KU LEUVEN

Testing the Standard Model in beta-decay: status and prospects

PSI 2016

October 20th, 2016

Nathal Severijns

KU Leuven University, Belgium

Outline

- **Exotic weak currents**

  scalar / tensor contributions

  β-ν correlation / beta asymmetry measurements

- **Nuclear / neutron beta decay versus LHC**

- **Weak magnetism**

- **Beta spectrum shape measurements**

1. Exotic weak currents (scalar, tensor)

a) β-ν correlation

$$a \, \frac{\vec{p}_e \cdot \vec{q}}{E_e E_\nu} \xrightarrow{\text{exp.}} \tilde{a} = \frac{a}{1 + b \, \frac{\gamma m_e}{E_e}} \qquad \text{with} \quad \gamma = \sqrt{1-(\alpha Z)^2}$$

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

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

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

Fierz term

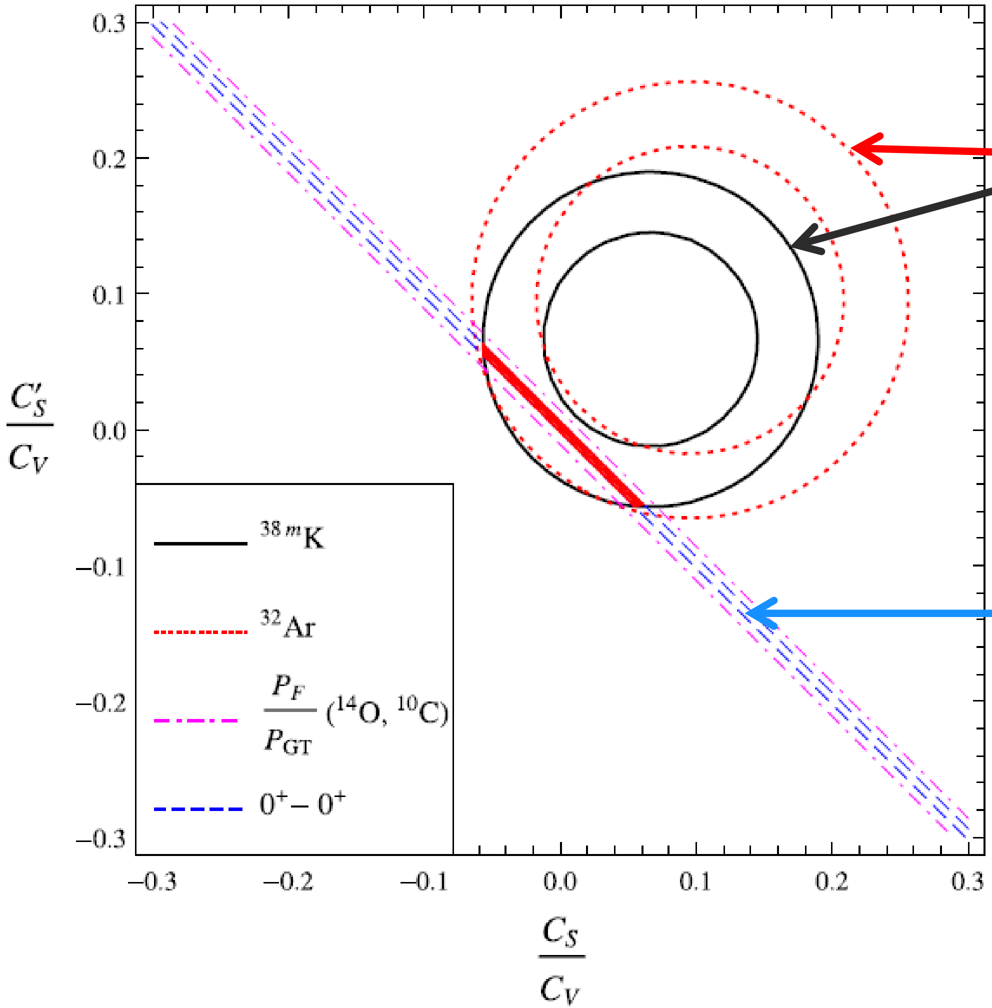
$$b_{GT} \cong Re \, \frac{C_T + C_T'}{C_A}$$

!!! for pure transitions weak interaction results are independent of nuclear matrix elements !!!

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

recoil corr. (induced form factors) ≈ 10^{-3} ; radiative corrections ≈ 10^{-4}

Limits on scalar currents



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

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

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

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

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

with

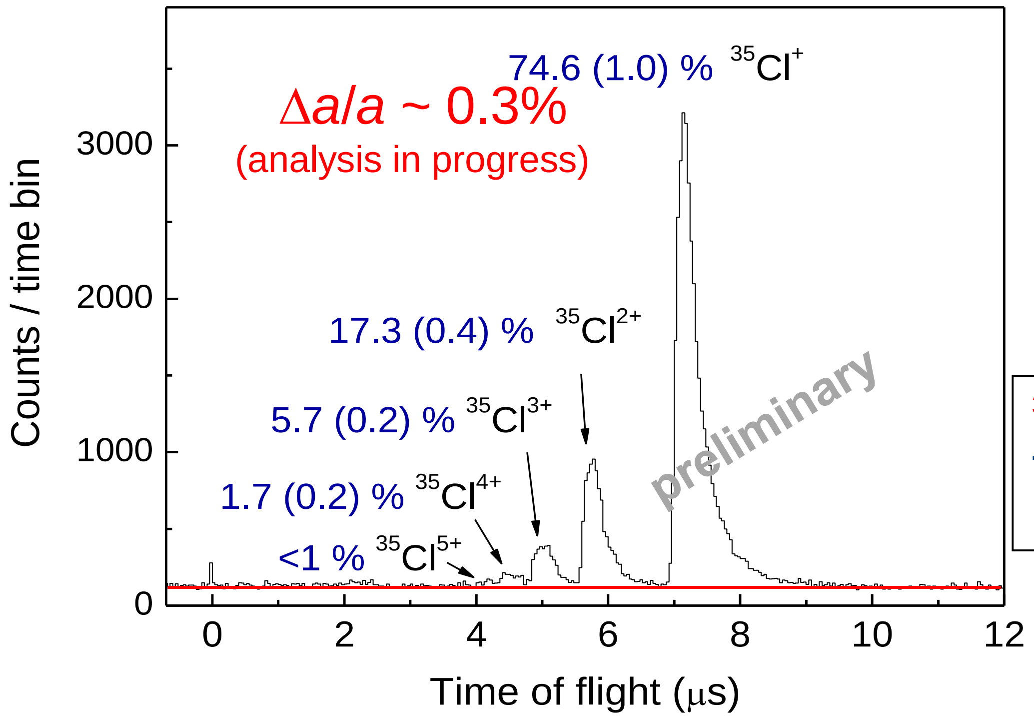
$$b'_F = \frac{\gamma m_e}{\langle E_e \rangle}\left(\frac{C_S + C'_S}{C_V}\right)$$ **(Fierz term)**

Hardy & Towner , Phys. Rev. C 91 (2015) 025501

KU LEUVEN

ongoing experiments in search for scalar weak currents:

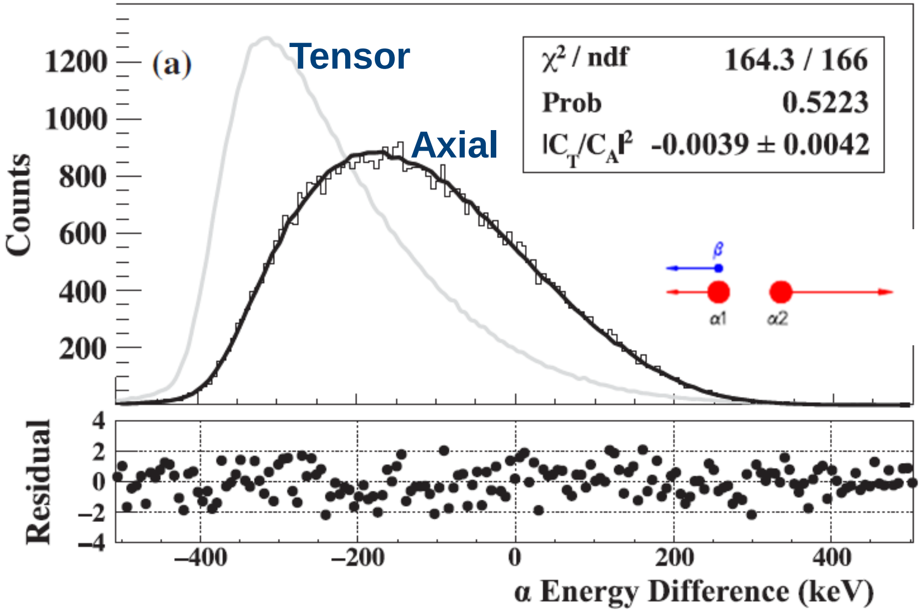
- TRINAT (MOT): ^{38m}K repeat (prep.)
- LPCTrap @ GANIL (Paul): ^{19}Ne, ^{35}Ar (analysis)
- Jerusalem (MOT): ^{19}Ne (prep.)
- TamuTrap, Texas A&M (Penning): ^{32}Ar, … (T = 2, βp) (prep.)
- WISARD @ ISOLDE (foil): ^{32}Ar, … (T = 2, βp) (prep.)



^{35}Cl charge state distrib. from the β decay of ^{35}Ar (LPCTrap - GANIL)

KU LEUVEN

Tensor currents - α-β-ν correlation with Paul-trapped ^{8}Li Ions



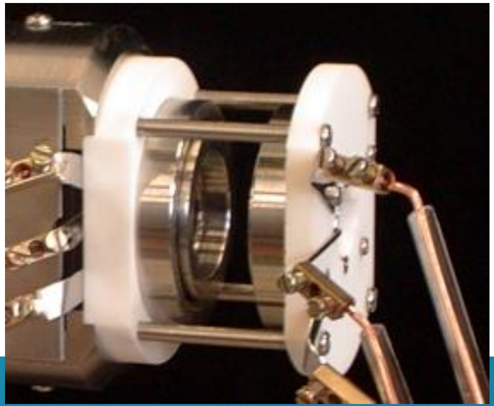
α-particle breakup of ^{8}Be*

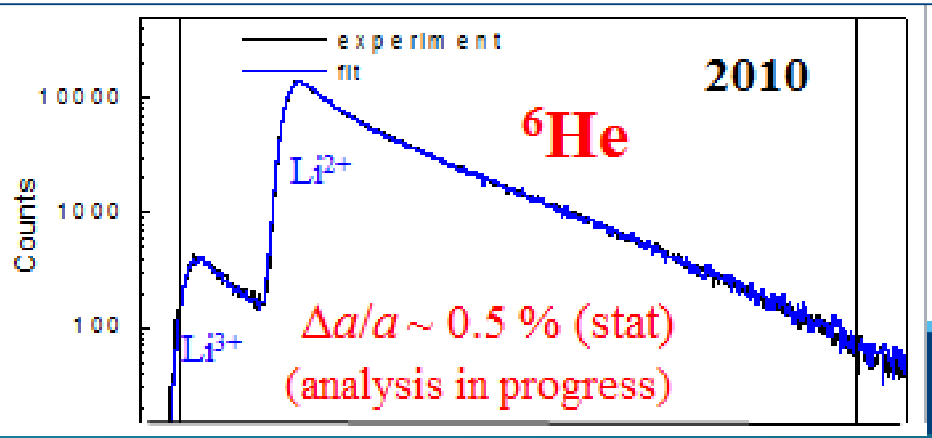
$a_{\beta\nu} = -0.3342\ (26)_{stat}\ (29)_{sys}$

M.G. Sternberg, G.Savard et al., PRL 115 (2015) 182501

Tensor currents - LPCTrap @ GANIL - ^{6}He

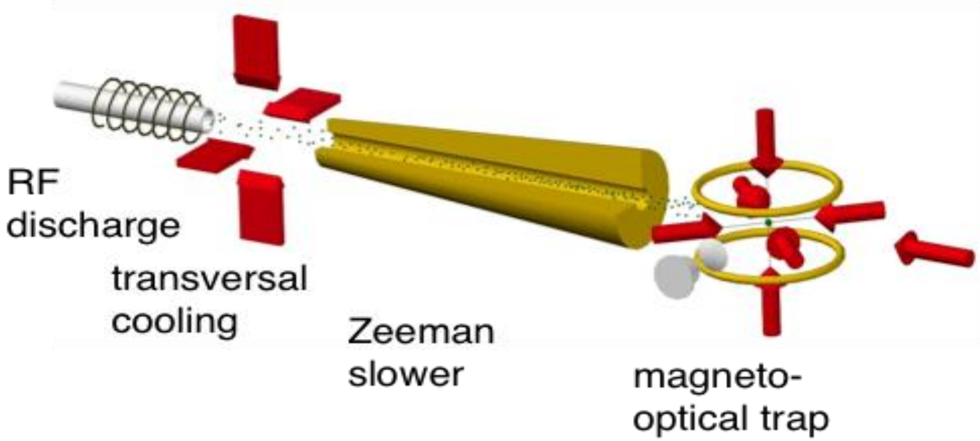
2006 (^{6}He): $a_{\beta\nu} = -0.3335(73)_{stat}(75)_{syst}$ X. Fléchard et al. J. Phys. G 38 (2011) 055101





Tensor currents - ^{6}He MOT Trap setup @ Univ. Washington, Seattle

P. Mueller, A. Garcia, et al.

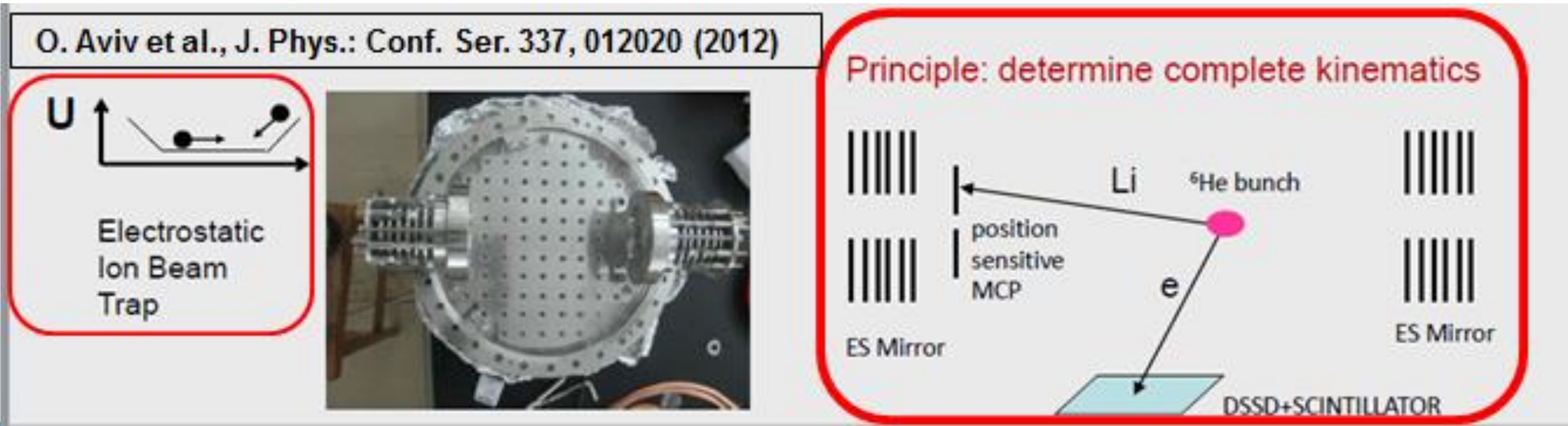


0.1 % measurement - 2015

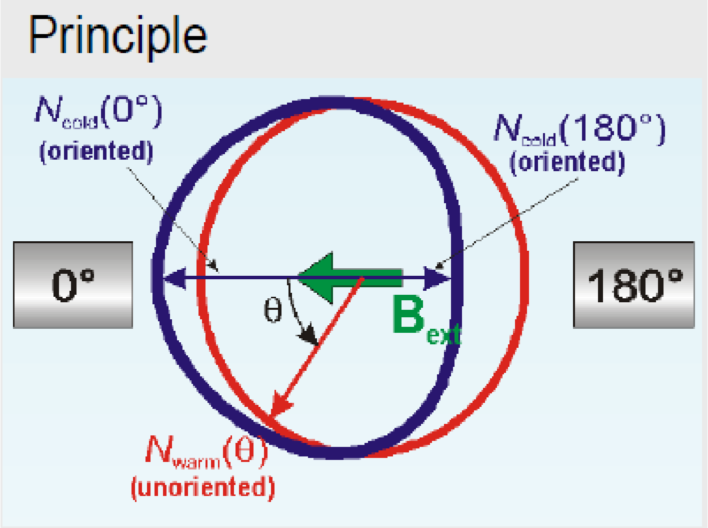
A. Knecht et al., NIM A 660 (2011) 43, Phys .Rev. C 86 (2012) 035506 & arXiv:1208.6433v2 [nucl-ex]

Tensor currents - ^{6}He EIB Trap (Weizmann Inst., Univ. Jerusalem, …)

(M. Hass, G. Ron et al.)



b) β-asymmetry parameter in nuclear beta decay



$$W(\theta) = \frac{N(\theta)_{pol}}{N(\theta)_{unpol}} = 1 + \tilde{A} \quad P \quad \frac{v}{c} \; Q \cos\theta$$

(P from independent meast.) Geant4

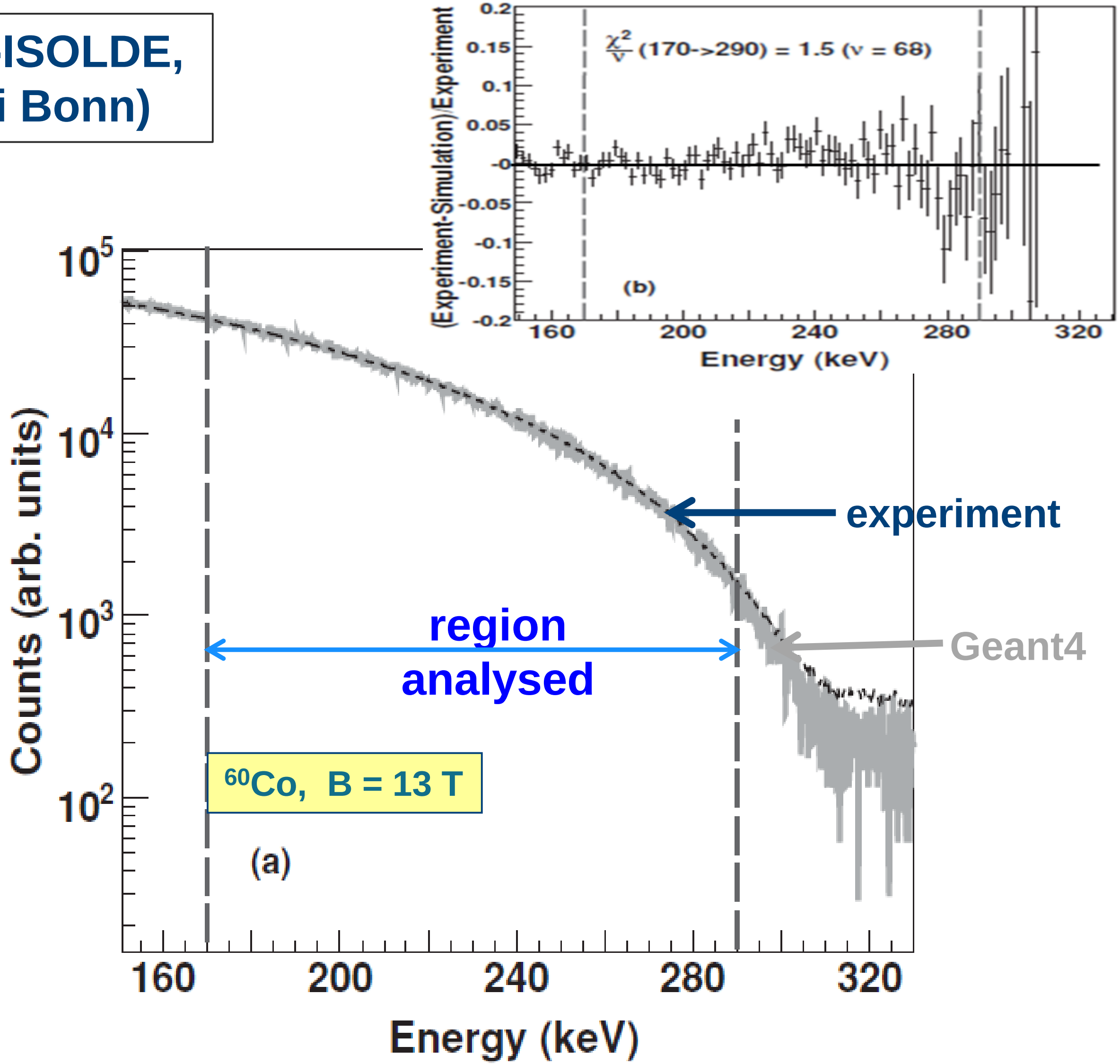
$$\tilde{A} = \frac{A}{1 + b'_{GT}} \quad \text{with} \quad b'_{GT} = \frac{\gamma m_e}{\langle E_e \rangle} \left(\frac{C_T + C'_T}{C_A} \right)$$

Analysis:

$$\frac{\left[W(\theta) - 1 \right]_{exp}}{\left[W(\theta) - 1 \right]_{Geant}} = \frac{\left[\tilde{A} \quad P \quad \frac{v}{c} \; Q \cos\theta \right]_{exp}}{\left[\tilde{A}_{SM} \quad P \quad \frac{v}{c} \; Q \cos\theta \right]_{Geant}} = \frac{\tilde{A}}{\tilde{A}_{SM}}$$

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

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



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

KU LEUVEN

^{60}Co<u>Cu</u> , $B_{ext} = 13$ T

^{114}In<u>Fe</u> , $B_{hf} = 27$ T

^{67}Cu<u>Fe</u> , $B_{hf} = 21$ T

$A_{exp}\,(^{60}\mathrm{Co}) = -1.014\,(12)_{stat}\,(16)_{syst}$

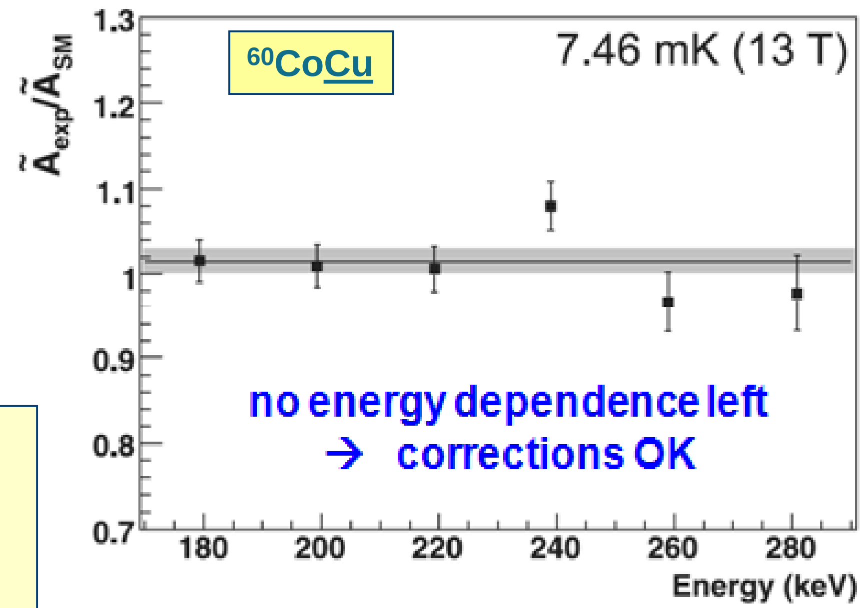
F. Wauters et al., Phys. Rev. C 82 (2010) 055502

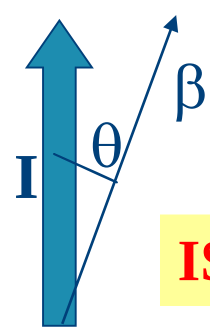
$A_{exp}\,(^{114}\mathrm{In}) = -0.990\,(10)_{stat}\,(10)_{syst}$

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

$A_{exp}\,(^{67}\mathrm{Cu}) = 0.587(8)_{stat}\,(12)_{syst}$

G. Soti et al., Phys. Rev. C 90 (2014) 035502

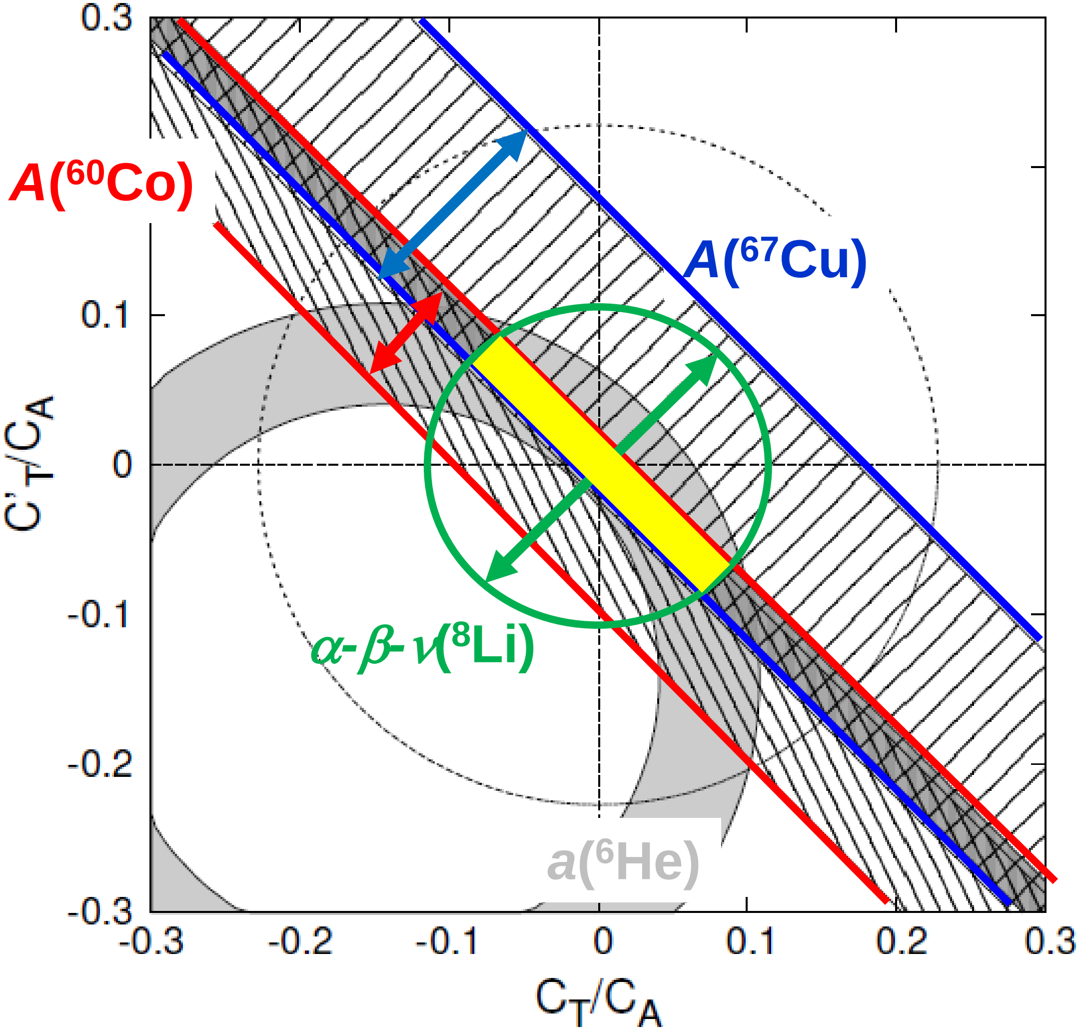




IS431-experiment

KU LEUVEN

Limits on tensor currents



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

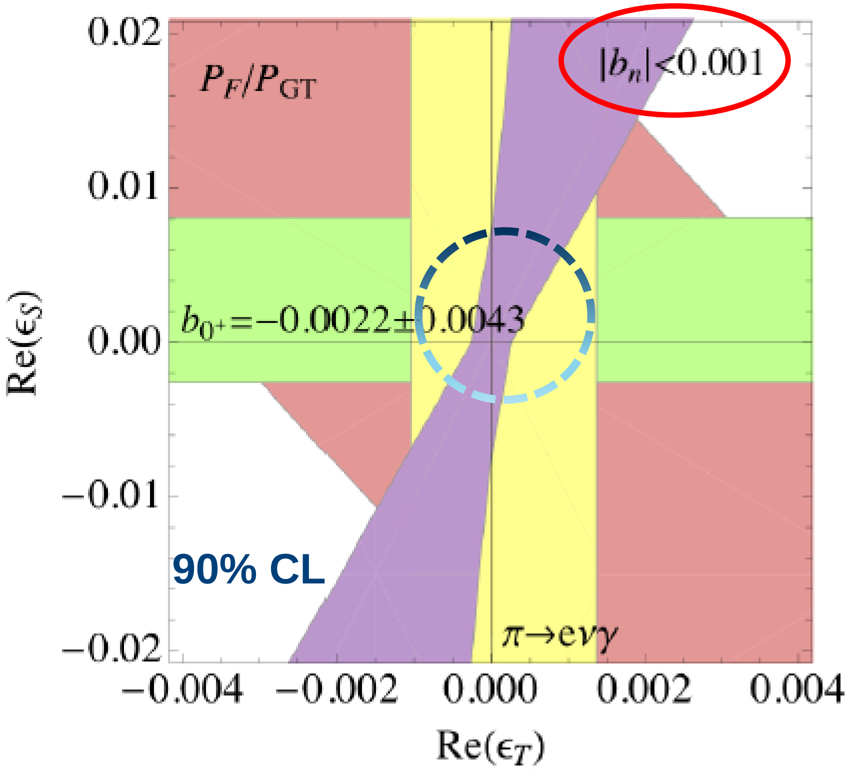
α-β-ν(^{8}Li)
M.G. Sternberg, G.Savard et al., PRL 115 (2015) 182501

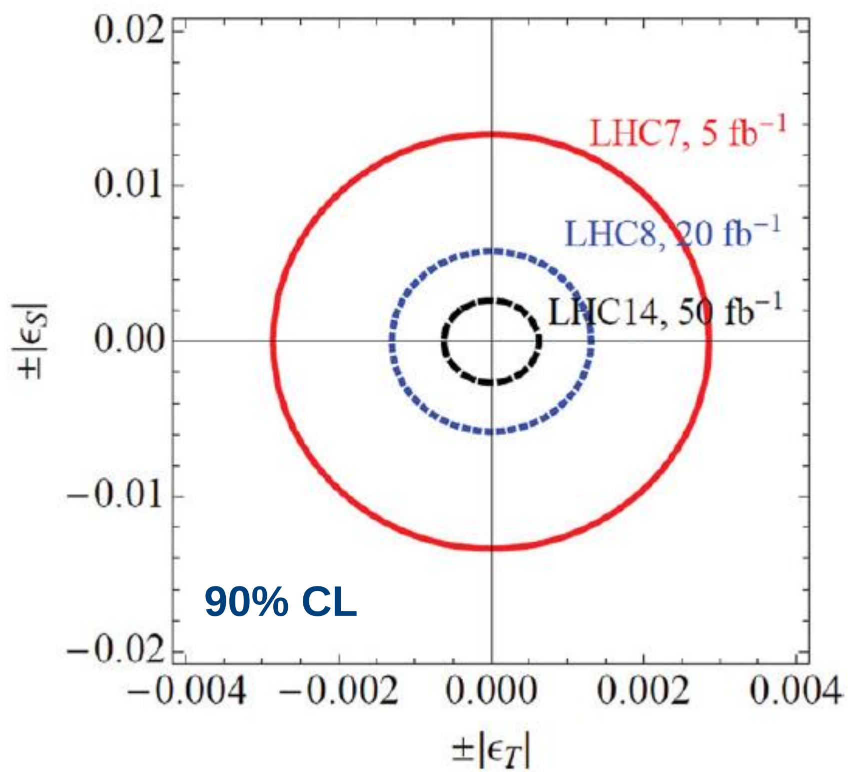
***A*(^{60}Co)**
F. Wauters, N.S. et al., PR C 82 (2010) 055502

***A*(^{67}Cu)**
G. Soti, N.S. et al., PR C 90 (2014) 035502

Also: Poster F. Lenaers – ^{35}Ar
PhD Behling 2015 – ^{37}K

2. Measurements in nuclear/neutron β decay in the LHC era





nuclear and neutron decay, pion decay

limits on scalar/tensor couplings obtained by CMS collaboration in *pp* → *e* + MET + *X* channel

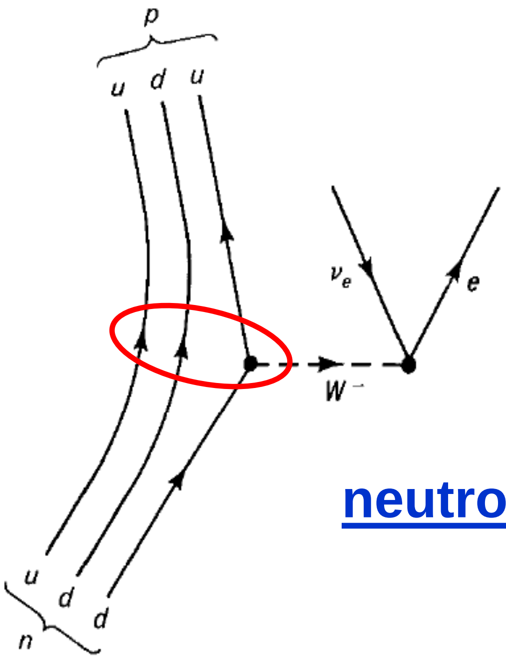
O. Naviliat-Cuncic and M. Gonzalez-Alonso
Annalen der Physik 525 (2013) 600.

V. Cirigliano, et al.,
J. High. Energ. Phys. 1302 (2013) 046

S. Chatrchyan et al. (CMS Collab.)
J. High. Energ. Phys. 08 (2012) 023

KU LEUVEN

3. Good knowledge of induced / recoil terms required



quark involved in β decay is not free
but bound in a nucleon
→ extra terms induced by strong interaction

neutron / nuclear beta decay:

weak magnetism b_{WM}

$$V_\mu(q^2) = \bar{p}[g_V(q^2)\gamma_\mu + g_M(q^2)\sigma_{\mu\nu}\frac{q_\nu}{2M}\cdot]n$$

$$A_\mu(q^2) = \bar{p}[g_A(q^2)\gamma_\mu\gamma_5 + ig_P(q^2)\frac{q_\mu}{m_e}\gamma_5]n$$

→ affects values for correlation coefficients at level of per mil to 1%

weak magnetism term b_{WM} (CVC) (N.S. et al., in prep.)

T = 1/2 $J^\pi \rightarrow J^\pi$ mirror β transitions

$$b_{WM}(\beta^\mp) = A\sqrt{\frac{J}{J+1}}\,M_F^0\;\mu^\mp$$

$$\mu^\mp = \mp(\mu_M - \mu_D)$$

$$c = g_A M_{GT} \quad \text{from } \Im t\text{-value}$$

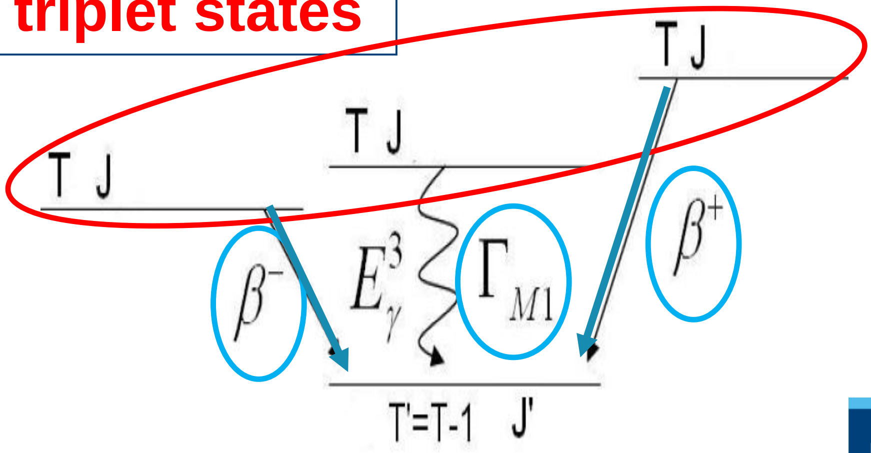
F.P. Calaprice and B.R. Holstein, NP A 273 (1976) 301

N. Severijns, I.S. Towner et al., PR C 78 (2008) 055501

GT β decays of isospin triplet states

$$b_\gamma^2 = 6\frac{\Gamma_{M1} M^2}{E_\gamma^3 \alpha}$$

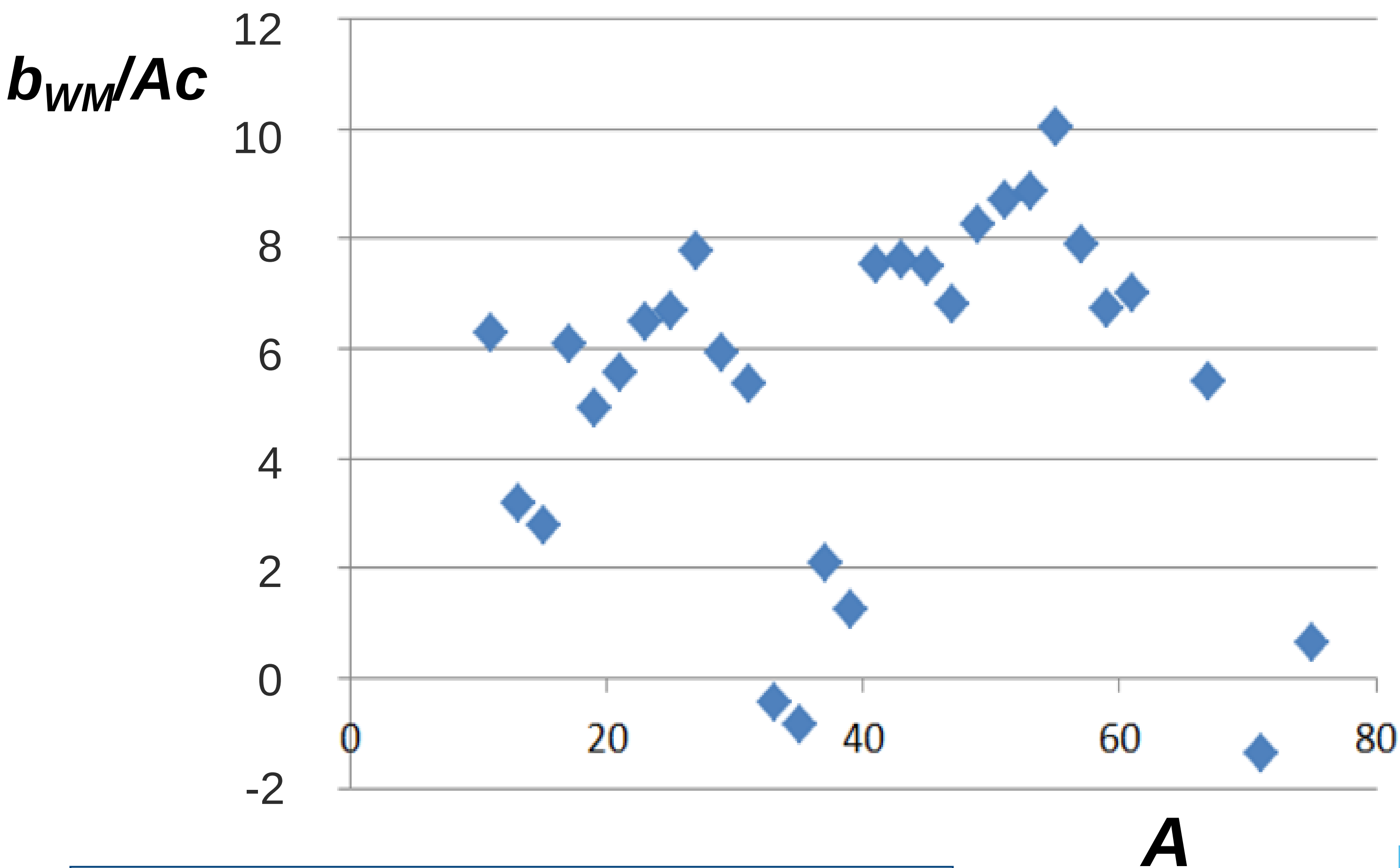
$$c = g_A M_{GT} \quad \text{from } ft\text{-value}$$



KU LEUVEN

weak magnetism term b_{WM} - experimental data

mirror β transitions: - updated Ft-values (A < 75; rel. prec. < 0.2% for A < 41)
- extracted weak magnetism form factor

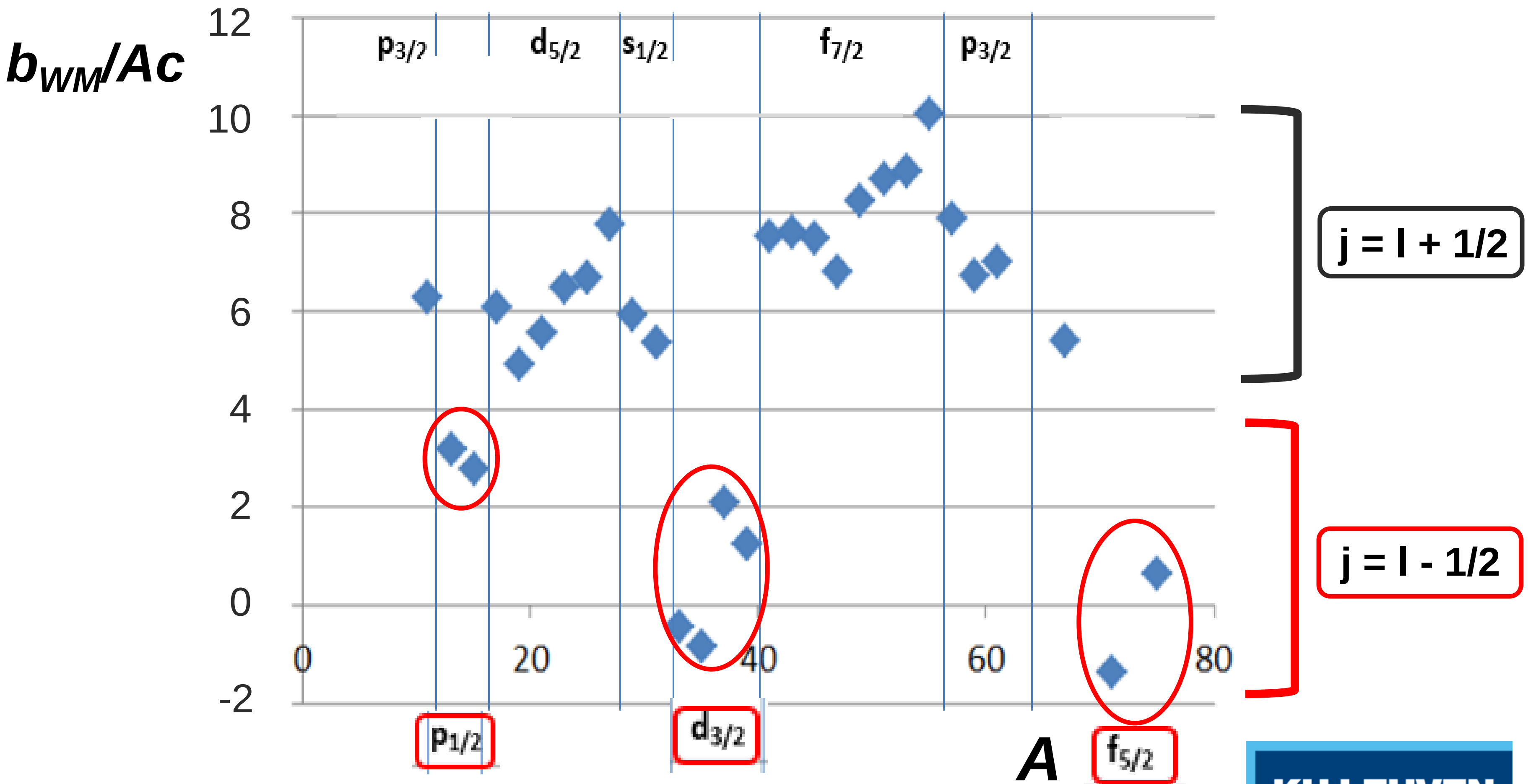


N. Severijns, I.S. Towner, et al., to be published

weak magnetism term b_{WM} - experimental data

mirror β transitions

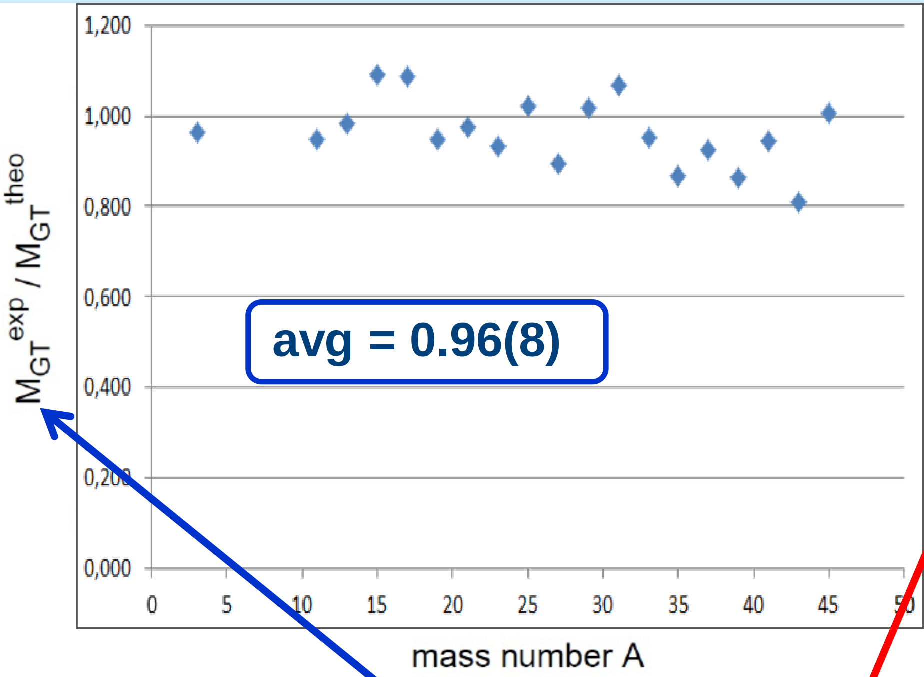
$$b_{WM} \approx \mu_p - \mu_n$$

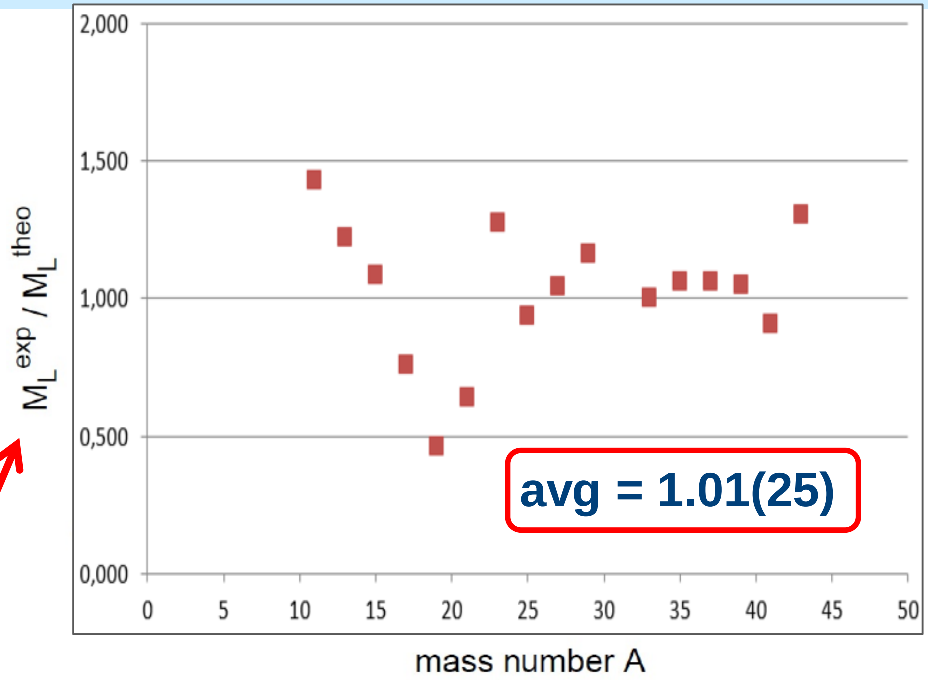


N. Severijns, I.S. Towner, et al., to be published

KU LEUVEN

weak magnetism b_{WM} - mirror β transitions





$$c \cong g_A \boxed{M_{GT}}$$

$$\frac{b_{WM}}{Ac} \cong \left[\frac{g_M}{g_A} + \frac{g_V}{g_A} \frac{\boxed{M_L}}{M_{GT}} \right]$$

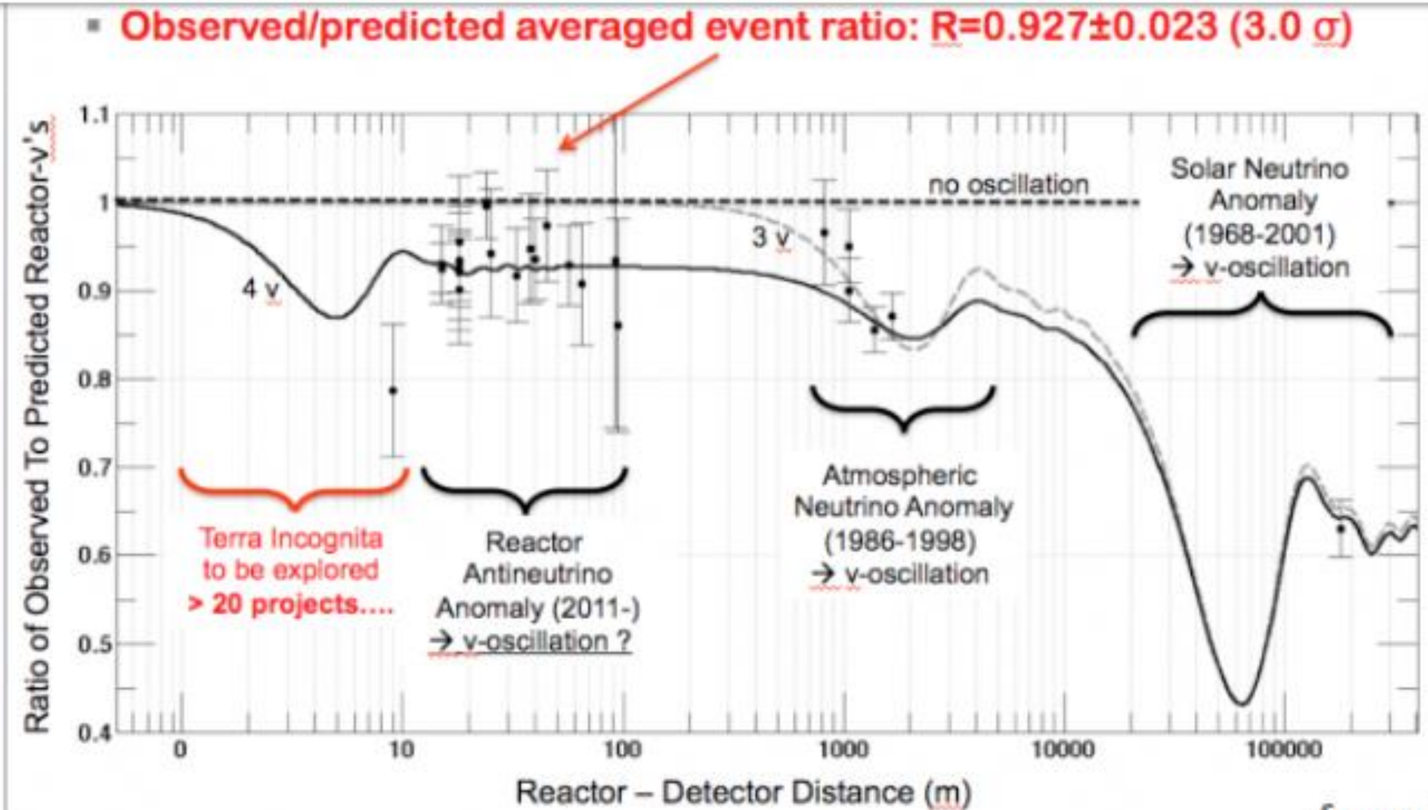
	$(b/Ac)^{exp} / (b/Ac)^{theo}$
mirror (A = 3-45)	**0.97(11)**
triplet (A = 6-30)	**1.01(15)**

N.S., I.S.Towner et al., to be published

B. R. Holstein, RMP 46 (1974) 789
F.P. Calaprice et al., PR C 15 (1977) 2178

KU LEUVEN

also of interest to Reactor Neutrino Anomaly



from Th. Lasserre

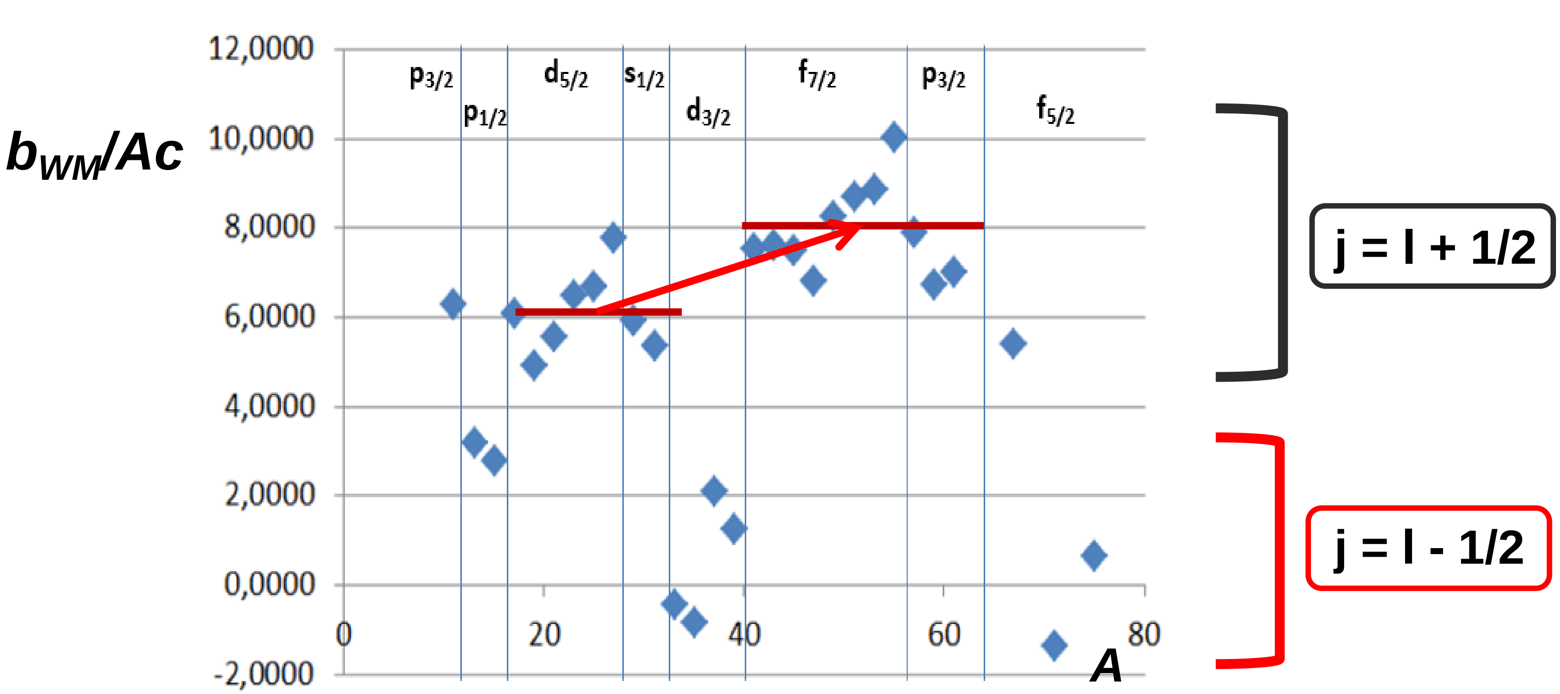
Mueller et al., Phys. Rev. C 83 (2011) 054615

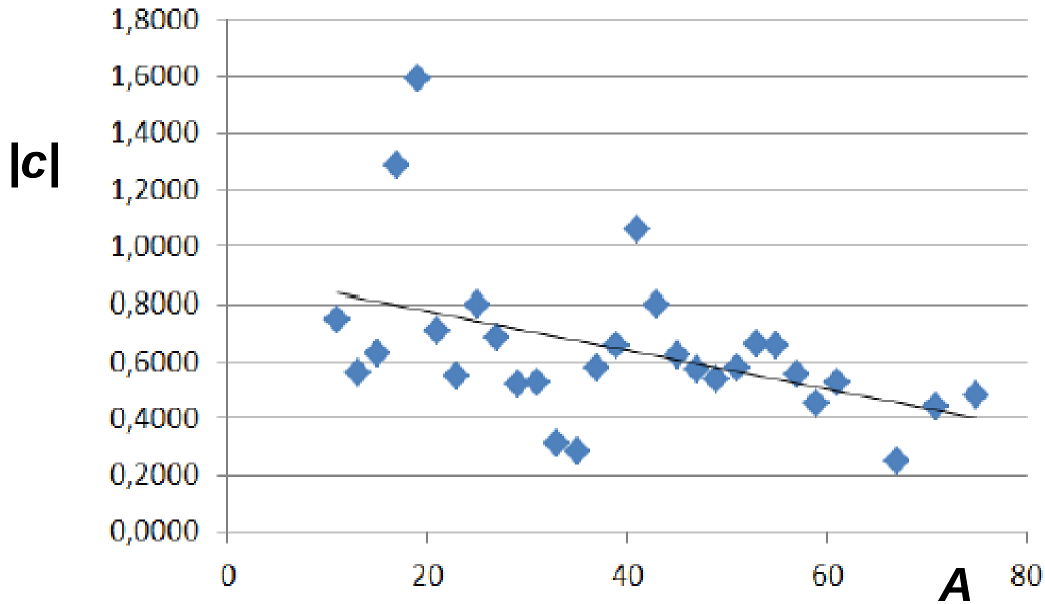
Too crude approximation for b_{WM} in fission fragment beta decays may be (in part) responsible (see also A.C. Hayes et al., PRL 112 (2014) 202501)

Poster by L. Hayen

KU LEUVEN

b/Ac vs. A





Effect on spectral shape:

$$1 + \delta_{WM} E$$

$$\rightarrow \frac{dN}{dE} = \frac{4}{3M_n}\frac{b}{Ac}$$

Shift of $\frac{dN}{dE}$ by 0.5% MeV^{-1}

$\rightarrow$ shift in ν-rate of $\approx$ -1%

New vistas and prospects in the LHC era

- **new generation of (trap-based) correlation experiments**

  → **towards 0.1% precision level**

- **precise β-spectrum shape measurements:**

$$d\Gamma \propto G_F\ F(Z,E)\left[1 + k\frac{1}{E_\beta} b_{Fierz} + k'\ E_\beta\, b_{WM}\right]$$

b_{Fierz} : scalar / tensor weak currents

b_{WM} : weak magnetism (Standard Model term)

- induced by strong interaction because decaying quark is not free but bound in a nucleon;
- is to be known better when reaching sub-percent precisions

Note the different energy dependence of both effects !!

4. β spectrum shape measurements

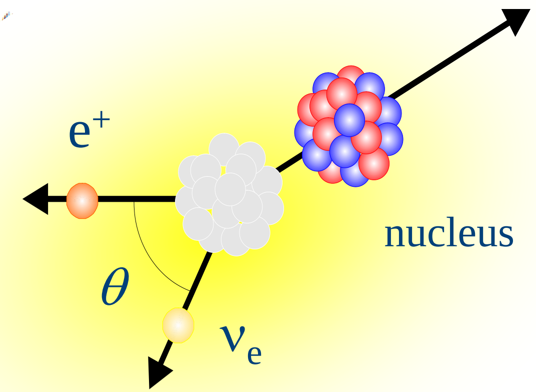
Table VI Overview of the features present in the β spectrum shape (Eq. (4)), and the effects incorporated into the Beta Spectrum Generator Code. Here the magnitudes are listed as the maximal typical deviation for medium Z nuclei with a few MeV endpoint energy. Some of these corrections fall off very 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))	
6	Atomic exchange	X (Eq. (63))	
7	Atomic mismatch	r (Eq. (76))	
8	Atomic screening	S (Eq. (54)) [a]	
9	Shake-up	See item 7 & Eq. (66) [b]	
10	Shake-off	See item 7 & Eq. (69) & χ_{ex}^{cont}	
11	Distorted Coulomb potential due to recoil	Q (Eq. (26))	
12	Diffuse nuclear surface	U (Eq. (20))	
13	Recoiling nucleus	R_N (Eq. (22))	
14	Molecular screening	ΔS_{Mol} (Eq. (81))	
15	Molecular exchange	Case by case	
16	Bound state β decay	Γ_b/Γ_c (Eq. (77))	
17	Neutrino mass	Negligible	
18	Forbidden decays	Not incorporated	

[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. … o be evaluated in a case by case scenario.

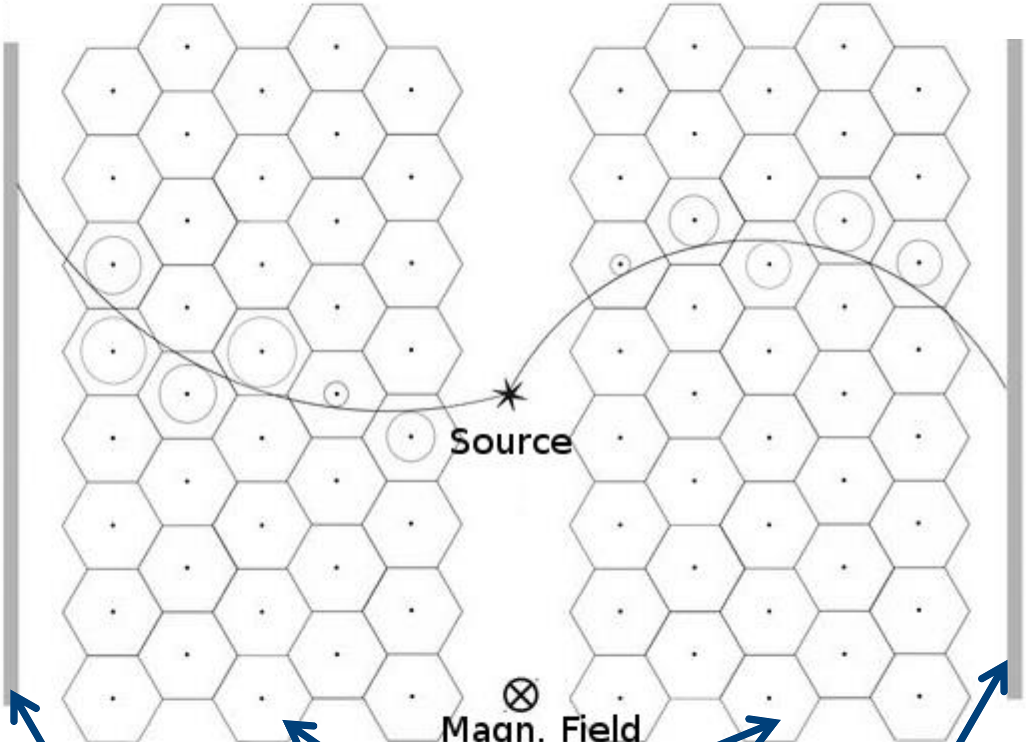
Analytical description + code, accurate to few 10^{-4} level

L. Hayen, N. Severijns et al., in prep.



Poster by L. Hayen

miniBETA spectrometer (Leuven / Krakow)



multi-wire drift chamber

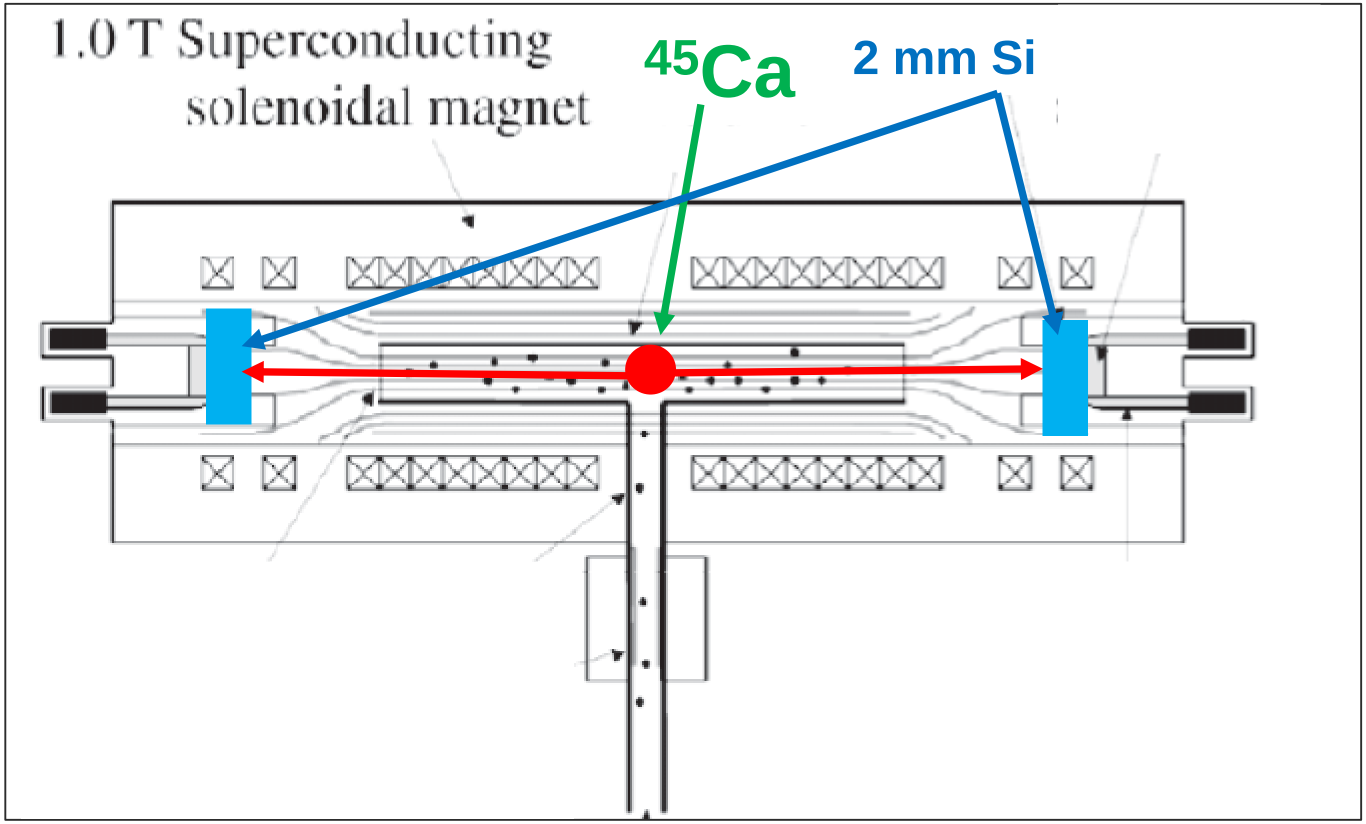
scintillator (later DSSDD)

double-Si spectrometer (Leuven / LANL, A. Young)

two 2 mm segmented **Si** detectors in B- field, replacing UCNA MWPCs

- **data in May 2016**
- **analysis ongoing**

Talk of J. Wexler

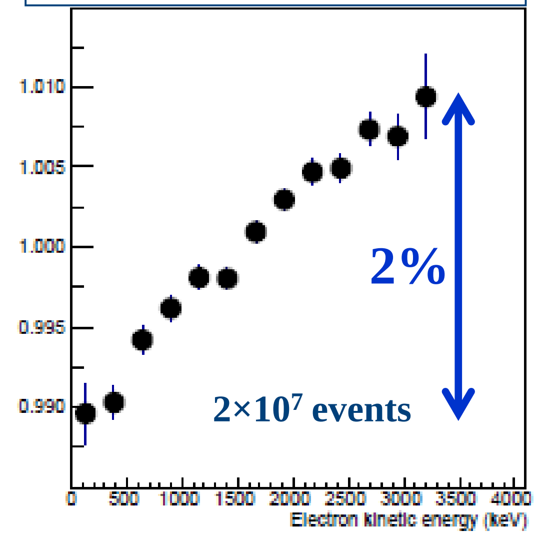


Beta energy spectrum shape in ^{6}He decay - NSCL/MSU
(O. Naviliat-Cuncic et al.)

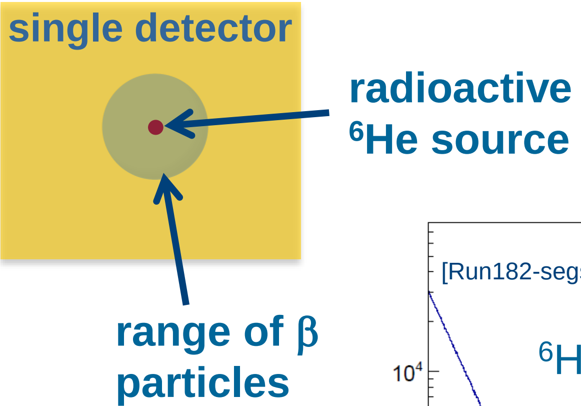
- **Long term goal**: Measure the **Fierz interference term** (b) in ^{6}He decay to search for weak tensor currents.
- **Current goal**: measure the **weak magnetism** (WM) form factor in ^{6}He decay for a tests of the strong form of CVC. The WM is the largest "hadronic SM background" in a measurement of b.

Poster of Xuejing Huyan

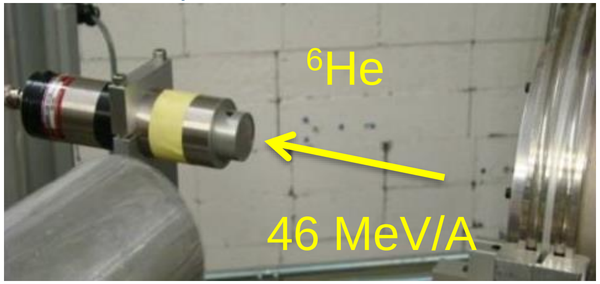
Effect of weak magnetism
(Monte-Carlo simulation)



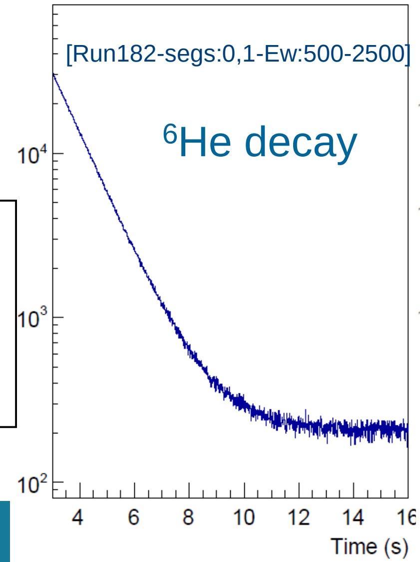
- **Principle**: use a **fragmented separated beam** to eliminate distortions in beta spectrum due to **back-scattering, out-scattering or dead-layers**.

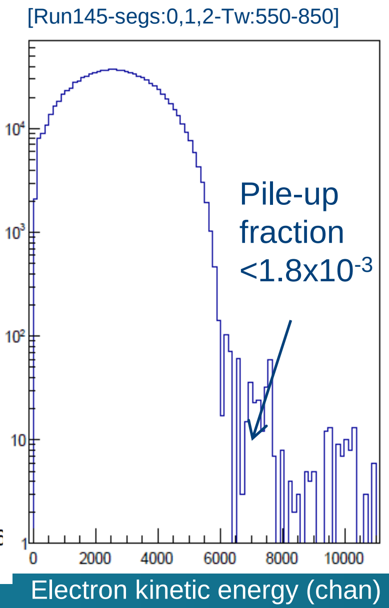


Experiment at NSCL

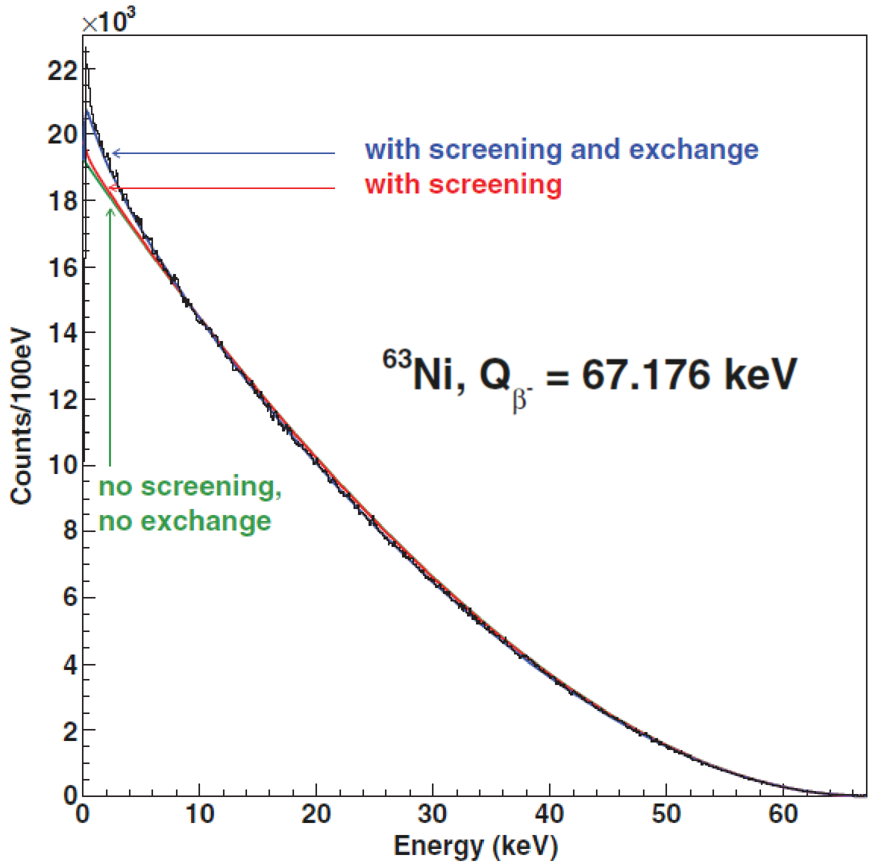


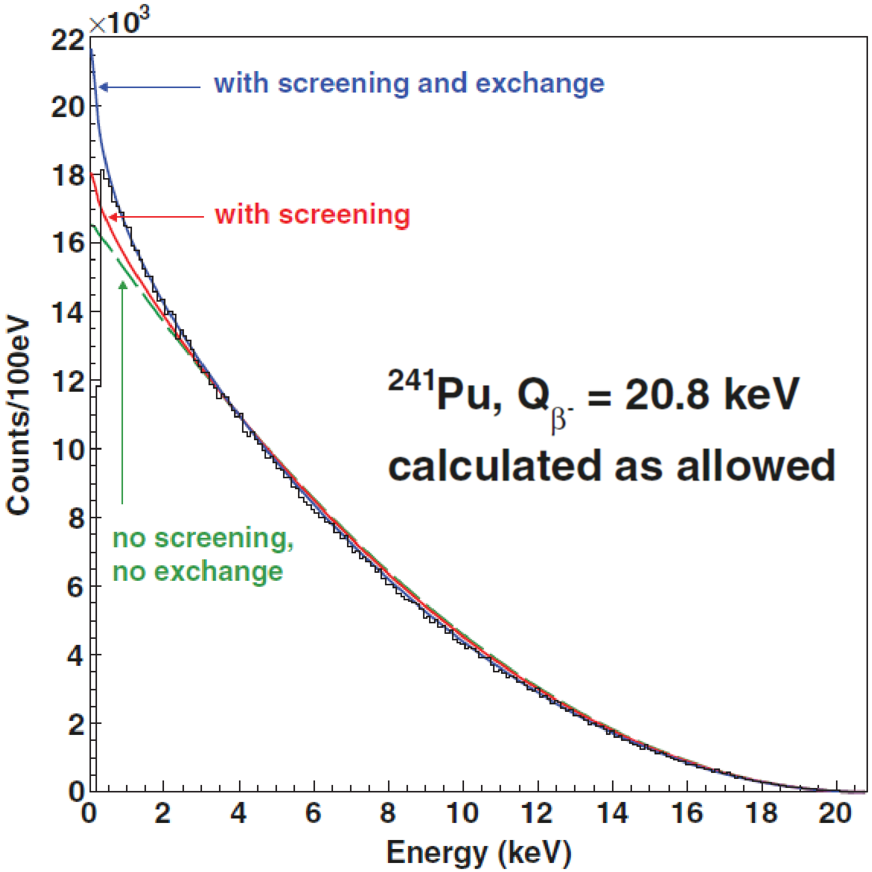
Collected statistics enables extracting the WM form factor at ~5% relative error





microcalorimeter measurements (CEA-Saclay)





X. Mougeot et al., PR A 86 (2012) 042506 and PR A 90 (2014) 012501

Conclusions and Outlook

1. **β-ν correlation** and **β asymmetry** measurements + **Ft-values**

→ improved limits on **scalar** and **tensor** type weak currents;

2. searches for new physics (bosons) at **low energies are competitive** with direct searches at **LHC** for 10^{-3} precisions of *b* and beyond

many experiments **ongoing** or **in preparation / planned**

3. at sub-0.5% level of precision have to include effects induced by strong interaction

→ largest is **weak magnetism**

→ best observable: **beta-spectrum shape**

scalar / tensor currents & **weak magnetism**

KU LEUVEN

distribution in
- **electron and neutrino directions** and in
- **electron energy**

from **polarized nuclei :**

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

$d\Gamma_0$

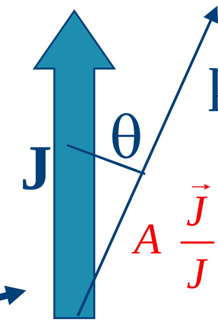
nuclear matrix elements

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

β-ν correlation

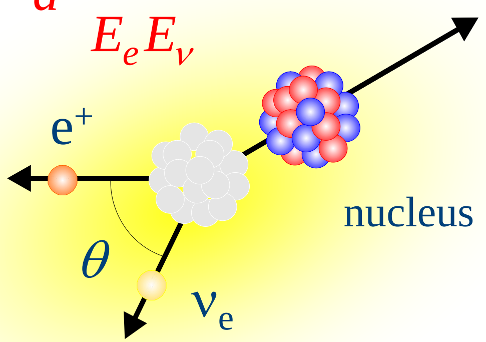
Fierz interference term (b ≡ 0 in standard model)

β-asymmetry



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

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



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

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

KU LEUVEN

the Standard Model and beyond:

* C_A = -1.27 (g_A/g_V = -1.2699(7) 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- and A-currents)

% level → ~ 300 GeV
per mille level → ~ 2 TeV

experimental upper limits: $|C_T^{(\,'\,)}/C_A|$ and $|C_S^{(\,'\,)}/C_V|$ at few % level
(neutron and nuclear β-decay)

N.S., O. Naviliat-Cuncic and M. Beck, Rev. Mod. Phys. 78 (2006) 991,
J. Nico, J. Phys. G 39 (2009) 104001,
D. Dubbers and M.G. Schmidt, Rev. Mod. Phys. 83 (2011) 1111,
V. Cirigliano et al., Prog. Part. Nucl. Phys. 71 (2013) 93,
F. Wauters et al., Phys. Rev. C 89 (2014) 025501,
B.R. Holstein, J. Phys. G 41 (2014) 114001.

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

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:

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

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

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

T. Bhattacharya et al., Phys. Rev. D 85 (2012) 054512

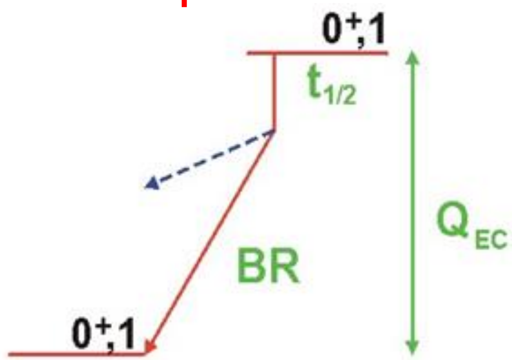
V. Cirigliano, et al., J. High. Energ. Phys. 1302 (2013) 046

O. Naviliat-Cuncic and M. Gonzalez-Alonso, Annalen der Physik 525 (2013) 600.

V. Cirigliano, et al., Progr. Part. Nucl. Phys. 71 (2013) 93

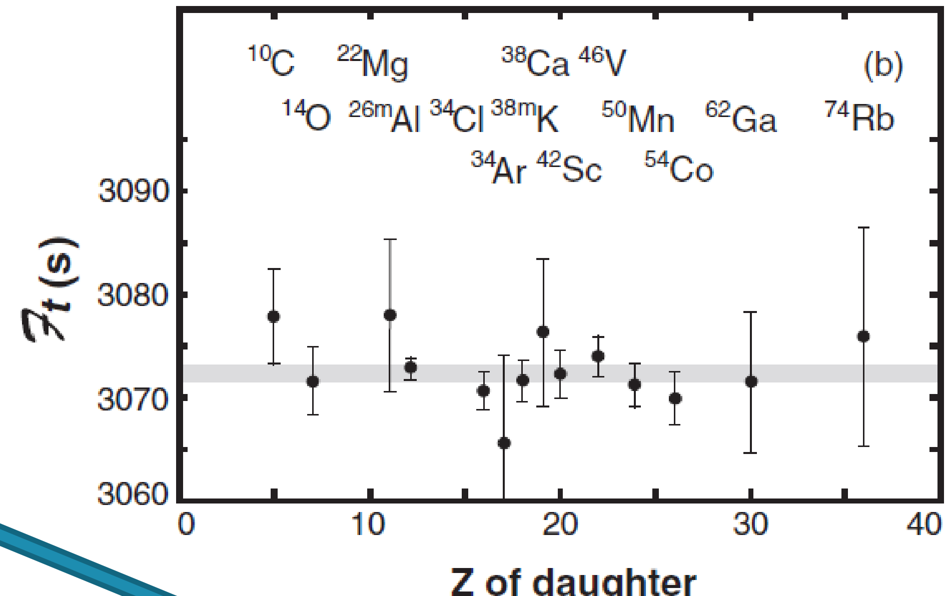
V_{ud} quark mixing matrix element & CKM unitarity

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



$|V_{ud}| = 0.97417(21)$

Hardy & Towner, PR C 91 (2015) 025501



$\mathcal{F}t^{0^+\rightarrow 0^+}$ = 3072.27(72) s

$$|V_{ud}|^2 + |V_{us}|^2 + |V_{ub}|^2 = 0.99978(55)$$

$|V_{us}| = 0.2253(8)$ (PDG14)

Hardy & Towner , Phys. Rev. C 91 (2015) 025501

prospects - 1

1. **pure Fermi transitions:** - new data to improve Ft values
   - testing isospin corrections δ_C
   - nucleus-independent radiative correction Δ_R

2. **neutron decay:** - lifetime (tSPECT, …)
   - beta-asymmetry parameter *A* (PERKEO, UCNA)
   - $\beta\nu$-correlation *a* (*a*SPECT, Nab, AbBa, aCORN, …)

3. **T = 1/2 mirror β transitions:**

$$Ft^{mirror}\left(1+\frac{f_A}{f_V}\rho^2\right) = 2Ft^{0^+\to 0^+} = \frac{K}{G_F^2 V_{ud}^2 (1+\Delta_R^V)}$$

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

N.S. , I.S. Towner et al.,
Phys. Rev. C 78 (2008) 055501

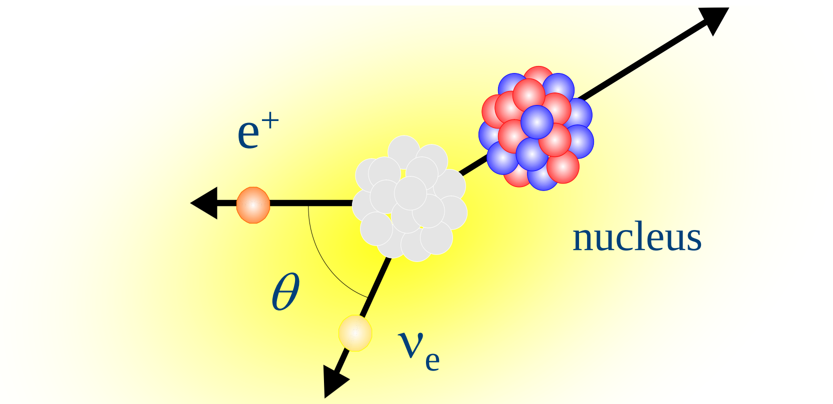
$|V_{ud}| = 0.9719(17)$

O. Naviliat-Cuncic & N.S., PRL 102 (2009) 142302

KU LEUVEN

6. β spectrum shape measurements

$$N(p)dp = Kp^2(W - W_0)^2 \cdot F(Z,p) \cdot L_0 \cdot C \cdot R_n \cdot RC \cdot S(E)dp$$



- phase space factor x constants
- *F(Z,p)*: Fermi function
- L_0 & *C*: finite size of nucleus
- R_n : finite mass of nucleus
- *RC*: radiative corrections
- *S(E)*: spectrum shape factor

$$\boxed{\frac{dN}{dE} \approx 1 + \frac{4}{3M_n}\frac{b_{WM}}{Ac}E_e \quad \Rightarrow \quad \approx 0.8\ \%\ \mathrm{MeV}^{-1}}$$

(for a pure GT transition and neglecting terms ∝ $1/M^2$ and ∝ m_e^2/E)

→ $$d\Gamma \propto G_F\ F(Z,E)\left[1 + k'\boxed{b_{WM}\ E_\beta} + k''\boxed{\frac{b_{Fierz}}{E_\beta}}\right]$$

KU LEUVEN