Nab: precise experimental study of unpolarized neutron beta decay

Dinko Počanić, (for the Nab collaboration)

University of Virginia

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of the Am. Phys. Soc. and Phys. Soc. of Japan
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6–11 Oct 2014

Neutron beta decay observables (SM)

$$\frac{\mathrm{d}w}{\mathrm{d}E_e \mathrm{d}\Omega_e \mathrm{d}\Omega_\nu} \simeq p_e E_e (E_0 - E_e)^2$$

$$\times \left[1 + a \frac{\vec{p}_e \cdot \vec{p}_\nu}{E_e E_\nu} + b \frac{m}{E_e} + \langle \vec{\sigma}_n \rangle \cdot \left(A \frac{\vec{p}_e}{E_e} + B \frac{\vec{p}_\nu}{E_\nu} \right) + \dots \right]$$

where in SM:

$$a = \frac{1 - |\lambda|^2}{1 + 3|\lambda|^2} \qquad A = -2 \frac{|\lambda|^2 + Re(\lambda)}{1 + 3|\lambda|^2}$$

$$B = 2 \frac{|\lambda|^2 - Re(\lambda)}{1 + 3|\lambda|^2} \qquad \lambda = \frac{G_A}{G_V} \text{ (with } \tau_n \Rightarrow \text{CKM } V_{ud}\text{)}$$

also proton asymmetry: $C = \kappa(A + B)$ where $\kappa \simeq 0.275$.

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$\Rightarrow$ SM **overconstrains** a, A, B observables in n β decay!
Fierz interf. term b brings add'l. sensitivity to non-SM processes!

Goals of the Nab experiment (at SNS, ORNL)

- Measure the e–ν correlation a in neutron decay with precision

  $\Delta a/a \simeq 10^{-3}$ or $\sim 50\times$ better than:

	-0.1054 ± 0.0055	Byrne et al '02
current results:	-0.1017 ± 0.0051	Stratowa et al '78
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- Measure b (Fierz interf. term) in n decay with $\Delta b \simeq 3 \times 10^{-3}$

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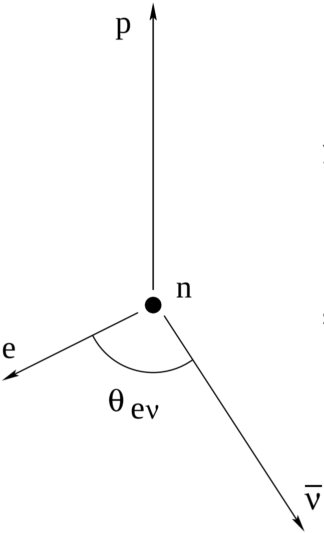
Motivation:

- multiple independent determinations of λ (test of CKM unitarity),
- independent and competitive limits on S, T currents (BSM).

Electron–neutrino angle from E_e and E_p



Conservation of momentum in **n** beta decay,

$$\vec{p}_p + \vec{p}_e + \vec{p}_\nu = 0\,,$$

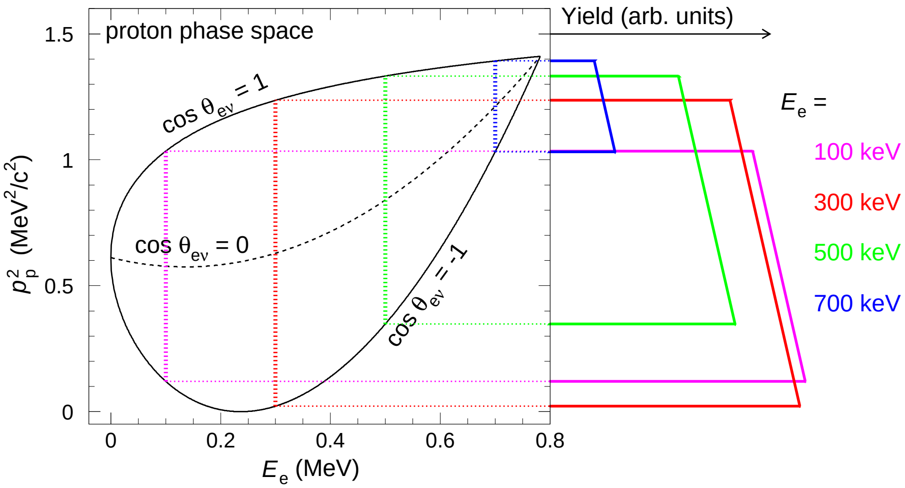
yields

$$p_p^2 = p_e^2 + 2 p_e p_\nu \cos\theta_{e\nu} + p_\nu^2\,.$$

Neglecting proton recoil energy, $E_e + E_\nu = E_0$, so that $p_\nu = E_0 - E_e$. Therefore:

$\cos\theta_{e\nu}$ is uniquely determined by measuring E_e and E_p (or $p_p \Rightarrow \mathrm{TOF}_p$).

Nab measurement principles: proton phase space



NB: For a given E_e, $\cos\theta_{e\nu}$ is a function of p_p^2 only.

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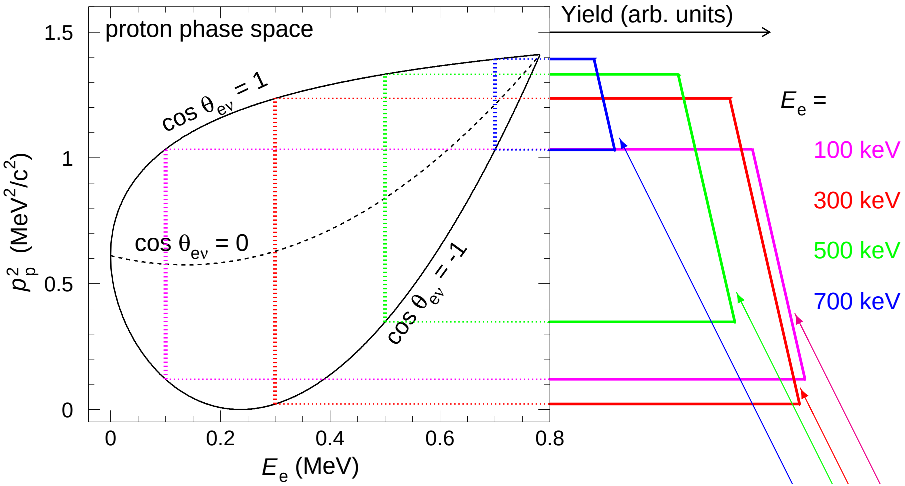


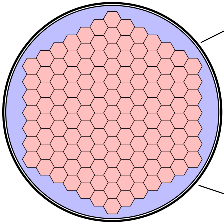
Slope ∝ **a**

NB: For a given E_e, $\cos\theta_{e\nu}$ is a function of p_p^2 only.

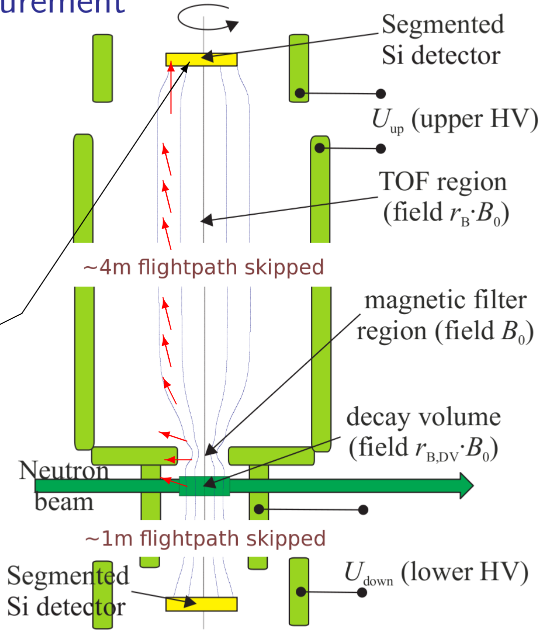
Numerous consistency checks are built-in!

Nab principles of measurement

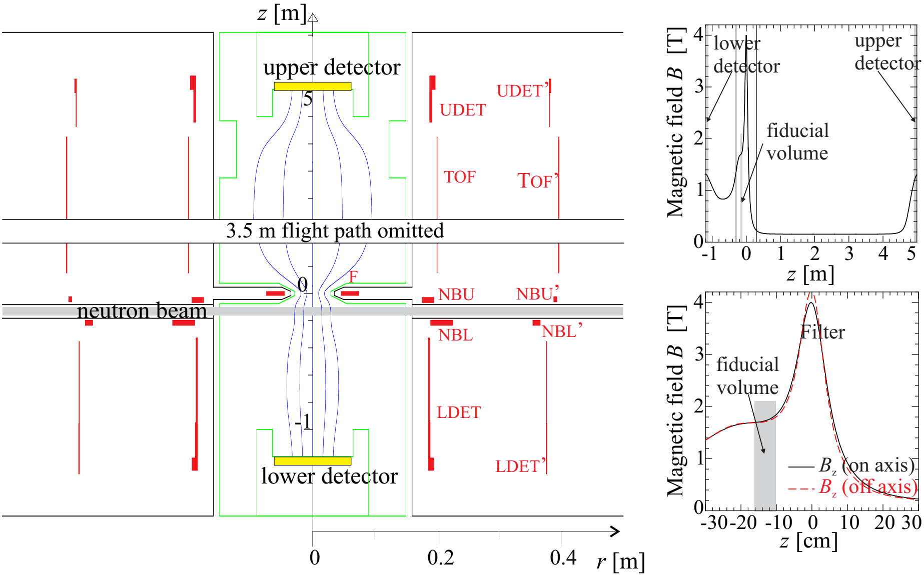
- Collect and detect both electrons and protons from neutron beta decay.
- Measure E_e and TOF_p and reconstruct decay kinematics
- Segmented Si det's:



LANL/Micron development

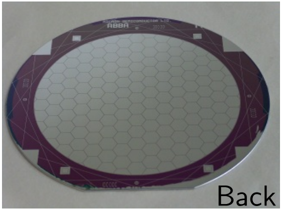


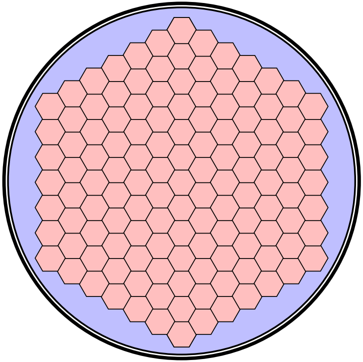
Spectrometer Coil design and $\vec{B}$ field profile



Nab Si detectors (LANL-Micron development)

- 15 cm diameter
- full thickness: 2 mm
- dead layer ≤100 nm
- 127 pixels





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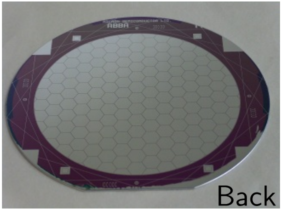

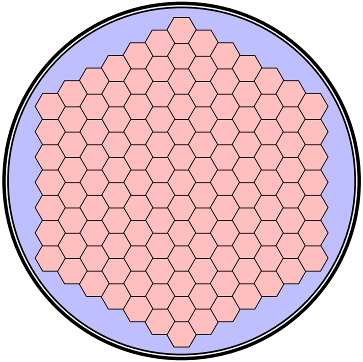

These look lovely, but how well do they work?

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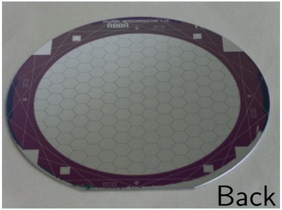
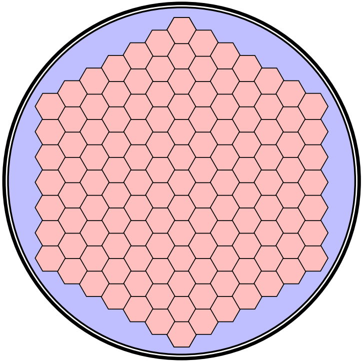
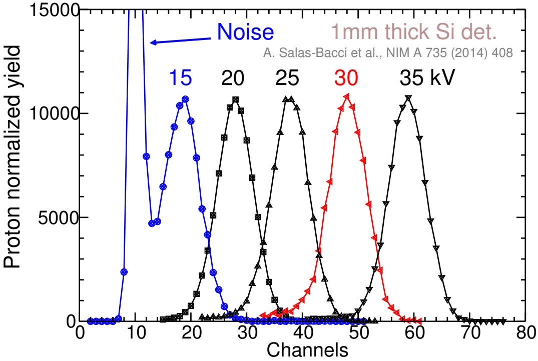
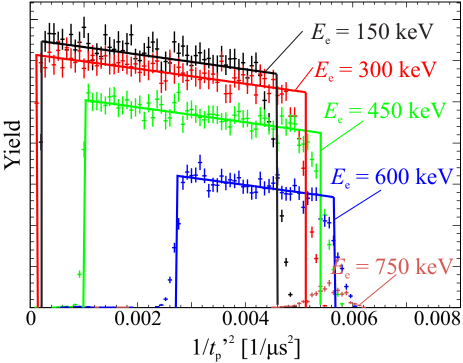






Analysis strategy (methods "A" and "B")



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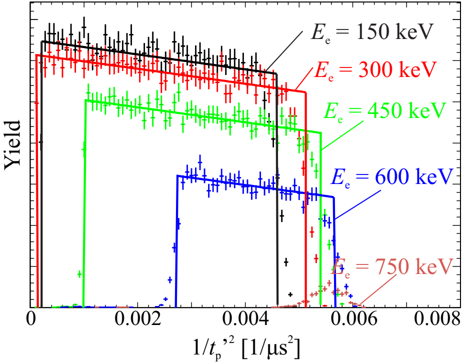

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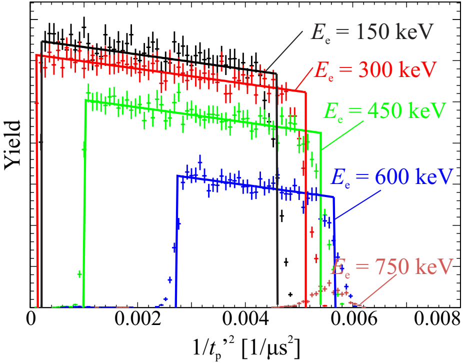

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- as well as a **HYBRID OF THE TWO METHODS**.

Projected statistical uncertainties for a and b

Statistical uncertainties for a

$E_{e,min}$	0	100 keV	100 keV	300 keV	100 keV
$t_{p,max}$	–	–	40 μs	40 μs	30 μs
σ_a	$2.4/\sqrt{N_u}$	$2.5/\sqrt{N_u}$	$2.5/\sqrt{N_u}$	$2.6/\sqrt{N_u}$	$2.8/\sqrt{N_u}$
$\sigma_a{}^\dagger$	$2.5/\sqrt{N_u}$	$2.6/\sqrt{N_u}$	$2.7/\sqrt{N_u}$	$2.7/\sqrt{N_u}$	$3.1/\sqrt{N_u}$
$\sigma_a{}^\S$	$4.1/\sqrt{N_u}$	$4.1/\sqrt{N_u}$	$4.1/\sqrt{N_u}$	$4.1/\sqrt{N_u}$	$4.4/\sqrt{N_u}$

† with $\mathbf{E}_{\text{calib}}$ and $\mathbf{L}_{\text{TOF}}$ variable; § using inner 70% of $\mathbf{p}_\mathbf{p}^2$ data.

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Statistical uncertainties for **b**

$E_{\mathrm{e,min}}$	0	100 keV	200 keV	300 keV
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$\sigma_{\mathbf{b}}{}^{\dagger\dagger}$	$7.7/\sqrt{N}$	$10.3/\sqrt{N}$	$16.3/\sqrt{N}$	$27.7/\sqrt{N}$

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Nab systematic uncertainties: Method B

Experimental parameter		$(\Delta a/a)_{\mathrm{SYST}}$
Magnetic field:	curvature at pinch	5×10^{-4}
	ratio $r_{\mathrm{B}} = B_{\mathrm{TOF}}/B_0$	2.5×10^{-4}
	ratio $r_{\mathrm{B,DV}} = B_{\mathrm{DV}}/B_0$	3×10^{-4}
L_{TOF}, length of TOF region		(*)
U inhomogeneity:	in decay / filter region	5×10^{-4}
	in TOF region	1×10^{-4}
Neutron beam:	position	4×10^{-5}
	width	2.5×10^{-4}
	Doppler effect	small
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Adiabaticity of proton motion		1×10^{-4}
Detector effects:	E_{e} calibration	(*)
	E_{e} resolution	5×10^{-4}
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Accidental coinc's	(will subtract out of time coinc)	small
Residual gas	ongoing parametric studies	small
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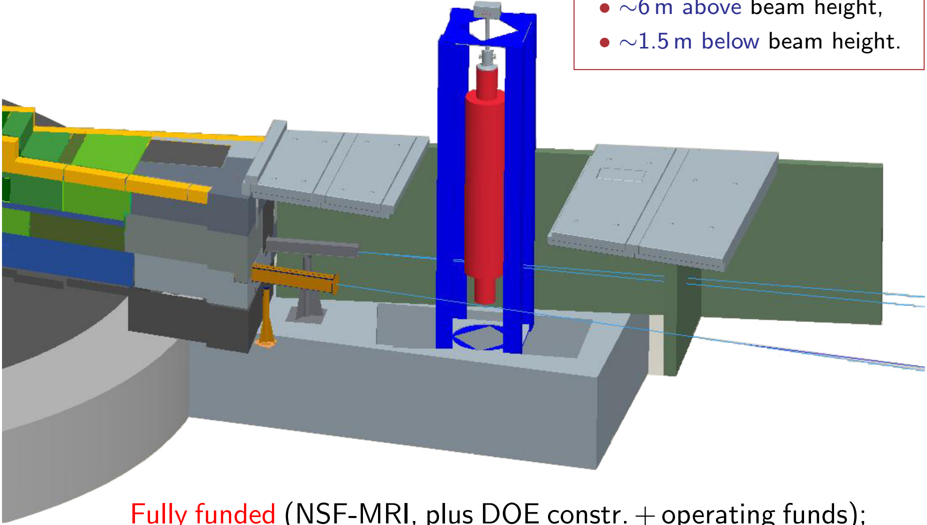
Nab apparatus in FnPB/SNS

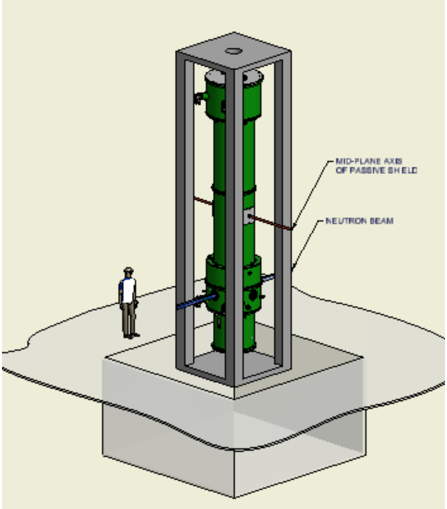
Apparatus extends:

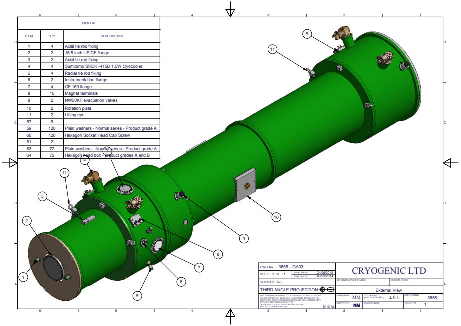
- ∼6 m above beam height,
- ∼1.5 m below beam height.

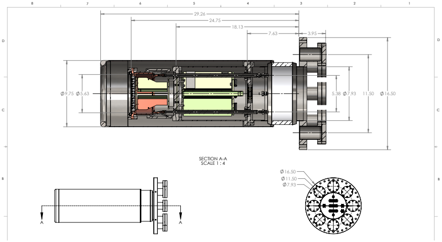


Fully funded (NSF-MRI, plus DOE constr. + operating funds);
Project so far on track to be ready for beam in early 2016.

Status: some drawings of the Nab apparatus







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Home page: http://nab.phys.virginia.edu

Current Nab collaboration

R. Alarcon[a], L.P. Alonzi[2§], S. Baeßler[b*], S. Balascuta[a], A. Barkan[a], L. Barron Palos[c], N. Birge[i], J.D. Bowman[d†], L. Broussard[m], J. Byrne[e], J.R. Calarco[f], T. Chupp[g], V. Cianciolo[d], C. Crawford[h], N. Fomin[i], E. Frlež[b], M.T. Gericke[j], F. Glück[k], G.L. Greene[d,i], R.K. Grzywacz[i], V. Gudkov[l], D. Harrison[j], F.W. Hersman[f], T. Ito[m], H. Li[b], M.F. Makela[m], J. Martin[o], P.L. McGaughey[m], S.A. Page[j], S.I. Penttilä[d‡], D. Počanić[b†], K.P. Rykaczewski[d], A. Salas-Bacci[b], E.M. Scott[i], A. Sprow[h], J. Thomison[d], Z. Tompkins[b§], W.S. Wilburn[m], A.R. Young[p], B. Zeck[p].

[a]Arizona State University
[b]University of Virginia
[c]UNAM, Mexico
[d]Oak Ridge National Lab
[e]University of Sussex
[f]Univ. of New Hampshire
[g]University of Michigan
[h]University of Kentucky
[i]University of Tennessee
[j]University of Manitoba
[k]Uni. Karlsruhe/RMKI Budapest
[l]University of South Carolina
[m]Los Alamos National Lab
[o]University of Winnipeg
[p]North Carlolina State Univ.
[†]Co-spokesmen
[*]Project Manager
[‡]On-site Manager

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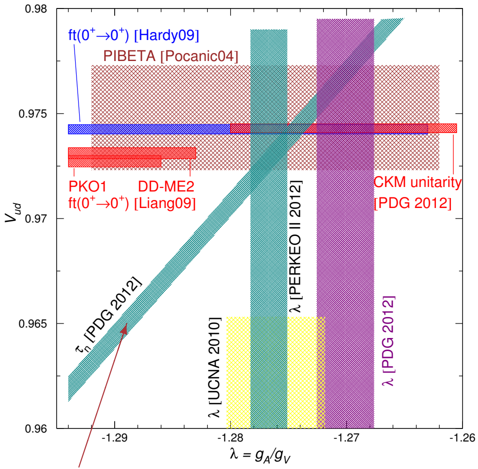
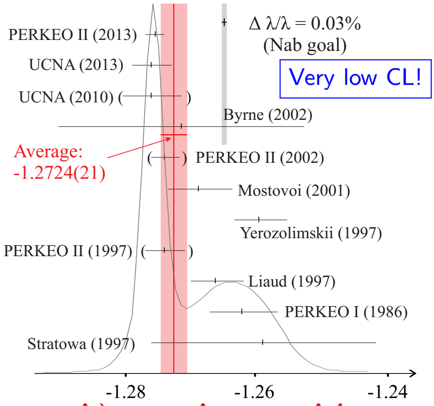
Current status of V_{ud} and λ, from n decay

…remains an unresolved mess:





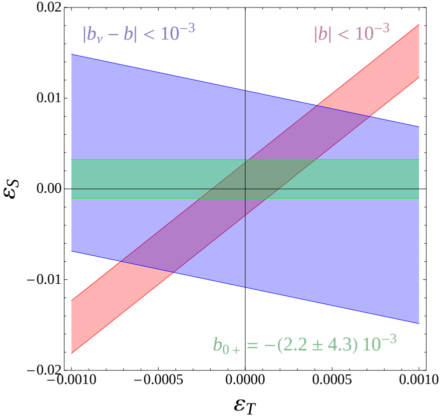
$$\tau_n^{-1} \propto |V_{ud}|^2 |g_V|^2 (1 + 3|\lambda|^2)$$

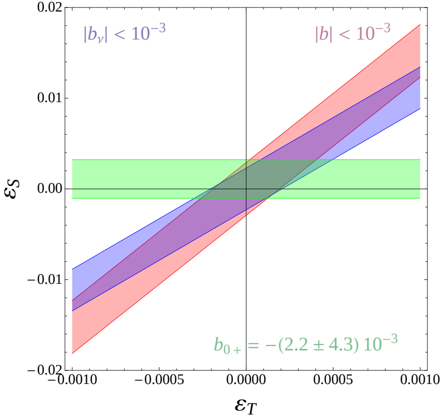
$$\frac{\Delta\lambda}{\lambda} \simeq 0.27 \frac{\Delta a}{a} \simeq 0.24 \frac{\Delta A}{A}$$

λ sensitivity to a, A is **similar**.

- Nab+abBA ⇒ several independent $\sim 0.03\%$ determinations of λ,
- Combined with b ⇒ new limits on non-SM terms, esp. Tensor.

Limits on T, S couplings from beta decay





Measurement of b with $\delta b < 10^{-3} \Rightarrow\ >$ 4-fold improvement on the current limit for ϵ_T from $\pi^+ \to e^+\nu\gamma$ decay.

From T. Bhattacharya, V. Cirigliano, S.D. Cohen, A. Filipuzzi, M. González-Alonso, M.L. Graesser, R. Gupta, H-W. Lin, Phys. Rev. D 85 (2012) 054512.