Precision Measurements with Pions

Measurements of $(\pi \rightarrow e\nu)/(\pi \rightarrow \mu\nu)$ Branching Ratio

Toshio Numao

TRIUMF
π→eν decay

the first experimental success is the long-awaited observation of a pion decaying into an electron and a neutrino, August 1958.

CERN PS’s first successful exp.
History of $\pi \to e\nu$ decay
SM branching ratio calculations

\[
R^0_{e/\mu} = \frac{\Gamma(\pi \to e\nu)}{\Gamma(\pi \to \mu\nu)} = \frac{g_e^2 m_e^2 (m_\pi^2 - m_e^2)^2}{g_\mu^2 m_\mu^2 (m_\pi^2 - m_\mu^2)^2}
\]

\[= 1.284 \times 10^{-4}\]

\[
R^{th}_{e/\mu} = \frac{\Gamma(\pi \to e\nu + \pi \to e\nu\gamma)}{\Gamma(\pi \to \mu\nu + \pi \to \mu\nu\gamma)} = R^0_{e/\mu}(1 + 3\alpha/\pi \ln(m_e/m_\mu))
\]

\[= 1.233 \times 10^{-4}\]

Inputs: \(F_A/F_\nu, F_\pi \ldots \) : \(\pi \to e\nu\gamma, \) pion life

References:
- Kinoshita 1959
- Marciano, Sirlin 1993
- Cirigliano, Rosell 2007
$\pi \rightarrow e\nu\gamma$

$F_V = 0.0258(17)$
$F_A = 0.0117(17)$
$F_T = (-0.6 \pm 2.8) \times 10^{-4}$

PRL 103 051802 (2009)
\[ \Gamma_\pi = \frac{G_F^2 f_\pi^2}{4\pi m_\pi^3} \left| V_{ud} \right|^2 \sum_{l=e,\mu} m_l^2 (m_\pi^2 - m_l^2)^2 \]

Beamline experiment

26.0231((50)(84)) ns '95 TRIUMF
26.0361(52) ns '95 Koptev...

“New” result by Primex group will be published soon.
Present Status of $\pi \rightarrow e\nu$ Measurements

$$R_{e/\mu}^{SM} = 1.2352 \pm 0.0001 \times 10^{-4}$$

$$R_{e/\mu}^{\text{exp}} = 1.2265 \pm 0.0034 \pm 0.0044 \times 10^{-4} \text{ (TRIUMF, '92)}$$
$$R_{e/\mu}^{\text{exp}} = 1.2346 \pm 0.0035 \pm 0.0036 \times 10^{-4} \text{ (PSI, '93)}$$

Two new initiatives for $0.1\%$ measurements
- PIENU at TRIUMF
- PEN at PSI
### $\mu$-$e$ Lepton Universality

#### $W$ decays

\[
R_{e/\mu}^W = \frac{\Gamma(w \to e\nu)}{\Gamma(w \to \mu\nu)} \propto \frac{g_e^2}{g_\mu^2}
\]

#### $M \to l\nu$ decays

\[
R_{e/\mu}^\pi = \frac{\Gamma(\pi \to e\nu)}{\Gamma(\pi \to \mu\nu)} \propto \frac{g_e^2}{g_\mu^2} \frac{m_e^2}{m_\mu^2}
\]

<table>
<thead>
<tr>
<th>Mode</th>
<th>$g_e/g_\mu$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\pi$--$e\nu/\pi$--$\mu\nu$</td>
<td>0.9985 ± 0.0016</td>
</tr>
<tr>
<td>$K$--$e\nu/K$--$\mu\nu$</td>
<td>1.0018 ± 0.0026</td>
</tr>
<tr>
<td>$\tau$--$e\nu/\tau$--$\mu\nu$</td>
<td>1.0001 ± 0.0020*</td>
</tr>
<tr>
<td>$\nu e/\nu\mu$ scatt.</td>
<td>1.10 ± 0.05</td>
</tr>
<tr>
<td>$W$ decays</td>
<td>0.999 ± 0.011</td>
</tr>
<tr>
<td>$K$--$\pi e\nu/K$--$\pi \mu\nu$</td>
<td>0.9979 ± 0.0025</td>
</tr>
</tbody>
</table>

*to be updated.
Beyond the Standard Model

New PS interaction

\[ 1 - \frac{R_{e/\mu}^\text{New}}{R_{e/\mu}^{SM}} \sim \pm \left( \frac{2\pi}{G_\mu} \right) \frac{1}{\Lambda_{eP}^2} \frac{m_\pi^2}{m_e(m_d + m_u)} \]

\[ \sim \left( \frac{1\text{TeV}}{\Lambda_{eP}} \right)^2 \times 10^3 \]

0.1 % measurement \( \Rightarrow \Lambda \sim 1000\text{TeV} \)

Marciano…
Beyond the Standard Model

Minimal SUSY SM

R-Parity Violating SUSY

Lowest chargino mass

Ramsey-Musolf... PRD76 095017 (2007)
Beyond the Standard Model

**MSSM LFV**

\[ lH^\pm \nu_\tau \rightarrow \frac{g_2}{\sqrt{2}} \frac{m_\tau}{M_W} \Delta_R^{3l} \tan^2 \beta \quad l = e, \mu \]

A few $x 10^{-4}$ deviation is expected.

Masiero, Paradisi, …

**Massive neutrino**

Others

- Leptoquarks
- Extra Higgs
- Excited gauge bosons
- Compositeness
- $\text{SU}(2) \times \text{SU}(2) \times \text{SU}(2) \times \text{U}(1)$
- …

![Graph showing neutrino mass vs. $|\langle \ell \rangle|^2$](image)
Method

\[ A(\pi \rightarrow e\nu) \] normalized by the number of stopped pions.
- \( T_0 \), decay in flight, acceptance...

\[ \frac{A(\pi \rightarrow e\nu)}{A(\pi \rightarrow \mu\nu)} \]  
Czapek et al.
- Acceptance difference,...

\[ \frac{A(\pi \rightarrow e\nu)}{A(\pi \rightarrow \mu \rightarrow e)} \]  
Britton et al.
- Pion life, Energy dependent cross section...

Common uncertainty
- Low energy tail of the \( \pi \rightarrow e\nu \) peak.
Fit both time spectra simultaneously and obtain the ratio.

Correct for low-energy tail (~2%) and energy dependent acceptance (~0.3%).
Old (TRIUMF E248) experiment

\[ R = (1.2265 \pm 0.0034 \pm 0.0044) \times 10^{-4} \]

Measured positrons from

\[ \pi \rightarrow e\nu \quad (\tau = 26\text{ns}) \]
\[ \pi \rightarrow \mu\nu \]
\[ \mu \rightarrow e\nu\nu \quad (\tau = 2\mu\text{s}) \]

- small solid angle
- pile-up (neutron)
- material along e+/s pass
- distortion in time spectra
NaI in beam
Solid angle = 20 %
Separated beam
Ring counter (CsI)
π, e tracking
Close T1 to targ.

Lower beam rate (70 kHz)
pion/positron > 50

Setup of the TRIUMF experiment E1072
PIENU Detector

NaI

CsI’s

WC

Beam cntr.

Target
Time spectra (PIENU)

2009 data

\( \pi \rightarrow e\nu \)

\(-10x\) less BG in \( \pi \rightarrow e\nu \) region.
BG is from neutral PU.
More \( n \) shield, more distance.
- Twice wider time range.
To fit \( \exp(-\lambda t), \exp(-2\lambda t), \text{const.} \)
- Lower-rate/cleaner beam.
Low energy tail

Tail can be suppressed by CsI.

NaI doesn’t see $n$ separation energy if $n$ escapes (published in NIM).

Response function of the calorimeter was measured with a positron beam at various angles.
Tail correction

$\pi - e\nu$

$T\pi + \Delta Ee$

$\pi - \mu - e$

$T\pi + \Delta Ee + E\mu$

Timing cut

Timing + Energy cuts

4 MeV
Empirical Tail correction

2009 data

- Time and target-pulse information suppresses $\pi \rightarrow \mu \rightarrow e$ decays.
- Upstream tracking suppresses Decay In Flight events.
- Combined tracking further suppresses DIF events.
- Expected improvement $0.25\% \rightarrow 0.03\%$ (combined with 30x statistical improvement)

2009 data

$\pi^+ \rightarrow e^+ \nu$

$\pi^+ \rightarrow \mu^+ \nu$

Decays in Flight Events
The PEN apparatus

- stopped $\pi^+$ beam
- active target counter
- 240-det. CsI(p) calo.
- central tracking
- digitized PMT signals
- stable temp./humidity
PIENU
Accumulate 3 M clean events by the end of 2010
Another 3 M events in 2011

PEN
Accumulated 5 M clean events.
Running for another 5 M events in 2010.
## Summary of uncertainties

<table>
<thead>
<tr>
<th>Source</th>
<th>Old Triumf</th>
<th>PIENU</th>
<th>PEN</th>
</tr>
</thead>
<tbody>
<tr>
<td>Statistical</td>
<td>0.0028</td>
<td>0.0005</td>
<td>0.0002</td>
</tr>
<tr>
<td>Low-energy tail</td>
<td>0.0025</td>
<td>0.0003</td>
<td></td>
</tr>
<tr>
<td>Accept diff.</td>
<td>0.0011</td>
<td>0.0003</td>
<td>0.0002</td>
</tr>
<tr>
<td>Pion life</td>
<td>0.0009</td>
<td>0.0002</td>
<td></td>
</tr>
<tr>
<td>Other</td>
<td>0.0011</td>
<td>0.0003</td>
<td>0.0002</td>
</tr>
<tr>
<td>Total</td>
<td>0.0047</td>
<td>0.0006</td>
<td>0.0005</td>
</tr>
</tbody>
</table>
For normalization

Pion Beta Decays

- \( V_{ud} \) measurement.

\[
R = [1.036 \pm 0.004 \pm 0.005] \times 10^{-8}
\]

\[
V_{ud} = 0.9728(30)
\]

\[
0.9738(5) \quad \text{Nucl. } \beta \text{ decay}
\]

-π-ev is not rare decay---it is used even for normalization.
-Precision measurement of π-ev provides the best test of μ-e universality.
-π-ev is sensitive to the presence of PS interactions---physics beyond the SM.
-Two experimental results at <0.1 % precision are expected to come out in a few years.