The Nab Experiment: Present Status

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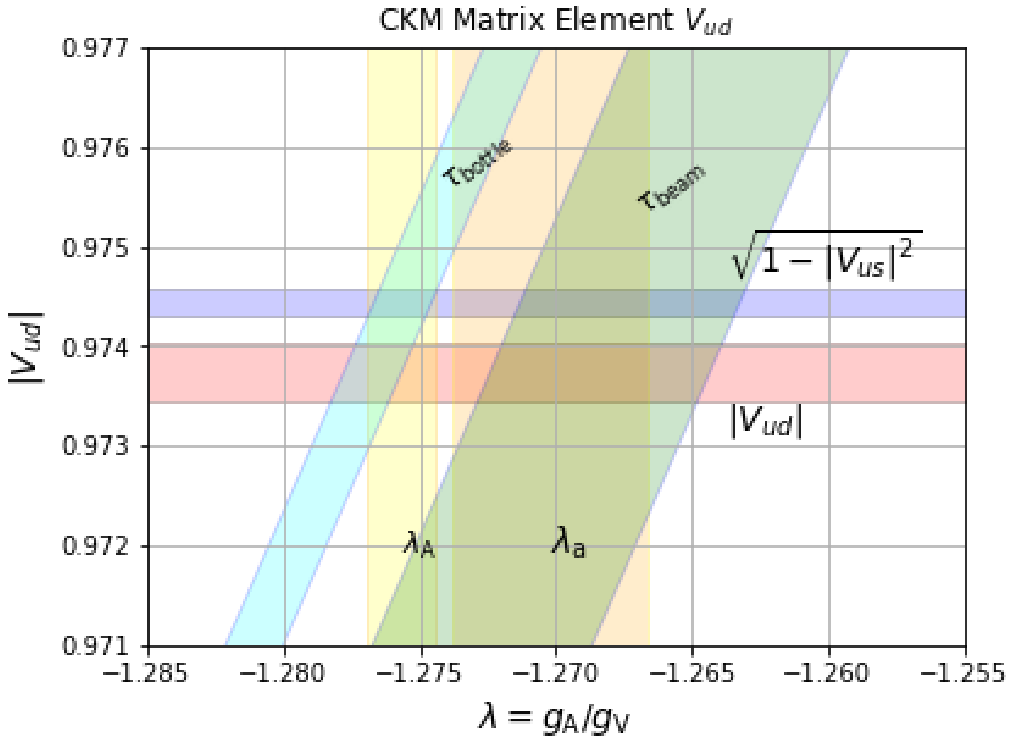
Beta-Decay: Why Use Neutrons?

- Neutrons are the simplest β-decay:
  - $n \rightarrow p^{+} + e^{-} + \bar{\nu}_e$
  - $|V_{ud}|^2 = \frac{5099.3 \text{ s}}{\tau_n (1+3\lambda^2)(1+\Delta_R)}$
- Experimentally Determine:
  - τ_n: Neutron Lifetime
  - $\lambda = g_A / g_V$: Ratio of coupling constants
- Theoretically Easier:
  - No nuclear structure corrections!
  - Inner radiative correction Δ_R
- To compete with $0^+ \rightarrow 0^+$ measurements:
  - $\Delta\tau_n / \tau_n < 3 \times 10^{-4}$ (or $\Delta\tau_n < 0.3$ s)
  - $\Delta\lambda / \lambda < 1 \times 10^{-3}$ (or $\Delta\lambda < 1 \times 10^{-3}$)



Tension between V_{ud} and V_{us}!

See: Cirigliano *et al*, J. High Energ. Phys. 2022, 152

Tension between different methods of determining τ_n, λ!

Data from:

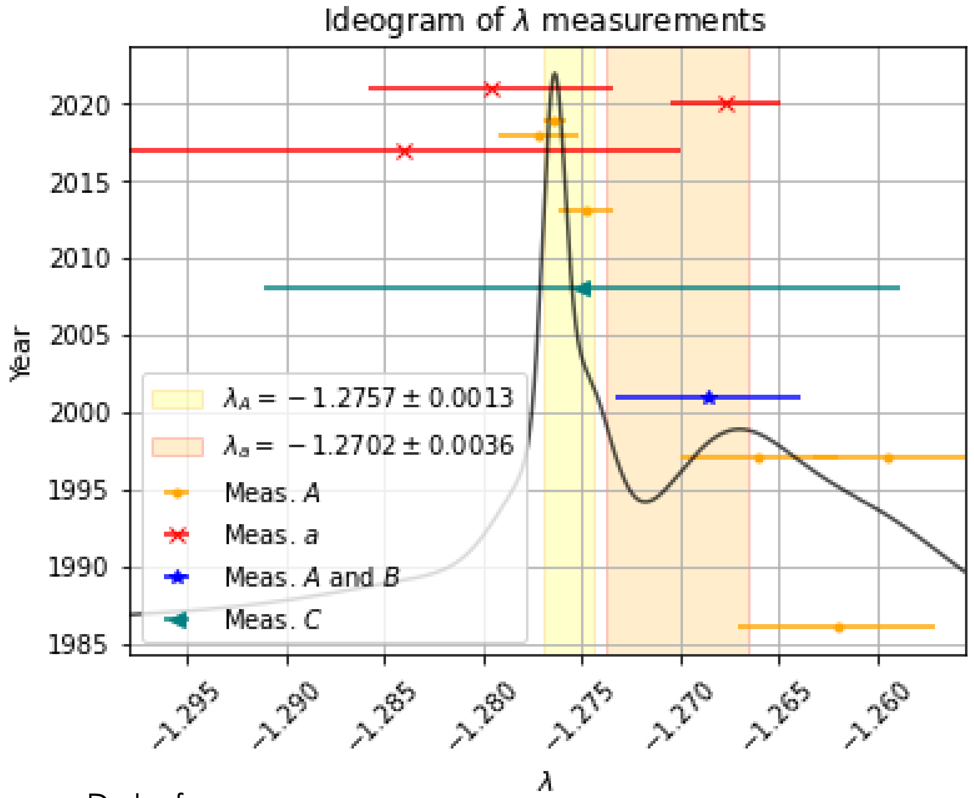
- Workman, R. L. *et al*, Particle Data Group (2022)

How to Measure λ?

Decay rate of the neutron is proportional to:

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

- These correlation terms (asymmetries) relate to $\lambda = g_A/g_V$:
  - $a = \frac{1-\lambda^2}{1+3\lambda^2}$
  - $A = -2\frac{\lambda^2+\lambda}{1+3\lambda^2}$
- Fierz Interference term b couples to scalar (g_S), tensor (g_T) currents in weak interaction
  - Non-zero g_S, g_T is new physics



Data from:
- Workman, R. L. *et al*, Particle Data Group (2022)

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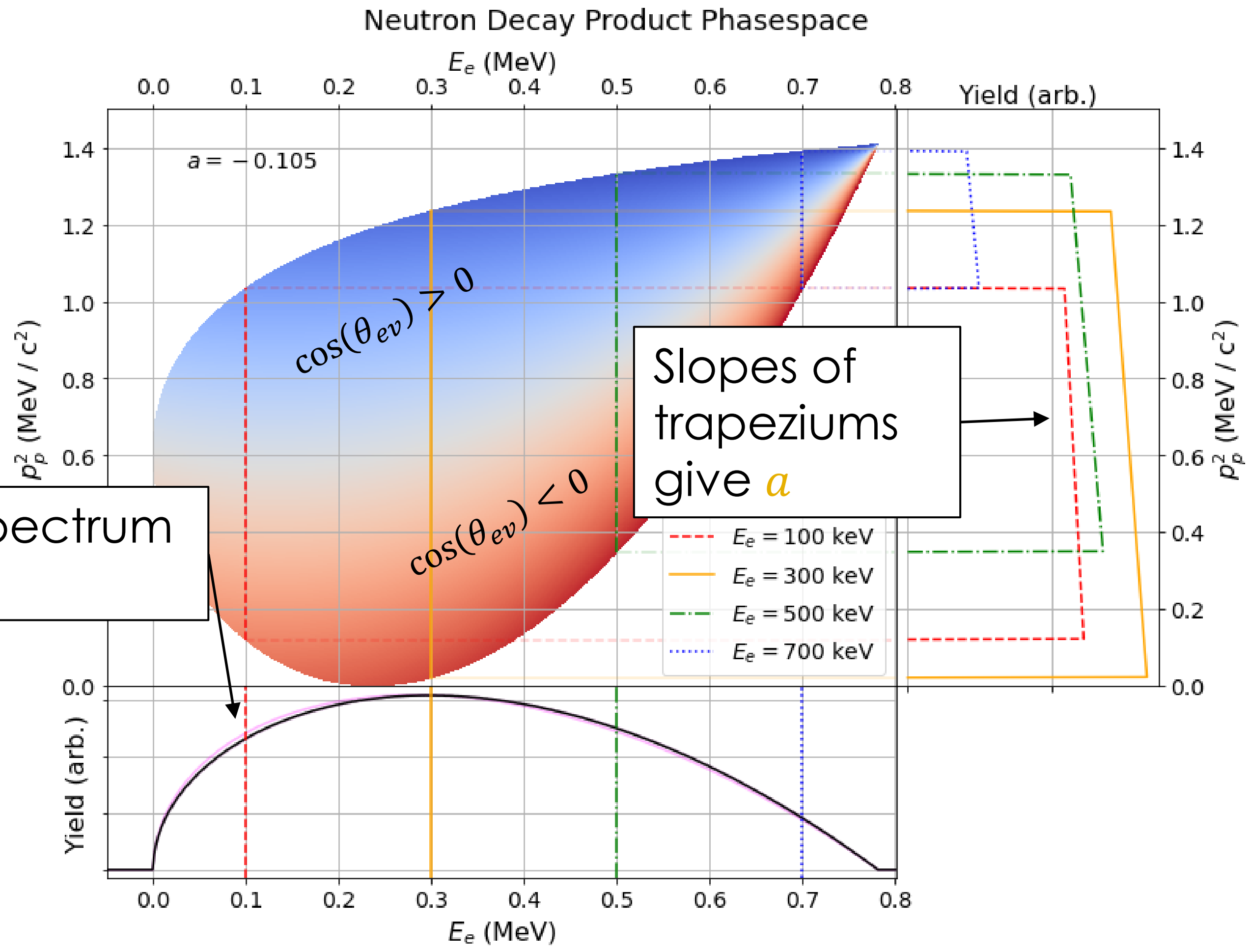
Kinematics of Unpolarized Neutron β-Decay

- 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:
  - Relativistic Energy (for $i \in \{n, p^+, e^-, \nu\}$):
    - $E_i^2 = \vec{p_i}^2 + m_i^2$
  - 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…

Shape of e^- spectrum gives b



Slopes of trapeziums give a

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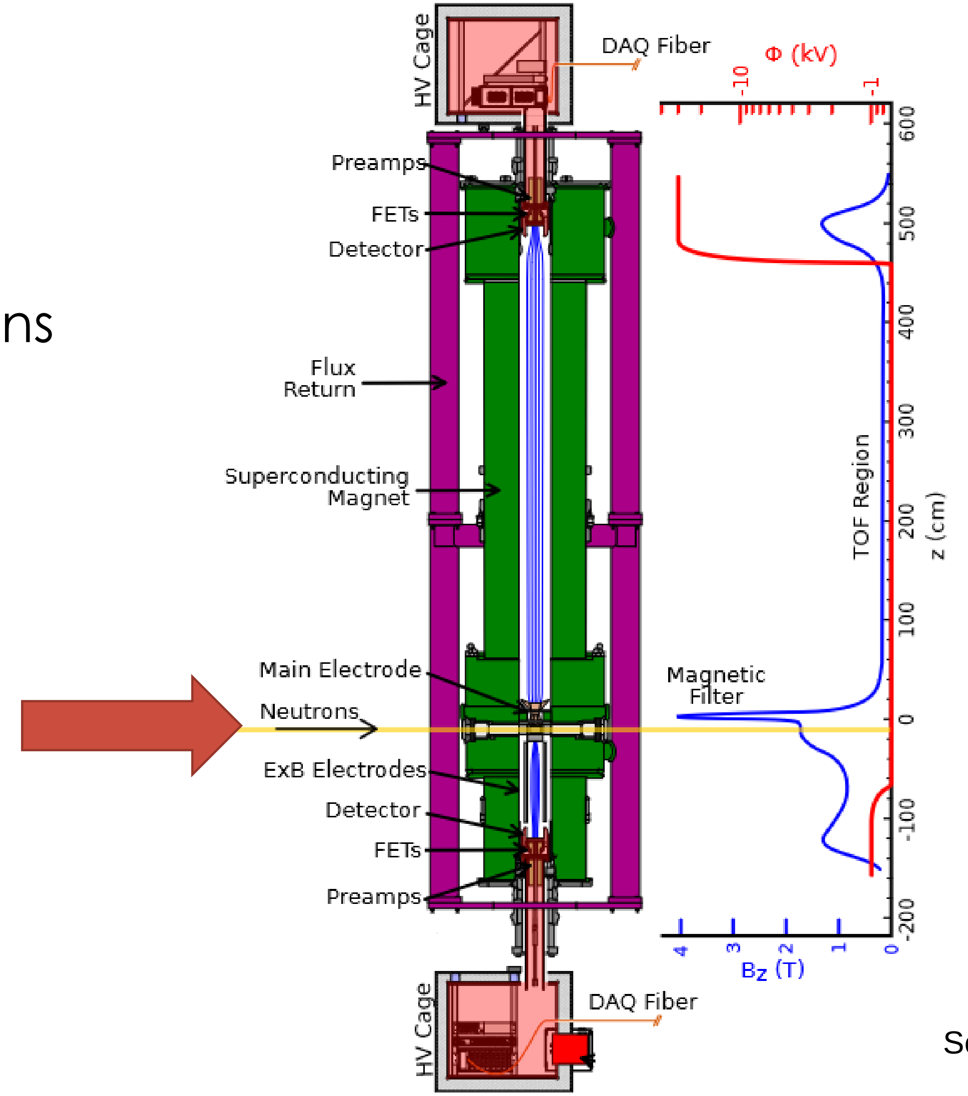
Reconstructing β-Decay Product Kinematics

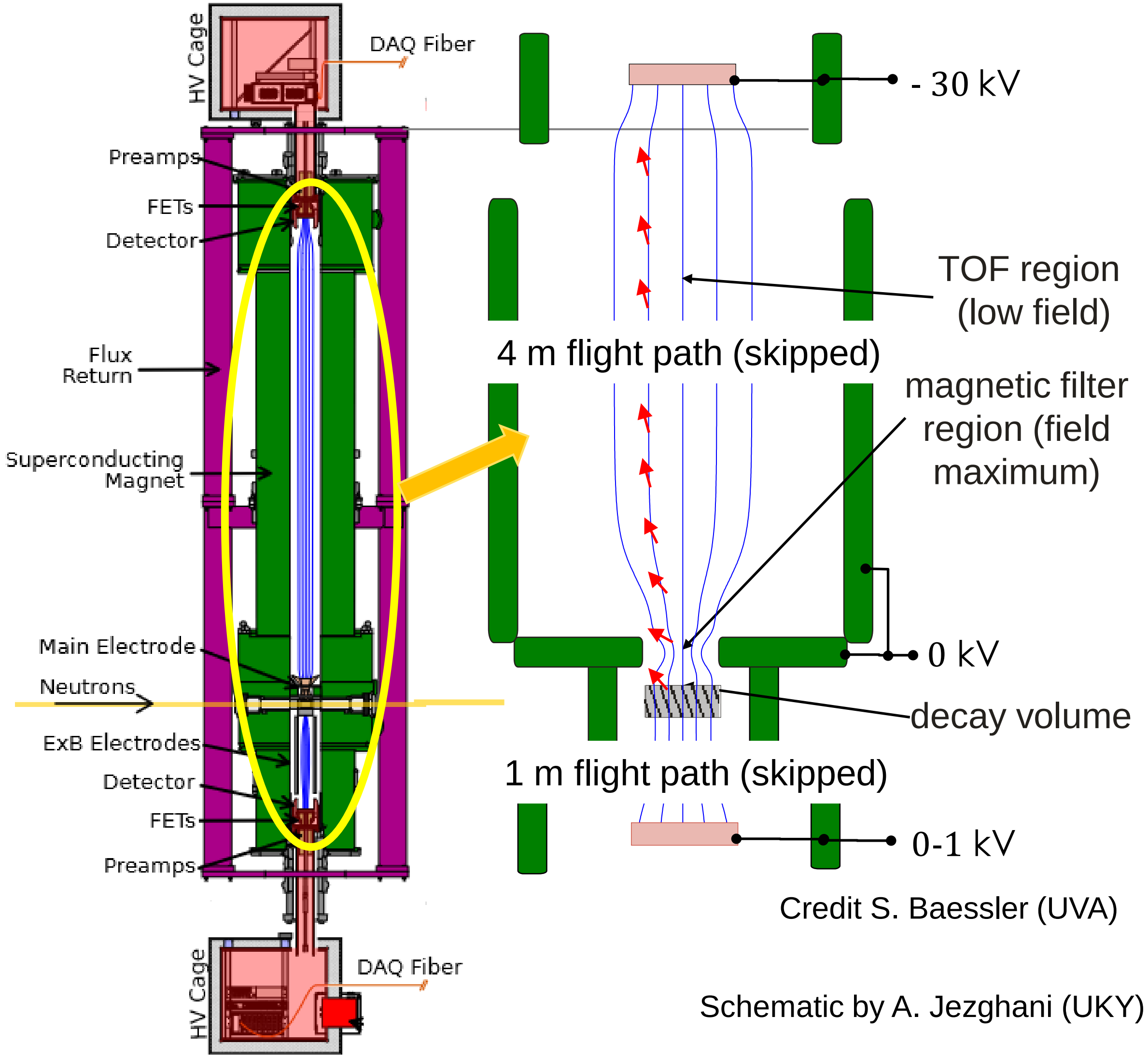
- Use an asymmetric (7m long) spectrometer
- Beam of cold spallation neutrons



Schematic by A. Jezghani (UKY)

Reconstructing β-Decay Product Kinematics

- Use an asymmetric (7m long) spectrometer
- Beam of cold spallation neutrons
- Magnetic fields guide decay products
  - High-field decay region
  - Low-field time of flight region longitudinalizes momentum

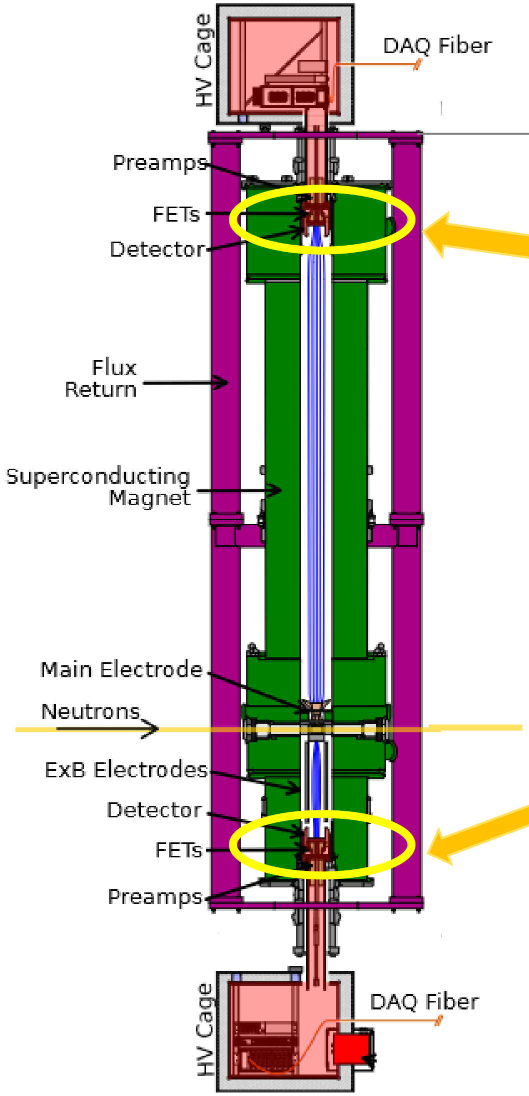


Credit S. Baessler (UVA)

Schematic by A. Jezghani (UKY)

Reconstructing β-Decay Product Kinematics

- Use an asymmetric (7m long) spectrometer
- Beam of cold spallation neutrons
- Magnetic fields guide decay products
  - High-field decay region
  - Low-field time of flight region longitudinalizes momentum
- 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



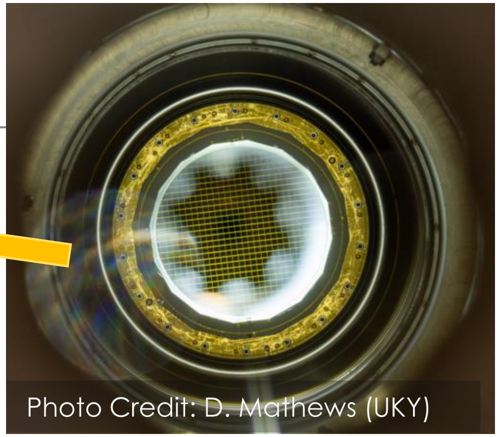


Photo Credit: D. Mathews (UKY)

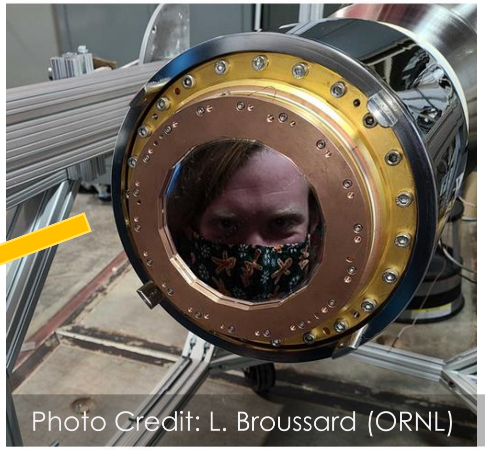
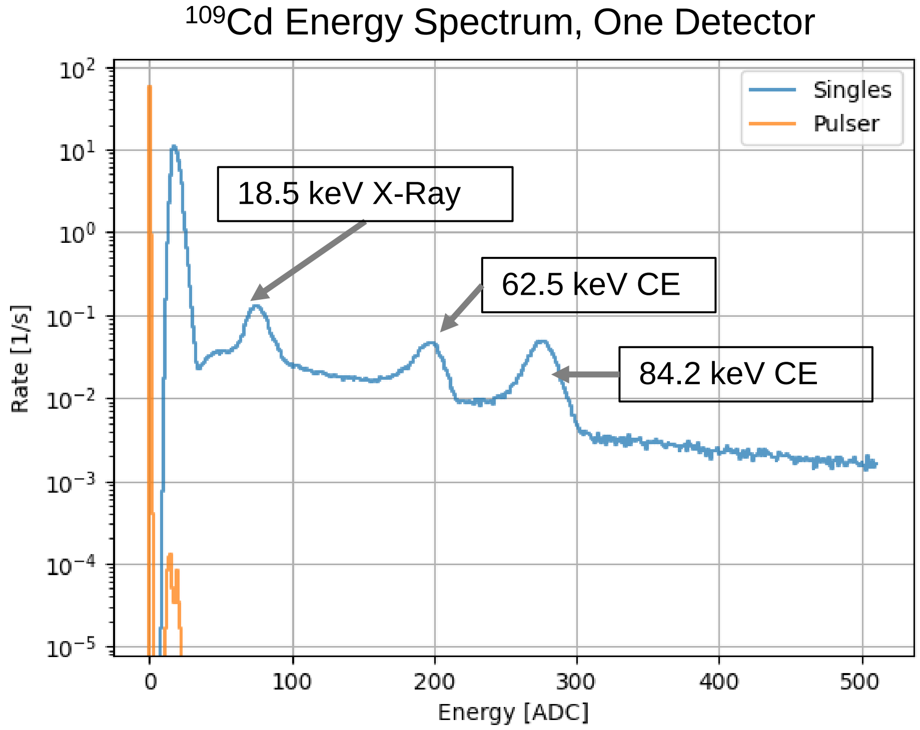


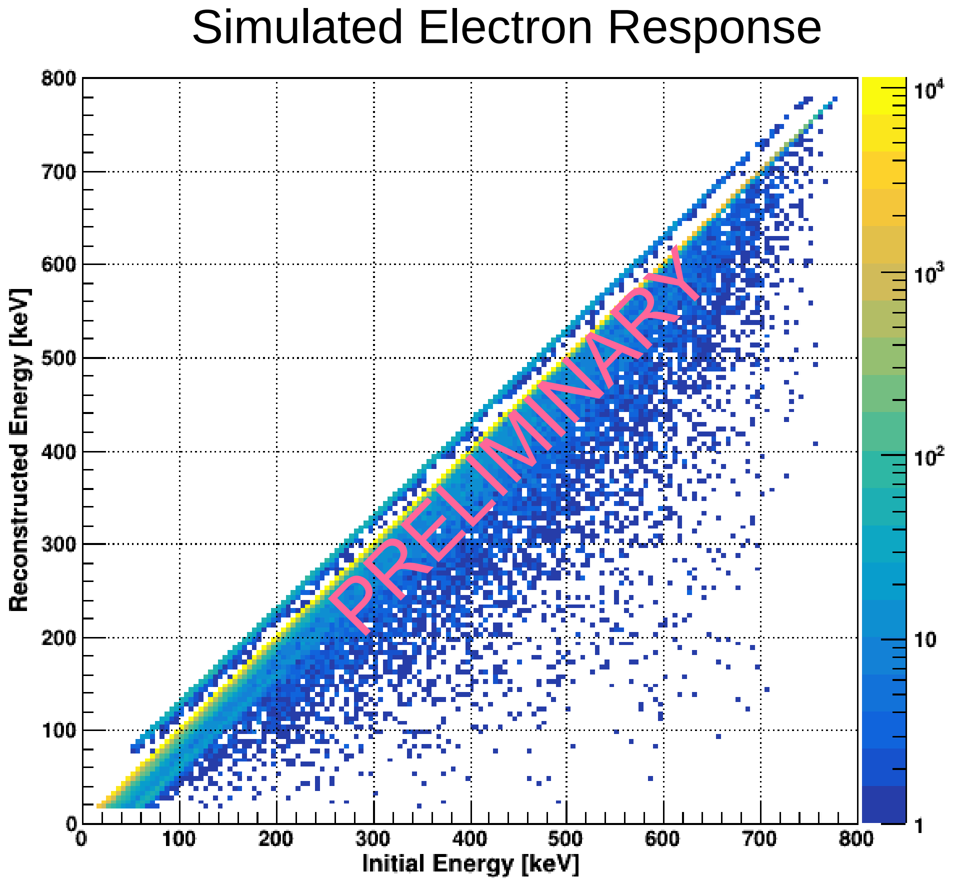
Photo Credit: L. Broussard (ORNL)

Schematic by A. Jezghani (UKY)

Electron Response Function

- Need to understand $E_{e,meas}$ for each E_e to 1%
  - Fast + Linear electronics response
  - Electron bounce history
  - Energy loss in detector due to Bremsstrahlung
- Simulate detector response and measure

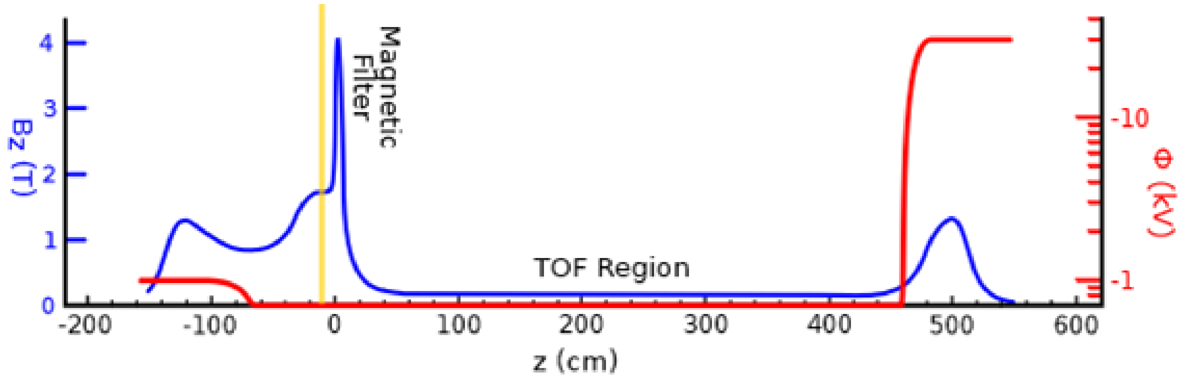




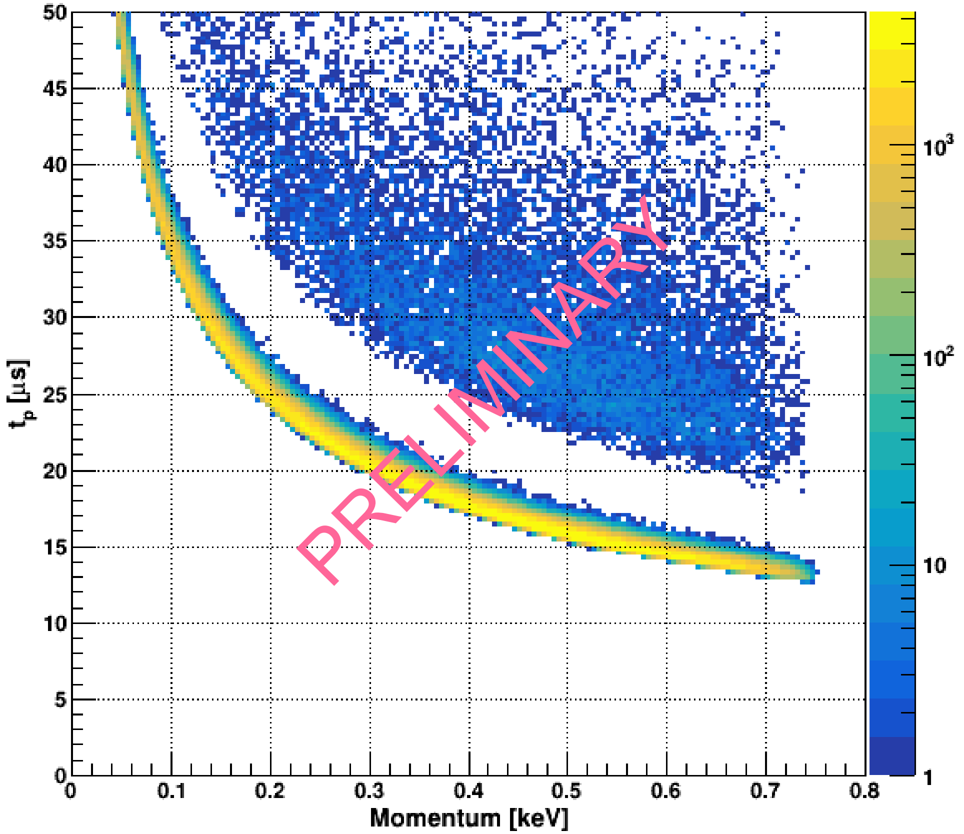
Go to J.H. Choi's talk! (*Friday, 0930 in Kings 1*)

Determining p_p from Time of Flight

- Charged particle (p^+) moving through EM field:
  - $t_p = \frac{m_p}{p_p} \int_{z_0}^{L} \frac{dz}{\sqrt{1 - \frac{B(z)}{B_0} \sin^2(\theta_0) + \frac{q(V(z) - V_0)}{E_0}}}$
  - Smearing of response due to θ_0, z_0
  - High magnetic field rejects p^+ with:
    - $\cos(\theta_0) < \sqrt{1 - B_0/B_f} \sim 0.7$



Simulated Proton Response



Fry et al. EPJ Web of Conferences 219, 04002 (2019)

Target Uncertainties for a and b

- Leading uncertainties:
  - Magnetic Field (only a)
  - Detector Effects (both a and b)
  - Neutron Beam (only a)
- Goal precision:
  - $\Delta a / a \sim (1 \times 10^{-3})_{tot.}$
  - $\Delta \lambda / \lambda \sim (4 \times 10^{-4})_{tot.}$
  - $\Delta b \sim (3 \times 10^{-3})_{tot.}$
- 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}

Target Uncertainties for a and b

Nab Talks	Session
H. Rahangdale	D05:00007
R. Godri	F04:00007

- – Detector Effects (both a and b)

Nab Talks	Session
A. Mendelsohn	D05:00004
H. Acharya	F04:00004
L. Christie	F04:00005
M. Gervais	F04:00006
A. Nelsen	F04:00008
J.H. Choi	L11:00003
A. Richburg	Poster DB02.00099

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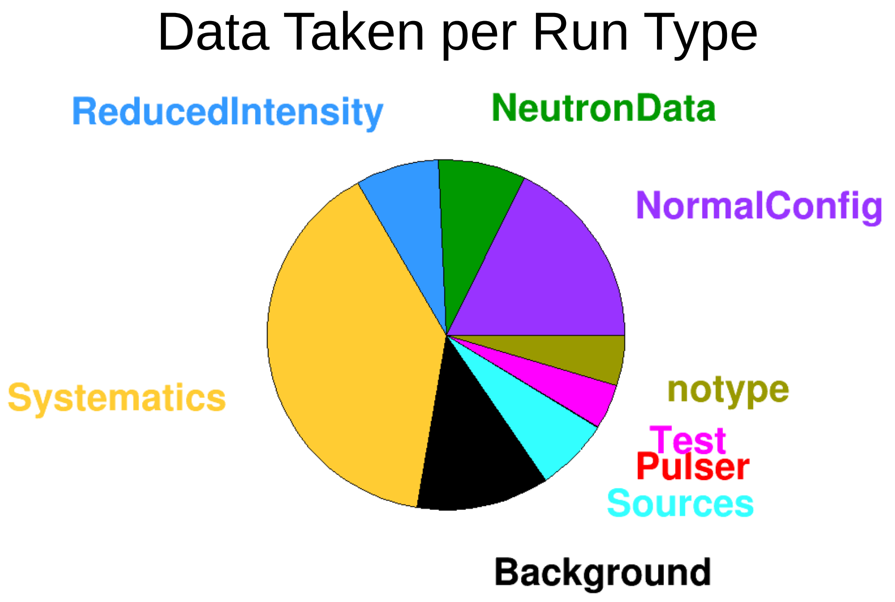
Summer Commissioning + Data Taking

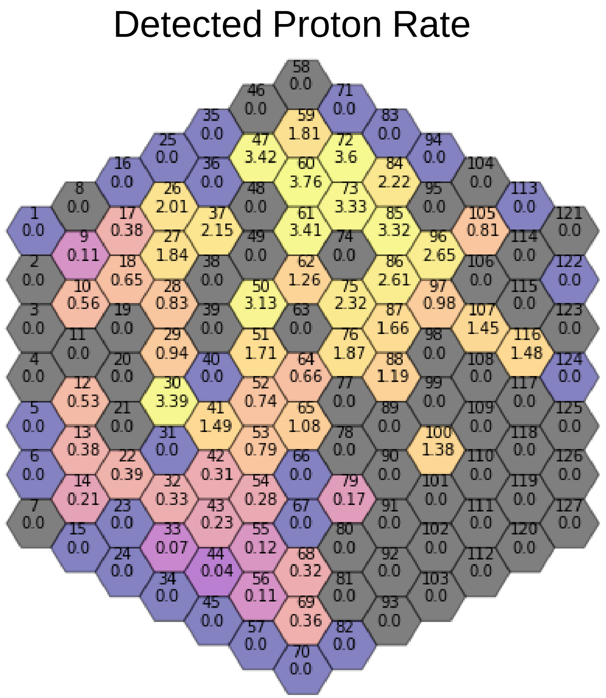
- First time with 2 detectors in working magnet with high voltage and neutrons!



- Normal Data Taking = 20%
- Systematics (+ Reduced Intensity) = 46.7%
- Background = 12.0%

Chart Credit: J. H. Choi (NCSU)

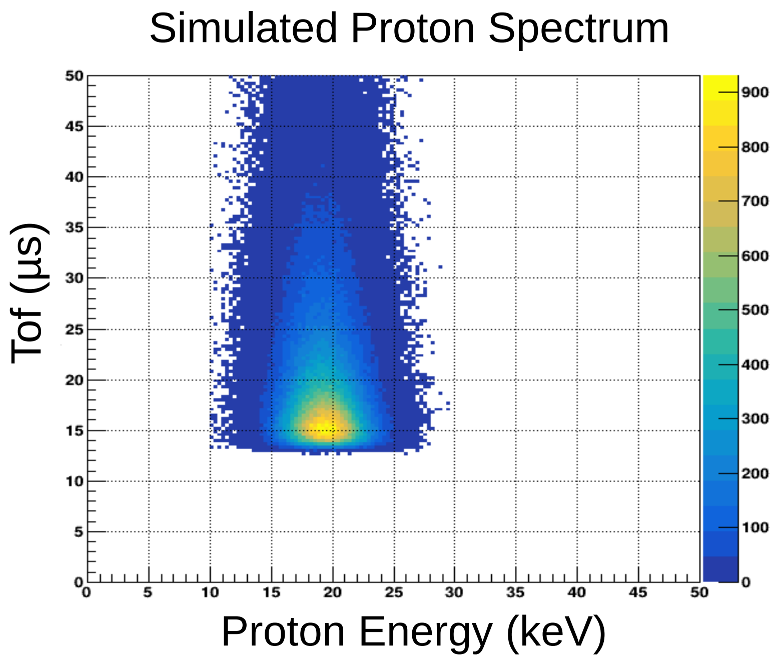
- Caveat: Electronics and Detector Issues
  - Electronics unstable
  - Parts of detector system unresponsive
  - Lower detector underdepleted

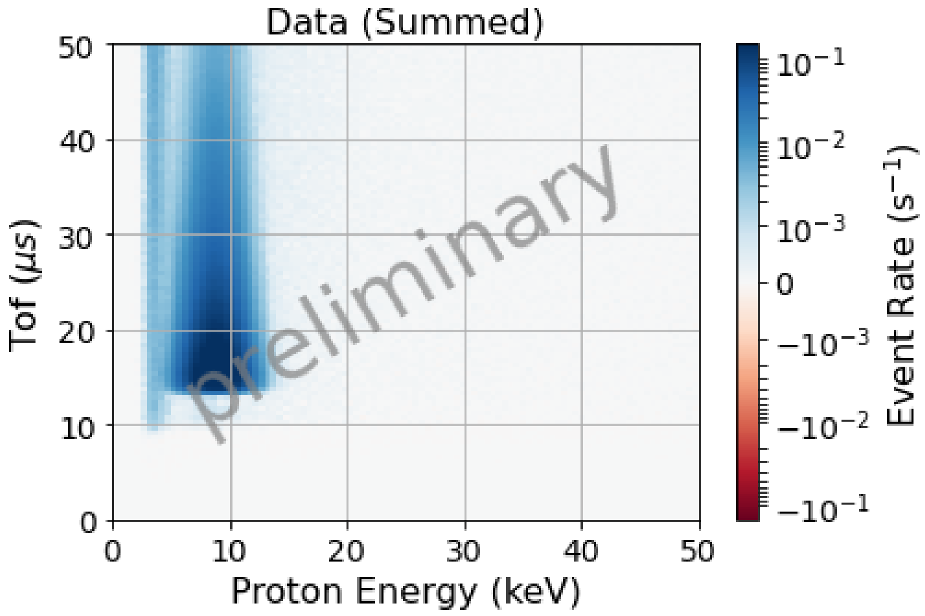


- Upgrade of detector system underway

Proton Response

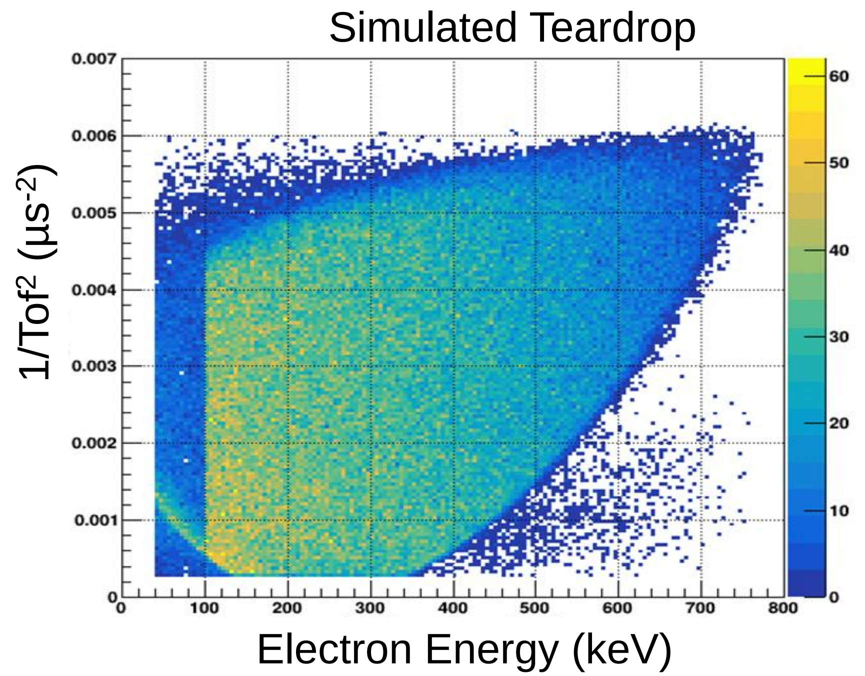
- We see protons!
  - Observed p^+, e^- coincidence rate in our detectors $\sim 50\ n/s$
- Proton peak lower than expected
  - Expected 20 keV for -30 kV detector voltage
  - See peak at ~10 keV, lower than expected

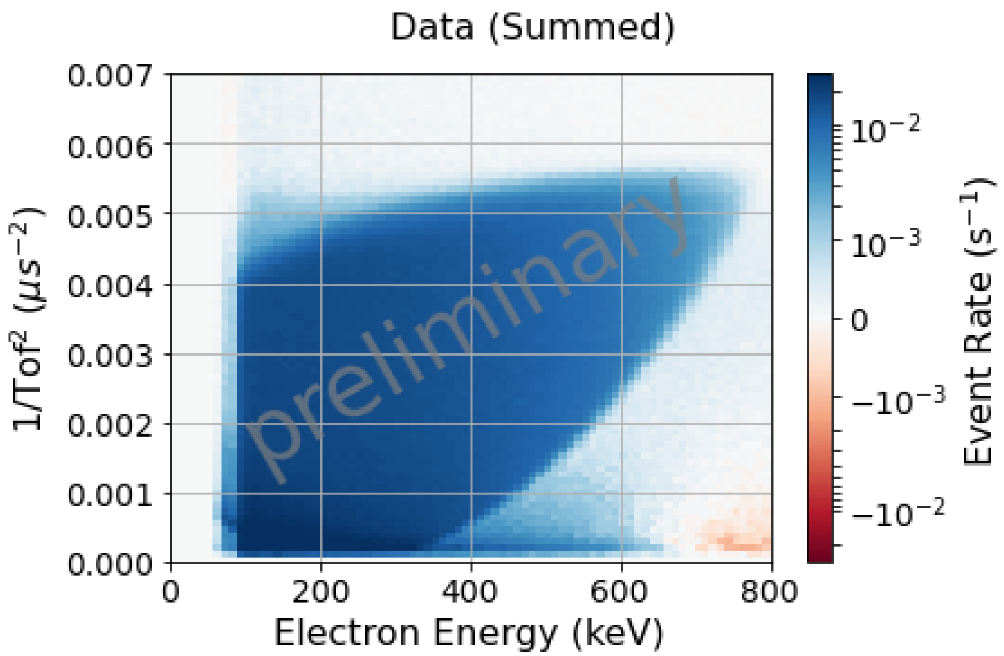




Neutron Decays!

- First Full-Phasespace Reconstruction of Neutron Decay!
- Measured 1.6e7 coincidences above background
  - Corresponds to $(\Delta a/a)_{stat} \sim 1.1 \times 10^{-2}$
  - Detector response leads to large (presently unquantified) systematic shifts





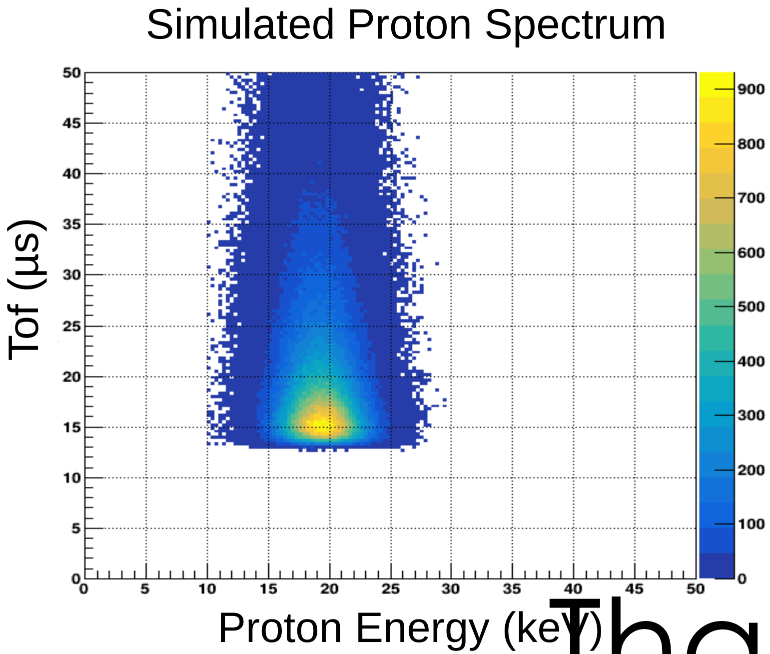
The Nab Collaboration

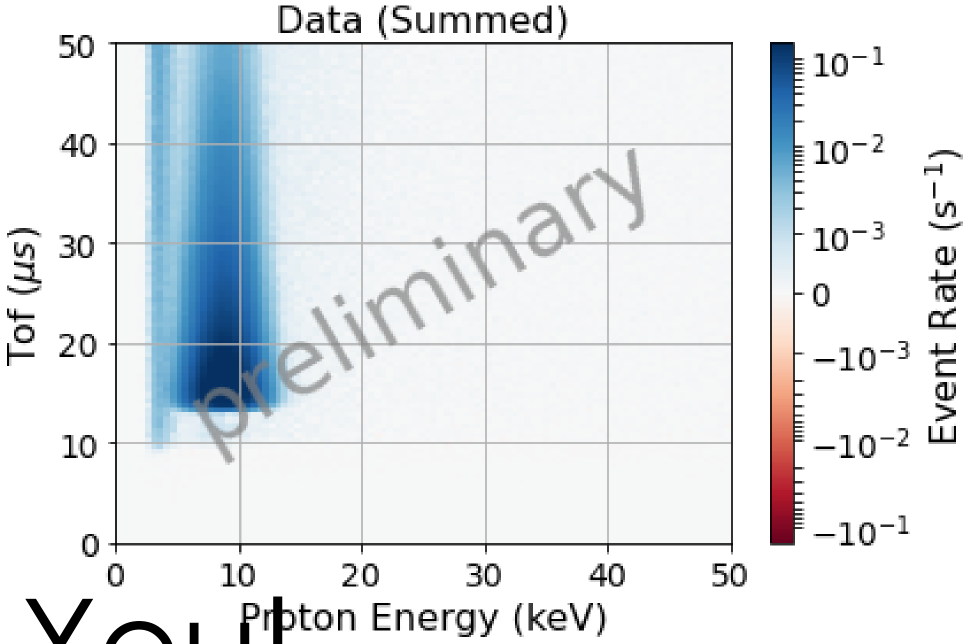
- Nab Collaborating Institutions:

Oak Ridge National Laboratory
Los Alamos National Laboratory
University of Virginia
The University of Tennessee Knoxville
Arizona State University
NC State University
Massachusetts Institute of Technology
University of Kentucky
University of Michigan
EKU Eastern Kentucky University
The University of Tennessee Chattanooga
Universidad Nacional Autónoma de México
University of Manitoba
The University of Winnipeg
GT
WKU
Universität Karlsruhe (TH)
Forschungsuniversität • gegründet 1825
University of South Carolina

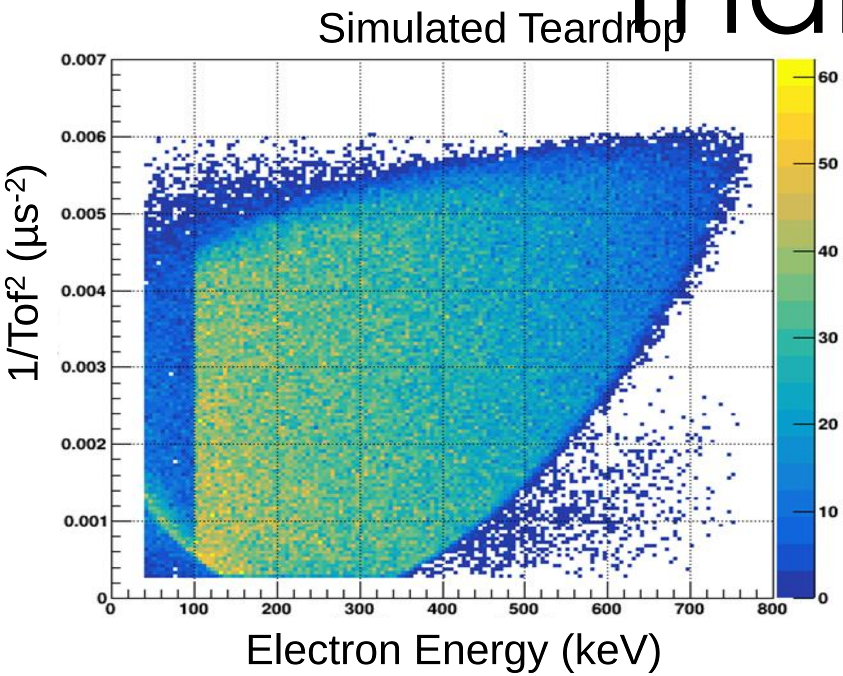
Main Project Funding:

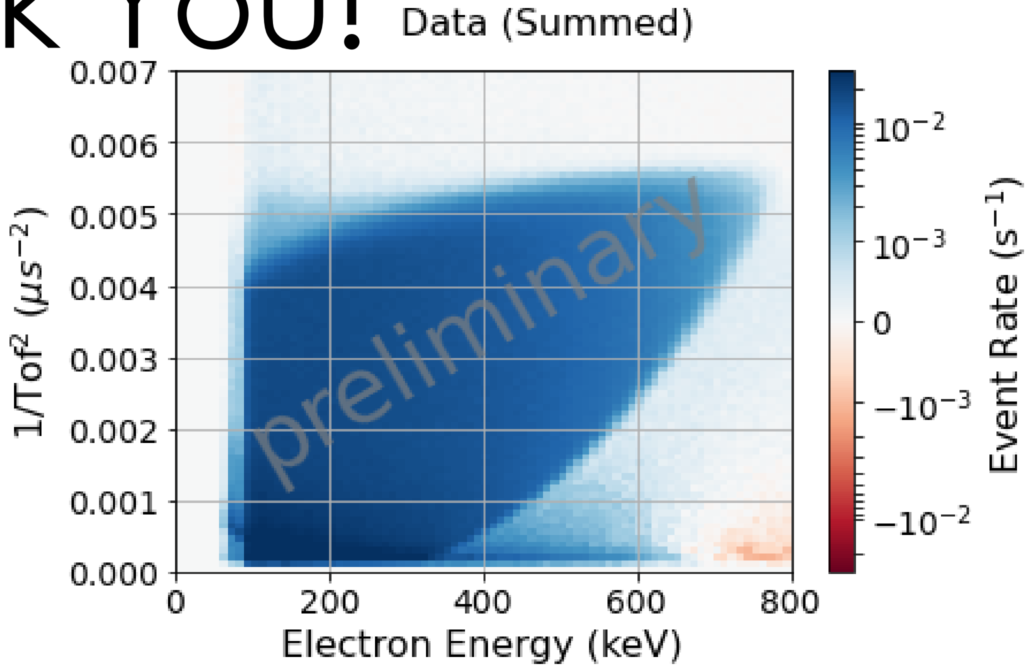
NSF
U.S. Department of Energy Office of Science
Oak Ridge National Laboratory
University of Virginia


Simulated Proton Spectrum
Tof (µs)
Proton Energy (keV)


Data (Summed)
Tof (µs)
Proton Energy (keV)
Event Rate (s⁻¹)
preliminary

Thank You!


Simulated Teardrop
1/Tof² (µs⁻²)
Electron Energy (keV)


Data (Summed)
1/Tof² (µs⁻²)
Electron Energy (keV)
Event Rate (s⁻¹)
preliminary

Extra Slides (Nab)

Full Systematics Budget a

Experimental Parameter	Parameter Breakdown	Design Specifications or Other Comments	$(\Delta a / a)_{sys.}$
Magnetic Field	Curvature at Pinch	$\Delta\gamma/\gamma = 2\%$ with $\gamma = d^2 B_z(z)/dz^2/B_z(0)$	5.3×10^{-4}
	Ratio $r_B = B_{TOF}/B_0$	$(\Delta r_B)/r_B = 1\%$	2.2×10^{-4}
	Ratio $r_{B,DV} = B_{DV}/B_0$	$(\Delta r_{B,DV})/r_{B,DV} = 1\%$	1.8×10^{-4}
Electric Potential Inhomogeneity	In Decay Volume / Filter Region	$\lvert U_F - U_{DV}\rvert < 10$ mV	5×10^{-4}
	In TOF Region	$\lvert U_F - U_{TOF}\rvert < 200$ mV	2.2×10^{-4}
Neutron Beam	Position	$\Delta\overline{z_{DV}} < 2$ mm	1.7×10^{-4}
	Profile	Slope at edges $< 10\%$ / cm	2.5×10^{-4}
	Doppler Effect	Analytical Correction	$< 1 \times 10^{-4}$
	Unwanted Beam Polarization	$\lvert\overline{P_n}\rvert \ll 10^{-4}$	1×10^{-4}
Detector Effects	Electron Energy Calibration	$\Delta E < 0.2$ 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}
Adiabaticity of Proton Motion			1×10^{-4}
Electron TOF		Analytical Correction	$< 1 \times 10^{-4}$
Residual Gas		$P < 2 \times 10^{-9}$ torr	3.8×10^{-4}
TOF in Acceleration Region		$\Delta r_{ground\ el.} < 0.5$ mm	3×10^{-4}
Background/Accidental Coincidences		Will subtract out of time coinc.	$< 1 \times 10^{-4}$
Length of the TOF Region		Fitted Parameter in Analysis	N/A
Sum			1.2×10^{-3}

Systematic Reach for b

Experimental Parameter	Parameter Breakdown	Design Specifications or Other Comments	$(\Delta b\ /\ b)_{sys.}$
Detector Calibration and Response	Gain Factor	Fitted Parameter in Analysis	N/A
	Offset	$\Delta_{off} < 0.08$ keV	1×10^{-3}
	Nonlinearity Determination	|Maximum Discrepancy| < 0.07 keV	1×10^{-3}
	Full Width-Half Mean Determination	Negligible	N/A
	Tail	$\Delta_{tail} < 1\%$	1×10^{-3}
Time of Flight Cut		$\text{TOF Cut} > 22$ μs	5×10^{-4}
Neutron beam polarization		Negligible	N/A
Proton Detection Efficiency		Negligible	N/A
Edge effect		Detection Radius < 2.9 cm	1×10^{-3}
Sum			2.2×10^{-3}

PhD Thesis H. Li, UVA

Statistical Reach of Nab

- Expect 1600 decays/second in decay volume
  - 12.7% of protons go to upper detector
  - 200 protons/second
- Can see 3.8×10^8 events in 6 weeks
  - $(\Delta a/a)_{stat} \sim 2 \times 10^{-3}$
  - $\Delta b_{stat} \sim 2 \times 10^{-4}$ (but really parasitic)
- Over 2 years of dedicated running, reach 4.4×10^9 protons in upper detector
  - $(\Delta a/a)_{stat} \sim 7 \times 10^{-4}$
  - $\Delta b_{stat} \sim 7 \times 10^{-5}$

$E_{e,min}$ (keV)	0	100	100	100
$t_{p,max}$ (μs)	∞	∞	40	30
Δa (N_u, a, b)	$2.4/\sqrt{N_u}$	$2.5/\sqrt{N_u}$	$2.7/\sqrt{N_u}$	$3.0/\sqrt{N_u}$
$+ E_{cal}$, L_{TOF}	$2.6/\sqrt{N_u}$	$2.7/\sqrt{N_u}$	$2.9/\sqrt{N_u}$	$3.2/\sqrt{N_u}$
+ 75% of data	$3.4/\sqrt{N_u}$	$3.5/\sqrt{N_u}$	$3.8/\sqrt{N_u}$	$4.4/\sqrt{N_u}$
+10% bkg.	$4.4/\sqrt{N_u}$	$4.6/\sqrt{N_u}$	$4.7/\sqrt{N_u}$	$5.2/\sqrt{N_u}$

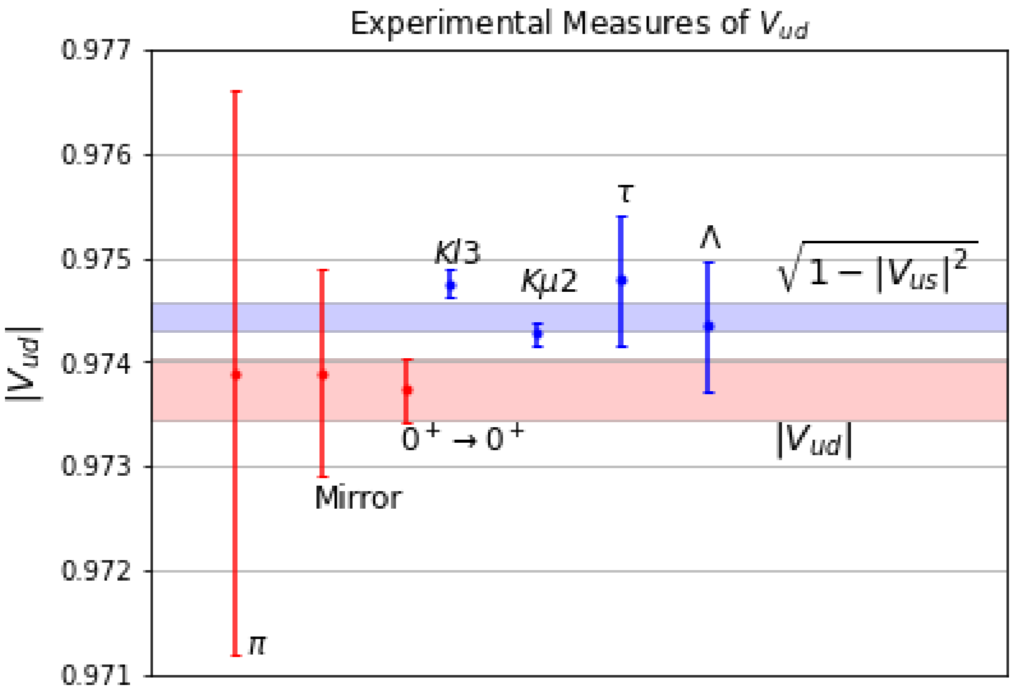
D. Počanić, UVA

$E_{e,min}$ (keV)	0	100	200	300
Δb (N, a, b)	$7.5/\sqrt{N}$	$10.1/\sqrt{N}$	$15.6/\sqrt{N}$	$26.3/\sqrt{N}$
$+ E_{cal}$	$9.1/\sqrt{N}$	$12.7/\sqrt{N}$	$20.4/\sqrt{N}$	$36.0/\sqrt{N}$

H. Li, UVA

Experimental Probes of CKM Unitarity

- Precision measurements of CKM (quark-mixing matrix) unitarity:
  - $|V_{ud}|^2 + |V_{us}|^2 + |V_{ub}|^2 = 1 + \Delta_{BSM}$
    - $\begin{pmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{pmatrix}$
- Measurements of V_{ud}:
  - Most precise "Superallowed" $0^+ \to 0^+$ decays
  - Require radiative and nuclear structure corrections ($0^+ \to 0^+$, Mirrors)
- Measurements of V_{us}:
  - Most precise from Kaon decays
  - Tension between different decay channels
- Presently 2.2σ discrepancy!



Data from:

- Workman, R. L. *et al*, Particle Data Group (2022)
- J. C. Hardy and I. S. Towner, Physical Review C 102, 045501 (2020)
- L. Hayen, Physical Review D 103, 113001 (2021)

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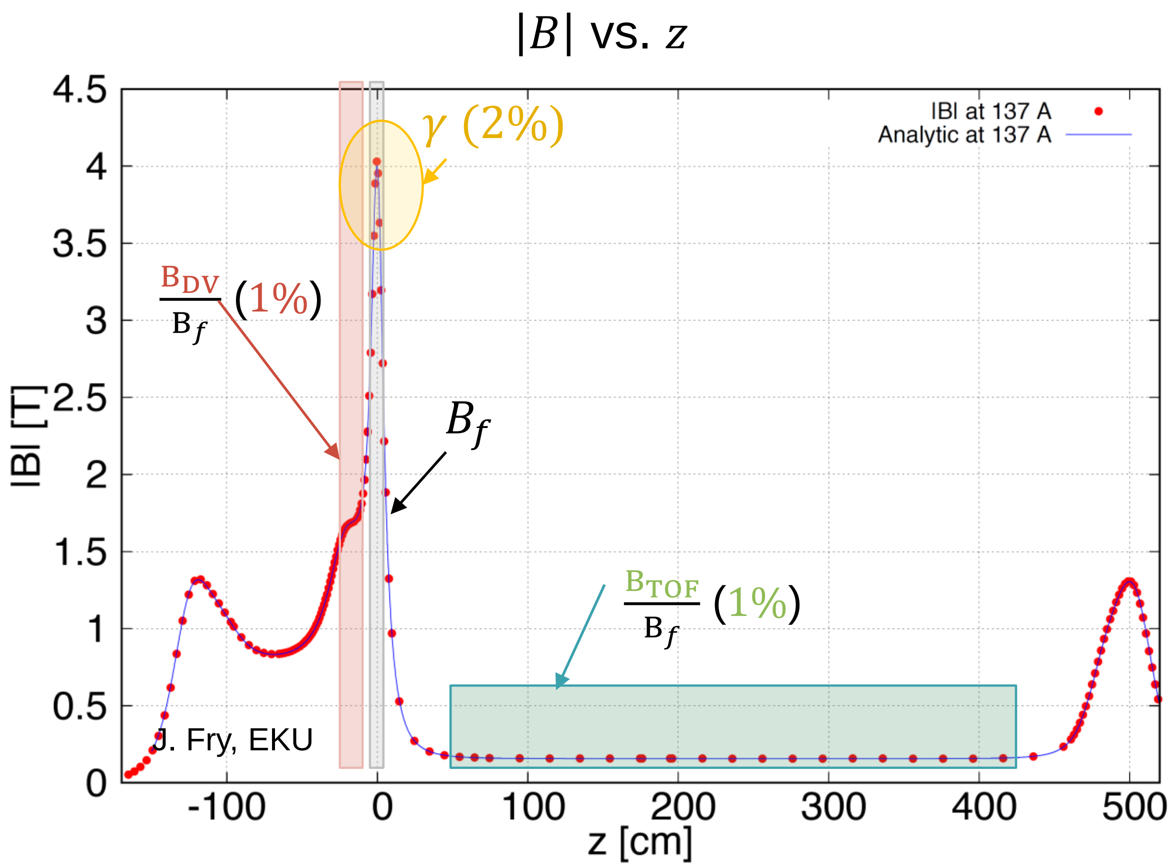
Characterization of Magnetic Field

- Need to understand $B(z)$ to determine t_p
  - Have done measurements with Hall probe
  - Good agreement with simulation
- Analysis of magnetometry data ongoing

Magnetic Field	Target Uncertainty	$(\Delta a\ /\ a)_{sys.}$
Curvature at Pinch γ	$\Delta\gamma/\gamma = 2\%$	5.3×10^{-4}
Ratio $r_{B,\mathrm{TOF}} = B_{TOF}/B_f$	$(\Delta r_{B,\mathrm{TOF}})/r_{B,\mathrm{TOF}} = 1\%$	2.2×10^{-4}
Ratio $r_{B,DV} = B_{DV}/B_f$	$(\Delta r_{B,DV})/r_{B,DV} = 1\%$	1.8×10^{-4}
SUM		6.0×10^{-4}



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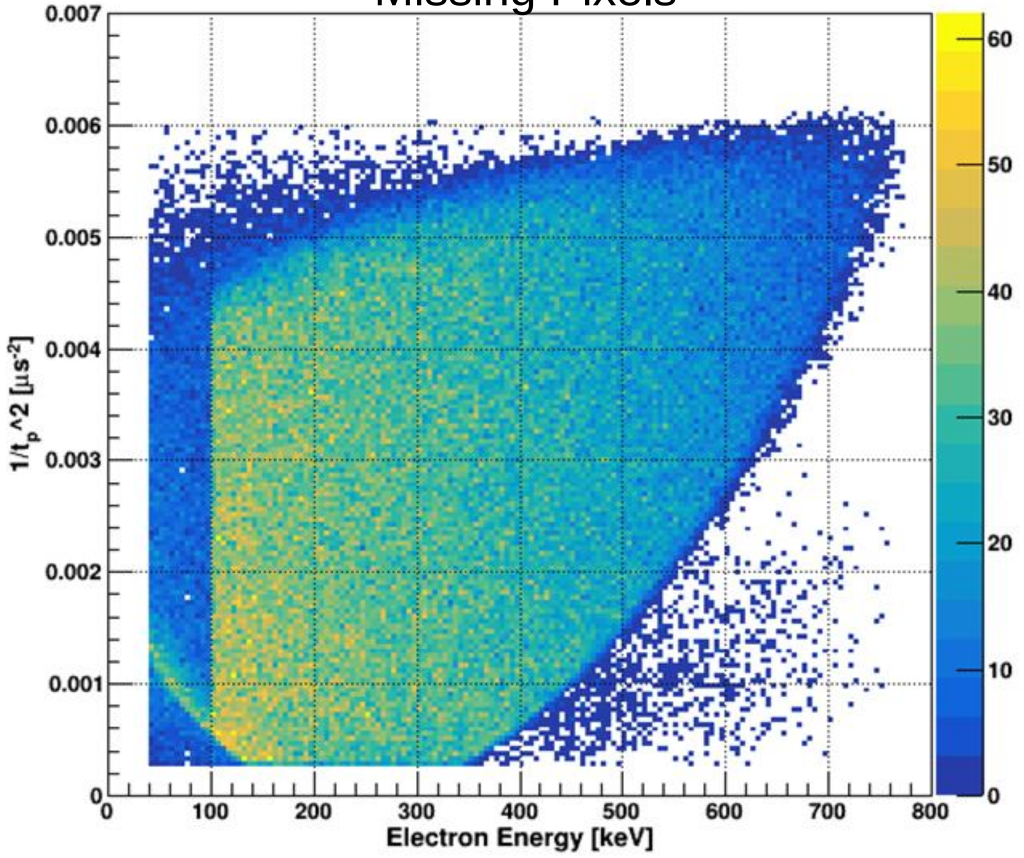
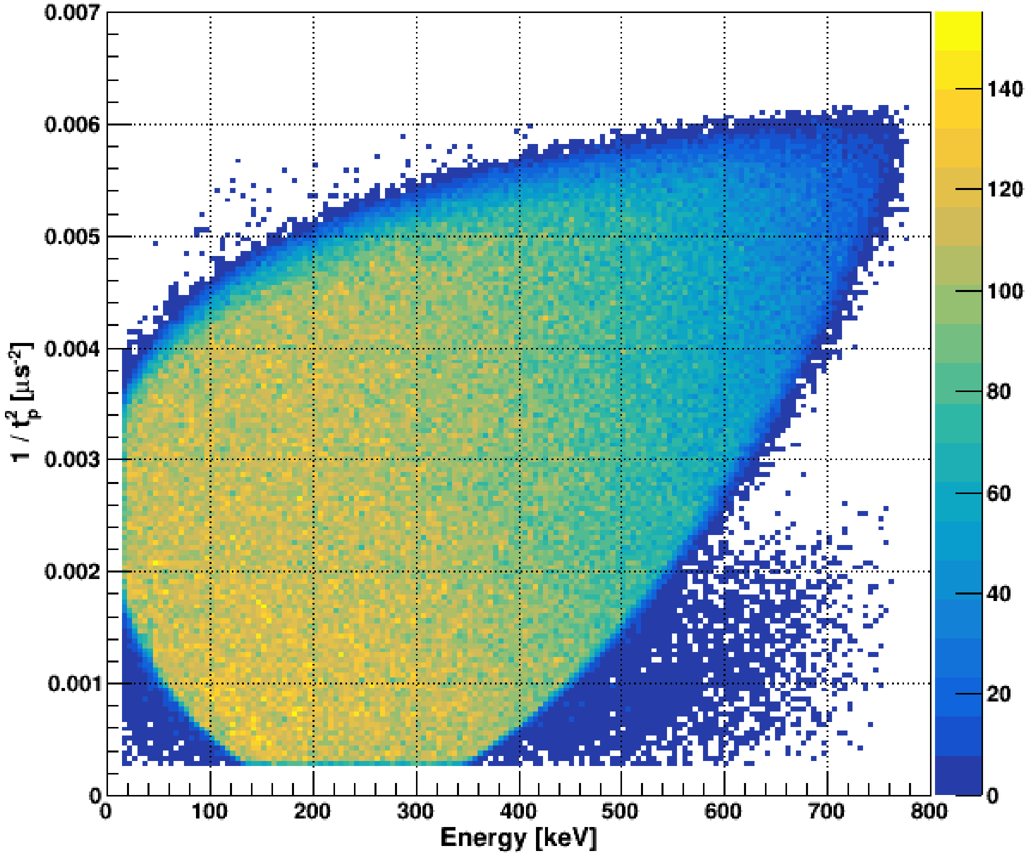
Distortion of Teardrop Due To Missing Pixels

Simulated Teardrop,
Missing Pixels



Simulated Teardrop
Uniform Threshold



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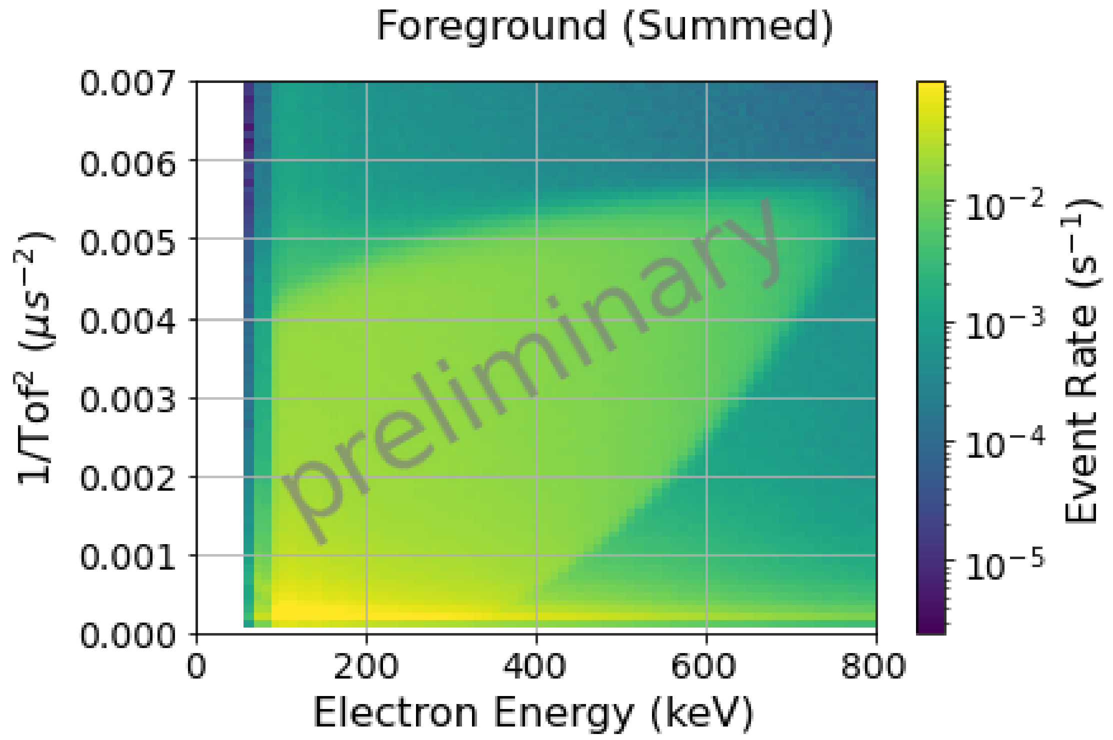
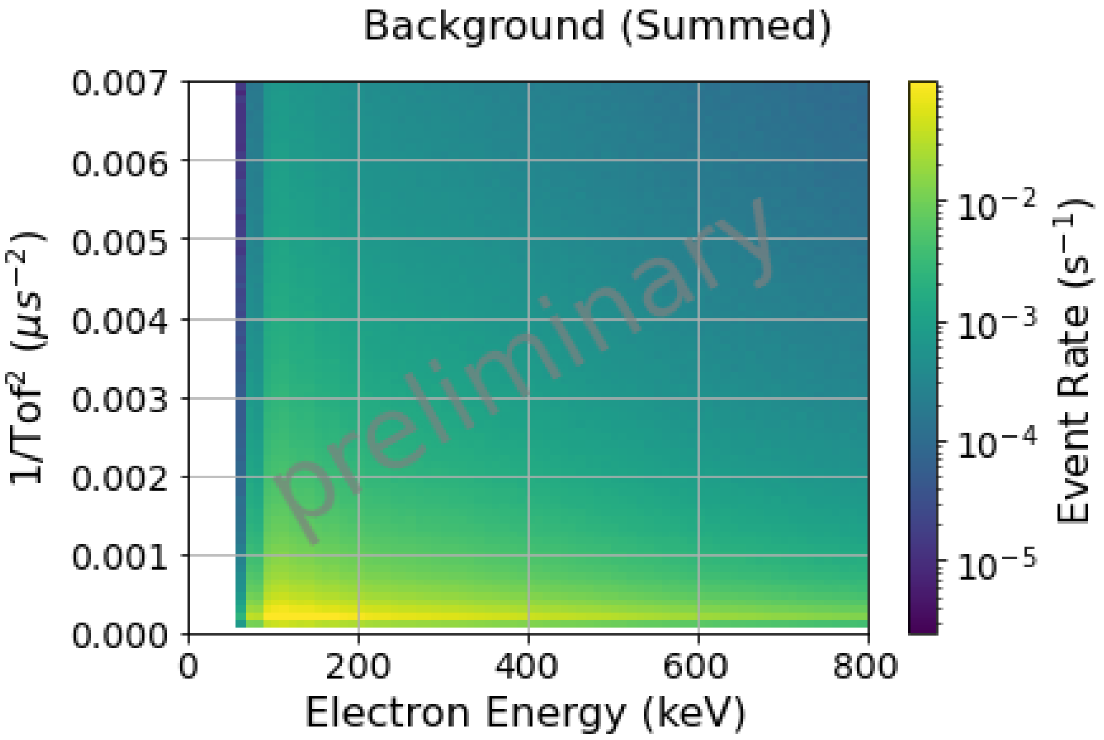
Foreground and Background

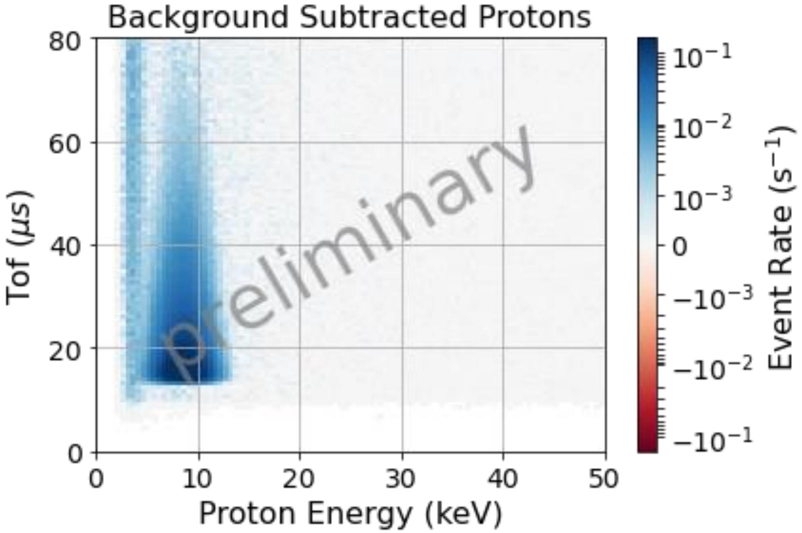


23.2e6 counts

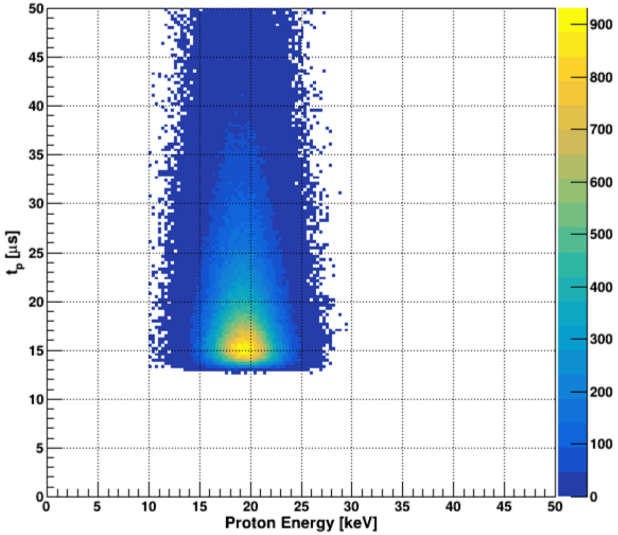


6.8e6 counts

Coincidence Timing Distribution

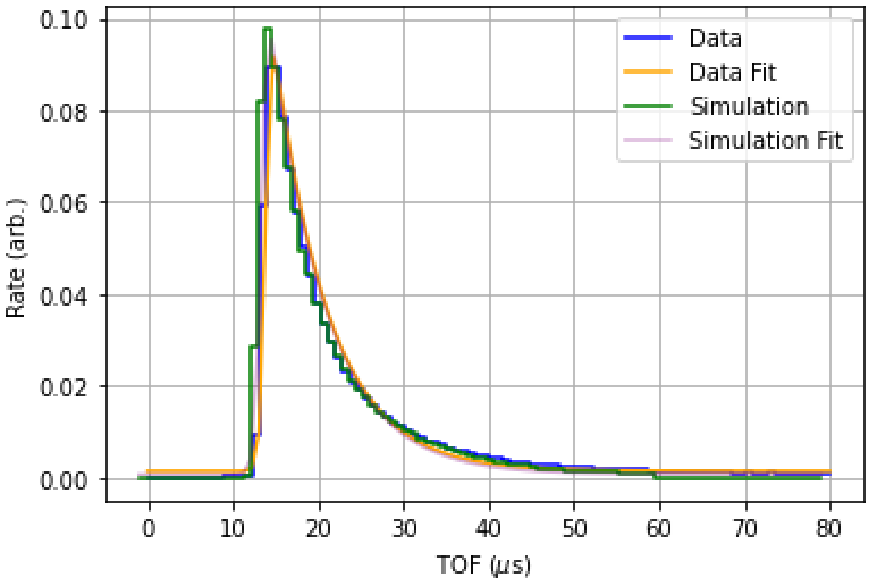


Simulated Proton Spectrum



- 500 ns difference between simulation and data

Projection Along All Energies



Looking Forward: pNab

Use the same apparatus to measure A, B

- Add a neutron beam polarizer
- 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!