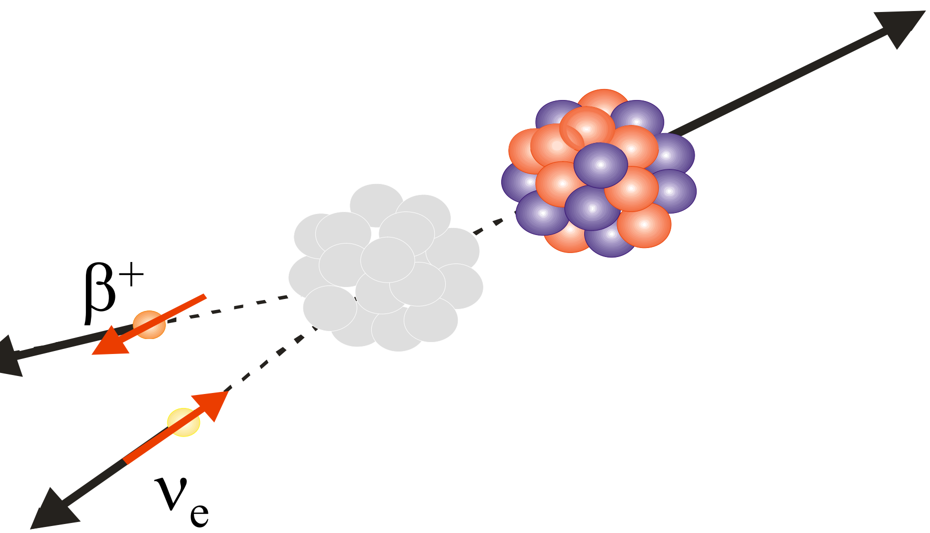
Testing Parity Violation in Nuclear β Decay



PAVI 09

Bar Harbor, June 21-26, 2008

Nathal Severijns – Rob Timmermans

K. Univ.Leuven, Belgium - KVI-Groningen, The Netherlands

1. **Experiment of Wu et al.**

   past and present

2. ***Superallowed $0^+ \rightarrow 0^+$ pure Fermi transitions***

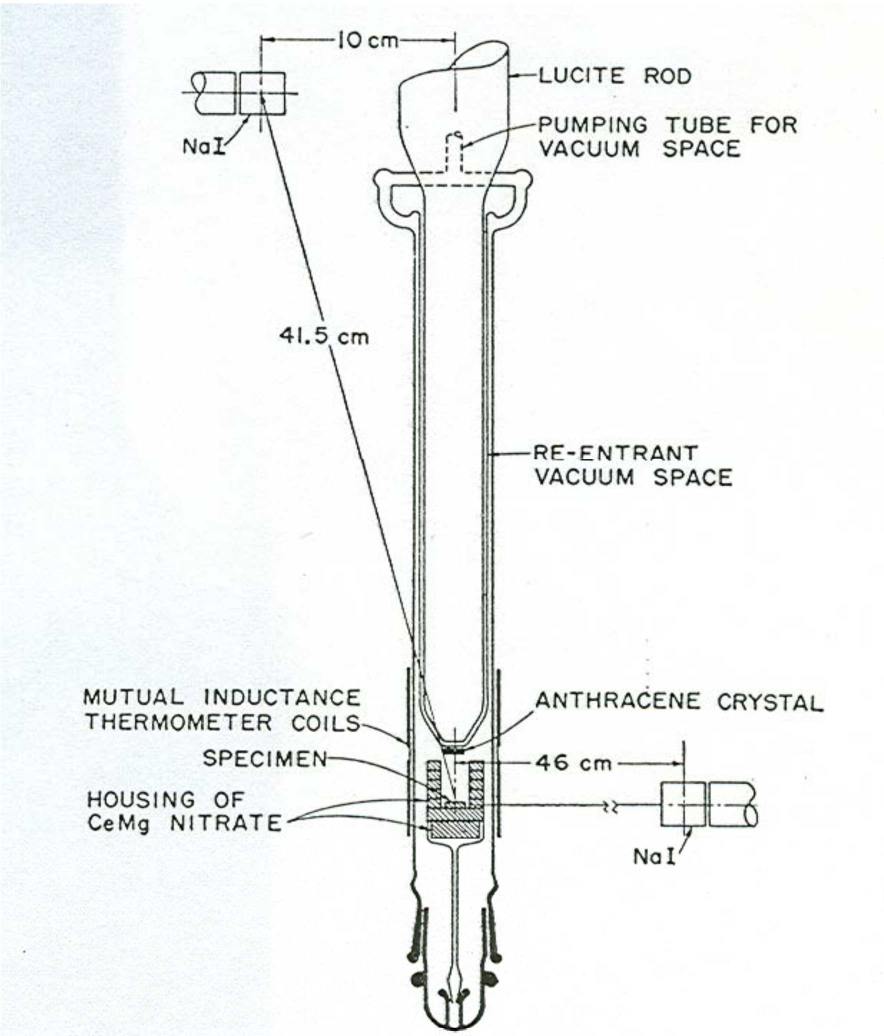
3. **Longitudinal polarization of β particles**

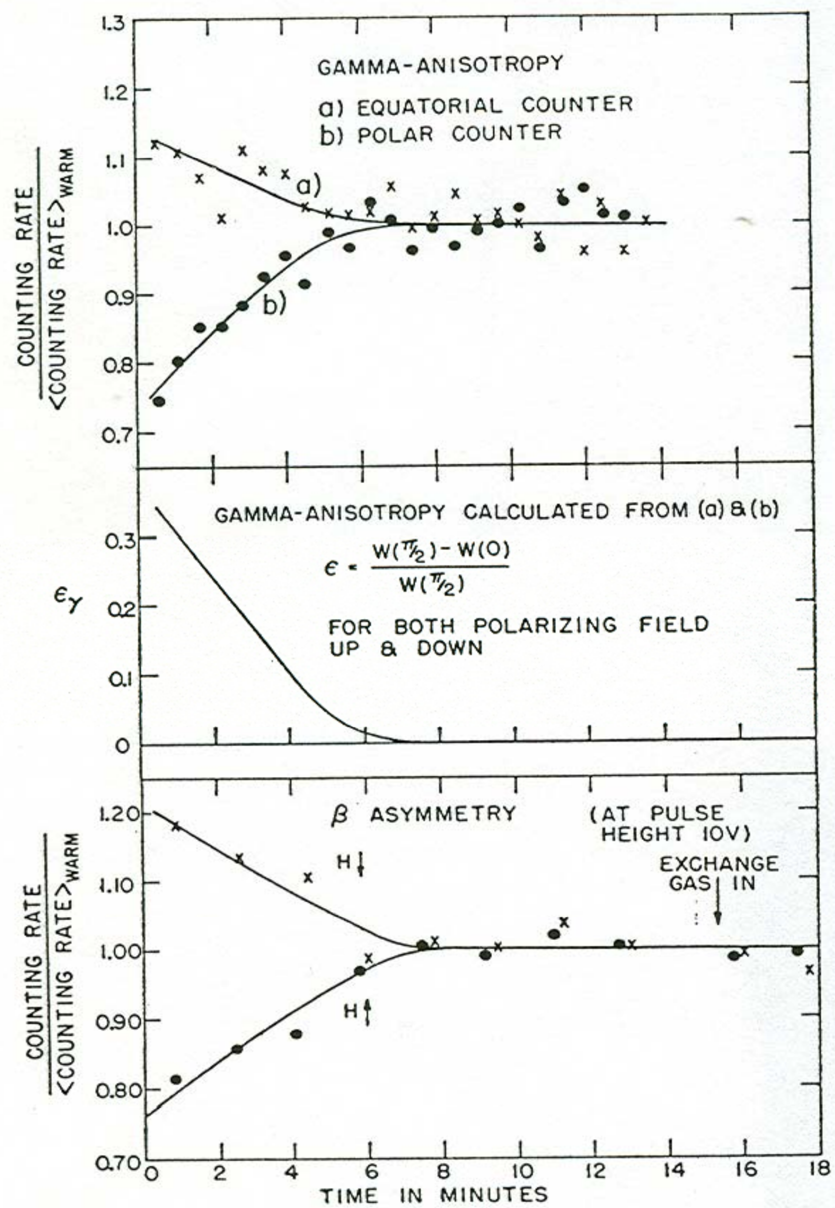
   unpolarized and polarized nuclei

4. **Beta and neutrino asymmetries in neutron decay**

5. **Conclusions and prospects**

^{60}Co parity violation experiment – Wu et al. 1957





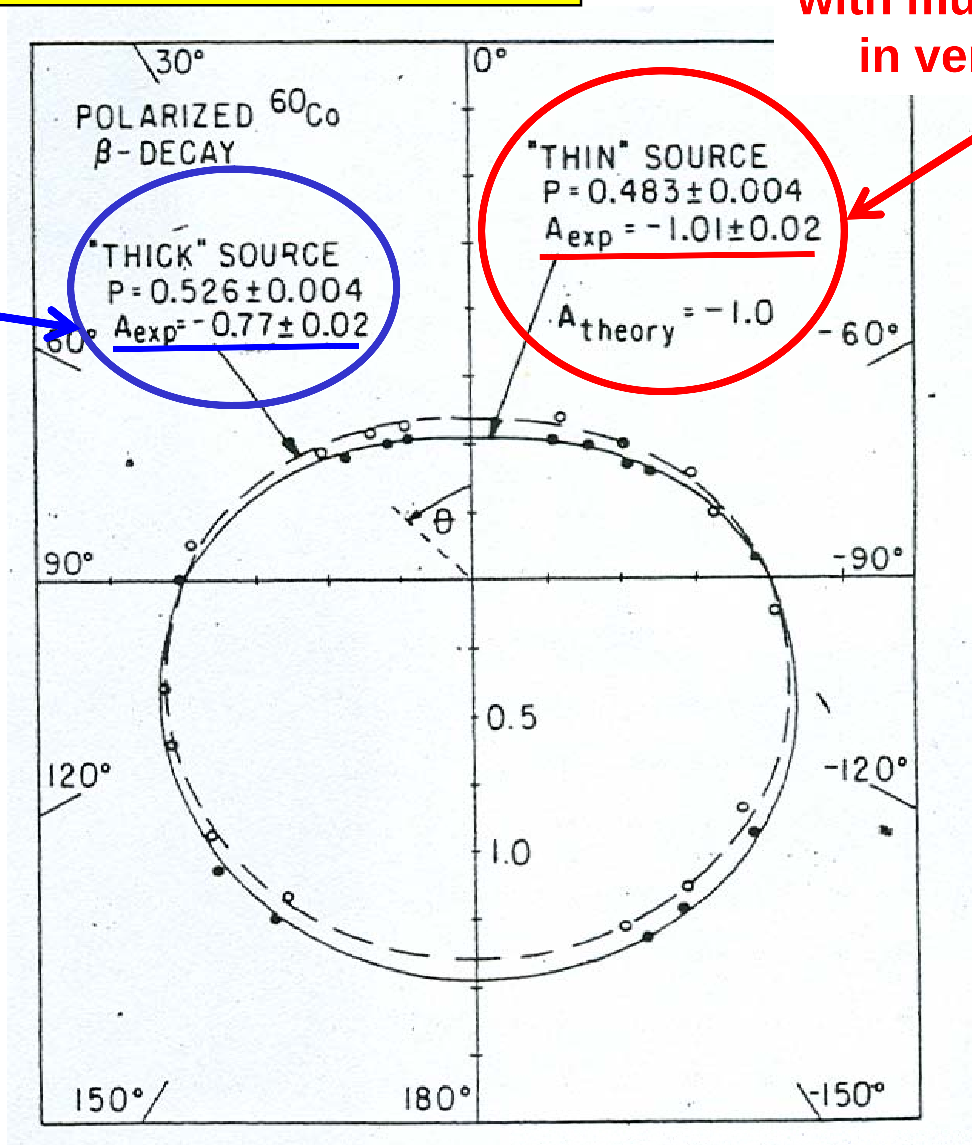
experimental set-up ↑ results →

[C.S. Wu et al., PR 105 (1957) 1413]

^{60}Co parity violation experiment - 2
Wu et al. 1980

1980 experiment; with much improved setup and in very low magnetic field

conditions of experiment iln 1957



L.M. Chirovsky, C.S. Wu et al., Phys. Lett. 94B (1980) 127 & Nucl. Instr. & Meth. 219 (1984) 103

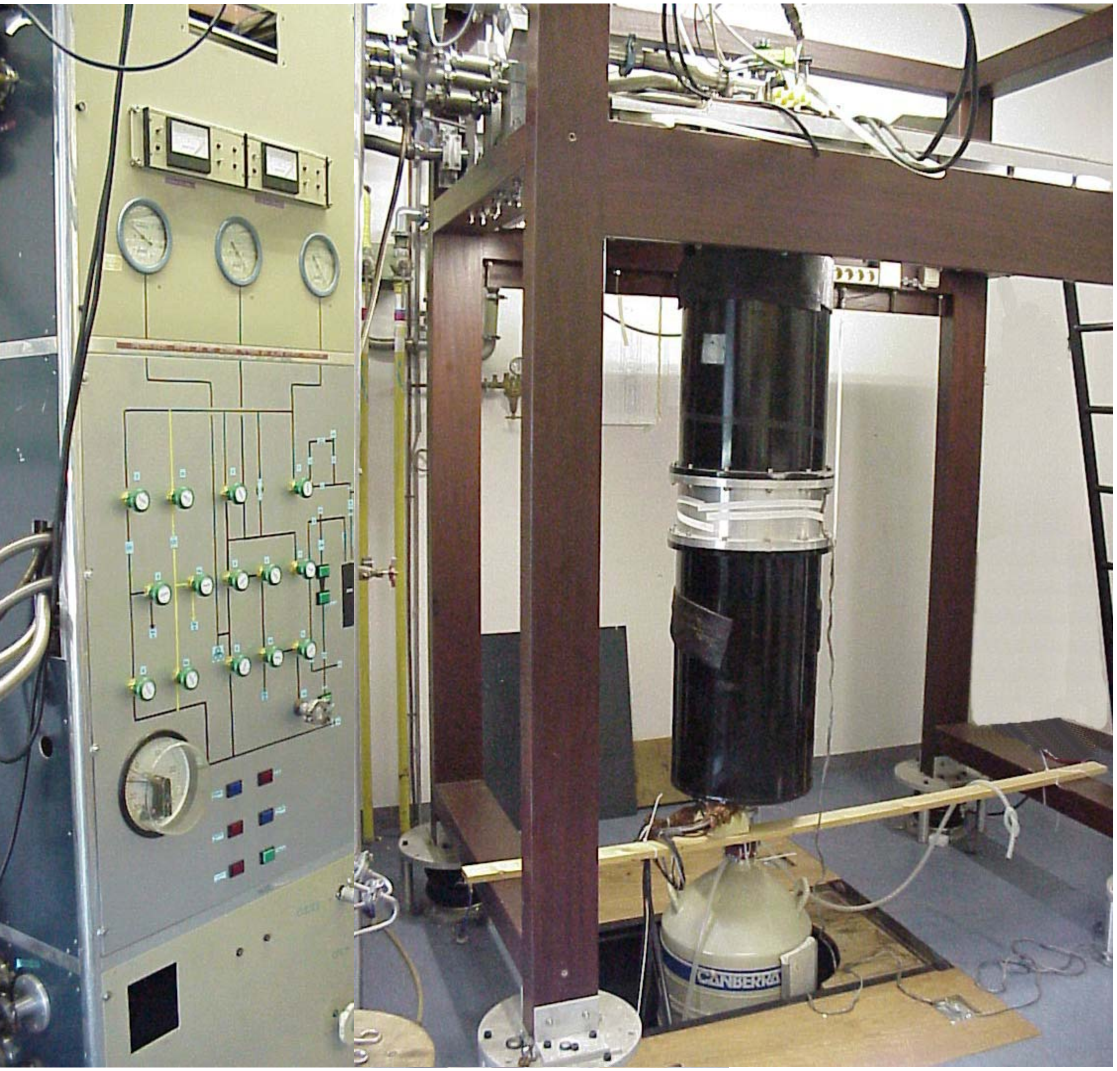
^{60}Co parity violation experiment - 3

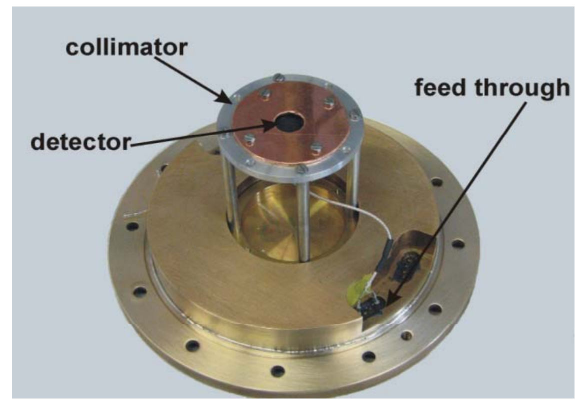
Severijns et al. 2009

in 13 T external polarizing field;

used Geant 4.8.1 to account for :

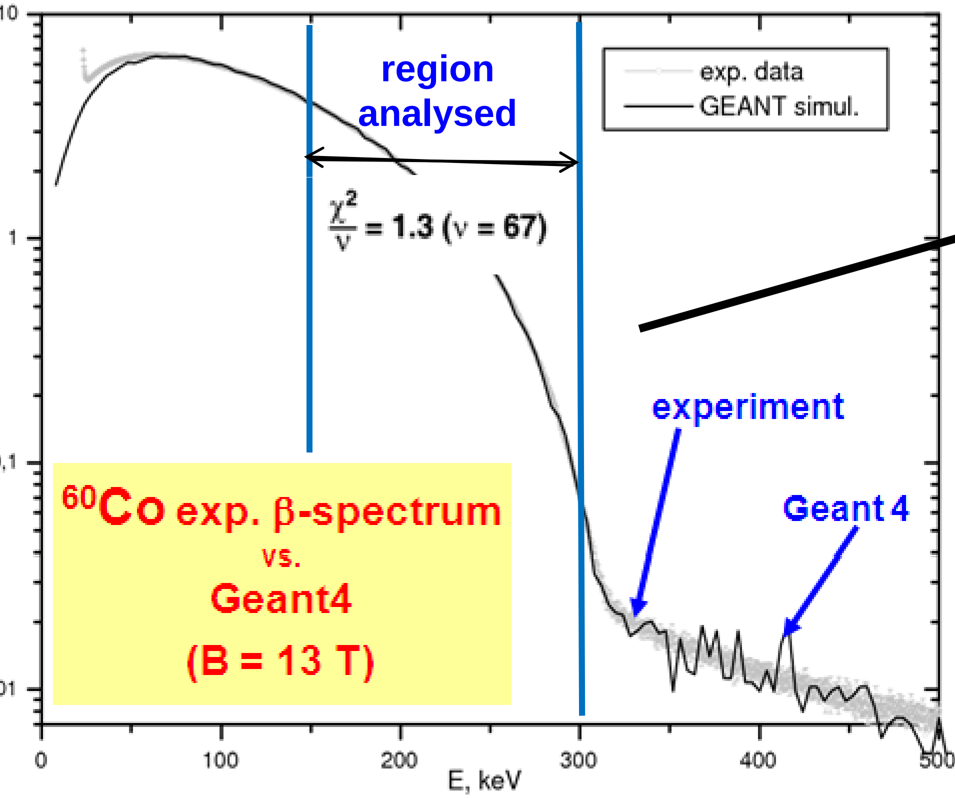
- **detection geometry**
- **magnetic field effects**
- **scattering**





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

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



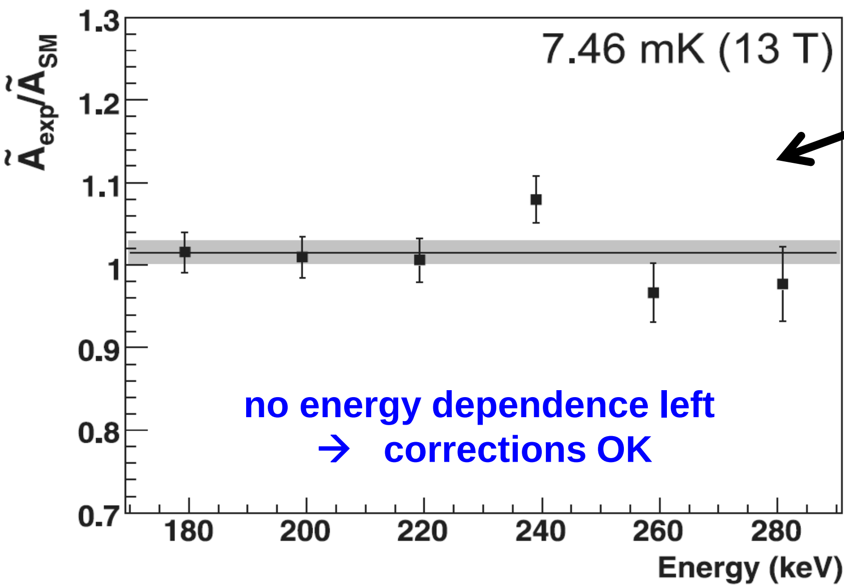
$$W(\theta) = \frac{N(\theta)_{pol}}{N(\theta)_{unpol}} = 1 + \tilde{A} \quad P \left(\frac{v}{c} \, Q \cos\theta \right)$$

(P from anisotropy of γ-rays)

Geant 4

Analysis of measured and simulated spectra:

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



A = - 1.014 (12)$_{stat}$ (16)$_{syst}$

(preliminary)

F. Wauters, N. Severijns et al., to be published

Superallowed 0+ → 0+ pure Fermi transitions

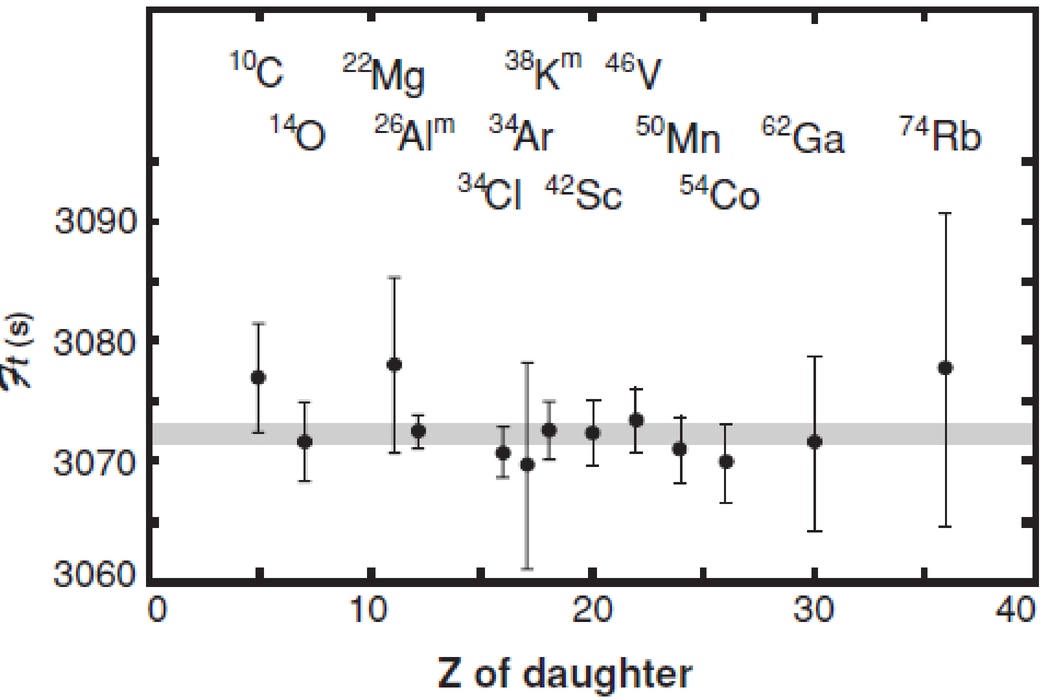
corrected ft-value for superallowed pure Fermi transitions :

nucleus dependent — nucleus independent

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

calculated

experiment



J.C. Hardy & I.S. Towner, Phys. Rev. C 79 (2009) 055502

$$\overline{\mathcal{F}t} = 3071.81 \pm 0.83 \text{ s}$$

(M)LRS-models

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

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

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

ζ = -0.00003 ± 0.00030

- Very strong restriction on value of L-R mixing angle ζ

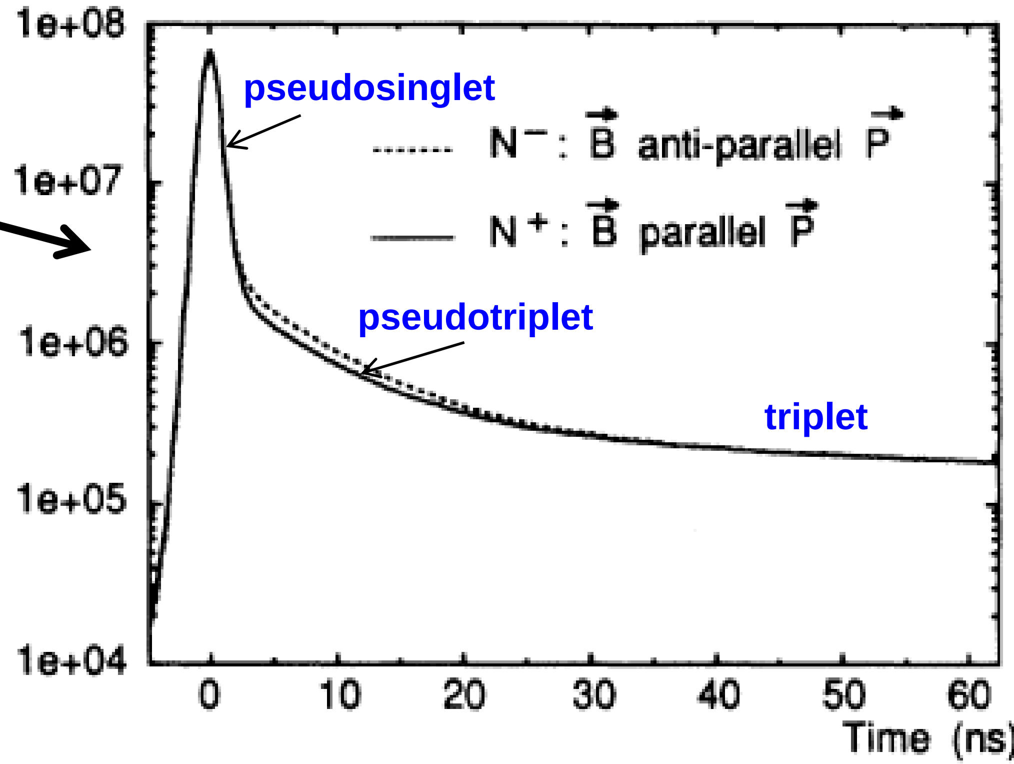
Longitudinal polarization of positrons

experimental quantity

$$P_F / P_{GT} = 1 - 8\,\delta\zeta$$

with: P_F (P_{GT}) beta particle longitudinal polarization in pure Fermi (Gamow-Teller) transition

positronium (Ps) hyperfine spectroscopy: populations of Ps hyperfine states depend on beta particle longitudinal polarization



results

$P_{^{14}O} / P_{^{10}C} = 0.9996(37)$ [1]

$P_{^{26m}Al} / P_{^{30}P} = 1.003(4)$ [2]

$P_{^{26m}Al}$ & $P_{^{25}Al}$ [3]

→ $-4 \times 10^{-4} < \delta\zeta < 7 \times 10^{-4}$

[1]) A.S. Carnoy et al., PRL 65 (1990) 3249, PR C43 (1991) 2825
[2]) V.A. Wichers et al., PRL 58 (1987) 1821
[3]) M. Skalsey et al., PR C 39 (1989) 986

Longitudinal polarization of positrons emitted by polarized nuclei

experimental quantity

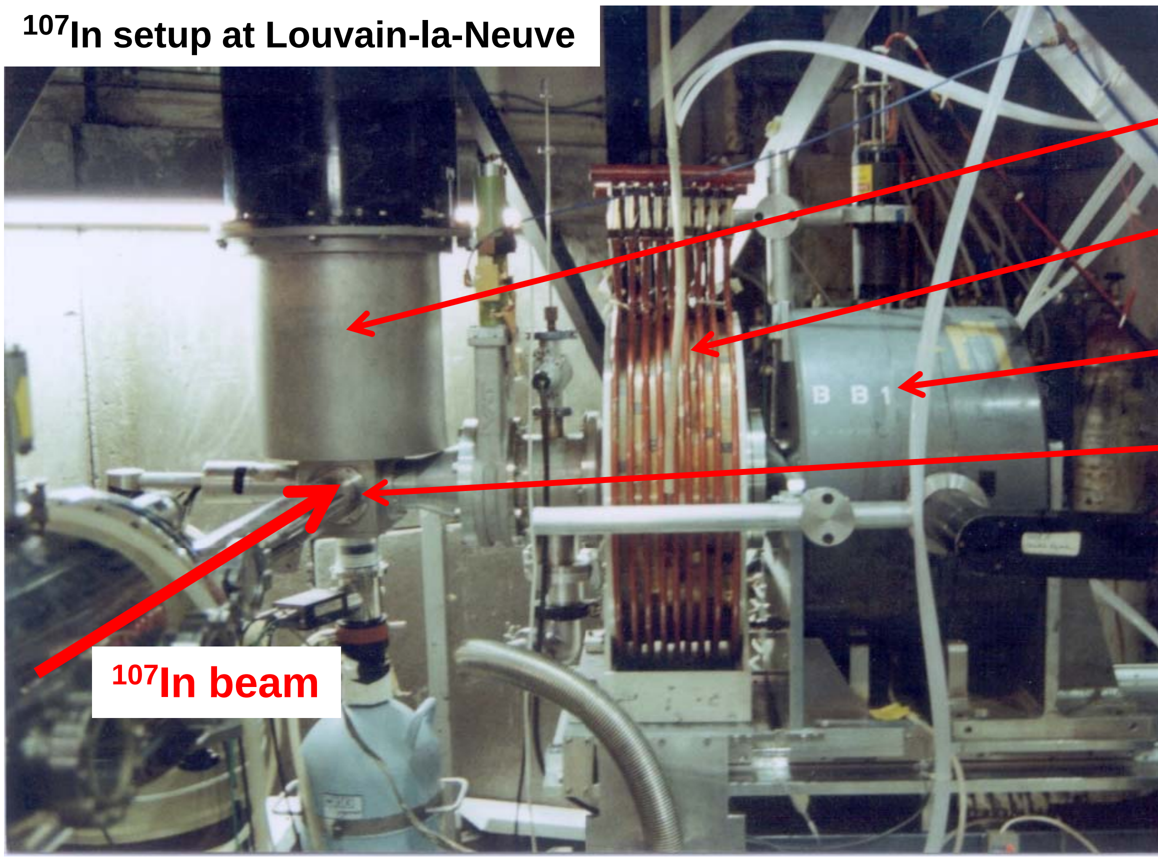
$$R \equiv P^- / P^+ = R_{SM} [1 + k \Delta]$$

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

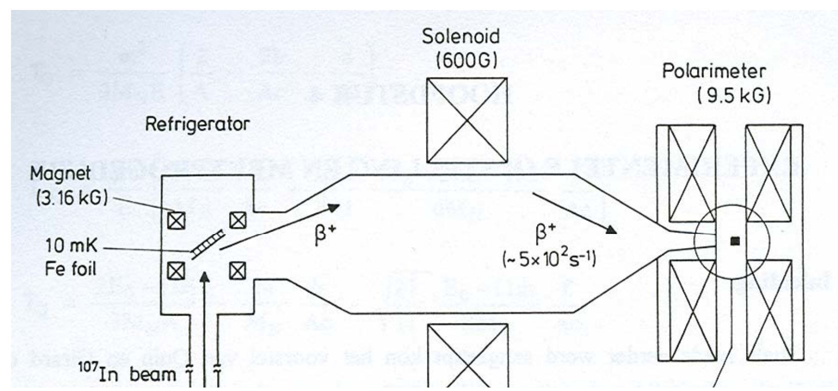
positronium (Ps) hyperfine spectroscopy

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

^{107}In setup at Louvain-la-Neuve

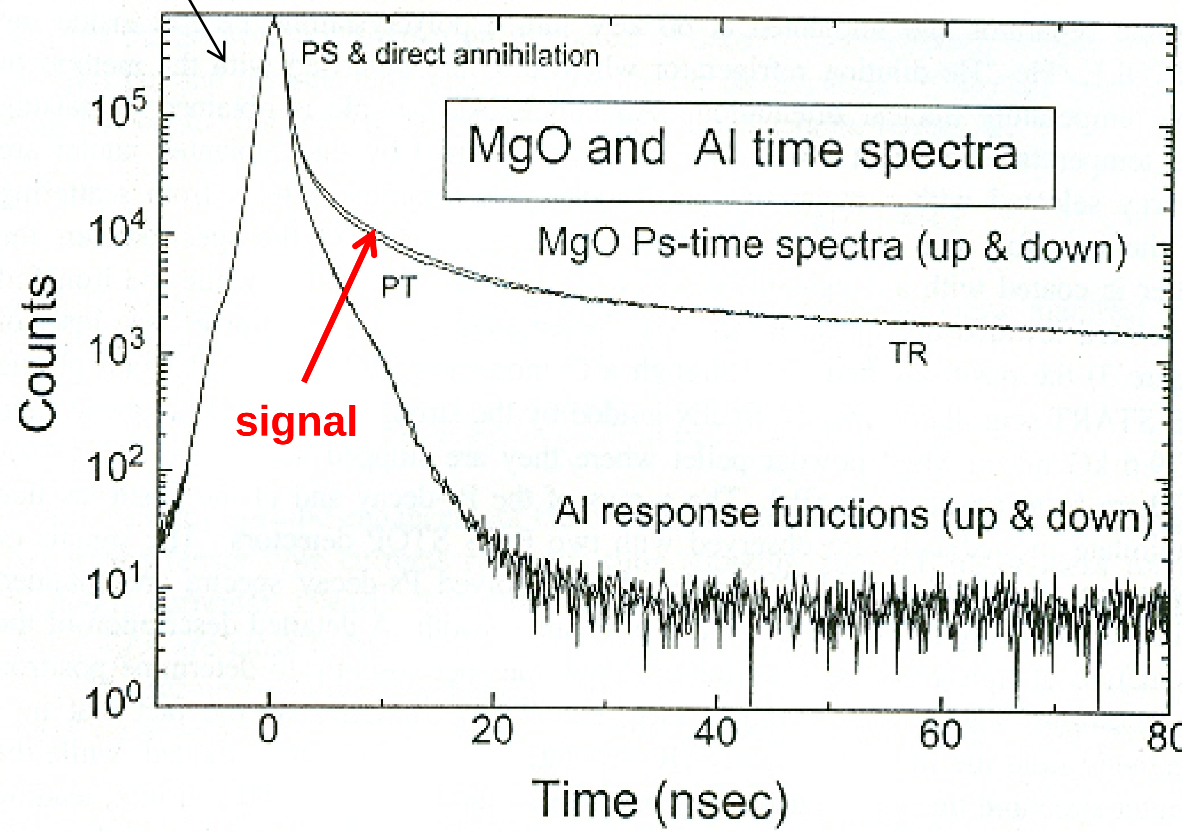


- **dilution refrigerator**
- **β spectrometer coil**
- **polarimeter magnet**
- **polarized ^{107}In sample at 10 mK**



positronium (Ps) hyperfine spectroscopy used

example of ^{107}In positronium time spectrum)



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

Neutron decay

3 observables: **depend on δ, ζ, $\lambda = g_A/g_V$ and V_{ud}**

- lifetime τ_n:

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

- beta asymmetry *A* in polarized neutron decay

$A_{LRS} = A_{SM}\,[\,1 - 2\,\delta^2 - a_1\,\zeta^2 - a_2\,\delta\zeta\,]$ **with** $A_{SM} = -2\dfrac{\lambda^2 + \lambda}{1 + 3\lambda^2} \cong -0.1175$

- neutrino asymmetry *B* in polarized neutron decay

$B_{LRS} = B_{SM}\,[\,1 - 2\,\delta^2 - 1.21\,\zeta^2 - 2.42\,\delta\zeta\,]$ **with** $B_{SM} = 2\dfrac{\lambda^2 - \lambda}{1 + 3\lambda^2} \cong 0.9875$

neutron lifetime τ

Data set dominated by two strongly differing results:

τ_n = 885.7 $\pm$ 0.9_{stat} $\pm$ 0.4_{syst} s   Arzumanov et al., Phys. Lett. B 483 (2000) 15

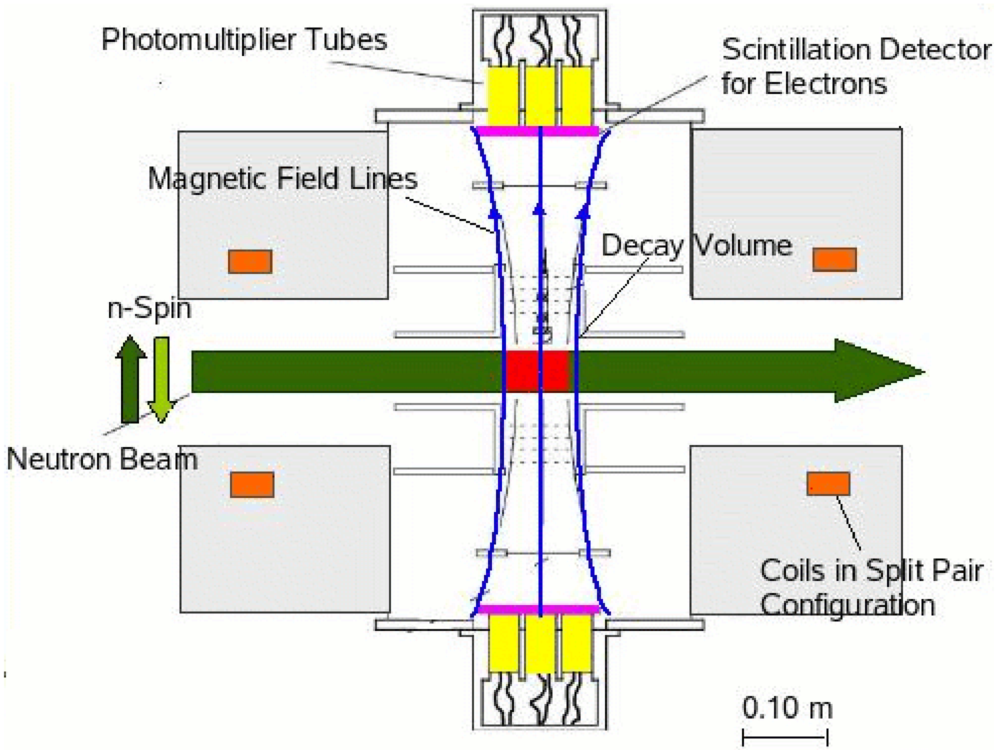
difference of 6.5 stand.dev. !

τ_n = 878.5 $\pm$ 0.7_{stat} $\pm$ 0.3_{syst} s   Serebrovet al., Phys. Lett. B 605 (2005) 72

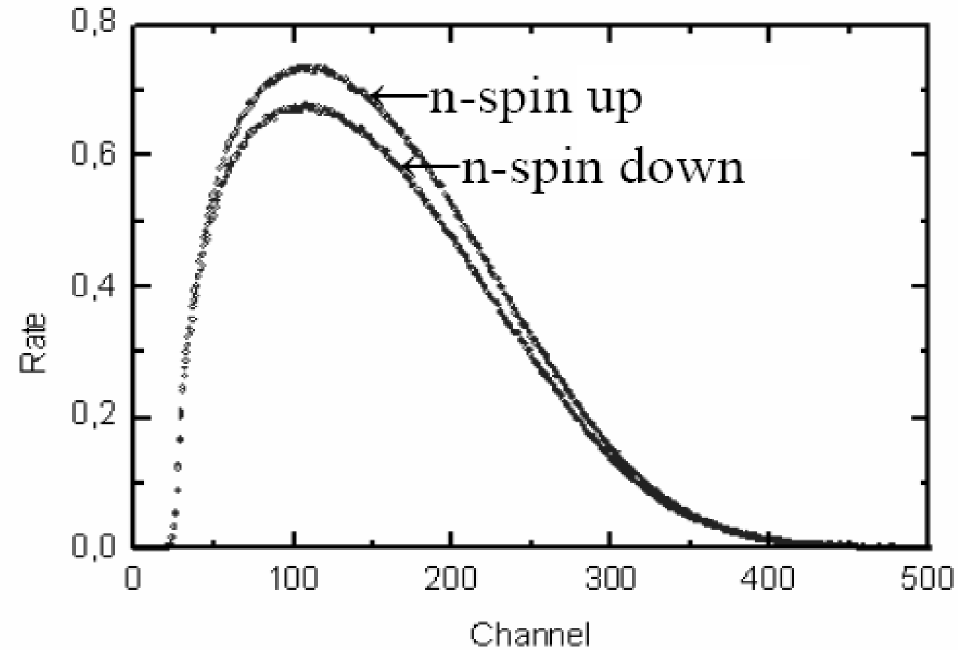
Note: - both results obtained with material storage of neutrons (special wall coating)

- new measurement with magnetic storage @ ILL (Ehzov et al., to be publ.) in agreement with Serebrov et al.

β asymmetry *A* in polarized neutron decay



PERKEO-II setup – H. Abele et al.



Results :

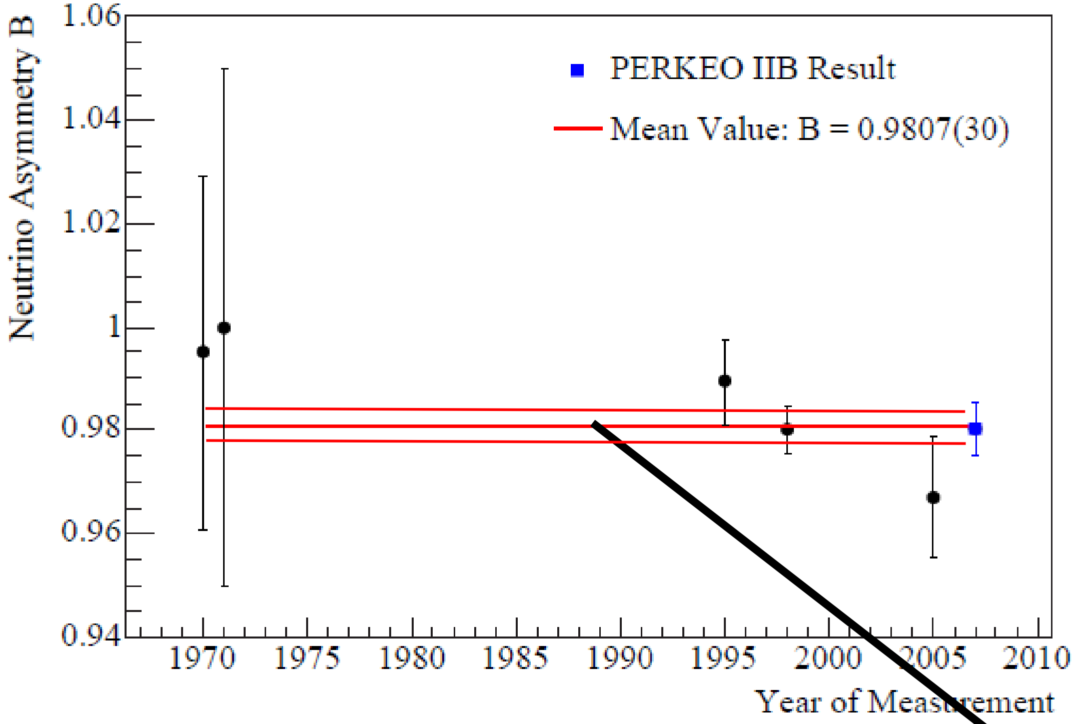
A_n (PERKEO II) = -0.11933(34)

(average of 3 results)

H. Abele, Prog. Nucl. Part. Phys. 60 (2008) 1

(hyperbolical region in (δ, ζ)-plane)

neutrino asymmetry *B* in polarized neutron decay



Most precise results :

B_n = 0.9801(46)

A.P. Serebrov et al., JETP 86 (1998) 1074

B_n = 0.9802(50)

M. Schumann, H. Abele et al., PRL 99 (2007) 191803

experimental quantity :

$$B_{LRS} = B_{SM} [\, 1 - 2\,\delta^2 - 1.21\,\zeta^2 - 2.42\,\delta\zeta \,]$$

$$B_{SM} = 2\,(\lambda^2 - \lambda)\,/\,(1 + 3\lambda^2) = 0.9875(1)$$

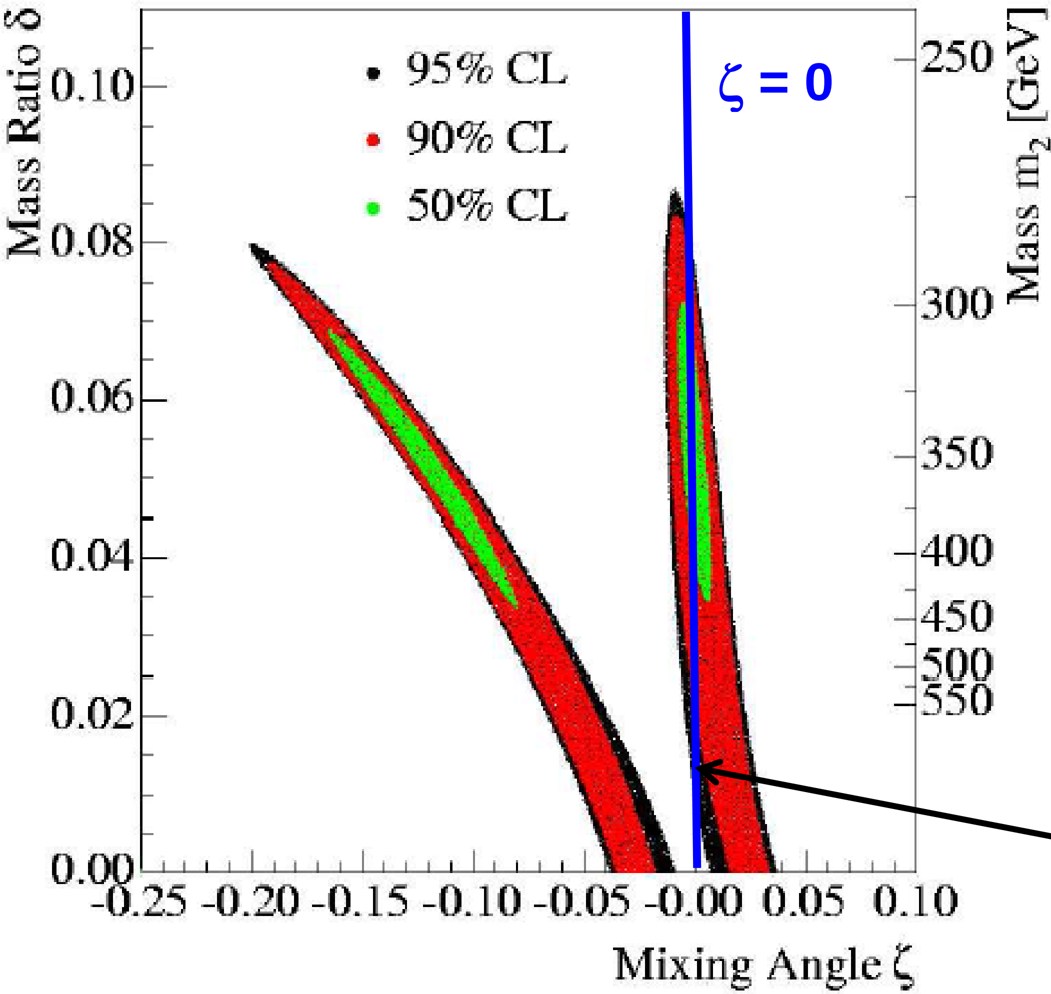
with $\lambda = g_A/g_V = -1.2699(7)$

w. avg. : B_n = 0.9807(30)

$M_{W_2} > 280$ GeV/c^2 (90 % C.L.)

(elliptical region in (δ, ζ)-plane)

combined limits from neutron decay (τ_n, A, B)



Input data:

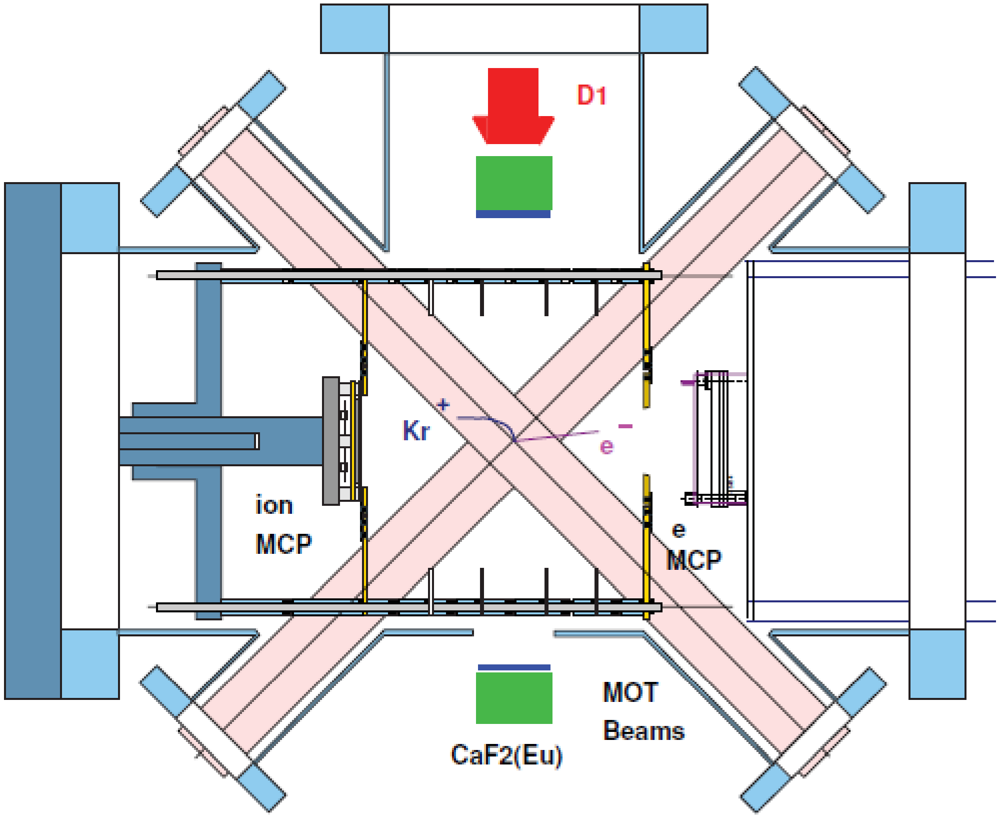
τ_n : Serebrov et al.

A_n : 3 PERKEO II results
(hyperbolical region)

B_n : world average
(elliptical region)

in principle very sensitive but unfortunately
very large uncertainty due to steepness of allowed contour

Neutrino asymmetry in polarized nuclear beta decay



TRINAT MOT trap @ TRIUMF

$$B_\nu^{SM} = -0.779(6)$$
$$B_\nu(^{37}K) = -0.755(24)$$

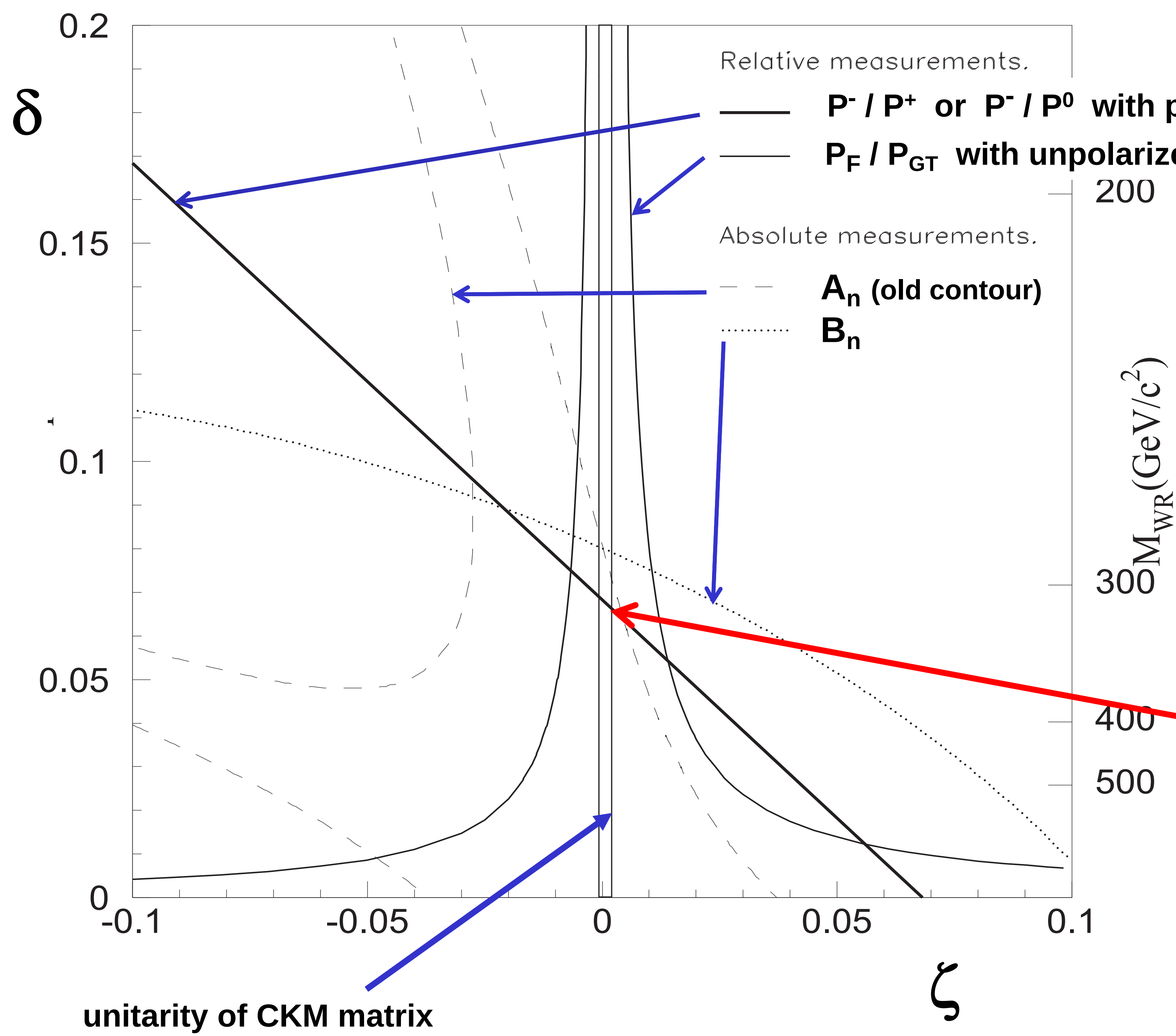
only 5 % precision -

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

shapes of differrent constraints



(M)LRS-models

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

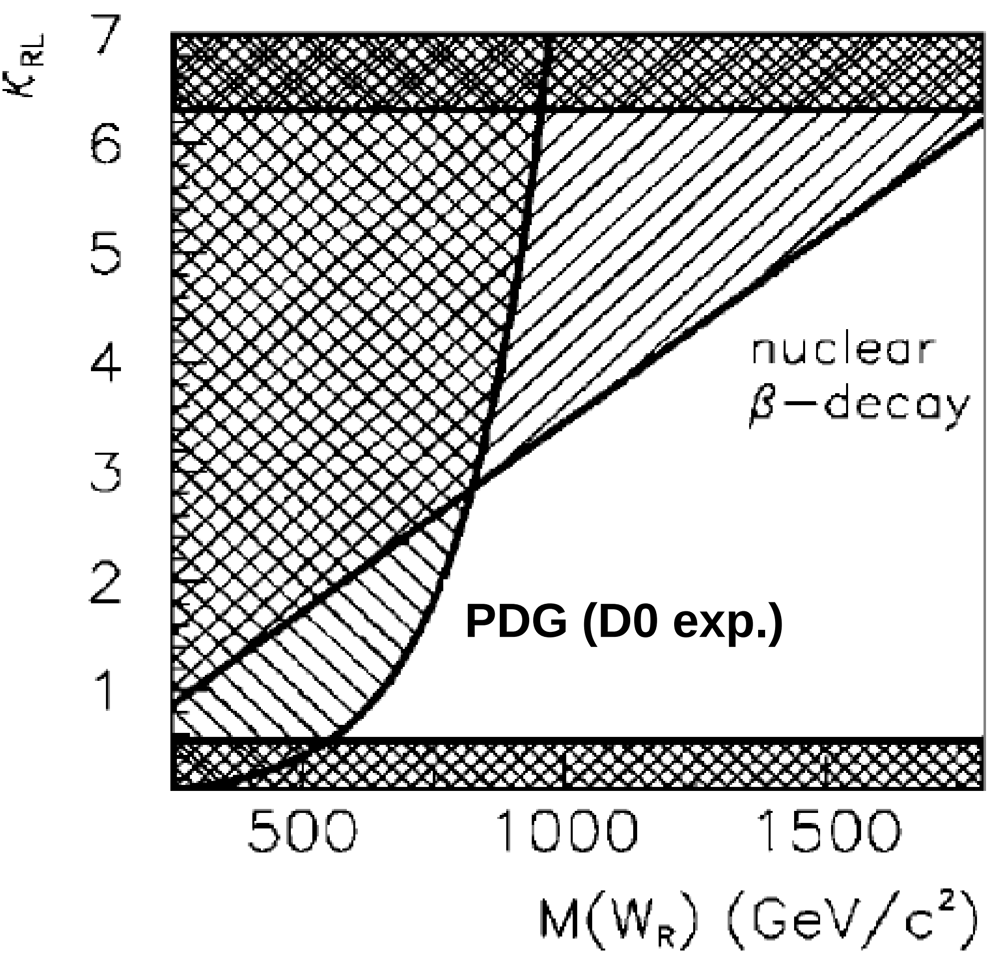
$W_2 = W_L \sin\zeta + W_R \cos\zeta$

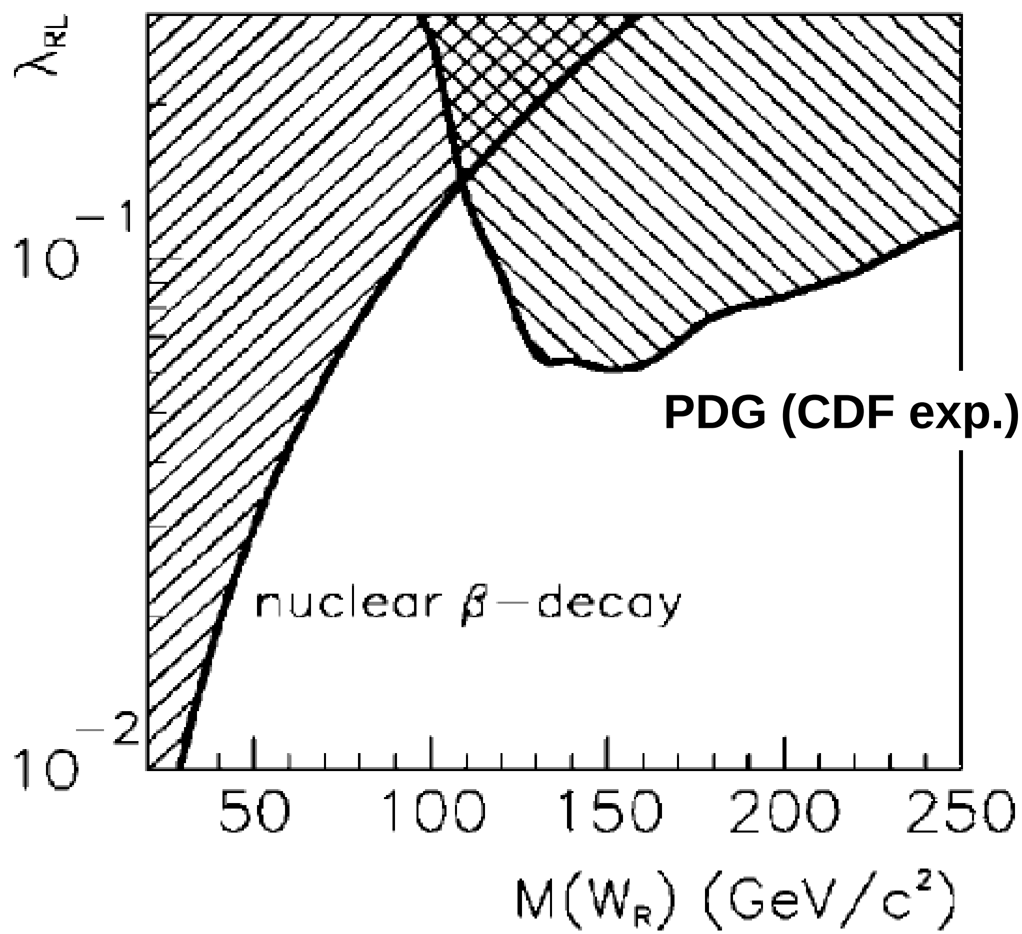
$\delta = m_1^2 / m_2^2$

320 GeV/c²

(90 % C.L.)

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





$\kappa_{RL} = g_R / g_L$

shaded areas are excluded

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

Conclusion and prospects:

1. RHC constraints from β decay and collider experiments are complimentary in general LRS models.

2. Neutron decay: β particle and neutrino asymmetry parameters

$$A^{\varsigma=0} = A_{SM}(1-2\delta^2)$$
$$B^{\varsigma=0} = B_{SM}(1-2\delta^2)$$

Combined limits in principle very sensitive, but large uncertainties due to shape.

→ **restrict to B_n and improve precision (e.g. PERKEO III)**

e.g. if ΔB_n = 0.0020 → 400 GeV/c^2 sensitivity (90 % C.L.)

if ΔB_n = 0.0005 → 565 GeV/c^2 sensitivity (90 % C.L.)

3. Relative beta 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 $\beta^2 = A_{exp}$!)

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

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)

→ **similar precision achievable as in measurements of B_n**

4. Theory

New V, A interactions can arise :

- in left-right symmetric models,
- in models with exotic fermions,
- in models involving leptoquarks, and also
- in composite models.

For all these models
improvements of the beta decay limits on δ and/or ζ
(or more generally a_{RR} and/or a_{RL} in the so-called helicity projection formalism)
would provide new information.

P. Herczeg, Prog. Part. Nucl. Phys. 46 (2001) 413