PEN and Nab: new precision tests of lepton and quark-lepton universality

Dinko Počanić

Institute for Nuclear and Particle Physics, University of Virginia

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This talk will address the question:

In the **LHC era**, can the study of the decays and properties of **light unstable particles**, e.g., **pions**, **muons** and **neutrons** help us to improve our:

- understanding of the **weak interaction**,
- understanding of the limits of the **Standard Model**, and
- searches for any physics that may lie **beyond the SM** ?

Sensitive study topics focus on strong SM principles:

(a) **quark-lepton universality**,

(b) **lepton universality**.

Outline

The PIBETA & PEN experiments at PSI

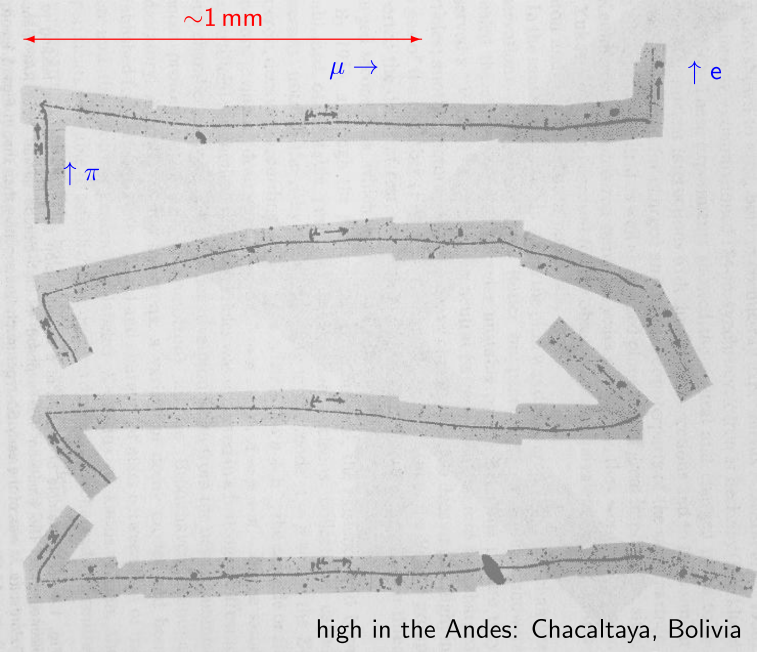
- The $\pi^+ \to \pi^0 e^+ \nu$ (π_{e3}), pion beta decay
- The $\pi^+ \to e^+ \nu_e$ (π_{e2}), electronic decay
- The $\pi^+ \to e^+ \nu_e \gamma$ ($\pi_{e2\gamma}$), radiative electronic decay

Neutron decay measurements: Nab and abBA

- Motivation and goals of Nab/abBA
- Nab measurement principles and apparatus

Summary

Pion discovery: Cecil Powell et al., emulsion tracks 1947



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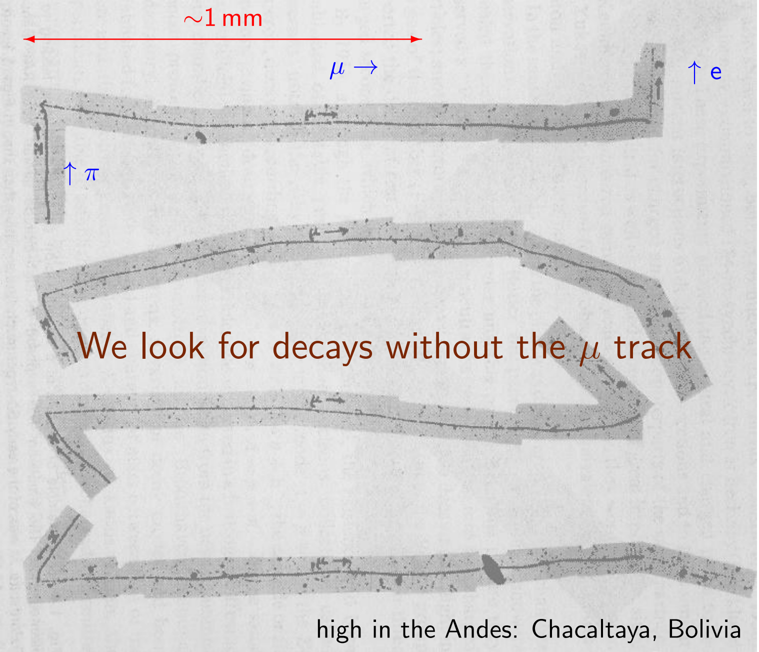

Known and measured pion and muon decays

	Decay	BR	
$\pi^+ \to$	$\mu^+\nu$	$0.9998770\,(4)$	$(\pi_{\mu 2})$
	$\mu^+\nu\gamma$	$2.00\,(25) \times 10^{-4}$	$(\pi_{\mu 2\gamma})$
	$\mathrm{e}^+\nu$	$1.230\,(4) \times 10^{-4}$	$(\pi_{\mathrm{e}2})$
	$\mathrm{e}^+\nu\gamma$	$7.39(5) \times 10^{-7}$	$(\pi_{\mathrm{e}2\gamma})$
	$\pi^0\mathrm{e}^+\nu$	$1.036\,(6) \times 10^{-8}$	$(\pi_{\mathrm{e}3},\ \pi_\beta)$
	$\mathrm{e}^+\nu\mathrm{e}^+\mathrm{e}^-$	$3.2\,(5) \times 10^{-9}$	(π_{e2ee})
$\pi^0 \to$	$\gamma\gamma$	$0.98798\,(32)$	
	$\mathrm{e}^+\mathrm{e}^-\gamma$	$1.198\,(32) \times 10^{-2}$	(Dalitz)
	$\mathrm{e}^+\mathrm{e}^-\mathrm{e}^+\mathrm{e}^-$	$3.14\,(30) \times 10^{-5}$	
	$\mathrm{e}^+\mathrm{e}^-$	$6.2\,(5) \times 10^{-8}$	
$\mu^+ \to$	$\mathrm{e}^+\nu\bar{\nu}$	~ 1.0	(Michel)
	$\mathrm{e}^+\nu\bar{\nu}\gamma$	$0.014\,(4)$	(RMD)
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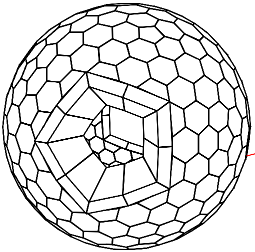
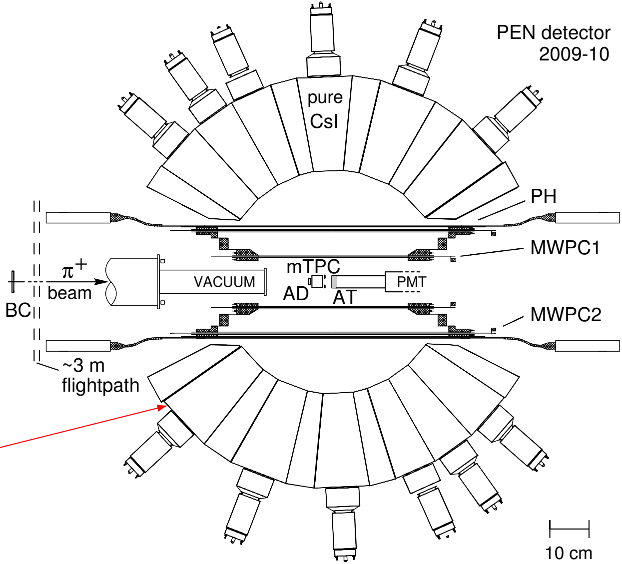
The PIBETA/PEN apparatus

- πE1 beamline at PSI
- stopped π^+ beam
- active target counter
- 240-detector, spherical pure CsI calorimeter
- central tracking
- beam tracking
- digitized waveforms
- stable temp./humidity





Pion beta (π_{e3}) decay:

$$\pi^+ \to \pi^0 e^+ \nu_e$$

$$\mathbf{BR} \sim 10^{-8}$$

A theoretically clean path to access CKM V_{ud}

π_{e3} decay: quark-lepton (Cabibbo) universality

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

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

is replicated in hadronic weak decays

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

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

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

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

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

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π_{e3} decay rate in the SM (a pure vector $0^- \to 0^-$ decay)

A pure test of **quark-lepton universality**:

$$\Gamma = \Gamma_0(1+\delta_\pi) = \frac{G_F^2|V_{ud}|^2\Delta^5}{30\pi^3} f(\epsilon,\Delta)\left(1-\frac{\Delta}{2m_+}\right)^3 (1+\delta_\pi)\,,$$

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where

$$\Delta = m_+ - m_0 = 4.5936(5)\,\text{MeV} \qquad \text{and} \qquad \epsilon = \left(\frac{m_e}{\Delta}\right)^2 \simeq \frac{1}{81}$$

while

$$f(\epsilon,\Delta) = \sqrt{1-\epsilon}\left(1 - \frac{9}{2}\epsilon - 4\epsilon^2\right) + \frac{\epsilon^2}{4}\ln\left(\frac{1-\sqrt{1-\epsilon}}{\sqrt{\epsilon}}\right) - \frac{3}{7}\frac{\Delta^2}{(m_+ + m_0)^2} \simeq 0.941$$

and $\delta_\pi \sim 0.035$ is the sum of radiative/loop corrections with $\sim 0.05\%$ relative uncertainty.

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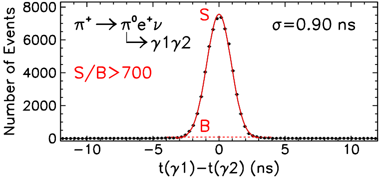
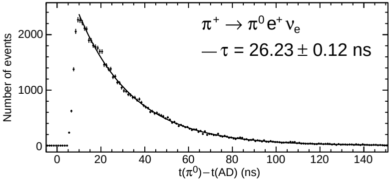
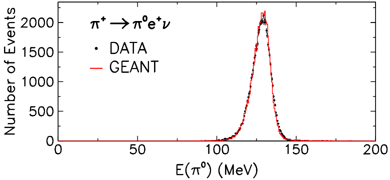
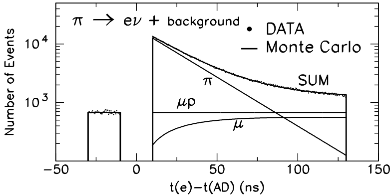
Prior to 2004, Γ and B measured with about 4 % precision.

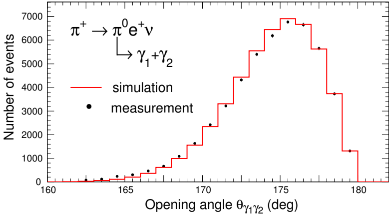
PIBETA results [PRL **93**, 181803 (2004)]

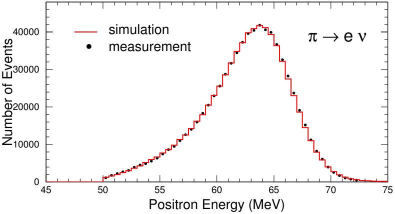












PIBETA result for $\pi^+ \to \pi^0 e^+ \nu$ (π_β) decay [PRL **93**, 181803 (2004)]

Pion beta decay yield normalized to recorded $\pi \to e\nu$ events:

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

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

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

SM Prediction (PDG):

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

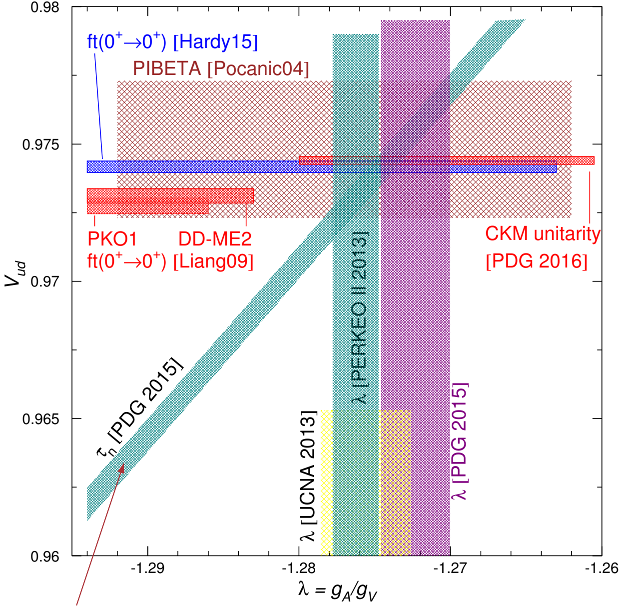
$(1.005 - 1.007 \times 10^{-8}$ excl. rad. corr.)

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

PDG 2016: $V_{ud} = 0.97417(21)$

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

Current status of V_{ud}:



Neutron β decay results need to be sorted out before returning to π_{e3}.

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

The electronic (π_{e2}) decay:

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

$$\mathbf{BR \sim 10^{-4}}$$

π_{e2} decay: SM calculations, lepton universality

- Early evidence for $V - A$ nature of weak interaction.

$$R^{\pi}_{e/\mu} = \frac{\Gamma(\pi \to e\bar{\nu}(\gamma))}{\Gamma(\pi \to \mu\bar{\nu}(\gamma))} = \frac{g_e^2}{g_\mu^2}\,\frac{m_e^2}{m_\mu^2}\,\frac{(1 - m_e^2/m_\mu^2)^2}{(1 - m_\mu^2/m_\pi^2)^2}\,\left(1 + \delta R_{e/\mu}\right)$$

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

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WHY SHOULD WE CARE?

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

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

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

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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 $\boxed{\Lambda_S \leq 60\,\text{TeV}}$.

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

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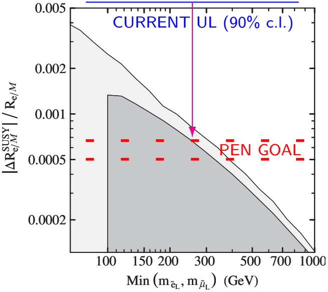
In general multi-Higgs models with charged-Higgs couplings

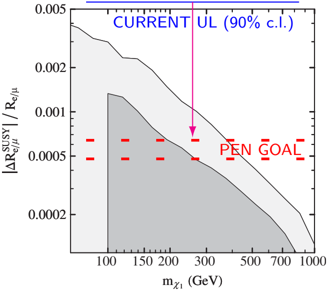
$\lambda_{e\nu} \approx \lambda_{\mu\nu} \approx \lambda_{\tau\nu}$, at 0.1 % precision, $R^\pi_{e\mu}$ probes $\boxed{m_{H^\pm} \leq 400\,\text{GeV}}$.

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

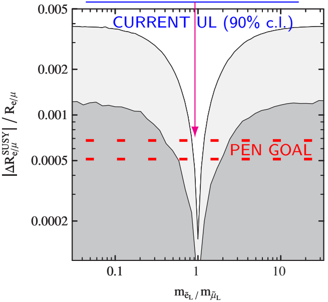
minimal selectron, smuon masses:



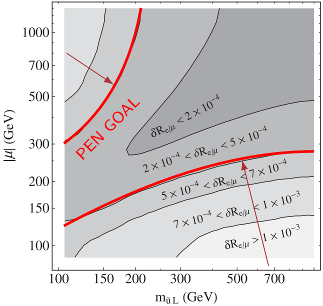
lowest mass chargino:



slepton mass degeneracy:



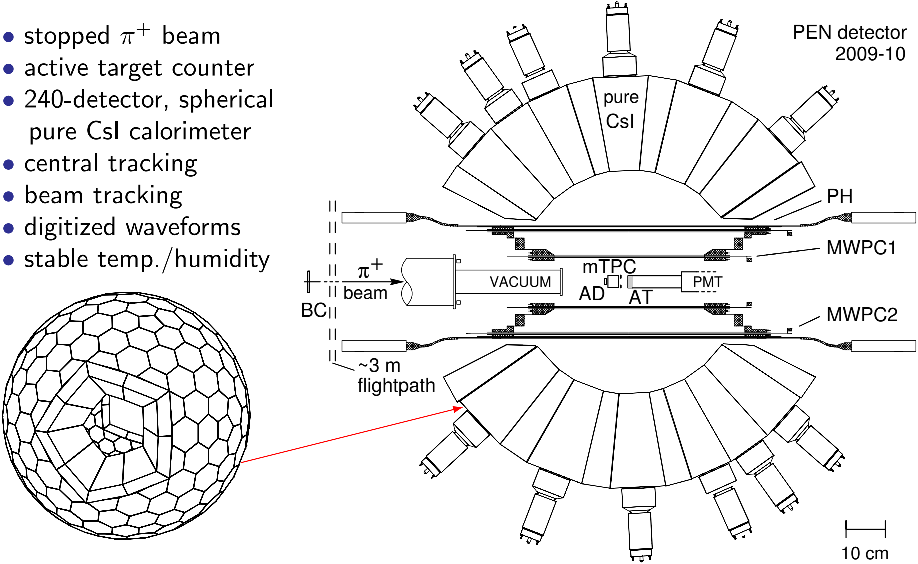
Higgsino mass param's. μ, $m_{\tilde{u}_L}$:



(R parity violating scenario constraints also discussed.)

The PEN/PIBETA apparatus

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



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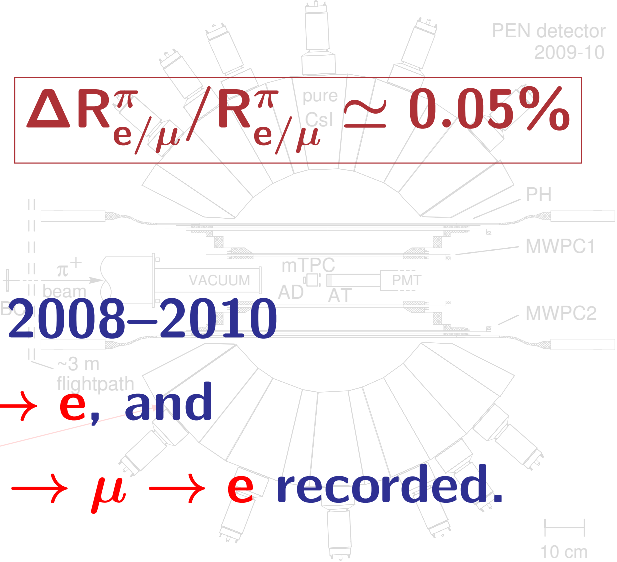
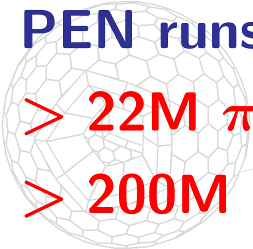




PEN Goal: $\Delta R^{\pi}_{e/\mu}/R^{\pi}_{e/\mu} \simeq 0.05\%$

PEN runs: 2008–2010

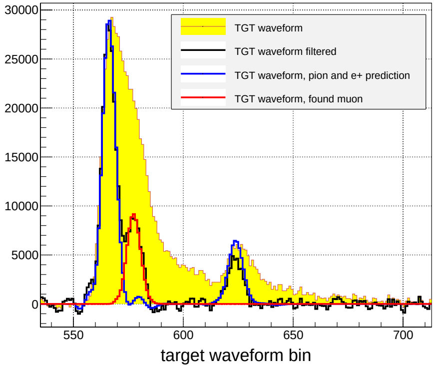
$>$ 22M $\pi \to e$, and

$>$ 200M $\pi \to \mu \to e$ recorded.

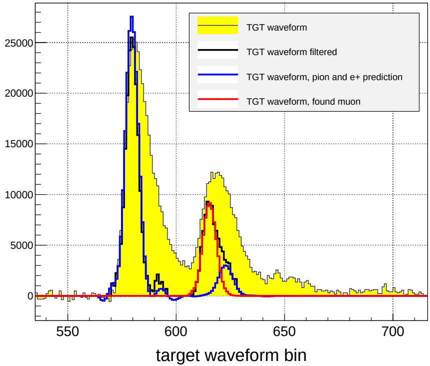
Highlights and challenges of PEN analysis (under way)

Active target waveforms: separating the decay particle pulses!

Early pion decay (extremely common)

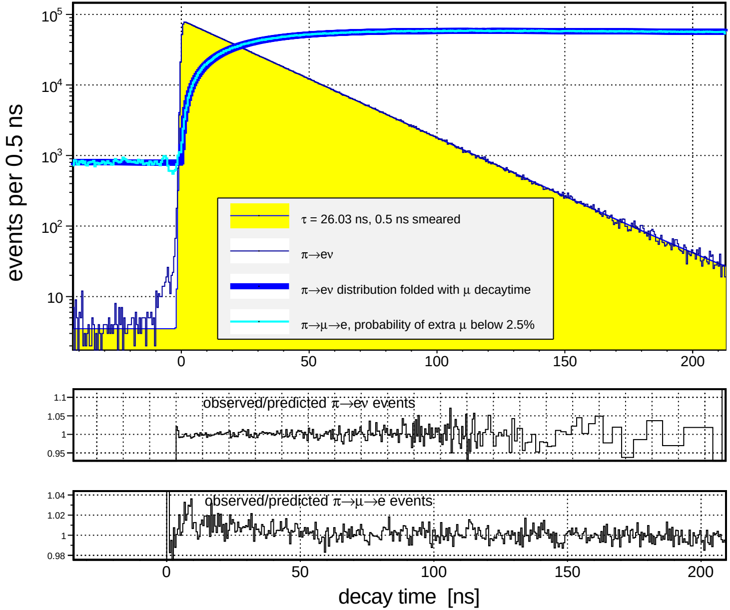


Early muon decay (still annoying)



- π and e^+ pulse time and amplitude predicted from other detector systems (mTPC, MWPCs, PH)!
- Waveform system functions evaluated based on prompt hadronic events.
- Hypotheses with/without a μ pulse evaluated.

PEN: agreement with predictions (2010 data analysis)



Radiative electronic ($\pi_{e2\gamma}$) decay:

$$\pi^+ \to e^+ \nu_e \gamma$$

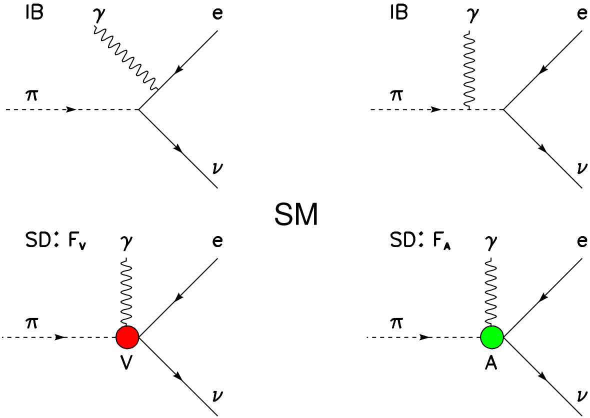
$$\mathbf{BR}_{\text{non-IB}} \sim 10^{-7}$$

Physics of

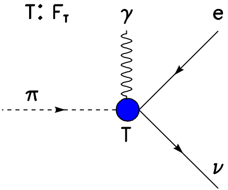
$\pi^+ \to e^+\nu\gamma$ (RPD):

QED IB terms:

and SD V, A terms:



A tensor interaction, too?



Exchange of S=0 leptoquarks

P Herczeg, PRD 49 (1994) 247

The $\pi \to e\nu\gamma$ amplitude and FF's

The IB amplitude (QED **uninteresting!**):

$$M_{\rm IB} = -i\frac{eG_F V_{ud}}{\sqrt{2}} f_\pi m_e \epsilon^{\mu *}\bar{e}\left(\frac{k_\mu}{kq} - \frac{p_\mu}{pq} + \frac{\sigma_{\mu\nu}q^\nu}{2kq}\right) \times (1-\gamma_5)\,\nu\,.$$

The structure-dependent amplitude (**interesting!**):

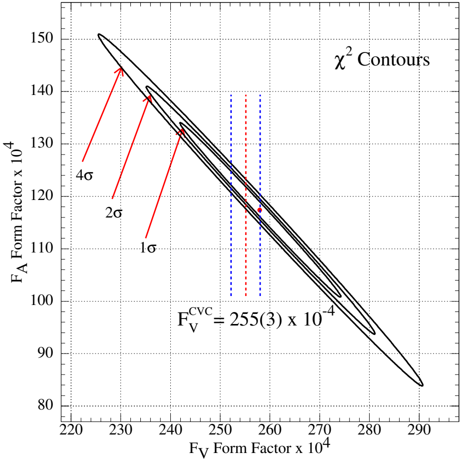
$$M_{\rm SD} = \frac{eG_F V_{ud}}{m_\pi\sqrt{2}}\epsilon^{\nu *}\bar{e}\gamma^\mu(1-\gamma_5)\nu \times \left[F_V\epsilon_{\mu\nu\sigma\tau}p^\sigma q^\tau + iF_A(g_{\mu\nu}pq - p_\nu q_\mu)\right]\,.$$

The SM branching ratio ($x = 2E_\gamma/m_\pi$; $y = 2E_e/m_\pi$),

$$\frac{d\Gamma_{\pi e2\gamma}}{dx\,dy} = \frac{\alpha}{2\pi}\Gamma_{\pi e2}\Bigg\{IB\,(x,y) + \left(\frac{m_\pi^2}{2f_\pi m_e}\right)^2 \times \left[(F_V + F_A)^2\,\mathbf{SD}^+\,(x,y) + (F_V - F_A)^2\,SD^-\,(x,y)\right] + \frac{m_\pi}{f_\pi}\left[(F_V + F_A)\,S^+_{\rm int}\,(x,y) + (F_V - F_A)\,S^-_{\rm int}\,(x,y)\right]\Bigg\}\,.$$

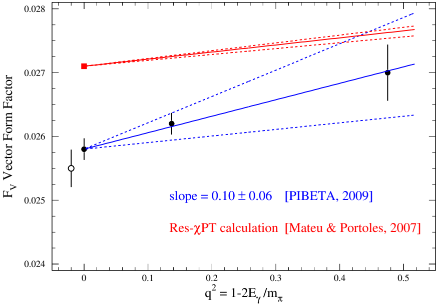
PIBETA results for $\pi \to e\nu\gamma$

Best values of pion Form Factor Parameters:



Combined analysis of 1999-01 and 2004 data sets

[Bychkov et al., PRL **103**, 051802 (2009)]



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

$\mathbf{F_V = 0.0258 \pm 0.0017}$	$(8\times)$
$\mathbf{F_A = 0.0119 \pm 0.0001}^{\text{exp}}_{(F_V^{CVC})}$	$(16\times)$
$\mathbf{a = 0.10 \pm 0.06}$ ($\mathbf{q^2}$ dep of $\mathbf{F_V}$)	(∞)
$\mathbf{-5.2 \times 10^{-4} < F_T < 4.0 \times 10^{-4}}$	90 % C.L.

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

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

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

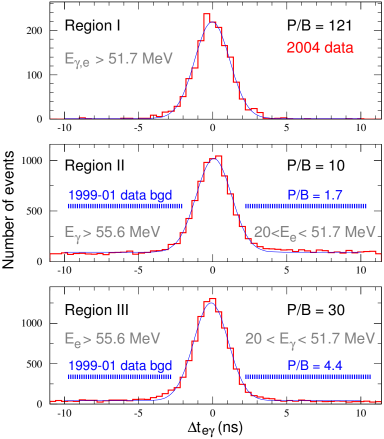
$$\tau_{\pi^0} = (8.5 \pm 1.1) \times 10^{-17}\,\text{s}$$

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

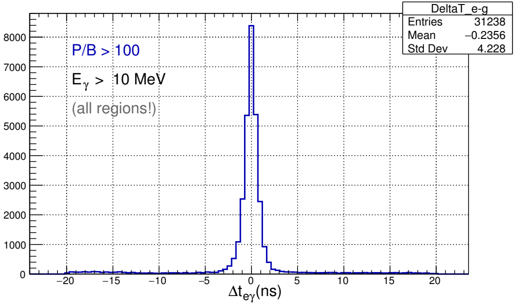
How PEN data will improve $\pi \to e\nu\gamma$ analysis

We compare accidental coincidence rates in 3 generations of data:

PIBETA data



Current PEN data



Neutron beta decay

program

SNS (NIST)

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:

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

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

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 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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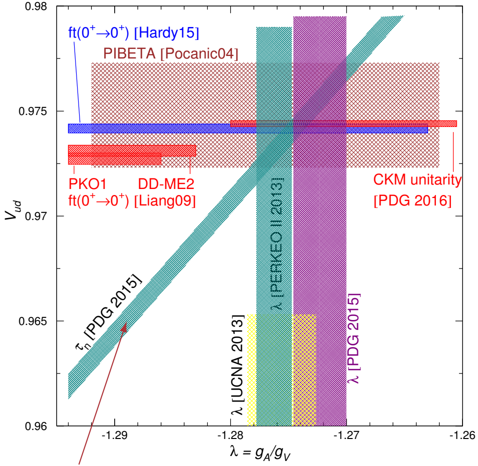
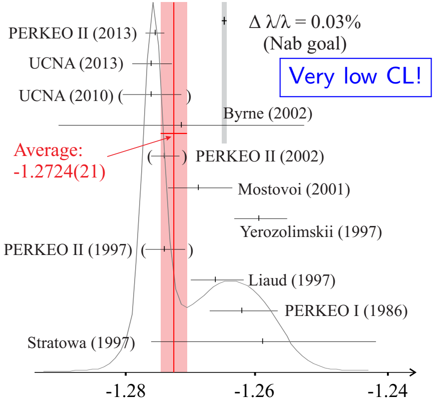
Motivation:

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

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

. . . remains an unresolved mess:





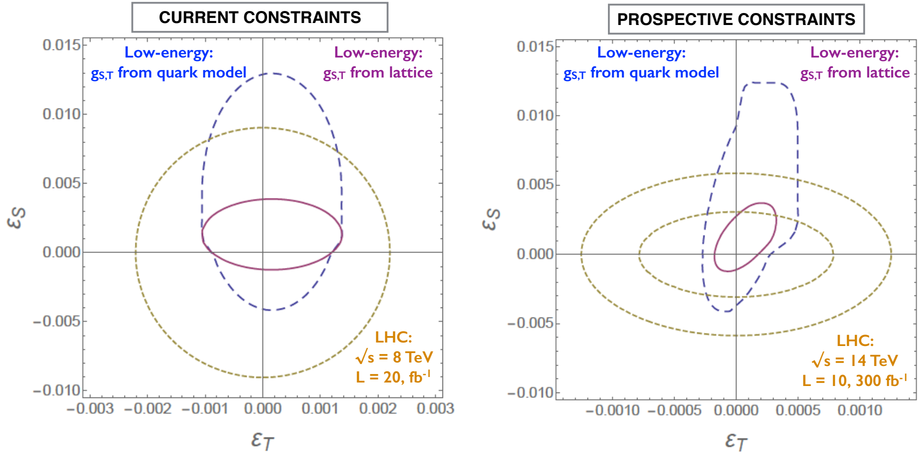
$\tau_n^{-1} \propto |V_{ud}|^2 |g_V|^2 (1 + 3|\lambda|^2)$

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

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.

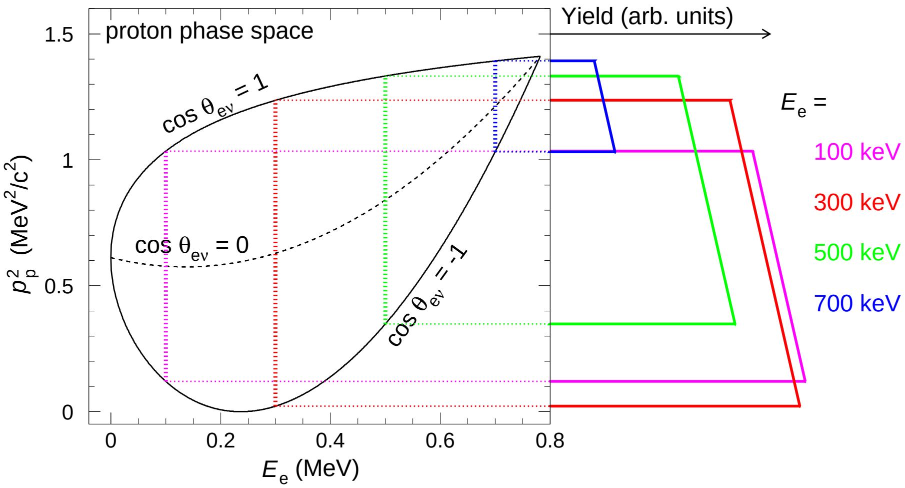
Limits on T, S couplings from beta decay



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.

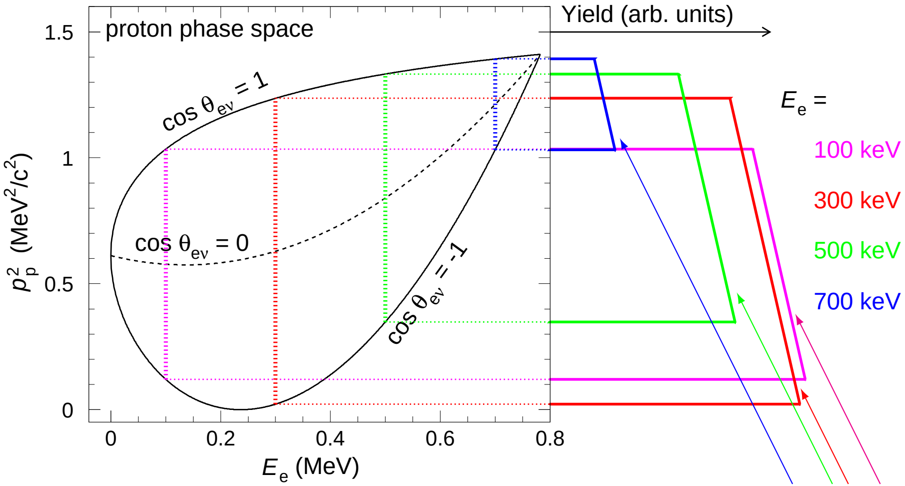
From Bhattacharya, Cirigliano, et al., PRD **94** (2016) 054508 [arXiv 1606.07049].

Nab measurement principles: proton phase space



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

Nab measurement principles: proton phase space



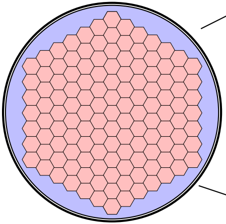
NB: For a given E_e, $\cos\theta_{e\nu}$ is a function of p_p^2 only.

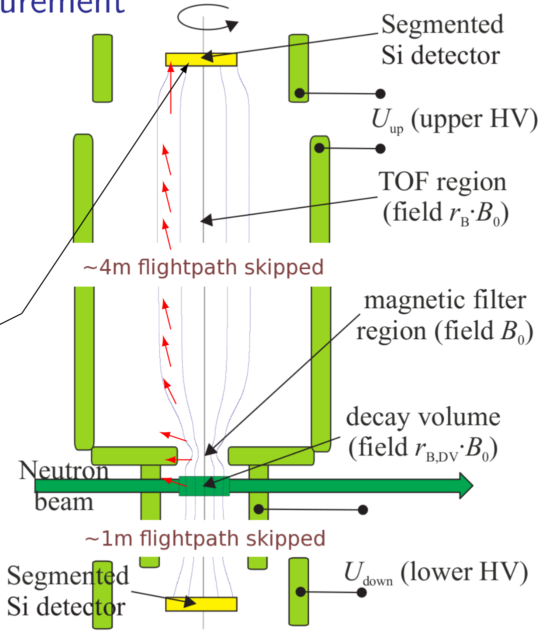
Slope $\propto$ **a**

Numerous consistency checks are built-in!

Nab principles of measurement

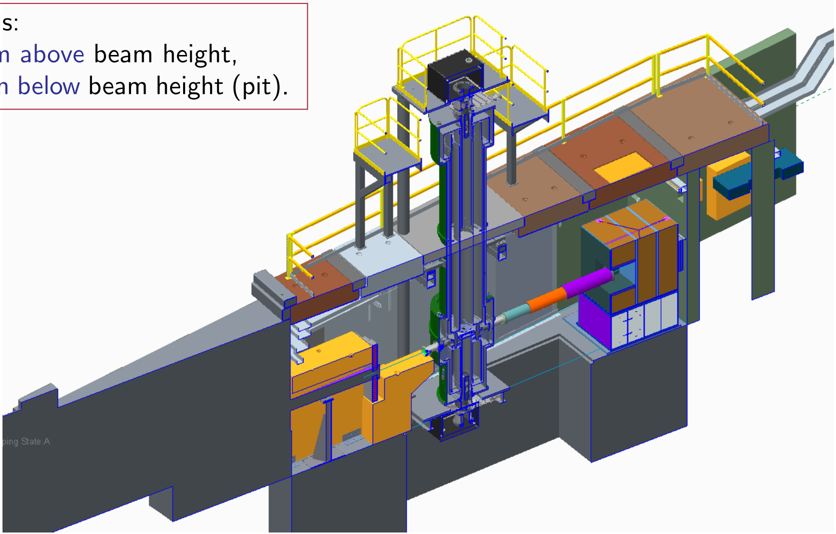
- Collect and detect both electron and proton from neutron beta decay.
- Measure E_e and TOF_p and reconstruct decay kinematics
- Segmented Si det's:





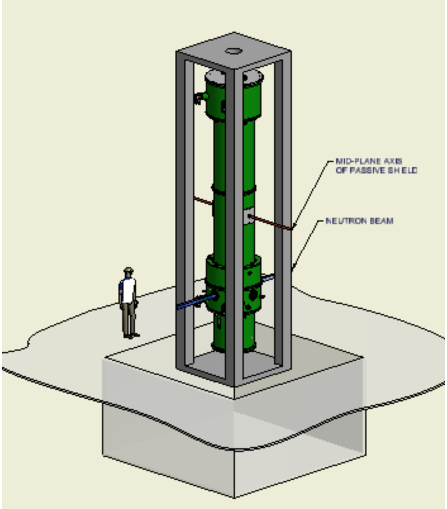
Nab apparatus in FnPB

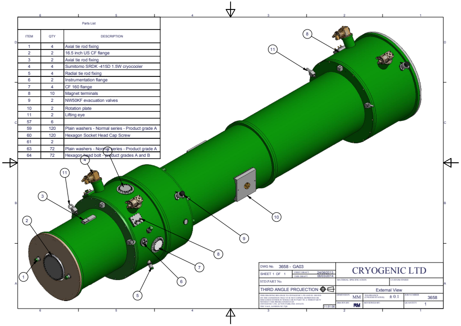
extends:
- $\sim$6 m above beam height,
- $\sim$2 m below beam height (pit).



Designed to measure **a**, **b** with: $\frac{\Delta a}{a} \simeq 10^{-3}$ and $\Delta b \simeq 3 \times 10^{-3}$.

Some images of the Nab apparatus





Precision study of π and n decays in PEN and Nab

- A significant experimental effort is under way (in PEN, Nab, and in other experiments) to make use of the unparalleled theoretical precision in the weak interactions of the lightest particles.
- Information obtained is complementary to collider results, and important for the proper interpretation of the latter.
- Significant improvements in precision for BSM limits stemming from tests of lepton- and quark-lepton universality are forthcoming in the near future.
- Decision on future measurement of $\pi^+ \to \pi^0 e^+ \nu$ will await results of current neutron beta decay experiments.

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

Current PEN collaborators

L. P. Alonzi[a], V. A. Baranov[b], W. Bertl[c], M. Bychkov[a], Yu.M. Bystritsky[b], E. Frlež[a], C. Glaser[a §], V.A. Kalinnikov[b], N.V. Khomutov[b], A.S. Korenchenko[b], S.M. Korenchenko[b], M. Korolija[d], N.P. Kravchuk[b], N.A. Kuchinsky[b], M. Lehman[a §], A. Palladino[a,c], D. Počanić[a †], P. Robmann[e], A.M. Rozhdestvensky[b], P. Truöl[e], A. van der Schaaf[e †], E.P. Velicheva[b], M. Vitz[a §], V.P. Volnykh[b],

[a] *U. of Virginia, USA* [b] *JINR Dubna, Russia* [c] *PSI, Switzerland*
[d] *IRB, Zagreb, Croatia* [e] *Uni. Zürich, Switzerland*

Current Nab collaborators

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

[a] *Arizona S.U.* [b] *U. of Virginia* [c] *ORNL* [d] *UNAM, Mexico*
[e] *U. of Tennessee* [f] *U. of Michigan* [g] *U. of Kentucky* [h] *U. of Manitoba*
[i] *Uni. Karlsruhe* [j] *U. of S. Carolina* [k] *LANL* [ℓ] *U. of Winnipeg*
[m] *N. Carolina S.U.*

† Co-spokesmen * Project Manager ‡ On-site Manager § Current students

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