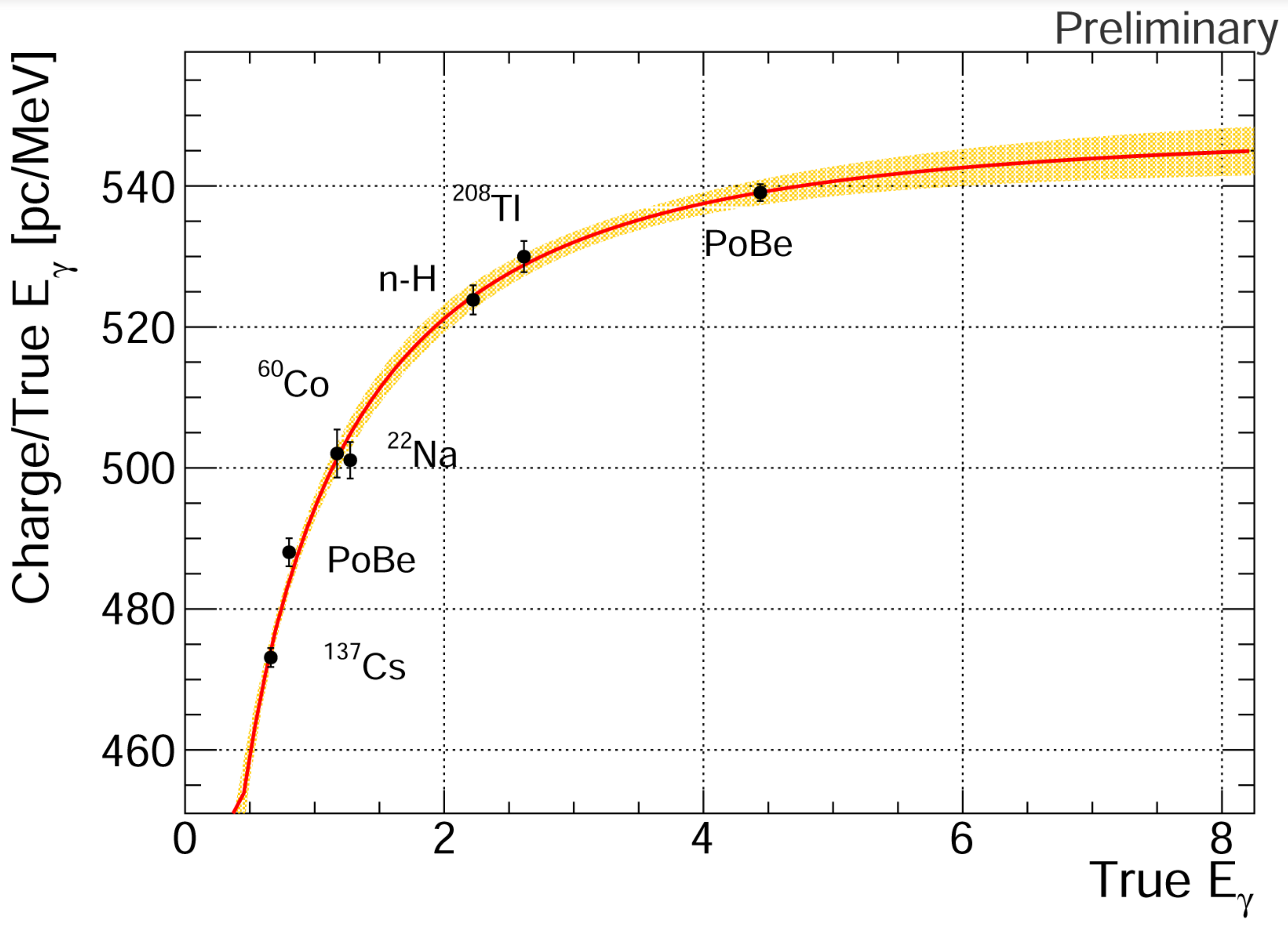


Energy Reconstruction (III)

Uniformity Correction

Stability Correction

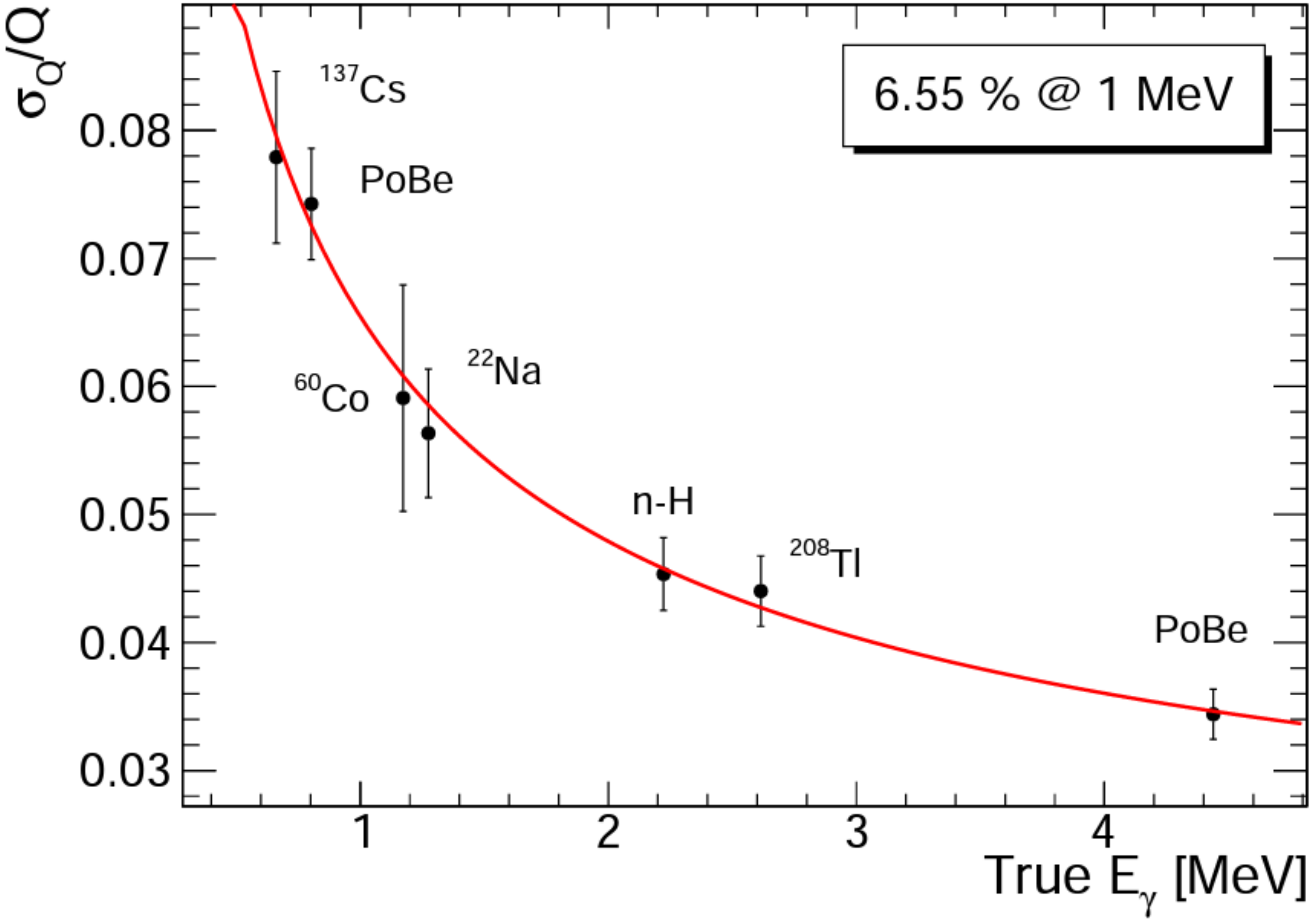
Charge to E Correction



Fitting function:

$$\frac{Q}{E_\gamma} = (p_0 + p_1 E_\gamma)\left(1 + p_2 \exp\left[-p_3\sqrt{E_\gamma}\right]\right)$$

Energy Resolution



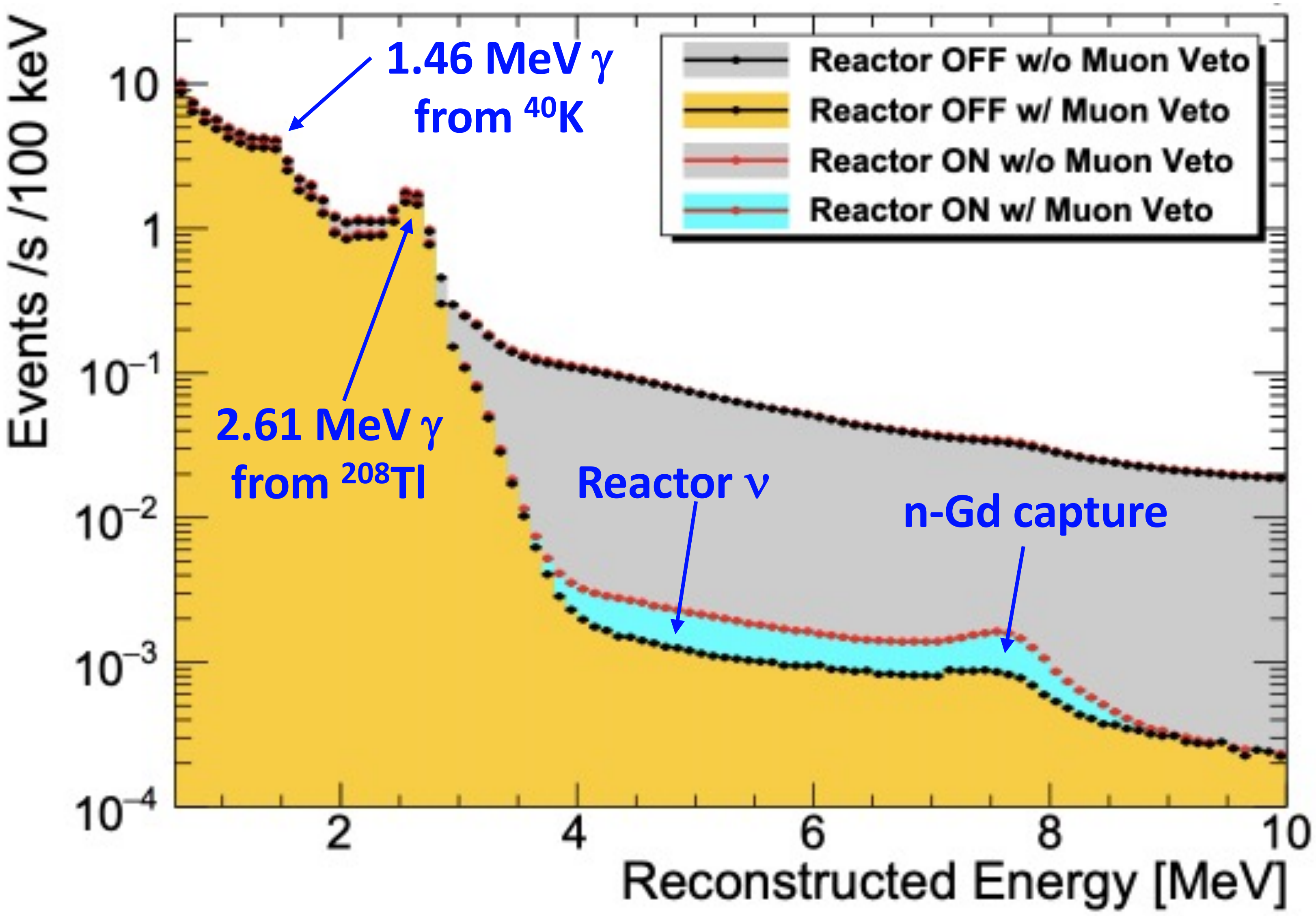
All source data are combined here.

- Initial E resolution: 5.5%
- Final E resolution : 7.3%

Fitting function

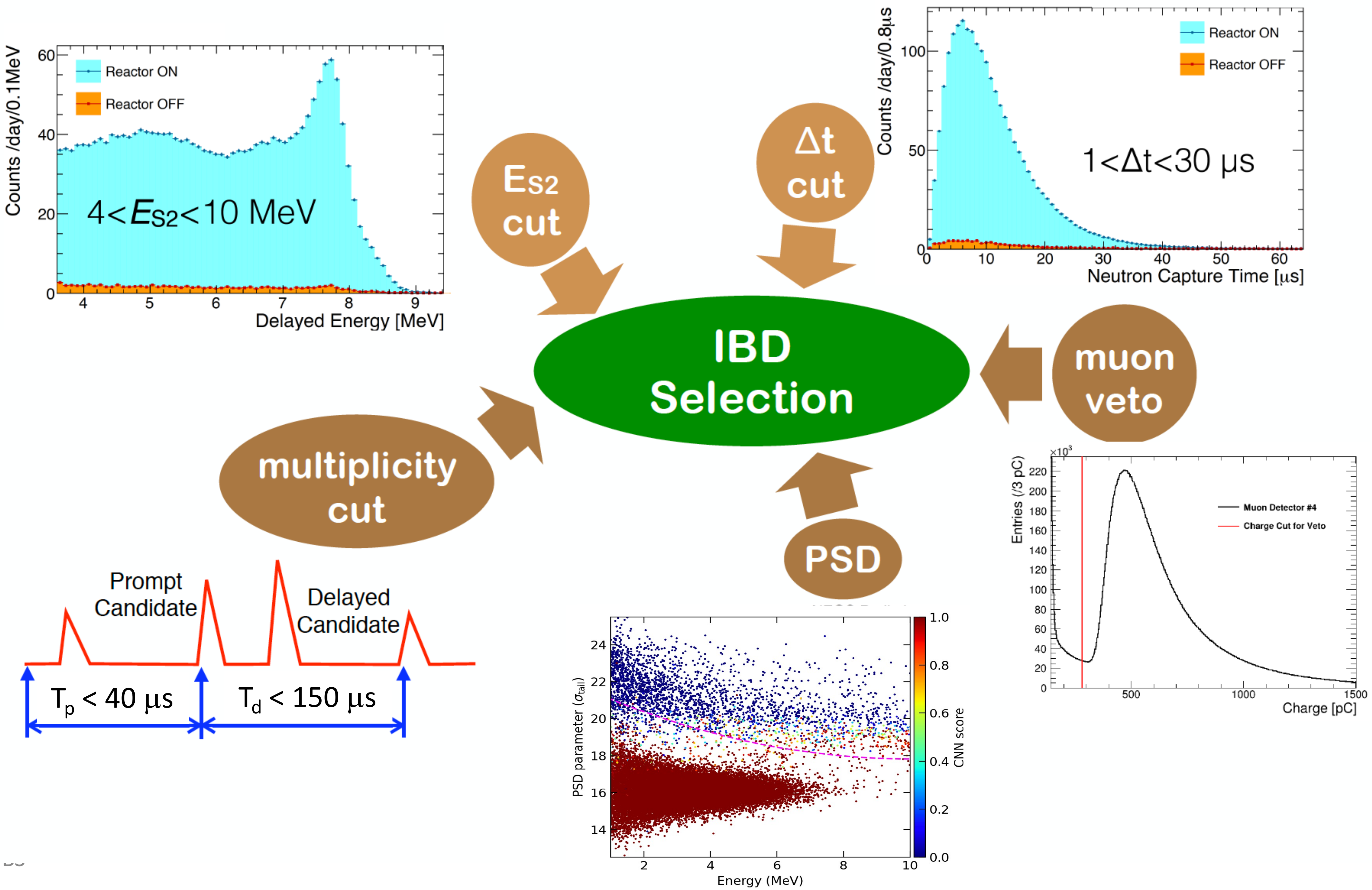
$$\frac{\sigma}{E_{\mathrm{recon}}} = \sqrt{\frac{p_0^2}{E_{\mathrm{recon}}} + p_1^2 + \frac{p_2^2}{E_{\mathrm{recon}}^2}}$$

Single Event Spectrum



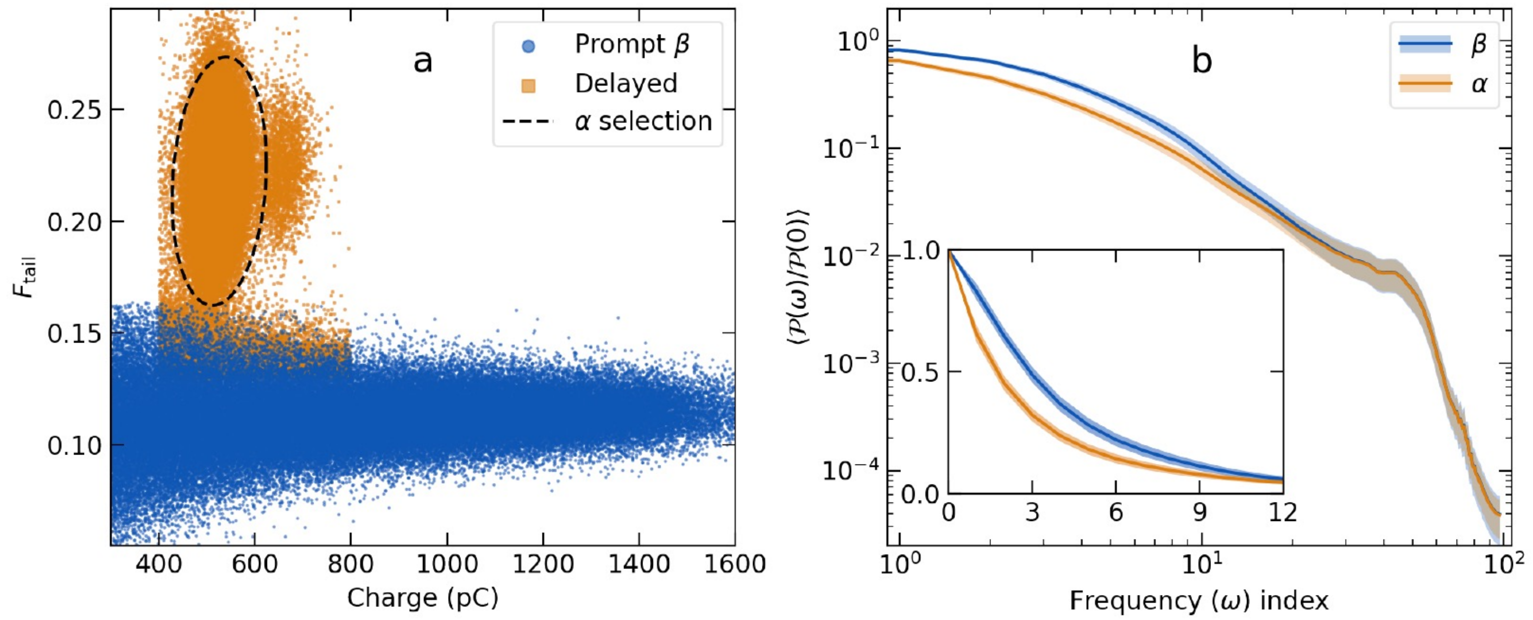
- Muon rate: ~260 Hz
- About 80% single events survive after muon veto cuts

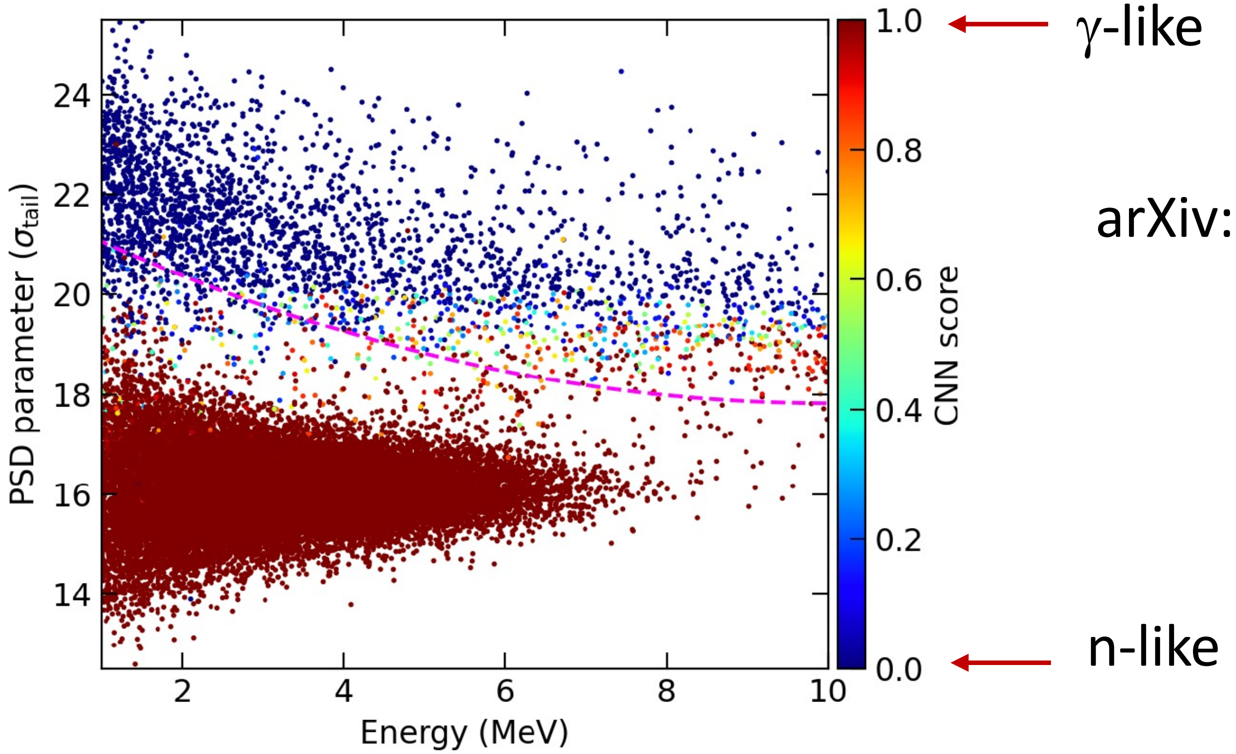
IBD Selection



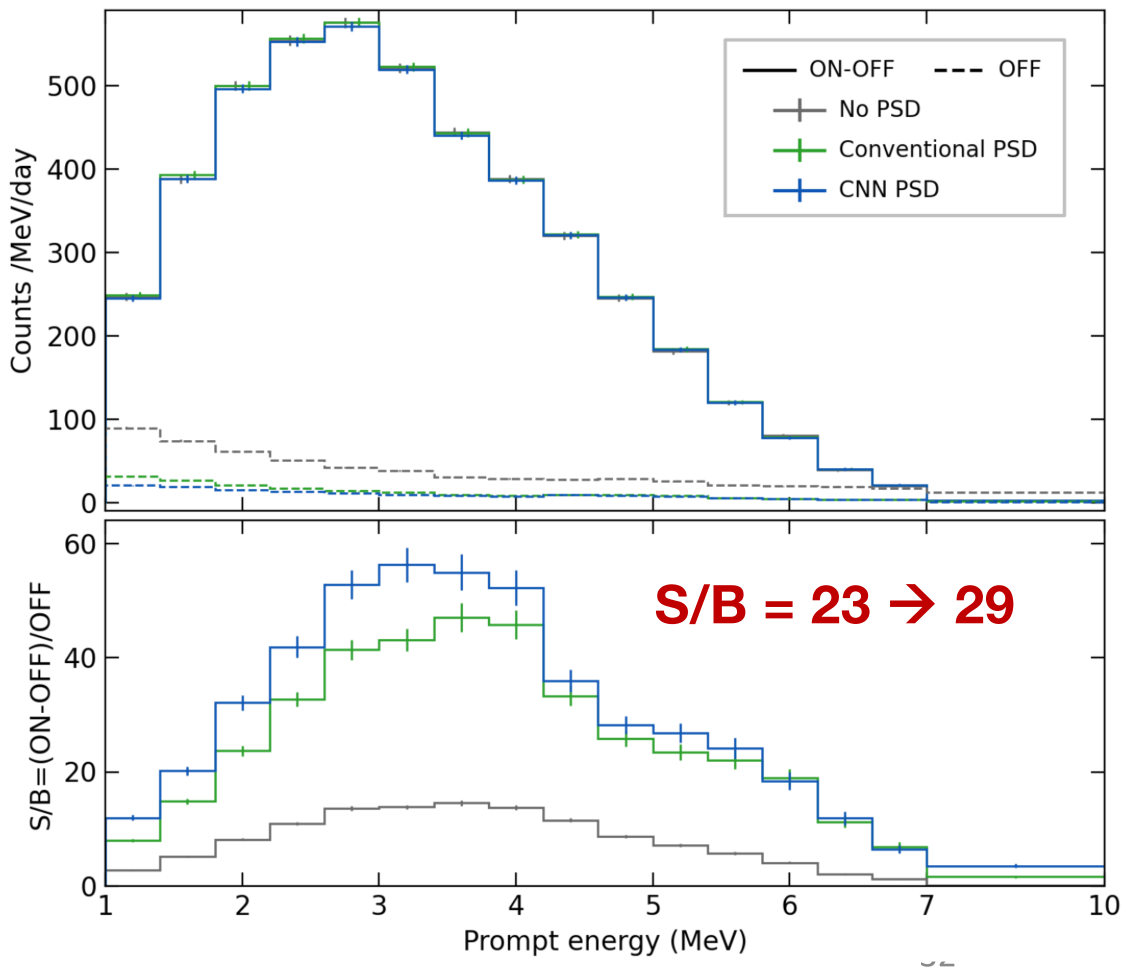
PSD Cut: CNN

- CNN + waveform (FFT)
- Low energy background reduced by up to 40% compared to Q_tail/Q_total method.

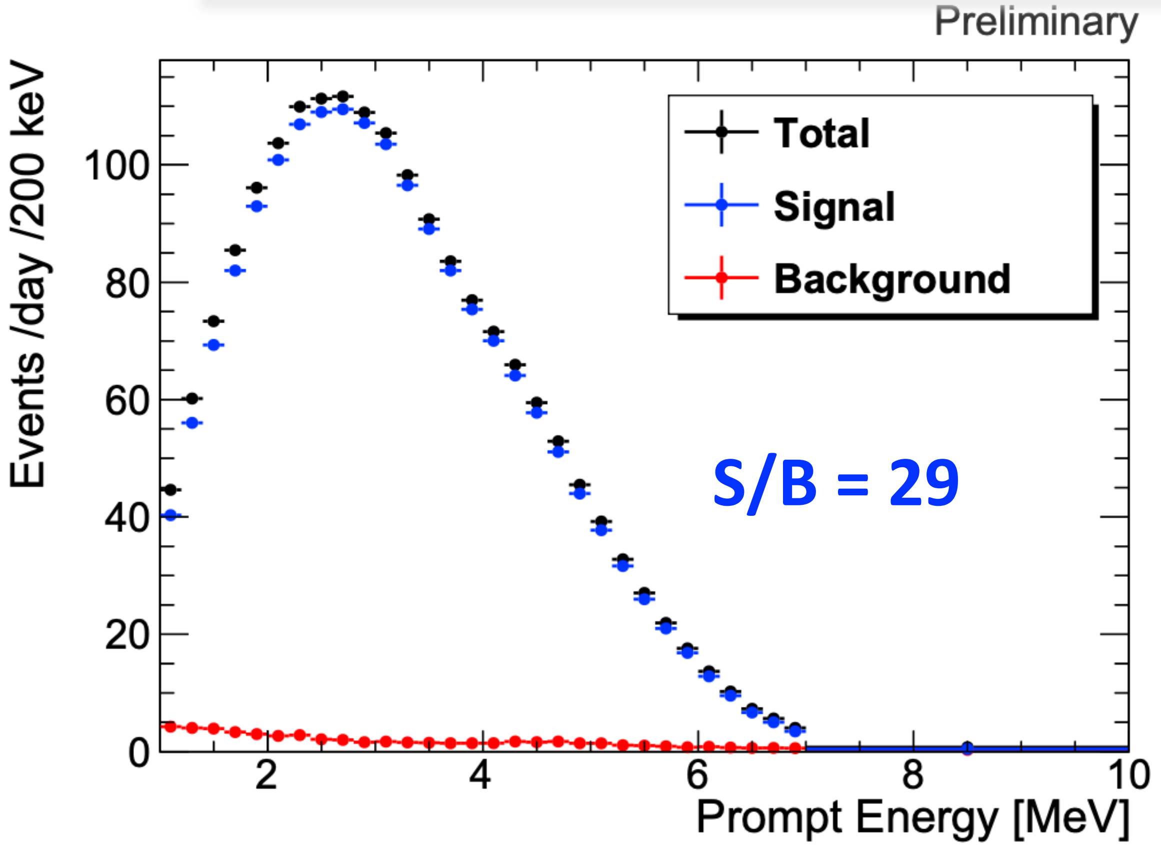


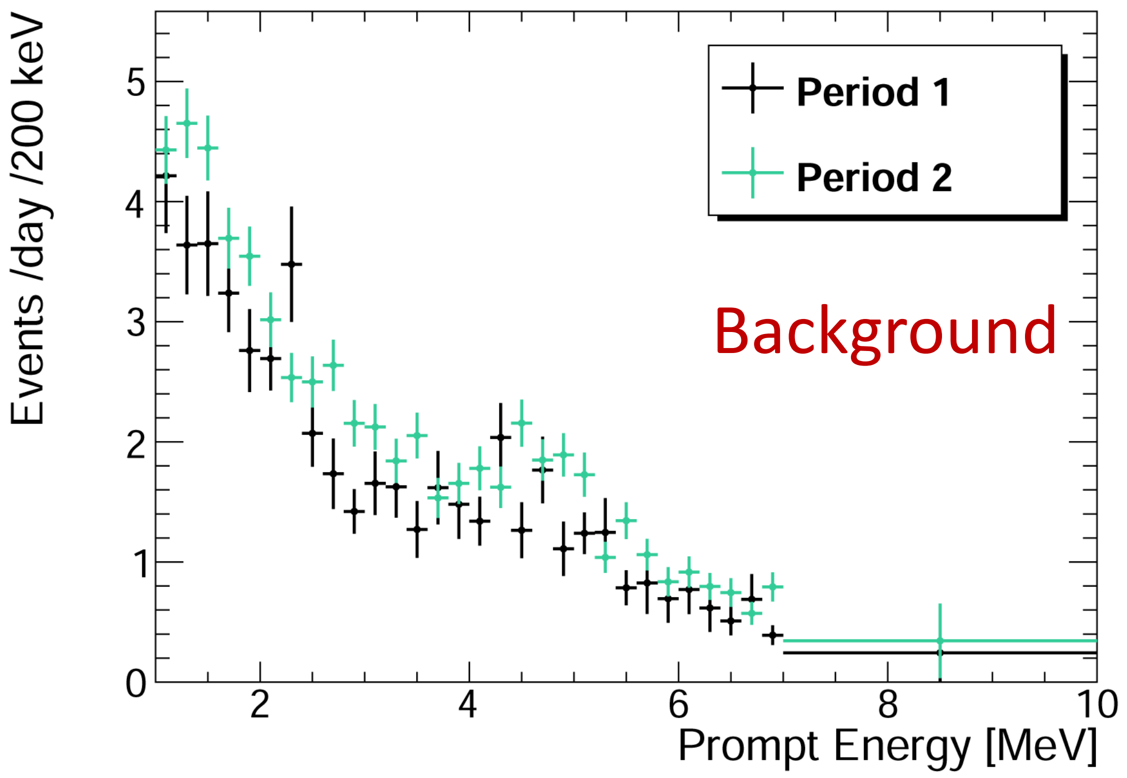


arXiv:2211.07892

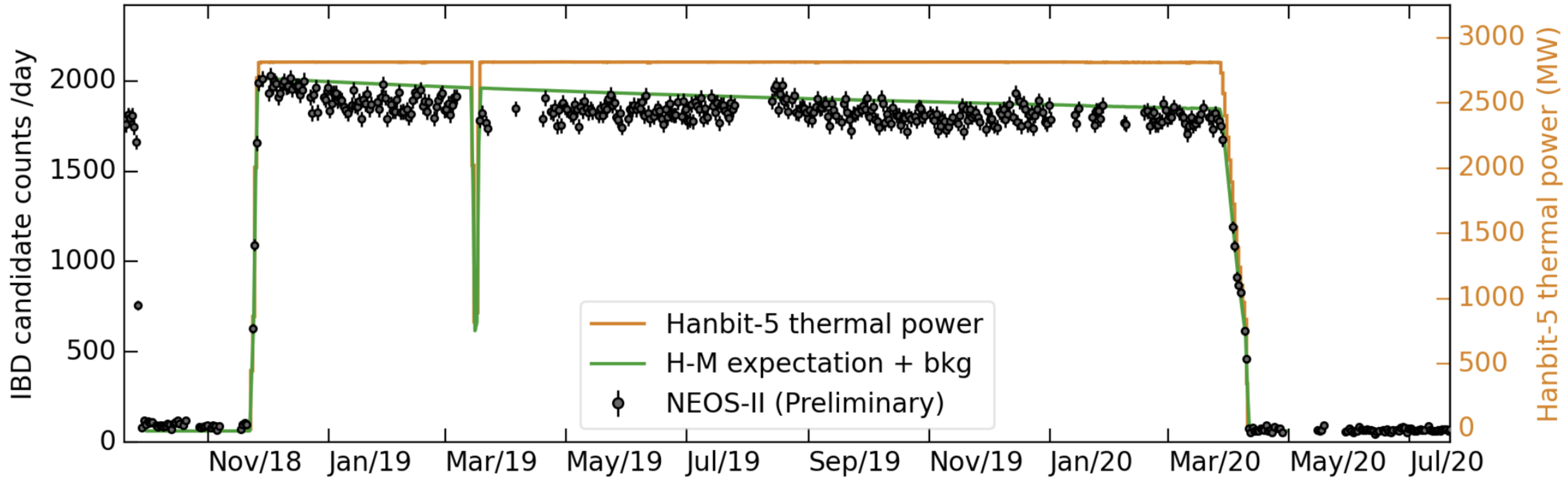


IBD Candidates & Background

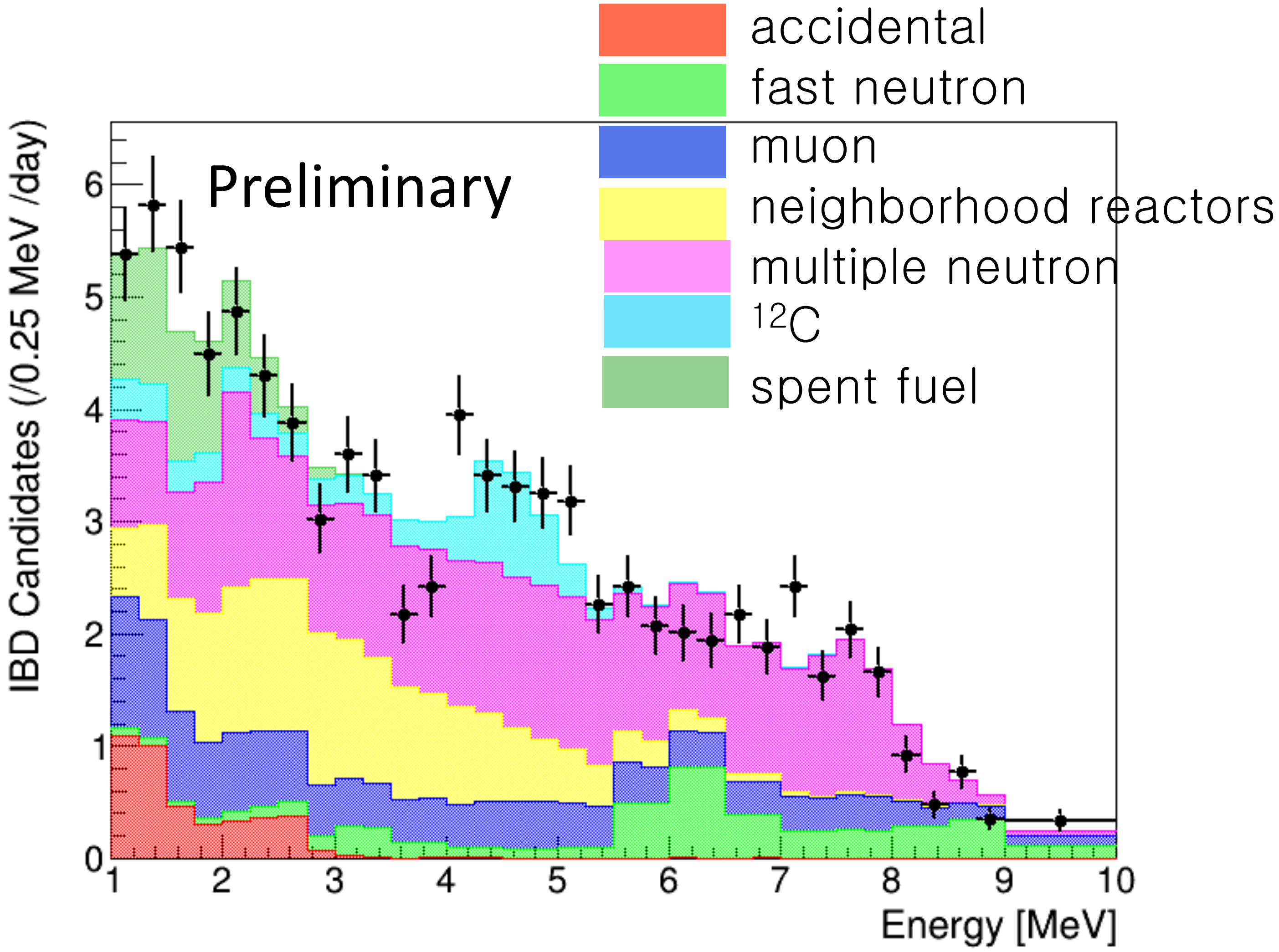




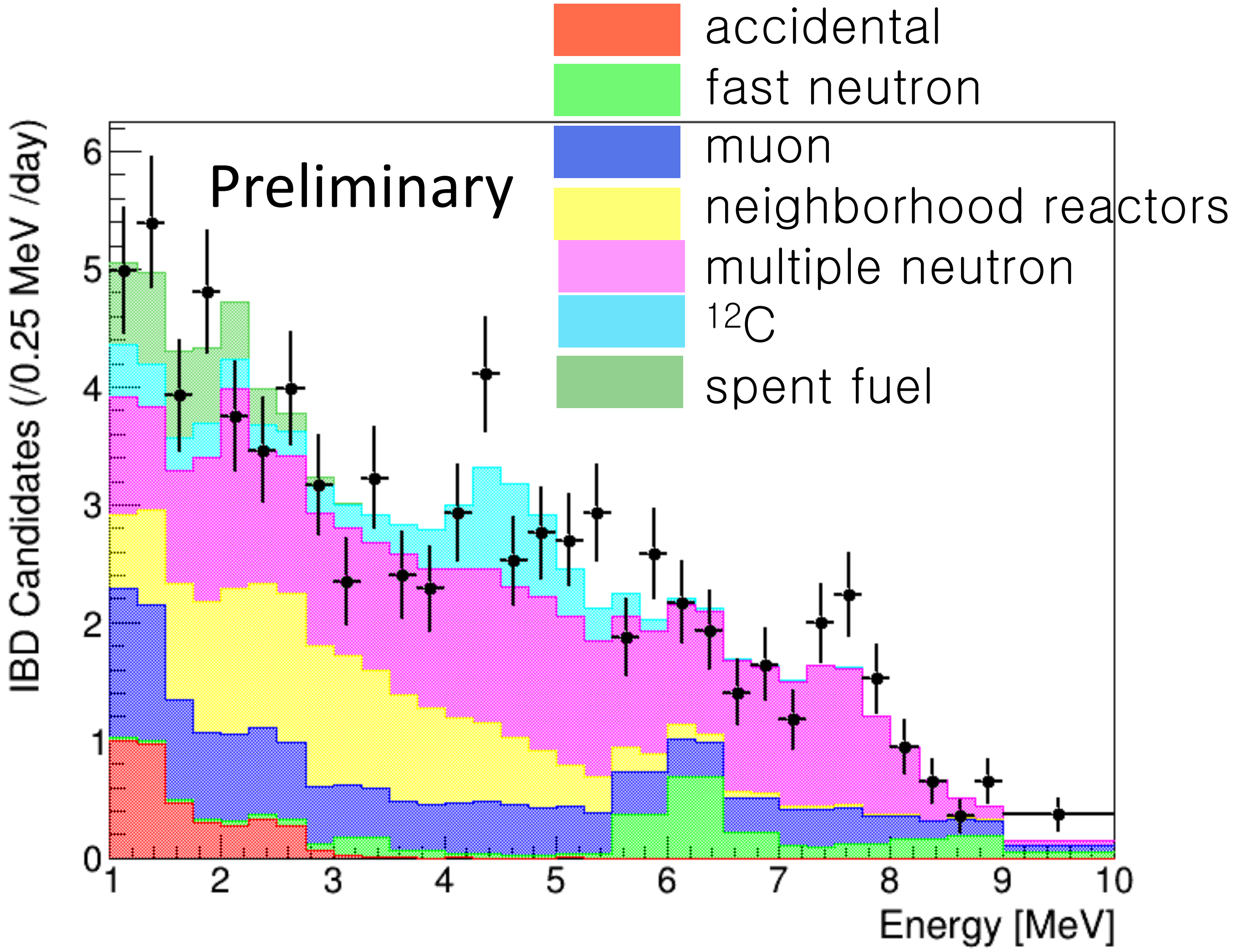
- ❑ **IBD Candidates:** (1846.1 +/-2.2)/day
- ❑ **Background:** (61.3 +/- 0.4)/day
- ❑ IBD Signal: (1784.8 +/-2.1)/day



NEOS-II Background Compositions

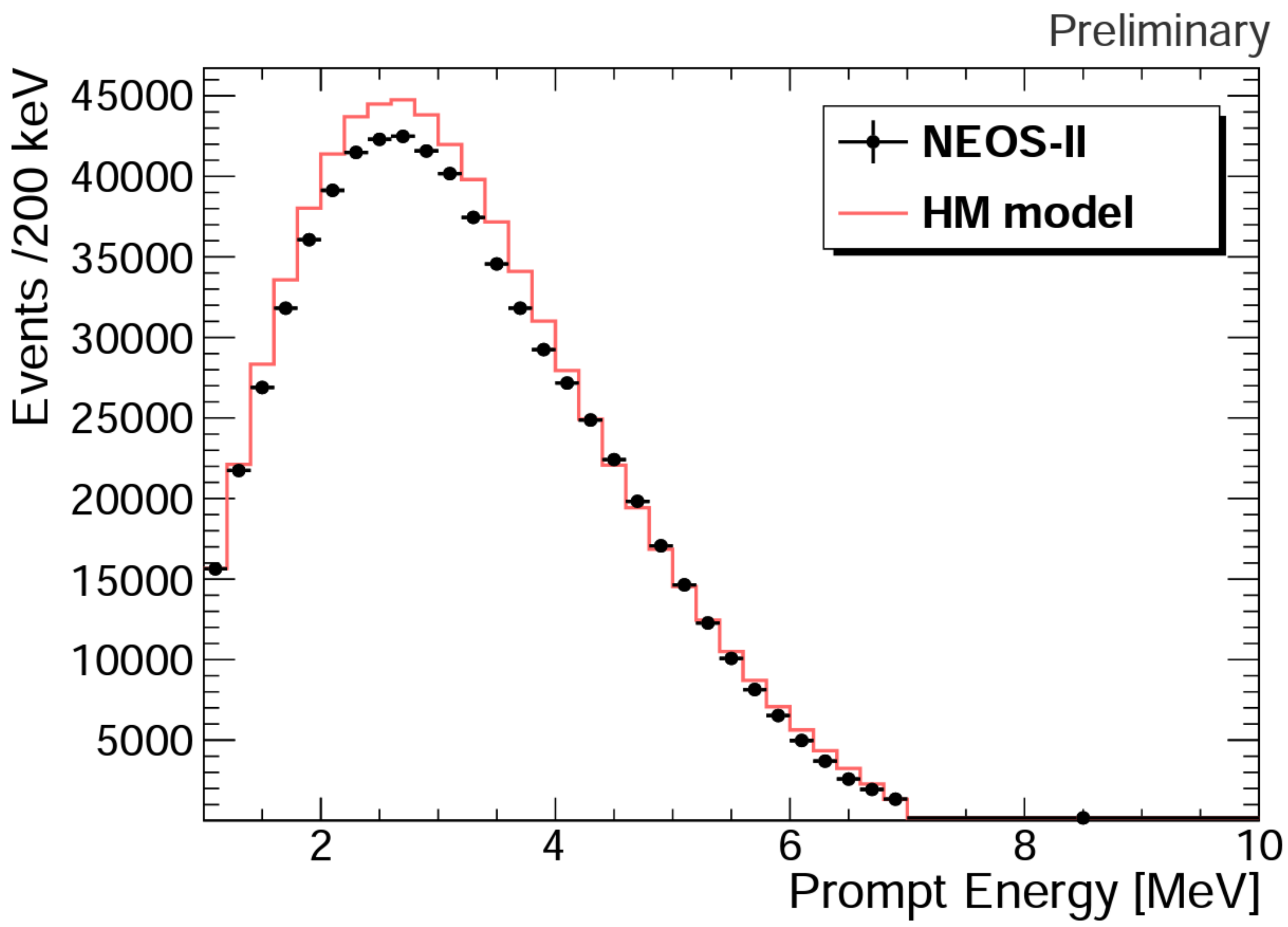


Reactor-OFF 1 (45 live days)

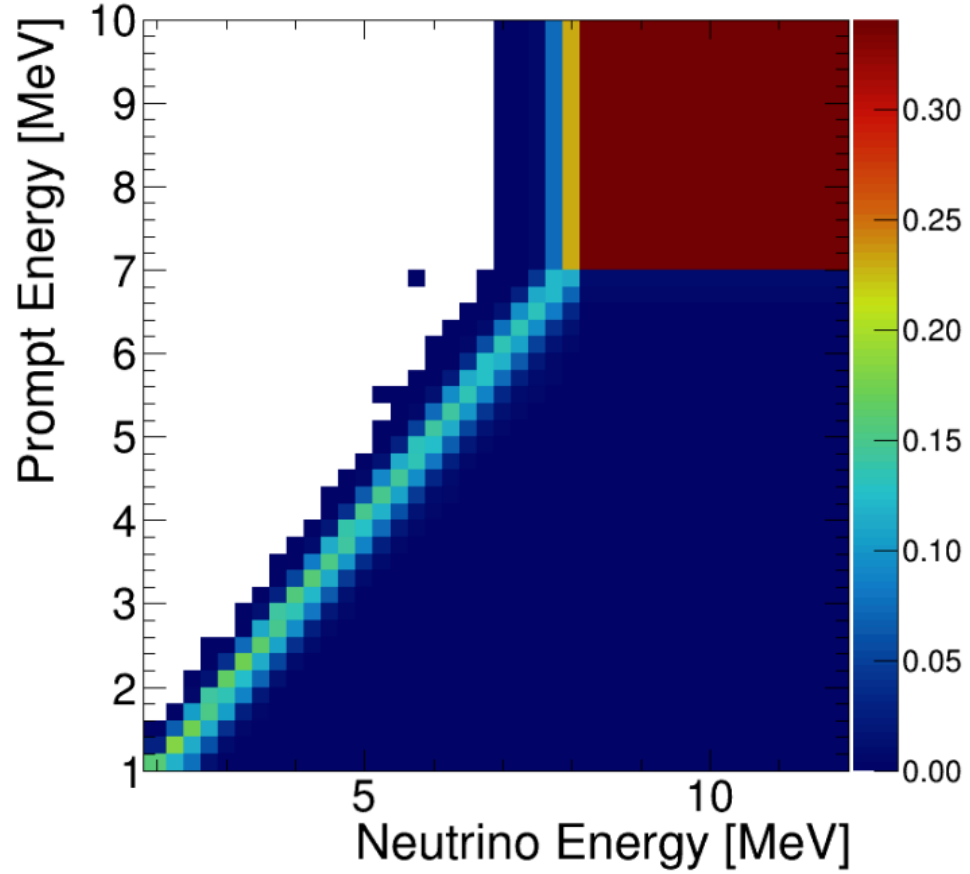


Reactor-OFF 2 (67 live days)

IBD Prompt Spectrum



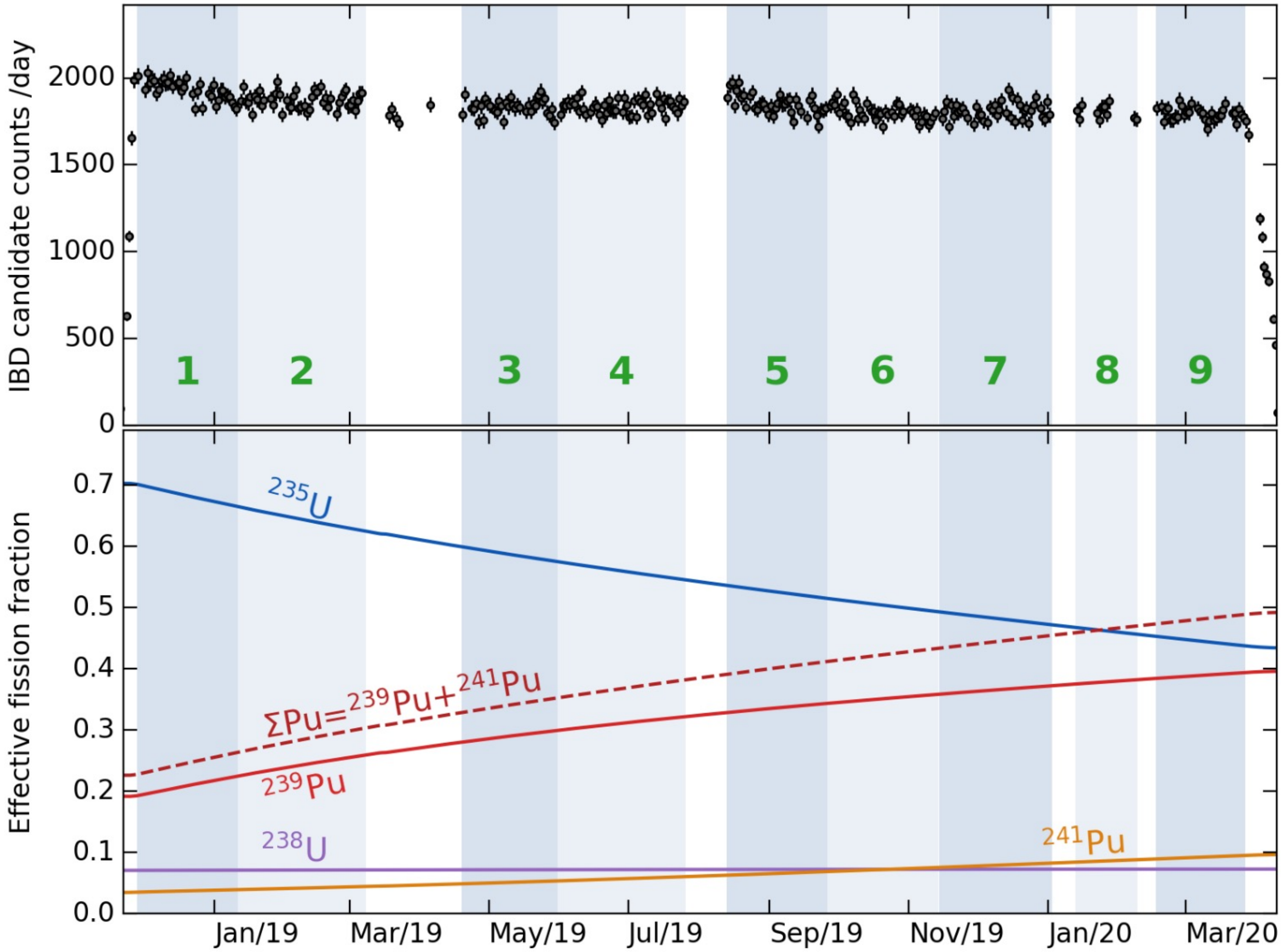
- Huber-Mueller (HM) model applying
  (1) NEOS-I detector matrix
  (2) NEOS-II energy resolution



- The Averaged Fission Fractions

Fission Isotope	^{235}U	^{239}Pu	^{238}U	^{241}Pu
NEOS-II	0.57	0.30	0.07	0.06

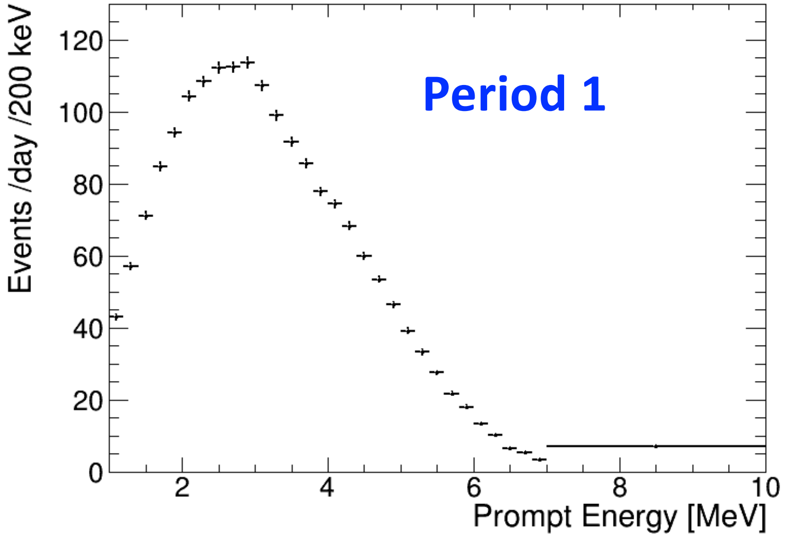
9 Groups of Data



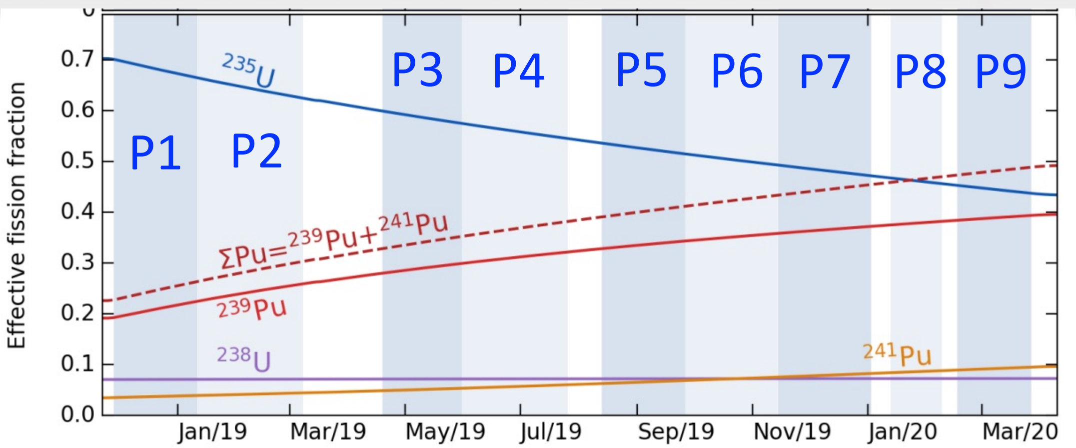
- Data is grouped into 9 to observe the evolution of reactor ν flux/shape.

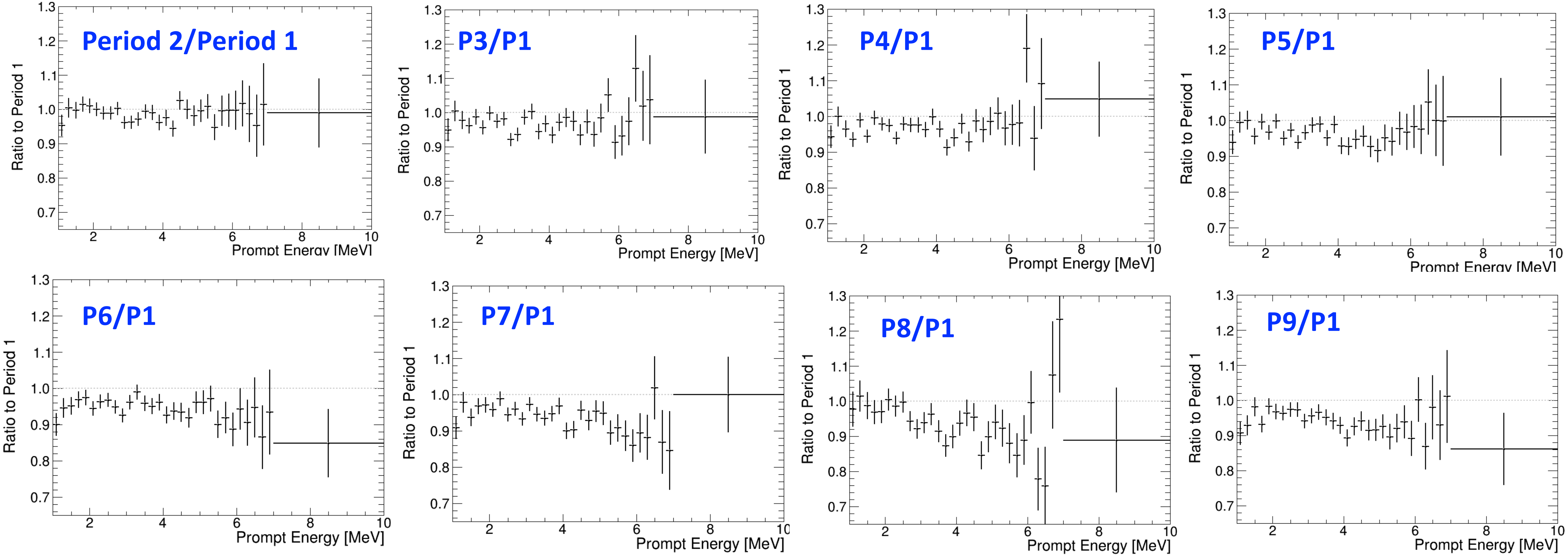
- IBD selection cuts are applied to each group of data to keep the same detection efficiency.

Evolution of Reactor ν spectra



Preliminary Plots





Chi2 Formula

$$\chi^2 = \sum_i^{N_E} \sum_j^{N_t} \frac{\left(M_{ij}^{on} - (1+\beta)\frac{T^{on}}{T^{off}} M_{ij}^{off} - S_{ij}\right)^2}{U_{ij}} + \left(\frac{\alpha}{\sigma_\alpha}\right)^2 + \left(\frac{\beta}{\sigma_\beta}\right)^2 + \eta^2 + \sum_m^{N_{EC}} \xi_m^2 + \left(\frac{\lambda}{\sigma_\lambda}\right)^2 + \left(\frac{\zeta}{\sigma_\zeta}\right)^2$$

- α: Normalization (2%)
- β: Background (6%)
- η: E scale
- ξ_m: E correlated (PSD, E_d, ΔT)
- λ: ^{238}U IBD yield (20%)
- ζ: ^{241}Pu IBD yield (20%)

N_E = 31 (# of E bins, i)
N_t = 9 (# of data sets, j)
N_{EC} = 3 (# of E corr bkg, m)

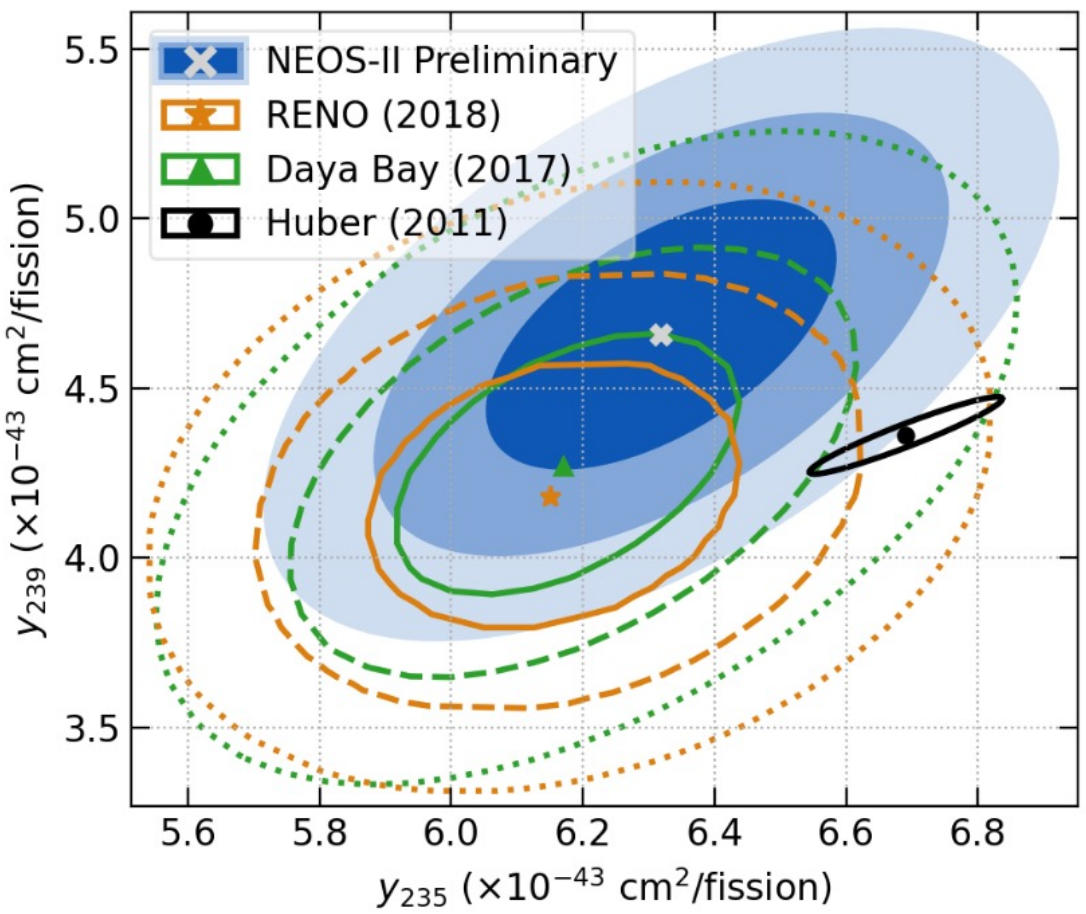
$$S_{ij} = (1+\alpha)\left(1+\eta\sigma_{ij}^{\eta}\right)\prod_m^{3}\left(1+\xi_m\sigma_{im}^{\xi}\right) \times \frac{N_p}{4\pi L^2}\epsilon_{ij}^{d} T_j^{on} \sum_k^{N_{iso}} F_{jk} X_k^{eq} y_{ik}$$

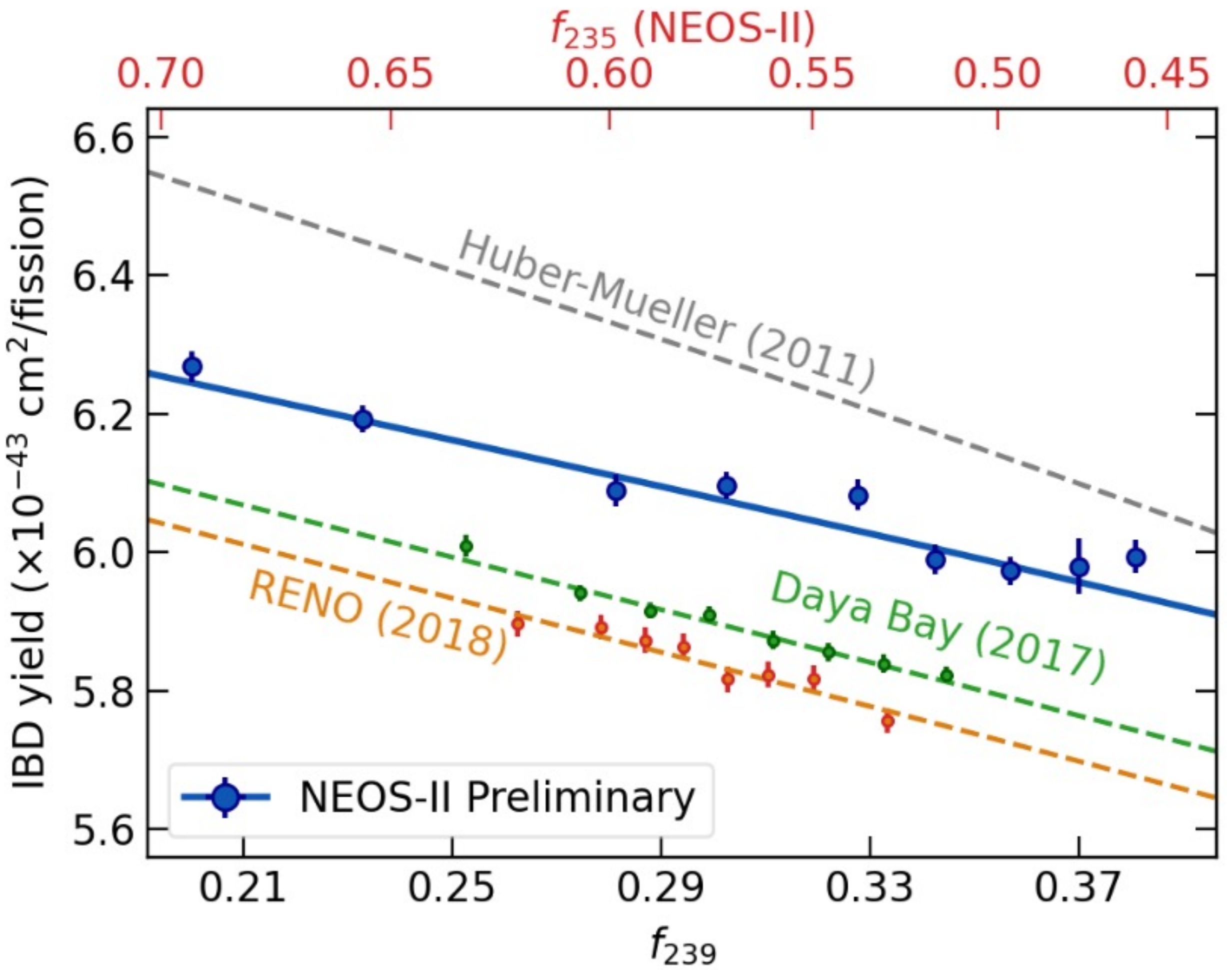
$$F_{jk} = f_{jk}\frac{P_{th}}{\sum_l f_l E_l}$$

X_k^{eq}: off-equilibrium correction

$$y_{ik} = \sigma_i(E_\nu)\phi_{ik}(E_\nu)$$

IBD Yields

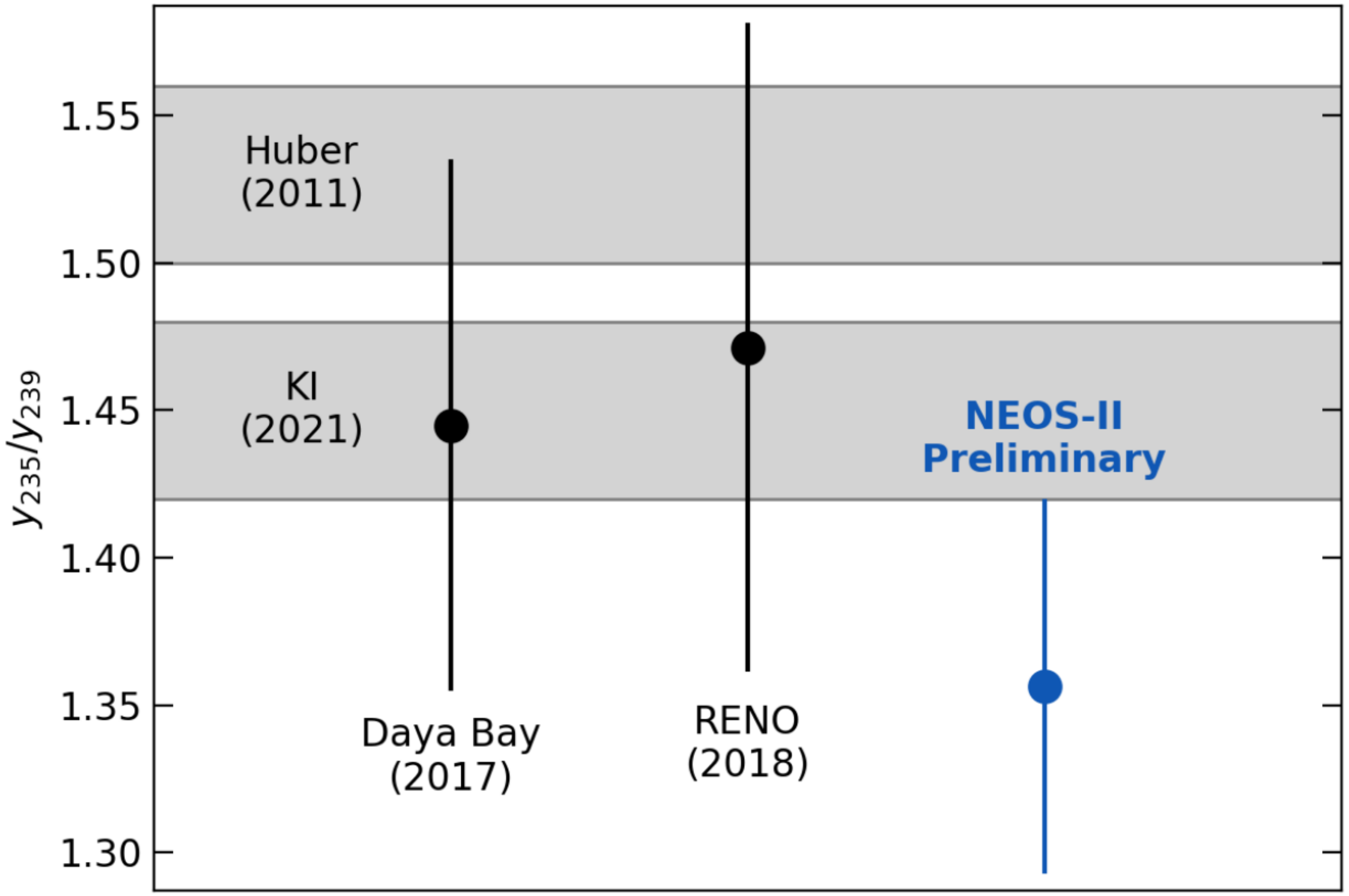




$\chi^2 = 233/217$

- Detection efficiency: $45 \pm 1.3\%$ (not finalized yet.)
- $y_{235}/y_{239} = 1.36 \pm 0.06$
  - $y_{235} = 6.32 \pm 0.18\ [10^{-43}\mathrm{cm}^2/\mathrm{fission}]$
  - $y_{239} = 4.66 \pm 0.26\ [10^{-43}\mathrm{cm}^2/\mathrm{fission}]$

IBD Yield Ratio



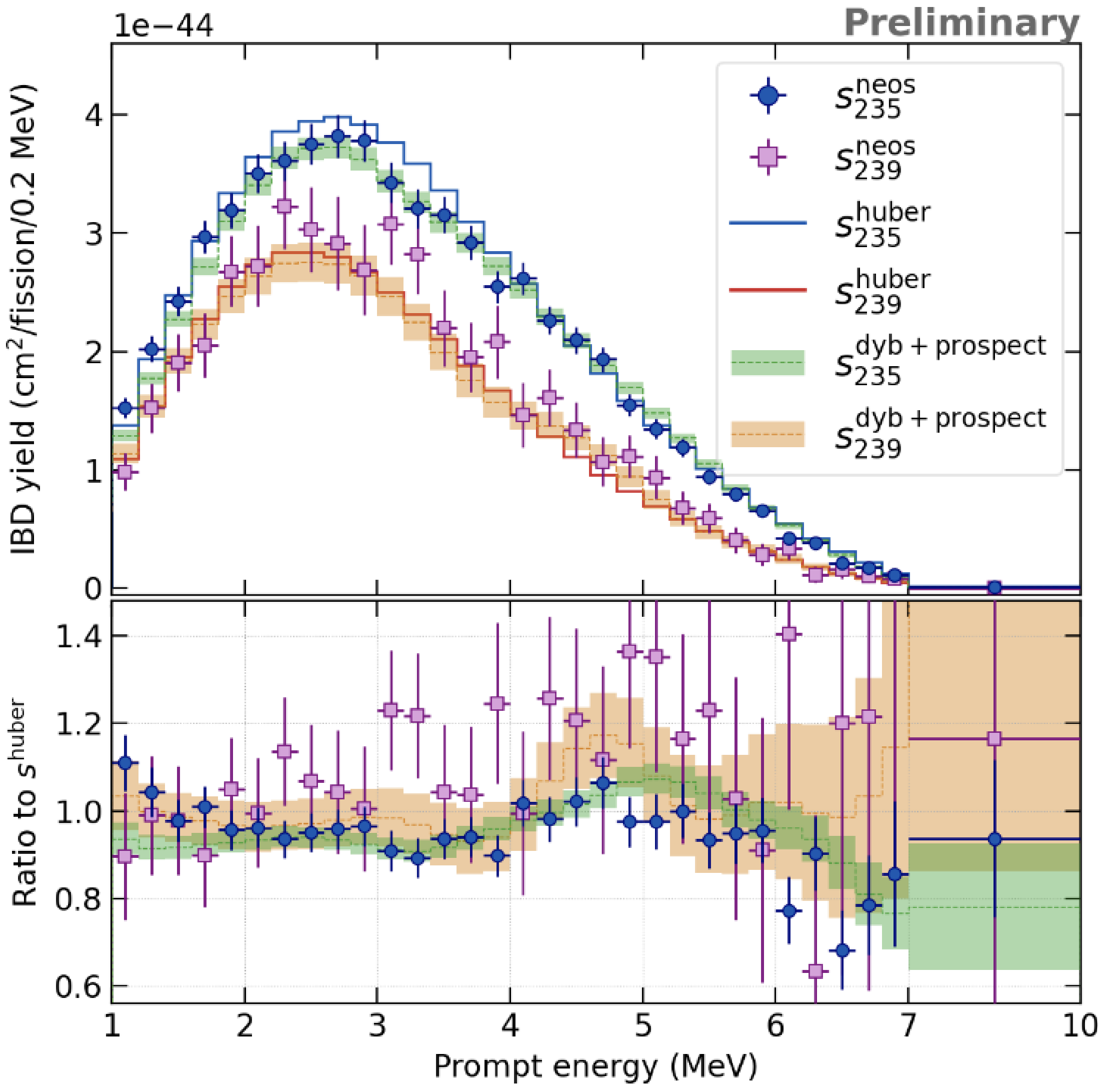
<u>KI (2021) model</u>:
V. Kopeikin et al.
"Reevaluating reactor antineutrino spectra with new measurements of the ratio between ^{235}U and ^{239}Pu β spectra"
PRD 104, L071301 (2021)

NEOS-II:
y_{235}/y_{239} = 1.36 +/- 0.06

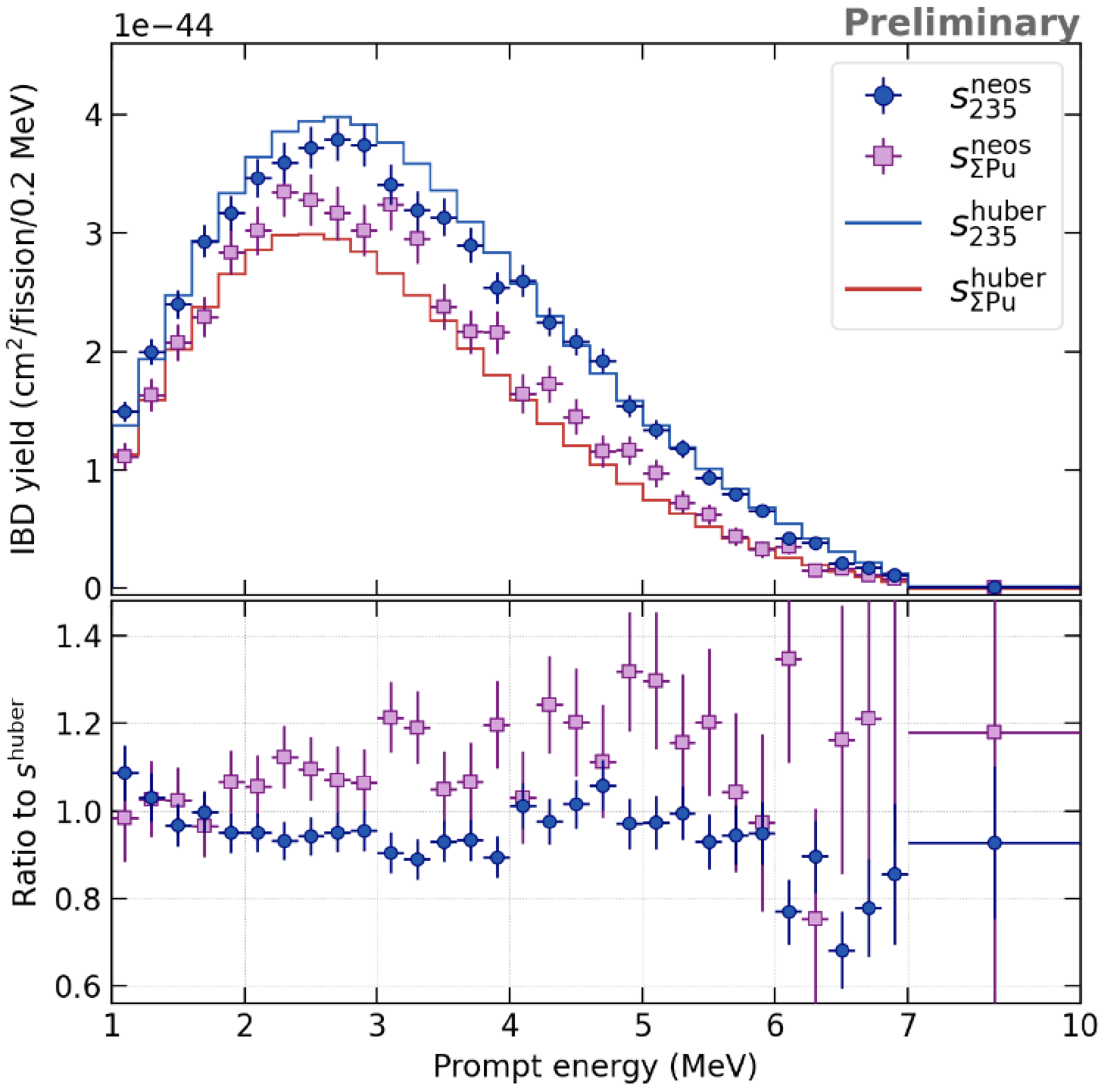
→ NEOS-II result has a tension with the Huber model.

Spectral Decomposition

- ^{235}U & ^{239}Pu $\chi^2 =$ 233/217

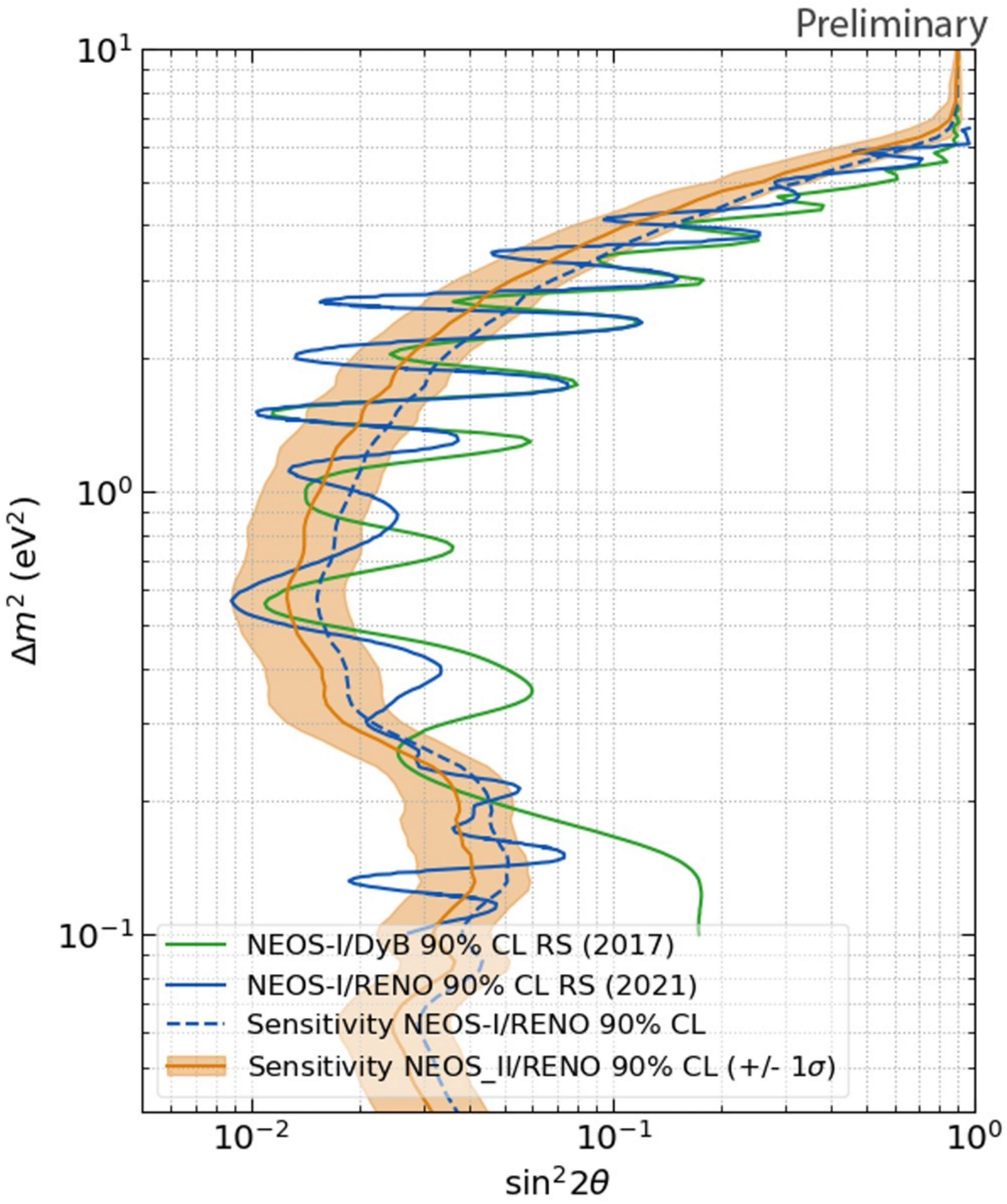


- ^{235}U & ΣPu $\chi^2 =$ 236/217



→ The "5 MeV bump" is seen in ^{235}U but is not conclusive for Pu.

Sterile Neutrino Search Sensitivity



- Rate+Shape analysis is on-going.
- Slightly better sensitivity
  due to statistical improvement.
- A preliminary result is expected soon.

Summary

- ❑ NEOS-II successfully measured prompt E spectrum from reactor ν using 388 (112) days of reactor-on (off) data.

- ❑ NEOS-II is one of the two VSBL reactor experiments which took data for **a full fuel cycle** of a commercial reactor.

- ❑ Light Yield decrease was well handled. Its effect is marginal.

- ❑ IBD Yields & spectral decomposition analysis is being finalized.
  - Sterile neutrino search results would be expected soon.

- ❑ There might be a new opportunity beyond NEOS-II.