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

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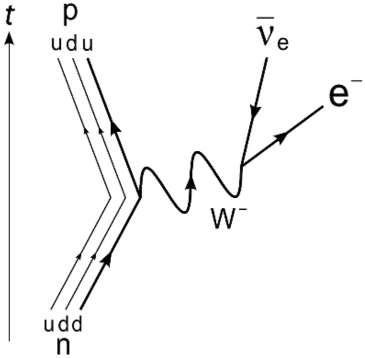
CKM unitarity cond.: $\Delta V^2 = 1 - (|V_{ud}|^2 + |V_{us}|^2 + |V_{ub}|^2) \stackrel{?}{=} 0,$ $\Leftarrow$ [best test available!]
stringently tests the SM. $\boxed{\text{Until 2004 appeared violated by} \sim 3\sigma!}$

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 $\boxed{g_A = G_F V_{ud}\lambda = G_F G_A}$.

Dynamics and observables

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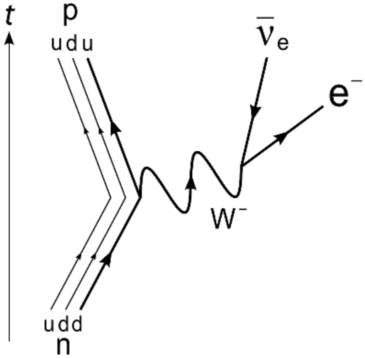

where $\boxed{g_V = G_F V_{ud} = G_F G_V}$ and $\boxed{g_A = G_F V_{ud}\lambda = G_F G_A}$.

$G_F \simeq 1.1664 \times 10^{-11}\ \text{MeV}^{-2}$
(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:

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

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

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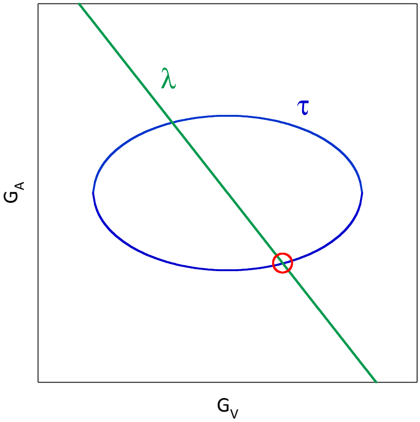
- neutron lifetime τ_n (counting neutrons)
- ratio $\lambda = G_A/G_V$ (decay correlations)



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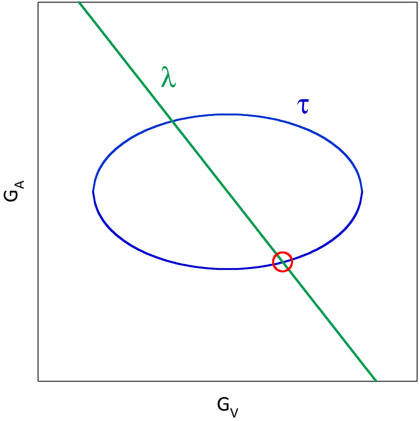

Key questions:

- 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:

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

The $(V-A)$ SM prescribes $b = b_\nu = 0$, and: ($b \neq 0$ signals S,T components)

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

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

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$\Rightarrow$ 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 $\boxed{\Delta a/a \simeq 10^{-3}}$, or $\sim 10\times$ better than:

$$\text{current results, } a = \begin{array}{ll} -0.091\,(39) & \text{Grigorev et al 1968,} \\ -0.1017\,(51) & \text{Stratowa et al 1978,} \\ -0.1054\,(55) & \text{Byrne et al 2002,} \\ -0.10779\,(183) & \text{Wietfeldt et al 2023 (aCORN),} \\ -0.10402\,(84) & \text{Beck et al 2024 (aSPECT).} \end{array}$$

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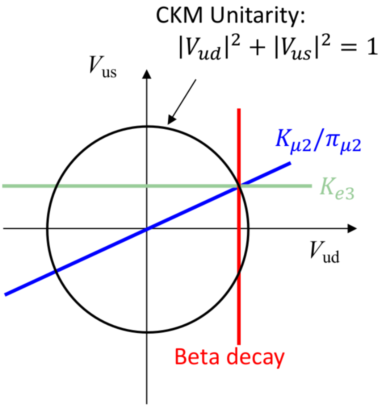
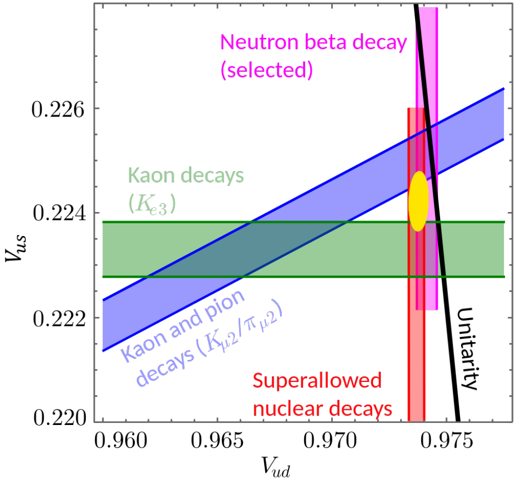
Motivation:

- 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

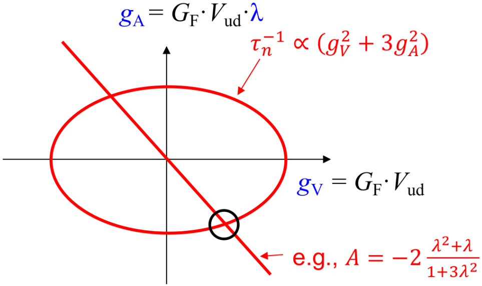


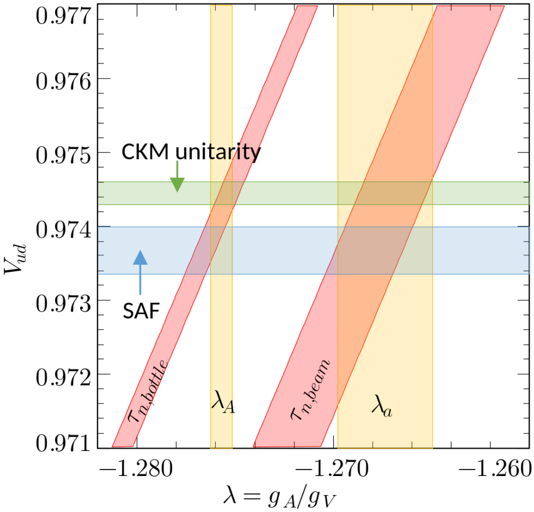
$K_{\mu 2}$: $K \to \mu\bar{\nu}$; $\pi_{\mu 2}$: $\pi \to \mu\bar{\nu}$;
K_{e3}: $K \to \pi e \bar{\nu}_e$ (all K charge states).



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

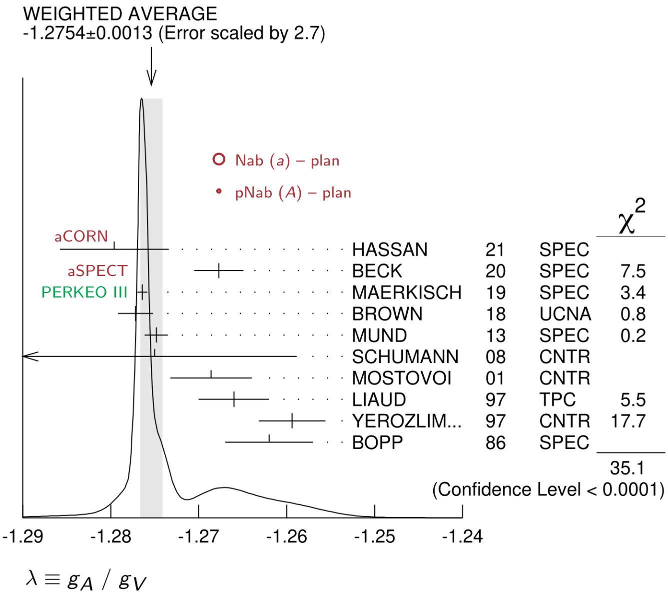
PDG 2024 on the evaluation of $\lambda = g_A/g_V$:

- 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.



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Basic approach: $(n \to p + e^- + \bar{\nu}_e)$

- 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).

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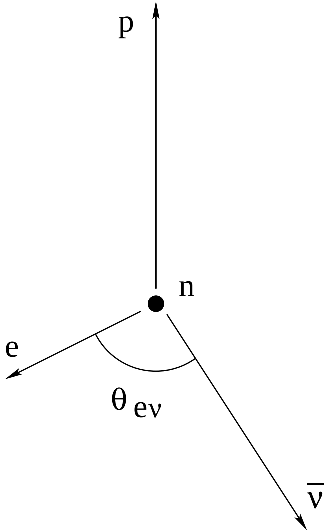
A complex magneto-electrostatic apparatus is required to guide particles (nearly) adiabatically to detectors.

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

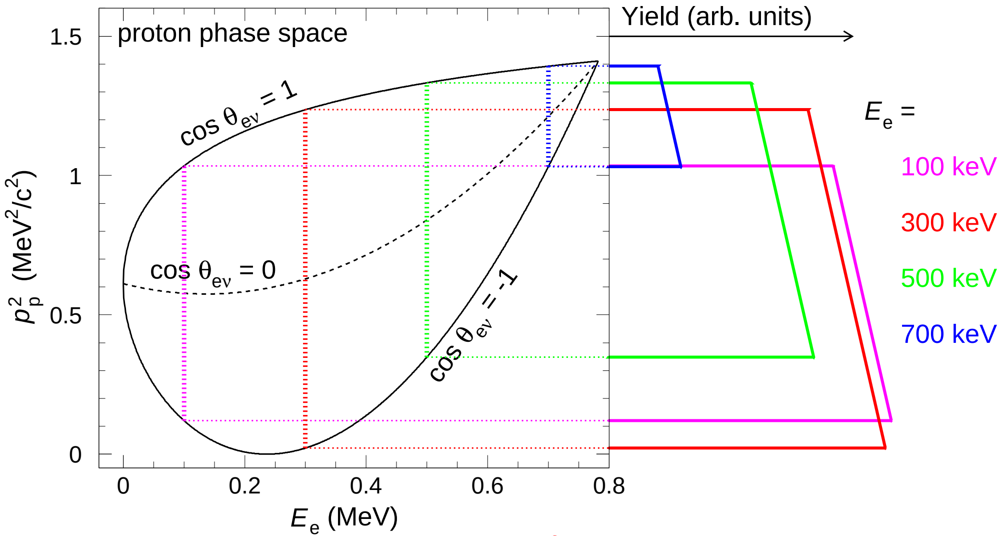
$$p_p^2 = p_e^2 + 2p_e p_\nu \cos\theta_{e\nu} + p_\nu^2\,.$$

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

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

$\Rightarrow \cos\theta_{e\nu}$ 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.

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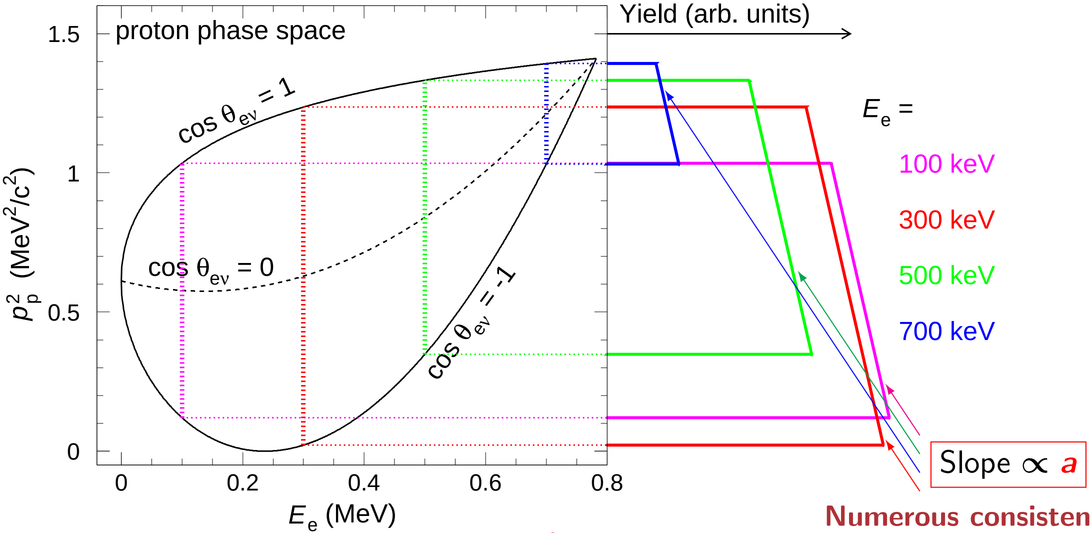

Numerous consistency checks are built-in!

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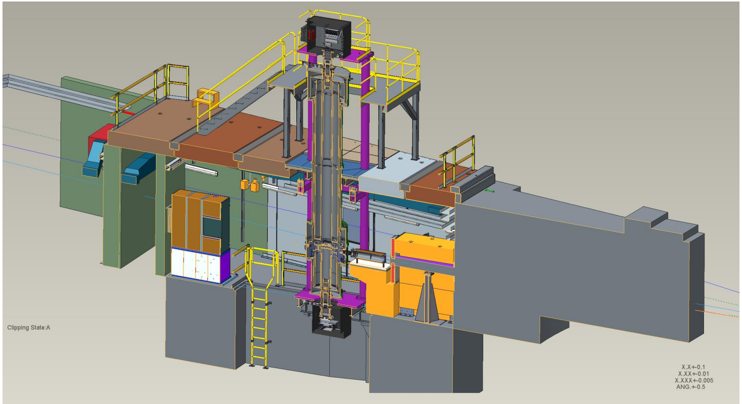
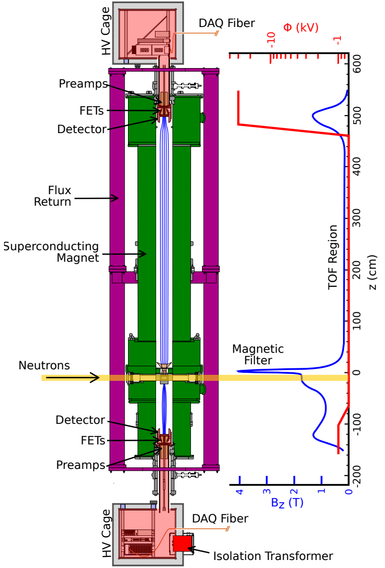
Nab apparatus (overview)

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) $\Rightarrow$ must collect, guide them, and relate TOF to p_p!

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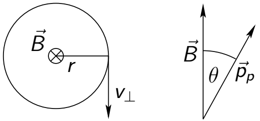
Method how: **adiabatic longitudinalization**;
protons (and e's) gyrate around $\vec{B}$ field lines



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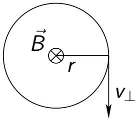

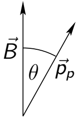

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$$L = mv_\perp r = \frac{m^2 v^2 \sin^2\theta}{eB} = \text{const.},$$

or:

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

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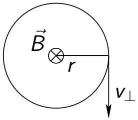

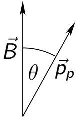

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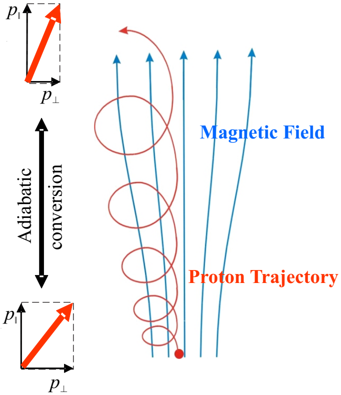
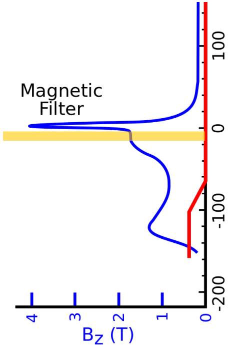


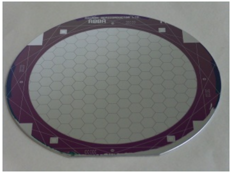


Nab Si detector basics

(LANL-Micron development)

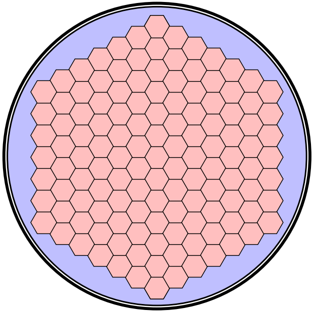
- 15 cm diameter
- full thickness: 2 mm
- dead layer ≤100 nm
- 127 pixels

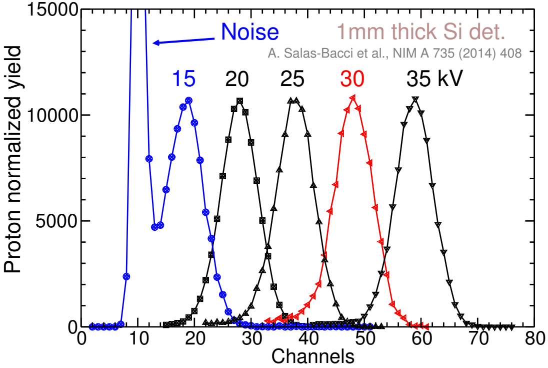
Front



Back

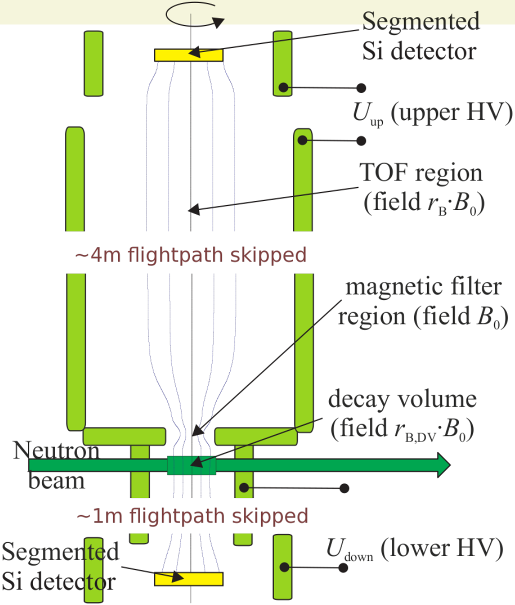
Pixel geometry:





Apparatus and running configurations

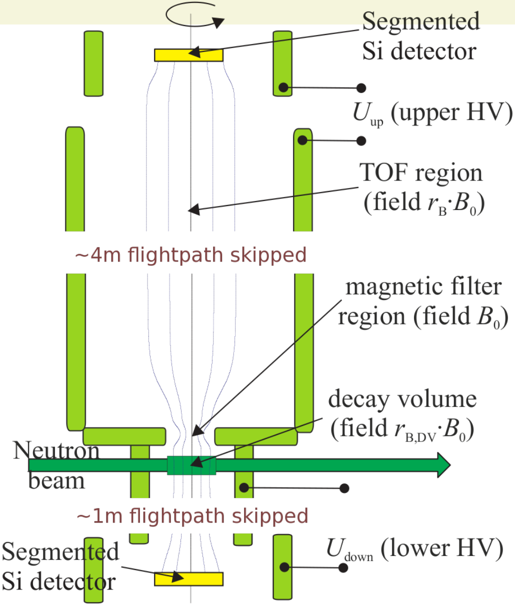
- **Nab-*a***: detect protons in upper, electrons in both detectors; $U_{up} = -30\,\text{kV}$, $U_{down} = 0\,\text{kV}$ (or $-1\,\text{kV}$); b measured parasitically!.



Apparatus and running configurations

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

- Nab-*b*: detect electrons in both, protons in lower detector; $U_{\text{up}} = 0\,\text{kV}$ (up to $+1\,\text{kV}$), $U_{\text{down}} = -30\,\text{kV}$. 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.

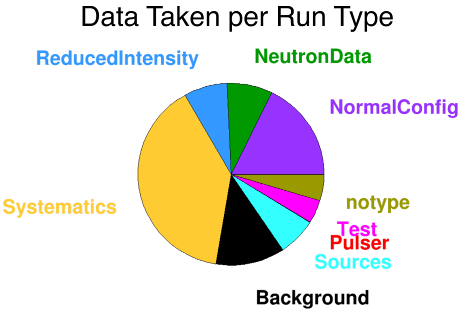
Note: making regular systematics-motivated measurements during main DAQ adds running time.

Nab systematic uncertainties: Method B

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

2023 commissioning and first Nab data

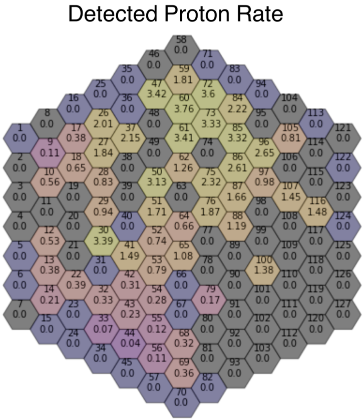
- First run with 2 detectors, HV, B all on,



- normal data taking $\sim 20\%$
- systematics + reduced int. $\sim 47\%$
- background $\sim 12\%$

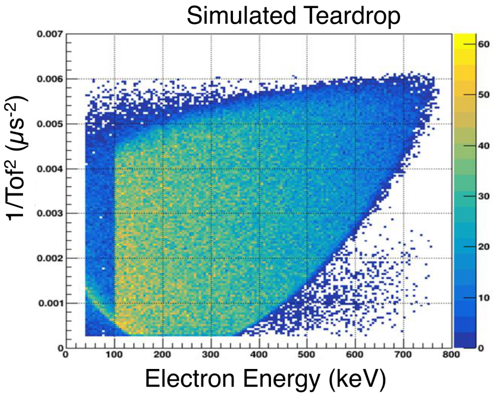
However, there were electronics and detector issues:

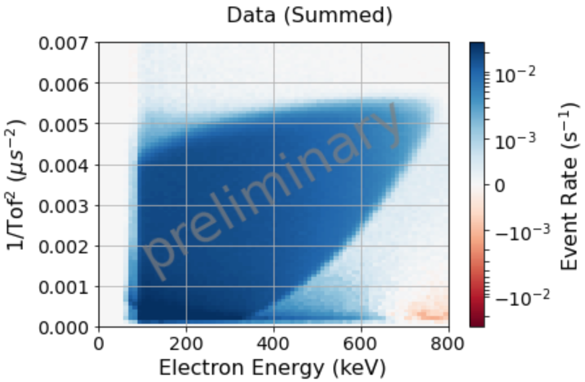
- electronics unstable w/all pixels on,
- certain channels unresponsive (el./contacts),
- lower detector underdepleted



A peak at the physics result from 2023 Nab commissioning

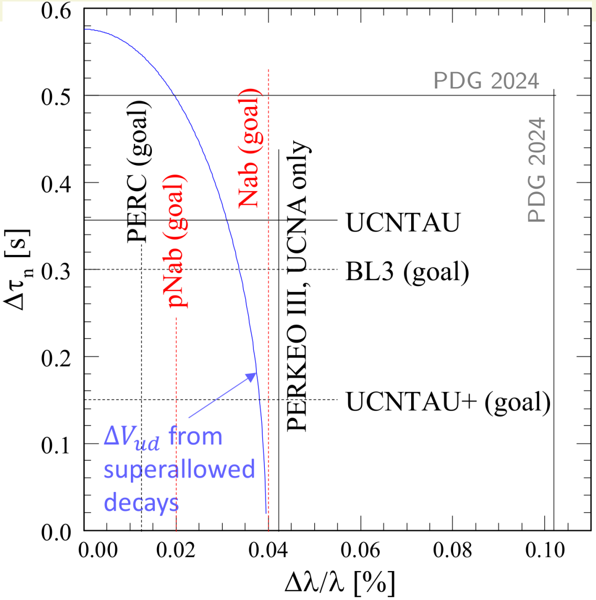
- First measurement of n β-decay e-p coincidences covering most of phase space.
- Proof of principle of Nab demonstrated (event stats correspond to $\Delta a/a \sim 1.1 \times 10^{-2}$).
- Challenges remain in understanding observed shifts in detector response.





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)

Further Latin American collaboration warmly invited!

Major funding: