Spectrum modelling overview

Patrick Huber

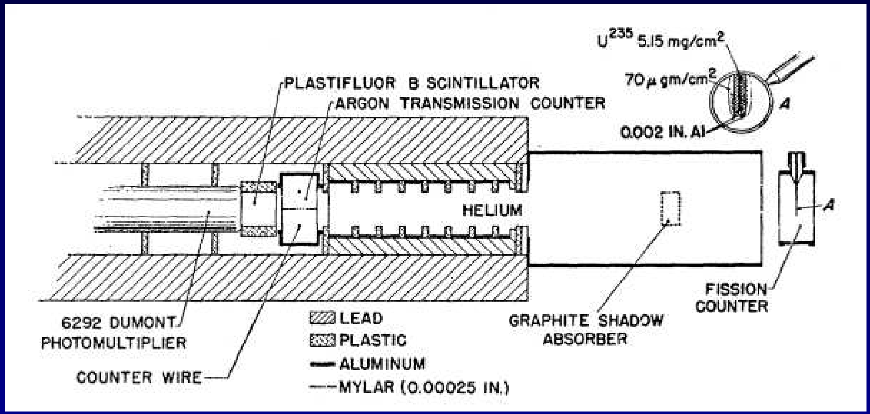
Center for Neutrino Physics – Virginia Tech

2nd IAEA Technical Meeting on Nuclear Data Needs
for Antineutrino Spectra Applications
January 16–20, 2023, Vienna, Austria

Not exactly a new problem

Free Antineutrino Absorption Cross Section. II. Expected Cross Section from Measurements of Fission Fragment Electron Spectrum*

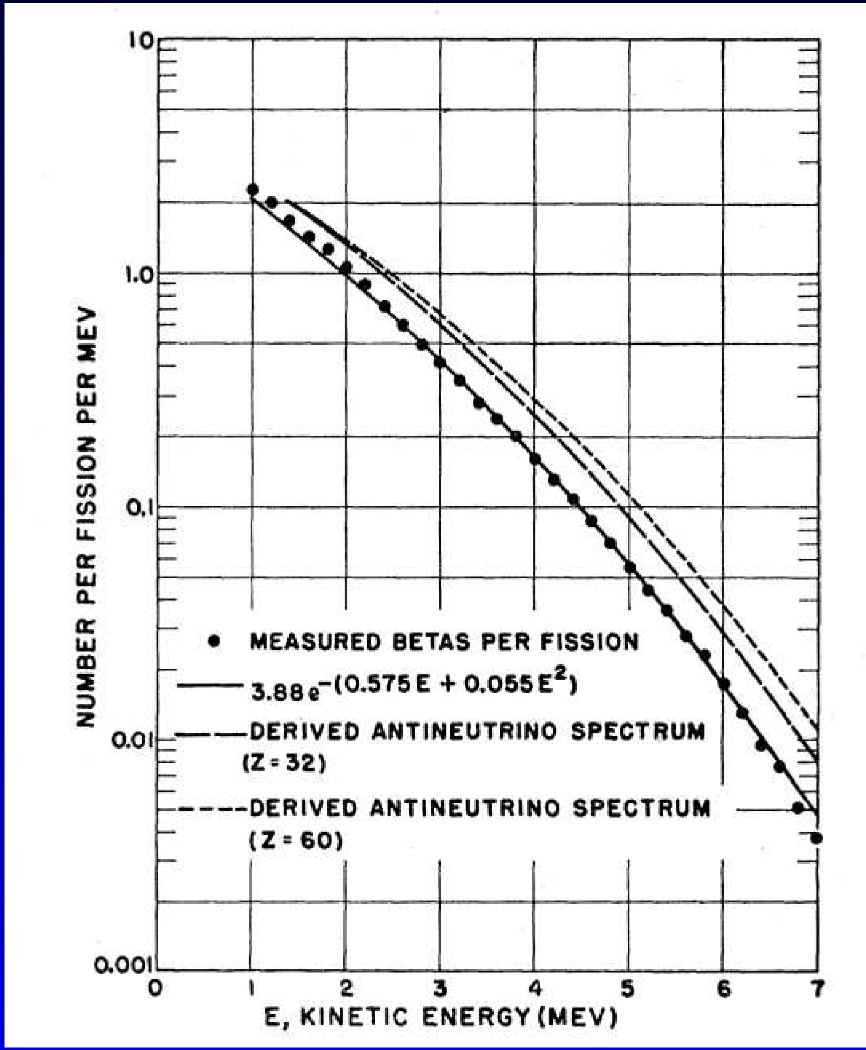
R. E. Carter, F. Reines, J. J. Wagner, and M. E. Wyman†
Los Alamos Scientific Laboratory, University of California, Los Alamos, New Mexico
(Received September 8, 1958)



Neutron beam guide (outside of reactor)

Direct fission rate measurement using a in situ fission chamber.

Coincidence between proportional counter and scintillator to reject γs

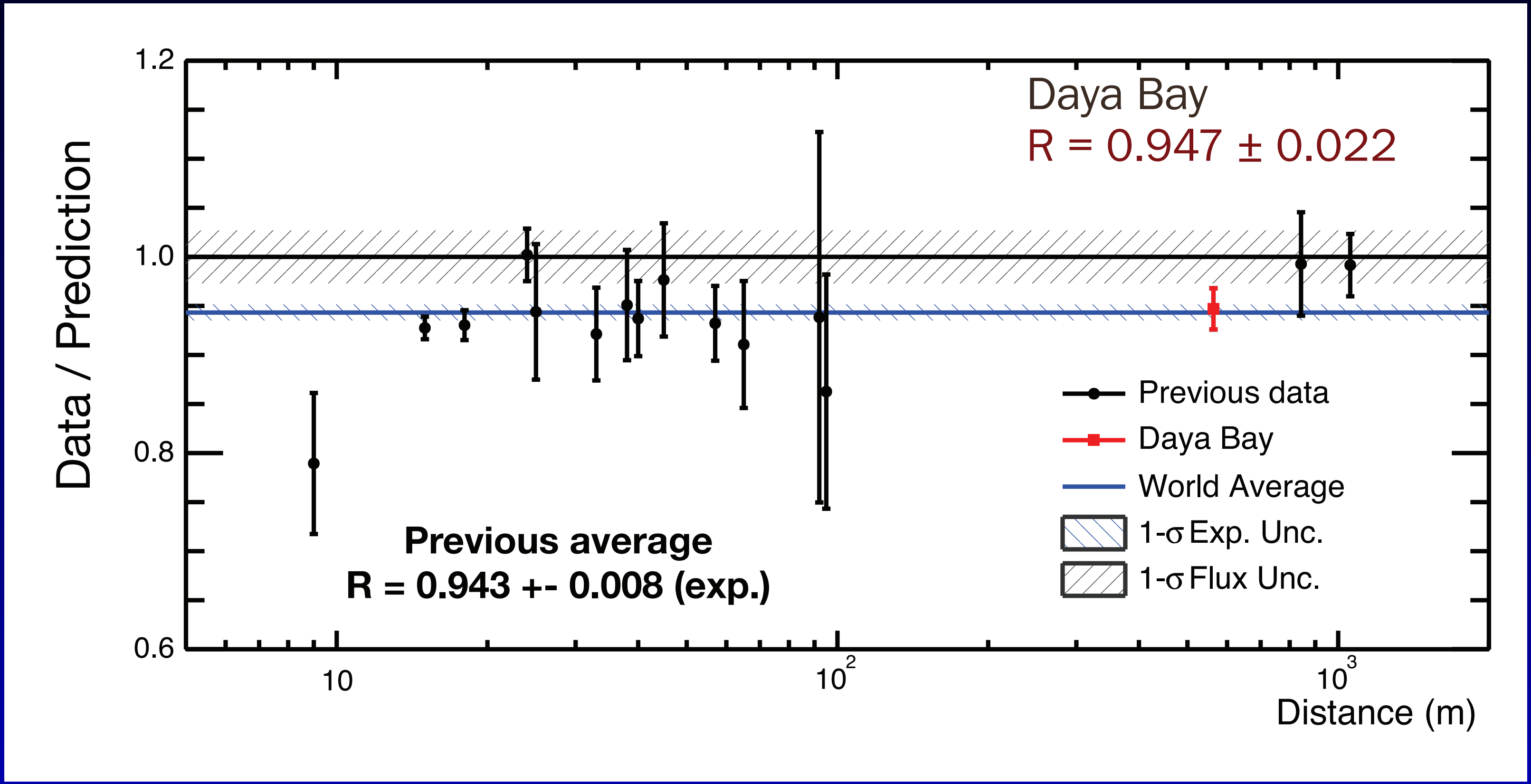


Caveats

- The rate anomaly and spectrum anomaly will be discussed separately
- The authors for nearly everything I show are here, so I may re-direct questions to the actual experts

The Rate Anomaly

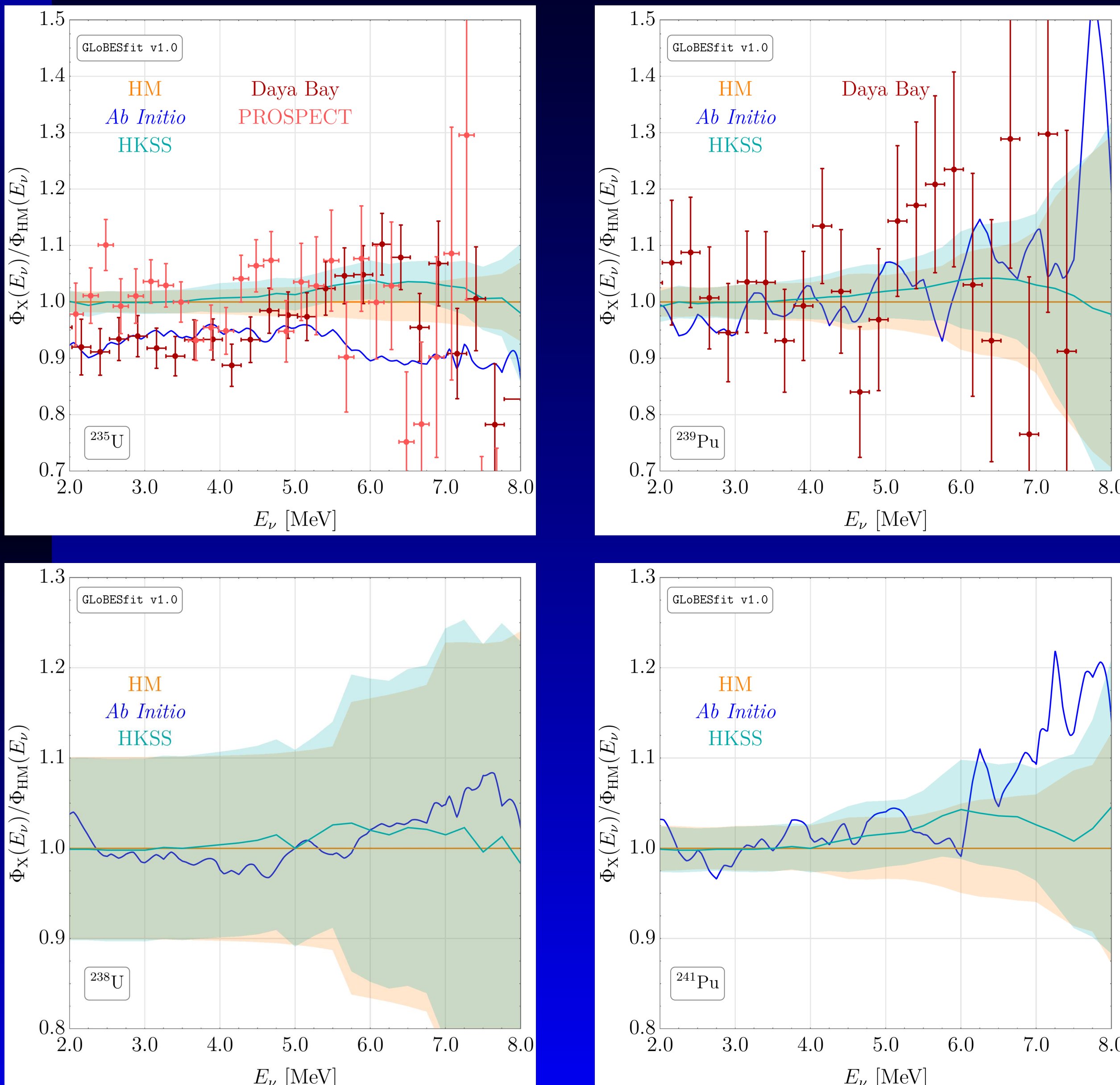
The reactor anomaly



Daya Bay, 2014

Mueller *et al.*, 2011, 2012 – where have all the neutrinos gone?

Status quo early 2021



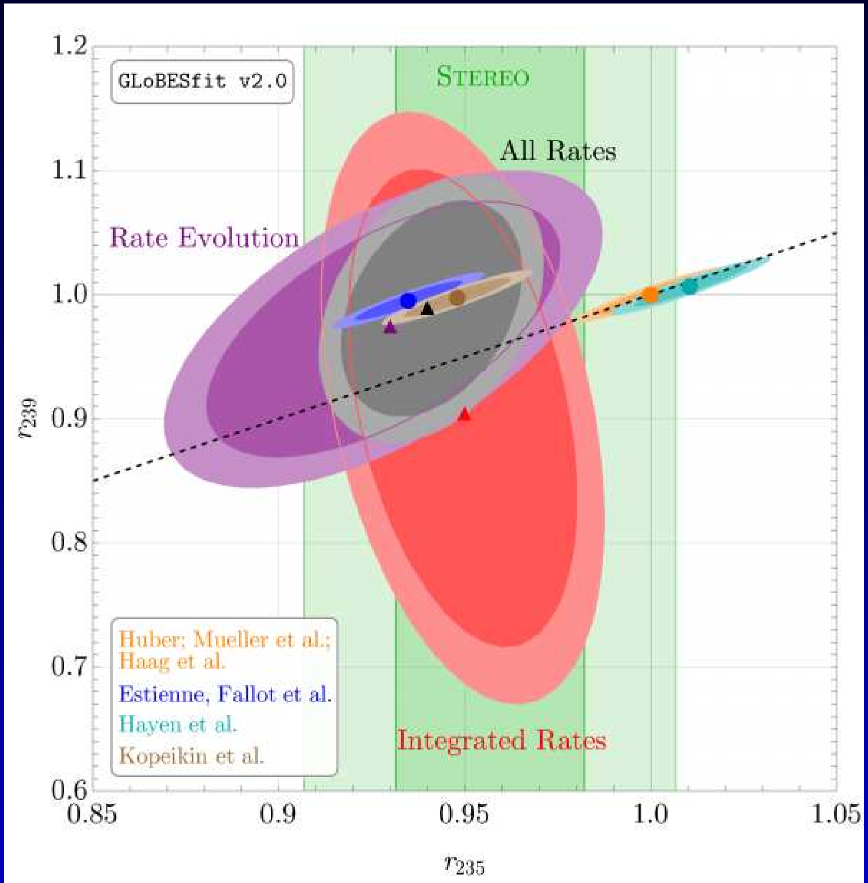
3 different flux models, data from 2 different experiments

Except for U235:
+ the models agree within error bars
+ the models agree with neutrino data

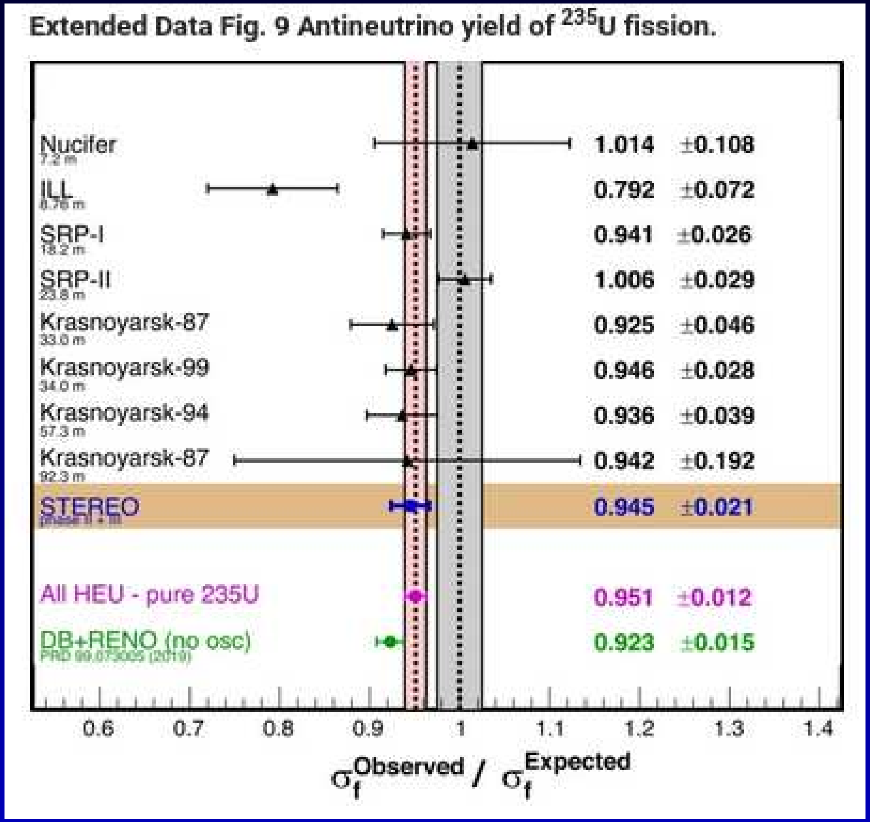
U235 has smallest error bars, not surprising that discrepancies show up first.

Berryman, PH, 2020

Fuel evolution



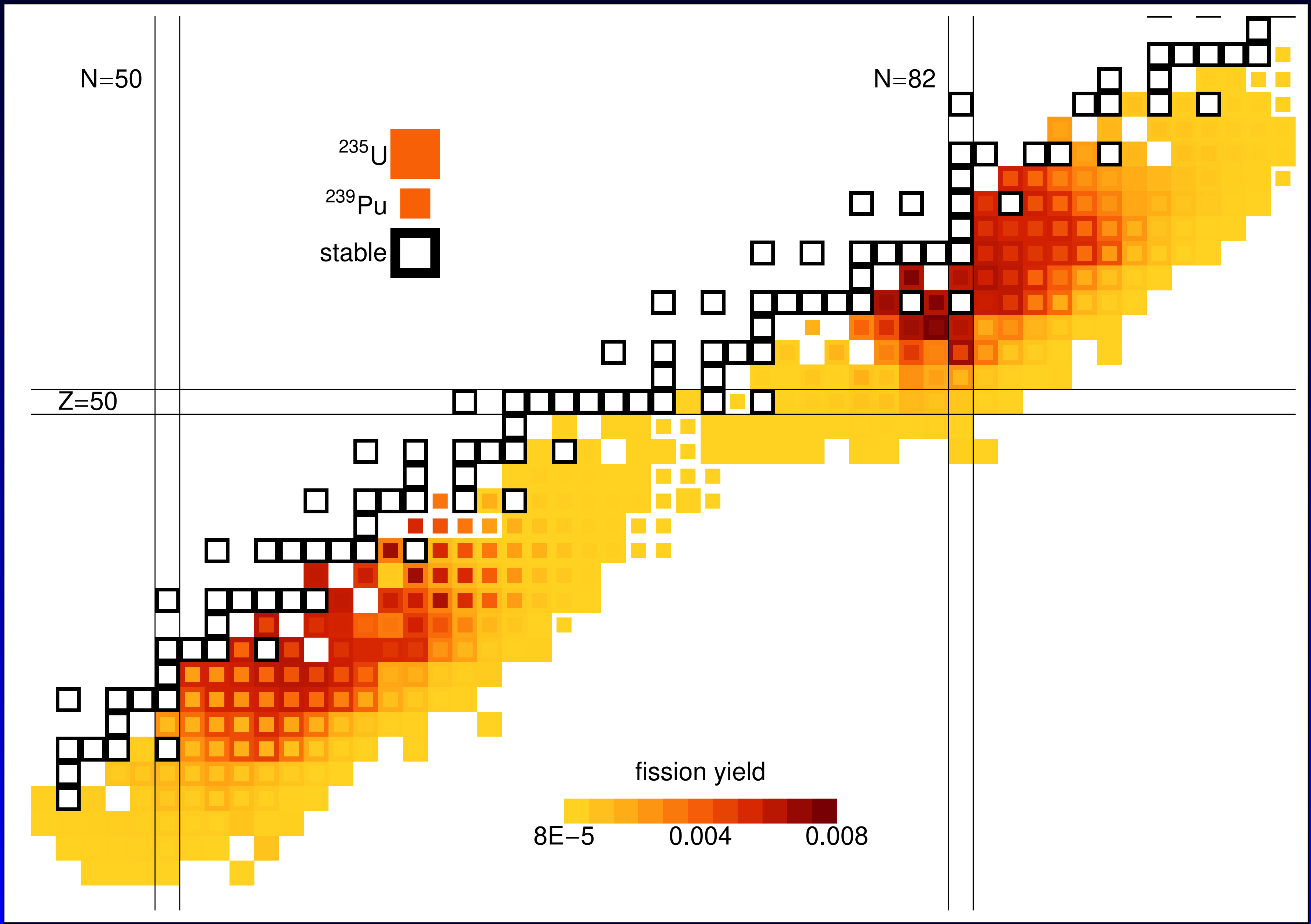
Berryman, PH, 2020, 2022



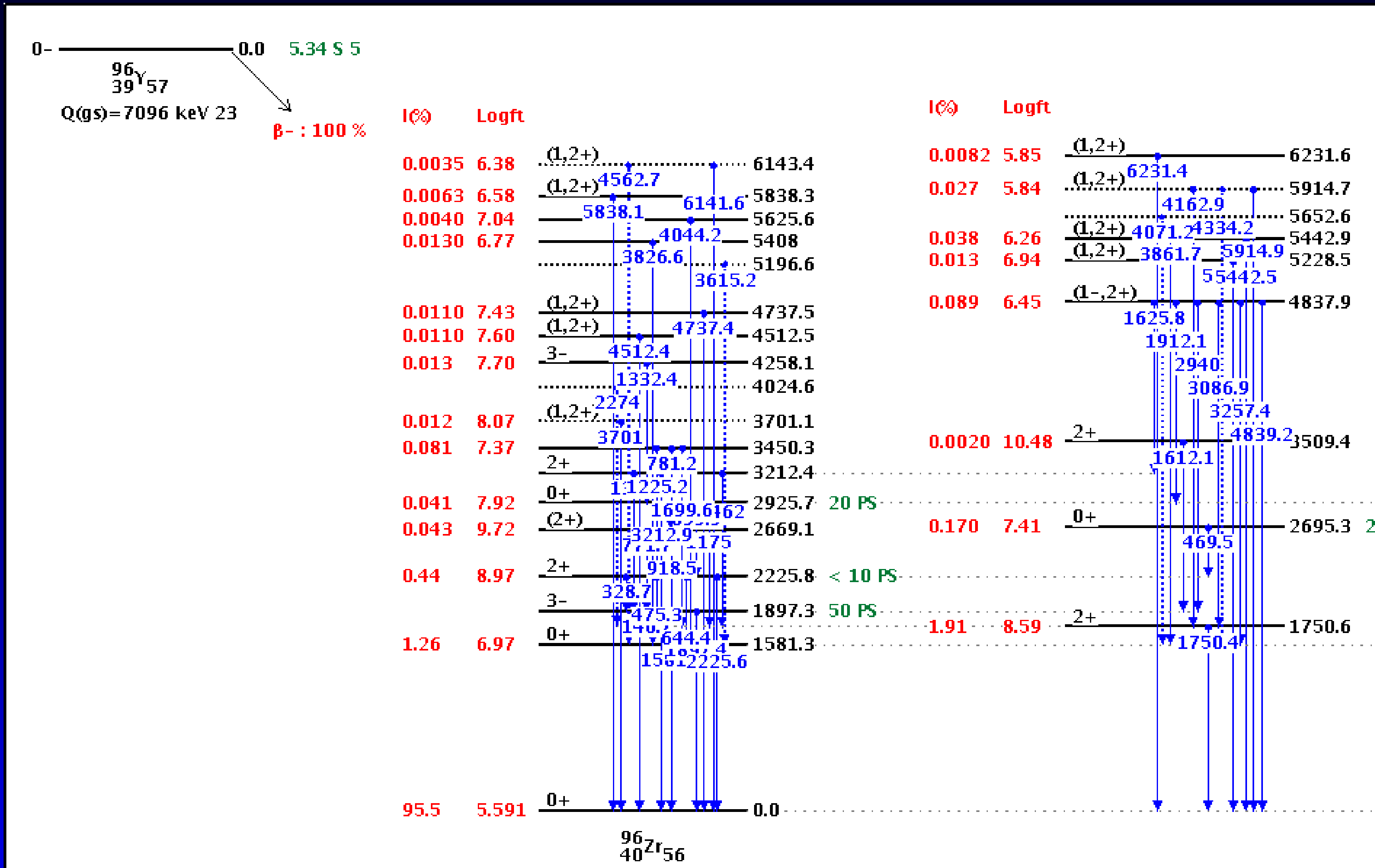
STEREO, 2023

U235 seems to "own" all of the deficit.

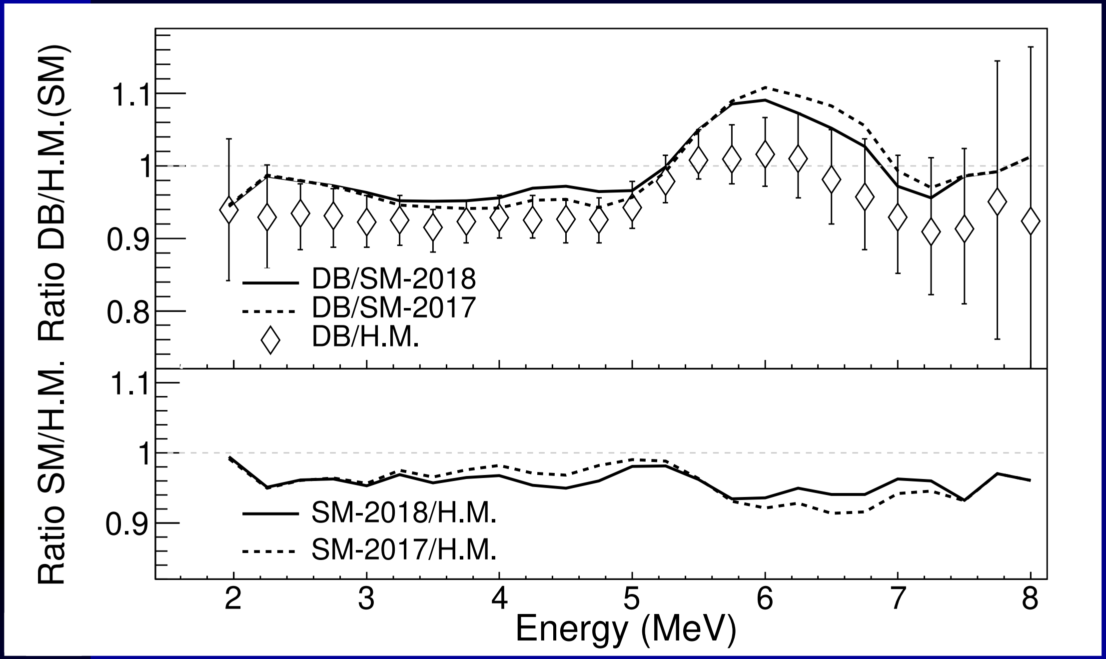
Why is this so complicated?

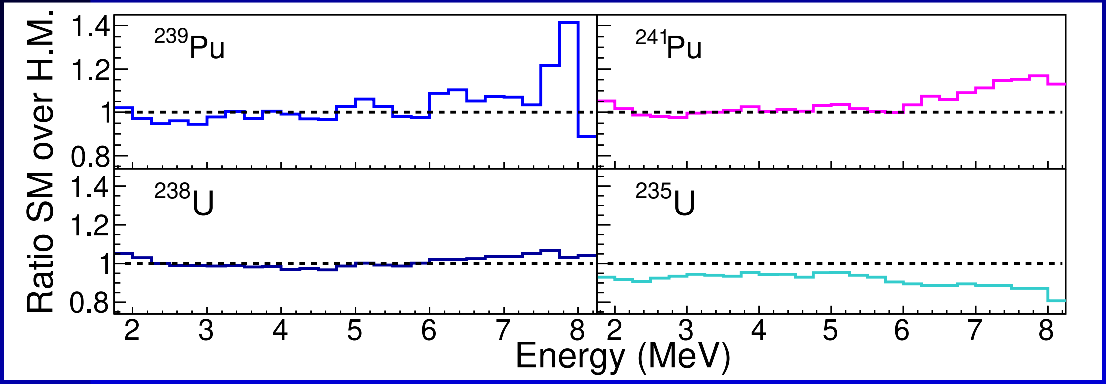


β-branches



Summation method – EF





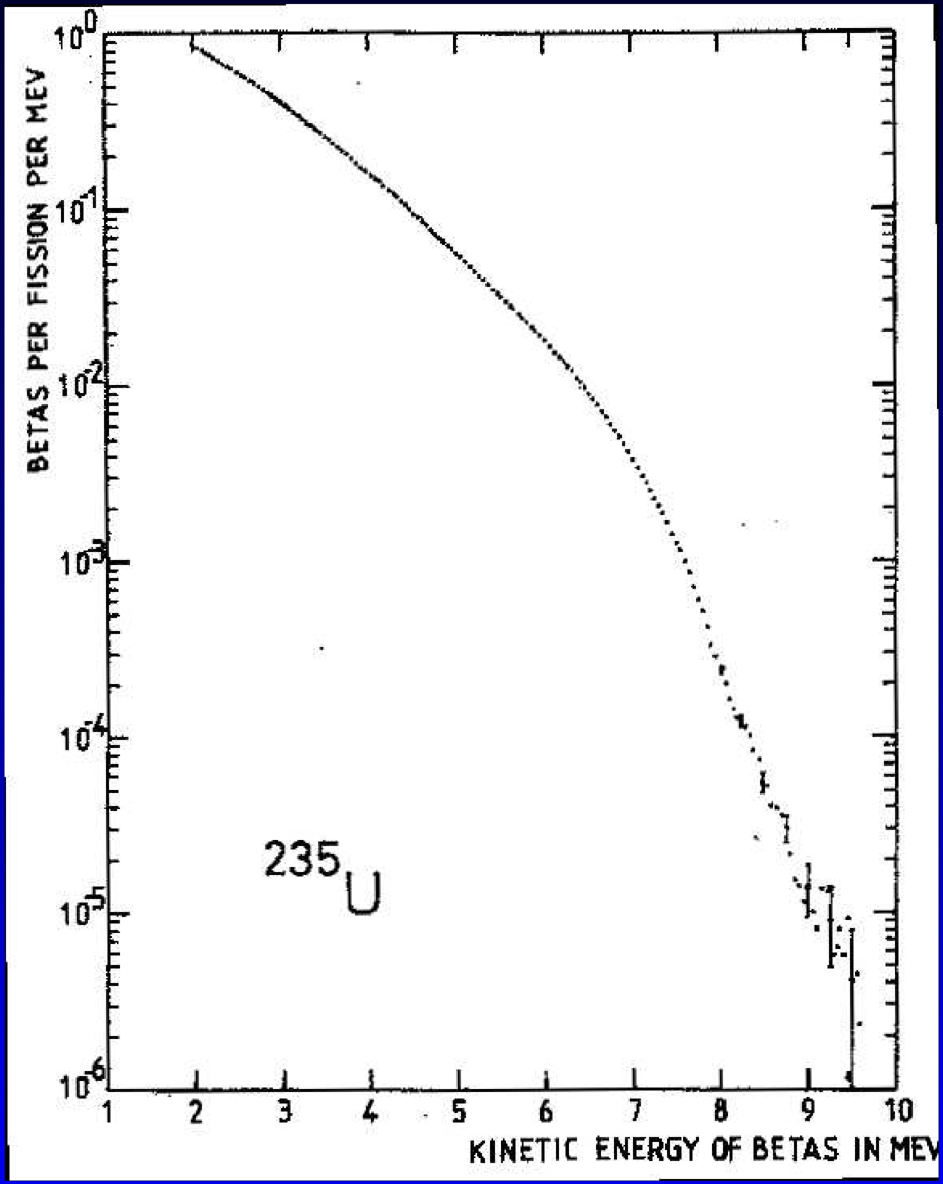
Estienne *et al.*, 2019

Take fission yields from database.

Take beta decay information from database.

For the most crucial isotopes use β-feeding functions from total absorption γ spectroscopy.

Conversion method – HM



Schreckenbach, *et al.* 1985.

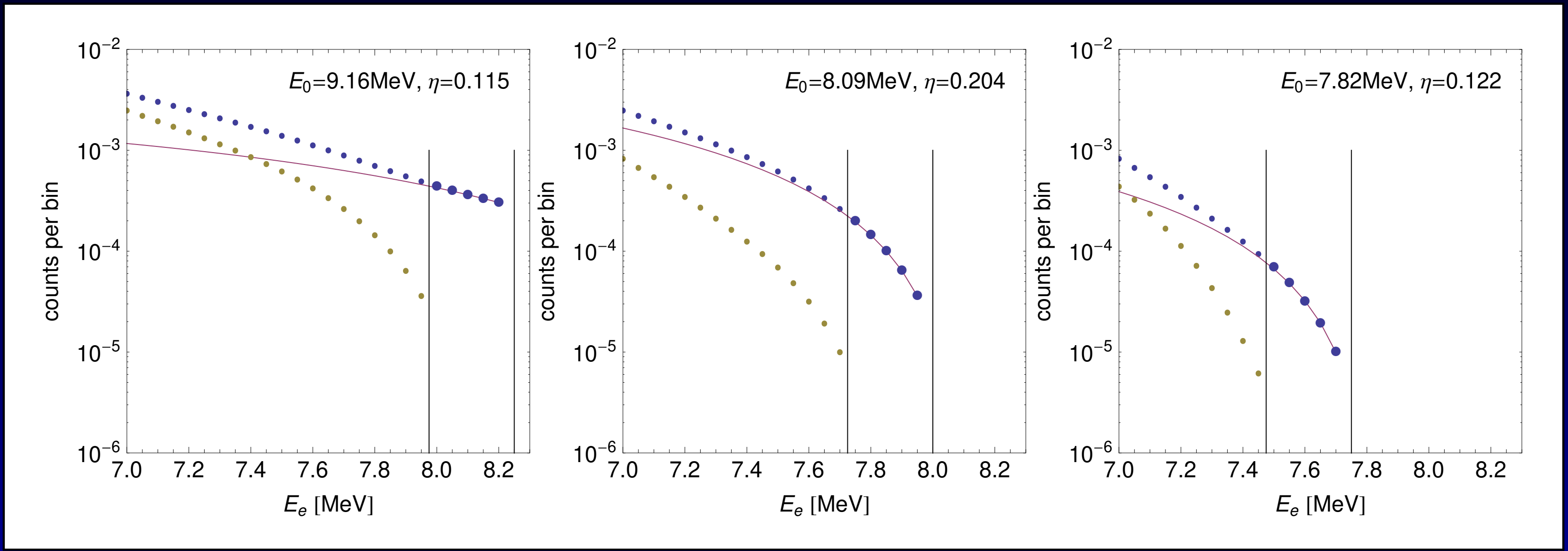
^{235}U foil inside the High Flux Reactor at ILL

Electron spectroscopy with a magnetic spectrometer

Same method used for ^{239}Pu and ^{241}Pu

Mueller *et al.*, 2011; PH, 2011

Virtual branches



1 – fit an allowed β-spectrum with free normalization η and endpoint energy E_0 the last s data points

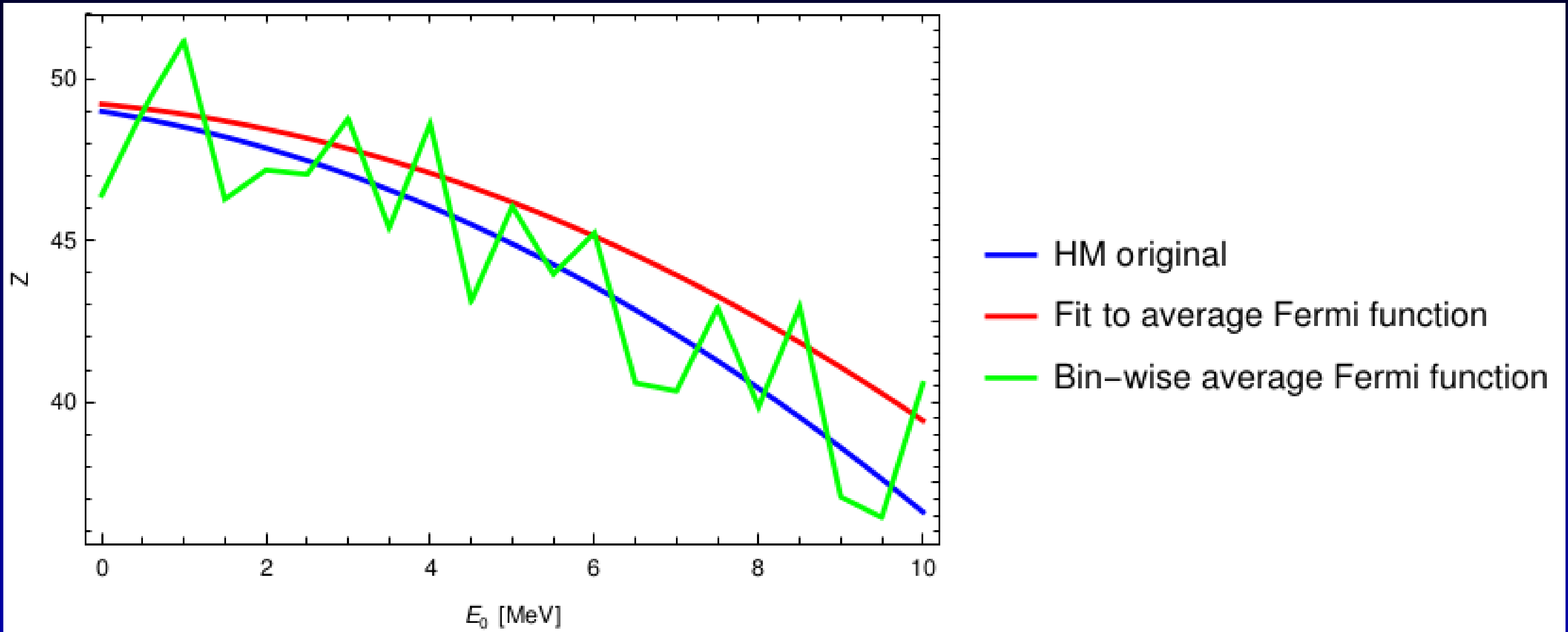
2 – delete the last s data points

3 – subtract the fitted spectrum from the data

4 – goto 1

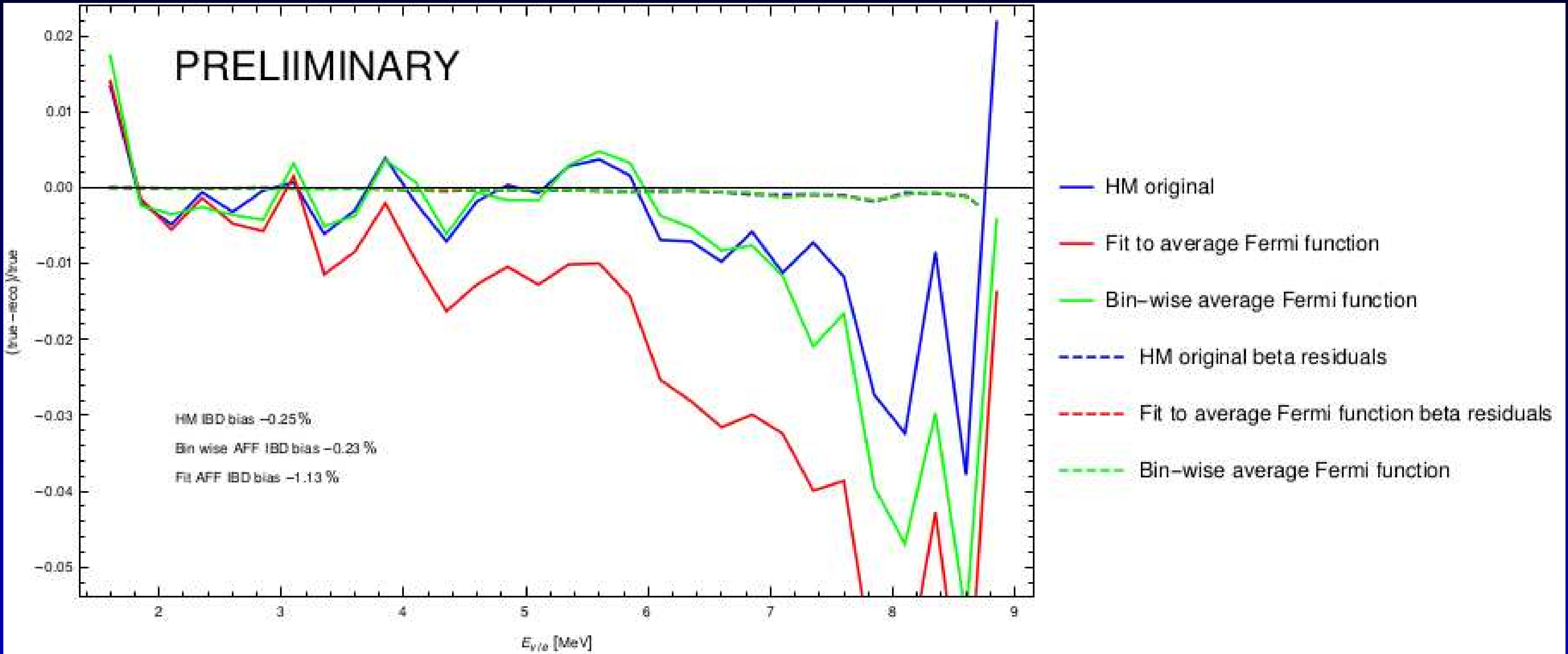
Invert each virtual branch using energy conservation into a neutrino spectrum and add them all.

Zeff – how to parametrize



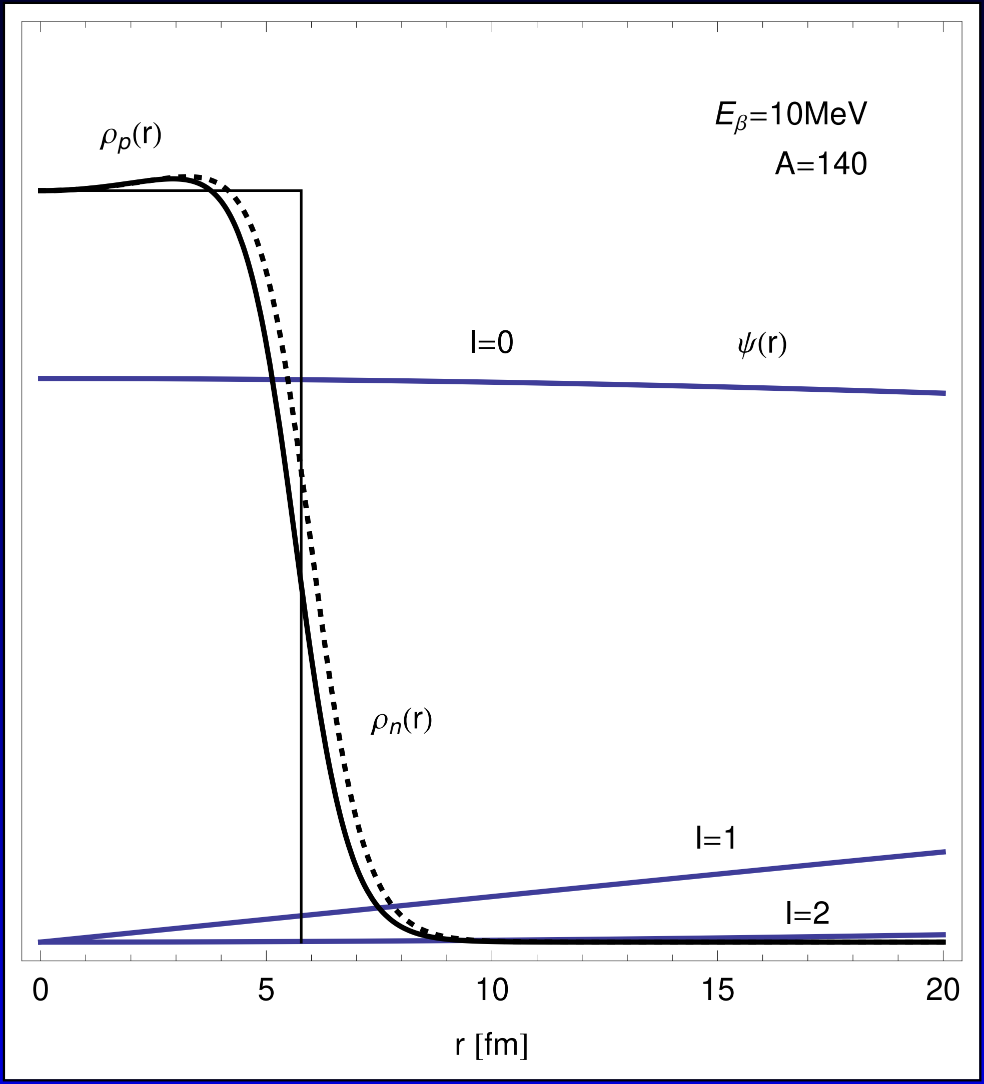
Hayes *et al.* point out that the details of how the parameterization for Z_{eff} is done could bias the neutrino spectrum.

Zeff – comparison



Using ν and beta spectrum derived from the same summation calculation allows to test how well the different methods reproduce the ν spectrum – fit to average Fermi function leads to large bias.

Forbidden decays



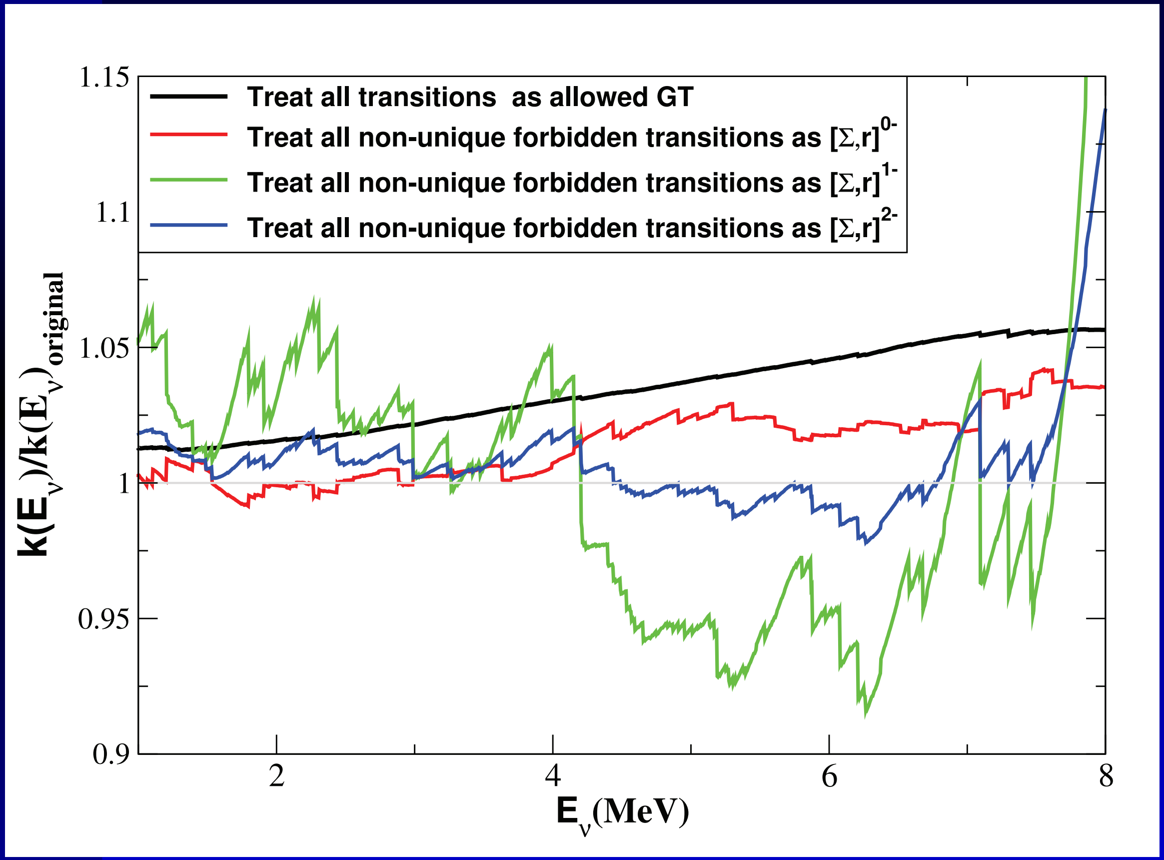
$e, \bar{\nu}$ final state can form a singlet or triplet spin state J=0 or J=1

Allowed:
s-wave emission ($l = 0$)

Forbidden:
p-wave emission ($l = 1$) or $l > 1$

Significant nuclear structure dependence in forbidden decays$\rightarrow$ **sizable uncertainties?**

Forbidden decays

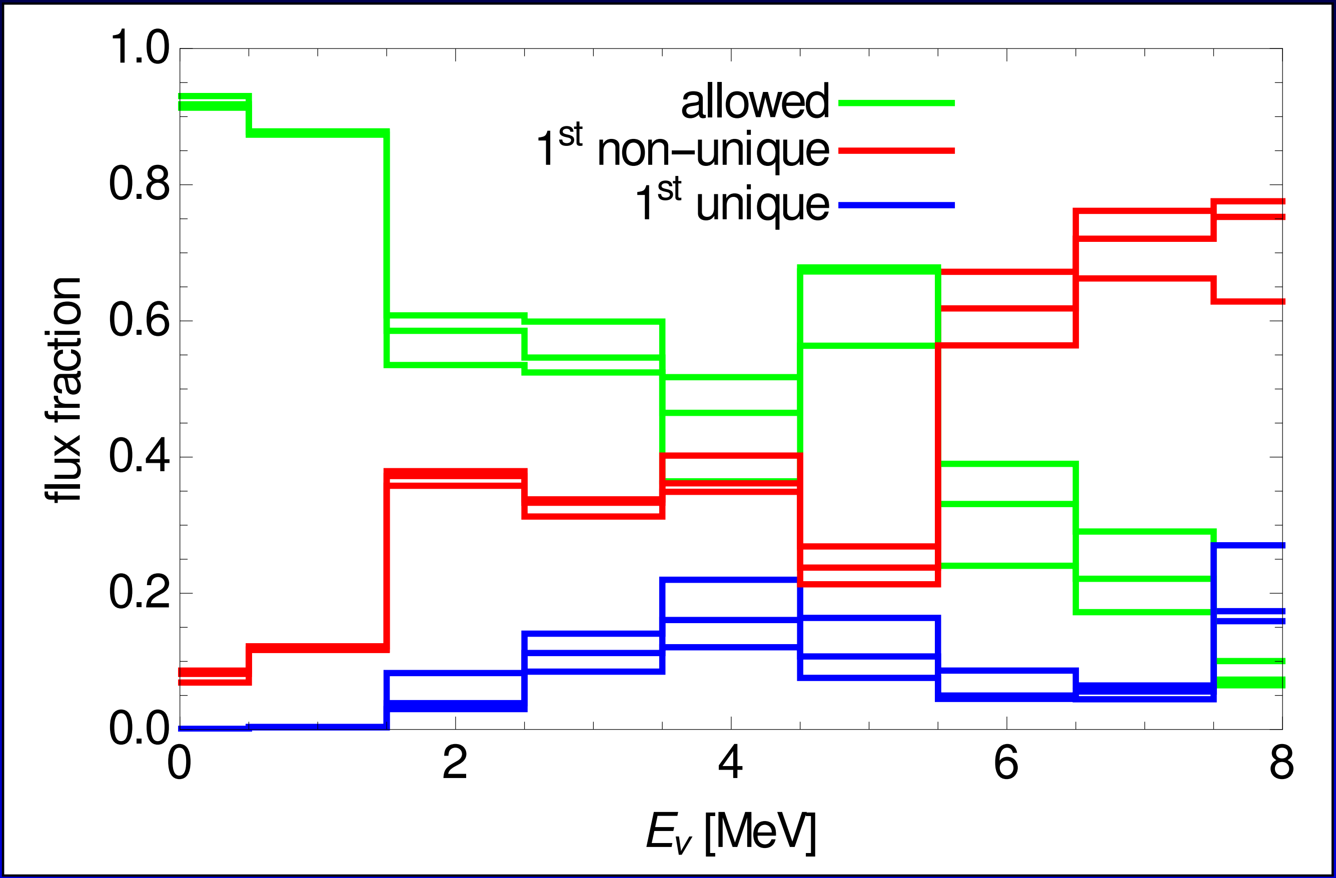


Hayes *et. al*, 2013 point out that in non-unique forbidden decays a unknown mixture of different operators is involved.

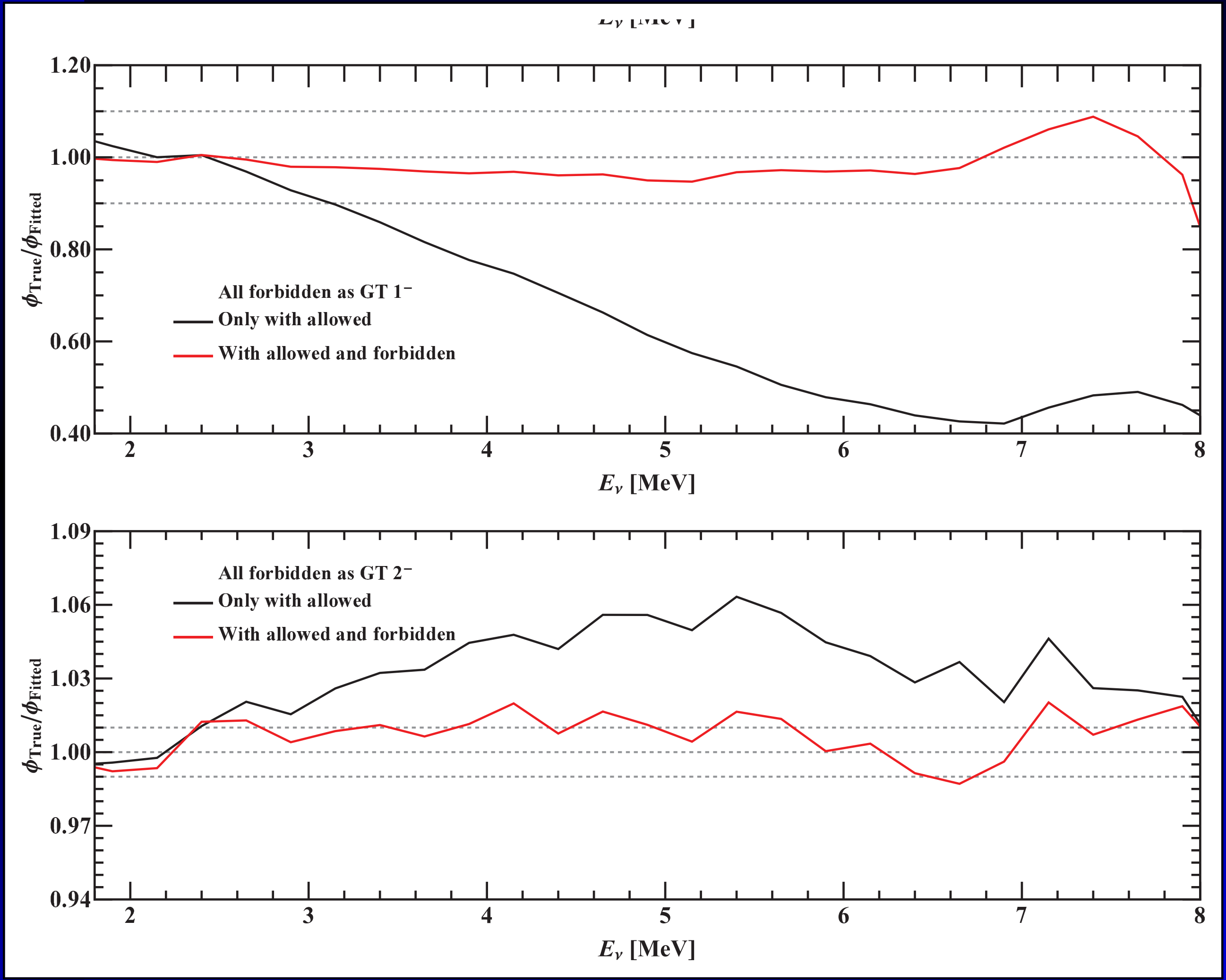
Potential source of uncertainty.

How many forbidden decays?

Based on JEFF fission yields and using ENSDF spin-parity assignments



A way forward?



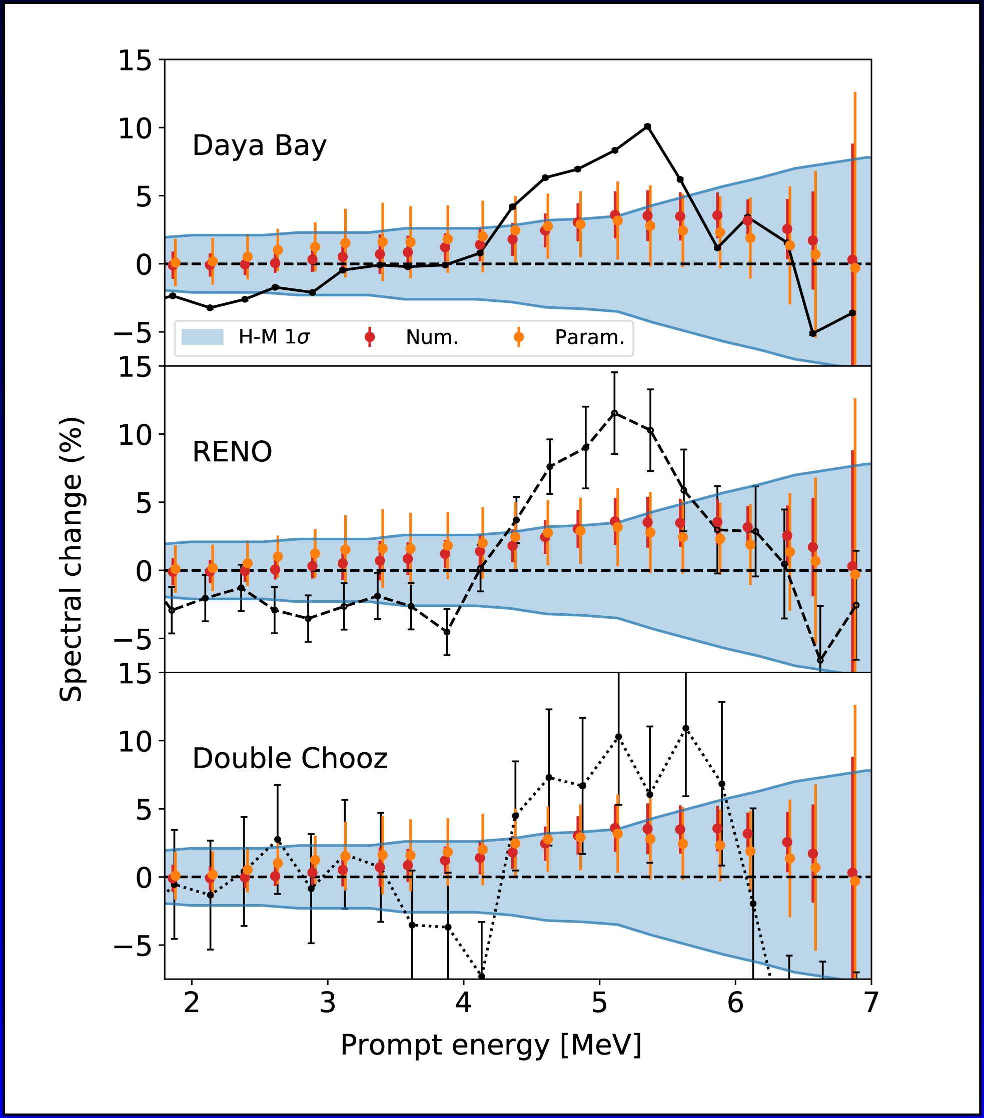
If we knew on a statistical basis the mixture of operators as a function of endpoint energy, errors could be greatly reduced.

NB: based on synthetic spectra.

Li, Zhang, 2019

Maybe computational approaches exist?
see *e.g.* Hayen *et al*, 2018

Shell model – HKSS



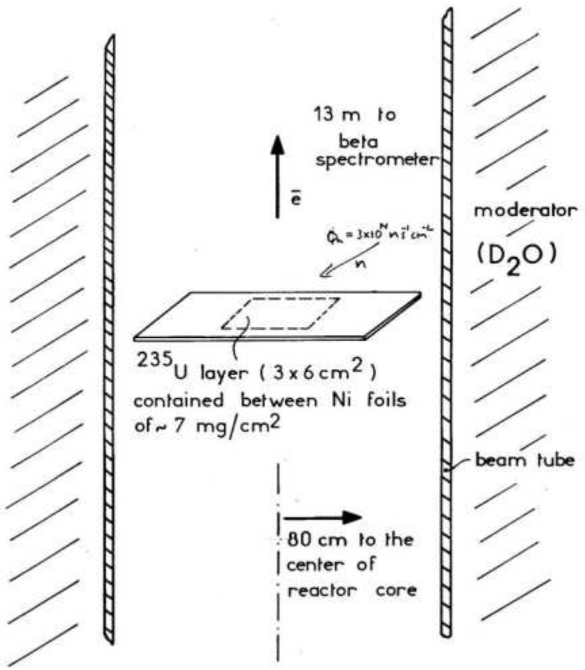
Hayen, *et al.* 2019

Forbidden decays major source of systematic.

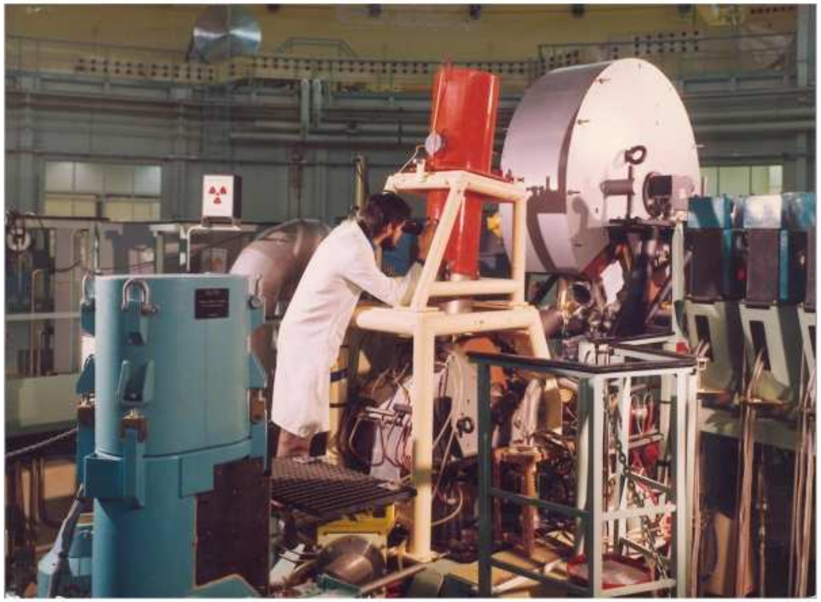
Microscopic shell model calculation of 36 forbidden isotopes, otherwise similar to HM.

Increases the IBD rate anomaly by 40%, but the uncertainty increases by only 13% relative to HM

Kill BILL?



SCHEMATIC VIEW OF THE TARGET SITE



Magnetic BILL spectrometer at ILL, 1972-1991

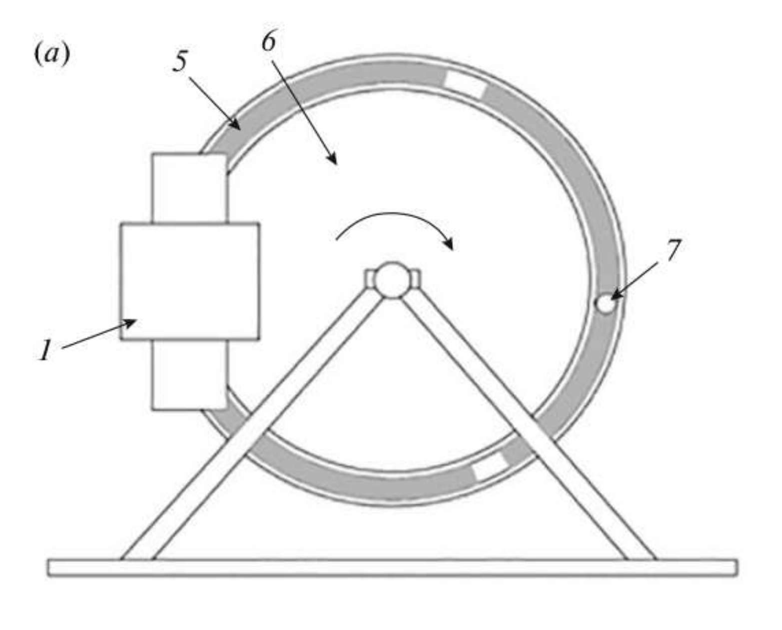
(Electron detector in focal plane: multi chamber proportional counter in transmission, rear mounted scintillator in coincidence)

Neutron flux calibration standards different for U235 and Pu239: 207Pb and 197Au respectively.

Combined with potential differences in neutron spectrum – room for a 5% shift of U235 normalization?

A. Letourneau, A. Onillon, AAP 2018

2021 beta measurement

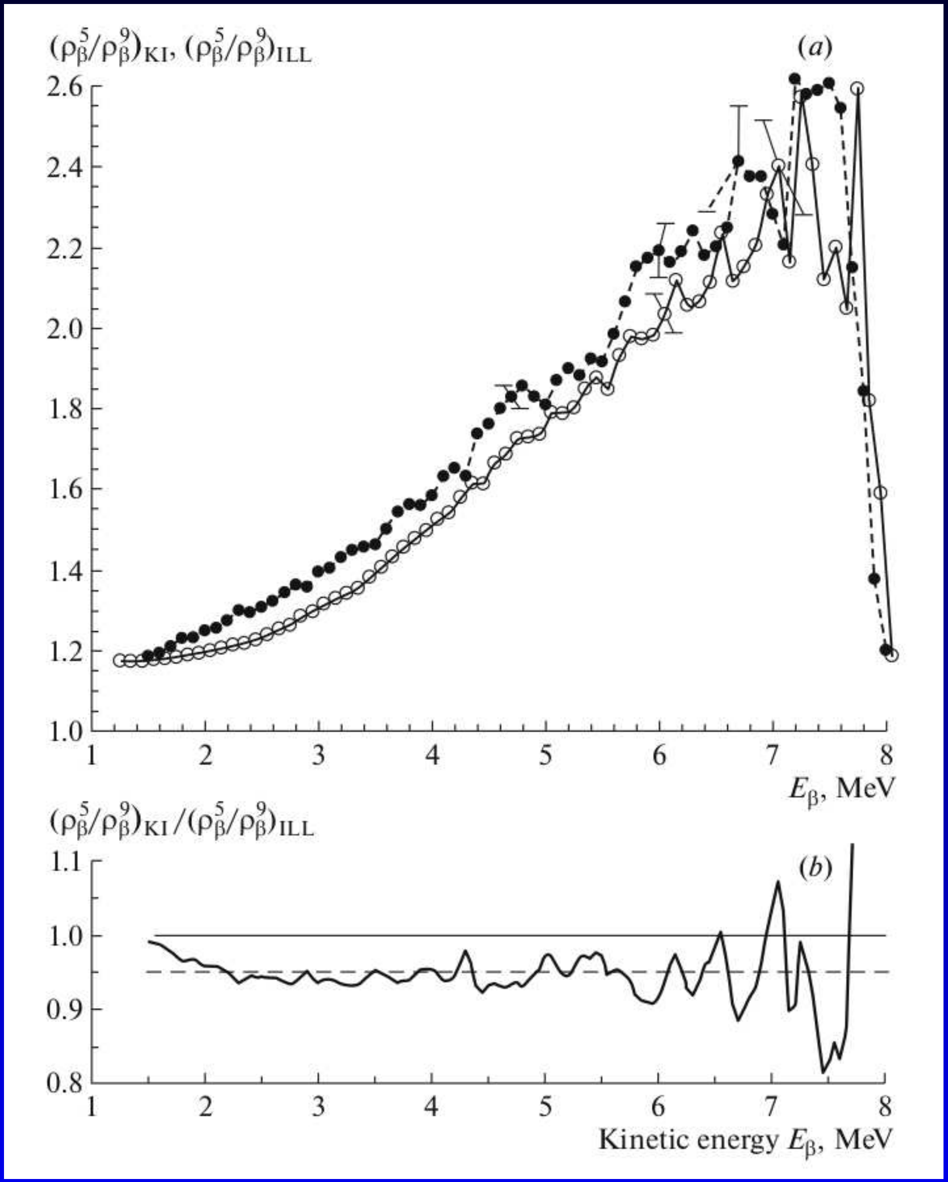


Relative measurement of U235 and Pu239 targets under identical conditions.

Beta detection with stilbene.

This slide and the following are based on V. Kopeikin, M. Skorokhvatov, O. Titov (2021) and V. Kopeikin , Yu. Panin, A. Sabelnikov (2020) and we will refer to this as the Kurchatov Institute (KI) data.

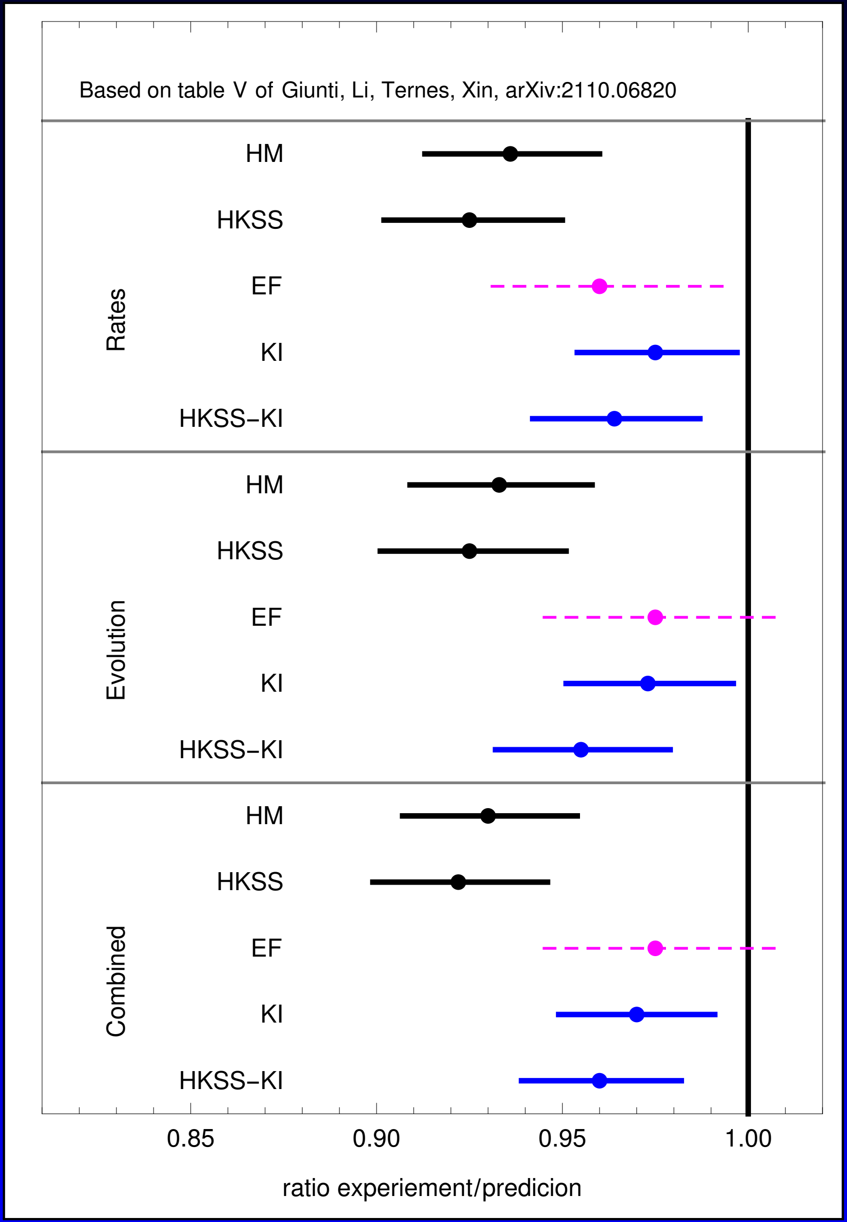
2021 beta results



At relevant energies the new measurement is about 5% below the previous one

Systematics is difficult in these measurements, but no obvious issues.

2021 beta impact



HM – conversion
HKSS – conversion
+ forbidden decays
EF – summation
unclear theory error
KI – HM + KI data
HKSS+KI – HKSS +KI

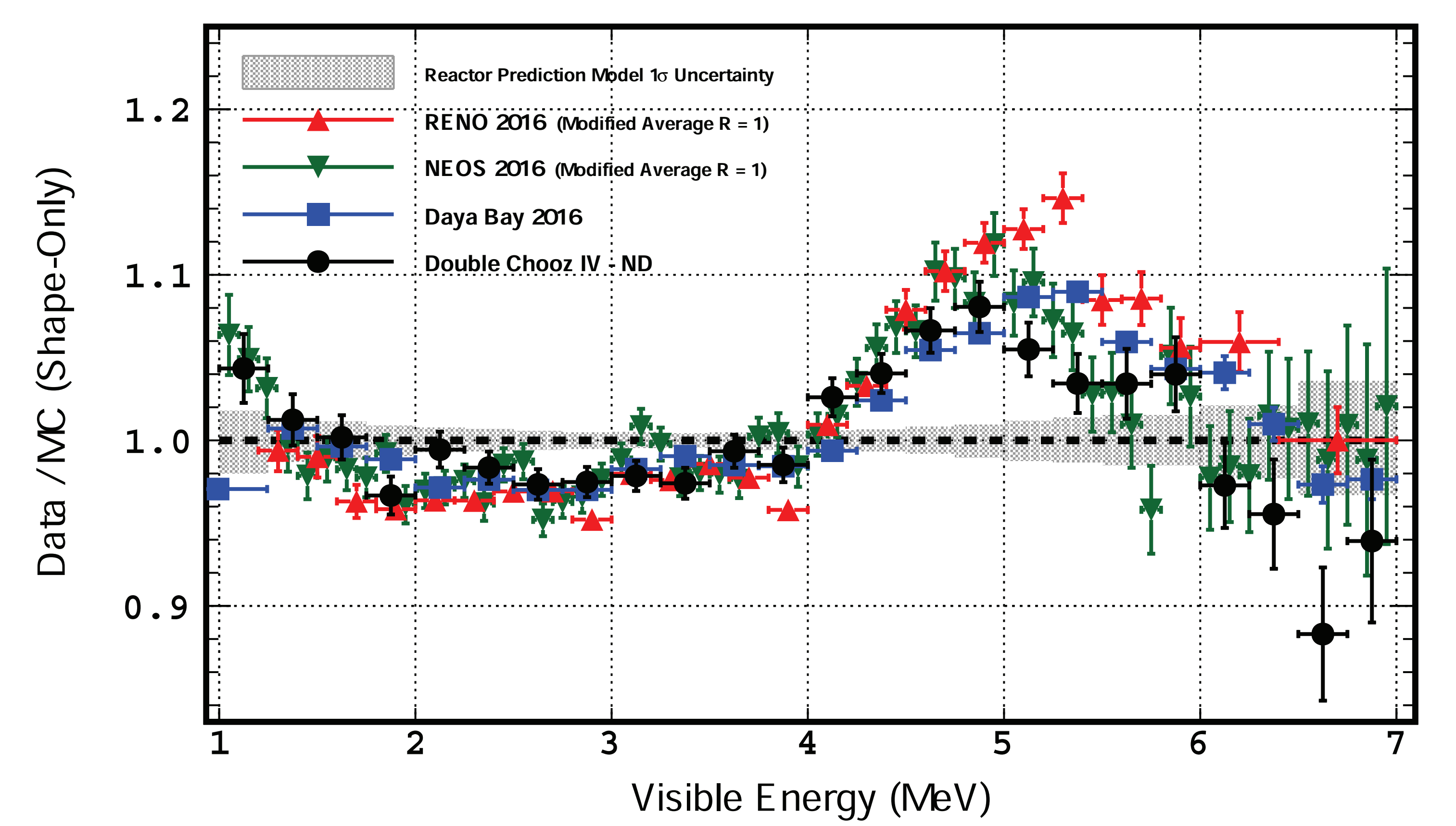
With the KI correction agreement between summation and conversion improved.

RAA significance reduced to less than 2σ

The Spectrum Anomaly

aka the 5 MeV Bump

The 5 MeV bump



Double Chooz 2019

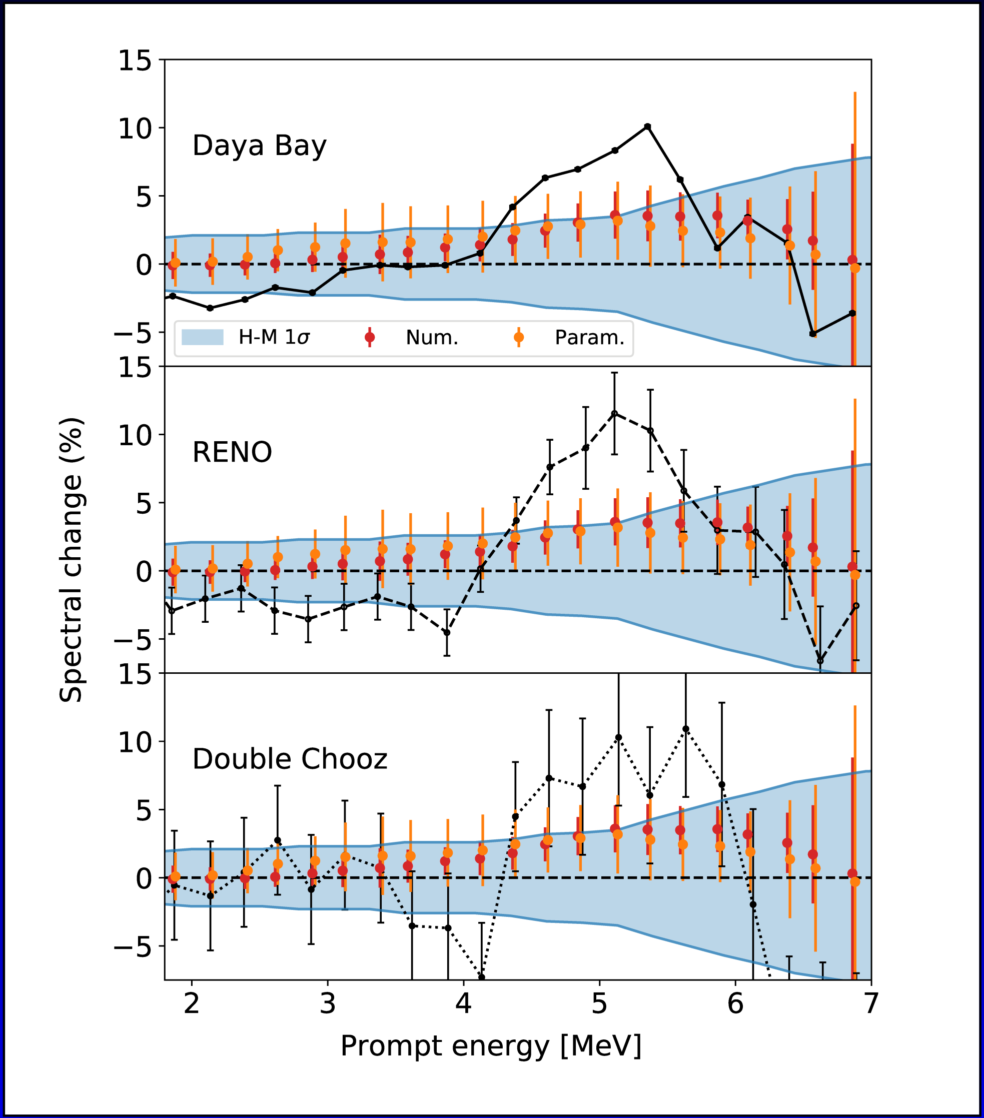
Contains only 0.5% of all neutrino events – not important for sterile neutrinos

Yet, statistically more significant than the RAA!

Things which are not the cause

- Fissión yields Dwyer, Langford, 2014; Hayes, *et al.* 2015; Sonzogni, *et al.* 2016
- Neutron spectrum Hayes, Vogel, 2016; Littlejohn *et al.* 2018
- New Physics Brdar, Berryman, PH, 2018

Shell model – HKSS



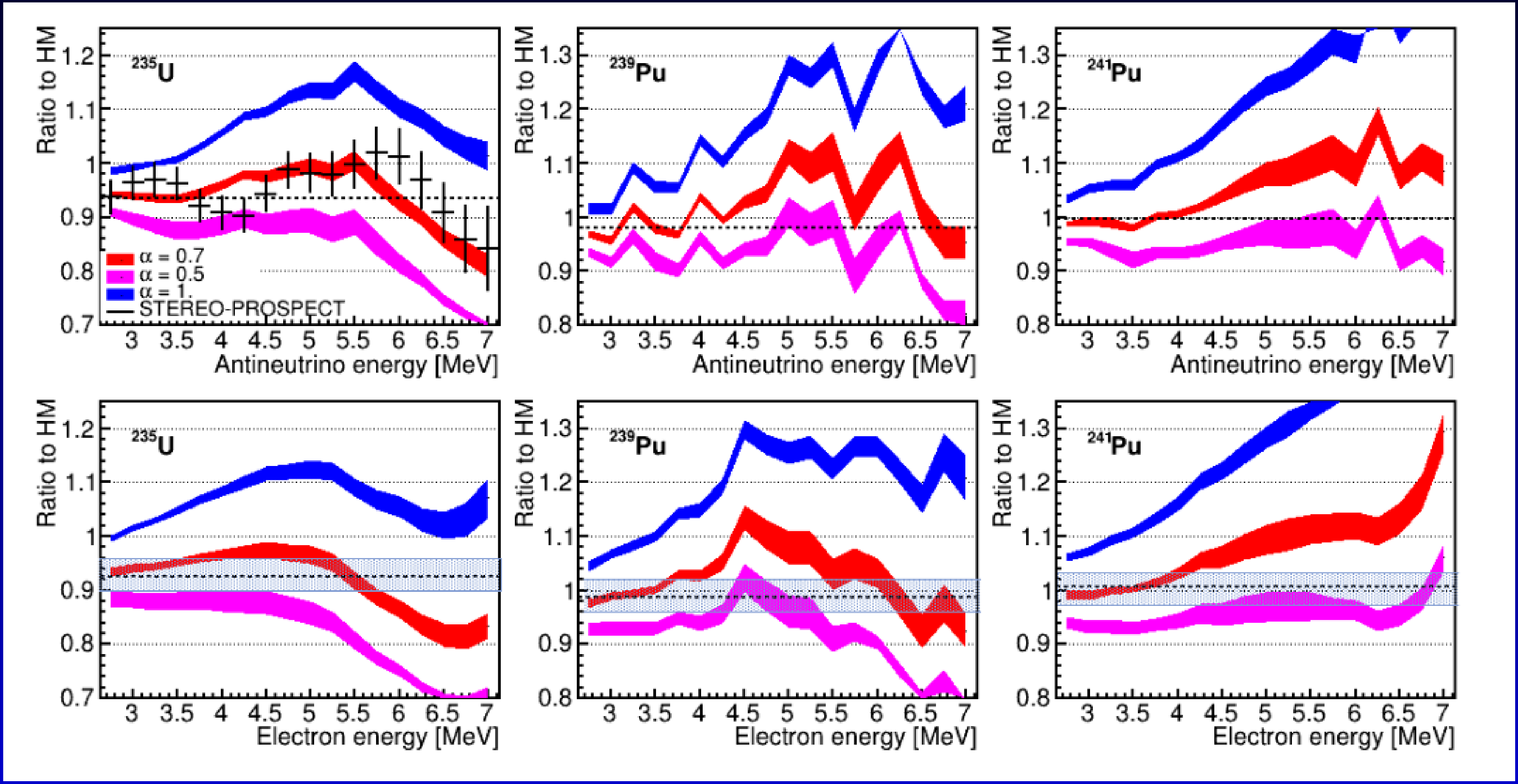
Hayen, *et al.* 2019

Forbidden decays major source of systematic.

Microscopic shell model calculation of 36 forbidden isotopes, otherwise similar to HM.

Increases the IBD rate anomaly by 40%, but the uncertainty increases by only 13% relative to HM

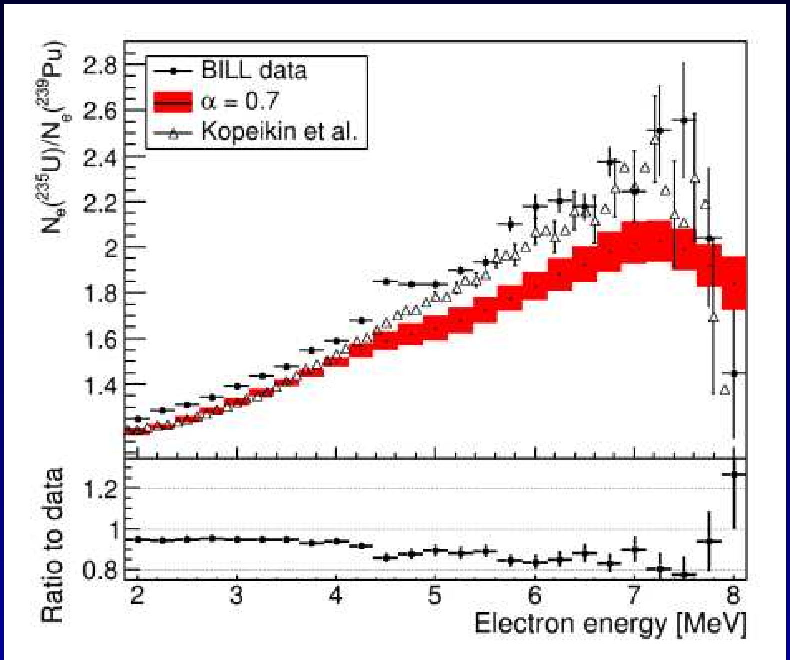
Beta feeding functions



Letourneau *et al.* 2022

Simple single parameter model for beta feeding functions, parameter determined from TAGS data.

Beta feeding functions



Letourneau *et al.* 2022

This would require a shape distortion in both the Schreckenbach (magnetic spectrometer) and Kurchatov (scintillator) beta measurements between U235 and Pu239…

Summary – Rates

- The Kurchatov result for the U235/Pu239 beta ratio seems to bring all neutrino data and all calculations into agreement on the rate
- Subleading corrections may remain from forbidden decay, beta feeding, conversion systematics etc. – comparable to experimental systematics from the reactor and detector

Is there any more work needed?

Who would be the end user for improved predictions (=smaller error bars)?

Or is this essentially solved?

Summary – Spectrum

- In absolute terms this is a small effect (0.5% of all IBD) only visible due to the fantastic precision of recent neutrino data.
- So far all models which explain the bump also have do discard some other pieces of data.
- In particular, obtaining a sufficiently large bump in neutrinos spoils the agreement with beta data (both ILL and Kurchatov)

JUNO-TAO will provide new very precise neutrino spectrum data – do we need a new beta measurement with a matched level of precision?

Theory uses parameterized phenomenological models – how can we improved that?