PIENU Experiment at TRIUMF:
A precision measurement of $\pi \to e\nu$ decay

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12. Stefan-Meyer-Institut
• Motivation
• Experiment
• Analysis
• Results
  • $\pi \rightarrow e\nu$
  • Massive neutrino
• Conclusion
Motivation: Decays $\pi^+ \rightarrow e^+\nu$ and $\pi^+ \rightarrow \mu^+\nu$

Standard Model:

$$R_{e/\mu}^{SM} = \frac{\Gamma(\pi \rightarrow e^+\nu + \pi \rightarrow e^+\nu\gamma)}{\Gamma(\pi \rightarrow \mu^+\nu + \pi \rightarrow \mu^+\nu\gamma)} = 1.2352(1) \times 10^{-4}$$

Calculated to extreme precision 0.01%
$\pi^+ \rightarrow \mu^+\nu$ is preferred due to helicity suppression (V-A)

Experimental result:


$$R_{e/\mu}^{exp} = 1.231(4) \times 10^{-4}$$

Large gap $O(10^2)$ in precision between Theory and Measurement

PIENU: aims at <0.1% in BR measurement

So does PEN experiment at PSI
Motivation

Beyond the Standard Model

- Non universality
- Pseudoscalar interaction: helicity suppression → very attractive effective mass reach

$$1 - \frac{R_{e/\nu}^{\text{New}}}{R_{e/\nu}^{\text{SM}}} \sim \pm \frac{\sqrt{2}\pi}{G_\mu} \frac{1}{\Lambda_{eP}^2} \frac{m_\pi^2}{m_e(m_d + m_u)} \sim \left( \frac{1 \text{TeV}}{\Lambda_{eP}} \right)^2 \times 10^3$$

0.1% BR → $\Lambda_{eP} \sim 1000 \text{ TeV}$

- Others:

Massive $\nu$'s

Scalar couplings

R-Parity violation SUSY

<table>
<thead>
<tr>
<th>Decay mode</th>
<th>$(g_\mu/g_e)^2$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\tau \rightarrow \mu$ / $\tau \rightarrow e$</td>
<td>$1.0018 \pm 0.0014$</td>
</tr>
<tr>
<td>$\pi \rightarrow \mu$ / $\pi \rightarrow e$</td>
<td>$1.0021 \pm 0.0016$</td>
</tr>
<tr>
<td>$K \rightarrow \mu$ / $K \rightarrow e$</td>
<td>$0.996 \pm 0.005$</td>
</tr>
<tr>
<td>$K \rightarrow \pi \mu$ / $K \rightarrow \pi e$</td>
<td>$1.002 \pm 0.002$</td>
</tr>
<tr>
<td>$W \rightarrow \mu$ / $W \rightarrow e$</td>
<td>$0.997 \pm 0.010$</td>
</tr>
</tbody>
</table>

The pion decay branching ratio is one of the most precise tests of charged current lepton universality

Agreement with SM → constraints for BSM
Disagreement with SM → New Physics
Experiment: Technique

- Separated pion beam, pions stop in active target
- Simultaneous data collection
- Same final state
- Same acceptance

- Discrimination of the decay mode
  - Energy deposit in calorimeter
- Estimation of raw branching ratio
  - Simultaneous fitting of two time spectra pi-e and pi-mu-e (high and low energy region)

Important corrections:
- Tail correction
- piDIF
- Acceptance

8 mm thick Active target

Range: ~1mm

π⁺: 4 Mev

Energy deposit in calorimeter

Energy deposit in target

Time spectrum $t_e - t_\pi$
Experiment: Lessons from E248

**E248:**
- \( R = 1.2265 \pm 0.0034 \text{(stat)} \pm 0.0044 \text{(sys)} \times 10^{-4} \)
- \( 10^5 \pi \rightarrow \nu_e \) were collected for a month
- Systematic and statistical errors of the same order

**Main sources of uncertainties:**
- Low energy tail
  - Large piDIF contribution
  - 20% events in tail region
- Small (2%) acceptance
  - Low statistics
  - Large acceptance correction
Experiment: PIENU Detector Concept

Large NaI crystal near target
• Large solid angle (25%)
• High resolution: \( \sim 1\% \sigma \) at 70 MeV/c

CsI crystal array (annular)
• Extends NaI Calorimeter
• Reduces e+ low energy (<50 MeV) tail (8% → 2%)

Si-strips + MWPC
• Tracking of particles upstream and downstream of the target
• Reduces \( \pi \) decays in flight

Fast readout digitizers
• 500MHz FADC for Scintillators (8 usec)
• 60MHz FADC for Crystals
• Pileup rejection and Pulse Shape Fit
Lineshape measurement ready

- The calorimeter part is mobile so can be exposed to the positron beam at different angles
- The Target assembly is removable
- Detailed measurement of the crystal response
Experiment: Beamline

- Beam positrons suppression
  - Degrader after the first bending magnet
  - Collimator after the second one
  - Another magnet to avoid neutral particles produced in the collimator coming to the detector
- Beam composition
  - $\pi$ (82%)
  - $\mu$ (14%)
  - $e^+$ (<2%)

Experiment: Realization

Mechanical Design and Realization
- NaI/CsI calorimeter needs to be mobile for response (lineshape) measurements
- Scintillator array modularity for test measurements
- Minimize scattering of the decay positrons and maximize acceptance

Assembled and commissioned in 05/2009
Experiment: Realization
Experiment: Trigger

- NIM based logic
- Basic trigger (Prescale)
  - $E_{\text{inc}} > \text{thr}$
  - incoming/decay particles are in [-300,500]ns interval
- Prescaled x16
- Early time: [4,40]ns
- TIGC (NaI+CsI > thr)
  - generated by a special VME module monitoring amplitudes in NaI/CsI channels
Experiment: Trigger and rates

Other Triggers:
- Cosmic trigger (CsI calibration)
- Beam positron (Energy calibration)
- Xe lamp trigger (CsI gain monitoring system)

Typical rates

<table>
<thead>
<tr>
<th>Trigger</th>
<th>Rate [Hz]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Pion stop in target</td>
<td>$5 \times 10^4$</td>
</tr>
<tr>
<td><strong>Physics Triggers</strong></td>
<td></td>
</tr>
<tr>
<td>Early trigger</td>
<td>160</td>
</tr>
<tr>
<td>TIGC trigger</td>
<td>170</td>
</tr>
<tr>
<td>Prescale trigger</td>
<td>240</td>
</tr>
<tr>
<td><strong>Other Triggers</strong></td>
<td></td>
</tr>
<tr>
<td>Cosmics trigger</td>
<td>15</td>
</tr>
<tr>
<td>Beam Positron trigger</td>
<td>5</td>
</tr>
<tr>
<td>Xe lamp trigger</td>
<td>2</td>
</tr>
<tr>
<td><strong>Total Trigger</strong></td>
<td>600</td>
</tr>
</tbody>
</table>
Experiment: History

<table>
<thead>
<tr>
<th>Year</th>
<th>Month</th>
<th>Events</th>
</tr>
</thead>
<tbody>
<tr>
<td>2005</td>
<td>Dec.</td>
<td>Proposal approved by TRIUMF</td>
</tr>
<tr>
<td>2006</td>
<td></td>
<td>Detector design and test</td>
</tr>
<tr>
<td>2007</td>
<td></td>
<td>Detector construction and beam tests in M9</td>
</tr>
<tr>
<td>2008</td>
<td>May</td>
<td>Beam test in M13</td>
</tr>
<tr>
<td>2008</td>
<td>Oct.</td>
<td>M13 beam channel extension completed</td>
</tr>
<tr>
<td>2008</td>
<td>Oct.-Nov.</td>
<td>Test in M13 with most of the detectors</td>
</tr>
<tr>
<td>2009</td>
<td>May</td>
<td>PIENU detector completed</td>
</tr>
<tr>
<td>2009</td>
<td>May-Sep.</td>
<td>Run-I (1M)</td>
</tr>
<tr>
<td>2009</td>
<td>Oct.-Dec.</td>
<td>Run-II (0.5M)</td>
</tr>
<tr>
<td>2010</td>
<td>March</td>
<td>Temperature controlled enclosure completed</td>
</tr>
<tr>
<td>2010</td>
<td>Apr.-Sep.</td>
<td>Run-III (4M)</td>
</tr>
<tr>
<td>2011</td>
<td>Aug.</td>
<td>Systematic studies with beam</td>
</tr>
<tr>
<td>2011</td>
<td>Sept-Oct.</td>
<td>Lineshape measurements</td>
</tr>
<tr>
<td>2011</td>
<td>Nov.</td>
<td>Run-V (2M)</td>
</tr>
<tr>
<td>2012</td>
<td>Jul.-Dec.</td>
<td>Run VI (4M)</td>
</tr>
</tbody>
</table>

December 2012 was the last month of data collection 13-14M $\pi \to e\nu$ were collected (before analysis cuts)
Analysis: Outline

- General Method
- Blind Analysis
- “Raw” branching ratio extraction
- Tail Correction
- Other corrections
  - Bhabha scattering
  - Muon decays-in-flight
  - Acceptance

The results presented in the following are based on ~1/10 of the statistics collected and are PRELIMINARY
Analysis: Method

- Divide the Positron Energy Spectrum in 2 Regions

- Consider the Corresponding Time Spectra

- Extract the BR by Fitting the Time Spectra Simultaneously

- Apply Corrections
Before we start.....

Data is blinded by altering the number (yield) of PIENU decays based on Target Energy
Basic cuts:
- fiducial (beam profile in WC1,2)
- pion selection (dE/dX in B1, B2; TOF)
- pileup (no extra activity from -6.4us to the end of observation interval)
- acceptance
Analysis: Data 2010

- Simultaneous Fit of the Time Spectra:
  - Total $\chi^2$/DoF = 1.1
  - t<0 region constrain backgrounds

- Backgrounds
  - $\pi \rightarrow \mu \rightarrow e$ plus pileup
  - "old muon" plus NaI/CsI hit
  - "old muon" plus resolution
  - pion radiative decay

- Background
  - "old muon" decays
Analysis: Tail Correction

Low energy Tail correction

- Most significant correction (~2%)
- Two approaches are taken:
  - Lower limit value (direct observation using data with $\pi \rightarrow \mu \rightarrow e$ suppressed, i.e. Suppressed Spectrum)
  - Upper limit value (modelling based on special lineshape data when NaI/CsI is exposed to positron beam at different angles)
Analysis: Lower Limit

- Cuts applied to final energy spectrum to further suppress $\pi \rightarrow \mu \rightarrow e$:

<table>
<thead>
<tr>
<th>Cuts</th>
<th>Low energy fraction [%]</th>
<th>Signal efficiency [%]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Time</td>
<td>99.0</td>
<td>82.85</td>
</tr>
<tr>
<td>Total Energy *</td>
<td>30.7</td>
<td>76.80</td>
</tr>
<tr>
<td>Kink</td>
<td>18.4</td>
<td>93.14</td>
</tr>
<tr>
<td>S3 *</td>
<td>17.7</td>
<td>99.99</td>
</tr>
<tr>
<td>Pulse Shape *</td>
<td>16.7</td>
<td>99.46</td>
</tr>
</tbody>
</table>
**Analysis: Lower Limit**

- Tail can be estimated if background shape is known
- Background events: piDIF, muDIF
- piDIF shape obtained from data (late decays)
- muDIF is MC
- Target total energy cut removes a fraction of Bhabha scattering events, this is accounted for later when final tail correction value is calculated
Analysis: Bhabha Correction

- MC based
- +0.70% to tail fraction
First observation of the **PHOTO-NUCLEAR**
peaks in NaI crystal response to
monochromatic positron beam

Peaks are consistent with neutrons escaping

This effect isn`t properly modeled in G4 and
influences the amount of low energy tail
Analysis: Upper Limit

- NaI/CsI was exposed to a monochromatic 70MeV positron beam at different angles
- Energy spectra were used to tune MC (no Hadronic interactions) to reproduce the main peak
- The difference between the number of tail events in MC and data for each angle was parametrized
- Tail value is calculated as MC tail plus photo-nuclear correction based on parametrization of difference above

Because positron beam has finite momentum bite and possibly tails in momentum distribution this method overestimates the amount of tail events (Upper Limit)
Analysis: Tail Correction Summary

- Lower limit $0.87 \pm 0.12\%$
  with Bhabha correction $1.57 \pm 0.12\%_{\text{stat. + syst.}}$

- Upper limit $1.7 \pm 0.1\%_{\text{syst.}}$

- Procedures are not finalized yet but we seem to be able to control systematics at desired level
Analysis: Acceptance Correction

Acceptance Correction is small, but has to rely on the MC.

Various systematic effects are estimated. Deviations are within statistical uncertainty.

MC validation effort focusing on
- Bhabha scattering
- Multiple scattering
- Annihilation in flight
Is underway...

### Table: Acceptance Ratio at R=60 mm

<table>
<thead>
<tr>
<th>Case</th>
<th>Description</th>
<th>Ratio of acceptances</th>
</tr>
</thead>
<tbody>
<tr>
<td>( \pi ) stop in Tg</td>
<td>[mm]</td>
<td></td>
</tr>
<tr>
<td>I.a)</td>
<td>( z = 0.08 ) (nominal)</td>
<td>0.9994</td>
</tr>
<tr>
<td>I.b)</td>
<td>( z = +1 )</td>
<td>0.9997</td>
</tr>
<tr>
<td>I.c)</td>
<td>( z = -1 )</td>
<td>0.9993</td>
</tr>
<tr>
<td>I.d)</td>
<td>( \sigma = 1% )</td>
<td>0.9996</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Displacement [mm]</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>II.a)</td>
<td>( z ) WC3 = +2</td>
</tr>
<tr>
<td>II.b)</td>
<td>( z ) WC3 = -2</td>
</tr>
<tr>
<td>II.c)</td>
<td>( z ) S3 = +0.2</td>
</tr>
<tr>
<td>II.d)</td>
<td>( z ) S3 = -0.2</td>
</tr>
<tr>
<td>III.a)</td>
<td>( x ) WC3 = +0.2</td>
</tr>
<tr>
<td>III.b)</td>
<td>( x ) WC3 = -0.2</td>
</tr>
<tr>
<td>III.c)</td>
<td>( y ) WC3 = +0.2</td>
</tr>
<tr>
<td>III.d)</td>
<td>( y ) WC3 = -0.2</td>
</tr>
<tr>
<td>III.e)</td>
<td>( x ) S3 = +0.02</td>
</tr>
<tr>
<td>III.f)</td>
<td>( x ) S3 = -0.02</td>
</tr>
<tr>
<td>III.g)</td>
<td>( y ) S3 = +0.02</td>
</tr>
<tr>
<td>III.h)</td>
<td>( y ) S3 = -0.02</td>
</tr>
</tbody>
</table>

R at WC3 for various \( \pi^+ \) momenta
Analysis: muDIF Correction

- Positrons from muDIF can have energy above Michel end point, their time distribution is the same as for $\pi \rightarrow e\nu$
- They are indistinguishable from $\pi \rightarrow e\nu$
- MC based correction is applied
- $0.9976 \pm 0.0002$ in value
Other Systematics:

- Energy dependence of $t_0$
- Tracking detector inefficiencies and acceptance
- WC3 inefficiency
- S3 inefficiency
- Multiple hits in WC3

Found to be negligible
Analysis: Correction Summary/Results

<table>
<thead>
<tr>
<th>Process</th>
<th>Correction</th>
<th>Uncertainty</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>stat.</td>
</tr>
<tr>
<td>&quot;Raw&quot; Branching ratio ((\times 10^{-4}))</td>
<td></td>
<td>syst.</td>
</tr>
<tr>
<td>t_0 energy dependence</td>
<td>x0.9993</td>
<td>/</td>
</tr>
<tr>
<td>Muon Decay in Flight</td>
<td>x0.9976</td>
<td>/</td>
</tr>
<tr>
<td>Low energy tail</td>
<td>x1.0173</td>
<td>/</td>
</tr>
<tr>
<td>Acceptance tail correction</td>
<td>x0.9998</td>
<td>/</td>
</tr>
<tr>
<td>Total Correction</td>
<td>x1.0139</td>
<td>/</td>
</tr>
</tbody>
</table>

Total Branching Ratio

\[
R_{e/\mu}^{\text{exp}} = \frac{\Gamma(\pi \rightarrow e \nu + \pi \rightarrow e \nu \gamma)}{\Gamma(\pi \rightarrow \mu \nu + \pi \rightarrow \mu \nu \gamma)} = (1.229 \pm 0.003 \text{ (stat.)} \pm 0.002 \text{ (syst.)}) \times 10^{-4}
\]

Preliminary

Analysis is in progress. Further possible improvements:

- looser pileup cuts (increase statistics; 40% is removed by it)
- better acceptance optimization
- better technique to extract tail and acceptance corrections
Analysis: Massive neutrinos in $\pi^+ \rightarrow e^+\nu$

**Suppressed spectrum**
Massive $\nu_i$ will appear as additional peak in the $\pi \rightarrow e^+\nu$ energy spectrum

![Graph showing energy spectrum with no cut, 35 degree cut, and e+ beam cuts.]

No extra peaks due to $\nu_i$ found, and limits are obtained:

Further improvement is possible with more statistics and better understanding of the lineshape.

**Heavy $\nu$**

\[ \frac{\Gamma(\pi \rightarrow e\nu_i)}{\Gamma(\pi \rightarrow e\nu_e)} = |U_{ei}|^2 \rho_e \]

**Kinematic factor**

Summary

- All the correction estimation results are preliminary and the “raw” branching ratio blind analysis correction is not revealed yet!

- PiENu experiment at TRIUMF finished collecting data. Analysis is under way.

- Systematics is under control, factor of 10 more statistics available.

- Results are coming out.


- We are moving toward achieving the goal of <0.1% accuracy on $R_{e/\mu}^{\text{exp}} = \frac{\Gamma(\pi^{\rightarrow} e^{\nu} + \pi^{\rightarrow} e^{\nu} \gamma)}{\Gamma(\pi^{\rightarrow} \mu^{\nu} + \pi^{\rightarrow} \mu^{\nu} \gamma)}$ measurement.
Thank you!