3 Precision Measurements in Rare Pion Decays

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(PIBETA/PEN Collaboration)

The PIBETA Collaboration performs a research program on rare π and μ decays at PSI. Two decay modes are presently being studied:

- $\pi^+ \to e^+\nu_e\gamma$
  Data taken parasitically with the $\pi^+ \to \pi^0 e^+\nu_e$ experiment showed 20% deviations from the Standard Model prediction in the kinematic region of high E_γ and low E_{e^+}. To clarify the situation a dedicated experiment was performed in the year 2004 and first results became available last year. These new data showed no anomaly and allowed very significant improvements in the determination of the vector and axial-vector form factors F_V and F_A. Using the conserved-vector-current hypothesis (CVC) F_V is connected with the lifetime of neutral pions. The value of F_A is model-dependent.

- $\pi^+ \to e^+\nu_e$
  This decay mode offers the most sensitive test of lepton universality in charged-current interactions. During 2005 extensive beam studies were performed at PSI. A proposal by the PEN Collaboration to measure the branching ratio with a precision of O(0.1%) was accepted with high priority by the PSI Program Advisory Committee in February 2006.

3.1 The $\pi^+ \to e^+\nu_e\gamma$ decay

The $\pi^+ \to e^+\nu_e\gamma$ decay was recorded during $\pi^+ \to \pi^0 e^+\nu_e$ data taking (1). This was the first time that this decay mode was studied with a setup with almost complete geometric acceptance. Two decades ago we studied this decay (2) and its Dalitz correction $\pi^+ \to e^+\nu_e e^+e^-$ (3) and more recently the corresponding kaon modes $K^+ \to e^+\nu_e e^+e^-$, $K^+ \to \mu^+\nu_\mu e^+e^-$, and $K^+ \to e^+\nu_e\mu^+\mu^-$. These decays proceed via a combination of inner bremsstrahlung (IB) and two structure dependent (SD$^+$, SD$^-$) amplitudes. Whereas inner bremsstrahlung bears no information of interest the structure dependent contribution allows a determination of meson form factors which, in turn, are an important input into chiral perturbation theory. Figure 3.1 shows the relative contributions to the distribution of photon and electron energies.

In the first data taken with the PIBETA setup 20% deviations were observed in the kinematic region of high E_γ and low E_{e^+}. This kinematic region could not be studied in earlier measurements because of the high level of accidental coincidences with positrons from $\mu \to e\nu\overline{\nu}$

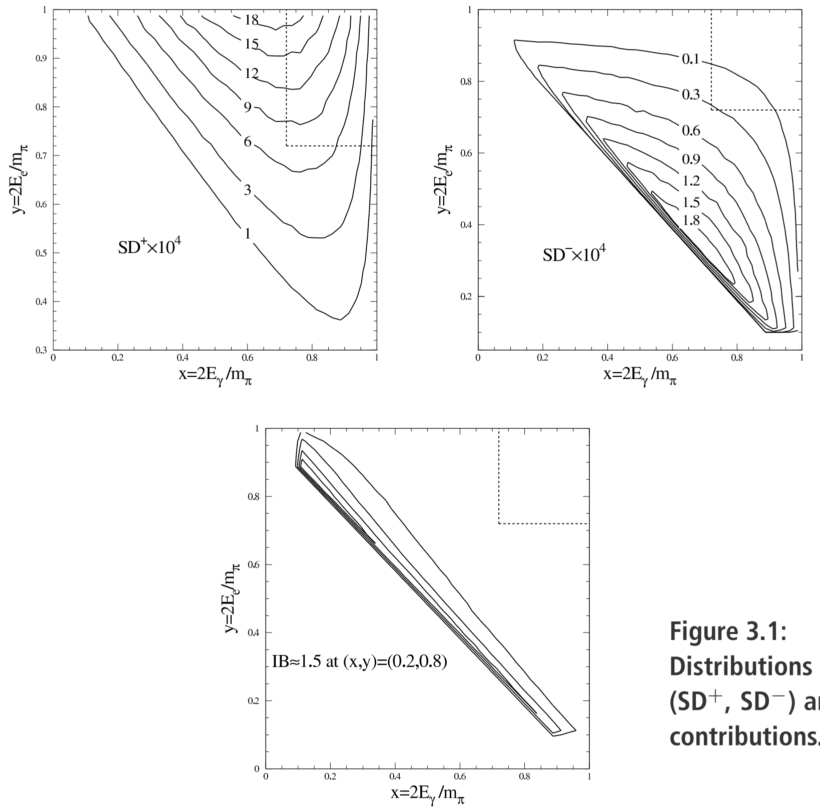

Figure 3.1:
Distributions of the structure dependent (SD^+, SD^-) and inner Bremsstrahlung (IB) contributions.

decay. To clarify the situation a dedicated measurement (4) was performed at reduced beam intensity for which we contributed an improved active target. Thanks to the improved conditions almost background free data could be collected as is demonstrated in Fig. 3.2.

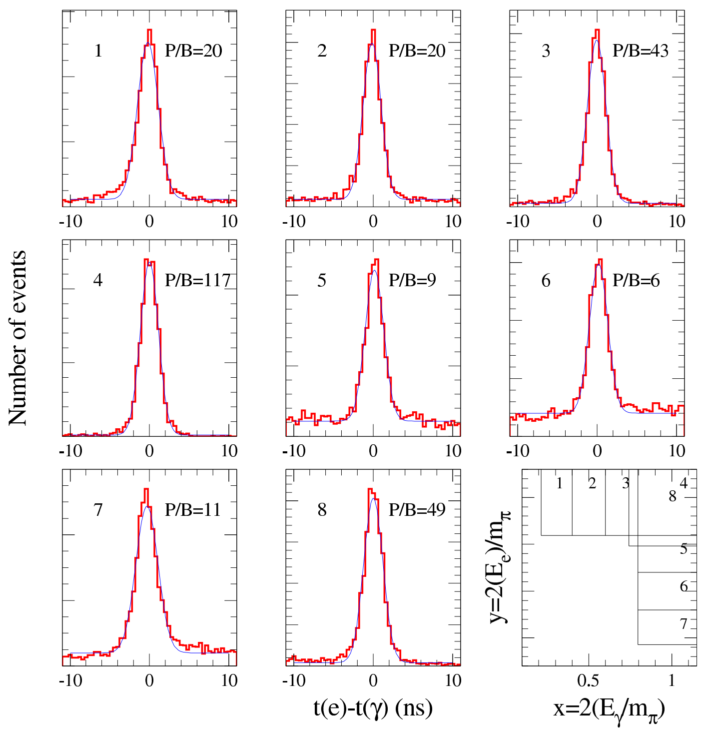

Figure 3.2:
Signal histograms for eight kinematic regions defined in the last panel.

The fit of the form factors to these data resulted in:

$$F_A = 0.0118 \pm 0.0003 \quad (3.1)$$
$$F_V = 0.0262 \pm 0.0015 \quad (3.2)$$
$$a = 0.241 \pm 0.093 \ , \quad (3.3)$$

where a describes the momentum dependence of the form factors which was never determined before. These results were obtained without any constraints or theoretical hypotheses. Earlier measurements usually resulted in a value for F_A/F_V only. This ratio is directly connected to the pion polarizability α_E defined by: $\vec{p} = \alpha_E \times \vec{E}$ ($\vec{p}$ pion electric dipole moment) through:

$$\alpha_E = \frac{2\alpha}{8\pi^3 m_\pi f_\pi^2} \times \frac{F_A}{F_V} = (2.81 \pm 0.07) \times 10^{-4}\ \mathrm{fm}^3 \ , \quad (3.4)$$

where the numerical value was determined using our new results.

As mentioned above F_A and F_V also give constraints on terms (l_9 and l_{10}) of the Lagrangian of Chiral Perturbation Theory:

$$l_9 + l_{10} = \frac{1}{32\pi^2}\frac{F_A}{F_V} = (1.42 \pm 0.04) \times 10^{-3} \ . \quad (3.5)$$

[1] **Precise measurement of the pion axial form factor in the $\pi^+ \to e^+\nu\gamma$ 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 $\pi^+ \to e^+\nu\gamma$ anomaly**,
PSI Proposal R-04-01.1, E. Frlež and D. Počanić spokesmen, January 2004.

3.2 A precision determination of the $\pi^+ \to e^+\nu$ branching ratio

As was discussed in last year's annual report the $\pi^+ \to e^+\nu$ / $\pi^+ \to \mu^+\nu$ branching ratio is 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. Two experiments (1; 2) contribute to the present world average (3) for the measured value:

$$R^{\mathrm{exp}}_{e/\mu} = 1.230(4) \times 10^{-4} \quad (3.6)$$

During the years 1999/2001 the PIBETA experiment recorded a huge sample of $\pi^+ \to e^+\nu$ decays. Although the measurements were not optimized for this decay mode a clear $\pi^+ \to e^+\nu$ signal was 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. The statistical uncertainty associated with the number of observed $\pi^+ \to e^+\nu$ events is totally negligible in this data set.

In February 2006 a proposal by the now-called PEN Collaboration (4) was accepted with high priority at PSI. It is planned to take first test data with the new setup in the year 2006 which will be followed by two years of real data taking. 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 would be used with the aim of reaching a double pulse resolution $O(1$ ns) in the target detector. During a test period

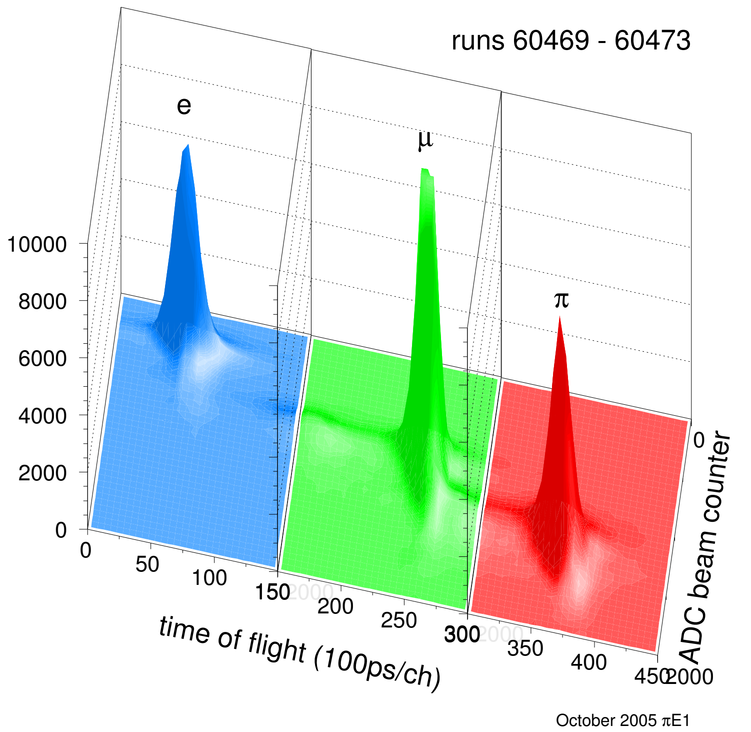

Figure 3.3: Distribution of flight time along the last ≈4 m of the πE1 beamline and energy loss in a moderator counter. Results from our 2005 tests at PSI. Pions, muons and electrons are clearly separated. This information will be crucial in estimating the contribution from pion decay in flight in the final data. The time of flight will also allow a precise determination of the pion momentum.

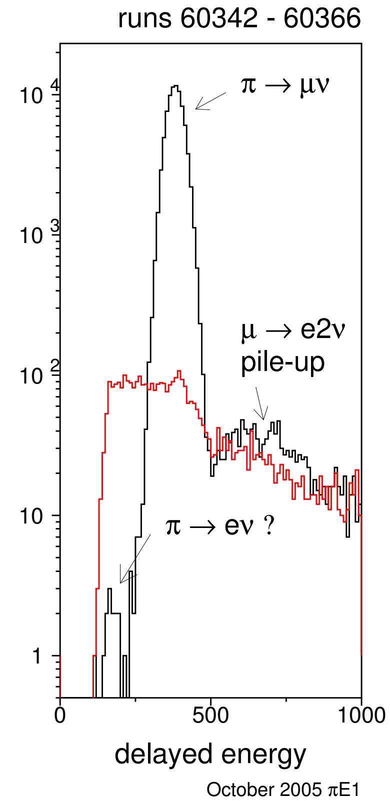

Figure 3.4: Secondary (black) and tertiary (red) target signals. The secondary signals are totally dominated by muons from pion decay at rest. The very low background left of the peak is close to the level expected from $\pi \to e\nu$.

of several weeks at PSI we learned, however, that these novel photo-detectors are very fast indeed but show a strong ringing after the signal. For this reason it was decided to use very fast (0.7 ns risetime) standard photomultipliers instead. During the tests at PSI we also tried to tune the beam to the lowest possible momentum (≈ 70 MeV/c as compared to ≈ 120 MeV/c for PIBETA running). At these lower momenta the range straggling is much reduced leading to a better definition of the pion stop distribution. At the other hand, because of the 26 ns pion lifetime the pion rate at the exit of the πE1 channel drops quickly towards lower momenta where the beam contains orders of magnitude more electrons and muons. This problem could be solved by inserting a thin degrader halfway the channel. After the degrader pions have lower momenta than the other particles which can be exploited to suppress electrons and muons. As can be seen from Fig. 3.3 the selected beam contains similar amounts of π, μ and e which can be easily distinguished on the basis of their velocity and dE/dx.

The $\pi \to e\nu$ decays are distinguished from $\pi \to \mu\nu$ decays followed by $\mu \to e\nu\overline{\nu}$ on the basis of the different positron energy distributions and the different decay time distributions. A major source of systematic errors is the uncertainty in the low-energy tail of the $\pi \to e\nu$ decay caused by shower leakage in the electromagnetic calorimeter and nuclear interactions producing neutrons. It is thus important to be able to measure a $\pi \to e\nu$ spectrum with as little $\pi \to \mu\nu$ contamination as possible. For this reason we checked during the tests at πE1 the ability to distinguish $\pi \to e$ events from $\pi \to \mu \to e$ events on the basis of target signals alone. Here one exploits the fact that muons from pion decay at rest are mon-energetic, have a range of only 2 mm and deposit their full kinetic energy in the target. As is demonstrated in Fig.3.4 it is possible to distinguish the two components in the amplitude distribution for secondary particles observed in the target shortly after a pion stop.

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

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

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

[4] **Precise Measurement of the $\pi^+ \to e^+\nu$ Branching ratio**,
D. Pocanic and A. van der Schaaf spokesmen, PSI Proposal R-05-01.1.