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Probing physics beyond the Standard Model in neutron and nuclear beta decay

UniGe Seminar - Geneva

November 6th, 2019

Nathal Severijns

KU Leuven University, Belgium

Outline

- V_{ud} and CKM-unitarity
  - → Ft-values ($t_{1/2}$, BR, Q_{EC})
- searches for exotic S and T currents
  - → βν-correlation
  - → β-asymmetry
- searches for Time Reversal Violation
  - → R-correlation
  - → EDM measurements

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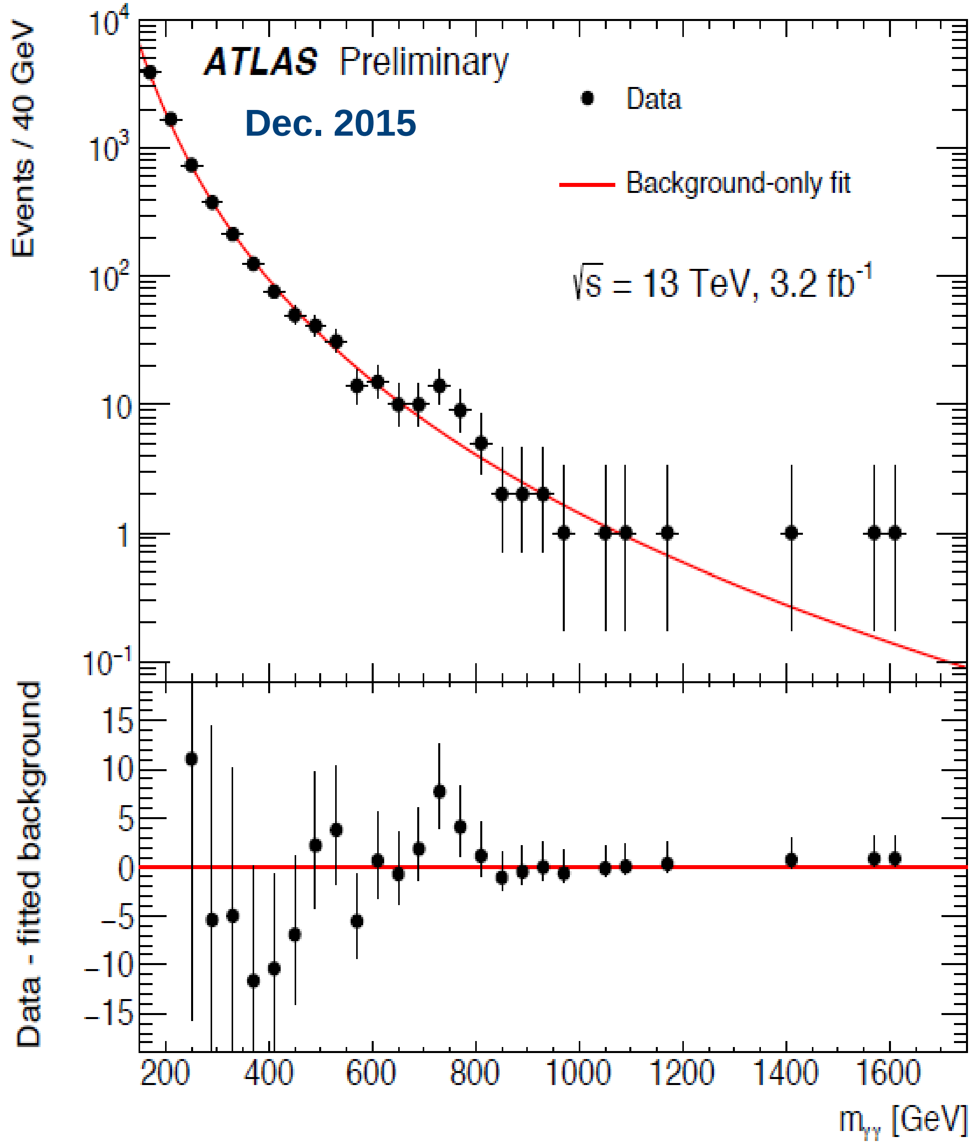
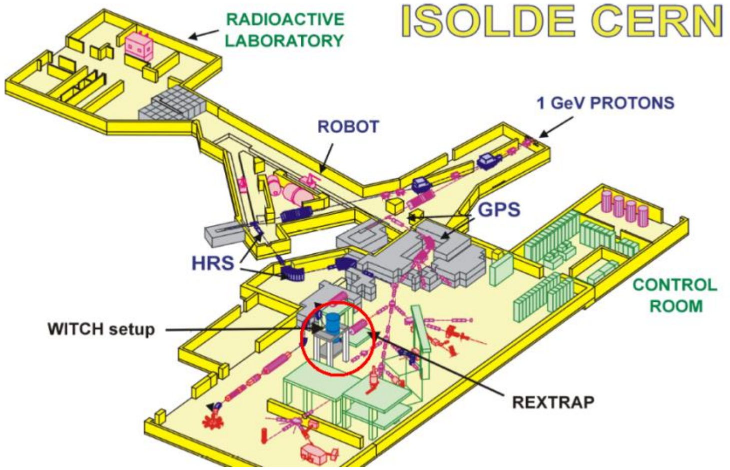
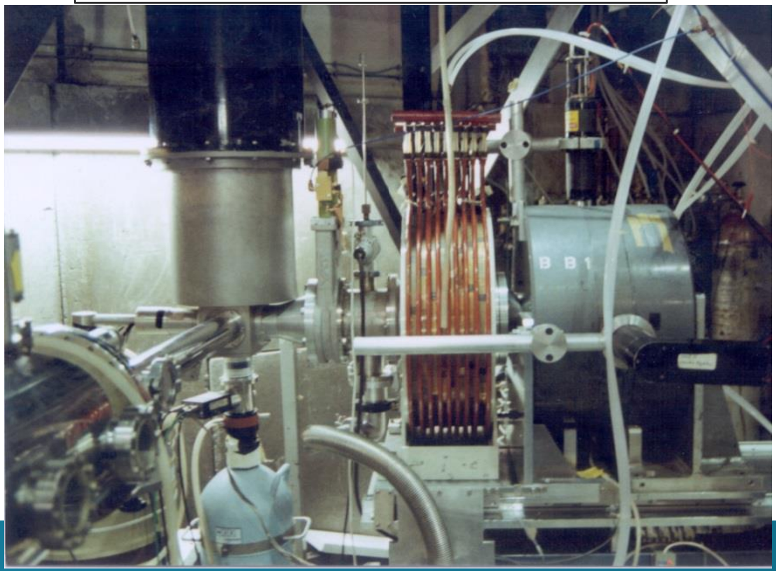
Experiments at the frontiers of standard theory



Precision frontier

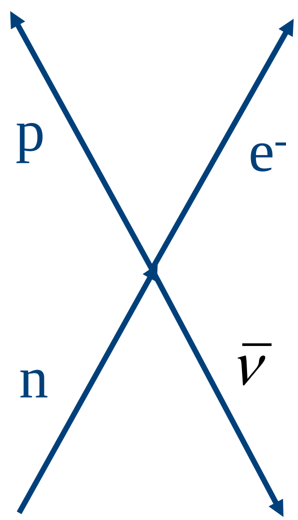


$$\tilde{A} = A_{SM}\left[1 - k\left(C_T + C_T^{'}\right)\right]$$



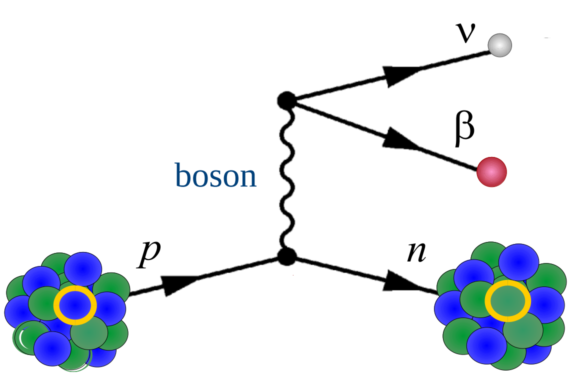
1. Structure of the weak interaction in β decay

β-decay Hamiltonian (Lee & Yang, 1956) :



$$H_\beta / g \;\propto\; (\bar{p}\, 1\, n)\;[\bar{e}\; 1\;(C_S + C_S'\gamma_5)\,\nu\,]$$
$$+\;(\bar{p}\,\gamma_\mu\, n)\;[\bar{e}\;\gamma_\mu\;(C_V + C_V'\gamma_5)\,\nu\,]$$
$$+\;\frac{1}{2}(\bar{p}\,\sigma_{\mu\nu}\, n)\;[\bar{e}\;\sigma_{\mu\nu}\;(C_T + C_T'\gamma_5)\,\nu\,]$$
$$-\;(\bar{p}\,\gamma_\mu\gamma_5\, n)\;[\bar{e}\;\gamma_\mu\gamma_5(C_A + C_A'\gamma_5)\,\nu\,]$$
$$+\;\underbrace{(\bar{p}\,\gamma_5\, n)}_{\approx 0}\;[\bar{e}\;\gamma_5\;(C_P + C_P'\gamma_5)\,\nu\,]$$

f



with γ_i (i = 1, 2, 3, 4) Dirac matrices $(\gamma_5 = \gamma_1\gamma_2\gamma_3\gamma_4)$

and $\sigma_{\mu\nu} = -\frac{i}{2}(\gamma_\mu\gamma_\lambda - \gamma_\lambda\gamma_\mu)$

P-violation if $C_i \neq 0$ and $C_i' \neq 0$

T-violation if $\mathrm{Im}(C_i^{(')}/C_j) \neq 0$

the Standard Model and beyond:

* $C_V \equiv 1$; $C_A = -1.27$ (g_A/g_V 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,A)

5% level → ~ 350 GeV
per mille level → ~ 2.5 TeV

$$C_i \propto \frac{M_W^2}{M_{new}^2}$$

experimental upper limits: $|C_T^{(\,'\,)}/C_A|$ and $|C_S^{(\,'\,)}/C_V|$ at several % level
(neutron and nuclear β-decay)

N.S., O. Naviliat-Cuncic and M. Beck, Rev. Mod. Phys. 78 (2006) 991,
J. Nico, J. Phys. G 39 (2009) 104001,
D. Dubbers and M.G. Schmidt, Rev. Mod. Phys. 83 (2011) 1111,
V. Cirigliano et al., Prog. Part. Nucl. Phys. 71 (2013) 93,
O. Naviliat-Cuncic and M. Gonzalez-Alonso, Annalen der Physik 525 (2013) 600.
F. Wauters et al., Phys. Rev. C 89 (2014) 025501,
B.R. Holstein, J. Phys. G 41 (2014) 114001
M. Gonzalez-Alonso, O. Naviliat-Cuncic and N.S., Prog.Part.Nucl.Phys. 104 (2019) 165

* no time reversal violation
  (except for the CP-violation described by the phase in the CKM matrix)

Precision meas^ts in nuclear/neutron β decay in the LHC era

if particles that mediate new interactions are above threshold for LHC

→ Effective Field Theory allowing

direct comparison of low-energy and collider constraints

low-scale O(1 GeV) effective Lagrangian for semi-leptonic transitions (contributions from W-exchange diagrams and four-fermion operators)

link betw. EFT couplings ε_i and Lee-Yang nucleon-level effect. couplings C_i:

$$C_i = \frac{G_F(0)}{\sqrt{2}} V_{ud} \bar{C}_i \quad \text{with} \quad \bar{C}_S = g_S(\varepsilon_S + \tilde{\varepsilon}_S), \; \bar{C}_T = 4 g_T(\varepsilon_T + \tilde{\varepsilon}_T), \; \ldots$$

$$\varepsilon_i, \tilde{\varepsilon}_i \approx v^2/\Lambda_{BSM}^2 \quad \text{with} \quad v = (2\sqrt{2}\, G_F^{(0)})^{-1/2} \approx 170 \text{ GeV}$$

$$\text{if } \Lambda_{BSM} \sim 5 \text{ TeV} \;\rightarrow\; \varepsilon_i \sim 10^{-3}$$

g_S = 1.02(11)

g_T = 0.987(55)

(lattice-calc.)

M. González-Alonso et al., Ann. der Phys. 525 (2013) 600

T. Bhattacharya, et al., Phys. Rev. D 94 (2016) 054508

T. Bhattacharya et al., Phys. Rev. D 85 (2012) 054512

V. Cirigliano, et al., J. High. Energ. Phys. 1302 (2013) 046

O. Naviliat-Cuncic and M. González-Alonso, Annalen der Physik 525 (2013) 600.

V. Cirigliano, et al., Progr. Part. Nucl. Phys. 71 (2013) 93

Major observables in β decay

decay rate

$d\Gamma_0$

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

nuclear matrix elements, M_F and M_{GT}

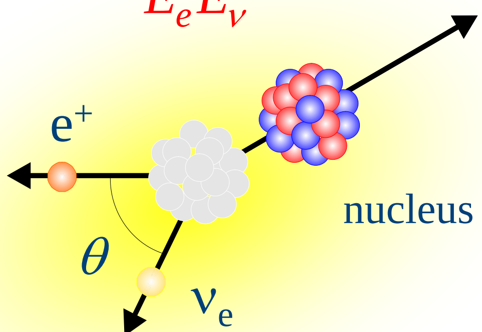
$$\mathrm{x} \left\{ 1 + a\frac{\vec{p}_e \cdot \vec{q}}{E_e E_\nu} + b_{Fierz}\frac{\gamma m_e}{E_e} + A\frac{\vec{J}}{J} \cdot \frac{\vec{p}_e}{E_e} + R\,\vec{\sigma} \cdot \frac{\vec{J}}{J} \,\mathrm{x}\, \frac{\vec{p}_e}{E_e} + \ldots \right\}$$

β-ν correlation

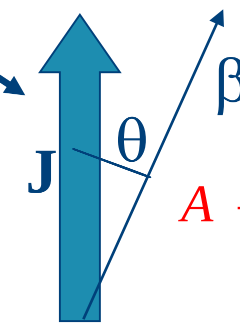
Fierz interference term (b ≡ 0 in standard model)

β-asymmetry

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



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



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

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

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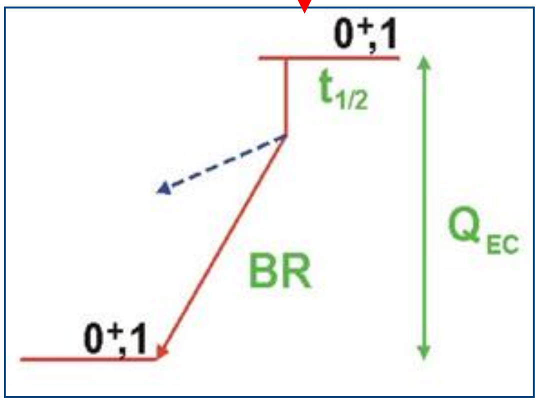
V_{ud} quark mixing matrix element & CKM unitarity

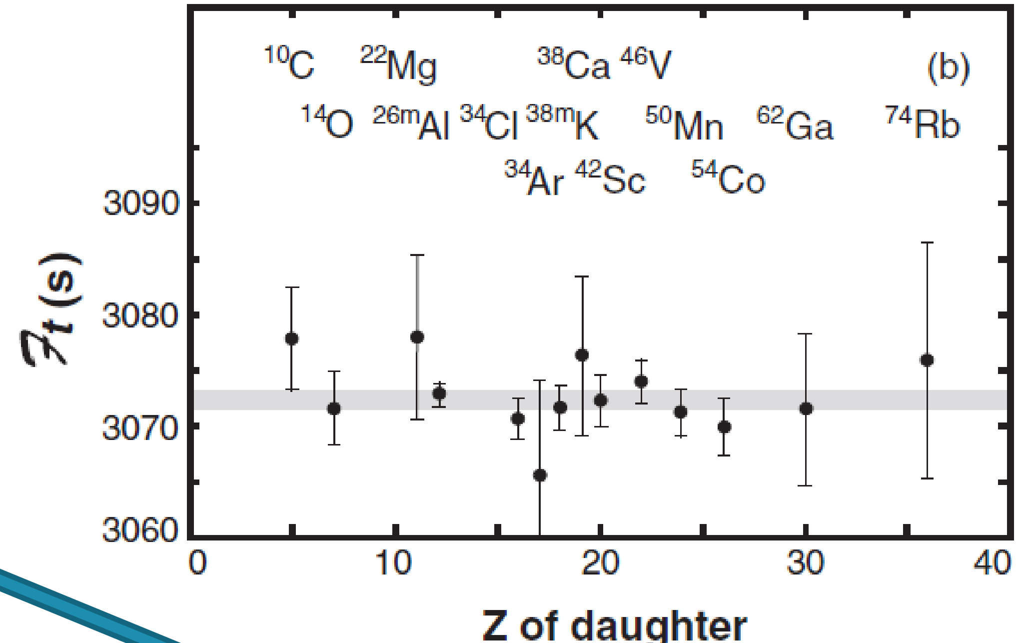
$$\mathcal{F}t^{0^+\to 0^+} \equiv f_V t^{0^+\to 0^+} \left(1+\delta_{NS}^V-\delta_C^V\right)\left(1+\delta_R'\right) = \frac{K}{2G_F^2 V_{ud}^2 C_V^2 \left(1+\Delta_R^V\right)}$$

from experiment

nucleus dependent corrections

nucleus independent





$|V_{ud}| = 0.97420(21)$

Hardy & Towner, PR C 91 (2015) 025501
and arXiv 1807.01146

$\mathcal{F}t^{0^+\to 0^+}$ = 3072.27(72) s

with $|V_{us}| = 0.2243(5)$ (Particle Data Group 2018)

$$|V_{ud}|^2+|V_{us}|^2+|V_{ub}|^2 = 0.99939(47)$$

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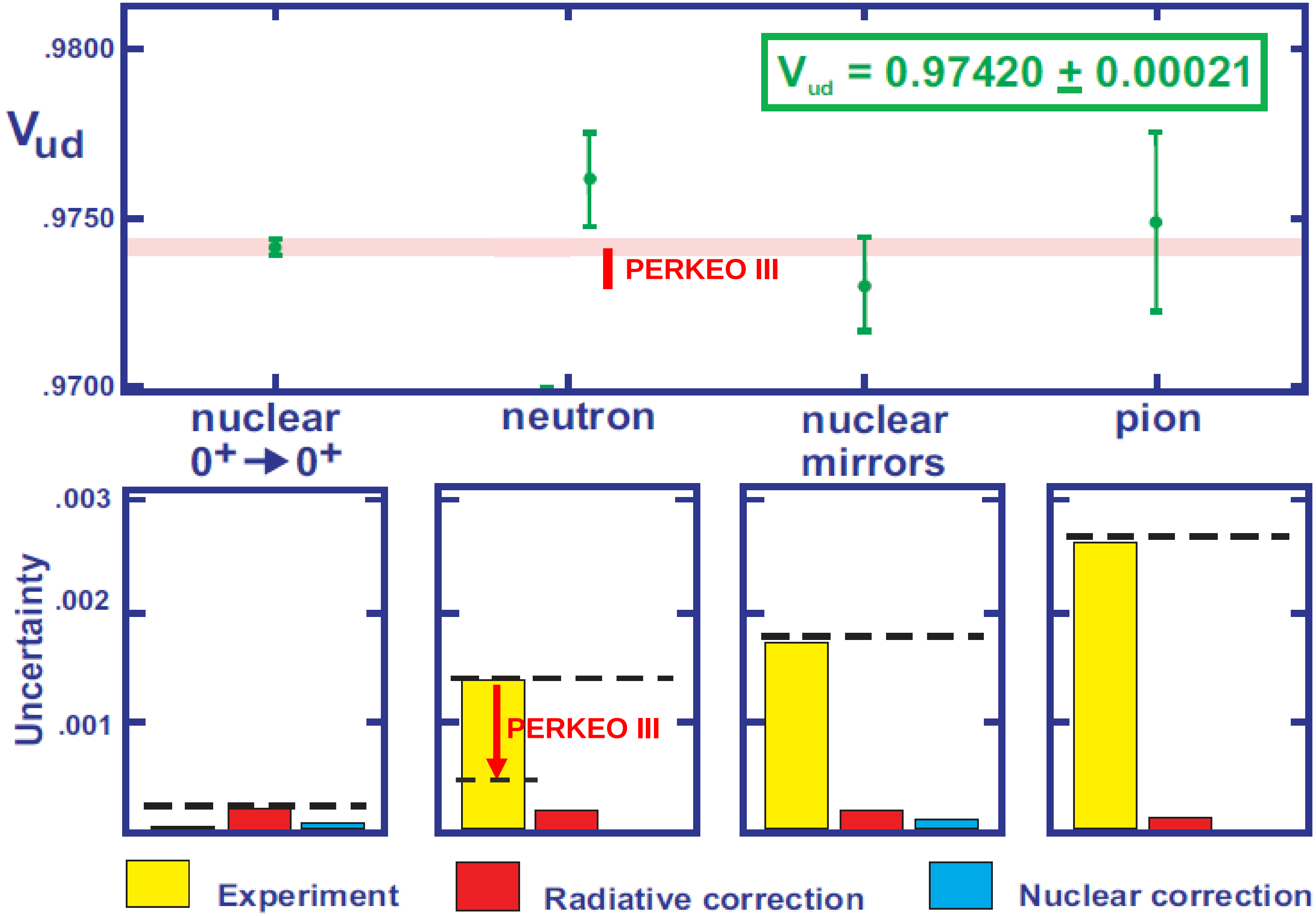

$$\mathcal{F}t = ft(1 + \delta'_R)[1 - (\delta_C - \delta_{NS})] = \frac{K}{2G_V^2\,(1 + \Delta_R)}$$

Radiative correction Δ_R

$$|V_{ud}|^2 \propto \frac{1}{Ft\,(1+\Delta_R)}$$

$(1 + \Delta_R) = 0.02361(38)$ - W. J. Marciano and A. Sirlin, Phys. Rev. Lett. 96, 032002 (2006)

$\sim 3\,\sigma$

$(1 + \Delta_R) = 0.02467(22)$ - M. Gorchtein, M. Ramsey-Musolf et al., PRL 121, 241804 (2018)

V_{ud} (nuclear β-decay) = 0.97420(21) → 0.97370(14)

$$\sum |V_{ui}|^2 = 0.99939(47) \rightarrow 0.99842(47)$$

$$\Delta_{SM} = 1.3\,\sigma \rightarrow 3.3\,\sigma\,!$$

a sign of new physics, or is something not yet fully under control?

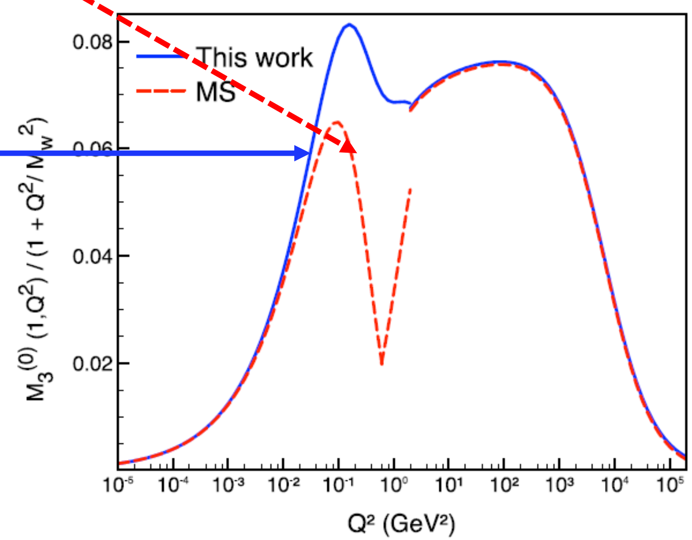

FIG. 5. Log-linear plot of $M_3^{(0)}(1,Q^2)[1+Q^2/M_W^2]^{-1}$ as a function of Q^2. The blue curve is the result of our parametrization in Eq. (12), and the red curve is the piecewise parametrization used by [MS]. For a given parametrization, the contribution to $\square_{\gamma W}^{VA}$ is proportional to the area under the curve, see Eq. (9).

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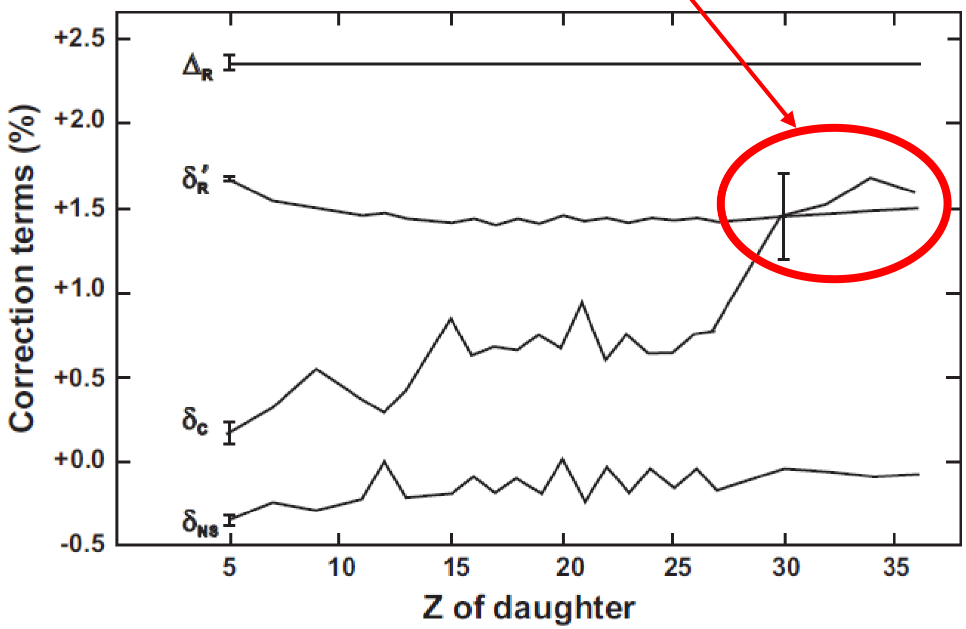
Radiative correction Δ_R and V_{ud}

$$\mathcal{F}t = ft(1 + \delta'_R)[1 - (\delta_C - \delta_{NS})] = \frac{K}{2G_V^2 (1 + \Delta_R)}$$

Is isospin symmetry correction δ_c still not well under control?

Can be tested by:

- higher precision on V_{ud}(neutron): no δ_c correction in n-decay, no V_{ud}(n) should NOT show this effect
- better precision on V_{ud}(mirror nuclei): also require the δ_c correction, and so should show same effect as $0^+ \rightarrow 0^+$ decays (best cases are isotopes with Z > 30)



Radiative correction Δ_R and V_{us}(Kaon)

Is V_{us} sufficiently well under control?

Particle Data Group 2018: $|V_{us}| = 0.2231(8)$ $K_{\ell 3}$ decays
$|V_{us}| = 0.2253(7)$ $K_{\mu 3}$ decays
} $|V_{us}| = 0.2243(5)$

further: $K_{\ell 3}$ decays determine $f_+(0)|V_{us}| = 0.2265(4)$
with form factor $f_+(0) = 0.969(3)$

$K_{\mu 3}$ decays require form factor ratio $f_{K+} / f_{\pi+} = 1.193(3)$

all these form factors obtained from lattice QCD calculations

(S. Aoki et al. [FLAG], Eur. Phys. J. C77 (2017) 112)

while also: $|V_{us}| = 0.2250(27)$ hyperon decays
$|V_{us}| = 0.2216(15)$ τ decays

(both not included in average)

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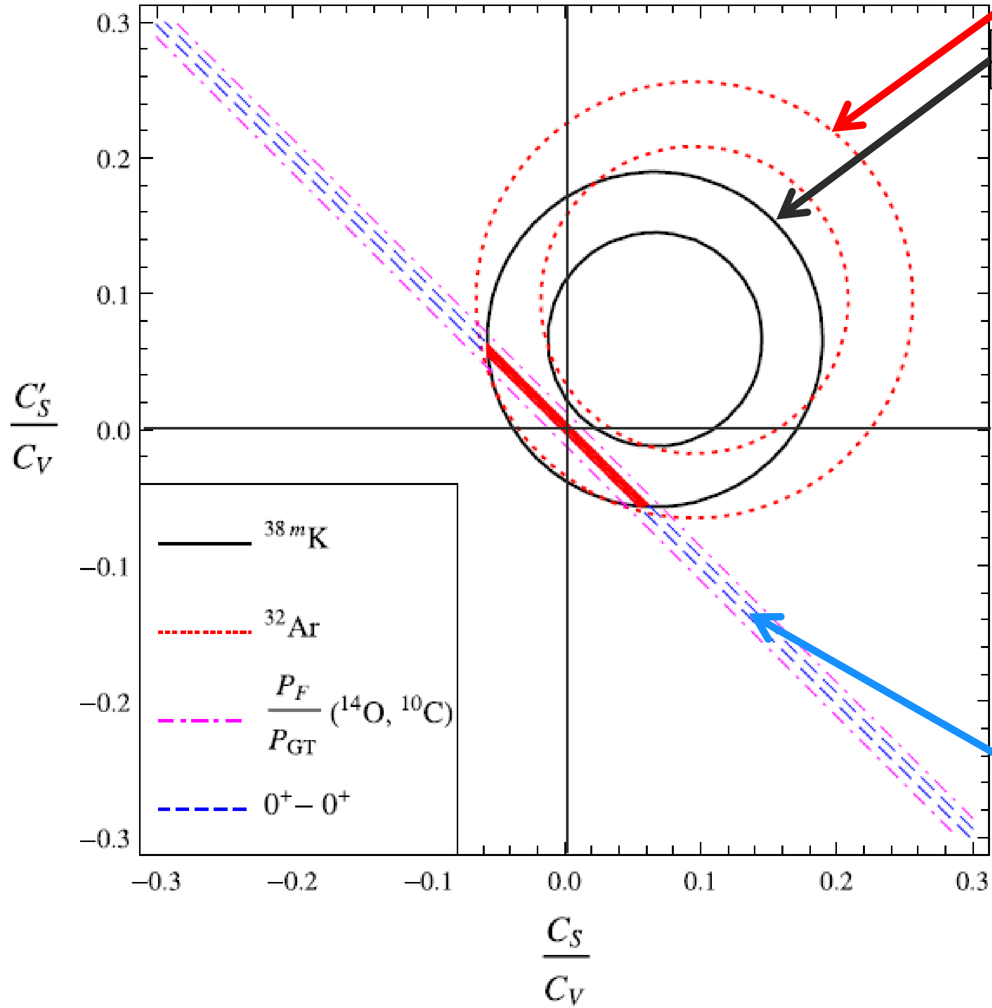
Limits on scalar currents



B. R. Holstein, J. Phys. G 41 (2014) 114001

^{32}Ar: Adelberger et al., PRL 83 (1999) 1299

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

$$\tilde{a} = \frac{a}{1 + b\frac{\gamma m_e}{E_e}}$$

βν correlation

Fierz interference term

with:

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

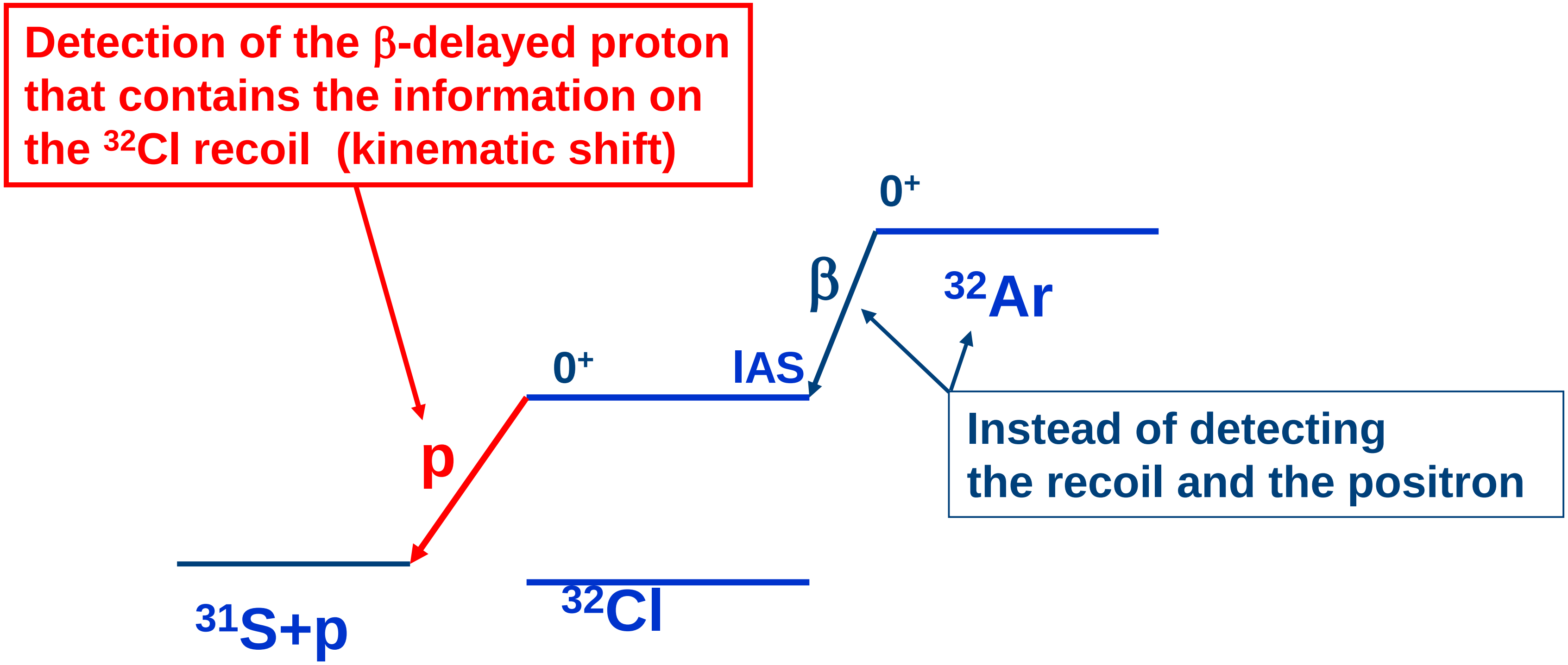
$$b'_F = \frac{\gamma m_e}{\langle E_e \rangle}\left(\frac{C_S + C'_S}{C_V}\right)$$

$$\mathcal{F}t^{0^+\rightarrow 0^+} = \frac{K}{2G_F^2 V_{ud}^2 C_V^2 \left(1 + \Delta_R^V\right)} \frac{1}{(1 + b'_F)}$$

Hardy & Towner , Phys. Rev. C 91 (2015) 025501

WISARD = Weak-interaction studies with Ar32 decay

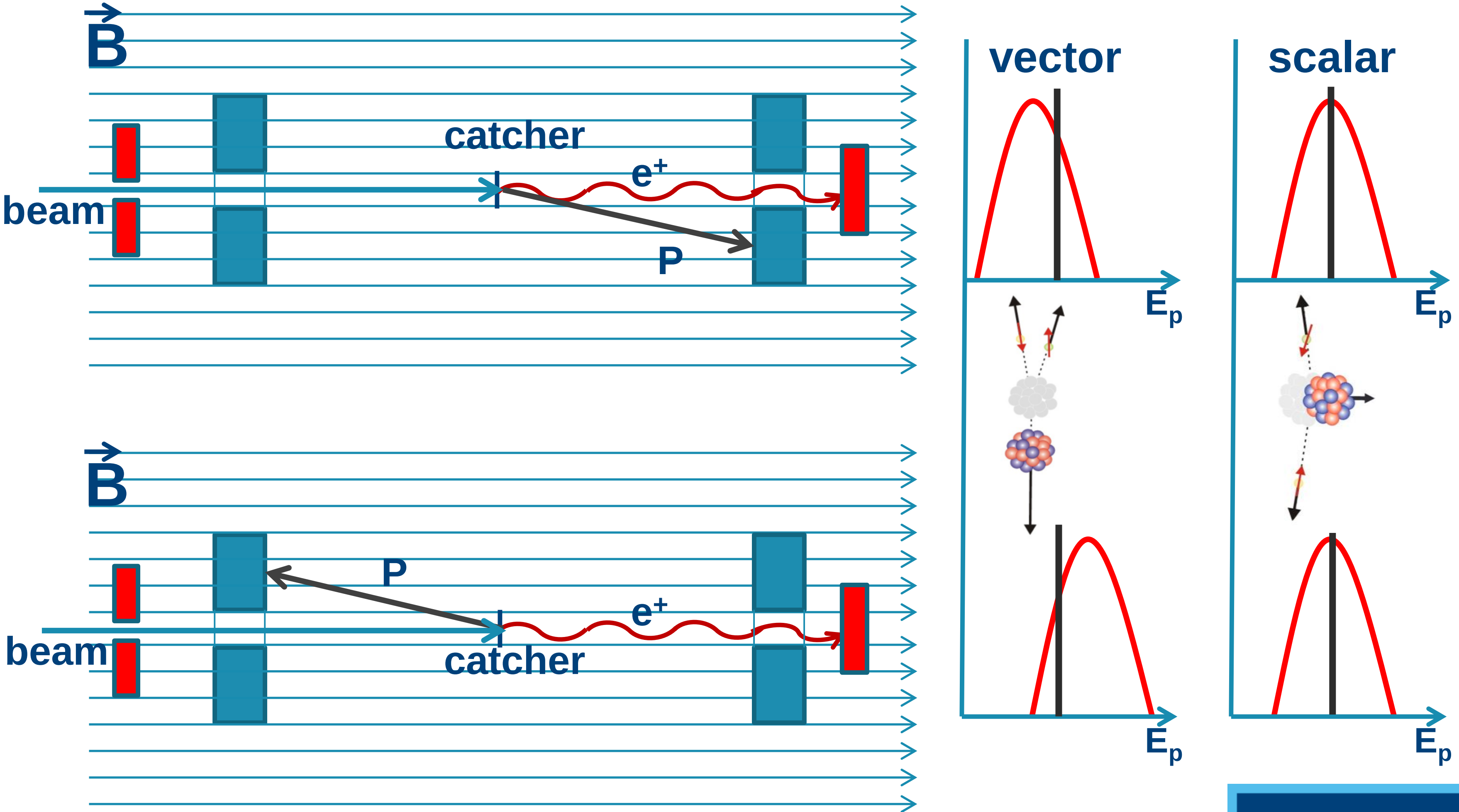
coll. Bordeaux, Leuven, LPC Caen, NPI-Prague, ISOLDE



WISARD = Weak-interaction studies with Ar32 decay

coll. Bordeaux, Leuven, LPC Caen, NPI-Prague

➔ measure protons and positrons in two hemispheres



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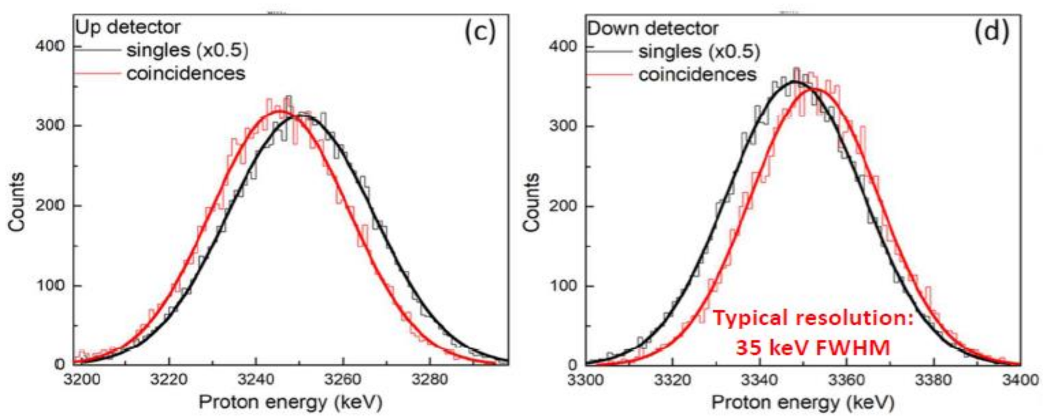
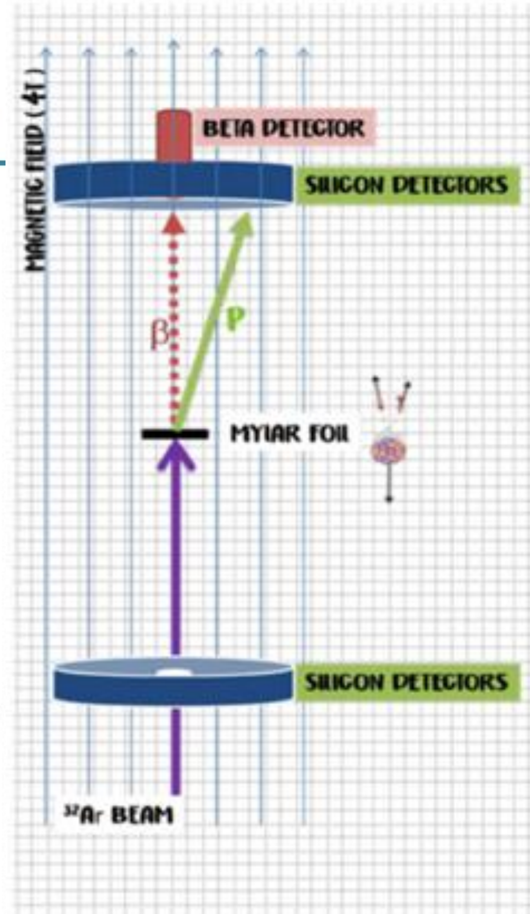
WISArD *Weak Interaction Studies with ^{32}Ar Decay*

first results: (nov. 2018)

Proton peak examples (Fermi transition):





Average shift:
Δ = 4.49(3) keV

by means of MC calculations:

$$\tilde{a}^{F}_{\beta\nu} = \mathbf{1.01(3)_{(stat)}(2)_{(syst)}} \qquad \tilde{a}^{GT}_{\beta\nu} = \mathbf{-0.29(9)_{(stat)}(2)_{(syst)}}$$

$$(\tilde{a}^{F}_{\beta\nu,SM} = 1.00) \qquad (\tilde{a}^{GT}_{\beta\nu,SM} = -0.33)$$

δ(a) = 0.1 % within reach with improved setup (in prep.) - ISOLDE

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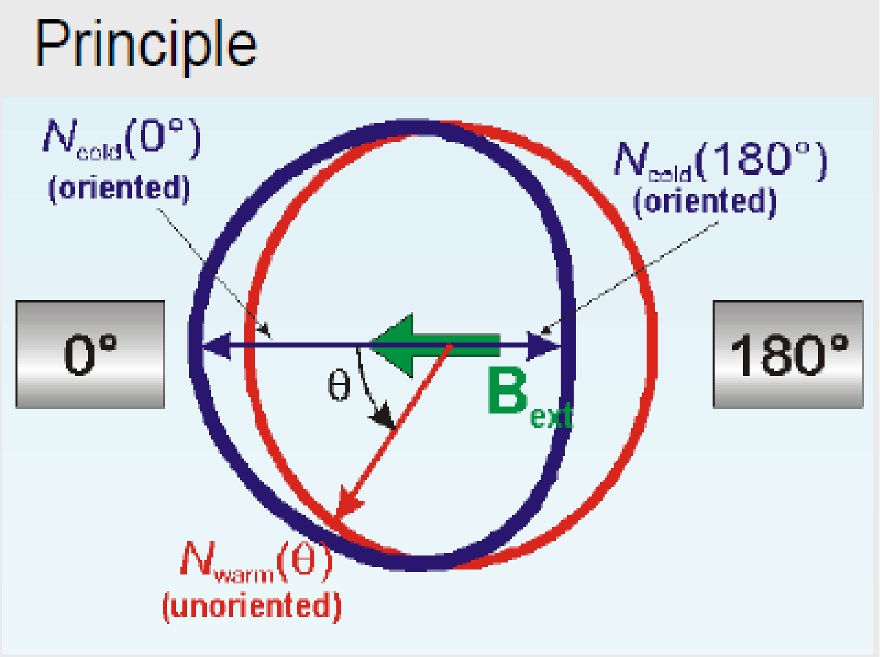
Courtesy: B. Blank

V. Araujo-Escalona, X. Flechard et al., arXiv:1906.05135

Tensor currents - β-asymmetry with polarized nuclei

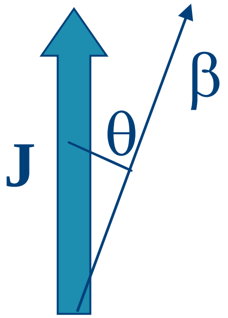


$$W(\theta) = \frac{N(\theta)_{pol}}{N(\theta)_{unpol}} \rightarrow \tilde{A} = \frac{A}{1 + b'_{GT}}$$

$$b'_{GT} = \frac{\gamma m_e}{\langle E_e \rangle}\left(\frac{C_T + C'_T}{C_A}\right)$$

Low-Temperature Nuclear Orientation

- temperatures down to 5 mK
- magnetic fields of O(10-100 T)



IS431-experiment

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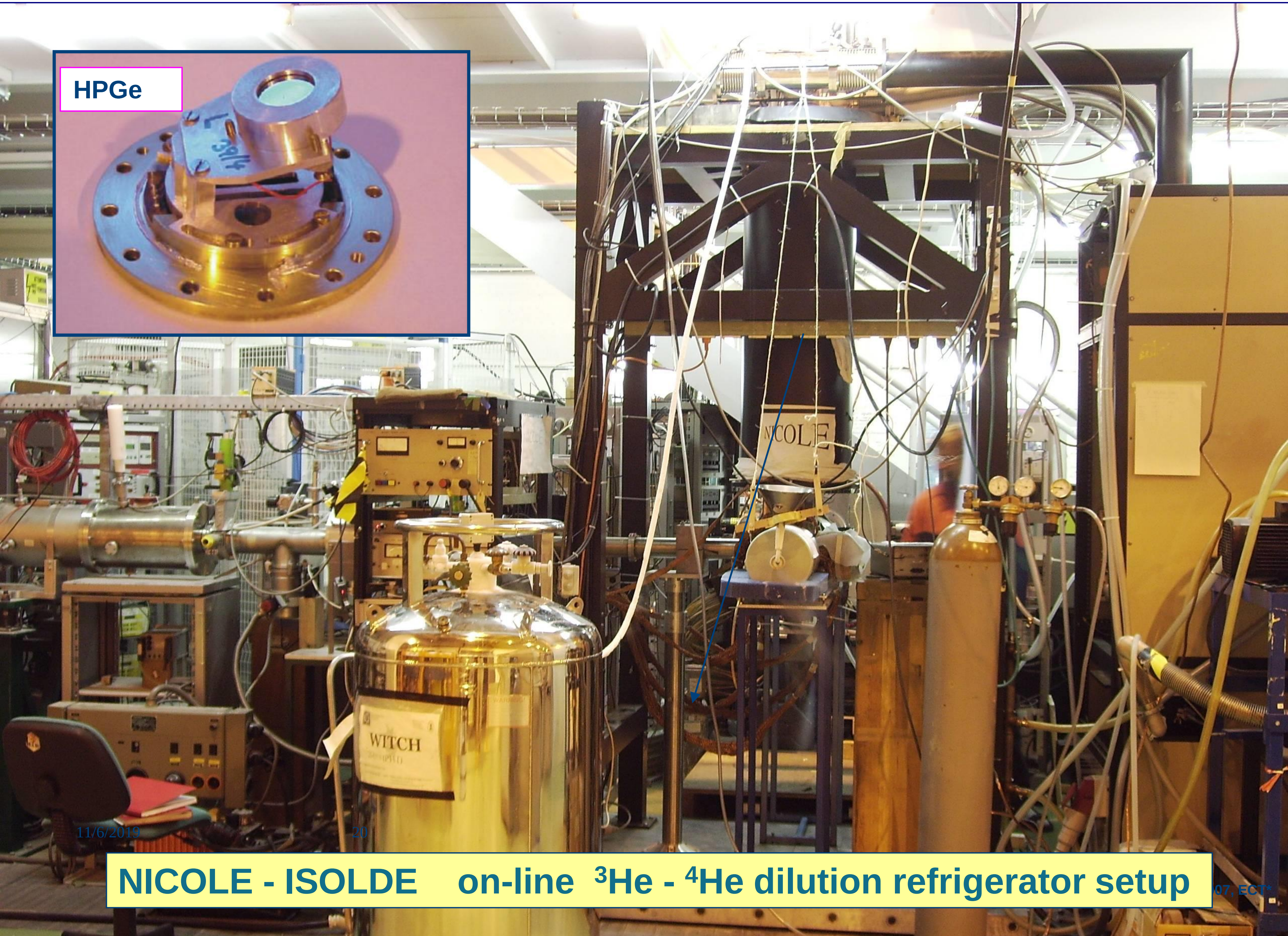


NICOLE - ISOLDE on-line ^{3}He - ^{4}He dilution refrigerator setup

(KU Leuven, NICOLE-ISOLDE, NPI Rez-Prague, Uni Bonn)

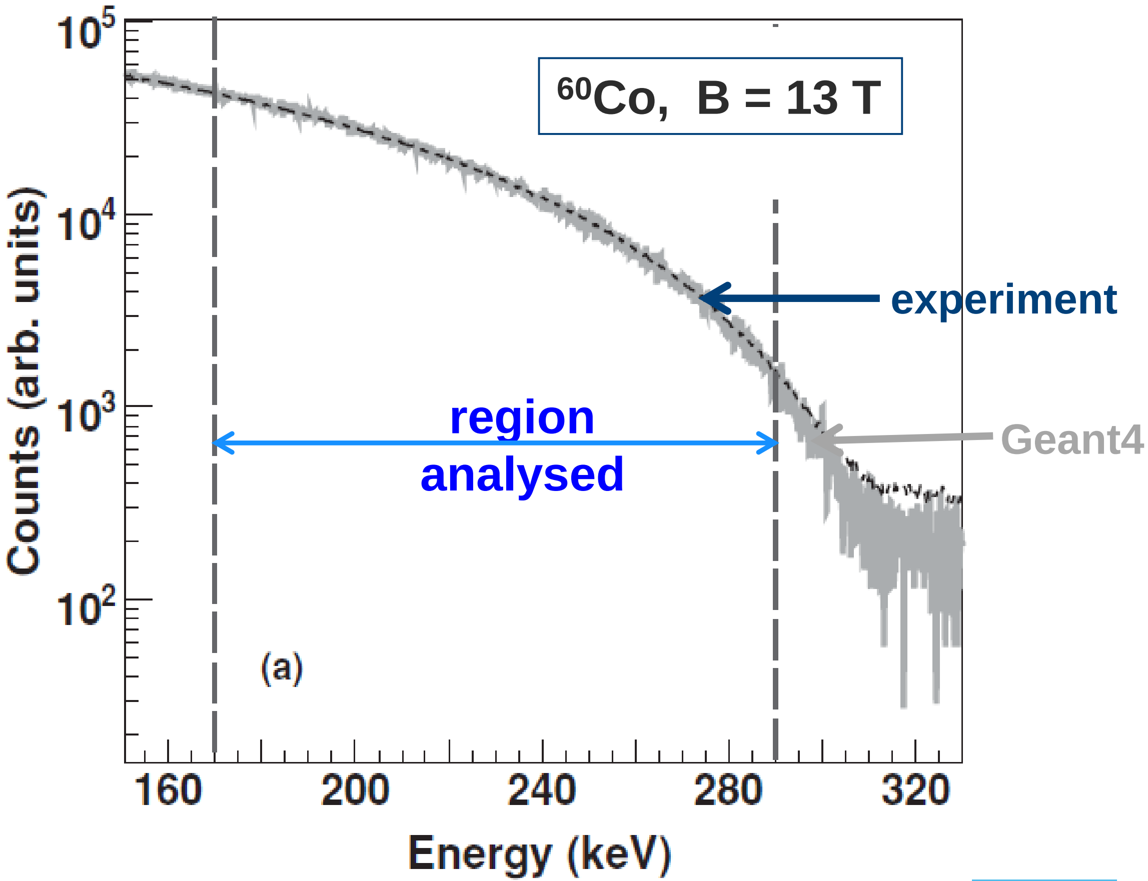
A_{exp} (^{60}Co) = - 1.014 $(12)_{stat}$ $(16)_{syst}$

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

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

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

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



F. Wauters et al.,
Phys. Rev. C 82 (2010) 055502
Nucl. Instr. Meth. A 604 (2009) 563

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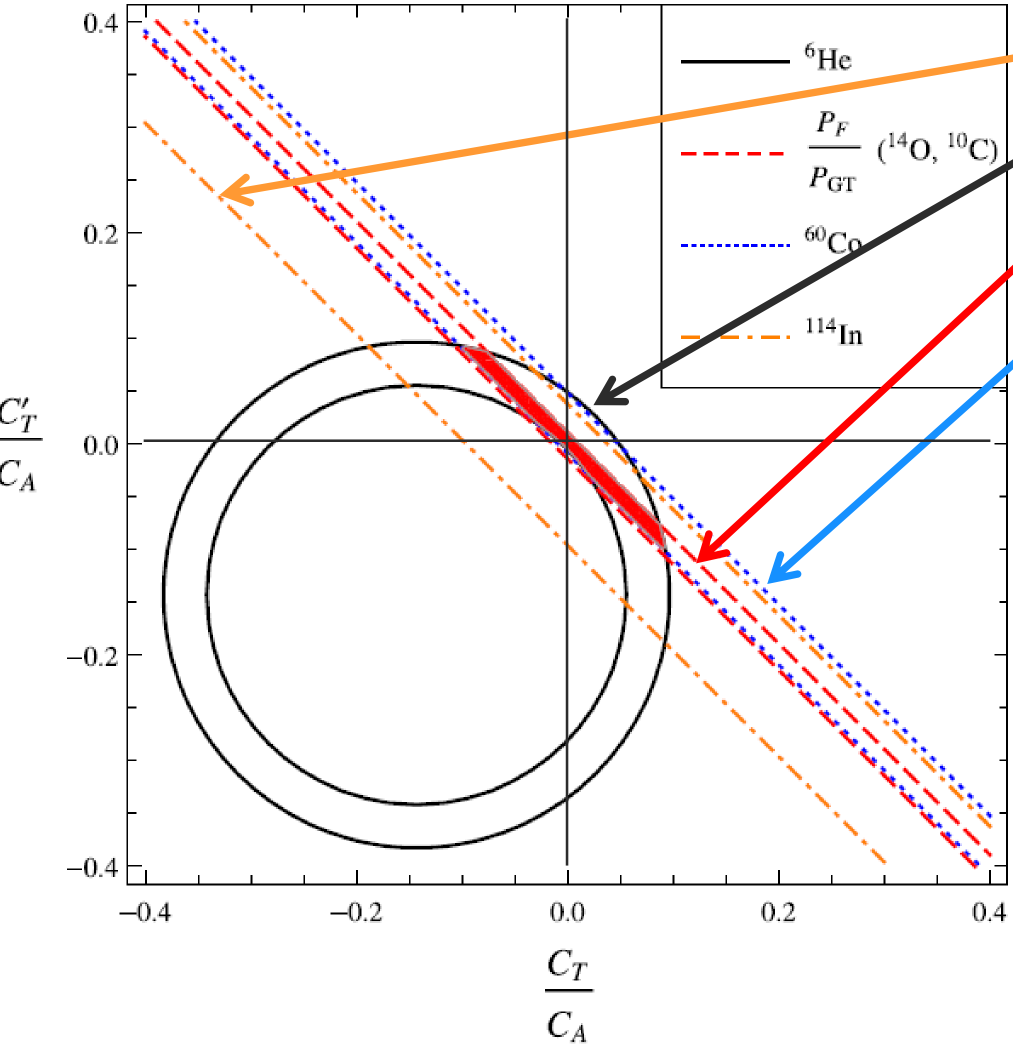
Limits on tensor currents



B. R. Holstein, J. Phys. G 41 (2014) 114001

A(^{114}In) F. Wauters et al., PR C 80 (2009) 062501(R)

a(^{6}He) C.H. Johnson et al., PR 132 (1963) 1149

^{14}O,^{10}C A.S. Carnoy et al., Phys. Rev. C 43 (1991) 2825

A(^{60}Co) F. Wauters et al., PR C 82 (2010) 055502

$$\tilde{A} = \frac{A}{1 + b'_{GT}}$$

β asymmetry param.

Fierz interference term

with:

$$A_{GT} \cong -1$$

$$b'_{GT} = \frac{\gamma m_e}{\langle E_e \rangle}\left(\frac{C_T + C'_T}{C_A}\right)$$

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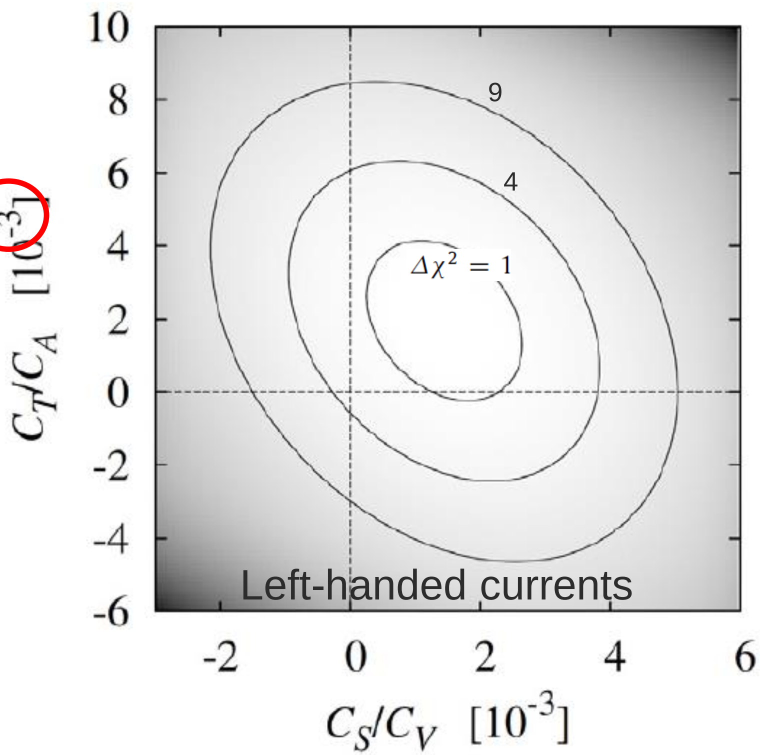
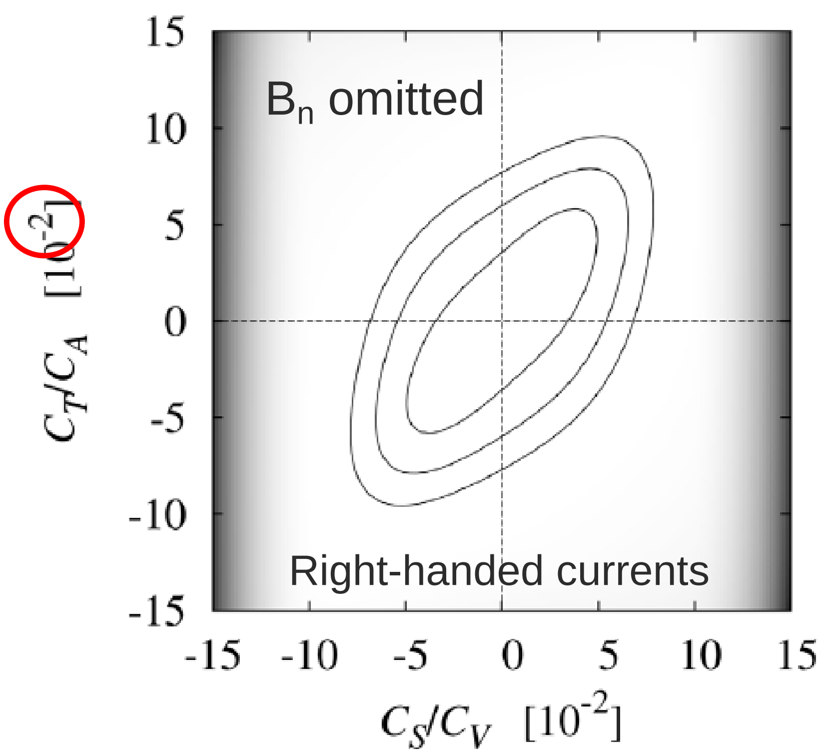
Constraints on (real) scalar and tensor coupling constants

$$C_i = \frac{G_F(0)}{\sqrt{2}} V_{ud} \bar{C}_i \quad \text{with} \quad \bar{C}_S = g_S(\varepsilon_S + \tilde{\varepsilon}_S),\ \bar{C}_T = 4g_T(\varepsilon_T + \tilde{\varepsilon}_T),\ \ldots$$

Lee-Yang coupling constants

EFT coupling constants





M. González-Alonso et al. / Progress in Particle and Nuclear Physics 104 (2019) 165–223

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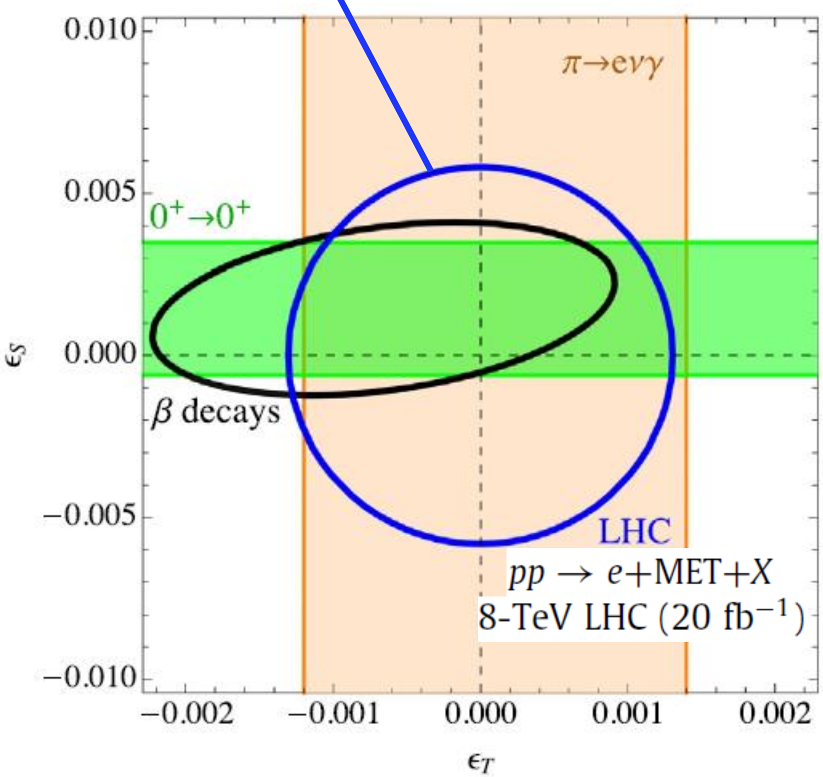
Comparison to Large Hadron Collider

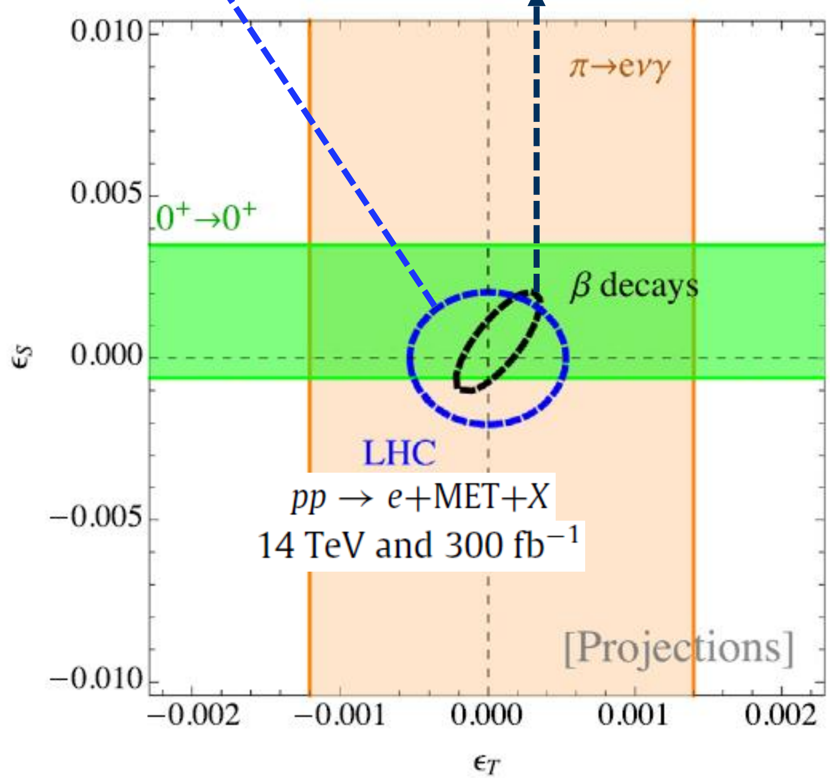
90% C.L. constraints on ε_S, ε_T

assuming:
$\Delta(\tau_n)$ = 0.1 s
$\Delta(b_n)$ = 0.001
$\delta(A_n)$ = 0.1 %
$\delta(a_n)$ = 0.1 %

O. Naviliat-Cuncic, M. González-Alonso, Ann. Phys. (Berl.) 525 (2013) 600



T. Bhattacharya et al., Phys. Rev. D 85 (2012) 054512



M. González-Alonso et al. / Progress in Particle and Nuclear Physics 104 (2019) 165–223

The challenge then is to reach precisions of:

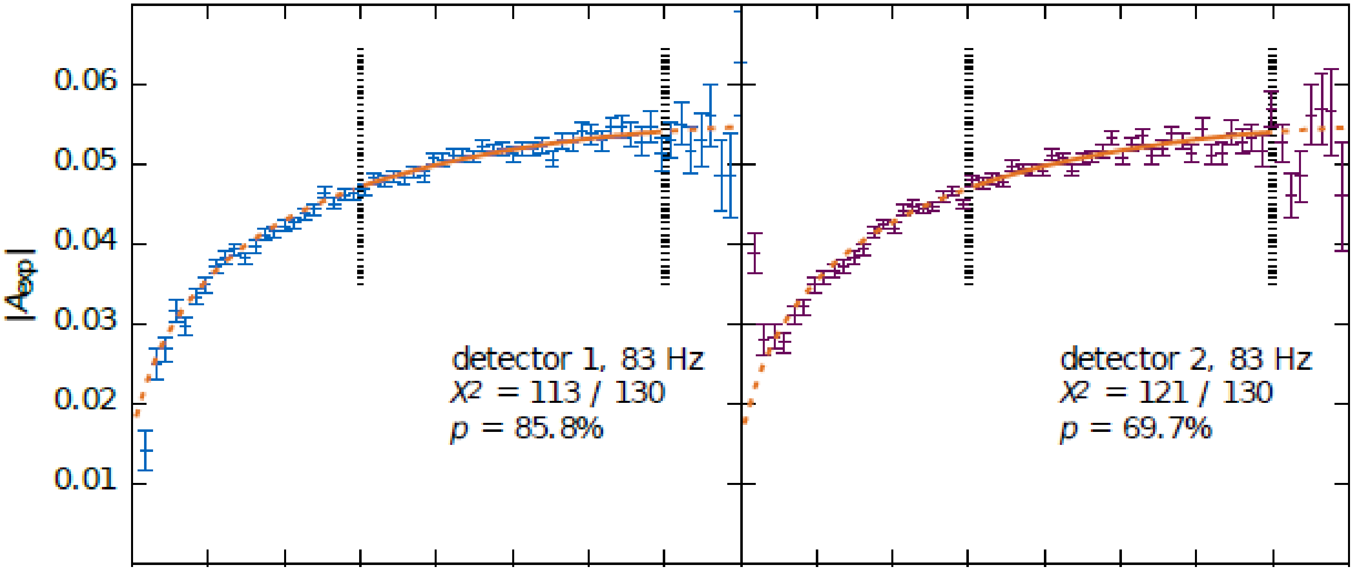
(all within reach in the next decade!)

- $\Delta(\tau_n)$ = 0.1 s → **current world average τ_n = (879.7 ± 0.8) s**

- $\delta(A_n)$ = 0.1 % → **PERKEO III - ILL** - B. Markisch et al., PRL 112 (2019) 242501

A_n = -0.11985(21) → **$\delta(A_n)$ = 0.2 %**

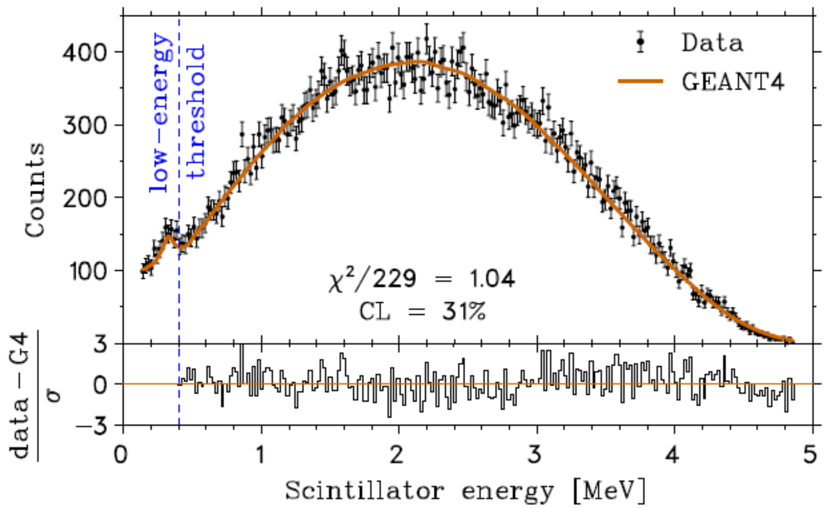
(about 2.5 times more precise than any previous measurement)



- $\delta(A_n)$ = 0.1 % → **TRINAT - TRIUMF III** - B. Fenker et al., PRL 120 (2018) 062502

A_{37K} = -0.5707(19) → $\delta(A_n)$ = 0.3 %

(about 4 times more precise than any previous measurement)



- $\delta(a_n)$ = 0.1 % → **aSPECT - ILL / FRM II** - M. Beck et al., arXiv:1908.04785v1

a_n = -0.10430(84) **(about 6 times more precise than any previous measurement)**

↓

$\delta(A_n)$ = 0.8 %

- **$\Delta(b_{n,F/GT}) = 0.001$**

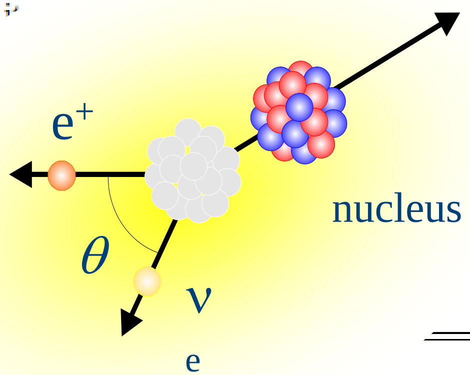
  & QCD corrections (weak magnetism) → **beta-spectrum shape measurements**

Table VI Overview of the features present in the β spectrum shape (Eq. (4)), and the effects incorporated into the Beta Spectrum Generator Code. Here the magnitudes are listed as the maximal typical deviation for medium Z nuclei with a few MeV endpoint energy. Some of these corrections fall off very quickly (e.g. the exchange correction, X) but can be sizeable in a small energy region. Varying Z or W_0 can obviously allow for some migration within categories for several correction terms.

Item	Effect	Formula	Magnitude
1	Phase space factor	$pW(W_0 - W)^2$	Unity or larger
2	Traditional Fermi function		
3	Finite size of the nucleus		10^{-1}-10^{-2}
4	Radiative corrections		
5	Shape factor		
6	Atomic exchange		
7	Atomic mismatch		
8	Atomic screening	S (Eq. (54))	10^{-3}-10^{-4}
9	Shake-up	See item 7	
10	Shake-off	See	
11	Distorted Coulomb potential due to recoil		
12	Diffuse nuclear surface		
13	Recoiling nucleus		
14	Molecular screening		
15	Molecular exchange		
16	Bound state β decay		Smaller than $1 \cdot 10^{-4}$
17	Neutrino mass		
18	Forbidden decays		

Analytical description + code, accurate to few 10^{-4} level

L. Hayen, N. Severijns et al., Rev. Mod. Phys. 90 (2018) 015008



[a] Here the Salvat potential of Eq. (57) is used with
[b] The effect of shake-up on screening was discussed in
[c] Shake-off influences on screening and exchange correction ... in Sec. VI.C.2. This has to be evaluated in a case by case scenario.

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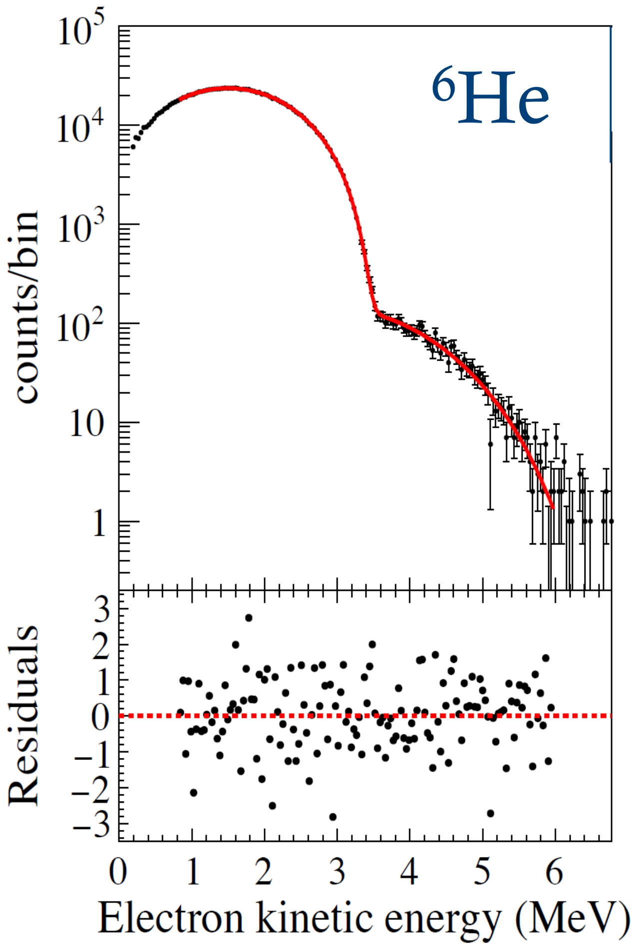
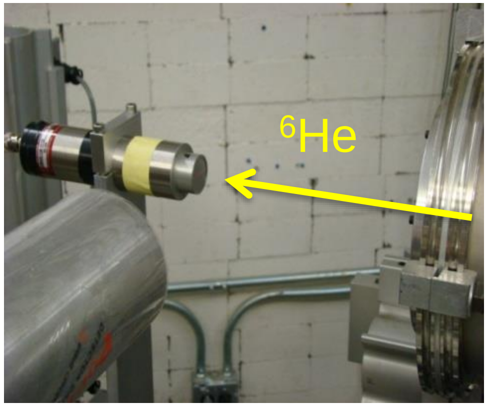
Fit β-spectra over 4 orders of magnitude in rate

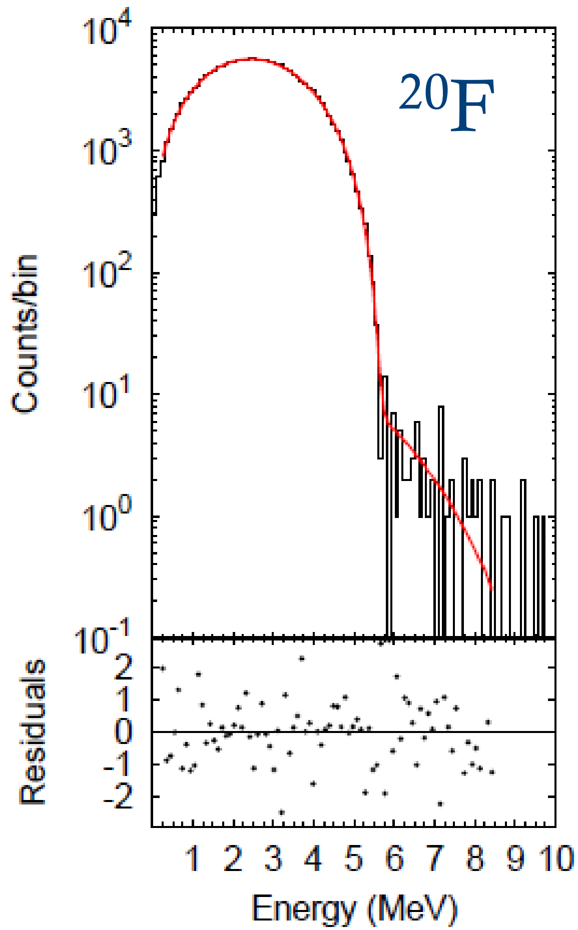
Xueying Huyan (PhD, MSU, 2019)





calorimetric technique (NSCL-MSU) and use of a radioactive beam, eliminates the effect of electron backscattering on detectors

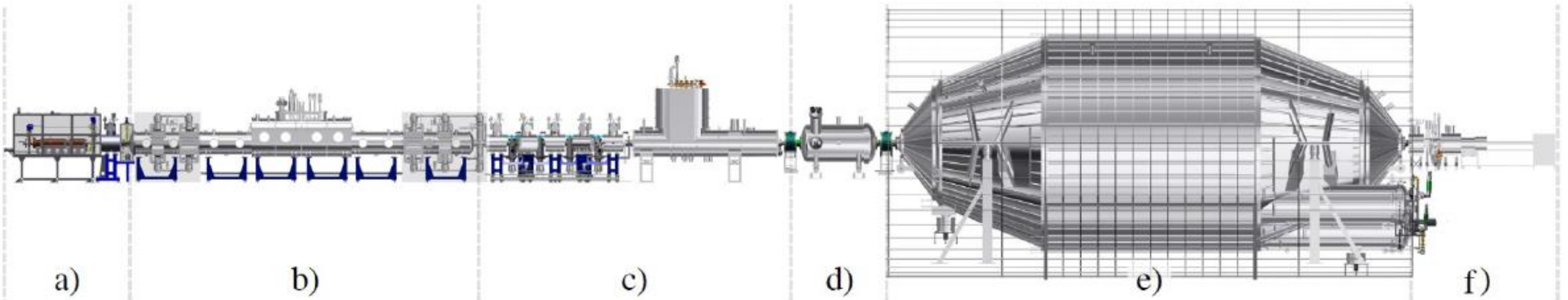
Max Hughes (PhD, MSU, 2019)

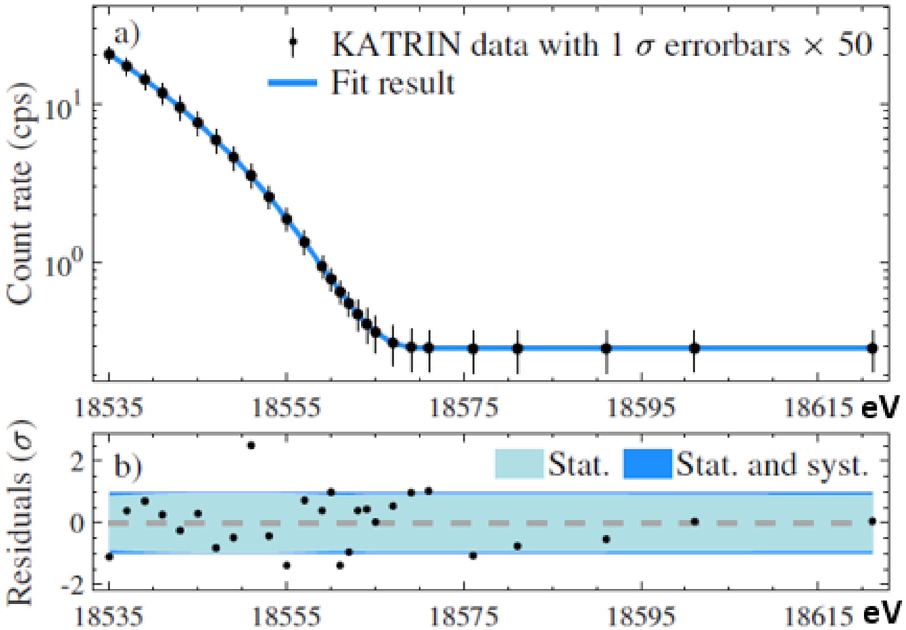


~100 spectra with CsI(Na) and NaI(Tl)
Expected total sensitivity: 4×10^{-3}

~55 spectra collected with CsI(Na)
Expected total sensitivity: 7×10^{-3}

Karlsruhe Tritium Neutrino Experiment KATRIN





electron (anti-)neutrino mass < 1.1 eV

(90 % C.L.; 4 weeks of data)

best direct determination of the electron (anti-)neutrino mass ever !

arXiv:1909.0604

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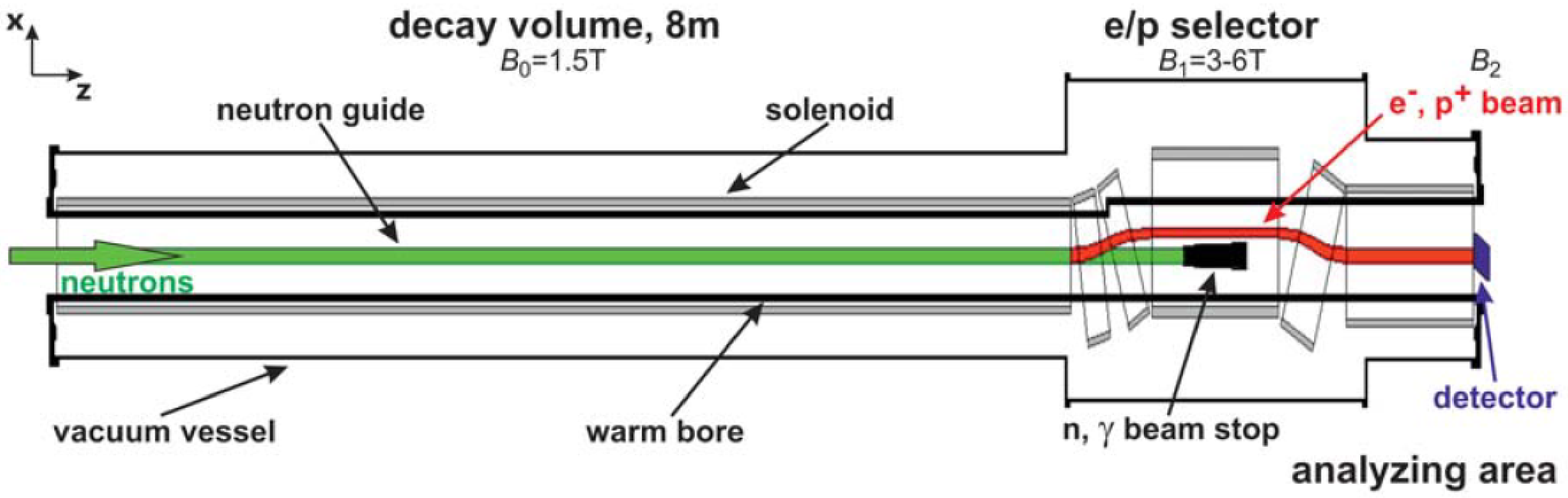
Future progress in n-decay: PERC facility - FRM II - ESS



- strong longitudinal magnetic field will collect decay electrons and protons
- both polarized and unpolarized neutrons for correlation measurements
- detector set ups for specific observables can be installed
- specific design to reduce systematic effects
- expect order of magnitude increase in measurement precision (10^{-4} level !!)

Dubbers et al., Nucl. Inst. Meth. A 596 (2008) 238
Konrad et al., Journal of Physics: Conf. Ser. 340 (2012) 012048

Outline

- V_{ud} and CKM-unitarity
  - → Ft-values ($t_{1/2}$, BR, Q_{EC})
- searches for exotic S and T currents
  - → βν-correlation
  - → β-asymmetry
- searches for Time Reversal Violation
  - → R-correlation
  - → EDM measurements

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R-correlation: $\boldsymbol{\sigma} \cdot R \frac{\langle \mathbf{J} \rangle}{J} \times \frac{\mathbf{p}_e}{E_e}$ sensitive to T-violating S,T interactions

Today: $R_{8Li} = 0.0009(22)$ nTRV Coll, A. Kozela et al., Phys. Rev. C 85 (2012) 045501

$R_n = 0.004(13)$ R. Huber et al., Phys. Rev. Lett. 90 (2003) 202301

Coming:

$$\frac{d^3\Gamma}{dE_e d\Omega_e d\Omega_\nu} \sim 1 + a\frac{\mathbf{p}}{E_e}\cdot\frac{\mathbf{q}}{E_\nu} + b\frac{m_e}{E_e} + \frac{\langle \mathbf{J} \rangle}{J}\cdot\left[A\frac{\mathbf{p}}{E_e} + B\frac{\mathbf{q}}{E_\nu} + D\frac{\mathbf{p}}{E_e}\times\frac{\mathbf{q}}{E_\nu}\right]$$
$$+\sigma_\perp\cdot\left[H\frac{\mathbf{q}}{E_\nu} + L\frac{\mathbf{p}}{E_e}\times\frac{\mathbf{q}}{E_\nu} + N\frac{\langle \mathbf{J} \rangle}{J} + R\frac{\langle \mathbf{J} \rangle}{J}\times\frac{\mathbf{p}}{E_e}\right]$$
$$+\sigma_\perp\cdot\left[S\frac{\langle \mathbf{J} \rangle}{J}\frac{\mathbf{p}}{E_e}\cdot\frac{\mathbf{q}}{E_\nu} + U\frac{\mathbf{q}}{E_\nu}\frac{\langle \mathbf{J} \rangle}{J}\cdot\frac{\mathbf{p}}{E_e} + V\frac{\mathbf{q}}{E_\nu}\times\frac{\langle \mathbf{J} \rangle}{J}\right]$$

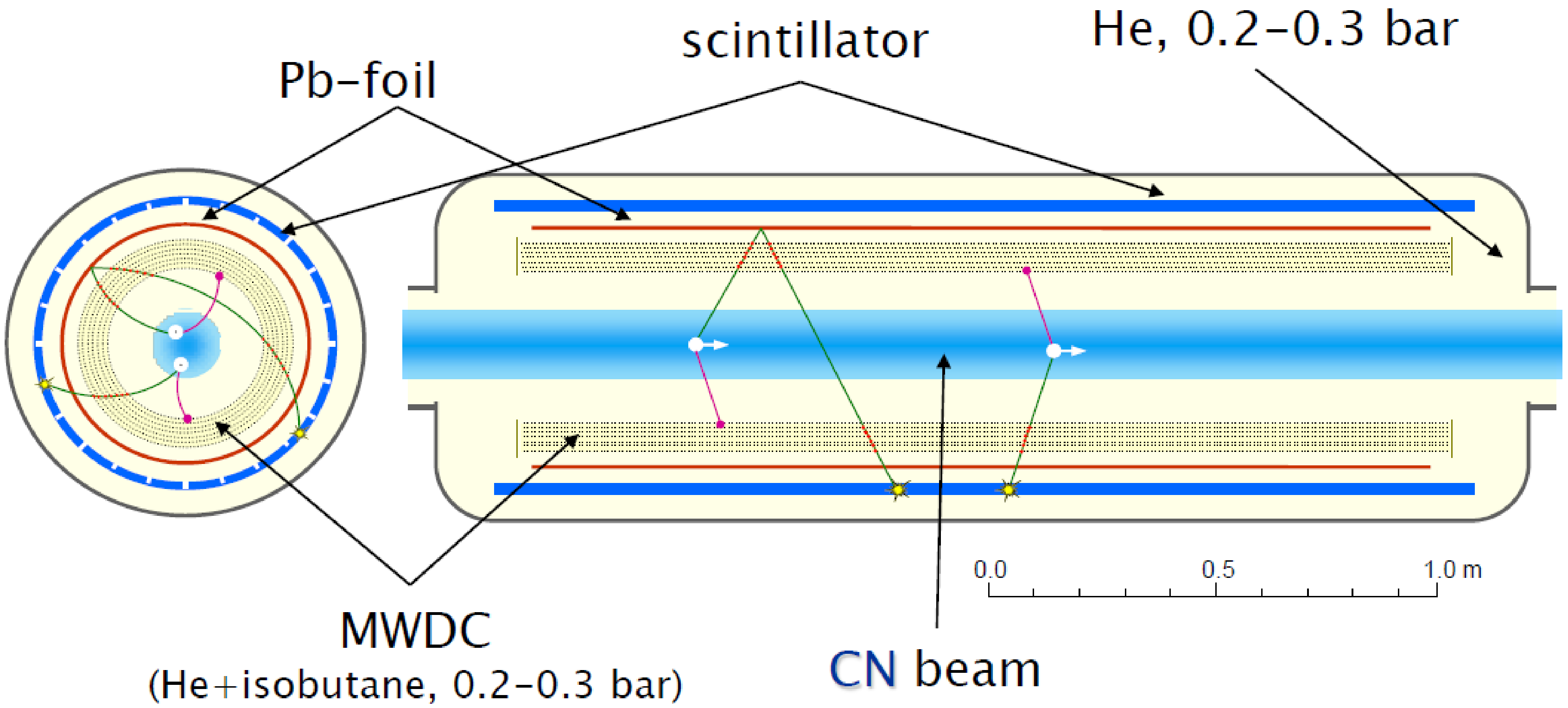
BRAND project
(ILL-Grenoble;
ESS-Lund)

- measure 11 correlations simultaneously → perform gloal analysis
- sensitive to both Time Rev. conserving and violating S and T interactions:

$$X = X_{SM} + X_{FSI} + c_1\,\mathrm{ReS} + c_2\,\mathrm{ReT} + c_3\,\mathrm{ImS} + c_4\,\mathrm{ImT}$$

BRAND project

- measure transverse electron polarization
- Mott scattering
- particle tracking
- vertex reconstruction



Outline

- V_{ud} and CKM-unitarity
  - → Ft-values ($t_{1/2}$, BR, Q_{EC})
- searches for exotic S and T currents
  - → $\beta\nu$-correlation
  - → β-asymmetry
- searches for Time Reversal Violation
  - → R-correlation
  - → EDM measurements

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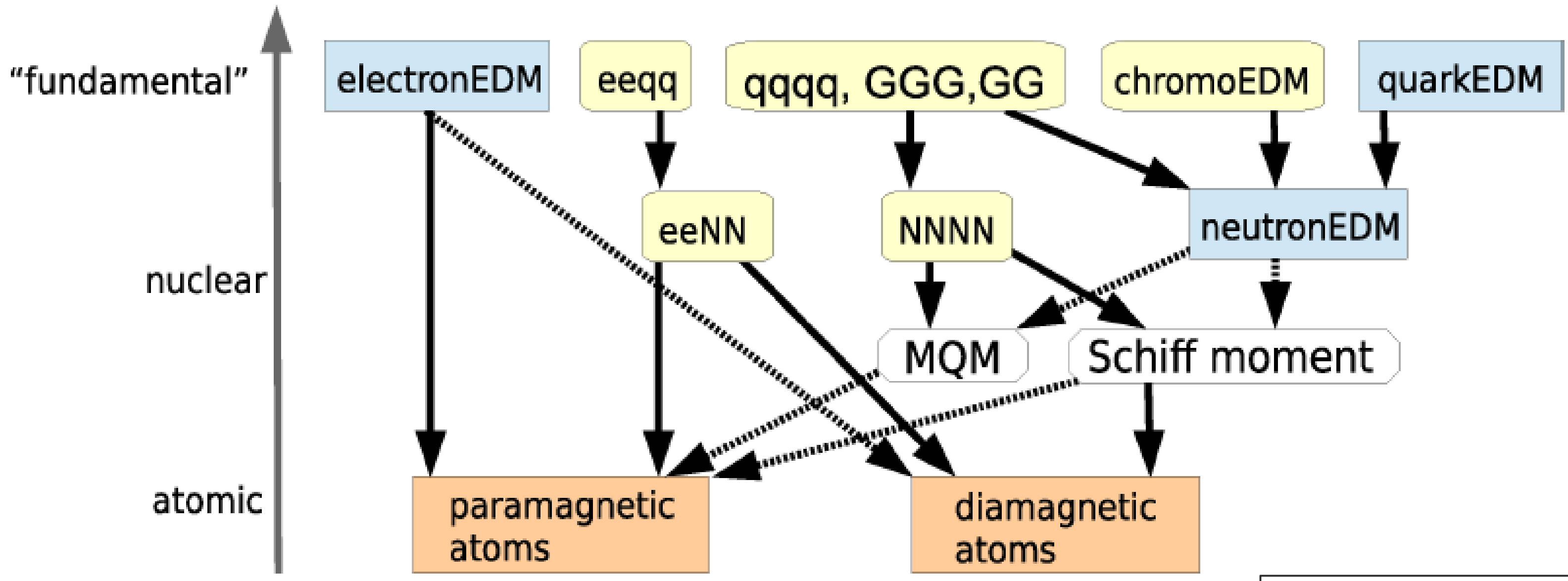
Electric Dipole Moments - the matter-antimatter problem

CP violating sources contribute to EDMs in various systems at different energy scales



F. Kuchler, Universe 2019, 5, 56;

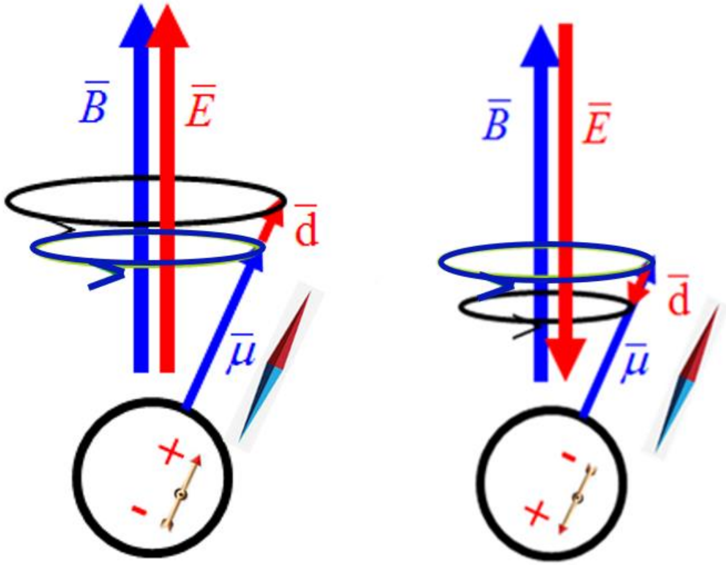
Fundamental particle EDMs (blue boxes) , as wells as

CP-odd interactions between electrons (e) , quarks (q) and gluons (G) (yellow boxes)

lead to

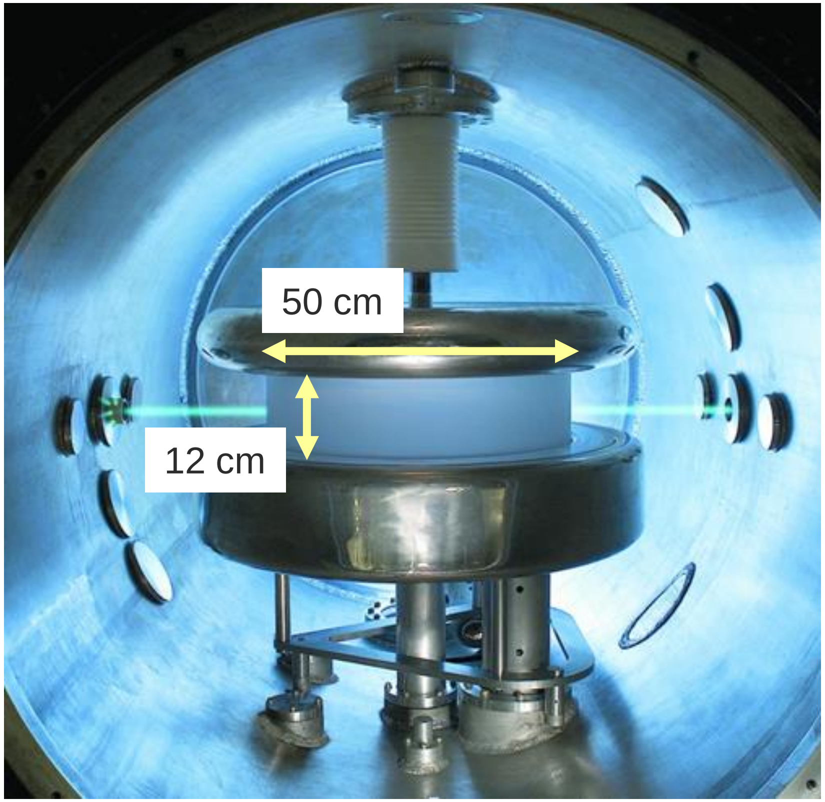
EDMs of complex systems like atoms (orange boxes) .

e.g. the nEDM experiment at PSI - testing CP-violation



$$d_n = \pi\hbar(f_{n,\uparrow\downarrow} - f_{n,\uparrow\uparrow})/2E$$

$B_0 = 1\ \mu T$
E = 12 kV/cm



sensitivity (300 days data taking) : $\boldsymbol{\sigma_{\mathrm{raw}} = 0.94 \times 10^{-26} e\ cm}$
(relative unblinding OK)

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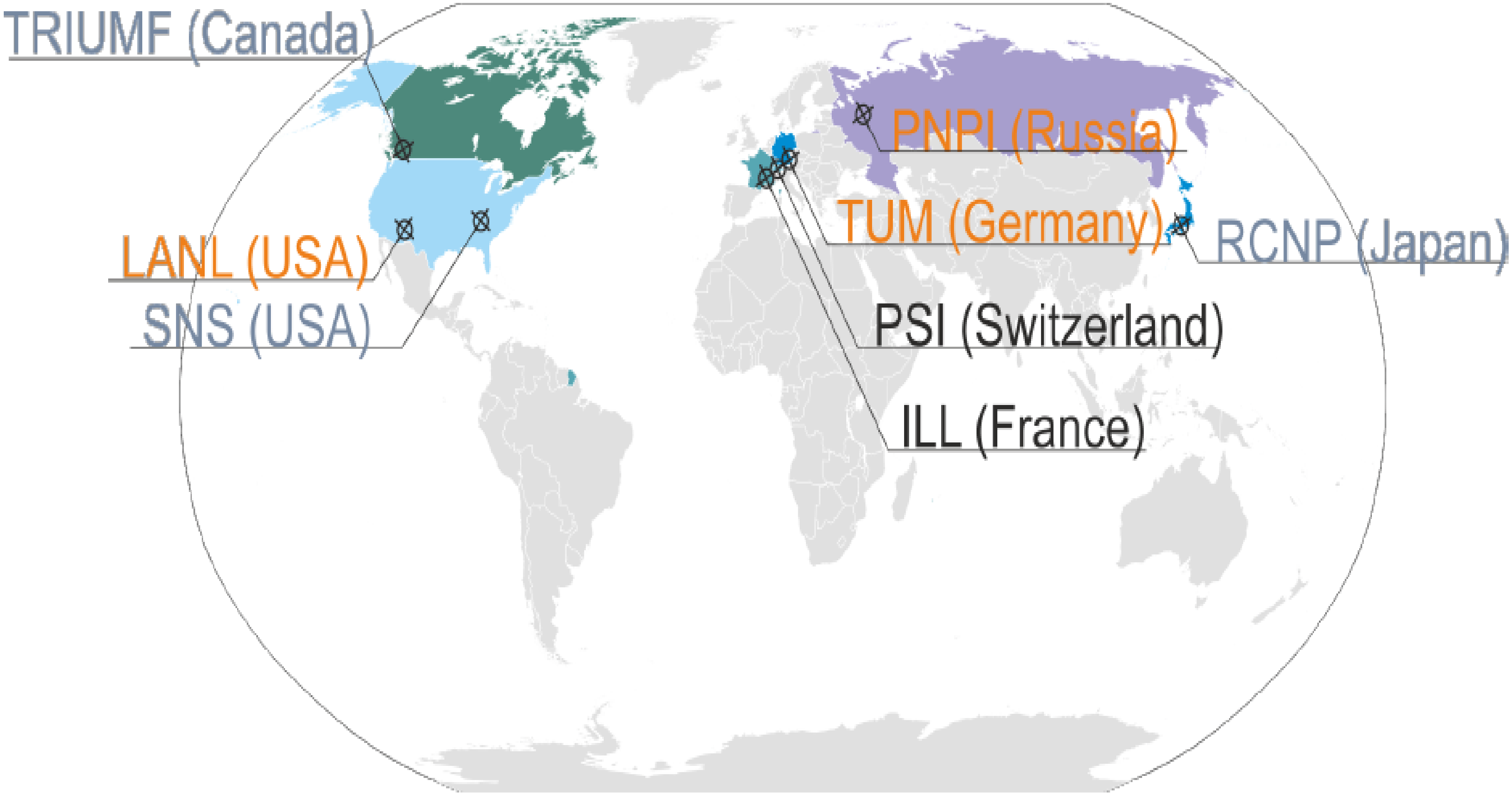
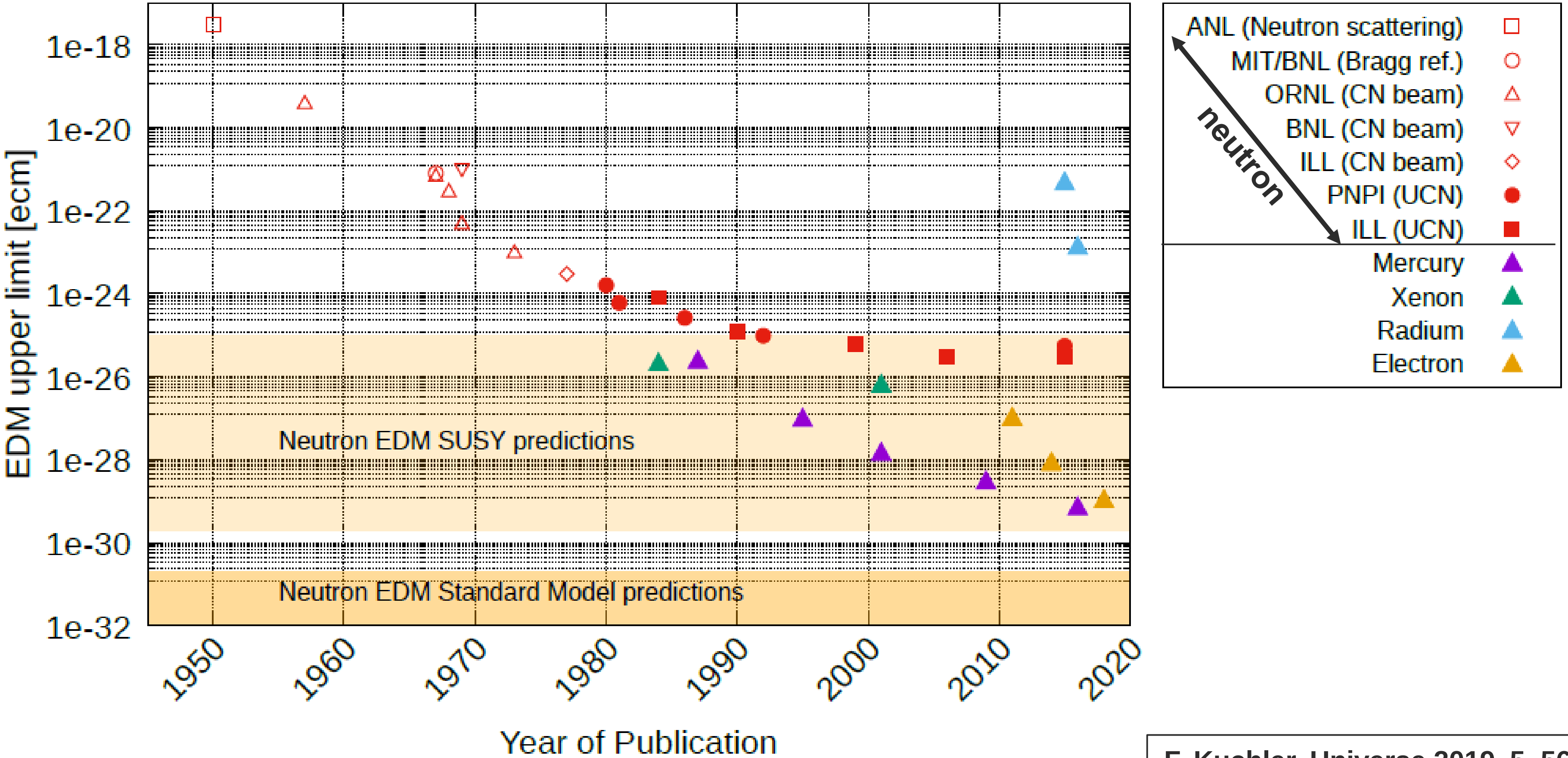
Worldwide neutron EDM efforts



Evolution of EDM searches in different systems



F. Kuchler, Universe 2019, 5, 56

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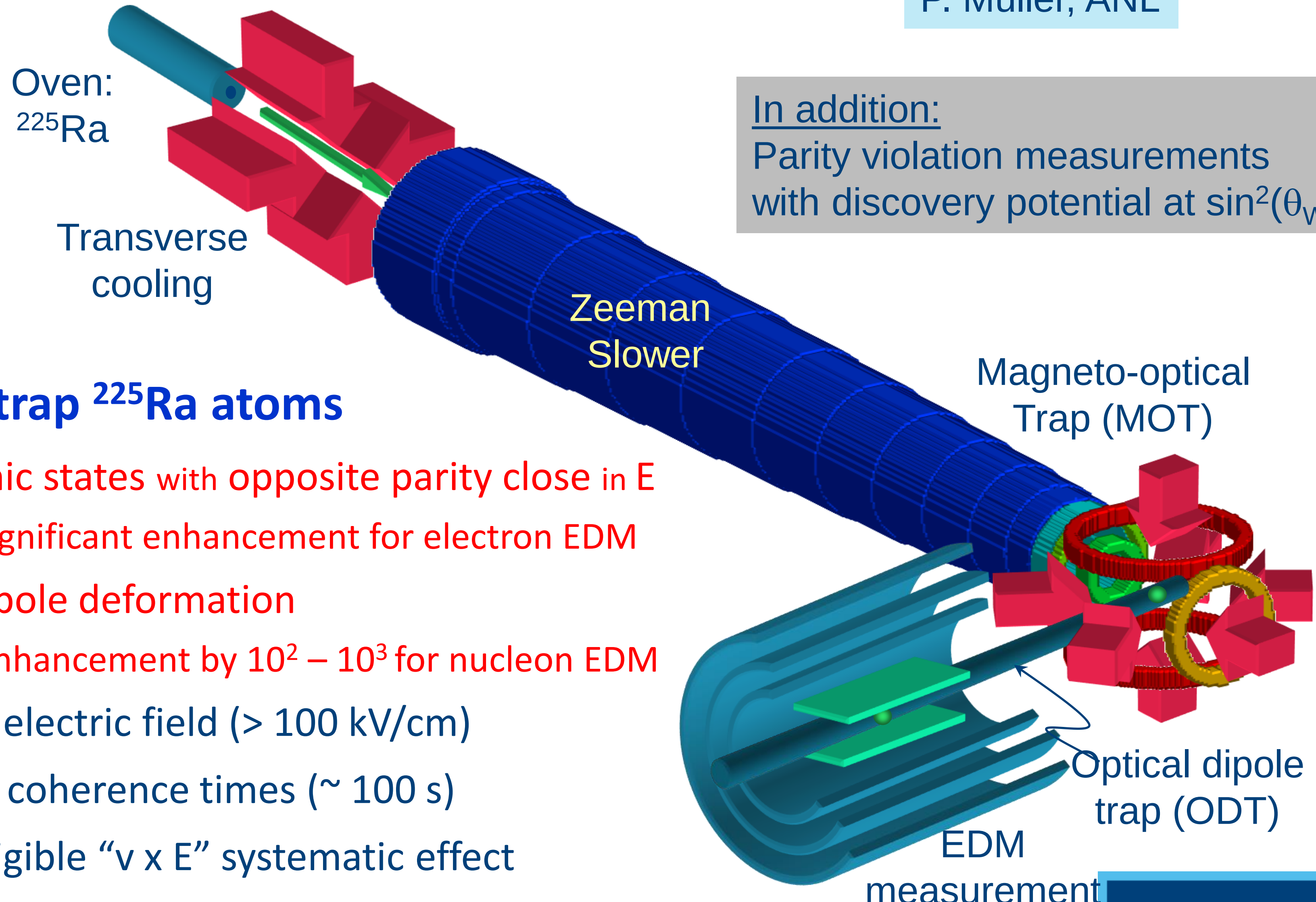
EDM measurements on ^{225}Ra

P. Müller, ANL



<u>In addition:</u>
Parity violation measurements with discovery potential at $\sin^2(\theta_W)$

Why trap ^{225}Ra atoms

- atomic states with opposite parity close in E
  → significant enhancement for electron EDM
- octupole deformation
  → enhancement by $10^2 - 10^3$ for nucleon EDM
- High electric field (> 100 kV/cm)
- Long coherence times (~ 100 s)
- Negligible "v x E" systematic effect

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Courtesy of Peter Müller

Status and recent progress of searches for permanent EDMs

	Neutron	Electron	^{199}Hg	^{129}Xe	^{255}Ra
	90% C.L.	90% C.L.	90% C.L.	90% C.L.	90% C.L.
Exp. upper limit (*e* cm)	**3.0×10^{-26}** [1]	9.4×10^{-29} [2]	2.6×10^{-29} [3]	6.6×10^{-27} [4]	**1.4×10^{-24}** [5]
	↓	↓ molecular	↓	↓	quadr. def.
	to appear [6]	**1.1×10^{-29}** [7]	**6.1×10^{-30}** [8]	**1.2×10^{-27}** [9]	
SM prediction (*e* cm)	**$\sim 10^{-31} - 10^{-32}$**	**$\sim 10^{-38}$**	**$\sim 10^{-34}$**	**$\sim 10^{-34}$**	**-**

[1] Pendlebury et al., Phys. Rev. D 92 (2015) 092003 → [6] nEDM Collaboration - PSI (2020)
[2] De Mille, Gabrielse et al., Science 343 (2014) 269 → [7] De Mille, Gabrielse et al., Nature 562 (2018) 355
[3] Heckel, Fortson et al., Phys. Rev. Lett. 102 (2009) 101601 → [8] Heckel, Fortson et al., Phys. Rev. Lett. 116 (2016) 161601
[4] Chupp et al., Phys. Rev. Lett. 86 (2001) 22 → [9] Fierlinger et al., Phys. Rev. Lett. 123 (2019) 143003
[5] Mueller et al., Phys. Rev. C 94 (2016) 025501

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+ weaker limits on EDM of μ, p, τ, $\nu_{e,\mu}$, ν_τ, Λ (e.g. Jungmann, Nucl.Phys. A 751 (2005) 87c)

Conclusions and Outlook

1. **Ft-values, βν correlation** and **β asymmetry** measurements +

→ extract V_{ud} and test **unitarity of CKM matrix**

→ improved limits on **scalar** and **tensor** type weak currents;

2. searches for new physics (bosons) at **low energies remain competitive** with direct searches at **LHC** if **O(10^{-3}) precisions** are reached

many experiments **ongoing** or **in preparation / planned**

3. **correlation** and **EDM measurements** in neutron and radioactive nuclei also contribute to **searches for T-violation**

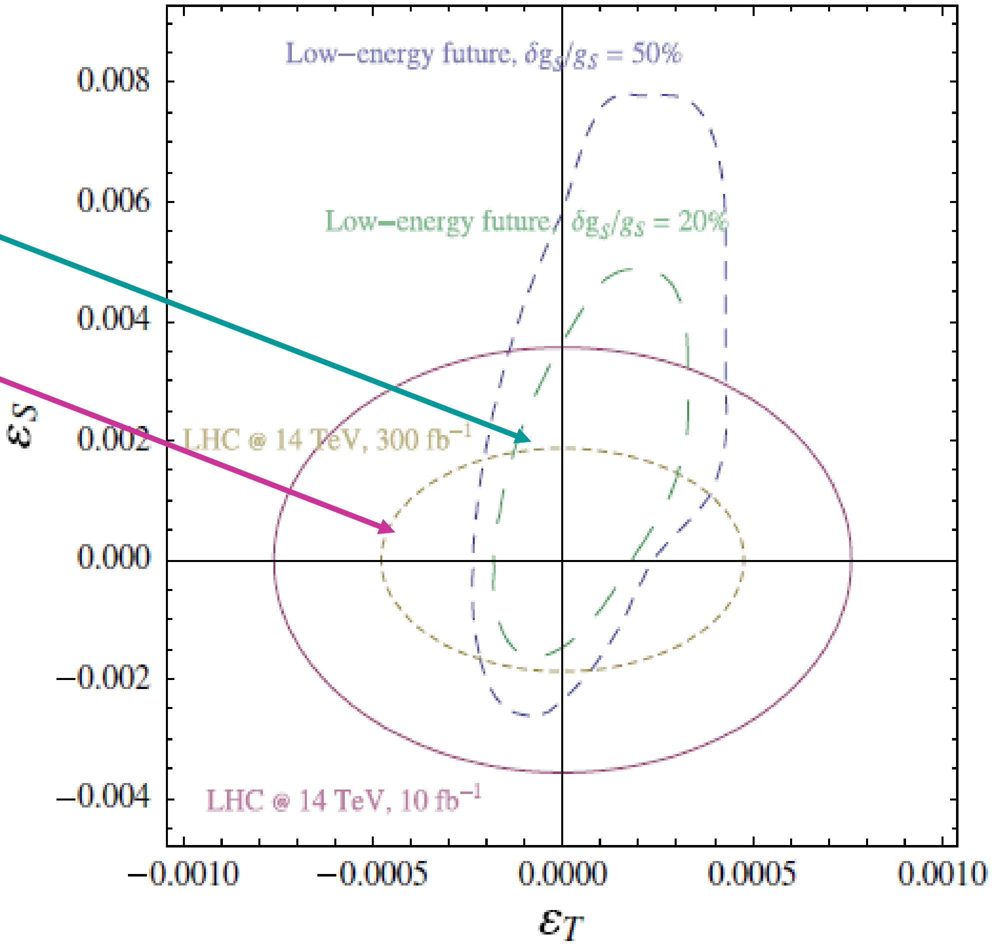
Measurements in nuclear/neutron β decay in the LHC era

e.g. limits on scalar/tensor couplings

nuclear & neutron decay, pion decay + future 10^{-3} precision on b_{Fierz} for n

LHC limits for the channel *pp* → *e* + MET + *X*

T. Bhattacharya et al.
PHYSICAL REVIEW D 85, 054512 (2012)



see also e.g. :

**O. Naviliat-Cuncic and M. Gonzalez-Alonso
Annalen der Physik 525 (2013) 600.**

**V. Cirigliano, et al.,
J. High. Energ. Phys. 1302 (2013) 046**

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Total β-decay rate (not observing correlations between spin and momentum vectors):

$$\int d\Gamma = \lambda \ \text{(decay constant)} \qquad \left(\lambda = \frac{1}{\tau} = \frac{\ln 2}{t_{1/2}} \right)$$

$$= \frac{\ln 2}{t_{1/2}} = \frac{G_F^2 \ V_{ud}^2}{K'} \ \xi \int d\Gamma_0$$

$$= \frac{G_F^2 \ V_{ud}^2}{K'} (C_V^2 \ M_F^2 + C_A^2 \ M_{GT}^2) \int F(\pm Z, E_e) \ p_e \ E_e \ (E_0 - E_e)^2 \ dE_e \ d\Omega_e \ d\Omega_\nu$$

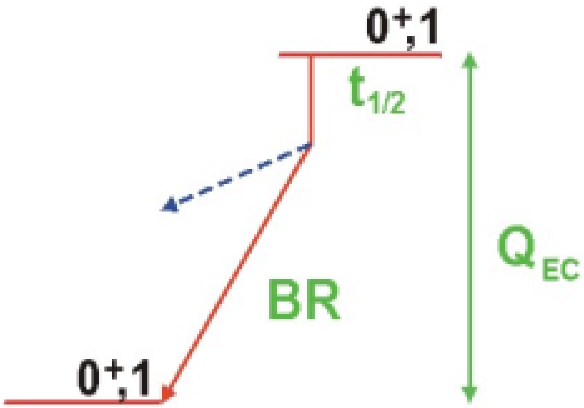
$$f_V \propto Q_{EC}^5$$

For an individual β transition:

partial half-life: $t = t_{1/2} \left[\frac{1 + P_{EC}}{BR} \right]$

and

$$f_V t = \frac{K}{G_F^2 \ V_{ud}^2} \ \frac{1}{C_V^2 \ M_F^2 + C_A^2 \ M_{GT}^2}$$



$$K / (\hbar c)^6 = 2\pi^3 \hbar \ln 2 / (m_e c^2)^5$$

For the superallowed $0^+ \rightarrow 0^+$ pure Fermi transitions :

$$\mathcal{F}t^{0^+\to 0^+} \equiv f_V t^{0^+\to 0^+} \left(1+\delta_{NS}^V-\delta_C^V\right)\left(1+\delta_R'\right) = \frac{K}{2G_F^2\; V_{ud}^2\; C_V^2\left(1+\Delta_R^V\right)}$$

from experiment — nucleus dependent corrections — nucleus independent

- radiative correction $\delta_R' = \delta_1 + \delta_2 + \delta_3$ (order α, $Z\alpha^2$, $Z^2\alpha^3$)

  leading order α: exchange of γ or Z-boson between p and e^-

- nucleus-independent radiative correction $\Delta_R = 0.02361(38)$

  (W.J. Marciano and A. Sirlin, PRL 96 (2006) 032002)

- nuclear structure-dependent radiative correction δ^V_{NS}
- Coulomb (isospin) correction $\delta^V_c = \delta^V_{c1} + \delta^V_{c2}$
  - difference in configuration mixing
  - difference in radial part of wave functions

(I.S. Towner & J.C. Hardy, Rep. Prog. Phys. 73 (2010) 046301)

2. Exotic weak currents (scalar, tensor)

a) β-ν correlation

$$a\,\frac{\vec{p}_e\cdot\vec{q}}{E_e E_\nu} \xrightarrow{\text{exp.}} \tilde{a} = \frac{a}{1 + b\,\frac{\gamma m_e}{E_e}} \qquad \text{with} \quad \gamma=\sqrt{1-(\alpha Z)^2}$$

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

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

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

Fierz term

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

!!! for pure transitions weak interction results are independent of nuclear matrix elements !!!

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

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

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ongoing experiments in search for scalar weak currents:

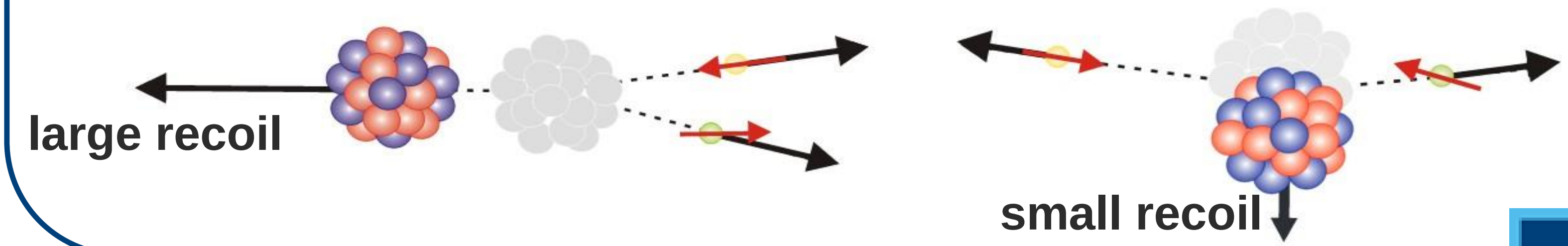
- TRINAT	(MOT):	^{38m}K repeat	(prep.)
- LPCTrap @ GANIL	(Paul):	^{19}Ne, ^{35}Ar	(analysis)
- Jerusalem	(MOT):	^{19}Ne	(prep.)
- TamuTrap, Texas A&M	(Penning):	^{32}Ar, … (T = 2, βp)	(prep.)
- WISARD @ ISOLDE	(foil):	^{32}Ar, … (T = 2, βp)	(prep.)

Standard Model
Vector currents

New Physics?
Scalar currents

$dW/d\Omega = 1 + p_e.p_\nu/E_e E_\nu$

$dW/d\Omega = 1 - p_e.p_\nu/E_e E_\nu$



prospects - 1

1. **pure Fermi transitions:** - new data to improve Ft values
   - testing isospin corrections δ_C
   - nucleus-independent radiative correction Δ_R

2. **neutron decay:** - lifetime (tSPECT, …)
   - beta-asymmetry parameter *A* (PERKEO, UCNA)
   - $\beta\nu$-correlation *a* (*a*SPECT, Nab, AbBa, aCORN, …)

3. **T = 1/2 mirror β transitions:**

$$Ft^{mirror}\left(1+\frac{f_A}{f_V}\rho^2\right) = 2Ft^{0^+\rightarrow 0^+} = \frac{K}{G_F^2 V_{ud}^2 (1+\Delta_R^V)}$$

$$\rho = \frac{C_A M_{GT}}{C_V M_F}$$

N.S. , I.S. Towner et al.,
Phys. Rev. C 78 (2008) 055501

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

O. Naviliat-Cuncic & N.S., PRL 102 (2009) 142302

weak magnetism term b_{WM} (CVC)

T = 1/2 $J^\pi \rightarrow J^\pi$ mirror β transitions

$$b_{WM}(\beta^{\mp}) = A\sqrt{\frac{J}{J+1}}\, M_F^0\ \mu^{\mp}$$

e.g. F.P. Calaprice and B.R. Holstein
Nucl. Phys. A 273 (1976) 301

$$\mu^{\mp} = \mp(\mu_M - \mu_D)$$

$$\mathcal{F}t^{mirror} \equiv f_V t(1+\delta_R')(1+\delta_{NS}^V - \delta_C^V) = \frac{2\mathcal{F}t^{0^+\rightarrow 0^+}}{\left(1+\frac{f_A}{f_V}\rho^2\right)}$$

$$\rho \cong g_A M_{GT}^0 = c$$

N. Severijns, I.S. Towner et al.,
Phys. Rev. C 78 (2008) 055501

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weak magnetism term b_{WM} (Impulse Approximation)

$$b_{WM} \cong A\,(g_M M_{GT} + g_V M_L)$$

$$c \cong g_A M_{GT}$$

$$\frac{b_{WM}}{Ac}$$

A: mass of nucleus

g_M: weak magn. coupl. const. = 4.706 (= μ_p-μ_n)

g_V: vector coupl. const. = 1

g_A: axial-vector coupl. const. = 1.00 (quenched)

Matrix element	Operator form
M_{GT}	$\langle\beta\|\Sigma\tau_i^{\pm}\vec{\sigma}_i\|\alpha\rangle$
M_L	$\langle\beta\|\Sigma\tau_i^{\pm}\vec{l}_i\|\alpha\rangle$

B. R. Holstein, Rev. Mod. Phys. 46 (1974) 789

F.P. Calaprice et al., Phys. Rev. C 15 (1977) 2178

New vistas and prospects in the LHC era

- **new generation of (trap-based) correlation experiments**

  → **towards 0.1% precision level**

- **precise β-spectrum shape measurements:**

$$d\Gamma \propto G_F \; F(Z,E) \left[1 + \mathrm{k} \frac{1}{E_\beta} b_{Fierz} + k' \, E_\beta \, b_{WM} \right]$$

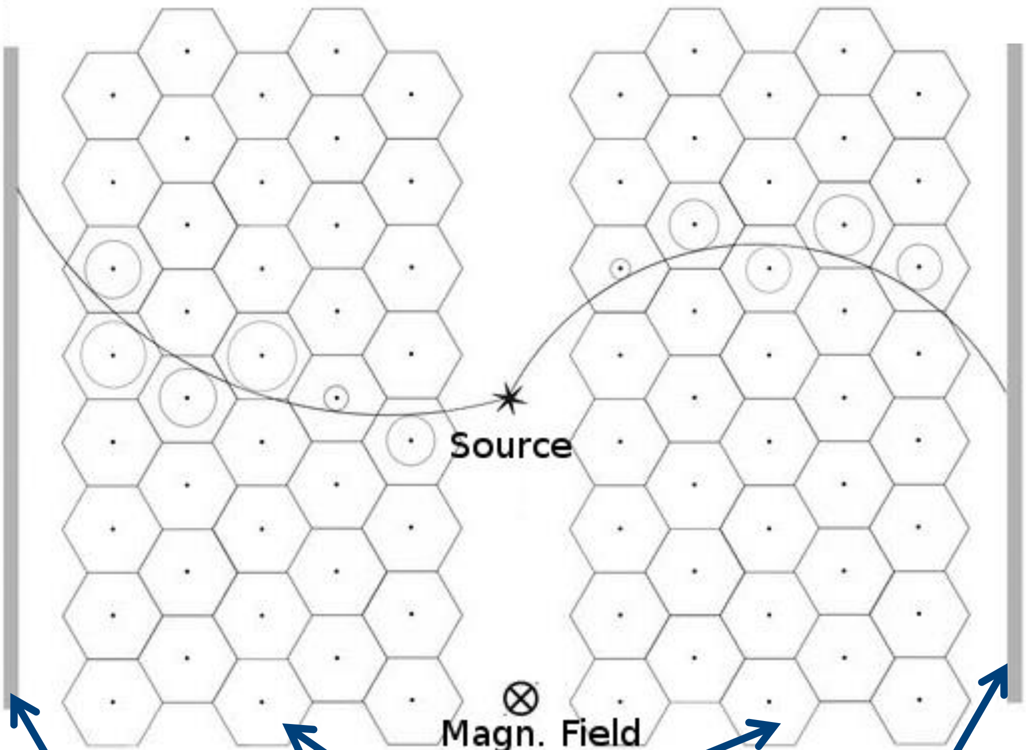
b_{Fierz} : scalar / tensor weak currents

b_{WM} : weak magnetism (Standard Model term)

- induced by strong interaction because decaying quark is not free but bound in a nucleon;
- is to be known better when reaching sub-percent precisions

Note the different energy dependence of both effects !!

miniBETA spectrometer (Leuven / Krakow)

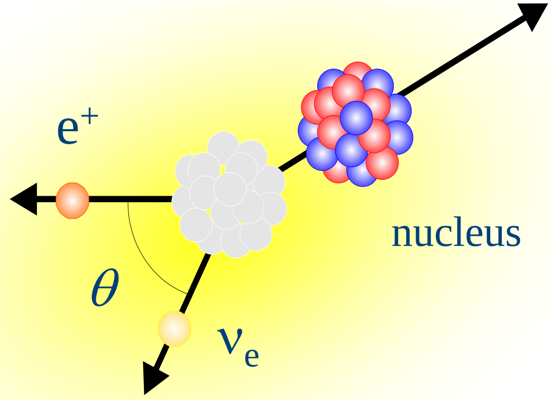


multi-wire drift chamber

scintillator (later DSSDD)

6. β spectrum shape measurements

$$N(p)dp = Kp^2(W - W_0)^2 \cdot F(Z,p) \cdot L_0 \cdot C \cdot R_n \cdot RC \cdot S(E)dp$$



- phase space factor x constants
- *F(Z,p)*: Fermi function
- *L_0* & *C*: finite size of nucleus
- *R_n* : finite mass of nucleus
- *RC*: radiative corrections
- *S(E)*: spectrum shape factor

$$\frac{dN}{dE} \approx 1 + \frac{4}{3M_n}\frac{b_{WM}}{Ac}E_e \quad \Rightarrow \quad \approx 0.8\ \%\ \mathrm{MeV}^{-1}$$

(for a pure GT transition and neglecting terms $\propto 1/M^2$ and $\propto m_e^2/E$)

→ $$d\Gamma \propto G_F\ F(Z,E)\left[1 + k'\, b_{WM}\ E_\beta + k''\, \frac{b_{Fierz}}{E_\beta}\right]$$