Tests of Standard Model limits in the light flavor sector

Dinko Počanić

University of Virginia

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- Rather than giving a comprehensive review, this talk will focus on a small subset: π, μ and n decays to introduce and illustrate the field.

Outline

Overview of π, μ decays and recent experiments

Radiative muon decay, $\mu^+ \to \mathrm{e}^+\nu\bar{\nu}\gamma$ (new result)

The $\pi_{\mathrm{e}2}$ decay, $\pi^+ \to \mathrm{e}^+\nu_\mathrm{e}$ (current work)

Correlations in neutron beta decay (experiment being built)

Summary

Known and measured pion and muon decays

	Decay	BR		
$\pi^+ \to$	$\mu^+\nu$	0.9998770 (4)	($\pi_{\mu 2}$)	
	$\mu^+\nu\gamma$	$2.00\,(25) \times 10^{-4}$	($\pi_{\mu 2\gamma}$)	
	$e^+\nu$	$1.230\,(4) \times 10^{-4}$	(π_{e2})	✓
	$e^+\nu\gamma$	$7.39(5) \times 10^{-7}$	($\pi_{e2\gamma}$)	✓
	$\pi^0 e^+\nu$	$1.036\,(6) \times 10^{-8}$	(π_{e3}, π_β)	✓
	$e^+\nu e^+e^-$	$3.2\,(5) \times 10^{-9}$	(π_{e2ee})	
$\pi^0 \to$	$\gamma\gamma$	0.98798 (32) ✓		
	$e^+e^-\gamma$	$1.198\,(32) \times 10^{-2}$	(Dalitz)	
	$e^+e^-e^+e^-$	$3.14\,(30) \times 10^{-5}$		
	e^+e^-	$6.2\,(5) \times 10^{-8}$		
$\mu^+ \to$	$e^+\nu\bar{\nu}$	~ 1.0 ✓	(Michel)	
	$e^+\nu\bar{\nu}\gamma$	0.014 (4) ✓	(RMD)	
	$e^+\nu\bar{\nu}e^+e^-$	$3.4\,(4) \times 10^{-5}$		

Recent measurements of π, μ allowed decay

- $\pi^+ \to \pi^0 e^+ \nu_e$ .... PIBETA ('99–'01)
  - SM checks related to CKM unitarity
- $\pi^+ \to e^+ \nu_e \gamma$(or e^+e^-) .... PIBETA ('99–'04), PEN ('06–'10)
  - F_A/F_V, π polarizability (χPT calibration)
  - tensor coupling besides $V - A$ (?)
- $\mu^+ \to e^+ \nu_e \bar{\nu}_\mu$ .... TWIST ('03–'04)
  - departures from $V - A$ in $\mathcal{L}_{weak}$
- $\mu^+ \to e^+ \nu_e \bar{\nu}_\mu \gamma$(or e^+e^-) ....PIBETA ('04), PEN ('06–'10)
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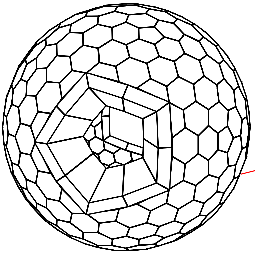
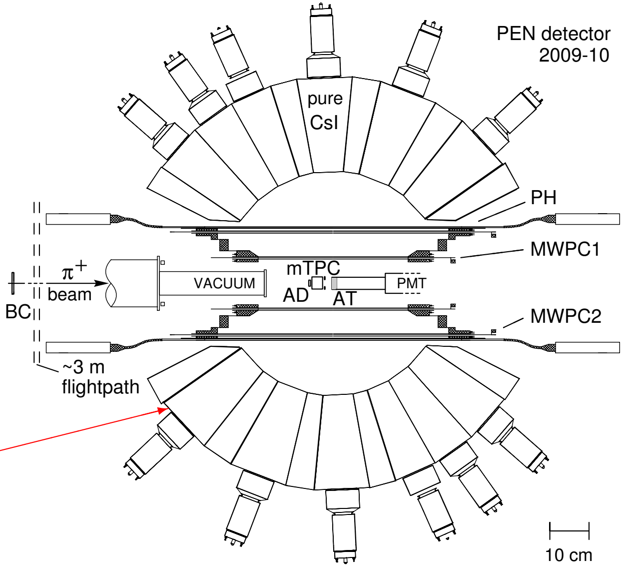
- $\pi^+ \to e^+ \nu_e$ .... { PEN ('06–'10), PiENu ('06–) }
  - e-μ universality
  - P, S coupling besides $V - A$
  - ν sector anomalies, Majoron searches, m_{h+}, PS l-q's, V l-q's, ...
  - search for signs of SUSY (MSSM)

The PIBETA/PEN apparatus

- stopped π^+ beam
- active target counter
- 240-detector, spherical pure CsI calorimeter
- central tracking
- beam tracking
- digitized waveforms
- stable temp./humidity





Prior results

- Pion beta decay: $\pi^+ \to \pi^0 e^+ \nu_e$
- Radiative pion decay: $\pi^+ \to e^+ \nu_e \gamma$

(the PIBETA experiment)

Quark-Lepton (Cabibbo) Universality

The basic weak-interaction **V-A** form (e.g., μ decay):

$$\mathcal{M} \propto \langle e|l^\alpha|\nu_e\rangle \to \bar{u}_e\gamma^\alpha(1-\gamma_5)u_\nu$$

is replicated in hadronic weak decays

$$\mathcal{M} \propto \langle p|h^\alpha|n\rangle \to \bar{u}_p\gamma^\alpha(G_V - G_A\gamma_5)u_n \quad \text{with} \quad G_{V,A} \simeq 1\ .$$

Departure from $G_V = 1$ (**CVC**) comes from weak quark (Cabibbo) mixing:
$G_V = G_\mu \cos\theta_C (= G_\mu V_{ud}) \quad \cos\theta_C \simeq 0.97$

3 **q** generations lead to the Cabibbo-Kobayashi-Maskawa (CKM) matrix (1973):
$$\begin{pmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{pmatrix}$$

CKM unitarity cond.: $\Delta V^2 = 1 - (|V_{ud}|^2 + |V_{us}|^2 + |V_{ub}|^2) \stackrel{?}{=} 0$,
stringently tests the SM.

Until 2004 appeared violated by $\sim 3\sigma$!

PIBETA result for $\pi^+ \to \pi^0 e^+ \nu$ (π_β) decay [PRL **93**, 181803 (2004)]

$$B_{\pi\beta}^{\text{exp-t}} = [1.040 \pm 0.004\,(\text{stat}) \pm 0.004\,(\text{syst})] \times 10^{-8}\,,$$

$$B_{\pi\beta}^{\text{exp-e}} = [1.036 \pm 0.004\,(\text{stat}) \pm 0.004\,(\text{syst}) \pm 0.003\,(\pi_{e2})] \times 10^{-8}\,,$$

McFarlane et al. [PRD 1985]: $B = (1.026 \pm 0.039) \times 10^{-8}$

SM Prediction (PDG):

$B = \quad 1.038 - 1.041 \times 10^{-8} \quad$ (90% C.L.)

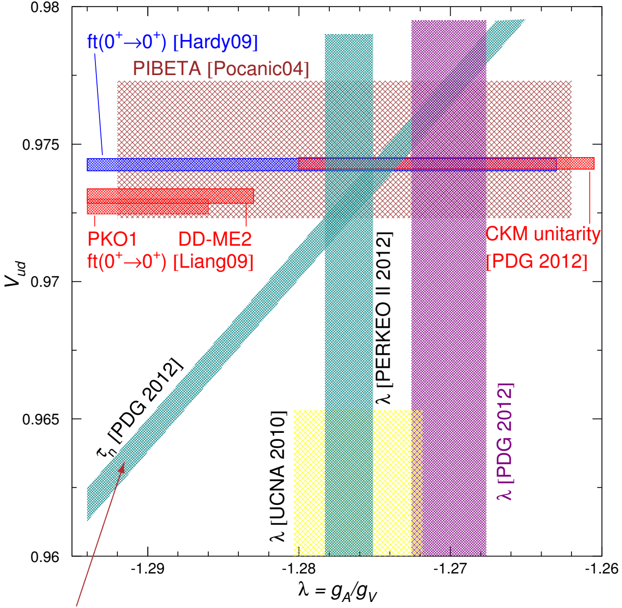
$\quad\quad (1.005 - 1.007 \times 10^{-8} \quad$ excl. rad. corr.)

$\Rightarrow$ Most sensitive test of CVC/radiative corr. in a meson to date!

PDG 2012: $V_{ud} = 0.97425(22)$

PIBETA: $V_{ud} = 0.9748(25)$ or $V_{ud} = 0.9728(30)$.

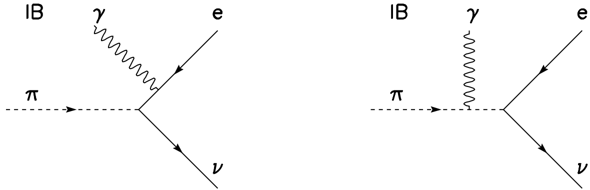
Current status of V_{ud}:



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

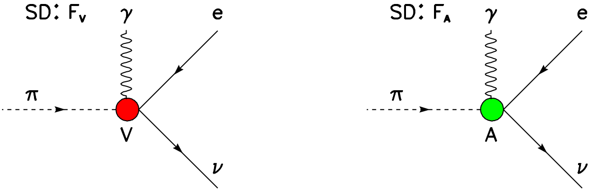
Radiative pion decay
$\pi^+ \to e^+\nu\gamma$ (RPD):

QED IB terms:

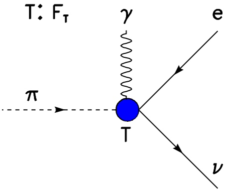


SM

and SD V, A terms:



A tensor interaction, too?



Exchange of S=0 leptoquarks

P Herczeg, PRD 49 (1994) 247

Summary of PIBETA results on $\pi \to e\nu\gamma$ [PRL **103**, 051802 (2009)]

$\mathbf{F_V = 0.0258 \pm 0.0017}$	$(\mathbf{14\times})$
$\mathbf{F_A = 0.0119 \pm 0.0001}^{\text{exp}}_{(\mathrm{F_V^{CVC}})}$	$(\mathbf{16\times})$
$\mathbf{a = 0.10 \pm 0.06}$ ($\mathbf{q^2}$ dep of $\mathbf{F_V}$)	(∞)
$-5.2 \times 10^{-4} < F_T < 4.0 \times 10^{-4}$	90 % C.L.

$\mathbf{B_{\pi_{e2\gamma}}(E_\gamma > 10\,\text{MeV}, \theta_{e\gamma} > 40^\circ) = 73.86(54) \times 10^{-8}}$ $(\mathbf{17\times})$

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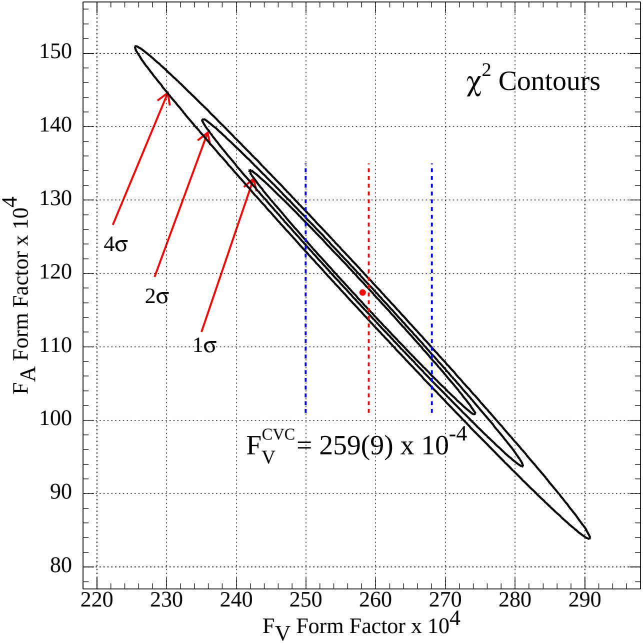
At L.O. $(l_9 + l_{10})$, F_V is related to pion polarizability and π^0 lifetime

$$\alpha_E^{LO} = -\beta_M^{LO} = (2.783 \pm 0.023_{exp}) \times 10^{-4}\ \text{fm}^3$$

$$\tau_{\pi^0} = (8.5 \pm 1.1) \times 10^{-17}\,\text{s}$$

- current PDG avg: 8.52 (12)
- PrimEx PRL '10: 8.32 (23)



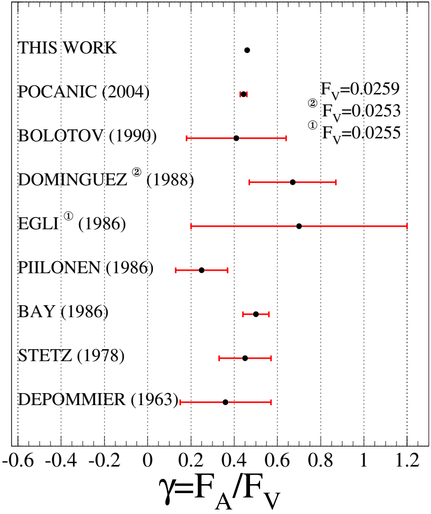
Best values of pion form factor parameters:

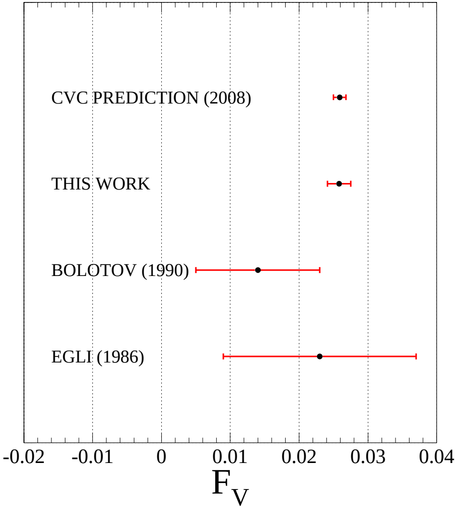
Combined analysis of 1999-2001 and 2004 data sets

[PRL **103**, 051802 (2009)]

strong limit:
$SD^+ \propto (F_V + F_A)^2$
weak limit:
$SD^- \propto (F_V - F_A)^2$

Experimental History of Pion F_A and F_V





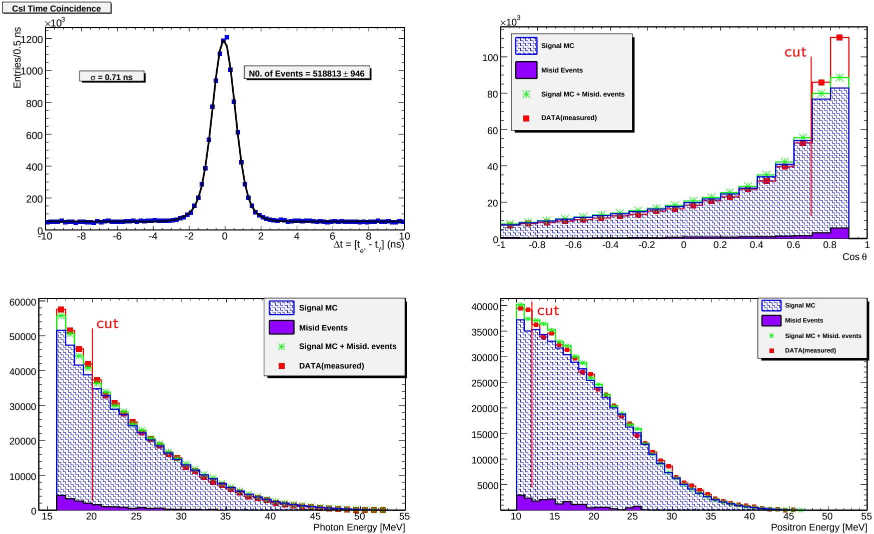
Radiative muon decay:

$$\mu^+ \to e^+ \nu \bar{\nu} \gamma$$

PIBETA: 2004 runs

(PEN: 2008–2010 runs)

Radiative muon decay, $\mu^+ \to e^+\nu\bar{\nu}\gamma$, (new analysis of 2004 data)



"Split clumps" very well accounted for!

RMD preliminary results, cont'd.

Preliminary result for RMD branching ratio (thesis E. Munyangabe):

$$B_{\text{exp}} = 4.365\,(9)_{\text{stat.}}\,(42)_{\text{syst.}} \times 10^3\,, \qquad \boxed{\mathbf{29}\times}$$

$$B_{\text{SM}} = 4.342\,(5)_{\text{stat-MC}} \times 10^3 \qquad (\text{for } E_\gamma > 10\,\text{MeV},\ \theta_{e\gamma} > 30^\circ)$$

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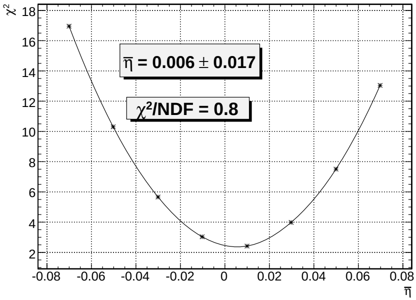

NB: preliminary results!

Analysis of PS subset:
$13\,\text{MeV} < E_\gamma < 45\,\text{MeV}$, and
$10\,\text{MeV} < E_{e^+} < 43\,\text{MeV}$, yields

$$\bar{\eta} = 0.006\,(17)_{\text{stat.}}\,(18)_{\text{syst.}}\,, \quad \text{or}$$

$$\bar{\eta} < 0.028 \quad (68\%\text{CL})\,.$$

$\boxed{\sim \mathbf{4\times}}$ better than best previous experiment (Eichenberger et al, 84).

What to do with Michel parameters?

For $\mu \to e\nu_\mu\bar{\nu}_e\gamma$: $\left(x = \frac{E_e}{E_{max}} \text{ and } y = \frac{E_\gamma}{E_{max}}\right)$

$$\frac{d^3B(x,y,\theta)}{dx\,dy\,2\pi\,d(\cos\theta)} = f_1(x,y,\theta) + \bar{\eta} f_2(x,y,\theta) + (1 - \frac{4}{3}\rho) f_3(x,y,\theta)$$

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$$\rho = \frac{3}{4} - \frac{3}{4}\left[|g^V_{LR}|^2 + |g^V_{RL}|^2 + 2|g^T_{LR}|^2 + 2|g^T_{RL}|^2 + \Re(g^S_{RL}g^{T*}_{RL} + g^S_{LR}g^{T*}_{LR})\right] \stackrel{\text{SM}}{\equiv} \mathbf{\frac{3}{4}},$$

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Combined with η, δ, ρ, parameters of OMD (TWIST), a global fit will yield model-independent limits on non–**(V − A)** couplings.

The π_{e2} decay:

$\pi^+ \to e^+\nu$

Primary motivation for PEN
(data runs 2008–10)

$\pi^+ \to e^+\nu_e$ decay (π_{e2}): SM calculations; measurements

- Early evidence for $V - A$ nature of weak interaction.
- Modern SM calculations: $R^{\pi}_{e/\mu} = \left.\frac{\Gamma(\pi \to e\bar{\nu}(\gamma))}{\Gamma(\pi \to \mu\bar{\nu}(\gamma))}\right|_{\text{CALC}} =$

$$\begin{cases} 1.2352\,(5) \times 10^{-4} & \text{Marciano and Sirlin, [PRL } \mathbf{71} \text{ (1993) 3629]} \\ 1.2354\,(2) \times 10^{-4} & \text{Finkemeier, [PL B } \mathbf{387} \text{ (1996) 391]} \\ 1.2352\,(1) \times 10^{-4} & \text{Cirigliano and Rosell, [PRL } \mathbf{99} \text{ (2007) 231801]} \end{cases}$$

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$$\left.\frac{\Gamma(\pi \to e\bar{\nu}(\gamma))}{\Gamma(\pi \to \mu\bar{\nu}(\gamma))}\right|_{\text{EXP}} = 1.230(4) \times 10^{-4};$$

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- Strong SM helicity suppression amplifies sensitivity to PS terms ("door" for New Physics) by factor $2m_\pi/m_e(m_u + m_d) \approx 8000$.
- $\mathbf{R^{\pi}_{e/\mu}}$ tests lepton universality: in SM $\mathbf{e}$, $\boldsymbol{\mu}$, $\boldsymbol{\tau}$ differ by Higgs couplings only; there could also be new S or PS bosons with non-universal couplings (New Physics).

Reach of π_{e2} decay beyond the SM (New Physics)

$$\mathcal{L}_{\rm NP} = \left[\pm \frac{\pi}{2\Lambda_V^2} \bar{u}\gamma_\alpha d \pm \frac{\pi}{2\Lambda_A^2} \bar{u}\gamma_\alpha\gamma_5 d \right] \bar{e}\gamma^\alpha(1-\gamma_5)\nu$$
$$+ \left[\pm \frac{\pi}{2\Lambda_S^2} \bar{u} d \pm \frac{\pi}{2\Lambda_P^2} \bar{u}\gamma_5 d \right] \bar{e}(1-\gamma_5)\nu\,, \quad (\Lambda_i \ \ldots \text{scale of NP})$$

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At $\Delta R^\pi_{e/\mu}/R^\pi_{e/\mu} = 10^{-3}$, π_{e2} decay is directly sensitive to:

$$\boxed{\Lambda_P \leq 1000\,\text{TeV}} \qquad \text{and} \qquad \boxed{\Lambda_A \leq 20\,\text{TeV}}\,,$$

and indirectly, through loop effects to $\boxed{\Lambda_S \leq 60\,\text{TeV}}$.

Reach of π_{e2} decay beyond the SM (New Physics)

$$\mathcal{L}_{NP} = \left[\pm\frac{\pi}{2\Lambda_V^2}\bar{u}\gamma_\alpha d \pm \frac{\pi}{2\Lambda_A^2}\bar{u}\gamma_\alpha\gamma_5 d\right]\bar{e}\gamma^\alpha(1-\gamma_5)\nu$$

$$+\left[\pm\frac{\pi}{2\Lambda_S^2}\bar{u}d \pm \frac{\pi}{2\Lambda_P^2}\bar{u}\gamma_5 d\right]\bar{e}(1-\gamma_5)\nu\,, \quad (\Lambda_i \text{ ... scale of NP})$$

CKM unitarity and superallowed Fermi nuclear decays currently limit:

$$\Lambda_V \geq 20\,\text{TeV}, \qquad \text{and} \qquad \Lambda_S \geq 10\,\text{TeV}\,.$$

At $\Delta R^\pi_{e/\mu}/R^\pi_{e/\mu} = 10^{-3}$, π_{e2} decay is directly sensitive to:

$$\boxed{\Lambda_P \leq 1000\,\text{TeV}} \qquad \text{and} \qquad \boxed{\Lambda_A \leq 20\,\text{TeV}}\,,$$

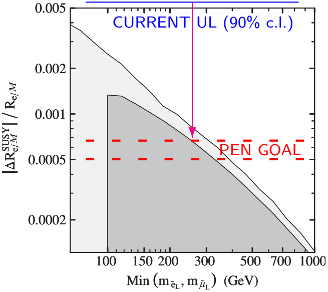
and indirectly, through loop effects to $\boxed{\Lambda_S \leq 60\,\text{TeV}}$.

In general multi-Higgs models with charged-Higgs couplings

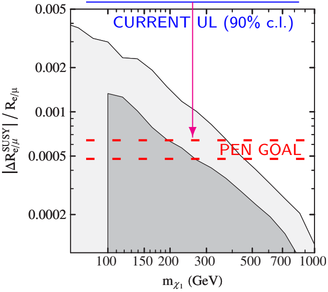
$\lambda_{e\nu} \approx \lambda_{\mu\nu} \approx \lambda_{\tau\nu}$, at 0.1 % precision, $R^\pi_{e\mu}$ probes $\boxed{m_{H^\pm} \leq 400\,\text{GeV}}$.

MSSM calculations (R parity cons.) [Ramsey-Musolf et al., PR D**76** (2007) 095017]

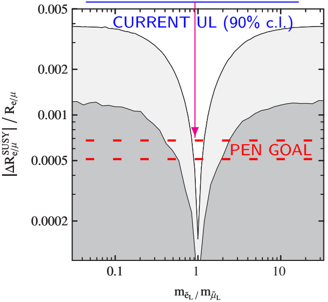
minimal selectron, smuon masses:



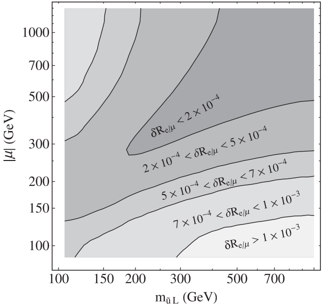
lowest mass chargino:



slepton mass degeneracy:



Higgsino mass param's. μ, $m_{\tilde{u}_L}$:



(R parity violating scenario constraints also discussed.)

Other processes and limits; status of PEN

From $\pi \to e\nu$, additional constraints on:

- pseudoscalar and vector leptoquarks,
- neutrino sector anomalies through lepton universality,
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- heavy neutrinos.

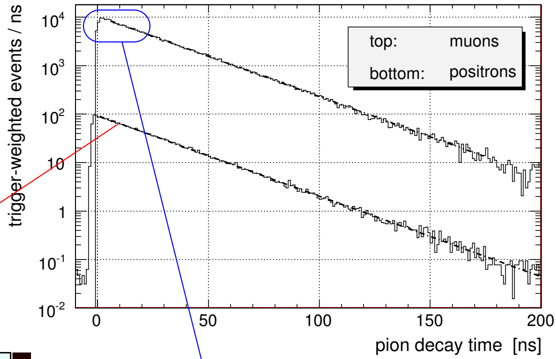
Current status of PEN:

- Data acquisition runs in 2008, 2009, 2010 completed.
- Collected: $> 22\,\mathrm{M}\ \pi \to e$ events, $> 200\,\mathrm{M}\ \pi \to \mu \to e$ events.
- Comprehensive, blinded maximum likelihood analysis in progress.

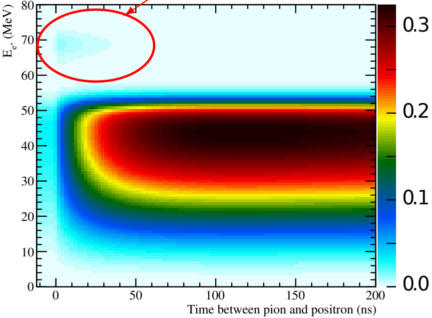
Pion decays in TGT

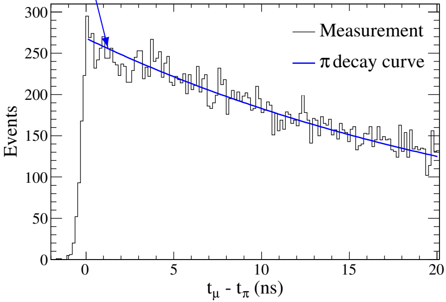
$\tau_{\pi\to\mu} = 26.21(5)\,\text{ns} \Rightarrow$

$\tau_{\pi\to e} = 26.02(8)\,\text{ns} \Rightarrow$



positron E vs t



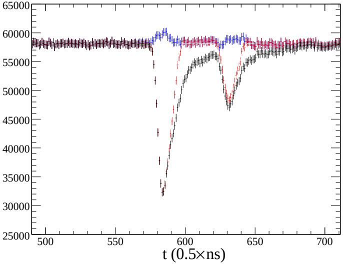


Target waveform fitting: (A. Palladino)

(1) Shape (filter) wf signals, (2) Use predicted π_{stop}(DEG) and e^{+}(PH) wf's,
(3) Fit with 2 and 3-peak wf's; compare χ^2 values.

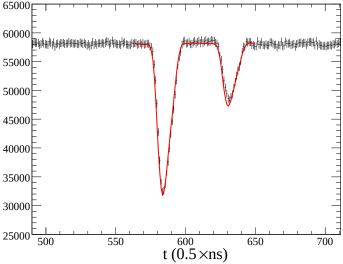
Raw + shaped wf's

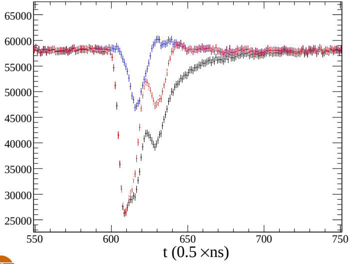
Shaped wf's + predicted fits



Typical 2-peak
$\pi \rightarrow e$ event

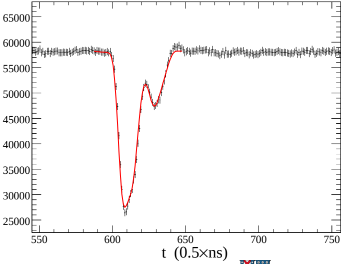
Blue trace: no "third" (muon) signal



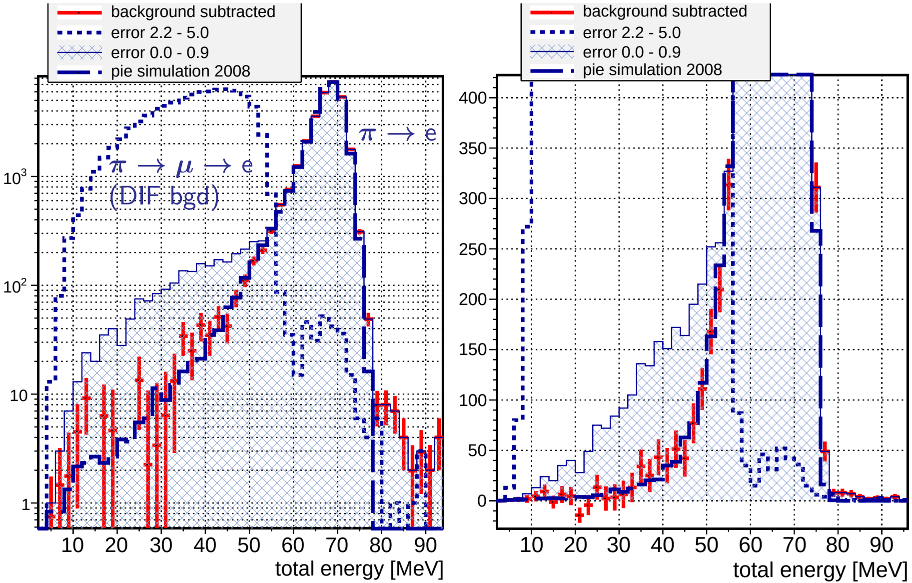


Typical 3-peak
$\pi \rightarrow \mu \rightarrow e$ event

Blue trace:
putative "third" (muon) signal



Key PEN systematic: low E "tail" response



Correlations in **n** beta decay:

Nab and ABba/PANDA experiments

(apparatus under construction)

Neutron beta decay observables (SM)

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

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

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where in SM:

$$a = \frac{1 - |\lambda|^2}{1 + 3|\lambda|^2} \qquad A = -2\frac{|\lambda|^2 + Re(\lambda)}{1 + 3|\lambda|^2} \qquad b \equiv 0$$

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

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

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

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

Goals of the Nab experiment (at SNS, ORNL)

- Measure the electron-neutrino parameter **a** in neutron decay

with accuracy of $\boxed{\frac{\Delta a}{a} \simeq 10^{-3}}$ or $\sim 50\times$ better than:

current results:	-0.1054 ± 0.0055	Byrne et al '02
	-0.1017 ± 0.0051	Stratowa et al '78
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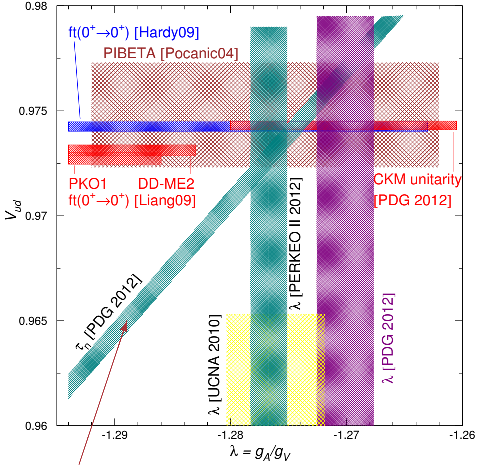
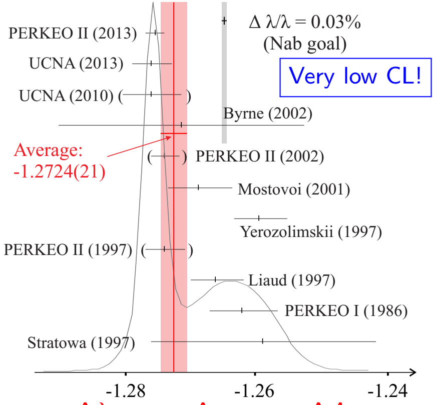
- **Nab** will be followed by the **ABba/PANDA** polarized program to measure **A**, electron, and **B/C**, neutrino/proton, asymmetries with $\simeq 10^{-3}$ relative precision, an independent measurement of λ.

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

. . . remains an unresolved mess:





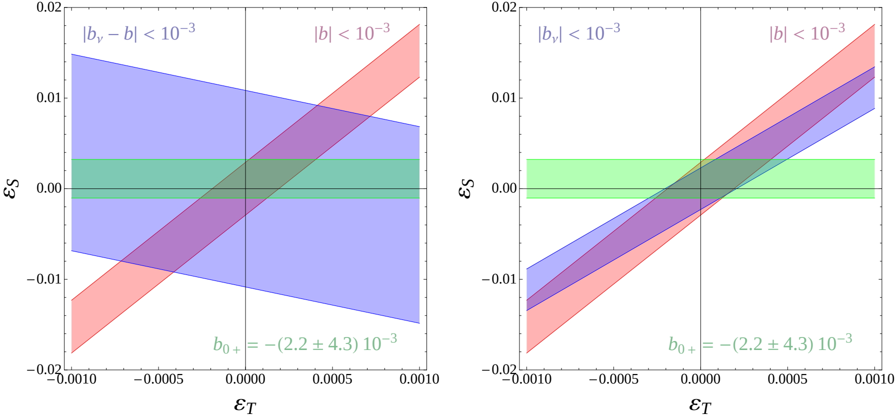
$$\frac{\Delta\lambda}{\lambda} \simeq 0.27\frac{\Delta a}{a} \simeq 0.24\frac{\Delta A}{A}$$

λ sensitivity to a, A is **similar**.

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

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

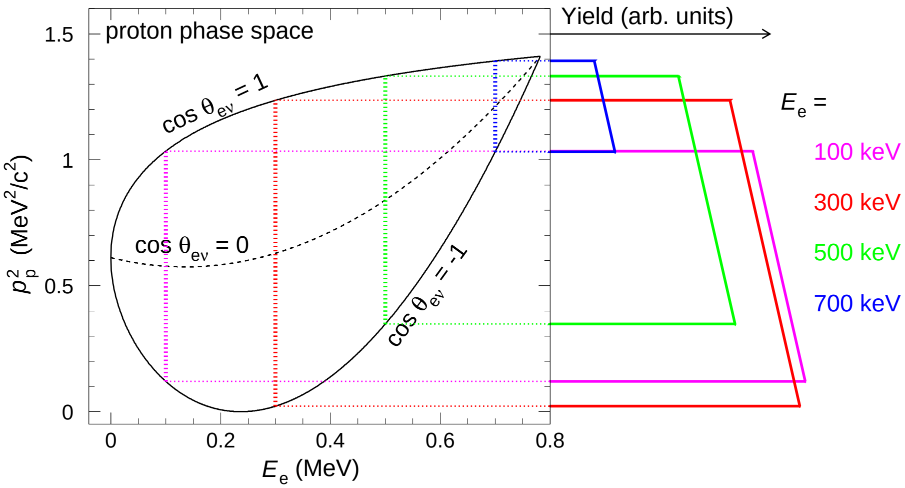
Limits on T, S couplings from beta decay



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.

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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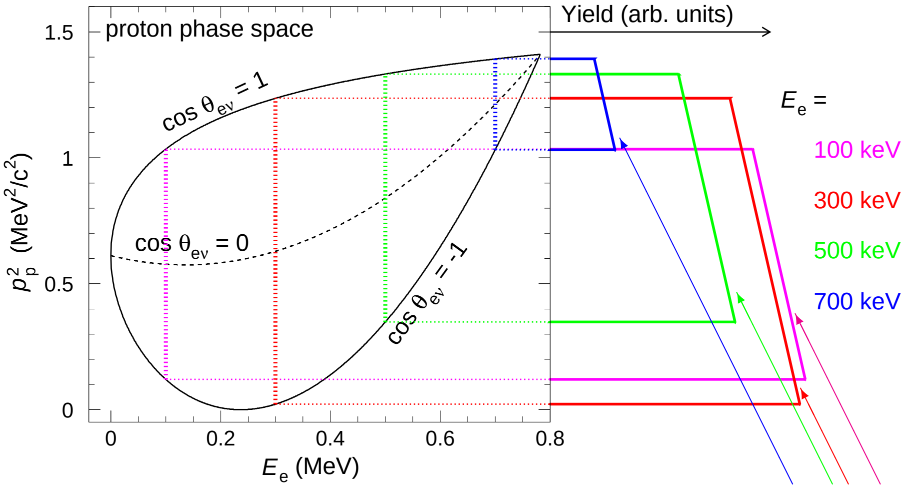


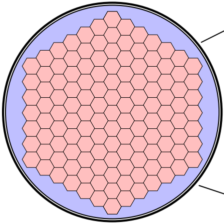
NB: For a given E_e, $\cos\theta_{e\nu}$ is a function of p_p^2 only.

Slope $\propto$ **a**

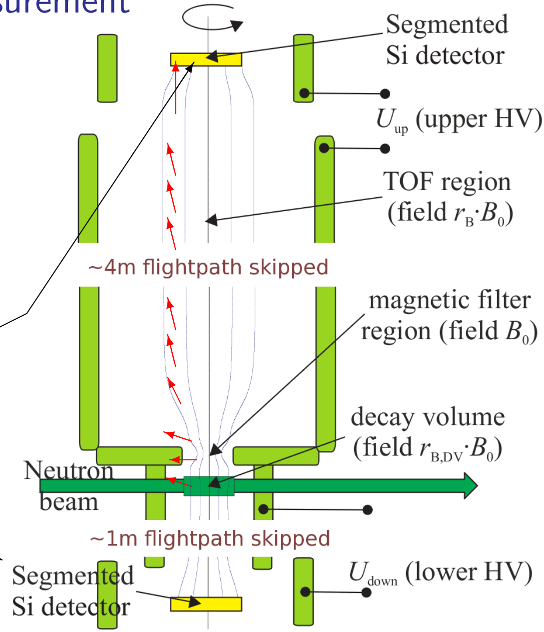
Numerous consistency checks are built-in!

Nab principles of measurement

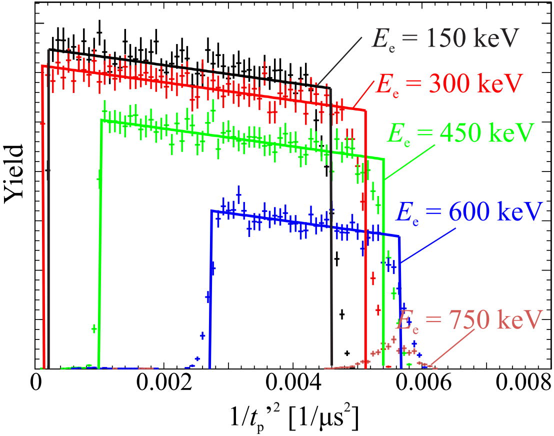
- Collect and detect both electron and proton from neutron beta decay.
- Measure E_e and TOF_p and reconstruct decay kinematics
- Segmented Si det's:



LANL/Micron development



Analysis strategy



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

Nab systematic uncertainties: (expt not stat limited)

Experimental parameter		$(\Delta a/a)_{\rm SYST}$
Magnetic field:	curvature at pinch	5×10^{-4}
	ratio $r_{\rm B} = B_{\rm TOF}/B_0$	2.5×10^{-4}
	ratio $r_{\rm B,DV} = B_{\rm DV}/B_0$	3×10^{-4}
$L_{\rm TOF}$, length of TOF region		(*)
U inhomogeneity:	in decay / filter region	5×10^{-4}
	in TOF region	1×10^{-4}
Neutron Beam:	position	4×10^{-4}
	width	2.5×10^{-4}
	Doppler effect	small
	unwanted beam polarization	small
Adiabaticity of proton motion		1×10^{-4}
Detector effects:	$E_{\rm e}$ calibration	(*)
	$E_{\rm e}$ resolution	5×10^{-4}
	Proton trigger efficiency	2.5×10^{-4}
Accidental coincidences		small
Residual gas		small
Background		small
Sum		1×10^{-3}

(*) Free fit parameter

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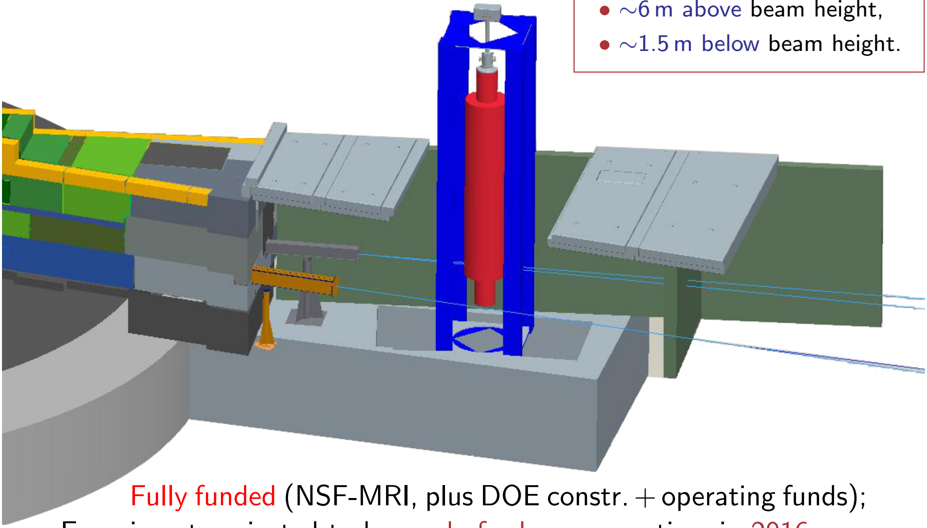
Nab apparatus in FnPB/SNS

Apparatus extends:

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



Fully funded (NSF-MRI, plus DOE constr. + operating funds);
Experiment projected to be ready for beam sometime in 2016.

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Home pages: http://pen.phys.virginia.edu
http://nab.phys.virginia.edu