ISOL-France Meeting, March 17, 2021

WISArD – InESS
(^{114}In Energy Spectrum Shape)

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Physics motivations

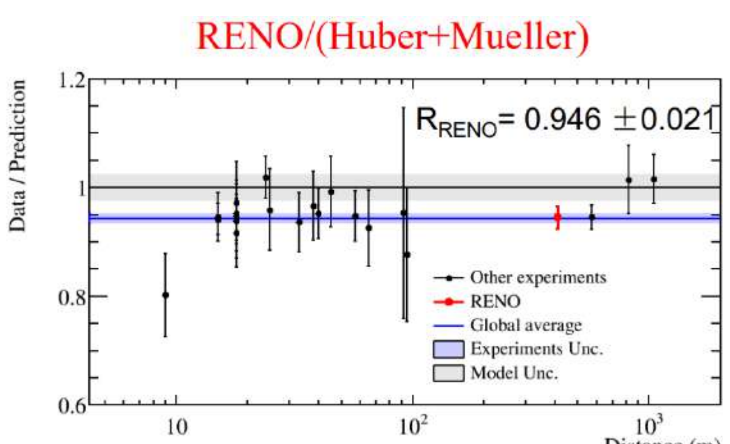
Many still open questions in both **neutrino** and **nuclear** physics:

RENO, South Korea

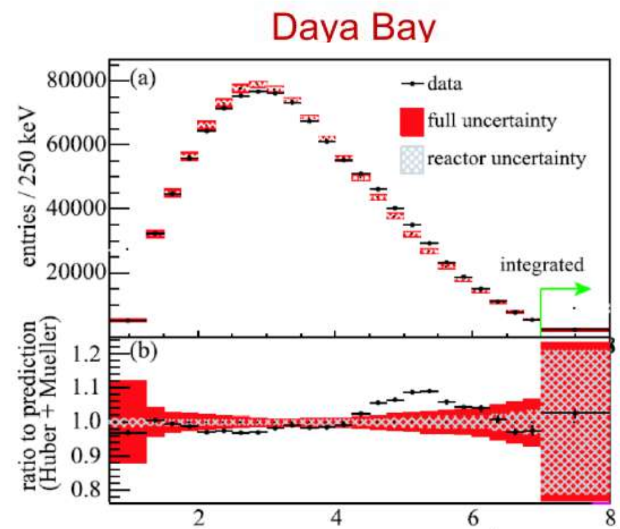
Daya Bay experiment, China

1 **Reactor Antineutrino Anomaly & Reactor bump**

→ nuclear reactors → fission → n-rich fragments → β-decays → ν spectra
→ experimental ν flux is systematically lower than theoretically predicted
→ bump of ν at E ≈ 5 MeV



RENO, PRL 116, 211801 (2016)



Daya Bay, CPC 41, 1 (2017) 013002

Fairly unexplained ν spectrum shape

→ possible existence of non-SM sterile neutrinos

→ shortcoming in theoretical flux calculations → **δ_{WM} weak magnetism term (main contribution)**

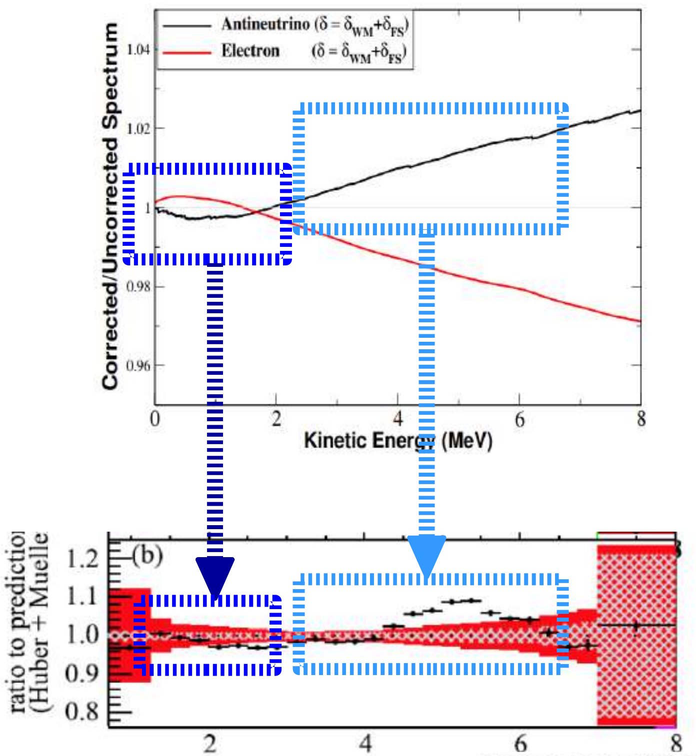
1

Physics motivations

Many still open questions in both **neutrino** and **nuclear** physics:

1 **Reactor Antineutrino Anomaly & Reactor bump**

δ_{WM} correction has different effects on ν spectra



Daya Bay, CPC 41, 1 (2017) 013002

It can be inferred by **precise GT β-spectrum shape measurements**

Classification	ΔJ^{π}	Fractional Weak Magnetism Correction $\delta_{WM}(E_e)$
Gamow-Teller:		
Allowed	1^+	$\frac{2}{3}\left[\frac{\mu_v - 1/2}{M_N g_A}\right](E_e\beta^2 - E_\nu)$
1^{st} F.	0^-	0
1^{st} F. ρ_A	0^-	0
1^{st} F.	1^-	$\left[\frac{\mu_v - 1/2}{M_N g_A}\right]\left[\frac{(p_e^2+E_\nu^2)(\beta^2 E_e - E\nu) + 2\beta^2 E_e E_\nu (E_\nu - E_e)/3}{(p_e^2+E_\nu^2 - 4\beta^2 E_\nu E_e/3)}\right]$
Uniq. 1^{st} F.	2^-	$\frac{3}{5}\left[\frac{\mu_v - 1/2}{M_N g_A}\right]\left[\frac{(p_e^2+E_\nu^2)(\beta^2 E_e - E\nu) + 2\beta^2 E_e E_\nu (E_\nu - E_e)/3}{(p_e^2+E_\nu^2)}\right]$
Fermi:		
Allowed	0^+	0
1^{st} F.	1^-	0
1^{st} F. $\vec{J}_V$	1^-	-

A. Hayes, P. Vogel, Annu. Rev. Nucl. Part, 66, 219–244 (2016)

δ_{WM} never measured before in the fission fragment mass range (A >70)

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Physics motivations

Many still open questions in both **neutrino** and **nuclear** physics:

2 **Standard Model of weak interaction**

Nuclear β decay is described by the following Lorentz-invariant Hamiltonian:

Hadronic terms **Leptonic terms**

$$\begin{aligned} H_\beta = \frac{G_F}{\sqrt{2}} V_{ud} \Big[& \left(\bar{\psi}_p \gamma_\mu \psi_n\right) \left(\bar{\psi}_e \gamma^\mu \left(C_V + C'_V \gamma_5\right) \psi_\nu\right) \\ - & \left(\bar{\psi}_p \gamma_\mu \gamma_5 \psi_n\right) \left(\bar{\psi}_e \gamma^\mu \gamma_5 \left(C_A + C'_A \gamma_5\right) \psi_\nu\right) \\ + & \left(\bar{\psi}_p \psi_n\right) \left(\bar{\psi}_e \left(C_S + C'_S \gamma_5\right) \psi_\nu\right) \\ + & \frac{1}{2} \left(\bar{\psi}_p \sigma_{\lambda\mu} \psi_n\right) \left(\bar{\psi}_e \sigma^{\lambda\mu} \left(C_T + C'_T \gamma_5\right) \psi_\nu\right) \\ + & h.c. \end{aligned}$$

Operators

- **coupling constants**
- **γ matrices**

STANDARD MODEL: V-A theory

- Only vector and axial-vector contributions: $C_V = 1$, $C_A = -1.27$ $C_S = C_S' = C_T = C_T' = 0$

BEYOND STANDARD MODEL

- Search for deviation from β-theory → scalar and tensor contribution?

Physics motivations

Many still open questions in both **neutrino** and **nuclear** physics:

2 **Standard Model of weak interaction**

Information on the C_S and C_T coupling constants can be retrieved experimentally from a precise measurement of the energy distribution of e- in β-decays:

$$N(W)dW = \frac{G_V^2 V_{ud}^2}{2\pi^3} F_0(Z,W)\, L_0(Z,W)\, U(Z,W)\, D_{FS}(Z,W,\beta_2)\, R(W,W_0)\, R_N(W,W_0,M) \times Q(Z,W)\, S(Z,W)\, X(Z,W)\, r(Z,W)\, C(Z,W)\, D_C(Z,W,\beta_2)\, pW(W_0-W)^2\, dW \equiv \frac{G_V^2 V_{ud}^2}{2\pi^3} K(Z,W,W_0,M)\, A(Z,W)\, C'(Z,W)\, pW(W_0-W)^2\, dW. \quad (1)$$

SIMPLIFYING:

$$N(W)dW \propto 1 + \frac{\gamma}{W} b_{Fierz} \pm \frac{4}{3}\frac{W}{M}\delta_{WM}$$

where:

- $\gamma = \sqrt{1-(\alpha Z)^2}$
- W = total energy of the e-
- M = average mass of mother and daughter nuclei

Fermi →

$$b^F_{Fierz} = Re\left(\frac{C_S + C'_S}{C_V}\right), \quad \delta^F_{WM} = 0$$

Gamow-Teller →

$$b^{GT}_{Fierz} = Re\left(\frac{C_T + C'_T}{C_A}\right), \quad \delta^{GT}_{WM} \neq 0$$

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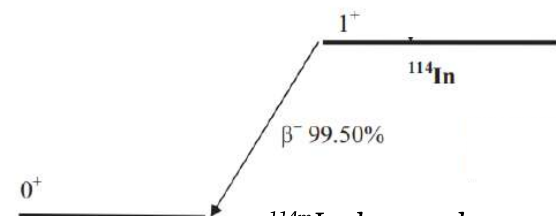
(1) L. Hayen, N. Severijns, arXiv:1709.07530 (2017)

WISArD – InESS (^{114}In Energy Spectrum Shape)

EXPERIMENTALLY

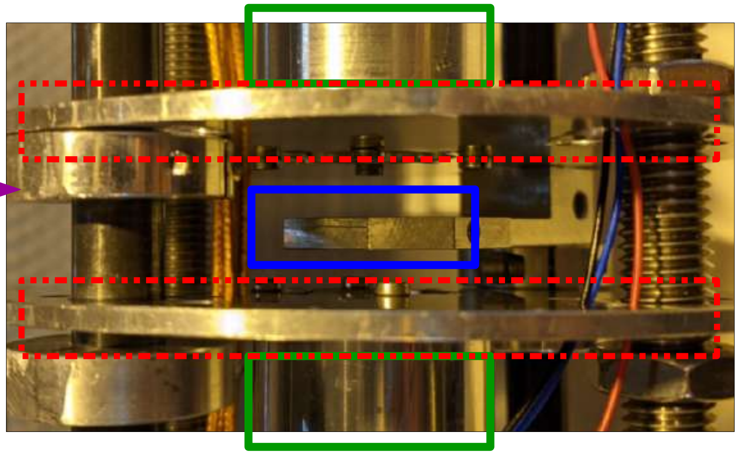
- ^{114}In radioactive source → pure allowed GT decay, Q_β = 2.2 MeV
- β- decay
  → e- emitted → B field → 2 plastic scintillators coupled with SiPMs
- B field up to 9 T



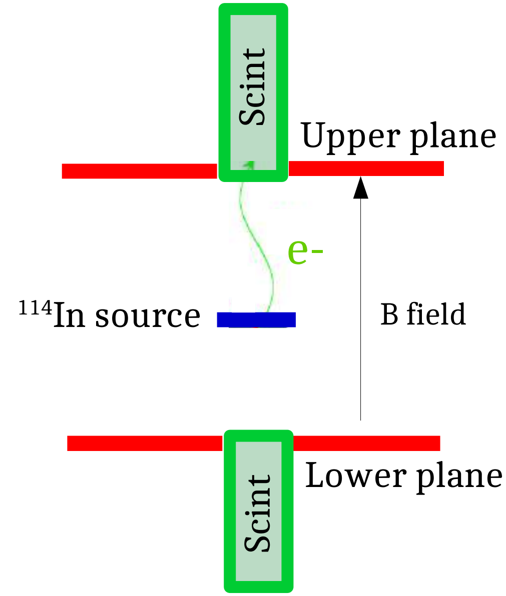
^{114m}In decay scheme

ISOLDE hall, CERN

WISArD tower



WISArD detectors



Experimental campaign at ISOLDE (November - December 2020)

WISArD – InESS (^{114}In Energy Spectrum Shape)

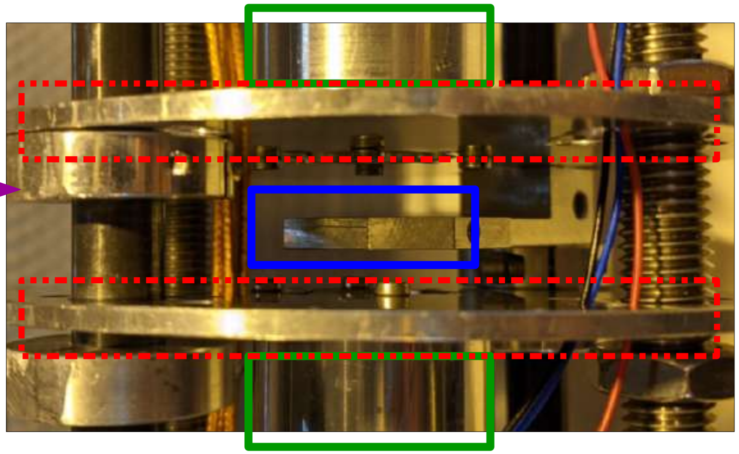
EXPERIMENTALLY

- ^{114}In radioactive source → pure allowed GT decay, Q_β = 2.2 MeV
- β- decay
  → e- emitted → B field → 2 plastic scintillators coupled with SiPMs
- B field up to 9 T

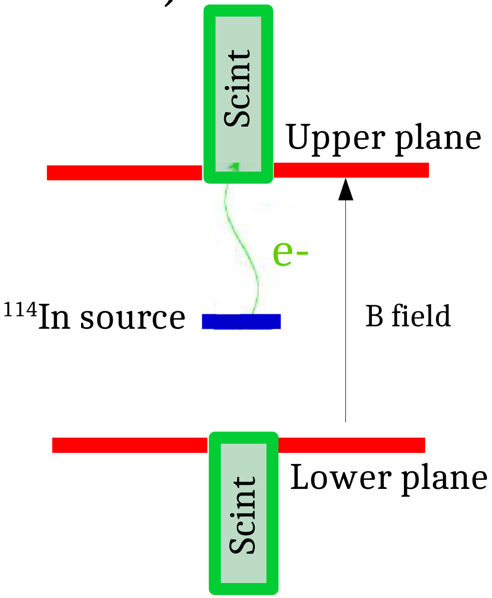
✓ **4π solid angle (high statistics)**
✓ **Closed system (complete spectrum reconstruction)**
✓ **Appropriate QDC window (τ = 250 ns)**

ISOLDE hall, CERN

WISArD tower



WISArD detectors

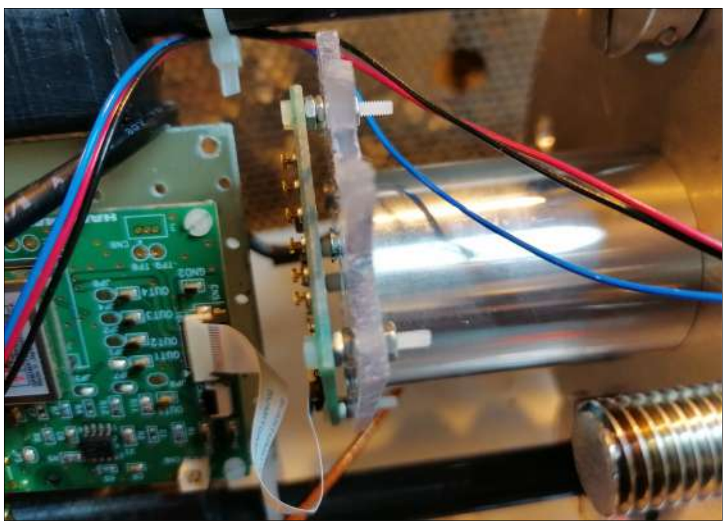


Experimental campaign at ISOLDE (November - December 2020)

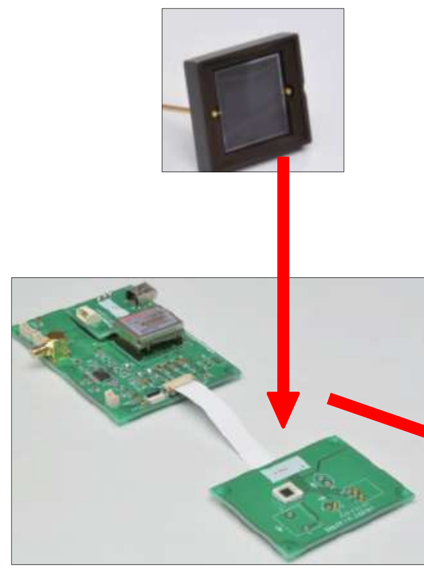
Experimental set-up

- 2 plastic scintillators (d = 20 mm, L = 50 mm)
- 2 SiPMs (Hamamatsu S13360-CS, photosensitive area 6x6 mm^2) assembled on 2 driver circuits (Hamamatsu C12332-01)
  - → tested in CENBG in February 2020 (e- spectrometer and LED)
  - → HV can be set via USB connection → possibility to adapt gain at lower temperatures

- FASTER acquisition system (LPC Caen)



Scintillator coupled to SiPM and connected to the driver circuit



SiPM connected to the driver circuit

WISArD tower to be placed inside the magnet
Detectors are covered for tests at room temperature

Detectors assembly completed and optimised (November 2020)

Experimental program – December 2020

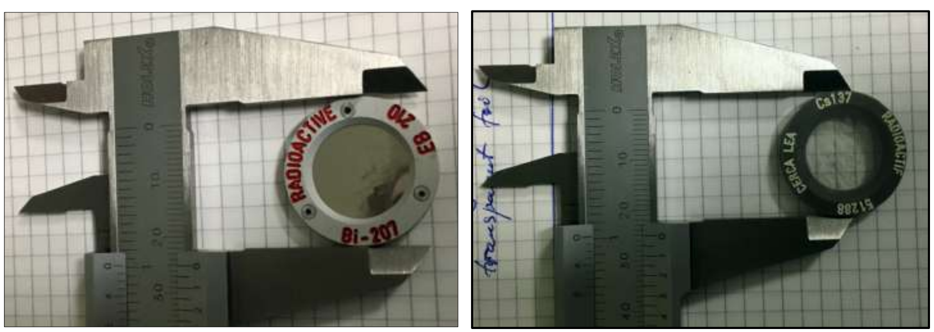
- **Calibration runs (preliminary tests):**
  - ^{207}Bi source → 2 peaks from electron conversion at known energies (~470 and 970 keV)
  - ^{137}Cs source → 1 peak from electron conversion at known energy (~620 keV)
  - ^{90}Sr source → continuum beta spectrum, comparable to ^{114}In (endpoint ~2.2 MeV)

→ measurements acquired at different B field values (comparison with 2019 WISArD data taking)

- **^{114}In runs (final tests):**

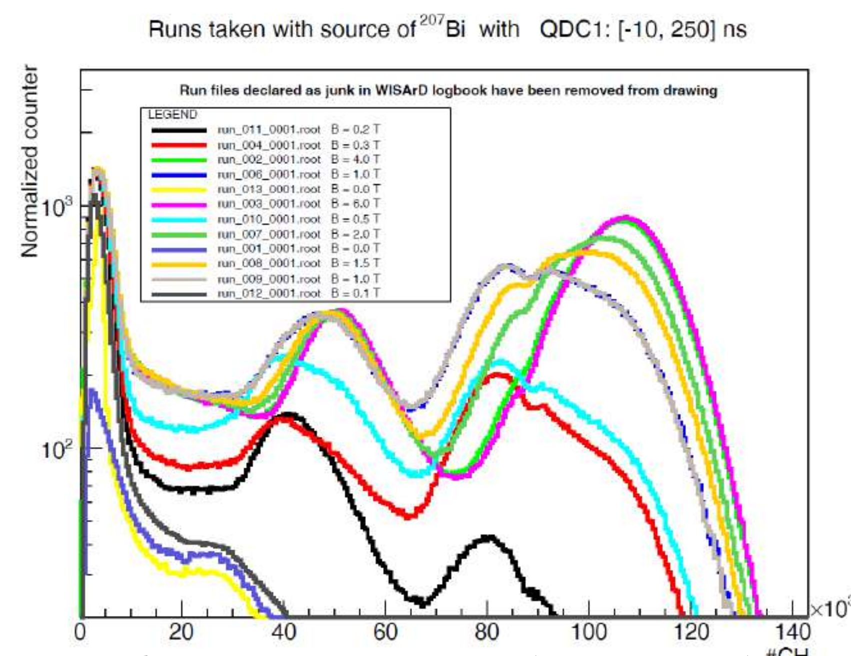
→ measurements taken at different B field values and activities (A = 1 kBq, A = 5 kBq)

<u>TOTAL OF 56 runs acquired</u>



Element	Mass	Activity / kBq	Date
Bi	207	21.78	08.03.2018
Cs	137	38.02	08.03.2018

Commercial calibration sources



Calibration runs superimposed (2019 campaign)

Experimental program – December 2020

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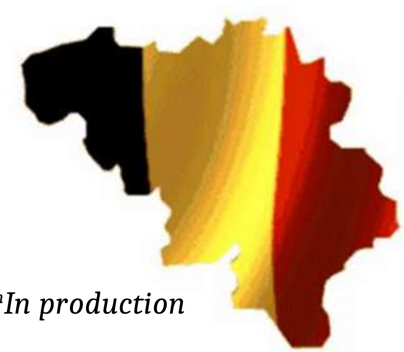
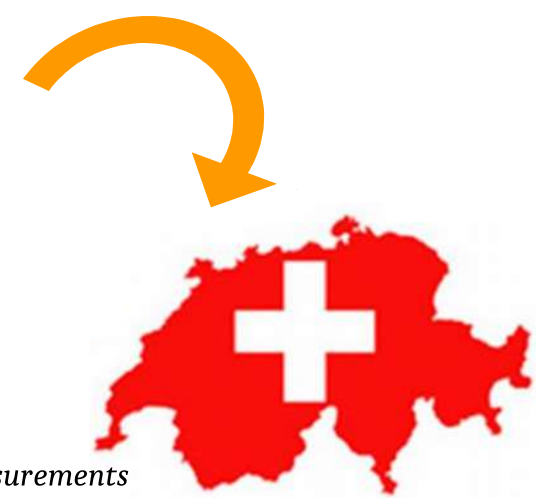
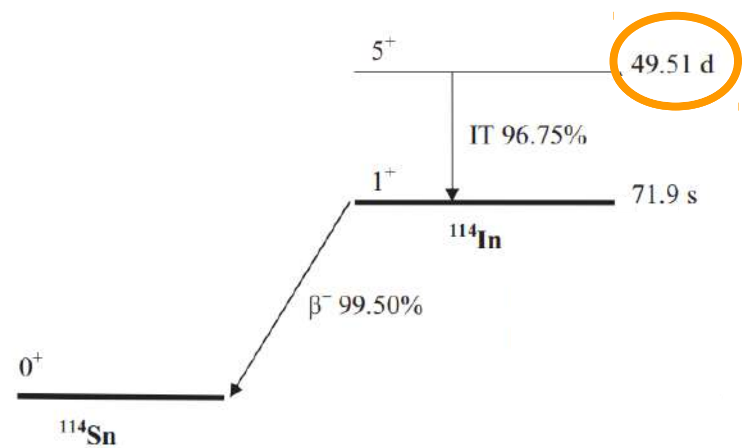


^{114m}In production



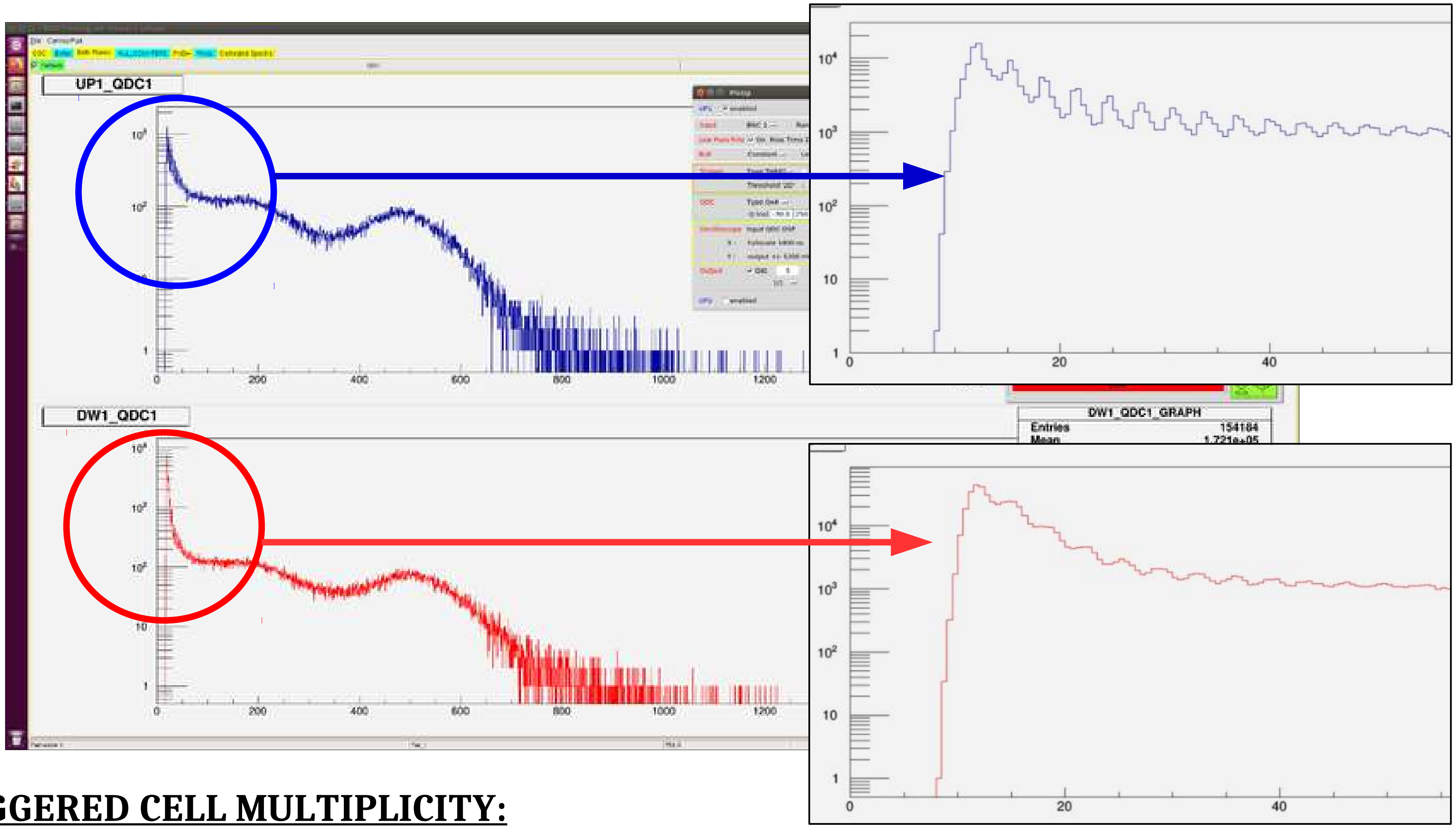
^{114m}In measurements



^{114m}In decay scheme

Experimental programme

All runs with all sources → **oscillatory behaviour** at lower energies (e.g. ^{207}Bi)



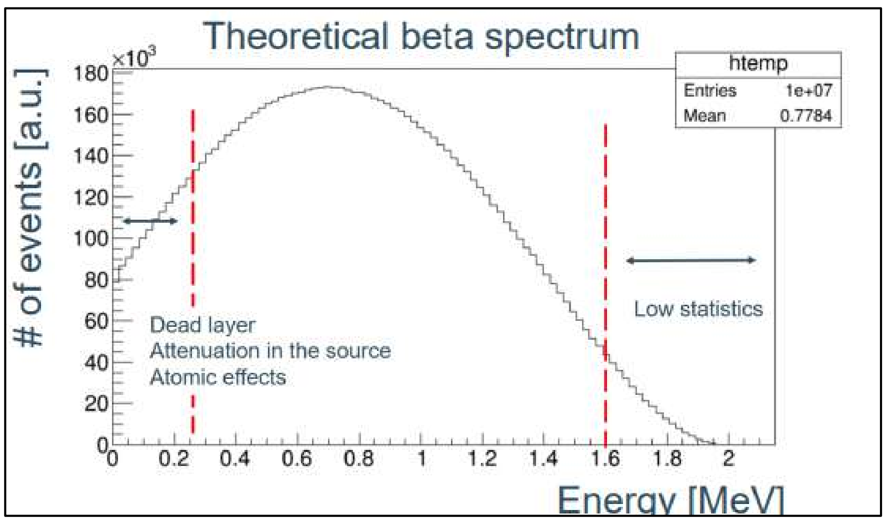
TRIGGERED CELL MULTIPLICITY:

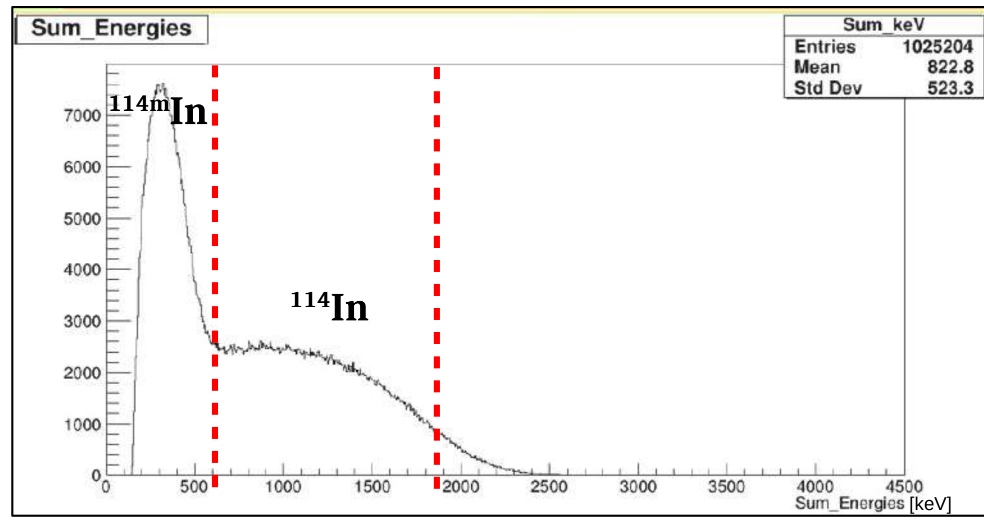
- $N_{exp\ peaks} = N_{photons} * \Delta e_{photonLosses} * R_{siPM/Scint} * QE_{ff} = 15 \div 20$
- Assuming that difference in charge between two adjacent peaks correspond to one photon → consistent with measurements → **high SiPMs resolution**

Conclusions & outlook

Ongoing analysis

- Reconstruction of the β-spectrum shape of the ^{114}In
- Comparison with theoretical Beta Spectrum Generator (BSG) code
- Precise determination ($<10^{-3}$) of the weak magnetism term and the Fierz term
  - → reactor antineutrino anomaly, reactor bump
  - → possible existence of a tensor current (physics BSM)





SYSTEMATICS EFFECTS:

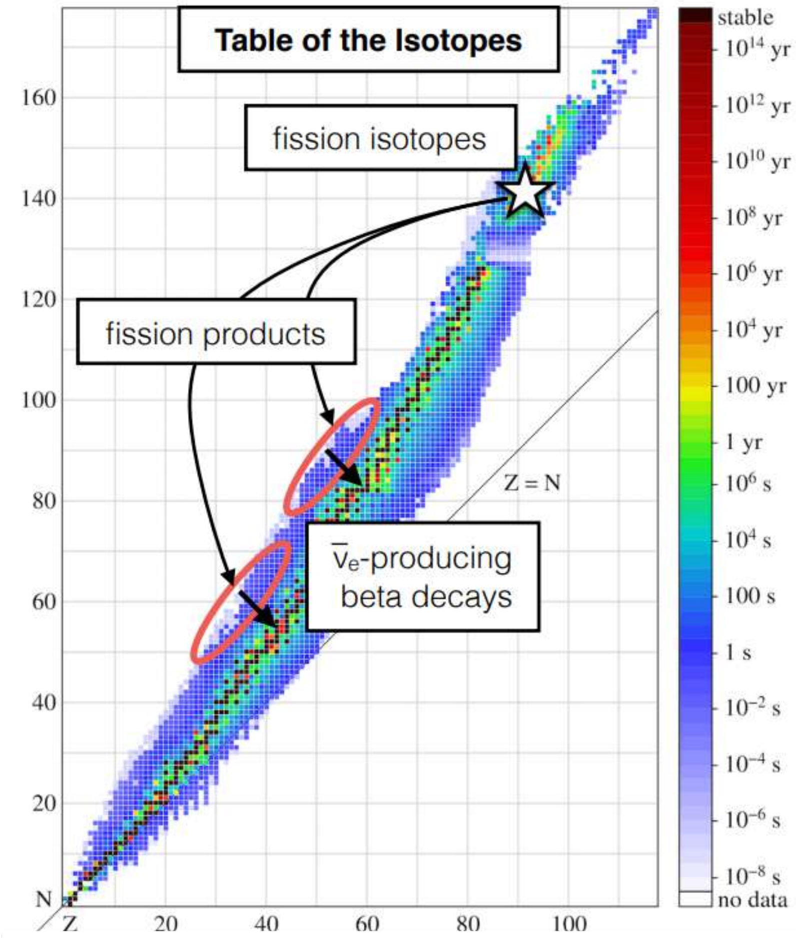
- Energy losses inside the source Mylar foil
  - → Geant4 simulations
- SiPM cell triggering probability
  - → numerical simulations, combinatorics
- Signal pile-up
  - → Geant4 simulations → time decay distribution

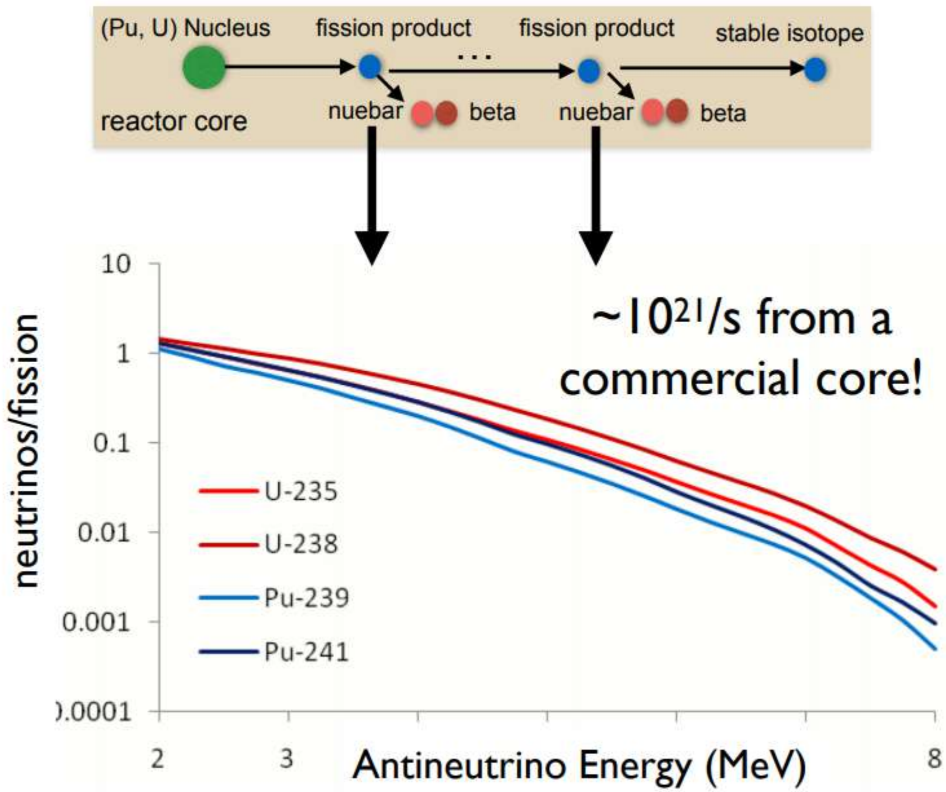
Thanks for attention!

P. Alfaurt, P. Ascher, **D. Atanasov**, **B. Blank**, **F. Cresto**, L. Daudin, **X. Fléchard**, M.Gerbaux, J. Giovinazzo, S. Grévy, T. Kurtukian-Nieto, E. Liénard, **N. Severijns**, **S. Vanlangendonck**, M. Versteegen, D. Zakoucky

Backup slides

Neutrinos – nuclear reactors





F. Cresto

Reactor neutrino detection - IBD

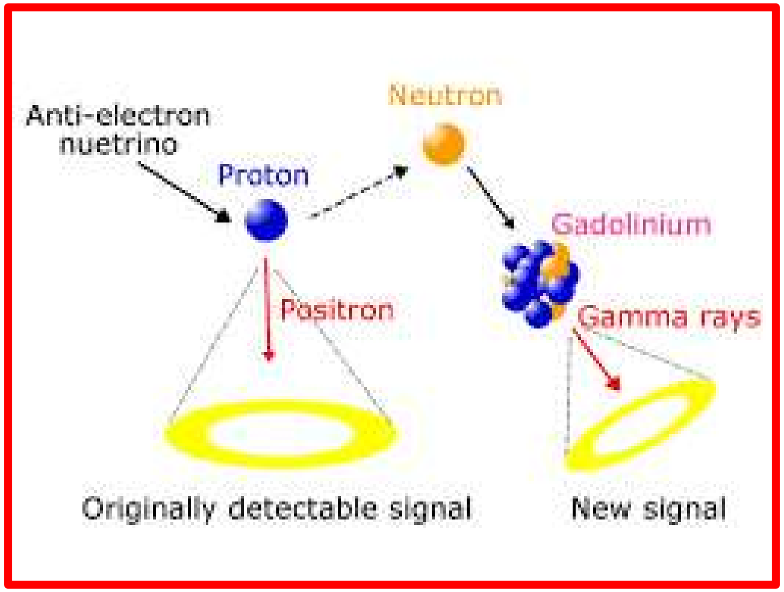
Inverse beta decay (IBD):

$$\overline{\nu}_e + p \rightarrow e^+ + n$$

$$E_{\overline{\nu}} \approx T_{e^+} + 1.8 \text{ MeV}$$

The positron carries most of the $\overline{\nu}_e$ energy

Gd-LS



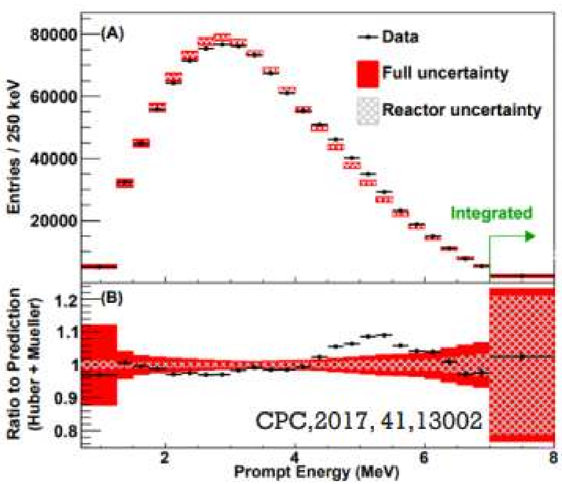
$$S(E_{\overline{\nu}}) = c \cdot f \cdot s(E_{\overline{\nu}}) \cdot \sigma(E_{\overline{\nu}})$$

- f: isotope fission fraction
- $s(E_{\overline{\nu}})$: isotope neutrino spectrum
- $\sigma(E_{\overline{\nu}})$: IBD cross section
- c: reactor thermal power, energy released per fission, baseline, target protons, detection efficiency, oscillation, etc.

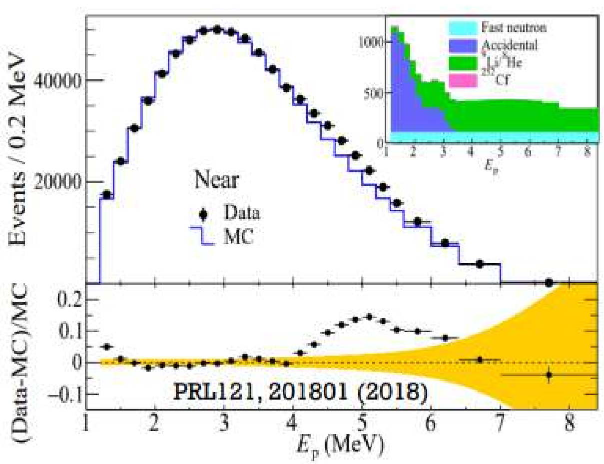
Reactor bump

Bump in 4-6 MeV prompt energy (5-7 MeV neutrino energy)
observed independently in 2014 by three ϑ_{13} experiments
(Pontecorvo – Maki – Nagagawa – Sakata matrix)

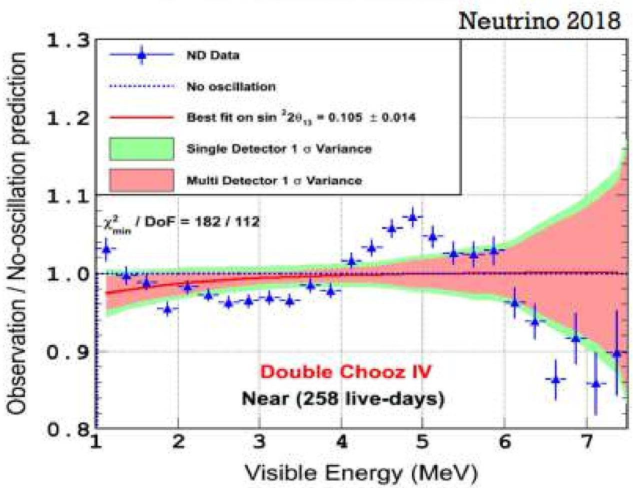
Daya Bay



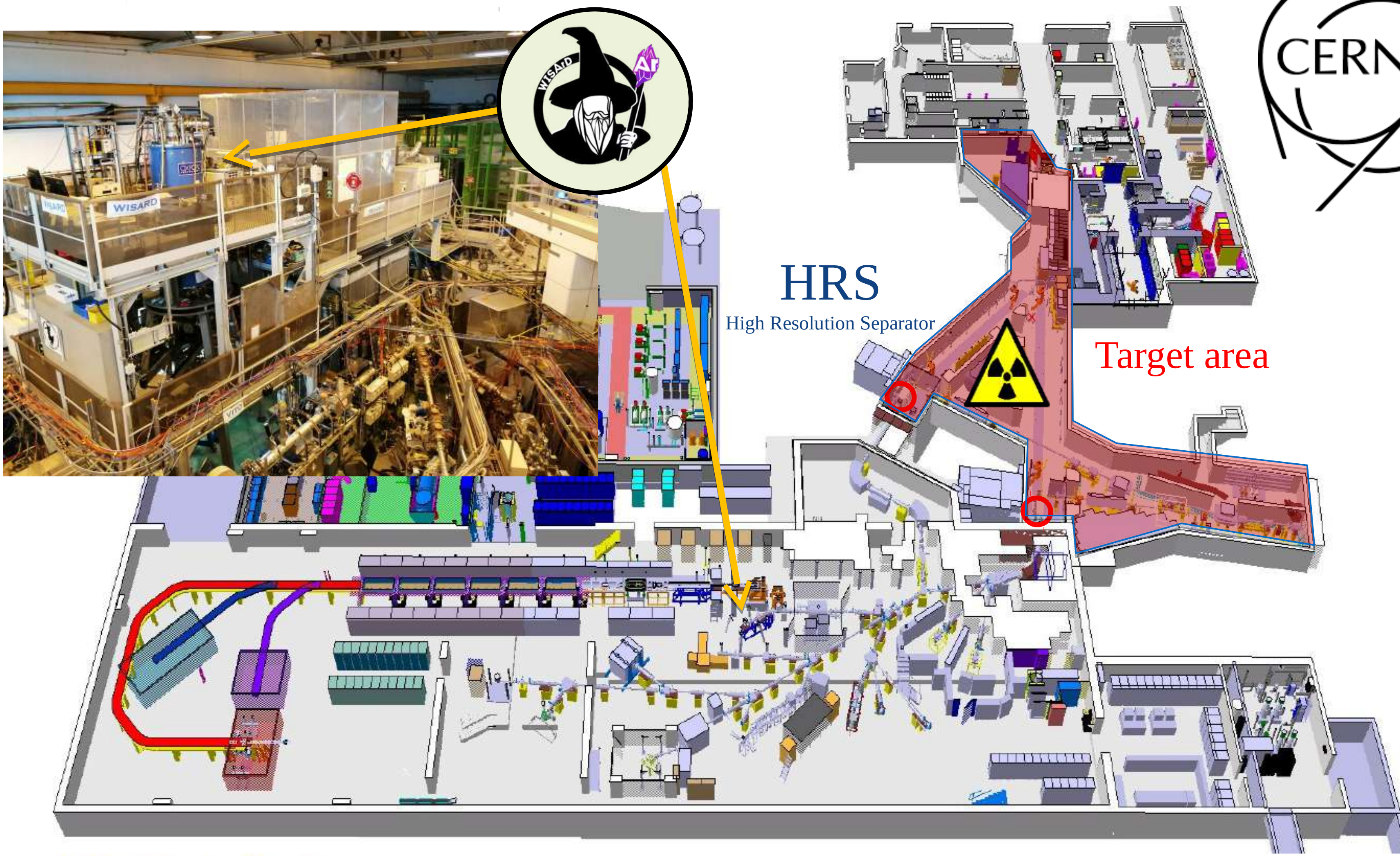
RENO



Double Chooz



ISOLDE experimental hall - CERN



María J G Borge and Klaus Blaum, J. Phys. G: Nucl. Part. Phys. 45 (2018) 010301

The Standard Model of weak interaction (3)

Information on the theoretical coupling constants can be retrieved experimentally from a precise measurement of the energy distribution of e- in β-decays:

$$N(W)dW = \frac{G_V^2 V_{ud}^2}{2\pi^3} F_0(Z,W)\, L_0(Z,W)\, U(Z,W)\, D_{FS}(Z,W,\beta_2)\, R(W,W_0)\, R_N(W,W_0,M) \qquad (2)$$

$$\times\; Q(Z,W)\, S(Z,W)\, X(Z,W)\, r(Z,W)\, C(Z,W)\, D_C(Z,W,\beta_2)\, pW(W_0-W)^2\, dW$$

$$\equiv \frac{G_V^2 V_{ud}^2}{2\pi^3} K(Z,W,W_0,M)\, A(Z,W)\, C'(Z,W)\, pW(W_0-W)^2\, dW.$$

Effect	Formula	Magnitude
Phase space factor	$pW(W_0-W)^2$	Unity or larger
Fermi function	F_0	
Finite size of the nucleus	L_0	
Radiative corrections	R	
Shape factor	C	$10^{-1}-10^{-2}$
Atomic exchange	X	
Atomic mismatch	r	
Atomic screening	S	
Shake-up & Shake-off	See Atomic mismatch	
Isovector correction	C_I	
Diffuse nuclear surface	U	$10^{-3}-10-4$
Nuclear deformation	D_{FS} & D_C	
Recoil Coulomb correction	Q	
Recoiling nucleus	R_N	
Molecular screening	ΔS_{Mol}	
Molecular decay	Case by case	
Bound state β decay	Γ_b/Γ_c	smaller than 1×10^{-4}
Neutrino mass	negligible	

- Corrections on Fermi function
- Nuclear structure corrections
- Atomic and molecular corrections
- Radiative corrections

SIMPLIFYING:

$$N(W)dW \propto 1 + \frac{\gamma}{W} b_{Fierz}$$

where:

- $\gamma = \sqrt{1-(\alpha Z)^2}$
- W = total energy of the e-

B5

[2] L. Hayen, N. Severijns, arXiv:1709.07530 (2017)