Nab: a precise measurement of correlations in unpolarized neutron beta decay

Dinko Počanić, for the Nab Collaboration

University of Virginia

13 January 2026

Workshop 26-95W: *Testing the Standard Model in Charged-Weak Decays*

INSTITUTE for NUCLEAR THEORY

University of Washington, Seattle,12 – 16 January 2026

Outline of the talk

Nab experiment: a precise measurement of

a, the electron-neutrino correlation, and

b, the Fierz interference term,

in unpolarized *neutron* beta decay.

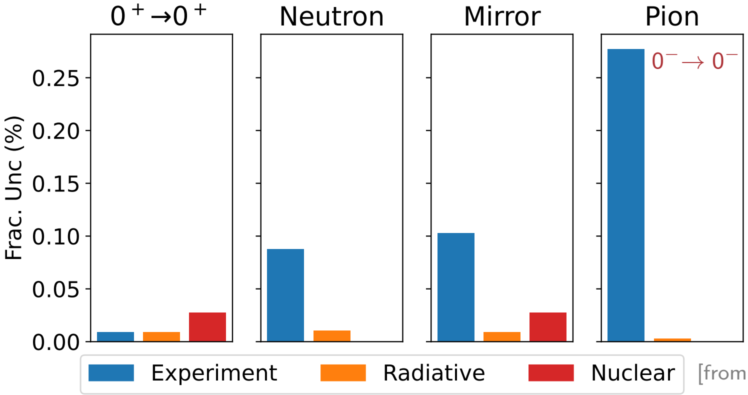
1. Motivation for the experiment
2. Principles of measurement,
3. Systematic and statistical uncertainties,
4. Current status of Nab and the path forward.

Nab motivation and goals

Neutron β decay and q-ℓ universality
provide a precise path to CKM V_{ud}
and a test of CKM matrix unitarity

Beta decays of interest in determining V_{ud}

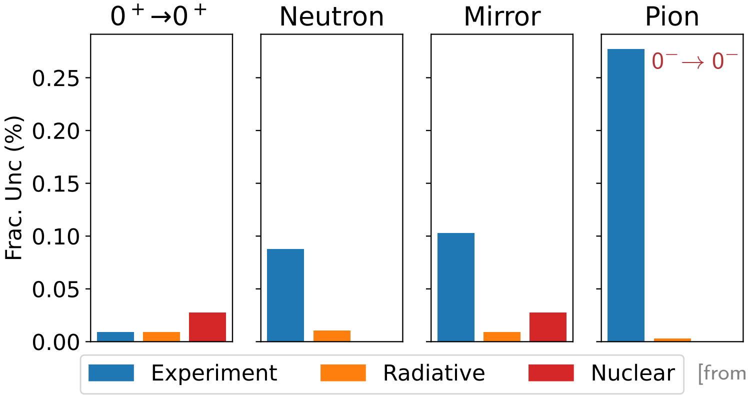
We compare the fractional uncertainties in extracting V_{ud} from the leading β decay processes:



[from 2023 White Paper]

Beta decays of interest in determining V_{ud}

We compare the fractional uncertainties in extracting V_{ud} from the leading β decay processes:



[from 2023 White Paper]

Pion β decay (π^+_{e3}) wins hands down in SM theoretical reliability, but is handicapped by 10^{-8} branching ratio.
Note: at 10^{-4} precision level, $|V_{ub}|^2 \simeq 5 \times 10^{-5}$ does not play a role $\Rightarrow$ back to Cabibbo 2×2 mixing.

V_{ud} from neutron decay

Neutron $(J^P = {}^1\!/_2^+)$ decay combines the Fermi (V) and Gamow-Teller (A) terms. Rate/lifetime of neutron decay is given by:

$$\Gamma_n = \frac{1}{\tau_n} = (1 + 3\lambda^2)\frac{G_F^2\, V_{ud}^2}{2\pi^3}\, f_{\mathrm{Fermi}}^{Z=1}(E_{\mathrm{max}}) \qquad \text{yielding} \qquad |V_{ud}|^2 = \frac{5024.7\,\mathrm{sec}}{\tau_n(1+3\lambda^2)(1+\Delta_R)}.$$

V_{ud} from neutron decay

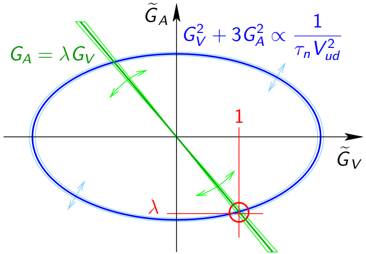
Neutron $(J^P = {}^1\!/\!{}_2{}^+)$ decay combines the Fermi (V) and Gamow-Teller (A) terms. Rate/lifetime of neutron decay is given by:

$$\Gamma_n = \frac{1}{\tau_n} = (1 + 3\lambda^2)\frac{G_F^2 V_{ud}^2}{2\pi^3} f_{\text{Fermi}}^{Z=1}(E_{\max}) \qquad \text{yielding} \qquad |V_{ud}|^2 = \frac{5024.7\,\text{sec}}{\tau_n(1 + 3\lambda^2)(1 + \Delta_R)}.$$

We therefore need to measure:

(a) ***n*** lifetime, τ_n, and

(b) $\lambda = {}^{G_A}\!/\!{}_{G_V}$ (decay correlations)



V_{ud} from neutron decay

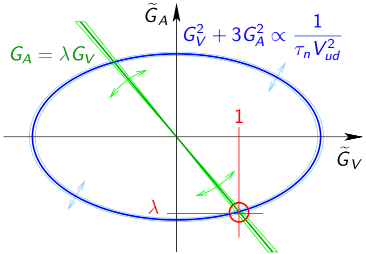
Neutron ($J^P = {}^1\!/_2^+$) decay combines the Fermi (V) and Gamow-Teller (A) terms. Rate/lifetime of neutron decay is given by:

$$\Gamma_n = \frac{1}{\tau_n} = (1+3\lambda^2)\frac{G_F^2 V_{ud}^2}{2\pi^3} f_{\text{Fermi}}^{Z=1}(E_{\max}) \qquad \text{yielding} \qquad |V_{ud}|^2 = \frac{5024.7\,\text{sec}}{\tau_n(1+3\lambda^2)(1+\Delta_R)}.$$

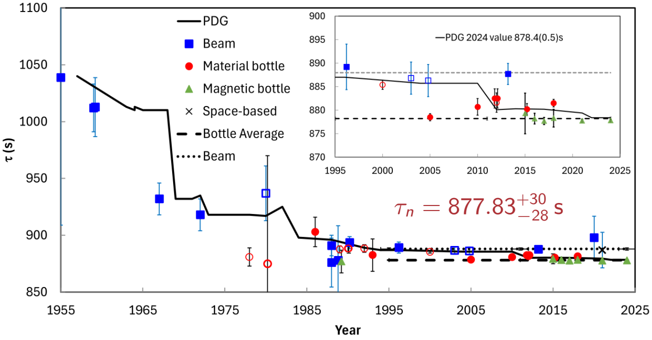
We therefore need to measure:

(a) $\boldsymbol{n}$ lifetime, τ_n, and

(b) $\lambda = {}^{G_A}\!/_{G_V}$ (decay correlations)



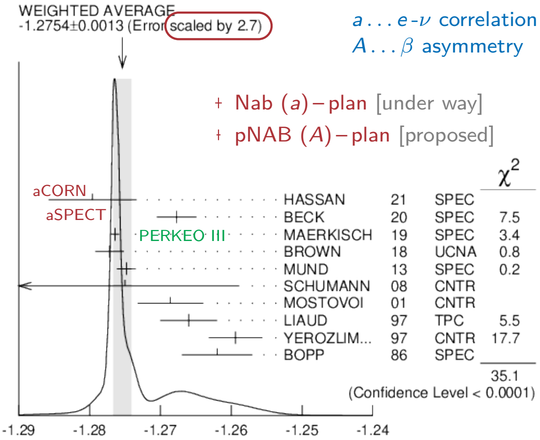
(a) is already under control (UCNτ, 2025):



[UCNτ Collab, PRC **111** (2025) 045501]

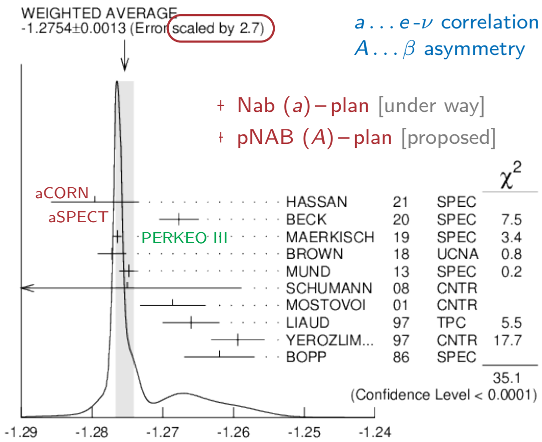
V_{ud} from neutron decay: $\lambda = G_A/G_V$

$a \ldots e\text{-}\nu$ correlation
$A \ldots \beta$ asymmetry

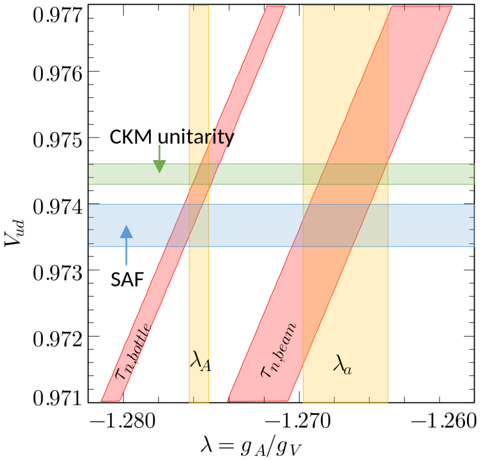


V_{ud} from neutron decay: $\lambda = G_A/G_V$

$a \ldots e$-ν correlation
$A \ldots \beta$ asymmetry

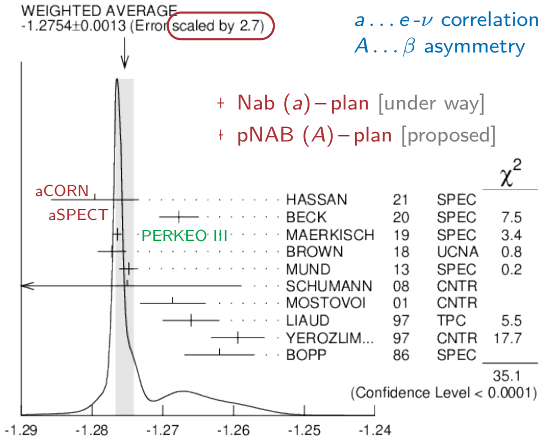


Recall: $|V_{ud}|^2 = \dfrac{5024.7\,\text{sec}}{\tau_n(1+3\lambda^2)(1+\Delta_R)}$.

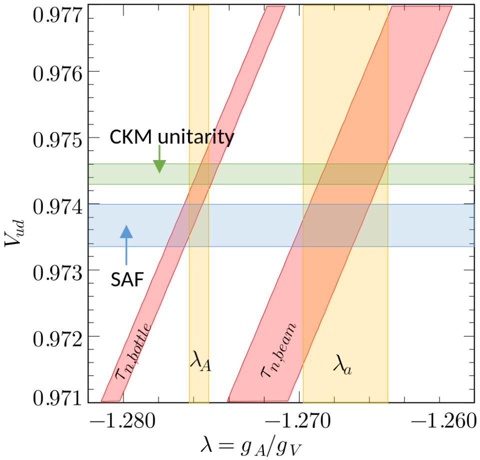


V_{ud} from neutron decay: $\lambda = G_A/G_V$

$a \ldots e$-ν correlation
$A \ldots \beta$ asymmetry



Recall: $|V_{ud}|^2 = \dfrac{5024.7\,\text{sec}}{\tau_n(1+3\lambda^2)(1+\Delta_R)}$.



[this talk]

Currently running: Nab (SNS) [W. Schreyer's talk]
In preparation: pNAB (") . . . mod. Nab apparatus: A
PERC (Munich) . . . an all-new facility

Nab (and pNAB) focus on $\lambda = G_A/G_V \Rightarrow$ [for a cleaner V_{ud}^{CKM}]

General Lorentz invariant differential beta decay rate at leading order is:

$$\frac{d^5\Gamma}{dE_e d\Omega_e d\Omega_\nu} \propto \rho(E_e) \times \left\{1 + a\frac{\vec{p}_e \cdot \vec{p}_\nu}{E_e E_\nu} + b\frac{m}{E_e} + \langle\vec{\sigma}_n\rangle \cdot \left[A_0\frac{\vec{p}_e}{E_e} + \left(B_0 + b_\nu\frac{m_e}{E_e}\right)\frac{\vec{p}_\nu}{E_\nu}\right] + \ldots\right\}$$

Nab (and pNAB) focus on $\lambda = G_A/G_V \Rightarrow$ [for a cleaner $V_{ud}^{\rm CKM}$]

General Lorentz invariant differential beta decay rate at leading order is:

$$\frac{d^5\Gamma}{dE_e d\Omega_e d\Omega_\nu} \propto \rho(E_e) \times \left\{ 1 + a\frac{\vec{p}_e\cdot\vec{p}_\nu}{E_e E_\nu} + b\frac{m}{E_e} + \langle\vec{\sigma}_n\rangle \cdot \left[A_0 \frac{\vec{p}_e}{E_e} + \left(B_0 + b_\nu \frac{m_e}{E_e}\right)\frac{\vec{p}_\nu}{E_\nu}\right] + \ldots \right\}$$

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

$b, b_\nu \neq 0$ would signal presence of S,T int's.

e-ν correl.

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

β asymm.

$$A_0(\lambda) = -2\frac{|\lambda|^2 + Re(\lambda)}{1+3|\lambda|^2}$$

ν asymm.

$$B_0(\lambda) = 2\frac{|\lambda|^2 - Re(\lambda)}{1+3|\lambda|^2}$$

$\lambda = \frac{G_A}{G_V}$ (with $\tau_n \Rightarrow$ $V_{ud}^{\rm CKM}$) .

Proton asymmetry:

$C = \kappa(A+B)$ [with $\kappa \simeq 0.275$] .

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

Nab (and pNAB) focus on $\lambda = G_A/G_V \Rightarrow$ [for a cleaner $V_{ud}^{\rm CKM}$]

General Lorentz invariant differential beta decay rate at leading order is:

$$\frac{d^5\Gamma}{dE_e d\Omega_e d\Omega_\nu} \propto \rho(E_e) \times \left\{ 1 + a\frac{\vec{p}_e\cdot\vec{p}_\nu}{E_eE_\nu} + b\frac{m}{E_e} + \langle\vec{\sigma}_n\rangle \cdot \left[A_0\frac{\vec{p}_e}{E_e} + \left(B_0 + b_\nu\frac{m_e}{E_e}\right)\frac{\vec{p}_\nu}{E_\nu}\right] + \ldots \right\}$$

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

$b, b_\nu \neq 0$ would signal presence of S,T int's.

e-ν correl.

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

β asymm.

$$A_0(\lambda) = -2\frac{|\lambda|^2 + Re(\lambda)}{1+3|\lambda|^2}$$

ν asymm.

$$B_0(\lambda) = 2\frac{|\lambda|^2 - Re(\lambda)}{1+3|\lambda|^2}$$

$\lambda = \frac{G_A}{G_V}$ (with $\tau_n \Rightarrow$ $V_{ud}^{\rm CKM}$) .

Proton asymmetry:

$C = \kappa(A+B)$ [with $\kappa \simeq 0.275$] .

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

Nab goals: $\frac{\Delta a}{a} \simeq 10^{-3}$, and $\Delta b \simeq 3\times 10^{-3}$ [$\sim 10\times$ better than existing results.]

pNAB goal: $\frac{\Delta A}{A} \simeq 10^{-3}$ [competitive with PERC; better than PERKEO III].

Both Nab and pNAB bring about new measurement techniques.

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,	43%
$-0.1017\,(51)$	Stratowa et al 1978,	5.0%
$-0.1054\,(55)$	Byrne et al 2002,	5.2%
$-0.10779\,(183)$	Wietfeldt et al 2023 (aCORN),	1.7%
$-0.10402\,(84)$	Beck et al 2024 (aSPECT).	0.81%

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,	43%
$-0.1017\,(51)$	Stratowa et al 1978,	5.0%
$-0.1054\,(55)$	Byrne et al 2002,	5.2%
$-0.10779\,(183)$	Wietfeldt et al 2023 (aCORN),	1.7%
$-0.10402\,(84)$	Beck et al 2024 (aSPECT).	0.81%

- 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).

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,	43%
$-0.1017\,(51)$	Stratowa et al 1978,	5.0%
$-0.1054\,(55)$	Byrne et al 2002,	5.2%
$-0.10779\,(183)$	Wietfeldt et al 2023 (aCORN),	1.7%
$-0.10402\,(84)$	Beck et al 2024 (aSPECT).	0.81%

- 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.

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,	43%
$-0.1017\,(51)$	Stratowa et al 1978,	5.0%
$-0.1054\,(55)$	Byrne et al 2002,	5.2%
$-0.10779\,(183)$	Wietfeldt et al 2023 (aCORN),	1.7%
$-0.10402\,(84)$	Beck et al 2024 (aSPECT).	0.81%

- 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).

Nab measurement method and apparatus

How to accomplish the goals of Nab?

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

How to accomplish the goals of Nab?

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

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

- 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).

How to accomplish the goals of Nab?

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

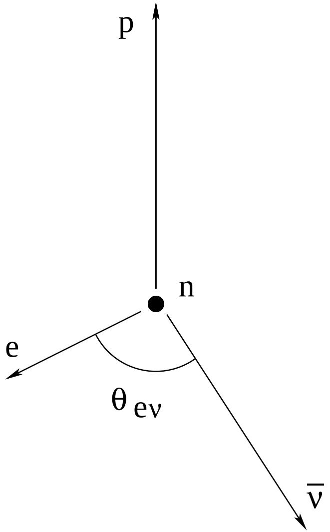
Basic approach: $(n \to p + e^- + \bar{\nu}_e)$

- 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).

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

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

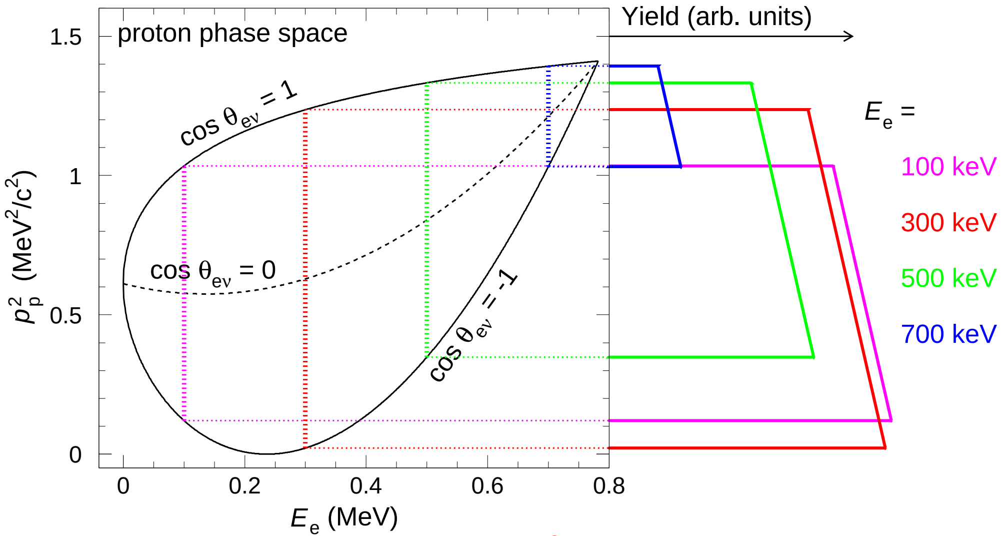
Neglecting the proton recoil energy*, we have $E_e + E_\nu = E_0$, or, $p_\nu = E_0 - E_e$. Therefore:

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

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

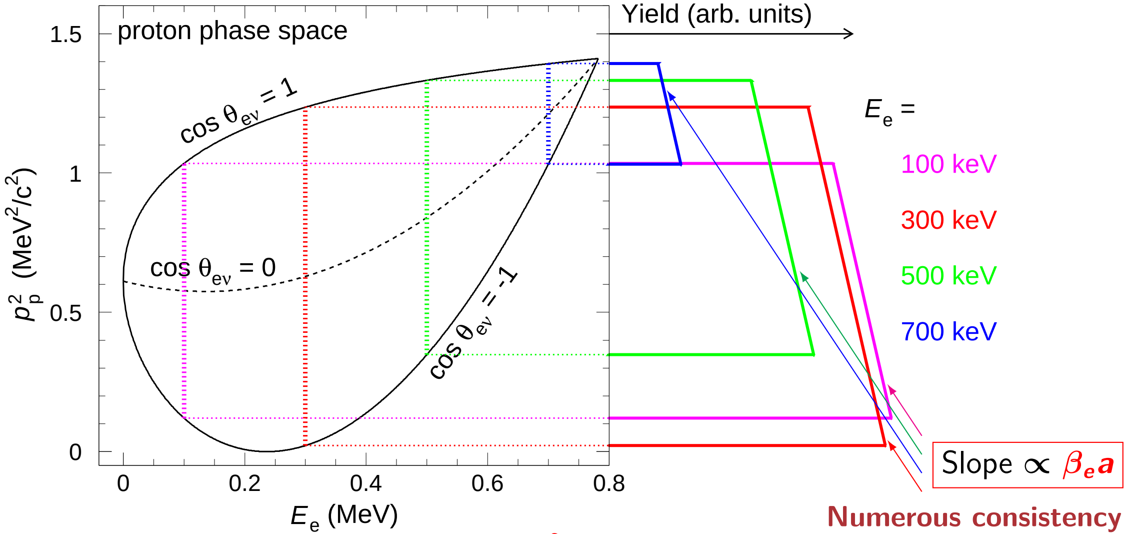
* proton recoil correction is applied a posteriori.

Nab measurement principles: proton phase space



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

Nab measurement principles: proton phase space



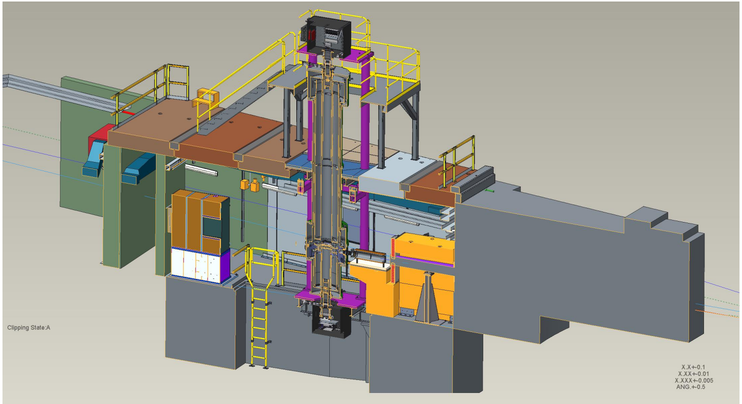
Numerous consistency checks are built-in!

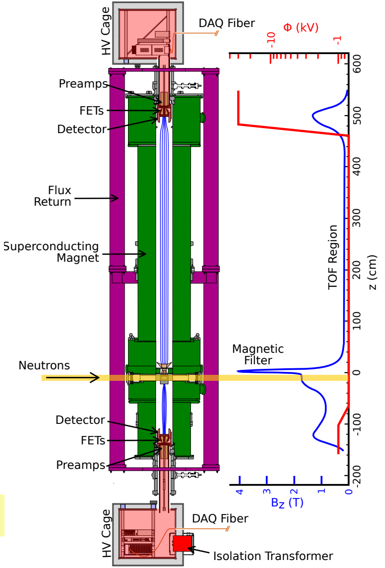
NB: For a given E_e, $\cos\theta_{e\nu}$ is a function of p_p^2 only.

Nab apparatus (overview)

custom magneto-electrostatic asymmetric spectrometer:

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





Nab has completed commissioning and is taking physics data

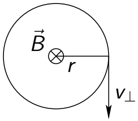
Why such complicated field profilles? — protons fly in all directions!

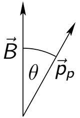
(not just straight to a small detector) ⇒ must collect, guide them, and relate TOF to p_p!

Why such complicated field profilles? — protons fly in all directions!

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

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





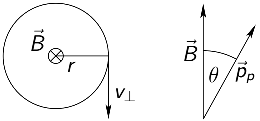
$$\frac{mv_\perp^2}{r} = ev_\perp B, \text{ or}$$

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

Why such complicated field profilles? — protons fly in all directions!

(not just straight to a small detector) $\Rightarrow$ 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:

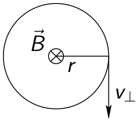
$$L = mv_\perp r = \frac{m^2 v^2 \sin^2\theta}{eB} = \text{const.},$$

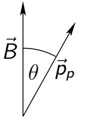
or:

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

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

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





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

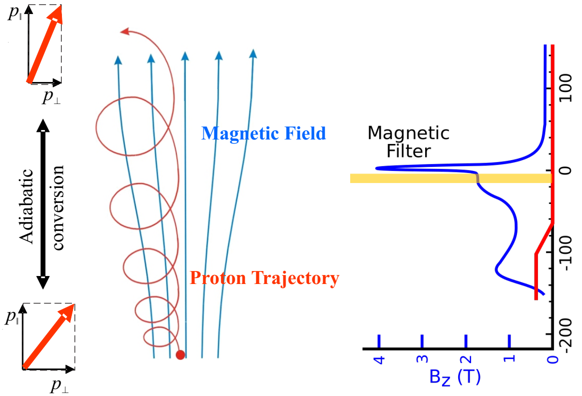
$$r = \frac{mv_\perp}{eB} .$$

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

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

or:

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



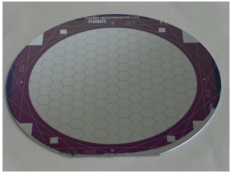
Longitudinalization after the magnetic filter sharpens correlation of proton TOF and $|\vec{p}_0|$.

Nab Si detector basics

(LANL-Micron development)

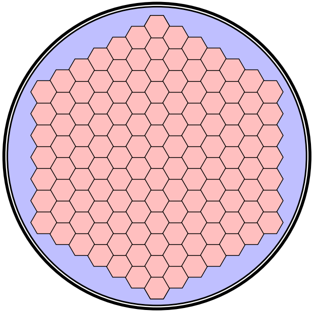
- 15 cm diameter
- full thickness: 2 mm
- dead layer ≤100 nm
- 127 pixels

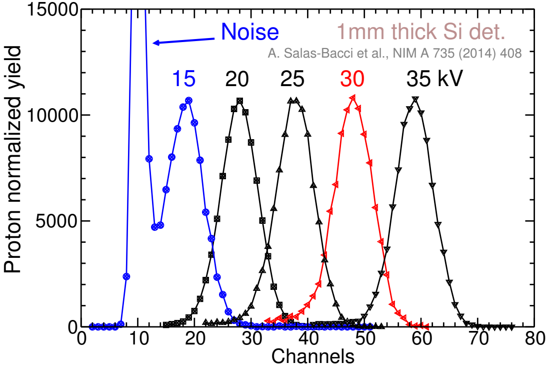
Front



Back

Pixel geometry:

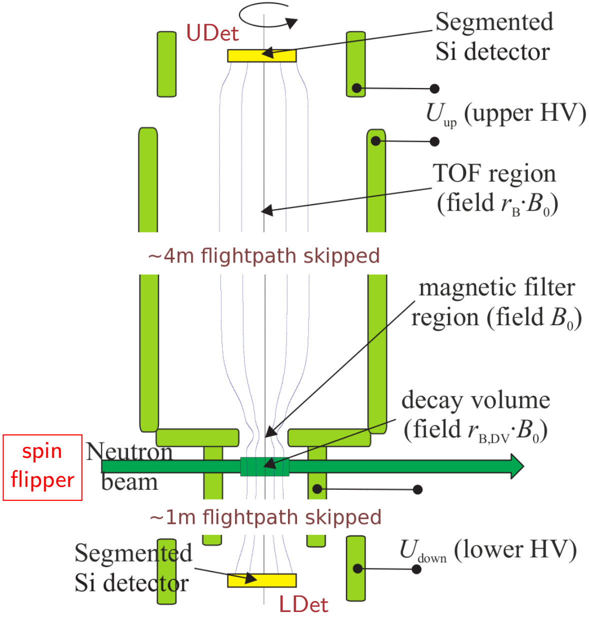




Nab running configurations

Nab − *a*	particle detection
	protons: in UDet electrons: in LDet & UDet
	$U_{up} = -30\,\mathrm{kV}$, $U_{down} = 0\,\mathrm{kV}$ (or $-1\,\mathrm{kV}$); *b* measured parasitically!

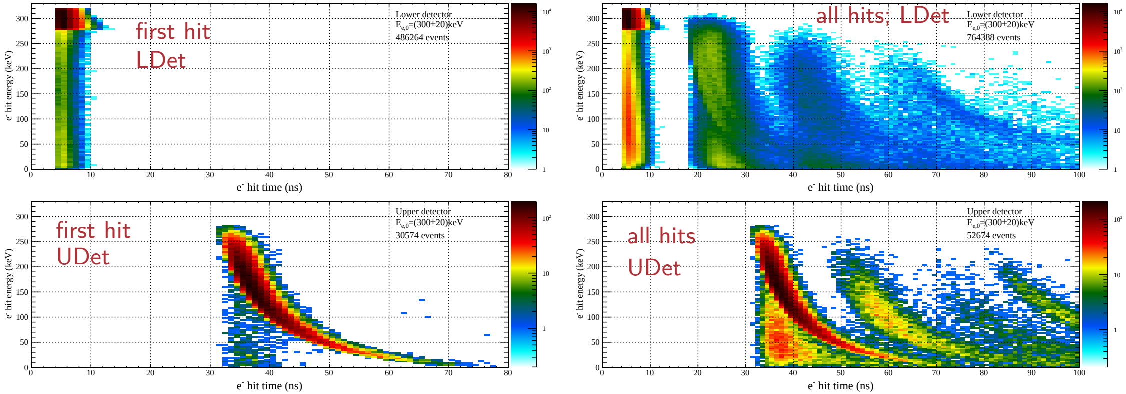
Nab − *b*	particle detection
	protons: in LDet electrons: in LDet & UDet
pNAB config.	$U_{up} = 0\,\mathrm{kV}$, (up to $+1\,\mathrm{kV}$) $U_{down} = -30\,\mathrm{kV}$; full *e*-*p* coinc. coverage; LDet: increased rate; $\Delta t(e\text{-}p)$ reduced $\sim \times 1/5$.



Hermeticity for electron detection

Electrons can back-scatter with considerable probability ($\sim 15\%$ or higher), leaving only a fraction of $E_{e,0}$ in the first hit $\Rightarrow$ **major challenge for "a" determination!**

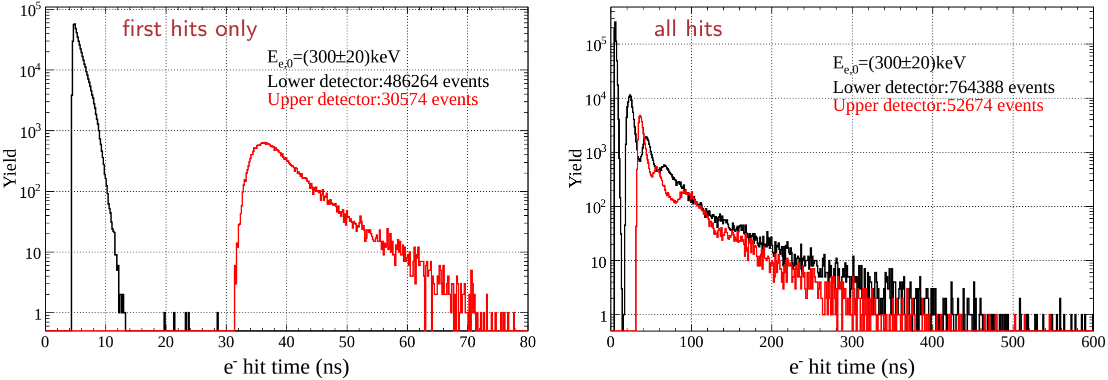
Consider plots of E_e^{hit} vs. t_{hit} [MC simulation, $E_{e,0} = 300 \pm 20\,\text{keV}$]:



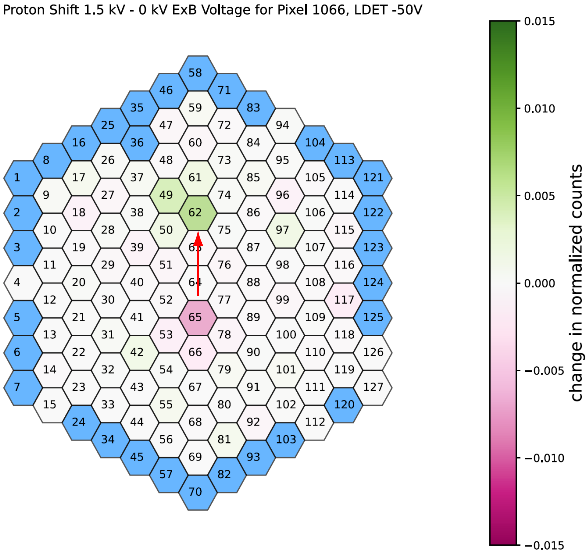
Hermeticity for electron detection (extended time view)

One-dim. plots of hit times in LDet and UDet:

First hits are done in 80 ns back-scattered hits extend ∼500 ns and beyond.



Protons back-scatter, too!



Protons can back-scatter from the lower Si detector, make their way to UDet, and be detected there as a false coincidence.

Red arrow:

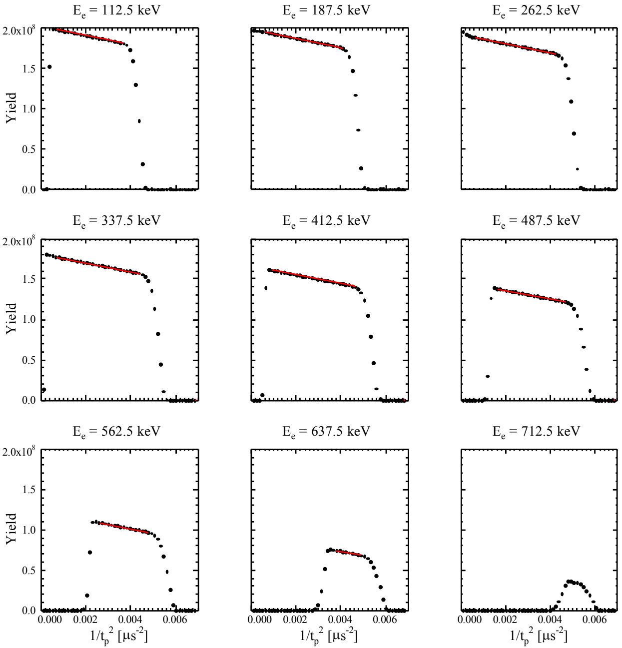
The custom $E \times B$ electrode system designed by S. Baessler, built at UVA and implemented below the n beam by his group, can deflect the back-scattered proton into pixels shifted outside the coincidence circle of the electron.

(analysis by A. Hagemeier)

Analysis strategies

Key issue: shape of the yield $P_t(1/t_p^2)$ for a fixed E_e is distorted by the spectrometer detection function $\Phi(1/t_p^2, p_p^2)$.

- We rely on edges of $P_t(1/t_p^2, E_e)$ to determine and verify shape of detection function $\Phi(1/t_p^2, p_p^2)$;
- Shown are model generated events, randomly shifted to reflect counting statistics;
- Central $\sim 75\%$ portion of $P_t(1/t_p^2)$ used to extract ***a*** — red fit. Note: events with $E_e > 650\,\text{keV}$ will not contribute to fits of parameter ***a***.



Planned analysis methods for extraction of *a*

Several distinct approaches are pursued:

A. parametrize edges and width of $\Phi(1/t_p^2, p_p^2)$ by fitting; use central part of Φ ($\sim 75\%$) to extract ***a*** in a multiparameter fit, and

B. specify all possible parameters of Φ by direct measurement; $\Rightarrow$ treat ***a***, $\boldsymbol{\mu = \overline{1/t_p^2}(p_p) \propto L_{TOF}^{eff}}$, and $\boldsymbol{N_{decays}}$ as free parameters in a two-step fitting procedure,

H. as well as a hybrid of the two methods.

The analysis is fully blinded.

Projected statistical uncertainties for a

Statistical uncertainties σ_a for an SM fit [$b \equiv 0$]

varied $\Downarrow$		0	100 keV	100 keV	100 keV	300 keV
	$E_{\mathrm{e,min}}$:	0	100 keV	100 keV	100 keV	300 keV
	$t_{\mathrm{p,max}}$:	–	–	40 μs	30 μs	40 μs
N_u, a		$2.4/\sqrt{N_u}$	$2.4/\sqrt{N_u}$	$2.6/\sqrt{N_u}$	$2.8/\sqrt{N_u}$	$3.1/\sqrt{N_u}$
+ E_{calib}, L_{TOF}		$2.6/\sqrt{N_u}$	$2.6/\sqrt{N_u}$	$2.8/\sqrt{N_u}$	$3.1/\sqrt{N_u}$	$3.5/\sqrt{N_u}$
+ use 75%§		$3.3/\sqrt{N_u}$	$3.4/\sqrt{N_u}$	$3.6/\sqrt{N_u}$	$4.0/\sqrt{N_u}$	$4.6/\sqrt{N_u}$
+ 10% bgd.†		$4.3/\sqrt{N_u}$	$4.4/\sqrt{N_u}$	$4.5/\sqrt{N_u}$	$4.9/\sqrt{N_u}$	$5.5/\sqrt{N_u}$

Statistical uncertainties σ_a for a BSM fit [variable b]

varied $\Downarrow$						
	$E_{\mathrm{e,min}}$:	0	100 keV	100 keV	100 keV	300 keV
	$t_{\mathrm{p,max}}$:	–	–	40 μs	30 μs	40 μs
N_u, a, b		$2.4/\sqrt{N_u}$	$2.5/\sqrt{N_u}$	$2.7/\sqrt{N_u}$	$3.0/\sqrt{N_u}$	$3.6/\sqrt{N_u}$
+ E_{calib}, L_{TOF}		$2.6/\sqrt{N_u}$	$2.7/\sqrt{N_u}$	$2.9/\sqrt{N_u}$	$3.2/\sqrt{N_u}$	$3.9/\sqrt{N_u}$
+ use 75%§		$3.4/\sqrt{N_u}$	$3.5/\sqrt{N_u}$	$3.8/\sqrt{N_u}$	$4.4/\sqrt{N_u}$	$5.1/\sqrt{N_u}$
+ 10% bgd.†		$4.4/\sqrt{N_u}$	$4.6/\sqrt{N_u}$	$4.7/\sqrt{N_u}$	$5.2/\sqrt{N_u}$	$6.3/\sqrt{N_u}$

§ fits for a use only the inner 75% of p_p^2 data.

† background can be greater than 10% (optimum BGD rejection is under study).

N_u . . . number of protons detected in upper detector.

Nab event rates and running times

In 2025, following the SNS beam power upgrade and the redesign of the neutron production target + moderator, we have observed the rate of $\sim$170 true e-p coincidences/s.

We plan to collect samples of $1 - 2 \times 10^9$ events in several multi-week runs.

The total time needed to complete the full program must account for the

- necessary systematic study runs,
- background event rate that has to be subtracted,
- necessary periodic calibrations,
- realistic "up time" fraction (based on combined readiness of our apparatus plus availability of the n beam), and
- the statistical precision goal of Nab: $\boxed{\sigma_a/a \simeq 7 \times 10^{-4}}$.

With all factors accounted for, we arrive at an estimated end of Nab beam time data acquisition by the end of calendar year 2028.

Nab systematic uncertainties

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 (depends 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: regular systematics-motivated measurements during main DAQ adds running time.

Nab systematic uncertainties: (Method B)

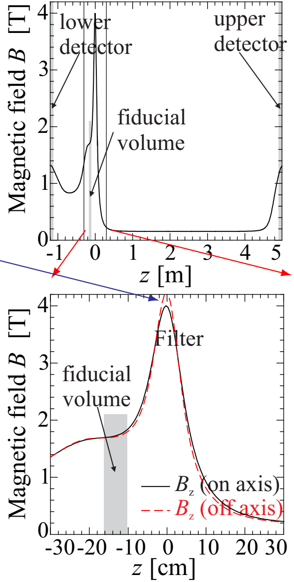
Experimental parameter		Principal specification (comment)	$(\Delta a/a)_{\mathrm{SYST}}$
Magnetic field:	curvature at pinch	$\Delta\gamma/\gamma = 2\%$ with $\gamma = (\mathrm{d}^2 B_z(z)/\mathrm{d}z^2)/B_z(0)$	5.3×10^{-4}
	ratio $r_{\mathrm{B}} = B_{\mathrm{TOF}}/B_0$	$(\Delta r_B)/r_B = 1\%$	2.2×10^{-4}
	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	$\Delta\langle P_{\mathrm{n}}\rangle < 2 \cdot 10^{-5}$ (with spin flipper)	1×10^{-4}
Adiabaticity of proton motion			1×10^{-4}
Detector effects:	E_{e} calibration	$\Delta E_{\mathrm{e}} < 200\,\mathrm{eV}$	$2 \cdot 10^{-4}$
	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)	$\Delta t_{\mathrm{p}} < 0.3\,\mathrm{ns}$	3.9×10^{-4}
electron TOF		(analytical correction)	small
TOF in acceleration region		$\Delta r_{\mathrm{GROUND\ EL.}} < 0.5\,\mathrm{mm}$ (preliminary)	3×10^{-4}
BGDs/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}

A critical systematics: $\vec{B}$ field

Experimental parameter	$(\Delta a/a)_{\text{SYST}}$
Magnetic field:	
... curvature at pinch	5.3×10^{-4}
... ratio $r_B = B_{TOF}/B_0$	2.2×10^{-4}
... ratio $r_{B,DV} = B_{DV}/B_0$	1.8×10^{-4}
Overall sum	1.2×10^{-3}

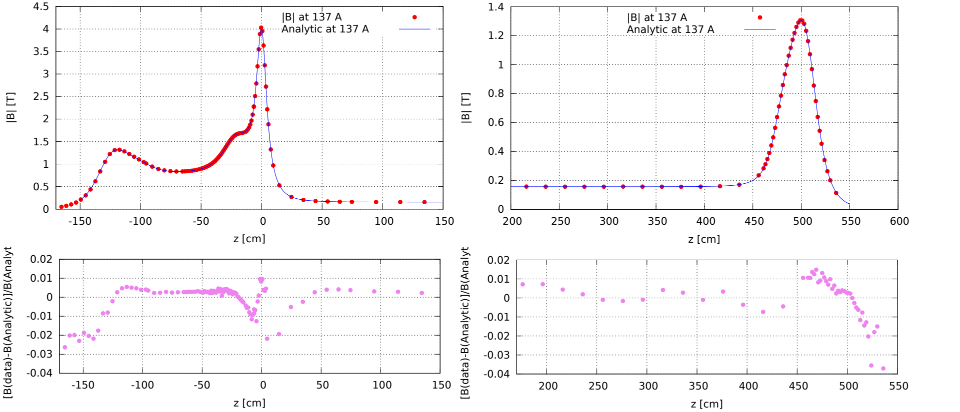
Steps:

1. Measure field map (relative measurement).
2. Determine position of electron and proton flux tubes in field map.



Nab spectrometer $\vec{B}$ mapping at the SNS

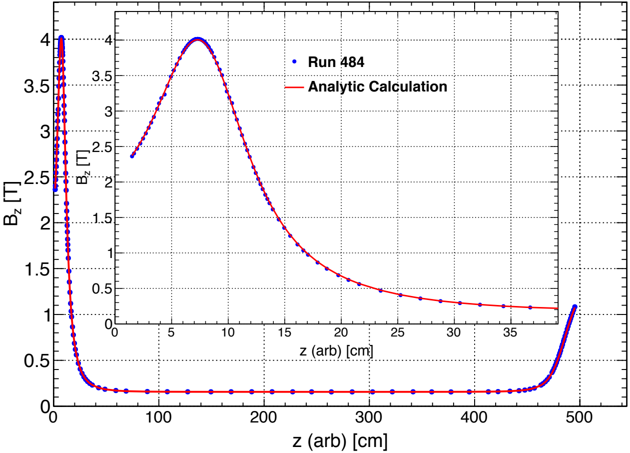
On-axis acceptance measurements of the Nab spectrometer magnetic field (in horizontal orientation, Mar. 2018) yielded spot-on results (plotted below).

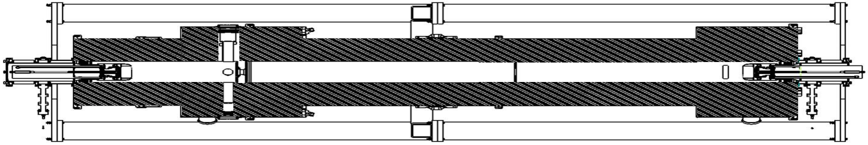


Precision $\vec{B}$ field mapping: **on axis**

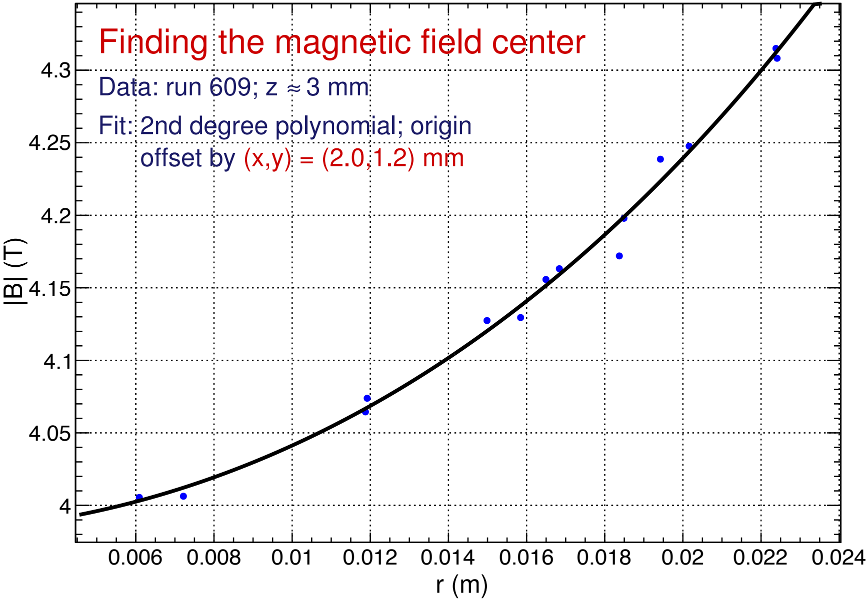
Full field map (on- and off-axis, vertical spectrometer in situ), summer 2019.

Filter and TOF regions, as shown:



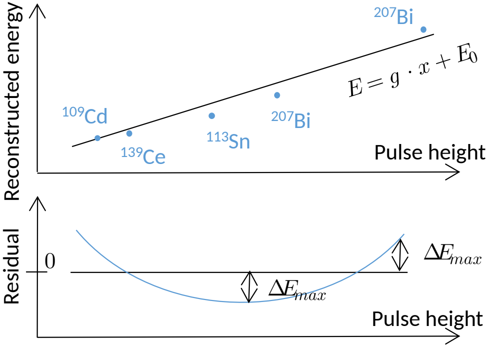


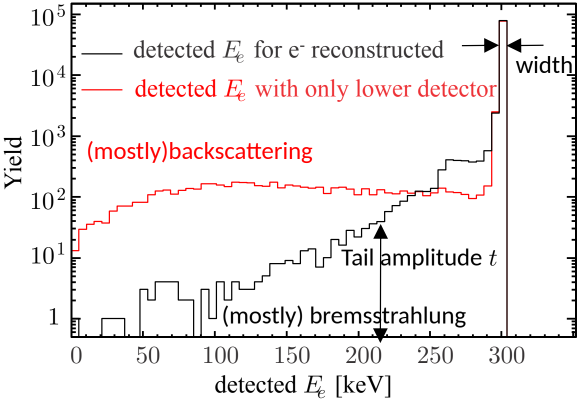
Precision $\vec{B}$ field mapping: **finding the field center**



Electron energy response

Experimental parameter	$(\Delta a/a)_{\rm SYST}$
Detector effects:	
...shape of E_e response	4.4×10^{-4}
Overall sum	1.2×10^{-3}

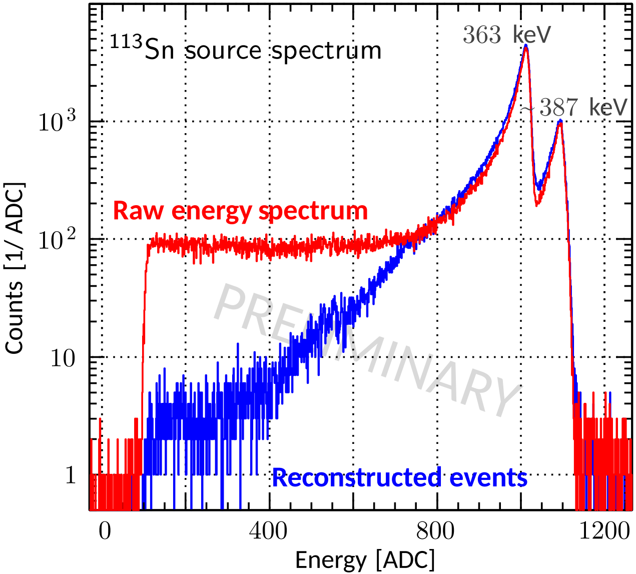




We use the hermiticity of the Nab spectrometer for back-scattered e^-'s to sum up the energy depositions of the scattered e.

After re-summation, there remains a smaller "tail" dominated by the Bremsstrahlung events.

Actually observed electron response



Quite effective reconstruction of E_e demonstrated.

Remaining distortion of E_e response: due to Bremsstrahlung.

Nab requires an in depth study of BS, more than sufficient to constrain the electron response tail for pNAB.

Electron response parameters: systematic uncertainties

How well do we need to understand the detector response in Nab (and pNAB)?

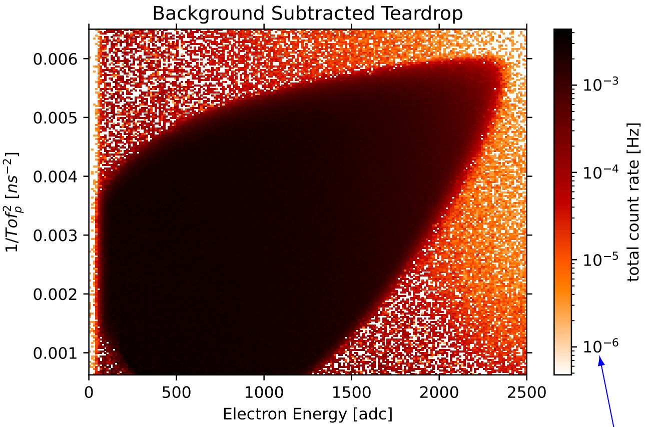
Specifications for ↦ / ↲ Parameter ↴	$\Delta a = 3 \cdot 10^{-5}$ (Nab)	$\Delta b = 10^{-3}$ (Nab)	$\Delta A = 3 \times 10^{-5}$ (pNAB)
gain factor ($\Delta g/g$)	fit parameter	fit parameter	0.0018 ✓
offset E_0	0.3 keV	0.06 keV	~~0.2 keV~~ 0.3 keV
nonlinearity ($\lvert\Delta E_{\max}\rvert$)	1.5 keV ✓	0.06 keV	0.3 keV
peak width (Δw)	1 keV ✓	–	10 keV ✓
tail to peak ratio (Δt)	0.01%	0.2%	2.4%

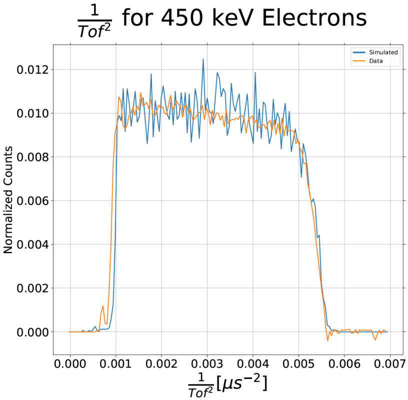
currently 0.37 keV

✓ as of Apr. 2025 (Jin Ha Choi, NCSt)

Nab has met, or is close to meeting, the goals for all above parameters except the tail ratio, for which there is a program of study in place.

A sample of recent Nab data (fall 2025)





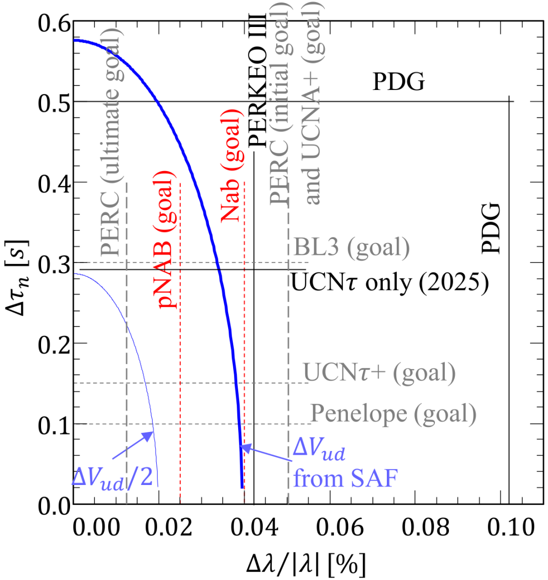
Note log scale!

(A. Hagemeier)

Future prospects

Near-term outlook: CKM V_{ud}

- CKM unitarity is currently violated by $\sim 2\sigma - 3\sigma$. Nuclear, K and n decays are under scrutiny.
- With improved accuracy, n decay should dominate V_{ud} determination.
- Diverse experimental techniques are needed to sort inconsistencies in the data.
- A combination of experiments, including Nab, pNAB and PERC, are aiming for: $\Delta\lambda/\lambda \sim 2 \cdot 10^{-4}$, $\Delta b, \Delta b_\nu \sim 10^{-3}$; τ_n experiments aim for: $\Delta\tau_n \lesssim 0.3\,\mathrm{s}$.
- Nab is taking data; its design allows for pNAB with modest changes.
- It remains to be seen if mirror nuclei beta decays will become competitive.



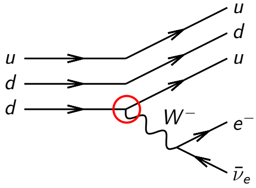
The collaboration

Collaborating institutions:

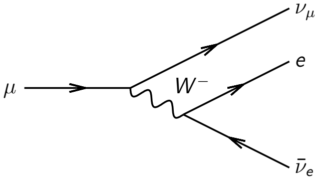
Major funding:

Additional slides:

Because of weak interaction mixing of quark flavors, the $qq'W$ and $\ell\ell'W$ vertices differ by a factor: the CKM matrix element $V_{qq'}$ in processes like these:

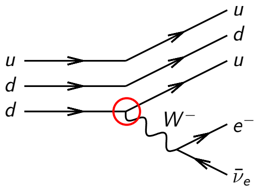


and

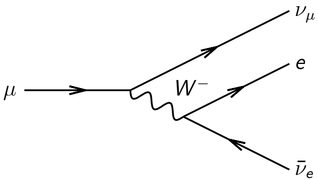


The muon decay rate defines the weak constant $\boldsymbol{G_F}$. $\Rightarrow$ Precise determination of the β decay rate yields $\boldsymbol{V_{ud}}$, **after corrections**.

Because of weak interaction mixing of quark flavors, the $qq'W$ and $\ell\ell'W$ vertices differ by a factor: the CKM matrix element $V_{qq'}$ in processes like these:



and



The muon decay rate defines the weak constant G_F. $\Rightarrow$ Precise determination of the β decay rate yields V_{ud}, **after corrections**.

Suitable processes for precise determination of V_{ud} are

(a) Superallowed Fermi $0^+ \to 0^+$ nuclear beta decays,

(b) neutron beta decay,

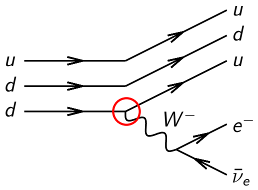
(c) "mirror" nuclear beta decays,

(d) pion beta decay.

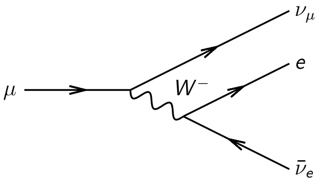
None of these is perfect in every way, so all are pursued.

Beta decays: $q\ell$ (Cabibbo) universality (an experimenter's view)

Because of weak interaction mixing of quark flavors, the $qq'W$ and $\ell\ell'W$ vertices differ by a factor: the CKM matrix element $V_{qq'}$ in processes like these:



and



The muon decay rate defines the weak constant G_F. $\Rightarrow$ Precise determination of the β decay rate yields V_{ud}, **after corrections**.

Suitable processes for precise determination of V_{ud} are

(a) Superallowed Fermi $0^+ \to 0^+$ nuclear beta decays,

(b) neutron beta decay,

(c) "mirror" nuclear beta decays,

(d) pion beta decay.

None of these is perfect in every way, so all are pursued.

Why do we care to know V_{ud} so precisely?

- ΔV_{ud} dominates the unceraintyin

$$\Delta V_1 = 1 - (V_{ud}^2 + V_{us}^2 + V_{ub}^2) .$$

- Deviation from $\Delta V_1 = 0$ would allow room for a 4$^{\text{th}}$ quark generation,
- Sensitive to non-$(V - A)$ interactions and certain BSM processes