PEN experiment: a precise test of lepton universality

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Known and measured pion and muon decays

	Decay	BR	
$\pi^+ \rightarrow$	$\mu^+\nu$	$0.9998770\,(4)$	$(\pi_{\mu 2})$
	$\mu^+\nu\gamma$	$2.00\,(25) \times 10^{-4}$	$(\pi_{\mu 2\gamma})$
	$\mathrm{e}^+\nu$	$1.230\,(4) \times 10^{-4}$	$(\pi_{\mathrm{e}2})$
	$\mathrm{e}^+\nu\gamma$	$7.39(5) \times 10^{-7}$	$(\pi_{\mathrm{e}2\gamma})$
	$\pi^0\mathrm{e}^+\nu$	$1.036\,(6) \times 10^{-8}$	$(\pi_{\mathrm{e}3},\ \pi_\beta)$
	$\mathrm{e}^+\nu\mathrm{e}^+\mathrm{e}^-$	$3.2\,(5) \times 10^{-9}$	(π_{e2ee})
$\pi^0 \rightarrow$	$\gamma\gamma$	$0.98798\,(32)$	
	$\mathrm{e}^+\mathrm{e}^-\gamma$	$1.198\,(32) \times 10^{-2}$	(Dalitz)
	$\mathrm{e}^+\mathrm{e}^-\mathrm{e}^+\mathrm{e}^-$	$3.14\,(30) \times 10^{-5}$	
	$\mathrm{e}^+\mathrm{e}^-$	$6.2\,(5) \times 10^{-8}$	
$\mu^+ \rightarrow$	$\mathrm{e}^+\nu\bar{\nu}$	~ 1.0	(Michel)
	$\mathrm{e}^+\nu\bar{\nu}\gamma$	$0.014\,(4)$	(RMD)
	$\mathrm{e}^+\nu\bar{\nu}\mathrm{e}^+\mathrm{e}^-$	$3.4\,(4) \times 10^{-5}$	

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The electronic (π_{e2}) decay:

$$\pi^+ \rightarrow e^+\nu$$

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

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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WHY SHOULD WE CARE?

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

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

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CKM unitarity and superallowed Fermi nuclear decays currently limit:

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

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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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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 $\boxed{m_{H^\pm} \leq 400\,\text{GeV}}$.

Lepton universality (and neutrinos)

From:

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

$$R_{\tau/\pi} = \frac{\Gamma(\tau \to e\bar{\nu}(\gamma))}{\Gamma(\pi \to \mu\bar{\nu}(\gamma))} = \frac{g_\tau^2}{g_\mu^2} \frac{m_\tau^3}{2m_\mu^2 m_\pi} \frac{(1 - m_\pi^2/m_\tau^2)^2}{(1 - m_\mu^2/m_\pi^2)^2} (1 + \delta R_{\tau/\pi})$$

one can evaluate:

$$\left(\frac{g_e}{g_\mu}\right)_\pi = 0.9996 \pm 0.0012 \quad \text{and} \quad \left(\frac{g_\tau}{g_\mu}\right)_{\pi\tau} = 1.0030 \pm 0.0034\,.$$

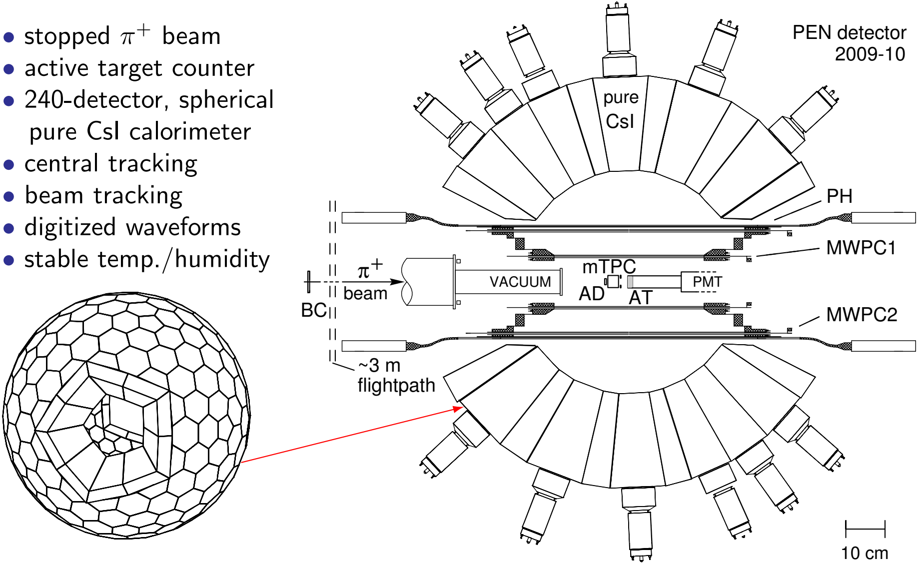
For comparison,

$$\left(\frac{g_e}{g_\mu}\right)_W = 0.999 \pm 0.011 \quad \text{and} \quad \left(\frac{g_\tau}{g_e}\right)_W = 1.029 \pm 0.014\,.$$

- significant consequences in the **neutrino sector**;
- interesting limits on **MSSM extension observables**.

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



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

- stopped π^+ beam
- active target counter
- 240-detector, spherical pure CsI calorimeter
- central tracking
- beam tracking
- digitized waveforms
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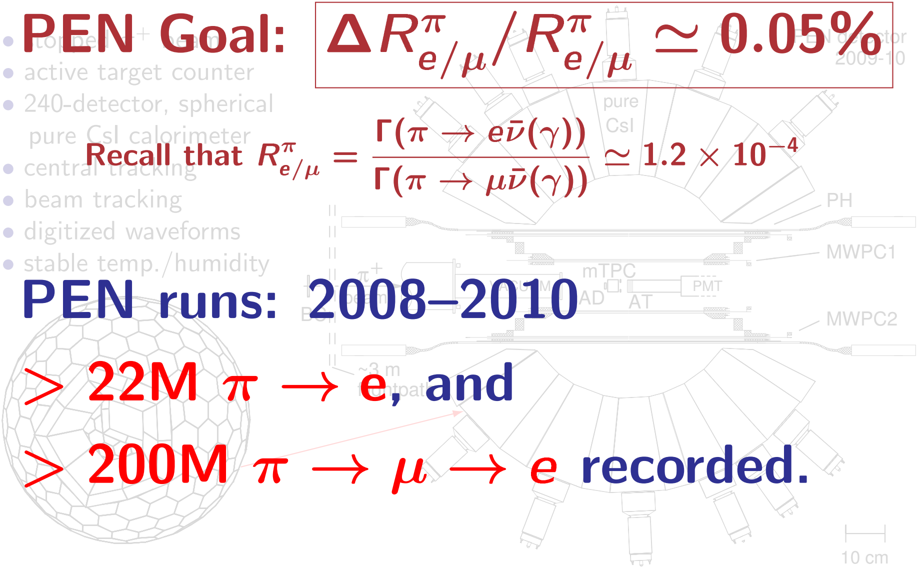
Recall that $R^{\pi}_{e/\mu} = \dfrac{\Gamma(\pi \to e\bar{\nu}(\gamma))}{\Gamma(\pi \to \mu\bar{\nu}(\gamma))} \simeq 1.2 \times 10^{-4}$

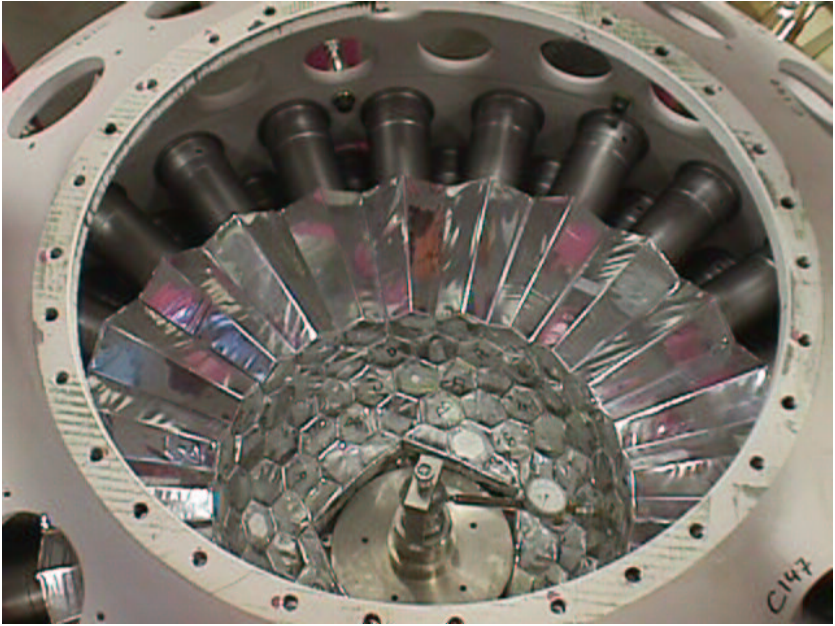


PEN runs: 2008–2010

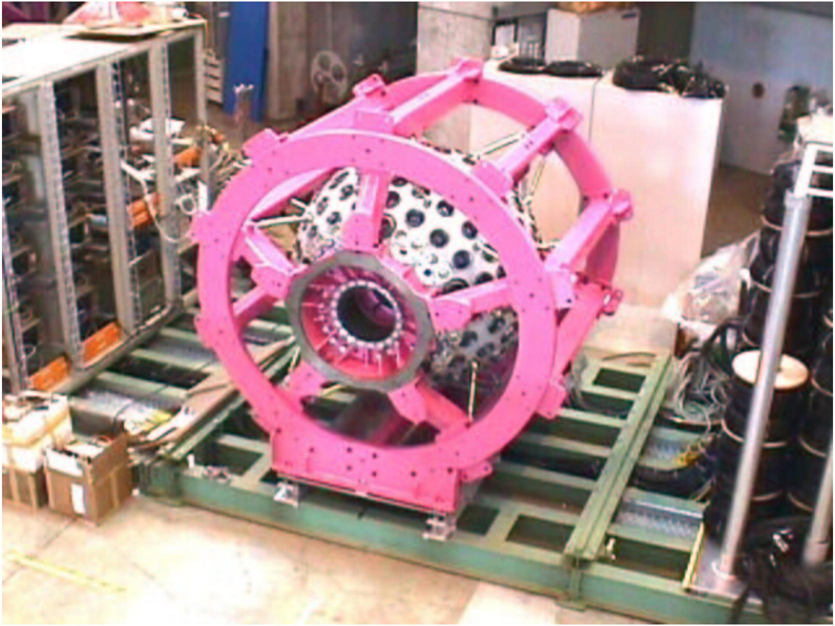
> 22M $\pi \to$ e, and

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

PIBETA Detector Assembly



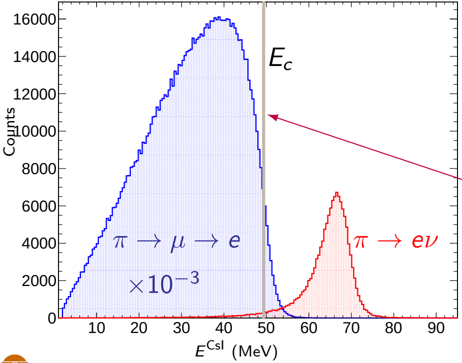
PIBETA Detector on Platform



Given that:

- timing gates affect number of π_{e2} and $\pi \to \mu \to e$ observations, and
- MWPC efficiency depends on energy,

we have: $$R_{e/\mu}^{\pi\text{-exp}} = \frac{N_{\pi\to e\nu}^{\text{peak}}(1+\epsilon_{\text{tail}})}{N_{\pi\to\mu\nu}} \underbrace{\frac{f_{\pi\to\mu\to e}(T_e)}{f_{\pi\to e\nu}(T_e)}}_{r_f} \underbrace{\frac{\epsilon(E_{\mu\to e\nu\bar\nu})_{\text{MWPC}}}{\epsilon(E_{\pi\to e\nu})_{\text{MWPC}}}}_{r_\epsilon} \underbrace{\frac{A_{\pi\to\mu\to e}}{A_{\pi\to e\nu}}}_{r_A}$$



E_c = cutoff energy

N = number of events

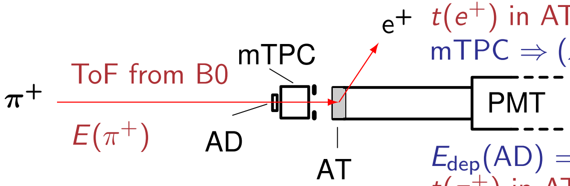
A = acceptance

$\epsilon_{\text{tail}}(E_c)$ = tail to peak ratio

$\epsilon(E)_{\text{MWPC}}$ = efficiency of MWPC

$f(T_e)$ = probability from time

Discriminating π_{e2} and $\pi_{\mu 2}$ in TGT



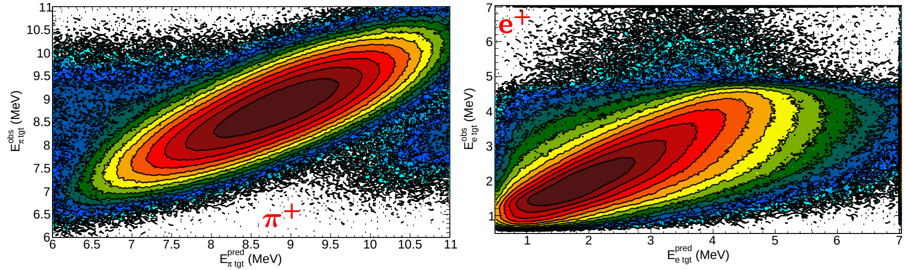
$t(e^+)$ in AT predicted from t(PH)

mTPC $\Rightarrow (x, y)$ of $\pi_{\rm stop}$ in AT

$E_{\rm dep}$(AD) $\Rightarrow E_{\rm dep}, z$ of $\pi_{\rm stop}$ in AT

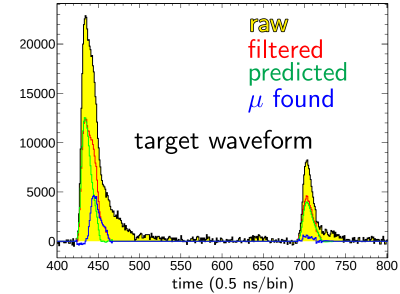
$t(\pi^+)$ in AT predicted from t(AD)

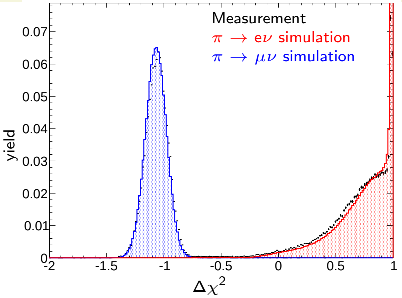
Predicted π^+ and e^+ energies agree VERY well with observations:

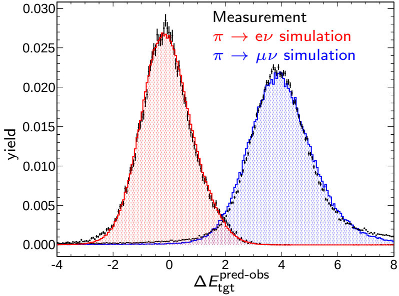


$\Rightarrow$ *E* and *t* predictions are used for $\pi_{e2}/\pi_{\mu 2}$ discrimination.

Discrimination and waveforms







$\Delta\chi^2$ uses predicted and observed timings and energies

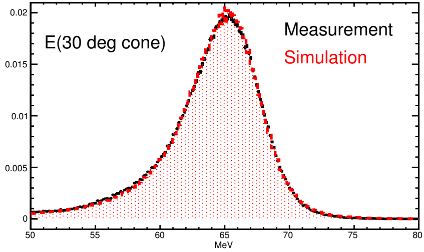
Evaluate 2 peak fit $\Rightarrow \chi_2^2$

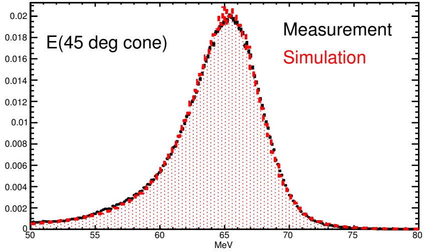
Evaluate 3 peak fit $\Rightarrow \chi_3^2$

$\Delta\chi^2 = \chi_2^2 - \chi_3^2$ (normalized)

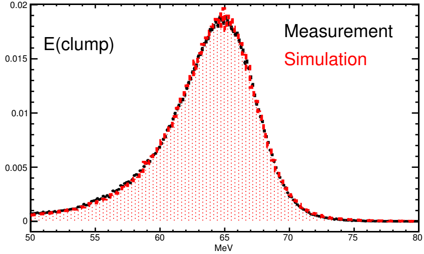
$\pi \to \mu\nu$ and $\pi \to e\nu$ will be used to train a likelihood analysis.

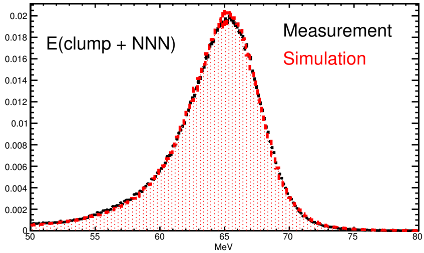
Gain matching the 240 calorimeter modules





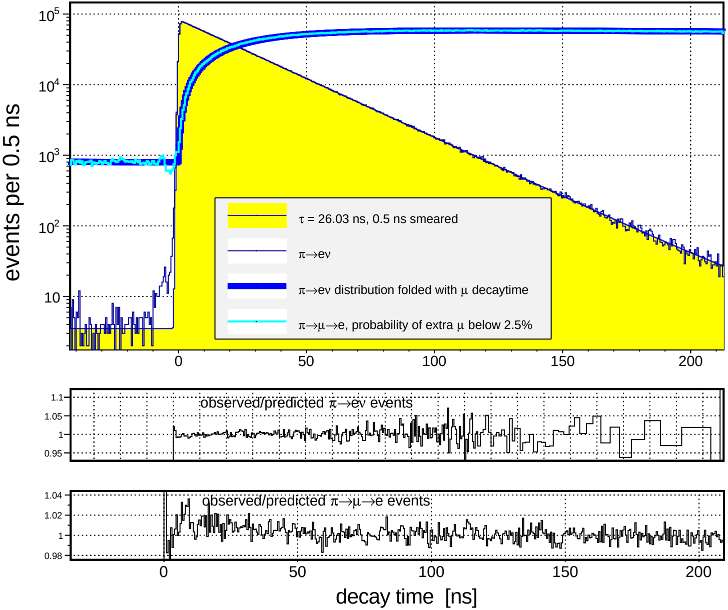
NNN = next to nearest neighbors



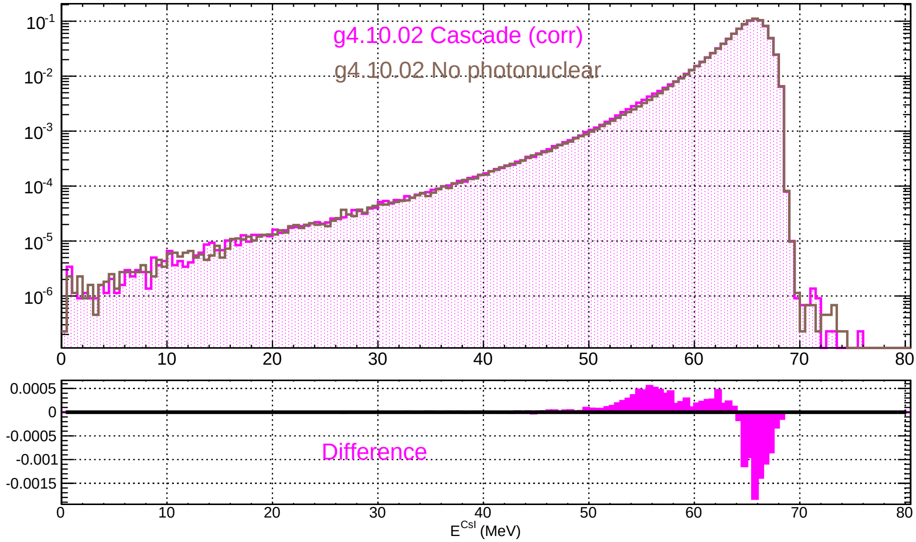


(C. Glaser)

Agreement with predictions (2010 data subset)

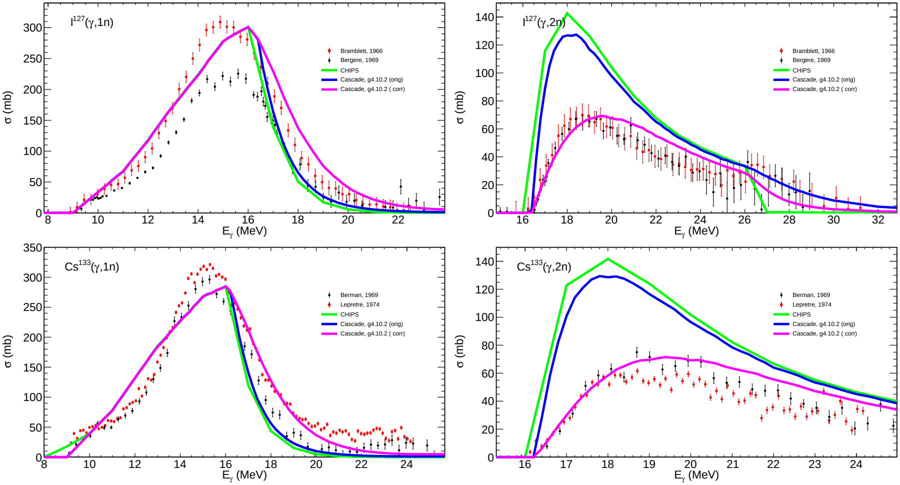


Low E “tail” response in MC simulation



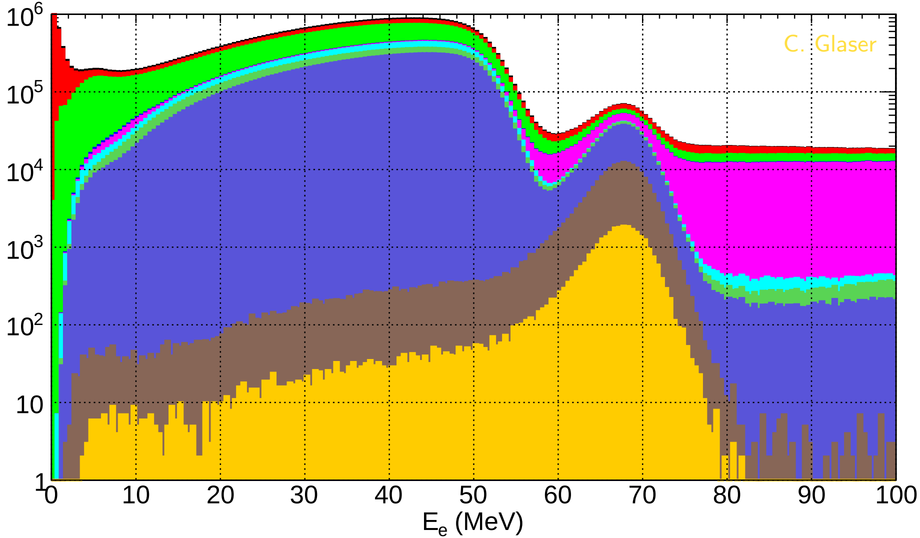
Getting the photonuclear processes right is a challenge.

Photonuclear cross sections and models



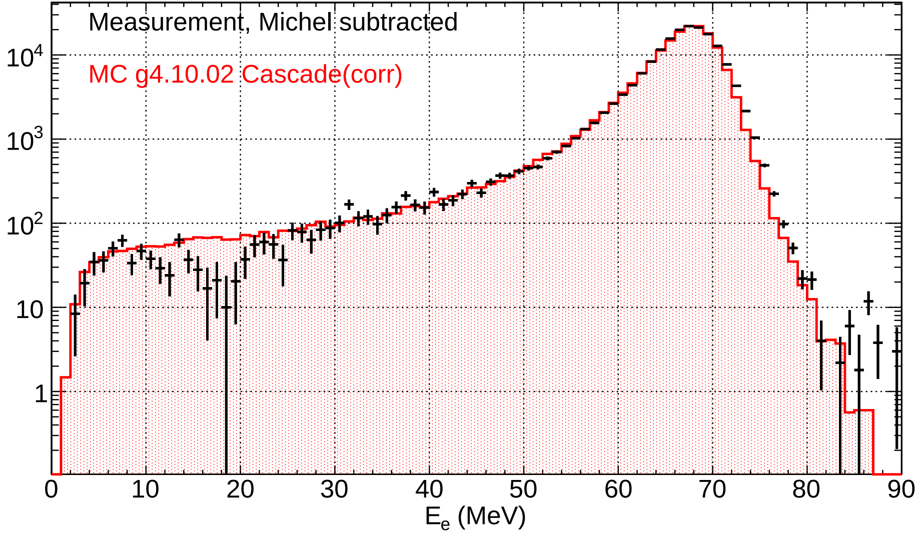
(V. Baranov, Dubna)

Low energy "tail" in positron response (measured, 2010 data)



Analysis of a dedicated "tail" trigger designed to suppress early $\pi \to \mu \to e$ events ($t \leq 50\,$ns). Successive cuts add restrictions.

LE tail: comparison simulation vs. measurement (2010 subset)



(C. Glaser, V.A Baranov)

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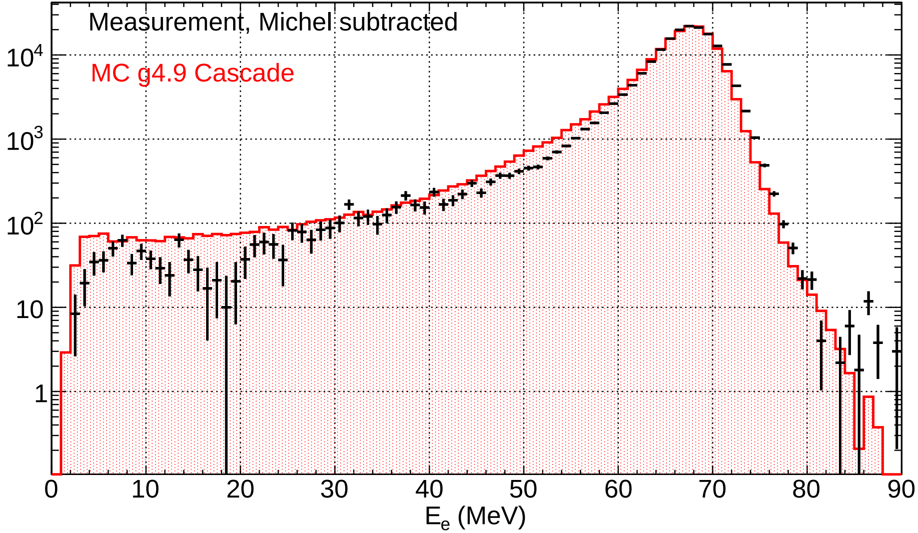
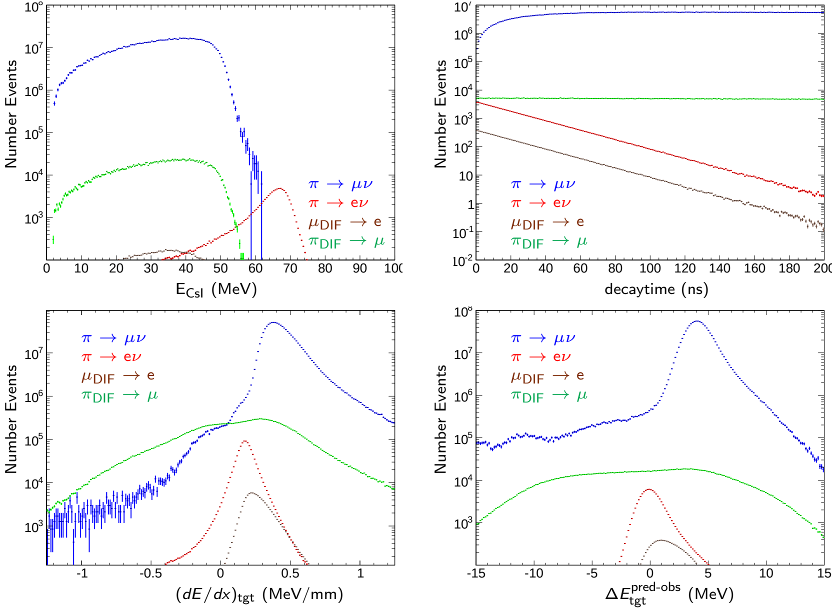


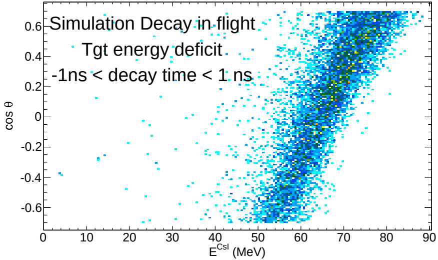
(C. Glaser, V.A Baranov)

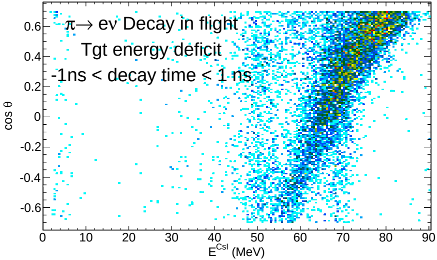
Decay in flight (DIF) Observables



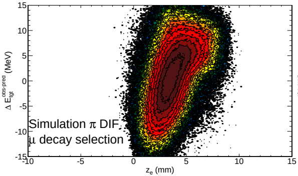
Decays in flight: simulation vs. measurement

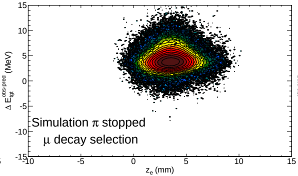
$\pi_{\mathrm{DIF}} \rightarrow e\nu$ decays: (C. Glaser)

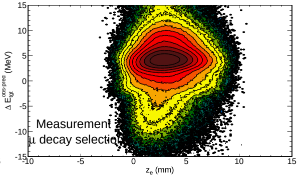




$\pi_{\mathrm{DIF}} \rightarrow \mu_{\mathrm{STOPPED}} \rightarrow e$:







Uncertainty Budget

$$R^{\pi\text{-exp}}_{e/\mu} = \frac{N^{\text{peak}}_{\pi\to e\nu}(1+\epsilon_{\text{tail}})}{N_{\pi\to\mu\nu}} \frac{f_{\pi\to\mu\to e}(T_e)}{f_{\pi\to e\nu}(T_e)} \frac{\epsilon(E_{\mu\to e\nu\bar{\nu}})_{\text{MWPC}}}{\epsilon(E_{\pi\to e\nu})_{\text{MWPC}}} \frac{A_{\pi\to\mu\to e}}{A_{\pi\to e\nu}}$$

r_f r_ϵ r_A

Type	Observable	Value	$\Delta R^{\pi}_{e/\mu}/R^{\pi}_{e/\mu}$
Systematic:	$\Delta\epsilon_{\text{tail}}$	$\simeq 0.025$	$\begin{cases} \simeq 0.001^{\text{exp}} \\ 2\times 10^{-4}\Big\|^{\text{MC}}_{\text{goal}} \end{cases}$
	r_f	0.046	1.8×10^{-4}
	r_ϵ	$\simeq .99$	$< 10^{-4}$
	r_A	$\simeq 1$	$\simeq 10^{-4}$
	$N_{\pi_{\text{DIF}}\to e\nu}/N_{\pi\to e\nu}$	$< 2\times 10^{-3}$	$10^{-6} - 10^{-5}$
	$N_{\pi_{\text{DIF}}\to\mu\nu}/N_{\pi\to\mu\nu}$	2.3×10^{-3}	$10^{-6} - 10^{-5}$
	$N_{\mu_{\text{DIF}}\to e\nu\bar{\nu}}/N_{\mu\to\nu\bar{\nu}}$	1.4×10^{-4}	$10^{-6} - 10^{-5}$
Statistical:	$\Delta N_{\pi\to e\nu}/N_{\pi\to e\nu}$		$\simeq 2.9\times 10^{-4}$
Overall	goal		5×10^{-4}

Summary: studies of pion (and muon) allowed decays

- A significant experimental effort is under way (in PEN, PiENu and 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 therefore valuable for their proper interpretation.
- Notable improvements in precision for
  - $\pi \to e\nu$ branching ratio,
  - $\pi \to e\nu\gamma$ (F_V, $F_T^{\rm ul}$), and
  - $\mu \to e\nu\bar{\nu}\gamma$,

  await in the near future.

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

Review: Počanić, Frlež, van der Schaaf, J.Phys.G. **41** (2014) 114002; (arXiv:1407.2865)

Current and former PIBETA and PEN collaborators

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Additional slides

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

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

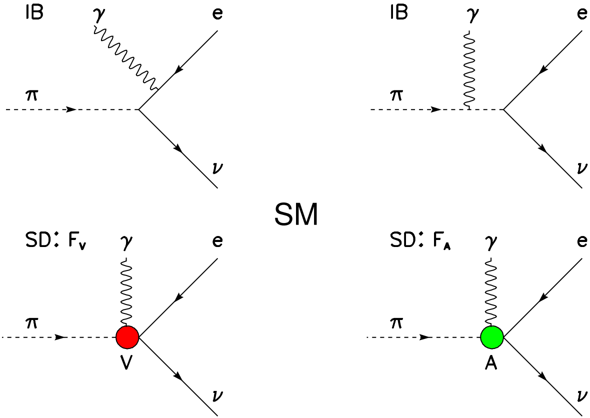
$$BR_{\text{non-IB}} \sim 10^{-7}$$

(Essential "companion" to $\pi \rightarrow e\nu$ decay)

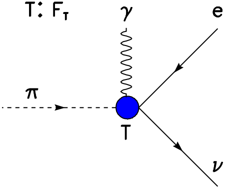
Physics of
$\pi^+ \to e^+\nu\gamma$ (RPD):

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!**):

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

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

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

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

$$\begin{aligned} \frac{\mathrm{d}\Gamma_{\pi e2\gamma}}{\mathrm{d}x\,\mathrm{d}y} = & \frac{\alpha}{2\pi} \Gamma_{\pi e2} \Big\{ IB\,(x,y) + \left(\frac{m_\pi^2}{2 f_\pi m_e} \right)^2 \\ & \times \left[(F_V + F_A)^2\, \boldsymbol{SD}^{+}\,(x,y) + (F_V - F_A)^2\, SD^{-}\,(x,y) \right] \\ & + \frac{m_\pi}{f_\pi} \left[(F_V + F_A)\, S^{+}_{\mathrm{int}}\,(x,y) + (F_V - F_A)\, S^{-}_{\mathrm{int}}\,(x,y) \right] \Big\} . \end{aligned}$$

Pre-2004 data on pion form factors

$$|F_V| \stackrel{\text{CVC}}{=} \frac{1}{\alpha}\sqrt{\frac{2\hbar}{\pi\tau_{\pi^0}m_\pi}} = 0.0255(3)\ .$$

$F_A \times 10^4$	reference
106 ± 60	Bolotov et al. (1990)
135 ± 16	Bay et al. (1986)
60 ± 30	Piilonen et al. (1986)
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116 ± 16	world average (PDG 2004)

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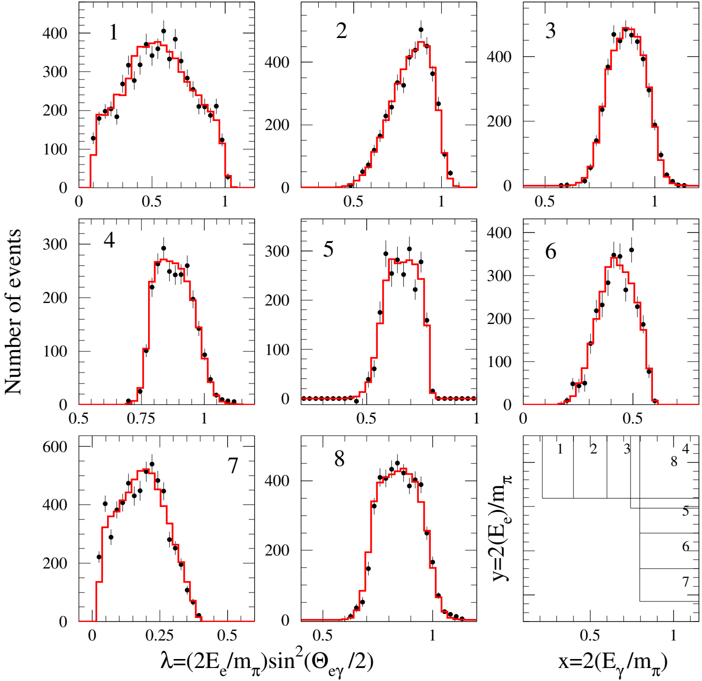
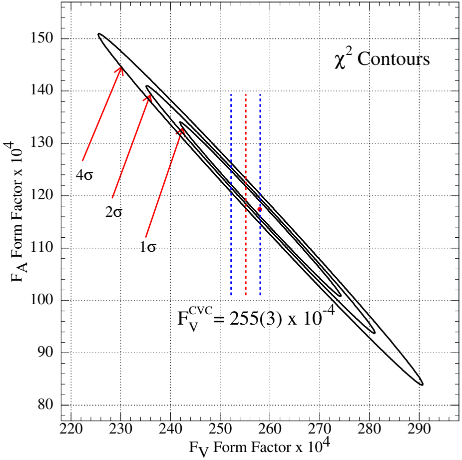
$F_A \times 10^4$	reference	note
106 ± 60	Bolotov et al. (1990)	$(F_T = -56 \pm 17)$
135 ± 16	Bay et al. (1986)	
60 ± 30	Piilonen et al. (1986)	
110 ± 30	Stetz et al. (1979)	
116 ± 16	world average (PDG 2004)	

PIBETA $\pi_{e2\gamma}$ differential distributions (2009 analysis)



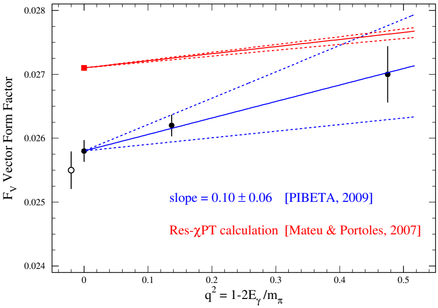
PIBETA results for $\pi \to e\nu\gamma$

Best values of pion Form Factor Parameters:



Combined analysis of all PIBETA data sets

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



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

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

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

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

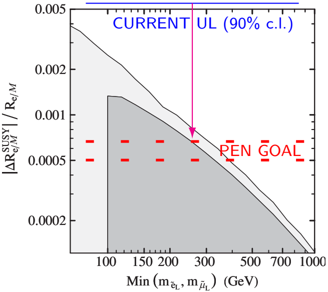
$$\alpha_E^{\text{LO}} = -\beta_M^{\text{LO}} = (2.783 \pm 0.023_{\text{exp}}) \times 10^{-4}\ \text{fm}^3$$

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

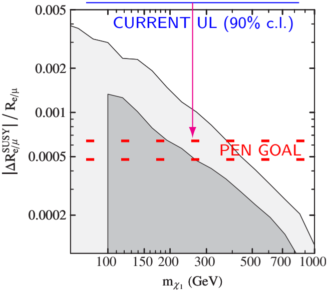
- current PDG avg: 8.52 (12)
- PrimEx PRL '10: 8.32 (23)

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

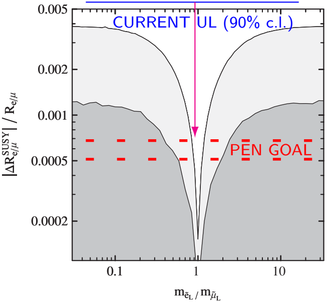
minimal selectron, smuon masses:



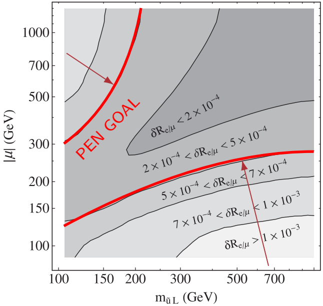
lowest mass chargino:



slepton mass degeneracy:



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



(R parity violating scenario constraints also discussed.)