PEN/PIENU: is $g_e = g_\mu$?

a new round of $B_{\pi \to e\nu}$ measurements

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1 theoretical considerations

Most theoretical (and experimental!) uncertainties cancel when studying the branching ratio:

$$B \equiv \frac{\Gamma[\pi^+ \to e^+\nu_e(\gamma)]}{\Gamma[\pi^+ \to \mu^+\nu_\mu(\gamma)]}$$

In lowest order $B$ is the product of a phase-space factor and a helicity factor:

$$B = \left(1 - \frac{m_\mu^2}{m_\pi^2}\right)^{-2} \times \frac{m_\pi^2}{m_\mu^2} = 5.4869 \times 2.3390 \times 10^{-5} = 1.2834 \times 10^{-4}$$

complete calculation: $1.2353 \times 10^{-4}$.

SM predictions and measured values for $R^P_{e/\mu}$ ($P = \pi, K$)

<table>
<thead>
<tr>
<th></th>
<th>$\Gamma_{\pi^+ \to e^+\nu_e}/\Gamma_{\pi^+ \to \mu^+\nu_\mu}$</th>
<th>$\Gamma_{K^+ \to e^+\nu_e}/\Gamma_{K^+ \to \mu^+\nu_\mu}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>theory</td>
<td>$1.2353(1) \times 10^{-4}$</td>
<td>$2.477(1) \times 10^{-5}$</td>
</tr>
<tr>
<td>experiment</td>
<td>$1.2312(37) \times 10^{-4}$</td>
<td>$2.488(12) \times 10^{-5}$</td>
</tr>
</tbody>
</table>

Allowing for a flavour dependence of $g$ transition probabilities should be multiplied with $g_l^2$.

### Charged Lepton Universality Tests

<table>
<thead>
<tr>
<th>Decay</th>
<th>$g_e/g_\mu$</th>
<th>$g_\tau/g_\mu$</th>
<th>$g_\tau/g_e$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\pi^+ \to \bar{l}\nu_l$</td>
<td>0.9985 $\pm$ 0.0016</td>
<td>1.039 $\pm$ 0.013</td>
<td>1.036 $\pm$ 0.014</td>
</tr>
<tr>
<td>$K^+ \to \bar{l}\nu_l$</td>
<td>1.0018 $\pm$ 0.0026</td>
<td>0.996 $\pm$ 0.005</td>
<td></td>
</tr>
<tr>
<td>$K^+ \to \pi\bar{l}\nu_l$</td>
<td>0.998 $\pm$ 0.002</td>
<td>0.979 $\pm$ 0.017</td>
<td></td>
</tr>
<tr>
<td>$\tau^+ \to \bar{l}\nu\bar{\nu}$</td>
<td>0.9998 $\pm$ 0.0020</td>
<td>1.0006 $\pm$ 0.0022</td>
<td>1.0005 $\pm$ 0.0023</td>
</tr>
<tr>
<td>$W^+ \to \bar{l}\nu_l$</td>
<td>0.997 $\pm$ 0.010</td>
<td></td>
<td></td>
</tr>
<tr>
<td>$\tau \to \pi$ / $\pi \to \mu$</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>$\tau \to K$ / $K \to \mu$</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>$\tau \to e \times \tau_\mu/\tau_\tau$</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>$\tau \to \mu \times \tau_\mu/\tau_\tau$</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

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**Limits on Charged Lepton Non-universality**

Lots of excitement and creativity by model builders after this LHCb result:\(^3\):

\[
\Gamma(B^+ \rightarrow K^+ \mu^+ \mu^-)/\Gamma(B^+ \rightarrow K^+ e^+ e^-) = 0.745^{+0.090}_{-0.074}(\text{stat})\pm0.036(\text{syst})
\]

a 2.6\(\sigma\) deviation!

theoretical considerations

Minimal Supersymmetric Standard Model
Fig. 1b-d contribute to $l$-universality violation.
A scan was made over all MSSM parameters.
Violations could be several times larger than the next-future experimental uncertainty.

FIG. 9. Contours indicate the largest values of $\delta R_{e/\mu}^{\text{SUSY}}$ obtained by our numerical parameter scan (26), as a function of $|\mu|$ and $m_{\tilde{\tau}_1}$. The solid shaded regions correspond to the largest values of $\delta R_{e/\mu}^{\text{SUSY}}$ within the ranges indicated. All values of $\delta R_{e/\mu}^{\text{SUSY}}$ correspond to parameter points which satisfy the LEP II bound.
2 the $\pi \rightarrow e\nu$ experiments

S: last beam defining scintillator
T: active target
a single BGO crystal is 20 cm deep

1992 TRIUMF result$^4$: $B = (1.2265 \pm 0.0034\text{(stat)} \pm 0.0044\text{(syst)}) \times 10^{-4}$
1993 PSI result$^5$: $B = (1.2350 \pm 0.0035\text{(stat)} \pm 0.0036\text{(syst)}) \times 10^{-4}$
combined: $B = (1.2312 \pm 0.0035) \times 10^{-4}$

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2.1 PEN$^6$ and PIENU$^7$ teams

Systematic errors play a crucial role so it is very fortunate there are two experiments (like ATLAS and CMS at the LHC)


$^6$PEN Collaboration, PSI experiment R-05-01 (2005), D. Počanić and A. van der Schaaf, spokespersons

2.2 PIENU

NaI(Tl) diameter and depth: 48 cm
the $\pi \rightarrow e\nu$ experiments

2.3 PEN

![Diagram of PEN setup]

**Detector Setup 2010**

Situation: 29.05.2010

- **Lead Wall**
- **Solution**
- **Photomultiplier Module** Hamamatsu H2431-50
- **CsI**
- **PV**
- **MWPC1**
- **MWPC2**
- **Active Target Mini TPC**
- **Active Degrader**
- **Beam 10 cm**
- **y**
- **z**

**Target Region**

1. **degrader**
2. **mini TPC**
3. **target scintillator**
4. **inner MWPC**

**Measurements**

- **CMC: $g_\nu = g_\nu^\nu$**
PEN results:

beam counter energy versus time of flight between beam counter and active degrader at beam momentum $75 \text{ MeV/c}$.

Time of flight is used not only for pion selection but also for an accurate energy determination, event by event.

Correlations between the position coordinates of $\pi^+$ and $e^+$ for $e^+$ moving vertically (left) and horizontally (right).

$x_{\pi^+}$ is based on charge division, $y_{\pi^+}$ on drift time.

Mini TPC trajectories. The beam spot, limited by a $\varnothing = 20\text{ mm}$ lead collimator upstream of the target, is off-center in $x$ for best suppression of beam $e^+$ situated further to the left.
4 target waveform analysis

Examples of target waveforms and their analysis.

The panels on the left illustrate the novel loss-free PEN signal shaping based on vector multiplication. The $\pi$ and $e^+$ signals are NOT adjusted but predictions based on the information of the surrounding detectors. The only free parameter is the location of the muon signal.

The panel on the right shows a PIENU example.
PEN results:

Target waveform analysis for $\pi \rightarrow \mu \rightarrow e$ decay chains in which the three signals are well-separated. Signal quenching by high ionization density has been corrected. Positrons, which timed the trigger, are situated around waveform bin 700. The muons are situated to their left and mono-energetic with $T = 4.1 \text{MeV}$ since they originate in $\pi$ decay at rest. The pions deposit typically 11 MeV.
$\pi^+$ target energy versus the predicted value based on time of flight and observed degrader energy.

$e^+$ target energy versus path length. Observed mean $dE/dx$ is 1.81 MeV/cm, or 1.73 MeV/g.

Pion waveforms before (upper panel) and after (lower panel) subtraction of the predicted signal.

$\Delta(\chi^2)$ of the target waveform for $\pi \rightarrow e$ and for $\pi \rightarrow \mu \rightarrow e$. The algorithm always returns a value in the region shown.
5  the key observables, $e^+$ energy and decaytime

5.1  low-energy tail

PIENU NaI(Tl) energy spectra with 70 MeV $e^+$ beam for central showers at various $\theta$. The final plot shows the resulting fraction with energy deposit below 54 MeV.  

the key observables, $e^+$ energy and decaytime

PEN indirectly measures $p_\nu$ in $\pi \to e\nu\gamma$ since $\vec{p}_\nu + \vec{p}_e + \vec{p}_\gamma = 0$.

So $E_{obs} + p_{obs}c = m_\pi c^2$.

This moves such events out of the low-energy tail.

E+pc distributions for increasing number of selection conditions that suppress the $\pi \to \mu \to e$ branch:

- **a:** Tail-trigger events, recorded irrespective of the CsI signals but pre-scaled 1:10.
- **b:** Main-trigger events, pre-scaled 1:64 in the tail-region.
- **c:** $\pi \to e\nu$ simulation
5.2 decay time

PEN year 2010 $\pi \rightarrow e\nu$ decaytime distribution showing an extremely low accidental background. Also shown are the $\pi \rightarrow \mu \rightarrow e$ distribution and its prediction, obtained by folding the $\pi \rightarrow e\nu$ result with $\tau_\mu$. Note the perfect agreement between observation and prediction.

Fraction of $\pi \rightarrow \mu \rightarrow e$ events with a $\pi - e^+$ time delay in a window $t \pm 50$ ns, versus $t$. The distribution peaks at 131.4 ns but falls less than $10^{-5}$ when moving 1 ns away from that value.
6  \( \pi \rightarrow e\nu\gamma \)

\[
\frac{d^2\Gamma_{\pi\rightarrow e\nu\gamma}}{dxdy} = \frac{d^2\Gamma_{IB}}{dxdy} + \frac{d^2\Gamma_{SD}}{dxdy} + \frac{d^2\Gamma_{INT}}{dxdy}
\]

The structure-dependent contribution is not helicity-suppressed
The interference term is small.

\[
\frac{d^2\Gamma_{SD}}{dxdy} \propto [(F_V + F_A)^2SD^+ + (F_V - F_A)^2SD^-]
\]

\(F_V\) and \(F_A\) are vector and axial-vector form factors.

Sofar only the region not populated by radiative muon decay (so either \(E_e\) or \(E_\gamma\) is above \(m_\mu/2\)) was studied.

PIBETA\(^9\):
(PEN predecessor)

Cosine $\epsilon\gamma$ opening angle versus energy sharing.

Top: PEN 2009/10 data are compared to GEANT predictions. The region shown contains 33140 measured events.

Bottom: relative contributions of the $SD^+$, $SD^-$ and IB components as known to the SIMULATOR. $SD^-$ contributes up to 6%.

These measurements require a large solid angle and a modular calorimeter to reconstruct the photon. The PIENU setup does not offer this.

Thanks to the powerful target waveform analysis and the trigger for data readout based on the total CsI energy, PEN succeeded in measuring $\pi \rightarrow e\nu\gamma$ in full phase-space.
7 decays in flight

Evidence for $\pi \to \mu \bar{\nu}$ decay in flight.

Events are selected with $e^+$ energy between 30 and 50 MeV.
Measured distributions are compared with simulation, where the muon decayed at rest or in flight.

The two top rows: events with well separated target signals, either three (typical for $\pi^-\mu^-e^-$) or just two (as expected for decay in flight).

The bottom row shows all events.

$z_e$: starting position of the $e^+$ along the beam line (from MWPCs).
$z_\pi$: final position of the $\pi^+$ from the target energy.

Target energy balance: total energy minus predictions for $\pi^+$ and $e^+$. 
Evidence for $\pi^+ \rightarrow e^+ \nu$ decay in flight.

a: $\pi^+ \rightarrow \mu^+ \rightarrow e^+$ distribution

b: $\pi^+ \rightarrow e^+ \nu$ in flight requires no stopping material and leads to decay vertices in front of the target without any target signal (horizontal band around -10 MeV).

c: Selection of these events.
The $e^+$ energy shows the $\theta$ dependence expected for Lorentz broadening.
The region below 50 MeV was pre-scaled 1:64 in the readout trigger.
Forward contributions are from scattered beam and $\mu^+$ decays in the degrader.
8  a first result from PIENU

Based on $\approx 10\%$ of all recorded data.
$0.5 \times 10^6 \pi \rightarrow e\nu$ events enter the time analysis.

![Graphs showing decay-time analysis of $e^+$ energy below and above 52 MeV.](image)

Decay-time analysis of events with $e^+$ energy below (a) or above (b) 52 MeV. At this cut the tail-fraction amounts to $3.16 \pm 0.12\%$.

1992 TRIUMF result: $B = (1.2265 \pm 0.0034{\text{stat}} \pm 0.0044{\text{syst}}) \times 10^{-4}$
1993 PSI result: $B = (1.2350 \pm 0.0035{\text{stat}} \pm 0.0036{\text{syst}}) \times 10^{-4}$
combined: $B = (1.2312 \pm 0.0035) \times 10^{-4}$
2015 TRIUMF result\(^\text{10}\): $B = (1.2344 \pm 0.0023{\text{stat}} \pm 0.0019{\text{syst}}) \times 10^{-4}$
new average: $B = (1.2329 \pm 0.0019) \times 10^{-4}$

9 Outlook

PEN finished data-taking five years ago and has been studying these data in great detail ever since. Energy, time and geometry calibrations are done and most features observed are understood and reproduced by simulation.

The question remains when one might expect to “open the box” and finish the project by publishing the branching ratio. Unfortunately, that question can’t be answered for sure but it should happen within the next year.

It is likely that PIENU will be finished by then as well so a significant reduction in the experimental error of the world average can be anticipated.