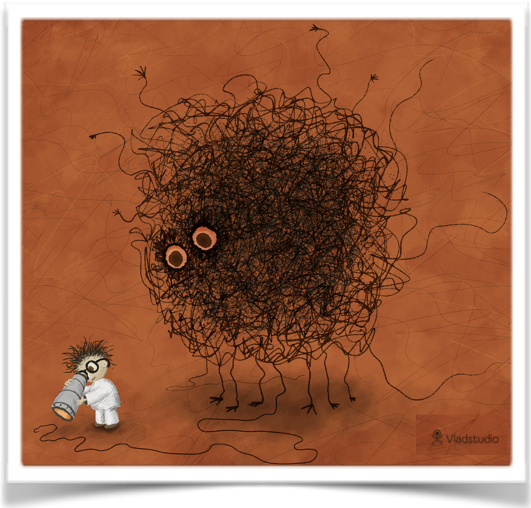
Precision measurements in nuclear beta decay at ISOLDE

& Atomic PV

Physics Beyond Colliders Workshop — Nov 2017

Martín González-Alonso (CERN-TH)
Stephan Malbrunot-Ettenauer (CERN-ISOLDE)



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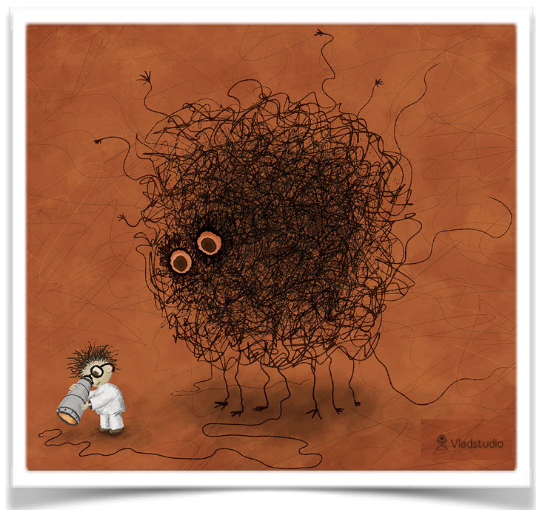
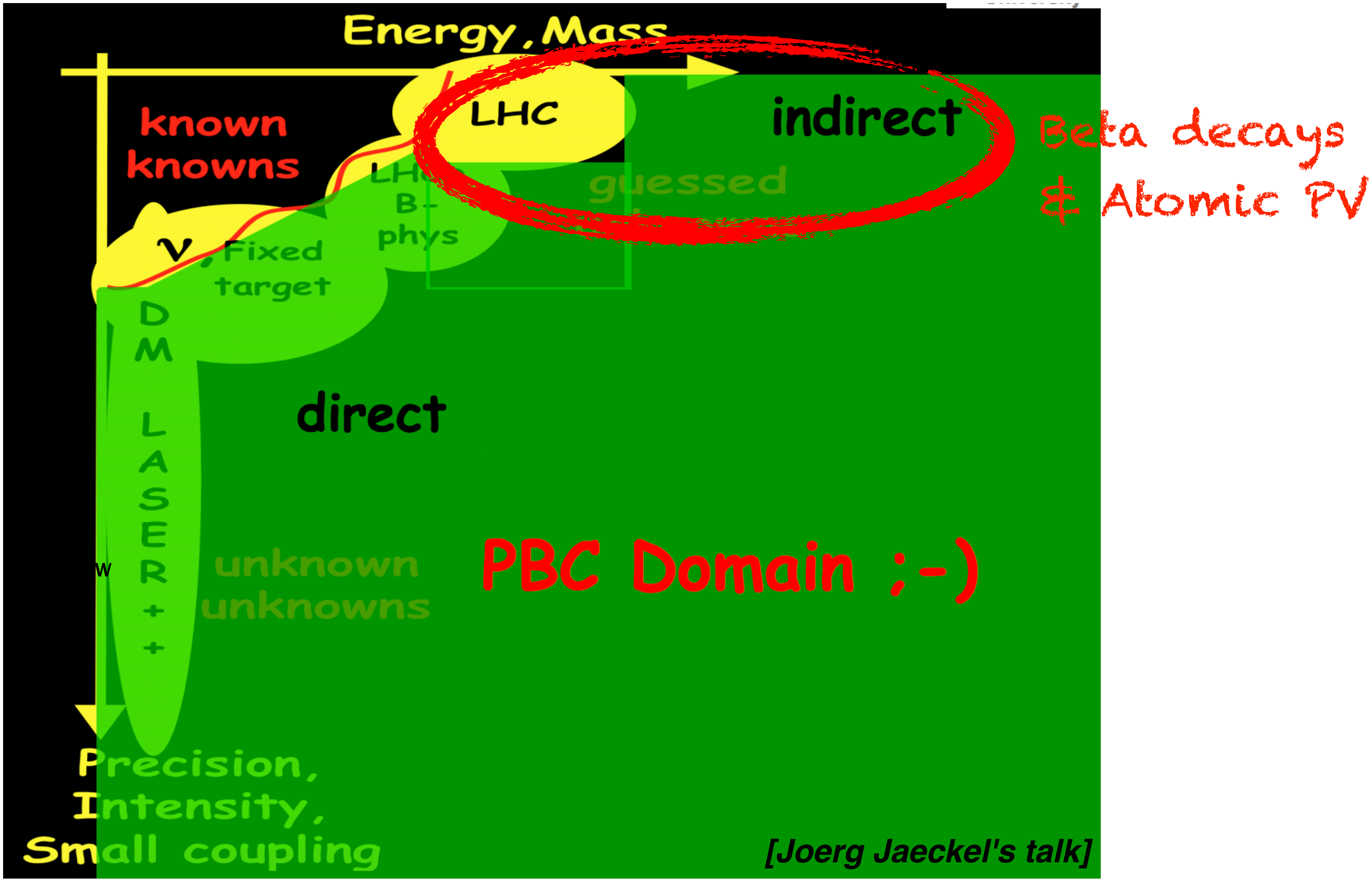
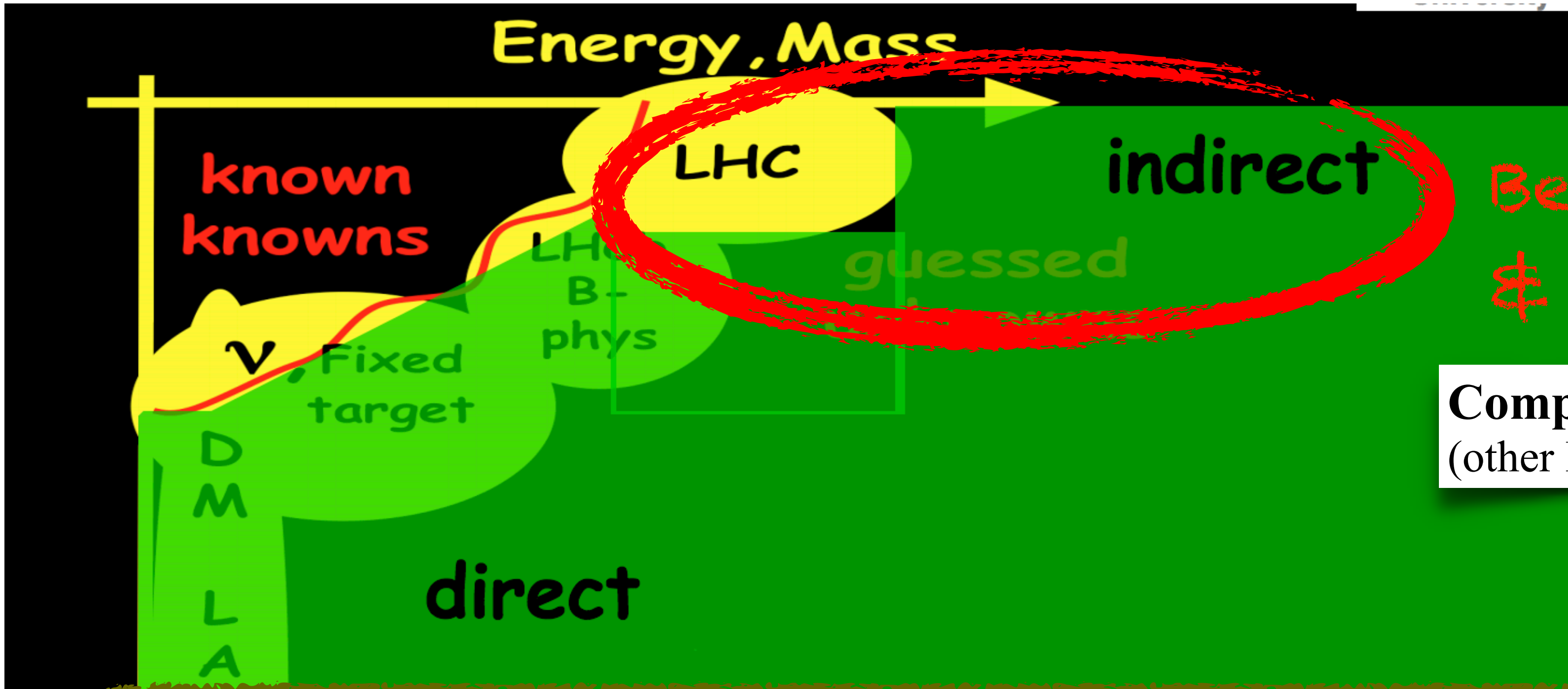
Outline



Introduction



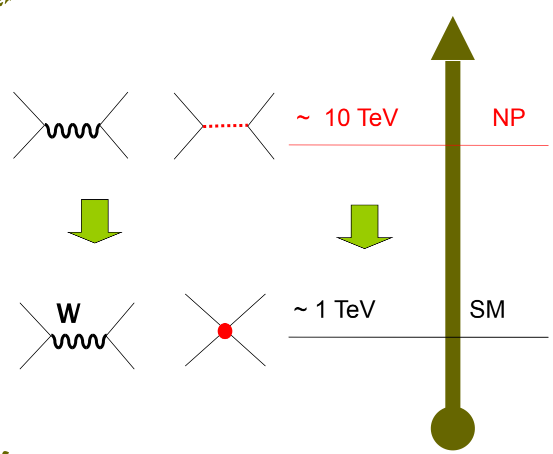
Introduction



Beta decays & Atomic PV

Competitive NP probes?
(other EWPO & LHC)

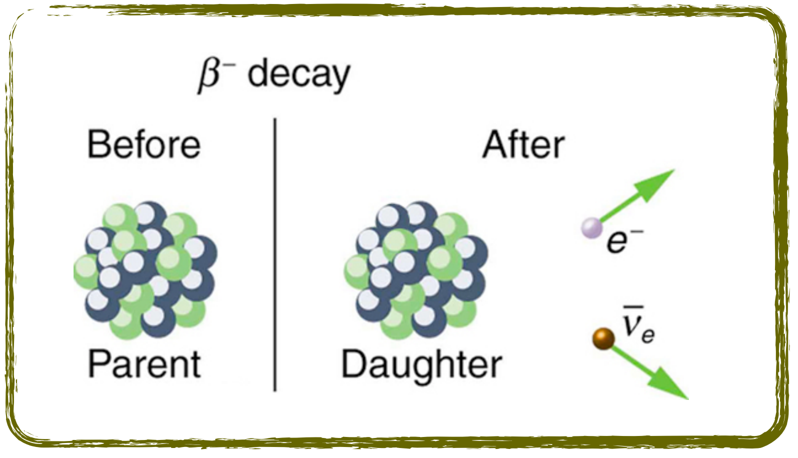
SMEFT



$$\mathcal{L} = \mathcal{L}(\phi, \phi_\Lambda)$$

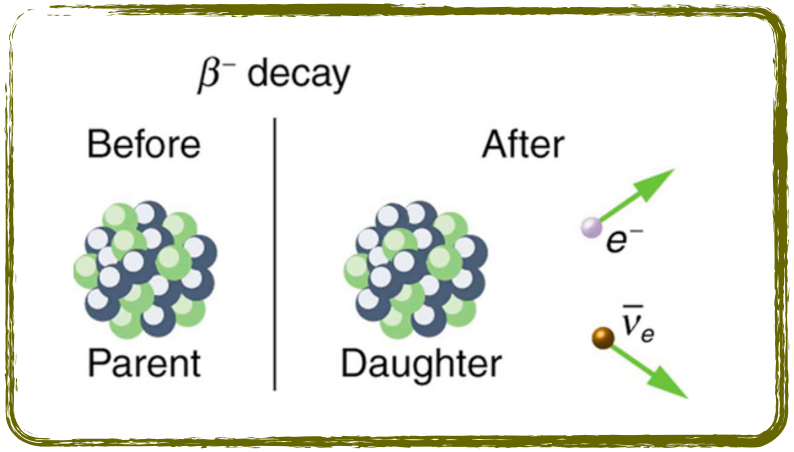
$$\mathcal{L}_{eff.} = \mathcal{L}_{SM} + \frac{1}{\Lambda^2} \sum \alpha_i \mathcal{O}_i$$

Nuclear beta decays



n→p e ν **d→u e ν**

Nuclear beta decays



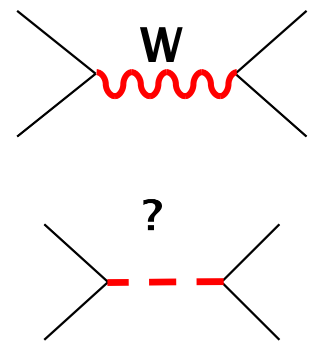
n→p e ν → **d→u e ν**

$$\mathcal{L}_{d\to u\ell^-\bar{\nu}_\ell} = -\frac{4G_F V_{ij}}{\sqrt{2}}\left[\bar{\ell}_L\gamma_\mu\nu\cdot\bar{u}\gamma^\mu d_L \;+\; \sum_{\rho\delta\Gamma}\epsilon^{\Gamma}_{\rho\delta}\,\bar{\ell}_\rho\Gamma\nu\cdot\bar{u}\Gamma d_\delta\right]$$

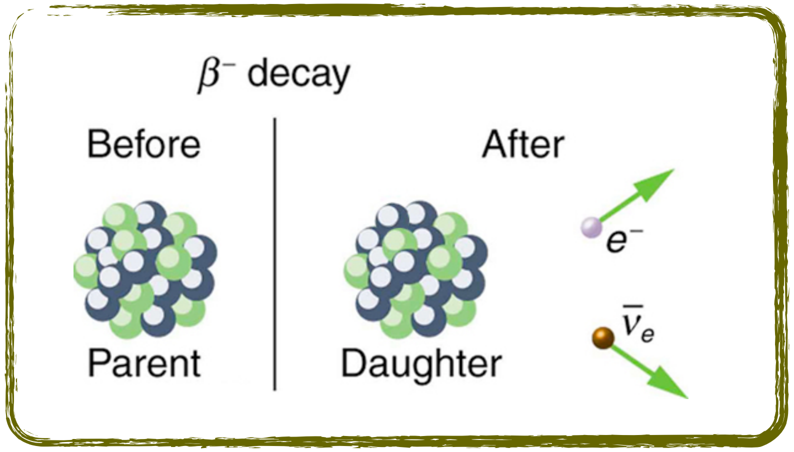
V, A, S, P, T

$$G_F \sim \frac{1}{M_W^2}$$

$$G_F\varepsilon_i \sim \frac{1}{M_{NP}^2}$$



Nuclear beta decays



→ n→p e ν → d→u e ν

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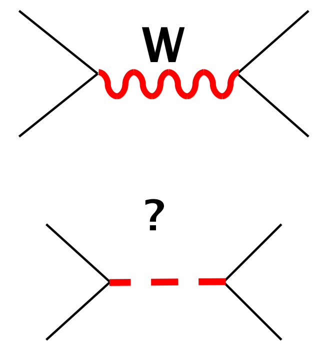


V, ~~A~~, S, ~~P~~, T

π→ e ν

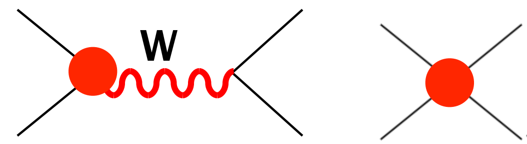
Nuclear matrix element?
→ neutron/pion better suited

Non-SM vector interactions

- NP "hidden" $\tilde{V}_{ud} = V_{ud}(1+\delta_{NP})$

δg_L^{Wq}

$$\Delta_{\rm CKM} \equiv |\tilde{V}_{ud}|^2 + |\tilde{V}_{us}|^2 + |\tilde{V}_{ub}|^2 - 1 = 2\left(-\delta g_L^{W\ell} + \delta g_L^{Zu} - \delta g_L^{Zd} - c_{lq}^{(3)} + c_{\ell\ell}^{(3)}\right)$$



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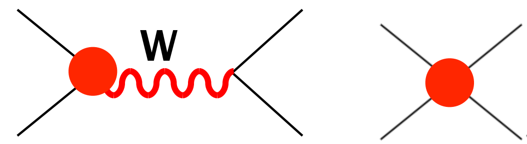

- NP probable through precise V_{ud}, V_{us} extractions
  → (Ft-values) superallowed beta decays!

$$\begin{pmatrix} \tilde{V}_{ud} \\ \tilde{V}_{us} \end{pmatrix} = \begin{pmatrix} 0.97416(21) \\ 0.22484(64) \end{pmatrix} \rightarrow \Delta_{\rm CKM} = -(4.6 \pm 5.2) \times 10^{-4}$$

[Hardy & Towner'14, MGA & Martin Camalich'16, Flavianet'17]

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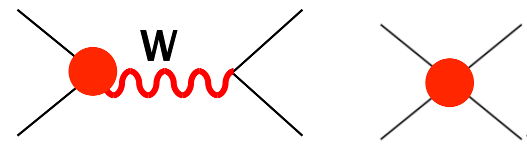

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[Hardy & Towner'14, MGA & Martin Camalich'16, Flavianet'17]

- Competitive?

[From Falkowski, MGA & Mimouni, 2017]

$$\begin{pmatrix} \delta g_L^{W\ell} \\ \delta g_L^{Zu} \\ \delta g_L^{Zd} \\ c_{\ell\ell}^{(3)} \\ c_{\ell q}^{(3)} \end{pmatrix} \times 10^3 = \begin{pmatrix} 0.15 \pm 0.18 \\ 0.48 \pm 0.45 \\ -0.05 \pm 0.27 \\ -0.40 \pm 0.37 \\ -1.11 \pm 0.89 \end{pmatrix}_{\rm LEP/EWPO} \quad \text{vs.} \quad \begin{pmatrix} 0.23 \pm 0.26 \\ -0.23 \pm 0.26 \\ 0.23 \pm 0.26 \\ 0.23 \pm 0.26 \\ -0.23 \pm 0.26 \end{pmatrix}_{\Delta_{CKM}}$$

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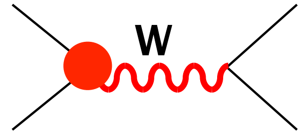

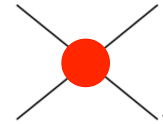

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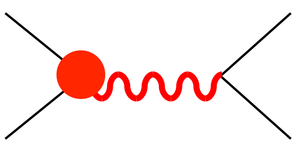

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LHC can't compete here

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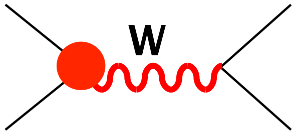

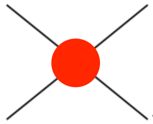


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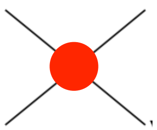

$pp \to e^+e^-$
LHC reaching this level…
HL-LHC x10


[Falkowski, MGA & Mimouni'17, Greljo & Marzocca'17]

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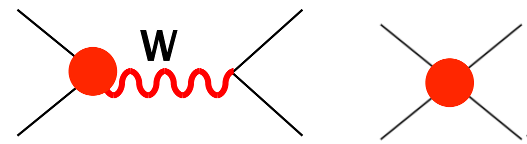

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[Hardy & Towner'14, MGA & Martin Camalich'16, Flavianet'17]

- Competitive probe!
  - Important to improve the bound, or strengthen its reliability;
  - Error dominated by theory (RC);

Scalar & Tensor interactions

- They affect differential distributions
  → nuclear matrix element cancel!
  → precise SM predictions;

$$\frac{d\Gamma(\mathbf{J})}{dE_e d\Omega_e d\Omega_\nu} \sim \xi(E) \left\{ 1 + a \frac{\mathbf{p}_e \cdot \mathbf{p}_\nu}{E_e E_\nu} + b \frac{m_e}{E_e} + A \frac{\mathbf{p}_e}{E_e} \frac{\mathbf{J}}{J} + (B + b_B \frac{m_e}{E_e}) \frac{\mathbf{p}_\nu}{E_\nu} \frac{\mathbf{J}}{J} \right\}$$

$$\mathbf{b} = \#\, \mathbf{g_S}\, \boldsymbol{\varepsilon}_\mathbf{S} + \#\, \mathbf{g_T}\, \boldsymbol{\varepsilon}_\mathbf{T}$$

$$\langle p | \bar{u} d | n \rangle \qquad \langle p | \bar{u} \sigma_{\mu\nu} d | n \rangle$$

- Hadronic matrix elements do not cancel
  → huge recent progress: $\delta g_{S,T} < 10\%$
  [backup slide]

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$\mathbf{b} = \#\, g_S\, \varepsilon_S + \#\, g_T\, \varepsilon_T$

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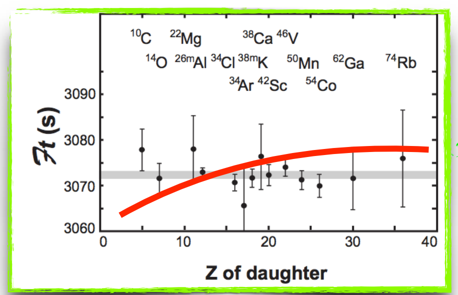

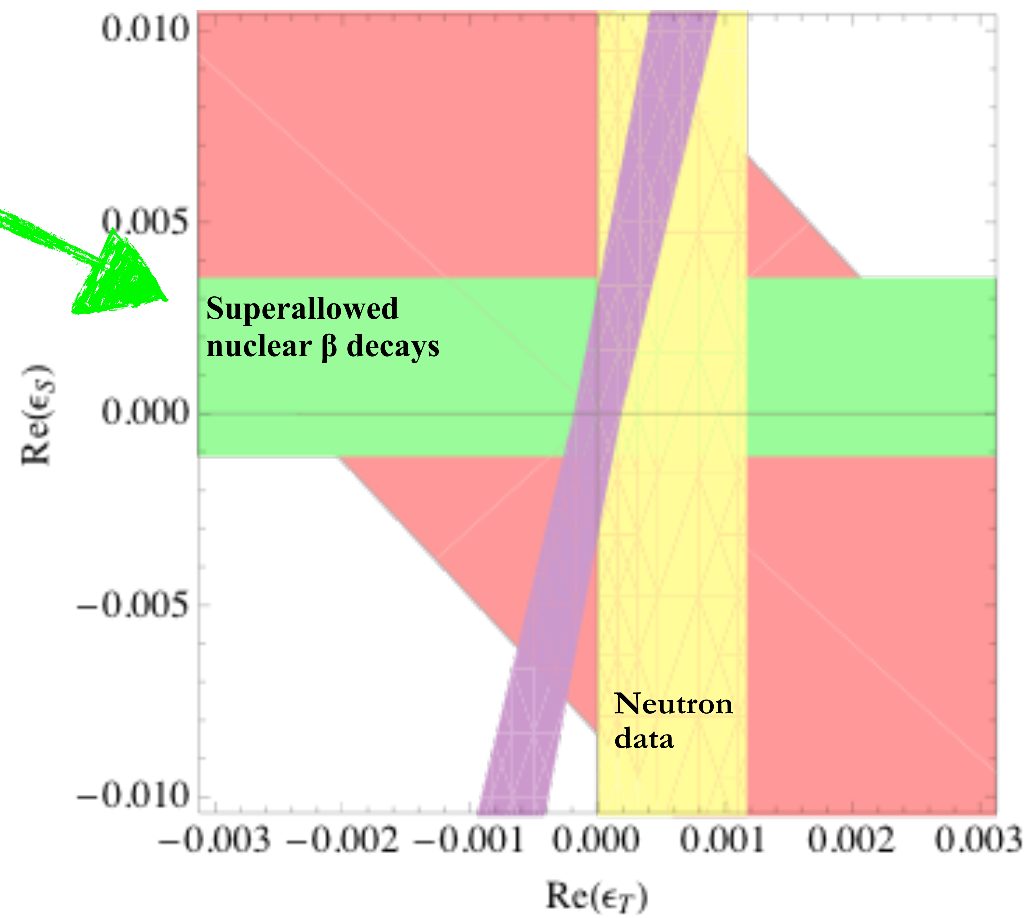

[Hardy & Towner'14,
Wauters, Garcia & Hong'13]
Pattie, Hickerson & Young'13,
MGA & Naviliat-Cuncic'13]

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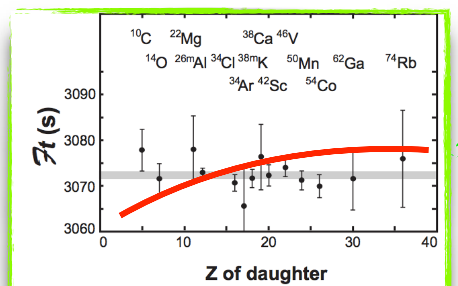
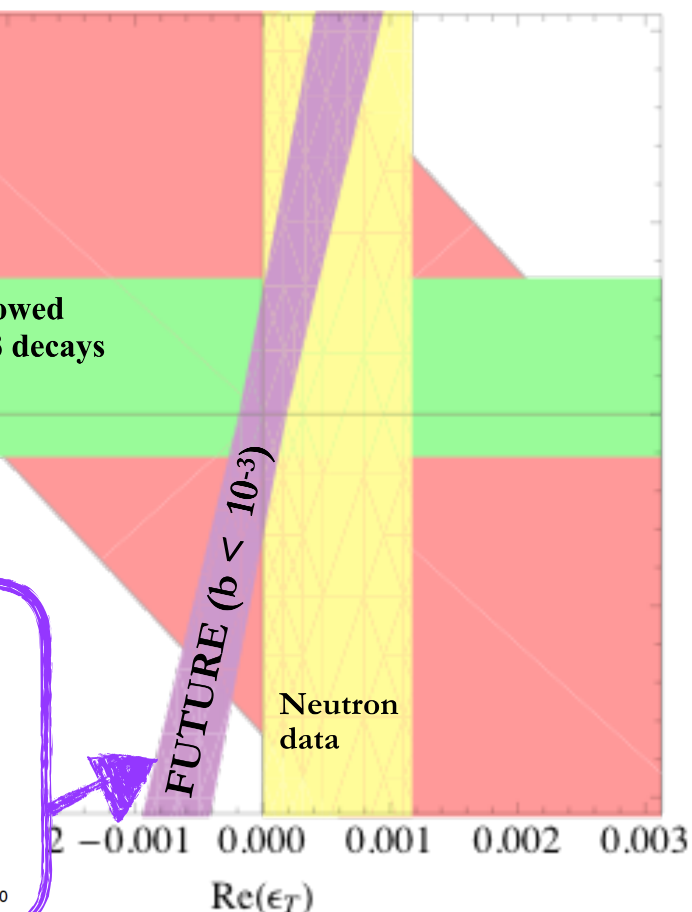
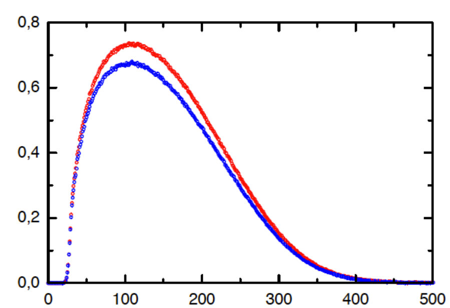




Future: shape measurements?

"we present an analytical description of the allowed β spectrum shape accurate to ~10^{-4} *down to 1 keV for low to medium Z nuclei, thereby extending the work by previous authors by nearly an order of magnitude."*
[Hayen et al., Rev.Mod.Phys. 1709.07530]



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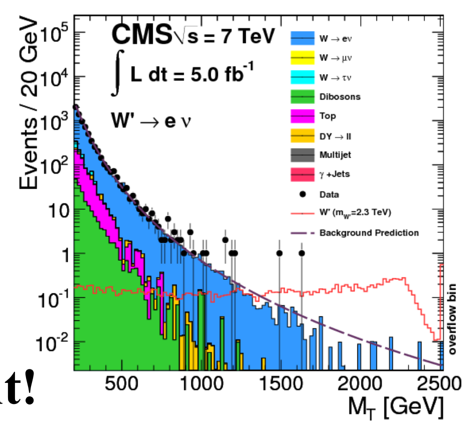
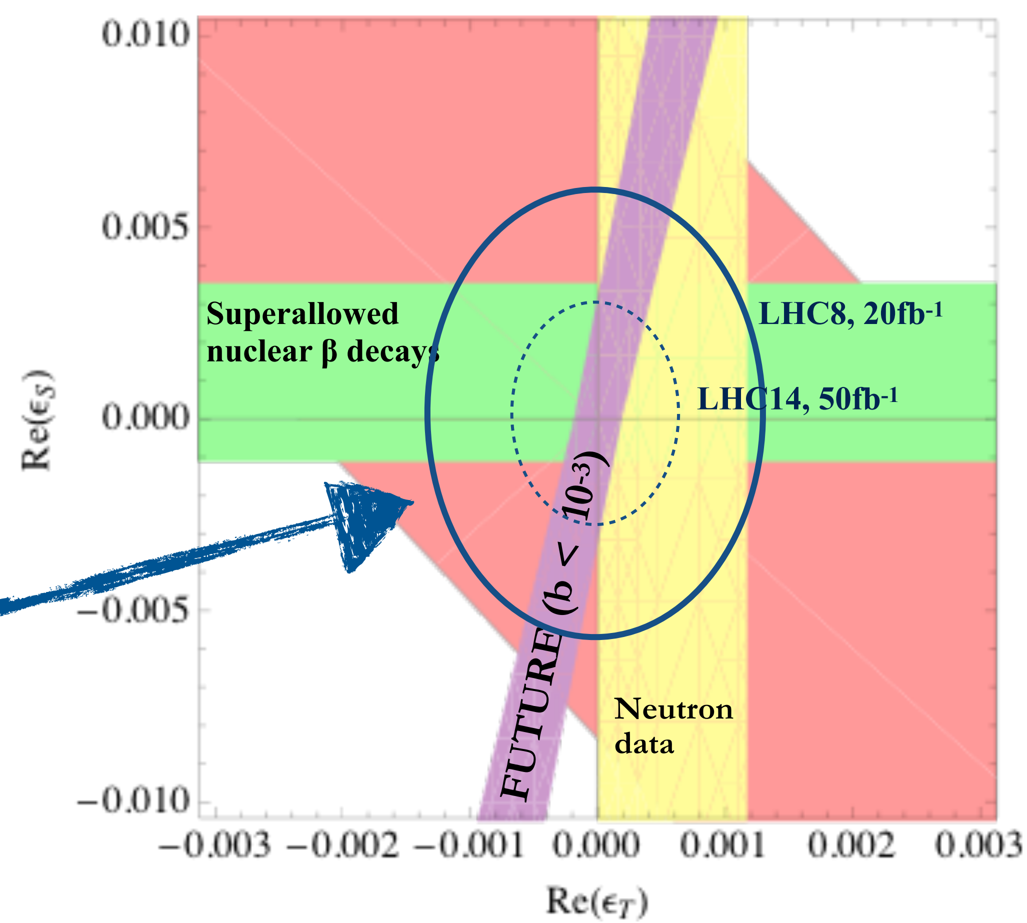
  [backup slide]

- Competitive w LHC?

Drell-Yan
$pp \to e^+ \nu$

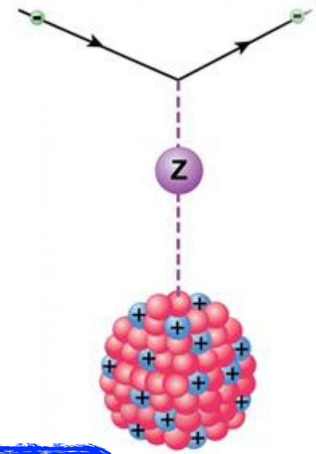
Contact interactions:
E^2/v^2 enhancement!





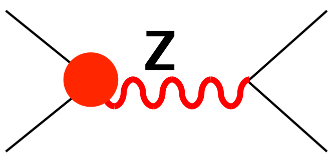
[Cirigliano, MGA & Graesser '2012]

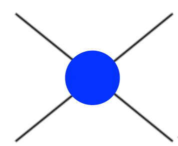
Atomic PV



$$Q_W(Z,N) = -2\left((2Z+N)g_{AV}^{eu} + (Z+2N)g_{AV}^{ed}\right)$$

$$\begin{aligned}
g_{AV}^{e_J u} &= -\frac{1}{2} + \frac{4}{3}s_\theta^2 - \left(\delta g_L^{Zu} + \delta g_R^{Zu}\right) + \frac{3-8s_\theta^2}{3}\left(\delta g_L^{Ze_J} - \delta g_R^{Ze_J}\right) + \frac{1}{2}\left[c_{lq}^{(3)} - c_{lq} - c_{lu} + c_{eq} + c_{eu}\right]_{JJ11}, \\
g_{AV}^{e_J d} &= \frac{1}{2} - \frac{2}{3}s_\theta^2 - \left(\delta g_L^{Zd} + \delta g_R^{Zd}\right) - \frac{3-4s_\theta^2}{3}\left(\delta g_L^{Ze_J} - \delta g_R^{Ze_J}\right) + \frac{1}{2}\left[-c_{lq}^{(3)} - c_{lq} - c_{ld} + c_{eq} + c_{ed}\right]_{JJ11},
\end{aligned}$$





Atomic PV

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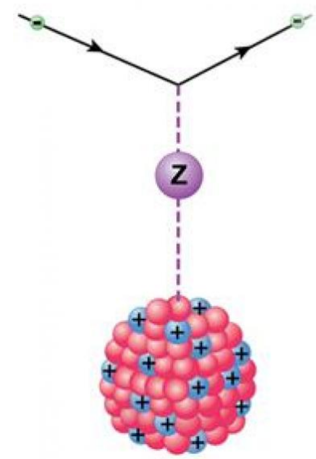

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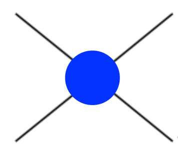

$$\bar{\ell}_1\gamma_\mu\ell_1 \cdot \bar{q}_1\gamma^\mu q_1$$

Atomic PV

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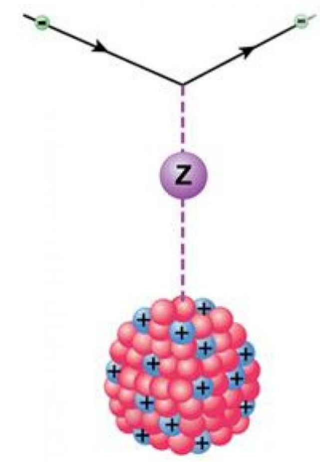


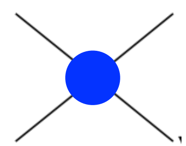
$Q_W^{\mathrm{Cs}} = -72.62 \pm 0.43$

[Wood et al., Science, 1997]

	$c_{lq} \times 10^3$
APV	1.6 ± 1.1
QWEAK	-2.3 ± 4.0
PVDIS	24 ± 35
LEP-2	-42 ± 28

$$\ldots s_\theta^2 \left(\delta g_L^{Ze_J} - \delta g_R^{Ze_J}\right) + \frac{1}{2}\left[c_{lq}^{(3)} - c_{lq} - c_{lu} + c_{eq} + c_{eu}\right]_{JJ11},$$

$$\ldots \left(\delta g_L^{Ze_J} - \delta g_R^{Ze_J}\right) + \frac{1}{2}\left[-c_{lq}^{(3)} - c_{lq} - c_{ld} + c_{eq} + c_{ed}\right]_{JJ11},$$



$$\bar{\ell}_1 \gamma_\mu \ell_1 \cdot \bar{q}_1 \gamma^\mu q_1$$

[Falkowski, MGA & Mimouni, 2017]

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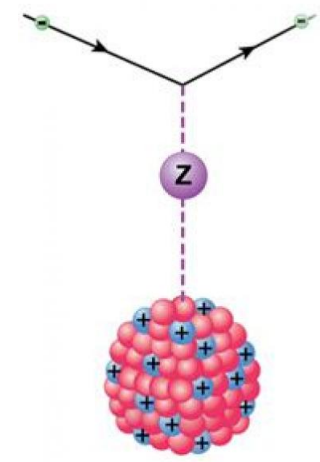

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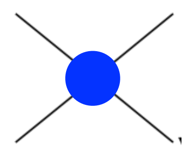

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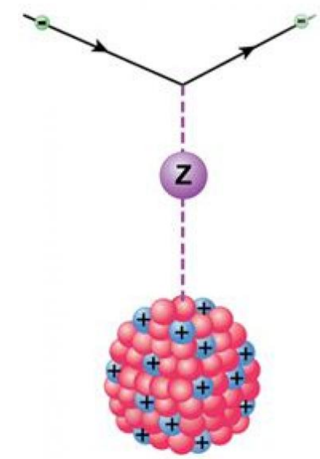

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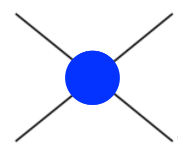

$$\bar{\ell}_1\gamma_\mu\ell_1 \cdot \bar{q}_1\gamma^\mu q_1$$

LHC run 2 & HL-LHC
→ ~10^{-4} level bounds
[Greljo-Marzocca, 2017]

[Falkowski, MGA & Mimouni, 2017]

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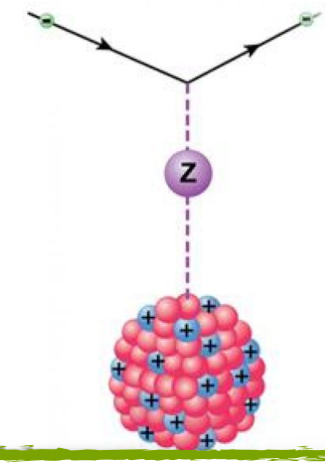

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EUROPEAN ORGANIZATION FOR NUCLEAR RESEARCH

Letter of Intent to the ISOLDE and Neutron Time-of-Flight Committee

Laser Cooling of Ra ions for Atomic Parity Violation

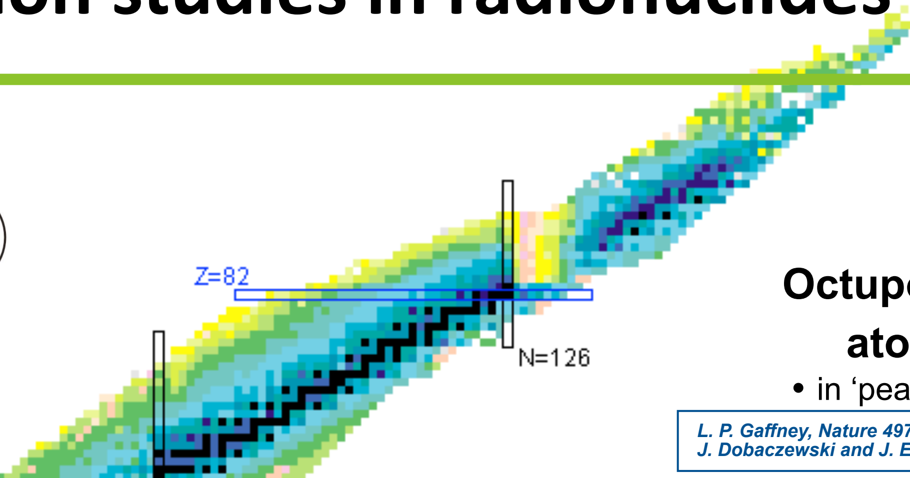
May 31, 2017

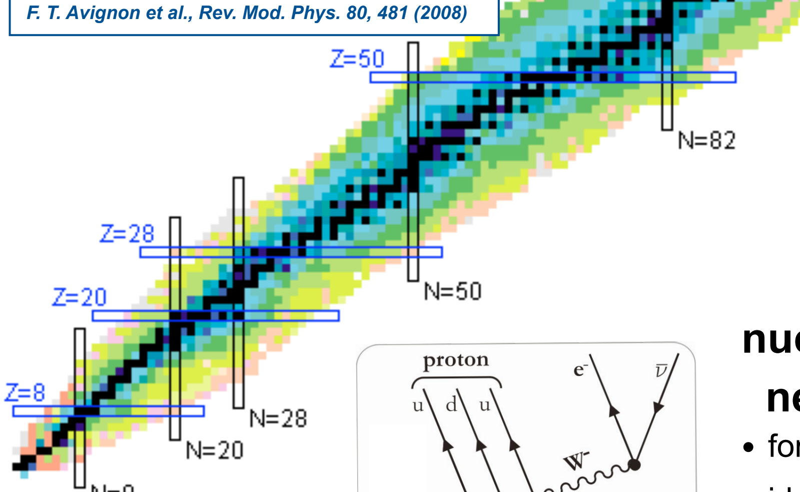
L. Willmann[1], K. Jungmann[1], N. Severijns[2], K. Wendt[3]

"The ion Ra+ renders the possibility for a 5x improvement in the accuracy of $\sin^2\theta_w$ within 1 week of measurement time"

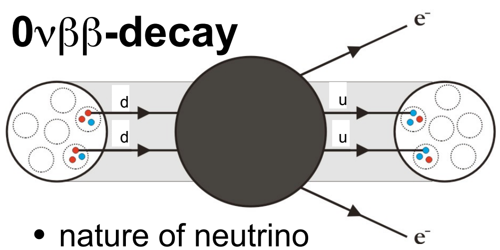
[Falkowski, MGA & Mimouni, 2017]

weak interaction studies in radionuclides





0νββ-decay



- nature of neutrino
- nuclear matrix elements
- effective Majorana mass

F. T. Avignon et al., Rev. Mod. Phys. 80, 481 (2008)

Octupole enhanced atomic EDMs

- in ‘pear shaped’ nuclei

L. P. Gaffney, Nature 497, 199–204 (2013)
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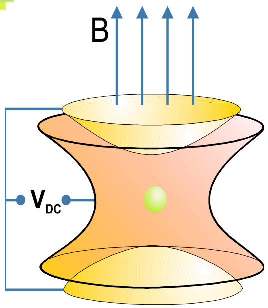
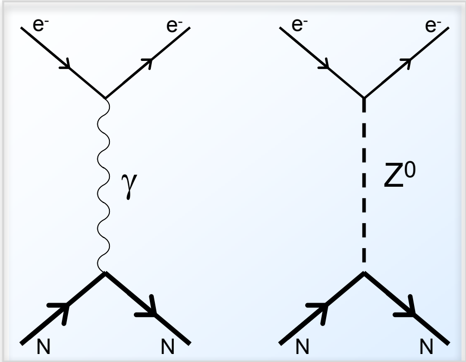


nuclear masses for neutrino physics

- for ν mass measurements
- identify best cases for 0νϵϵ

S. Eliseev et al., Ann. Phys. 525, 707 (2013)



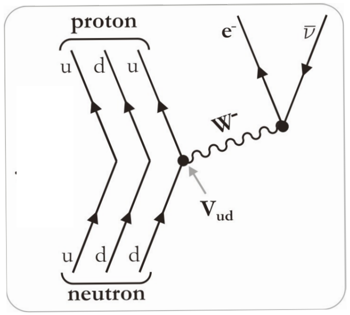
atomic parity violation

- access $\sin^2(\Theta_W)$ at low energy
- strong enhancement in (radioactive) Fr or Ra^+

S. Aubin et al., Hyp. Int. 214, 163 (2013),
L. Willmann et al., CERN-INTC-2017-069 / INTC-I-196

β decays

- V_{ud} of CKM matrix
- CKM unitarity test
- limits on scalar & tensor currents
- …



J. C. Hardy and I. S. Towner, Phys. Rev. C 91, 025501 (2015)
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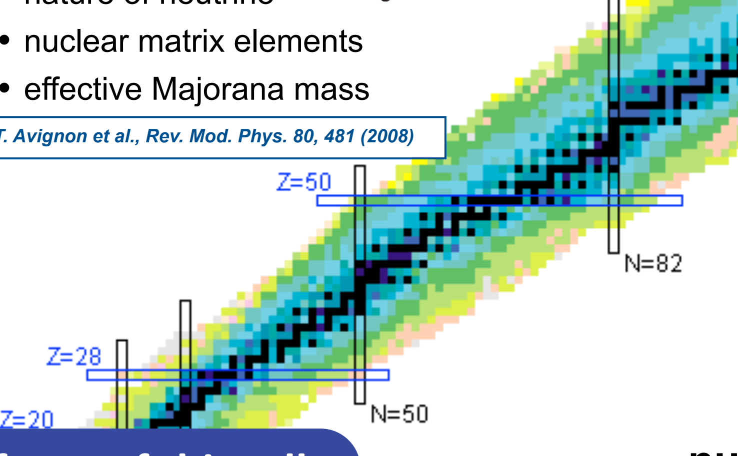
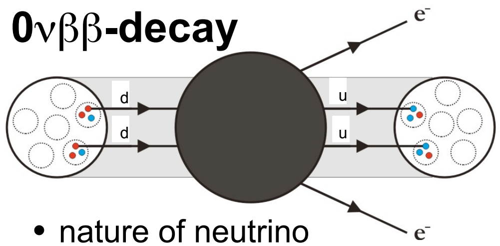
weak interaction studies in radionuclides



$0\nu\beta\beta$-decay



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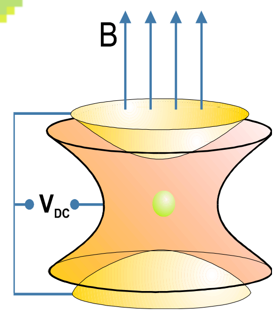

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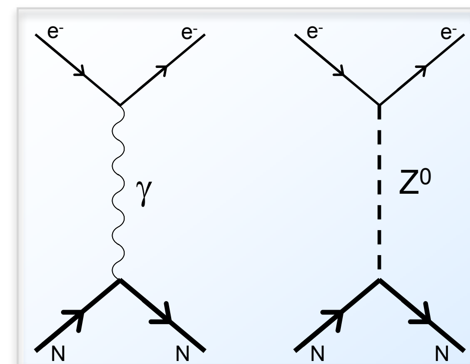

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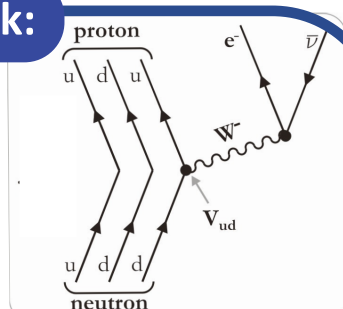
focus of this talk:

β decays



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compare to K. Blaum, PCB workshop 2016

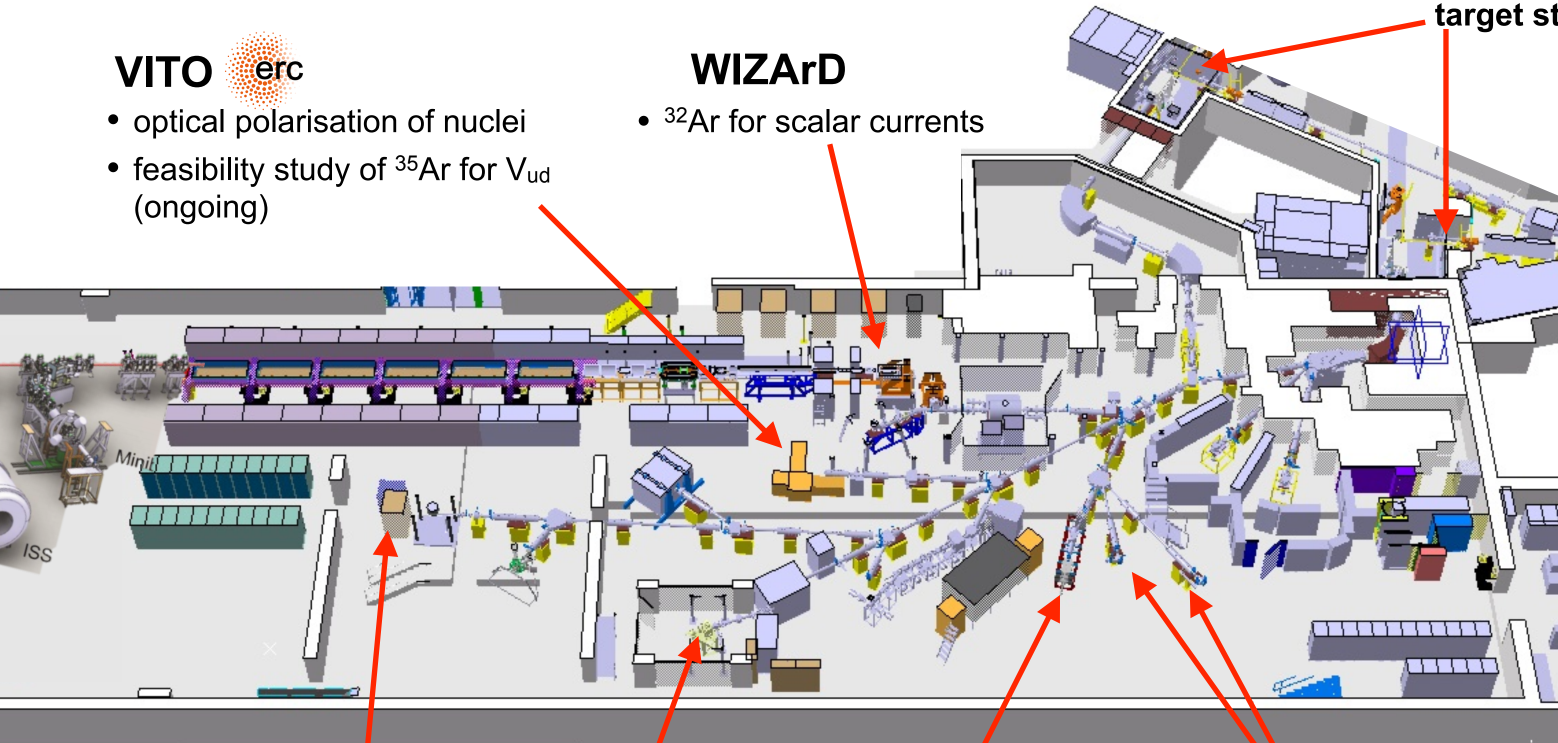
weak interaction studies in β decays at ISOLDE

target stations

1.4 GeV protons

VITO erc
- optical polarisation of nuclei
- feasibility study of ^{35}Ar for V_{ud} (ongoing)

WIZArD
- ^{32}Ar for scalar currents



NICOLE
- dilution refrigerator setup
- recently: ^{60}Co, ^{67}Cu for limits on tensor currents

ISOLTRAP
- Penning trap
- precise transition energies

COLLAPS
- laser spectroscopy
- charge radius of superallowed ^{26m}Al as input for theory (ongoing)

beamlines for ‘traveling setups’
- branching ratio (^{10}C, ^{37}K)
- half-lives (recently $^{38,39}Ca$, ^{37}K)
- β spectrum: **miniBETA**

MR-ToFs & MIRACLS erc

towards new opportunities for
- ISOLDE beam purification
- optical pumping for polarised nuclei

N. Severijns and B. Blank, J. Phys. G: Nucl. Part. Phys. 44, 074002 (2017)

ISOLDE

weak interaction studies in β decays at ISOLDE

example 2: in preparation

VITO erc
- optical polarisation of nuclei
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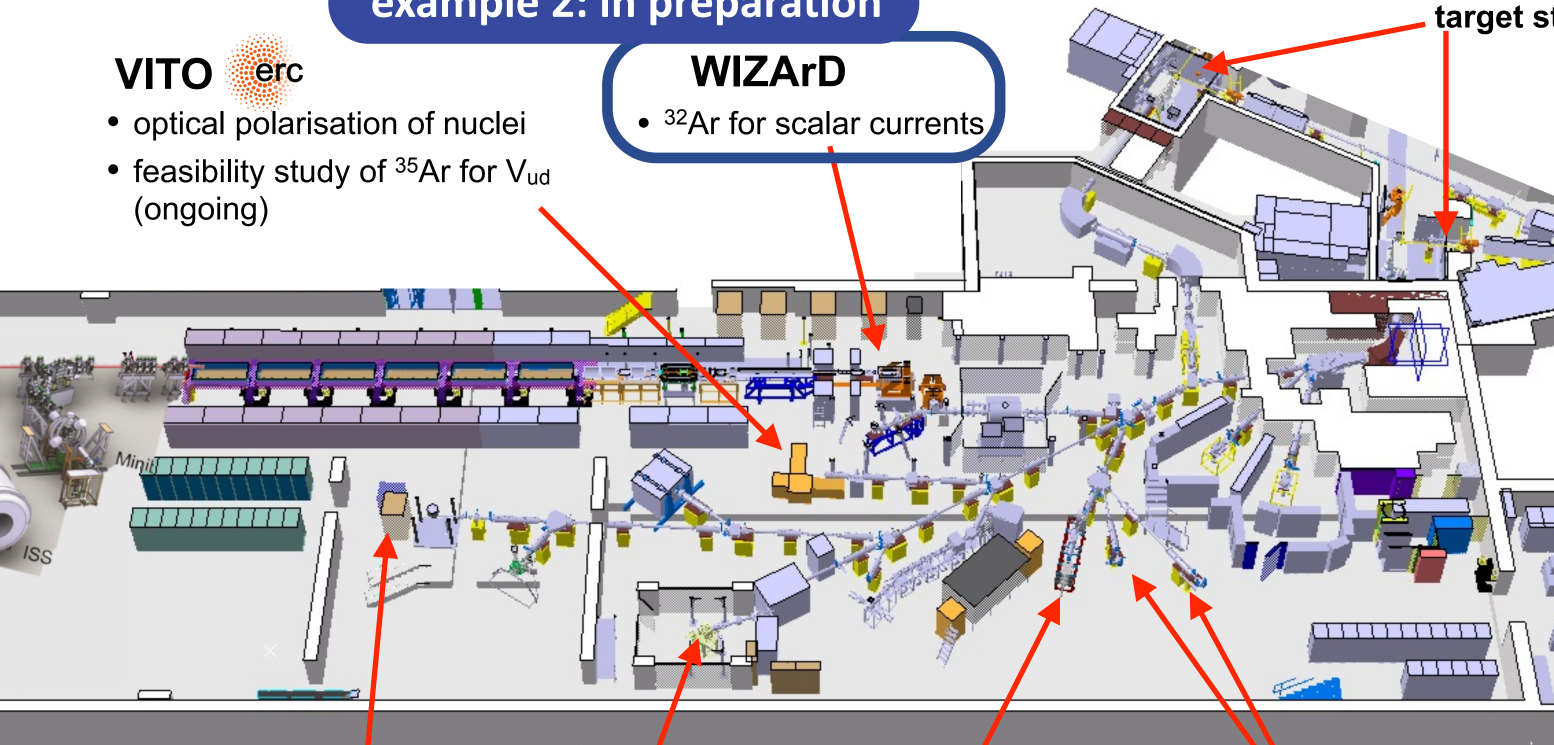
WIZArD
- ^{32}Ar for scalar currents

target stations

1.4 GeV protons



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beamli… **ps'**

example 1: ongoing
- branching ratio (^{10}C, ^{37}K)
- half-lives (recently ^{38,39}Ca, ^{37}K)
- β spectrum: **miniBETA**

example 3: future use@ISOLDE

MR-ToFs & MIRACLS erc

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- ISOLDE beam purification
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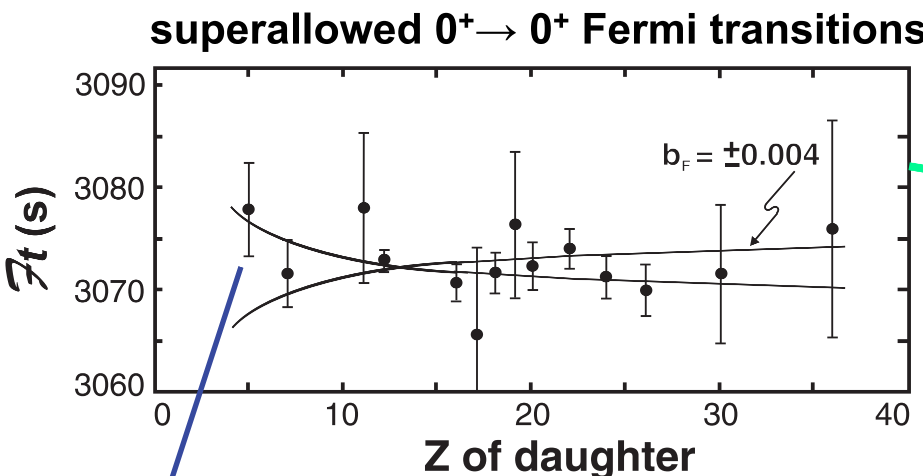
N. Severijns and B. Blank, J. Phys. G: Nucl. Part. Phys. 44, 074002 (2017)

Fierz term, scalar currents, and the case of ^{10}C



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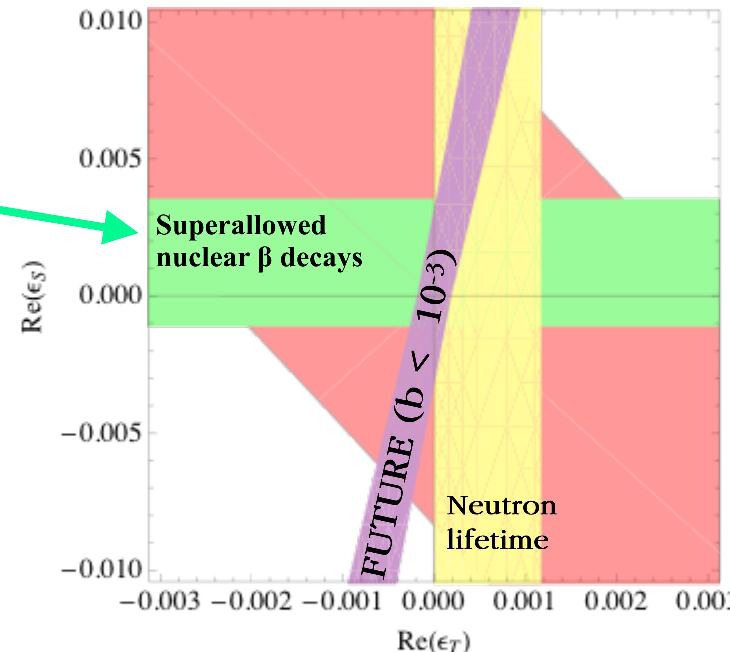
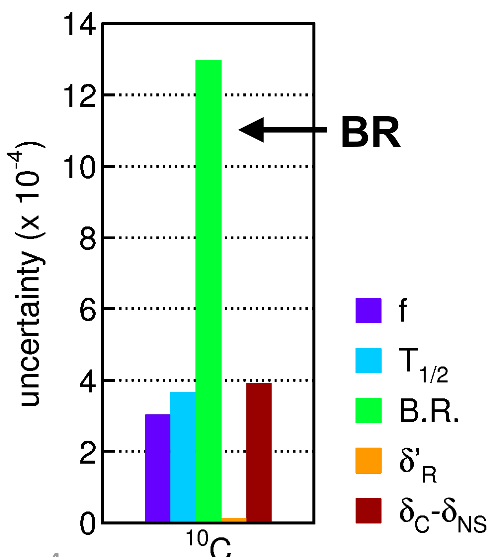


^{10}C

- high sensitivity to scalar currents
- limited by **BR**

G. Savard et al, PRL 74, 1521 (1995)
B.K. Fujikawa et al., PLB 449, 6(1999)



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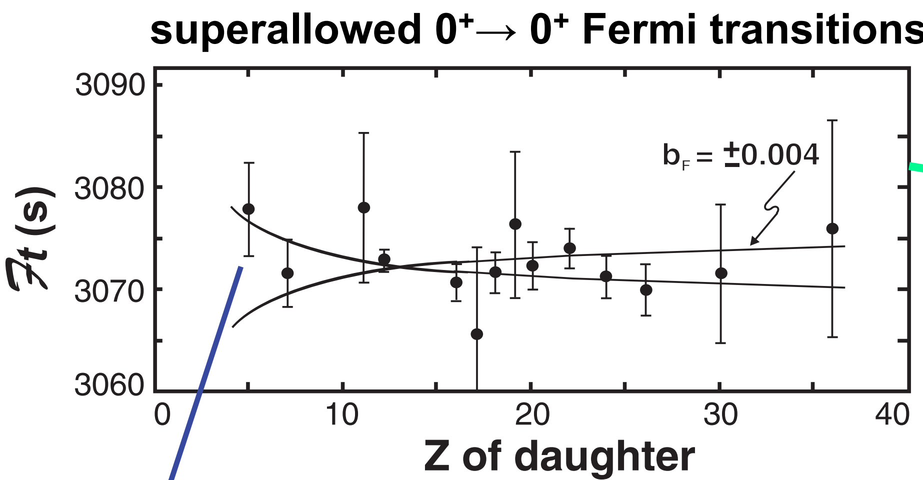

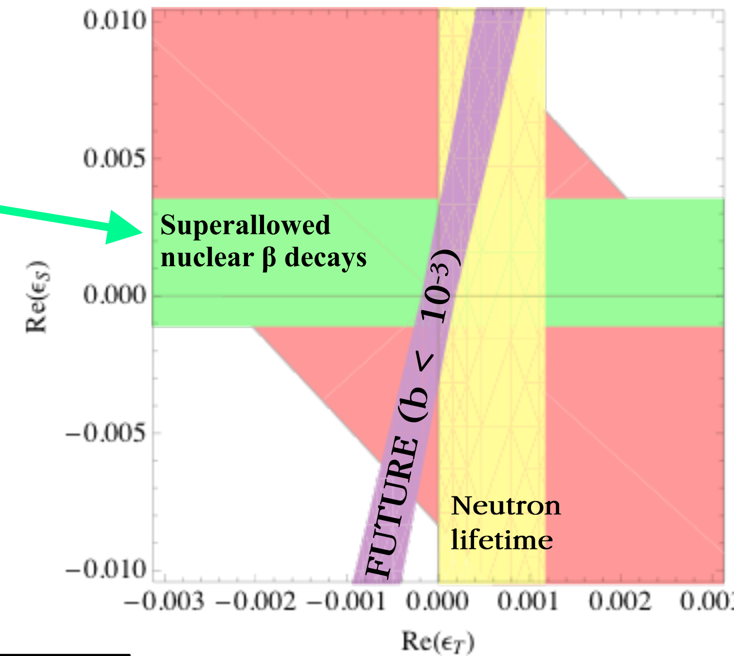

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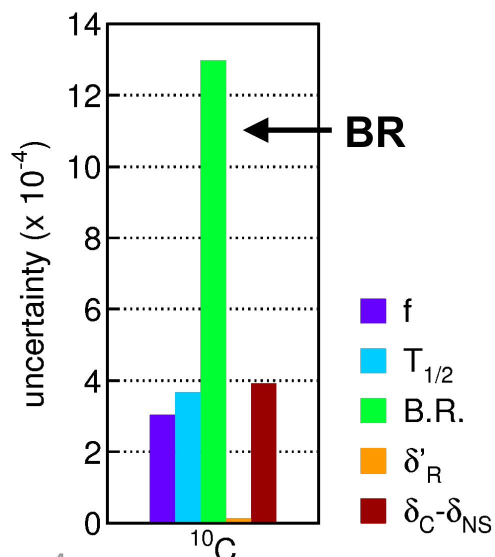
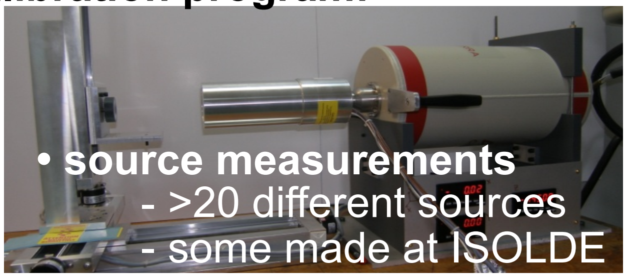
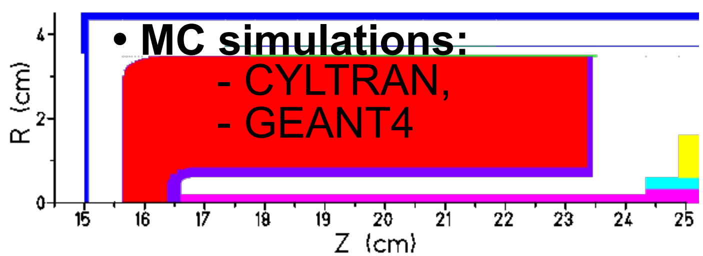


motivates new measurements with state-of-the-art detectors

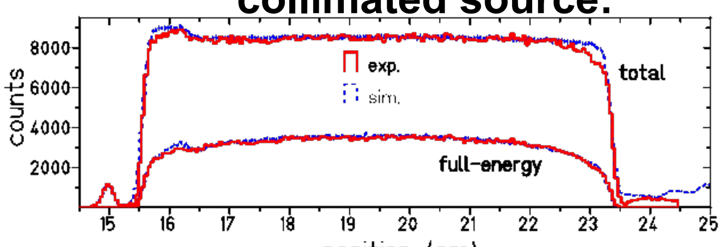
HPGe detector with high precision efficiency

calibration program:

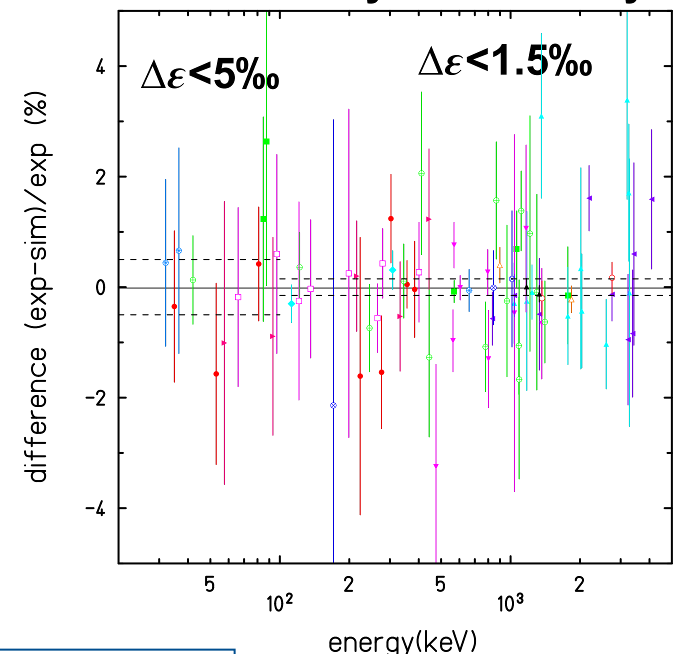




• scan of the crystal with collimated source:



Results for remaining uncertainty in efficiency



B. Blank et al., NIM A 776, 34 (2015)

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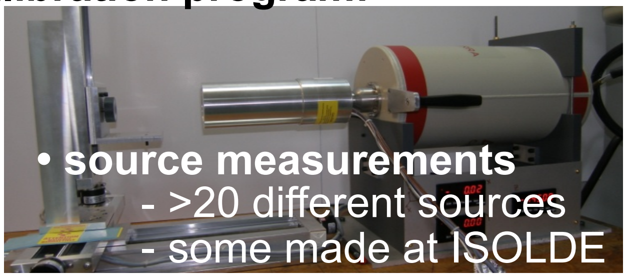
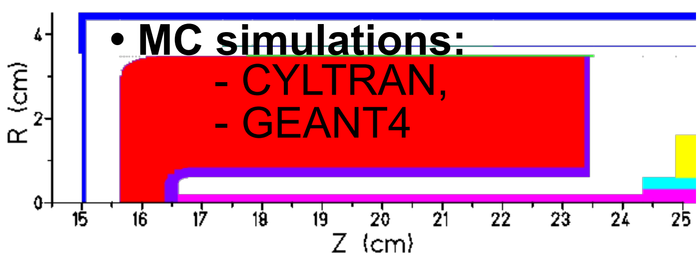


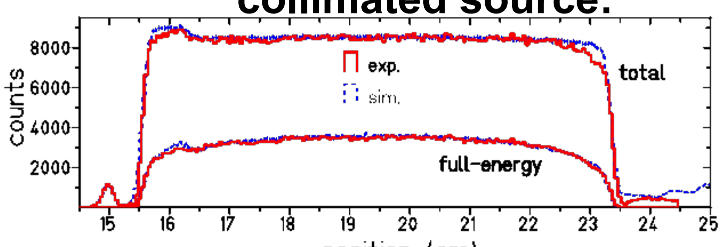
- **source measurements**
  - >20 different sources
  - some made at ISOLDE

- **x-ray photography**



- **MC simulations:**
  - CYLTRAN,
  - GEANT4

- **scan of the crystal with collimated source:**



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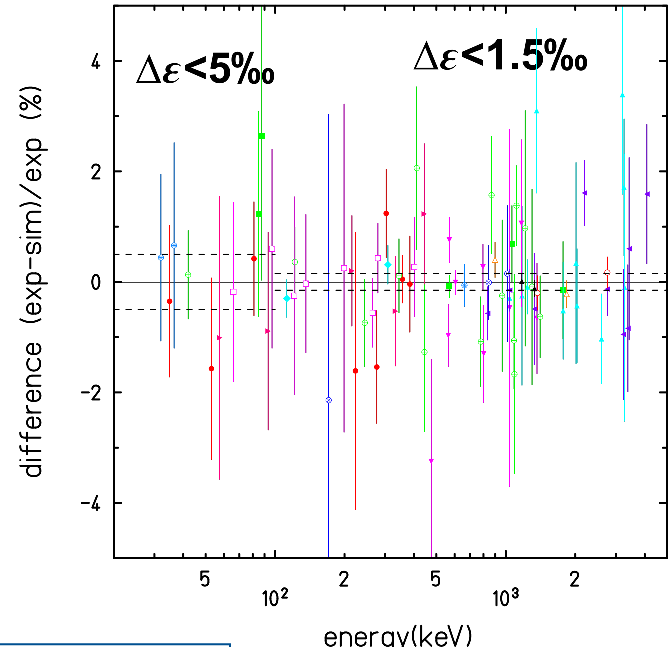


B. Blank et al., NIM A 776, 34 (2015)

status BR of ^{10}C

- goal: <0.15% in BR
- focus on systematics
- 1st data taking completed at ISOLDE
- analysis ongoing
- would benefit of future beam purification capabilities at ISOLDE

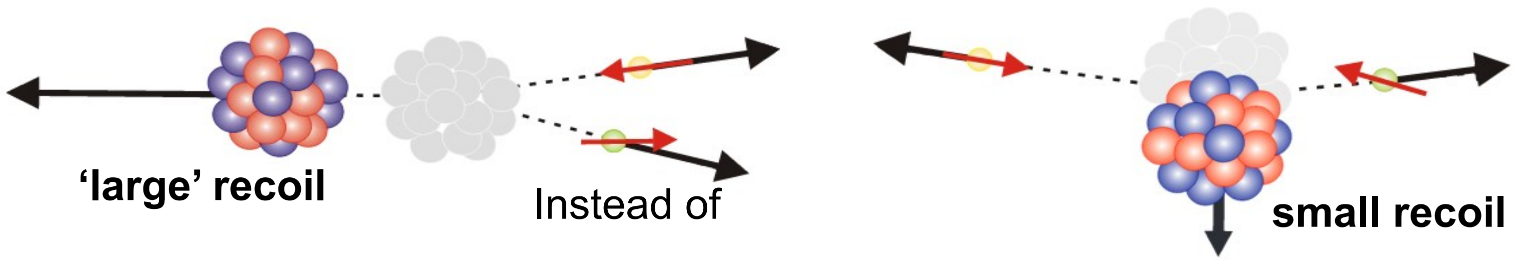
WISArD: Weak-interaction studies with ^{32}Ar decay

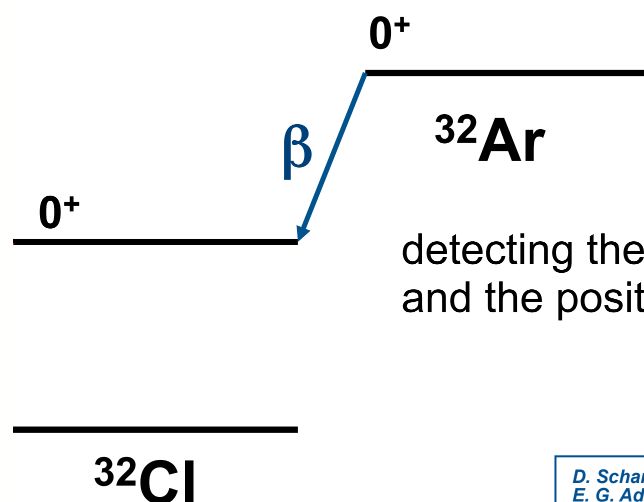
Standard Model
Vector currents

$$\frac{dW}{d\Omega} = 1 + \frac{p_e \cdot p_\nu}{E_e E_\nu}$$

New Physics
Scalar currents

$$\frac{dW}{d\Omega} = 1 - \frac{p_e \cdot p_\nu}{E_e E_\nu}$$





detecting the recoil
and the positron

D. Schardt and K. Riisager, ZPA 345, 265 (1993)
E. G. Adelberger et al., PRL 83 (1999) 1299

WISArD: Weak-interaction studies with ^{32}Ar decay

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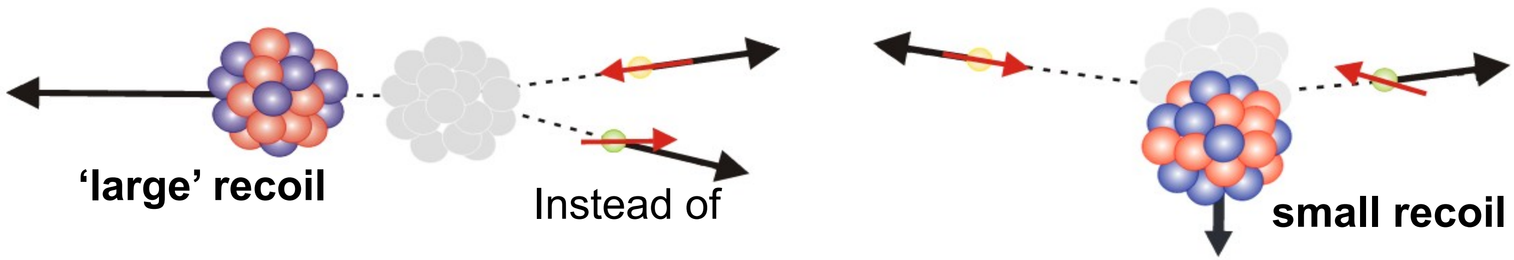
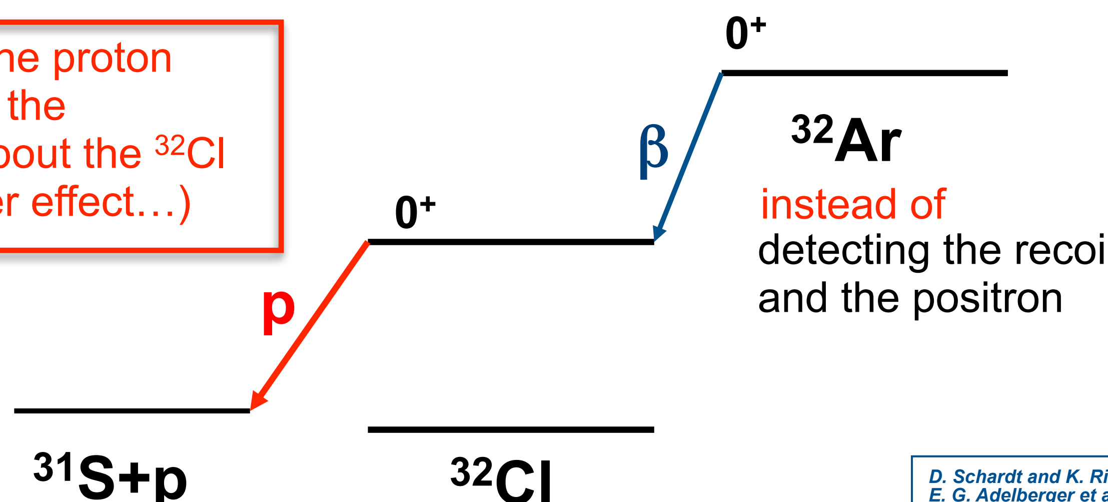


Detection of the proton that contains the information about the ^{32}Cl recoil (Doppler effect…)



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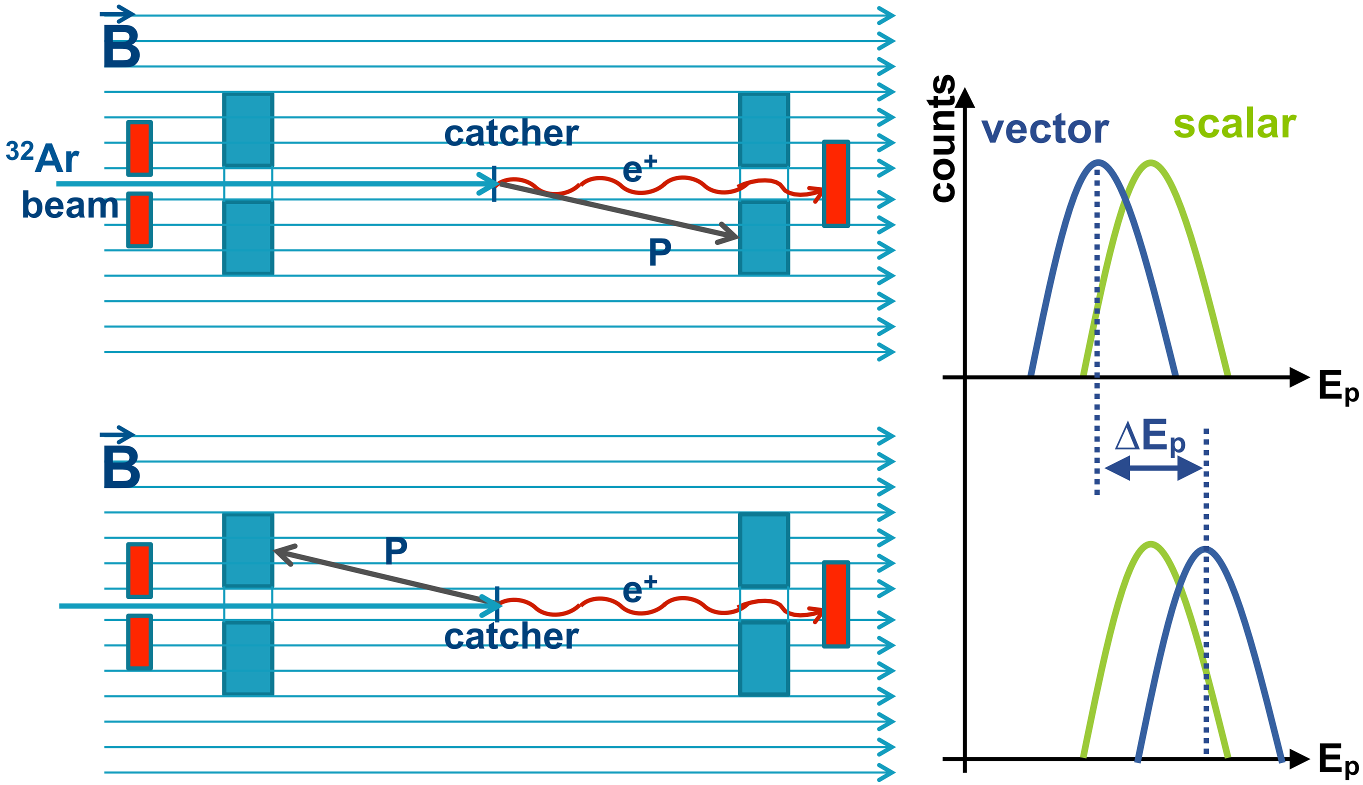


- major advance over previous experiments: ΔE_p measurement (instead of E_p)
- goal: limit on **$a_{\beta\nu}$ of the order of 0.1%** (factor ~6 improvement)
- timeline: proof-of-principle before LS2, data taking after LS2

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

N. Severijns and B. Blank, CERN-INTC-2016-050 / INTC-I-172 (2016)

precision measurement of β spectrum

- β-spectrum shape:

$$d\Gamma_{BSM} = d\Gamma_{SM}\left(1 + k\frac{1}{E_\beta}b_F\right)$$

Fierz term: scalar / tensor weak currents

- requires accurate knowledge of shape of SM β-spectrum (to a few parts in 10^{-4})

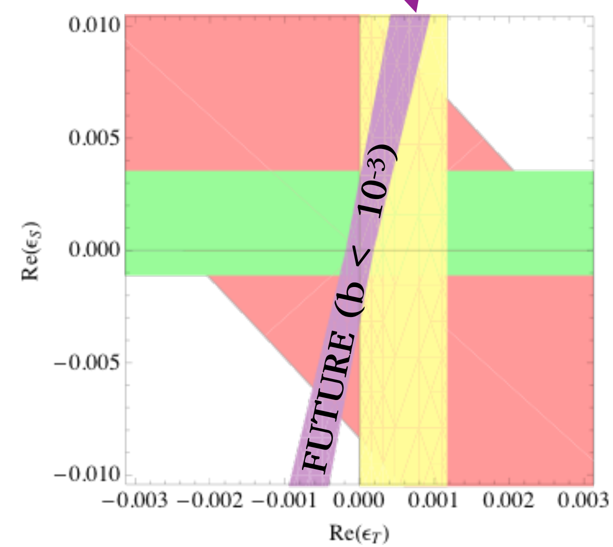
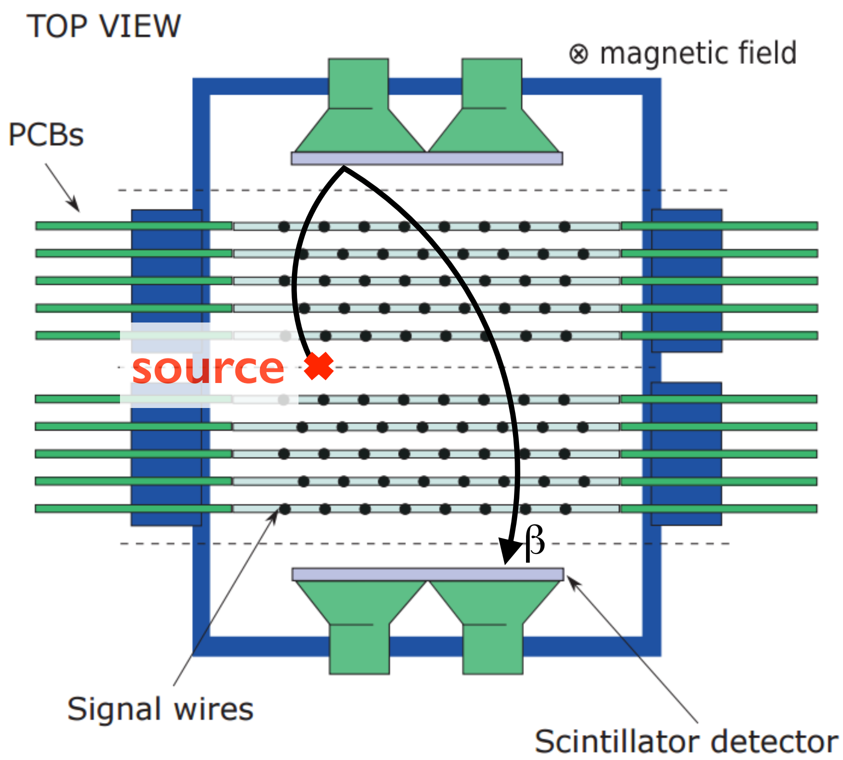


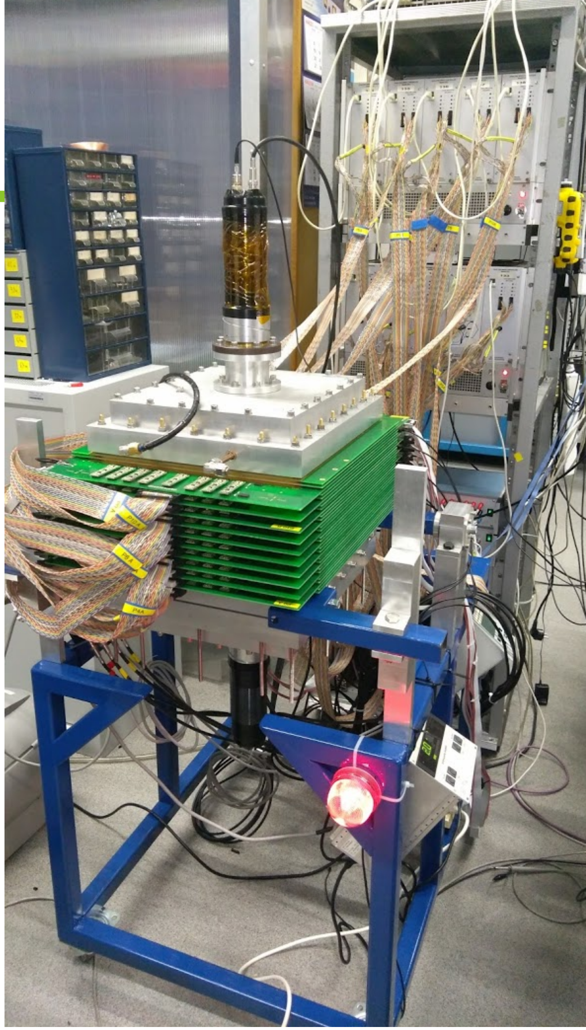
Table VII Overview of the features present in the β spectrum shape (Eq. (4)), and the effects incorporated into the Beta Spectrum Generator Code (Hayen and Severijns, TBP). Here the magnitudes are listed as the maximal typical deviation for medium Z nuclei with a few MeV endpoint energy. Some of these 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	F_0 (Eq. (6))	
3	Finite size of the nucleus	L_0 (Eq. (16))	10^{-1}-10^{-2}
4	Radiative corrections	R (Eq. (47))	
5	Shape factor	C (Eq. (100) and (105))	
6	Atomic exchange	X (Eq. (157))	
7	Atomic mismatch	r (Eq. (170))	
8	Atomic screening	S (Eq. (144)) [a]	10^{-3}-10^{-4}
9	Shake-up	See item 7 & Eq. (160) [b]	
10	Shake-off	See item 7 & Eq. (163) & χ_{ex}^{cont} (Eq. (164)) [c]	
11	Isovector correction	C_I (Eq. (113))	
12	Distorted Coulomb potential due to recoil	Q (Eq. (45))	
13	Diffuse nuclear surface	U (Eqs. (25) and (29))	
14	Nuclear deformation	D_{FS} (Eq. (40)) & D_C (Eq. (135))	
15	Recoiling nucleus	R_N (Eq. (41))	
16	Molecular screening	ΔS_{Mol} (Eq. (176))	
17	Molecular exchange	Case by case	
18	Bound state β decay	Γ_b/Γ_c (Eq. (171)) [d]	Smaller than $1 \cdot 10^{-4}$
19	Neutrino mass	Negligible	
20	Forbidden decays	Not incorporated	

Hayen et al., accepted Rev.Mod.Phys., arXiv:1709.07530

mini-BETA





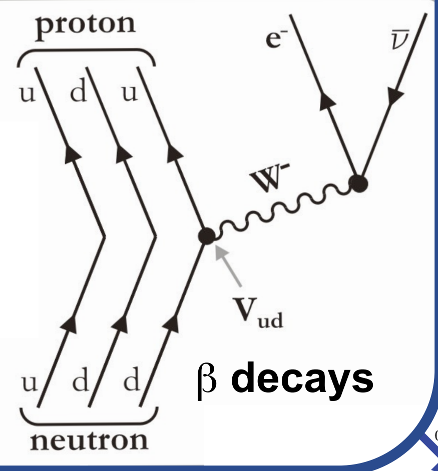
- **Concept:** energy detector (scintillator) + backscattering recognition (drift chamber)
- **status:** tracking of cosmic muons and β of ^{90}Sr source
- **goals:** first ^{114}In, later 'online'

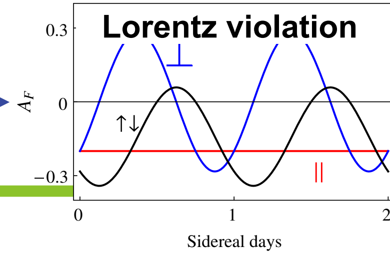
  aimed precision in β-spectrum: ~0.1 %

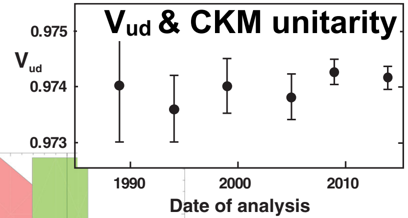
collaboration Leuven, Krakow

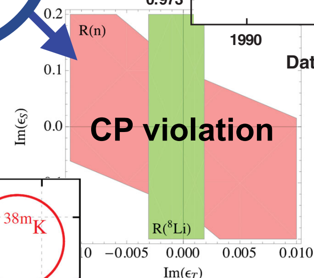
K. Lojek et al., Nucl. Instrum. Meth. Phys. Res. A 611 (2009) 284.
K. Lojek et al., Nucl. Instrum. Meth. Phys. Res. A 802 (2015) 38.

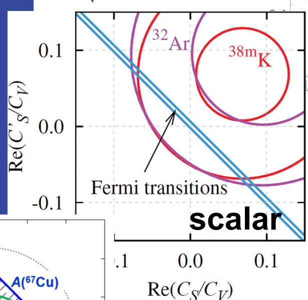
weak interaction studies in β decays

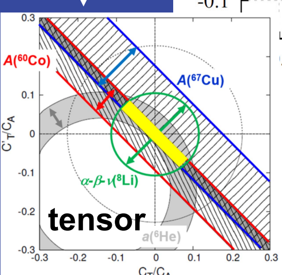










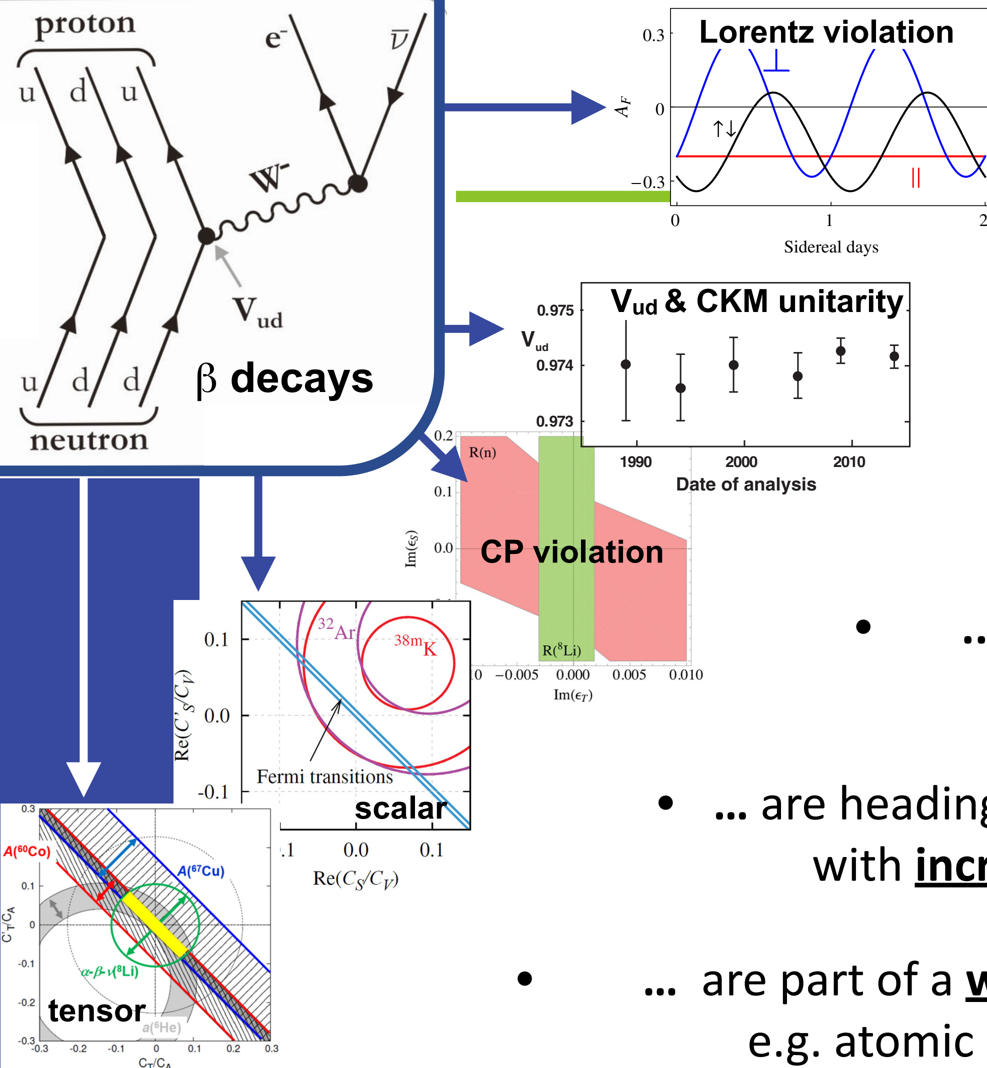


- … offer **high sensitivity** for BSM
- … provide **unique bounds on vertex corrections (V_{ff})**
- … are **complementary for contact interact.** (eeqq) with similar sensitivity as LHC
- … are heading towards **new generation of experiments** with **increased precision** (e.g. 0.1% in correl. exp.)
- … are part of a **wide ISOLDE program on weak interaction** e.g. atomic parity violation in radioactive Ra ions (KVI)
- … rely on **high yields and purity of rare isotope beams** at **ISOLDE**

improved further by MR-TOF traps as developed at ISOLTRAP or MIRACLS

J. C. Hardy and I. S. Towner, Phys. Rev. C 91, 025501 (2015)
N. Severijns and O. Naviliat-Cuncic, Phys. Scr. T152, 014018 (2013)
V. Cirigliano et al., Prog. Part. Nucl. Phys. 71, 93 (2013)
O. Naviliat-Cuncic and M. Gonzalez-Alonso, Ann. Phys. 525, 600 (2013)
K. K. Vos et al., Rev. Mod. Phys. 87, 1483 (2015)

weak interaction studies in β decays



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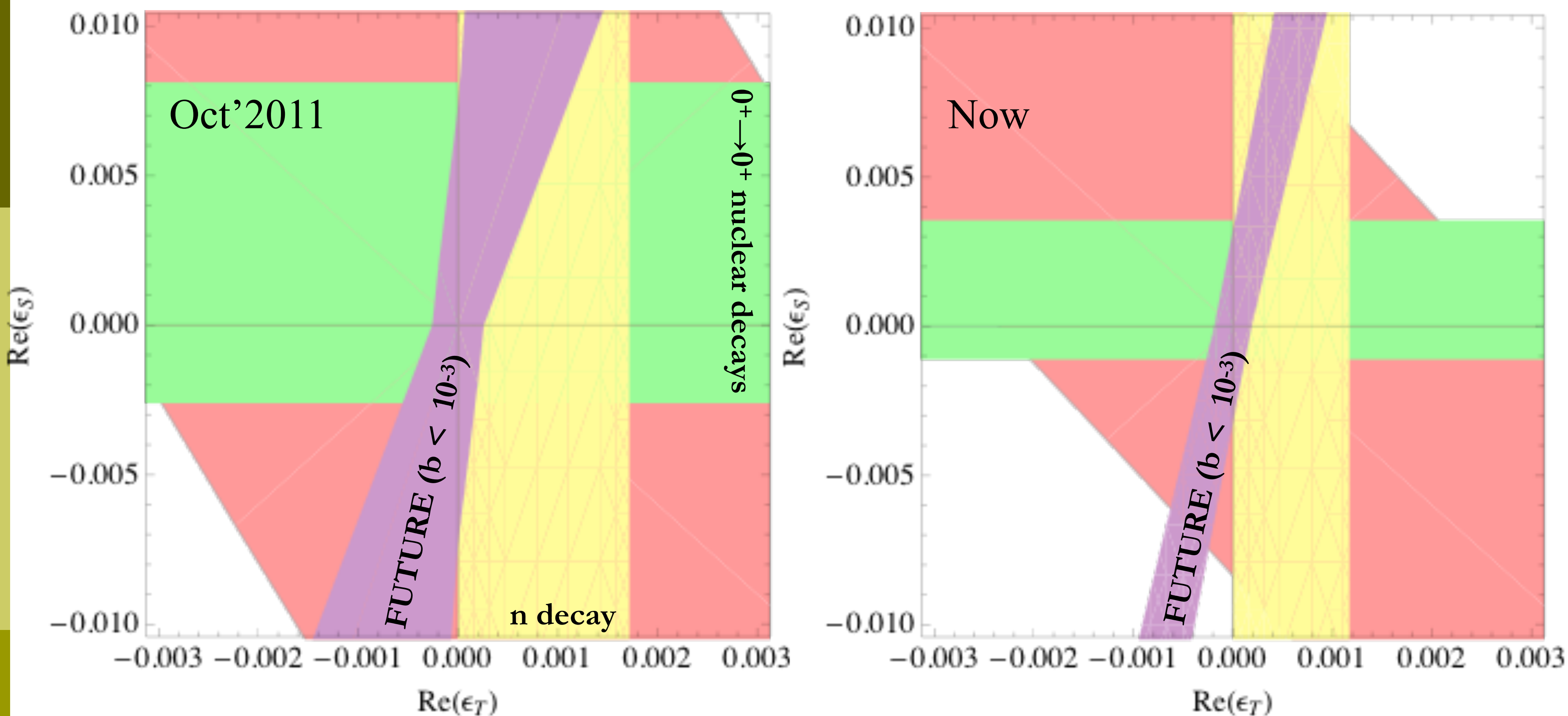
Backup slides

Theory input: g_S, g_T

$\langle p|\bar{u}d|n\rangle \rightarrow g_S$

$\langle p|\bar{u}\sigma_{\mu\nu}d|n\rangle \rightarrow g_T$



$g_S = 0.80(40)$
$g_T = 1.05(35)$

[Bhattacharya et al. Phys.Rev.D85 (2012)]

$g_S = 0.97(13)$

[MGA & Martin Camalich, Phys.Rev.Lett. 112 (2014)]

$$g_S = \frac{(M_n - M_p)_{QCD}}{m_d - m_u} g_V$$

$g_T = 0.987(55)$

[PNDME Phys.Rev.D94 (2016)]

Atomic PV

$$\mathcal{L}_{APV} = \frac{1}{2v^2}\left(g_{AV}^{eu}\ \bar{e}\gamma_\mu\gamma_5 e\cdot\bar{u}\gamma^\mu u + g_{AV}^{ed}\ \bar{e}\gamma_\mu\gamma_5 e\cdot\bar{d}\gamma^\mu d\right)$$

$Q_W^{\mathrm{Cs}} = -72.62 \pm 0.43$

$(ee)(qq)$

[in 10^{-3} units]

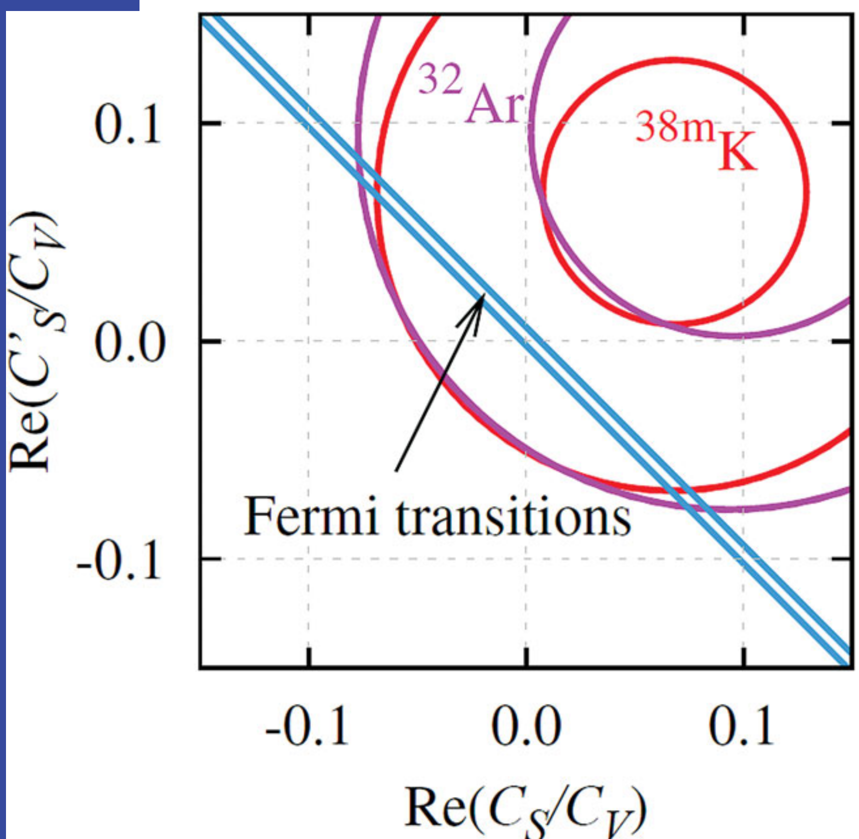
	$[c_{\ell q}^{(3)}]_{1111}$	$[c_{\ell q}]_{1111}$	$[c_{\ell u}]_{1111}$	$[c_{\ell d}]_{1111}$	$[c_{eq}]_{1111}$	$[c_{eu}]_{1111}$	$[c_{ed}]_{1111}$
CHARM	-80 ± 180	700 ± 1800	370 ± 880	-700 ± 1800	x	x	x
APV	27 ± 19	$\mathbf{1.6 \pm 1.1}$	$\mathbf{3.4 \pm 2.3}$	$\mathbf{3.0 \pm 2.0}$	$\mathbf{-1.6 \pm 1.1}$	$\mathbf{-3.4 \pm 2.3}$	$\mathbf{-3.0 \pm 2.0}$
QWEAK	7.0 ± 12	-2.3 ± 4.0	-3.5 ± 6.0	-7 ± 12	2.3 ± 4.0	3.5 ± 6.0	7 ± 12
PVDIS	-8 ± 12	24 ± 35	38 ± 48	-77 ± 96	-77 ± 96	-12 ± 17	24 ± 35
SAMPLE	-8 ± 45	x	-17 ± 90	17 ± 90	x	-17 ± 90	17 ± 90
β decays	$\mathbf{0.38 \pm 0.28}$	x	x	x	x	x	x
LEP-2	3.5 ± 2.2	-42 ± 28	-21 ± 14	42 ± 28	-18 ± 11	-9.0 ± 5.7	18 ± 11

$\mathrm{LHC}_{1.5}$	$-0.70^{+0.66}_{-0.74}$	$2.5^{+1.9}_{-2.5}$	$2.9^{+2.4}_{-2.9}$	$-1.6^{+3.4}_{-3.0}$	$1.6^{+1.8}_{-2.2}$	$1.6^{+2.5}_{-1.5}$	$-3.1^{+3.6}_{-3.0}$
$\mathrm{LHC}_{1.0}$	$-0.84^{+0.85}_{-0.92}$	$3.6^{+3.6}_{-3.7}$	$4.4^{+4.4}_{-4.7}$	$-2.4^{+4.8}_{-4.7}$	$2.4^{+3.0}_{-3.2}$	$1.9^{+2.5}_{-1.9}$	$-4.6^{+5.4}_{-4.1}$
$\mathrm{LHC}_{0.7}$	$-1.0^{+1.4}_{-1.5}$	5.9 ± 7.2	7.4 ± 9.0	-3.6 ± 8.7	3.8 ± 5.9	$2.1^{+3.8}_{-2.9}$	-8 ± 10

[Falkowski, MGA & Mimouni, 2017]

BACKUP

scalar



tensor