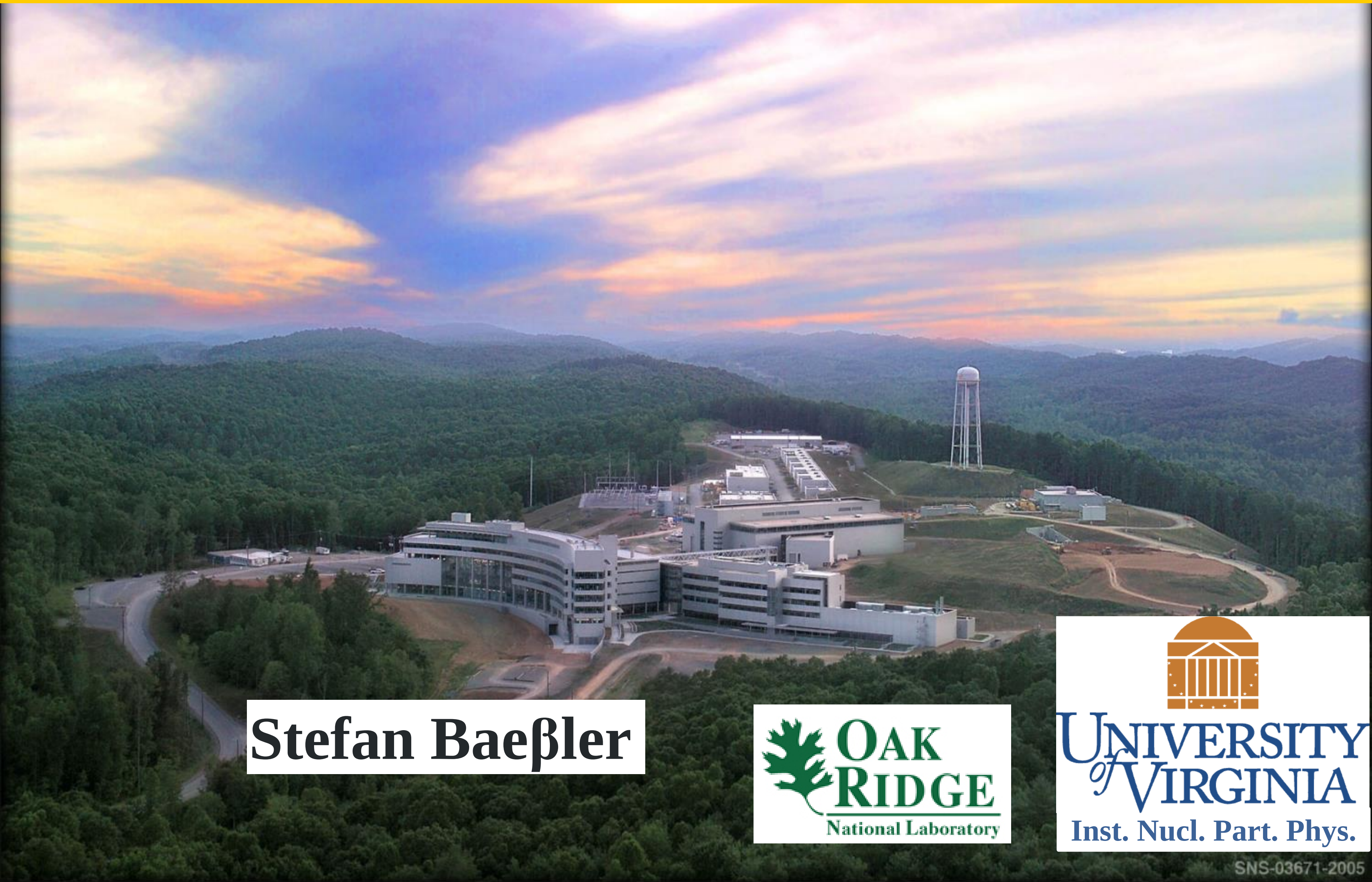
Study of Neutron Beta Decay with the Nab experiment

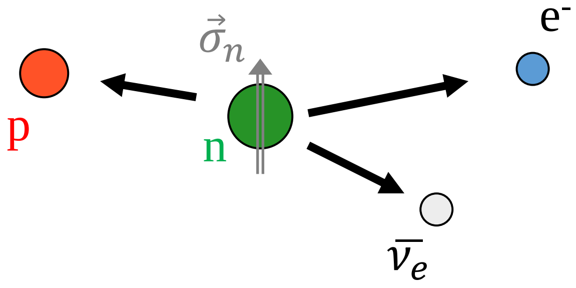


Stefan Baeßler

Oak Ridge National Laboratory

University of Virginia
Inst. Nucl. Part. Phys.

Correlation coefficients in neutron beta decay



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

Nonzero b or b_ν indicates S,T

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

$$d\Gamma \propto \varrho(E_e)\left(1 + a\frac{p_e}{E_e}\cos(\vec{p}_\nu, \vec{p}_e) + b\frac{m_e}{E_e} + A_0\frac{p_e}{E_e}\cos(\vec{\sigma}_n, \vec{p}_e) + \left(B_0 + b_\nu\frac{m_e}{E_e}\right)\cos(\vec{\sigma}_n, \vec{p}_\nu)\right)$$

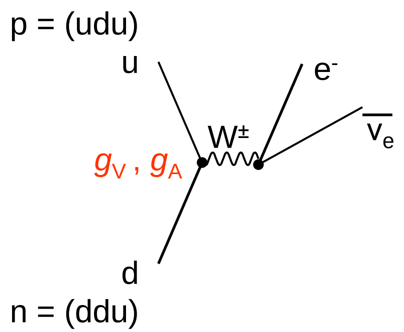
$a_0 = a_0(\lambda)$ with $\lambda = g_A/g_V$

$A_0 = A_0(\lambda)$

C.F. v. Weizsäcker, Z. f. Phys. 102,572 (1936), M. Fierz, Z. f. Phys. 104, 553 (1937), J.D. Jackson et al., PR 106, 517 (1957)

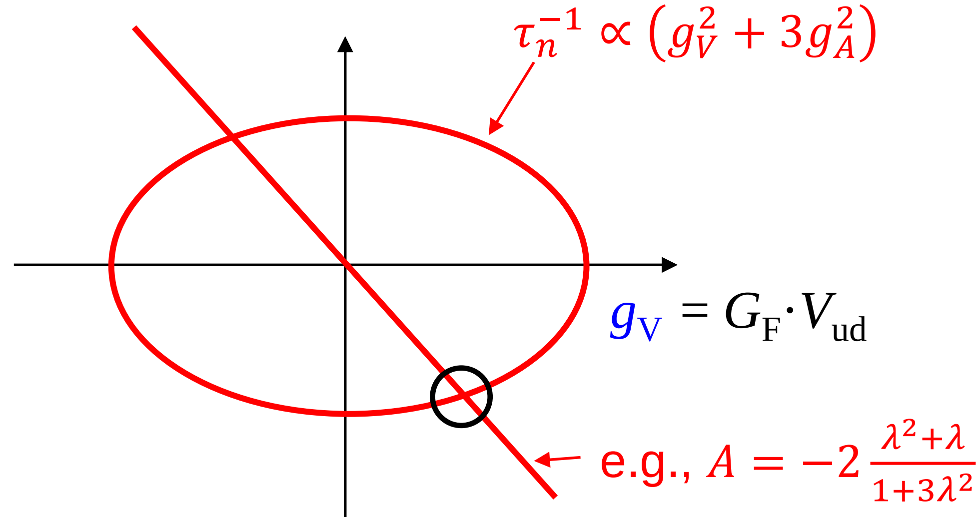
The coupling constants of semileptonic weak interactions

Coupling Constants in Neutron Decay

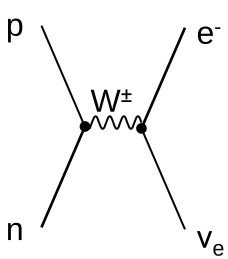


$$n \rightarrow p + e^- + \overline{\nu}_e$$

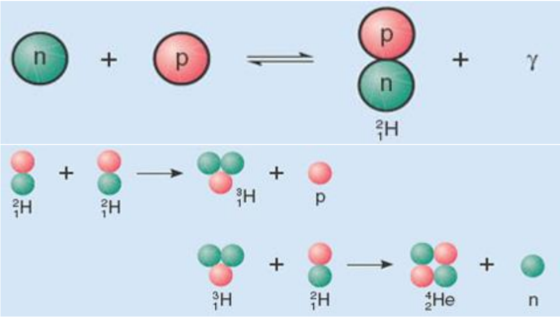
$g_A = G_F \cdot V_{ud} \cdot \lambda$



Primordial Nucleosynthesis

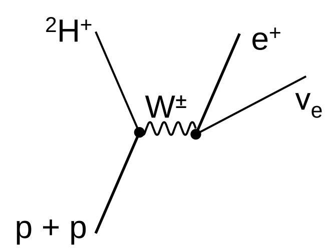


$$n + \nu_e \leftrightarrow p + e^-$$



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

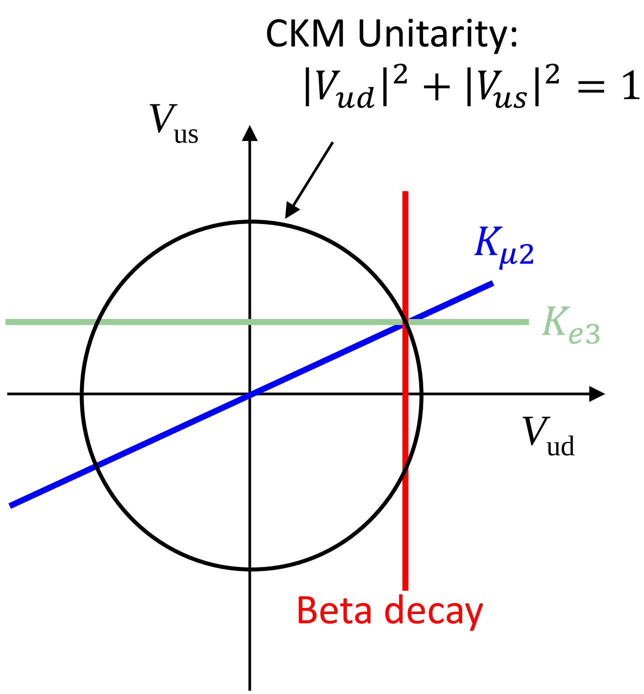
Testing the Standard Model, here, CKM unitarity

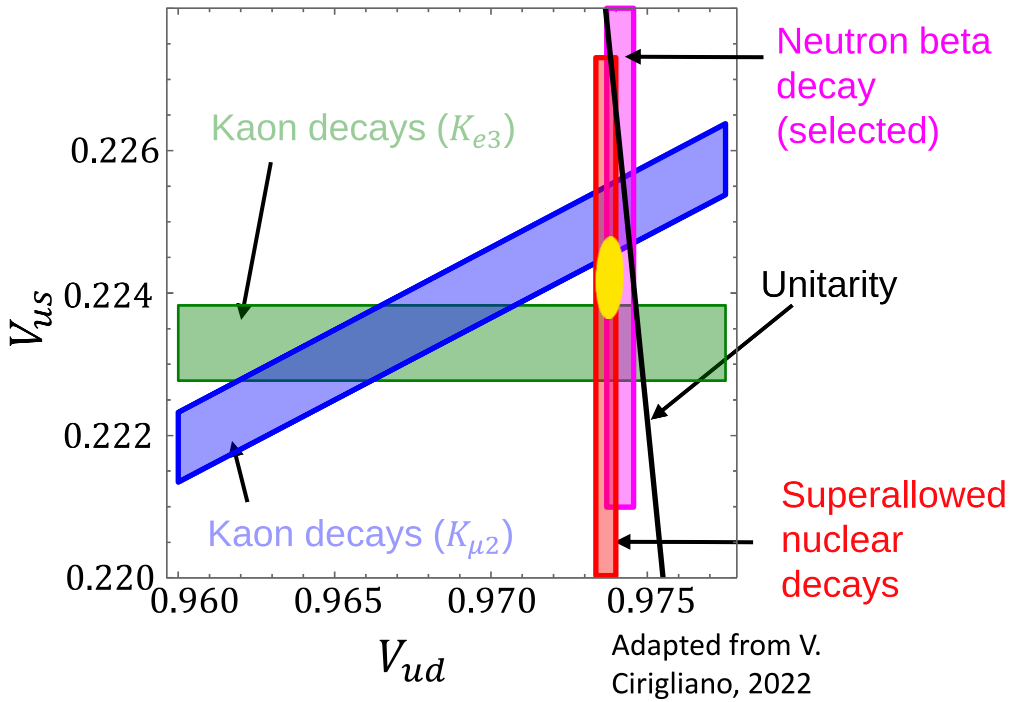
Cabbibo Kobayashi Maskawa (CKM) matrix:

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

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

$$|V_{ud}|^2 + |V_{us}|^2 + |V_{ub}|^2 = 1 \text{ (theory)}$$





Adapted from V. Cirigliano, 2022

Apparently, The unitarity test fails by 2.8σ (from this work).

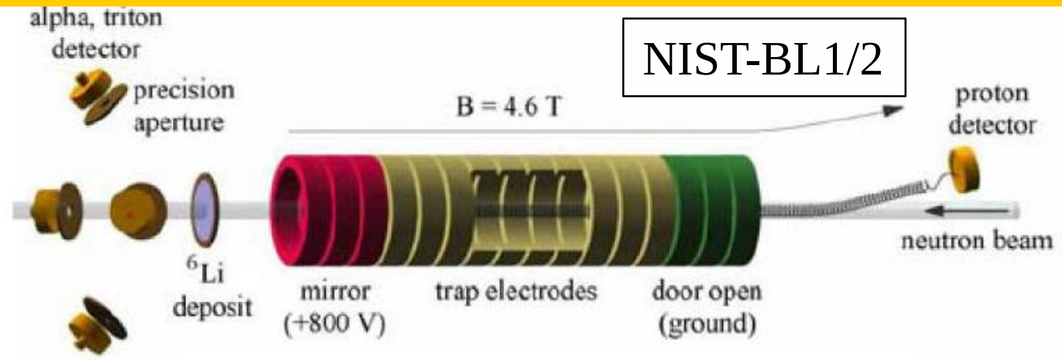
This talk: Neutron beta decay input, next talk: theory input

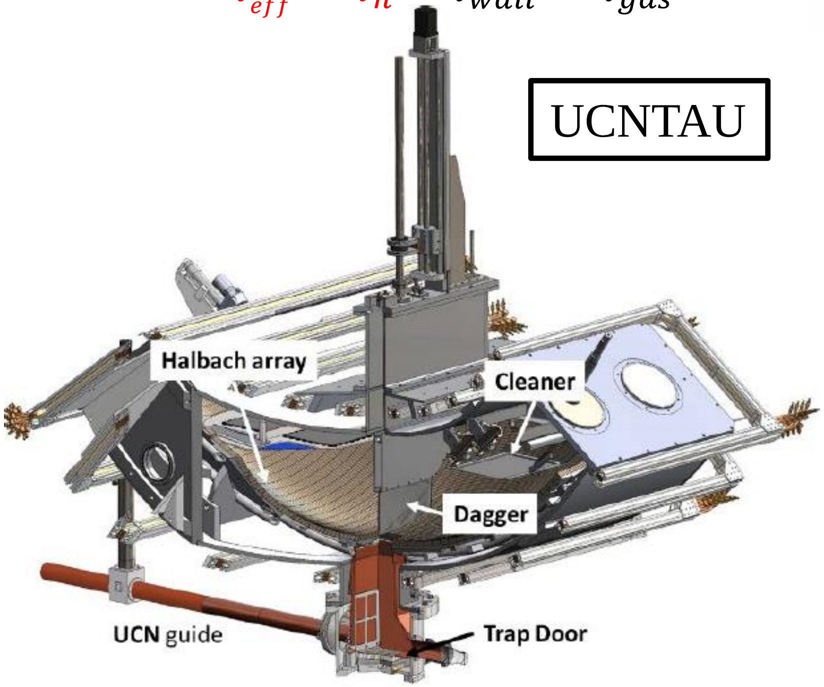
Neutron beta decay lifetime

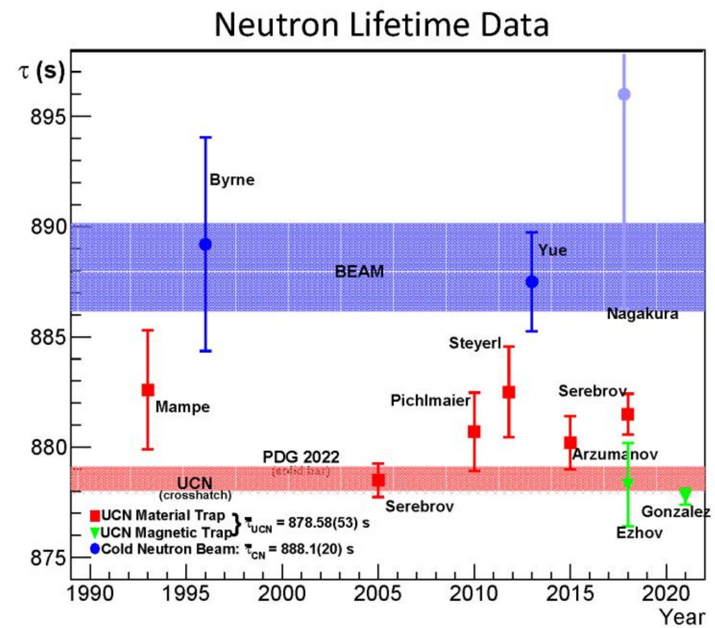
Beam: Decay rate: $\frac{dN}{dt} = \frac{N}{\tau_n}$

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

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





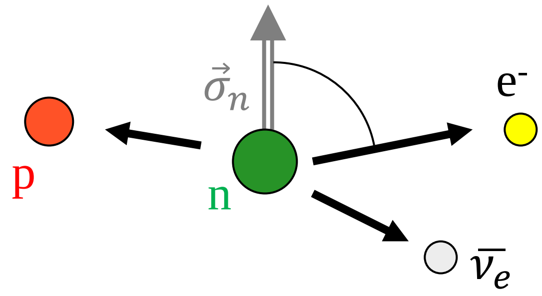


Courtesy A. Young

Discrepancy between beam and bottle may be real (decay into dark particle, not otherwise detected, or an experiment error. Previous analysis uses only last data point. Many new experiments:

- Magnetic bottles (UCNTAU+, LANL, τSPECT, TRIGA Mainz; PENELOPE, TU München)
- Beam Lifetime BL2 and BL3, NIST
- UCNProBe, LANL: UCN trap in which both decay rate and neutron count decay are observed.

The Beta Asymmetry A in neutron beta decay

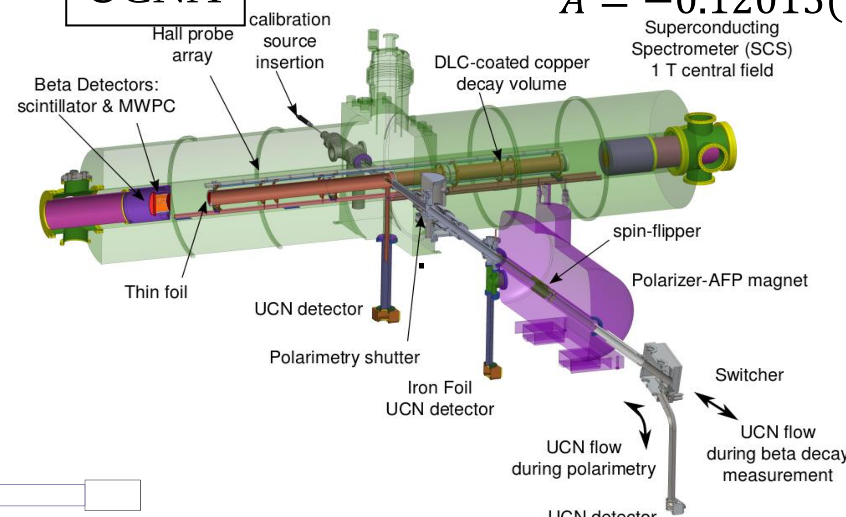


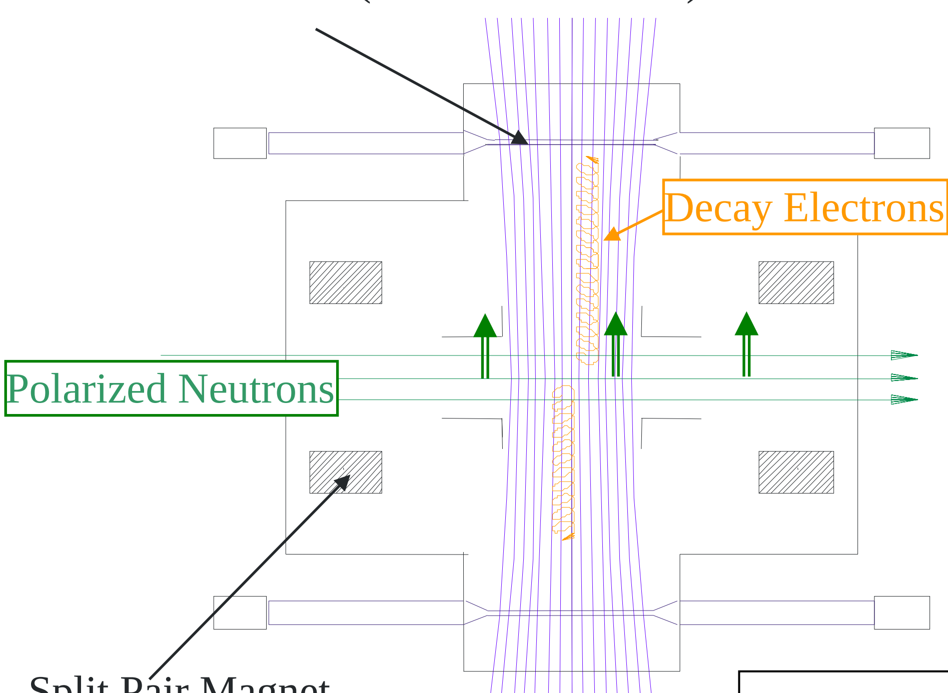
UCNA

Final result of UCNA:

$A = -0.12015(34)_{stat}\,(63)_{sys}$

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





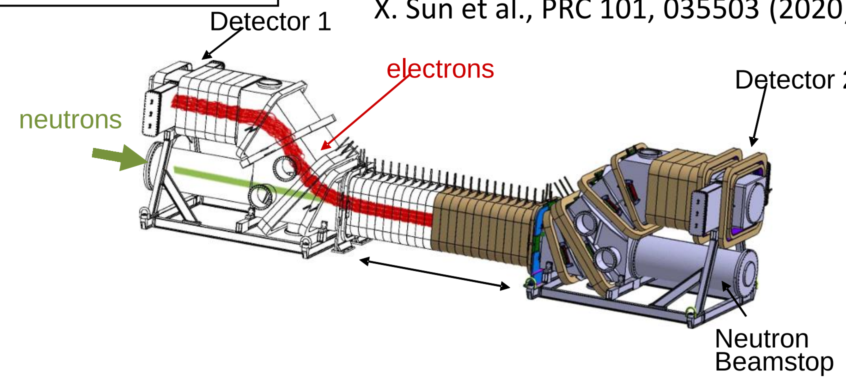
PERKEO II

$A = -0.11972(+53/-65)$ D. Mund et al., PRL 110, 172502 (2013)

PERKEO III

$b = 0.066(41)_{stat}\,(24)_{sys}$

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



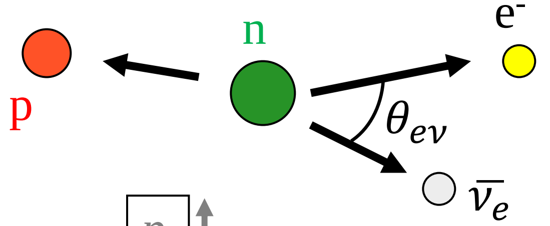
$A = -0.11985(17)_{stat}\,(12)_{sys}$

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

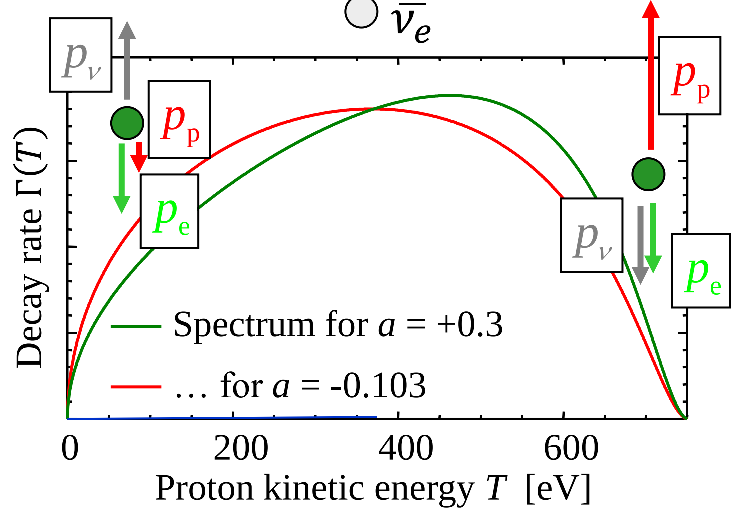
$b = 0.017(20)_{stat}\,(3)_{sys}$

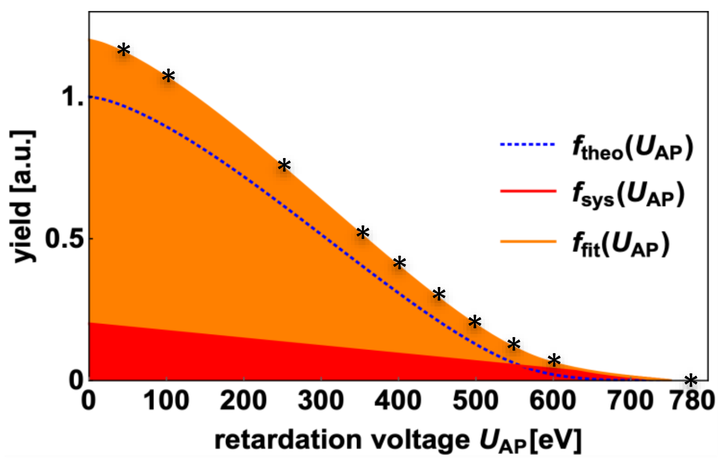
H. Saul et al., PRL 125, 112501 (2020)

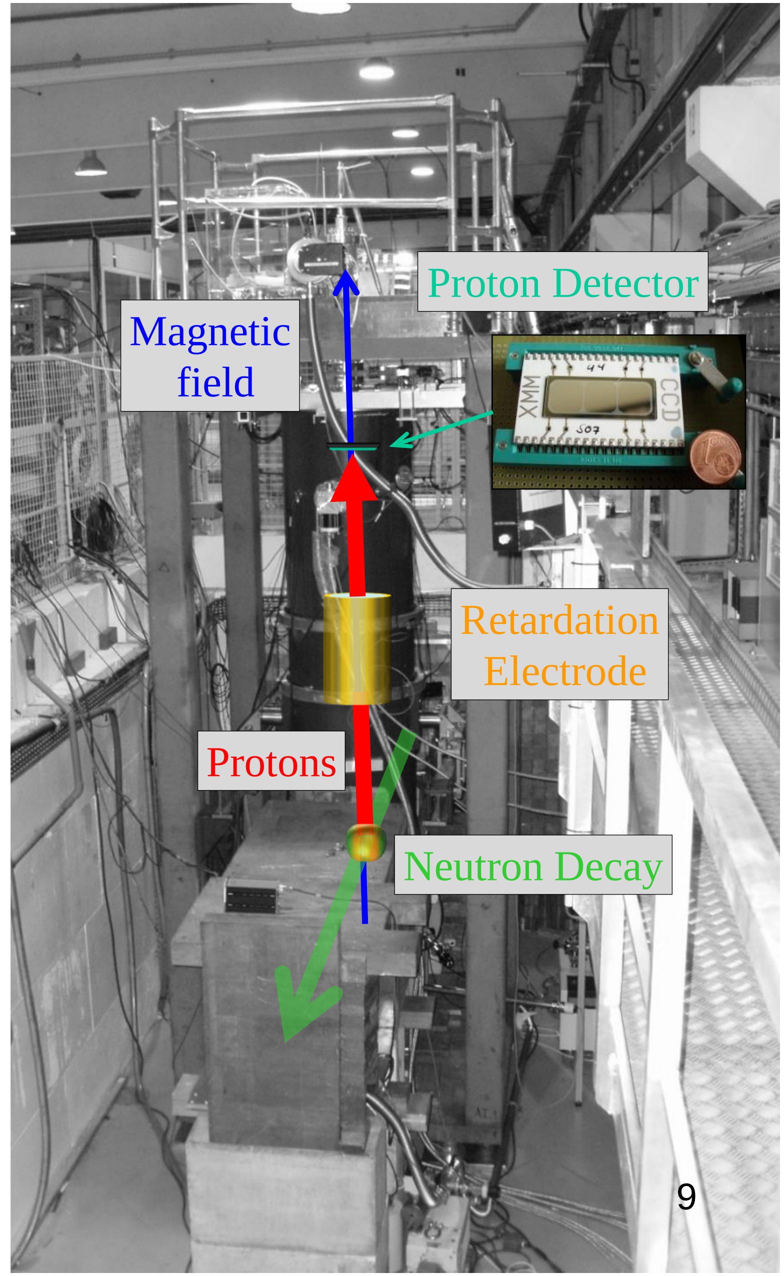
aSPECT @ ILL Grenoble (lead institution: JGU Mainz)



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



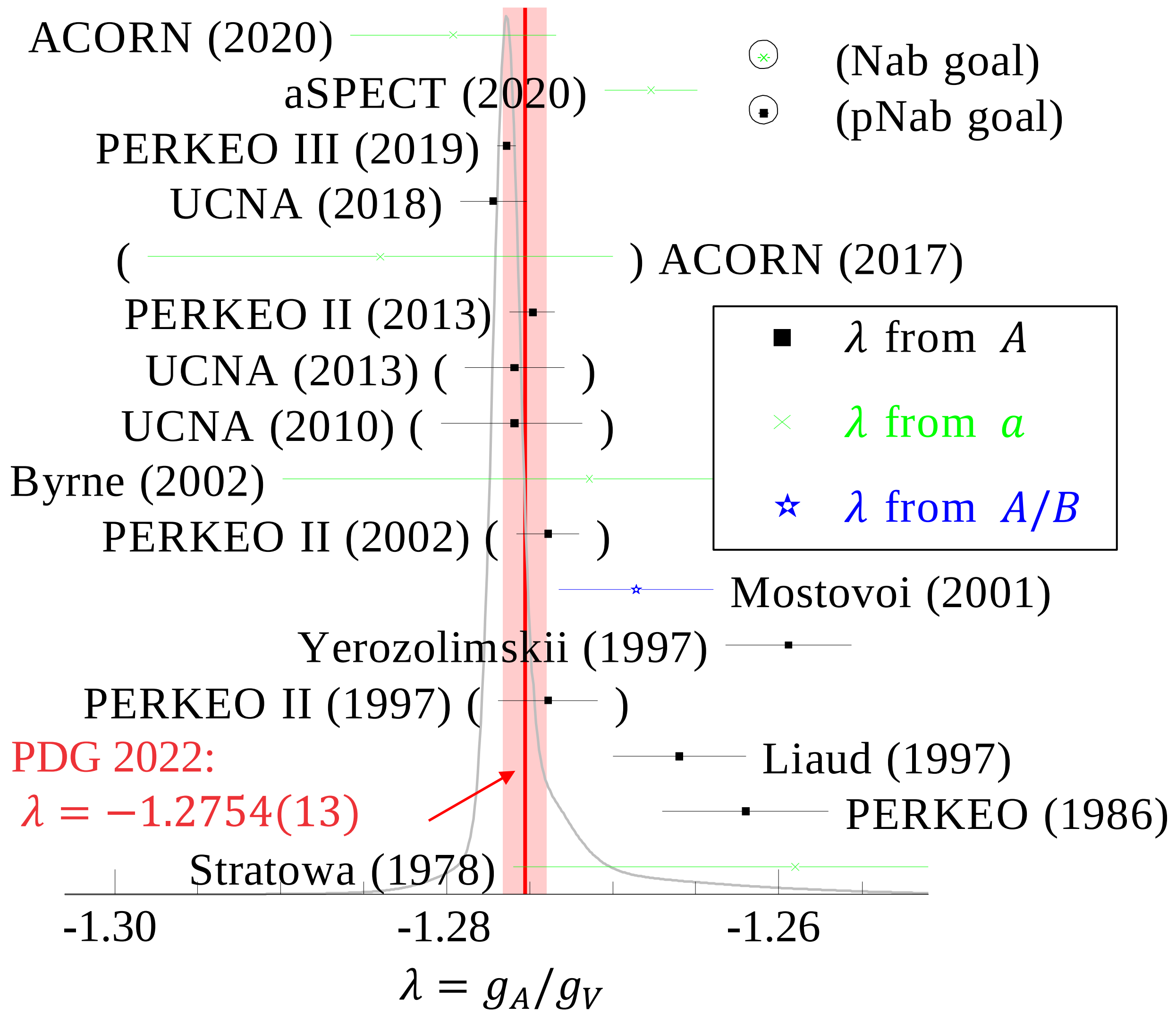




Recent result $a = -0.10402(82)$

PRC 101, 055506 (2020), updated in arXiV: 2308.16170

Determination of lambda in neutron beta decay



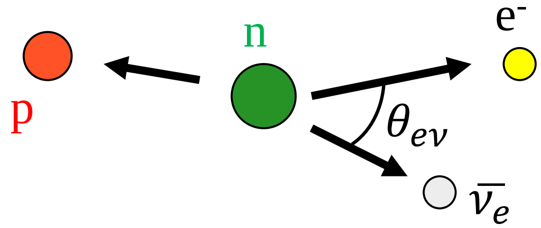
Most experiments measure the beta asymmetry A to determine λ. Most recent: PERKEO III.

Result confirmed with UCNA., no puzzle.

BUT: λ from neutrino electron correlation coefficient a is different by 3σ (or: aSPECT and PERKEO III disagree)

A positive value for b could explain, but is in tension with other experiments.

The Nab experiment

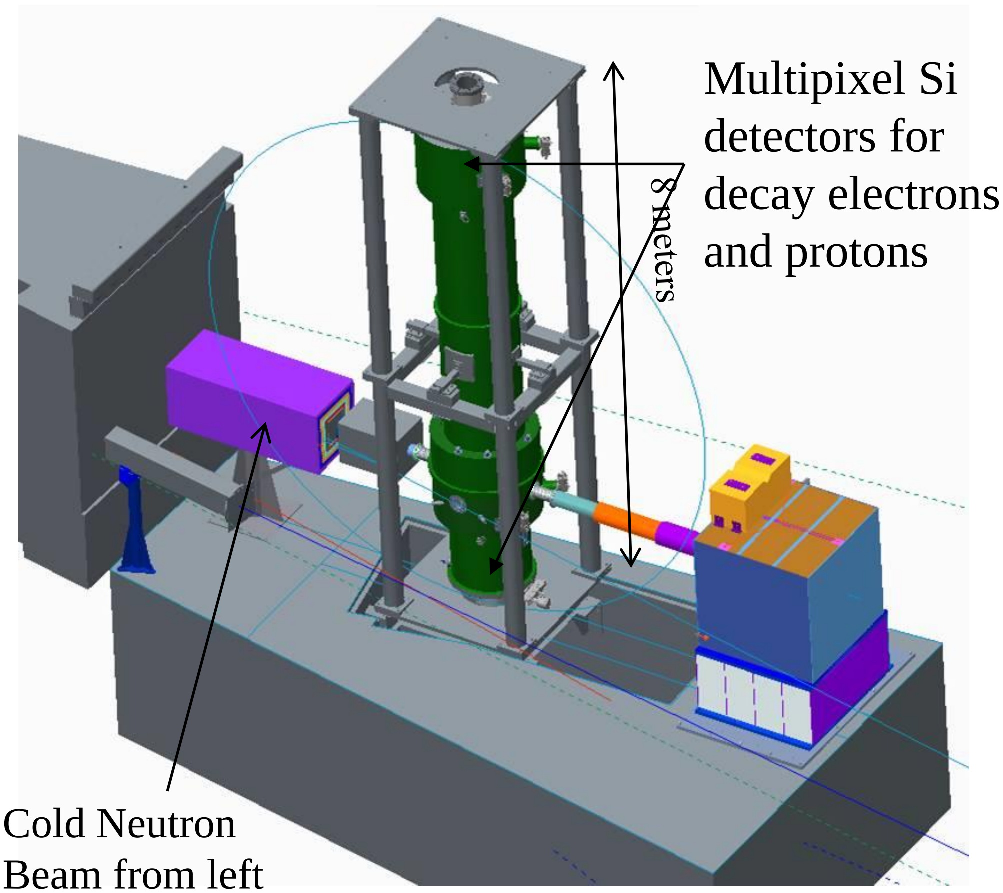


$$d\Gamma \propto \varrho(E_e)\left(1 + a\frac{p_e}{E_e}\cos\theta_{e\nu} + b\frac{m_e}{E_e}\right)$$

Measurement of electron energy spectrum gives the Fierz term b.

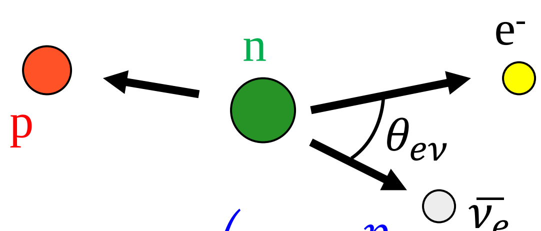
Measurement of a from measurement of proton and electron energy.

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)

Idea of the cos $\theta_{e\nu}$ spectrometer Nab @ SNS

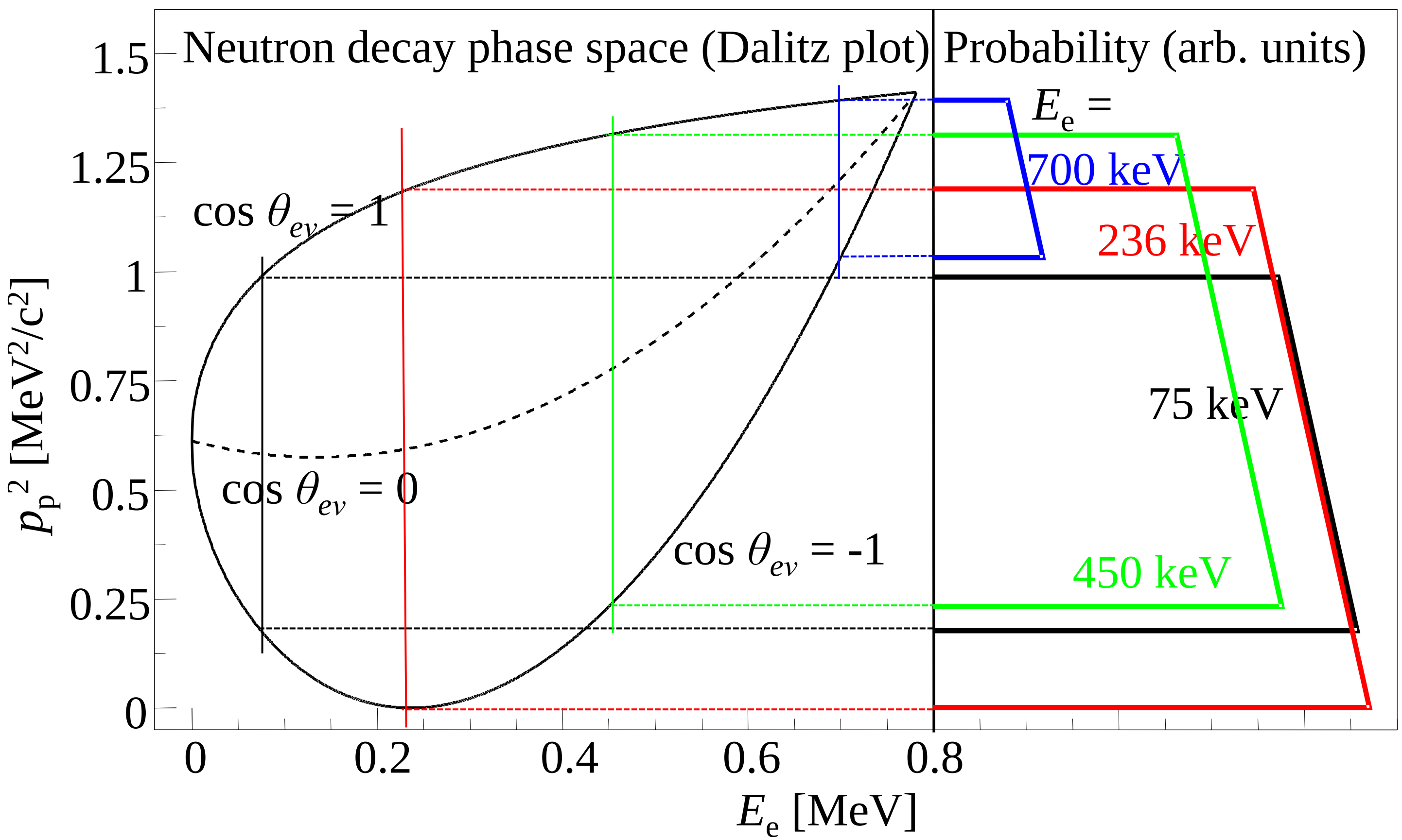


$$d\Gamma \propto \varrho(E_e)\left(1 + a\frac{p_e}{E_e}\cos\theta_{e\nu} + b\frac{m_e}{E_e}\right)$$

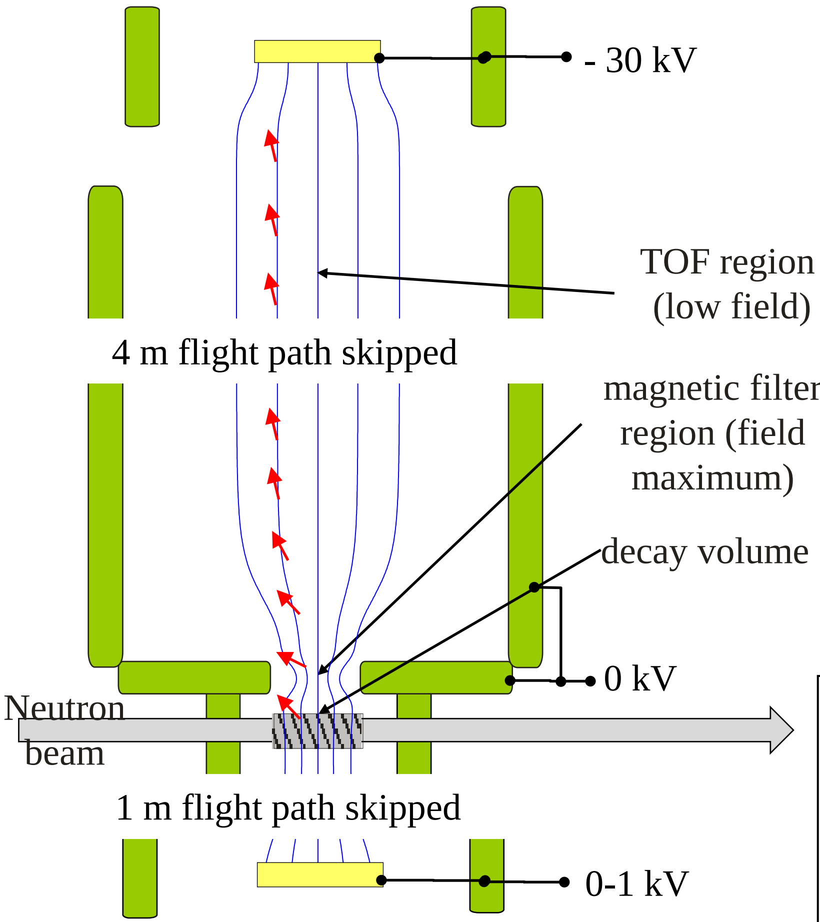
- Energy Conservation in Infinite Nuclear Mass Approximation: $E_\nu = E_{e,max} - E_e$
- Momentum Conservation:

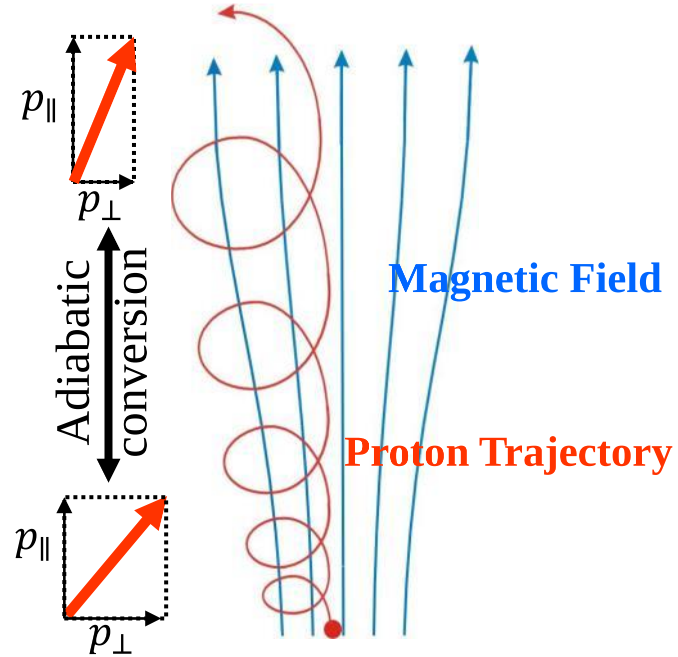
$$p_p^2 = p_e^2 + p_\nu^2 + 2p_e p_\nu \cos\theta_{e\nu}$$

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



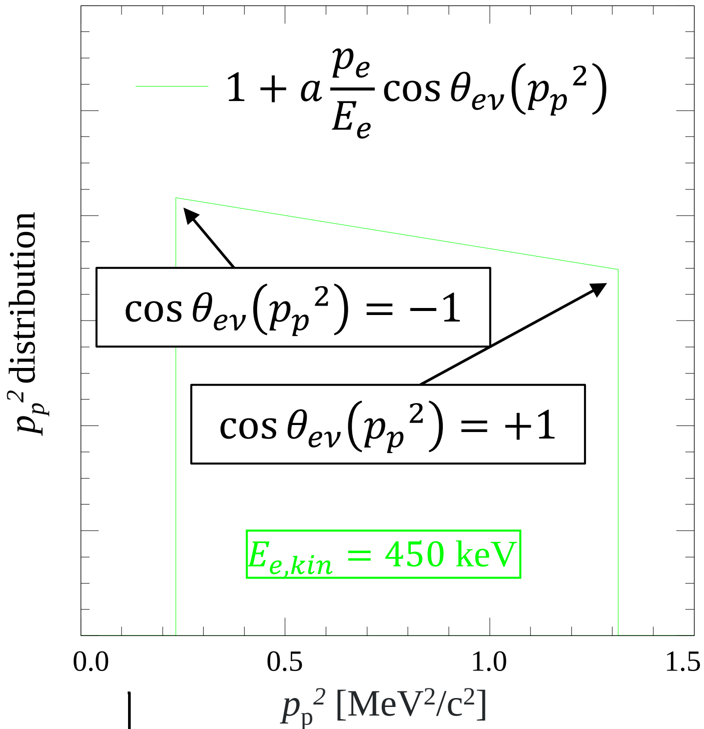
Nab spectrometer principle: measurement of E_e and t_p





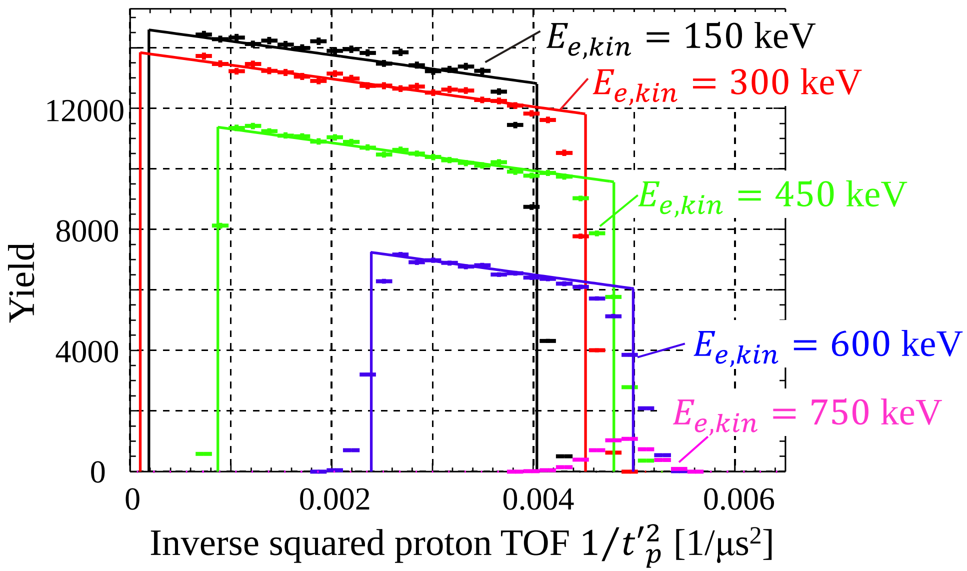
- Measurement of $E_{e,kin}$ and t_p for each event; protons only in upper detector
  - → $1/t_p^2$ gives an estimate for p_p^2, magnetic field shape gives a narrow detector response function
- Two detector geometry allows to suppress electron backscattering

Simulated Nab data analysis



$$t_p = \frac{m_p \cdot \text{spectrometer length}}{p_p\text{−component along } \vec{B}}$$

Full GEANT4 spectrometer simulation:



Data analysis: Use edge to determine or verify the spectrometer TOF response function.

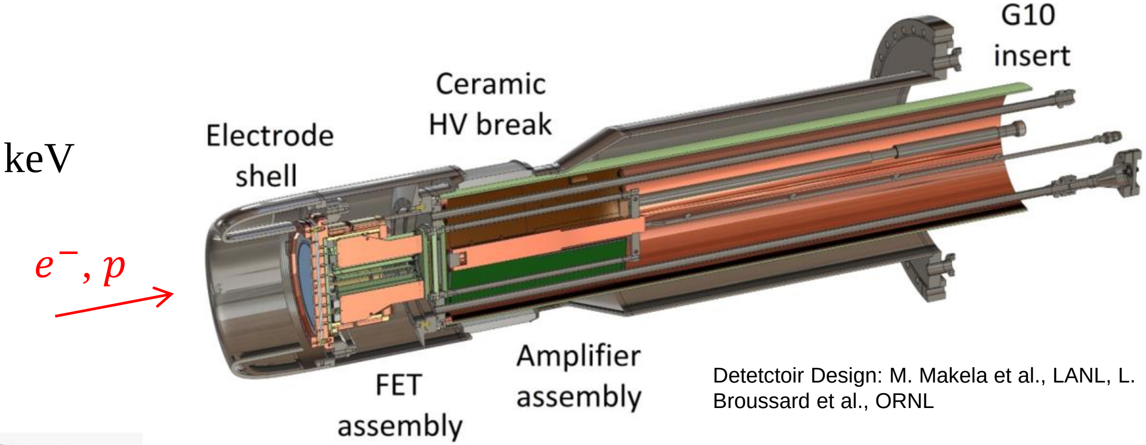
Then, use central part to determine slope and correlation coefficient a. Need agreement for all.

Nab experiment status

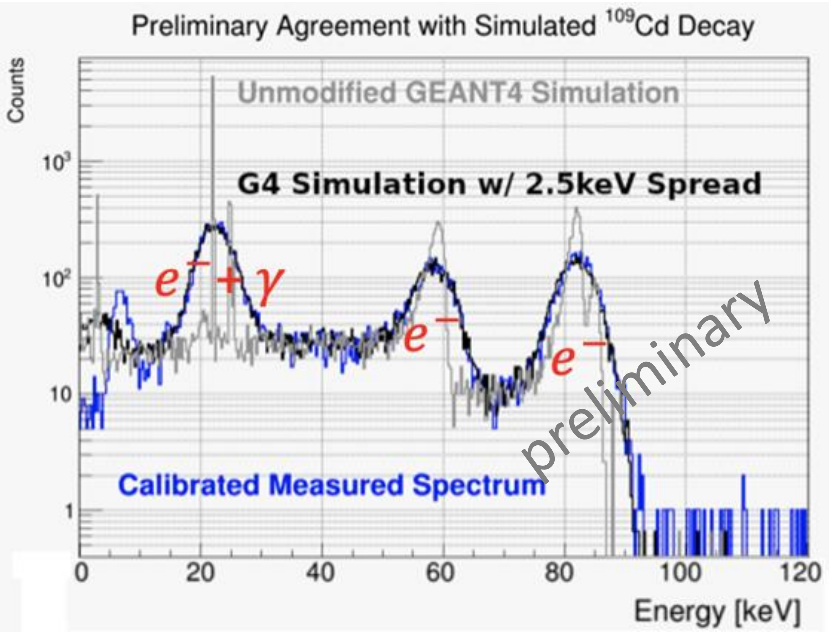
- Nab experiment installation completed September 2021
- Now in commissioning phase, that is, the collaboration is working on understanding all subsystems

Status of Nab experiment: Characterization of Detector

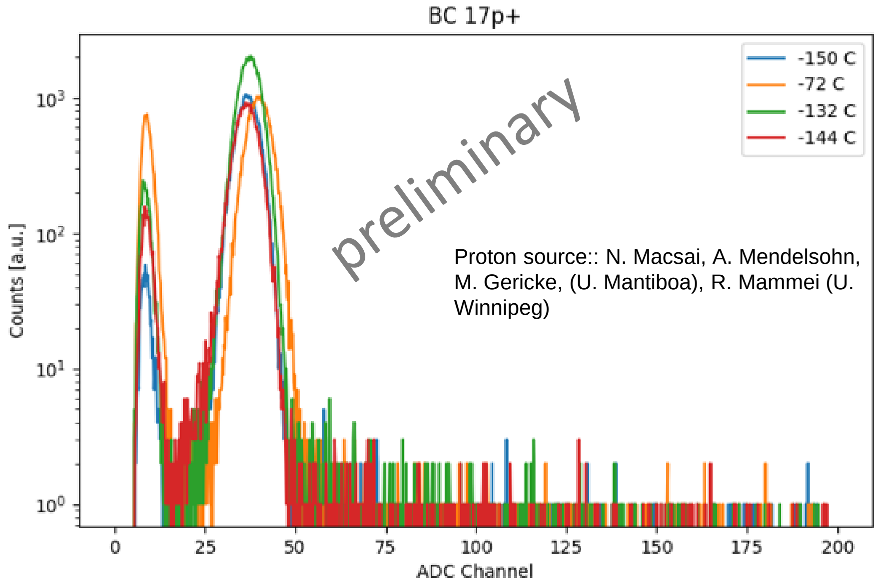
- 127 pixel Si detector, 2 mm thick
- Energy resolution a few keV
- Lower (proton) detection threshold 10 keV
- Detector transit time bias sub-ns



Detetctoir Design: M. Makela et al., LANL, L. Broussard et al., ORNL



Electron detection



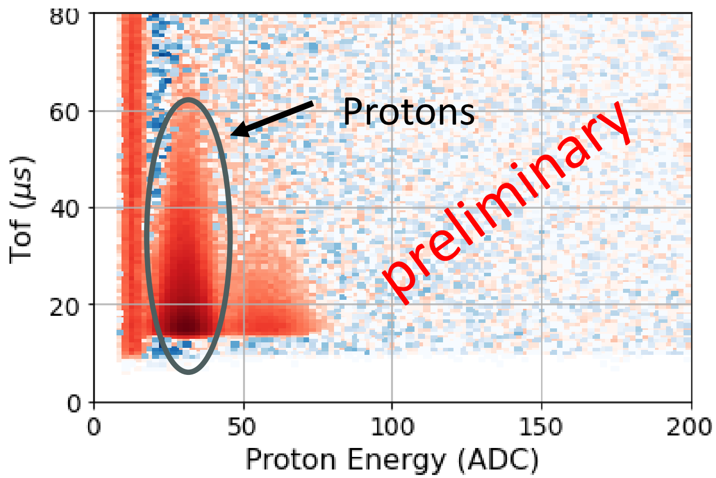
Proton source:: N. Macsai, A. Mendelsohn, M. Gericke, (U. Mantiboa), R. Mammei (U. Winnipeg)

Proton detection

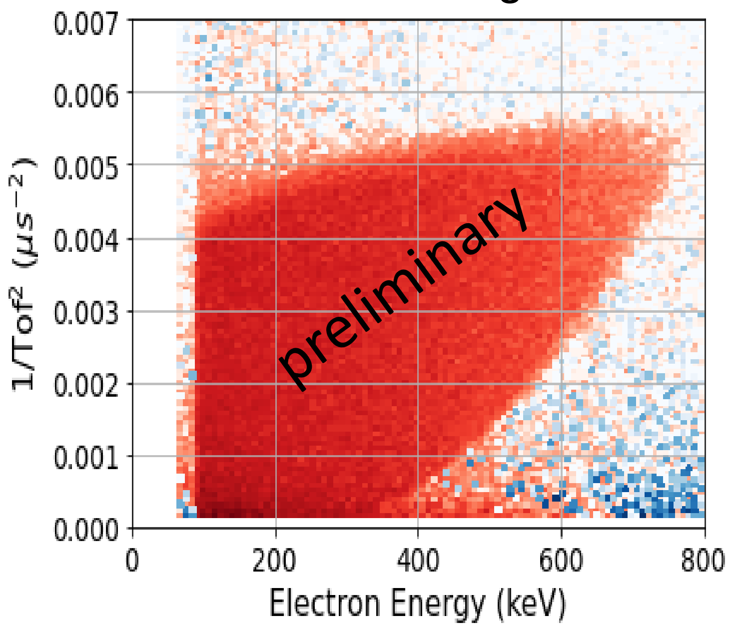
Analysis: NC STATE UNIVERSITY Jin Ha Choi, Leendert Hayen TUNL

First look at commissioning data (preliminary!)

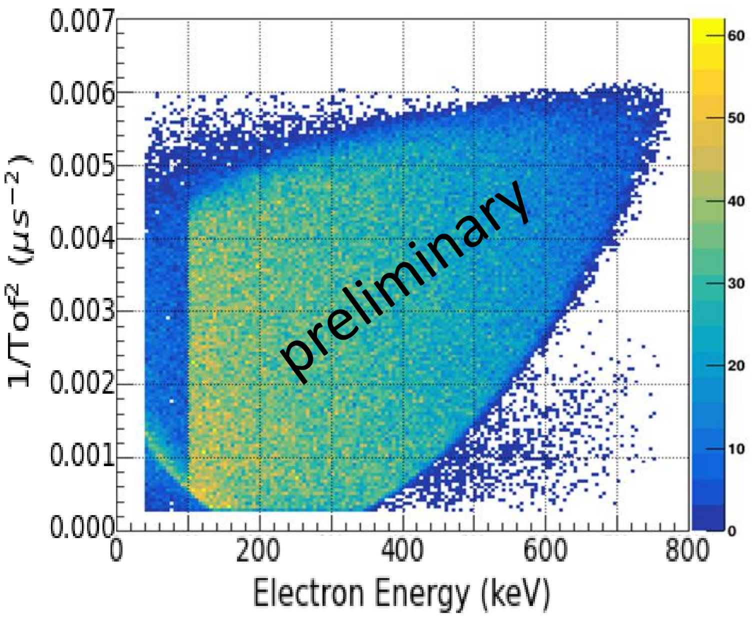
- Commissioning data taking started in July 2023.
- Some problems with detector system found which we have to work on.
- However, proof-of-principle has been achieved:
- Right: Trigger of proton candidate signal after electron candidate signal.
- Bottom: Comparison of 2D histograms



Commissioning data



Simulation



Preliminary Analysis: Frank Gonzales, ORNL

pNab: Measurement of correlation coefficients with polarized neutrons

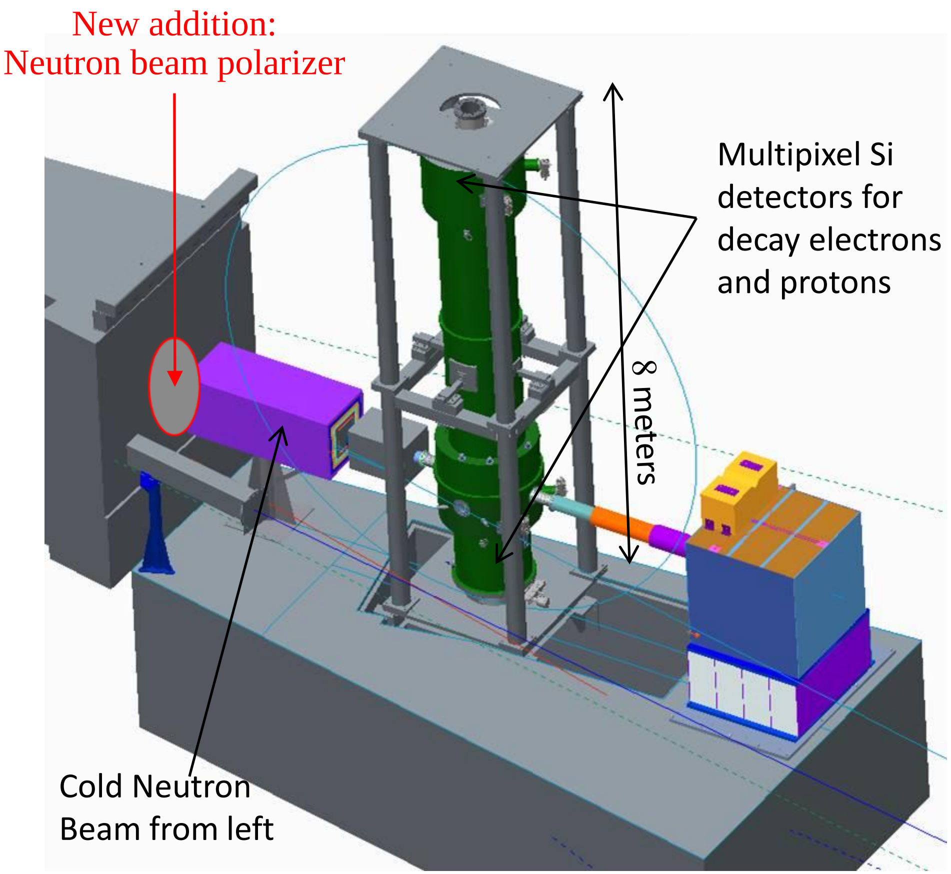
b or b_ν may indicate S,T

$B_0 \neq B_0(\lambda)$ may indicate V+A

$$d\Gamma \propto \varrho(E_e)\left(1 + a\frac{p_e}{E_e}\cos(\vec{p}_\nu,\vec{p}_e) + b\frac{m_e}{E_e} + A_0\frac{p_e}{E_e}\cos(\vec{\sigma}_n,\vec{p}_e) + \left(B_0 + b_\nu\frac{m_e}{E_e}\right)\cos(\vec{\sigma}_n,\vec{p}_\nu)\right)$$

$a_0 = a_0(\lambda)$

$A_0 = A_0(\lambda)$

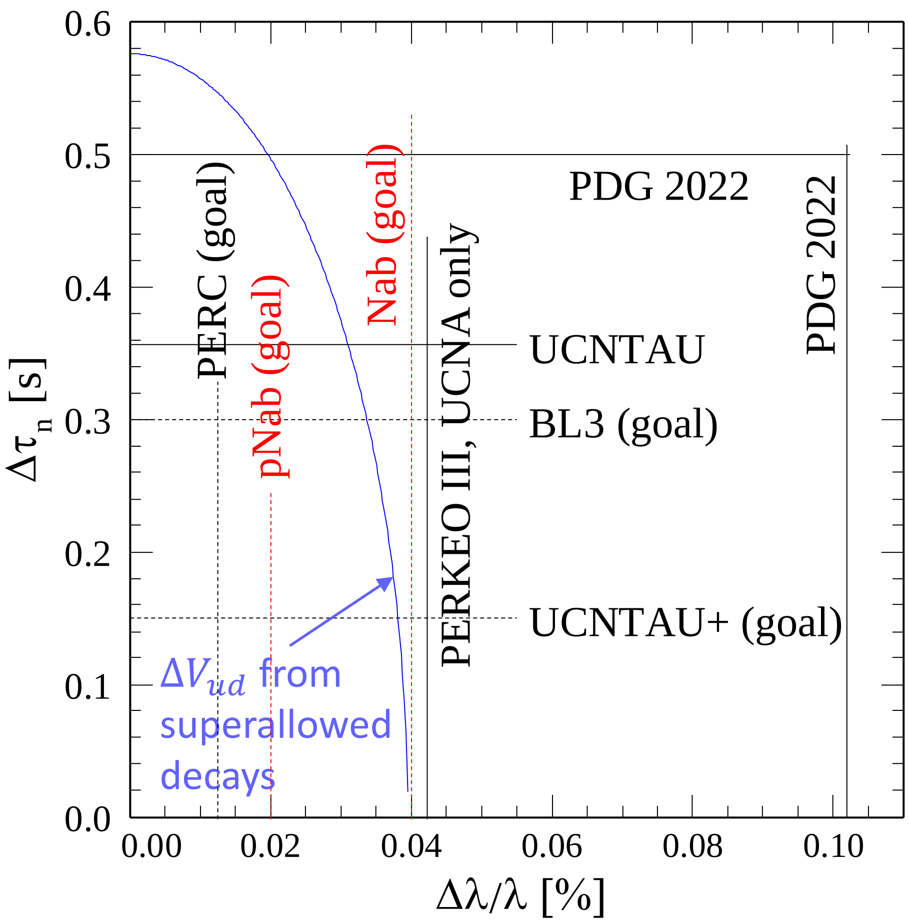


Goal: $\frac{\Delta A}{A} \sim 8 \cdot 10^{-4}$

Update on motivation for nab and pNab: λ

V_{ud} from neutron beta decay:

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



- Need better accuracy in τ_n and λ to fulfill the long-standing hope to base the CKM unitarity test on neutrons. Improving on λ has the largest impact.
- We need variation in experiment techniques to investigate inconsistent results (aSPECT vs. PERKEO III just as much as the long-standing beam vs. bottle lifetime experiments controversy).
- With Nab and pNab, we can measure both a and A coefficients in the same apparatus.

Summary

The BIG PUZZLE: IS THE STANDARD MODEL OF ELEMENTARY PARTICLE PHYSICS FINALLY BREAKING?

- Currently, unitarity of the CKM matrix is violated by about $2-3\sigma$. This test is based on V_{ud} from superallowed nuclear decays and Kaon decays. Selected neutrons decay experiments contribute. All inputs are under scrutiny. $2-3\sigma$ is not usually considered a big deal, but should be understood.
- Neutron beta decay could replace nuclear beta decay if experiments gain accuracy. There is steady, albeit slow progress. Theoretically, that would be cleaner.
- Physics goal for neutron beta decay should be at least $\Delta\tau_n \sim 0.3$ s and $\Delta\lambda/|\lambda| \sim 3 \cdot 10^{-4}$ (for unitarity test), or $\Delta b \sim 10^{-3}$ or and $\Delta b_\nu \sim 10^{-3}$. Several experiments (UCNTAU, BL3, PERC, Nab, pNab) promise to get there.
- It is insufficient to just do one experiment for each input, we need to understand current discrepancies.

The Nab collaboration

Nab collaborating institutions:

Oak Ridge National Laboratory
Los Alamos National Laboratory
University of Virginia
The University of Tennessee Knoxville
Arizona State University
NC State University
Massachusetts Institute of Technology
University of Kentucky
University of Michigan
Eastern Kentucky University
The University of Tennessee Chattanooga
University of Manitoba
The University of Winnipeg
GT

University of South Carolina,
Universität Karlsruhe (TH),
Universidad Nacional
Autónoma de México,
Western Kentucky University

Main project funding:

NSF
U.S. Department of Energy
Office of Science
Oak Ridge National Laboratory
University of Virginia