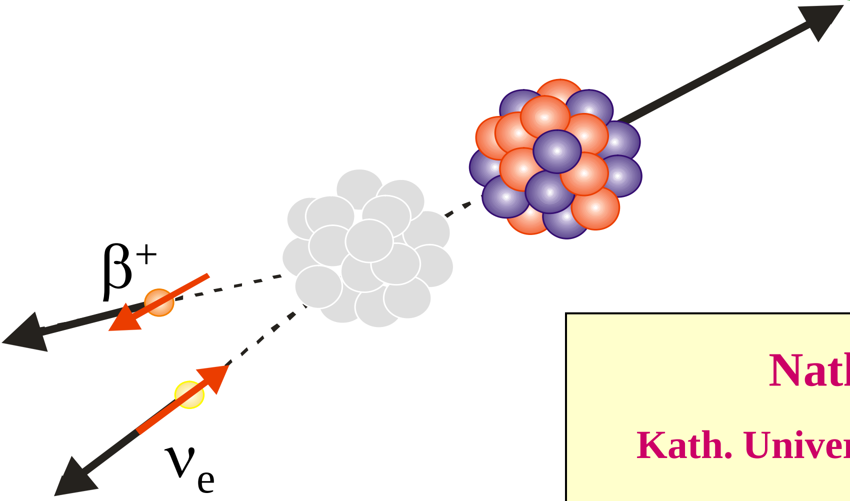
Correlation measurements in beta decay probing physics beyond the standard model

Symmetries in Subatomic Physics

Groningen, June 18-22, 2012



Nathal Severijns

Kath. Universiteit Leuven, Belgium

Outline

- **structure of the weak interaction**

  physics: scalar or tensor components

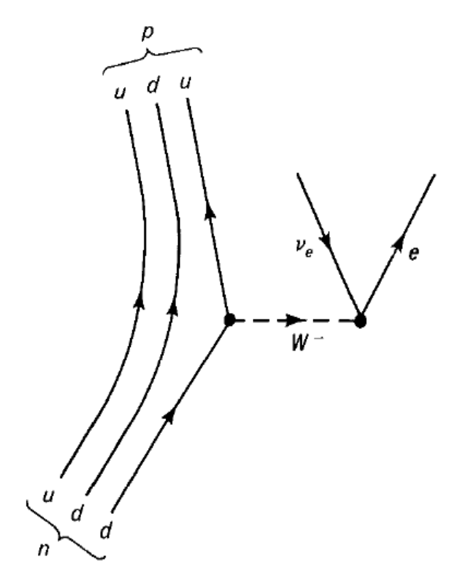
  observables: βν correlation, β-asymmetry parameter

- **parity symmetry**

  observable: polarization-asymmetry correlation

the Standard Model and beyond:

* $C_V = 1$ (CVC)
* $C_A = -1.27$ ($g_A/g_V = -1.2699(7)$ 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)

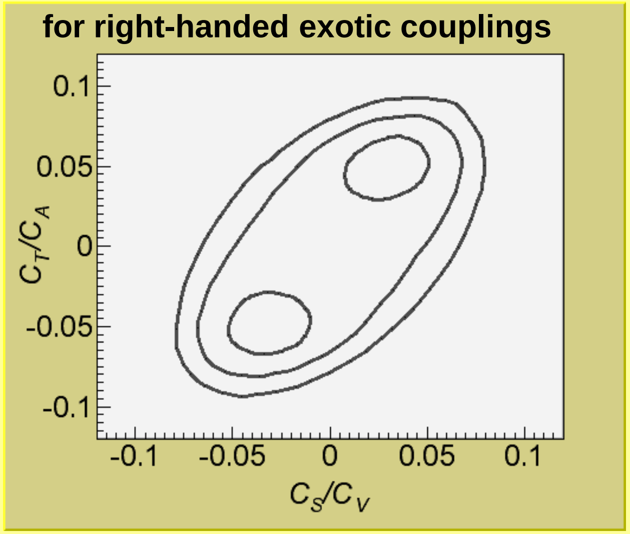
experimental upper limits:

(neutron and nuclear β-decay)

$$\left| C_T^{(\,'\,)} / C_A \right| < 0.09$$

$$\left| C_S^{(\,'\,)} / C_V \right| < 0.07 \qquad (95\%\ \text{CL})$$

from: N. Severijns, M. Beck, O. Naviliat-Cuncic, Rev. Mod. Phys. 78 (2006) 991



(1σ, 2σ and 3σ contours of equal χ^2)

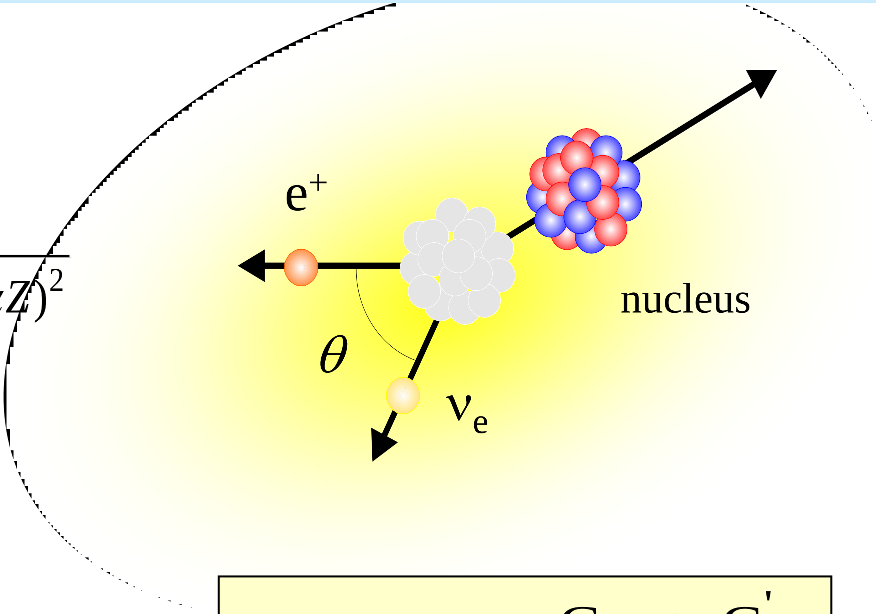
* **no time reversal violation**

(except for the CP-violation described by the phase in the CKM matrix)

The βν correlation

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

or $$\tilde{a} = \frac{a}{1 + b\,\frac{\gamma m_e}{E_e}}$$ with $\gamma = \sqrt{1-(\alpha Z)^2}$



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

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

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

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

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

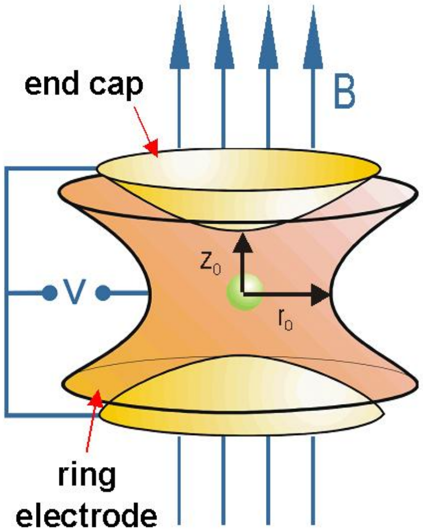
!!! for pure transitions weak interaction info independent of nuclear matrix elements !!!

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

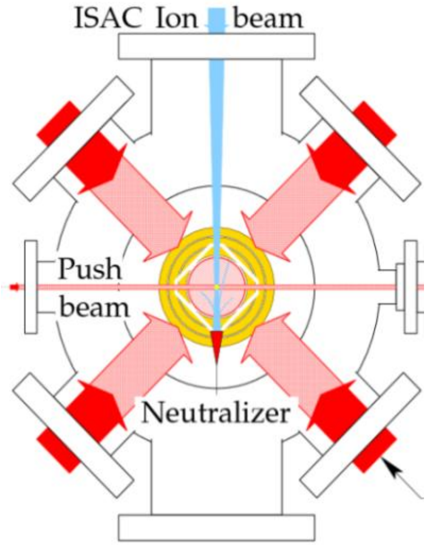
Ion/atom traps for βν correlation measurements

Particle traps: ideal sources

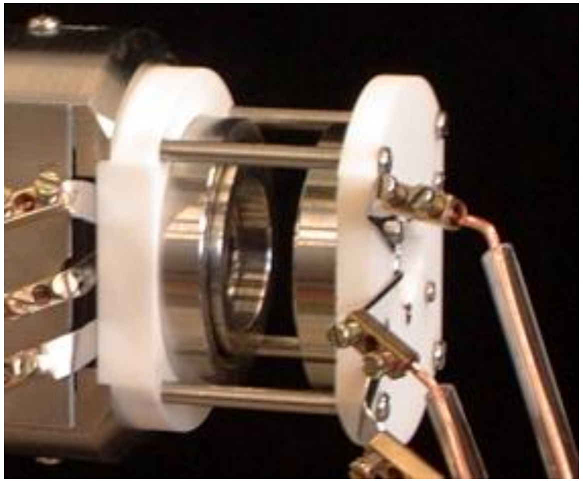
- sample is **isotopically pure**
- localized in a small volume
- atoms decay at rest
- **detection of recoil ion**
- **negligible source scattering**
- potential for polarized sample



Penning



MOT



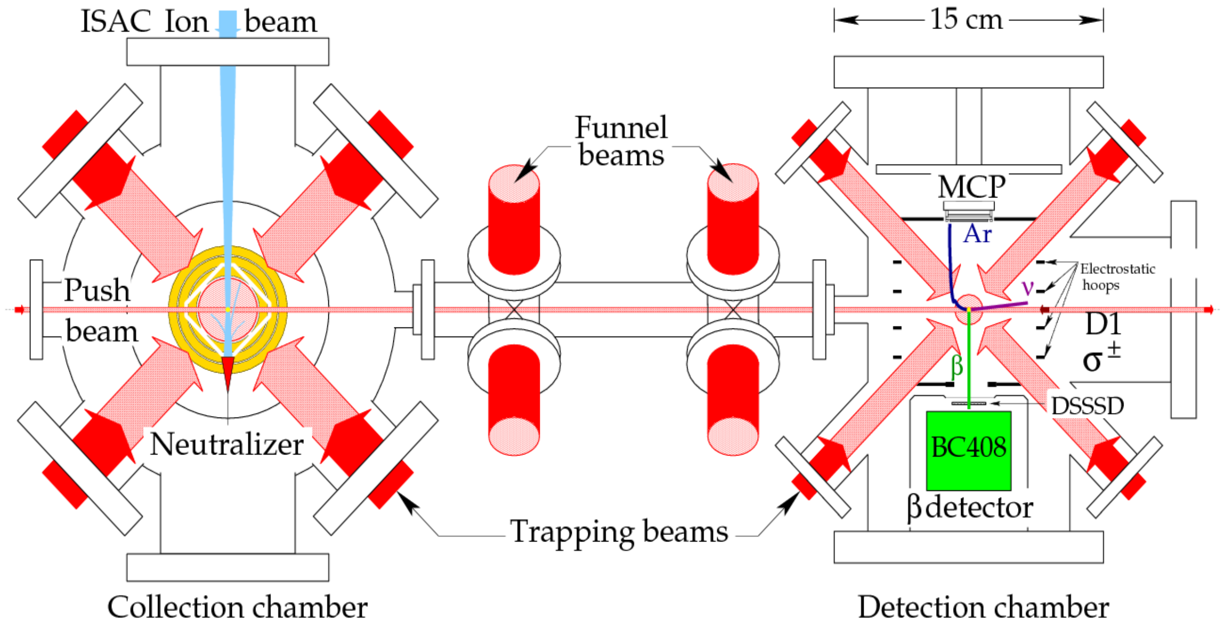
Paul

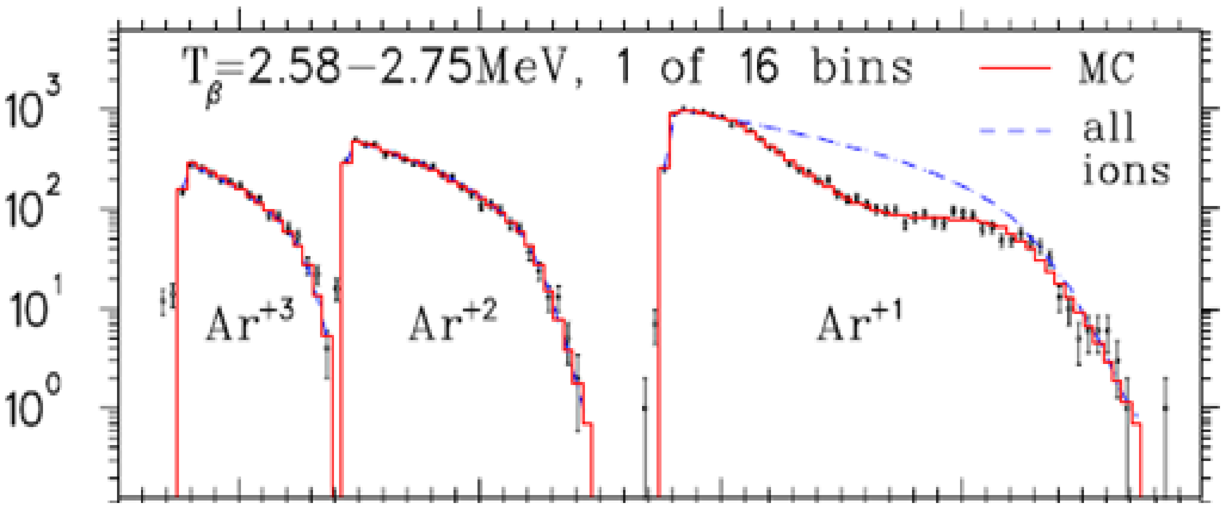
TRINAT MOT trap at TRIUMF-ISAC – ^{38m}K - scalar

search for scalar couplings

$$^{38m}\mathrm{K} \rightarrow {}^{38}\mathrm{Ar} + e^{+} + \nu$$

superallowed $0^+ \rightarrow 0^+$
pure Fermi transition
($t_{1/2}$ = 0.95 s)



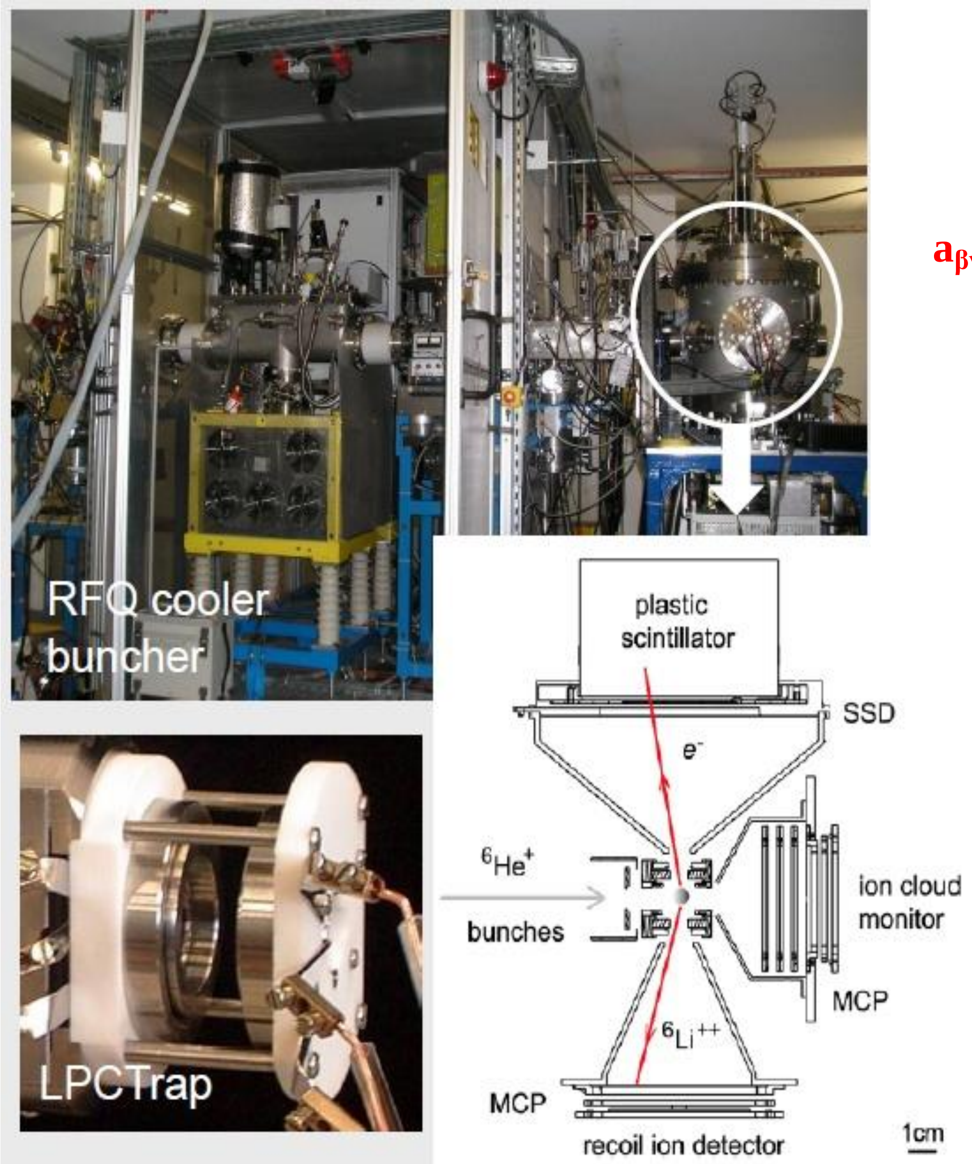


$$\tilde{a} = a \Big/ \left[1 + \frac{\gamma m_e}{E_e} b \right]$$

$$= 0.9981 \pm 0.0030 \pm 0.0035$$

A. Gorelov, J. Behr et al., Phys. Rev. Lett. 94 (2005) 142501

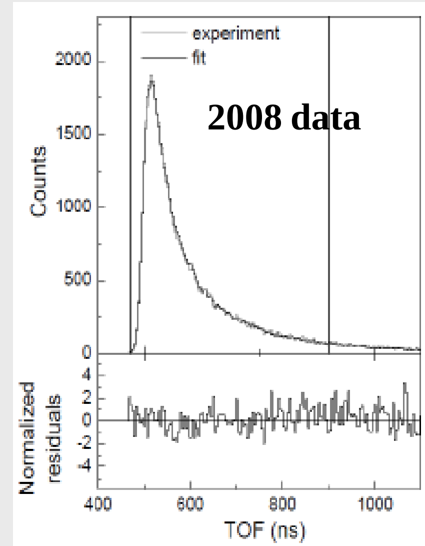
LPCTrap @ GANIL - ^{6}He - tensor

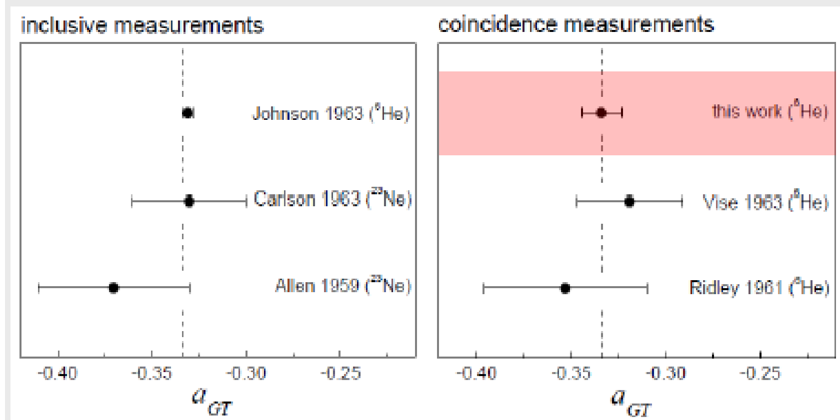


- First result

X. Fléchard *et al.*, JPG **38** (2011) 055101

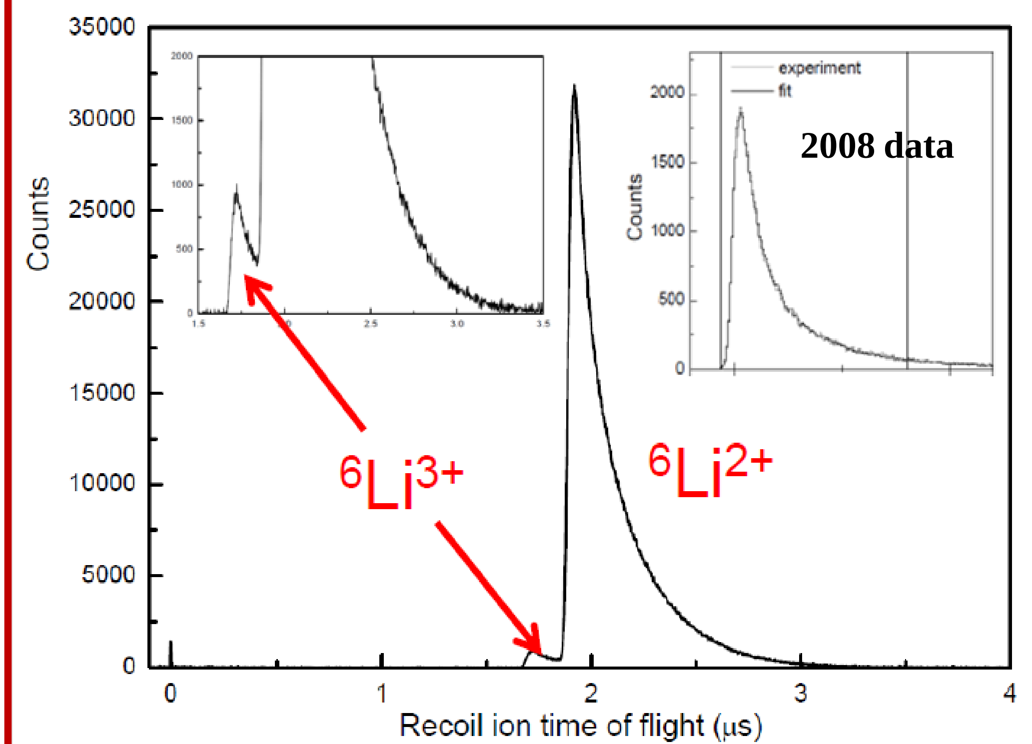
$$a_{\beta\nu} = -0.3335(73)_{stat}(75)_{syst}$$



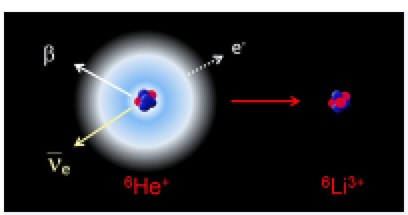


3.1% precision result: the most precise in a GT decay, from a measurement in coincidences.

New TOF measurement with modified setup



Nov. 2010 – much improved statistics



Helium Ions Give Electrons the Shake-Off

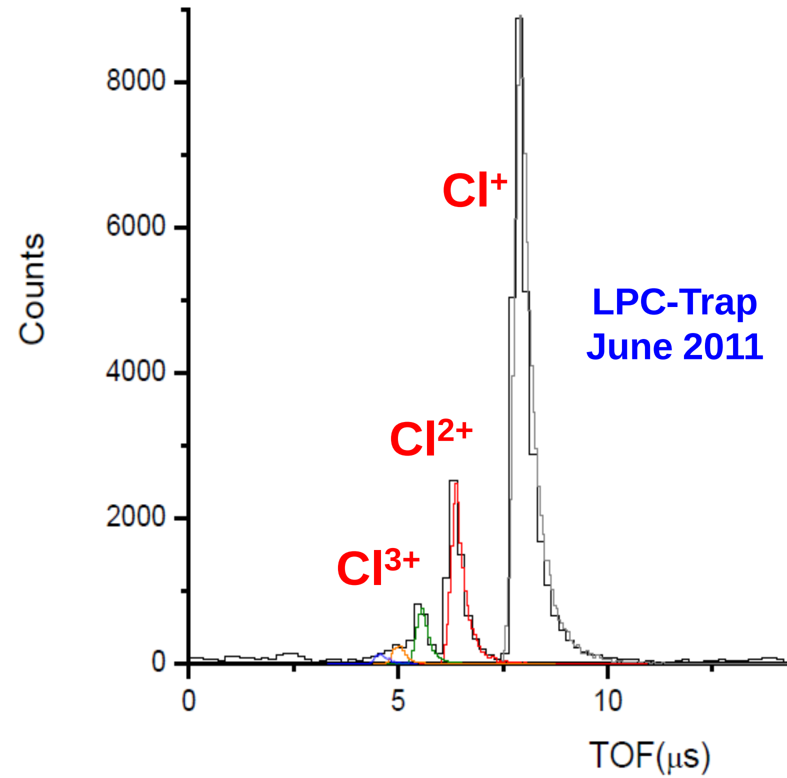
June 14, 2012

Singly ionized helium-6 is an ideal atom for testing the quantum mechanical response of electrons to a decaying nucleus.

C. Couratin et al., PRL 108 (2012) 243201

New project – ^{35}Ar

first data in June 2011

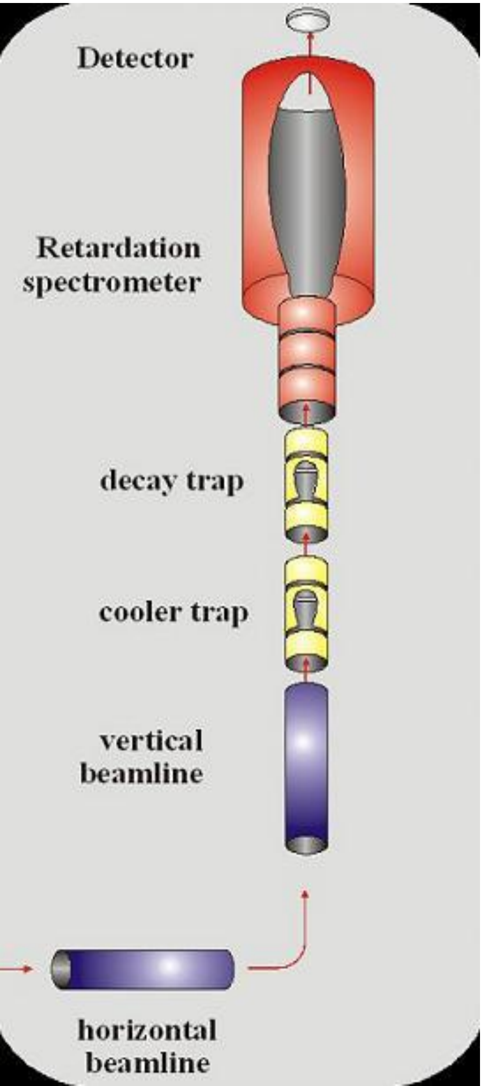


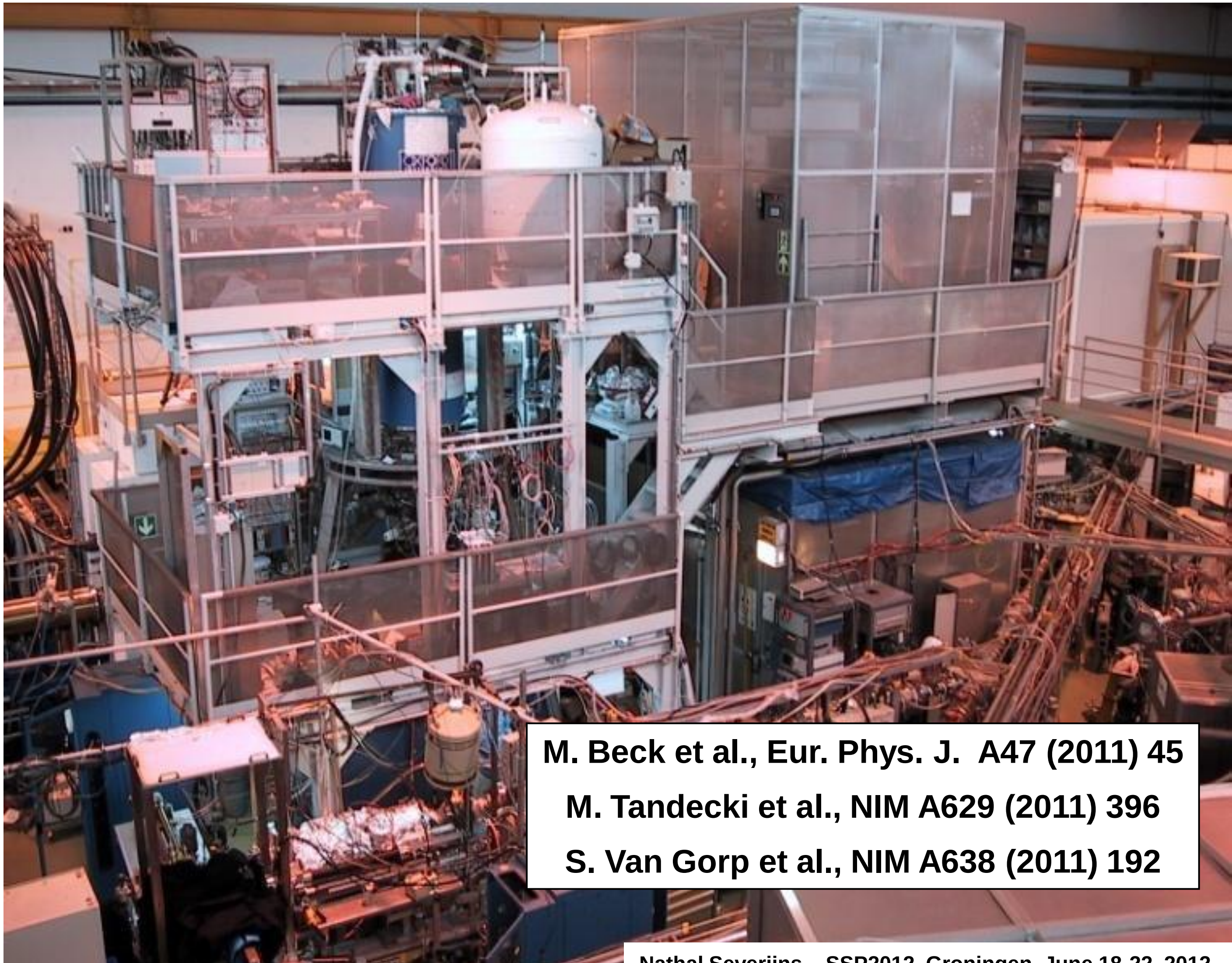
WITCH @ ISOLDE - ^{35}Ar - scalar

(K.U.Leuven, Univ. Munster, ISOLDE, NPI Rez-Prague, LPC-Caen)

Goal : determine βν correlation for ^{35}Ar with $(\Delta a/a)_{stat} \leq 0.5$ %

→ measure energy spectrum of recoiling ions with a retardation spectrometer



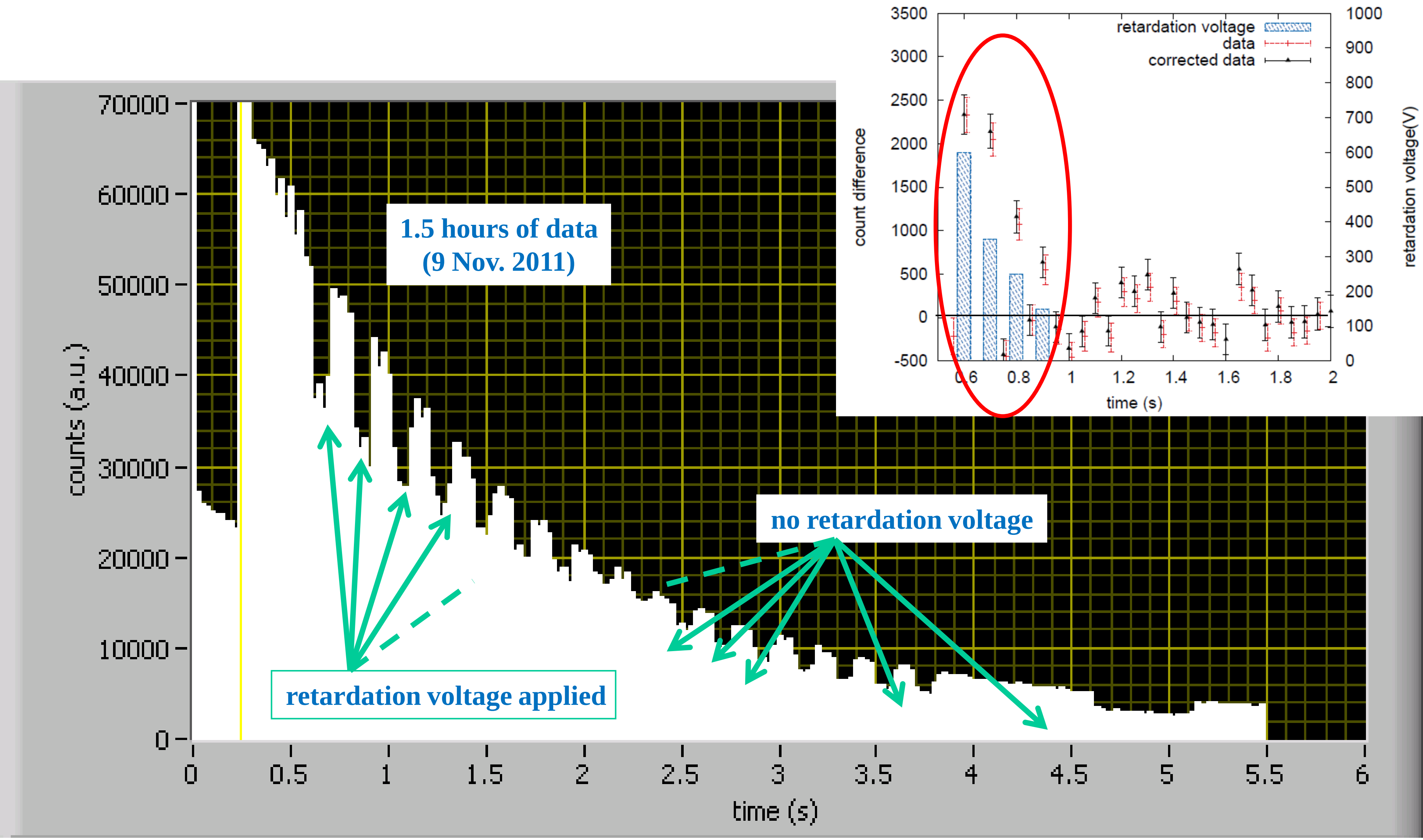


M. Beck et al., Eur. Phys. J. A47 (2011) 45

M. Tandecki et al., NIM A629 (2011) 396

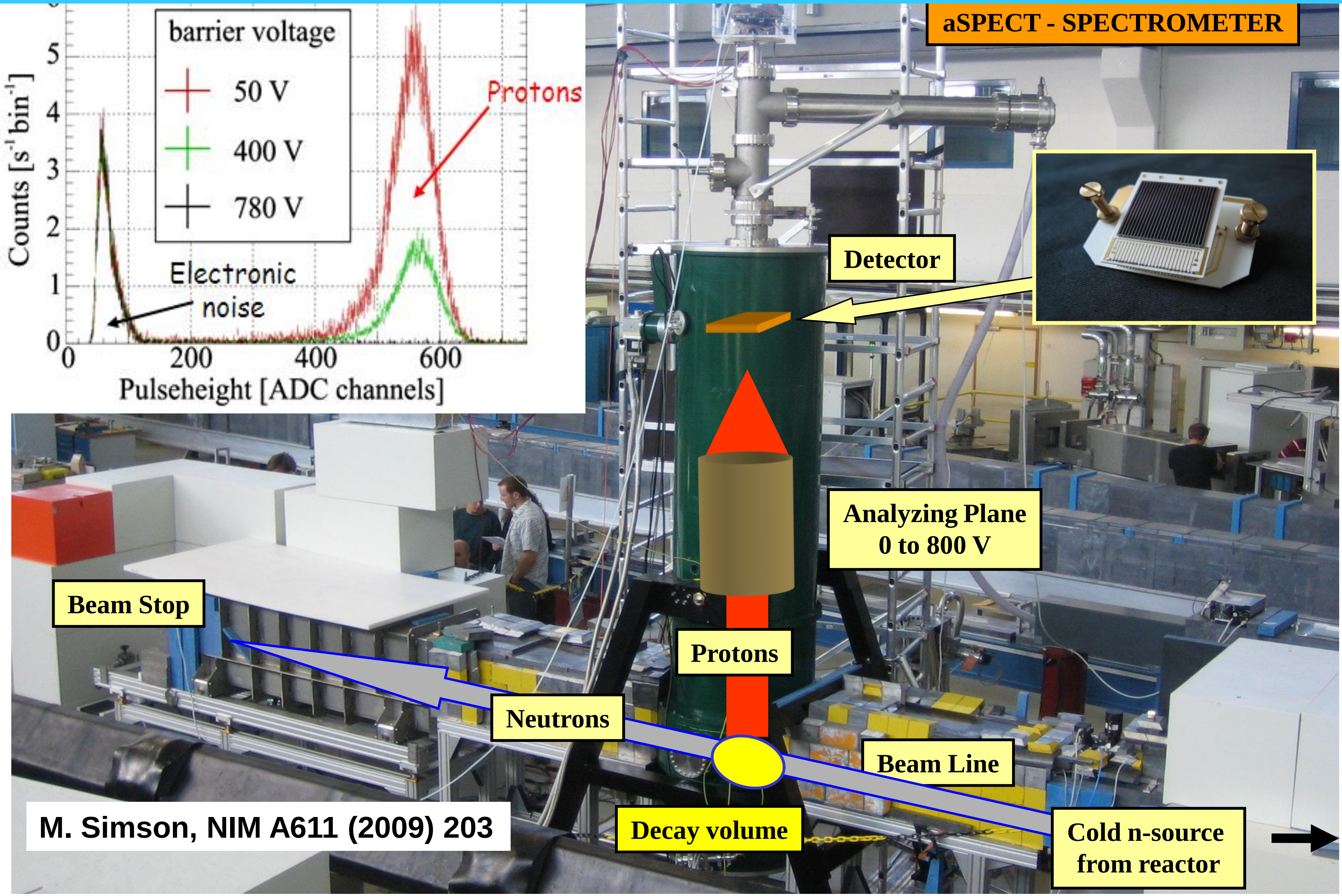
S. Van Gorp et al., NIM A638 (2011) 192

First results with ^{35}Ar from the WITCH experiment - June and Nov 2011



aSPECT retardation spectrometer for n-decay

(Mainz, Karlsruhe, Virginia - W. Heil et al.)



M. Simson, NIM A611 (2009) 203

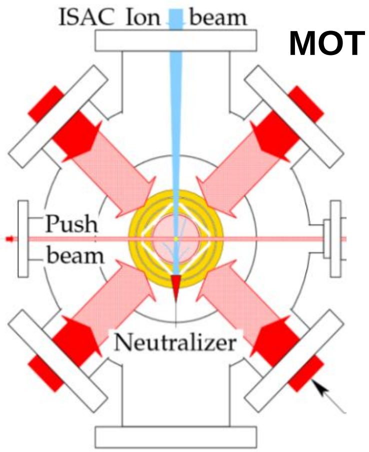
Most precise βν correlation measurements

^{32}Ar – Adelberger et al., PRL 83 (1998) 1299

$$\tilde{a} = 0.9989 \pm 0.0052_{stat} \pm 0.0039_{syst} \qquad (\tilde{a}_{SM} = 1)$$

^{6}He - C. Jonhson et al., PR (1963) 055101

$$\tilde{a} = -0.3308 \pm 0.0030 \qquad (\tilde{a}_{SM} = -0.3333)$$

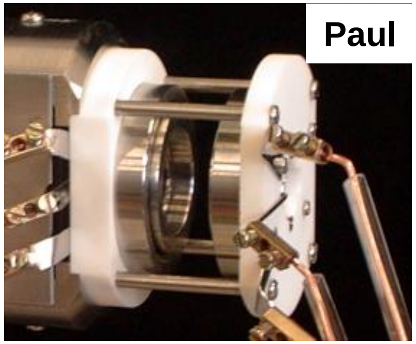


^{38m}K – A. Gorelov, J.A. Behr et al., PRL 94 (2005) 142501

$$\tilde{a} = 0.9981 \pm 0.0030_{stat} \pm 0.0034_{syst} \qquad (\tilde{a}_{SM} = 1)$$

^{21}Na – P. Vetter, S.J. Freedman et al., PR C 77 (2008) 035502

$$\tilde{a} = 0.5502 \pm 0.0038_{stat} \pm 0.0046_{syst} \qquad (\tilde{a}_{SM} = 0.5587(27))$$



^{6}He - X. Flechard et al., J. Phys. G 38 (2011) 055101

$$\tilde{a} = -0.3335 \pm 0.0073_{stat} \pm 0.0075_{syst} \quad (\tilde{a}_{SM} = -0.3333)$$

Present βν correlation projects

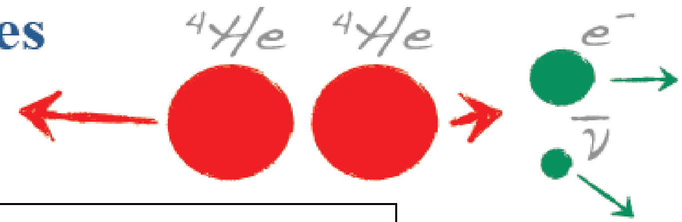
precision goals: 0.5 % → 0.1 %

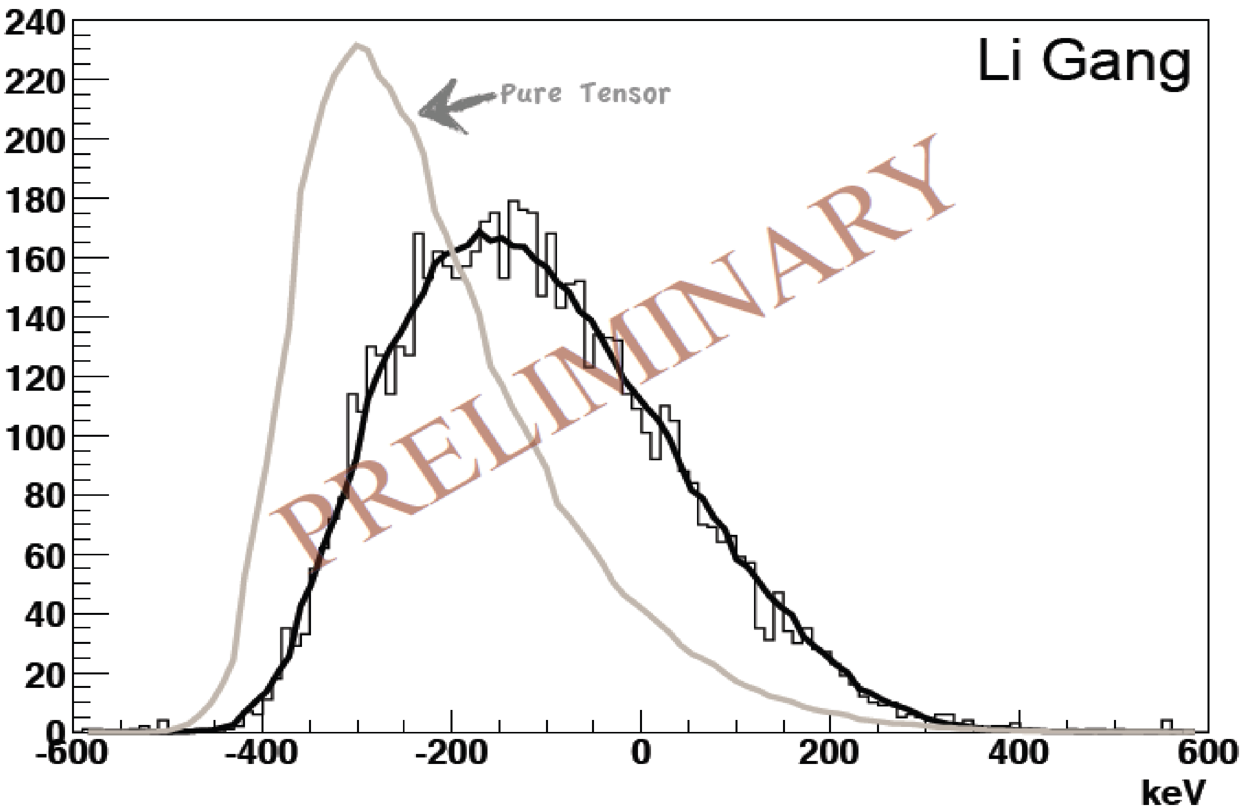
Fermi (*)	(*) pure or dominant
Mixed	
Gamow-Teller (*)	

Parent	*Technique*	*Group, Lab*	
^{35}Ar	Penning trap	Leuven+/ISOLDE	collaboration - first data June 2011
^{35}Ar	Paul trap	LPC+/GANIL	
^{38m}K	MOT	SFU+/TRIUMF	**Gorelov et al., PRL 94 (2005) 142501;** upgrade in progress
^{21}Na	MOT	Berkeley	**Vetter et al., PRC 77 (2008) 035502;** upgrade in progress
^{21}Na	MOT	KVI-Groningen	in progress
^{6}He	Paul trap	LPC+/GANIL	**X. Fléchard et al., J.Phys.G 38 (2011) 055101** upgrade in progress
^{8}Li	Paul trap; βα	ANL+	in progress
^{6}He	MOT	ANL+/CENPA	in progress
^{6}He/^{8}Li	EIBT	WIS (SOREQ)	in progress
^{8}He	βγ	NSCL+	in progress

First Results with β-α-α Coincidences

- Preliminary results from shift in α energies for α parallel to electron





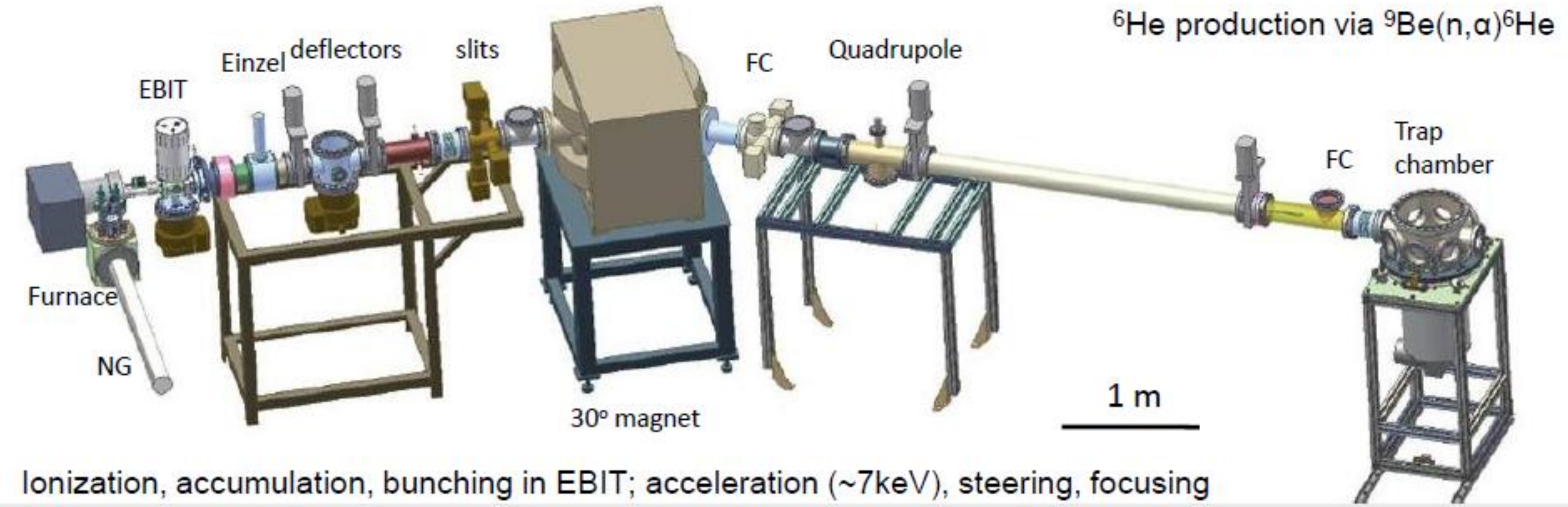
- Data from ~20,000 β–α–α coincidences collected at the end of test run
- Preliminary analysis suggests ~1% statistical uncertainty in 'a'
- ~1% systematic uncertainty dominated by uncertainty in dead layer

WIRED

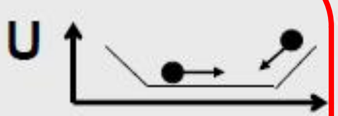
Weizmann Institute Radioactive Electrostatic Device

ISRAEL SCIENCE FOUNDATION

^{6}He production via $^{9}Be(n,\alpha)^{6}He$

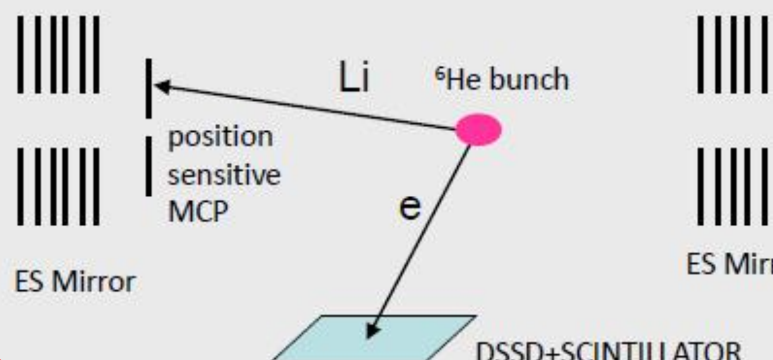


Ionization, accumulation, bunching in EBIT; acceleration (~7keV), steering, focusing



Electrostatic Ion Beam Trap

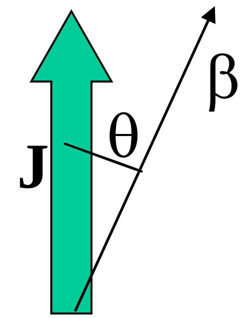
Principle: determine complete kinematics



The β asymmetry parameter

$$W(\theta) = 1 + \tilde{A}\,\frac{\bar{J}}{J}\cdot\frac{\bar{p}}{E_e}$$

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



for a pure Gamow-Teller transition :

$$\tilde{A}(\beta^{\mp}) \cong \lambda_{J'J}\left[\mp 1 + \frac{\gamma m}{E_e}\,\mathrm{Re}\left(\frac{C_T + C_T'}{C_A}\right)\right]$$

$$\left[\gamma = \sqrt{1-(\alpha Z)^2}\right]$$

$\Delta\tilde{A} = 0.01$ → **(for $\gamma m/E_e \cong 0.5$)** **Re [(C_T+C_T') / C_A] < 0.033** **(90% CL)**

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

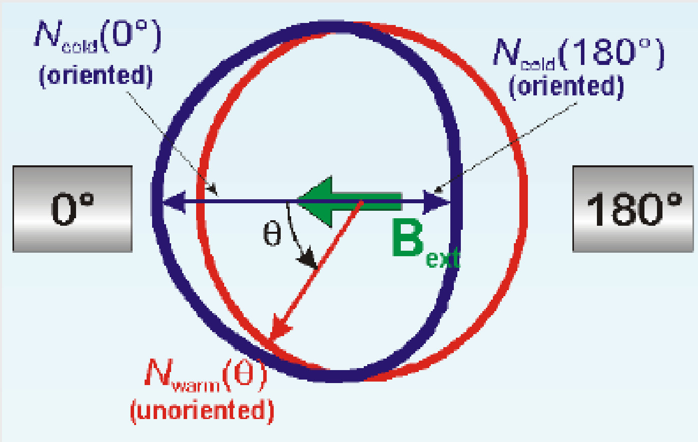
recoil corr. (induced form factors) ≈ 10^{-3} ; radiative corrections ≈ 10^{-4}

***A_{GT}* independent of nuclear matrix elements**

β-asymmetry parameter: a new approach

(K.U.Leuven, NICOLE-ISOLDE, NPI Rez-Prague, Uni Bonn)

Principle

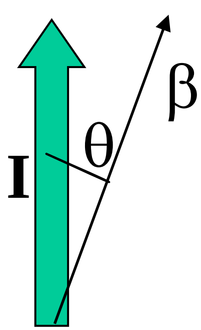


F. Wauters, I. Kraev, D. Zakoucky, N. Severijns et al.

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

(P from anisotropy of γ-rays) **Geant 4**

^{60}Co<u>Cu</u> , B_{ext} = 13 T
^{114}In<u>Fe</u> , B_{hf} = 27 T



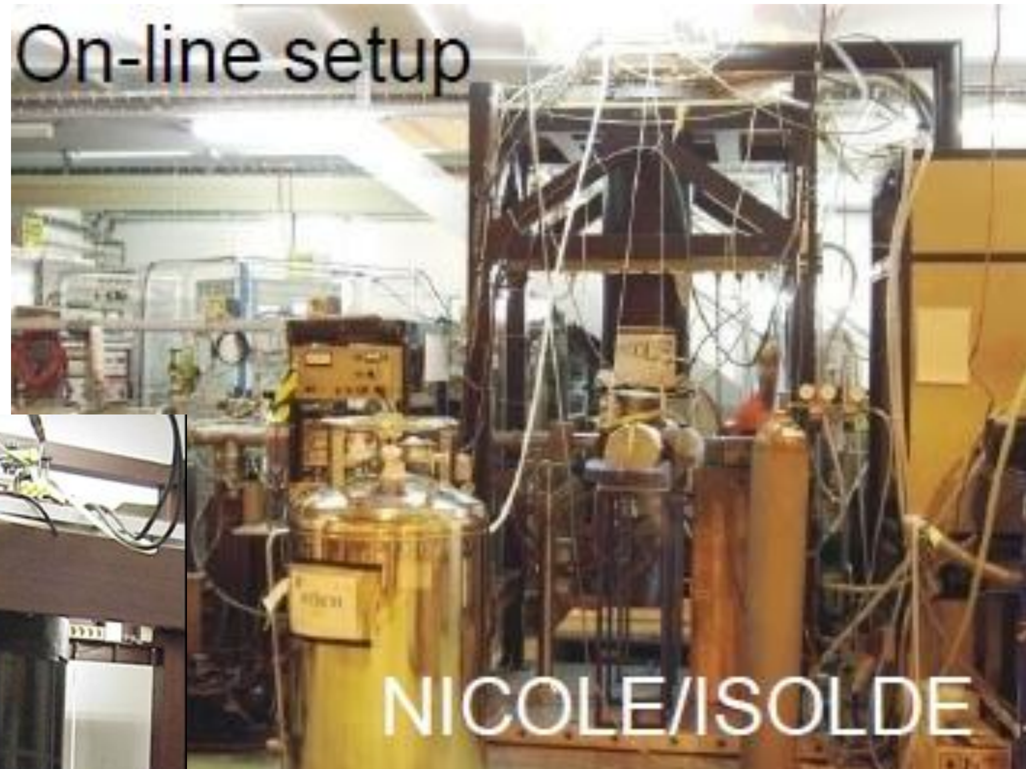
Analysis:

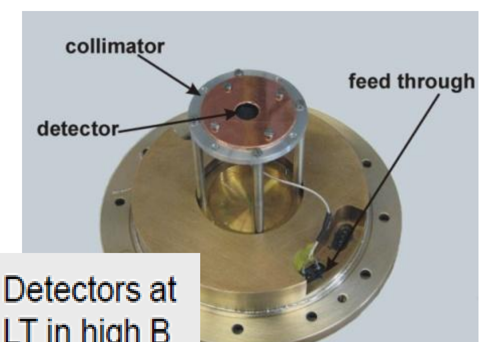
$$\frac{[W(\theta) - 1]_{exp}}{[W(\theta) - 1]_{Geant}} = \frac{\left[\tilde{A}^{\beta^{\mp}} \; P \; \frac{v}{c} \; Q \cos\theta\right]_{exp}}{\left[\tilde{A}^{\beta^{\mp}}_{SM} \; P \; \frac{v}{c} \; Q \cos\theta\right]_{Geant}} = \frac{\tilde{A}^{\beta^{\mp}}}{\tilde{A}^{\beta^{\mp}}_{SM}}$$

IS431-experiment

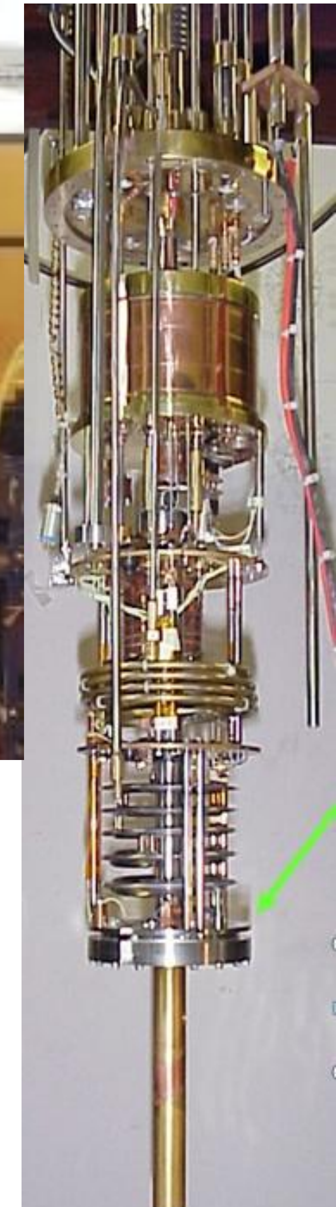
β asymmetry parameter – Leuven / ISOLDE

ISOLDE - NICOLE
Louvain-la-Neuve - KOOL
Leuven





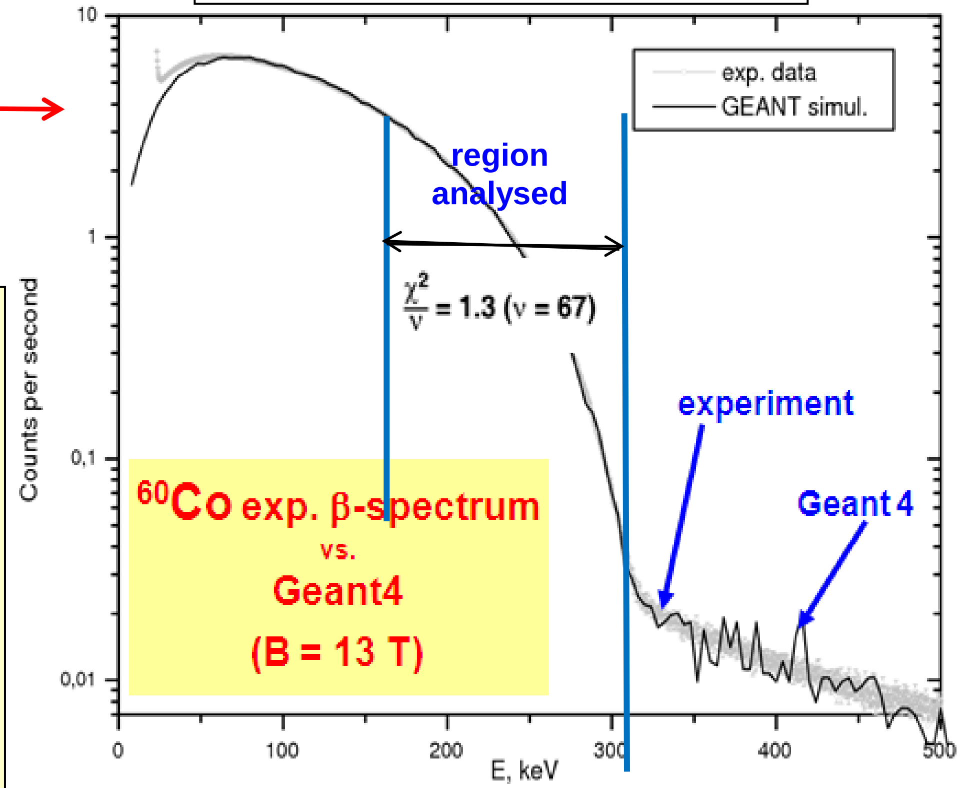
Detectors at LT in high B fields.



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

Geant4

F. Wauters et al., NIM A 609 (2009) 156



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

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

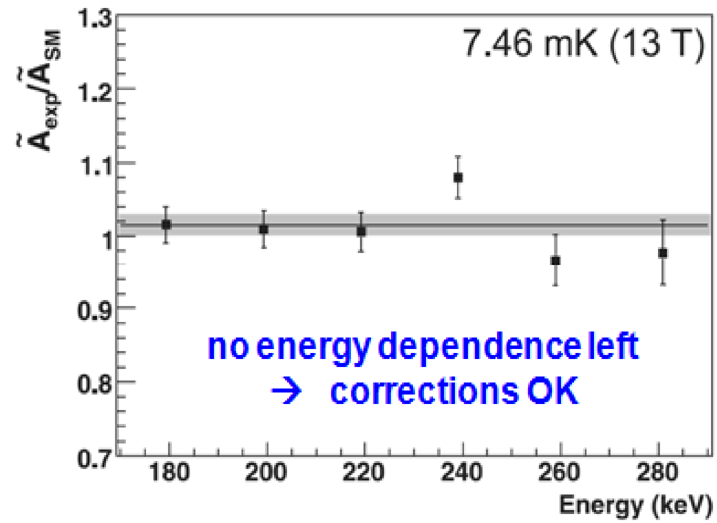
F. Wauters et al., Phys. Rev. C 82 (2010) 055502

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

$(A_{SM} = -0.996(3))$

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

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



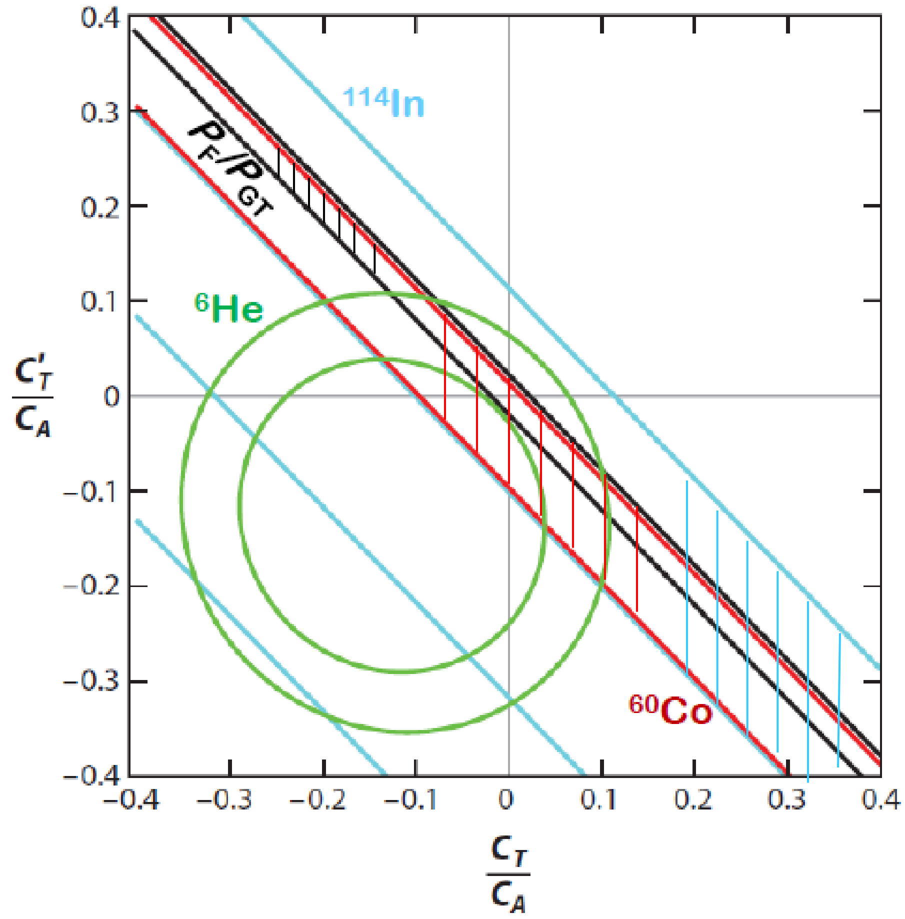
major systematic errors:

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

Constraints on exotic weak couplings

Within JTW phenomenological parameterization for allowed beta decay

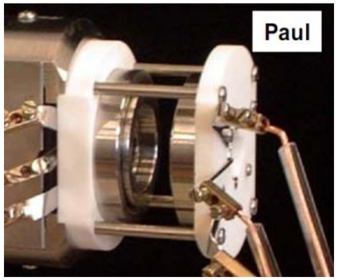
N. S. and O. Naviliat-Cuncic, Ann. Rev. Nucl. Part. Sci. 61 (2011) 23



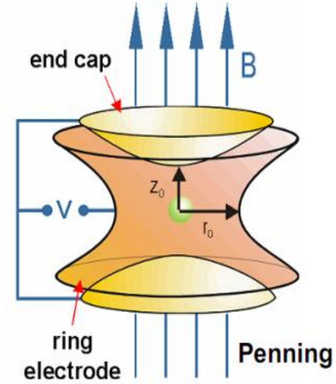
JTW: Jackson, Treiman and Wyld, NP 4 (1957) 206

Next step 1: polarizing atoms/ions in a particle trap

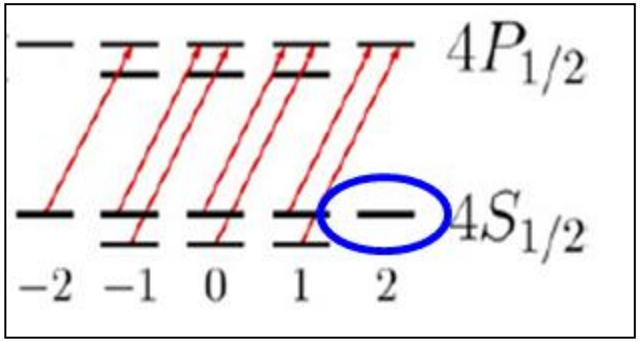
- **Paul trap :** **optical pumping of ion cloud in magnetic holding field**
  (LPC-GANIL)

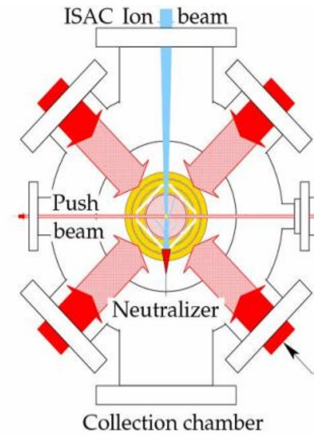


- **Penning trap :** **collinear polarization by optical pumping in beam line before trap**
  (WITCH-ISOLDE, DESIR)

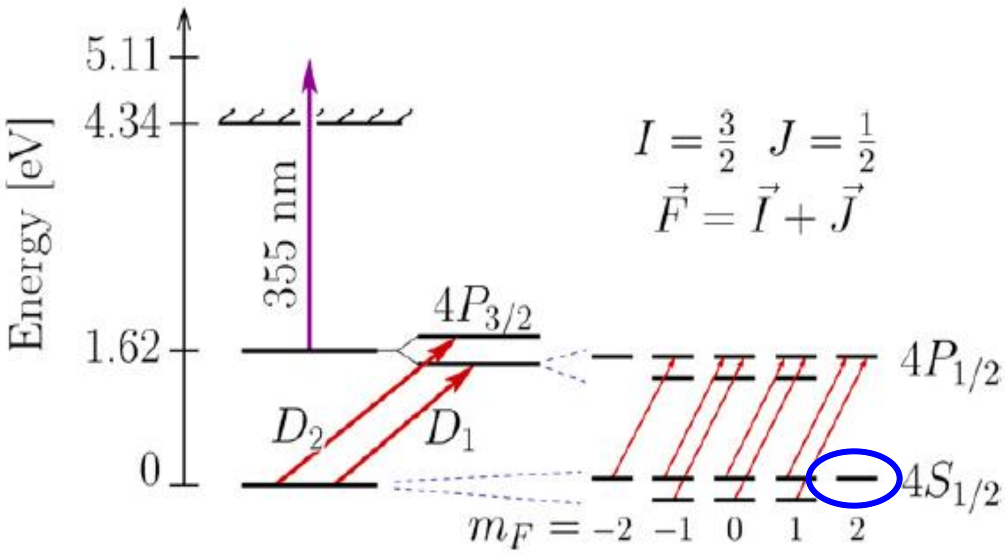


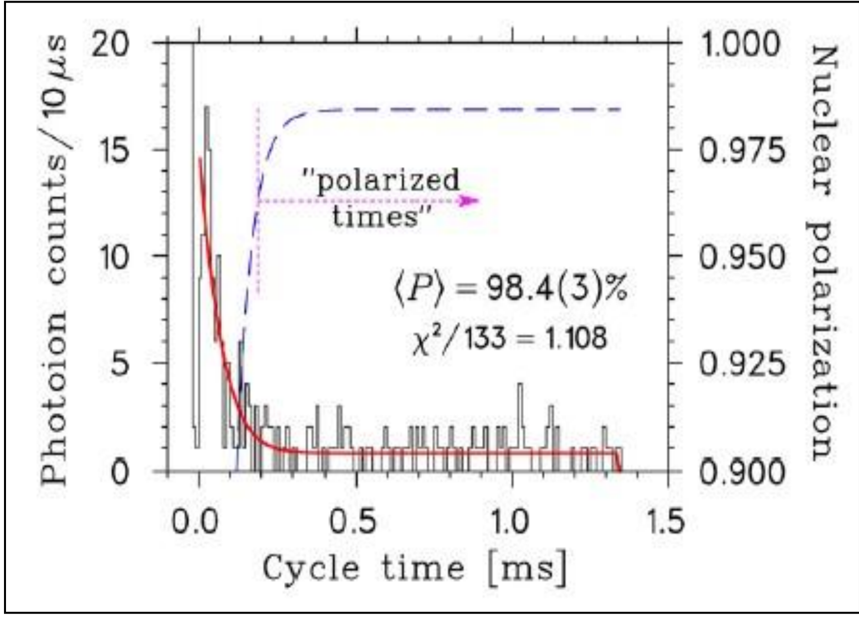
- **MOT trap :** **optical pumping of ion cloud in magnetic holding field**
  (TRIUMF, Berkeley, KVI)





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

$$P = 0.53 \pm 0.03$$

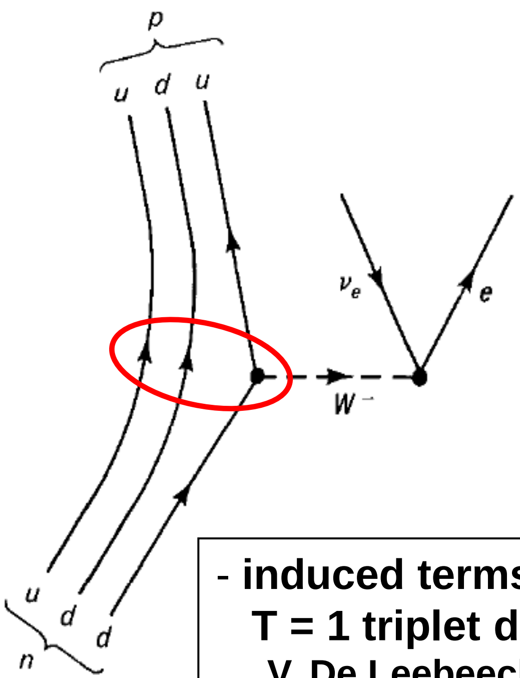
D. Melconian, J.A. Behr et al., Phys. Lett. B 649 (2007) 370

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

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

$$A_{recoil}^{^{80}Rb} = (A_\beta + B_\nu)^{^{80}Rb} = 0.015\ (29)\ (19) \qquad [\, (A_\beta + B_\nu)^{SM} = 0\ ]$$

Next step 2: include recoil / induced corrections

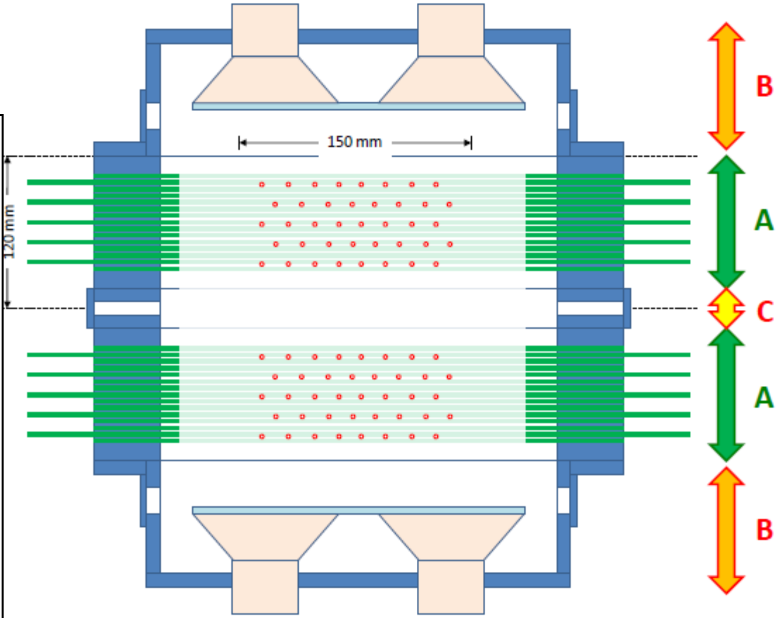


due to strong interaction, because weakly decaying quark is not free but bound in a nucleon

- effects of few permille
- dominant = 'weak magnetism'

- induced terms for mirror nuclei and T = 1 triplet decays, up to A = 45 :
  V. De Leebeeck, I.S. Towner, N.S. to be published

- experimental study:
  new β spectrometer for precision β spectrum shape measurements (MWDC + E-detectors)
  Leuven-Krakow collaboration



Outline

- **structure of the weak interaction**
  - physics: scalar or tensor components
  - observables: $\beta\nu$ correlation, β-asymmetry parameter

- **parity symmetry**
  - observable: polarization-asymmetry correlation

Testing parity violation in nuclear β-decay → 'beyond' the experiments of Wu et al.

Manifest Left-Right Symmetric models

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

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

$\delta = m_1^2 / m_2^2 \quad ; \quad \zeta \leq 0.0001$

Experimental observable

$$R \equiv P^- / P^+ = R_{SM} [\, 1 + k\, (\delta + \zeta)^2 \,]$$

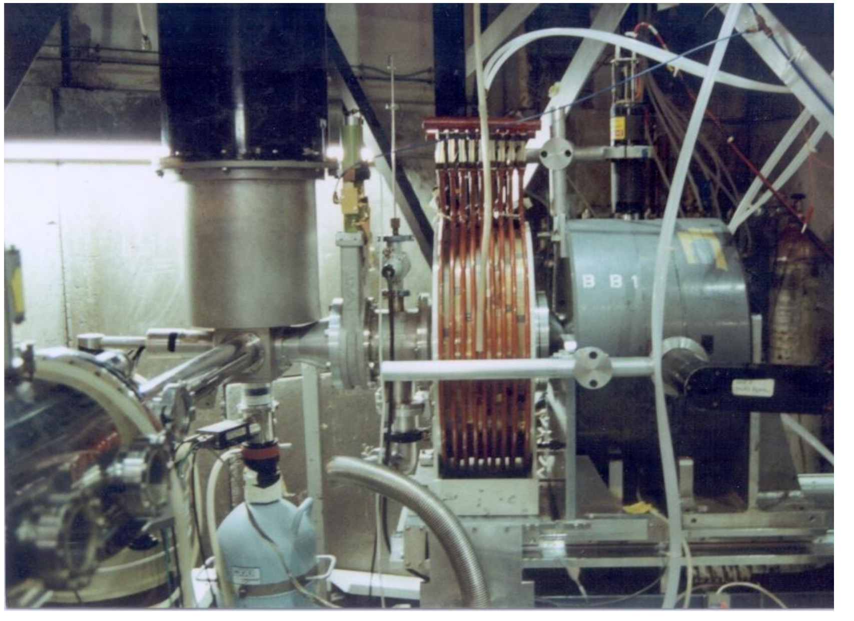
ratio of the **longitudinal polarisation of positrons emitted anti-parallel and parallel to the spin of the nuclei**

physics beyond the Standard Model

observable	isotope	$(\delta + \zeta)^2$	
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: $(\delta + \zeta)^2 = 0.0017(14)$

→ $m_2 > 320$ GeV/c^2 (90% CL)



experiments at Louvain-la-Neuve
and at the Paul Scherrer Institute

1) N. Severijns et al., PRL 70 (1993) 4047, PRL 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

Status of present limits

Nuclear β-decay

N. Severijns and O. N-C ARNPS **61** (2011) 23

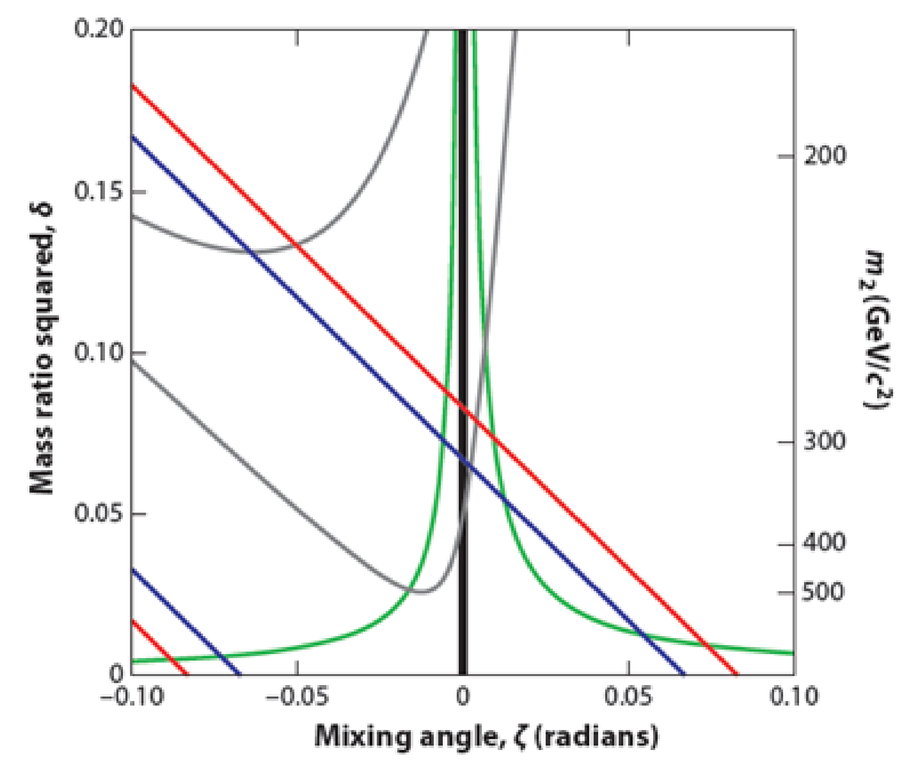
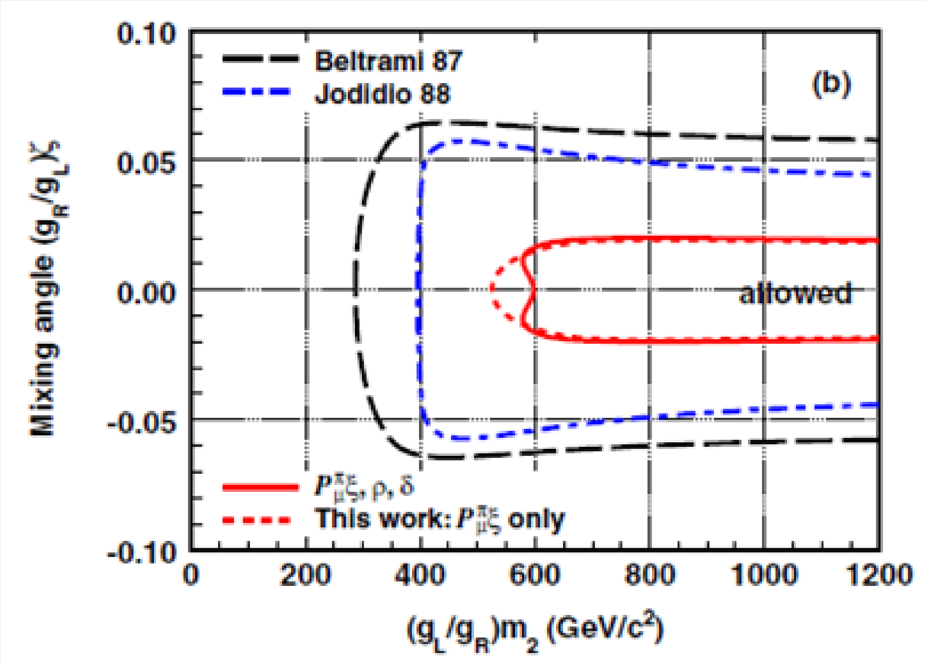


Figure 4

Constraints on the right-handed current parameters δ and ζ from measurements of different observables in nuclear β decay, including the test of unitarity of the quark-mixing matrix (*black*) (14); measurements of the β-asymmetry parameter in the decays of ^{19}Ne (*gray*) (25, 88), ^{114}In (39), and ^{60}Co (40) (*red*); relative measurements of the longitudinal polarization of β particles in pure Fermi (F) and Gamow-Teller (GT) transitions (P_F/P_{GT}) (*green*) (100, 101); and relative measurements of the longitudinal polarization of β particles emitted from polarized nuclei (*blue*) (105–107). The regions bounded by the colored lines are allowed.

μ-decay (TWIST@TRIUMF)

J.F. Bueno *et al.*, PRD **84** (2011) 032005



Neutrino asymmetry in polarized neutron decay

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

Results :

$B_n = 0.9801(46)$

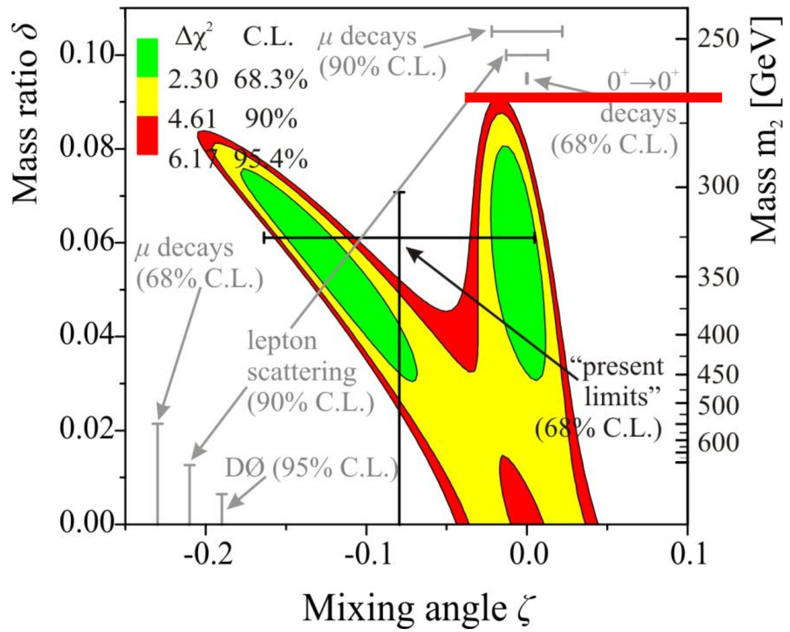
A.P. Serebrov et al., JETP 86 (1998) 1074

I.A. Kuznetsov et al., PRL 75 (1995) 794

$B_n = 0.9802(50)$

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

$M_{W_2} > 270\ GeV/c^2$ (90 % C.L.)

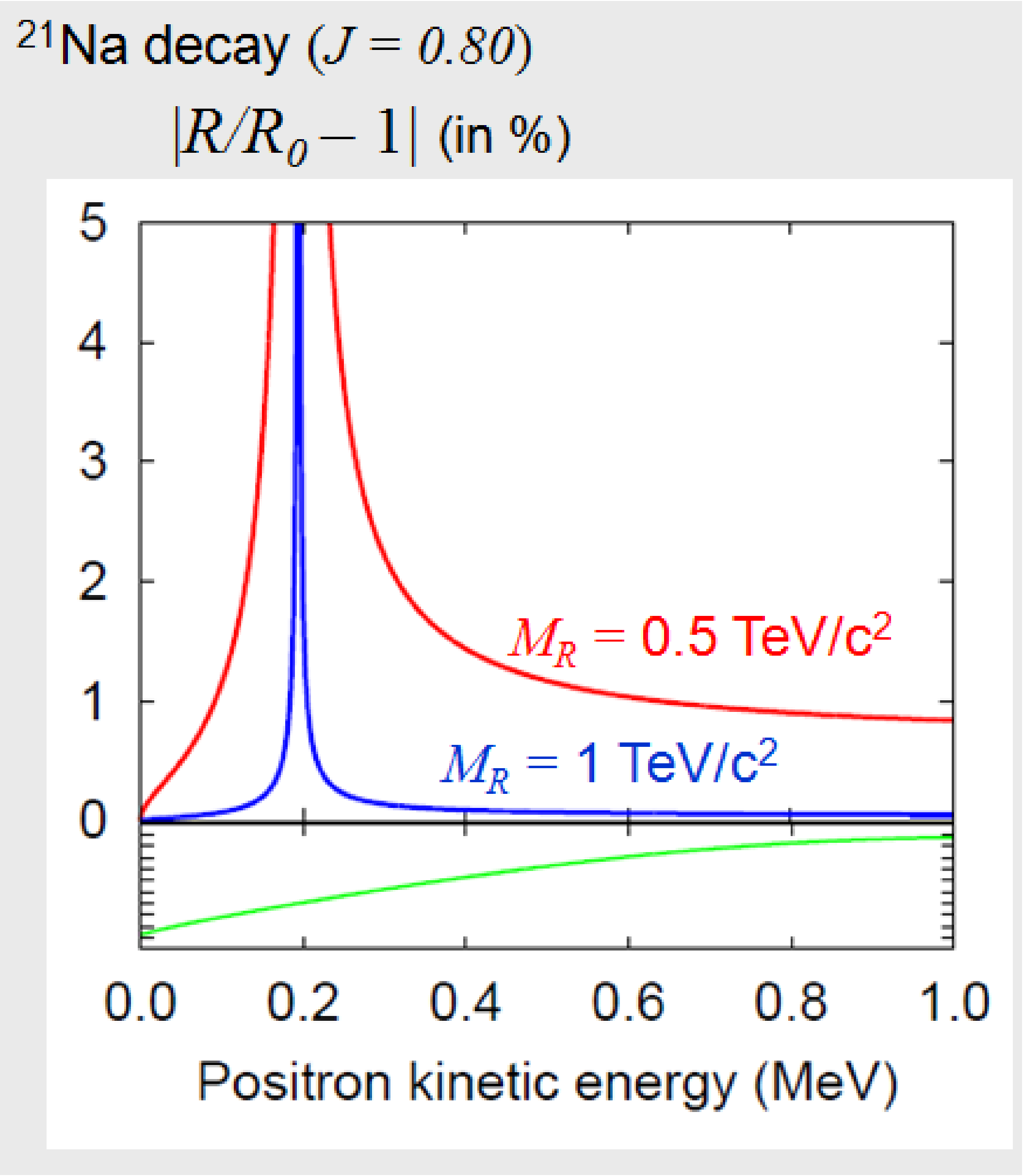


G. Konrad et al., arXiv:1007.3027

future experiments

(PERC setup – D. Dubbers et al. NIM A (2008))

→ 500 to 600 GeV/c^2 sensitivity (90 % C.L.)



New polarisation-asymmetry correlation measurement

- double-arm polarimeter
- 2 Tesla field (analyzing power)
- ^{23}Mg for controlling systematics
- good energy resolution is critical

NSCL-Michigan State Univ.

courtesy O. Naviliat-Cuncic

Summary

Recent measurements of **βν angular correlation** and **β asymmetry parameter** for nuclear β decays → improved limits on **scalar and tensor** charged weak currents;

New βν correlation measurements using different methods are ongoing/planned (nuclear decays and free neutron decay);

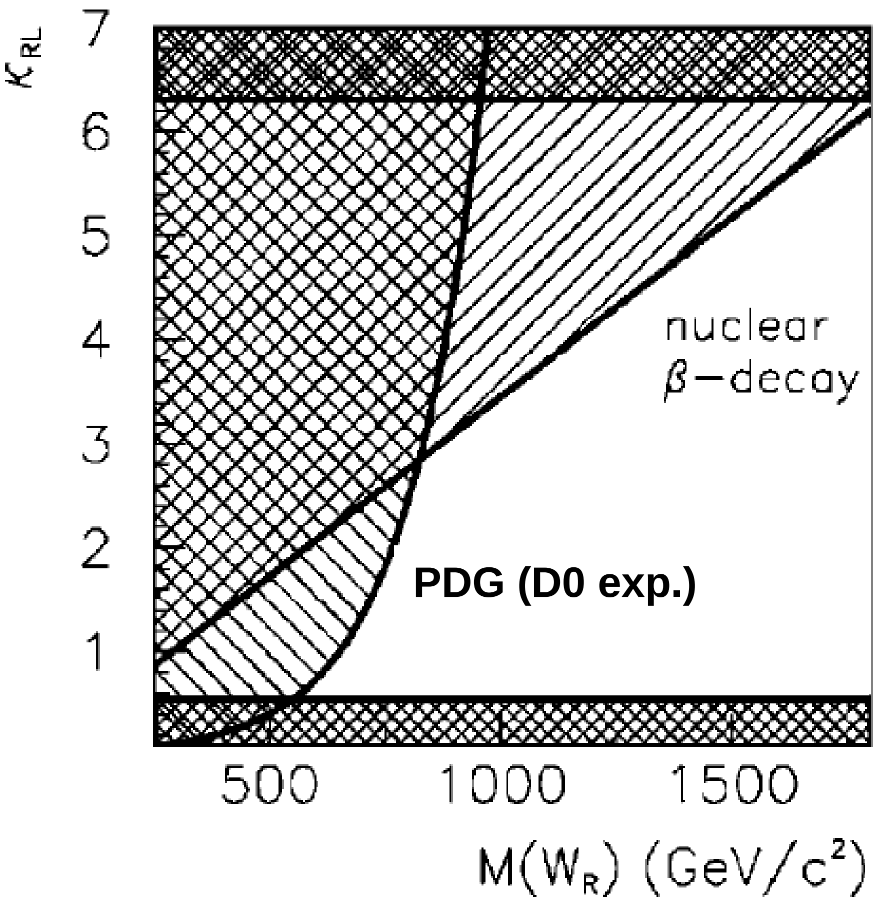
Further development of **polarized samples in particle traps** will significantly enlarge the possibilities to search for exotic currents and test symmetries of weak interaction;

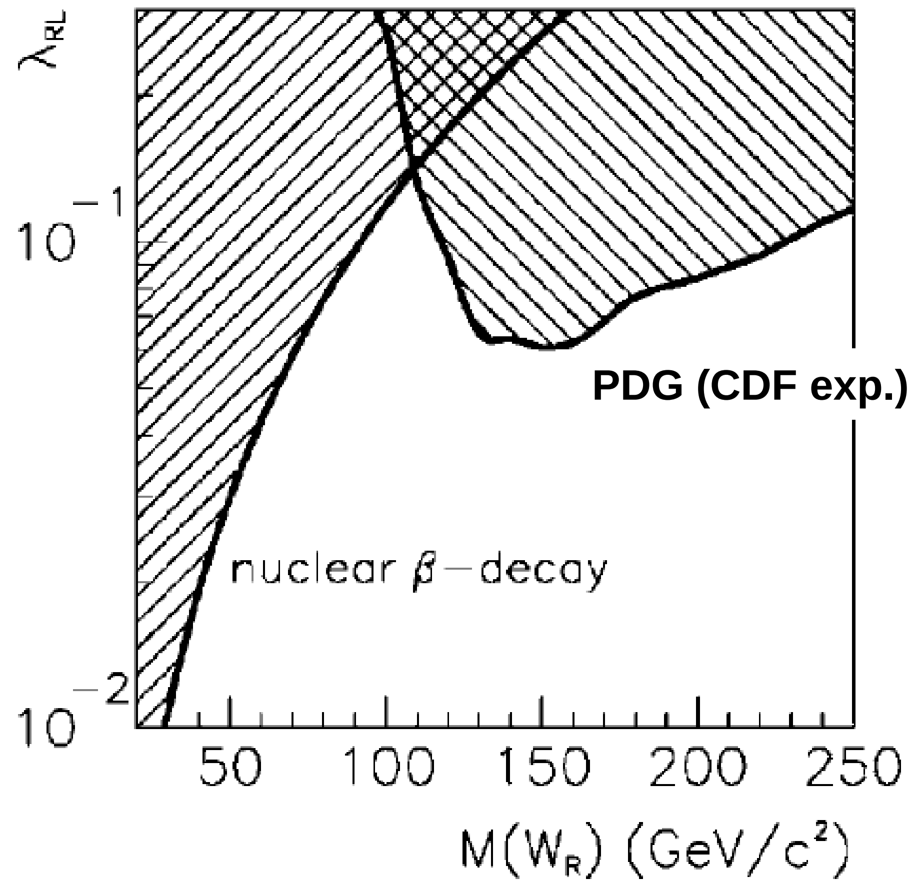
This also requires **induced terms** as well as radiative corrections to be included.

New **polarization asymmetry correlation** measurement **sensitive to P violation** planned.

→ **many new results to be expected in the coming years**

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





$\kappa_{RL} = g_R / g_L$

shaded areas are excluded

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

E. Thomas et al., Nucl. Phys. A 694 (2001) 559