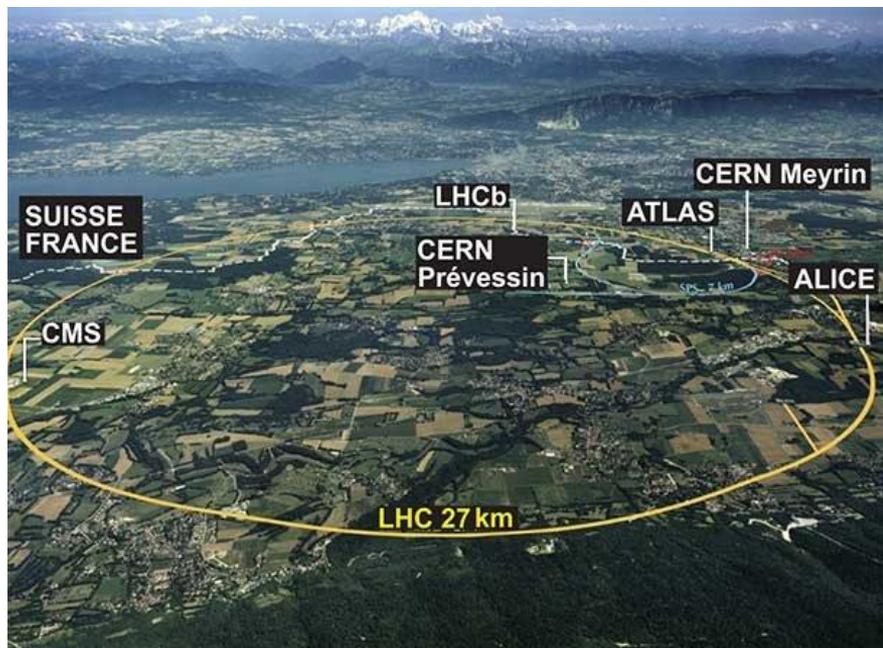# α, β pulse shape discrimination in silicon detectors

Louis Varriano, Isaac Kunen, Christian Nave,
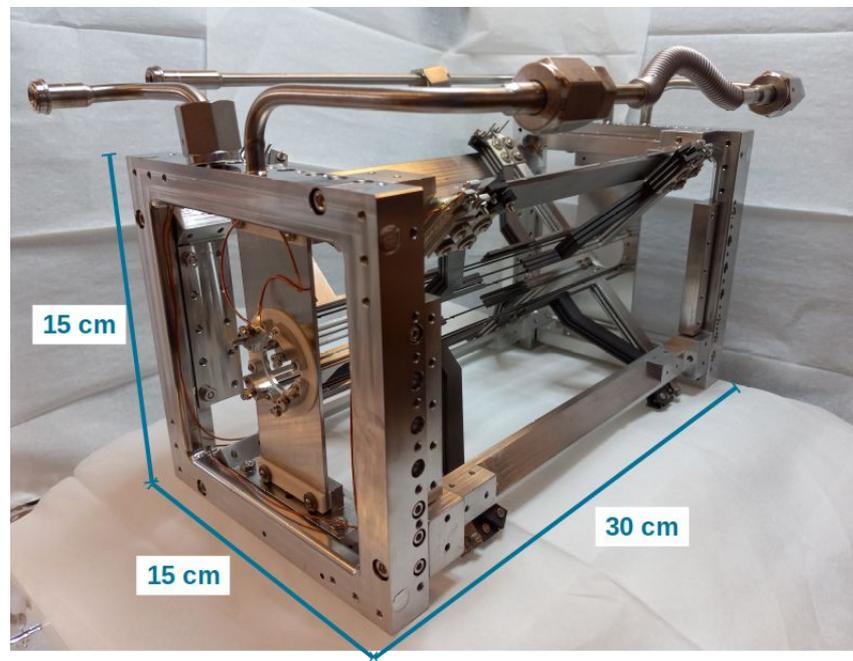Forest Tschirhart

University of Washington
8 October 2025

Instruments to investigate the Standard Model

Instruments to investigate the Standard Model

Weak interaction probes are rigorous test of SM

General β decay Hamiltonian:

$$H_\beta = g\left[\sum_i (\bar\psi_p \Lambda_i \tau_\pm \psi_n)\left(\bar\psi_e \Lambda_i (C_i + C_i'\gamma_5)\psi_\nu\right)\right] + h.c$$

i : Scalar (S), Vector (V), Tensor (T),
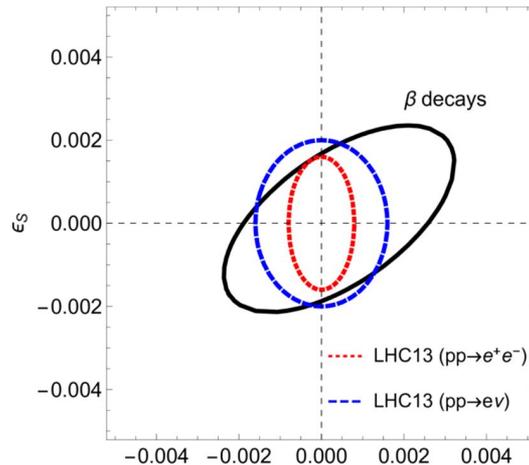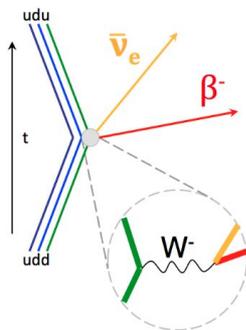 Axial Vector (A), & Pseudoscalar (P)

Λ_i : Corresponding operator for each interaction

Applying Fermi's Golden Rule,

$$\Gamma(E)dE_e = \frac{2\pi}{\hbar}|H_{fi}|^2\frac{dn}{dE_o} \quad \text{where} \quad H_{fi} = \int H_\beta \, d\mathbf{r}_1 d\mathbf{r}_2 ... d\mathbf{r}_A$$

We obtain the Decay Rate:

$$\frac{d\Gamma}{dE_e d\Omega_e d\Omega_\nu} \propto F(Z, E_e) p_e E_e (E_0 - E_e)^2 \left(1 + a_{\beta\nu}\frac{\vec{p_e}\cdot\vec{p_\nu}}{E_e E_\nu} + b_{Fierz}\frac{m_e}{E_e}\right) + \vec\sigma\left(G\frac{\vec{p_e}}{E_e} + H\frac{p_\nu}{E_\nu}\cdots\right.$$

A. Falkowski, M. González-Alonso, and O. Naviliat-Cuncic, J. High Energ. Phys. 2021, 126 (2021).

$$a_{\beta\nu} = -\frac{1}{3}\frac{(C_A^+)^2 - (C_T^+)^2 - (C_T^-)^2}{(C_A^+)^2 + (C_T^+)^2 + (C_T^-)^2}$$

$$b_{Fierz} = \pm 2\frac{C_A^+ C_T^+}{(C_A^+)^2 + (C_T^+)^2 + (C_T^-)^2}$$

- *S* (scalar) and *T* (tensor) terms might be present with small coefficients → BSM physics.

- **β-decays currently ~competitive with LHC results → several experiments planned to continue pushing these down**

- Additionally, can test CKM unitarity, test theories about the weak interaction in nuclei, and even directly search for dark matter, …
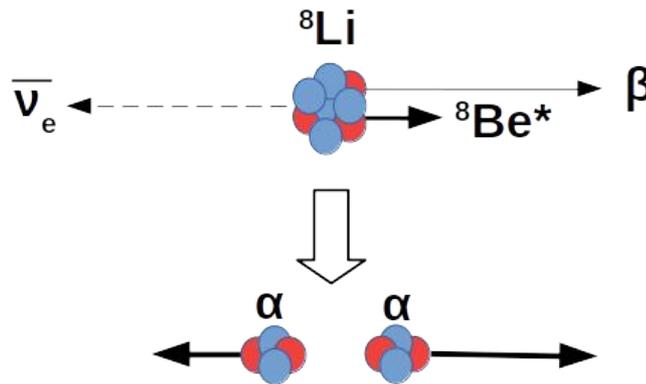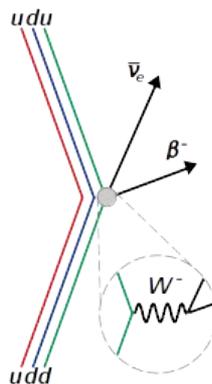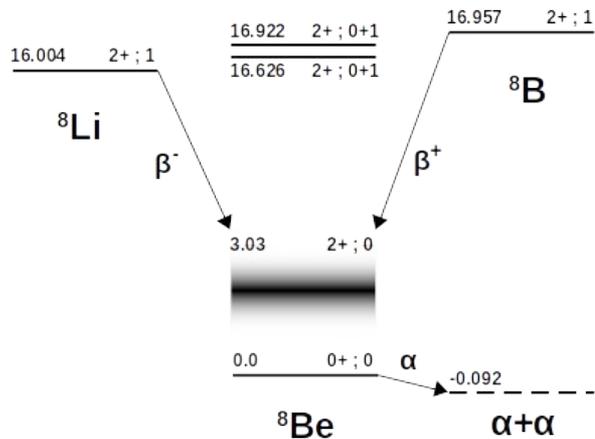
- **Detect all charged decay products → can reconstruct the neutrino!**

- Recoil energy spectrum sensitive to *a* and *b* terms

- α energy difference ΔE_α spectrum contains same information but reduces detector systematics!

- Axial-vector: leptons preferentially emitted in opposite directions → smaller recoil, smaller ΔE_α

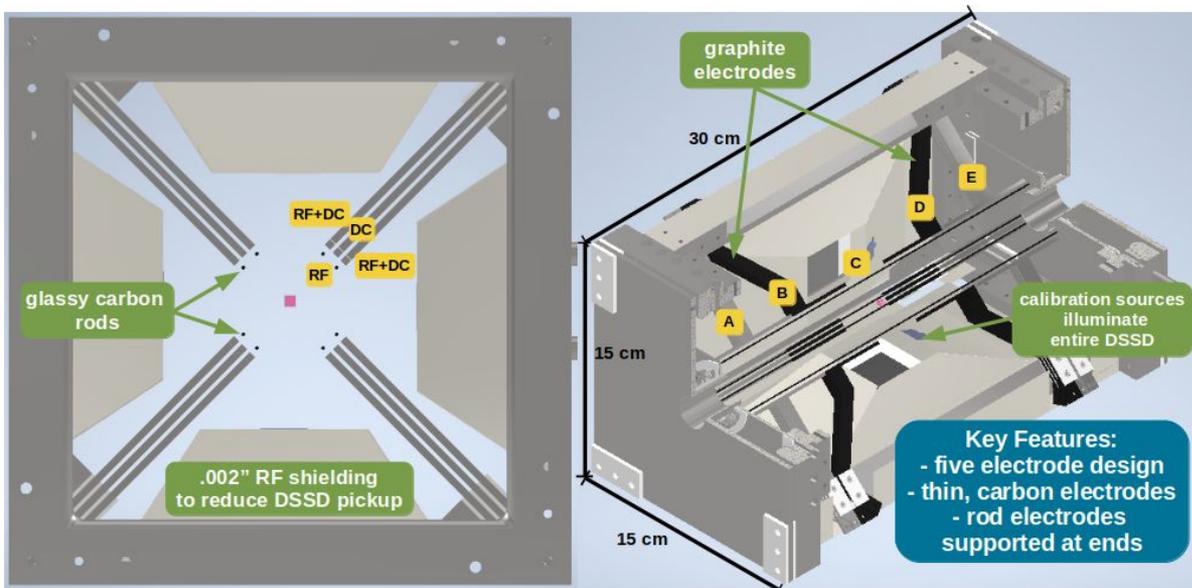- Tensor: leptons preferentially emitted in same direction → larger recoil, larger ΔE_α

$$dW = dW_0 \varepsilon \left[1 + \frac{p_e \cdot p_\nu}{E_e E_\nu} a_{\beta\nu} + \frac{\Gamma m_e}{E_e} b_{Fierz} + \ldots \right]$$

$$a_{\beta\nu} = -\frac{1}{3} \frac{(C_A^+)^2 - (C_T^+)^2 - (C_T^-)^2}{(C_A^+)^2 + (C_T^+)^2 + (C_T^-)^2}$$

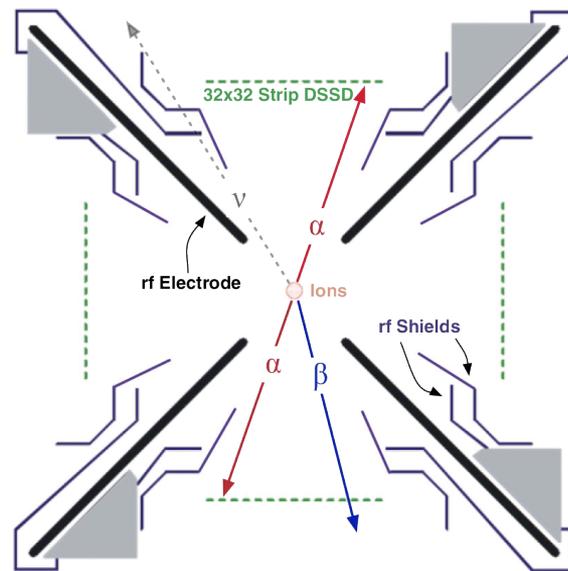$$b_{Fierz} = \pm 2 \frac{C_A^+ C_T^+}{(C_A^+)^2 + (C_T^+)^2 + (C_T^-)^2}$$
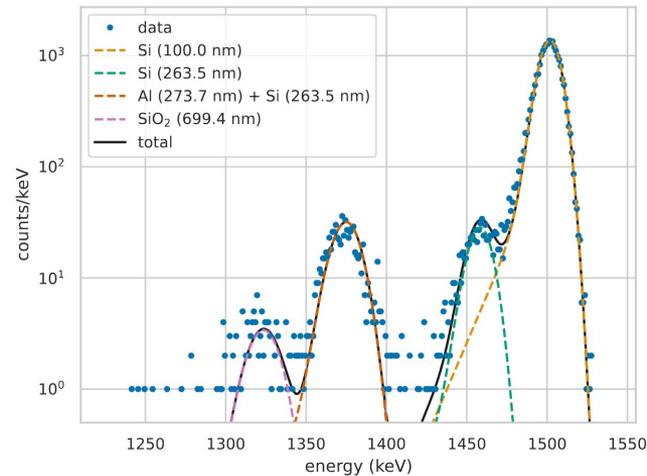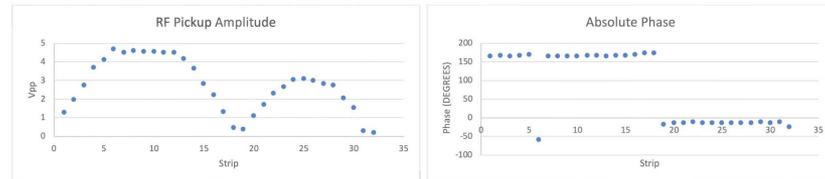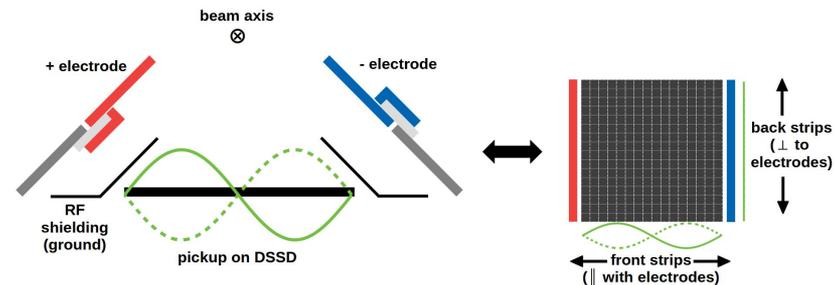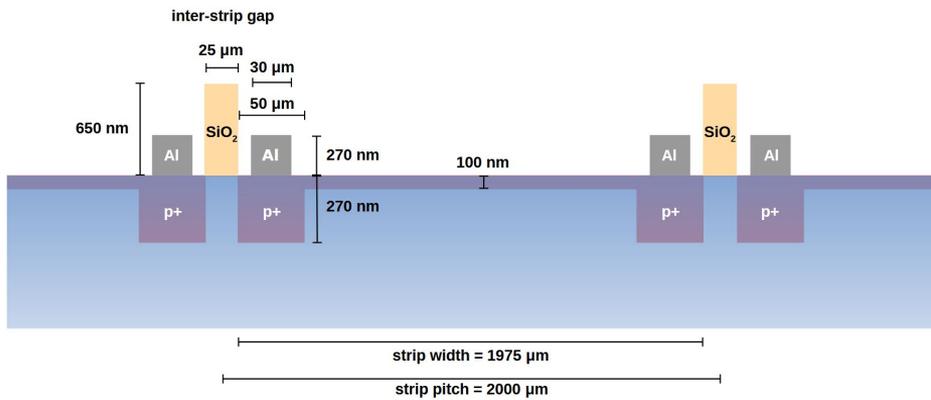
The Beta-decay Paul Trap (BPT) at ANL

L. Varriano et al., NIM A **1058**, 168818 (2024).

- Linear Paul trap with open geometry → RF & DC gradient + He buffer gas + LN$_2$ cooling → traps ion in few mm^3 region in center

- Surround by four 64×64 mm^2, 1 mm thick double-sided silicon strip detectors (DSSDs) to detect α energy and position and β position
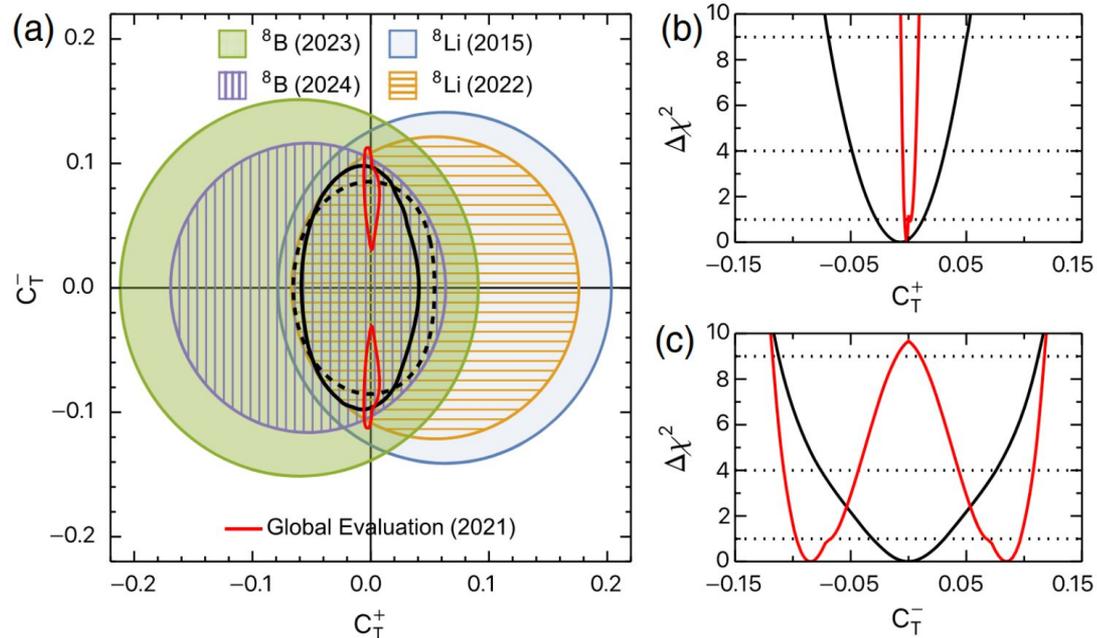
DSSDs in BPT

- 32x32 strip (2 mm pitch) Micron BB7 DSSD, 100 nm windows, 1mm thick

- RF pickup mitigated by notch filters and long shaping items (4 us)

- Cooled to ~80 K

- Average front and back strip energies for up to 30% resolution improvement

- Care greatly about surface features

- Low event rate of ~few hundred Hz
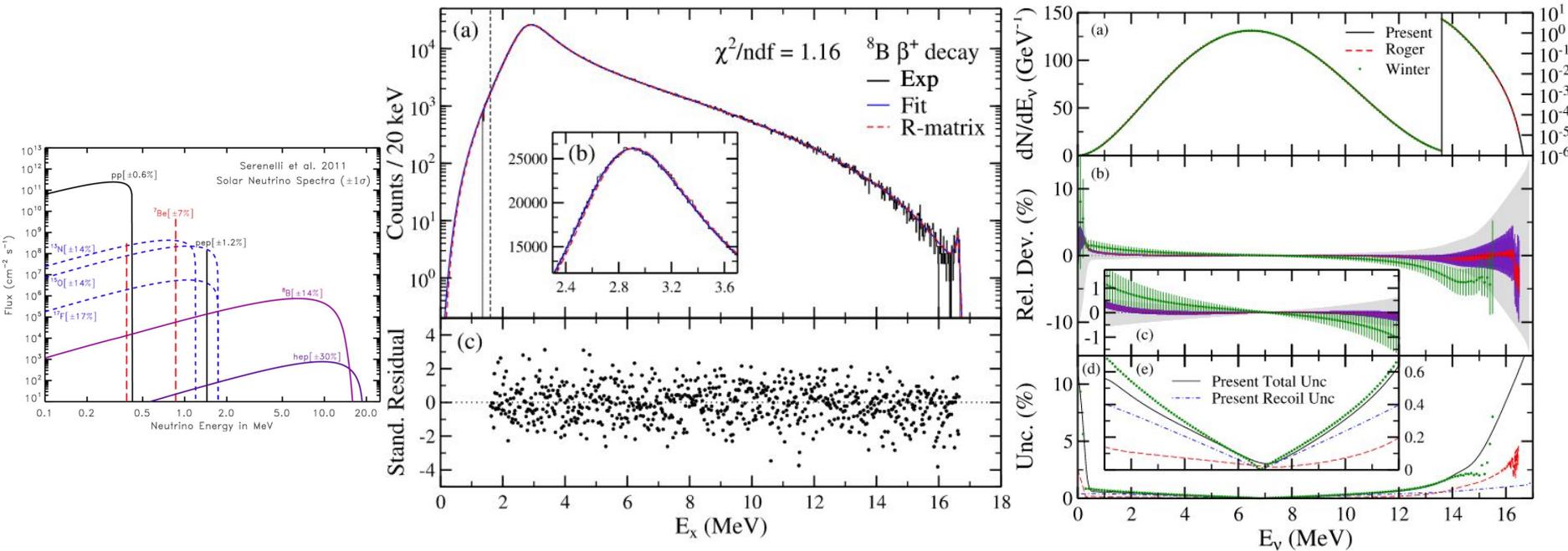
Recent ⁸B and ⁸Li results

- Joint limit from ^{8}B and ^{8}Li measurements

- **Combining results from mirror decays greatly improves power**

- Best limit on C_T from low-energy experiments

B. Longfellow et al., Phys. Rev. Lett. **132**, 142502 (2024)

*global evaluation here is only from β-decays
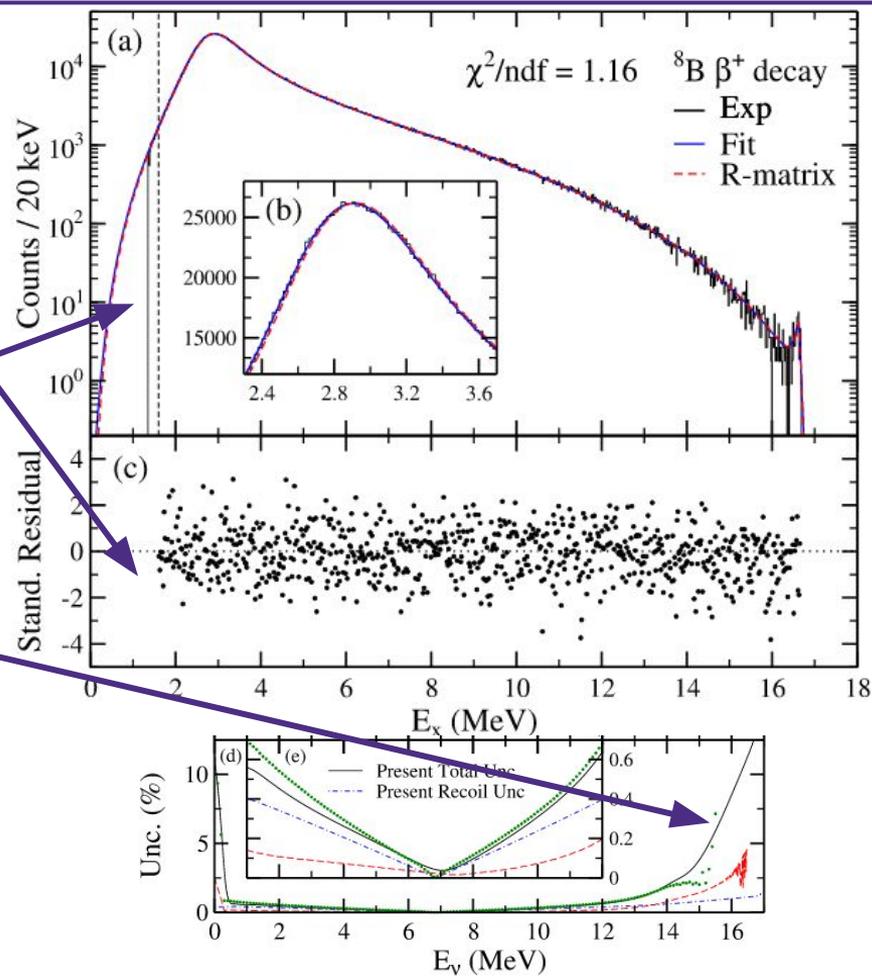
^{8}B unoscillated neutrino spectrum

B. Longfellow et al., Phys. Rev. C **107**, L032801 (2023)

- **First measurement with trapped ions**

- α summed energy spectrum is used to infer neutrino spectrum

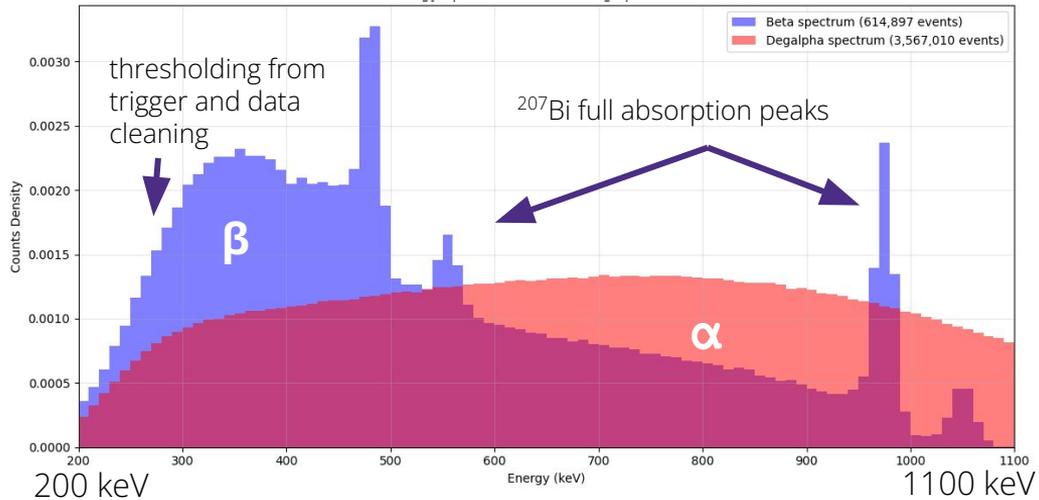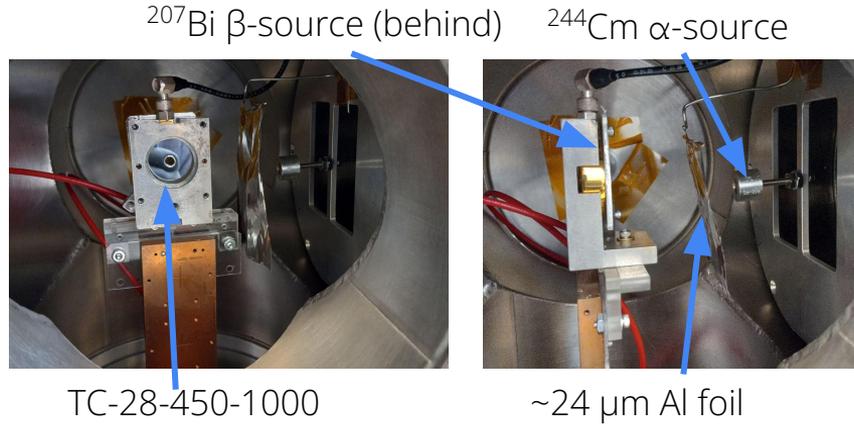- For higher statistics (~4×), use double-coincidence events

A problem

- BPT uses a single layer of detectors with analog electronics - worry about β scattering, which is a big systematic uncertainty.

- Can only distinguish between α and β by amount of deposited energy → leads to uncertainty on particle type at α energies < ~700 keV.

- Lowest energy α → highest energy neutrinos, where experiments would like to have the best knowledge of spectrum shape.

- **Can we distinguish between α and β with pulse shape discrimination?**

Test with a simple detector

- Ortec C Series partially depleted silicon surface barrier detector, ~1 mm depleted region

- Mesytec MSI-8 preamp and CAEN DT5730 digitizer 500 MS/s, 14 bit

- ^{207}Bi chosen for conversion electrons at 1 MeV (lower energy lines also present)

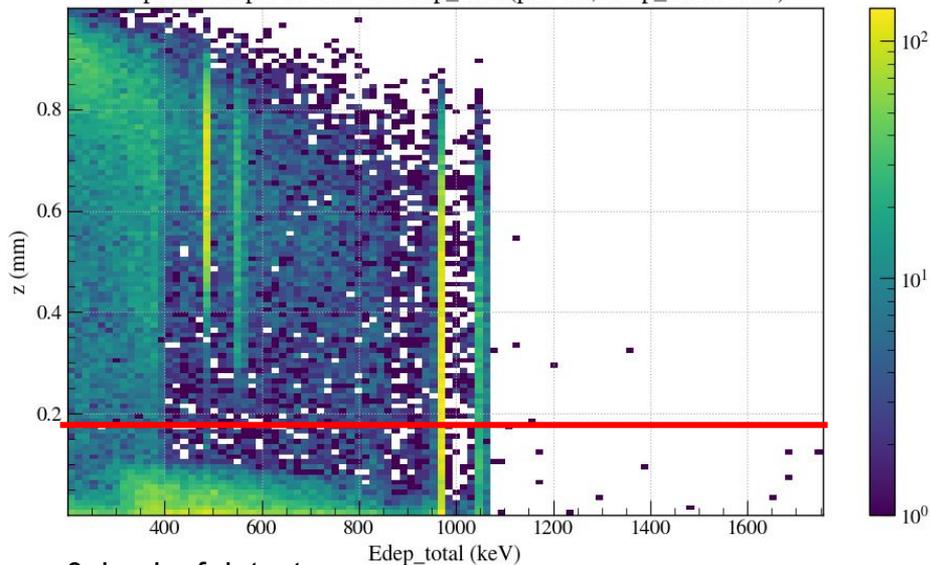- degrade ^{244}Cm α to < ~1 MeV with Al foil

Isaac Kunen

Forest Tschirhart

CJ Nave

^{207}Bi β-source (behind) ^{244}Cm α-source

TC-28-450-1000   ~24 μm Al foil

thresholding from trigger and data cleaning

^{207}Bi full absorption peaks

β

α

200 keV   1100 keV

Comparison to simulation

- Expect largest difference in waveform for β that reach back of detector ("MIP-like")

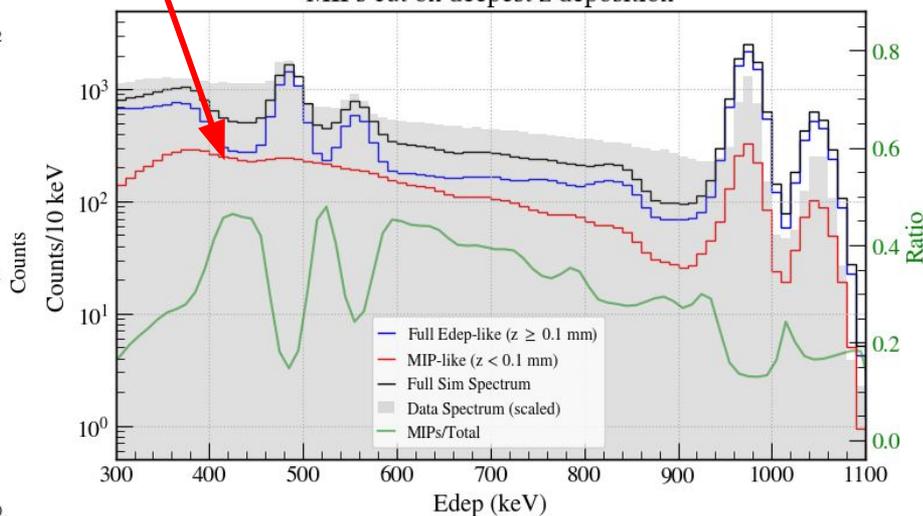- Simulations show that data not quite as "MIP-like" as desired → better (higher energy) β source needed

z = 1, front of detector
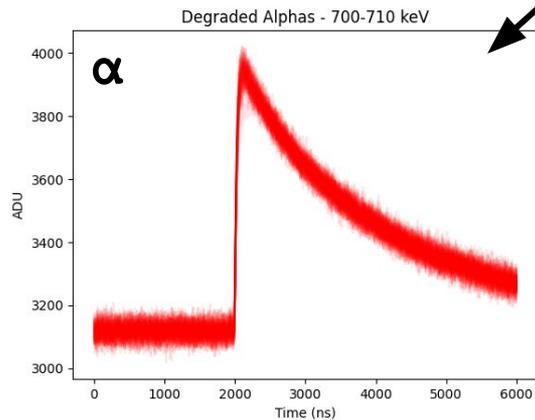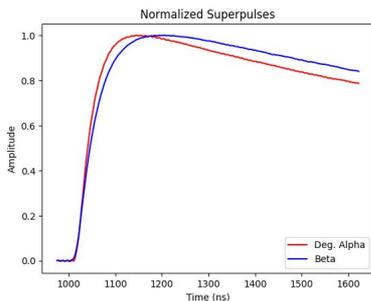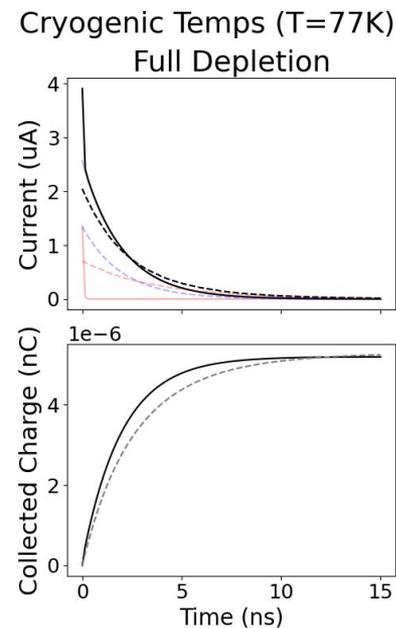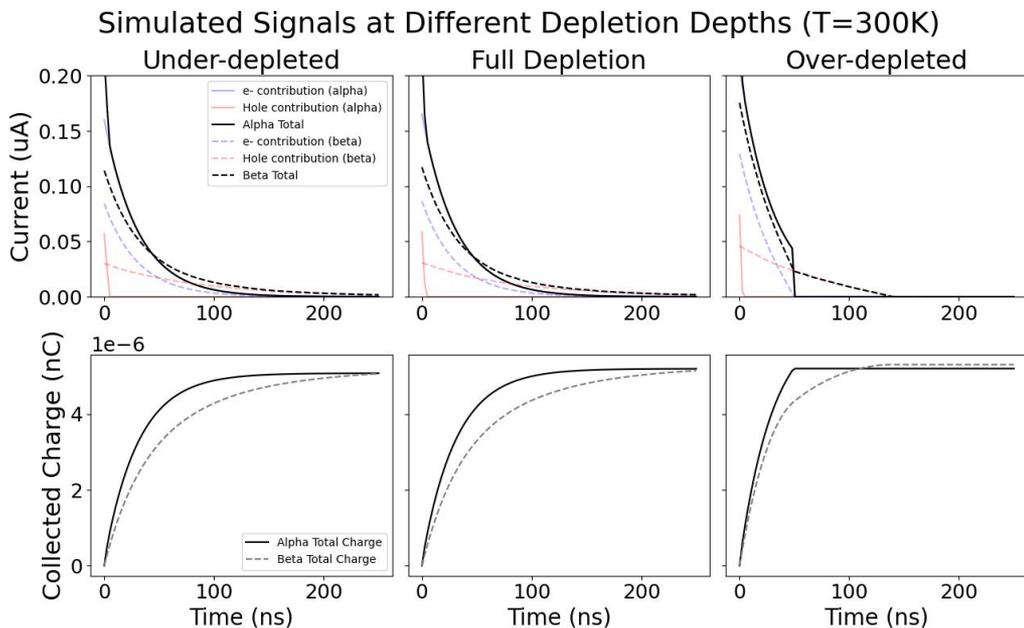

z = 0, back of detector
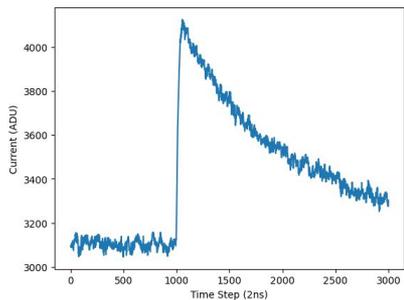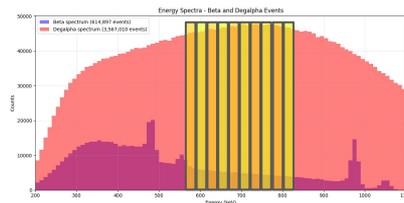
Example waveforms

Simulated waveforms

- Basic simulation of charge drift without electronics response - shows rough agreement with data

- At cryogenic temperatures, will need much faster digitizer (~GS/s)

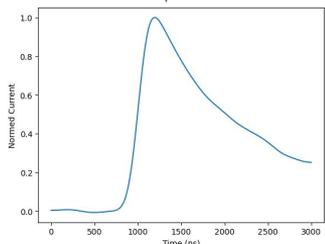# Model creation - looking mostly at simple models

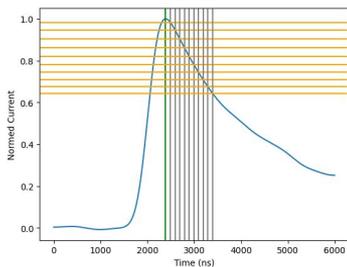Assign Energy (calibrated, trap filter)

Train & Evaluate Various Models

Stick to simple, explainable models.

Had good luck with good old logistic regression.

$$P(X) = \frac{1}{1 + \exp(-\beta_0 - \beta \cdot X)}$$

Select Data

Experimented with different training sets to see how this impacted prediction.

For each range, kept identical number of alphas/betas in 10 keV bands.

Smoothed, Normed

Try to erase the energy: just keep the pulse shape.

Compute Features

~80 metrics based on pulse & derivative; easy to calculate

Performance dependent on training range

Model Performance Comparison - Accuracy Across Energy Bands

Model Performance Comparison - Accuracy w/ Subset of Features

Comparing Models w/ Varying # of Features

- Accuracy okay so far (~85%) - more work to be done

- Seems that features of trained energy range are learned well - not clear that MIP-like events being identified
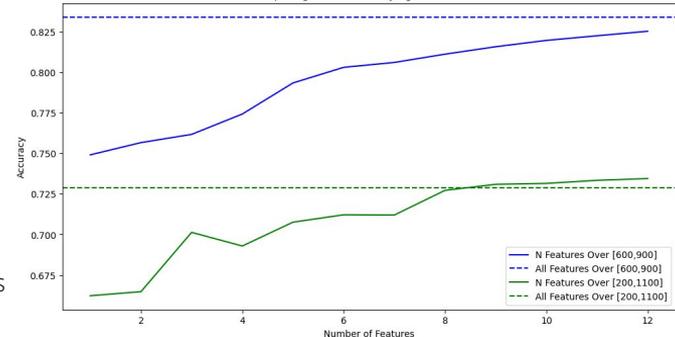
Top 5 features:

1: f_time_50pct
2: f_derivative_val_100ns
3: f_trap_950ns
4: f_derivative_avg_100ns
5: f_trap_ratio_900ns_over_100ns

Conclusion and next steps

- **Improved particle ID for BPT would lead to reduced uncertainty in ^{8}B neutrino spectrum shape at highest energies**

- Promising performance in PSD-based α, β discrimination in simple (non-optimal) system

- More data with higher-energy β source and second detector to directly tag MIPs

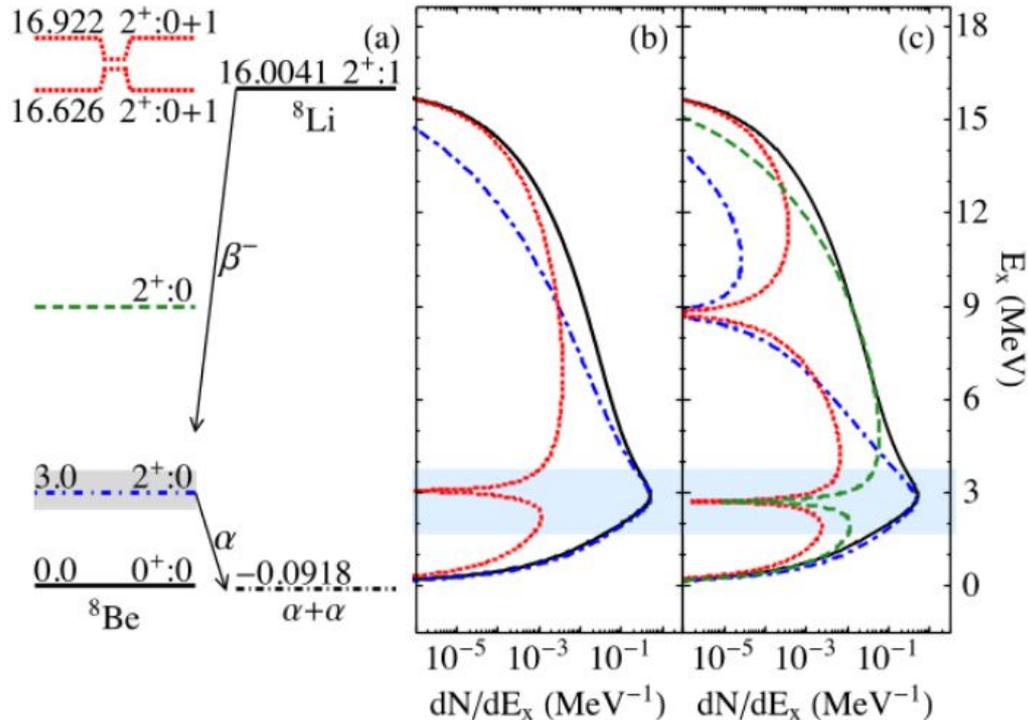- Cryogenic temperatures will require higher digitization rates

Isaac Kunen

Forest Tschirhart

CJ Nave

2^+ "intruder" state influence on $|C_T/C_A|^2$

- SA-NCSM predicts a broad 2^+, T=0 state near 9 MeV.

- R-matrix fits provides equally good fits with and without this state. Scattering phase shift data do not confirm / exclude this state, either.

- **Reduced E_x range in $|C_T/C_A|^2$ measurement to limit influence of possible "intruder" state.**

- May be possible to determine existence of this intruder by looking at $|C_T/C_A|^2$ dependence on E_x and agreement with SM.

- M. T. Burkey et al., PRL **128** 202502 (2022).