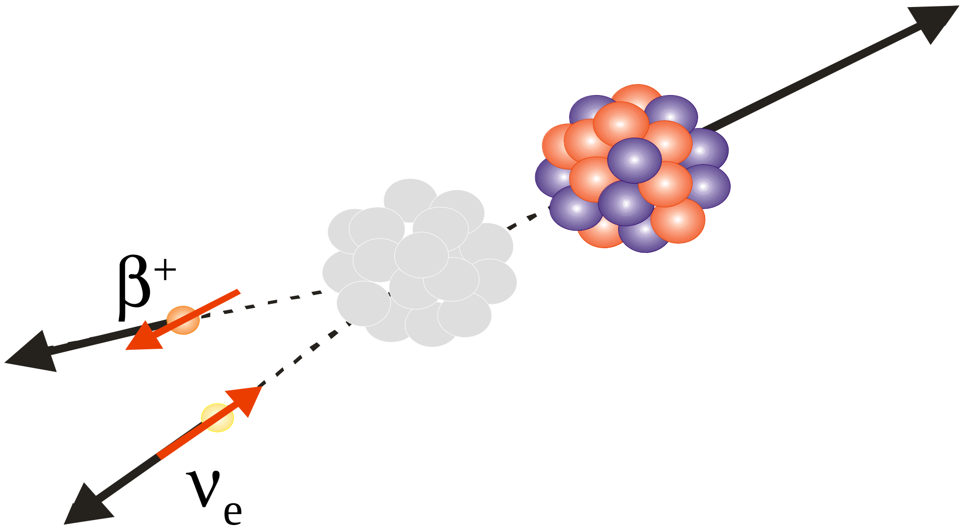
Fundamental interactions experiments with polarized trapped nuclei



DESIR meeting
Leuven, 26-28 May 2010

Nathal Severijns

Kath. University Leuven, Belgium

1. **searches for exotic weak currents (non V-A)**

   - tensor currents
   - scalar currents

2. **symmetry tests**

   - parity
   - time reversal / CP violation

3. **determine V_{ud} and test CVC**

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

from **polarized nuclei :**

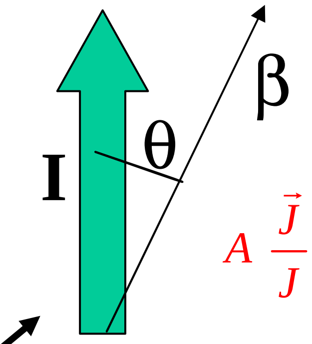
Correlation measurements

$$\omega\,(\langle \vec{J}\rangle \,|\, E_e,\Omega_e,\Omega_\nu)\; dE_e\; d\Omega_e\; d\Omega_\nu$$

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

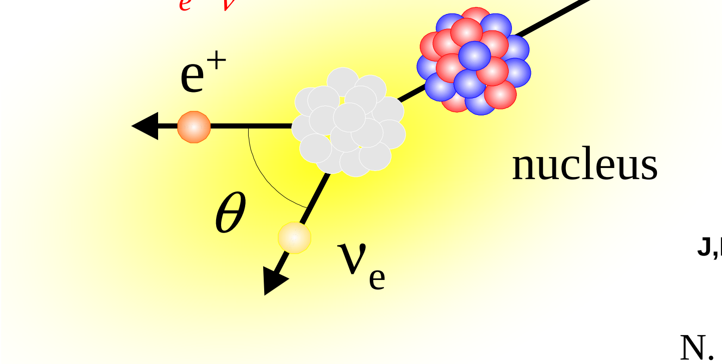
$$\text{x}\quad \xi\;\left\{ 1 \;+\; a\,\frac{\vec{p}_e\cdot\vec{q}}{E_e E_\nu} \;+\; b\,\frac{\gamma m_e}{E_e} \;+\; A\,\frac{\vec{J}}{J}\cdot\frac{\vec{p}_e}{E_e} \;+ R\;\vec{\sigma}\cdot\frac{\vec{J}}{J}\,\text{x}\,\frac{\vec{p}_e}{E_e} + \ldots \right\}$$

β-ν correlation | **Fierz interference term (b ≡ 0 in standard model)** | **β-asymmetry** | **R-correlation**



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

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



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

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

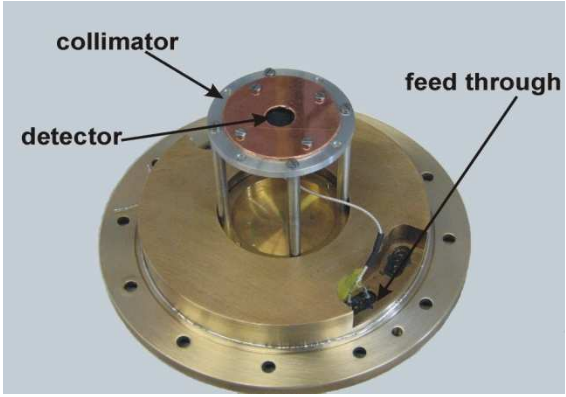
^{114}In and ^{60}Co beta asymmetry parameter, A

Wauters et al.

in 13 T external polarizing field;

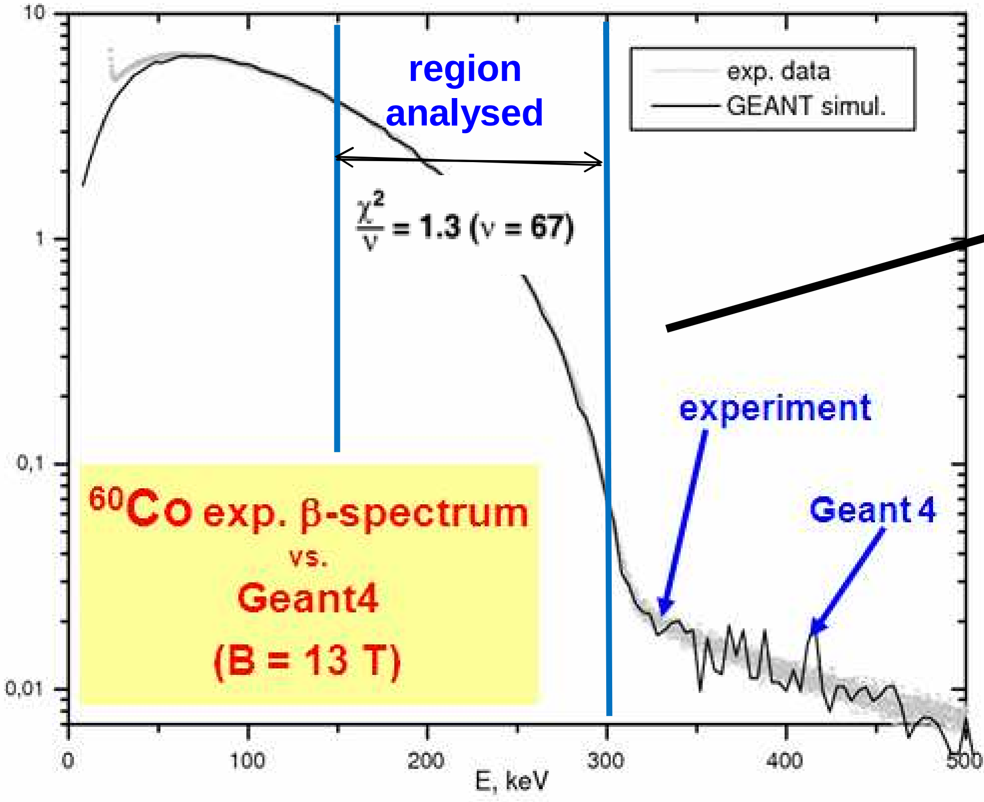
used GEANT4 code to account for :

- **detection geometry**
- **magnetic field effects**
- **scattering**



Si p-I-n diode
(500 μm, ∅ = 9 mm)
operating at 10 K

Leuven ^{3}He - ^{4}He dilution refrigerator setup



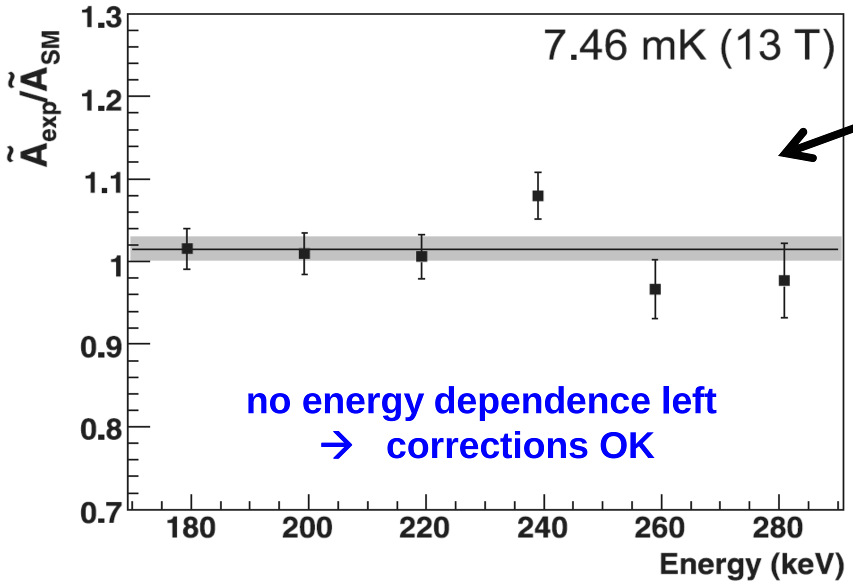
$$W(\theta) = \frac{N(\theta)_{pol}}{N(\theta)_{unpol}} = 1 + \tilde{A} \;\; P \; \frac{v}{c} \; Q \cos\theta$$

(P from anisotropy of γ-rays)

Geant 4

Analysis of measured and simulated spectra:

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



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

(A_{SM} = -0.987(9))

F. Wauters et al., submitted

A_{exp} (^{114}In) = - 0.994 (10)$_{stat}$ (10)$_{syst}$

(A_{SM} = -1.000)

(most precise result for $A_{nuclear}$ ever !)

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

(^{67}Cu in progress)

major systematic errors:

- performance of GEANT code (scattering)
- determination of nuclear polarization

(M)LRS-models

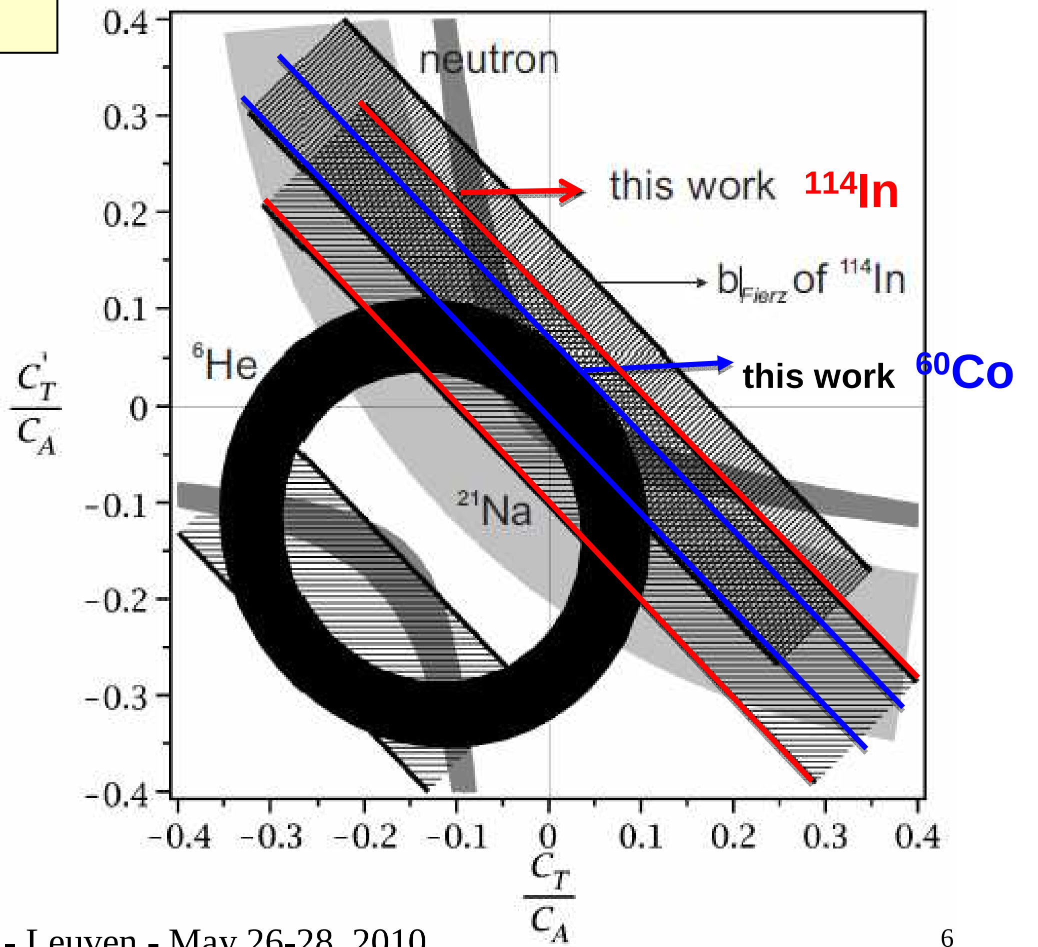
$W_1 = W_L \cos\zeta - W_R \sin\zeta$

$W_2 = W_L \sin\zeta + W_R \cos\zeta$

$\delta = m_1^2 / m_2^2$

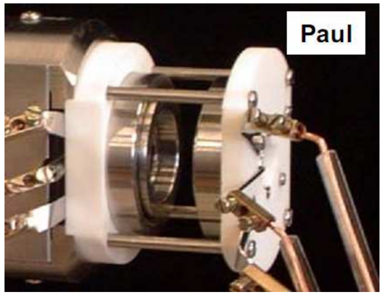
^{114}In : M(W_2) > 230 GeV/c^2 (90% C.L.)

^{60}Co : M(W_2) > 245 GeV/c^2 (90% C.L.)

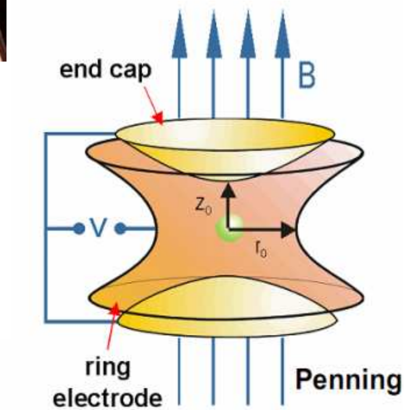


Polarizing atoms/ions in a particle trap:

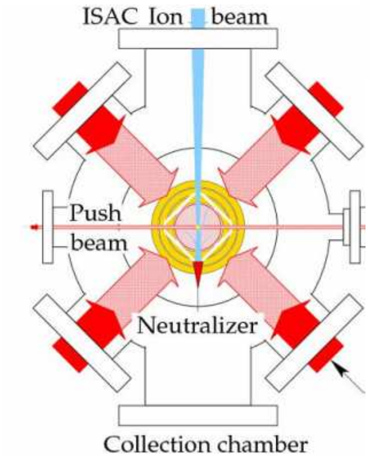
- **Paul trap :** optical pumping of ion cloud
  (LPC-GANIL) in magnetic holding field



- **Penning trap :** collinear polarization by optical pumping
  (WITCH-ISOLDE, DESIR) in beam line before trap

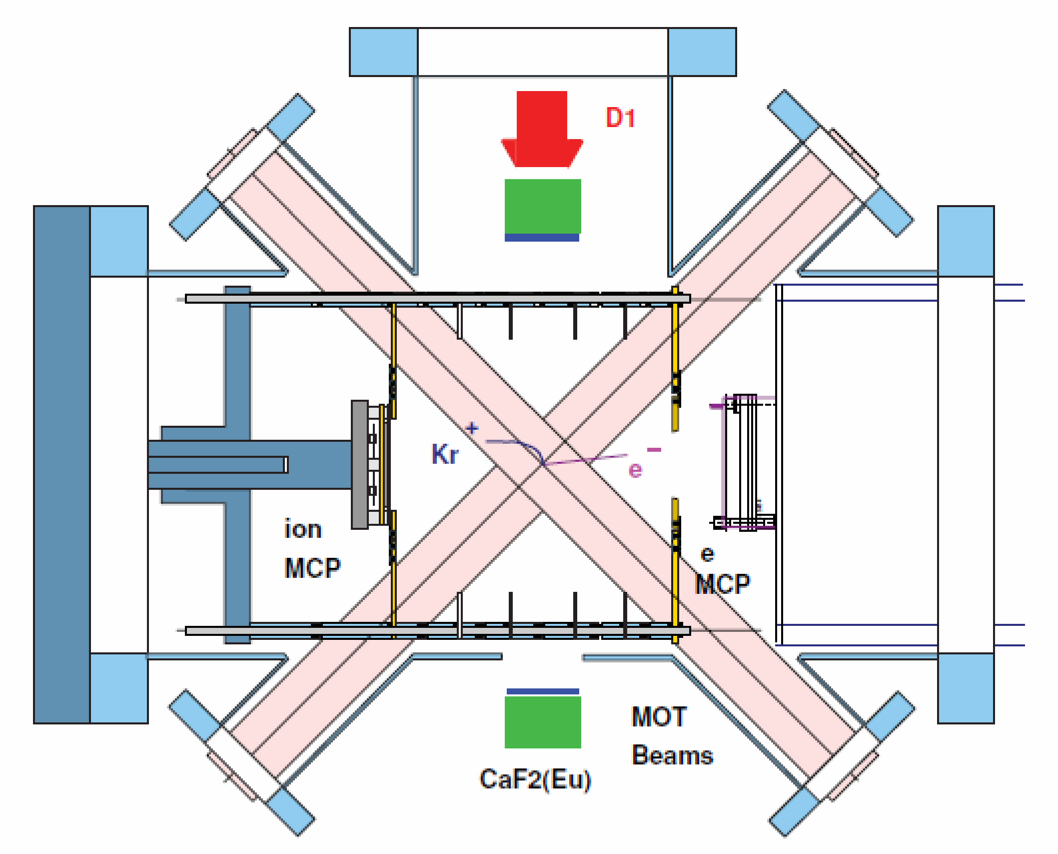


- **MOT trap :** optical pumping of ion cloud
  (TRIUMF, Berkeley, KVI) in magnetic holding field



Alternative : stop ions in superfluid He and
polarize by optical pumping (cf. talk by T. Shimoda)

Example of polarized atoms in MOT: neutrino asymmetry parameter for ^{37}K



TRINAT MOT trap @ TRIUMF

$$B_\nu(^{37}K) = -0.755(24)$$

$$B_\nu^{SM} = -0.779(6)$$

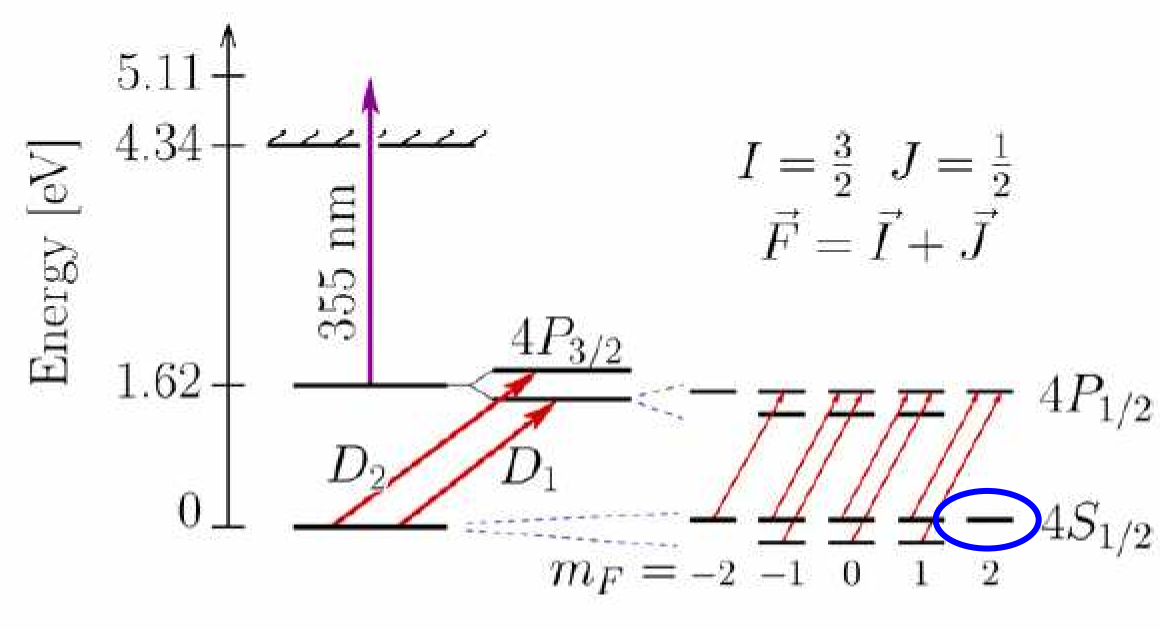
5 % precision

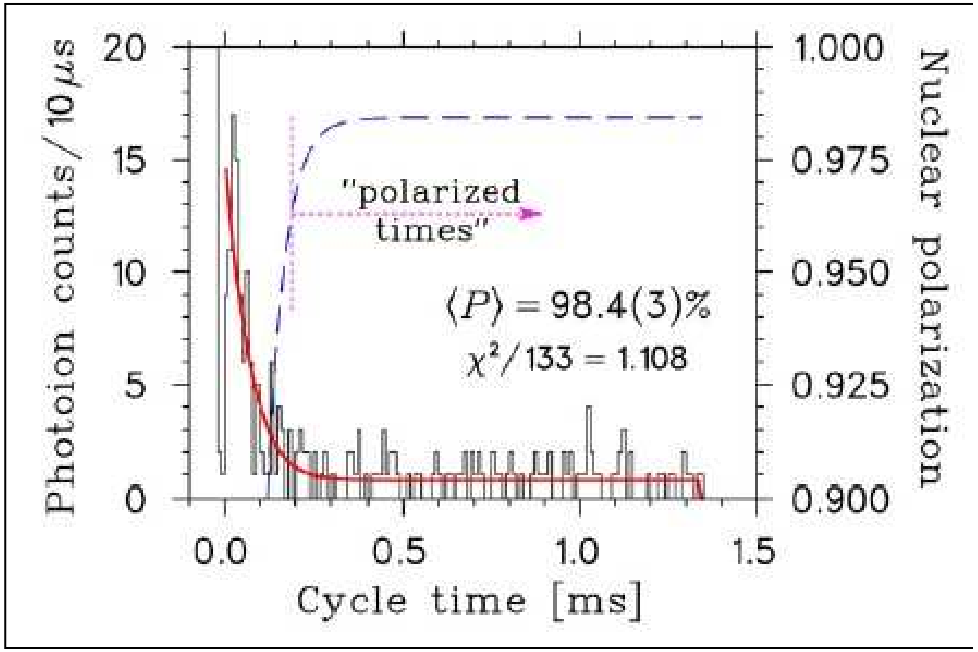
very difficult to determine nuclear polarization precisely !

M_{W_2} > 180 GeV/c^2 (90 % C.L.)

^{37}K – D. Melconian, J.A. Behr et al., Phys. Lett. B 649 (2007) 370

Polarization by optical pumping and determination of nuclear polarization via photoionization in a MOT





^{37}K	$\langle P_{\sigma^+} \rangle = (+97.7 \pm 0.4^{+0.2}_{-0.5})\%$ $\langle P_{\sigma^-} \rangle = (-95.8 \pm 1.0^{-0.4}_{+1.3})\%$
^{80}Rb	$P = 0.53 \pm 0.03$

D. Melconian, J.A. Behr et al., Phys. Lett. B 649 (2007) 370

J.R.A. Pitcairn, J.A. Behr et al., Phys. Rev. C79 (2009) 015501

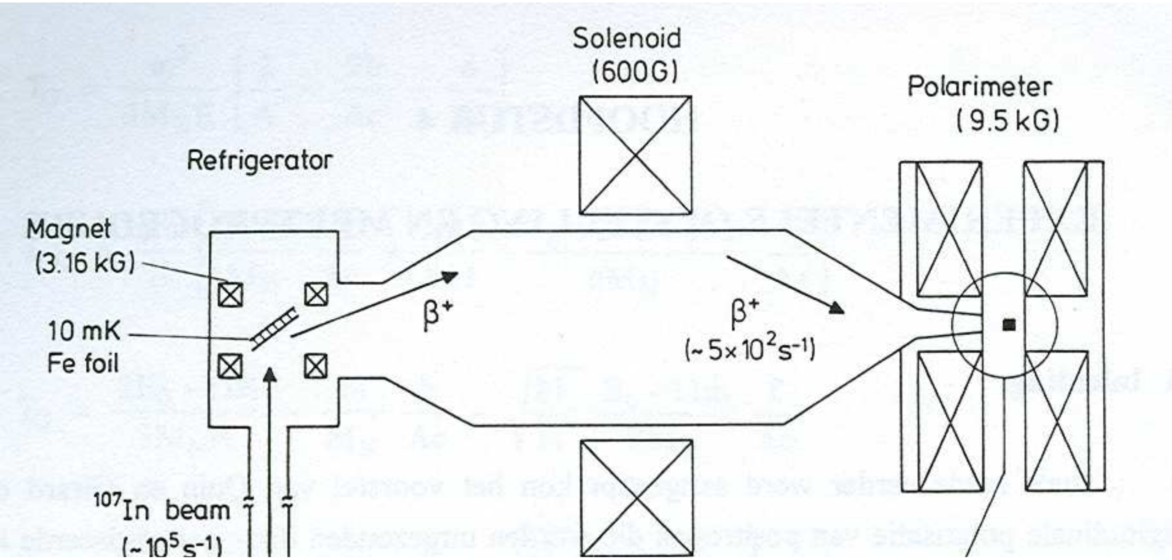
Longitudinal polarization of positrons emitted by polarized nuclei

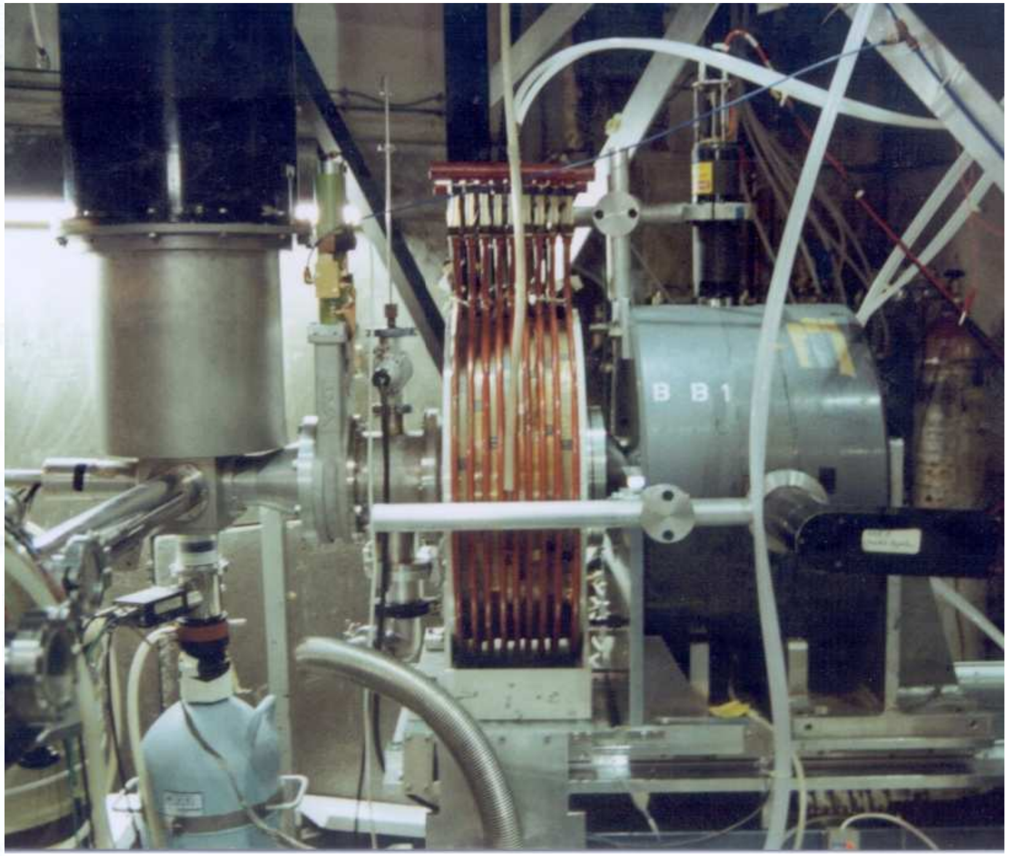
experimental quantity

$$R \equiv P^- / P^+ = R_{SM} [\, 1 + k\,\Delta \,]$$

$$\Delta = (\,\delta + \zeta\,)^2$$

with : P^- (P^+) is β particle longitudinal polarization for β's emitted opposite to (in the direction of) the polarized nuclear spin vector (P^0 for unpolarized nuclei)





(M)LRS-models

$$W_1 = W_L \cos\zeta - W_R \sin\zeta$$

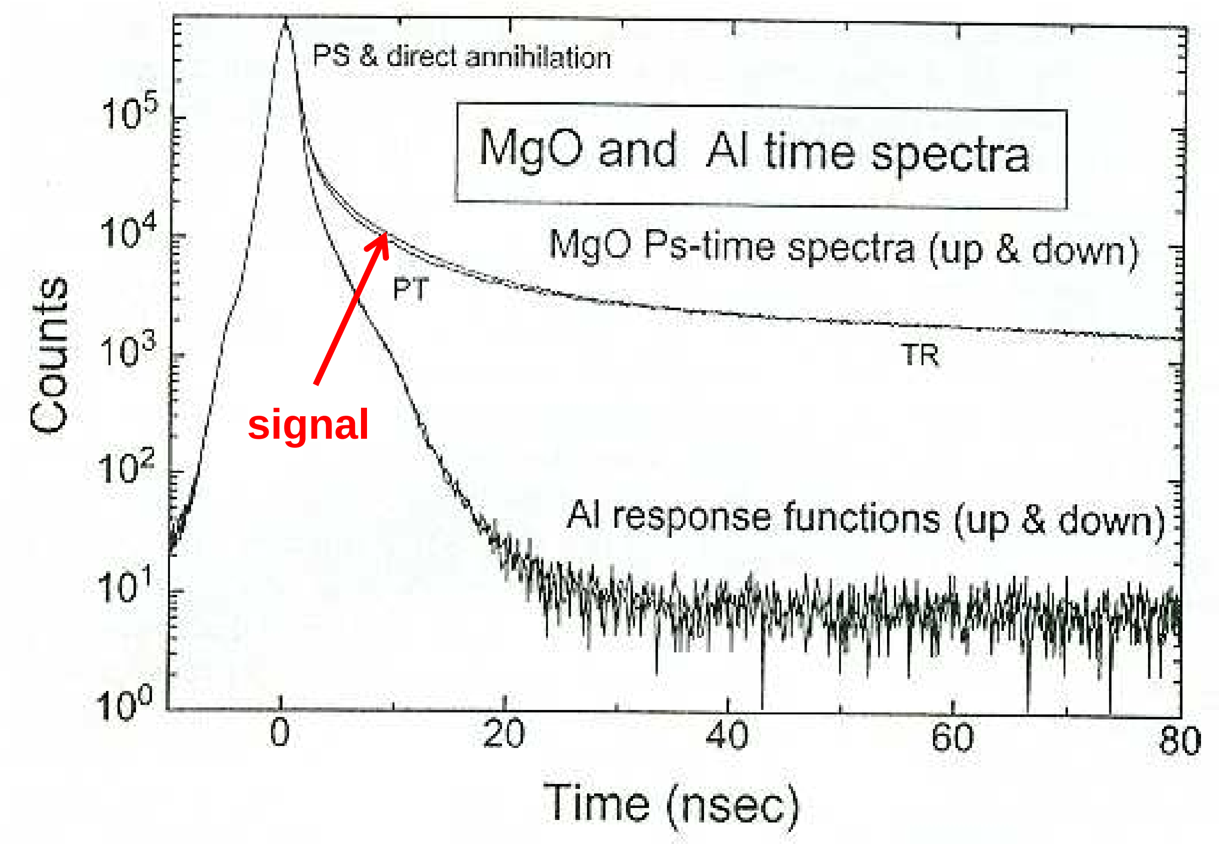
$$W_2 = W_L \sin\zeta + W_R \cos\zeta$$

$$\delta = (M_{W1})^2 / (M_{W2})^2$$

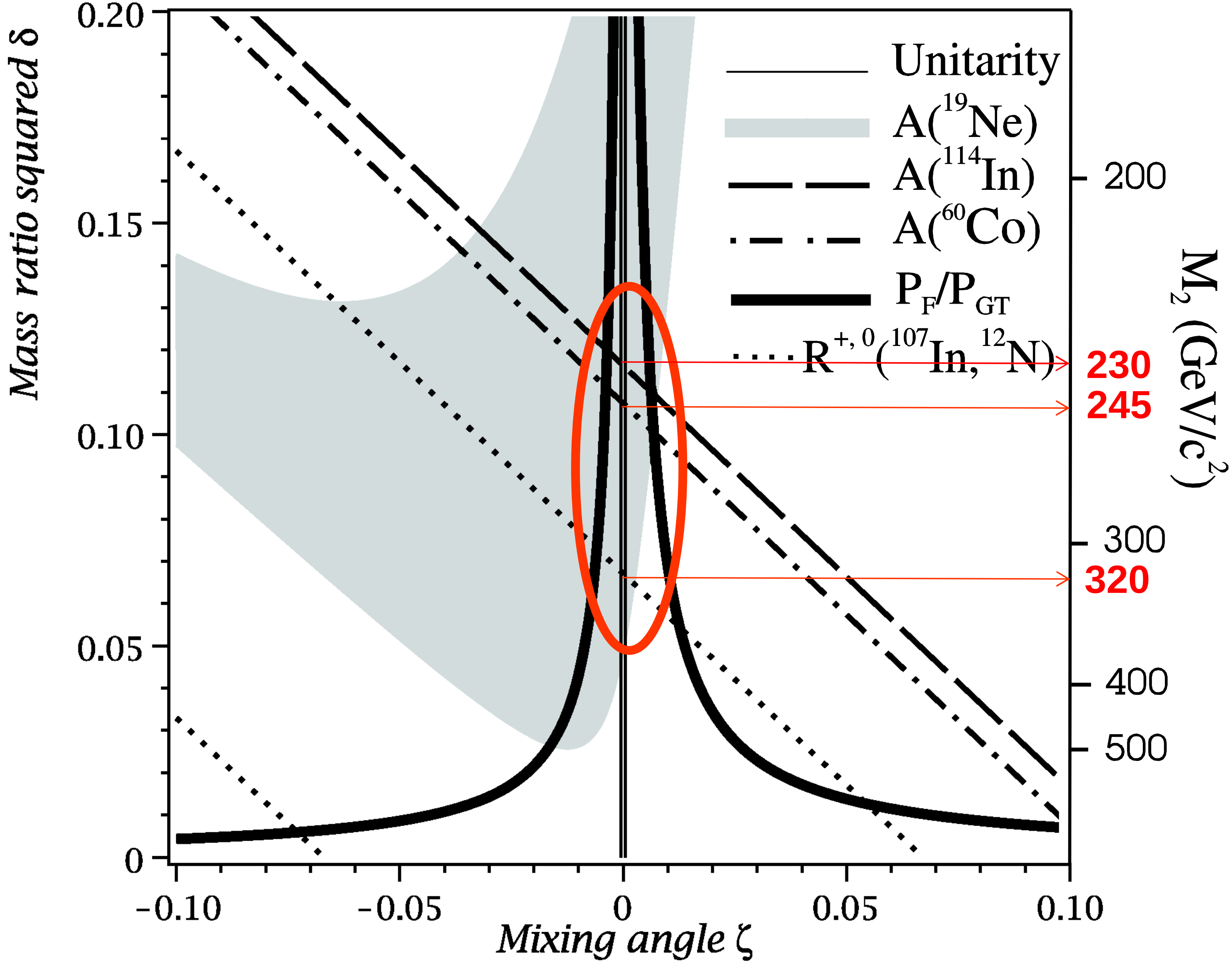
Results :

observable	nucleus	$(\delta + \zeta)^2$	
P^- / P^+	^{107}In	-0.0003(58)	1)
P^- / P^+	^{12}N	0.0064(76)	2)
P^- / P^+	^{12}N	-0.0001(34)	3)
P^- / P^0	^{107}In	0.0021(17)	4)
average		0.0017(14)	

M_{W_2} > 320 GeV/c^2 (90 % C.L.)



1) N. Severijns et al., PRL 70 (1993) 4047, 73 (1994) 611
2) M. Allet et al., Phys. Lett. B363 (1996) 139
3) E. Thomas et al., Nucl. Phys. A694 (2001) 559
4) N. Severijns et al., Nucl. Phys. A629 (1998) 423c


0.20
0.15
0.10
0.05
0
Mass ratio squared δ
-0.10
-0.05
0
0.05
0.10
Mixing angle ζ
Unitarity
A(19Ne)
A(114In)
A(60Co)
PF/PGT
R+, 0(107In, 12N)
200
300
400
500
M2 (GeV/c2)
230
245
320

3. Relative positron polarization measurements with polarized nuclei

$$R \equiv \frac{P^-}{P^+} = R_0 \left[1 - \frac{8\beta^2 A_{exp}}{\beta^4 - A_{exp}^2} (\delta + \zeta)^2 \right] \quad \text{with} \quad R_0 = \frac{\left[\beta^2 - A_{exp}\right]\left[1 + A_{exp}\right]}{\left[\beta^2 + A_{exp}\right]\left[1 - A_{exp}\right]}$$

sensitivity
factor *k*
(>> for $\beta^2 = A_{exp}$!)

$$A_{exp} = \beta\, P\, A \langle \cos\theta \rangle$$

β = v/c ; P = nuclear polarization

Isotope	k	sensitivity to M_{W2} [GeV/c²] (90% C.L.)
^{17}F	32.2	604
^{21}Na	12.5	477
^{25}Al	15.7	505
^{41}Sc	18.8	528
^{12}N	17.9	522
^{107}In	25.7	571

(for P = 0.80, and a 1% precision on R/R_0)

→ **significant potential compared to present lower limit of 320 GeV/c²**

T = 1/2 superallowed mirror transitions

$$\mathcal{F}t^{\text{mirror}} \equiv f_V t (1+\delta'_R)(1+\delta^V_{NS}-\delta^V_C) = \frac{2\mathcal{F}t^{0^+\to 0^+}}{\left(1+\frac{f_A}{f_V}\rho^2\right)}$$

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

Parent nucleus	$\mathcal{F}t$ (s)	$\delta\mathcal{F}t$ (%)
^{3}H	1135.3 ± 1.5	0.13
^{11}C	3933 ± 16	0.41
^{13}N	4682.0 ± 4.9	0.10
^{15}O	4402 ± 11	0.25
^{17}F	2300.4 ± 6.2	0.27
^{19}Ne	1718.4 ± 3.2	0.19
^{21}Na	4085 ± 12	0.29
^{23}Mg	4725 ± 17	0.36
^{25}Al	3721.1 ± 7.0	0.19
^{27}Si	4160 ± 20	0.48
^{29}P	4809 ± 19	0.40
^{31}S	4828 ± 33	0.68
^{33}Cl	5618 ± 13	0.23
^{35}Ar	5688.6 ± 7.2	0.13
^{37}K	4562 ± 28	0.61
^{39}Ca	4315 ± 16	0.37
^{41}Sc	2849 ± 11	0.39
^{43}Ti	3701 ± 56	1.51
^{45}V	4382 ± 99	2.26

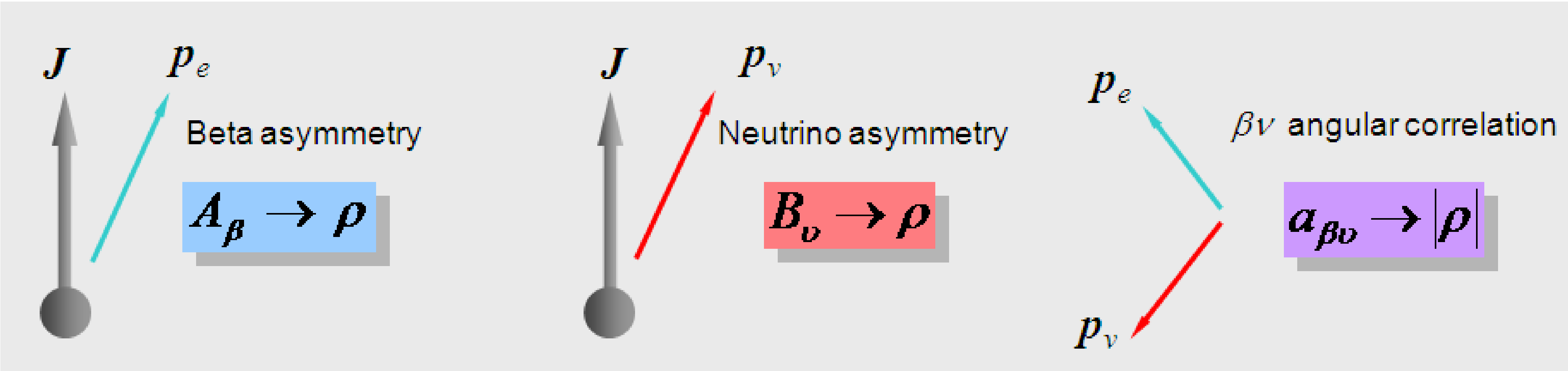
$$Ft_0 = Ft^{mirror}\left(1+\frac{f_A}{f_V}\rho^2\right) = 2Ft^{0^+\to 0^+}$$

$$= \frac{K}{G_F^2 V_{ud}^2 (1+\Delta_R^V)}$$

← **accuracy of 0.1 % to 0.4 % for most cases**

[NS, I.S. Towner et al., Phys. Rev. 78 (2008) 0555501]

- **extract mixing ratio** $\rho = C_A M_{GT} / C_V M_F$ **from correlation measurements:**



- **there are 35 candidates between ^{3}H and ^{83}Mo, near the N = Z line**

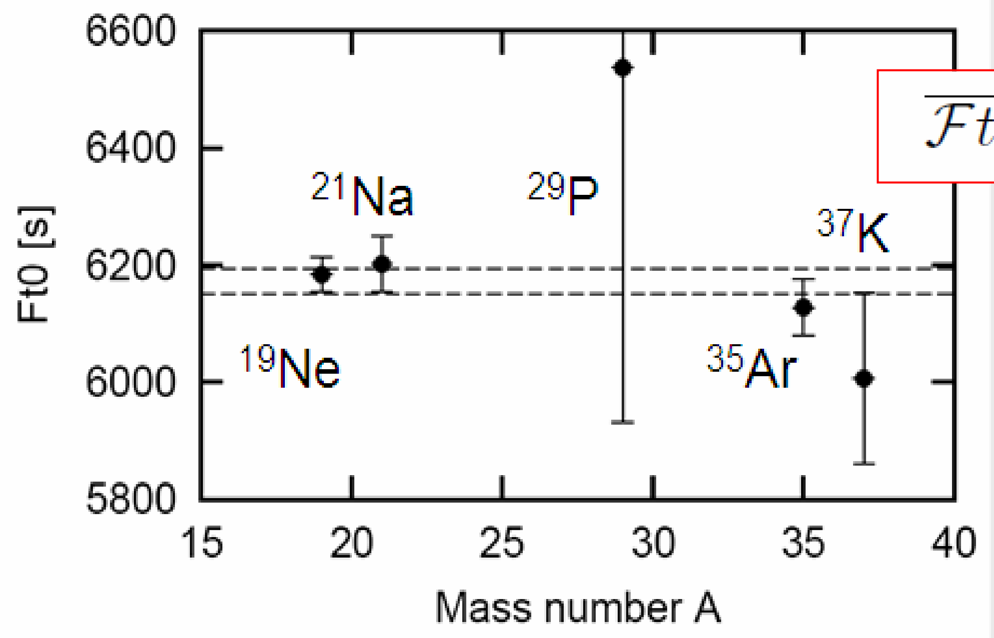
  (best are the ones with A < 45 about)

- **correlation measurements have been carried out for:**

  ^{17}F, ^{19}Ne, ^{21}Na, ^{29}P, ^{35}Ar and ^{37}K

Is the strength of the vector coupling the same in all *T=1/2* transitions ?

[O. Naviliat-Cuncic & N.S., Phys. Rev. Lett. 102 (2009) 142302



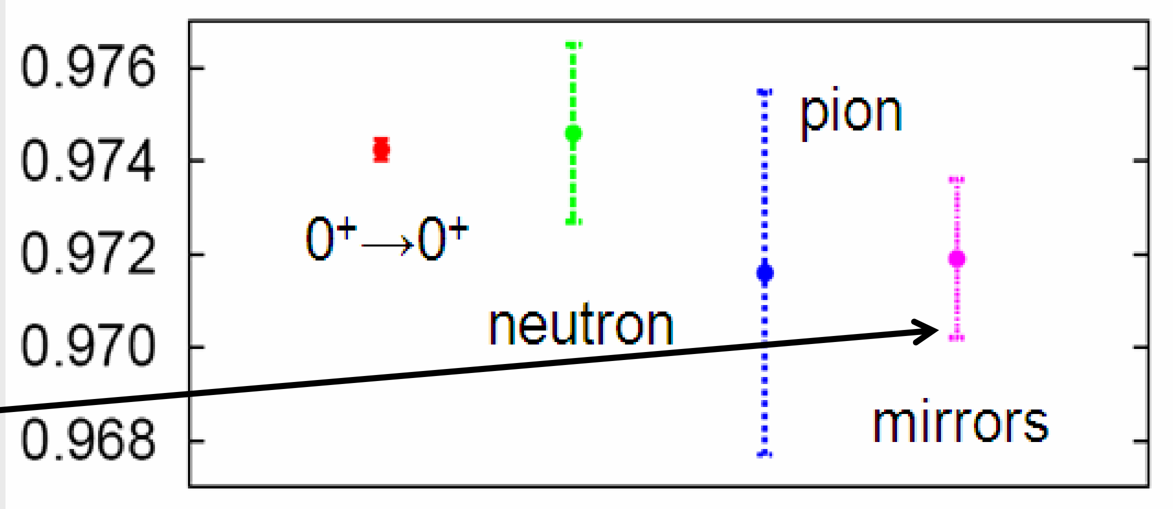
$$Ft_0 = 2Ft(0^+ \rightarrow 0^+)$$

$$\overline{\mathcal{F}t}_0 = 6173 \pm 22\ \mathrm{s}$$

- First consistent test of CVC from a set of nuclear transitions other than super-allowed pure Fermi

- New value of $|V_{ud}|$

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



reduce by new measurements of Ft values and correlation coefficients

- **sensitivity of a and A for mirror nuclei, best cases :**

Isotope	$\beta\nu$ correlation: Δa = 0.5 %		β asymmetry parameter ΔA= 0.5 %	
	ΔV_{ud} (present Ft-value)	ΔV_{ud} (no error from Ft)	ΔV_{ud} (present Ft-value)	ΔV_{ud} (no error from Ft)
^{3}H	0.0011	0.0010	0.0011	0.0009
^{13}N	0.0017	0.0017	-	-
^{15}O	0.0020	0.0016	-	0.0020
^{17}F	0.0018	0.0014	-	-
^{19}Ne	0.0014	0.0010	0.0014	0.0011
^{25}Al	0.0020	0.0018	-	-
^{29}P	-	0.0018	0.0024	0.0014
^{33}Cl	0.0021	0.0018	0.0013	0.0006
^{35}Ar	0.0019	0.0018	0.0007	0.0004

requires δ(Ft)~ 5 x 10^{-4} i.e. factor 2 -10 better

Note: - ΔV_{ud} from $a_{\beta\nu}$ for all mirror transitions up to ^{39}Ca $\leq$ 0.0018 if no error from Ft

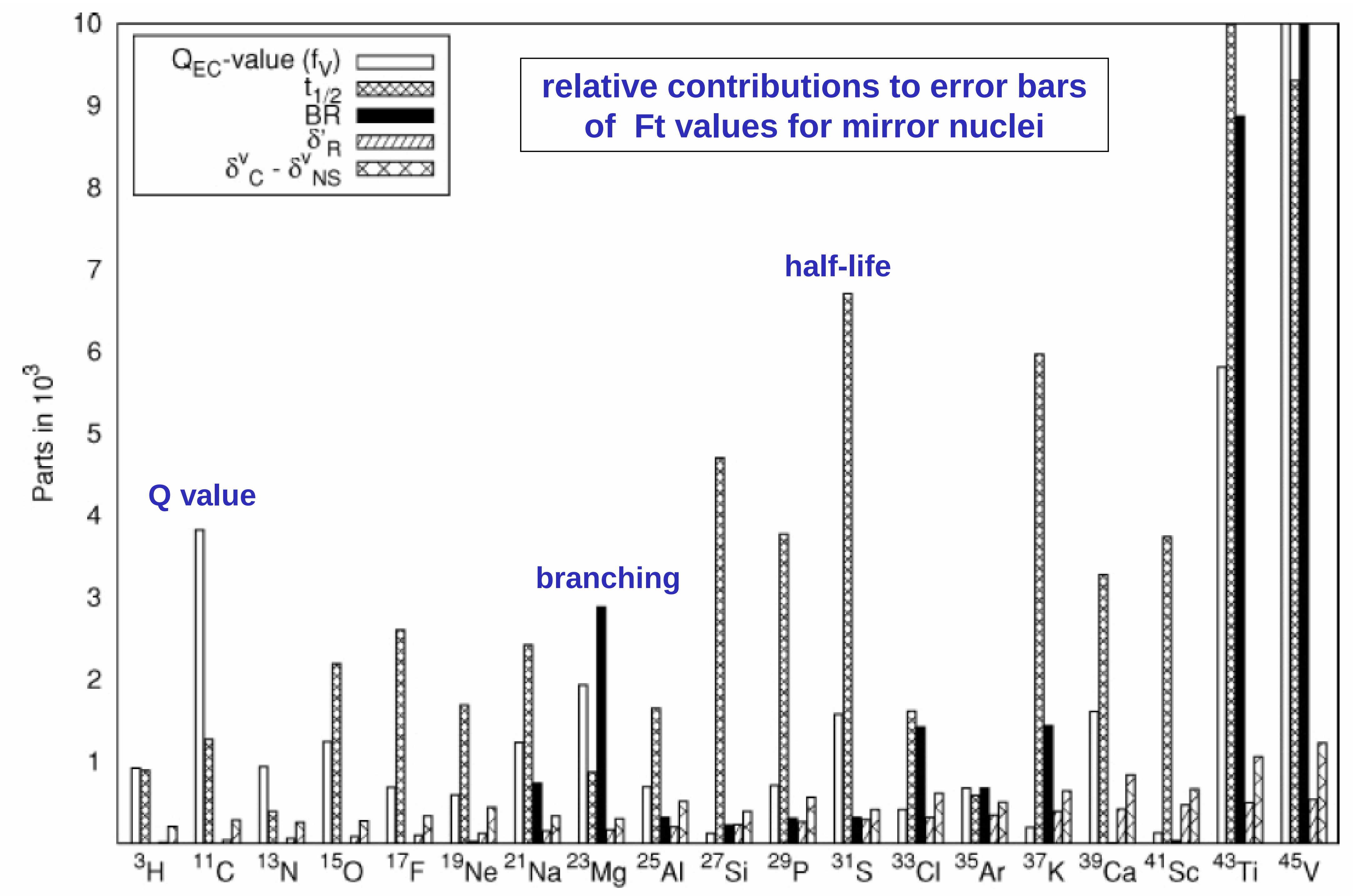
- $|V_{ud}|$ ($0^+ \rightarrow 0^+$) = 0.97425 $\pm$ 0.00022 and $|V_{ud}|$ (mirror) = 0.9719 $\pm$ 0.0017

B. Time reversal

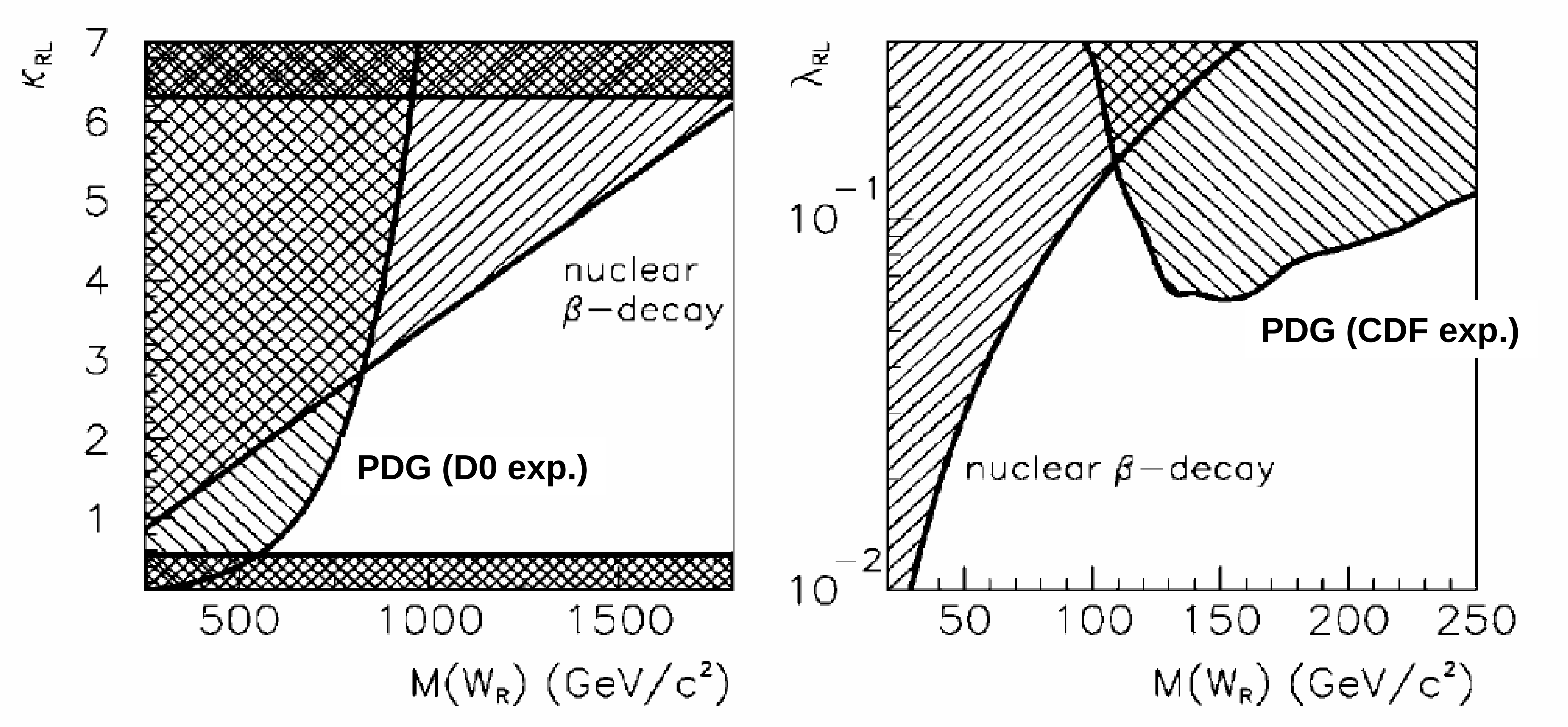
1. ***D triple correlation***

2. ***R triple correlation***

this is for another talk ….


relative contributions to error bars
of Ft values for mirror nuclei
Q_{EC}-value (f_V)
$t_{1/2}$
BR
δ'_R
$\delta^V_C - \delta^V_{NS}$
Parts in 10^3
Q value
branching
half-life
^{3}H
^{11}C
^{13}N
^{15}O
^{17}F
^{19}Ne
^{21}Na
^{23}Mg
^{25}Al
^{27}Si
^{29}P
^{31}S
^{33}Cl
^{35}Ar
^{37}K
^{39}Ca
^{41}Sc
^{43}Ti
^{45}V

Complimentarity of beta decay RHC results and collider results, in general LRS models



$\kappa_{RL} = g_R / g_L$

shaded areas are excluded

$\lambda_{RL} = V_{ud}^R / V_{ud}^L$