The Nab Experiment and Manitoba's proton source

RUSSELL MAMMEI (UNIVERSITY OF WINNIPEG)

INTERSECTIONS OF PARTICLE AND NUCLEAR PHYSICS

AUGUST 29-SEPTEMBER 4TH 2022

Thanks to postdoc Frank Gonzales (ORNL-SNS) for a set of slides to start from

Neutron Beta-Decay and V_{ud}

Neutron decay:

- $n \rightarrow p^{+} + e^{-} + \bar{\nu}_e$
- $|V_{ud}|^2 = \frac{5099.3\ \mathrm{s}}{\tau_n\ (1+3\ \lambda^2)(1+\Delta_R)}$

Experimentally Determine:

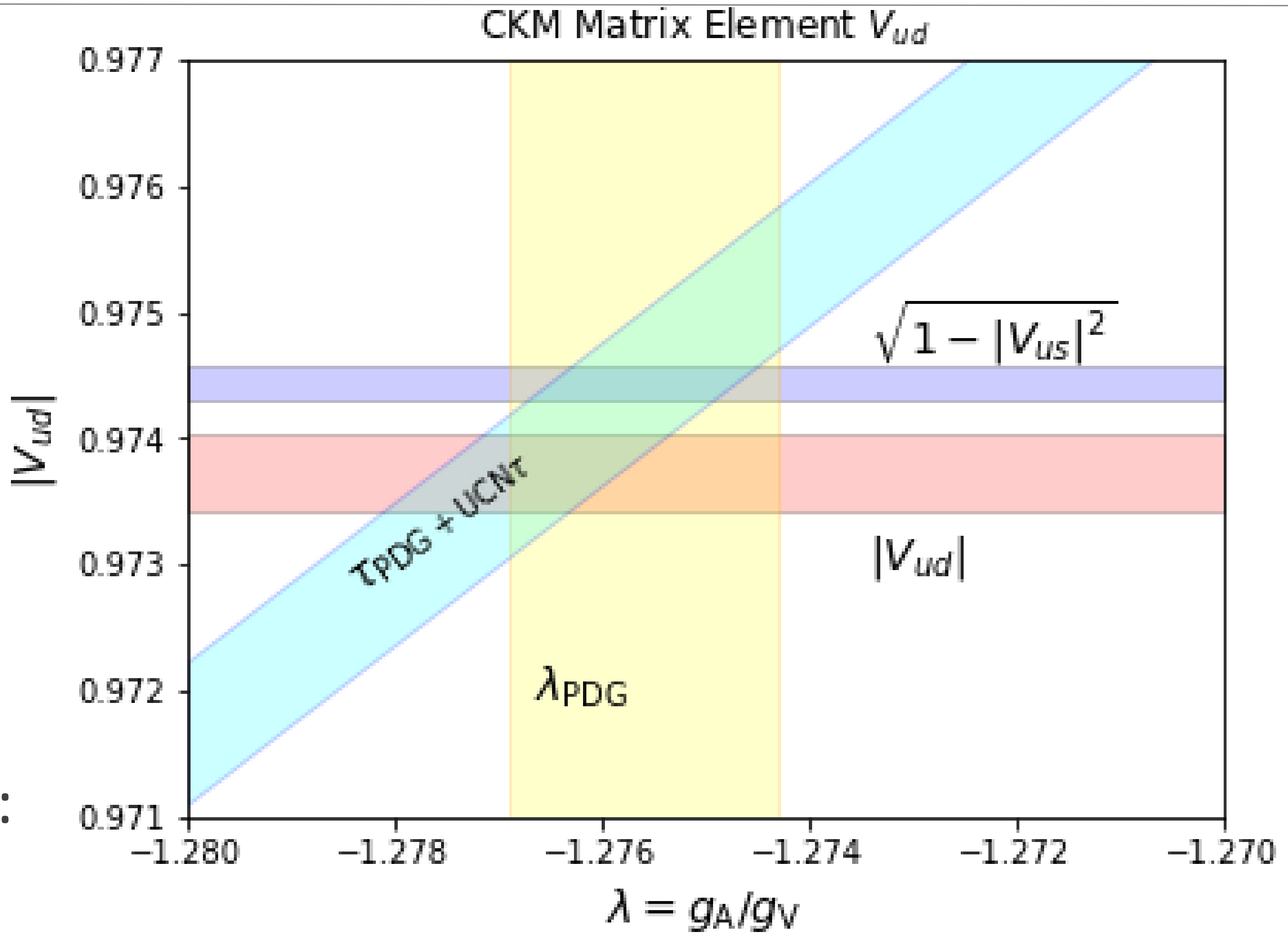
- τ_n: Neutron Lifetime
- $\lambda = \frac{g_A}{g_V}$: Ratio of coupling constants

Theoretically determine:

- Inner radiative correction Δ_R
- No nuclear structure corrections!

To compete with other measurements:

- $\frac{\Delta\tau}{\tau} < 3 \times 10^{-4}$ (or $\Delta\tau < 0.3$ s)
- $\frac{\Delta\lambda}{\lambda} < 1 \times 10^{-3}$ (or $\Delta\lambda < 1 \times 10^{-3}$)



Zyla et. al Particle Data Group (2020)
F. Gonzalez et al, Physical Review Letters 127, 162501 (2021)

Alphabet Soup: How to get λ

Decay rate of the neutron is proportional to:

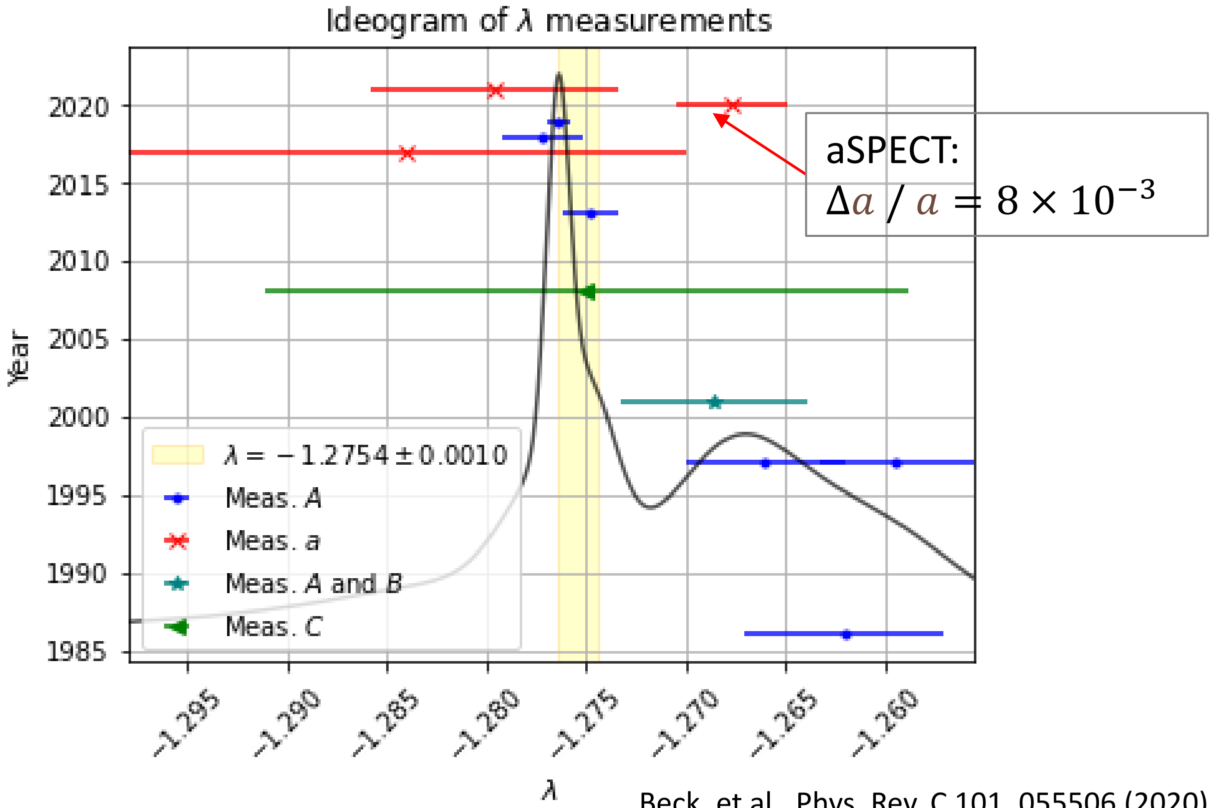
$$\frac{d\Gamma^3}{dE_e d\Omega_e d\Omega_\nu} \sim p_e E_e E_\nu^2 (1+3\lambda^2)\left[1 + b\frac{m_e}{E_e} + a\frac{\vec{p_e}\cdot\vec{p_\nu}}{E_e E_\nu} + \langle\vec{\sigma_n}\rangle \cdot \left(A\frac{\vec{p_e}}{E_e} + B\frac{\vec{p_\nu}}{E_\nu}\right) + \cdots\right]$$

At leading order, these correlation terms can be written:

- $a = \frac{1-\lambda^2}{1+3\lambda^2}$ $\qquad \frac{\partial a}{\partial \lambda} = \frac{-8\lambda}{(1+3\lambda^2)^2} \approx 0.30$
- $A = -2\frac{\lambda^2+\lambda}{1+3\lambda^2}$ $\qquad \frac{\partial A}{\partial \lambda} = 2\frac{(\lambda-1)(3\lambda+1)}{(1+3\lambda^2)^2} \approx 0.37$
- $B = 2\frac{\lambda^2-\lambda}{1+3\lambda^2}$ $\qquad \frac{\partial B}{\partial \lambda} = 2\frac{(\lambda+1)(3\lambda-1)}{(1+3\lambda^2)^2} \approx 0.076$

Fierz Interference term b couples to g_S, g_T

- Modify correlations: $X_{meas} = \frac{X}{1+b\frac{m_e}{E_e}}$
- Non-zero b is new physics!



Beck, et al., Phys. Rev. C 101, 055506 (2020)

Nab Goal: $\Delta a / a = 1.4 \times 10^{-3}$

Zyla et. al Particle Data Group (2020)
Hassan et al., Phys. Rev. C 103, 045502 (2021)

Kinematics of Unpolarized Neutron β-Decay

For unpolarized neutrons:

- $d\Gamma^3 \propto 1 + a\frac{|\vec{p_e}|\,|\vec{p_\nu}|}{E_e E_\nu}\cos(\theta_{e\nu}) + b\frac{m_e}{E_e}$

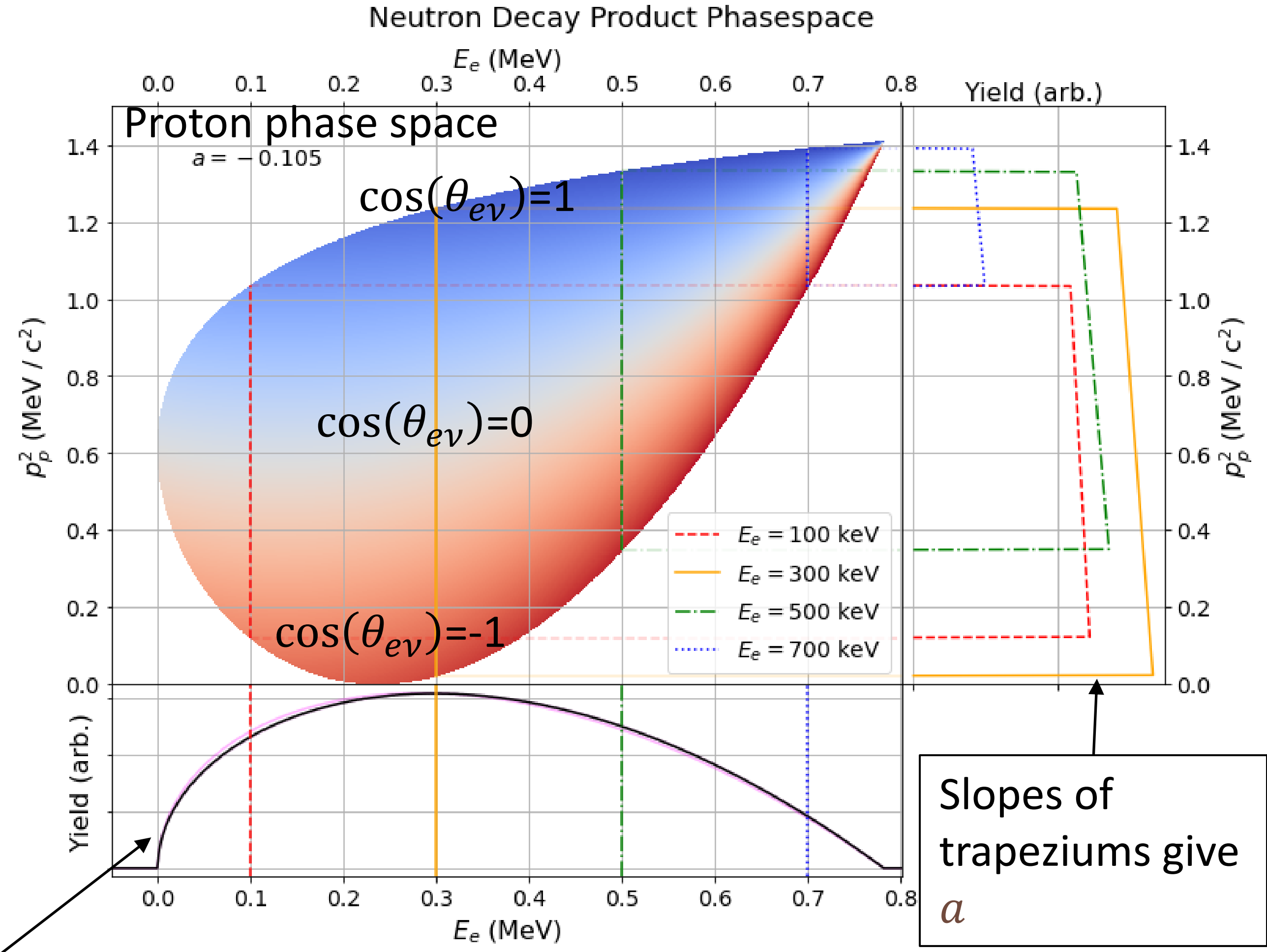
Relativistic kinematics:

- For $i \in \{n, p^+, e^-, \nu\}$, can relate $E_i^2 = \vec{p_i}^2 + m_i^2$
- Conservation of E: $E_\nu = E_n - (E_e + E_p)$
- Conservation of $\vec{p}$: $\cos(\theta_{e\nu}) = \frac{\vec{p_p}^2 - \vec{p_e}^2 - \vec{p_\nu}^2}{2|\vec{p_e}||\vec{p_\nu}|}$

After some algebra, find $d\Gamma^3(E_e, p_p^2)$

- If we can reconstruct E_e, p_p^2 for each decay, we can extract a, b…

We measure E_e directly. We get p_p from t_p(ToF between electron hit and proton hit)



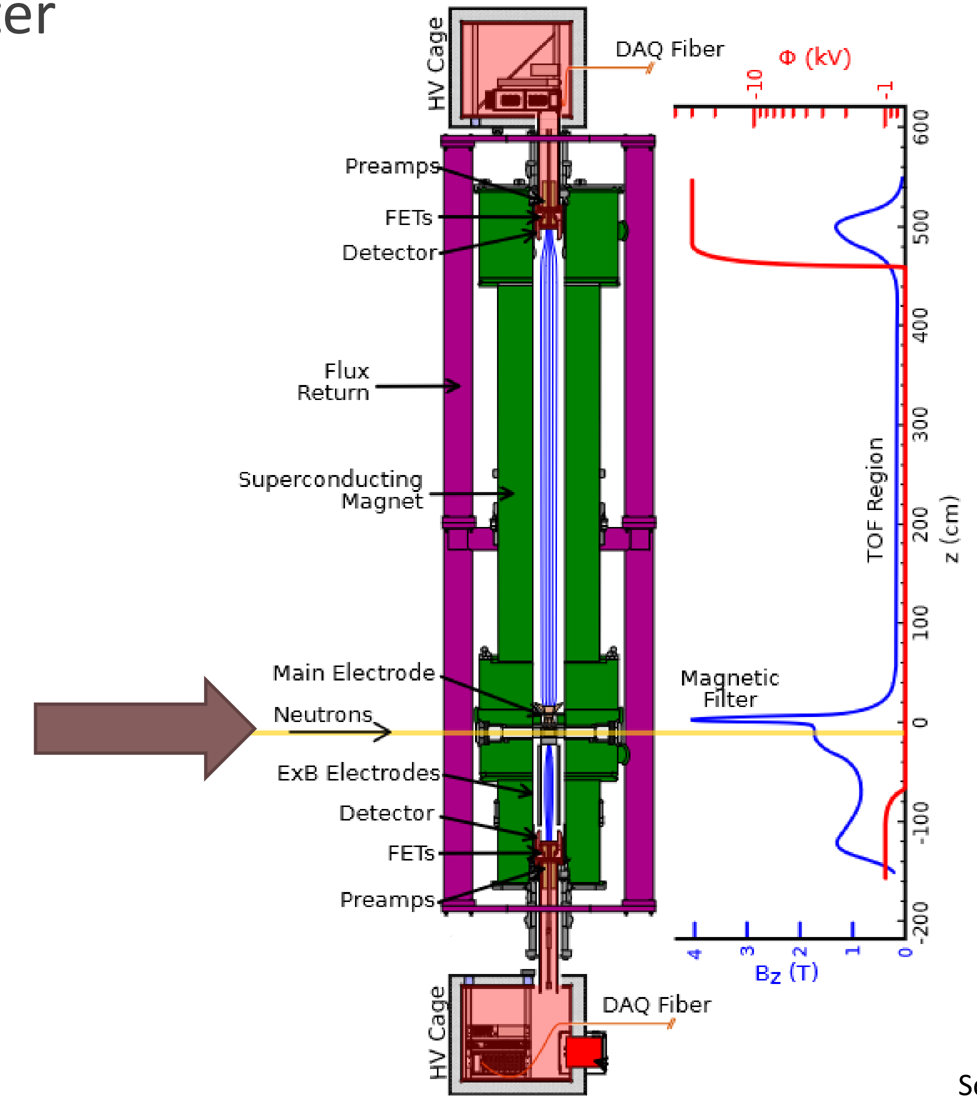
Shape of e^- spectrum gives b

Slopes of trapeziums give a

Reconstructing β-Decay Product Kinematics

Use an asymmetric (7m long) spectrometer

Beam of cold spallation neutrons



Schematic by A. Jezghani, UKY

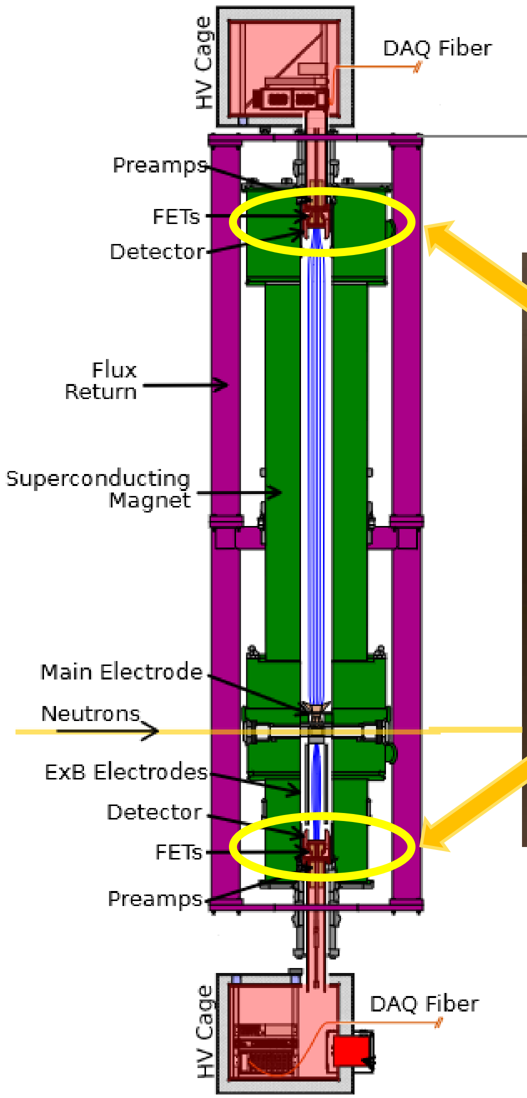
Reconstructing β-Decay Product Kinematics

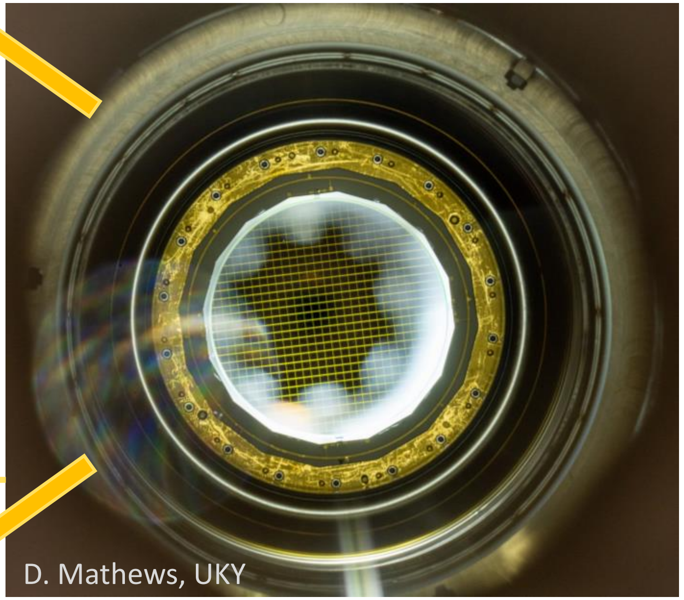
Use an asymmetric (7m long) spectrometer

Beam of cold spallation neutrons

Detect coincident p^+ and e^- at one of two silicon detectors

- E_e measured in detector
- $|\overrightarrow{p_p}|$ determined from proton time of flight





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Reconstructing β-Decay Product Kinematics

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Beam of cold spallation neutrons

Detect coincident p^+ and e^- at one of two silicon detectors

- E_e measured in detector
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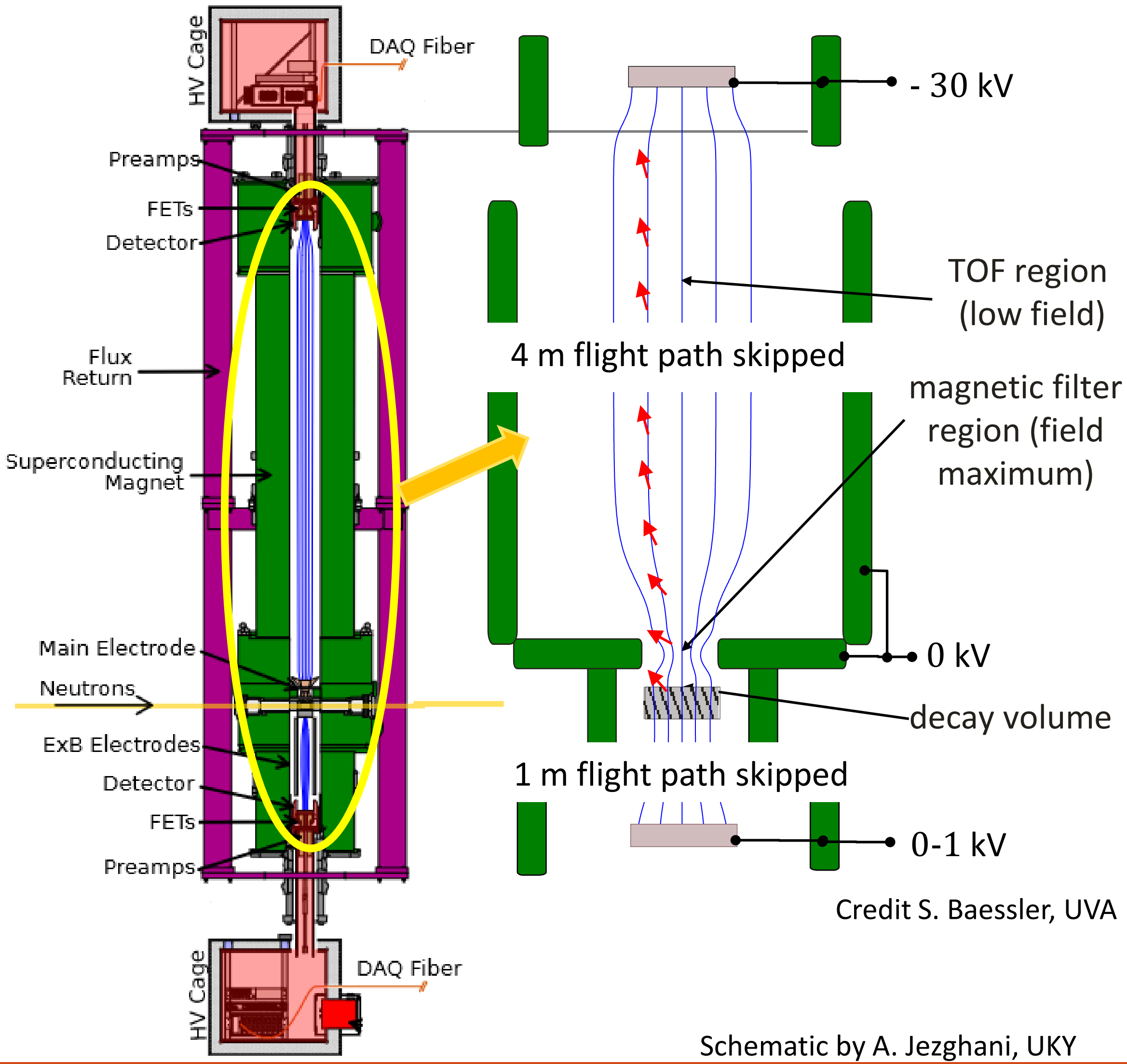
Magnetic fields guide decay products

- High-field decay region
- Low-field time of flight region longitudinalizes momentum

Detector at HV to accelerate protons past dead layer (can change which detector)



Schematic by A. Jezghani, UKY

Target Uncertainties for a and b

Leading uncertainties:

- Neutron Beam (only a)
- Magnetic Field (only a)
- **Detector Effects (both a and b)**

Goal precision:

- $\Delta a/a = \pm(1.4 \times 10^{-3})_{tot.}$
- $\Delta\lambda/\lambda = \pm(4.2 \times 10^{-4})_{tot.}$
- $\Delta b = \pm(2.2 \times 10^{-3})_{tot.}$

Not statistically limited!

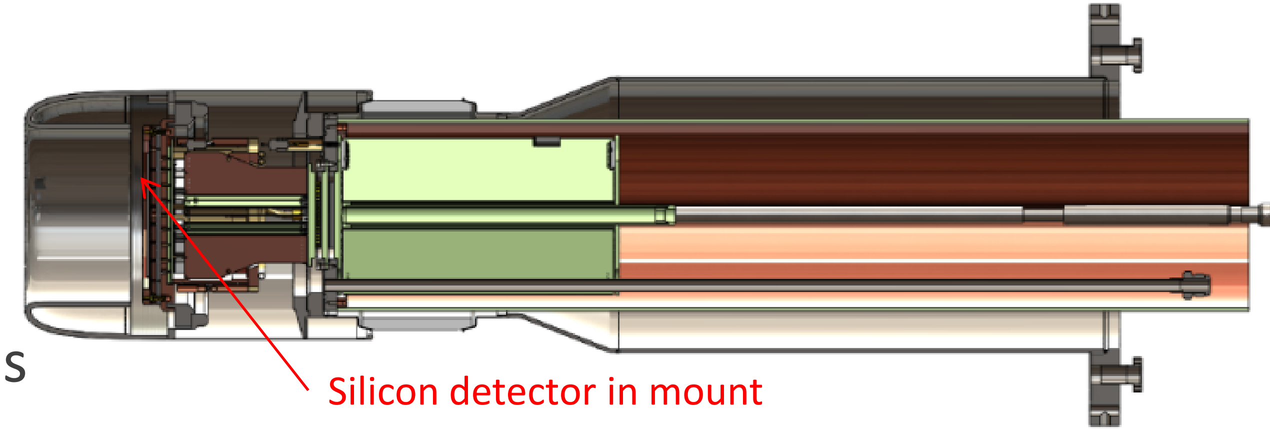
Experimental Parameter	$(\Delta a\ /\ a)_{sys.}$
Magnetic Field	6.0×10^{-4}
Electric Potential Inhomogeneity	5.5×10^{-4}
Neutron Beam	3.3×10^{-4}
Adiabaticity of Proton Motion	1×10^{-4}
Detector Effects	7.1×10^{-4}
Electron TOF	$< 1 \times 10^{-4}$
Residual Gas	3.8×10^{-4}
TOF in Acceleration Region	3×10^{-4}
Background/Accidental Coincidences	$< 1 \times 10^{-4}$
Length of the TOF Region	N/A
SUM	1.2×10^{-3}

Extracting E_e with Silicon Detectors

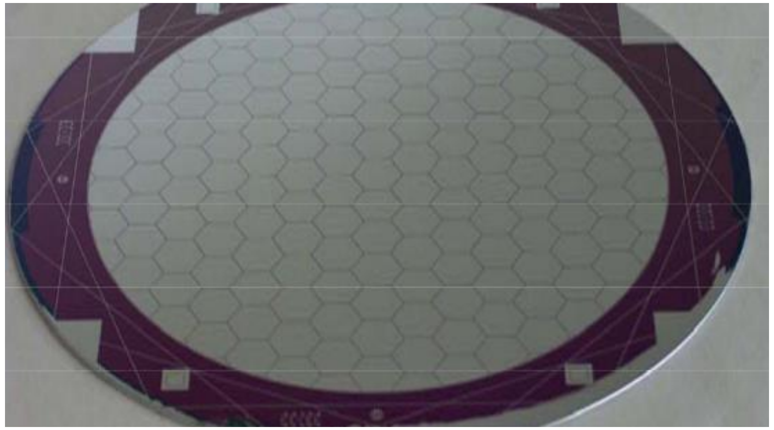
Segmented silicon detector

- produced by Micron Inc.
- 2 or 1.5mm thick with 11.5 cm diameter active area
- 127 hexagonal pixels read out individually
- Deadlayer ~ 100 nm

Float detector mount at -30 kV to see protons



Detector Effects	Target Uncertainty	$(\Delta a\ /\ a)_{sys.}$
Electron Energy Calibration	$\Delta E_e < 0.2$ keV	2×10^{-4}
Shape of Electron Energy Response	fraction of events in tail to 1%	4.4×10^{-4}
Proton Trigger Efficiency	$\epsilon_p < 100$ ppm / keV	3.4×10^{-4}
TOF Shift due to Detector/Electronics	$\Delta t_p < 0.3$ ns	3.9×10^{-4}
SUM		7.1×10^{-4}

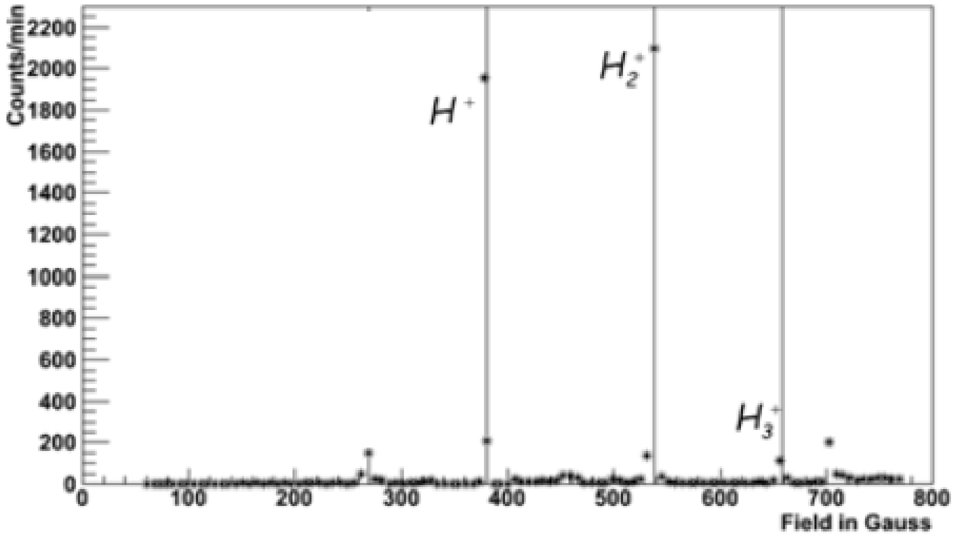


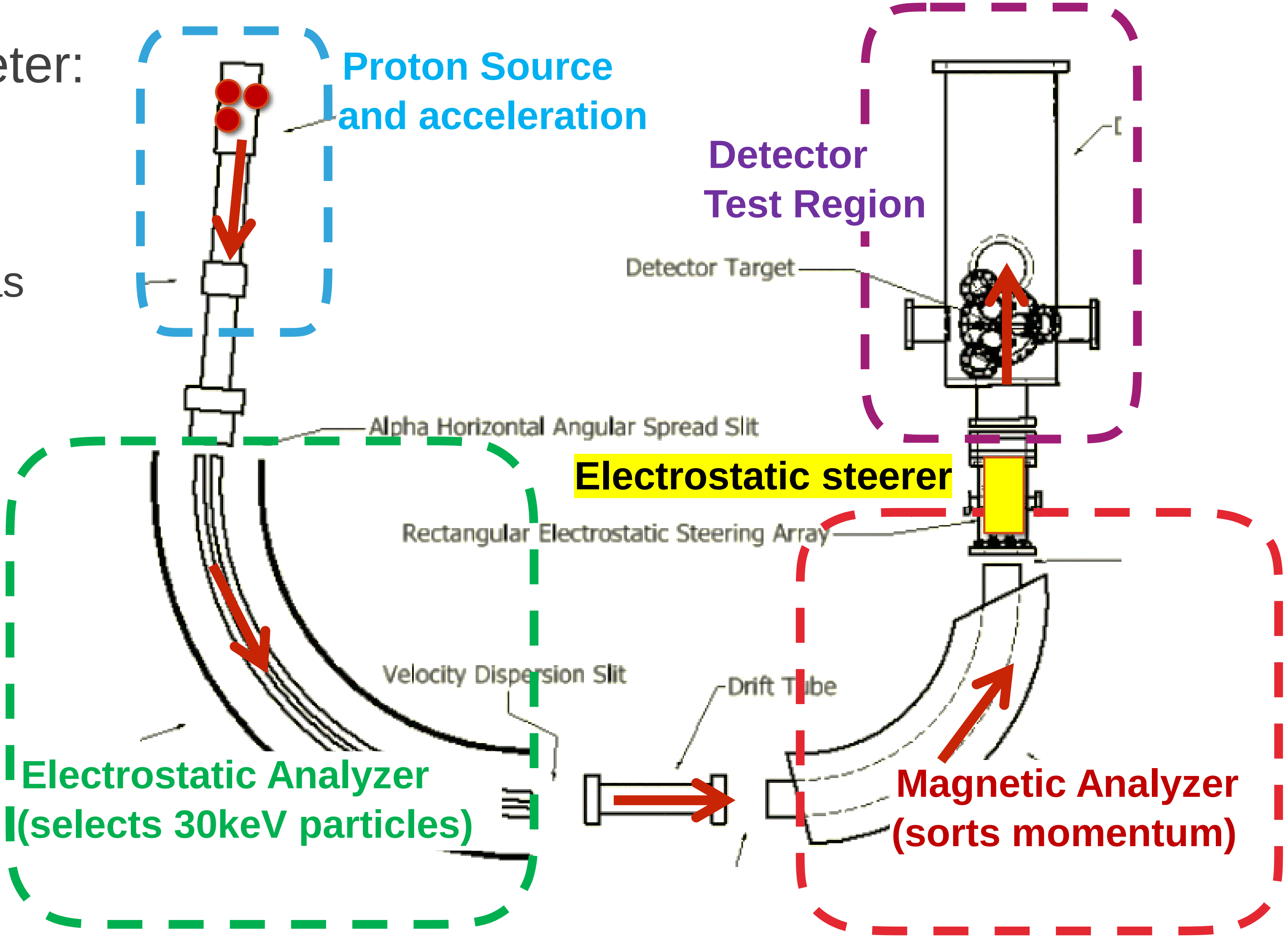
Manitoba II Proton Source

Double focussing mass spectrometer: energy and momentum focusing

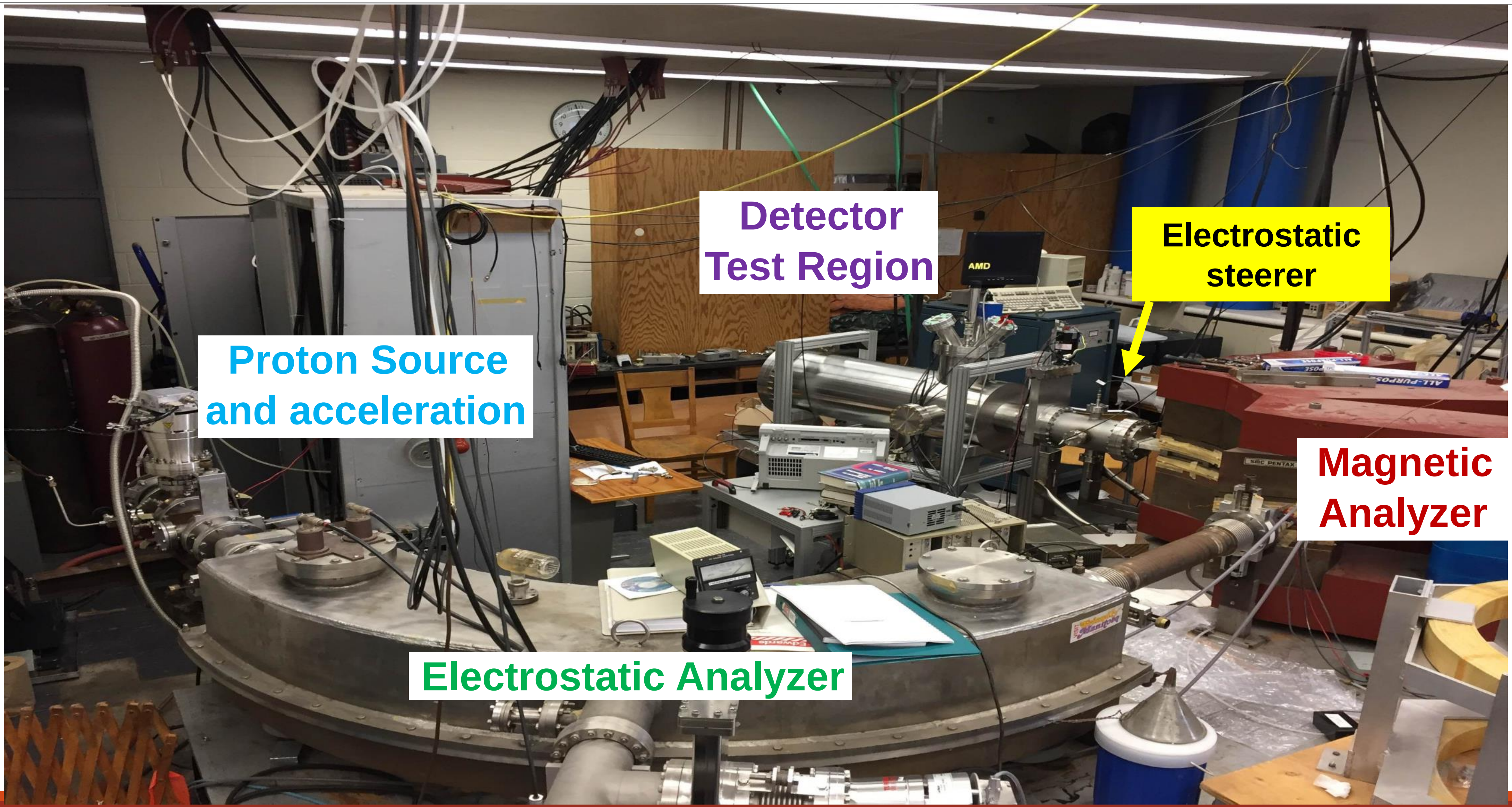
Penning Ion Gauge Hydrogen-Argon Gas Discharge Source

Electrostatic steerer deflects beam to detection location



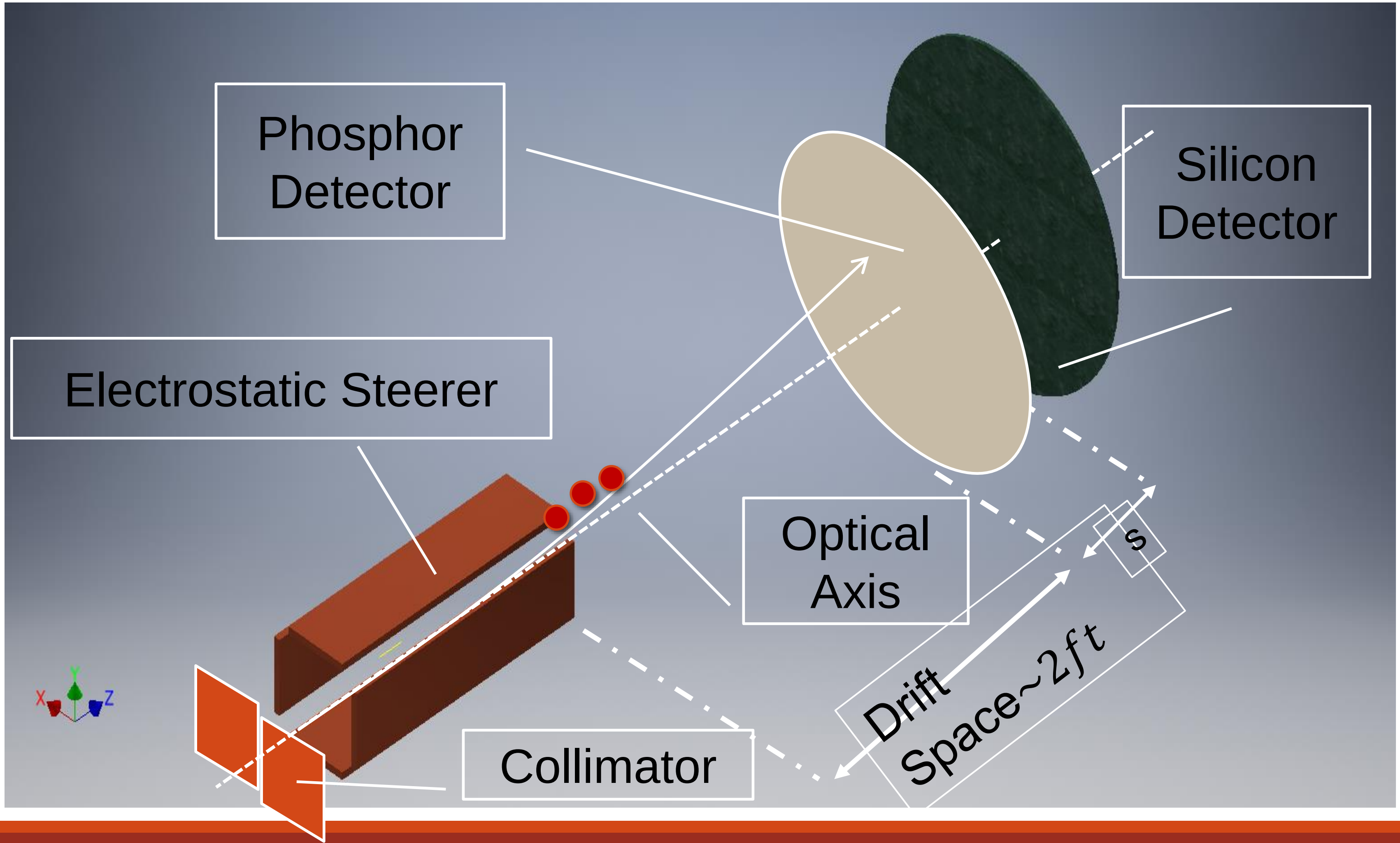


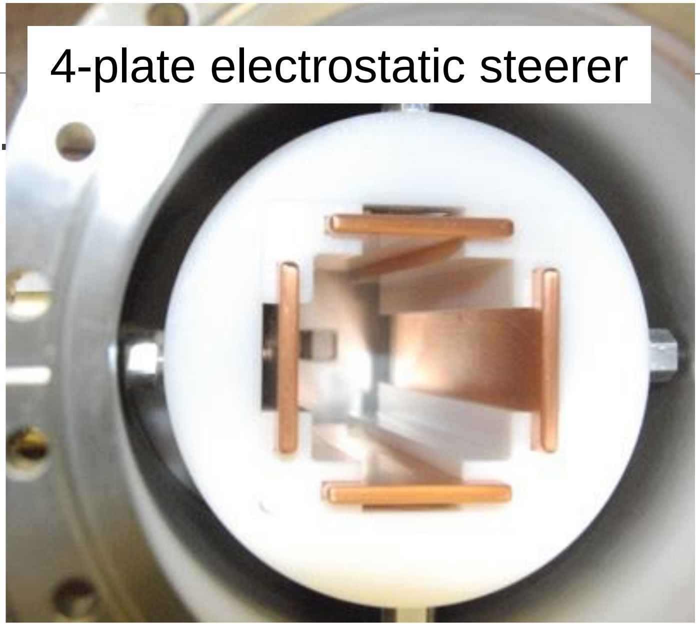
Manitoba II Proton Source (photo)

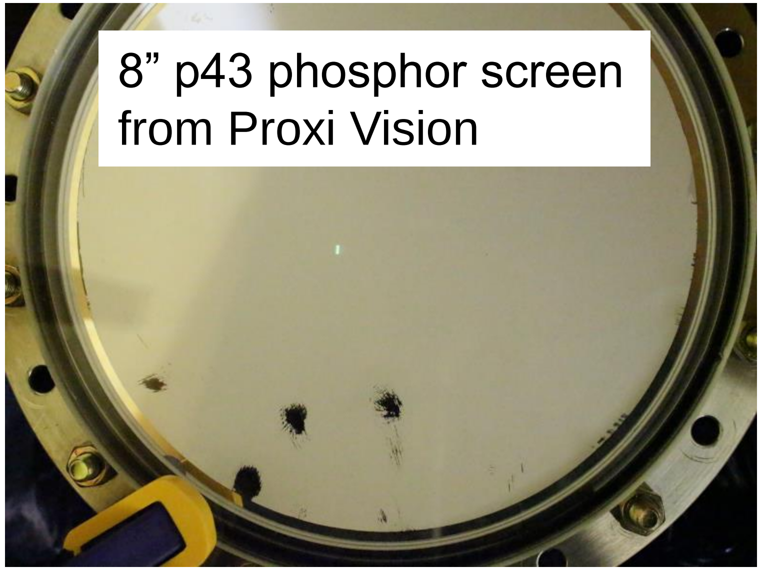


Where's the Beam?

"See" protons using a Large Diameter Phosphor Screen and camera.





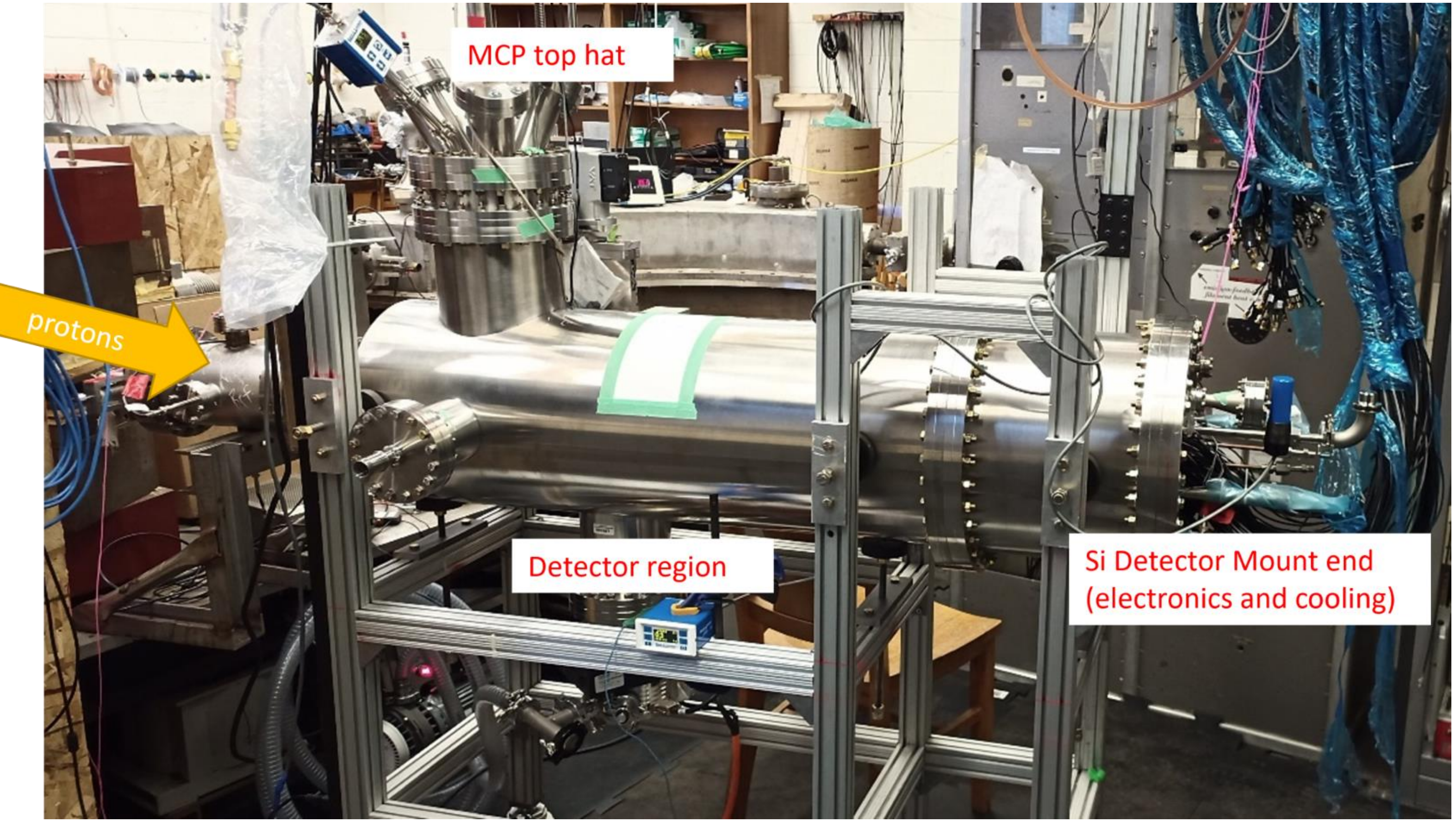


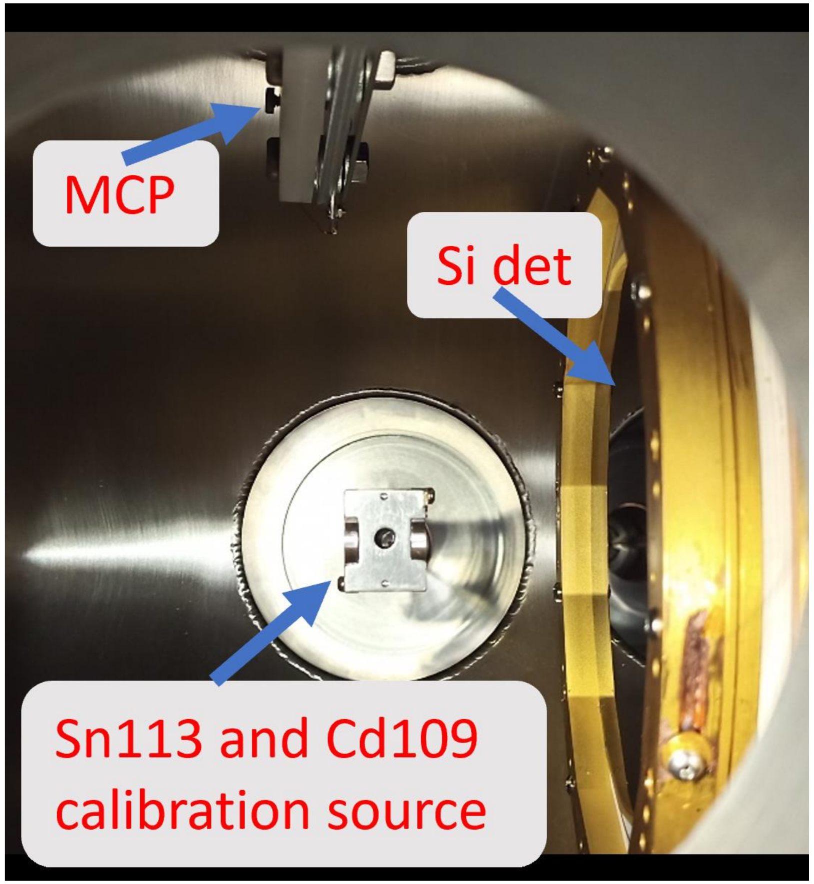
Testing the Steerer

Nic Macsai, graduate student, with the phosphor screen/camera shroud

Proton beam as seen by Phosphor screen while sweeping the steerer in 500V increments

Si Detector installed at Manitoba

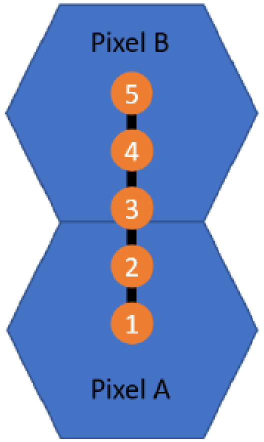


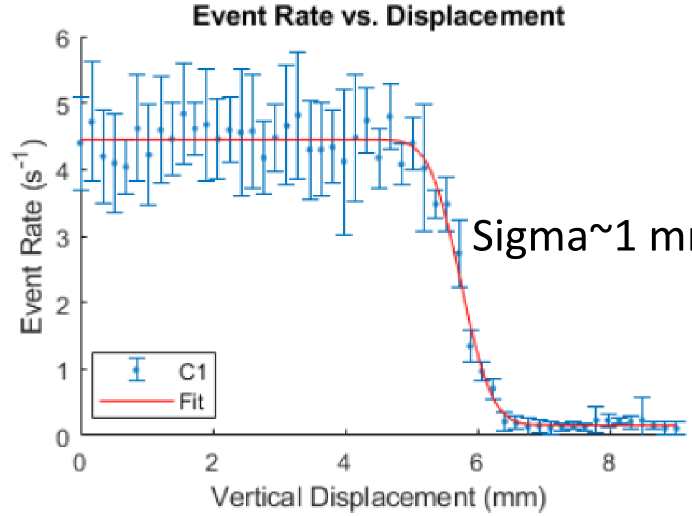


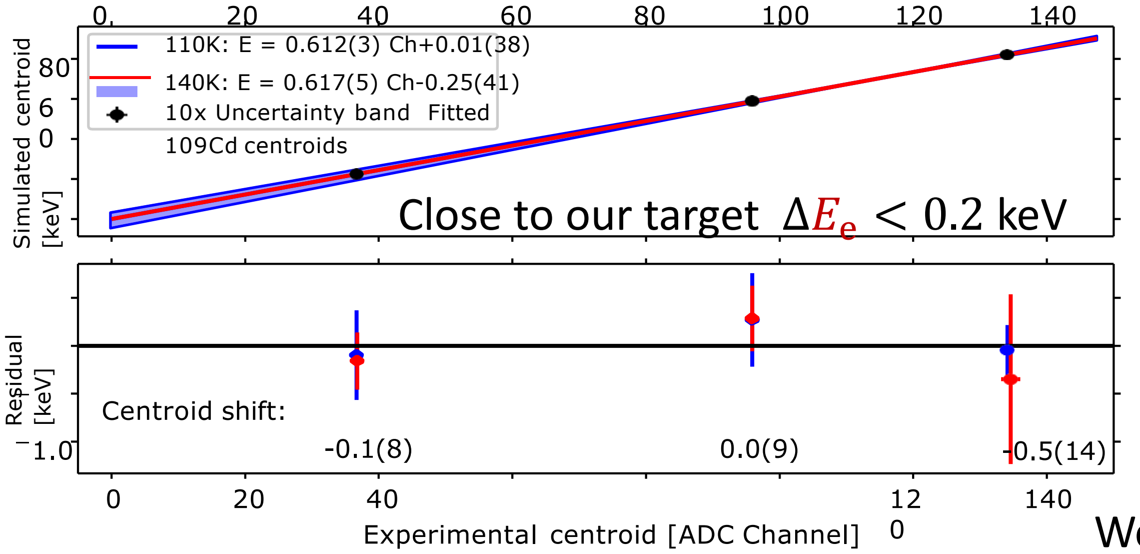
Si Detector Testing at Manitoba

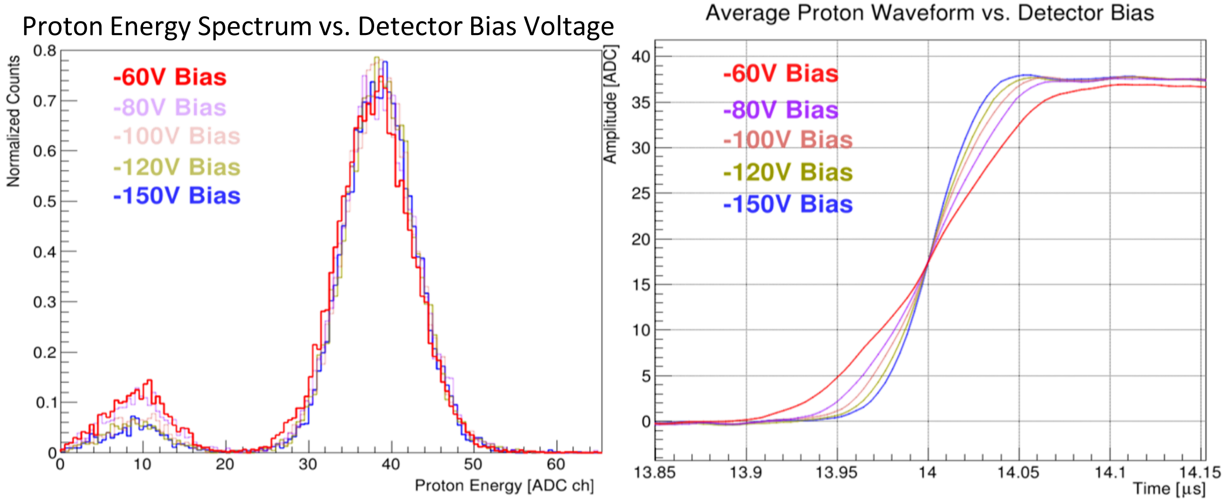
What to investigate:

Measure relative proton trigger efficiency and pulse shape vs:
Pixel Radius
Temperature of Detector
Bias of Detector (the E field in the detector) (-30-320 V)
Energy of Protons (25, 30, and 25 keV)
Protons Near Pixel Boundaries
Used Cd 109 and Sn113 sources to calibrate ADC spectra









Working on publication describing the proton source and tests results

Current Status and Timeline

Both mounts installed in Nab spectrometer May 25, 2022

Uof Manitoba undergrad
August Mendelsohn

SNS beamtime Summer 2022

- Cool magnet and detectors at the same time
- DAQ sync and time of flight resolution
- Beam polarization measurements
- Electron source calibration system check

SNS beamtime Winter of 2022/23

- Test fixed items and 2nd commissioning

SNS beamtime Summer of 2023

- Physics Data

SNS Shuts down Fall 23/Spring 24

- Upgrade Beam power on spallation target

Hope to get "a" statistics only paper out during this time.

Nice Review Article:

Precise Measurements of the Decay of Free Neutrons

Dirk Dubbers[1] and Bastian Märkisch[2]

[1]Physikalisches Institut, Universität Heidelberg, Im Neuenheimer Feld 226, 69120 Heidelberg, Germany

[2]Physik-Department, Technische Universität München, James-Franck-Straße 1, 85748 Garching, Germany

June 04, 2021

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https://arxiv.org/abs/2106.02345

Quotes:

The new neutron and nuclear data permit exclusion of deviations from the V–A structure of the SM well below the 10^{-3} level, two orders of magnitude better than 15 years ago.

Limits on Wilson coefficients from low-energy experiments are generally more precise and require fewer assumptions than the corresponding high-energy limits.

neutron and other β decay experiments compare well with and are in part complementary to limits derived from LHC experiments

Summary: Uncertainties for a and b

Can reach:

- $\Delta a/a = \pm(7 \times 10^{-4})_{stat.} \pm (1.2 \times 10^{-3})_{sys.}$
- $\Delta\lambda/\lambda = \pm(2.1 \times 10^{-4})_{stat.} \pm (3.6 \times 10^{-4})_{sys.}$
- $\Delta b = \pm(7 \times 10^{-5})_{stat.} \pm (2.2 \times 10^{-3})_{sys.}$

Present tasks:

- Profiling beam in spectrometer
- Measuring beam polarization
- Commissioning the entire apparatus

Can reach a competitive a in one SNS run cycle (~2months)

Experimental Parameter	$(\Delta a \,/\, a)_{sys.}$
Magnetic Field	6.0×10^{-4}
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Neutron Beam	3.3×10^{-4}
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Length of the TOF Region	N/A
SUM	1.2×10^{-3}

The Nab Collaboration

R. Alarcon[a], A. Atencio[k], S. Baeßler[b,c] (Project Manager), S. Balascuta[a], L. Barrón Palos[n], T.L. Bailey[m], K. Bass[i], N. Birge[i], A. Blose[f], D. Borissenko[b], M. Bowler[b], J.D. Bowman[c] (Co-Spokesperson), L. Broussard[c], A.T. Bryant[b], J. Byrne[d], J.R. Calarco[c,i], J. Choi[m], J. Caylor[i], L. Christie[i], T. Chupp[o], T.V. Cianciolo[c], C. Crawford[f], M. Cruz[i], X. Ding[b], G. Dodson[r], W. Fan[b], W. Farrar[b], N. Fomin[i], E. Frlež[b], J. Fry[q], M.T. Gericke[g], M. Gervais[f], F. Glück[h], R. Godri[i] , F. Gonzalez[c], G.L. Greene[c,i], R.K. Grzywacz[i], V. Gudkov[j], J. Hamblen[e], L. Hayen[m], C. Hayes[m], C. Hendrus[o], K. Imam[i], T. Ito[k], A. Jezghani[f], H. Li[b], M. Makela[k], N. Macsai[g], J. Mammei[g], R. Mammei[l], M. Martinez[a], D.G. Mathews[f], M. McCrea[f], P. McGaughey[k], C.D. McLaughlin[b], A. Mendelsohn[g], J. Mirabal-Martinez[k], P.E. Mueller[c], A. Nelsen[f], I. Novikov[p], D. van Petten[b], S.I. Penttilä[c] (On-site Manager), D.E. Perryman[i], J. Pierce[c], D. Počanić[b] (Co-Spokesperson), H. Presley[i], Y. Qian[b], J. Ramsey[c], G. Randall[a], G. Riley[i], K.P. Rykaczewski[c], A. Salas-Bacci[b], S. Samiei[b], A. Saunders[c], E.M. Scott[i], T. Shelton[f], S.K. Sjue[k], A. Smith[b], E. Smith[k], E. Stevens[b], L. Tinius[b], J.W. Wexler[m], R. Whitehead[i], W.S. Wilburn[k], A.R. Young[m], B.Zeck[m], M. Zemke[i]

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Main project funding: NSF, U.S. Department of Energy Office of Science, University of Virginia, Arizona State University, NSERC CRSNG, Oak Ridge National Laboratory

Backup

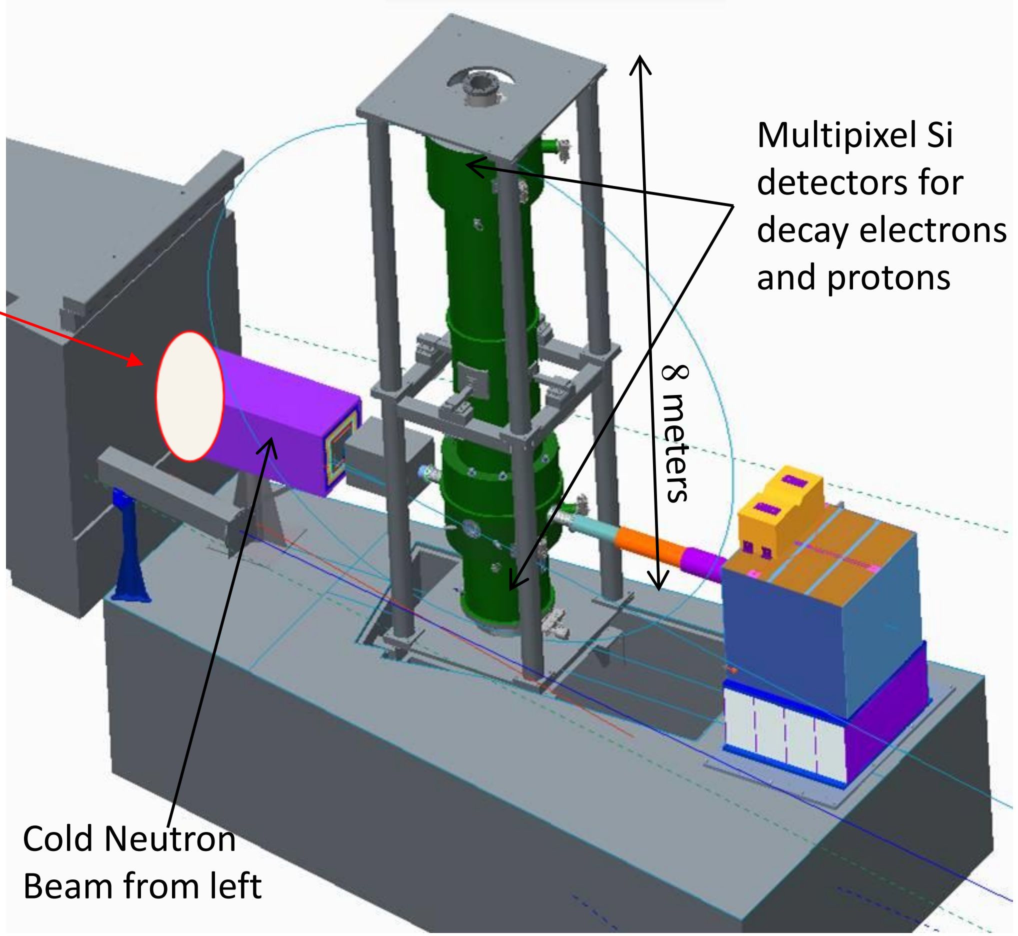
Looking Forward: pNab

Use the same apparatus to measure A, B

- Add a neutron beam polarizer
  - (used for the NPDGamma)
- Goals:
  - $\Delta A/A \leq 10^{-3}$
  - $\Delta B/B \leq 10^{-3}$

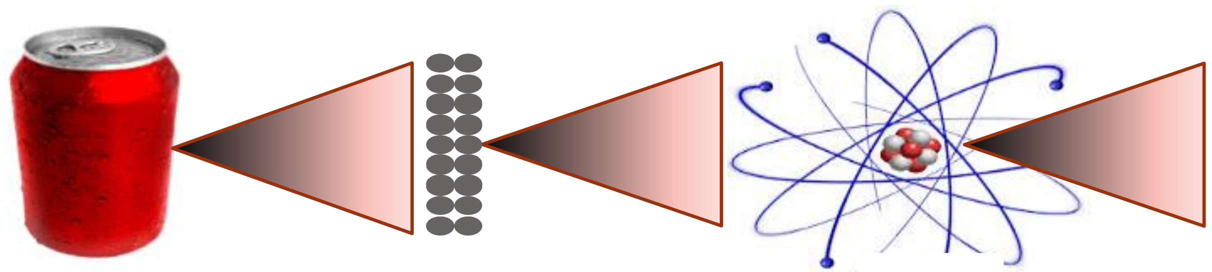
Uncertainties in previous experiments:

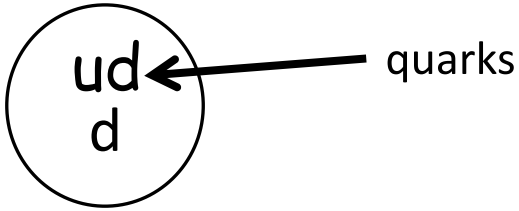
- Statistics
  - Sufficient for competitive measurements of A
- Detector Effects
  - Already high enough detector energy resolution
  - Sufficient time resolution
- Background
  - Coincidence detection to suppress background
- Polarization
  - Utilize crossed supermirrors or ^{3}He



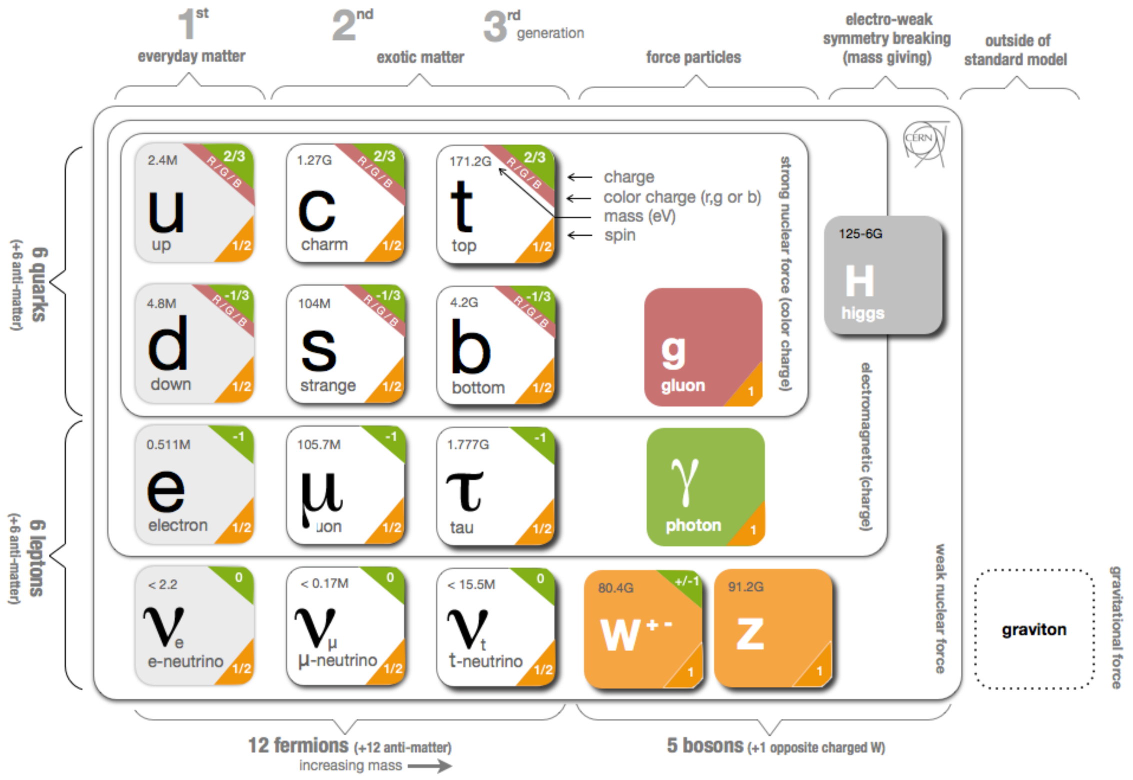
Different Systematics

The Standard Model





It’s the 90th anniversary of Chadwick’s discovery of the neutron



Infographic from CERN’s 2012 WEBFEST
http://cds.cern.ch/journal/CERNBulletin/2012/35/News%20Articles/1473657

CKM matrix

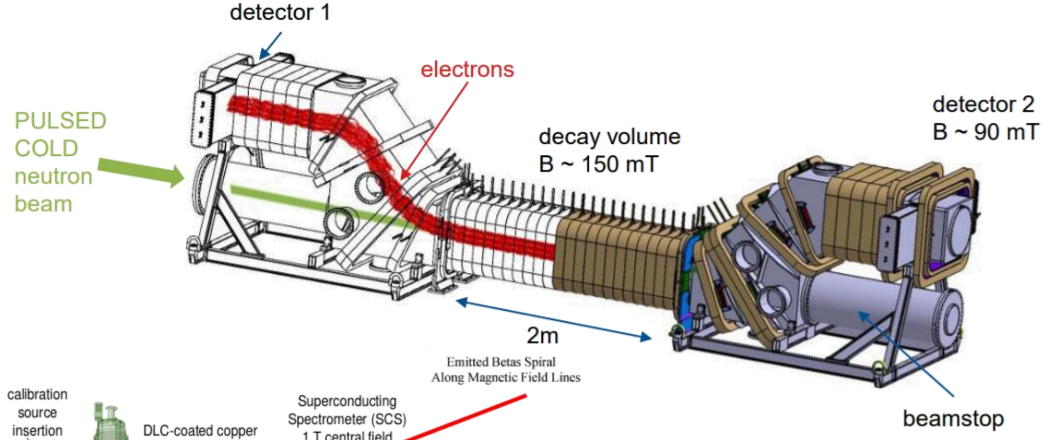
$$\begin{pmatrix} d' \\ s' \\ b' \end{pmatrix} = \begin{pmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{pmatrix} \cdot \begin{pmatrix} d \\ s \\ b \end{pmatrix}$$

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

λ Measurements at the 0.1% Level

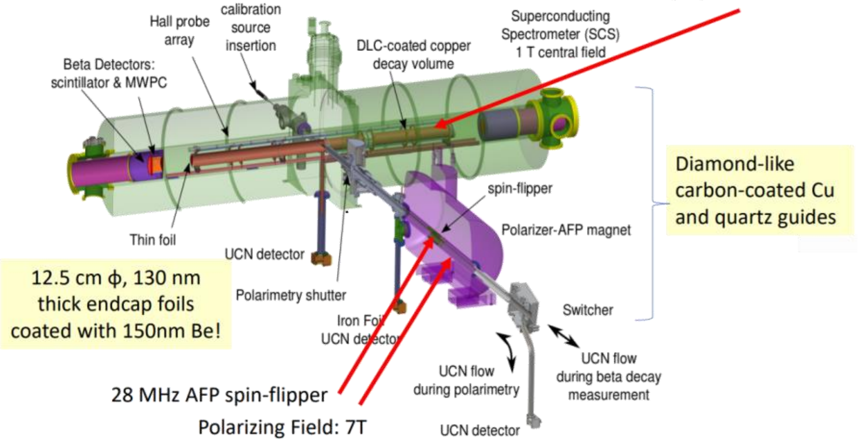
PERKEO III: ($\Delta\lambda/\lambda = 4.4 \times 10^{-4}$)

- Symmetric design allows for counting of backscattered e^-
- Pulsed polarized n beam gives control over backgrounds
- $-0.018 \leq b \leq 0.052$ (90% CL)



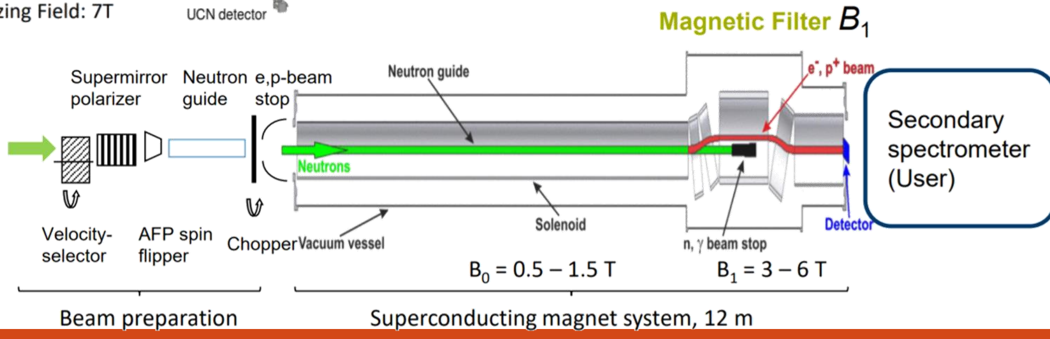
UCNA: ($\Delta\lambda/\lambda = 1.7 \times 10^{-3} \rightarrow 4 \times 10^{-4}$)

- Low energy UCN ($\lesssim 220$ neV) easy to polarize
- n have long residency time ($\sim$20 s) in spectrometer
- Detector (and other) upgrades funded by LDRD
- $-0.012 \leq b \leq 0.144$ (90 % CL)



PERC: (Goal: $\Delta\lambda/\lambda \sim 1 \times 10^{-4}$)

- Beamline that delivers decay products



B. Märkisch et al., Phys. Rev. Lett. 122, 242501 (2019)

Brown et al., Phys. Rev. C 97, 035505 (2018)

X. Wang, C. Ziener et al., EPJ Web Conf. 219, 04007 (2019

Saul, et al., Phys. Rev. Lett. 125, 112501 (2020)

Sun, et al., Phys. Rev. C 101, 035503 (2020)

Experimental Probes of CKM Unitarity

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

Measurements of V_{ud}:

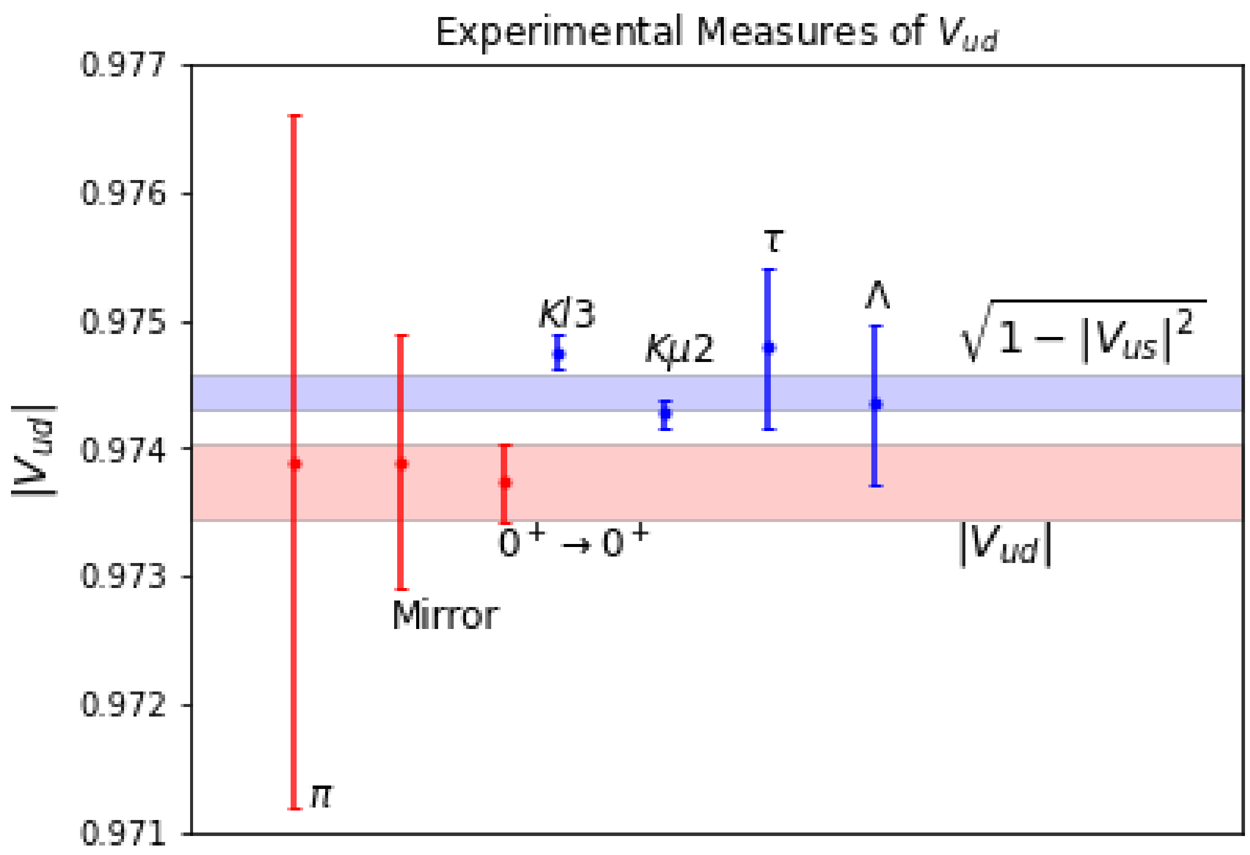
- Most precise "Superallowed" $0^+ \rightarrow 0^+$ decays
- Also limits from Mirror nuclei and Pions
- Require radiative and nuclear structure corrections ($0^+ \rightarrow 0^+$, Mirrors)

Measurements of V_{us}:

- Most precise from Kaon decays
- Some tension between different decay channels
- Also limits from τ and Λ hyperons

$V_{ub} \ll V_{ud}$ and V_{us} so it's negligible

Most precise measurements disagree!



Zyla et. al Particle Data Group (2020)
J. C. Hardy and I. S. Towner, Physical Review C 102, 045501 (2020)
L. Hayen, Physical Review D 103, 113001 (2021)

The Nab Experiment at SNS

Converting e^- and p^+ to signals

Semiconductor diodes!

- Small bandgap (~1.1 eV in Silicon)
- Can add contaminants to change number of electrons
- P-N Junction only allows field in one direction
- Increase field by applying external bias voltage

Particle hits detector

- Produces electrons + holes
- **Counting speed dependent on $\vec{E}$, temperature, depth of radiation, etc.**