The pNab Experiment: Angular Correlation Measurements with Polarized Neutrons

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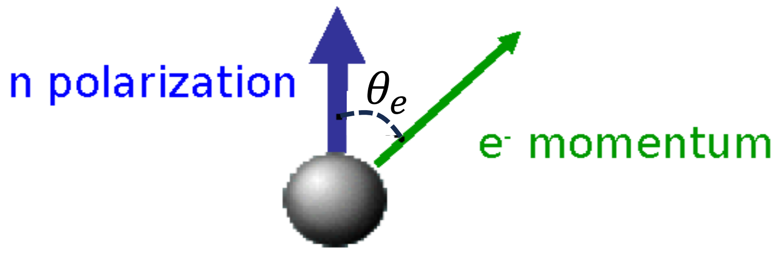
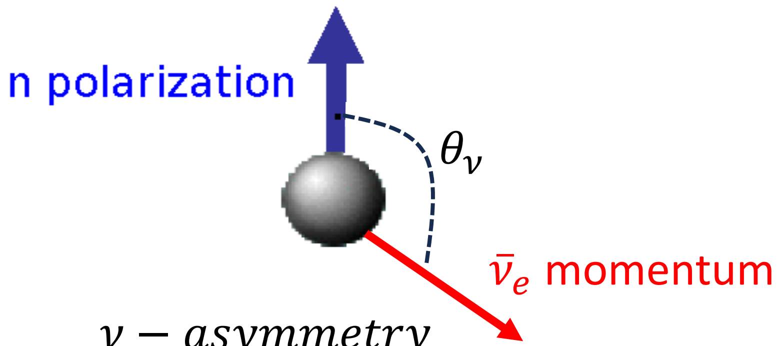
pNab: adapt the existing Nab spectrometer to permit measurements of angular correlations with **spin-polarized** neutrons

- **Improved** sensitivity to $\lambda = g_A/g_V$ (and probably also significantly improved sensitivity to exotic couplings)
- **Different** and complementary systematic uncertainties to Nab (allows an investigation of current tension in data set for λ with the same instrument)
- **Leverages** the considerable development of the Nab spectrometer to date



$\beta - asymmetry$



$\nu - asymmetry$

Outline

- Motivation for Angular Correlations Measurements (Part II)
- The Neutron Global Data Set
- The pNab Experiment
    - Principle of Operation (β-asymmetry)
    - Error Budget (β-asymmetry)

        Statistics

        Polarization

        Electron event reconstructiom
- Nab and pNab current status
- Outlook and Conclusions

Motivation for Angular Correlation Measurements in Neutron Decay: Part II

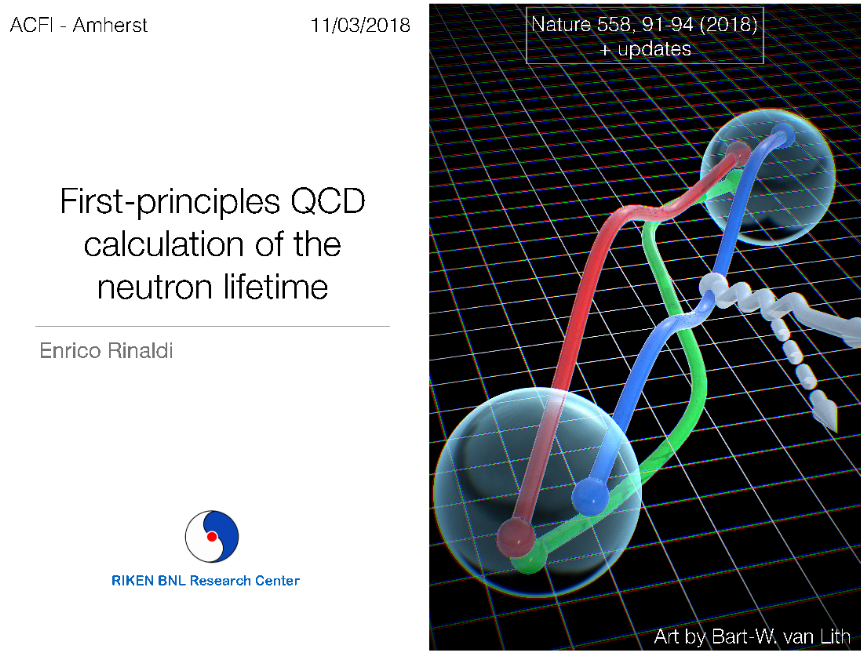
Already heard from Love's talk that angular correlation measurements directly determine $\lambda = g_A/g_V$

Important for CKM Unitarity tests…

Expand on some points of interest!

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

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Surprises!

Percent-level shifts (same scale as recoil-order corrections) in the measured 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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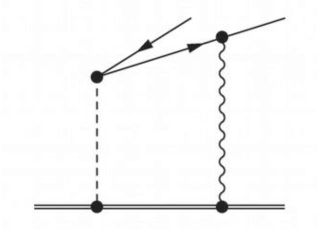

Amazing to find new corrections of this size in 2022 !

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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!

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

weak eigenstates

Cabibbo Kobayashi Maskawa (CKM) matrix

mass eigenstates

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

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

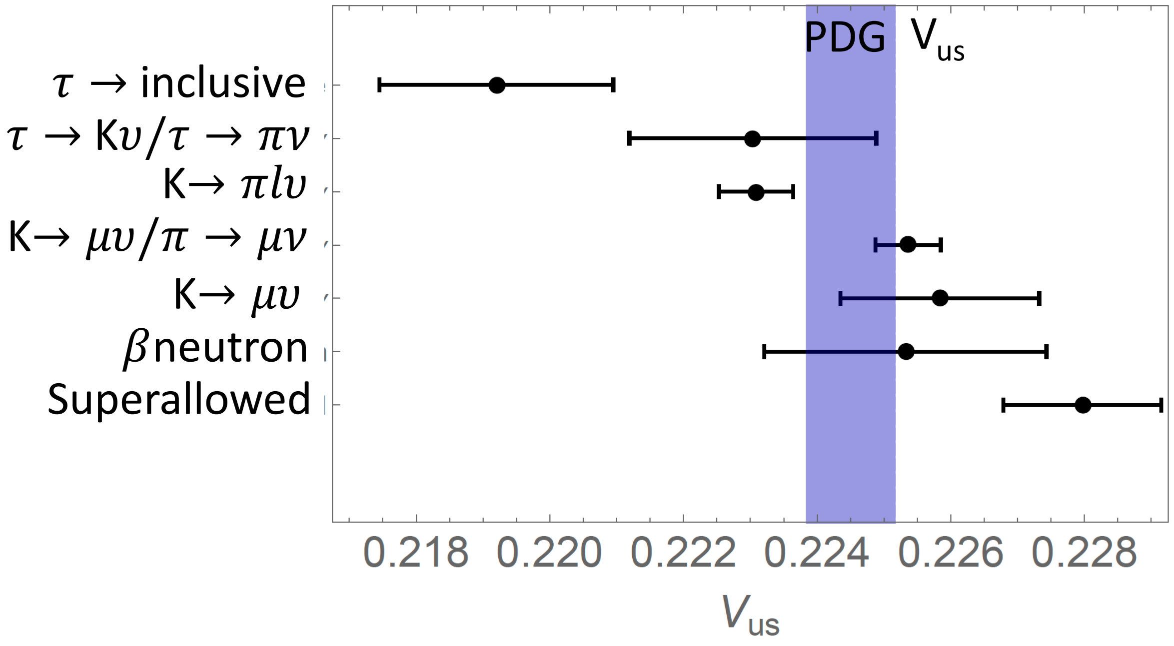
Sensitive to BSM V,A couplings!

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!)

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

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]

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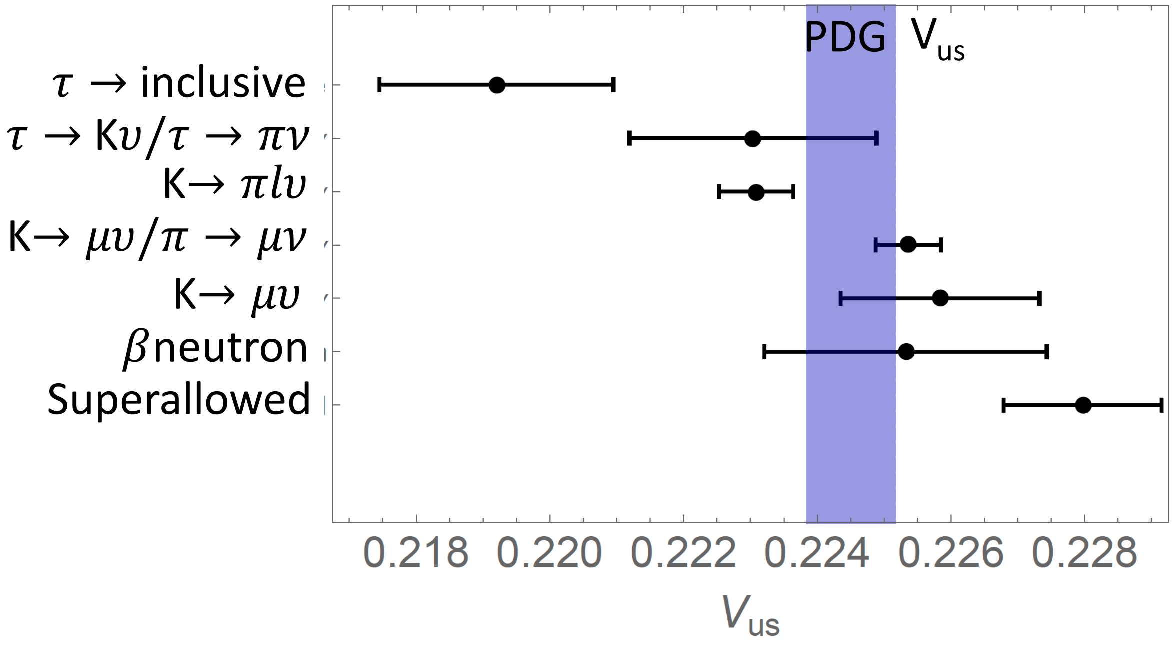

use $0^+ \to 0^+$ currently

$<V_{us}>= 0.22431(85)$ 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 uncertainty targets: lifetime – 0.3 s (current most precise, UCNtau with 0.36 s)

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

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

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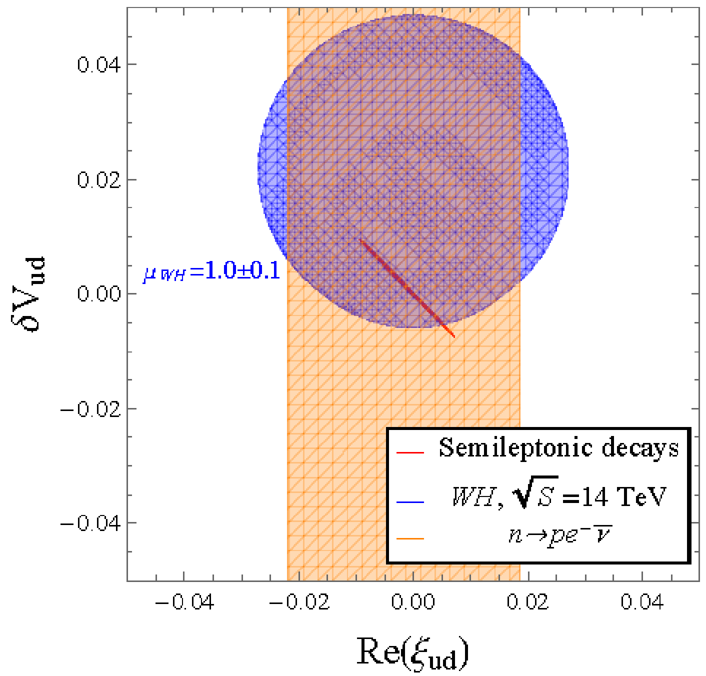
- **New Physics** Constraints
  - Input for CKM unitarity test
  - Direct test for BSM Axial couplings (combine with lattice)

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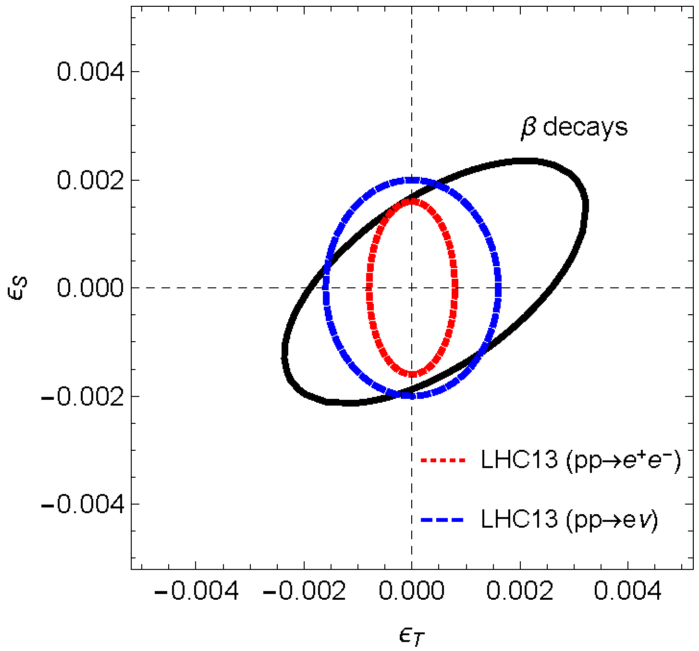
  - Input for CKM unitarity test
  - Direct test for BSM Axial couplings (combine with lattice)
  - New paths to sensitivity to exotic couplings

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)



Comprehensive analysis of beta decays within and beyond the Standard Model

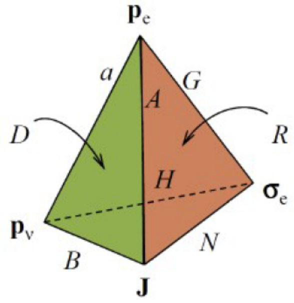
Adam Falkowski,[a] Martín González-Alonso,[b] and Oscar Naviliat-Cuncic[c,d]

[JHEP04(2021)126]

Beta Decay Parameters

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

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



On-going or planned efforts to measure:

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

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

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

Theoretical analysis to determine λ in good shape

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

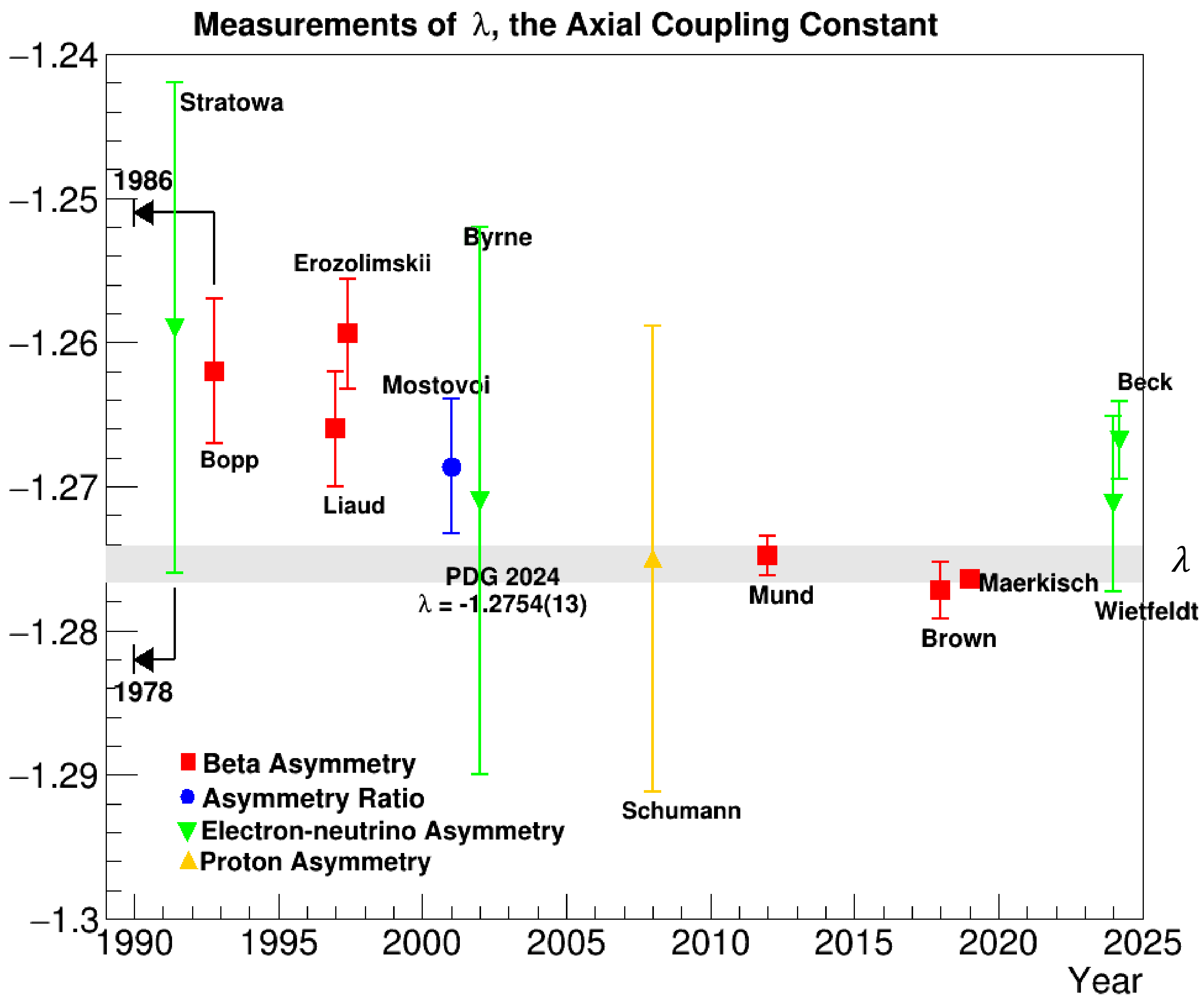
- Identification of cases with enhanced sensitivity to asymmetry
- Suppression of experimental sensitivity to detection efficiency and energy reconstruction errors

Enhance sensitivity, suppress uncertainty

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

The Neutron Global Dataset

Special thanks to D. Salvat, C.-Y Liu, F. Wietfeldt for slides

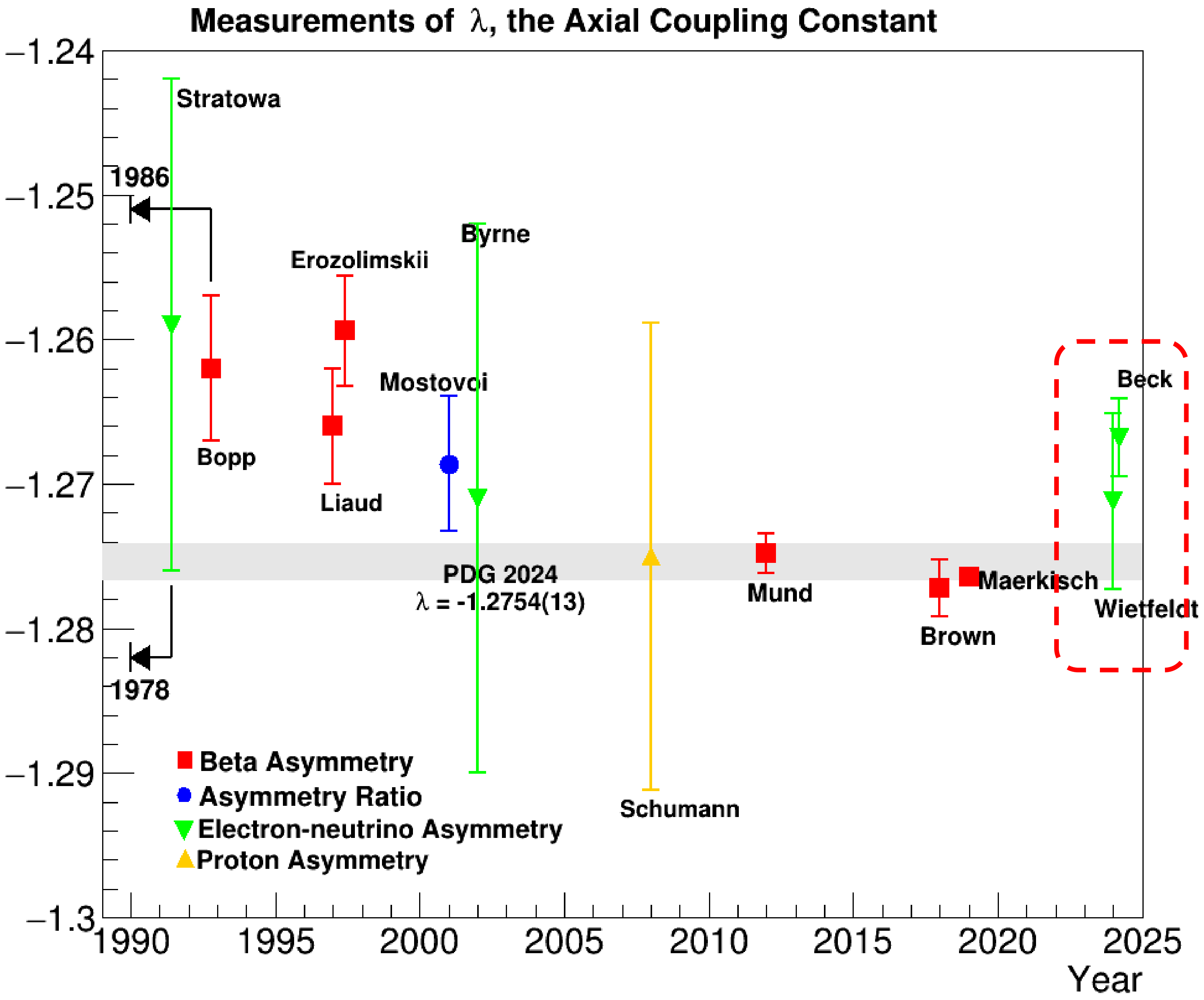


PDG 2025

$$\lambda = -1.2753(13)$$

~0.1%

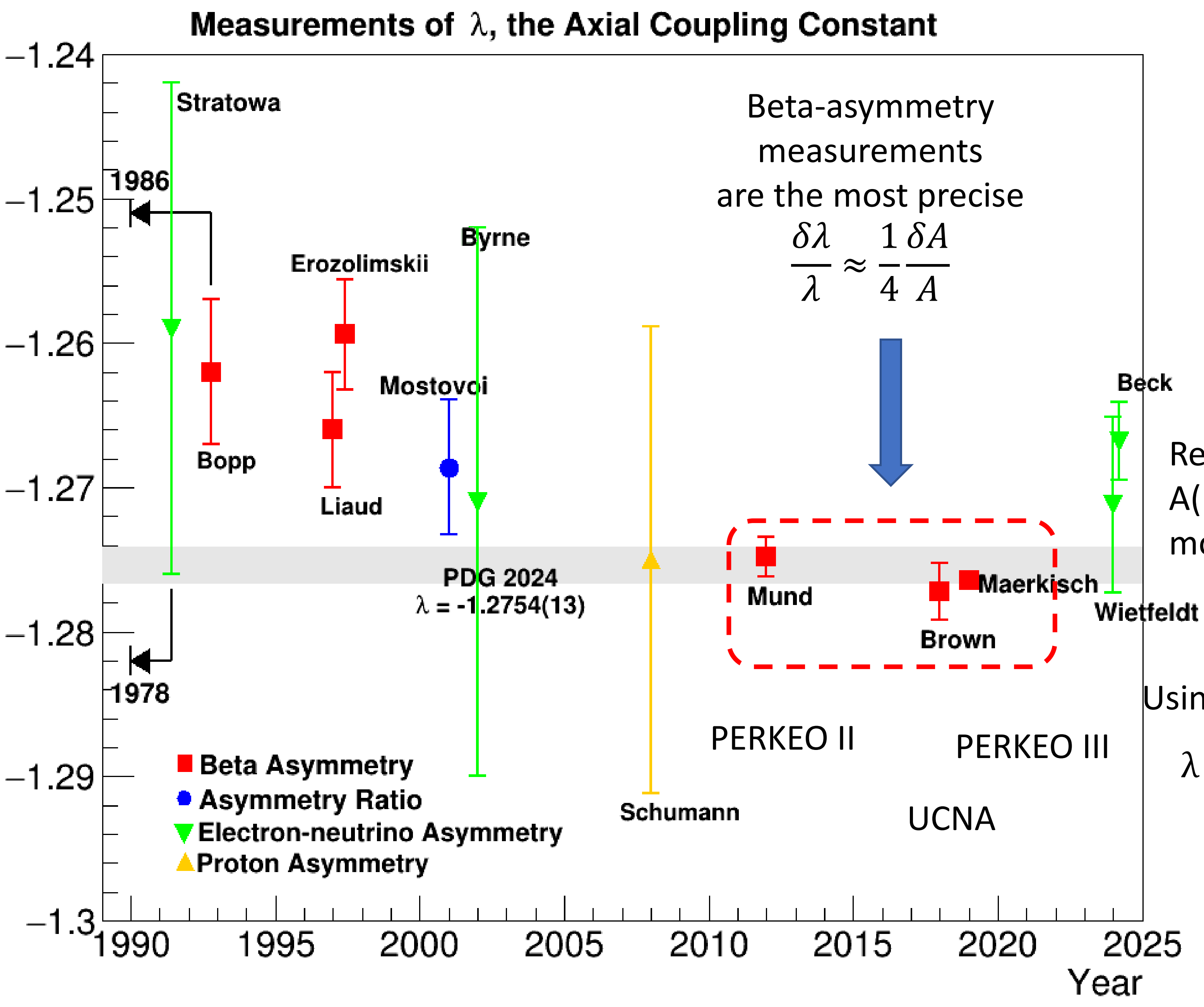
Scale factor 2.7 due to scatter



Scatter driven strongly by $\beta - \bar{\nu}_e$ correlation result of aSPECT

Nab can help resolve… (Love's talk)

Scale factor 2.7 due to scatter

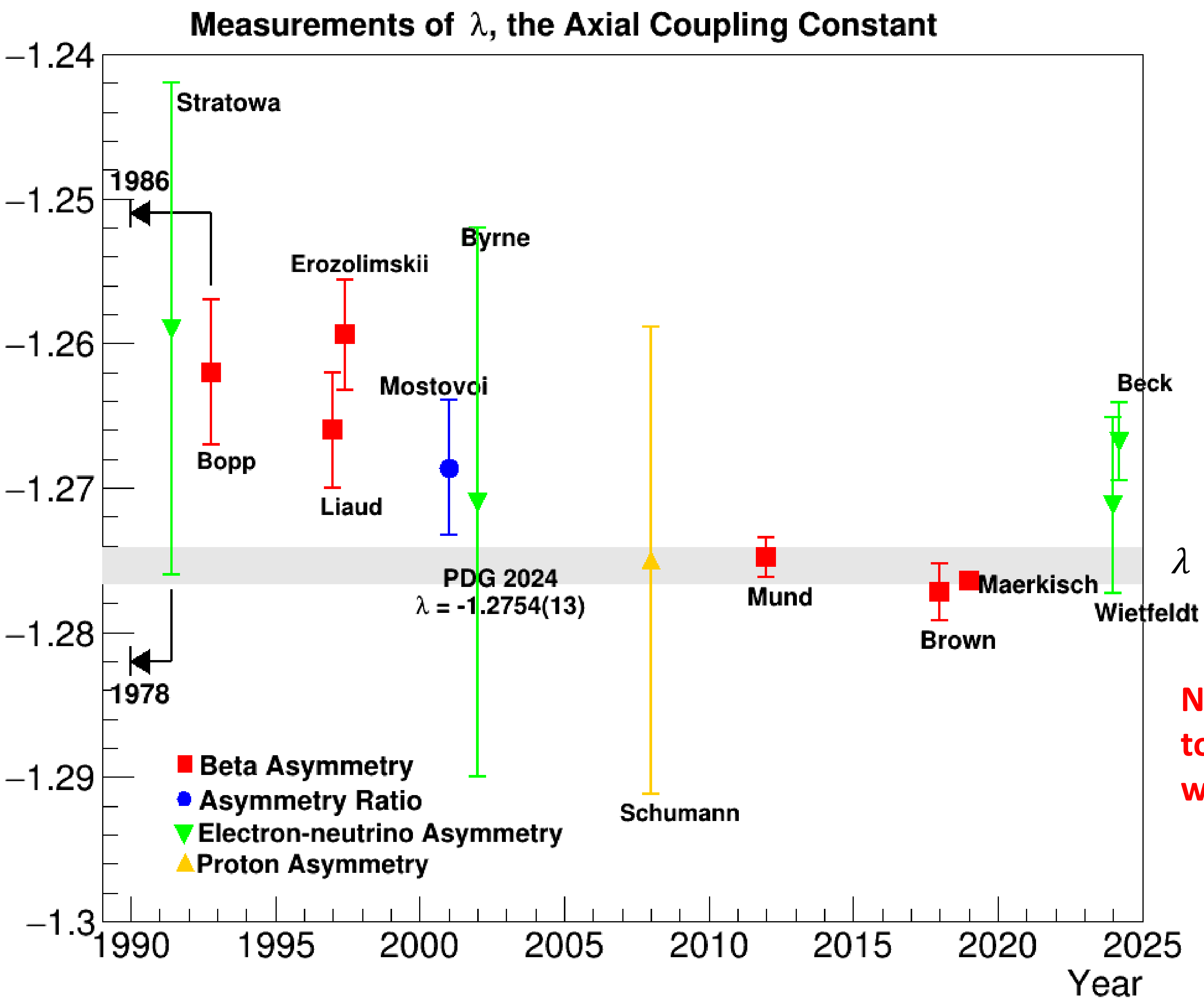


Recent measurements of A(E) for neutron agree, with most precise PERKEO III

Using only recent beta asym:

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

Reminder: ~.0003 is unitarity target!



PDG 2025

$$\lambda = -1.2753(13)$$

~0.1%

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

“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.

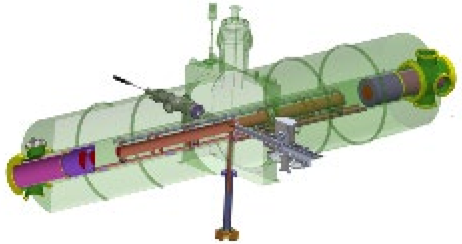
Conclusion: higher precision values from measurements of the beta-neutrino correlation and the beta-asymmetry are needed to confirm the current discrepancy between angular correlation results, and to validate the current status of the Cabibbo Anomaly -- **Nab and pNab well motivated**!

Angular Correlations

Most precise measurements to date were beta-asymmetry measurements

Two most recent:

for UCN

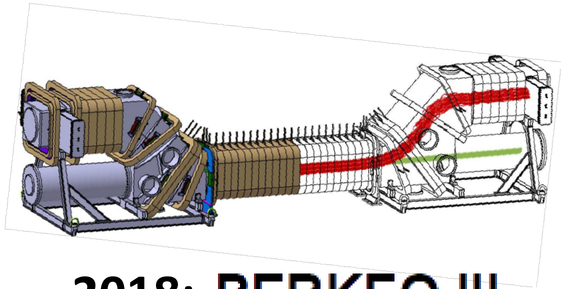


2017:

A_0=-0.12015(71)

UCN at LANL

For CN

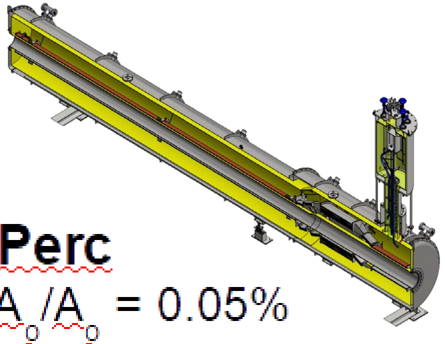


2018: PERKEO III

dA_0/A_0 = 0.18 %

Chopped CN at ILL

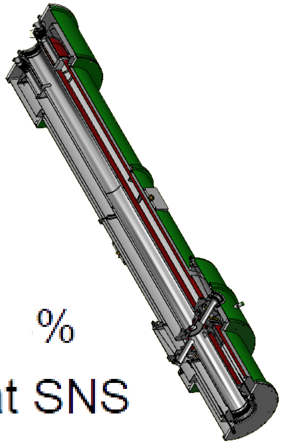
Planned or in development over next 5 years (BRAND planned for ESS)



Perc

dA_0/A_0 = 0.05%

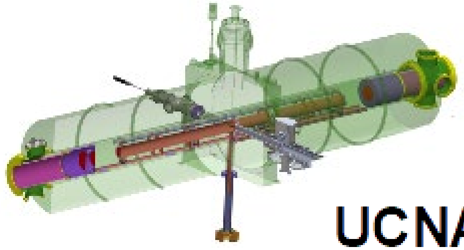
Chopped CN at FRM II



Nab

da_0/a_0 = 0.1 %

Pulsed CN at SNS



UCNA+

$dA_0/A_0 < 0.2\%$

UCN at LANL

Angular Correlations

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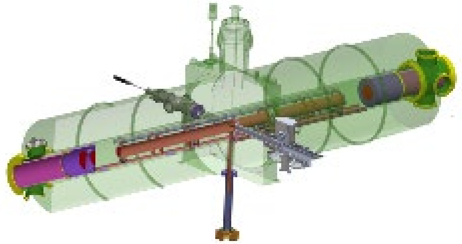
for UCN



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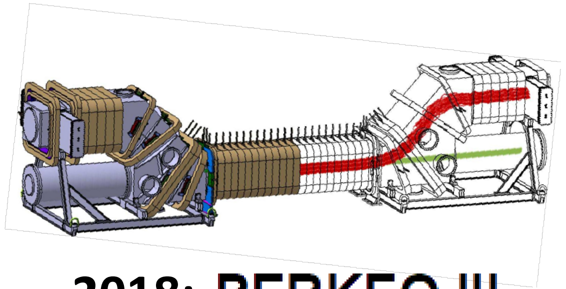

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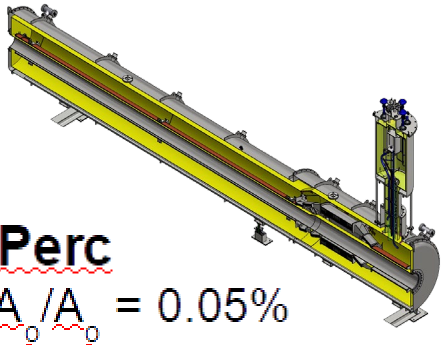
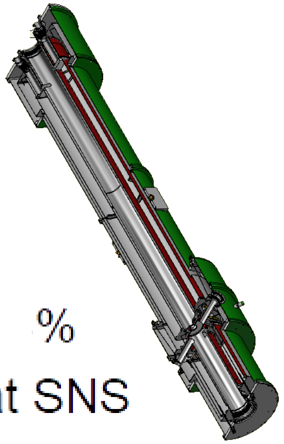


Perc

dA_0/A_0 = 0.05%

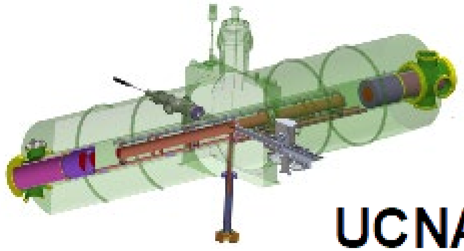
Chopped CN at FRM II

Nab



da_0/a_0 = 0.1 %

Pulsed CN at SNS



UCNA+

$dA_0/A_0 < 0.2\%$

UCN at LANL

pNab !

The pNab Concept

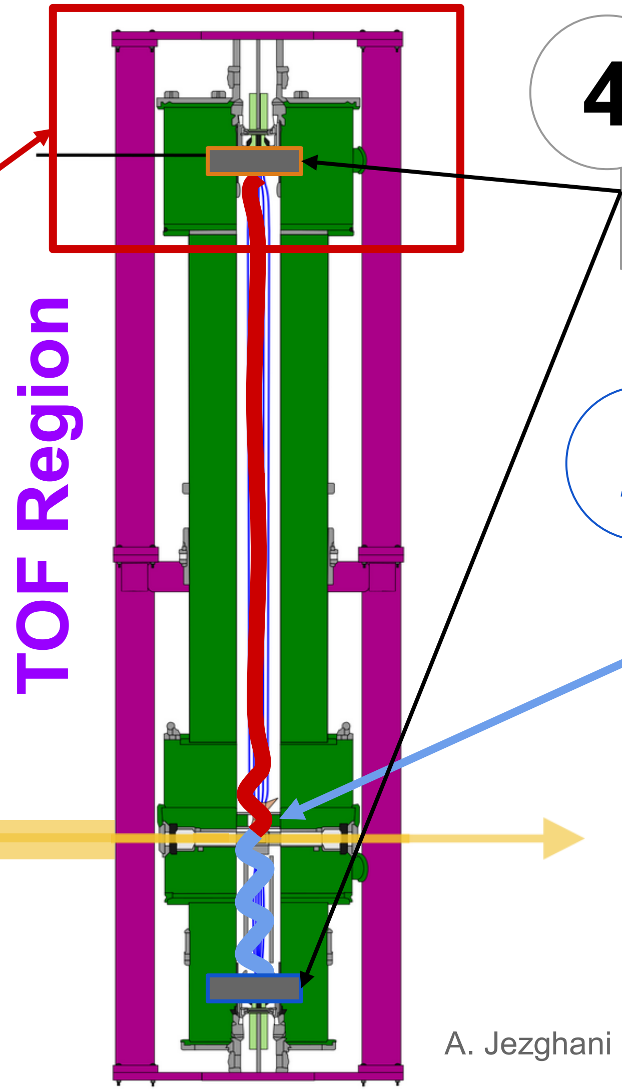
Layout of the Nab Spectrometer (remember Love's talk)

3
Upper Detector System is at -30 kV

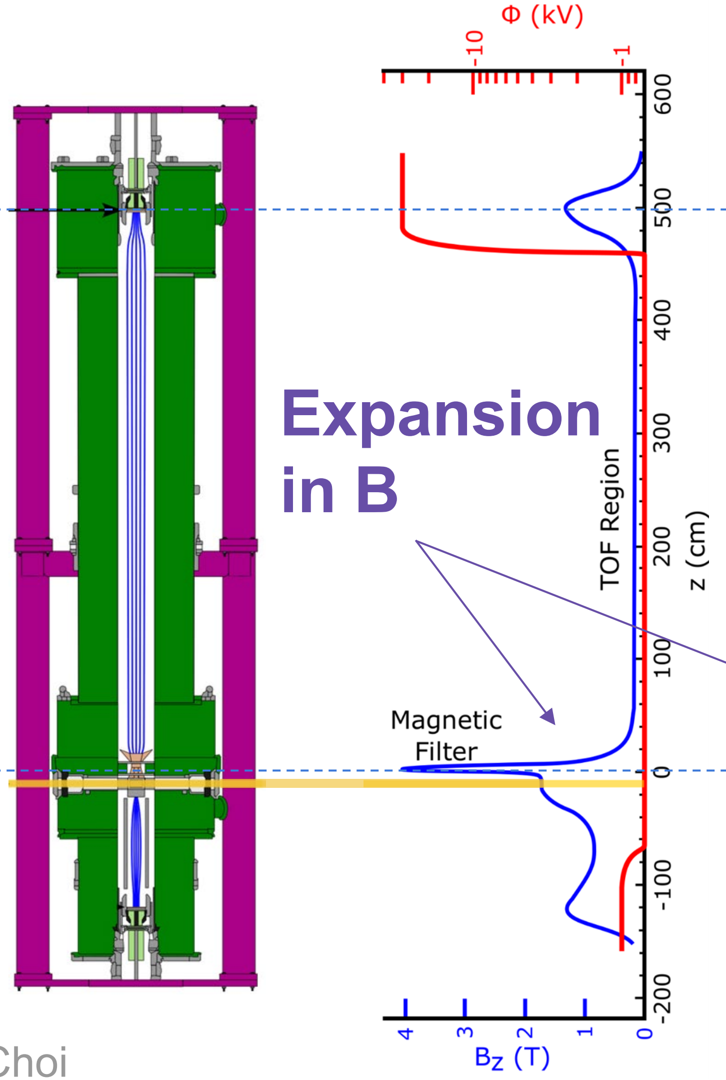
4
Silicon detectors

2
Decay Products & Time-Of-Flight Region

1
Neutron Beam

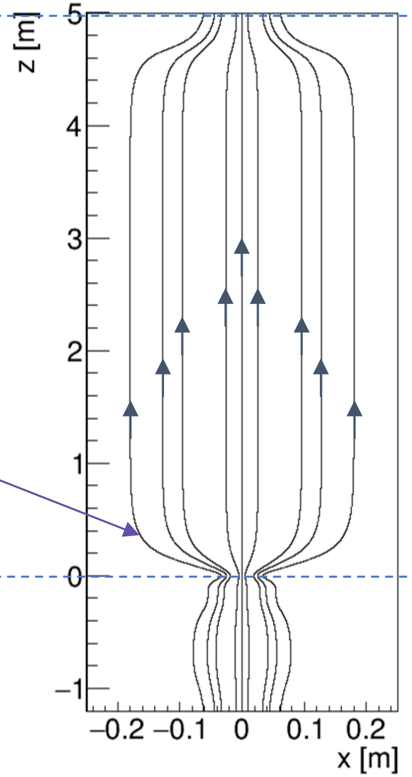


Time-of-Flight Spectroscopy

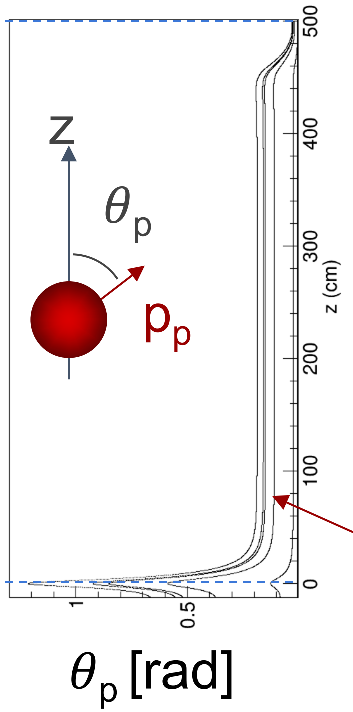


Expansion in B

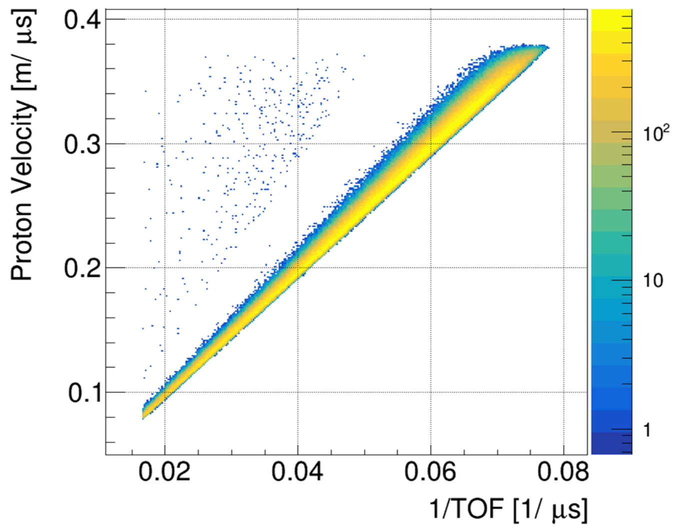
Magnetic Fieldline



proton momentum direction



Simulated Velocity vs. 1/ TOF

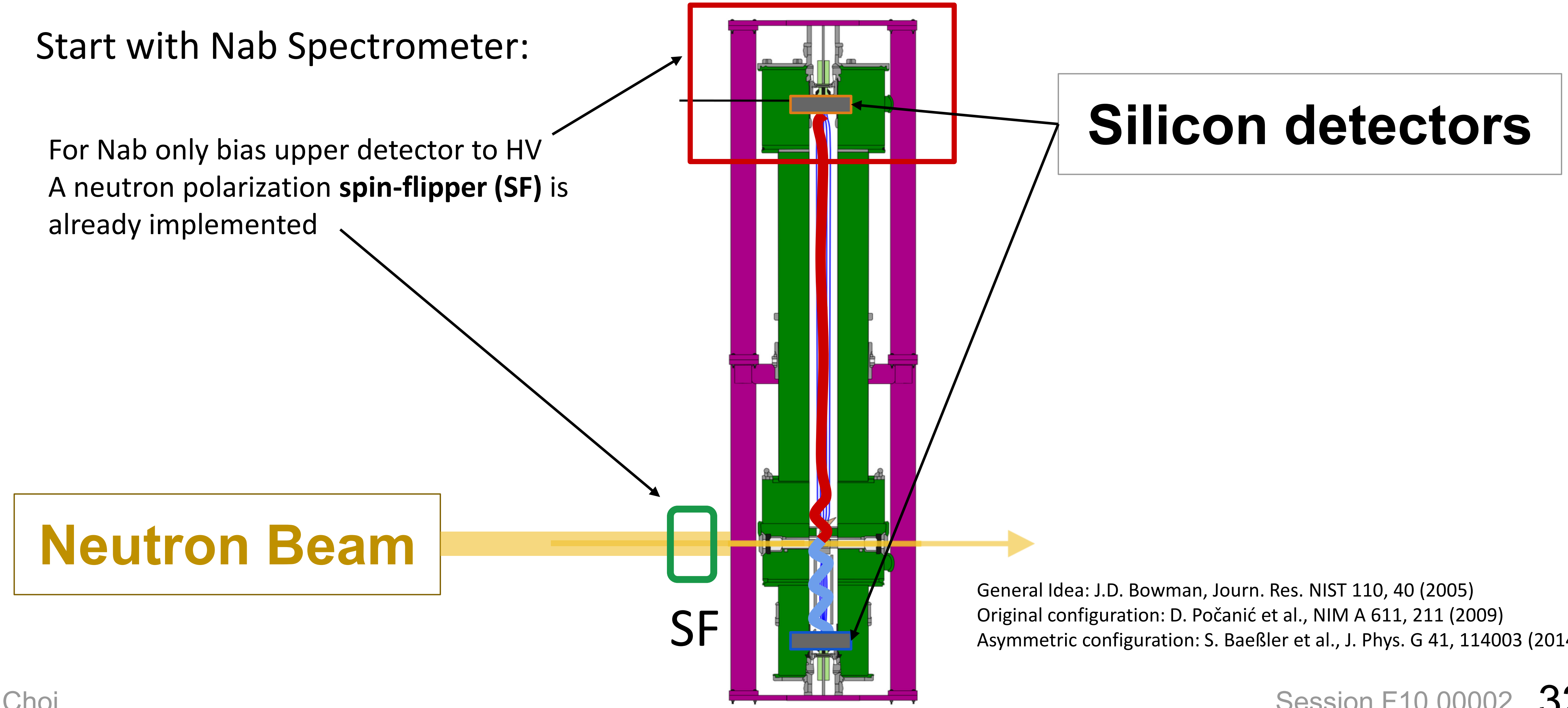


Proton momentum **longitudinalize** and results in **mostly linear relationship** between proton velocity & inverse-TOF

pNab Concept

Start with Nab Spectrometer:

For Nab only bias upper detector to HV
A neutron polarization **spin-flipper (SF)** is already implemented



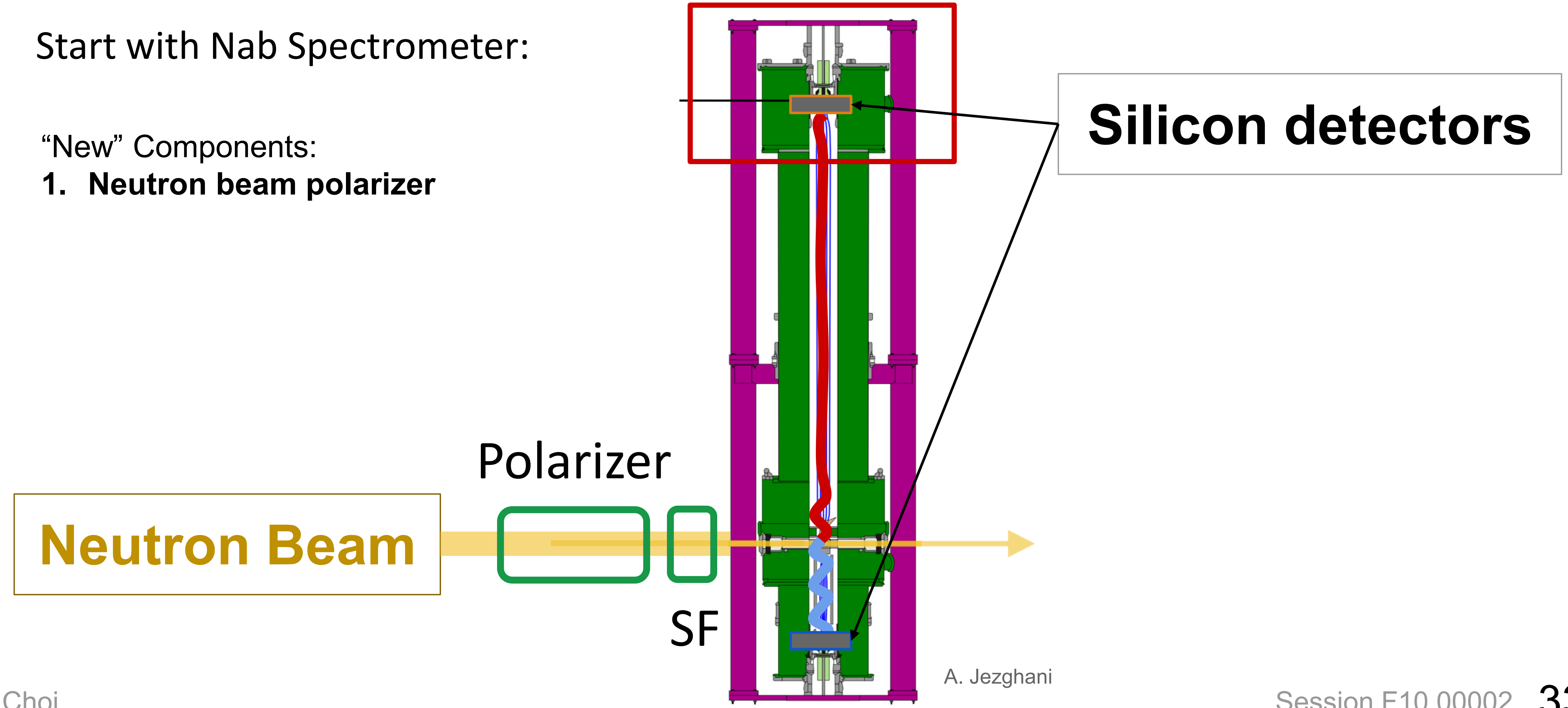
General Idea: J.D. Bowman, Journ. Res. NIST 110, 40 (2005)
Original configuration: D. Počanić et al., NIM A 611, 211 (2009)
Asymmetric configuration: S. Baeßler et al., J. Phys. G 41, 114003 (2014)

pNab Concept

Start with Nab Spectrometer:

"New" Components:

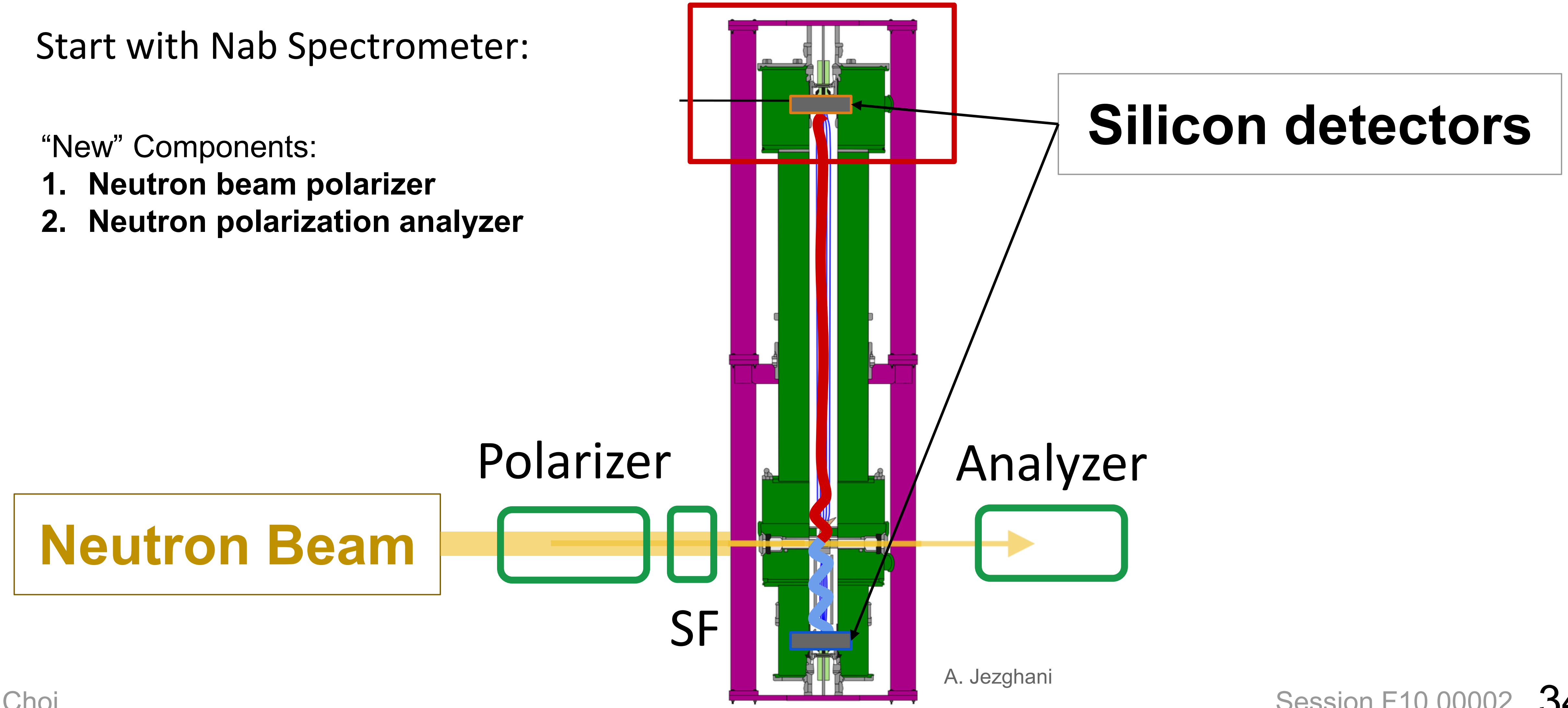
1. **Neutron beam polarizer**



pNab Concept

Start with Nab Spectrometer:

"New" Components:
1. **Neutron beam polarizer**
2. **Neutron polarization analyzer**

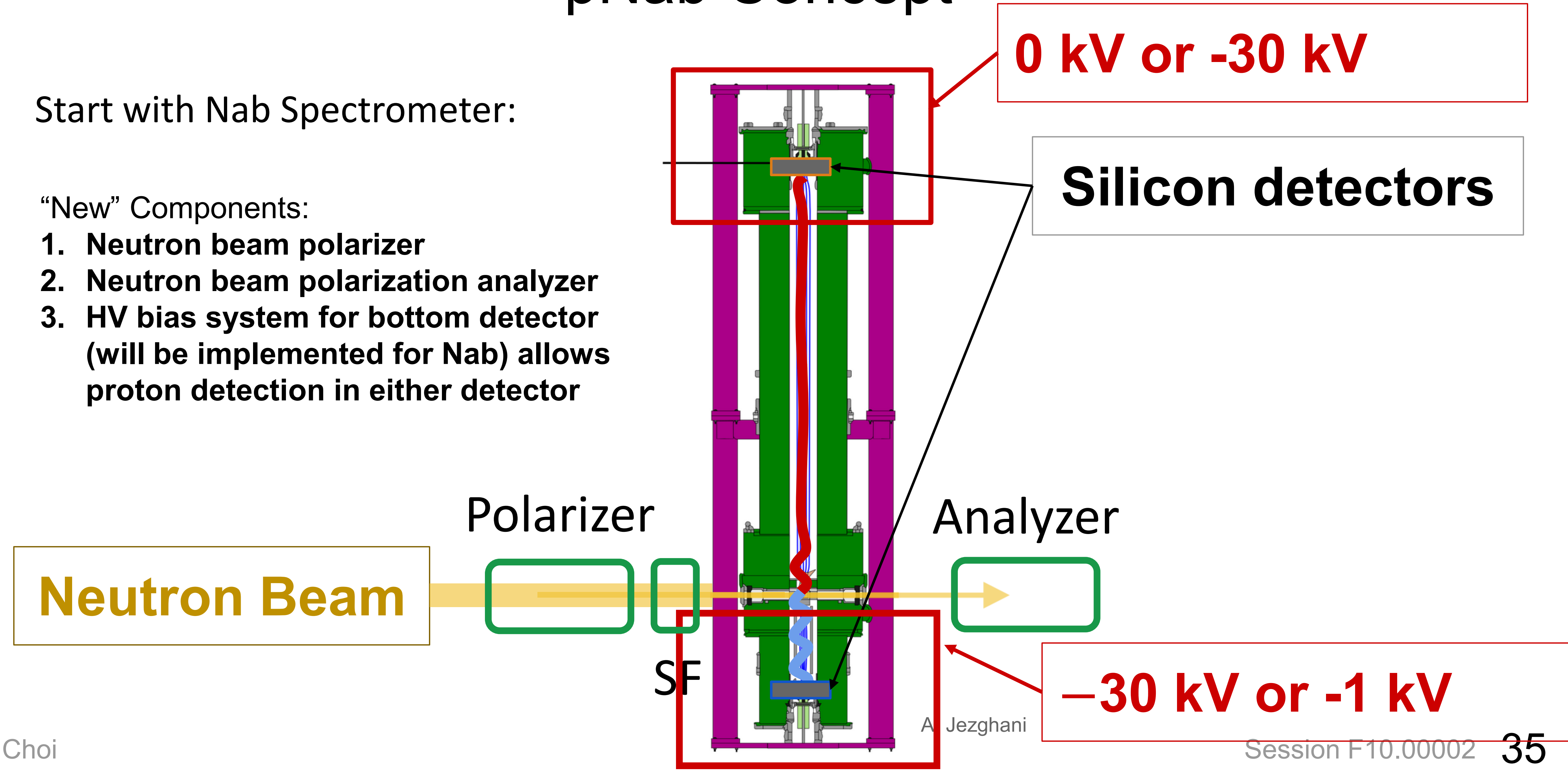


pNab Concept

Start with Nab Spectrometer:

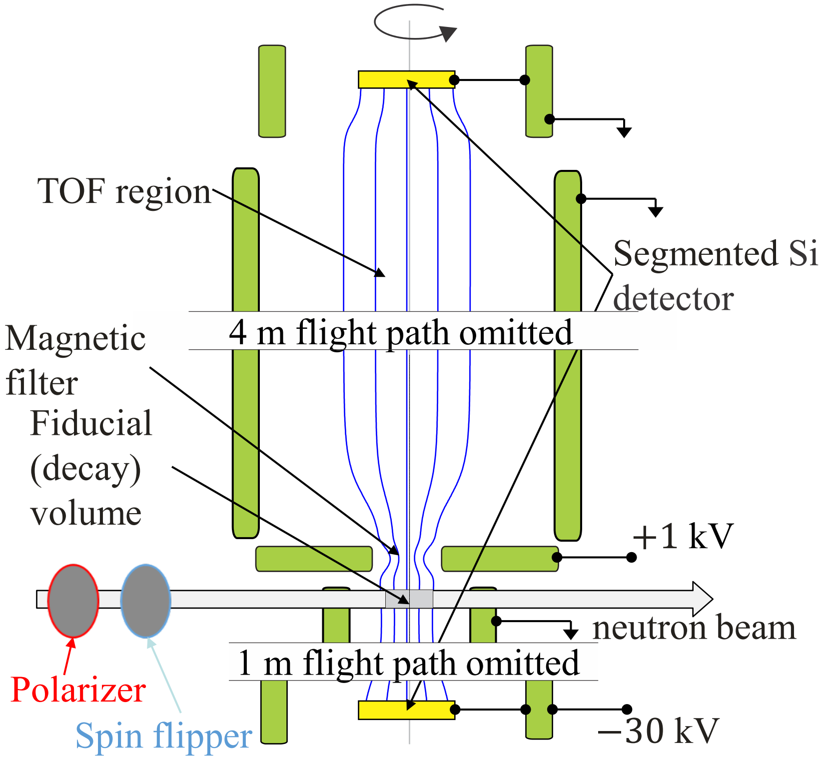
"New" Components:

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



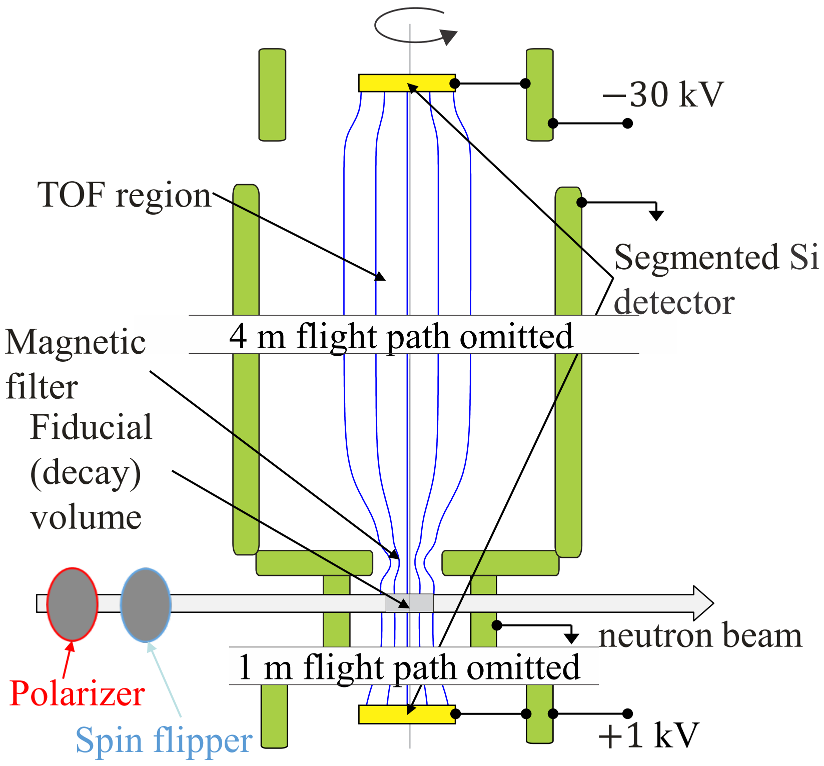
pNab measurement modes

Proton detection in lower detector



- Beta asymmetry A coefficient in pNAB
- **All** protons detected at lower detector, electrons in both

Proton detection in upper detector



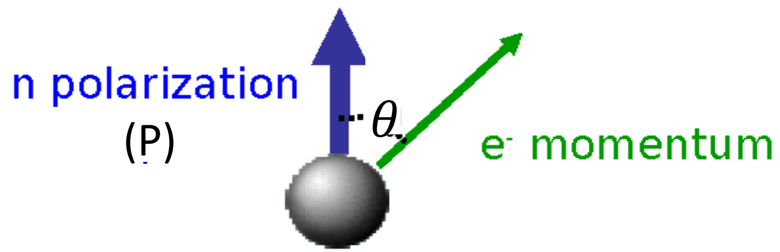
- B coefficient with polarizer in pNAB.
- **Protons that pass the magnetic filter** are detected at upper detector, electrons in both

β –Asymmetry

pNab analysis and many slides: S. Baessler

The Global Dataset: Angular Correlations

Example: the beta asymmetry



R = R_o(1 + (v/c) P A(E) cosθ)

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

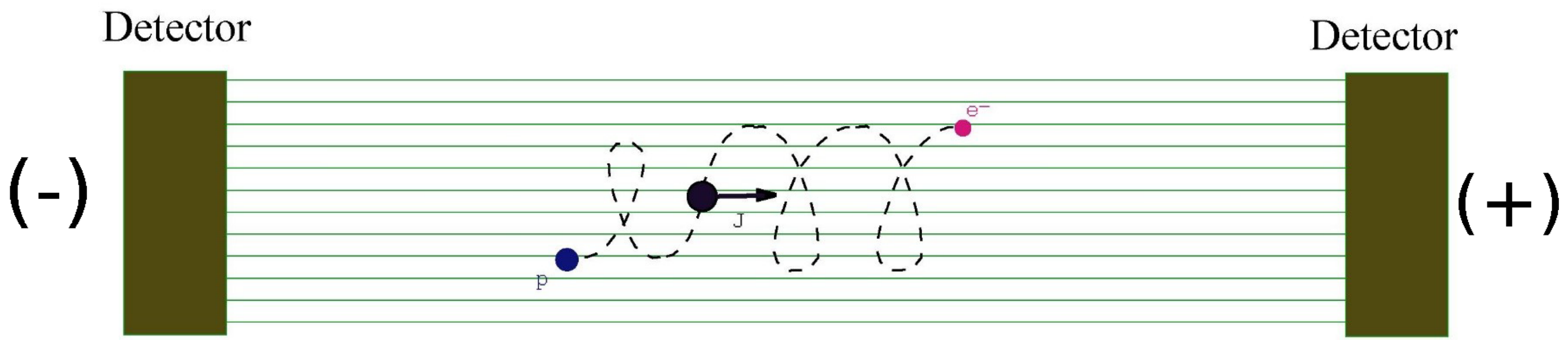
$$A_\beta(0) = \frac{2|\lambda| - 2\lambda^2}{(1+3\lambda^2)} \approx -0.1$$ (leading order)

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

Recent work establishes precision level for $\lambda \sim 10^{-4}$

Measurement Challenges

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



Magnetic Field

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

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

Many sources of error -- systematic uncertainties provide limits in most cases!

Must determine:

- Beta rates
- Beta spectra
- <cosθ>
- Polarization

Systematic effects:

Backgrounds

Calibration/Linearity

Scattering (esp. backscattering)

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

And of course, entirely different experimental technique than $\beta - \bar{\nu}$ correlation measurements…

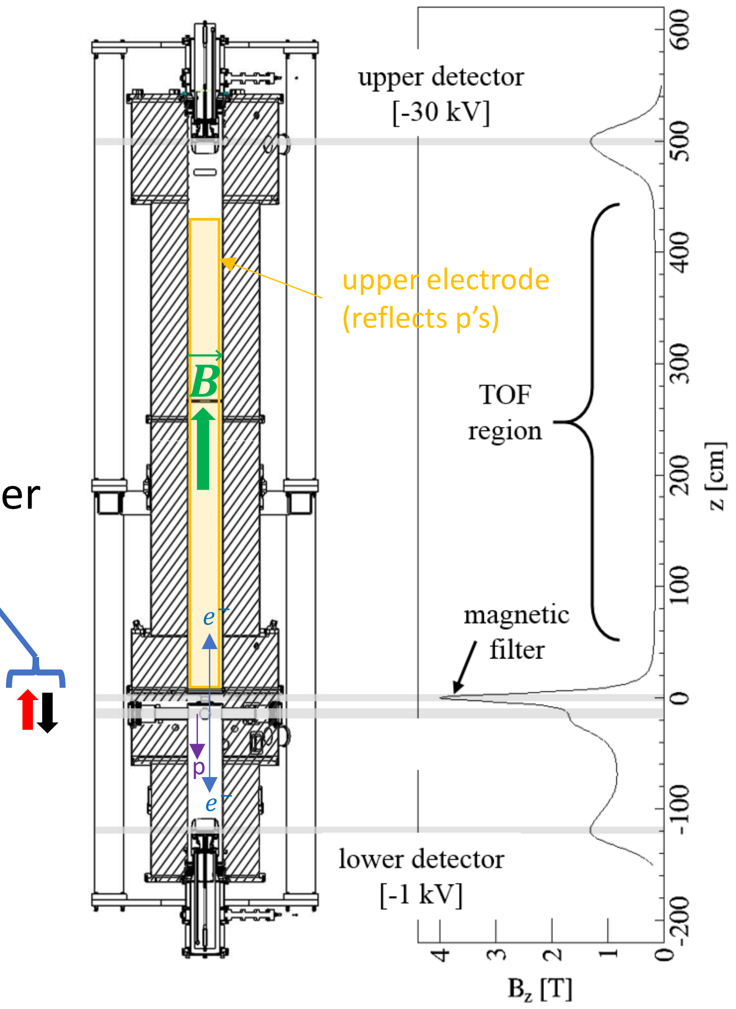
pNab β –Asymmetry Mode

Detector 1: N_1

Neutron polarization
∥ or ∦ to spectrometer
magnetic field

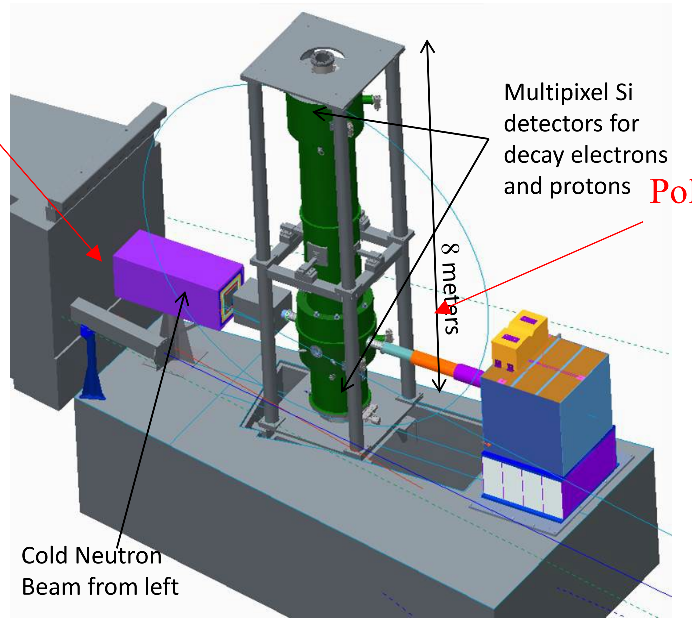
neutron beam

Detector 2: N_2



- 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
- All protons detected in lower detector (reflected from upper electrode)
- Timing signals used to determine initial hit direction when e^- bounces off one detector and hits other ("backscattering")

New addition:
Neutron beam polarizer

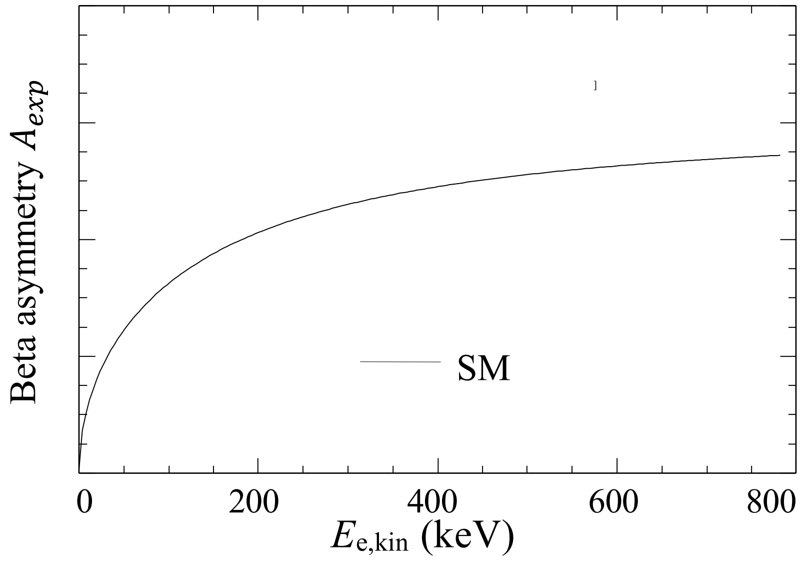


New addition:
Polarization analyzer

Statistical Uncertainty for *A* from Beta Asymmetry

Beta asymmetry

$$A_{exp} = \frac{N_e^{\uparrow}(E_{e,kin}) - N_e^{\downarrow}(E_{e,kin})}{N_e^{\uparrow}(E_{e,kin}) + N_e^{\downarrow}(E_{e,kin})}$$
$$= A P_{\mathrm{n}} \frac{p_e}{E_e} \langle \cos(\vec{\sigma}_{\mathrm{n}}, \vec{p}_e) \rangle \quad \text{(in SM)}$$



Statistical uncertainty budget:

lower E_e cutoff	none	100 keV	200 keV
ΔA (SM)	$4.3/\sqrt{N}$	$\mathbf{4.8/\sqrt{N}}$	$7.8/\sqrt{N}$

→ $(\Delta A/A)_{stat} = 7 \cdot 10^{-4}$ **can be reached in 1-2 years** (with $5 \cdot 10^9$ events detected)

Promising!

S. Baessler

Notes: higher useful event rate than Nab – all decays used!
implementation also results in higher sensitivity!

Estimated Systematic Uncertainty Budget for Beta Asymmetry *A*

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

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	$\mathbf{< 1 \cdot 10^{-3}}$

S. Baessler

Systematic Uncertainty Budget for Beta Asymmetry *A*

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

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	$\boxed{\mathbf{< 1 \cdot 10^{-3}}}$

S. Baessler

Uncertainty ~ 0.025% in λ, at target sensititivity for Cabbibo Anomaly!

Systematic Uncertainty Budget for Beta Asymmetry A

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

Significant advantage, primary motivation for coincidence mode

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	$\mathbf{< 1 \cdot 10^{-3}}$

S. Baessler

Systematic Uncertainty Budget for Beta Asymmetry *A*

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

Absolute polarimetry required!

Contribution to Uncertainty	$\mathbf{\Delta A/A}$
1. Neutron beam polarization	$\boxed{5 \cdot 10^{-4}}$
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	$\mathbf{< 1 \cdot 10^{-3}}$

S. Baessler

Neutron Beam Polarization

Require $\Delta P_\mathrm{n}/P_\mathrm{n} = 5 \cdot 10^{-4}$. Note that in past experiments, that this was the most challenging source of uncertainty. Requires construction of equipment to polarize, spin-flip (so polarization pointing either parallel or antiparallel to spectrometer magnetic field), and measure (analyze) the polarization. Appropriate spin-flipper technology has been developed for several different experiments.

Plan A: Use Solid State Polarizer in V bender geometry (SSPV). Developed at ILL and optimized for very high polarization that doesn't allow for much non-uniformity (non-uniformity is the main problem in polarization measurement).

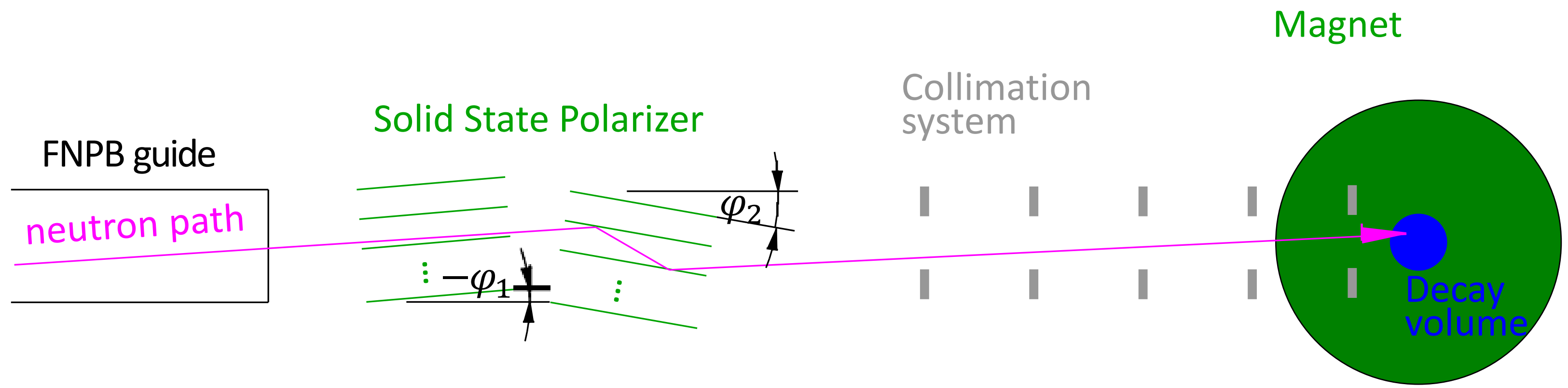
Plan B: The original proposal for pNAB was to use a Helium-3 polarizer, due to the possibility to obtain an in-situ measurement of the polarization at a pulsed source.

Both plans require **measurement of the polarization**: This measurement requires opaque (thick) He-3 cells. Measurement techniques have been developed for previous asymmetry experiments PERKEO-II, PERKEO-III, and Perc.

Content: S. Baessler Errors: A. Young

Neutron Beam Polarization, Solid State Polarizer (Plan A)

Idea: Very high polarization efficiency doesn't allow for much non-uniformity



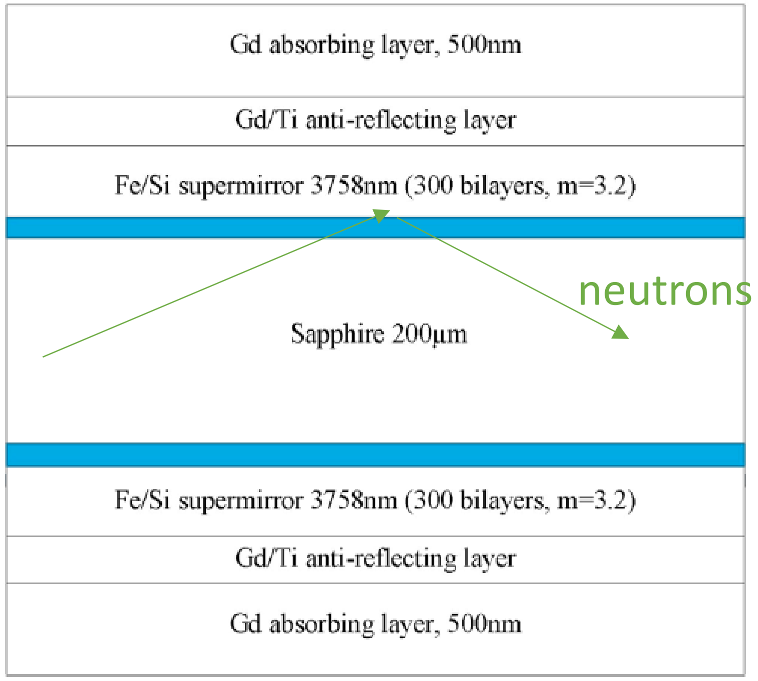
- New solid state SM polarizer consist of two stacks of 180 parallel sapphire plates in V geometry (SSPV).
- Developed at Institute Laue-Langevin (ILL), Grenoble

A.K. Petoukhov et al., Rev. Sci. Instrum. 94, 023304 (2023)

- Reoptimized for Fundamental Physics Beamline at Spallation Neutron Source (J. Pioquinto, UVa):

Transmission: 40% (of all neutrons) just behind polarizer, degrades to 20% (of all neutrons at this place) in the fiducial volume of the experiment, **in straight line**

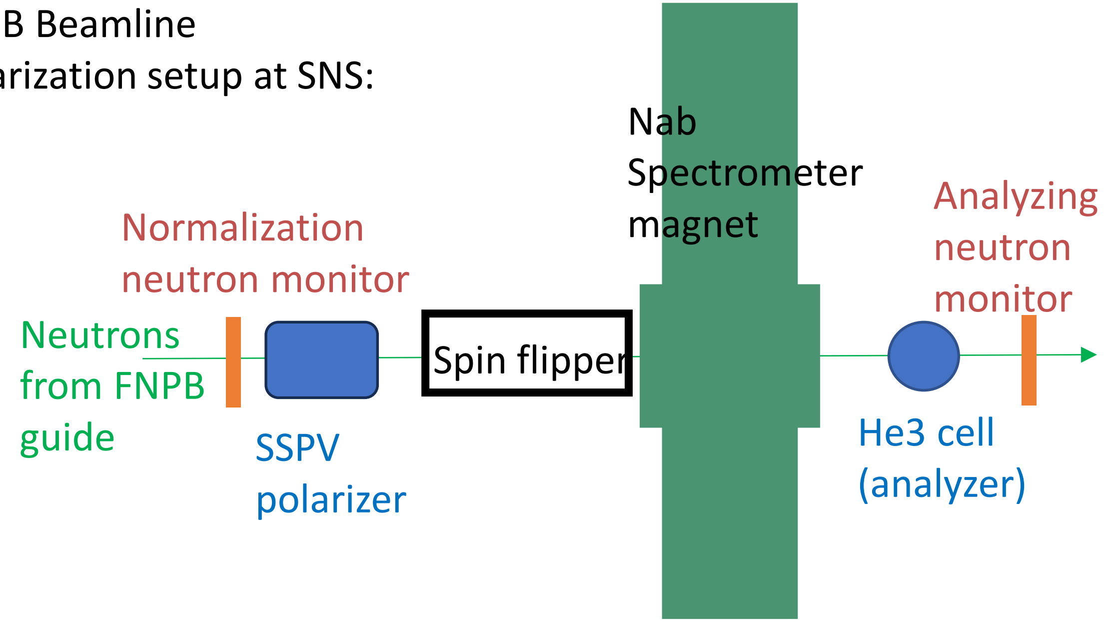
Polarization: $P_n = 99.5\%$



S. Baessler

Polarization Measurement in Plan A

FNPB Beamline
polarization setup at SNS:



Polarization is analyzed with He-3 spin filter. Transmission of neutrons through a cell with polarized gas is dependent on neutron wavelength, but for a cylindrical He-3 cell only weakly on position or angle. To minimize systematics, we want a few “thick” cells.

We can determine beam polarization from three measurements (as a function of neutron wavelength λ): He polarization up, He polarization down, He unpolarized:

$$T_{up/down} = (1 \pm P_n \tanh(\kappa P_{He}))e^{-\kappa} \cosh(\kappa P_{He})$$

with $\kappa = 0.0733 \cdot p[\mathrm{atm}] \cdot \lambda[\text{Å}] \cdot l[\mathrm{cm}]$

$$T_0 = e^{-\kappa}$$

Goal: $\Delta P_n = 5 \cdot 10^{-4}$ (comparison: PERKEO III had $\Delta P_n = 6 \cdot 10^{-4}$ with a much less uniform polarization, ILL team plans $\Delta P_n = 1 \cdot 10^{-4}$).

Uncertainty budget for beta asymmetry *A*

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

Detector response to electrons

1. **Energy reconstruction**
2. **Direction reconstruction**

Contribution to Uncertainty	$\mathbf{\Delta A/A}$
1. Neutron beam polarization	$5 \cdot 10^{-4}$
2. Electron detector response	$\boxed{5 \cdot 10^{-4}}$
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	$\mathbf{< 1 \cdot 10^{-3}}$

S. Baessler

Uncertainty budget for beta asymmetry *A*

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

4 1 2 3

Detector response to electrons

1. **Energy reconstruction**
2. **Direction reconstruction**

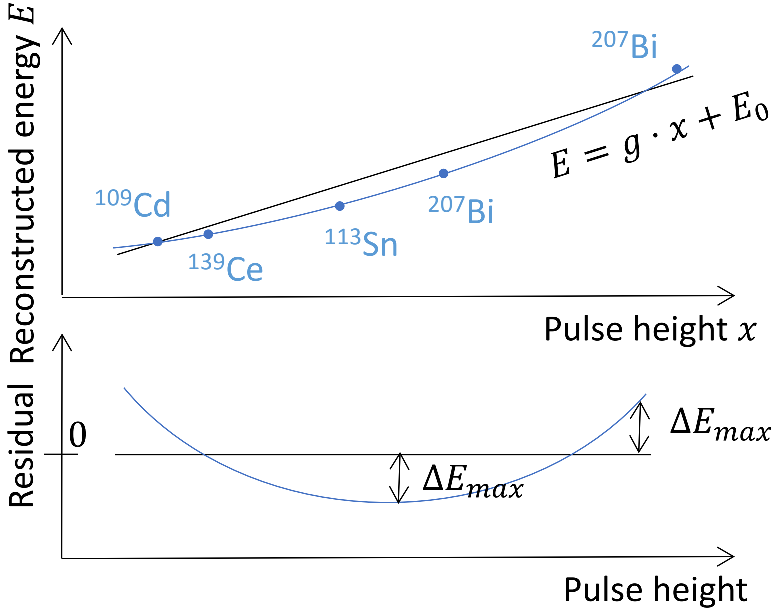
Beta Direction Reconstruction

Although the initial direction of emitted betas can be determined by which detector the beta hits first…if the beta deposits too little energy, the first scatter can be missed, resulting in assigning the primary direction to the wrong detector – diluting the asymmetry!

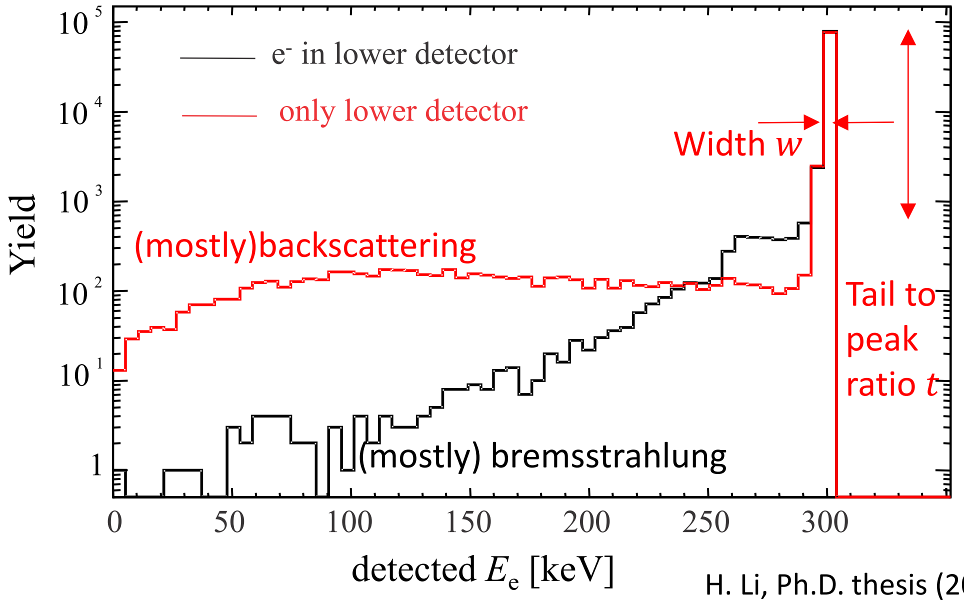
Expected to be a smaller component of error/uncertainty budget (based on PERKEO II/III) – but depends strongly on (hardware and analysis) thresholds and noise in the system -- evaluate in detail as a part of Nab!

Detector systematics -- energy reconstruction specifications

Electron energy calibration:



Detector response in Si detector for incoming E_e = 300 keV,
(Maximum impact angle of electrons is 12°, due to filter)



H. Li, Ph.D. thesis (2021)

Specification for	$\Delta a = 3 \cdot 10^{-5}$ **in Nab**	$\Delta A = 3 \cdot 10^{-5}$ **in pNAB**	$\Delta b = 5 \cdot 10^{-4}$ **in Nab**
gain factor ($\Delta g/g$)	fit parameter	0.0018	fit parameter
Offset E_0	0.3 keV	0.2 keV	0.03 keV
nonlinearity (ΔE_{max})	1.5 keV	0.3 keV	0.03 keV
peak width	1 keV	10 keV	3 keV
tail amplitude (Δt of peak)	10^{-4}	0.024	10^{-3}

S. Baessler

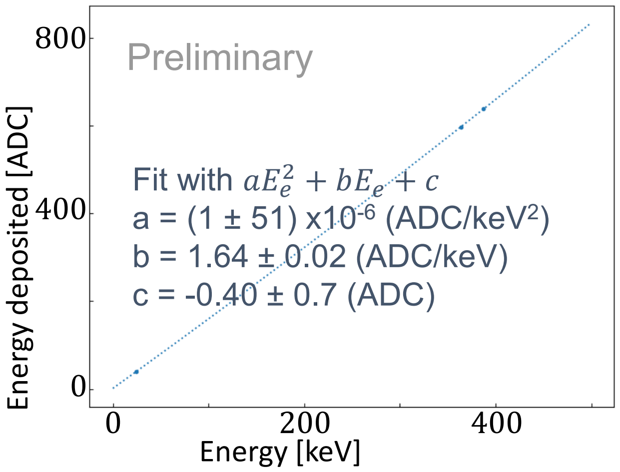
Note the synergy: Detector specifications for pNAB do not go beyond what will have to achieve in Nab anyway.

Detector systematics – status

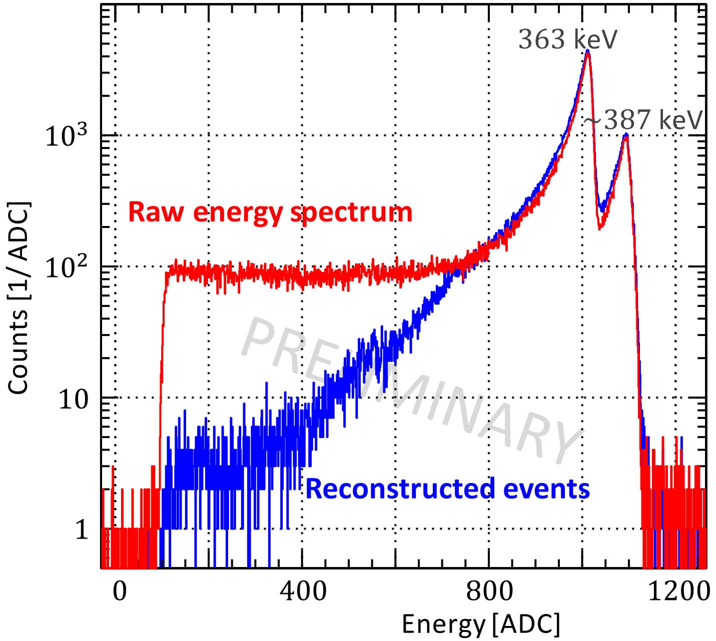
Current status of detector calibration – generally working to specs, but needs high precision campaign to verify.
Status:

- Energy-to-channel relation known to a few hundreds of eV (for one source and few pixels) – close to goal
- Stability acceptable for at least a short period
- Peak width of detector response function is < 5 keV.
  L.B. et al., NIM A 849, 83 (2017)
- Tail in response function clearly identified. Quantitative assessment needs new (open) radioactive sources.

^{113}Sn quadratic calibration model:

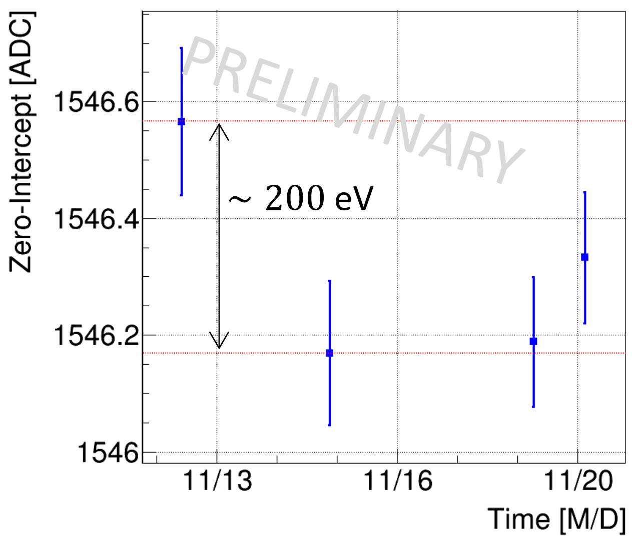


A. Shelby, NCSU



J. Choi, NCSU

^{207}Bi Calibration - Zero Intercept



J. Choi, NCSU

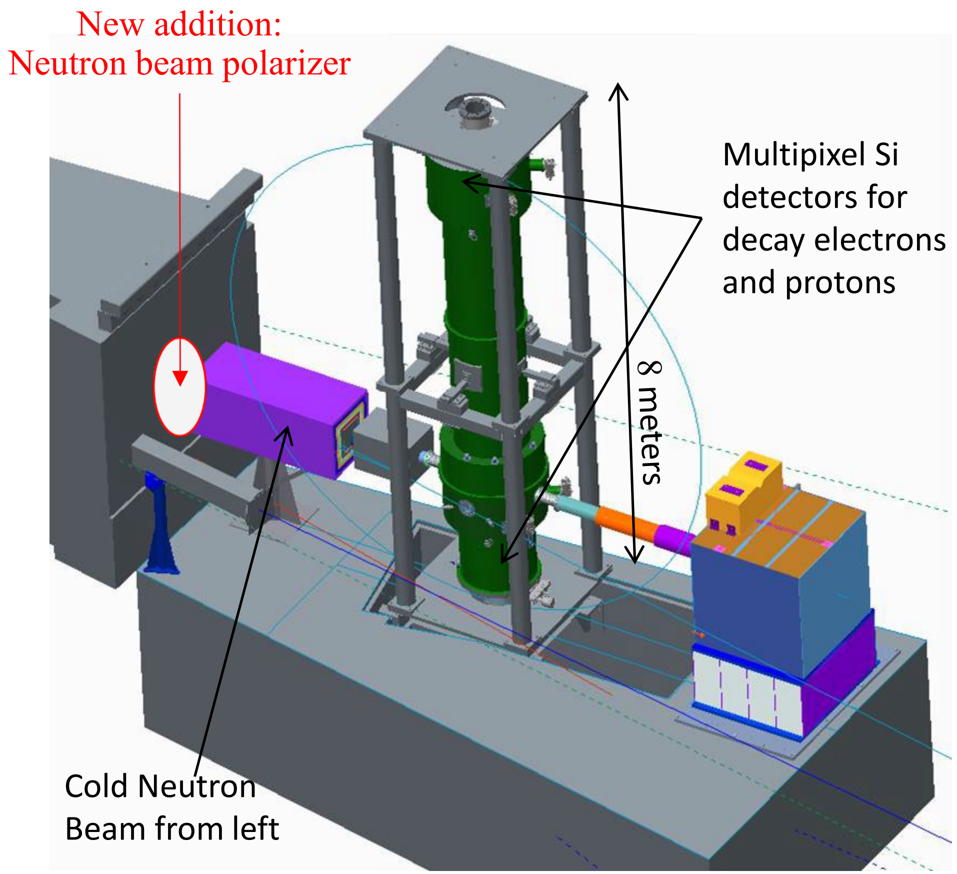
pNAB: the proton-related observables

b or b_ν may indicate S,T

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

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

$a = a(\lambda)$



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)

Nab and pNab Status

Nab and pNab: a “to-do” list

- In the next roughly 9 months, Nab is targeting a below 1% precision measurement of the $\beta - \nu$ correlation, hopefully setting the standard for this observable and defining objectives for the ultimate precision of ~ 0.1%. These objectives will include
  - Developing ability to detect protons in lower detector (or suppress protons in lower detector) and appropriate biasing of the upper electrode
  - Characterizing missed backscatter fractions
  - Implementing the spin-flipper to eliminate potential residual polarization effects
  - Completing the charactacterization of energy response
- pNab also requires implementing
  - a Polarizer
  - Measurements of the polarization

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]

(The pNab Collaboration)

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[h] Massachusetts Institute of Technology, Cambridge, MA 02139, USA
[i] Department of Physics and Astronomy, University of Tennessee, Knoxv
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[k] Department of Chemistry and Physics, Univ. of Tennessee-Chattanoog
[l] Laboratoire de Physique Corpusculaire, Caen, France
[m] Partnership for an Advanced Computing Environment, Georgia Institu
[n] Los Alamos National Laboratory, Los Alamos, NM 87545, USA
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[p] Department of Physics, University of Manitoba, Winnipeg, Manitoba,

1 July 2024

Abstract: The Nab and pNab collaborations are und

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)

[a] *Department of Physics, University of Virginia, Charlottesville, VA 22904–4714, USA*
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[c] *Department of Physics, Arizona State University, Tempe, AZ 85287–1504, USA*

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

Conclusions and Outlook:

pNab leverages the considerable effort poured into developing Nab – with essentially all of its operational specifications satisfied by the working Nab experiment except a functioning polarizer and polarization analyzer. Measurement of observables with polarized neutrons provides significant new handles on systematic errors and higher sensitivity to λ and exotic couplings than Nab.

Feasible solutions (polarized 3He cells and supermirror polarizers) have already been demonstrated which can be implemented for pNab – there do not seem to be any technological barriers to moving forward.

Together with Nab, it may be possible to address the current discrepancies in the global data set for λ between the $\beta - \nu$ correlation and the β −asymmetry

pNab **can have a significant impact on the Cabbibo anomaly (on its own)**, potentially confirming the large violation of unitarity observed with superallowed nuclear decay data, but without the nuclear structure uncertainties. The V_{ud} uncertainty expected is about 0.25%, which can be compared to Nab, where current projections are about 0.4%. Observation of polarized angular correlations will also offer access to higher precision constraints on exotic couplings.

The Nab Collaboration

Oak Ridge National Laboratory

University of Virginia

NC State University

The University of Tennessee Knoxville

Los Alamos National Laboratory

EKU Eastern Kentucky University

The University of Tennessee Chattanooga

Massachusetts Institute of Technology 1861 Mens et Manus

ASU Arizona State University

University of Manitoba

UK University of Kentucky

GT

University of Michigan

Universidad Nacional Autónoma de México

Montclair State University

The University of Winnipeg

WKU

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