ν spectrum emitted by a reactor

The prediction of reactor ν spectrum is the dominant source of systematic error for single detector experiments

Reactor data

Thermal power, $\delta Pth \leq 1\%$

Reactor evolution codes

Fraction of fissions from isotope *k*, $\delta\alpha_k$=few % but large anti-correl @ fixed P_{th}

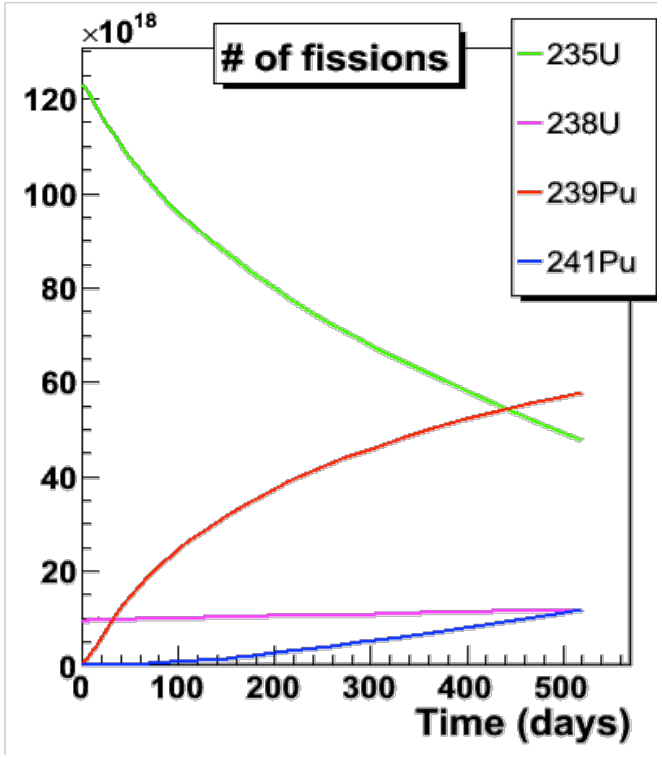
$$\Phi_\nu(E,t) = \frac{P_{th}(t)}{\sum_k \alpha_k(t) E_k} \times \sum_k \alpha_k(t) S_k(E)$$

Nuclear databases

E relased per fissions of isotope *k*, $\delta E_k \approx 0.3\%$

ν spectrum per fission

This work !



$$k = {}^{235}U, {}^{238}U, {}^{239}Pu, {}^{241}Pu$$

The guts of $S_k(E)$

Sum of all fission products' activities

$$S_k(E) = \sum_{fp=1}^{N_{fp}} \mathcal{A}_{fp}(T) \times S_{fp}(E)$$

Sum of all β-branch of each fission product

$$S_{fp}(E) = \sum_{b=1}^{N_b} BR_{fp}^b \times S_{fp}^b(Z_{fp}, A_{fp}, E_{0fp}^b, E)$$

Theory of β-decay

$$S_{fp}^b = \underbrace{K_{fp}^b}_{\text{Norm.}} \times \underbrace{\mathcal{F}(Z_{fp}, A_{fp}, E)}_{\text{Fermi function}} \times \underbrace{pE(E - E_{0fp}^b)^2}_{\text{Phase space}}$$

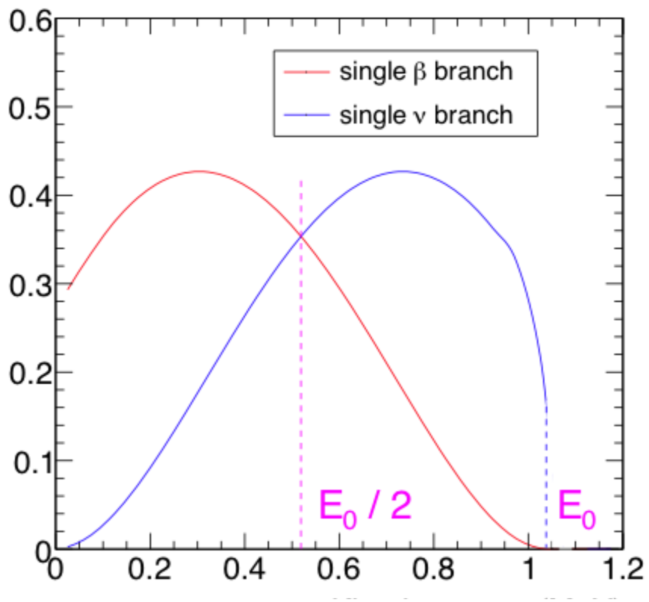
$$\times \quad \underbrace{C_{fp}^b(E)}_{\text{Shape factor}} \times \underbrace{\left(1 + \delta_{fp}^b(Z_{fp}, A_{fp}, E)\right)}_{\text{Correction}}$$

$$\delta_{fp}^b(Z_{fp}, A_{fp}, E) = \delta_{QED}(E) + A_C(Z_{fp}, A_{fp}) \times E + A_W \times E$$

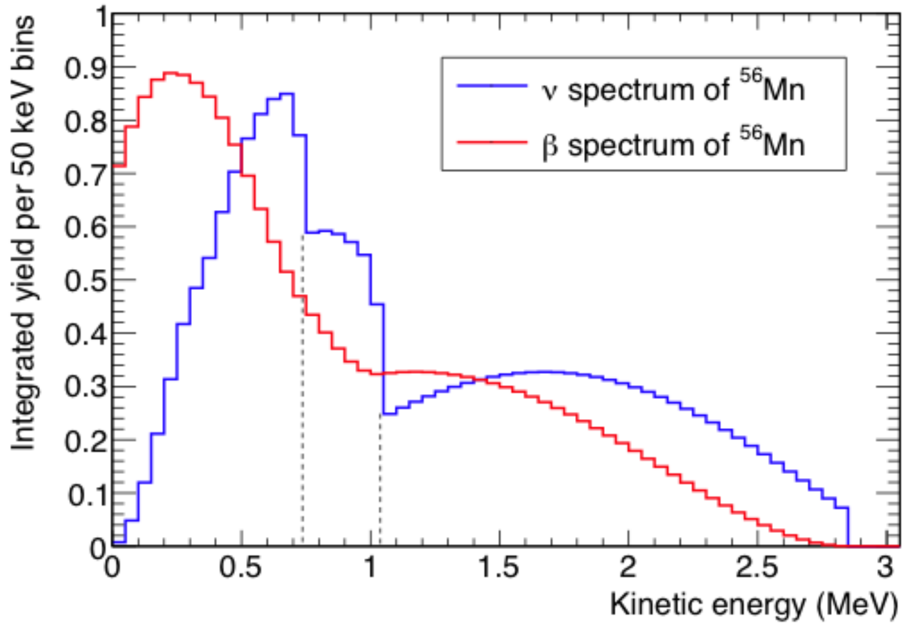
e^- spectrum ⟷ ν spectrum

• Exact conversion requires complete knowledge from fission yield down to β-transition between parent ground (or isomeric)-state and daughter states

β-branch level



Fission product level



• **Lot of relevant quantities**: Z, A, End-points, J^π, nuclear matrix elements, branching ratios, fission yields, life time… **but scarce data as E_0 increases → integral electron spectra**.

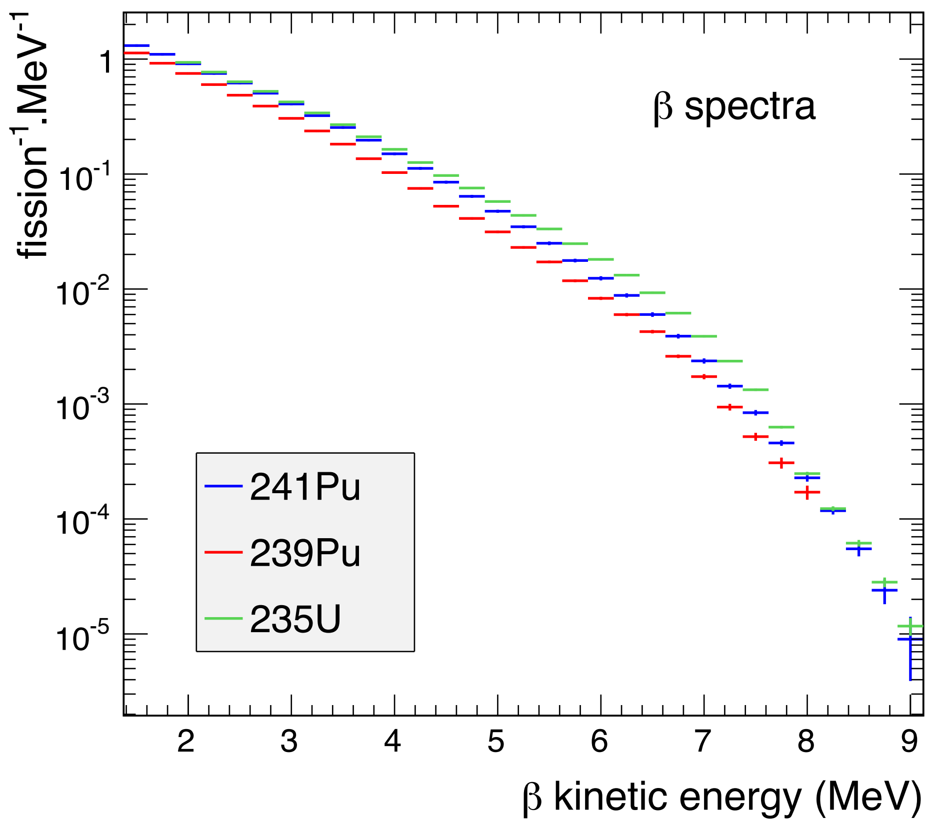
Anchor point of ILL electron data

Accurate measurements @ ILL in the 80's:

- High resolution magn. spectrometer
- Intense and pure thermal neutron spectrum from the core.
- Extensive use of reference internal conversion electron lines
  - → Normalization
  - → Shape via $\varepsilon_{det}(E)$

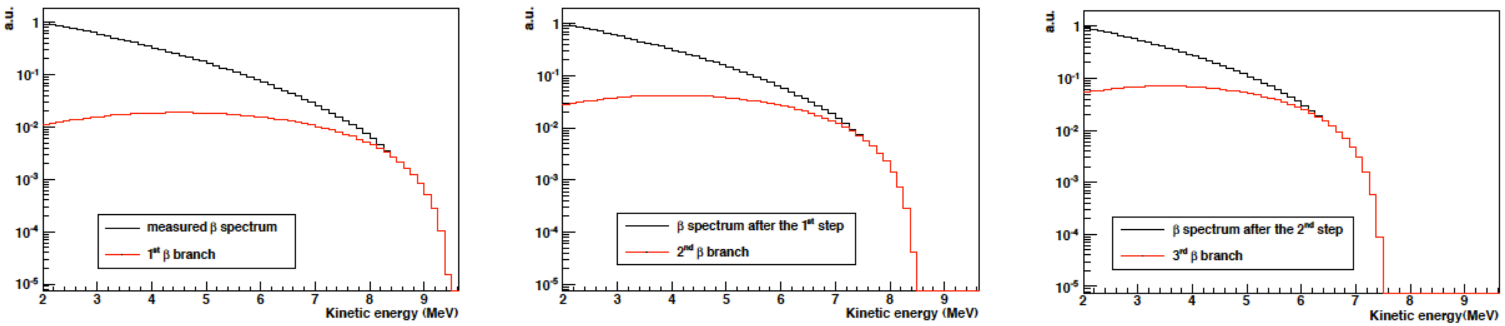
Unique reference to be met by any other measurement or calculation

Total electron spectra from the β-decays of ^{235}U, ^{239}Pu and ^{241}Pu fission products.



ILL data: conversion to ν spectra

Lost info of single β-branches → fit e^- (50 keV bins) spectrum with a sum of 30 effective branches



- All theory included in these effective branches but:

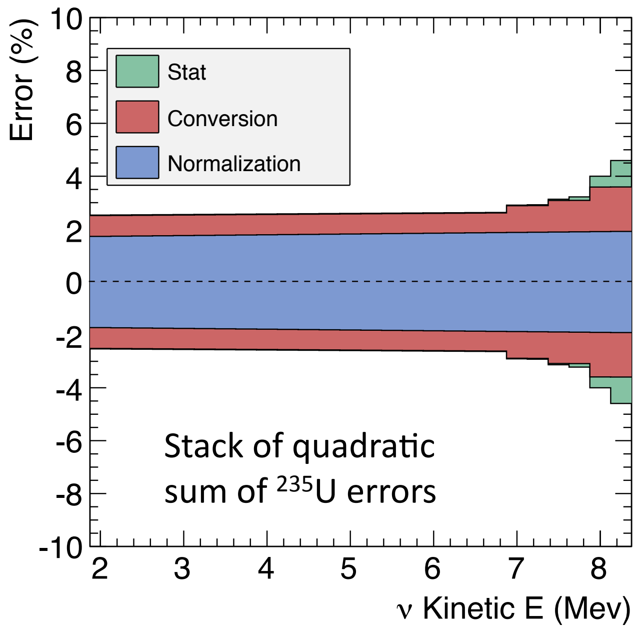
  - What Z? : Mean fit on nuclear data *Z=f(E0)*

$$Z(E_0) \approx 49.5 - 0.7E_0 - 0.09E_0^2, \quad Z \geq 34$$

  - What A_{CW}? : effective correction

$$\Delta N_\nu^{C,W}(E_\nu) \approx 0.65 \times (E_\nu - 4MeV) \quad \%$$

- Conversion error from envelop of all numerical studies



Ab initio approach… do we have the guts?

MURE evolution code: core composition and off equilibrium effects

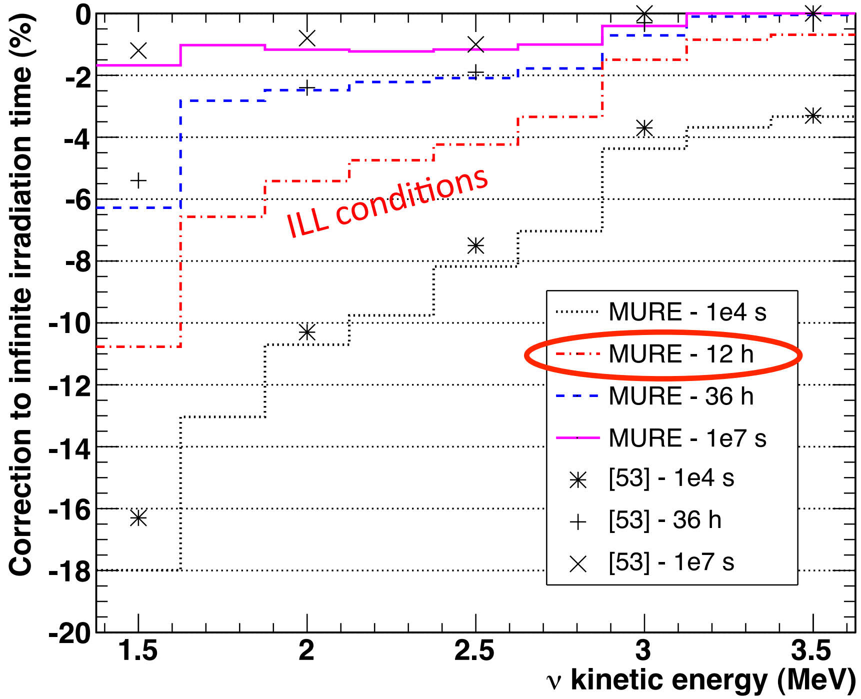
(Subatech Nantes)

$$S_k(E) = \sum_{fp=1}^{N_{fp}} \mathcal{A}_{fp}(T) \times S_{fp}(E)$$

• Full simulation of reactor core
→ absolute prediction of isotopes inventory.

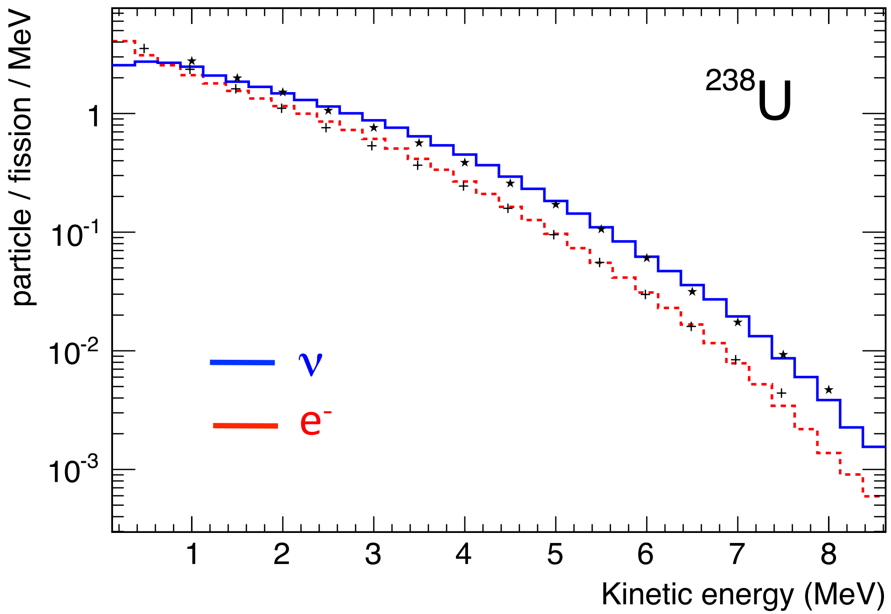
• Relative off-equilibrium effect: close to beta-inverse threshold, a significant fraction of the ν spectrum takes weeks to reach equilibrium
→ Sizeable correction in the ν oscillation range that depends on the exact chronology of ILL data taking.

Relative change of ν spectrum w.r.t. infinite irradiation time

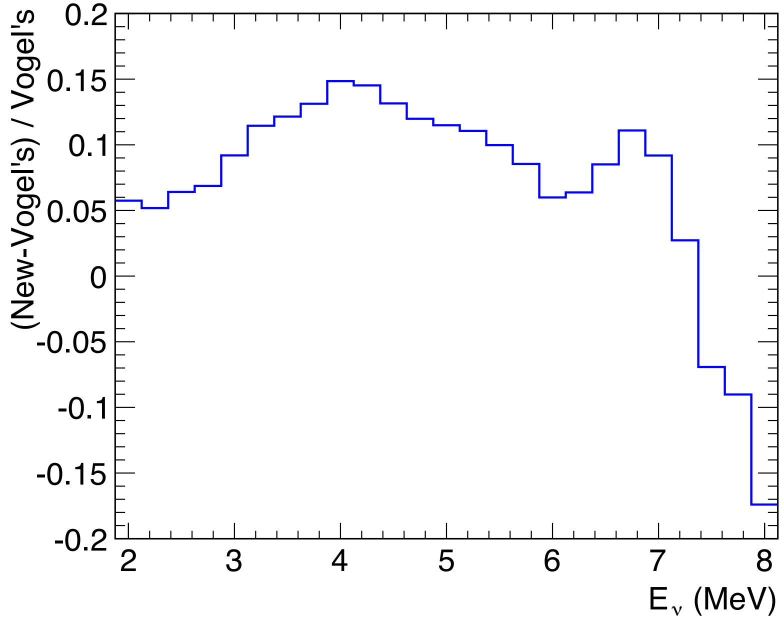


^{238}U spectrum

Comparison with Vogel's calculations, Phys. Rev. C24, 1543 (1981)



ν residues



energie atomique • energies alternatives

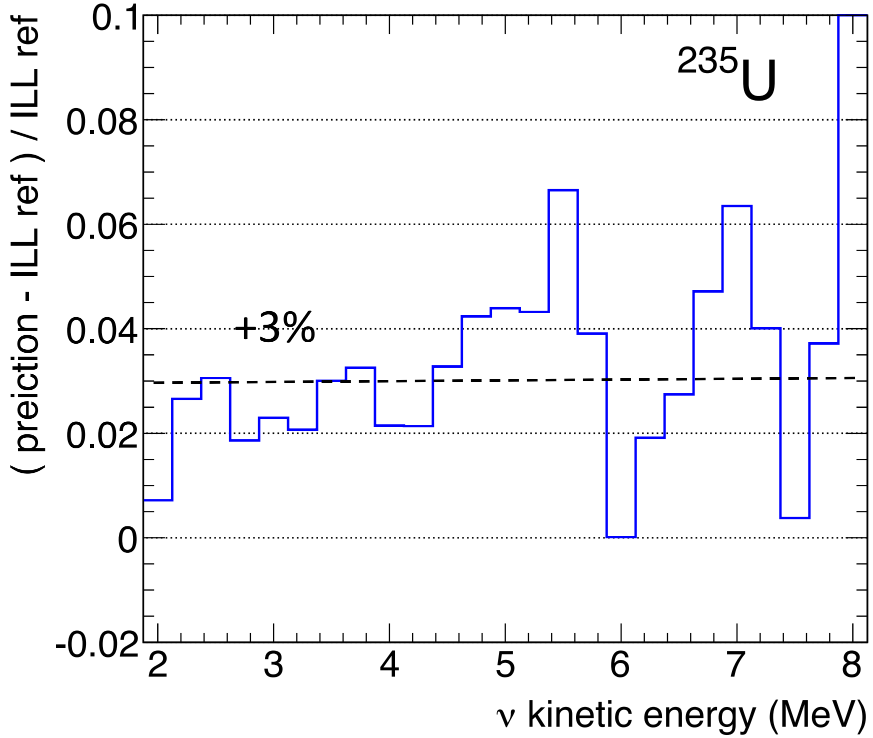
Improved conversion

Deviation from ILL converted spectrum

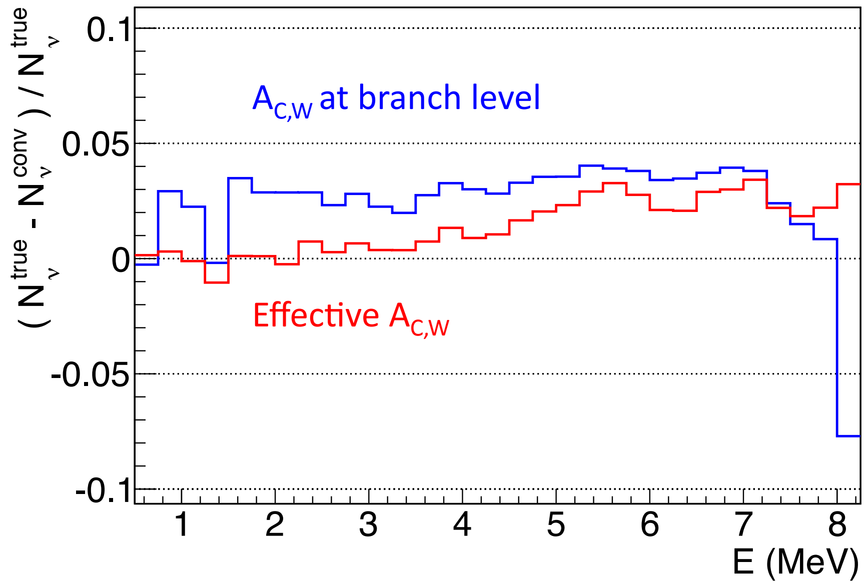
- ~+3% normalization shift with respect to ILL converted ν spectrum

- Similar result for all isotopes.

(New-ILL)/ILL

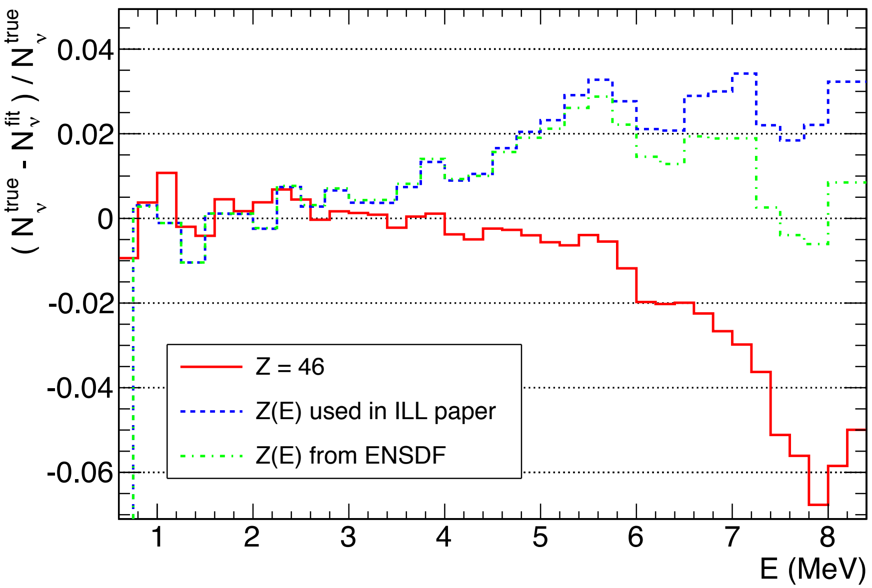


Origin of the 3% shift



- **E <4 MeV**: deviation from effective linear $A_{C,W}$ correction of ILL data

$$\Delta N_{\nu}^{C,W}(E_{\nu}) \approx 0.65 \times (E_{\nu} - 4MeV) \quad \%$$

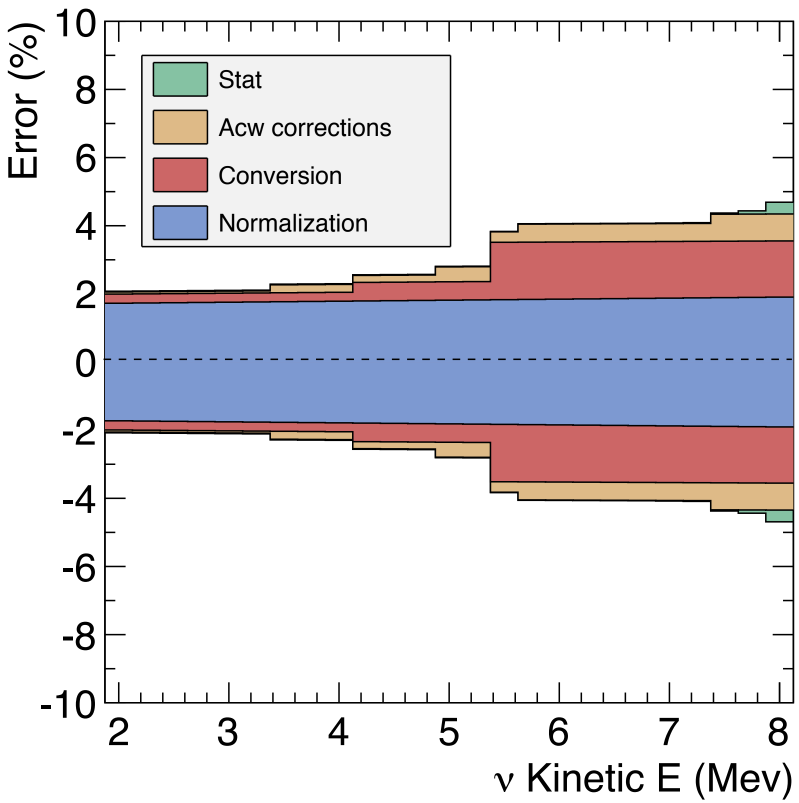


- **E >4 MeV**: mean fit of $Z(E_0)$ doesn't take into account the very large dispersion of Z around the mean curve

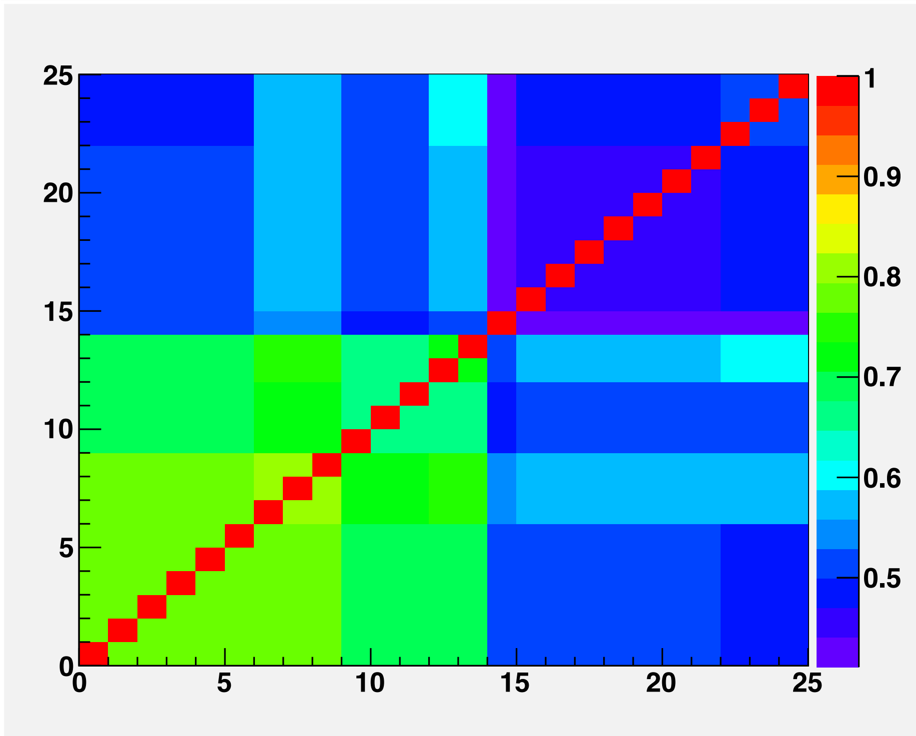
$$Z(E_0) \approx 49.5 - 0.7E_0 - 0.09E_0^2, \quad Z \geq 34$$

Error budget

Stack of quadratic sum of ^{238}U errors



^{235}U bin-to-bin correlation matrix (25x25 bins, 2-8 MeV)



(100% bin to bin correl from norm and A_{CW})

Outlook - Discussion

• More refined treatment of normalization error (impact on global fit of reactor experiments).

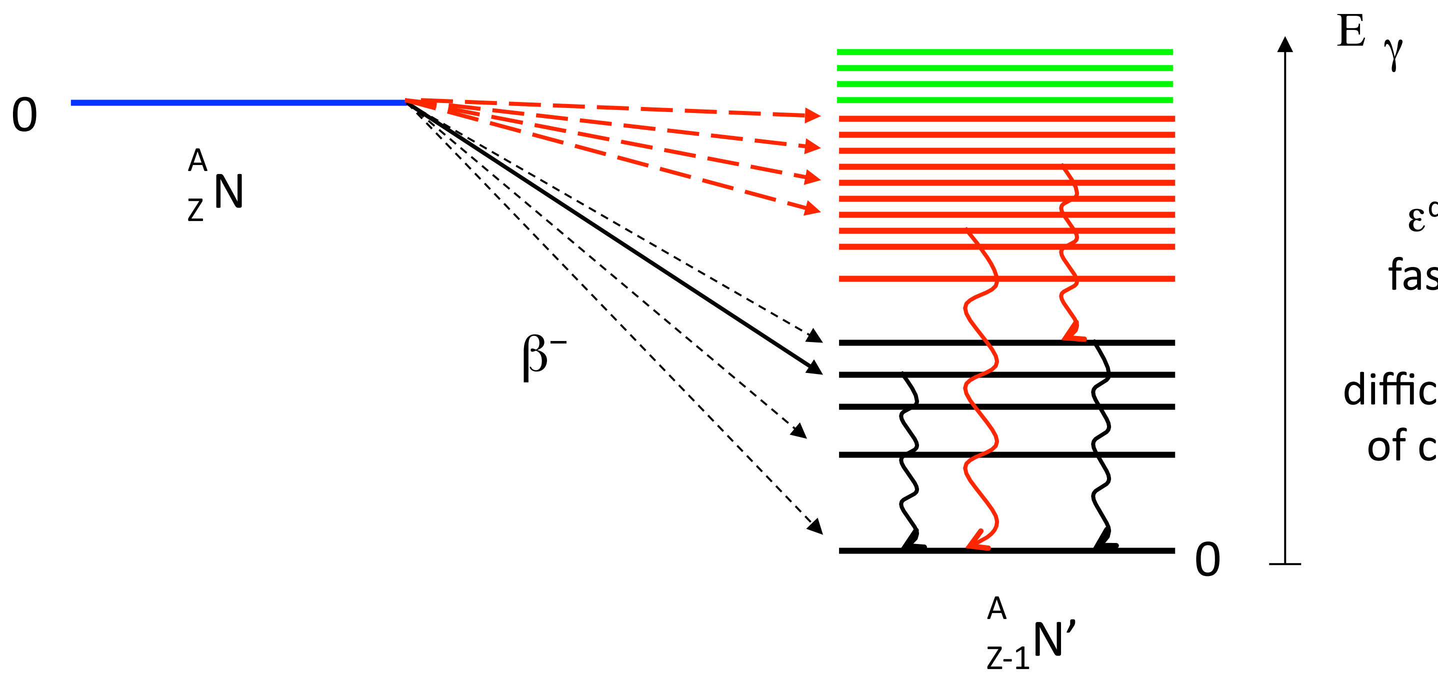
• Exploit ILL e^- data in 50 keV bins (reduce conversion error)

• Better estimate of $A_{C,W}$ corrections and associated error?

• Details on chronology of ILL measurement for more accurate off-equilibrium effects.

Pandemonium

Bias of β-decay scheme deduced from (e^-,γ) coincidence:

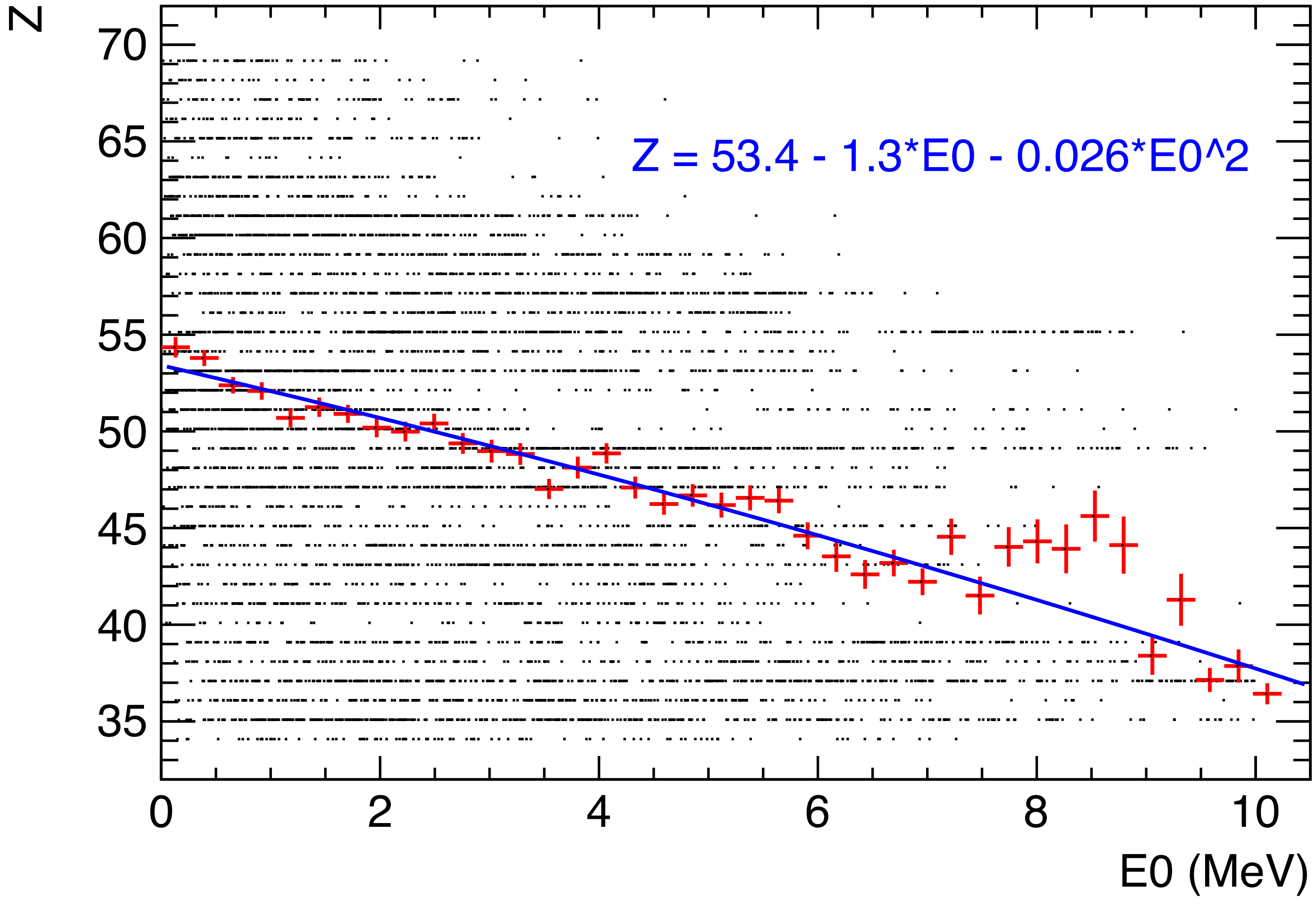


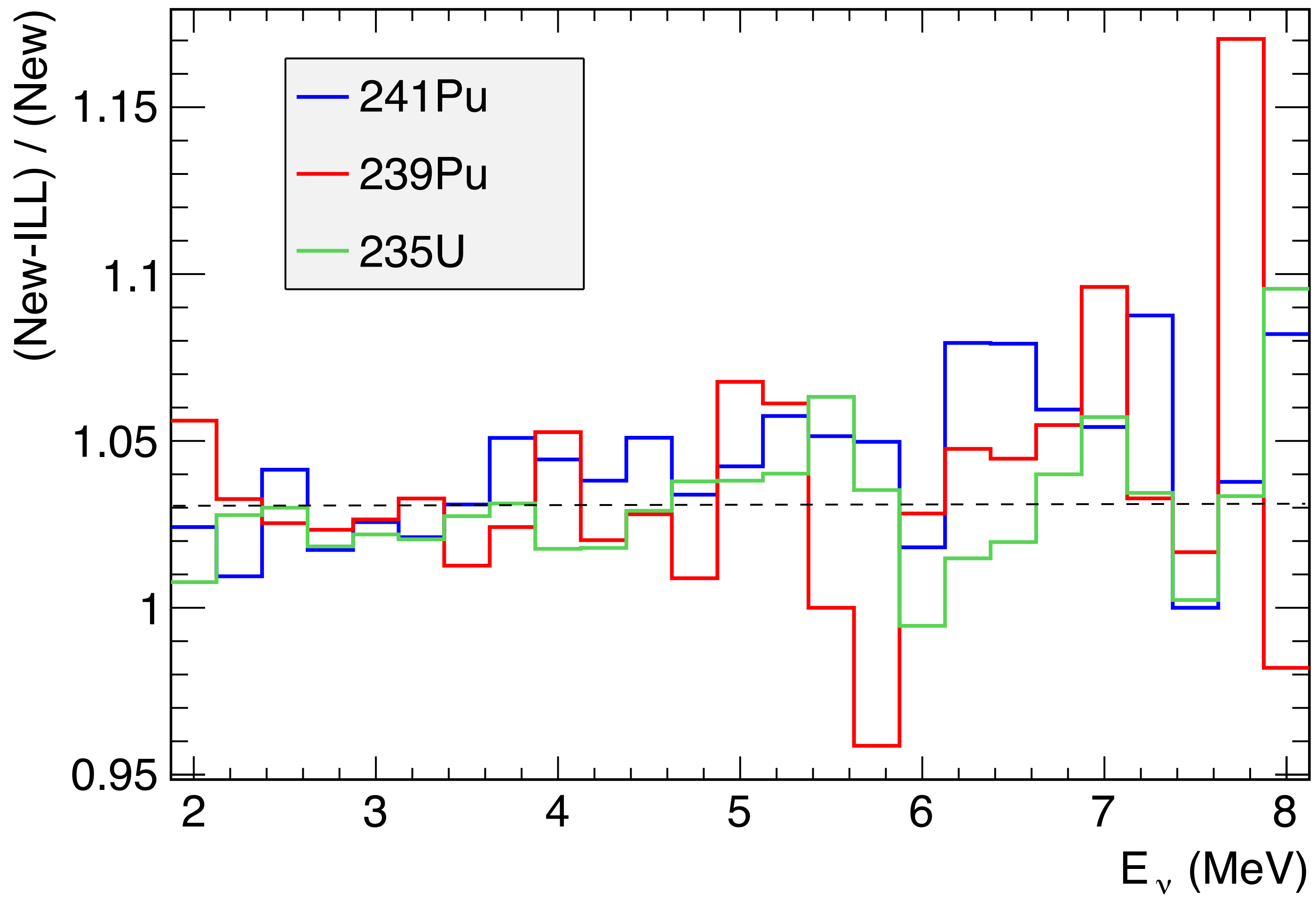
ε^{det} drops fast with E_γ
+
difficult analysis of continuum

- Underestimation of the low E part of the spectrum
- Overestimation of the high E part
- Missed γ are attributed to GS transition.

Solution is Total Absorption Gamma Spectrometers (detect total E of γ chain)

Z versus End-point energy




241Pu
239Pu
235U
(New-ILL) / (New)
1.15
1.1
1.05
1
0.95
2
3
4
5
6
7
8
E_ν (MeV)