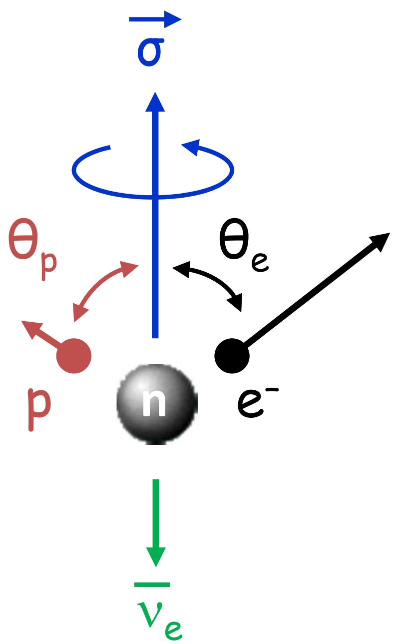
Neutron Decay Correlations

Brad Plaster, University of Kentucky



Recent (experimental) review articles:

S. Baessler, J.D. Bowman, S. Penttila, and D. Pocanic, J. Phys. G **41** (2014) 114003

A.R. Young et al., J. Phys. G **41** (2014) 114007

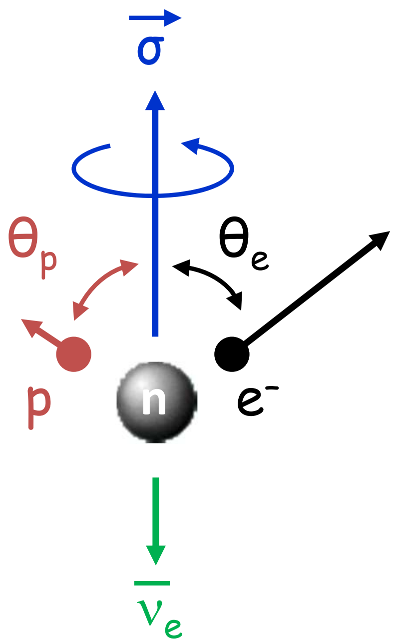
QCD for New Physics at the Precision Frontier
October 2, 2015

What can be measured ?

$$\frac{d\Gamma}{d\Omega_e d\Omega_\nu dE_e} \propto p_e E_e (E_0 - E_e)^2 \times \left[1 + a \frac{\vec{p}_e \cdot \vec{p}_\nu}{E_e E_\nu} + b \frac{m_e}{E_e} + \langle \vec{\sigma}_n \rangle \cdot \left(A \frac{\vec{p}_e}{E_e} + B \frac{\vec{p}_\nu}{E_\nu} + D \frac{\vec{p}_e \times \vec{p}_\nu}{E_e E_\nu} \right) \right]$$

Jackson, Treiman, and Wyld (1957)

$$B = B_0 + b_\nu \frac{m_e}{E_e}$$



Weak Interaction Physics

$a_0, A_0 \;\rightarrow\; g_A$

BSM Physics

Fierz Terms b, b_ν ; D

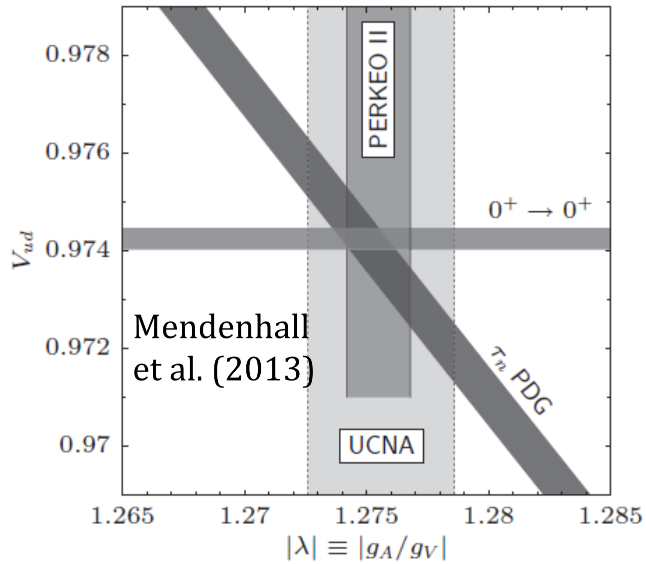
Final-State Polarization:
$R, N, \ldots \;\rightarrow$ BSM

Radiative Decay:
Triple Products $\rightarrow$ BSM

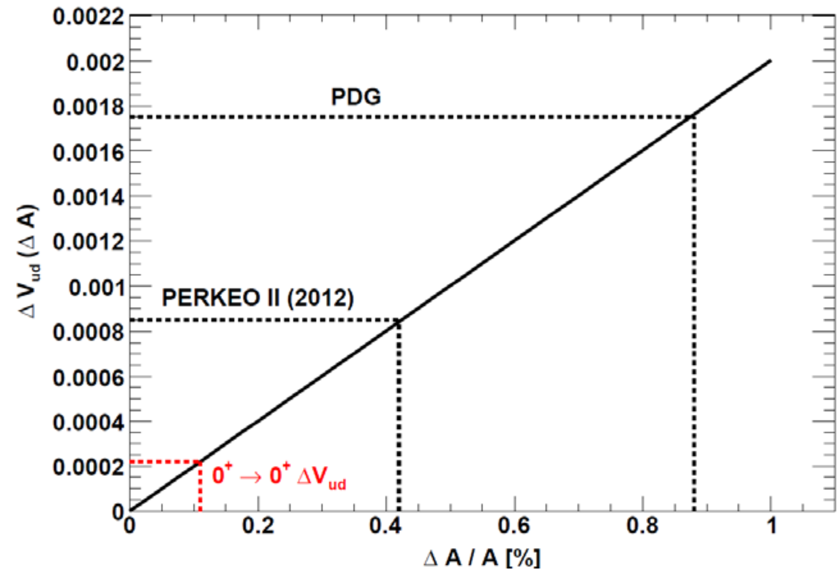
Precision Goals

$$|V_{ud}|^2 = \frac{4908.7(1.9)\ \text{sec}}{\tau_n(1+3g_A^2)}$$

Marciano & Sirlin (2006)
Czarnecki, Marciano, & Sirlin (2004)



Mendenhall et al. (2013)

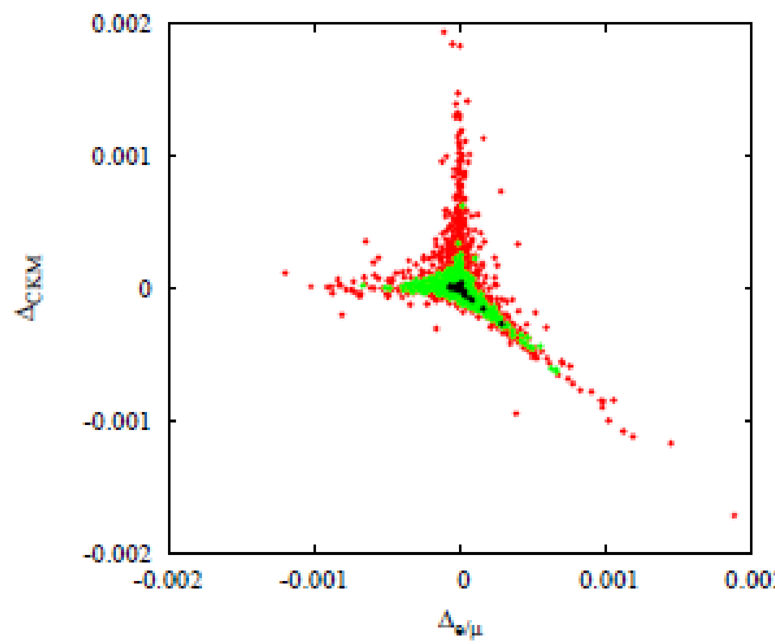


$$V_{ud}^{0^+\to 0^+} = 0.9742(2)^*$$

$$V_{ud}^{n} = 0.9758(5)_\tau(16)_{g_A}(2)_{RC}$$

$$\frac{|V_{ud}^{0^+\to 0^+}|^2}{|V_{ud}^{n\to pe\bar{\nu}}|^2} = 1 + b_{0^+}^{\text{BSM}}\frac{I_1(\tilde{x}_0)}{I_0(\tilde{x}_0)} - b_n^{\text{BSM}}\left(\frac{I_1(x_0)}{I_0(x_0)} - \frac{6\lambda^2}{1+3\lambda^2}c\right)$$

Bhattacharya et al. (2012)

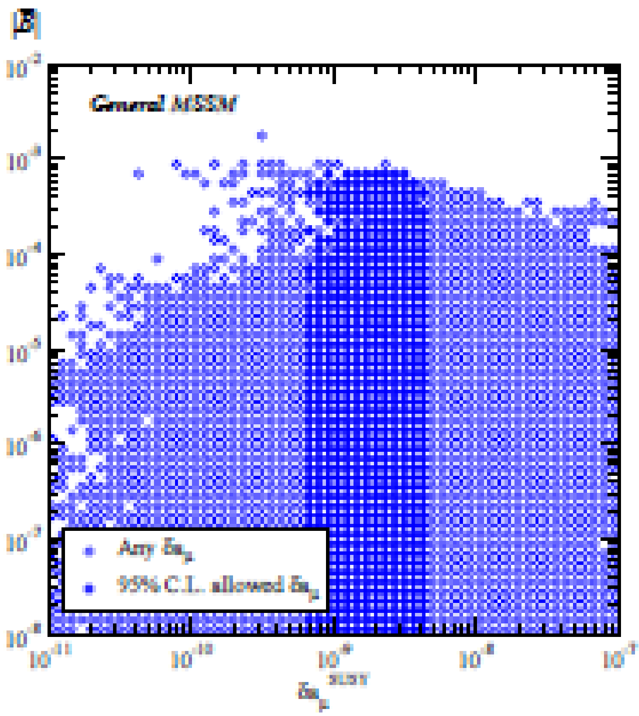


Bauman, Erler, and Ramsey-Musolf (2013)

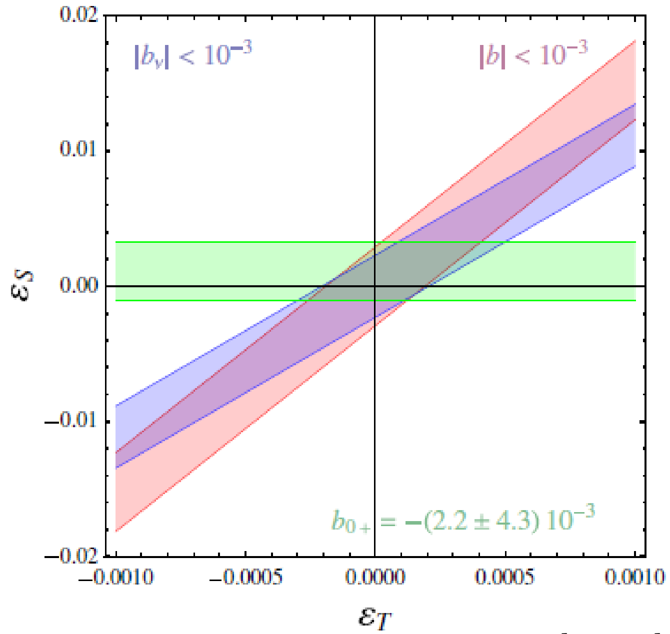
$$R_{e/\mu} = \frac{\Gamma[\pi^+ \to e^+\nu(\gamma)]}{\Gamma[\pi^+ \to \mu^+\nu(\gamma)]}$$

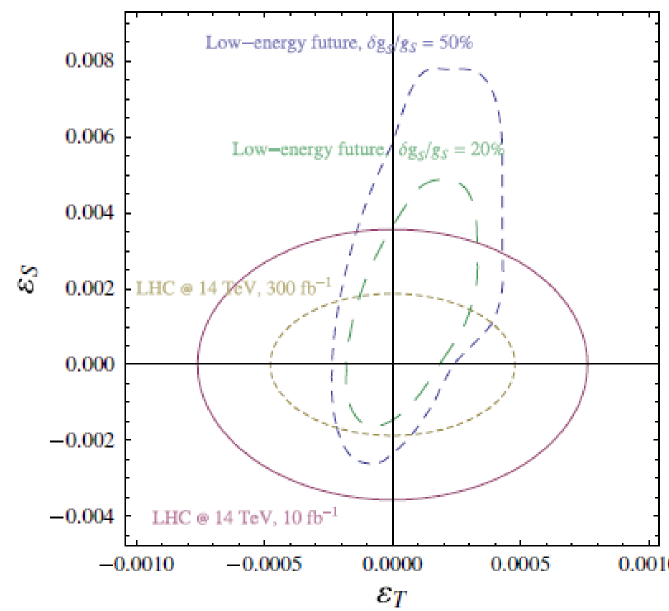
* Updated $0^+ \to 0^+$ V_{ud} : J.C. Hardy and I.S. Towner, PRC 91, 025501 (2015) 0.97417(21)

Precision Goals



Profumo, Ramsey-Musolf,
and Tulin (2007)

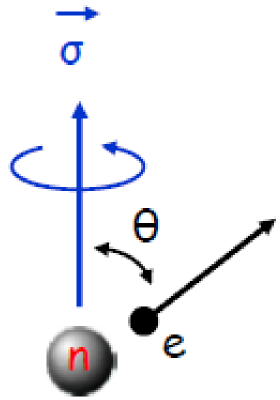




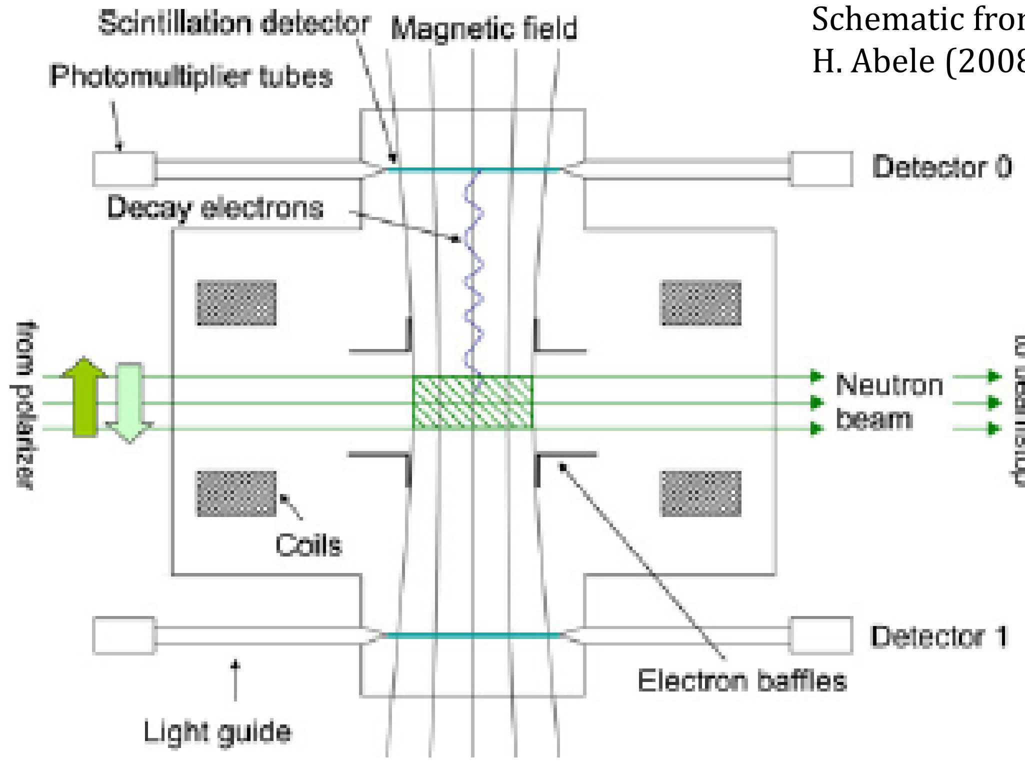
Bhattacharya et al. (2012)

Overwhelming Message:
Aim for < 10^{-3} precision

"*A*" Correlation: $\vec{\sigma}_n \cdot \vec{p}_e$



Schematic from:
H. Abele (2008)

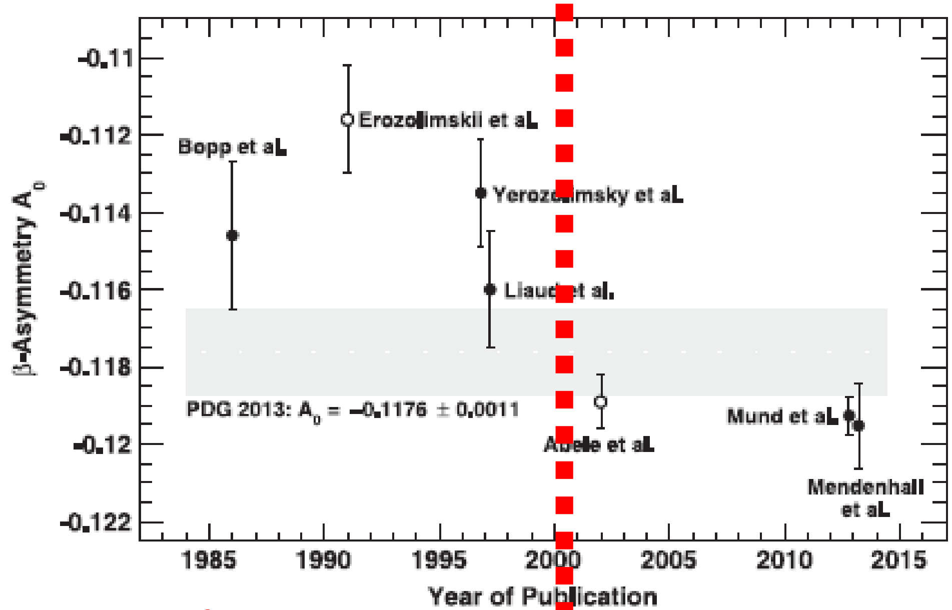


$$A_0 = -2\frac{|g_A|(|g_A|-1)}{1+3g_A^2}$$

$$A_{\text{exp}} \equiv \frac{N(\cos\theta_e > 0) - N(\cos\theta_e < 0)}{N(\cos\theta_e > 0) + N(\cos\theta_e < 0)} = \beta\langle\cos\theta\rangle \frac{A}{1 + b_{\text{BSM}}\frac{m_e}{E_e}} P_n$$

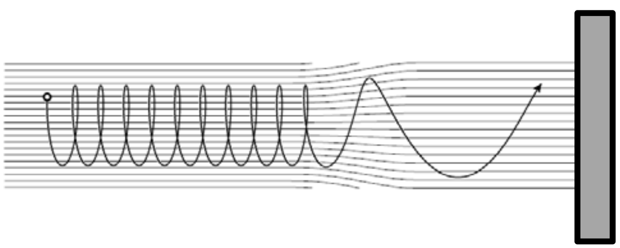
$$= \frac{1}{2}\beta \frac{A}{1 + b_{\text{BSM}}\frac{m_e}{E_e}} P_n$$

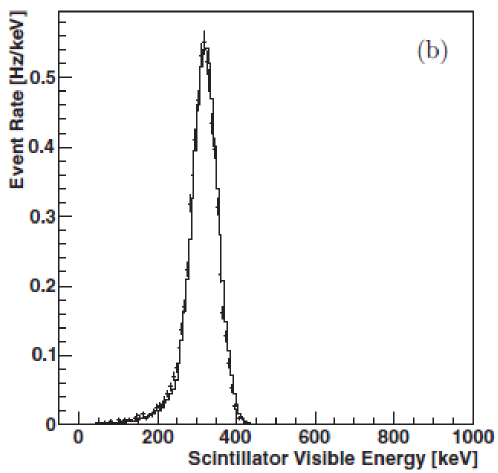
“*A*” Correlation: $\vec{\sigma}_n \cdot \vec{\mathbf{p}}_e$

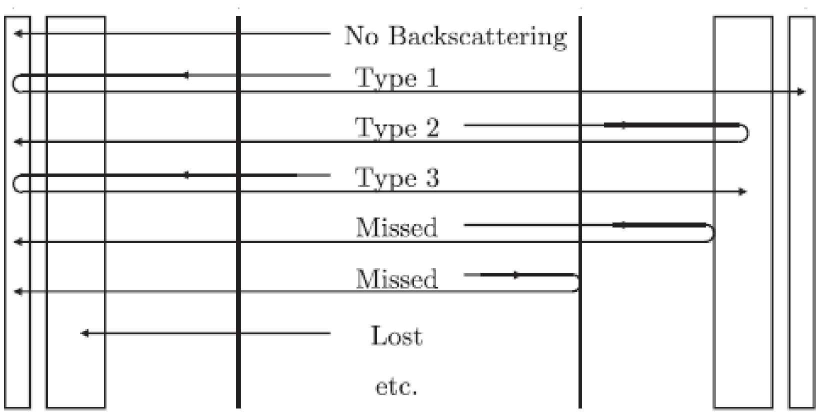


Systematic Corrections ~3 – 23 %

Systematic Corrections < 1%



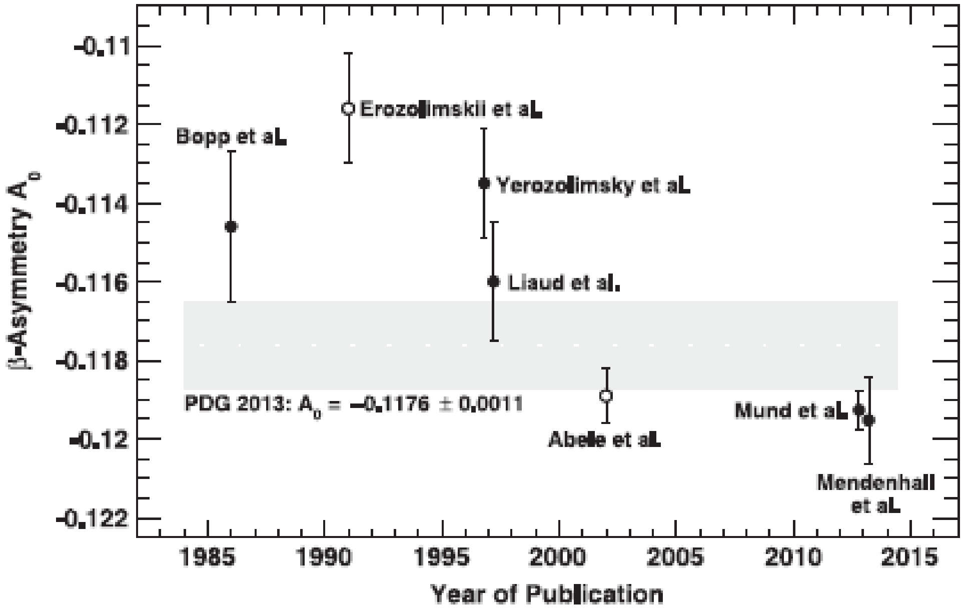




BP et al., PRC 86, 055501 (2012)
M.P. Mendenhall et al., PRC 87, 032501 (2013)

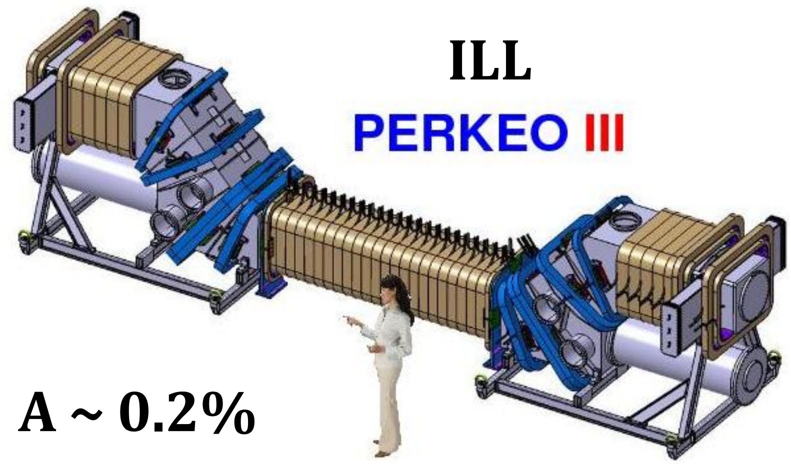
M.P. Mendenhall, Ph.D. thesis (2014)

“A” Correlation: $\vec{\sigma}_n \cdot \vec{p}_e$



ILL

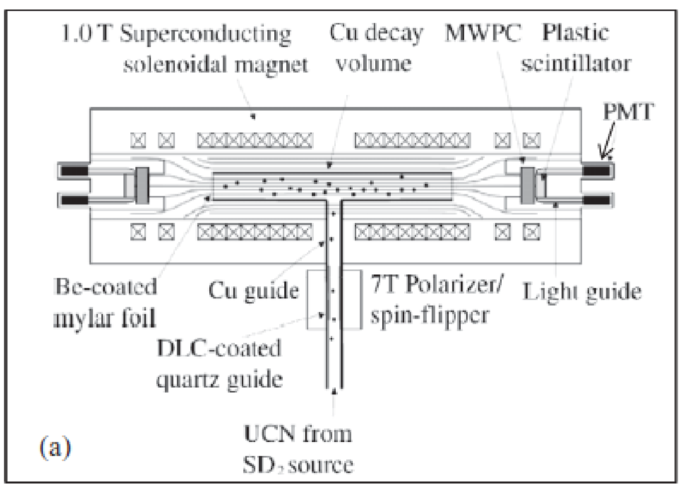
PERKEO III

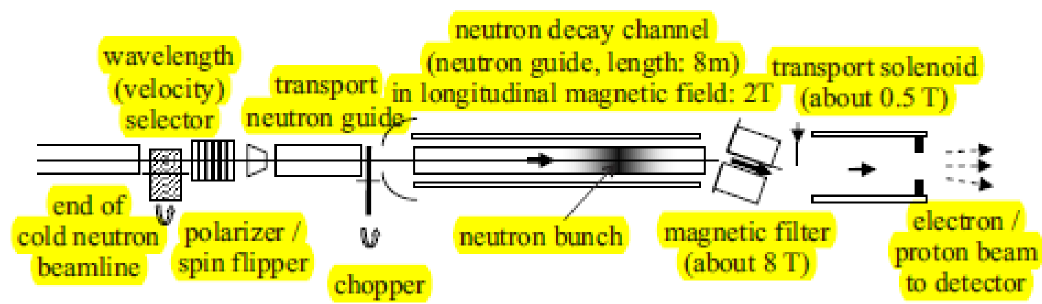


A ~ 0.2%

UCNA
LANL

A < 0.6%





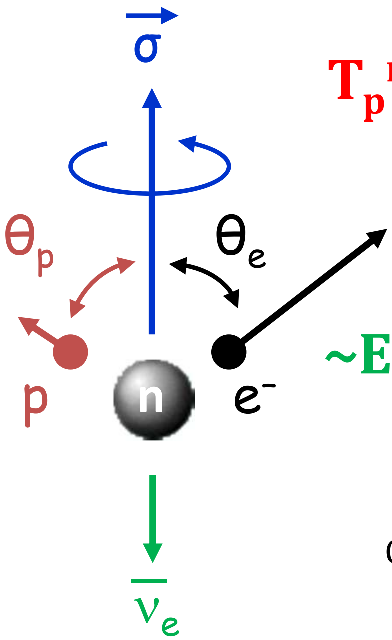
PERC (FRM-II, Munich)

A, B, a, b, … < 0.1%

B. Maerkisch, arXiv:1410.4220
D. Dubbers et al., NIM A 596, 238 (2008)

Baessler, Bowman, Penttila, and Pocanic (2014)

"*a*" Correlation: $\vec{p}_e \cdot \vec{p}_\nu$



$T_p^{max} \sim$ 750 eV

~Equal sensitivity as 'A' to g_A

'*a*' vs. 'A' recoil terms:
Gardner & Zhang (2001)

e-$\bar{\nu}_e$ ANGULAR CORRELATION COEFFICIENT *a*

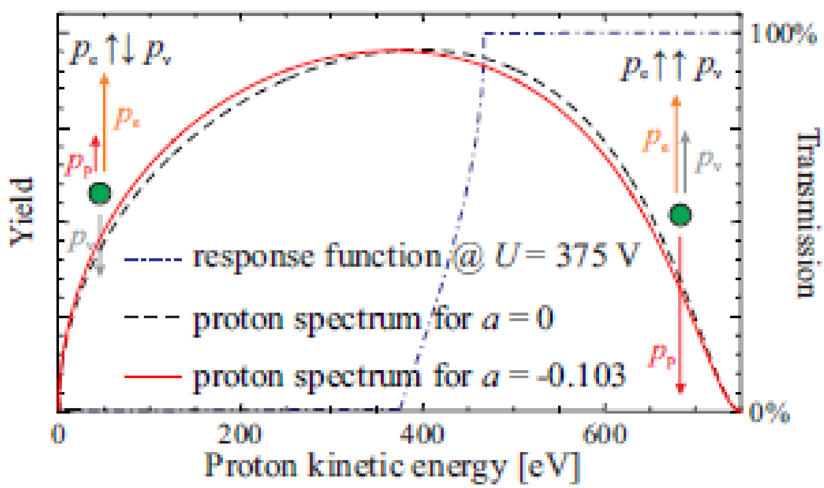
For a review of past experiments and plans for future measurements of the *a* parameter, see WIETFELDT 05. In the Standard Model, *a* is related to $\lambda \equiv g_A/g_V$ by $a = (1 - \lambda^2) / (1 + 3\lambda^2)$; this assumes that g_A and g_V are real.

VALUE	DOCUMENT ID		TECN	COMMENT
−0.103 ±0.004 OUR AVERAGE				
−0.1054±0.0055	BYRNE	02	SPEC	Proton recoil spectrum
−0.1017±0.0051	STRATOWA	78	CNTR	Proton recoil spectrum
−0.091 ±0.039	GRIGOREV	68	SPEC	Proton recoil spectrum
• • • We do not use the following data for averages, fits, limits, etc. • • •				
−0.1045±0.0014	[53] MOSTOVOI	01	CNTR	Inferred

[53] MOSTOVOI 01 calculates this from its measurement of $\lambda = g_A/g_V$ above.

aSPECT:

2013: few %
PERC: 0.3%



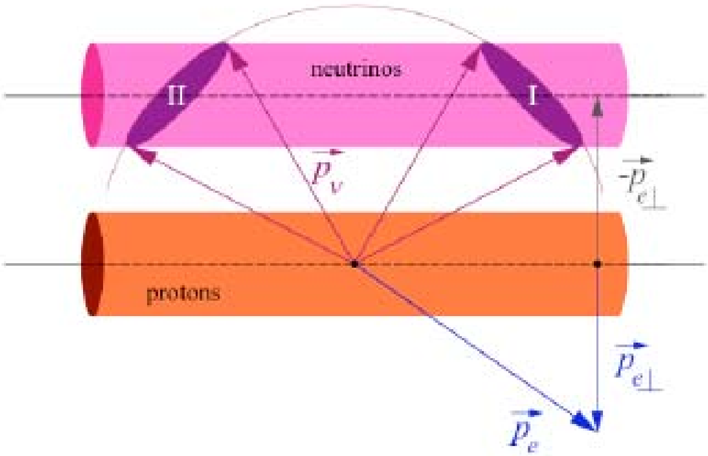
Kinematics:

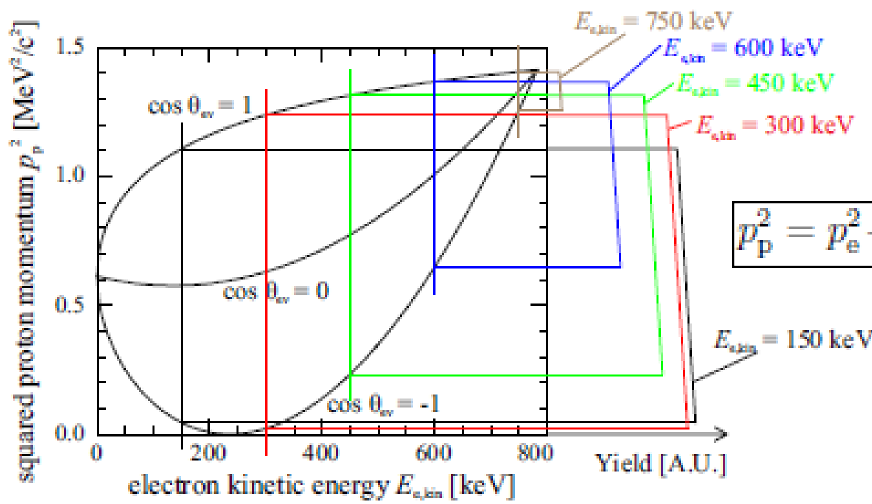
$$\vec{p}_p = -(\vec{p}_e + \vec{p}_\nu)$$

Proton TOF ~ $1/p_p$

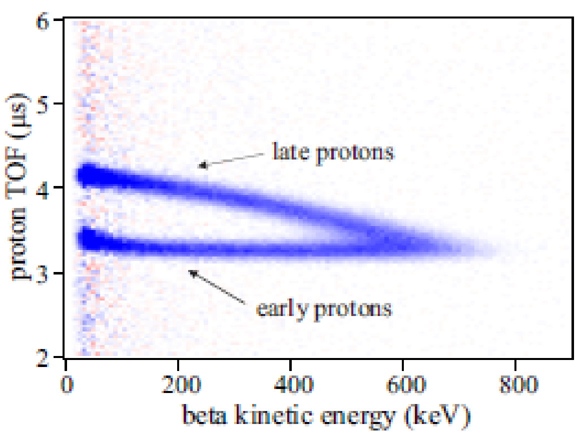
Baessler, Bowman, Penttila, and Pocanic (2014)
G. Konrad et al. (2009)

"a" Correlation: $\vec{p}_e \cdot \vec{p}_\nu$ $\cos\theta_{e\nu}$

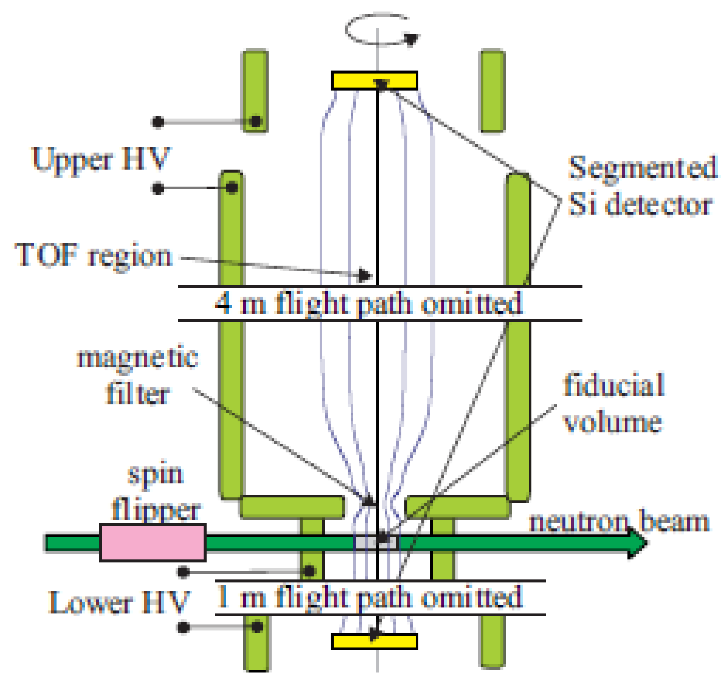




$$p_p^2 = p_e^2 + p_\nu^2 + 2 p_e p_\nu \cos\theta_{e\nu}$$



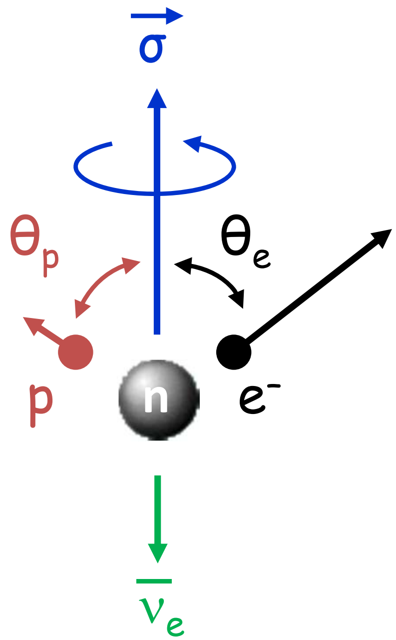
aCORN at NIST:
2013: ~3% (stat), ~2-3% (syst)
Current Run: ~1%



Nab at SNS:
Construction
a ~ 0.2%

Baessler, Bowman, Penttila, and Pocanic (2014)
F. Wietfeldt et al. (2015)

"B" Correlation and Fierz Term b_ν



$$\vec{\sigma} \cdot \vec{p}_\nu$$

$$B = B_0 + b_\nu \frac{m_e}{E_e}$$

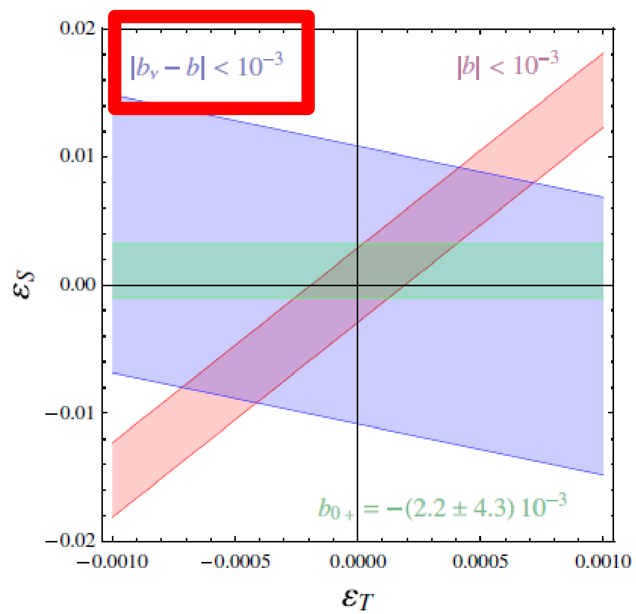
$$B_{\exp}(E_e) = \frac{Q_{--}(E_e) - Q_{++}(E_e)}{Q_{--}(E_e) + Q_{++}(E_e)}$$

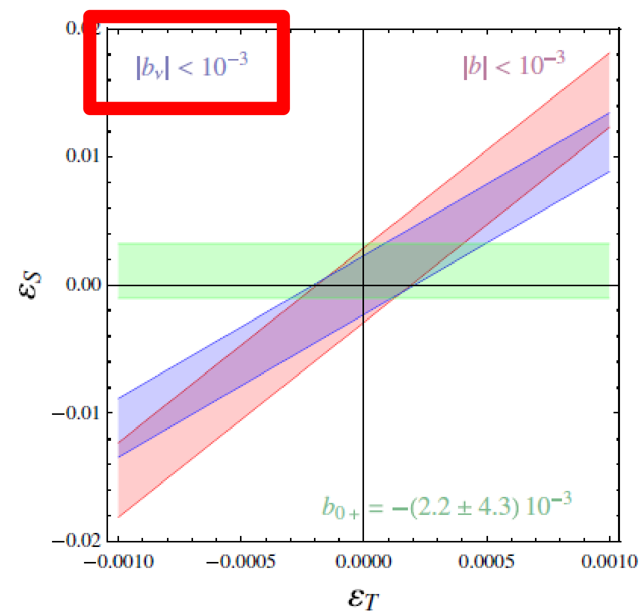
$$\propto B_0 + \frac{m_e}{E_e}\left[\frac{1+3\lambda^2}{2\lambda(1+\lambda)} b_\nu - b\right]$$

$$\approx b_\nu - b$$

$$b^{\rm BSM} = \frac{2}{1+3\lambda^2}[g_S\epsilon_S - 12\lambda g_T\epsilon_T]$$
$$\approx 0.34 g_S\epsilon_S - 5.22 g_T\epsilon_T,$$
$$b_\nu^{\rm BSM} = \frac{2}{1+3\lambda^2}[g_S\epsilon_S\lambda - 4g_T\epsilon_T(1+2\lambda)]$$
$$\approx 0.44 g_S\epsilon_S - 4.85 g_T\epsilon_T.$$

Bhattacharya et al. (2012)



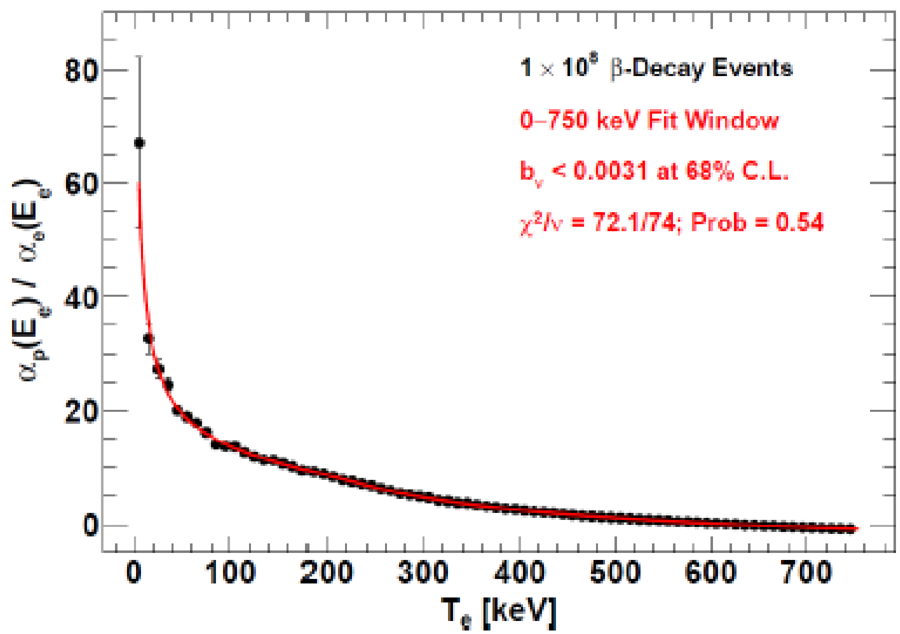


"B" Correlation and Fierz Term b_ν

Measure $\dfrac{\text{proton asymmetry}}{\text{electron asymmetry}}$

BP, Sjue, Wexler, and Young (in prep)

Differential Analysis:



Integral Analysis:

$$\langle \alpha_p \rangle = \frac{\int dE_e\, w_s(E_e)\,(Q^p_-) - \int dE_e\, w_s(E_e)\,(Q^p_+)}{\int dE_e\, w_s(E_e)\,(Q^p_-) + \int dE_e\, w_s(E_e)\,(Q^p_+)}$$

$$\langle \alpha_e \rangle = \frac{\int dE_e\, w_s(E_e)\,(Q^e_-) - \int dE_e\, w_s(E_e)\,(Q^e_+)}{\int dE_e\, w_s(E_e)\,(Q^e_-) + \int dE_e\, w_s(E_e)\,(Q^e_+)}$$

$\sim 0.3\sigma$ sensitivity to $b_\nu = 10^{-3}$
with $N = 1 \times 10^8$

Additional advantage: removes leading order dependence on polarization and detector efficiency (Mostovoi et al, Phys. Atomic Nucl. 64, 1955 (2001)).**– need to integrate with other e-p coincidence and spectrum measurements for best sensitivity!**

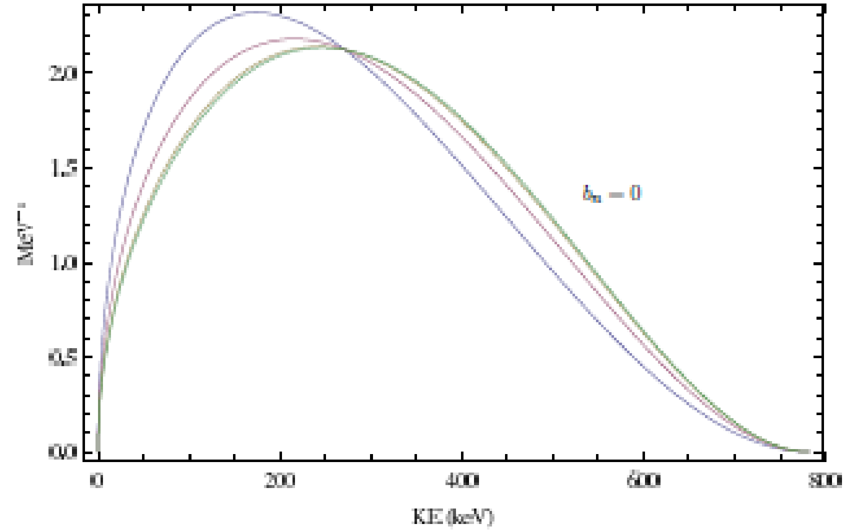
Fierz Term *b*

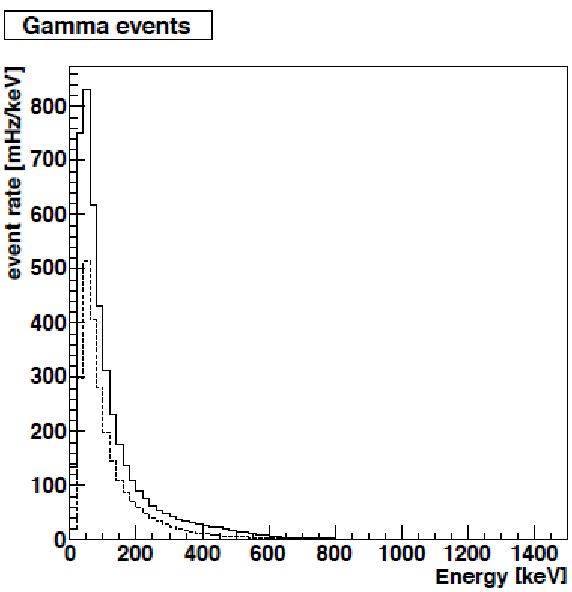
$$\frac{d\Gamma}{d\Omega_e d\Omega_\nu dE_e} \propto p_e E_e (E_0 - E_e)^2 \times \left[1 + a\frac{\vec{p}_e \cdot \vec{p}_\nu}{E_e E_\nu} + b\frac{m_e}{E_e} + \right.$$

Nab at SNS: $\sim 10^{-3}$

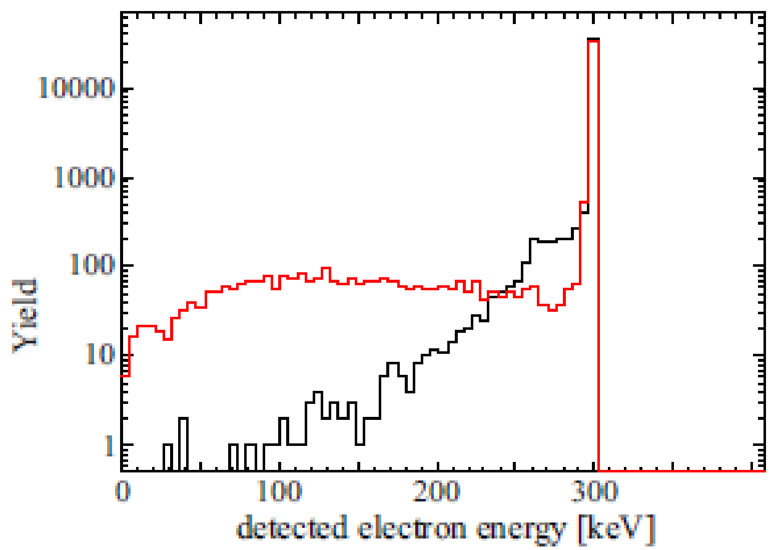
PERC: $< 10^{-3}$

K.P. Hickerson, Ph.D. thesis (2013)





M.P. Mendenhall, Ph.D. thesis (2014)



Baessler, Bowman, Penttila, and Pocanic (2014)

Global Fit – Theory Uncertainties

$$\langle p(p')|\bar{u}\gamma^\mu d|n(p)\rangle \equiv \bar{u}_p(p')\left[f_1(q^2)\gamma^\mu - i\frac{f_2(q^2)}{M}\sigma^{\mu\nu}q_\nu + \frac{f_3(q^2)}{M}q^\mu\right]u_n(p)\,,$$

$$\langle p(p')|\bar{u}\gamma^\mu\gamma_5 d|n(p)\rangle \equiv \bar{u}_p(p')\left[g_1(q^2)\gamma^\mu\gamma_5 - i\frac{g_2(q^2)}{M}\sigma^{\mu\nu}\gamma_5 q_\nu + \dots\right]u_n(p)\,,$$

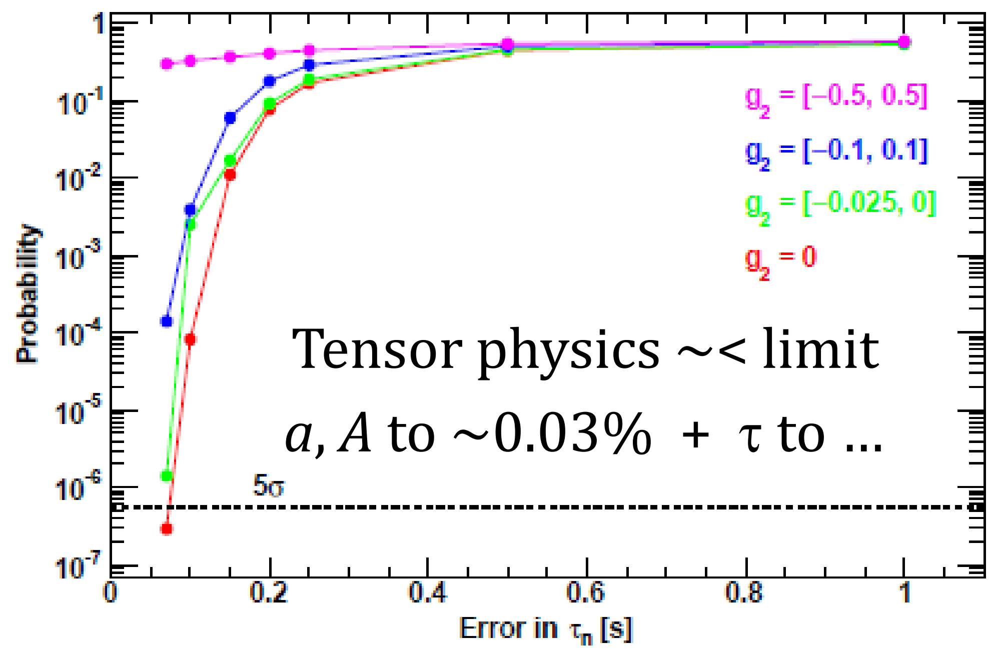
$$a_{\rm exp} = \frac{1}{2}\beta\frac{a_1}{1 + b_{\rm BSM}\frac{m_e}{E_e} + \frac{1}{3}a_2\beta^2}, \qquad A_{\rm exp} = \frac{1}{2}\beta\frac{A}{1 + b_{\rm BSM}\frac{m_e}{E_e}}.$$

"Rfit" Scheme:

$$\chi^2 = \sum_{i=1}^{N_{\rm exp}}\left(\frac{x_{{\rm exp},i} - x_{\rm theo,i}}{\sigma_{{\rm exp},i}}\right)^2 - 2\ln\mathcal{L}_{\rm calc}(\{y_{\rm calc}\}),$$

where

$$-2\ln\mathcal{L}_{\rm calc}(\{y_{\rm calc}\}) \equiv \begin{cases} 0, & \forall\, y_{{\rm calc},i} \in [y_{{\rm calc},i} \pm \delta y_{{\rm calc},i}] \\ \infty, & \text{otherwise} \end{cases}$$



Tensor physics ~< limit

a, A to ~0.03% + τ to ...

Summary

Exciting time for neutron decay measurements of angular correlations

Should soon realize new experiments with $\sim 10^{-3}$ precision

I acknowledge support under DOE Awards DE-FG02-08ER41557 and DE-SC0014622

Extra

Second-Class Currents (SCC): f_3 , g_2

Poorly known recoil-order matrix elements can mimic or obscure Scalar and Tensor interactions !

Universality of g_V in $0^+ \to 0^+$

$$m_e f_3 / M g_V \; = \; -0.0011(13)$$

$$|f_3| < \mathcal{O}(1)$$

J.C. Hardy and I.S. Towner, PRC 79, 055502 (2009)

Mirror Transitions

Comparison of *ft* Values

$$|g_2| < 0.2$$

D.H. Wilkinson, EPJA 7, 307 (2000)

Lattice QCD*: $\Xi^0 \to \Sigma^+ \ell \nu$

$$f_3/g_V = 0.14(9)$$

$$g_2/g_A = 0.68(18)$$

suppressed by $m_d/m_s \sim 0.05$

S. Sasaki and T. Yamazaki, PRD 79, 074508 (2009)

QCD Sum Rule Techniques

$$g_2/g_A = -0.0152(53)$$

H. Shiomi, Nucl. Phys. A 603, 281 (1996)

* Tension with B.R. Holstein, PRD 26, 698 (1982) : $f_3/f_1 = g_2/g_1$

Sensitivity to b_ν

1×10^8 Events