Spectral Measurement of Anti-neutrino Disappearance via Neutron Capture on Hydrogen at Daya Bay

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on behalf of the Daya Bay Collaboration

Neutrino Mixing

➢ **Neutrino mixing:**

Pontecorvo-Maki-Nakagawa-Sakata (1962)

Flavor Eigen state $|\nu_\alpha\rangle = \sum_{i=1}^{3} U^*_{\alpha i} |\nu_i\rangle$ Mass Eigen state

$$U = \begin{pmatrix} \cos\theta_{12} & \sin\theta_{12} & 0 \\ -\sin\theta_{12} & \cos\theta_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix} \begin{pmatrix} \cos\theta_{13} & 0 & \sin\theta_{13}e^{-i\delta} \\ 0 & 1 & 0 \\ -\sin\theta_{13}e^{i\delta} & 0 & \cos\theta_{13} \end{pmatrix} \begin{pmatrix} 1 & 0 & 0 \\ 0 & \cos\theta_{23} & \sin\theta_{23} \\ 0 & -\sin\theta_{23} & \cos\theta_{23} \end{pmatrix} \ldots\ldots$$

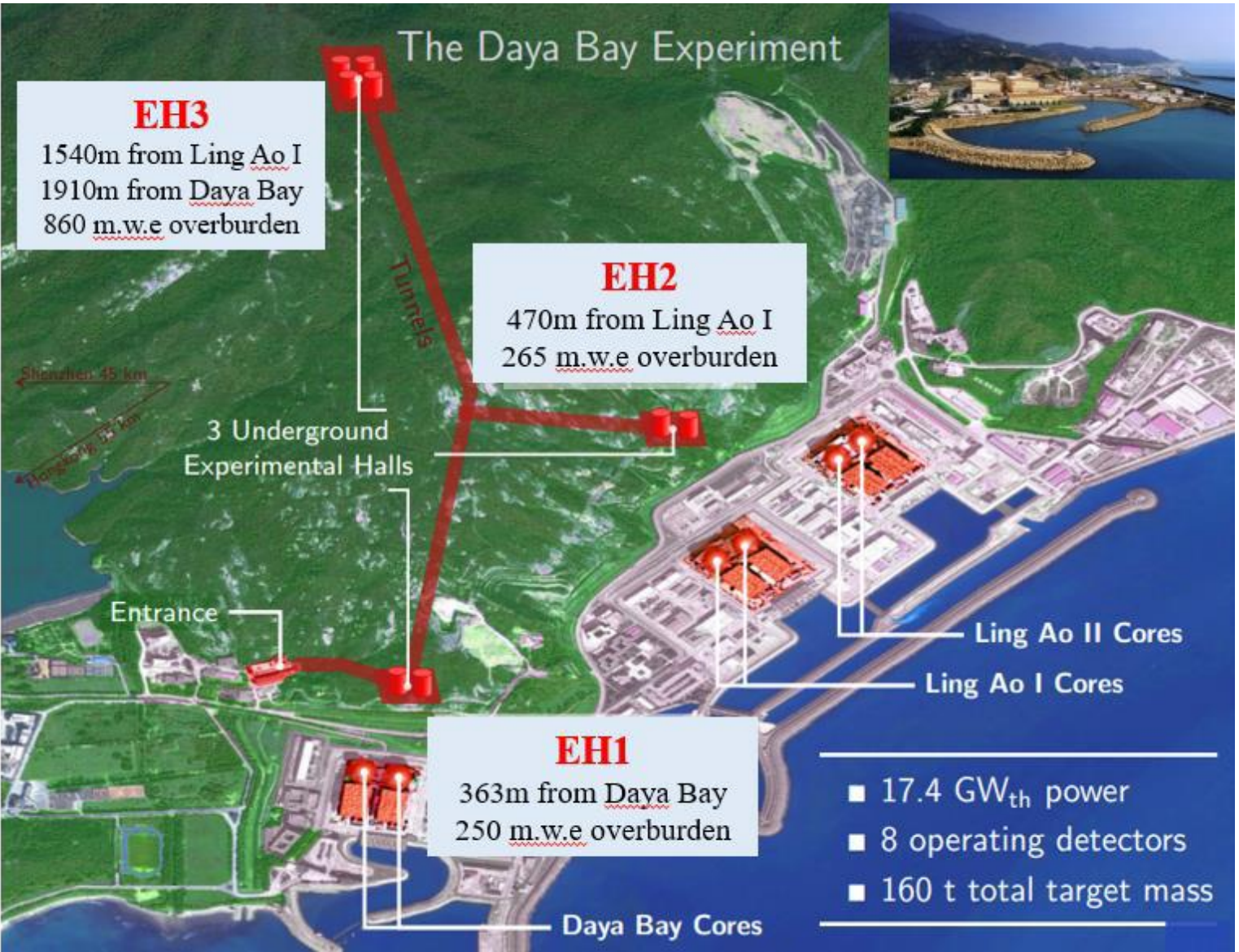
Parameter	bestfit value($\pm 1\sigma$)
$\sin^2 2\theta_{12}$	0.846 ± 0.021
$\sin^2 2\theta_{23}$	$0.999^{+0.001}_{-0.018}$ (NH)
$\sin^2 2\theta_{13}$	$(9.3 \pm 0.8) \times 10^{-2}$

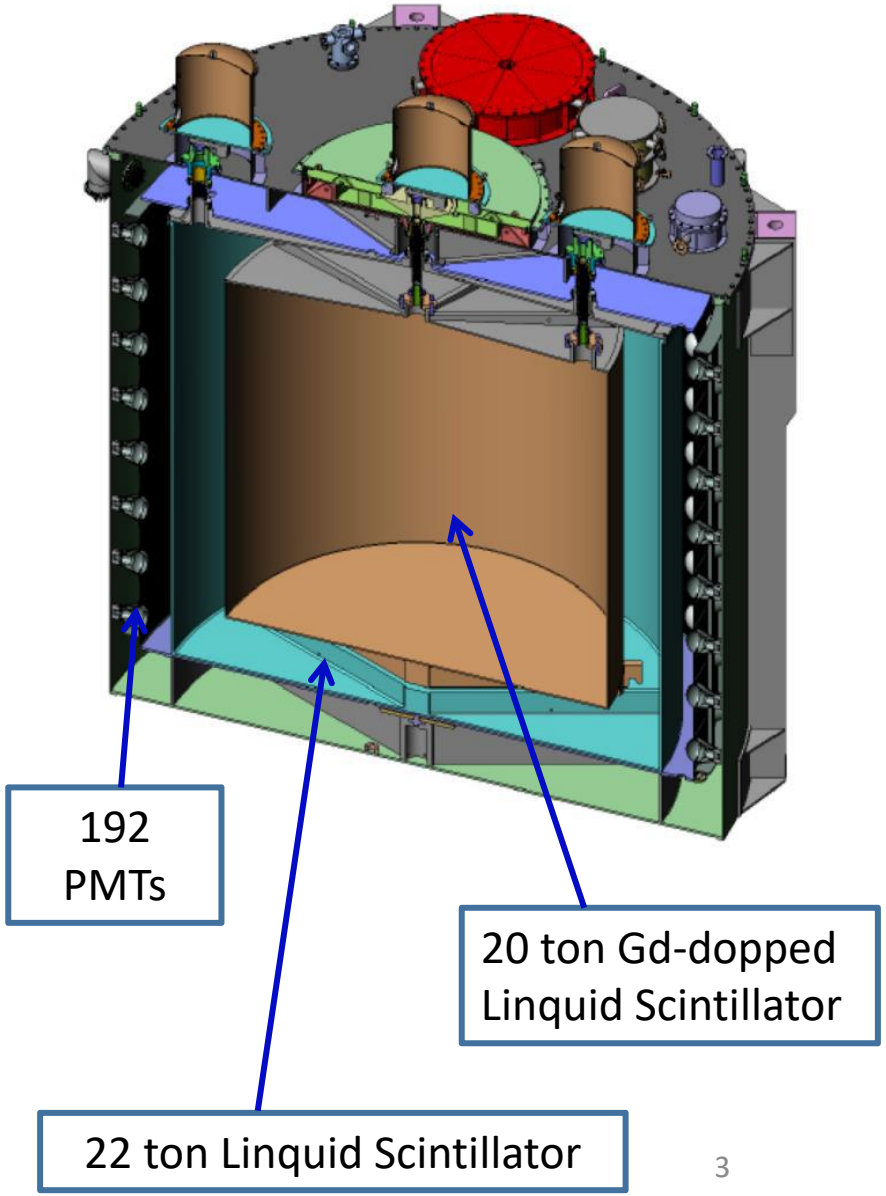
PDG2014

Parameter	bestfit value($\pm 1\sigma$)
Δm^2_{21}	$(7.53 \pm 0.18) \times 10^{-5}\,\mathrm{eV}^2$
Δm^2_{32}	$(2.44 \pm 0.06) \times 10^{-3}\,\mathrm{eV}^2$ (NH)

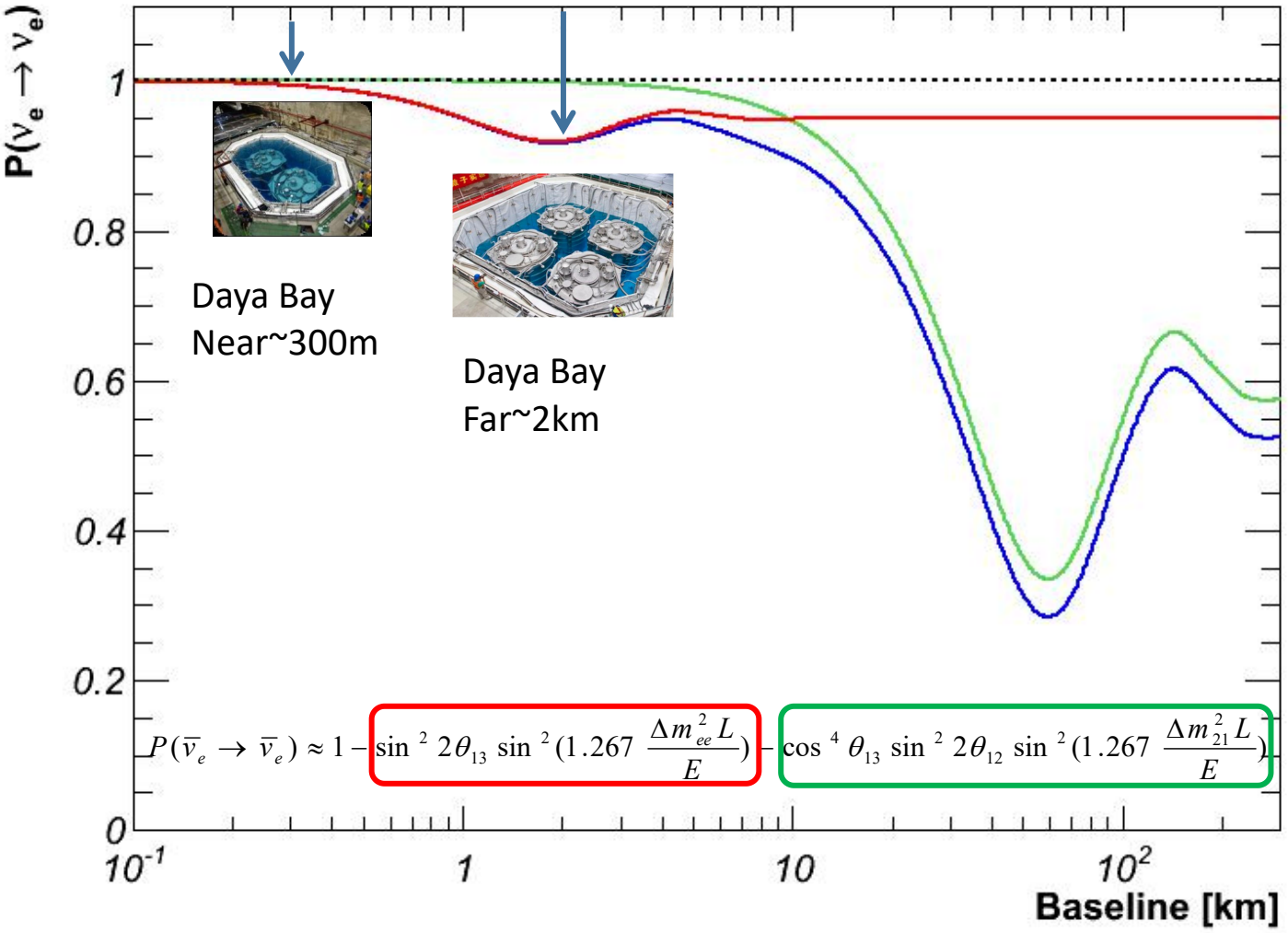
- Summary of neutrino mixing angle
- Summary of neutrino mass-squared difference

Dayabay Experiment





Reactor Antineutrino Oscillation

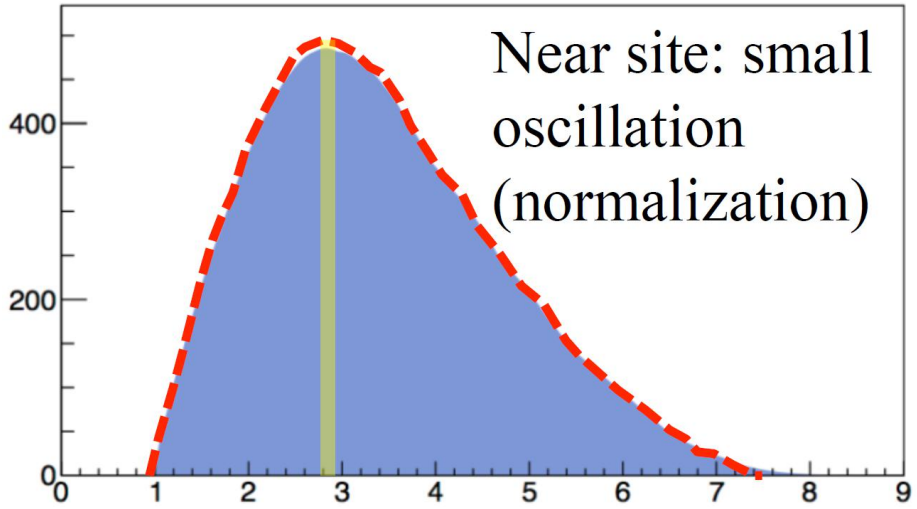


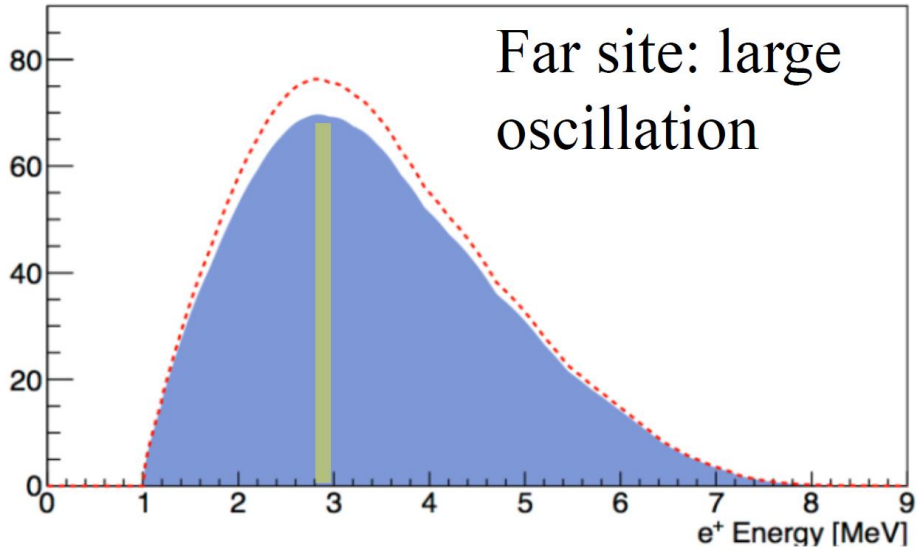
No CP phase term
Negligible matter effect

Far / Near relative measurement

$$\Delta m^2_{ee} \approx \cos^2 2\theta_{12} |\Delta m^2_{31}| + \sin^2 2\theta_{12} |\Delta m^2_{32}|, \Delta m^2_{32} \approx |\Delta m^2_{ee}| \pm 5.2 \times 10^{-5} eV^2 \text{ for NH(-)/IH(+)}$$

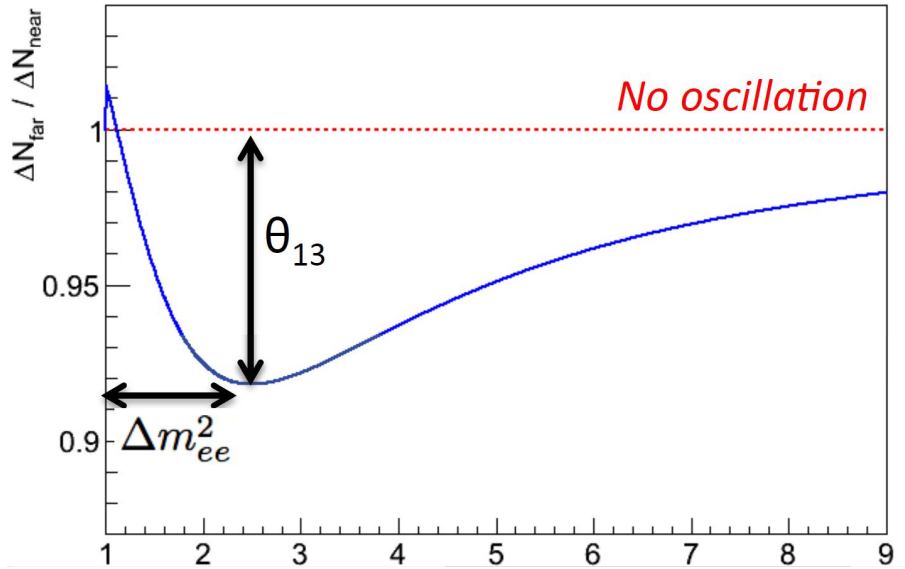
Measuring Mass Splitting via Spectral Distortion





rate and shape comparison

Precise spectral measurement give constraint to both $\sin^2 2\theta_{13}$ and Δm^2_{ee}



Good understanding of detector response is needed!

Antineutrino Detection

- Inverse Beta Decay (IBD):

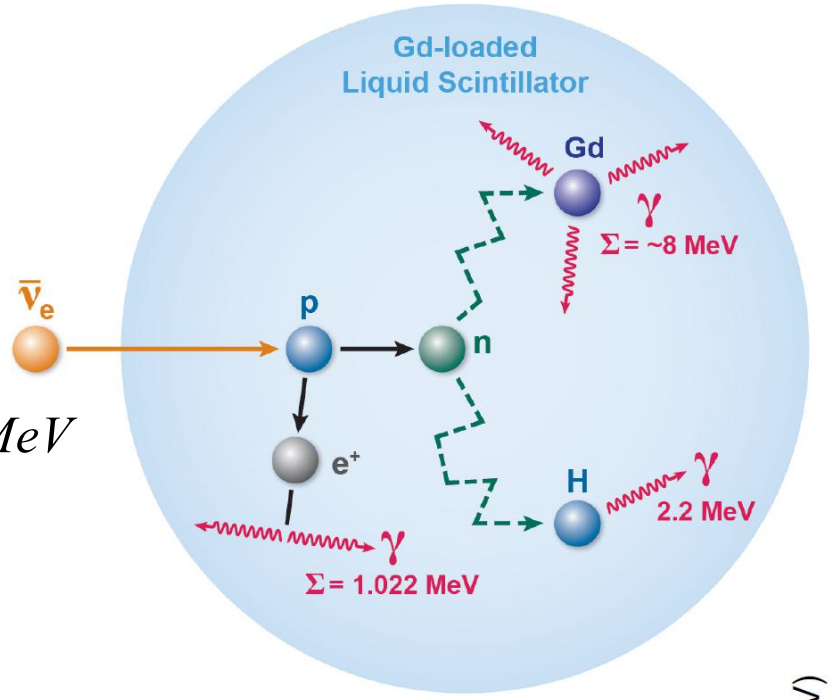
$$\bar{\nu}_e + p \rightarrow e^+ + n$$

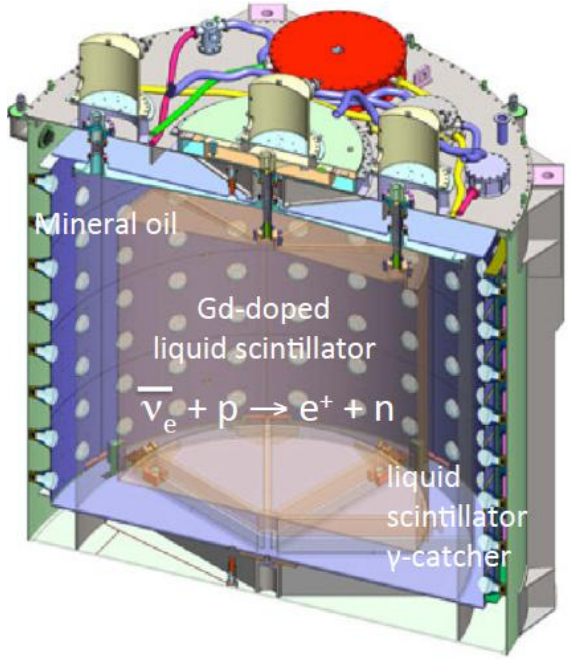
$$e^+ + e^- \rightarrow 2\gamma$$

$$n + H \rightarrow H + \gamma(2.2MeV)$$

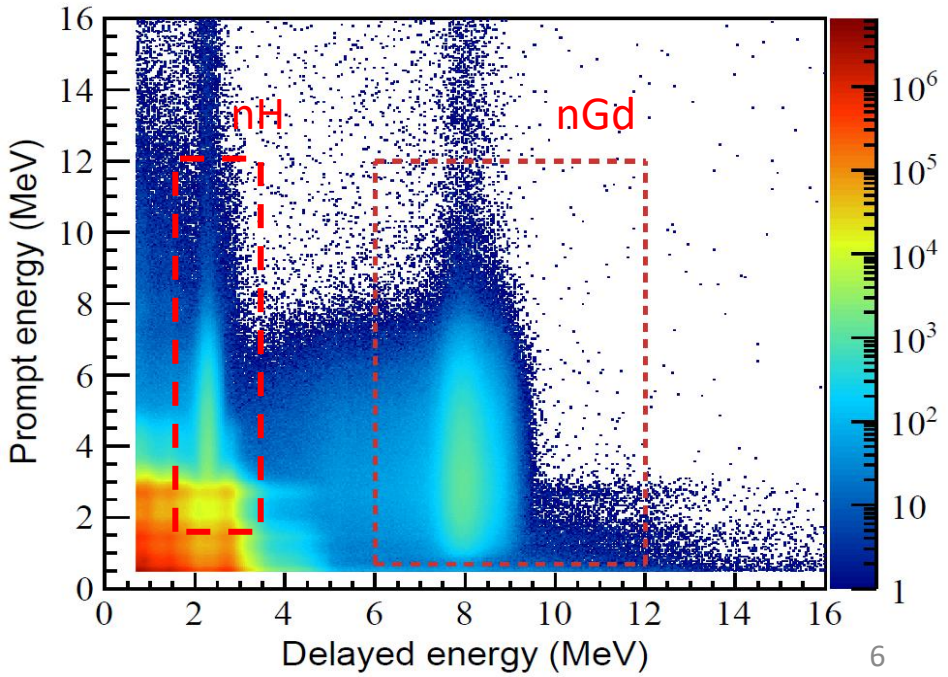
$$\text{Prompt energy} \approx E_{\bar{\nu}_e} - 0.8MeV$$

$$\text{Delayed energy}: 2.2\text{MeV}$$



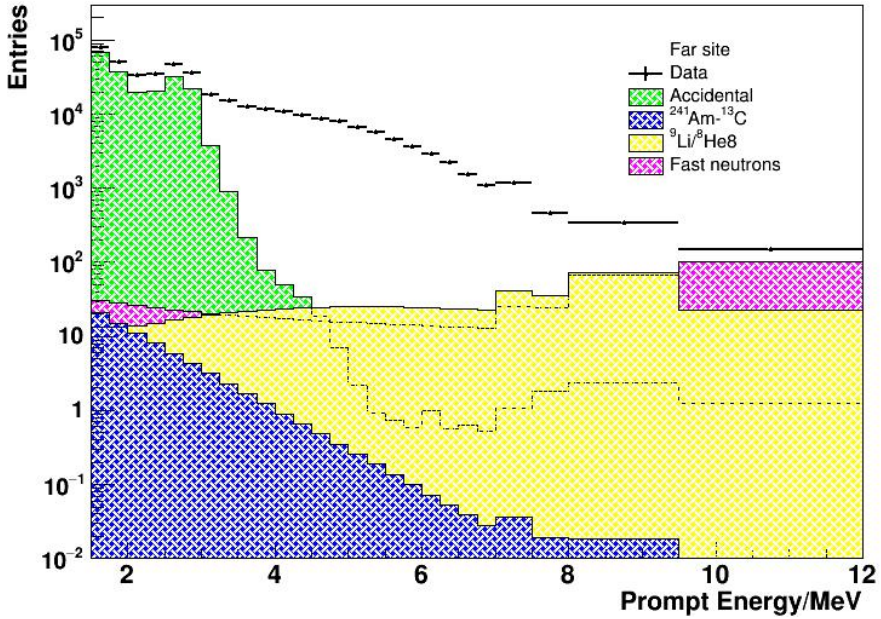


- nH(neutron capture on hydrogen) analysis
  - advantage
    - equivalent statistics to the nGd sample
    - largely different systematic errors
  - challenge
    - larger energy leakage in LS region
    - 12% (51%) accidental background at near (far) site



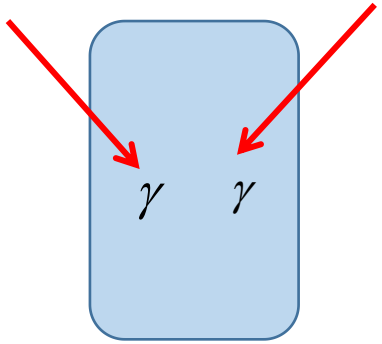
nH Signal and Backgrounds

- nH IBD pair selection criteria:
  - Muon veto cut
  - Prompt energy cut : [1.5,12]MeV
  - Delayed energy cut : $\mu \pm 3\sigma$
  - Capture time cut : [1,400]us
  - Distance(prompt and delayed) cut : [0,500]mm
  - Multiplicity Cut



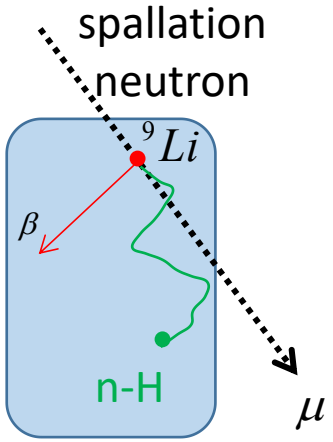
- Main Backgrounds:

B/S:far(~51%),near(~12%)



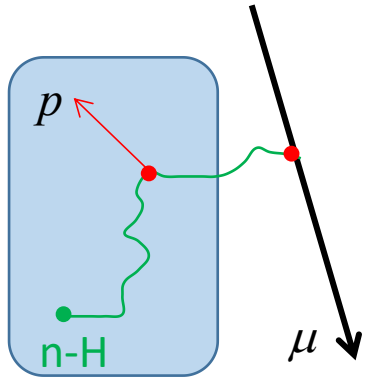
Accidental

B/S:~0.3%



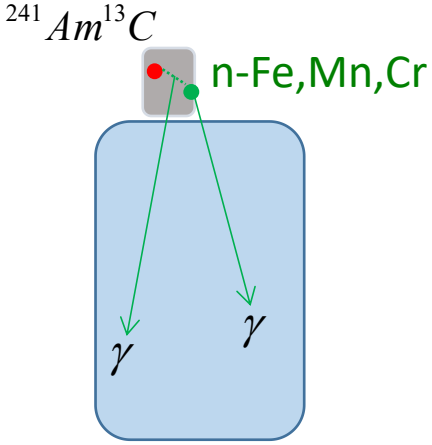
^{9}Li

B/S:~0.4%



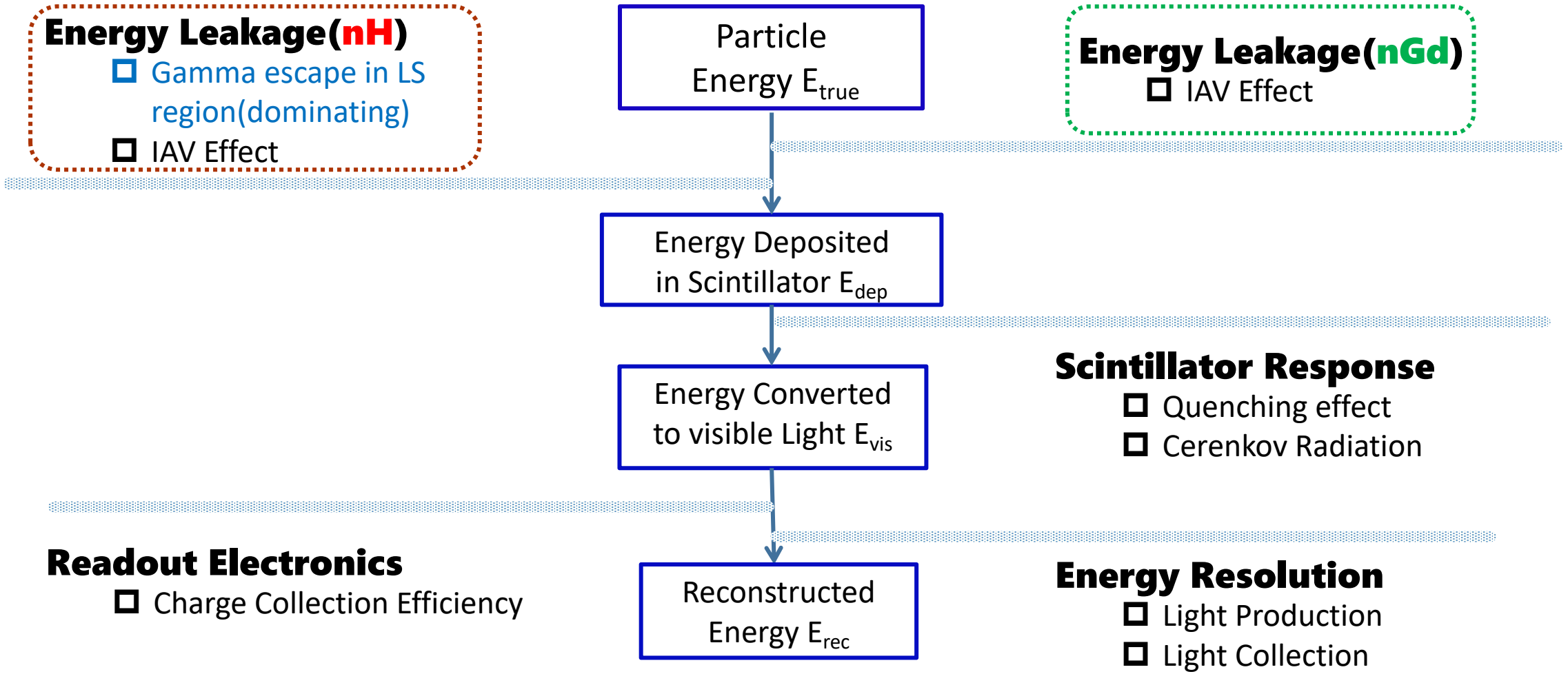
Fast neutron

B/S:~0.01%



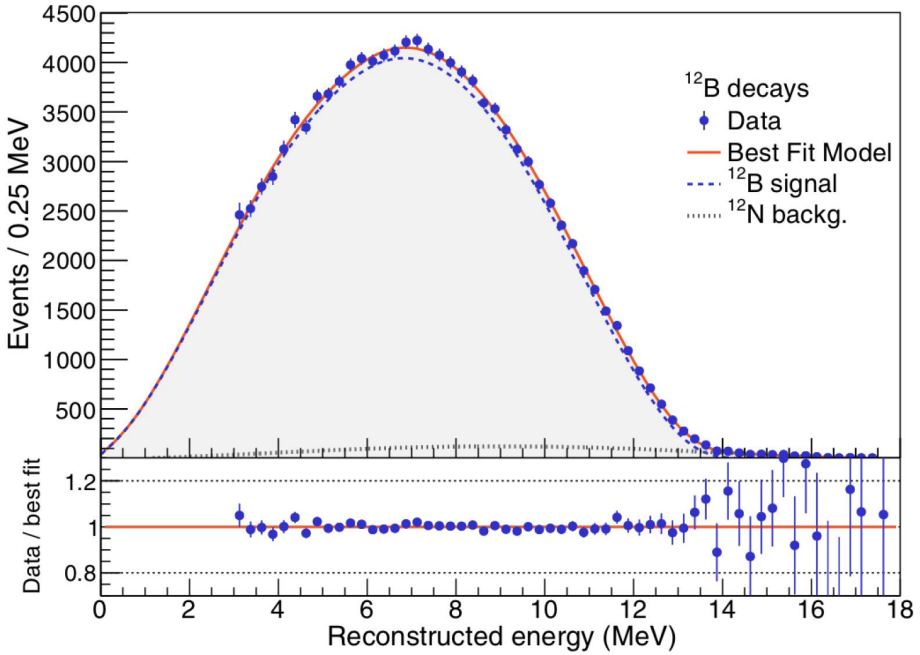
^{241}Am^{13}C

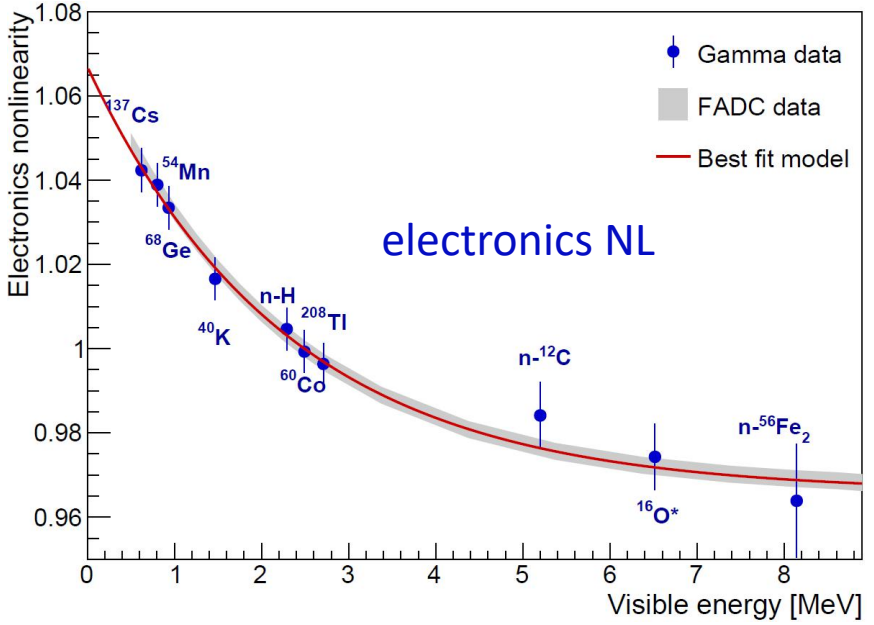
Energy Response Model

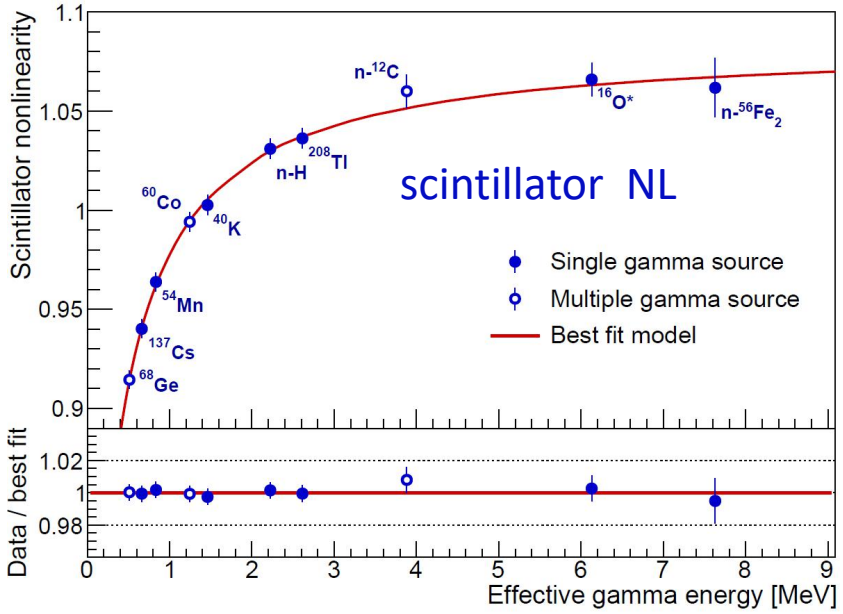


Energy Response used for nGd

- Non-linearity model built based on various gamma peaks and the continuous ^{12}B spectrum

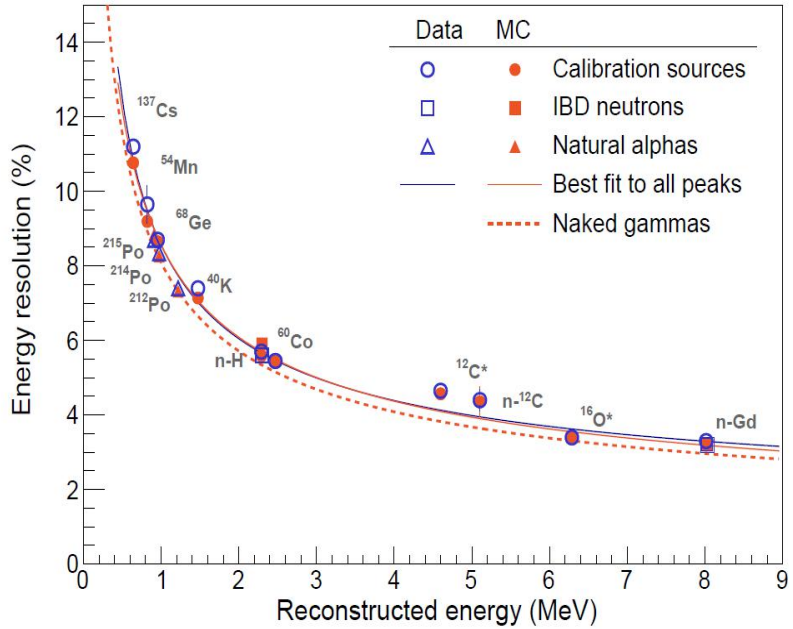


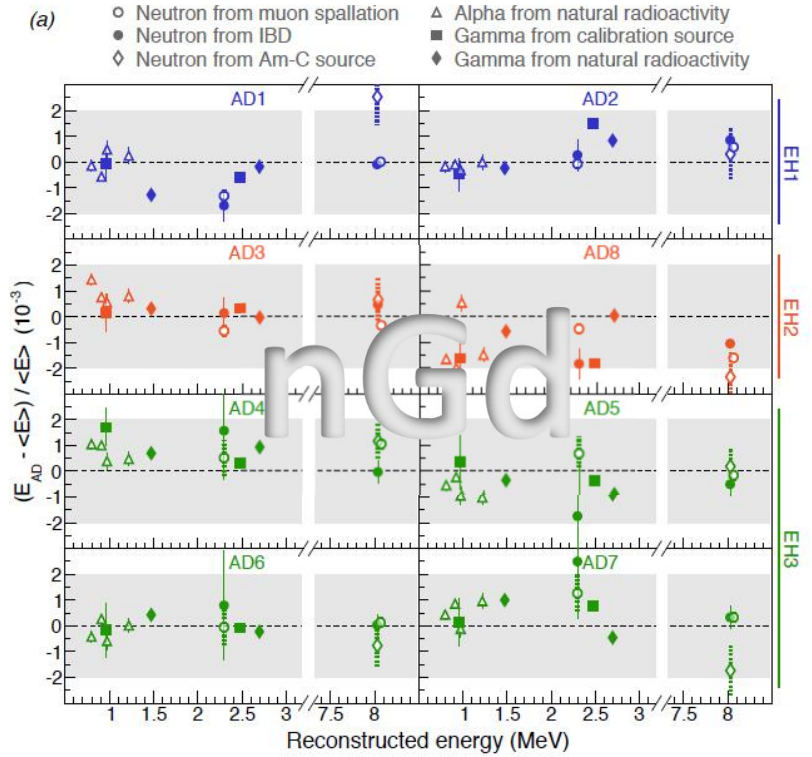


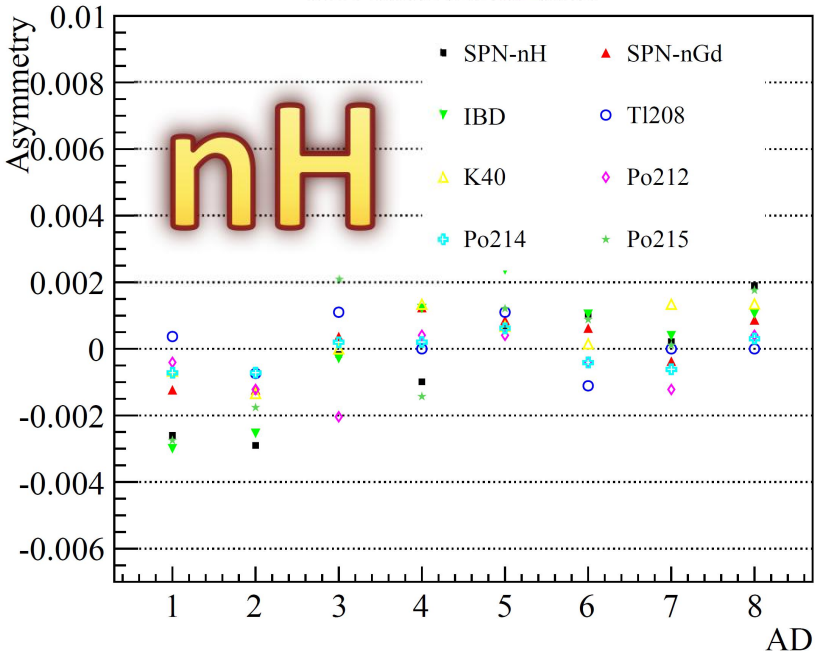


Energy Reconstruction

- Energy resolution: $\frac{\sigma_E}{E} = \sqrt{a^2 + \frac{b^2}{E} + \frac{c^2}{E^2}}$
  - a : Residual Spacial Non-Uniformity Resolution
  - b : Photon Statistics
  - c : Dark Noise/PMT effects
- AD-by-AD differences:
  - Different calibration source used .
  - Relative energy scale uncertainty < 0.2% (0.4%)for nGd (nH)







From nGd Response to nH Response

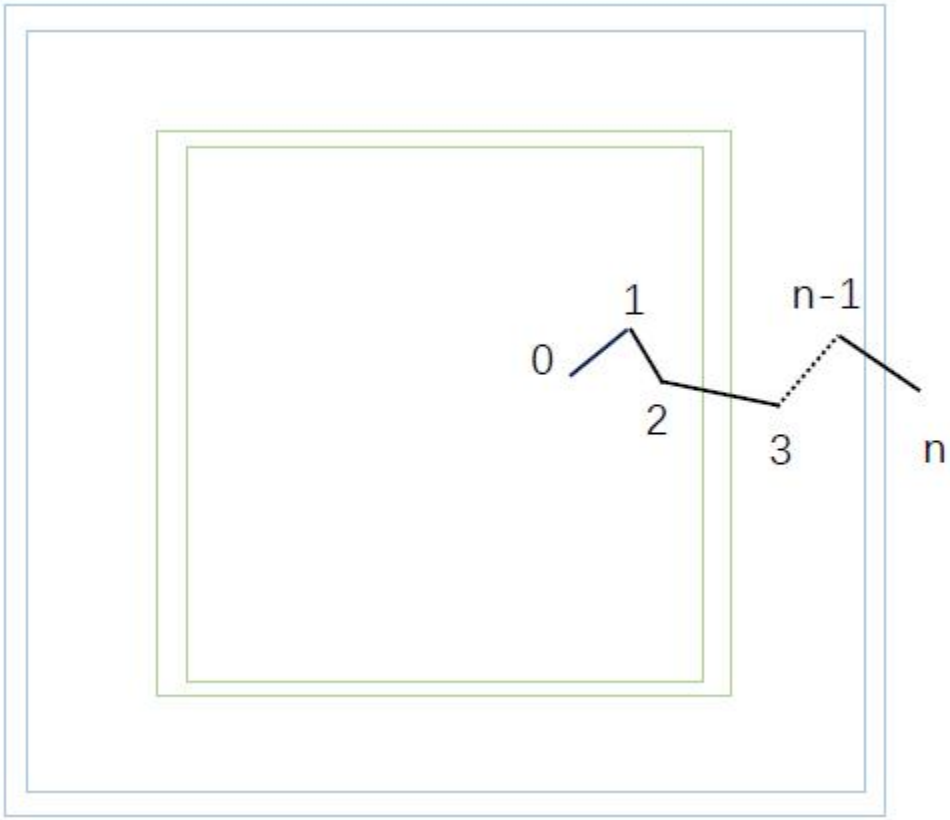
- Larger energy leakage :
  - IAV effect
  - gamma escape in LS region(dominating)
  - modeled by Monte-Carlo

$$\begin{array}{l} 0 \to 1 \to 2 \to 3 \ldots\ldots \text{n-1} \to \text{n} \\ \hline E_0 \to E_1 \to E_2 \to E_3 \ldots\ldots E_{n-1} \to E_n \end{array}$$

- Only Energy deposit in scintillator could transform to visible energy

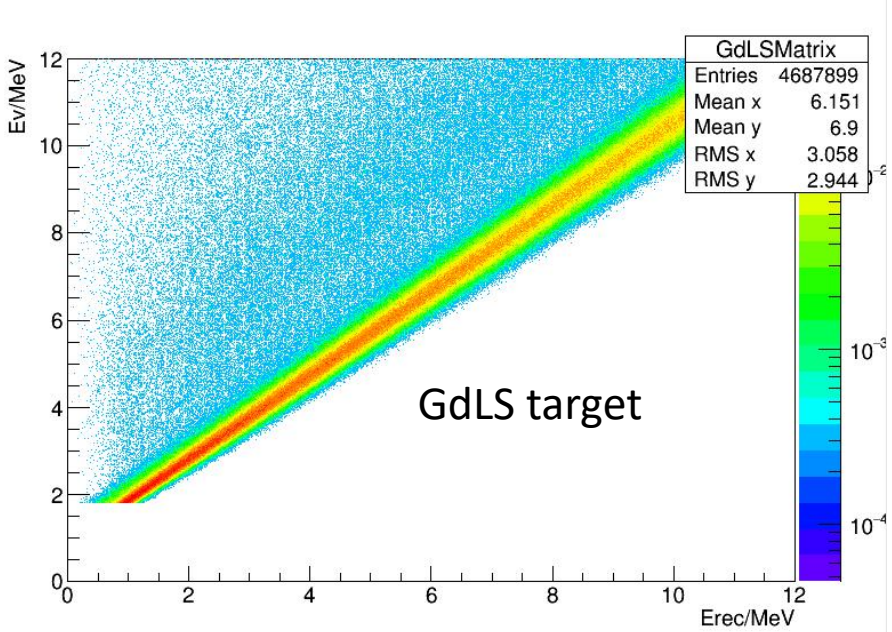
$$E_k \to E_{k+1} : E_{vis} = E_k f_{scin}(E_k) - E_{k+1} f_{scin}(E_{k+1})$$

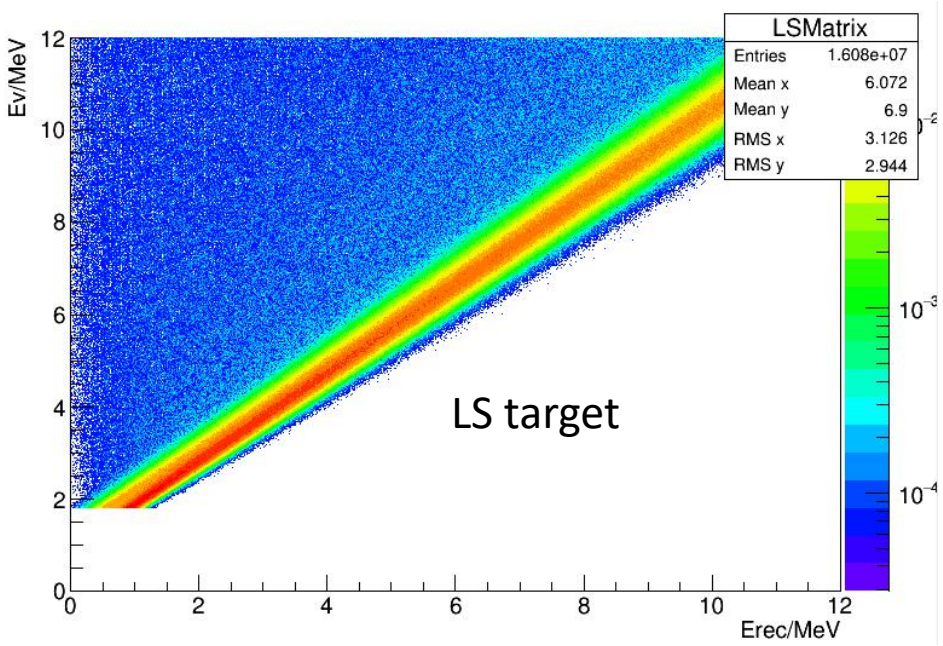
e^+/γ steps simulation diagram

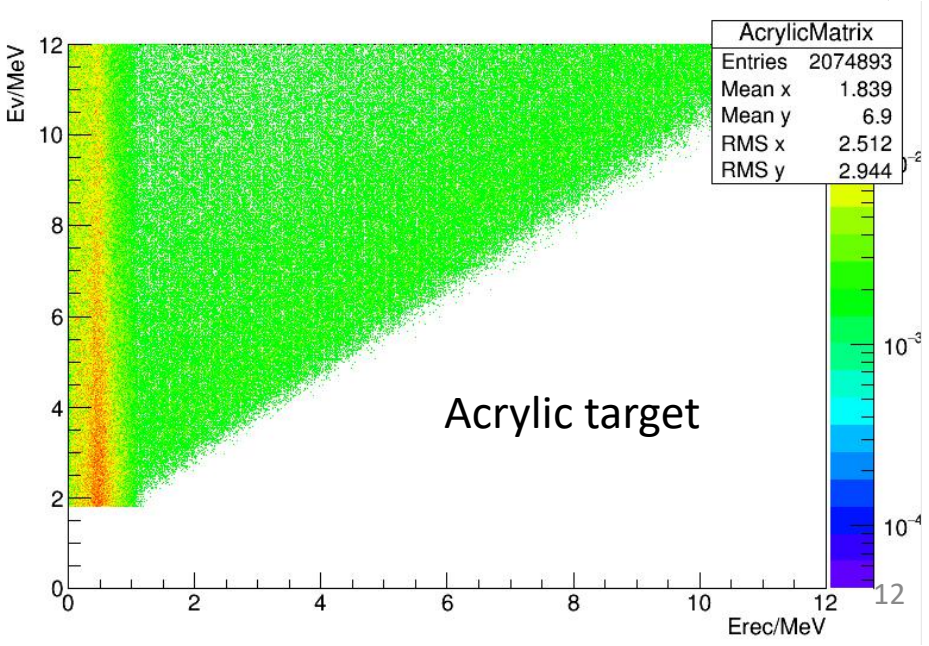


nH Energy Response Model

- Model construction
  - Energy leakage
  - Energy non-linearity
  - Non-uniformity
  - Energy resolution







Model Validation Using B12 Data

- Chi2 definition: $\chi^2 = \frac{(M_i - T_i)^2}{M_i}$, $T_i = n \cdot [\alpha N_i + (1-\alpha) B_i]$

  M_i : measured events in bin i

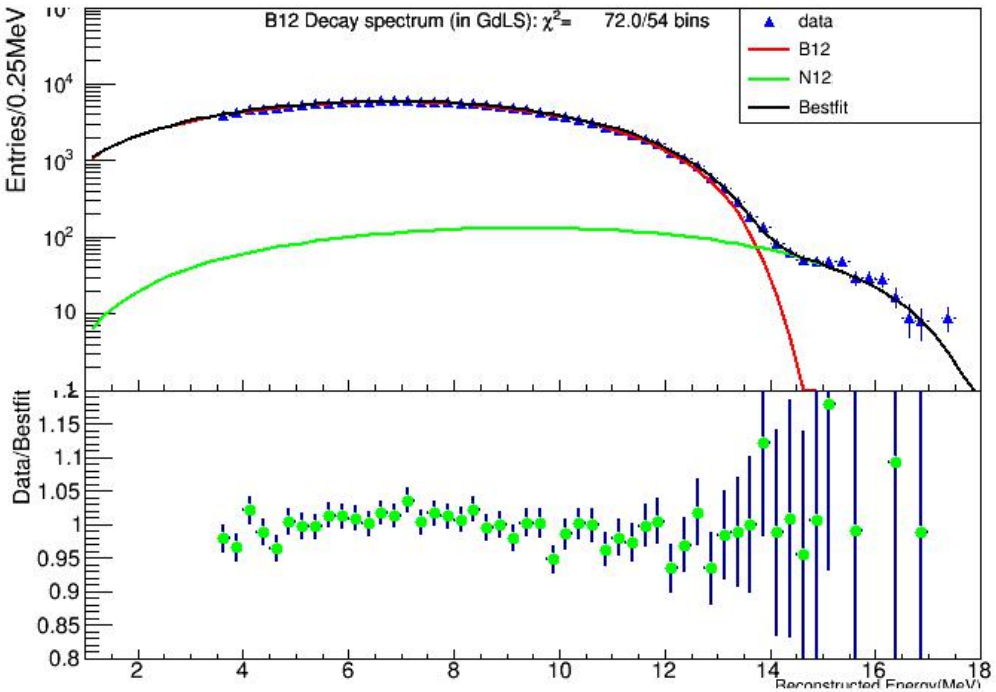
  T_i : predicted events in bin i

  α : N12 fraction

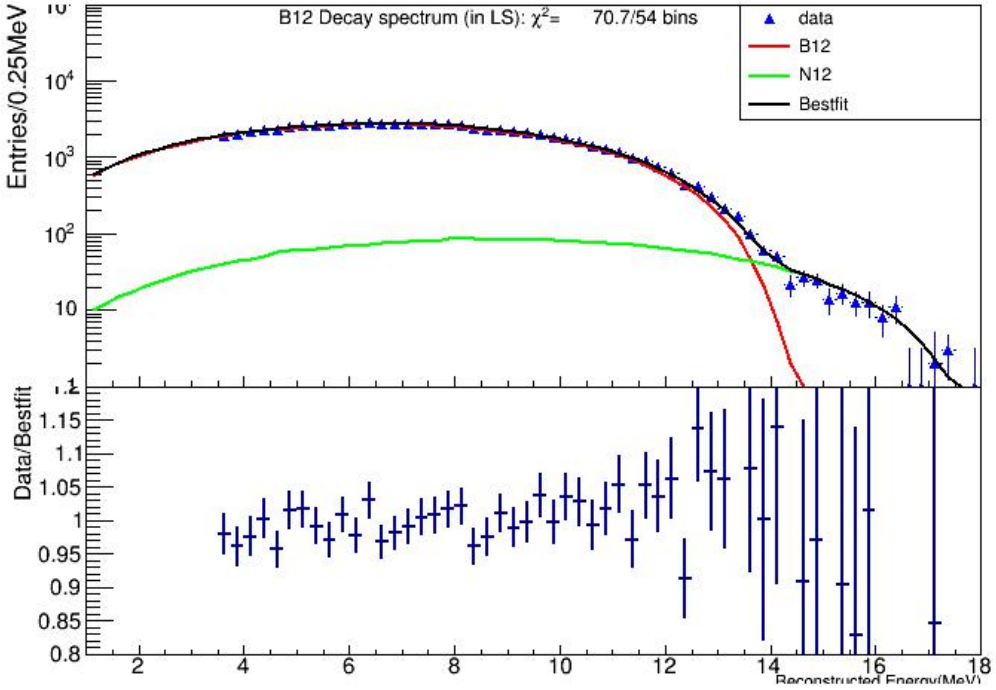
- Fit range : 4~18MeV

nH Energy Model validated well using B12 Data !

GdLS region comparison



LS region comparison

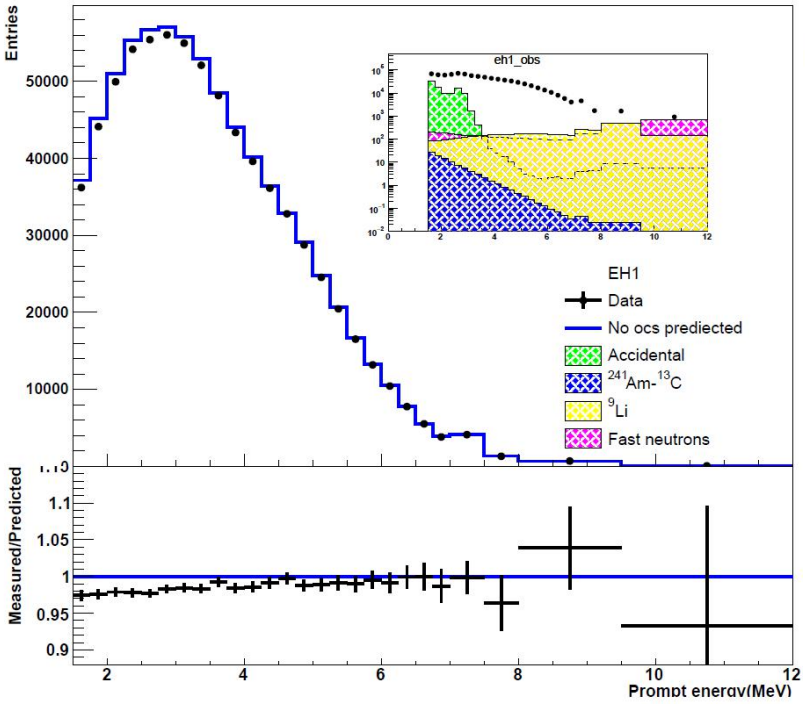


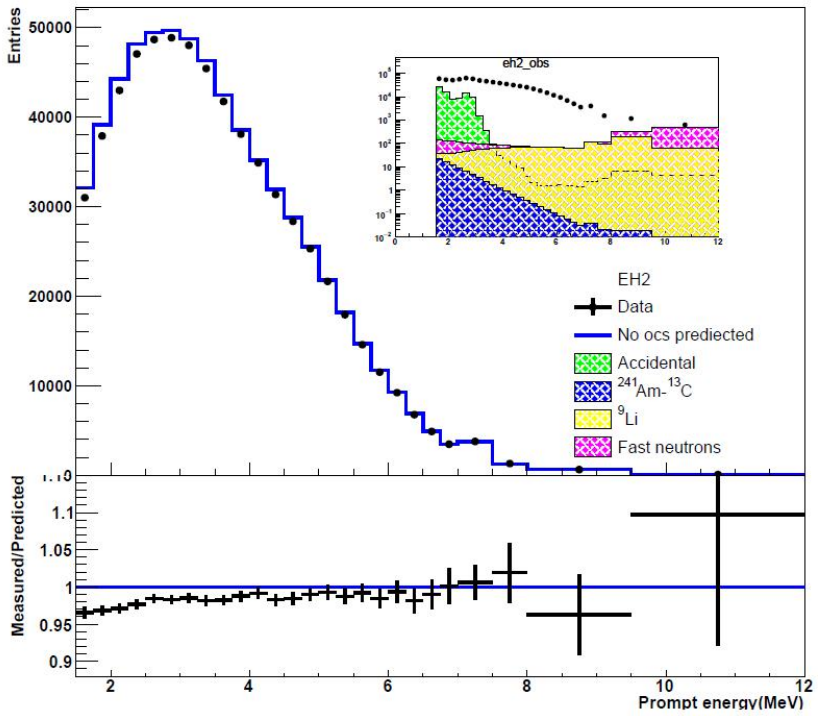
Systematic Errors

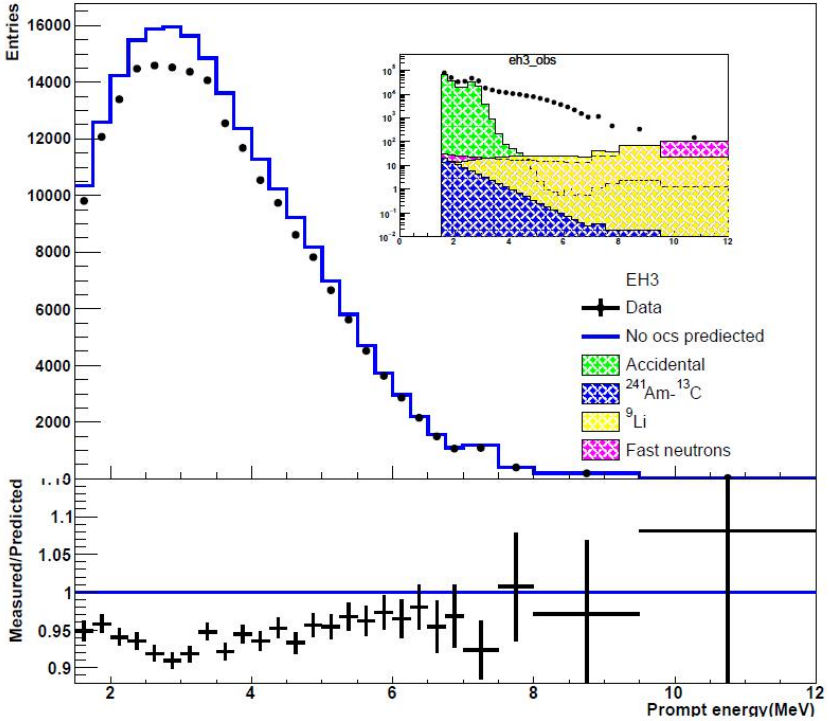
	name	description	sigma value	correlation	counts
Reactor part	α_r^{th}	thermal power	0.5%	Uncorrelated between reactors	6
	α_r^{eq}	non-equilibrium	30%	Uncorrelated between reactors	6
	α_r^{sp}	spent-fuel	100%	Uncorrelated between reactors	6
	α_r^{f}	fission fraction	5%	Uncorrelated between reactors	6
	α_R	bin-to-bin correlated	free	Correlated between reactors	1
	α_R^i	bin-to-bin uncorrelated	free	Uncorrelated between reactors	26
Detector part	α_d^{eff}	relative detection efficiency	0.44%	Uncorrelated between ADs	8
	α_d^{IAV}	IAV effect	100%	Uncorrelated between ADs	8
	α_l^{NL}	non-linearity	100%	Correlated between ADs	4
	α_d^{scale}	relative energy scale	0.5%	Uncorrelated between ADs	8
Background part	α_{acc}^{d}	accidental background	0.2%,0.18%,0.07%	Uncorrelated between ADs	8
	α_{li9}^{hall}	Li9 background	43%,45%,41%	Uncorrelated between sites	3
	α_{fast-n}^{hall}	fast-n background	11%,11%,18%	Uncorrelated between sites	3
	α_{AmC}	AmC background	50%	Correlated between ADs	1

Spectral Distortion

- Predicted(no oscillation) and obversed(subtracted backgrounds)
  - determined by bestfit.
- Data with only statistical errors.
- Spectrum distortion
  - baseline related
  - energy related







Summary

- Independent mearsurement of $\sin^2 2\theta_{13}$ and Δm^2_{ee} from nH
  - Find baseline and energy related spectrum distortion
  - Plan to present final result this summer

- **Thank you for your attention !**