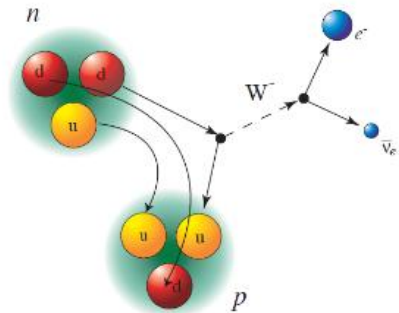


# Probing new physics with Neutron Beta Decay



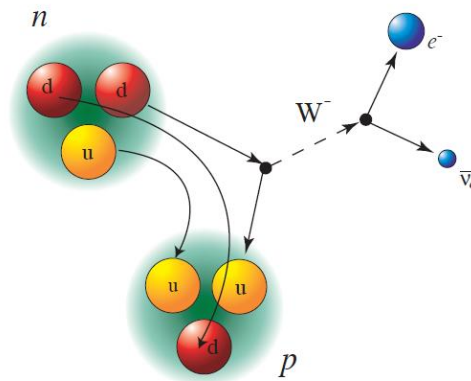
Nadia Fomin

June 26, 2026



# Why study neutron beta decay?

- Prototype for all weak decays of hadrons and leptons
- Input to tests of the Standard Model
- Input to Big Bang Nucleosynthesis models



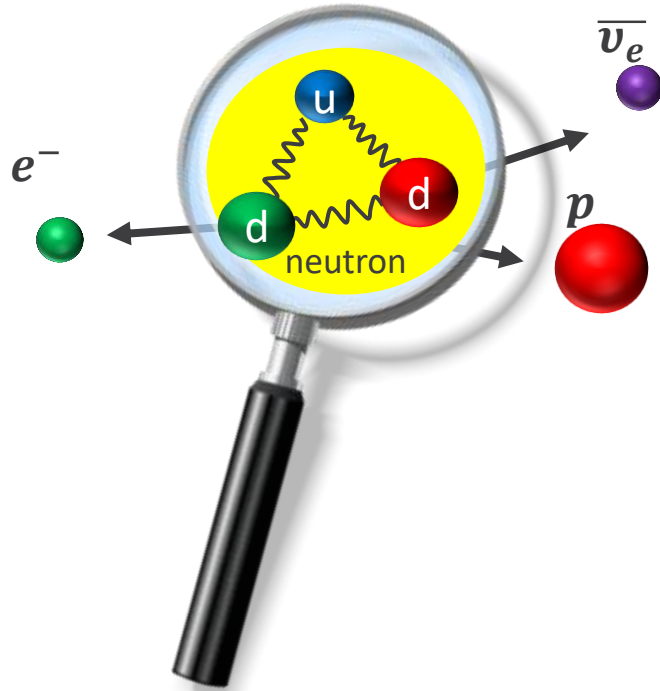
## What do we study?

- Neutron Lifetime ( $\tau_N$ )
- Correlations among decay parameters ( $\lambda$ )



$$V_{ud} \propto \frac{1}{\tau_N(1 + 3\lambda^2)}$$

# The weak interaction

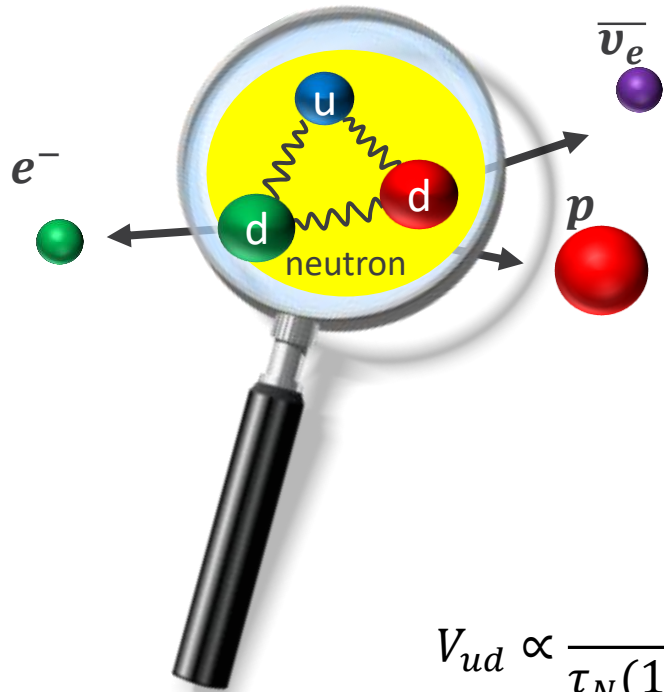


Weak interaction is the only one that can change quark/lepton flavor

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

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

# The weak interaction



Weak interaction is the only one that can change quark/lepton flavor

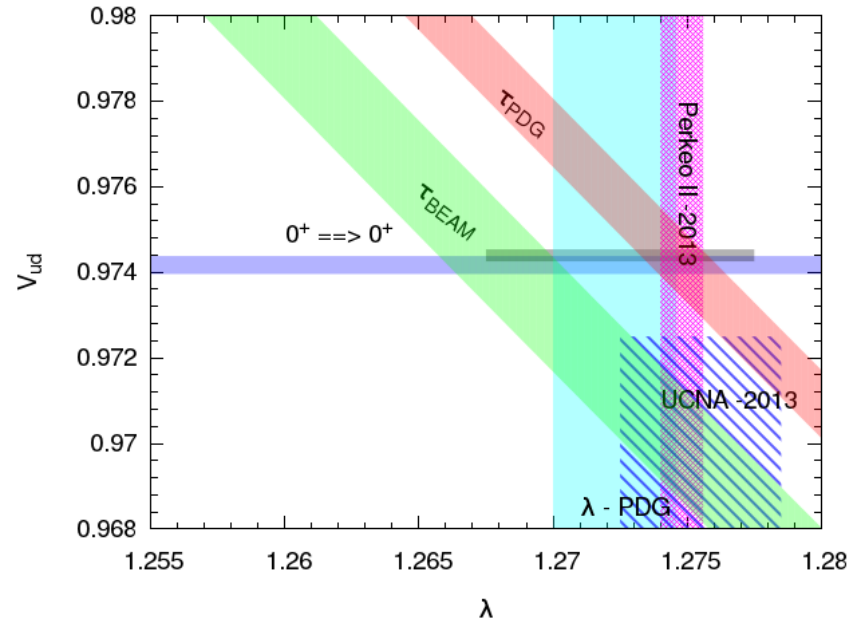
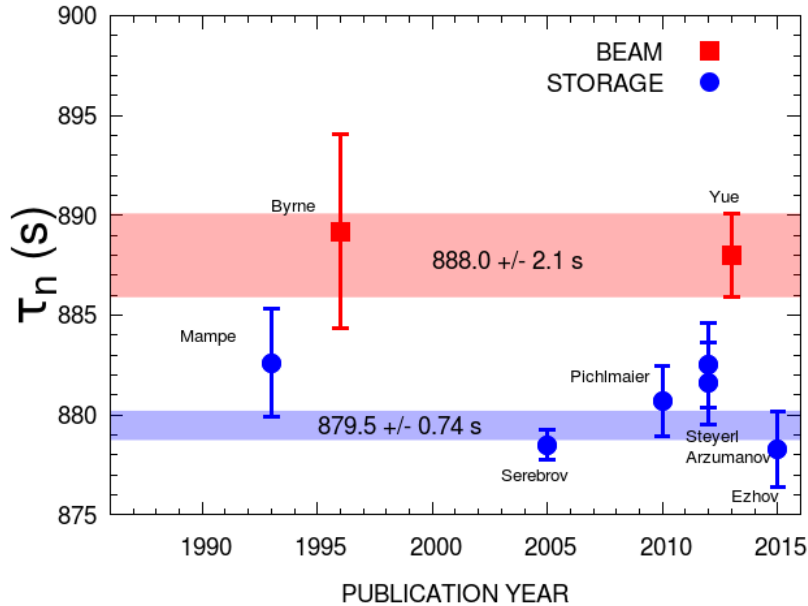
$$\begin{pmatrix} \mathbf{d}' \\ \mathbf{s}' \\ \mathbf{b}' \end{pmatrix} = \begin{pmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{pmatrix} \begin{pmatrix} \mathbf{d} \\ \mathbf{s} \\ \mathbf{b} \end{pmatrix}$$

$$V_{ud} \propto \frac{1}{\tau_N(1 + 3\lambda^2)}$$

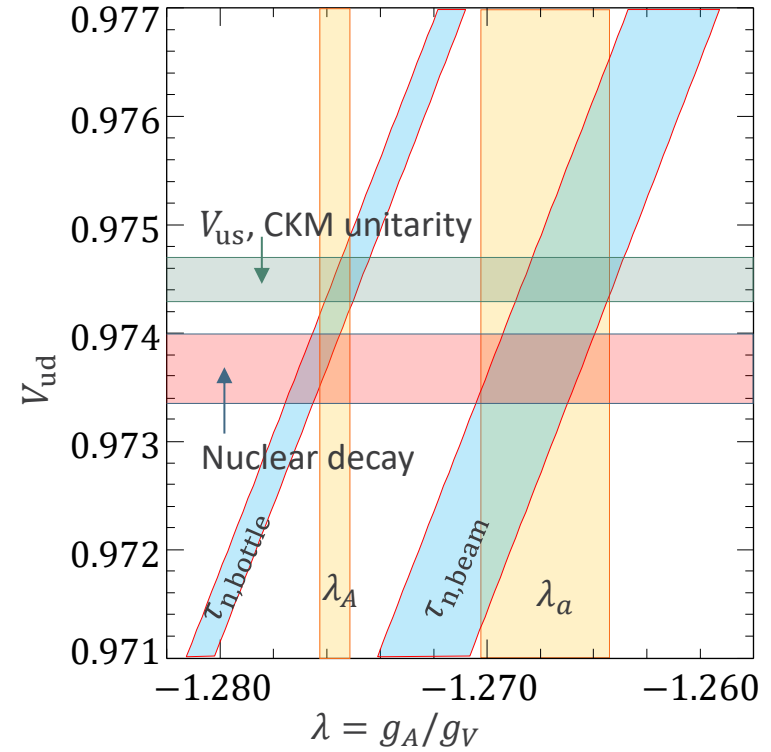
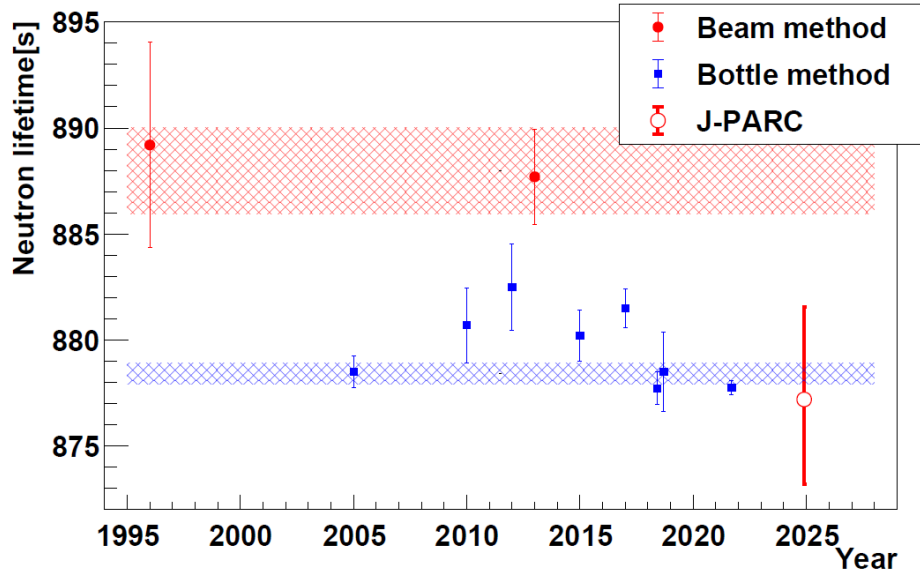
$$|V_{ud}|^2 + |V_{us}|^2 + |V_{ub}|^2 = 1$$

"Vector magnifying glass" by AlphaZeta, CC0 1.0

# In 2016, there was a bit of tension

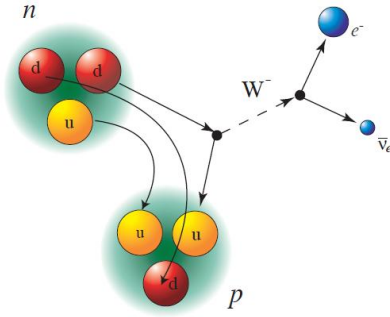


# Today...there's more tension

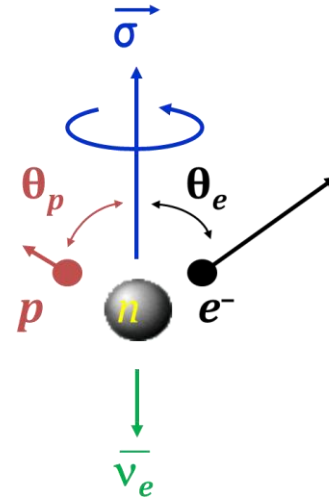


# Observables in neutron $\beta$ decay

$$dw \propto \rho(E_e) \cdot (1 + 2|\lambda|^2) \cdot \left\{ 1 + a \frac{\vec{p}_e \cdot \vec{p}_\nu}{E_e E_\nu} + b \frac{m_e}{E_e} + \vec{\sigma}_n \cdot \left( A \frac{\vec{p}_e}{E_e} + B \frac{\vec{p}_\nu}{E_\nu} + D \frac{\vec{p}_e \times \vec{p}_\nu}{E_e E_\nu} \right) \right\}$$

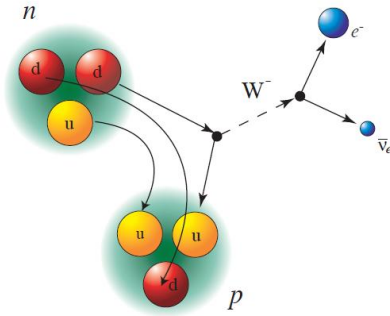


$$\lambda = \frac{g_A}{g_V}$$

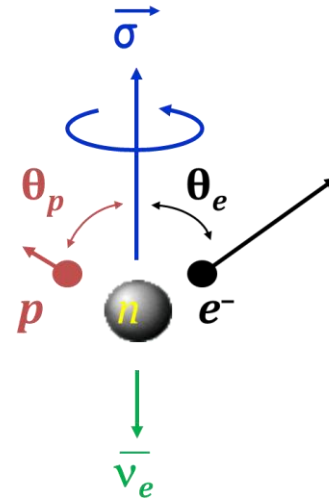


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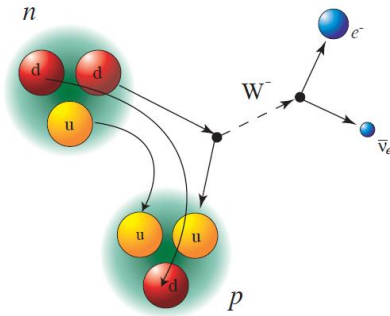


$$\lambda = \frac{g_A}{g_V}$$

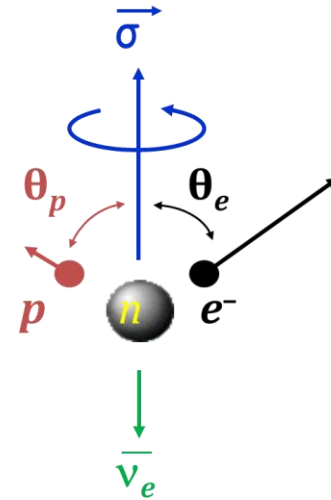


# Observables in neutron $\beta$ decay

$$dw \propto \rho(E_e) \cdot (1 + 2|\lambda|^2) \cdot \left\{ 1 + a \frac{\vec{p}_e \cdot \vec{p}_\nu}{E_e E_\nu} + b \frac{m_e}{E_e} + \bar{\sigma}_n \cdot \left( A \frac{\vec{p}_e}{E_e} + B \frac{\vec{p}_\nu}{E_\nu} + D \frac{\vec{p}_e \times \vec{p}_\nu}{E_e E_\nu} \right) \right\}$$



Need lifetime  
*and*  $\lambda$  for  $V_{ud}$



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

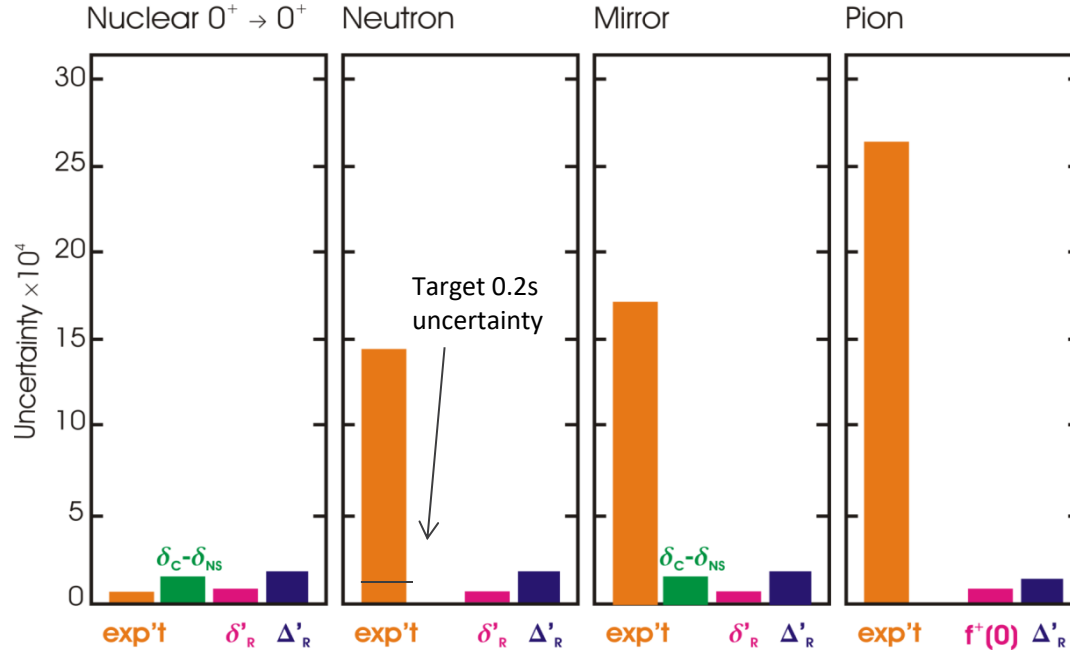
$$V_{ud} = \frac{(4908 \pm 1.9)s}{\tau_N(1 + 3\lambda^2)}$$

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

$$A = -2 \frac{\lambda^2 + \lambda}{1 + 3\lambda^2}$$

# It's an old slide, but it still checks out

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



Hardy and Towner, Ann. Phys. 525, 443 (2013)

*A measurement in the  $10^{-4}$  range can probe BSM physics.*

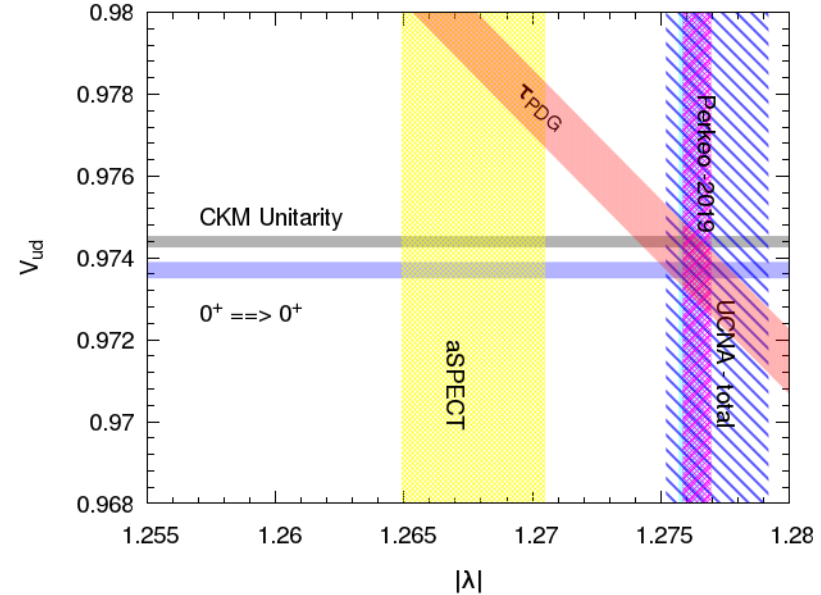
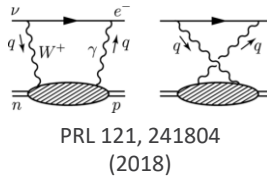
# $V_{ud}$ from nuclear beta decay

- Defined primarily by superallowed Fermi (vector)  $0^+ \rightarrow 0^+$

$$Ft \equiv ft (1 + \delta_R)(1 - (\delta_c - \delta_{NS})) = \frac{K}{2(G_F V_{ud})^2 (1 + \Delta_R^V)}$$

$$V_{ud} = 0.97367(11)_{exp}(13)_{\Delta_R^V}(27)_{NS} (\sim 0.03\%)^1$$

- 2018 Paradigm shift: new framework to understand  $\gamma W$ -box diagram
  - Radiative corrections smaller uncertainty + shift<sup>2</sup>
  - Nucleus dependent corrections now a limiting uncertainty<sup>3</sup>
  - Active area of continued development, challenging to resolve
- Strong need for precision data from other systems (neutron)



Courtesy of L. Broussard

[1] PDG, Phys. Rev. D 110, 030001 (2024)

[2] PRL 121 241804 (2018); PRD 100 073008 (2019), PRD 101 111301

(2020), PRD 104 033003 (2021), PRD 103 113001 (2021)

[3] PRL 123 042503 (2019), PRD 101 111301 (2020)

# $V_{ud}$ from neutron beta decay

- Neutron decay inputs

- $\lambda = g_A/g_V$  from measurement; lattice calcs are %-level
- Decay lifetime
- Decay correlations

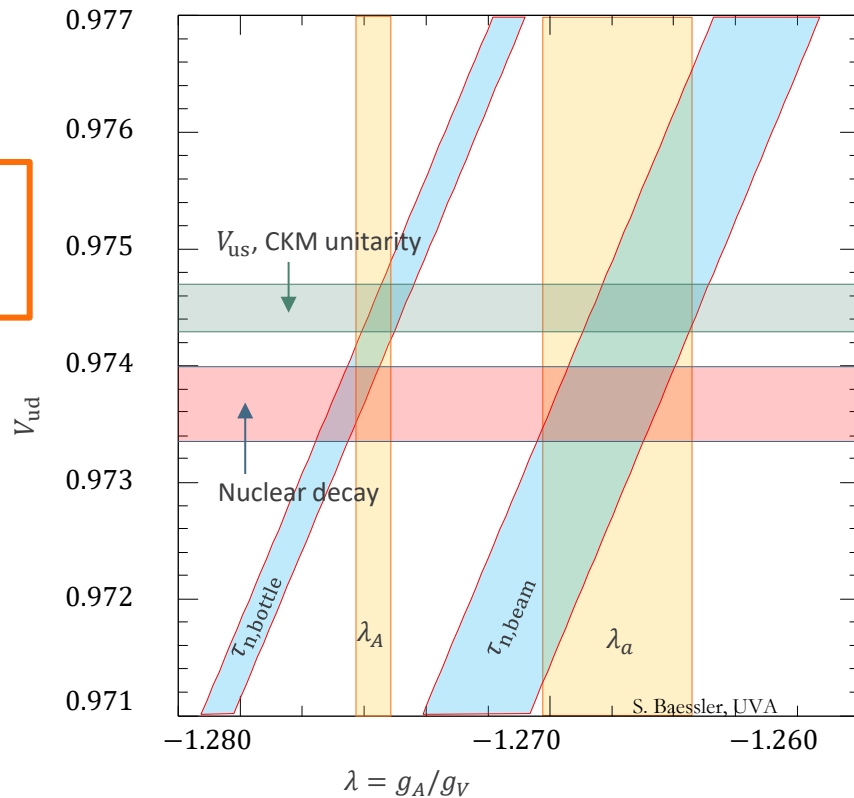
Approximate targets\*

- $\tau_n < 0.3$  s
- $\lambda < 0.03\%$

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

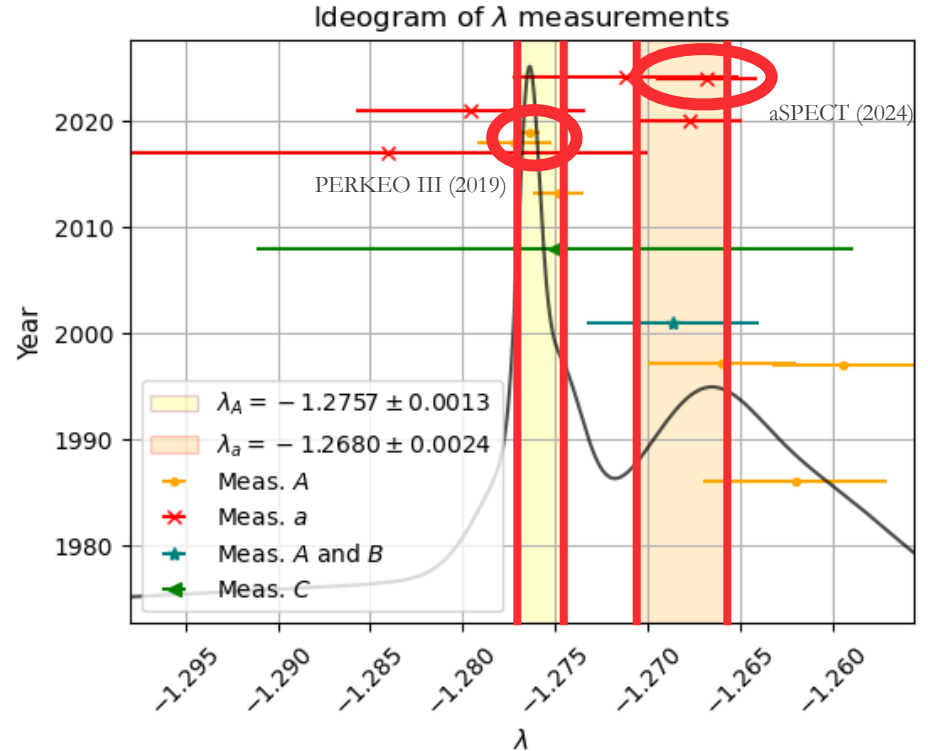
$$V_{ud} = 0.97441(28)\tau_n(82)\lambda(13)\Delta_R^V \quad (\sim 0.1\%)$$

- Tension between different methods of determining  $\tau_n$ ,  $\lambda$



# Current landscape in decay correlations

- Tension in  $\lambda$  measurements
- Most precise determinations of  $\lambda$  from **A** (PERKEO III) and **a** (aSPECT) are not compatible!
  - Disagreement at level of  $3\sigma$

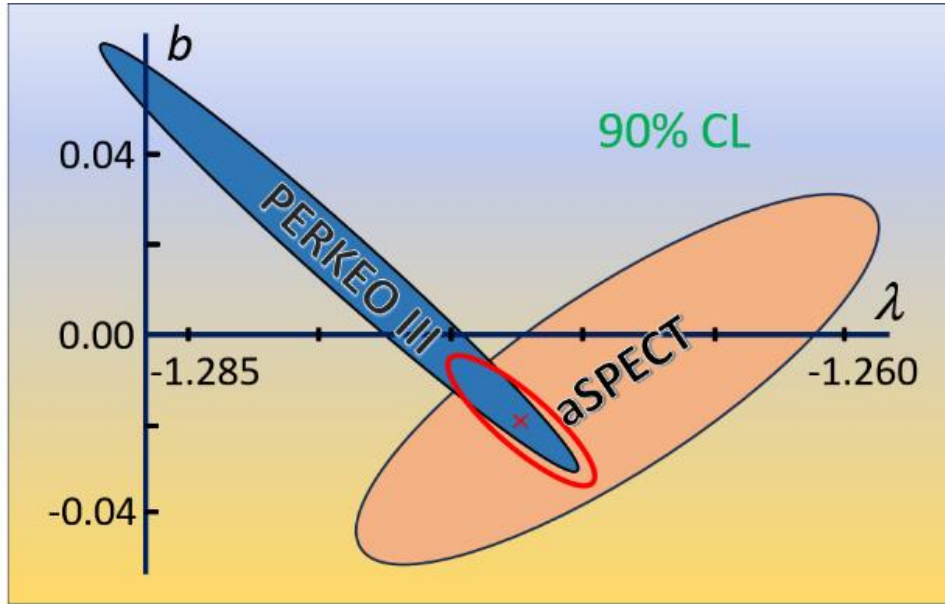


Courtesy of L. Broussard

Plot from: F. Gonzalez (ORNL) Data from:  
[Workman, R. L. et al, Particle Data Group \(2022\)](#)

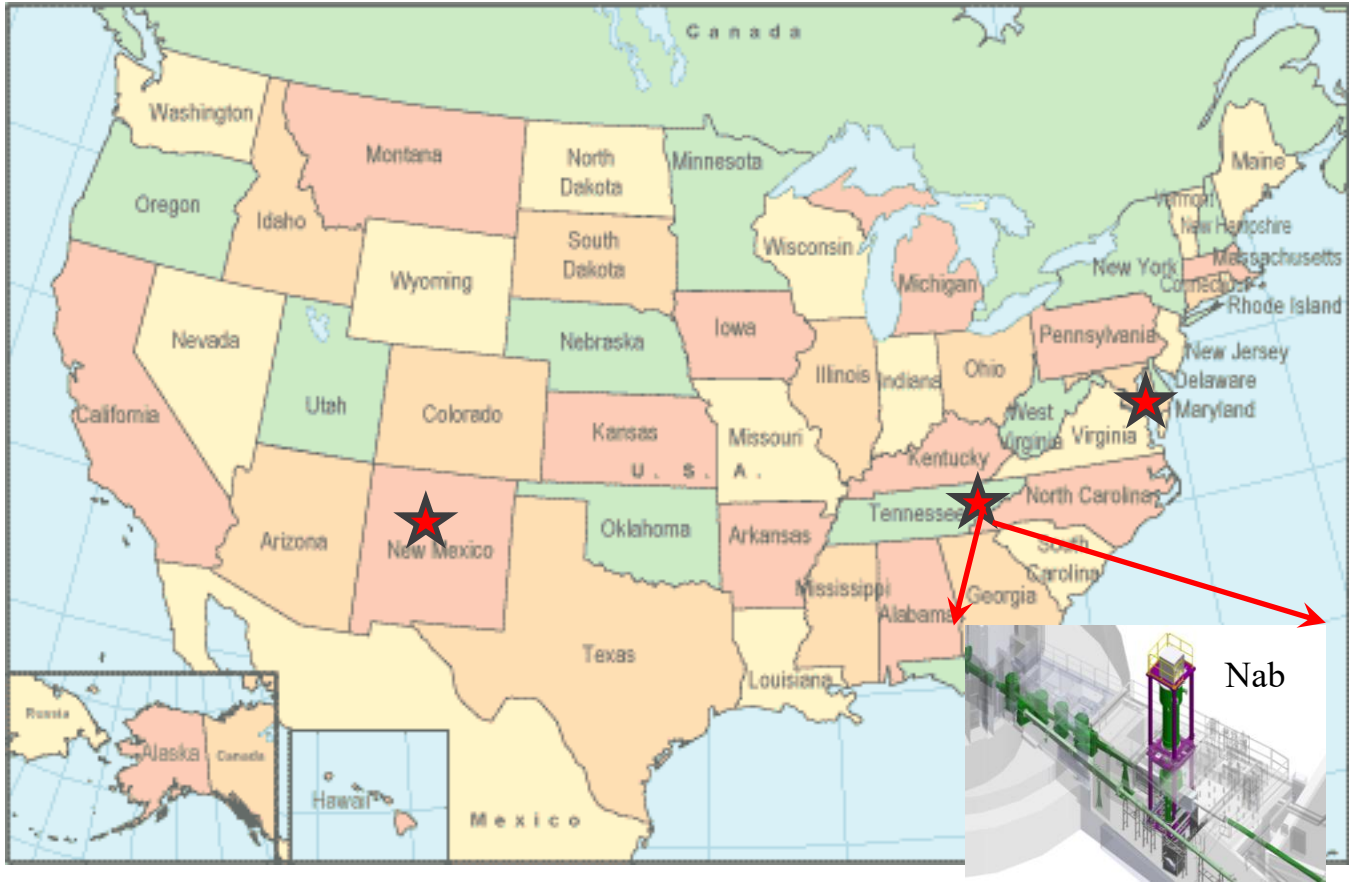
# Current landscape in decay correlations

- Tension in  $\lambda$  measurements
- Most precise determinations of  $\lambda$  from **A** (PERKEO III) and **a** (aSPECT) are not compatible!
  - Disagreement at level of  $3\sigma$
- Intriguing possibility: hint of influence of Fierz term **b**
- Combined analysis:
  - $\lambda_c = -1.2724(13)$
  - $b_c = -0.0184(65)$  ( $2.8\sigma$  from SM)
- New experiments are needed to illuminate situation



Plot from: F. Gonzalez (ORNL) Data from:  
[Workman, R. L. et al, Particle Data Group \(2022\)](#)

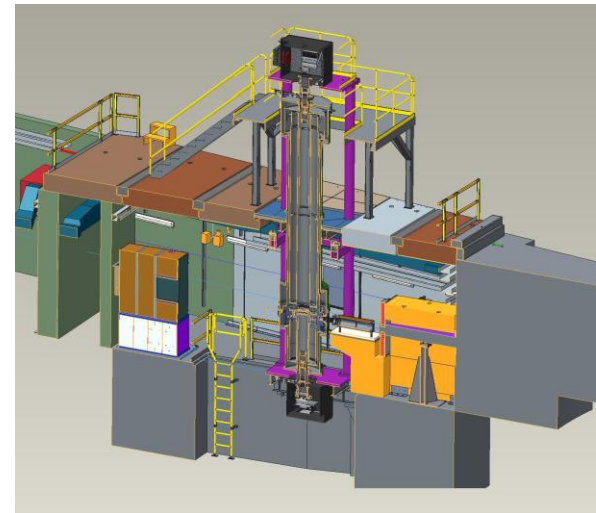
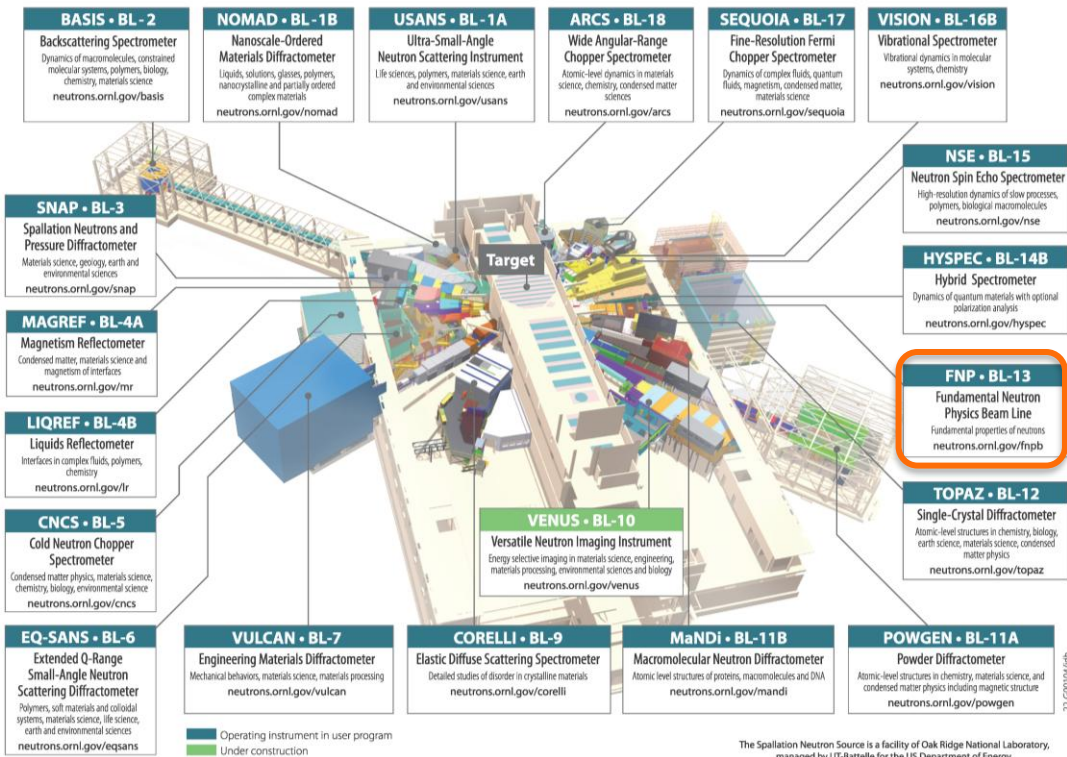
# The Nab Experiment



# Spallation Neutron Source at ORNL (1.8 MW)



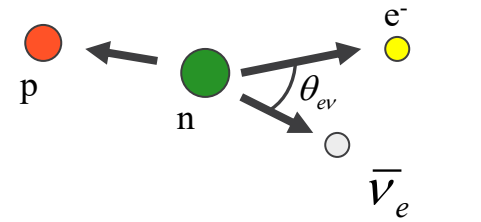
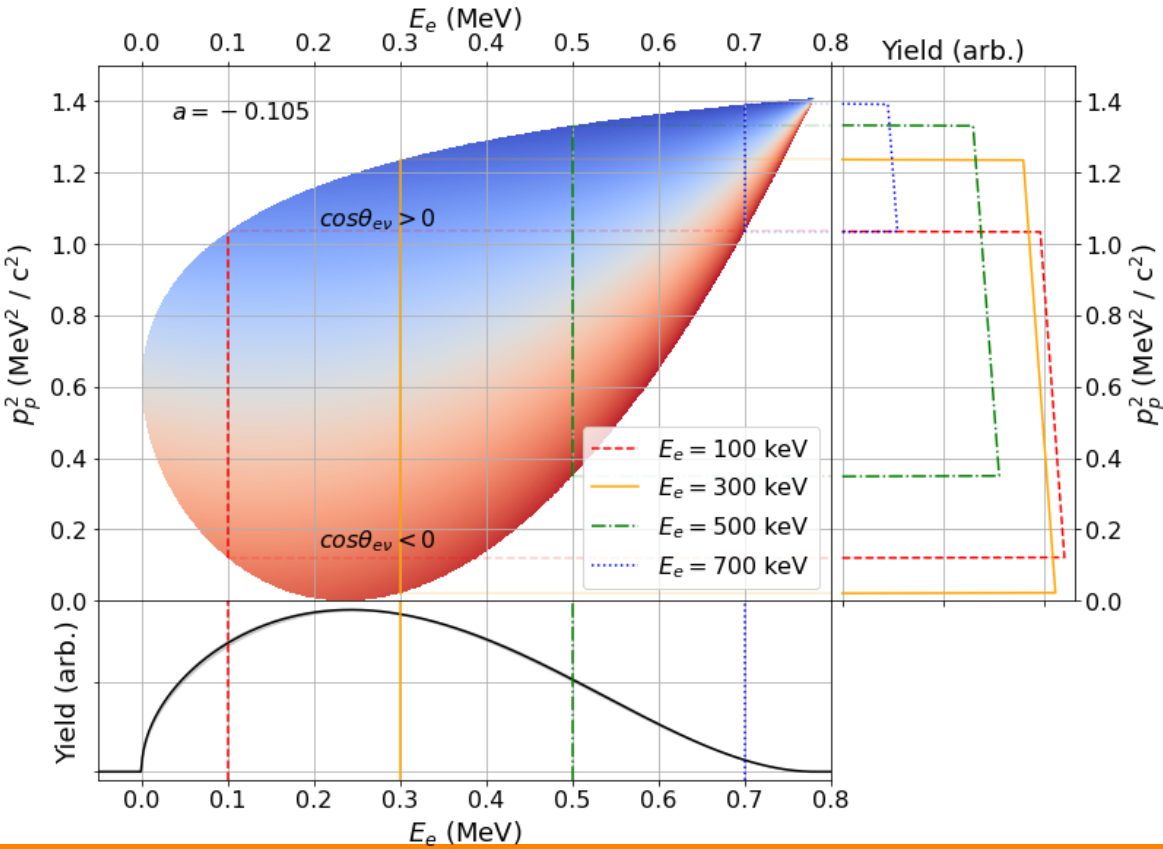
# Spallation Neutron Source at ORNL (1.8 MW)



The Spallation Neutron Source is a facility of Oak Ridge National Laboratory, managed by UT-Battelle for the US Department of Energy.

22-CO004M/gh

# Idea of the $\cos \theta_{ev}$ spectrometer Nab @ SNS



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

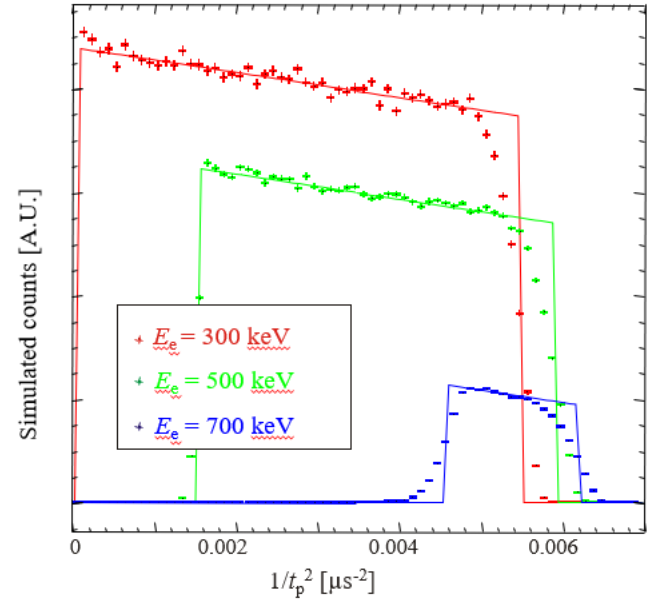
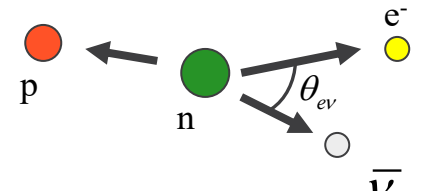
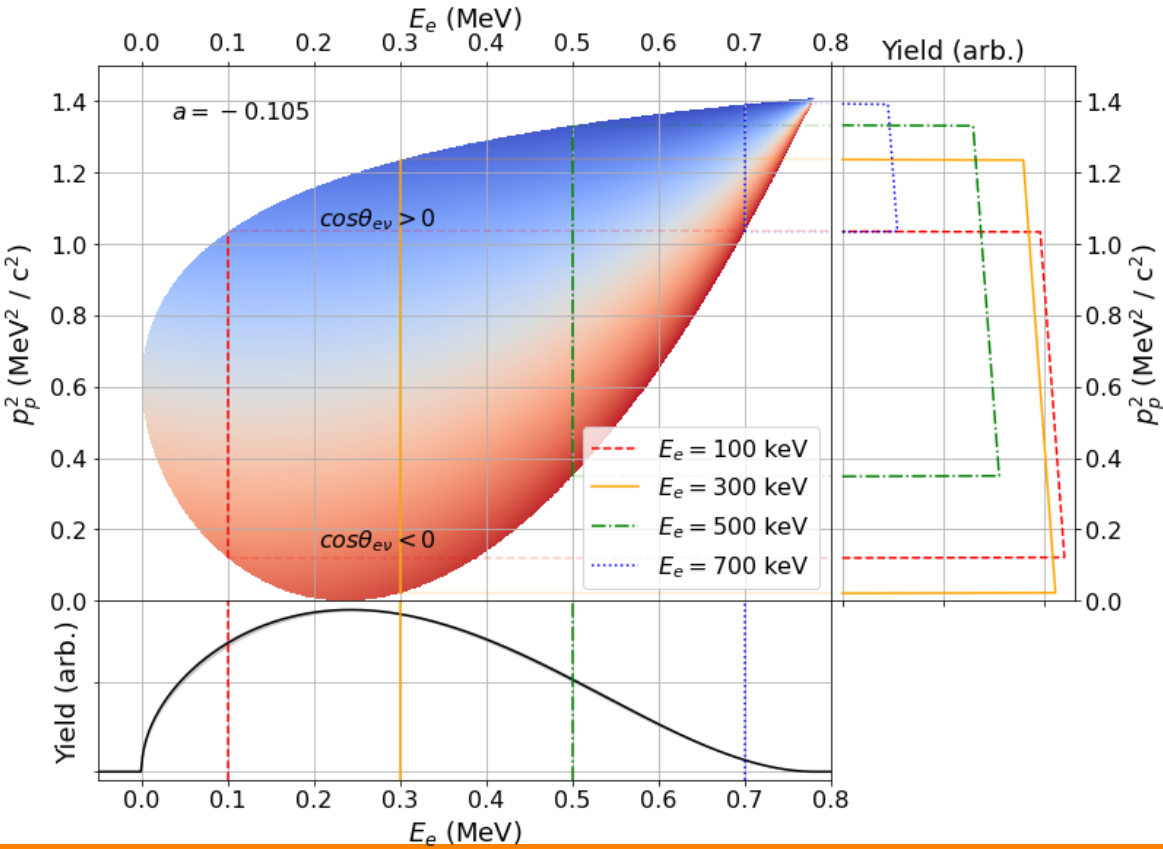
Edges:

$$(p_p^2)_{\min, \max} = (p_e \pm p_\nu)^2$$

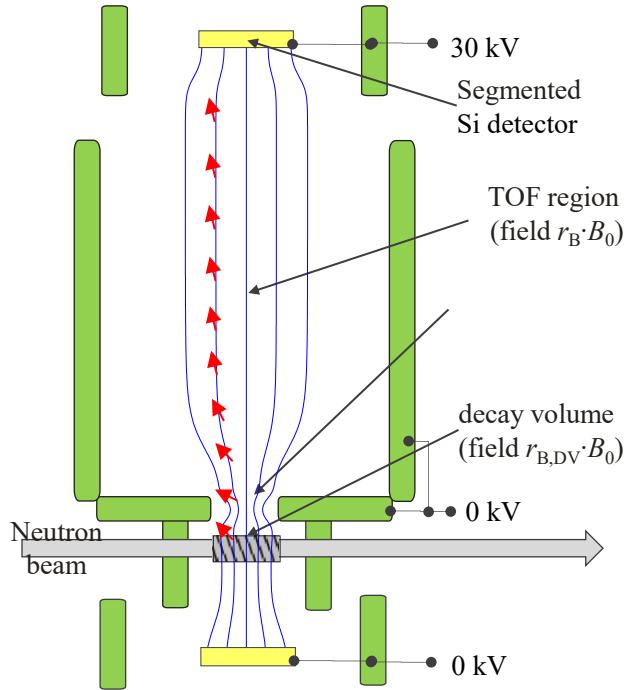
Slope:

$$\propto \left[ 1 + a \frac{p_e}{E_e} \cos \theta_{ev} (p_p^2) \right]$$

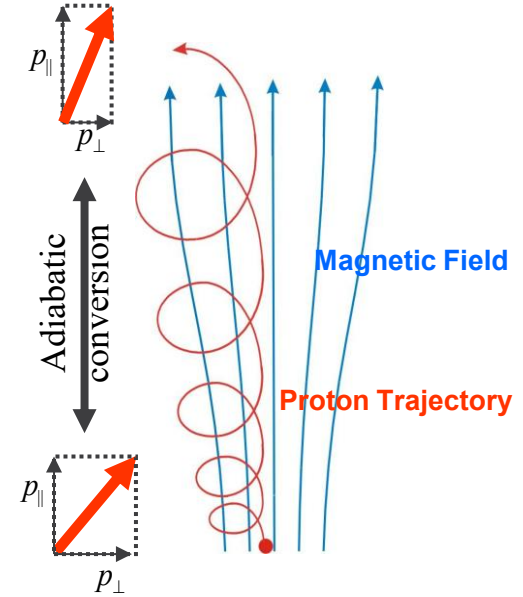
# Idea of the $\cos \theta_{ev}$ spectrometer Nab @ SNS



# Nab – first $\beta$ -decay experiment at the SNS



- Measure beta decay parameters  $a, b$ :  
 $\Delta a/a \approx 1e-3$   
 $\Delta b \approx 3e-3$
- Detect electron and proton from neutron beta decay
- Measure electron energy spectrum and proton TOF  $\rightarrow$  reconstruct decay kinematics
- Segmented Si detectors for decay particles



# Nab experiment

- Unique features
  - World's largest cryogen-free magnet [1]
  - Novel thick, large area silicon detector system [2]
  - Fast, powerful NI-based DAQ with flexible logic [3]
- Progress to date:
  - 2019 – Magnet mapping campaign [1]
  - 2021 – Experiment installation
  - 2022 – Beam polarization studies; magnet cooldown failure
  - 2023 – Commissioning campaign [4]
  - 2024 – Detector system upgrades
  - 2025 – Data-taking underway

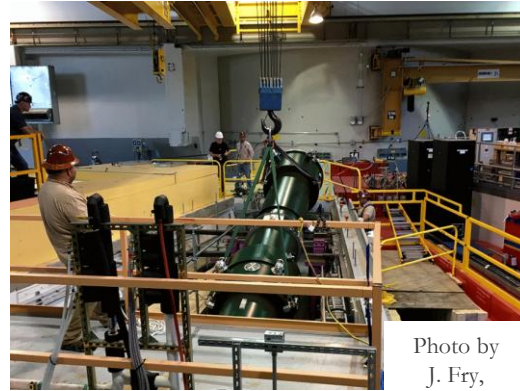
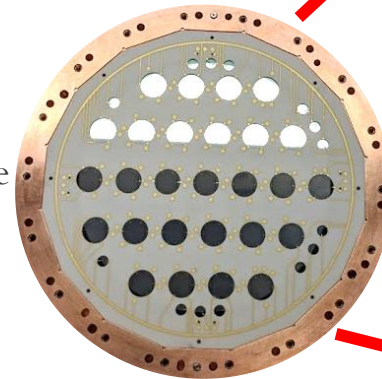
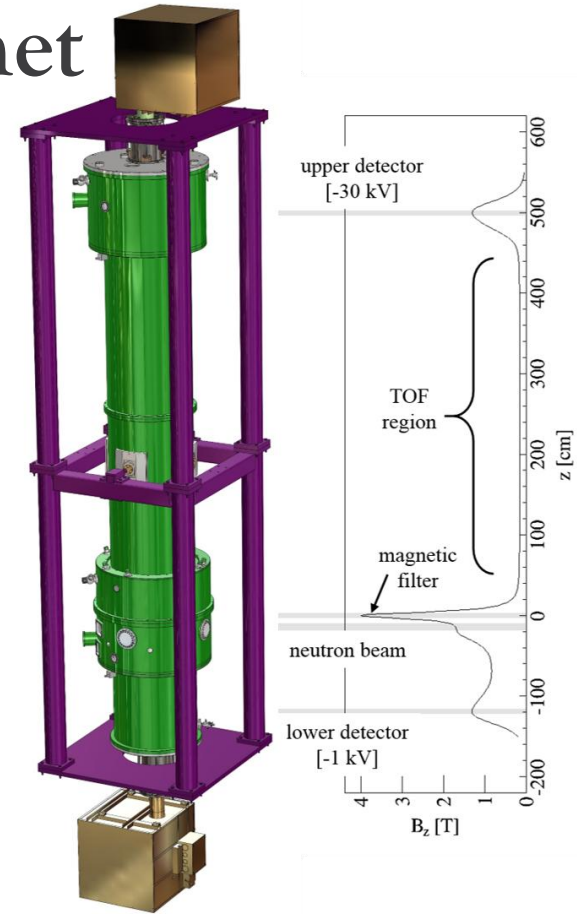
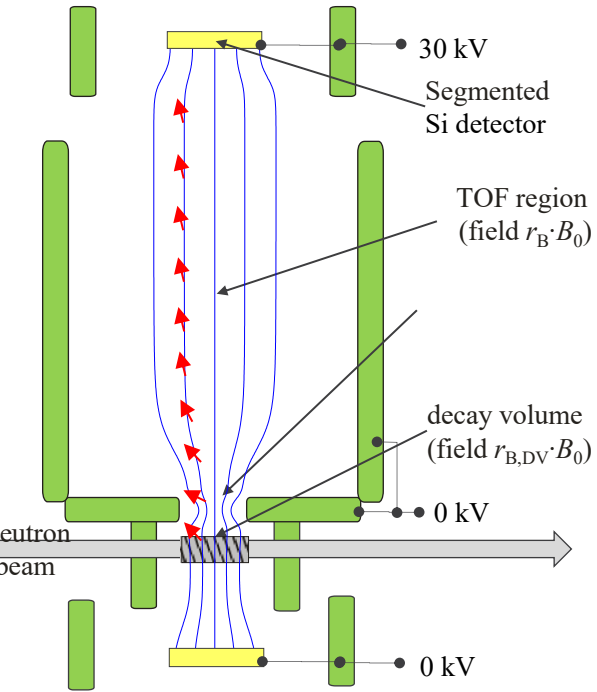


Photo by  
J. Fry,  
ECU



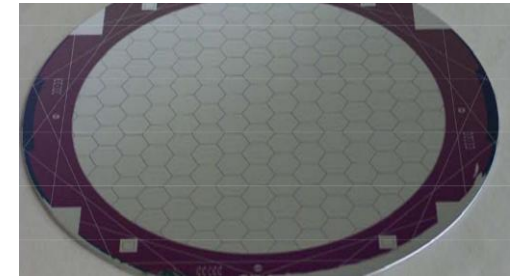
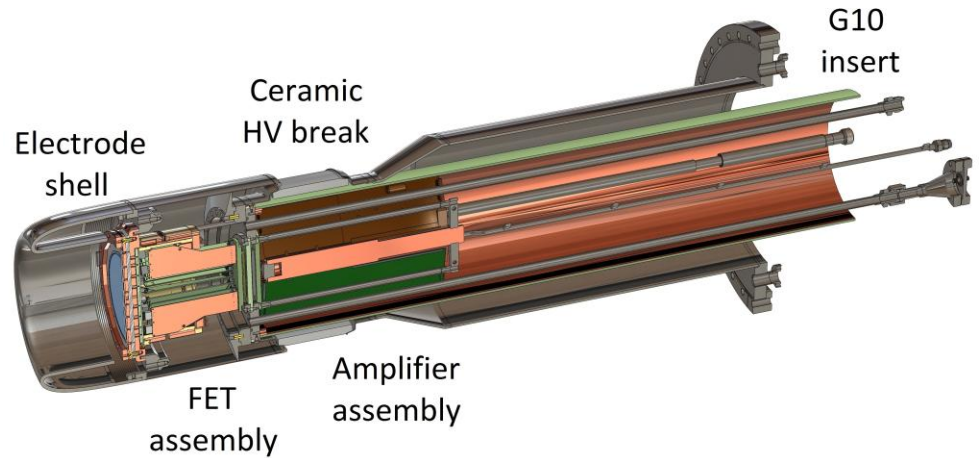
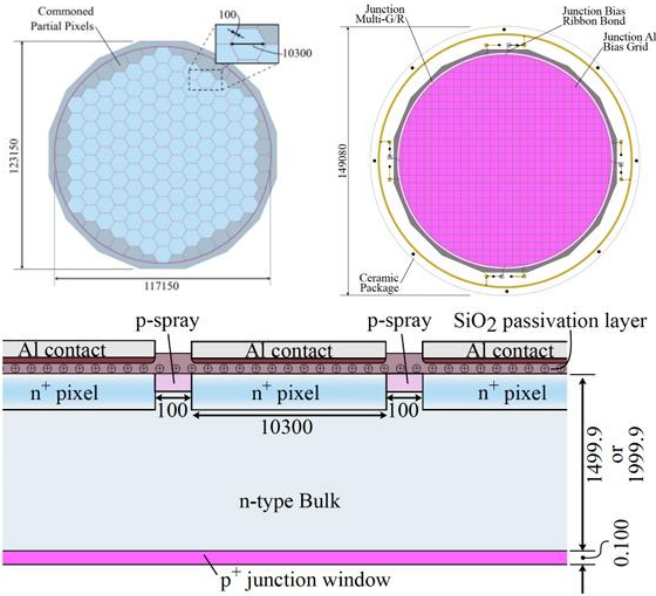
[1] EPJ Web Conf **219** 04002 (2019)  
[2] NIMA **735** (2014) 408; NIMA **849** (2017) 83; J. Phys: ConfSer. **876** 012005 (2017); PRC **107** (2023) 065503  
[3] NIMA **1071** (2025) 170079  
[4] EPJ Web Conf **303** (2024) 05001

# World's largest cryogen-free magnet



# Inside the Nab Detector System

- Silicon
- 1.5 or 2 mm thick
- 127 pixels



# First Full Dalitz Plot Measurement in Neutron $\beta$ -Decay using the Nab Spectrometer and Implications for New Physics

101 hours of production  
data taken in 2023

Francisco M. Gonzalez,<sup>1,\*</sup> Jin Ha Choi,<sup>2,3</sup> Himal Acharya,<sup>4</sup> Skylar Clymer,<sup>5</sup> Andrew Hagemeyer,<sup>6</sup> David G. Mathews,<sup>1,4</sup> August Mendelsohn,<sup>7</sup> Austin Nelsen,<sup>4</sup> Hitesh Rahangdale,<sup>8</sup> Love Richburg,<sup>8</sup> Ricardo Alarcon,<sup>5</sup> Ariella Atencio,<sup>9</sup> Stefan Baeßler,<sup>6,1</sup> Thomas Bailey,<sup>2,3</sup> Noah Birge,<sup>8</sup> Dennis Borissenko,<sup>6</sup> Michael Bowler,<sup>6</sup> Leah J. Broussard,<sup>1</sup> Albert T. Bryant,<sup>6</sup> Jimmy Caylor,<sup>8</sup> Tim Chupp,<sup>10</sup> Christopher Crawford,<sup>4</sup> R. Alston Croley,<sup>4</sup> Micah Cruz,<sup>8</sup> George Dodson,<sup>11</sup> Wenjiang Fan,<sup>6</sup> Deion Fellers,<sup>12</sup> Nadia Fomin,<sup>8</sup> Emil Frlež,<sup>6</sup> Matthew Frost,<sup>13</sup> Jason Fry,<sup>14</sup> Duncan Fuehne,<sup>15</sup> Michael T. Gericke,<sup>7</sup> Michelle Gervais,<sup>4</sup> Corey Gilbert,<sup>1</sup> Ferenc Glück,<sup>16</sup> Rebecca Godri,<sup>8</sup> Geoff L. Greene,<sup>8,1</sup> William Greene,<sup>8</sup> Josh Hamblen,<sup>17</sup> Paul Harmston,<sup>8,†</sup> Leendert Hayen,<sup>18,2</sup> Carter Hedinger,<sup>6</sup> Chelsea Hendrus,<sup>10</sup> Sean Hollander,<sup>1</sup> Kavish Imam,<sup>8</sup> Erik B. Iverson,<sup>13</sup> Aaron Jezghani,<sup>19</sup> Chenyang Jiang,<sup>13</sup> Huangxing Li,<sup>6</sup> Nick Macsai,<sup>7</sup> Mark Makela,<sup>20</sup> Russell Mammei,<sup>21</sup> Ricky Marshall,<sup>6</sup> Madelyn Martinez,<sup>5</sup> Mark McCrea,<sup>4</sup> Pat McGaughey,<sup>20</sup> Sean McGovern,<sup>6</sup> David McLaughlin,<sup>6</sup> Jacqueline Mirabal-Martinez,<sup>20</sup> Paul Mueller,<sup>1</sup> Andrew Mullins,<sup>4</sup> William Musk,<sup>6</sup> Jordan O’Kronley,<sup>8</sup> Seppo I. Penttilä,<sup>1</sup> D. Elliot Perryman,<sup>8,†</sup> Josh Pierce,<sup>22</sup> Jason A. Pioquinto,<sup>6</sup> Dinko Počanić,<sup>6</sup> Hunter Presley,<sup>8</sup> John Ramsey,<sup>1</sup> Glenn Randall,<sup>5</sup> Zachary Raney,<sup>6</sup> Jackson Ricketts,<sup>17</sup> Grant Riley,<sup>20,8</sup> Americo Salas-Bacci,<sup>6</sup> Sepehr Samiei,<sup>6</sup> Alexander Saunders,<sup>1</sup> Wolfgang Schreyer,<sup>1</sup> E. Mae Scott,<sup>8,§</sup> Thomas Shelton,<sup>4</sup> Aryaman Singh,<sup>6</sup> Alexander Smith,<sup>6</sup> Erick Smith,<sup>20</sup> Eric Stevens,<sup>6</sup> R. J. Taylor,<sup>2,2</sup> Leonard Tinius,<sup>6</sup> Isaiah Wallace,<sup>8</sup> Jonathan Wexler,<sup>2,3</sup> W. Scott Wilburn,<sup>20</sup> A. R. Young,<sup>2,3</sup> and B. Zeck<sup>2,3</sup>

(Nab Collaboration)

<sup>1</sup>Physics Division, Oak Ridge National Laboratory, Oak Ridge, TN 37831, USA

<sup>2</sup>Department of Physics, North Carolina State University, Raleigh, NC 27695, USA

<sup>3</sup>Triangle Universities Laboratory, Duke University, Durham, NC 27708, USA

<sup>4</sup>Department of Physics and Astronomy, University of Kentucky, Lexington, KY 40506, USA

<sup>5</sup>Department of Physics, Arizona State University, Tempe, AZ 85287, USA

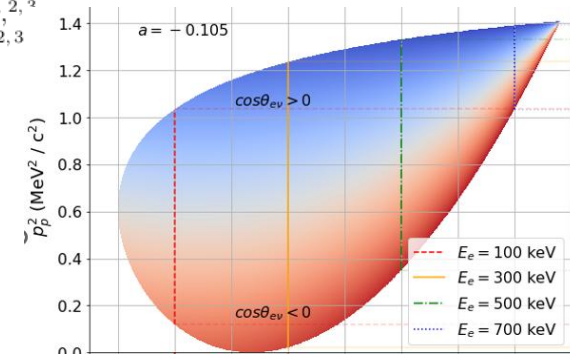
<sup>6</sup>Department of Physics, University of Virginia, Charlottesville, VA 22904, USA

<sup>7</sup>Department of Physics, University of Manitoba, Winnipeg, MB R3T 2N2, Canada

<sup>8</sup>Department of Physics and Astronomy, University of Tennessee, Knoxville, TN 37996, USA

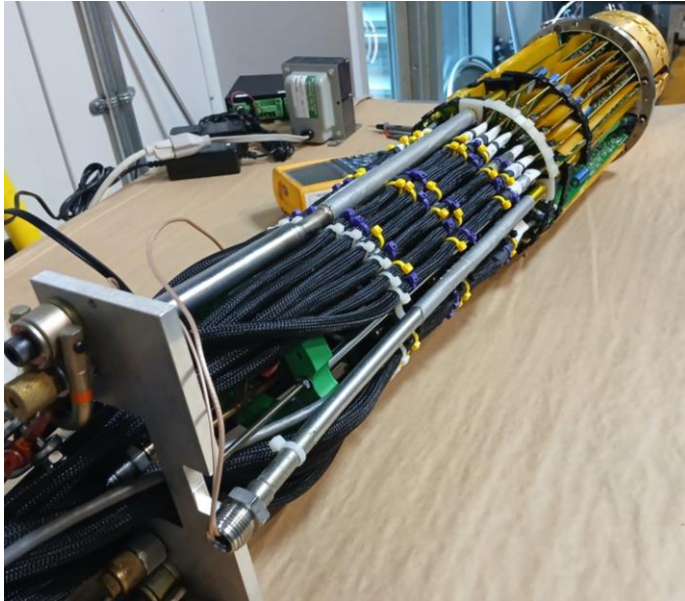
<sup>9</sup>Department of Physics, Drexel University, Philadelphia, PA 19104, USA

<sup>10</sup>Department of Physics, University of Michigan, Ann Arbor, MI 48109, USA



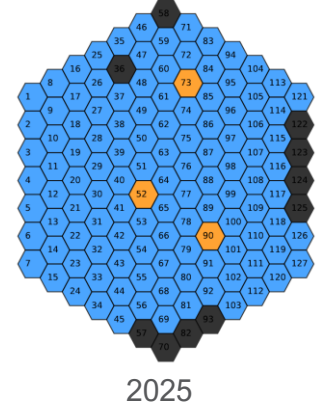
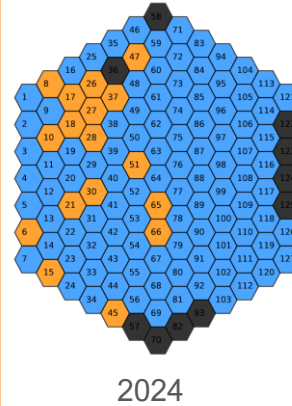
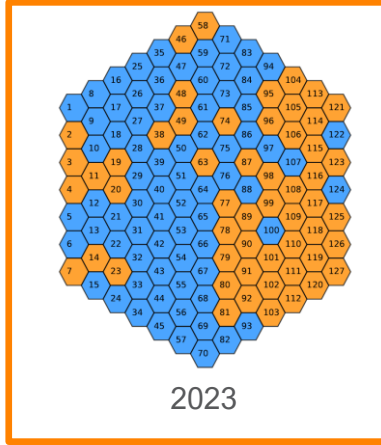
Phys.Rev.C 113 (2026) 3, 035501

# Detector Studies



Blue - Upper detector functional pixels

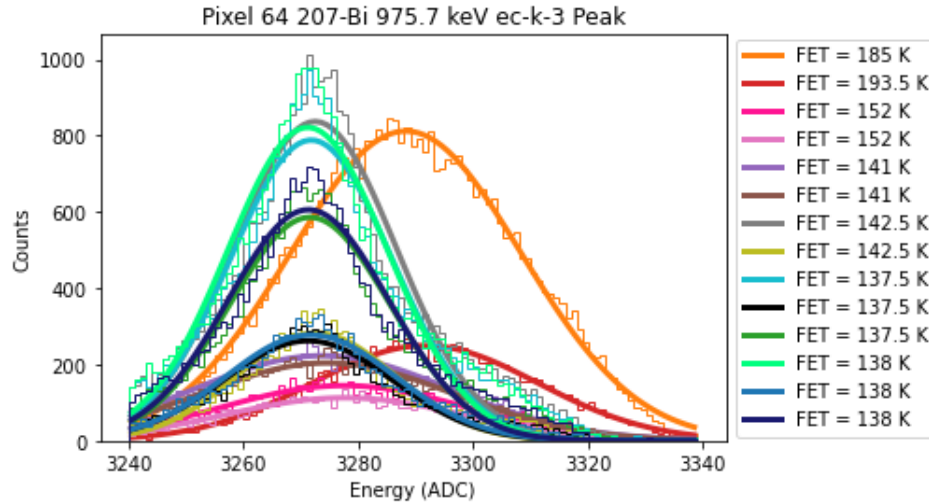
Courtesy of W. Schreyer



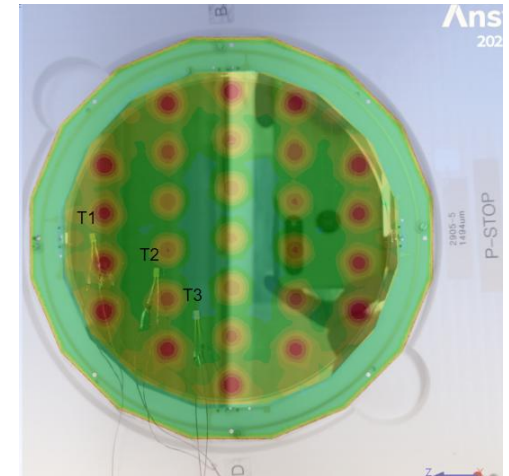
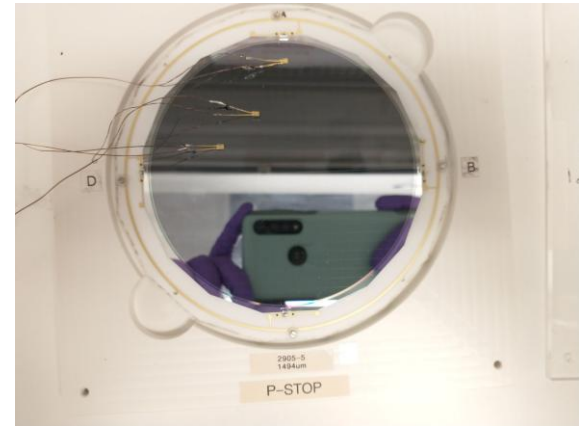
- Electronics
- Dead layer
- Temperature effects
- Detector efficiency
- Detector electric field profile



# Detector Temperature Studies



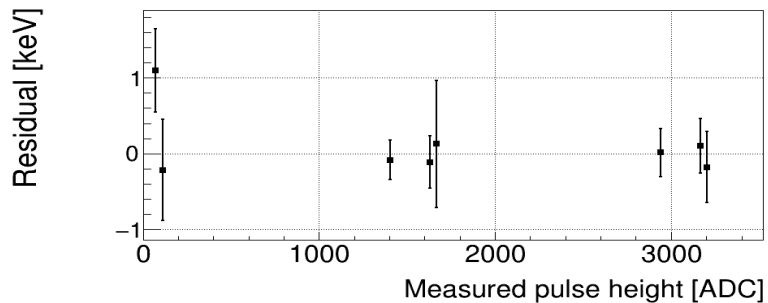
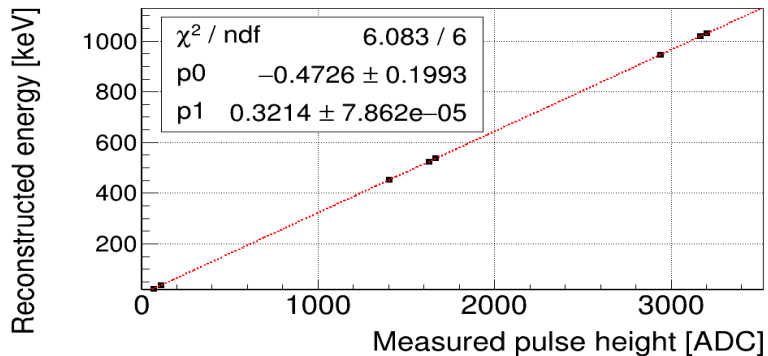
- Detector cooling system is capable of very stable ( $< 0.2$  K) temperature regulation
- Study gain variation with temperature
- Detector thermal profile measurements



<https://arxiv.org/abs/2601.05115> (in press at NIMA)

# Energy Calibration

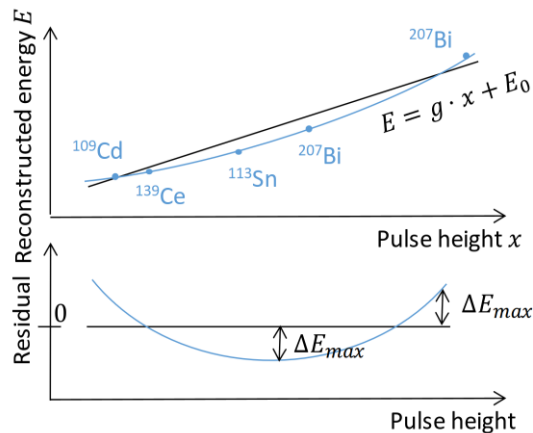
## Calibration of Pixel 48



$^{207}\text{Bi}$ ,  $^{113}\text{Sn}$ ,  $^{109}\text{Cd}$ ,  $^{148}\text{Gd}^*$

Specification for	$\Delta a = 3 \cdot 10^{-5}$ in Nab	$\Delta A = 3 \cdot 10^{-5}$ in pNAB
gain factor ( $\Delta g / g$ )	fit parameter	<b>0.18% ✓</b>
Offset $E_0$ ( $\Delta E_0$ )	<b>0.3 keV</b>	0.2 keV
nonlinearity ( $\Delta E_{\text{max}}$ )	<b>1.5 keV ✓</b>	0.3 keV
peak width ( $\Delta w$ )	<b>1 keV ✓</b>	<b>10 keV ✓</b>
tail amplitude ( $\Delta t$ of peak)	$10^{-4}$	0.024

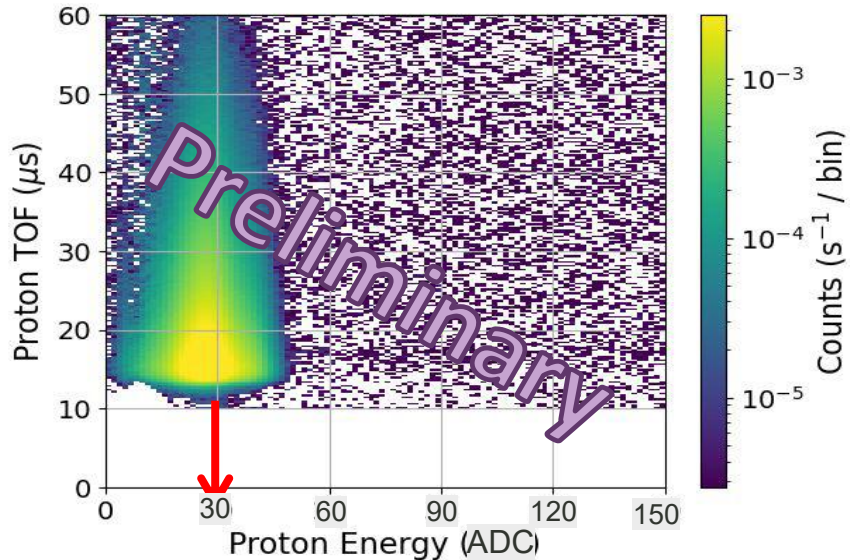
## Electron energy calibration:



# Summer 2023

First full phase space reconstruction of neutron  $\beta$  decay ( $E_e > 100$  keV)

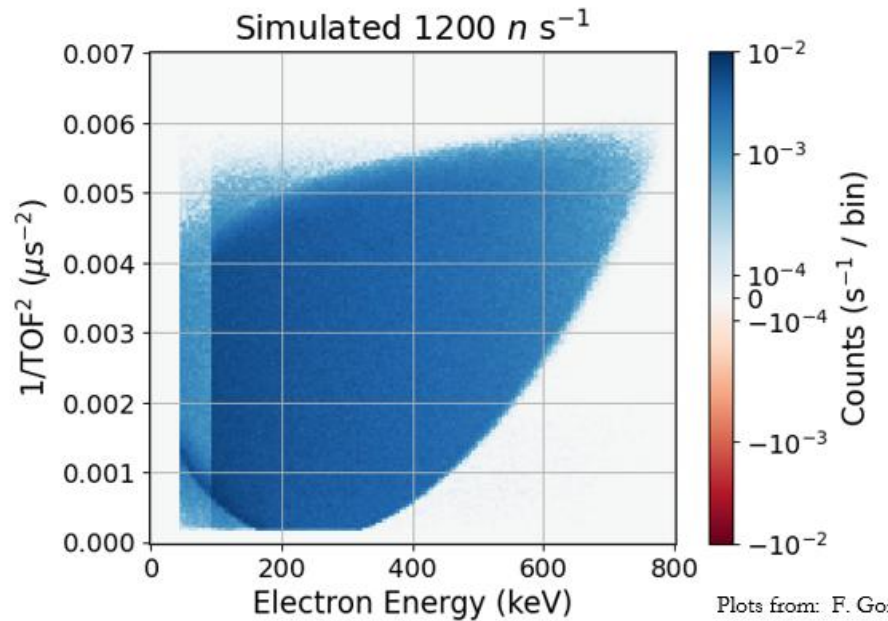
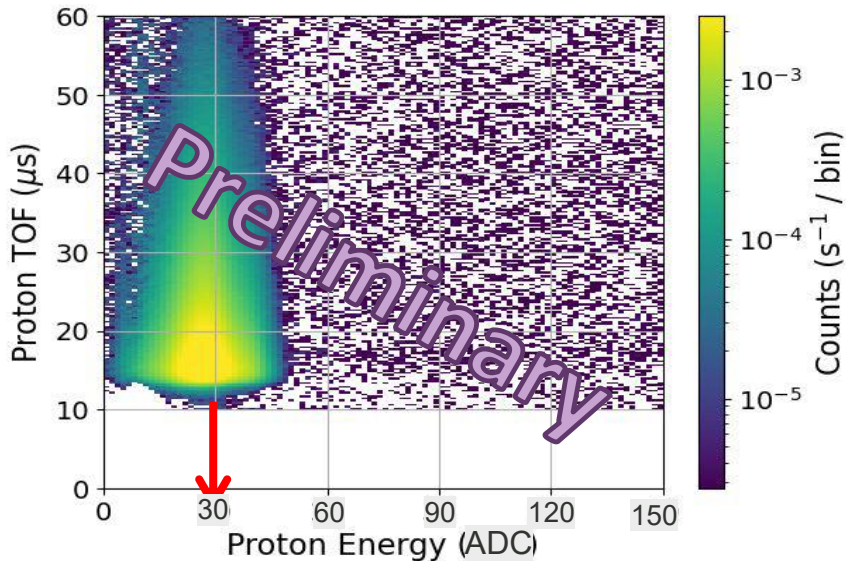
$1.6 \times 10^7$  events above background =  $(\Delta a/a)_{stat} \sim 1\%$  (final goal  $< 0.1\%$ )



- Successfully detected protons
- Identified electron-proton coincidences

# Summer 2023

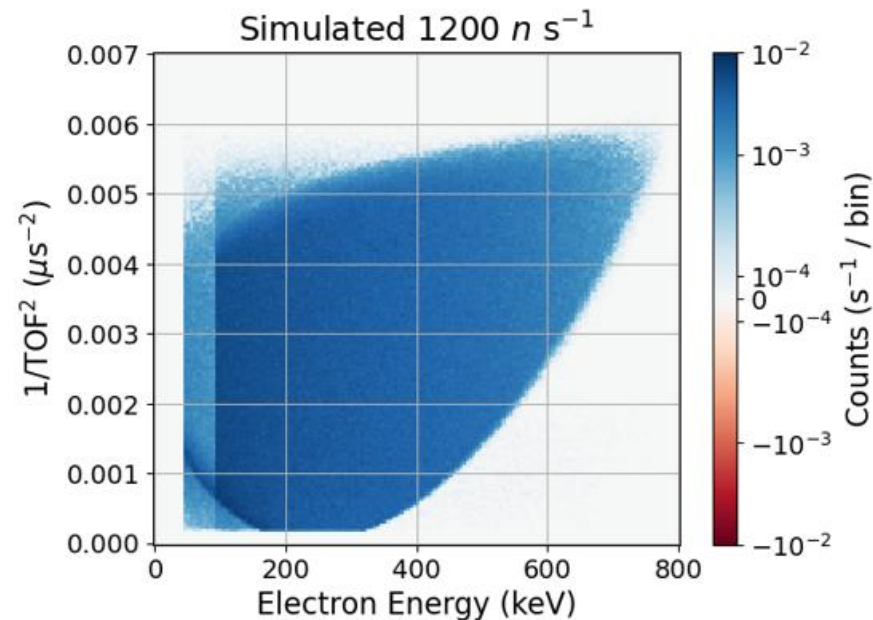
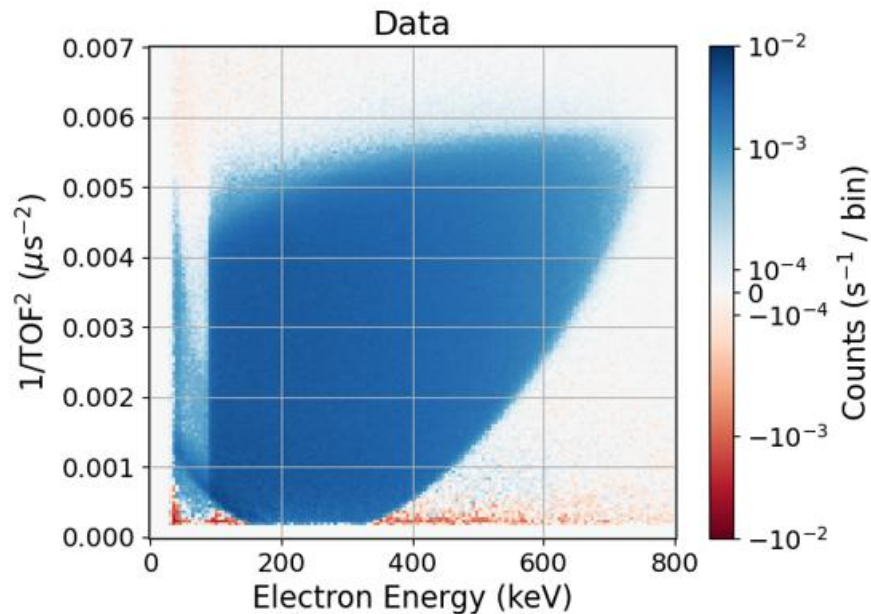
First full phase space reconstruction of neutron  $\beta$  decay ( $E_e > 100$  keV)  
1.6e7 events above background =  $(\Delta a/a)_{stat} \sim 1\%$  (final goal  $< 0.1\%$ )



# Summer 2023

First full phase space reconstruction of neutron  $\beta$  decay ( $E_e > 100$  keV)

$1.6 \times 10^7$  events above background =  $(\Delta a/a)_{stat} \sim 1\%$  (final goal  $< 0.1\%$ )

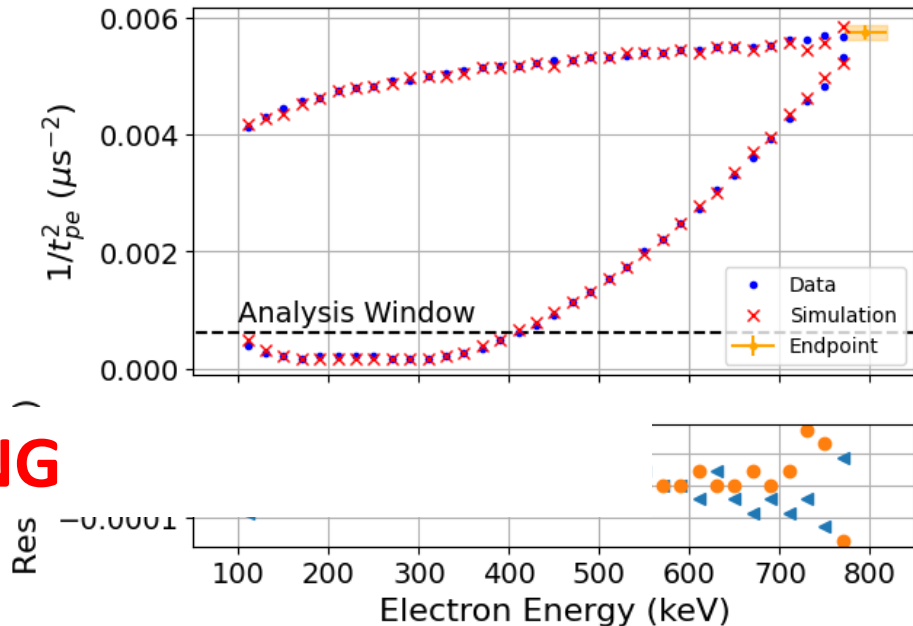
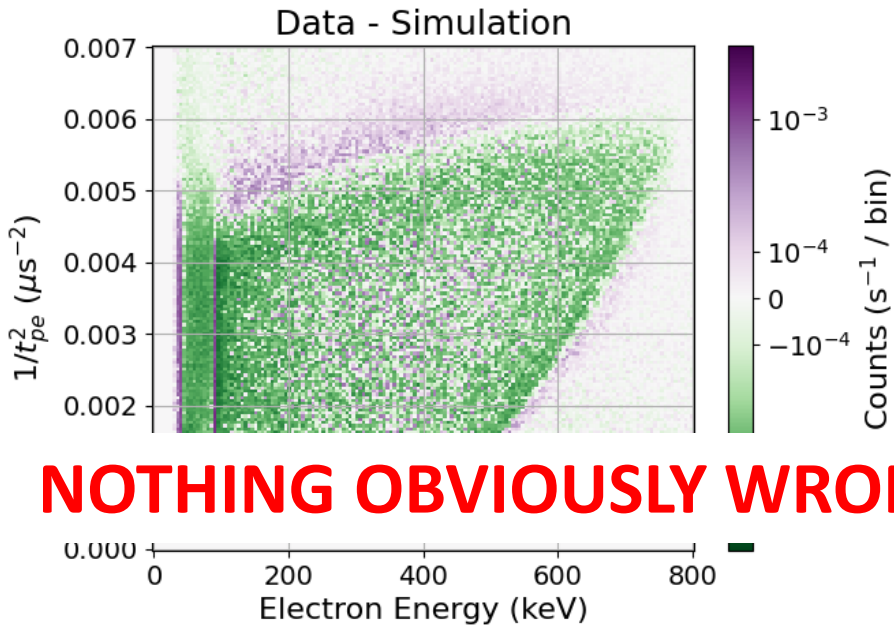


Plots courtesy of F. Gonzalez

# Summer 2023

First full phase space reconstruction of neutron  $\beta$  decay ( $E_e > 100$  keV)

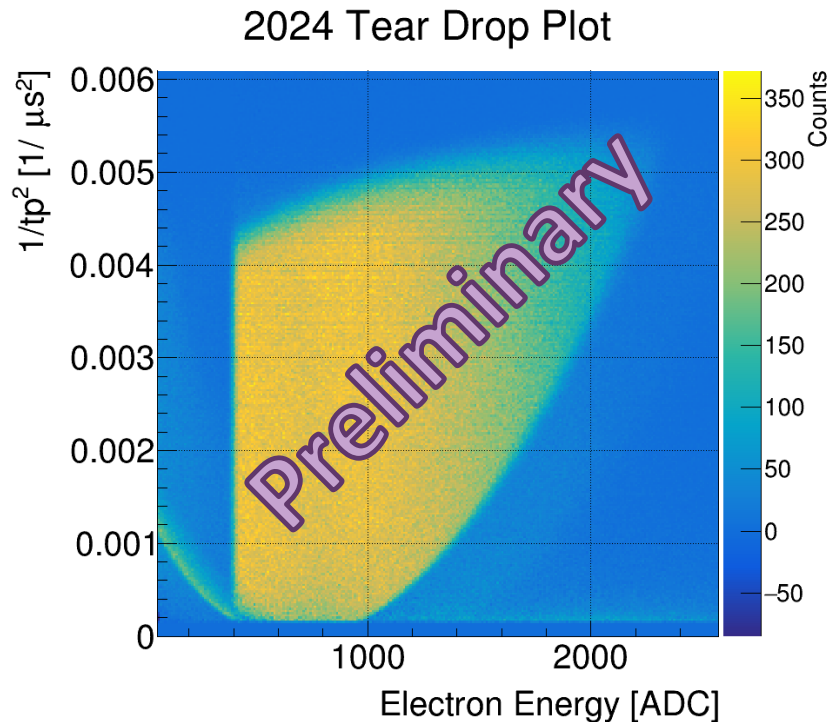
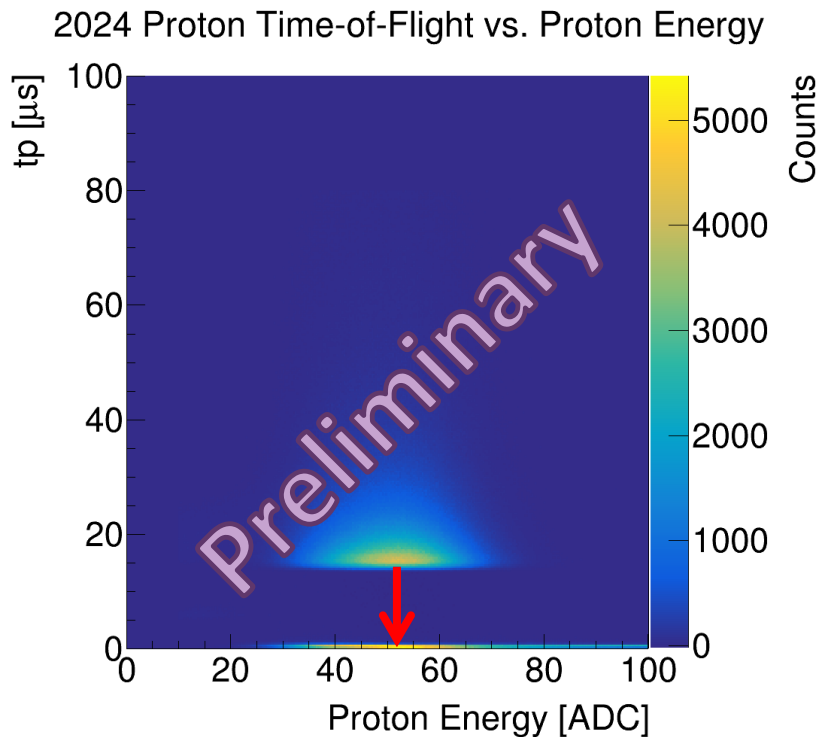
$1.6 \times 10^7$  events above background =  $(\Delta a/a)_{stat} \sim 1\%$  (final goal  $< 0.1\%$ )



**NOTHING OBVIOUSLY WRONG**

# Fall 2024/Spring 2025

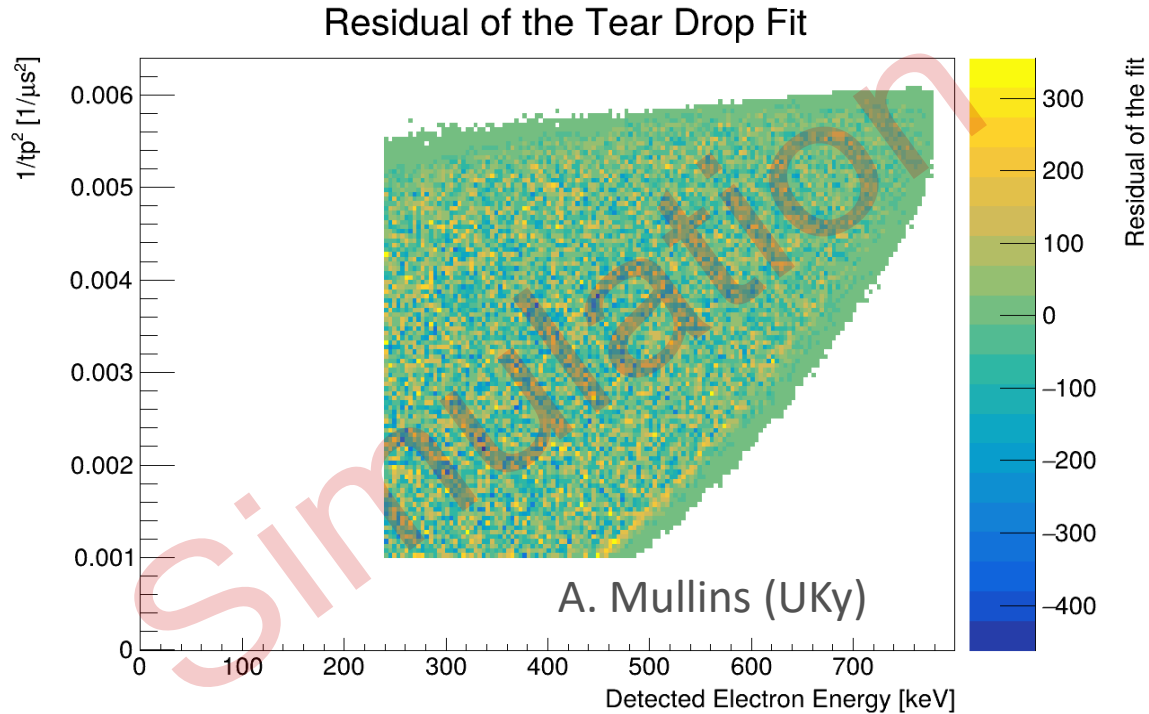
## Transitioning to Production Running



# Fitting Progress (simulated data)

$$a = -0.1032 \pm 0.0006$$

$$\chi^2_\nu = 11485/10502 = 1.094$$

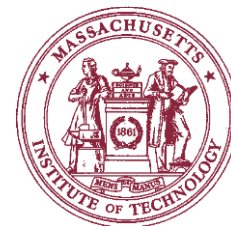




# The Nab Collaboration



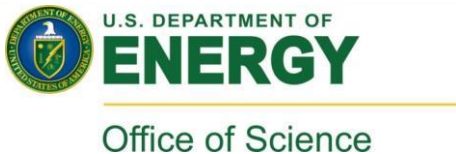
EASTERN KENTUCKY UNIVERSITY



Universität Karlsruhe (TH)  
Forschungsuniversität • gegründet 1825

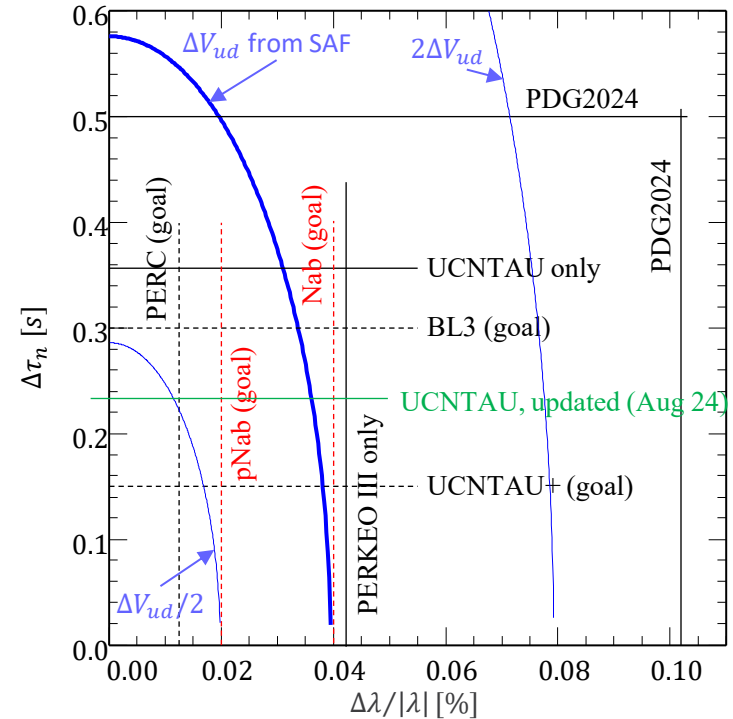
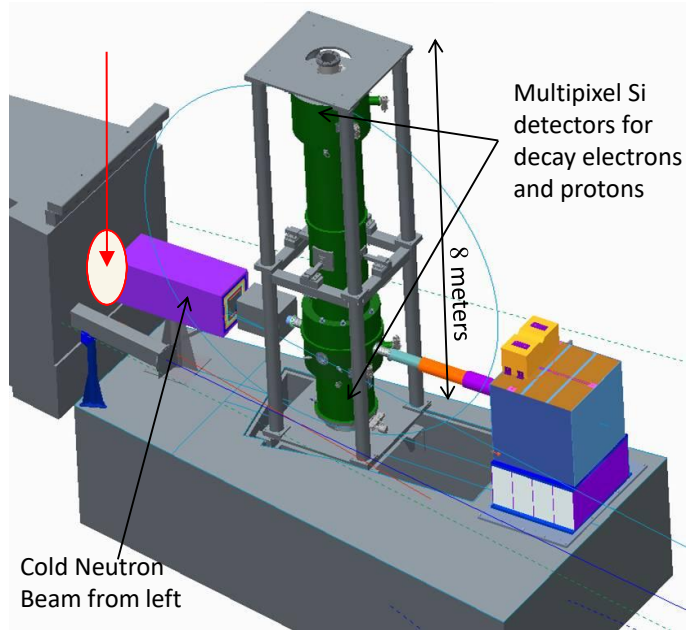


Main project funding:



# Nab and pNAB: $\lambda$ for CKM Unitarity test

With Nab and pNAB, we can measure both  $a$  and  $A$  correlation coefficients in the *same apparatus*.



# Thank you

# Backups