Neutron Beta Decay as a test of the Standard Model and probe of new physics

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APS GPMFC Workshop 2023

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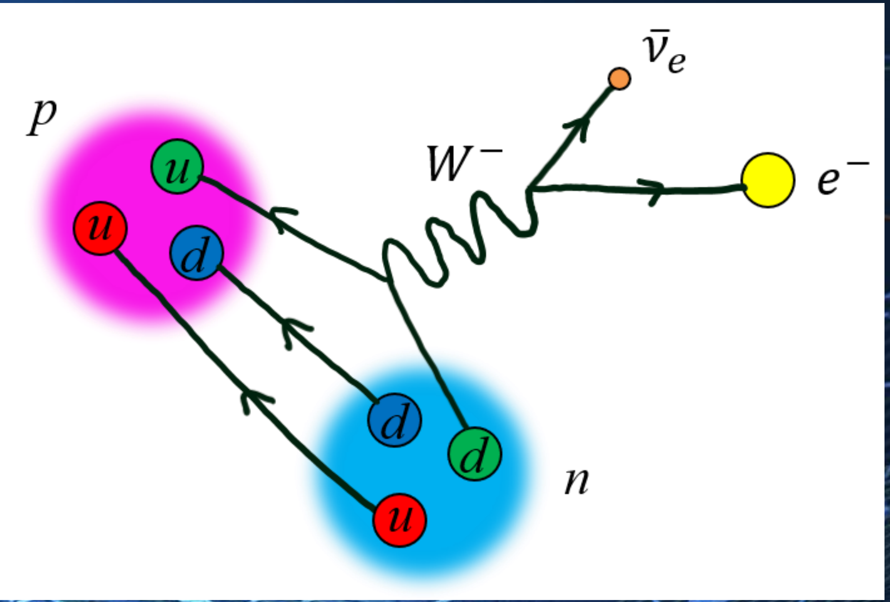
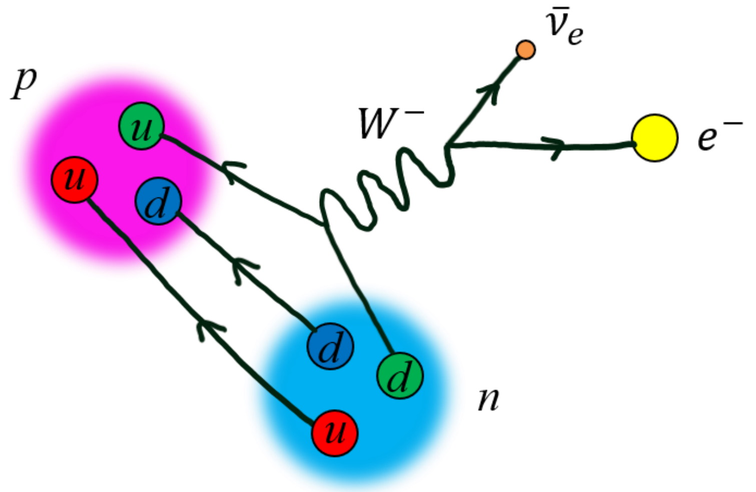


National Institute of Standards and Technology
U.S. Department of Commerce

PHYSICAL MEASUREMENT LABORATORY

Neutron Beta Decay



- Free neutron is unstable: $\tau_n \approx 15$ min
- Main decay channel: $n \rightarrow p + e^- + \bar{\nu}_e$

  $0 < E_e < 783$ keV $\qquad 0 < E_p < 751$ eV
- Other decay modes

  $n \rightarrow p + e^- + \bar{\nu}_e + \gamma$ $\qquad$ BR(>1keV) $\approx 3 \times 10^{-3}$ *Nature* **444,** (2006) PRL **116**, 242501 (2016)

  $n \rightarrow H + \bar{\nu}_e$ $\qquad$ BR $\approx 4 \times 10^{-6}$

  $E_{\bar{\nu}} = 783$ keV $\qquad E_H$ =326.5 eV
- Exotic Decay Modes?

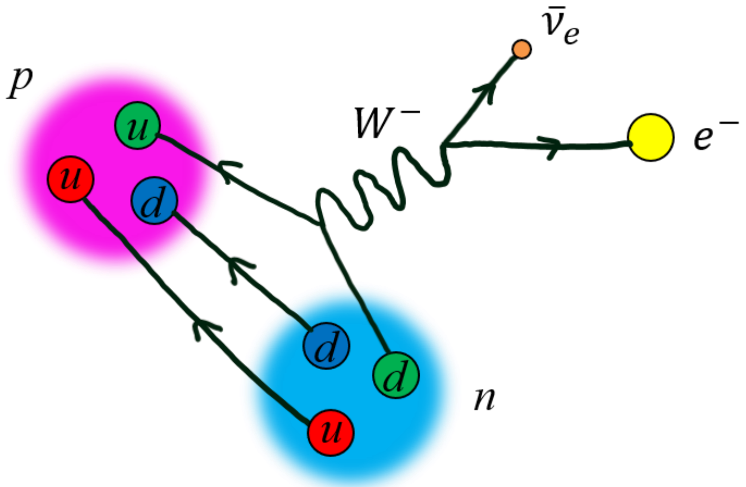
  $n \rightarrow X$

Fundamental Semileptonic Decay

$$d + \nu_e \leftrightarrow u + e^-$$

Neutron beta decay sets weak interaction rates which govern many processes:

Primordial element formation (BBN) (^{2}H, ^{3}He, ^{4}He, ^{7}Li, …)	$n + e^+ \rightarrow p + \bar{\nu}_e$ $p + e^- \rightarrow n + \nu_e$ $n \rightarrow p + e^- + \bar{\nu}_e$
Solar cycle	$p + p \rightarrow {}^2H + e^+ + \nu_e$ $p + p + e^- \rightarrow {}^2H + \nu_e$
Neutron star formation	$p + e^- \rightarrow n + \nu_e$
(anti)neutrino detection	$\nu_e + n \rightarrow e^- + p$ $\bar{\nu}_e + p \rightarrow e^+ + n$



Also gives couplings:

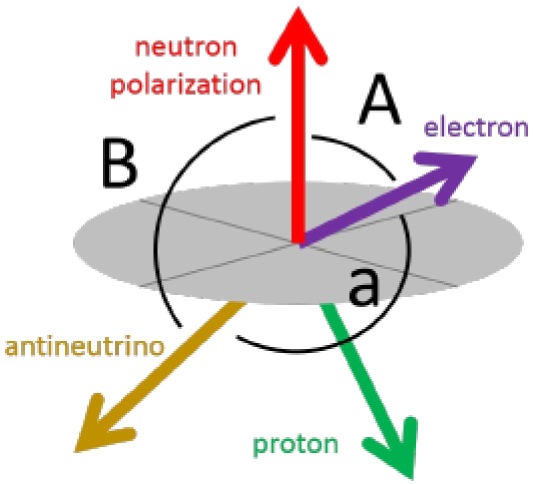
CKM unitarity, new physics

Neutron Beta Decay Correlations

$$\frac{d\Gamma}{dE_e d\Omega_e d\Omega_\nu} \propto g_v^2(1+3\lambda^2)p_e E_e (E_0 - E_e)^2 \times \left[1 + b\frac{m_e}{E_e} + a\frac{\vec{p}_e \cdot \vec{p}_\nu}{E_e E_\nu} + \langle\vec{\sigma_n}\rangle \cdot \left(A\frac{\vec{p}_e}{E_e} + B\frac{\vec{p}_\nu}{E_\nu} + D\frac{\vec{p}_e \times \vec{p}_\nu}{E_e E_\nu}\right)\right]$$

Electron-antineutrino correlation

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



Spin-electron asymmetry

$$A = -2\frac{|\lambda|^2 + |\lambda|\cos\varphi}{1 + 3|\lambda|^2}$$

Spin-antineutrino asymmetry

$$B = 2\frac{|\lambda|^2 - |\lambda|\cos\varphi}{1 + 3|\lambda|^2}$$

Neutron Lifetime

$$\tau_n \propto \frac{1}{|V_{ud}|^2|g_v^2|(1 + 3\lambda^2)}$$

Coupling ratio

$$\lambda = \frac{|g_A|}{|g_V|}e^{i\varphi}$$

Combinations of τ_n and asymmetry coefficients yields g_V, g_A, V_{ud}

Test of Unitarity of CKM matrix

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

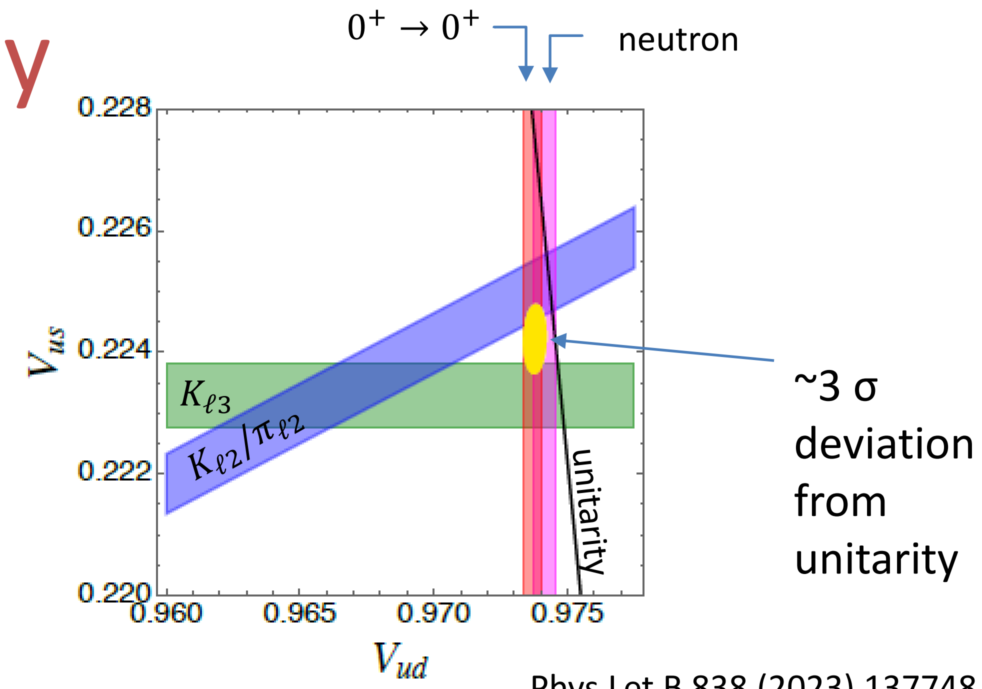
F16.00008 – Seng

CKM Unitarity

$$V_{CKM} = \begin{pmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{pmatrix}$$

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

- $|V_{us}|$ from high energy experiments
- $|V_{ud}|$ from
  - $0^+ \rightarrow 0^+$ nuclear beta decays (most precise, $\Delta V_{ud} \sim 1.1 \times 10^{-4}$, but includes both radiative and nuclear corrections)
  - Neutron beta decay (no nuclear corrections, but a competitive result requires ~10^{-4} experimental precision)
- Deviation from unitarity suggests possible new physics (e.g. right-handed currents)



Phys Let B 838 (2023) 137748

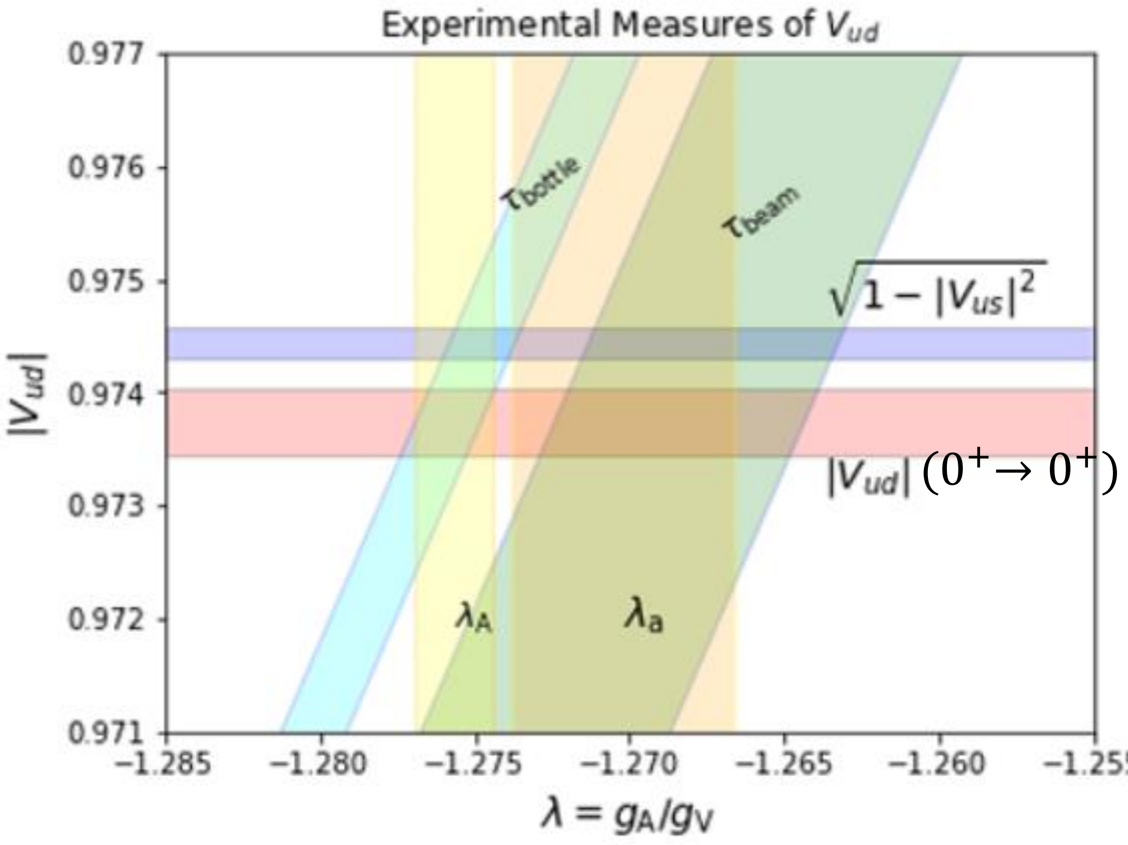
V_{ud} from neutron beta decay

- Requires two measurements: τ_n and $\lambda = g_A/g_V$
  - τ_n can be measured using more than one method
  - λ comes from a measurement of one or more correlations, typically A and/or a.

$$|V_{ud}|^2 \propto \frac{K}{\tau_n |g_v^2| (1 + 3\lambda^2)}$$

- To be competitive with $0^+ \rightarrow 0^+$ requires
  - $\frac{\Delta\lambda}{\lambda} < 0.03\ \%$
  - $\Delta\tau < 0.3\ s$

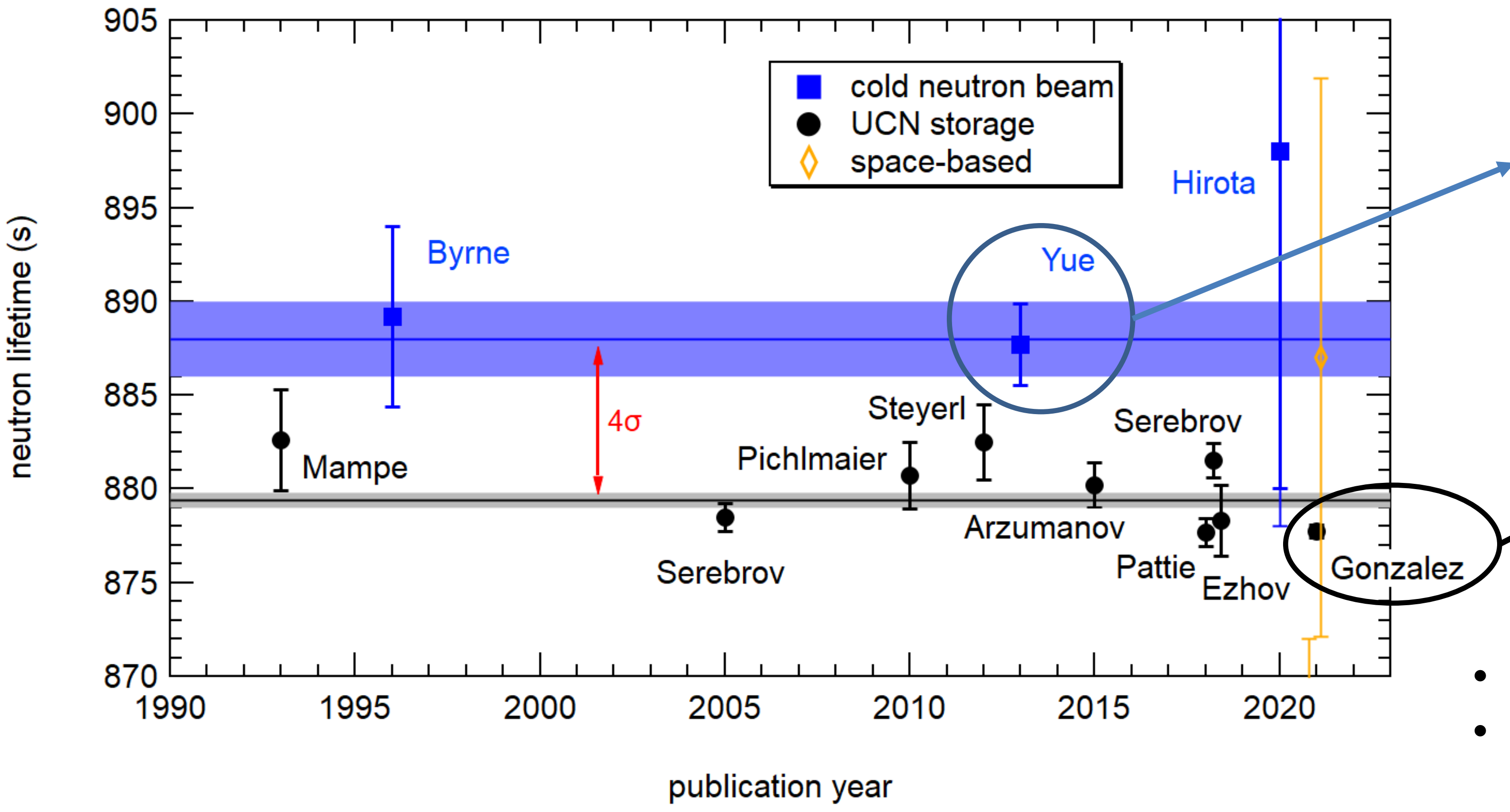
This is the goal of the US neutron beta decay program over the next 5+ years



Experimental Challenges in neutron beta decay

- **The lifetime is too long.** For a typical cold beam, 10^{-6} decay in the detector volume. In the case of neutron bottles, one must deal with systematics over a 15 minute period.
- **Neutrons are hard to manipulate.** One must cool them over many decades of energy before magnetic fields, gravity, and optical potentials become relevant.
- **The decay antineutrino is unobservable, while the decay proton has an endpoint energy of only 751 eV.**
- **The destiny of almost all neutrons is to become a potential background event** via capture and activation.

1. Neutron lifetime τ_n



Most precise Beam:

$\tau_n = 887.1 \pm 2.2$ s

PRL **111**, 222501 (2013)

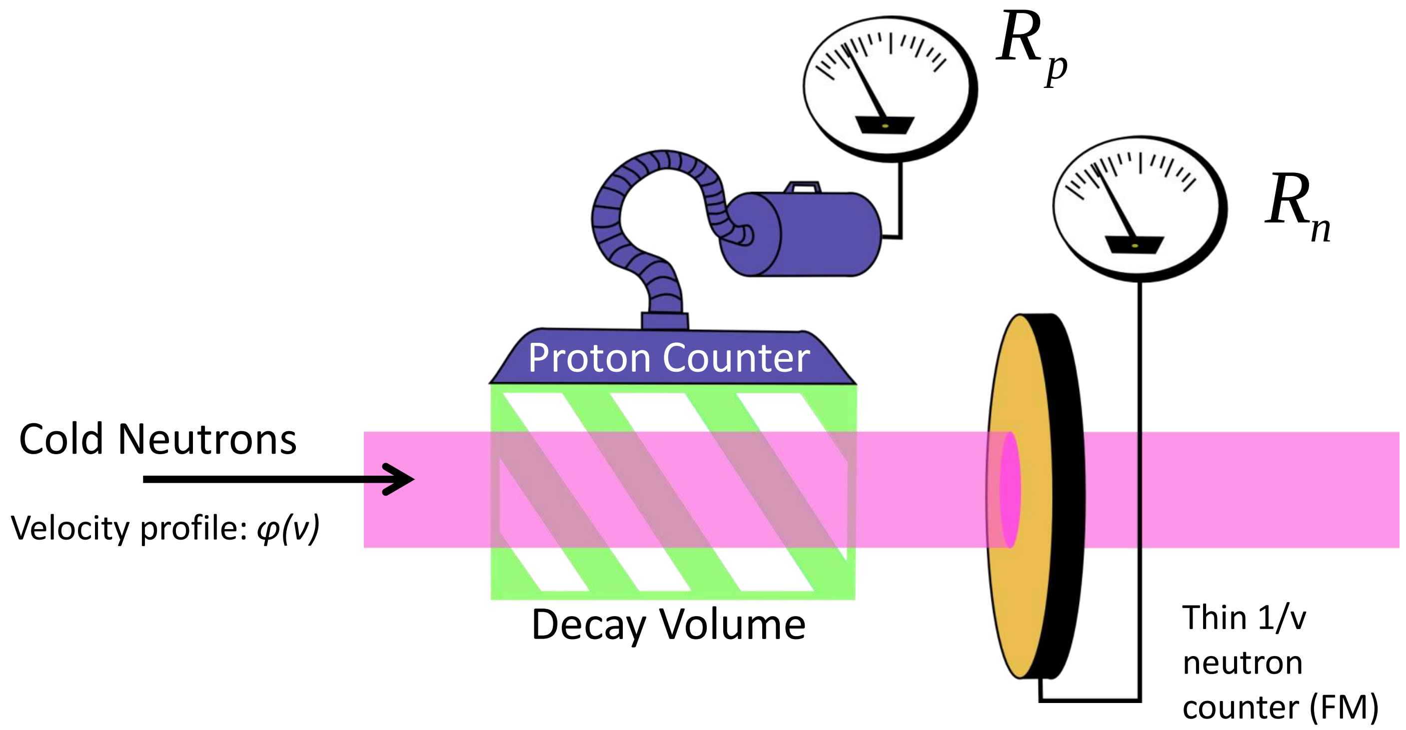
Most precise Bottle:

$\tau_n = 877.75 \pm 0.28^{+0.22}_{-0.16}$ s

PRL **127**, 162501 (2021)

- Difference is nearly 10s!
- Need to resolve/understand this discrepancy to have an improved determination of V_{ud}.
  - Systematic effects?
  - New physics?

How to Measure τ_n in a Beam

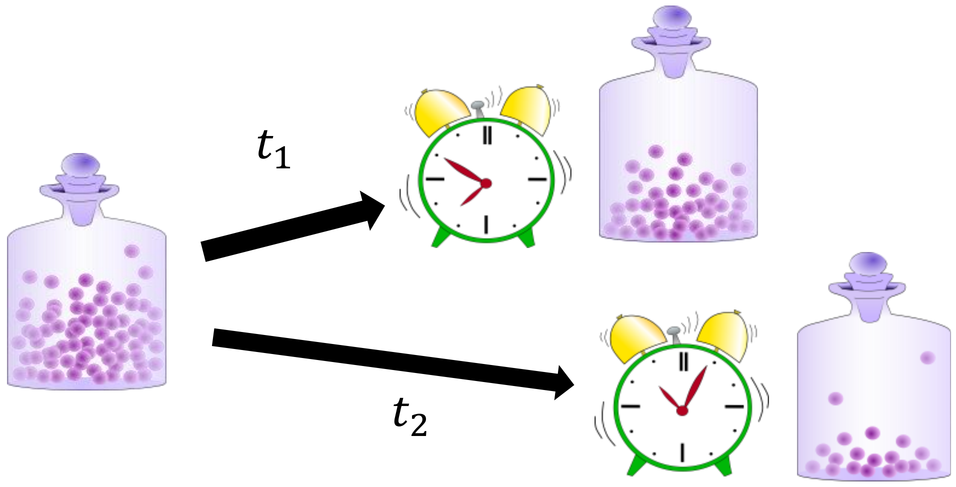


- Requires absolute counting of neutrons and one or more decay products (protons and/or electrons)
- Counts the number of neutrons that decay via the normal decay channel $n \rightarrow p + e + \bar{\nu}$

FM absorbs neutrons as 1/v
So it's calibrated at thermal velocity

$$\tau_n = \frac{R_n \varepsilon_p L_{\text{det}}}{R_p \varepsilon_{th} v_{th}}$$

How to Measure τ_n in a Bottle



$$\tau_{storage} = \frac{(t_2 - t_1)}{\ln\left(\frac{N(t_1)}{N(t_2)}\right)}$$

where $\frac{1}{\tau_{storage}} = \frac{1}{\tau_n} + \frac{1}{\tau_{trap}}$

Ideally $\tau_{trap} \gg \tau_n$

UCNτ is a nearly "lossless" bottle where holding times exceed τ_n, allowing for the first bottle measurement with no extrapolation

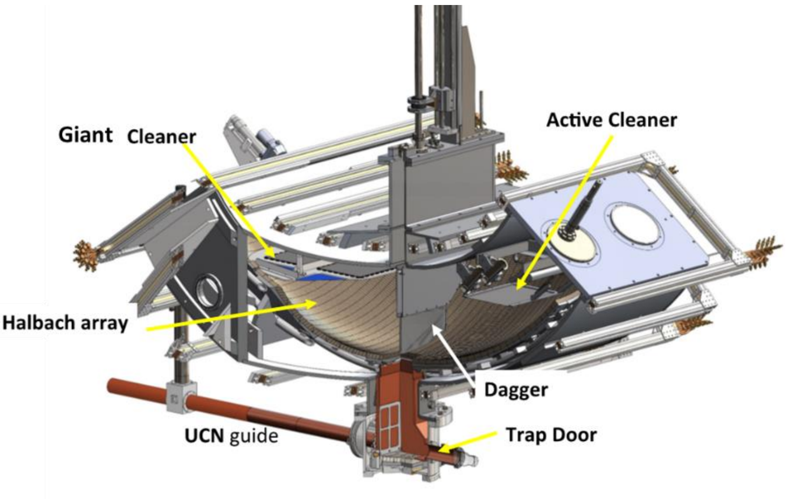
- Have to account for loss mechanisms, complicated neutron orbits
- Storage can be in either material or magnetic trap/bottle
- Counts the total number of neutrons that decay, regardless of decay channel (including possible exotic decay modes)
- In principle can also measure n_p and/or n_e as in beam experiment as a direct test (e.g. UCNProbe)

Recent/ongoing (mostly US) efforts on the neutron lifetime

UCNτ

- Most precise measurement
- Only τ_n measurement with systematic corrections smaller than uncertainty
- $\Delta\tau = 0.3\ s$ (stats limited)

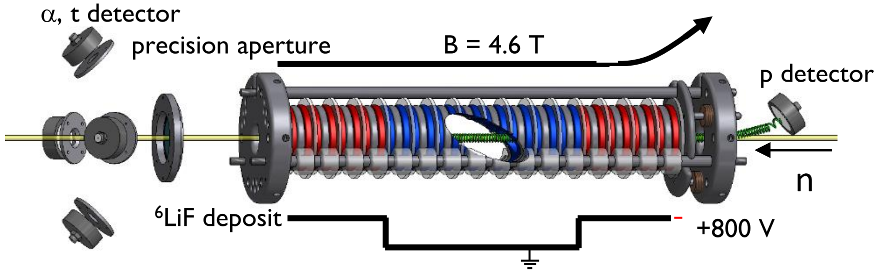
PRL **127** 162501 (2021)

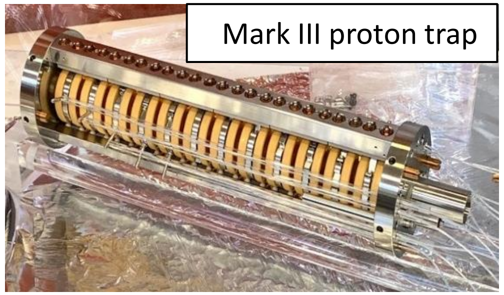


BL2

D07.00008 – S.H.

- Update of current best beam result
- Will resume data taking as son as NIST reactor restarts (est. summer 2023)
- $\Delta\tau < 2\ s$

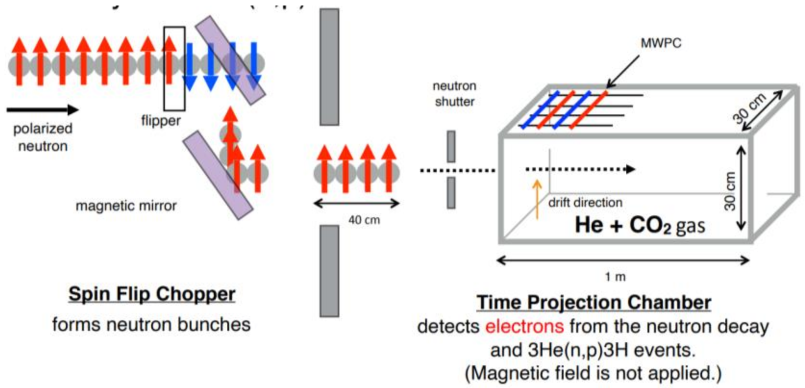




JPAC Beam Lifetime (Japan)

- Beam lifetime using TPC to simultaneously measure decay electrons and neutrons using 3He(n,p)3Hreaction
- $\Delta\tau < 1\ s$
- Current result $\Delta\tau \sim 20\ s$

Prog. Theor. Exp. Phys. 2020 123C02



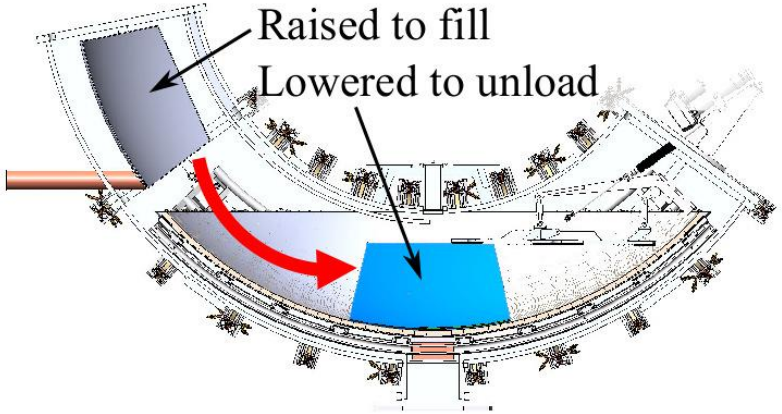
Plus additional recent UCN efforts in Europe…

Future (US) efforts on the neutron lifetime

UCNτ+

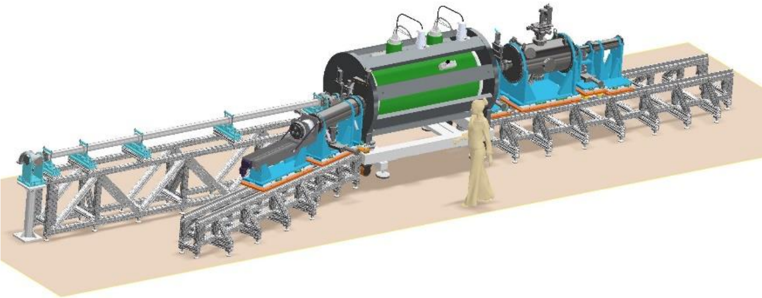
G15.00007 – Musedinovic

- Next-gen UCN bottle experiment
- UCN "elevator" loading – increase trapped UCN 10x
- $\Delta\tau < 0.1\ s$
- Currently under construction; commissioning later this year (2023)



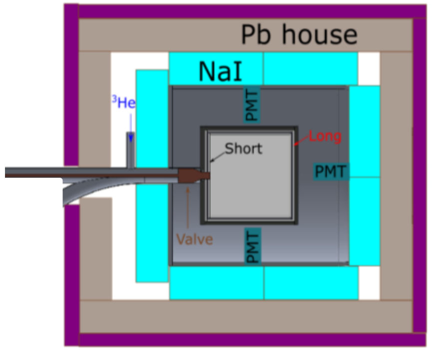
BL3

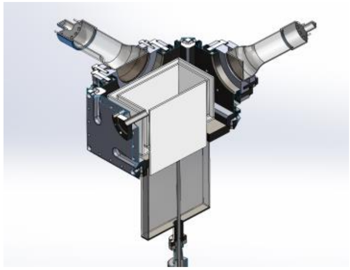
- Next-gen beam lifetime
- Larger volume; larger, segmented proton detector; higher rates
- $\Delta\tau < 0.3\ s$
- Mid-scale instr. funding (2022 – 2025)



UCNProbe

- "Beam"-style experiment using UCN
- two-layer deuterated phoswich scintillator box to store UCN and detect beta decay electrons
- $\Delta\tau < 2\ s$
- Finalizing design and hardware procurement
- Planned commissioning in 2025

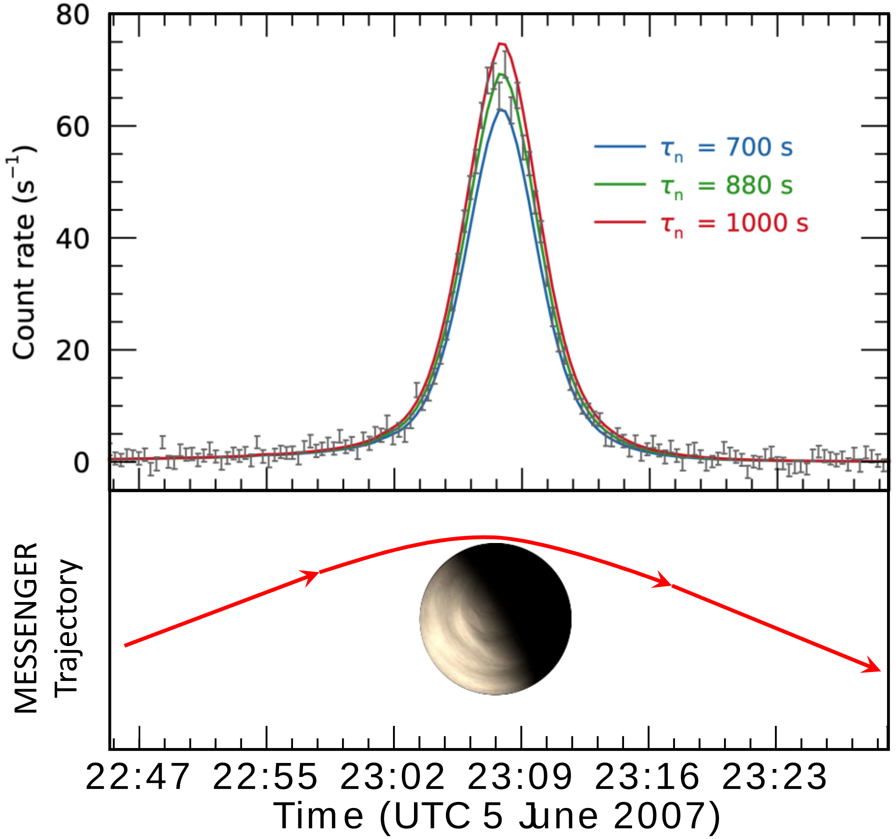




Plus additional UCN efforts in Europe and ongoing beam efforts in Japan…

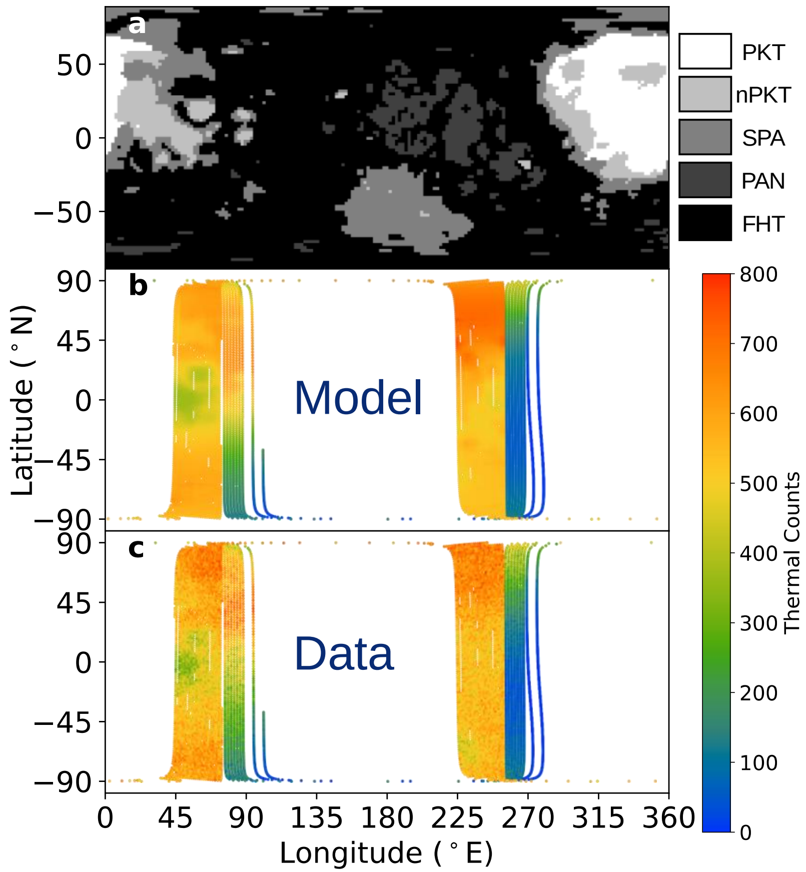
Space-based measurement of τ_n using data from Lunar Prospector and MESSENGER

MESSENGER: flyby of Venus used in combination with the first flyby of Mercury to measure τ_n (*Wilson et al.*, 2000a).



Lunar Prospector: lunar model includes variable composition by defining a set of regions that correspond to major compositional regions (*Wilson et al.*, 2000b).

Dedicated Mission could potentially achieve competitive (few s or better) result; feasibility needs to be studied



$$\tau_n = 780 \pm 60_{\rm stat} \pm 70_{\rm syst}\ \ {\rm s}$$

$$\tau_n = 887 \pm 14_{\rm stat}{}^{+7}_{-3}\,{}_{\rm syst}\ {\rm s}$$

Phys. Rev. Research **2**, 023316 (2020)

PRC **104** 045501 (2021)

2. Neutron Beta-decay Asymmetries

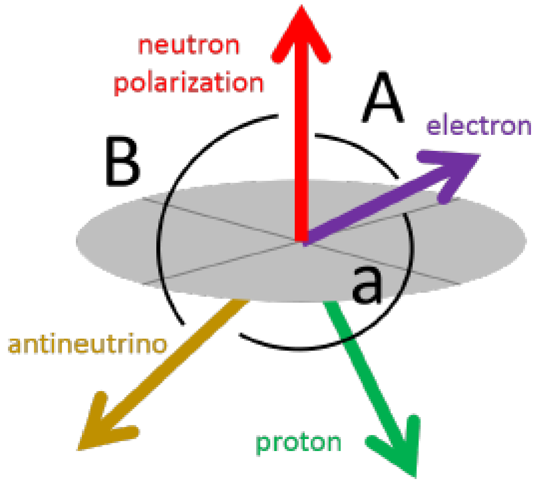
$$\frac{d\Gamma}{dE_e d\Omega_e d\Omega_\nu} \propto g_\nu^2(1+3\lambda^2)p_e E_e (E_0 - E_e)^2 \times \left[1 + b\frac{m_e}{E_e} + a\frac{\vec{p}_e \cdot \vec{p}_\nu}{E_e E_\nu} + \langle\vec{\sigma_n}\rangle \cdot \left(A\frac{\vec{p}_e}{E_e} + B\frac{\vec{p}_\nu}{E_\nu} + D\frac{\vec{p}_e \times \vec{p}_\nu}{E_e E_\nu}\right)\right]$$

Electron-antineutrino correlation

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

Beta asymmetry

$$A = -2\frac{|\lambda|^2 + |\lambda|\cos\varphi}{1 + 3|\lambda|^2}$$



Used to determine λ for V_{ud} $\rightarrow$ test CKM unitarity

Need $\frac{\Delta\lambda}{\lambda} < 0.03\ \%$

Neutrino asymmetry

$$B = 2\frac{|\lambda|^2 - |\lambda|\cos\varphi}{1 + 3|\lambda|^2}$$

deviations may indicate V+A

Triple Correlation

$$D = 2\frac{|\lambda|\sin\varphi}{1 + 3|\lambda|^2}$$

Non-zero value would indicate time-reversal violation

Fierz interference

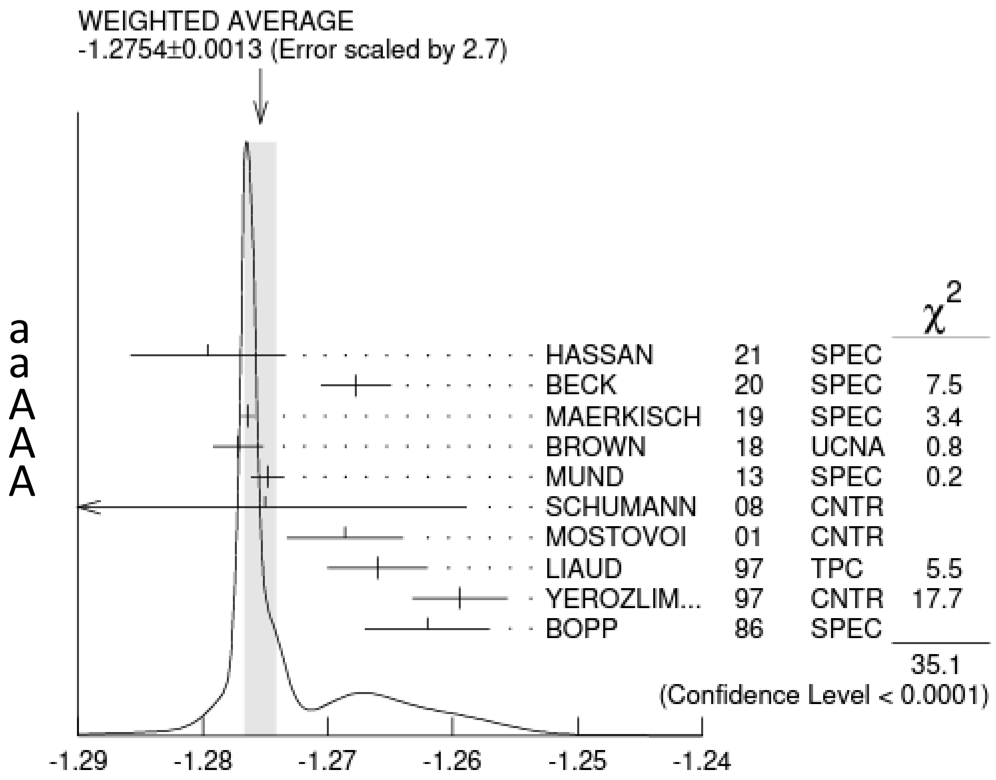
$$b = 0$$

Non-zero value may indicate S, T

Need $\Delta b < 10^{-3}$ to set competitive limits

2. Neutron Beta-decay Asymmetries

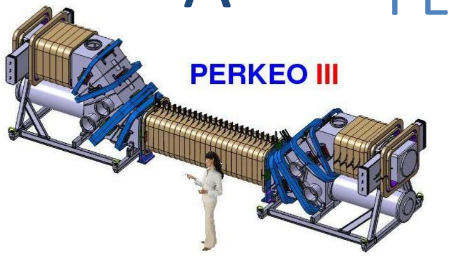
PDG2022 determination of λ



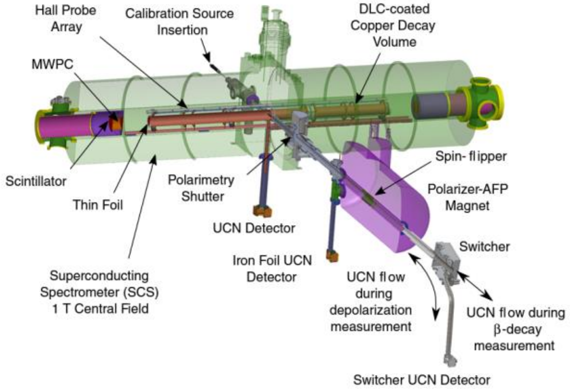
- Like the lifetime, there is a fair amount of scatter, with seemingly two camps.
- The recent aSPECT (BECK) result is a bit of an outlier compared to other recent experiments
- Need consistency between measurements for V_{ud}

Neutron beta decay asymmetry landscape

A



PERKEO III $\frac{\Delta A}{A} = 0.2\ \%$ PRL **122**,242501(2019)



UCNA $\frac{\Delta A}{A} = 0.67\ \%$

PRC **97**, 035505 (2018)

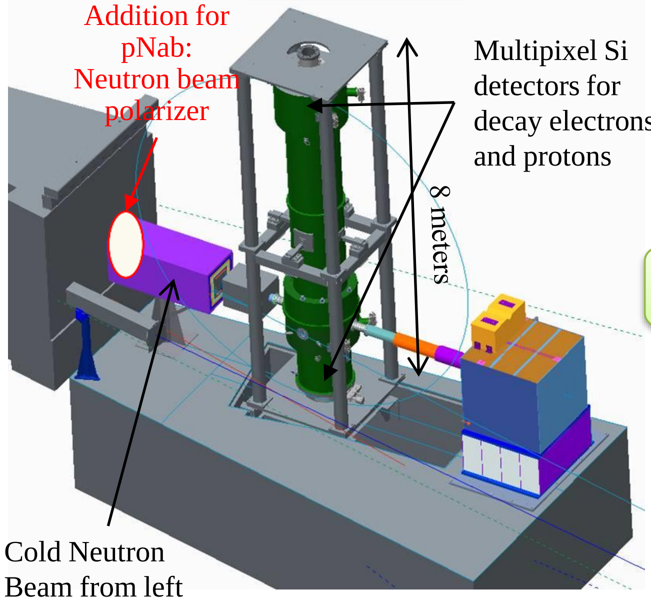
UCNA+ $\frac{\Delta A}{A} < 0.2\ \%$

- Data taking starting around 2025?

F16.00001 – Singh
F16.00002 – Gupta

$\frac{\Delta A}{A} < 0.08\ \%$ pNab

- Data taking finished 2026 (summer)

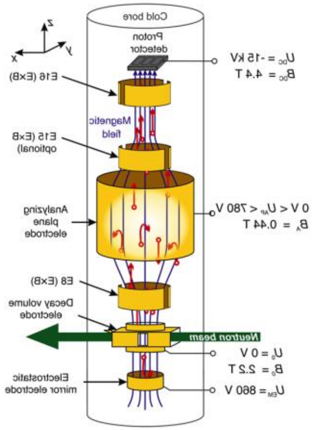


Plus PERC in Europe: $\frac{\Delta A}{A} < 0.04\ \%$, uncertain schedule

a

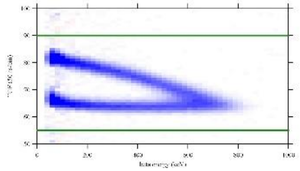
aSPECT $\frac{\Delta a}{|a|} = 0.8\ \%$

PRC **101**,055506(2020)



aCORN $\frac{\Delta a}{|a|} = 1.9\ \%$

PRC **103**,045502(2021)



D07.00005 – Fry

Nab $\frac{\Delta a}{|a|} < 0.1\ \%$

$\Delta b = 3 \times 10^{-3}$

- Transition from commissioning to data taking 2023 (summer)
- Data taking finished 2025 (summer)

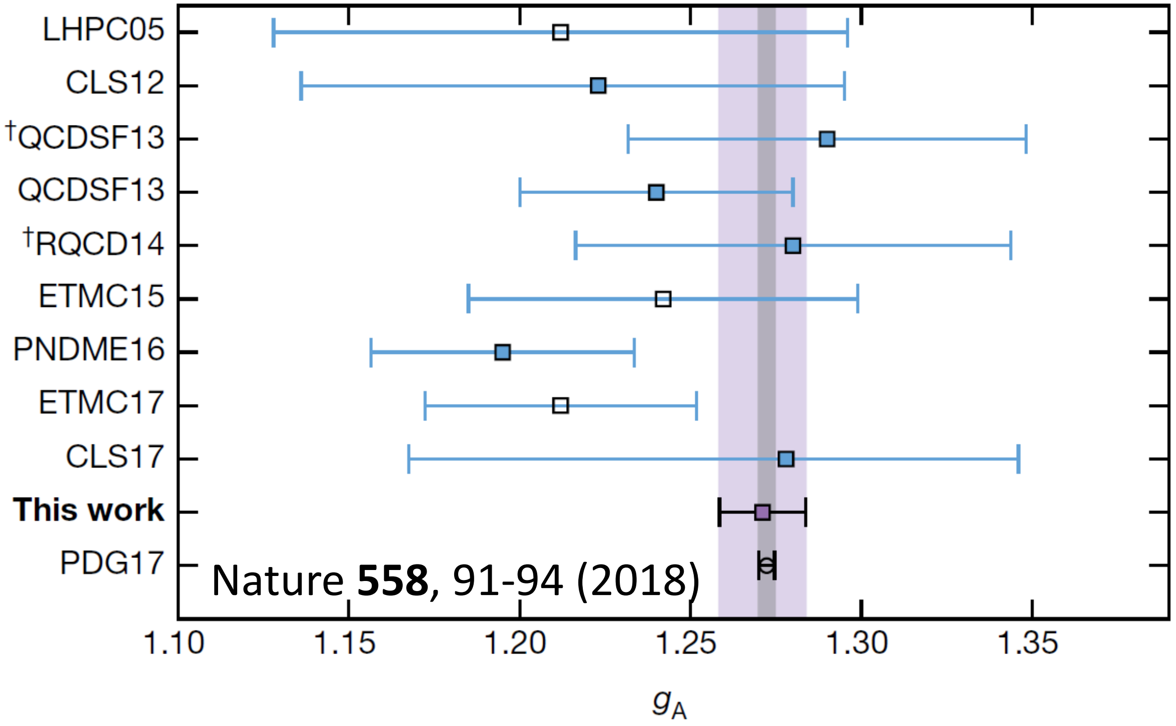
Lattice QCD Calculation

Lattice QCD calculations have reached 1 % precision on g_A

- Precision is largely limited by calculation resources (stats)
- Precision of 0.1 % to 0.2 % may be possible on the 5 year timescale (comparable to measurements)

Use Standard Model "Master Equation" to convert g_A to τ_n:

$$|V_{ud}|^2 \tau_n (1 + 3{g_A}^2)(1 + \Delta_R^V) = 5024.7s$$



Comparisons with experimental values could help illuminate new physics

Exotic Physics Explanations for the τ_n bottle/beam discrepancy

- Dark decay channel   PRL **120**, 191801 (2018)
  - Experimental constraints from searches for gammas plus exotic particle
  - Theoretical constraints using neutron star observations
- Mirror neutrons
- Hidden neutrons
- Other non-SM decay channels
- Other new physics beyond standard model

Active area both theoretically and experimentally

Summary

- Neutron beta decay is poised to provide important tests of the standard model and probe BSM physics through CKM Unitarity tests and Fierz interference.
- The US neutron beta decay program is centered around understanding the Cabibbo Anomaly in the CKM matrix, which involves two main goals over the next long range plan period:
  - Resolve the neutron lifetime discrepancy and establish a robust determination of τ_n at the 0.3 s level or better
    - UCNτ and UCNτ+ (LANL); BL2 and BL3 (NIST); UCNProbe (LANL)
  - Improve the determination of λ to 0.03% or better to be competitive with $0^+ \rightarrow 0^+$
    - Nab (ORNL); pNab (ORNL); UCNA+ (LANL)
- Prospects are high

Thanks to S. Baessler, Z. Tang, S. Clayton, and others for figures and information

Questions?