Pion electronic decay and lepton universality

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Topics discussed in this talk

Why we study the pion electronic decay (a brief motivation)
The PEN experimental method and challenges
Current status of the PEN analysis
    A word on pion radiative decays
Near term plans and future prospects

Known and measured pion and muon decays

decay		B.R.		physics interest
$\pi^+ \to$	$\mu^+\nu$	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})	$\Leftarrow$ lepton universality, beyond SM terms (T,...)
	$e^+\nu\gamma$	$7.39(5) \times 10^{-7}$	$(\pi_{e2\gamma})$	$\Leftarrow$ BSM terms (T,...), form fact's: $F_A^{(\pi)}, F_V^{(\pi)}, \ldots$
	$\pi^0 e^+\nu$	$1.036\,(6) \times 10^{-8}$	(π_{e3})	$\Leftarrow$ quark-lepton universality (V_{ud}), BSM loops
	$e^+\nu e^+ e^-$	$3.2\,(5) \times 10^{-9}$	(π_{e2ee})	
$\pi^0 \to$	$\gamma\gamma$	0.98798 (32)		$\Leftarrow$ χ anomaly, low energy chiral parameters
	$e^+e^-\gamma$	$1.198\,(32) \times 10^{-2}$	(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)	$\Leftarrow$ beyond SM weak interaction terms
	$e^+\nu\bar{\nu}\gamma$	0.014 (4)	(RMD)	
	$e^+\nu\bar{\nu}e^+e^-$	$3.4\,(4) \times 10^{-5}$		

π_{e2} decay: SM calculations, lepton universality

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

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

- Modern SM calc's.:

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

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- Experimental world average is 23× less accurate than SM calculations! $[1.2327(23) \times 10^{-4}]$

(following publication of the PiENu result: A. Aguilar-Arevalo et al., PRL **115** (2015) 071801)

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

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

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

DIRECTLY		INDIRECTLY (LOOPS)
$\Lambda_P \leq 1000\,\text{TeV}$,	$\Lambda_A \leq 20\,\text{TeV}$	$\Lambda_S \leq 60\,\text{TeV}$.

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

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Further interesting limits on certain SUSY extensions, as well as in the neutrino sector, become accessible at $\Delta R^\pi_{e/\mu}/R^\pi_{e/\mu} < 10^{-3}$.

Summary of PiBeta and PEN goals

Goals of the **PiBeta** experiment (data runs 1999-2004):

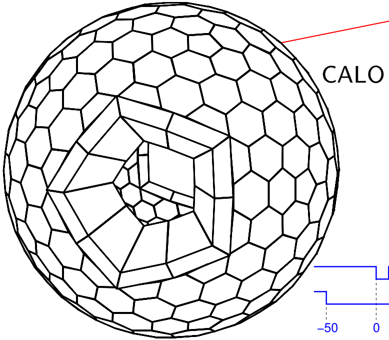
	Decay	$\mathcal{O}$(B.R.)	Goal $\delta R/R$	Attendant SM limits
$\pi_{e3(\gamma)}$:	$\pi^+ \to \pi^0 e^+ \nu_e(\gamma)$	$R^\pi_{e3(\gamma)} \sim 10^{-8}$	$\sim 5 \times 10^{-3}$	CKM V_{ud} & related
$\pi_{e2\gamma}$:	$\pi^+ \to e^+ \nu_e \gamma$	$R^\pi_{e2\gamma} \sim 10^{-7}$	$\leq 1 \times 10^{-2}$	$F^\pi_A, F^\pi_V, F^\pi_T$; χPT l.e.c.
RMD:	$\mu^+ \to e^+ \nu_e \bar{\nu}_\mu \gamma$	$R^\pi_{e2\gamma} \sim 10^{-3}$	$\leq 1 \times 10^{-2}$	Michel param.: $\bar{\eta}$

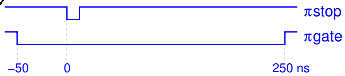
Goals of the **PEN** experiment (data runs 2008-2010):

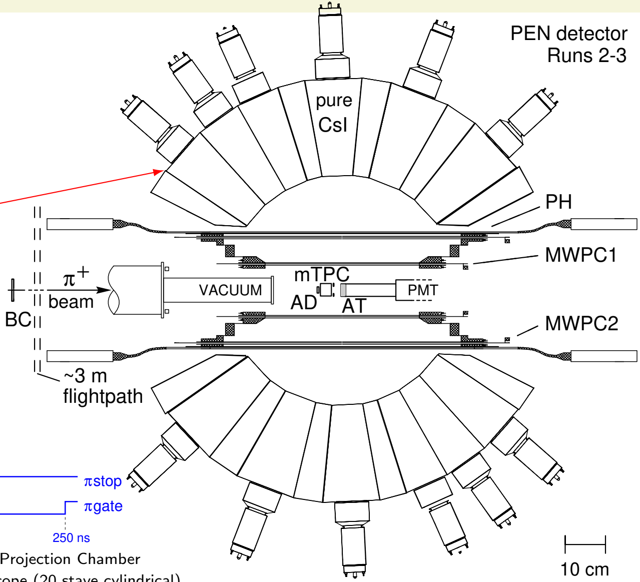
	Decay	$\mathcal{O}$(B.R.)	Goal $\delta R/R$	Attendant SM limits
$\pi_{e2(\gamma)}$:	$\pi^+ \to e^+ \nu_e(\gamma)$	$R^\pi_{e2(\gamma)} \sim 10^{-4}$	$\sim 5 \times 10^{-4}$	lept. univ.; non-$V-A$, ...
$\pi_{e2\gamma}$:	$\pi^+ \to e^+ \nu_e \gamma$	$R^\pi_{e2\gamma} \sim 10^{-7}$	$\sim 1 \times 10^{-2}$	improve F^π_V & limit on F^π_T
RMD:	$\mu^+ \to e^+ \nu_e \bar{\nu}_\mu \gamma$	$R^\pi_{e2\gamma} \sim 10^{-6}$	$\sim 1 \times 10^{-2}$	improve $\bar{\eta}$

The PEN apparatus

- πE1 beam at PSI
- stopped π^+ beam
- beam tracking
- central tracking
- beam tracking
- fast-digitized wf's
- 240-elem. $12X_0$ spherical pure-CsI calo.
- tightly controlled temp/humidity/gains



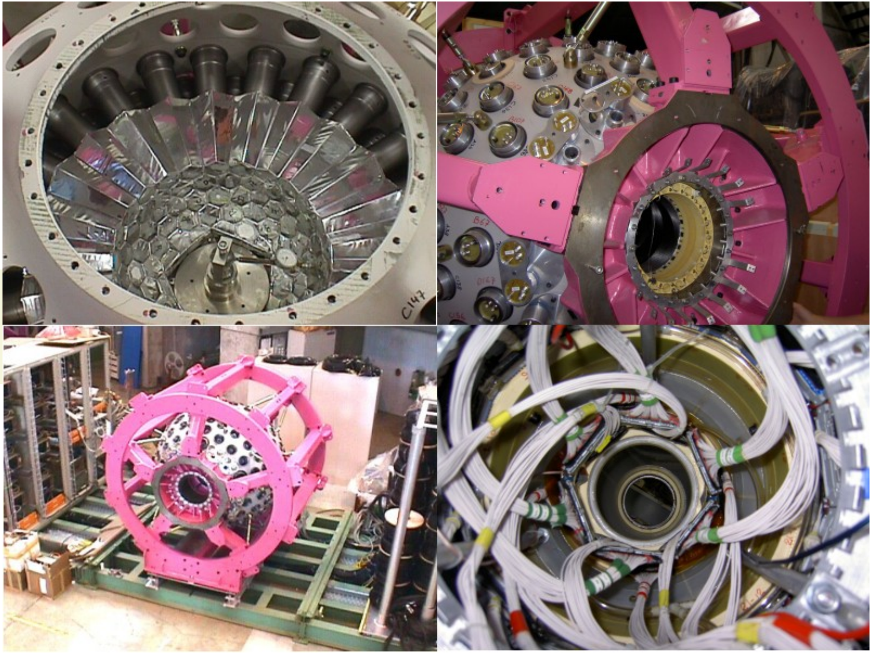




BC: Beam Counter
AD: Active Degrader
AT: Active Target

mTPC: mini-Time Projection Chamber
PH: Plastic Hodoscope (20 stave cylindrical)
MWPC: Multi-Wire Proportional Chamber (cylindrical)

A few photos of the PiBeta/PEN apparatus:



PEN measurement principles for $R^{\pi}_{e/\mu}$; key challenges

Basic principle: record pion decays at rest in a beam stopping target[1] and count each:

(a) $\pi_{e2(\gamma)}$: $\pi^+ \to e^+\nu_e(\gamma)$, and (b) $\pi_{\mu2(\gamma)}$: $\pi^+ \to \mu^+\nu_\mu(\gamma)$ decay event

during an observation time window, and evaluate the yield ratio (a)/(b), applying corrections.

- As (a) and (b) cannot be fully identified in AT alone, use CALO and tracking detectors.
- Identify (b) through the subsequent decay $\mu^+ \to e^+\nu_e\bar{\nu}_\mu(\gamma)$.

[1] A decay in flight measurement would present a wholly different set of challenges.

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Key challenges in achieving sub-10^{-3}, or sub-10^{-4} precision are of **systematic** nature:

- accurately **identify** processes (weak decay, hadronic interaction, etc.) for each event,
- accurately **count** and **sort** each type of decay event (without skipping/mislabeling any).

This requires full tracking and detection of beam and decay particles' interactions with matter.

Also required: minimizing mass (especially passive) in the particle path to AT/CALO, and maximizing detection efficiency and resolution: E, t and spatial.

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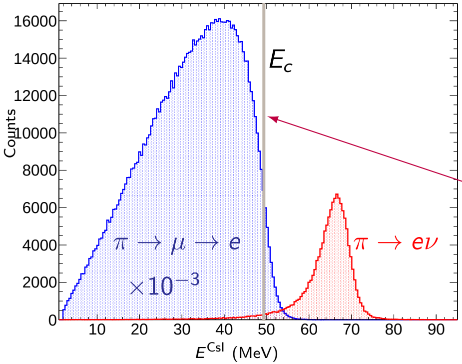
Experimental branching ratio ($R_{e/\mu}^{\pi\text{-exp}}$)

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

we have:

$$R_{e/\mu}^{\pi\text{-exp}} = \frac{N_{\pi\to e\nu}^{\text{peak}}(1+\epsilon_{\text{tail}})}{N_{\pi\to\mu\nu}} \underbrace{\frac{f_{\pi\to\mu\to e}(T_e)}{f_{\pi\to e\nu}(T_e)}}_{r_f} \underbrace{\frac{\epsilon(E_{\mu\to e\nu\bar\nu})_{\text{MWPC}}}{\epsilon(E_{\pi\to e\nu})_{\text{MWPC}}}}_{r_{\text{PC}}} \underbrace{\frac{A_{\pi\to\mu\to e}}{A_{\pi\to e\nu}}}_{r_A} \underbrace{\frac{\epsilon_{\text{pileup}}}{\epsilon_{\delta\chi^2}}}_{r_{\text{cut}}}$$



E_c = cutoff energy

N = number of events

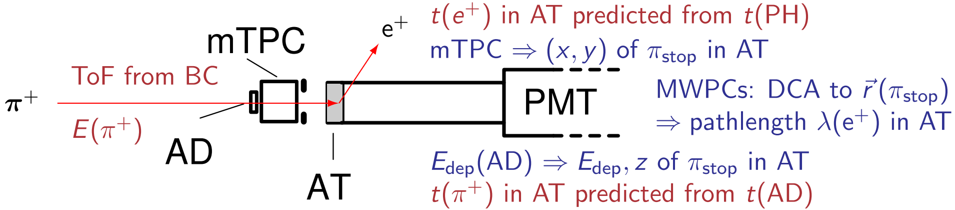
A = acceptance

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

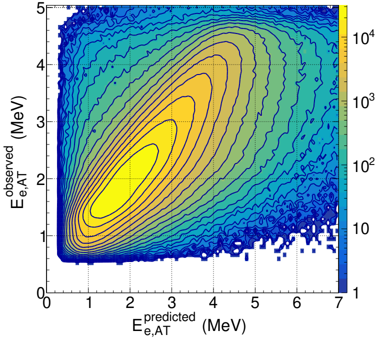
$\epsilon(E)_{\text{MWPC}}$ = efficiency of MWPC

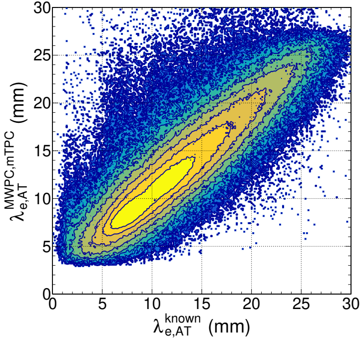
$f(T_e)$ = probability from time

Discriminating π_{e2} and $\pi_{\mu2}$ in active target (AT)



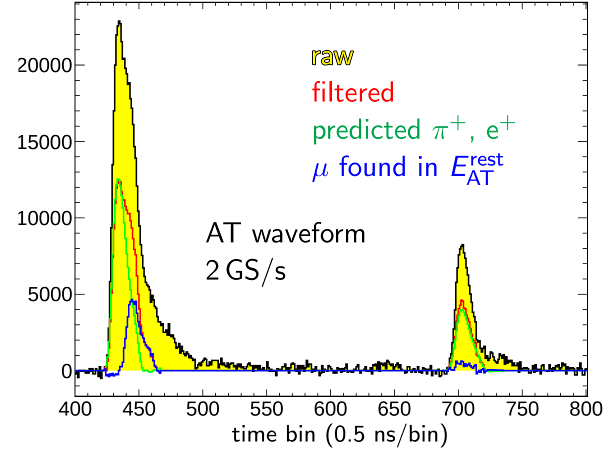
Predicted/known and reconstr. $\boldsymbol{\pi^+}$, $\mathbf{e^+}$ energies/pathlengths in AT agree VERY well:

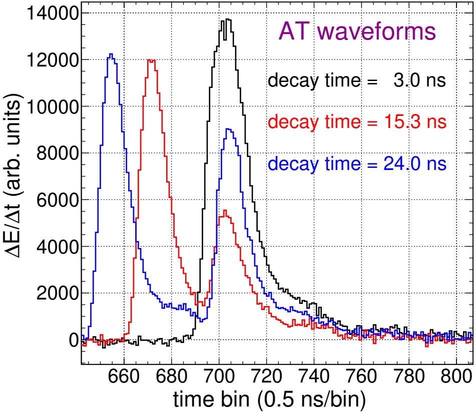




$\Rightarrow$ E and t predictions are used for $\pi_{e2}/\pi_{\mu2}$ discrimination.

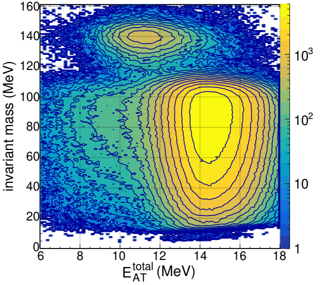
Decay type discrimination and target waveforms

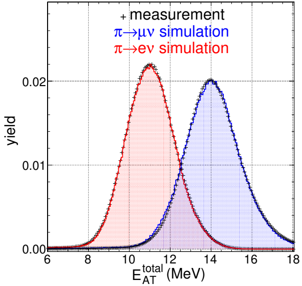


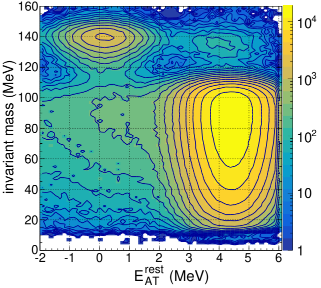


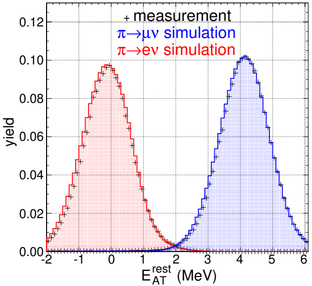
$E_{AT}^{rest} = E_{AT}^{total} - (E_{\pi,AT}^{predicted} + E_{e,AT}^{predicted})$ is evaluated binwise, and scanned to test for presence of μ peak: $\Delta\chi^2 \propto \chi^2_{3\text{-peak}} - \chi^2_{2\text{-peak}}$ (normalized); calculated binwise for each event/waveform (no fit!).

Select stages of suppressing $\pi_{\mu 2}$ decays in the π_{e2} "tail"



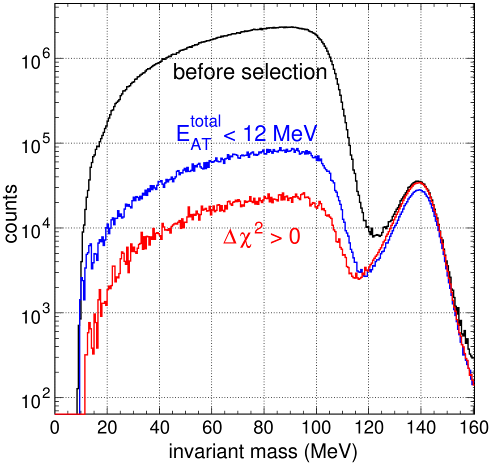




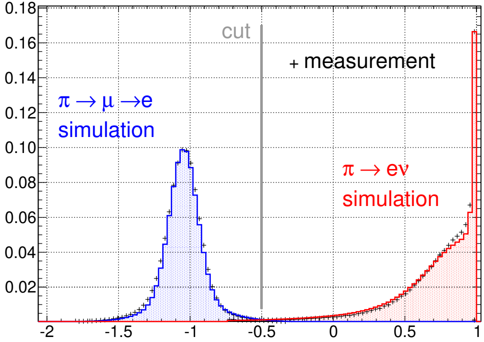


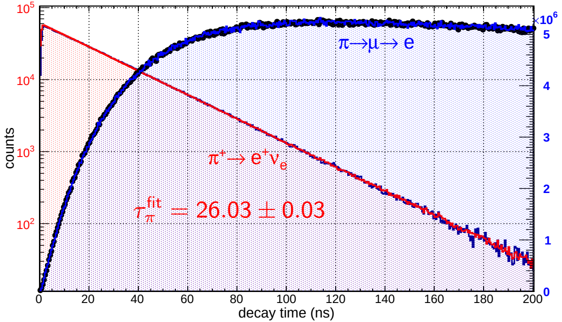
Recall: $E_{AT}^{rest} = E_{AT}^{total} - (E_{\pi,AT}^{predicted} + E_{e,AT}^{predicted})$

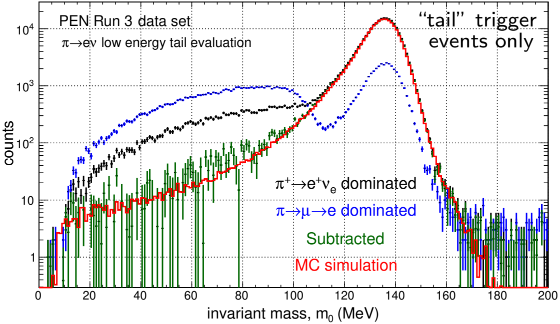
$\Delta\chi^2$ sensitive to presence of μ peak



Results of $\Delta\chi^2$ $\pi_{e2}/\pi_{\mu 2}$ sorting



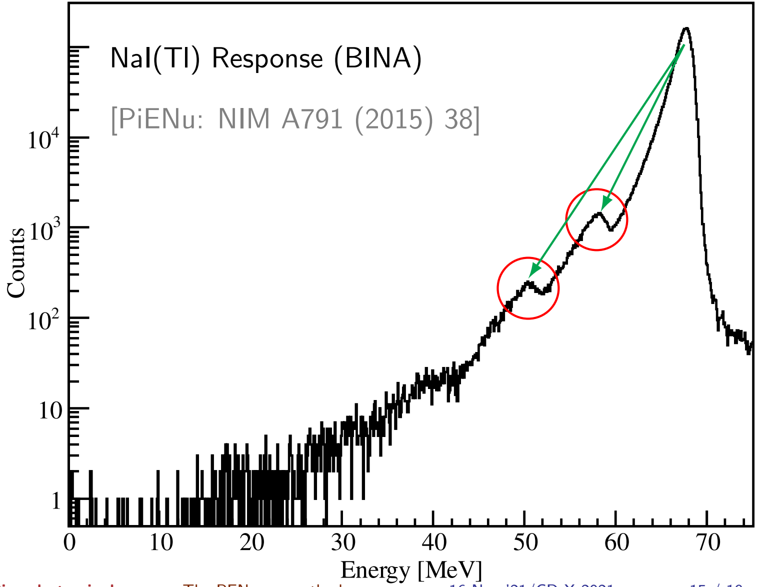




Exp. subtracted "tail" not accurate enough!
⇒ must rely on simulations for final ×4 factor.

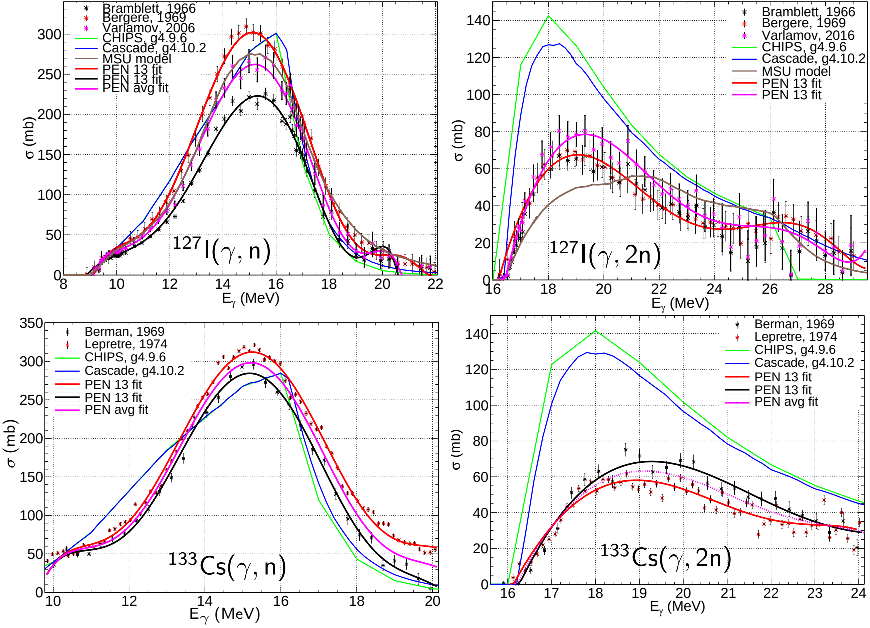
Tail fraction: photoneutron reactions

(γ, xn) reactions on calorimeter nuclei, Cs and I, shift counts from the main peak to the "tail" region if the neutrons are undetected.



Photoneutron cross sections, $\sigma(\gamma, xn)$

- Many inconsistencies among the data sets;
- Geant4 descriptions inadequate, often miss data by a wide margin.
- PEN was forced to implement its own parametrization in Geant4 (C. Glaser).
- This procedure works at the PEN goal precision, but would be inadequate at higher precision.



Current status of the PEN uncertainty analysis

Type	Observable	Value	$\Delta R^{\pi}_{e/\mu}/R^{\pi}_{e/\mu}$
Systematic:	$\Delta\epsilon_{\text{tail}}$: low-$E$ "tail" fraction*	$\simeq 0.038$	$\simeq 0.001^{\text{exp}}$; $2\times 10^{-4}\big\|^{\text{MC}}_{\text{goal}}$
	r_f: observed decay fractions	0.0441	$< 10^{-4}$
	r_{PC}: ratio of MWPC efficiencies	$\simeq .99$	$< 10^{-4}$
	r_A: acceptance ratio (blinded)	$\simeq 1$	$\leq 10^{-4}$
	r_{cut}: cut efficiency ratio	$\simeq 1.0153$	$\leq 4\times 10^{-4}$
	$N_{\pi_{\text{DIF}}\to e\nu}/N_{\pi\to e\nu}\ \|^{\dagger}$	$< 2\times 10^{-3}$	$10^{-6} - 10^{-5}$
	$N_{\pi_{\text{DIF}}\to \mu\nu}/N_{\pi\to \mu\nu}\ \|^{\dagger}$	2.3×10^{-3}	$10^{-6} - 10^{-5}$
	$N_{\mu_{\text{DIF}}\to e\nu\bar{\nu}}/N_{\mu\to \nu\bar{\nu}}\ \|^{\dagger}$	1.4×10^{-4}	$< 10^{-5}$
Statistical:	$\Delta N_{\pi\to e\nu}/N_{\pi\to e\nu}$		$\simeq 3\times 10^{-4}$
Overall	goal		5×10^{-4}

* Depends on the invariant mass cutoff, here $m_0 = 117.5$ MeV, which minimizes overall uncertainty.

† π_{DIF}: pion decay in flight; μ_{DIF}: muon decay in flight .

Radiative decays: physics rich, accessible in PEN

1. $\pi^+ \to e^+\nu_e\gamma$ and 2. $\mu^+ \to e^+\nu_e\bar{\nu}_\mu\gamma$.

Arguably our most impactful result to date is the high precision measurement of $R^{\pi}_{e2\gamma}$ and limit on F_T that has provided the best constraint on ϵ_T, the weak **tensor** coupling.

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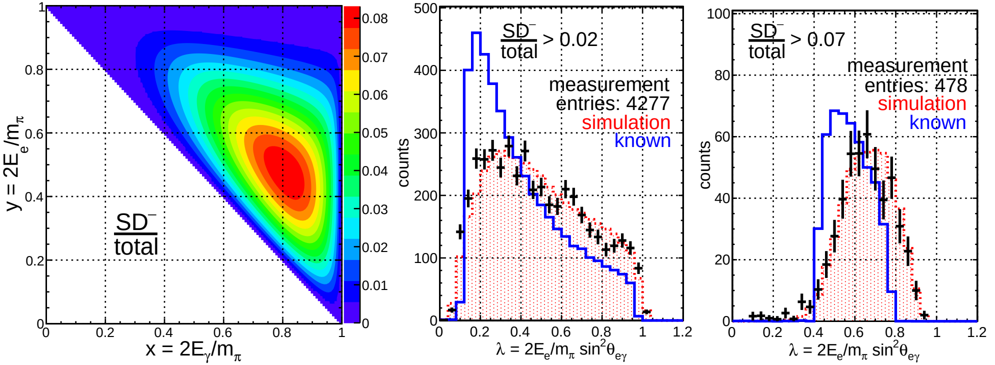
New PEN data (subset below) offer first glimpse at elusive $SD^- \propto (F_V - F_A)^2$ term:



Summary and prospects

- The blinded PEN analysis is in the final round of parameter tuning, and checks of efficiencies, acceptancies, and all relevant systematics.
- Prior to unblinding, PEN collaboration plans to publish a series of technical papers presenting details of analysis underpinning the $R^{\pi}_{e/\mu}$ evaluation. First in the series [Glaser et al., NIM A **1010** (2021) 165460] focused on performance of the mTPC and its impact on $R^{\pi}_{e/\mu}$ systematics. Papers on G4 MC simulation, AT wf processing, calorimeter, photoneutron corrections, etc., are under preparation.
- PEN analysis is on course to reach the target precision of $\Delta R^{\pi}_{e/\mu}/R^{\pi}_{e/\mu} \simeq 5 \times 10^{-4}$.
- PiENu collaboration at TRIUMF has published a $\Delta R^{\pi}_{e/\mu}/R^{\pi}_{e/\mu} \simeq 2.4 \times 10^{-3}$ result [Aguilar-Arevalo et al., PRL **115** (2015) 071901] in excellent agreement with SM predictions. PiENu plan to produce an improved result in the near future.
- In addition to $R^{\pi}_{e/\mu}$, PEN collaboration plans to produce new physics results in radiative π and μ decays.
- The physics of PEN and PiBeta remains germane as ever. PIONEER, a new experiment with a large acceptance fast CALO, is under preparation (LoI stage) [Mazza, arXiv:2111.05375]. Stay tuned!

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