Experimental low energy tests of lepton universality

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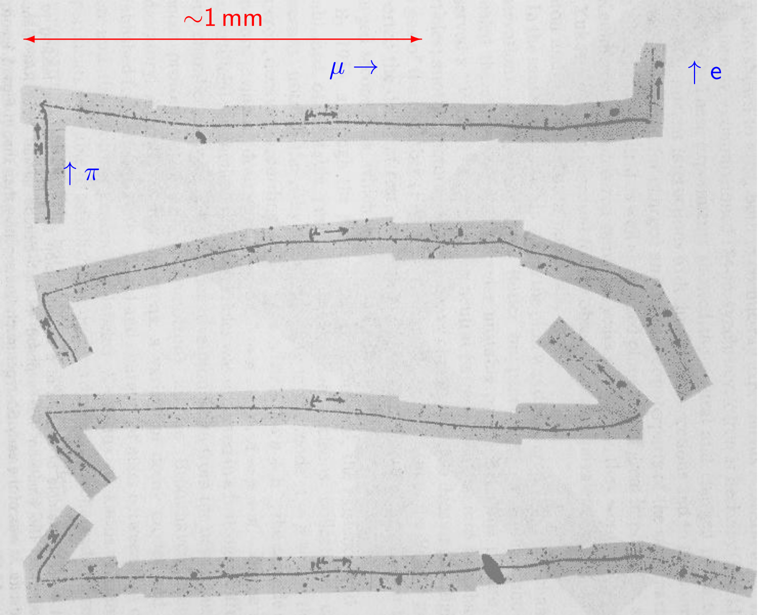
Pion discovery: Cecil Powell et al., emulsion tracks 1947



high in the Andes: Chacaltaya, Bolivia

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})
	$e^+\nu\gamma$	$7.39(5) \times 10^{-7}$	$(\pi_{e2\gamma})$
	$\pi^0 e^+\nu$	$1.036\,(6) \times 10^{-8}$	$(\pi_{e3},\ \pi_\beta)$
	$e^+\nu e^+e^-$	$3.2\,(5) \times 10^{-9}$	(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)
	$e^+\nu\bar{\nu}e^+e^-$	$3.4\,(4) \times 10^{-5}$	

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The electronic ($\pi_{\mathbf{e2}}$) decay:

$$\pi^+ \to \mathrm{e}^+\nu$$

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

π_{e2} decay: SM calculations, lepton universality

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

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

- Modern SM calculations: $R^{\pi}_{e/\mu} = \left.\frac{\Gamma(\pi \to e\bar{\nu}(\gamma))}{\Gamma(\pi \to \mu\bar{\nu}(\gamma))}\right|_{\text{CALC}} =$

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

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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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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

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

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

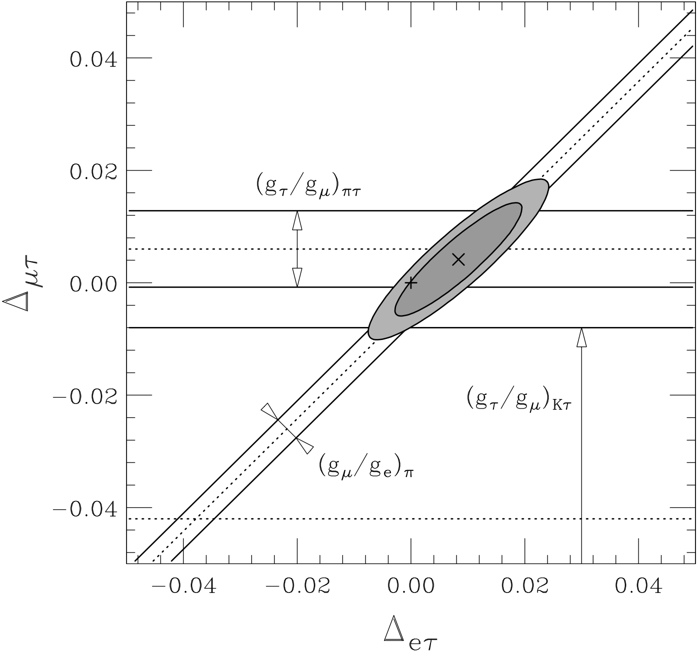
one can evaluate

$$\left(\frac{g_e}{g_\mu}\right)_\pi = 1.0021 \pm 0.0016 \quad \text{and} \quad \left(\frac{g_\tau}{g_\mu}\right)_{\pi\tau} = 1.0030 \pm 0.0034\,.$$

For comparison

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

[Presently allowed level of LUV could account for "NuTeV anomaly."]

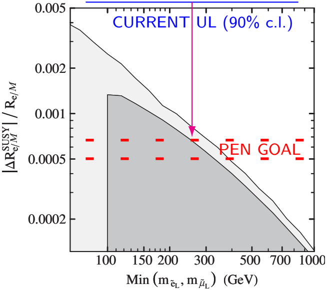


Loinaz et al., PRD **70** (2004) 113004

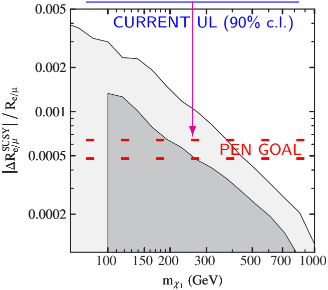
$$\Delta_{\ell\ell'} = 2\left(\frac{g_\ell}{g_{\ell'}} - 1\right)$$

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

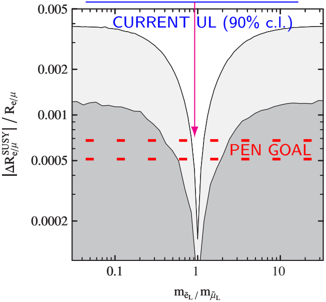
minimal selectron, smuon masses:



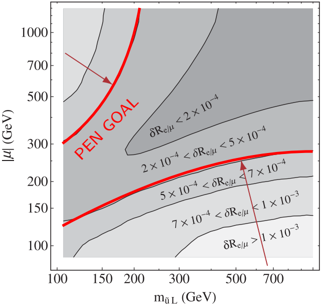
lowest mass chargino:



slepton mass degeneracy:



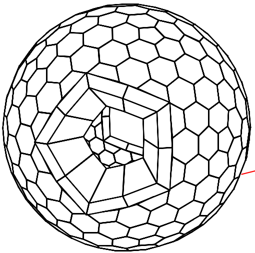
Higgsino mass param's. μ, $m_{\tilde{u}_L}$:

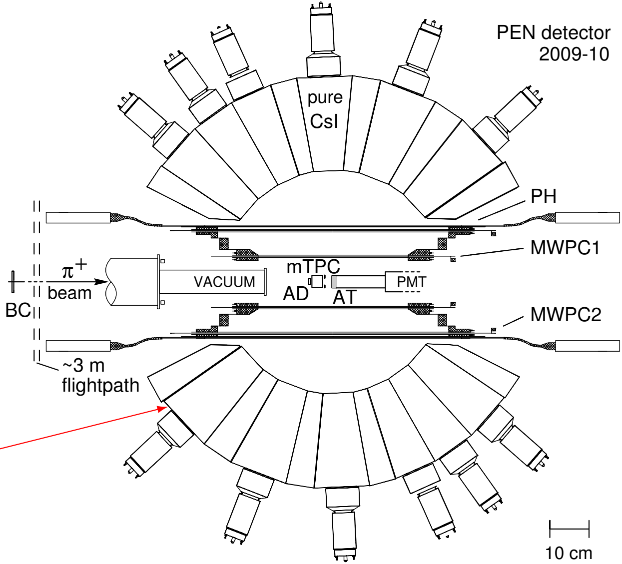


(R parity violating scenario constraints also discussed.)

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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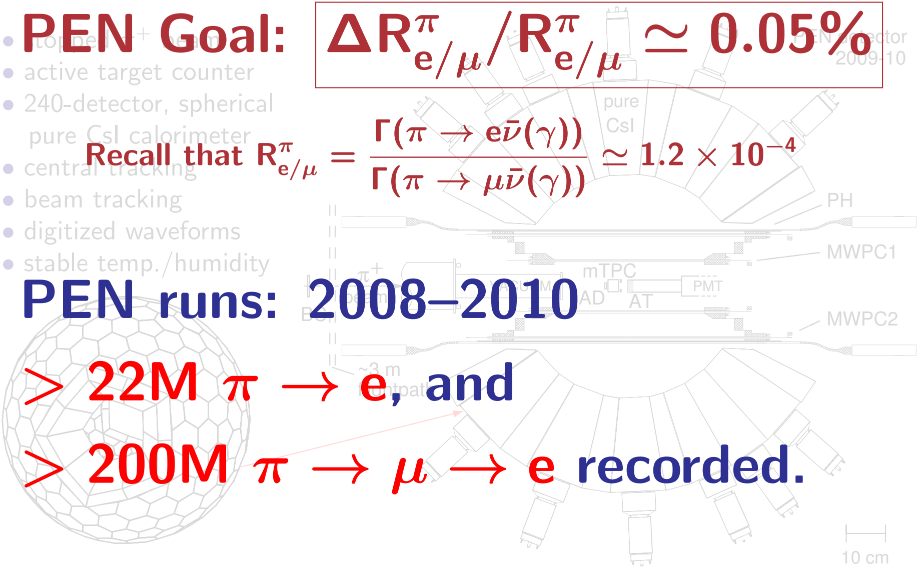


PEN Goal: $\boxed{\Delta R^{\pi}_{e/\mu}/R^{\pi}_{e/\mu} \simeq 0.05\%}$

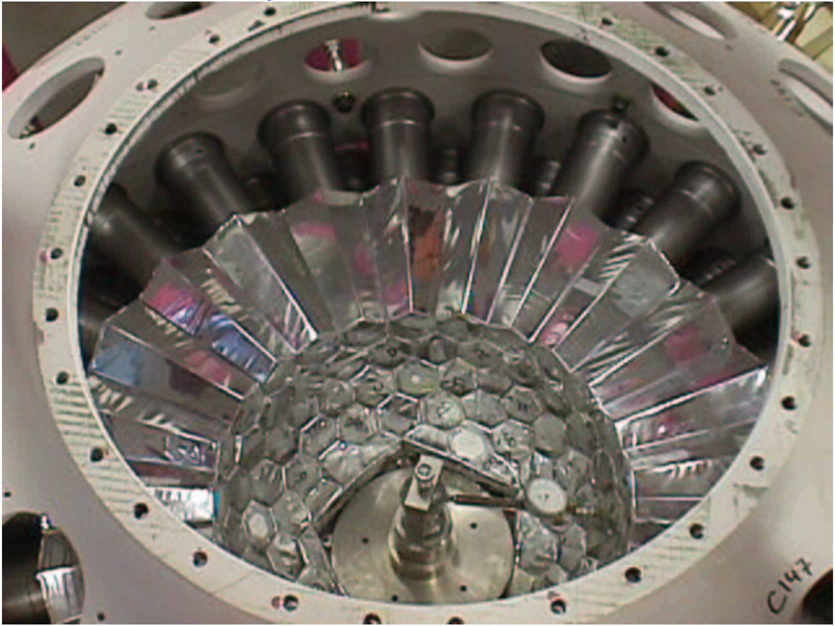
Recall that $R^{\pi}_{e/\mu} = \dfrac{\Gamma(\pi \to e\bar{\nu}(\gamma))}{\Gamma(\pi \to \mu\bar{\nu}(\gamma))} \simeq 1.2 \times 10^{-4}$

PEN runs: 2008–2010

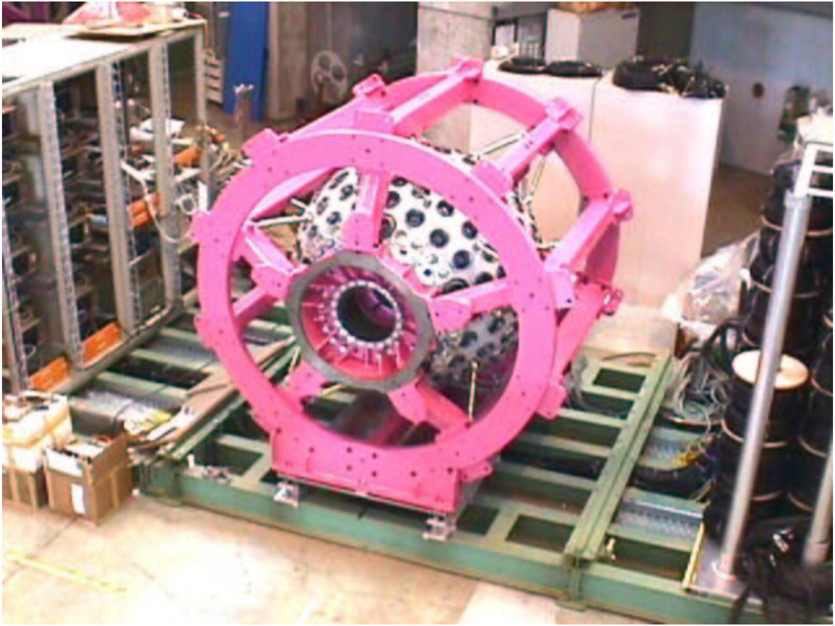
$> 22\text{M}\ \pi \to e$, **and**

$> 200\text{M}\ \pi \to \mu \to e$ **recorded.**

PIBETA Detector Assembly



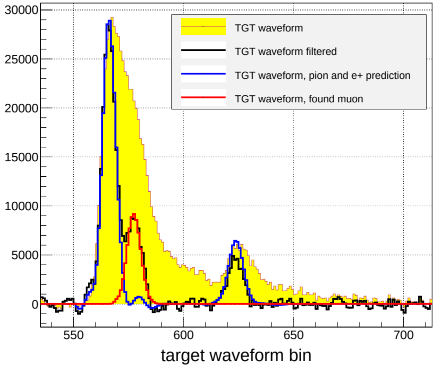
PIBETA Detector on Platform



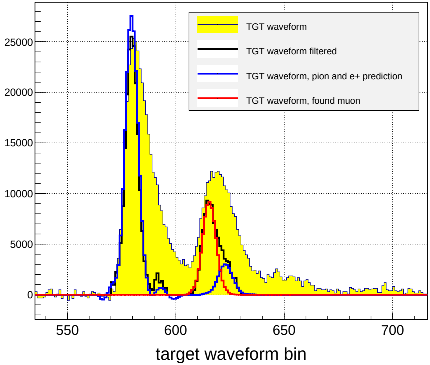
Highlights and challenges of PEN analysis (under way)

Active target waveforms: separating the decay particle pulses!

Early pion decay (extremely common)

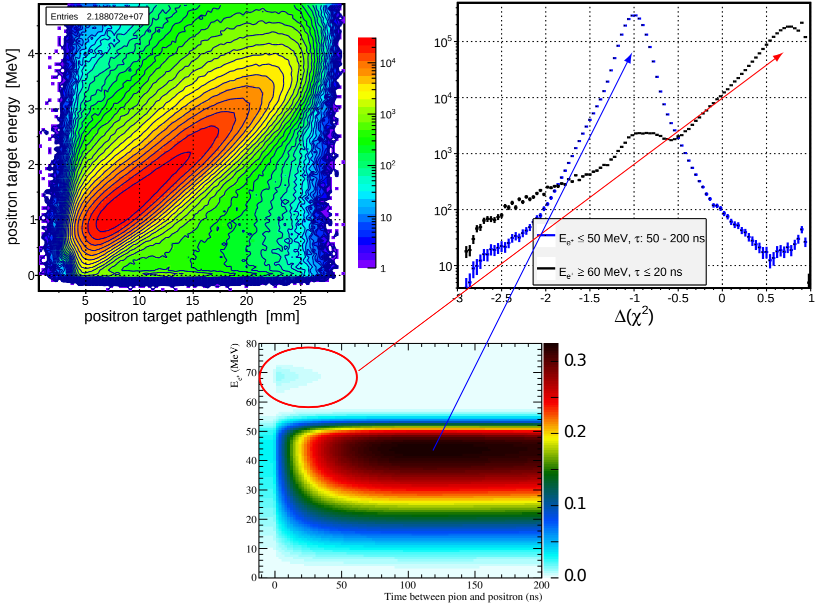


Early muon decay (still annoying)

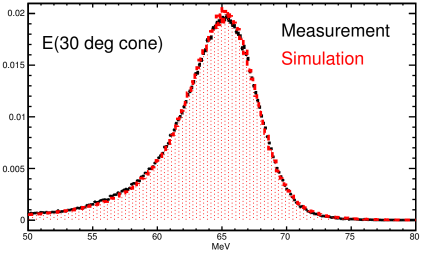


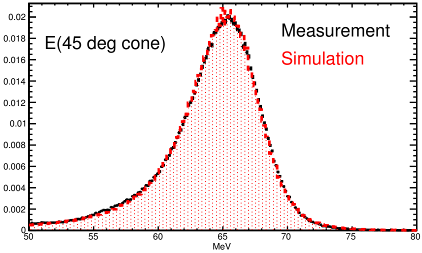
- π and e^+ pulse time and amplitude predicted from other detector systems (mTPC, MWPCs, PH)!
- Waveform system functions evaluated based on prompt hadronic events.
- Hypotheses with/without a μ pulse evaluated.

PEN: separating $\pi \to e$ and $\pi \to \mu \to e$ events

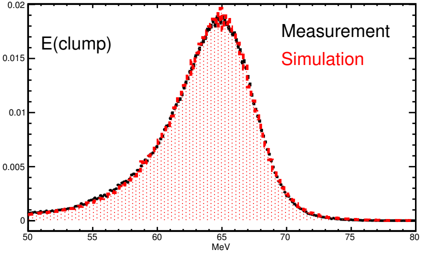


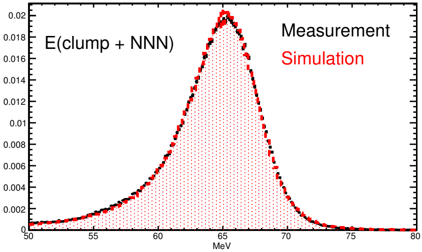
PEN: matching the 240 calorimeter modules



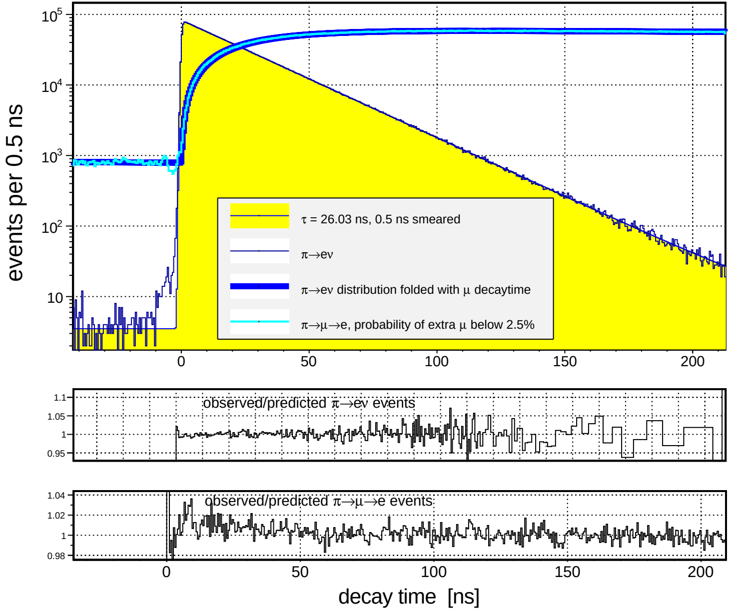


NNN = next to nearest neighbors

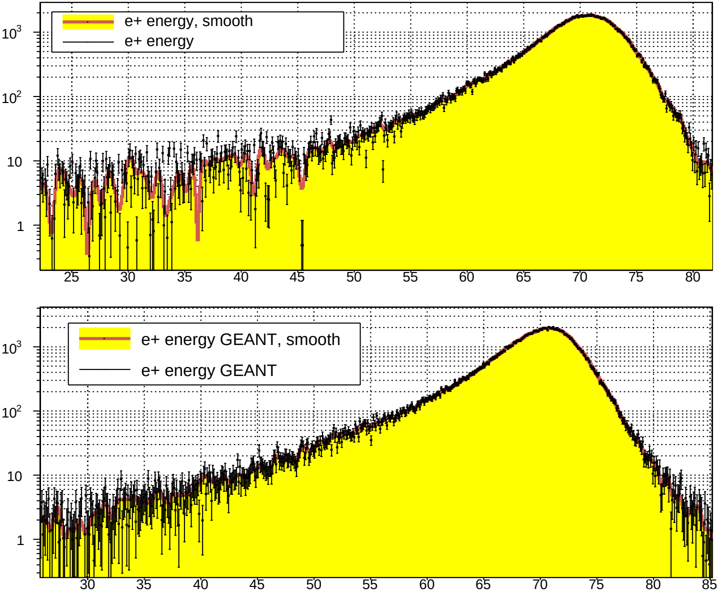




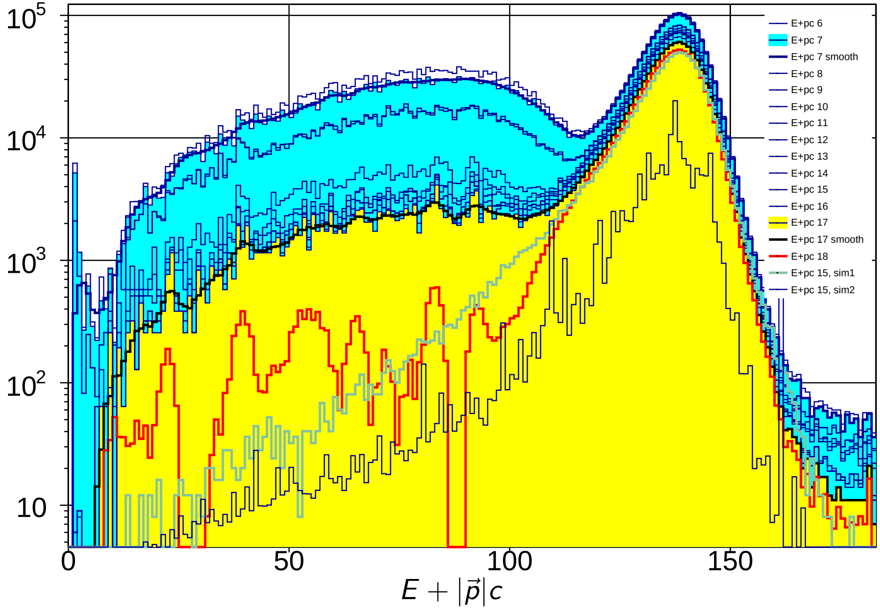
PEN: agreement with predictions (2010 data analysis)



PEN: low E "tail" response (preliminary)



PEN: "tail" in inv. mass response (1/4 data)



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

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

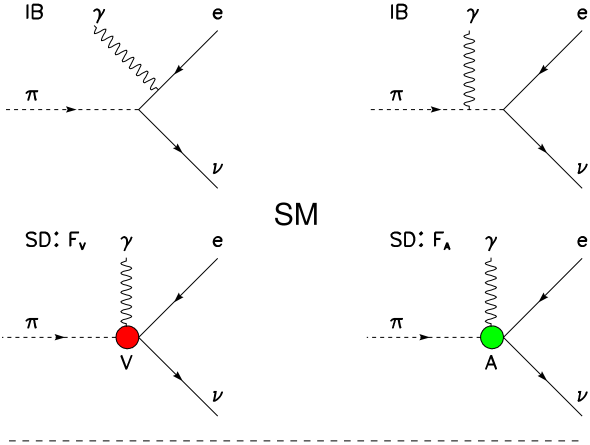
$$\mathbf{BR}_{\text{non-IB}} \sim 10^{-7}$$

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

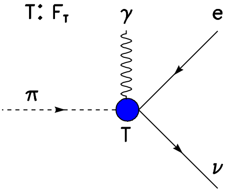
Physics of
$\pi^+ \to e^+\nu\gamma$ (RPD):

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!**):

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

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

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

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

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

Pre-2004 data on pion form factors

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

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

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$F_A \times 10^4$	reference	note
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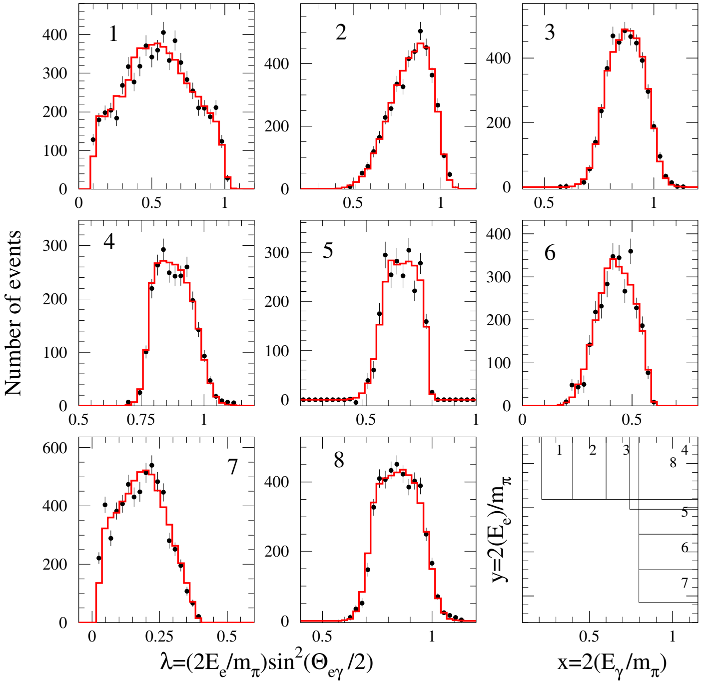
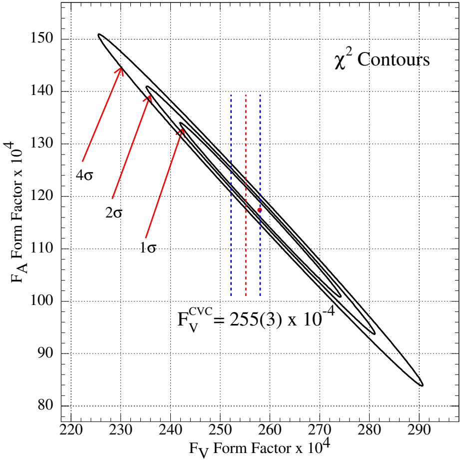
60 ± 30	Piilonen et al. (1986)	
110 ± 30	Stetz et al. (1979)	
116 ± 16	world average (PDG 2004)	

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



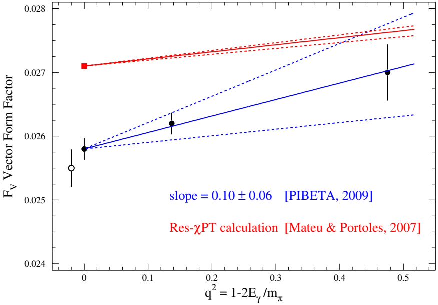
PIBETA results for $\pi \to e\nu\gamma$

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)]

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

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

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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)

Precision studies of allowed decays of pions (and muons)

- 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^{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)

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