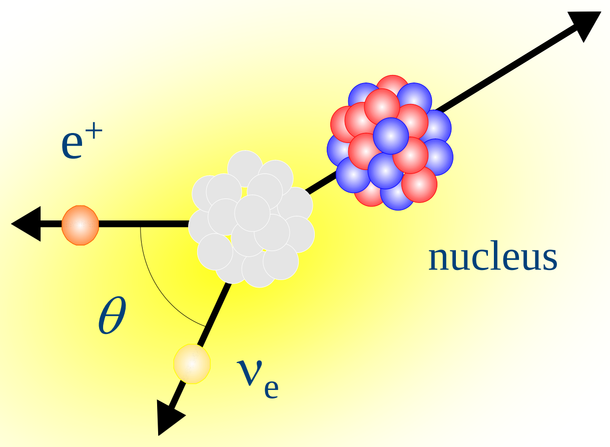
Weak Interaction Studies

ISOL- France Workshop VI
Institut Pluridisciplinaire Hubert Curien
Strasbourg
27-29 June 2024



Nathal Severijns

KU Leuven, Belgium

1. Formalism (basic aspects)

2. Ft values of $0^+ \rightarrow 0^+$ transitions, mirror nuclei, and neutron: determining V_{ud}

3. Correlations (*a*, *A*)
   - → Scalar and Tensor current searches
   - → global analysis
   - → need for including small SM corrections; recoil, radiative

4. Beta-spectrum shape to determine Fierz term and weak magnetism

1. **Formalism (basic aspects)**

2. - Ft values of $0^+ \rightarrow 0^+$ transitions, mirror nuclei, and neutron: in search for V_{ud}

3. Correlations (*a, A*)
   - → Scalar and Tensor current searches
   - → global analysis
   - → need for including small SM corrections; recoil, radiative

4. Beta-spectrum shape to determine Fierz term and weak magnetism

KU LEUVEN

Beta-decay hamiltonian

1956: Lee & Yang

1957: M_{me} Wu and collaborators observed (maximal) violation of parity

Hamiltonian for beta decay (e.g. $\rightarrow$ p e^- $\bar{\nu}_e$) :

$$H = g \sum_{i} \underbrace{\left(\overline{\psi}_p O_i \psi_n \right)}_{H_\mu} \left\{ \underbrace{\overline{\psi}_e O_i \left(C_i + C_i' \gamma_5 \right) \psi_\nu}_{L^\mu} \right\} + \text{h.c.},$$

$$\text{with} \quad i = S, V, T, A, P$$

and the operators O_i expressed as Dirac γ matrices

the Standard Model and beyond:

5% level → O(350 GeV)
per mille level → O(2.5 TeV)

- $C_V \equiv 1$; $|C_A| = 1.27$ (g_A/g_V from n-decay)
- $C_V{}' = C_V$ & $C_A{}' = C_A$ (maximal P-violation)
- $C_S = C_S{}' = C_T = C_T{}' = C_P = C_P{}' \equiv 0$ (only V,A)

$$C_i \propto \frac{M_W^2}{M_{new}^2}$$

experimental upper limits on $\left|C_T^{(\,'\,)}/C_A\right|$ and $\left|C_S^{(\,'\,)}/C_V\right|$

N. Severijns and O. Naviliat-Cuncic, Annu. Rev. Nucl. Part. Sci. 61 (2011) 23
V. Cirigliano et al., Prog. Part. Nucl. Phys. 71 (2013) 93,
B.R. Holstein, J. Phys. G 41 (2014) 114001
M. Gonzalez-Alonso, O. Naviliat-Cuncic and N.Severijns, Prog. Part. Nucl. Phys. 104 (2019) 165
A. Falkowski, M. Gonzalez-Alonso, O. Naviliat-Cuncic, JHEP 04 (2021) 126
D. Dubbers and B. Märkish, Annu. Rev. Nucl. Part. Sci. 71 (2021) 139
A. Falkowski, M. Gonzalez-Alonso, O. Naviliat-Cuncic, N. Severijns, Eur. Phys. J. A 59 (2023) 113
A. Falkowski, M. Gonzalez-Alonso, et al., arXiv:2112.07688v2
N. Severijns, I.S. Towner et al., Phys. Rev. C 107 (2023) 015502

- **no time reversal violation**
  (except for the CP-violation described by the phase in the CKM matrix)

KU LEUVEN

Fermi's Golden Rule

$$\Gamma = \frac{2\pi}{\hbar} \left|\mathcal{H}_{\mathrm{if}}\right|^2 \rho_{\mathrm{f}}$$

Transition probability

Matrix element of the interaction

Density of final states

$$\boxed{\frac{dn_f}{dE_f} = \frac{V^2}{4\pi^4\hbar^6c^3} \cdot (Q - T_e)^2 p^2 dp}$$

KU LEUVEN

Major Observables in Beta Decay

$\bar{p}$: momentum of β particle
$\bar{q}$: momentum of neutrino
E: energy of beta/neutrino
m: electron rest mass
$\bar{J}$: spin of nucleus
$\gamma = \sqrt{(1-(\alpha Z)^2}$
σ: spin direction of beta

differential decay rate

$$d\Gamma \propto \underbrace{F(\pm Z, E_e)}_{\text{Fermi function}} \; \underbrace{p_e\, E_e\, (E_0 - E_e)^2\, dE_e\, d\Omega_e\, d\Omega_\nu}_{\text{phase space}} \; \xi$$

$d\Gamma_0$

$C_i^{(')}$ and nuclear matrix elements, M_F and M_{GT}

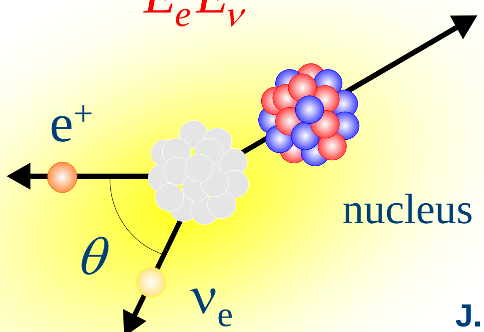
$$\times \left\{ 1 + a\frac{\vec{p}_e \cdot \vec{q}}{E_e E_\nu} + b_{Fierz}\frac{\gamma m_e}{E_e} + A\frac{\vec{J}}{J}\cdot\frac{\vec{p}_e}{E_e} + D\frac{\vec{J}}{J}\cdot\frac{\vec{p}_e}{E_e}\times\frac{\vec{q}}{E_\nu} + \ldots \right\}$$

β-ν correlation

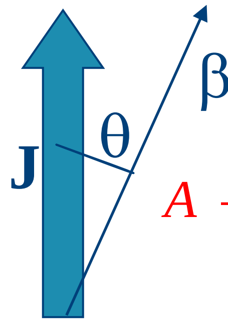
Fierz interference term (b ≡ 0 in standard model)

β-asymmetry

$$a\,\frac{\vec{p}_e \cdot \vec{q}}{E_e E_\nu}$$



$$\tilde{X} = \frac{X}{1 + b\,\frac{\gamma m}{E_e}} \quad \text{with } \gamma = \sqrt{(1-(\alpha Z)^2}$$



$$A\,\frac{\vec{J}}{J}\cdot\frac{\vec{p}_e}{E_e}$$

J.D. Jackson, S.B. Treiman, H.W. Wyld, Nucl. Phys. 4 (1957) 206

$$\xi = M_F^2\left[|C_V|^2 + |C'_V|^2 + |C_S|^2 + |C'_S|^2\right] + M_{GT}^2\left[|C_A|^2 + |C'_A|^2 + |C_T|^2 + |C'_T|^2\right]$$

$$a\,\xi = M_F^2\left[|C_V|^2 + |C'_V|^2 - |C_S|^2 - |C'_S|^2\right] - \frac{M_{GT}^2}{3}\left[|C_A|^2 + |C'_A|^2 - |C_T|^2 - |C'_T|^2\right]$$

$$b\,\xi = \pm 2\,\mathrm{Re}\left[M_F^2\left(C_S C_V^* + C'_S C'^*_V\right) + M_{GT}^2\left(C_T C_A^* + C'_T C'^*_A\right)\right]$$

$$A\,\xi = 2\,\mathrm{Re}\left[\mp\lambda_{J'J}\, M_{GT}^2\left(C_A C'^*_A - C_T C'^*_T\right) - \delta_{J'J}\sqrt{\frac{J}{J+1}}\, M_F M_{GT}\left(C_V C'^*_A + C'_V C_A^* - C_S C'^*_T - C'_S C_T^*\right)\right]$$

$$\lambda_{J'J} = \begin{cases} 1 & J \to J' = J-1 \\ \dfrac{1}{J+1} & J \to J' = J \\ -\dfrac{1}{J+1} & J \to J' = J+1 \end{cases}$$

<u>with</u>: $M_{F(GT)}$ = Fermi(Gamow-Teller) nuclear matrix element

$C_i^{(\prime)}$ = coupling constants of the S, V, A, T weak interactions

Ft value of the $0^+ \rightarrow 0^+$ superallowed β decays

- **for a general (mixed F/GT) beta transition one has (no correlations):**

$$ft = \frac{K}{G_F^2\ V_{ud}^2} \frac{1}{[M_F^2 C_V^2 + M_{GT}^2 C_A^2]}$$

(neglecting b_{Fierz})

- **$0^+ \rightarrow 0^+$ transitions are pure Fermi → only Vector current present**

$$f_V t^{0^+\rightarrow 0^+} = \frac{K}{G_F^2\ V_{ud}^2} \frac{1}{M_F^2 C_V^2}$$

BUT: in reality (including also small percent-level corrections):

$$\mathcal{F}t^{0^+\rightarrow 0^+} \equiv f_V t^{0^+\rightarrow 0^+} (1 + \boxed{\delta_{NS}^V} - \boxed{\delta_C^V})(1 + \boxed{\delta_R'}) = \frac{K}{2 G_F^2\ V_{ud}^2\ C_V^2\ (1 + \boxed{\Delta_R^V})}$$

Note: $|M_F|^2 = T(T+1) - T_i T_f$ and $T = \frac{|N-Z|}{2}$ → **for $0^+ \rightarrow 0^+$ pure Fermi transitions $|M_F|^2 = 2$**

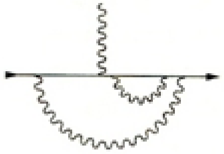
KU LEUVEN

$$\mathcal{F}t^{0^+\to 0^+} \equiv f_V t^{0^+\to 0^+}\left(1+\boxed{\delta^V_{NS}}-\boxed{\delta^V_C}\right)\left(1+\boxed{\delta'_R}\right) = \frac{K}{2G_F^2\, V_{ud}^2\, C_V^2\left(1+\boxed{\Delta^V_R}\right)}$$

- **radiative correction $\delta_R' = \delta_1 + \delta_2 + \delta_3$ (order α, $Z\alpha^2$, $Z^2\alpha^3$)**
  leading order α: exchange of γ or Z-boson between p and e^-
- **nucleus-independent radiative correction $\Delta_R = 0.02454(19)$**
- **nuclear structure-dependent radiative correction δ^V_{NS}**
- **Coulomb (isospin) correction $\delta^V_c = \delta^V_{c1} + \delta^V_{c2}$**
  - **difference in configuration mixing between initial and final states**
  - **difference in radial part of wave functions**

(I.S. Towner & J.C. Hardy, Rep. Prog. Phys. 73 (2010) 046301)

radiative correction of order α^2, e.g.:



KU LEUVEN

Beta-Neutrino correlation - 1

$$d\Gamma = d\Gamma_0 \;\; \xi \;\; \left\{ 1 + \frac{\bar{p}\cdot\bar{q}}{E_e E_\nu} a + \frac{\gamma m}{E_e} b \right\}$$

βν-correlation coefficient

Fierz interference term

$\bar{p}$: momentum of beta particle
$\bar{q}$: momentum of neutrino
E: energy
m: electron rest mass
$\bar{J}$: spin of nucleus
$\gamma = \sqrt{(1-(\alpha Z)^2}$

count rate

$$\frac{\boxed{\cancel{d\Gamma_0} \, \xi \;\; \left\{ 1 + \frac{\bar{p}\cdot\bar{q}}{E_e E_\nu} a + \frac{\gamma m}{E_e} b \right\}}}{\boxed{\cancel{d\Gamma_0} \, \xi \;\; \left\{ 1 + \frac{\gamma m}{E_e} b \right\}}} = 1 + \boxed{\frac{a}{1 + \frac{\gamma m}{E_e} b}} \; \frac{\bar{p}\cdot\bar{q}}{E_e E_\nu}$$

normalization with source strength

$\tilde{a}$

J.D. Jackson, S.B. Treiman, H.W. Wyld, Nucl. Phys. 4 (1957) 206 & Phys. Rev. 106 (1957) 517

KU LEUVEN

Beta-Neutrino correlation - 2

$$a\,\frac{\vec{p}_e\cdot\vec{q}}{E_eE_\nu} \xrightarrow{\text{exp.}} \boxed{\tilde{a} = \frac{a}{1 + b\,\dfrac{\gamma m_e}{E_e}}}$$

with $\gamma = \sqrt{1-(\alpha Z)^2}$

$$a_F \cong 1 - \frac{|C_S|^2 + |C_S'|^2}{|C_V|^2}$$

$$a_{GT} \cong -\frac{1}{3}\left[1 - \frac{|C_T|^2 + |C_T'|^2}{|C_A|^2}\right]$$

$$b_F \cong Re\,\frac{C_S + C_S'}{C_V}$$

Fierz term

$$b_{GT} \cong Re\,\frac{C_T + C_T'}{C_A}$$

(assuming maximal P-violation and T-invariance for V and A interactions)

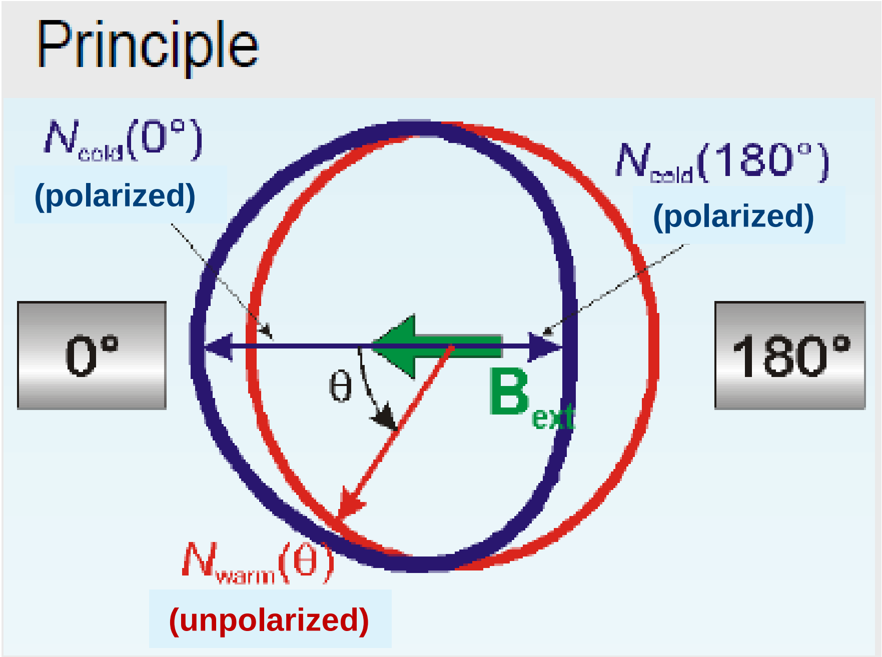
Neglecting recoil corr. (induced form factors) $\approx 10^{-3}$ and radiative corrections $\approx 10^{-4}$

!!! for pure transitions correlation coefficients (*a, A, B*, …) are independent of nuclear matrix elements !!!

KU LEUVEN

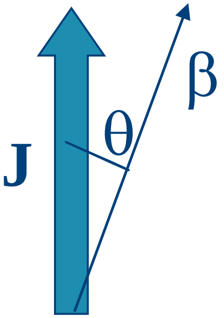
Beta-Asymmetry parameter

Requires the nuclei / neutrons be polarized !!



$$W(\theta) = \frac{N(\theta)_{pol}}{N(\theta)_{unpol}} \rightarrow \tilde{A} = \frac{A}{1 + b\,\frac{\gamma m_e}{E_e}}$$

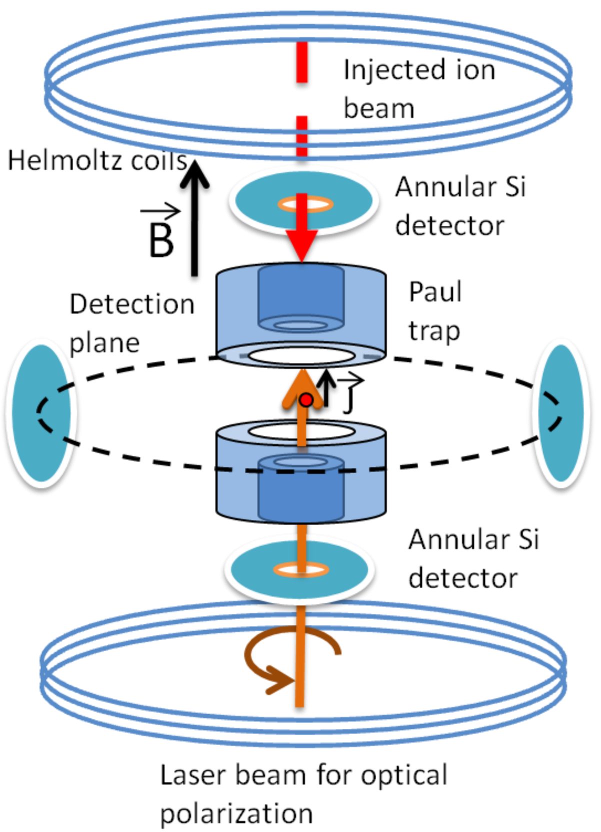
$$\boxed{b_{GT} = \left(\frac{C_T + C_T'}{C_A}\right)}$$

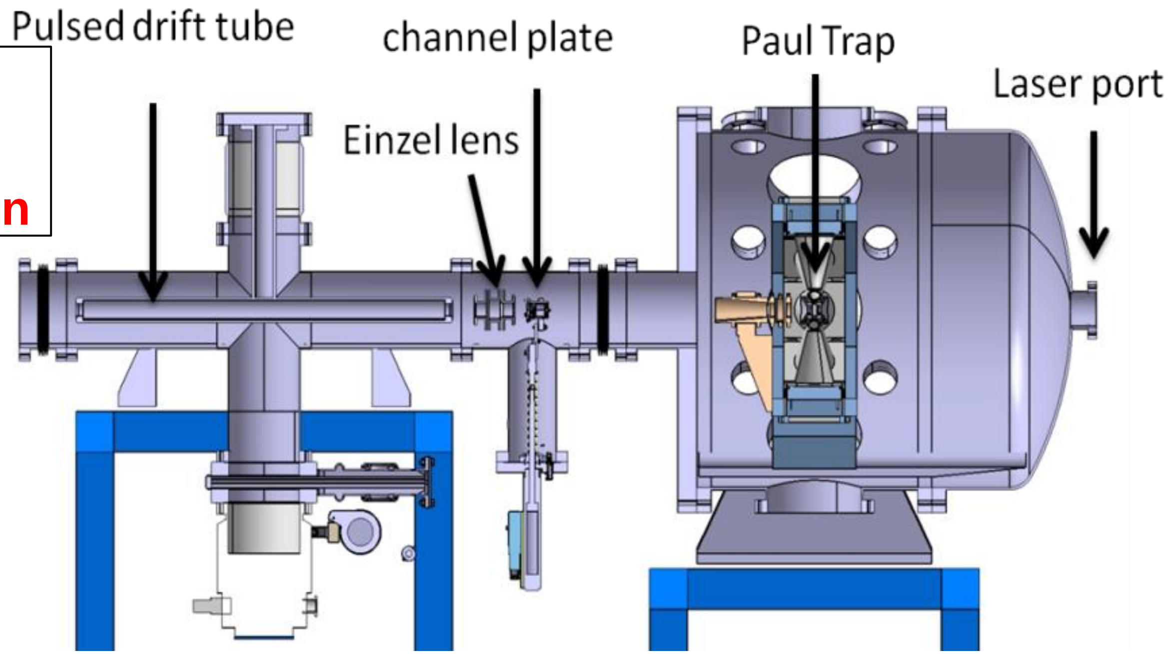


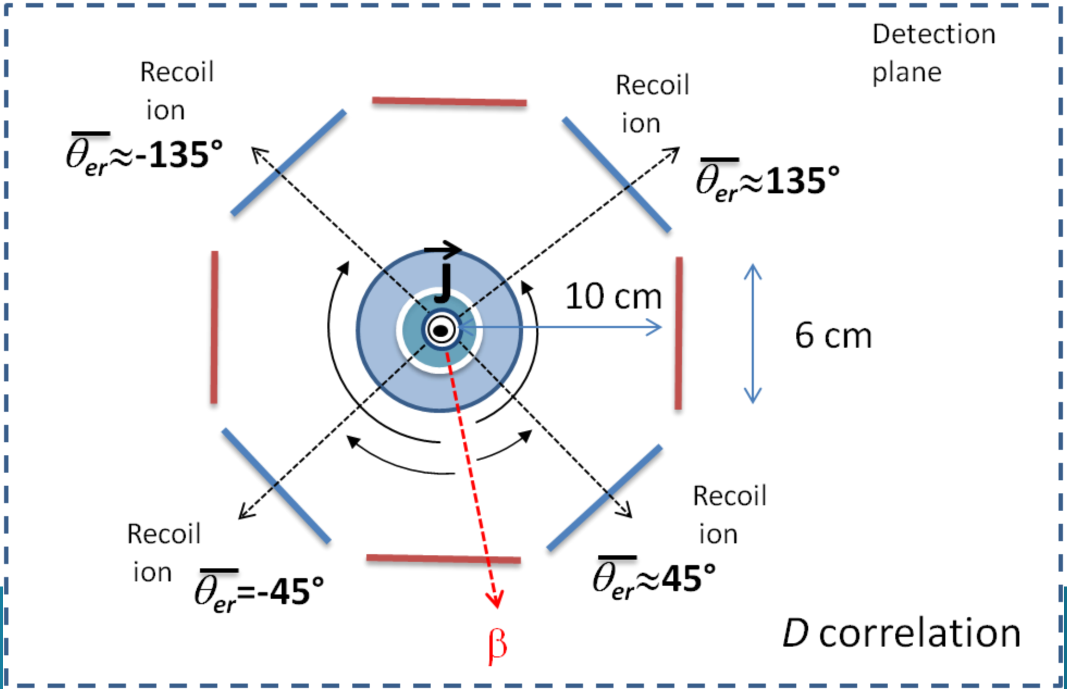
KU LEUVEN

MORA@JYFL-DESIR

T-reversal violating D-correlation







1. Formalism (basic aspects)

2. - Ft values of $0^+ \rightarrow 0^+$ transitions, mirror nuclei, and neutron: in search for V_{ud}

3. Correlations (a, A)
   - → Scalar and Tensor current searches
   - → global analysis
   - → need for including small SM corrections; recoil, radiative

4. Beta-spectrum shape to determine Fierz term and weak magnetism

KU LEUVEN

Ft value of the $0^+ \to 0^+$ decays

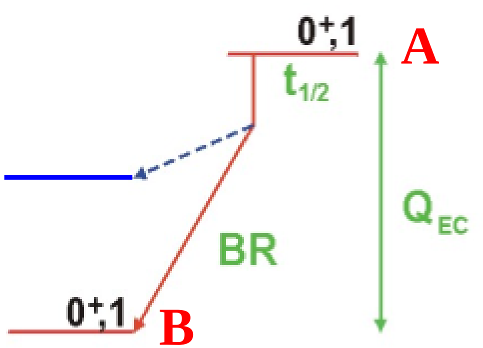
for $0^+ \to 0^+$ transitions, with only the <u>vector</u> current (selection rules) and including the small (% level) corrections:

$$\underbrace{\mathcal{F}t^{0^+\to 0^+}}_{\text{corrected } ft\text{-value}} \equiv \underbrace{f_V\, t^{0^+\to 0^+}}_{\text{from experiment}} \underbrace{(1+\boxed{\delta_{NS}^V}-\boxed{\delta_C^V})\,(1+\boxed{\delta'_R})}_{\text{nucleus dependent corrections (to be calculated)}} = \underbrace{\frac{K}{2G_F^2\, V_{ud}^2\, C_V^2\,(1+\boxed{\Delta_R^V})}}_{\text{nucleus independent}}$$

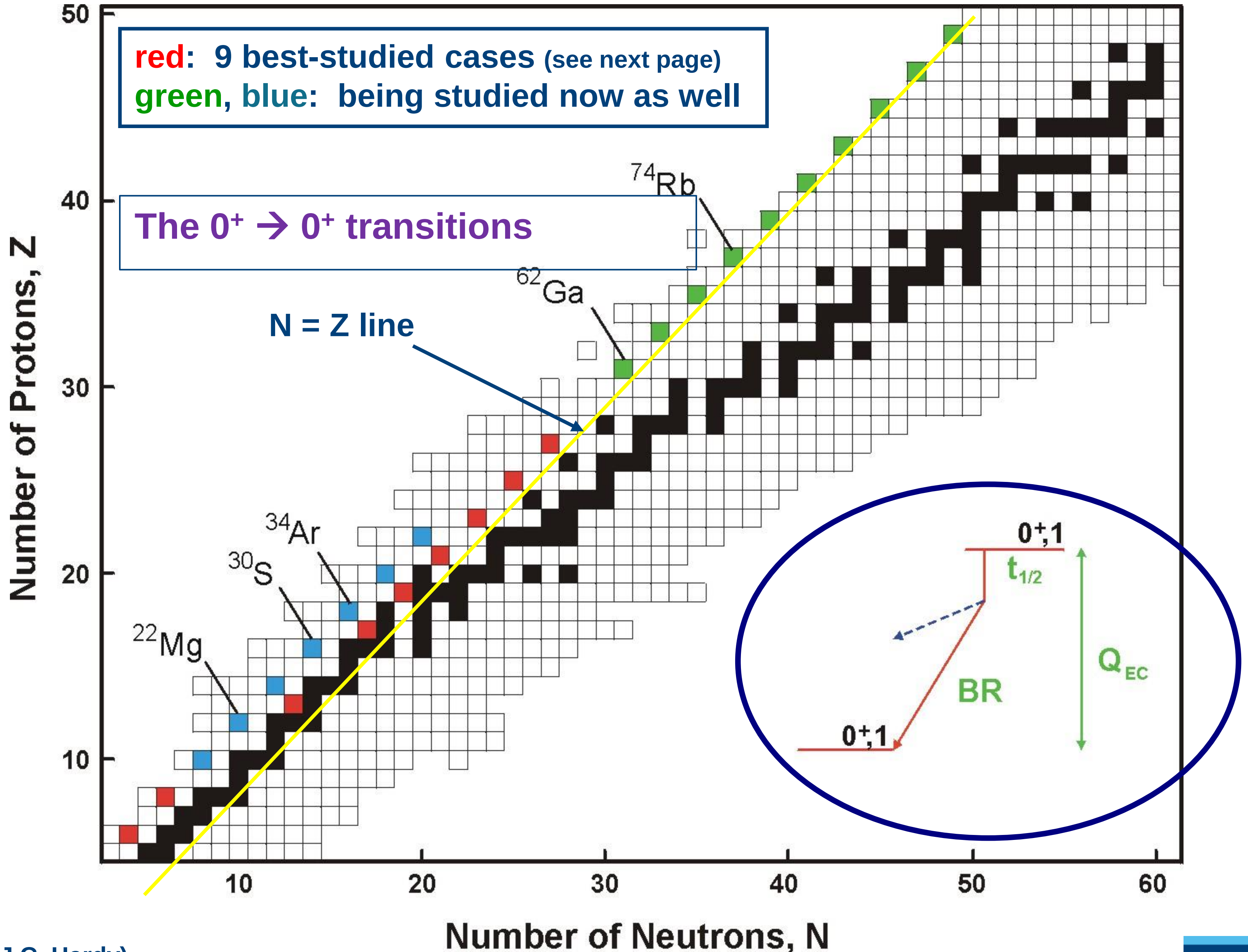
with :

$$f = \int \underbrace{F(\pm Z, W)\; S(\pm Z, W)\; (W - W_0)^2\; p\, W\, dW}_{Q_{EC}}$$

$$t = \underbrace{\ln 2\;\tau}_{t_{1/2}} \left(\frac{1 + P_{EC}}{BR} \right)$$

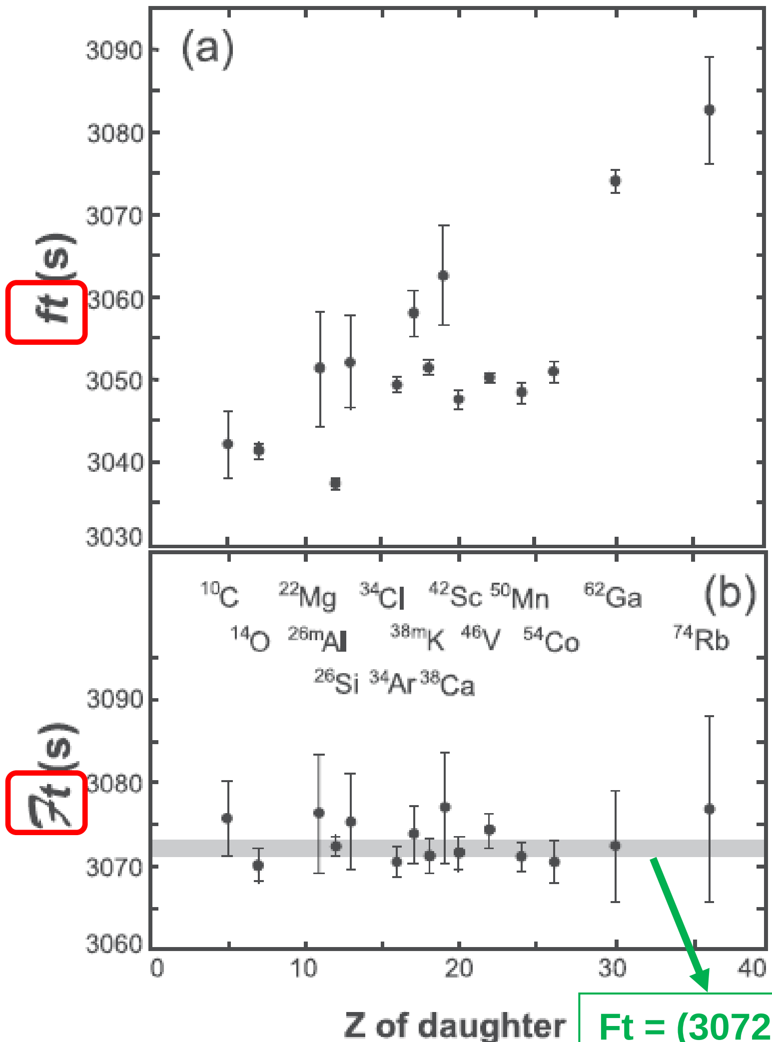


J.C. Hardy and I.S. Towner, Phys. Rev. C 102 (2020) 045501



(J.C. Hardy)

KU LEUVEN



Ft = (3072.24 ± 1.85) s

FIG. 3. (a) In the top panel are plotted the uncorrected experimental ft values for the 15 precisely known superallowed transitions as a function of the charge on the daughter nucleus. (b) In the bottom panel, the corresponding $\mathcal{F}t$ values are given; they differ from the ft values by the inclusion of the correction terms δ'_R, δ_{NS}, and δ_C. The horizontal gray band gives one standard deviation around the average $\overline{\mathcal{F}t}$ value. All transitions are labeled by their parent nuclei.

The nuclear corrections do matter !!

- **ft value, but no δ_R', δ_c or δ_{NS} :**

$$\boxed{ft}\ \cancel{(1+\delta_R')(1-\delta_c+\delta_{NS})}$$

- **Ft value, with all corrections :**

$$\boxed{Ft} = ft\ (1+\delta_R')(1-\delta_c+\delta_{NS})$$

→ nuclear corrections seem to be OK, but they contribute significantly to the uncertainty (next slide)

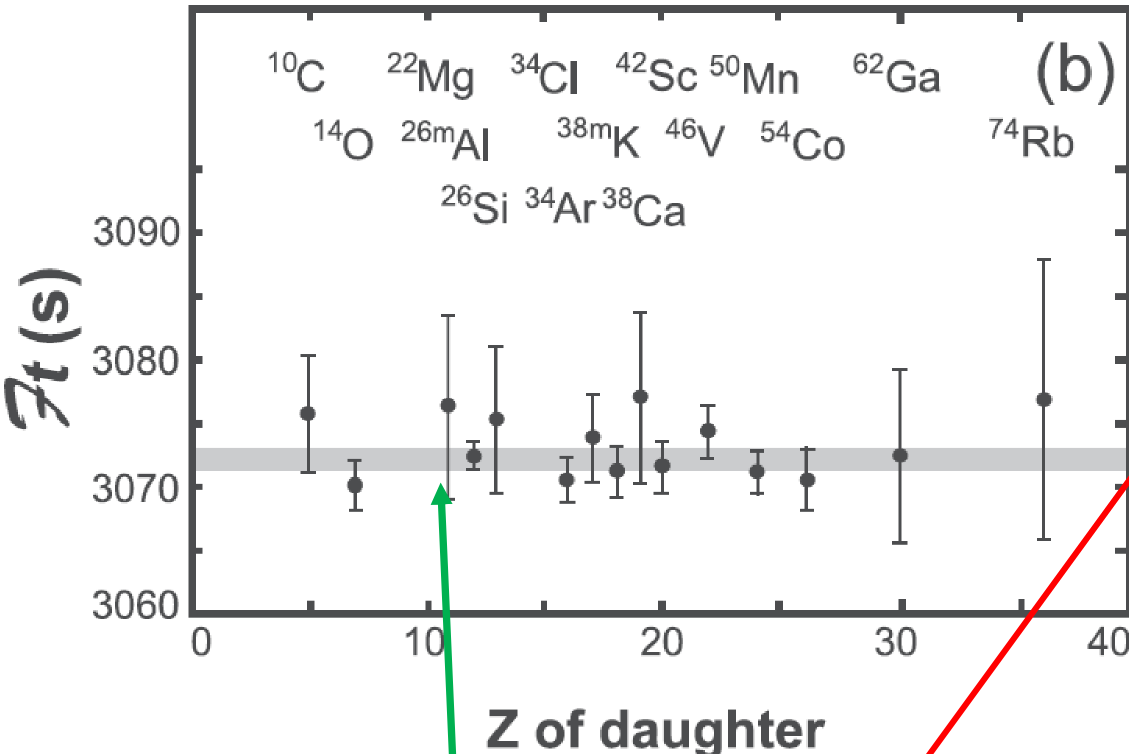
→ new calculations needed + measurements for nuclei with large corrections

J.C. Hardy, I.S. Towner, Phys. Rev. C 102 (2020) 045501

KU LEUVEN

Present situation

J.C. Hardy and I.S. Towner,
Phys. Rev. C 102 (2020) 045501



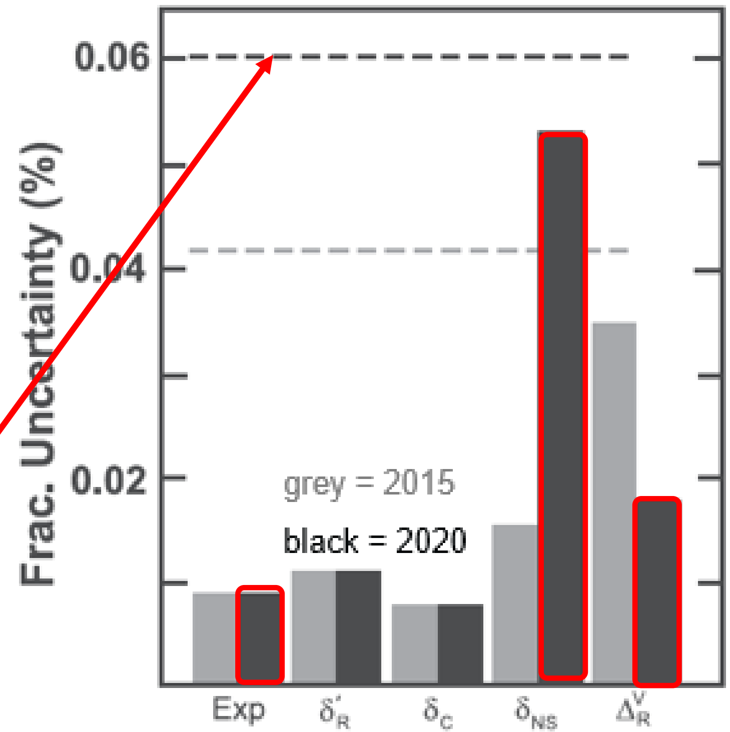


FIG. 8. Uncertainty budget for $|V_{ud}|^2$ as obtained from superallowed $0^+ \to 0^+$ β decay. The contributions are separated into five categories: experiment, the transition-dependent part of the radiative correction (δ'_R), the nuclear-structure-dependent terms δ_C and δ_{NS}, and the transition-independent part of the radiative correction Δ_R^V. The gray bars give the contributions in 2015 [7] while the black bars represent the present survey. The gray and black dashed lines give the corresponding total uncertainties.

$\langle \mathcal{F}t \rangle = (3072.24 \pm 1.85)$ s

$\rightarrow$ $|V_{ud}|^2 = 0.94815(60)$

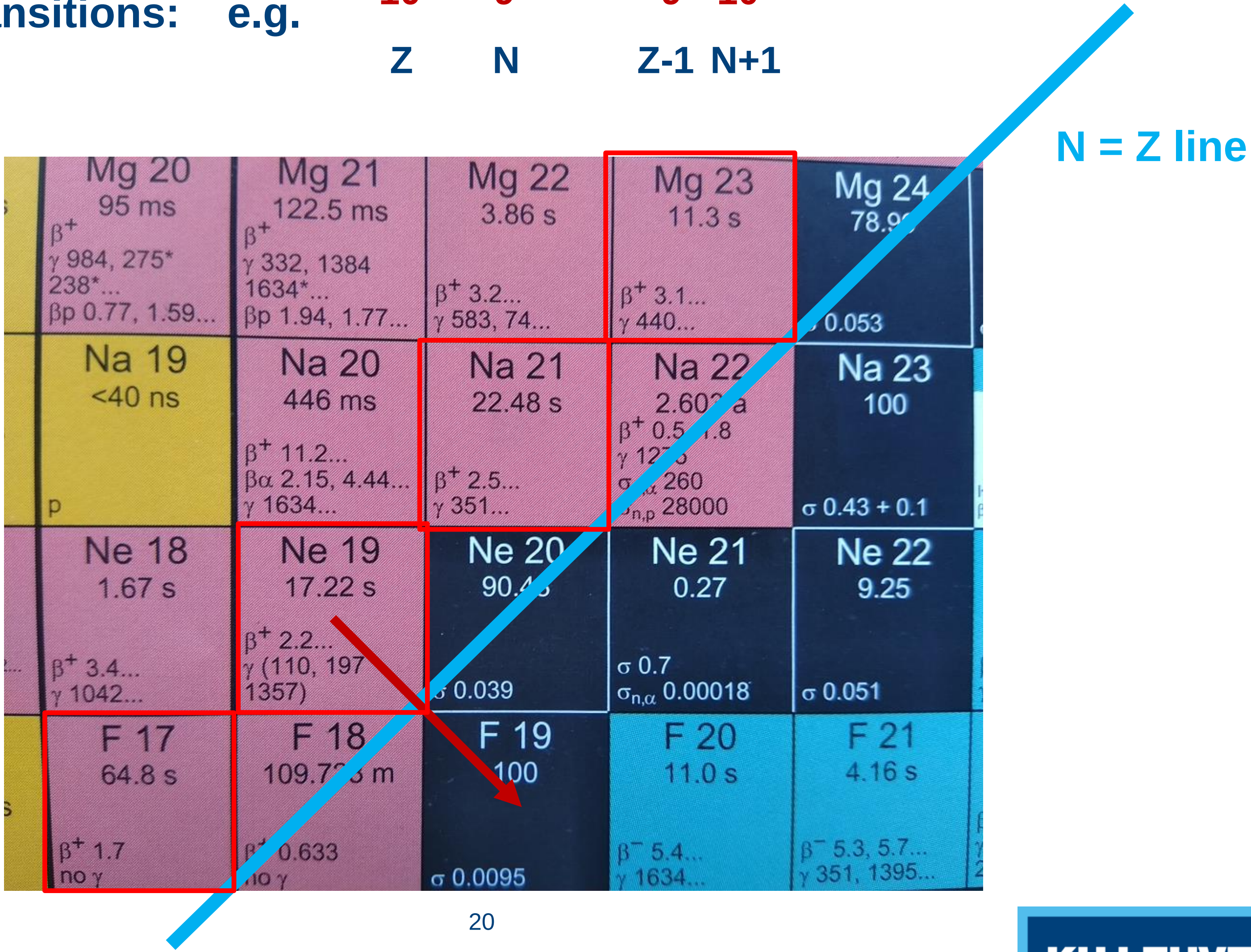
and $|V_{ud}| = 0.97373(31)$

KU LEUVEN

Ft values of mirror β transitions

Mirror beta transitions: e.g. $^{19}_{10}Ne_{9} \rightarrow \, ^{19}_{9}F_{10}$

Z N Z-1 N+1



KU LEUVEN

Ft value of superallowed mirror β transitions

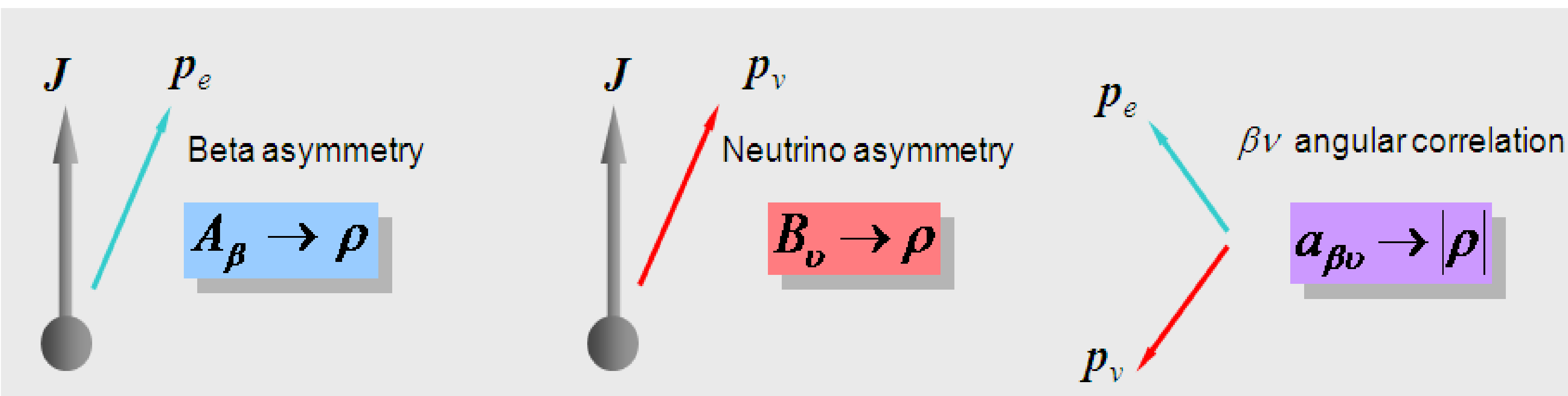
For the mixed F/GT mirror beta transition one has

apart from pure F part, $M_F^2 C_V^2$, now also a GT part, i.e. $M_{GT}^2 C_A^2$

$$\rightarrow \quad Ft^{mirror}\left(1+\frac{f_A}{f_V}\rho^2\right) = \frac{K}{G_F^2 V_{ud}^2 C_V^2 (1+\Delta_R^V)}$$

Extracting V_{ud} for mirror nuclei (and the neutron) thus requires the experimental determination of: Q_{EC}, $t_{1/2}$, BR, and $\rho = C_A M_{GT} / C_V M_F$

from correlation measurements



correlation meas.ts are available for: n, ^{19}Ne, ^{21}Na, ^{29}P, ^{35}Ar and ^{37}K

The special case of free neutron decay

$$\boxed{\mathcal{F}t^{\mathrm{mirror}}} \equiv \underbrace{f_V t}(1+\delta_R')(1+\cancel{\delta_{NS}^V}-\cancel{\delta_C^V}) = \frac{K}{G_F^2 V_{ud}^2}\frac{1}{\underbrace{\boxed{|M_F^0|^2}}_{=1} C_V^2 (1+\Delta_R^V)\boxed{\left(1+\frac{f_A}{f_V}\rho^2\right)}} \qquad \textbf{(1)}$$

$$\rho = C_A M_{GT} / C_V M_F$$

with :

$$f_V = \int \underbrace{F(\pm Z,W)\, S(\pm Z,W)\, (W-W_0)^2\, p\, W\, dW}_{Q_{EC}}$$

$$t = \underbrace{\ln 2\, \tau}_{t_{1/2}} \left(\frac{1+P_{EC}}{BR}\right)$$

- $M_F^2 = 1$
- $M_{GT}^2 = 3$
- $C_V \equiv 1$
- BR = 100 %
- $P_{EC} = 0$

$$\lambda \equiv C_A/C_V = g_A/g_V$$

For the neutron :

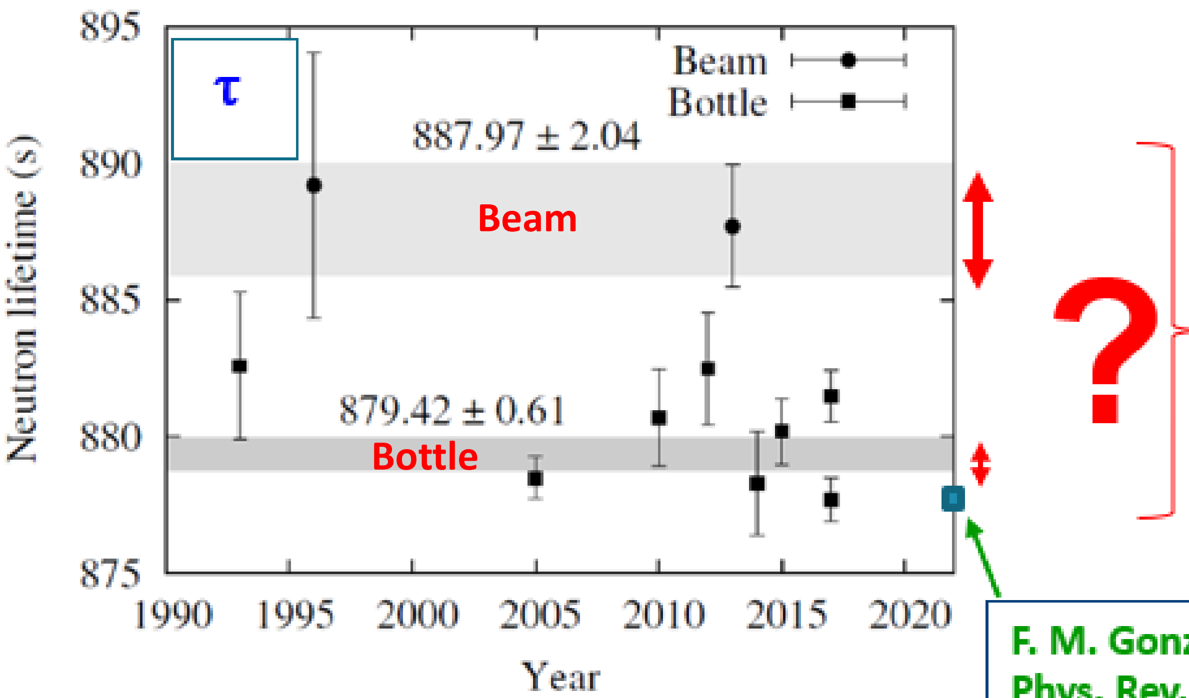
$$\rho^2 = C_A^{\ 2} M_{GT}^{\ 2} / C_V^{\ 2} M_F^{\ 2} = 3\, C_A^{\ 2} / C_V^{\ 2} \equiv 3\,\boxed{\lambda^2}$$

so that Eq. (1):

$$\boxed{f_n \tau_n (1+\delta_R) = \frac{K/\ln 2}{G_F^2 V_{ud}^2 (1+\Delta_R^V)(1+3\lambda^2)}}$$

with $f_n (1+\delta_R) = 1.71489(2)$ and $\lambda \equiv C_A/C_V = g_A/g_V$

Neutron lifetime (present status)



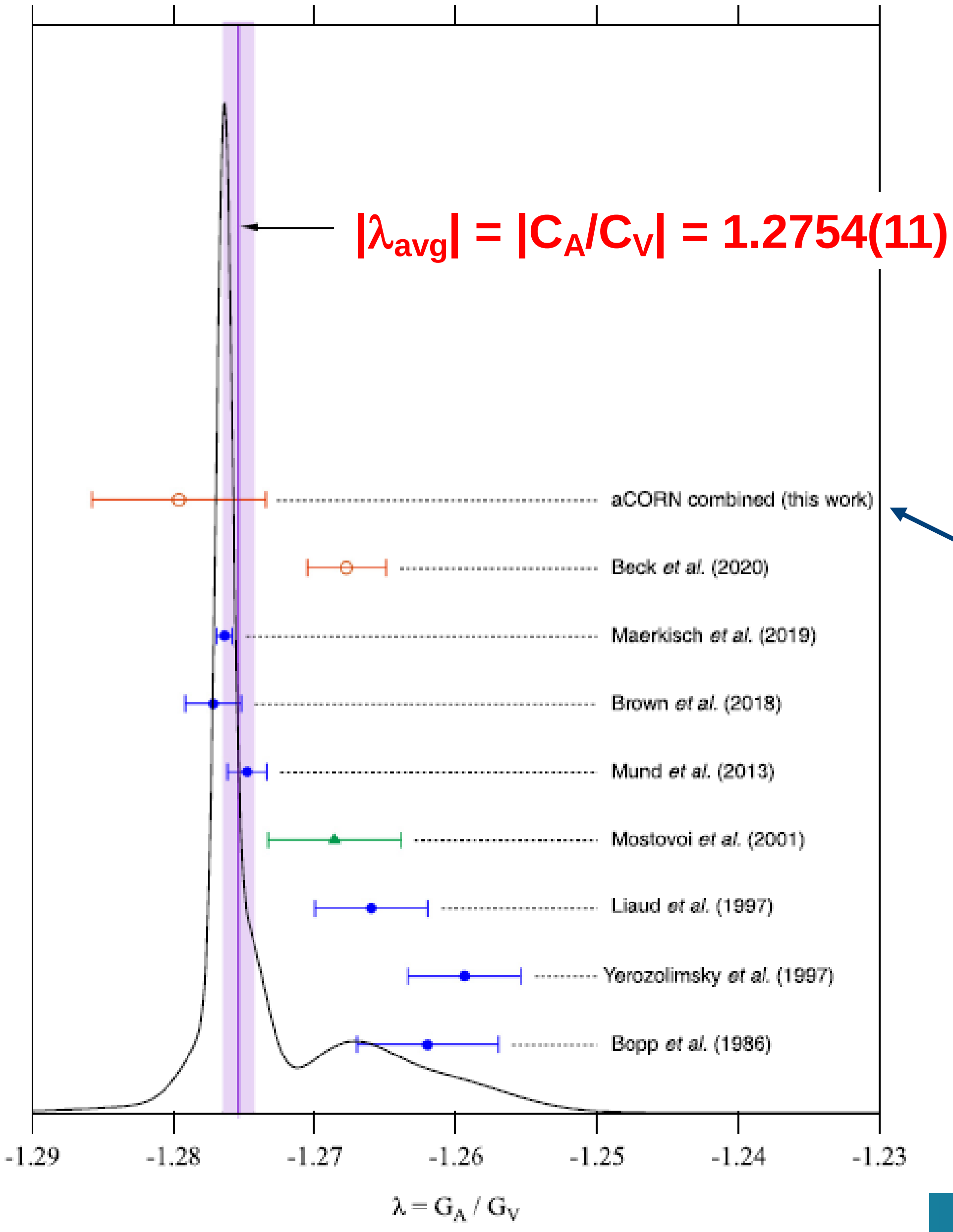
τ_n = 878.54(56) s

F. M. Gonzalez et al., Phys. Rev. Lett. 127 (2021) 162501

Figure 2: Overview of neutron lifetime results, separated into "beam" and "bottle" experiments (see also Table 7). The "bottle" experiments are performed with ultracold neutrons (UCN) stored in either a material bottle, a gravitational trap, or recently also a magneto-gravitational trap. Note the about four standard deviations tension between the weighted average values of both types of experiments. The uncertainty of the average of the "trap" measurements was scaled by a factor $\sqrt{\chi^2/\nu} \approx 1.52$ following the PDG prescription (Section 4.1).

from:
M. Gonzalez-Alonso, O. Naviliat-Cuncic, N. Severijns, Prog. Part. Nucl. Phys. 104 (2019) 165

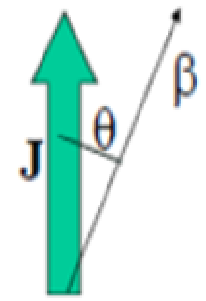
Neutron λ value (present status)



λ mainly from neutron beta-asymmetry parameter
(blue data points)

$$A_0 \equiv A_n = -2\frac{\lambda^2 + \lambda}{1 + 3\lambda^2}$$

With $\boxed{\lambda = \frac{g_A}{g_V} = \frac{C_A}{C_V}}$



M.T. Hassan et al., Phys. Rev. C 103 (2021) 045502
(and other references therein)

recent values for λ from beta-neutrino correlation
(orange data points)

$$a \equiv a_n = \frac{1 - \lambda^2}{1 + 3\lambda^2}$$

see also R.L. Workman *et al.* (Particle Data Group), Prog. Theor. Exp. Phys. 2022, 083C01 (2022)

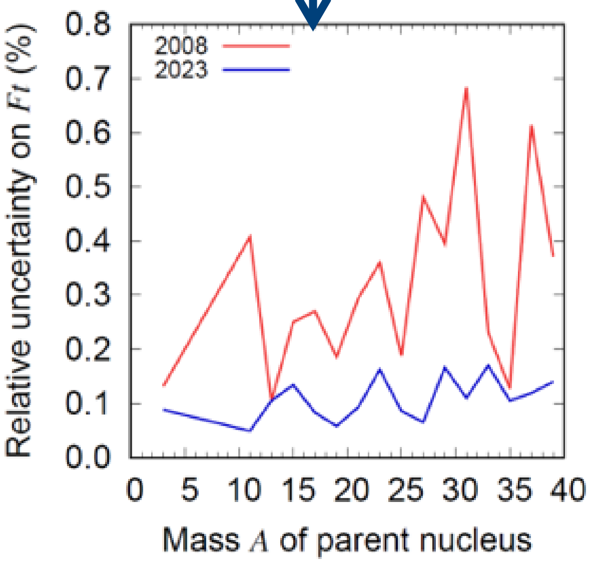
status for superallowed mirror β transitions

useful correlation measurements have been carried out for:

n, ^{19}Ne, ^{21}Na, ^{29}P, ^{35}Ar and ^{37}K

Parent nucleus	$\mathcal{F}t^{mirror}$ (s)	f_A/f_V	a	A	B	ρ	$\mathcal{F}t_0$ (s)
n	1043.58(67)	1.0000				+2.2091(15)[a]	6136.8(80)
^{19}Ne	1721.5(10)	1.0011		−0.0391(14) [341]		−1.5995(45)	6131(25)
^{19}Ne	1721.5(10)	1.0011		−0.03871(81) [69,342]		−1.6014(26)	6141(15)
^{21}Na	4073.0(38)	1.0020	0.5502(60) [62]			+0.7135(72)	6151(42)
^{29}P	4764.5(79)	1.0008		+0.681(86) [343]		+0.594(104)	6448(589)
^{35}Ar	5694.8(60)	0.9929		+0.49(10) [344]		+0.322(75)	6282(272)
^{35}Ar	5694.8(60)	0.9929		+0.427(23) [345]		+0.277(16)	6128(51)
^{37}K	4611.4(55)	0.9955			−0.755(24) [74]	−0.559(27)	6046(141)
^{37}K	4611.4(55)	0.9955		−0.5707(19) [35]		−0.5770(59)	6140(32)

from: N.S. et al., Phys. Rev. C 107 (2023) 015502



$$Ft_0 = Ft^{mirror}\left(1+\frac{f_A}{f_V}\rho^2\right) = \frac{K}{G_F^2 V_{ud}^2 (1+\Delta_R^V)}$$

(J.C. Hardy and I.S. Towner, Phys. Rev. C 102 (2020) 045501)

0.02454(19)

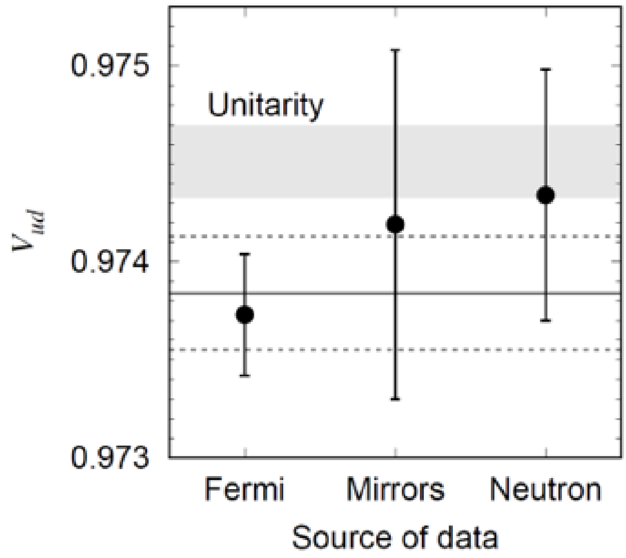
Note: on lattice (Ma 2308.16755) Δ_R^V = 0.02439(19)

Summarizing on V_{ud}

$|V_{ud}| = 0.97419(89)$
(mirrors / not neutron)

$|V_{ud}| = 0.97434(64)$
(neutron)

$|V_{ud}| = 0.97373(31)$
(pure Fermi transitions)



$|V_{ud}| = 0.97384(29)$

Further improvements for the mirror nuclei and neutron require:

- improved corrected Ft-values for T = 1/2 mirror transitions
- new and precise measurements of correlation coefficients,
  (e.g. $\beta\nu$-correlation coefficient *a* and beta asymmetry parameter *A*)
- new measurements of the lifetime and correlations (λ) for the neutron

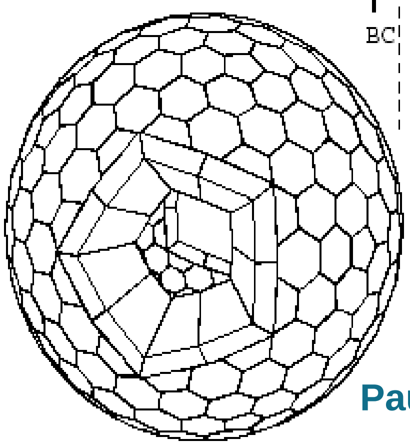
KU LEUVEN

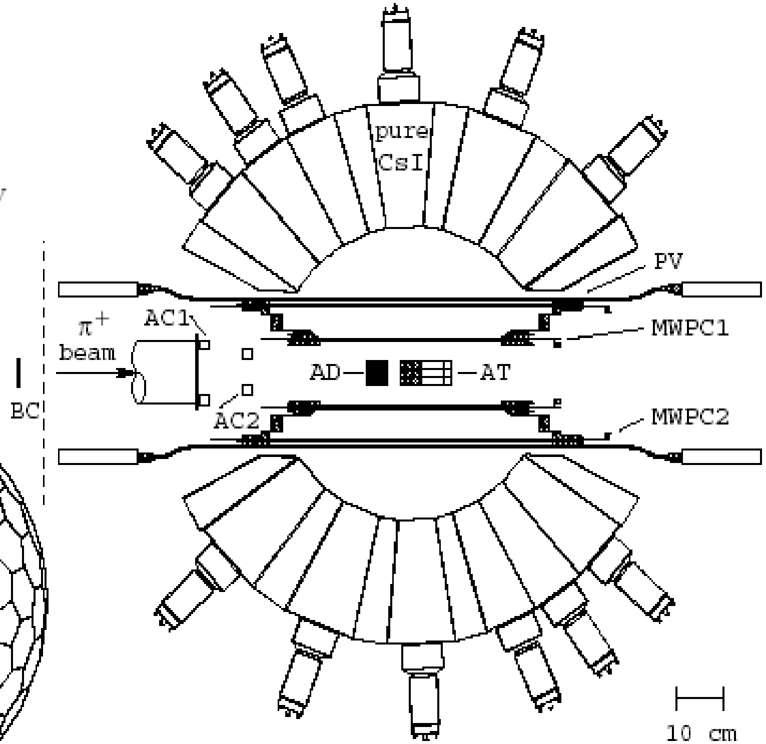
status for β decay of the neutral pion

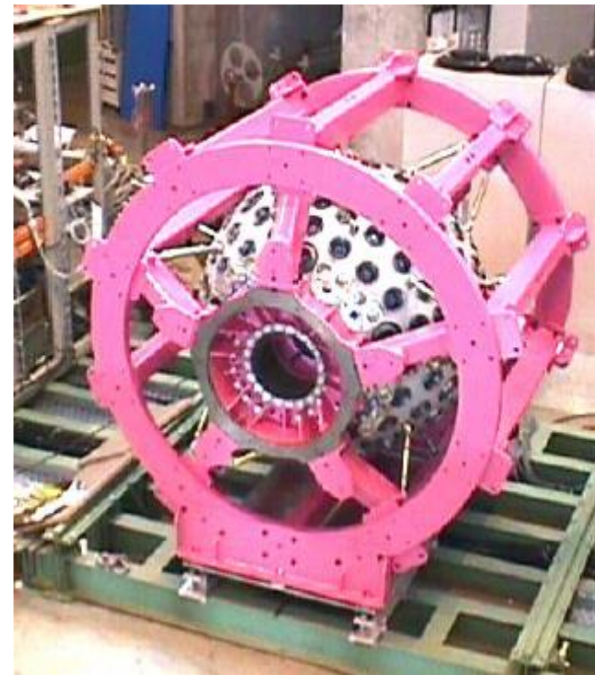
The PIBETA Experiment:

- stopped π^+ beam
- segmented active tgt.
- 240-det. CsI(p) calo.
- central tracking
- digitized PMT signals
- stable temp./humidity
- cosmic μ antihouse

pure Vector decay







Paul Scherrer Institute, Villigen, CH

D. Pocanic et al., PRL (2004) : $\mathrm{BR}(\pi^+ \rightarrow \pi^0\, e^+\, \nu) = 1.036(6) \times 10^{-8}$

$\rightarrow\ |V_{ud}{}^{\pi}| = 0.9742(26)$

see also: Towner & Hardy, Rep. Prog. Phys.72(2010)046301

testing unitarity of CKM quark mixing matrix

• **coupling of quark weak eigenstates to mass eigenstates in the Standard Model**

$$\begin{pmatrix} d' \\ s' \\ b' \end{pmatrix} = \begin{pmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{pmatrix} \begin{pmatrix} d \\ s \\ b \end{pmatrix} \Rightarrow \boxed{|V_{ud}|^2 + |V_{us}|^2 + |V_{ub}|^2 = 1 \;\; ??}$$

V_{ud} = 0.97384(29)	~ 95 %
V_{us} = 0.22430(80)	~ 5 %
V_{ub} = 0.00382(20)	~ 0 %

→ $\sum |V_{ui}|^2 = 0.9987(7)$

R.L Workman *et al.* (Particle Data Group), Prog. Theor. Exp. Phys. 2022, 083C01 (2022)
Hardy & Towner, Phys. Rev. C 10291, 045501 (2020)
Falkowski, Gonzalez-Alonso, Naviliat-Cuncic, Severijns, Eur. Phys. J. A 59 (2023) 113

1. Formalism (basic aspects)

2. - Ft values of $0^+ \rightarrow 0^+$ transitions, mirror nuclei, and neutron: in search for V_{ud}

3. **Correlations (*a, A*)**
   - → **Scalar and Tensor current searches**
   - → **global analysis**
   - → **need for including small SM corrections; recoil, radiative**

4. Beta-spectrum shape to determine Fierz term and weak magnetism

Major Observables in Beta Decay

$\bar{p}$: momentum of β particle
$\bar{q}$: momentum of neutrino
E: energy of beta/neutrino
m: electron rest mass
$\bar{J}$: spin of nucleus
$\gamma = \sqrt{(1-(\alpha Z)^2}$
σ: spin direction of beta

differential decay rate

$$d\Gamma = \underbrace{\underbrace{F(\pm Z, E_e)}_{\text{Fermi function}} \; \underbrace{p_e E_e (E_0 - E_e)^2 \, dE_e \, d\Omega_e \, d\Omega_\nu}_{\text{phase space}}}_{d\Gamma_0} \; \underbrace{\xi}_{\text{nuclear matrix elements, } M_F \text{ and } M_{GT}}$$

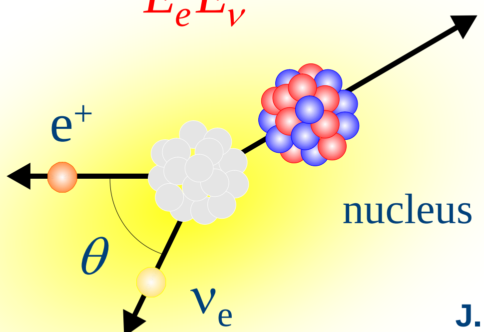
$$\times \left\{ 1 + a \frac{\vec{p}_e \cdot \vec{q}}{E_e E_\nu} + b_{Fierz} \frac{\gamma m}{E_e} + A \frac{\vec{J}}{J} \cdot \frac{\vec{p}_e}{E_e} + R\, \vec{\sigma} \cdot \frac{\vec{J}}{J} \mathrm{x} \frac{\vec{p}_e}{E_e} + \ldots \right\}$$

β-ν correlation

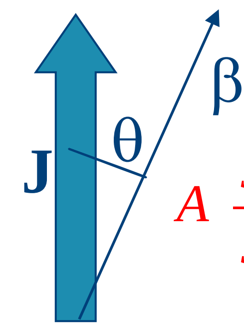
Fierz interference term (b ≡ 0 in standard model)

β-asymmetry

$$a \frac{\vec{p}_e \cdot \vec{q}}{E_e E_\nu}$$



$$\tilde{X} = \frac{X}{1 + b \frac{\gamma m}{E_e}} \quad \text{with } \gamma = \sqrt{(1-(\alpha Z)^2}$$

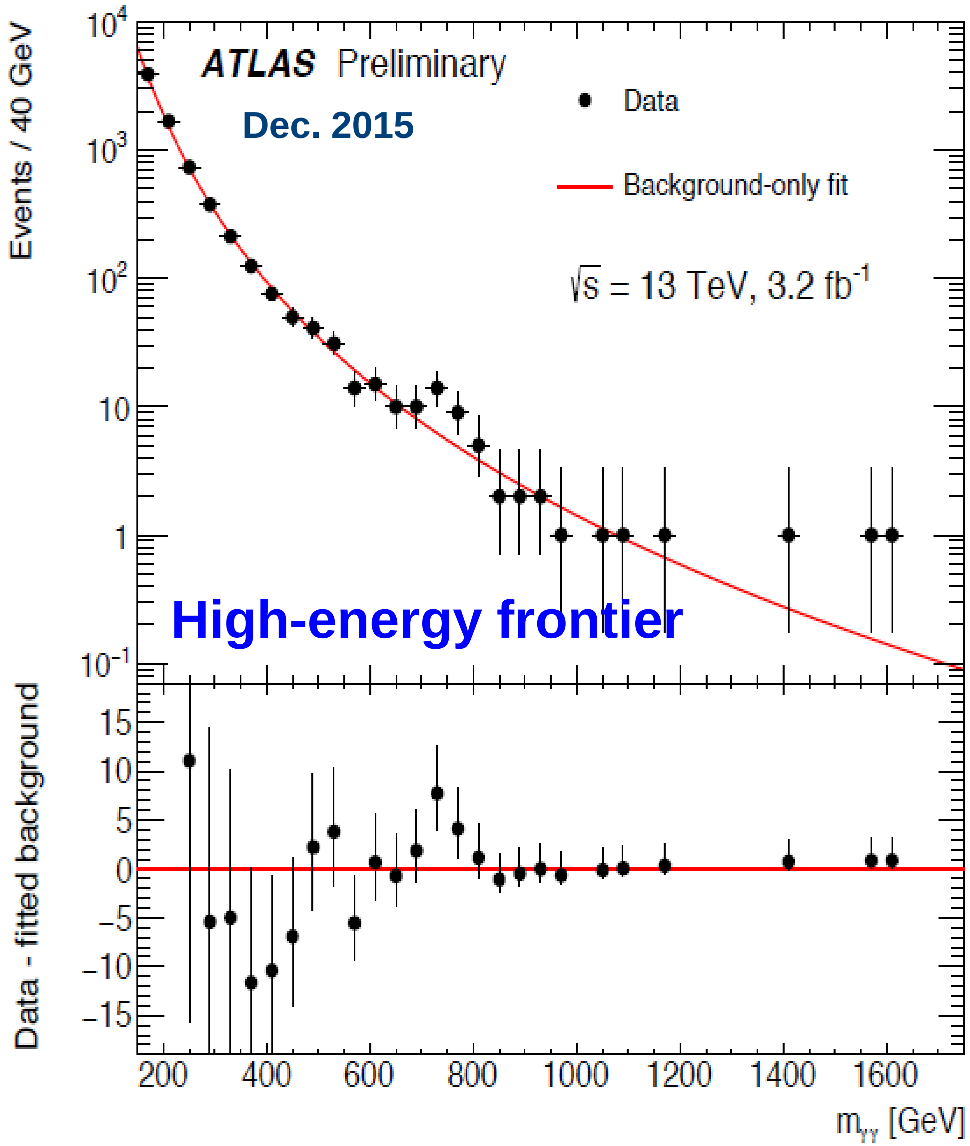


$$A \frac{\vec{J}}{J} \cdot \frac{\vec{p}_e}{E_e}$$

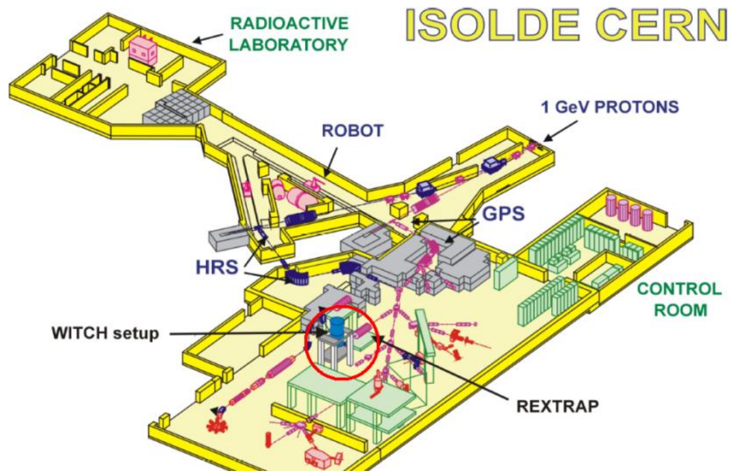
J.D. Jackson, S.B. Treiman, H.W. Wyld, Nucl. Phys. 4 (1957) 206

KU LEUVEN

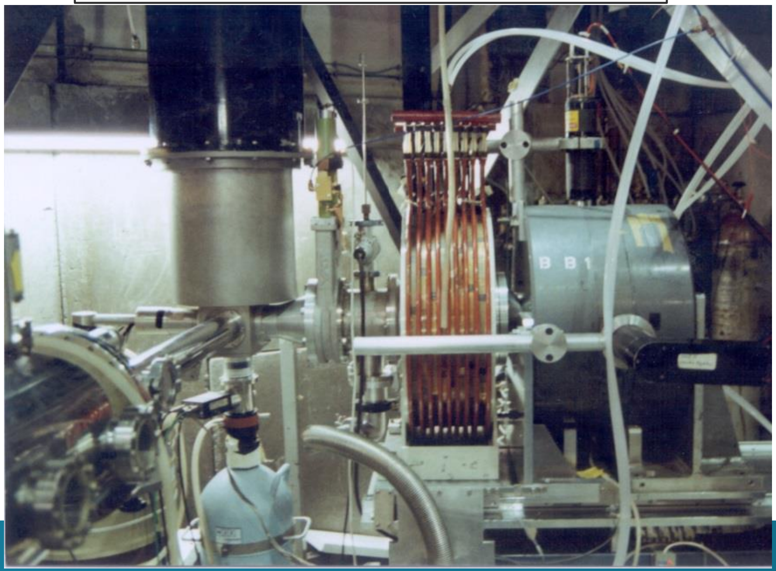
High-energy versus Precision frontier



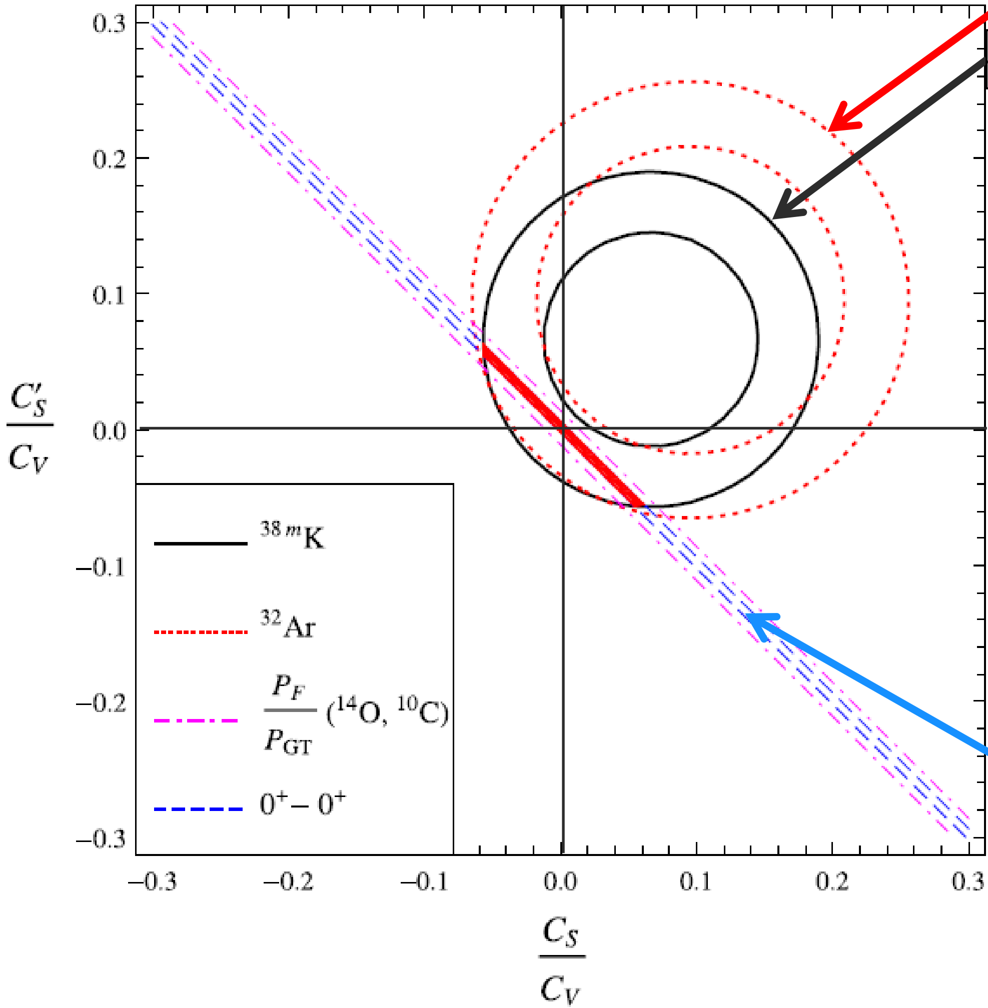
Precision frontier



$$\tilde{A} = A_{SM}\left[1 - k\left(C_T + C_T^{'}\right)\right]$$



Examples of limits on scalar currents



^{32}Ar: Adelberger et al., PRL 83 (1999) 1299

^{38m}K: Gorelov, Behr et al., PRL 94 (2005) 142501

$$\tilde{a} = \frac{a}{1 + b\,\frac{\gamma m_e}{E_e}}$$

βν correlation

Fierz interference term

with:

$$a_F \cong 1 - \frac{|C_S|^2 + |C_S'|^2}{|C_V|^2}$$

$$b_F' = \frac{\gamma m_e}{\langle E_e \rangle}\left(\frac{C_S + C_S'}{C_V}\right)$$

$$\mathcal{F}t^{0^+\to 0^+} = \frac{K}{2G_F^2 V_{ud}^2 C_V^2 \left(1 + \Delta_R^V\right)} \frac{1}{(1+b_F')}$$

Hardy & Towner , Phys. Rev. C 102 (2020) 045501

B. R. Holstein, J. Phys. G 41 (2014) 114001

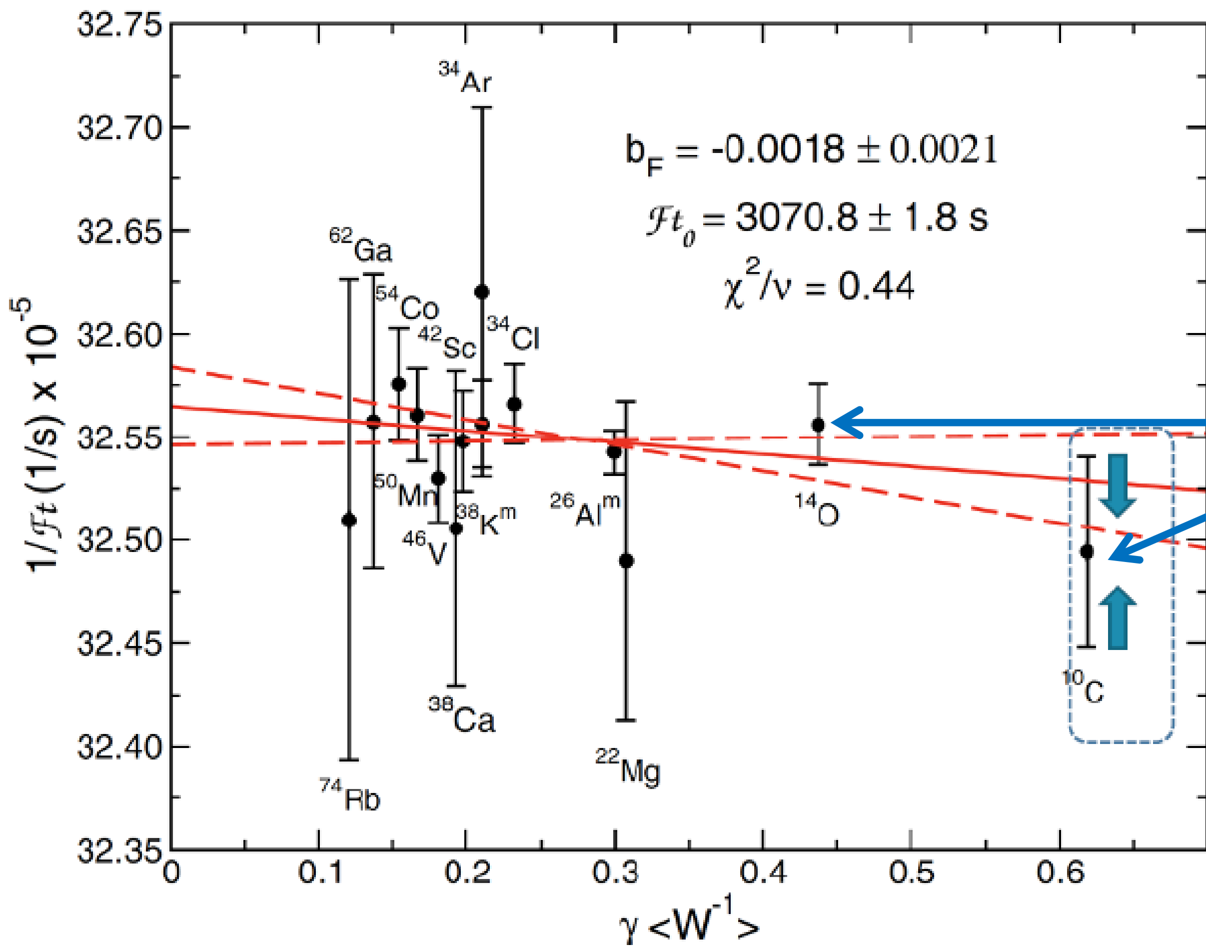
KU LEUVEN

$$\mathcal{F}t^{0^+\rightarrow 0^+} = \frac{K}{2G_F^2 V_{ud}^2 C_V^2 \left(1+\Delta_R^V\right)} \frac{1}{\left(1+b_F^{'}\right)}$$

$\rightarrow$ $b_F = -0.0018 \pm 0.0021$

Hardy & Towner , Phys. Rev. C 102 (2020) 045501

$$b_F^{'} = \frac{\gamma m_e}{\langle E_e \rangle}\left(\frac{C_S + C_S^{'}}{C_V}\right)$$



^{14}O and ^{10}C (very) sensitive to b_F

↓

new measurements planned

M. R. Dunlop et al., Phys. Rev. Lett. ***116****, 172501 (2016).*

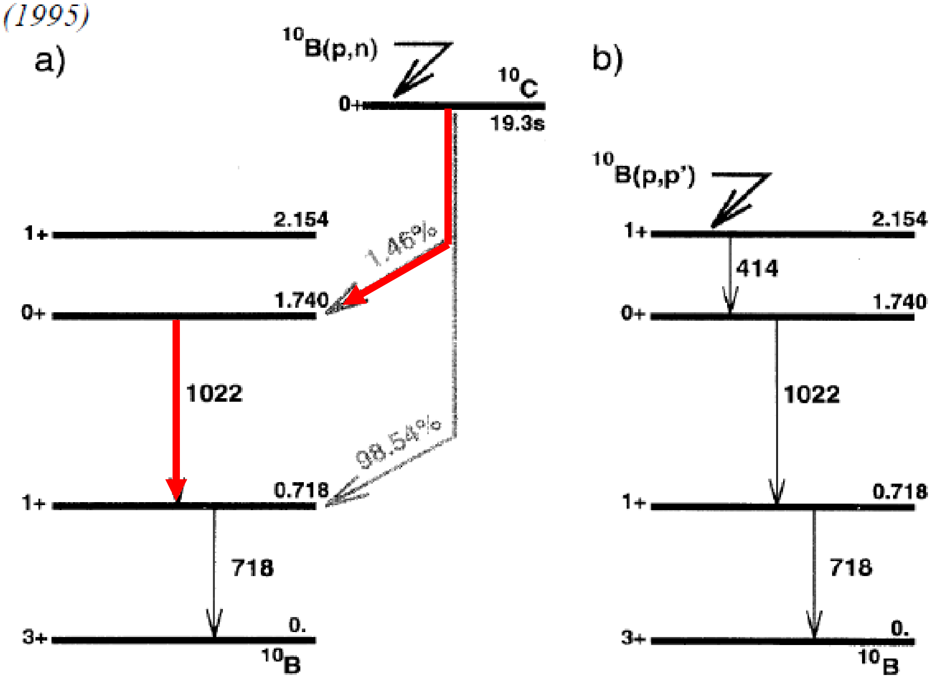
New measurement of ^{10}C BR value with AGATA als Legnaro Natl. Lab. (Jeongsu Ha et al.)

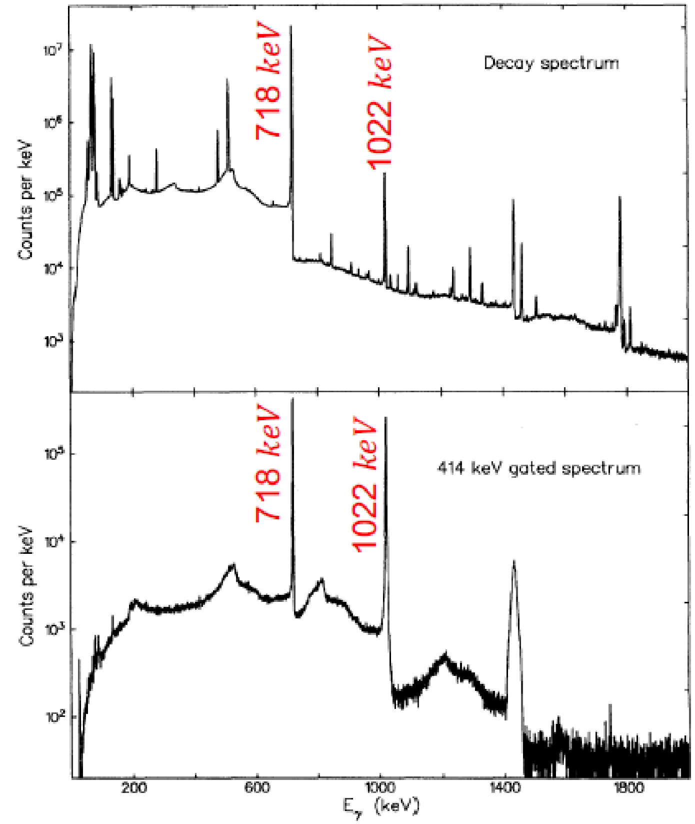
challenge: gamma-ray at 1022 keV → $BR(0^+ \rightarrow 0^+) = \frac{N_{1022}}{N_{718}} \cdot \frac{\varepsilon_{718}}{\varepsilon_{1022}}$

a) ^{10}B(p,n)^{10}C: superallowed β-decay count ratio measurement of ^{10}C

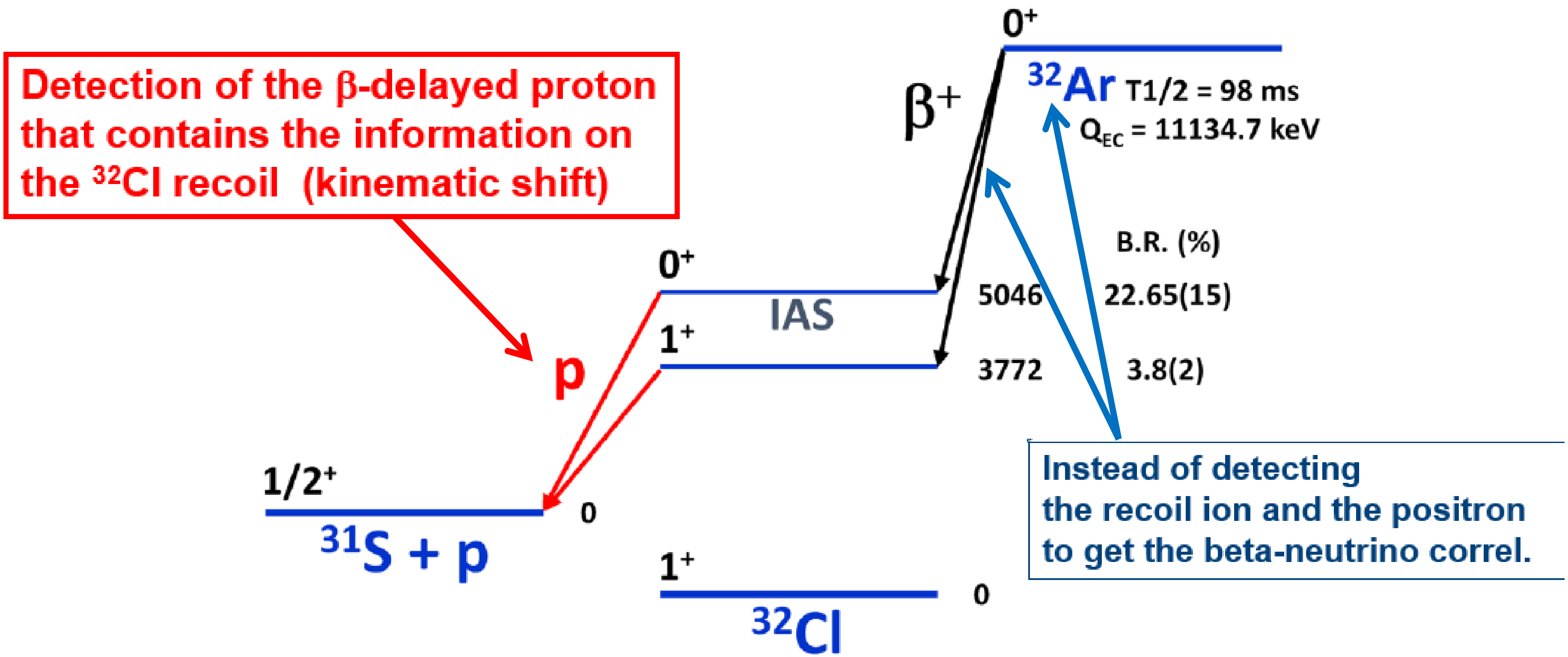
b) ^{10}B(p,p')^{10}B*: efficiency ratio $\varepsilon(718keV)/\varepsilon(1022keV)$ measurement

G. Savard et al., Phys. Rev. Lett 74, 1521 (1995)





WISArD = Weak-interaction studies with Ar32 decay



collab. Bordeaux, Leuven, LPC Caen, NPI-Prague, ISOLDE

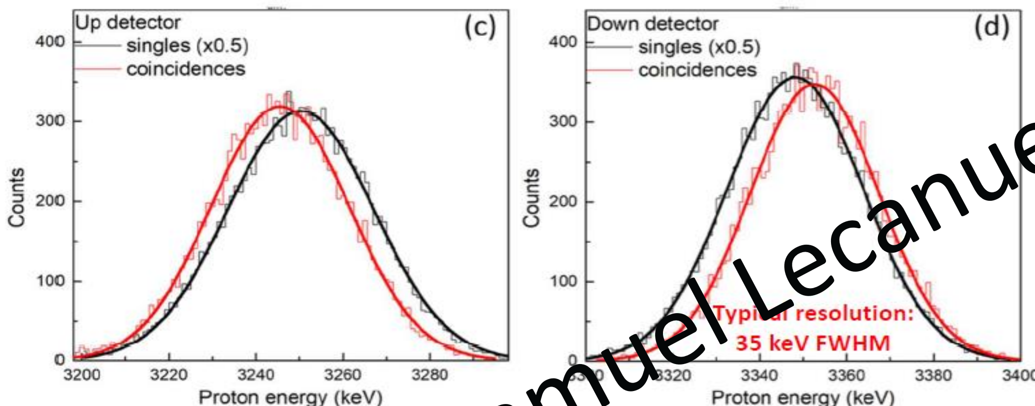
WISArD - 1

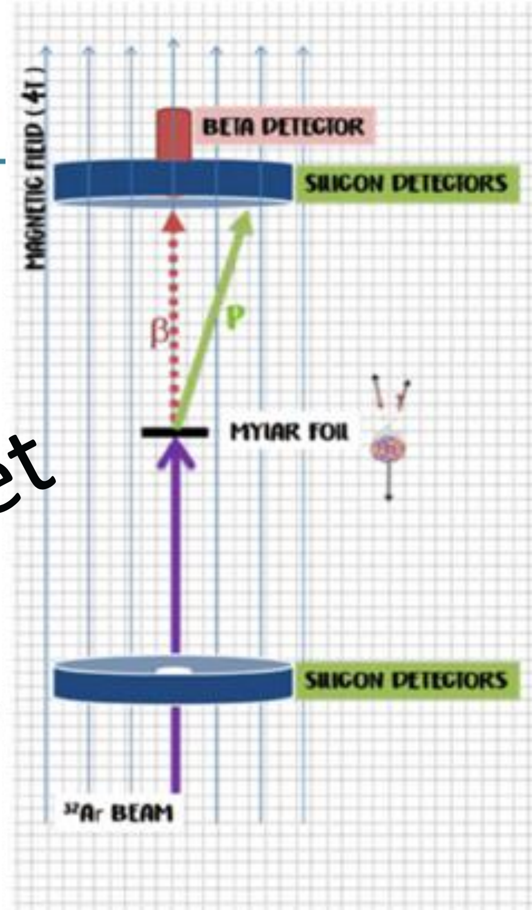
KU LEUVEN

WISArD *Weak Interaction Studies with ^{32}Ar Decay*

first results: (nov. 2018)

Proton peak examples (Fermi transition):





Average shift:
Δ = 4.49(3) keV

talk by Samuel Lecanuet

by means of MC calculations:

$$\tilde{a}^{F}_{\beta\nu} = \mathbf{1.01(3)_{(stat)}(2)_{(syst)}} \qquad \tilde{a}^{GT}_{\beta\nu} = \mathbf{-0.29(9)_{(stat)}(2)_{(syst)}}$$

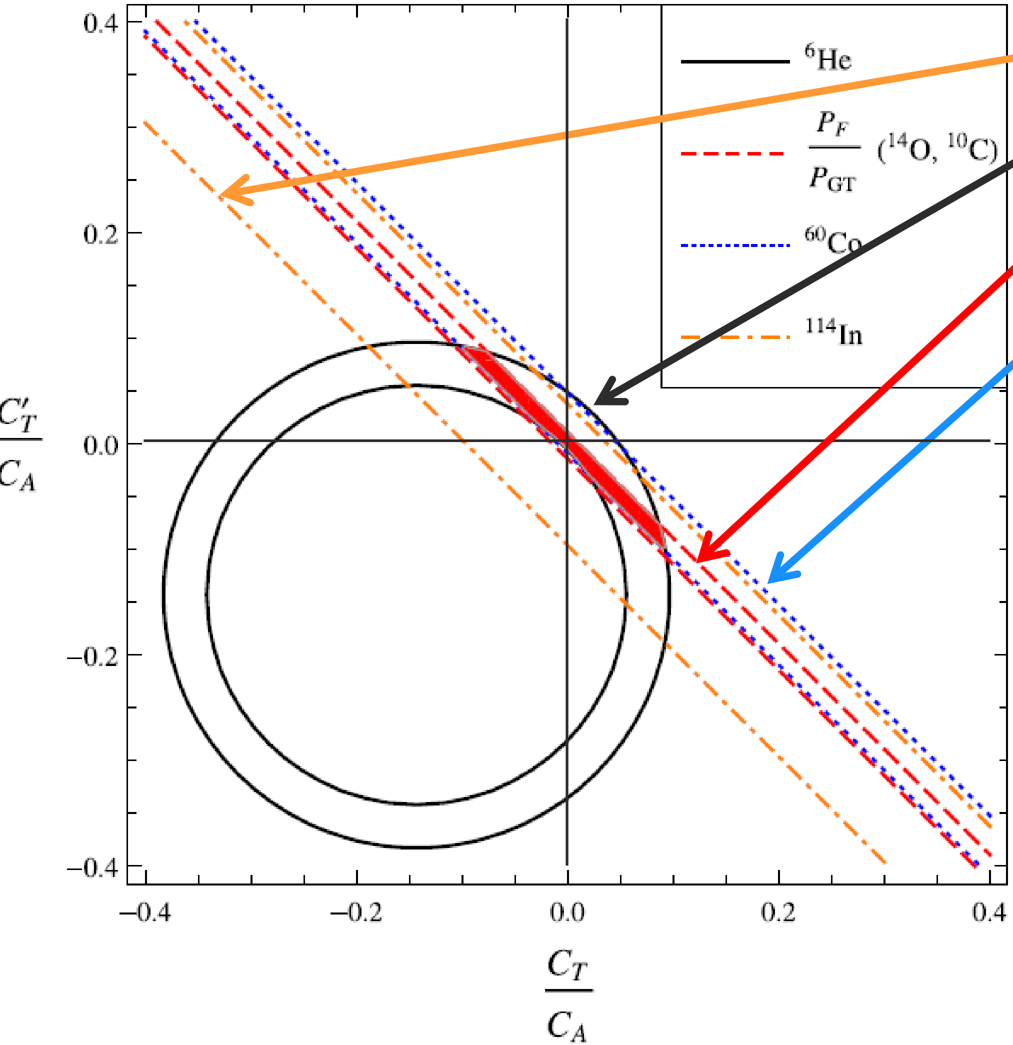
$$(\tilde{a}^{F}_{\beta\nu,SM} = 1.00\ ) \qquad (\ \tilde{a}^{GT}_{\beta\nu,SM} = -0.33\ )$$

δ(a) = 0.2 % can be reached with improved setup (in prep.) - ISOLDE

Courtesy: B. Blank

V. Araujo-Escalona, X. Flechard et al., Phys Rev C 101-2020-055501

Limits on tensor currents



$\tilde{A}$(^{114}In) F. Wauters et al., PR C 80 (2009) 062501(R)

a(^{6}He) C.H. Johnson et al., PR 132 (1963) 1149

^{14}O,^{10}C A.S. Carnoy et al., Phys. Rev. C 43 (1991) 2825

A(^{60}Co) F. Wauters et al., PR C 82 (2010) 055502

$$\tilde{A} = \frac{A}{1 + b'_{GT}}$$

β asymmetry param.

Fierz interference term

with:

$$A_{GT} \cong -1$$

$$b'_{GT} = \frac{\gamma m_e}{\langle E_e \rangle}\left(\frac{C_T + C'_T}{C_A}\right)$$

B. R. Holstein, J. Phys. G 41 (2014) 114001

KU LEUVEN

collab. KU Leuven, NICOLE-ISOLDE, NPI Rez-Prague, Uni Bonn)

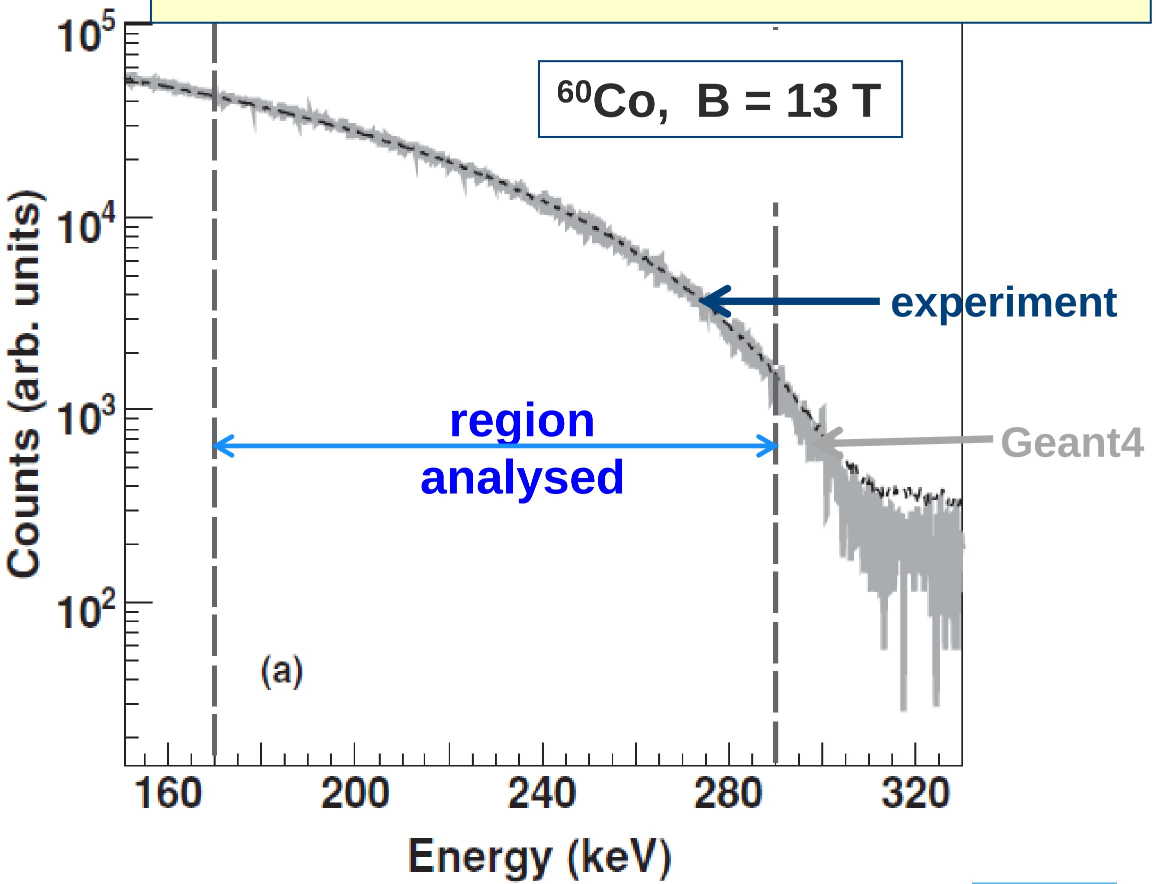
$\tilde{A}_{exp}$ (^{60}Co) = - 1.014 $(12)_{stat}$ $(16)_{syst}$

F. Wauters et al., Phys. Rev. C 82 (2010) 055502

$\tilde{A}_{exp}$ (^{114}In) = - 0.990 $(10)_{stat}$ $(10)_{syst}$

F. Wauters et al., Phys. Rev. C 80 (2009) 062501(R)

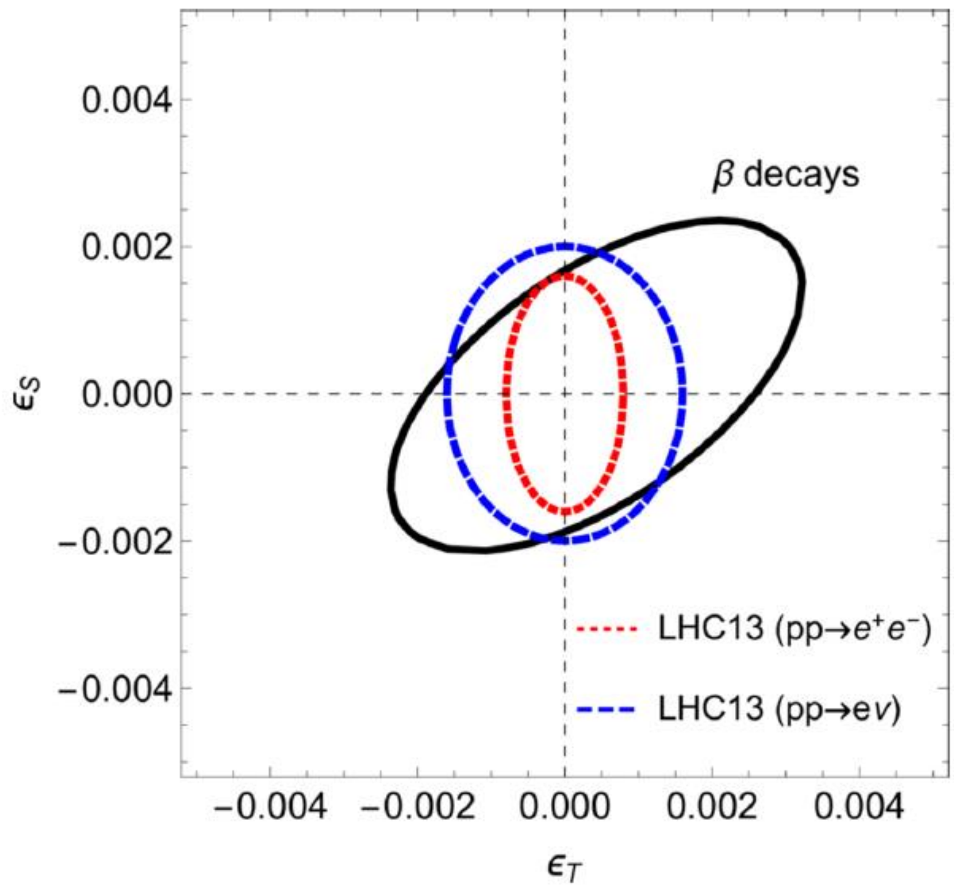
^{3}He - ^{4}He dilution refrigerator set-up



F. Wauters et al.,
Phys. Rev. C 82 (2010) 055502
Nucl. Instr. Meth. A 604 (2009) 563

KU LEUVEN

High-energy versus Precision frontier



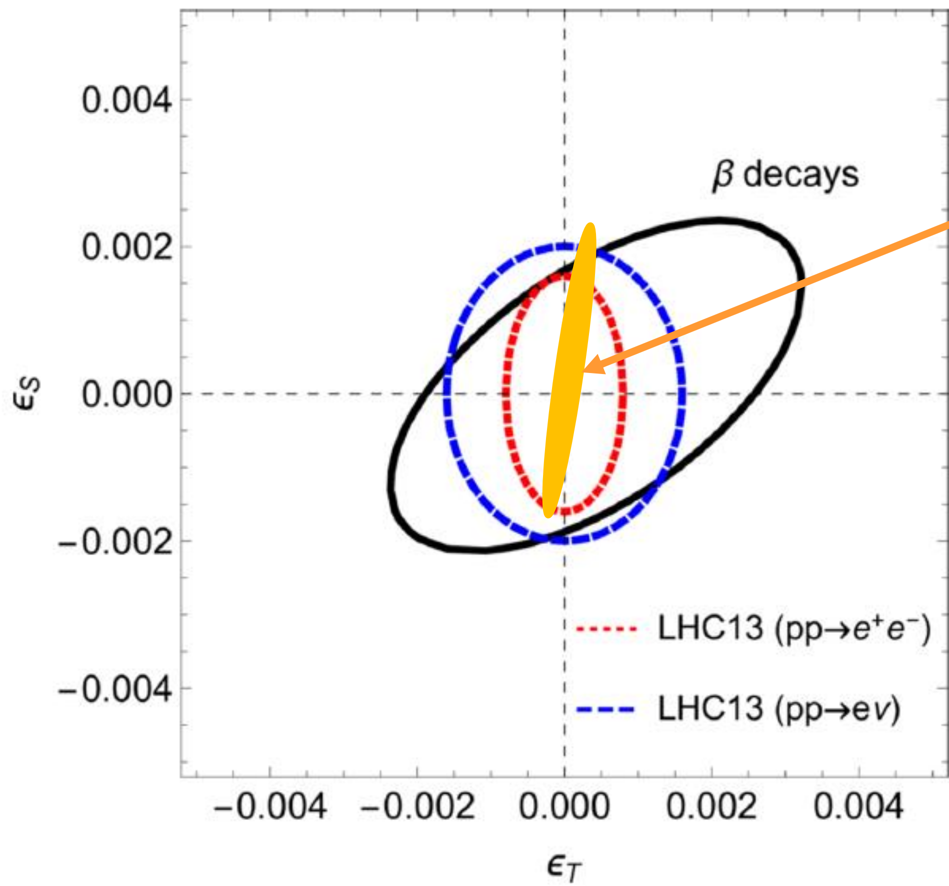
for details see
A. Falkowski, M. Gonzalez-Alonso,
and O. Naviliat-Cuncic,
JHEP 04 (2021) 126

$$C_i = \frac{G_F(0)}{\sqrt{2}} V_{ud} \bar{C}_i \quad \text{with} \quad \bar{C}_S = g_S(\varepsilon_S + \tilde{\varepsilon}_S),\ \bar{C}_T = 4g_T(\varepsilon_T + \tilde{\varepsilon}_T),\ \ldots$$

Lee-Yang coupling constants

EFT coupling constants

High-energy versus Precision frontier



Ambitious goal for our field:

$\Delta(\tau_n)$ = 0.1 s

$\Delta(b_{n,\ F/GT})$ = 0.001

$\delta(A_{n,\ F/GT})$ = 0.1 %

$\delta(a_{n,\ F/GT})$ = 0.1 %

and the current nuclear Ft-values

factor 3 to 8 still missing

for details see
A. Falkowski, M. Gonzalez-Alonso, and O. Naviliat-Cuncic, JHEP 04 (2021) 126

$$C_i = \frac{G_F(0)}{\sqrt{2}} V_{ud} \bar{C}_i \quad \text{with} \quad \bar{C}_S = g_S(\varepsilon_S + \tilde{\varepsilon}_S),\ \bar{C}_T = 4 g_T(\varepsilon_T + \tilde{\varepsilon}_T),\ \ldots$$

Lee-Yang coupling constants

EFT coupling constants

Towards precisions at the 0.1 % level

Measurements with absolute/relative precision of the order of 0.1 %

→ are of a different category !!

- Fermi transitions: include radiative and nuclear structure corrections

e.g.:

$$\mathcal{F}t^{0^+\rightarrow 0^+} \equiv f_V t^{0^+\rightarrow 0^+} (1 + \boxed{\delta_{NS}^V} - \boxed{\delta_C^V}) (1 + \boxed{\delta_R'}) = \frac{K}{2G_F^2 \, V_{ud}^2 \, C_V^2 \, (1 + \boxed{\Delta_R^V})}$$

- Mixed F/GT and GT transitions: ALSO include effects induced by strong interact.

(not for F because of selection rules & symmetries)

→ most important of these: weak magnetism

→ best observable: beta spectrum shape measurements

1. Formalism (basic aspects)

2. - Ft values of $0^+ \rightarrow 0^+$ transitions, mirror nuclei, and neutron: in search for V_{ud}

3. Correlations (*a, A*)
   - → Scalar and Tensor current searches
   - → global analysis
   - → need for including small SM corrections; recoil, radiative

4. **Beta-spectrum shape to determine Fierz term and weak magnetism**

KU LEUVEN

β spectrum shape (1st order)

differential decay rate

$\propto d\Gamma_0$

$$d\Gamma \propto \underbrace{F(\pm Z, E_e)}_{\text{Fermi function}} \; \underbrace{p_e\, E_e\, (E_0 - E_e)^2\, dE_e\, d\Omega_e\, d\Omega_\nu}_{\text{phase space}} \; \underline{\xi}$$

nuclear matrix elements, M_F and M_{GT}

$$\times \left\{ 1 + \cancel{a \frac{\vec{p}_e \cdot \vec{q}}{E_e E_\nu}} + b \frac{\gamma m_e}{E_e} + \cancel{A \frac{\vec{J}}{J} \cdot \frac{\vec{p}_e}{E_e}} + \cancel{R\, \vec{\sigma} \cdot \frac{\vec{J}}{J} \times \frac{\vec{p}_e}{E_e}} + \ldots \right\}$$

Fierz interference term
(b ≡ 0 in standard model)

$\gamma = \sqrt{(1-(\alpha Z)^2}$

$$d\Gamma = d\Gamma_0\, \xi \left[1 + \frac{\gamma m_e}{E_e} b_{Fierz} + k\, E_e\, b_{WM} \right]$$

additional term from weak magnetism

$\bar{p}$: momentum of β particle
$\bar{q}$: momentum of neutrino
E: total energy of beta/neutrino
m: electron rest mass
$\bar{J}$: spin of nucleus
$\gamma = \sqrt{(1-(\alpha Z)^2}$
σ: spin direction of beta

A brief intro to weak magnetism

For allowed beta decays (ΔJ = 0, 1) and in terms of '**form factors**' on has (notation of Holstein):

$a \cong g_V M_F$ Fermi form factor (weak int.)

$c \cong g_A M_{GT}$ Gamow-Teller form factor (weak int.)

$(b_{wm} \equiv b)$ $b \cong A\,(g_M M_{GT} + g_V M_L)$ weak magnetism form factor (strong int.)

$g_V = 1$

$g_A = +1.2754(11)$ for neutron,

$g_A \approx 1$ for nuclear decays

$g_M = \mu_p - \mu_n = 4.706$

in units of G_F

($g_V = G_F C_V$,

$g_A = G_F C_A$)

Matrix element	Operator form
M_F	$\langle\psi_f\|\Sigma\tau_i^{\pm}\|\psi_i\rangle$
M_{GT}	$\langle\psi_f\|\Sigma\tau_i^{\pm}\vec{\sigma}_i\|\psi_i\rangle$
M_L	$\langle\psi_f\|\Sigma\tau_i^{\pm}\vec{l}_i\|\psi_i\rangle$

so $c/a = g_A M_{GT} / g_V M_F = C_A M_{GT} / C_V M_F = \rho$

and for weak magnetism: $$\frac{b}{Ac} = \frac{1}{g_A}\left(g_M + g_V \frac{M_L}{M_{GT}}\right)$$ (A = nuclear mass)

B. R. Holstein, Rev. Mod. Phys. 46, 789 (1974); 48, 673(E) (1976)

H. Behrens and W. Bühring, Electron Radial Wave Functions and Nuclear Beta-Decay (Clarendon, Oxford, 1982).

For transitions from low-isospin states (near the N=Z line)

b **can be calculated from the Conserved Vector Current (CVC) principle**

(relates ***weak*** interaction properties to ***electromagnetic*** ones; **Feynman & Gell-Mann, 1958)**

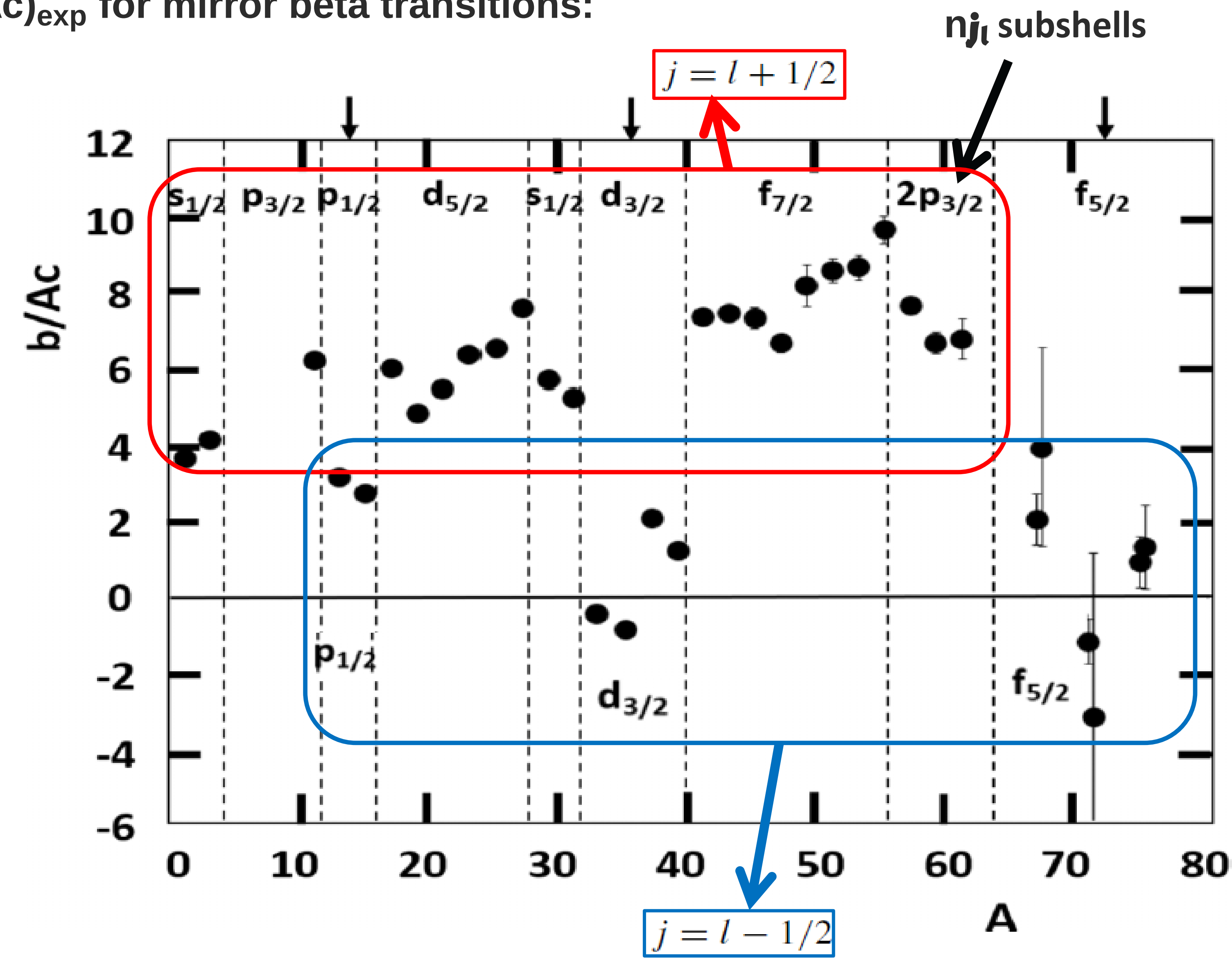
- **Mirror beta transitions (T = 1/2; J → J):** $b = \pm a A \sqrt{\frac{J+1}{J}} (\mu_f - \mu_i)$
- **Transitions from T = 1, 3/2, 2 isospin multiplet states:** $b^2 = \eta \frac{\Gamma_{M1}^{\text{iso}} \, 6 M^2}{\alpha E_\gamma^3}$

and get *c* from the ft value of the transition

$$\Rightarrow \quad \left(\frac{b}{Ac}\right)_{\text{exp}} = \frac{1}{g_A}\left(g_M + g_V \frac{M_L}{M_{GT}}\right)$$

KU LEUVEN

$(b/Ac)_{exp}$ for mirror beta transitions:

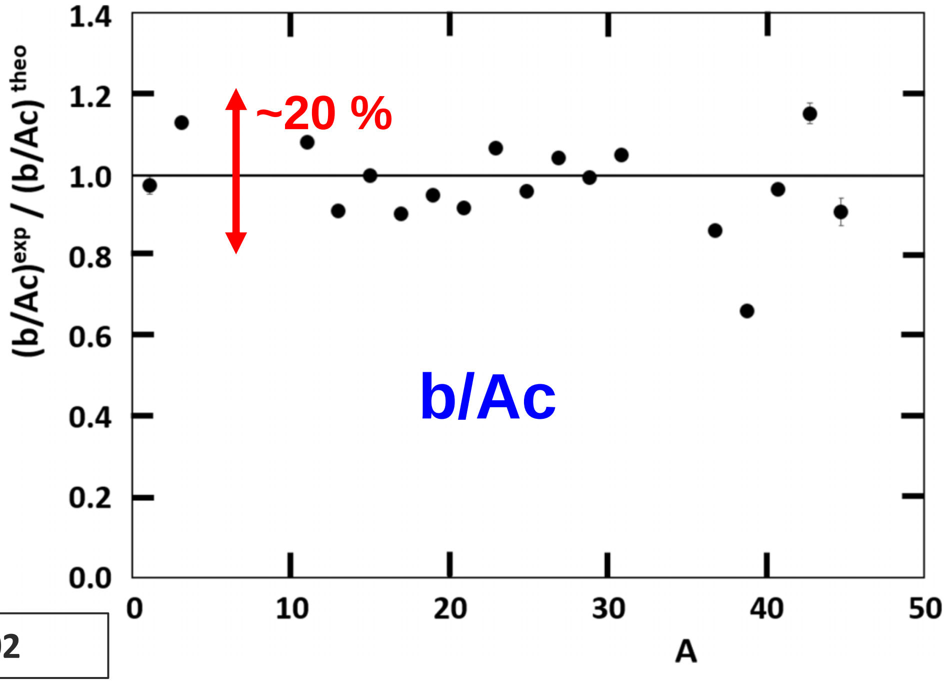


N. Severijns, I.S. Towner et al., Phys. Rev. C 107 (2023) 015502

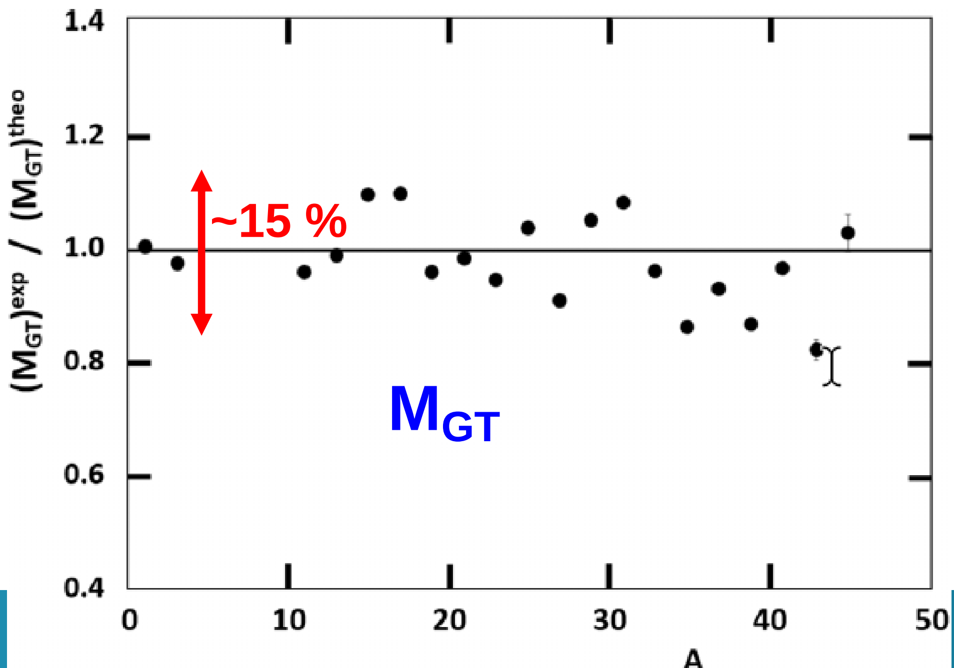
Shell model calculations (I.S. Towner):

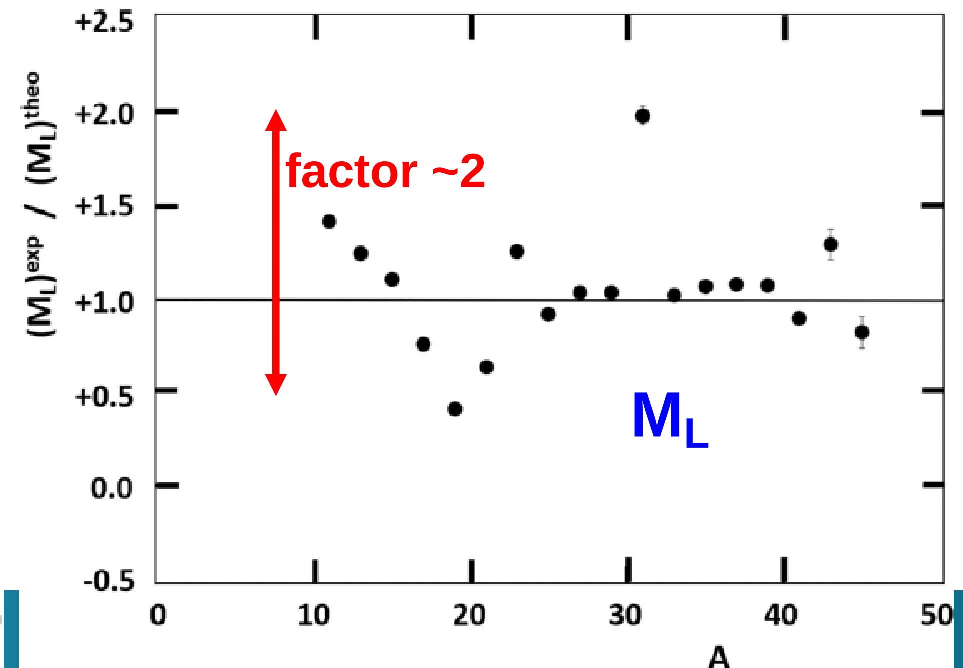
reproduce the values for b/Ac, M_{GT} and M_L well,

up to A= 55 (full fp-shell)



N. Severijns, I.S. Towner et al., Phys. Rev. C 107 (2023) 015502





$$\left(\frac{b}{Ac}\right)_{\text{exp}} = \frac{1}{g_A}\left(g_M + g_V\frac{M_L}{M_{GT}}\right)$$

~ 4.7

nuclear structure

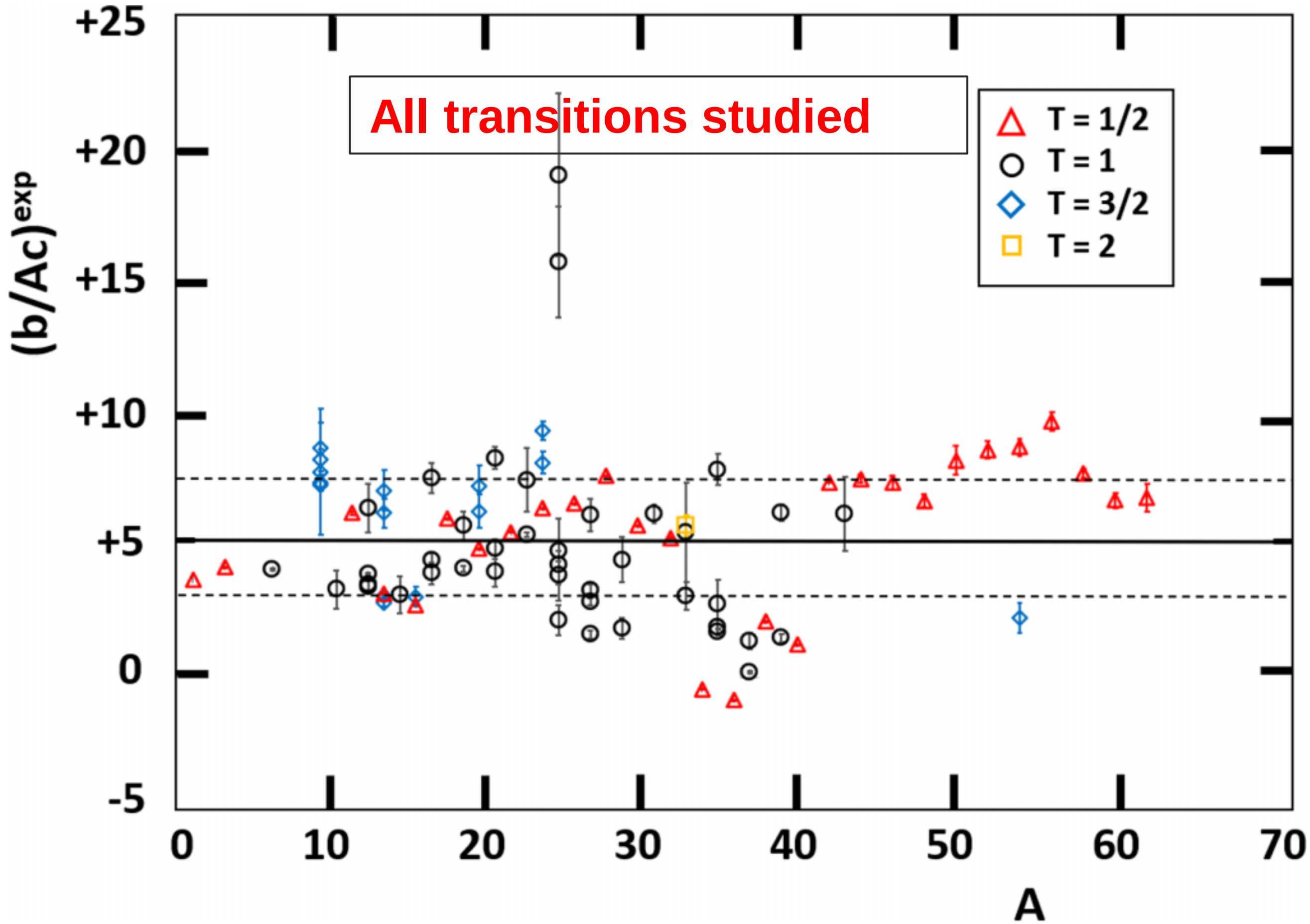
- mirror nuclei

precise values from nuclear magnetic moments

- states in T = 1, 3/2, … multiplets

shell model allows to predict with ~30% precision

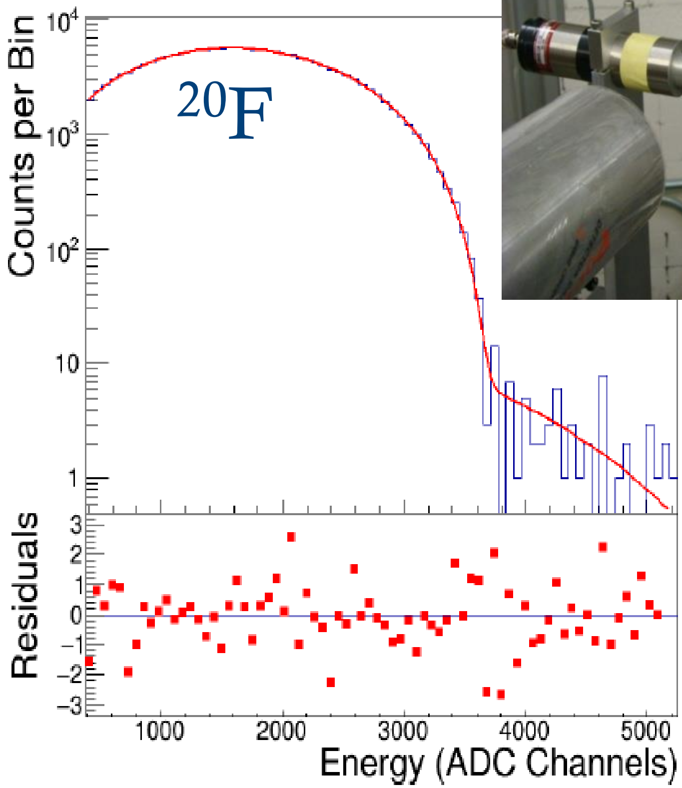
→ **measurements for all these can use these values for weak magn.**

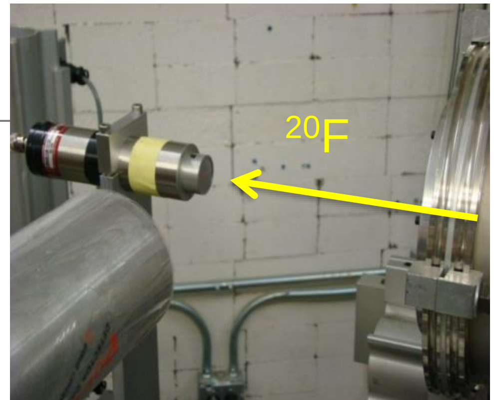


N. Severijns, I.S. Towner et al., Phys. Rev. C 107 (2023) 015502

Beta spectrum shape: measurements @ Michigan State Univ.

Xueying Huyan (PhD, MSU, 2019) — Max Hughes (PhD, MSU, 2019)





b_{WM} from $b^2 = \eta \frac{\Gamma_{M1}^{iso} 6 M^2}{\alpha E_\gamma^3}$ is 43.4

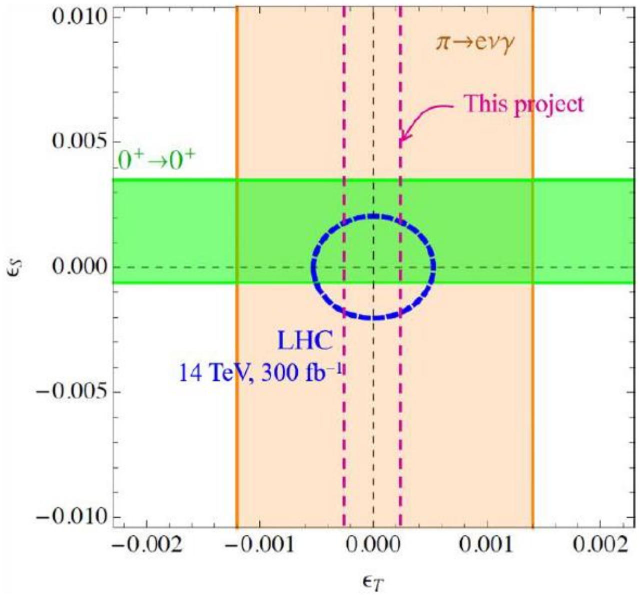
N. Severijns, I.S. Towner et al., PR C 107 (2023) 015502

Fit #	
1	b_{WM} = 41.0(19)(32)
	$b_{Fierz\text{-}GT}$ = 0
2	b_{WM} = 43.4
	$b_{Fierz\text{-}GT}$ = 0.0021(51)(84)

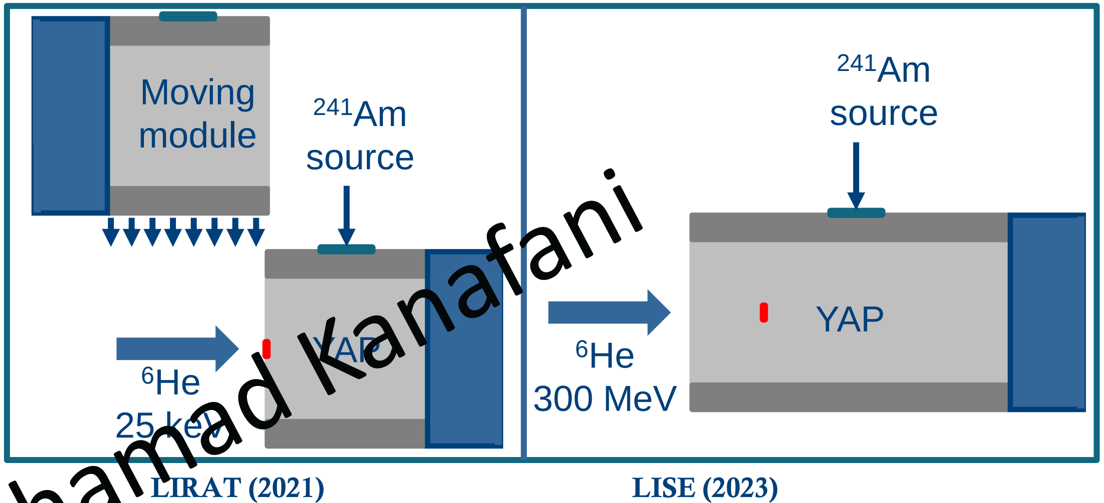
most precise result for b_{Fierz} ever !!

O. Naviliat-Cuncic: naviliat@nscl.msu.edu

Beta spectrum shape: bSTILED @ GANIL $(\Delta b_{GT} \sim 10^{-3})$

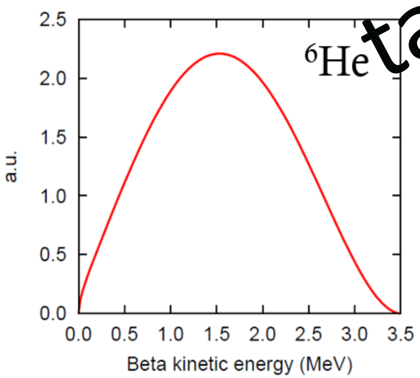


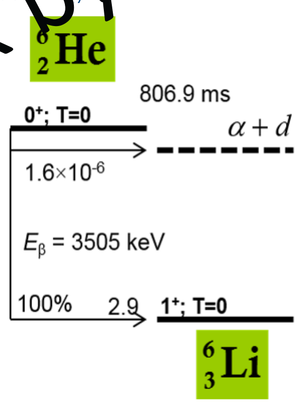
Eliminate electron backscattering: 4pi geometry achieved with two techniques
(low and high energy ^{6}He beams at GANIL)

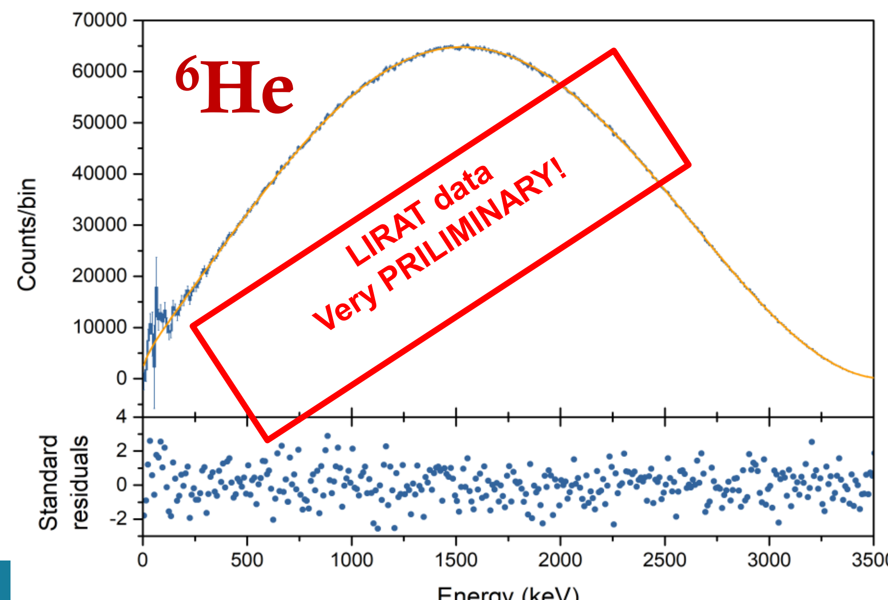


Most sensitive observable for b_{GT}: the beta energy spectrum in a well selected Gamow-Teller transition

Ideal candidate: the spectrum can theoretically be described with high accuracy



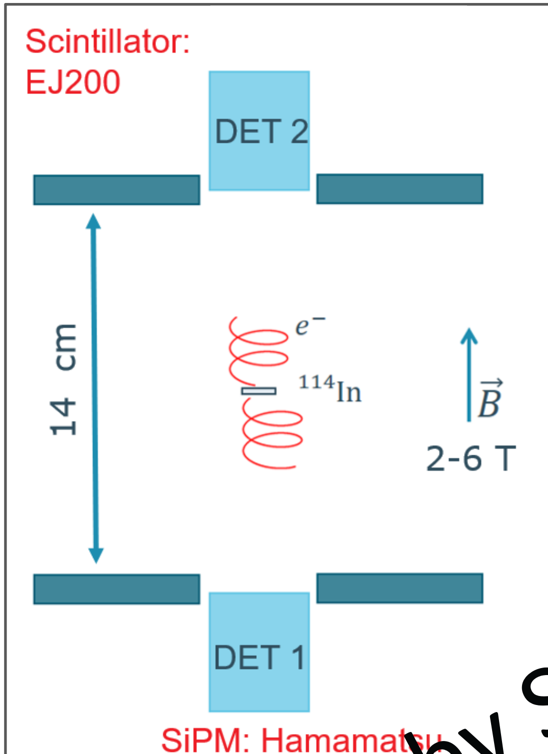




courtesy Xavier Flechard

talk by Mohamad Kanafani

Beta spectrum shape: InESS @ WISArD-ISOLDE



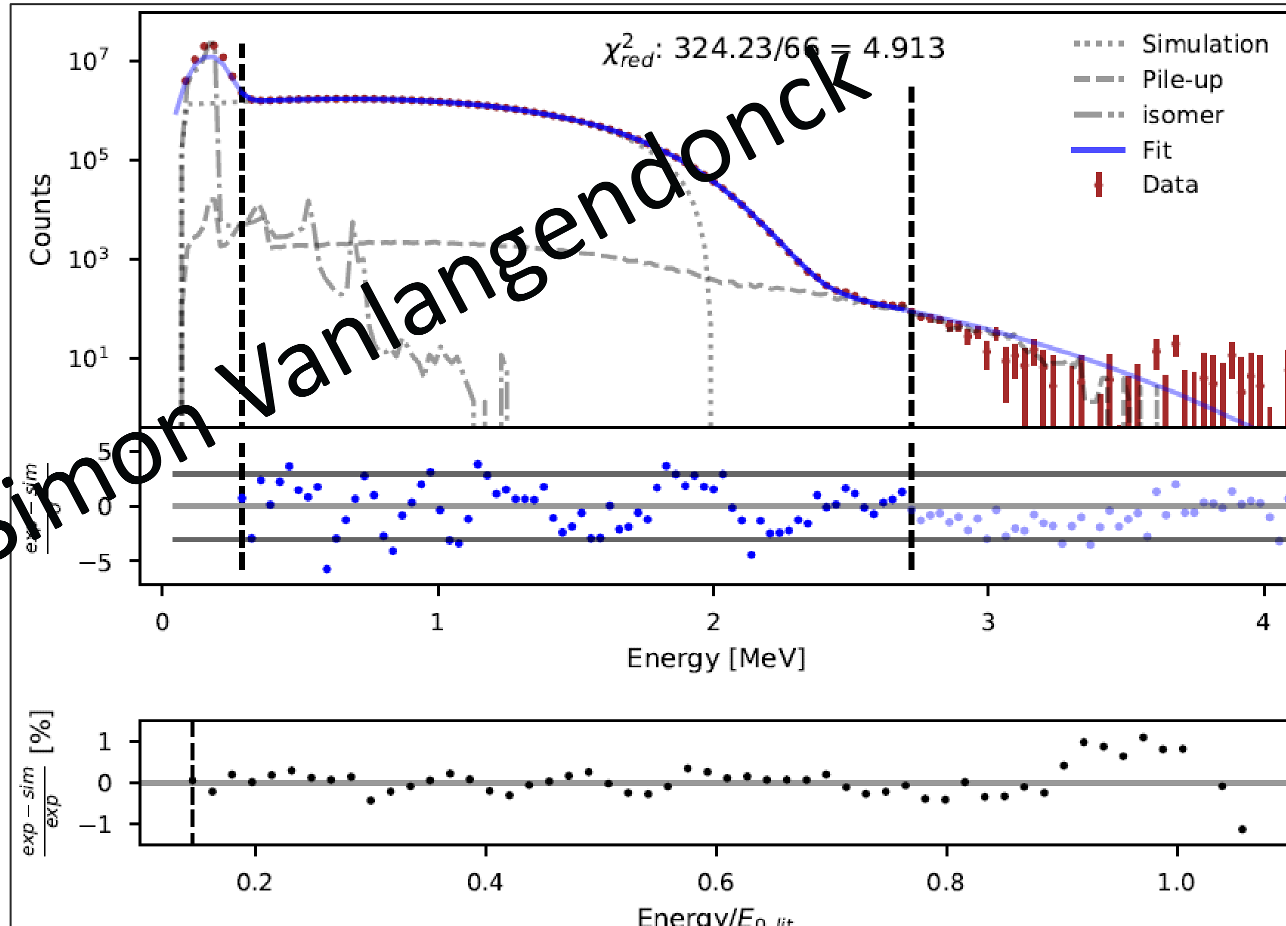
Simon Vanlangendonck, PhD Thesis, 2023

Bordeaux, Caen
Leuven, Prague

^{114}In: $1^+ \rightarrow 0^+$ pure GT transition, E_0 = 1.90 MeV

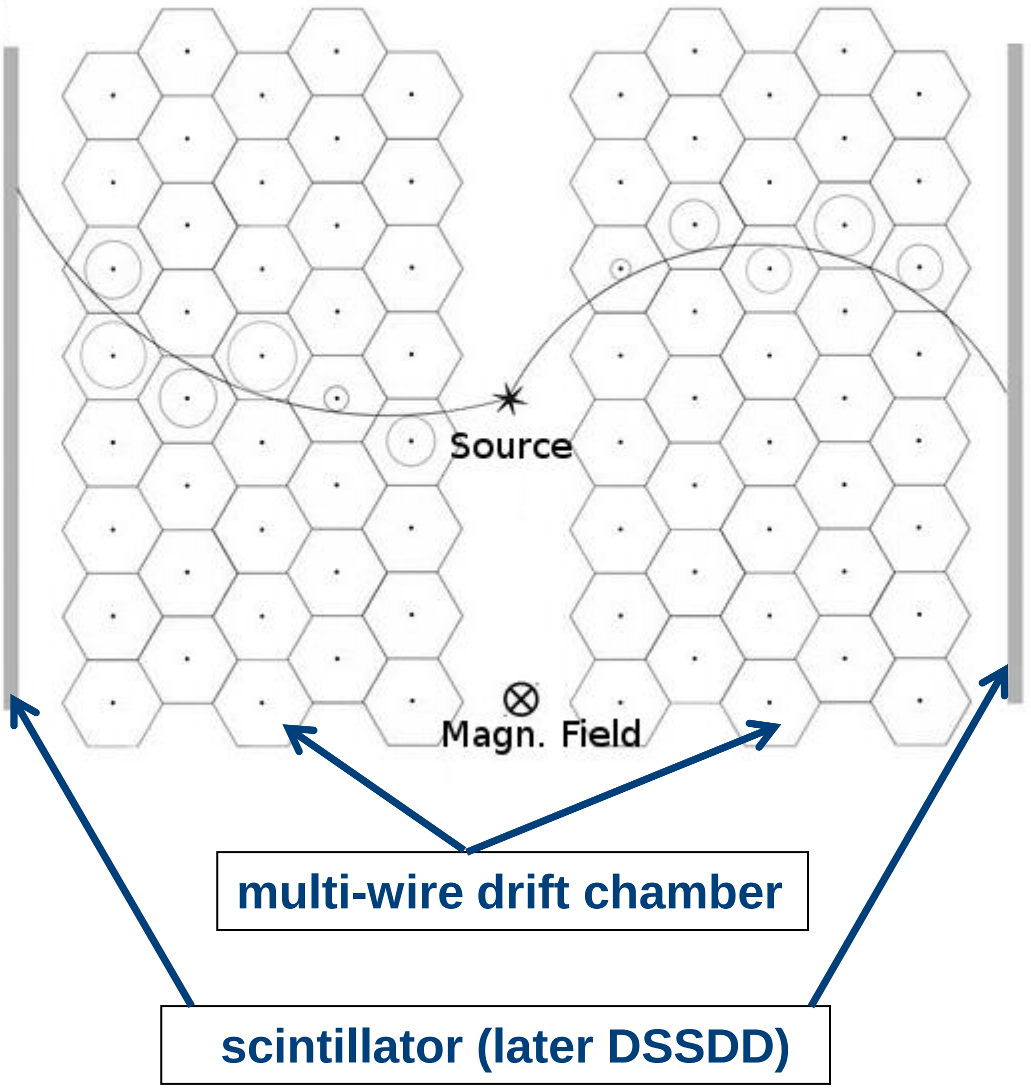
heaviest isotope for which wm is studied!!

twin-measurement with miniBETA project



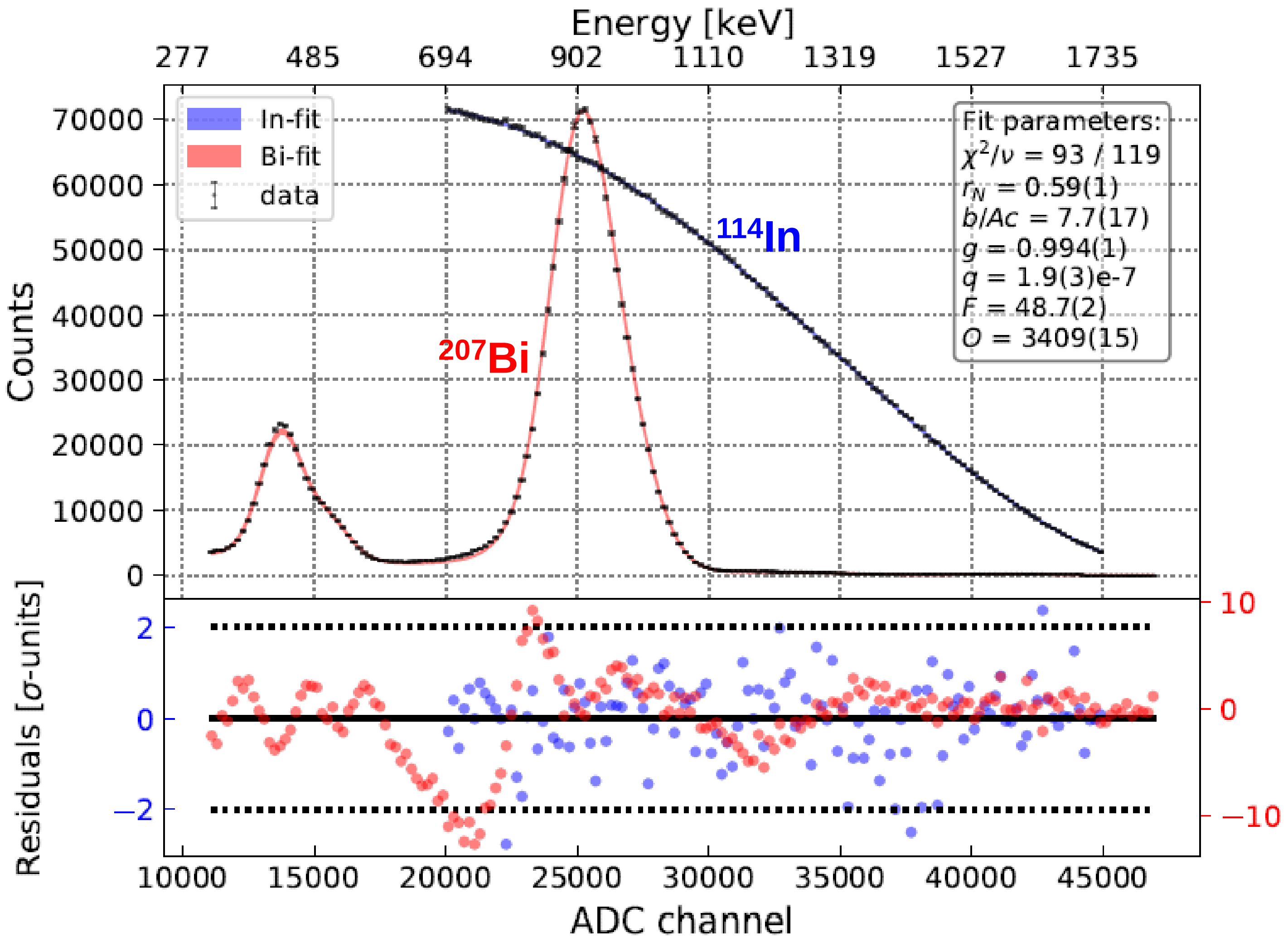
talk by Simon Vanlangendonck

measurements with miniBETA spectrometer (Leuven/Krakow)



twin-measurement with ^{114}In measurement in WISArD

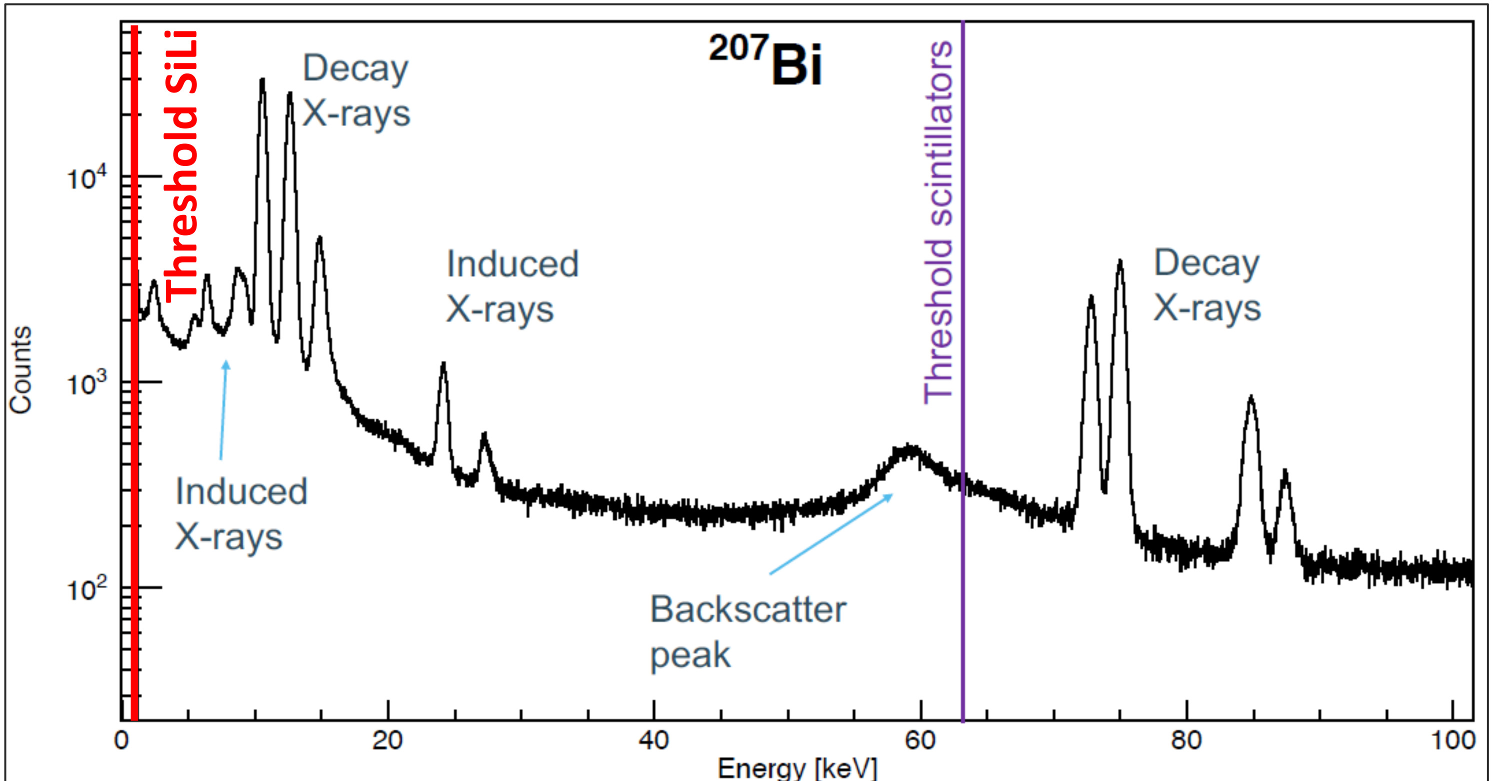
6-parameter fit to ^{114}In and ^{207}Bi spectra simultaneously, determining b/Ac



KU LEUVEN

Next step: <u>SiLi detectors</u> **for beta spectrum shape measurements - WISArD collaboration**

possible isotopes: ^{32}P, ^{90}Y, ^{114}In …



Using a high gain an energy threshold of 1.5 keV is reached. Lower energy region reveals induced X-rays.

Charlotte Knapen, Master's Thesis, 2023

KU LEUVEN

Beta spectrum shape: ongoing and planned measurements

- bSTILED	LPCCaen/GANIL	^{6}He	under analysis
- miniBETA	Leuven/Krakow	^{32}P	under analysis
- SiLi detectors	WISArD collab. (Bordeaux, Caen, Leuven, Prague)	^{32}P, ^{90}Y, ^{114}In	preparation
- microcalorim.	CEA	several	ongoing
- PERC	TUM, Heidelberg	n	preparation
- BRAND	Krakow Univ. et al.	n	preparation
- …			

KU LEUVEN

1. Formalism (basic aspects)

2. Ft values of $0^+ \rightarrow 0^+$ transitions, mirror nuclei, and neutron: determining V_{ud}

3. Correlations (*a, A*)
   - → Scalar and Tensor current searches
   - → global analysis
   - → need for including small SM corrections; recoil, radiative

4. Beta-spectrum shape to determine Fierz term and weak magnetism

Error budget for the individual transitions

J.C. Hardy and I.S. Towner,
Phys. Rev. C 102 (2020) 045501

the 15 best measured cases

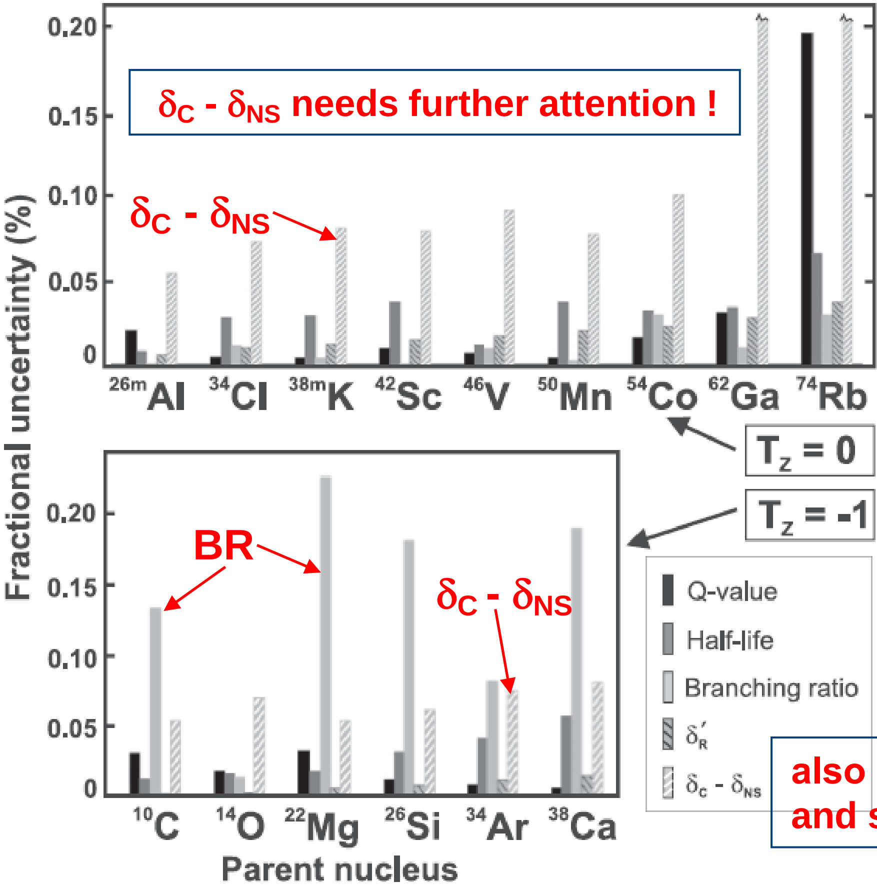
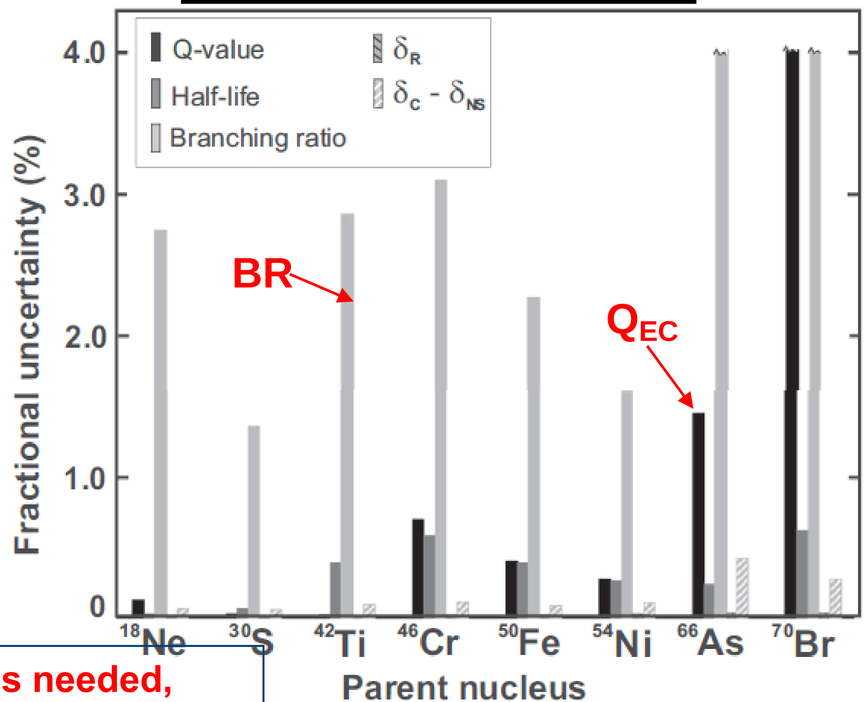


FIG. 4. Summary histogram of the fractional uncertainties attributable to each experimental and theoretical input factor that contributes to the final $\mathcal{F}t$ values for the 15 precisely measured superallowed transitions used in the $\mathcal{F}t$-value average. The two bars cut off with jagged lines at about 0.20% actually rise to 0.23% for ^{62}Ga and 0.29% for ^{74}Rb. The bars for δ'_R and δ_C-δ_{NS} include provision for systematic uncertainty as well as statistical. See text.

the 8 ‘upcoming’ cases



also BR’s needed, and some Q_{EC}-values

FIG. 5. Summary histogram of the fractional uncertainties attributable to each experimental and theoretical input factor that contributes to the final $\mathcal{F}t$ values for the eight tabulated superallowed transitions not known precisely enough to contribute to the $\mathcal{F}t$-value average. The three bars cut off with jagged lines at about 4.0% indicate that no useful experimental measurement has been made of those parameters. The bars for δ'_R and δ_C-δ_{NS} include provision for systematic uncertainty as well as statistical. See text.

status for superallowed mirror β transitions

useful correlation measurements have been carried out for:
n, ^{19}Ne, ^{21}Na, ^{29}P, ^{35}Ar and ^{37}K

Parent nucleus	$\mathcal{F}t^{\text{mirror}}$ (s)	f_A/f_V	a	A	B	ρ	$\mathcal{F}t_0$ (s)
n	1043.58(67)	1.0000				+2.2091(15)[a]	6136.8(80)
^{19}Ne	1721.5(10)	1.0011		−0.0391(14) [341]		−1.5995(45)	6131(25)
^{19}Ne	1721.5(10)	1.0011		−0.03871(81) [69,342]		−1.6014(26)	6141(15)
^{21}Na	4073.0(38)	1.0020	0.5502(60) [62]			+0.7135(72)	6151(42)
^{29}P	4764.5(79)	1.0008		+0.681(86) [343]		+0.594(104)	6448(589)
^{35}Ar	5694.8(60)	0.9929		+0.49(10) [344]		+0.322(75)	6282(272)
^{35}Ar	5694.8(60)	0.9929		+0.427(23) [345]		+0.277(16)	6128(51)
^{37}K	4611.4(55)	0.9955			−0.755(24) [74]	−0.559(27)	6046(141)
^{37}K	4611.4(55)	0.9955		−0.5707(19) [35]		−0.5770(59)	6140(32)

from: N.S. et al., Phys. Rev. C 107 (2023) 015502

[35] B. Fenker et al., Phys. Rev. Lett. **120**, 062502 (2018).
[62] P. A. Vetter, J. R. Abo-Shaeer, S. J. Freedman, and R. Maruyama, Phys. Rev. C **77**, 035502 (2008).
[69] D. Combs, G. Jones,W. Anderson, F. Calaprice, L. Hayen, and A. Young, arXiv:2009.13700.
[341] F. P. Calaprice, S. J. Freedman,W. C. Mead, and H. C. Vantine, Phys. Rev. Lett. **35**, 1566 (1975).
[342] G. Jones, A Measurement of the Beta Decay Asymmetry of 19Ne as a Test of the Standard Model, Ph.D. thesis, Princeton University, 1996 (unpublished), https://ui.adsabs.harvard.edu/abs/1996PhDT........10J/abstract.
[343] G. S. Masson and P. A. Quin, Phys. Rev. C **42**, 1110 (1990).
[344] J. D. Garnett, E. D. Commins, K. T. Lesko, and E. B. Norman, Phys. Rev. Lett. **60**, 499 (1988).
[345] A. Converse, et al., Phys. Lett. B **304**, 60 (1993).

KU LEUVEN

V_{us} from K-decay

TABLE IX. Results for $|V_{us}|$ obtained from the recent measurements of $|V_{us}|f_+(0)$ in neutral and charged kaon decays.

Experiment	Decay	$\lvert V_{us}\rvert f_+(0)$ [a]	$\lvert V_{us}\rvert$ [b]
E865	$K^+, e3$	0.2243(22)(7) [c]	0.2284(23)(20)
KTeV	$K_L, e3, \mu3$	0.2165(12) [d]	0.2253(13)(20)
NA48	$K_L, e3$	0.2146(16) [e]	0.2233(17)(20)
KLOE [f]	$K_L, e3, \mu3$	0.21673(59)	0.2255(6)(20) [g]
Weighted average			0.2254(21)

[a] For K$^+$ decay $f_+(0)=0.982(8)$, while for K$_L$ decay $f_+(0)=0.961(8)$ (see text).
[b] The first error is due to experimental uncertainties; the common error of 0.0020 is related to the uncertainty of $f_+(0)$.
[c] Sher *et al.* (2003).
[d] Alexopoulos *et al.* (2004).
[e] Lai *et al.* (2004).
[f] A result obtained at KLOE for the $K_S, e3$ decay is not included here as only a preliminary value, i.e., $|V_{us}|=0.2254(17)$ (Franzini, 2004), is available to date.
[g] Ambrosino *et al.* (2006a).

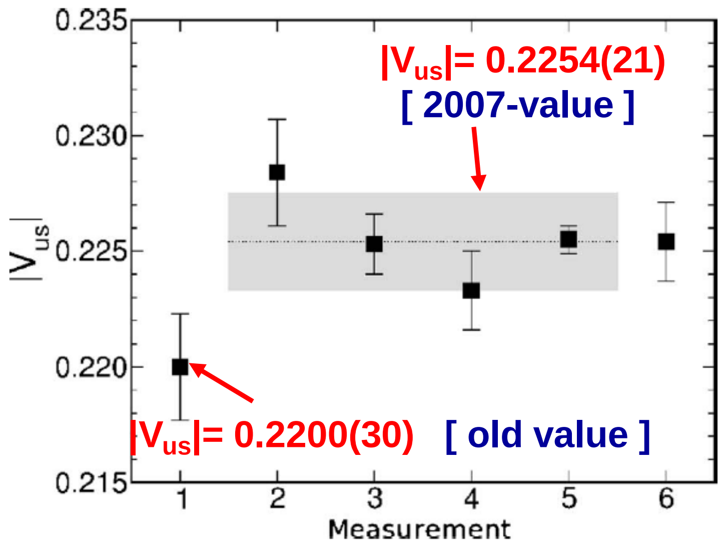


FIG. 14. Values for $|V_{us}|$ from the Particle Data Group analysis [1, Eidelman *et al.* (2004)] and from recent results in K decays [2, Sher *et al.* (2003); 3, Alexopoulos *et al.* (2004); 4, Lai *et al.* (2004); 5, Ambrosino *et al.* (2006a); 6, preliminary result from KLOE, Franzini *et al.* (2004)]. The shaded band indicates the weighted average of the published new results from K decays (measurements 2–5). See also Table IX.

2022-value : $|V_{us}|$= 0.2243(8)

P.A. Zyla *et al.* (Particle Data Group), Prog. Theor. Exp. Phys. 083C01 (2020) p.262

(form factor $f_+(0)$ takes into account SU(3) breaking and isospin symmetry breaking effects)

KU LEUVEN

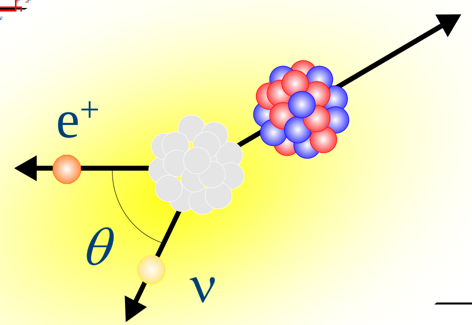
Beta spectrum shape

Analytical description + code, accurate to few 10^{-4} level

Table VI Overview of the features present in the β spectrum shape (Eq. (4)), and the effects incorporated into the Beta Spectrum Generator Code. Here the magnitudes are listed as the maximal typical deviation for medium Z nuclei with a few MeV endpoint energy. Some of these corrections fall off very quickly (e.g. the exchange correction, X) but can be sizeable in a small energy region. Varying Z or W_0 can obviously allow for some migration within categories for several correction terms.

Item	Effect	Formula	Magnitude
1	Phase space factor	$pW(W_0-W)^2$	Unity or larger
2	Traditional Fermi function	F_0 (Eq. (5))	
3	Finite size of the nucleus	L_0 (Eq. (17))	
4	Radiative corrections	R (Eq. (27))	
5	Shape factor	C (Eq. (125))	10^{-1}-10^{-2}
6	Atomic exchange	X (Eq. (63))	
7	Atomic mismatch	r (Eq. (76))	
8	Atomic screening	S (Eq.	
9	Shake-up	See	
10	Shake-off	S	
11	Distorted Coulomb potential due to recoil		10^{-3}-10^{-4}
12	Diffuse nuclear surface		
13	Recoiling nucleus		
14	Molecular screening		
15	Molecular exchange		
16	Bound state β decay		
17	Neutrino mass		
18	Forbidden decays		

$d\Gamma_0$



[a] Here the Salvat potential of Eq. (57) is used with X (Eq. (55)) set to unity.
[b] The effect of shake-up on screening was discussed in Sec. VI.C.1 with Eq. (66).
[c] Shake-off influences on screening and exchange corrections were discussed separately in Sec. VI.C.2. This has to be evaluated in a case by case scenario.

L. Hayen, N. Severijns et al., Rev. Mod. Phys. 90 (2018) 015008

Precision meas^ts in nuclear/neutron β decay in the LHC era

if particles that mediate new interactions are above threshold for LHC
→ Effective Field Theory allowing
direct comparison of low-energy and collider constraints

low-scale O(1 GeV) effective Lagrangian for semi-leptonic transitions
(contributions from W-exchange diagrams and four-fermion operators)

link betw. EFT couplings ε_i and Lee-Yang nucleon-level effect. couplings C_i:

$$\boxed{C_i = \frac{G_F(0)}{\sqrt{2}} V_{ud} \bar{C}_i \quad \text{with} \quad \bar{C}_S = g_S(\varepsilon_S + \tilde{\varepsilon}_S),\ \bar{C}_T = 4 g_T(\varepsilon_T + \tilde{\varepsilon}_T),\ \ldots}$$

$$\varepsilon_i, \tilde{\varepsilon}_i \approx v^2/\Lambda_{BSM}^2 \quad \text{with} \quad v = (2\sqrt{2}\, G_F^{(0)})^{-1/2} \approx 170\ \text{GeV}$$

$$\text{if } \Lambda_{BSM} \sim 5\ \text{TeV} \ \rightarrow\ \varepsilon_i \sim 10^{-3}$$

$g_S = 1.02(11)$
$g_T = 0.987(55)$
(lattice-calc.)

M. González-Alonso et al., Ann. der Phys. 525 (2013) 600
T. Bhattacharya, et al., Phys. Rev. D 94 (2016) 054508

T. Bhattacharya et al., Phys. Rev. D 85 (2012) 054512
V. Cirigliano, et al., J. High. Energ. Phys. 1302 (2013) 046
O. Naviliat-Cuncic and M. González-Alonso, Annalen der Physik 525 (2013) 600.
V. Cirigliano, et al., Progr. Part. Nucl. Phys. 71 (2013) 93

KU LEUVEN

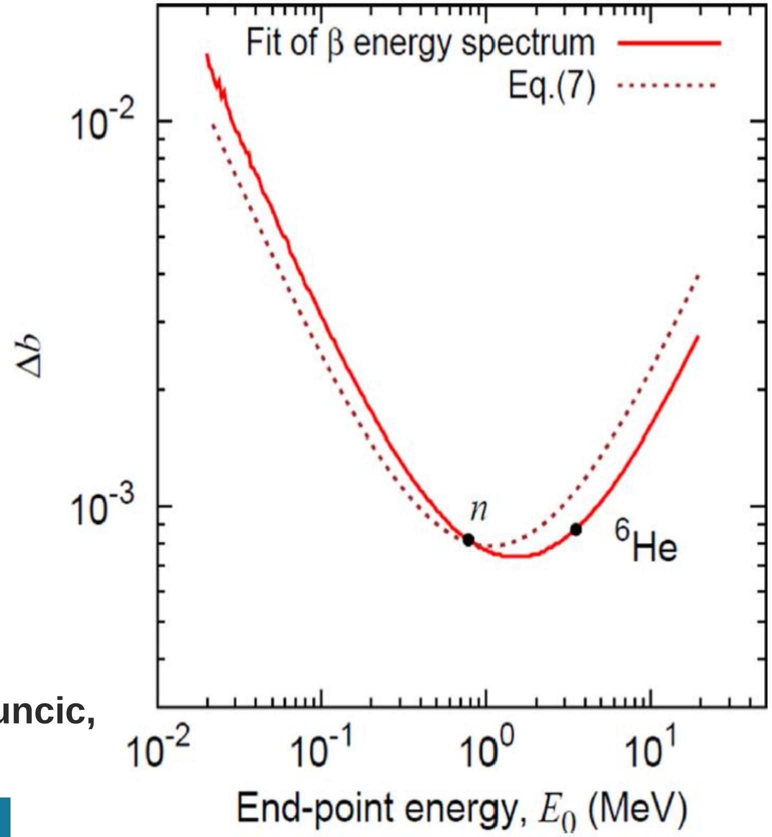
β-spectrum shape (no correlations observed, BUT including weak magn.):

$$d\Gamma = d\Gamma_0 \ \xi \left[1 + k \frac{1}{E_e} b_{Fierz} + k' \, E_e \, b_{WM} \right]$$

b_{Fierz} : scalar / tensor weak currents

- beyond Standard Model
- **now direct access** i.s.o. via e.g.

$$\tilde{a} = \frac{a}{1 + b \ \frac{\gamma m}{E_e}}$$



b_{WM} : weak magnetism (SM term)

- **induced by strong interaction**;
- is to be known better when reaching sub-percent precisions

M. González-Alonso, O. Naviliat-Cuncic, Phys. Rev. C 94 (2016) 035503

(b/Ac)exp for mirror beta transitions:

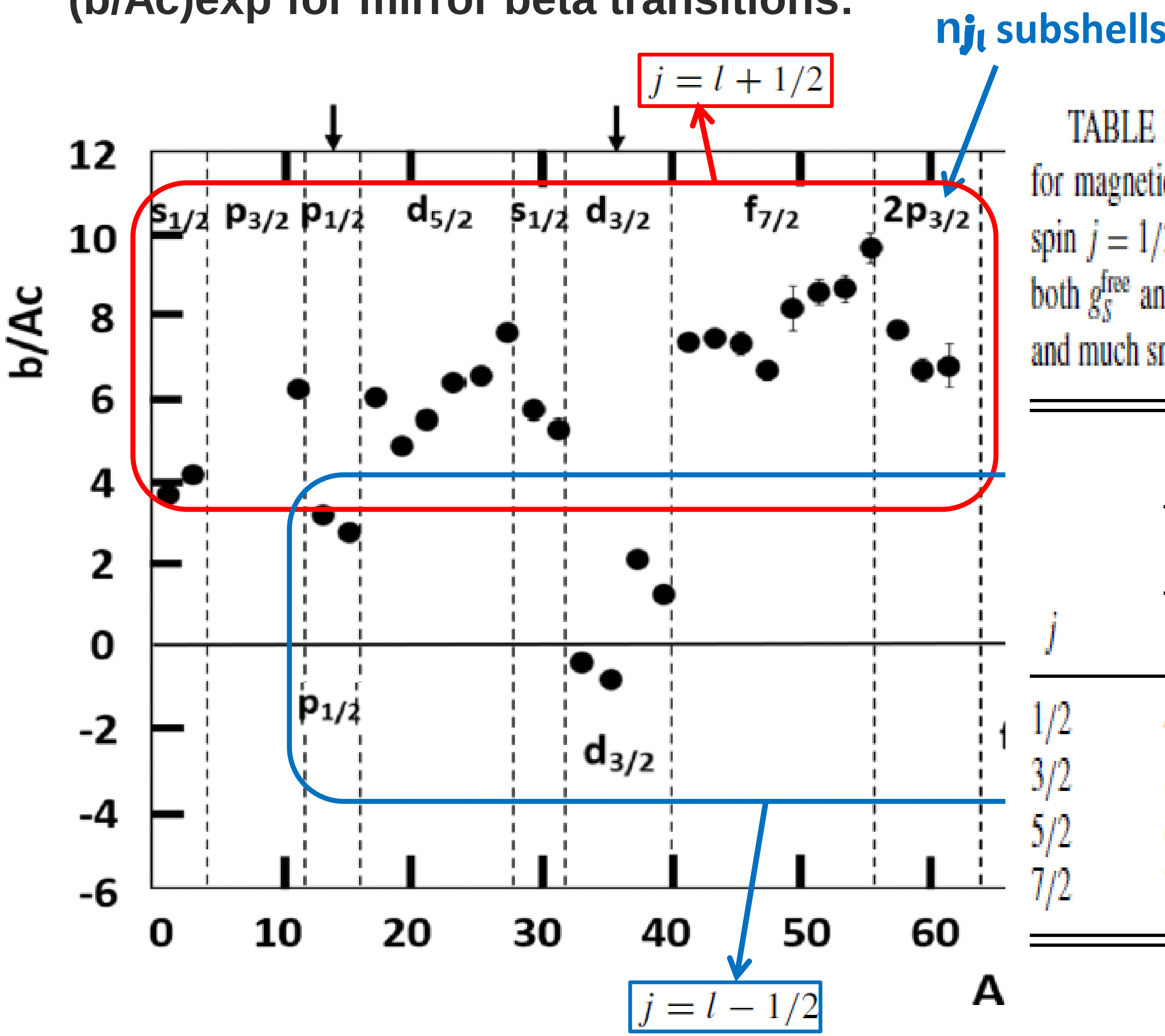


TABLE XVII. Differences, $\mu_p^{\mathrm{Sch}} - \mu_n^{\mathrm{Sch}}$, of the Schmidt values for magnetic moments of odd-proton and odd-neutron nuclei with spin $j = 1/2$ to $j = 7/2$, for $j = l + 1/2$ and $j = l - 1/2$, and for both g_S^{free} and $0.6 \times g_S^{\mathrm{free}}$. Large values are obtained for $j = l + 1/2$ and much smaller values for $j = l - 1/2$.

	$\mu_p^{\mathrm{Sch}} - \mu_n^{\mathrm{Sch}}$			
	$j = l + 1/2$		$j = l - 1/2$	
j	g_S^{free}	$0.6 \times g_S^{\mathrm{free}}$	g_S^{free}	$0.6 \times g_S^{\mathrm{free}}$
1/2	4.71	2.82	−0.90	−0.27
3/2	5.71	3.82	−1.02	+0.11
5/2	6.71	4.82	−0.50	+0.84
7/2	7.71	5.82	+0.23	+1.69

N. Severijns, I.S. Towner et al., Phys. Rev. C 107 (2023) 015502

KU LEUVEN

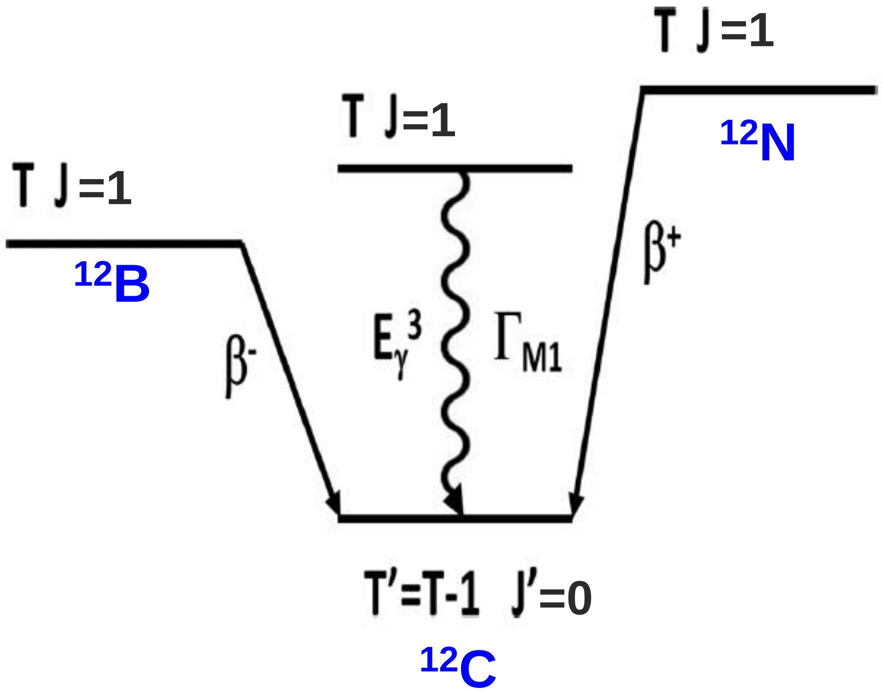
2. Beta transitions from T = 1 isospin triplet states

$$b^2 = \eta \frac{\Gamma_{M1}^{\text{iso}}\, 6\, M^2}{\alpha\, E_\gamma^3}$$

with: $$\Gamma_{M1}^{\text{iso}} = \frac{\hbar \ln 2}{t_{1/2}}$$

M = avg. mass of mother and daughter nucleus

$$\eta = (2J_i + 1)/(2J_f + 1)$$



c from: $$f_A t \equiv ft = \frac{2\,\mathcal{F}t^{0^+ \to 0^+}(1 + \Delta_R^V)}{(1 + \delta_R')\, c^2}$$

$\Rightarrow$ $$\left(\frac{b}{Ac}\right)_{\text{exp}}$$

KU LEUVEN

The challenge then is to reach precisions of:

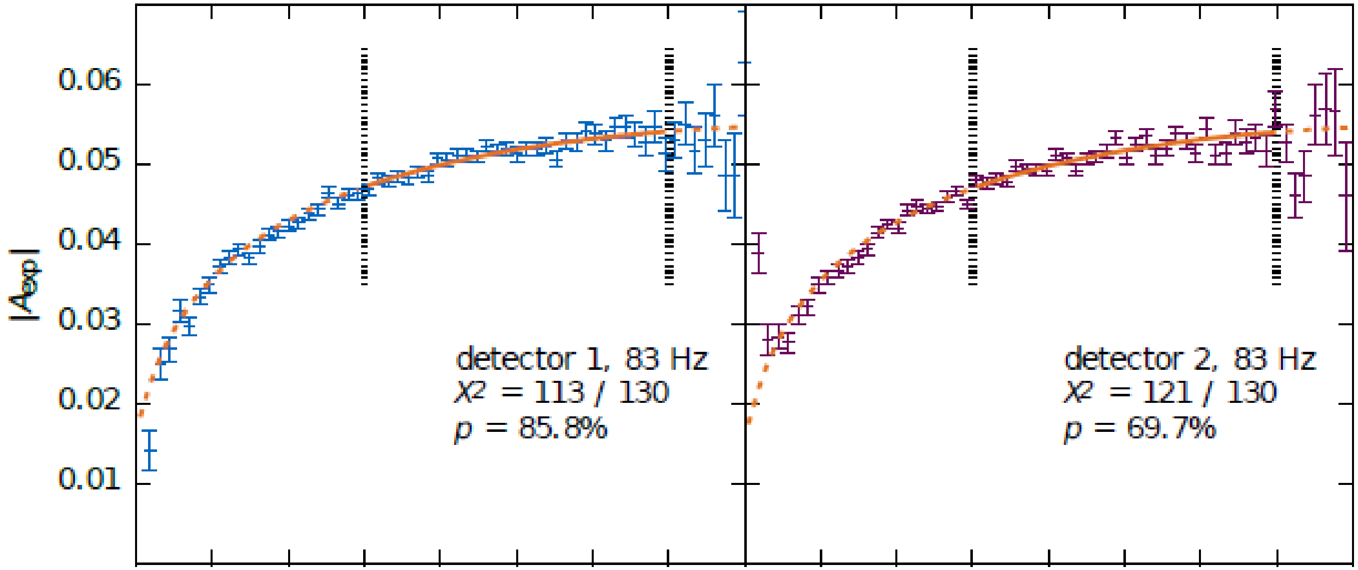
(~ within reach in this decade)

- $\Delta(\tau_n)$ = 0.1 s → **current world average τ_n = (879.7 ± 0.8)$_{2020}$ s** → **(878.5 ± 0.6)$_{2022}$ s**

- $\delta(A_n)$ = 0.1 % → **PERKEO III - ILL** - B. Markisch et al., PRL 112 (2019) 242501

A_n = -0.11985(21) → **$\delta(A_n)$ = 0.2 %**

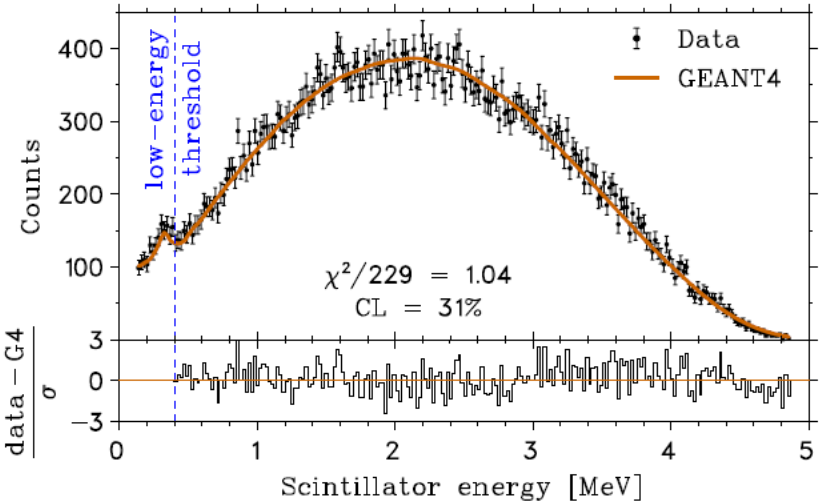
(about 2.5 times more precise than any previous measurement)



- $\delta(A_{F/GT}) = 0.1$ % → **TRINAT - TRIUMF III** - B. Fenker et al., PRL 120 (2018) 062502

$A_{37K} = -0.5707(19)$ → $\delta(A_n) = 0.3$ %

(about 4 times more precise than any previous measurement)



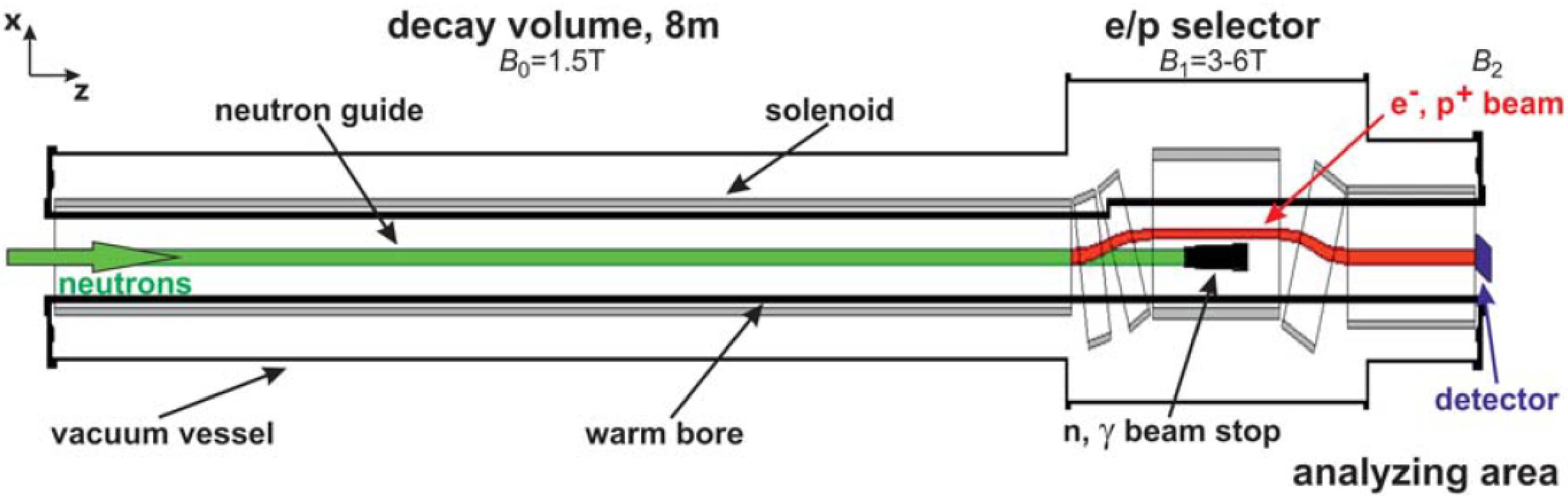
- $\delta(a_n) = 0.1$ % → **aSPECT - ILL / FRM II** - M. Beck et al., **Phys. Rev. C 101 (2020) 055506**

$a_n = -0.10430(84)$ **(about 6 times more precise than any previous measurement)**

$\delta(A_n) = 0.8$ %

KU LEUVEN

PERC facility - FRM II - ESS



- strong longitudinal magnetic field will collect decay electrons and protons
- both polarized and unpolarized neutrons for correlation measurements
- detector set ups for specific observables can be installed
- specific design to reduce systematic effects
- expect order of magnitude increase in measurement precision

Dubbers et al., Nucl. Inst. Meth. A 596 (2008) 238
Konrad et al., Journal of Physics: Conf. Ser. 340 (2012) 012048

KU LEUVEN

BRAND project

- measure transverse electron polarization
- particle tracking
- vertex reconstruction
- Mott scattering