Precision studies of *n* beta decay in Nab and pNab

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Outline

- Beta decay, esp. of the *neutron*, and the Standard Model,
- Physics motivation for Nab and pNab,
- Principles of measurement in the Nab experiment,
- Status and plans for Nab,
- pNab as extension of Nab,
- Summary and outlook.

Quark-lepton (Cabibbo) universality and β decays

The basic weak-interaction V-A form (e.g., μ decay):

$$\mathcal{M} \propto \langle e|\ell^\alpha|\nu_e\rangle \to \bar{u}_e\gamma^\alpha(1-\gamma_5)u_\nu$$

is replicated in hadronic weak decays

$$\mathcal{M} \propto \langle p|h^\alpha|n\rangle \to \bar{u}_p\gamma^\alpha(G_V - G_A\gamma_5)u_n \quad \text{with} \quad G_{V,A} \simeq 1 \ .$$

Departure from $G_V = 1$ (**CVC**) comes from weak quark (Cabibbo) mixing:
$G_V = G_\mu \cos\theta_C (= G_\mu V_{ud}) \quad \cos\theta_C \simeq 0.97$

3 q generations lead to the
Cabibbo-Kobayashi-Maskawa (CKM) matrix (1973): $\begin{pmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{pmatrix}$

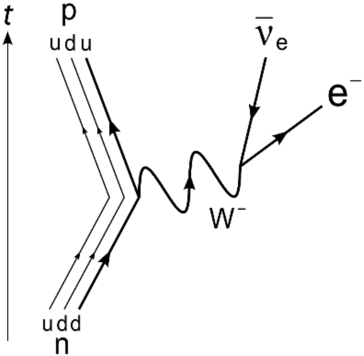
CKM unitarity cond.: $\Delta V^2 = 1 - (|V_{ud}|^2 + |V_{us}|^2 + |V_{ub}|^2) \overset{?}{=} 0$, ⇐ [best test available!]
stringently tests the SM. Until 2004 appeared violated by $\sim 3\sigma$!

Dynamics and observables

Basic beta decay Lagrangian for a baryon

$$\mathcal{L}_W(x) = -\frac{G_F}{\sqrt{2}} V_{ud} \left[\bar{\psi}_p(x)\gamma^\mu(1+\lambda\gamma^5)\psi_n(x)\right] \left[\bar{\psi}_e(x)\gamma_\mu(1-\gamma^5)\psi_\nu(x)\right]$$

$$= -\frac{1}{\sqrt{2}} \left[\bar{\psi}_p(x)\gamma^\mu(g_V+g_A\gamma^5)\psi_n(x)\right] \left[\bar{\psi}_e(x)\gamma_\mu(1-\gamma^5)\psi_\nu(x)\right]$$



where $\boxed{g_V = G_F V_{ud} = G_F G_V}$ and $\boxed{g_A = G_F V_{ud}\lambda = G_F G_A}$.

$G_F \simeq 1.1664 \times 10^{-11}\ \text{MeV}^{-2}$
(for our purposes, infinitely well determined in μ decay)

$\lambda \simeq -1.272$ (from correlations in neutron decay)

Rate of neutron decay/lifetime is given by:

$$\Gamma = \frac{1}{\tau_n} = (1+3\lambda^2)\frac{G_F^2 V_{ud}^2}{2\pi^3} f_{\text{Fermi}}^{Z=1}(E_{\max})$$

Extracting V_{ud} from n decay

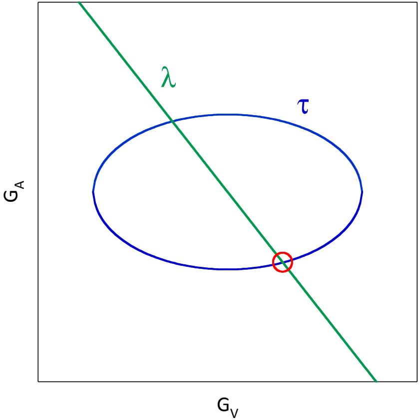
Evaluating the preceding relation we get:

$$|V_{ud}|^2 = \frac{4908.7(1.9)\,\text{sec}}{\tau_n(1+3\lambda^2)}, \quad \text{or}$$

$$\tau_n^{-1} = \text{const.}(G_V^2 + 3G_A^2)$$

We therefore need to measure:

- neutron lifetime τ_n (counting neutrons)
- ratio $\lambda = G_A/G_V$ (decay correlations)



Key questions:

- How thick (uncertain) are the τ_n ellipse and the λ line?
- How reliable and consistent are the results from different methods of τ_n and λ evaluation?

Neutron beta decay observables (SM)

General Lorentz invariant differential beta decay rate is:

$$\frac{\mathrm{d}w}{\mathrm{d}E_e \mathrm{d}\Omega_e \mathrm{d}\Omega_\nu} \propto \rho(E_e) \times \left\{ 1 + a \frac{\vec{p}_e \cdot \vec{p}_\nu}{E_e E_\nu} + b \frac{m}{E_e} + \langle \vec{\sigma}_n \rangle \cdot \left[A_0 \frac{\vec{p}_e}{E_e} + \left(B_0 + b_\nu \frac{m_e}{E_e} \right) \frac{\vec{p}_\nu}{E_\nu} \right] + \dots \right\}$$

The $(V-A)$ SM prescribes $b = b_\nu = 0$, and:

($b \neq 0$ signals S,T components)

(e-ν correlation) $a(\lambda) = \dfrac{1 - |\lambda|^2}{1 + 3|\lambda|^2}$ $\qquad$ $A_0(\lambda) = -2\dfrac{|\lambda|^2 + Re(\lambda)}{1 + 3|\lambda|^2}$ (β-asymmetry)

(ν-asymmetry) $B_0(\lambda) = 2\dfrac{|\lambda|^2 - Re(\lambda)}{1 + 3|\lambda|^2}$ $\qquad$ $\lambda = \dfrac{G_A}{G_V}$ (with $\tau_n \Rightarrow$ CKM V_{ud}) .

One can also define the proton asymmetry: $C = \kappa(A + B)$ where $\kappa \simeq 0.275$.

⇒ SM **overconstrains** a, A, B observables in n β decay . . . $(V + A)$!
Fierz interference terms b, b_ν enahnce sensitivity to non-SM processes (S, T)!

Current world data and goals of the Nab experiment (SNS, ORNL)

- Measure a, (e–ν correlation) in n decay with $\Delta a/a \simeq 10^{-3}$, or $\sim 10\times$ better than:

current results, $a =$

$-0.091\,(39)$	Grigorev et al 1968,
$-0.1017\,(51)$	Stratowa et al 1978,
$-0.1054\,(55)$	Byrne et al 2002,
$-0.10779\,(183)$	Wietfeldt et al 2023 (aCORN),
$-0.10402\,(84)$	Beck et al 2024 (aSPECT).

- Measure b (Fierz term) in n decay with $\Delta b \simeq 3\times 10^{-3}$, to be compared with:

current results, $b_n =$

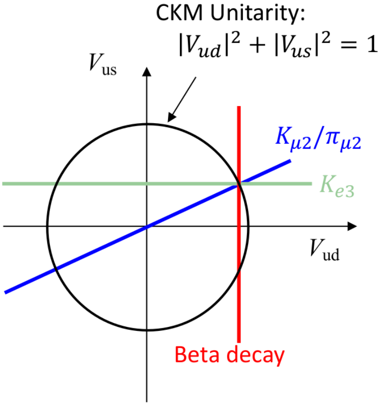
0.067^{+93}_{-66}	Hickerson et al 2017 (UCNA),
$0.017\,(21)$	Saul et al 2019 (Perkeo-III),
$-0.0098\,(193)$	Beck et al 2024 (aSPECT).

- **Nab** will be followed by the **pNab** polarized program to measure A, electron, and B/C, neutrino/proton, asymmetries with $\simeq 10^{-3}$ relative precision.

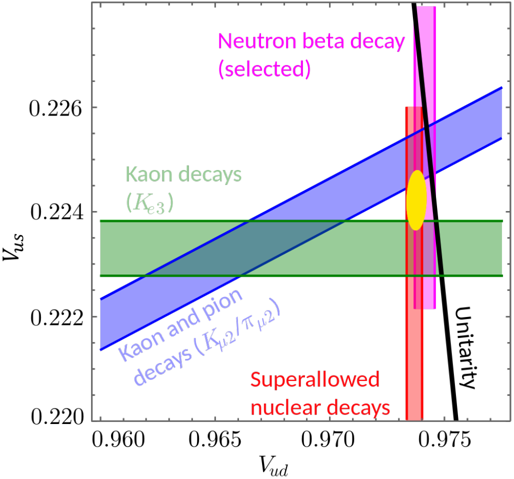
Motivation:

- multiple independent determinations of λ (test of CKM unitarity),
- independent and competitive limits on S, T currents (beyond SM).

CKM unitarity limits: current state of agreement

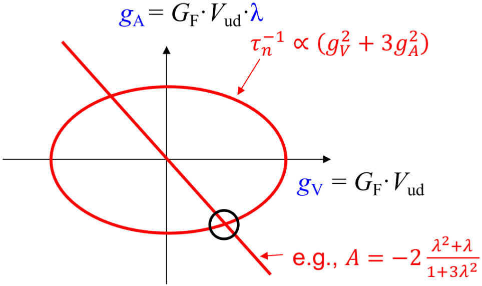


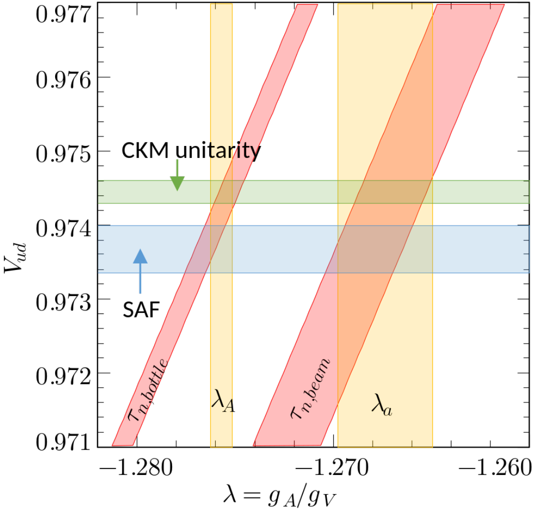
$K_{\mu 2}$: $K \to \mu\bar{\nu}$; $\pi_{\mu 2}$: $\pi \to \mu\bar{\nu}$;
K_{e3}: $K \to \pi e \bar{\nu}_e$ (all K charge states).



There are inconsistencies between the K decay sector (V_{us}) and the beta decay sector (V_{ud}).

$V_{ud} - \lambda$: current state of agreement for *n* beta decays





Inconsistencies remain in the *n* beta decay sector.

Full physics reach of *n* decay not yet met.

SAF: superallowed Fermi decays

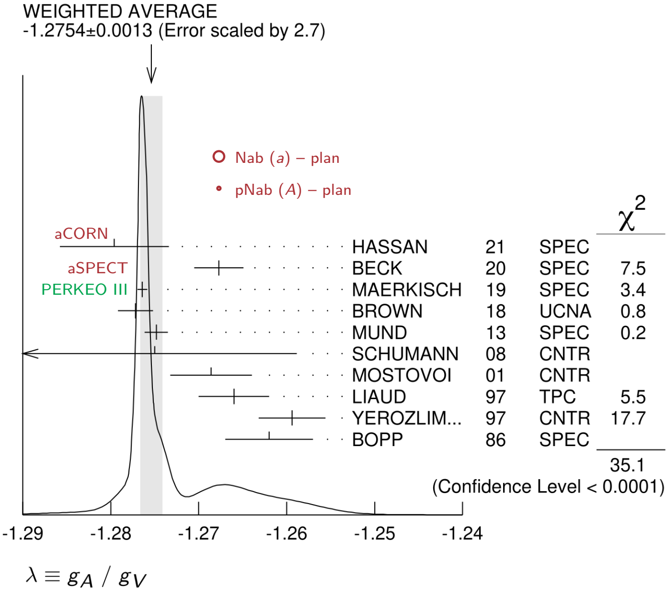
PDG 2024 on the evaluation of $\lambda = g_A/g_V$:

- λ value has drifted over time;
- λ is dominated by A results;
- recent evaluations of a are becoming competitive;
- inconsistencies in $\lambda(a)$ need to be resolved.

Sensitivity to λ:

$$\frac{\Delta\lambda}{\lambda} \simeq 0.27\frac{\Delta a}{a} \simeq 0.24\frac{\Delta A}{A}$$

Combined Nab and pNab will exceed the precision $\Delta\lambda$ of PERKEO III.



How to accomplish the goals of Nab?

$$\boxed{\text{Measure: } \frac{\Delta a}{a} \simeq 10^{-3} \text{ and } \Delta b \simeq 3 \times 10^{-3}.}$$

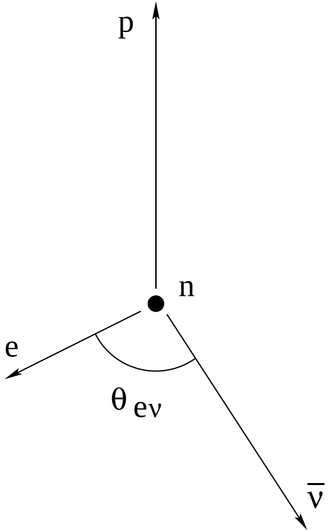
Basic approach: $(\mathrm{n} \rightarrow \mathrm{p} + \mathrm{e}^- + \bar{\nu}_\mathrm{e})$

- Detect electrons directly, in Si detectors,
- Measure electron energy in Si detectors,
- Detect protons, after acceleration, in Si detectors,
- Determine proton momentum from TOF over a long flightpath (electron provides start pulse).

A complex magneto-electrostatic apparatus is required to guide particles (nearly) adiabatically to detectors.

Location: FnPB at SNS.

Electron–neutrino angle from E_e and E_p



Conservation of momentum in **n** beta decay,

$$\vec{p}_p + \vec{p}_e + \vec{p}_\nu = 0\,,$$

yields

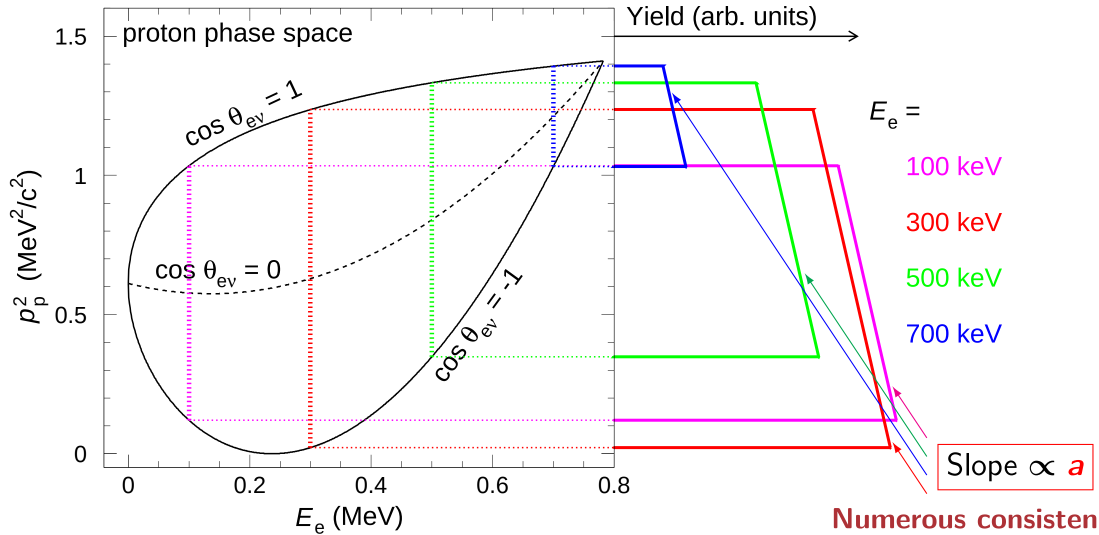
$$p_p^2 = p_e^2 + 2 p_e p_\nu \cos\theta_{e\nu} + p_\nu^2\,.$$

Neglecting the proton recoil energy we have $E_e + E_\nu = E_0$, or, $p_\nu = E_0 - E_e$. Therefore:

$$p_p^2 \simeq p_e^2 + 2 p_e (E_0 - E_e) \cos\theta_{e\nu} + (E_0 - E_e)^2\,.$$

$\Rightarrow$ $\cos\theta_{e\nu}$ is uniquely determined by measuring E_e and E_p (or $p_p \Leftrightarrow \mathrm{TOF}_p$).

Nab measurement principles: proton phase space



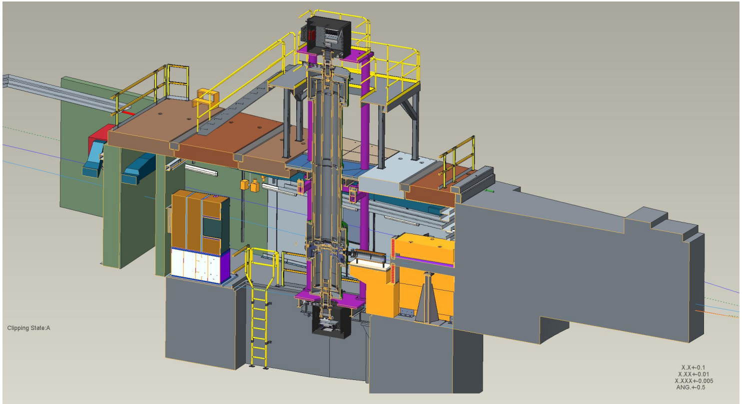
NB: For a given E_e, $\cos\theta_{e\nu}$ is a function of p_p^2 only.

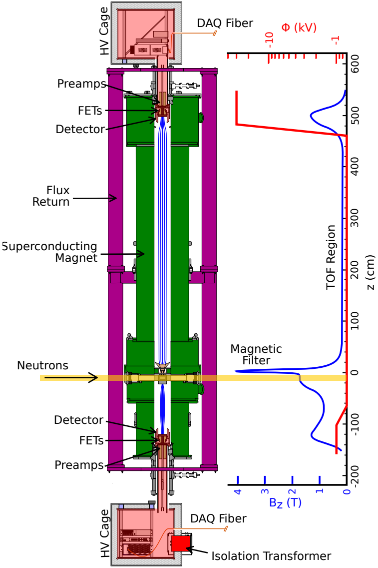
Numerous consistency checks are built-in!

Nab apparatus (overview)

custom magneto-el.static spectrometer:

Extends: ∼6 m above and ∼2 m below beam height (pit).



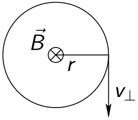


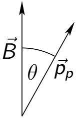
In commissioning; full Nab data taking in Jul/Aug '24

Why such complicated fields? — protons fly in all directions!

(not just straight to a small detector) ⇒ must collect, guide them, and relate TOF to p_p!

Method how: **adiabatic longitudinalization**;
protons (and e's) gyrate around $\vec{B}$ field lines





$$\frac{mv_\perp^2}{r} = ev_\perp B, \text{ or}$$

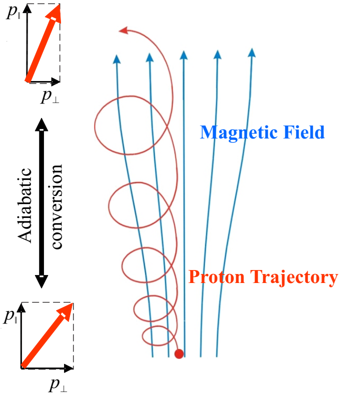
$$r = \frac{mv_\perp}{eB} .$$

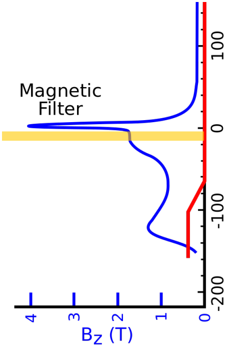
Conservation of $\vec{L}$ and energy yields:

$$L = mv_\perp r = \frac{m^2 v^2 \sin^2\theta}{eB} = \text{const.},$$

or:

$$\boxed{\sin\theta_{pB} \propto \sqrt{B}} .$$



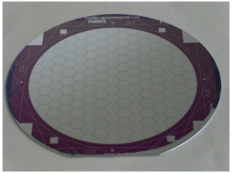


Nab Si detector basics

(LANL-Micron development)

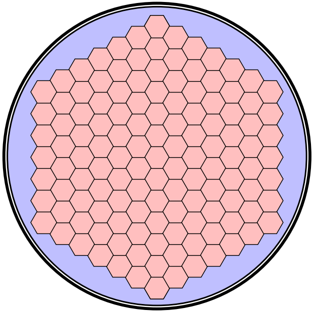
- 15 cm diameter
- full thickness: 2 mm
- dead layer ≤100 nm
- 127 pixels

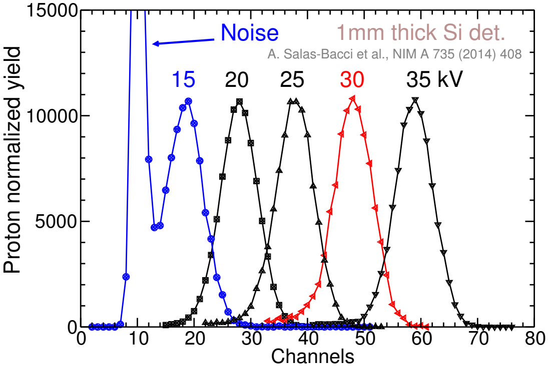
Front



Back

Pixel geometry:

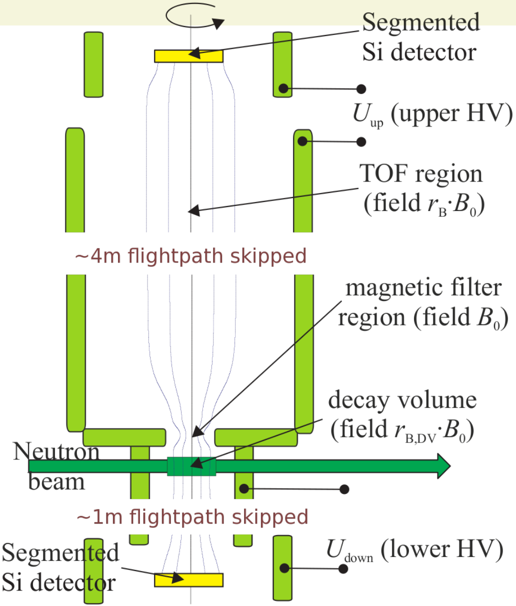




Apparatus and running configurations

- Nab-*a*: detect protons in upper, electrons in both detectors;
  $U_{\mathrm{up}} = -30\,\mathrm{kV}$,
  $U_{\mathrm{down}} = 0\,\mathrm{kV}$ (or $-1\,\mathrm{kV}$);
  b measured parasitically!.

- Nab-*b*: detect electrons in both, protons in lower detector;
  $U_{\mathrm{up}} = 0\,\mathrm{kV}$ (up to $+1\,\mathrm{kV}$),
  $U_{\mathrm{down}} = -30\,\mathrm{kV}$.
  full e–p coinc. coverage;
  LDet: increased rate;
  e-p coincidence time window reduced $\sim \times \frac{1}{5}$.



Main sources of uncertainties in Nab

- Physical properties of the instrument: magnetic and electric fields
  - relative field magnitudes, curvature , etc.,
  - relative geometry of electric and magnetic field distributions,
  - electric field inhomogeneity,
  - relative geometry of the neutron beam
- Physics of particle interactions with the apparatus:
  - electron backscattering (dep. on incident angle, E),
  - electron bremsstrahlung,
  - proton detection efficiency, etc.

All of these factors influence details of the detector response functions (for electrons and protons) and, hence, the extraction of a.

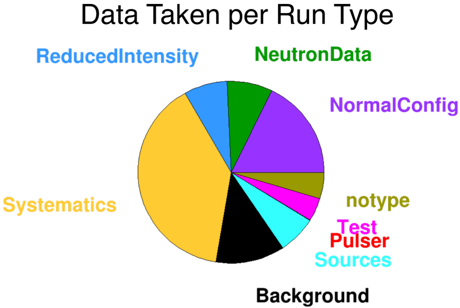
Note: making regular systematics-motivated measurements during main DAQ adds running time.

Nab systematic uncertainties: Method B

Experimental parameter		Principal specification (comment)	$(\Delta a/a)_{\mathrm{SYST}}$
Magnetic field:	curvature at pinch	$\Delta\gamma/\gamma = 2\%$ with $\gamma = (d^2B_z(z)/dz^2)/B_z(0)$	5.3×10^{-4}
	ratio $r_{\mathrm{B}} = B_{\mathrm{TOF}}/B_0$	$(\Delta r_B)/r_B = 1\%$	2.2×10^{-4}
	ratio $r_{\mathrm{B,DV}} = B_{\mathrm{DV}}/B_0$	$(\Delta r_{\mathrm{B,DV}})/r_{\mathrm{B,DV}} = 1\%$	1.8×10^{-4}
L_{TOF}, length of TOF region		(free fit parameter)	—
U inhomogeneity:	in decay / filter region	$\lvert U_{\mathrm{F}} - U_{\mathrm{DV}}\rvert < 10\,\mathrm{mV}$	5×10^{-4}
	in TOF region	$\lvert U_{\mathrm{F}} - U_{\mathrm{TOF}}\rvert < 200\,\mathrm{mV}$	2.2×10^{-4}
Neutron beam:	position	$\Delta\langle z_{\mathrm{DV}}\rangle < 2\,\mathrm{mm}$	1.7×10^{-4}
	profile (incl. edge effect)	slope at edges $< 10\%/\mathrm{cm}$	2.5×10^{-4}
	Doppler effect	(analytical correction)	small
	unwanted beam polarization	$\Delta\langle P_{\mathrm{n}}\rangle < 2\cdot10^{-5}$ (with spin flipper)	1×10^{-4}
Adiabaticity of proton motion			1×10^{-4}
Detector effects:	E_{e} calibration	$\Delta E_{\mathrm{e}} < 200\,\mathrm{eV}$	$2\cdot10^{-4}$
	shape of E_{e} response	$\Delta N_{\mathrm{tail}}/N_{\mathrm{tail}} \leq 1\%$	4.4×10^{-4}
	proton trigger efficiency	$\epsilon_{\mathrm{p}} < 100\,\mathrm{ppm/keV}$	3.4×10^{-4}
	TOF shift (det./electronics)	$\Delta t_{\mathrm{p}} < 0.3\,\mathrm{ns}$	3×10^{-4}
electron TOF		(analytical correction)	small
TOF in acceleration region		$\Delta r_{\mathrm{GROUND\ EL.}} < 0.5\,\mathrm{mm}$ (preliminary)	3.4×10^{-4}
BGD/accidental coincidences		(will subtract out of time coinc)	small
Residual gas		$P < 2\cdot10^{-9}$ torr	3.8×10^{-4}
Overall sum			1.2×10^{-3}

2023 commissioning and first Nab data

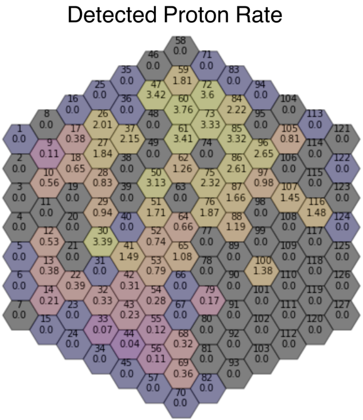
- First run with 2 detectors, HV, B all on,



- normal data taking ∼ 20%
- systematics + reduced int. ∼ 47%
- background ∼ 12%

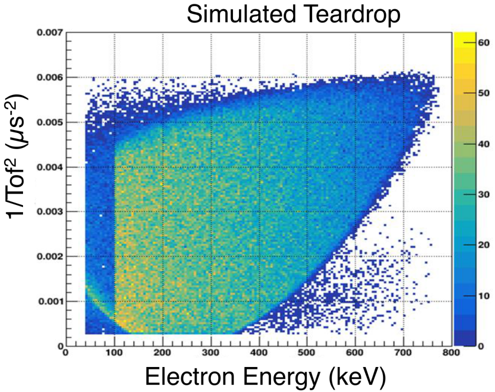
However, there were electronics and detector issues:

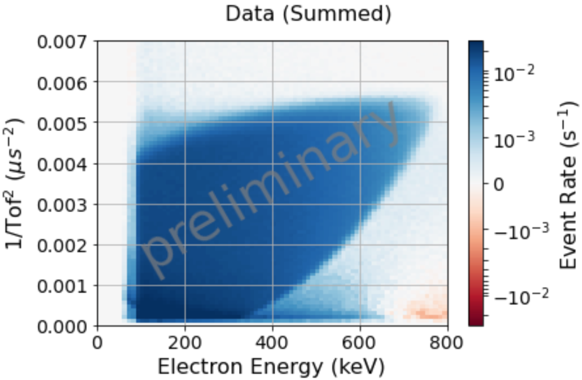
- electronics unstable w/all pixels on,
- certain channels unresponsive (el./contacts),
- lower detector underdepleted



A peak at the physics result from 2023 Nab commissioning

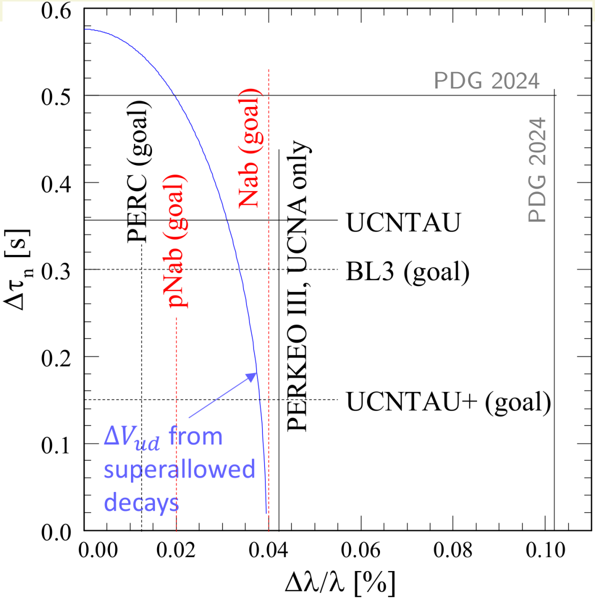
- First measurement of n β-decay e-p coincidences covering most of phase space.
- Proof of principle of Nab demonstrated (event stats correspond to $\Delta a/a \sim 1.1 \times 10^{-2}$).
- Challenges remain in understanding observed shifts in detector response.





Summary and outlook

- CKM unitarity is currently violated by $\sim 2-3\sigma$. Nuclear, K and n decays are under scrutiny.
- With improved accuracy, n decay could dominate V_{ud} determination.
- A range of experiments and techniques needed to sort inconsistencies in the data.
- A combination of experiments, including Nab and pNab, are needed to get to: $\Delta\lambda/\lambda \sim 3\cdot 10^{-4}$, $\Delta b, \Delta b_\nu \sim 10^{-3}$, and $\tau_n \sim 0.3\,\mathrm{s}$.
- Nab will start taking data once remaining technical issues are resolved).
- Additional apparatus needed for pNab is modest; Nab design accommodates pNab.



The collaboration

Collaborating institutions: (new groups are in the process of joining)

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

UK University of Kentucky

University of Michigan

EKU Eastern Kentucky University

The University of Tennessee Chattanooga

Universidad Nacional Autónoma de México

University of Manitoba

The University of Winnipeg

GT

Universität Karlsruhe (TH)
Forschungsuniversität • gegründet 1825

University of South Carolina

Further Latin American collaboration warmly invited!

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