Probing new physics with reactor (anti)neutrinos

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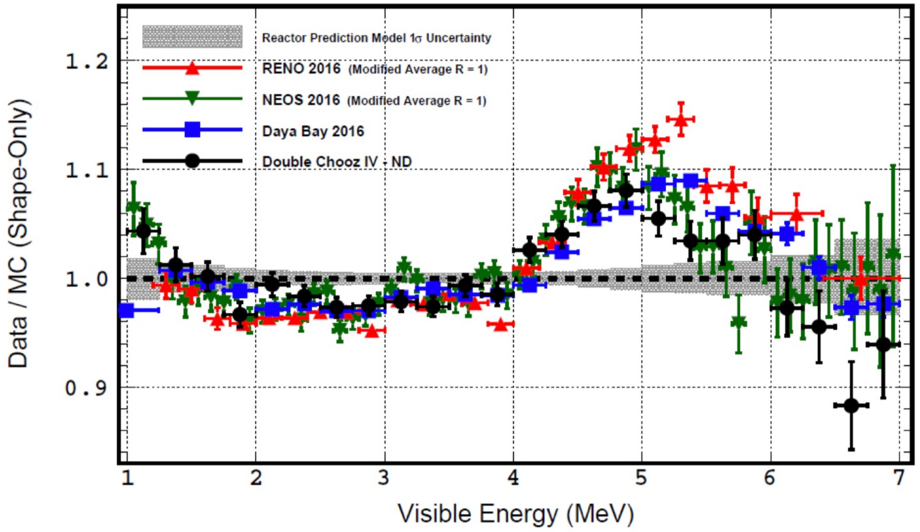
The STEREO experiment

Reactor (anti)neutrinos anomalies

In nuclear reactors, $\bar{\nu}_e$ emitted from the β decay of fission fragments:

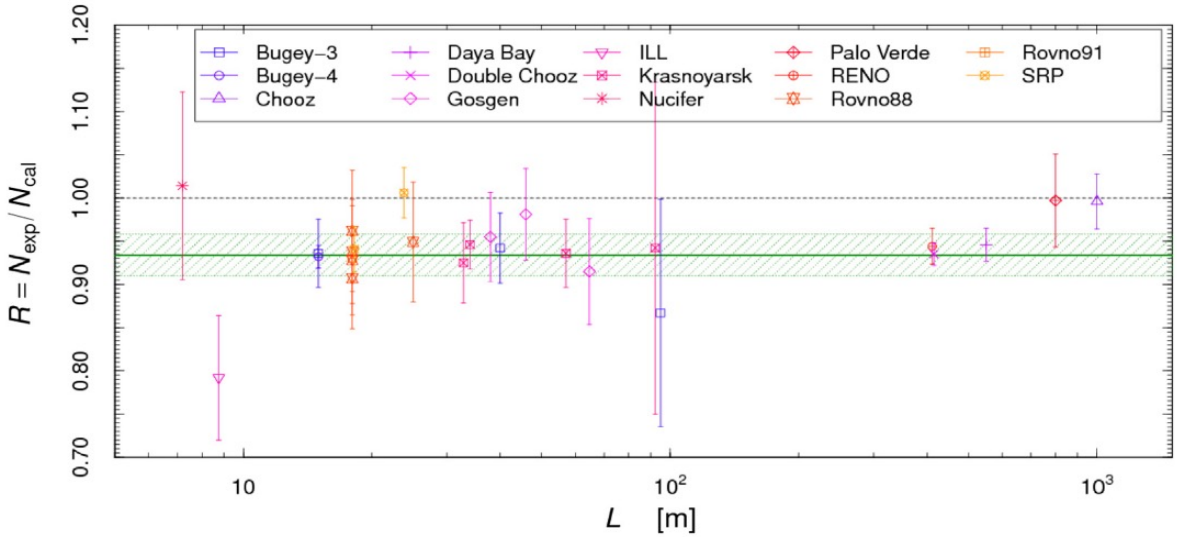
- Research reactors **H**ighly **E**nriched in **U**ranium (**HEU**) : **pure ^{235}U** fuel
- Commercial reactors **L**owly **E**nriched in **U**ranium (**LEU**) : **mixed ^{235}U + Pu** (+ ^{238}U) fuel



``5 MeV Bump''

~10% spectral disortion w.r.t. Huber-Mueller prediction.

Nature Physics 16, pp. 558–564 (2020)



Reactor Antineutrino Anomaly (RAA)

~6% global rate deficit at short-baseline w.r.t. Huber-Mueller prediction.

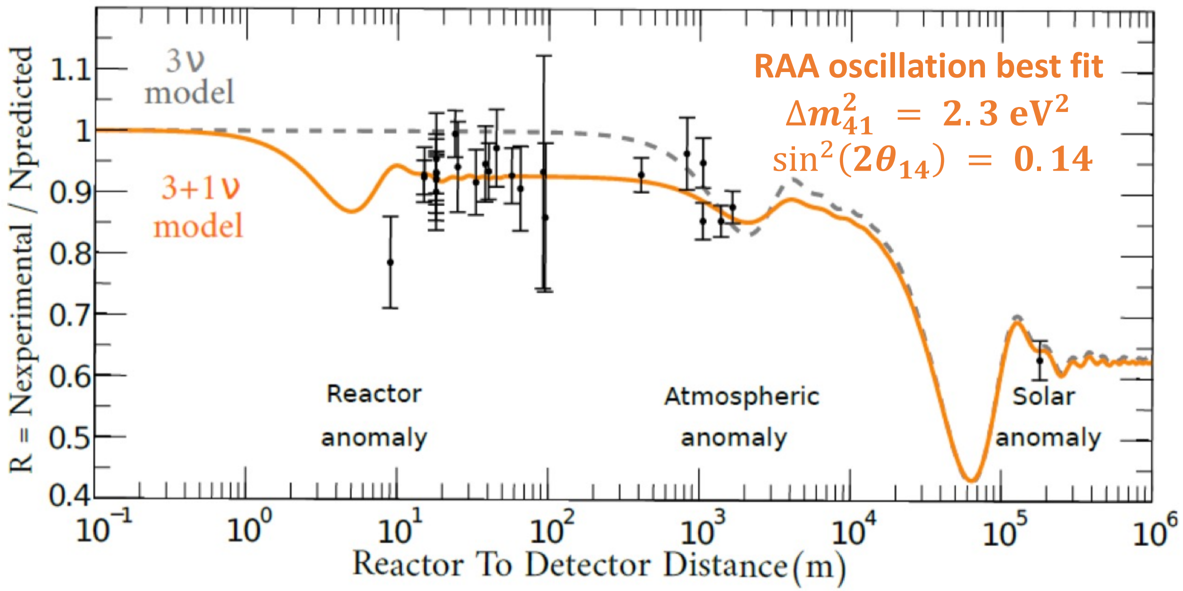
Progress in Particle and Nuclear Physics 111, 103736 (2020)

Biased prediction or new physics ?

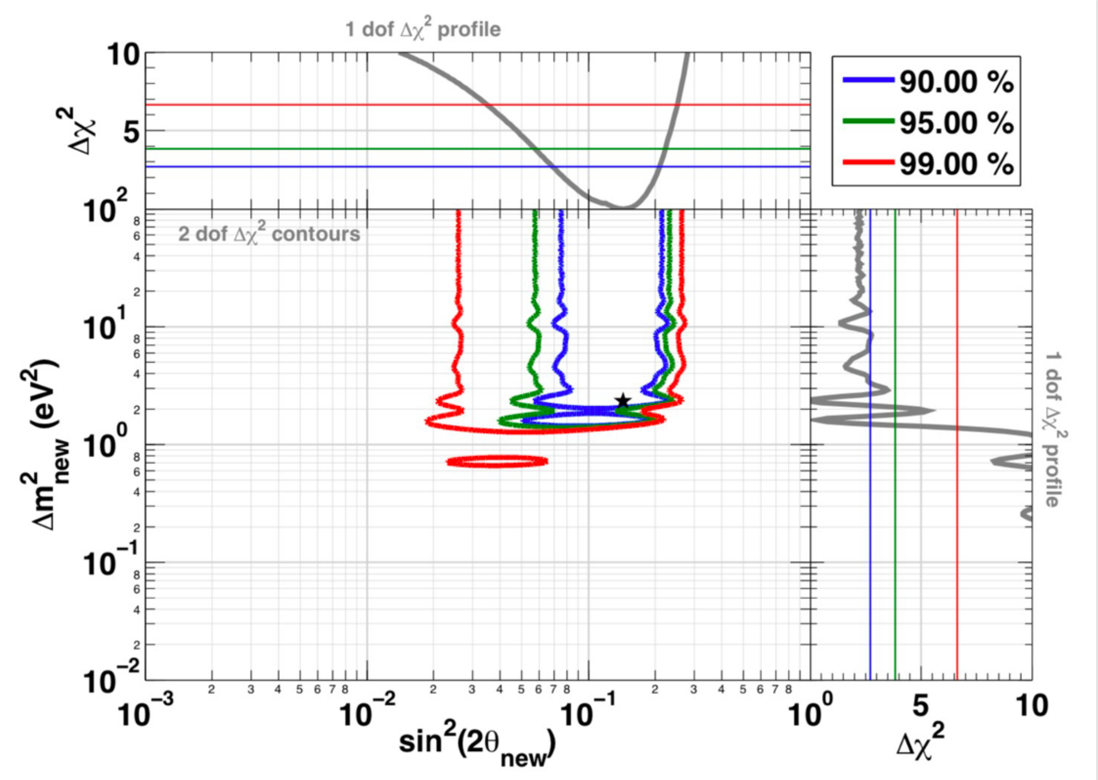
Rate anomaly and sterile neutrino

Short-baseline deficit ↔ Signature of a new oscillation ?

$$\begin{pmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \\ \nu_s \end{pmatrix} = U_{PMNS}^{3+1} \cdot \begin{pmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \\ \nu_4 \end{pmatrix}$$



PRD 83, 073006 (2011)

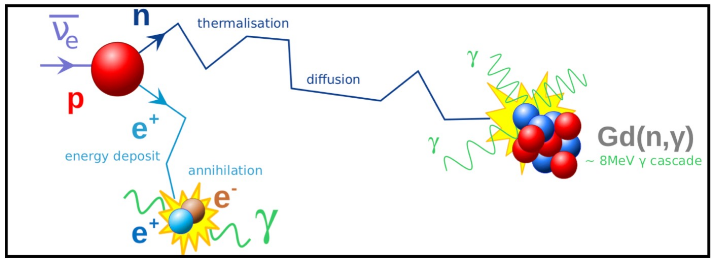


STEREO provides a complete study of all anomalies for a pure ^{235}U antineutrino spectrum (HEU experiment).

STEREO experiment

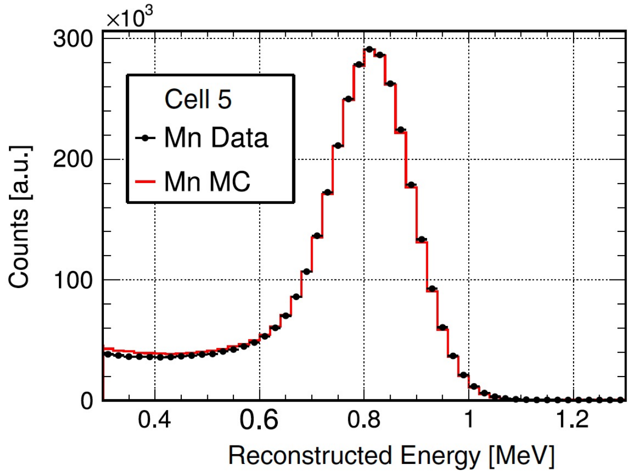
Detection Principle : Inverse beta-decay (IBD)

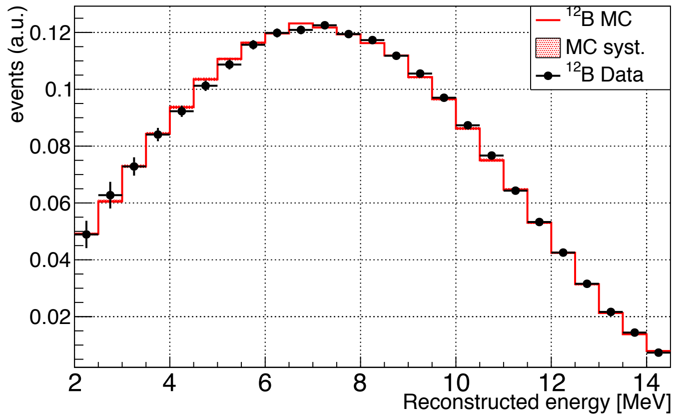
$\bar{\nu}_e + p \rightarrow e^+ + n$ $\quad$ $E_{\bar{\nu}_e} = E_{e^+} - 0.782[\text{MeV}]$

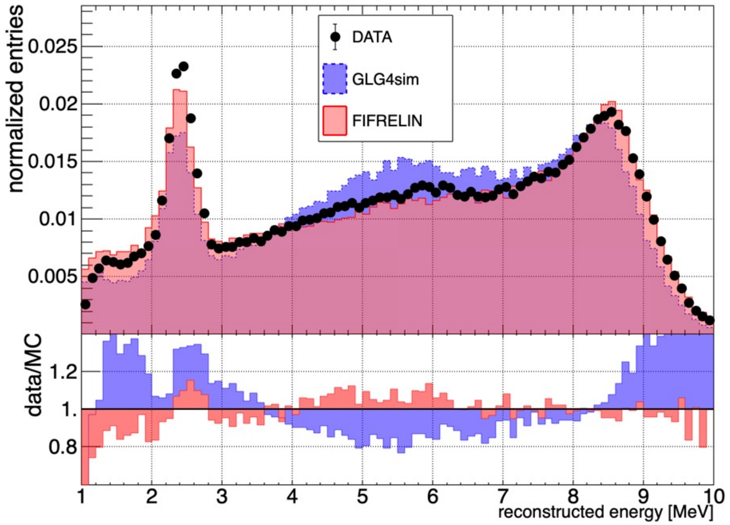


- **Insights on the pure contribution of ^{235}U to the reactor anomalies.**
- **Test of sterile hypothesis**, with a model-independent oscillation analysis.
- **Precision** measurement of the absolute **antineutrino rate and spectrum shape**.

- Antineutrino source: **HEU** research reactor of Institut Laue-Langevin (Grenoble, France).
- **Very short-baseline** (9-11m) & **Compact core** + Segmented detector, with **6 identical cells**.
- **Accurate** determination of the **detector response**.







Control of detector response

Energy scale derived from a **global fit** of:

- Calibration data taken with point-like radioactive sources in each cell, at different heights.
- Cosmogenic ^{12}B beta spectrum ($Q_\beta = 13.4$ MeV).

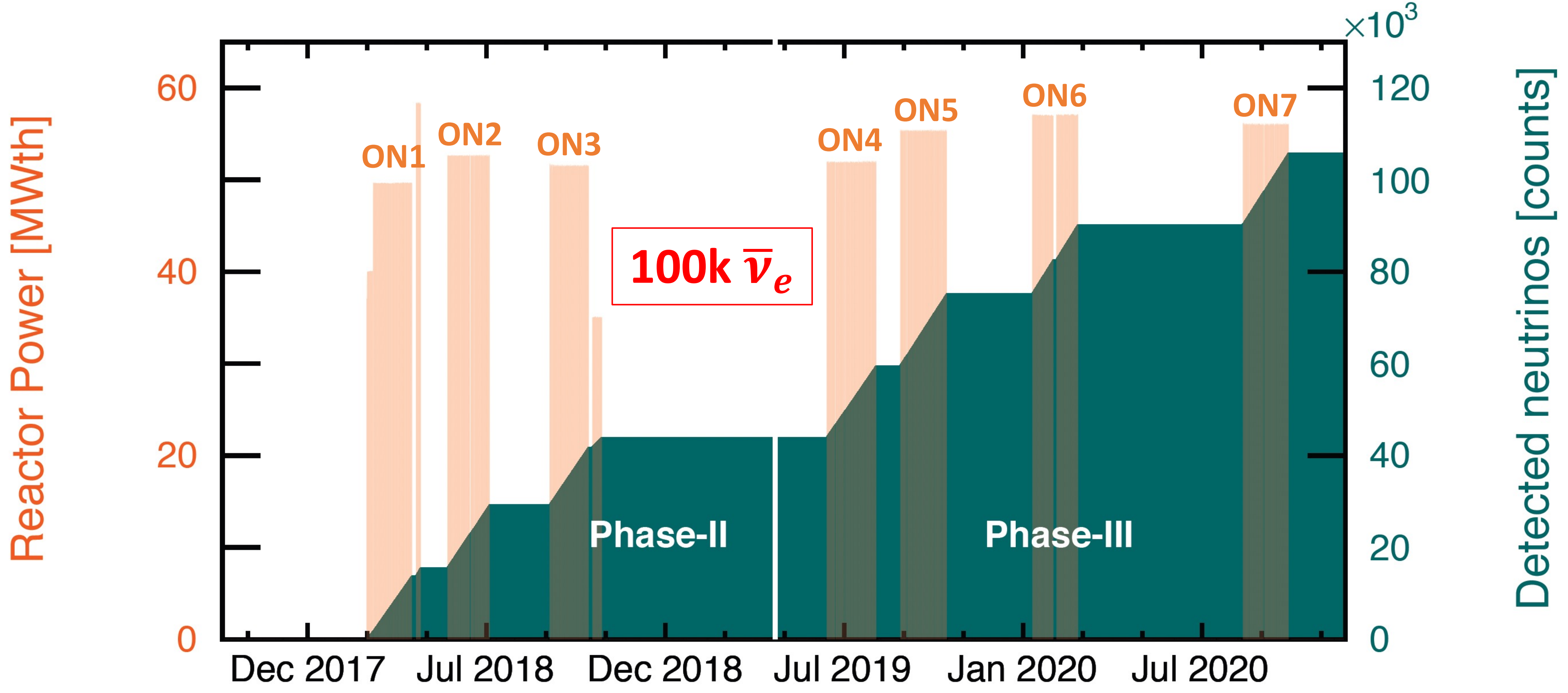
Data-MC residuals contained within a ±1% band for all cells

Phys. Rev. D, 102:052002, 2020

Improvement of the MC gamma cascade after a n-capture in Gd with the FIFRELIN code

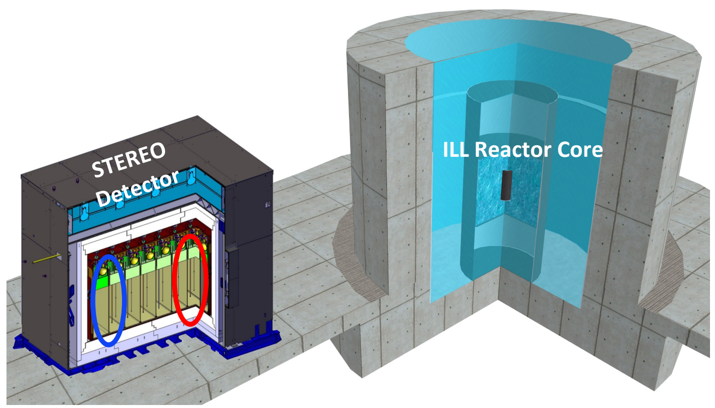
arXiv:2207.10918

3 years of data taking…

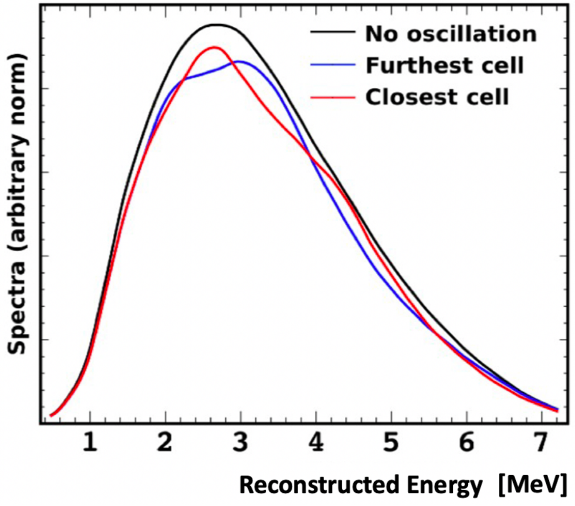


$< S{:}B > \sim 1 \leftrightarrow$ 274 days-ON and 520 days-OFF for background subtraction.

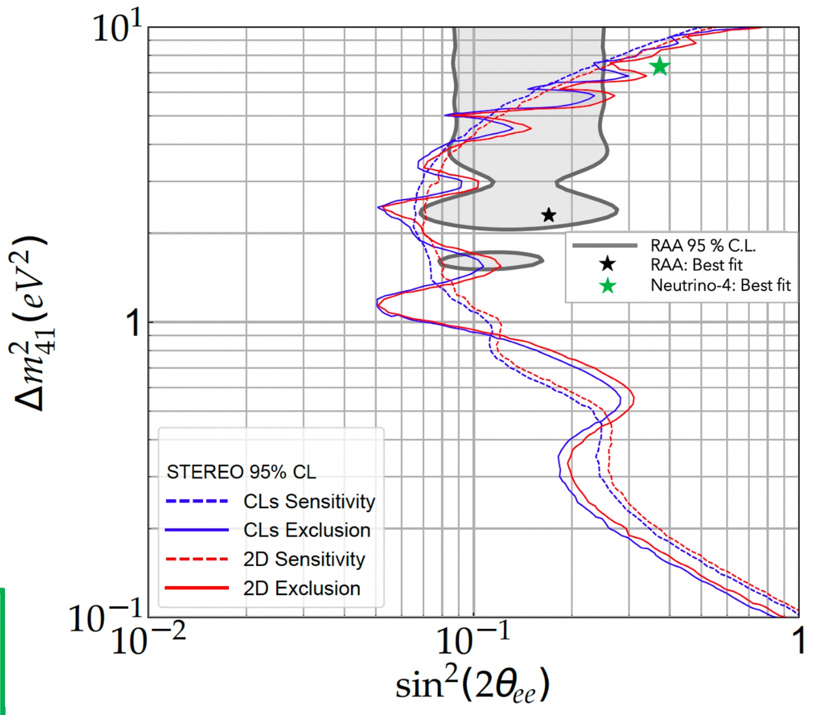
Analysis of STEREO data



STEREO sterile neutrino search



- **Prediction-free analysis.**
- **2D Feldman-Cousins** and **CLs** approaches → Compatible results
- **No-oscillation hypothesis not rejected** (p-value = 0.52).
  - ➢ RAA best fit excluded at ~4σ.
  - ➢ Neutrino-4 best fit excluded at ~3.3σ.



arXiv:2210.07664

Sterile neutrino hypothesis disfavored with high CL.

$$||X||_M^2 := X^T M X$$

STEREO ^{235}U spectrum – Unfolding procedure

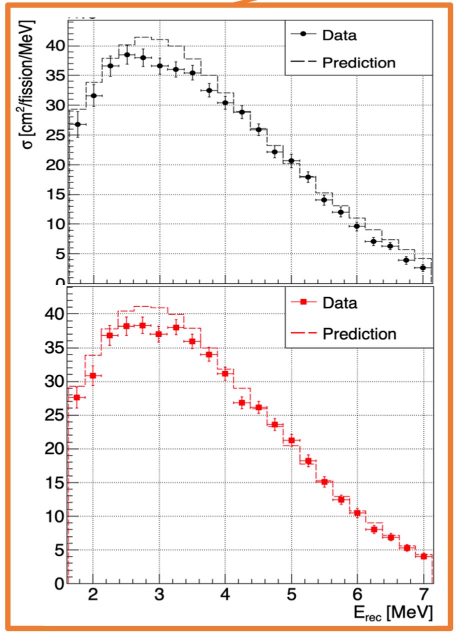
Goal: **Provide a reference ^{235}U antineutrino spectrum in antineutrino energy space, free of detector effects.**

- Analytical minimization of regularized χ^2:

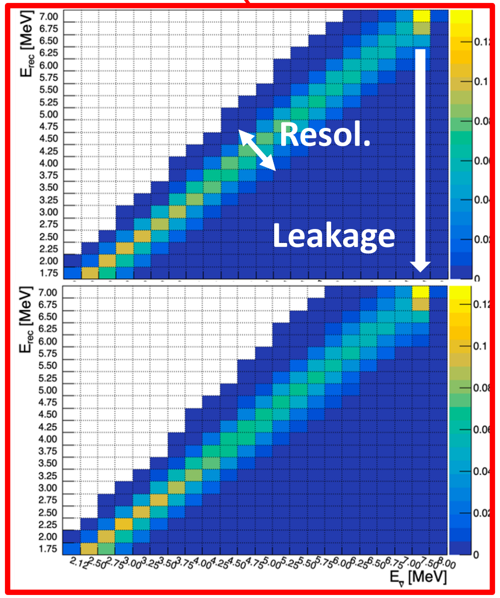
$$\chi^2(\Phi) = \left|\left| \begin{bmatrix} D_{II} \\ D_{III} \end{bmatrix} - \begin{bmatrix} R_{II} \\ R_{III} \end{bmatrix} \cdot \Phi \right|\right|^2_{V^{-1}_{II+III}} + \lambda * ||\Phi||^2_{M_{HM}}$$

Regularization term

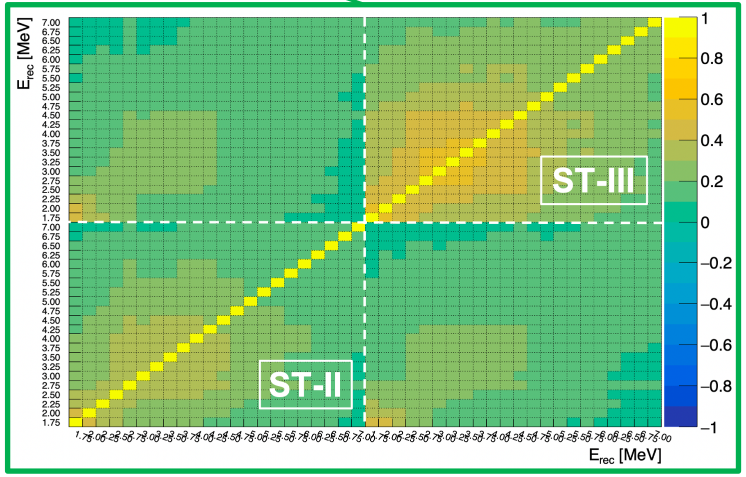
- $\lambda * \sum_i \left(\frac{\Phi_{i+1}}{\Phi^{HM}_{i+1}} - \frac{\Phi_i}{\Phi^{HM}_i} \right)^2$: penalty term on the bin-to-bin fluctuations, wrt. a **prior shape Φ^{HM} (Huber ^{235}U spectrum)**.



Data Spectra

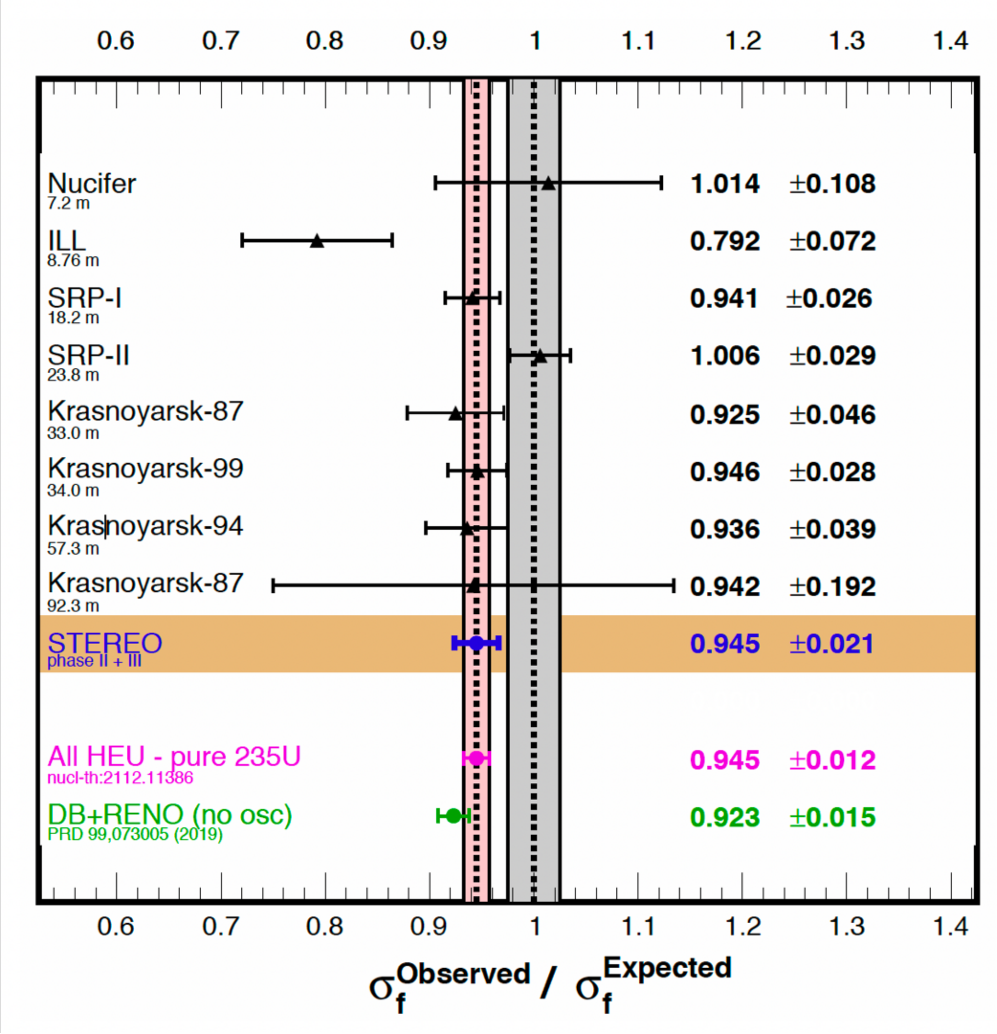


Response matrix



Experimental Covariance matrix

STEREO ^{235}U spectrum – Rate analysis



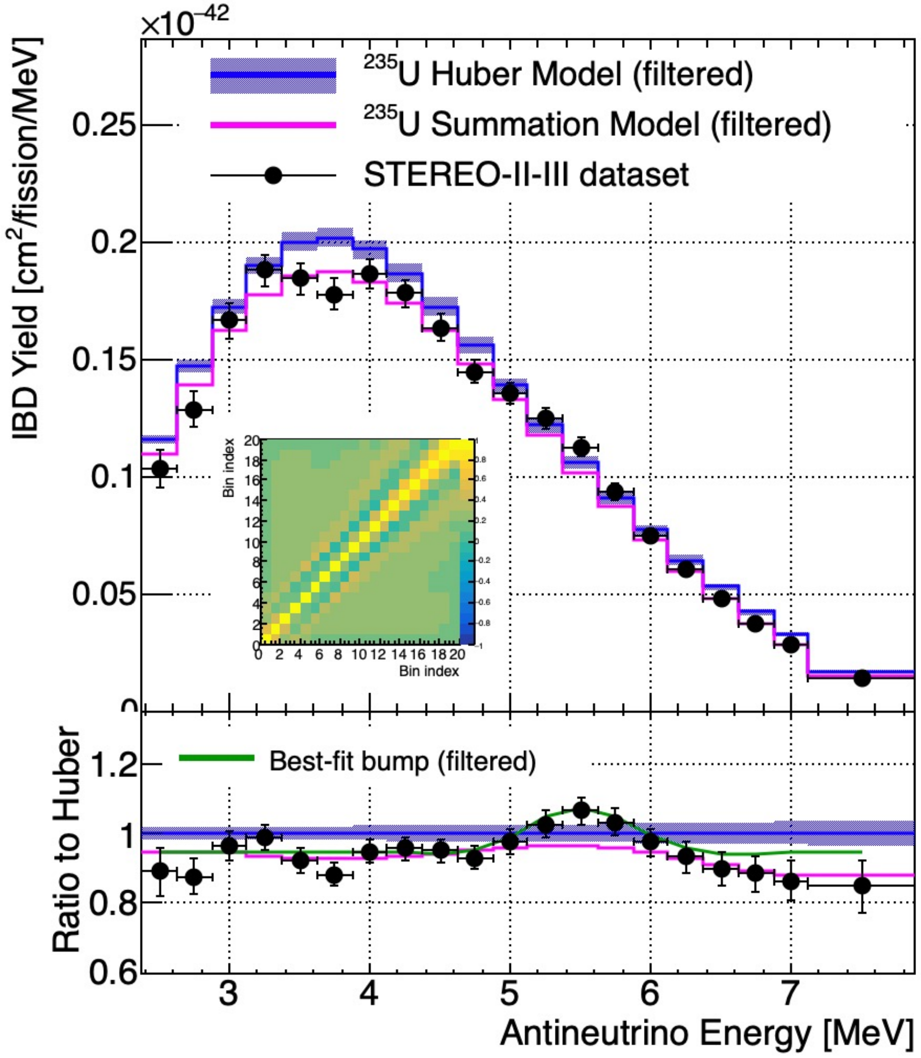
arXiv:2210.07664

- **Global deficit** w.r.t. Huber prediction for ^{235}U:

$$(5.5 \pm 2.1\ [\text{stat} + \text{syst}])\%$$

- **Most accurate measurement** of ^{235}U fission yield, in agreement with the world average.

STEREO ^{235}U spectrum – Shape analysis



arXiv:2210.07664

$$Pred_{A,\mu,\sigma}(E) = HM(E) \cdot \alpha \left(1 + A \cdot \exp\frac{(E-\mu)^2}{2\sigma^2}\right)$$

- ***Unbiased*** minimization of:

$$\chi^2(A,\mu,\sigma) = \left(\Phi - A_c \cdot Pred_{A,\mu,\sigma}\right)^T V_\Phi^{-1}\left(\Phi - A_c \cdot Pred_{A,\mu,\sigma}\right)$$

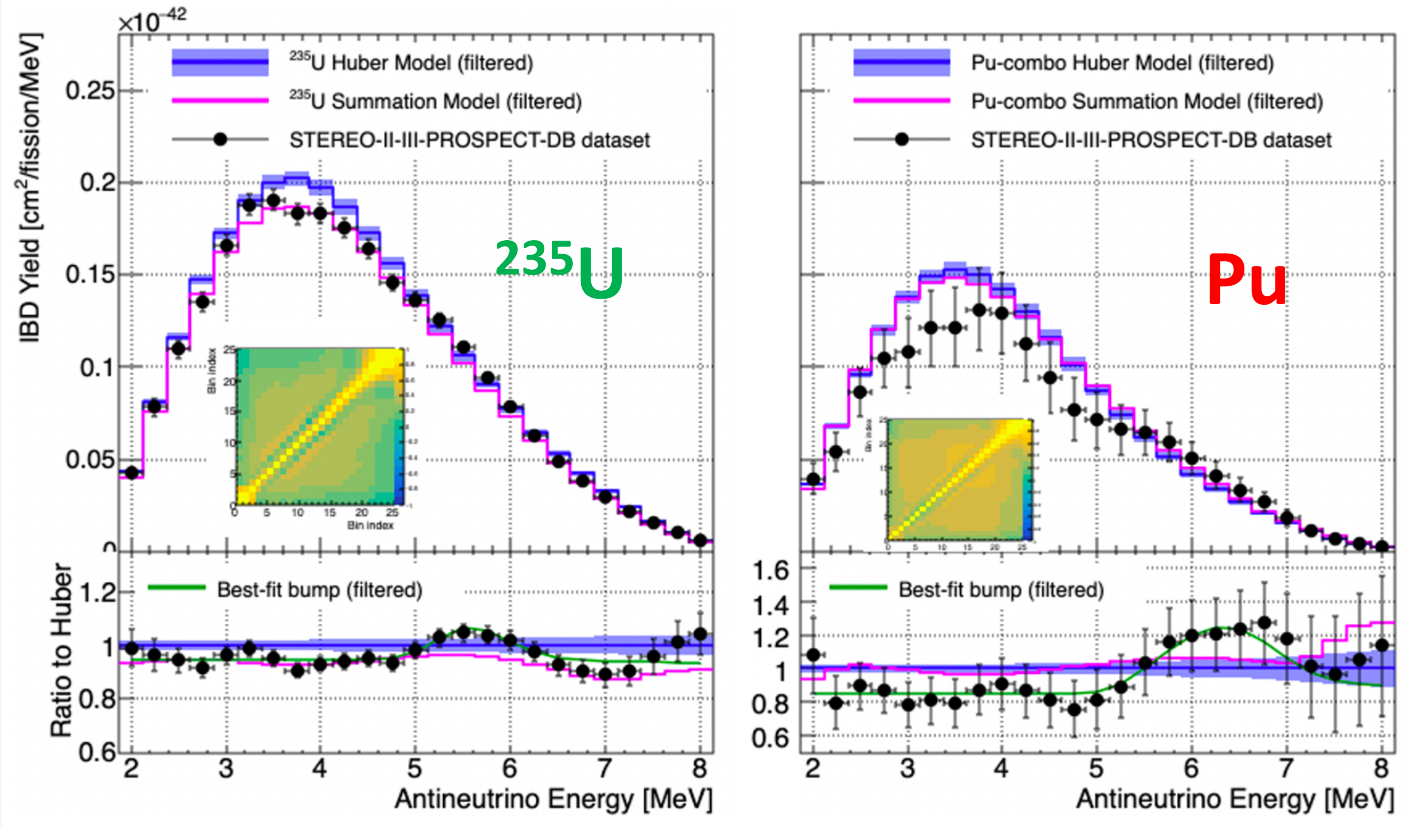
- **Local event excess** wrt. Huber around 5.5 MeV for ^{235}U with **4.6σ** significance.

$$A = (15.6 \pm 5.2)\ \%$$
$$\mu = (5.500 \pm 0.092)\ \mathrm{MeV}$$
$$\sigma = (0.308 \pm 0.143)\ \mathrm{MeV}$$

Global analysis of reactor $\bar{\nu}_e$ spectra

HEU + LEU Global shape analysis

- ^{235}**U** data from the PROSPECT experiment $(\sim 50\text{k}\ \bar{\nu}_e)$ – *Phys. Rev. Lett. 122, 251801*
- ^{235}**U** + **Pu** global data from the Daya Bay experiment $(\sim 3500\text{k}\ \bar{\nu}_e)$ – *Chin. Phys. C, 45:073001, 2021*



^{235}U Best-fit bump params (4.7σ):

$$A = (14.4 \pm 3.4)\%$$
$$\mu = (5.593 \pm 0.092) MeV$$
$$\sigma = (0.330 \pm 0.097) MeV$$

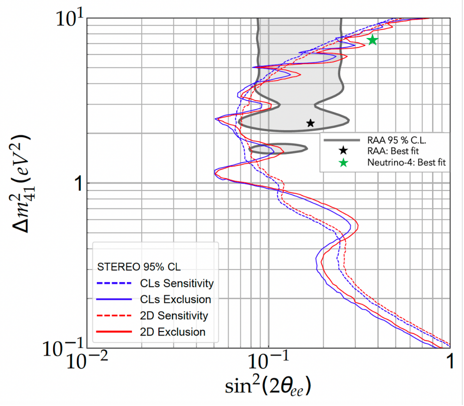
Pu Best-fit bump params (2.3σ):

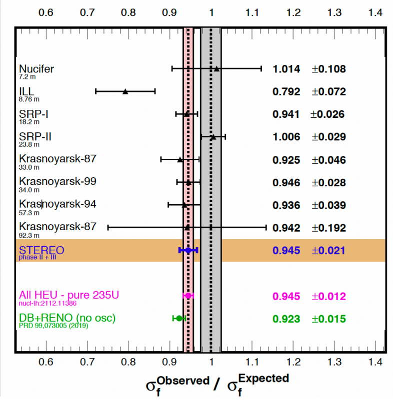
$$A = (50.4 \pm 15.2)\%$$
$$\mu = (6.325 \pm 0.268) MeV$$
$$\sigma = (0.531 \pm 0.244) MeV$$

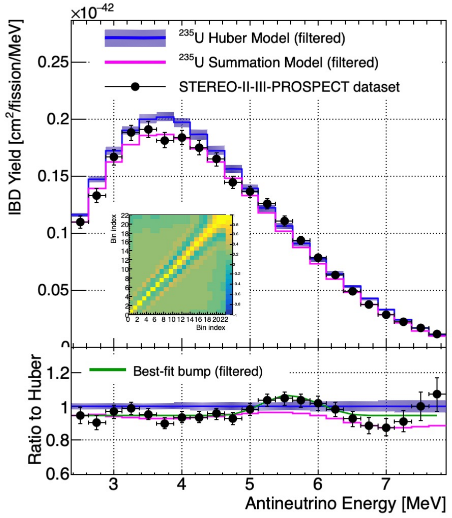
Conclusions

Most accurate measurement of the ^{235}U spectrum to date, providing a **complete study of the reactor anomalies**:

- **Sterile neutrino hypothesis disfavored**.
- (5.5 ± 2.1)% rate deficit observed in ^{235}U pointing to a **biased prediction normalization** as the main origin of the RAA.
- **4.6σ local distortion** around 5.5 MeV, with unbiased best-fit params.
- Extension to a global analysis of ^{235}U + Pu data.





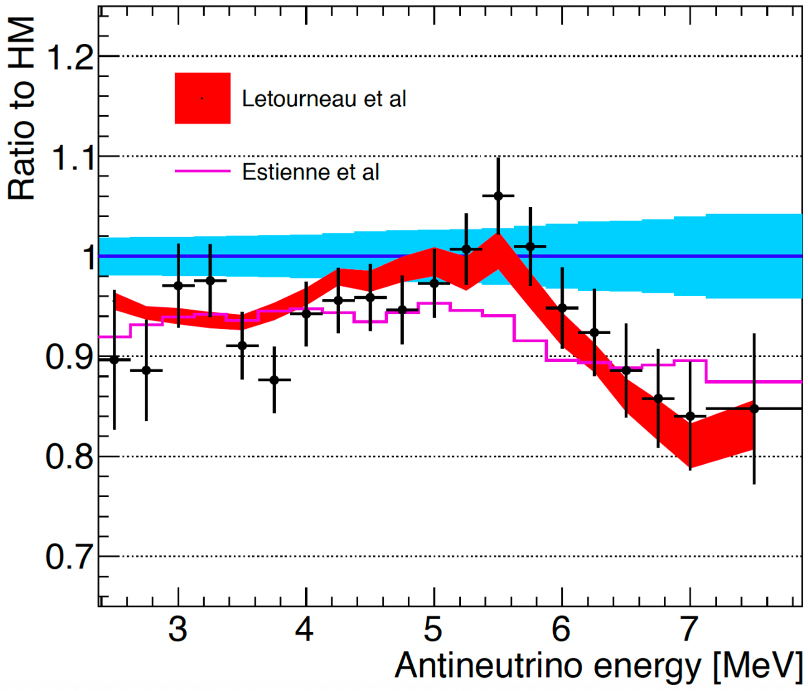


Outlook

Precise reference antineutrino spectrum from the fission of ^{235}U:

- ❑ **Spectrum expressed in true antineutrino energy** available for the upcoming high precision reactor antineutrino experiments.

- ❑ ***Shift of paradigm***: precision of the direct neutrino measurements constrains the nuclear observables. Latest summation model calculations showed the critical impact of the correction of the pandemonium effect.

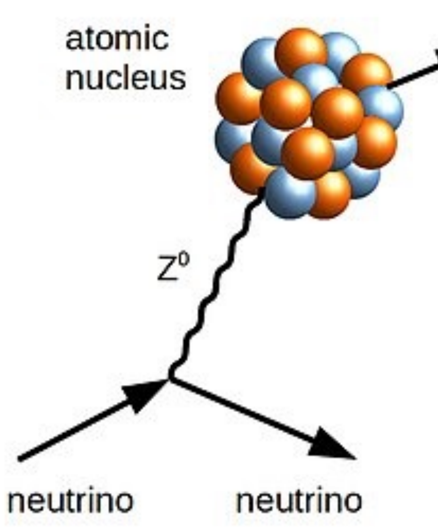


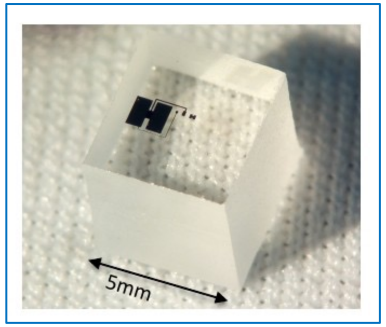
arXiv.2205.14954

The NUCLEUS experiment

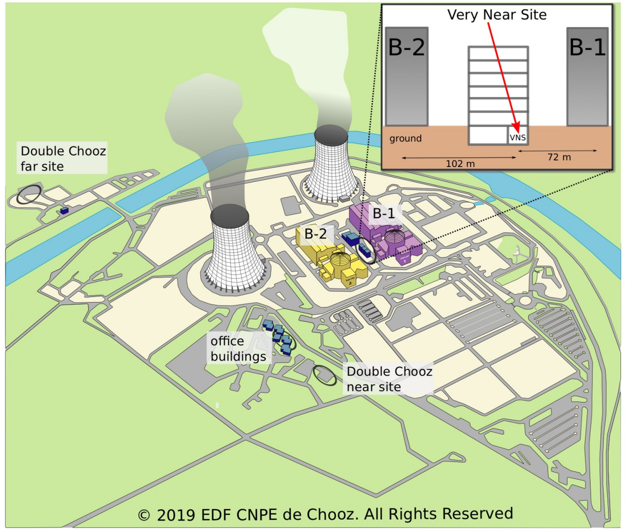
NUCLEUS: a CEνNS experiment

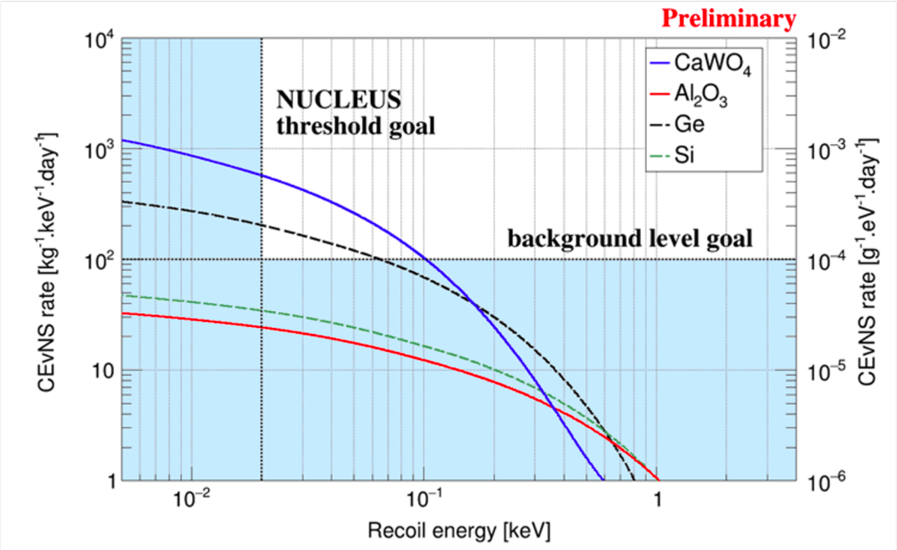
- CEνNS : neutral current interaction with sub-keV nuclear recoil → **Ultra-low threshold technology** (cryogenic calorimeters – 20 eV threshold).
- $\sigma_{CE\nu NS} \propto N^2$: potential for enhanced neutrino detection efficiency wrt. standard IBD channel.
- Good knowledge of reactor antineutrino spectrum + Measurement of a new neutrino-matter interaction → **low energy probe of the SM**.





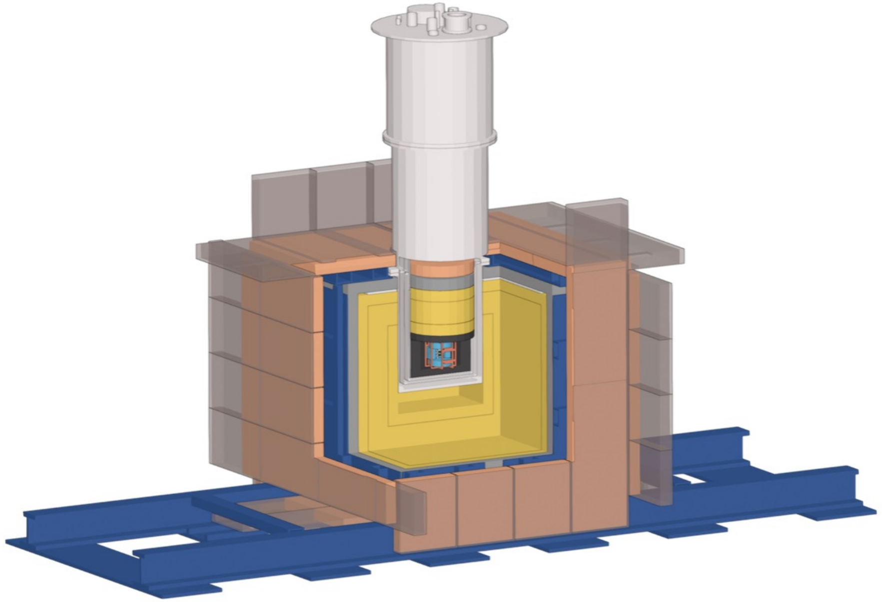
$CaWO_4$ crystal

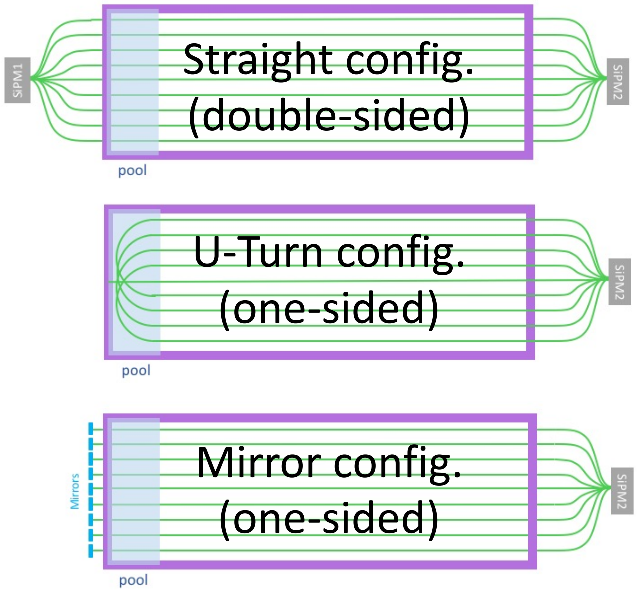


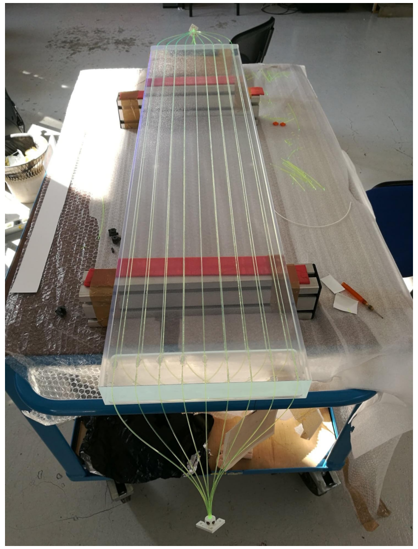


Expected background

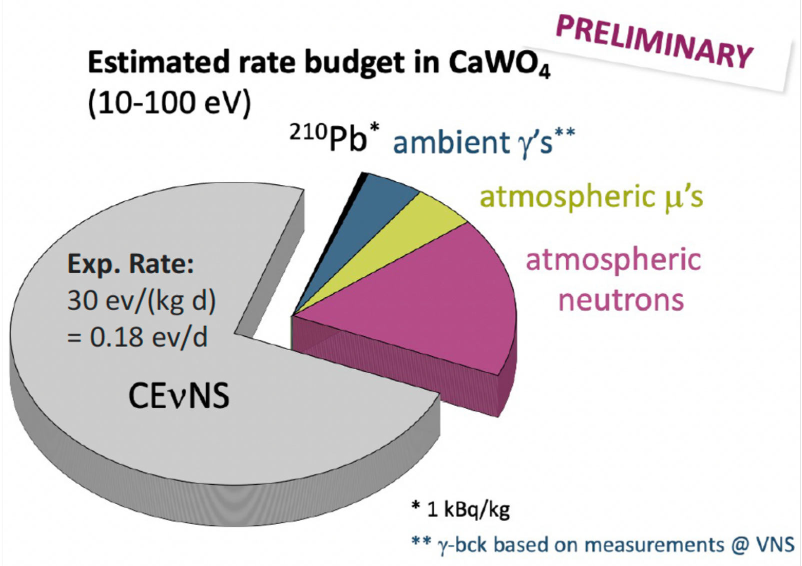
- Low counting rate expected for the signal → requires efficient background rejection.
- Background dominated by atmospheric neutrons and muons.
- I worked on the rejection of the atmospheric muon background → **Full commissioning of the muon veto prototype** *JINST 17 T05020*



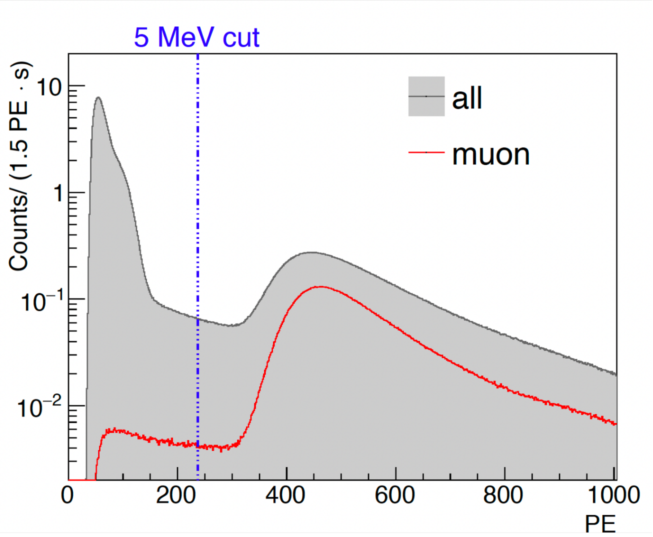


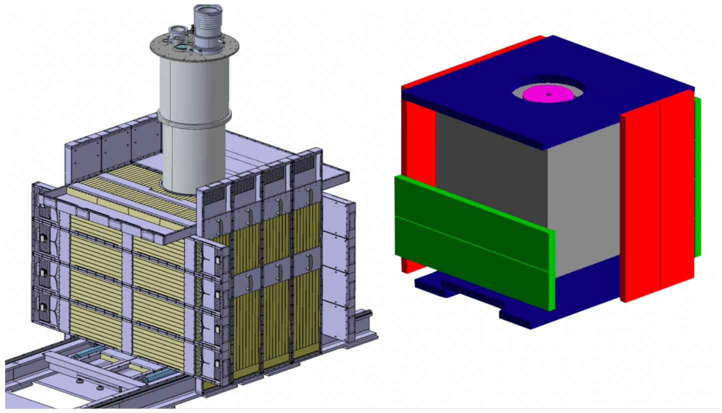


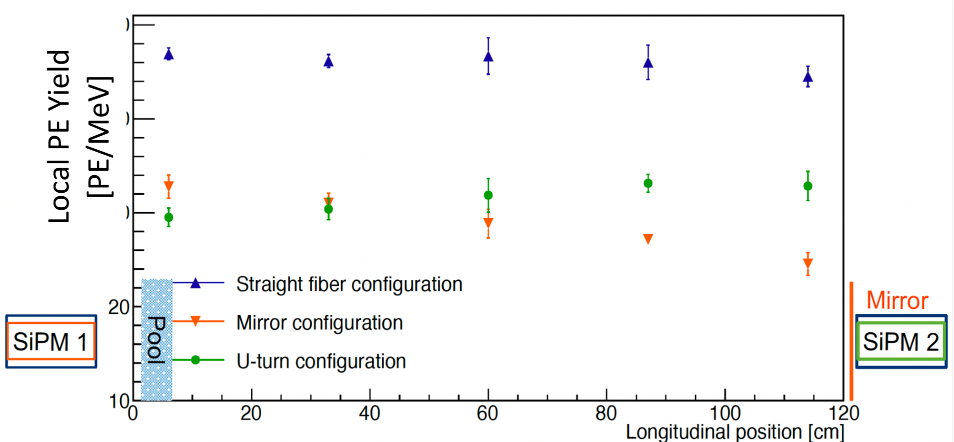
5cm-thick plastic scintillator



Characterization of the panel performance







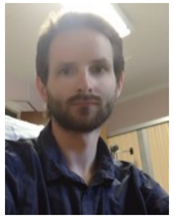
- ❑ Satisfactory gamma/muon separation:
  - ➢ **Key point to ensure a moderate dead-time**
- ❑ Geometrical simulation to derive the overall efficiency of the NUCLEUS muon veto:
  - ➢ **99.7% muon tagging efficiency**

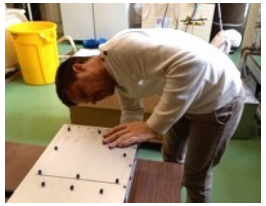
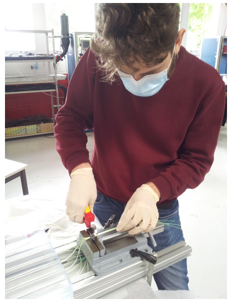
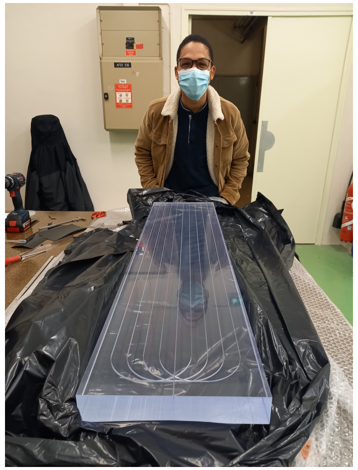
    V. Savu, PhD thesis (2021)
- ❑ Quantification of the light yield and response homogeneity, for each optical fiber configuration.

Fiber Configuration	PE Yield [PE/MeV]	Inhomogeneities
Straight (double-sided)	~ 47	~ 2%
U-turn (one-sided)	~ 32	~ 11%
Straight + mirrors (one-sided)	~ 30	~ 30%

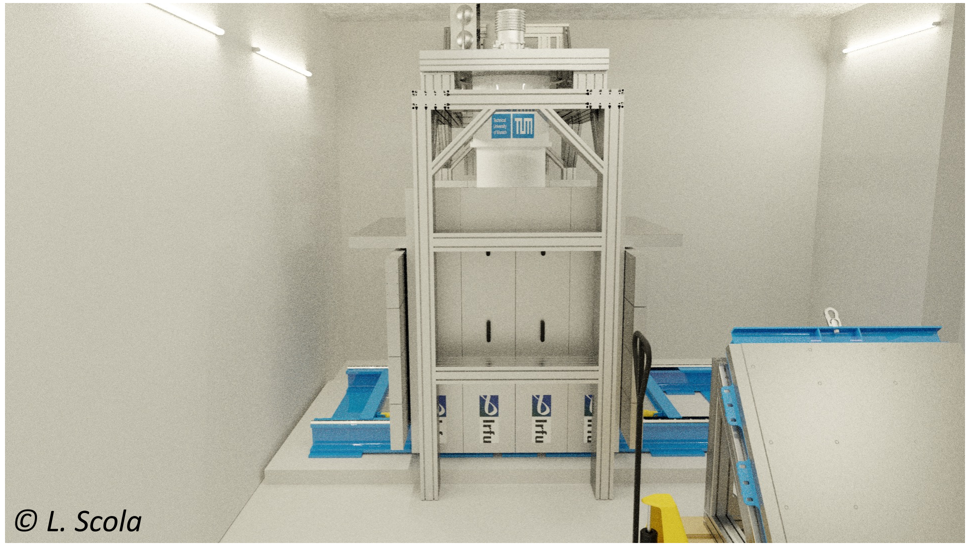
Outlook







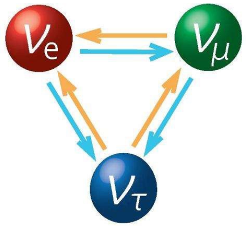
Upcoming blank assembly in Munich and first physics run in 2024 !

All thanks go to the mounting team and the « Bureau d'Études » (Loris, Nicolas, Gilles) !

Thank you for your attention !

Back-up

Neutrino oscillations



$$\begin{pmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \end{pmatrix} = U_{PMNS} \cdot \begin{pmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \end{pmatrix}$$

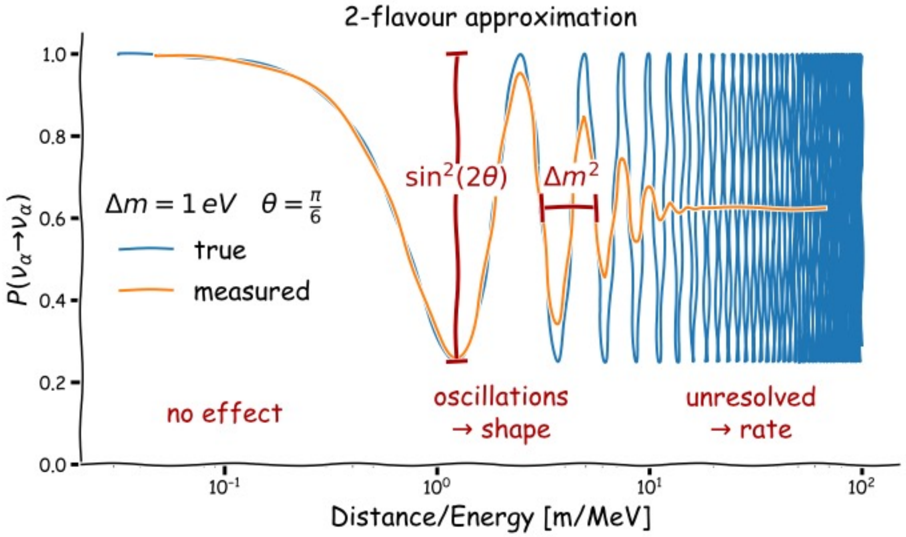
flavor eigenstates

mass eigenstates (m_1, m_2, m_3)

Parameterized by ($\theta_{13}, \theta_{23}, \theta_{12}, \delta_{CP}$)

Need to measure θ_{12},θ_{23},θ_{13} and Δm^2_{21},Δm^2_{31}

$$P_{\nu_\alpha \to \nu_\beta}(L, E) = \sin^2(2\theta) \sin^2\left(1.27 \frac{\Delta m^2[eV^2] \cdot L[km]}{E[MeV]}\right)$$



Δm^2_{21} [eV²]	Δm^2_{31} [eV²]
$7.4 \cdot 10^{-5}$	$2.5 \cdot 10^{-3}$

~ factor 30 discrepant

→ **Decoupling of oscillation regimes**

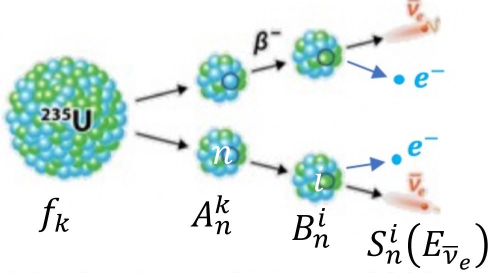
$\sin^2\theta_{12}$	$\sin^2\theta_{23}$	$\sin^2\theta_{13}$
~ 0.3	~ 0.4	**~ 0.02**

Reactor (anti)neutrino spectrum

Reactor Antineutrino Flux

β^- decay of fission fragments from:

- ^{235}U, ^{238}U, ^{239}Pu, ^{241}Pu (**LEU**)
- ^{235}U-only (**HEU**)

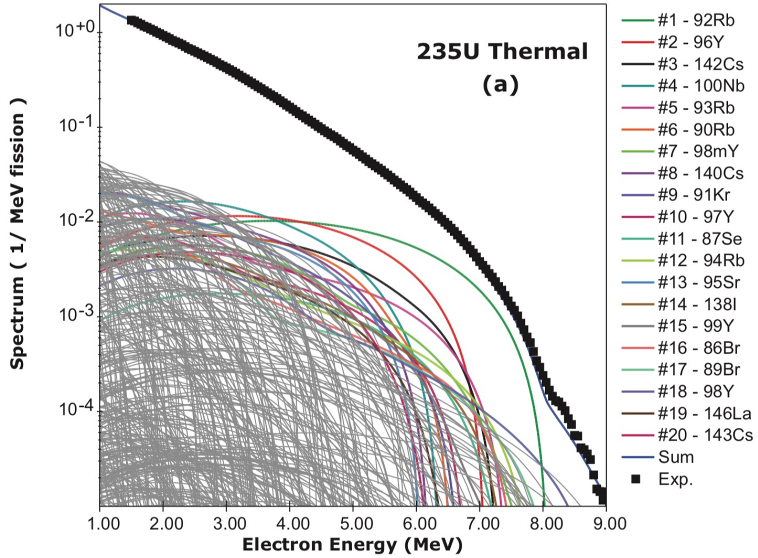


Emitted $\bar{\nu}_e$ spectrum given by:

❑ **« Summation » method**

➢ Sum up the $\bar{\nu}_e$ spectrum of all β^- decay branches of all fission fragments, based on the nuclear data bases:

$$S(E_{\bar{\nu}_e}) = \sum_k f_k \cdot \sum_n A_n^k \cdot \sum_i B_n^i \cdot S_n^i(E_{\bar{\nu}_e})$$



PRC 91, 011301(R) (2015)

(~ 10 000 β transitions)

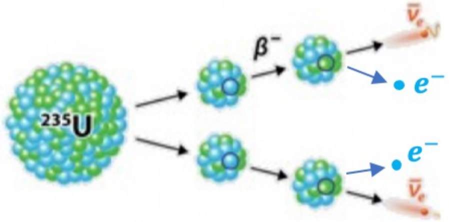
➢ **Drawback: suffers from *incompleteness* and *biases* of data bases.**

Reactor (anti)neutrino spectrum

Reactor Antineutrino Flux

β^- decay of fission fragments from:

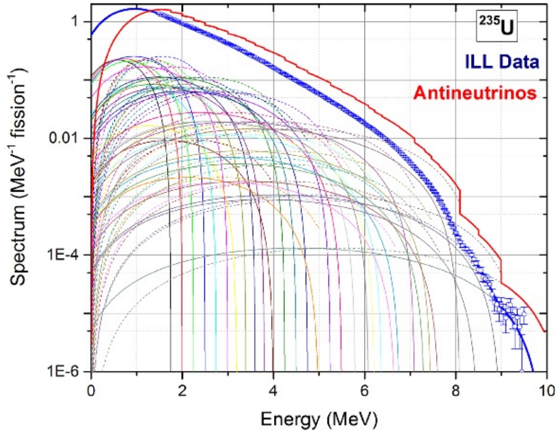
- ^{235}U, ^{238}U, ^{239}Pu, ^{241}Pu (**LEU**)
- ^{235}U-only (**HEU**)



Emitted $\bar{\nu}_e$ spectrum given by:

❑ **« Conversion » method**

➢ Measure the aggregate e^- spectrum for ^{235}U, ^{239}Pu and ^{241}Pu (HFR, ILL – 1980s) / for ^{238}U (FRM, Garching – 2014)

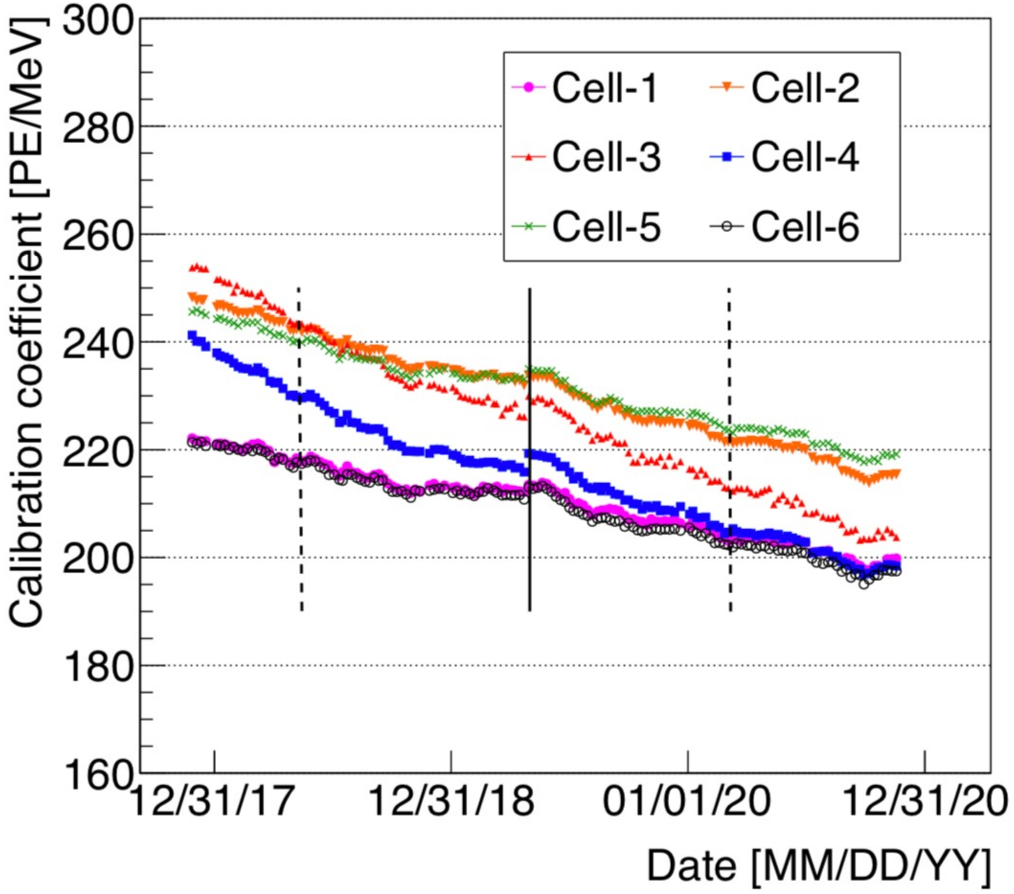


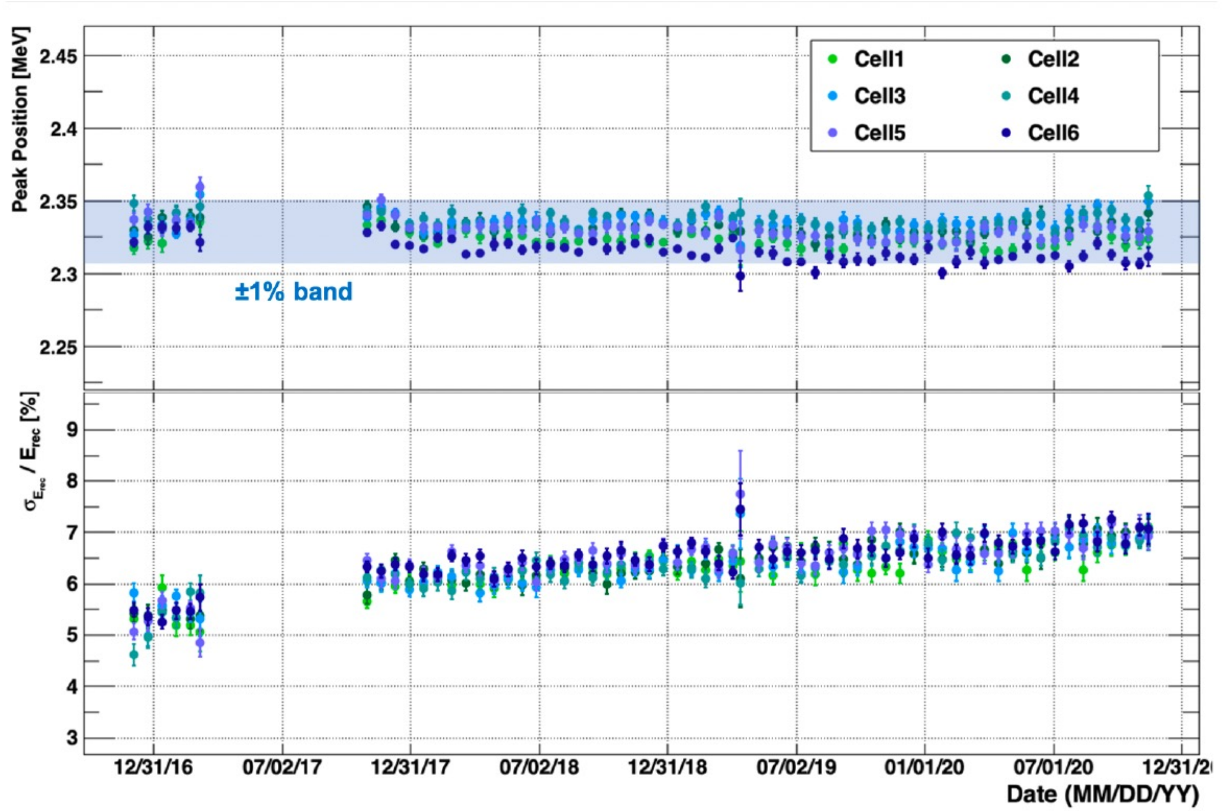
Convert into an $\bar{\nu}_e$ spectrum, by fitting the e^- spectrum with a set of **30 virtual β branches**

Updated conversion procedure

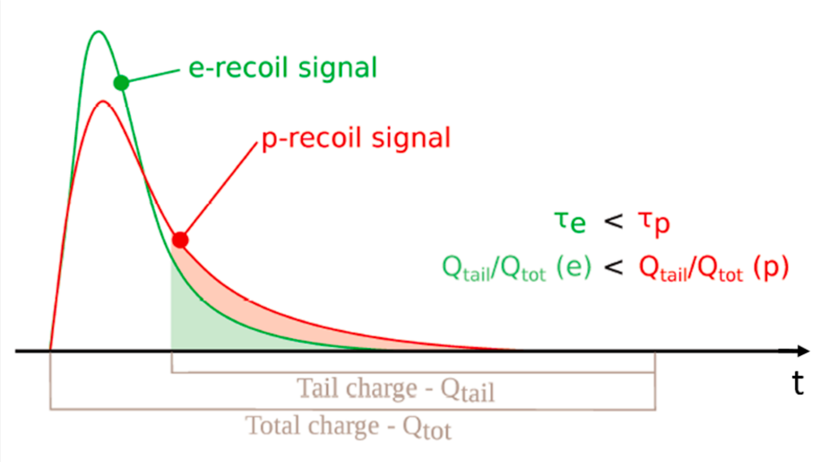
➢ **Huber-Mueller model** – *PRC 84, 024617 (2011), PRC 83, 054615 (2011)*

STEREO Detector Response

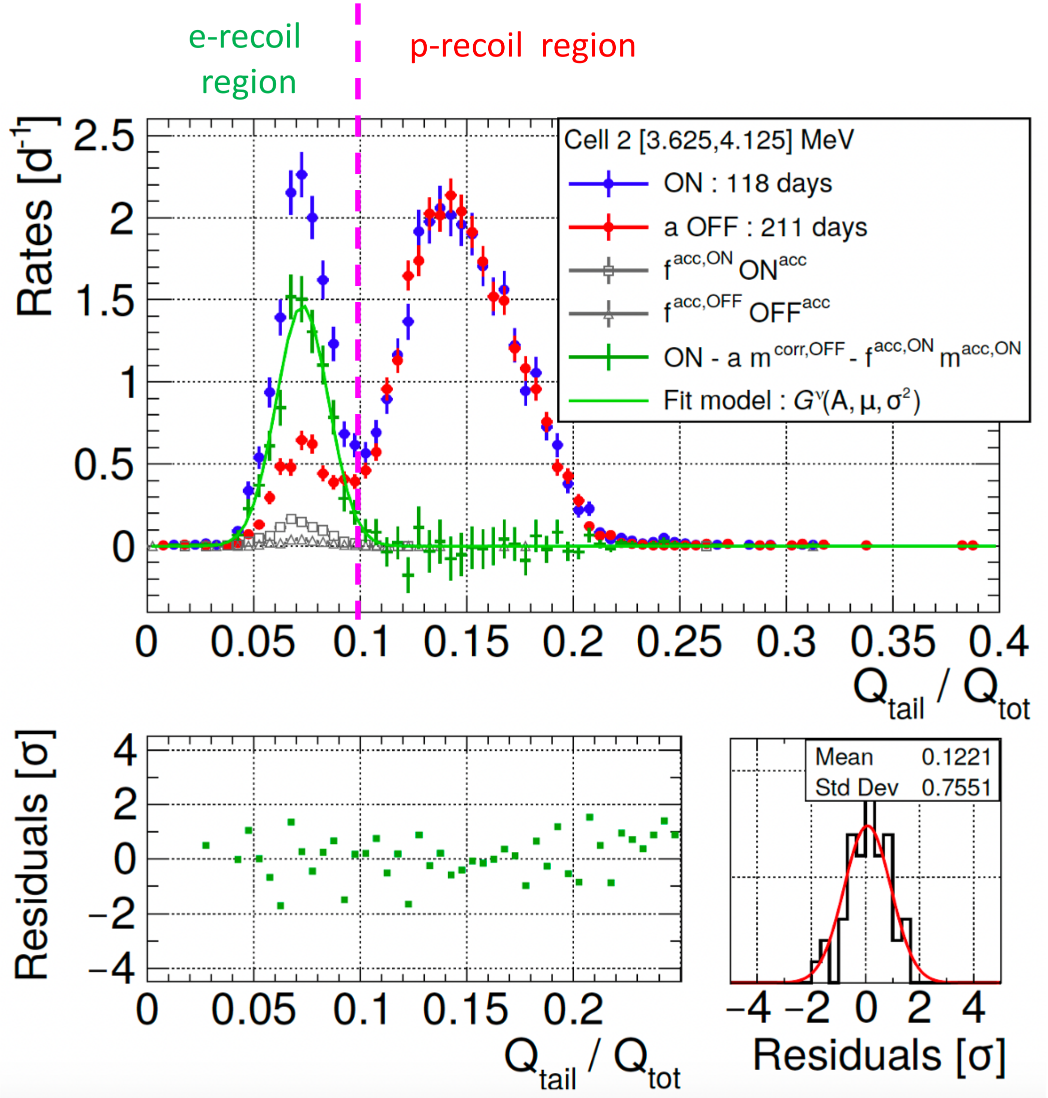




Antineutrino signal extraction

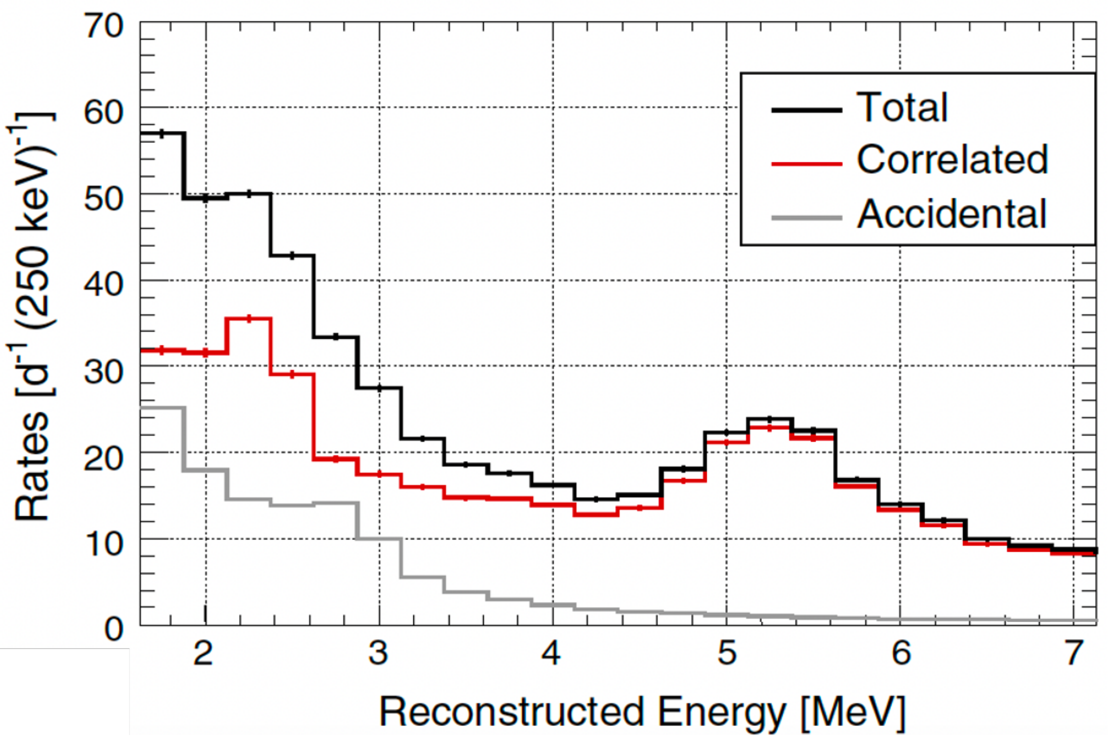


Pulse Shape Discrimination (PSD)

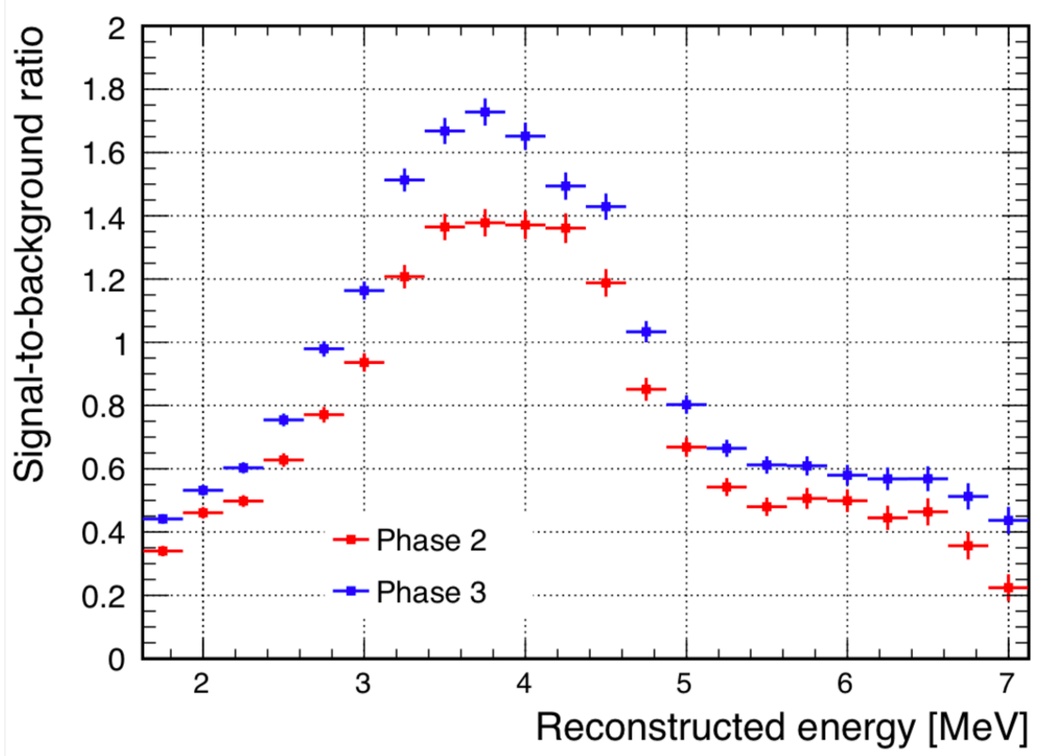


- PSD spectrum of **reactor-ON** and **reactor-OFF** data.
- **<u>Proven to be very stable in shape</u>** and anti-correlation of rate with P_{atm} accounted for by a free normalization parameter a.
- Gaussian fit to extract the **neutrino signal** in the e-recoil region.

Signal-to-background ratio

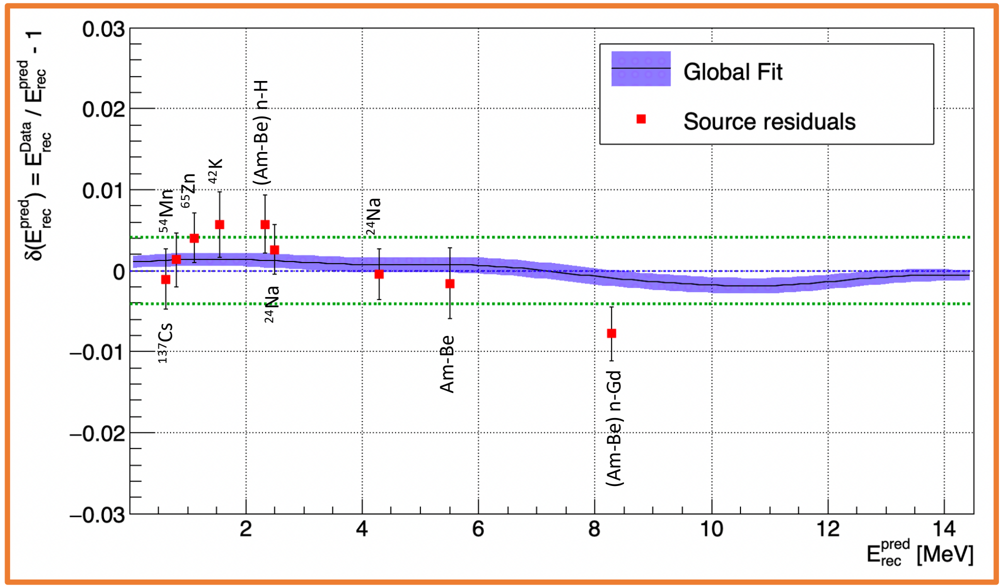


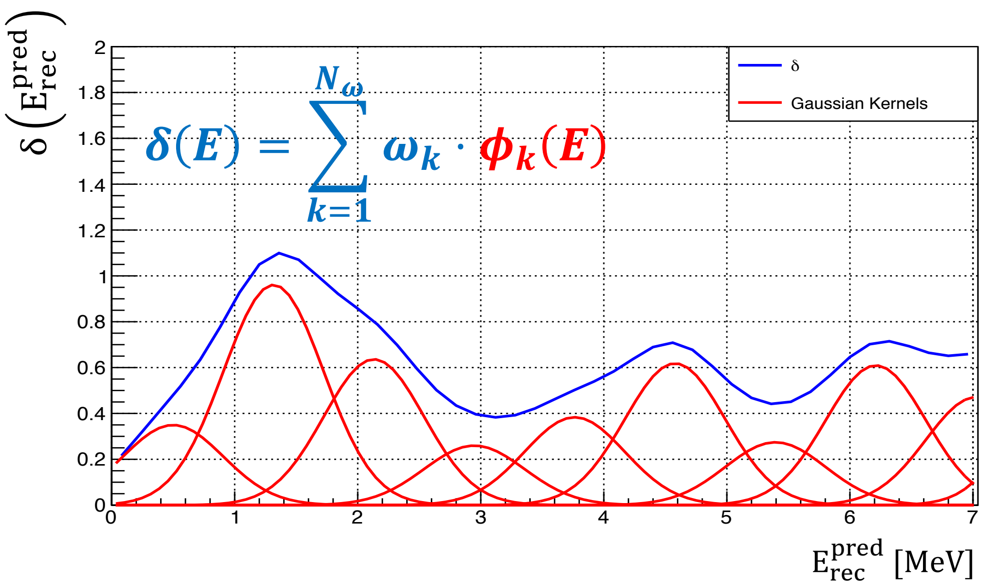
Correlated and accidental background

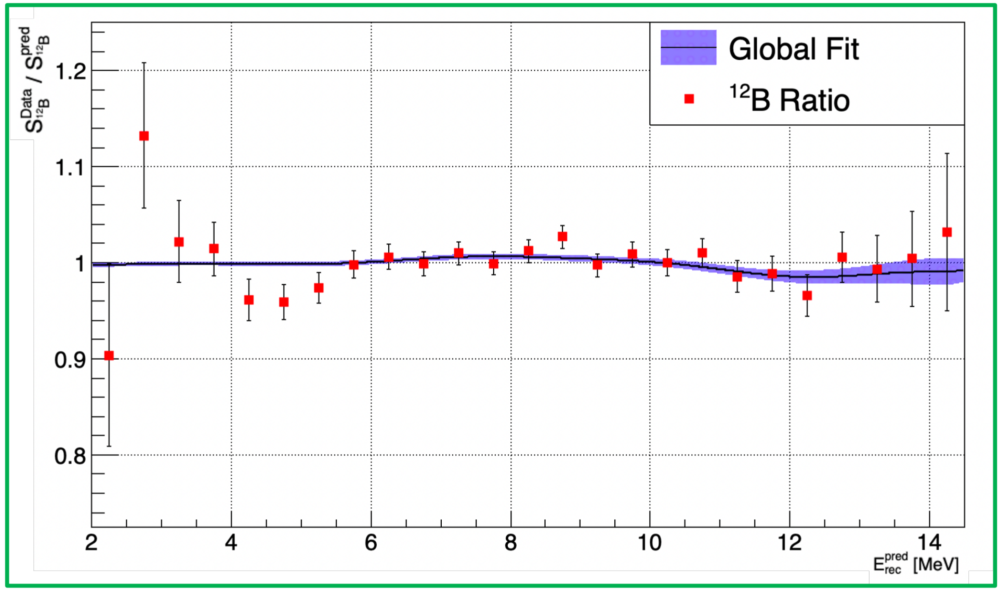


S/B ratio

Simultaneous Fit of Source points + continuous ^{12}B spectrum







Calibration:

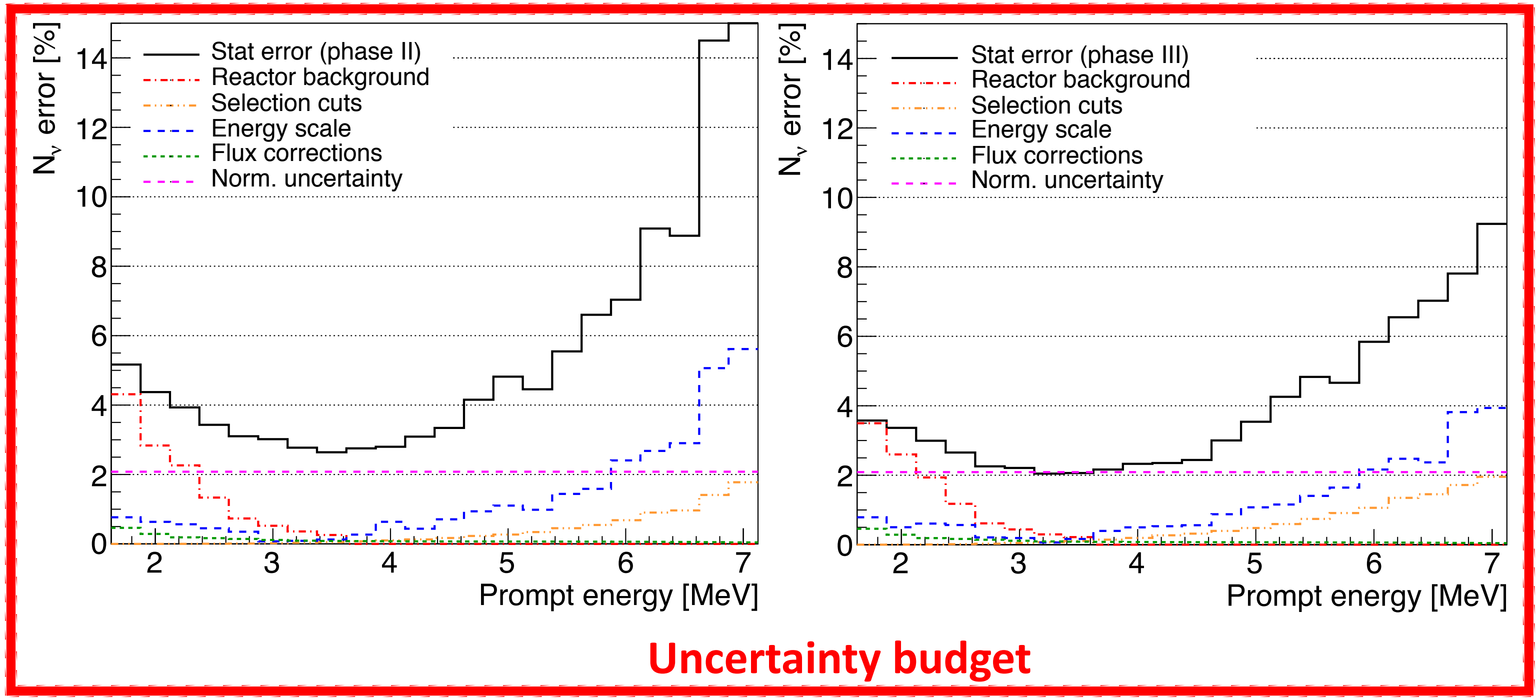
$$R_{calib}^{estimator}\left(E_{rec}^{pred}\right) = \frac{E_{rec}^{data}}{E_{rec}^{pred}} - 1 = \delta(E)$$

^{12}B Spectrum:

$$R_{spec}^{estimator}\left(E_{rec}^{pred}\right) = 1 - \delta(E) - E\delta(E)\frac{\left(S_{^{12}B}^{pred}\right)'(E)}{S_{^{12}B}^{pred}(E)} - E\delta'(E)$$

G. Mention et al., Phys. Lett. B 773, 307-312 (2017)

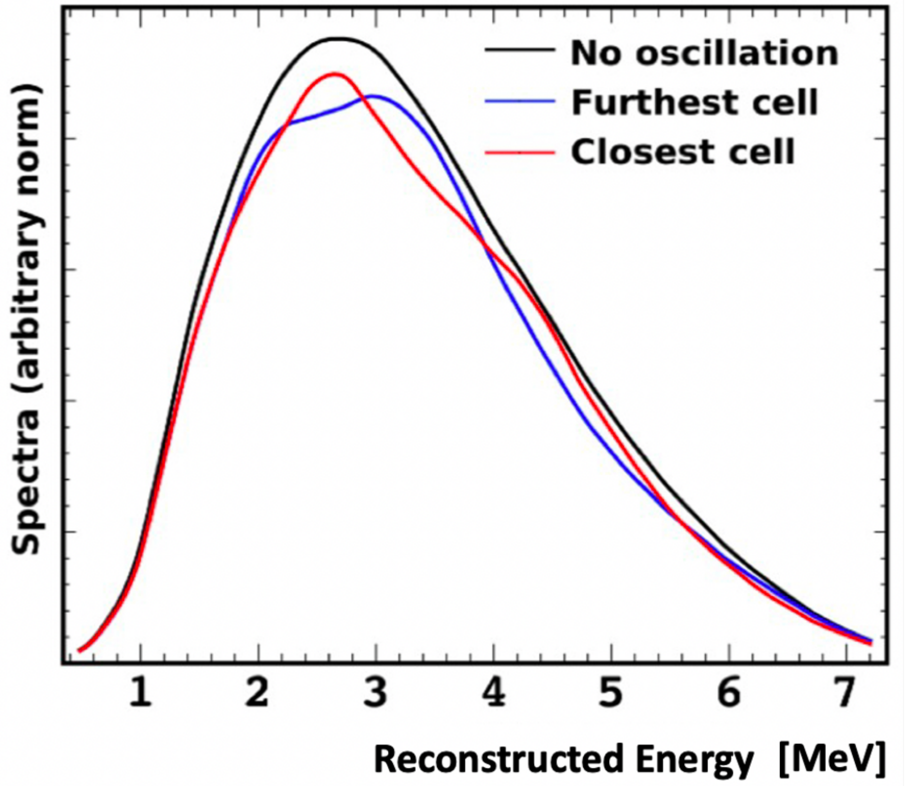
Systematics summary



b. Oscillation analysis systematics

Type	Source	Nuisance parameter	Uncertainty	Correlations: Energy	Correlations: Cell	Correlations: Phase
Energy scale	Energy reconstruction	$\alpha_l^{\mathrm{EscaleC}}$	1%	1	0	1
	Time stability	$\alpha^{\mathrm{EscaleU}}$	0.25%	1	1	0
Signal	Selection cuts	α^{Cuts}	0% to 2%	1	1	1
	Reactor background	$\alpha_l^{\mathrm{ReactorBg}}$	5% to 0%	1	0	1
Normalization	Relative cell volume	$\alpha_l^{\mathrm{NormU}}$	0.83%	1	0	1
	Neutron efficiency		0.63%	1	0	0.91
	Relative norm ph-2/ph-3	$\alpha^{\mathrm{II\ vs\ III\ norm}}$	1.5%	1	1	-

STEREO sterile neutrino search



$$\chi^2(\phi, \vec{\alpha}, \sin^2(2\theta_{ee}), \Delta m^2_{41}) =$$

$$\sum_{p}^{N_{phases}} \sum_{c}^{N_{cells}} \sum_{i}^{N_{Ebins}} \left(\frac{D_{p,c,i} - \phi_i M_{p,c,i}(\sin^2(2\theta_{ee}), \Delta m^2_{41}, \vec{\alpha})}{\sigma_{c,i}} \right)^2 + pull\ terms$$

Measured spectrum in each cell.

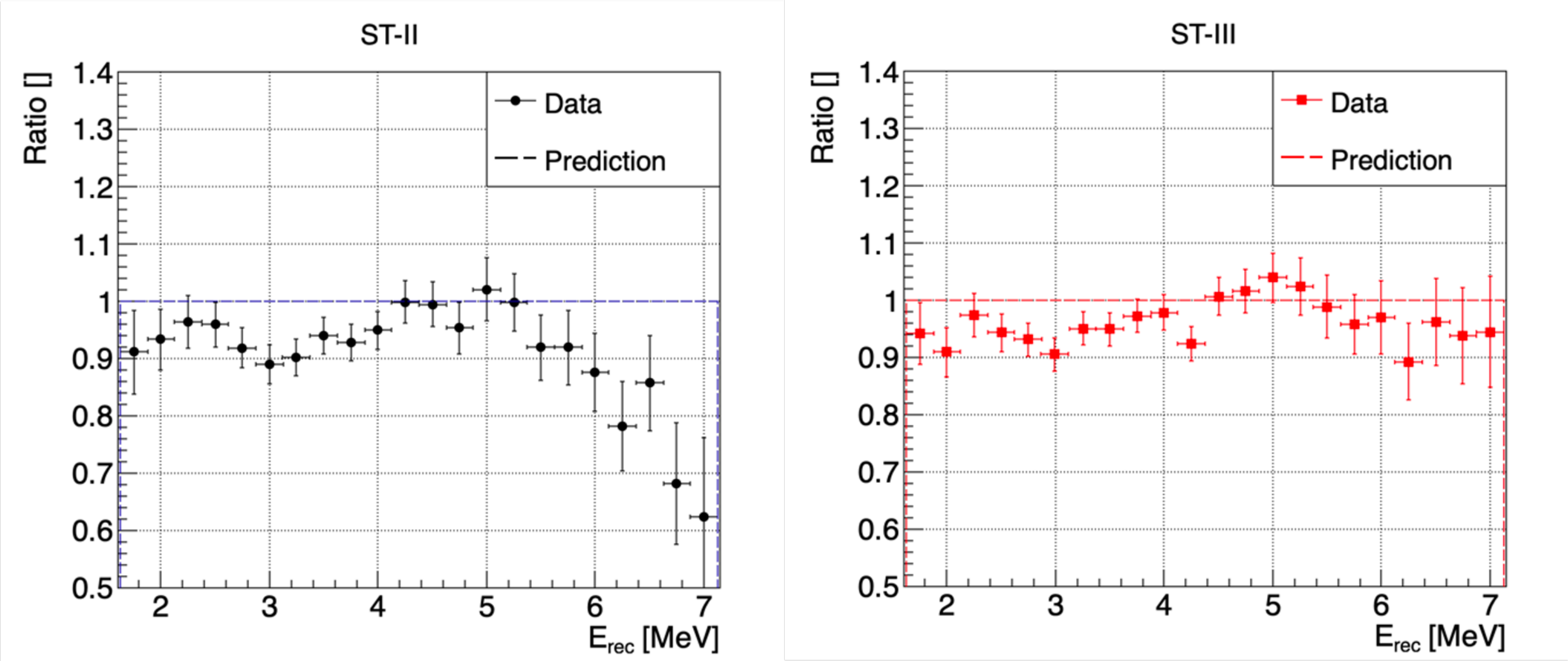
Non-oscillated model: free parameter of the fit

Simulated spectrum

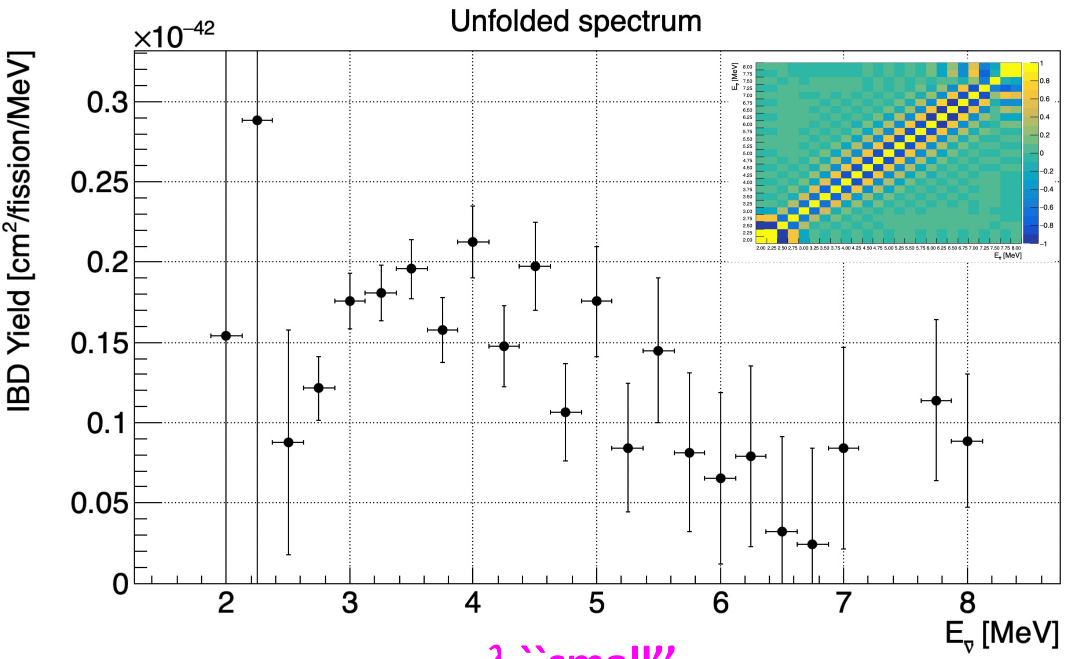
Nuisance parameters

Prediction-free analysis

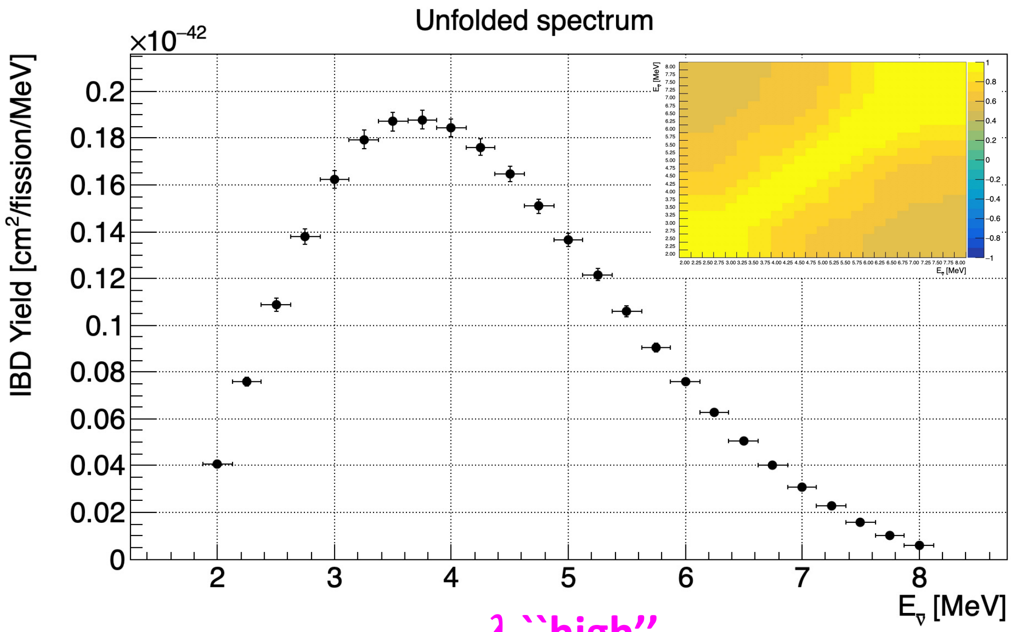
STEREO ^{235}U measured spectrum



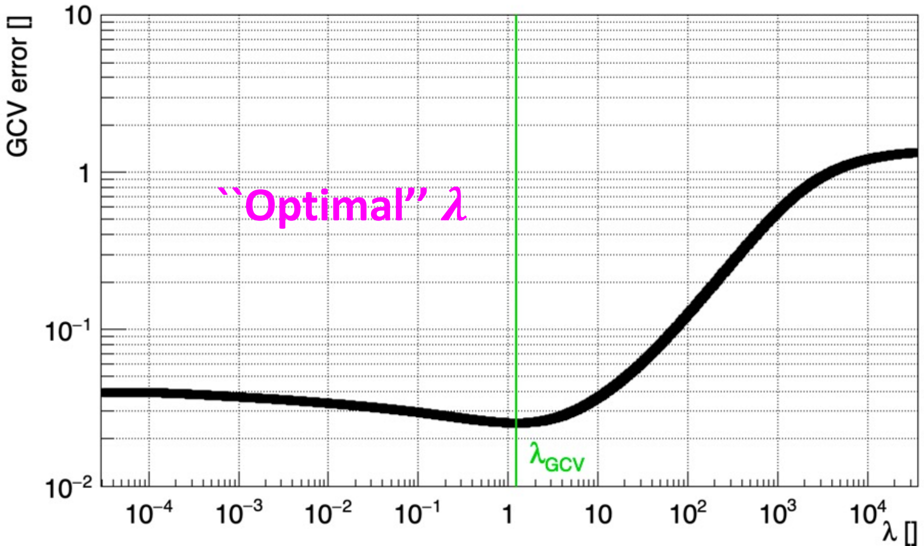
Impact of regularization



λ ``small''



λ ``high''



- **Minimization of the Generalized Cross-Validation (GCV) error.** *Technometrics Vol. 21 N°2, May 1979*

GCV criterion / Filter matrix

Solution of the Tikhonov unfolding

$$\hat{\Phi} = \left(R^T V^{-1} R + \lambda M\right)^{-1} R^T V^{-1} D$$
$$:= H(\lambda) D$$

$$H(\lambda) = \left(R^T V^{-1} R + \lambda M\right)^{-1} R^T V^{-1}$$

Filter matrix

$$H(\lambda) = \underbrace{\left(I_{N_\Phi} + \lambda \left(R^T V^{-1} R\right)^{-1} M\right)^{-1}}_{:=A_c(\lambda)} \cdot H(0)$$

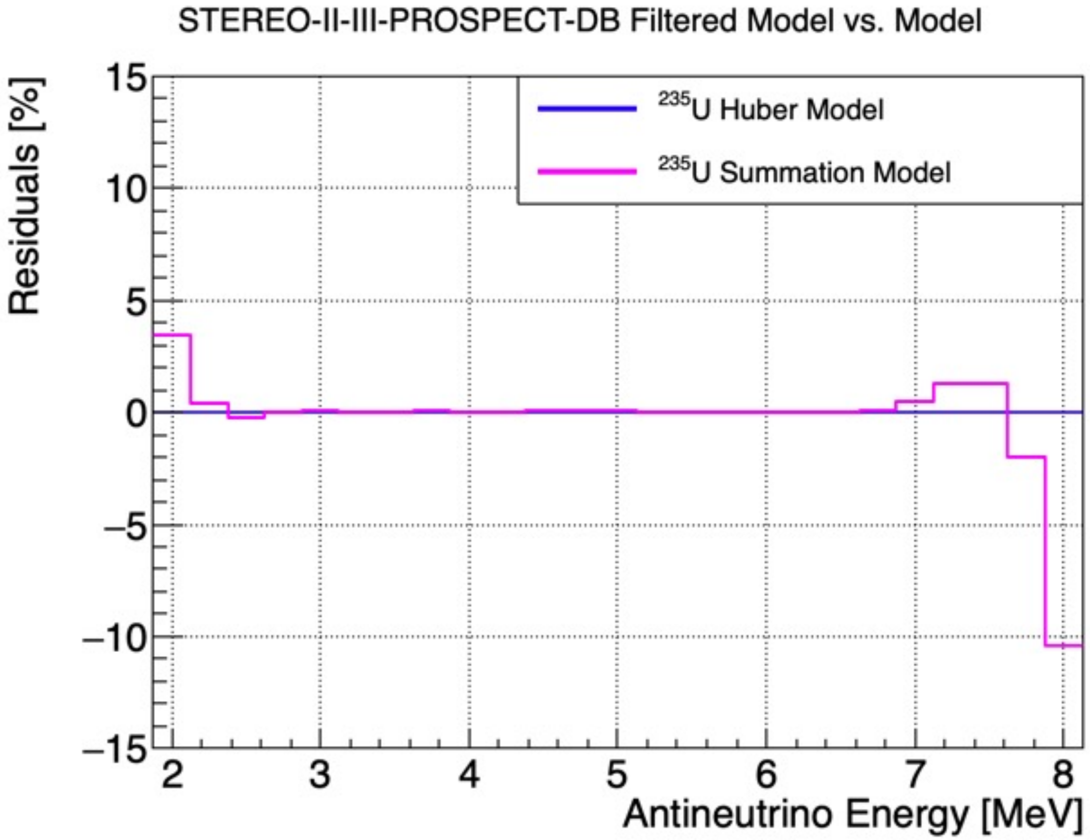
GCV criterion

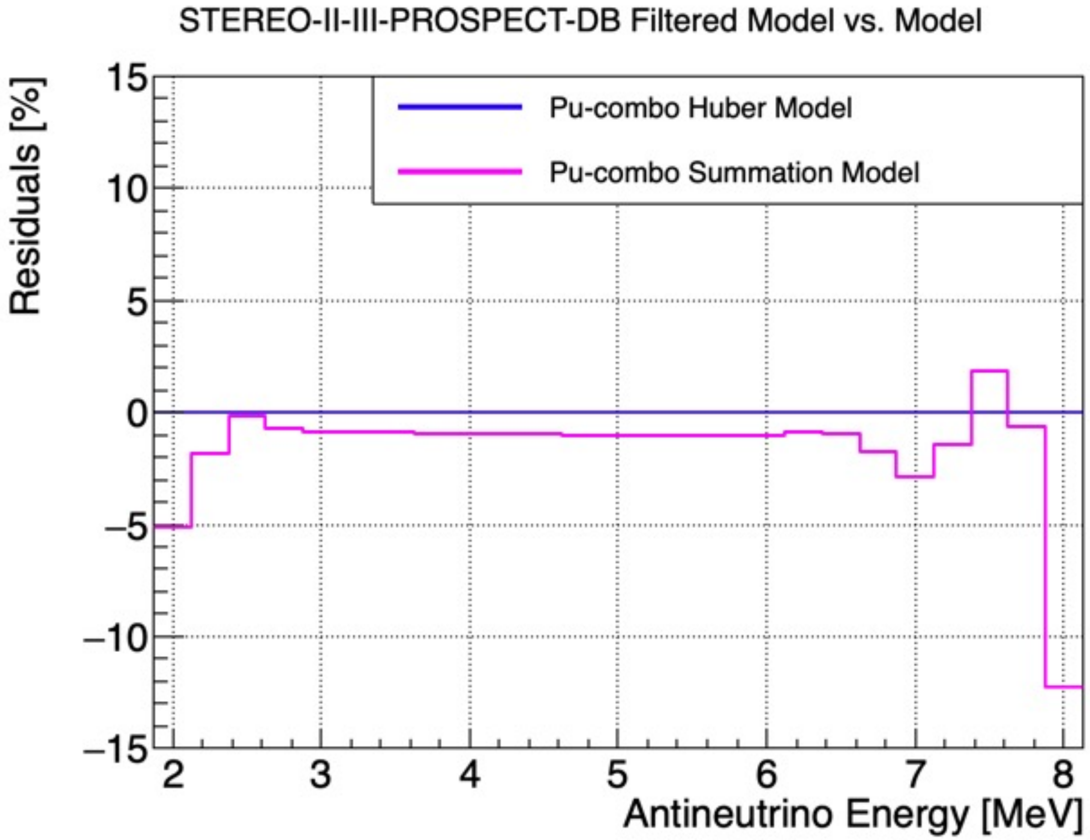
$$GCV(\lambda) = \frac{\left\| D - \hat{D} \right\|_{V^{-1}}^2}{\left(Tr\left[I - H_D(\lambda)\right]\right)^2}$$
$$= \frac{\left\| \left(I - H_D(\lambda)\right) D \right\|_{V^{-1}}^2}{\left(Tr\left[I - H_D(\lambda)\right]\right)^2}$$

« Effective number of degrees of freedom » $\in [N_D - N_\Phi, N_D]$

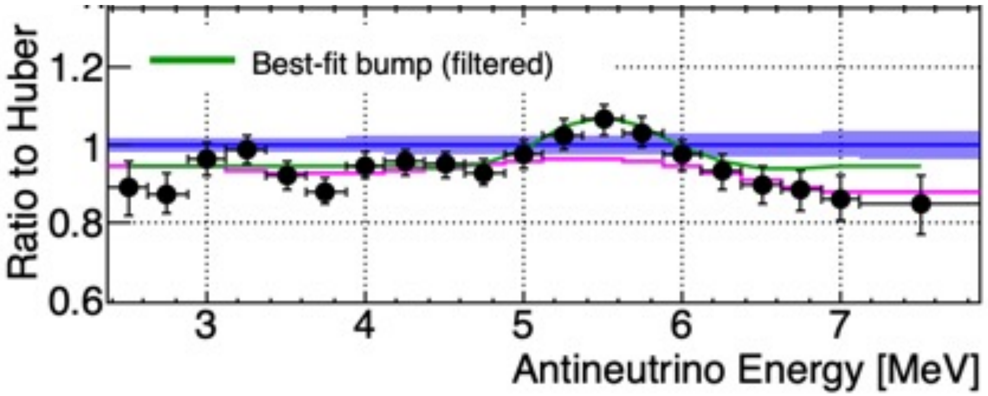
where $\hat{D} = R \cdot \hat{\Phi}$ and $H_D(\lambda) = R \cdot H(\lambda)$

Filtered Models vs Models





STEREO shape analysis



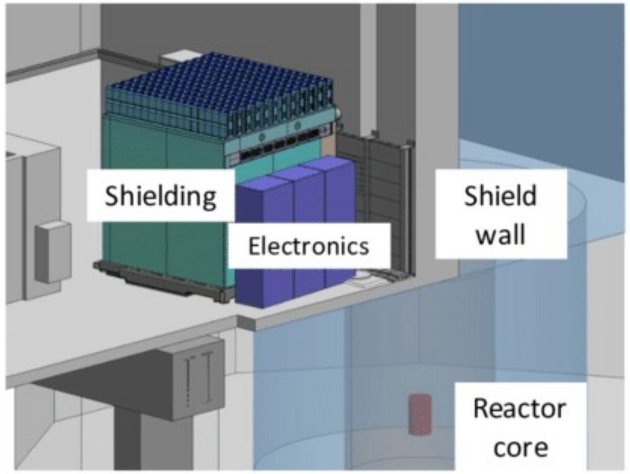
$$Pred(E) = HM(E) \cdot \alpha \left(1 + A \cdot \exp \frac{(E-\mu)^2}{2\sigma^2}\right)$$

ST-II-III Best-fit bump	Antineutrino Energy space		Reconstructed Energy space
	w/o. Filter $\chi^2 = (\Phi - Pred)^T V_\Phi^{-1} (\Phi - Pred)$	w. Filter $\chi^2 = (\Phi - A_c \cdot Pred)^T V_\Phi^{-1} (\Phi - A_c \cdot Pred)$	w. Response $\chi^2 = (D - R \cdot Pred)^T V^{-1} (D - R \cdot Pred)$
A [%]	14.4 ± 3.6	$\mathbf{15.6 \pm 5.2}$	15.5 ± 5.1
μ [MeV]	5.505 ± 0.089	$\mathbf{5.500 \pm 0.092}$	5.500 ± 0.092
σ [MeV]	0.339 ± 0.112	$\mathbf{0.308 \pm 0.143}$	0.311 ± 0.143
Significance	4.6σ	$\mathbf{4.6\sigma}$	4.6σ

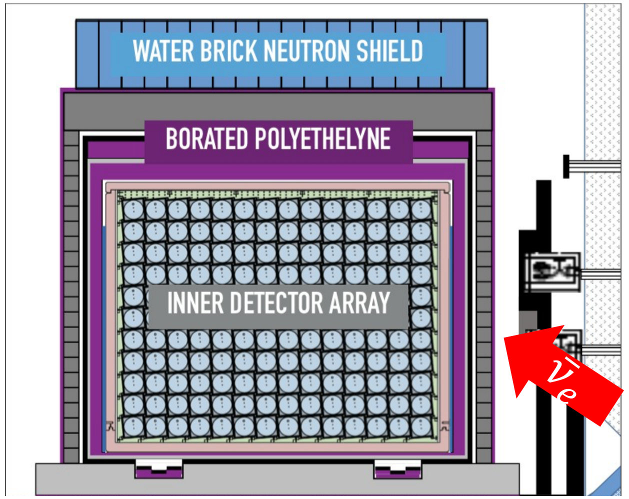
$$(\Phi, V_\Phi, A_c) \leftrightarrow (D, V, R)$$

HEU + LEU Global analysis

HEU experiment: PROSPECT



HFIR Experimental site (Oak Ridge, USA)



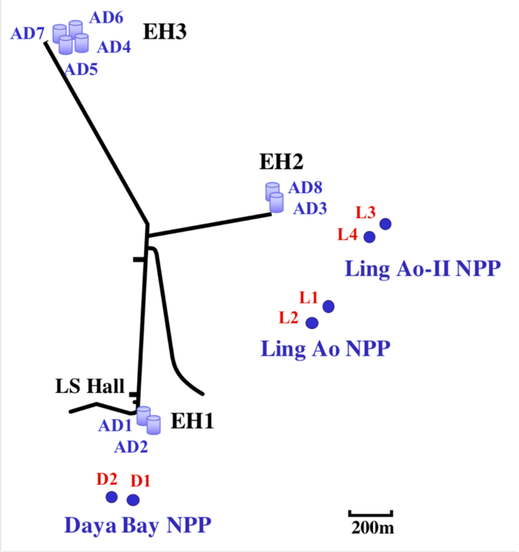
PROSPECT Detector

50k $\overline{\nu}_e$

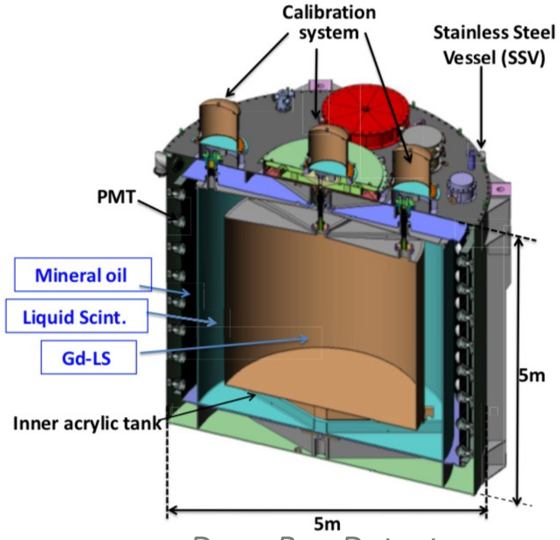
^{235}U

^{235}U
+
Pu
+
(^{238}U)

LEU experiment: Daya Bay



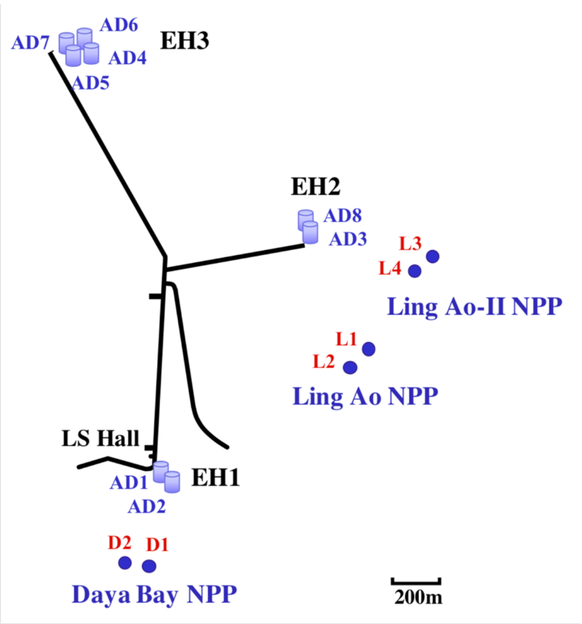
Day Bay nuclear power complex (Shenzhen, China)



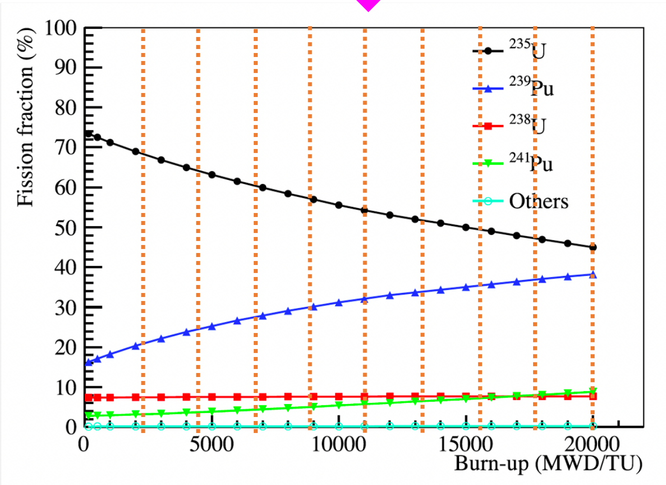
Daya Bay Detector

3500k $\overline{\nu}_e$

HEU + LEU Global analysis : Daya Bay experiment

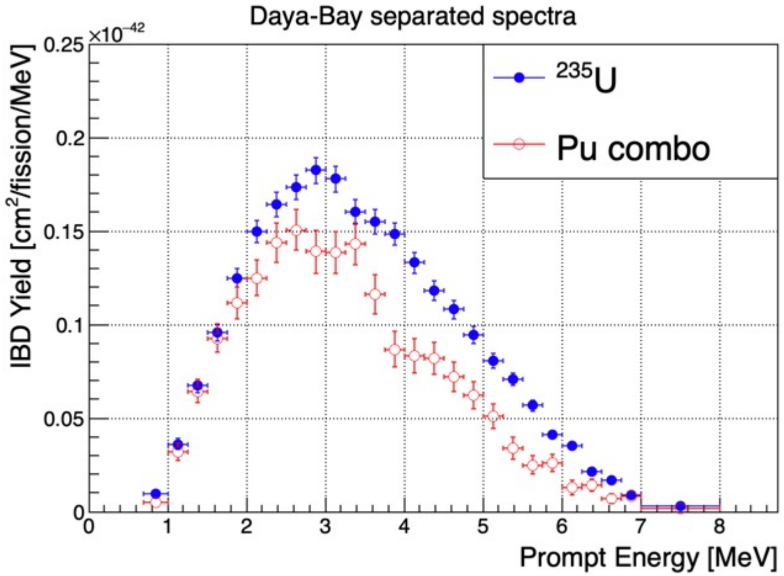


Reactor burn-up simulation



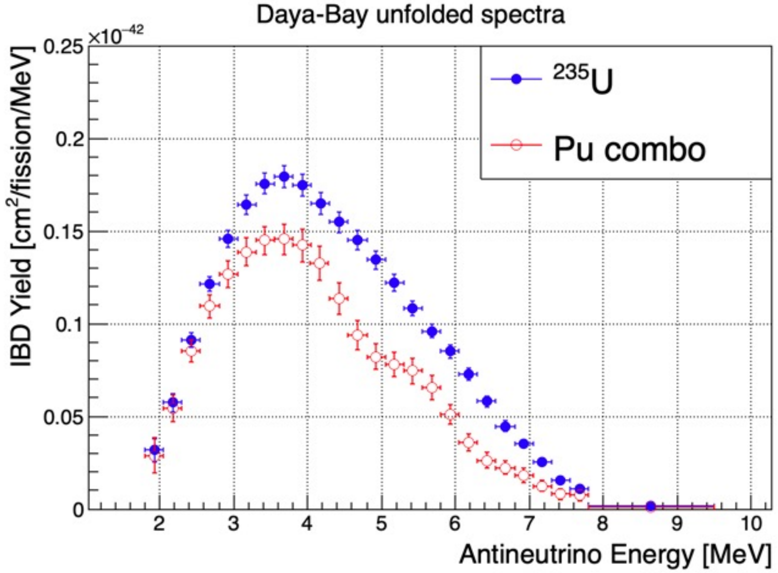
^{235}U/Pu combo separation

Pu combo
= ^{239}Pu + ^{241}Pu



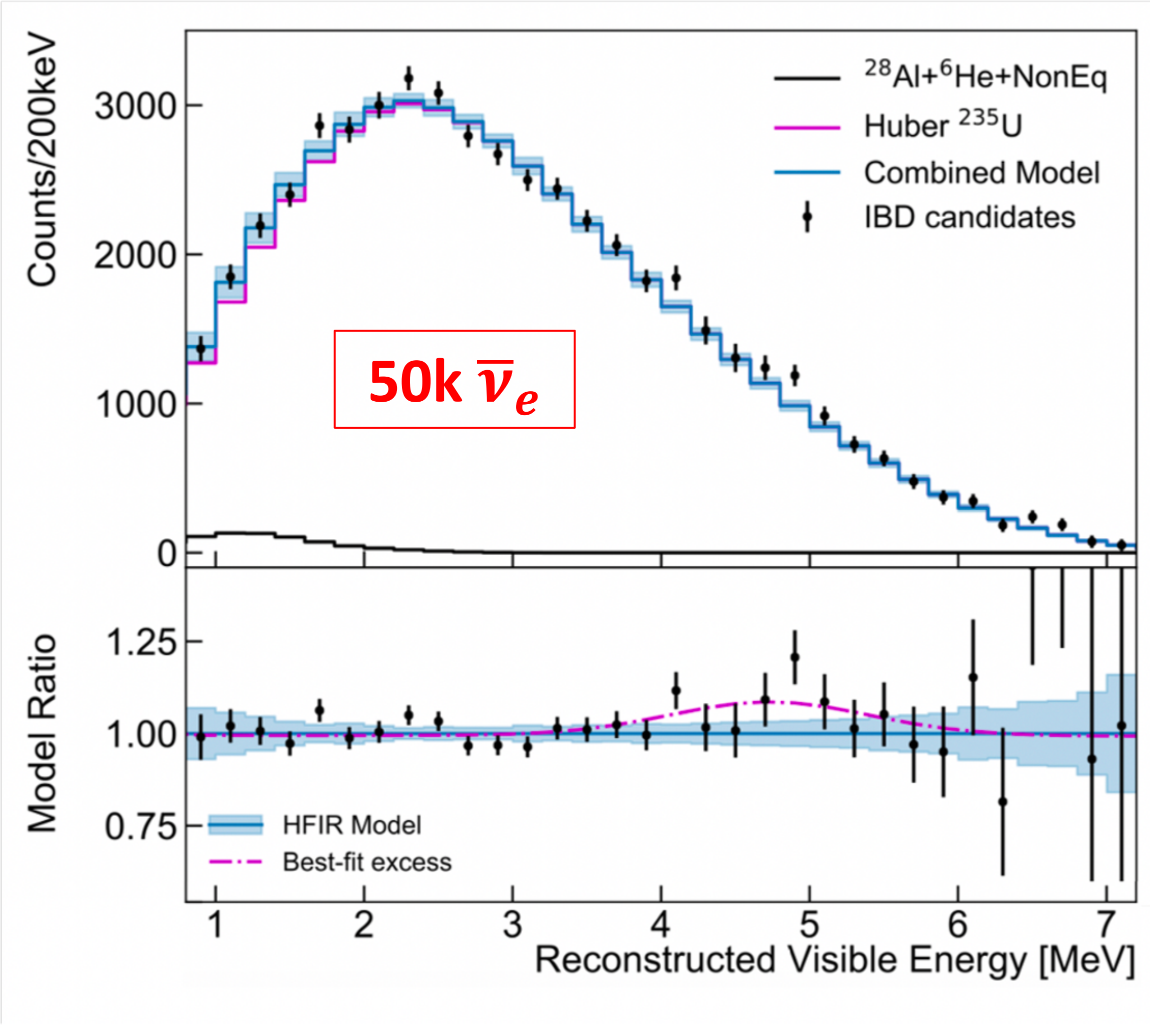
PRL 123, 111801 (2019)

Wiener-SVD unfolding



Chinese Phys. C 45 073001 (2020)

HEU + LEU Global analysis : PROSPECT spectrum



- ❑ Hints for local event excess around 5 MeV.
- ❑ No absolute normalization of PROSPECT spectrum.
  → Normalized to STEREO spectrum.
- ❑ Minimization of the χ^2:

$$\chi^2(\Phi) = \left|\left|D_{HEU} - R_{HEU} \cdot \Phi\right|\right|^2_{V^{-1}_{HEU}} + \boldsymbol{\lambda} * \left|\left|\Phi\right|\right|^2_{\boldsymbol{M_{HM}}}$$

where: $D_{HEU} = \begin{bmatrix} D_{ST-II+III} \\ D_{PR} \end{bmatrix}, R_{HEU} = \begin{bmatrix} R_{ST-II+III} \\ R_{PR} \end{bmatrix}$

➢ **Update of the joint STEREO-PROSPECT analysis** of *PRL 128, 081802 (2022)* with the full STEREO dataset.

$$||X||_M^2 := X^T M X$$

HEU + LEU Global analysis

- Minimize analytically:

$$\chi^2(\Phi^{U5}, \Phi^{Pu}) =$$

$$\left|\left|D_{HEU} - R_{HEU} \cdot \Phi^{U5}\right|\right|^2_{V_{HEU}^{-1}}$$ **HEU Data**

$$+ \left|\left|D_{DB} - R_{DB} \cdot \left(< f_{235} > \Phi^{U5} + (< f_{239} > + < f_{241} >)\Phi^{Pu} + < f_{238} > \Phi^{\mathrm{U8}}_{\mathrm{HM}}\right)\right|\right|^2_{V_{DB}^{-1}}$$ **LEU Data**

$$+ \lambda^{U5} \cdot \left|\left|\Phi^{U5}\right|\right|^2_{M_{HM}^{U5}}$$

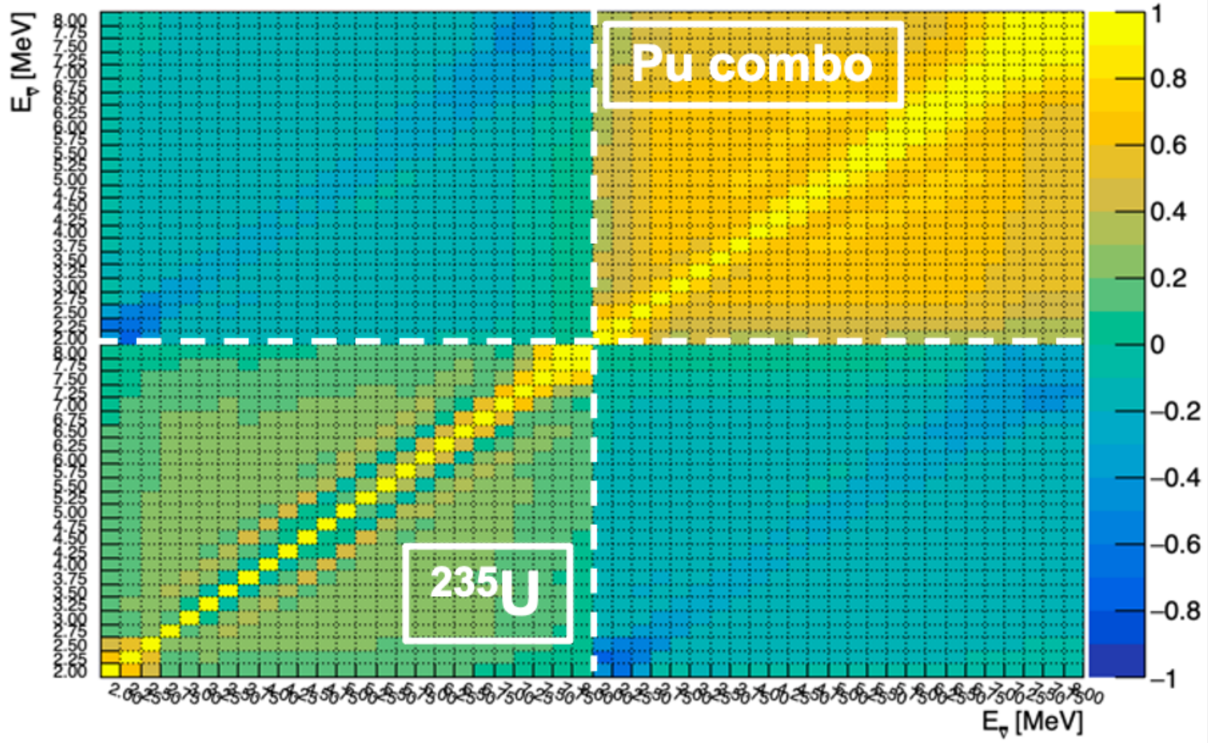
$$+ \lambda^{Pu} \cdot \left|\left|\Phi^{Pu}\right|\right|^2_{M_{HM}^{Pu}}$$ **Regularization**

λ^{U5} tuned with GCV criterion.

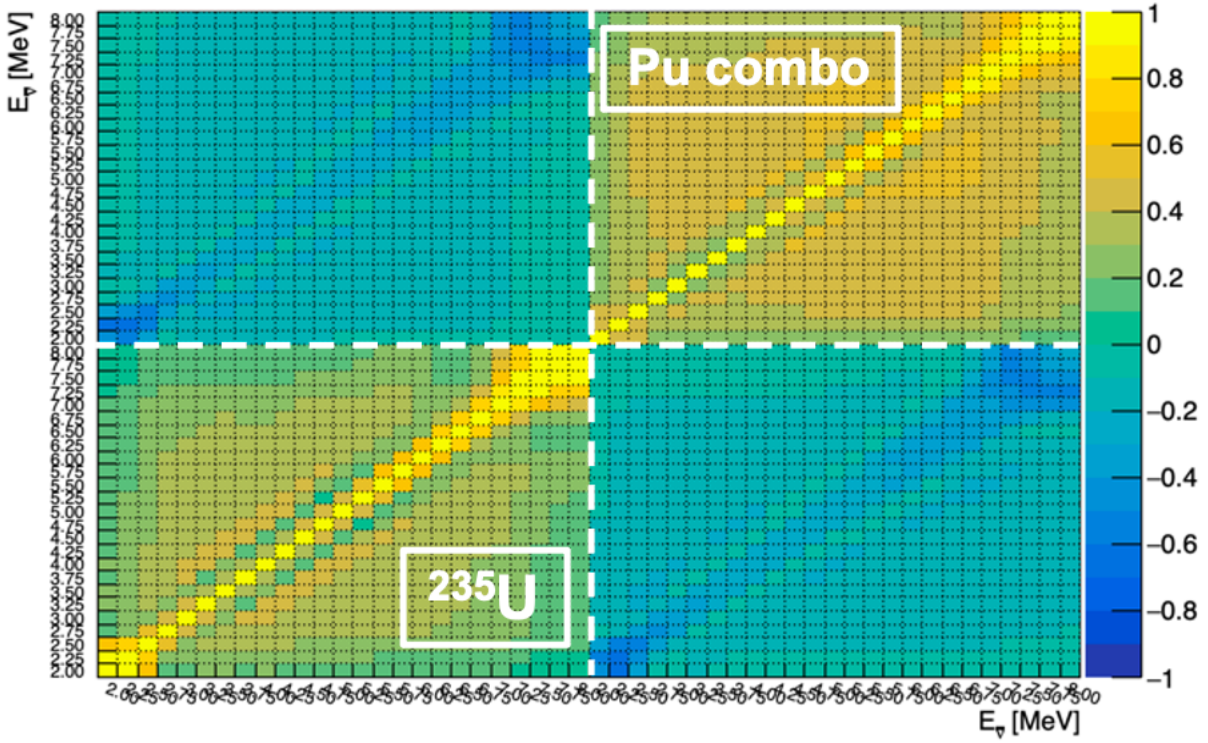
Heuristic criterion to set Pu regularization strength, beyond the standard GCV criterion

$$\frac{\lambda^{Pu}}{\lambda^{U5}} = \frac{\mathrm{Trace}\left(M_{HM}^{U5}\right) \cdot \mathrm{Trace}\left((< f_{239} > + < f_{241} >)^2 \cdot R_{DB}^T V_{DB}^{-1} R_{DB}\right)}{\mathrm{Trace}(M_{HM}^{Pu}) \cdot \mathrm{Trace}(R_{ST}^T V_{ST}^{-1} R_{ST} + R_{PR}^T V_{PR}^{-1} R_{PR} + < f_{235} >^2 \cdot R_{DB}^T V_{DB}^{-1} R_{DB})} \sim \mathbf{0.1}$$

Regularization power in HEU+LEU unfolding

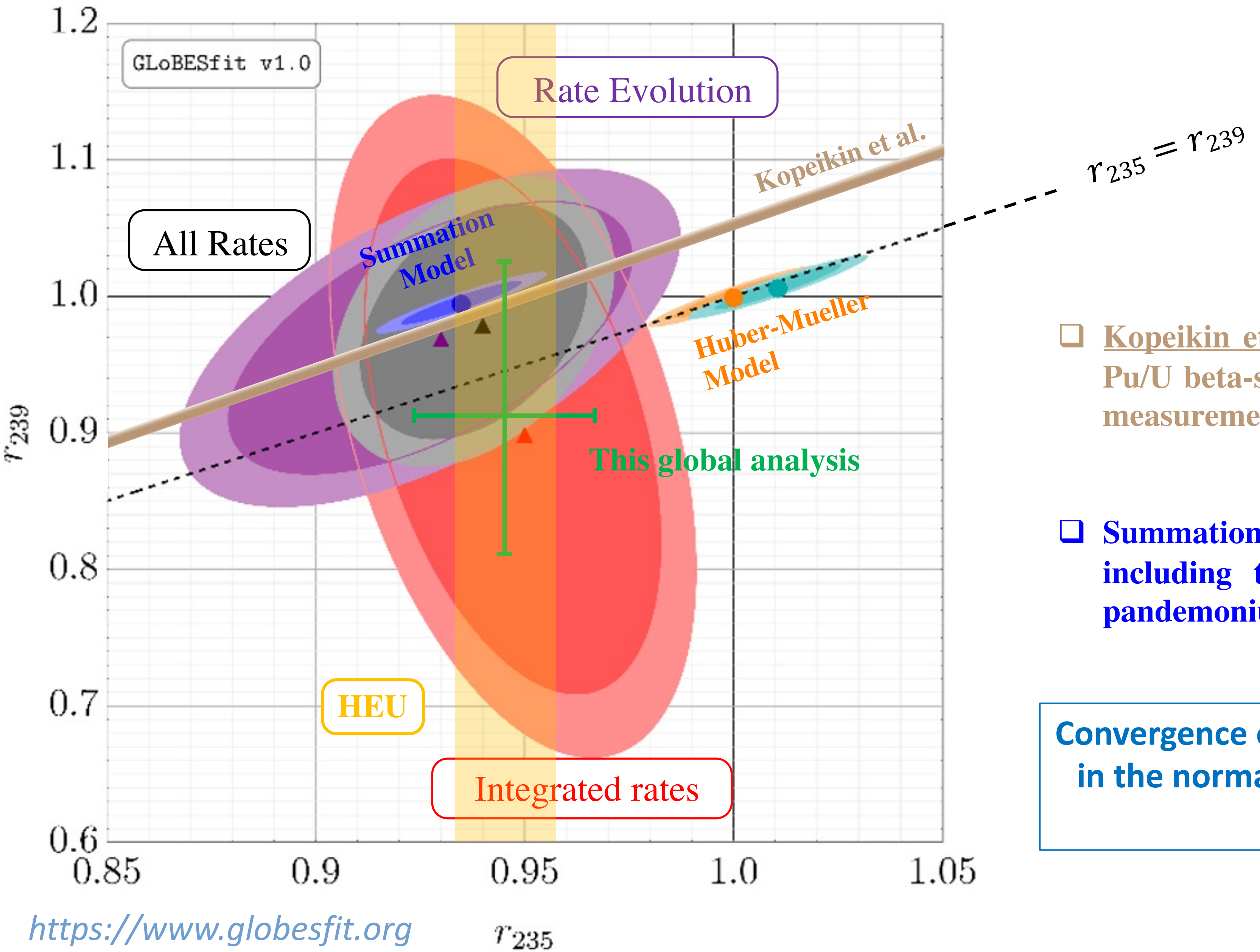


Same regu. strengths but different regu. powers



Different regu. strengths but same regu. powers

HEU + LEU Global rate analysis (HEU = ST)



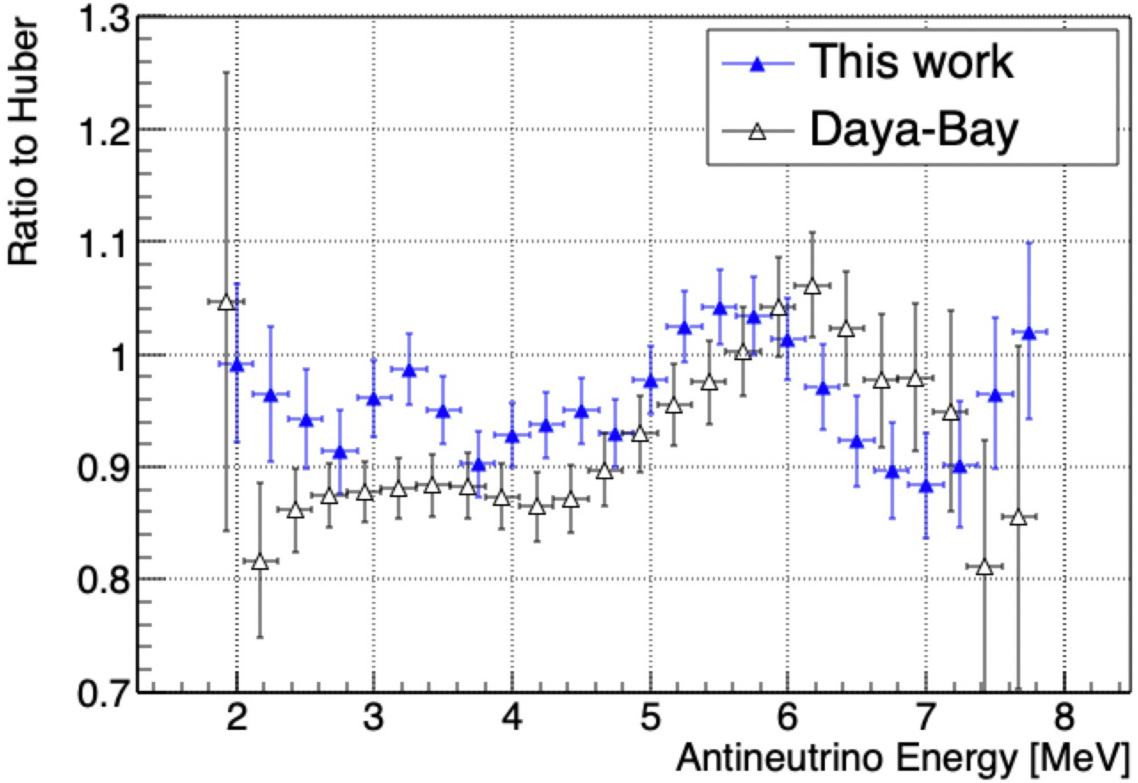
https://www.globesfit.org

- <u>Kopeikin et al.</u> : new measurement of the ratio of Pu/U beta-spectra → 5% deviation w.r.t. the initial measurement at ILL.
- **Summation Model (Estienne et al.): calculations including the latest TAGS data, correcting the pandemonium effect for relevant nuclei**

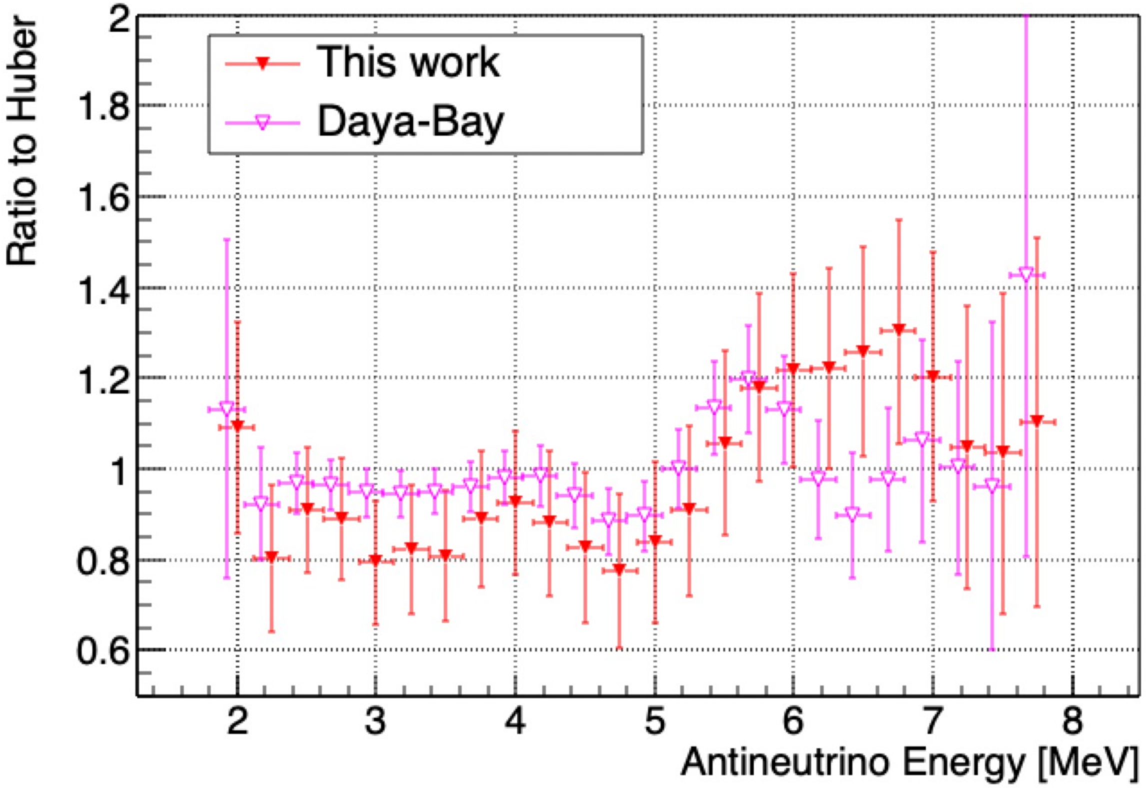
Convergence of experimental hints pointing to a bias in the normalization of predicted ^{235}U as the main explanation of the RAA.

This work vs. Daya Bay analysis

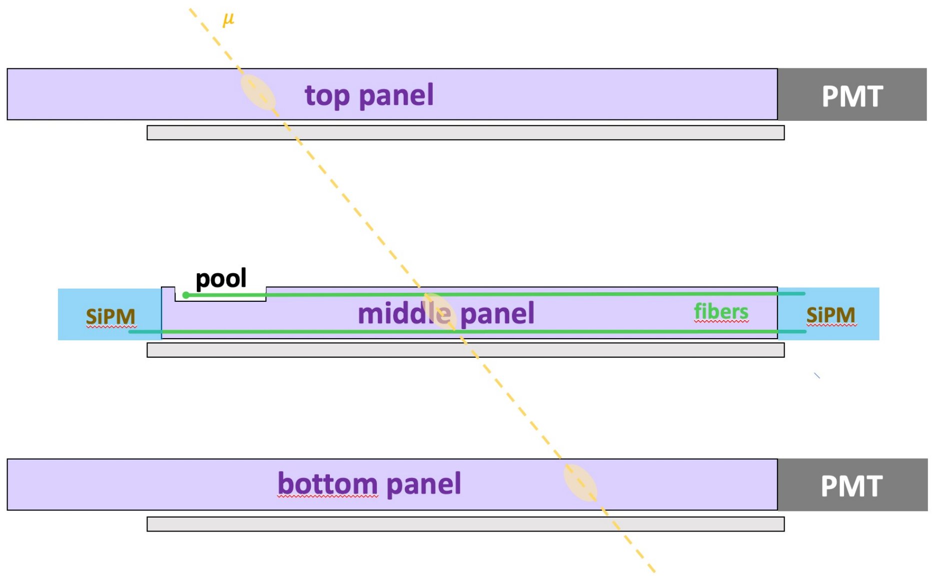
^{235}U comparison

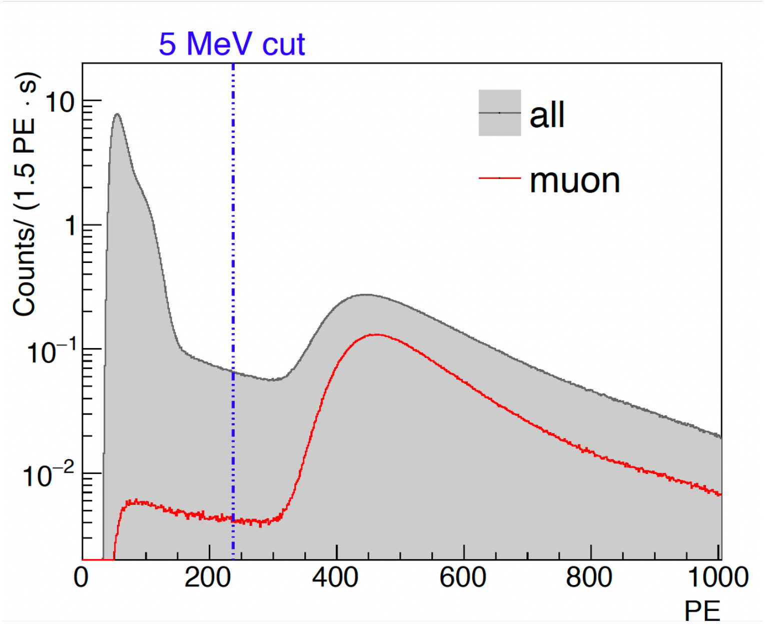


Pu comparison



Identification and Separation power



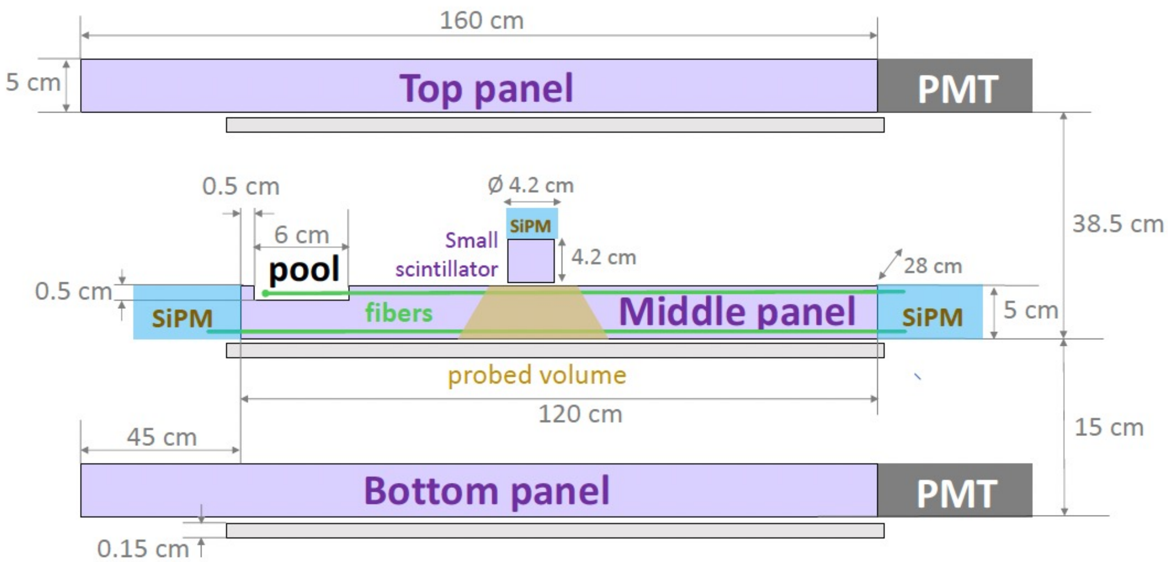


- ❑ Satisfactory gamma/muon separation.
  - ➢ Large plateau to set the detection threhold
  - ➢ **Key point to ensure a moderate dead-time**

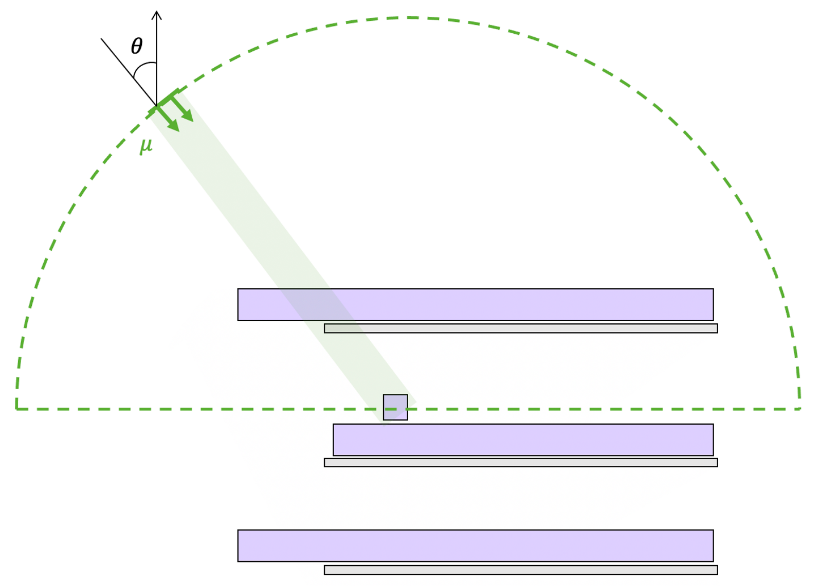
- ❑ Muon identification power of one panel $\sim 97\%$.

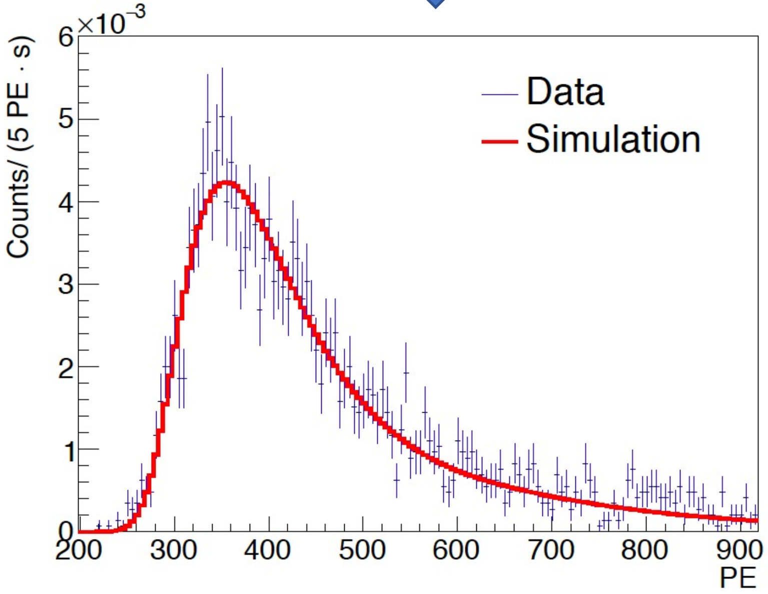
Response homogeneity

- Mounting of the test stand, to select local muon events in the prototype panel.



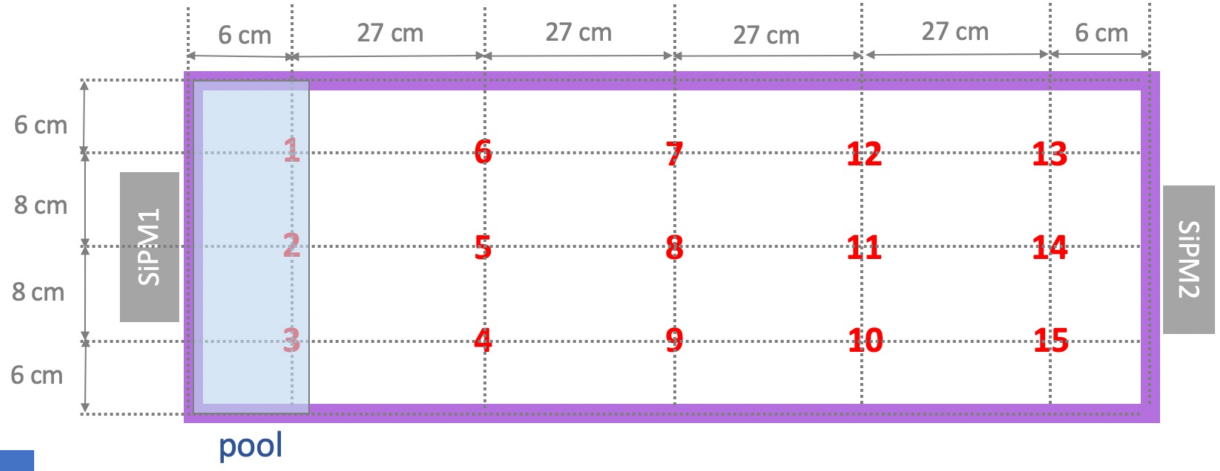
- GEANT4 simulation of the test bench, coupled to a simple poissonian response model, to compare the simulation and the data.



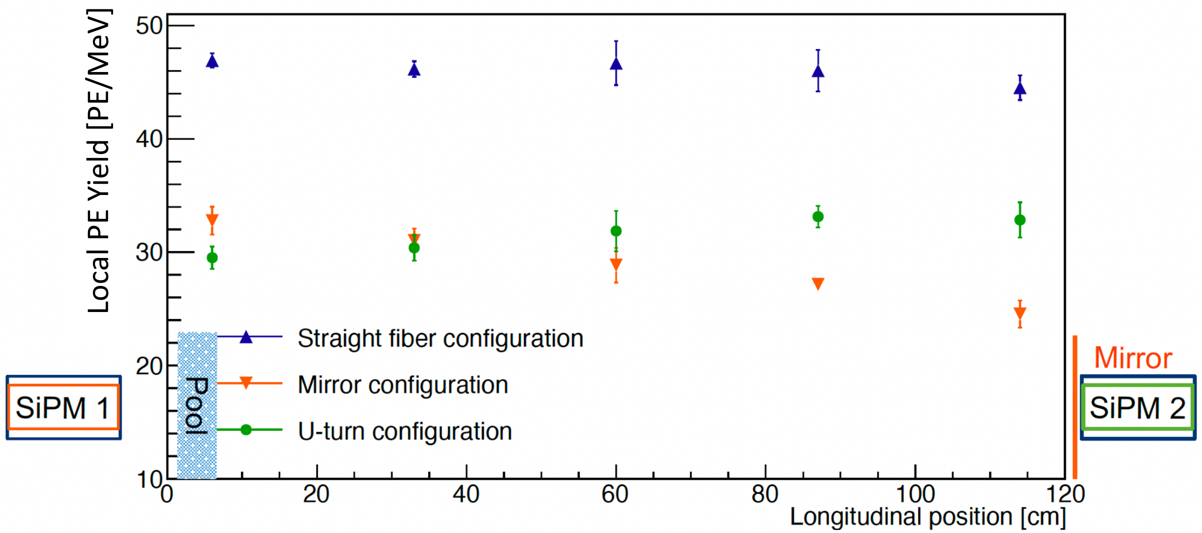


Response homogeneity

Quantification of the response homogeneity, for each optical fiber configuration.



Fiber Configuration	PE Yield [PE/MeV]	Inhomogeneities
Straight (double-sided)	~ 47	~ 2%
U-turn (one-sided)	~ 32	~ 11%
Straight + mirrors (one-sided)	~ 30	~ 30%



Double-sided and U-turn configurations meet the specifications.