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Fundamental Tensor Charge from Experiments

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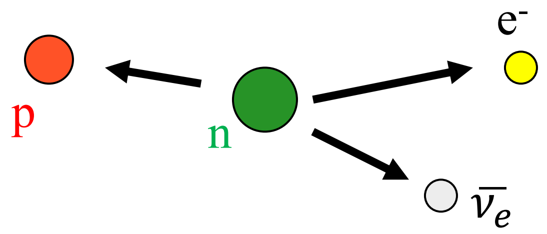
University of Virginia and Oak Ridge National Lab

Outline

- Test of the unitarity of the CKM matrix in the first row with neutron beta decay
- Hints for a tensor charge at the nucleon level from neutron beta decay
- How to interpret a non-zero tensor charge at the nucleon level



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Standard model physics: Quark mixing

- Is the Cabbibo Kobayashi Maskawa (CKM) matrix unitary?

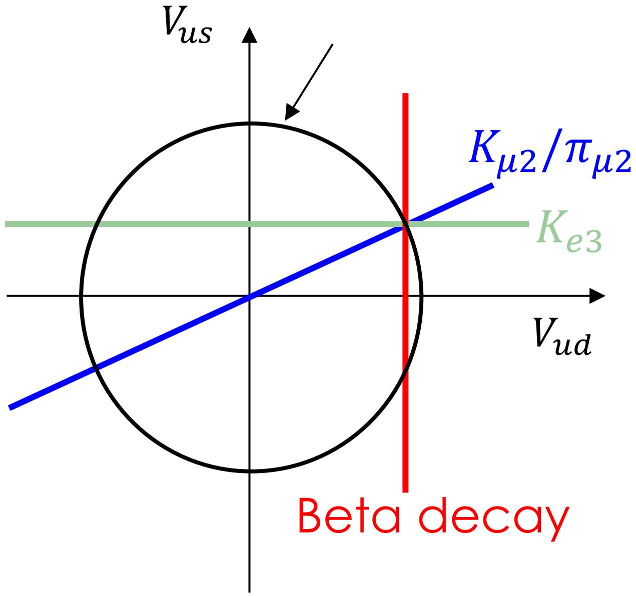
$$\begin{pmatrix} d' \\ s' \\ b' \end{pmatrix} = \begin{pmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{pmatrix} \cdot \begin{pmatrix} d \\ s \\ b \end{pmatrix}$$

- Most precise test:

$$|V_{ud}|^2 + |V_{us}|^2 + \cancel{|V_{ub}|^2} \stackrel{?}{=} 1$$

negligible

CKM Unitarity:
$|V_{ud}|^2 + |V_{us}|^2 = 1$



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

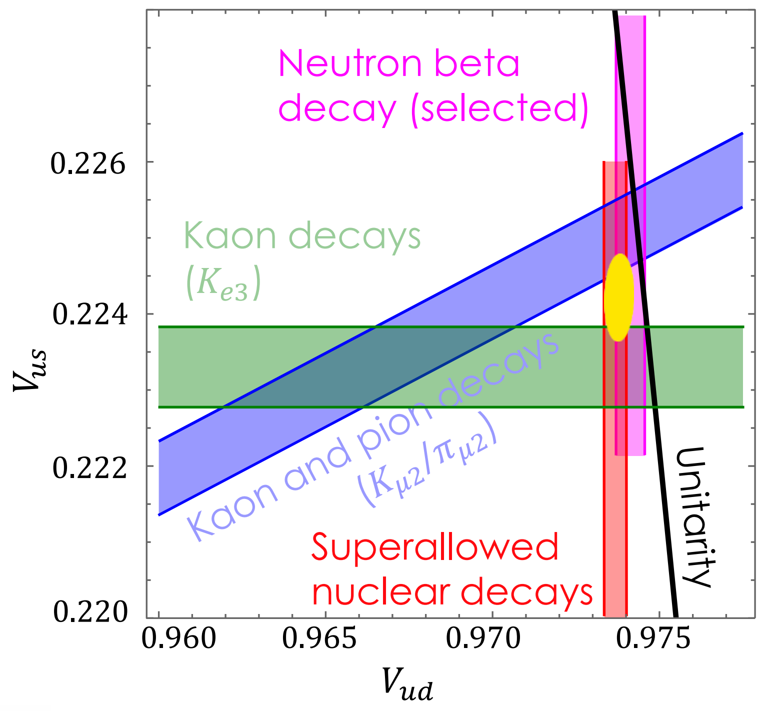
- With superallowed beta decay and select neutron beta decay - 2.8σ deviation – see picture.

- Only superallowed beta decay and several(?) scale factors:

$$|V_{ud}|^2 + |V_{us}|^2 + |V_{ub}|^2 = 0.9983(6)(4) \overset{!}{<} 1$$

negligible

From: PDG 2025



From: 2023 Nuclear Physics Long Range Plan for Nuclear Science, similar to Cirigliano et al., Phys. Lett. B 838 (2023) 137748

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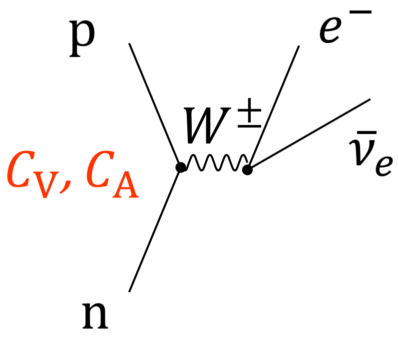
Observables in Neutron beta decay



Coupling constants in weak interaction:

Vector coupling: $C_V = V_{\mathrm{ud}} \cdot G_{\mathrm{F}}$

Axialvector coupling: $C_A = V_{\mathrm{ud}} \cdot G_{\mathrm{F}} \cdot \lambda$

$$\lambda = \frac{C_A}{C_V}$$

Fermi constant G_{F} is precisely known from muon lifetime

Observables in neutron beta decay, as a function of coupling constants:

$$\tau_n^{-1} \propto \left(C_V^2 + 3C_A^2\right) = V_{\mathrm{ud}} \cdot G_{\mathrm{F}}(1 + 3\lambda^2)$$

Nonzero b or b_ν indicates S,T

$B_0 \neq B_0(\lambda)$ indicates V+A

$$\frac{d^3\Gamma}{dE_e d\Omega_e d\Omega_\nu} \propto \rho(E_e)\left[1 + a\frac{p_e}{E_e}\cos(\vec{p}_\nu, \vec{p}_e) + b\frac{m_e}{E_e} + A\frac{p_e}{E_e}\cos(\vec{\sigma}_n, \vec{p}_e) + \left(B_0 + b_\nu \frac{m_e}{E_e}\right)\cos(\vec{\sigma}_n, \vec{p}_\nu)\right]$$

J.D. Jackson et al., PR 106, 517 (1957)

$a = a(\lambda)$

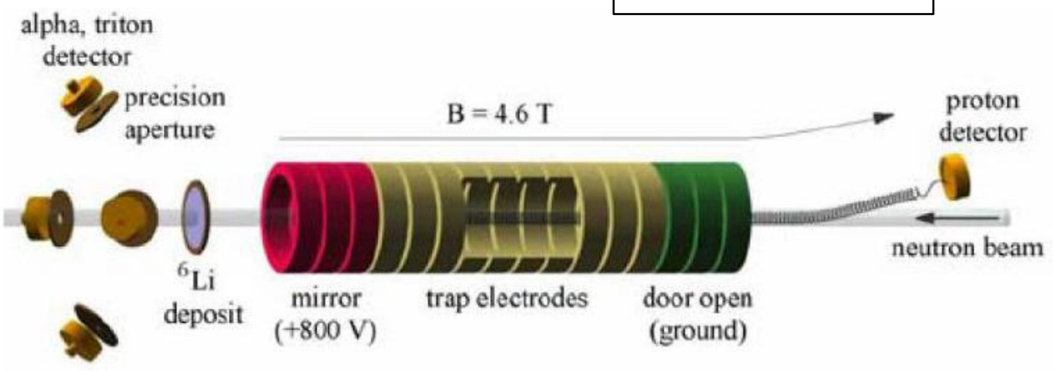
$A = A(\lambda)$

- SM analysis: Combine neutron lifetime with either beta asymmetry A or neutrino electron correlation a to determine V_{ud} and test unitarity of CKM matrix.
- BSM analysis: determine Fierz term b or neutrino Fierz term b_ν (THIS CONFERENCE!)

Experiments: Neutron Lifetime

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

NIST-BL1/2/3



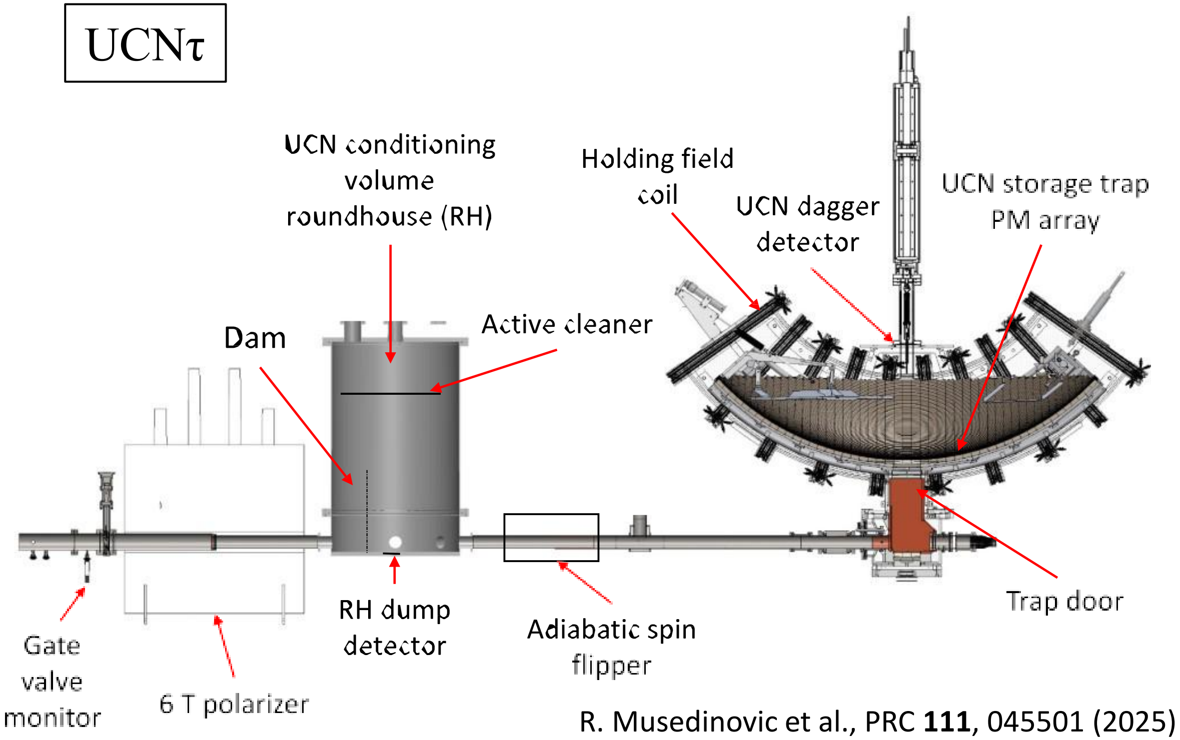
J.S. Nico et al., PRC **71**, 055502 (2005)

$$\tau_{\mathrm{n,beam-average}} = 888.0(20)\ \mathrm{s}$$

Bottle: Neutron counts: $N = N_0 e^{-\frac{t}{\tau_{eff}}}$

with $\frac{1}{\tau_{eff}} = \frac{1}{\tau_n} + \frac{1}{\tau_{wall}} + \frac{1}{\tau_{gas}}$

UCNτ



R. Musedinovic et al., PRC **111**, 045501 (2025)

$$\tau_{\mathrm{n,bottle-average}} = 878.4(5)\ \mathrm{s}$$

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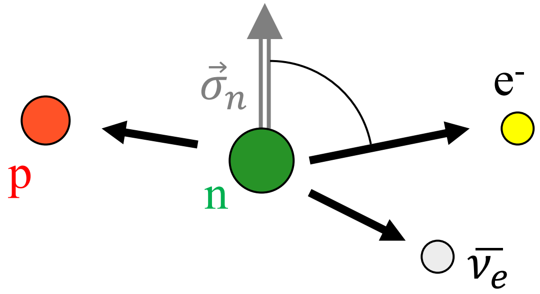
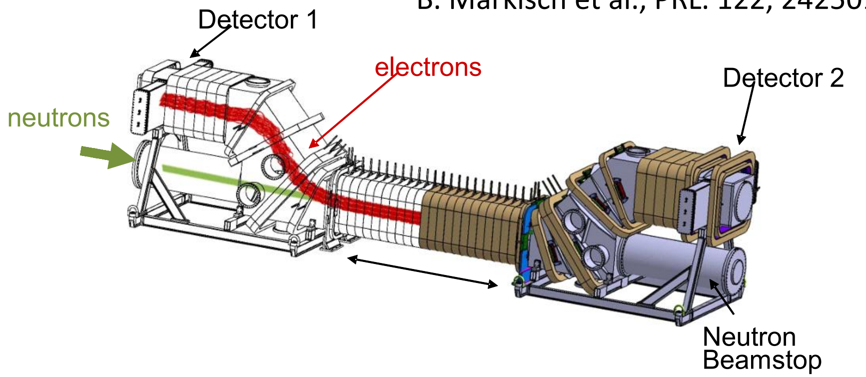
Experiments: The beta asymmetry A



$$\frac{d^2\Gamma}{dE_e d\Omega_e} \propto \rho(E_e)\left[1 + A\frac{p_e}{E_e}\cos(\vec{\sigma}_n, \vec{p}_e)\right]$$

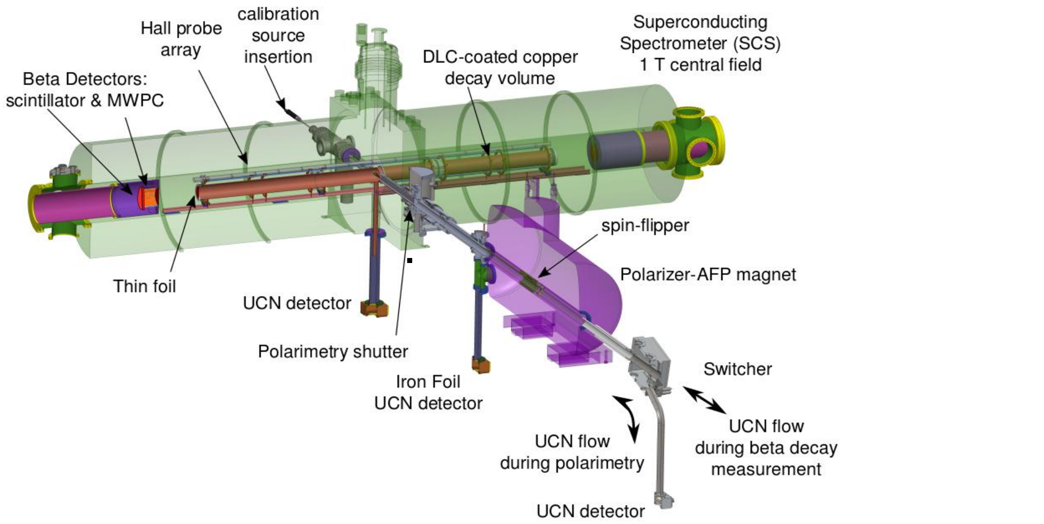
PERKEO III - SM: $A = -0.12015(34)_{stat}\ (63)_{sys}$

B. Märkisch et al., PRL. 122, 242501 (2019)

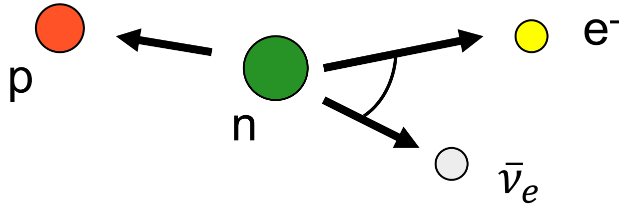


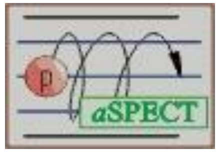
UCNA - SM: $A = -0.12015(34)_{stat}\ (63)_{sys}$

M. Brown et al., PRC **97,** 035505 (2018)



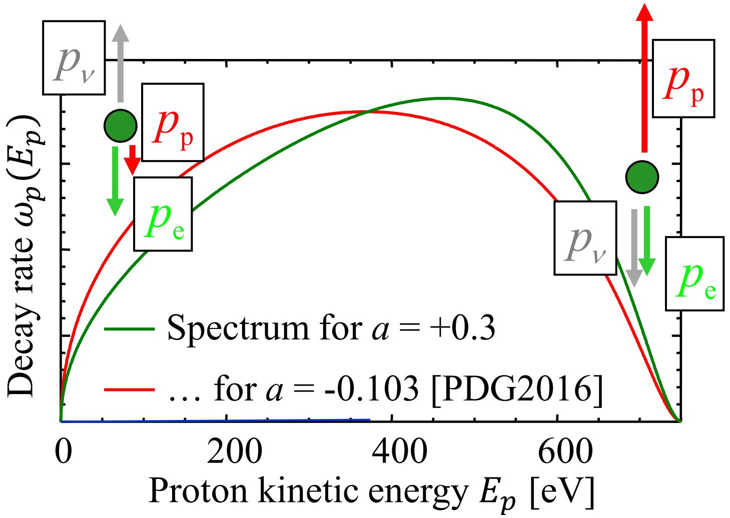
The neutrino electron correlation coefficient a

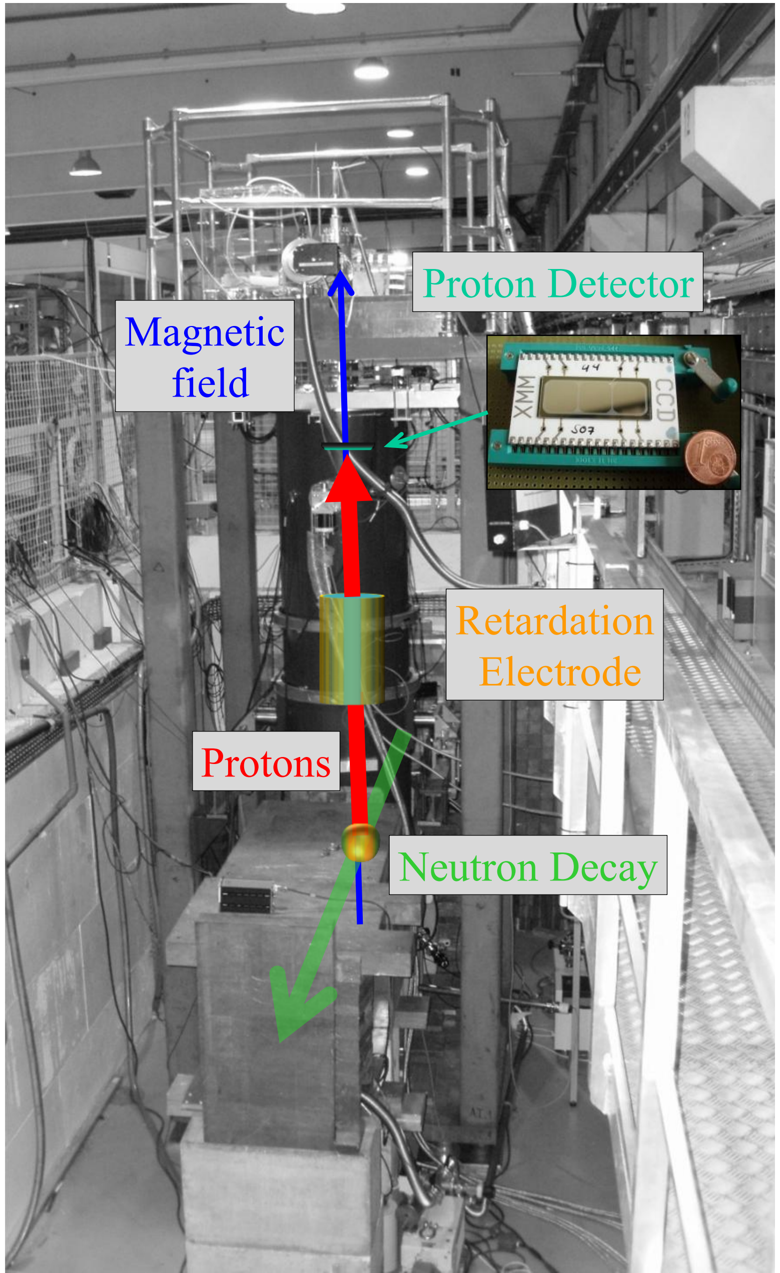




$$\frac{d^3\Gamma}{dE_e d\Omega_e d\Omega_\nu} \propto \rho(E_e)\left[1 + a\frac{p_e}{E_e}\cos(\vec{p}_\nu, \vec{p}_e)\right]$$

C.F. v. Weizsäcker, Z. f. Phys. 102,572 (1936), M. Fierz, Z. f. Phys. 104, 553 (1937)





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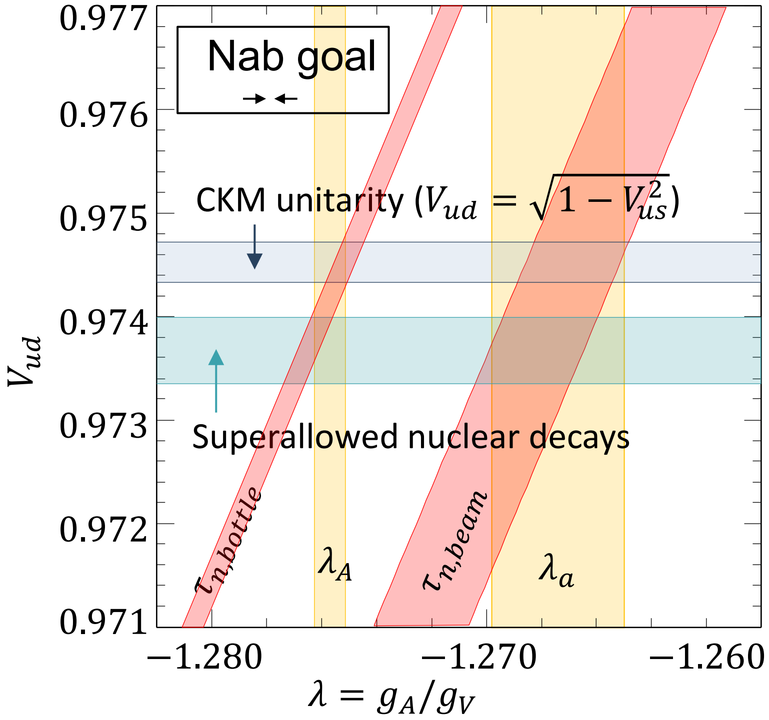
Status of V_{ud} from neutron beta decay

- V_{ud} from neutron beta decay

$$|V_{ud}|^2 = \frac{5099.33\ \text{s}}{\tau_n(1+3\lambda^2)(1+\Delta_R)}$$

- Neutron beta decay data inconsistent (in SM).

(data up to 2025)



The SM requires $\lambda_a = \lambda_A$. The discrepancy needs resolution.

Could be that at least one experiment is wrong. OR ...

"One needs to discuss the results one has, not the ones one wants to have…" (K. Kleinknecht)

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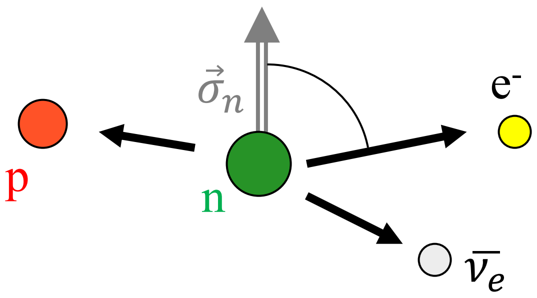
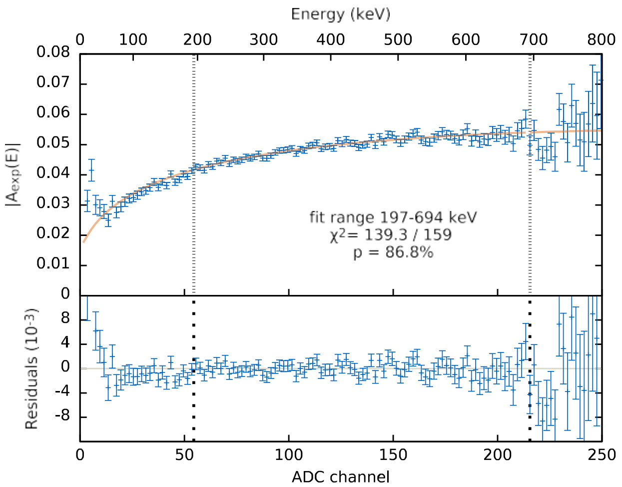
BSM analysis: The beta asymmetry A



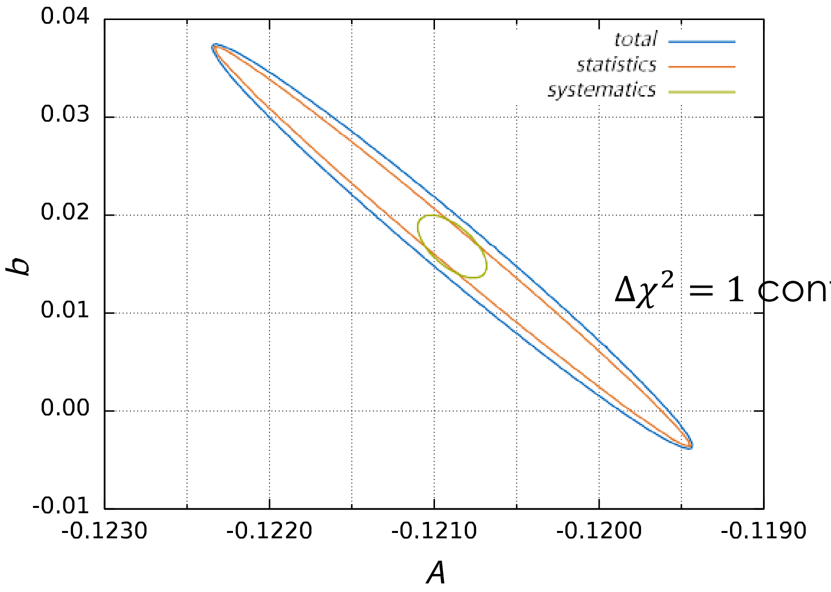
$$\frac{d^2\Gamma}{dE_e d\Omega_e} \propto \rho(E_e)\left[1 + b\frac{m_e}{E_e} + A\frac{p_e}{E_e}\cos(\vec{\sigma}_n, \vec{p}_e)\right]$$

$$|A_{exp}| = \frac{N^\uparrow - N^\downarrow}{N^\uparrow + N^\downarrow} \propto |A|\beta/2(1 + b\frac{m_e}{E_e})$$



PERKEO III - BSM: $b = 0.017(20)_{stat}\ (3)_{sys}$

H. Saul et al., PRL 125, 112501 (2020)



UCNA - BSM: $b = 0.066(41)_{stat}\ (24)_{sys}$

X. Sun et al., PRC 101, 035503 (2020)

Takeaway: More negative A looks similar to positive b

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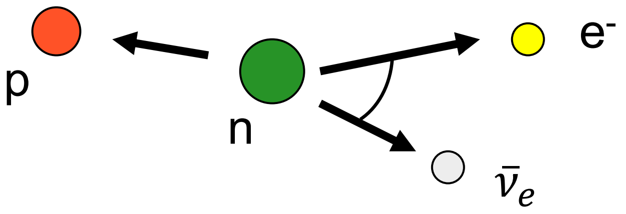
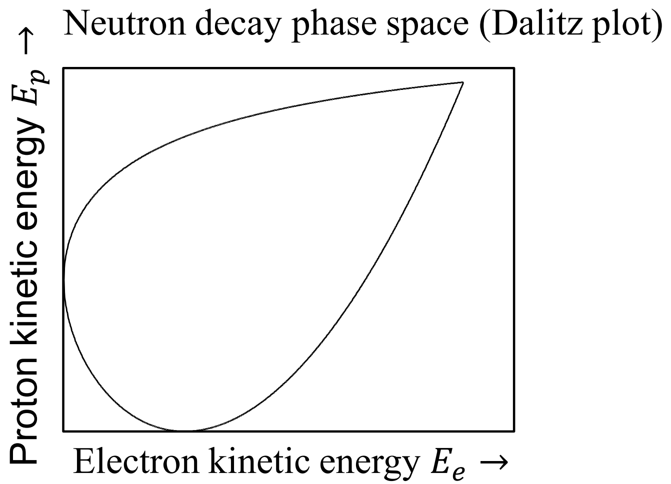
The neutrino electron correlation coefficient a



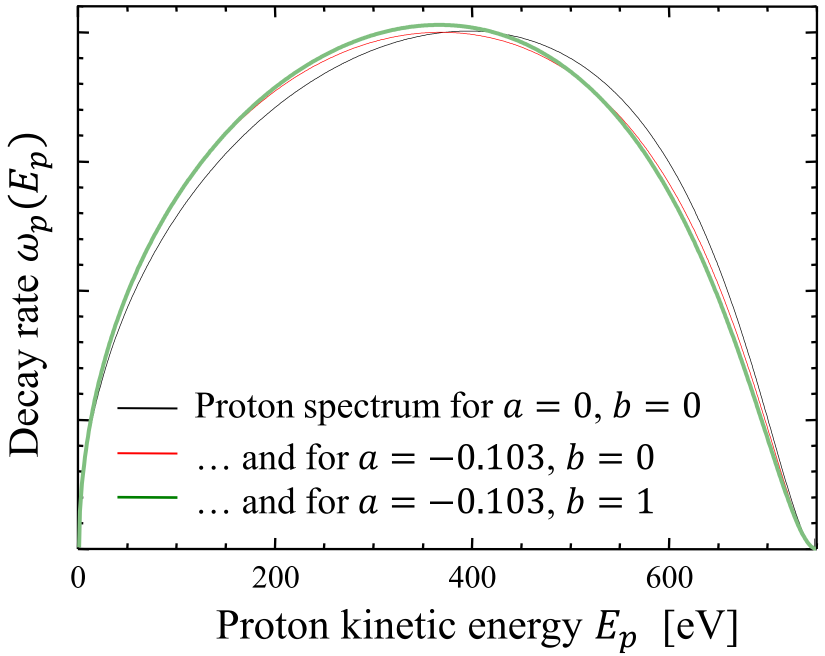
$$\frac{d^3\Gamma}{dE_e d\Omega_e d\Omega_\nu} \propto \rho(E_e)\left[1 + a\frac{p_e}{E_e}\cos(\vec{p}_\nu, \vec{p}_e) + b\frac{m_e}{E_e}\right]$$

C.F. v. Weizsäcker, Z. f. Phys. 102,572 (1936), M. Fierz, Z. f. Phys. 104, 553 (1937)

Sensitivity of the proton spectrum to *a* and *b*:



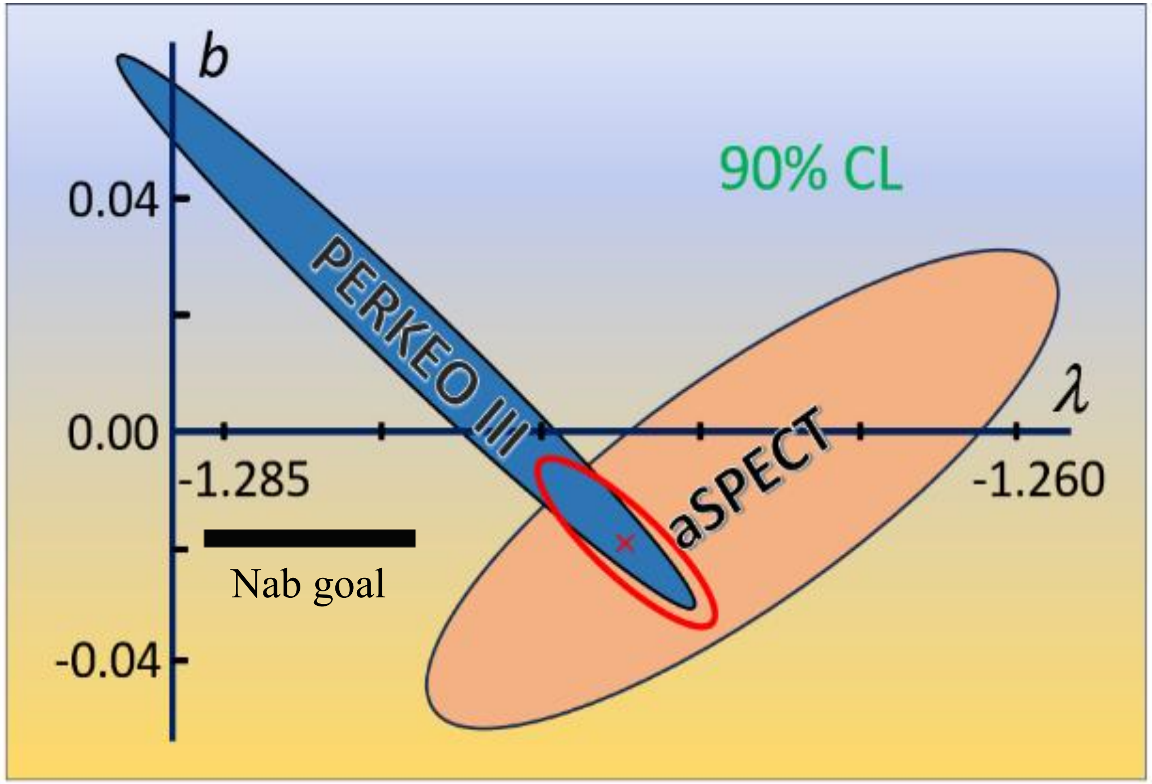
Positive b means more low energy electrons, and more low and mid-energy protons



Takeaway: More negative a looks similar to positive b

Possible resolution / Search for tensor currents

- Neither beta asymmetry nor neutrino-electron correlation measurements alone favor non-zero Fierz term.
- The combination does, reconciles λ values and requires $b_c = -0.0184(65)$
- Goal of Nab-b:
  $$\Delta b \leq 3 \cdot 10^{-3}$$



Plot from: W. Heil (Mainz)

Re-analyzed aSPECT result: M. Beck et al., PRL 132, 102501 (2024)

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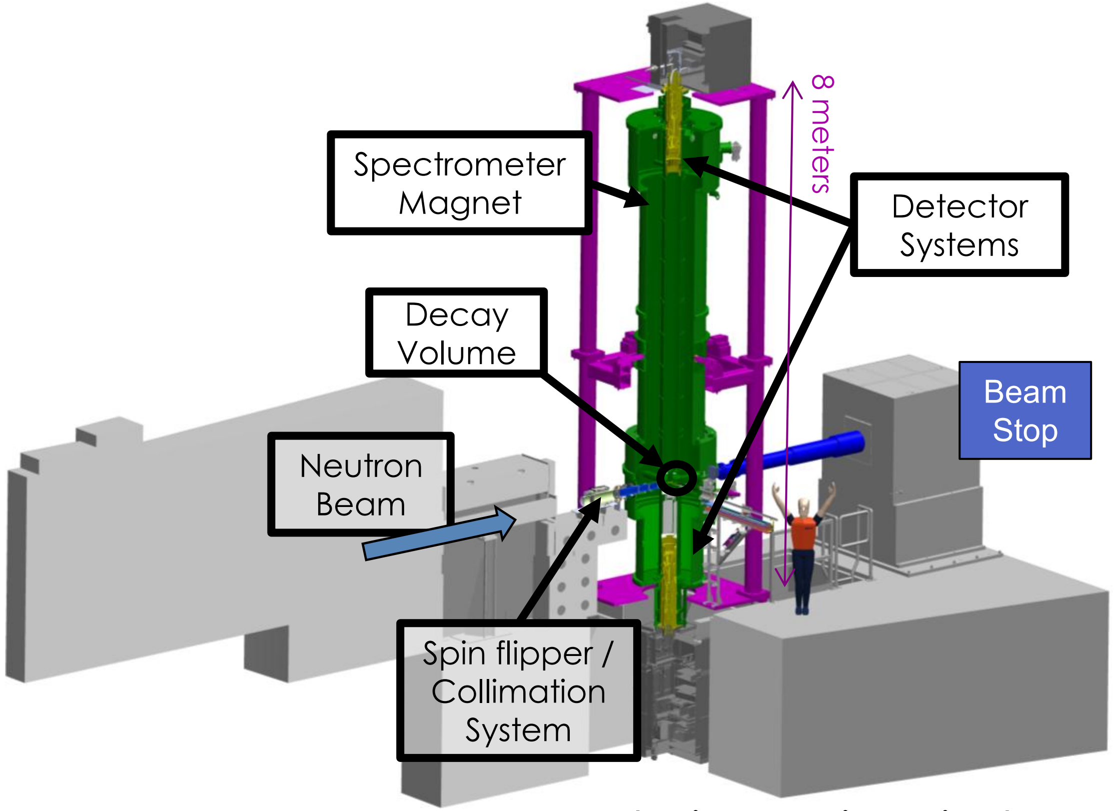
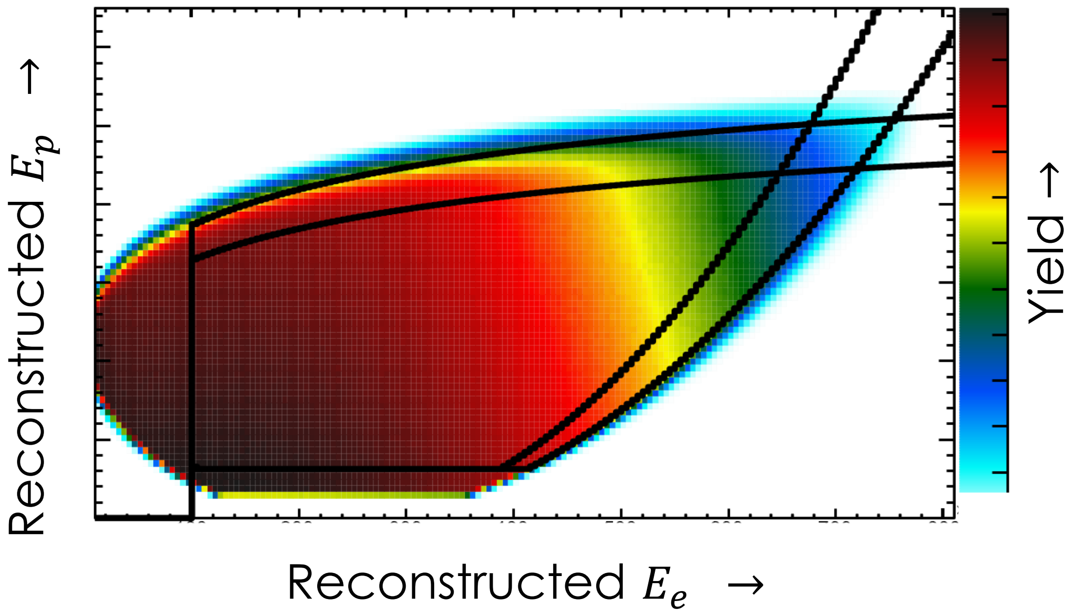
New experiments confirm or refute physics interpretation

Nab and pNab @ SNS @ ORNL



Goal: Obtain a, b, A, and b_ν from, 2D distribution of electron and proton kinetic energy



New measurement technique gives independent (and much more precise, see last slide) result.

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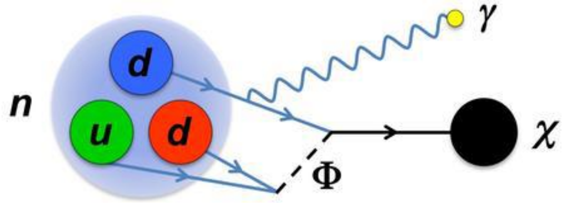
Discussion of (λ_c, b_c): Neutron lifetime puzzle

Joint analysis allows to compute $\tau_c = 894.2(42)\ s$ from $\lambda_c, b_c, V_{\mathrm{ud}}$

Could be exiting solution of neutron lifetime puzzle. too. There is a series of papers about the possibility that the trap lifetime is really lower than the beam lifetime due to neutron decay into dark particles: Fornal & Grinstein, PRL 120, 191801 (2018)

- $n \to \chi\gamma$ ($m_n > m_\chi > m_p$; $0.8\ \mathrm{MeV} < E_\gamma < 1.7\ \mathrm{MeV}$, BR $\sim 1\%$): undetected in UCNA.
- $n \to \chi\varphi$ (not necessarily detectable)
- $n \to \chi e^+ e^-$ (undetected in PERKEO II and UCNA)



Z. Tang et al, PRL Phys. Rev. Lett. 121, 022505, X. Sun et al., PRC 97, 052501 (2018), M. Klopf et al., PRL 122, 222503 (2019)

In SM analysis, V_{ud} and λ favor the lower neutron lifetime from bottles, inconsistent with the simpler dark decay explanations.

Alternative fix:
Neutron oscillations into mirror neutrons, may be turned off (or on) with magnetic field

Z. Berezhiani, EPJC 79,484 (2019), A. Serebrov et al., PLB 663, 181 (2008), L.J. Broussard et al., PRL 128, 212503 (2022), …

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Discussion of (λ_c, b_c): Possible tensor charge

Plot on the left summarizes searches for beta decay processes where the charged lepton has anormal helicity (S and T interactions with coupling constants C_S^+ and C_T^+, respectively).

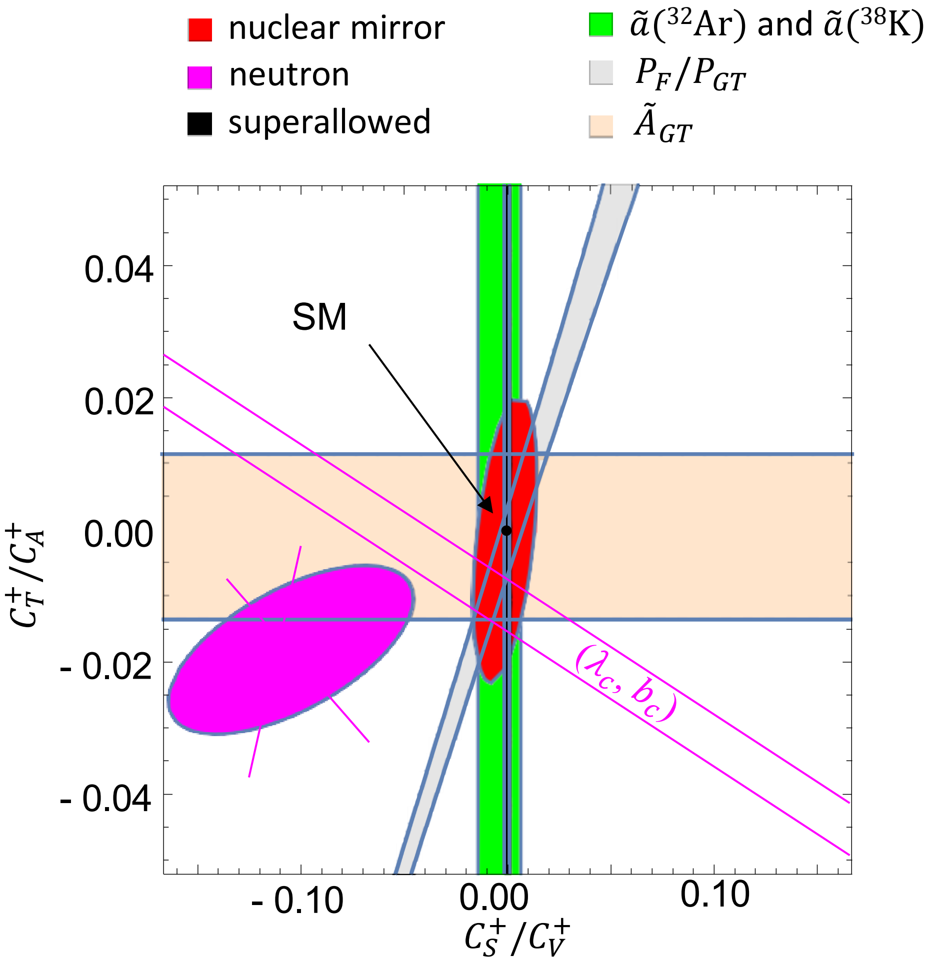
> From Falkowski: "We encourage once again experimental groups to analyze the data including the Fierz term *b*, especially once higher precision is reached." – Point taken. Their neutron ellipse, which is said to be away from SM due to aSPECT and B_n, was drawn before our BSM analysis was available, and needs correction.

We add a corrected pink band for $b_c \approx 0.34\frac{C_S^+}{C_V^+} + 1.66\frac{C_T^+}{C_A^+}$.

The combined (λ_c, b_c) is consistent with nuclear decay studies, including the more recent study on Li-8 β Decay.

M.T. Burkey, PRL 128, 202502 (2022)

As we have a very tight limit on C_S^+ from superallowed decays, it makes sense to discuss the combined result as non-zero tensor coupling $\frac{C_T^+}{C_A^+} = -0.011(4)$



From A. Falkowski et al, JHEP 04, 126 (2021)

Effective field theory for beta decay at quark level

Effective low-energy Lagrangian:

$$\mathcal{L}_{eff} = -\sqrt{2}G_F V_{ud}\Big[(1+\epsilon_L)\cdot\bar{e}\gamma_\mu(1-\gamma_5)\nu_e\cdot\bar{u}\gamma^\mu(1-\gamma_5)d$$
$$+\epsilon_R\cdot\bar{e}\gamma_\mu(1-\gamma_5)\nu_e\cdot\bar{u}\gamma^\mu(1+\gamma_5)d$$
$$+\epsilon_S\cdot\bar{e}(1-\gamma_5)\nu_e\cdot\bar{u}d$$
$$+\epsilon_T\cdot\bar{e}\sigma_{\mu\nu}(1-\gamma_5)\nu_e\cdot\bar{u}\sigma^{\mu\nu}(1-\gamma_5)d$$
$$-\epsilon_P\cdot\bar{e}\gamma_\mu(1-\gamma_5)\nu_e\cdot\bar{u}\gamma_5 d$$

+ terms with $\tilde{\epsilon}$ that involve righthanded ν_e

$$+\text{h.c.}\Big]$$

Unobservable, due to limits from pion decay

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

Connection with traditional coupling constants from nuclear and neutron physics:

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

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

Note that some authors omit this factor 4

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Discussion of fundamental tensor charge

- We need to get out of our “nest” (the nuclear community) to make these studies directly relevant for fundamental physics
- With the form factor g_T, we can determine the fundamental tensor coupling ϵ_T.
- Its most precise determination is from theory (Lattice QCD): $g_T = 0.989(33)$

R. Gupta et al., PRD 98, 034503 (2018)

- Alternatively, g_T can be tied to experimental data ($g_T = g_T^u - g_T^d$ and $g_T^q = \int_0^1 dx \left(h_1^q(x) - h_1^{\bar{q}}(x) \right)$, where $h_1^q(x)$ and $h_1^{\bar{q}}(x)$ transversity parton distribution functions). It is not necessary to matcvh the uncertainty of Lattice QCD, $(\Delta g_T)/g_T \sim 20\%$ is a worthy goal. A. Courtoy et al., PRL 115, 162001 (2015)
- From $(C_T^+)/(C_A^+)$ before and g_T from the Lattice, we obtain $\epsilon_T = 0.0035(12)$
- Our ϵ_T can compared to limits from radiative pion decay (see next talk)

M. Bychkov et al., PRL 103, 051802 (2009)

- … or to LHC limits for $p + p \rightarrow e^+ + e^- + X$

R. Gupta et al., PRD 98, 034503 (2018)

Both of those favor the absence of a tensor charge at this level.

The take-away

1. Experiments in neutron beta decay contribute to most sensitive test of the unitarity of the CKM matrix, however different results are inconsistent in a SM analysis.
2. Inconsistency could be due to an experimental error – New experiments Nab and pNab at currently being performed at ORNL aim to uncover such an error with new technique, and aim to improve overall accuracy.
3. Inconsistency could point to new physics – a non-zero tensor coupling C_T^+ at the nucleon level. This opens the question how to connect to fundamental tensor coupling ϵ_T at quark level.
4. For the connection, we need to g_T, either from theory (Lattice-QCD), or from experiment (THIS COMMUNITY)