WONDRAM 2021

STATE OF THE ART

EXPERIMENTAL PROBES OF REACTOR FLUX AND SPECTRA

T.J. Langford
Yale University

Wright Laboratory Yale

DIVERSE SUITE OF CURRENT ANTINEUTRINO EXPERIMENTS

θ_{13}

Daya Bay, Double Chooz, RENO

Multiple large-volume detectors

significant overburden

LEU Power Reactors

vSBL

DANSS, PROSPECT, STEREO, SoLiD

Compact, segmented detectors

surface-deployment

HEU Research Reactors

REACTOR MONITORING

miniChandler, ISMRAN, Panda

varied overburden

~25m baselines

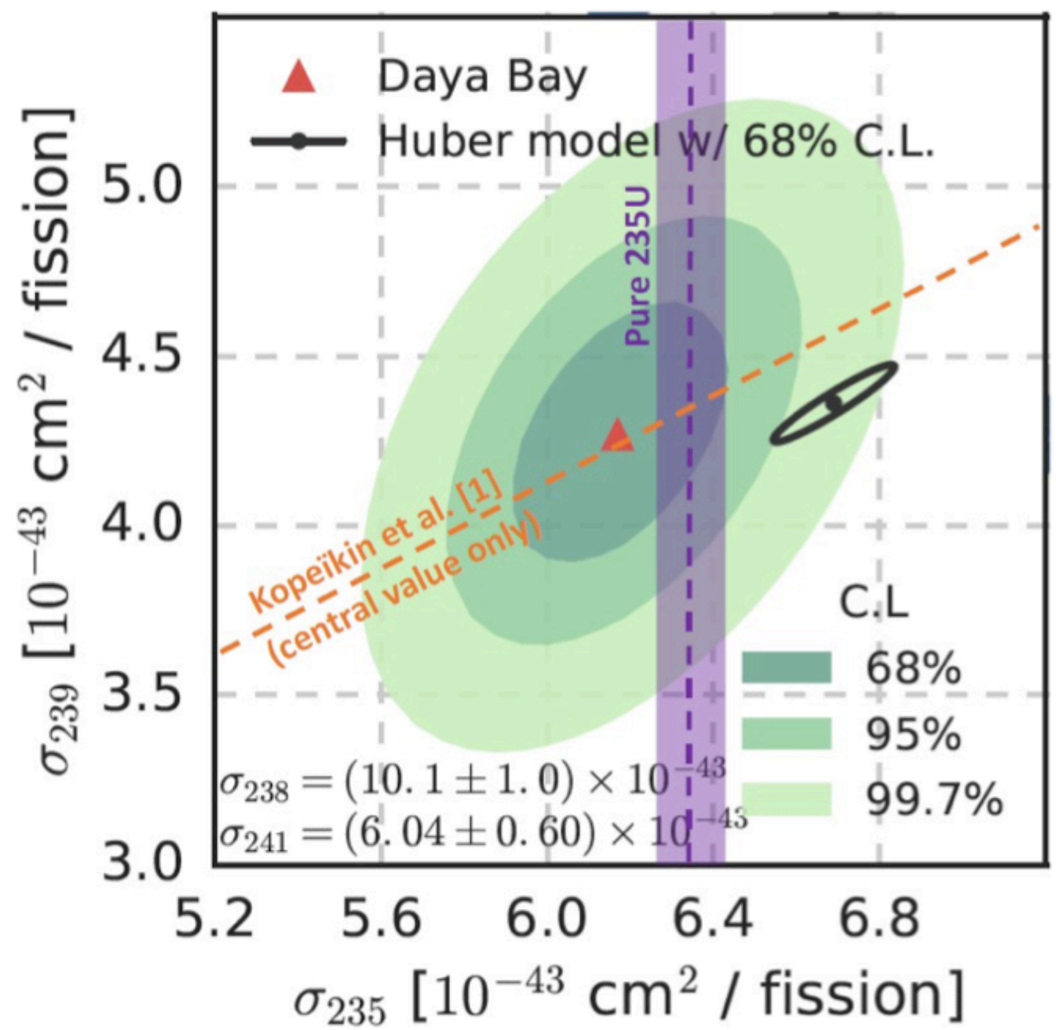
LEU Power Reactors

Only a selection of experiments…

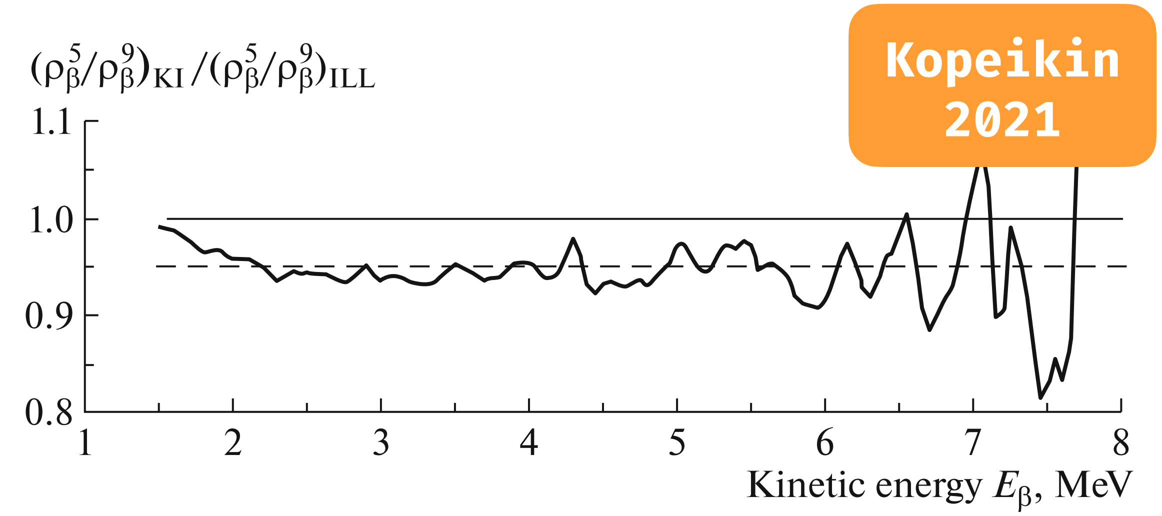
ISOTOPIC ANTINEUTRINO YIELD IN 2021

- **LEU:** time evolution extracts yield from ^{235}U and ^{239}Pu
- **HEU:** measure ^{235}U directly, but lower power and higher backgrounds
- **2021 Status:** evidence points to a deficit in ^{235}U, good agreement between ^{239}Pu data and prediction
- Recent beta-decay measurements from *Kopeikin et al.* consistent with a problem in ^{235}U not ^{239}Pu

U/Pu cross sections per fission ↓



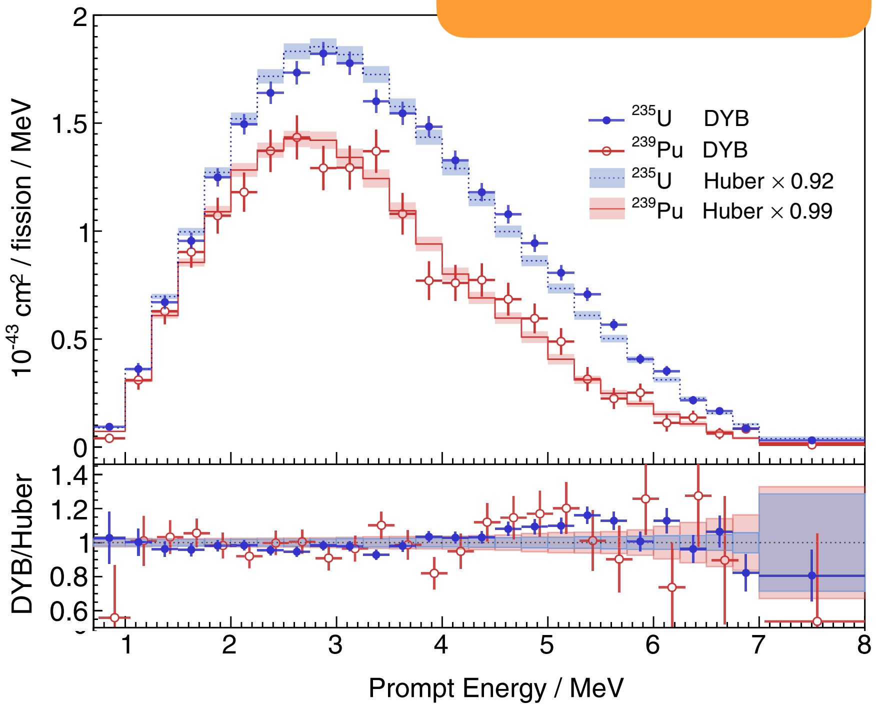
(from M. Licciardi's talk at Moriond 2021)



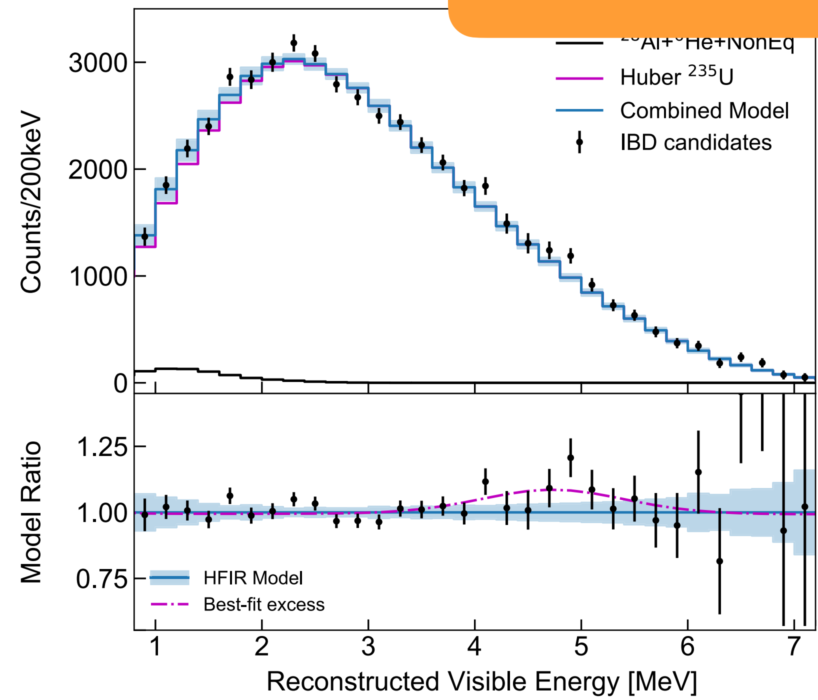
Kopeikin 2021

ISOTOPIC ANTINEUTRINO SPECTRUM SHAPE IN 2021

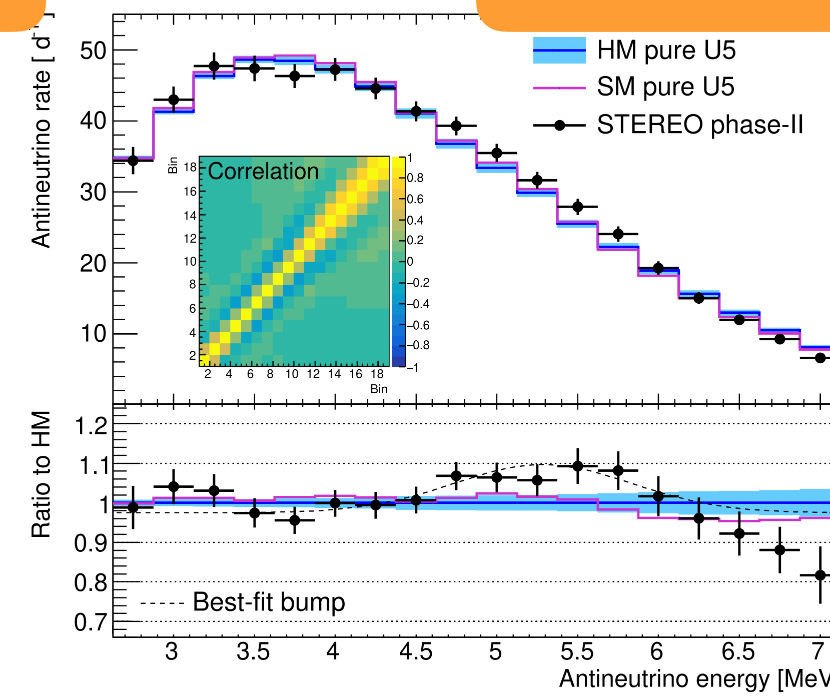
Daya Bay 2019
^{235}U and ^{239}Pu



PROSPECT 2021
^{235}U from HEU



STEREO 2021
^{235}U from HEU

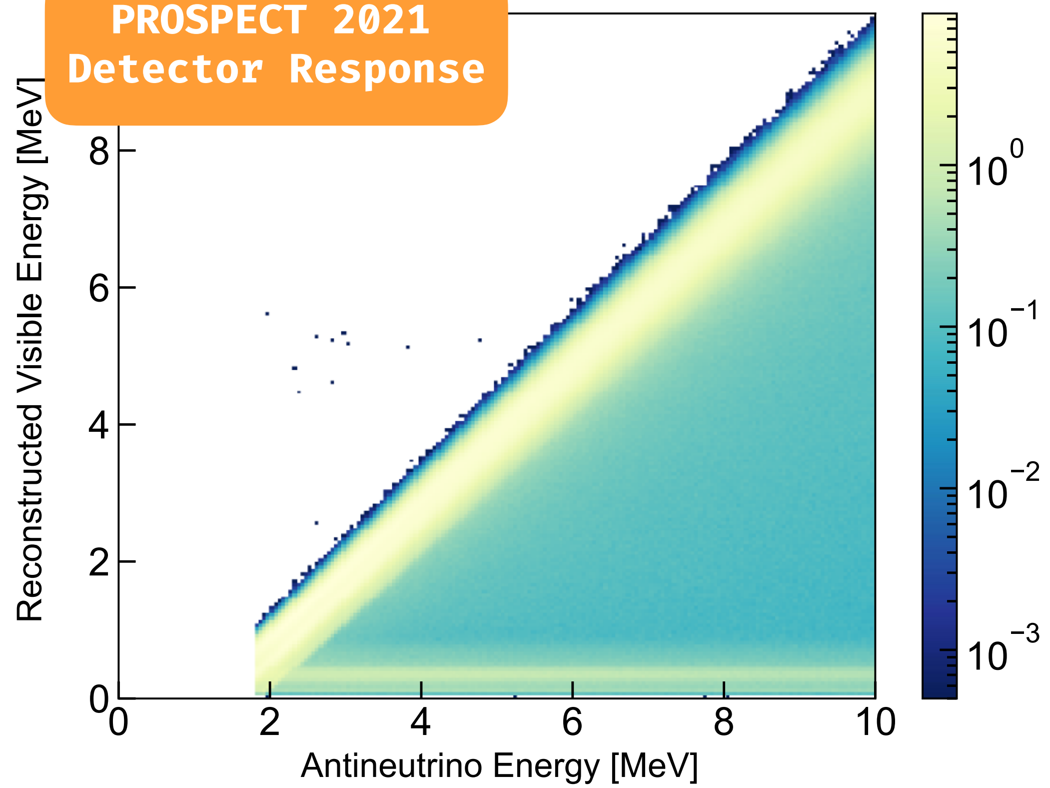


- **LEU:** time evolution extracts ^{235}U and ^{239}Pu, complications from ^{238}U/^{241}Pu
- **HEU:** measure ^{235}U directly, high backgrounds and complicated detector response
- *New results remove detector response via unfolding (Prompt => Antineutrino)*
- **2021 Status:** evidence points to disagreements in spectral shape in both ^{235}U and ^{239}Pu when compared to either beta-conversion or summation

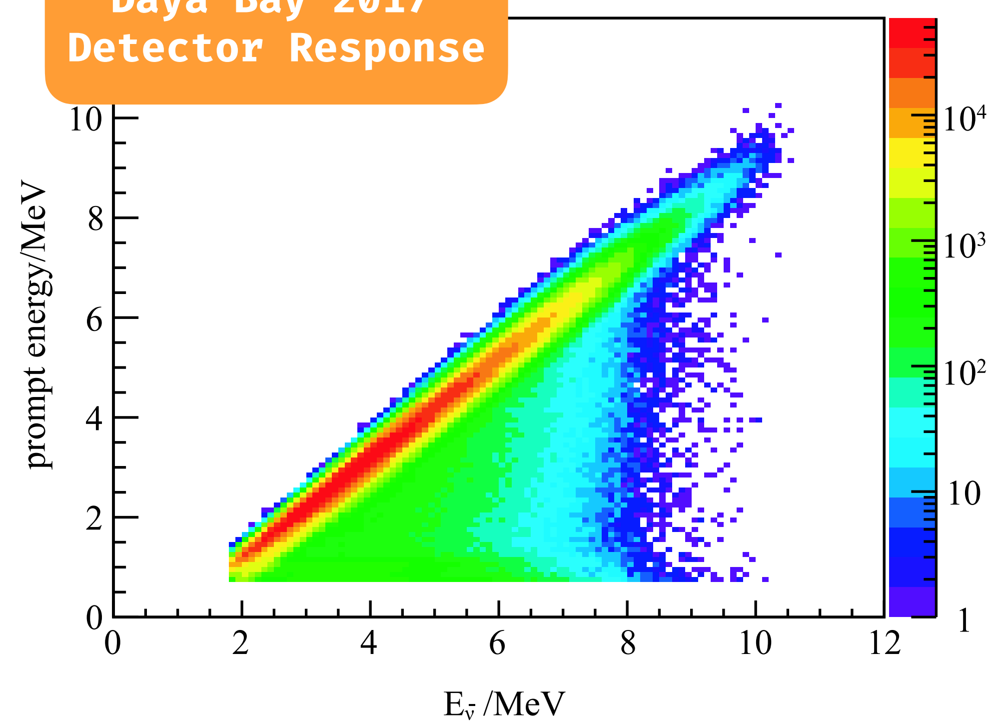
EXPERIMENTAL UNCERTAINTIES AND "UNIVERSAL" RESULTS

- Experimental uncertainties are complicated and often only fully understood by the collaboration
- **Detector:**
  - escaping energy, nonlinearity, calibration, resolution, thresholds, …
- **Experimental:**
  - exposure, reactor power/fuel, distance, …
- **Analysis:**
  - statistics, modeling, assumptions, …
- *More than can fit in a letter-length publication*
- **Final results should be as free from these experiment-specific things as possible**
- Shift from reporting experiment-specific to universal quantities:
  - **Prompt Energy => Antineutrino Energy**
  - **Detected Rate => Isotopic Neutrino Yield**

PROSPECT 2021 Detector Response

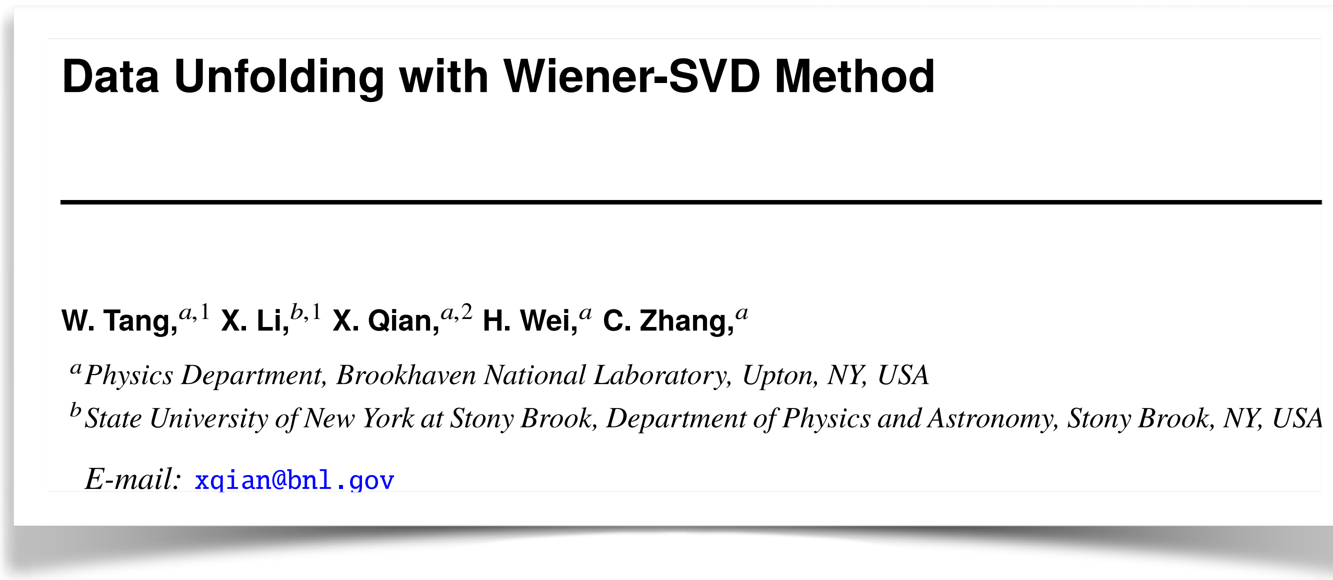


Daya Bay 2017 Detector Response



UNFOLDING REACTOR NEUTRINO SPECTRA

- Standard approach: compare theoretical models to data in the "experimental" space
    - Adjust model to account for detector effects
    - Perform any high-level analyses in "Prompt" or "Visible" energy space
- Since each experiment is unique, these spaces don't line up, and often have different treatments of detector effects
    - *Can't directly compare measurements*
- To remove these detector effects the response matrix needs to be inverted (which it can't be)
- Apply regularization while inverting balancing noise and bias, produce a true energy spectrum
    - *Comparisons between measurements and theory happen in the "true" neutrino space*


Data Unfolding with Wiener-SVD Method

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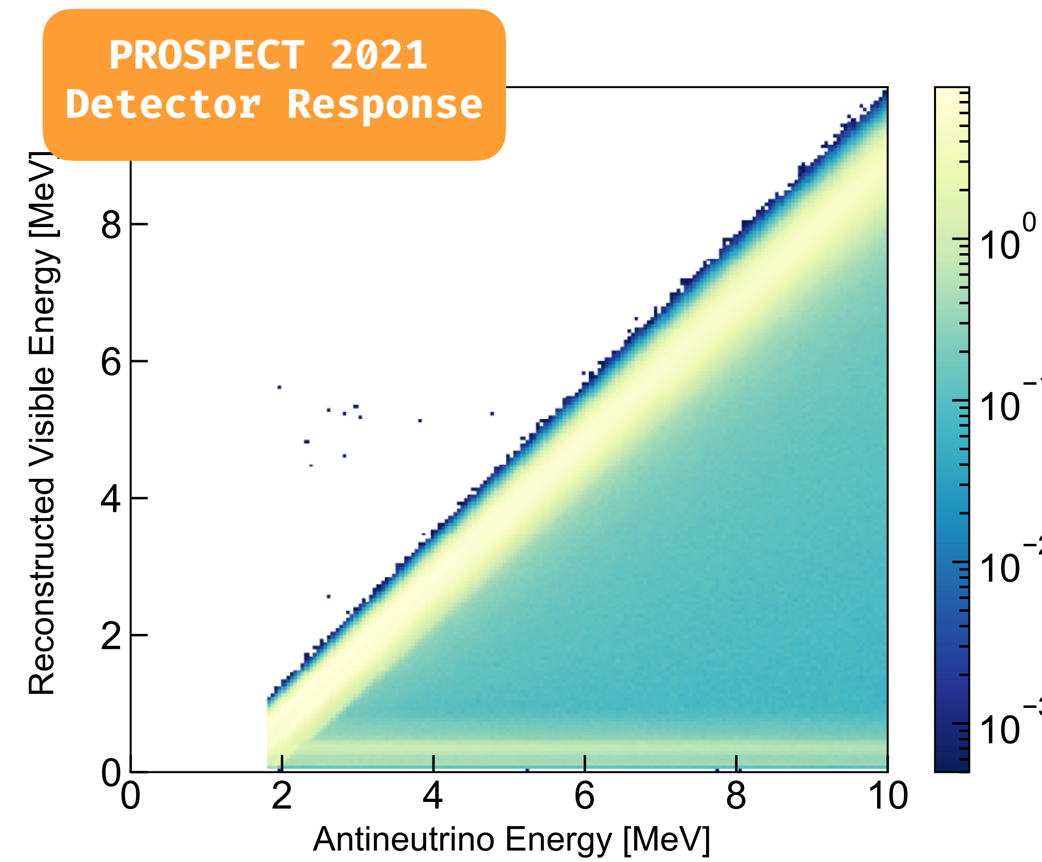
[b] *State University of New York at Stony Brook, Department of Physics and Astronomy, Stony Brook, NY, USA*

E-mail: xqian@bnl.gov



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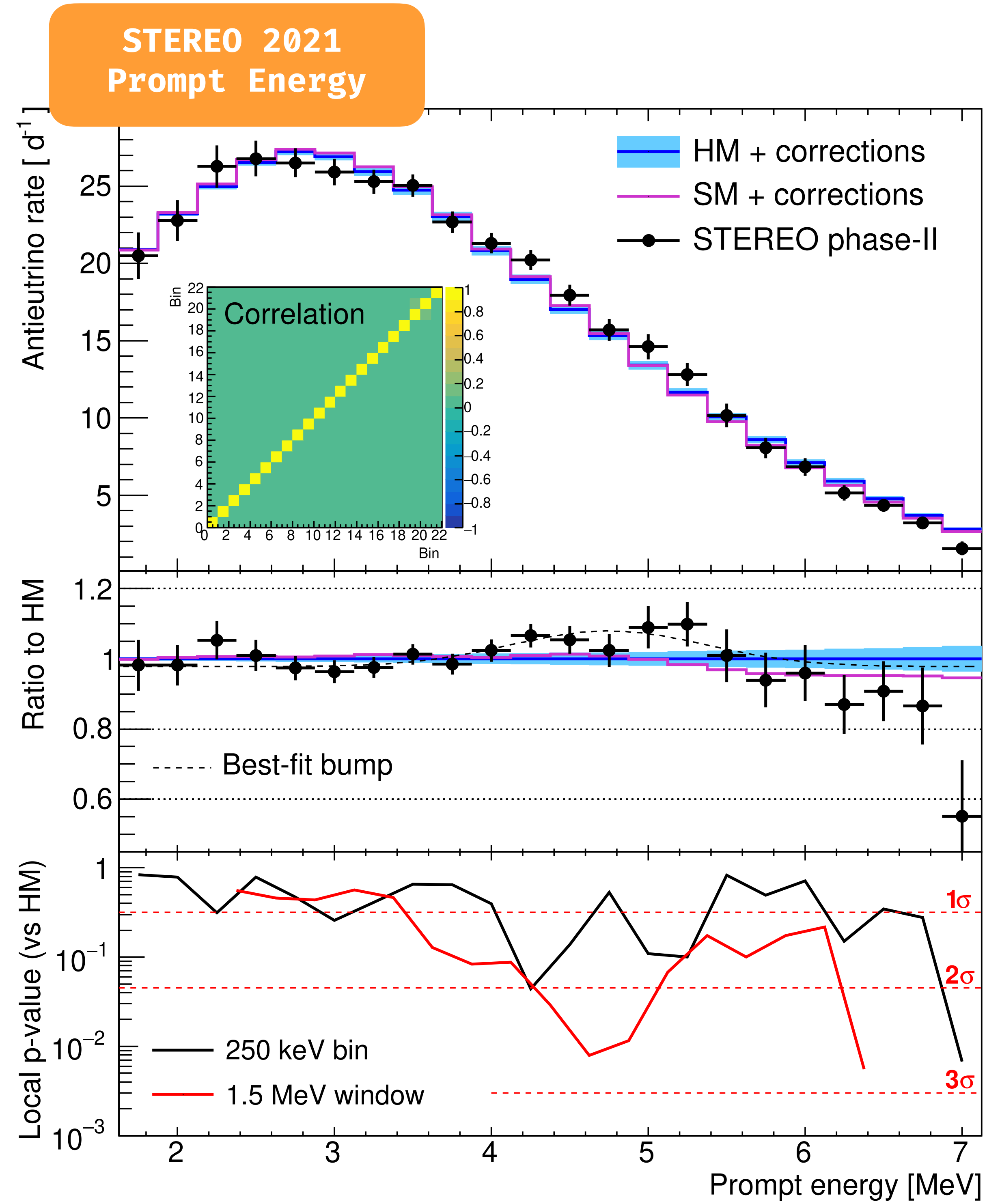

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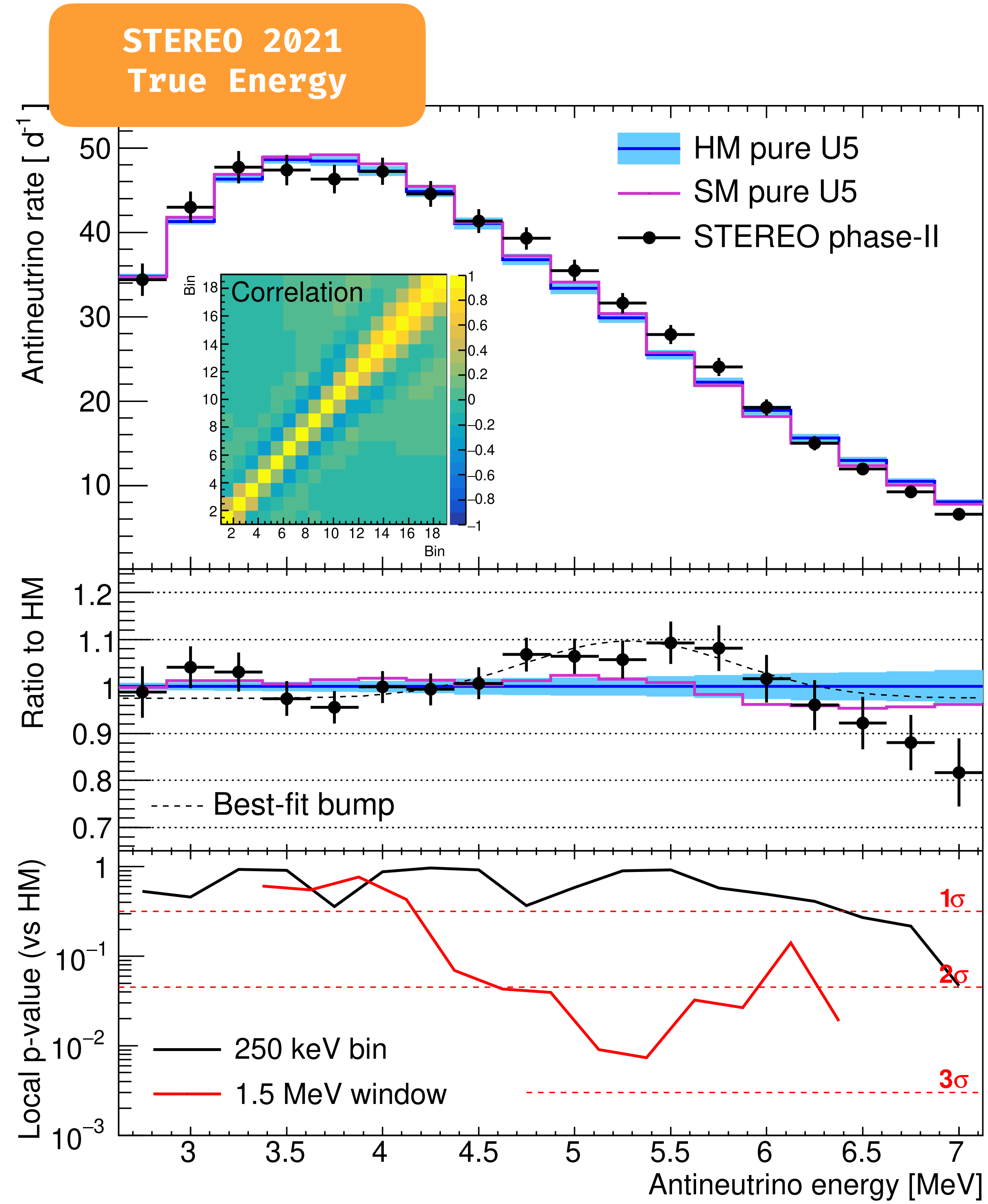
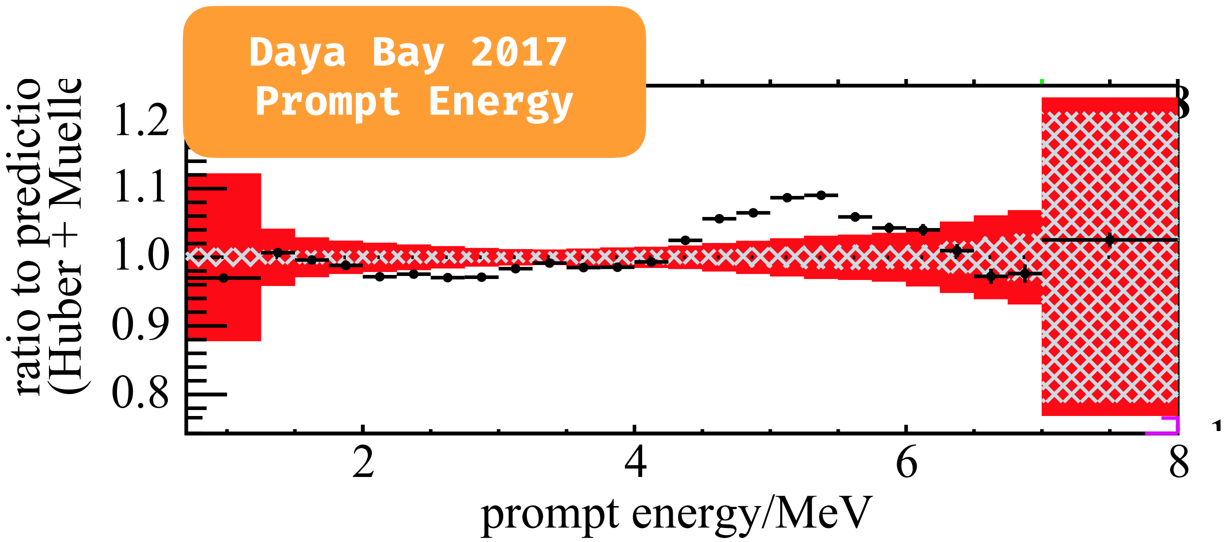
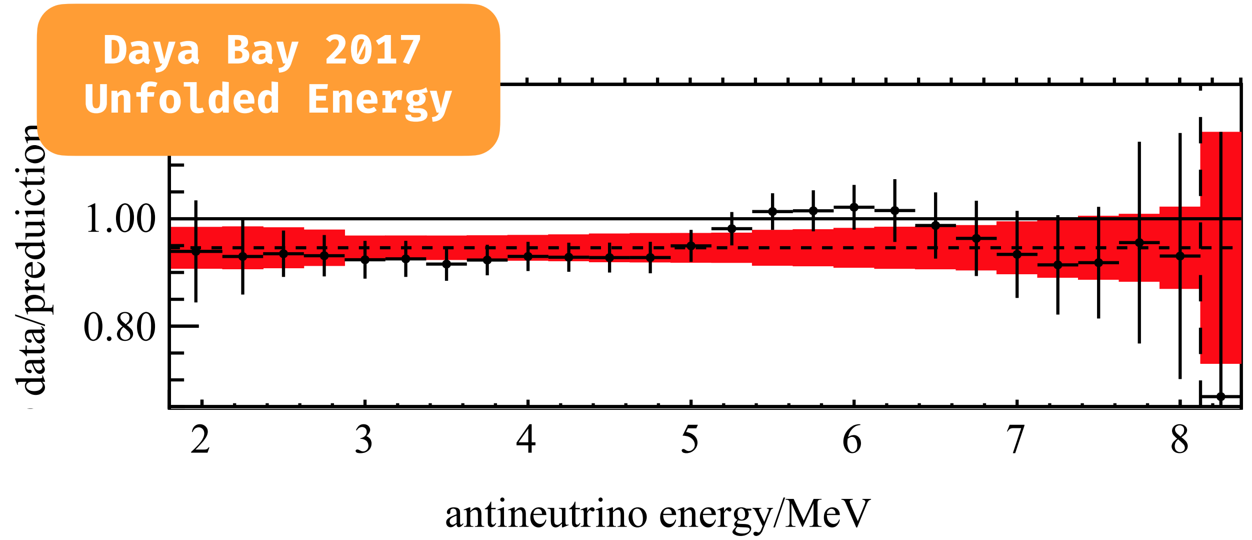


UNFOLDING UNCERTAINTIES AND SUBTLETIES

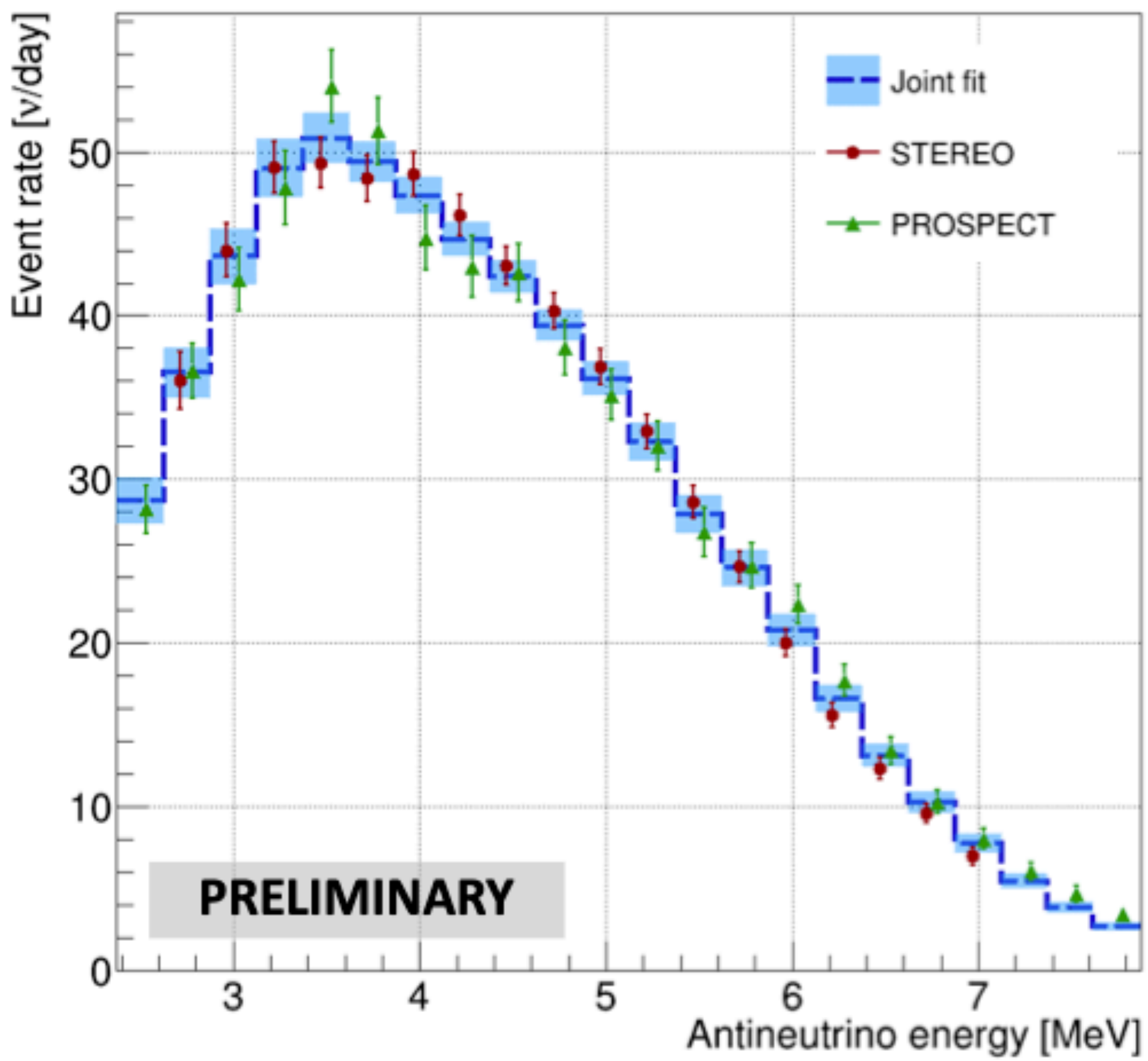




- Unfolding comes at a cost of decreased resolution and increased bin-to-bin correlation
  - Regularization smooths the spectrum, severity depends on the uncertainties
- Increased uncertainties from the unfolding process need to be accounted for
- Comparisons between theory and measurements need to use a smearing filter matrix to account for reduced resolution

JOINT ANALYSES BETWEEN EXPERIMENTS

- Combining reactor spectral measurements is non-trivial at the moment
- PROSPECT/Daya Bay and PROSPECT/STEREO are working on jointly unfolding their ^{235}U measurements
- **Analysis Goals:**
    1. Demonstrate consistency between independent results
    2. Increase statistical power, decrease systematic uncertainties, and produce unfolded spectra for community use
- Discovered many subtle differences between analyses and experiments that stumped even the insiders!
- **Potential for a combination of all three experiments to produce real "community" spectra for ^{235}U and ^{239}Pu**



(from M. Licciardi's talk at Moriond 2021)

PRESERVING DATA FOR FUTURE SCIENTISTS

- Too often data are scattered and incomplete, leaving results impossible to reproduce without "insider knowledge"
  - Combining different experiments is nearly impossible by outsiders
  - Example: aggregation of ^{235}U neutrino yield by the 2011 Mention et al. paper
- It should be a priority of each experiment to produce data in a format that future generations can use
  - Common format that includes detector info, data, uncertainties, experimental conditions, and example code
  - Publicly accessible and citable (via DOI or similar)
- **Community-developed "standard" flux and spectrum data that can be used directly**

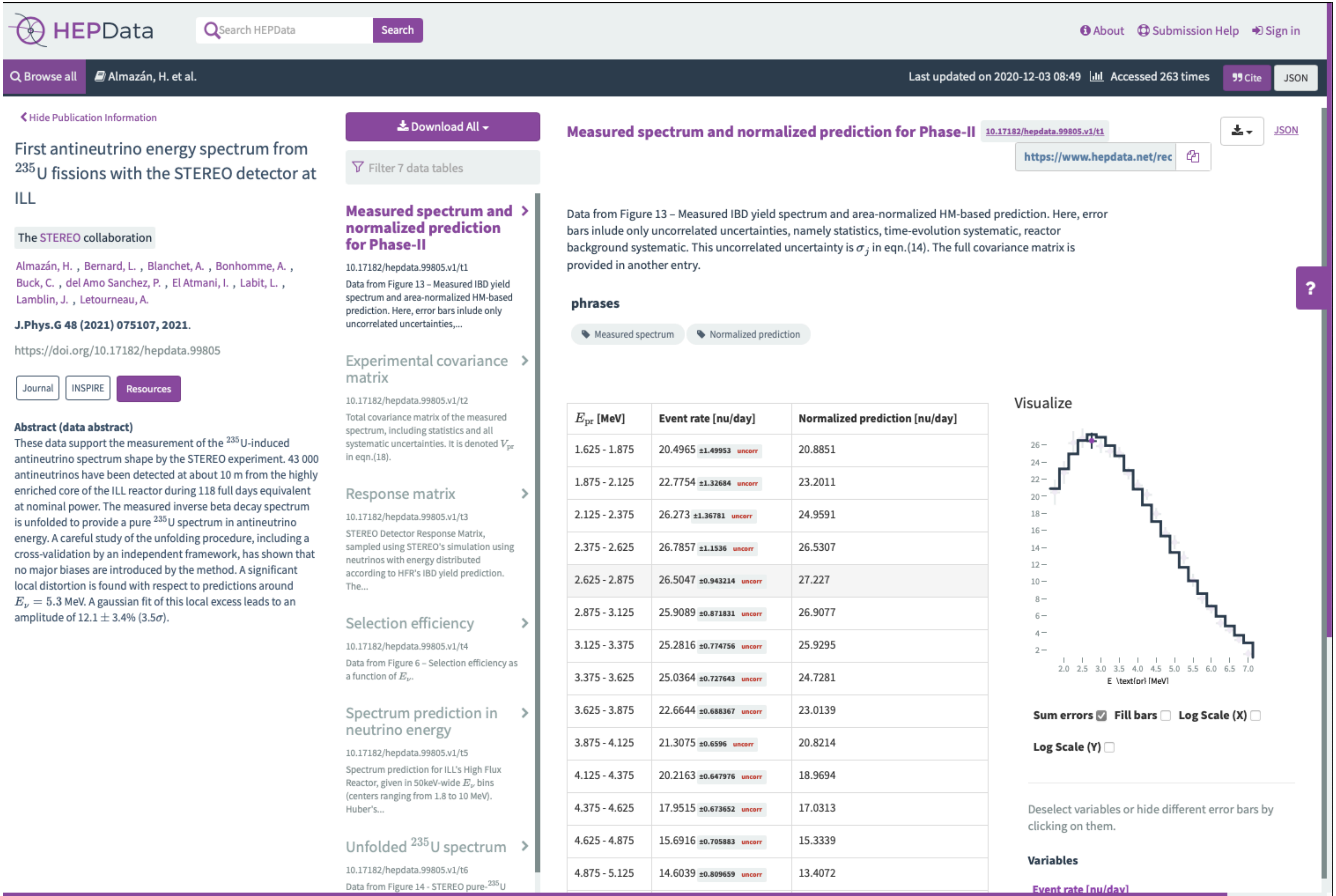
zenodo

HEPData

Repository for publication-related High-Energy Physics data

σigmA

HEPDATA EXAMPLE: STEREO SPECTRUM MEASUREMENT



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First antineutrino energy spectrum from ^{235}U fissions with the STEREO detector at ILL

The STEREO collaboration

Almazán, H. , Bernard, L. , Blanchet, A. , Bonhomme, A. , Buck, C. , del Amo Sanchez, P. , El Atmani, I. , Labit, L. , Lamblin, J. , Letourneau, A.

J.Phys.G 48 (2021) 075107, 2021.

https://doi.org/10.17182/hepdata.99805

Journal | INSPIRE | Resources

Abstract (data abstract)

These data support the measurement of the ^{235}U-induced antineutrino spectrum shape by the STEREO experiment. 43 000 antineutrinos have been detected at about 10 m from the highly enriched core of the ILL reactor during 118 full days equivalent at nominal power. The measured inverse beta decay spectrum is unfolded to provide a pure ^{235}U spectrum in antineutrino energy. A careful study of the unfolding procedure, including a cross-validation by an independent framework, has shown that no major biases are introduced by the method. A significant local distortion is found with respect to predictions around $E_\nu = 5.3$ MeV. A gaussian fit of this local excess leads to an amplitude of $12.1 \pm 3.4\%$ (3.5σ).

Download All

Filter 7 data tables

Measured spectrum and normalized prediction for Phase-II >
10.17182/hepdata.99805.v1/t1
Data from Figure 13 – Measured IBD yield spectrum and area-normalized HM-based prediction. Here, error bars inlude only uncorrelated uncertainties,...

Experimental covariance matrix >
10.17182/hepdata.99805.v1/t2
Total covariance matrix of the measured spectrum, including statistics and all systematic uncertainties. It is denoted V_{pr} in eqn.(18).

Response matrix >
10.17182/hepdata.99805.v1/t3
STEREO Detector Response Matrix, sampled using STEREO's simulation using neutrinos with energy distributed according to HFR's IBD yield prediction. The...

Selection efficiency >
10.17182/hepdata.99805.v1/t4
Data from Figure 6 – Selection efficiency as a function of E_ν.

Spectrum prediction in neutrino energy >
10.17182/hepdata.99805.v1/t5
Spectrum prediction for ILL's High Flux Reactor, given in 50keV-wide E_ν bins (centers ranging from 1.8 to 10 MeV). Huber's...

Unfolded ^{235}U spectrum >
10.17182/hepdata.99805.v1/t6
Data from Figure 14 - STEREO pure-^{235}U

Measured spectrum and normalized prediction for Phase-II

10.17182/hepdata.99805.v1/t1 | https://www.hepdata.net/rec | JSON

Data from Figure 13 – Measured IBD yield spectrum and area-normalized HM-based prediction. Here, error bars inlude only uncorrelated uncertainties, namely statistics, time-evolution systematic, reactor background systematic. This uncorrelated uncertainty is σ_j in eqn.(14). The full covariance matrix is provided in another entry.

phrases

Measured spectrum | Normalized prediction

E_{pr} [MeV]	Event rate [nu/day]	Normalized prediction [nu/day]
1.625 - 1.875	20.4965 ±1.49953 uncorr	20.8851
1.875 - 2.125	22.7754 ±1.32684 uncorr	23.2011
2.125 - 2.375	26.273 ±1.36781 uncorr	24.9591
2.375 - 2.625	26.7857 ±1.1536 uncorr	26.5307
2.625 - 2.875	26.5047 ±0.943214 uncorr	27.227
2.875 - 3.125	25.9089 ±0.871831 uncorr	26.9077
3.125 - 3.375	25.2816 ±0.774756 uncorr	25.9295
3.375 - 3.625	25.0364 ±0.727643 uncorr	24.7281
3.625 - 3.875	22.6644 ±0.688367 uncorr	23.0139
3.875 - 4.125	21.3075 ±0.6596 uncorr	20.8214
4.125 - 4.375	20.2163 ±0.647976 uncorr	18.9694
4.375 - 4.625	17.9515 ±0.673652 uncorr	17.0313
4.625 - 4.875	15.6916 ±0.705883 uncorr	15.3339
4.875 - 5.125	14.6039 ±0.809659 uncorr	13.4072

Visualize

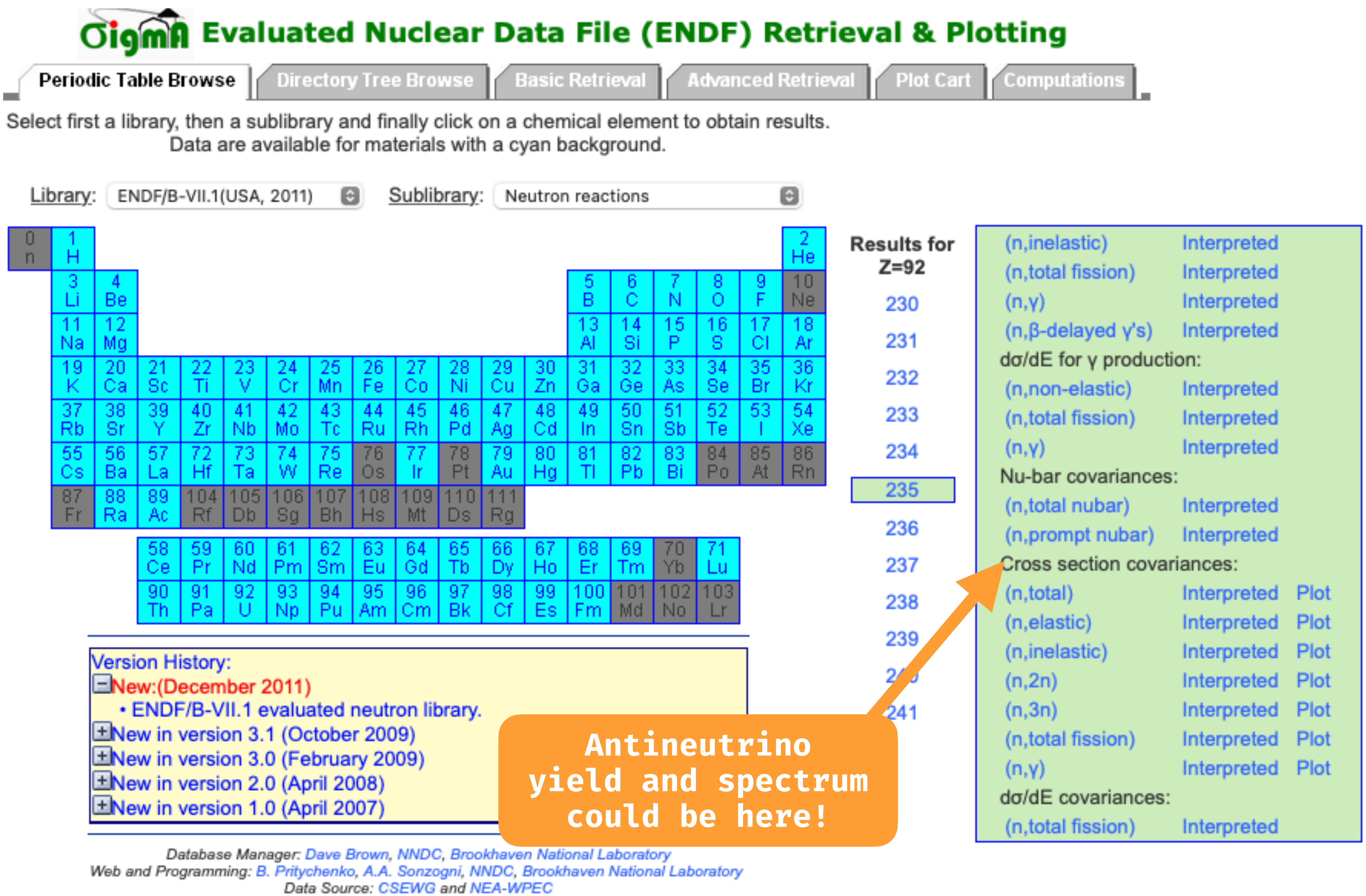
Sum errors | Fill bars | Log Scale (X) | Log Scale (Y)

Deselect variables or hide different error bars by clicking on them.

Variables

Event rate [nu/day]

PROPOSAL: INTEGRATION INTO NNDC SIGMA



Antineutrino yield and spectrum could be here!

OUTLOOK

- There continue to be new results from a diverse set of reactor antineutrino experiments
- Leveraging these data we are gaining a clearer picture of the antineutrino yield and energy spectrum
  - **Yield:** Indications of a data/model mismatch for ^{235}U
  - **Spectrum:** data/model mismatch for (at least) ^{235}U and ^{239}Pu
- Enhanced sensitivity can be enabled by combining data across experiments
- We need to prioritize preserving our data for future analyses, including all the details that don't fit in a five page letter
- **Should develop a "community standard" for data archival and build an accessible repository of these data**