BSM with Single Nuclear Beta Decays

INT—June, 2018

Alejandro Garcia
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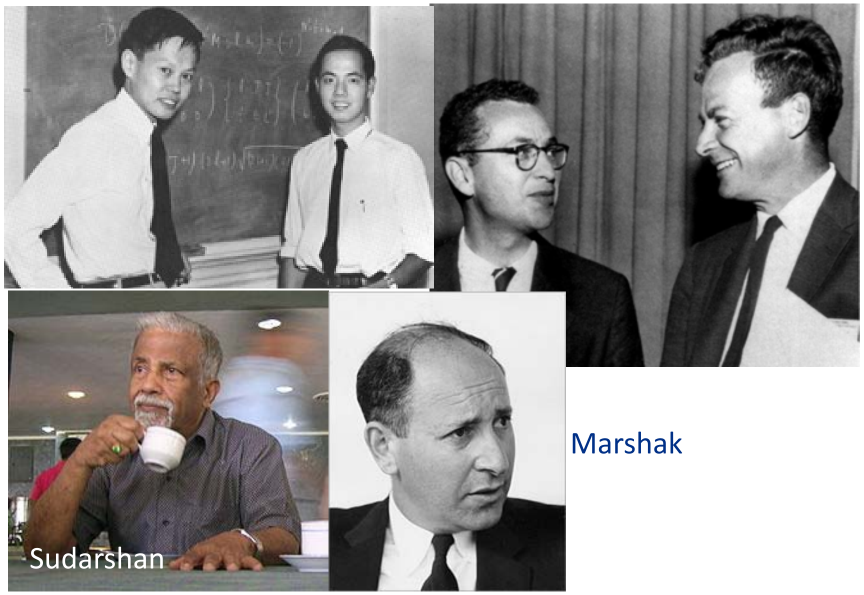
Broken symmetry: charged weak current in SM only sensitive to *L*.

$$\bar{\psi}_e O^\mu \psi_\nu = \bar{\psi}_e^{L}\, \gamma^\mu \psi_\nu^{L}$$

Sorting this out took much effort and ingenuity to come out of confusing times



From “The 7% solution” article in *Surely you are joking, Mr. Feynman!*

When I came back to the United States, I wanted to know what the situation was with beta decay. I went to Professor Wu's laboratory at Columbia, and she wasn't there, spinning to the left in the beta decay, came out on the right in some cases. Nothing fit anything. When I got back to Caltech, I asked some of the experimenters what the situation was with beta decay. I remember three guys, Hans Jensen, Aaldert Wapstra, and Felix Boehm, sitting me down on a little stool, and starting to tell me all these facts: experimental results from other parts of the country, and their own experimental results. Since I knew those guys, and how careful they were, I paid more attention to their results than to the others. Their results, alone, were not so inconsistent; it was all the others plus theirs.

Finally they get all this stuff into me, and they say, "The situation is so mixed up that even some of the things they've established for years are being questioned - such as the beta decay of the neutron is S and T. It's so messed up. Murray says it might even be V and A."

I jump up from the stool and say, "Then I understand EVVVVVERYTHING!"

Nuclear beta decay: beyond *V-A*?

We still like the parametrization of Lee and Yang.

Standard Model

Right-handed

$$H_{V,A} = \sum_{i=V,A} \bar{\Psi}_f \, O_i^{\mu} \Psi_0 \left[(C_i + C_i{}') \, \bar{e}^L \, O_{i,\mu} \nu_e{}^L + (C_i - C_i{}') \, \bar{e}^R O_{i,\mu} \nu_e{}^R \right]$$

$$O_i^{\mu} = \begin{cases} \gamma^{\mu} & i = V \\ \gamma^{\mu}\gamma_5 & i = A \end{cases}$$

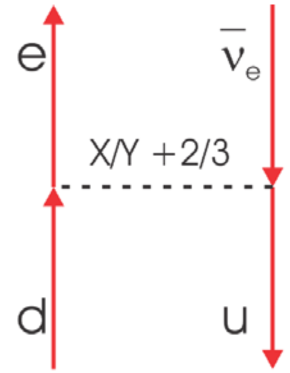
chirality flipping

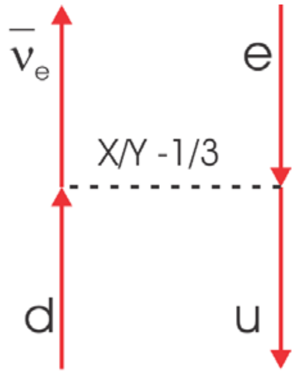
$$H_{S,T} = \sum_{i=S,T} \bar{\Psi}_f \, O_i \;\; \Psi_0 \left[(C_i + C_i{}') \, \bar{e}^R \, O_i \nu_e{}^L + (C_i - C_i{}') \, \bar{e}^L O_i \nu_e{}^R \right]$$

$$O_i = \begin{cases} 1 & i = S \\ \sigma^{\mu\nu} & i = T \end{cases}$$

Modern context: Chirality-flipping as means of detection of new physics.

Small contribution that
could be detected with
precision experiments





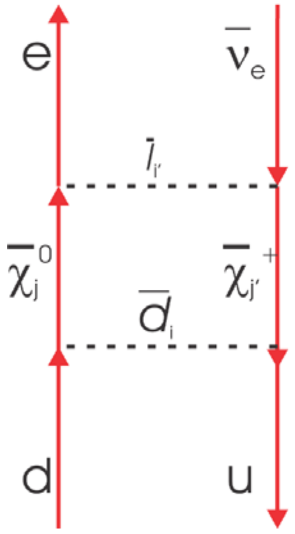
Leptoquarks:
X: scalar; Y: Vector
Predicted by
Grand Unified Theories
Herczeg
RPP **46**, 413 (2001).

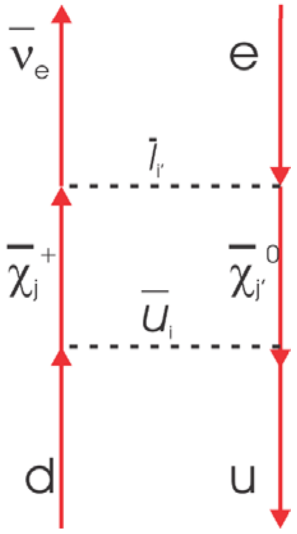
Recent reviews:

Vos, Wilschut, Timmermans,
Rev. Mod. Phys. **87**, 1483 (2015)

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

Gonzalez-Alonso, Naviliat-Cuncic,
Severijns
hep-ph 1803.08732



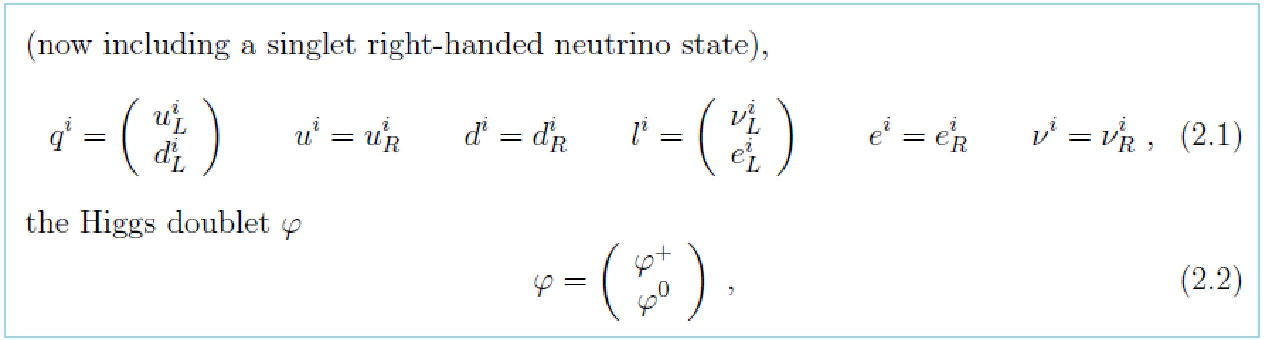


Predicted by
Supersymmetric
Theories
Profumo, Ramsey-Musolf, Tulin
Phys. Rev. D **75**, 075017 (2007)

Likely something not
considered so far…

Modern context: EFT connection to hep.

From Cirigliano, Gonzalez-Alonso, Graesser
J. High Energy Phys. **02,** 046 (2013)



(now including a singlet right-handed neutrino state),

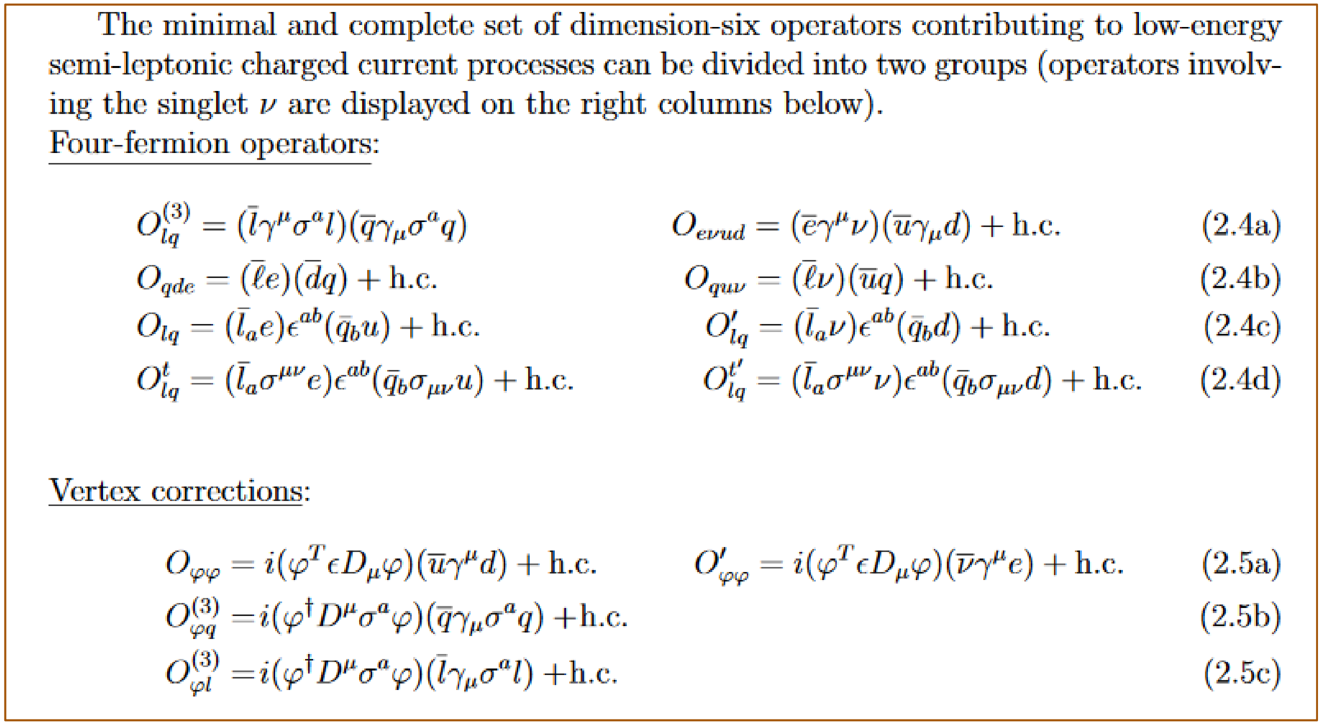
$$q^i = \begin{pmatrix} u^i_L \\ d^i_L \end{pmatrix} \qquad u^i = u^i_R \qquad d^i = d^i_R \qquad l^i = \begin{pmatrix} \nu^i_L \\ e^i_L \end{pmatrix} \qquad e^i = e^i_R \qquad \nu^i = \nu^i_R\,, \tag{2.1}$$

the Higgs doublet φ

$$\varphi = \begin{pmatrix} \varphi^+ \\ \varphi^0 \end{pmatrix}\,, \tag{2.2}$$

Likely something not considered so far…

the fields



The minimal and complete set of dimension-six operators contributing to low-energy semi-leptonic charged current processes can be divided into two groups (operators involving the singlet ν are displayed on the right columns below).

Four-fermion operators:

$$O^{(3)}_{lq} = (\bar{l}\gamma^\mu\sigma^a l)(\bar{q}\gamma_\mu\sigma^a q) \qquad O_{e\nu ud} = (\bar{e}\gamma^\mu\nu)(\bar{u}\gamma_\mu d) + \text{h.c.} \tag{2.4a}$$

$$O_{qde} = (\bar{\ell}e)(\bar{d}q) + \text{h.c.} \qquad O_{qu\nu} = (\bar{\ell}\nu)(\bar{u}q) + \text{h.c.} \tag{2.4b}$$

$$O_{lq} = (\bar{l}_a e)\epsilon^{ab}(\bar{q}_b u) + \text{h.c.} \qquad O'_{lq} = (\bar{l}_a \nu)\epsilon^{ab}(\bar{q}_b d) + \text{h.c.} \tag{2.4c}$$

$$O^t_{lq} = (\bar{l}_a\sigma^{\mu\nu}e)\epsilon^{ab}(\bar{q}_b\sigma_{\mu\nu}u) + \text{h.c.} \qquad O^{t\prime}_{lq} = (\bar{l}_a\sigma^{\mu\nu}\nu)\epsilon^{ab}(\bar{q}_b\sigma_{\mu\nu}d) + \text{h.c.} \tag{2.4d}$$

Vertex corrections:

$$O_{\varphi\varphi} = i(\varphi^T\epsilon D_\mu\varphi)(\bar{u}\gamma^\mu d) + \text{h.c.} \qquad O'_{\varphi\varphi} = i(\varphi^T\epsilon D_\mu\varphi)(\bar{\nu}\gamma^\mu e) + \text{h.c.} \tag{2.5a}$$

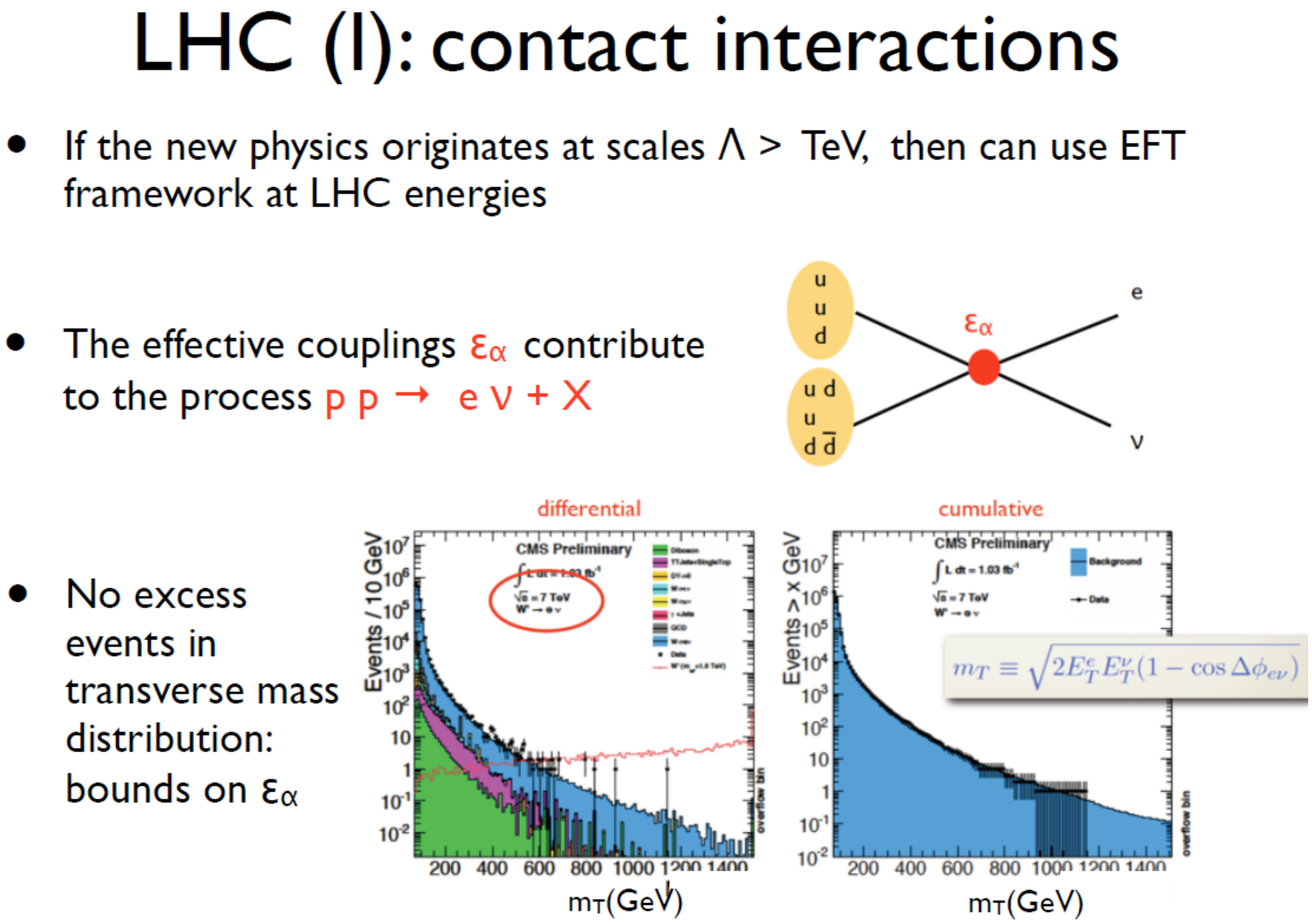
$$O^{(3)}_{\varphi q} = i(\varphi^\dagger D^\mu\sigma^a\varphi)(\bar{q}\gamma_\mu\sigma^a q) + \text{h.c.} \tag{2.5b}$$

$$O^{(3)}_{\varphi l} = i(\varphi^\dagger D^\mu\sigma^a\varphi)(\bar{l}\gamma_\mu\sigma^a l) + \text{h.c.} \tag{2.5c}$$

the d=6 ops.

Connection to LHC data via EFT calculations

Cirigliano et al.
PPNP **71**, 93 (2013)



LHC (I): contact interactions

- If the new physics originates at scales Λ > TeV, then can use EFT framework at LHC energies
- The effective couplings ε_α contribute to the process $p\,p \rightarrow e\,\nu + X$
- No excess events in transverse mass distribution: bounds on ε_α

$m_T \equiv \sqrt{2E_T^e E_T^\nu(1-\cos\Delta\phi_{e\nu})}$

Nuclear beta decay: beyond *V-A*?

Great progress in lattice evaluation of the nucleon form factors, so we can translate.

$$C_i = \frac{G_F}{\sqrt{2}} V_{ud} \bar{C}_i$$

$$\bar{C}_V = g_V (1 + \epsilon_L + \epsilon_R)$$

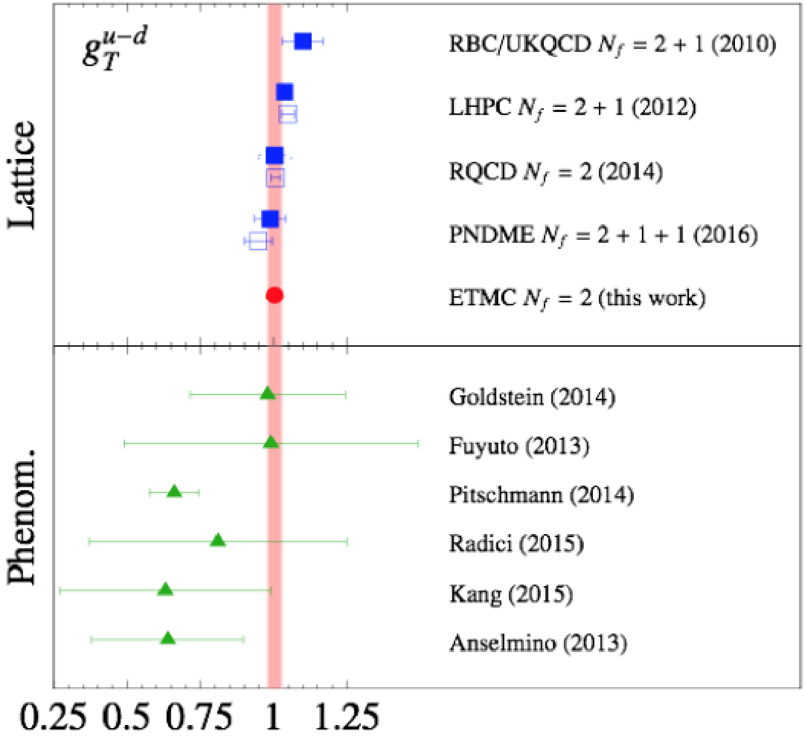
$$\bar{C}_A = -g_A (1 + \epsilon_L - \epsilon_R)$$

$$\bar{C}_S = g_S \epsilon_S$$

$$\bar{C}_T = 4 g_T \epsilon_T,$$

Charge	Value	Ref.
g_A	1.278(33)	[33]
g_T	0.987(55)	[32]
g_S	1.02(11)	[24]
g_P	349(9)	[24]

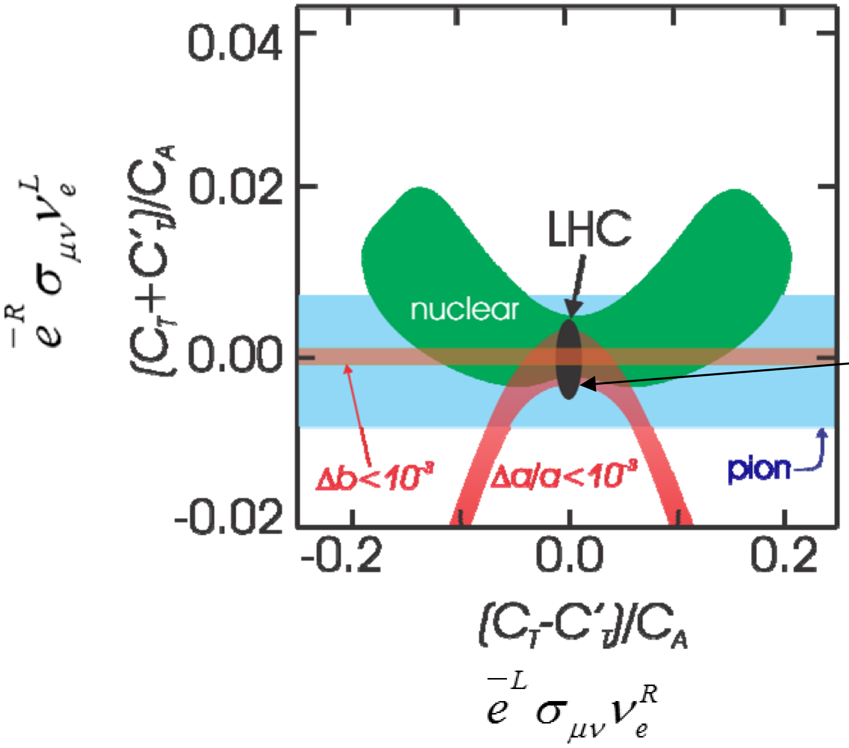
From Gonzalez-Alonso et al. arXiv:1803.08732v1



Precision beta decay versus others:
Can “precision” compete with “energy”?

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

Answer: yes, but to compete with LHC need sensitivity $\frac{C_T}{C_A} \lesssim 6 \times 10^{-3}$



F. Wauters et al.
PRC **89**, 025501
(2014)

Best limits now from LHC
PRD **94**, 054508 (2016)

Nuclear beta decay: Fierz interference and other correlations

Example for axial decay of unpolarized parent

Standard Model

chirality flipping

$$H_A = \bar{\Psi}_f \gamma^\mu \gamma_5 \Psi_0 \left[(2C_A)\, \bar{e}^L \gamma_\mu \gamma_5\, \nu_e{}^L\right] +$$

$$\bar{\Psi}_f\, \sigma^{\mu\nu}\, \Psi_0 \left[(C_T + C_T{}')\, \bar{e}^R \sigma_{\mu\nu} \nu_e{}^L + (C_T - C_T{}')\, \bar{e}^L \sigma_{\mu\nu} \nu_e{}^R\right]$$

Decay rate:

$$dw \approx dw_0 \left(1 + b\,\frac{m}{E_e} + a\,\frac{\vec{p}_e}{E_e} \cdot \frac{\vec{p}_\nu}{E_\nu}\right)$$

$$a \approx -\frac{1}{3}\left(1 - \frac{C_T^2 + C'^2_T}{2\, C_A^2}\right)$$

β-ν correlation

$$b \approx \pm(C_T + C_T{}')/C_A$$

Fierz interference

Fierz interference has highest sensitivity.

$$b_F \approx \pm \frac{(C_S + C_{S'})}{C_V}$$

Linear in the small couplings

$$b_{GT} \approx \pm \frac{(C_T + C_{T'})}{C_A}$$

Correlation experiments measure the ratio of "the red" to "the blue":

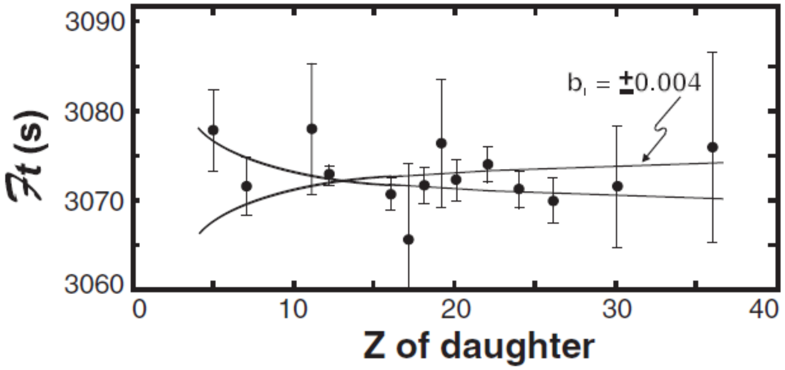
$$dw \approx dw_0 \left(1 + b\,\frac{m}{E_e} + a\,\frac{\vec{p}_e}{E_e} \cdot \frac{\vec{p}_\nu}{E_\nu} \right)$$

Even without explicitly detecting E_e there is sensitivity to b. But the sensitivity is decreased by the $\frac{m}{E_e}$ factor.

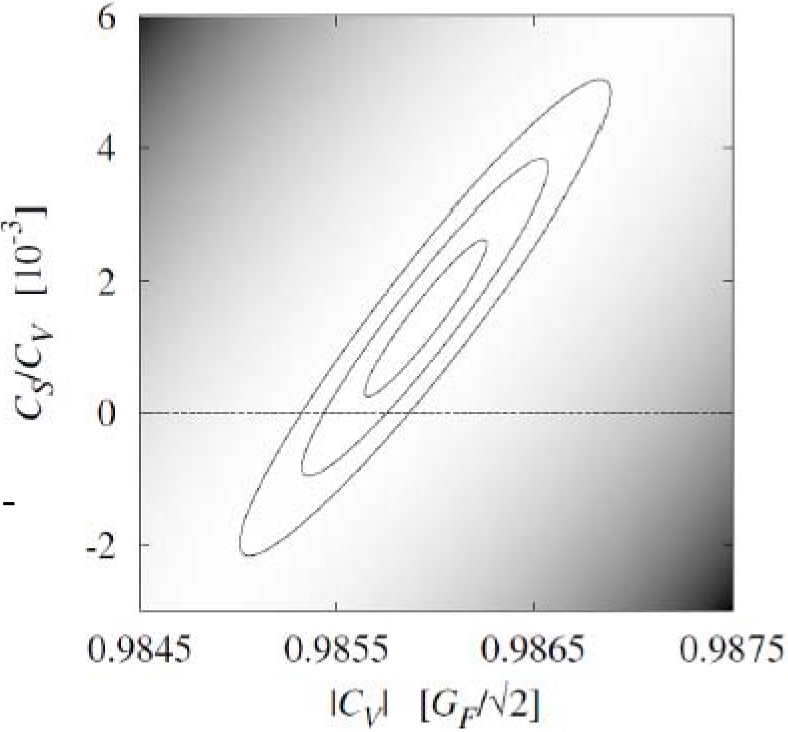
Best limits on scalar currents from $0^+ \rightarrow 0^+$ ft values

Hardy and Towner

PHYSICAL REVIEW C **91**, 025501 (2015)



$$dw \approx dw_0 \left(1 + b\,\frac{m}{E_e} + a\,\frac{\vec{p}_e}{E_e}\cdot\frac{\vec{p}_\nu}{E_\nu}\right)$$



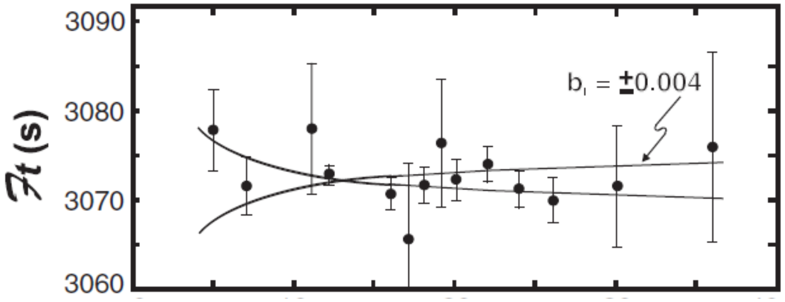
Gonzalez-Alonso, Naviliat-Cuncic, Severijns
hep-ph 1803.08732

Best limits on scalar currents from $0^+ \to 0^+$ ft values

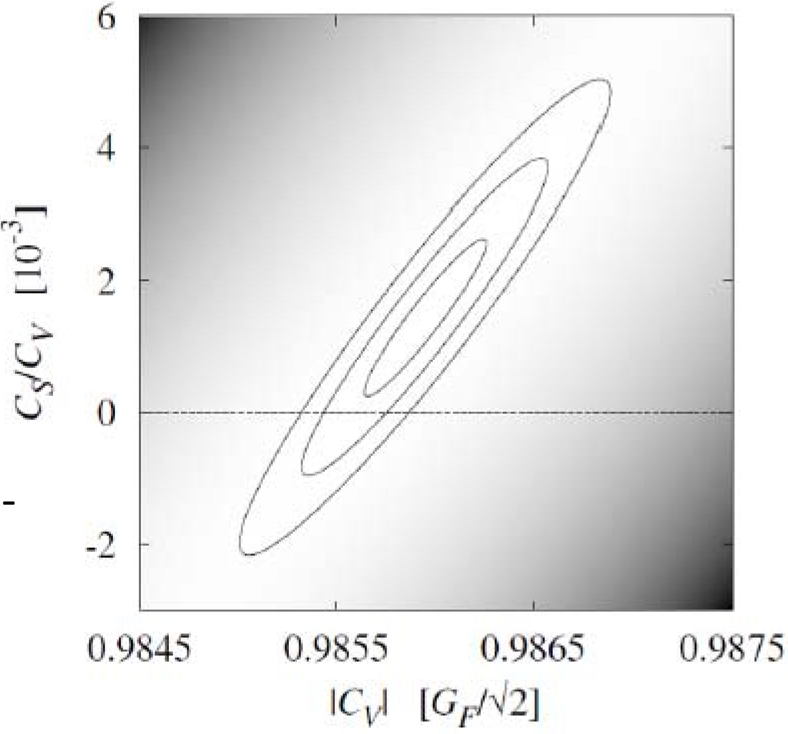
Hardy and Towner

PHYSICAL REVIEW C **91**, 025501 (2015)

$$\boxed{dw \approx dw_0 \left(1 + b\,\frac{m}{E_e} + a\,\frac{\vec{p}_e}{E_e}\cdot\frac{\vec{p}_\nu}{E_\nu}\right)}$$



This “source of uncertainty” is usually neglected when extracting V_{ud}



Gonzalez-Alonso, Naviliat-Cuncic, Severijns
hep-ph 1803.08732

Precision β decay: many ongoing experimental efforts.

- Neutron decay:
  - aCORN (little-a)
  - Nab (little-a, little-b)
  - UCNA (little-a, little-b, A)
  - PERKEO (A)
  - PERC (little-a , little-b)
- ^{6}He and Ne isotopes little-a; ^{16}N first forbidden decay spectrum at SARAF, Israel
- ^{6}He and ^{20}F little-b at MSU
- ^{8}Li little-a at Israel-MIT
- ^{8}Li-^{8}B little-a at ANL
- little-a, little-b, A, B with trapped ^{37}K, ^{38}K at TRIUMF
- ^{6}He little-a; ^{6}He, ^{14}O, ^{19}Ne, little-b at Seattle

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- ^{6}He little-a; ^{6}He, ^{14}O, ^{19}Ne, little-b at Seattle

But I will concentrate only on a couple of little-b measurements

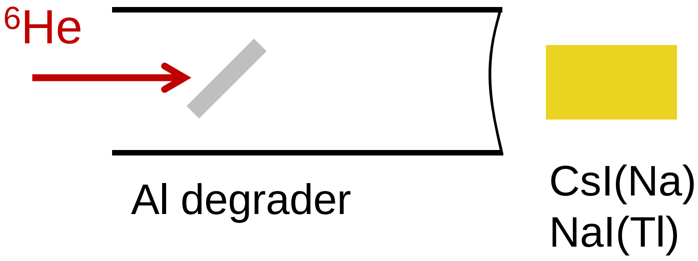
Beta spectrometry to directly search for Fierz

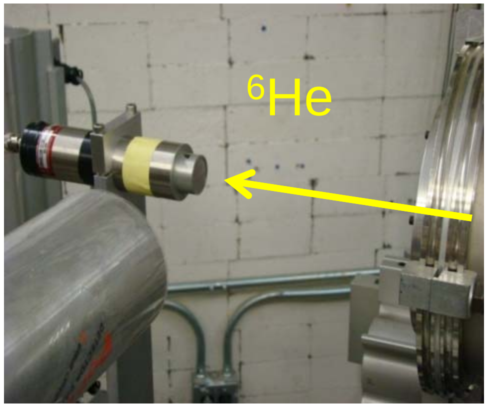
A variety of methods possible for beta spectroscopy:

- Scintillators
- Magnetic spectrometers
- *RxB* drift (PERC, aiming at $\frac{C_T}{C_A} \lesssim 10^{-3}$)
- Si detectors (Nab, aiming at $\frac{C_T}{C_A} \lesssim 10^{-3}$)
- Implantation into scintillators (MSU)
- Cyclotron Radiation

Naviliat-Cuncic et al. at MSU:
Measurement with ^{6}He

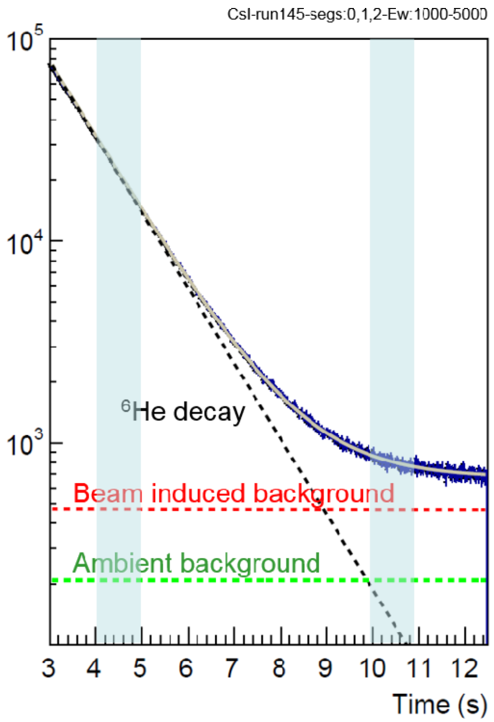
^{6}He beam: 46 MeV/nucleon after degrader



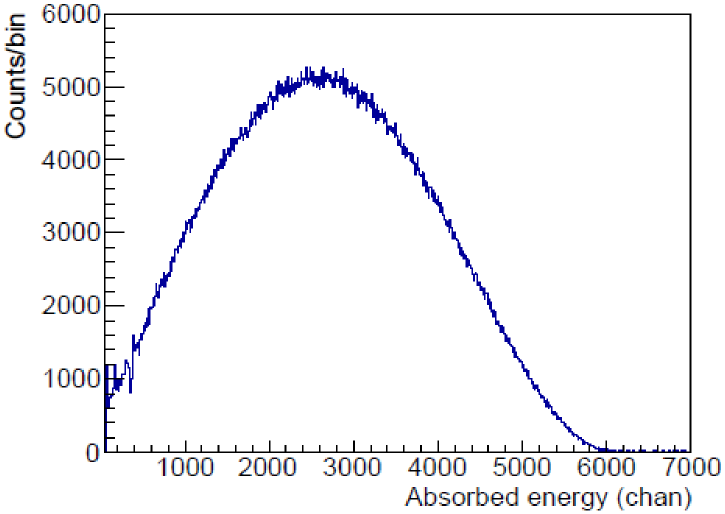


Detectors:

- CsI(Na) (2"×2"×5")
- NaI(Tl) (Ø3"×3")
- (Ø1"×1") CsI(Na)
- (Ø1"×1") NaI(Tl)



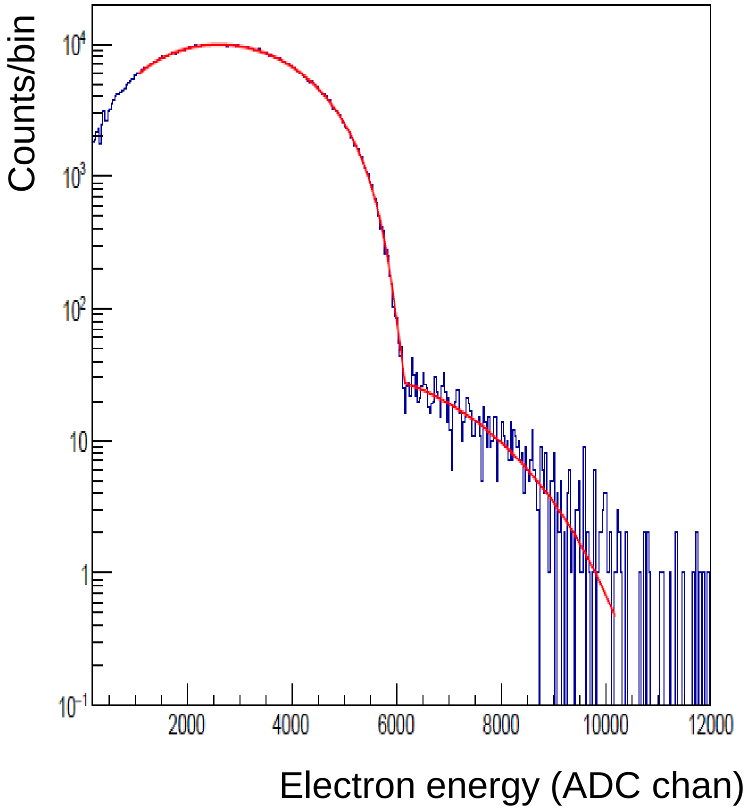
Background subtracted spectrum



MICHIGAN STATE UNIVERSITY

O. Naviliat-Cuncic: naviliat@nscl.msu.edu

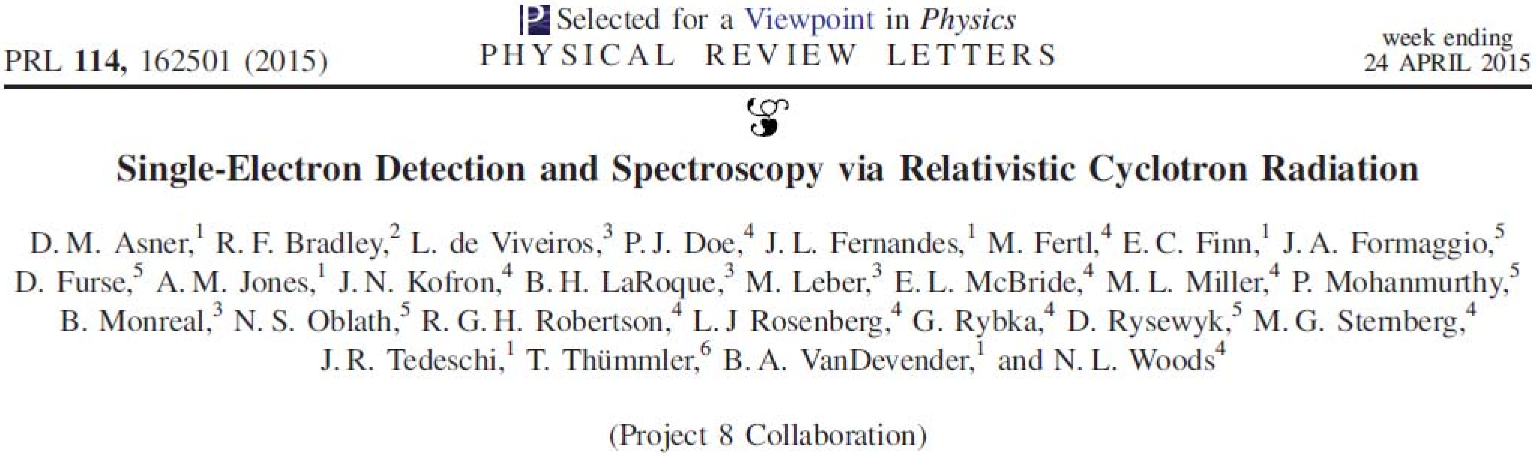
Naviliat-Cuncic et al. at MSU:
Data analysis and status (^{6}He)



- Analysis of spectra by a Monte-Carlo fit.
- Systematic effects associated with difference in Geant-4 for the description of Bremsstrahlung escape has been studied in detail: X. Huyan et al., NIMA **879** (2018) 134
- Calibration and non-linearity effects have been studied by Monte-Carlo: X. Huyan et al., Acta Phys. Pol. B **49** (2018) 249
- The “classical” radiative correction of the β particle energy requires special consideration for a calorimetric technique: X. Huyan et al., in preparation
- For each of the two large sets of collected data, the experiment has reached a statistical precision of:
    - 6% on the Weak Magnetism form factor
    - 2.6×10^{-3} on the Fierz term

MICHIGAN STATE UNIVERSITY

New idea: CRES technique



Selected for a Viewpoint in *Physics*

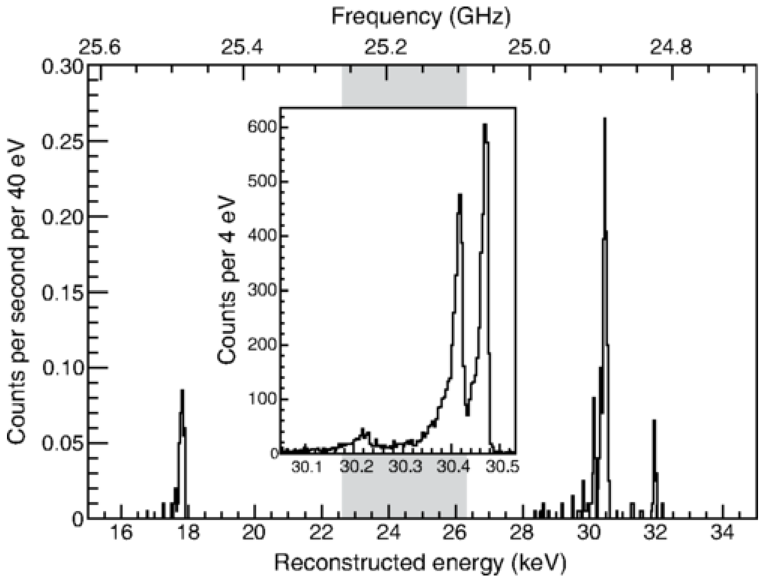
PRL **114,** 162501 (2015) PHYSICAL REVIEW LETTERS week ending 24 APRIL 2015

Single-Electron Detection and Spectroscopy via Relativistic Cyclotron Radiation

D. M. Asner,[1] R. F. Bradley,[2] L. de Viveiros,[3] P. J. Doe,[4] J. L. Fernandes,[1] M. Fertl,[4] E. C. Finn,[1] J. A. Formaggio,[5] D. Furse,[5] A. M. Jones,[1] J. N. Kofron,[4] B. H. LaRoque,[3] M. Leber,[3] E. L. McBride,[4] M. L. Miller,[4] P. Mohanmurthy,[5] B. Monreal,[3] N. S. Oblath,[5] R. G. H. Robertson,[4] L. J Rosenberg,[4] G. Rybka,[4] D. Rysewyk,[5] M. G. Sternberg,[4] J. R. Tedeschi,[1] T. Thümmler,[6] B. A. VanDevender,[1] and N. L. Woods[4]

(Project 8 Collaboration)

Project 8 collaboration gets FWHM/E $\approx 10^{-3}$ resolution for conversion electrons of 18-32 keV.



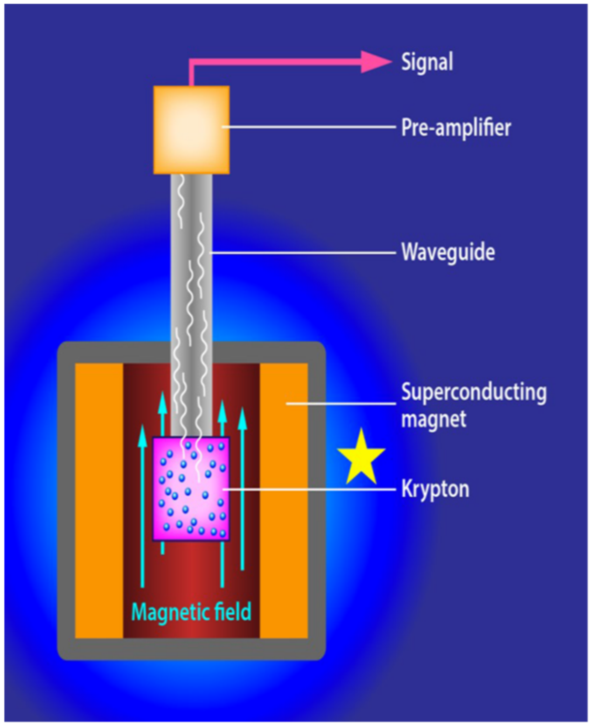
Can the technique be applied to a beta continuum with E_β = 0 – 4 MeV ?

New idea: CRES technique

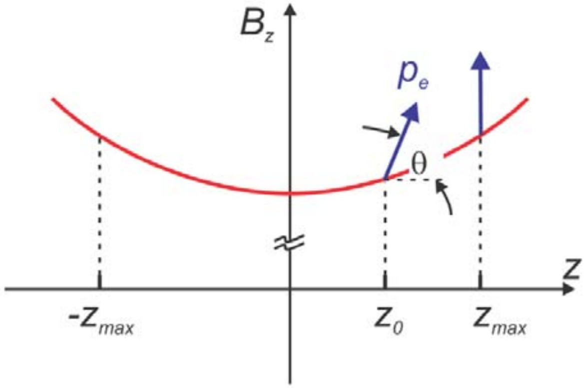
Project 8 (Phase I) in a nutshell

Looking at Tritium decay to get ν mass. Electrons emitted in an RF guide within an axial *B* field. Antenna at end detects cyclotron radiation.

$$\omega = \frac{qB}{E}$$



Electrons of ~ 30 keV from a gaseous source were let to decay within a 1 Tesla field with additional coils to set up a *magnetic trap*:



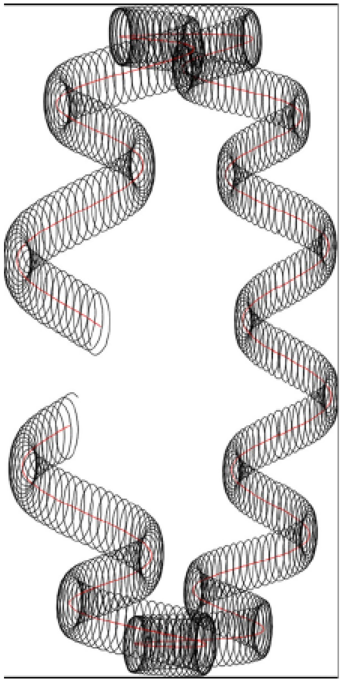
Longitudinal comp. of momentum decreases as *B* increases up to return point, z_{max}. Axial oscillations with ω_z.

New idea: CRES technique

Some details

Motion can be thought off as cyclotron orbits, axial oscillations and magnetron motion.

$$\omega_c : \omega_z : \omega_{mag} =$$
$$\sim 1 : 4 \times 10^{-3} : 2 \times 10^{-5}$$



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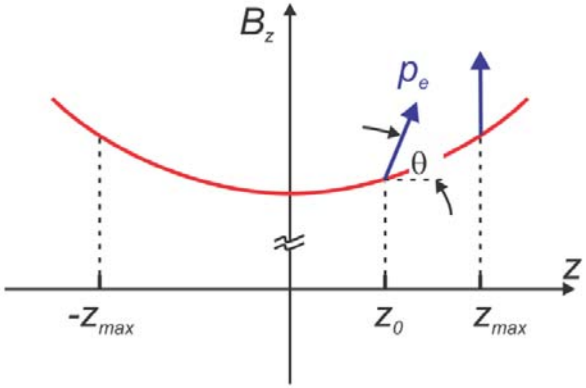

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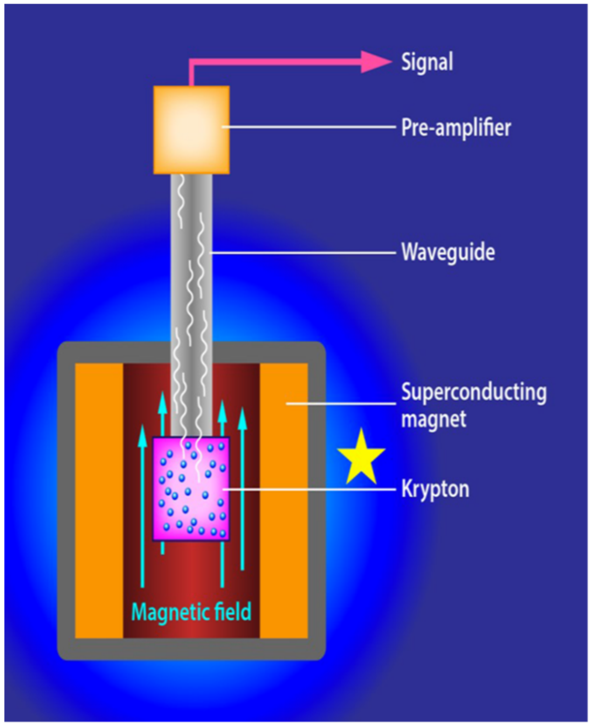
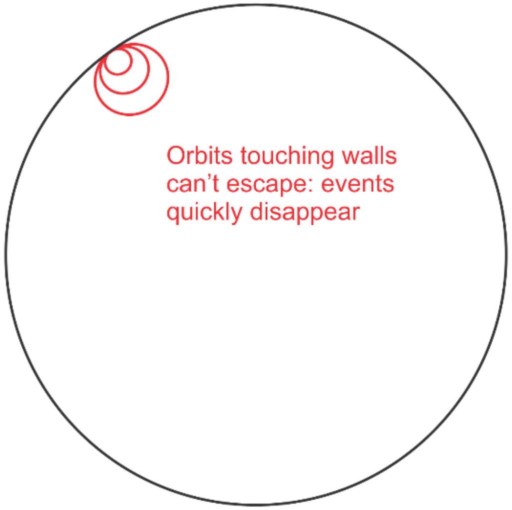


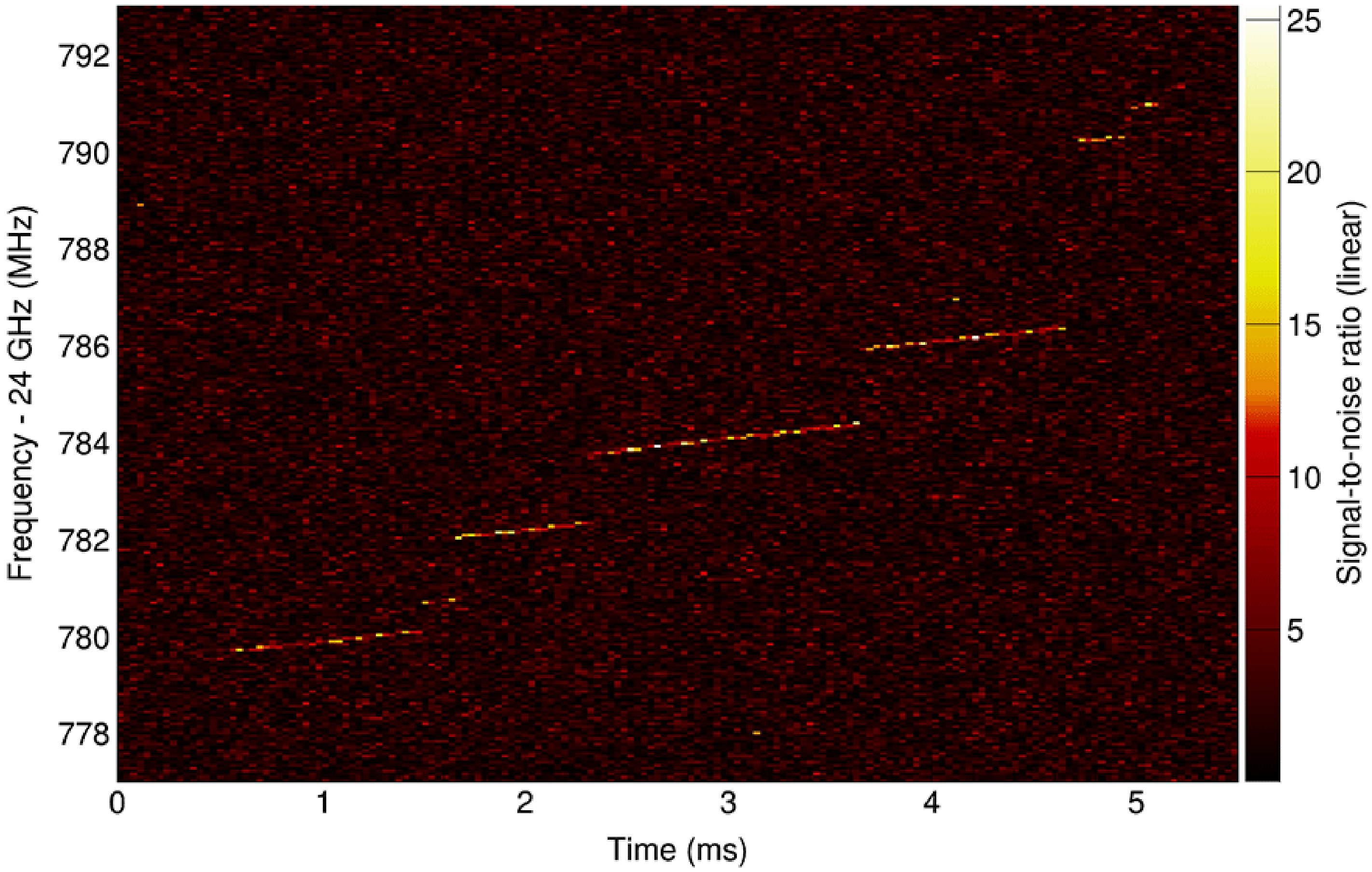
Advantage

Electrons hitting walls quickly (<1 ns) loose energy and disappear.
No signal from these



For the same reason: background radiation hitting walls does not generate signals.

Project-8 data



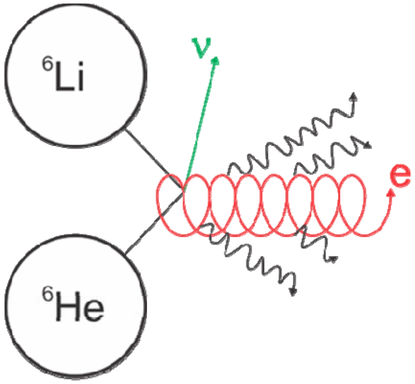
$$\omega = \frac{qB}{E}$$

Power from a single electron orbiting in a magnetic field versus time and the frequency of the electron's orbit. The straight streaks correspond to the electron losing energy (and orbiting faster) as it radiates. The jumps correspond to the loss of energy when the electron collides with an atom or molecule.
[Asner et al. [PRL **114,** 162501]

Emerging ^{6}He little-*b* collaboration

W. Byron[1], M. Fertl[1], A. Garcia[1], G. Garvey[1], B. Graner[1], B. Graner[1], M. Guigue[4], D. Hertzog[1], K.S. Khaw[1], P. Kammel[1], A. Leredde[2], P. Mueller[2], N. Oblath[4], R.G.H. Robertson[1], G. Rybka[1], G. Savard[2], D. Stancil[3], H.E. Swanson[1], B.A. Vandeevender[4], F. Wietfeldt[5], A. Young[3]

[1]*University of Washington,*
[2]*Argonne National Lab,*
[3]*North Carolina State University,*
[4]*Pacific Northwest National Laboratory*
[5]Tulane University

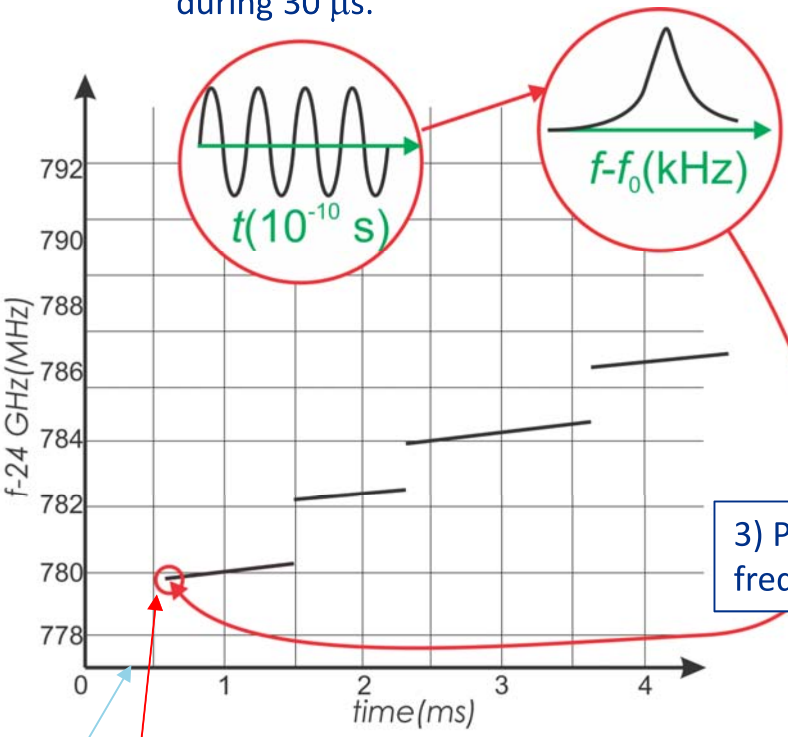


- **Goals:**
  - measure "little *b*" to better than 10^{-3} in ^{6}He.
  - Highest sensitivity to tensor couplings

- **Technique**
  - Use Cyclotron Radiation Emission Spectroscopy. Similar to Project 8 setup for tritium decay.
  - Need to extend the technique to higher energy betas and to a precision determination of a continuum spectrum.

Advantages of the CRES technique

- **Measures beta energy at creation, before complicated energy-loss mechanisms.**
- High resolution allows debugging of systematic uncertainties.
- Room photon or e scattering does not yield background.
- 6He in gaseous form works well with the technique.
- 6He ion-trap (shown by others to work) allows sensitivity higher than any other proposed.
- Counts needed not a big demand on running time.



1) Take a wave during 30 μs.

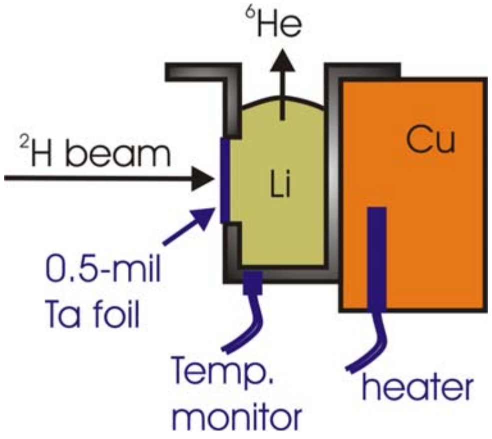
2) Fourier analysis.

3) Plot peak frequency.

Initial frequency → *E*

$$\omega = \frac{qB}{E}$$

Time bins ~ 30 μs.



^{6}He source at Seattle

10^{10} ^{6}He/s in clean lab in a stable fashion.

Statistics

compare decay densities to neutron sources

UCN: 10^3 UCN/cc → ≈ 1 (decay/s)/cc
CN: 10^{10} CN/s cm2 →2×10^5 CN/cc ≈ 10^2 (decay/s)/cc
^{6}He: ≈ 10^6 (decay/s)/cc

6HeCRES at Seattle

Phase I: proof of principle

2 GHz bandwidth.

Show detection of cycl. radiation from 6He.

Study power distribution.

Mission for next three years

Phase II: first measurement ($b < 10^{-3}$)

6 GHz bandwidth.

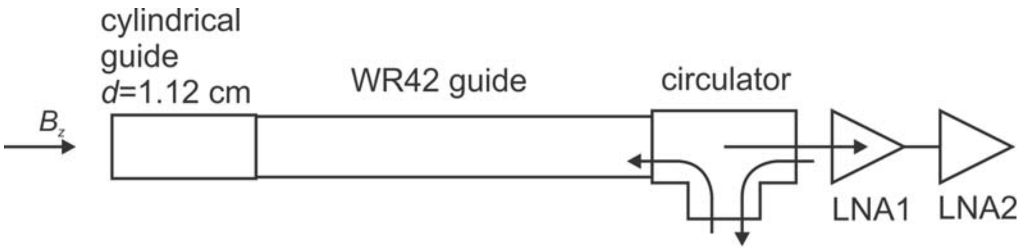
6He and 19Ne measurements.

Phase III: ultimate measurement ($b < 10^{-4}$)

ion-trap for no limitation from geometric effect.

Attached to FRIB would measure spectra from any nucleus.

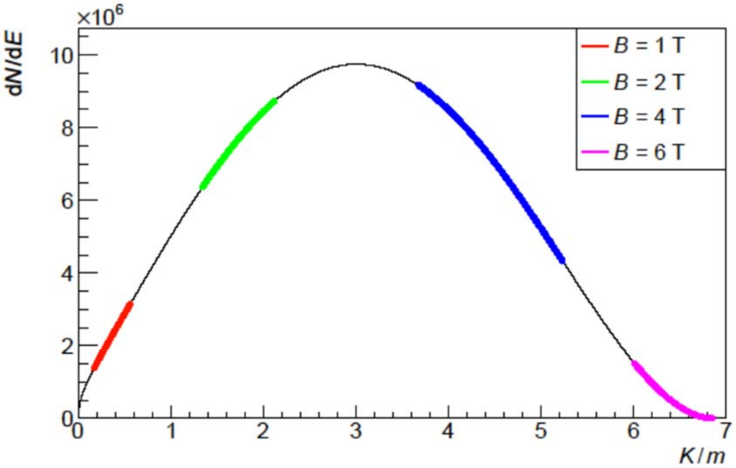
^{6}He little-*b* measurement at Seattle



Stage	Rate (1/s)
Incoming atoms	2×10^9
Decays within trap	1×10^6
Trapped betas	3×10^4
Trapped betas (not hitting walls)	1×10^4
Events observed within frequency window	1×10^3

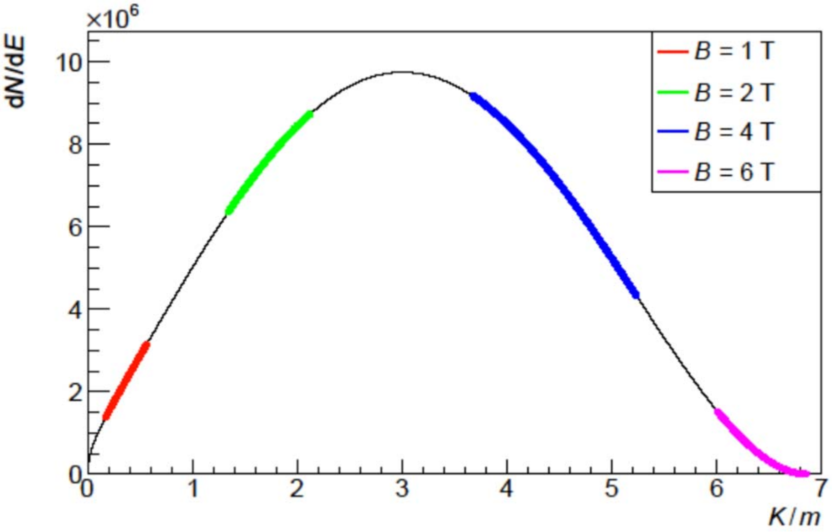
Frequency band: *f*=18-24 GHz.

Monte Carlo simulation of observation in
Few days of running

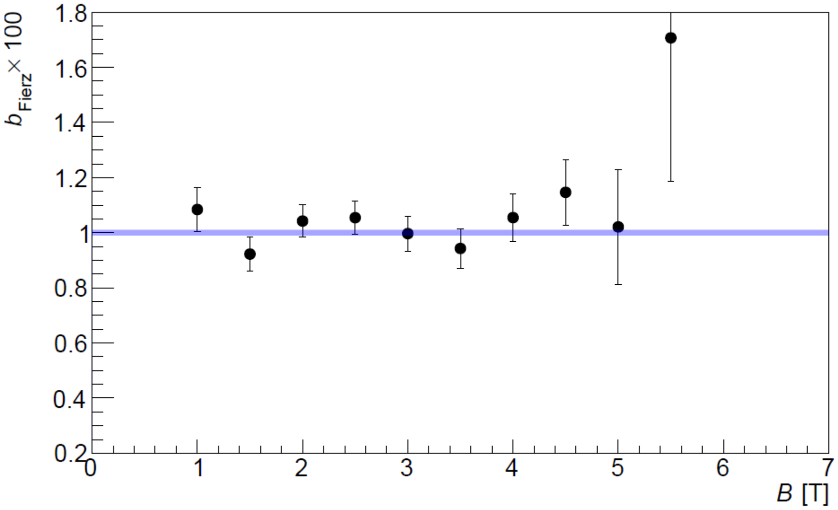


^{6}He little-*b* measurement at Seattle

Monte Carlo simulation of observation in
Few days of running

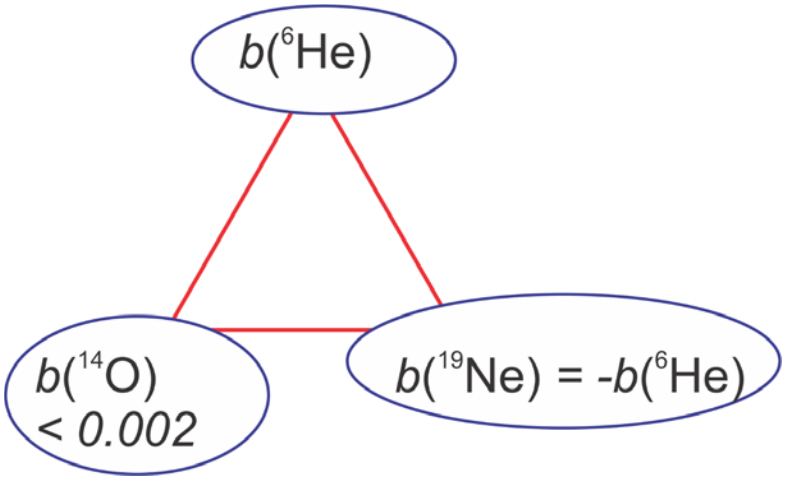


Extracting little *b* vs. *B* field
Few days of running each point
(assumed b_{MC} = 0.01)



^{6}He little-*b* measurement at Seattle

Check on signature by measuring ^{14}O and ^{19}Ne:



$b(^{6}\mathrm{He})$

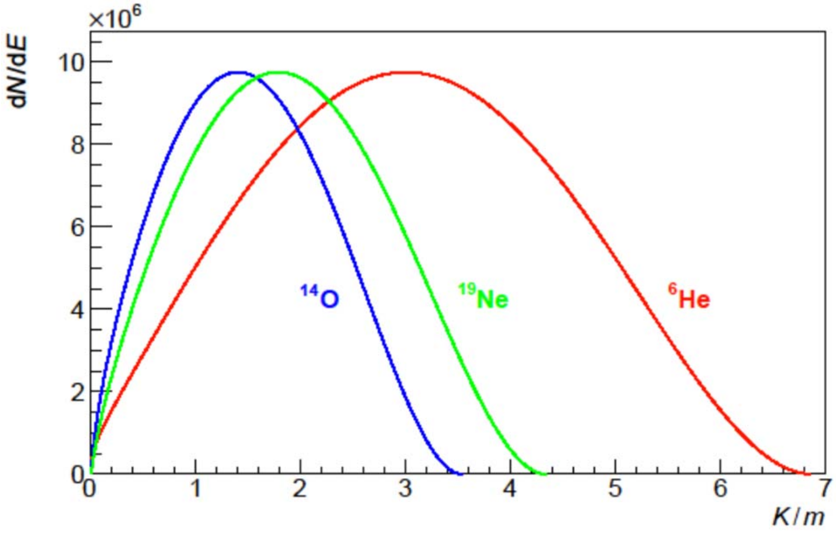
$b(^{14}\mathrm{O})$ < 0.002

$b(^{19}\mathrm{Ne}) = -b(^{6}\mathrm{He})$

Both ^{14}O and ^{19}Ne can be produced in similar quantities as ^{6}He at CENPA.

^{14}O as CO (T_{freeze} = 68 K) Previous work at Louvain and TRIUMF.

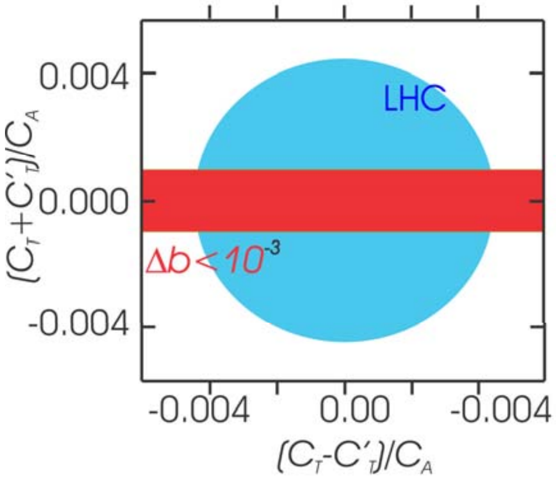
^{19}Ne source developed at Princeton appropriate.



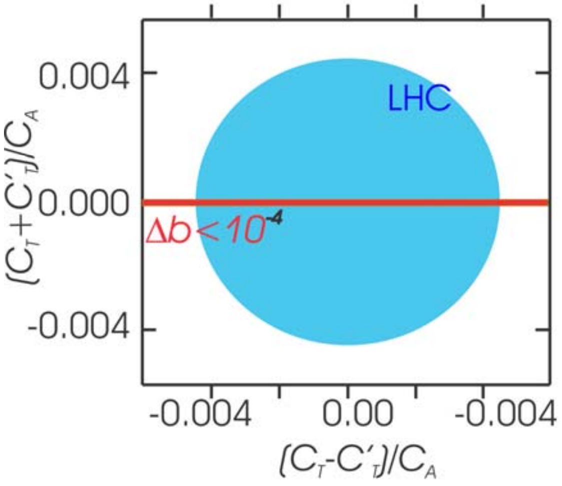
Potential reach (Monte Carlo simulations)

Phase III:
Future development,
couple to an ion trap

Effect	Δb No trap	Ion trap
Magnetic field uncertainties	10^{-4}	$< 10^{-4}$
Wall effect uncertainties	10^{-3}	
RF pickup uncertainties	10^{-4}	10^{-5}
Misidentification of events	10^{-4}	5×10^{-5}



Phase II



Applications: coupling CRES with radioactive ion trap. Benchmarks for nuclear structure and 2b decays

2β decays depend on $(g_A)^4$: can one determine g_{A} versus A?

Suhonen et al. suggest extracting g_{A} using forbidden decays (PRC **96**, 024317 (2017)).

CRES technique coupled to an ion trap with FRIB would allow for systematically measuring a broad range of spectra.

JOEL KOSTENSALO AND JOUNI SUHONEN

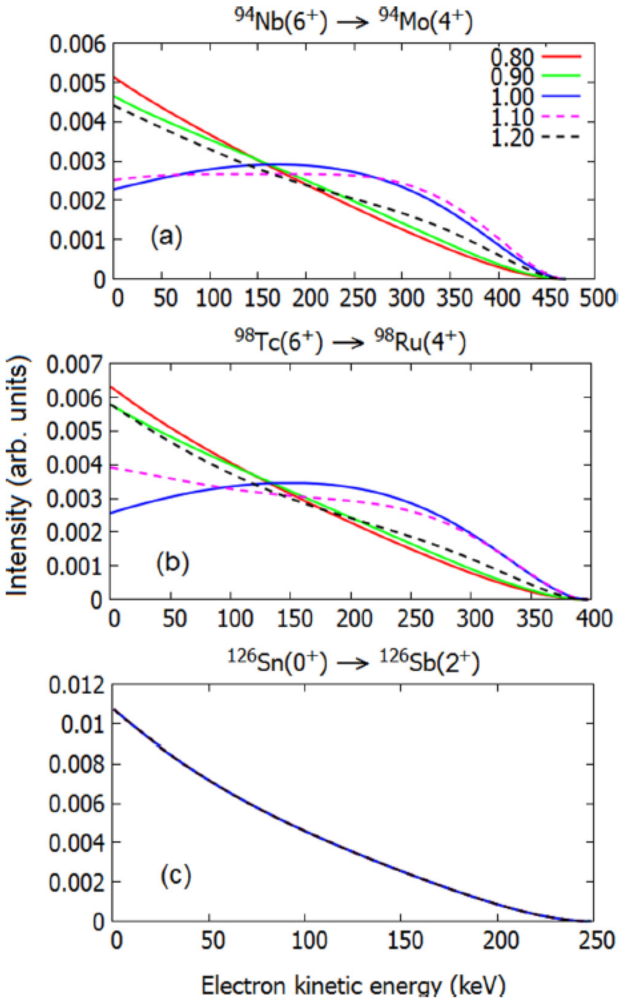


FIG. 2. Same as Fig. 1 but for the second-forbidden nonunique decays of ^{94}Nb [panel (a)], ^{98}Tc [panel (b)], and ^{126}Sn [panel (c)].

Applications: coupling CRES with radioactive ion trap.
Benchmarks for nuclear structure and 2b decays

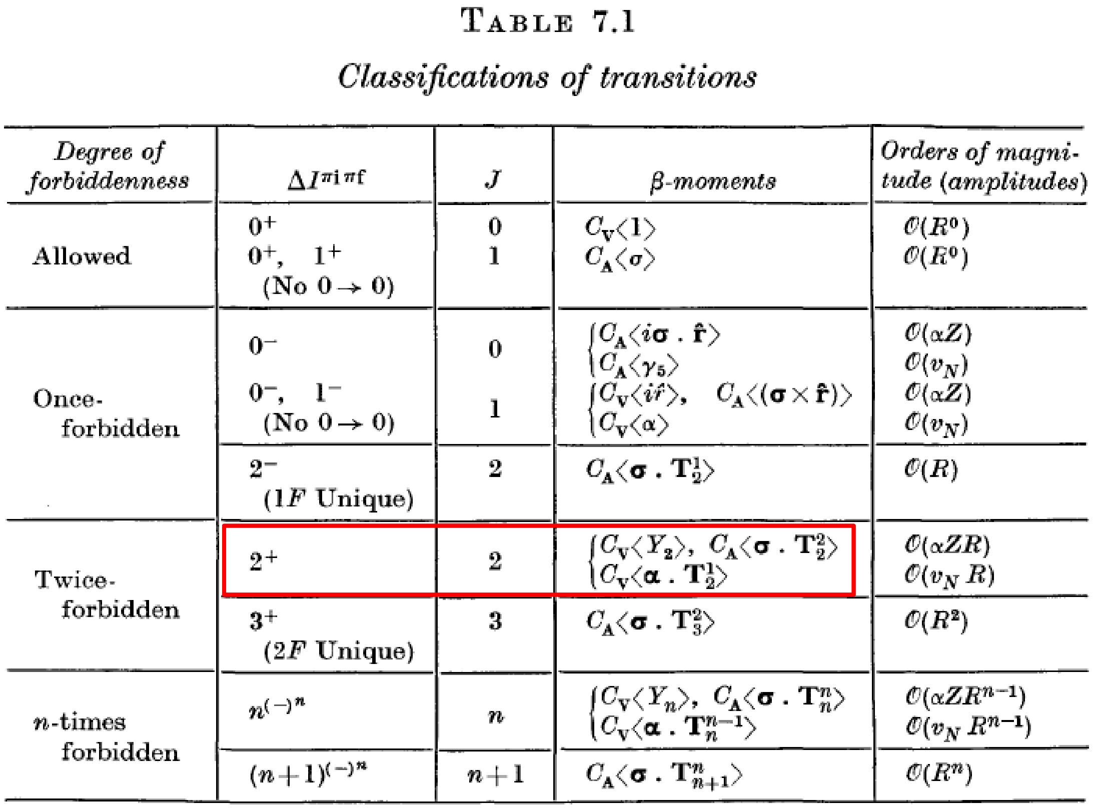


TABLE 7.1

Classifications of transitions

Degree of forbiddenness	$\Delta I^{\pi_i \pi_f}$	J	*β-moments*	*Orders of magnitude (amplitudes)*
Allowed	0^+	0	$C_V\langle 1\rangle$	$\mathcal{O}(R^0)$
	$0^+,\quad 1^+$ (No $0\rightarrow 0$)	1	$C_A\langle \sigma\rangle$	$\mathcal{O}(R^0)$
Once-forbidden	0^-	0	$\begin{cases} C_A\langle i\boldsymbol{\sigma}\,.\,\hat{\mathbf{r}}\rangle \\ C_A\langle \gamma_5\rangle \end{cases}$	$\mathcal{O}(\alpha Z)$ $\mathcal{O}(v_N)$
	$0^-,\quad 1^-$ (No $0\rightarrow 0$)	1	$\begin{cases} C_V\langle i\mathbf{r}\rangle, \quad C_A\langle(\boldsymbol{\sigma}\times\hat{\mathbf{r}})\rangle \\ C_V\langle \alpha\rangle \end{cases}$	$\mathcal{O}(\alpha Z)$ $\mathcal{O}(v_N)$
	2^- ($1F$ Unique)	2	$C_A\langle\boldsymbol{\sigma}\,.\,\mathbf{T}_2^1\rangle$	$\mathcal{O}(R)$
Twice-forbidden	2^+	2	$\begin{cases} C_V\langle Y_2\rangle, \; C_A\langle\boldsymbol{\sigma}\,.\,\mathbf{T}_2^2\rangle \\ C_V\langle\boldsymbol{\alpha}\,.\,\mathbf{T}_2^1\rangle \end{cases}$	$\mathcal{O}(\alpha ZR)$ $\mathcal{O}(v_N R)$
	3^+ ($2F$ Unique)	3	$C_A\langle\boldsymbol{\sigma}\,.\,\mathbf{T}_3^2\rangle$	$\mathcal{O}(R^2)$
n-times forbidden	$n^{(-)^n}$	n	$\begin{cases} C_V\langle Y_n\rangle, \; C_A\langle\boldsymbol{\sigma}\,.\,\mathbf{T}_n^n\rangle \\ C_V\langle\boldsymbol{\alpha}\,.\,\mathbf{T}_n^{n-1}\rangle \end{cases}$	$\mathcal{O}(\alpha ZR^{n-1})$ $\mathcal{O}(v_N R^{n-1})$
	$(n+1)^{(-)^n}$	$n+1$	$C_A\langle\boldsymbol{\sigma}\,.\,\mathbf{T}_{n+1}^n\rangle$	$\mathcal{O}(R^n)$

JOEL KOSTENSALO AND JOUNI SUHONEN

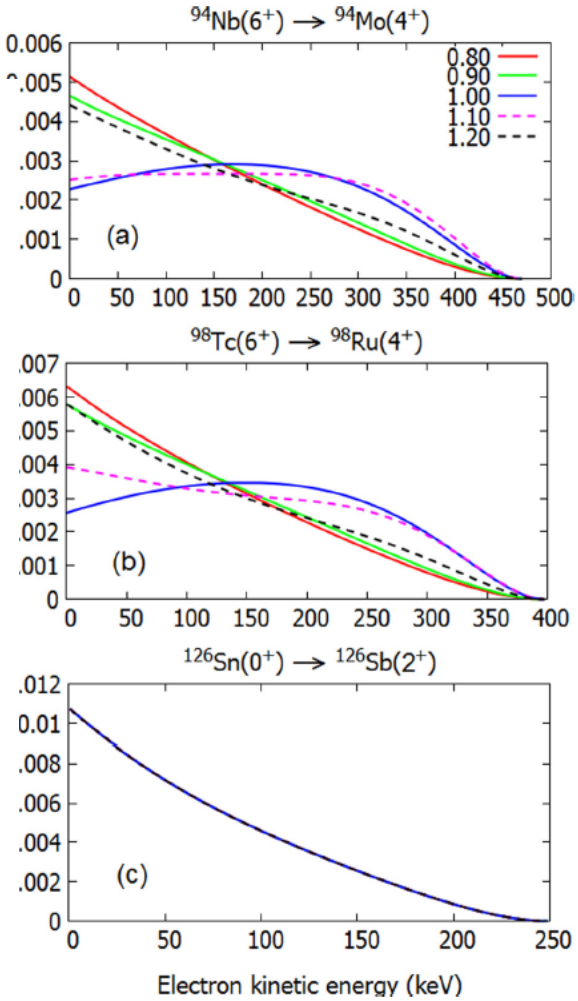
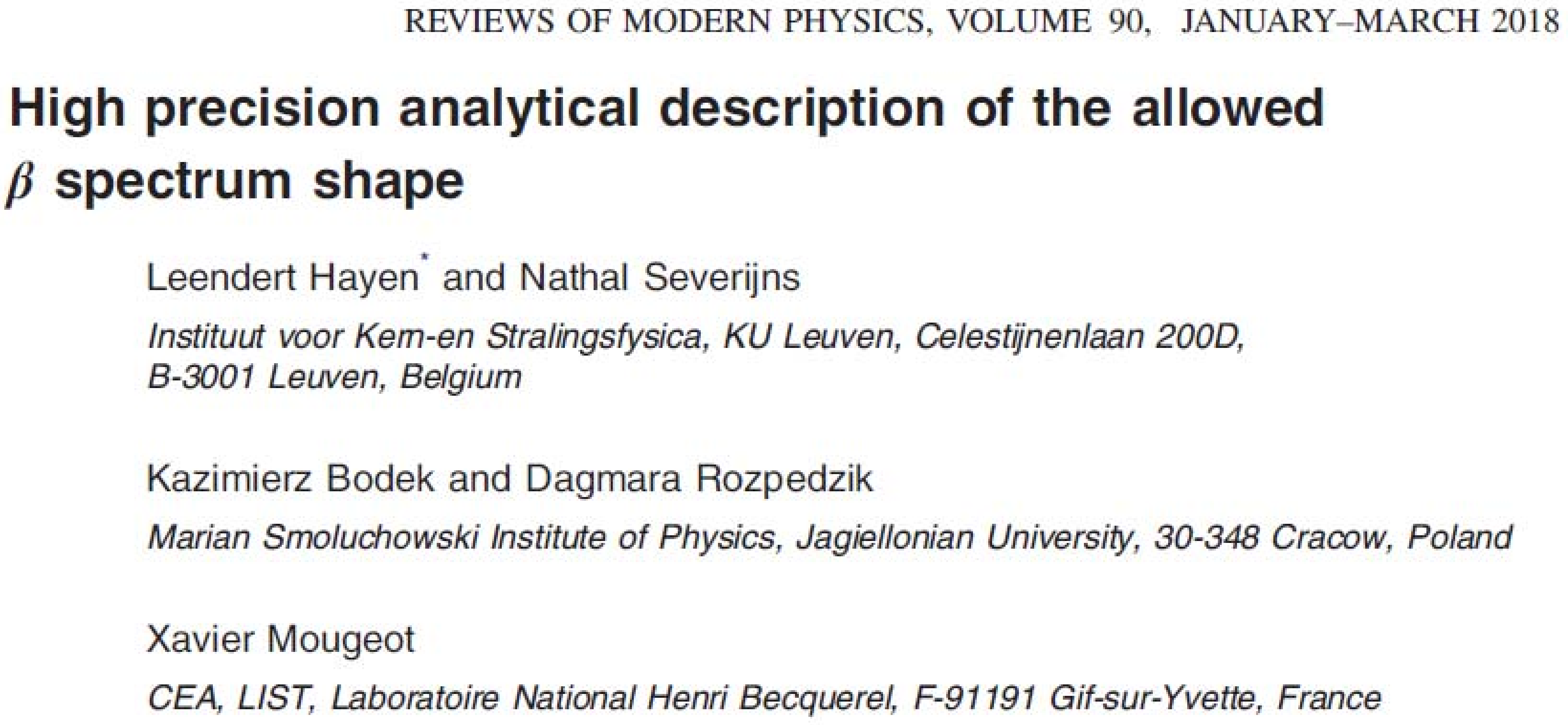


FIG. 2. Same as Fig. 1 but for the second-forbidden nonunique decays of ^{94}Nb [panel (a)], ^{98}Tc [panel (b)], and ^{126}Sn [panel (c)].

Back to BSM: Is theory on good grounds?

Recent article summarizing our present methods:
claims good to $few \times 10^{-4}$



REVIEWS OF MODERN PHYSICS, VOLUME 90, JANUARY–MARCH 2018

High precision analytical description of the allowed β spectrum shape

Leendert Hayen[*] and Nathal Severijns

Instituut voor Kern-en Stralingsfysica, KU Leuven, Celestijnenlaan 200D,
B-3001 Leuven, Belgium

Kazimierz Bodek and Dagmara Rozpedzik

Marian Smoluchowski Institute of Physics, Jagiellonian University, 30-348 Cracow, Poland

Xavier Mougeot

CEA, LIST, Laboratoire National Henri Becquerel, F-91191 Gif-sur-Yvette, France

Back to BSM: Is theory on good grounds?

Recent article summarizing our present methods: claims good to $few\ \times 10^{-4}$

- **Is this on solid base?**
- **Can we go 1 order of magnitude beyond?**

H 2018

Hi

β spectrum shape

Leendert Hayen* and Nathal Severijns

Instituut voor Kern-en Stralingsfysica, KU Leuven, Celestijnenlaan 200D,
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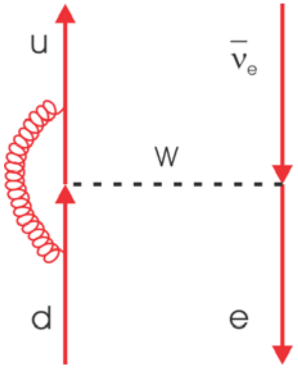
Xavier Mougeot

CEA, LIST, Laboratoire National Henri Becquerel, F-91191 Gif-sur-Yvette, France

Nuclear structure issues to reach $b < 10^{-3}$

Recoil-order corrections and the SM contribution to little *b*



Weak CC nucleon current:

$$\langle p|V^\mu|n\rangle = \langle p|g_V\gamma^\mu + g_{WM}\,\sigma^{\mu\nu}q_\nu|n\rangle$$
$$\langle p|A^\mu|n\rangle = \langle p|g_A\gamma^\mu\gamma_5 + g_P\,q^\mu\gamma_5|n\rangle$$

Dominant factor in recoil-order correction is interference between WM and GT:

$$R(E) \approx R_0\left(2\frac{E}{m} - \frac{E_0}{m} - \frac{m}{E}\right)$$

with $R_0 \approx \frac{2m}{3M}\frac{\langle WM\rangle}{\langle\sigma\rangle} \sim 10^{-3}$.

For ^{6}He: R_0 determined to ~ 2% by connection to γ decay of analogue in ^{6}Li.

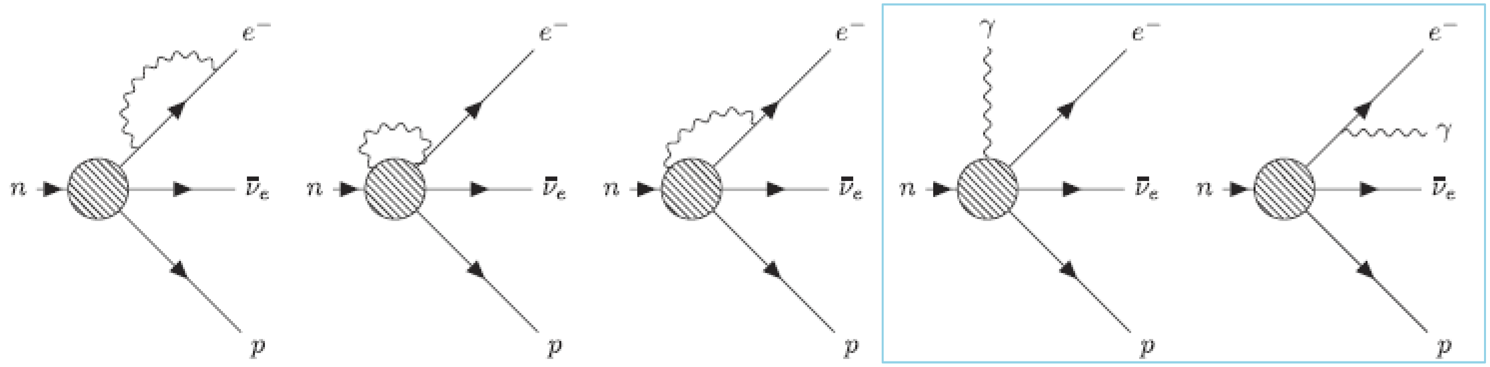
Other recoil-order correction (pseudo-induced term) suppressed for ^{6}He.

How about ^{19}Ne? ^{14}O?

Radiative corrections

From Hayen et al.
Rev.Mod.Phys. **90**, 015008 (2018)

Order-α



inner bremsstrahlung

Order-$Z\alpha^2$

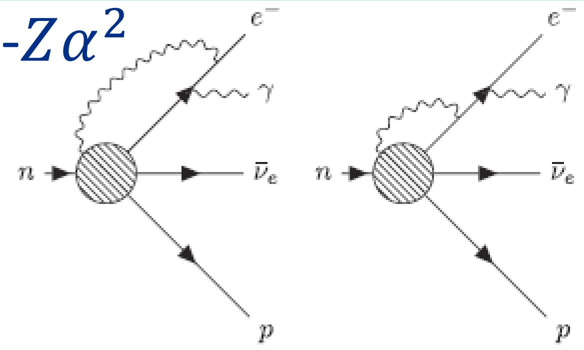


FIG. 3. Dominant Feynman diagrams for the order $Z\alpha^2$ corrections. The first of these already contains a correction present in the product $F_0\delta_1$ and has to be explicitly subtracted. Three more

Back to BSM: Is theory on good grounds?

- Cirigliano/Ramsey-Musolf et al. organizing a workshop at Amherst on neutron and nuclear beta decay.
- Gazit-Phillips-et al. proposing workshop at ECT* on SM predictions for precision nuclear beta decay experiments.
- A. Young/Ramsey-Musolf et al. proposing workshop at INT for next year on neutron and nuclear beta decay issues.

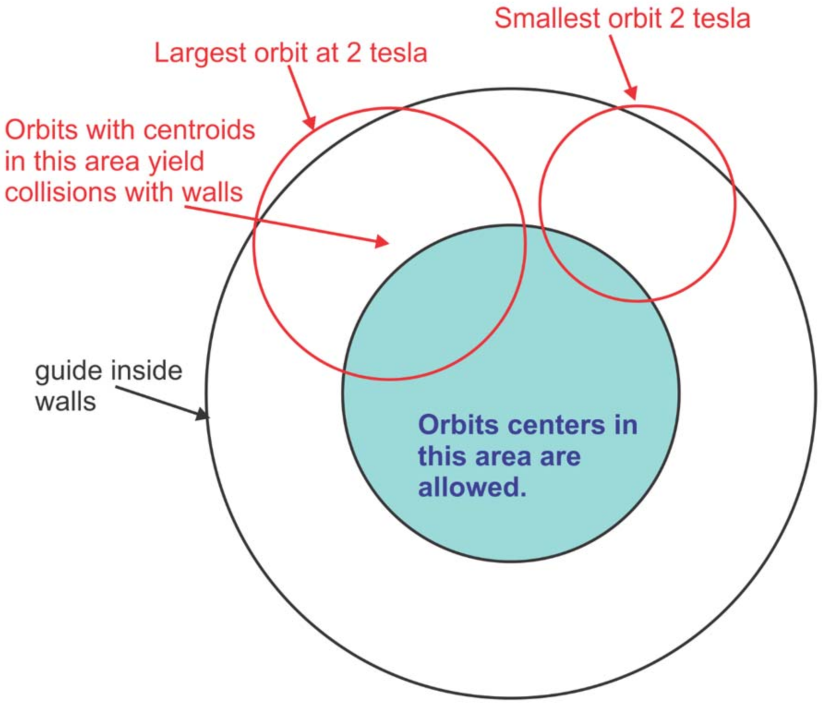
Conclusions

- Most sensitive way forward seems direct detection of Fierz interference.
- Difficult to avoid systematic distortions. Several techniques being pursued.
- Calculating SM contributions to allow most sensitive searches non trivial. Need theory help!

End

^{6}He little-b measurement at Seattle

Obvious worry: efficiency depends on energy.



Cross sectional view of guide with electron orbit. For this radius there is a dead region shown by the white frame on the blue area.

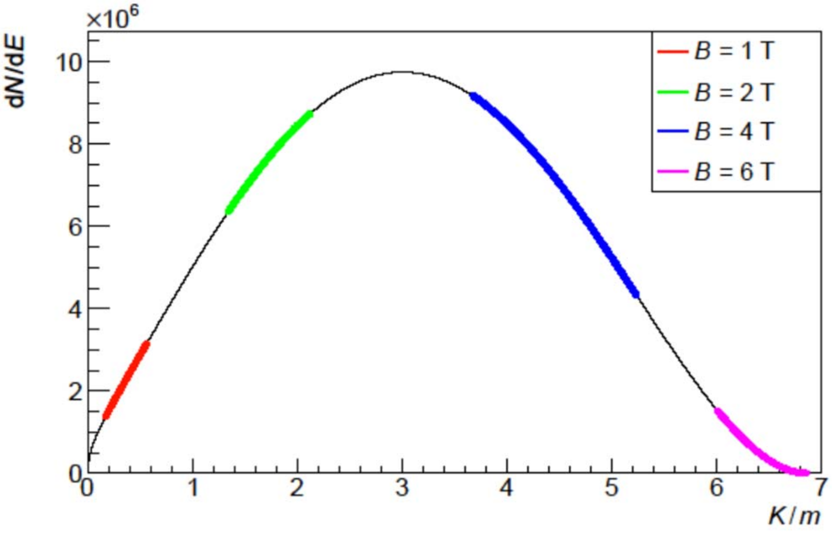
Since blue area depends on energy there is a systematic distortion of the spectrum

Can be studied by varying the *B* field.

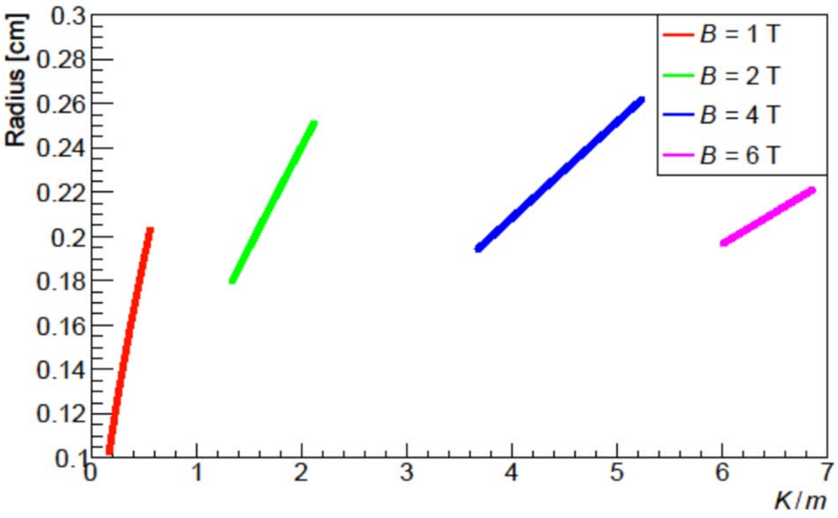
^{6}He little-*b* measurement at Seattle

Obvious worry: efficiency depends on energy.
Can study by varying *B* field.

Monte Carlo simulation of observation in
Few days of running



Radii vs. *B* field
Can use this to check geometric effect



“Doppler effect” and power into sidebands

Wave generated by the electron:

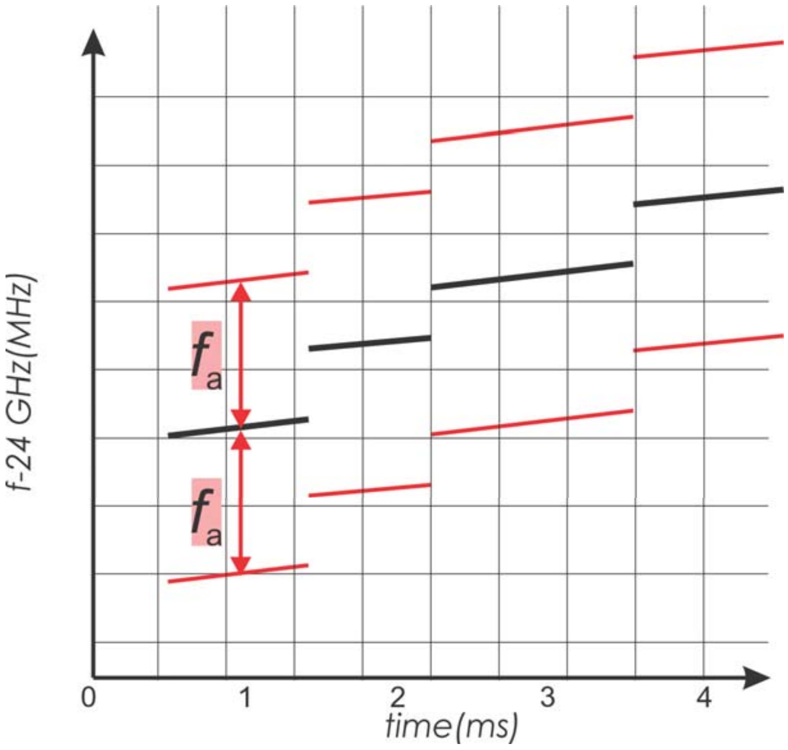
$$e^{i(\beta z-\omega t)}$$

Amplifier observes frequency:

$$\omega + \beta\,\dot{z}0/\omega$$

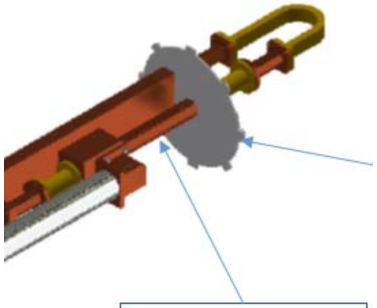
“Doppler effect” depends on axial speed of the electron.

Axial oscillations lead to frequency modulation. Power goes to sidebands.



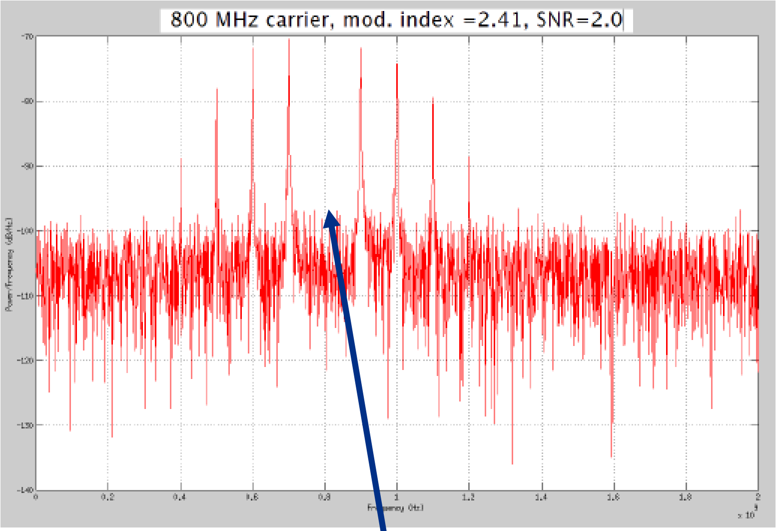
“Doppler effect” and power into sidebands

Strategy to bypass possible Doppler effect issues.



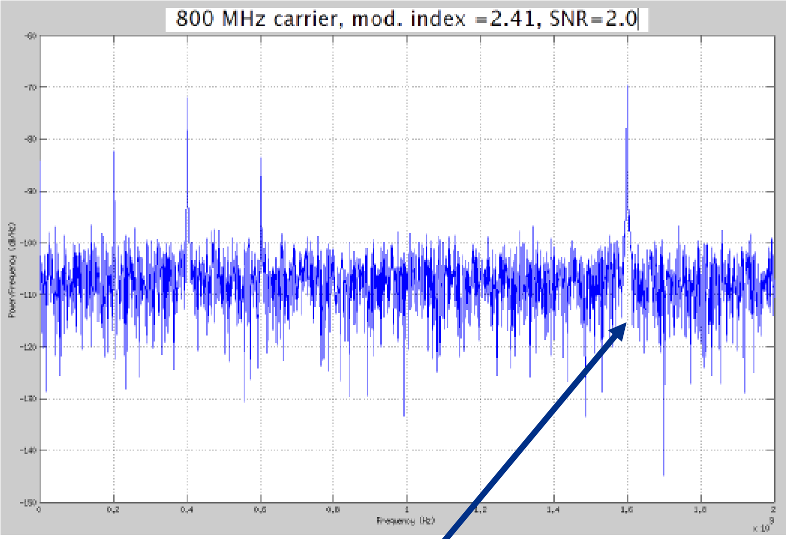
Decay volume

Reading only from one end:
Doppler effect generates sidebands



Correct ω missing.

Reading from both ends and making product



Correct 2ω strong.

PHYSICAL REVIEW C 96, 042501(R) (2017)

First direct constraints on Fierz interference in free-neutron β decay

UCNA collaboration

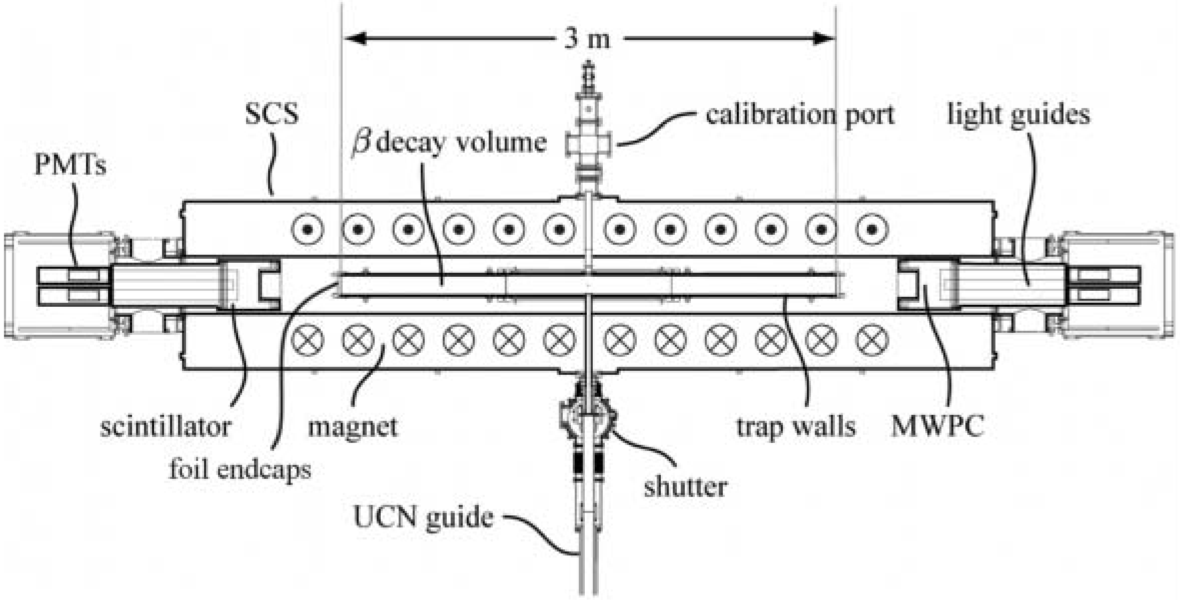
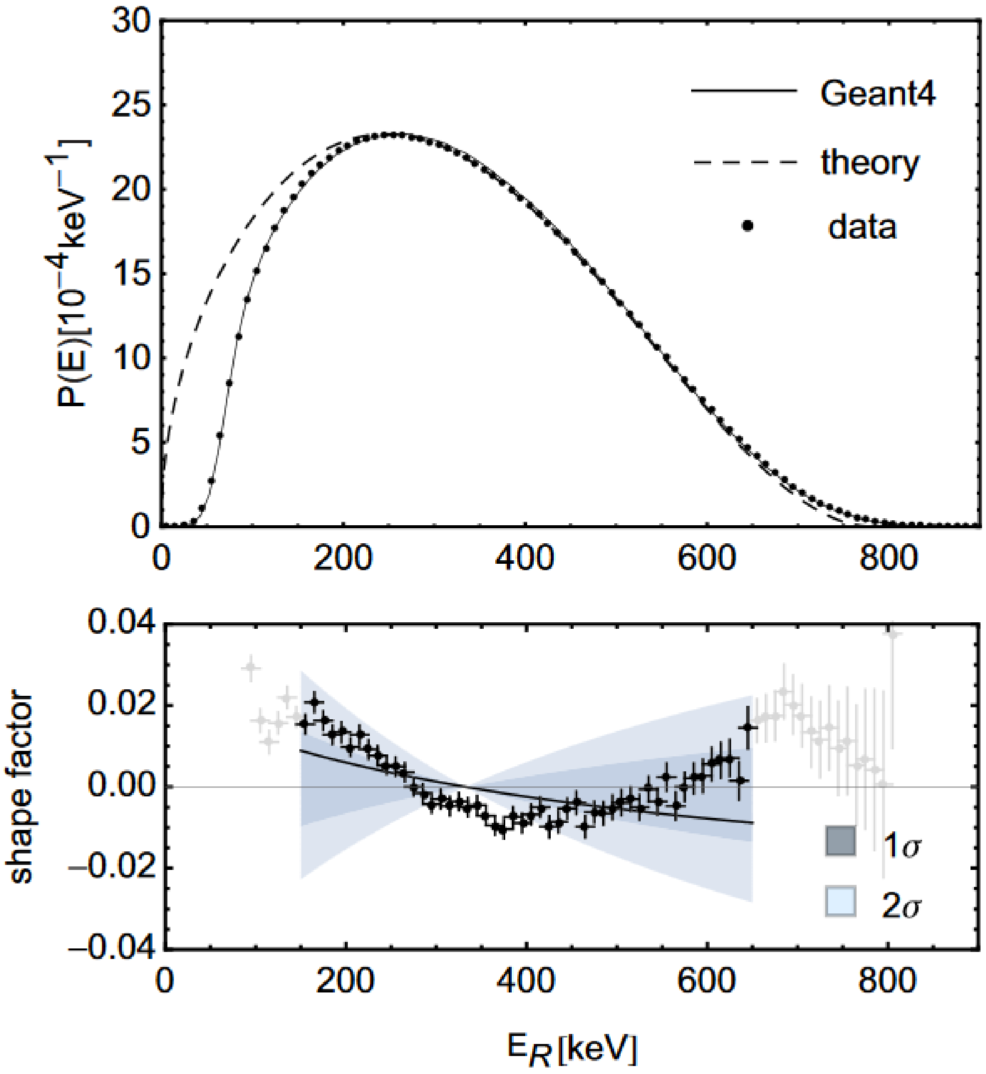


FIG. 1. Schematic diagram of the UCNA spectrometer.



UCNA collaboration

$$b_n = 0.067 \pm 0.005_{\text{stat}}{}^{+0.090}_{-0.061}{}_{\text{sys}}$$

~8 % accuracy over ~1 MeV

Magnetic spectrometer produced at Madison

L. D. Knutson et al.
Rev. Sci. Instr. **82**, 073302 (2011)

^{14}O branch
P. A. Voytas et al.
Phys. Rev. C **92**, 065502 (2015)

^{14}O spectrum
E. A. George et al.
Phys. Rev. C **90**, 065501 (2014)

^{66}Ga spectrum
G. W. Severin et al.
Phys. Rev. C **89**, 057302 (2014)

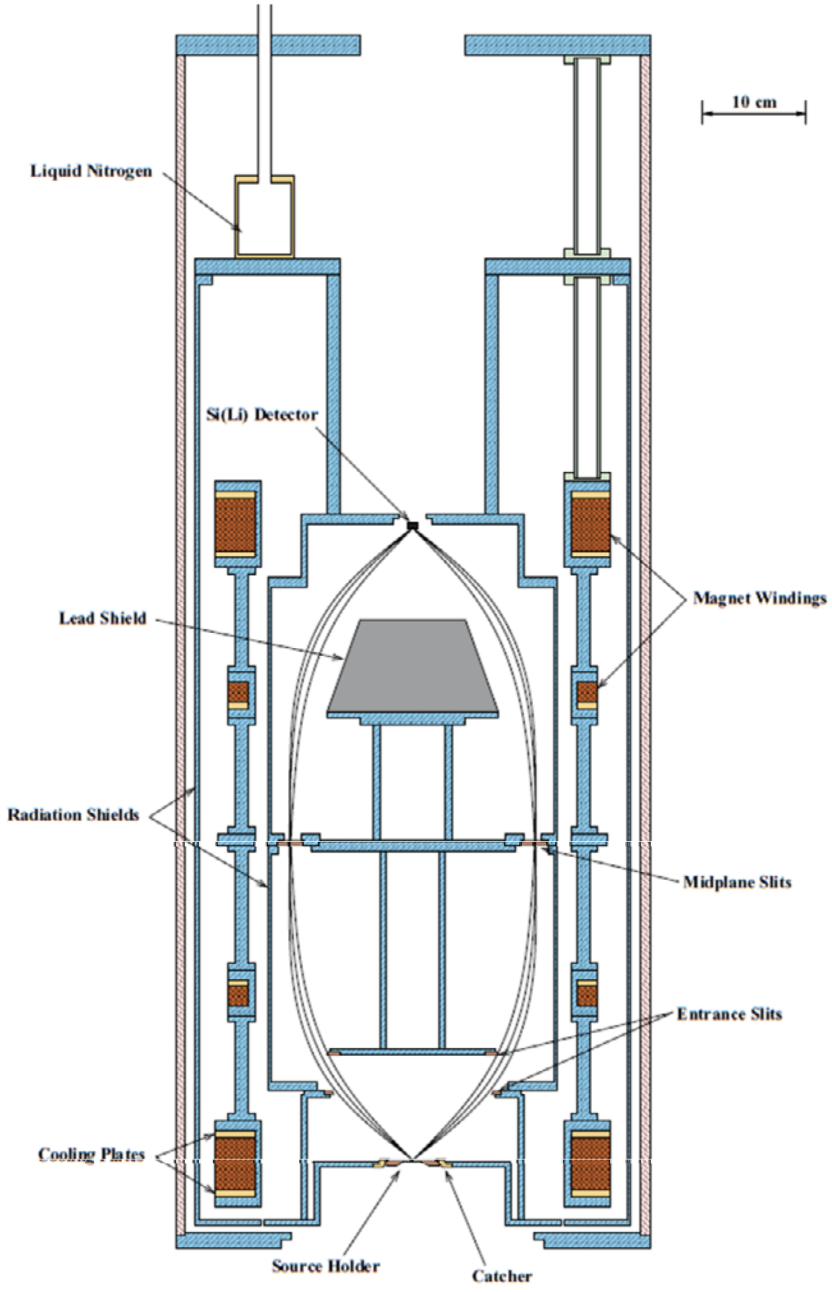


FIG. 1. (Color online) Schematic diagram of the superconducting beta spectrometer.

Magnetic spectrometer produced at Madison

^{14}O spectrum
E. A. George et al.
Phys. Rev. C **90**, 065501 (2014)

^{66}Ga spectrum
G. W. Severin et al.
Phys. Rev. C **89**, 057302 (2014)

~1% accuracy over few MeV's

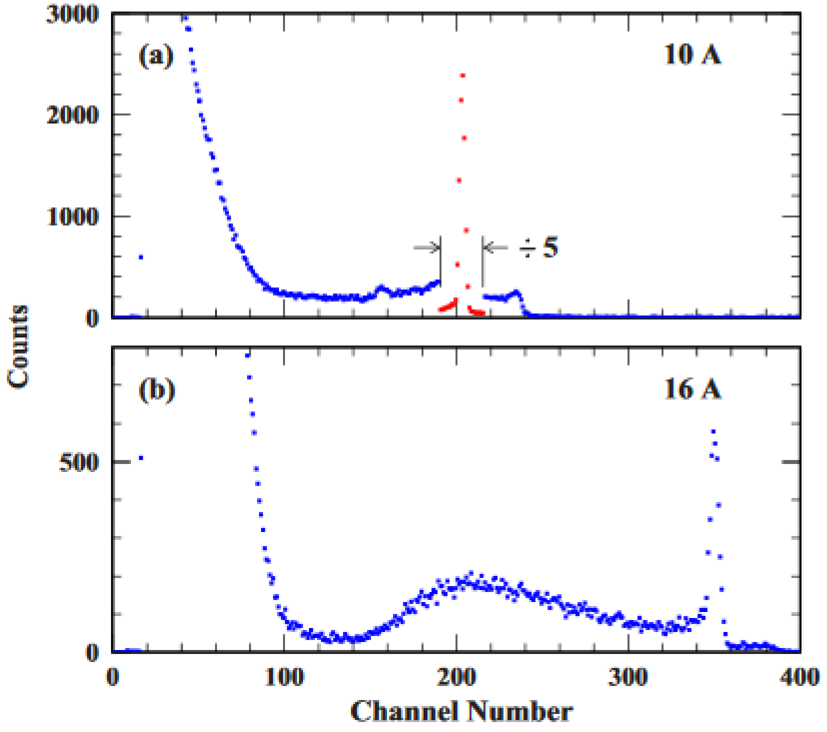


FIG. 6. (Color online) Accumulated Si(Li) spectra for all data taken at two spectrometer currents. Panel (a) shows the 10 A data which correspond to about 2.9 × 10^{10} decays, while the 16 A data in panel (b) correspond to 3.1 × 10^{10} decays.

Neutron decay:

RXB spectrometer in combination with
PERC at TU Wien, Vienna

X. Wang, G.Konrad, H.Abele
NIM A **701**, 254 (2013)

PERC: *Proton and Electron Radiation Channel*
Magnetic system to transport large numbers of betas and protons from neutron beta decay for spectroscopy.

Beta drift in *y* direction \prop p_b

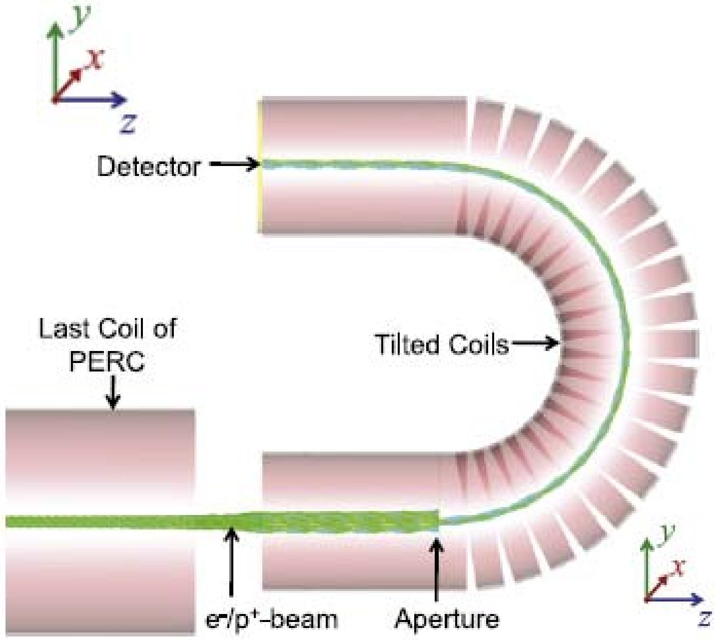
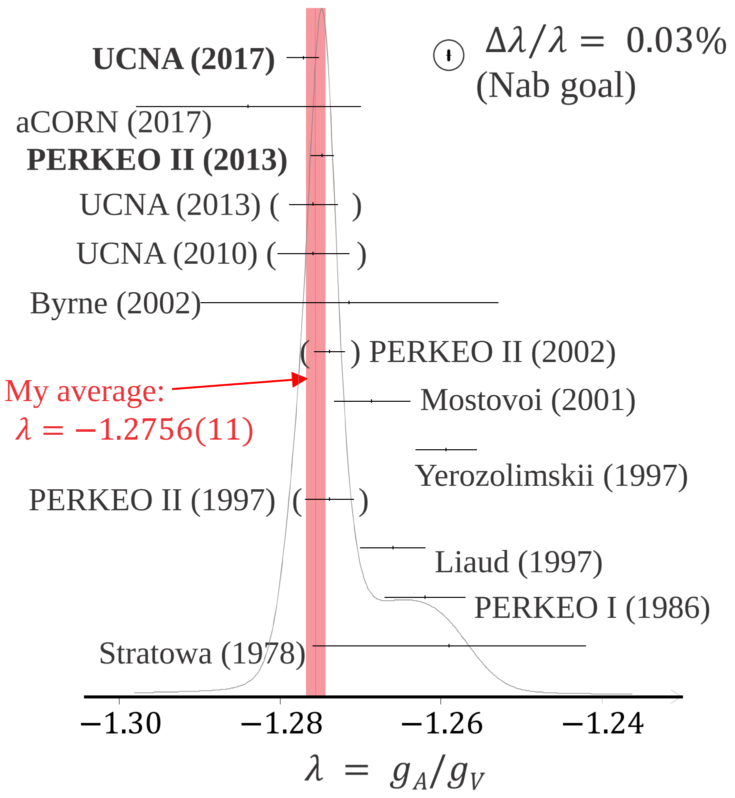


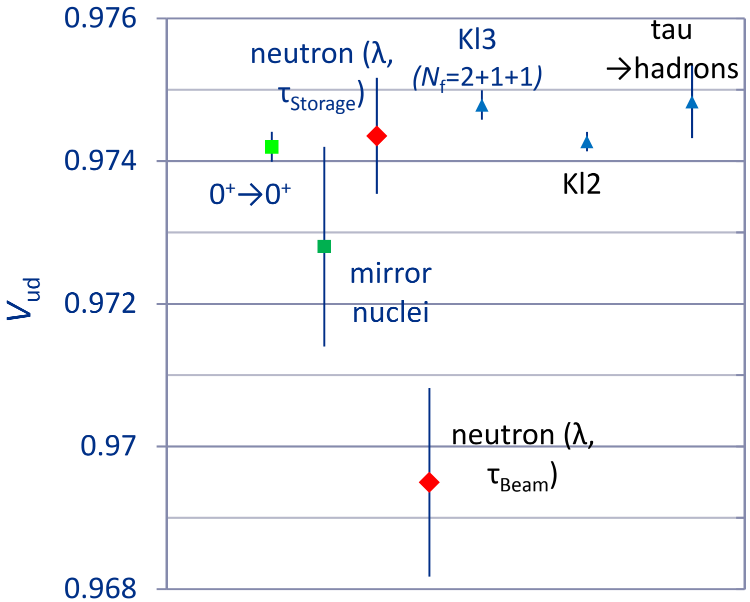
Fig. 5. The design of the $\mathbf{R} \times \mathbf{B}$ drift spectrometer at the end of PERC, and the simulated trajectories of e^-/p^+.

The measurement of neutron beta decay observables with the Nab spectrometer

The **physics goal** of Nab is:

- Determination of $\lambda = g_A/g_V$, the ratio of the standard model coupling constants in semileptonic weak interactions
- Test of the unitarity of the Cabbibo-Kobayashi-Maskawa matrix
- Search for novel interactions that manifest themselves as scalar and tensor interactions at low energies.

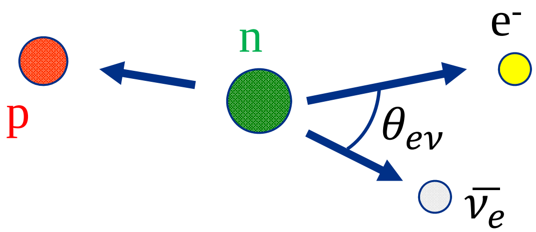




For neutron data to be competitive, want:
$\Delta\tau_n/\tau_n \sim 0.3$ s (and resolve discrepancy)
$\Delta\lambda/\lambda \sim 0.03\%$

From Steffan Baessler

Idea of Nab @ SNS



$$d\Gamma \propto \varrho(E_e)\left(1 + a\frac{p_e}{E_e}\cos\theta_{e\nu} + b\frac{m_e}{E_e}\right)$$

Kinematics in Infinite Nuclear Mass Approximation:

- Energy Conservation:

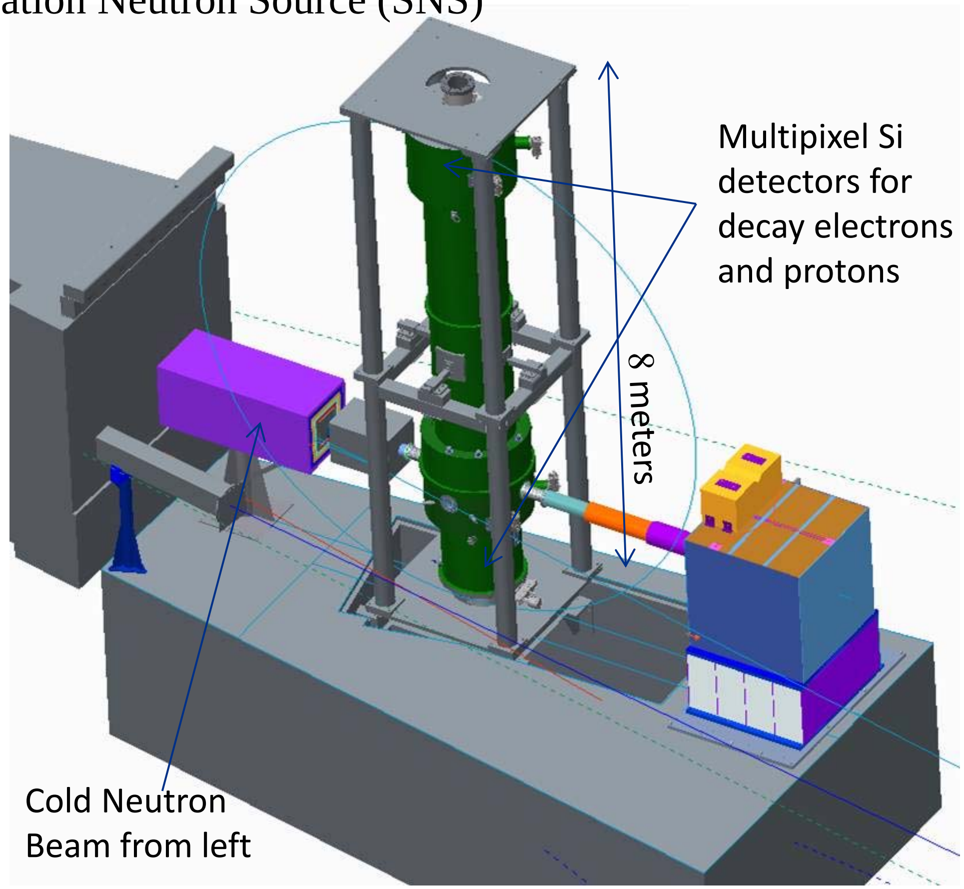
$$E_\nu = E_{e,max} - E_e$$

- Momentum Conservation:

$$p_p^2 = p_e^2 + p_\nu^2 + 2p_e p_\nu \cos\theta_{e\nu}$$

(p_p is inferred from proton time-of-flight)

Nab @ Fundamental Neutron Physics Beamline (FNPB) @ Spallation Neutron Source (SNS)

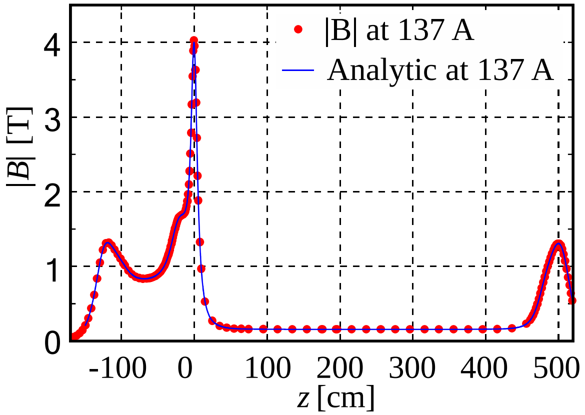


General Idea: J.D. Bowman, Journ. Res. NIST 110, 40 (2005)
Original configuration: D. Počanić et al., NIM A 611, 211 (2009)
Asymmetric configuration: S. Baeßler et al., J. Phys. G 41, 114003 (2014)

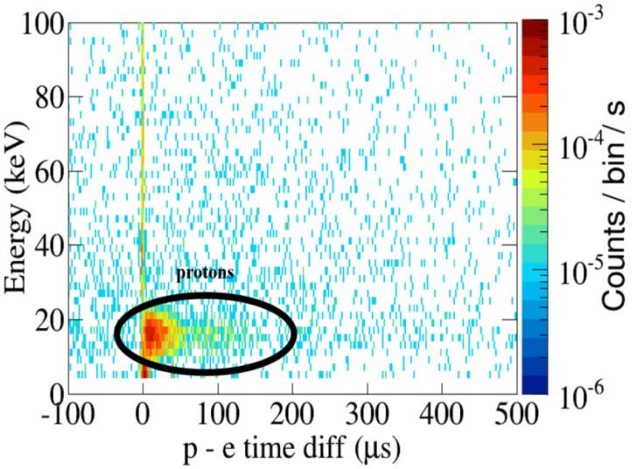
From Steffan Baessler

Status of Nab

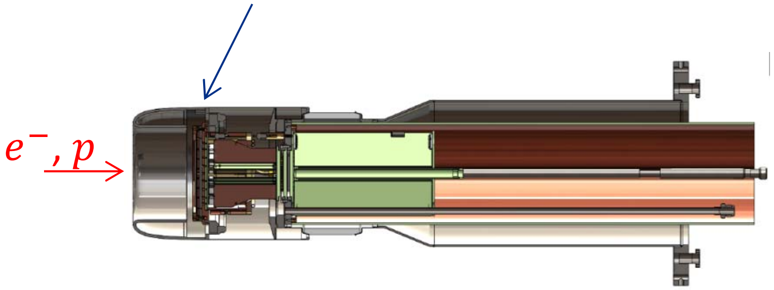
After long delays, the custom-built spectrometer **magnet** has been **tested successfully** at the manufacturer and is now at beamline.



Detector prototype testing in UCNB: Shown are decay electrons and protons from UCN decay.

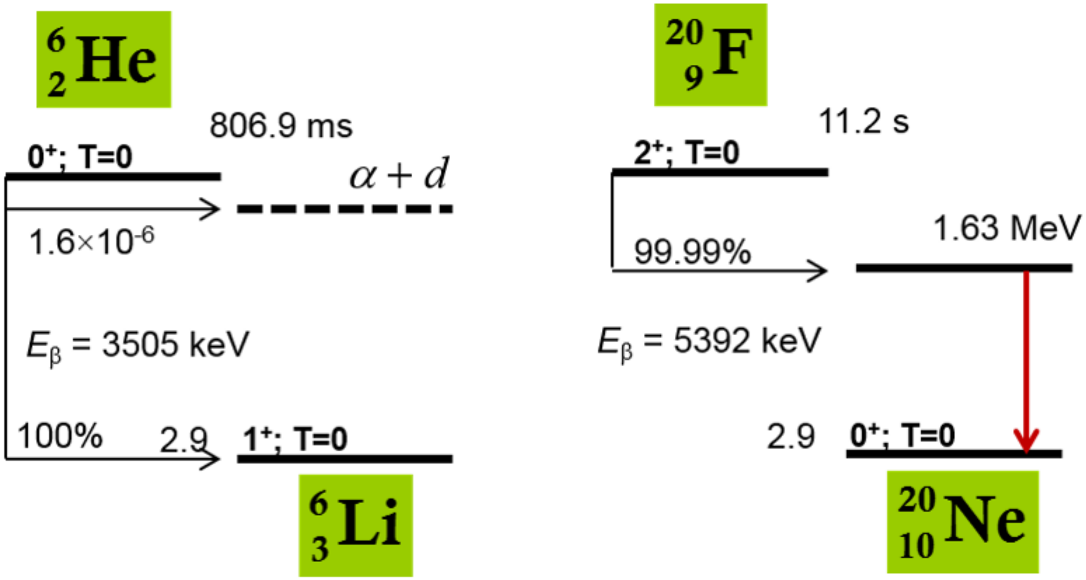


Silicon detector in mount



Commissioning and data taking is expected to start in late 2018.

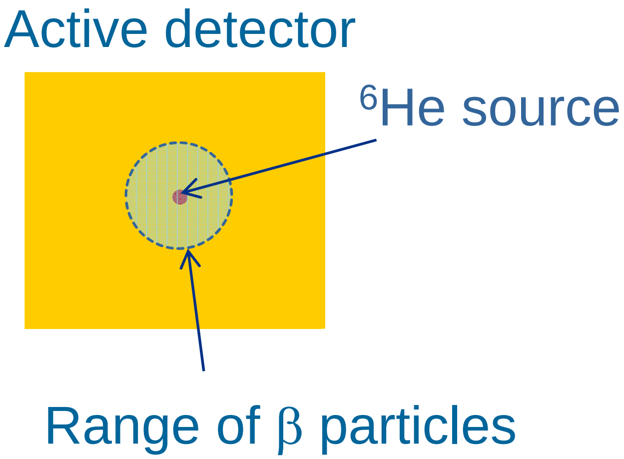
Selection of Sensitive Transitions to b_{GT}



M. Gonzalez-Alonso and O. N.-C
Phys. Rev. C **94** (2016) 035503

- Effects of *induced weak currents* are well under control and serve as sensitivity test of the experimental technique.

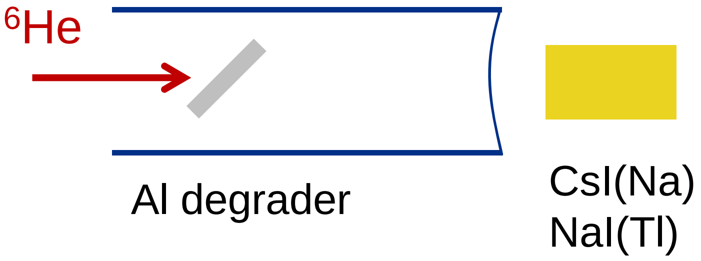
- Implement a calorimetric technique using a radioactive beam, which eliminates the effect of electron backscattering on detectors.

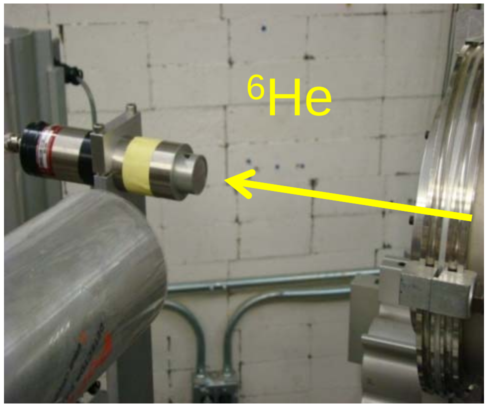


O. Naviliat-Cuncic: naviliat@nscl.msu.edu

Measurement with ^{6}He

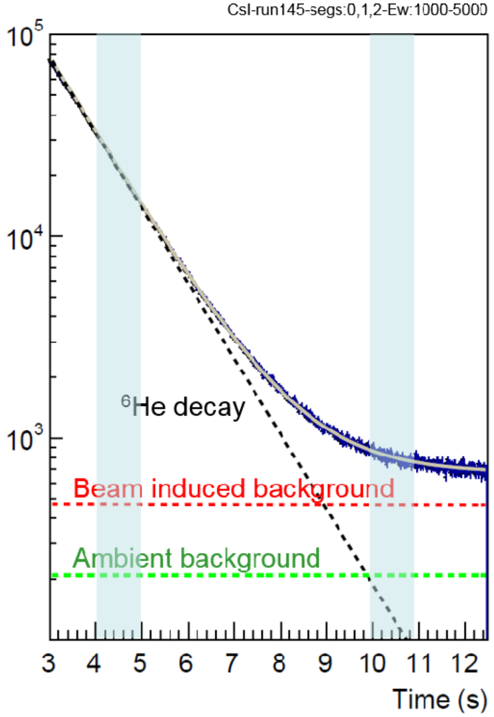
^{6}He beam: 46 MeV/nucleon after degrader



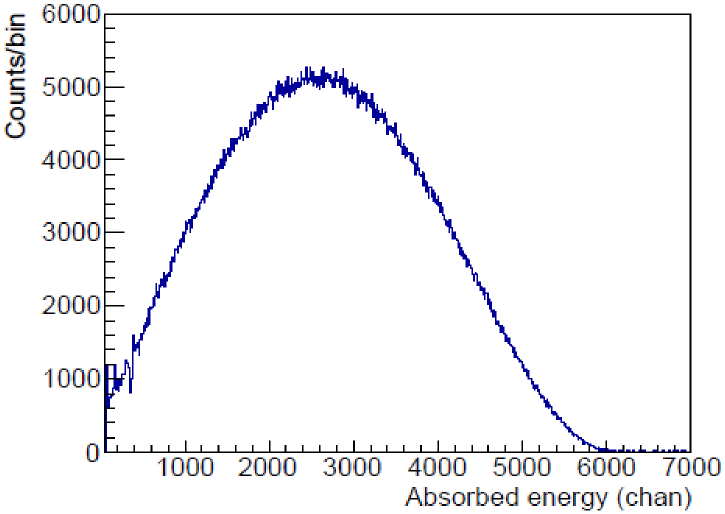


Detectors:

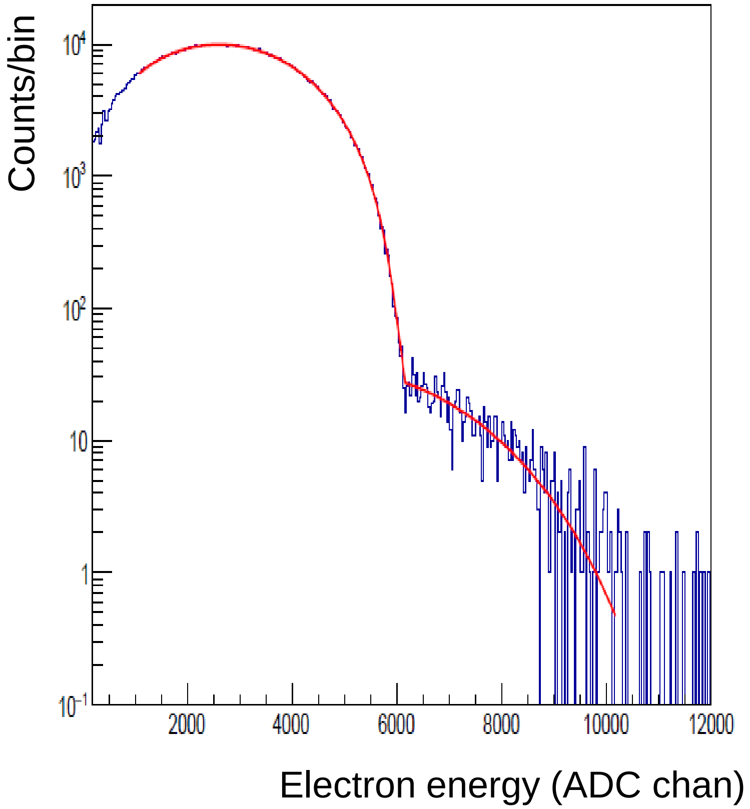
- CsI(Na) (2"×2"×5")
- NaI(Tl) (Ø3"×3")
- (Ø1"×1") CsI(Na)
- (Ø1"×1") NaI(Tl)



Background subtracted spectrum



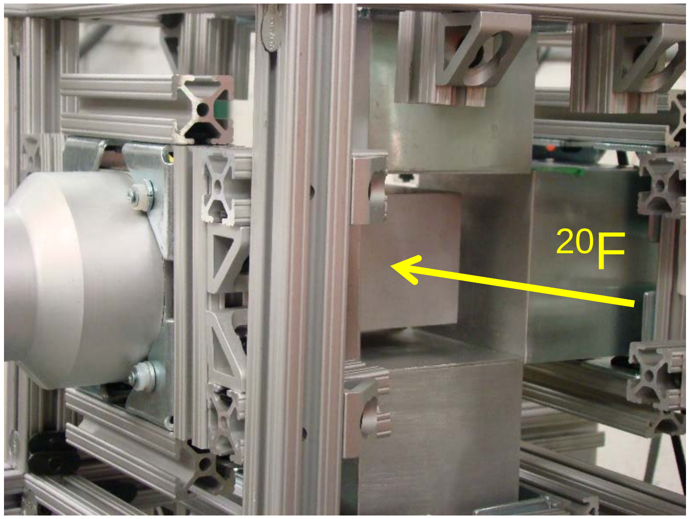
Data analysis and status (^{6}He)



- Analysis of spectra by a Monte-Carlo fit.
- Systematic effects associated with difference in Geant-4 for the description of Bremsstrahlung escape has been studied in detail: X. Huyan et al., NIMA **879** (2018) 134
- Calibration and non-linearity effects have been studied by Monte-Carlo: X. Huyan et al., Acta Phys. Pol. B **49** (2018) 249
- The "classical" radiative correction of the β particle energy requires special consideration for a calorimetric technique: X. Huyan et al., in preparation

- For each of the two large sets of collected data, the experiment has reached a statistical precision of:
    - 6% on the Weak Magnetism form factor
    - 2.6×10^{-3} on the Fierz term

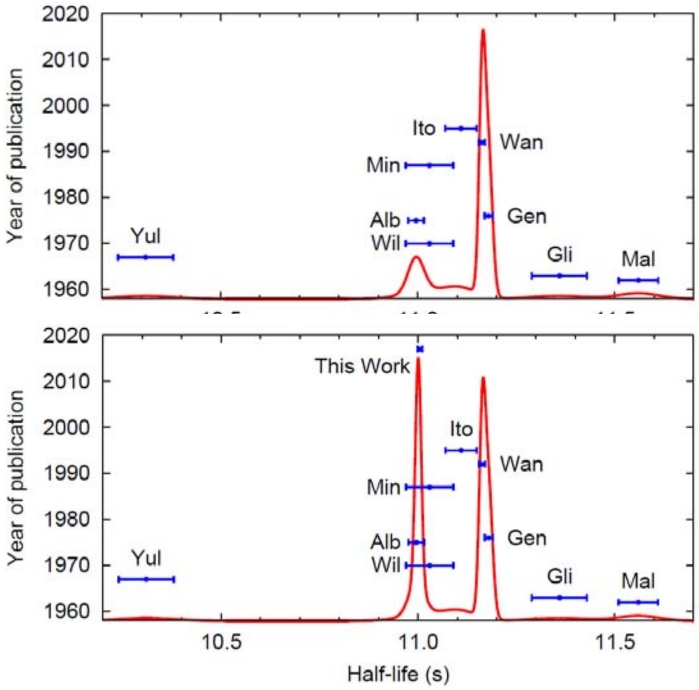
Measurement with ^{20}F



- ^{20}F beam: 132 MeV/nucleon before implantation
- Detectors: (2”x2”x4”) CsI(Na) for implantation and β detection; 4 (3”x3”x3”) CsI(Na) for γ ray.
- Data analysis proceeds similarly to ^{6}He. The Monte-Carlo of summing effects and the cuts on spectra are more complicated due to the γ ray.

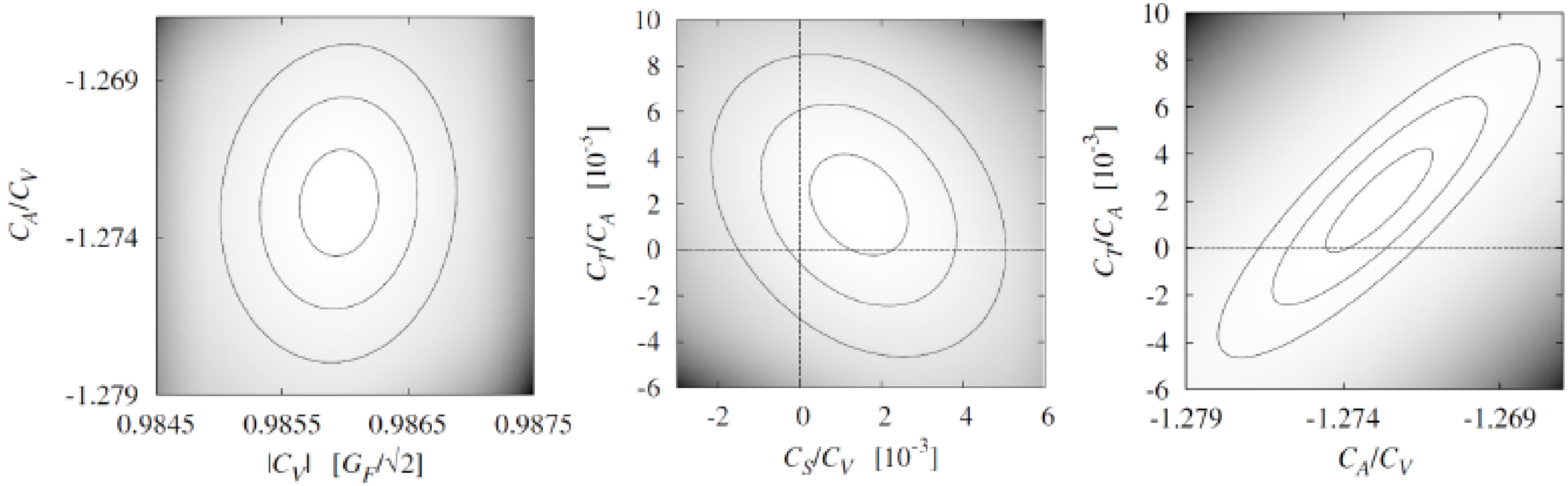
- During the data analysis, we have reported a new value of the ^{20}F half-life.
- The value is at variance by 17 standard deviations from the literature value and adds new tension to the current data set.

- M. Huges et al., [arxiv:1805.05800] accepted for publication in PRC.



Gonzalez-Alonso, Naviliat-Cuncic, Severijns
hep-ph 1803.08732

Bounds from $Ft(0^+ \to 0^+)$ and neutron decays



^{6}He little-*b* measurement at Seattle

Goal: measure “little *b*” to 10^{-3} or better in ^{6}He

Stats not a problem.

Starting construction during summer 2018.