Rare decay studies in the PEN experiment

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Outline

Prior results

$\pi^+ \to \pi^0 e^+ \nu$ (π_β decay)

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

Radiative muon decay, $\mu^+ \to e^+ \nu \bar{\nu} \gamma$ (new)

The π_{e2} decay, $\pi^+ \to e^+ \nu_e$

Status and prospects

Summary

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	✓	
	$e^+\nu\bar{\nu}\gamma$	$0.014\,(4)$	✓	
	$e^+\nu\bar{\nu}e^+e^-$	$3.4\,(4) \times 10^{-5}$		

Recent measurements of π, μ allowed decay

- $\pi^+ \to \pi^0 e^+ \nu_e$ ..... PIBETA ('99–'01)
  - SM checks related to CKM unitarity
- $\pi^+ \to e^+ \nu_e \gamma$(or e^+e^-) ..... PIBETA ('99–'04), PEN ('06–'10)
  - F_A/F_V, π polarizability (χPT calibration)
  - tensor coupling besides $V - A$ (?)
- $\mu^+ \to e^+ \nu_e \bar{\nu}_\mu$ ..... TWIST ('03–'04)
  - departures from $V - A$ in $\mathcal{L}_{weak}$
- $\mu^+ \to e^+ \nu_e \bar{\nu}_\mu \gamma$(or e^+e^-) ..... PIBETA ('04), PEN ('06–'10)
  - departures from $V - A$ in $\mathcal{L}_{weak}$
- $\pi^+ \to e^+ \nu_e$ ..... PEN ('06–'10), PiENu ('06–)
  - e-μ universality
  - pseudoscalar coupling besides $V - A$
  - ν sector anomalies, Majoron searches, m_{h+}, PS l-q's, V l-q's, ...
  - search for signs of SUSY (MSSM)

Prior results

(the PIBETA experiment)

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

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

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

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

SM Prediction (PDG):

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

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

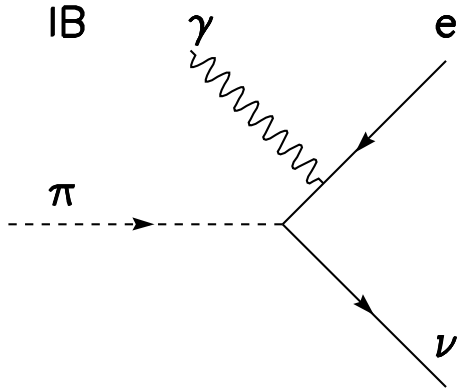
$\Rightarrow$ Most sensitive test of CVC/radiative corr. in a meson to date!

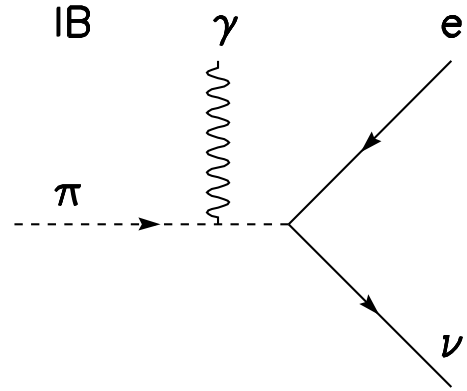
PDG 2012: $V_{ud} = 0.97425(22)$

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

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

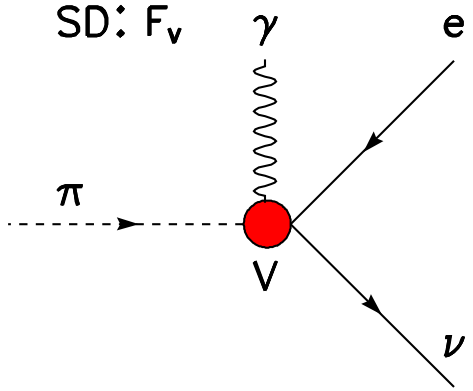
QED IB terms:

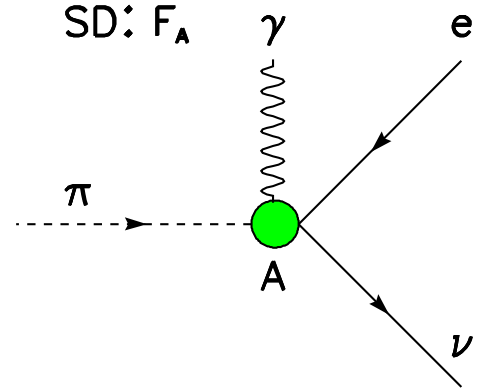




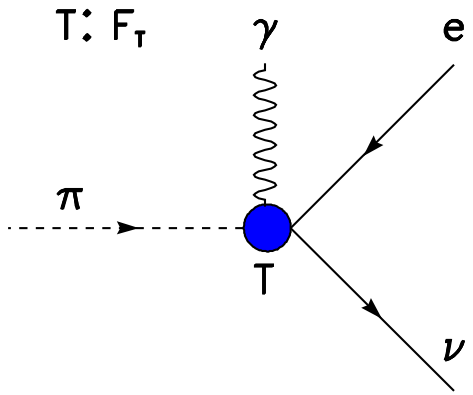
SM

and SD V, A terms:





A tensor interaction, too?



Exchange of S=0 leptoquarks

P Herczeg, PRD 49 (1994) 247

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

$\mathbf{F_V = 0.0258 \pm 0.0017}$	**(14×)**
$\mathbf{F_A = 0.0119 \pm 0.0001}^{\text{exp}}_{(F_V^{CVC})}$	**(16×)**
$\mathbf{a = 0.10 \pm 0.06}$ ($\mathbf{q^2}$ dep of $\mathbf{F_V}$)	**(∞)**
$\mathbf{-5.2 \times 10^{-4} < F_T < 4.0 \times 10^{-4}}$	90 % C.L.

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

Above results will be improved with the new PEN data analysis.

Note: F_V is related to pion polarizability and π^0 lifetime (at L.O.)

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

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

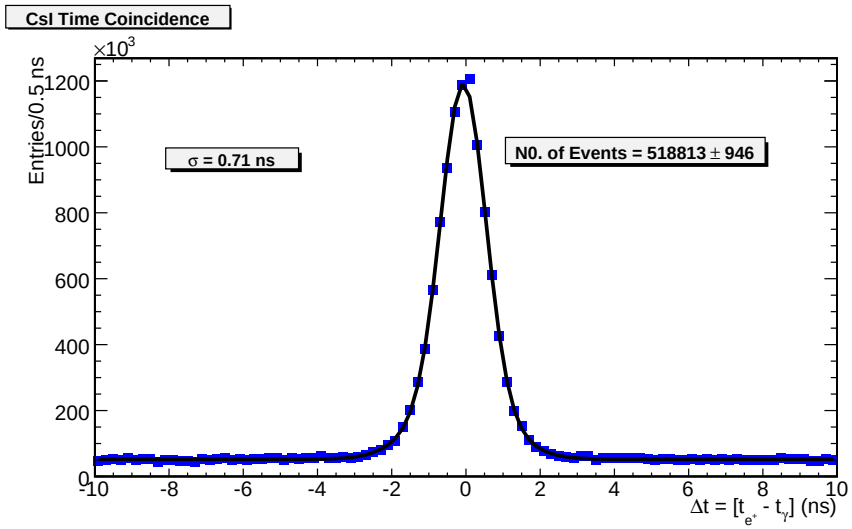
- current PDG avg: 8.4 (4)
- PrimEx PRL '10: 8.32 (23)

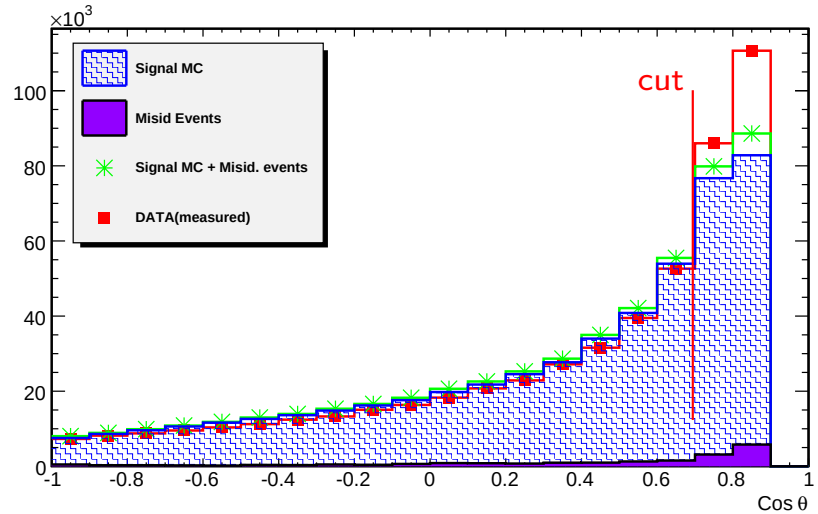
Radiative muon decay:

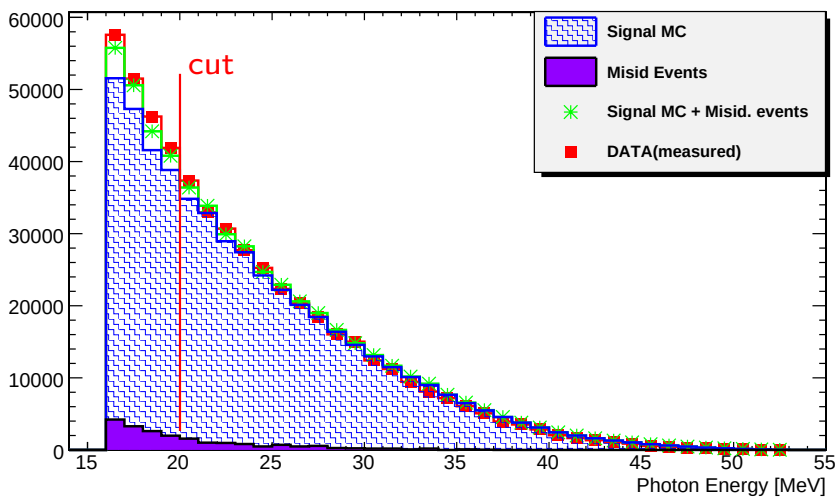
$$\mu^+ \to e^+ \nu \bar{\nu} \gamma$$

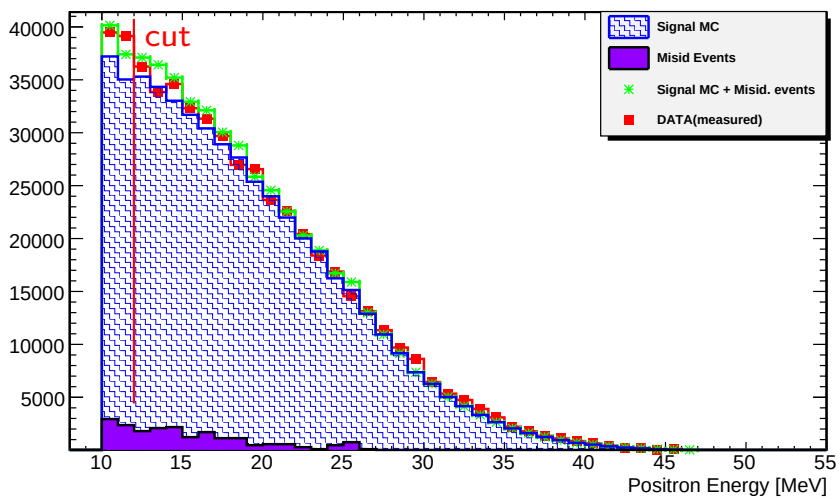
PIBETA: 2004 runs
(PEN: 2008–2010 runs)

Radiative muon decay, $\mu^+ \to e^+\nu\bar{\nu}\gamma$, (new analysis of 2004 data)







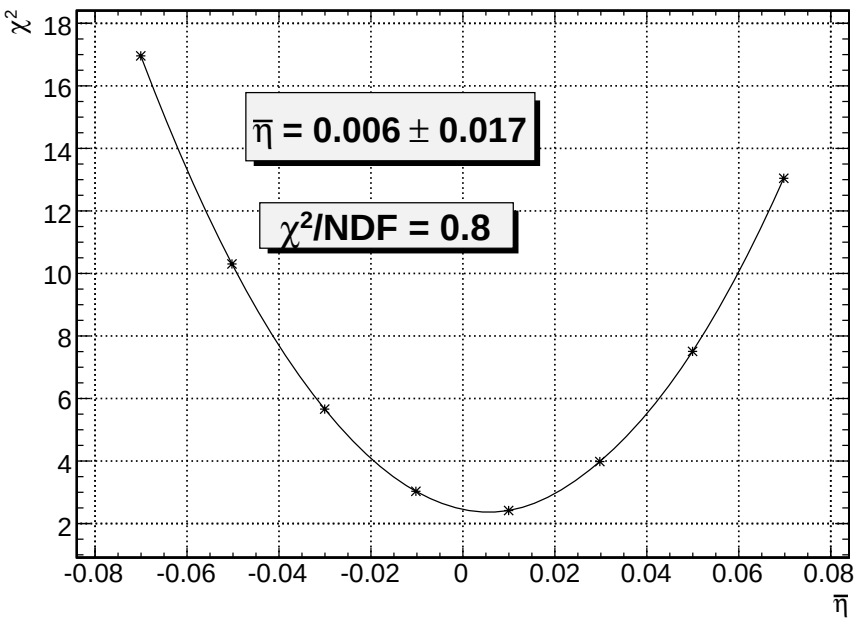


RMD preliminary results, cont'd.

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

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

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



NB: preliminary results!

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

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

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

$\boxed{\sim 4\times}$ better than best previous experiment (Eichenberger et al, 84).

The π_{e2} decay:

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

Primary motivation for PEN
(data runs 2008–10)

$\pi^+ \to e^+\nu_e$ decay (π_{e2}): SM calculations; measurements

- Early evidence for $V-A$ nature of weak interaction.
- Modern SM calculations: $R^{\pi}_{e/\mu} = \dfrac{\Gamma(\pi \to e\bar{\nu}(\gamma))}{\Gamma(\pi \to \mu\bar{\nu}(\gamma))}_{\text{CALC}} =$

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

- Experimental world average [PDG] is about $\boxed{\mathbf{40\times}}$ less accurate:

$$\frac{\Gamma(\pi \to e\bar{\nu}(\gamma))}{\Gamma(\pi \to \mu\bar{\nu}(\gamma))}_{\text{EXP}} = 1.230(4) \times 10^{-4}; \qquad \boxed{\text{PEN goal: } \frac{\Delta R}{R} \simeq 5 \times 10^{-4}}$$

- Strong SM helicity suppression amplifies sensitivity to PS terms ("door" for New Physics) by factor $2m_\pi/m_e(m_u + m_d) \approx 8000$.
- $\mathbf{R^{\pi}_{e/\mu}}$ tests lepton universality: in SM $\mathbf{e}$, $\boldsymbol{\mu}$, $\boldsymbol{\tau}$ differ by Higgs couplings only; there could also be new S or PS bosons with non-universal couplings (New Physics).

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

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

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 directly sensitive to:

$$\boxed{\Lambda_P \leq 1000\,\text{TeV}} \qquad \text{and} \qquad \boxed{\Lambda_A \leq 20\,\text{TeV}}\,,$$

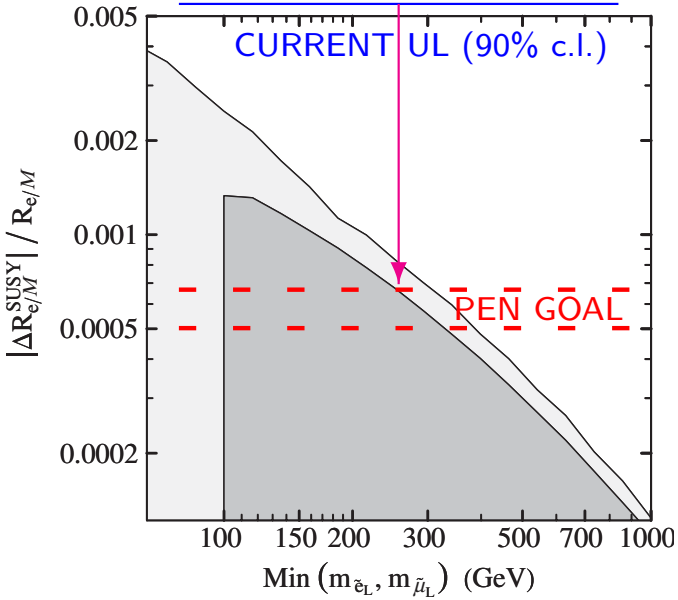
and indirectly, through loop effects to $\boxed{\Lambda_S \leq 60\,\text{TeV}}$.

In general multi-Higgs models with charged-Higgs couplings

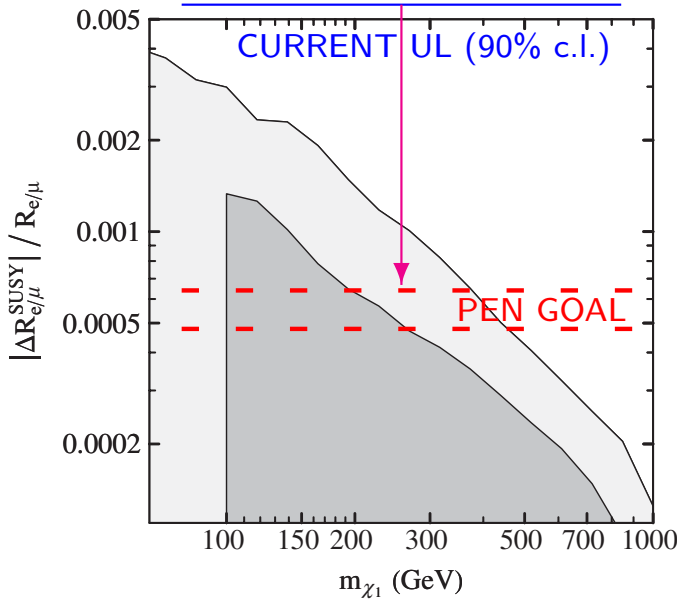
$\lambda_{e\nu} \approx \lambda_{\mu\nu} \approx \lambda_{\tau\nu}$, at 0.1 % precision, $R^\pi_{e\mu}$ probes $\boxed{m_{H^\pm} \leq 400\,\text{GeV}}$.

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

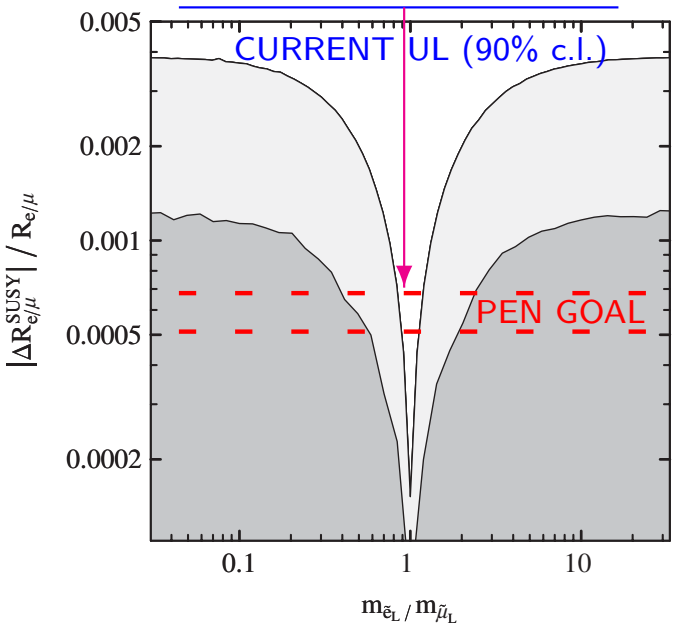
minimal selectron, smuon masses:



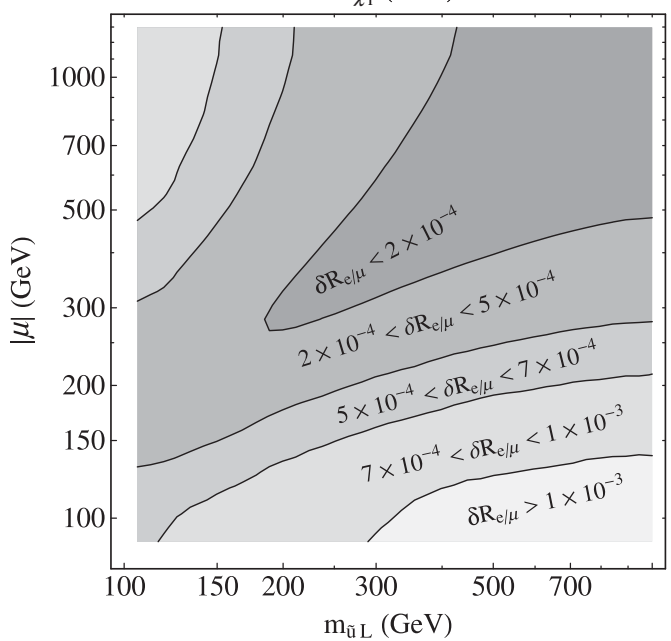
lowest mass chargino:



slepton mass degeneracy:



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



(R parity violating scenario constraints also discussed.)

Other processes and limits; status of PEN

- From $\pi \to e\nu$, additional constraints on:
  - pseudoscalar and vector leptoquarks,
  - neutrino sector anomalies through lepton universality,
  - heavy neutrinos.
- Expected improvements over prior PIBETA results on

  ⋆ Radiative pion decay $\pi \to e\nu\gamma$ (a critical PEN systematic):
  F_V, F_A, a, F_T,

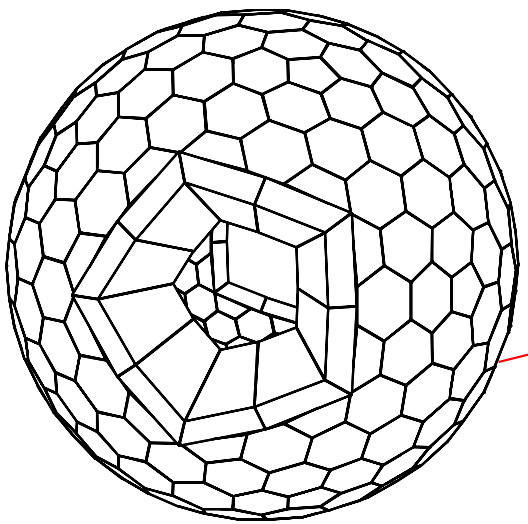
  ⋆ Radiative muon decay, $\mu \to e\nu\bar{\nu}\gamma$ (another key PEN systematic),
  $\Rightarrow$ limits on non-$(V-A)$ terms via:
  - Branching ratio,
  - Michel parameter $\bar{\eta}$.

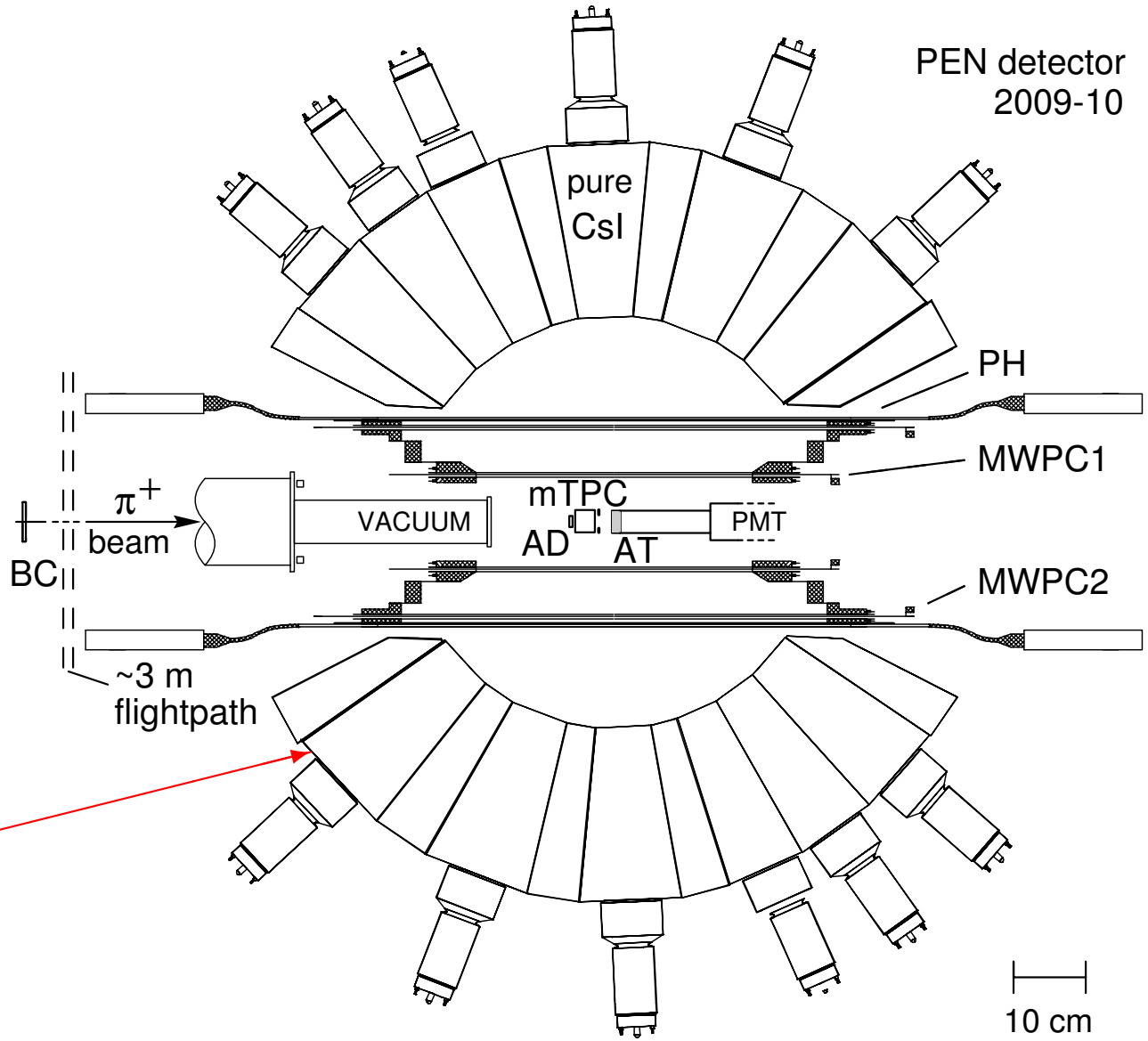
Current status of PEN:

- Data acquisition runs in 2008, 2009, 2010 (completed).
- Collected: $> 22\,\mathrm{M}$ $\pi \to e$ events, $> 200\,\mathrm{M}$ $\pi \to \mu \to e$ events.
- Comprehensive, blinded maximum likelihood analysis in progress.

The PIBETA/PEN apparatus

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

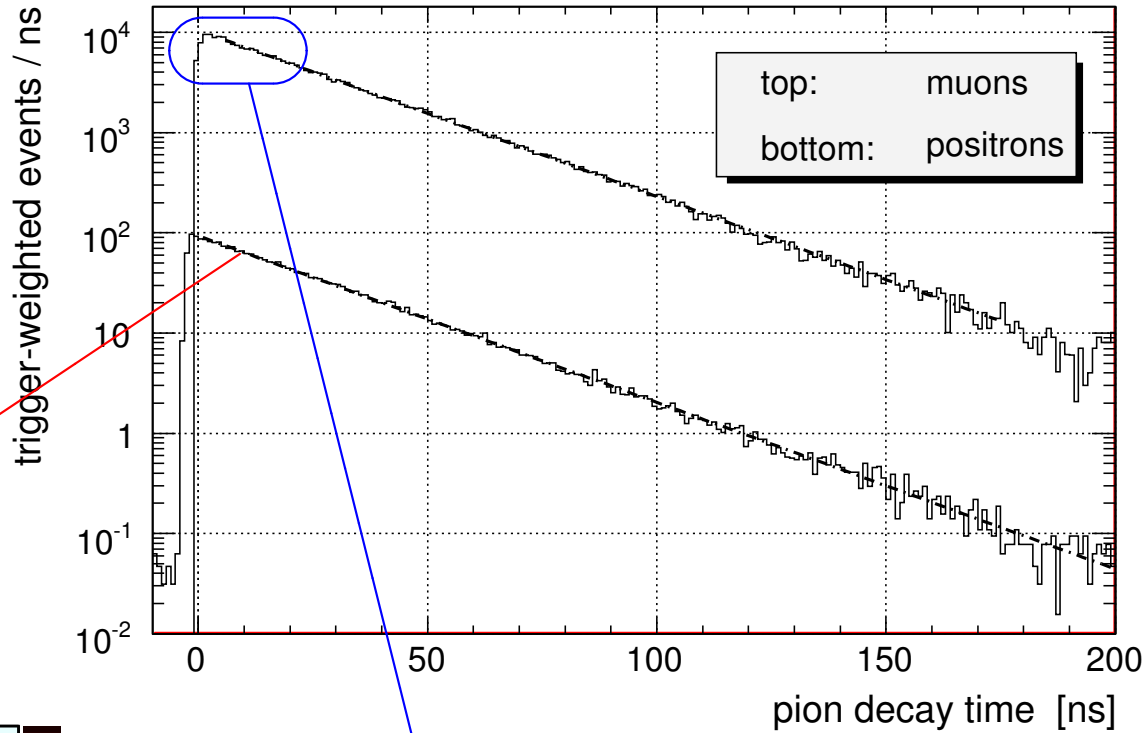




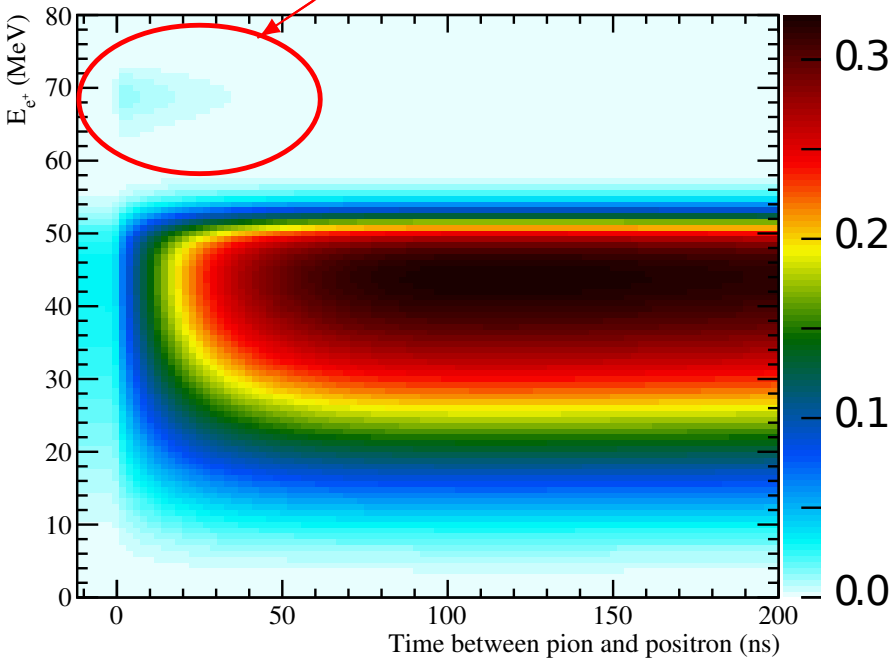
Pion decays in TGT

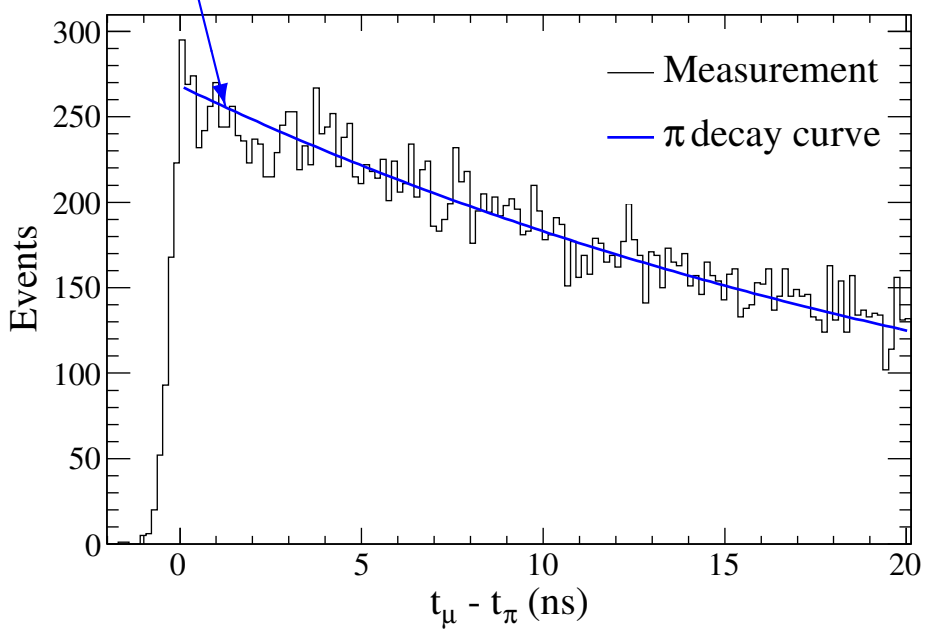
$\tau_{\pi\to\mu} = 26.21(5)\,\text{ns} \Rightarrow$

$\tau_{\pi\to e} = 26.02(8)\,\text{ns} \Rightarrow$



positron E vs t

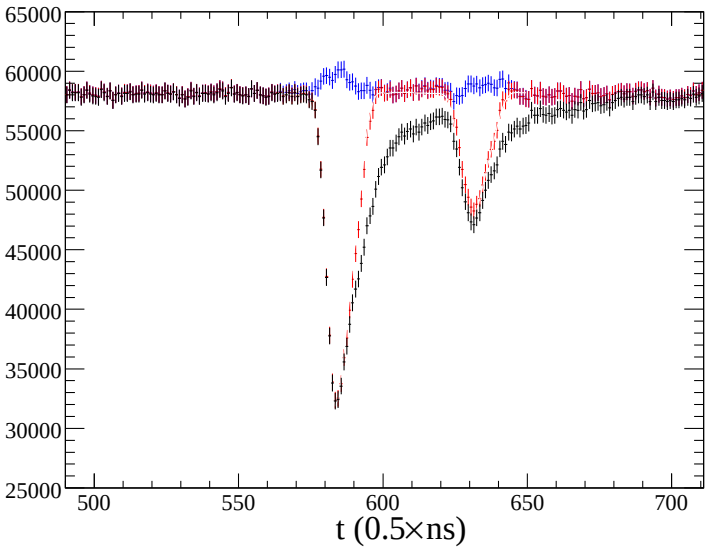




Target waveform fitting:

(1) Shape (filter) wf signals, (2) Use predicted π_{stop}(DEG) and e^+(PH) wf's,
(3) Fit with 2 and 3-peak wf's; compare χ^2 values.

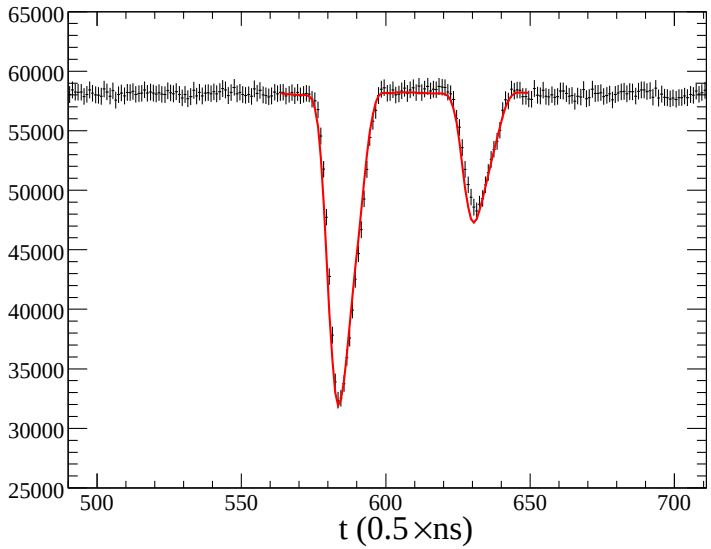
Raw + shaped wf's

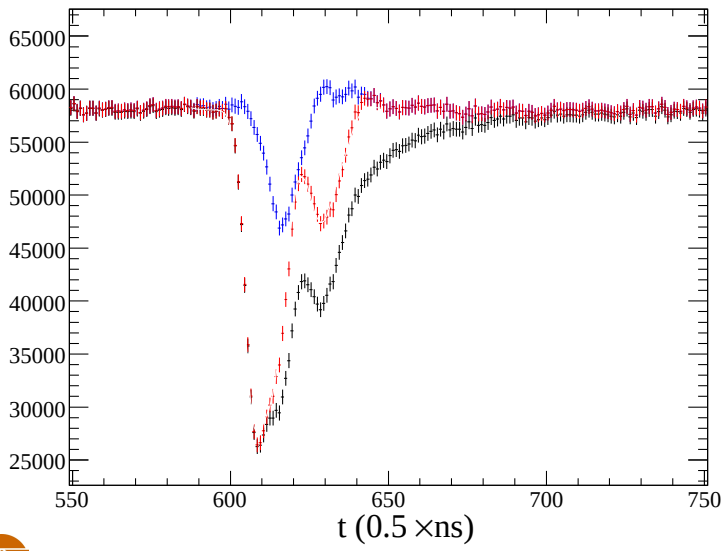


Typical 2-peak $\pi \rightarrow e$ event

Blue trace: no "third" (muon) signal

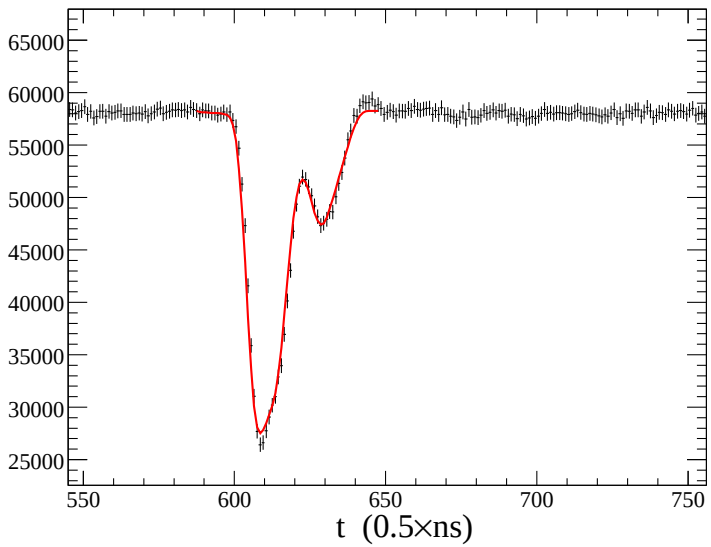
Shaped wf's + predicted fits



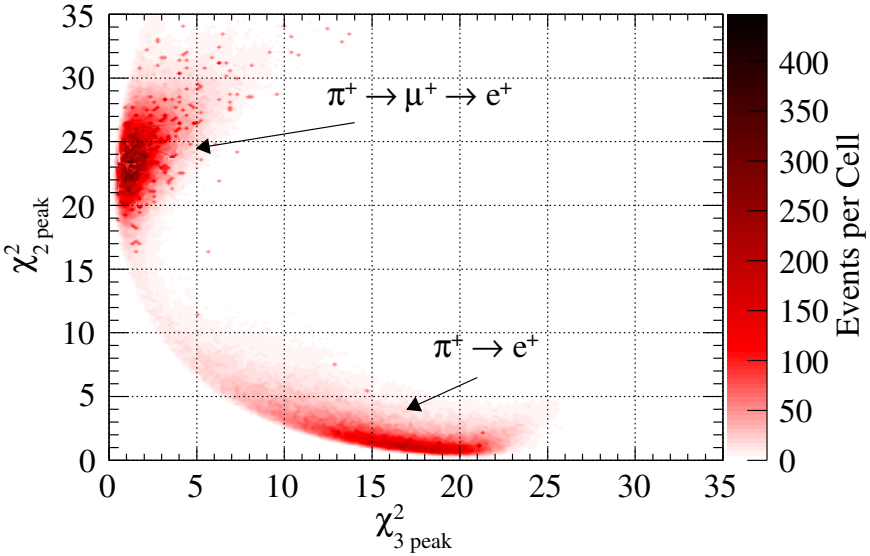


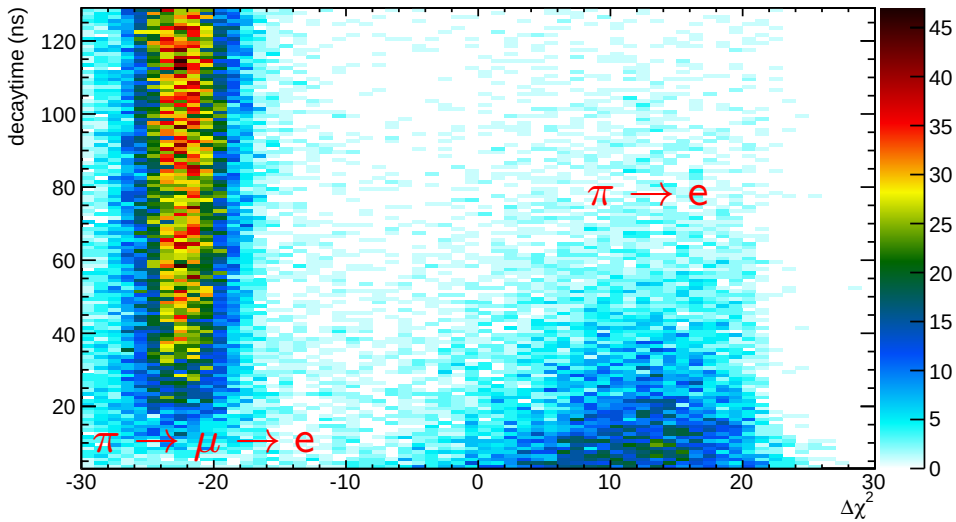
Typical 3-peak $\pi \rightarrow \mu \rightarrow e$ event

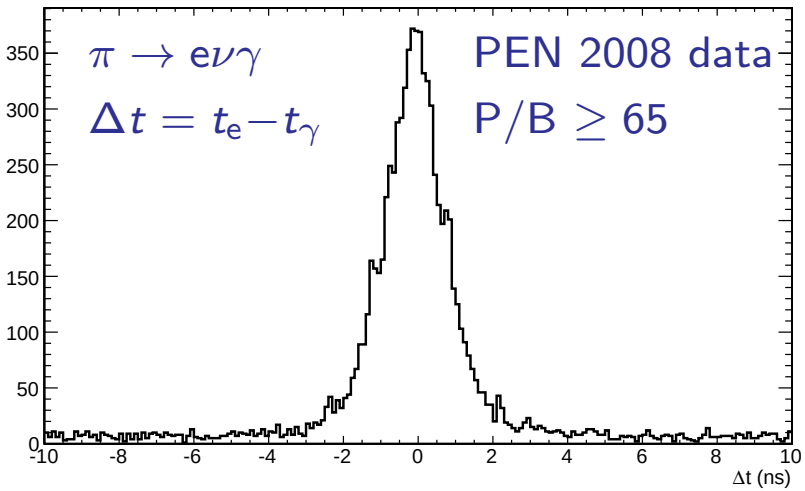
Blue trace: putative "third" (muon) signal



Selected PEN distributions (2008 data run)



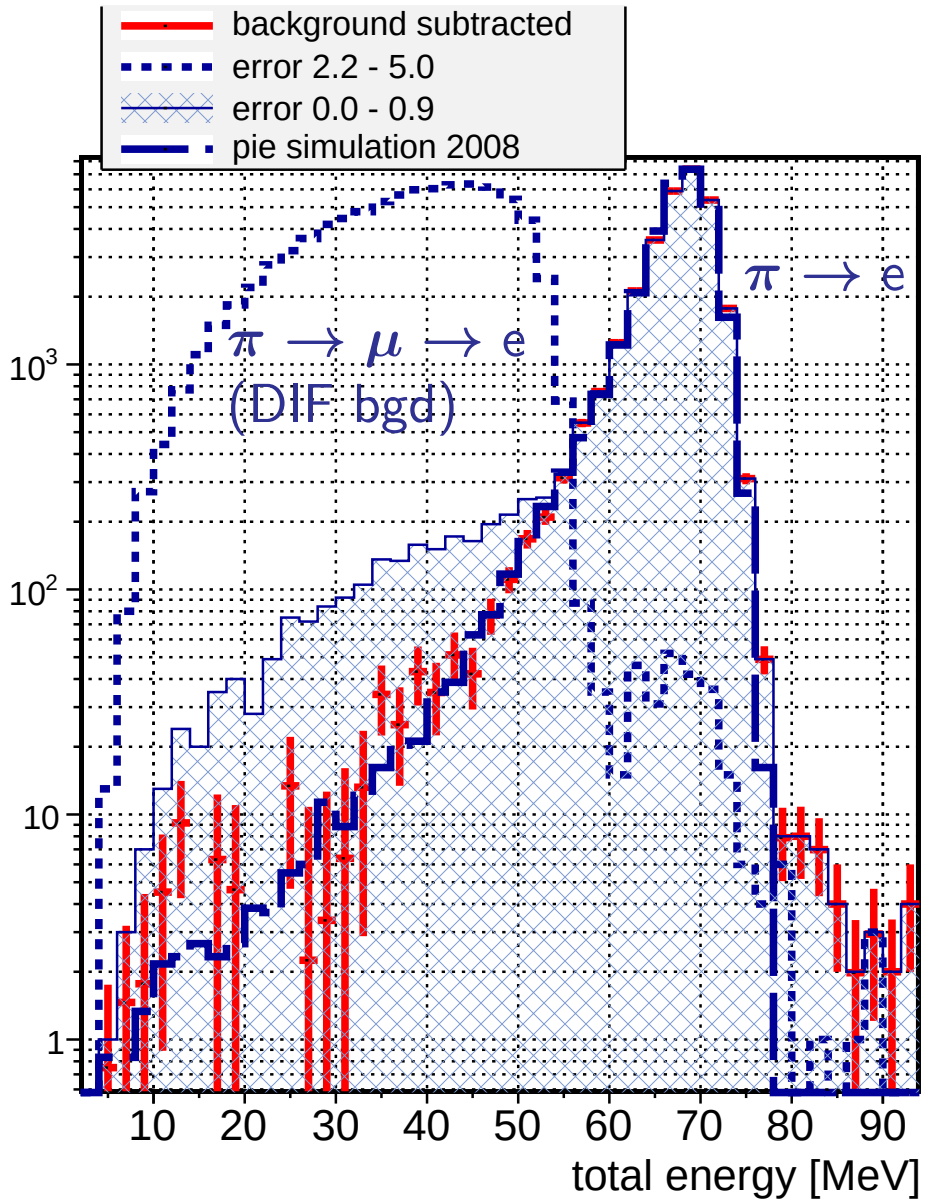


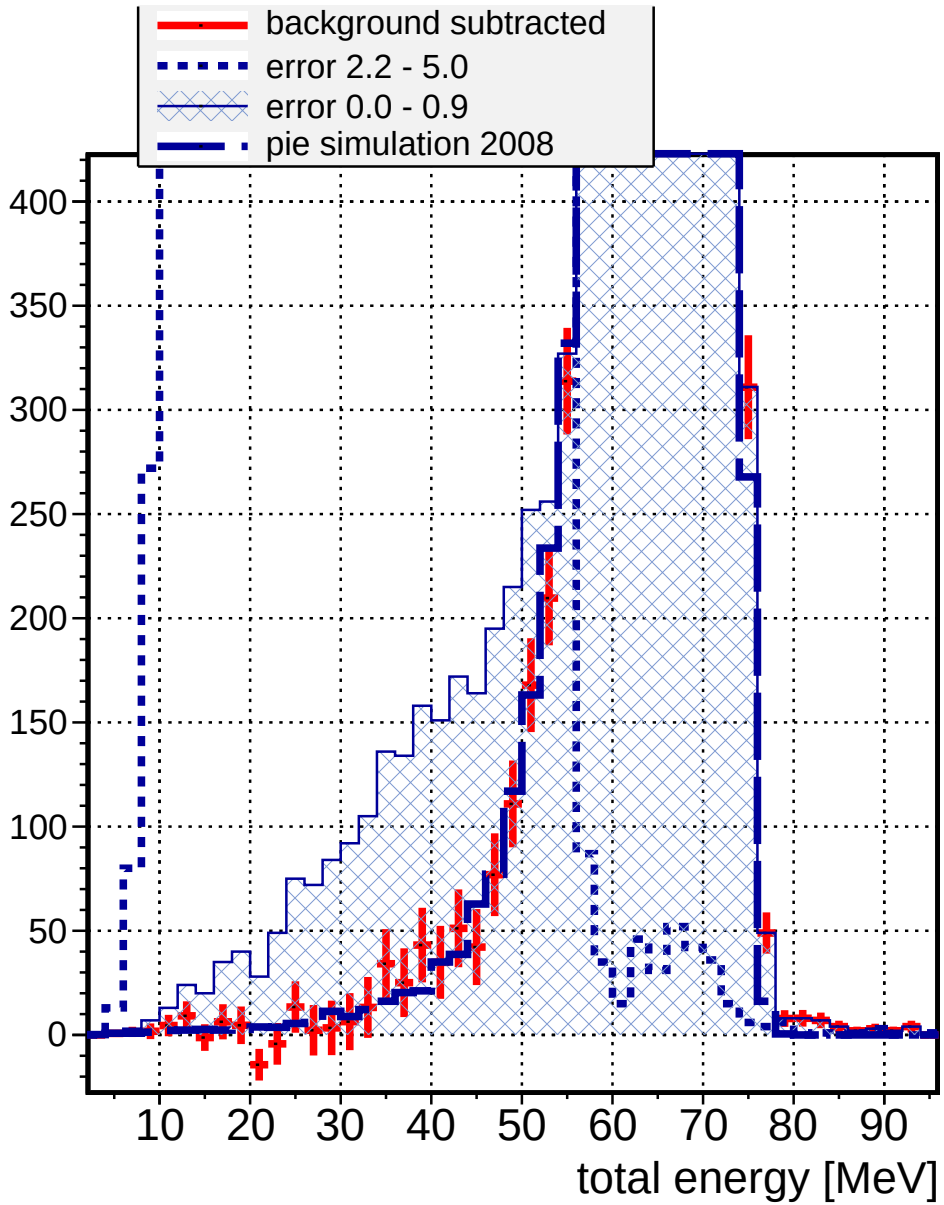


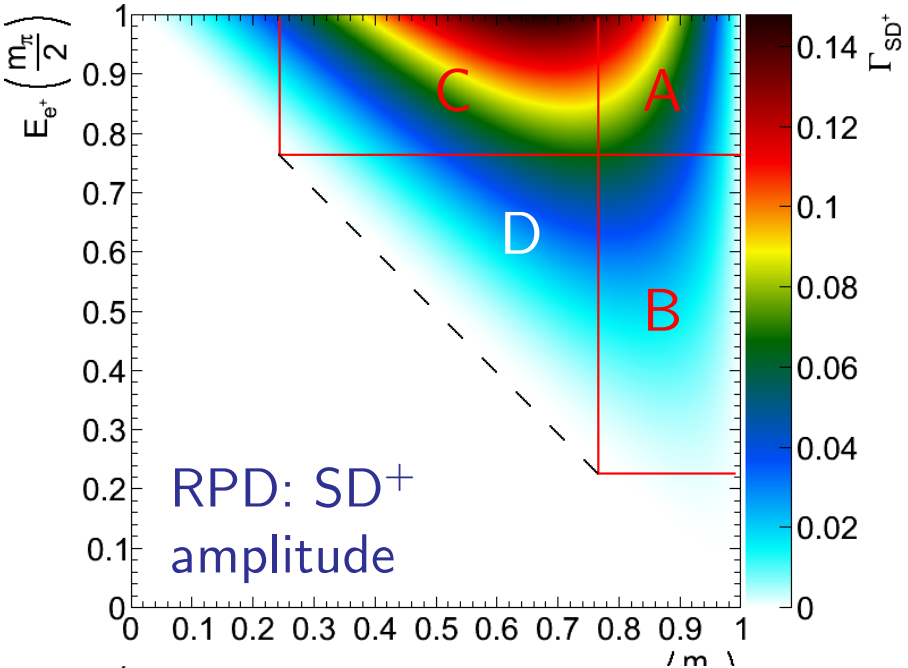
PEN improvements over PIBETA data:

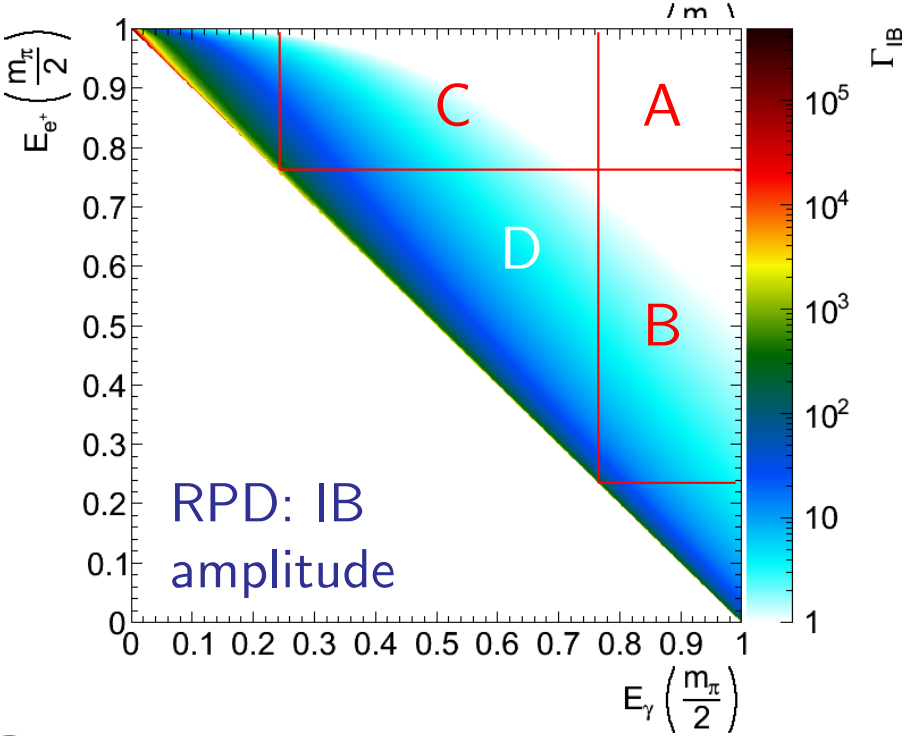
- suppression of muon decay events;
- superior P/B ratio for $\pi \to e\nu\gamma$;
- full GEANT4 description with synthetic MC data.

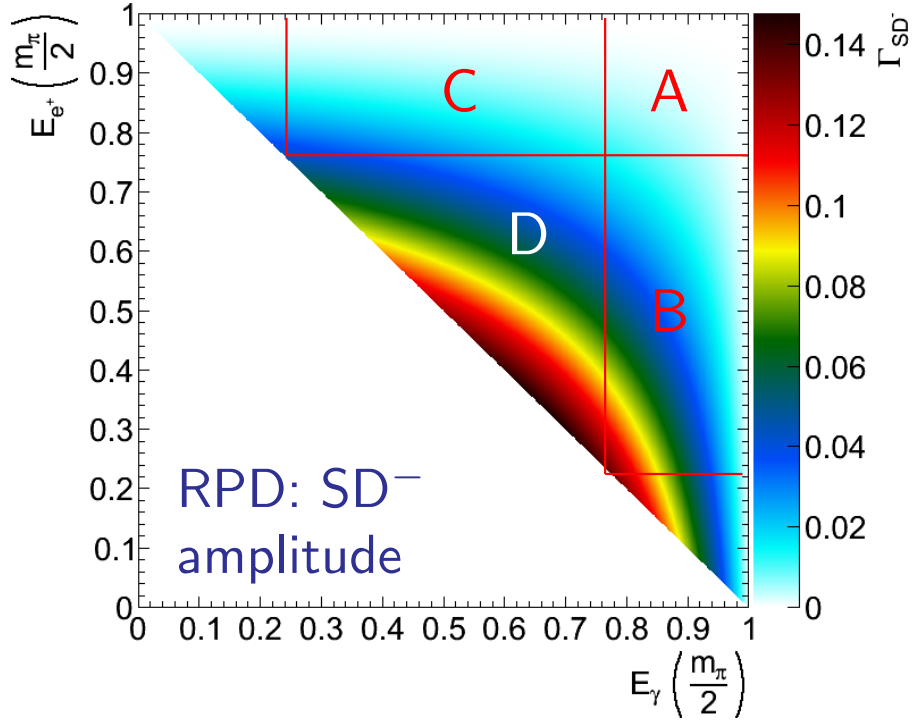
Key PEN systematic: low E "tail" response









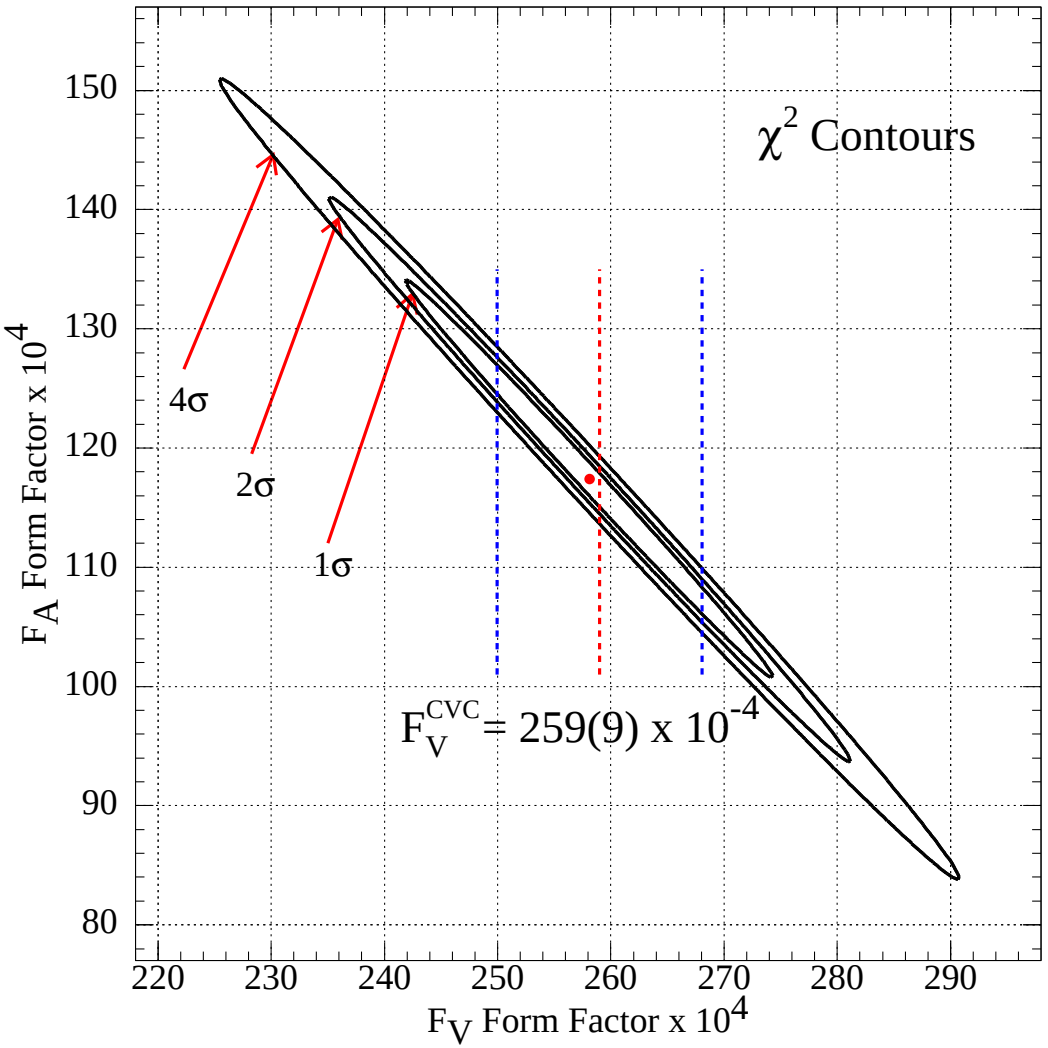


Thanks to

- low accidental bgds, and
- strong suppression of μ decays,

PEN data will enable evaluation of region D in $\pi^+ \to e^+\nu\gamma$ decay (RPD), i.e., new information on SD^-.

Constraints from PIBETA on pion FF's



⇐ Tight constraint on $F_V + F_A$ (SD^+ term);
weak constraint on $F_V - F_A$

Need to constrain SD^-!

⇒ Region D in PEN!

Study of allowed π and μ decays in PEN

- A significant experimental effort is under way (in PEN and in other experiments) to make use of the unparalleled theoretical precision in the weak interactions of the lightest particles.
- Information obtained is complementary to expected collider results, and valuable for their proper interpretation.
- Improvements in precision for
  - $\pi \to e\nu$,
  - $\pi \to e\nu\gamma$ (F_V, F_T^{ul}), and
  - $\mu \to e\nu\bar{\nu}\gamma$.

  to be achieved in the near future.
- Great projects for graduate students and postdocs—applications are invited.

Current and former PIBETA and PEN collaborators

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