Overview of Neutron Decay Angular Correlation Measurements

(and comments about β energy-dependent observables)

A. R. Young

North Carolina State University/Triangle Universities Nuclear Laboratory

Outline

- Motivation for Angular Correlations Measurements (mostly covered in Vincenzo's talk)
- The Neutron Global Data Set (Chen-Yu Liu's talk covered the lifetime)
- β-asymmetry Measurements "A"
  - PERKEO III → Perc
  - UCNA → UCNA+ (Steven Clayton's talk)
  - pNab (Wolfgang Schreyer's talk)

- $\beta - \bar{\nu}_e$ correlation Measurements "a"
  - aCORN and aSPECT (Stefan Baessler's talk)
  - Nab (Dinko Pocanic's talk)

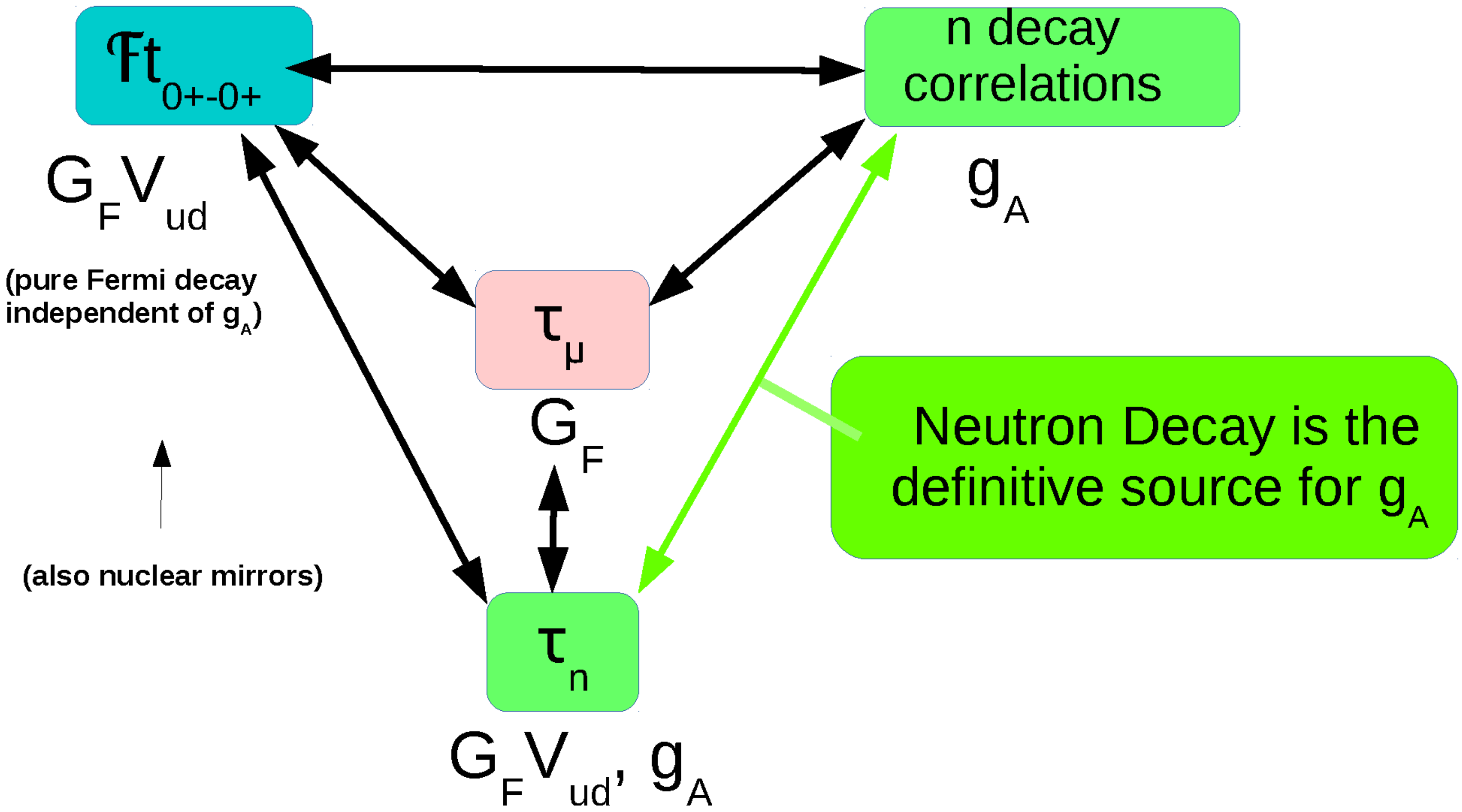
- Other correlations and exotic couplings
  - Spectrum measurements and Fierz Terms (Alejandro Garica's talk)
  - Measurements of proton observables with polarized neutrons
- Outlook and Conclusions

Motivation for Angular Correlation Measurements in Neutron Decay: Part II

Already heard from Vincenzo’s talk that beta-decay is a useful way to probe for new physics, emphasizing the impact of Unitarity tests

Expand on some points of interest (I hope)

SM parameters: G_F, V_{ud}, g_A – most precise experimental inputs



$\mathcal{F}t_{0+-0+}$

$G_F V_{ud}$

(pure Fermi decay independent of g_A)

(also nuclear mirrors)

n decay correlations

g_A

τ_μ

G_F

τ_n

$G_F V_{ud}$, g_A

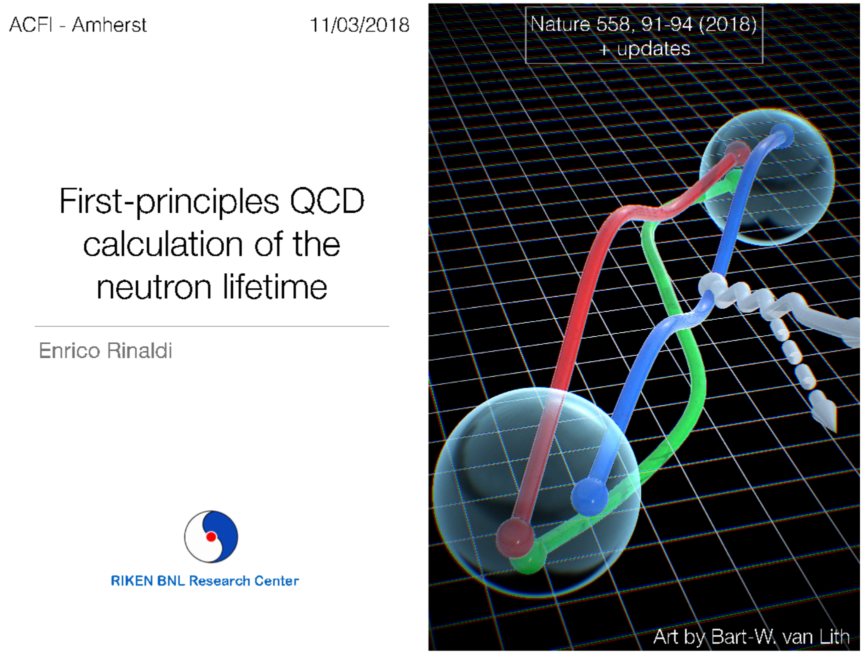
Neutron Decay is the definitive source for g_A

Neutron Data Impact

- g_A **has a critical impact on the neutron Lifetime,** input important (with sub-1% precision) for
  - Big bang nucleosynthesis (0.1% pred. of ^{4}He/H !)
  - Solar fusion rates
  - Reactor neutrino anomaly
- High precision target for lattice nucleon couplings possible, e.g. at < 1% level in g_A

LANL theory group
& Callat collaboration

Pushing precision envelope for QCD



ACFI - Amherst 11/03/2018

First-principles QCD calculation of the neutron lifetime

Enrico Rinaldi

RIKEN BNL Research Center

Nature 558, 91-94 (2018)
+ updates

Art by Bart-W. van Lith

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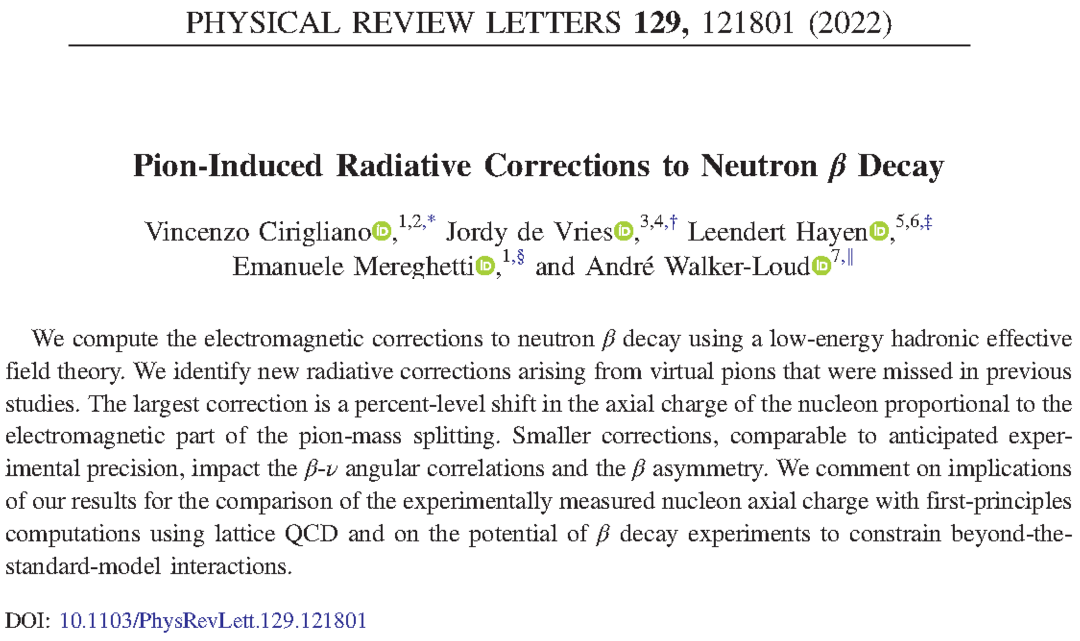
Surprises!

Percent-level shifts (same scale as recoil-order corrections) in the expected value of g_A due to pion-Induced radiative corrections

→incorporated into the measured value, but needed for *ab initio* calculations of g_A



PHYSICAL REVIEW LETTERS **129,** 121801 (2022)

Pion-Induced Radiative Corrections to Neutron β Decay

Vincenzo Cirigliano,[1,2,*] Jordy de Vries,[3,4,†] Leendert Hayen,[5,6,‡]
Emanuele Mereghetti,[1,§] and André Walker-Loud[7,∥]

We compute the electromagnetic corrections to neutron β decay using a low-energy hadronic effective field theory. We identify new radiative corrections arising from virtual pions that were missed in previous studies. The largest correction is a percent-level shift in the axial charge of the nucleon proportional to the electromagnetic part of the pion-mass splitting. Smaller corrections, comparable to anticipated experimental precision, impact the β-ν angular correlations and the β asymmetry. We comment on implications of our results for the comparison of the experimentally measured nucleon axial charge with first-principles computations using lattice QCD and on the potential of β decay experiments to constrain beyond-the-standard-model interactions.

DOI: 10.1103/PhysRevLett.129.121801

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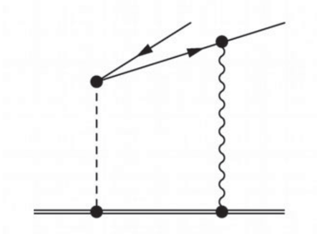

Amazing to find new corrections of this size in 2022 !

Surprises!

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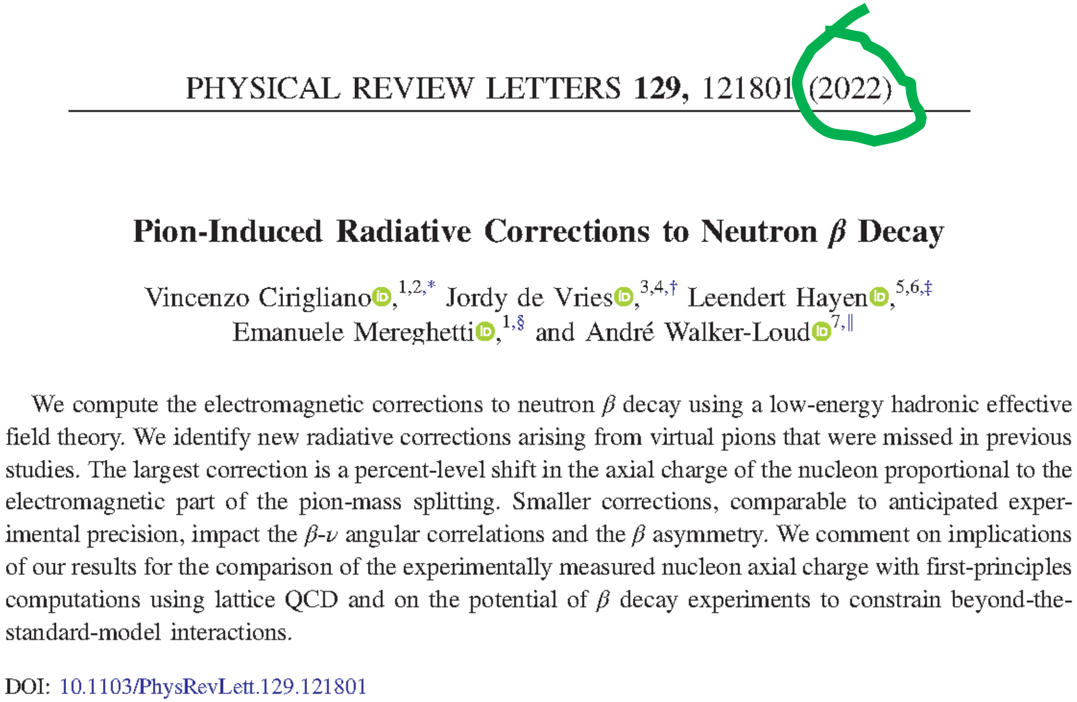

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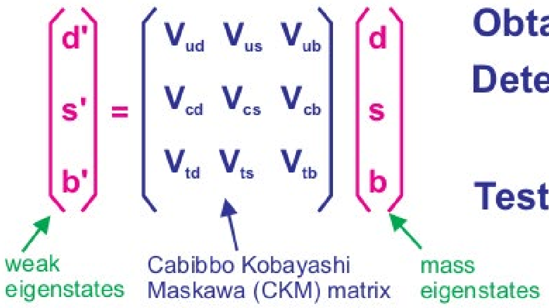
- **New Physics** Constraints
  - Input for CKM unitarity test

Unitarity Tests

In SM, u quark must couple to either d, s or b!



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

Obtain precise value of $G_V^2(1 + \Delta_R)$
Determine V_{ud}^2

$$\boxed{V_{ud}^2 = G_V^2/G_\mu^2}$$

Test CKM unitarity

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

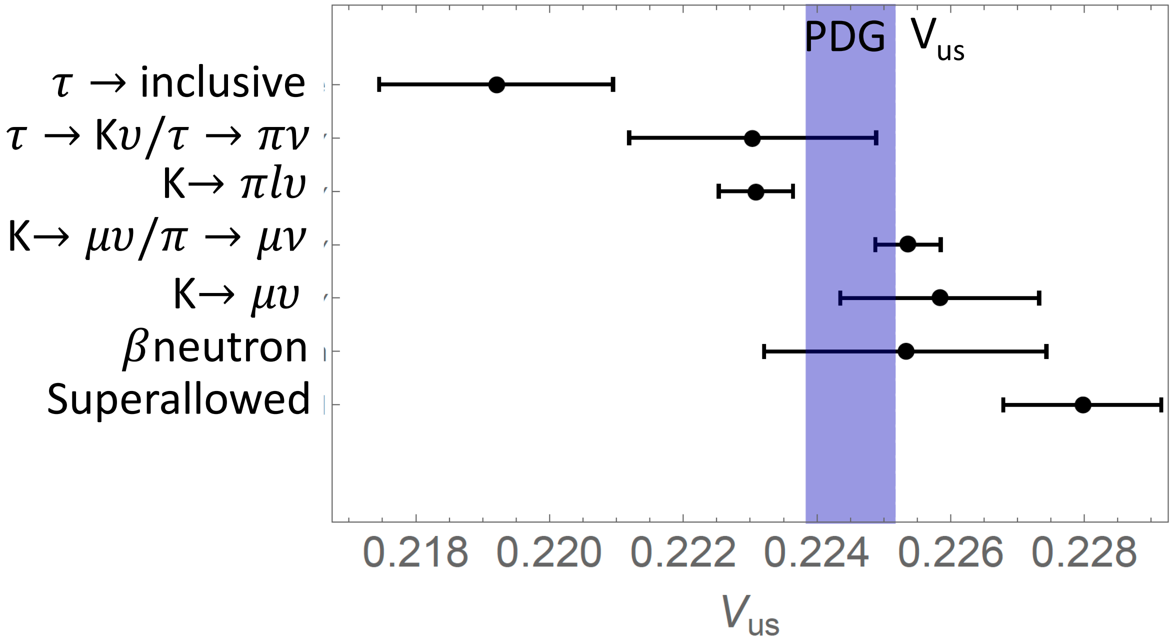
Sensitive to BSM V,A couplings!

High precision value for V_{ud} required! -- **LHC can not provide!** SM “backgrounds” too large (precision limited to ~ %)

Current status: compare measured values of V_{us} with unitarity prediction (should be consistent!)

$$|V_{ub}|^2 \ll 1 \Longrightarrow |V_{us}|^2 \overset{?}{=} 1- |V_{ud}|^2$$

The Cabbibo Anomaly: Unitarity Issues



decays involving strange quarks

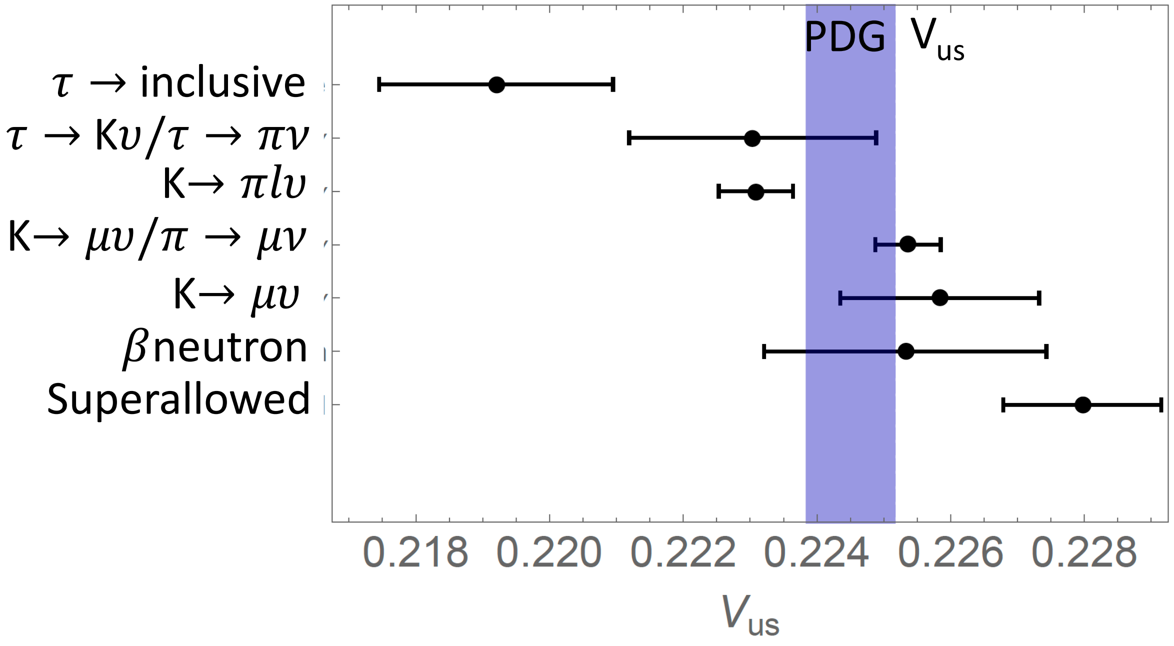
neutron

V_{us} predicted **from unitarity**

Should all provide the **same** value!

[Cirigliano, Díaz-Calderón, Falkowski, MGA & Rodríguez-Sánchez, 2112.02087]

The Cabbibo Anomaly: Unitarity Issues

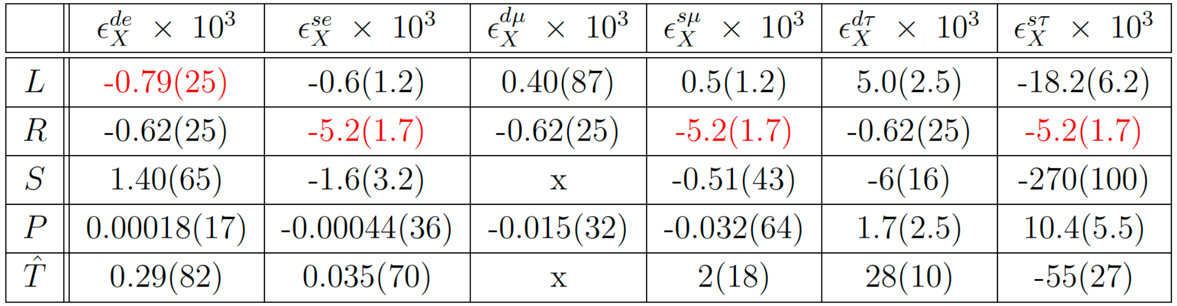


use $0^+ \rightarrow 0^+$ currently

$<V_{us}>$= 0.22431(85) S = 2.5 from PDG 2024

[Cirigliano, Díaz-Calderón, Falkowski, MGA & Rodríguez-Sánchez, 2112.02087]

1 operator at a time: [10^-3 units]



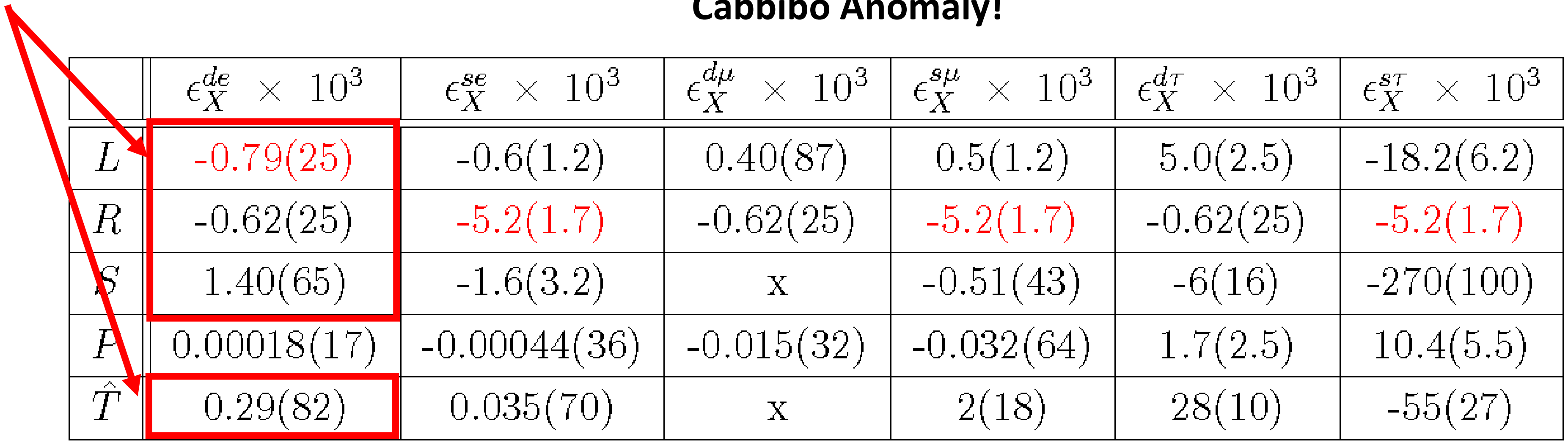
	$\epsilon_X^{de} \times 10^3$	$\epsilon_X^{se} \times 10^3$	$\epsilon_X^{d\mu} \times 10^3$	$\epsilon_X^{s\mu} \times 10^3$	$\epsilon_X^{d\tau} \times 10^3$	$\epsilon_X^{s\tau} \times 10^3$
L	-0.79(25)	-0.6(1.2)	0.40(87)	0.5(1.2)	5.0(2.5)	-18.2(6.2)
R	-0.62(25)	-5.2(1.7)	-0.62(25)	-5.2(1.7)	-0.62(25)	-5.2(1.7)
S	1.40(65)	-1.6(3.2)	x	-0.51(43)	-6(16)	-270(100)
P	0.00018(17)	-0.00044(36)	-0.015(32)	-0.032(64)	1.7(2.5)	10.4(5.5)
$\hat{T}$	0.29(82)	0.035(70)	x	2(18)	28(10)	-55(27)

At least two **separate** sources of BSM physics required, with both > 3σ

Lepton “non-universality” a possibility…

Neutron and nuclear
decays

Cabbibo Anomaly!



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Neutron can probe an important possible source of discrepancy: the nuclear structure corrections required to interpret $0^+ \rightarrow 0^+$ decays!

Neutron and nuclear decays

Cabbibo Anomaly!

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Neutron can probe an important possible source of discrepancy: the nuclear structure corrections required to interpret $0^+ \rightarrow 0^+$ decays!

Neutron uncertainty targets: lifetime – 0.3 s (current most precise, UCNtau with 0.30 s)

g_A ~ 0.03% (current most precise, PERKEO III with 0.044%)

Neutron Data Impact

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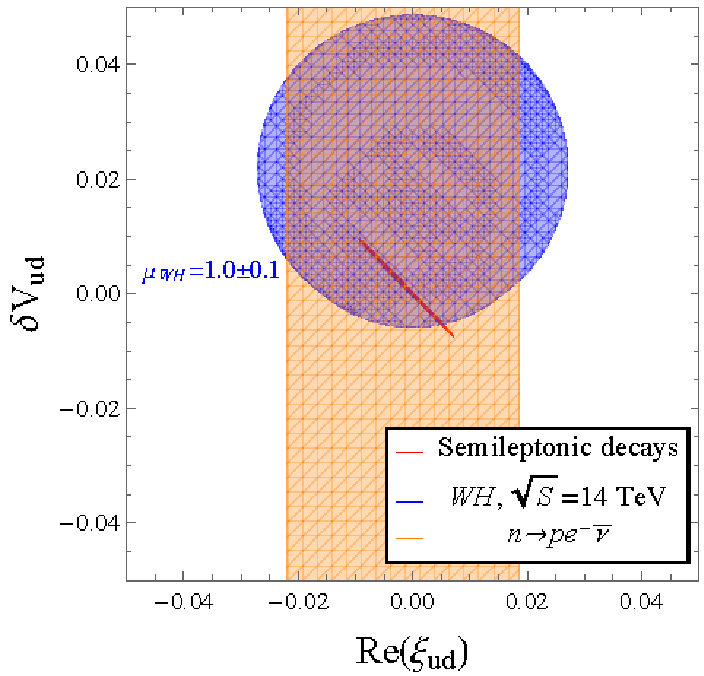
  - Reactor neutrino anomaly
  - High precision target for lattice nucleon couplings, .e.g. at < 1% level in g_A!

- **New Physics** Constraints
  - Input for CKM unitarity test
  - Direct test for BSM Axial couplings (combine with lattice)

Direct constraints on right-handed axial couplings

- Unitarity constraint can be combined with direct lattice calculation of g_A to probe for BSM axial vector couplings – constraints are also more stringent than those from LHC



Alioli, S., Cirigliano, V., Dekens, W., de Vries, J., and Mereghetti, E. Right-handed charged currents in the era of the Large Hadron Collider. JHEP 05, 086 (2017).

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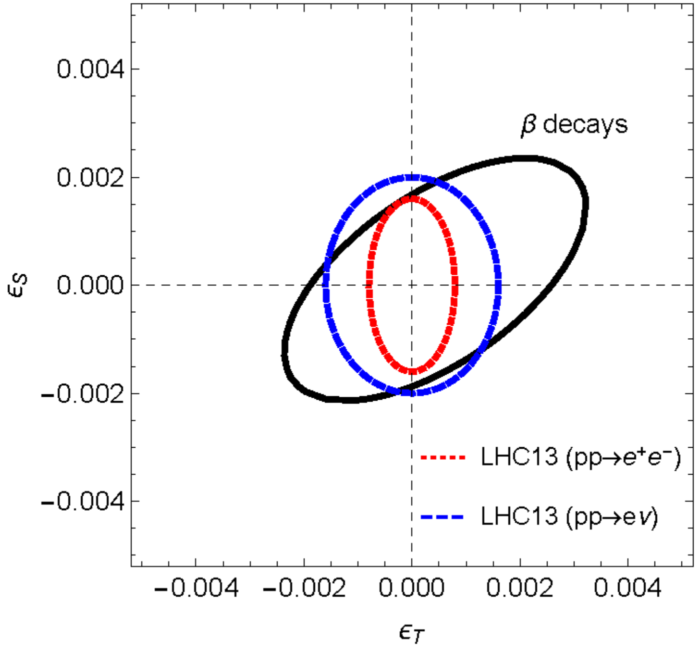
- **New Physics** Constraints
  - Input for CKM unitarity test
  - Direct test for BSM Axial couplings (combine with lattice)
  - New paths to sensitivity to exotic couplings

Beta Decay Constraints on Exotic Scalar and Tensor Couplings (for left-handed neutrinos)

- The decay rate (and differential distributions) are also influenced by potential contributions from BSM scalar and tensor couplings through Fierz terms (***b***), with sensitivity about the same as the LHC measurements (here LHC has a slight edge)

$$b = \mp \frac{1}{1+3\lambda^2}\left(2\frac{C_S}{C_V} + 6\lambda\frac{C_T}{C_A}\right)$$



Comprehensive analysis of beta decays within and beyond the Standard Model

Adam Falkowski,[a] Martín González-Alonso,[b] and Oscar Naviliat-Cuncic[c,d]

JHEP04(2021)126

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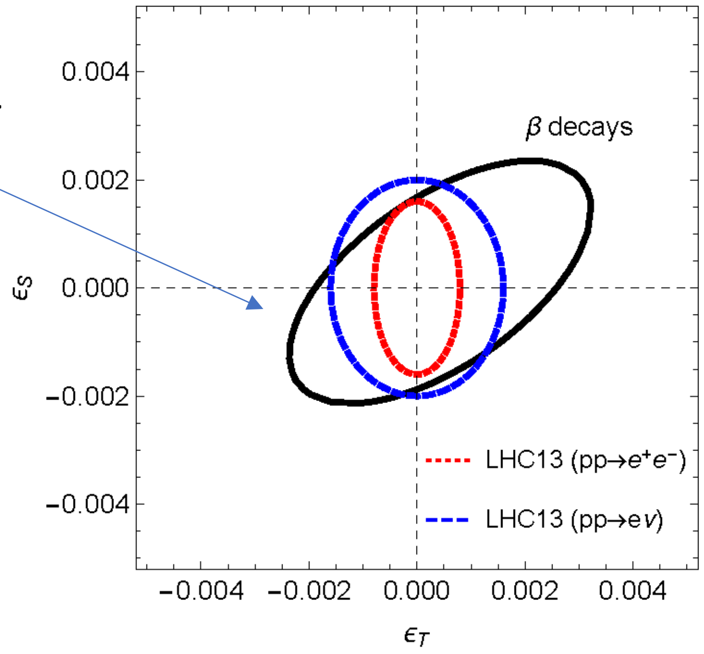
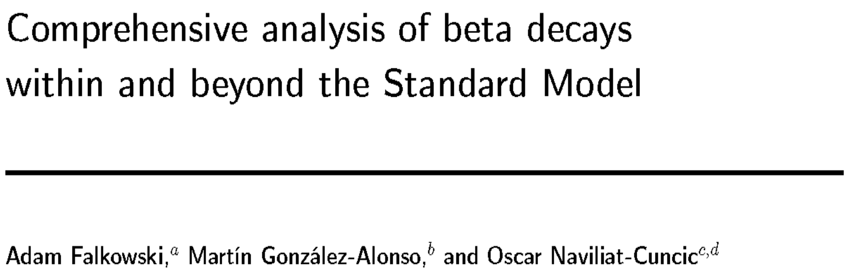
Input: n lifetime and correlations, Fermi & Mirror Decays

(included Beck et al.)

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Recent Theory Progress

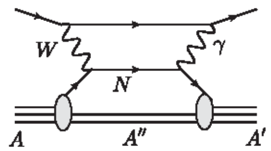


FIG. 2. Quasielastic contribution to the nuclear γW box.

- 2018: Dispersion analysis of hadronic loop contributions to the radiative corrections

  C.-Y. Seng, M. Gorchtein, H. H. Patel and M. J. Ramsey-Musolf, Physical Review Letters **121** (24), 241804 (2018).

  A. Czarnecki, W. J. Marciano and A. Sirlin, Physical Review D **100** (7), 073008 (2019).

- 2021: Self-consistent EFT analysis of all low energy beta decay data

  A. Falkowski, M. González-Alonso and O. Naviliat-Cuncic, Journal of High Energy Physics **2021** (4), 1-36 (2021).

- 2022: Analysis of τ decays and the Cabbibo Angle Anomaly

  V. Cirigliano, D. Díaz-Calderón, A. Falkowski, M. González-Alonso and A. Rodríguez-Sánchez, Journal of High Energy Physics **2022** (4), 1-61 (2022).

- 2023: Rigorous EFT Treatment of Radiative and Recoil Order Corrections for N Decay

  V. Cirigliano, W. Dekens, J. de Vries, E. Mereghetti and T. Tong, Journal of High Energy Physics **2024** (3), 1-69 (2024).

- 2023: Multi-component analysis of new physics scenarios with EFT

  V. Cirigliano, W. Dekens, J. de Vries, E. Mereghetti and T. Tong, Journal of High Energy Physics **2024** (3), 1-69 (2024).

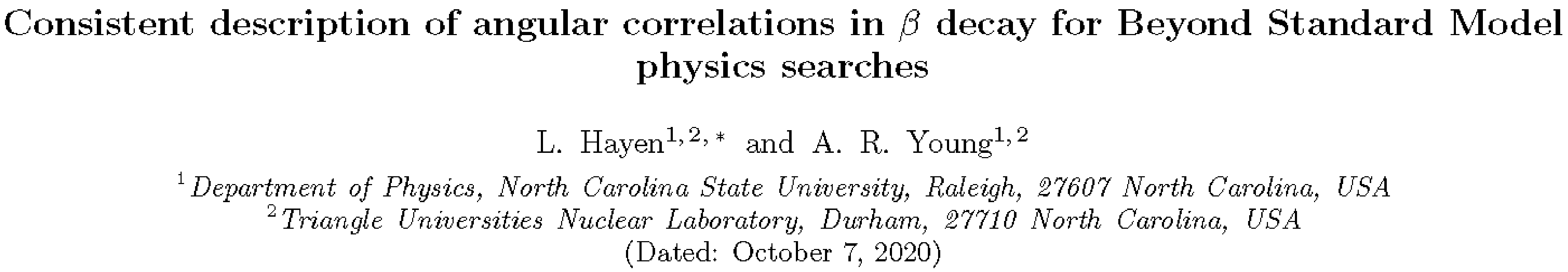
- 2024: Lattice Analysis of Hadronic Loop Contributions

- 2024: Rigorous EFT Treatment applied to superallowed decays

For neutron, theory good to 0.01% except hadronic contrib. to radiative corrections (0.02%)

Theoretical analysis to determine λ in good shape (certainly 0.1%)

ArXiv:2009.11364



Consistent description of angular correlations in β decay for Beyond Standard Model physics searches

L. Hayen[1,2,*] and A. R. Young[1,2]

[1] *Department of Physics, North Carolina State University, Raleigh, 27607 North Carolina, USA*
[2] *Triangle Universities Nuclear Laboratory, Durham, 27710 North Carolina, USA*
(Dated: October 7, 2020)

Collected results for asymmetries: **good for asymmetry precisions below 0.1%**

Consistent analysis of energy dependence

- $\mathcal{O}(\alpha)$ radiative corrections
- $\mathcal{O}(Z\alpha - Z\alpha^2)$ Coulomb effects
- Recoil order effects
- Bremsstrahlung emission
- Harmonized/translated notation

L. Hayen – explicit calculation of energy dependence for ^{19}Ne A coeff with precision $\frac{\delta A}{A} < 0.001$

Systematic uncertainty suppression

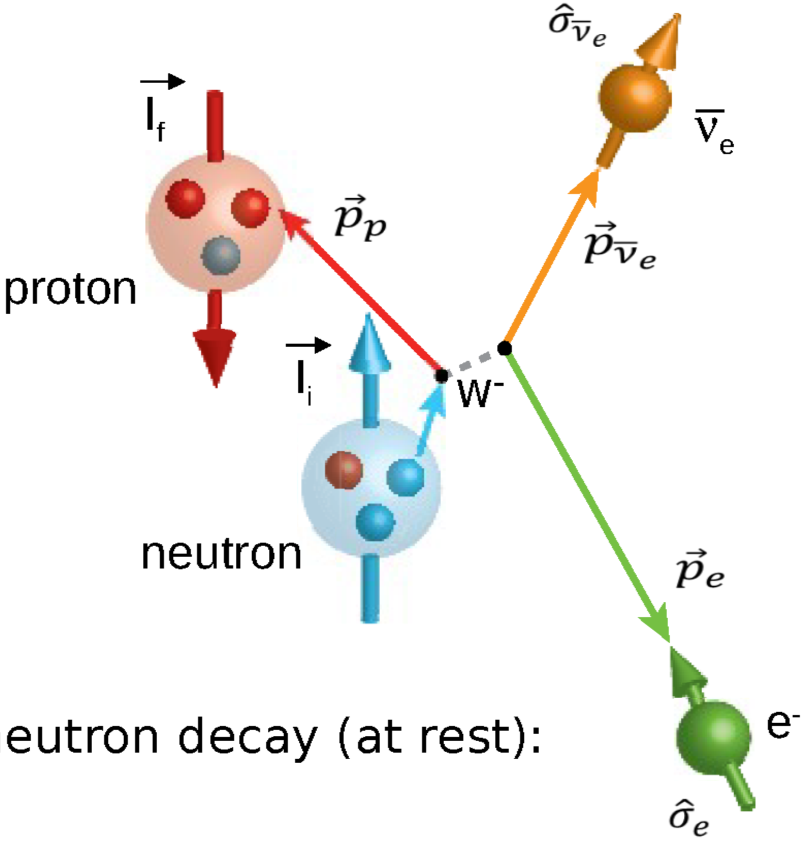
- Identification of cases with enhanced sensitivity to asymmetry
- Suppression of experimental sensitivity to detection efficiency and energy reconstruction errors

Enhance sensitivity, suppress uncertainty

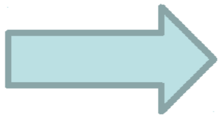
- BSM analysis of $\mathcal{F}t_0$ values

The Neutron Global Dataset

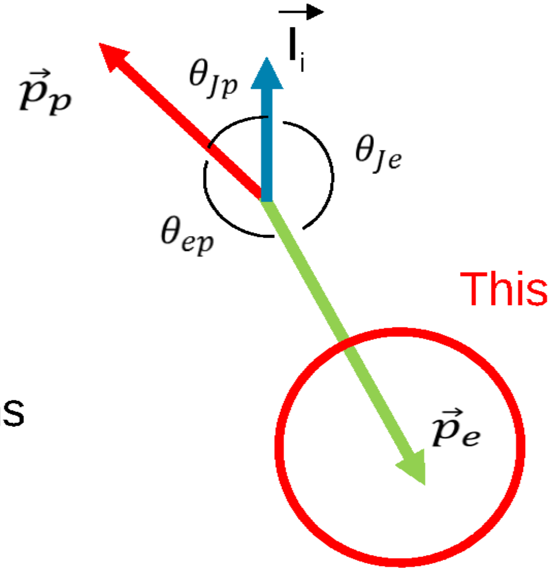
Beta Decay Observables



neutron decay (at rest):



Don't observe
final state spins
or neutrino



This talk

Many accessible observables

$\{\vec{I}_i, \vec{I}_f, \vec{p}_p, E_p, \hat{\sigma}_e, \vec{p}_e, E_e\}$

Decay rate

Energy spectrum: p, e

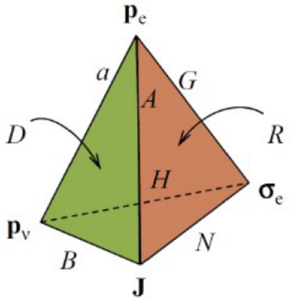
Directional distribution
(**angular correlations**)

Use momentum consv: $\vec{p}_{\bar{\nu}_e} = -\vec{p}_p - \vec{p}_e$

Beta Decay Parameters

Jackson, Treiman and Wyld (Phys. Rev. **106** and Nucl. Phys. **4**, 1957)

$$\frac{d^5W}{dE_e\,d\Omega_e\,d\Omega_{\nu_e}} = \overbrace{\frac{G_F^2|\boldsymbol{V_{ud}}|^2}{(2\pi)^5}p_e E_e (A_\circ - E_e)^2\xi}^{\text{basic decay rate}}\left(1 + \overbrace{\boldsymbol{a_{\beta\nu}}\frac{\vec{p}_e\cdot\vec{p}_{\nu_e}}{E_e E_{\nu_e}}}^{\beta-\nu\text{ correlation}} + \overbrace{\boldsymbol{b}\frac{\Gamma m_e}{E_e}}^{\text{Fierz term}} + \frac{\langle\vec{I}\rangle}{I}\cdot\left[\underbrace{\boldsymbol{A}_\beta\frac{\vec{p}_e}{E_e}}_{\beta\text{ asym}} + \underbrace{\boldsymbol{B}_\nu\frac{\vec{p}_\nu}{E_\nu}}_{\nu\text{ asym}} + \underbrace{\boldsymbol{D}\frac{\vec{p}_e\times\vec{p}_\nu}{E_e E_\nu}}_{T-\text{violating}}\right]\right) + \dots$$



Proton distribution inferred (consv of E & p)

On-going or planned efforts to measure:

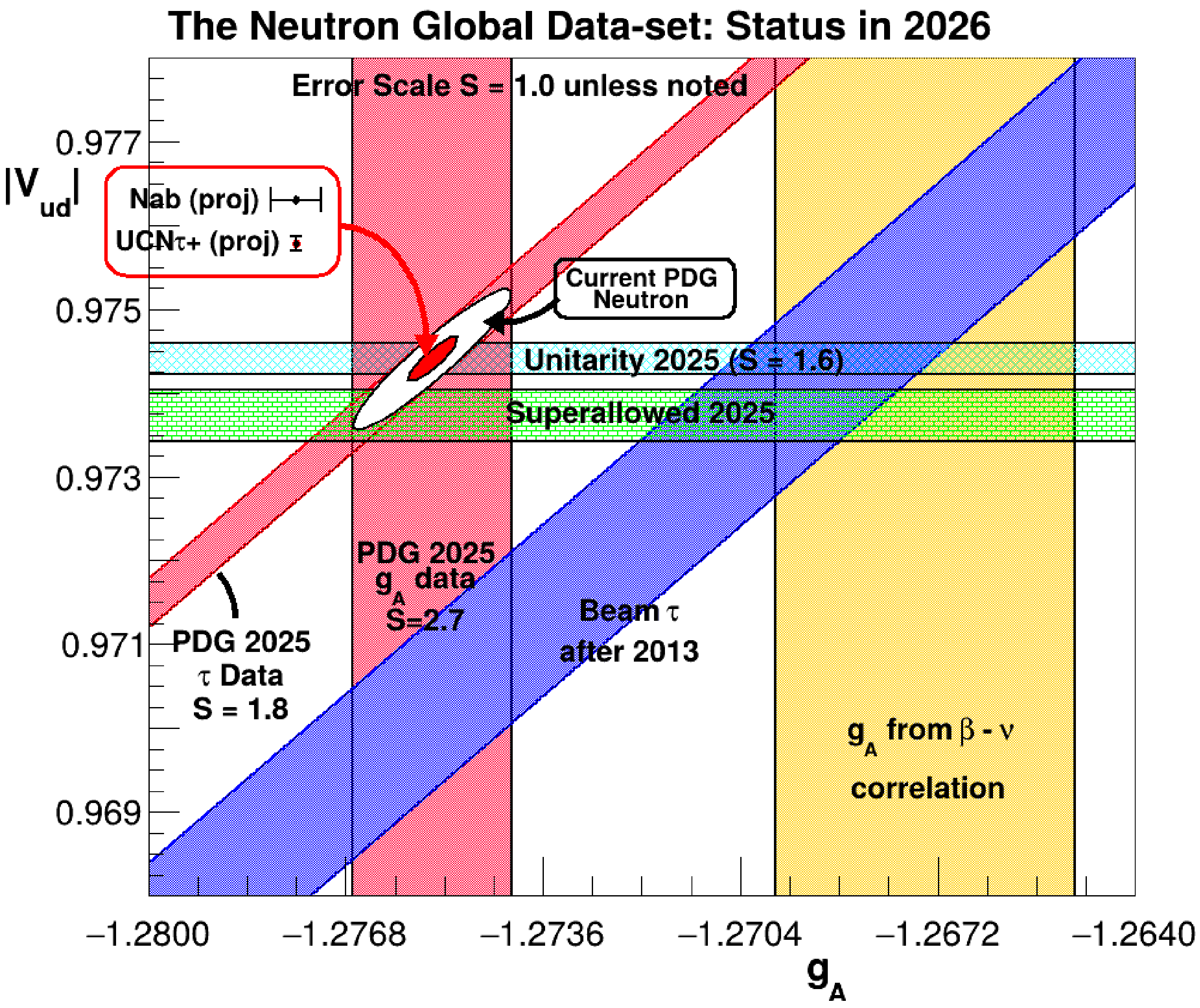
(1) **Decay rates and β-spectra** ($G_F V_{ud}, \xi, b$)

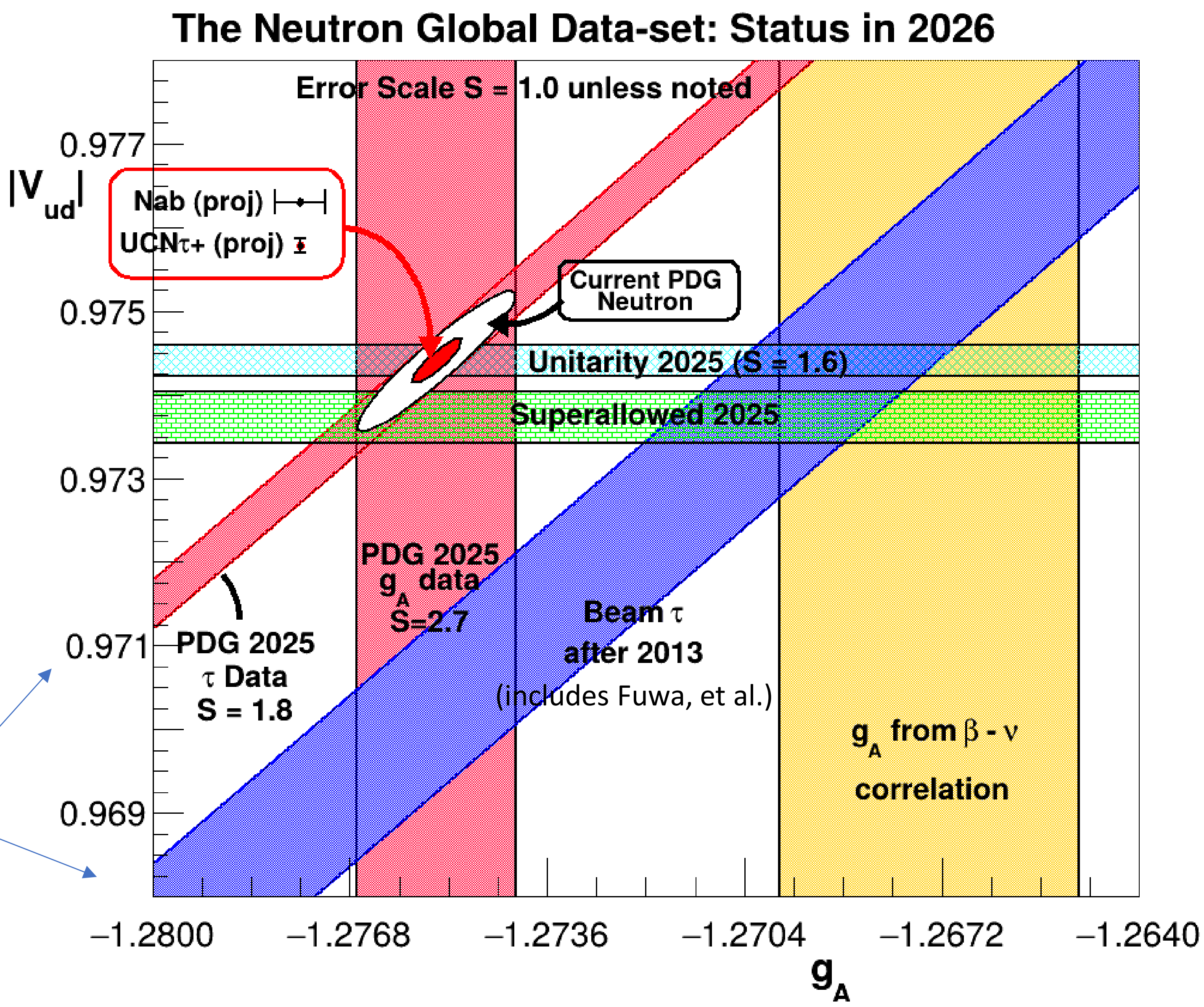
(2) **Unpolarized angular correlations** ($a_{\beta\nu}, b$) ← **aCORN, aSPECT, Nab**

(3) **Polarized angular correlations** (A_β, B_ν, b, b_ν) ← **Perc, pNab, UCNA+**

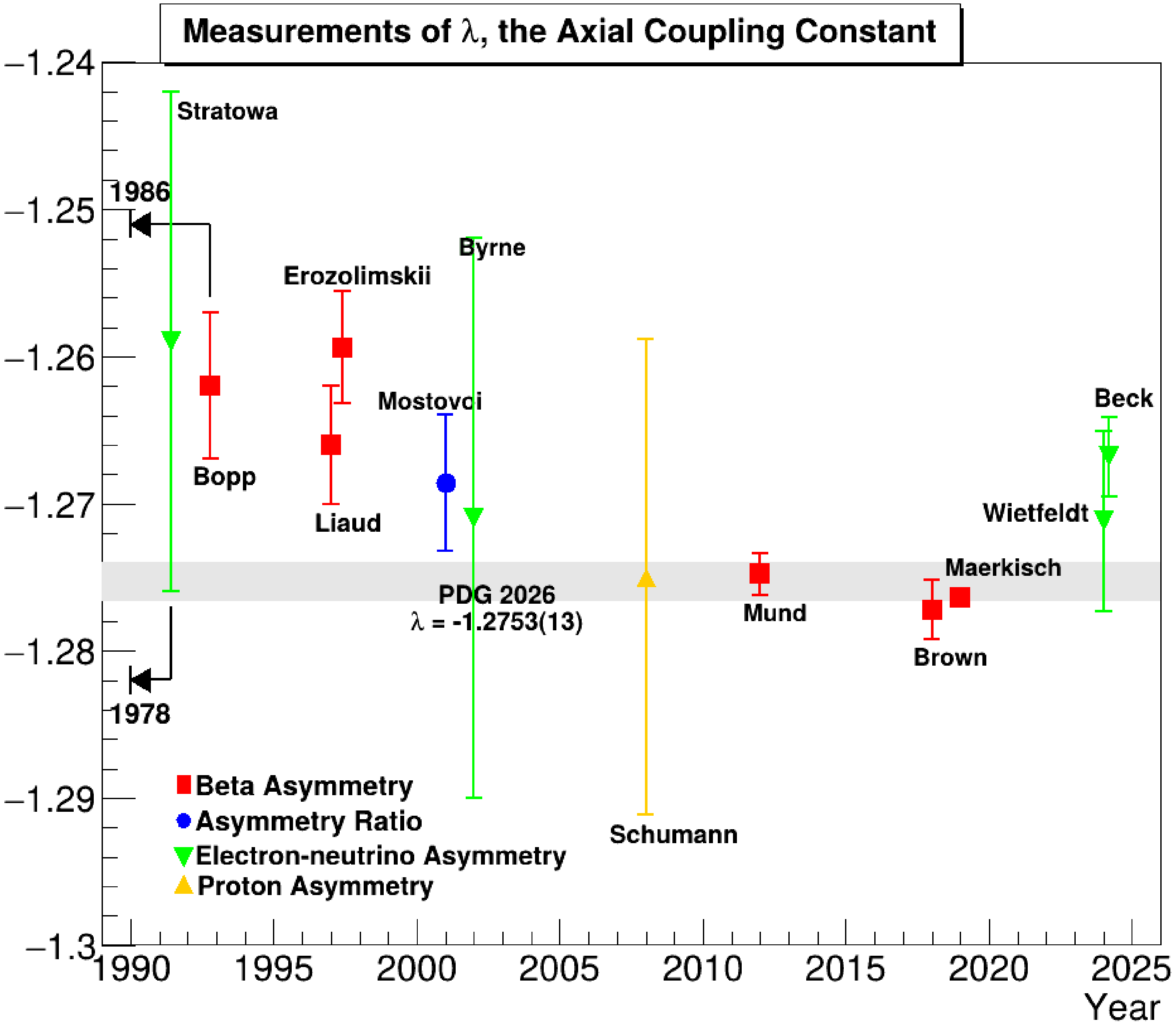
The PDG averages for the neutron are in reasonable agreement with unitarity and Fermi decays

There are internal discrepancies evident in these data…

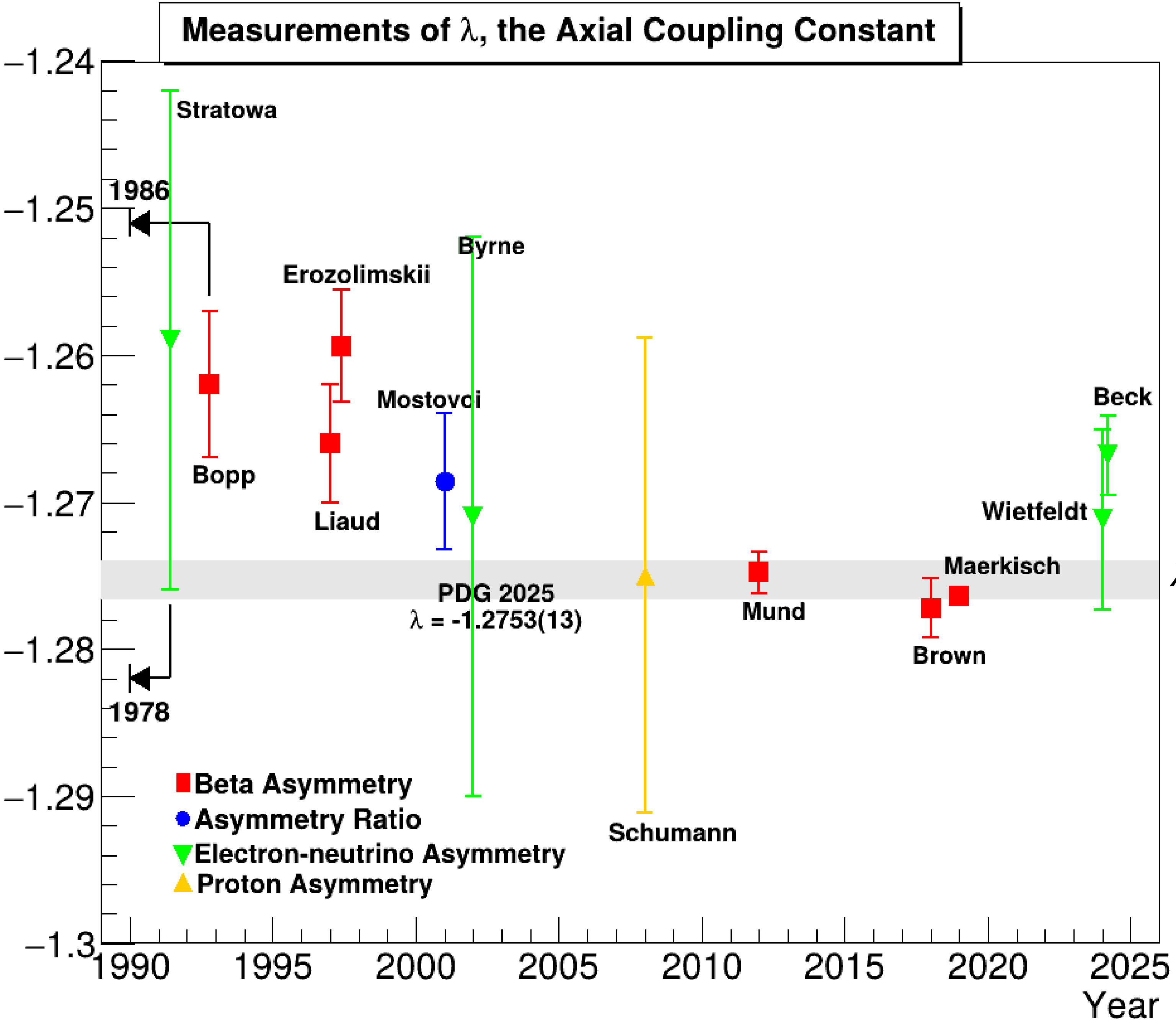




The “lifetime” puzzle Is addressed in Chen-Yu Liu’s talk



A_β and $a_{\beta\nu}$ are the most sensitive to λ

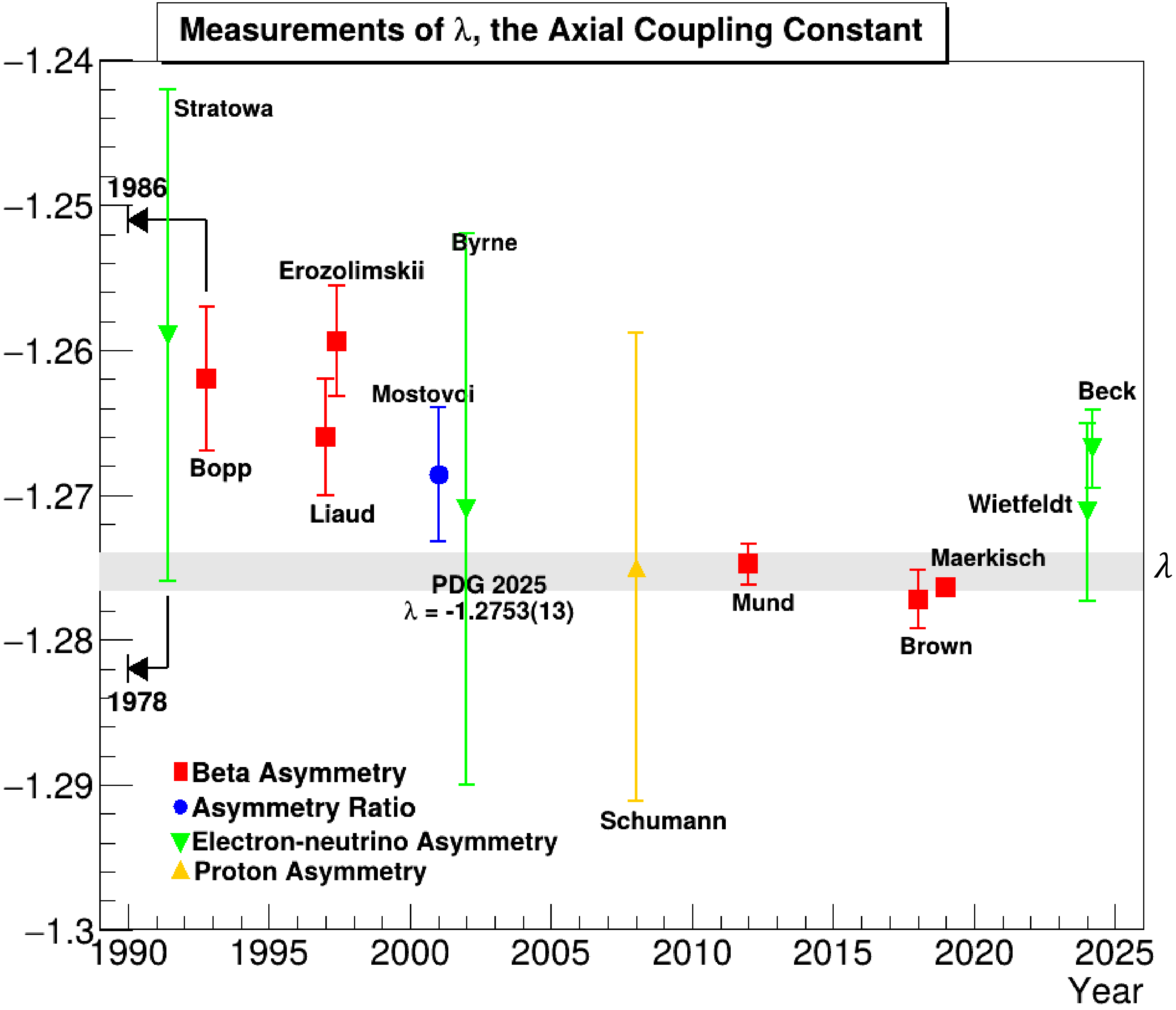


PDG 2025

$\lambda = -1.2754(13)$

~0.1%

Need a factor of 3 to be directly competitive with $0^+ \rightarrow 0^+$ decays!

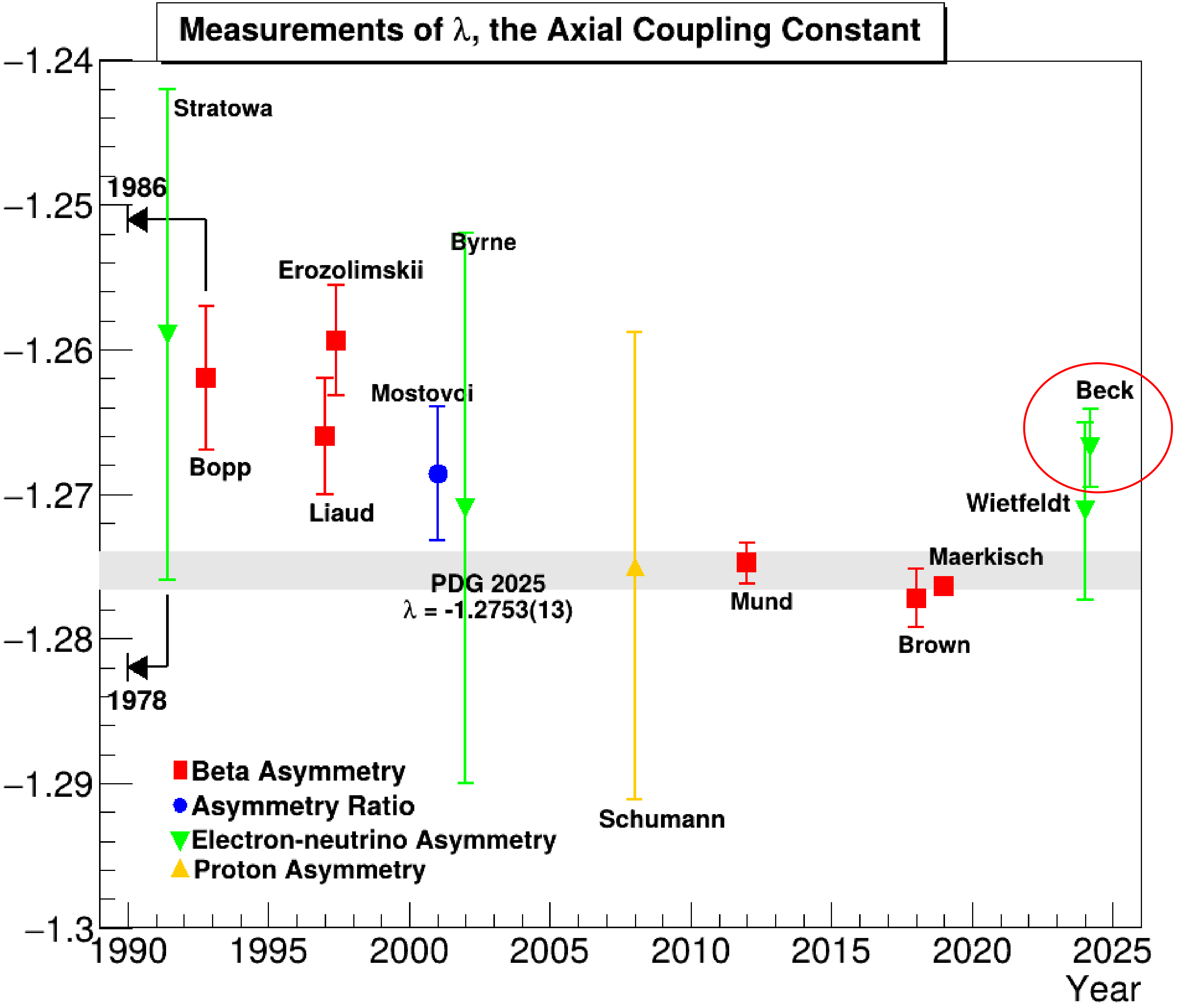


PDG 2025

$\lambda = -1.2754(13)$

~0.1%

Scale factor 2.7 due to scatter



Scatter primarily due to aSPECT measurement

“Takeaways” from the global data set

- The overall data set for the axial coupling constant g_A needs about a factor of 3 improvement in the uncertainty to have comparable precision to the current nuclear decay data for V_{ud}

- The axial coupling constant determined from beta asymmetry measurements does not agree well with that from the aSPECT experiment – the most precise measurement of the beta-neutrino correlation.

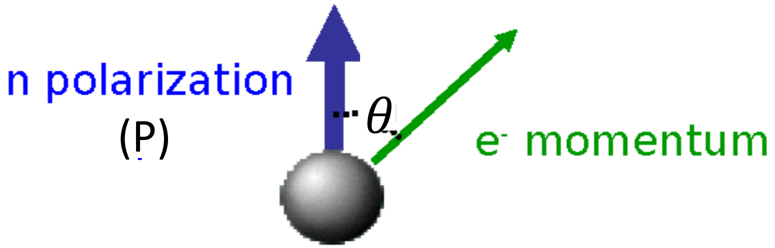
Conclusion: higher precision values from measurements of the beta-neutrino correlation and the beta-asymmetry are needed to confirm the current discrepancy between angular correlation results, and to validate the current status of the Cabibbo Anomaly

β-Asymmetry Measurements

Special thanks for figures from B. Maerkisch, D. Pocanic, S. Baessler, J. Choi

The Global Dataset: Angular Correlations

Example: the beta asymmetry



$$R = R_o(1 + (v/c)\ P\ A(E)\ \cos\theta)$$

β-asymmetry = A(E) in angular distribution of β

$$A_o = \frac{2|\lambda| - 2\lambda^2}{(1 + 3\lambda^2)} \approx -0.12$$ (leading order)

Ignoring recoil order terms – just a function of $\lambda = (C_A/C_V) = \rho/\sqrt{3}$

Recent work establishes precision level for $\lambda < \sim 10^{-3}$

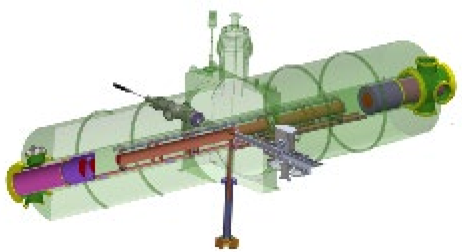
β-Asymmetry Measurements

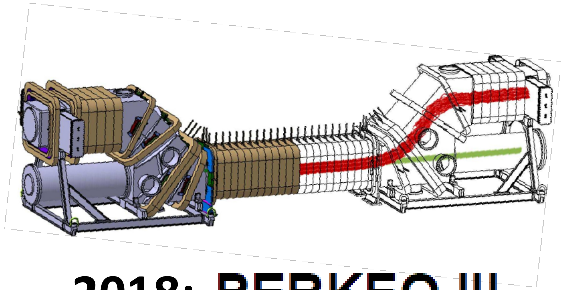
Most precise measurements to date were beta-asymmetry measurements

Two most recent:

for UCN

For CN





2017: UCNA

A_o=-0.12015(71)

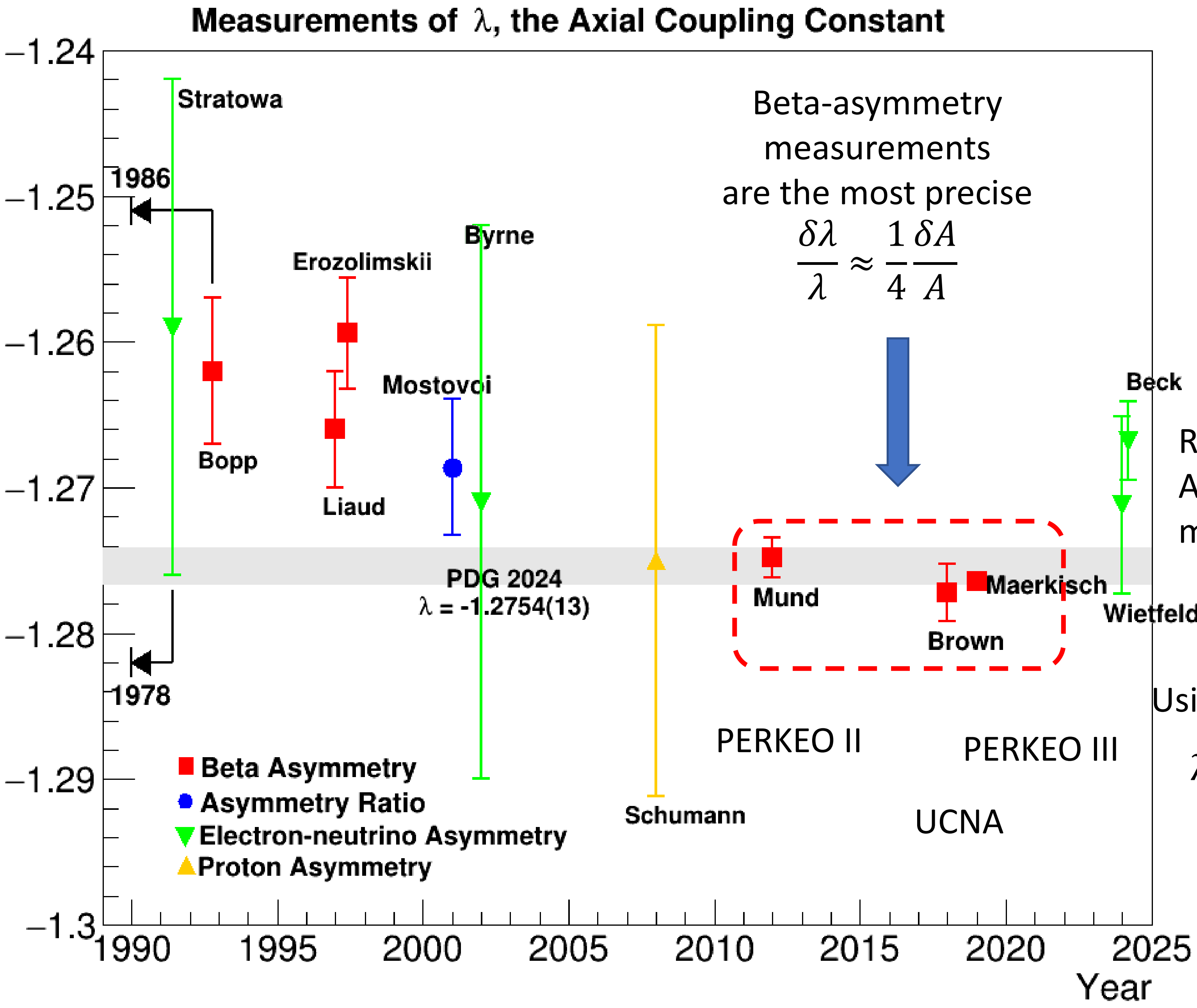
dA_o/A_o = 0.6%

UCN at LANL

2018: PERKEO III

dA_o/A_o = 0.18 %

Chopped CN at ILL



Beta-asymmetry measurements are the most precise

$$\frac{\delta\lambda}{\lambda} \approx \frac{1}{4}\frac{\delta A}{A}$$

PERKEO II

PERKEO III

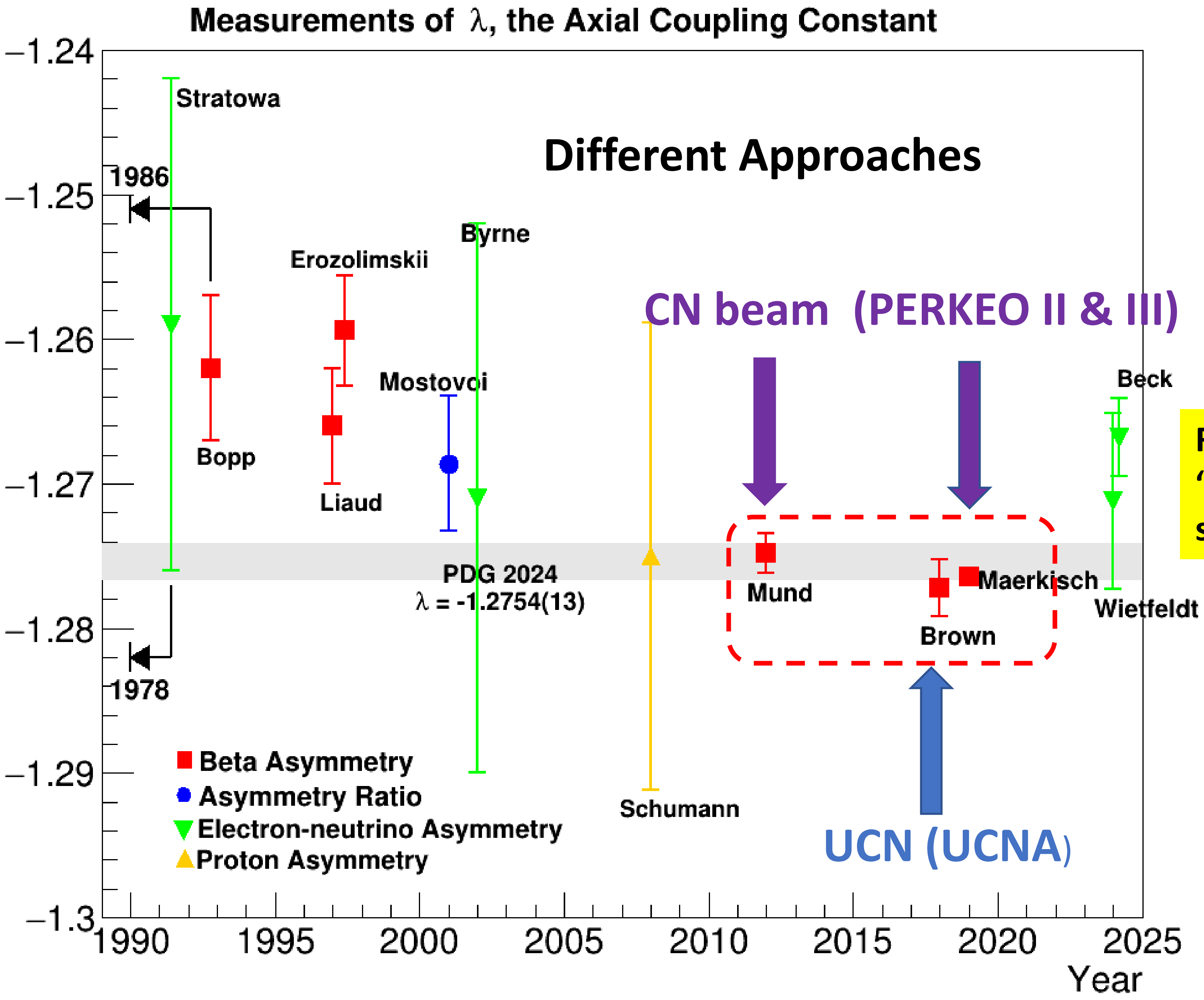
UCNA

Recent measurements of A(E) for neutron agree, with most precise PERKEO III

Using only recent beta asym:

$$\lambda = -1.2757(5),\ \mathrm{S}{=}1.2$$

Reminder: ~.00038 is unitarity target!



Different Approaches

CN beam (PERKEO II & III)

UCN (UCNA)

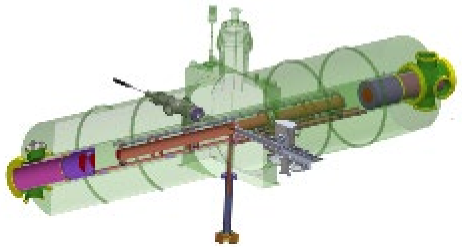
Robust assessment of “neutron-related” systematic uncertainties

β-Asymmetry Measurements

Most precise measurements to date were beta-asymmetry measurements

Two most recent:

for UCN



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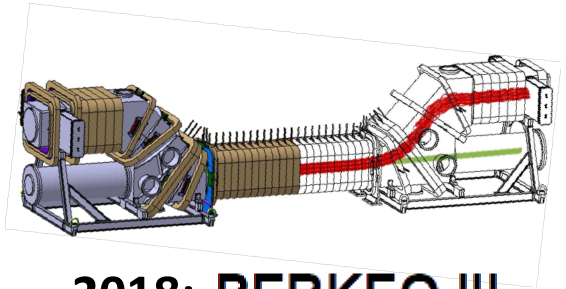
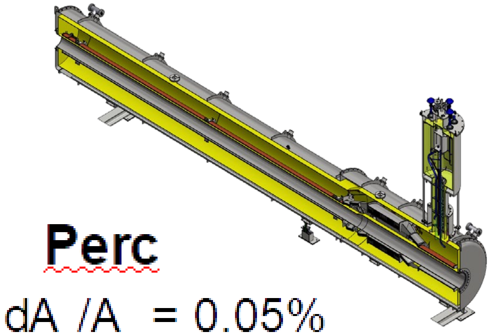


2018: PERKEO III

dA_o/A_o = 0.18 %

Chopped CN at ILL

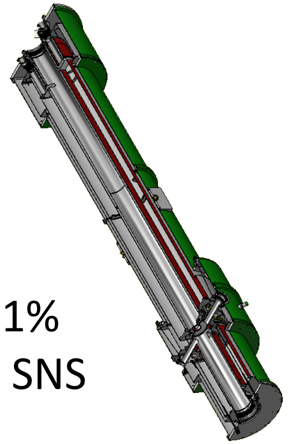
Planned or in development over next 5 years (BRAND planned for ESS)



Perc

dA_o/A_o = 0.05%

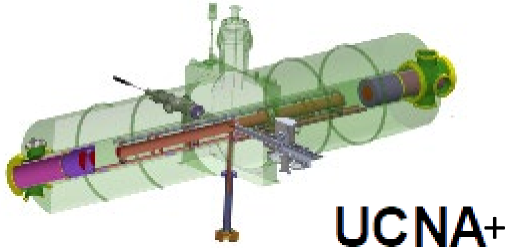
Chopped CN at FRM II



pNab

dA_o/A_o = 0.1%

Pulsed CN at SNS



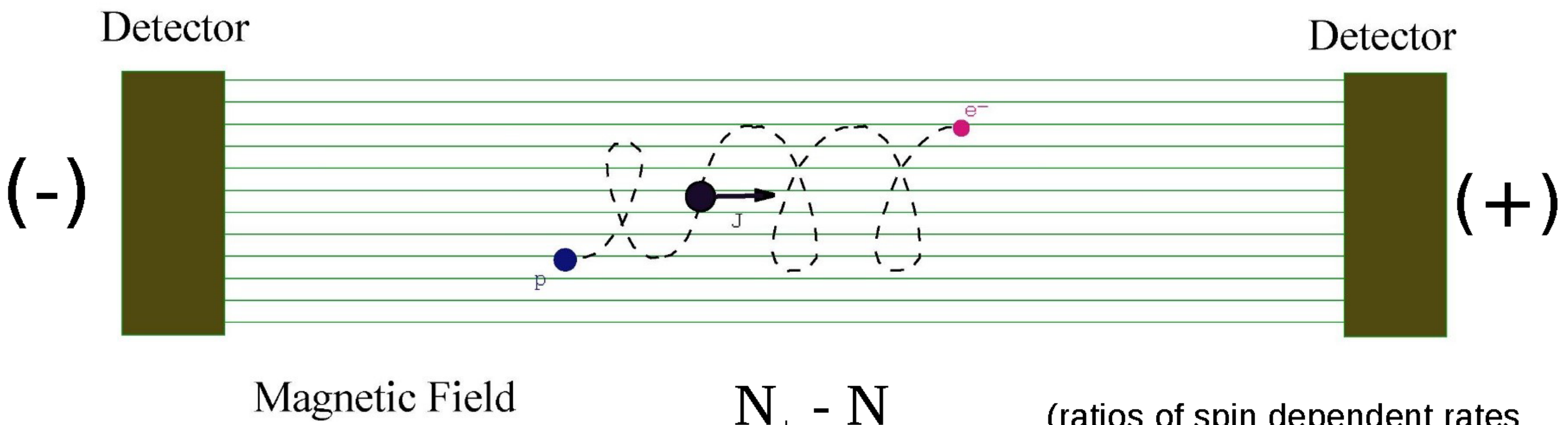
UCNA+

$dA_0/A_0 < 0.2\%$

UCN at LANL

β-Asymmetry Measurement Principle

β directional distribution: $1+P\frac{v}{c}A(E)\cos\theta$
(polarized neutrons)



$$A(E) \propto \frac{N_+ - N_-}{N_+ + N_-}$$

(ratios of spin dependent rates
are used to cancel efficiencies)

Must determine:	Systematic effects:
• Beta rates	Backgrounds
• Beta spectra	Calibration/Linearity
• <cosθ>	Scattering (esp. backscattering)
• Polarization	Absolute polarization required!

β-Asymmetry: Pros and Cons
("singles" expts like UCNA and PERKEO)

Advantages

- Not sensitive to absolute efficiency of detectors (super-ratio)
- Not sensitive to energy calibration or "linearity"
- Not sensitive to surface electric potentials
- Not (very) sensitive to timing
- Very sensitive to λ (so is $a_{\beta\nu}$, but not B_{ν})

Challenges

- Very sensitive to neutron –induced backgrounds (must be small and/or very stable and measurable)
- Absolute polarimetry required
- Sensitive to beta (back)-scattering

PERKEO III and Perc

β-asymmetry with cold neutron beams

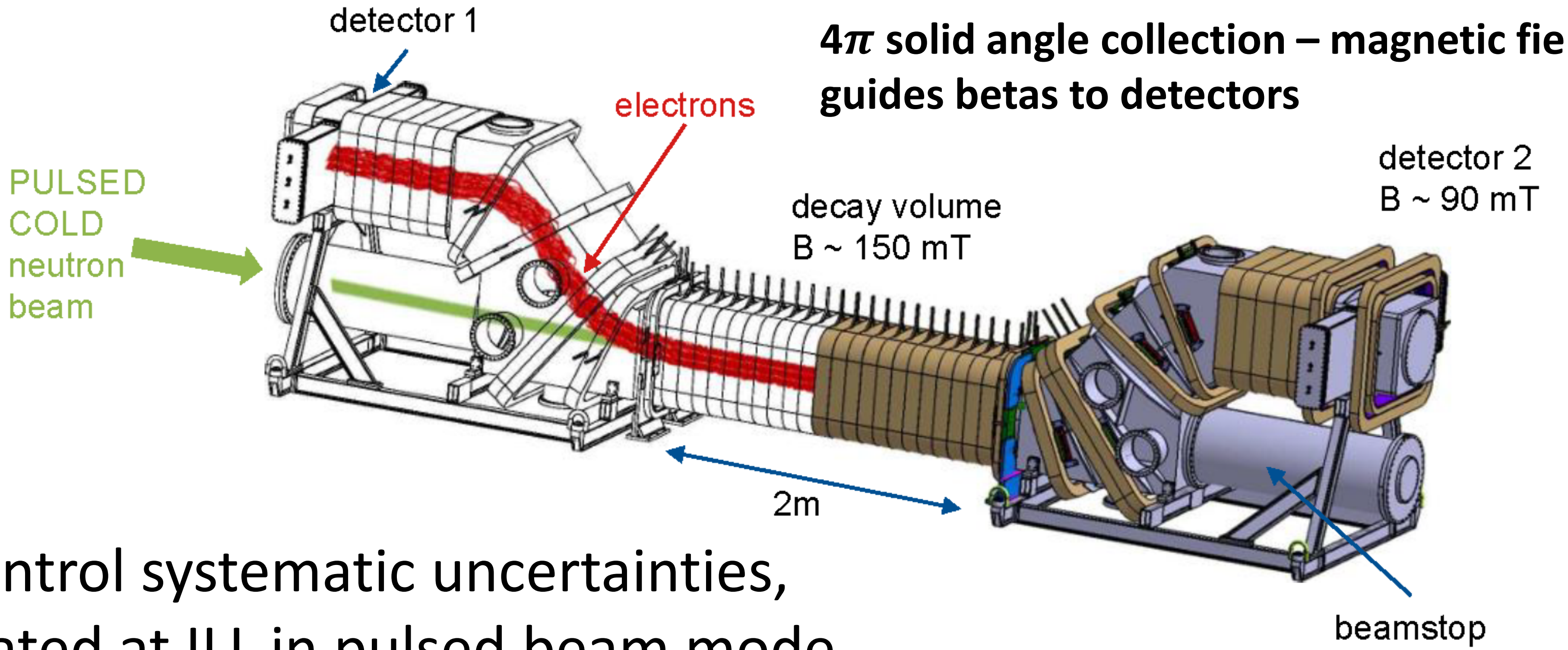
(current state of the art for angular correlation measurements)

spokesperson: B. Maerkisch

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

Spectrometer PERKEO III

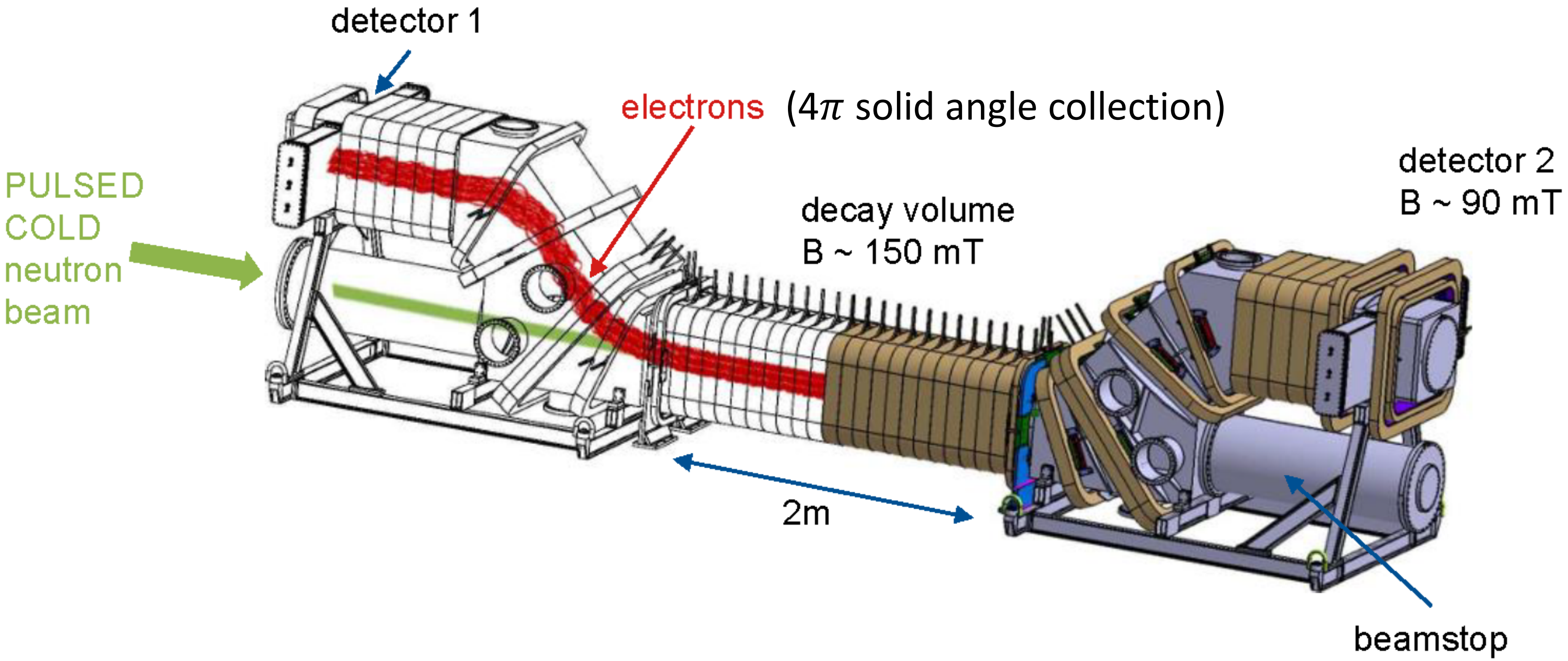
4π solid angle collection – magnetic field guides betas to detectors



To control systematic uncertainties, operated at ILL in pulsed beam mode…

Neutron Decay Rate is a Challenge!

Spectrometer PERKEO III



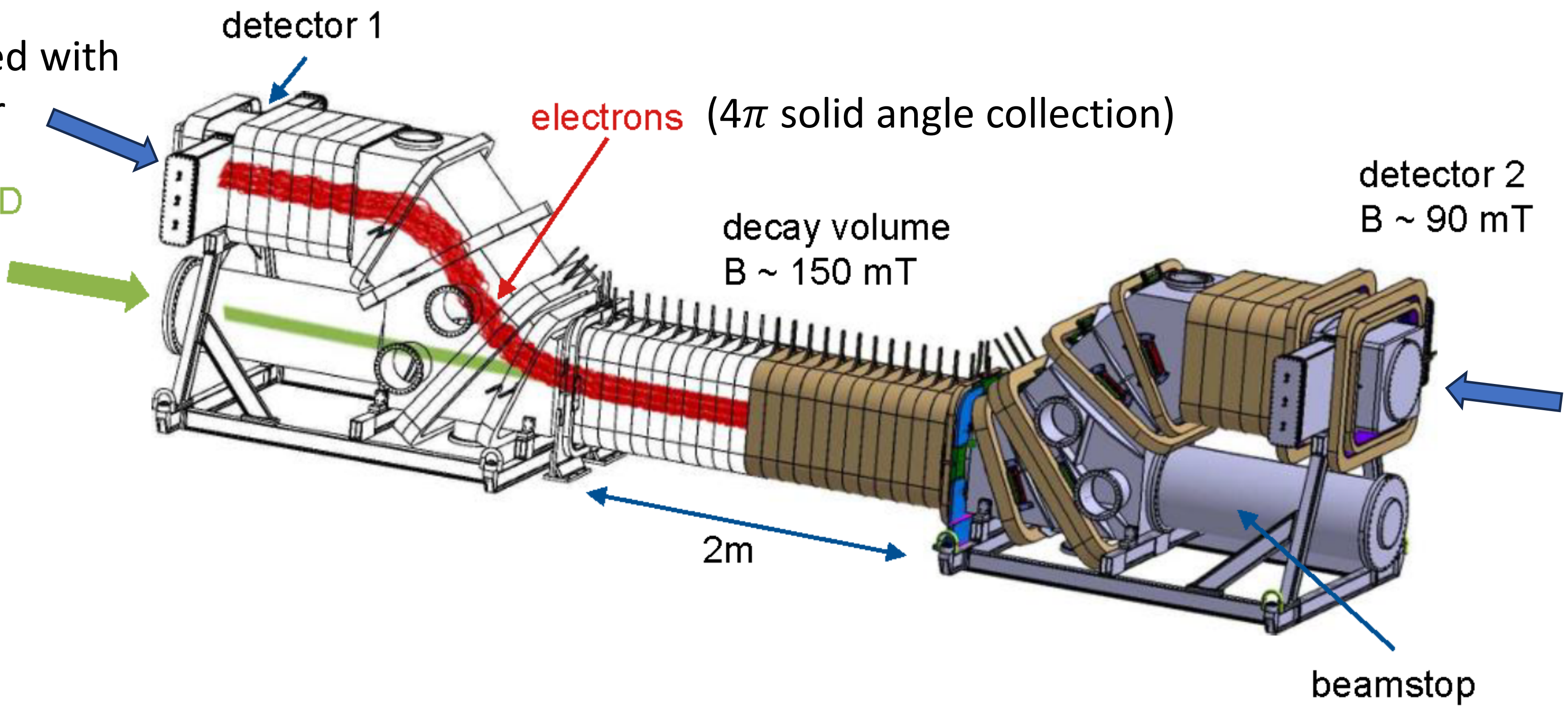
Operated at ILL in pulsed beam mode…

(suppress bkg and mirror correction)

~50.000 decays/s in *continuous* beam

time avg. ~200 s^{-1} in pulsed mode

Spectrometer PERKEO III



Electrons detected with plastic scintillator

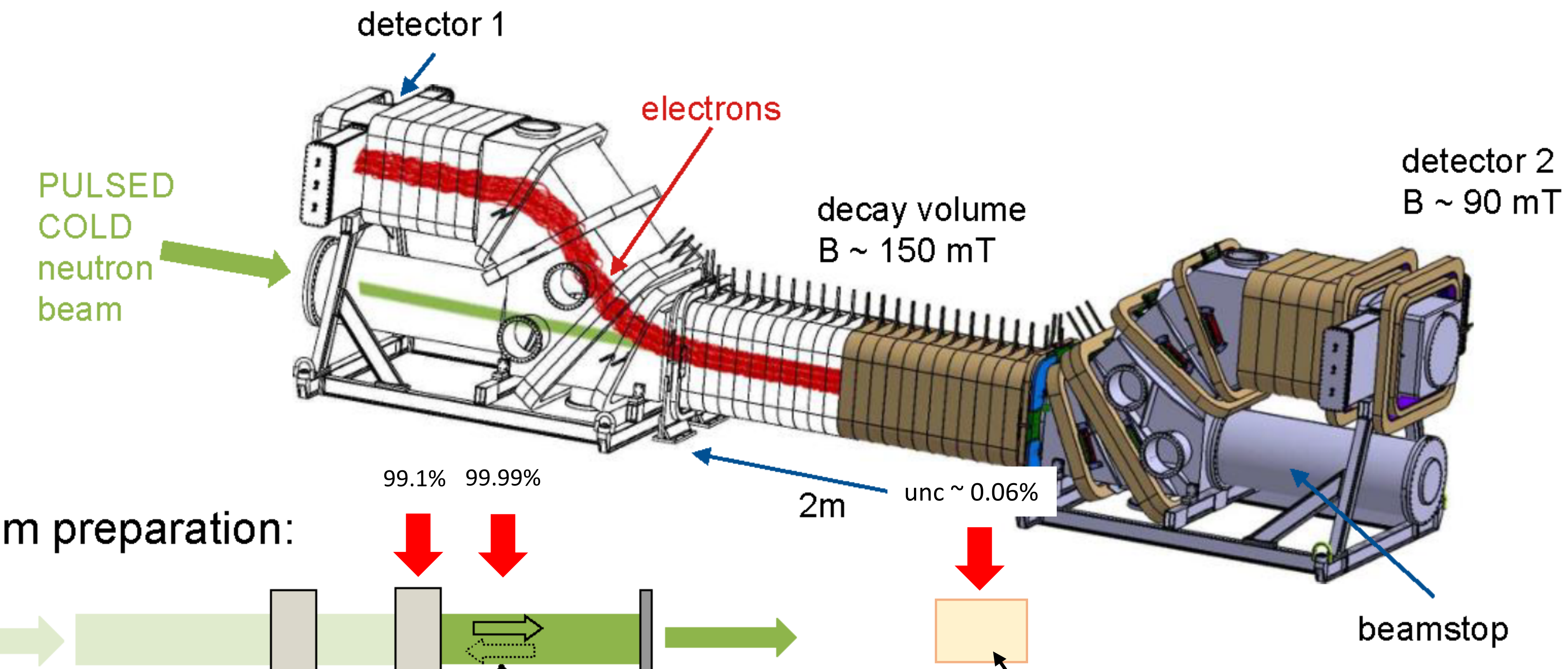
(4π solid angle collection)

Electrons detected with plastic scintillator

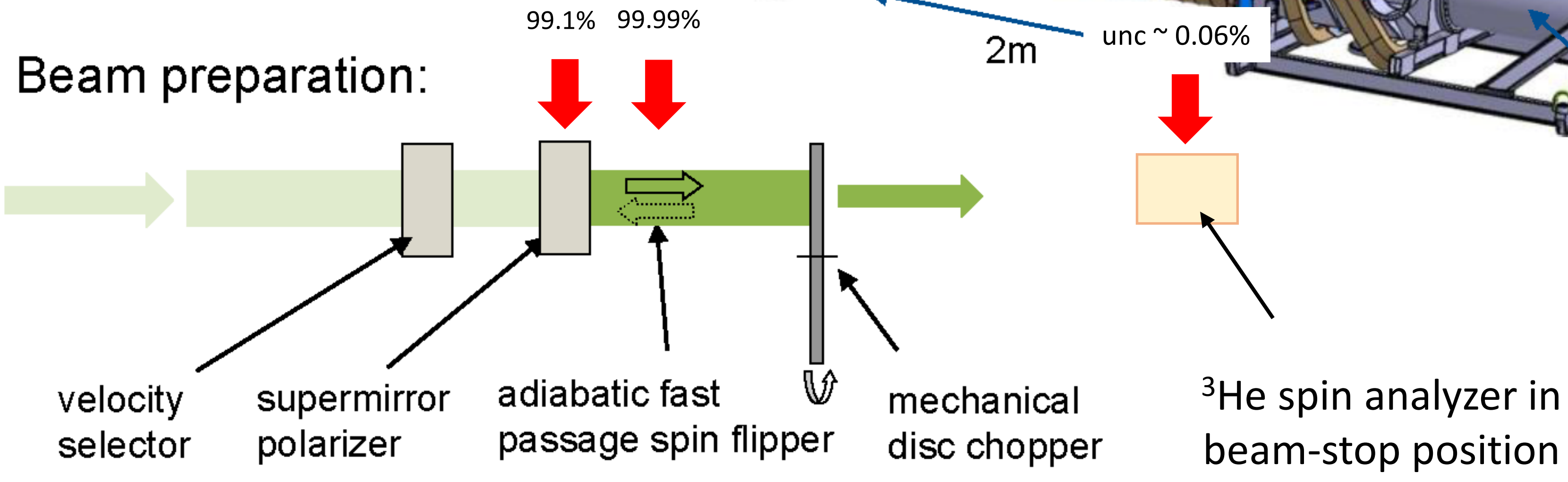
Guiding magnetic fields weaker near the detectors to create an “inverse pinch” to suppress backscatter

When both detectors are actually hit by a beta, use timing signals to determine initial emission direction

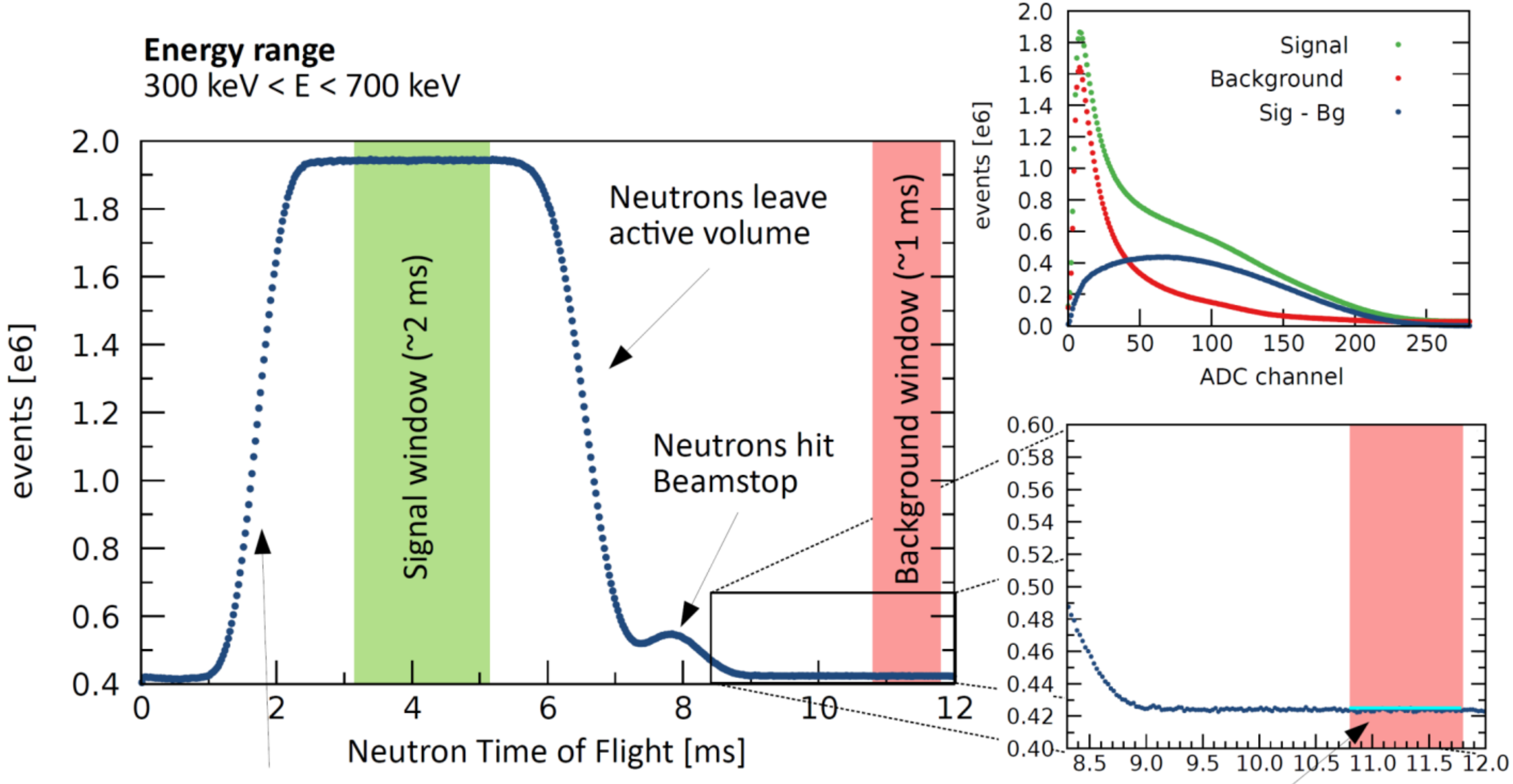
Spectrometer PERKEO III (Beam Polarization)



Beam preparation:



PERKEO III: Pulsed Neutron Beam



Energy range
300 keV < E < 700 keV

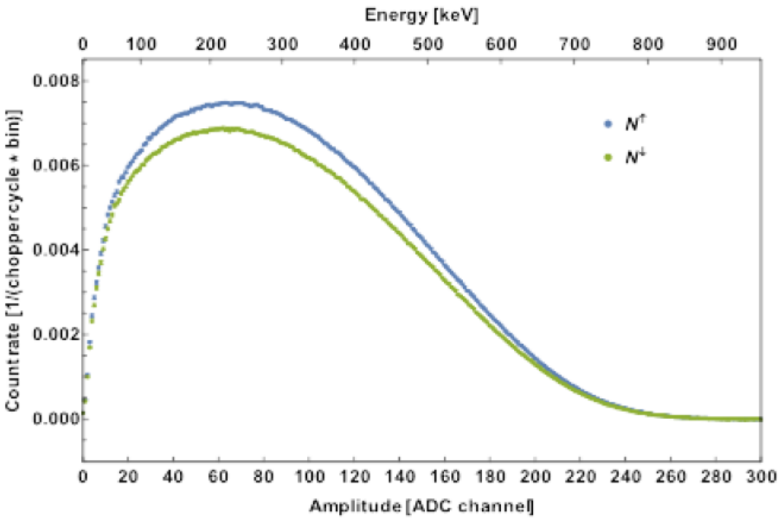
Neutrons leave active volume

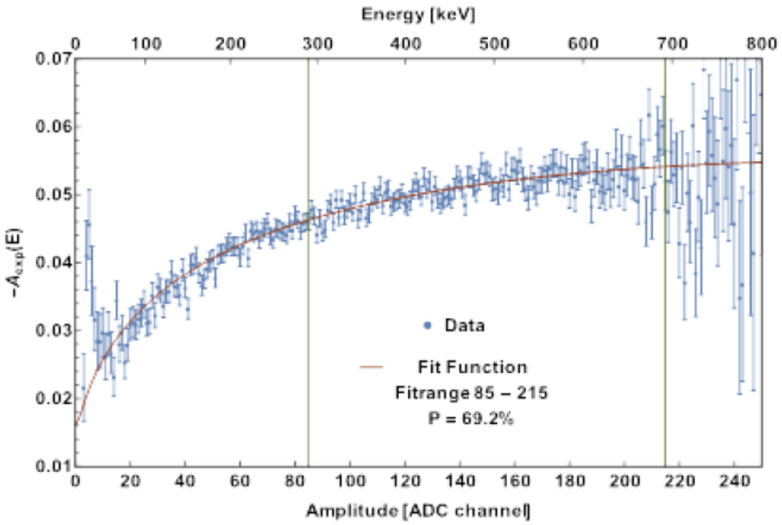
Neutrons hit Beamstop

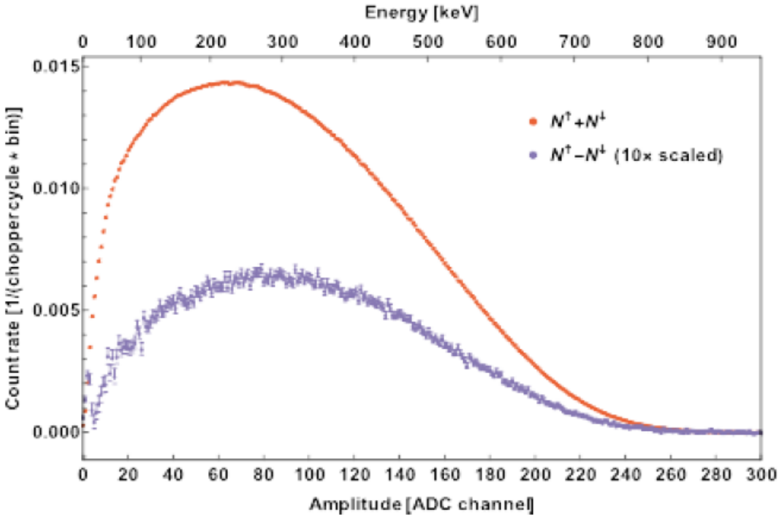
Neutrons enter active volume

Slope is zero compatible on 10^{-4} level

Asymmetry Extraction







$$A_{exp}(E_e) = \frac{N^{\uparrow}(E_e) - N^{\downarrow}(E_e)}{N^{\uparrow}(E_e) + N^{\downarrow}(E_e)} = \frac{1}{2} P_n \frac{v}{c} A$$

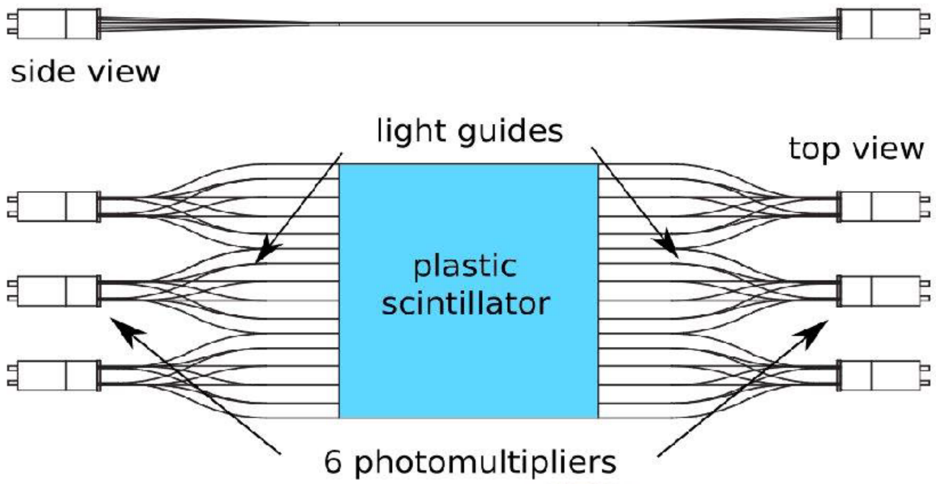
Largest neutron decay data set

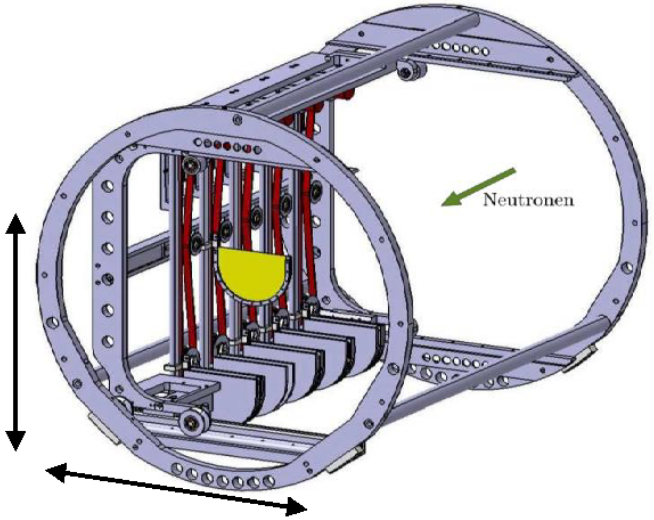
1 of 4 subsets shown

6×10^8 events in analysis

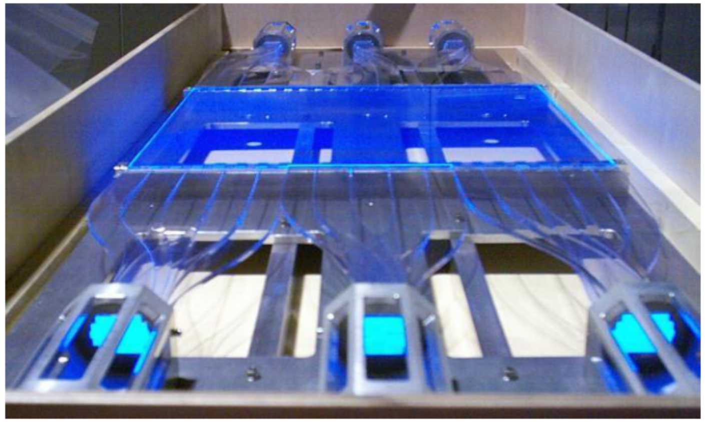
Statistical Uncertainty: $\Delta A/A = 14 \times 10^{-4}$

Electron Detector





Size ~ 40 x 40 cm²
Light output ~ 250 PE/MeV



Calibration with electron conversion sources:

- ^{207}Bi – 500 keV, 1.06 MeV, 2 Auger
- ^{137}Cs – 630 keV, 2 Beta Spectra
- ^{113}Sn – 370 keV, Auger
- ^{139}Ce – 130 keV

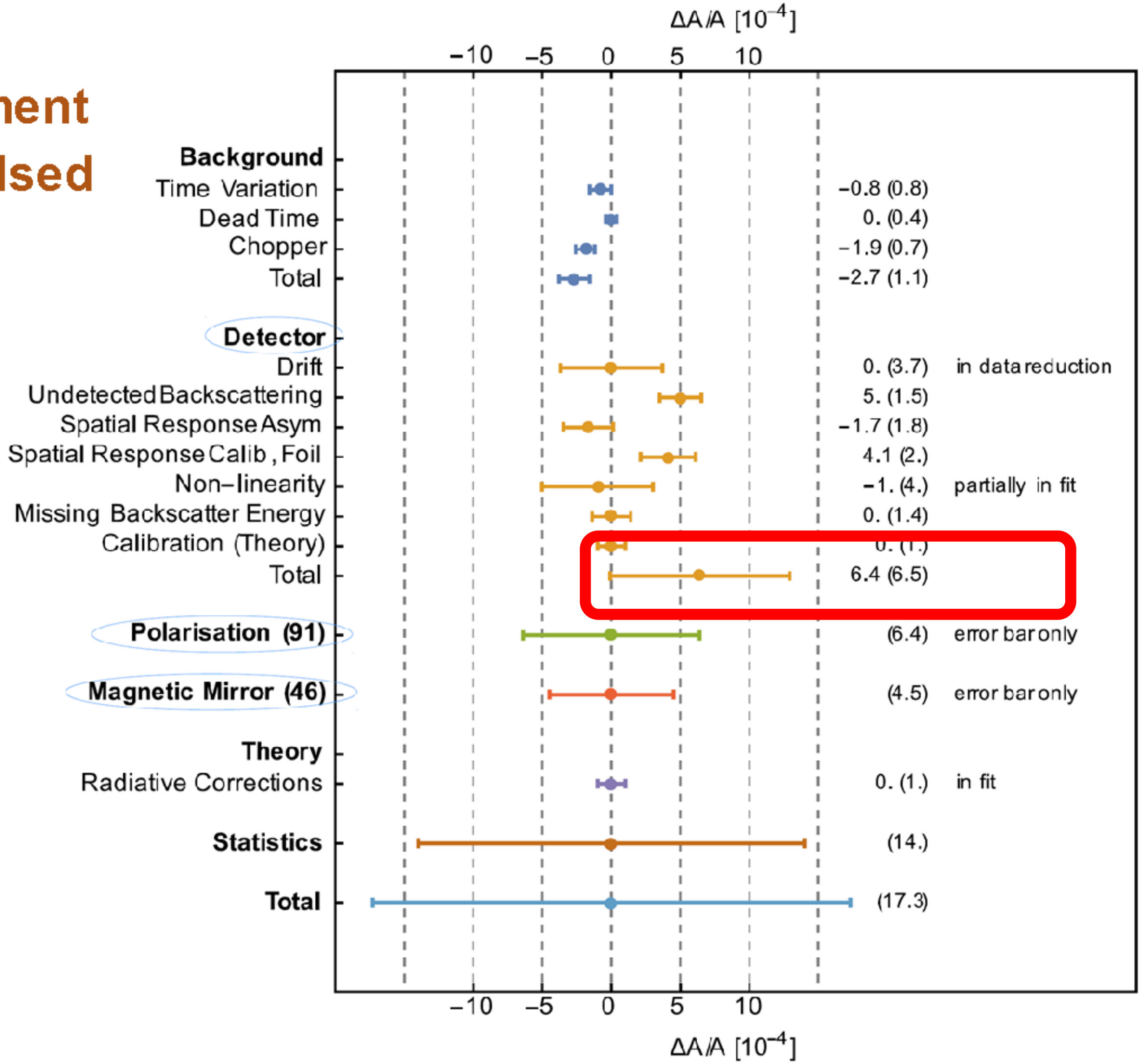
Hourly calibration

Full calibration set twice a day

Every few days complete 2D scan

Summary of Corrections and Uncertainties

First measurement of λ using a pulsed beam



Important Sources of Systematic Uncertainty (similar issues, different techniques!)

Detector Effects

Impressive: $6.4(6.5) \times 10^{-4}$

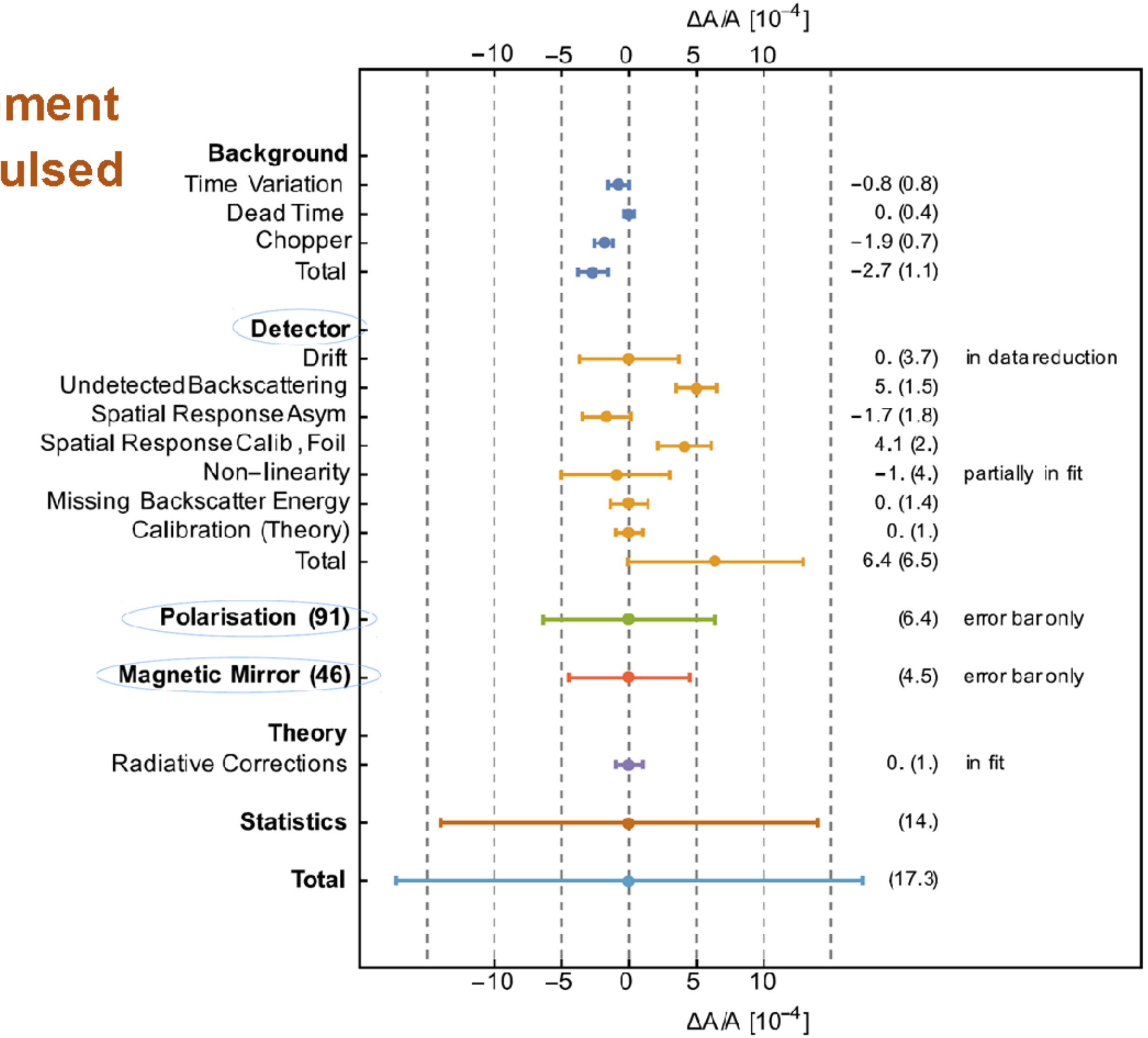
λ = −1.27641(56),
Δλ/λ = 4.4 × 10 −4

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

Summary of Corrections and Uncertainties

First measurement of λ using a pulsed beam

$\lambda = -1.27641(56)$,
$\Delta\lambda/\lambda = 4.4 \times 10 -4$



Important Sources of Systematic Uncertainty (similar issues, different techniques!)

Detector Effects

Polarization

Magnetic Mirror

Limited by statistics!

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

And the next generation for this team (spectrometer now at the MLZ):

Perc

Ultimate goal (phase II):

Goal for β-asymmetry: $\frac{\Delta\lambda}{\lambda} \rightarrow \sim 1.3\times\ 10\ -4$

Phase I: $\frac{\Delta\lambda}{\lambda} \rightarrow \sim$PERKEO III

PERC

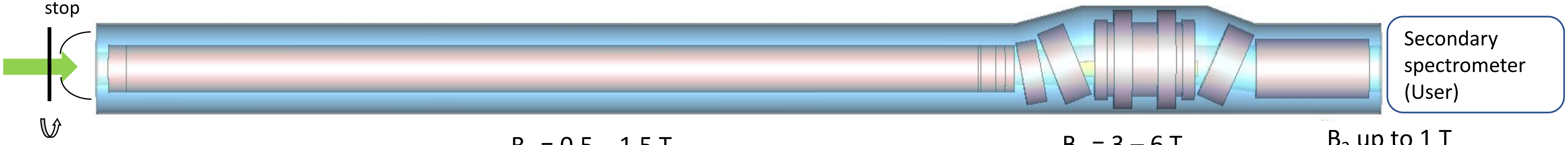
ATOMINSTITUT

JG|U

NEUTRONS FOR SCIENCE

SLOW NEUTRONS
DFG SPP 1491

PERC (Proton Electron Radiation channel) Facility at MLZ



e,p-beam stop

Active volume – 8m !

Magnetic filter

Detector region

Secondary spectrometer (User)

Mechanical Chopper

$B_0 = 0.5 – 1.5$ T

$B_1 = 3 – 6$ T

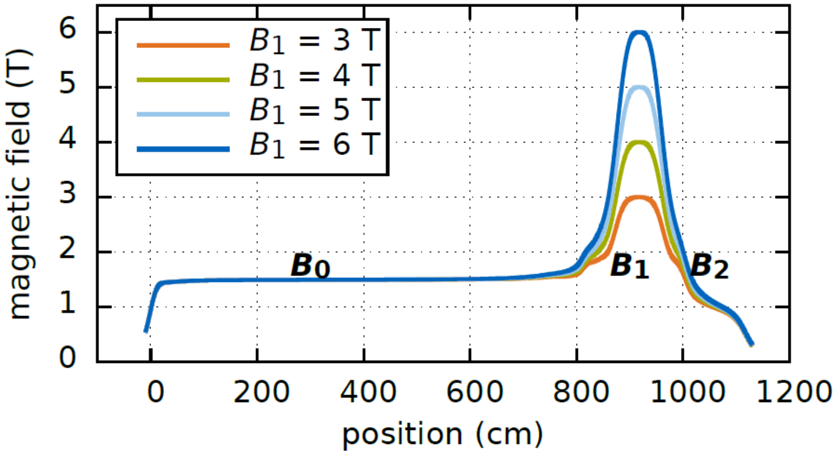
B_2 up to 1 T

Raw decay rate ~ ~30 kHz/m…

- (*pulsed, polarised*) cold **neutron beam** (6x6cm²)
- 8m long non-depolarising neutron guide as **active volume, $B_0 \sim 1.5\mathrm{T}$**
- **Magnetic filter** ($B_1 = 3$ - $6\mathrm{T}$) to enhance systematics ${}^{B_1}/_{B_0} = 2 \dots 12$

  separates e/p from neutrons, contains neutron beam stop,

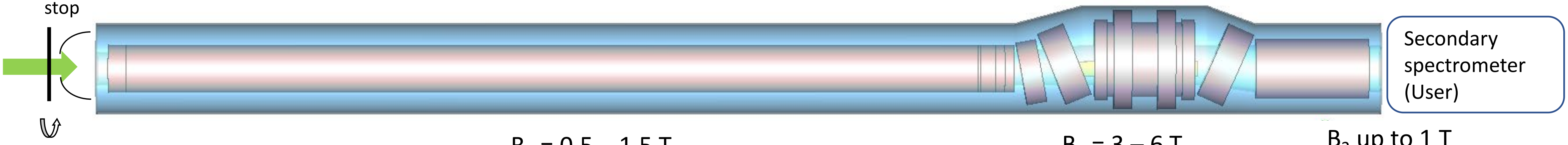
  limits max. angle of electrons / protons
- Source of electrons and protons to user-spectrometers:
  Observables: A, B, C, b, a



X. Wang, C. Ziener *et al*. (PERC Collaboration), EPJ Web Conf. 219, 04007 (2019)

D. Dubbers *et al.*, Nucl. Instr. Meth. A **596**, 238 (2008) and arXiv:0709.4440

PERC (Proton Electron Radiation channel) Facility at MLZ



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Raw decay rate ~ ~30 kHz/m…

- (*pulsed, polarised*) cold **neutron beam** (6x6cm²) x50 of PERKEO III !
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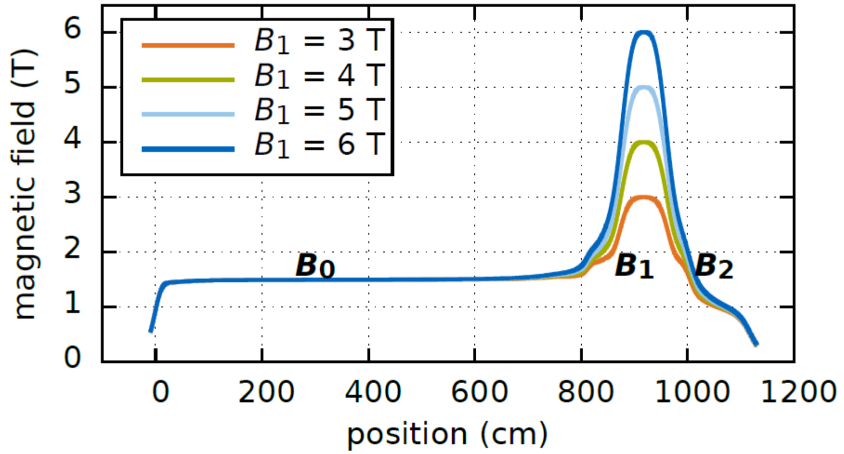
- **Magnetic filter** ($B_1 = 3$ - $6T$) to enhance systematics ${}^{B_1}/_{B_0} = 2 \dots 12$

  separates e/p from neutrons, contains neutron beam stop,

  limits max. angle of electrons / protons
- Source of electrons and protons to user-spectrometers:
  Observables: A, B, C, b, a

Groundwork has been laid!
Spectrometer installed
Beamline being built out…



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UCNA and UCNA+

(an upgrade of UCNA in an R&D phase at LANL)

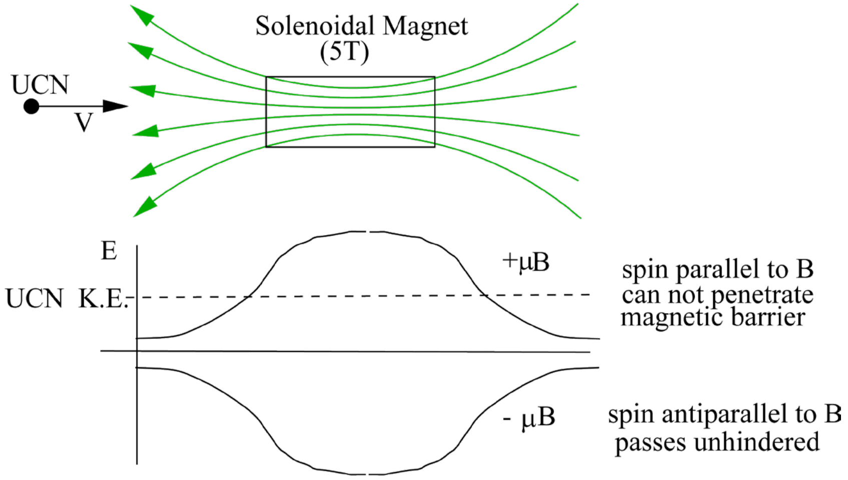
β-asymmetry with Ultracold Neutrons

spokespersons: R. W. Pattie and S. Clayton

UCNA controlled "neutron-related" systematic uncertainties differently from CN beams experiments

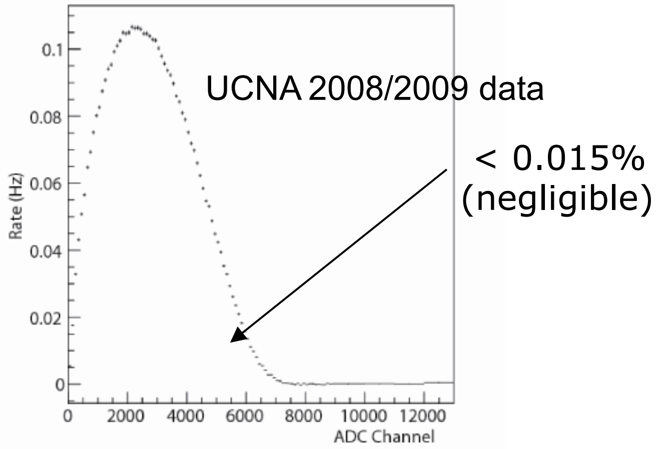
UCN provide a unique handle on key neutron-related systematic errors.

Polarization: "Potential barrier" polarization demonstrated effective alternative to supermirror/^{3}He cell technology with $P \geq 99.5\%$ and ultimate uncertainties at or below 0.1% level

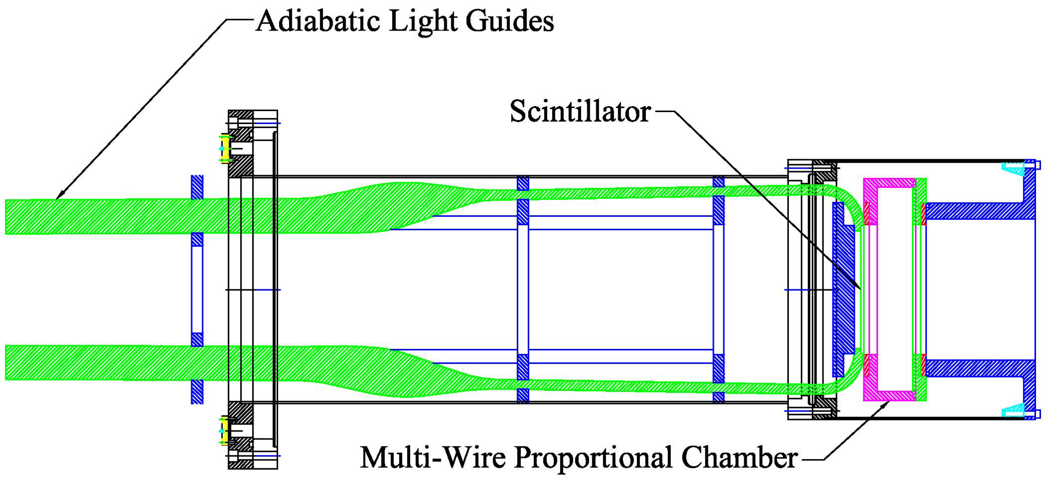


(note: neutron magnetic moment is negative)

Neutron generated backgrounds: small number of neutrons and low capture probability (long residency time) lead to order of magnitude improvement relative to (then) current cold neutron beams experiments



Motivation for Experimental Approach II: Detectors



Minimize backscatters

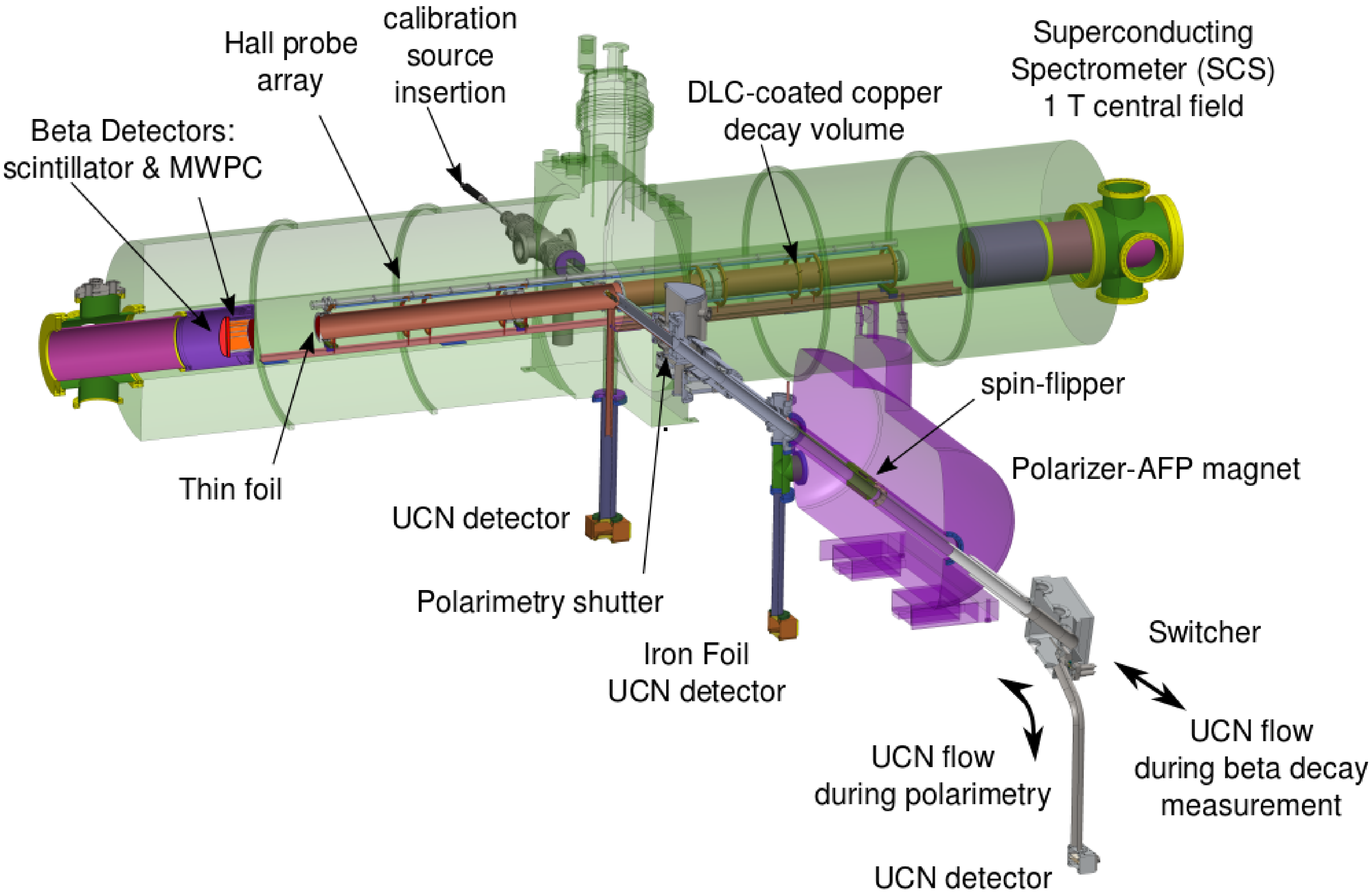
- Pinch geometry
- Low Z detectors

MWPC-scintillator coincidence

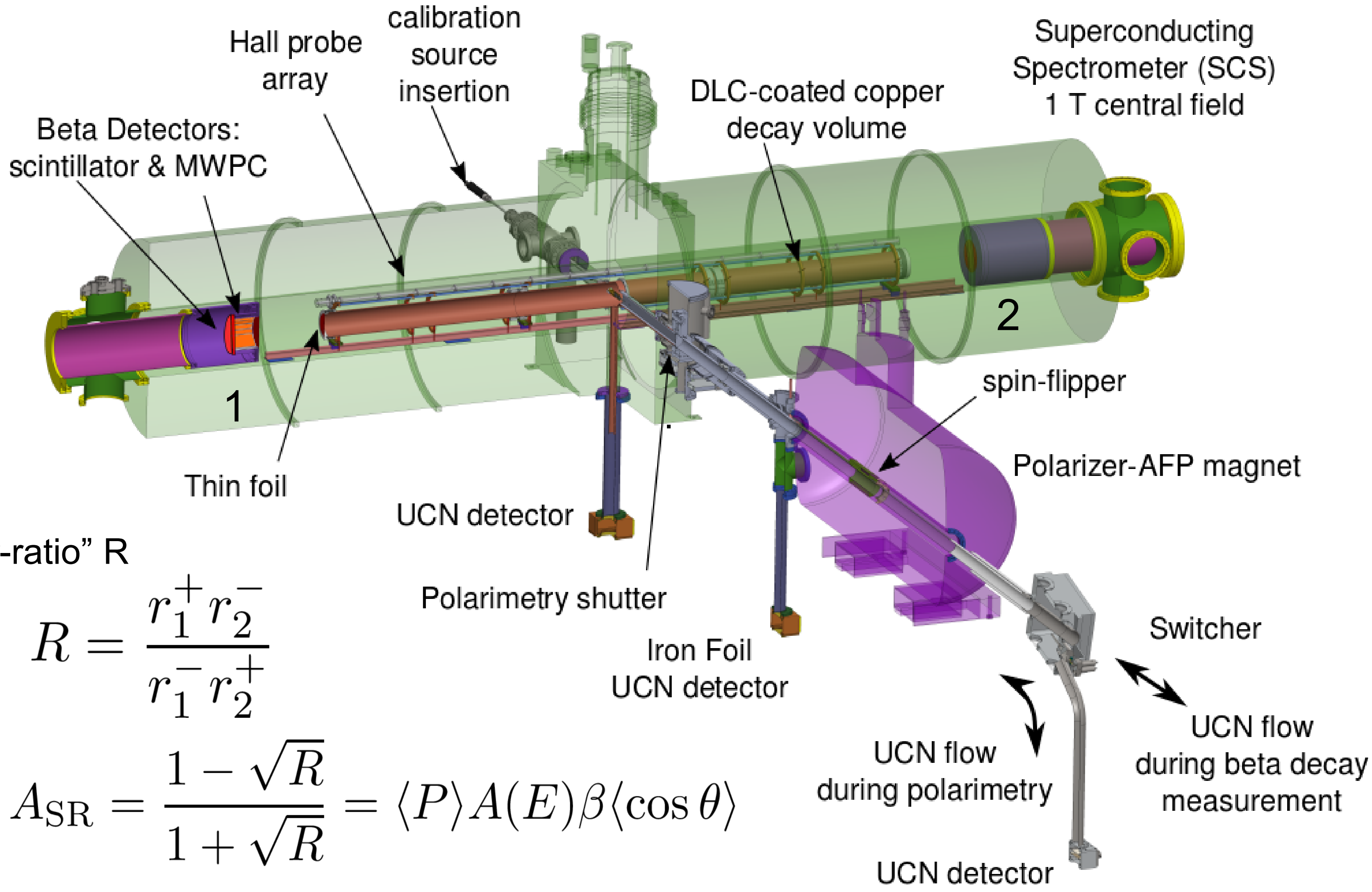
- Provide position sensitivity
  - Map position sensitive detection efficiency effects
  - Eliminate effect of apertures
  - Explore fiducial volume cuts
- Suppress ambient and neutron-generated backgrounds
- Assist in backscatter reconstruction

A price to pay for the MWPC: additional dead-layer energy loss and scattering relative to bare scintillator

UCNA: The Experimental Approach



Extracting the Raw Asymmetry



"Super-ratio" R

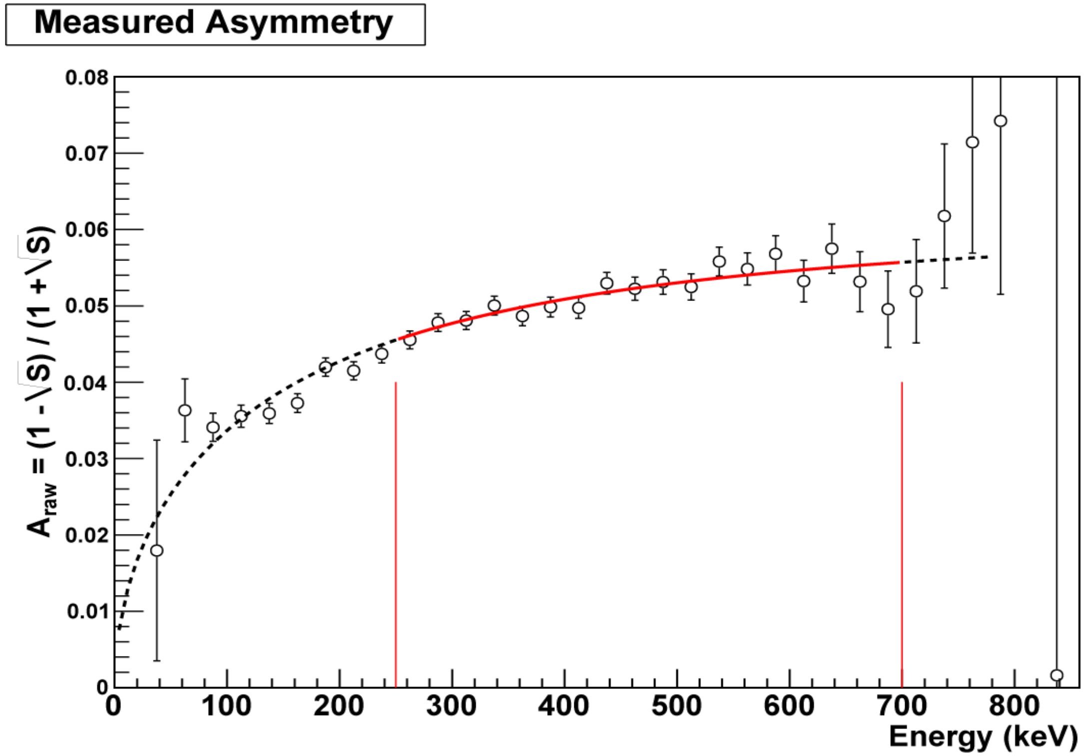
$$R = \frac{r_1^+ r_2^-}{r_1^- r_2^+}$$

$$A_{\text{SR}} = \frac{1-\sqrt{R}}{1+\sqrt{R}} = \langle P \rangle A(E) \beta \langle \cos\theta \rangle$$

Insensitive to rate variations & detector efficiencies to 1st order

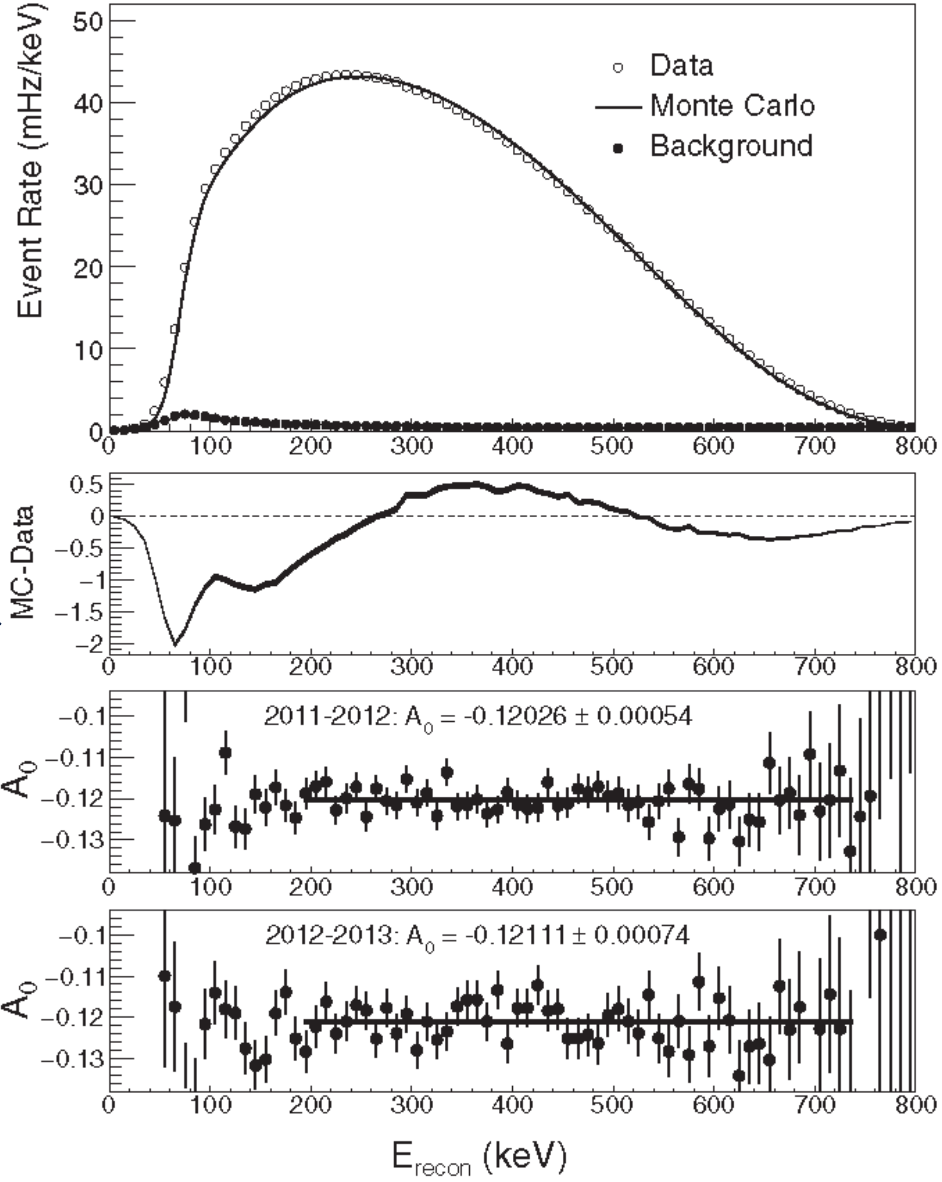
2018 Final Results for UCNA

Example “Raw” Asymmetry
(v/c dependence evident)



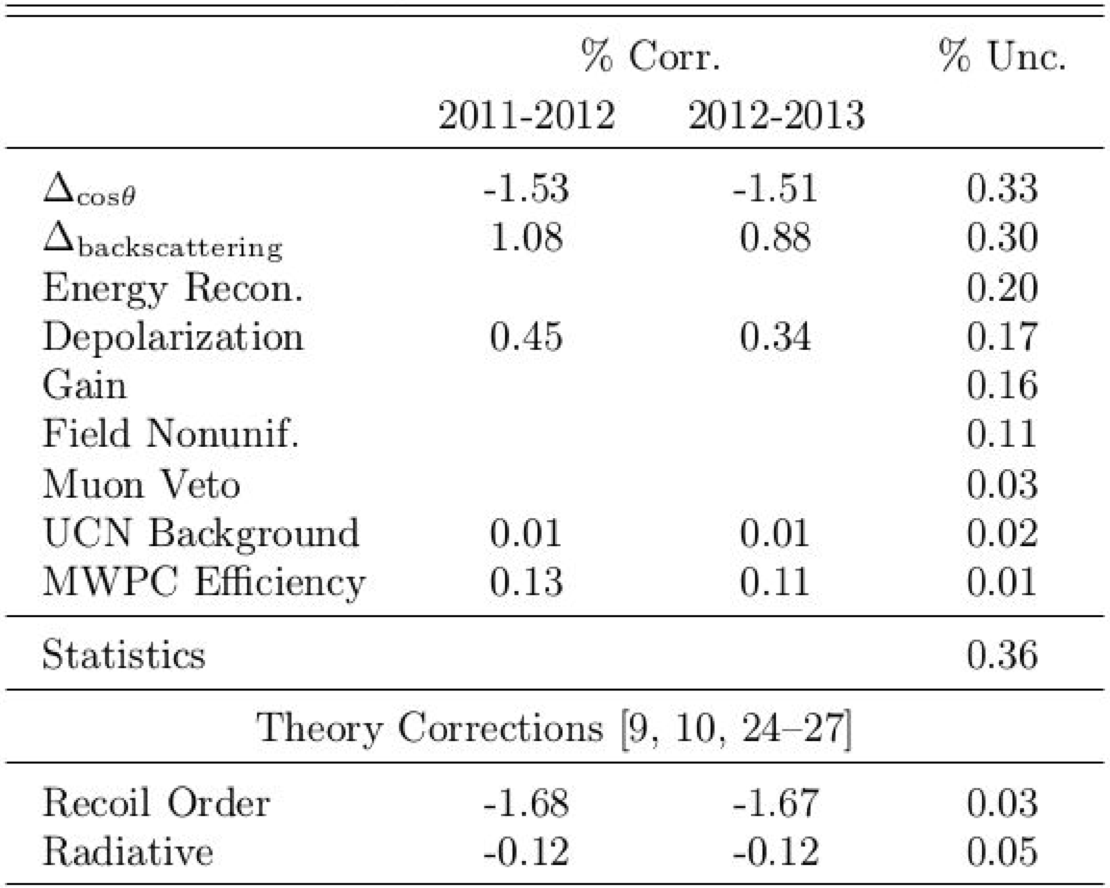
(measured in 2010)

Extract $A_0 \equiv \frac{2|\lambda|-\lambda^2}{1+3\lambda^2}$



UCNA Final Result (2018)

$$A_0 = -0.12054(44)_{\text{stat}}(68)_{\text{syst}}$$



	% Corr.		% Unc.
	2011-2012	2012-2013	
$\Delta_{\cos\theta}$	-1.53	-1.51	0.33
$\Delta_{\text{backscattering}}$	1.08	0.88	0.30
Energy Recon.			0.20
Depolarization	0.45	0.34	0.17
Gain			0.16
Field Nonunif.			0.11
Muon Veto			0.03
UCN Background	0.01	0.01	0.02
MWPC Efficiency	0.13	0.11	0.01
Statistics			0.36
Theory Corrections [9, 10, 24–27]			
Recoil Order	-1.68	-1.67	0.03
Radiative	-0.12	-0.12	0.05

total systematic unc for A: 0.55%

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

UCNA Final Result (2018)

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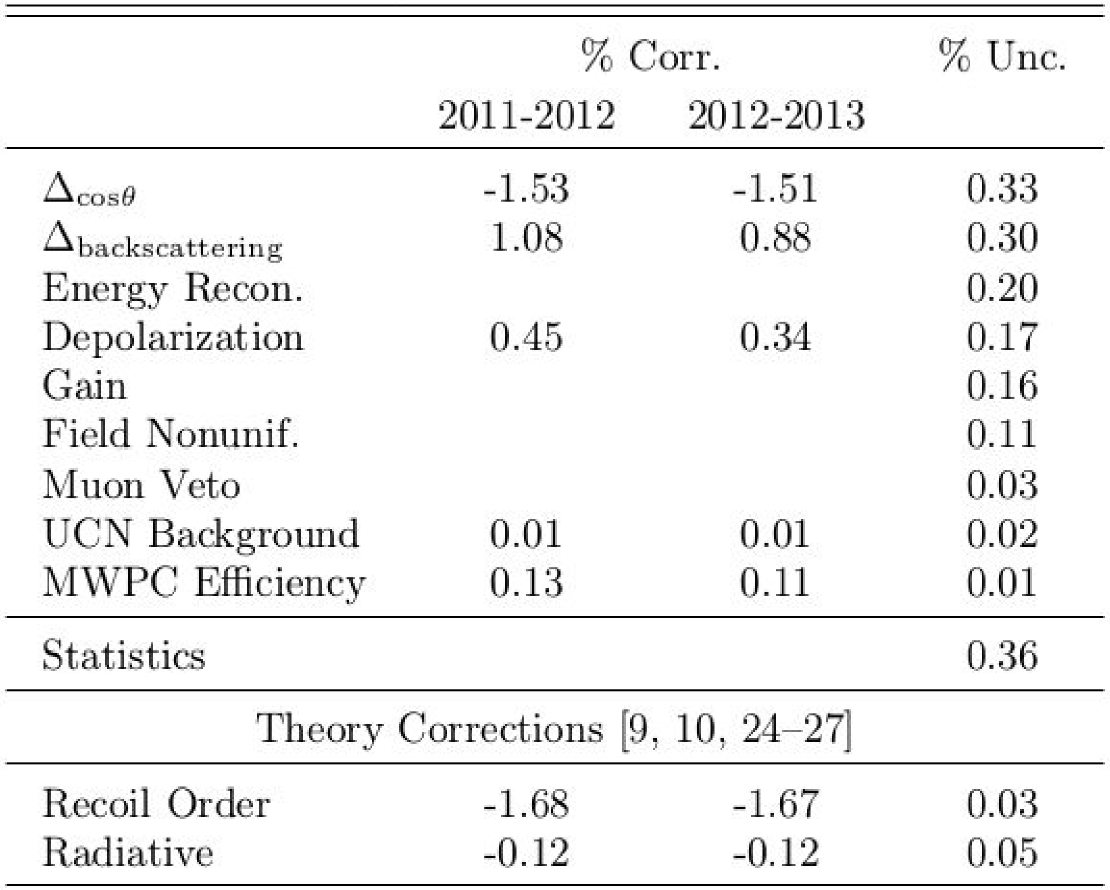

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Radiative	-0.12	-0.12	0.05

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

Combined result all UCNA:

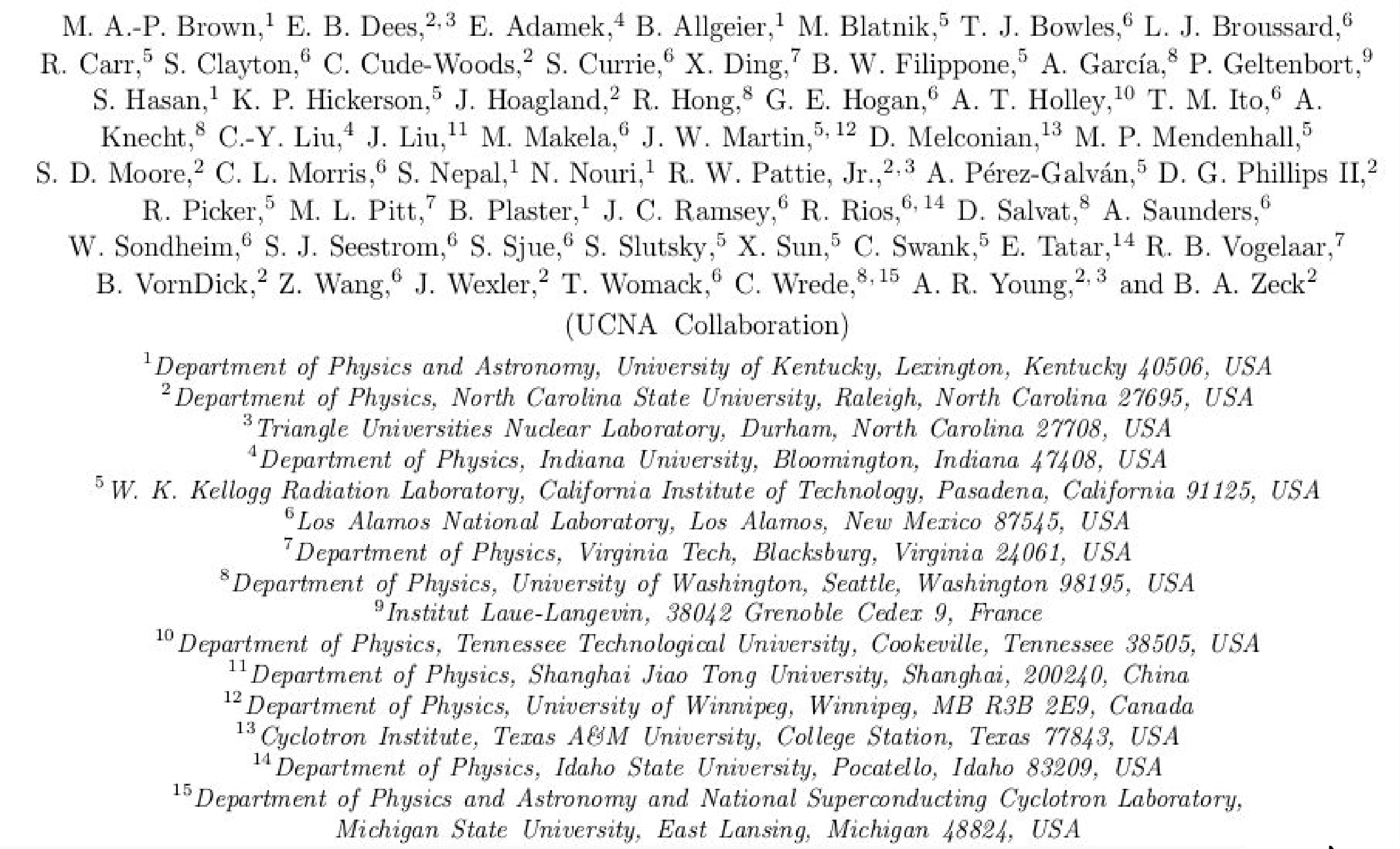
λ=−1.2772 ±0.0020

dλ/ λ = 0.16%

Still the most precise cross-check of PERKEO experiments…

total systematic unc for A: 0.55%

The UCNA Collaboration



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(UCNA Collaboration)

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This research was supported by the NSF, the Low Energy Nuclear Physics Division of the Department of Energy, the Nuclear Physics Division of the National Science Foundation, and Los Alamos National Laboratory, through the LDRD program

UCNA+: how to reduce error budget of UCNA by factor of at least 3?

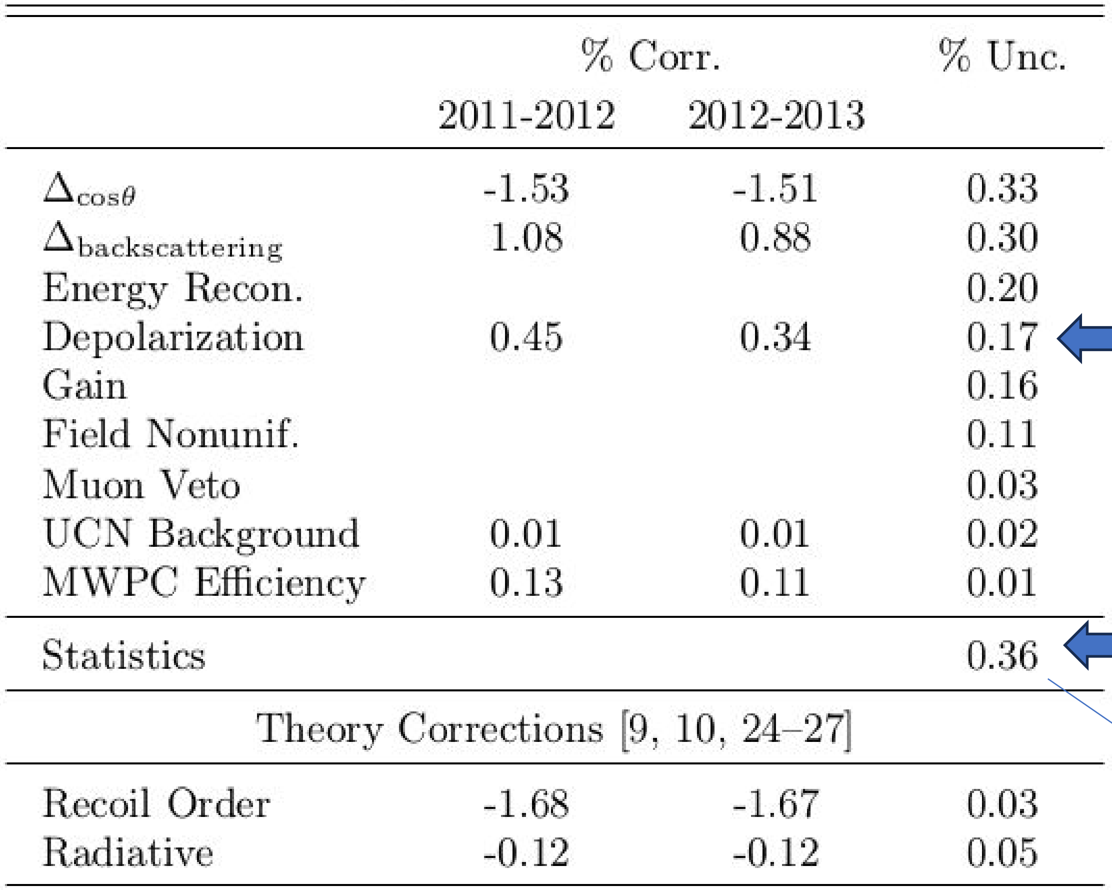
(Adapt from the existing experiment!)

Target Uncertainty for $A_o < 0.2\%$

Steve Clayton's talk

UCNA Final Result (2018)

$$A_0 = -0.12054(44)_{\mathrm{stat}}(68)_{\mathrm{syst}}$$



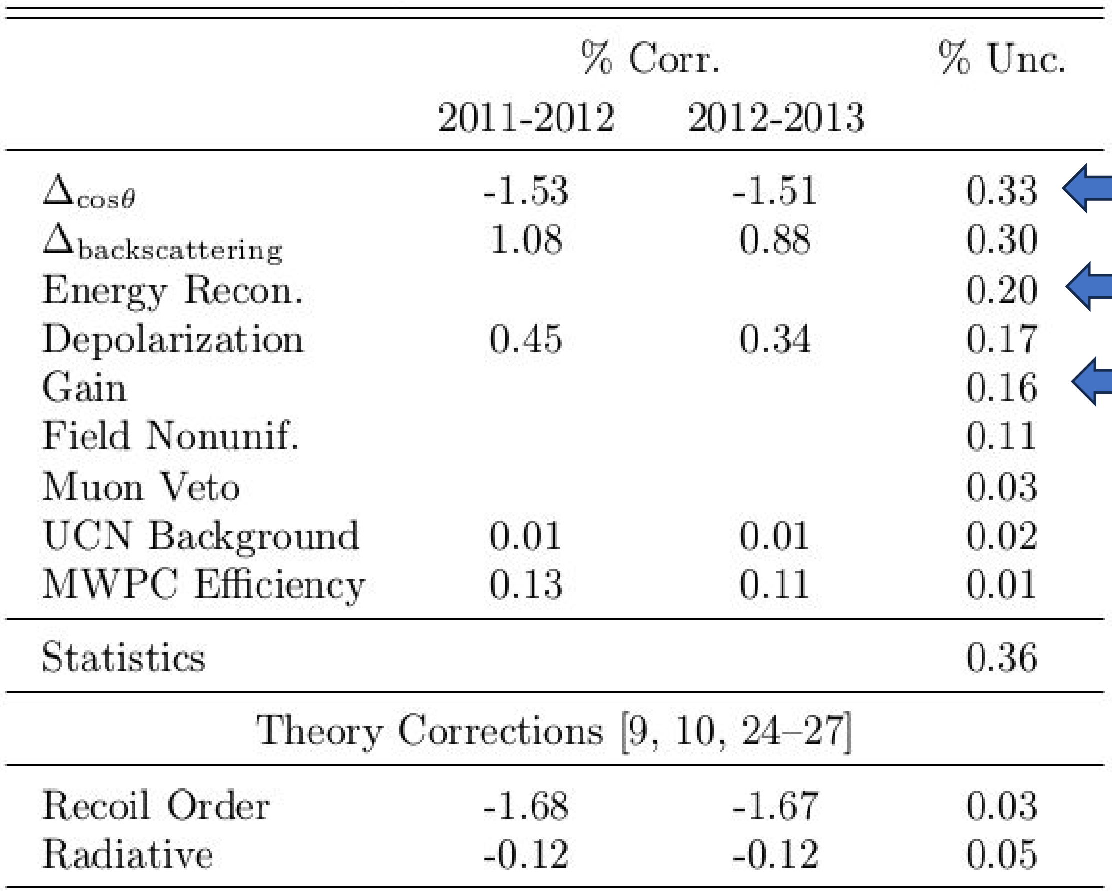
	% Corr.		% Unc.
	2011-2012	2012-2013	
$\Delta_{\cos\theta}$	-1.53	-1.51	0.33
$\Delta_{\mathrm{backscattering}}$	1.08	0.88	0.30
Energy Recon.			0.20
Depolarization	0.45	0.34	0.17
Gain			0.16
Field Nonunif.			0.11
Muon Veto			0.03
UCN Background	0.01	0.01	0.02
MWPC Efficiency	0.13	0.11	0.01
Statistics			0.36
Theory Corrections [9, 10, 24–27]			
Recoil Order	-1.68	-1.67	0.03
Radiative	-0.12	-0.12	0.05

Improved LANL UCN source: both unc should ~0.1%
~180 dps

(increasing min energy for analaysis window could push to 0.14%)

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

UCNA Final Result (2018)



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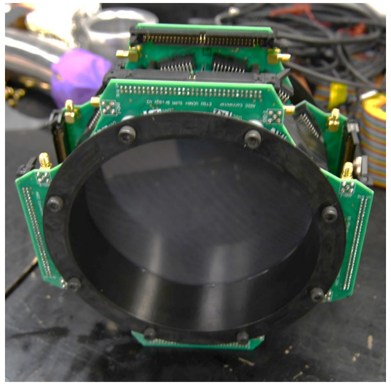
These require a new detector and calibration strategy!

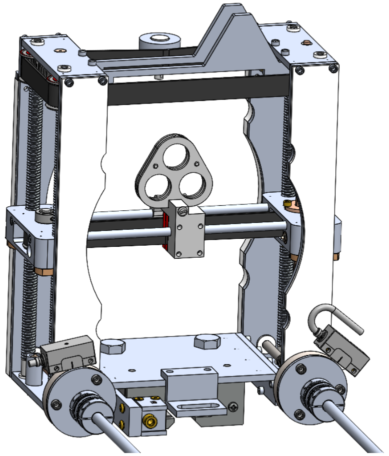
Detectors: Two, close-coupled, bare scintillators with SiPM readout (R. Pattie)

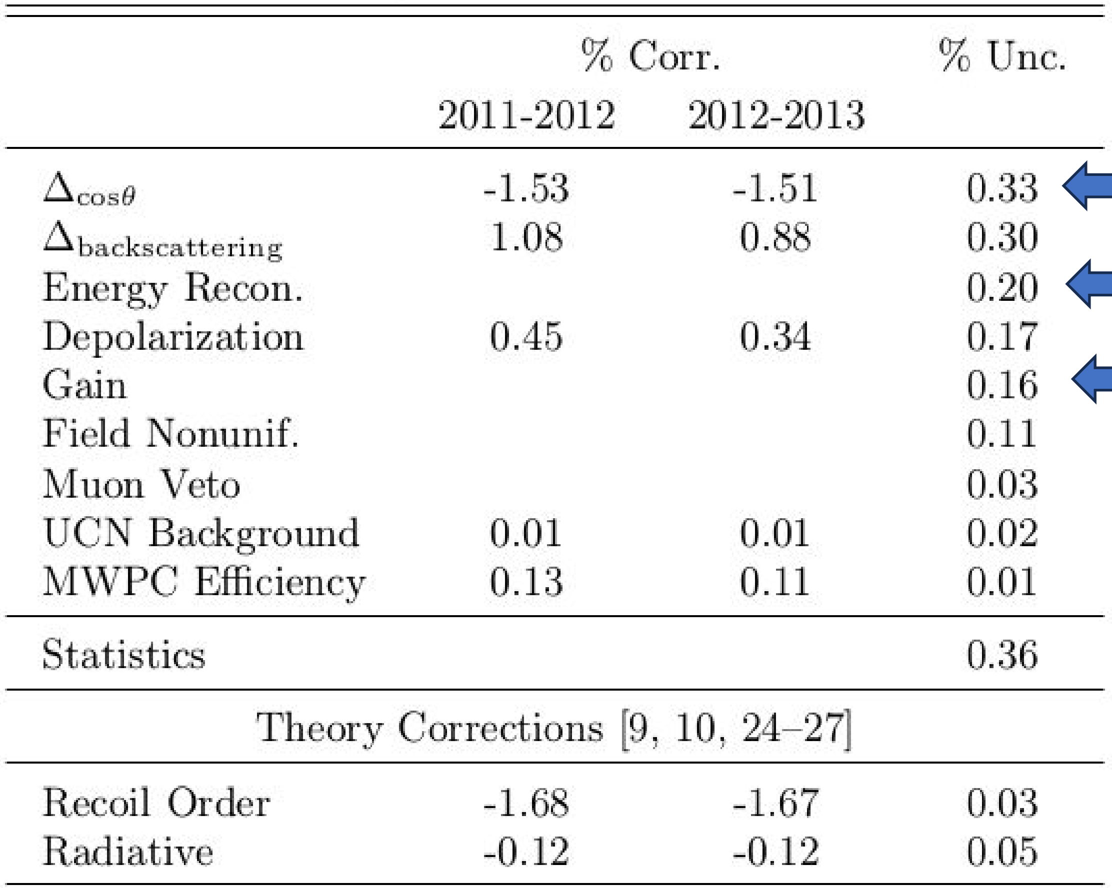
Calibration: 2D source scanner, integrated into decay volume – PERKEO III is model here…

UCNA Final Result (2018)

Prototypes now exist
for these upgrades!







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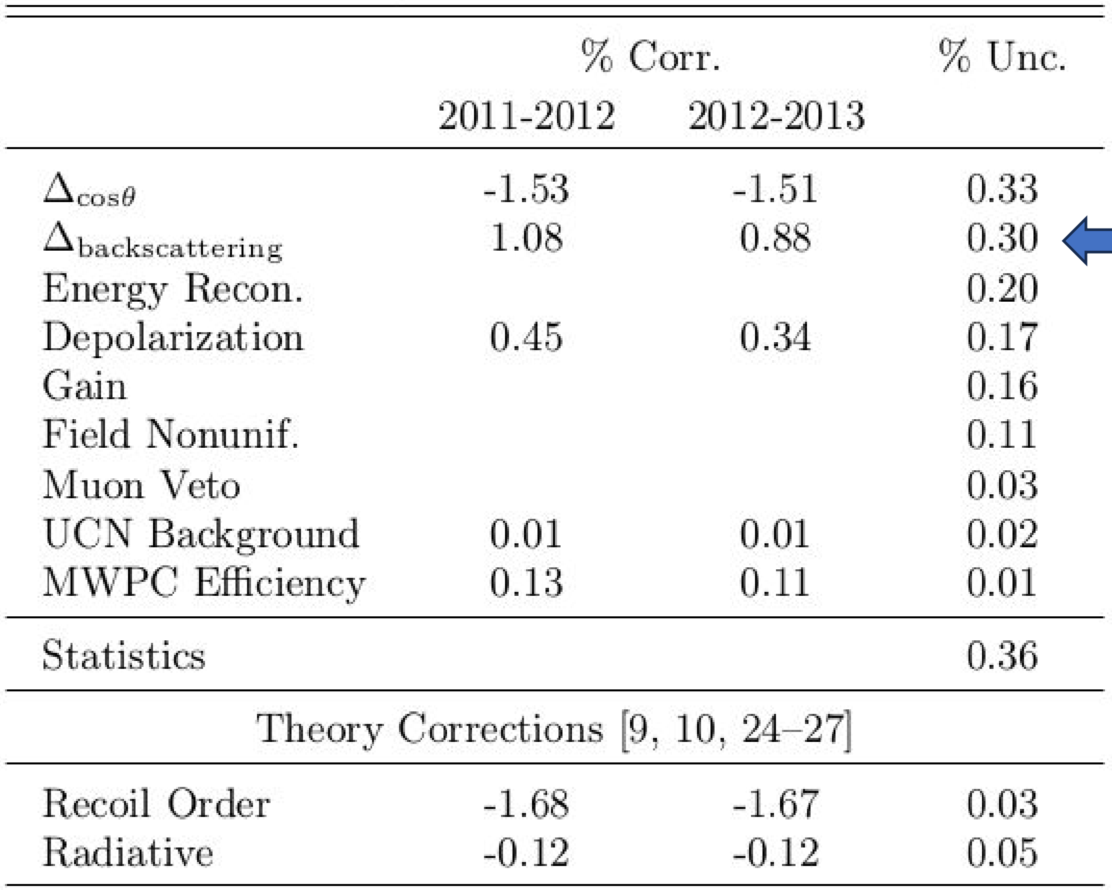
UCNA Final Result (2018)



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Radiative	-0.12	-0.12	0.05

Use thinnest foils, Possibly increase Energy of analysis window, **measure scattering**

Result: in 2 years of running it looks feasible to achieve target sensitivity if design specs can be achieved…

UCNA+ R&D Collaboration

- East Tennessee State University:
  - **J. Fry, A. Greathouse**, **R.E. McDonald IV, N. Meredith,** R. W. Pattie JR
- Indiana University/CEEM:
  - **M. Dawid,** W. Fox, M. Luxnat, D.J. Salvat, J. Vanderwerp, G. Visser, **D. Wong**
- Los Alamos National Lab:
  - M. C. Anderson, S. Clayton, R. Gupta, T.M. Ito, S. Lin, M. Makela, C. Morris, C. O'Shaughnessy, E. Renner, Z. Tang, Z. Wang
- North Carolina State University:
  - **J.H. Choi, K. Murer, R. Musedinovic, C. Cude-Woods**, L. Hayen, A.R. Young
- Oak Ridge National Laboratory:
  - F. Gonzalez, A. Saunders
- Tennessee Technical University:
  - A.T. Holley, **L. Chapman, C. Hasting, E. Upton, C. Shepherd**
- University of Kentucky:
  - **R. Gupta**, B. Plaster
- University of Illinois- Urbana Champaign
  - C.Y. Liu

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- Student researchers in bold.

pNab

(a proposed upgrade of the Nab experiment)

The order here is a little funny – but we will loop back to Nab…

Target Uncertainty for A_o ~ 0.1%

Wolfgang Schreyer's talk

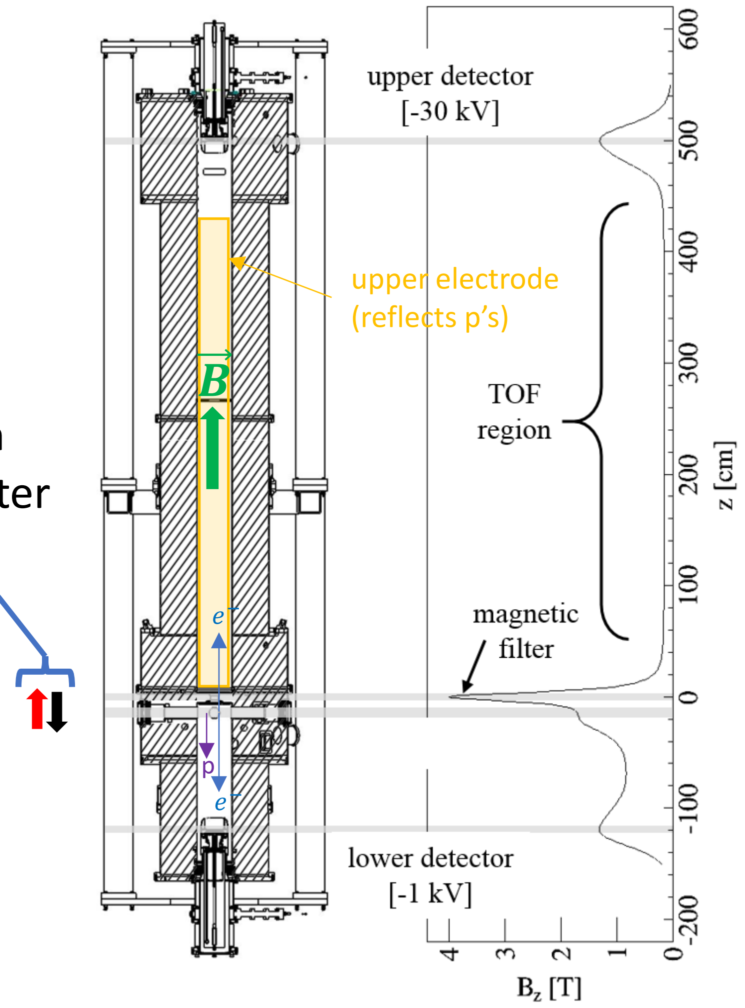
pNab β −Asymmetry Mode

Detector 1: N_1

Neutron polarization ∥ or ∦ to spectrometer magnetic field

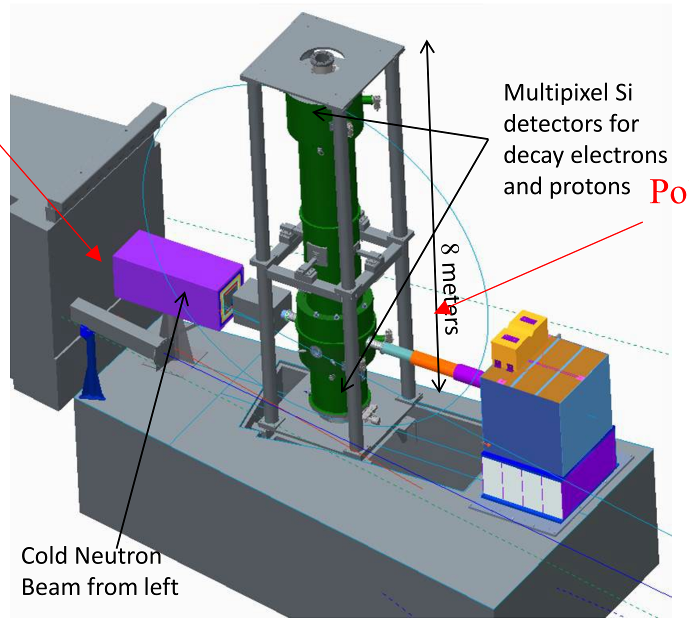
neutron beam

Detector 2: N_2



- Concept: once Nab is complete, use spectrometer with modifications to measure correlations with polarized neutrons
- Neutron polarization is oriented (by Spin-Flipper) to be parallel or antiparallel to spectrometer magnetic field
- Electrons detected in Si detectors at ends of spectrometer (similar to other β-asymmetry measurements)
- All protons detected in lower detector (reflected from upper electrode, coincidence just used to suppress backgrounds)

New addition:
Neutron beam polarizer



Multipixel Si detectors for decay electrons and protons

New addition:
Polarization analyzer

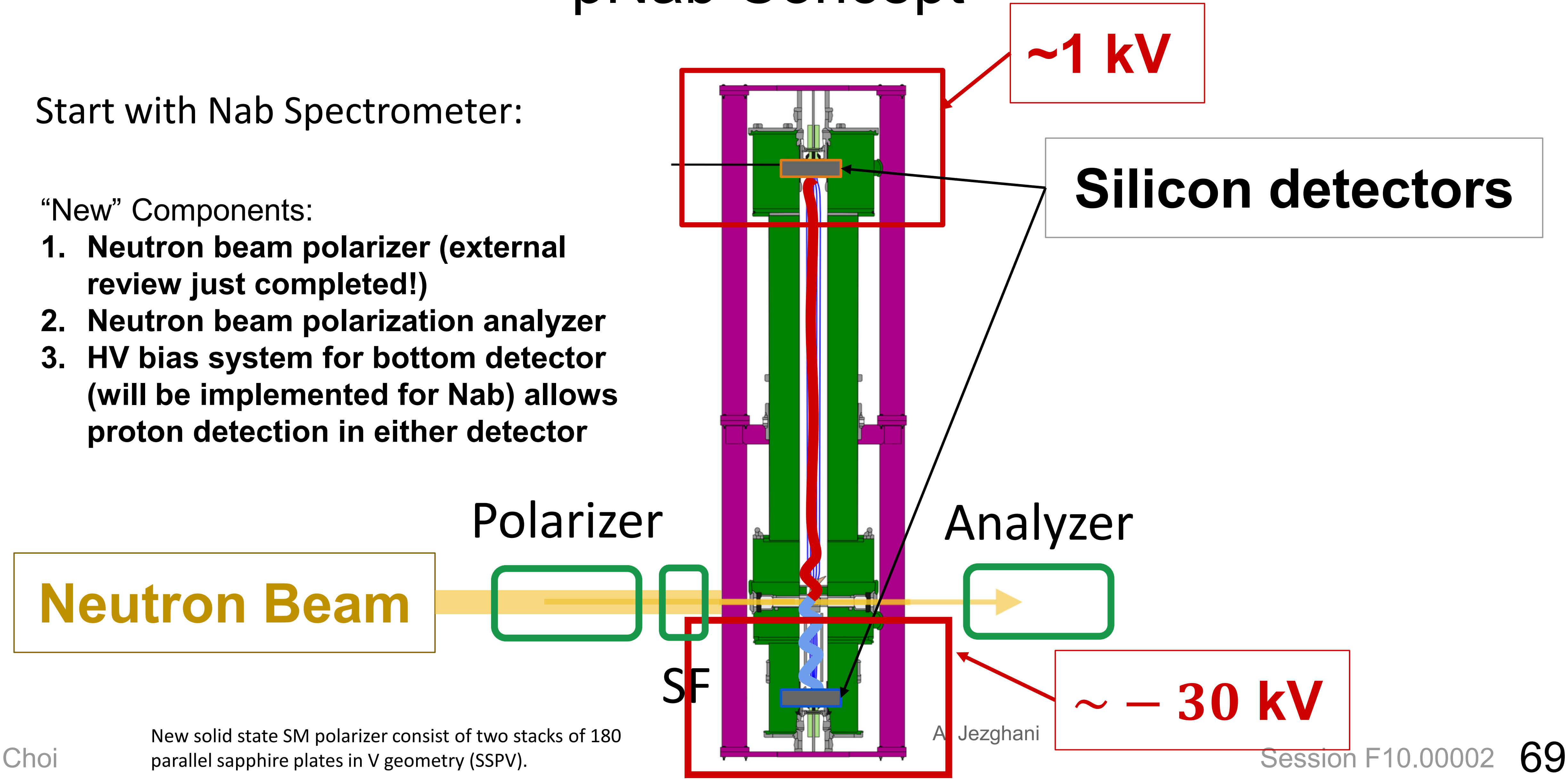
Cold Neutron Beam from left

pNab Concept

Start with Nab Spectrometer:

“New” Components:

1. **Neutron beam polarizer (external review just completed!)**
2. **Neutron beam polarization analyzer**
3. **HV bias system for bottom detector (will be implemented for Nab) allows proton detection in either detector**



New solid state SM polarizer consist of two stacks of 180 parallel sapphire plates in V geometry (SSPV).

A. Jezghani

Estimated Systematic Uncertainty Budget for Beta Asymmetry *A*

$$A_{exp} = \overset{\boxed{4}}{\frac{N_e^{\uparrow}(E_{e,kin}) - N_e^{\downarrow}(E_{e,kin})}{N_e^{\uparrow}(E_{e,kin}) + N_e^{\downarrow}(E_{e,kin})}} = A\,\overset{\boxed{1}}{P_{\mathrm{n}}}\,\overset{\boxed{2}}{\frac{p_e}{E_e}}\,\overset{\boxed{3}}{\langle\cos(\vec{\sigma}_{\mathrm{n}}, \vec{p}_e)\rangle}$$

Contribution to Uncertainty	$\mathbf{\Delta A/A}$
1. Neutron beam polarization	$5 \cdot 10^{-4}$
2. Electron detector response	$5 \cdot 10^{-4}$
3. Solid angle coverage of each detector	negligible
4. Statistical uncertainty	$7 \cdot 10^{-4}$
4b. Backgrounds: Unlike competition, we have e/p coincidence	uncertainty is small
Total	$\boxed{\mathbf{< 1 \cdot 10^{-3}}}$

Decay rate
~200 cps

S. Baessler

pNAB proposal

The pNAB proposal was submitted on July 1, 2024: http://nab.phys.virginia.edu/pNab_Proposal.pdf

Proposal for an experiment at the FnPB/SNS

pNab: a program of studies of beta decay of polarized free neutrons

R. Alarcon,[a] S. Baeßler,[b,c] L. Barrón Palos,[d] L. Broussard,[c] J.H. Choi,[e] T. Chupp,[f] C. Crawford,[g] G. Dodson,[h] N. Fomin,[i] J. Fry,[j] F. Gonzalez,[c] J. Hamblen,[k] L. Hayen,[l] A. Jezghani,[m] M. Makela,[n] R. Mammei,[o] A. Mendelsohn,[p] P. E. Mueller,[c] S. Penttilä,[c] J. Pioquinto,[b] B. Plaster,[g] D. Počanić,[b] A. Saunders,[c] W. Schreyer,[c] A. R. Young.[e]

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[f] University of Michigan, Ann Arbor, MI 48109, USA
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[j] Department of Physics, Geosciences, and Astronomy, Eastern Kentucky
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1 July 2024

Abstract: The Nab and pNab collaborations are und

PoS PROCEEDINGS OF SCIENCE

The pNAB experiment and the quest for ever better neutron beam polarization

S. Baeßler,[a,b,*] R. Alarcon,[c] L. Barrón Palos,[d] L. J. Broussard,[b] J. H. Choi,[e] T. Chupp,[f] C. B. Crawford,[g] G. Dodson,[h] N. Fomin,[i] J. Fry,[j] F. Gonzalez,[b] J. Hamblen,[k] L. Hayen,[l] A. Jezghani,[m] M. Makela,[n] R. Mammei,[o] A. Mendelsohn,[p] P. E. Mueller,[b] S. Penttilä,[b] J. A. Pioquinto,[a] B. Plaster,[g] D. Počanić,[a] A. Saunders,[b] W. Schreyer[b] and A. R. Young[e] (the pNAB collaboration)

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See also our paper, accepted for publication:
http://nab.phys.virginia.edu/PSTP2024_pNAB.pdf

Angular Correlation Summary

Many possibilities to contribute to Unitarity and global data set!
(potential to achieve parity with $0^+ \rightarrow 0^+$)

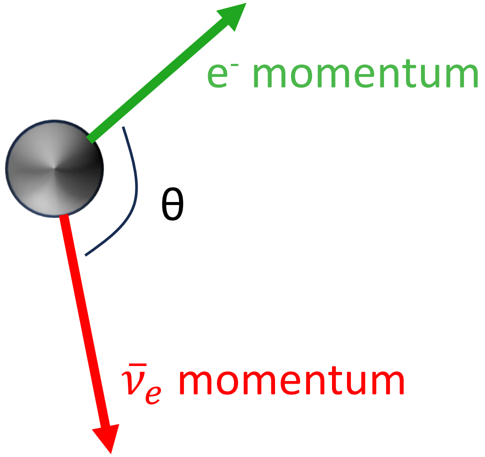
Experiment	Sensitivity to λ	Time-scale	Advantages
Perc	Phase I: ~ 4.4×10^{-4} Phase II: 1.5×10^{-4}	Uncertain, but 2-3 years minimum to start phase I data-taking (MLZ working to restart)	Enormous statistics Many components already tested Team well supported
UCNA+	$< 5.0 \times 10^{-4}$	Uncertain, but could start data-taking in 2-3 years	Based on existing, well characterized experiment Alternate methods to CN beams for neutron-based observables
pNab	$\sim 1.5 \times 10^{-4}$	Uncertain, but could start data-taking in 2-3 years	Excellent spectroscopy (Si dets) Moderate adaptation required from Nab

The $\beta - \bar{\nu}_e$ Correlation

Special thanks for figures from D. Pocanic, S. Baessler, J. Choi, F. Gonzalez

The Global Dataset: Angular Correlations

Example: the beta-neutrino correlation



$$R = R_o(1 + (v/c)\, a(E) \cos\theta)$$

$\beta - \bar{\nu}_e$correlation = a(E) in angular distribution of β relative to $\bar{\nu}_e$

$$a_o = \frac{1-\lambda^2}{(1+3\lambda^2)} \approx -0.10$$

(leading order)

Ignoring recoil-order terms, just a function of $\lambda = C_A/C_V$

Recent work establishes precision level for $\lambda \sim 10^{-3}$

How to Measure?

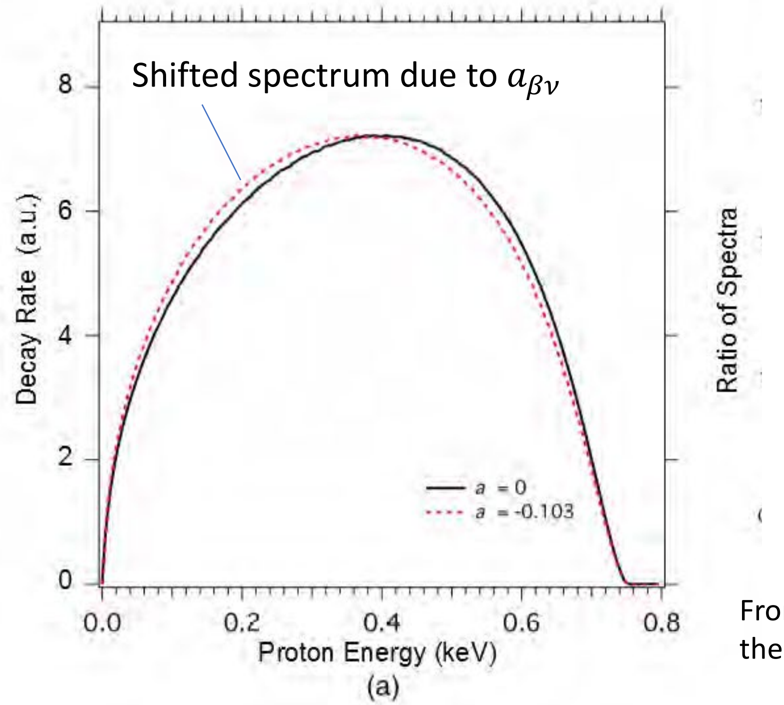
(1) It is not practical to measure the emitted $\bar{\nu}$ directly
(2) We can infer $\bar{\nu}$ emission directly through measurements of the proton and electron

$$\vec{p}_n = \vec{p}_e + \vec{p}_{\bar{\nu}} + \vec{p}_p \quad \Longrightarrow \quad \vec{p}_{\bar{\nu}} =- \vec{p}_e - \vec{p}_p$$

The $\beta - \bar{\nu}_e$ correlation determines the relative probability for $\bar{\nu}_e$ emission ∥ or ∦ to the electron.

When the electron and $\bar{\nu}_e$ are emitted parallel to each other (as opposed to isotropically): the proton is given a momentum boost relative to isotropic emission (defines the endpoint)!

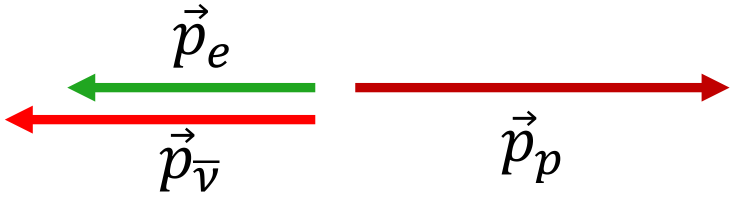
Measure the proton spectrum!


Shifted spectrum due to $a_{\beta\nu}$

(a)

From Hassan's thesis

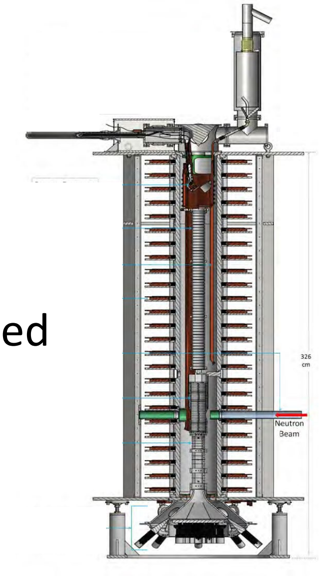
The negative value for a_o **enhances ∦ emission**, shifting average proton **spectrum lower**! (subtle effect)



$\beta - \bar{\nu}_e$ Correlation Measurements

The most recent measurements of the $\beta - \bar{\nu}_e$ correlation

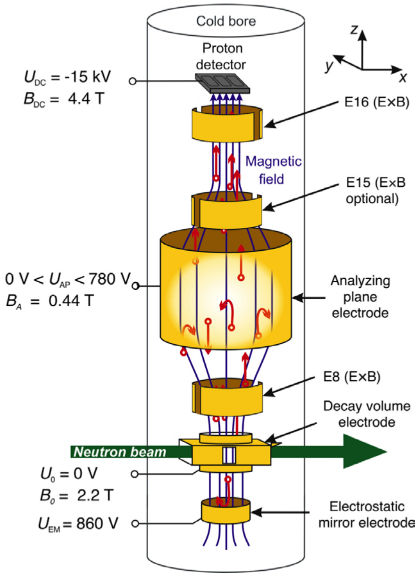
Proton-measurements selected along axis of beta emission



2021*: aCORN

da_o/a_o = 1.7%

CN beam at NIST



Retarding potential (MAC-E) spectromer

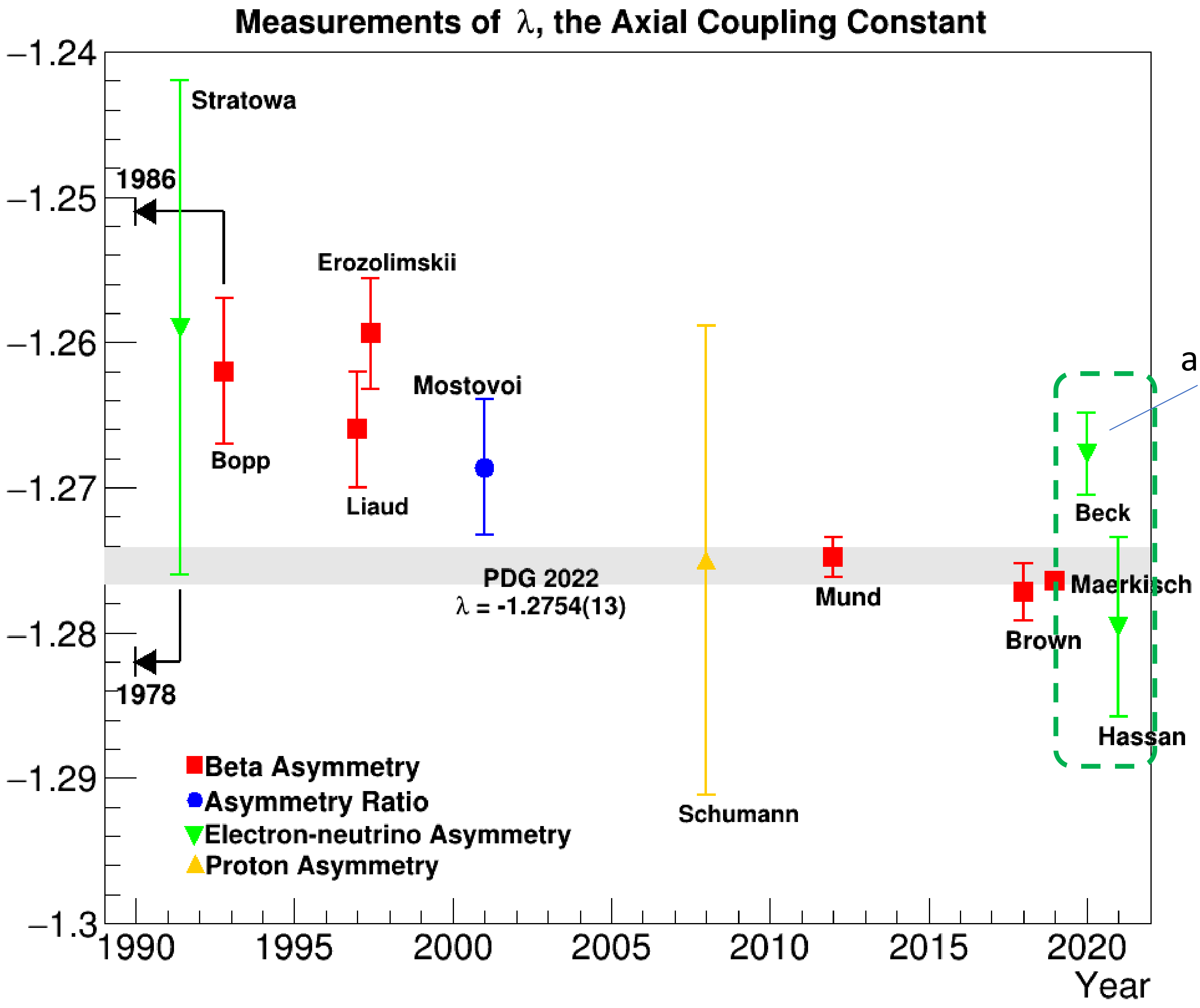
2020*: aSPECT

da_o/a_o = 0.8%

CN beam at ILL

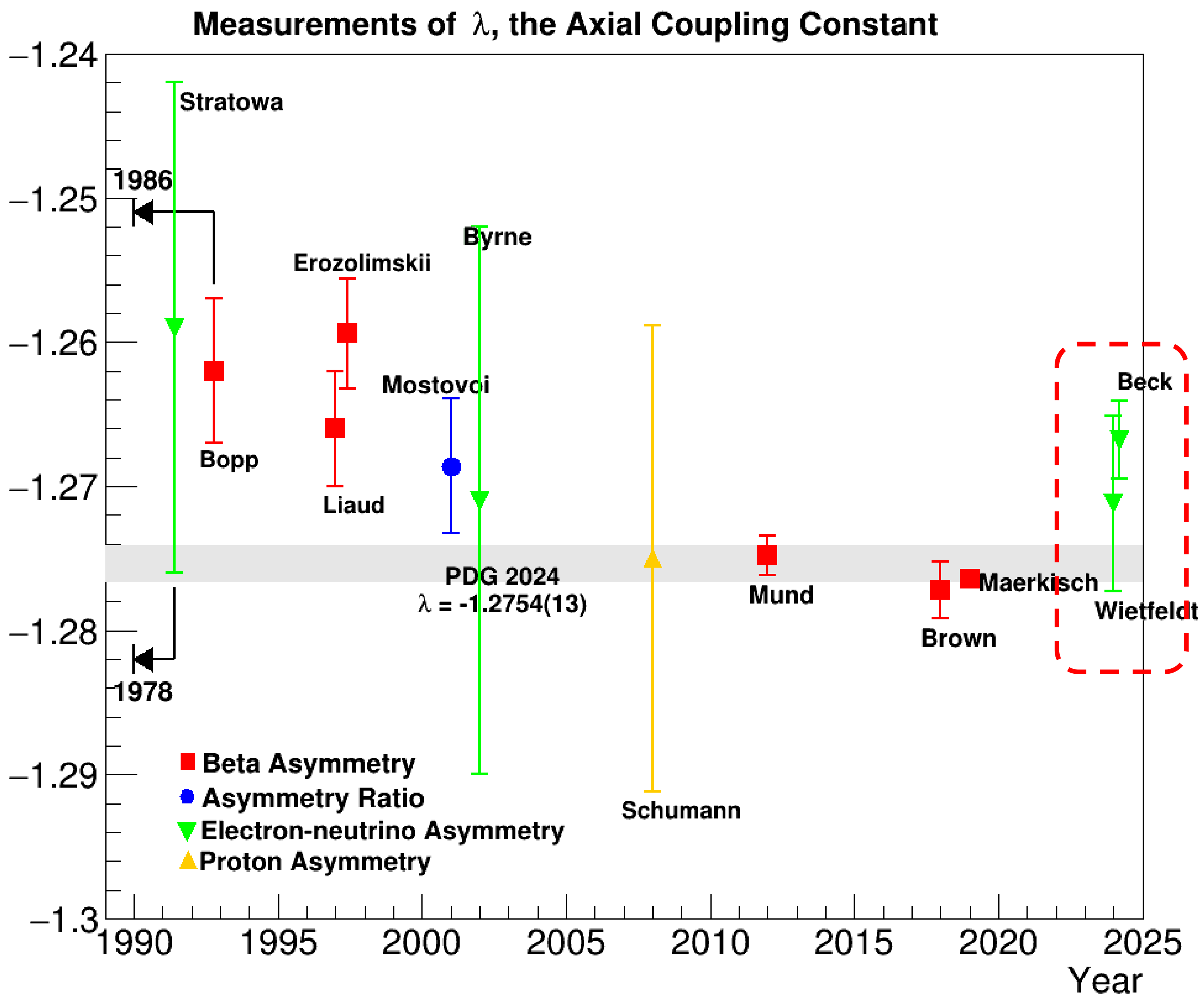
See Stefan Baessler's talk

Latest/most
Sensitive Results
for all groups



aSPECT

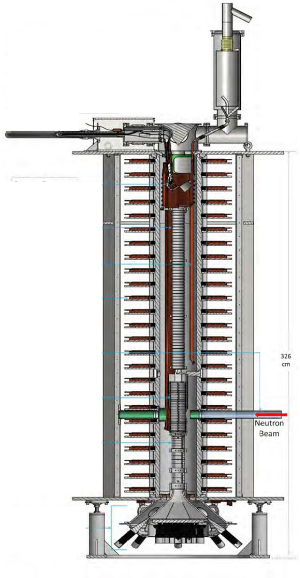
Note: although not as precise, aSPECT (Beck et al.) of “a” is impacting scatter for λ – now 2.7

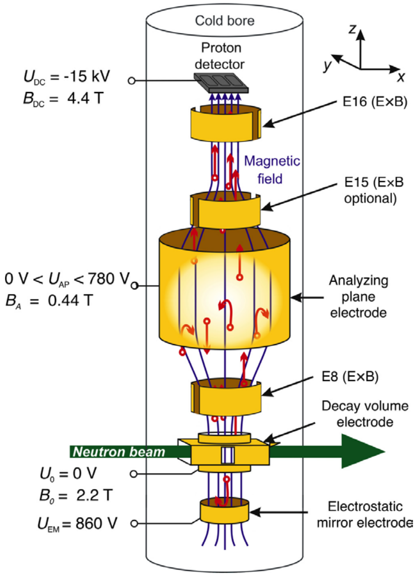


Radiative corrections
Applied to both
experiments…
(not much change to
Overall picture)

$\beta - \bar{\nu}_e$ Correlation Measurements

The most recent measurements of the $\beta - \bar{\nu}_e$ correlation





2021*: aCORN

da_o/a_o = 1.7%

CN beam at NIST

2020*: aSPECT

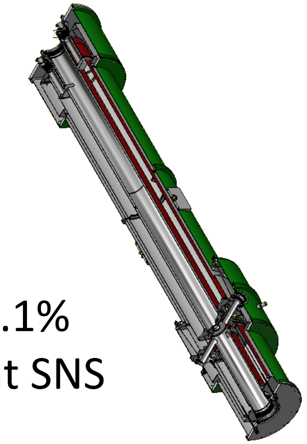
da_o/a_o = 0.8%

CN beam at ILL

See Stefan Baessler's talk

(2025 pub: 0.3% sensitivity possible)

Underway!



Nab

da_o/a_o = 0.1%

Pulsed CN at SNS

See Wolfgang Schreyer's talk

Nab at the SNS

Target Uncertainty for a_o ~ 0.1%

Dinko Pocanic's talk

Nab: Advantages and Challenges

Advantages

- No polarization required (polarization must be very small)
- Coincidence timing and detector segmentation reduce backgrounds
- Essentially entire phase space of decay accessible
- Very sensitive to λ

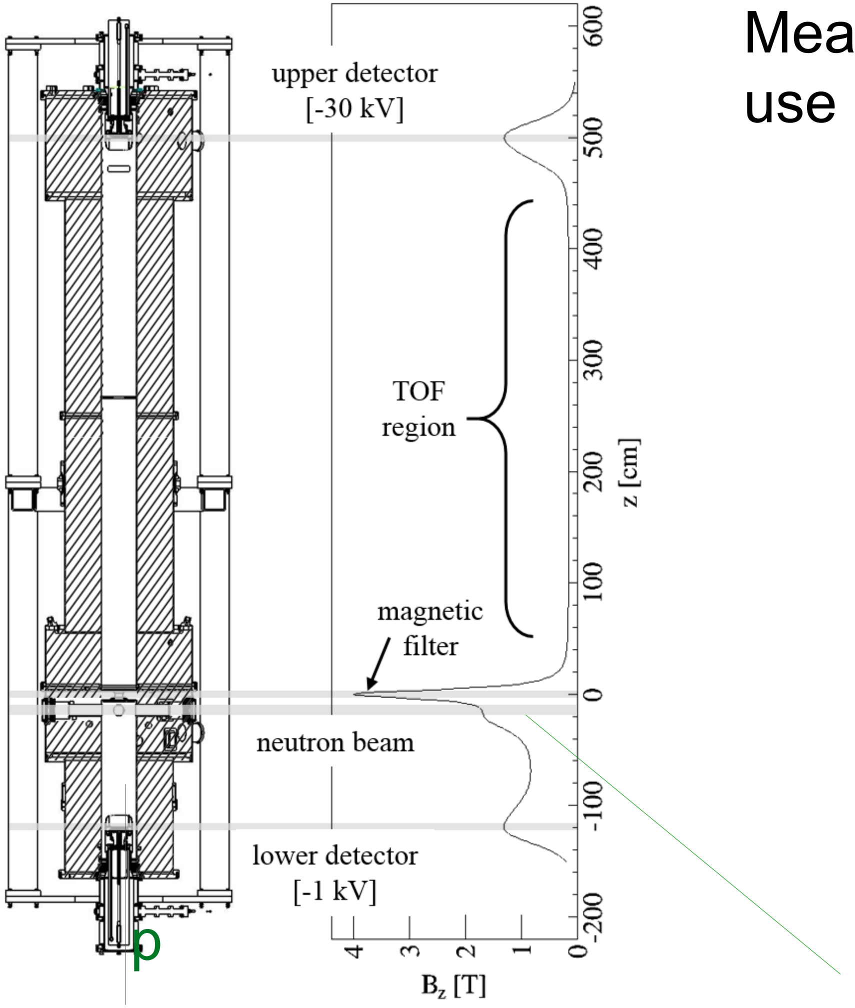
And:
i) Entirely different experimental technique than $\beta - asymmetry$ measurements…
ii) Can potentially resolve current tension in λ dataset

Challenges

- Sensitive to detector timing (must have bias less than ~ 0.5 ns)
- Sensitive the magnetic field "curvature" in decay volume
- Sensitive to electrostatic potentials in spectrometer
- Sensitive to energy reconstruction (e.g. bremsstrahlung losses)

Nab

~0.04% target precision for g_A



Measure momentum of protons through **time of flight**, then use conservation of momentum and energy to relate to $a_{\beta\nu}$

$$\vec{p}_p = \vec{p}_e + \vec{p}_\nu \rightarrow p_p^2 = p_e^2 + 2\vec{p}_e \cdot \vec{p}_\nu + p_\nu^2 \quad \& \quad p_\nu^2 \text{ from consv. of E}$$

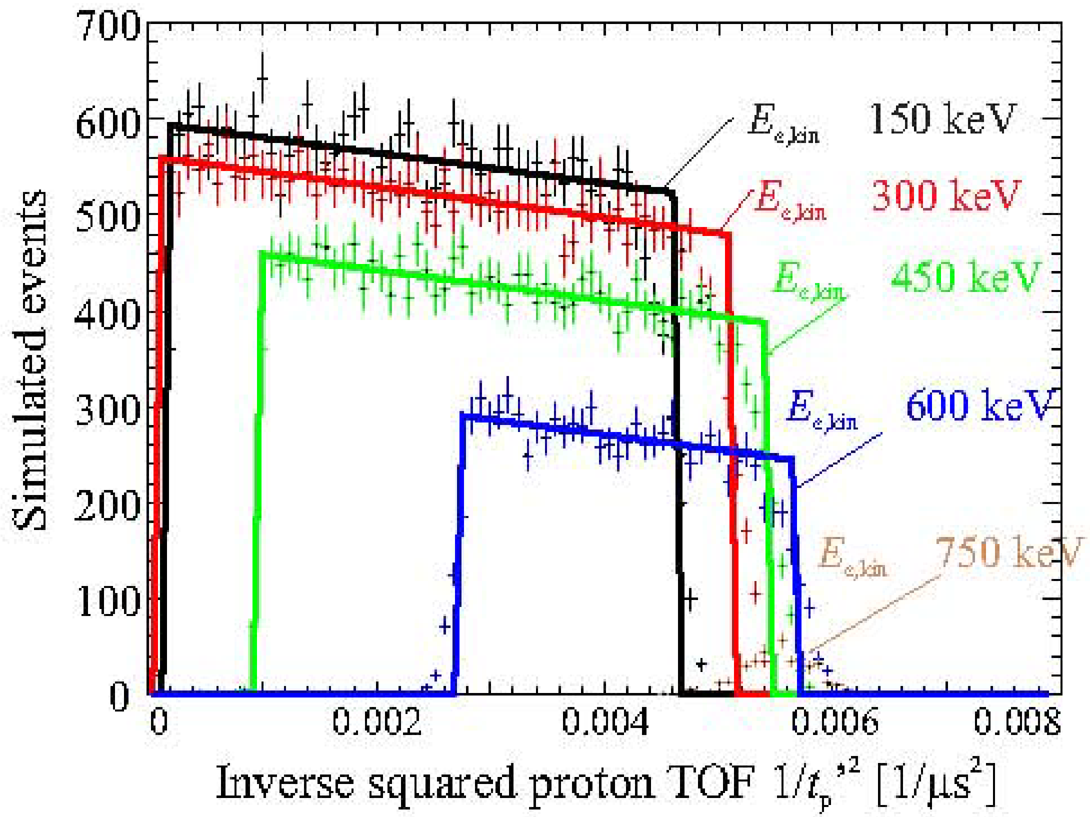
$$\boxed{P_p(p_\mathrm{p}^2) = \begin{cases} 1 + a\beta\frac{p_\mathrm{p}^2 - p_\mathrm{e}^2 - p_\nu^2}{2p_\mathrm{e}p_\nu} & \text{where } \left|\frac{p_\mathrm{p}^2 - p_\mathrm{e}^2 - p_\nu^2}{2p_\mathrm{e}p_\nu}\right| < 1 \\ 0 & \text{otherwise} \end{cases}}$$

Thin dead-layer, segmented Si detectors record electron “start” in either detector, proton “stop” in upper detector

$$p_p^2 \propto \frac{1}{\Delta t_{ep}^2}$$

Magnetic field “pinch”, long, low field TOF region optimize sensitivity to TOF

Nab



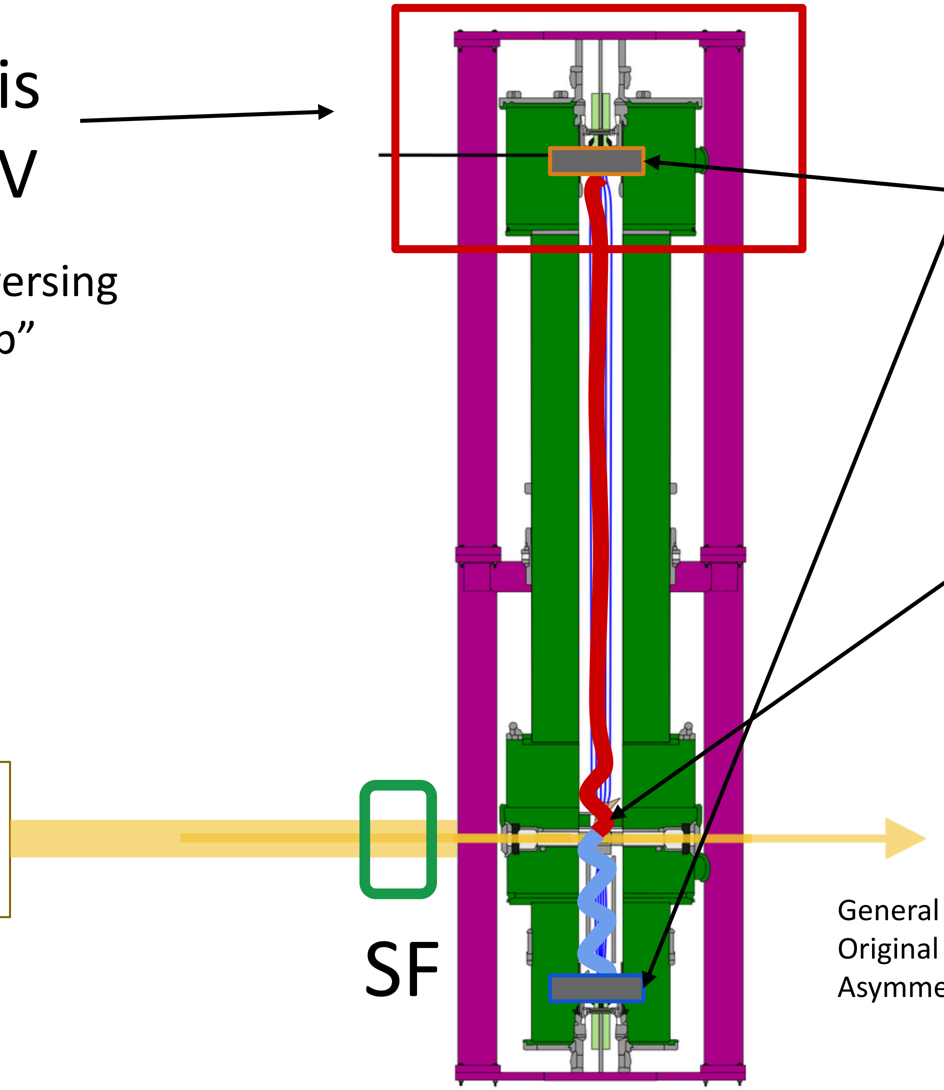
Arrange “cut” regions around beta energies

- Use central part of $P_t(1/t_p^2)$ ($\sim$ 70%) to extract **a**.

- Use edges to determine and verify shape of detection function $\Phi(1/t_{\mathrm{p}}^2, p_{\mathrm{p}}^2)$;

Slide from D. Pocanic

Nab Concept



(1) Electron energies summed. First hit provides “start” for TOF.

Upper detector is biased to ~-30 kV

Silicon detectors

(2) Protons detected after traversing TOF region, provide a “stop” ~11 to >60 µs after decay

Decay Region

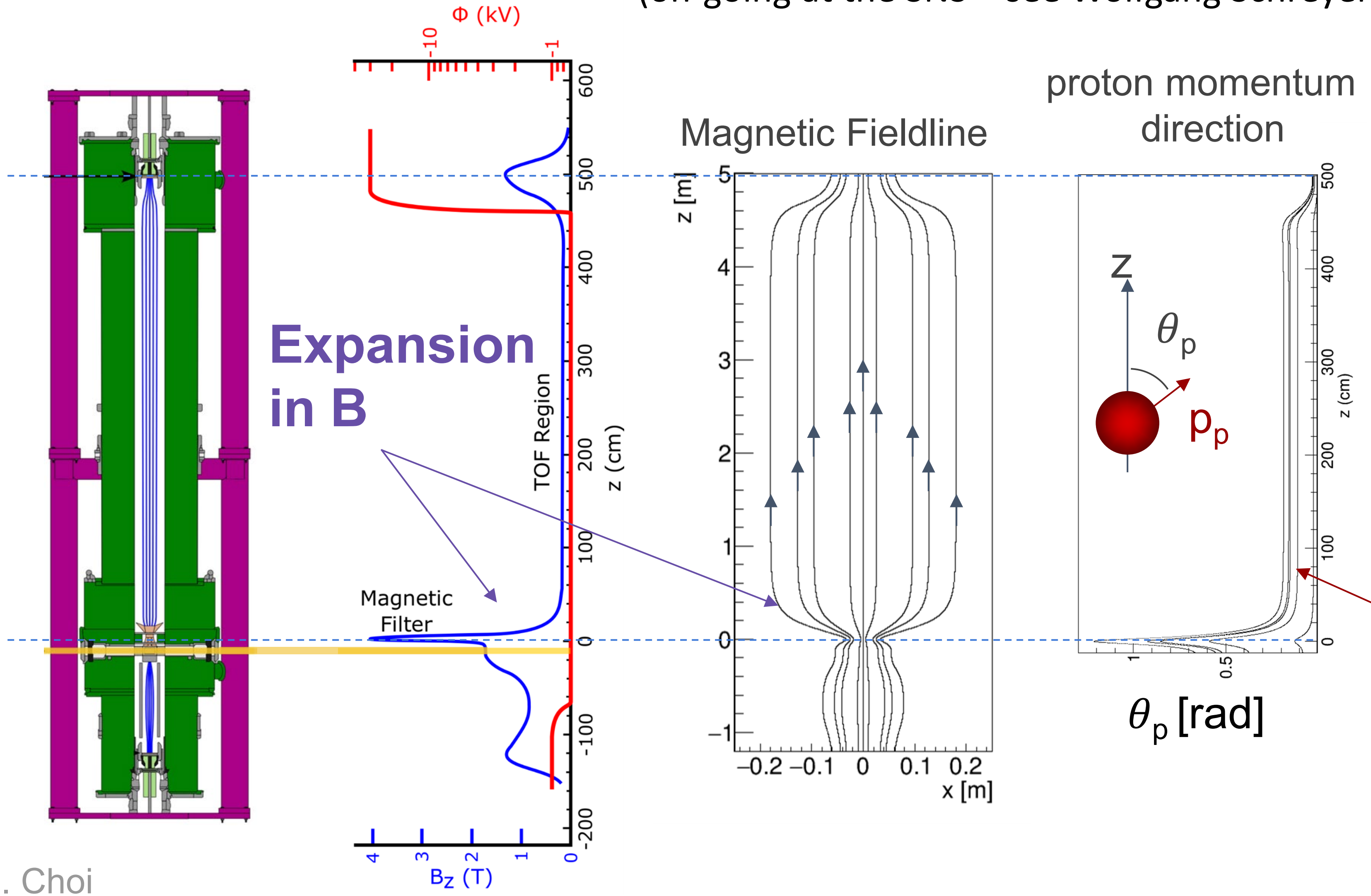
Neutron Beam

SF

General Idea: J.D. Bowman, Journ. Res. NIST 110, 40 (2005)
Original configuration: D. Počanić et al., NIM A 611, 211 (2009)
Asymmetric configuration: S. Baeßler et al., J. Phys. G 41, 114003 (2014)

Nab: Time-of-Flight Spectroscopy

The Nab experiment is designed to measure the $\beta - \bar{\nu}_e$ correlation through proton TOF
(on-going at the SNS – see Wolfgang Schreyer's talk!)



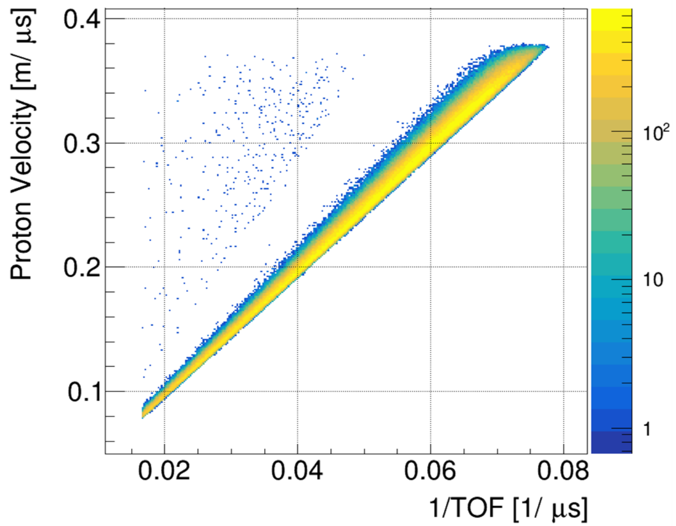
Expansion in B

Magnetic Fieldline

proton momentum direction

θ_p [rad]

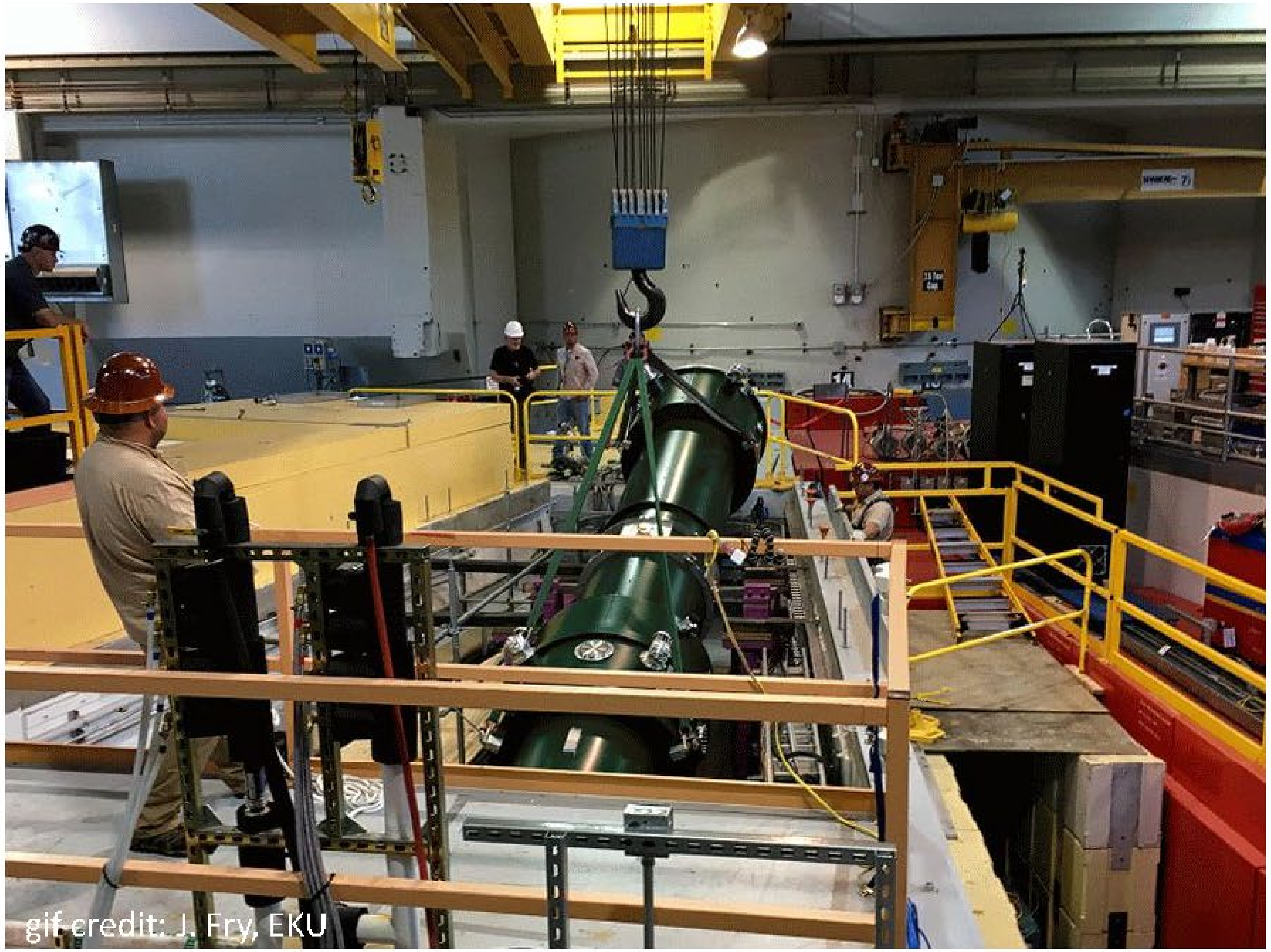
Simulated Velocity vs. 1/ TOF



Proton momentum **longitudinalize** and results in **mostly linear relationship** between proton velocity & inverse-TOF

The Nab Experiment at SNS

Spokespersons: Dinko Pocanic and Leah Broussard
(and David Bowman)



gif credit: J. Fry, EKU

Target Uncertainties for a

Leading uncertainties:

- Magnetic Fields (esp. “curvature” in decay vol”)
- Electric Potential inhomogeneity
- Detector effects (energy recon and timing)

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}

decay rate ~ 175 cps Statistics ~7×10^{-4}

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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[m] North Carolina State University, Raleigh, NC 27695-8202
[n] Universidad Nacional Autónoma de México, México, D.F. 04510, México
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[q] Eastern Kentucky University, Richmond, KY 40475
[r] Massachusetts Institute of Technology, Cambridge, MA 02139

Main project funding:

Angular Correlation Summary

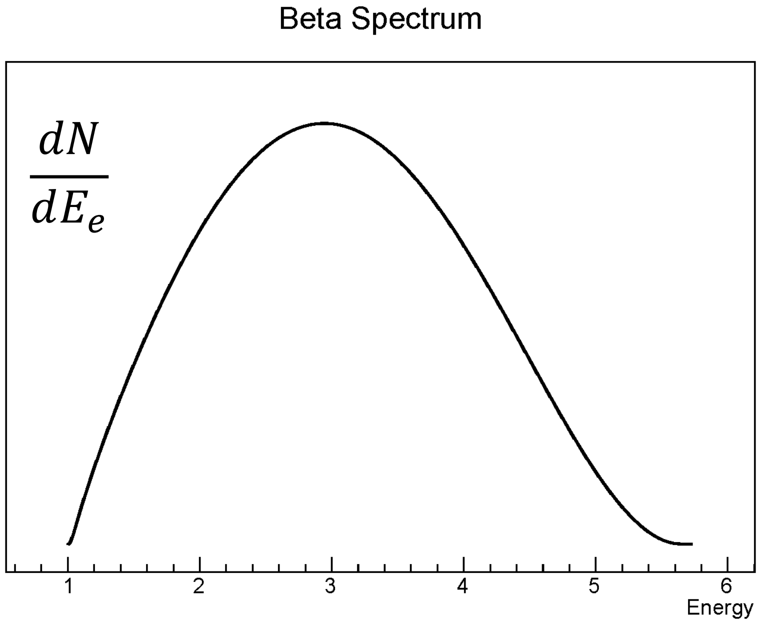
Many possibilities to contribute to Unitarity and global data set!
(potential to achieve parity with $0^+ \rightarrow 0^+$)

Experiment	Sensitivity to λ	Time-scale	Advantages
Perc	Phase I: ~ 4.4×10^{-4} Phase II: 1.5×10^{-4}	Uncertain, but 2-3 years minimum to start phase I data-taking (MLZ working to restart)	Enormous statistics Many components already tested Team well supported
UCNA+	$< 5.0 \times 10^{-4}$	Uncertain, but could start data-taking in 2-3 years	Based on existing, well characterized experiment Alternate methods to CN beams for neutron-based observables
pNab	~ 1.5×10^{-4}	Uncertain, but could start data-taking in 2-3 years	Excellent spectroscopy (Si dets) Moderate adaptation required from Nab
Nab	~ 4×10^{-4}	**Data-taking now**	Excellent spectroscopy (Si dets) Possible measurement of Fierz terms Possible extension to other correlations
aSPECT	~ 7.5×10^{-4}	?	Alternate methods to Nab

Other correlations and exotic couplings

β-Decay in the Standard Model: the β-spectrum

L. Hayen et al, Rev. Mod. Phys. **90**, 015008 (2018)



Isobaric analog decays $\left(\frac{1}{2}^+ \rightarrow \frac{1}{2}^+\right)$:

$$\frac{dW}{dE_e} = \frac{{G_F}^2|V_{ud}|^2}{(2\pi)^5}\underbrace{(1+\rho^2)}_{}\overbrace{F(E_e)p_eE_e(E_o-E_e)^2}^{}$$

→ Allowed spectrum determined primarily by phase space and the Fermi function

$+$recoil & radiative corrections → At and below ~1% level

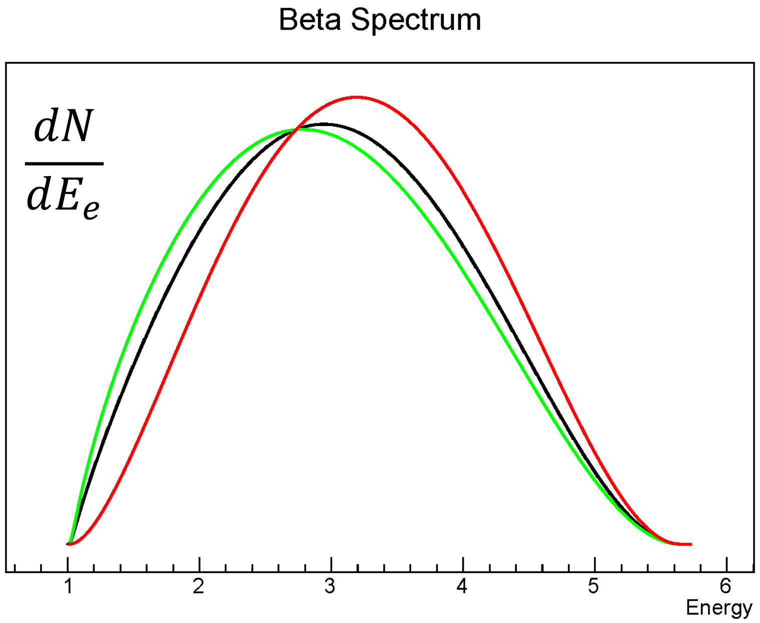
Matrix elements → $\rho \equiv \frac{\langle GT\rangle}{\langle F\rangle}$ =3λ (for neutron)

Scalar and Tensor Couplings: Fierz Interference

Sensitivity to exotic couplings to left-handed neutrinos through **interference terms**:

$$b = \mp \frac{1}{1+\rho^2}\left(2\frac{\boldsymbol{C_S}}{C_V} + 2\rho^2\frac{\boldsymbol{C_T}}{C_A}\right)$$

changes sign for electron vs. positron



b = 0

b = -1

b = +1

$$\frac{dW}{dE_e} = \frac{{G_F}^2|V_{ud}|^2}{(2\pi)^5}(1+\rho^2)F(E_e)p_eE_e(E_o - E_e)^2\left[1 + \boldsymbol{b}\frac{\Gamma m_e}{E_e}\right]$$

+recoil & radiative corrections

At present, **most promising approach** to improve involves measuring the beta spectrum using Cyclotron Resonance Emission Spectroscopy (CRES) using nuclei (first introduced for Project 8):

He6-CRES collaboration (spokesperson, A. Garcia):

Byron et al, PRL **131**, 082502 (2023)

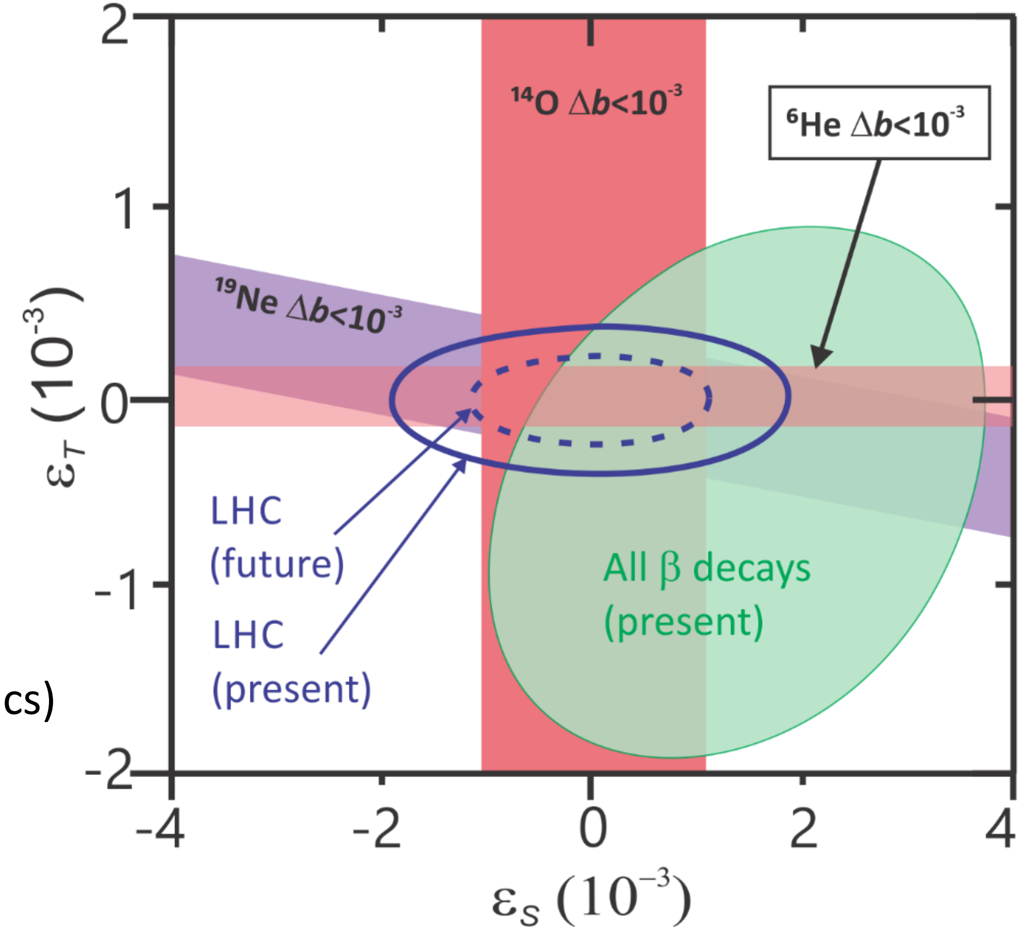
$$b \lesssim 10^{-3}$$

$$C_S = C_V \boxed{\varepsilon_S}$$

$$C_T = 4C_A \boxed{\varepsilon_T}$$

BSM

(new physics)



Three nuclear systems under study:

^{6}He: pure GT ($\rho = \infty$)

^{19}Ne: mixed F & GT ($\rho \approx 1.6$)

^{14}O: pure F ($\rho = 0$)

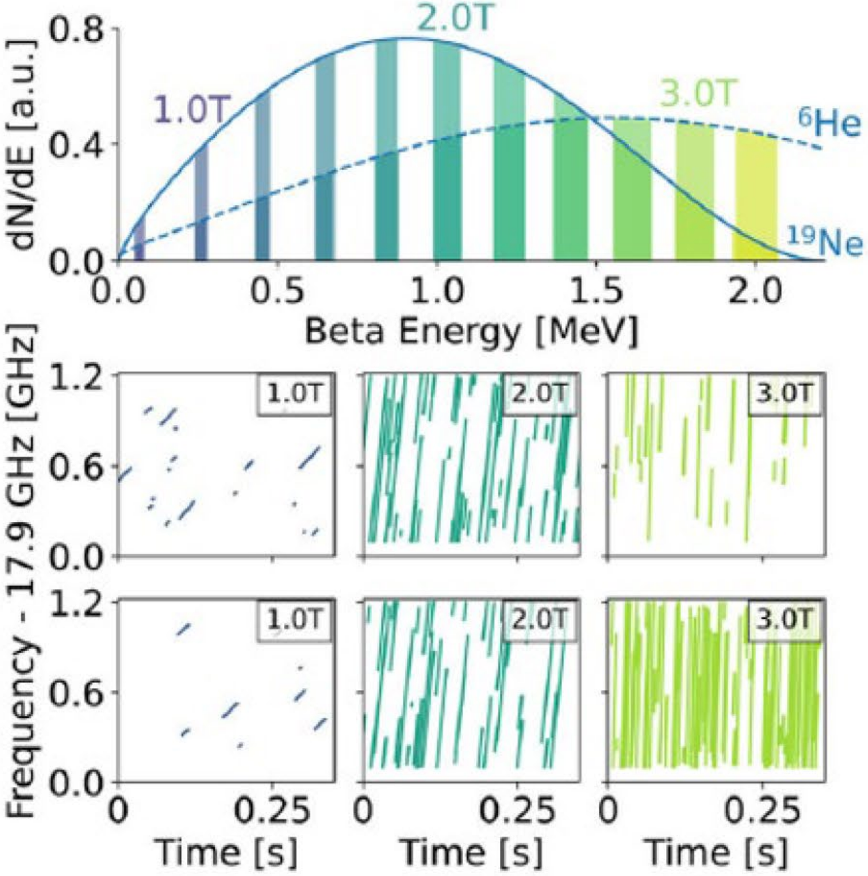
Neutron: mixed F & GT ($\rho \approx -2.2$)

Direct limits on Fierz Terms!

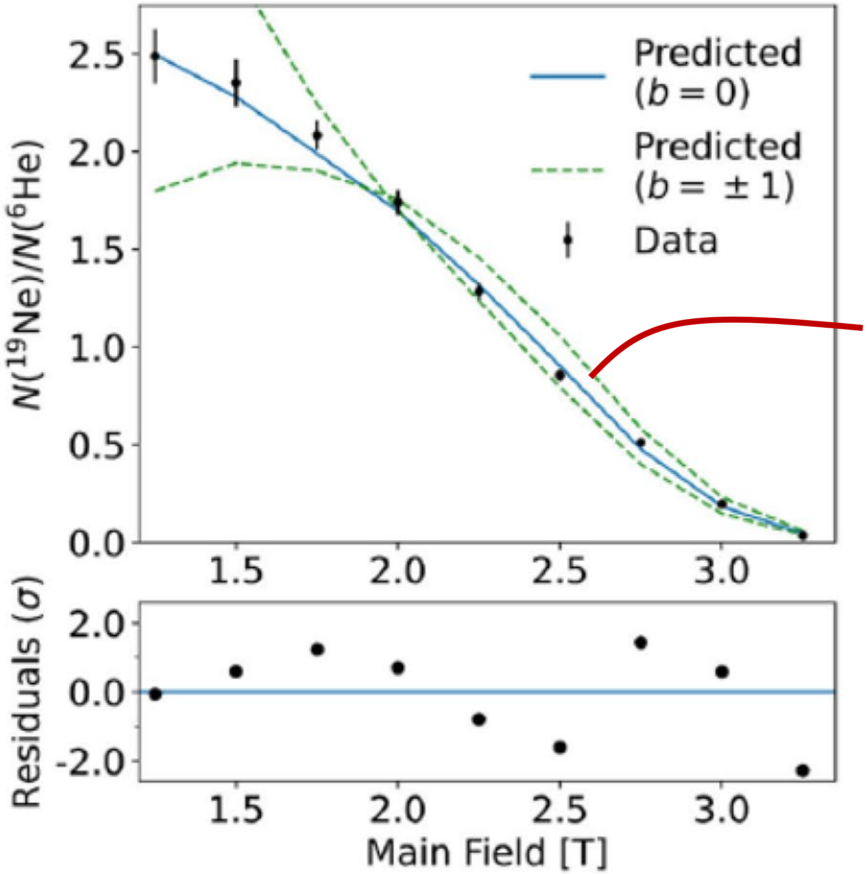
He6-CRES – ^{19}Ne and ^{6}He

Events from ^{6}He and ^{19}Ne :

- **First CRES measurements at $E > 30$ keV;**
- **First CRES measurement of positrons.**



90 minutes of total data for each isotope



Ratio of Spectra

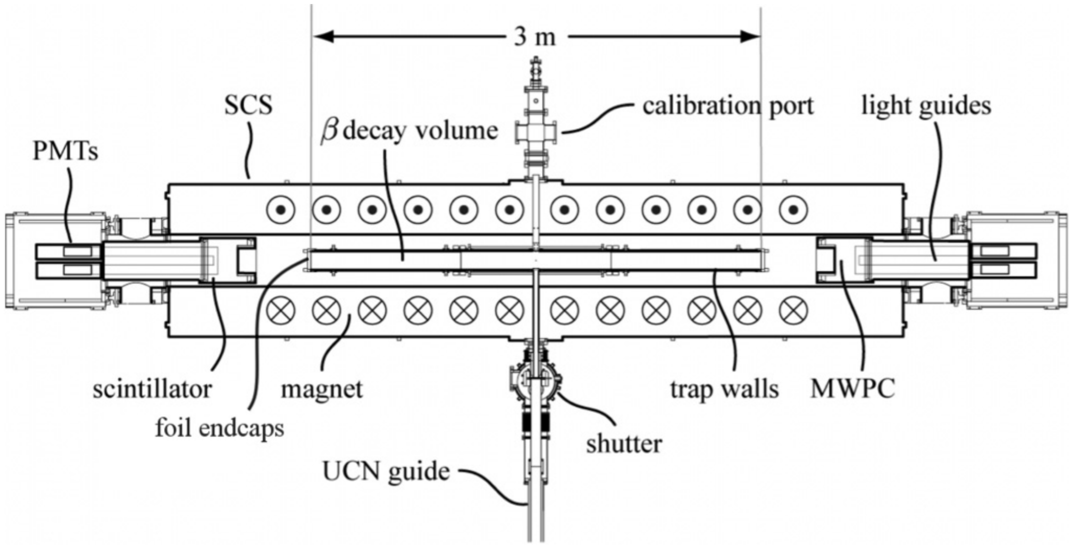
Well defined in SM, enhanced sensitivity to Fierz

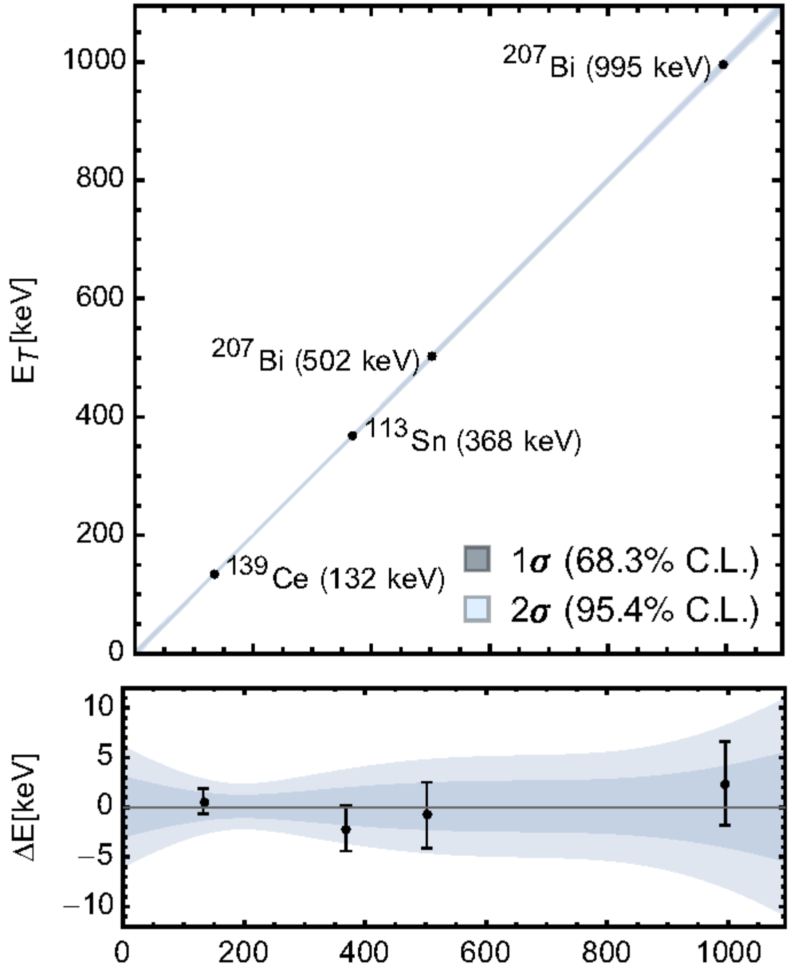
Publication: Byron et al, PRL **131**, 082502 (2023)

First direct constraints on Fierz interference in free-neutron *β* decay

Hickerson et al., PHYSICAL REVIEW C **96**, 042501(R) (2017)

UCNA experiment





Calibration/linearity

Fierz Terms from Angular Correlations – Direct Limits in Neutron Decay

Directly determine from beta energy dependence of Angular correlations (A_β):

UCNA: Improved limits on Fierz Interference using asymmetry measurements from the UCNA experiment.

Phys. Rev. C **101**, 035503 (2020**)**

Perkeo III: Limit on the Fierz Interference Term b from a Measurement of the Beta Asymmetry in Neutron Decay

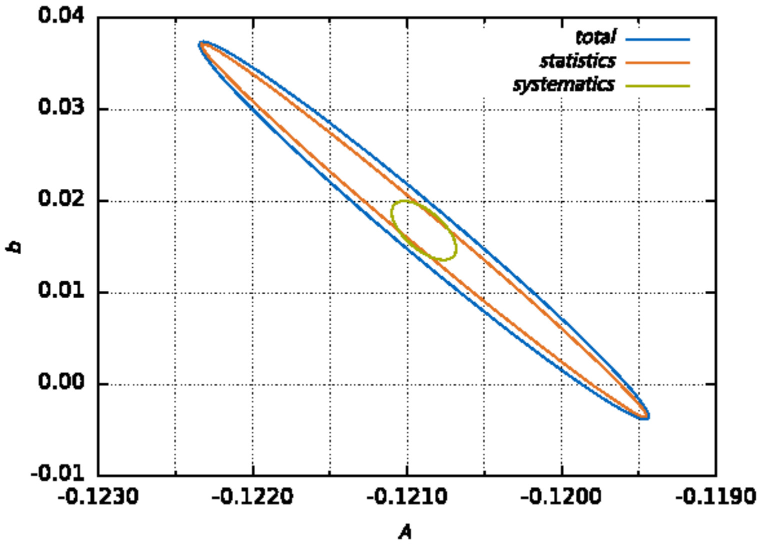
Phys. Rev. Lett. **125**, 112501 (2020)

Recent result for the TRINAT collaboration!

Conclusions: very insensitive to calibration (+)
strongly statistics limited (-)

From PERKEO III:

$-0.018 \leq b \leq 0.052.$ 90% CL



68% conf level for stats and statistics shown…

Fierz Terms from Angular Correlations – Direct Limits in Neutron Decay

- More on Fierz terms

Directly determine from beta energy dependence of Angular correlations (A_β):

UCNA: Improved limits on Fierz Interference using asymmetry measurements from the UCNA experiment.

Phys. Rev. C **101**, 035503 (2020)

Perkeo III: Limit on the Fierz Interference Term b from a Measurement of the Beta Asymmetry in Neutron Decay

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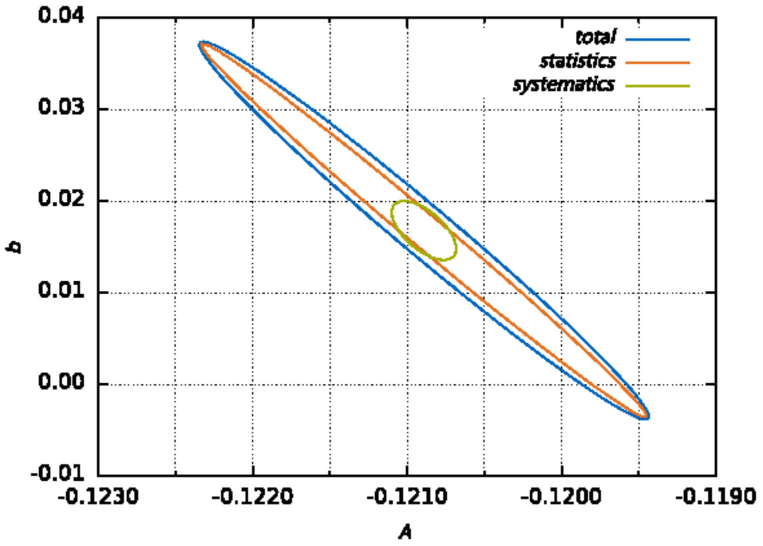


68% conf level for stats and statistics shown…

Conclusions: very insensitive to calibration (+)
strongly statistics limited (-)

Challenging to make competitive with LHC lmits…

(more on this if we have time…)

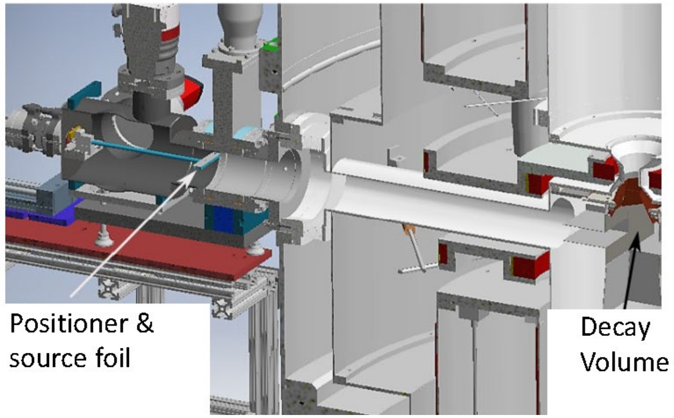
Fierz Terms from Angular Correlations – Direct Limits in Neutron Decay

Lessons learned from UCNA – direct spectrum measurements are **very sensitive to calibrations** (as opposed to less sensitive, with asymmetries)

For Nab, this means the Fierz measurement goal (~3×10^{-3}) requires at least **an order of magnitude more precise knowledge of some calibration parameters** than is required to measure $a_{\beta\nu}$

We are working on this…but we have more to do!

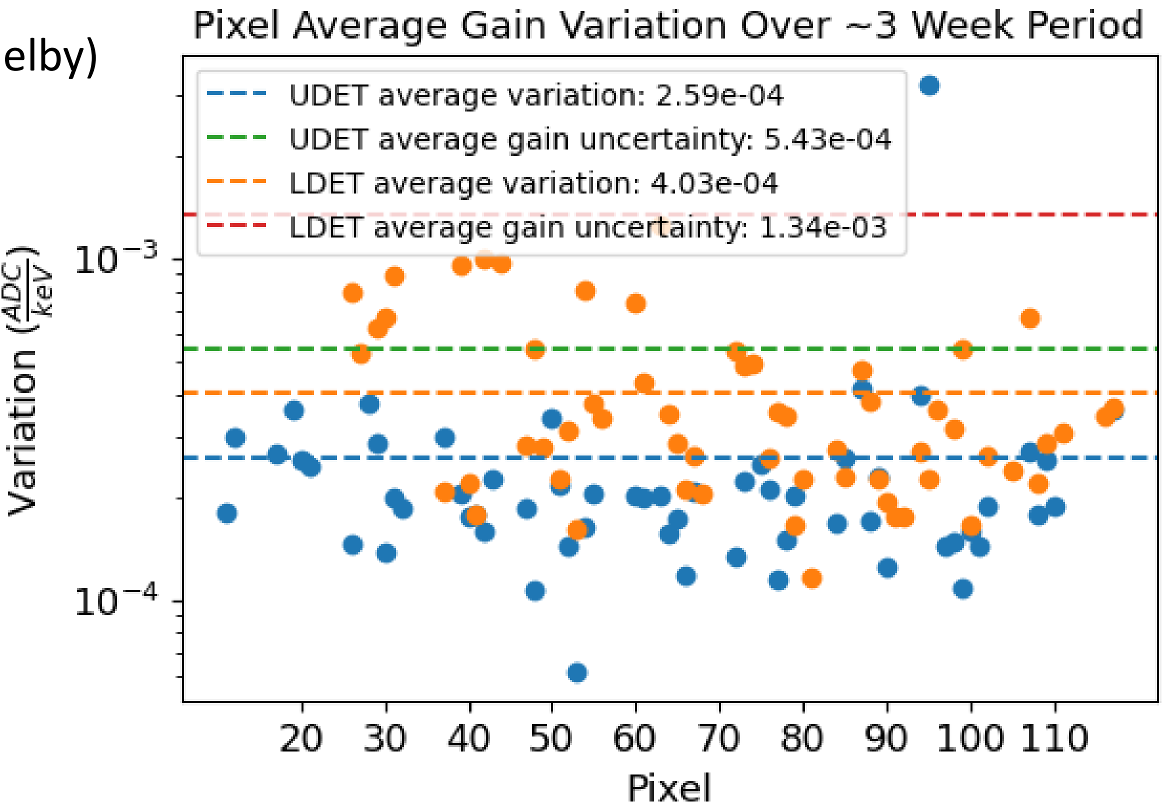
Example: A. Shelby's analysis of calibration data

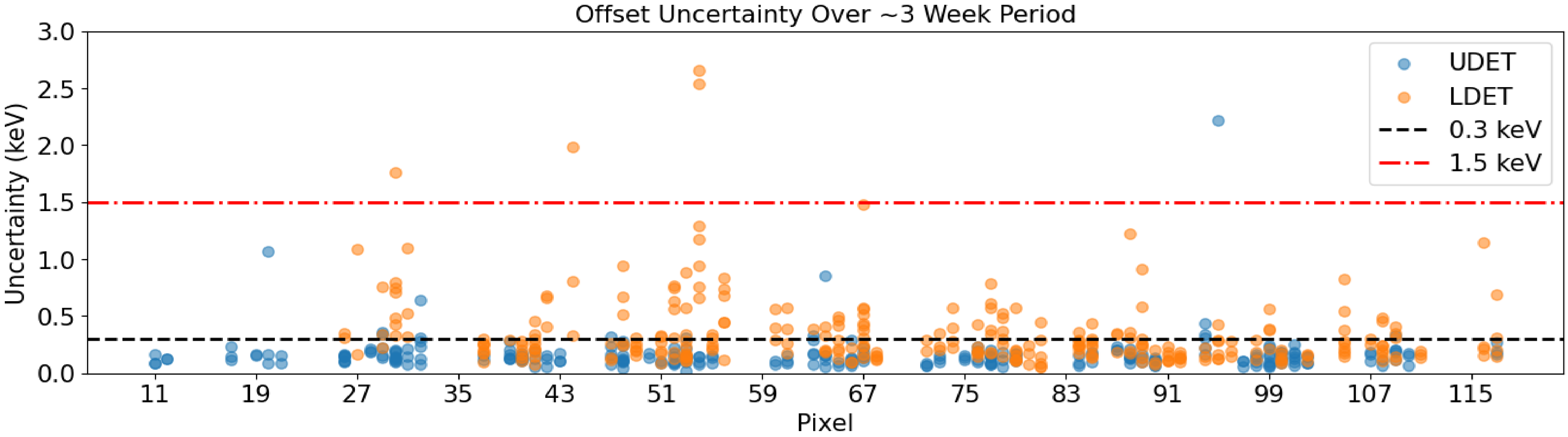


Linear Calibration Result Summary

(Sample analysis from A. Shelby)

- "Variation" plotted as the square root of the variance from a weighted average
- Found variation comparable to average gain uncertainty
  - One LDET outlier pixel not included
- Nab "little a" requirement 0.1% precision goal: offset uncertainty <0.3 keV (0.5% goal estimated <1.5 keV)
  - All pixels have at least one run that meets this goal





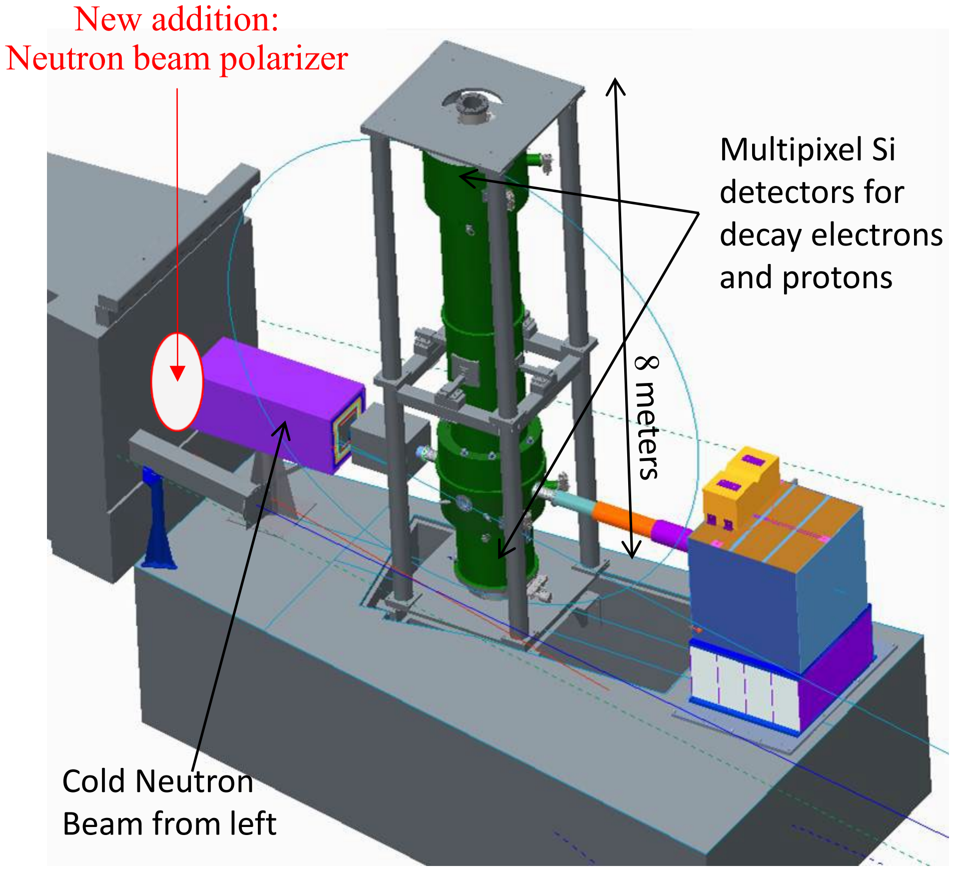
pNAB: the proton-related observables

b or b_ν may indicate S,T

$B_0 \neq B_0(\lambda)$ may indicate V+A

$$d\Gamma \propto \varrho(E_e)\left(1 + \boxed{a\frac{p_e}{E_e}\cos(\vec{p}_\nu,\vec{p}_e)} + b\frac{m_e}{E_e} + A\frac{p_e}{E_e}\cos(\vec{\sigma}_n,\vec{p}_e) + \boxed{\left(B_0 + b_\nu\frac{m_e}{E_e}\right)\cos(\vec{\sigma}_n,\vec{p}_\nu)}\right)$$

$a = a(\lambda)$



New addition:
Neutron beam polarizer

Multipixel Si detectors for decay electrons and protons

Cold Neutron Beam from left

Measurement of the ν –asymmetry with pNab together with the $\beta - \nu$ correlation with Nab provides multiple new paths to constraints on BSM exotic couplings and other BSM scenarios (in b and b_ν for example)

Measurements optimizing sensitivity to BSM are being developed

General Idea: J.D. Bowman, Journ. Res. NIST 110, 40 (2005)
Original configuration: D. Počanić et al., NIM A 611, 211 (2009)
Asymmetric configuration: S. Baeßler et al., J. Phys. G 41, 114003 (2014)

Conclusions and Outlook:

The current outlook for angular correlations measurements is promising. Nab is running, Perc is under construction and should run, and several other R&D projects (UCNA+, pNab) are well-developed enough to look quite feasible. At the targeted level, we can potentially

i) resolve (or confirm) the tension between the beta-asymmetry and beta-neutrino correlation measurements,

ii) provide a global data set with comparable or reduced uncertainty to the superallowed decays,

iii) Significantly improve inputs to more general fits to BSM scenarios.

Methods are under development to measure contributions from Fierz terms with goals of reaching 1×10^{-3} sensitivity, including direct spectroscopy measurements of the energy dependence of the spectrum and angular correlations. There are interesting possibilities associated with measurements of the neutrino asymmetry.

The He6-CRES collaboration is making steady progress towards direct spectrum measurements using Cyclotron Resonance Spectroscopy. Although some unique challenges exist for implementing this with neutrons, it is becoming evident that these measurements should be possible!