Search for exotic weak couplings with nuclear beta decay

Bertram Blank
LP2i Bordeaux

- Super-allowed 0^+ - 0^+ β decay: ^{10}C decay
- β–ν angular correlation measurements: WISArD
- Beta-shape measurement: InESS (^{114}In)

September 9 - 13, 2024

Hamiltonian: Lorentz invariance

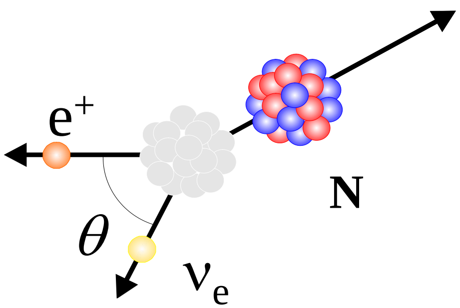
J.D. Jackson et al, Nucl. Phys. 4 (1957) 206
M. González-Alonso et al., Prog. Part. Nucl. Phys. 104, 165 (2019)

hadronic terms — leptonic terms

$$
\begin{aligned}
H = &\,(\overline{\psi_p}\gamma_\mu\psi_n)(C_V\overline{\psi_e}\gamma_\mu\psi_\nu + C'_V\overline{\psi_e}\gamma_\mu\gamma_5\psi_\nu)\\
&+(\overline{\psi_p}\gamma_\mu\gamma_5\psi_n)(C_A\overline{\psi_e}\gamma_\mu\gamma_5\psi_\nu + C'_A\overline{\psi_e}\gamma_\mu\psi_\nu)\\
&+(\overline{\psi_p}\psi_n)(C_S\overline{\psi_e}\psi_\nu + C'_S\overline{\psi_e}\gamma_5\psi_\nu)\\
&+\frac{1}{2}(\overline{\psi_p}\sigma_{\lambda\mu}\psi_n)(C_T\overline{\psi_e}\sigma_{\lambda\mu}\psi_\nu + C'_T\overline{\psi_e}\sigma_{\lambda\mu}\gamma_5\psi_\nu) + \text{Hermitian conj.}
\end{aligned}
$$

(pseudo-scalar term omitted...)

coupling constant — 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")

- $C_S, C_S', C_T, C_T', C_P, C_P' \neq 0$
- Search for new particles (HEP) ←→ deviation from theory in β decay experiments

high-energy frontier — precision frontier

β-decay probability

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

β–ν correlation coefficient
CP conserving

Fierz interference term
CP conserving

β-asymmetry parameter
P violating

ν-asymmetry parameter
P violating

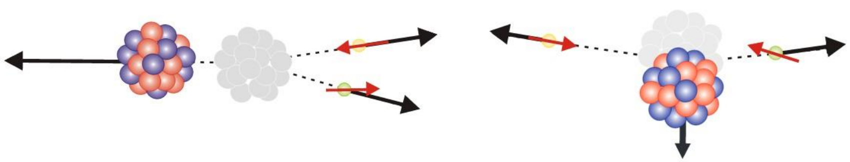
« D » coefficient
CP violating

for aligned spins only

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

pure Fermi transitions ΔJ=0

➪ S=0 : spin of leptons anti-parallel



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

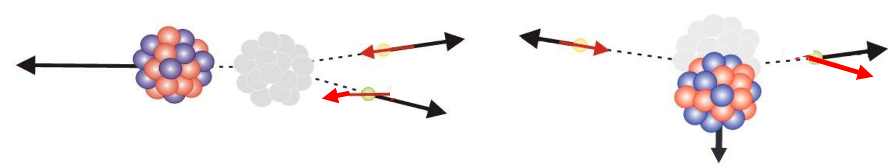
NP: scalar current
- Preferred emission angle: θ = 180°
- Minimum recoil energy

$$a^F_{\beta\nu} \cong 1 - \cancel{\frac{|C_S|^2+|C'_S|^2}{C_V^2}}$$

$$b^F_{\beta\nu} \cong \pm Re\left(\cancel{\frac{C_S+C'_S}{C_V}}\right)$$

pure Gamow-Teller transitions

➪ S=1 : spin of leptons parallel



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

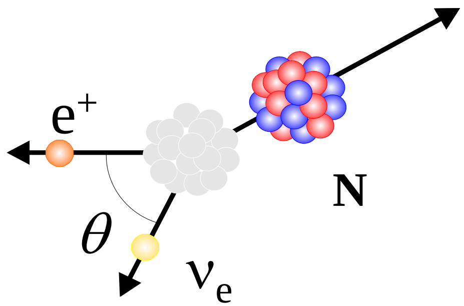
SM: axial-vector current
- Preferred emission angle: θ = 180°
- Minimum recoil energy

$$a^{GT}_{\beta\nu} \cong -\frac{1}{3}\left[1 - \cancel{\frac{|C_T|^2+|C'_T|^2}{C_A^2}}\right]$$

$$b^{GT}_{\beta\nu} \cong \pm Re\left(\cancel{\frac{C_T+C'_T}{C_A}}\right)$$

The nuclear laboratory: search for « beyond SM » physics

β-decay probability



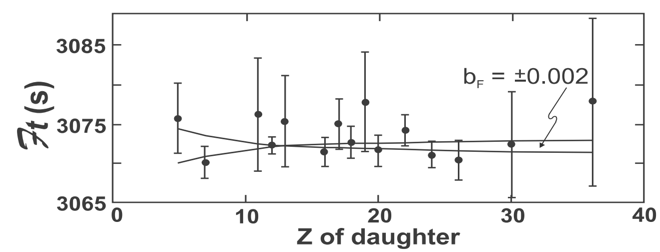
$$\frac{dW(\mathbf{J})}{dE_e d\Omega_e d\Omega_\nu} = \boxed{dW_0} \times \xi \left\{ 1 + \boxed{a} \frac{\mathbf{p_e} \cdot \mathbf{p}_\nu}{E_e E_\nu} + \boxed{b} \frac{m_e}{E_e} \right\}$$

phase space factor

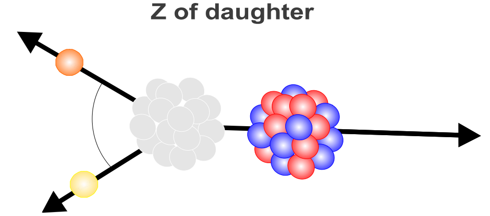
β–ν angular correlation coefficient

Fierz interference term = 0 (SM)

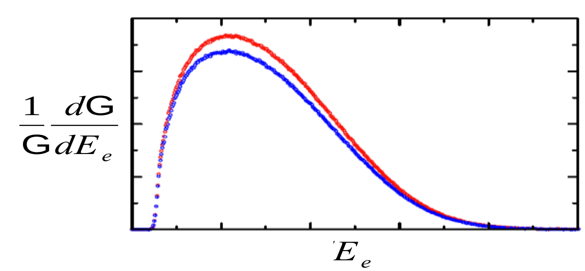
- effect on Ft values: $\mathcal{F}t \sim b \left\langle \frac{m_e}{E_e} \right\rangle$



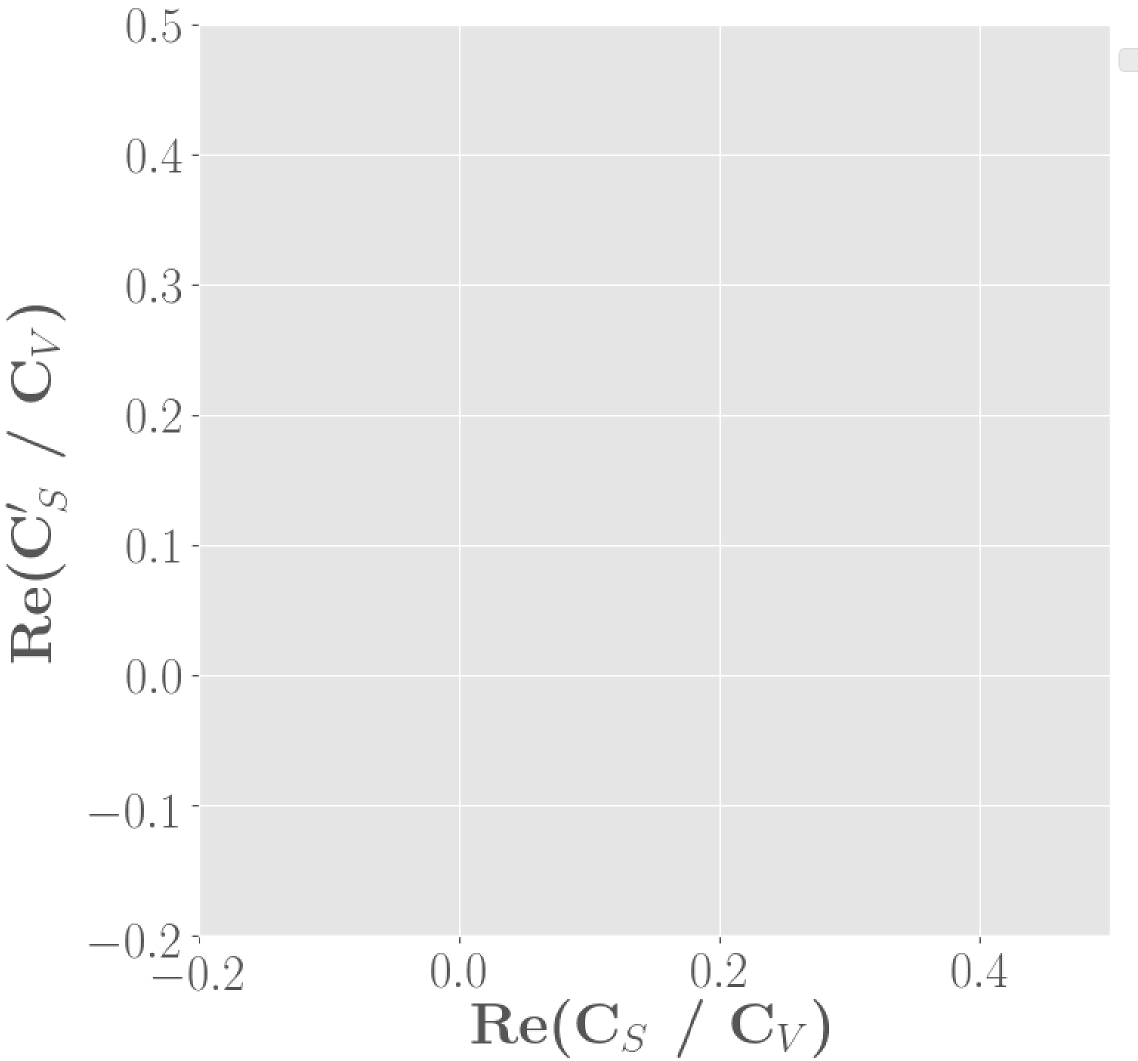
- effect on angular correlations



- effect on beta-spectrum shape

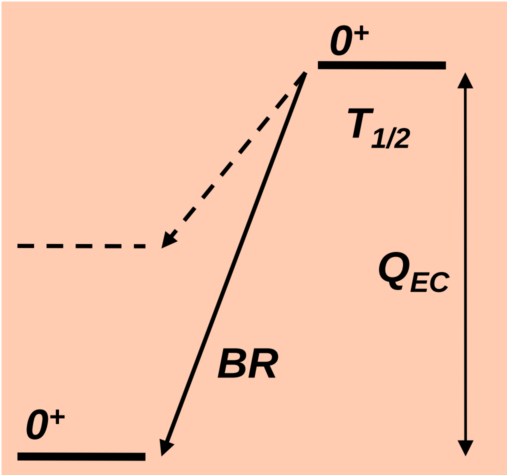


Limits on scalar currents (Fermi decays)



- **Super-allowed 0^+ - 0^+ β decay: ^{10}C decay**
- $\beta-\nu$ angular correlation measurements: WISArD
- Beta-shape measurement: InESS (^{114}In)

Nuclear beta decay: 0^+ - 0^+



$\underline{0^+ \rightarrow 0^+ :}$

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

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

f(nucl. structure) ~ 0.3-1.5%

f(weak interaction) ~ 2.4%

$$\begin{pmatrix} d' \\ s' \\ b' \end{pmatrix} = \begin{pmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{pmatrix} \begin{pmatrix} d \\ s \\ b \end{pmatrix}$$

weak eigenstates — Cabibbo Kobayashi Maskawa (CKM) matrix — mass eigenstates

Obtain precise value of G_V^2

Determine V_{ud}^2

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

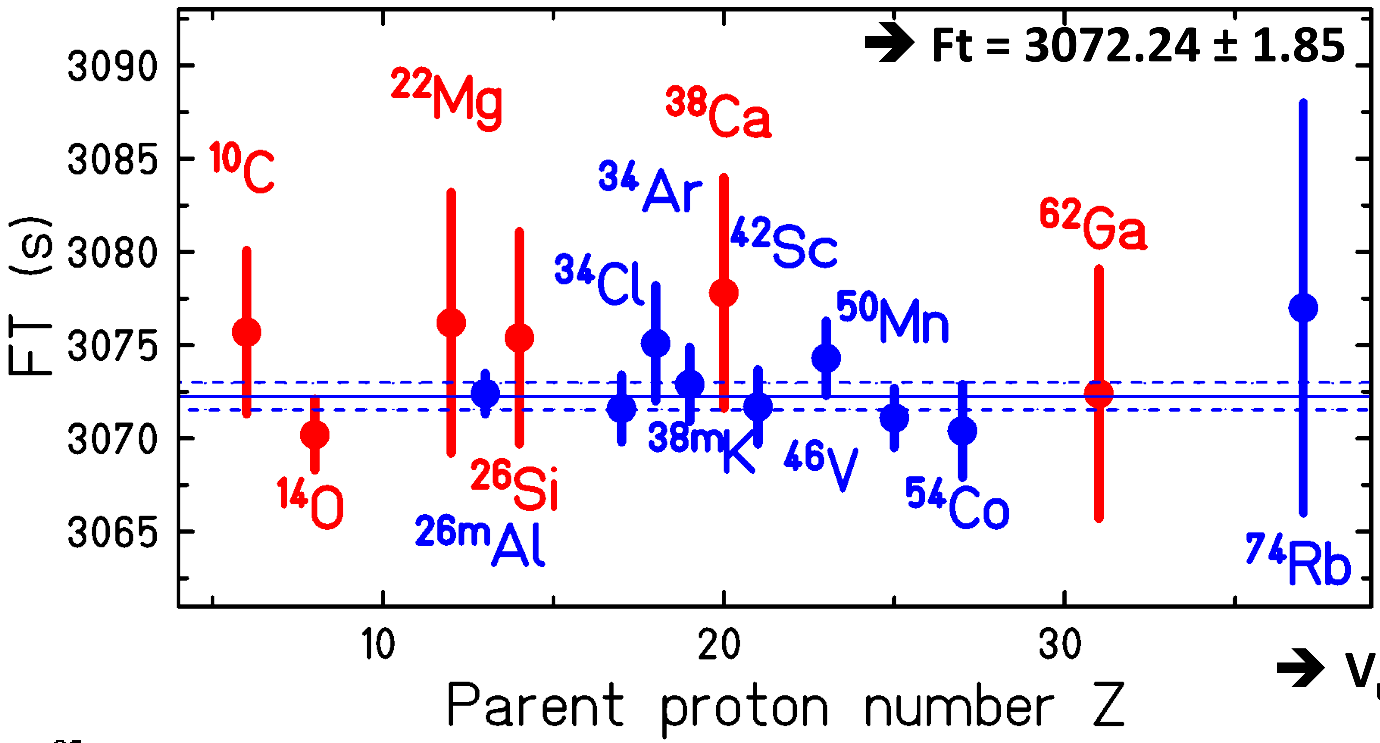
Test CKM unitarity

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

Precision measurements required: 10^{-3}

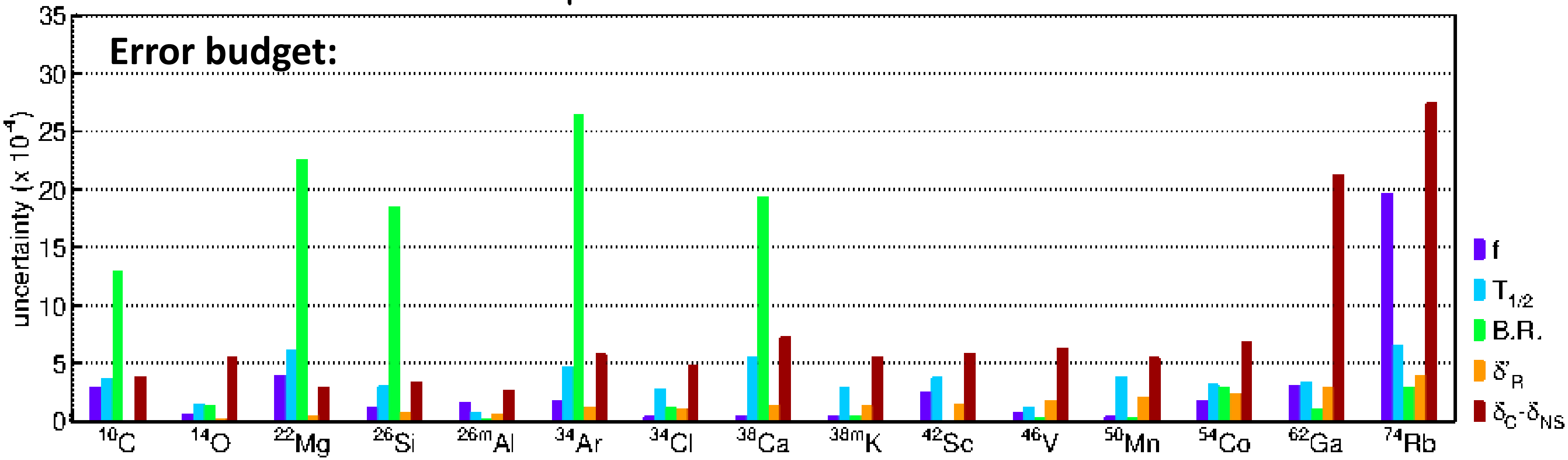
- ✓ Q_{EC} $\longrightarrow$ *mass measurements: $f \sim Q_{EC}^5$*
- ✓ $T_{1/2}$, *BR* $\longrightarrow$ *β-decay studies: $t = T_{1/2} / BR$*

$0^+ \rightarrow 0^+$ decays: present status



- 15 nuclei
- other nuclei under study:
  - ^{18}Ne
  - ^{22}Mg
  - ^{30}S

➔ $V_{ud} = 0.9740 \pm 0.0005$



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

- standard model assumption: only vector current

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

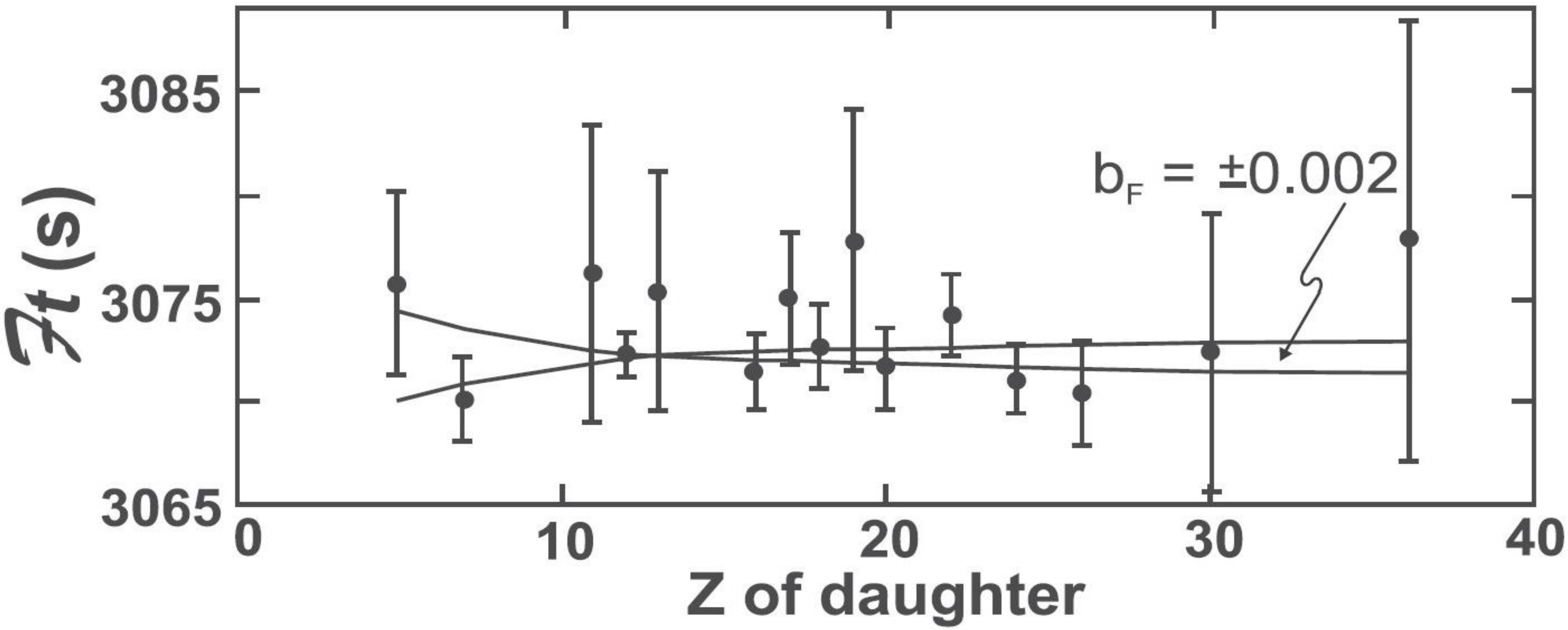
- if scalar currants, we obtain for $\mathcal{F}t$

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

- $\mathcal{F}t \Rightarrow \mathcal{F}t * \left(1 + \frac{b_F\, y}{<E>}\right)$, $y^2 = 1 - Z^2\alpha^2$

- limit on scalar current from term in $\mathcal{F}t$ function: $(1 + b_f\, y\, /\, <E>)$

0⁺ → 0⁺ decays: limits on exotic currents



- from β decay: $b_F = 0.000 \pm 0.002 \sim \left(\frac{C_s + C_s'}{C_V}\right)$
- valid only for left-handed currents

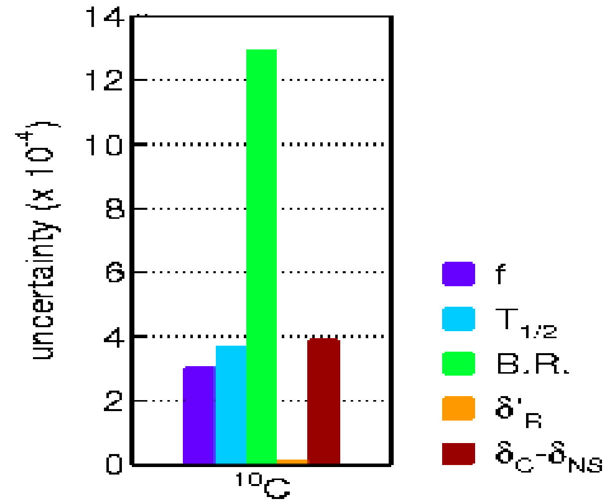
➔➔ improve on low-Z nuclei

Hardy & Towner, 2020

0+ → 0+ decays: ^{10}C error budget

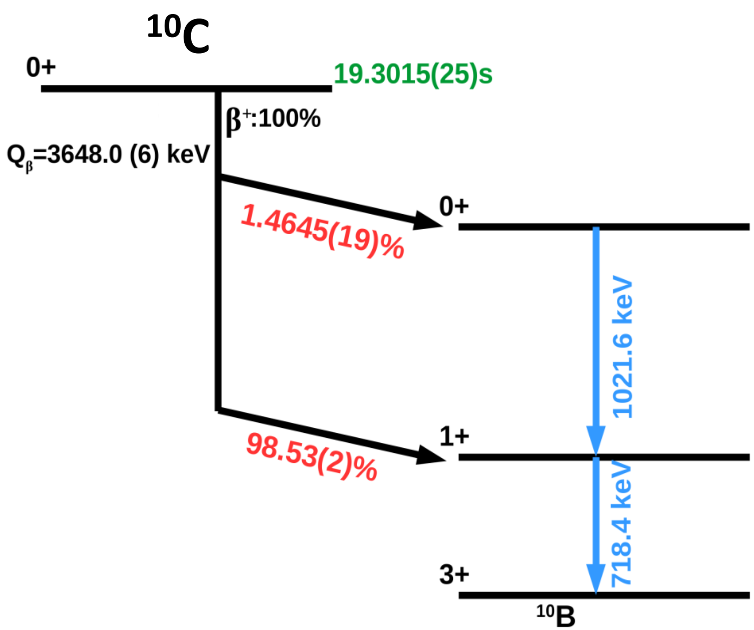
- BR by far largest error
- two precise measurements:
  - Savard et al.: 1.4625(25)% (PRL 74 (1995) 1521)
  - Fujikawa et al.: 1.4665(38)% (PLB 449 (1999) 6)

  → measurements with Ge multi-detector array



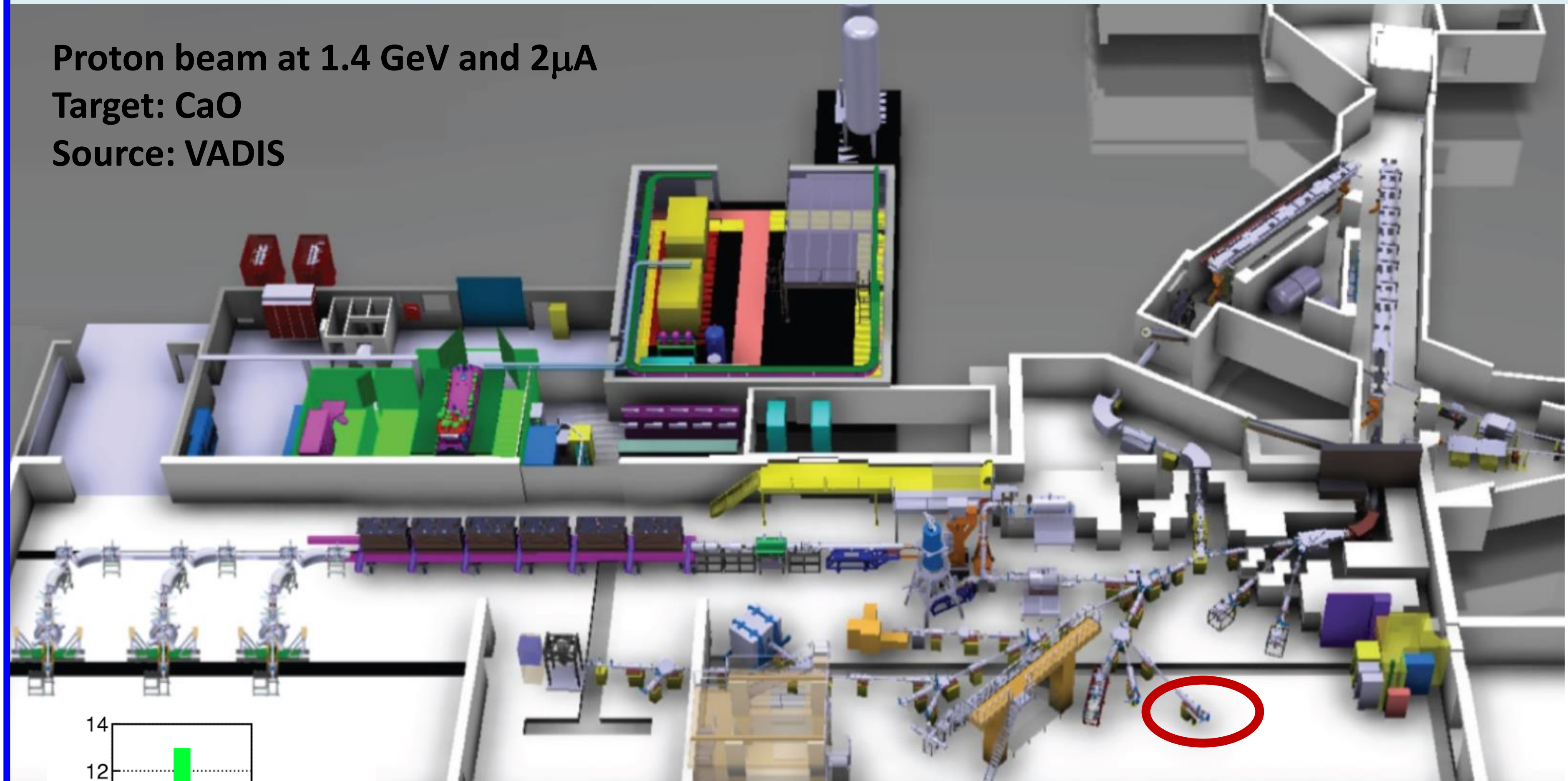
our approach:

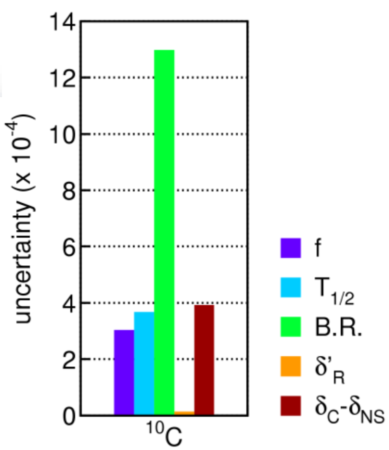
re-measuring the BR of ^{10}C
with out precisely calibrated
Germanium detector ($\Delta\varepsilon < 0.15\%$)

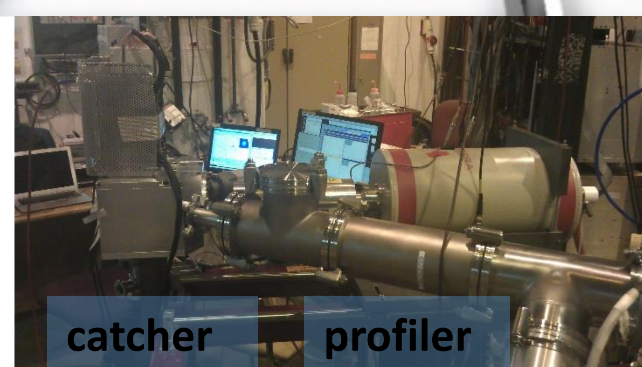


^{10}C measurement at ISOLDE

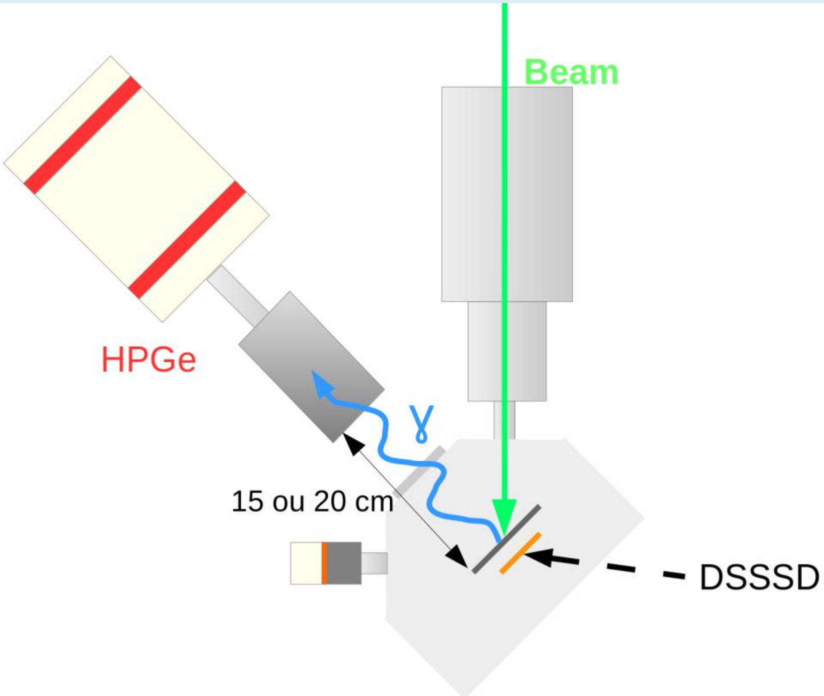
Proton beam at 1.4 GeV and 2μA
Target: CaO
Source: VADIS

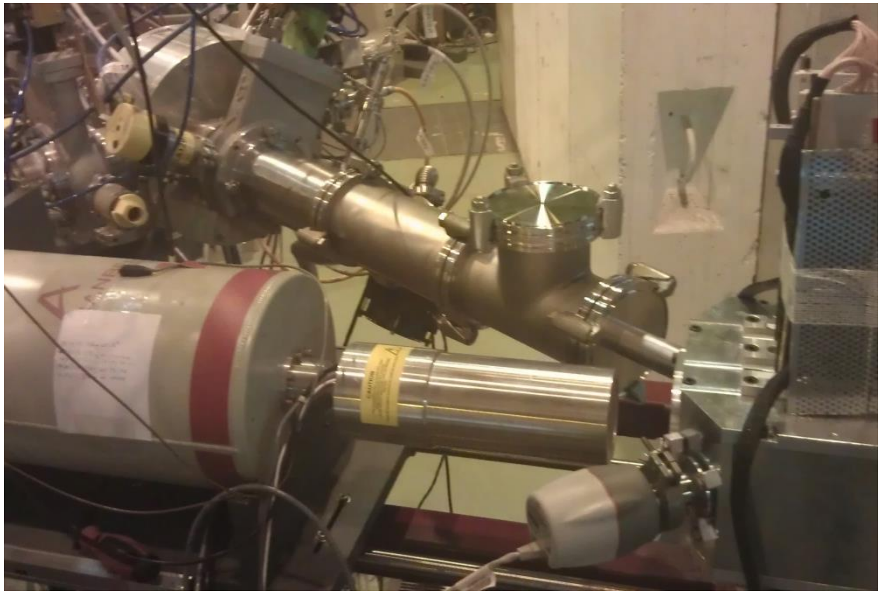


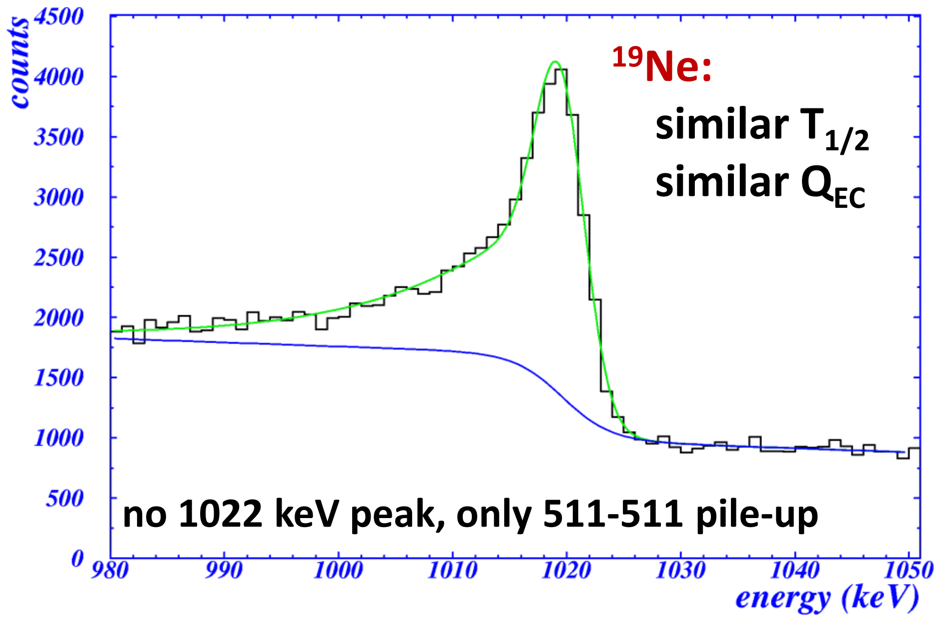


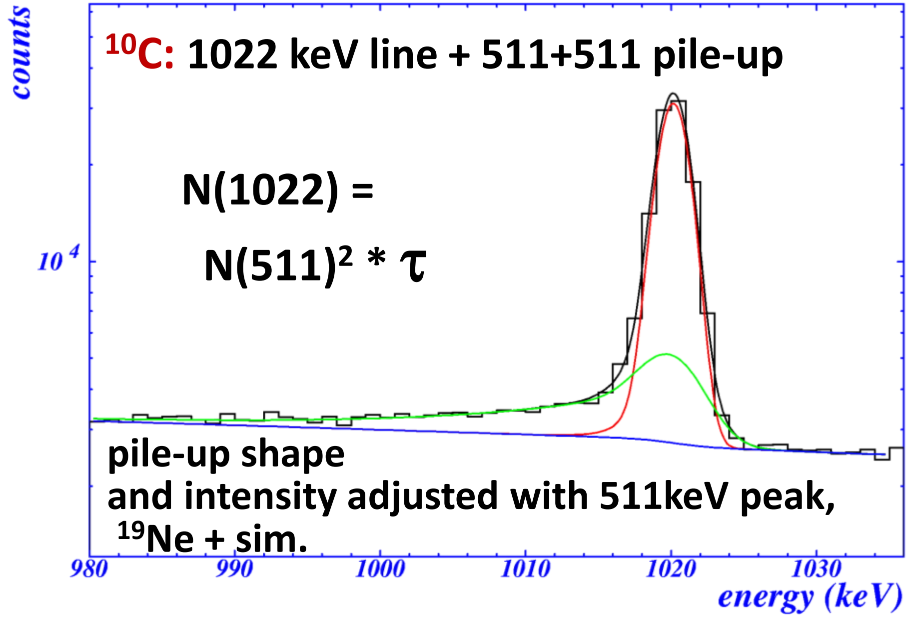


^{10}C experimental set-up and analysis procedure



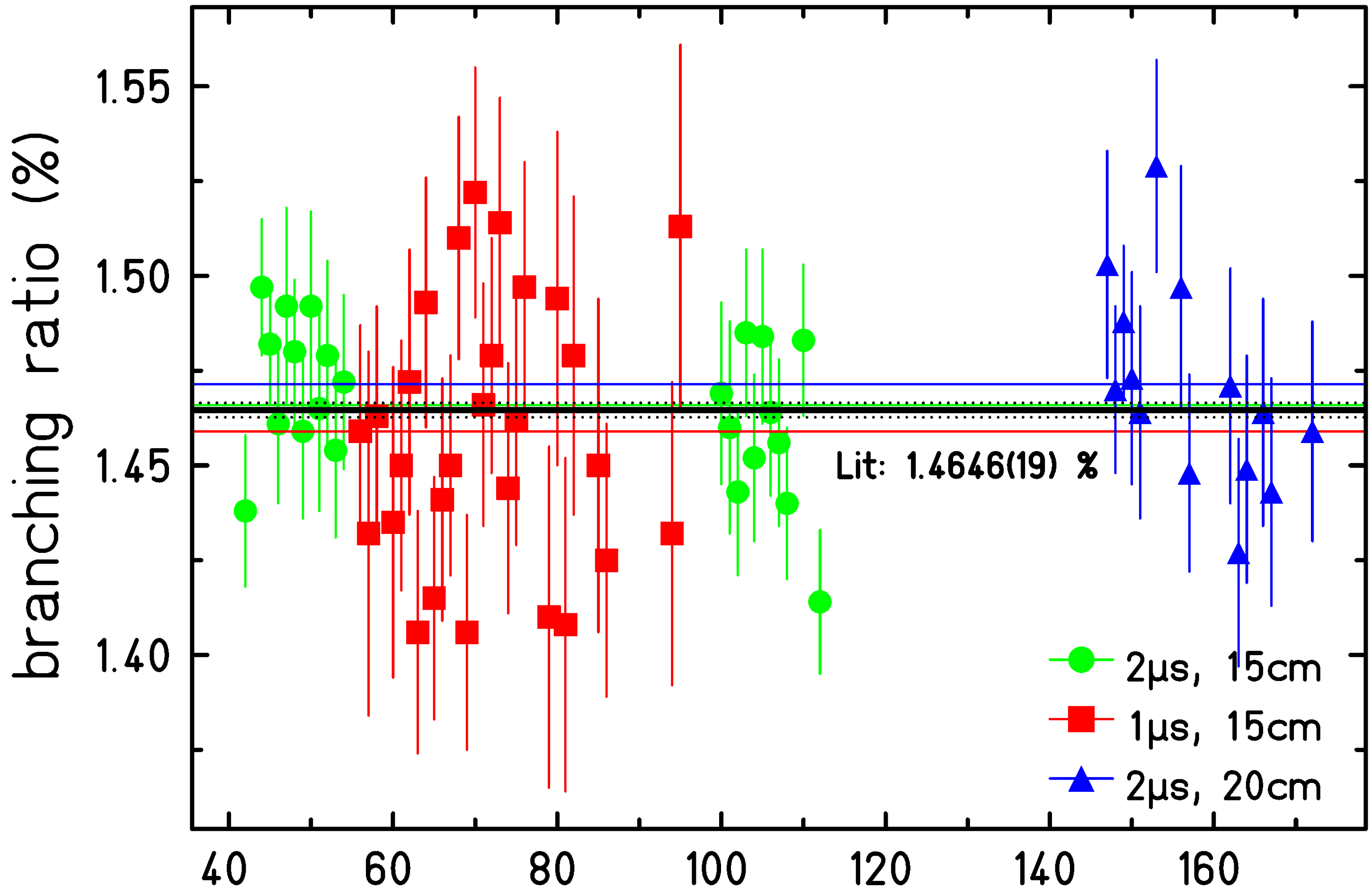






Super-allowed ranching ratio of ^{10}C

Blank et al., EPJA56 (2020) 156



Final result:

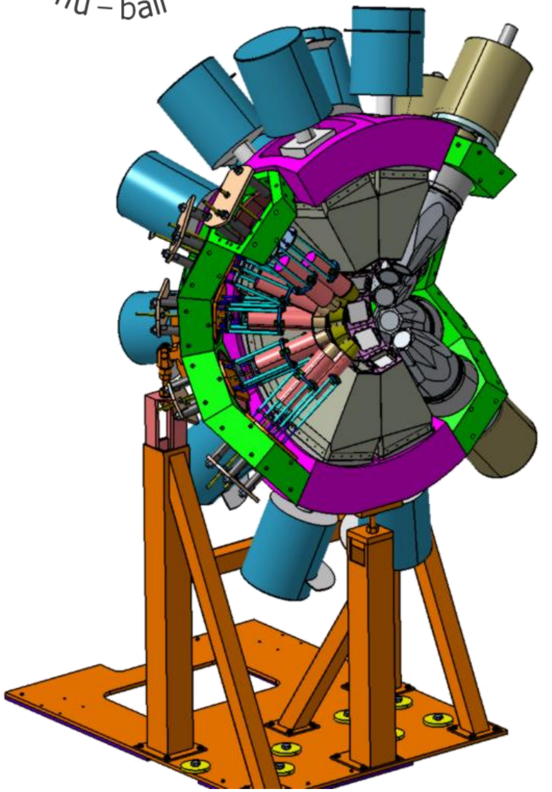
Literature:

next attempt:
- higher statistics: difficult…
- higher purity: MR-ToF selection

statistics: 0.0039 %

pile-up: 0.0030 %

^{10}C measurement at ALTO/Orsay

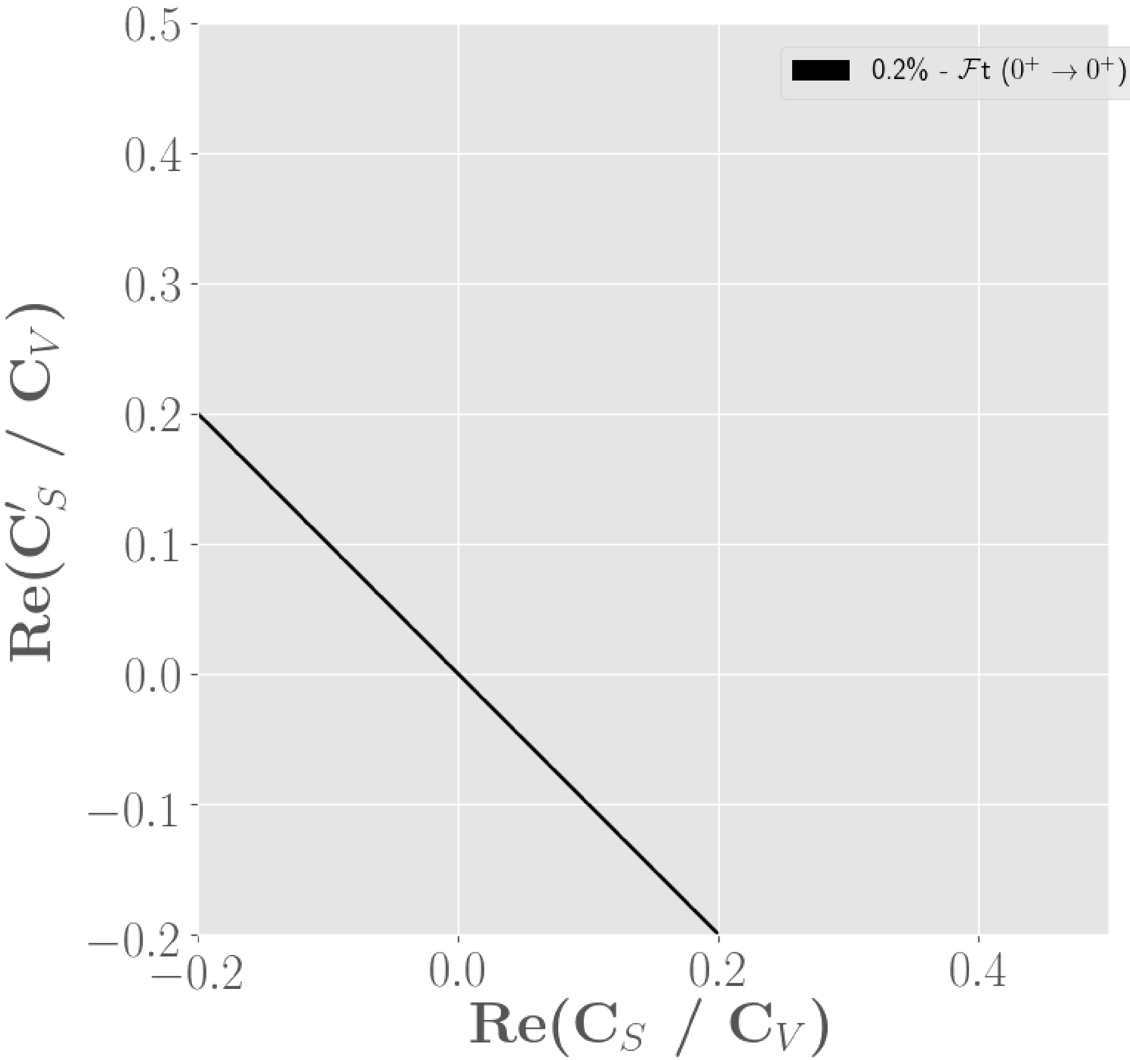


data under analysis…

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

similar experiment with AGATA at Legnaro: Jeongsu Ha et al.

Limits on scalar currents: 2018



$$b^{F}_{\beta\nu} \cong \pm Re\left(\frac{C_S + C'_S}{C_V}\right)$$

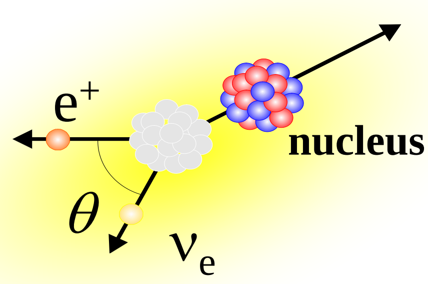
$$\leq \pm 0.002$$

J. Hardy & I. Towner, Phys. Rev. C102, 045501 (2020)

- Super-allowed 0^+ - 0^+ β decay: ^{10}C decay
- **$\beta-\nu$ angular correlation measurements: WISArD**
- Beta-shape measurement: InESS (^{114}In)

The WISArD experiment

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

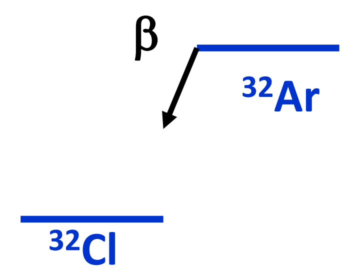


Pure Fermi transition (ΔJ=0, S=0):

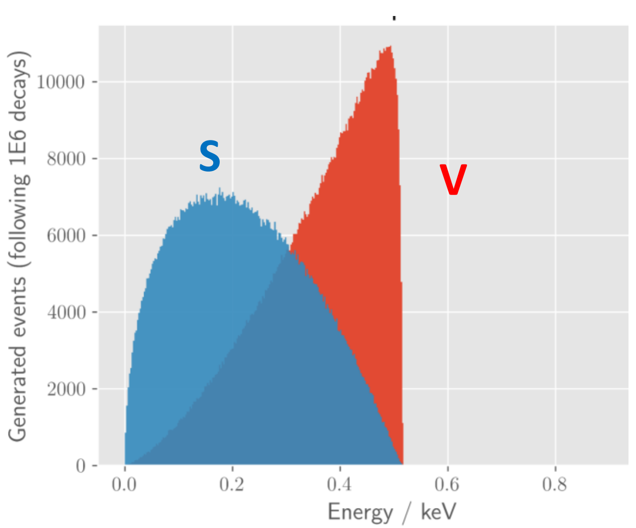
$$a_F \cong 1 - \frac{|C_S|^2 + |C'_S|^2}{|C_V|^2}$$

$$b_F \approx \pm Re\left(\frac{C_S + C'_S}{C_V}\right)$$

kinematic shift of nucleus ^{32}Cl



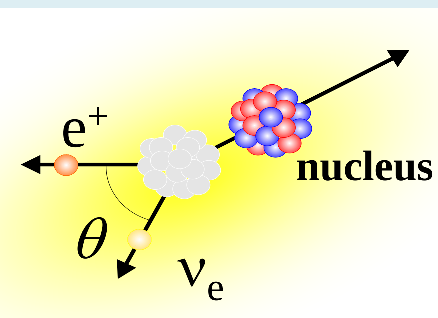
nuclear recoil:



ion traps: LPCTrap (^{6}He), TRINAT (^{38m}K), WITCH (^{35}Ar)

The WISArD experiment

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

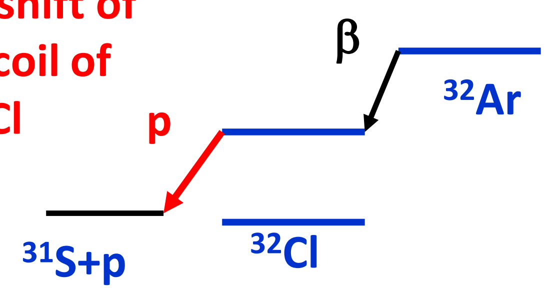


Pure Fermi transition (ΔJ=0, S=0):

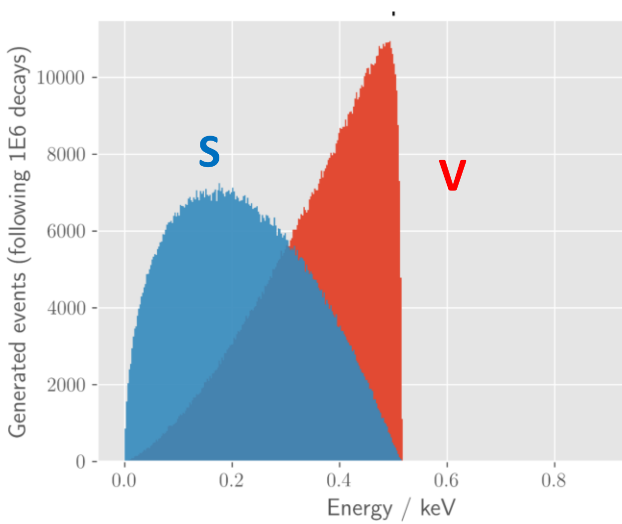
$$a_F \cong 1 - \frac{|C_S|^2 + |C'_S|^2}{|C_V|^2}$$

$$b_F \approx \pm Re\left(\frac{C_S + C'_S}{C_V}\right)$$

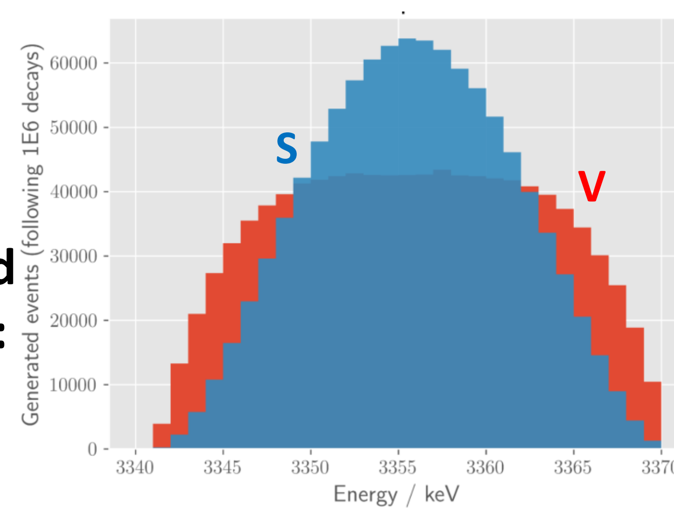
kinematic shift of proton: recoil of nucleus ^{32}Cl



nuclear recoil:



emitted proton:



ion traps: LPCTrap (^{6}He), TRINAT (^{38m}K), WITCH (^{35}Ar)

WISArD experiment at ISOLDE

First experiment: ISOLDE 1993

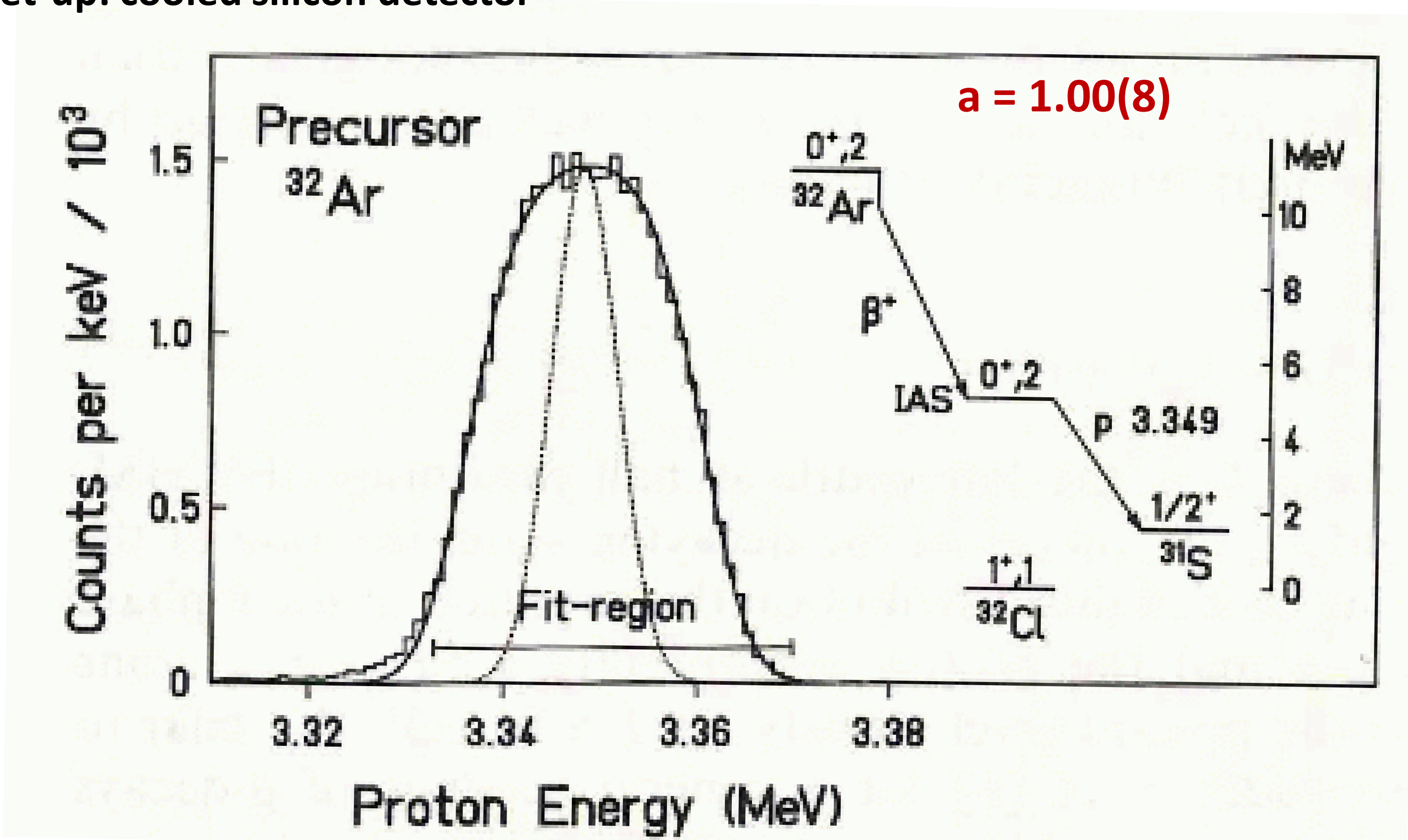
Beta-neutrino recoil broadening in β-delayed proton emission of ^{32}Ar and ^{33}Ar

D. Schardt[1], K. Riisager[2]

[1] GSI, Postfach 110552, W-6100 Darmstadt 11, Germany
[2] Institute of Physics and Astronomy, Aarhus University, DK-8000 Aarhus C, Denmark

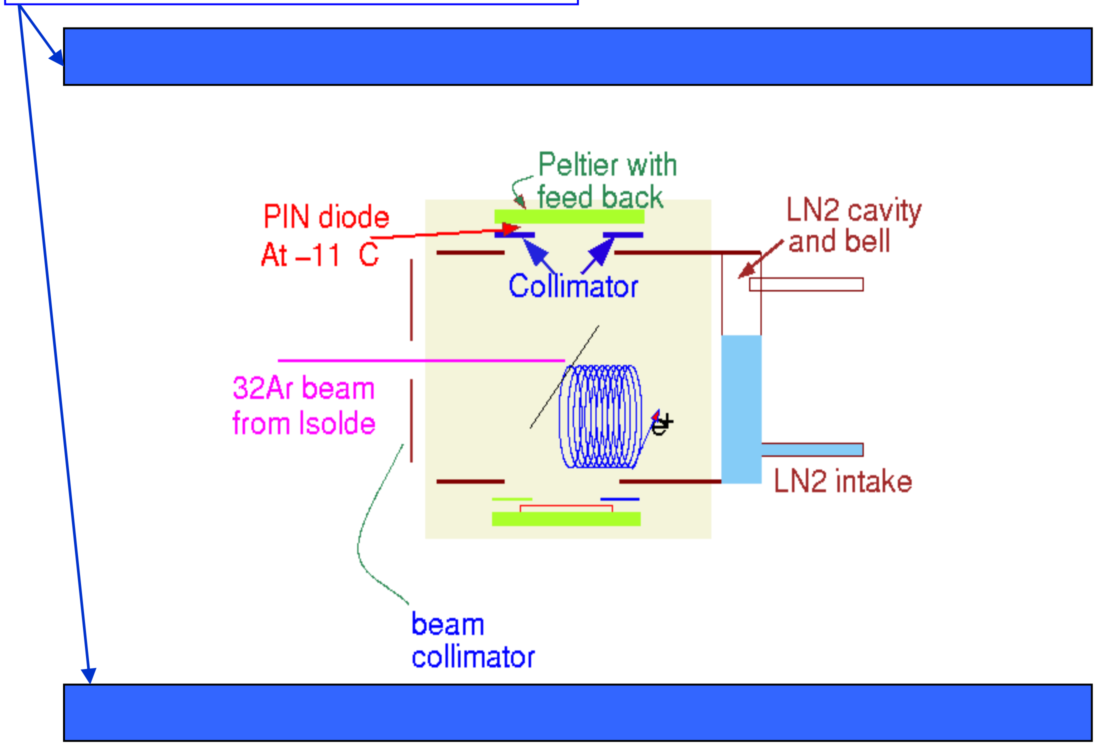
ZPA 345 (1993) 265

Set-up: cooled silicon detector

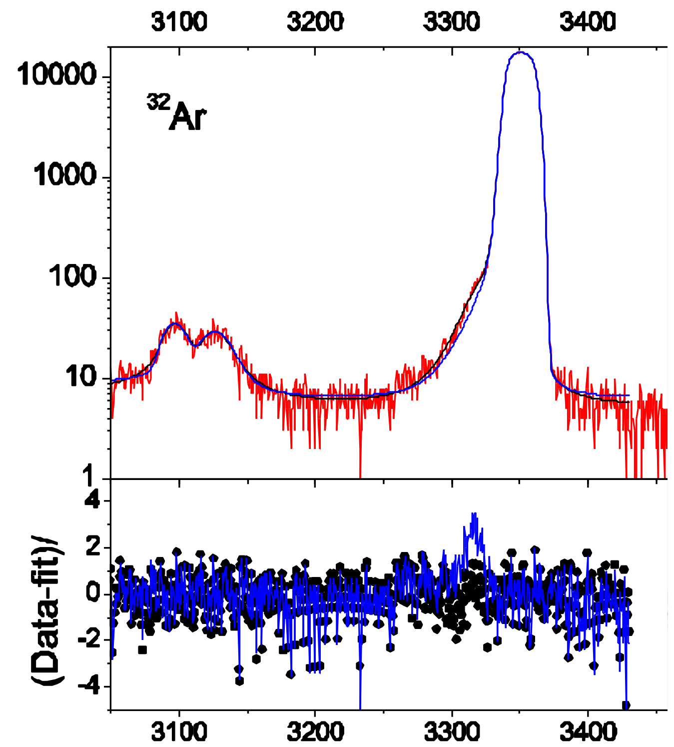


Second experiment: ISOLDE 1999

Super-conducting solenoid
B=3.5 Tesla



cooled detectors



Result:
ã=0.9989(65)

E. G. Adelberger et al., PRL 83 (1999) 1299
A. Garcia et al., Hyperfine Interact. 129 (2000) 237

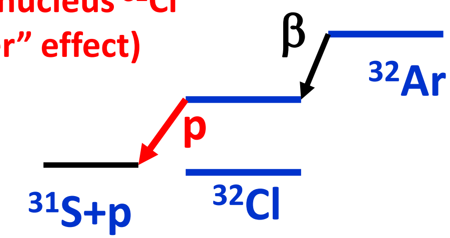
● ● ● The WISArD experiment

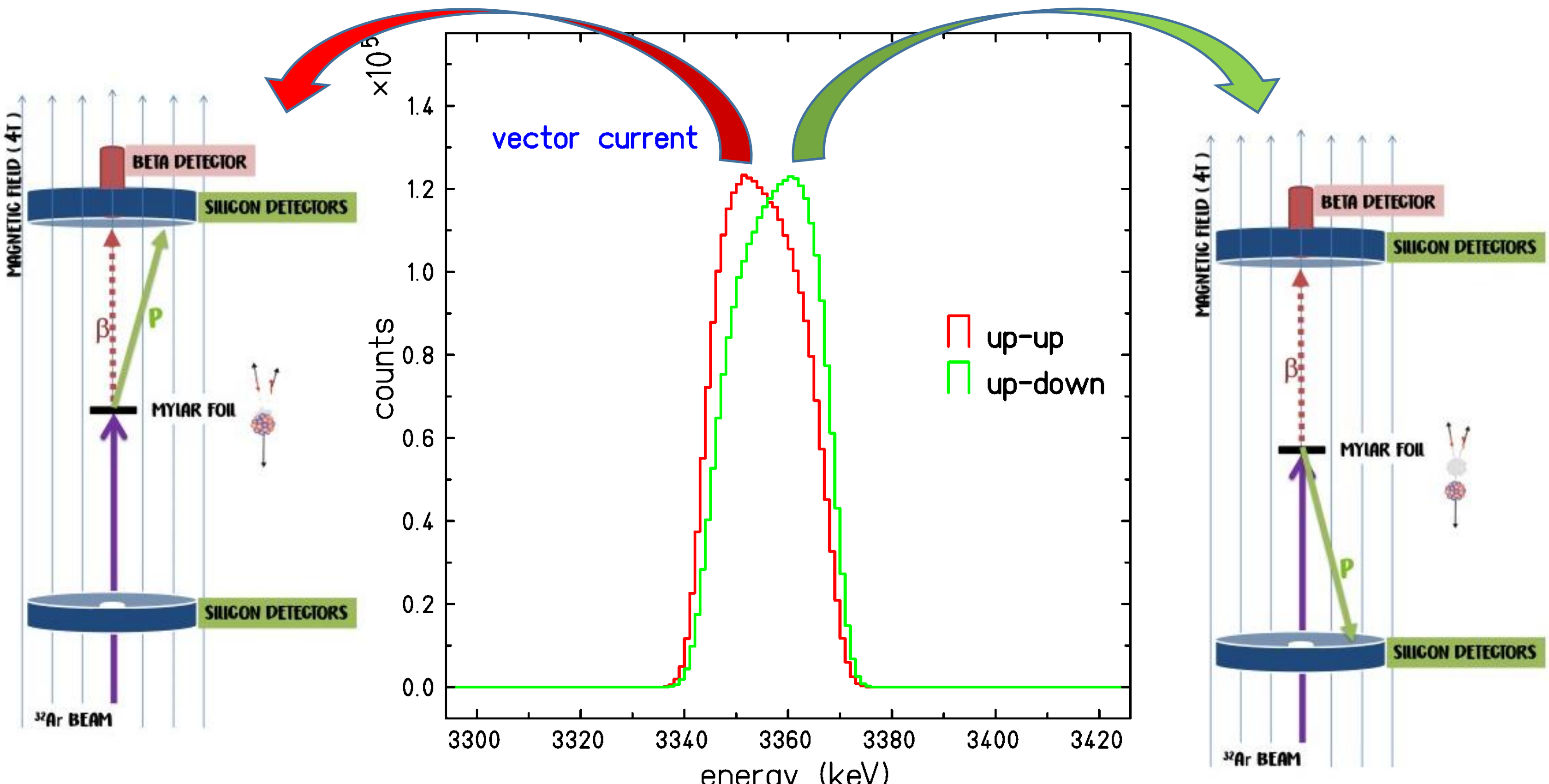
- **Principle: measurement of the recoil of nucleus via an indirect measurement: β-delayed proton in a magnetic field to guide the positrons**

➔ kinematical cuts with singles protons and e⁺ - coincident protons

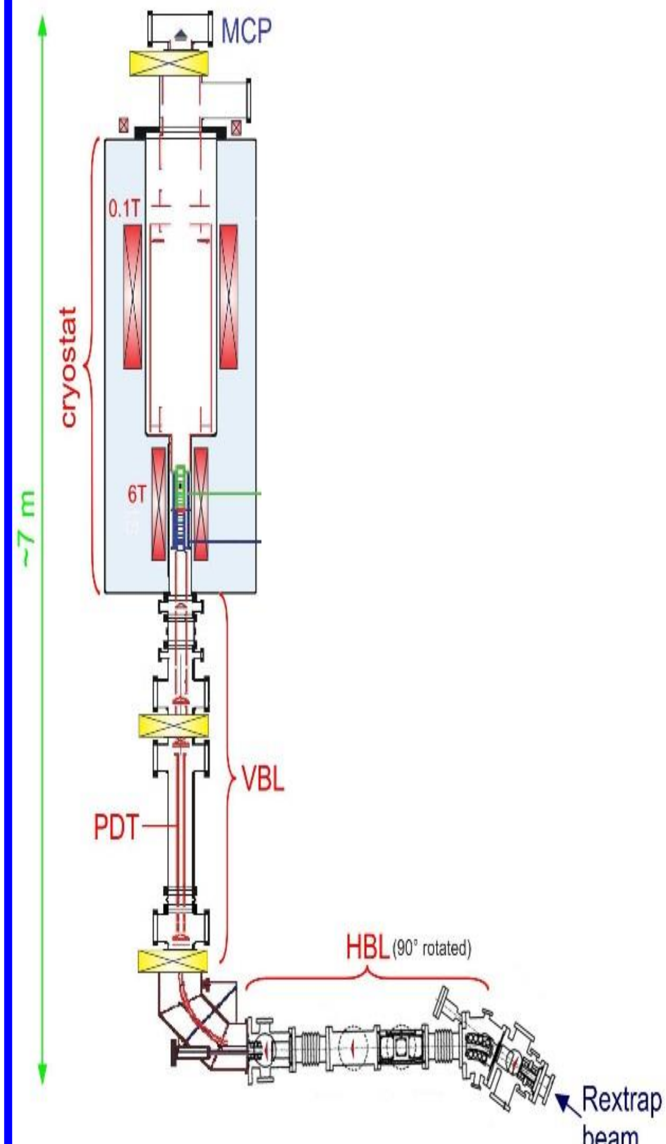
➔ increased sensitivity

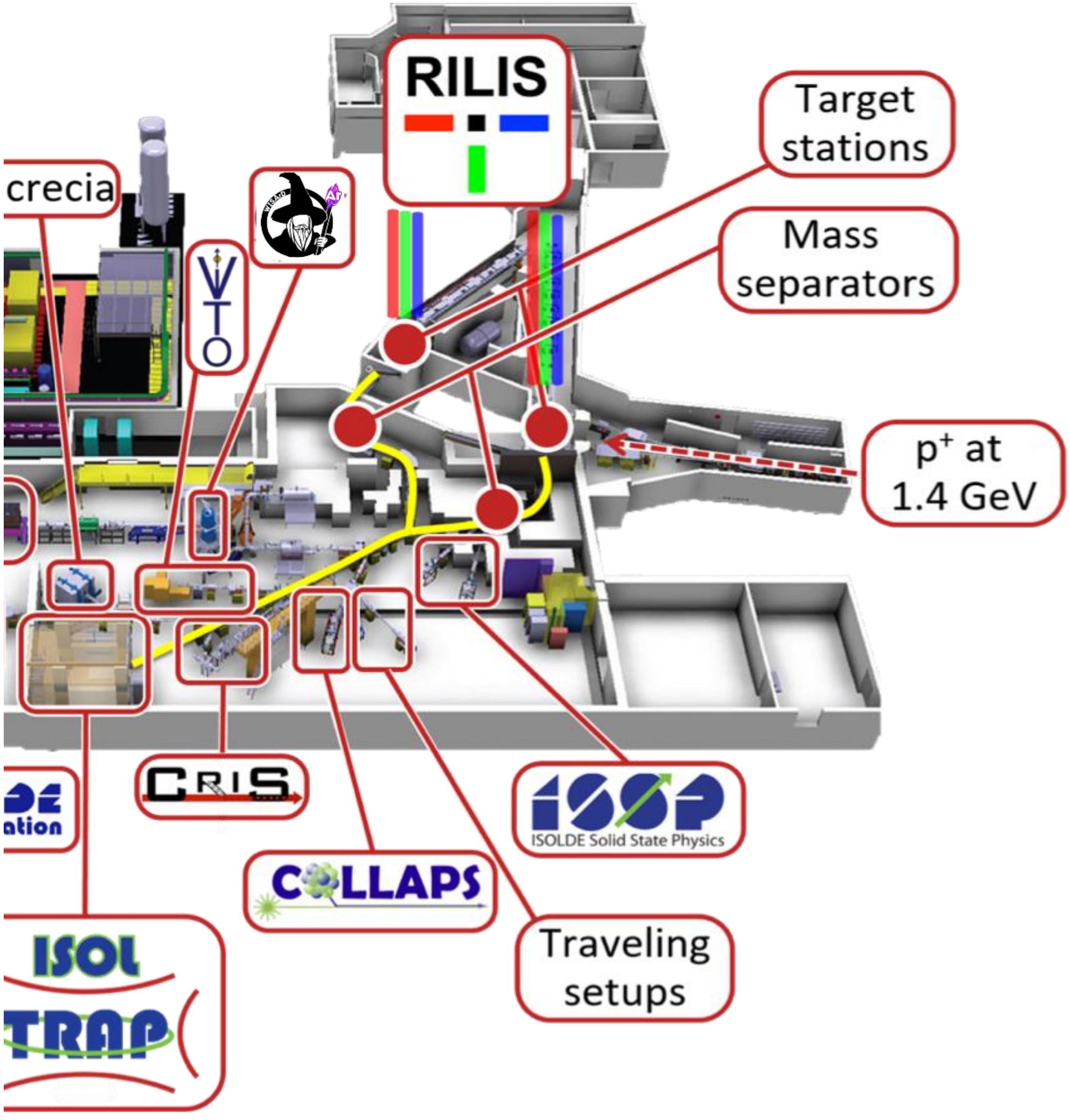
Detection of proton: recoil of nucleus ^{32}Cl ("Doppler" effect)





ISOLDE - CERN


MCP
0.1T
6T
cryostat
~7 m
VBL
PDT
HBL (90° rotated)
Rextrap beam


RILIS
Target stations
Mass separators
p+ at 1.4 GeV
crecia
VITO
CRIS
COLLAPS
ISOLDE Solid State Physics
Traveling setups
ISOL TRAP

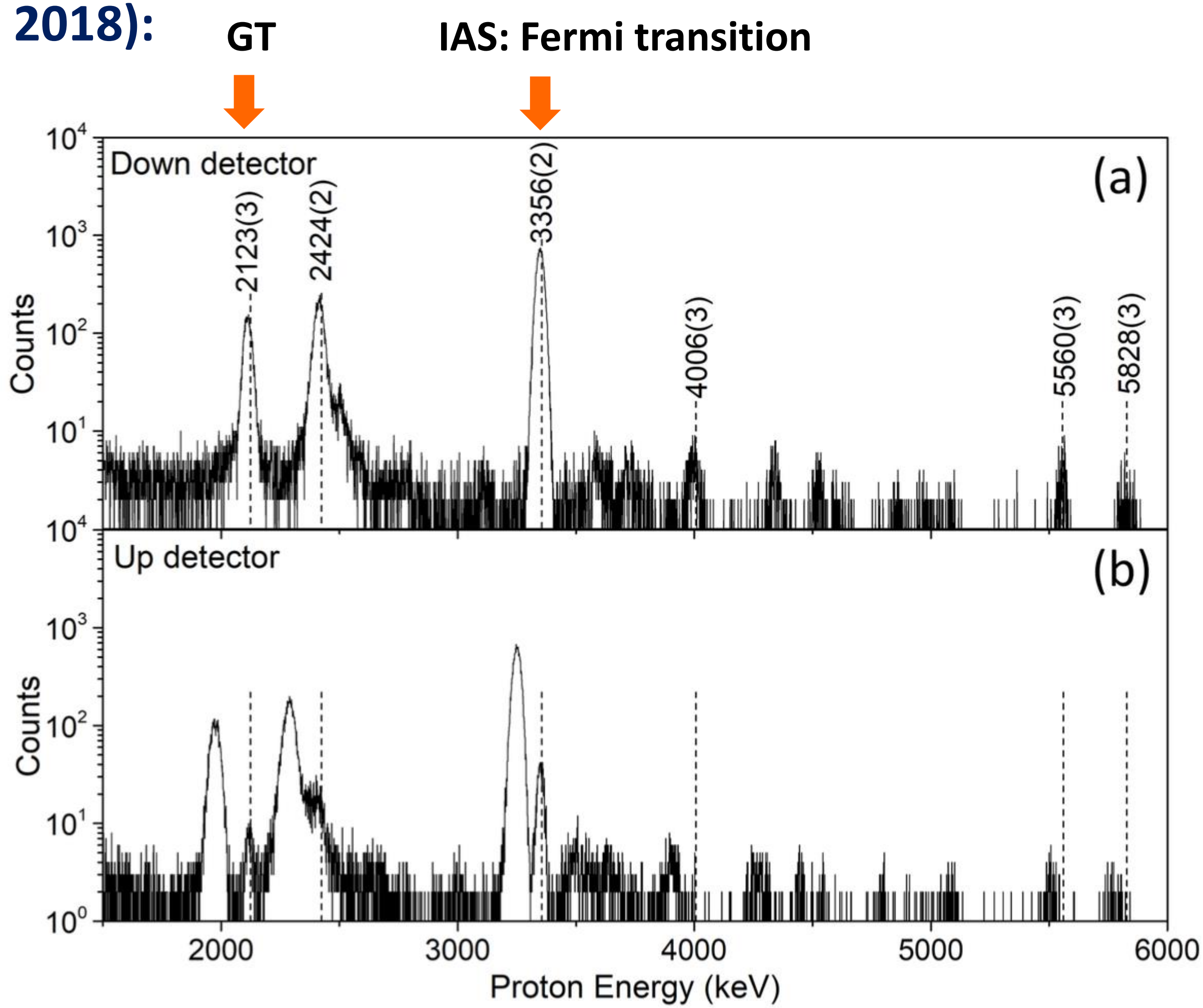
The WISArD experiment: proof-of-principles (2018)

first results (nov. 2018):

proton spectra:

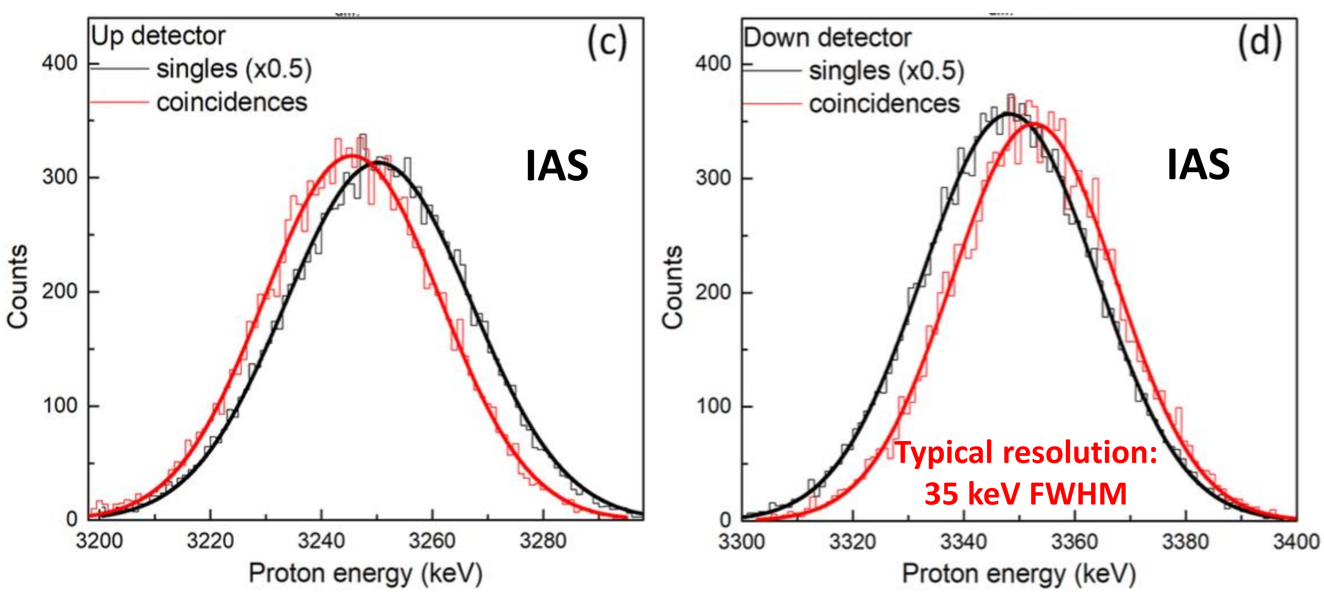
- E shift -> p detector dead layer

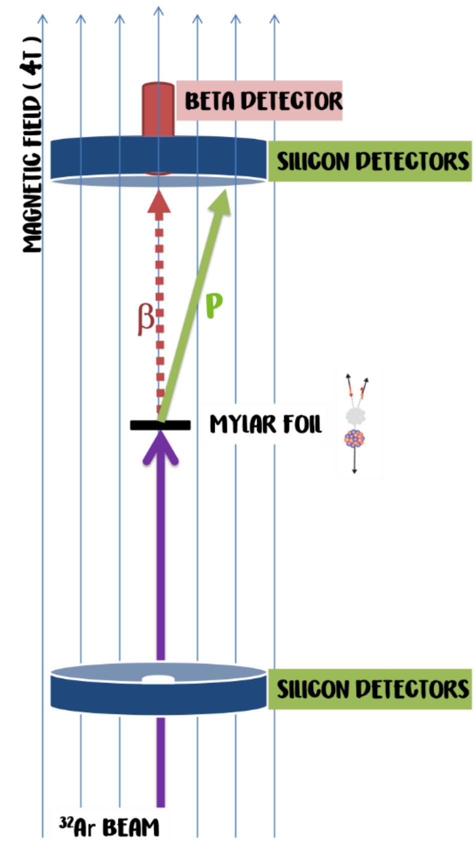
- E shift -> mylar foil + dead layer
- « shadow » peaks



V. Araujo-Escalona et al, PRC 101 (2020) 055501

first results: (nov. 2018)





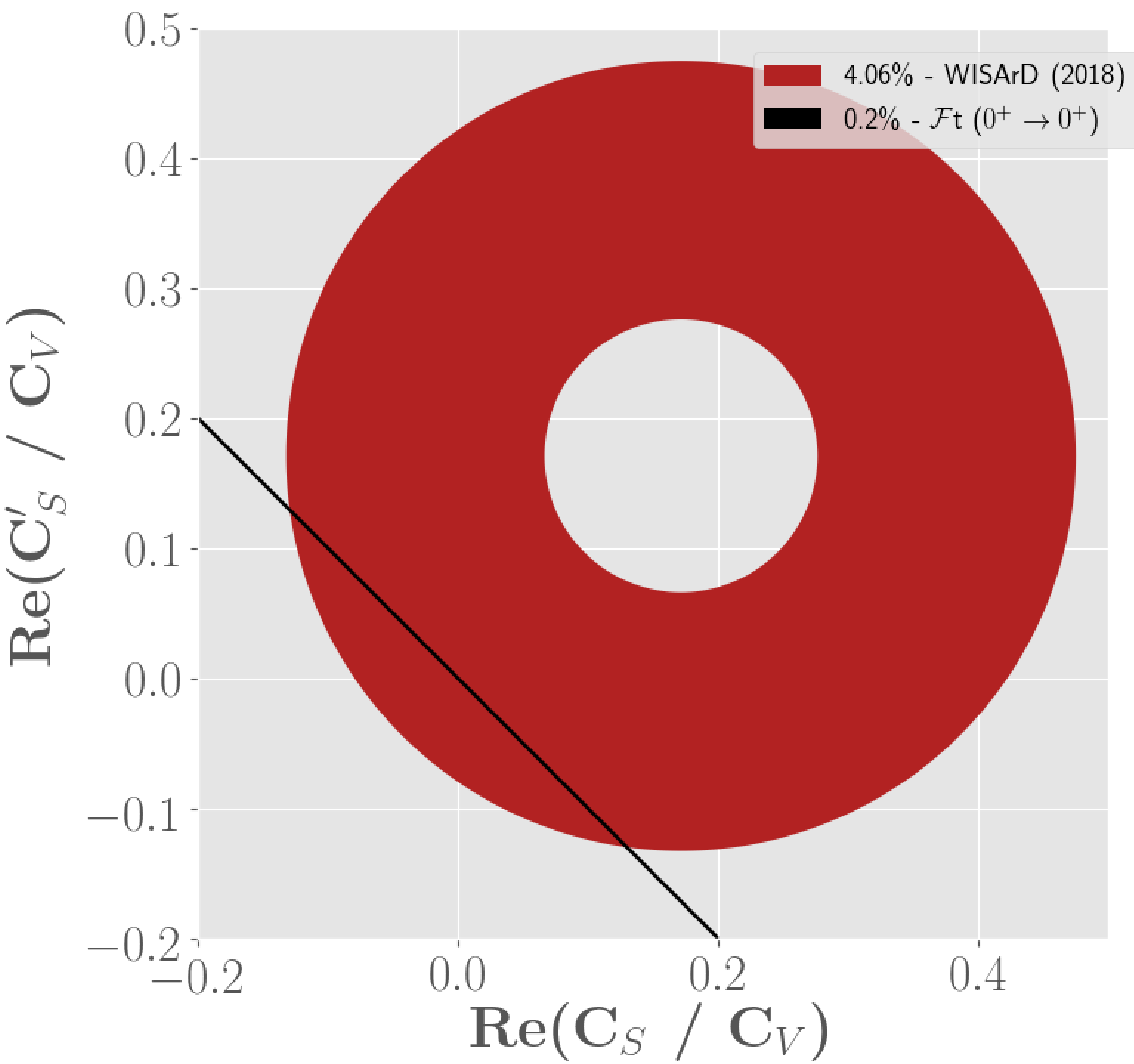
Average shift:
Δ = 4.49(3) keV

by means of GEANT4 MC calculations:

$$\tilde{a}_{\beta\nu}^{\mathrm{F}} = 1.01(3)_{(stat)}(2)_{(syst)} \qquad \tilde{a}_{\beta\nu}^{\mathrm{GT}} = -0.22(9)_{(stat)}(2)_{(syst)}$$

V. Araujo-Escalona et al, PRC 101 (2020) 055501

Limits on scalar currents: 2018



$$a_{\beta\nu}^{F} = 1.01(4) \quad (2018)$$

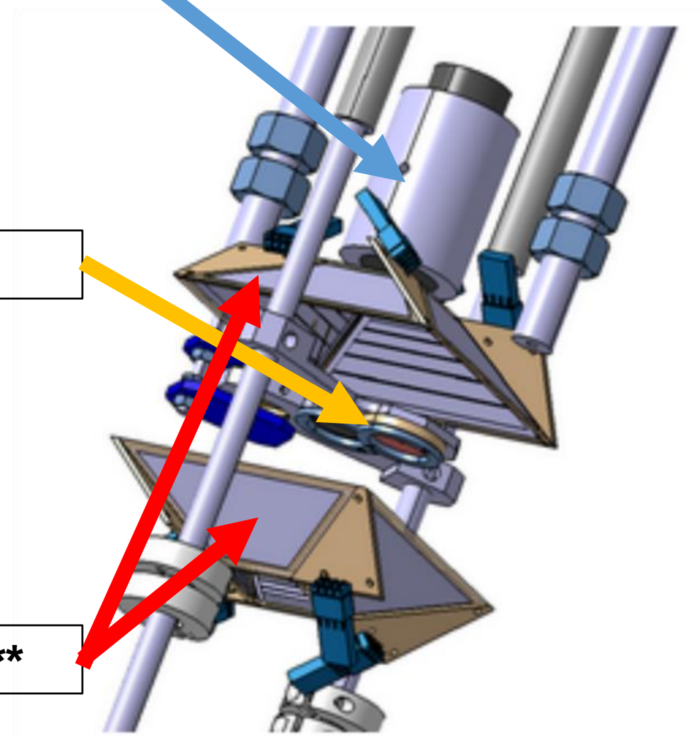
- after 35h collection
- $N_{coinc} \approx 1e5$
- 3^{rd} best result

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

WISArD upgrades 2019 - 2021

2018

2021



Beta detector* + SiPM

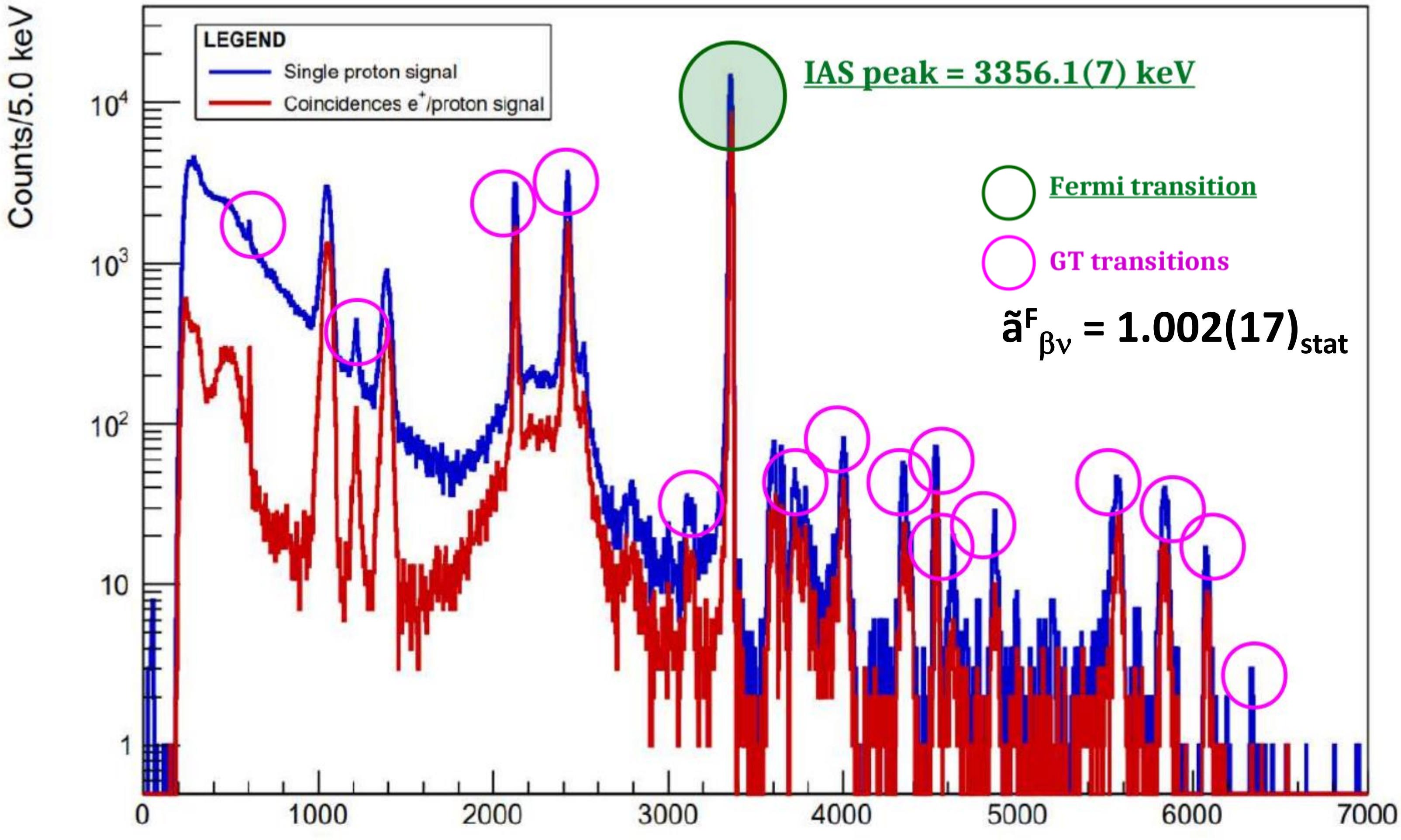
Catcher***

proton detectors planes**

* Plastic scintillator;
** Silicon surface-barrier (thickness = 300 µm);
*** Aluminized Mylar (thickness = 6.7 µm)

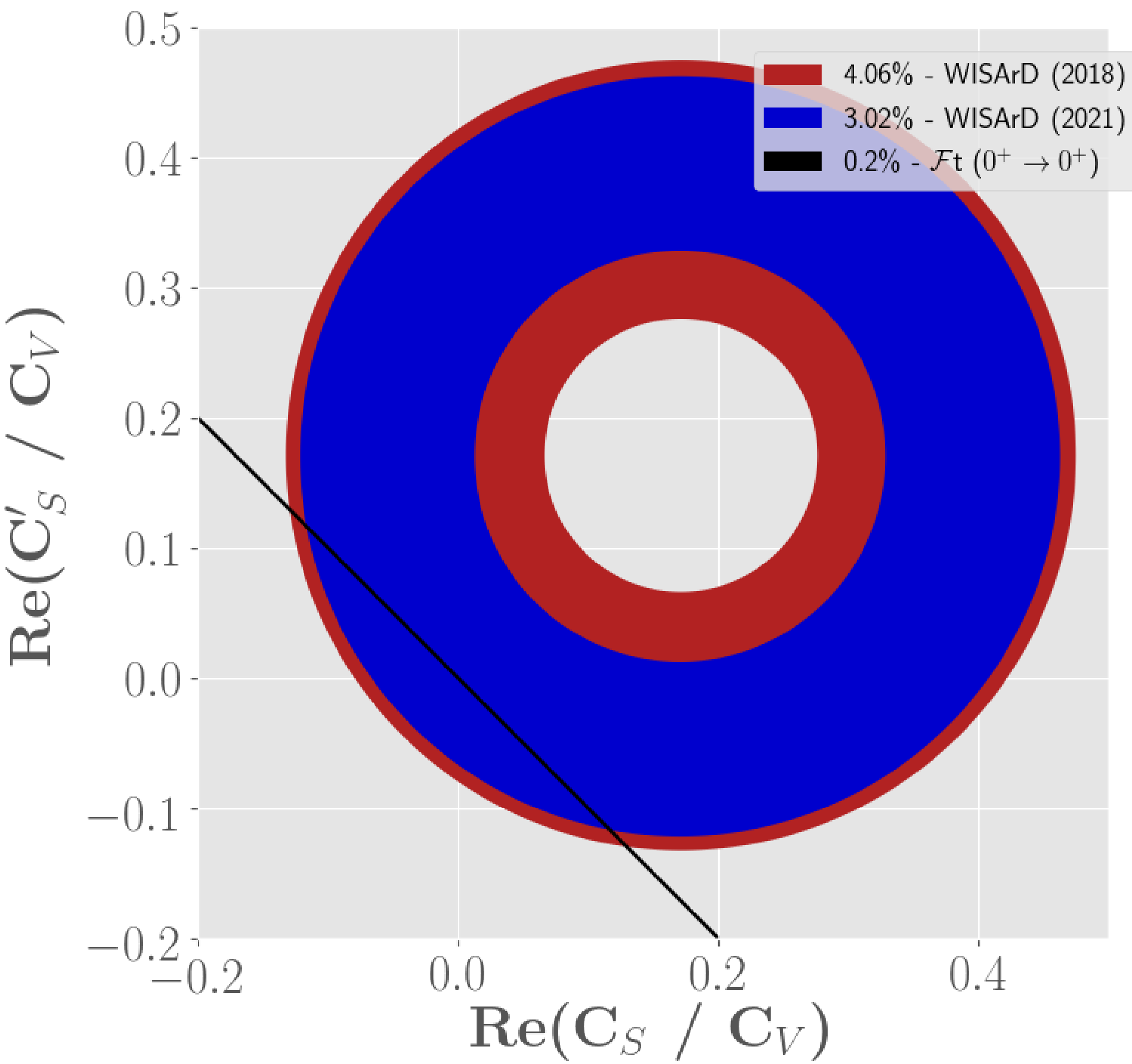
* Plastic scintillator – EJ200;
** MICRON single-sided silicon-strip (thickness = 300 µm);
*** Aluminized Mylar (thickness = 0.5 µm)

WISArD 2021 test experiment



^{32}Ar spectrum acquired with one silicon detector (Si3Down all strips, all 35 runs)

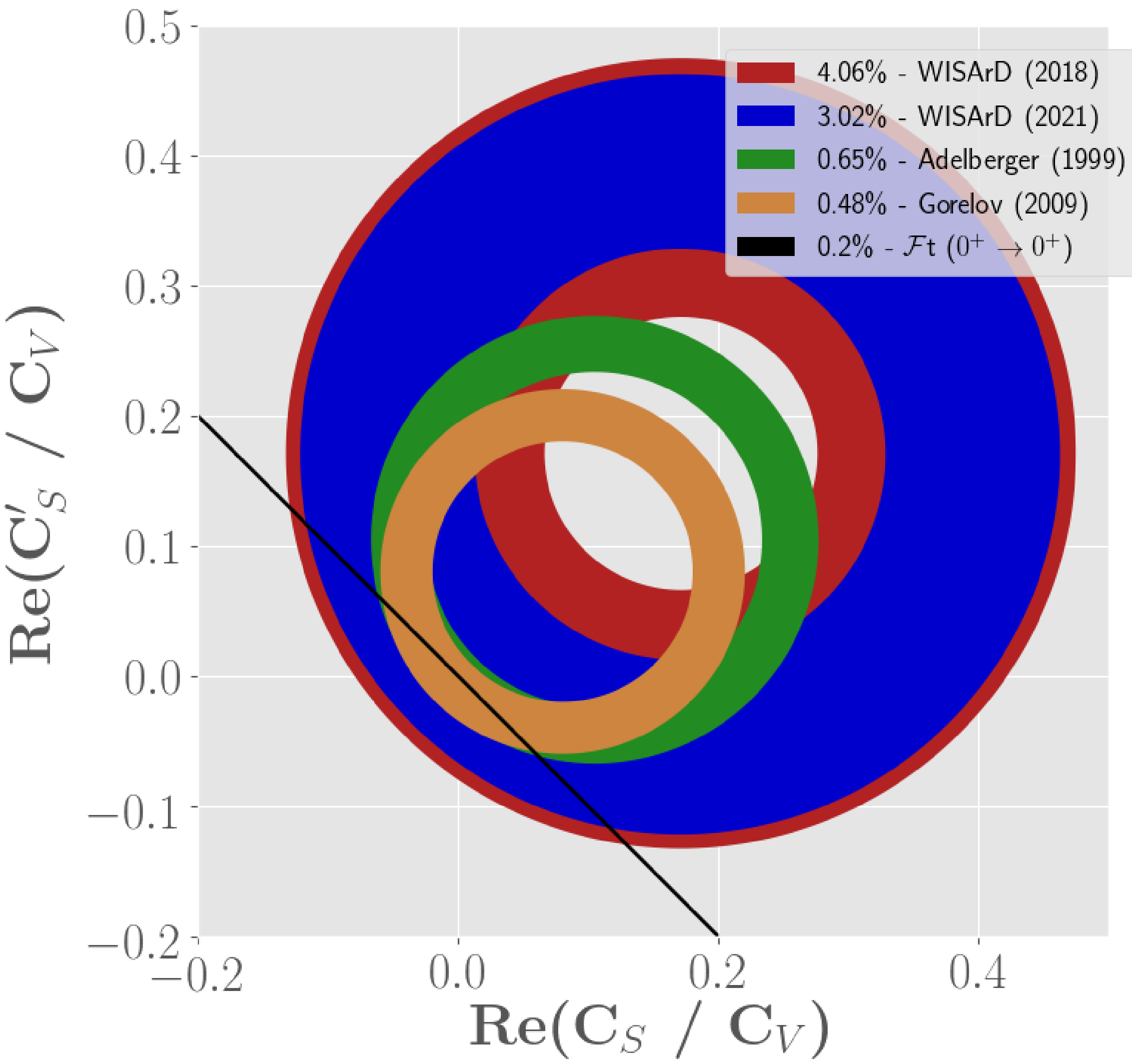
Limits on scalar currents: 2021



$a_{\beta\nu}^{F}$ = **1.01(4) (2018)**

$a_{\beta\nu}^{F}$ = **1.02(~3) (2021)**

Limits on scalar currents: 2024



$a^{\mathrm{F}}_{\beta\nu}$ **= 1.01(4) (2018)**

$a^{\mathrm{F}}_{\beta\nu}$ **= 1.02(~3) (2021)**

$a^{\mathrm{F}}_{\beta\nu}$ **= 0.9989(65) (Adelberger)**

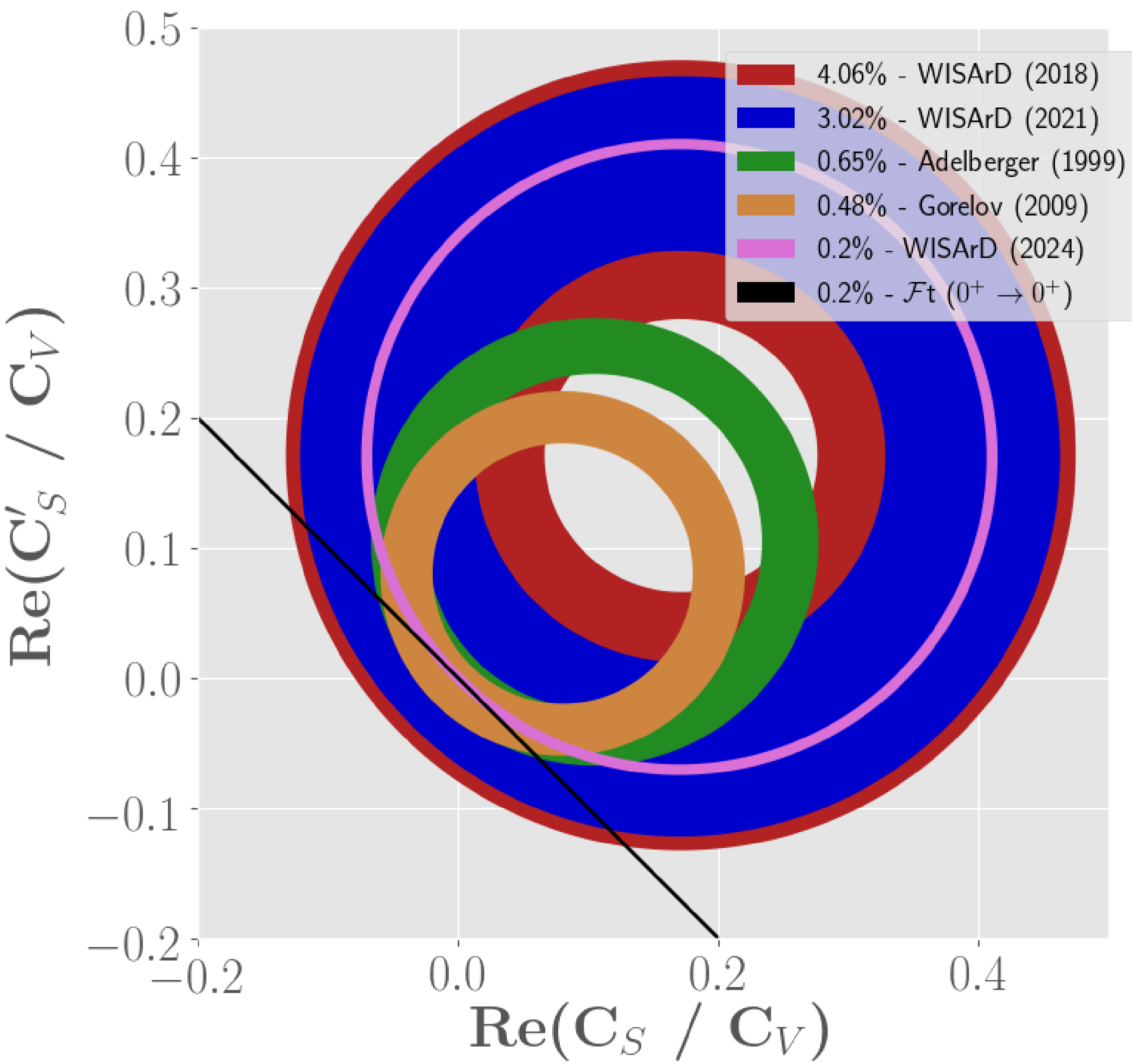
$a^{\mathrm{F}}_{\beta\nu}$ **= 0.9981(48) (Gorelov)**

WISArD: 2024

- all components work…
- new data taking in May 2024…

➔ aim of 0.1 - 0.2% precision on $a_{\beta\nu}$ and b

Limits on scalar currents: >2024



$a_{\beta\nu}^{F}$ = **1.01(4) (2018)**

$a_{\beta\nu}^{F}$ = **1.02(~3) (2021)**

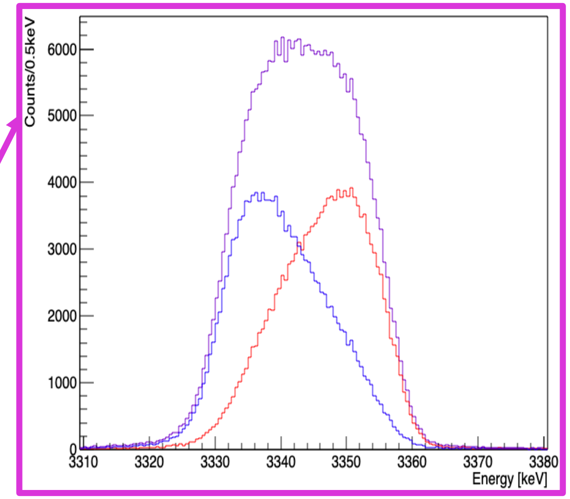
$a_{\beta\nu}^{F}$ = **0.9989(65) (Adelberger)**

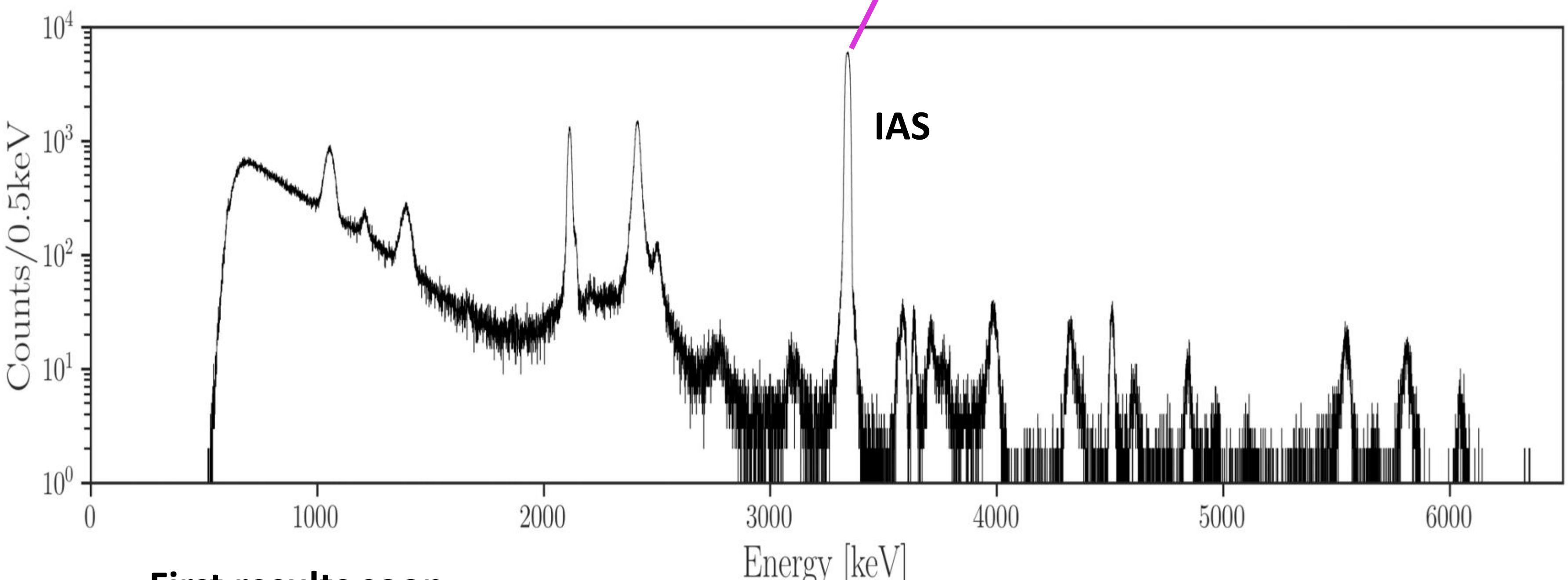
$a_{\beta\nu}^{F}$ = **0.9981(48) (Gorelov)**

$a_{\beta\nu}^{F}$ = **1.0000(20) (WISArD 2024)**

Limits on scalar currents: WISArD 2024

- 2.5 days with ^{32}Ar high production rate
- 2000 pps/μC
- 11 x 10^6 coincidence events
  ➪ 0.2% stat. uncertainty
- all detectors performing at nominal resolution





First results soon...

- Super-allowed 0^+ - 0^+ β decay: ^{10}C decay
- $\beta-\nu$ angular correlation measurements: WISArD
- **Beta-shape measurement: InESS (^{114}In)**

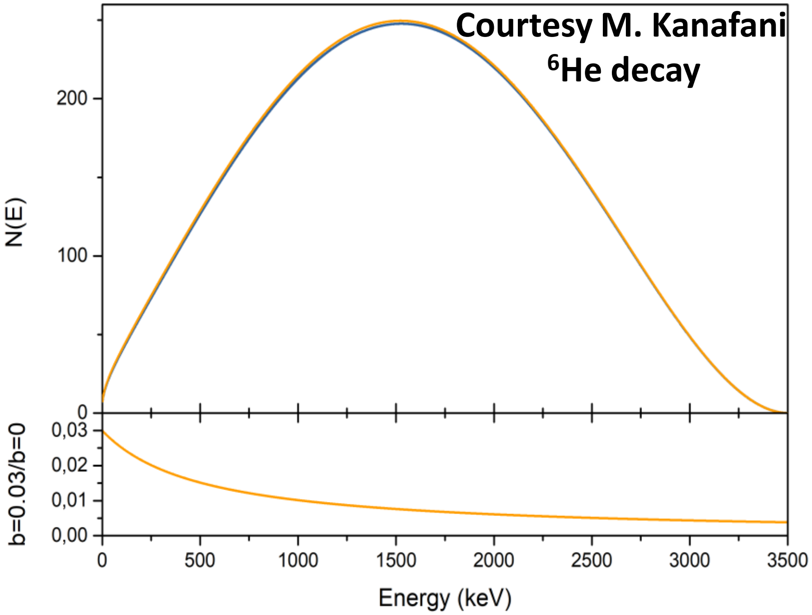
Beta spectrum shape measurement

Beta decay rate:

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

Beta decay rate of unpolarised nuclei:

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



Weak-Magnetism (b_{WM}):

$$\frac{dW(\mathbf{J})}{dE_e d\Omega_e d\Omega_\nu} = dW_0 \times \xi \left\{ 1 - \frac{2}{3}\frac{E_0}{Mc} b_{WM} + \frac{4}{3}\frac{E_e}{Mc} b_{WM} - \frac{2}{3}\frac{1}{Mc}\frac{1}{E_e} b_{WM} \right\}$$

➔ **Strong interaction induced effet, has to be controlled to extract Fierz term**

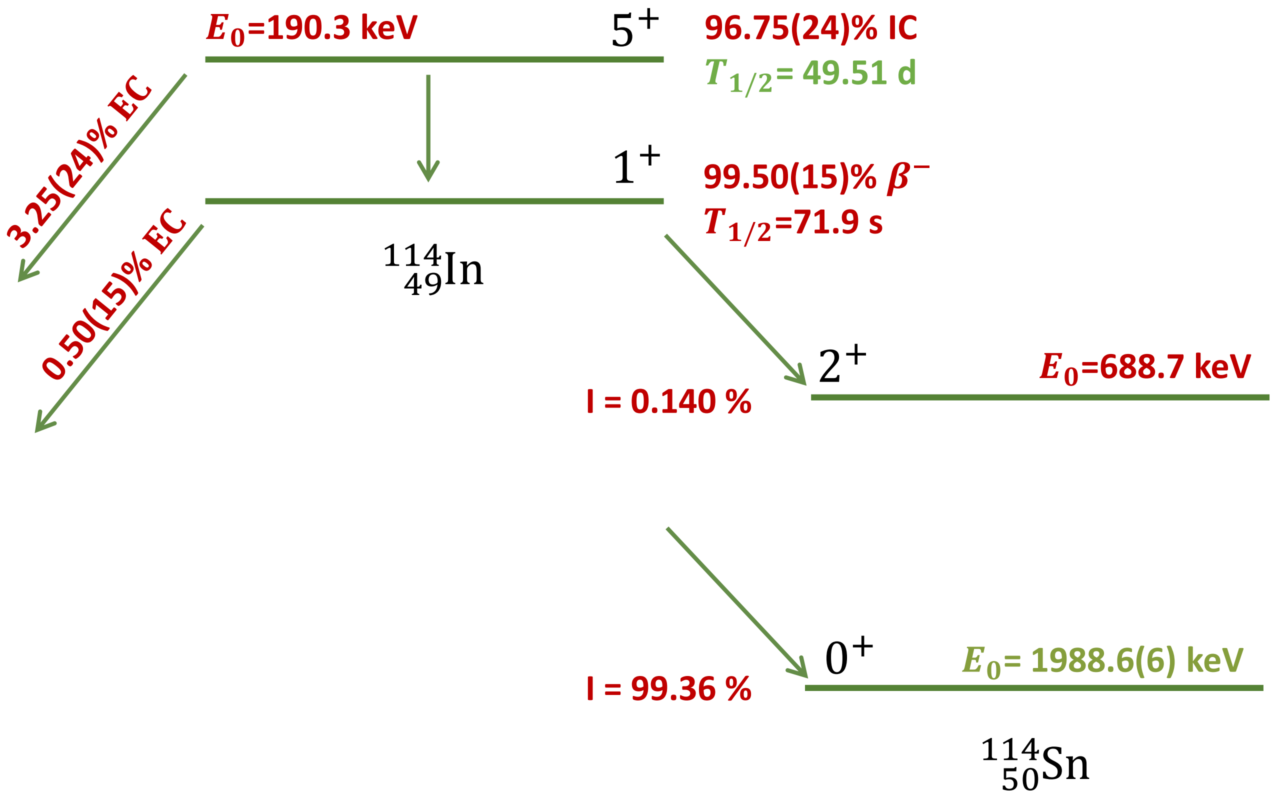
M. González-Alonso, O. Naviliat-Cuncic Phys. Rev. C 94 (2016)
L. Hayen et al, Rev. Mod. Phys. 90 (2018)

β-shape measurements:

^{114}In at WISArD/ISOLDE: InESS

Beta spectrum shape measurement

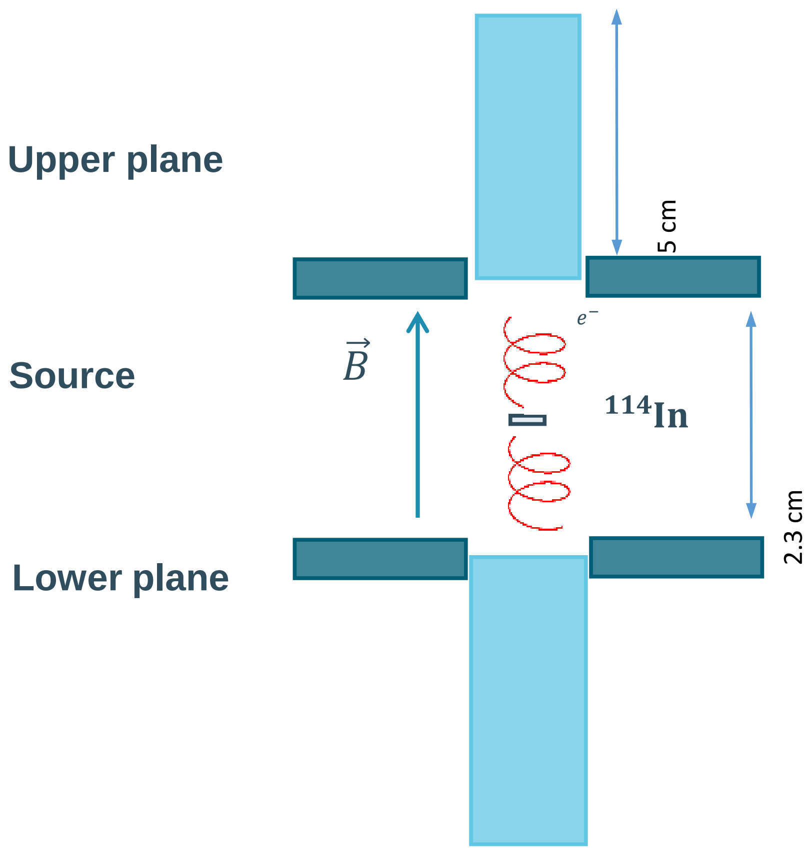
Beta-decay shape from ^{114}In:

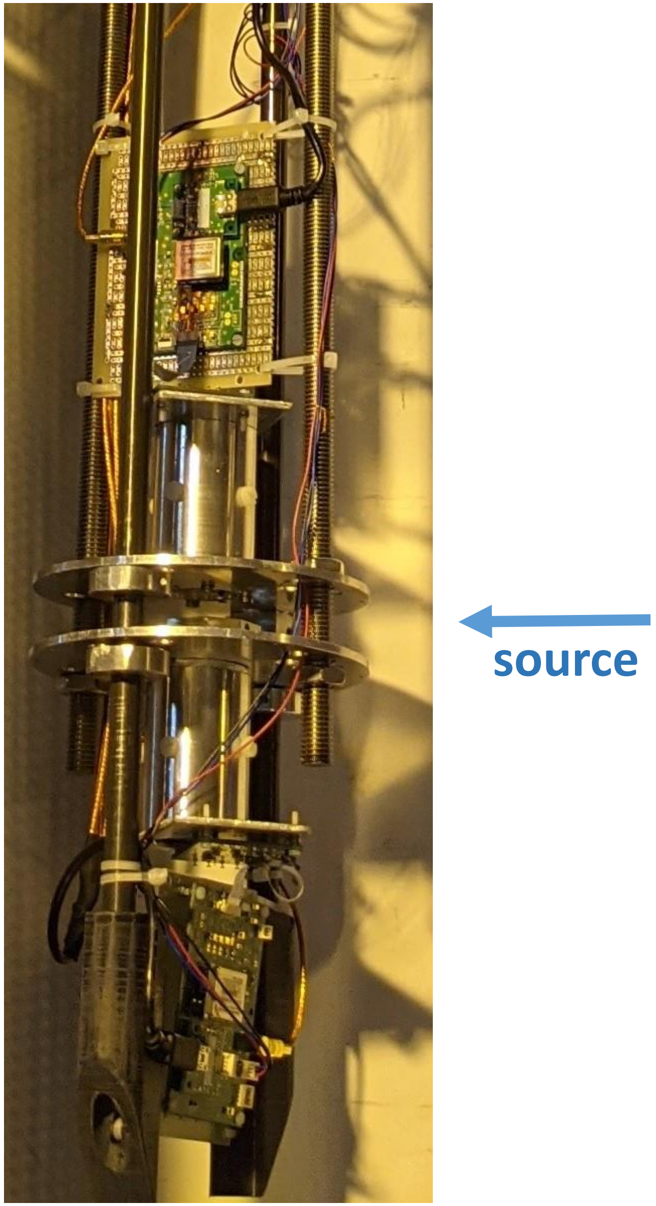


Courtesy S. Vanlangendonck

InESS @ WISArD

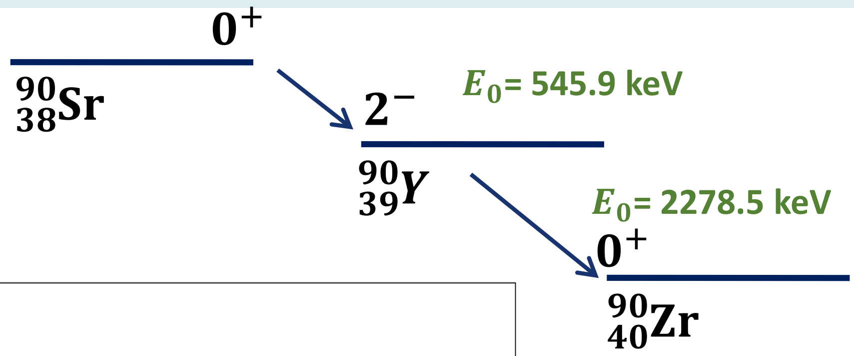
- **Closed geometry: B field**
  - **first try: InESS @WISArD**

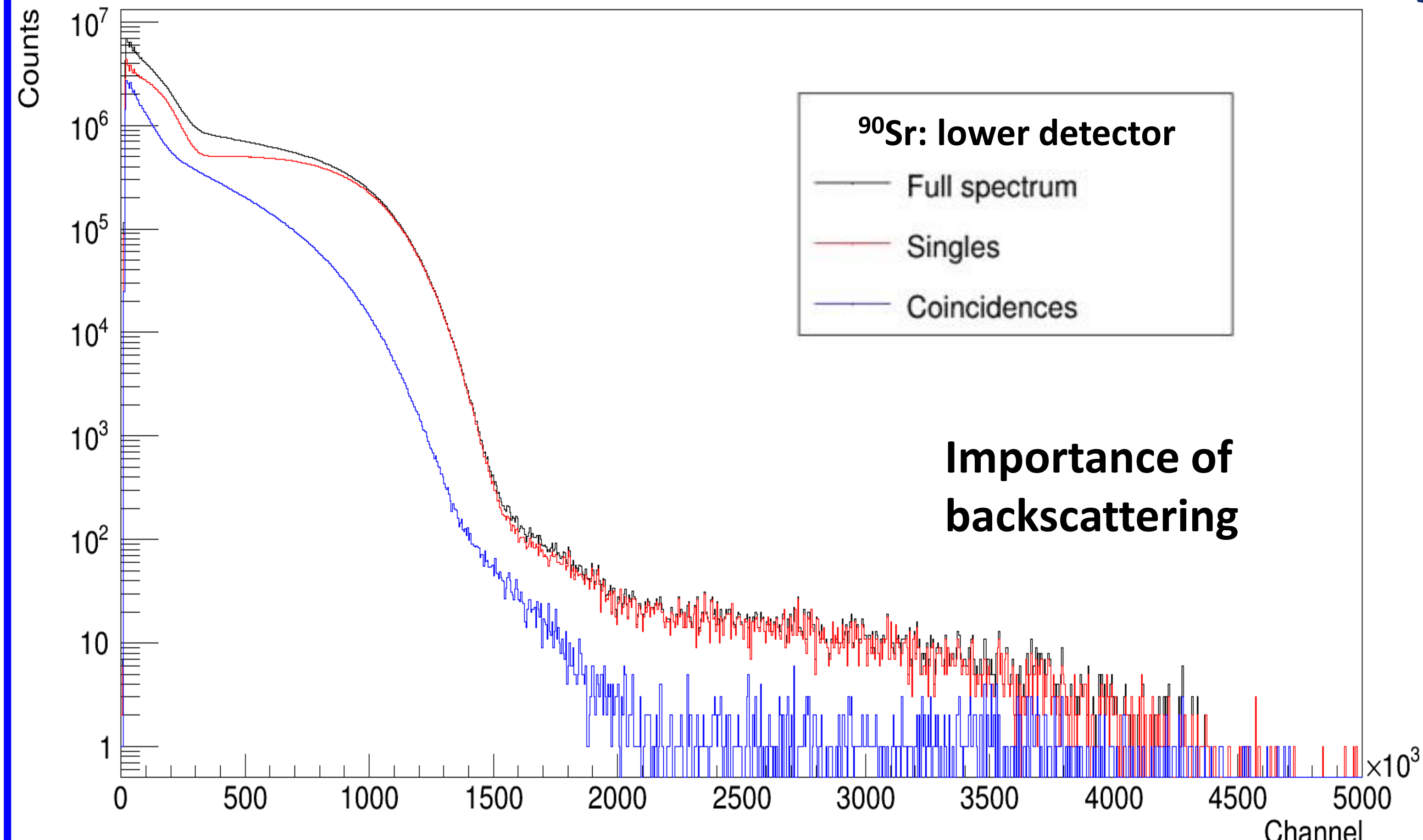




S. Vanlangendonck, WISArD collaboration

InESS @ WISArD: a few spectra

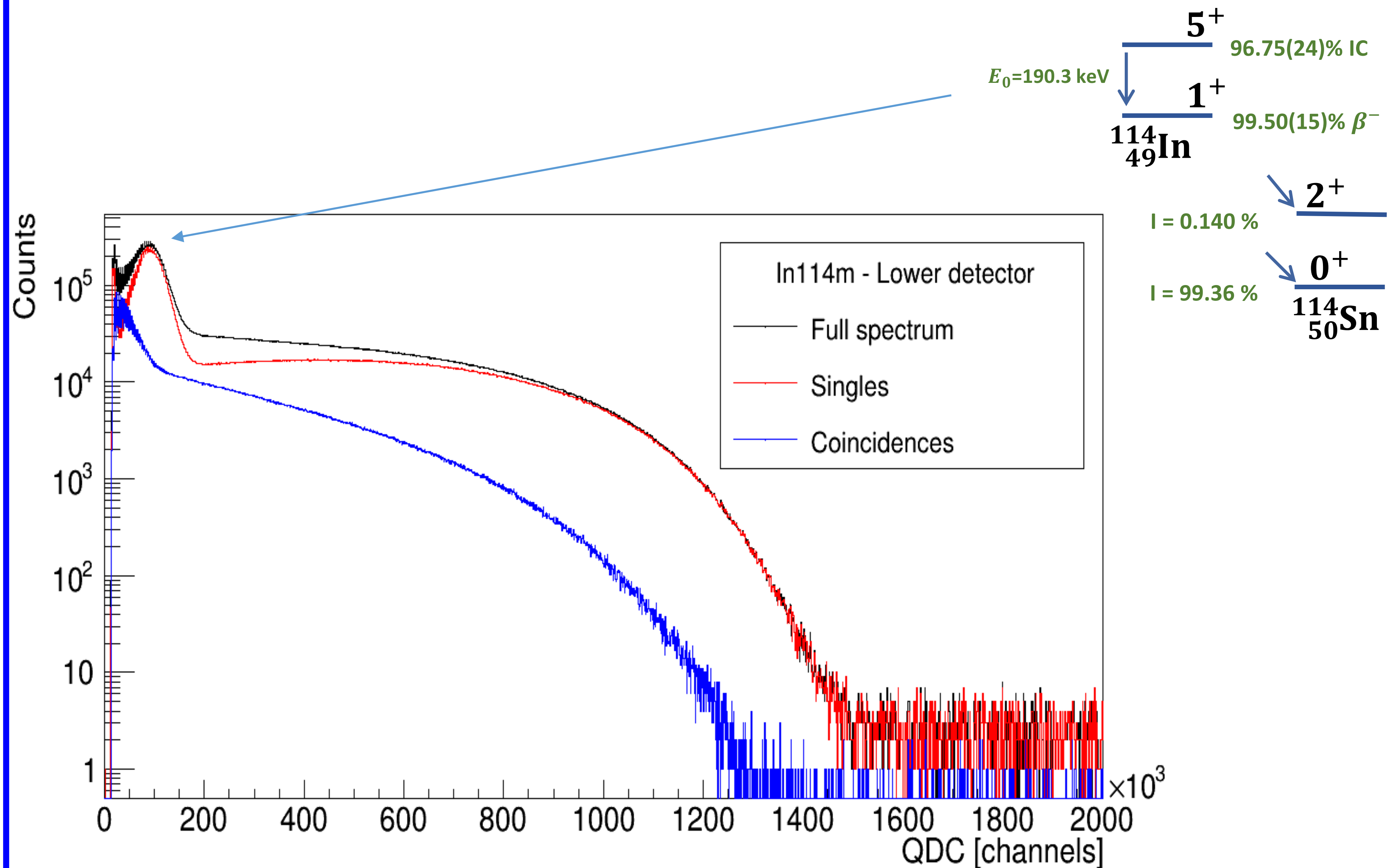




Importance of backscattering

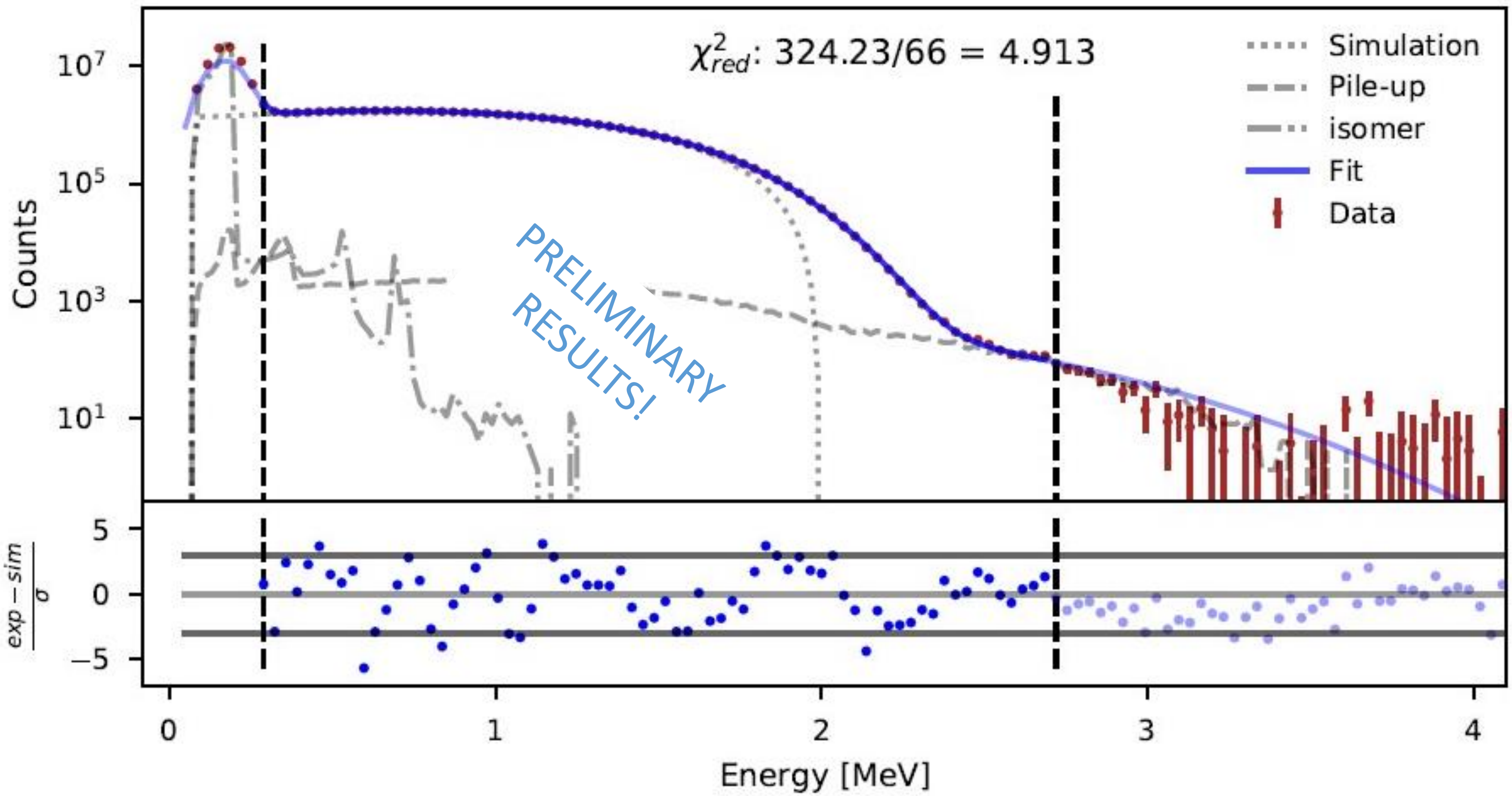
S. Vanlangendonck, PhD, WISArD collaboration

InESS @ WISArD: a few spectra



S. Vanlangendonck, PhD, WISArD collaboration

InESS @ WISArD: Comparison with simulations



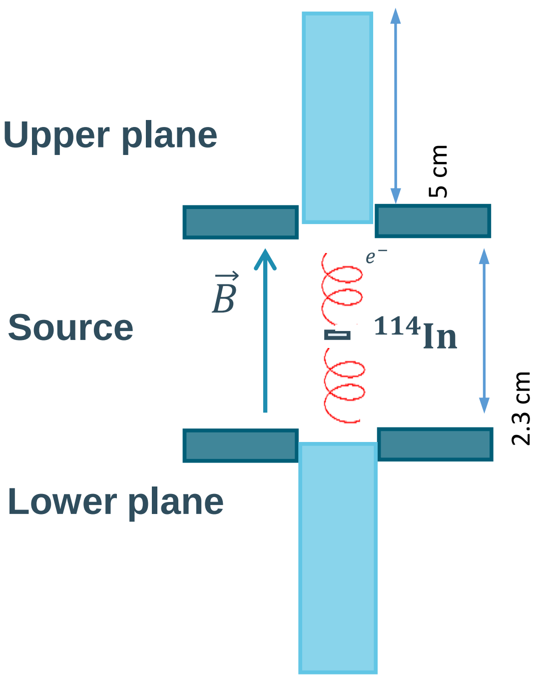
weak-magnetism term:

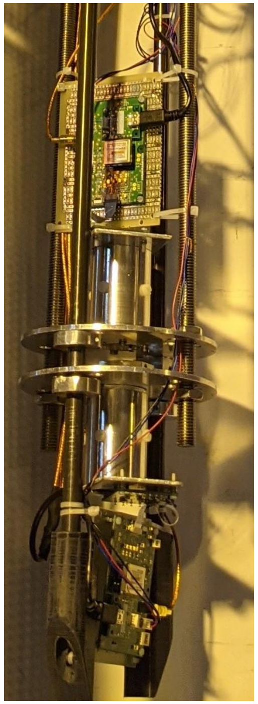
$b/Ac = 19.3(22)_{stat}(17)_{sys}$

S. Vanlangendonck, PhD, WISArD collaboration

● ● ● InESS @ WISArD

- **Closed geometry: B field**
  - first try: InESS @WISArD

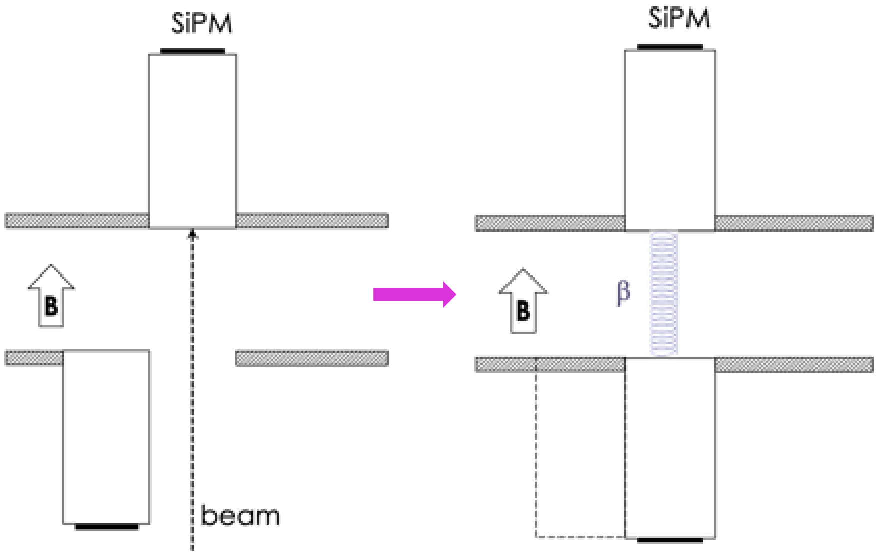




- **Next step:**
  - smaller half-life candidates
  - new set-up:

    direct implantation of RIB

    rotatable beta detector (e.g. ^{14}O)



+ replace scintillators by Si(Li) detectors

Summary

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

^{6}He @ LPC (Paul trap)
^{8}Li @ ANL (Paul trap)
^{8}B @ ANL (Paul trap)
^{6}He @ Seattle (MOT)
^{32}Ar @ ISOLDE (catcher foil)
^{32}Ar @ Texas A&M (Penning)
^{38m}K @ TRIUMF (MOT)
n @ aSPECT
...

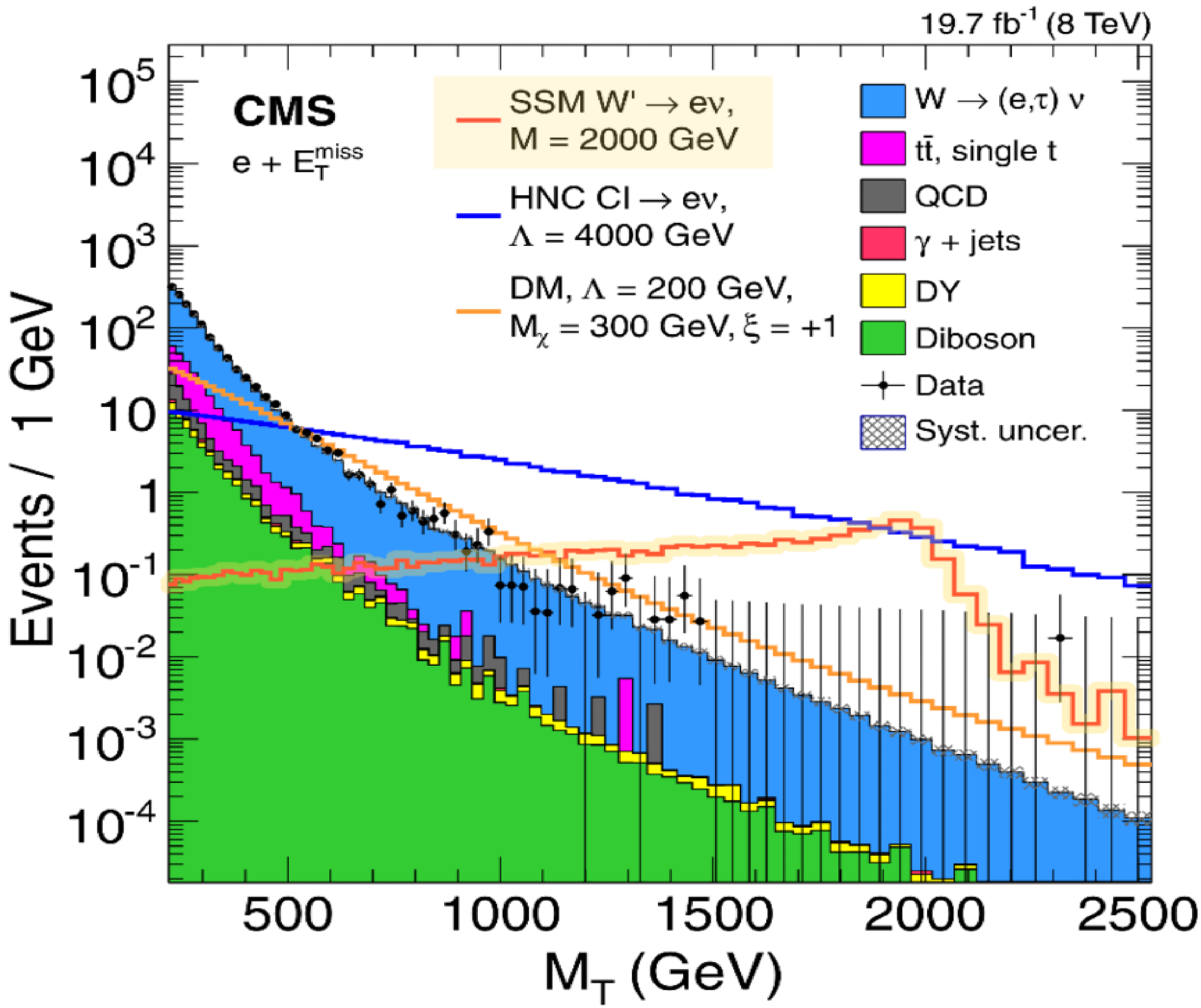
^{114}In @ ISOLDE
^{6}He @ LPC/GANIL (bSTILED)
^{6}He @ NSCL
^{20}F @ NSCL
....

THE MORA PROJECT
MATTER'S ORIGIN FROM RADIOACTIVITY

- large number of experiments ongoing
- aim is 0.1% of precision
- certainly impossible with present experiments to go much below…

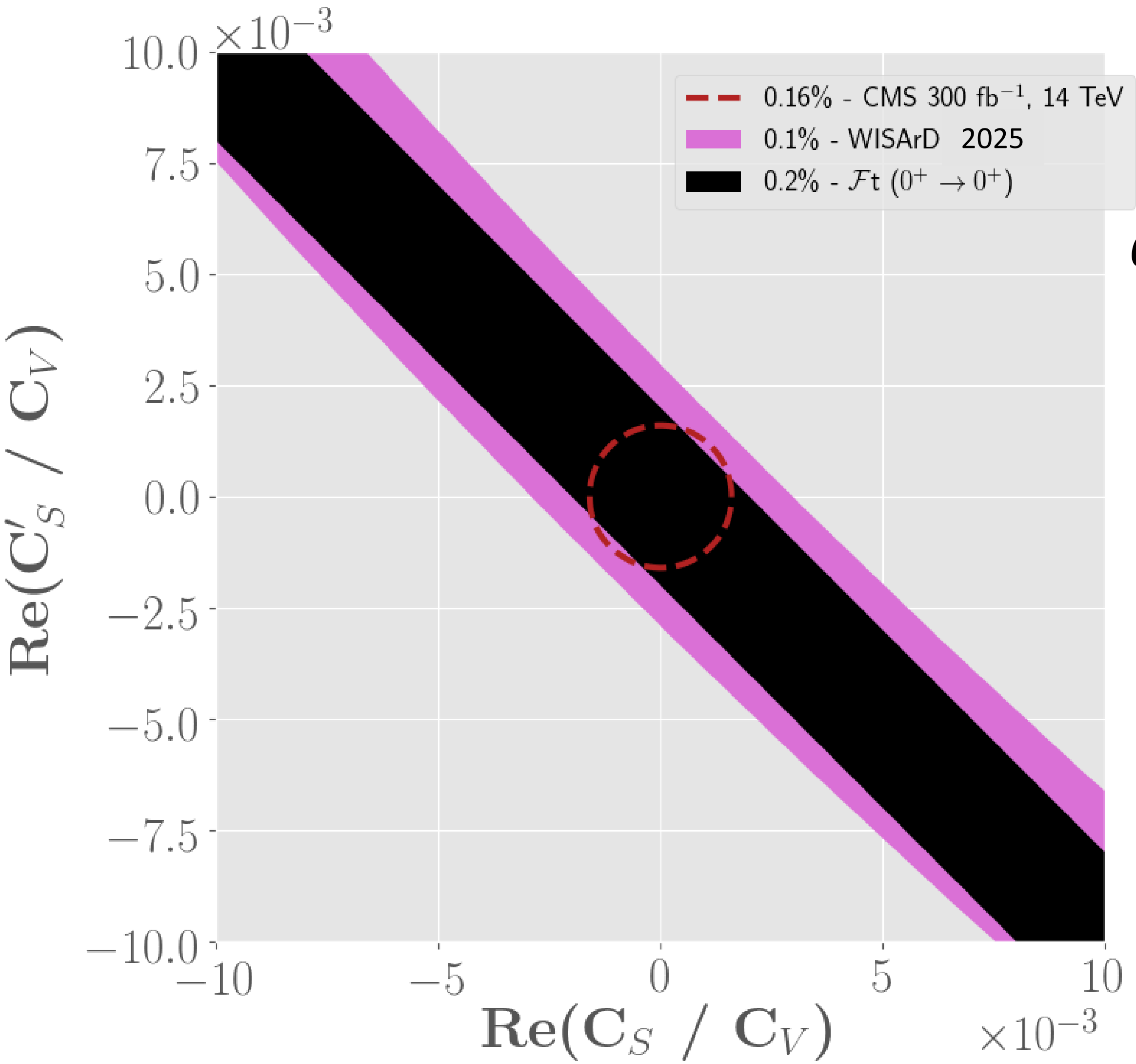
- with EFT, LHC and β-decay experiments can be compared directly

● ● ● LHC experiments



CMS Collaboration, Phys. Rev. D 91, 092005 (2015)

Present and future limits on scalar currents



$$a^{F}_{\beta\nu} = 1.0000(10)$$

(WISArD 2025)

Thanks for your attention

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Laboratoire de physique corpusculaire

ISOLDE

ibs Institute for Basic Science

sck cen

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