NuFact 20|21

The 22nd International Workshop on neutrinos from accelerators

Reactor antineutrino anomaly in light of recent flux model refinements

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On the basis of the work with *C. Giunti, Y.F. Li, C.A. Ternes*

NuFact 2021: The 22nd International Workshop on Neutrinos from Accelerators

Online Event

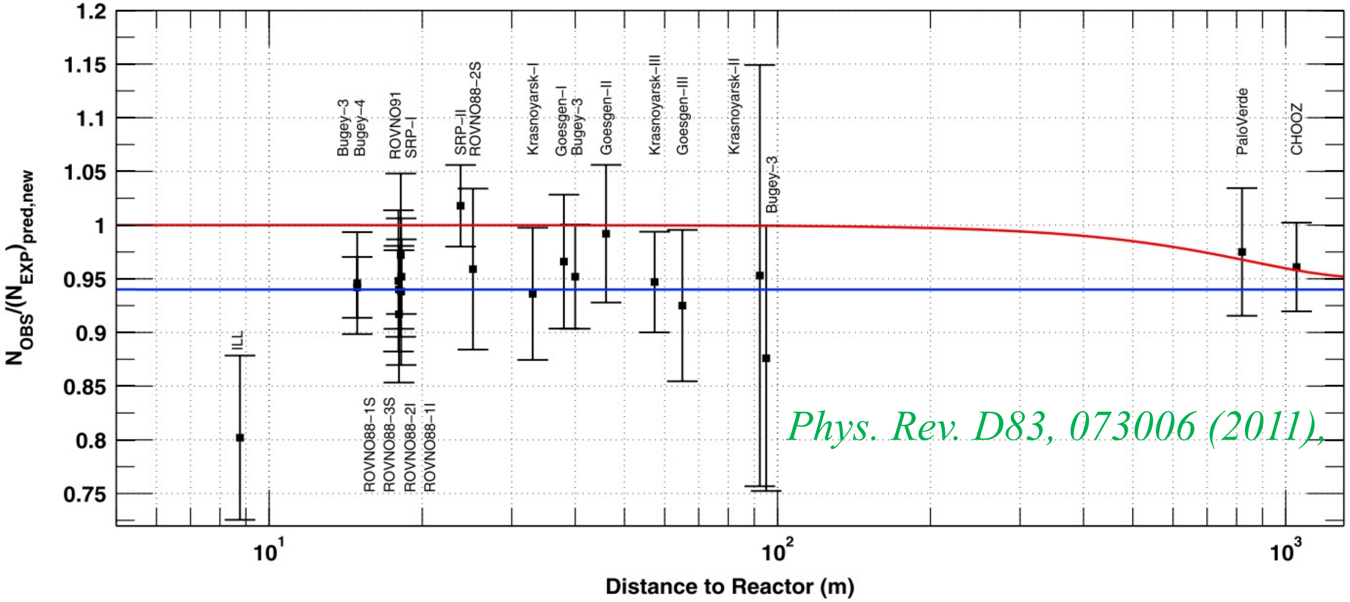
Outline

- Motivation
- New calculation of IBD yield
- Method of analysis
- Fit of reactor rates
- Fit of reactor fuel evolution data
- Best-fit model
- Summary

Part 1:
Motivation

Motivation

- Reactor antineutrino anomaly



Phys. Rev. D83, 073006 (2011).

mean averaged ratio:
$\bar{R} = 0.943 \pm 0.024$

- Reactor experiments data → test RAA for different models.

Models

- Huber-Mueller model *Phys. Rev. C 83, 054615 (2011)* *Phys. Rev. C 85, 029901 (2012)*
- Estienne-Fallot summation model *Phys. Rev. Lett. 123, no. 2, 022502 (2019)*
- Hayen-Kostensalo-Severijns-Suhonen model *Phys. Rev. C 100, no.5, 054323 (2019)*
- Recent Kurchatov Institute measurements *arXiv:2103.01684*
  - HM → KI model
  - HKSS → HKSS-KI model

Reactor data

- Reactor rates data (27)
  - 80s-90s, 2000s
  - Recent Prospect & STEREO
- Fuel evolution data (8+8)
  - Daya Bay
  - RENO

Part 2:
New calculation of IBD yield

Reactor flux models

- Theoretical reactor antineutrino spectra
  - Conversion method

    Measured β spectra → neutrino spectra
  - Summation method

    Sum all the decay branches database

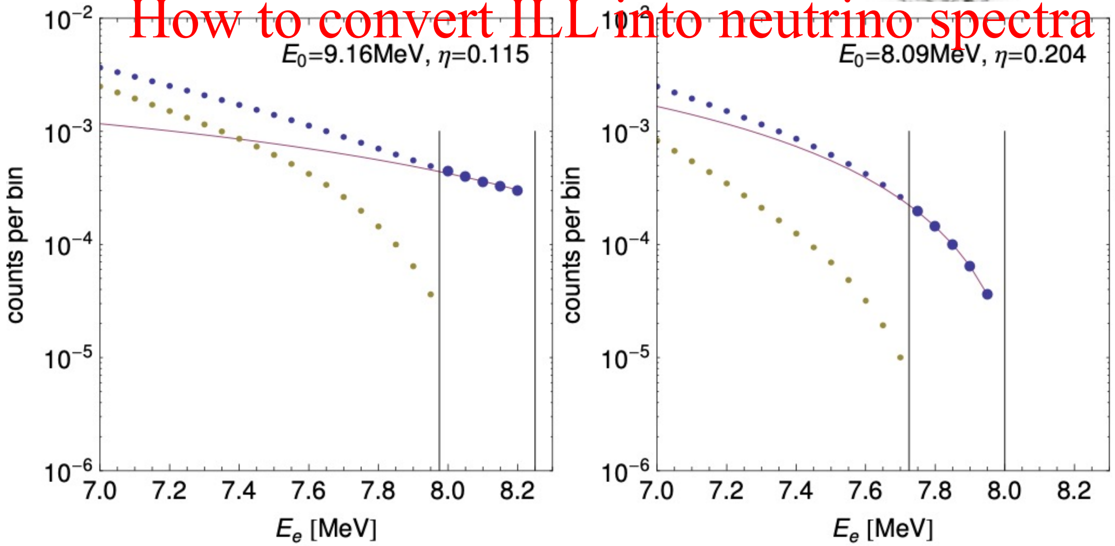
- Huber-Mueller model *Phys. Rev. C 85, 029901 (2012)*
  - ^{235}U, ^{239}Pu, ^{241}Pu : ILL β spectrum → neutrino spectrum *Phys. Rev. C 83, 054615 (2011)*
  - ^{238}U : sum all β decay branches
  - Allowed approximation

forbidden transition

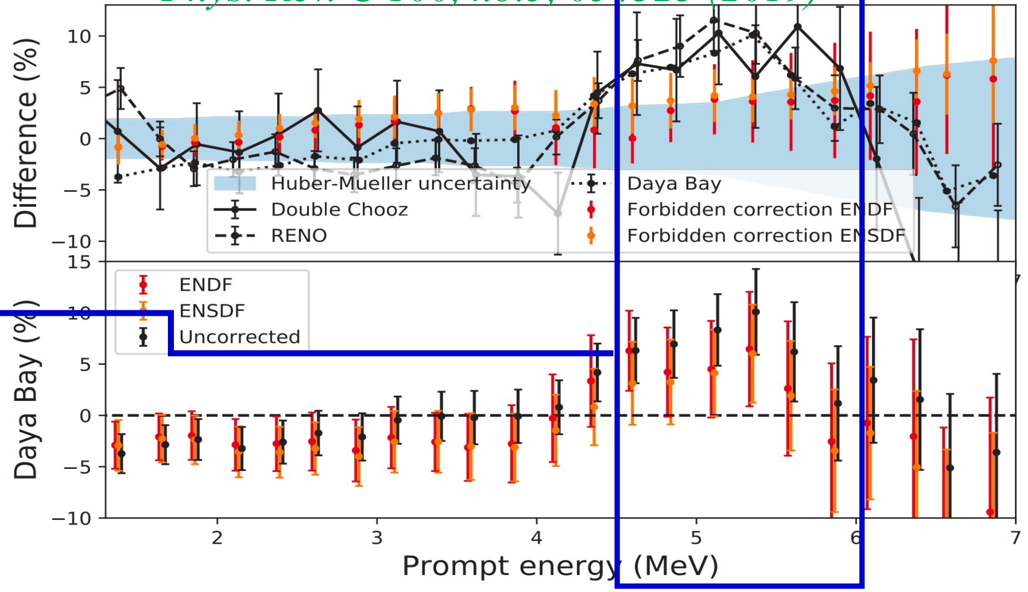
Partially explain “5 MeV bump”!

- HKSS model *Phys. Rev. C 100, no.5, 054323 (2019)*
  - Forbidden transition contribution

How to convert ILL into neutrino spectra



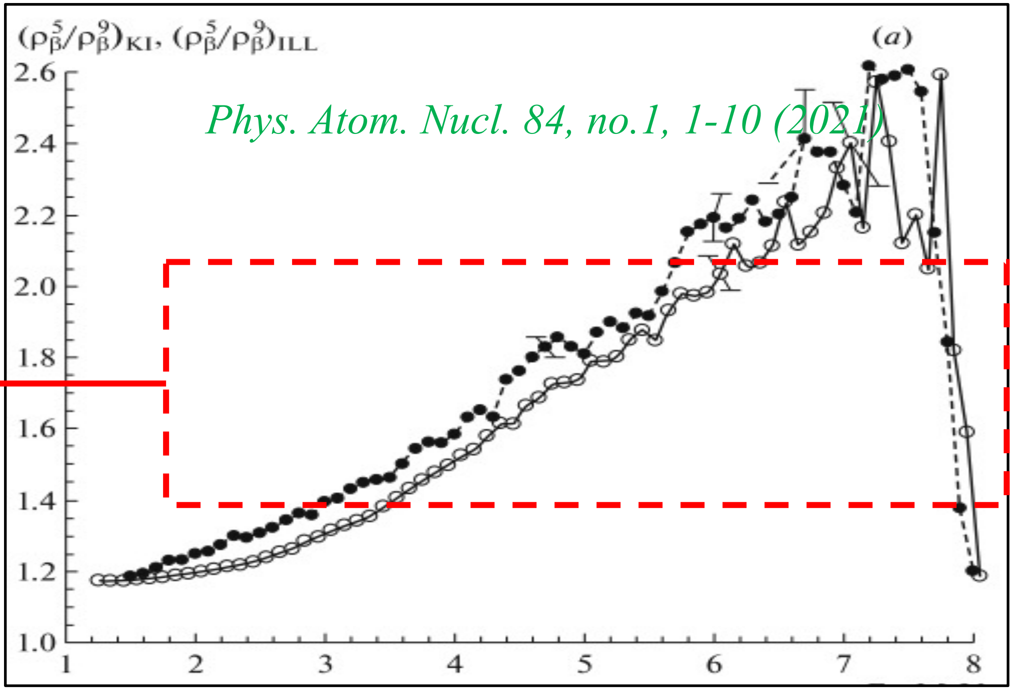
Phys. Rev. C 100, no.5, 054323 (2019)



Reactor flux models

- Kurchatov Institute model: *arXiv:2103.01684*
  - ^{235}U HM model + KI measurement
  - ^{238}U conversion spectrum + KI measurement
  - Pu spectra: same with HM model

- HKSS-KI model:
  - ^{235}U HKSS model + KI measurement
  - ^{238}U and Pu: same with HKSS model



Phys. Atom. Nucl. 84, no.1, 1-10 (2021)

The Kurchatov Institute measurement (open circles) directly measured the ratio of ^{235}U beta spectrum and ^{239}Pu beta spectrum, which is lower than HM model (closed circles) in most region.

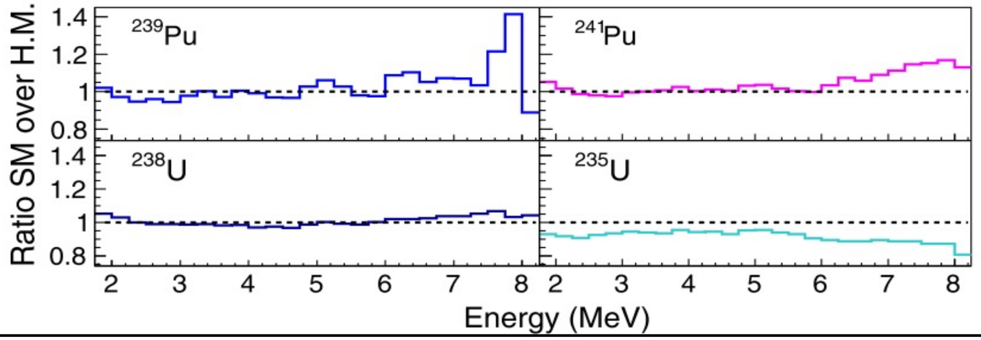
With the assumption of the unchanged ^{239}Pu comparing with ILL

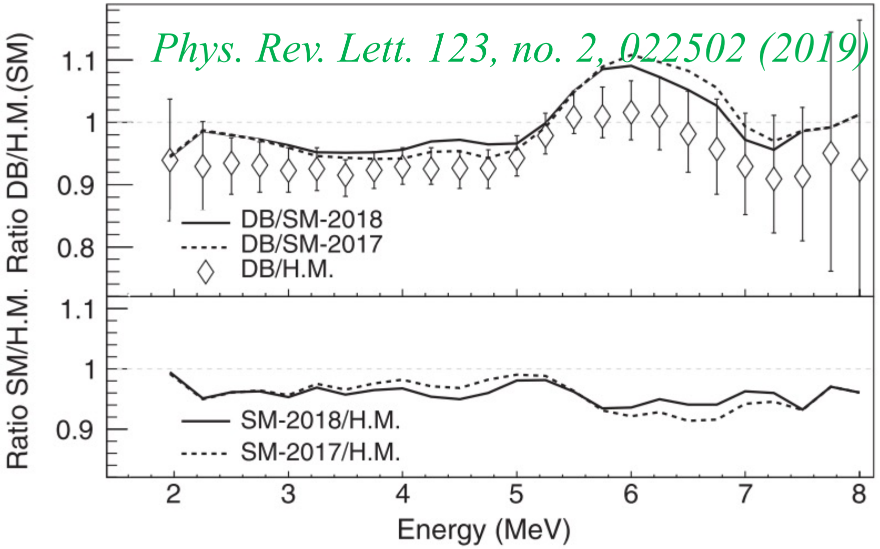
KI measurement: Reduction of ^{235}U !

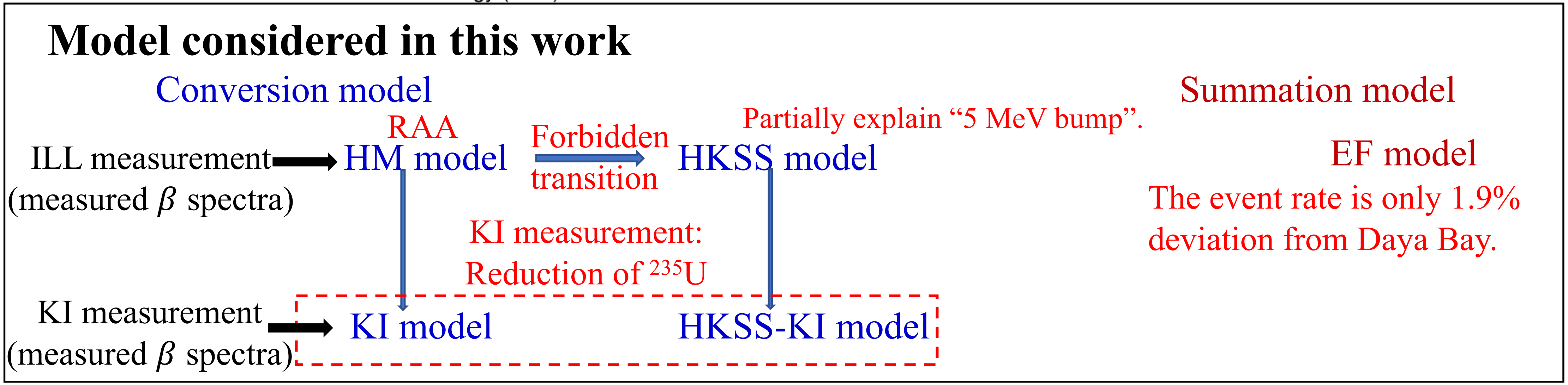
Reactor flux models

Phys. Rev. Lett. 123, no. 2, 022502 (2019)

- Estienne-Fallot summation model
  - Summation method
  - Nuclear database + Pandemonium-free data




Phys. Rev. Lett. 123, no. 2, 022502 (2019)



Model considered in this work

Conversion model

Summation model

ILL measurement (measured β spectra) → HM model

RAA

Forbidden transition → HKSS model

Partially explain "5 MeV bump".

KI measurement: Reduction of ^{235}U

KI measurement (measured β spectra) → KI model

HKSS-KI model

EF model

The event rate is only 1.9% deviation from Daya Bay.

Updated IBD yields

- IBD yield σ_f $\sigma_{f,a} = \sum_i f_i^a \sigma_i,$

  $i = 235, 238, 239,$ and 241 for ^{235}U, ^{238}U ^{239}Pu and ^{241}Pu.

- The individual IBD yield σ_i

$$\sigma_i = \int_{\underline{E_{\min}}}^{E_{\max}} dE\, \Phi_i(E)\, \underline{\sigma_{\mathrm{IBD}}(E)},$$

1. **IBD cross section:** *Phys. Rev. D60, 053003 (1999)*

   1st-order Vogel-Beacom IBD cross section w/ PDG 2020

0th-order cross section $\sigma_{tot}^{(0)} = \frac{2\pi^2/m_e^5}{f_{p.s.}^R \tau_n} E_e^{(0)} p_e^{(0)}$

Neutron lifetime $\tau_n = 879.4s$

Phase space factor $f_{p.s.}^R = 1.7152$

0th-order $E_e^{(0)} = E_\nu - \Delta,$

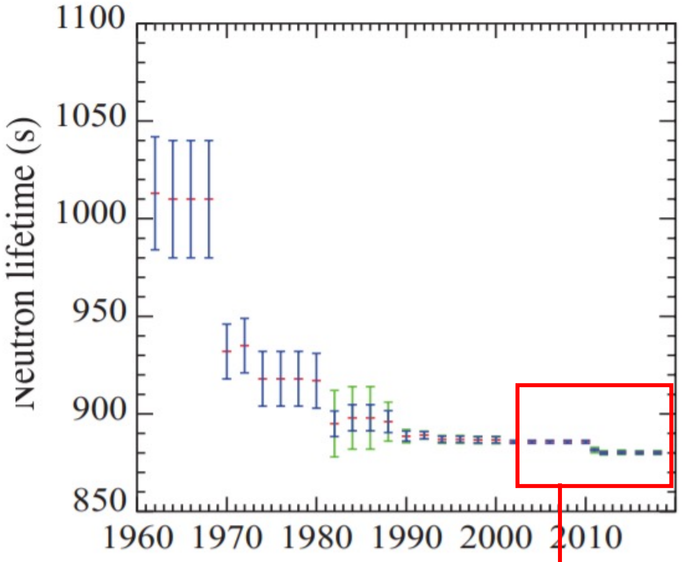
$$\Delta = M_n - M_p$$

1st-order

$$E_e^{(1)} = E_e^{(0)}\left[1 - \frac{E_\nu}{M}(1 - v_e^{(0)}\cos\theta)\right] - \frac{y^2}{M}$$

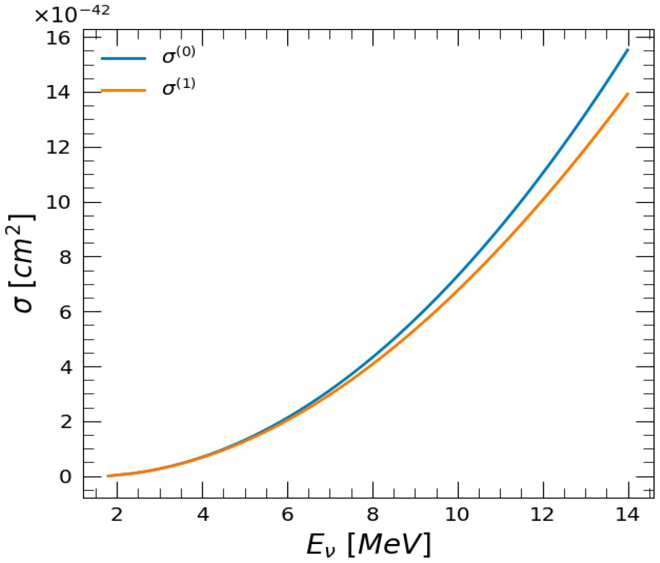
$$y^2 = (\Delta^2 - m_e^2)/2$$

2. **Integral energy regions**



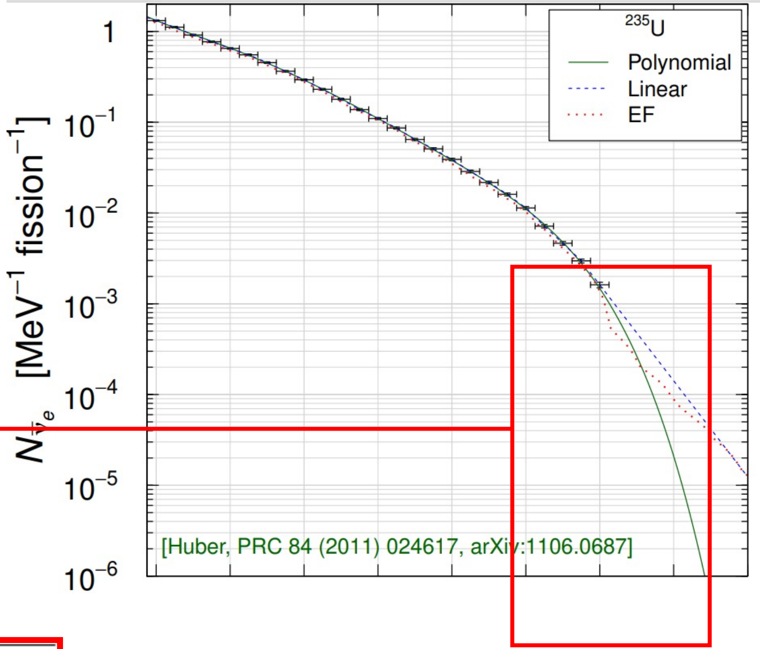
A historical perspective of values of neutron lifetime τ_n

0th and 1st order IBD cross section



Updated IBD yields

- The individual IBD yield σ_i
  1. **IBD cross section** *Phys. Rev. D60, 053003 (1999)*
  2. **Integral energy regions** (1.8→10.0 MeV)
     - Low energy region (1.8 → 8.0 MeV) extrapolate and interpolate with the original spectra.
     - High energy region approximation (8.0 → 10.0 MeV) EF summation model spectra with a very conservative 100% uncertainty.



[Huber, PRC 84 (2011) 024617, arXiv:1106.0687]

original IBD yields

Model	σ_{235}	σ_{238}	σ_{239}	σ_{241}
HM	6.69 ± 0.14	10.10 ± 0.82	4.40 ± 0.11	6.03 ± 0.13
EF	6.28 ± 0.31	10.14 ± 1.01	4.42 ± 0.22	6.23 ± 0.31
HKSS	6.74 ± 0.17	10.33 ± 0.85	4.43 ± 0.13	6.07 ± 0.16
KI	6.27 ± 0.13	9.34 ± 0.47	4.33 ± 0.11	6.01 ± 0.13

our selected IBD yields input

Model	σ_{235}	σ_{238}	σ_{239}	σ_{241}
HM	6.62 ± 0.16	10.09 ± 0.82	4.34 ± 0.13	6.02 ± 0.16
EF	6.23 ± 0.31	10.07 ± 1.00	4.37 ± 0.22	6.17 ± 0.31
HKSS	6.70 ± 0.17	10.19 ± 0.84	4.39 ± 0.13	6.09 ± 0.16
KI	6.29 ± 0.13	9.44 ± 0.48	4.34 ± 0.13	6.02 ± 0.16
HKSS-KI	6.36 ± 0.13	10.19 ± 0.84	4.39 ± 0.13	6.09 ± 0.16

Small contribution above 8 MeV:
0.3% for ^{235}U, 0.9% for ^{238}U,
0.2% for ^{239}Pu, 0.3% for ^{241}Pu.

Part 3:
Method of analysis

LSM with Wilks' theorem

How to treat the systematic theoretical uncertainties in the least-squares function.

Method A

Phys. Rev. D83, 073006 (2011)

JHEP 1706, 135 (2017)

A covariance matrix with experimental and theoretical uncertainties added in quadrature.

$$\chi^2 = \sum_{a,b} \left(\sigma^{\rm exp}_{f,a} - R^a_{\rm NP}\sigma^{\rm th}_{f,a}\right) \left(V^{\rm tot}\right)^{-1}_{ab} \left(\sigma^{\rm exp}_{f,b} - R^b_{\rm NP}\sigma^{\rm th}_{f,b}\right)$$

$$V^{\rm tot} = V^{\rm exp} + \underline{V^{\rm th}} \qquad \sigma^{\rm th}_{f,a} = \sum_i f^a_i \sigma^{\rm mod}_i .$$

A strongly-correlated theoretical matrix derived from the covariance matrix V_{ij}^{mod} among ^{235}U, ^{238}U, ^{239}Pu, and ^{241}Pu

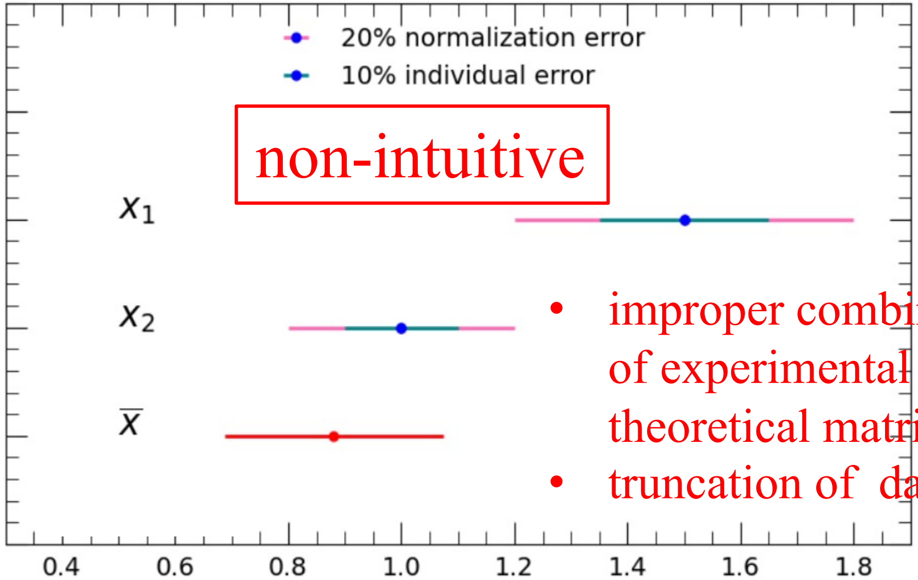
The method A will suffer the PPP!

Journal of Nuclear Science and Technology 31, 770 (1994).

Peelle's Pertinent Puzzle

strongly correlated data

the best-fit average can be lower than most of the data



non-intuitive

- improper combination of experimental and theoretical matrices
- truncation of data space.

LSM with Wilks' theorem

Method B *Phys. Rev. D87, 073018 (2013)*

Calculate the fit results considering only the experimental uncertainties and add by hand a global theoretical uncertainty to the final result.

hard to calculate

$$\chi^2 = \sum_{a,b} \left(\sigma^{\text{exp}}_{f,a} - R^a_{\text{NP}} \sigma^{\text{th}}_{f,a}\right) \left(V^{\text{exp}}\right)^{-1}_{ab} \left(\sigma^{\text{exp}}_{f,b} - R^b_{\text{NP}} \sigma^{\text{th}}_{f,b}\right)$$

Method C **Method C is adopted in this work!**

Phys.Rev.Lett. 120, 022503 (2018), Phys.Rev. D99, 073005 (2019)

Consider the theoretical uncertainties with appropriate pull terms

$$\chi^2 = \sum_{a,b} \left(\sigma^{\text{exp}}_{f,a} - R^a_{\text{NP}} \sigma^{\text{th}}_{f,a}\right) \left(V^{\text{exp}}\right)^{-1}_{ab} \left(\sigma^{\text{exp}}_{f,b} - R^b_{\text{NP}} \sigma^{\text{th}}_{f,b}\right)$$

$$+ \sum (r_i - 1) \left(\widetilde{V}^{\text{mod}}\right)^{-1}_{ij} (r_j - 1) ,$$

$$\sigma^{\text{th}}_{f,a} = \sum_i r_i f^a_i \sigma^{\text{mod}}_i . \quad \widetilde{V}^{\text{mod}}_{ij} = V^{\text{mod}}_{ij} / (\sigma^{\text{mod}}_i \sigma^{\text{mod}}_j)$$

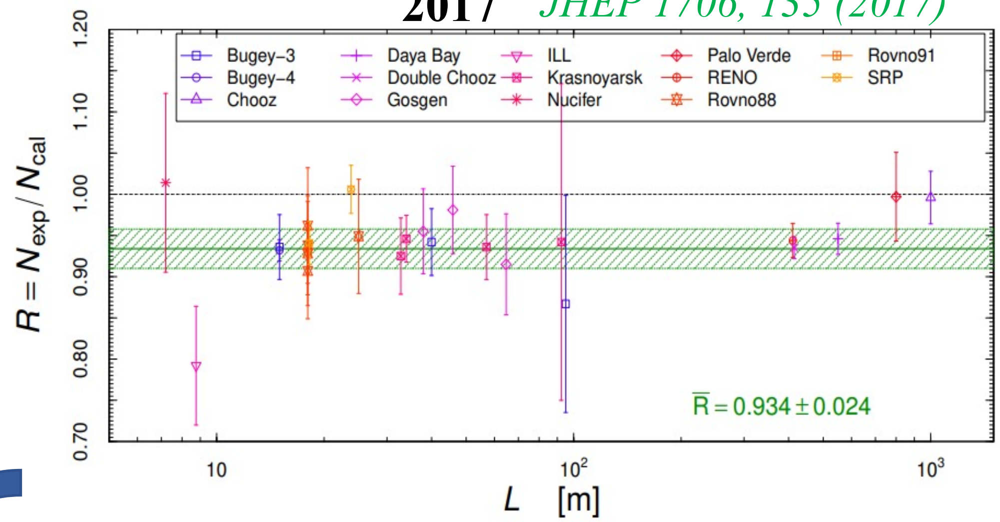
V_{ij}^{mod} covariance matrix for these four isotopes

PPP is avoided by decoupling the minimization of physical parameters from the minimization of pull coefficients!

Part 4:
Fit of reactor rates & evolution data

Fit of reactor rates

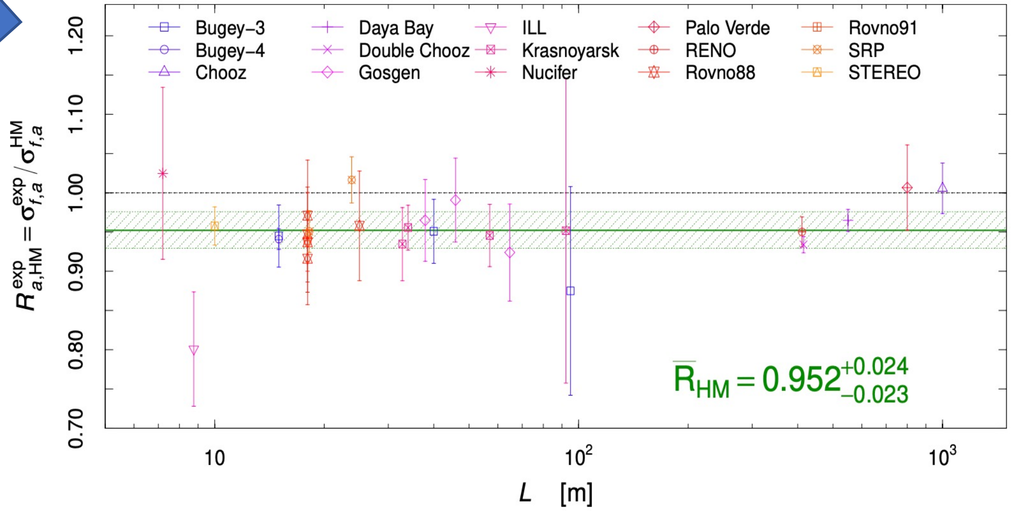
2017 *JHEP 1706, 135 (2017)*



HM model

Original HM IBD yield	Updated HM IBD yield
6.69 ± 0.14	6.62 ± 0.16
10.10 ± 0.82	10.09 ± 0.82
4.40 ± 0.11	4.34 ± 0.13
6.03 ± 0.13	6.02 ± 0.13

Our work



Work in 2017

RAA:2.8 σ

0.934 ± 0.024

w/ new IBD yields

Work in 2021

RAA:2.5 σ

0.940 ± 0.024

w/ method C

w/ method C

w/ new IBD yields

0.943 ± 0.024

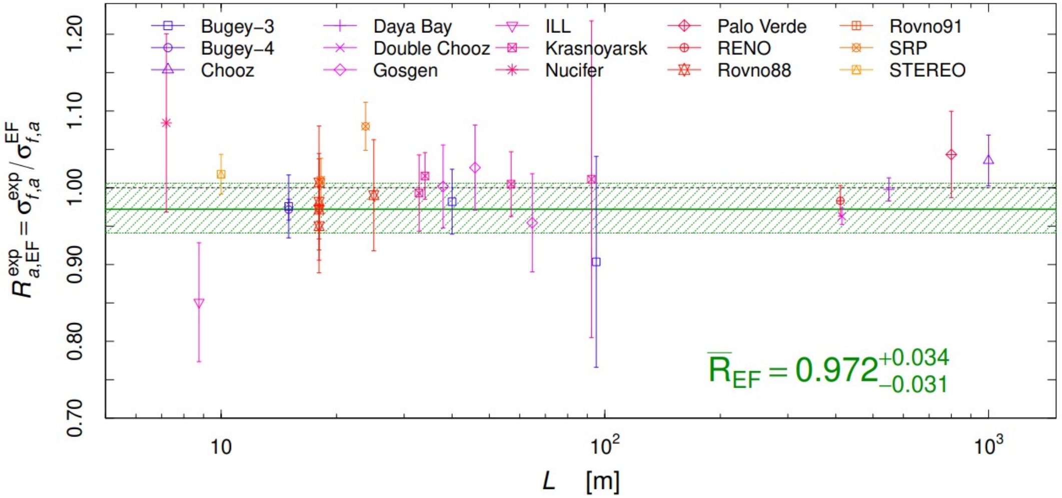
0.952 ± 0.024

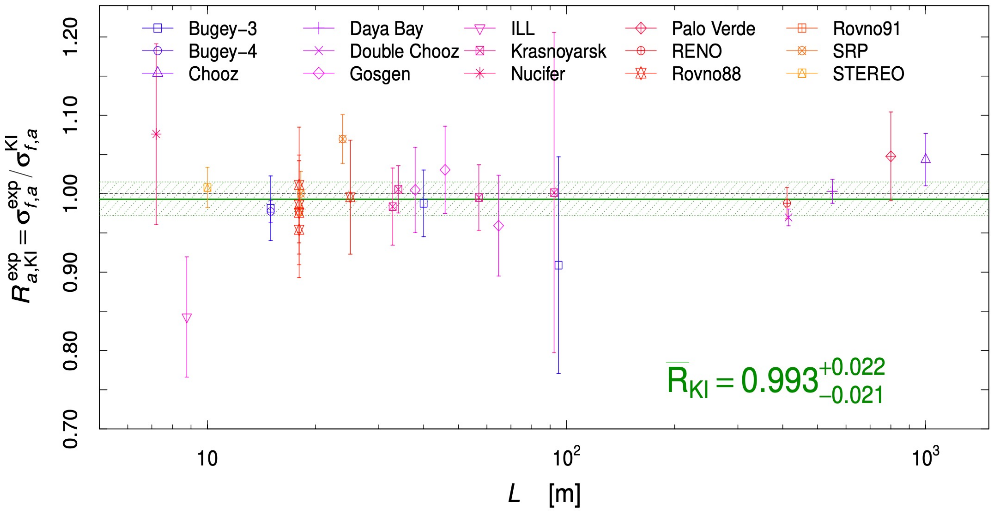
RAA:1.9 σ

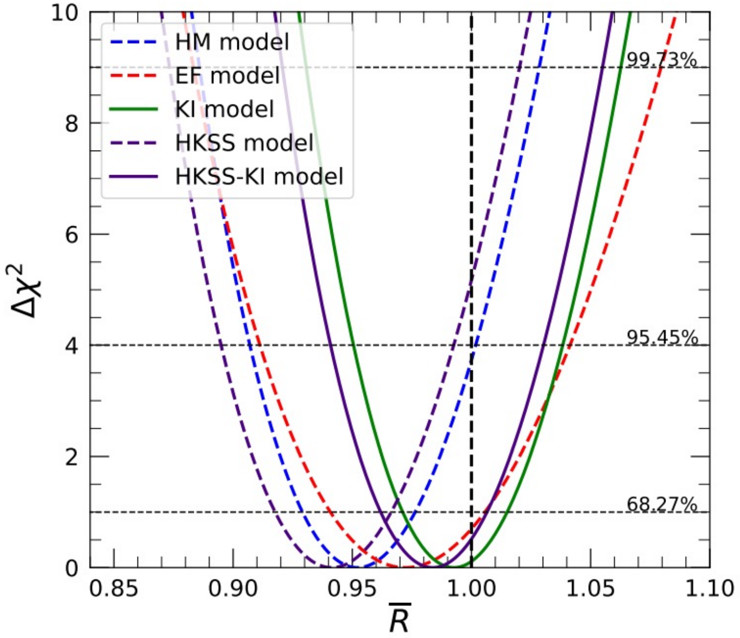
RAA:2.3σ

RAA: 2.8σ (2017) → 1.9σ (2021)

Fit of reactor rates







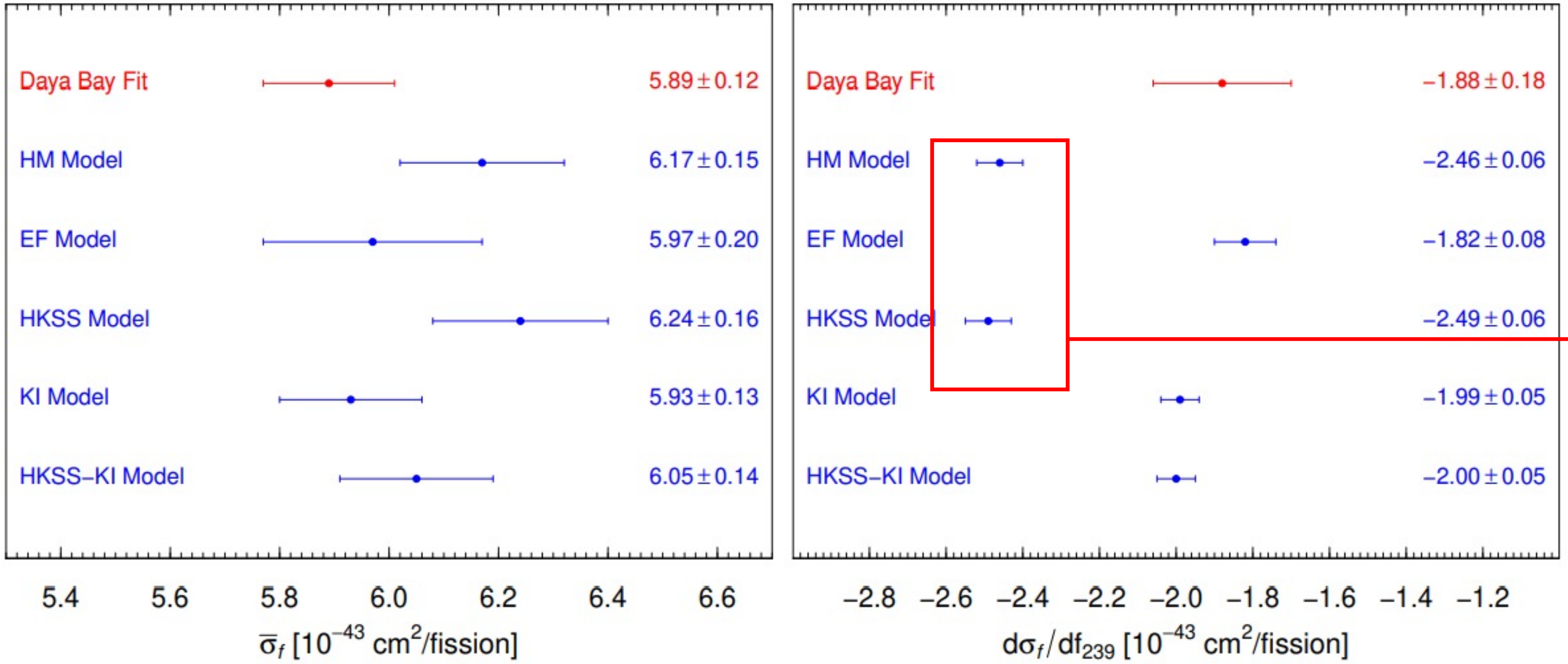
Model	$\overline{R}$	RAA
HKSS	$0.941^{+0.025}_{-0.023}$	2.3 σ
EF	$0.972^{+0.034}_{-0.031}$	0.9 σ
KI	$0.993^{+0.022}_{-0.021}$	0.3 σ
HKSS-KI	$0.982^{+0.022}_{-0.021}$	0.8 σ

These 3 models give RAA less than 1 σ .(No anomaly)

Fit of reactor fuel evolution data

To compare the fuel evolution data with the different model predictions, we first fit the evolution data with a linear function describing the IBD yield as a function of f_{239}

$$\sigma^{\rm lin}_{f,a} = \underline{\bar{\sigma}_f} + \frac{d\sigma_f}{\underline{df_{239}}}\left(f^a_{239} - \bar{f}_{239}\right),$$



(a) (b)

Fitting with evolution data of Daya Bay

When using RENO data, we have the similar results.

The HM and HKSS models are disfavored by the evolution data

Fig(b) fit of slope

- 3.1 σ for HM model
- 3.2 σ for HKSS model

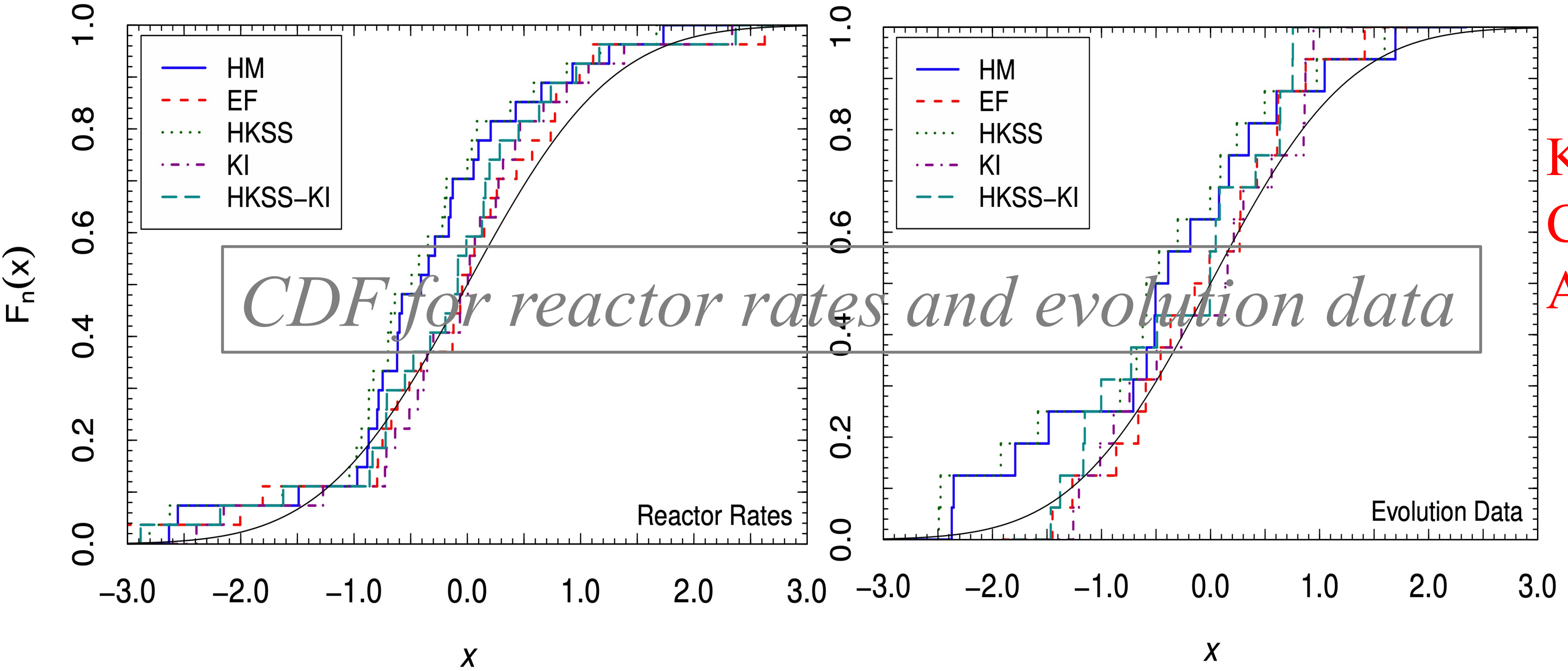
- EF, KI and HKSS-KI models give values of $\bar{\sigma}_f$ and $d\sigma_f/df_{239}$ that agree with the fit of the evolution data within the uncertainties.

Part 5:
Best-fit model

Statistic test

- χ^2 test: only shows the size of deviation not show the sign
  rejects none of the five models

$$x_a^{\text{mod}} = \sum_b \left(V^{\text{tot}}\right)_{ab}^{-1/2} \left(\sigma_{f,b}^{\text{exp}} - \sigma_{f,b}^{\text{mod}}\right)$$



CDF for reactor rates and evolution data

only size of deviation

χ^2 test

Shapiro-Wilk test

sign test positive or negative deviations

Kolmogorov-Smirnov test
Cramer-von Mises test
Anderson-Darling test

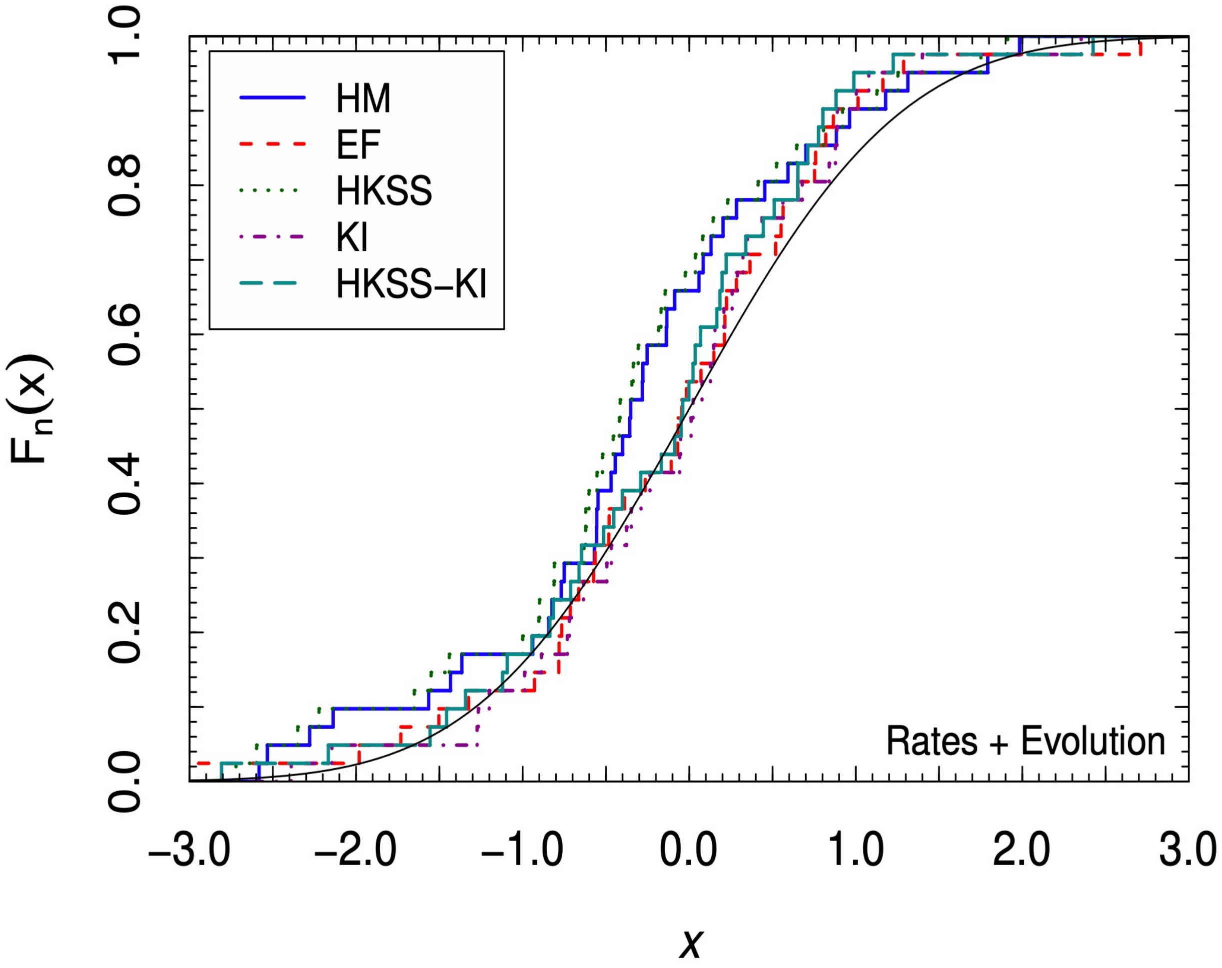
Journal of the Royal Statistical Society Series B 64, 281 (2002).

Z_K, Z_C, Z_A test

more powerful, based on likelihood ratio

Statistic test

p-value=0.05 → confidence level 95%



rates + evolution data

Test	HM	EF	HKSS	KI	HKSS-KI
χ^2	0.21	0.46	0.14	0.78	0.60
SW	0.37	0.28	0.38	0.69	0.58
sign	0.03	0.38	0.01	0.38	0.38
KS	0.08	0.81	0.04	0.82	0.56
CVM	0.06	0.78	0.03	0.76	0.47
AD	0.07	0.72	0.03	0.76	0.47
Z_K	0.001	0.22	0.0002	0.15	0.03
Z_C	0.11	0.60	0.04	0.86	0.62
Z_A	0.14	0.44	0.06	0.77	0.40

EF model is the best **summation** model;

KI model is the best **conversion** model.

Part 6:
Summary

Summary

HM model

RAA: $2.8\sigma \rightarrow 1.9\sigma$

- Updated IBD yields including high energy regions.
- Comparison of different fitting method

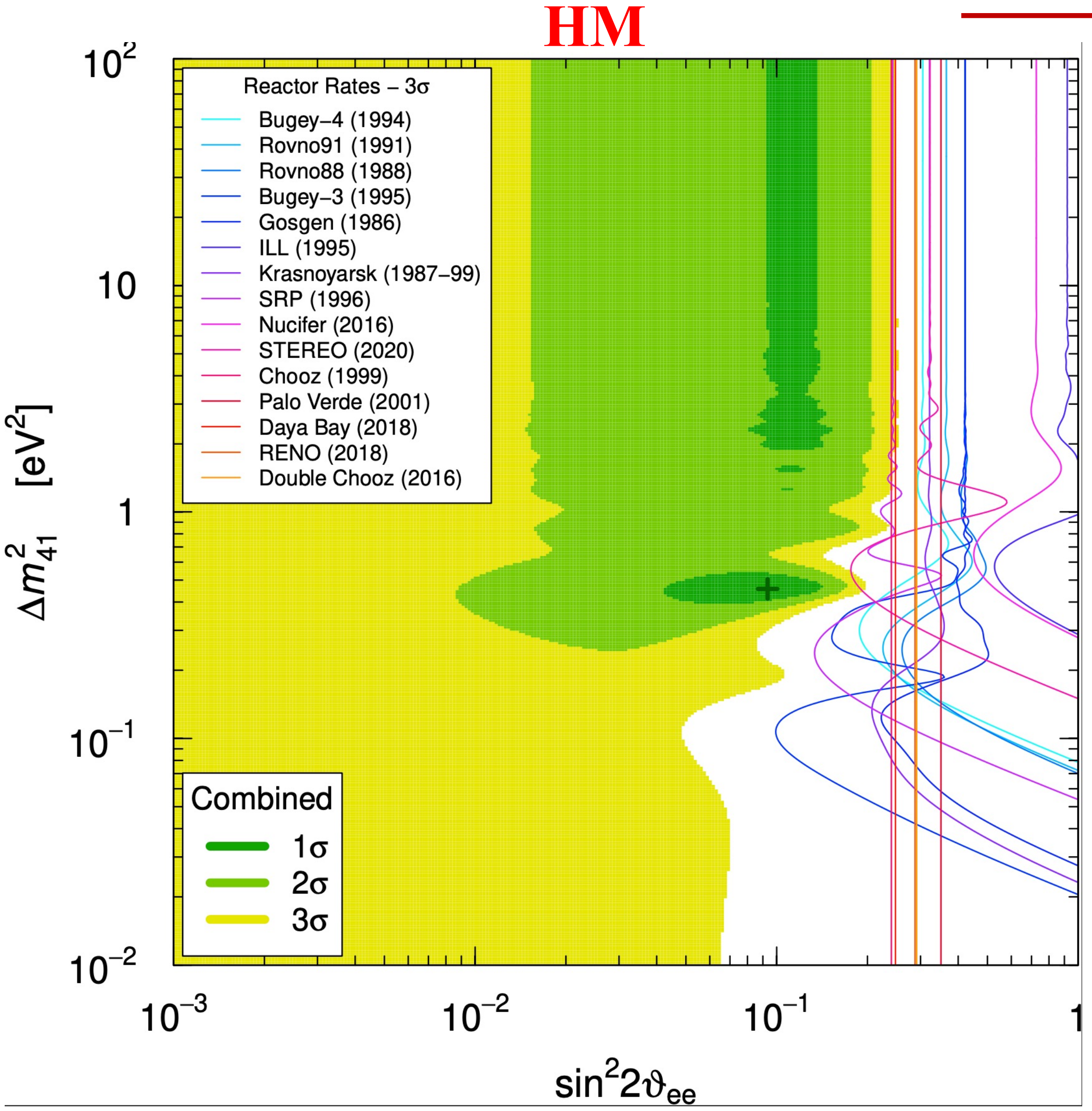
  With improved fitting method (Method C), the RAA seems smaller for all models (for HM, $2.5\sigma \rightarrow 1.9\sigma$) avoiding the PPP successfully.

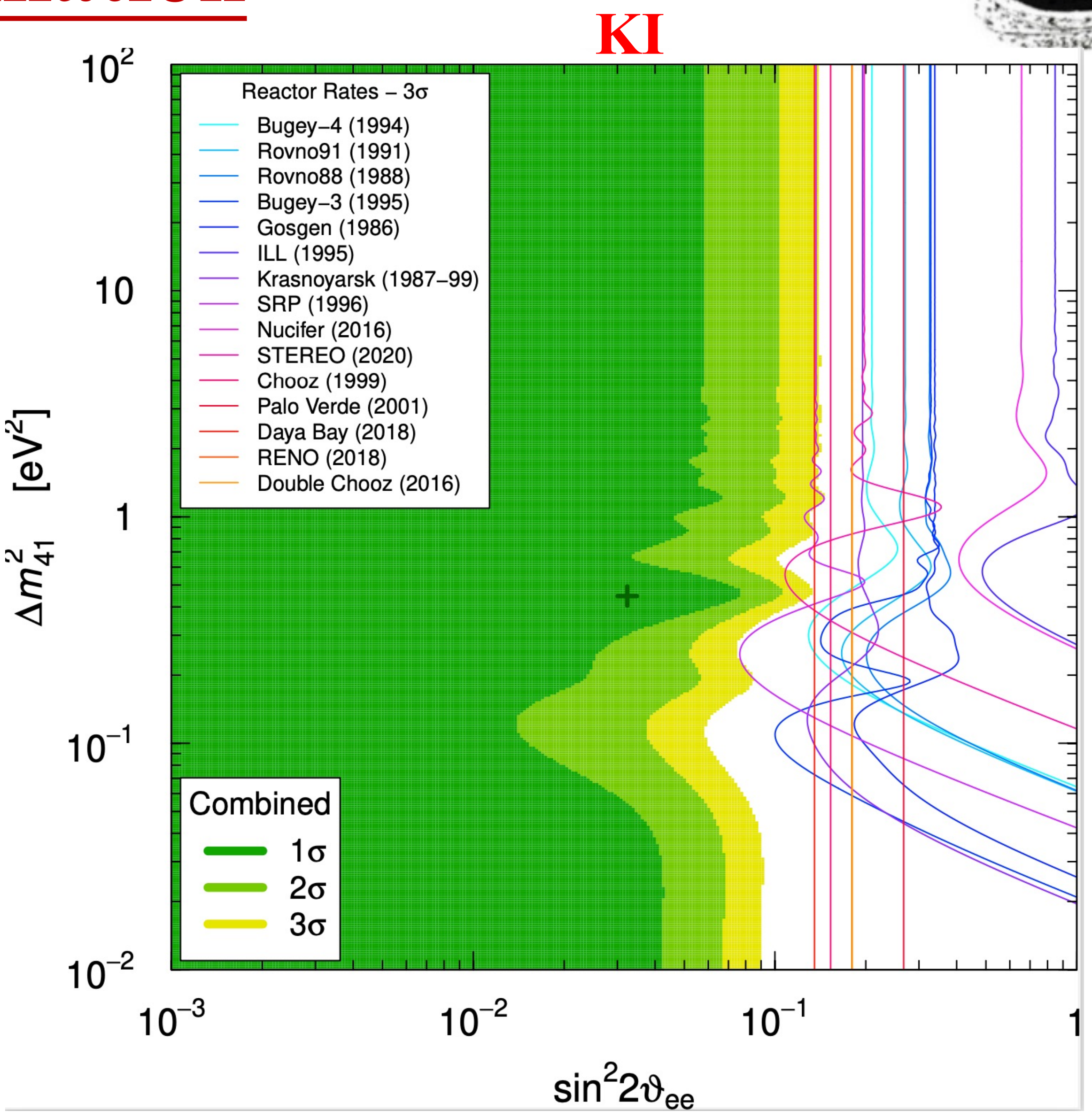
- As for the best-fit model, EF model is the best summation model, and KI model is the best conversion model.
- The KI measurement can pull down the rate deficit, which implies the reactor antineutrino anomaly might be caused by **mis-normalization** in ILL measurements. (need other experiments to confirm)
- Shape anomaly ("5 MeV Bump") is still not solved.

Thanks!

Backup

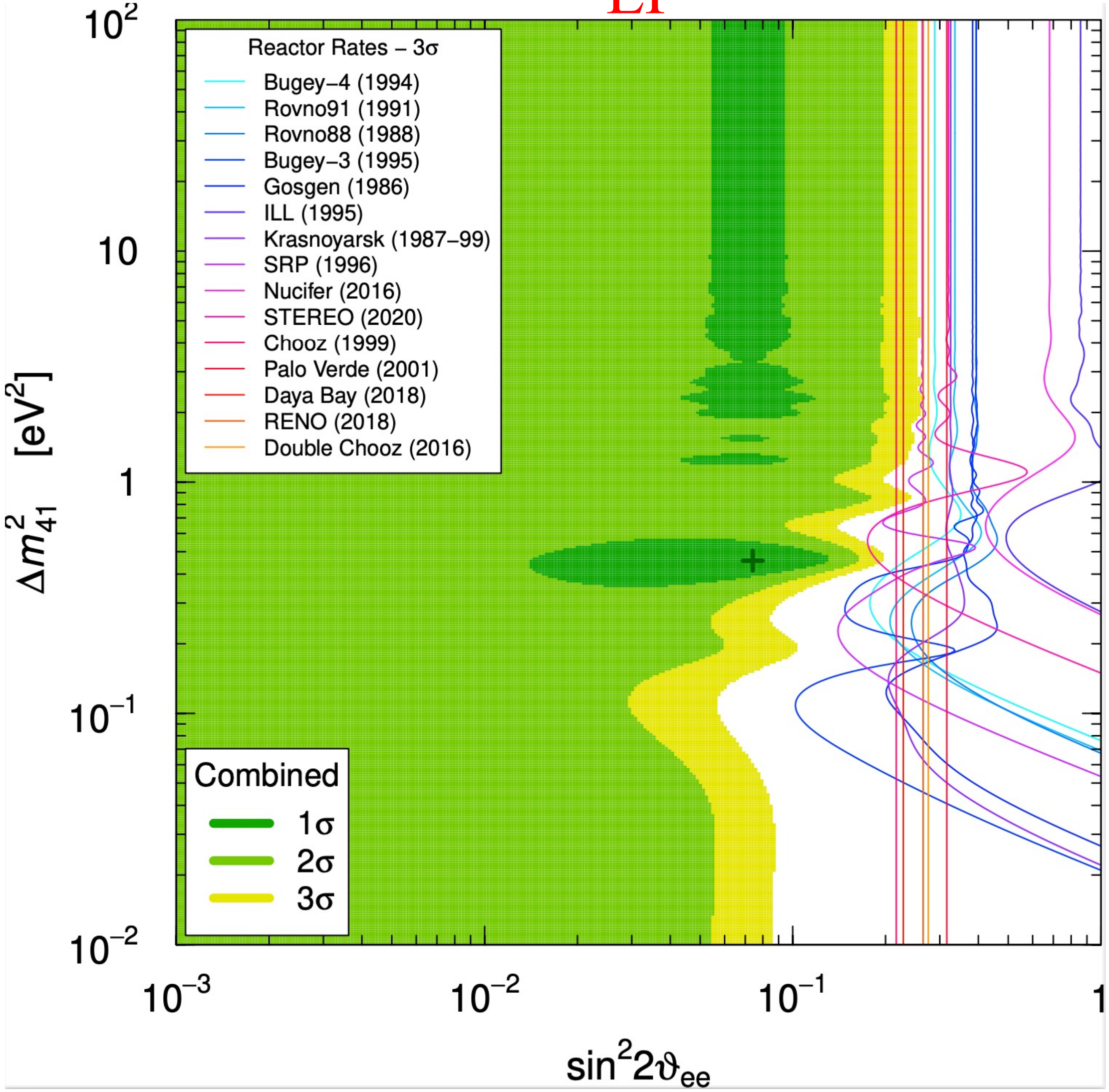
Oscillation





Oscillation

EF



HKSS-KI