6 Precision Measurements in Rare Pion Decays

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(PIBETA Collaboration)

Early in 2004 the Physik-Insitut joined the PIBETA Collaboration which performs a research project at the *Paul Scherrer Institut* (PSI) in Villigen, Switzerland on rare π and μ decays. Primary objective is the determination of the $\pi^+ \rightarrow \pi^0 e^+ \nu_e$ (pion beta decay) branching ratio with a precision of ≈ 0.4%, *i.e.* an order of magnitude better than achieved previously. This branching ratio, despite of its very low value of 10^{-8}, allows a direct determination of the CKM quark mixing matrix element V_{ud} with negligible theoretical uncertainties. The uncertainty in V_{ud} is the main limitation in tests of the unitarity of the CKM matrix which, in turn, is an important test of the validity of the Standard Model (SM) of particle physics.

The pion beta decay branching ratio is determined by observing photons from the subsequent $\pi^0 \rightarrow 2\gamma$ decay in a spherical electromagnetic calorimeter consisting of 240 pure-CsI crystals (see Fig. 6.1). The decay rate is normalized to the rate of $\pi^+ \rightarrow e^+ \nu_e$ decays observed simultaneously. This way various systematic uncertainties, such as the number of stopped pions, electronic dead time and detector solid angle, can be removed. Data taking for this decay mode took place in the years 1999/2001 and a preliminary result is available (1). Since the Physik-Institut is not part of this effort we will not go in more detail here.

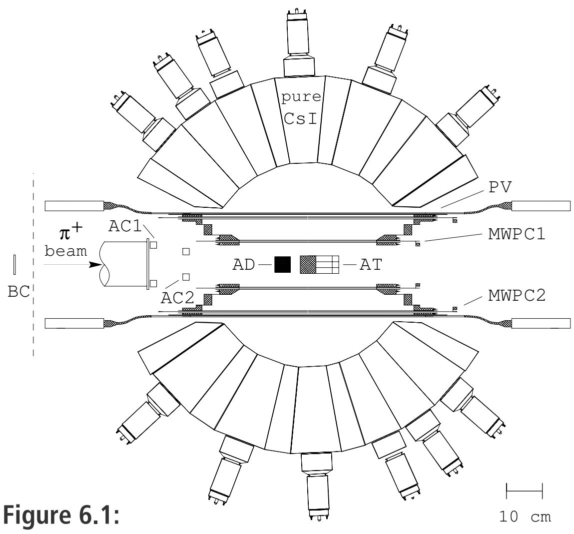

Figure 6.1:
The PIBETA detector.
BC: **beam counter,** AC1,2: **active beam collimators,** AD: **active degrader,** AT: **active target,** MWPC1,2: **cylindrical wire chambers,** PV: **plastic scintillating hodoscope. The pure-CsI calorimeter consist of 240 crystals.**

[1] Precise measurement of the $\pi^+ \rightarrow \pi^0 e^+ \nu_e$ branching ratio,
D. Pocanic *et al.*, Phys.Rev.Lett.**93** (2004) 181803 [arXiv:hep-ex/0312030].

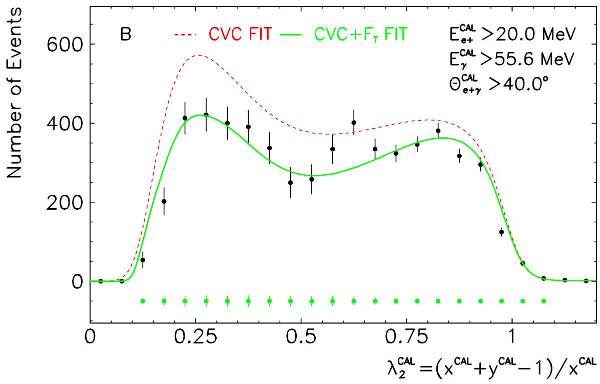

Figure 6.2:
$\pi^+ \rightarrow e^+\nu\gamma$ energy distribution for $E_\gamma > 55.8$ MeV and $E_{e^+} > 20$ MeV. x and y are the e^+ and γ energies, respectively, normalized to their endpoints $m_\pi c^2/2$. The quantity $\lambda \equiv (x+y-1)/x$ reaches its minimal value $\lambda = 0$ when e^+ and γ move in the same direction and its maximal value $\lambda = 1$ when e^+ and ν move together.

6.1 The $\pi^+ \rightarrow e^+\nu_e\gamma$ anomaly

The $\pi^+ \rightarrow e^+\nu_e\gamma$ decay was recorded during $\pi^+ \rightarrow \pi^0 e^+\nu_e$ data taking (1). This is the first time that this decay mode has been studied with a setup with almost complete geometric acceptance. Two decades ago we studied this decay (2) and its Dalitz correction $\pi^+ \rightarrow e^+\nu_e e^+ e^-$ (3) and more recently the corresponding kaon modes $K^+ \rightarrow e^+\nu_e e^+ e^-$, $K^+ \rightarrow \mu^+\nu_\mu e^+ e^-$, and $K^+ \rightarrow e^+\nu_e\mu^+\mu^-$ (see Sec. 4.1). These decays proceed via a combination of inner bremsstrahlung (IB) and structure dependent (SD) amplitudes. The latter allows a determination of meson form factors, which, in turn, are an important input into chiral perturbation theory.

Based on Dalitz distributions of 42209 events $\gamma \equiv F_A/F_V$ = 0.443(15), or F_A = 0.0115(4) with F_V = 0.0259. However, 20% deviations were observed in the kinematic region of high E_γ and low E_{e^+} (see Fig.6.2). This kinematic region could not be studied in earlier measurements because of the high level of accidental coincidences with positrons from $\mu \rightarrow e\nu\overline{\nu}$ decay. To clarify the situation a dedicated measurement (4) was performed at reduced beam intensity for which we contributed an improved active target. A preliminary analysis of these 2004 data indicates a reduction of accidental background by one order of magnitude which allows us to relax the selection criteria. Firm conclusions will have to await further analysis.

[1] **Precise measurement of the pion axial form factor in the $\pi^+ \rightarrow e^+\nu\gamma$ decay**,
E. Frlež *et al.*, Phys.Rev.Lett.**93** (2004) 181804 [arXiv:hep-ex/0312029].

[2] A. Bay *et al.*, Phys.Lett.B 174, 445 (1986).

[3] S. Egli *et al.*, Phys.Lett.B 222, 533 (1989).

[4] **Study of the $\pi^+ \rightarrow e^+\nu\gamma$ anomaly**,
PSI Proposal R-04-01.1, E. Frlež and D. Počanić spokesmen, January 2004.

6.2 A precision determination of the $\pi^+ \rightarrow e^+\nu$ branching ratio

The $\pi^+ \rightarrow e^+\nu$ / $\pi^+ \rightarrow \mu^+\nu$ branching ratio is presently the best test of μe universality, *i.e.* the equality of the couplings of $\mu\nu_\mu$ and $e\nu_e$ to the W boson. Recent results in τ decays provide tests for all three generations which start to approach but are still not as sensitive as the 10 year old results from pion decay. As mentioned above this branching ratio is used as a normalization in the determination of the $\pi^+ \to \pi^0 e^+ \nu$ branching ratio. Independent normalizations based on the number of pion stops are consistent within 1%. This means that the $\pi^+ \to \pi^0 e^+ \nu$ measurement results in a determination of the $\pi^+ \to e^+ \nu$ branching ratio with a precision of 1%. We are confident that a dedicated experiment at lower beam intensity and with improved detection systems in the beam should allow for an improvement by one order of magnitude.

Allowing for violations of universality of the couplings between W and a $l_i \overline{\nu_i}$ pair the tree level partial width of the decay of a pion into such pair is:

$$\begin{aligned} \Gamma^{\text{tree}}_{\pi\to e\overline{\nu}} &= \frac{g_e^2 g_{ud}^2 V_{ud}^2}{256\pi} \frac{f_\pi^2}{M_W^4} m_e^2 m_\pi (1 - \frac{m_e^2}{m_\pi^2})^2 \\ \Gamma^{\text{tree}}_{\pi\to \mu\overline{\nu}} &= \frac{g_\mu^2 g_{ud}^2 V_{ud}^2}{256\pi} \times \frac{f_\pi^2}{M_W^4} m_\mu^2 m_\pi (1 - \frac{m_\mu^2}{m_\pi^2})^2 \end{aligned} \tag{6.1}$$

leading to a branching ratio:

$$R^{\text{tree}}_{e/\mu} \equiv \frac{\Gamma^{\text{tree}}_{\pi\to e\overline{\nu}}}{\Gamma^{\text{tree}}_{\pi\to \mu\overline{\nu}}} = (\frac{g_e}{g_\mu} \times \frac{m_e}{m_\mu} \times \frac{1 - m_e^2/m_\pi^2}{1 - m_\mu^2/m_\pi^2})^2 \tag{6.2}$$

Radiative corrections lower this value by 3.74(1)% (1). Within the SM $g_e = g_\mu = 1$ which leads to a predicted value:

$$R^{\text{SM}}_{e/\mu} = 1.2350(5) \times 10^{-4} \tag{6.3}$$

Two experiments (2; 3) contribute to the present world average (4) for the measured value:

$$R^{\text{exp}}_{e/\mu} = 1.230(4) \times 10^{-4} \tag{6.4}$$

As a result μe universality has been tested at the level:

$$g_\mu / g_e = 1.0021(16) \tag{6.5}$$

Other constraints on violations of lepton universality can be derived from from W and τ branching ratios. More general quark-lepton universality can be tested (5). Violations of lepton universality have been discussed recently by Antonio Pich (6) and by Will Loinaz *et al.* (7). Figure 6.3 shows a graphic representation of the actual situation. As can be seen from the figure π and τ decays give the best constraints at present.

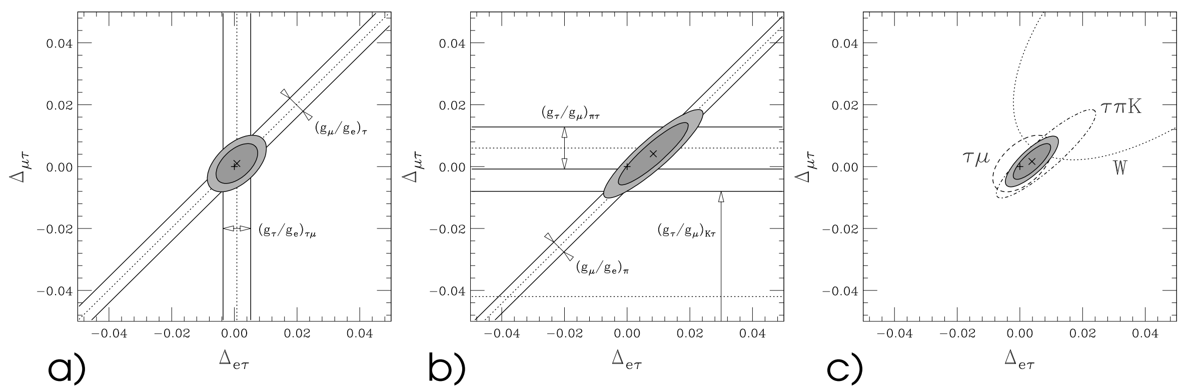

Figure 6.3:
Experimental constraints on violations of lepton universality. $\Delta_{ij} = 2(\frac{g_i}{g_j} - 1)$.
a: from τ decay, b: from π and K decay and c: combined result. From [7].

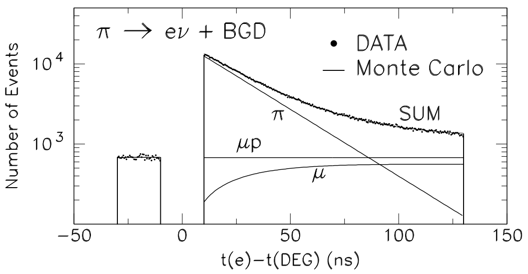

Figure 6.4:
Delay between pion stop and decay. The measured data (dots) are nicely described by $\pi^+ \to e^+$ decay, $\pi^+ \to \mu^+ \to e^+$ decay chain and pile-up (accidental coincidences). The prompt region which is contaminated by hadronic interactions has been removed at trigger level.

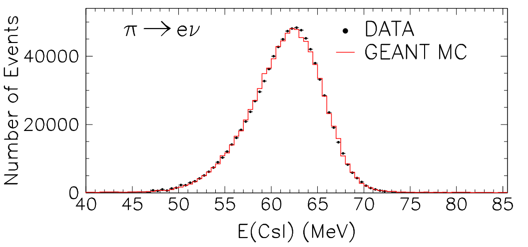

Figure 6.5:
Distribution of CsI total energy for $\pi^+ \to e^+\nu$ decays after background subtraction.

During the years 1999/2001 the PIBETA experiment recorded a huge sample of $\pi^+ \to e^+\nu$ decays. Figures 6.4 and 6.5 show time and energy distributions of decay electrons. Although the measurements were not optimized for this decay mode a clear $\pi^+ \to e^+\nu$ signal is observed with a total systematic error below $\approx 1\%$, i.e. within a factor 2-3 of the dedicated experiments. The main contribution to this uncertainty is in the determination of the number of stopped pions, a quantity which does not enter the determination of the $\pi^+ \to \pi^0 e^+\nu$ branching ratio. The statistical uncertainty associated with the number of observed $\pi^+ \to e^+\nu$ events is totally negligible in this data set. As will be discussed below we are confident that a dedicated experiment with improved beam monitoring and at reduced beam intensity should reach a precision of $O(0.1\%)$, a 3-4 fold improvement compared to the present world average.

Time table

At the January 2005 meeting of the PSI Program Advisory Committee a letter of intent for a measurement of the $\pi \to e\nu$ branching ration (8) was very well received and four weeks of beam time were granted for beam studies and detector tests. A full proposal will be submitted by the end of 2005.

Our group took over the responsibility to develop an ultra-fast beam monitoring system based on 0.6 ns scintillator and microchannel photomultipliers. Waveform digitizers with ≈ 5 GHz sampling rates will be used with the aim of reaching a double pulse resolution $O(1$ ns) in the target detector. We are investigating options for silicon strip detectors used to track the beam particles which is particularly useful to distinguish pions from halo muons. It is our aim to have most of the necessary R&D done before submission of the proposal.

[1] R. Decker and M. Finkemeier, Nucl.Phys.B 438, 17 (1995).

[2] G. Czapek *et al.*, Phys.Rev.Lett.70, 17 (1993).

[3] D.I. Britton *et al.*, Phys.Rev.Lett.68 (1992) 3000, D.I. Britton *et al.*, Phys.Rev.D 49, 28 (1994).

[4] S. Eidelman *et al.*, (Particle Data Group), Phys.Lett.B 592, 1 (2004).

[5] **Quark-Lepton Nonuniversality**, X.-Y. Li and E. Ma, XXIII ENFPC, Aguas de Lindoia, Brazil (2002), hep-ph/0301006.

[6] **Leptonic Probes of the Standard Model**, A. Pich, hep-ph/0210445,
The Standard Model of Particle Physics: Status and Low-Energy Tests, A. Pich, hep-ph/020611.

[7] **The NuTeV Anomaly, Lepton Unuiversality, and Non-Universal Neutrino-Gauge Couplings**, W. Loinaz *et al.*, Phys.Rev.D 70 (2004) 113004, hep-ph/0403306.

[8] **Precise Measurement of the $\pi^+ \to e^+\nu$ Branching ratio**, D. Pocanic *et al.*, PSI Letter of Intent R-05-01.0.