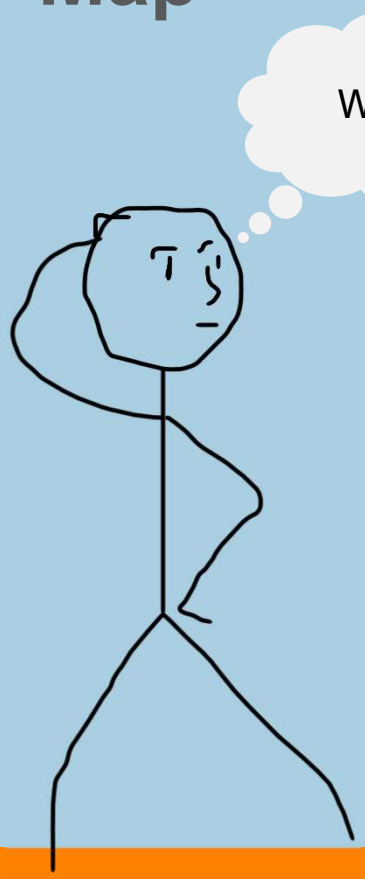
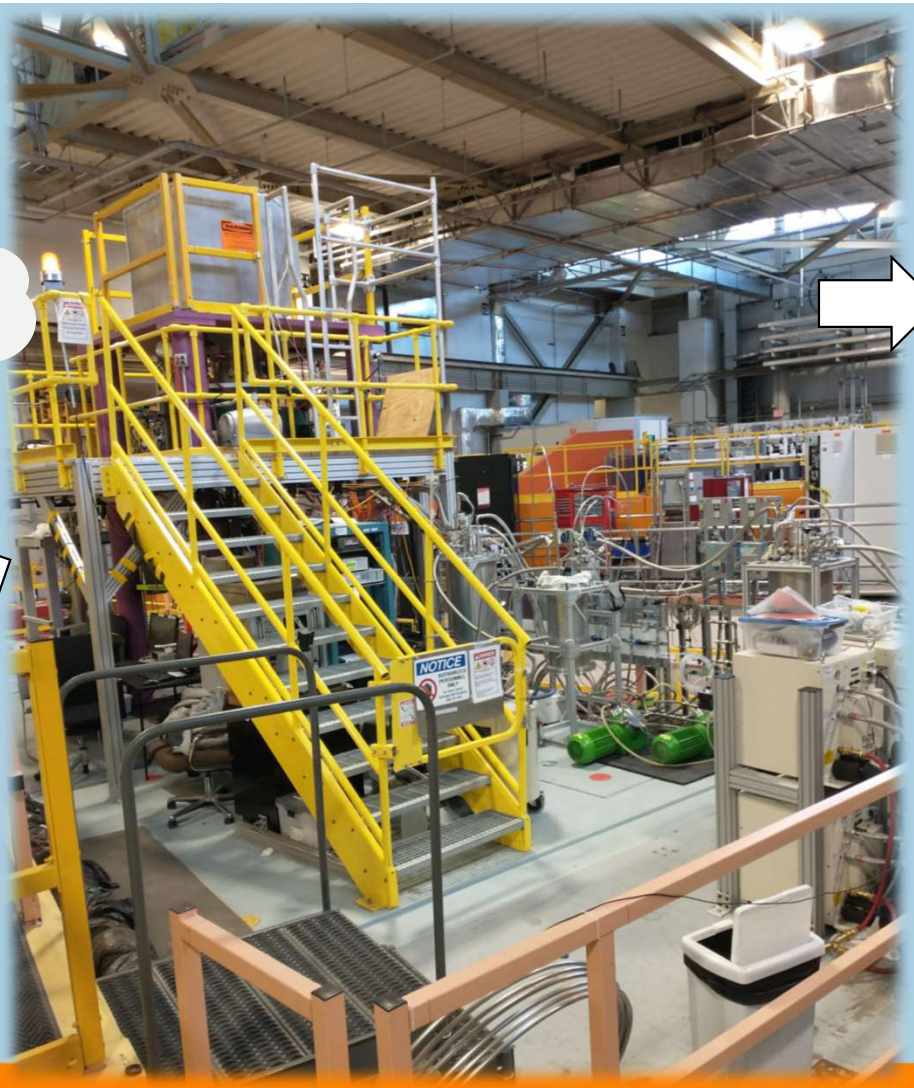
Nab (Neutron a and b): A High Precision Free Neutron Beta Decay Experiment at the Spallation Neutron Source

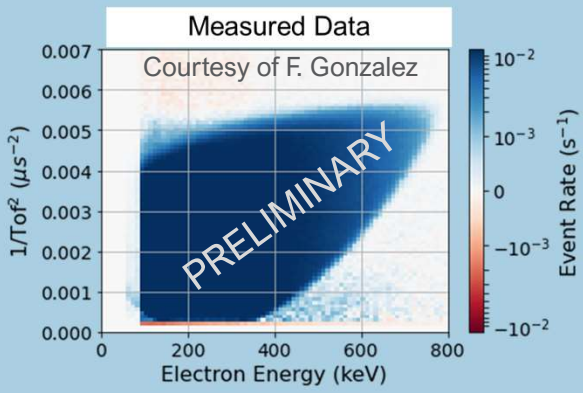
Presented by: Love Richburg |June 11th, 2025

THE UNIVERSITY OF TENNESSEE KNOXVILLE

Map


Why?


NOTICE

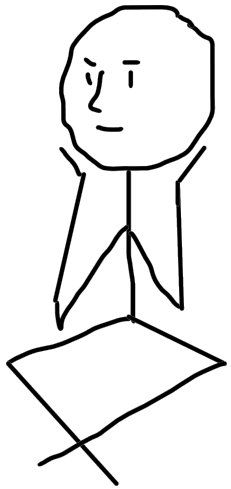

Measured Data
Courtesy of F. Gonzalez
PRELIMINARY
1/Tof² (μs⁻²)
0.007
0.006
0.005
0.004
0.003
0.002
0.001
0.000
0
200
400
600
800
Electron Energy (keV)
10⁻²
10⁻³
0
−10⁻³
−10⁻²
Event Rate (s⁻¹)

Goals

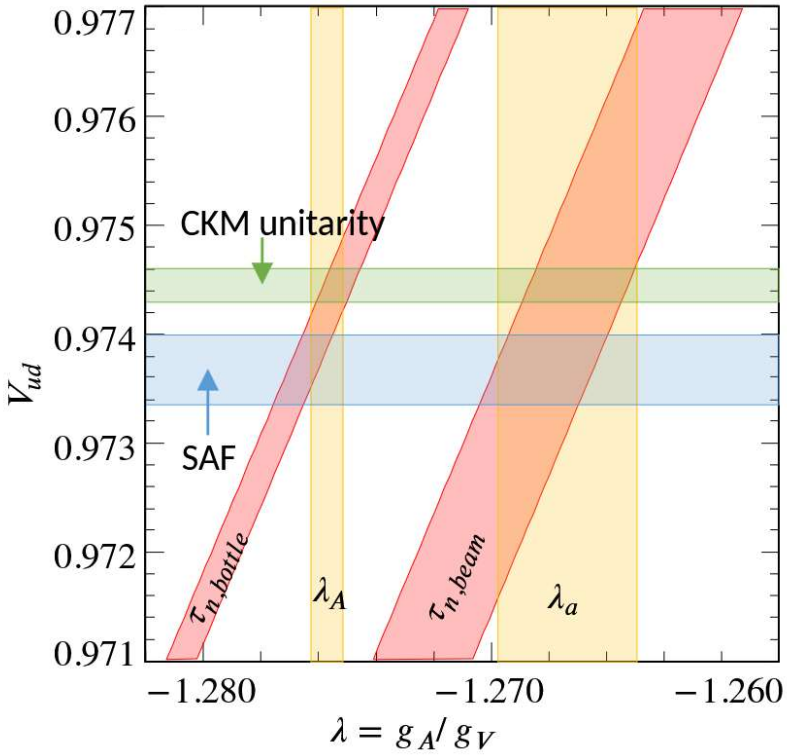
Physics Motivation

Why?

- We want to understand a parameter in the Standard Model (SM) better
- Measurements of parameters used to determine V_{ud} are in disagreement
- V_{ud} is used to make a unitarity check of the CKM quark mixing matrix



Current Status of V_{ud}



S. Baessler, et al, EPJ Web of Conferences 303, 05001 (2024)

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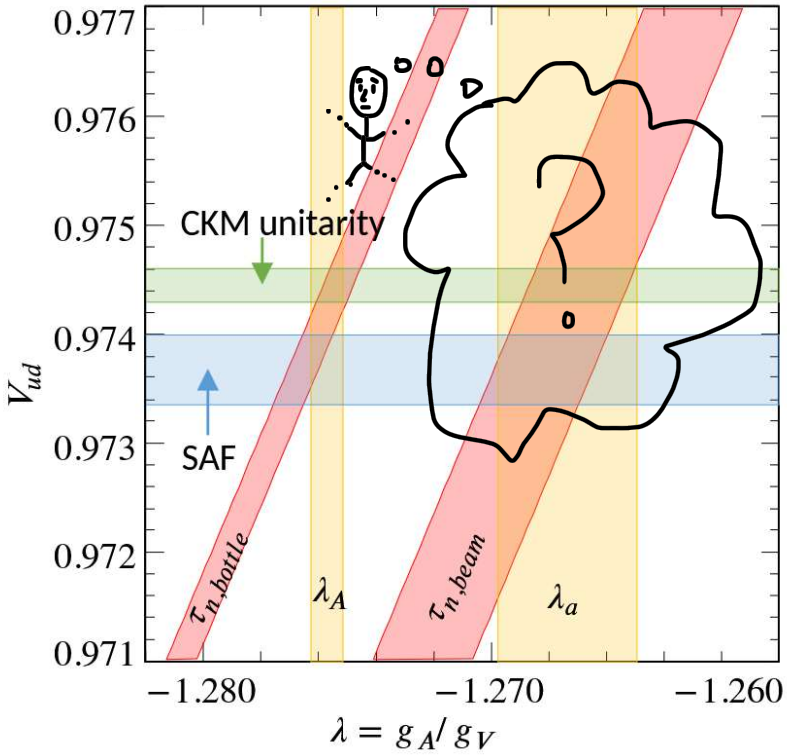

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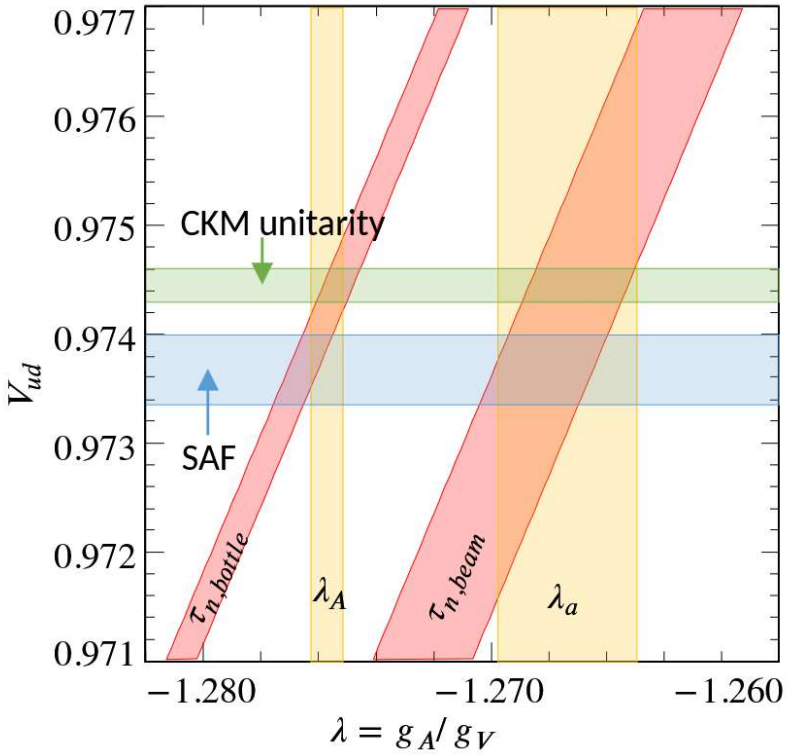
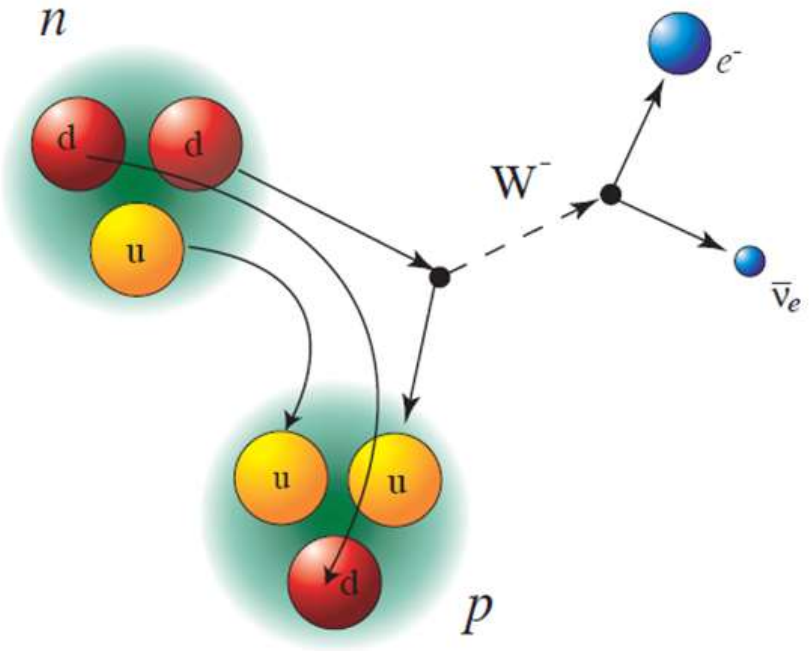


S. Baessler, et al, EPJ Web of Conferences 303, 05001 (2024)

Our Tool: Free Neutron Decay

- Neutrons are unstable outside of nuclei
- Will decay with a lifetime of 878.4 +/- 0.5 s (~15 min)
- $n^0 \rightarrow p^+ + \mathrm{e}^- + \bar{\nu}_e$



S. Navas *et al.* (Particle Data Group), Phys. Rev. D **110,** 030001 (2024) and 2025 update

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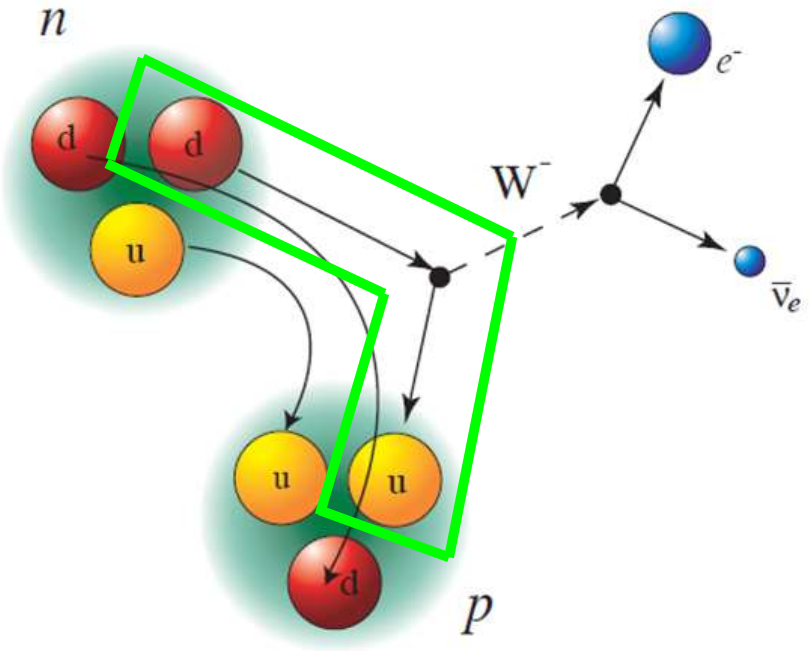
- $n^0 \rightarrow p^+ + \mathrm{e}^- + \bar{\nu}_e$
- $d \rightarrow u$ (quark transition)



S. Navas *et al.* (Particle Data Group), Phys. Rev. D **110,** 030001 (2024) and 2025 update

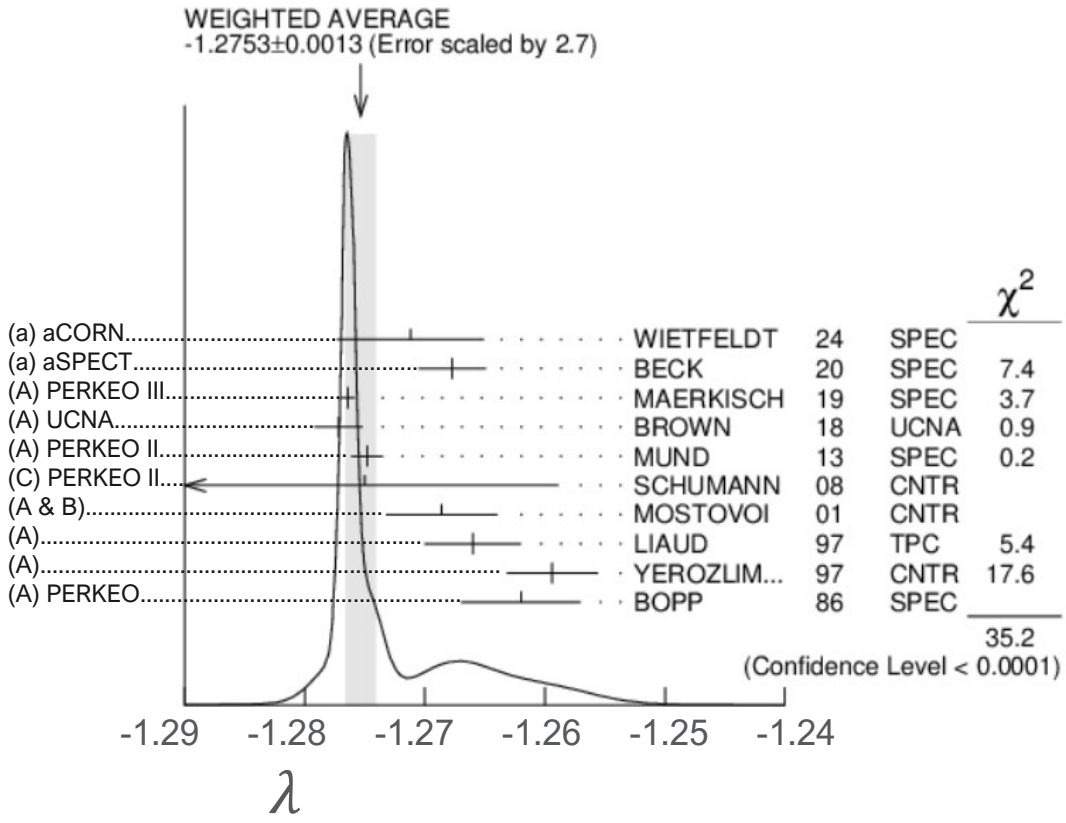
λ from Neutron Decay

Note that: $\lambda = \frac{g_A}{g_v} = -1.2753(13)$

$$a = \frac{1-\lambda^2}{1+3\lambda^2} \rightarrow \frac{\partial_\lambda a}{a} \approx -2.8$$

$$A = -2\frac{\lambda(\lambda+1)}{1+3\lambda^2} \rightarrow \frac{\partial_\lambda A}{A} \approx -3.2$$

$$B = 2\frac{\lambda(\lambda-1)}{1+3\lambda^2} \rightarrow \frac{\partial_\lambda B}{B} \approx 0.077$$



D. Dubbers and M. G. Schmidt
https://doi.org/10.1103/RevModPhys.83.1111

S. Navas *et al.* (Particle Data Group), Phys. Rev. D **110**, 030001 (2024) and 2025 update

CKM Unitarity Check with Nab

Nab → $a = \dfrac{1-\lambda^2}{1+3\lambda^2}$ (λ)

Neutron Lifetime Experiments → $\dfrac{1}{\tau_n} \propto |V_{ud}|^2 |g_v|^2 G_F{}^2 (1 + 3\lambda^2)$ (V_{ud})

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

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

$$\lambda = \frac{g_A}{g_v}$$

The Nab Experiment

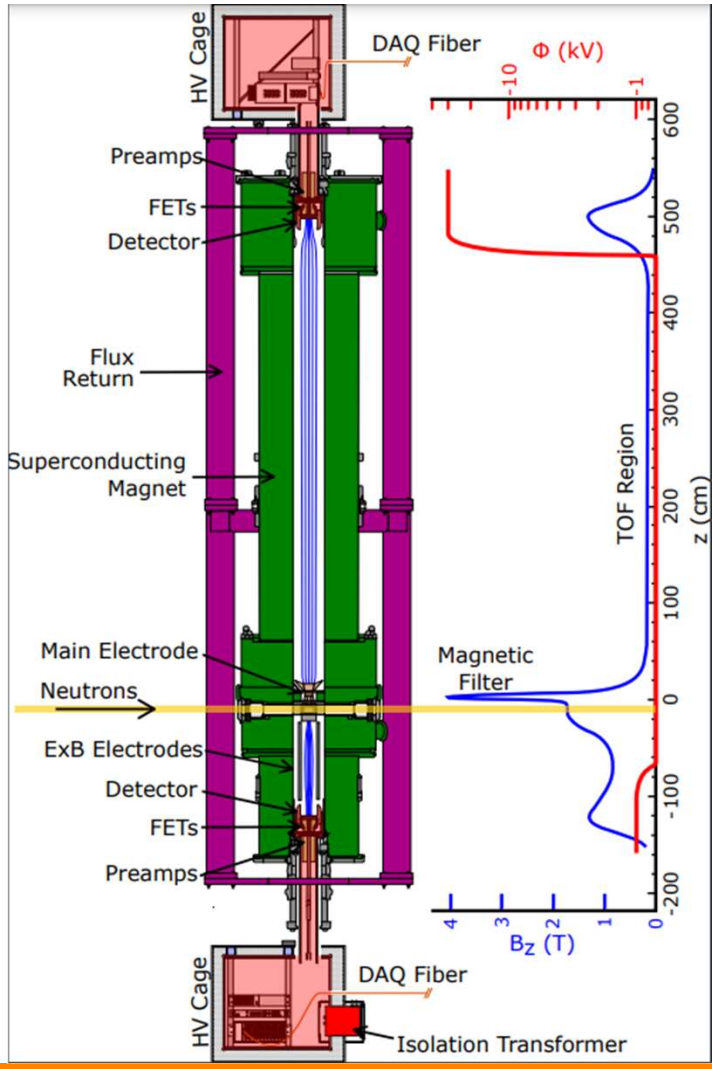
Nab: Neutron ‘a’ and ‘b’

- Nab is a high precision free neutron beta decay experiment
- ‘a’ – the electron neutrino correlation parameter; $\frac{\Delta a}{a} \approx 1 \times 10^{-3} \sim 0.1\%$
- ‘b’ – the Fierz interference term; $\Delta b \approx 3 \times 10^{-3}$
- These are coefficients in the expression for the unpolarized free neutron decay rate:

$$dW \propto \frac{1}{\tau} f(E_e) \left[1 + a\frac{\vec{p_e} \cdot \vec{p_\nu}}{E_e \cdot E_\nu} + b\frac{m_e}{E_e}\right]$$

‘a’ – CKM unitarity test

‘b’ – scalar/tensor coupling in weak interaction

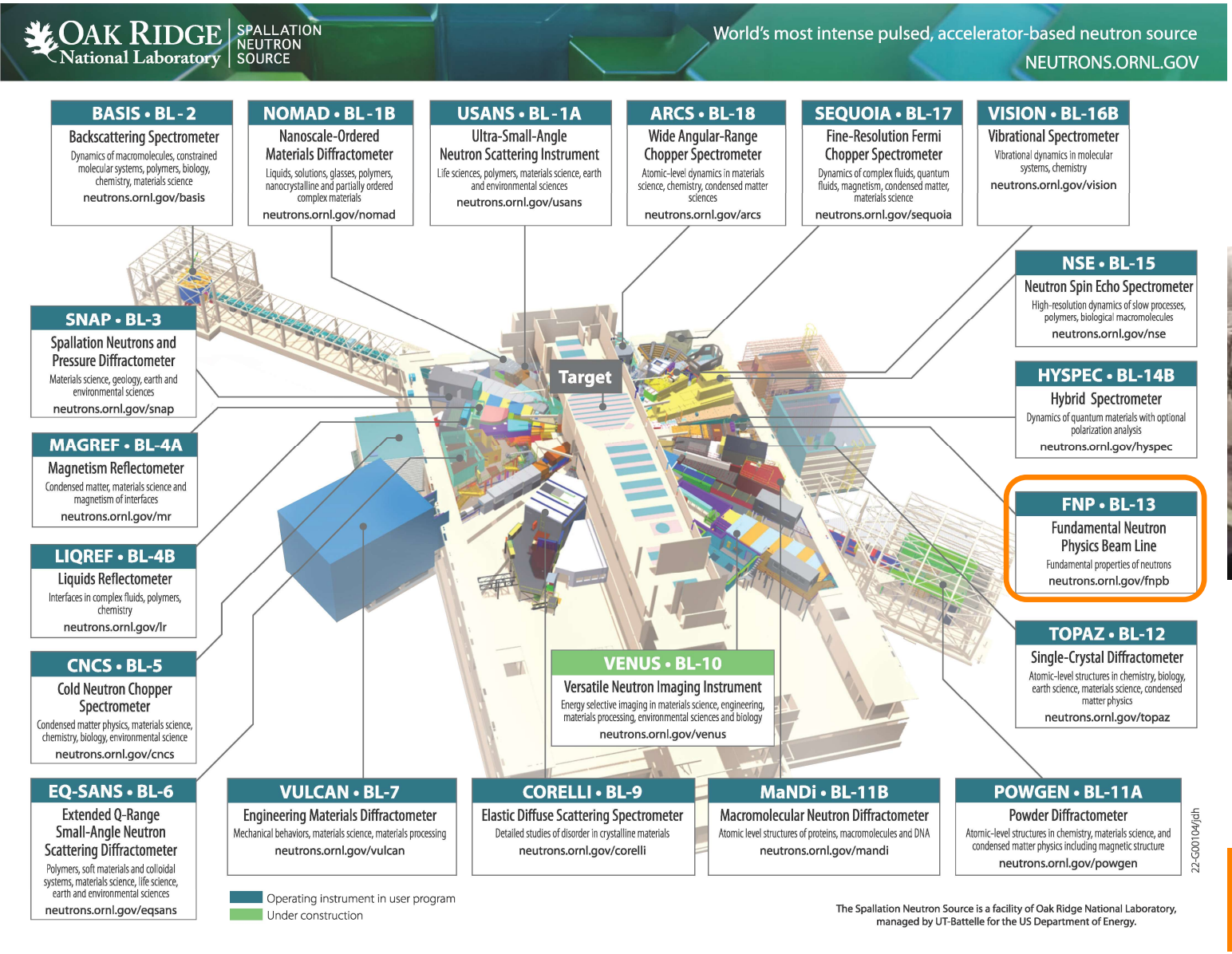


J.D. Jackson, S.B. Treiman, H.W. Wyld, Coulomb corrections in allowed beta transitions, Nuclear Physics, Volume 4, 1957, Pages 206-212, ISSN 0029-5582, https://doi.org/10.1016/0029-5582(87)90019-8.

SNS at Oak Ridge National Laboratory

Spallation Neutron Source

SNS Target Building



Liquid Mercury Target

https://neutrons.ornl.gov/virtual-tour

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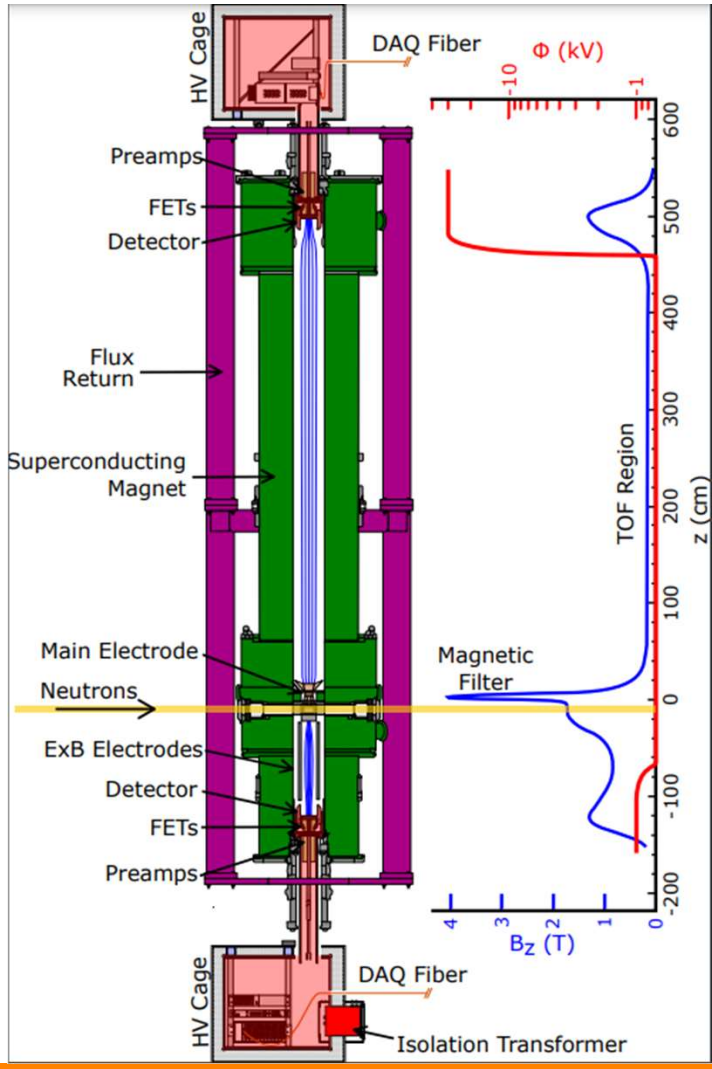
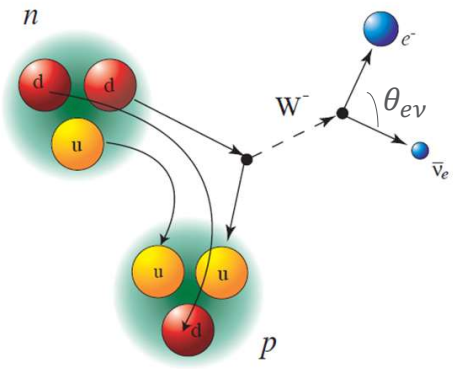
Measurement Method

- Measure electron energy and proton time of flight in coincidence
- Proton time of flight is used to extract proton momentum
- Two large area, thick, pixelated silicon detectors
- 7 m tall magnetic spectrometer
- Proton max energy ~751 eV
- Electron max energy ~782 keV

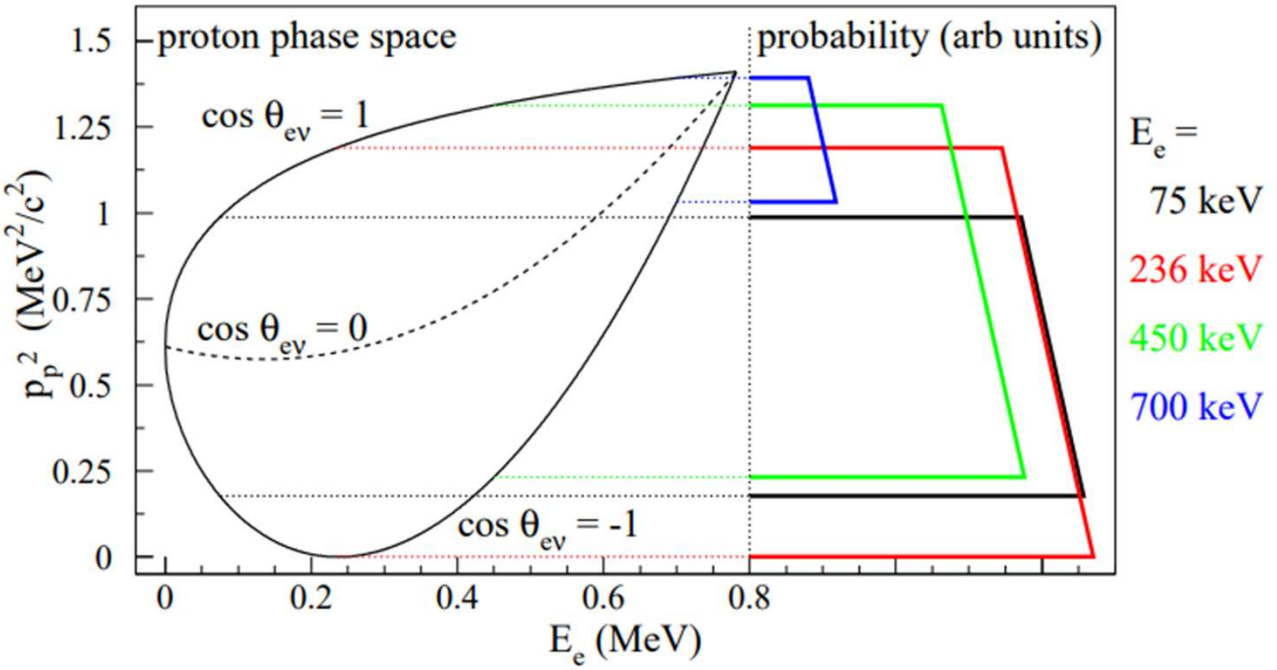


Proton Phase Space aka the Tear Drop

$$dW \propto \frac{1}{\tau} f(E_e) \left[1 + a \frac{\vec{p_e} \cdot \vec{p_\nu}}{E_e \cdot E_\nu} + b \frac{m_e}{E_e} + A \frac{\sigma_n \cdot \vec{p_e}}{E_e} + B \frac{\sigma_n \cdot \vec{p_\nu}}{E_\nu} + D \frac{\sigma_n \cdot (\vec{p_e} \times \vec{p_\nu})}{E_e E_\nu} \right]$$



$dw \propto 1 + a\beta \cos(\theta_{ev})$



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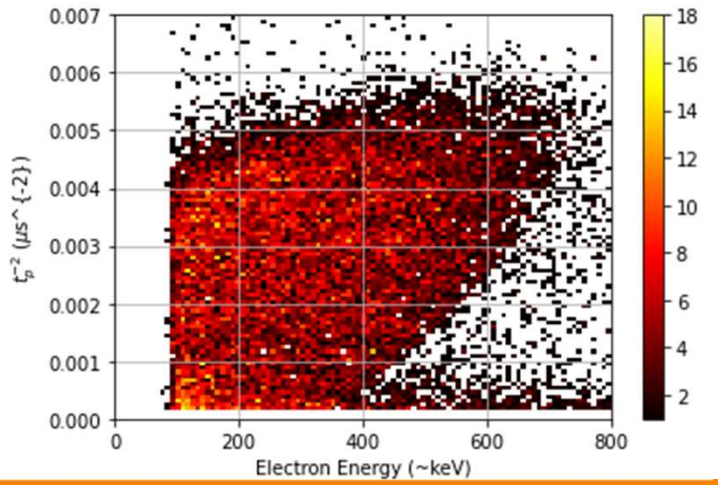
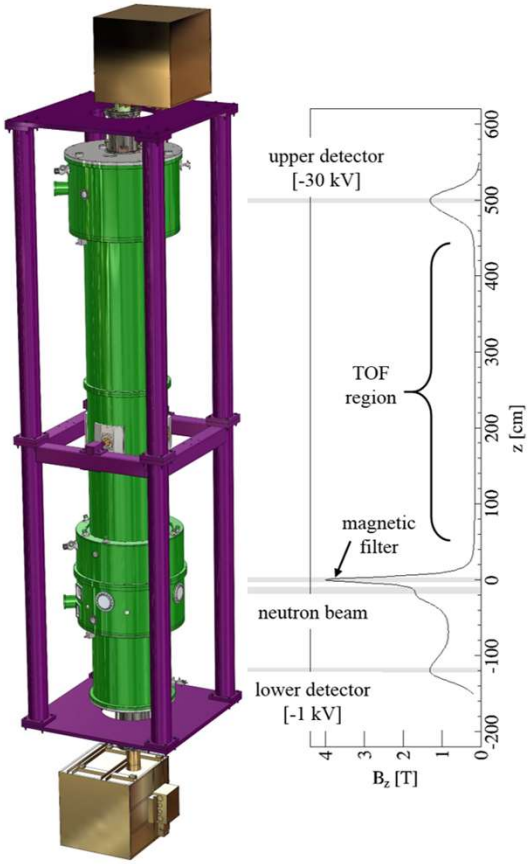
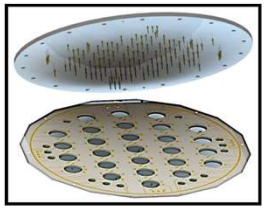
Taking Data Now!

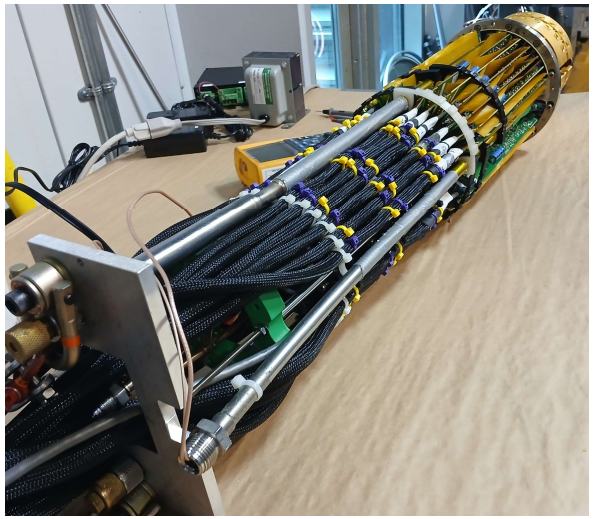
- Nab transitioned to production data taking mode in Fall 2024
- Concurrently, working to understand systematic uncertainties at high precision
- We can make tear drops (right, just a little one I made from less than a day worth of 2023 data)



Sub-System Efforts Towards Precision







Polarimetry

$$dW \propto \frac{1}{\tau} f(E_e) \left[1 + a \frac{\vec{p_e} \cdot \vec{p_\nu}}{E_e \cdot E_\nu} + b \frac{m_e}{E_e} + A \frac{\vec{\sigma_n} \cdot \vec{p_e}}{E_e} + B \frac{\vec{\sigma_n} \cdot \vec{p_\nu}}{E_\nu} \right]$$

neutron spin

- Residual polarization in the neutron beam can introduce bias
- Need an efficient spin flipper to make a precise measurement (1×10^{-4} level) of beam polarization
- If necessary, Nab will operate in a mode where the spin flipper is used to cancel the effect of any residual polarization
- Efforts to characterize candidate spin flippers have been underway
- The next step is to make a measurement of beam polarization with the selected flipper

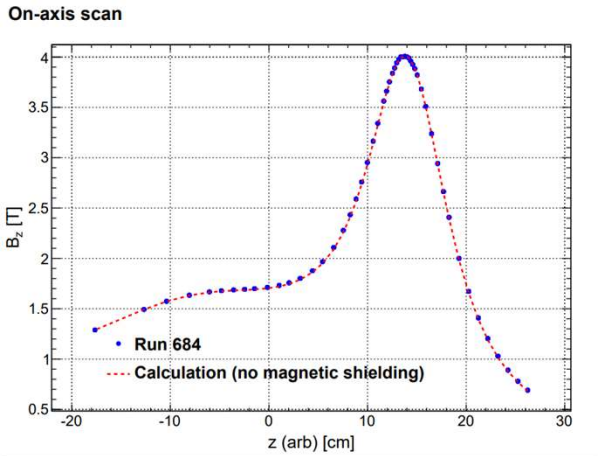
Rebecca Godri et al. Characterizing the AFP Spin Flipper for the Nab Experiment, 2025.

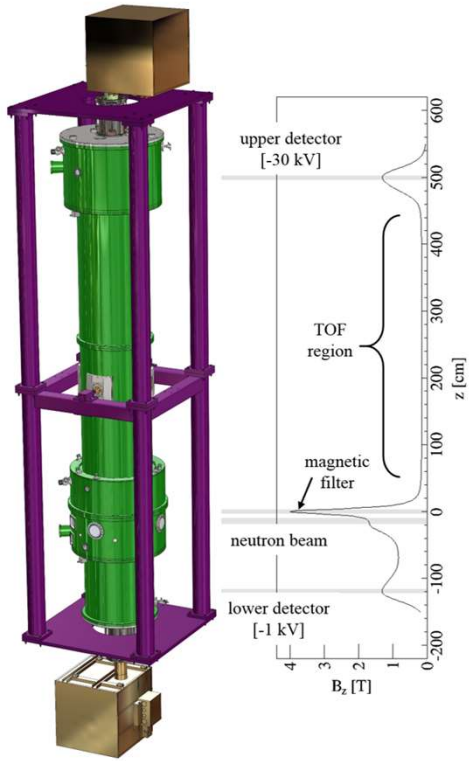
J.D. Jackson, S.B. Treiman, H.W. Wyld, Coulomb corrections in allowed beta transitions, Nuclear Physics, Volume 4, 1957, Pages 206-212, ISSN 0029-5582, https://doi.org/10.1016/0029-5582(87)90019-8.

Magnetometry

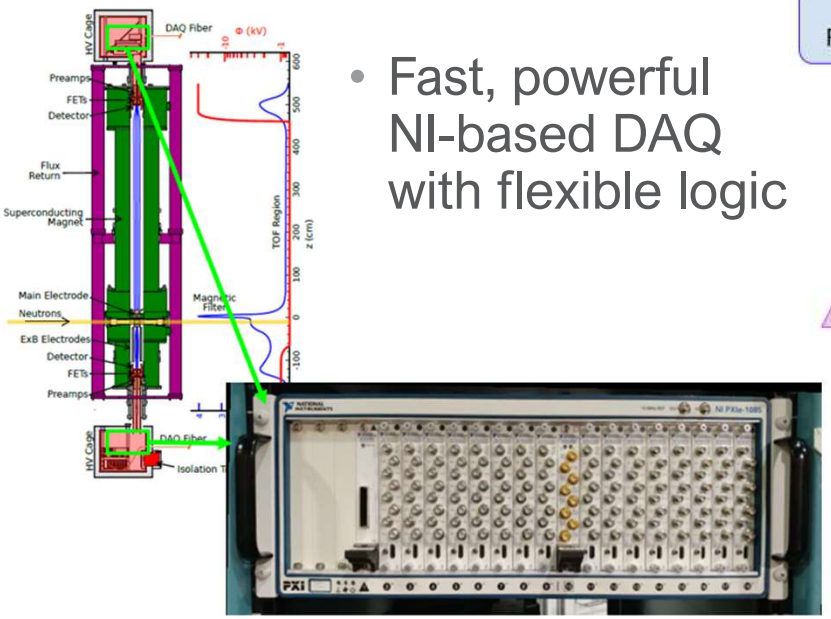
- Early scans are as expected (2019)
- Need to understand curvature at pinch and ratios of magnetic field in TOF region and DV with more precision
- Campaign planned for 2026 with new probe

$$B(z) = B_0[1 - \left(\alpha(z - z_0)\right)^2]$$

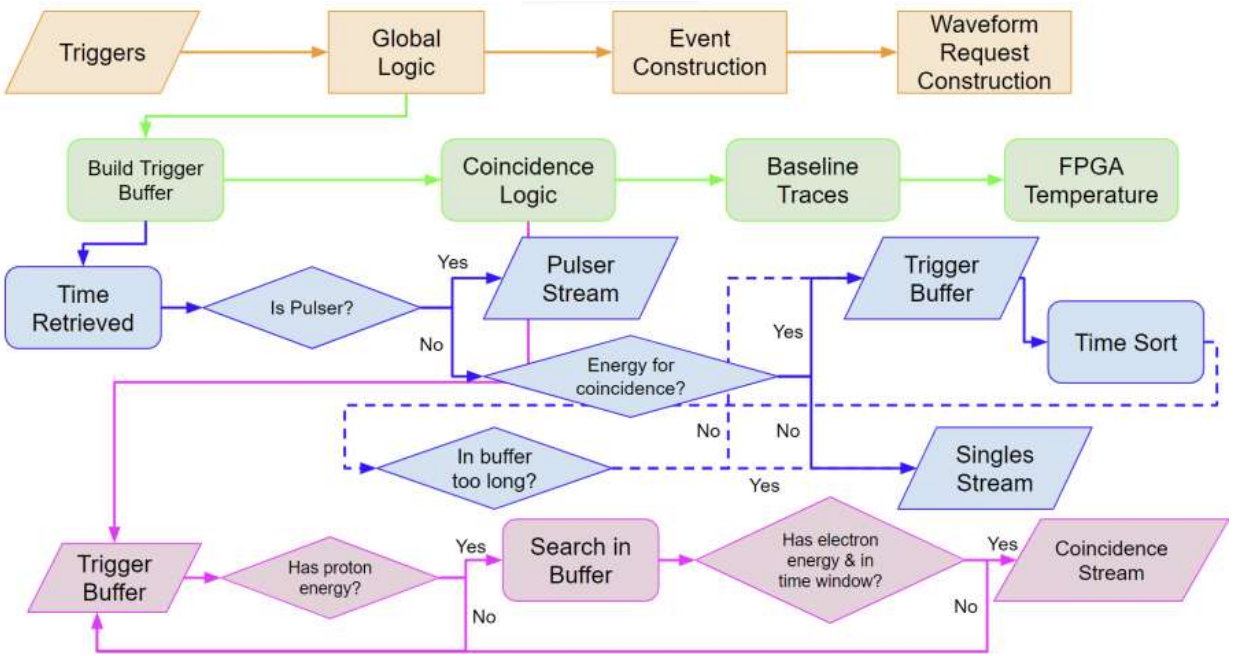




DAQ Studies



- Fast, powerful NI-based DAQ with flexible logic

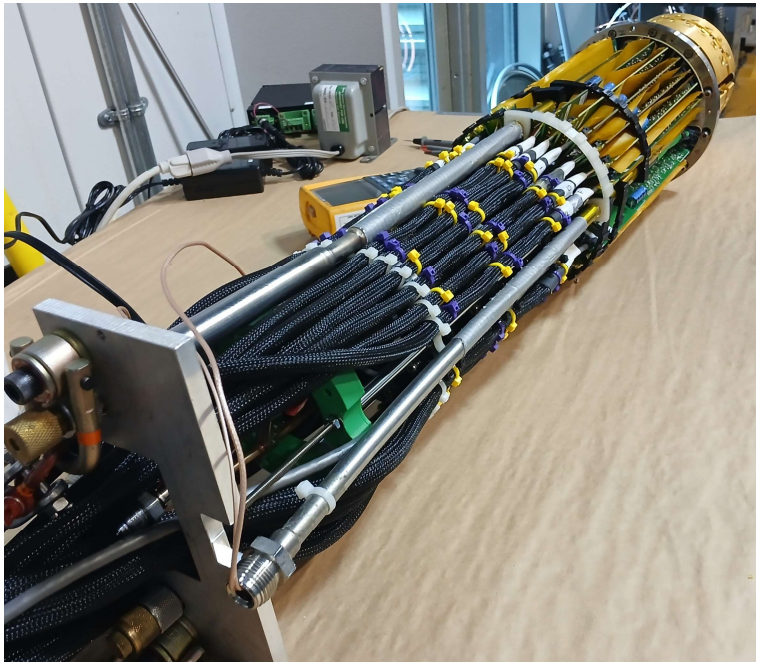


- Measurements of timing synchronization
- Studies to determine hardware thresholds and setting thresholds for the detectors

Courtesy of A. Nelsen

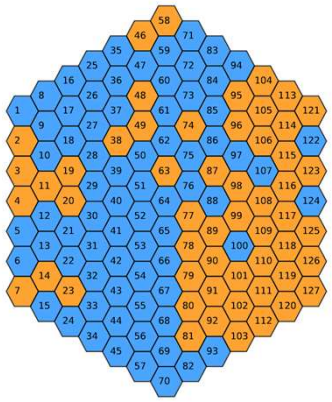
D. G. Mathews et al. A flexible data acquisition system architecture for the nab experiment, 2024.

Detector Studies

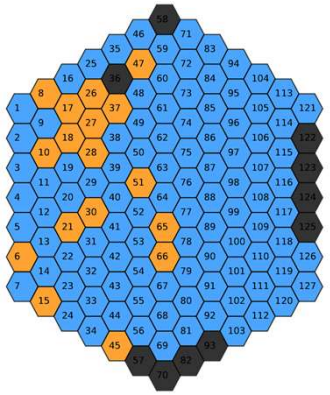


Blue - Upper detector functional pixels

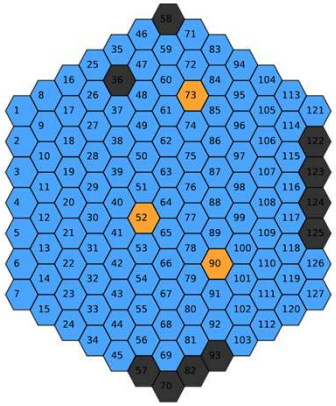
Courtesy of W. Schreyer



2023

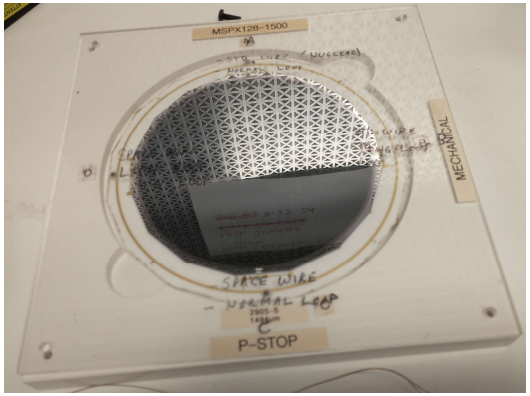


2024

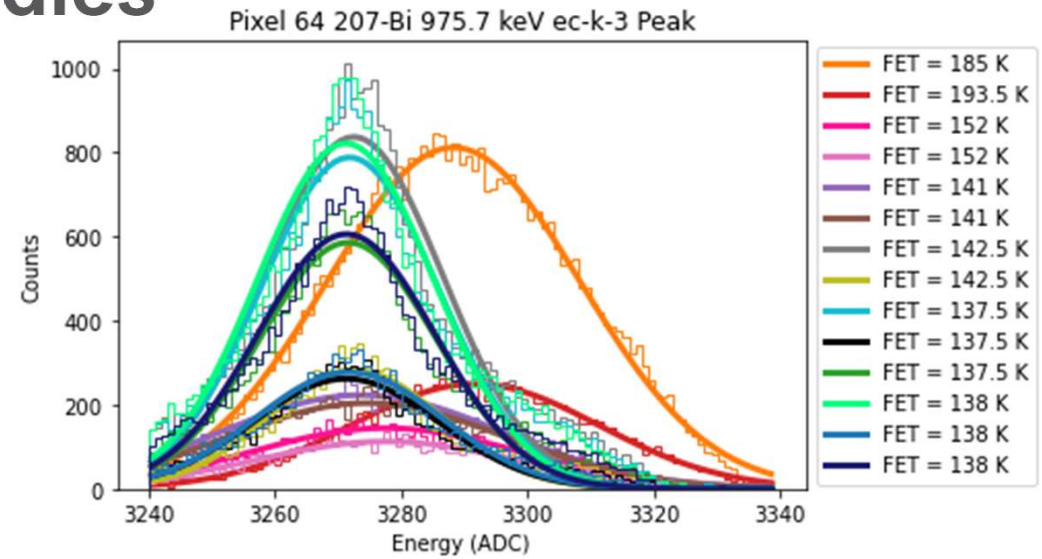


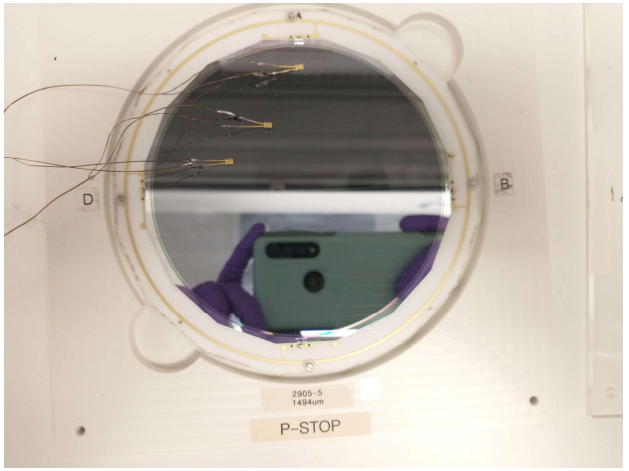
2025

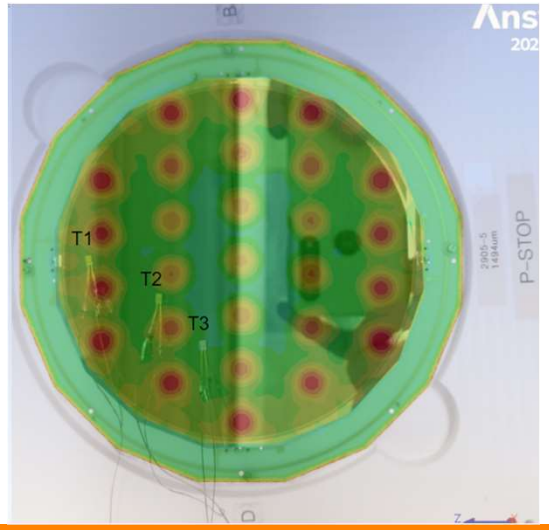
- Electronics
- Dead layer
- Temperature effects
- Detector efficiency
- Detector electric field profile



Detector Temperature Studies





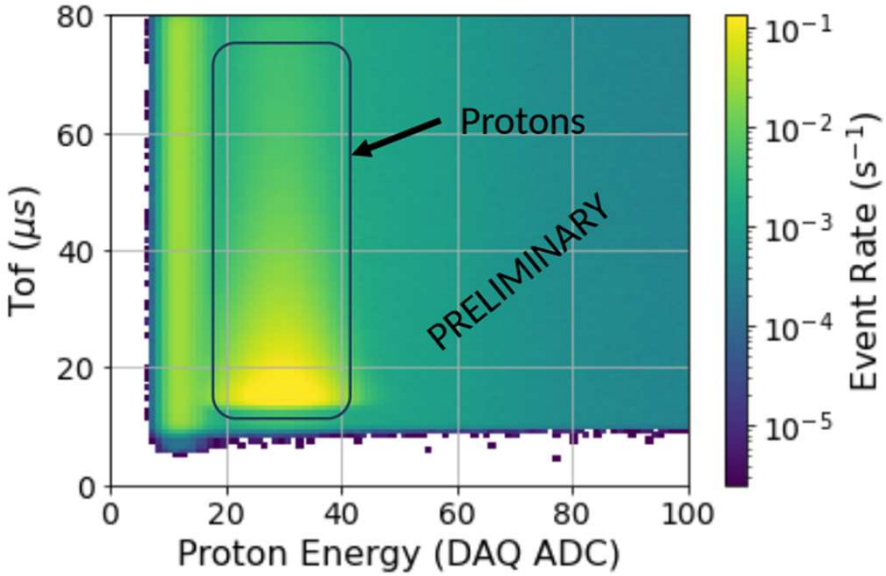


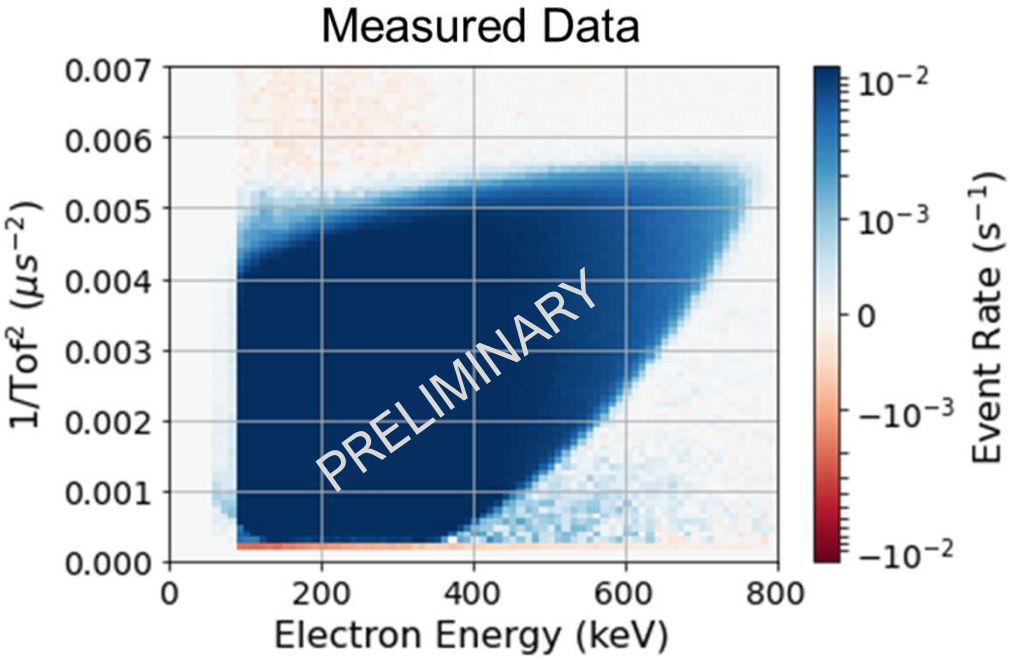
- Detector cooling system is capable of very stable (< 0.2 K) temperature regulation
- Study gain variation with temperature
- Detector thermal profile measurements

Teardrops

2023 Plots

- Commissioning data from 2023

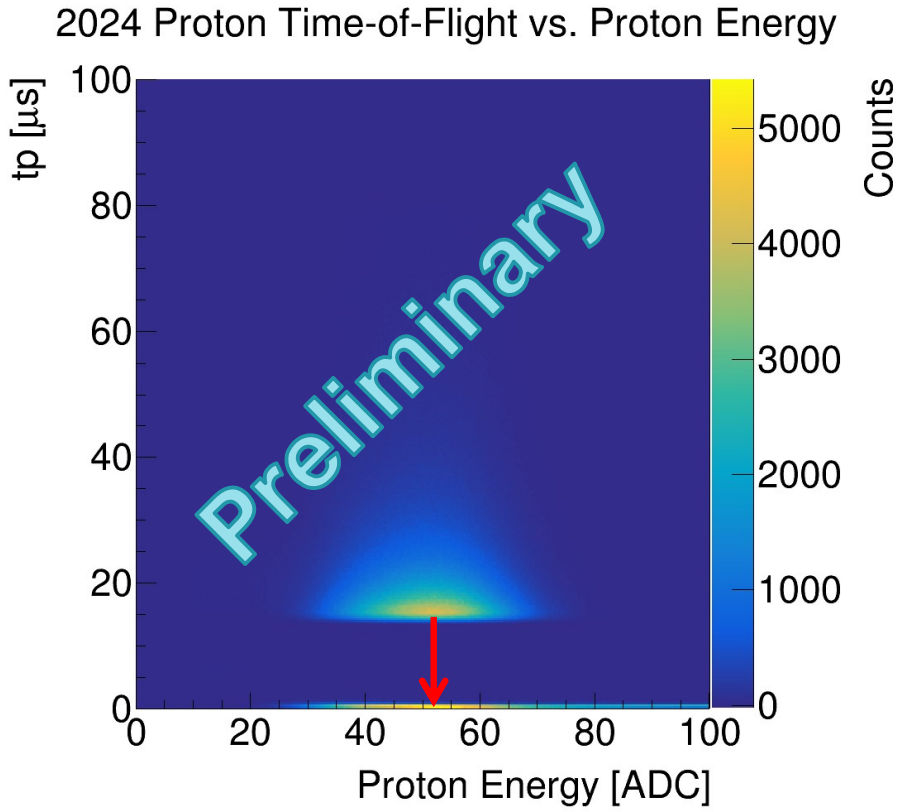


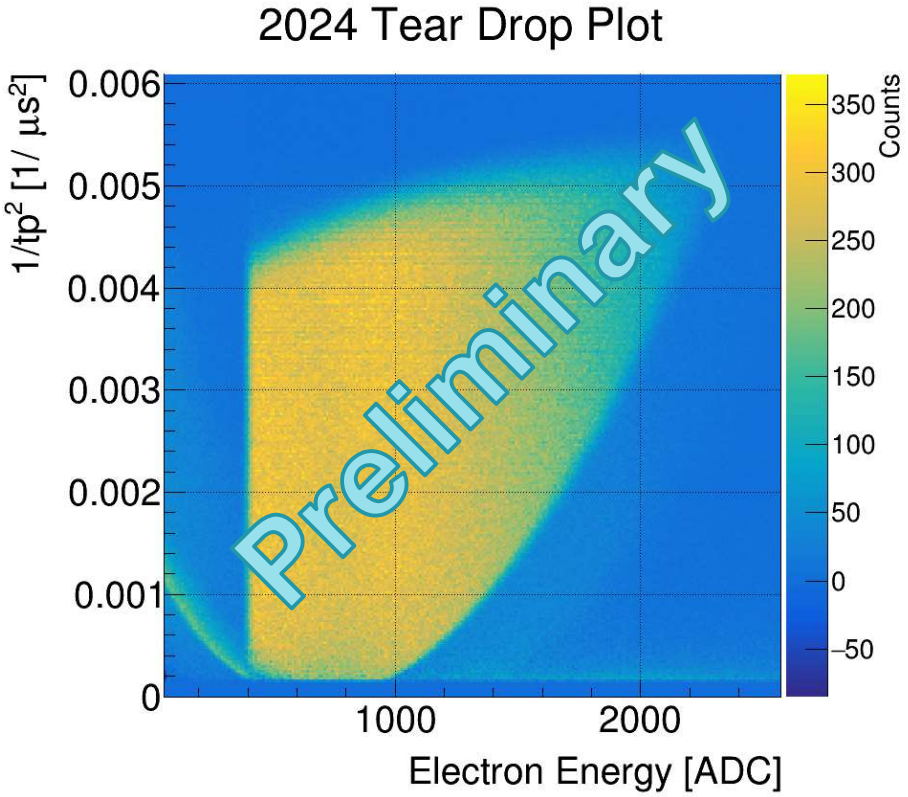


Courtesy of F. Gonzalez

Stefan Baeßler et al. Study of neutron beta decay with the nab experiment. *EPJ Web Conf.*, 303:05001, 2024.

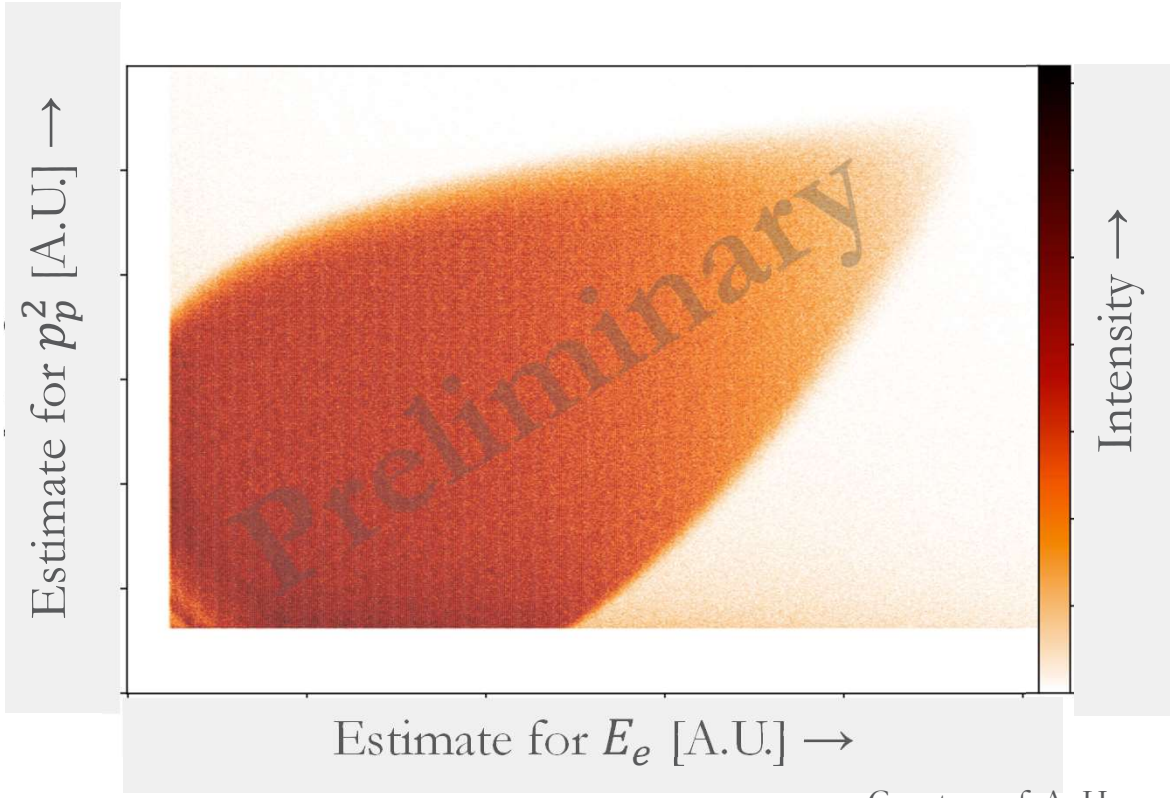
2024 Plots





Courtesy of J.H. Choi

2025 Plot



Courtesy of A. Hagemeier

Goals

Goals

Nab is both taking production data and performing critical systematic studies

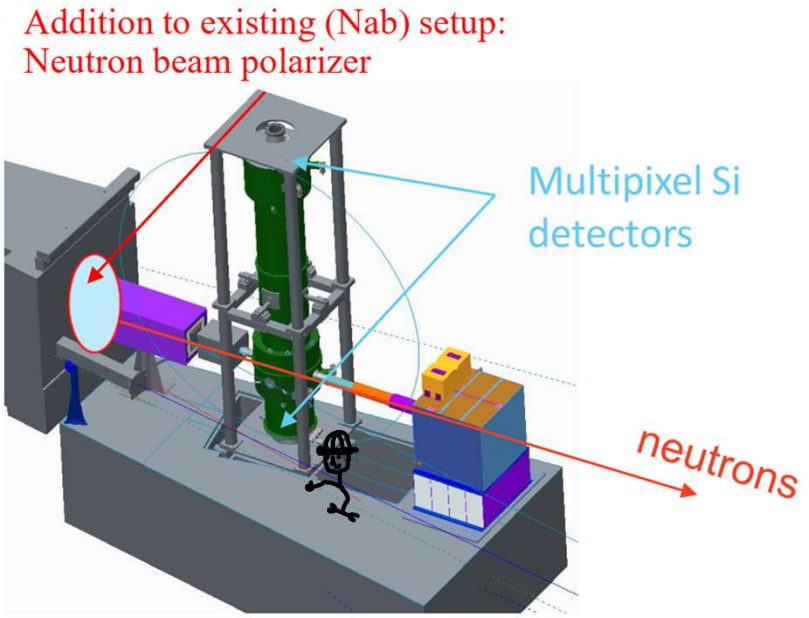
- We are taking data for a $\frac{\Delta a}{a} \approx \mathbf{0.5}\%$ measurement this year

Timeline

- Efforts towards $\frac{\Delta a}{a} \approx 0.5\%$ result in the next year
- Magnetometry campaign
- Polarimetry campaign
- Start data taking to reach necessary statistics for 0.1% measurement (2026)
- After Nab → pNab (to make precise beta asymmetry measurements with an augmented Nab apparatus)

See A. Young's talk right after this one!

"The PNab Experiment: Angular Correlation Measurements with Polarized Neutrons"



Courtesy of S. Baeßler

D. G. Mathews et al. A flexible data acquisition system architecture for the nab experiment, 2024.

Stefan Baeßler et al. Study of neutron beta decay with the nab experiment. *EPJ Web Conf.*, 303:05001, 2024.

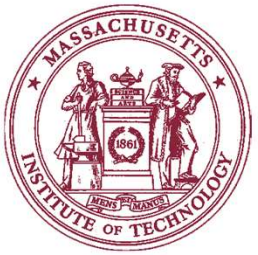
Leendert Hayen et al. Precision pulse shape simulation for proton detection at the nab experiment. *Phys. Rev. C*, 107:065503, Jun 2023.

Rebecca Godri et al. Characterizing the AFP Spin Flipper for the Nab Experiment, 2025.

THANK YOU!!

QUESTIONS?

The Nab Collaboration



Main Project Funding: