0^+ to 0^+ Ft values:

CKM unitarity test and search for scalar currents

Bertram Blank
LP2i Bordeaux

- **Super-allowed 0^+ - 0^+ β decay**
- **Search for scalar currents**

2nd Rencontre PhyNuBE:
Clustering and Symmetries in Nuclear physics
March 26 – 31, 2023

Standard model of weak interaction

- **Hamiltonian: Lorentz invariance**

J.D. Jackson et al, Nucl. Phys. 4 (1957) 206
M. González-Alonso et al., Prog. Part. Nucl. Phys. 104, 165 (2019)

hadronic terms — leptonic terms

$$H = (\overline{\psi_p}\gamma_\mu\psi_n)(C_V\overline{\psi_e}\gamma_\mu\psi_\nu + C_V'\overline{\psi_e}\gamma_\mu\gamma_5\psi_\nu) + (\overline{\psi_p}\gamma_\mu\gamma_5\psi_n)(C_A\overline{\psi_e}\gamma_\mu\gamma_5\psi_\nu + C_A'\overline{\psi_e}\gamma_\mu\psi_\nu) + (\overline{\psi_p}\psi_n)(C_S\overline{\psi_e}\psi_\nu + C_S'\overline{\psi_e}\gamma_5\psi_\nu) + \frac{1}{2}(\overline{\psi_p}\sigma_{\lambda\mu}\psi_n)(C_T\overline{\psi_e}\sigma_{\lambda\mu}\psi_\nu + C_T'\overline{\psi_e}\sigma_{\lambda\mu}\gamma_5\psi_\nu) + \text{Hermitian conj.}$$

(pseudo-scalar term omitted...)

Initial wave function — current — final wave function

- **Standard model: V-A theory**
  - $C_S = C_S' = C_T = C_T' = C_P = C_P' = 0$
  - Maximal violation of parity: $C_V = C_V'$ and $C_A = C_A'$
  - Time-reversal symmetry: C_V, C_V', C_A, C_A' real

- **Beyond standard model physics (new physics "NP")**
  - search for new particles (HEP), deviation from theory in nuclear β decay

Weak-interaction studies with nuclear beta decay

Ft-values

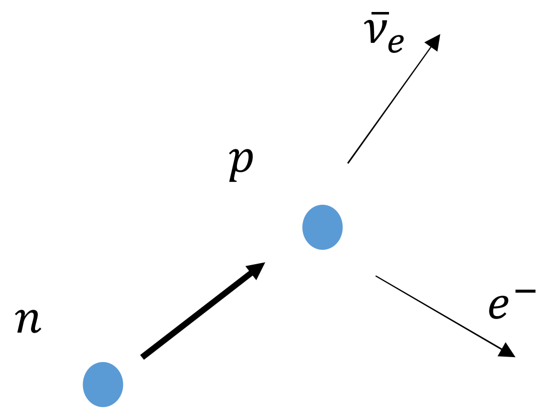
- Super-allowed Fermi decays
  - 0+ - 0+
  - Mirror beta decay

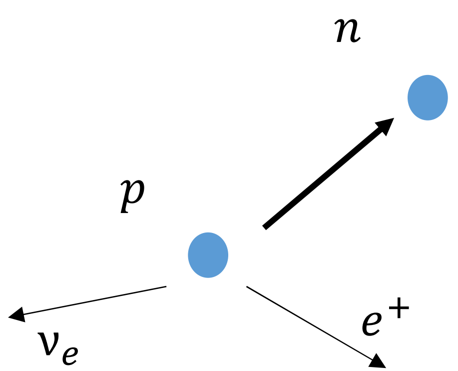
Beta correlation coefficients

- $a_{\beta\nu}$
- A_{β}
- B_{ν}

Shape of the beta energy spectrum

➔ **Aim for a precision $\leq 10^{-3}$**





THE MORA PROJECT
MATTER'S ORIGIN FROM RADIOACTIVITY

β-decay probability

$$\frac{dW(\mathbf{J})}{dE_e d\Omega_e d\Omega_\nu} = dW_0 \times \xi \left\{ 1 + a\frac{\mathbf{p_e}\cdot\mathbf{p}_\nu}{E_e E_\nu} + b\frac{m_e}{E_e} + \frac{<\mathbf{J}>}{J}\cdot\left[A\frac{\mathbf{p_e}}{E_e} + (B + b_B\frac{m_e}{E_e})\frac{\mathbf{p}_\nu}{E_\nu} + D\frac{\mathbf{p_e}\times\mathbf{p}_\nu}{E_e E_\nu}\right]\right\}$$

β–ν correlation coefficient
CP conserving
Access to C_S and C_T quadratically

Fierz interference term
CP conserving
Access to C_S and C_T linearly

« D » coefficient
CP violating
Acces to C_A, $C_A{}'$, C_V, $C_V{}'$ linearly

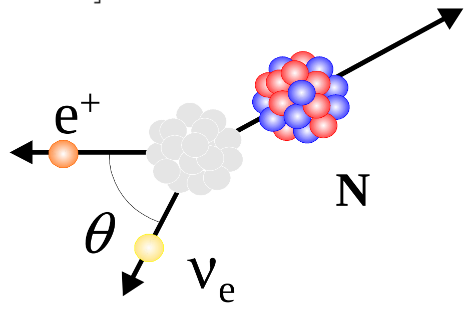
for aligned spins only

$$\frac{dW(\mathbf{J})}{dE_e d\Omega_e d\Omega_\nu} = dW_0 \times \xi \left\{ 1 + a\frac{\mathbf{p_e}\cdot\mathbf{p}_\nu}{E_e E_\nu} + b\frac{m_e}{E_e}\right\}$$

$$\xi = |M_F|^2\left[|C_V|^2 + |C'_V|^2 + |C_S|^2 + |C'_S|^2\right] - \frac{1}{3}|M_{GT}|^2\left[|C_A|^2 + |C'_A|^2 + |C_T|^2 + |C'_T|^2\right]$$

Standard model: V-A theory

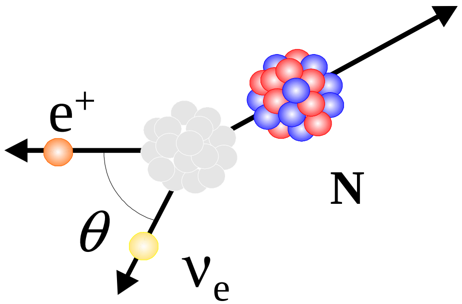
- **Only vector and axial-vector:** $C_S = C_S' = C_T = C_T' = 0$
- **Maximal violation of parity:** $C_V = C_V'$ and $C_A = C_A'$
- **Time-reversal symmetry:** C_V, C_V', C_A, C_A' real



Beyond standard model physics (new physics “NP”)

- search for new particles (HEP), deviation from theory of nuclear β decay

β-decay probability



$$dW = \boxed{dW_0}\left(1 + \boxed{a}\frac{\mathbf{p}_e \cdot \mathbf{p}_\nu}{E_e E_\nu} + \boxed{b}\frac{m_e}{E_e}\right)$$

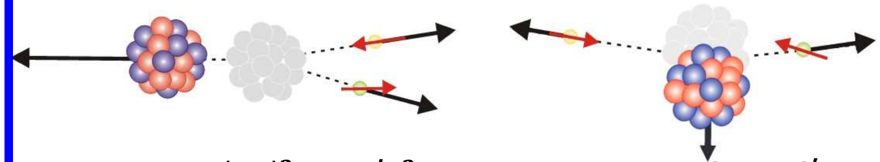
phase space factor

β–ν angular correlation coefficient

Fierz interference term = 0 (SM)

pure Fermi transitions ΔJ=0

➪ S=0 : spin of leptons anti-parallel



$$a^F_{\beta\nu} \cong 1 - \frac{|C_S|^2 + |C'_S|^2}{C_V^2} \qquad b^F_{\beta\nu} \cong \pm Re\left(\frac{C_S + C'_S}{C_V}\right)$$

SM: vector current

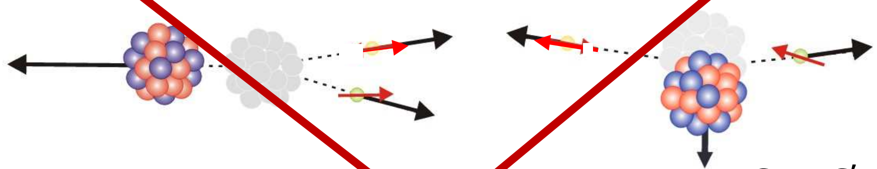
- Preferred emission angle: θ = 0°
- Maximum recoil energy

NP: scalar current

- Preferred emission angle: θ = 180°
- Minimum recoil energy

pure Gamow-Teller transitions

➪ S=1 : spin of leptons parallel



$$a^{GT}_{\beta\nu} \cong -\frac{1}{3}\left[1 - \frac{|C_T|^2 + |C'_T|^2}{C_A^2}\right] \qquad b^{GT}_{\beta\nu} \cong \pm Re\left(\frac{C_T + C'_T}{C_A}\right)$$

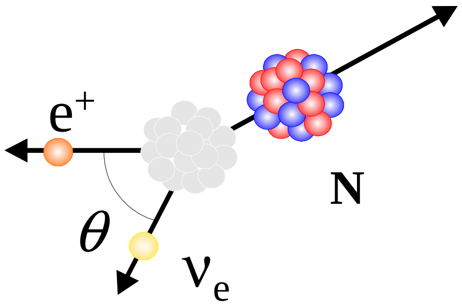
NP: tensor current

- Preferred emission angle: θ = 0°
- Maximum recoil energy

SM: axial-vector current

- Preferred emission angle: θ = 180°
- Minimum recoil energy

β-decay probability



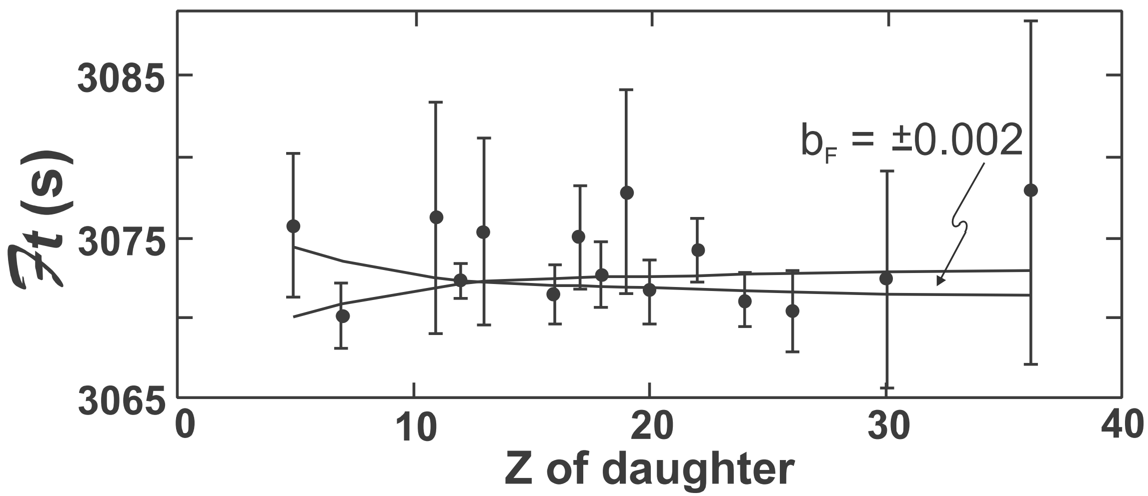
$$dW = \boxed{dW_0}\left(1 + \boxed{a}\frac{\mathbf{p}_e \cdot \mathbf{p}_\nu}{E_e E_\nu} + \boxed{b}\frac{m_e}{E_e}\right)$$

phase space factor

β–ν angular correlation coefficient

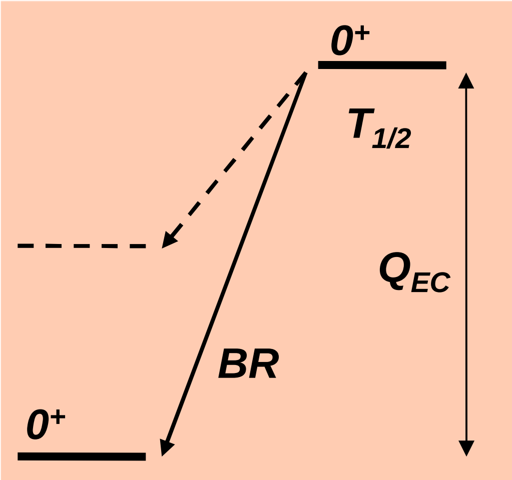
Fierz interference term = 0 (SM)

➔ indirect effect on Ft values: $\mathcal{F}t \sim b \left\langle \frac{m_e}{E_e} \right\rangle$



0^+ - 0^+ super-allowed β-decay probability

Nuclear beta decay: 0^+ - 0^+



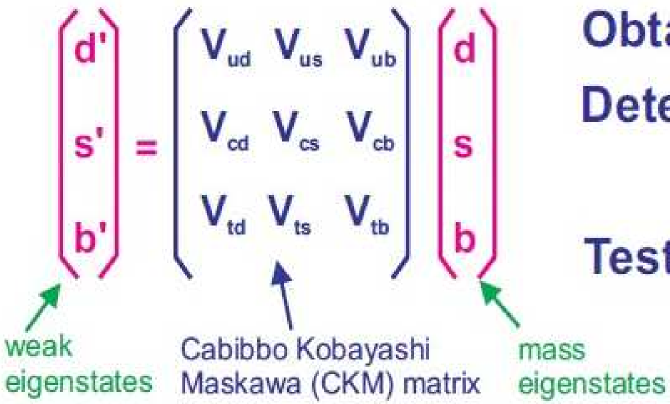
$0^+ \rightarrow 0^+$:

$$Ft = ft\,(1 + \delta_R')\,(1 - \delta_c + \delta_{NS}) = \frac{K}{G_V^2\,(1 + \Delta_R)\;\langle M_F \rangle^2} = cnst$$

f(Z, Q_{EC}) ~ 1.5%

f(nucl. structure) ~ 0.3-1.5%

f(weak interaction) ~ 2.4%



Obtain precise value of G_V^2

Determine V_{ud}^2

$V_{ud}^2 = G_V^2 / G_\mu^2$

Test CKM unitarity

$V_{ud}^2 + V_{us}^2 + V_{ub}^2 = 1$

➔ 1 – 3 σ tension

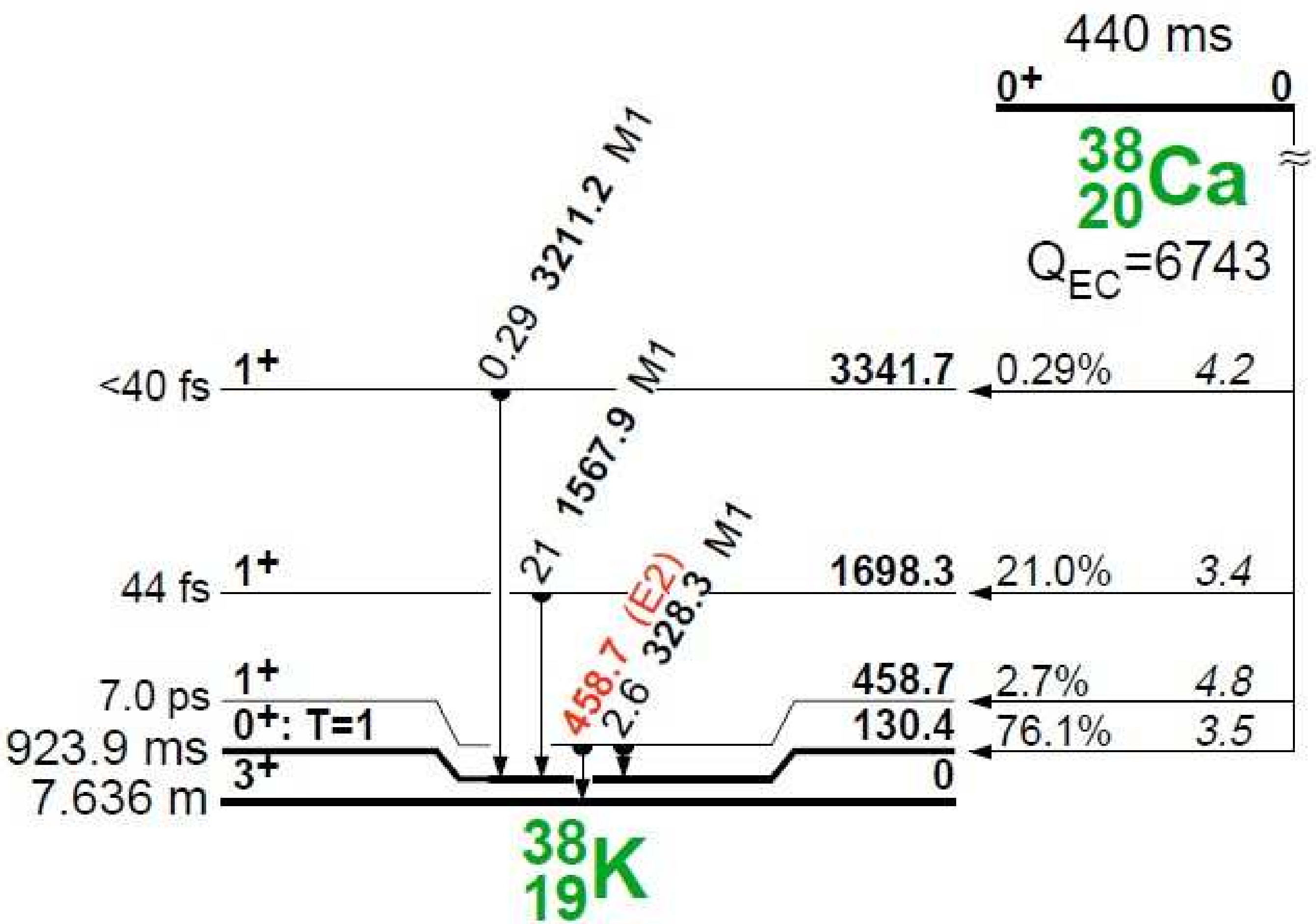
Precision measurements required: 10^{-3}

✓ Q_{EC} ⟶ *mass measurements: $f \sim Q_{EC}^5$*

✓ $T_{1/2}$, BR ⟶ *β-decay studies: $t = T_{1/2} / BR$*

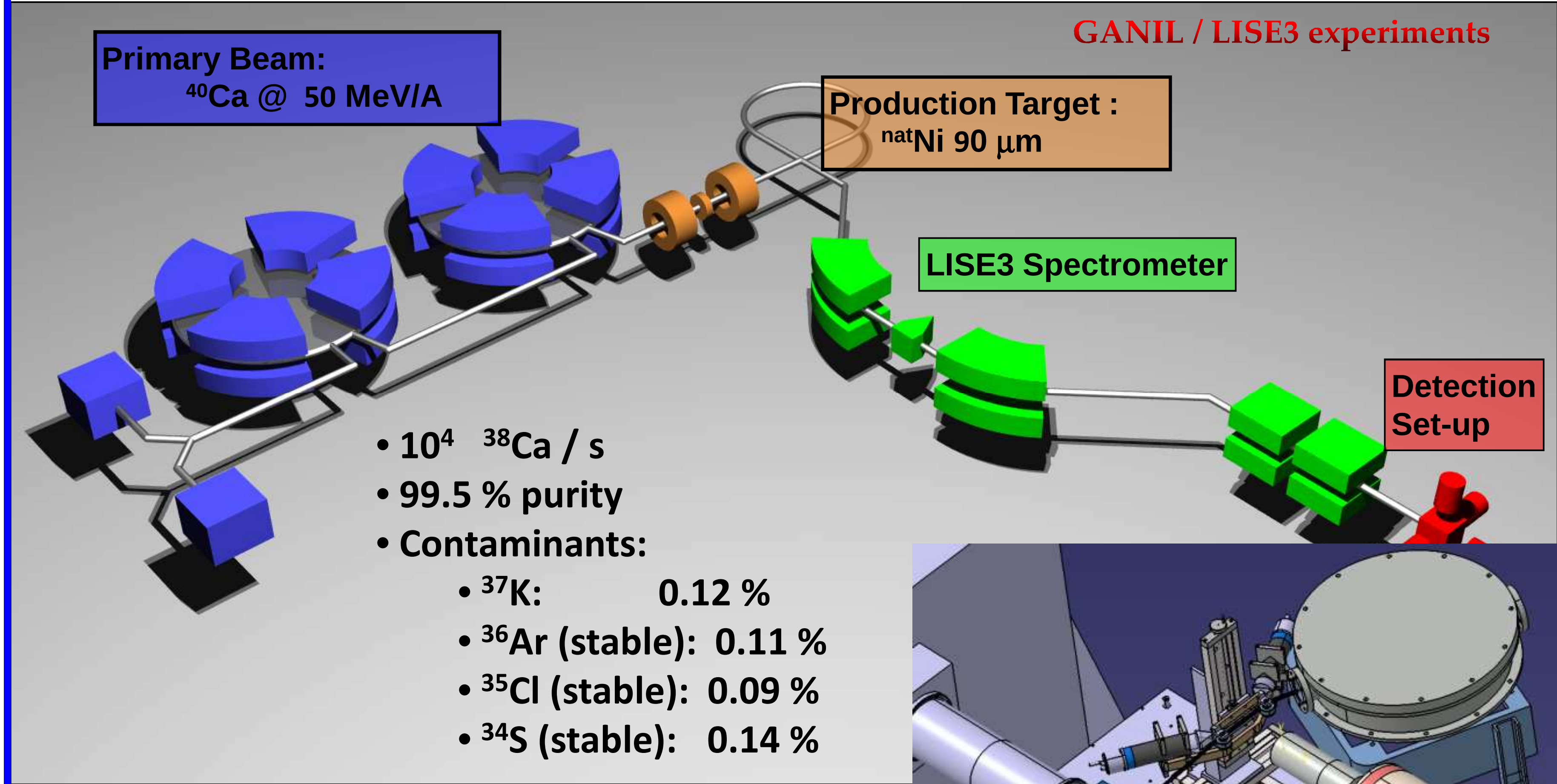
0^+ - 0^+ β decay: ^{38}Ca

Super-allowed Fermi transitions for T_z = -1

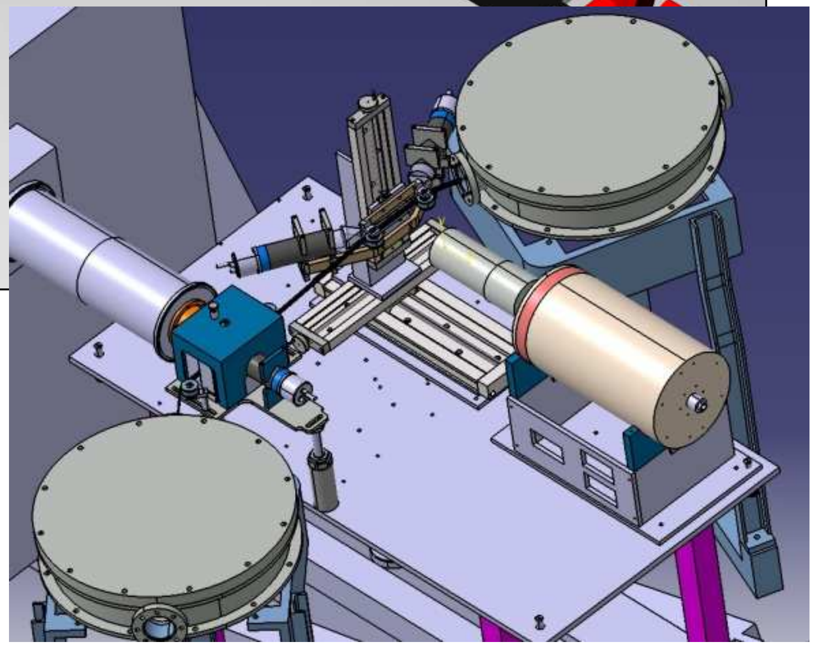


- many decay channels open
- strong non-analog transitions
- high precision of γ efficiency needed ➔ 0.1%

^{38}Ca production at GANIL/LISE3

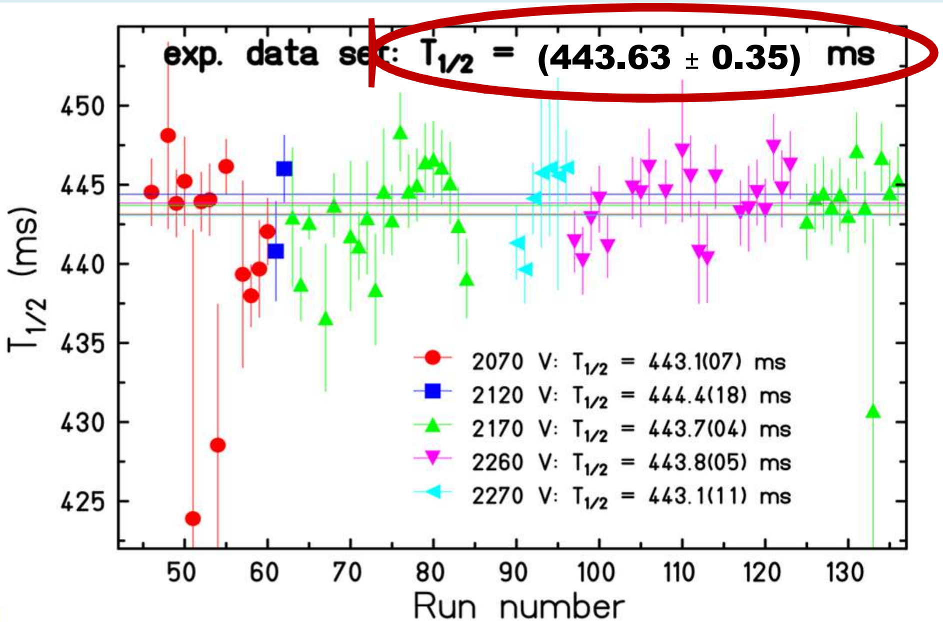


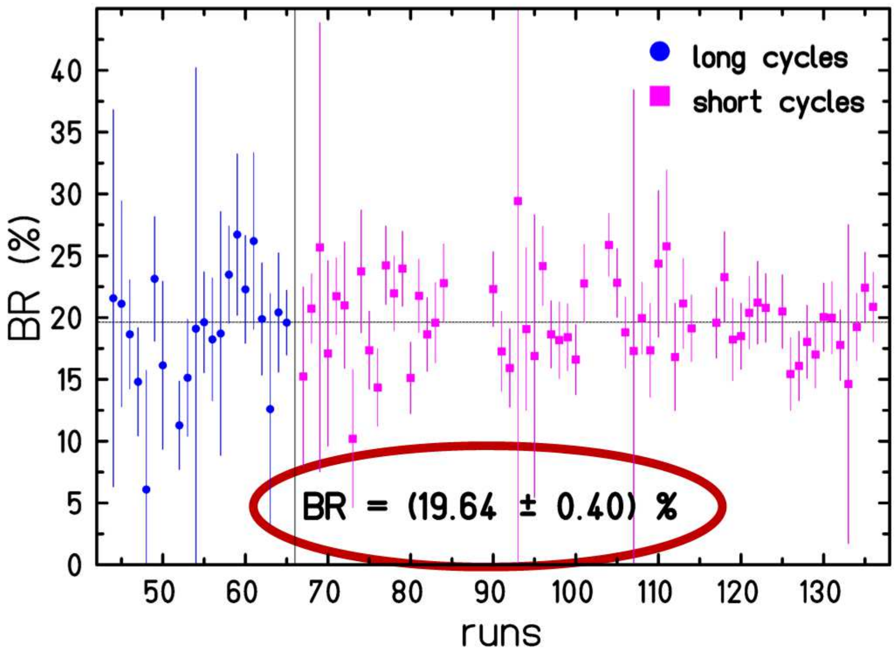
- 10^4 ^{38}Ca / s
- 99.5 % purity
- Contaminants:
  - ^{37}K: 0.12 %
  - ^{36}Ar (stable): 0.11 %
  - ^{35}Cl (stable): 0.09 %
  - ^{34}S (stable): 0.14 %



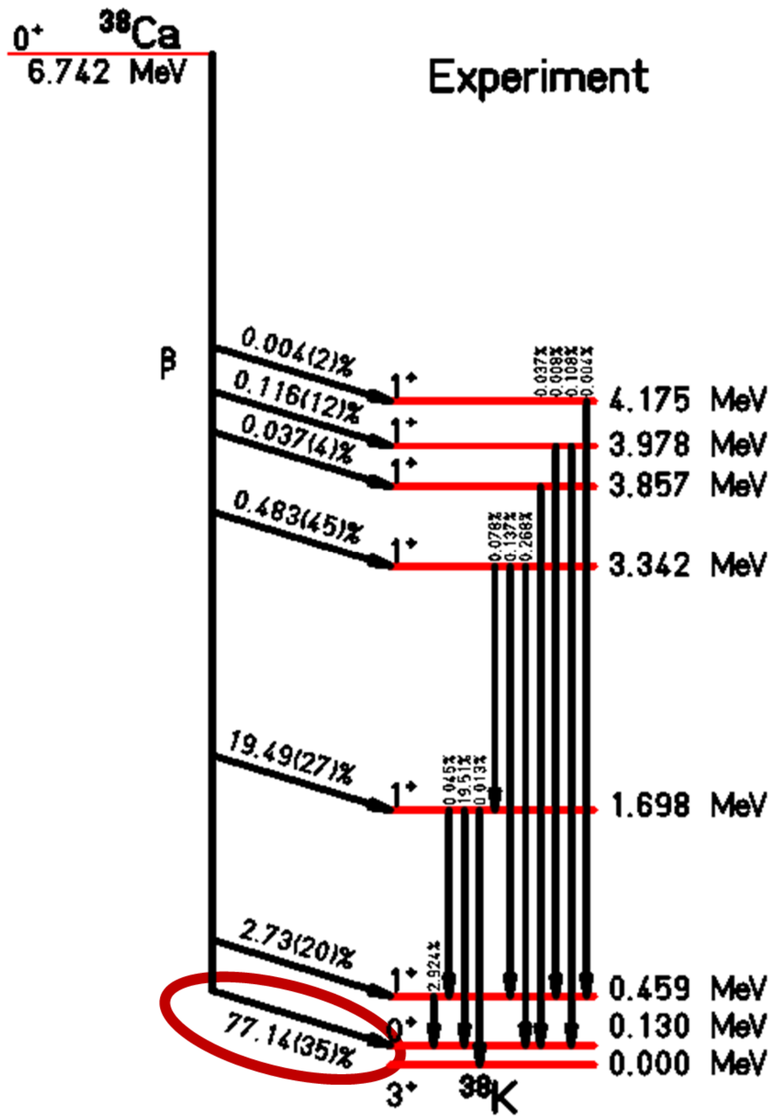
^{38}Ca branching ratios and half-life

B. Blank et al., EPJA 51 (2015) 8





Present work and Anderson et al.



³⁸Ca: result

B. Blank et al., EPJA 51 (2015) 8

- half-life:

Kavanagh *et al.* [26]	Gallmann *et al.* [27]	Zioni *et al.* [28]	Wilson *et al.* [29]	Blank *et al.* [20]	Park *et al.* [5]	Present	Average
470(20)	439(12)	450(70)	430(12)	443.8(19)	443.77(36)	443.63(35)	443.70(25)

➔➔ 443.70(25) ms

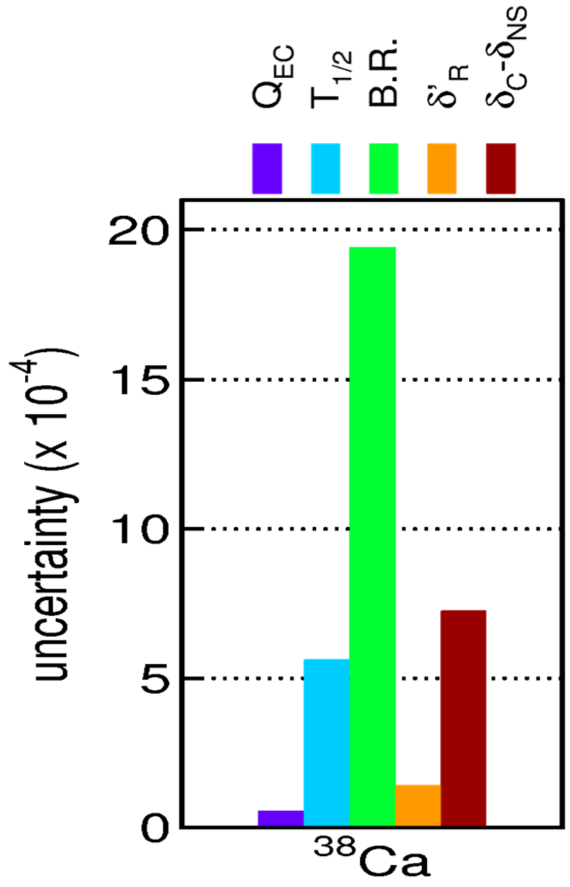
- BR (0^+ — 0^+): present: 77.09(35) %
  Park et al.: 77.28(16) %

➔➔ 77.25(15) %

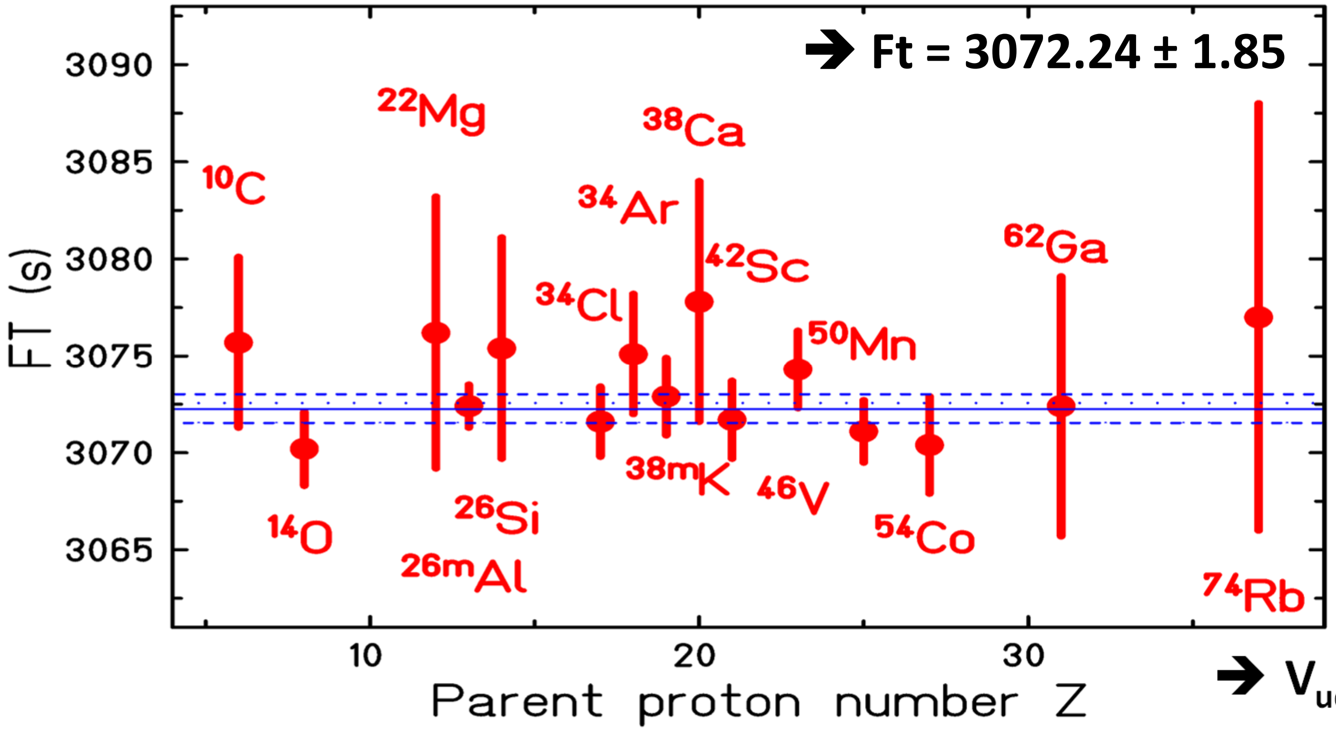
- Q value: Eronen et al.: 6612.11(7) keV

➔ ft = 3063.3(62) s

➔ $\mathcal{F}$t = 3077.5(67) s

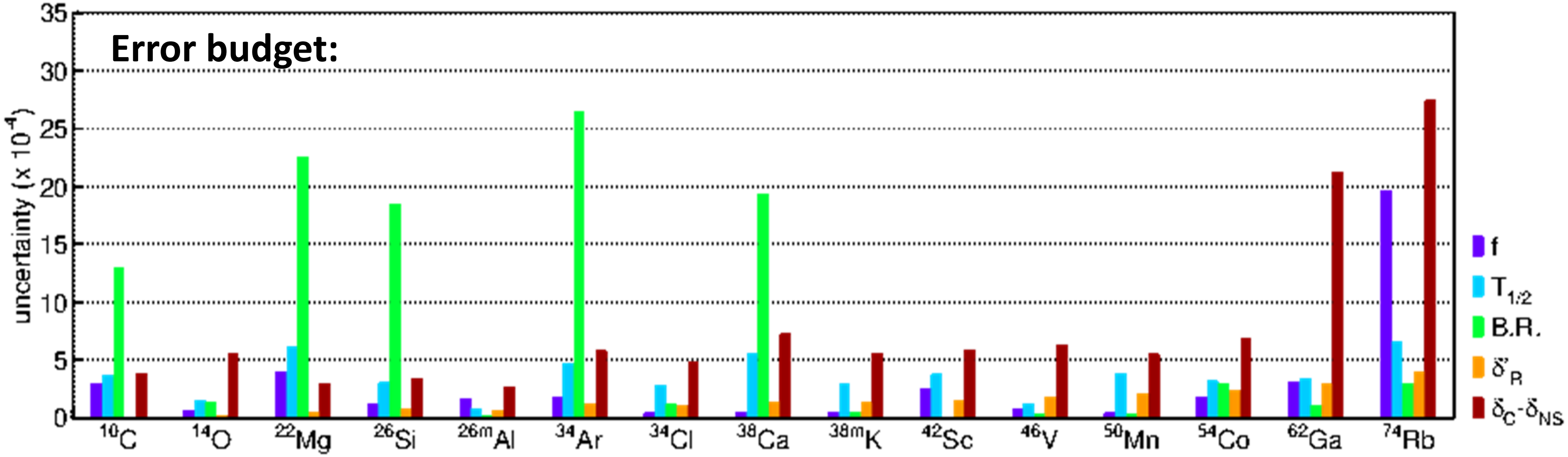


0⁺ → 0⁺ decays: present status



- 15 nuclei
- other nuclei under study:
  - ^{18}Ne
  - ^{30}S
  - ^{42}Ti
  - ^{58}Zn
  - + heavier to come

→ V_{ud} = 0.9740 ± 0.0005



V_{ud} from different source and unitarity of CKM matrix

0^+ - 0^+ decays:	$V_{ud} = 0.9740 \pm 0.0005$
mirror decays:	$V_{ud} = 0.9742 \pm 0.0009$
neutron decay:	$V_{ud} = 0.9743 \pm 0.0006$

→ →

$V_{ud} = 0.9741 \pm 0.0004$

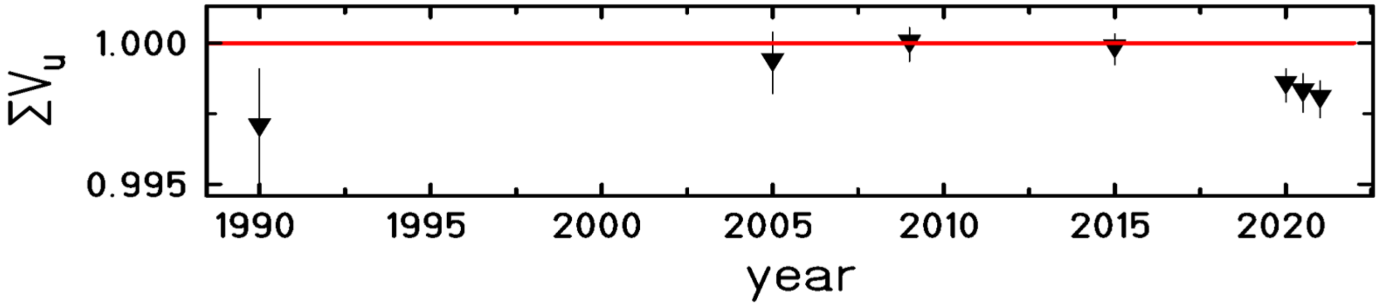
$V_{us} = 0.2243 \pm 0.0005$

$V_{ub} = (3.94 \pm 0.36) \times 10^{-3}$

$$V_{ud}^2 + V_{us}^2 + V_{ub}^2 = 0.9992 \pm 0.0007 \rightarrow 1.1\sigma$$

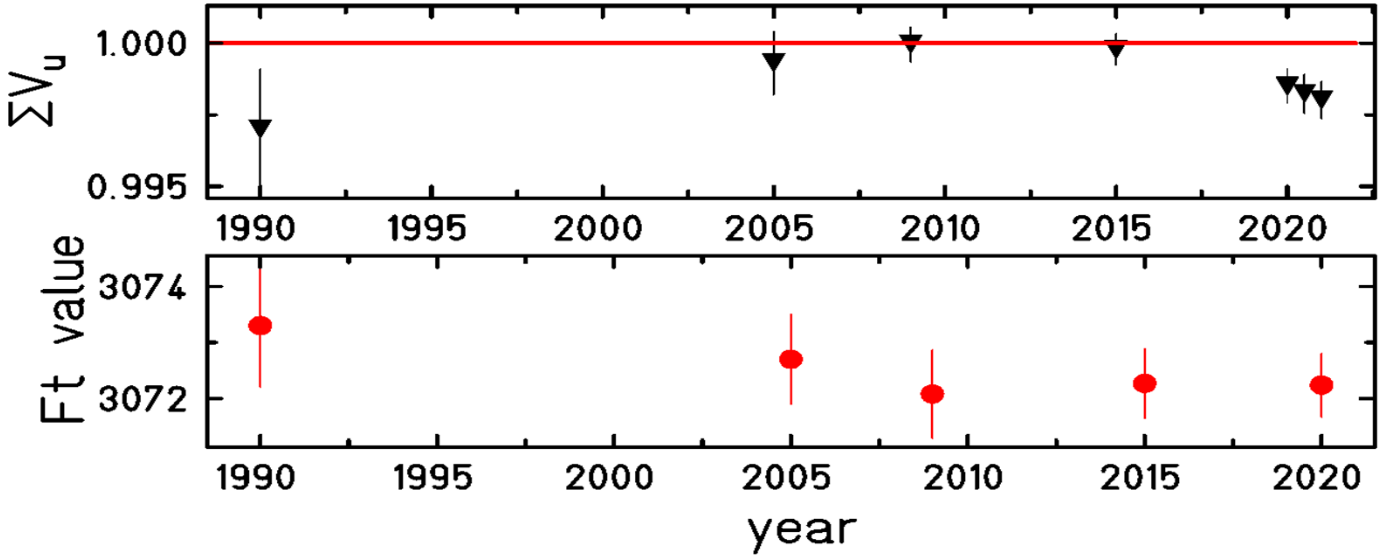
but also 3.1σ (see Hardy & Towner 2020)

Evolution of Σv_u , Ft, V_{ud}, V_{us} and Δ_R



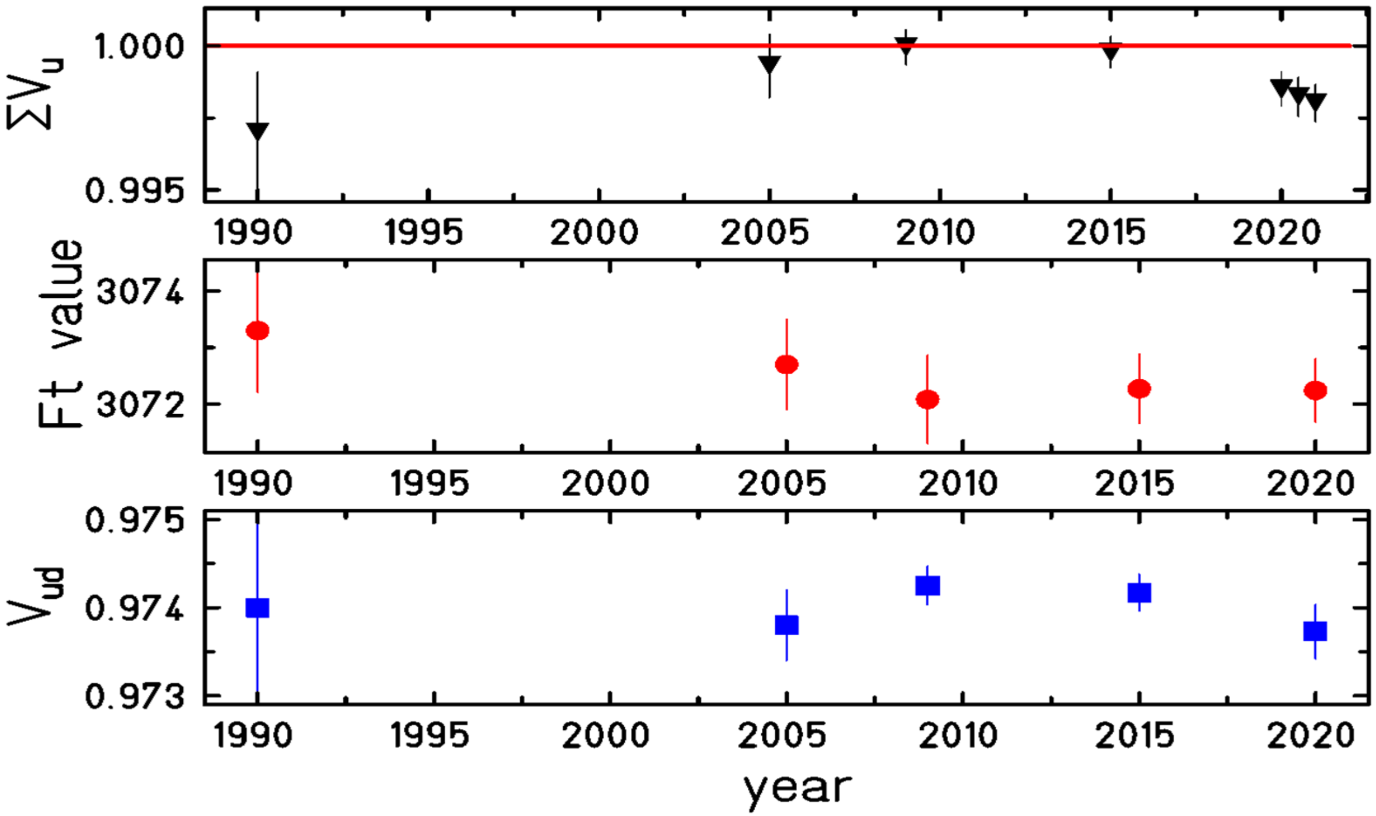
Hardy & Towner

Evolution of Σv_u , Ft, V_{ud}, V_{us} and Δ_R



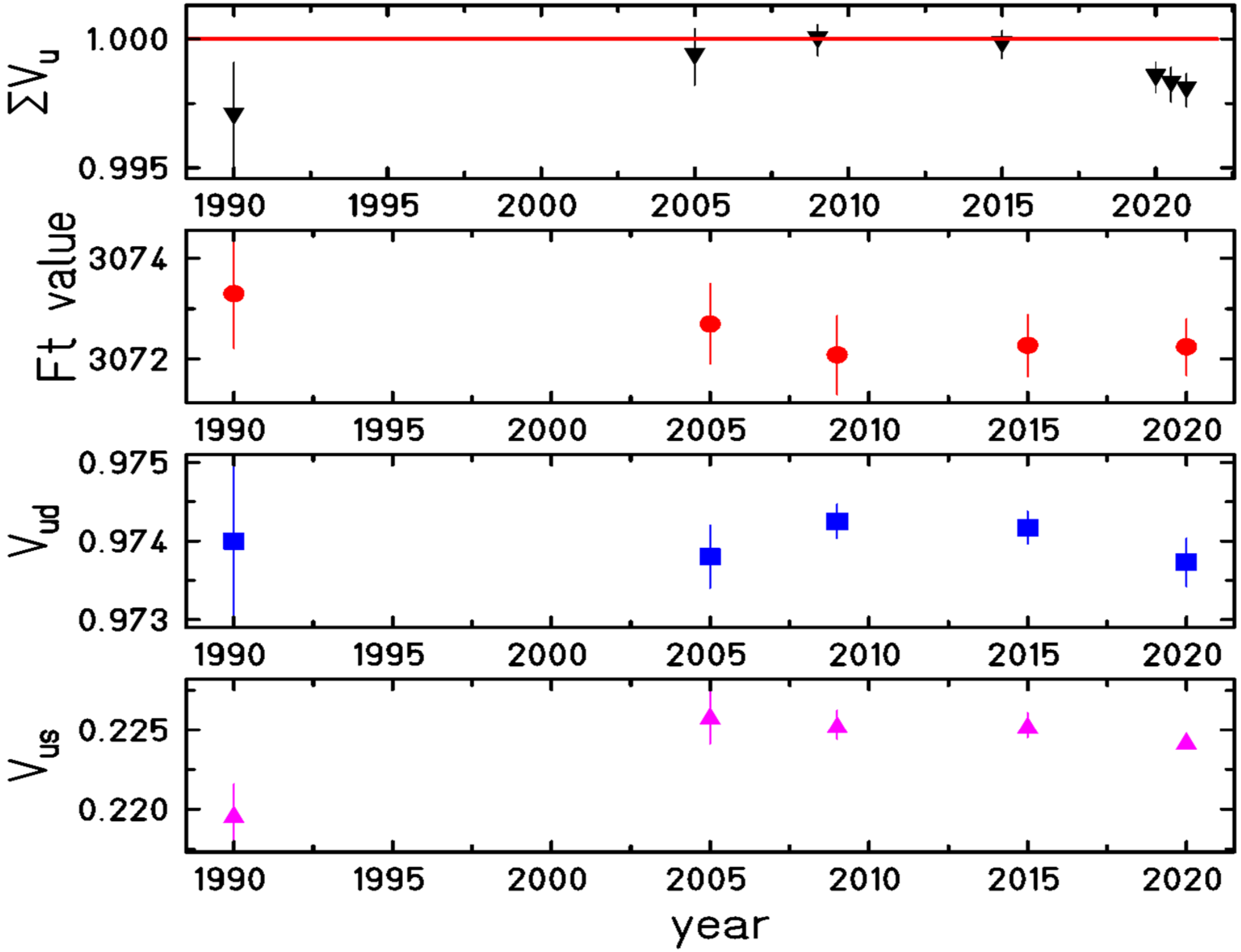
Hardy & Towner

Evolution of Σv_u , Ft, V_{ud}, V_{us} and Δ_R



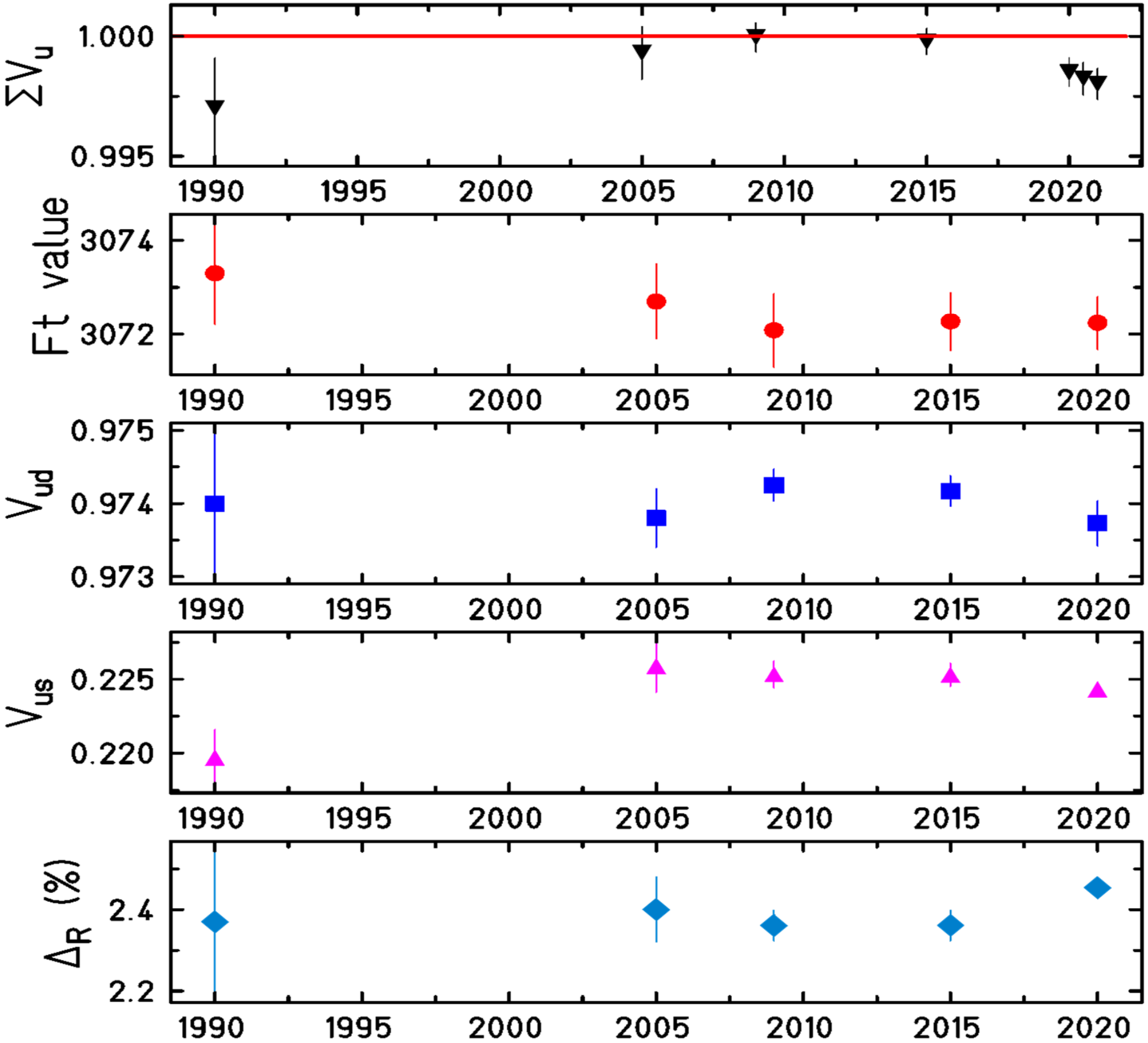
Hardy & Towner

Evolution of Σv_u, Ft, V_{ud}, V_{us} and Δ_R



Hardy & Towner

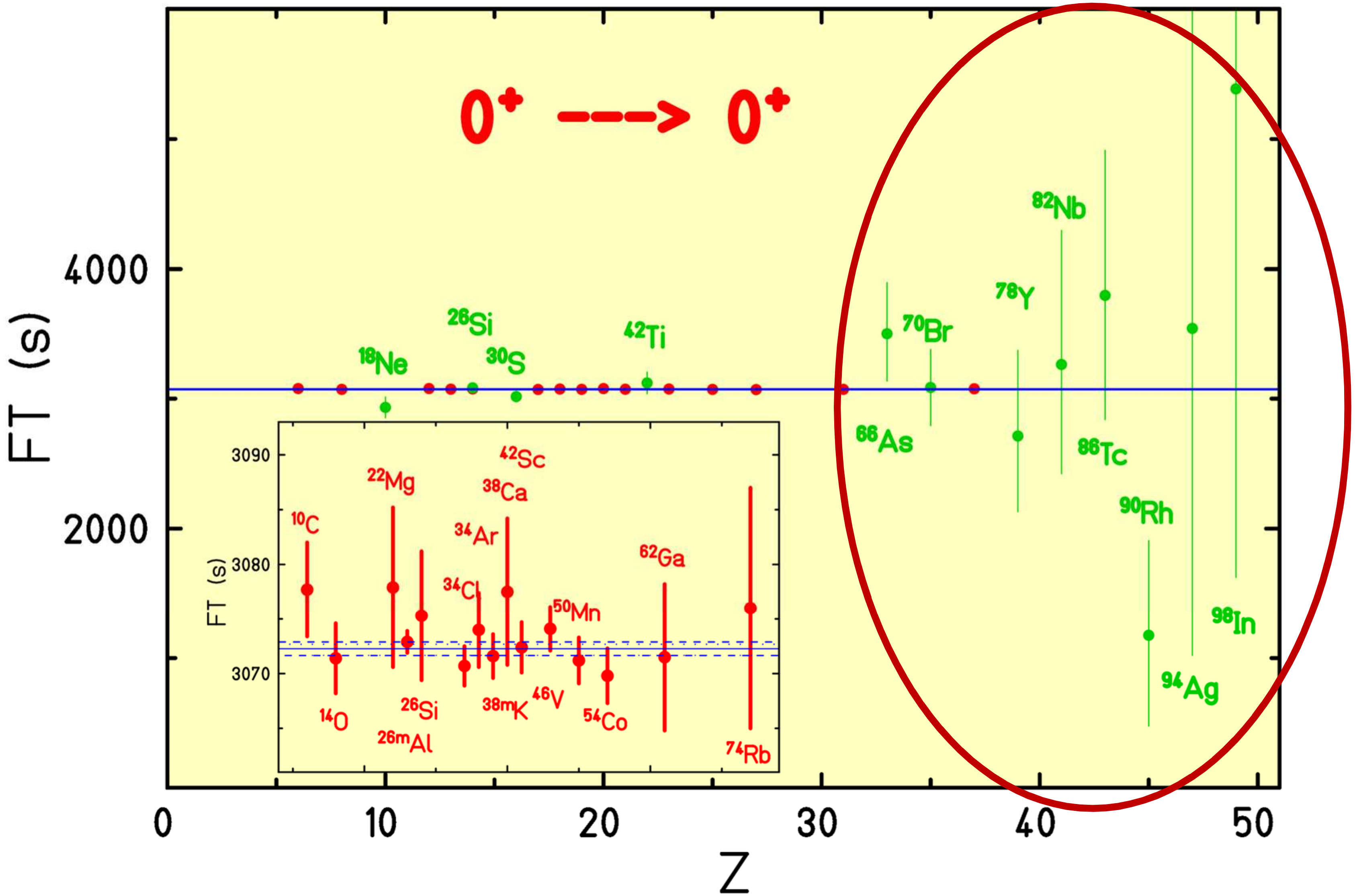
Evolution of Σv_u , Ft, V_{ud}, V_{us} and Δ_R



Hardy & Towner

Future measurements at GANIL

Heavy T_z = 0 nuclei



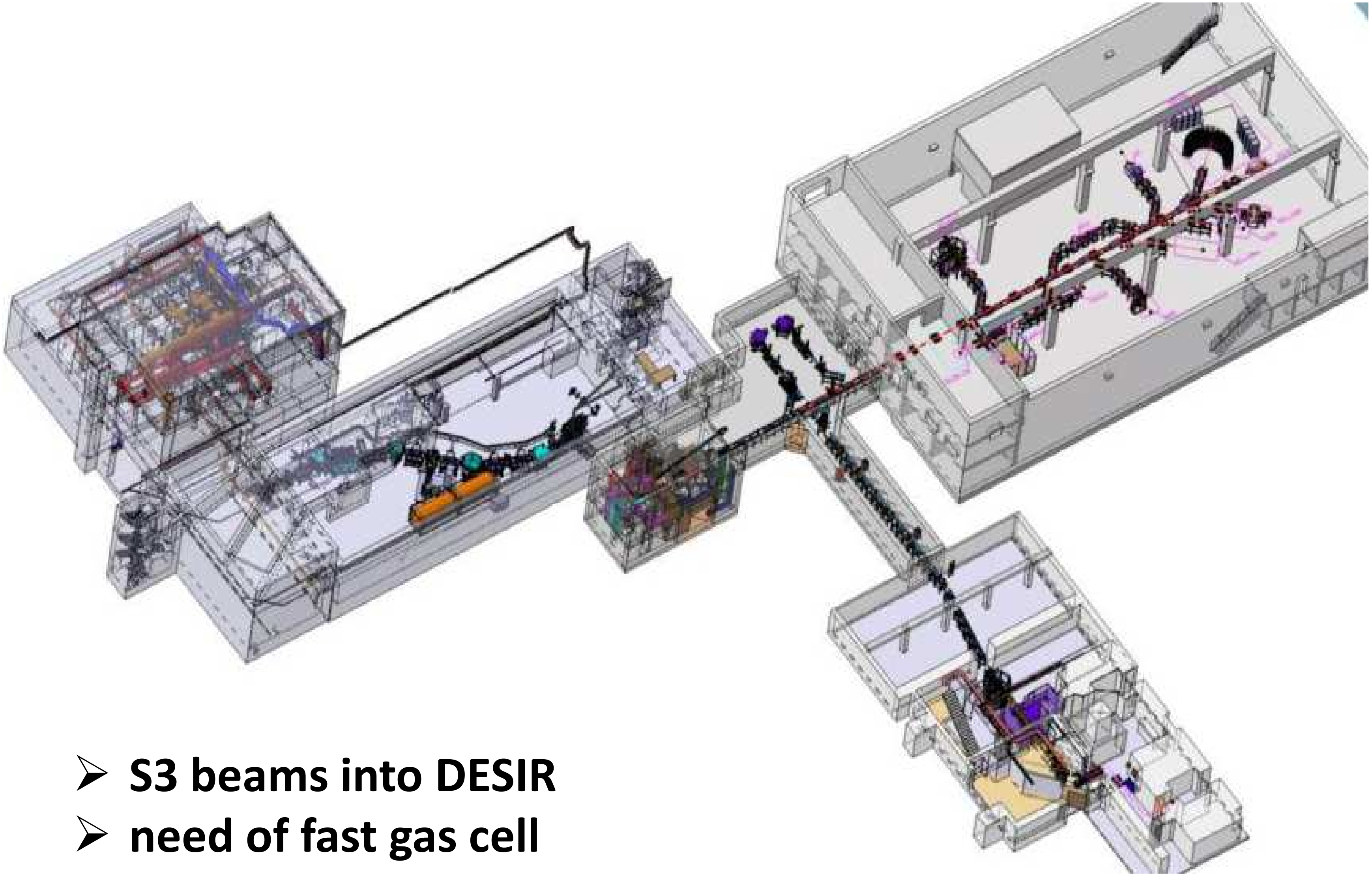
- test CVC on a much larger basis

Heavy T_z = 0 nuclei: production at S3-LEB

isotope	half-life (ms)	rate day I (pps)	rate day II (pps)	rate A/Q=7 (pps)	rate A/Q=7 fast cell (20ms) (pps)
^{66}As	95.77(23)	75	450	750	4000
^{70}Br	79 .1(8)	200	400	400	3000
^{74}Rb	64.78(3)	100	150	150	2000
^{78}Y	54(5)	10	10	15	300
^{82}Nb	50(5)	1.5	1.5	3	70
^{86}Tc	55(6)	1.5	1.5	3	50
^{90}Rh	15(7)	3e-4	4e-4	7e-4	30
^{94}Ag	37(18)	0.6	0.7	1	90
^{98}In	37(5)	5e-4	6e-4	1e-3	7e-2

➔ test CVC over a larger range of Z

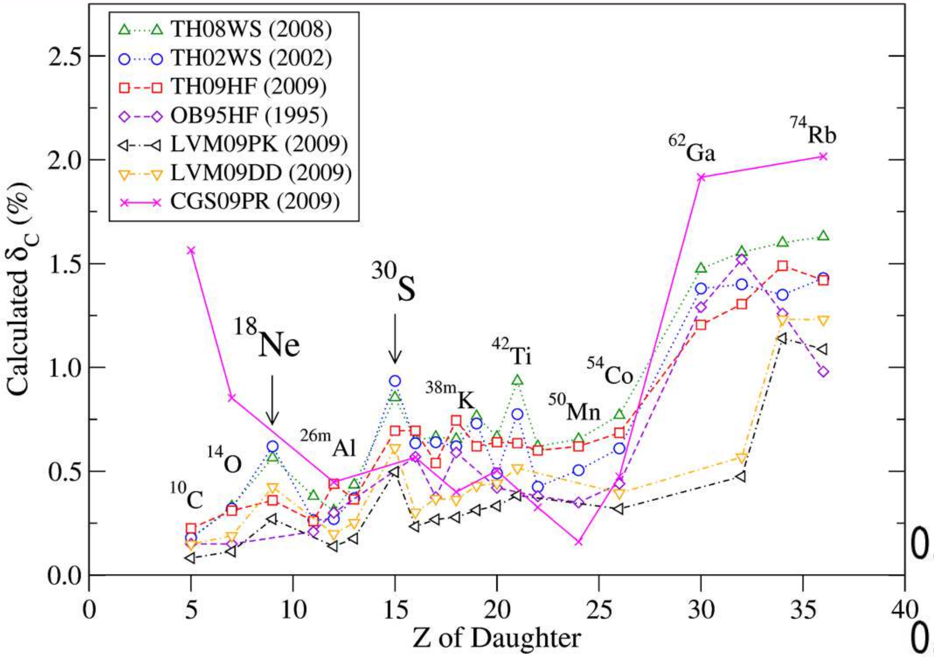
S3-LEB + DESIR



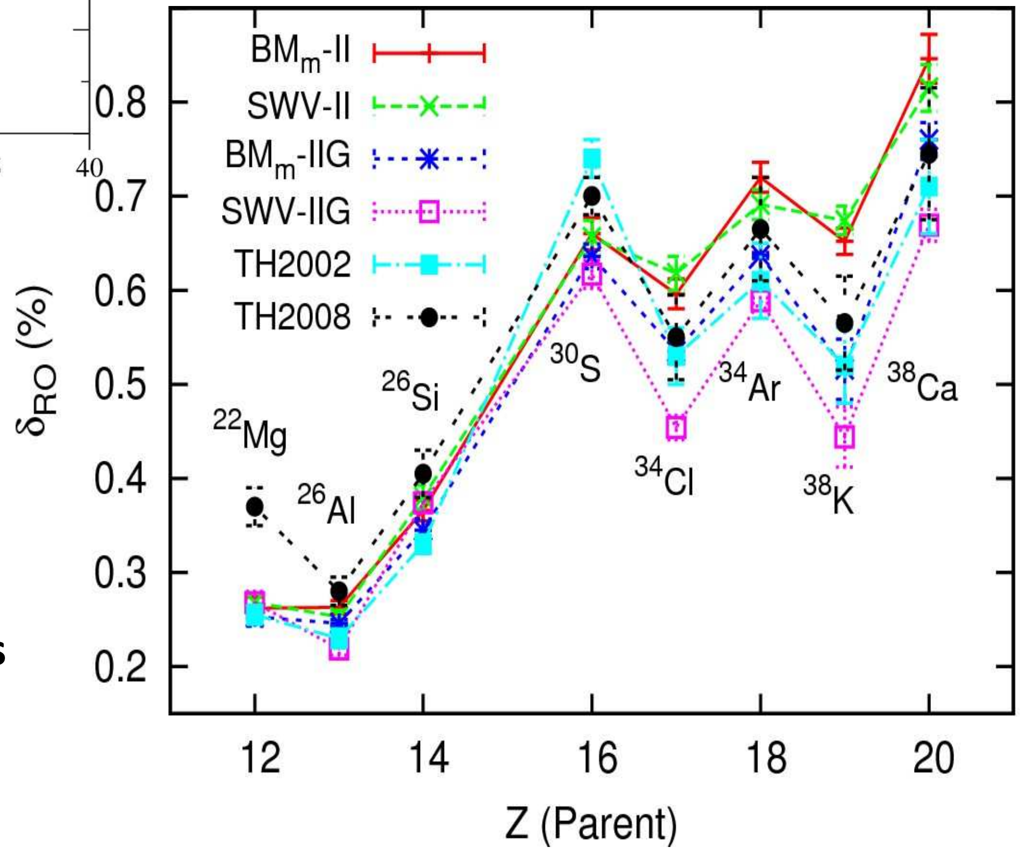
- S3 beams into DESIR
- need of fast gas cell
- purification with HRS + MR-TOF-MS or PIPERADE
- best place world-wide to do this

0⁺ → 0⁺ decays: new theoretical corrections for δ_c

N. Smirnova, Y. Lam, L. Xayavong et al.



previous calculations



new calculations

Search for scalar contributions

$0^+ \rightarrow 0^+$ decays: limits on exotic currents

- **standard model assumption: only vector current**

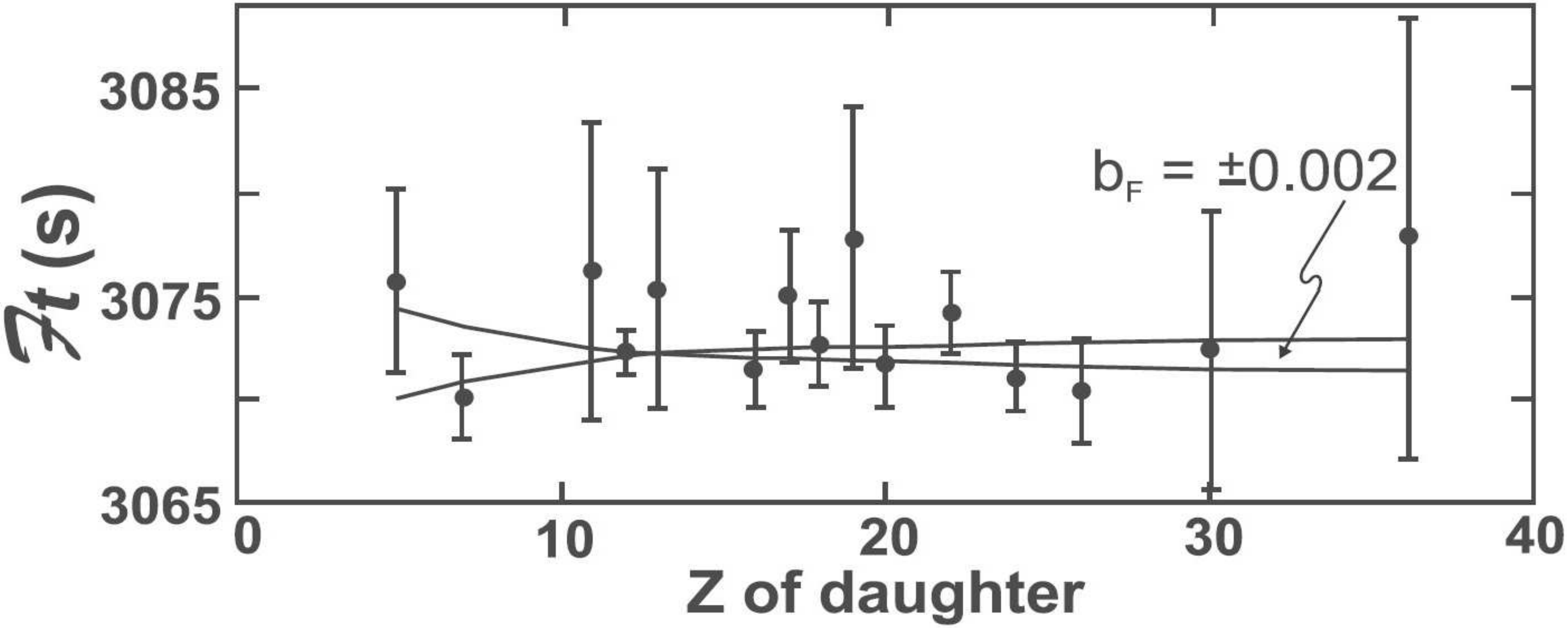
$$dW = dW_0\left(1 + a\frac{\mathbf{p}_e \cdot \mathbf{p}_\nu}{E_e E_\nu} + \cancel{b\frac{m_e}{E_e}}\right)$$

- **if scalar currants, we obtain for $\mathcal{F}t$**

$$dW = dW_0\left(1 + \cancel{a\frac{\mathbf{p}_e \cdot \mathbf{p}_\nu}{E_e E_\nu}} + b\frac{m_e}{E_e}\right)$$

- **$\mathcal{F}t \Rightarrow \mathcal{F}t * \left(1 + \frac{y\, bF}{<W>}\right)$, $y^2 = 1 - Z^2\alpha^2$**
- **limit on scalar current from term in $\mathcal{F}t$ function:** **$(1 + b_f\, y / <W>)$**

0⁺ → 0⁺ decays: limits on exotic currents

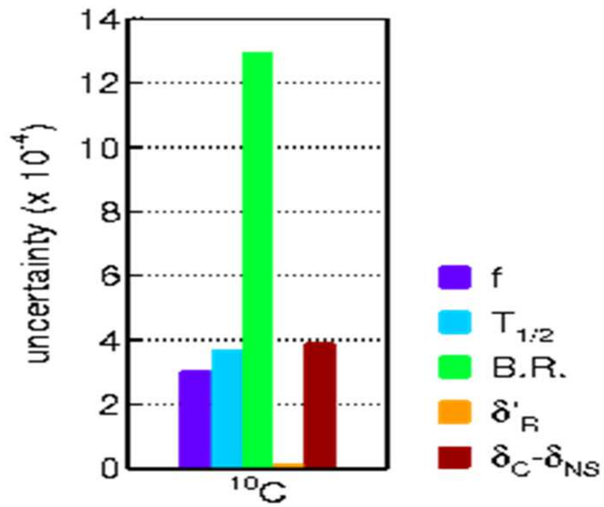


- from β decay: $b_F = 0.0000 \pm 0.0020 \sim \left(\frac{C_s + C_s'}{C_V} \right)$

➔➔ improve on low-Z nuclei

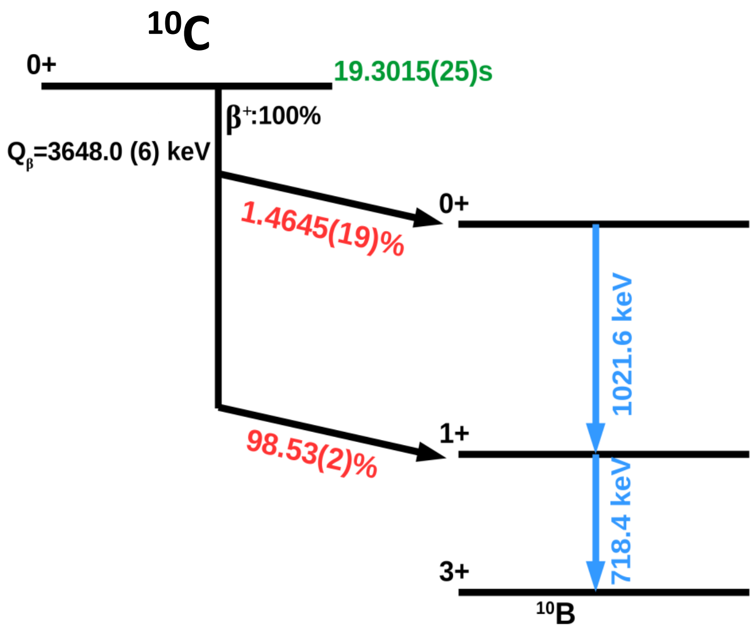
0⁺ → 0⁺ decays: ^{10}C error budget

- BR by far largest error
- two precise measurements:
  - Savard et al.: 1.4625(25)%
    (PRL 74 (1995) 1521)
  - Fujikawa et al.: 1.4665(38)%
    (PLB 449 (1999) 6)
  - ➔measurements with Ge multi-detector array



our approach:

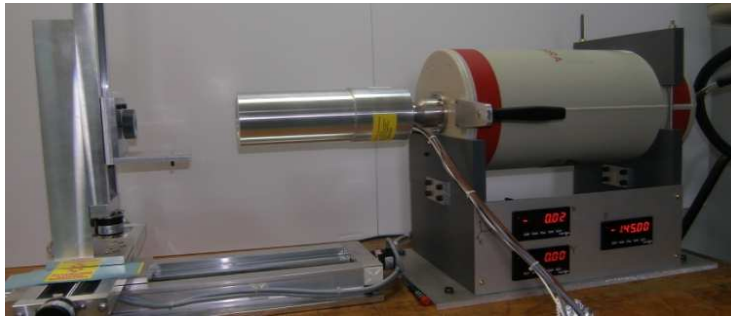
re-measuring the BR of ^{10}C with out precisely calibrated Germanium detector



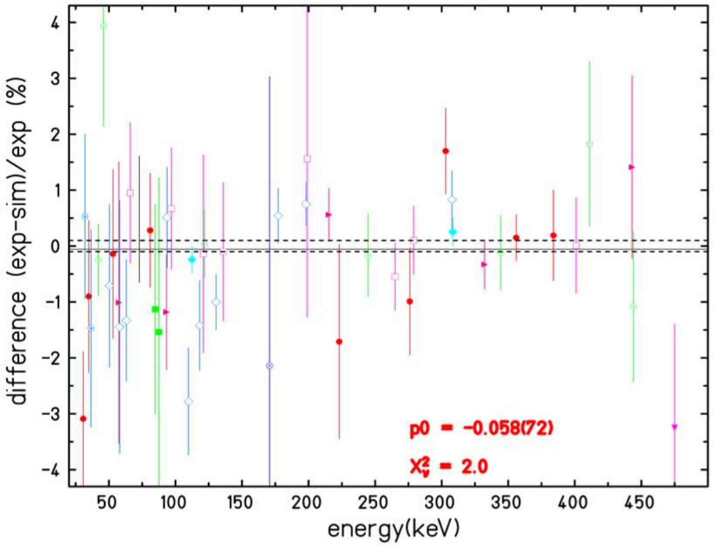
Calibration of germanium detector

B. Blank et al., NIMA776 (2015) 34

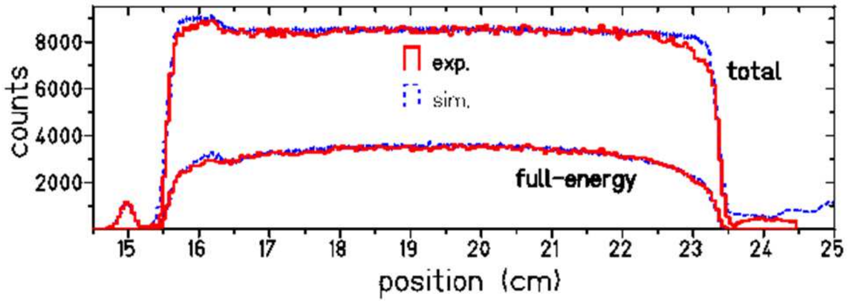
- $\Delta\varepsilon_{rel}$ = 0.1%, $\Delta\varepsilon_{abs}$ = 0.15%
- calibration programme of a HP Ge detector:
  - x-ray photography of detector
  - scan of the crystal at CSNSM Orsay
  - source measurements at CENBG, IPNO, ISOLDE
  - MC simulations: CYLTRAN, GEANT4

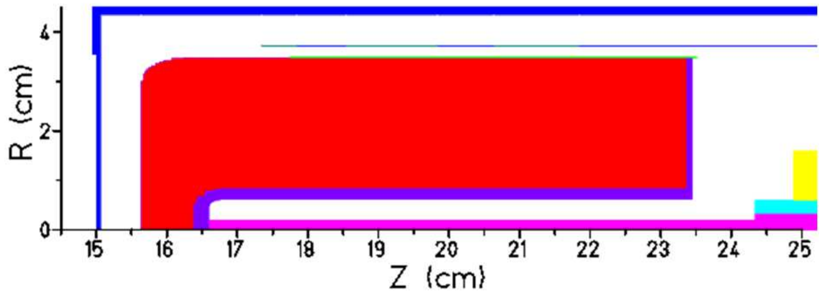


X-ray photography



Scan at CSNSM: ^{137}Cs strongly collimated





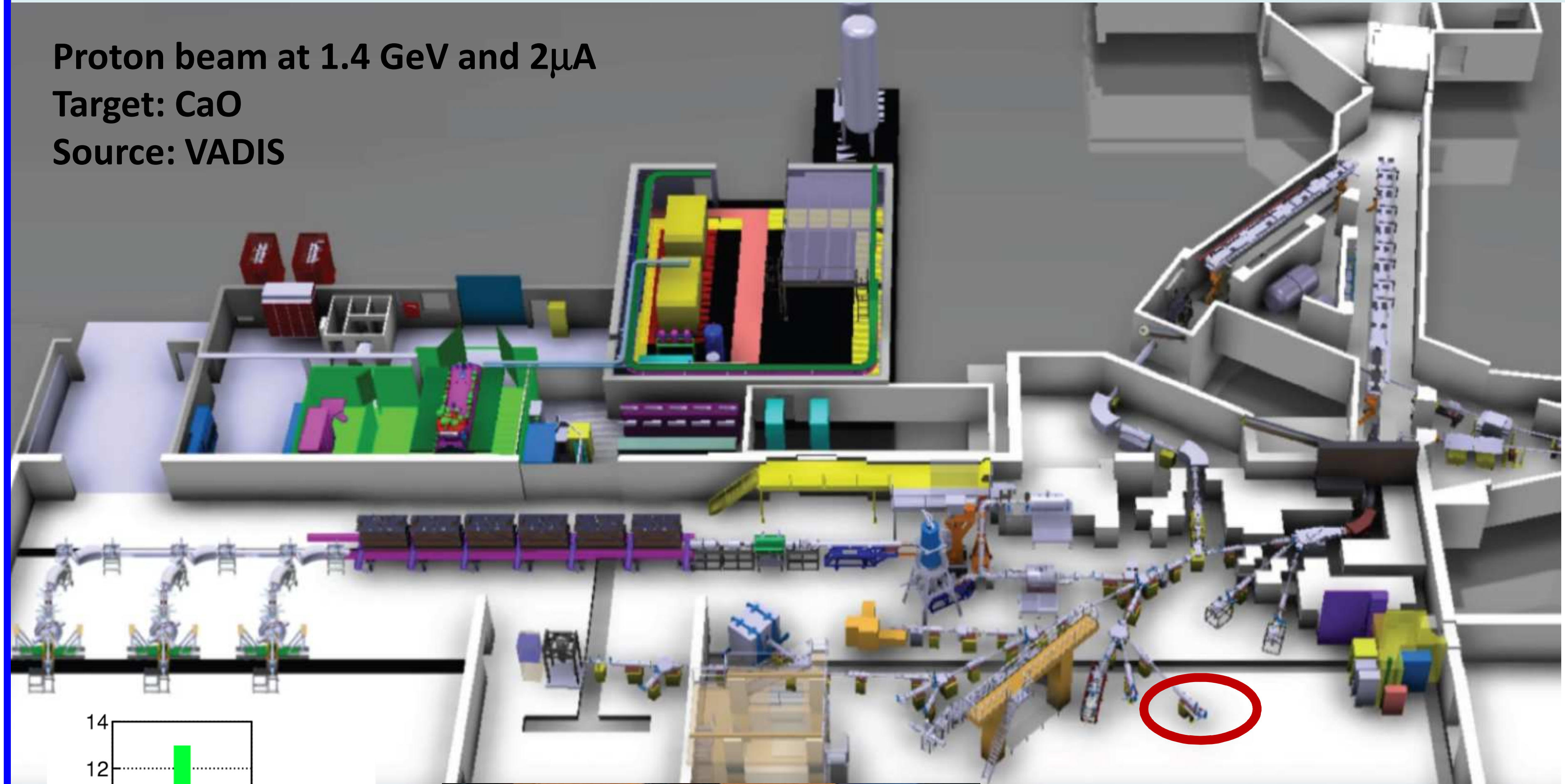
Relative detection efficiency:

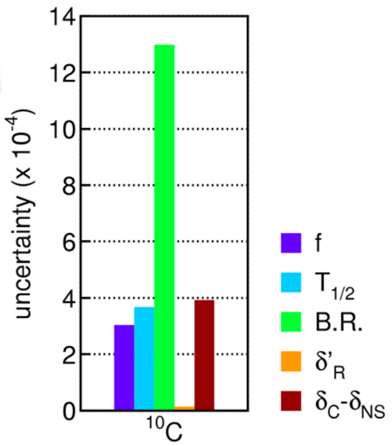
^{24}Na, ^{27}Mg, ^{48}Cr, ^{56}Co, ^{60}Co, ^{66}Ga, ^{75}Se, ^{88}Y, (^{109}Cd), ^{133}Ba, ^{134}Cs, ^{137}Ce, ^{152}Eu, ^{169}Yb, ^{180}Hf, ^{207}Bi

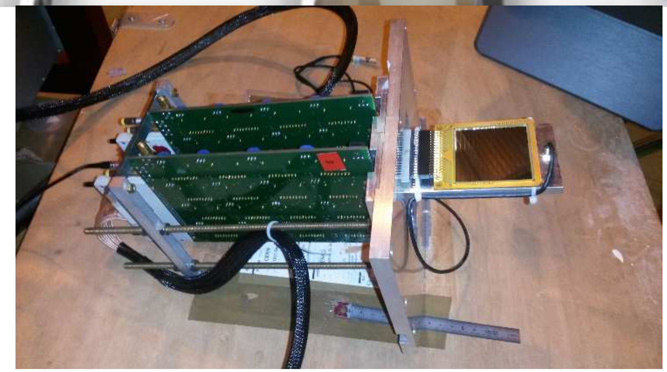
Peak/total: ^{22}Na, ^{38}K, ^{41}Ar, ^{51}Cr, ^{54}Mn, ^{57}Co, ^{58}Co, ^{60}Co, ^{65}Zn, ^{85}Sr, ^{137}Cs …ISOLDE, IPNO sources

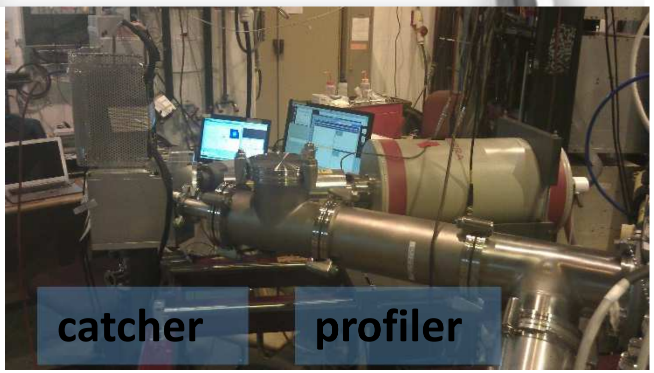
^{10}C measurement at ISOLDE

Proton beam at 1.4 GeV and 2μA
Target: CaO
Source: VADIS

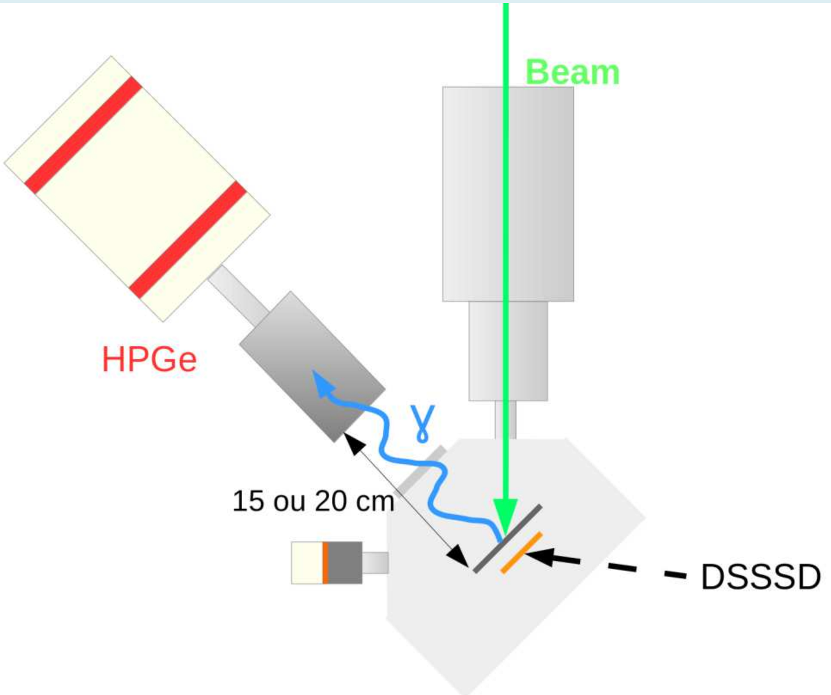


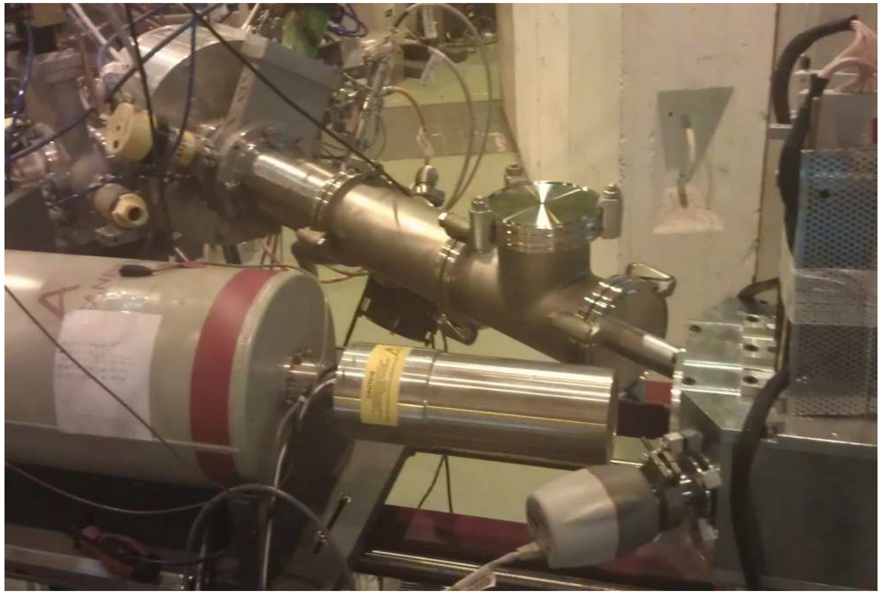


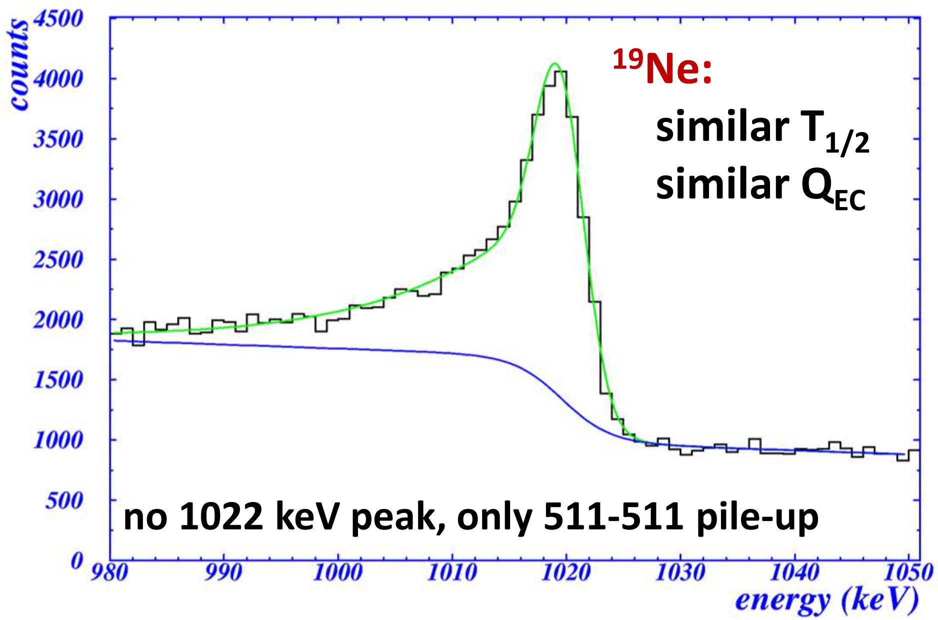


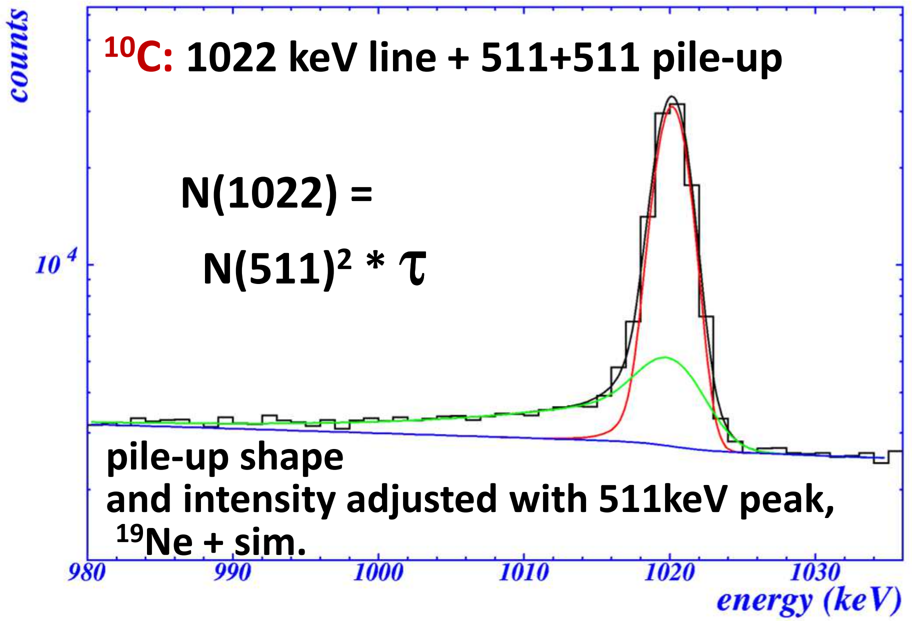


^{10}C experimental set-up and analysis procedure



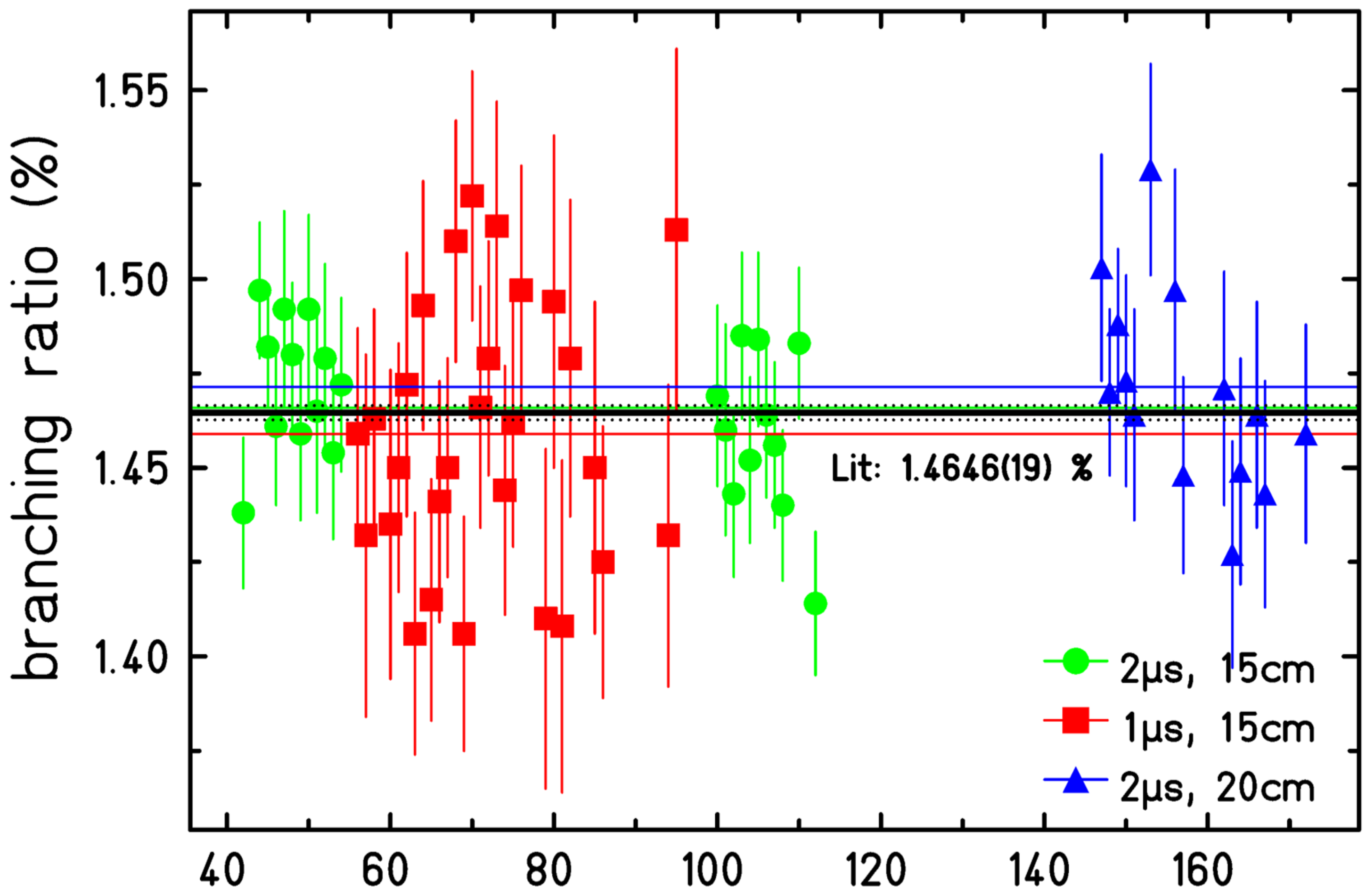






Super-allowed ranching ratio of ^{10}C

Blank et al., EPJA56 (2020) 156



next attempt:

- **higher statistics: difficult…**
- **higher purity: MR-ToF selection**

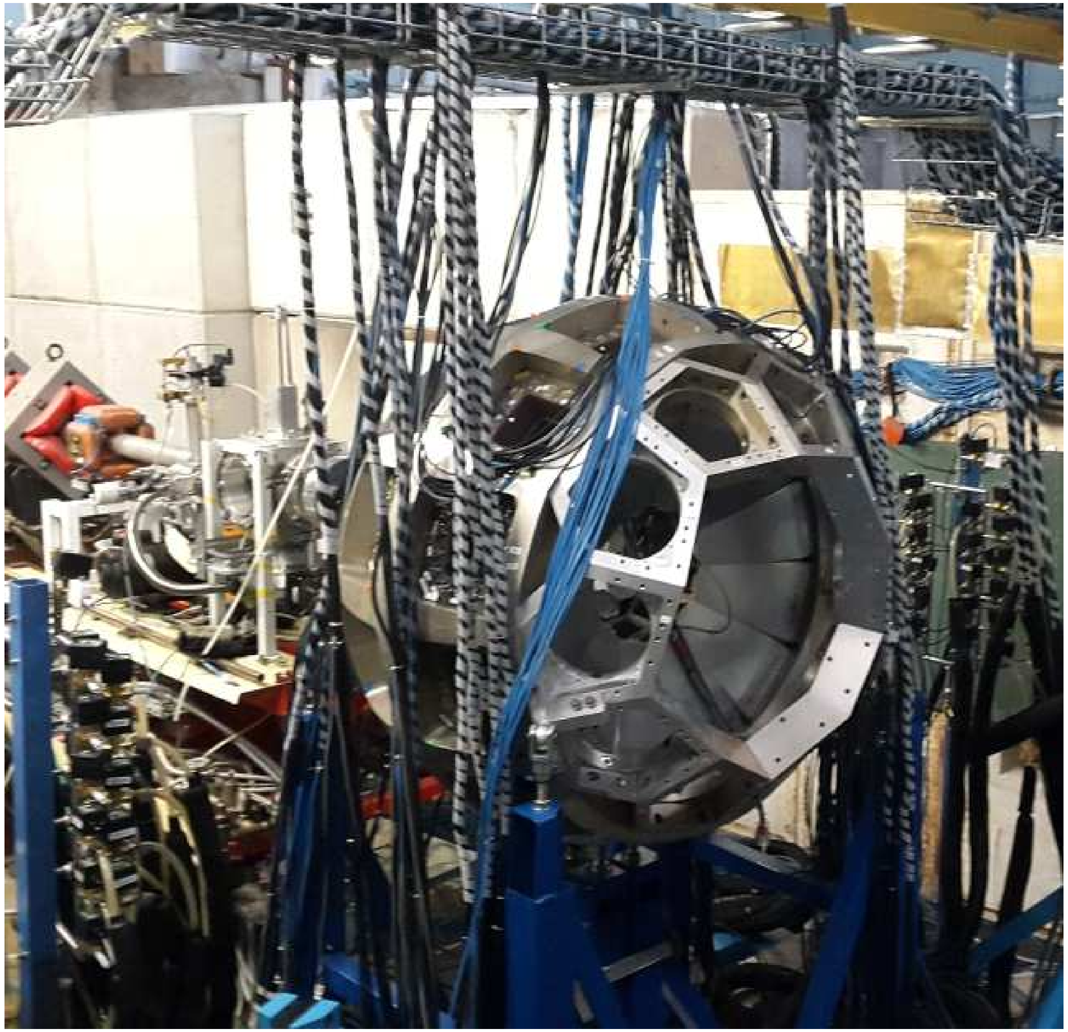
Final result:

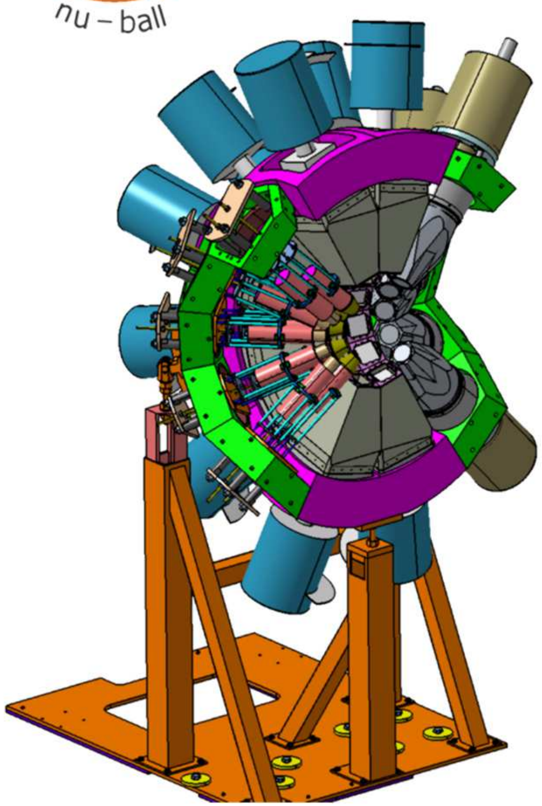
Literature:

statistics: 0.0039 %

pile-up: 0.0030 %

^{10}C measurement at ALTO/Orsay



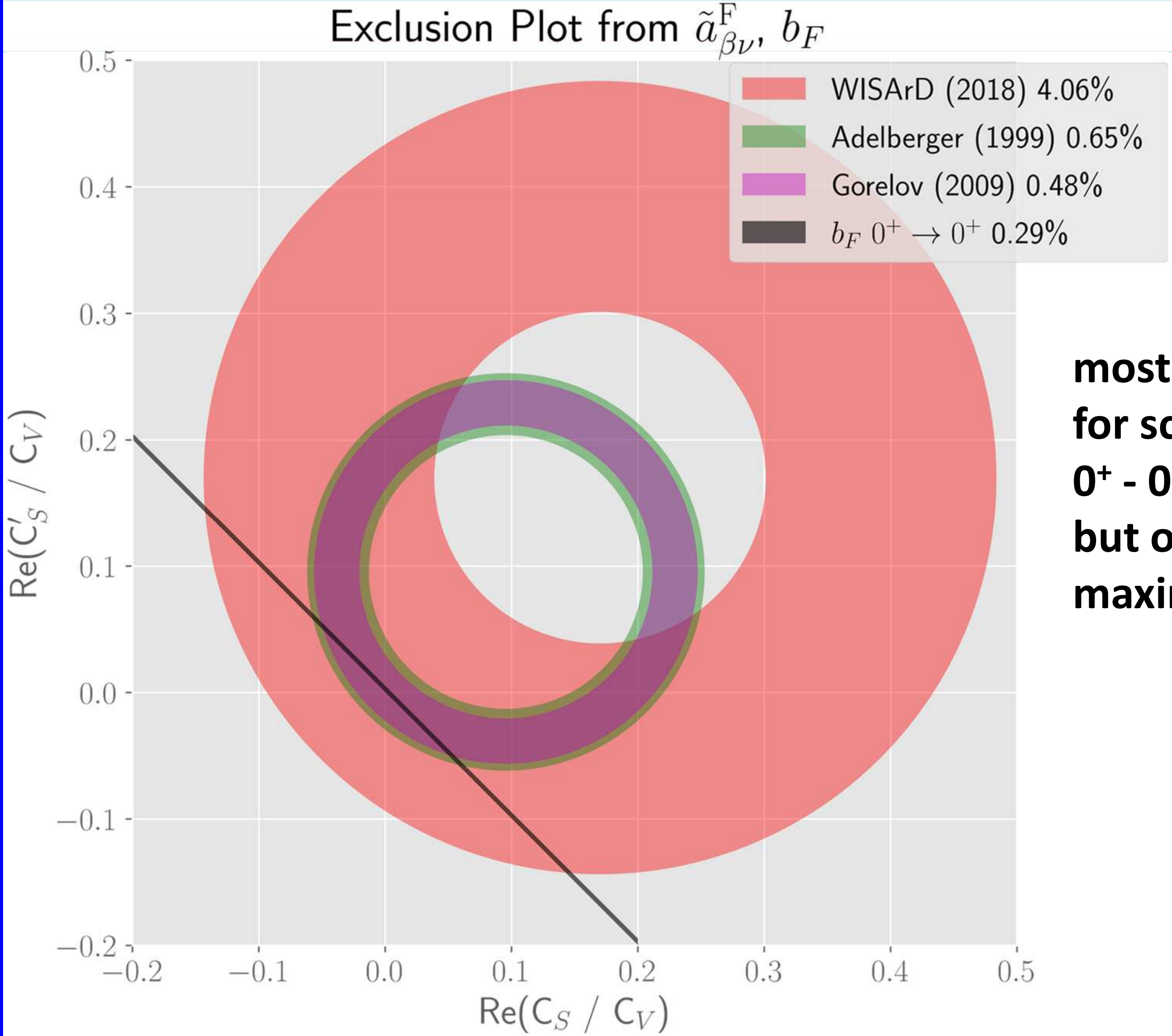


Scientific Manager: M. Lebois
Technical Manager: B. Genolini

100 Ge crystals: 5.5% @ 1 MeV
18 $LaBr_3$: 1.5% @ 1 MeV

data under analysis…. …also statistics limited

Conclusions



most stringent limits for scalar currents from 0^+ - 0^+ β decay, but only in model with maximal parity violation

V. Araujo-Escalona et al. Phys. Rev. C101, 055501 (2020)

Conclusions

- most stringent limits for scalar currents from 0^+ - 0^+ β decay, but only in model with maximal parity violation
  ➔ if no parity violation for scalar currents, no sensitivity

- need for improved Ft values for light nuclei ^{10}C, ^{14}O
- interest in heavier 0^+ - 0^+ decays to improve CVC condition
- more efforts needed from theory to better define corrections

Thanks for your attention