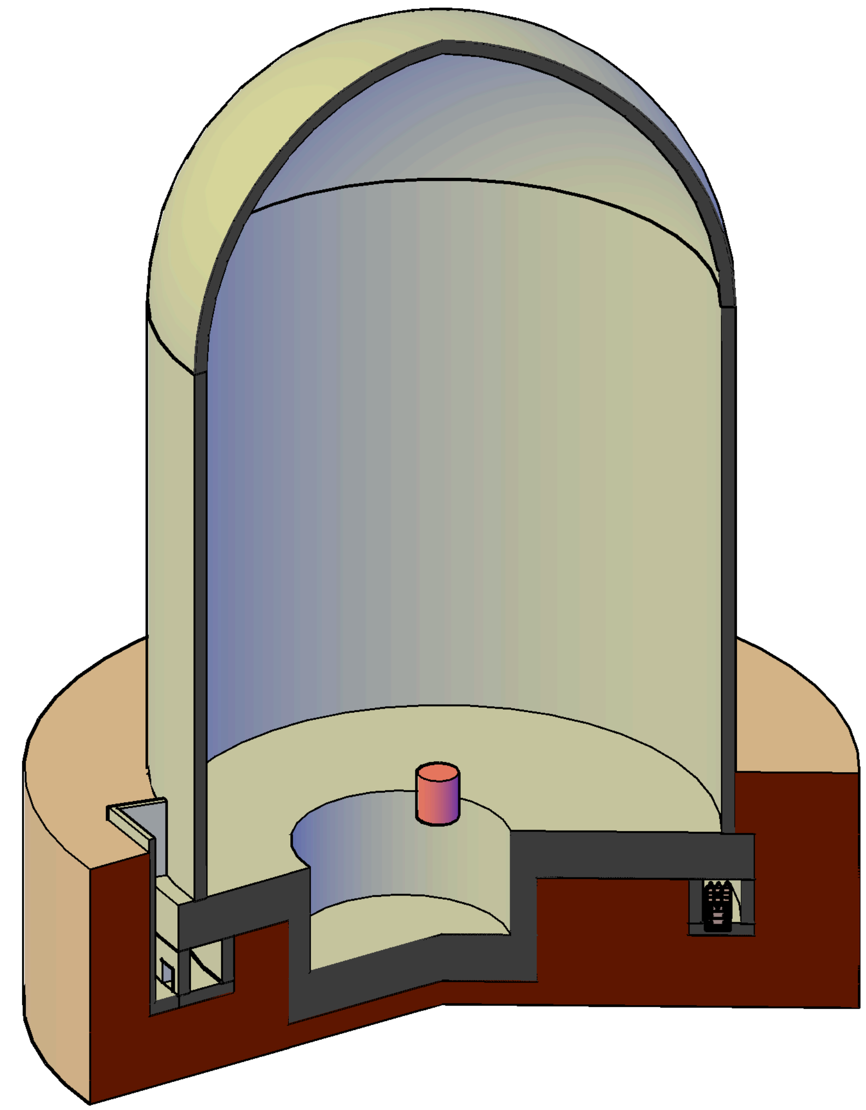
Neutrino **E**xperiment for **O**scillation at **S**hort Baseline



Aug 04 @ ICHEP 2016, Chicago

Yoomin Oh for NEOS Collaboration

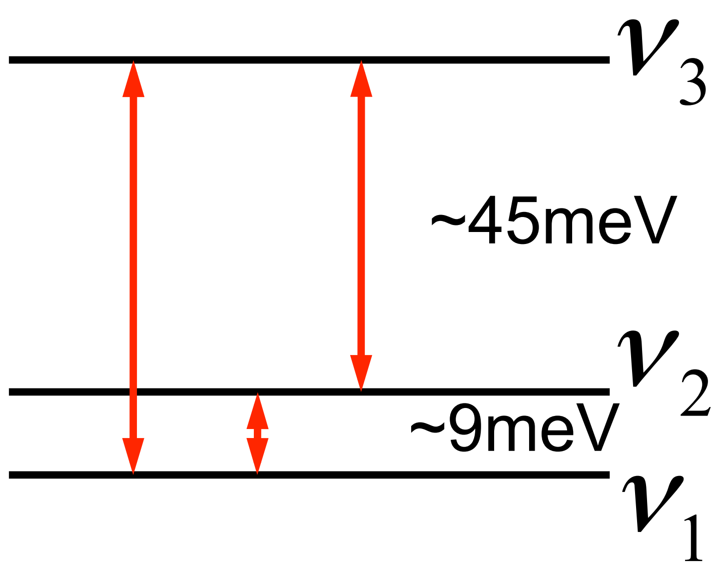
Center for **U**nderground **P**hysics, IBS

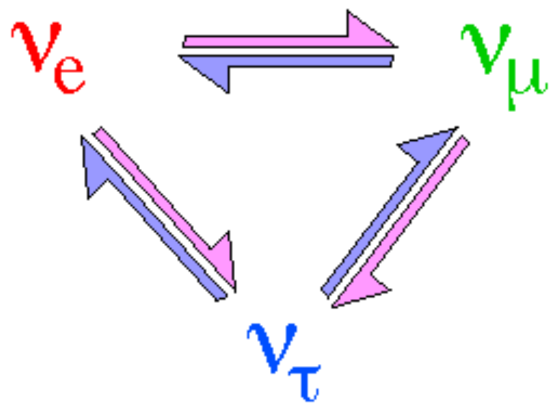
Center for Underground Physics

NEOS Collaboration

Hongjoo Kim, Jooyoung Lee,
Kyungkwang Joo, Ba Ro Kim,
Changhwan Jang, Siyeon Kim, Youngju Ko,
Kyungmin Seo, Jinyu Kim, Hyunsoo Kim,
Gwang-Min Sun, Boyoung Han,
Hyunseo Park,
Yeongduk Kim, Eun-ju Jeon, Jaison Lee, Moo-hyun Lee,
Yoomin Oh, Hyangkyu Park, Kang-soon Park

3 ν mixing and oscillation





$$\sin^2\theta_{13} = 0.023$$

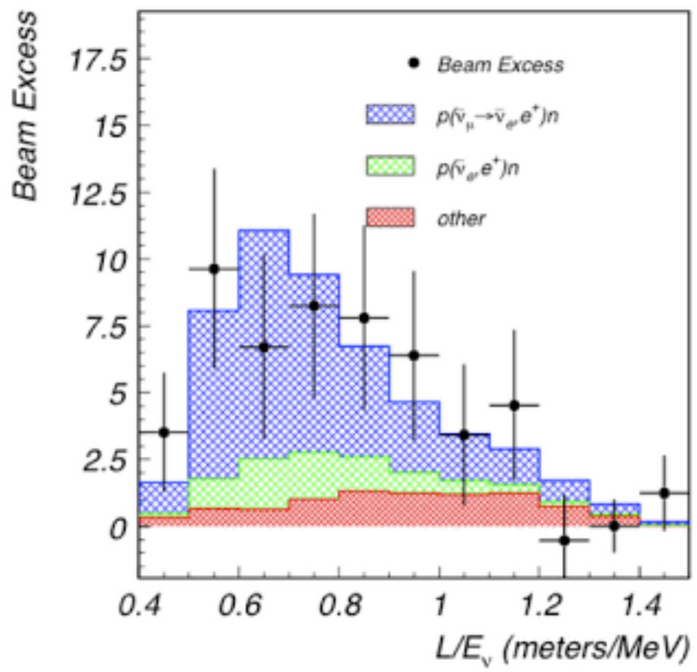
$$\Delta m^2_{21} = 7.54 \times 10^{-5}\,\mathrm{eV}^2,\ \sin^2\theta_{12} = 0.31,$$

$$\Delta m^2_{32} = 2.43 \times 10^{-3}\,\mathrm{eV}^2,\ \sin^2\theta_{23} = 0.44$$

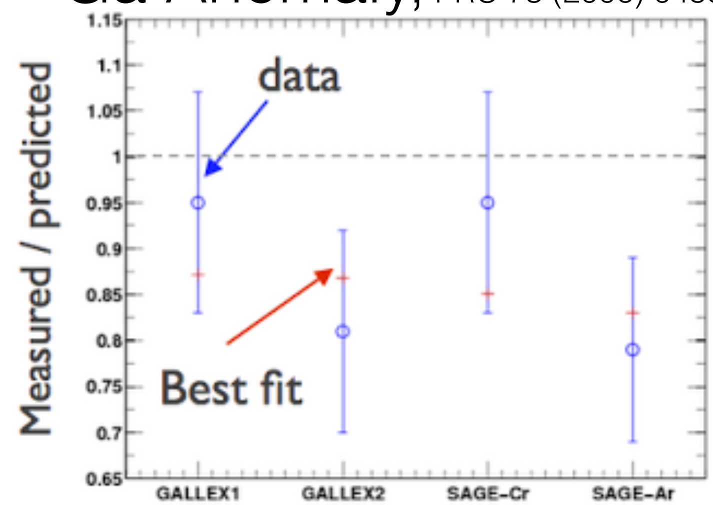
but…

More than 3?

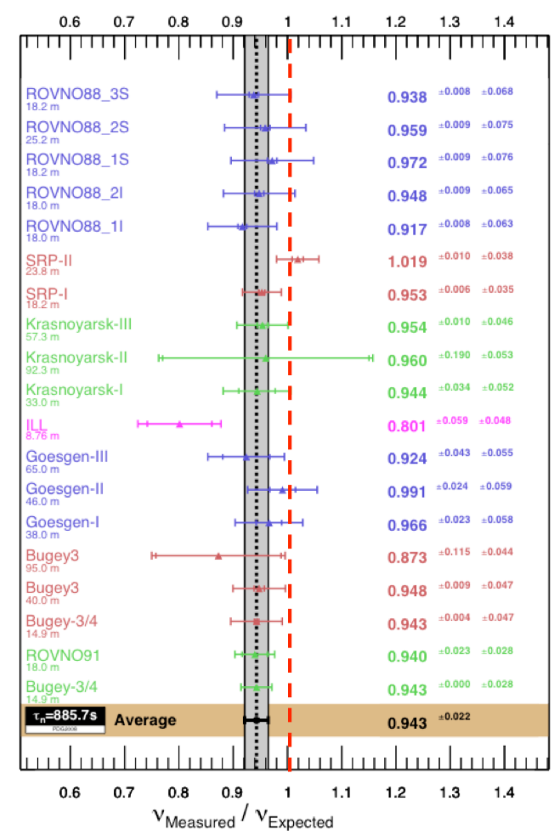
LSND, PRD 64 (2001) 112007



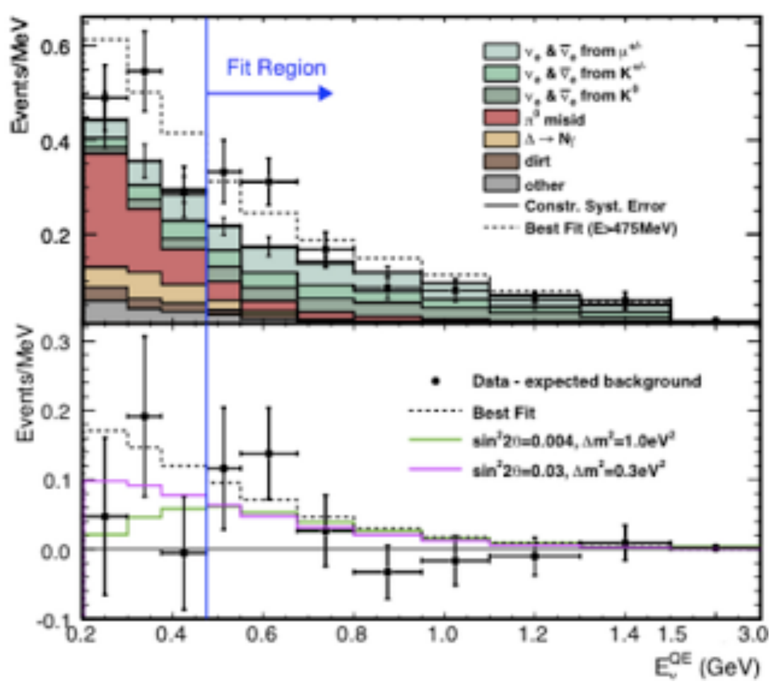
Ga Anomaly, PRC 73 (2006) 045805



Reactor Anomaly, arXiv:1204.5379

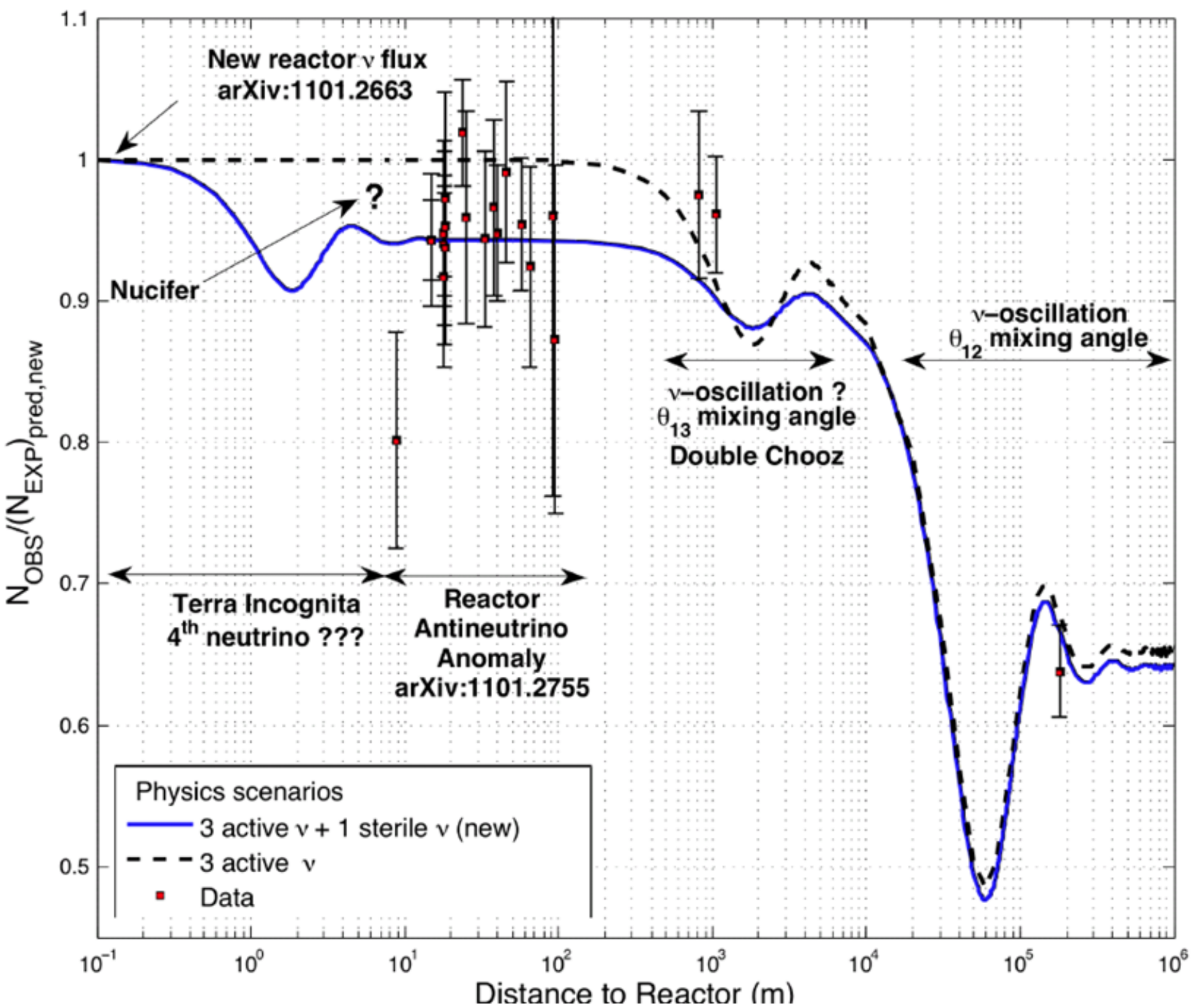


MiniBooNE, PRL 102 (2009) 101802

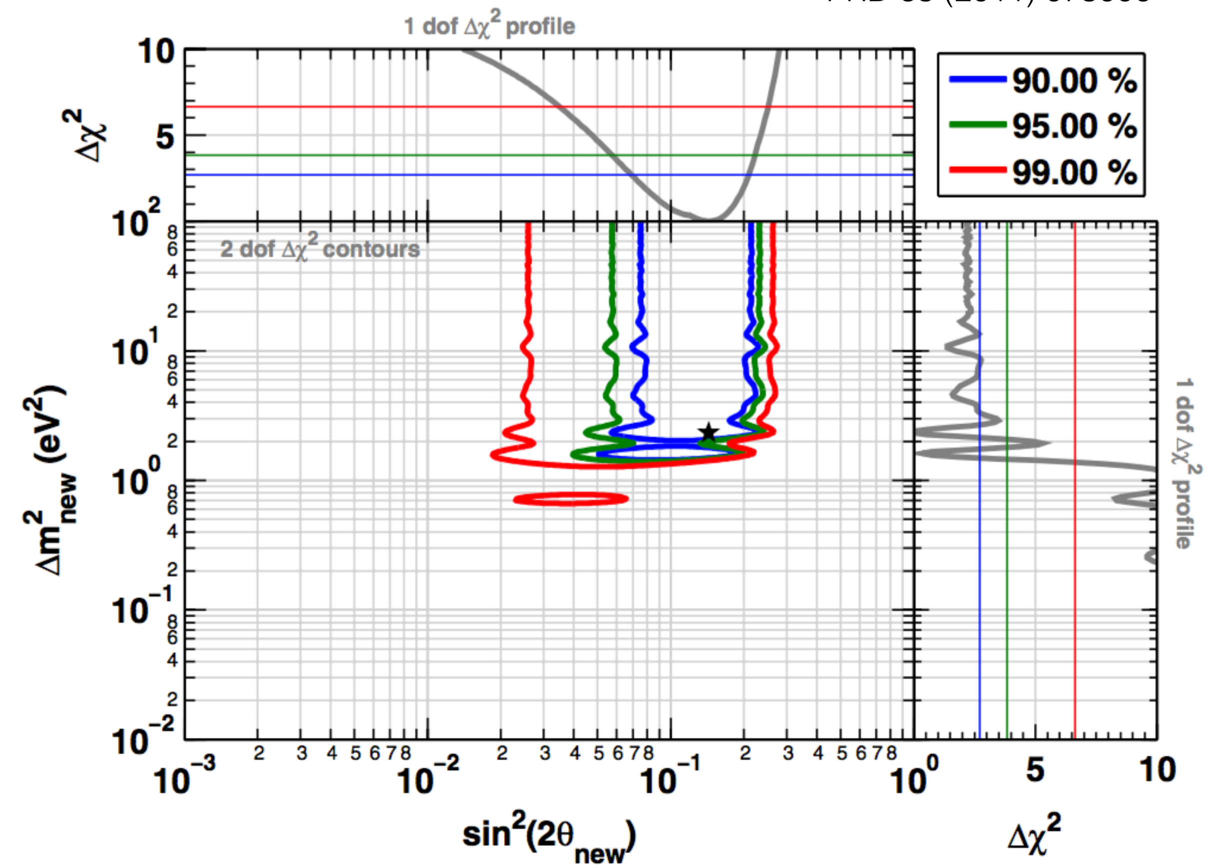


3+1 ν and Reactor SBL

$$P \simeq 1 - \sin^2 2\theta_{14} \sin^2\left(1.27 \Delta m^2_{41}\,[\mathrm{eV}^2] \frac{L\,[\mathrm{m}]}{E_\nu\,[\mathrm{MeV}]}\right)$$



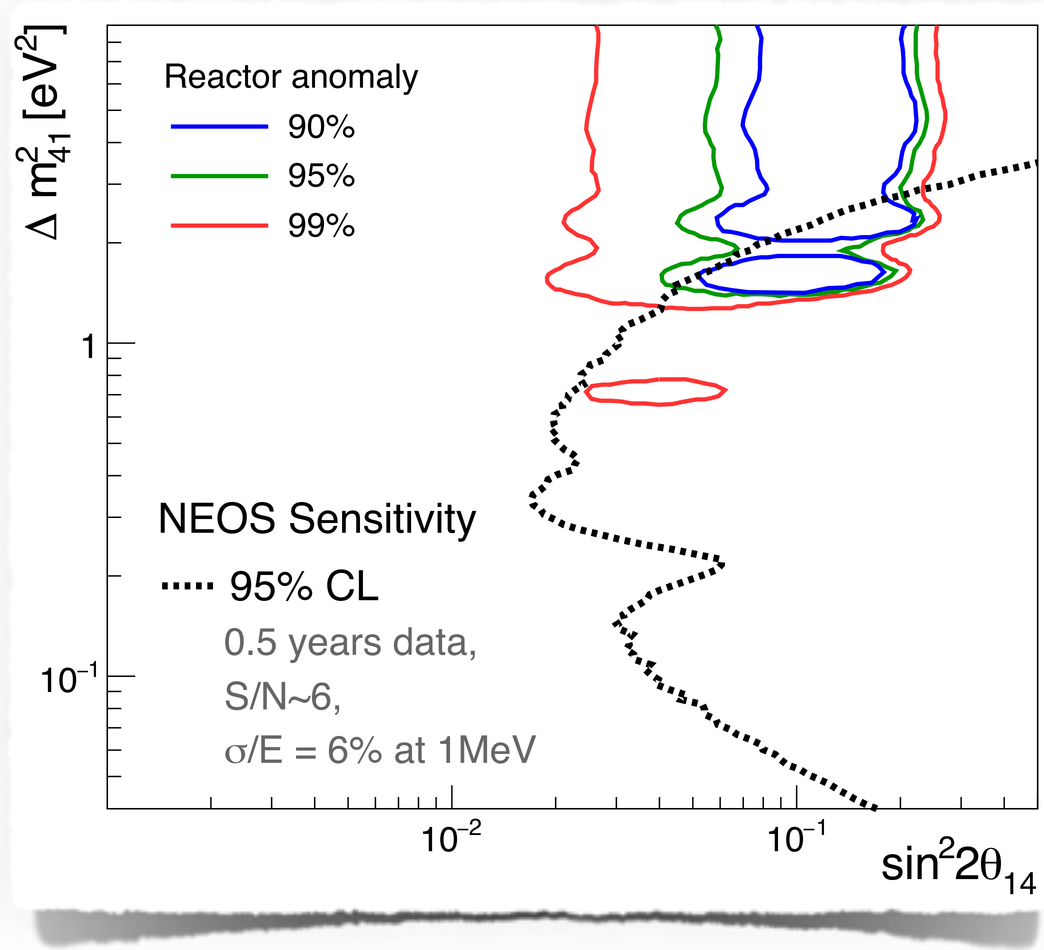
PRD 83 (2011) 073006

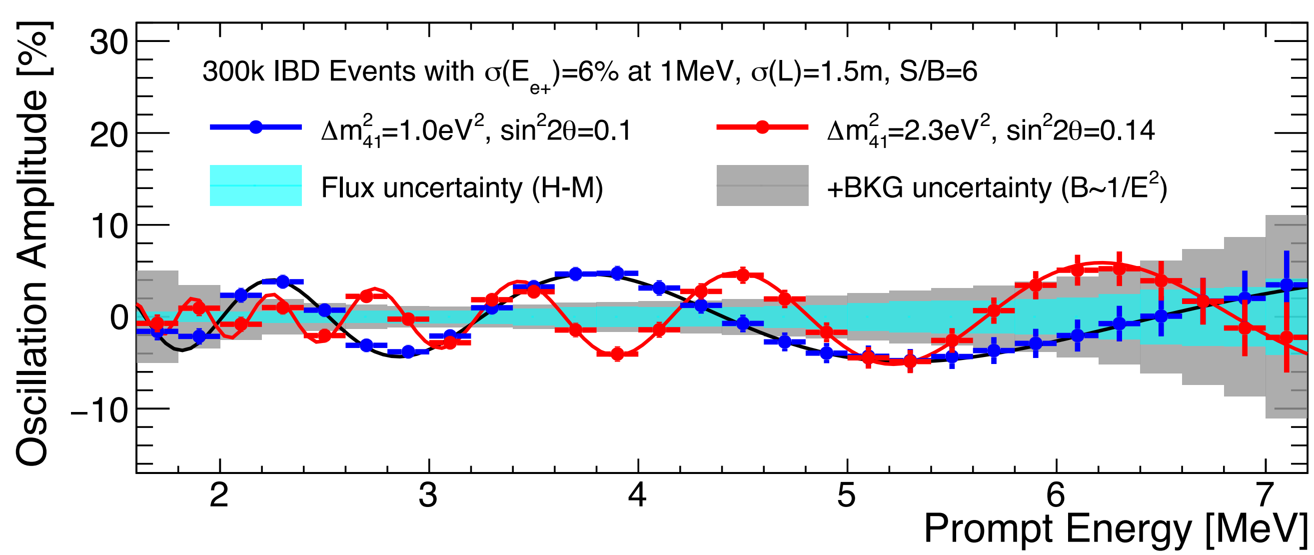


- Challenges in reactor SBL experiment
  — small size detector, safety and security
  — poor S/N ratio, lack of overburden
  — shielding from reactor induced bkg.

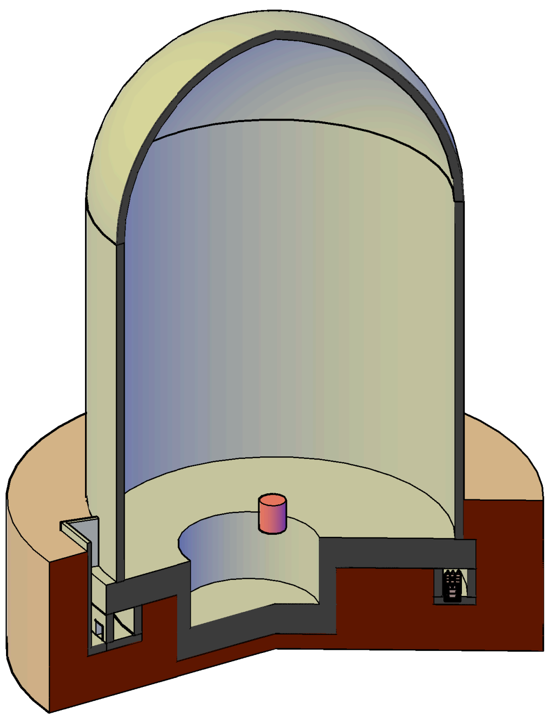
NEOS Experiment

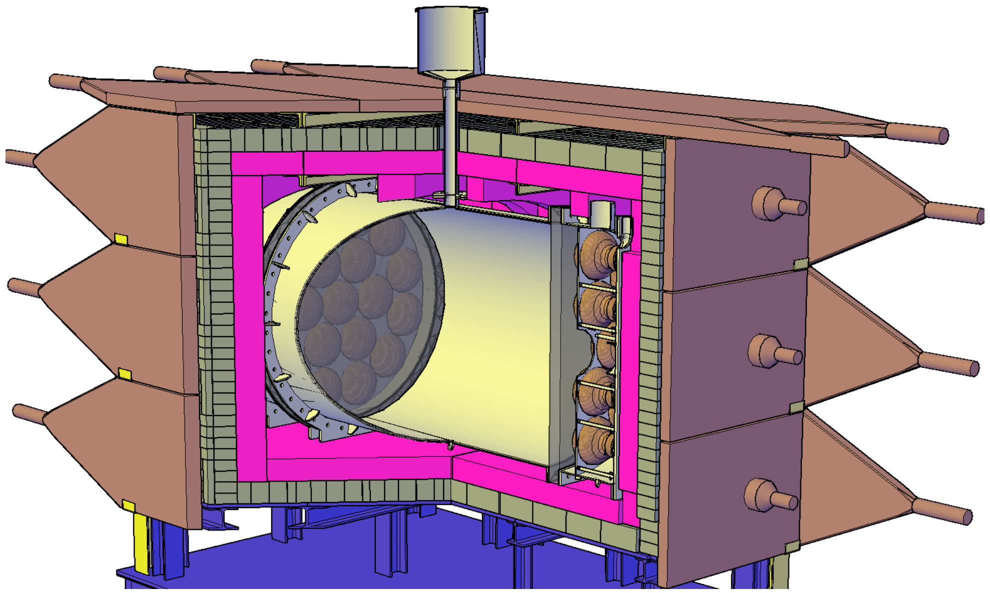
- 2.8 GWt commercial reactor
  — Hanbit NPP in Yeonggwang, Korea
  — core size: 3.1 m (ϕ), 3.8 m (H)
  — LEU fuel.
- Tendon Gallery
  — 24 m baseline
  — overburden > 20 mwe
- Homogeneous LS detector
  — 5% energy resolution @ 1 MeV
  — PSD capability
- Spectral shape analysis with a single detector/baseline measurement
  — dependence on reference spectrum



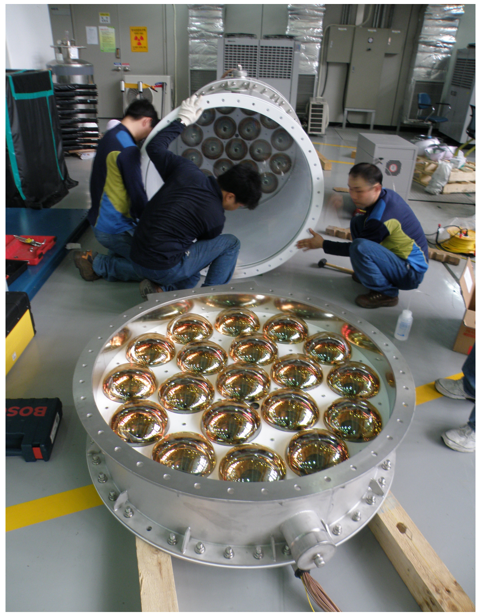


NEOS Detector



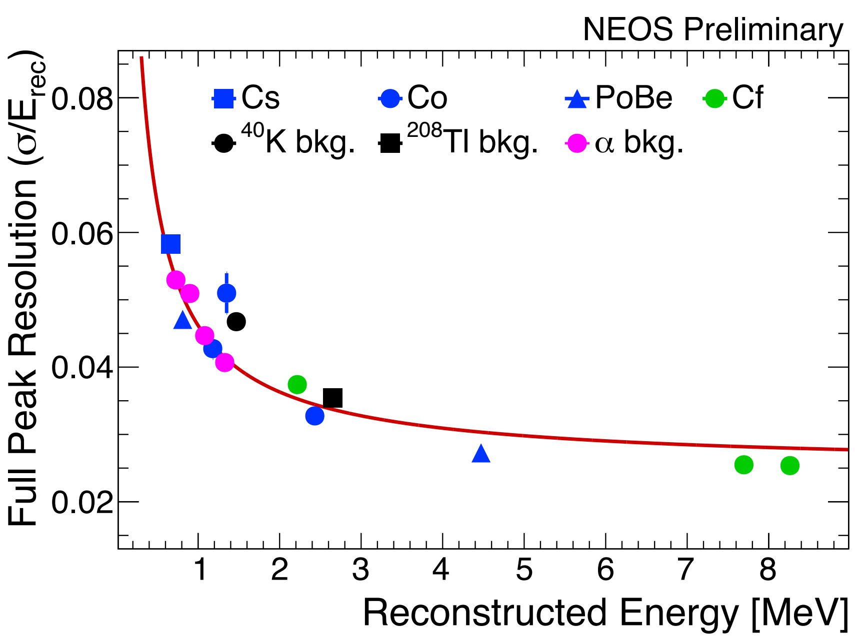


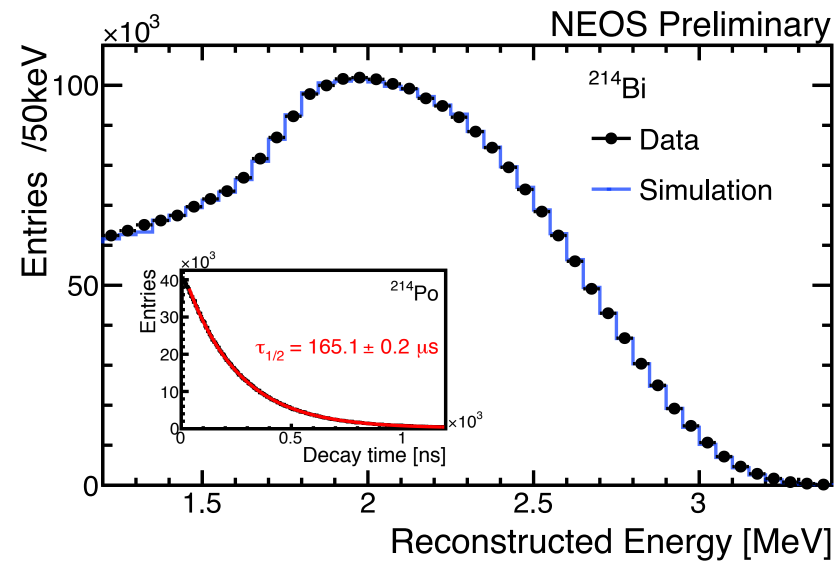
- Homogeneous LS target
  — 1008 L LAB+UG-F (9:1)
  — 0.5% Gd loaded
  — 38 PMT(8″) in mineral oil buffer
- Shieldings
  — 10 cm B-PE, 10 cm Pb
  — muon counter
- Data AcQuisition
  — 500 MS/s FADC (waveform)
  — 62.5 MHz SADC

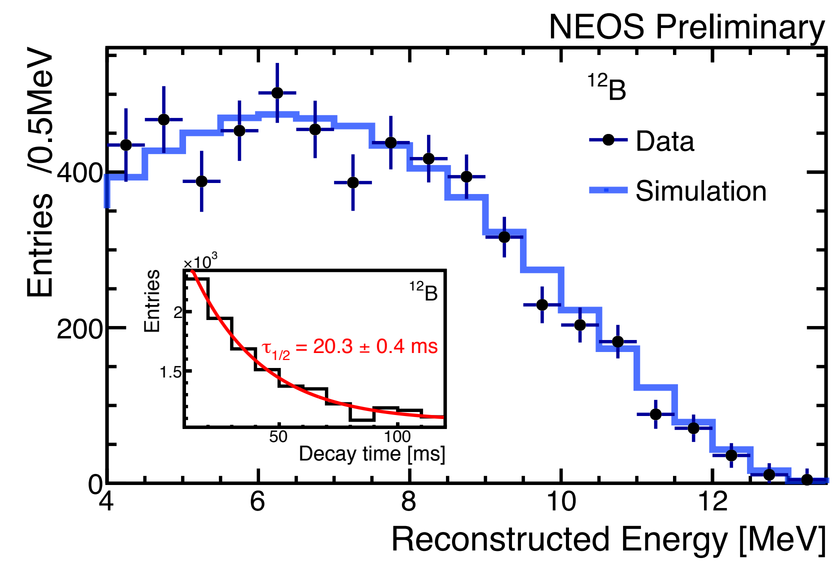


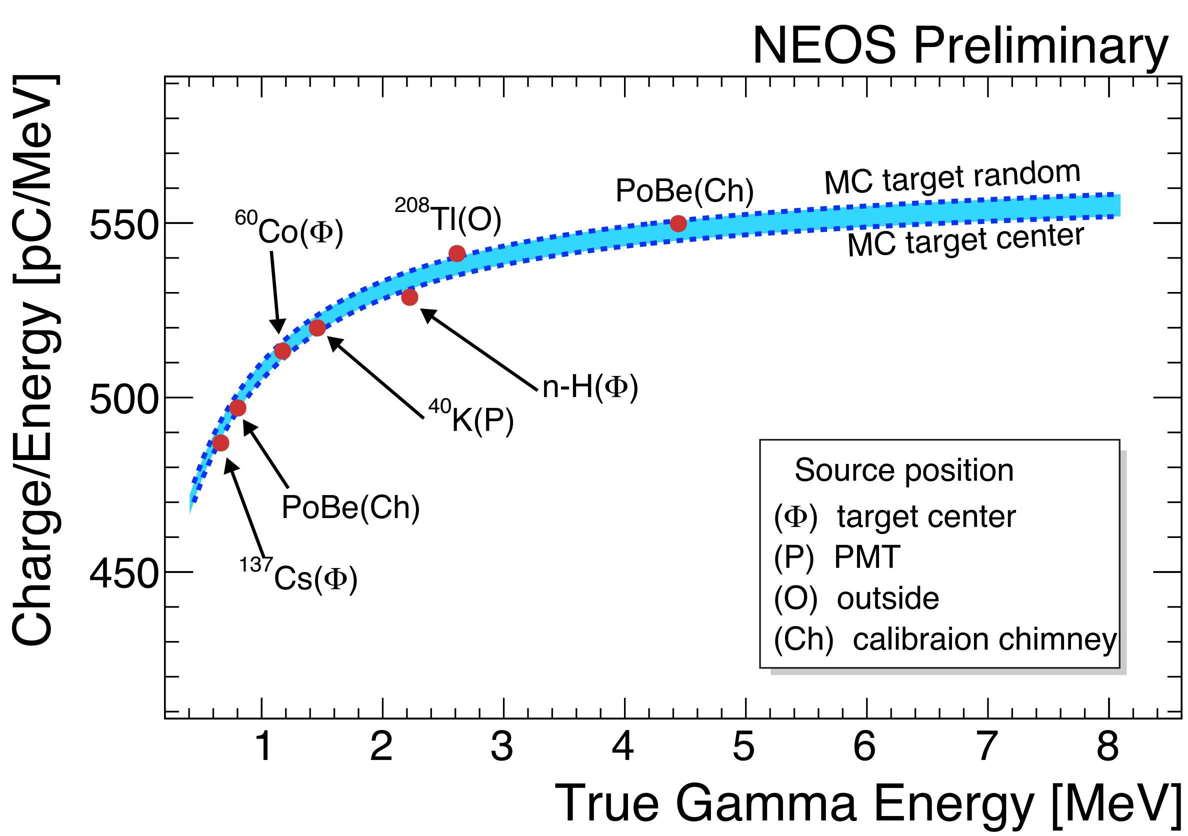
Detector responses

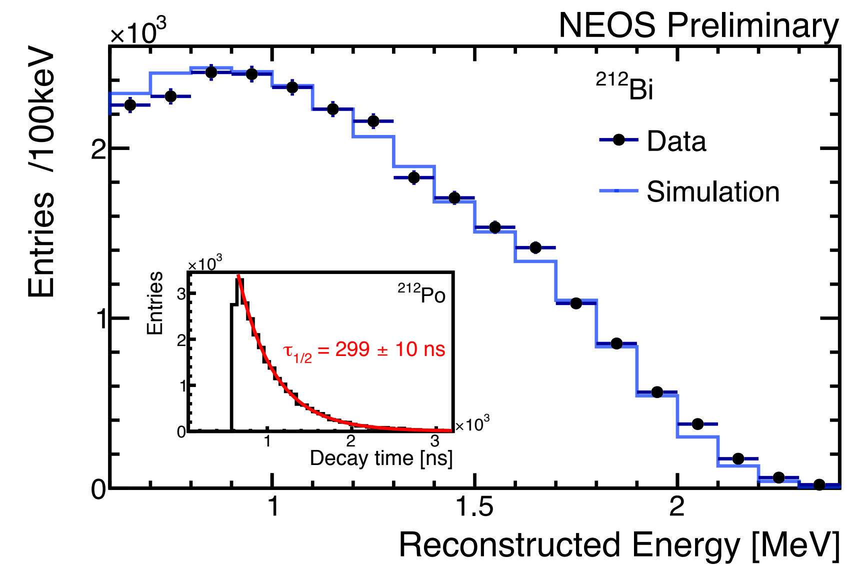
See Youngju Ko's poster on Saturday





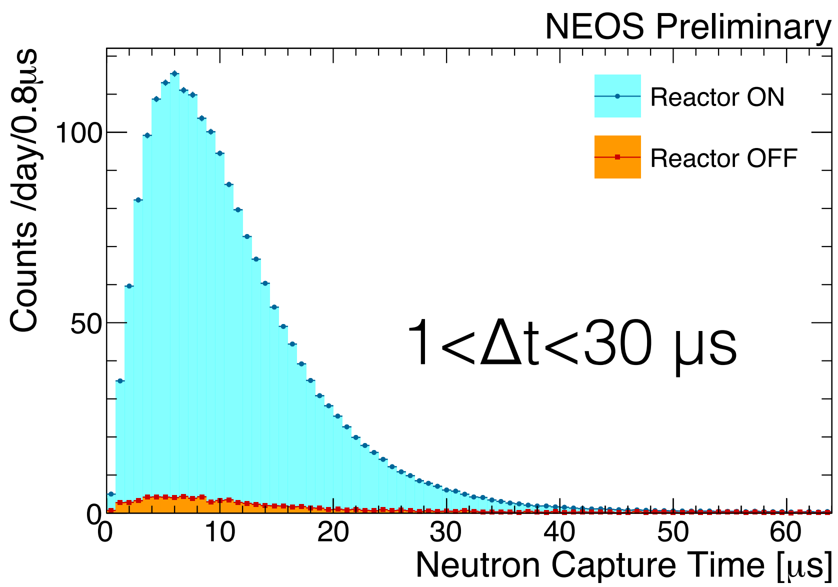


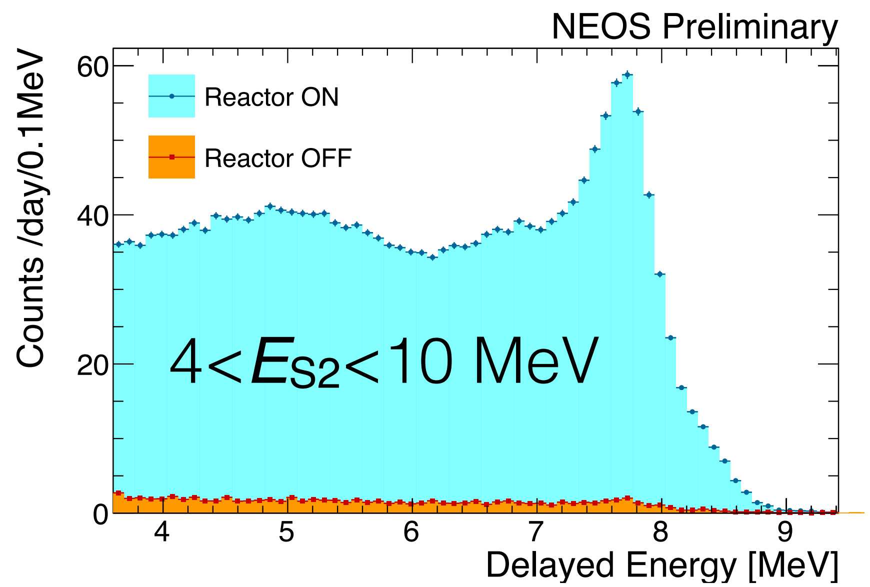


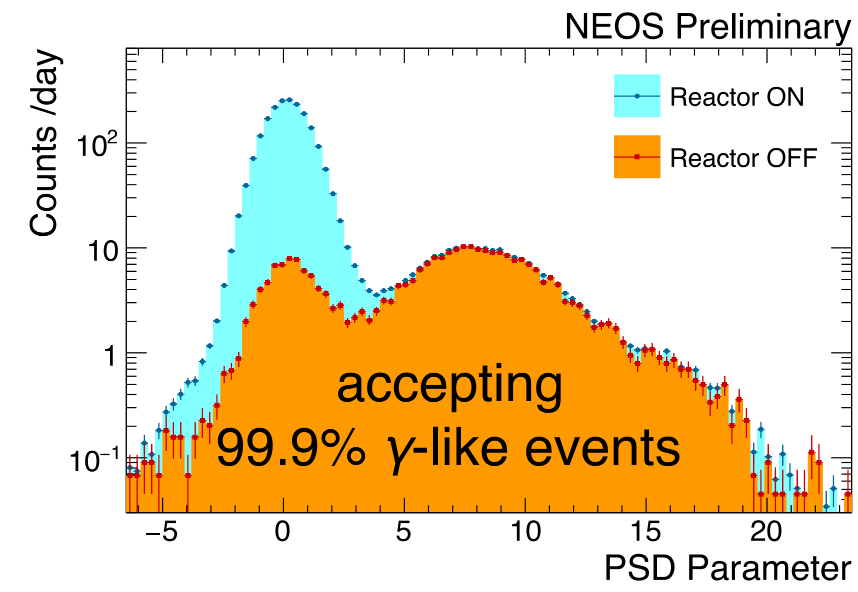


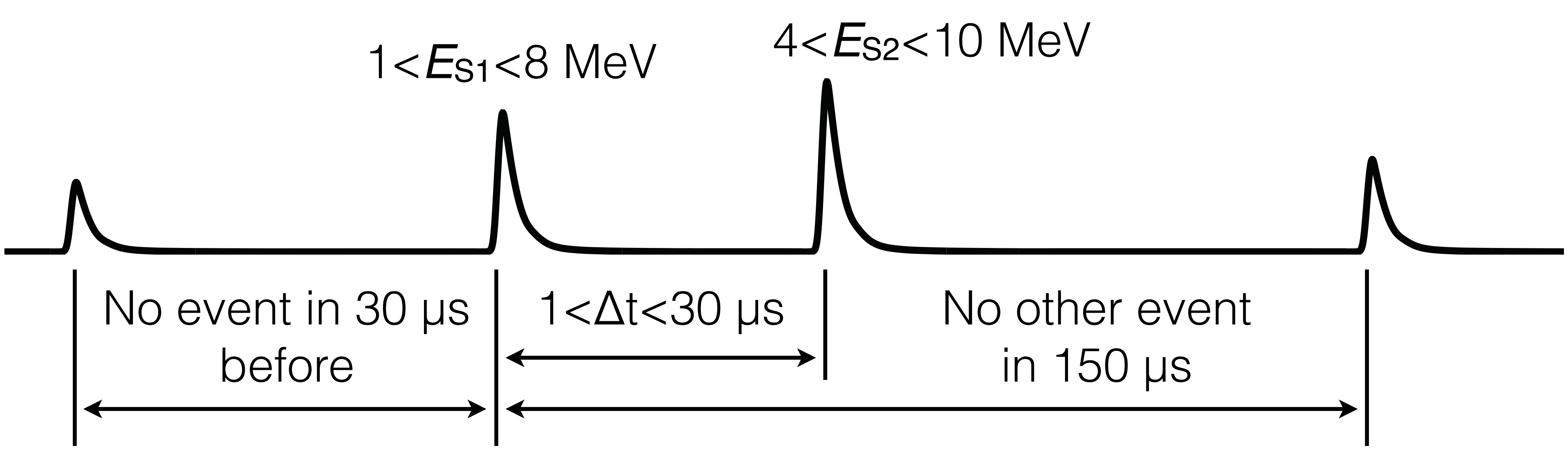
Data successfully reproduced by MC

IBD candidates





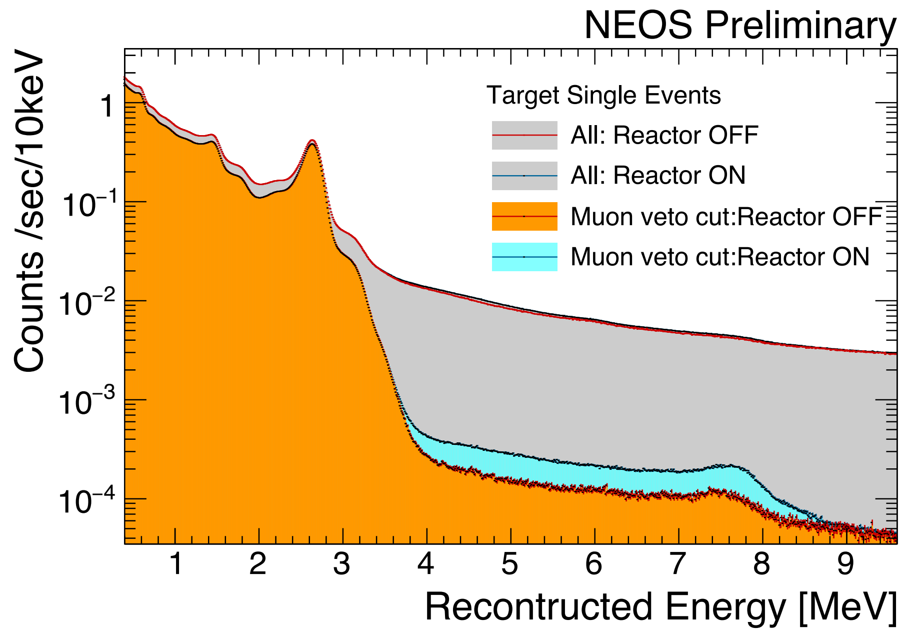


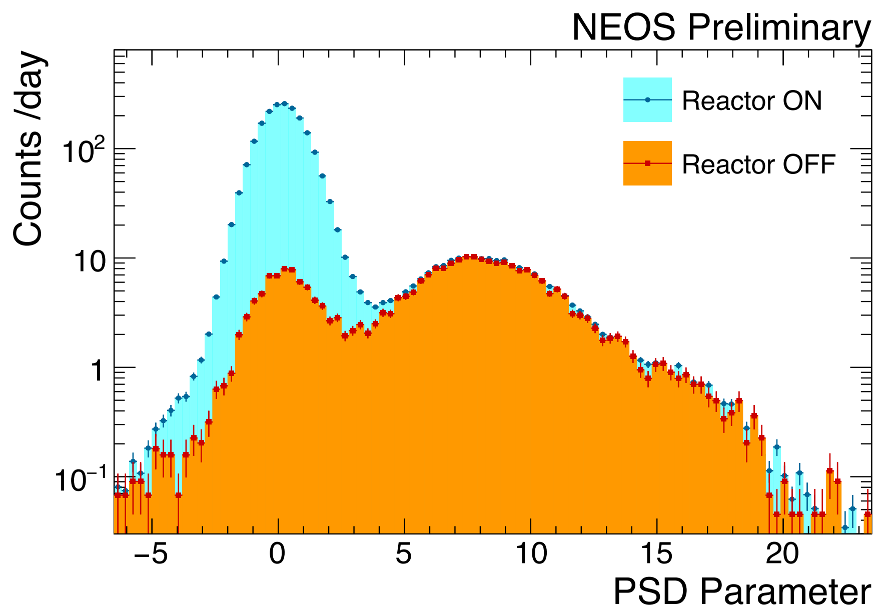


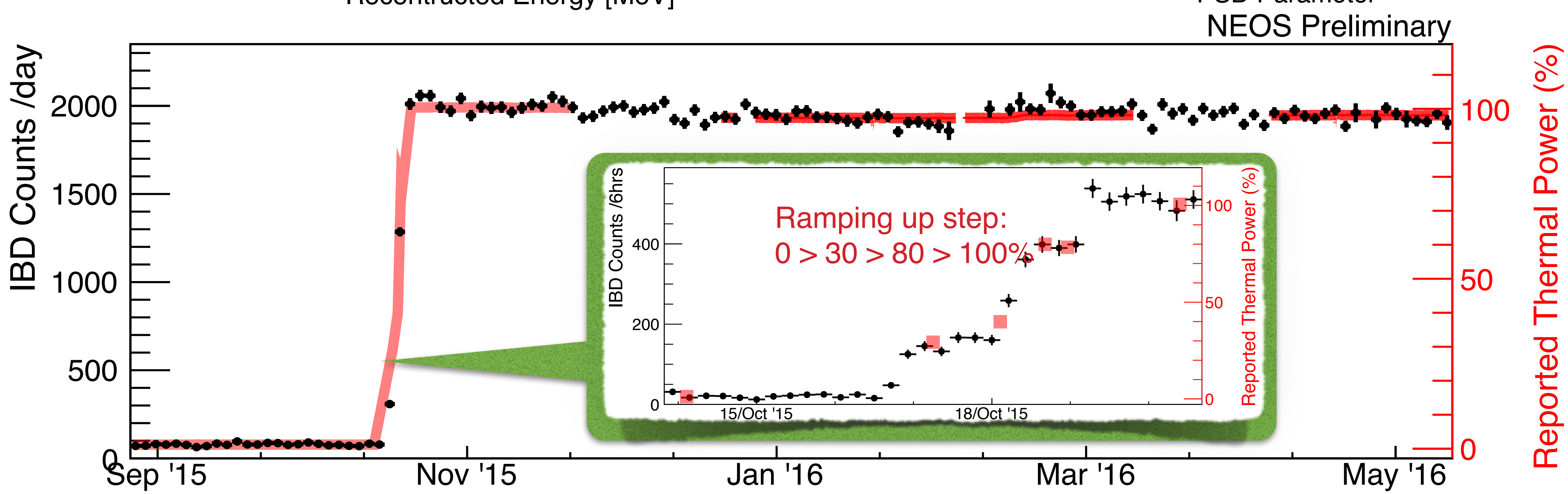
and 150 μs muon veto.

Reactor OFF > ON

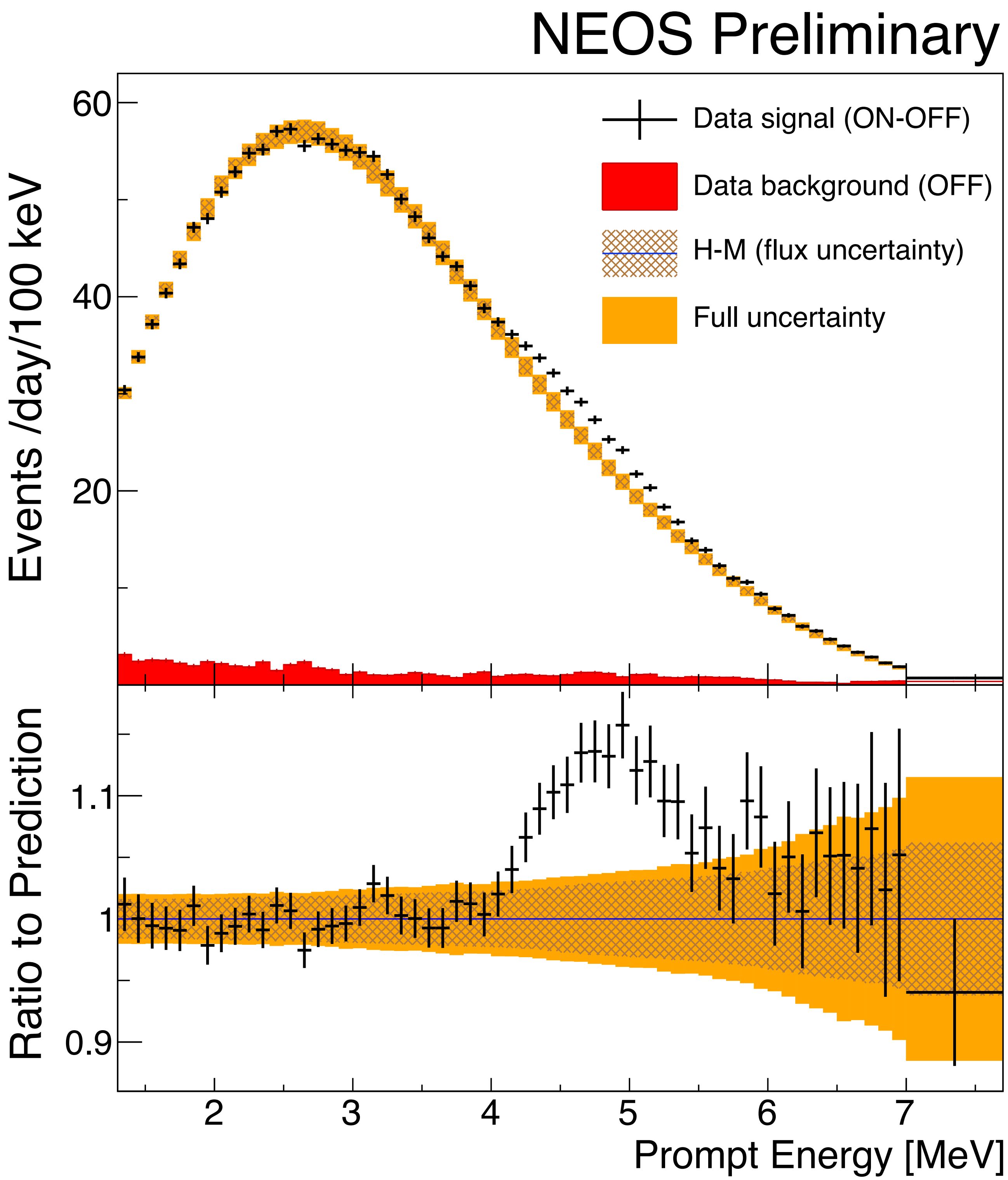
- IBD candidates: 81.2±1.2 /day (off), 1972.2±3.3 /day (on). S/N~23 (1<Es1<8 MeV)
- Background not fluctuated by the reactor operation.



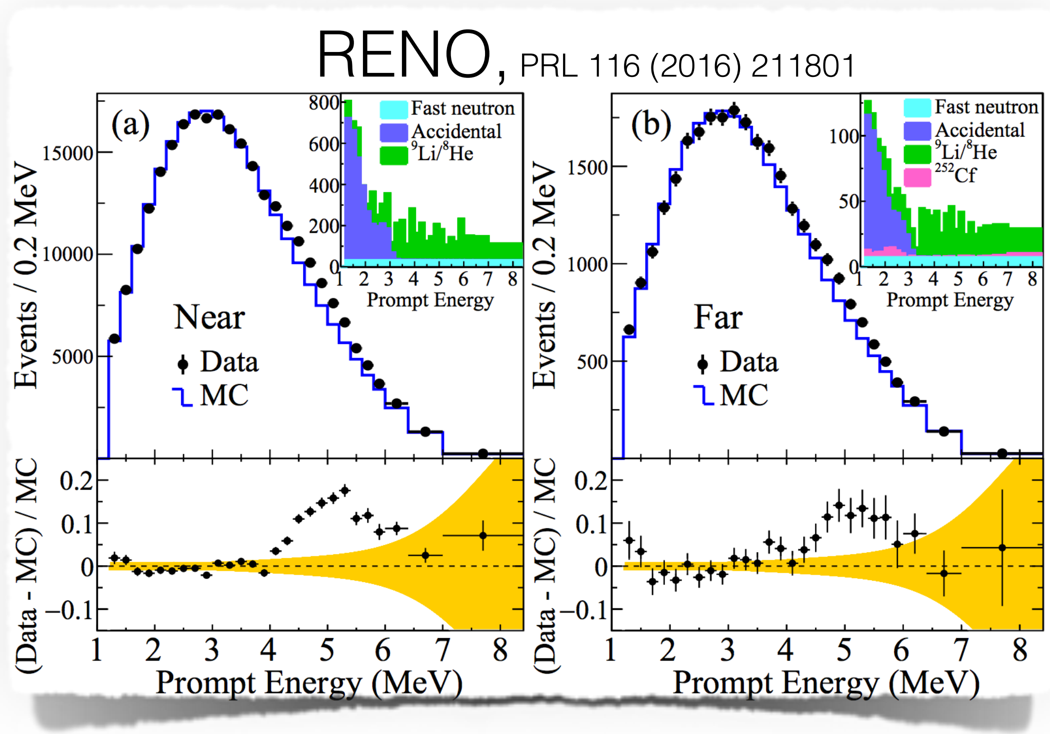




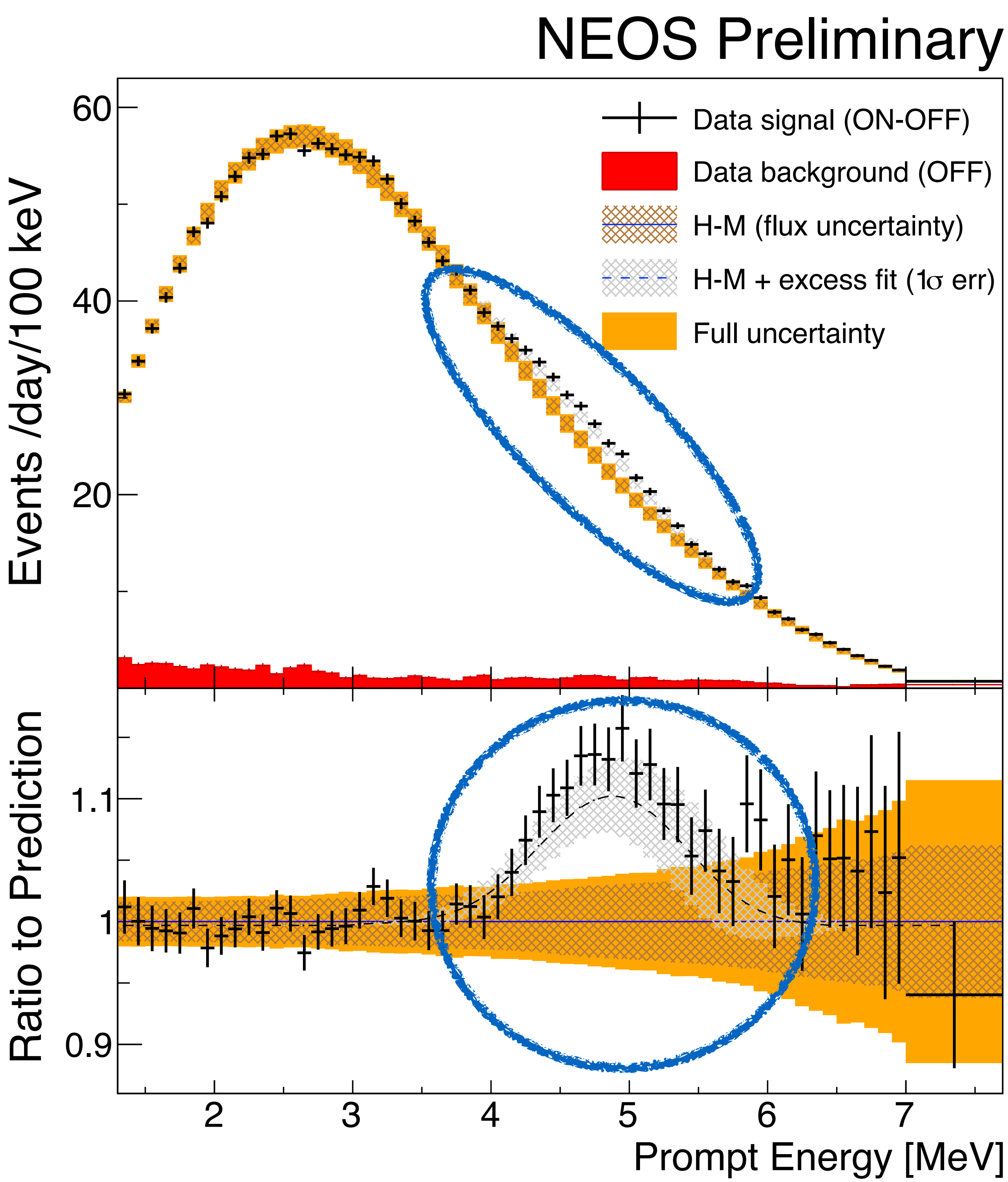
Prompt energy spectrum



- Prediction based on Huber's and Mueller's (H-M) flux calculation
- Uncertainty dominated by flux and energy scale
- Agreement but "bump"!
- Small deviations

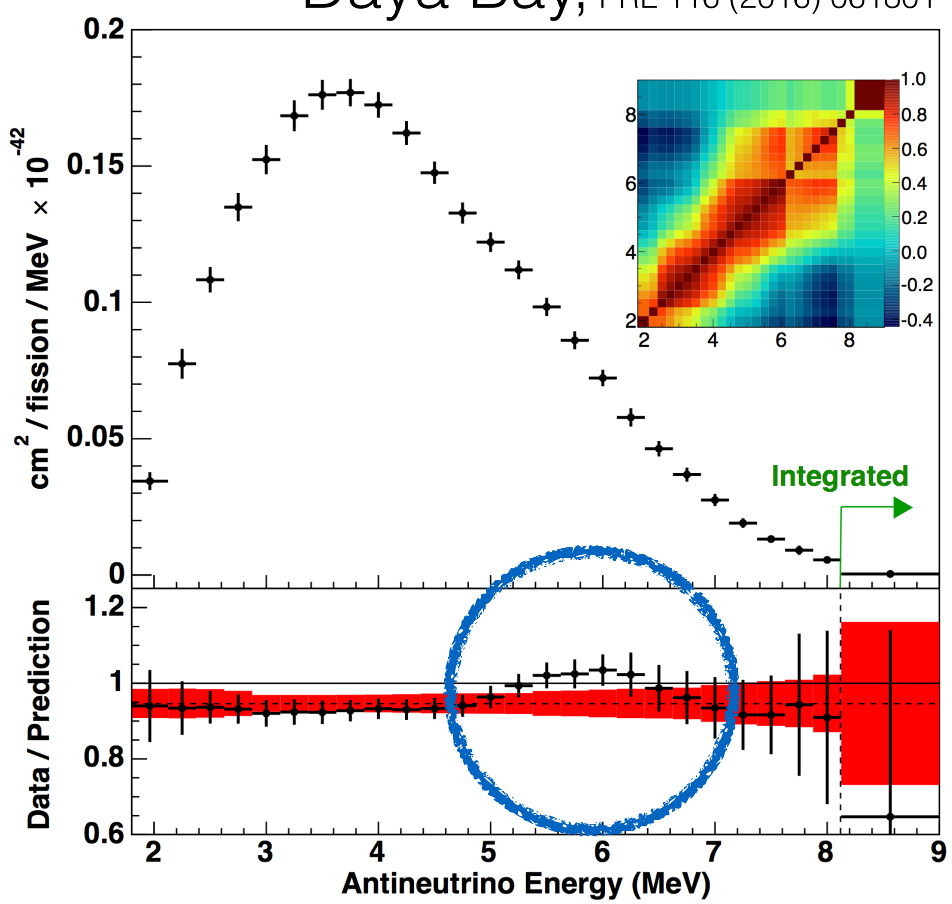


5 MeV excess

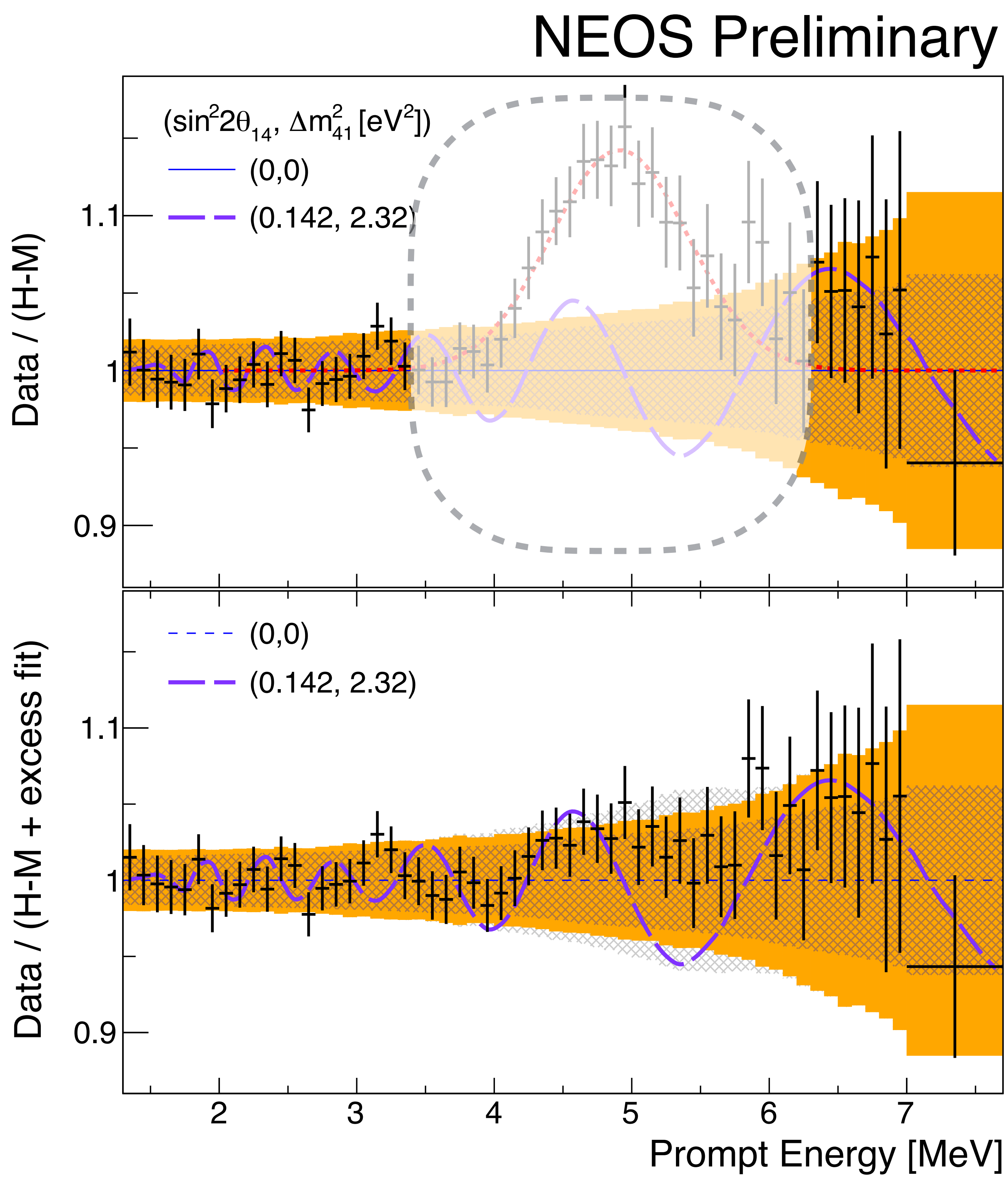


- Simply assuming Gaussian
- Daya Bay absolute flux + H-M
- Large fitting error
- Almost same location, size differs

Daya Bay, PRL 116 (2016) 061801



Oscillation and bump

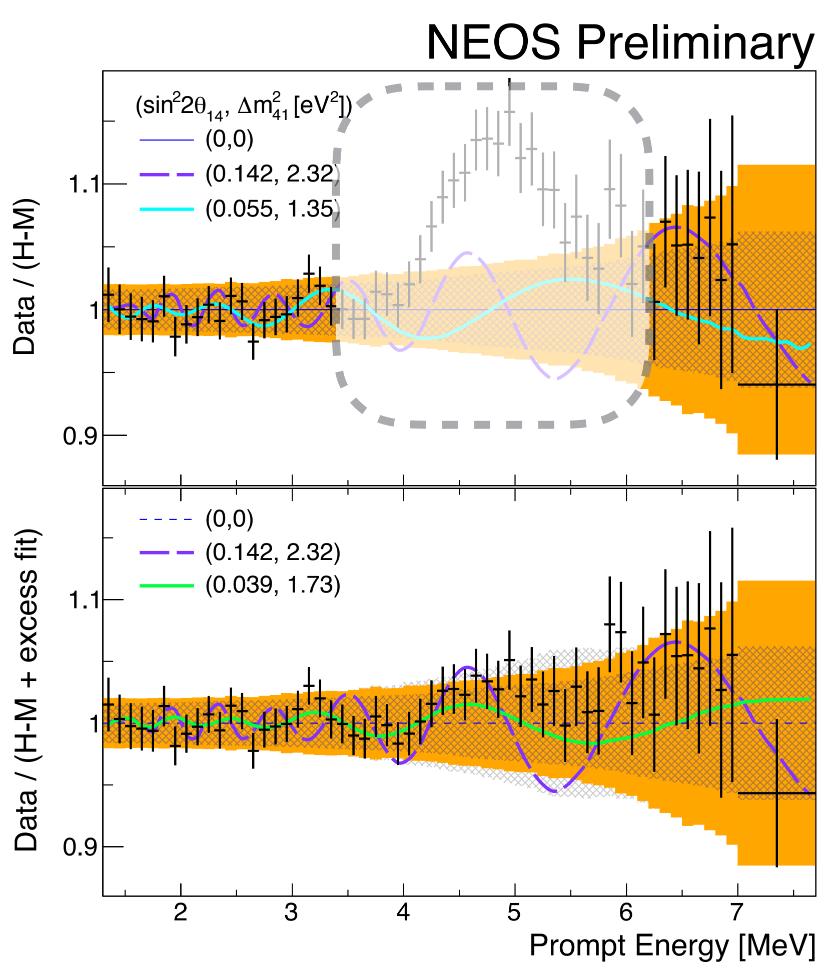


- Without 5 MeV excess
  — excluding 3σ of Gaussian
  — 3.4-6.3 MeV (29 bin)
  — loss of sensitivity
- With 5 MeV excess
  — possible bias from bump
  — assigning more error

χ^2 Analysis for Oscillation

$$\chi^2(\sin^2\theta_{14},\ \Delta m^2_{41}) = \sum_i \frac{[M_i - T'_i(\sin^2 2\theta,\ \Delta m^2_{41}) - B'_i]^2}{M_i + (t_{on}/t_{off})B_i} + \chi^2_{\text{penalty}}$$

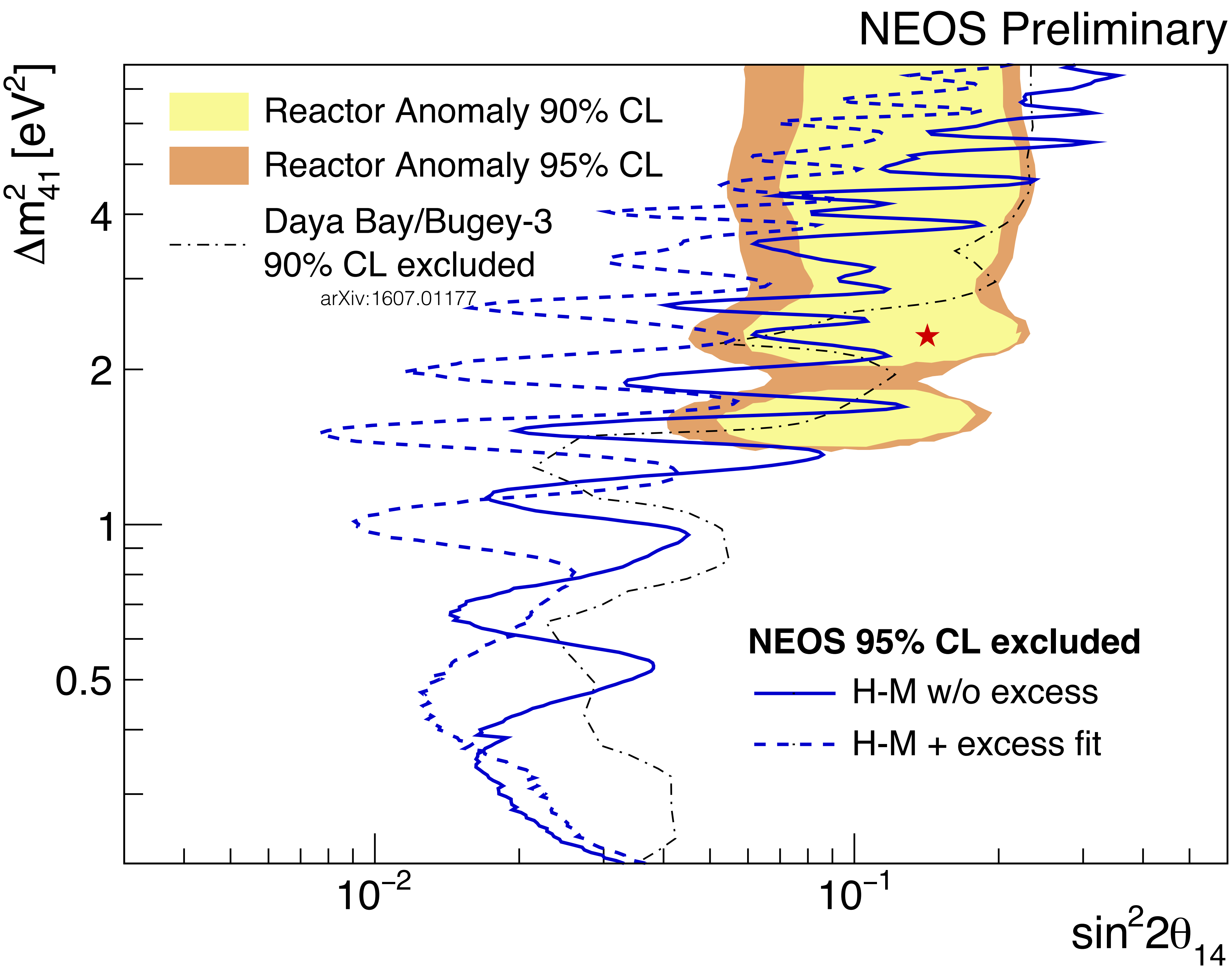
M_i : Measured IBD candidates in i 'th energy bin during reactor on,
T_i : Expected number, including oscillation params and systematics*,
B_i : Background events, scaled with on-off time ratio (t_{on}/t_{off}).



NEOS Preliminary

		H-M w/o bump	H-M w bump fit
χ^2	null	33.1	59.1
	minimum	25.5	47.9
	anomaly best fit	52.3	111
N_{DoF}		38	67
χ^2 minimum at		(0.055, 1.35 eV^2)	(0.039, 1.73 eV^2)
significance		2.00σ	2.68σ

Limits



NEOS Preliminary
Reactor Anomaly 90% CL
Reactor Anomaly 95% CL
Daya Bay/Bugey-3
90% CL excluded
arXiv:1607.01177
NEOS 95% CL excluded
H-M w/o excess
H-M + excess fit
Δm^2_{41} [eV^2]
4
2
1
0.5
10^{-2}
10^{-1}
$\sin^2 2\theta_{14}$

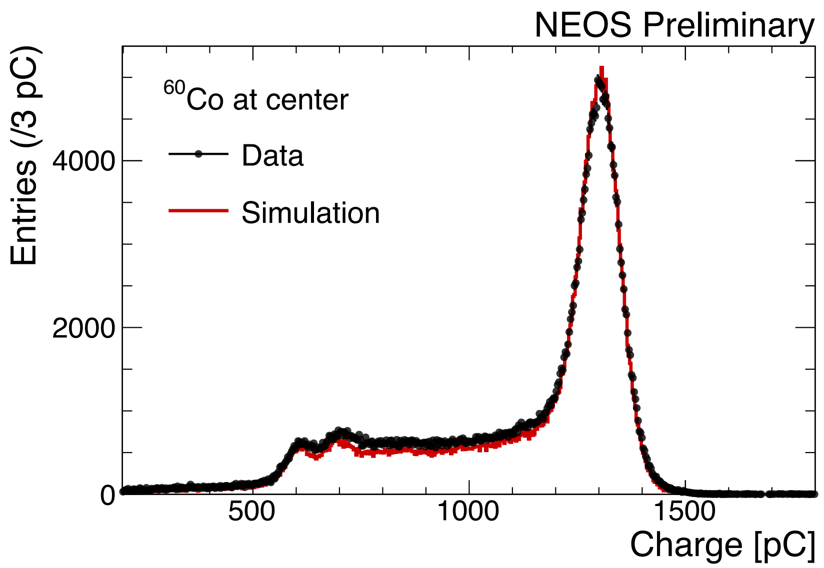
Summary

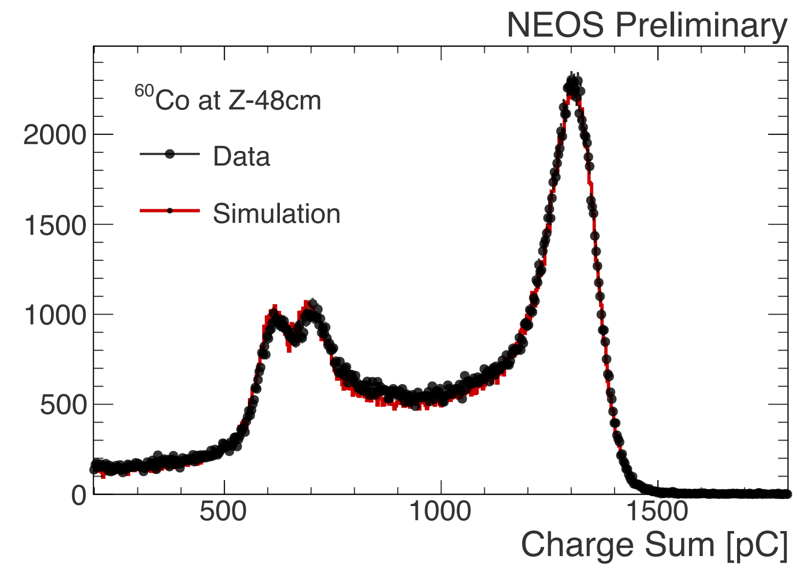
- Reactor $\overline{\nu}_e$ IBD spectrum is measured at 24 m baseline.
- 49 days' reactor off, 180 days' reactor on data accumulated.
  ~2000 IBD candidates/day with S/N~23 observed.
- 5 MeV excess seen at this short baseline, too.
- Part of allowed oscillation parameter space including reactor anomaly best fit is ruled out at 95% CL.
- On the bases of ν flux by Huber and Mueller with / without 5 MeV excess
  — 2.0σ / 2.7σ significances at (0.055, 1.35 eV^2) / (0.039, 1.73 eV^2).
  — Results may depend on ν-spectrum models.
- Analyses with other reference ν-spectra are on going.

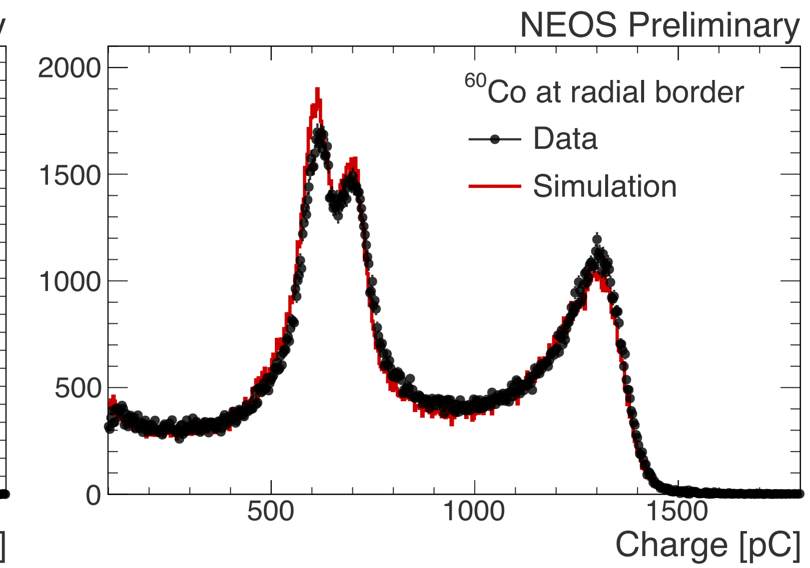
Result will be in arXiv soon.

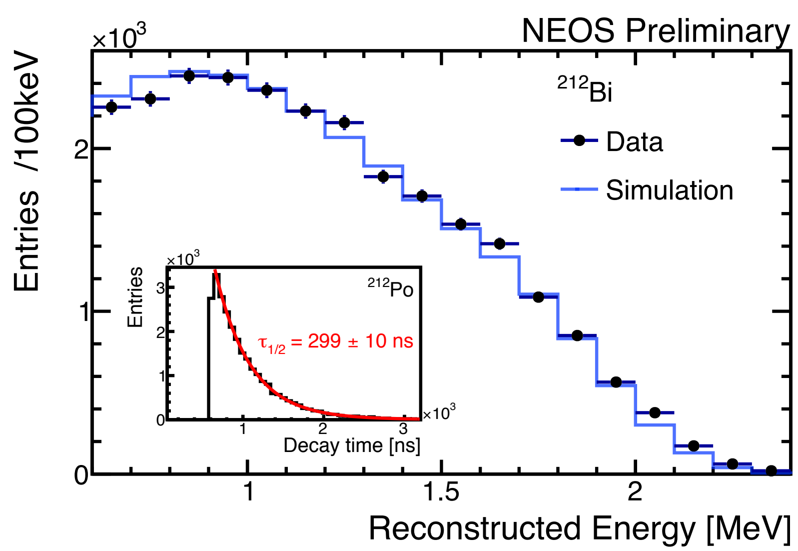
Backup

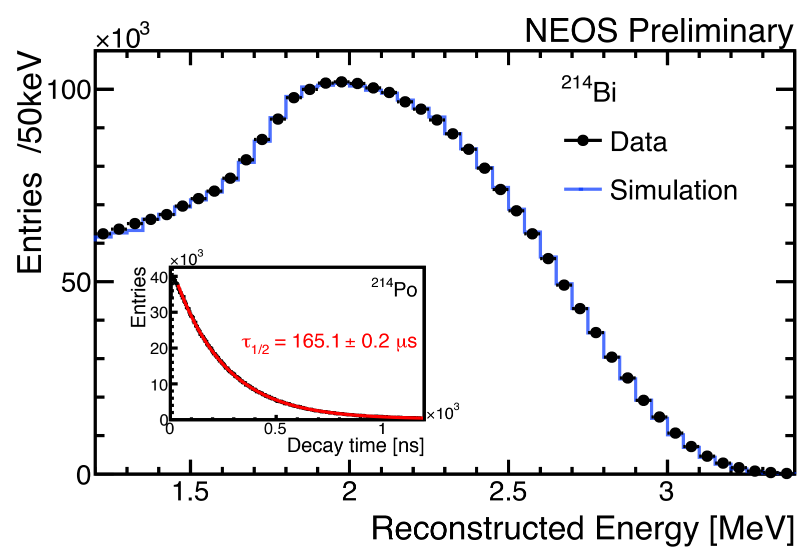
Detector responses

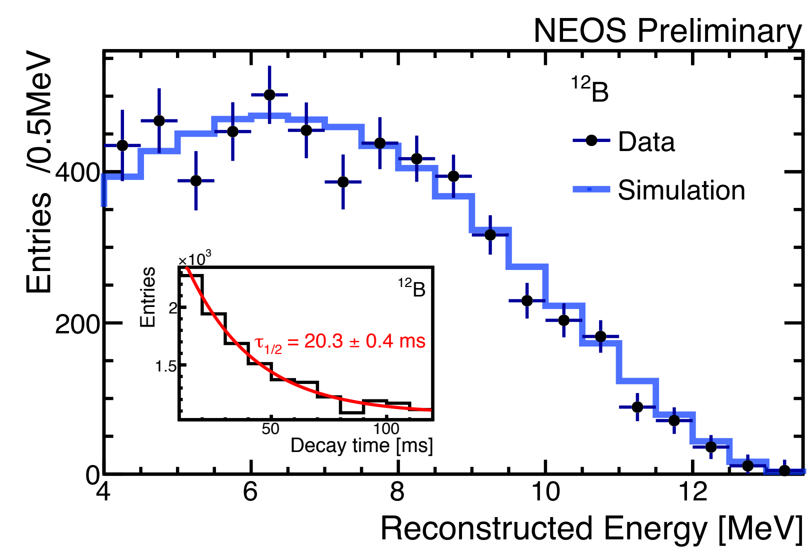












χ^2 and systematic uncertainties

$$\chi^2(\sin^2\theta_{14},\ \Delta m^2_{41}) = \sum_i \frac{[M_i - T'_i(\sin^2 2\theta,\ \Delta m^2_{41}) - B'_i]^2}{M_i + (t_{on}/t_{off})B_i} + \chi^2_{penalty}$$

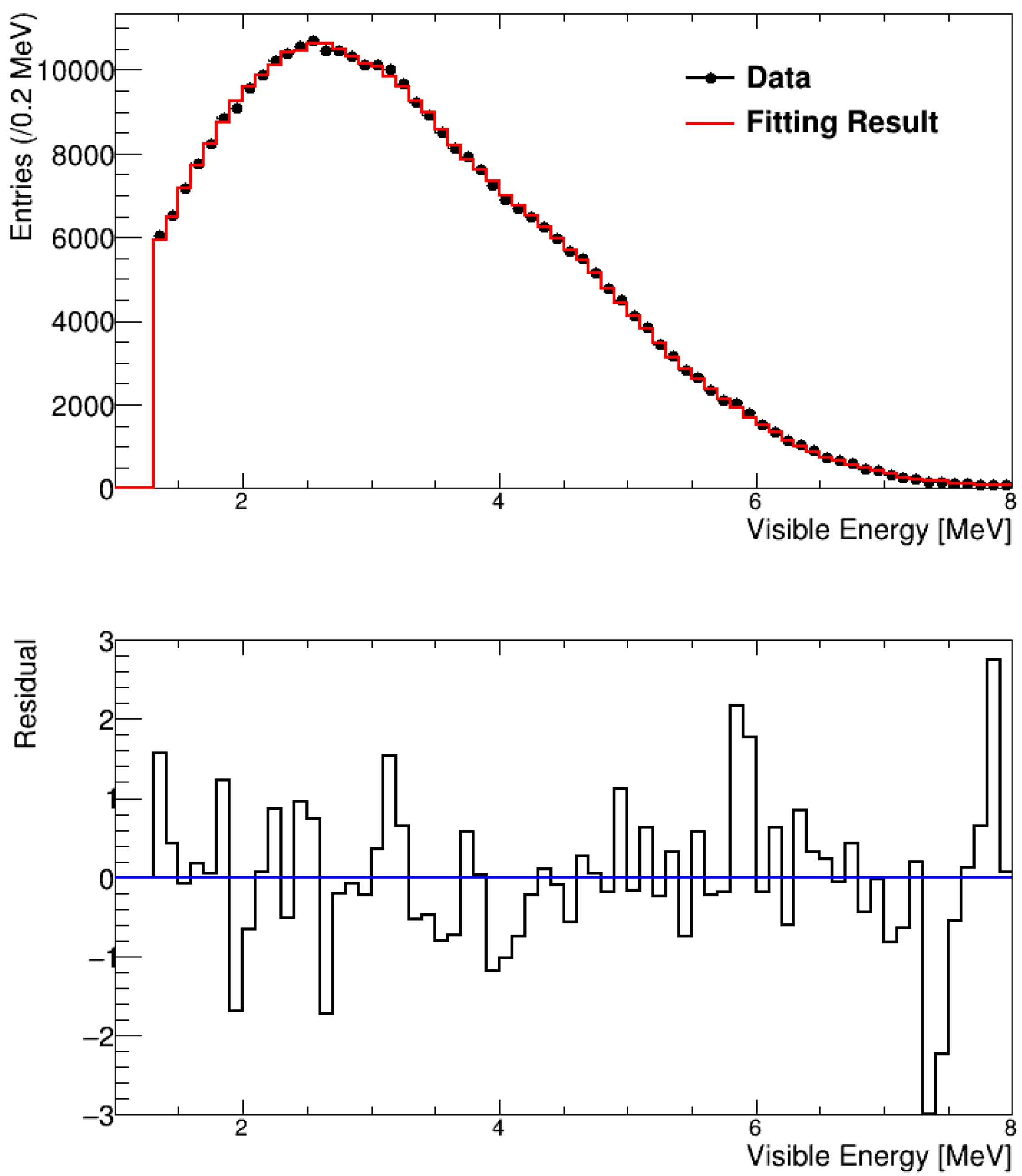
$$T'_i = (1 + \alpha_n + \alpha_f a_i + \alpha_{f,i})(T_i + \alpha_o T^o_i) + \alpha_\epsilon \frac{\partial(T_i + \alpha_o T^o_i)}{\partial \alpha_\epsilon}$$

$$B'_i = (1 + \alpha_b)B_i$$

$$\chi^2_{penalty} = \left(\frac{\alpha_n}{\sigma_n}\right)^2 + \left(\frac{\alpha_f}{\sigma_f}\right)^2 + \left(\frac{\alpha_o}{\sigma_o}\right)^2 + \sum_i \left(\frac{\alpha_{f,i}}{\sigma_{f,i}}\right)^2 + \left(\frac{\alpha_f}{\sigma_f}\right)^2 + \left(\frac{\alpha_b}{\sigma_b}\right)^2 + \left(\frac{\alpha_\epsilon}{\sigma_\epsilon}\right)^2$$

- α: nuisance parameter corresponding to systematic uncertainty σ
  σ_n = 1 : overall normalization of reference spectrum,
  $\sigma_f a_i$ / $\sigma_{f,i}$: correlated / uncorrelated flux uncertainties,
  σ_ε = 0.005 : energy scale uncertainty
  σ_b = 0.1 : for unknown background instability

$(\sin^2 2\theta, \Delta m_{41}{}^2) = (0.039, 1.73\ \mathrm{eV}^2)$

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 MIGRAD WILL VERIFY CONVERGENCE AND ERROR
MATRIX.
 FCN=47.9148 FROM MIGRAD
STATUS=CONVERGED    4983 CALLS         4984
TOTAL
                     EDM=1.56716e-05
STRATEGY= 1      ERROR MATRIX ACCURATE
  EXT PARAMETER
  NO.   NAME      VALUE
   1  escale      -5.76585e-04
   2  ac           1.26166e+00
   3  ac2          2.59532e-01
   4  ao           3.85812e-04
   9  alphai3      8.23562e-04
 ......
  75  alphai69     4.95195e-05
  76  beta        -3.91532e-02
```