New results on muon radiative decay
(PhD thesis Emmanuel Munyangabe, Aug 2012)

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Outline

PIBETA/PEN program, motivation and apparatus

Basic theory of muon decay

Results of the new analysis

PIBETA/PEN program of π, μ rare decay measurements

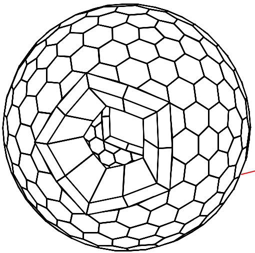
- $\pi^+ \to \pi^0 e^+ \nu_e$ .... PIBETA ('99–'01)
  - SM checks via *q*-*l* universality and CKM unitarity
- $\pi^+ \to e^+ \nu_e \gamma$(or e^+e^-) .... PIBETA ('99–'04), PEN ('06–'10)
  - $\mathbf{F_A}/\mathbf{F_V}$, π polarizability (χPT calibration)
  - tensor coupling besides $\mathbf{V} - \mathbf{A}$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

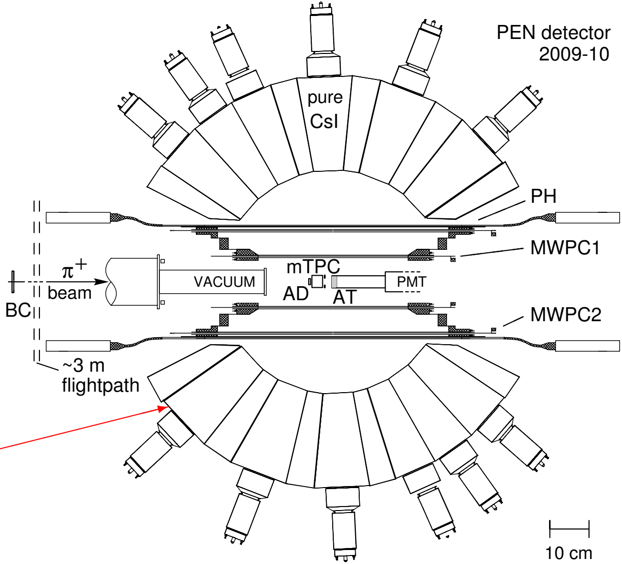
Observed pion and muon decays

	Decay	Branching ratio	Decay label	
$\pi^+ \longrightarrow$	$\mu^+\nu(\gamma)$	$0.9998770\,(4)$	$(\pi_{\mu 2})$	
$\begin{pmatrix}\tau \simeq \\ 26\text{ ns}\end{pmatrix}$	$\mu^+\nu\gamma$	$2.00\,(25) \times 10^{-4}$	$(\pi_{\mu 2\gamma})$	
	$e^+\nu(\gamma)$	$1.230\,(4) \times 10^{-4}$	(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})	
$\pi^0 \longrightarrow$	$\gamma\gamma$	$0.98798\,(32)$ ✓		
$\begin{pmatrix}\tau \simeq \\ 85\text{ as}\end{pmatrix}$	$e^+e^-\gamma$	$1.198\,(32) \times 10^{-2}$	(Dalitz)	
	$e^+e^-e^+e^-$	$3.14\,(30) \times 10^{-5}$		
	e^+e^-	$6.2\,(5) \times 10^{-8}$		
$\mu^+ \longrightarrow$	$e^+\nu\bar{\nu}(\gamma)$	~ 1.0 ✓		
$\begin{pmatrix}\tau \simeq \\ 2.2\,\mu\text{s}\end{pmatrix}$	$e^+\nu\bar{\nu}\gamma$	$0.014\,(4)$ ✓		
	$e^+\nu\bar{\nu}e^+e^-$	$3.4\,(4) \times 10^{-5}$		

PIBETA/PEN apparatus

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





Muon decay parameters: $\mu \longrightarrow e\bar{\nu}_e\nu_\mu$

$$\frac{d^2\Gamma}{dx\, d(\cos\theta)} = \frac{m_\mu}{4\pi^3} W_{e\mu}^4 G_F^2 \sqrt{x^2 - x_0^2} \times$$

$$\times \left[\mathbf{F_{IS}}(x) + P_{\mu^+} \cos\theta\, \mathbf{F_{AS}}(x)\right] \left[1 + \vec{P}_{e^+}(x,\theta) \cdot \hat{\zeta}\right]$$

Isotropic part:

$$\mathbf{F_{IS}}(x) = x(1-x) + \frac{2}{9}\rho(4x^2 - 3x - x_0^2) + \eta\, x_0(1-x)$$

Anisotropic part:

$$\mathbf{F_{AS}}(x) = \frac{1}{3}\xi\sqrt{x^2 - x_0^2}\left(1 - x + \frac{2}{3}\delta\left[4x - 3 + \left(\sqrt{1 - x_0^2} - 1\right)\right]\right)$$

where $x = \frac{E_e}{E_{max}}$, $x_0 = \frac{m_e}{E_{max}}$, and $E_{max} \simeq \frac{m_\mu}{2}$, .

Parameters of radiative muon decay: $\mu \longrightarrow e\bar{\nu}_e\nu_\mu\gamma$

$$\frac{d^3B(x,y,\theta)}{dx\,dy\,2\pi\,d(\cos\theta)} = f_1(x,y,\theta) + \bar{\eta} f_2(x,y,\theta) + (1-\frac{4}{3}\rho) f_3(x,y,\theta)$$

$$\rho = \frac{3}{4} - \frac{3}{4}\Big[|g^V_{LR}|^2 + |g^V_{RL}|^2 + 2|g^T_{LR}|^2 + 2|g^T_{RL}|^2 + \Re(g^S_{RL}g^{T*}_{RL} + g^S_{LR}g^{T*}_{LR})\Big] \stackrel{\text{SM}}{\equiv} \frac{3}{4},$$

$$\bar{\eta} = \left(|g^V_{RL}|^2 + |g^V_{LR}|^2\right) + \frac{1}{8}\left(|g^S_{LR} + 2g^T_{LR}|^2 + |g^S_{RL} + 2g^T_{RL}|^2\right) + 2\left(|g^T_{LR}|^2 + |g^T_{RL}|^2\right) \stackrel{\text{SM}}{\equiv} 0.$$

where $x = \frac{E_e}{E_{max}}$ and $y = \frac{E_\gamma}{E_{max}}$.

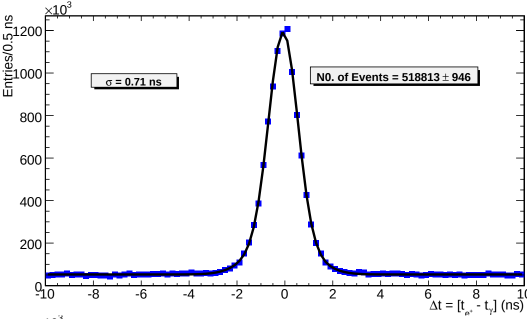
Radiative muon decay,

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

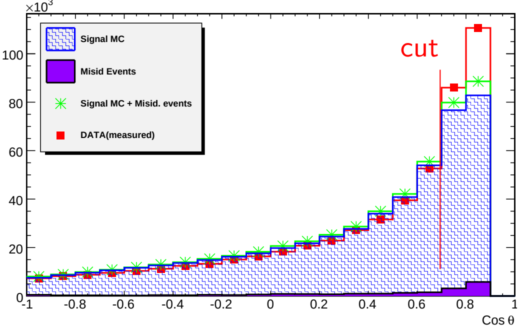
new analysis of 2004 data

(thesis E. Munyangabe)

$$\Delta t = t_e - t_\gamma \quad \longrightarrow$$



$$\cos\theta_{e\gamma} \quad \longrightarrow$$



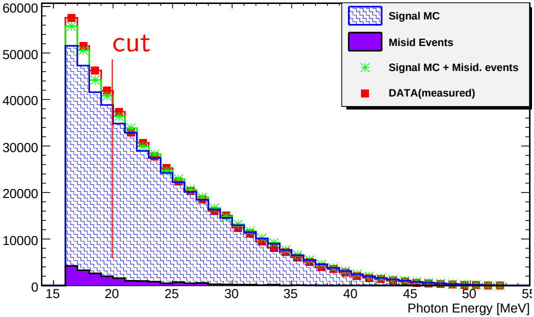
Radiative muon decay,

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

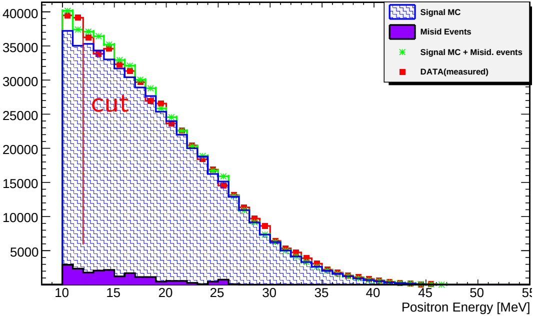
new analysis of 2004 data

(thesis E. Munyangabe)

$E_\gamma \longrightarrow$



$E_{e^+} \longrightarrow$



"Split clumps" very well accounted for!

RMD preliminary results: $\mathbf{B_{exp}}$ (thesis E. Munyangabe)

Preliminary RMD branching ratio for $E_\gamma > 10\,\text{MeV}$, $\theta_{e\gamma} > 30^\circ$:

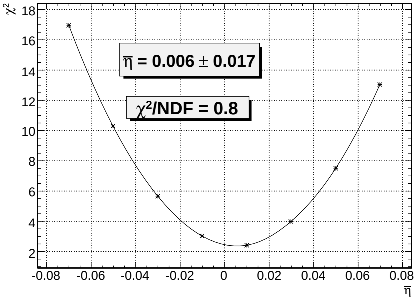
$B_{exp} = 4.365\,(9)_{stat}\,(42)_{syst} \times 10^{-3}$, **29×** improved precision

$B_{SM} = 4.342\,(5)_{stat\text{-}MC} \times 10^{-3}$ (based on > 500k RMD events)

Systematic uncertainty budget:

Quantity	Rel. syst. uncert. (%)
Photon energy calibration	0.73
Background subtraction	0.14
Positron energy threshold	0.26
Positron energy calibration	0.18
Photon energy threshold	0.41
Cosine opening angle	0.29
Time window selection	0.12
Misidentified events	0.03
Total relative syst. uncert.	0.96

RMD preliminary results: $\bar{\eta}$ (thesis E. Munyangabe)



$\bar{\eta}$: Most sensitive phase space subset:

$13\,\text{MeV} < E_\gamma < 45\,\text{MeV}$, and
$10\,\text{MeV} < E_{e^+} < 43\,\text{MeV}$,

yields:

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

or, in terms of an upper limit:

$$\bar{\eta} < \begin{cases} 0.023 & (68\%\text{CL}) \\ 0.029 & (90\%\text{CL}) \end{cases}$$

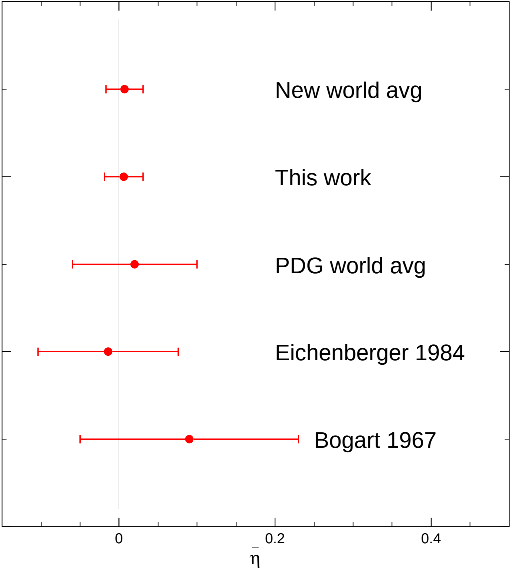
Quantity	$\delta\bar{\eta}$
Photon energy calibration	0.016
Background subtraction	0.003
Positron energy calibration	0.005
Cosine opening angle	0.006
Time window selection	0.002
Misidentified events	0.0003
Total systematic uncert.	0.018

⇐ Systematic uncertainty budget for $\bar{\eta}$.

History of $\bar{\eta}$

Our result is almost **4**× more precise than the best previous experiment (Eichenberger et al, 84).

(Further improvement expected with PEN data)



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