Beyond-standard model physics searches in neutron and nuclear beta decay

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Table of contents

Beyond-standard model physics searches in neutron and nuclear beta decay:

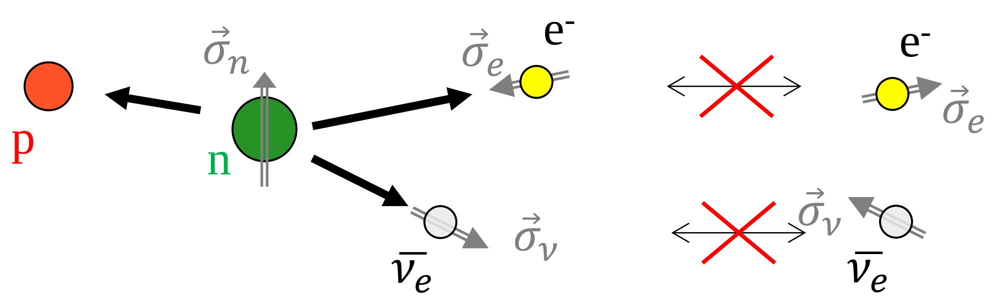
1. Is the Cabbibo Kobayashi Maskawa (CKM) matrix unitary?

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

Various unitarity tests possible; the most precise one is the one in the first row:

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

2. V-A structure of weak interaction: Scalar- and tensor (S,T) interactions, which could be mediated by non-standard intermediate bosons, causes beta decays with one of the leptons having the opposite helicity.



Established determination of V_{ud}

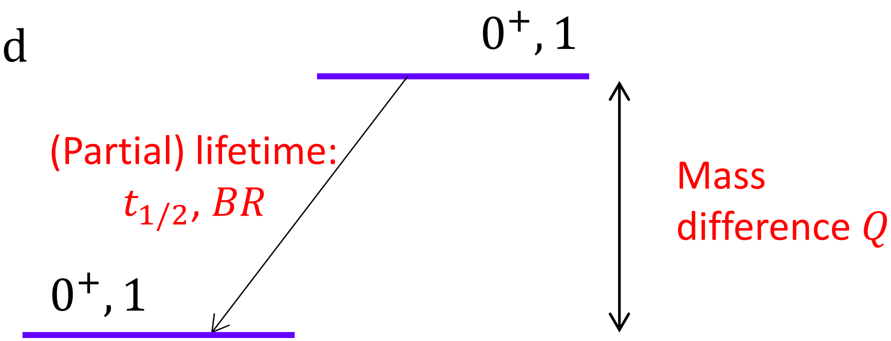
Use beta decay. Most precise in superallowed beta decays:

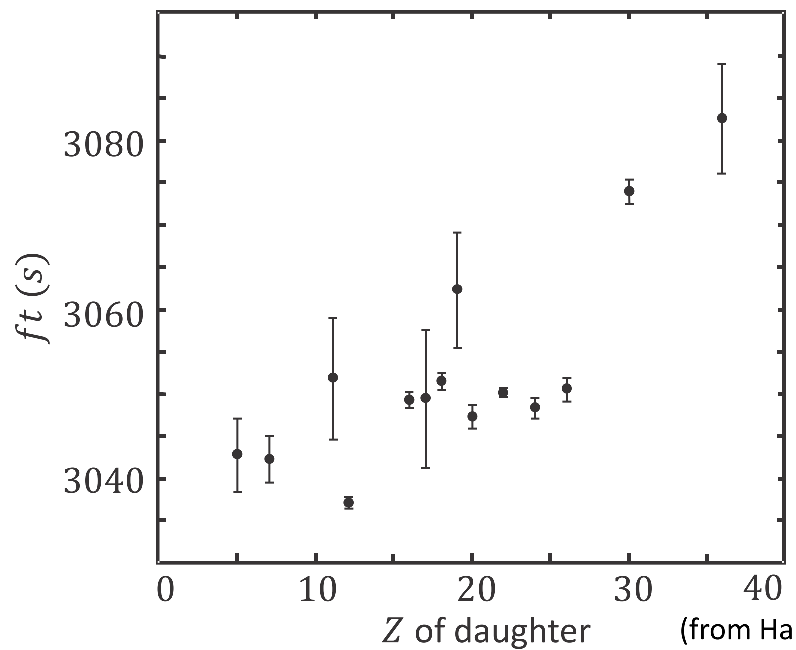
$$\frac{1}{f(E)t} = \frac{2\pi}{\hbar}|< fev|H|i >|^2$$

Integration:

$$\frac{1}{ft} = \frac{G_F^2 V_{ud}^2}{K}\underbrace{|< f|O|i >|^2}$$

Can be computed with precision only in some cases,
In which the nuclear wave function overlap is well-known.





(from Hardy, Towner, PRC 91, 025501 (2015))

For superallowed decays, $O = 1$ and $|< f|O|i >|^2 \approx 2$.

→ Good to a few percent, see left

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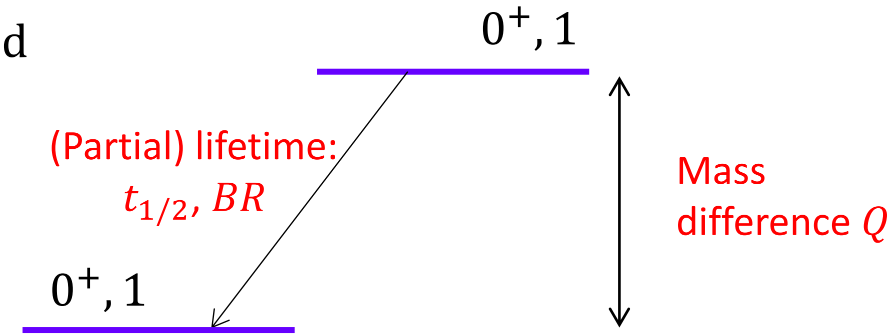

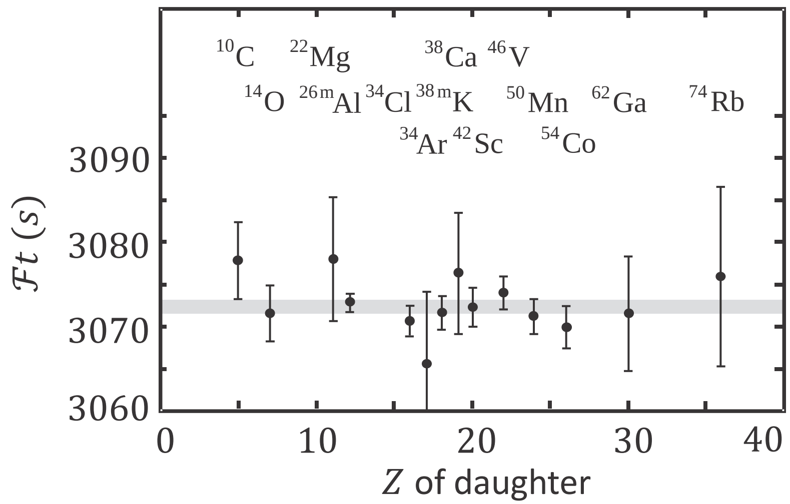

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Improvement: Apply corrections:

$$\mathcal{F}t = ft(1 + \delta_R')(1 + \delta_{NS} - \delta_C)$$

Energy-dependent rad. corr.

Isospin-breaking correction (to matrix element)

Nucleus-dependent rad. corr.

Inner rad. corr.

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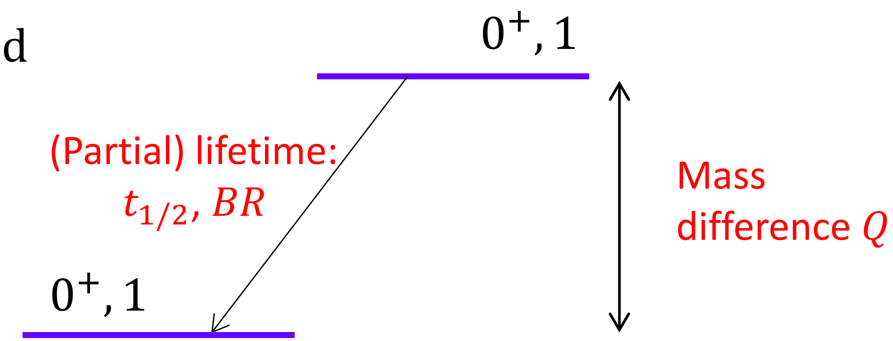

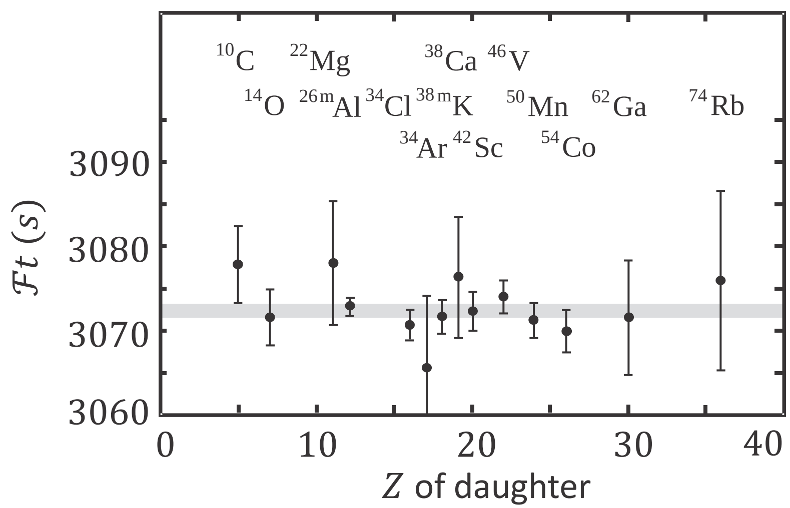

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This quantity contributes with largest uncertainty to V_{ud}

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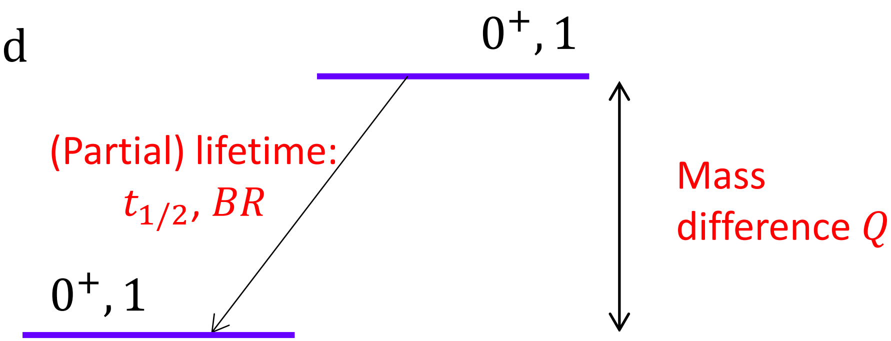
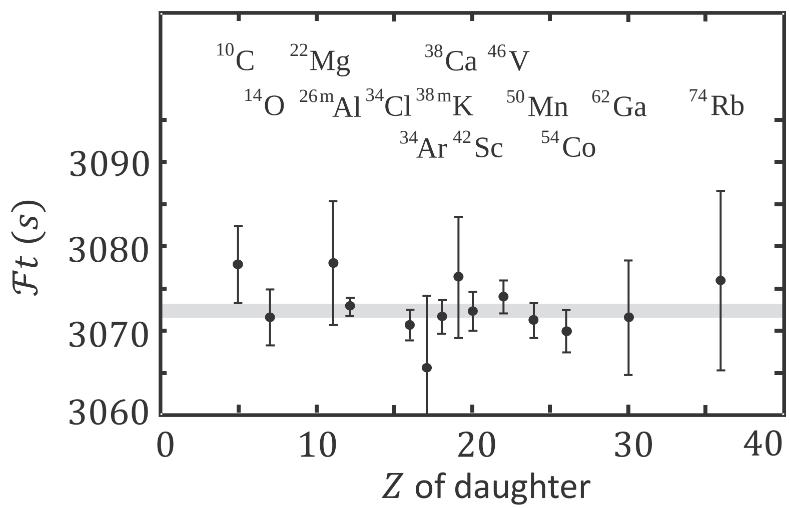


If there is an issue, it is believed to be the isospin-breaking correction that is nuclear structure dependent.



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Determination of V_{us}

1. Use Kl3 (Ke3 or Kμ3) semileptonic decays, e.g. $K_L \to \pi^+ + e^- + \bar{\nu}_e$:

$$\Gamma_{Kl3} = (known) \cdot \left|V_{us} f_+^{K\pi}(0)\right|^2 I_K^l \left(1 + \delta_{EM}^{Kl} + \delta_{SU(2)}^{Kl}\right)$$

Correction to phase space integral for charged Kaons

Lepton formfactor   phase space integral   Radiative correction

Current issue: $f_+^{K\pi}(0)$ needs to come from theory (Lattice-QCD). Present averages are:

N_f	$f_+^{K\pi}(0)$	V_{us}	PDG16 average, based on…
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$$\frac{\Gamma_{K\mu2}}{\Gamma_{\pi\mu2}} = \frac{|V_{us} f_+^K(0)|^2}{|V_{ud} f_+^\pi(0)|^2}(1 + \text{corrections})$$

Result is $V_{us} = 0.22540(53)_{exp}(19)_{RC}(49)_{Lat}$

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3. Use hadronic tau decays: E.g., $\tau \to K + \nu_\tau$

$\Gamma \propto |V_{us}|^2$ (with theory input)

Result is $V_{us} = 0.2202(15)$

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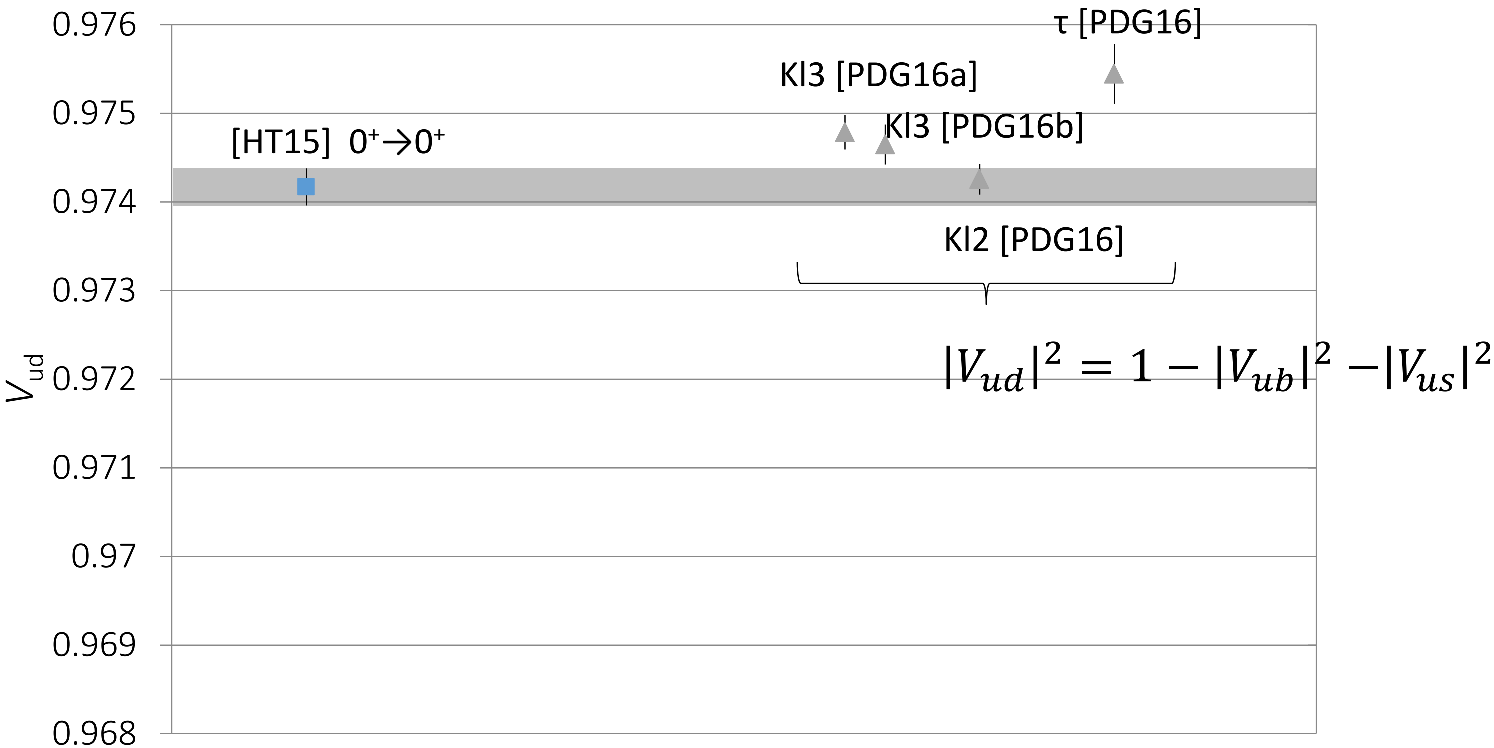
$\Gamma \propto |V_{us}|^2$ (with theory input)

Result is $V_{us} = 0.2202(15)$

NB: I haven't talked about V_{ub}. V_{ub} is determined from decays of B/D mesons. Its value, $V_{ub} = 4.12(37)(9) \cdot 10^{-3}$ is controversial, but small enough to be neglected here.

Test of CKM unitarity in the first row.

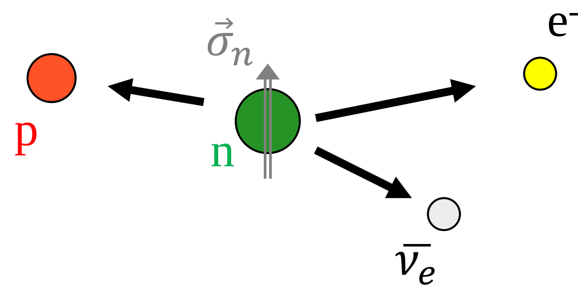


CKM Unitarity test ($|V_{ud}|^2 + |V_{us}|^2 + |V_{ub}|^2 = 1$) was perfect for a decade, after being off for even longer (Kaon experiment has moved). Now, updates of lattice calculations of the Kaon form factors put agreement in question.

Observables in Neutron Beta Decay

Observables in neutron beta decay, as a function of generally possible coupling constants (assuming only Lorentz-Invariance):

Jackson et al., PR 106, 517 (1957), C. F. v.Weizsäcker, Z. f. Phys. 102,572 (1936), M. Fierz, Z. f. Phys. 105, 553 (1937)



$$d\Gamma \propto \rho(E_e)\cdot\left(1+3|\lambda|^2\right)\cdot\left\{1 + a\frac{\vec{p}_e\cdot\vec{p}_\nu}{E_e E_\nu} + b\frac{m_e}{E_e} + \vec{\sigma}_n\cdot\left(A\frac{\vec{p}_e}{E_e} + B\frac{\vec{p}_\nu}{E_\nu} + D\frac{\vec{p}_e\times\vec{p}_\nu}{E_e E_\nu}\right)\right\}$$

Fierz interference term $b = 0$

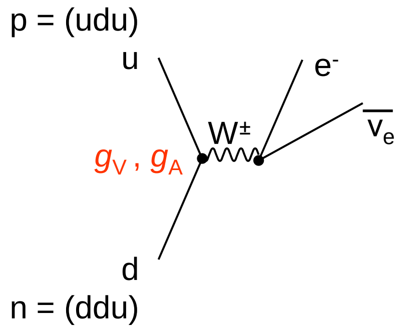
Beta-Asymmetry $A = -2\frac{|\lambda|^2 + \mathrm{Re}\,\lambda}{1+3|\lambda|^2}$

Neutrino-Electron-Correlation $a = \frac{1-|\lambda|^2}{1+3|\lambda|^2}$

Neutron lifetime $\tau_n^{-1} = \frac{2\pi}{\hbar} G_F^2 V_{ud}^{\;2}\left(1+3|\lambda|^2\right)\int \rho(E_e)$

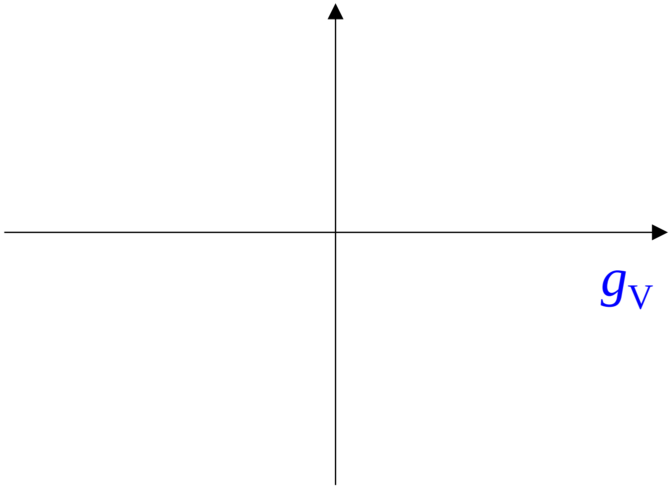
Coupling Constants of the Weak Interaction

Coupling Constants in Neutron Decay



$$n \rightarrow p + e^- + \overline{\nu}_e$$

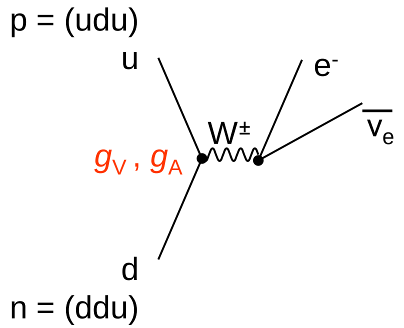
$$g_A = G_F \cdot V_{ud} \cdot \lambda$$



$$g_V = G_F \cdot V_{ud} \cdot 1$$

Coupling Constants of the Weak Interaction

Coupling Constants in Neutron Decay



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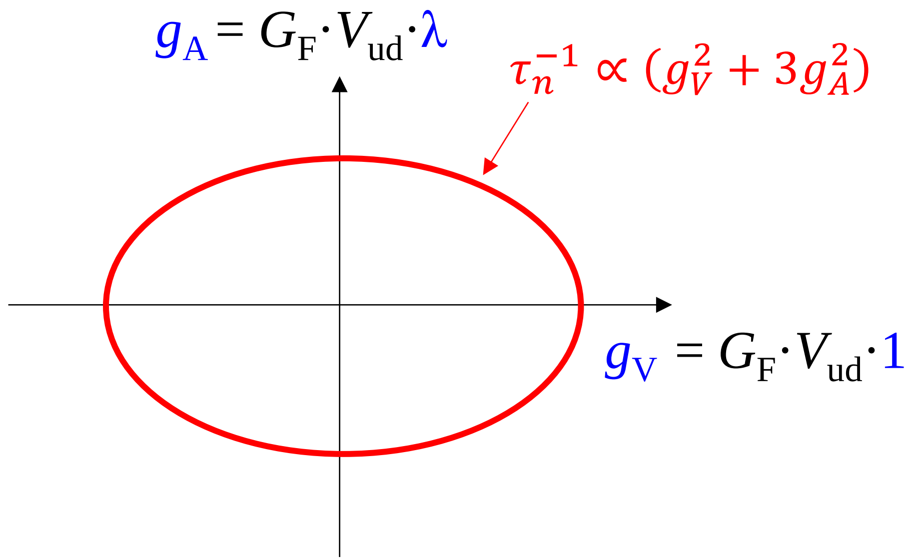

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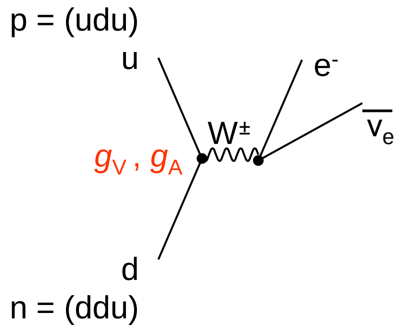

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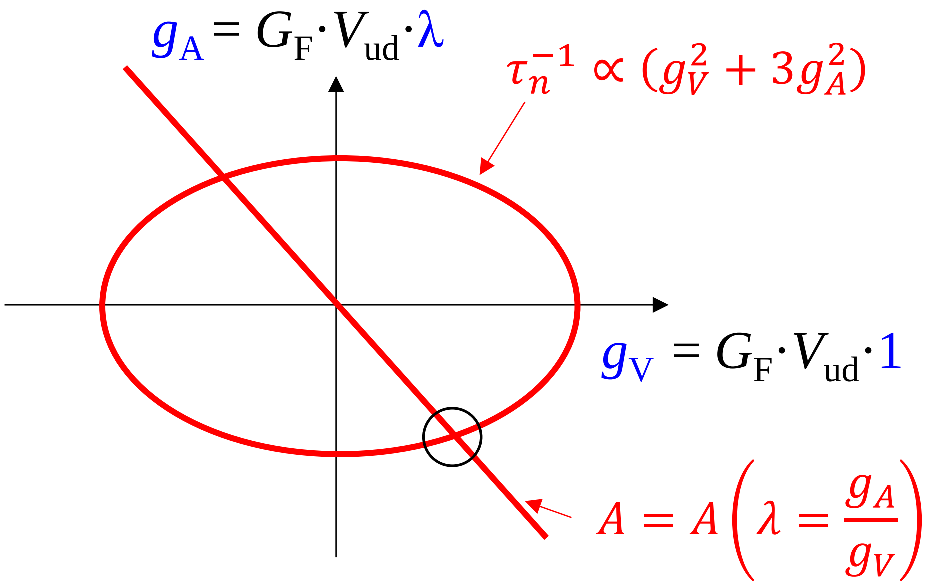

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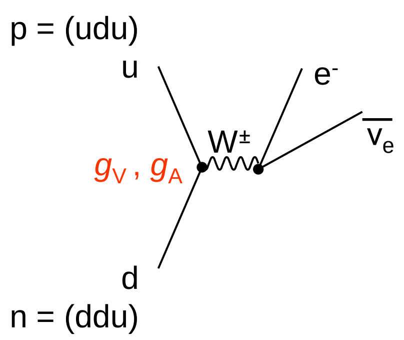

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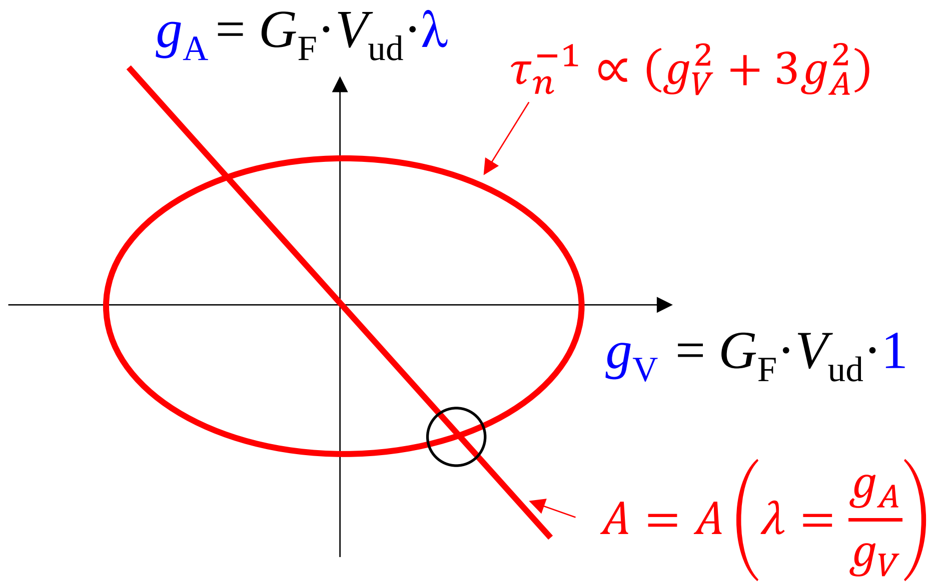
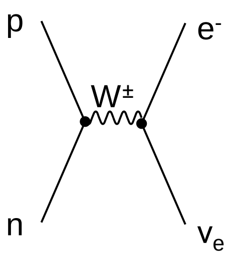
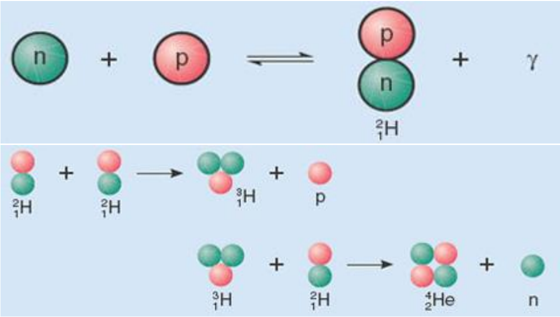


Primordial Nucleosynthesis

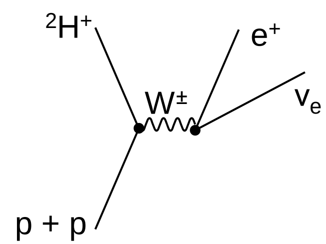


$n + \nu_e \leftrightarrow p + e^-$



Start of Big Bang Nucleosynthesis,
Primordial ^{4}He abundance

Solar cycle

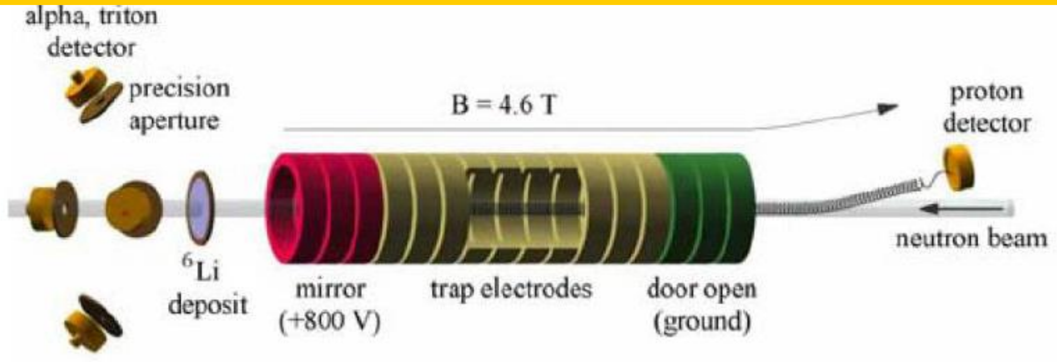


$p + p \rightarrow {}^2H^+ + e^+ + \nu_e$

Start of Solar Cycle, determines amount of
Solar Neutrinos

Neutron Lifetime Measurements

Beam: Decay rate: $\frac{dN}{dt} = \frac{N}{\tau_n}$



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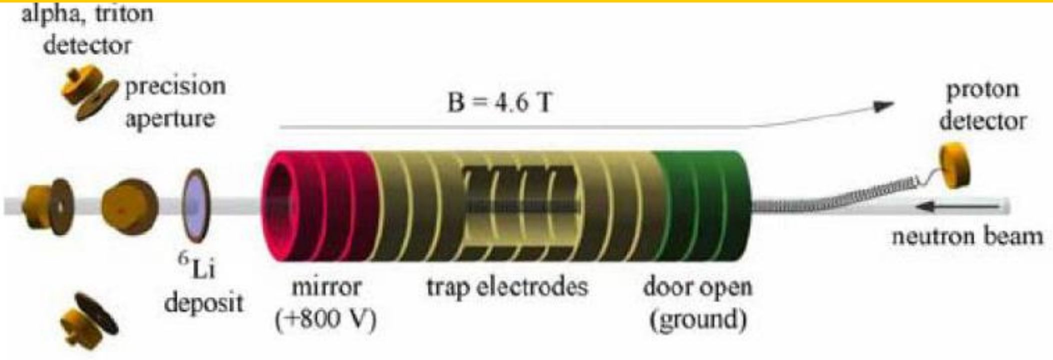

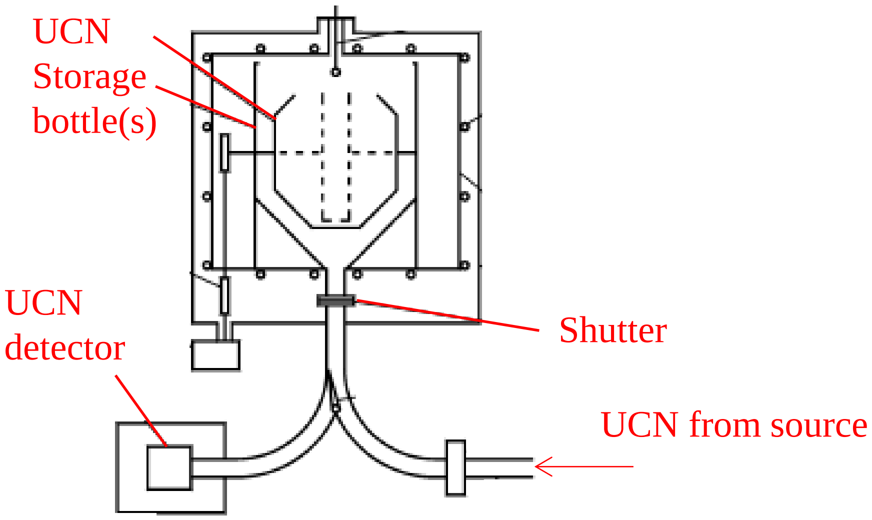

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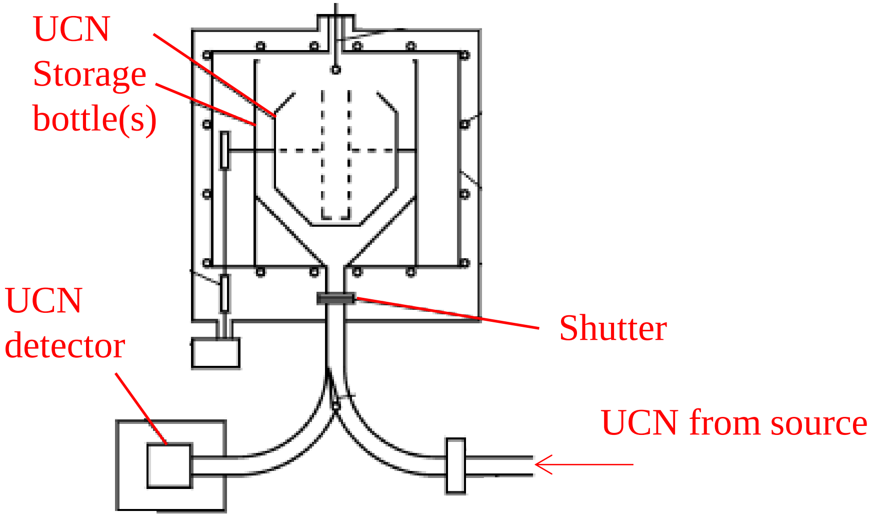

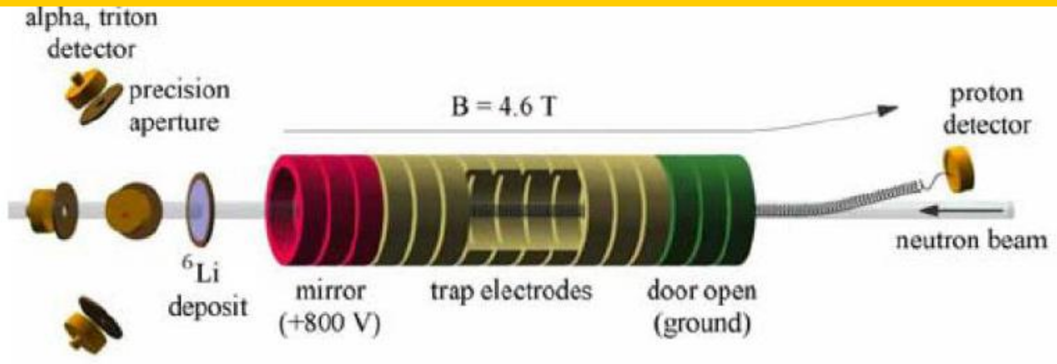

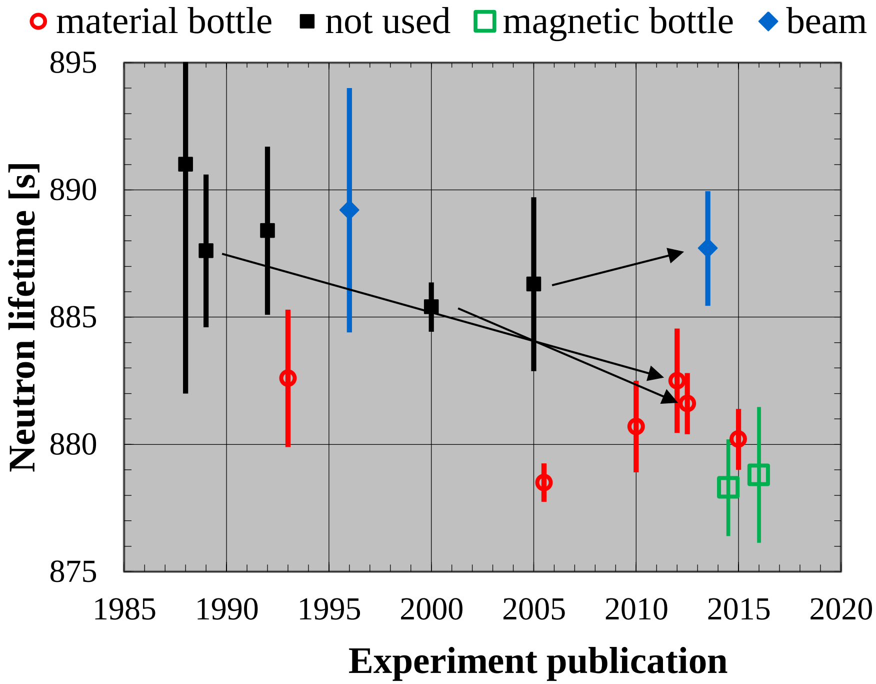

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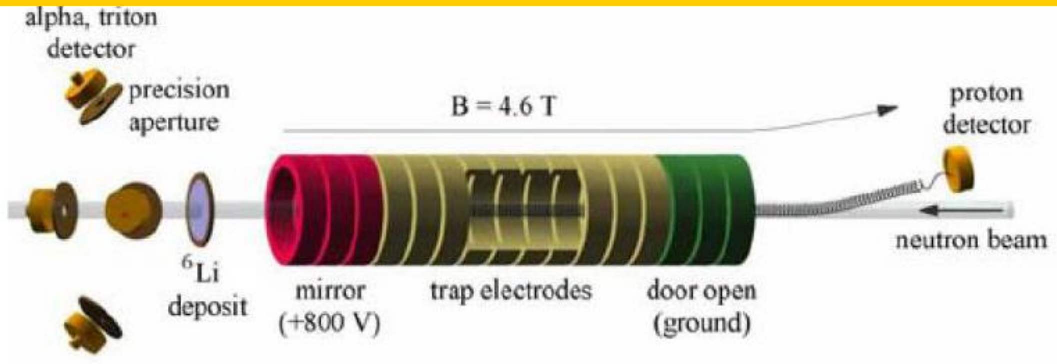
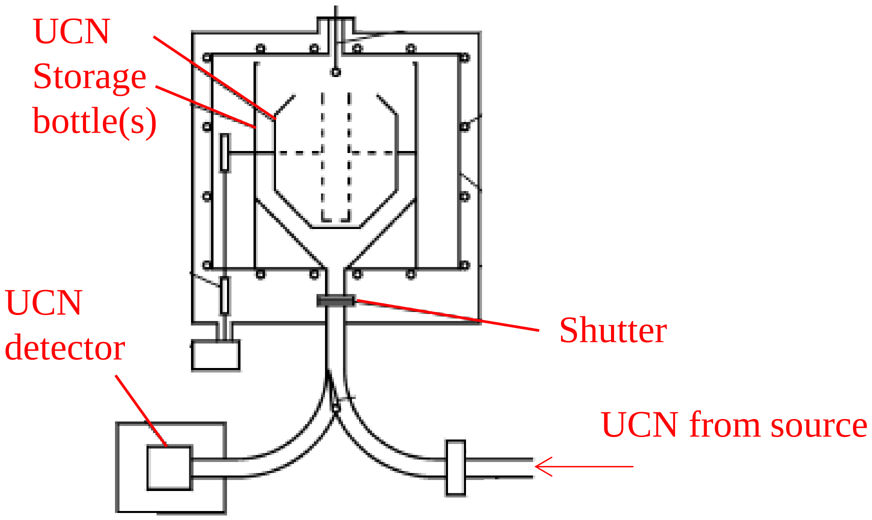
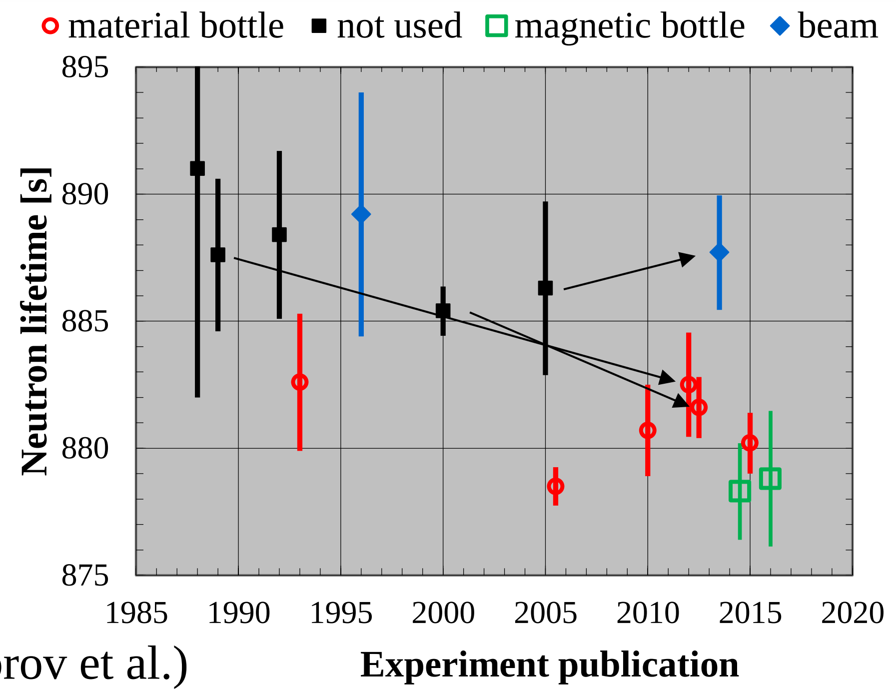


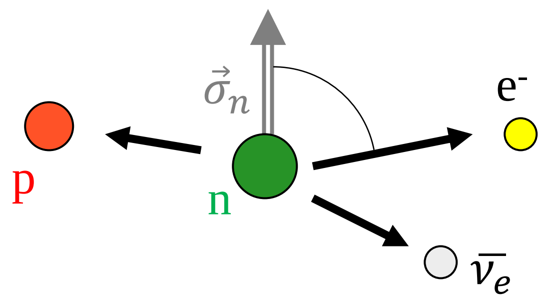


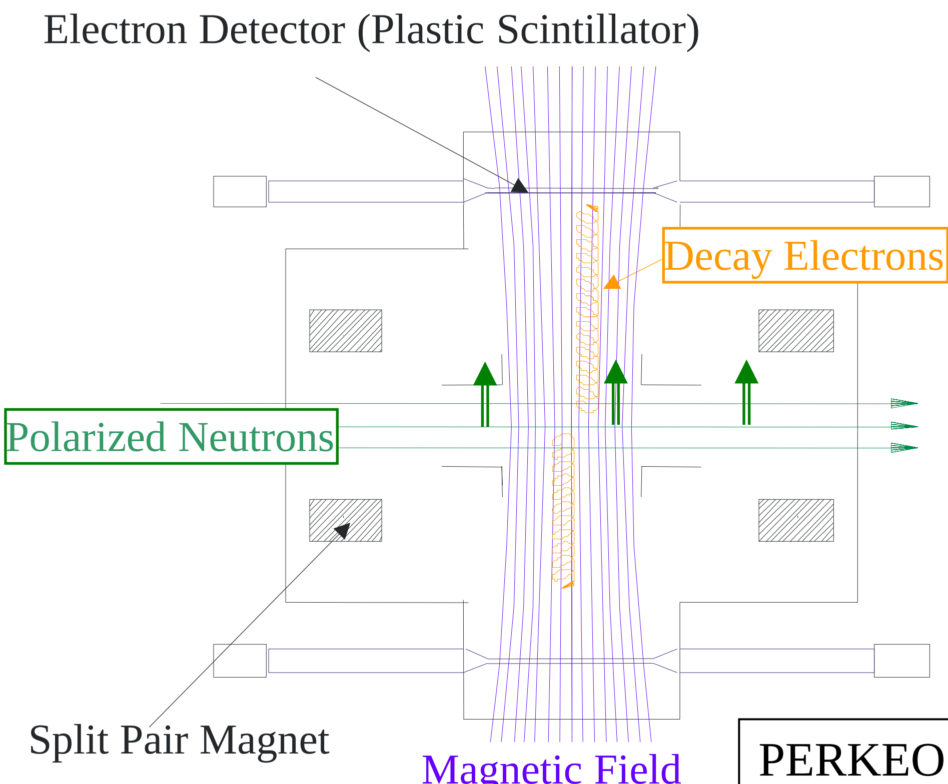


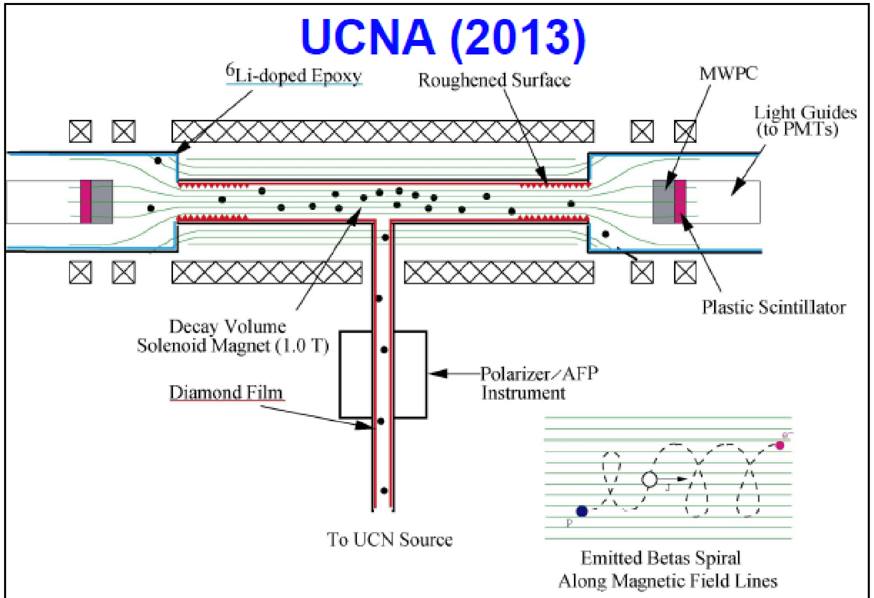
Many new experiments:

- Somehow improved material bottles (e.g. Serebrov et al.)
- Magnetic bottles (e.g. UCNτ, C.-Y. Liu et al., LANL; τSPECT, W. Heil, M. Beck et al., TRIGA Mainz; HOPE, O. Zimmer et al., ILL Grenoble, PENELOPE, S. Paul et al., TU München)
- Beam Lifetime (only at NIST)

The Beta Asymmetry







$\lambda = -1.2755(30)$

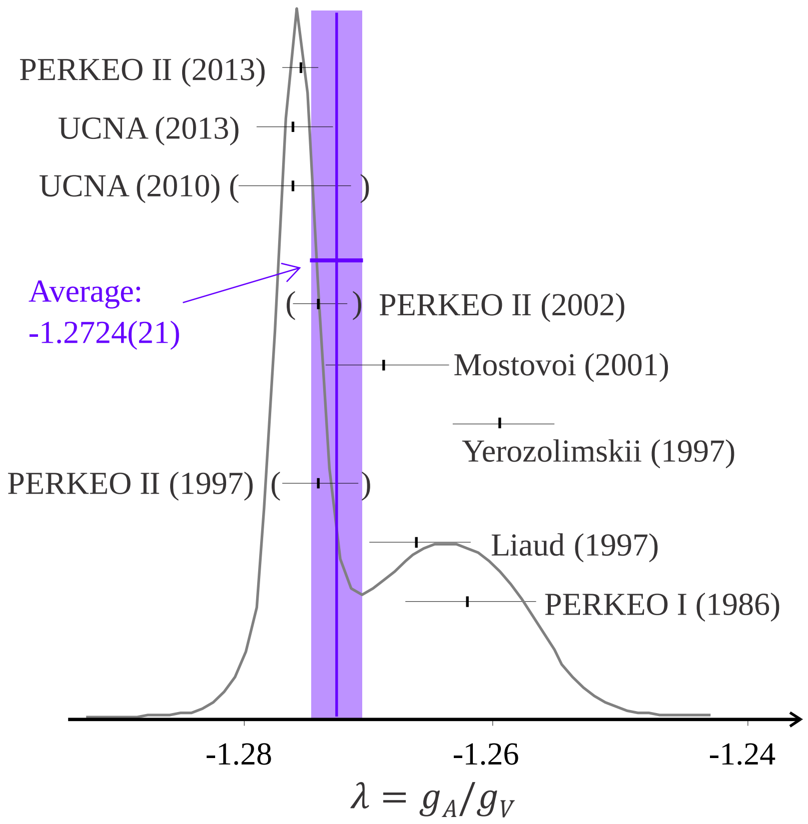
from M.P. Mendenhall et al., PRC 87, 032501 (2013)

Note: The PERKEO III collaboration plans to release their beta asymmetry result, with $\frac{\Delta A}{A} \sim 2 \cdot 10^{-3}$, corresponding to $\frac{\delta\lambda}{\lambda} \sim 7 \cdot 10^{-4}$, any day now.

$\lambda = -1.2748(+13/-14)$ from D. Mund et al., PRL 110, 172502 (2013)

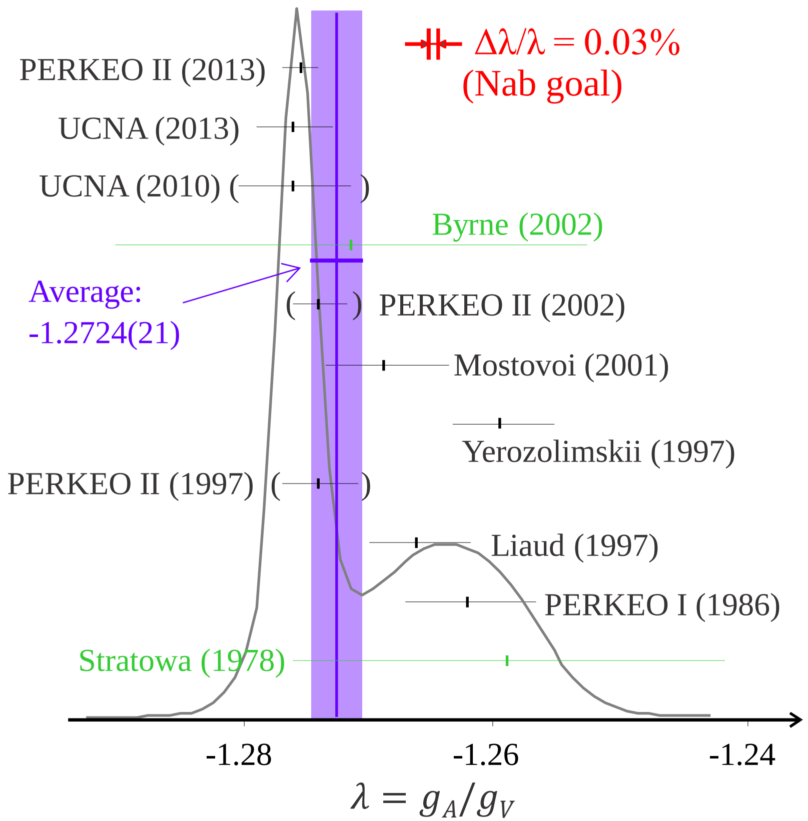
Determination of coupling constants

Determination of ratio $\lambda = g_A/g_V$ from
$A = -2(\mathrm{Re}\,\lambda + |\lambda|^2)/(1 + 3|\lambda|^2)$ or
$a = (1 - |\lambda|^2)/(1 + 3|\lambda|^2)$:



Determination of coupling constants

Determination of ratio $\lambda = g_A/g_V$ from
$A = -2(\mathrm{Re}\,\lambda + |\lambda|^2)/(1+3|\lambda|^2)$ or
$a = (1-|\lambda|^2)/(1+3|\lambda|^2)$:



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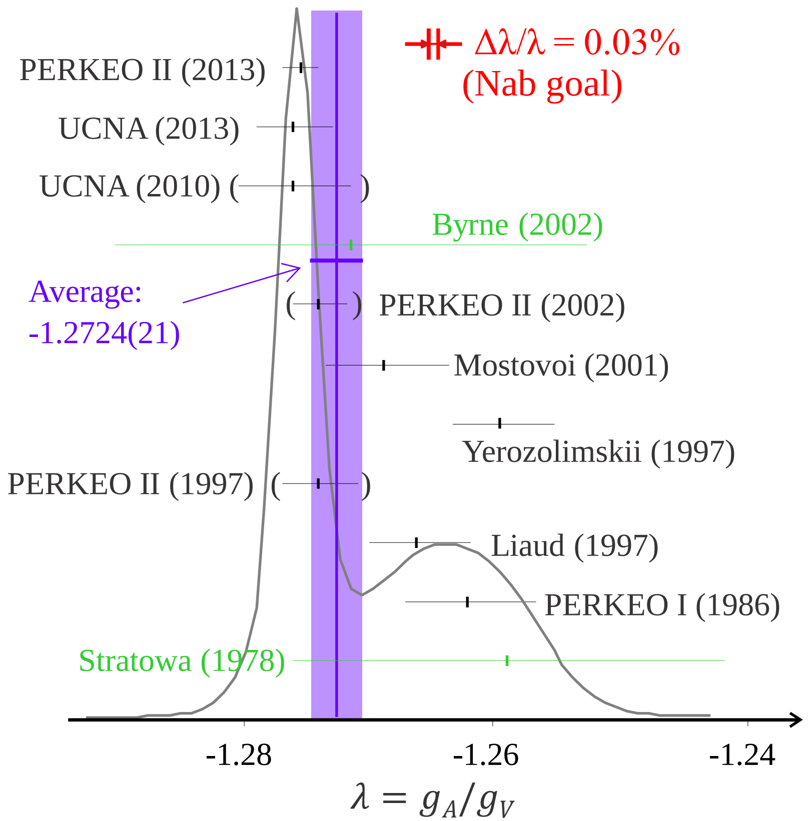
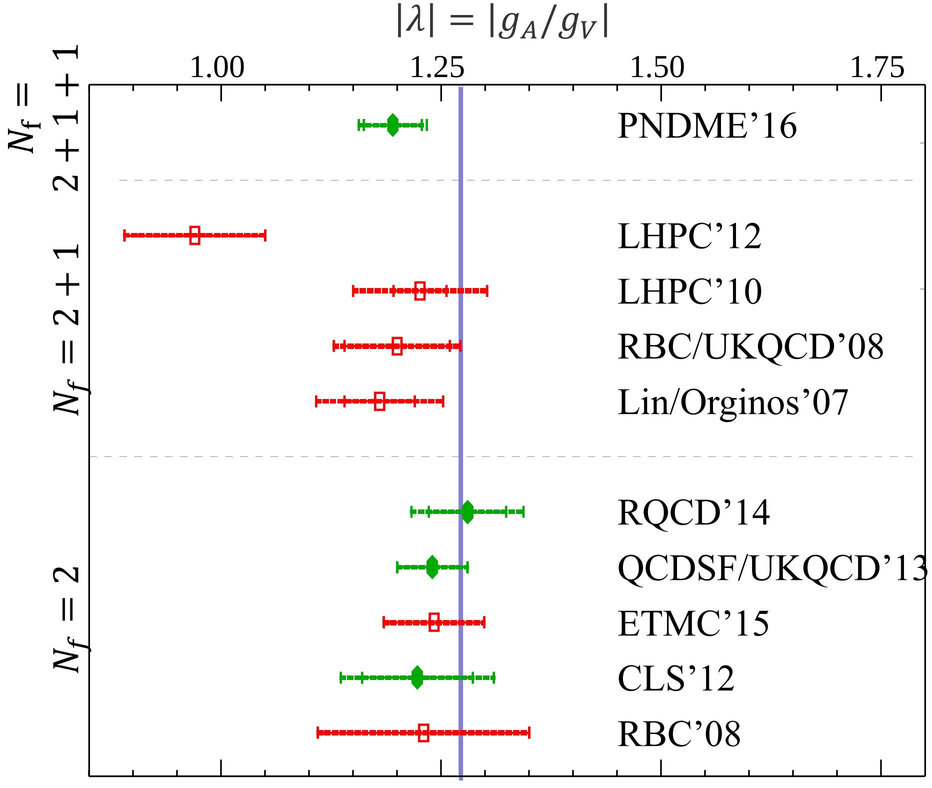
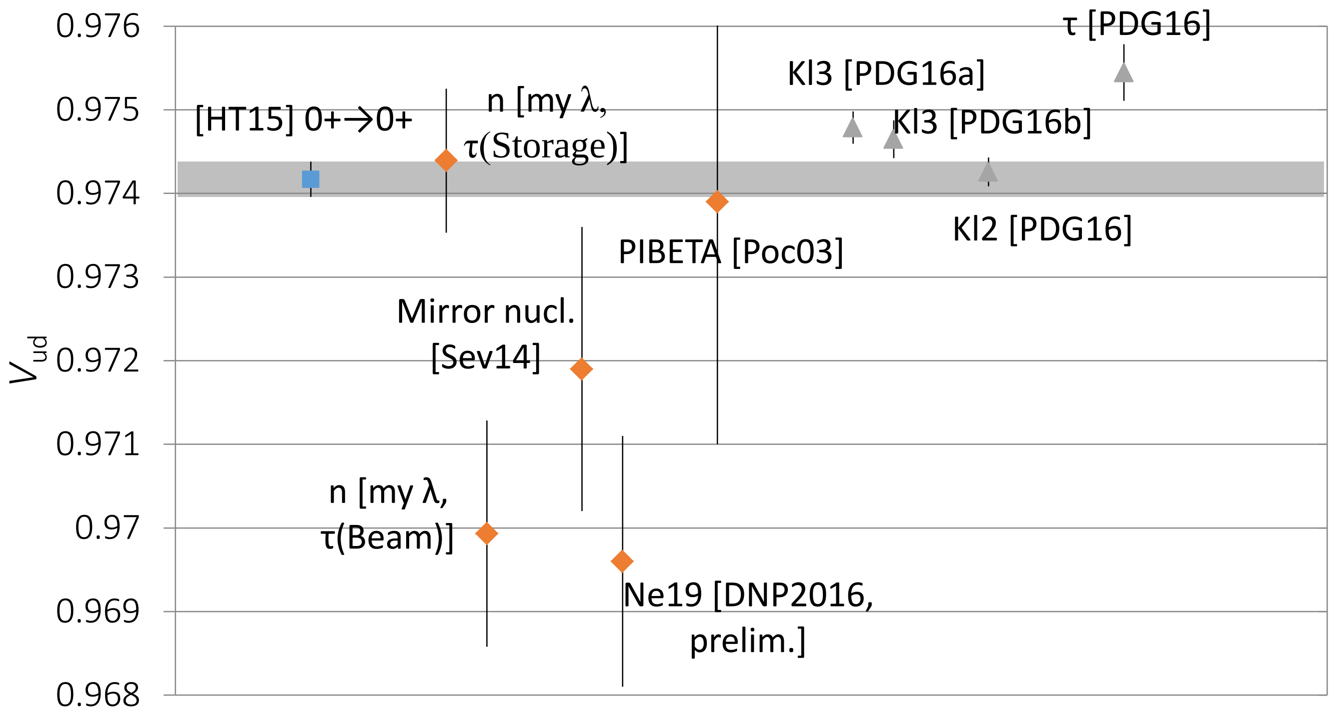


Note: λ should be fixed by standard model. However, precision of its calculation from first principles is insufficient:



Most recent 2+1+1 flavor Lattice-QCD result from PNDME: T. Bhattacharya et al., PRD 94, 054508 (2016)

Test of CKM unitarity in the first row.



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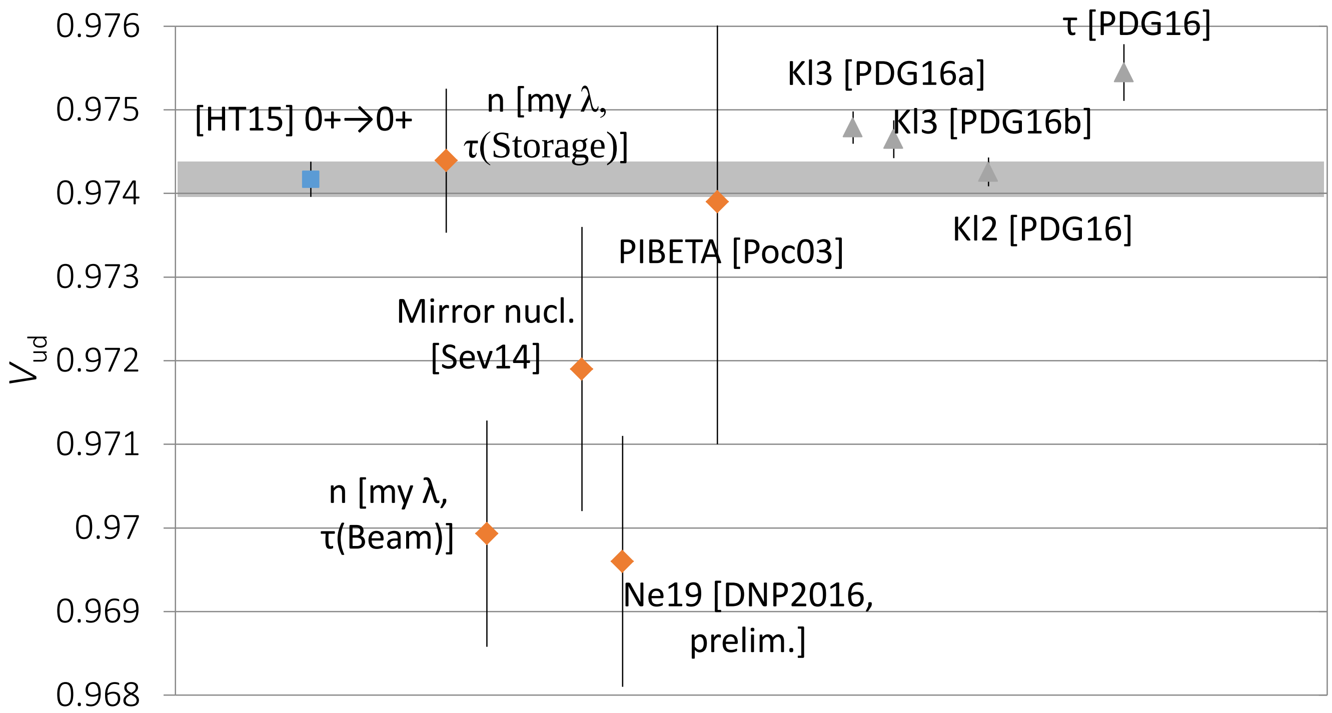


For neutron data to be competitive with superallowed decays, one wants:

1. $\Delta\tau_n/\tau_n \sim 0.3$ s

   (Neutron lifetime experiment underway were discussed earlier)

2. $\Delta\lambda/\lambda \sim 3 \cdot 10^{-4}$

The PERC facility @ FRM II

PERC facility:

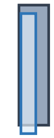
- Active decay volume in a 8 m long neutron guide
- e,p selector is magnetic Filter: phase space, systematics
- PERC can be coupled with various spectrometers
- PERC Magnet delivery planned for fall 2017
- Goal for beta asymmetry A:

$$\frac{\Delta A}{A} \leq 5 \cdot 10^{-4} \Leftrightarrow \frac{\Delta \lambda}{\lambda} \leq 2 \cdot 10^{-4}$$

(Requires 10^{-4} polarization control)!

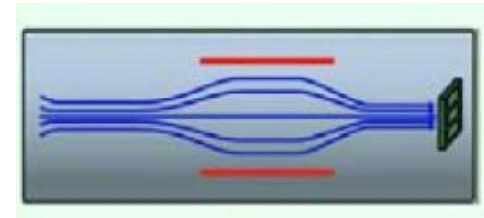
D. Dubbers et al., Nucl. Instr. Meth. A 596 (2008) 238 and arXiv:0709.4440

Electron or proton detector

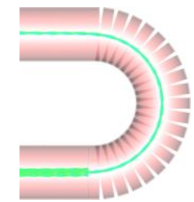


Scintillator (e-), Silicon, …

MAC-E filter (“aSPECT”)

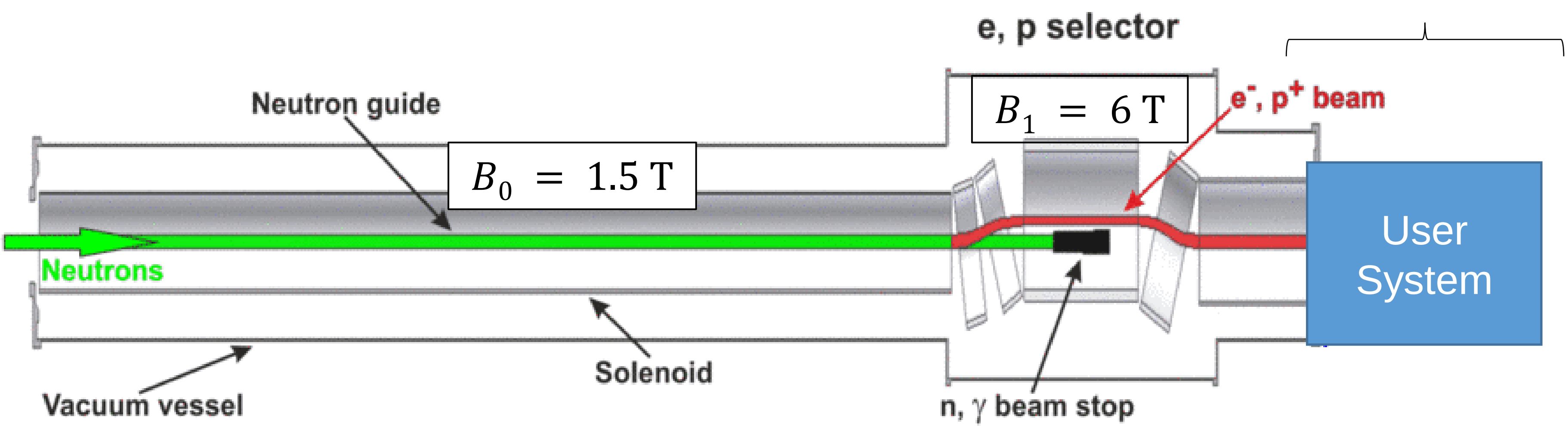


R×B spectrometer

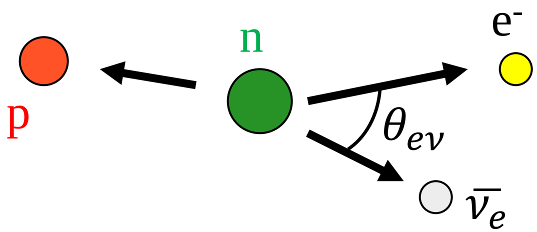


⋮

G. Konrad, SMI



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:

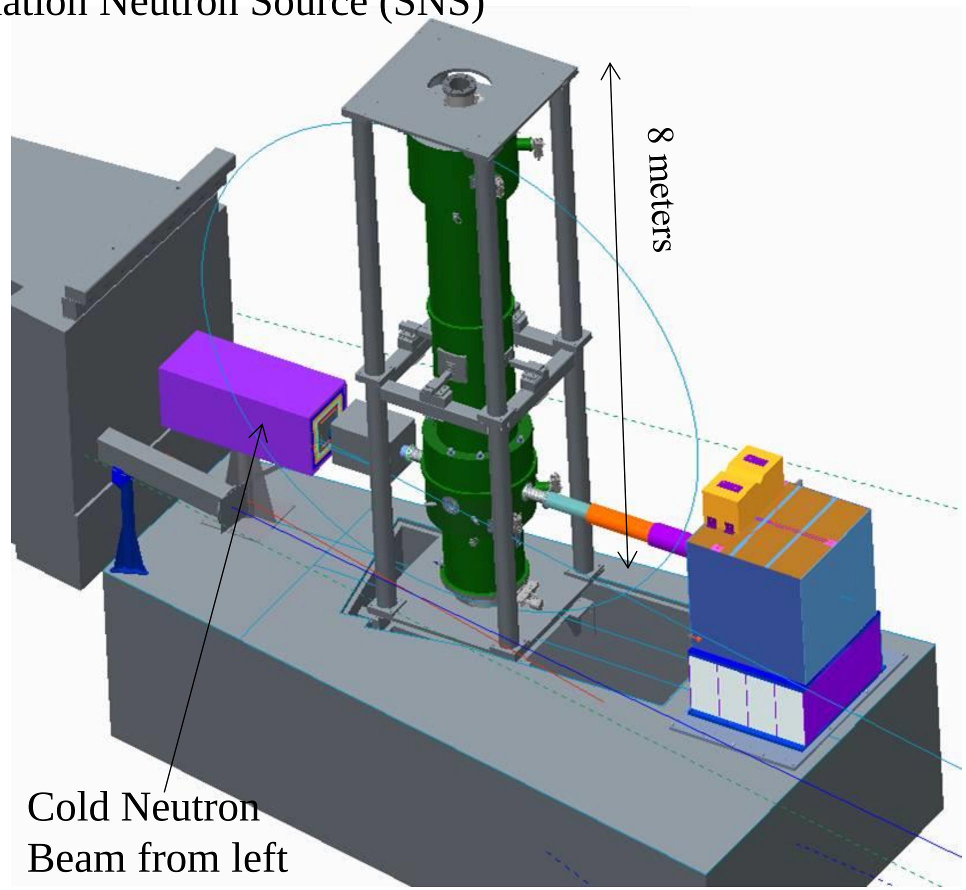
$$p_p^2 = p_e^2 + p_\nu^2 + 2p_e p_\nu \cos\theta_{e\nu}$$

Goal: Determine p_p^2, E_e spectrum

$$\frac{\Delta a}{a} \leq 10^{-3} \Leftrightarrow \frac{\Delta\lambda}{\lambda} \leq 3 \cdot 10^{-4}$$

(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)

What if the test of CKM unitarity fails?

Like all precision measurements, a failure of the unitarity test would not point to a single cause:
Various possibilities exist, among those are:

1. Heavy quarks:

$$\begin{pmatrix} d' \\ s' \\ b' \\ D' \end{pmatrix} = \begin{pmatrix} V_{ud} & V_{us} & V_{ub} & V_{uD} \\ V_{cd} & V_{cs} & V_{cb} & V_{cD} \\ V_{td} & V_{ts} & V_{tb} & V_{tD} \\ V_{Ed} & V_{Es} & V_{Eb} & V_{ED} \end{pmatrix} \cdot \begin{pmatrix} d \\ s \\ b \\ D \end{pmatrix}$$

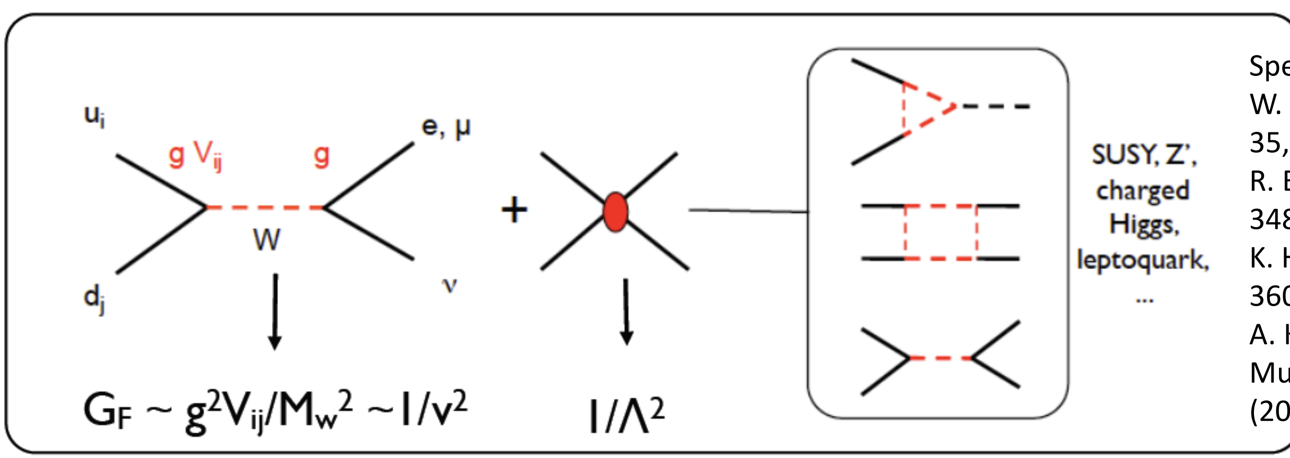
$$|V_{uD}|^2 = 1 - |V_{ub}|^2 - |V_{us}|^2 - |V_{ud}|^2$$

W. Marciano, A. Sirlin, PRL 56, 22 (1986)
P. Langacker, D. London, PRD 38, 886 (1988)

2. Exotic muon decays:

   All direct determinations of V_{ud} use G_F from muon lifetime. If the muon had additional decay modes ($\mu \rightarrow X + Y + \cdots$), G_F (and V_{ud}) would be determined wrong. E.g., $\mu^+ \rightarrow e^+ + \bar{\nu}_e + \nu_\mu$ (wrong neutrinos) would be very relevant for neutrino factories. K.S. Babu and S. Pakvasa, hep-ph/0204236

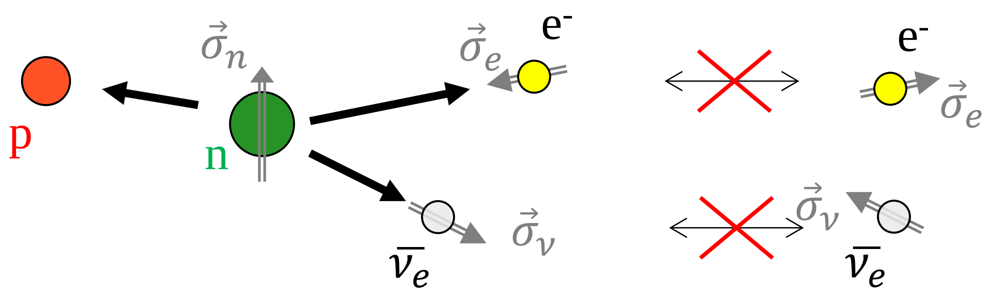
3. (Semi-)leptonic decays of nuclei through something other than exchange of $W^\pm$ bosons:



Specific models: E.g.
W. Marciano, A. Sirlin, PRD 35, 1672 (1987).
R. Barbieri et al., PLB 156, 348 (1985)
K. Hagiwara et al., PRL 75, 3605 (1995)
A. Kurylov, M. Ramsey-Musolf, PRL 88, 071804 (2000)

Energy scale of new physics: $\Lambda \geq 11$ TeV V. Cirigliano et al., NPB 830, 95 (2010)

Search for effective scalar (S) and tensor (T) interaction



Traditional low energy effective Lagrangian:

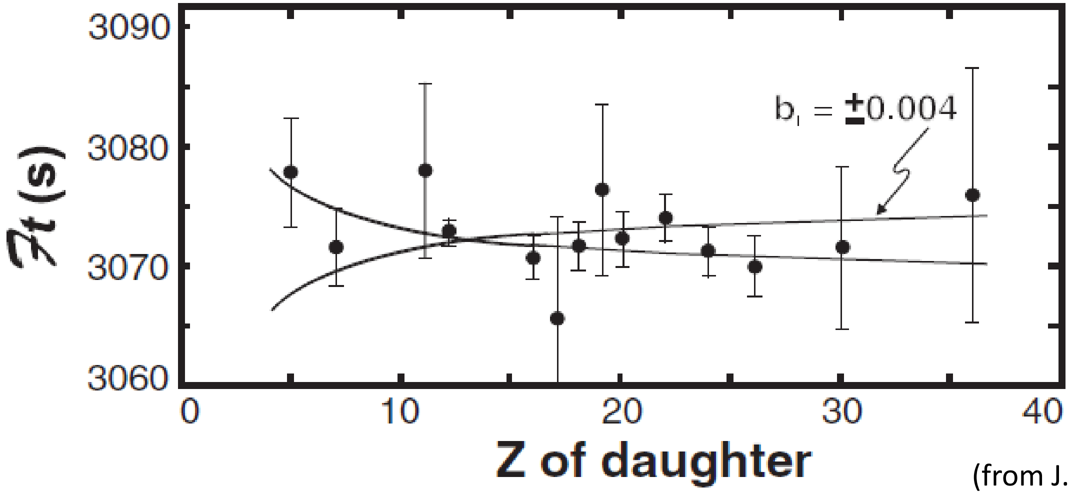
$$\begin{aligned}\mathcal{L}_{eff} = -\big[&C_V \bar{e}\gamma_\mu \nu_e \cdot \bar{p}\gamma^\mu n - C_V' \bar{e}\gamma_\mu\gamma_5 \nu_e \cdot \bar{p}\gamma^\mu n \\ &-\left(C_A \bar{e}\gamma_\mu\gamma_5 \nu_e \cdot \bar{p}\gamma^\mu \gamma_5 n - C_A' \bar{e}\gamma_\mu \nu_e \cdot \bar{p}\gamma^\mu\gamma_5 n\right) \\ &+C_S \bar{e}\nu_e \cdot \bar{p}n - C_S' \bar{e}\gamma_5\nu_e \cdot \bar{p}n \\ &+C_T \bar{e}\sigma_{\mu\nu}\nu_e \cdot \bar{p}\sigma^{\mu\nu} n - C_T' \bar{e}\sigma_{\mu\nu}\gamma_5\nu_e \cdot \bar{p}\sigma^{\mu\nu} n \\ &+C_P \cdot \bar{e}\gamma_5\nu_e \cdot \bar{p}\gamma_5 n - C_P' \cdot \bar{e}\nu_e \cdot \bar{p}\gamma_5 n \\ &+\text{h.c.}\big]\end{aligned}$$

- In SM, $C_V = C_V' = 1$, $C_A = C_A' = \lambda$, all others zero.
- The Fierz term is unique in that it is the only term that is first-order sensitive to S,T

$$\text{Decay rate} \propto \varrho(E)\left(1 + b\frac{m_e}{E}\right)$$

Search for effective scalar (S) and tensor (T) interaction

1. Low-Energy search for scalar current: Determine Fierz term $b_F = -(C_S + C_S')/C_V$ in superallowed Fermi decays: J. Hardy, I. Towner find $\frac{C_S + C_S'}{2C_V} = 0.0014(21)$ (90% CL)



(from J. Hardy, I. Towner, PRC 91, 025501 (2015))

Improvements possible with measurements using light nuclei

Search for effective scalar (S) and tensor (T) interaction

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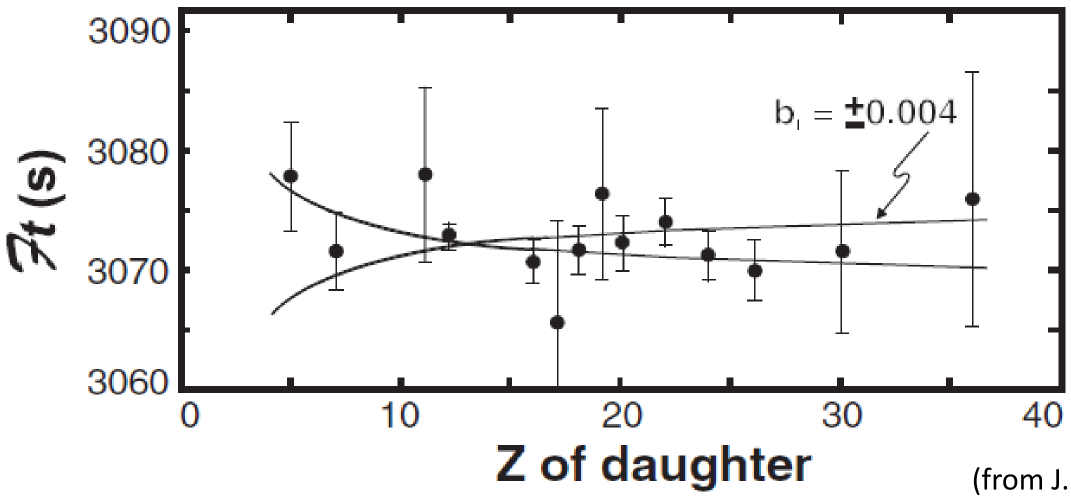

(from J. Hardy, I. Towner, PRC 91, 025501 (2015))

Improvements possible with measurements using light nuclei

2. Using this, and combination of $\mathcal{F}t^{-1} \propto \left(1 + b_F \frac{\gamma m_e}{E}\right)$, $\tau_n^{-1} \propto (1 + 3\lambda^2)\left(1 + b_n \frac{m_e}{E}\right)$ with $b_n \propto \left[\frac{C_S+C_S'}{C_V} + 3\frac{C_T+C_T'}{C_A}\right]$, and beta symmetry $A = A_0/\left(1 + b_n \frac{m_e}{E}\right)$ (for λ):

   R.W. Pattie et al. get $\frac{C_T+C_T'}{2C_A} = -0.0007(27)$ (90% CL)

   from R.W. Pattie Jr., PRC 88, 048501 (2013) & PRC 92, 069902(E) (2015)

   SB 2016 update: $\frac{C_T+C_T'}{2C_A} = -0.0009(24)$ (90% CL) after G. Konrad, ArXiV:1007:3027

   Resolution of neutron lifetime issue would give large improvement.

Effective field theory for beta decay at quark level

Effective low-energy Lagrangian:

$$\mathcal{L}_{eff} = -\frac{G_F V_{ud}}{\sqrt{2}}\Big[(1+\epsilon_L)\cdot \bar{e}\gamma_\mu(1-\gamma_5)\nu_e \cdot \bar{u}\gamma^\mu(1-\gamma_5)d$$
$$+\epsilon_R \cdot \bar{e}\gamma_\mu(1-\gamma_5)\nu_e \cdot \bar{u}\gamma^\mu(1+\gamma_5)d$$
$$+\epsilon_S \cdot \bar{e}(1-\gamma_5)\nu_e \cdot \bar{u}d$$
$$+\epsilon_T \cdot \bar{e}\sigma_{\mu\nu}(1-\gamma_5)\nu_e \cdot \bar{u}\sigma^{\mu\nu}(1-\gamma_5)d$$
$$-\epsilon_P \cdot \bar{e}\gamma_\mu(1-\gamma_5)\nu_e \cdot \bar{u}\gamma_5 d$$
$$+\text{ terms with } \tilde{\epsilon} \text{ that involve righthanded } \nu_e$$
$$+\text{h.c.}\Big]$$

Unobservable, suppressed with q/M_N

Unobservable, all corr. coeff. only sensitive in second order

Connection with traditional coupling constants from nuclear and neutron physics:

$$\frac{C_V + C_V'}{2} = \frac{G_F V_{ud}}{\sqrt{2}} g_V(1+\epsilon_L+\epsilon_R)$$
$$\frac{C_A + C_A'}{2} = -\frac{G_F V_{ud}}{\sqrt{2}} g_A(1+\epsilon_L-\epsilon_R)$$
$$\frac{C_S + C_S'}{2} = \frac{G_F V_{ud}}{\sqrt{2}} g_S\epsilon_S$$
$$\frac{C_T + C_T'}{2} = \frac{G_F V_{ud}}{\sqrt{2}} 4 g_T\epsilon_T$$

$$\bar{u}d = g_S\bar{p}n$$
$$\bar{u}\sigma_{\mu\nu}d = g_T\bar{p}\sigma_{\mu\nu}n$$
$$\ldots$$

Scalar(S) and tensor(T) interactions in beta decay

Other searches for Beyond Standard Model Physics: S,T interactions (fermions with “wrong” helicity), e.g. through W’ bosons; weak magnetism; second class currents; …

PHYSICAL REVIEW D **85,** 054512 (2012)

Probing novel scalar and tensor interactions from (ultra)cold neutr

Tanmoy Bhattacharya,[1] Vincenzo Cirigliano,[1] Saul D. Cohen,[2,5] Alberto Filipuzzi,[3] Mar
Michael L. Graesser,[1] Rajan Gupta,[1] and Huey-Wen Lin[5]
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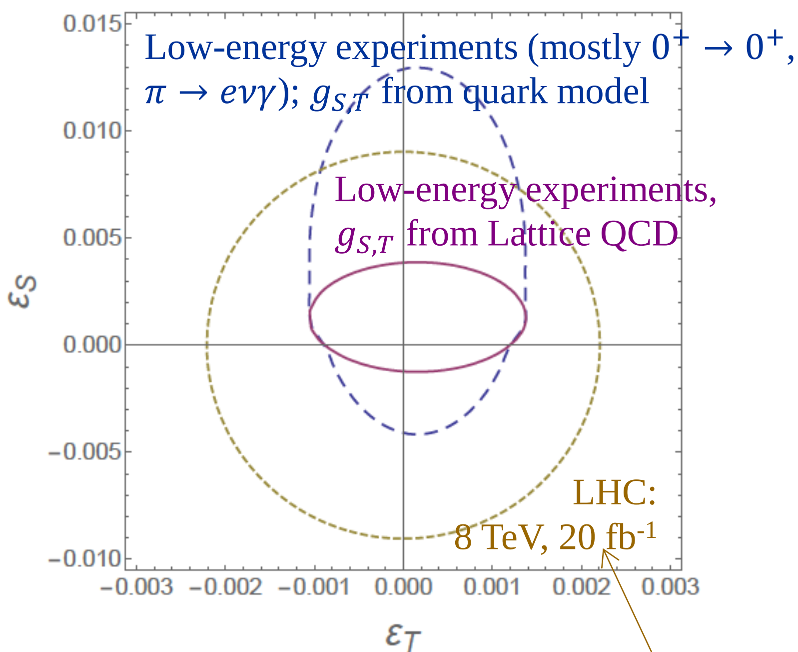
[2]*Center for Computational Science, Boston University, Boston, Massachusetts 02*
[3]*Departament de Física Teòrica, IFIC, Universitat de València-CSIC Apt. Correus 22085, E-4*
[4]*Department of Physics, University of Wisconsin-Madison, 1150 University Avenue, Madison,*
[5]*Department of Physics, University of Washington, Seattle, Washington 98195*
(Received 18 November 2011; published 30 March 2012)

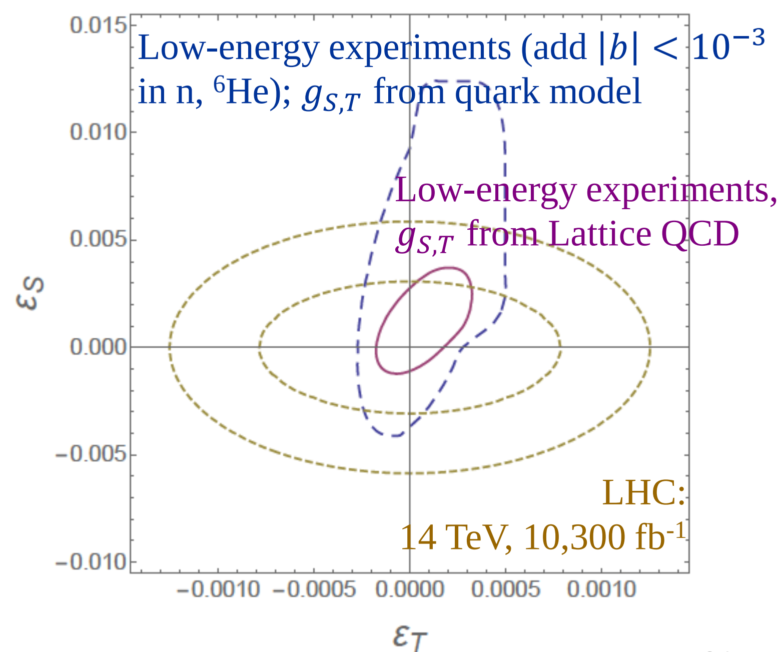
Scalar and tensor interactions were once competitors to the now well-established $V - A$
standard model weak interactions. We revisit these interactions and survey constraints f

PHYSICAL REVIEW D **94,** 054508 (2016)

Axial, scalar, and tensor charges of the nucleon from 2 + 1 + 1-flavor Lattice QCD

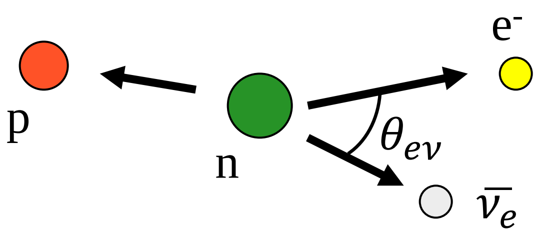
Tanmoy Bhattacharya,[1,*] Vincenzo Cirigliano,[1,†] Saul D. Cohen,[2,‡] Rajan Gupta,[1,§]
Huey-Wen Lin,[3,‖] and Boram Yoon[1,¶]
(Precision Neutron Decay Matrix Elements (PNDME) Collaboration)
[1]*Los Alamos National Laboratory, Theoretical Division T-2, Los Alamos, New Mexico 87545, USA*
[2]*Institute for Nuclear Theory, University of Washington, Seattle, Washington 98195, USA*
[3]*Physics Department, University of California, Berkeley, California 94720, USA*
(Received 14 July 2016; published 19 September 2016)



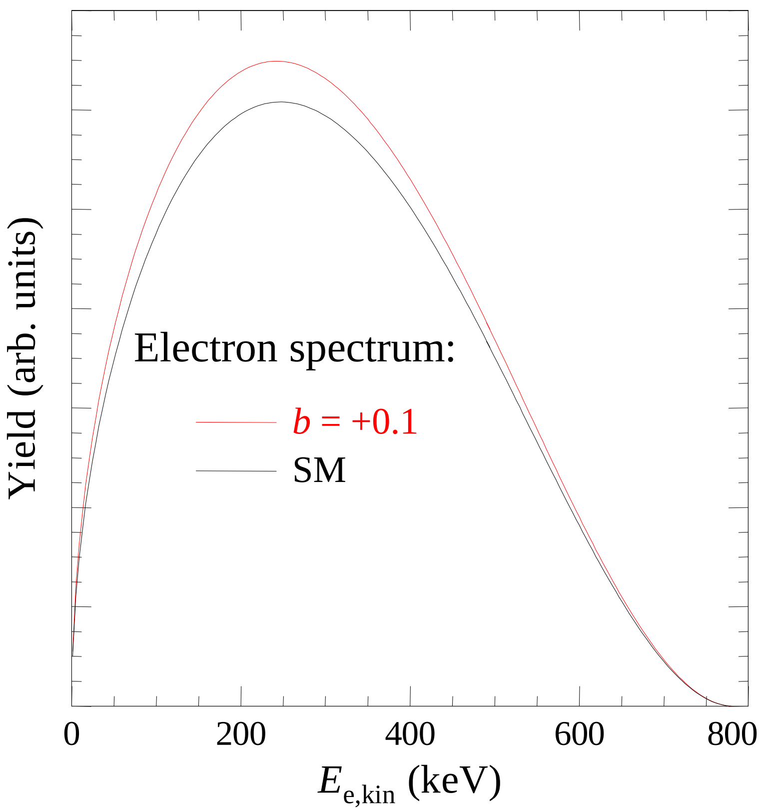


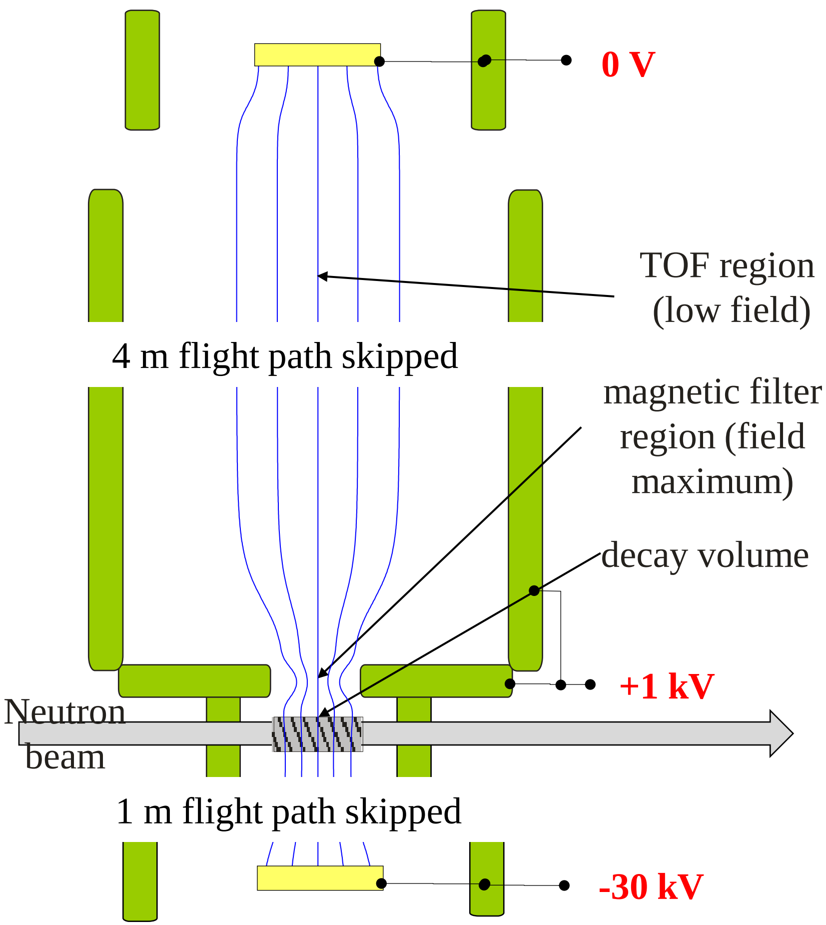
LHC-Search for $pp \to e + \nu +$ other stuff and $pp \to e + e +$ other stuff

The determination of the Fierz Interference term *b* in neutron decay with Nab



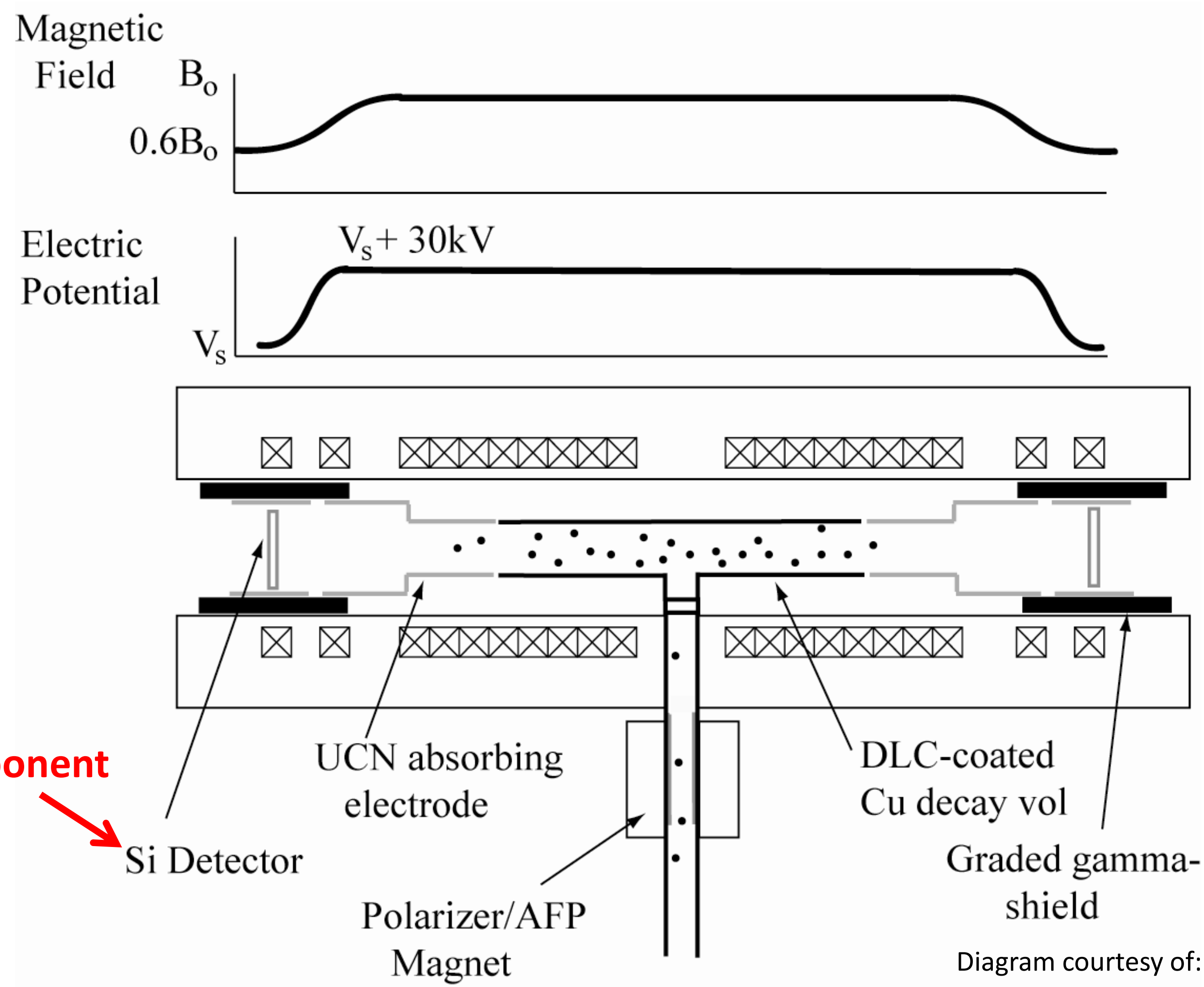
$$d\Gamma \propto \varrho(E_e)\left(1 + a\frac{p_e}{E_e}\cos\theta_{e\nu} + b\frac{m_e}{E_e}\right)$$





Goal: $b_n \leq 3 \cdot 10^{-3}$

The determination of the Fierz Interference term b_ν in neutron decay with UCNB @ LANL



Key component

Diagram courtesy of: Albert Young

$$B_{exp} = \frac{N^{--} - N^{++}}{N^{--} + N^{++}} \propto \frac{B + b_\nu m_e/E}{1 + b m_e/E}$$

Goal: $b_\nu \leq (2..3) \cdot 10^{-3}$

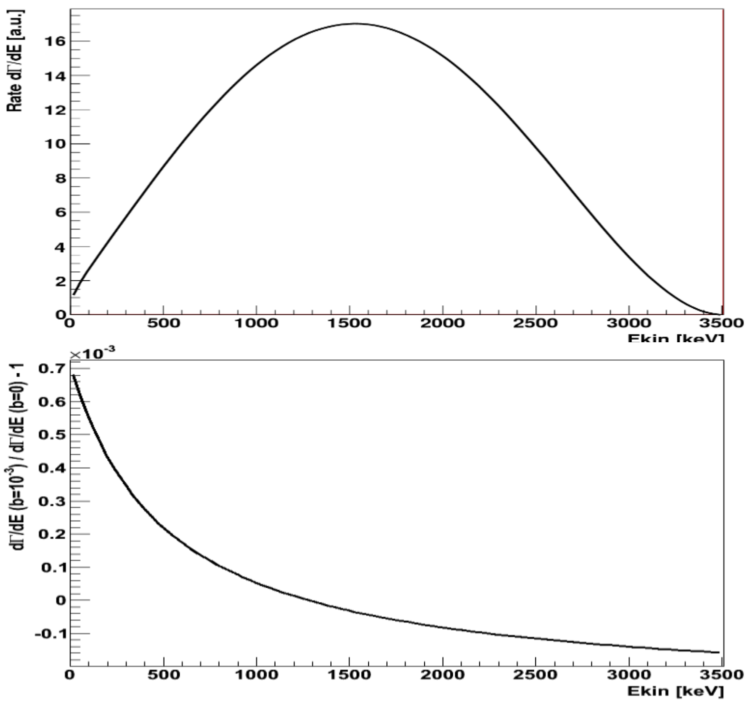
Fierz interference term *b* from He-6 beta decay

M. Fertl[1], A. Garcia[1], M. Guigue[4], P. Kammel[1], A. Leredde[2], P. Mueller[2], R.G.H. Robertson[1], G. Rybka[1], G. Savard[2], D. Stancil[3], M. Sternberg[1], H.E. Swanson[1], B.A. Vandeevender[4], A. Young[3]

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

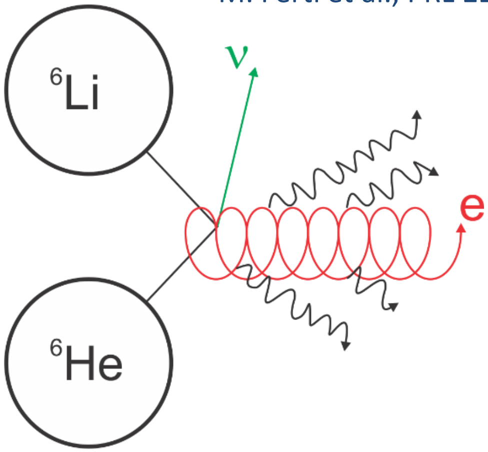
Goal: measure "little *b*" to 10^{-3} or better in ^{6}He

Statistics not a problem.

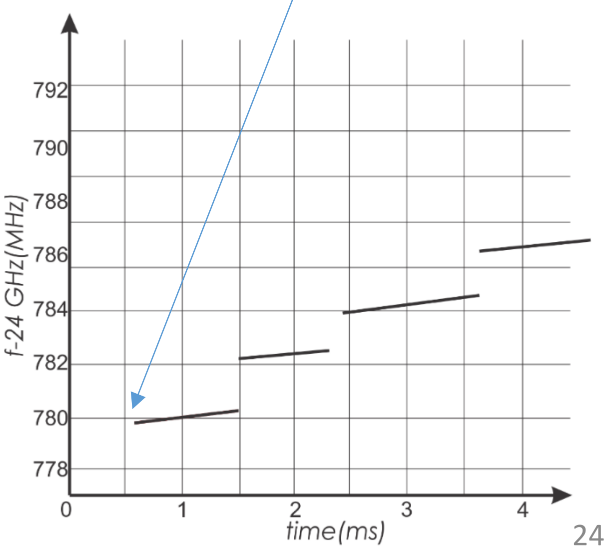


Use cyclotron radiation spectroscopy.
Similar to Project 8 setup for tritium decay.

M. Fertl et al., PRL **114**, 162501 (2015)



Determine e's energy at birth



Summary and outlook

- Measurement of coupling constants in weak interaction allows test of the unitarity of the CKM matrix is most precisely done in the first row; some tension (again). Substantial improvement of precision not in sight.
- Measurement of Fierz term in beta decay allows the search for new physics that manifests itself at low energies as scalar and/or tensor interaction. This is competitive to searches at LHC, and experimental improvements are likely in the near future.
- The latter needs form factors (g_S and g_T) to connect nuclear and quark-level description. Recent work in theory (Lattice QCD) determined them at the 10% level. Experimental verification desirable.

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Thank you for your attention!