Fundamental tensor charge from pion electronic decays

with prospects for using machine learning

Dinko Počanić

University of Virginia

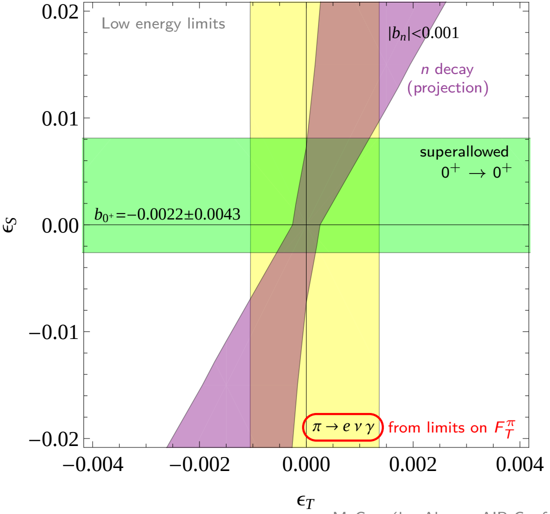
22 July 2026

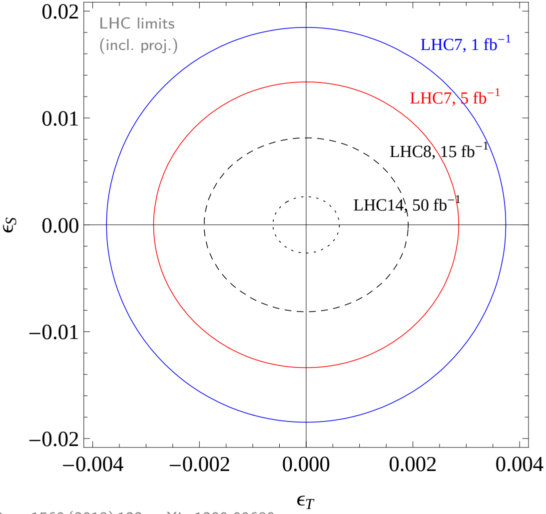
5th Workshop on Hadron Femtography
University of Virginia, Charlottesville, Virginia
20 – 24 July 2026

Topics discussed in this talk

Why focus on the pion electronic (radiative) decay?

Select limits on fund. non-SM couplings (not including recent n/nucl. results discussed by Stefan B):





M. González-Alonso, AIP Conf Proc 1560 (2013) 122, arXiv:1209.00689

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: $F_A^{(\pi)}, F_V^{(\pi)}$,...
	$\pi^0 e^+\nu$	$1.036\,(6) \times 10^{-8}$	(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.:

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

π_{e2} decay: SM calculations, lepton universality

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

$$R^{\pi}_{e/\mu} = \frac{\Gamma(\pi \to e\bar{\nu}(\gamma))}{\Gamma(\pi \to \mu\bar{\nu}(\gamma))} = \frac{g_e^2}{g_\mu^2} \underbrace{\frac{m_e^2}{m_\mu^2}}_{\sim 2.5 \times 10^{-5}} \frac{(1 - m_e^2/m_\mu^2)^2}{(1 - m_\mu^2/m_\pi^2)^2} (1 + \delta R_{e/\mu})$$

- Modern SM calc's.:

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

- Strong SM **helicity suppression** amplifies sensitivity to PS terms ("door" for New Physics) by factor $2m_\pi^2/[m_e(m_u + m_d)] \approx 11,000$.

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

$$R^{\pi}_{e/\mu} = \frac{\Gamma(\pi \to e\bar{\nu}(\gamma))}{\Gamma(\pi \to \mu\bar{\nu}(\gamma))} = \frac{g_e^2}{g_\mu^2}\underbrace{\frac{m_e^2}{m_\mu^2}}_{\sim 2.5\times 10^{-5}}\frac{(1-m_e^2/m_\mu^2)^2}{(1-m_\mu^2/m_\pi^2)^2}(1+\delta R_{e/\mu})$$

- Modern SM calc's.:

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

- Strong SM **helicity suppression** amplifies sensitivity to PS terms ("door" for New Physics) by factor $2m_\pi^2/[m_e(m_u+m_d)] \approx 11,000$.
- $\boldsymbol{R^{\pi}_{e/\mu}}$ tests lepton universality: in SM **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); repercussions also in the neutrino sector, SUSY, ALPS ...

π_{e2} decay: SM calculations, lepton universality

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

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

$\sim 2.5 \times 10^{-5}$

- Modern SM calc's.:

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

- Strong SM **helicity suppression** amplifies sensitivity to PS terms ("door" for New Physics) by factor $2m_\pi^2/[m_e(m_u + m_d)] \approx 11,000$.
- $\boldsymbol{R^{\pi}_{e/\mu}}$ tests lepton universality: in SM **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); repercussions also in the neutrino sector, SUSY, ALPS . . .
- 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)

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

(Λ_i . . . scale of NP)

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

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

(Λ_i . . . scale of NP)

CKM unitarity and superallowed Fermi nuclear decays currently limit:

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

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

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

(Λ_i ... 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 sensitive to:

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

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

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

(Λ_i . . . 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 sensitive to:

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

In general multi-Higgs models with uniform charged Higgs couplings $\lambda_{e\nu} \approx \lambda_{\mu\nu} \approx \lambda_{\tau\nu}$,

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

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

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

(Λ_i . . . 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 sensitive to:

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

In general multi-Higgs models with uniform charged Higgs couplings $\lambda_{e\nu} \approx \lambda_{\mu\nu} \approx \lambda_{\tau\nu}$,

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

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 objectives

Goals of the **PiBeta** experiment

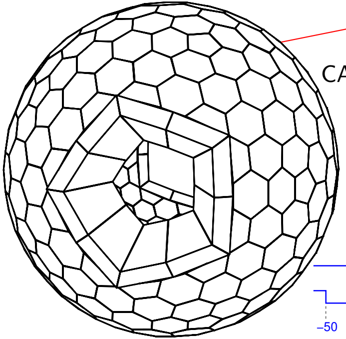
	Decay	$\mathcal{O}$(B.R.)	Goal $\delta R/R$	Attendant SM limits
$\pi_{e3(\gamma)}$:	$\pi^+ \to \pi^0 e^+ \nu_e(\gamma)$	$R^{\pi}_{e3(\gamma)} \sim 10^{-8}$	$\sim 5 \times 10^{-3}$	CKM V_{ud} & related
$\pi_{e2\gamma}$:	$\pi^+ \to e^+ \nu_e \gamma$	$R^{\pi}_{e2\gamma} \sim 10^{-7}$	$\leq 1 \times 10^{-2}$	$F^{\pi}_A, F^{\pi}_V, F^{\pi}_T$; 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.: $\bar{\eta}$

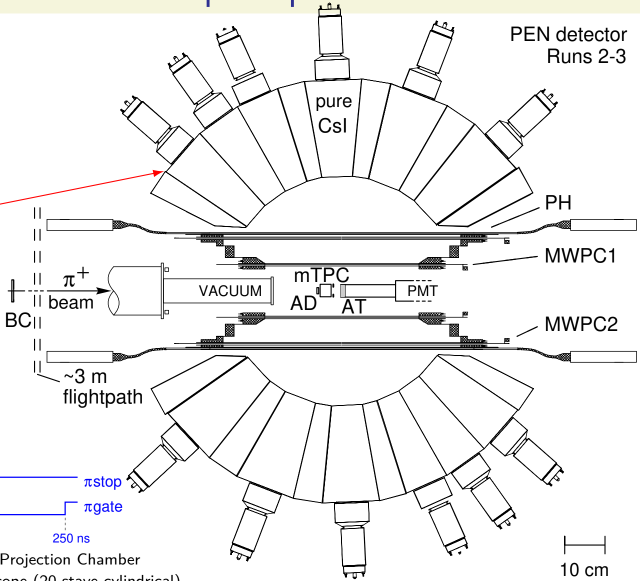
Goals of the **PEN** experiment:

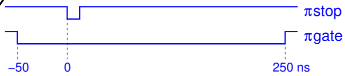
	Decay	$\mathcal{O}$(B.R.)	Goal $\delta R/R$	Attendant SM limits
$\pi_{e2(\gamma)}$:	$\pi^+ \to e^+ \nu_e(\gamma)$	$R^{\pi}_{e2(\gamma)} \sim 10^{-4}$	$\sim 5 \times 10^{-4}$	lept. univ.; non-$V{-}A$, ...
$\pi_{e2\gamma}$:	$\pi^+ \to e^+ \nu_e \gamma$	$R^{\pi}_{e2\gamma} \sim 10^{-7}$	$\sim 1 \times 10^{-2}$	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/PiBeta apparatus and measurement principles

- 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



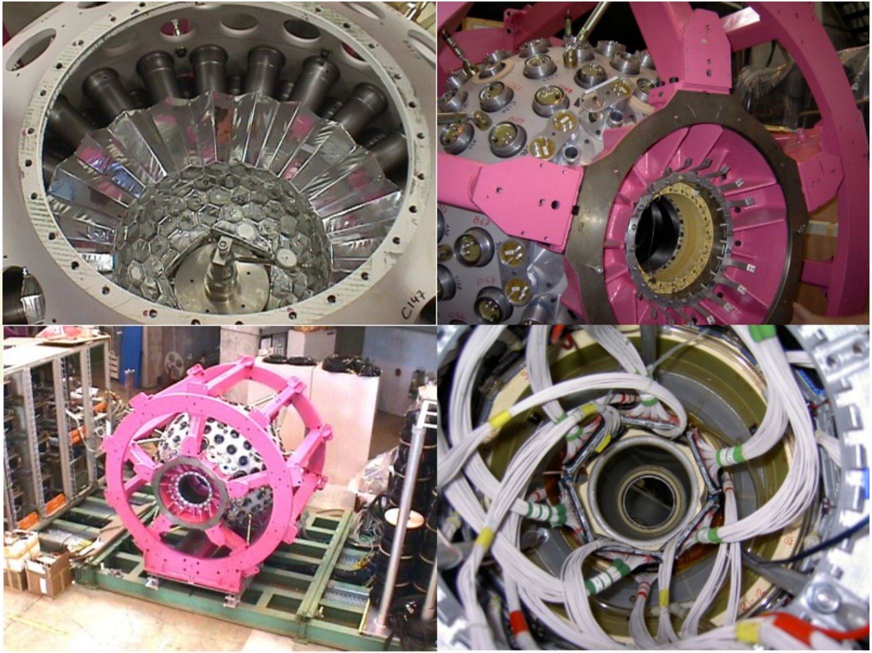




BC: Beam Counter
AD: Active Degrader
AT: Active Target

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.

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:

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

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 $\mu^+ \to e^+\nu_e\bar{\nu}_\mu(\gamma)$.

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.

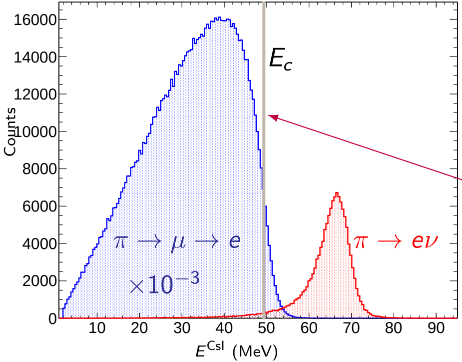
Also required: minimizing mass (especially passive) in the particle path to AT/CALO, and maximizing detection efficiency and resolution: E, t and spatial.

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

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

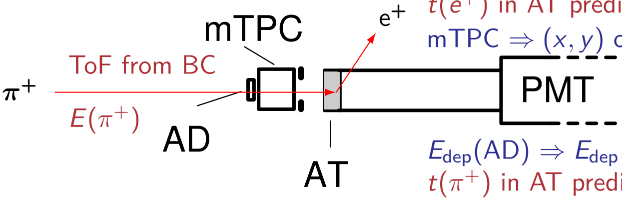
N = number of events

A = acceptance

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

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

$f(T_e)$ = probability from time



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

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

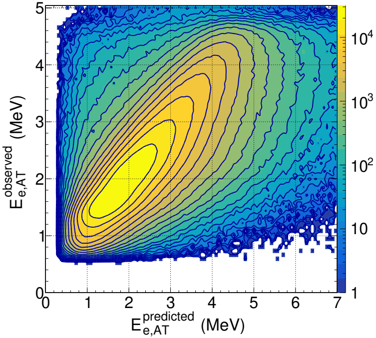
dist. closest approach

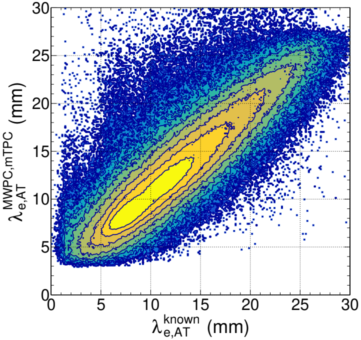
MWPCs: DCA to $\vec{r}(\pi_{stop})$ $\Rightarrow$ pathlength $\lambda(e^+)$ in AT

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

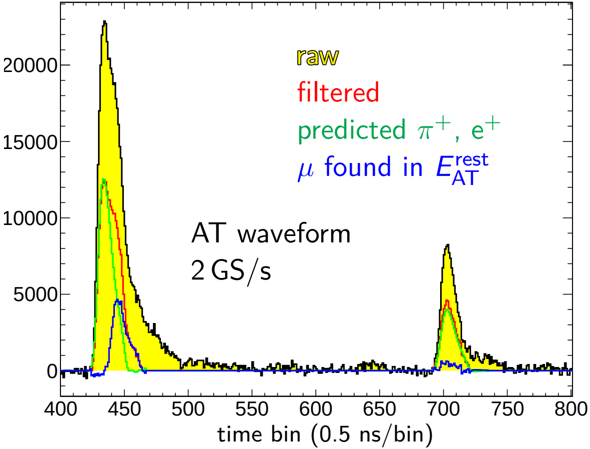
$t(\pi^+)$ in AT predicted from t(AD)

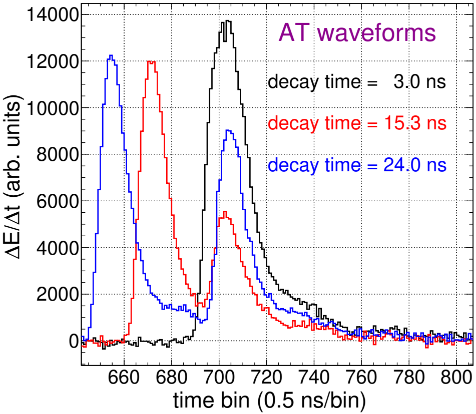
Predicted/known and reconstr. π^+, e^+ energies/pathlengths in AT agree VERY well:





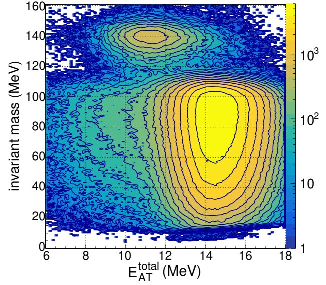
$\Rightarrow$ E and t predictions are used for $\pi_{e2}/\pi_{\mu 2}$ discrimination.

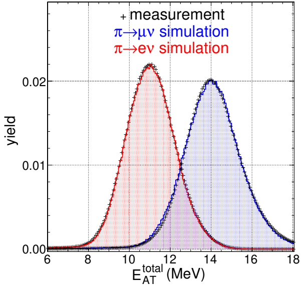


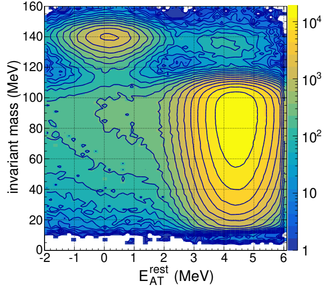


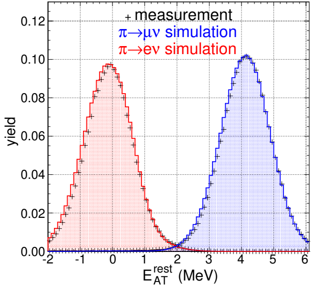
$E_{AT}^{rest} = E_{AT}^{total} - (E_{\pi,AT}^{predicted} + E_{e,AT}^{predicted})$ is evaluated binwise, and scanned to test for presence of μ peak: $\Delta\chi^2 \propto \chi^2_{3\text{-peak}} - \chi^2_{2\text{-peak}}$ (normalized); calculated binwise for each event/waveform (no fit!).

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



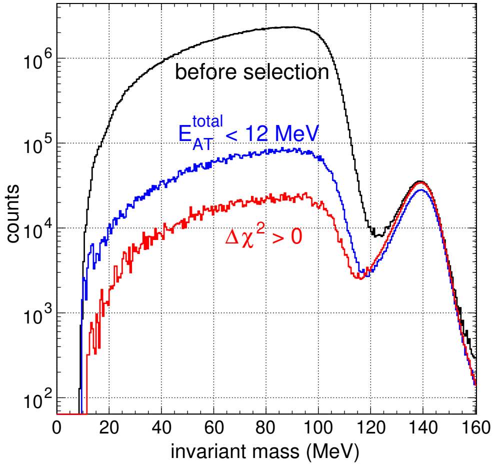




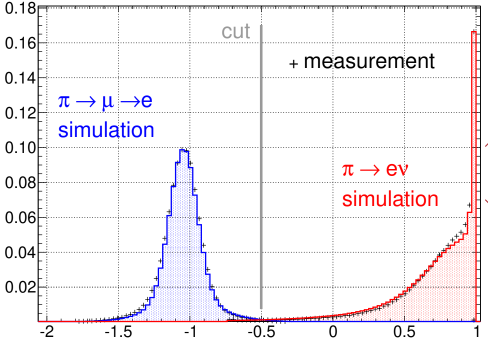


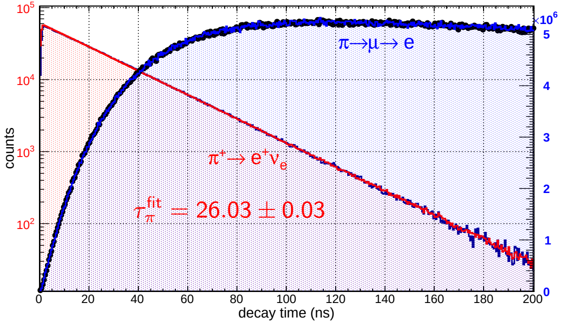
Recall: $E_{AT}^{rest} = E_{AT}^{total} - (E_{\pi,AT}^{predicted} + E_{e,AT}^{predicted})$

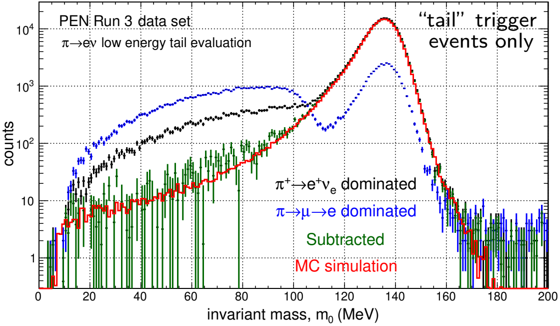
$\Delta\chi^2$ sensitive to presence of μ peak



Results of $\Delta\chi^2$ $\pi_{e2}/\pi_{\mu2}$ sorting







Exp. subtracted "tail" not accurate enough!

$\Rightarrow$ must rely on simulations for final $\times 4$ factor.

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

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

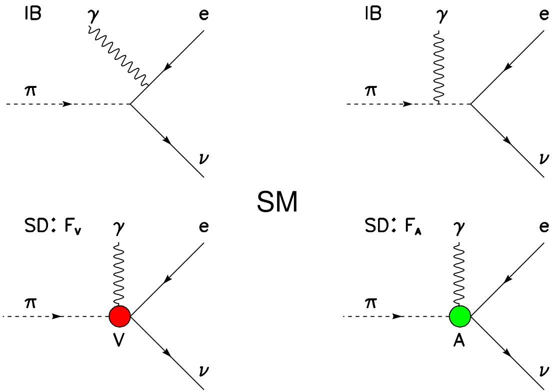
$$BR_{\text{non-IB}} \sim 10^{-7}$$

(unavoidable part of $\pi \to e\nu$ decay)

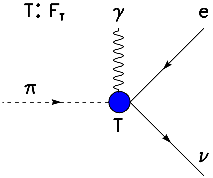
Physics of $\pi^+ \to e^+\nu\gamma$ (RPD):

QED IB terms:

and SD V, A terms:



A tensor interaction, too?



Exchange of S=0 leptoquarks

P Herczeg, PRD 49 (1994) 247

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

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

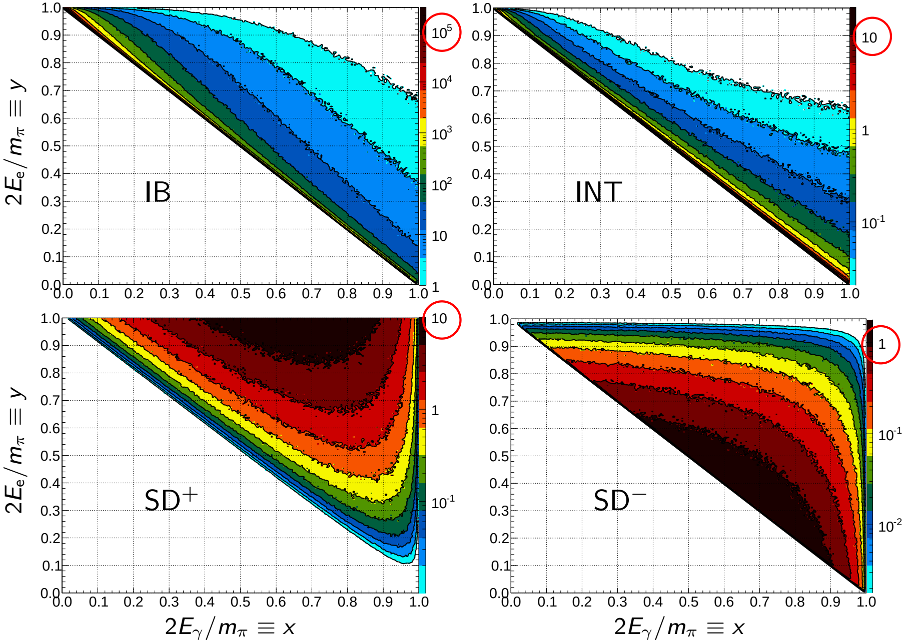
The structure-dependent amplitude (**interesting!**):

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

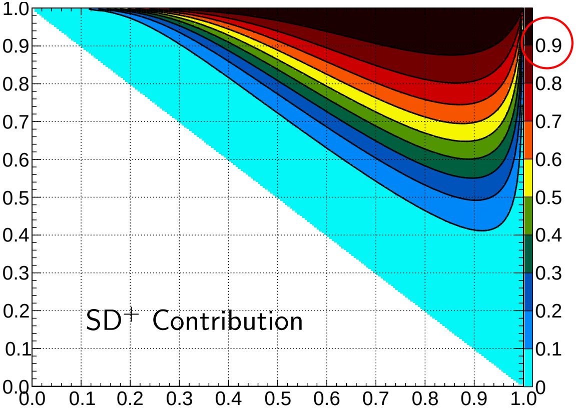
The SM branching ratio (with $x = 2E_\gamma/m_\pi$; $y = 2E_e/m_\pi$),

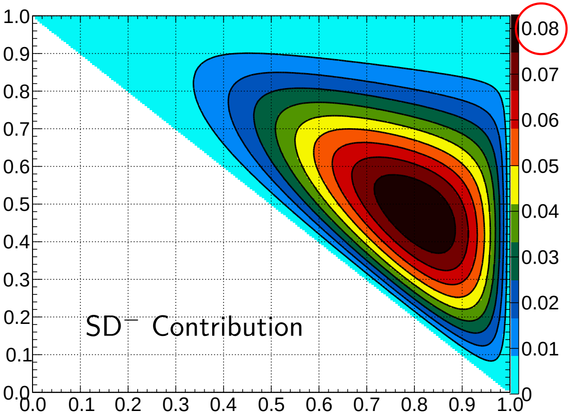
$$\frac{d\Gamma_{\pi e2\gamma}}{dx\,dy} = \frac{\alpha}{2\pi}\Gamma_{\pi e2}\Big\{ IB\,(x,y) + \left(\frac{m_\pi^2}{2f_\pi m_e}\right)^2 \times \left[(F_V+F_A)^2\, \boldsymbol{SD^+}\,(x,y) + (F_V-F_A)^2\, SD^-\,(x,y) \right] + \frac{m_\pi}{f_\pi}\left[(F_V+F_A)\, S^+_{\rm int}\,(x,y) + (F_V-F_A)\, S^-_{\rm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

Pion radiative decay regions



Best sensitivity for SD terms





SD^+ region favors high energy e^+ and γ's.

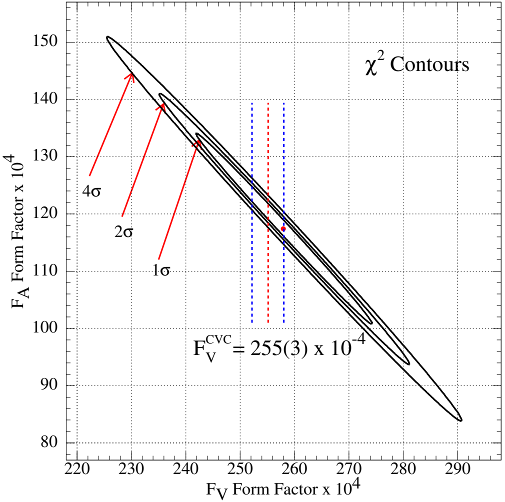
High energy track pairs occur with large opening angles.

Large solid angle coverage required $\Rightarrow$ good match to PEN!

SD^- is notoriously hard to measure directly.

PiBeta results for $\pi \to e\nu\gamma$ (PRL 2009)

Pion FF values and precision improvement factors (PIF) over previous work:

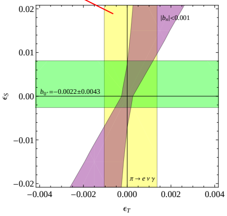


Observable	(PIF)
$F_V = 0.0258(17)$	$(8\times)$
$F_A = 0.0119(1)^{\text{exp}}_{(F_V^{CVC})}$	$(16\times)$
$a = 0.10(6)$ *	(∞)
$-5.2 < 10^4 \cdot F_T < 4.0$	90 % c.l.
$B_{\pi_{e2\gamma}} = 73.86(54) \times 10^{-8}$ †	$(17\times)$

* a . . . q^2 dependence of F_V

† for ($E_\gamma > 10$ MeV, and $\theta_{e\gamma} > 40°$)

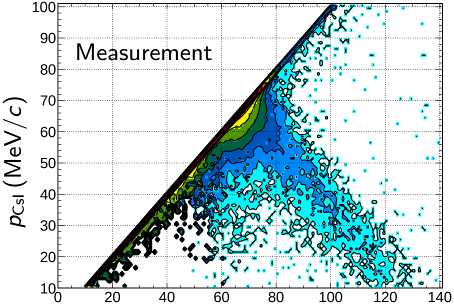
[Bychkov et al., PRL **103** (2009) 051802]



How can we do better?

$\Rightarrow$ make use of the PEN data.

Identifying hard radiative decays in PEN

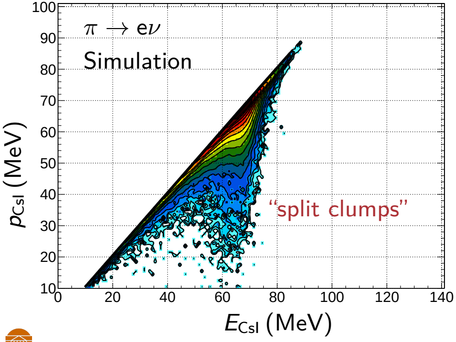


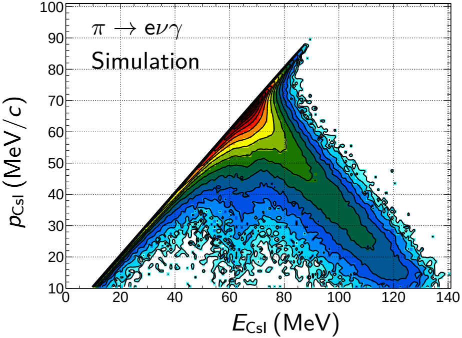
PEN indirectly measures p_ν in $\pi \to e\nu\gamma$

$\vec{p}_e + \vec{p}_\gamma = -\vec{p}_\nu \equiv \vec{p}_{obs}$; with:

$E_e + E_\gamma \equiv E_{obs}$

$E_{obs} + p_{obs}c = m_\pi c^2$

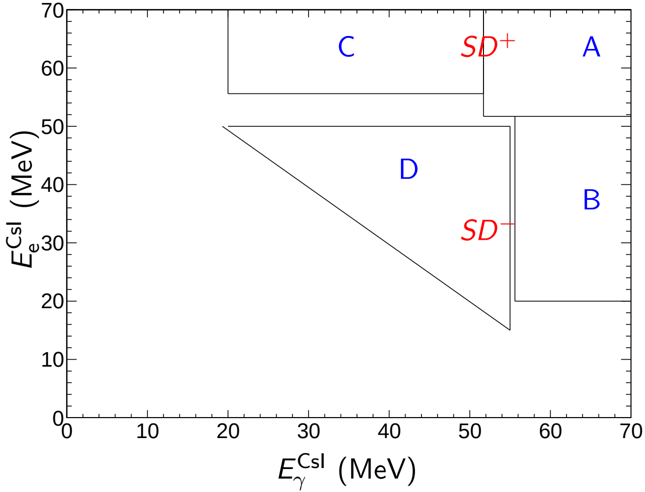




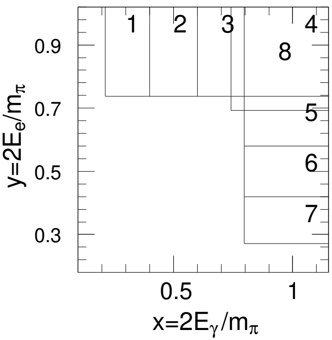
split clump: a photon separates and induces a detached shower

(analysis: C. Glaser)

Data regions (in PiBeta and PEN)



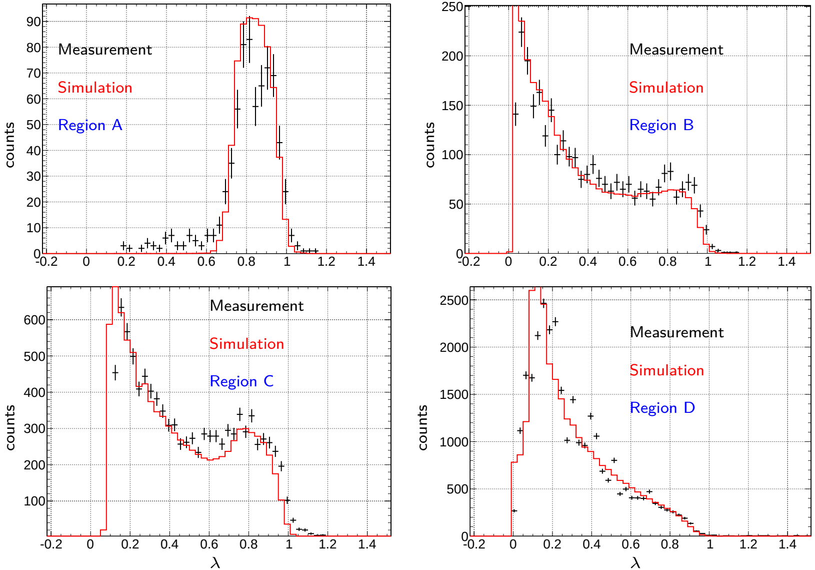
PiBeta final subdivision:



PiBeta (1999-01, 2004): regions A, B, and C.

[B was problematic in 1999-01 ⇒ resolved with 2004 data set].

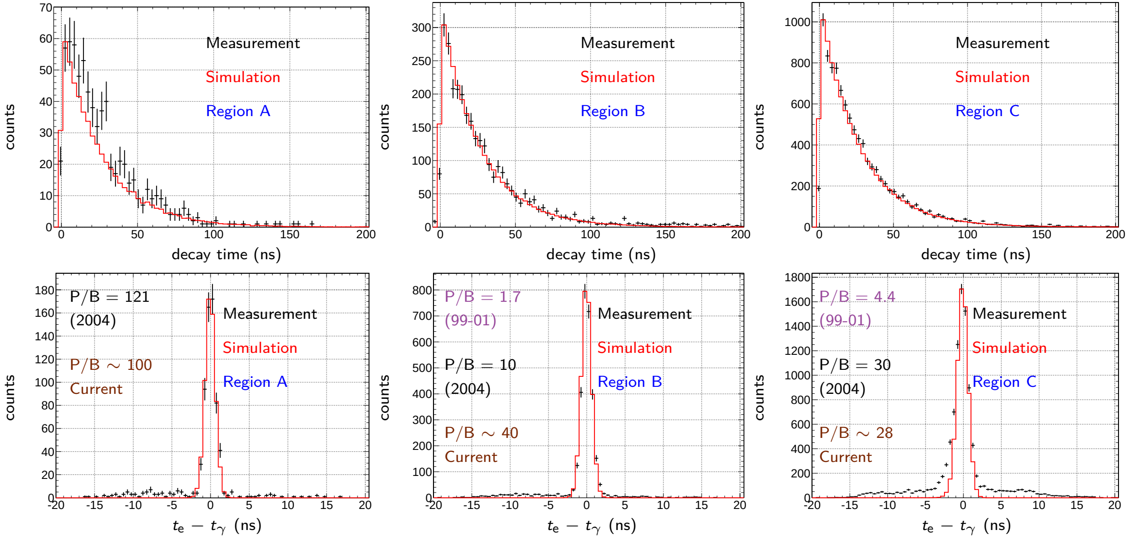
PEN Run 3 data



$$\lambda = 2E_e/m_\pi \sin^2(\theta_{e\gamma})$$

(C. Glaser)

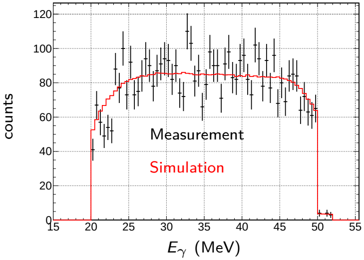
Timing for radiative decays in PEN

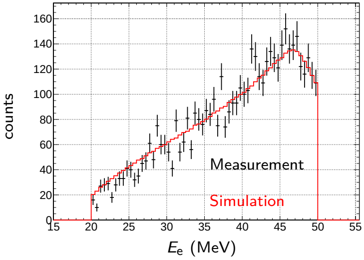


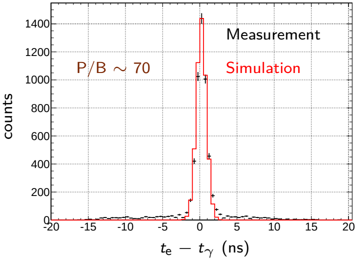
Measured spectra reflect instrumental response and event statistics.

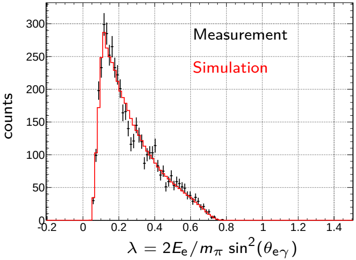
(C. Glaser)

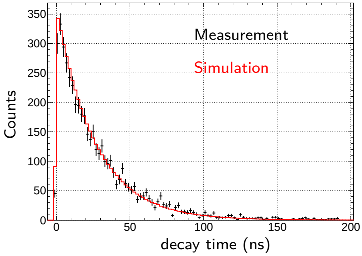
Region D: new in PEN







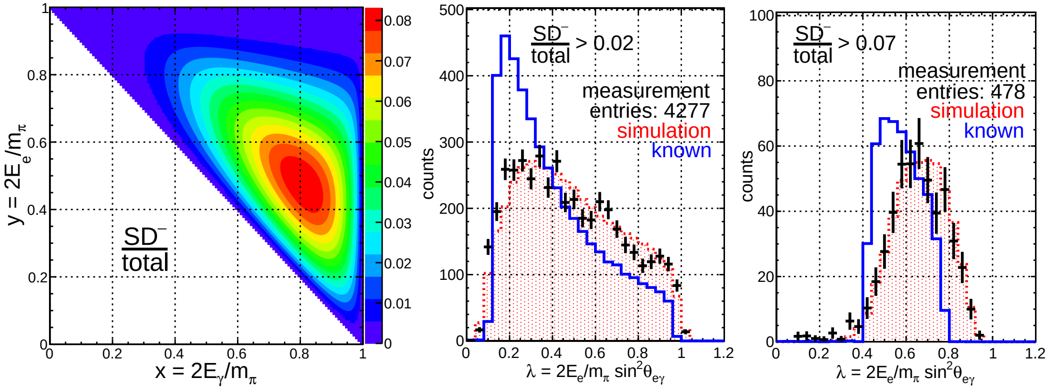




(C. Glaser)

1. $\pi^+ \to e^+\nu_e\gamma$ and 2. $\mu^+ \to e^+\nu_e\bar{\nu}_\mu\gamma$ (not discussed here).

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



(C. Glaser)

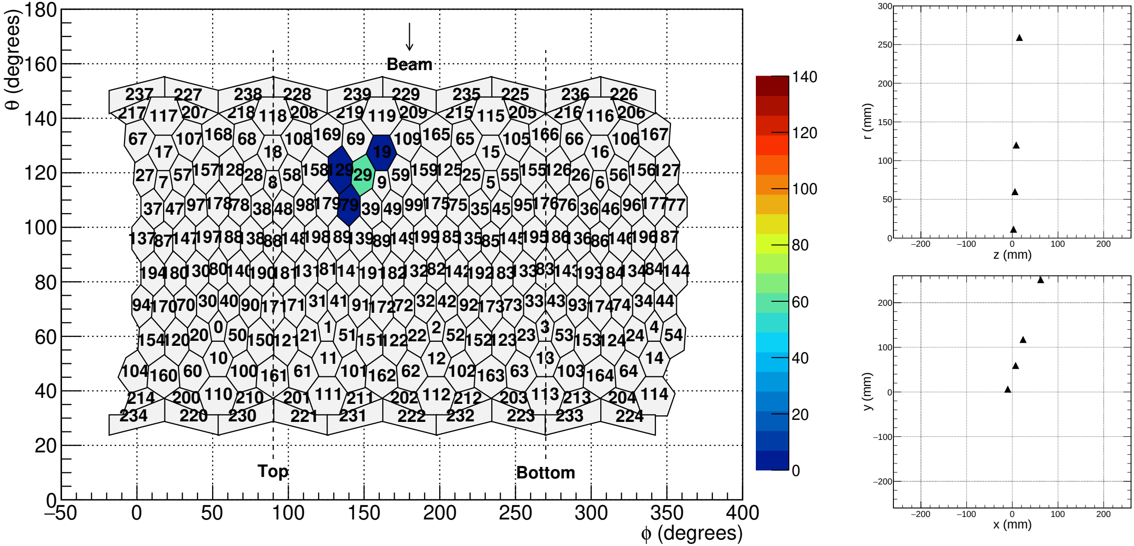
Opportunities for improvement through machine learning

We plan to focus on:

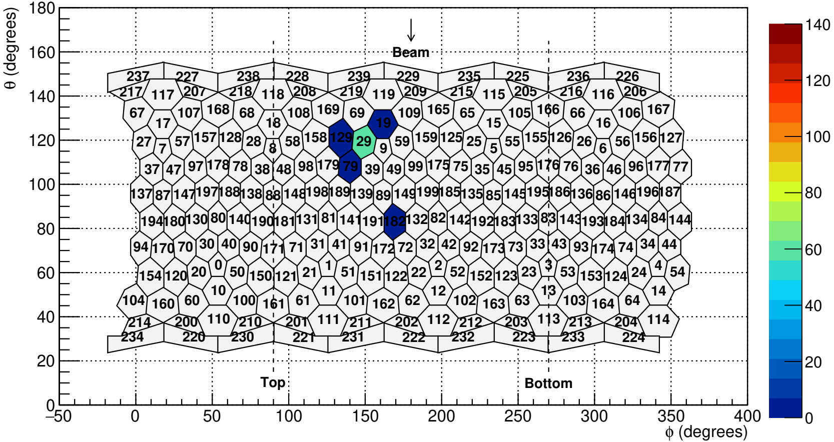
- train and sort between π_{e2} "tail" signal and Michel (μ-decay) background using E_{AT}^{rest} in the overlap region;
- train and sort between $\pi \to e\nu$ and $\pi \to \mu\nu$ in the AT waveform (overlap region);
- combine the two above for a multidimensional smart cut;
- train and sort pattern recognition algorithms (graphical) to distinguish:
  - $\pi \to e\nu(\gamma)$ events without a detectable photon with a single well defined shower,
  - $\pi \to e\nu(\gamma)$ events without a detectable photon and a separate, "split clump" shower,
  - $\pi \to e\nu\gamma$ events with detected photon in a separate well defined shower,
  - $\pi \to e\nu\gamma$ events with detectable energy photon and small e-γ opening angle, resulting in a single, unresolved shower,
  - complex $\pi \to e\nu$ events with detectable energy photon, large e-γ opening angle, and one or more split clumps.

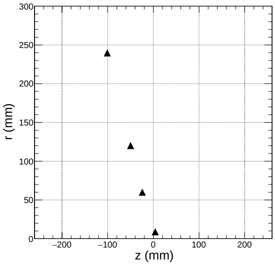
We review a few examples of simulated events below. (C. Glaser, UVA)

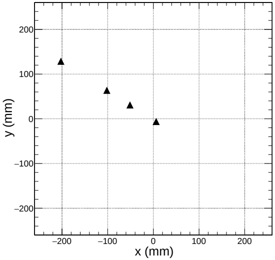
“Nonradiative” π_{e2} event – no split clump



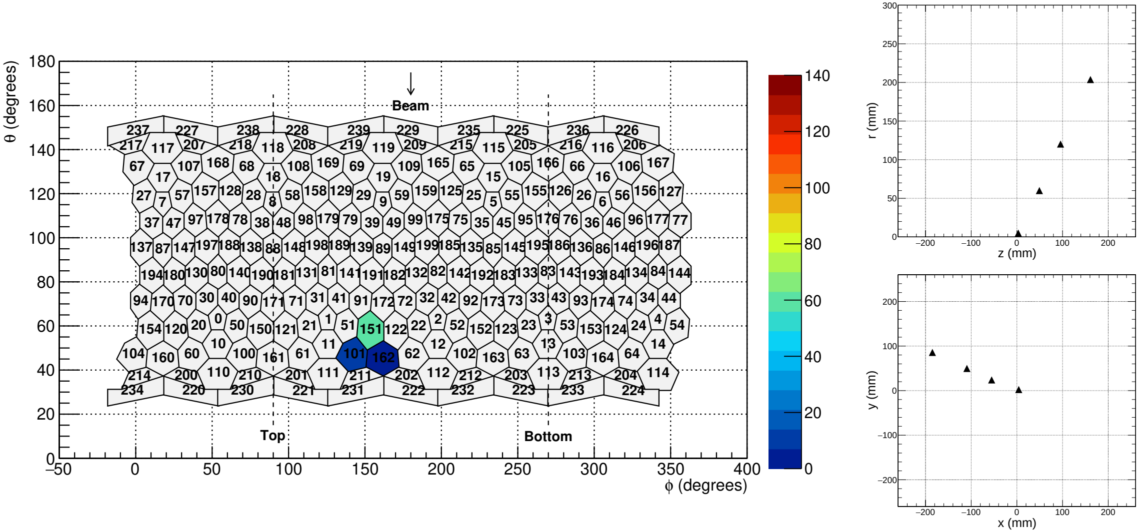
"Nonradiative" π_{e2} event – with split clump



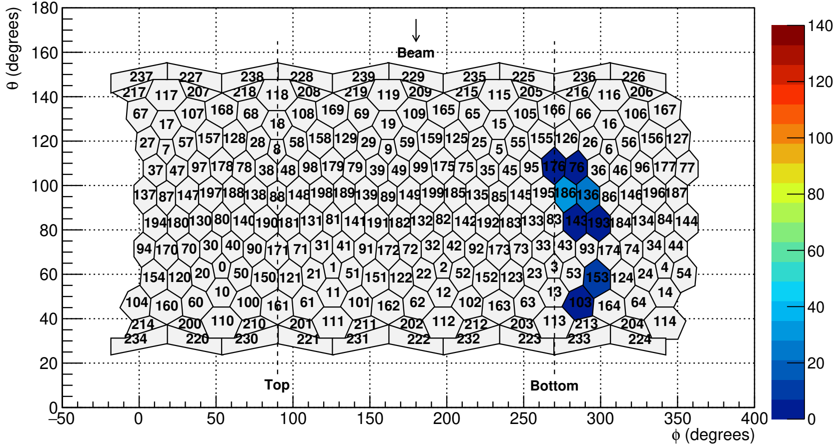


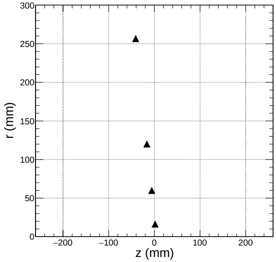


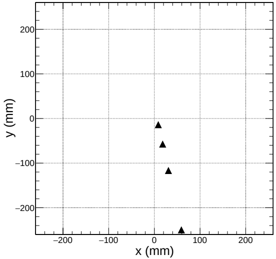
Radiative $\pi_{e2\gamma}$ event – one merged clump (small $\theta_{e\gamma}$)



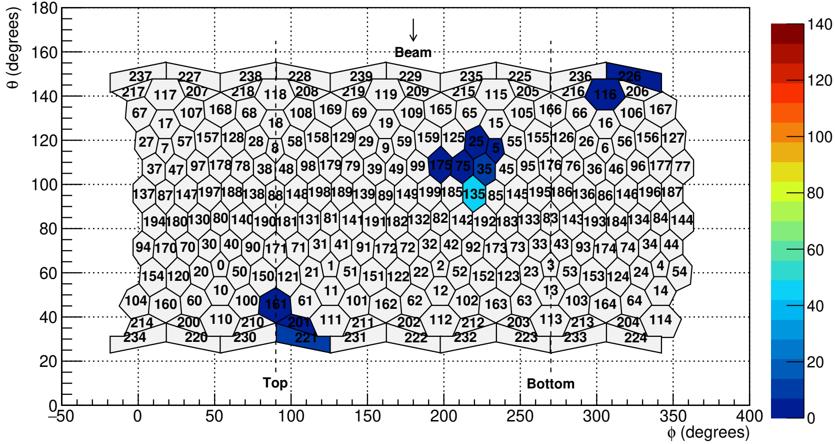
Radiative $\pi_{e2\gamma}$ event – two well separated clumps

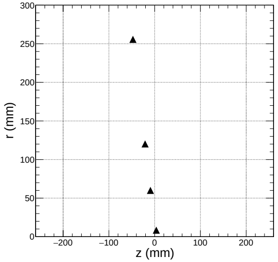


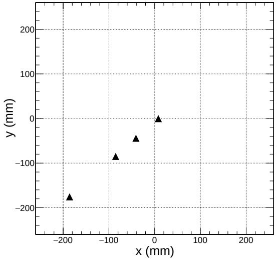




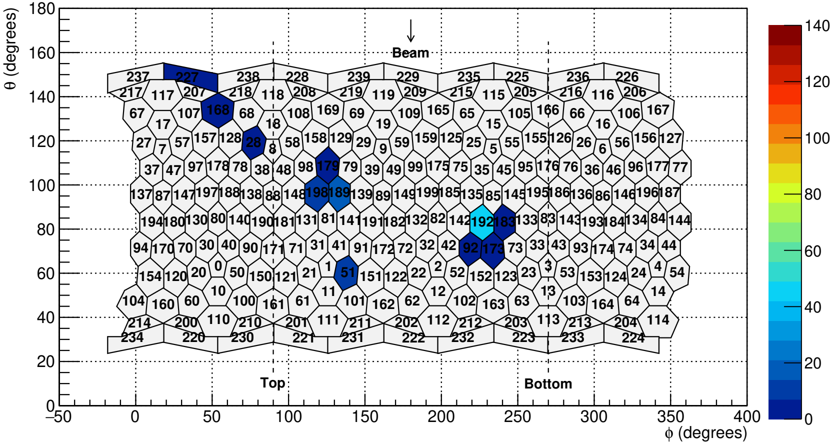
Radiative $\pi_{e2\gamma}$ event – three separate clumps

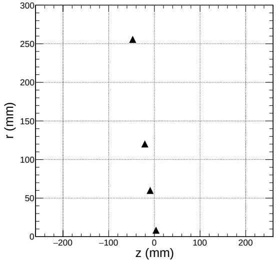


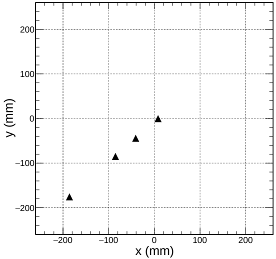




Radiative $\pi_{e2\gamma}$ event – multiple clumps







Summary

- The PEN analysis is in its final phase.
- Prior to analysis unblinding, the PEN collaboration plans to publish technical details of the analysis and systematics.
- In addition to $R^{\pi}_{e/\mu}$, PEN collaboration plans to produce new physics results in radiative π and μ decays. This includes an updated analysis of $F^{\pi}_{A,V,T} \Rightarrow \epsilon_T$.
- We are actively pursuing avenues of analysis improvement through the application of machine learning techniques.
- The physics of PEN and PiBeta remains as compelling as ever. PIONEER, a new experiment with a large acceptance fast CALO, is under preparation at PSI.

  Refs: [arXiv:2203.01981; arXiv:2203.05505]

Stay tuned!

Current and former PiBeta and PEN collaborators

L. P. Alonzi[a], K. Assamagan[a], V. A. Baranov[b], W. Bertl[c], C. Broennimann[c], S. Bruch[a], M. Bychkov[a], Yu.M. Bystritsky[b], M. Daum[c], T. Flügel[c], E. Frlež[a], R. Frosch[c], C. Glaser[a], K. Keeter[a], V.A. Kalinnikov[b], N.V. Khomutov[b], J. Koglin[a], A.S. Korenchenko[b], S.M. Korenchenko[b], M. Korolija[d], T. Kozlowski[e], N.P. Kravchuk[b], N.A. Kuchinsky[b], D. Lawrence[h], W. Li[a], R. C. Minehart[a], D. Mzhavia[b,f], E. Munyangabe[a], A. Palladino[a,c], D. Počanić[a]*, B. Ritchie[h], S. Ritt[a,c], P. Robmann[g], O.A. Rondon-Aramayo[a], A.M. Rozhdestvensky[b], T. Sakhelashvili[f], P.L. Slocum[a], L.C. Smith[a], R.T. Smith[a], N. Soić[d], U. Straumann[g], I. Supek[d], P. Truöl[g], Z. Tsamalaidze[f], A. van der Schaaf[g]*, E.P. Velicheva[b], V.P. Volnykh[b], Y. Wang[a], C. Wigger[c], H.-P. Wirtz[c], K. Ziock[a].

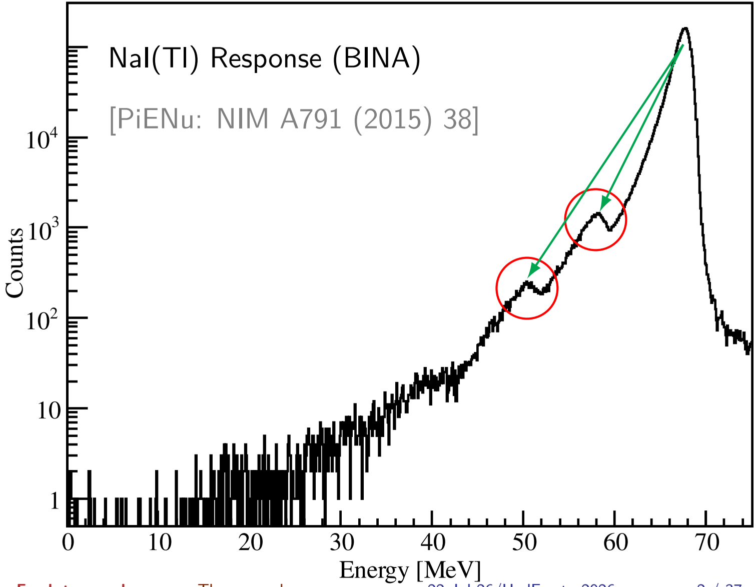
[a] *Univ. of Virginia, USA*
[b] *JINR, Dubna, Russia*
[c] *PSI, Switzerland*
[d] *IRB, Zagreb, Croatia*
[e] *Swierk, Poland*
[f] *IHEP, Tbilisi, Georgia*
[g] *Univ. Zürich, Switzerland*
[h] *Arizona State Univ., USA*

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

Extra slides

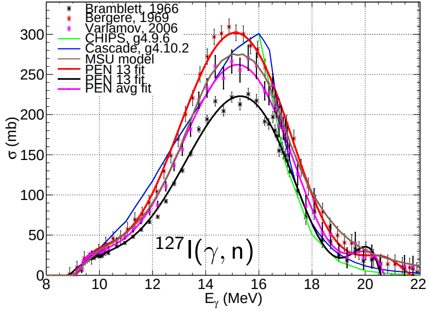
Tail fraction: photoneutron reactions

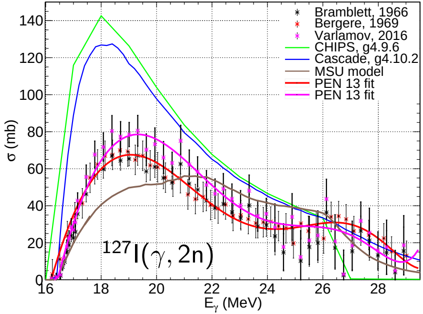
(γ, xn) reactions on calorimeter nuclei, Cs and I, shift counts from the main peak to the "tail" region if the neutrons are undetected.

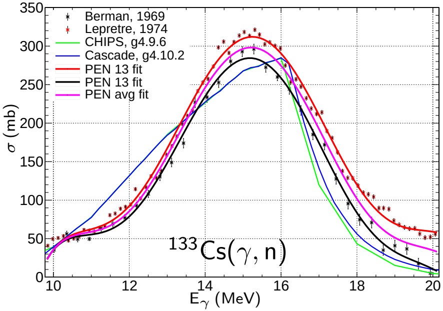


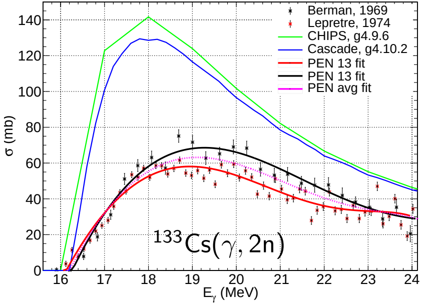
Photoneutron cross sections, $\sigma(\gamma, xn)$

- 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.

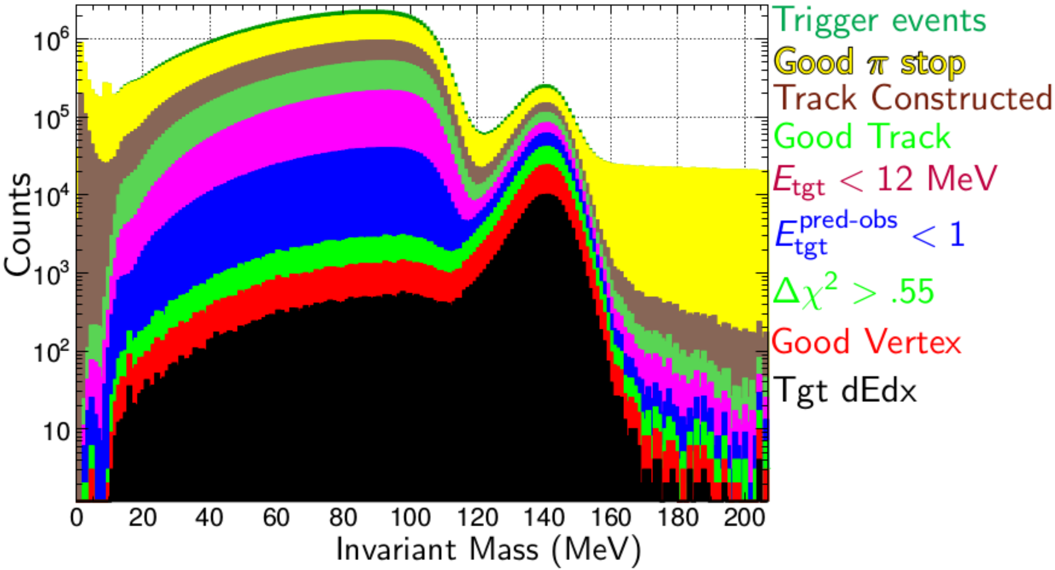




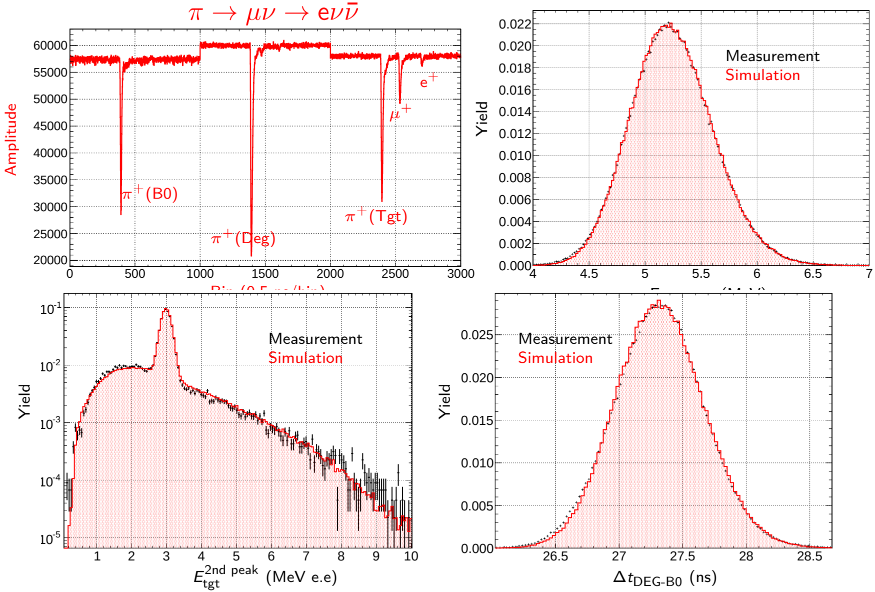




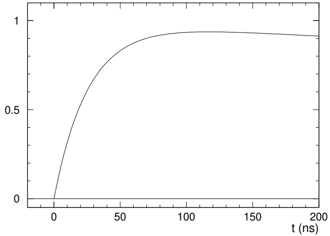
"Tail" trigger



Realistic simulation of beam detectors vs. measurement



$\pi \to \mu \to e$ ("Michel") timing selection: symmetric time window.



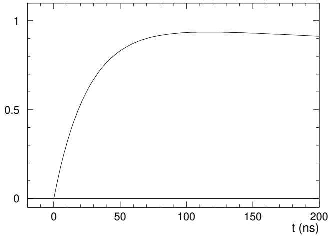
Choice of time interval, $f(T_e)$

$\pi \to \mu \to e$ ("Michel") timing selection: symmetric time window.

$$f_{\pi\text{-}\mu\text{-e}}(t) = \int_0^t f_{\pi\to\mu}(t-t')f_{\pi\to e}(t')dt' = \frac{1}{\tau_\mu - \tau_\pi}\left(e^{-t/\tau_\mu} - e^{-t/\tau_\pi}\right) .$$

$$\left|f_{\pi\text{-}\mu\text{-e}}\right|_{t-w}^{t+w} = \frac{2}{\tau_\mu - \tau_\pi}\left[\tau_\mu e^{-t/\tau_\mu}\sinh\frac{w}{\tau_\mu} - \tau_\pi e^{-t/\tau_\pi}\sinh\frac{w}{\tau_\pi}\right]$$

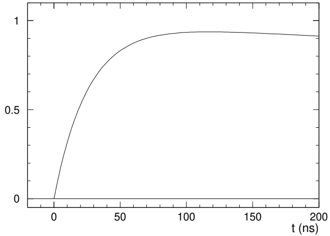
$$\delta f_{\pi\text{-}\mu\text{-e}} = \frac{2\delta t}{\tau_\mu - \tau_\pi}\left|e^{-t/\tau_\mu}\sinh\frac{w}{\tau_\mu} - e^{-t/\tau_\pi}\sinh\frac{w}{\tau_\pi}\right| \Rightarrow 0!!$$



Choice of time interval, $f(T_e)$

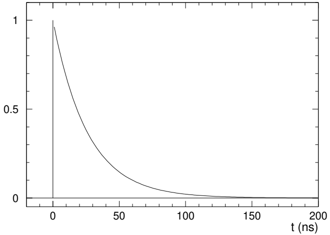
$\boldsymbol{\pi \to \mu \to e}$ ("Michel") timing selection: symmetric time window.

$$f_{\pi\text{-}\mu\text{-e}}(t) = \int_0^t f_{\pi\to\mu}(t-t')f_{\pi\to\text{e}}(t')dt' = \frac{1}{\tau_\mu - \tau_\pi}\left(e^{-t/\tau_\mu} - e^{-t/\tau_\pi}\right) .$$



$$\left| f_{\pi\text{-}\mu\text{-e}} \right|_{t-w}^{t+w} = \frac{2}{\tau_\mu - \tau_\pi}\left[\tau_\mu e^{-t/\tau_\mu}\sinh\frac{w}{\tau_\mu} - \tau_\pi e^{-t/\tau_\pi}\sinh\frac{w}{\tau_\pi}\right]$$

$$\delta f_{\pi\text{-}\mu\text{-e}} = \frac{2\delta t}{\tau_\mu - \tau_\pi}\left| e^{-t/\tau_\mu}\sinh\frac{w}{\tau_\mu} - e^{-t/\tau_\pi}\sinh\frac{w}{\tau_\pi}\right| \Rightarrow 0!!$$

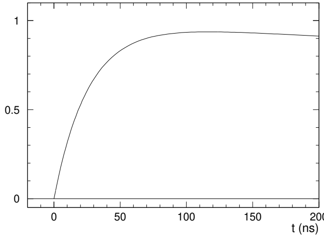


$\boldsymbol{\pi \to} \text{e}\boldsymbol{\nu(\gamma)}$ timing selection:

Choice of time interval, $f(T_e)$

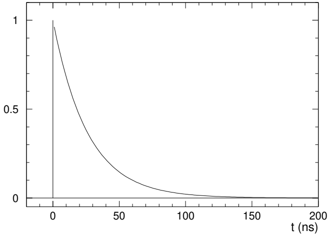
$\pi \to \mu \to e$ ("Michel") timing selection: symmetric time window.

$$f_{\pi\text{-}\mu\text{-e}}(t) = \int_0^t f_{\pi\to\mu}(t-t')f_{\pi\to e}(t')dt' = \frac{1}{\tau_\mu - \tau_\pi}\left(e^{-t/\tau_\mu} - e^{-t/\tau_\pi}\right) .$$



$$\left| f_{\pi\text{-}\mu\text{-e}} \right|_{t-w}^{t+w} = \frac{2}{\tau_\mu - \tau_\pi}\left[\tau_\mu e^{-t/\tau_\mu}\sinh\frac{w}{\tau_\mu} - \tau_\pi e^{-t/\tau_\pi}\sinh\frac{w}{\tau_\pi}\right]$$

$$\delta f_{\pi\text{-}\mu\text{-e}} = \frac{2\delta t}{\tau_\mu - \tau_\pi}\left| e^{-t/\tau_\mu}\sinh\frac{w}{\tau_\mu} - e^{-t/\tau_\pi}\sinh\frac{w}{\tau_\pi}\right| \Rightarrow 0!!$$

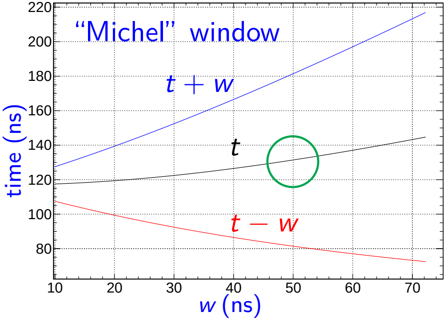


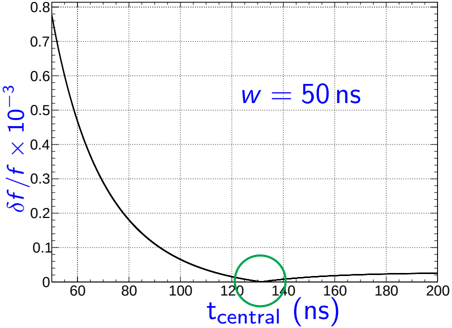
$\pi \to e\nu(\gamma)$ timing selection:

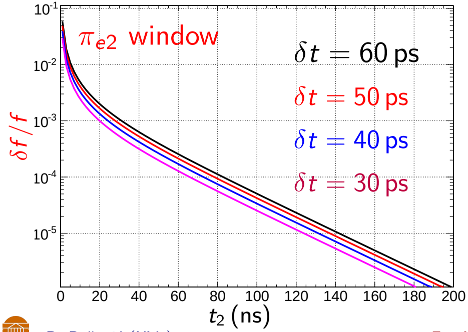
$$f_{\pi\to e\nu}(t_1, t_2) = \frac{1}{\tau_\pi}\int_{t_1}^{t_2} e^{-t/\tau_\pi} = e^{-t_1/\tau_\pi} - e^{-t_2/\tau_\pi}$$

Choose $t_1 < 0$: $\delta f_{\pi\to e\nu} = \dfrac{\delta t}{\tau_\pi} e^{-t_2/\tau_\pi}$.

Analysis requires: δt, w, t and t_2.







r_f: decay time windows

$\pi \to \mu\nu \to e\nu\bar{\nu}(\gamma)$

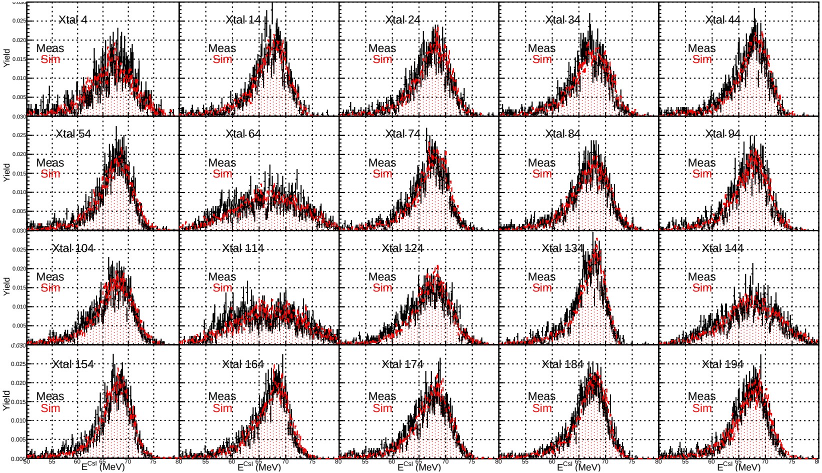
$\delta r_f / r_f$ negligible

$\pi \to e\nu(\gamma)$

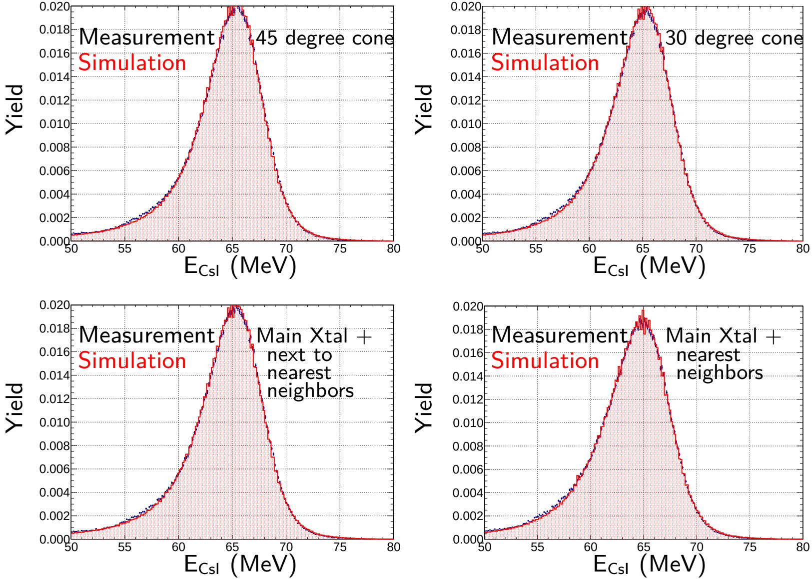
$\delta r_f / r_f$ negligible for $t_2 \gtrsim 90$ ns

CsI EM Calorimeter: realistic simulation

- different detector response, non-uniformities, $\Delta\Omega$ coverage;
- 240 PMTs, with slightly different properties, opt. couplings.



CsI simulation cont'd.



The PEN uncertainty budget

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

Lepton universality (and neutrinos)

From:

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

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

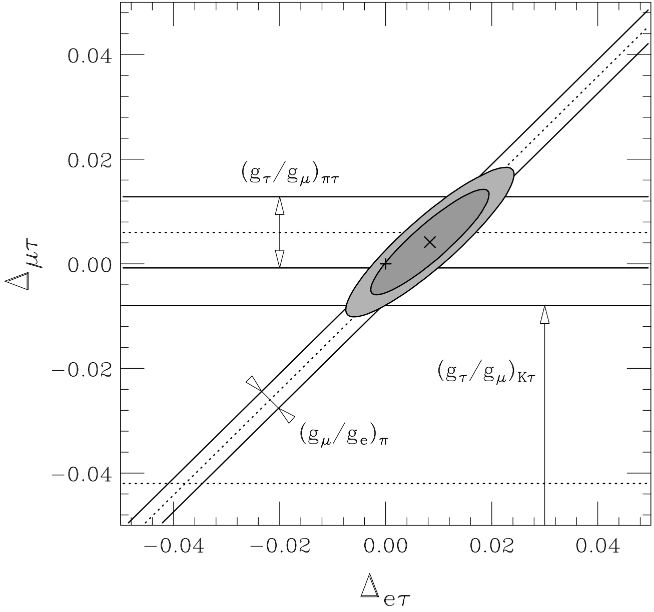
one can evaluate:

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

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**.



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

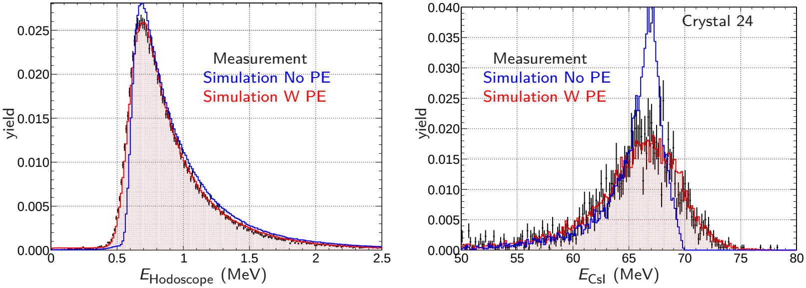
$$\Delta_{\ell\ell'} = 2\left(\frac{g_\ell}{g_{\ell'}} - 1\right)$$

Canonical Geant gives energies, timings, and positions

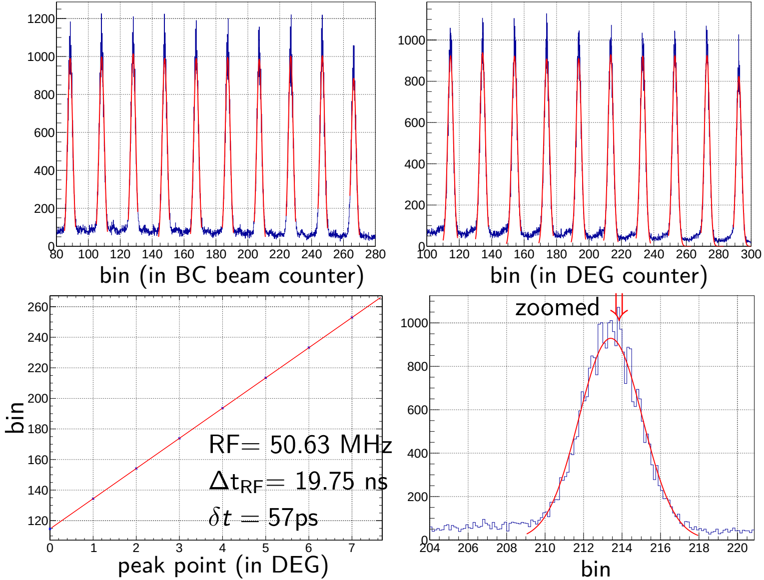
Requires additional physics input to simulate full detector response

In the Experiment:

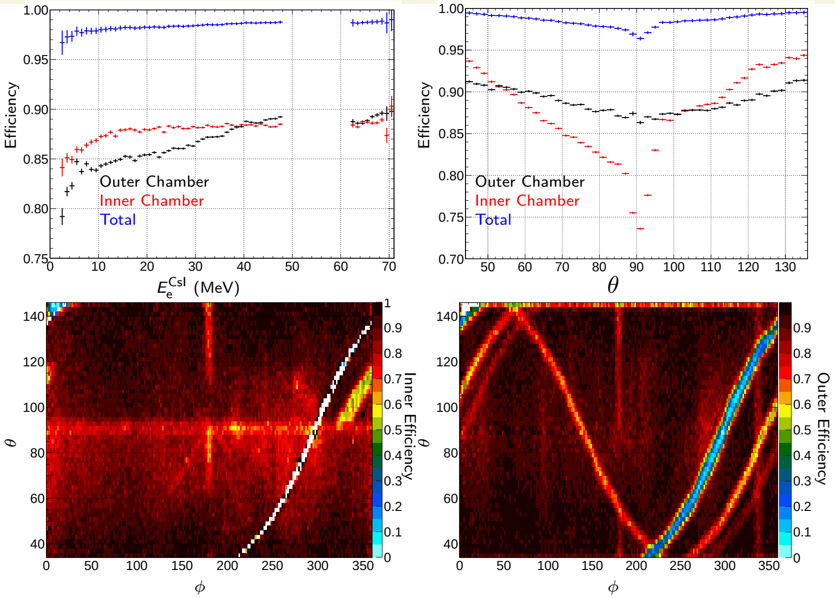
- digitized energies and timings of detector elements
- mTPC, beam counters, and target waveforms
- photoelectron statistics smear signal



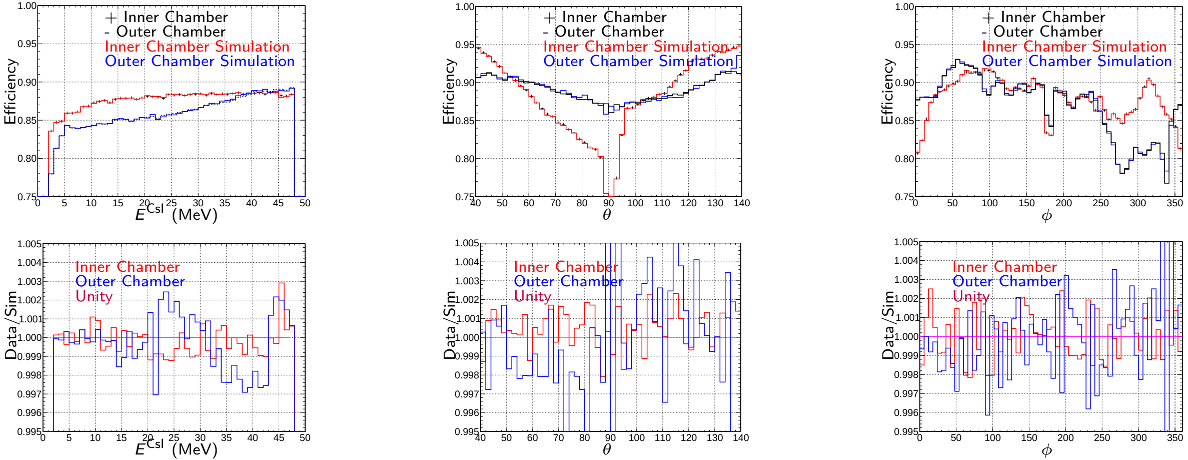
r_f: δt for beam particles



Chamber efficiencies



Chamber efficiencies: simulation



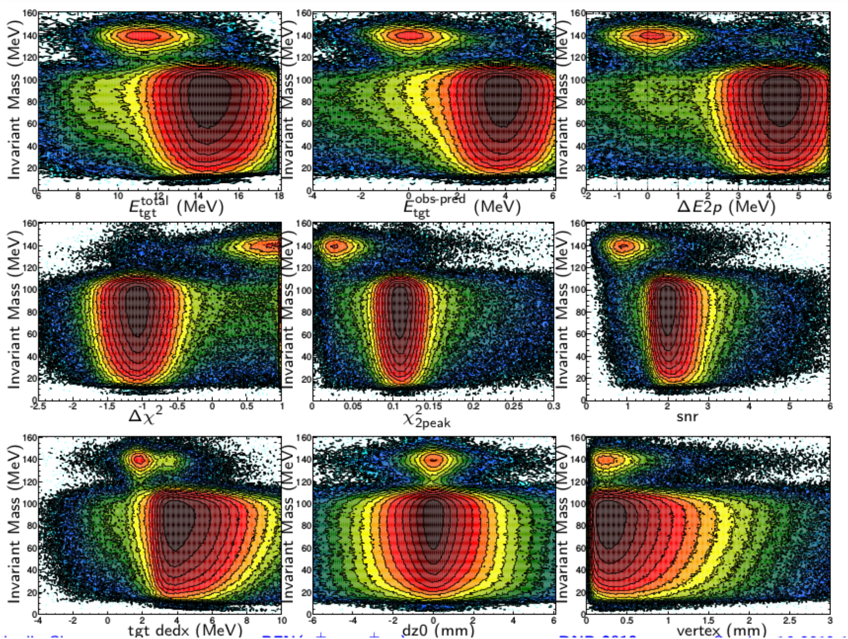
$\mathrm{d}E/\mathrm{d}x = g(E)$ in chamber gas $\quad \pi \to e^+\nu_e \quad$ 70 MeV monoenergetic

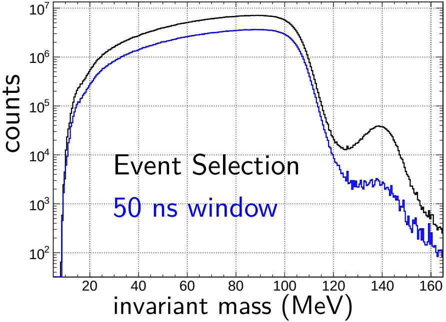
$\mu \to e\nu\bar{\nu} \quad 0 - 52.5$ MeV spectrum

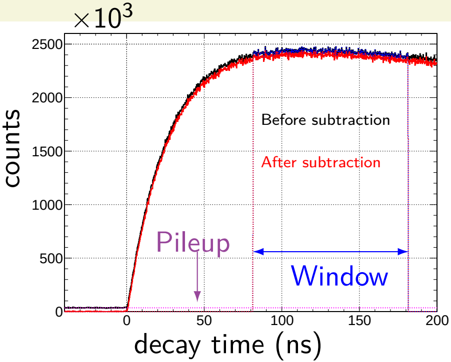
Monte Carlo is weighted to simulate chamber efficiencies

Absorbed into acceptances (blinded)

Observables to aid discrimination







$$N_{\pi\text{-}\mu\text{-e, Run 2}} = (5203.57 \pm 0.32) \times 10^5$$

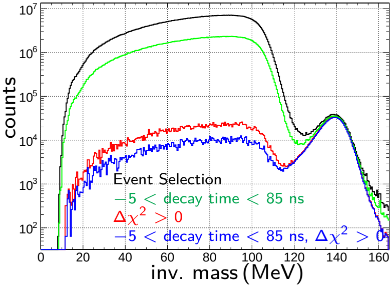
$$N_{\pi\text{-}\mu\text{-e, Run 3}} = (9545.50 \pm 0.44) \times 10^5$$

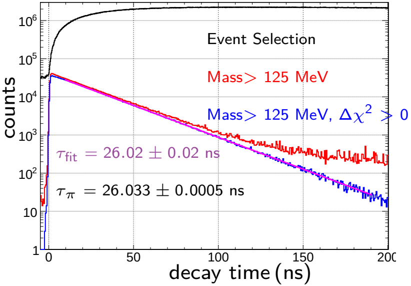
$$\delta N_{\pi\text{-}\mu\text{-e, Run 2}} / N_{\pi\text{-}\mu\text{-e, Run 2}} = 6.2 \times 10^{-5}$$

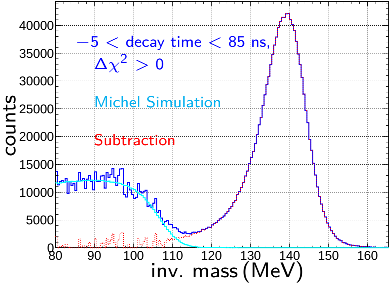
$$\delta N_{\pi\text{-}\mu\text{-e, Run 3}} / N_{\pi\text{-}\mu\text{-e, Run 3}} = 4.6 \times 10^{-5}$$

contribution to $\Delta R^{\pi}_{e/\mu} / R^{\pi}_{e/\mu}$ ... not significant

r_N: number of $\pi_{e2(\gamma)}$ events







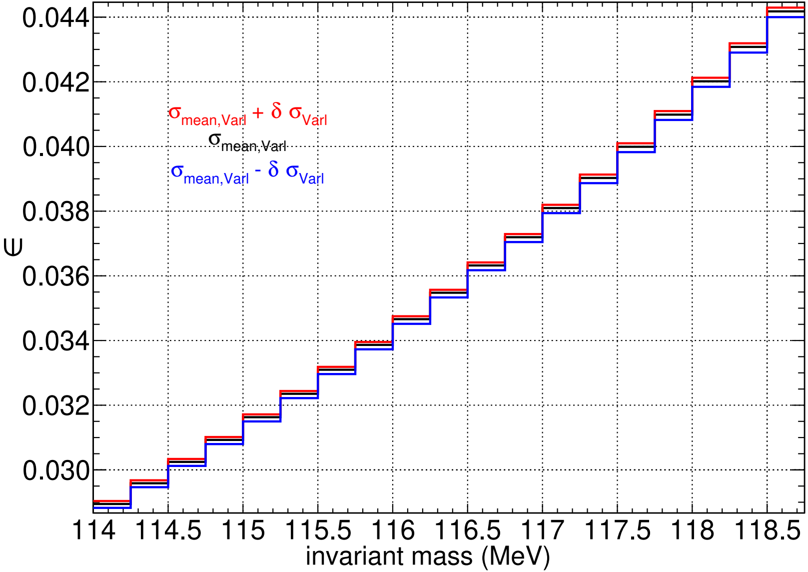
Waveform cut is needed, $\epsilon \sim 97\%$

$$N_{\pi e2(\gamma),\text{ Run 2}} = 1387431 \pm 1179.91$$

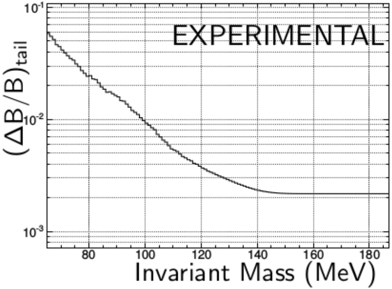
$$N_{\pi e2(\gamma),\text{ Run 2}} = 2383805 \pm 1545.93$$

$$\frac{\delta N_{\pi e2(\gamma),\text{ Rn 2\&3}}}{N_{\pi e2(\gamma),\text{ Rn 2\&3}}} \simeq 5.1 \times 10^{-4}$$

π_{e2} tail including photoneutron corrections



MC simulated vs. experimental π_{e2} tail

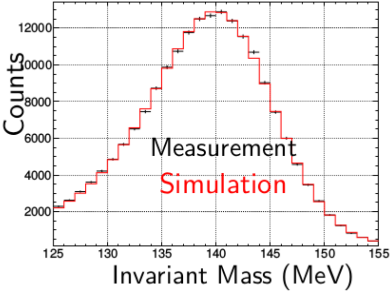


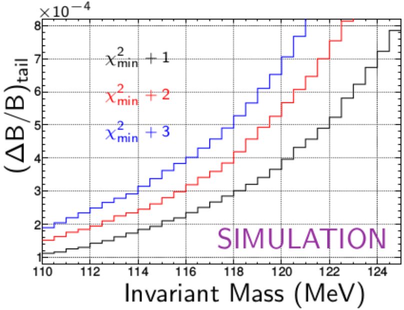
Simulation unavoidable!

Systematics from :

Gain Variation

Photo-nuclear physics





Pre-2004 data on pion form factors

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

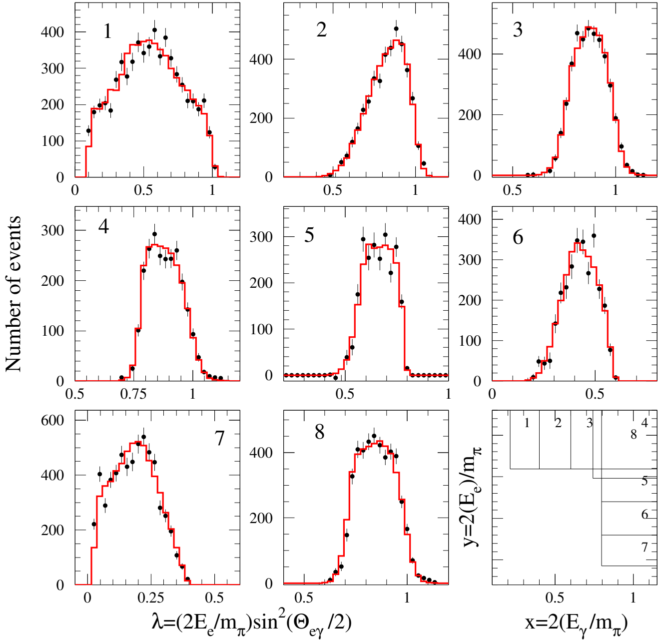
$F_A \times 10^4$	reference
106 ± 60	Bolotov et al. (1990)
135 ± 16	Bay et al. (1986)
60 ± 30	Piilonen et al. (1986)
110 ± 30	Stetz et al. (1979)
116 ± 16	world average (PDG 2004)

Pre-2004 data on pion form factors

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

$F_A \times 10^4$	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 of 1999-01, 2004 data sets.



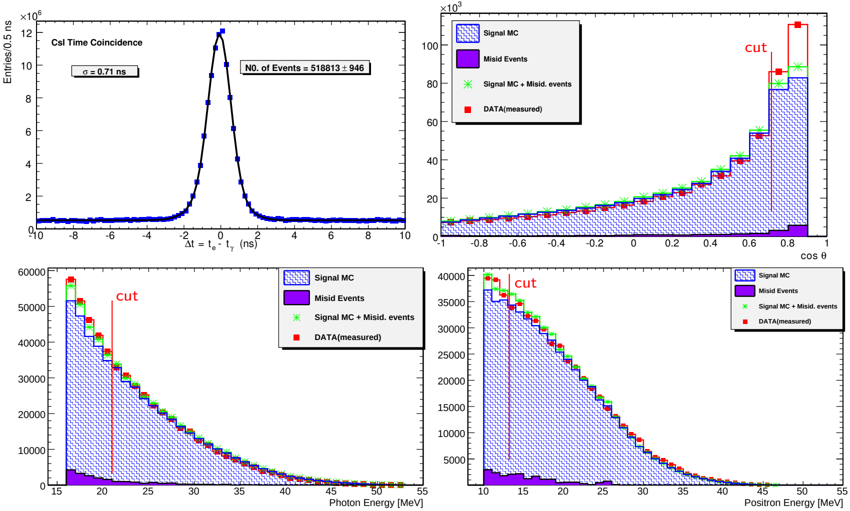
Radiative muon decay:

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

$BR \sim 10^{-3}$ for energetic γ's

- Sensitive to admixtures beyond $V - A$
- Limiting factor in $\mu \to e\gamma$ LFV searches

RMD: $\mu^+ \to e^+\nu\bar{\nu}\gamma$, [E. Munyangabe's analysis of 2004 PIBETA data]



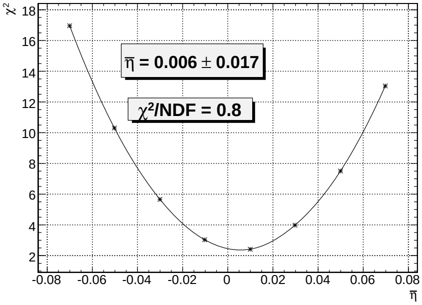
"Split clumps" very well accounted for! ~30-fold improvement in precision of the RMD *BR*.
~4-fold improvement over best previous limit on $\bar{\eta}$ Michel parameter.

RMD preliminary results, cont'd.

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

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

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



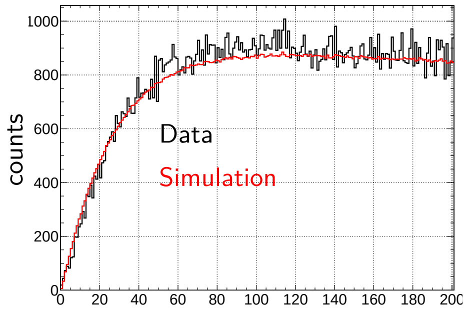
Analysis of PS subset:
$13\,\text{MeV} < E_\gamma < 45\,\text{MeV}$, and
$10\,\text{MeV} < E_{e^+} < 43\,\text{MeV}$, yields

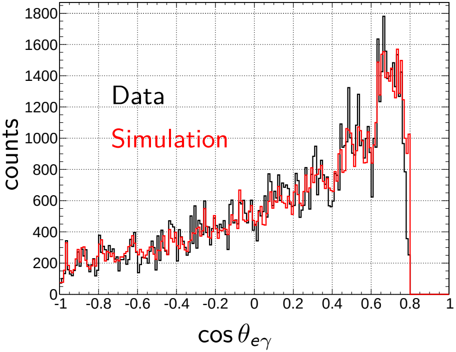
$$\bar{\eta} = 0.006\,(17)_{\rm stat.}\,(18)_{\rm syst.}\,, \quad \text{or}$$

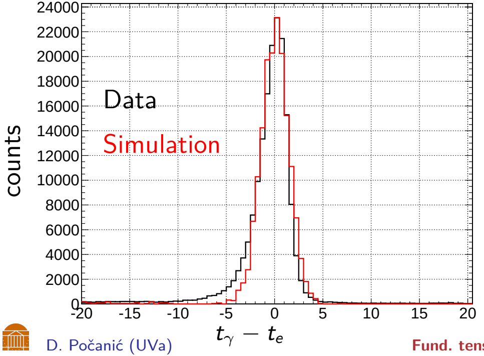
$$\bar{\eta} < 0.028 \quad (68\%\text{CL})\,.$$

$\sim$ 4× better than best previous experiment (Eichenberger et al, 84).

NB: preliminary results!



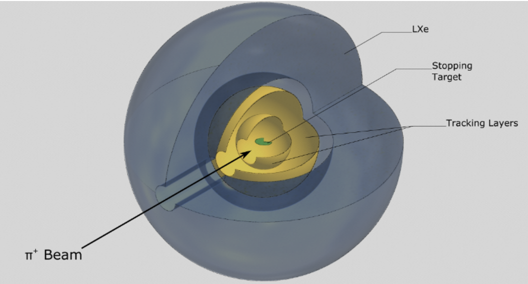


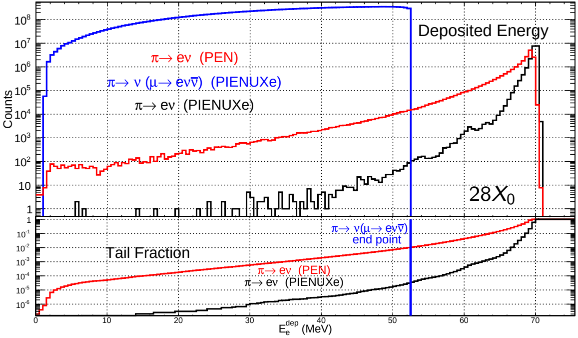


PEN RMD plots (Run 3 data set)

Simple track requirement,
Data selection using target cuts,
Adding coverage to PiBeta data set.

Ready for new BR and $\bar{\eta}$ evaluations.





Concept for an improved RarePi experiment

Goals:

1. $(\Delta R/R)^{\pi}_{e/\mu} < 10^{-4}$ (to match theory),
2. $(\Delta R/R)^{\pi}_{e3} \sim 2-3 \times 10^{-3}$ (per W. Marciano).

A possible setup:

- stopped π^+ in active target with full tracking,
- main detector: liquid Xe,
- $\langle r^{\pi}_{\rm stop} \rangle \sim 1.5 - 2 \times 10^6\,{\rm s}^{-1}$,
- with $T^{\rm live}_{\rm run} \sim 3 \times 10^7\,{\rm s}$ ($>$ 2 calendar years):
- $N^{\pi}_{e2(\gamma)} > 5 \times 10^9$: $(\Delta R^{\pi}_{e/\mu}/R)_{\rm stat} < 2 \times 10^{-5}$;
- $N^{\pi}_{e3(\gamma)} \geq 4 \times 10^5$: $(\Delta R^{\pi}_{e3}/R)_{\rm stat} < 2 \times 10^{-3}$.

Matching the theoretical precision in π_{e3} decay would require substantially higher beam stop rates and further attention to the target and central tracking detectors.