New results in rare pion and muon decays

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Outline

Overview of allowed π and μ decays

Apparatus and method

Prior results

$\pi^+ \to e^+\nu$ decay: motivation

Current status and plans

Summary

Known and measured pion and muon decays

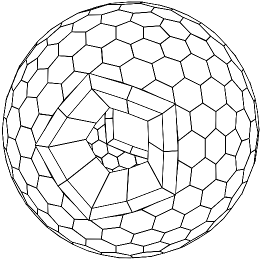
	Decay	*BR*		
$\pi^+ \rightarrow$	$\mu^+\nu$	0.9998770 (4)	($\pi_{\mu 2}$)	
	$\mu^+\nu\gamma$	$2.00\,(25) \times 10^{-4}$	($\pi_{\mu 2\gamma}$)	
	$e^+\nu$	$1.230\,(4) \times 10^{-4}$	(π_{e2})	✓
	$e^+\nu\gamma$	$1.61\,(23) \times 10^{-7}$	($\pi_{e2\gamma}$)	✓
	$\pi^0 e^+\nu$	$1.025\,(34) \times 10^{-8}$	(π_{e3}, π_β)	✓
	$e^+\nu e^+ e^-$	$3.2\,(5) \times 10^{-9}$	(π_{e2ee})	
$\pi^0 \rightarrow$	$\gamma\gamma$	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^-	$6.2\,(5) \times 10^{-8}$		
$\mu^+ \rightarrow$	$e^+\nu\bar{\nu}$	~ 1.0 ✓		
	$e^+\nu\bar{\nu}\gamma$	0.014 (4) ✓		
	$e^+\nu\bar{\nu}e^+e^-$	$3.4\,(4) \times 10^{-5}$		

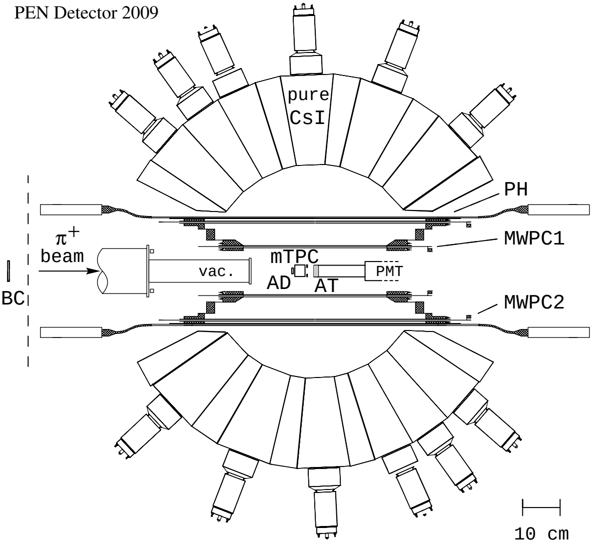
Recent π, μ allowed decay measurements

- $\pi^+ \to \pi^0 e^+ \nu_e$ .... PIBETA ('99–'01)
  - SM checks related to CKM unitarity
- $\pi^+ \to e^+ \nu_e \gamma$(or e^+e^-) .... PIBETA ('99–'04), PEN ('06–)
  - $\mathbf{F_A/F_V}$, π polarizability (χPT calibration)
  - tensor coupling besides $\mathbf{V-A}$ (?)
- $\mu^+ \to e^+ \nu_e \bar{\nu}_\mu$ .... TWIST (2003–04)
  - departures from $\mathbf{V-A}$ in $\mathcal{L}_{\mathrm{weak}}$
- $\mu^+ \to e^+ \nu_e \bar{\nu}_\mu \gamma$(or e^+e^-) .... PIBETA ('04), PEN ('06–)
  - departures from $\mathbf{V-A}$ in $\mathcal{L}_{\mathrm{weak}}$
- $\pi^+ \to e^+ \nu_e$ .... { PEN (2006–) / PiENu ('06–) }
  - **e**-μ universality
  - pseudoscalar coupling besides $\mathbf{V-A}$
  - ν sector anomalies, Majoron searches, $\mathbf{m_{h^+}}$, PS **l-q**'s, V **l-q**'s, ...
  - search for signs of SUSY (MSSM)

The PIBETA/PEN apparatus

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





PIBETA result for 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):

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

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

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

PDG 2010: $V_{ud} = 0.97425(22)$

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

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

$$\mathbf{F_V = 0.0258 \pm 0.0017} \qquad (14\times)$$

$$\mathbf{F_A = 0.0119 \pm 0.0001^{exp}_{(F_V^{CVC})}} \qquad (16\times)$$

$$\mathbf{a = 0.10 \pm 0.06} \ (\mathbf{q^2} \text{ dep of } \mathbf{F_V}) \qquad (\infty)$$

$$\mathbf{-5.2 \times 10^{-4} < F_T < 4.0 \times 10^{-4}} \qquad 90\,\%\ \text{C.L.}$$

Derived pion polarizability and π^0 lifetime (at L.O.):

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

$$\tau_{\pi^0} = (8.5 \pm 1.1) \times 10^{-17}\ \text{s} \quad \begin{cases} \text{current PDG avg: } 8.4\,(4) \\ \text{PrimEx PRL '10: } 7.82\,(22) \end{cases}$$

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

Similar improvements from muon radiative decay forthcoming

Above results will be improved with new PEN data analysis.

$\pi \to e\nu$ decay: SM calculations; measurements

Modern theoretical calculations: $B_{\text{calc}} = \left.\frac{\Gamma(\pi \to e\bar{\nu}(\gamma))}{\Gamma(\pi \to \mu\bar{\nu}(\gamma))}\right|_{calc} =$

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

Experiment, world average [current PDG]:

$$\left.\frac{\Gamma(\pi \to e\bar{\nu}(\gamma))}{\Gamma(\pi \to \mu\bar{\nu}(\gamma))}\right|_{exp} = (1.230 \pm 0.004) \times 10^{-4}$$

N.B.:

PEN, PiENu aim at: $\frac{\delta B}{B} \simeq 5 \times 10^{-4}$

π_{e2} Decay and the SM

$B(\pi_{e2})$ in SM dominated by $(V - A)$ helicity suppression. Deviations primarily due to PS int. terms. Most general 4-fermion π_{e2} amplitude:

$$\frac{G_F}{\sqrt{2}}\Big[\left(\bar{d}\gamma_\mu\gamma^5 u\right)\left(\bar{\nu}_e\gamma^\mu\gamma^5(1-\gamma^5)e\right) f^e_{\mathrm{AL}} + f^e_{\mathrm{PL}}\left(\bar{d}\gamma^5 u\right)\left(\bar{\nu}_e\gamma^5(1-\gamma^5)e\right)\Big] + \text{r.h. } \nu \text{ term}$$

In the SM: $f^\ell_{\mathrm{AL}} = 1$, while $f^\ell_{\mathrm{xR}} = f^\ell_{\mathrm{Px}} = 0$, with $\ell = e, \mu$.

Strong helicity suppression amplifies sensitivity to f^e_{PL}:

$$\frac{B^{\mathrm{obs}}_{\pi e2} - B^{\mathrm{SM}}_{\pi e2}}{B^{\mathrm{SM}}_{\pi e2}} = \frac{\Delta B}{B^{\mathrm{SM}}} = \ldots \simeq \frac{2m^2_\pi}{m_e(m_u + m_d)} f^e_{\mathrm{PL}} \simeq \boxed{7700 f^e_{\mathrm{PL}}}\ !$$

Tgt accuracy of the PEN experiment, $\Delta B/B \simeq 5 \times 10^{-4}$, translates into attractive mass limits:

Example mass bounds from PEN goal accuracy

(a) Charged Higgs, $m_{\mathrm{H}+}$ [Shanker, NP B204 (82) 375]

Given a mixing angle suppression $S \approx 10^{-2}$, we get

$$f^e_{\mathrm{PL}} \approx S \frac{m_t m_\tau}{m^2_{\mathrm{H}+}} \qquad \text{yielding} \qquad \boxed{m_{\mathrm{H}+} > 6.9\,\mathrm{TeV}}.$$

(b) Pseudoscalar leptoquarks, m_{P}

Given an estimated effective Yukawa coupling of $y \simeq 1/250$, we can find m_{P}, mass of the color-triplet PS l-q:

$$f^e_{\mathrm{PL}} \approx \frac{\sqrt{2}}{G_F} \frac{y^2}{2m^2_{\mathrm{P}}} \qquad \text{yielding} \qquad \boxed{m_{\mathrm{P}} > 3.8\,\mathrm{TeV}}.$$

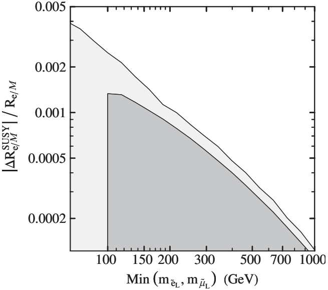
(c) Vector leptoquarks, M_G

Following Shanker who assumes gauge coupling $g \simeq g_{\mathrm{SU(2)}}$, we get:

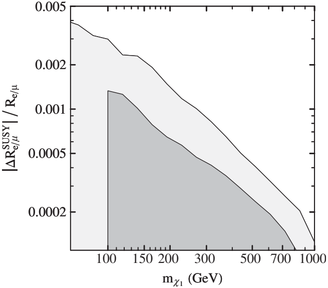
$$f^e_{\mathrm{PL}} \approx \frac{4M^2_W}{M^2_G} \qquad \text{yielding} \qquad \boxed{M_G > 630\,\mathrm{TeV}}.$$

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

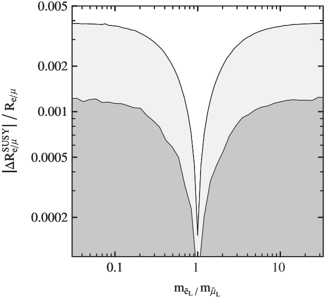
minimal selectron, smuon masses:



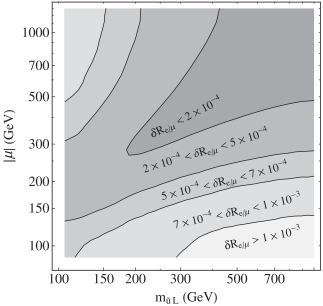
lowest mass chargino:



slepton mass degeneracy:



Higgsino mass param. μ and $m_{\tilde{u}_L}$:



RPV scenario constraints also discussed.

Lepton universality (and neutrinos)

From

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

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

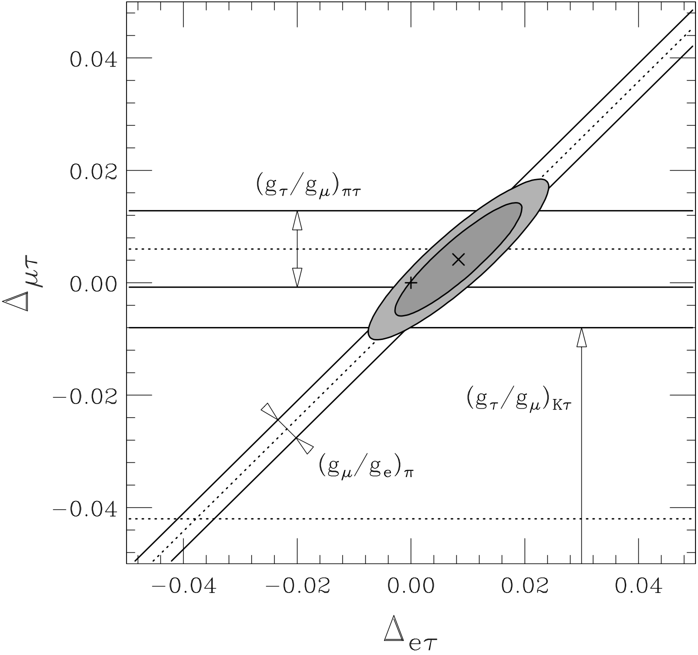
one can evaluate

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

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.”]



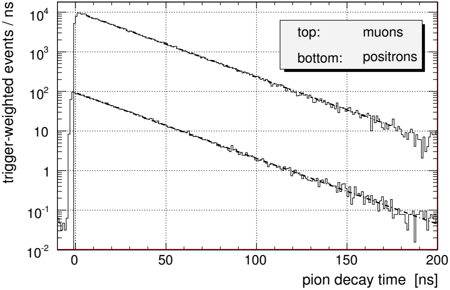
Loinaz et al., PRD **70** (2004) 113004

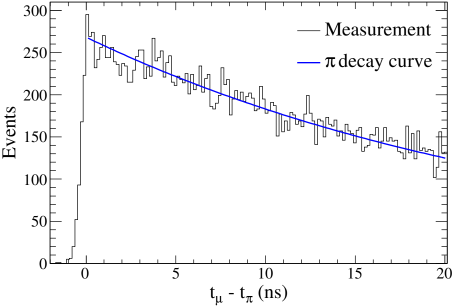
$$\Delta_{\ell\ell'} = 2\left(\frac{g_\ell}{g_{\ell'}} - 1\right)$$

PEN experiment: status and plans

- Approved in 2006; development runs: 2007, '08; data runs '09, '10.
- Improved beam tracking (miniTPC) implemented in '09, '10 runs.
- $> 20\,\mathrm{M}\ \pi_{e2}$'s recorded $\Rightarrow (\delta B/B)_{\mathrm{stat}} \simeq 2 \times 10^{-4}$.

Illustration: decays in the target detector (2008 run):





Pulse Shaping

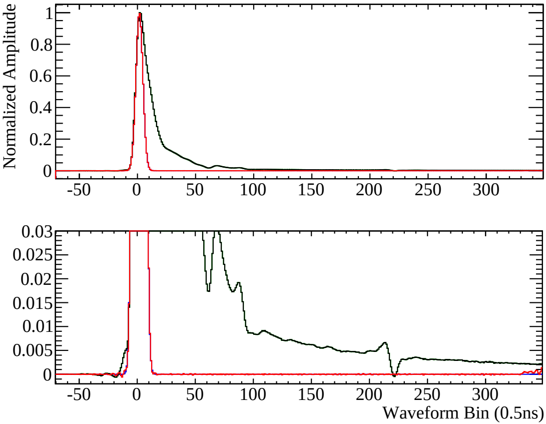
Developed an iterative program to create a digital adaptive filter.

Input:

- Averaged system response waveform array, w_i
- Desired waveform array, $\tilde{w}_i$

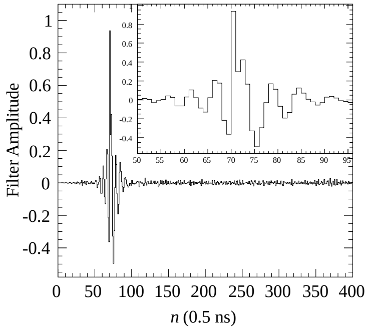
Output:

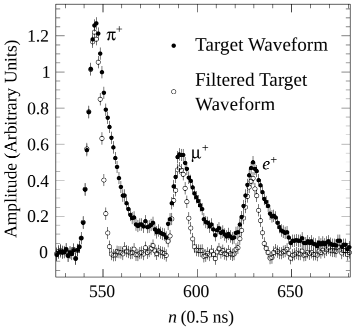
- Shaping array ("Filter"), s_i



Pulse Shaping: $\tilde{w}_i = \sum_{k=k_{\min}}^{k_{\max}} s_k w_j$ where $k \equiv i - j$

Pulse Shaping

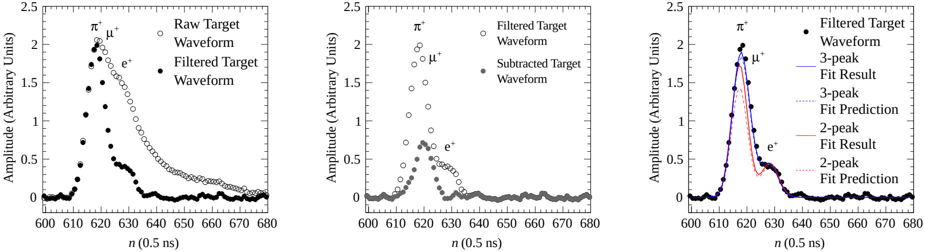




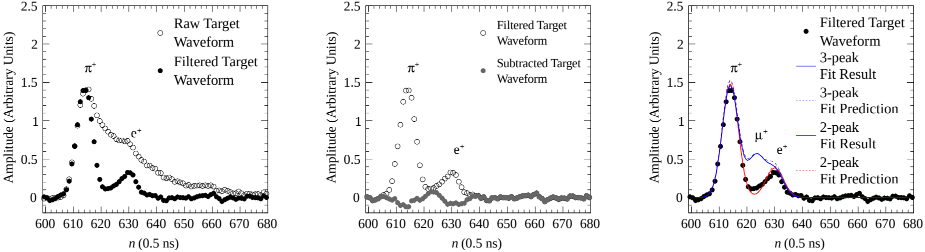
- Filtering (Shaping) isolates the monoenergetic muon for energy calibration.

★ A. Palladino, A. van der Schaaf, D. Počanić, "*Reconstructing Detector Waveforms with Overlapping Pulses*," to be submitted for publication, 2012.

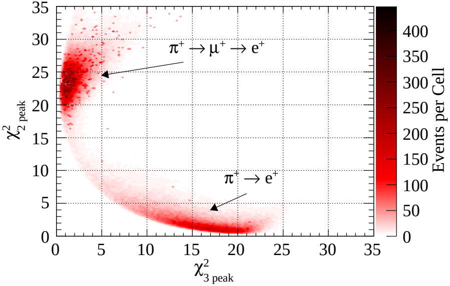
$\pi^+ \to \mu^+ \to e^+$ Event, Waveform Fit

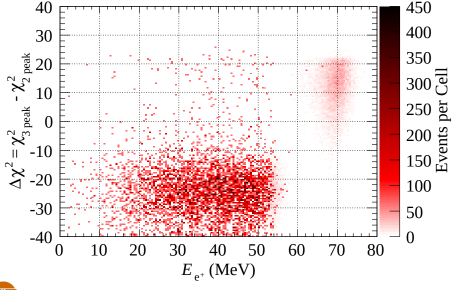


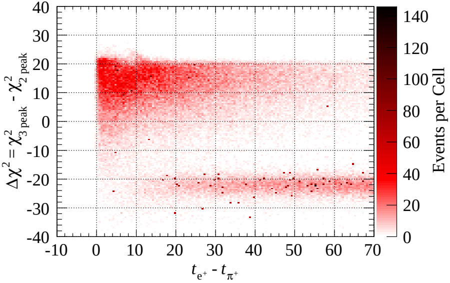
$\pi^+ \to e^+$ Event, Waveform Fit



Waveform Fitting Results







Maximum Likelihood Analysis

One likelihood function encompassing many observables and processes.

$$\mathcal{L}\left(\overrightarrow{x}_e\ ;\ f_m\right) = \prod_{e=1}^{\mathcal{N}} \left[\sum_{m=1}^{M} f_m\, P_m(\overrightarrow{x}_e)\right]$$

where $\mathcal{N}$ is the number of events, and

$(\overrightarrow{x}_e)$ are the observables

- Time between π^+ and e^+
- Total Positron Energy
- "Probability" of Pile-up

$$\text{“}P\text{“}_{\text{pile-up}} = \ln\left[\sum_{k=1}^{\ell} e^{-|dt_k|/\tau_\mu}\right]$$

- Pion Decay Vertex
- etc.

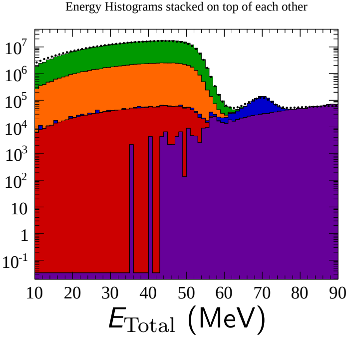
(f_m) fraction of process m

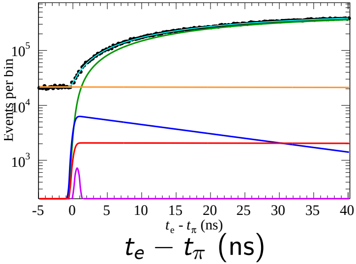
- $f_{\pi_{e2}}$, $\pi^+ \to e^+$
- $f_{\pi_{\mu 2}}$, $\pi^+ \to \mu^+ \to e^+$
- $f_{\rm Acc}$, Accidentals / Pile-up
- $f_{\rm DIF}$, Pion Decays-in-flight
- $f_{\rm Had}$, Proton
- $f_?$, etc.

Model: Probability Distribution Functions, P_m

$$\mathcal{L}\left(\overrightarrow{E}_{\mathrm{Total}}\,,\ \overrightarrow{\Delta t}\ ;\ f_{\pi_{e2}}, f_{\pi_{\mu 2}}, f_{\mathrm{Acc}}, f_{\mathrm{DIF}}, f_{\mathrm{Had}}\right)$$

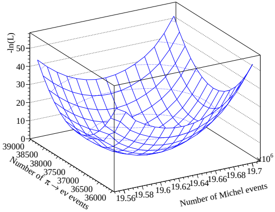
- $\pi_{\mu 2}$
- π_{e2}
- Accidental Coincidence
- π Decay-in-flight
- Hadronic (proton)

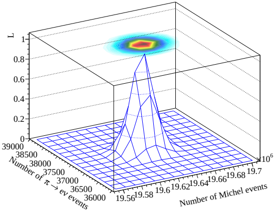


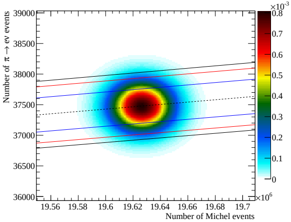


Practicality: Negative Log Likelihood

$\ell = -\ln\mathcal{L}$ $\mathcal{L} = e^{-\ell}$ $N_{\pi\to e}$ vs. $N_{\pi\to\mu\to e}$







Preliminary Result (Blinded)

$R^{\mathrm{ML}}_{\pi_{e2}} = [1.112 \pm 0.002(\mathrm{stat.})] \times 10^4$

$\frac{\Delta R^{\mathrm{ML}}_{\pi_{e2}}}{R^{\mathrm{ML}}_{\pi_{e2}}} = 0.0018$

$R^{\mathrm{PDG}}_{\pi_{e2}} = [1.230 \pm 0.004(\mathrm{comb.})] \times 10^4$

$\frac{\Delta R^{\mathrm{PDG}}_{\pi_{e2}}}{R^{\mathrm{PDG}}_{\pi_{e2}}} = 0.0033$

Summary

- *A significant experimental effort is under way 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 necessary for their proper interpretation.*
- *Orders of magnitude improvement in precision has been achieved; more lie in store.*
- *Modest scale of investment of resources required.*
- *Unique opportunity for scientific advancement.*
- *Great projects for graduate students and postdocs—full range of professional training.*

Current and former PIBETA and PEN collaborators

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