Nab: precise experimental study of unpolarized neutron beta decay

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Division of Nuclear Physics
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28 – 31 October 2015

Neutron beta decay observables (SM)

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

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

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:

current results:	-0.1054 ± 0.0055	Byrne et al '02
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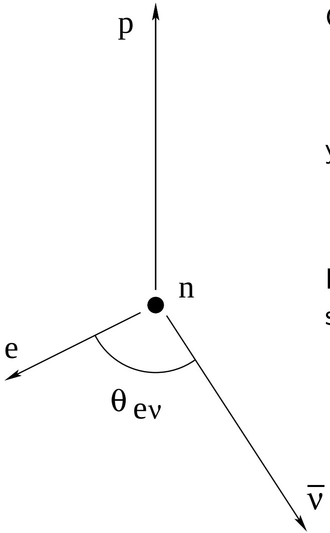
Motivation:

- 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,

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

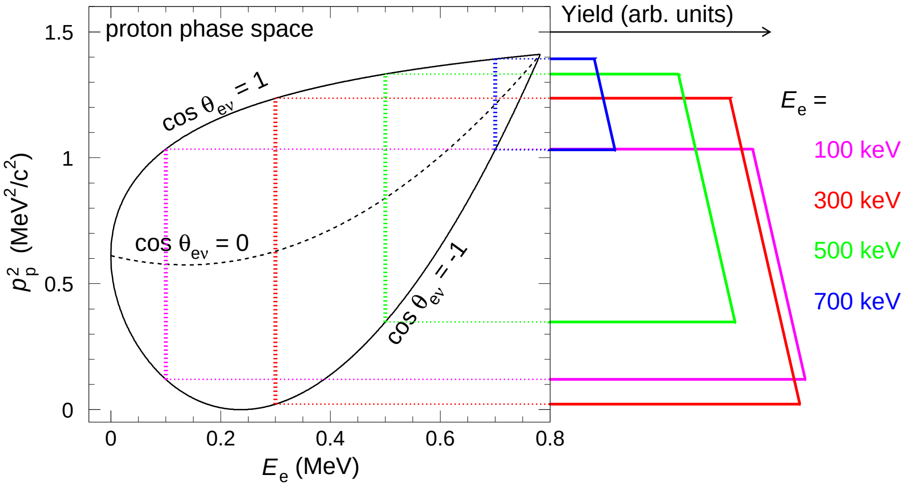
yields

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

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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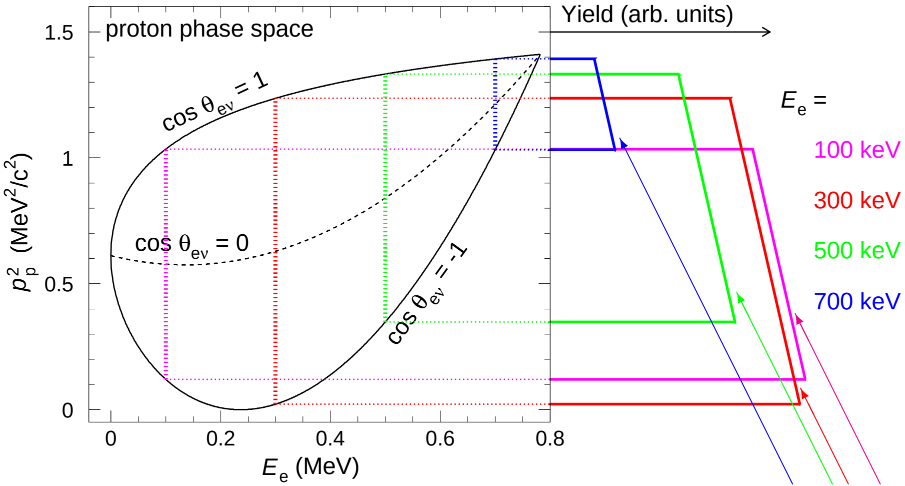

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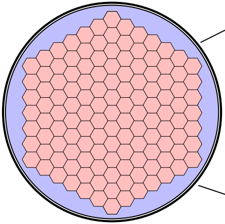
Slope $\propto$ **a**

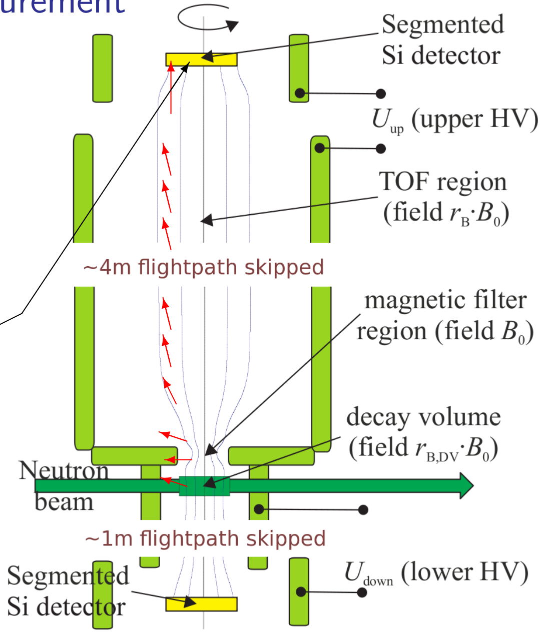
Numerous consistency checks are built-in!

Nab principles of measurement

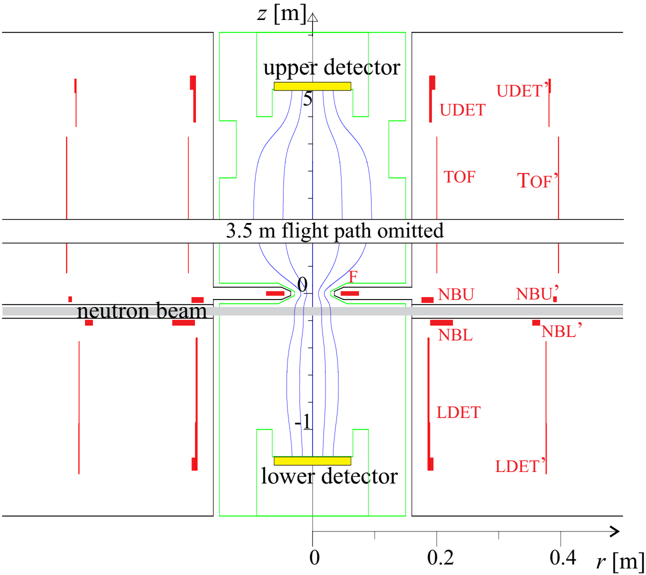
- Collect and detect both electrons and protons from neutron beta decay.
- Measure E_e and TOF_p and reconstruct decay kinematics
- Segmented Si det's:

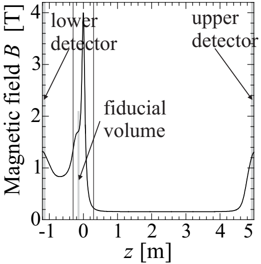


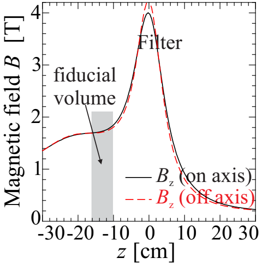
LANL/Micron development



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

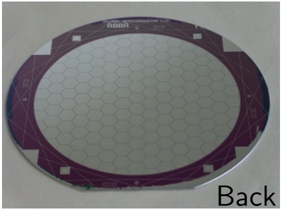


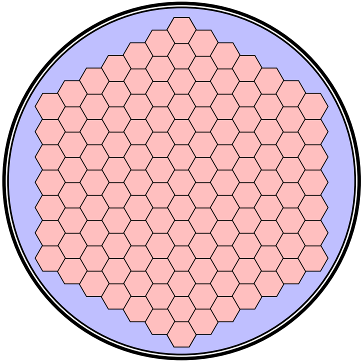




Nab Si detectors (LANL-Micron development)

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





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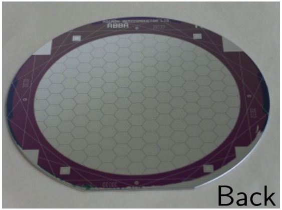

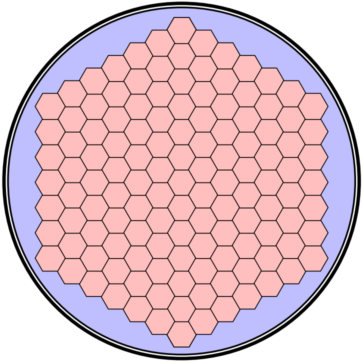

How well do they work?

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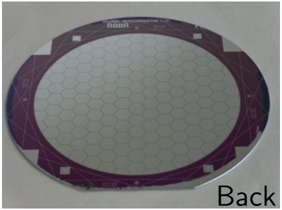
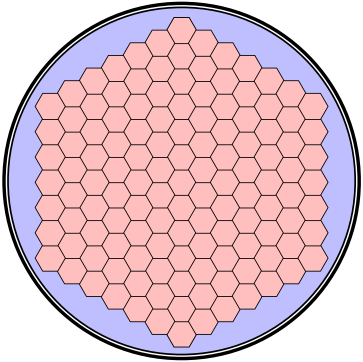
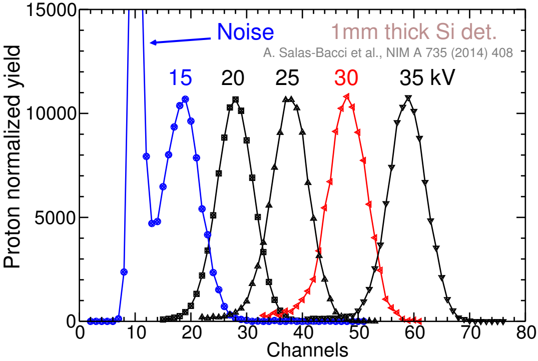
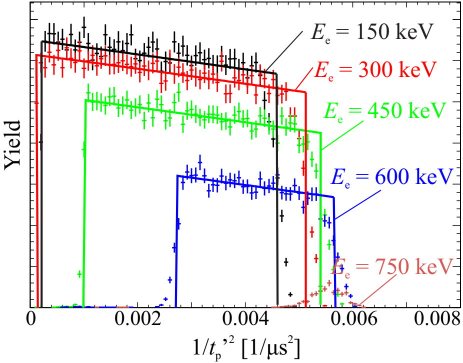






Analysis strategy (methods "A" and "B")



- Use edges to determine and verify shape of detection function $\Phi(p_p, 1/t_p)$;
- Use central part of $P_t(1/t_p^2)$ ($\sim$ 70%) to extract **a**.

A. parametrize edges and width of $\Phi(p_p, 1/t_p)$ by fitting; use central part of Φ ($\sim$ 70%) to extract **a** in a multiparameter fit, and

B. specify accessible parameters of Φ by direct measurement; $\Rightarrow$ treat **a**, $\mu = \overline{1/t_p^2}(p_p)$, and $\mathbf{N}_{\text{decays}}$ as free parameters in a two-step fit,

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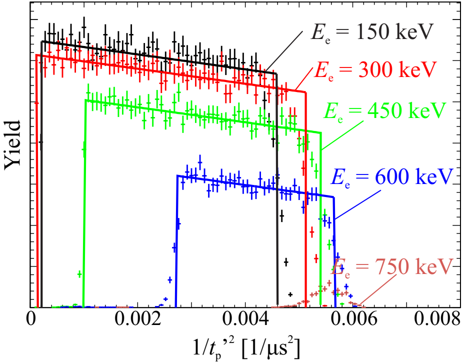

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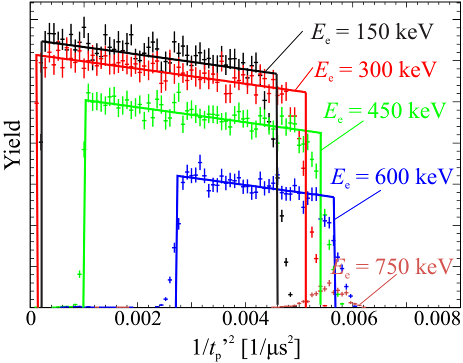

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Projected statistical uncertainties for **a** and **b**

Statistical uncertainties for **a**

$E_{\mathrm{e,min}}$	0	100 keV	100 keV	100 keV	300 keV
$t_{\mathrm{p,max}}$	–	–	40 μs	30 μs	40 μs
$\sigma_{\mathbf{a}}$	$2.4/\sqrt{N_u}$	$2.4/\sqrt{N_u}$	$2.6/\sqrt{N_u}$	$2.8/\sqrt{N_u}$	$3.1/\sqrt{N_u}$
$\sigma_{\mathbf{a}}{}^{\dagger}$	$2.6/\sqrt{N_u}$	$2.6/\sqrt{N_u}$	$2.8/\sqrt{N_u}$	$3.1/\sqrt{N_u}$	$3.5/\sqrt{N_u}$
$\sigma_{\mathbf{a}}{}^{\S}$	$3.3/\sqrt{N_u}$	$3.4/\sqrt{N_u}$	$3.6/\sqrt{N_u}$	$4.0/\sqrt{N_u}$	$4.6/\sqrt{N_u}$

† with $\mathbf{E}_{\mathrm{calib}}$ and $\mathbf{L}_{\mathrm{TOF}}$ variable; § using inner 75% of $\mathbf{p}_{\mathbf{p}}^{2}$ data.

[N_u . . . number of protons detected in upper detector.]

Statistical uncertainties for **b**

$E_{\mathrm{e,min}}$	0	100 keV	200 keV	300 keV
$\sigma_{\mathbf{b}}$	$7.5/\sqrt{N}$	$10.1/\sqrt{N}$	$15.6/\sqrt{N}$	$26.3/\sqrt{N}$
$\sigma_{\mathbf{b}}{}^{\dagger\dagger}$	$7.7/\sqrt{N}$	$10.3/\sqrt{N}$	$16.3/\sqrt{N}$	$27.7/\sqrt{N}$

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Nab systematic uncertainties: Method B

Experimental parameter		$(\Delta a/a)_{\text{SYST}}$
Magnetic field:	curvature at pinch	5×10^{-4}
	ratio $r_{\text{B}} = B_{\text{TOF}}/B_0$	2.5×10^{-4}
	ratio $r_{\text{B,DV}} = B_{\text{DV}}/B_0$	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
	unwanted beam polarization	small
Adiabaticity of proton motion		1×10^{-4}
Detector effects:	E_{e} calibration	(*)
	E_{e} resolution	5×10^{-4}
	Proton trigger efficiency	2.5×10^{-4}
Accidental coinc's	(will subtract out of time coinc)	small
Residual gas	ongoing parametric studies	small
Background	ongoing parametric studies	small
Overall sum		1×10^{-3}

(*) Free fit parameter

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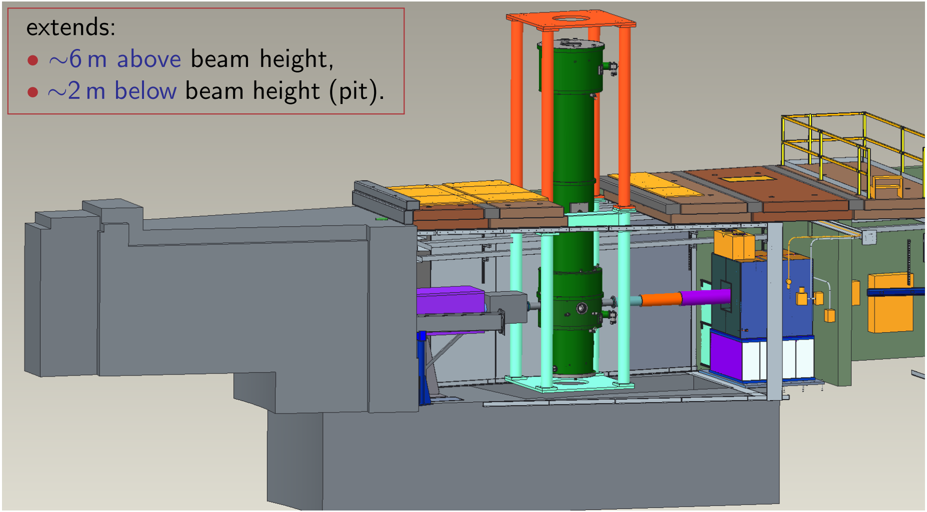
Nab apparatus in FnPB/SNS

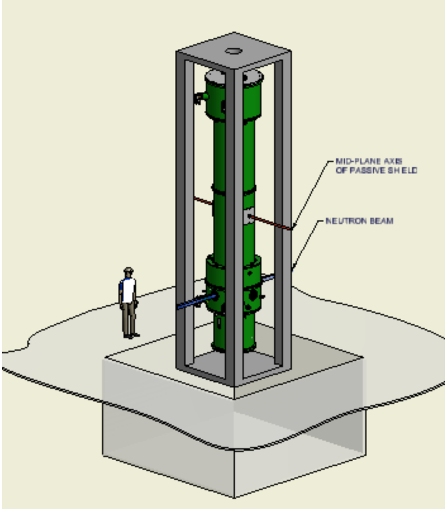


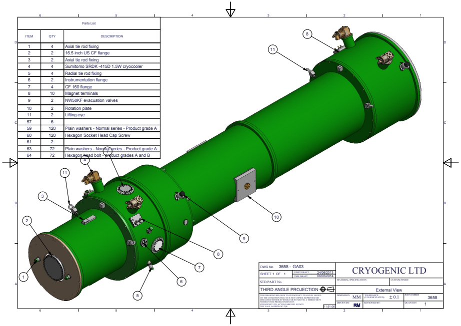
extends:

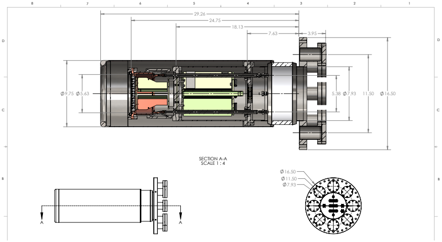
- ∼6 m above beam height,
- ∼2 m below beam height (pit).

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

Status: some drawings of the Nab apparatus







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

Active and recent Nab collaborators (as of Oct 2015)

R. Alarcon[a], S. Baeßler[b,c*], S. Balascuta[a§], L. Barrón Palos[d], N. Birge[e§], D. Borissenko[b§], J.D. Bowman[c†], L. Broussard[m,c], J. Byrne[f], J.R. Calarco[g], T. Chupp[h], V. Cianciolo[c], C. Crawford[i], J. DuBois[b§], W. Fan[b§], W. Farrar[b§], N. Fomin[e], E. Frlež[b], J. Fry[b], M.T. Gericke[j], F. Glück[k], G.L. Greene[c,e], R.K. Grzywacz[e], V. Gudkov[ℓ], C. Hendrus[h§], F.W. Hersman[g], T. Ito[m], H. Li[b§], M.F. Makela[m], J. Martin[n], M. Martinez[a§], P.L. McGaughey[m], C.D. McLaughlin[b§], P. Mueller[c], S.A. Page[j], D. van Petten[§], S.I. Penttilä[c‡], D. Počanić[b†], N. Roane[b§], K.P. Rykaczewski[c], A. Salas-Bacci[b], E.M. Scott[e§], A. Smith[b§], A. Sprow[i§], E. Stevens[b§], J. Wexler[o§], R. Whitehead[e§], W.S. Wilburn[m], A.R. Young[o].

[a]Arizona State U.	[b]U. of Virginia	[c]ORNL
[d]UNAM, Mexico	[e]U. of Tennessee	[f]U. of Sussex
[g]U. New Hampshire	[h]U. of Michigan	[i]U. of Kentucky
[j]U. of Manitoba	[k]Uni. Karlsruhe	[ℓ]U. of South Carolina
[m]LANL	[n]U. of Winnipeg	[o]N. Carolina State U.
[*]Project Manager	[†]Co-spokesmen	[‡]On-site Manager

[§]Nab students, or recent Nab students

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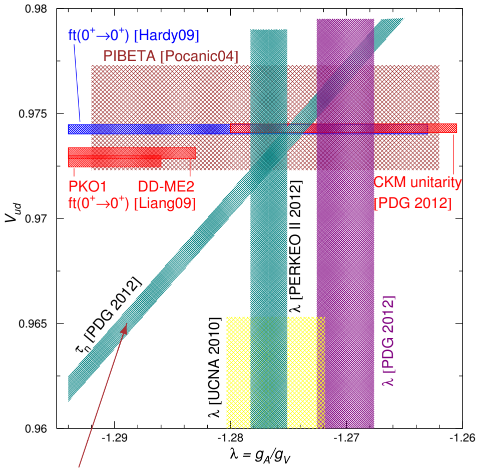
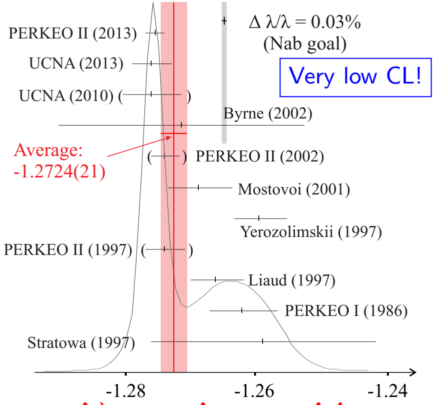
Current status of V_{ud} and λ, from n decay

... remains an unresolved mess:





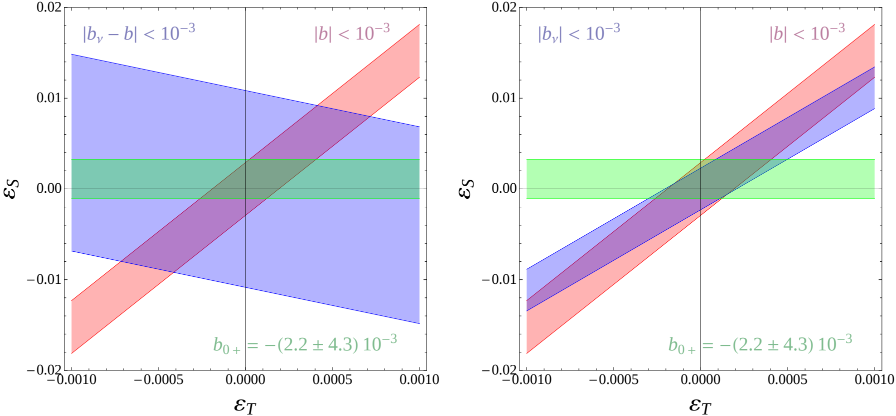
$\tau_n^{-1} \propto |V_{ud}|^2 |g_V|^2 (1 + 3|\lambda|^2)$

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

λ sensitivity to a, A is **similar**.

- Nab+abBA ⇒ several independent ∼ 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.