5 Precision measurements in pion decay

P. Robmann, A. van der Schaaf and U. Straumann

in collaboration with: University of Virginia, Charlottesville, USA; Institute for Nuclear Studies, Swierk, Poland; JINR, Dubna, Russia; Paul Scherrer Institut, Villigen, Switzerland and Rudjer Bošković Intitute, Zagreb, Croatia

(PEN Collaboration)

Within the Standard Model the decay $\pi \rightarrow e\nu$ is helicity suppressed ($\Gamma_{\pi\rightarrow e\nu}/\Gamma_{\pi\rightarrow\mu\nu} \approx m_e^2/m_\mu^2/(1-m_\mu^2/m_\pi^2)^2 \approx 1.2\times10^{-4}$) which makes it sensitive to a number of hypothetical exotic contributions. In the radiative decay $\pi \rightarrow e\nu\gamma$ the trivial inner-bremsstrahlung contribution is helicity suppressed as well and structure-dependent contributions dominate in large parts of the observable phase space. For the decay $\pi \rightarrow e\nu$ data taking just started. New results from our $\pi \rightarrow e\nu\gamma$ measurements have recently become available (1).

5.1 Testing lepton universality, the $\pi^+ \rightarrow e^+\nu$ decay

The experiment aims at improving the accuracy in the determination of the $\pi \rightarrow e\nu/\pi \rightarrow \mu\nu$ branching ratio by an order of magnitude (2). See past year's annual report for an introduction to the concept of lepton universality and a discussion of theoretical scenarios that might result in violations.

During a three-months measuring period in 2007 feasibility tests were performed at a pion stop rate of only 10^3/s. Our institute supplied a new set of beam counters and the associated 8 GHz transient recorders. We also refurbished the cylindrical scintillator hodosope situated in between the tracking detectors and the spherical CsI calorimeter. A preliminary analysis revealed no show-stoppers and the PSI program advisory committee gave green light to a first production run in 2008. By the time of writing data are taken at a 5×10^3/s stop rate which soon will be increased to 10^4/s giving 3×10^4 observed $\pi \rightarrow e\nu$ decays per day which should bring down the statistical error to O(10^{-3}) in 2008, significantly below the present uncertainty of the world average for the branching ratio ($1.231(4) \times 10^{-4}$).

5.2 Pion substructure revealed in the $\pi^+ \rightarrow e^+\nu\gamma$ decay

In the standard description of radiative pion decay the decay amplitude has contributions from inner bremsstrahlung (IB), structure dependent radiation (SD$^\pm$), and interference terms. The structure dependent amplitude is parameterized by F_V and F_A, vector and axial vector form factors, respectively (see Ref. (3) for a comprehensive review). The conserved vector current (CVC) hypothesis relates F_V to the π^0 lifetime, yielding F_V=0.0259(9). Chiral symmetry (ChPT) calculations (4; 5; 6) give a value for F_A in the range 0.010–0.014.

Early experimental studies were limited by relatively low event statistics. The authors evaluated $\gamma \equiv F_A/F_V$ resulting in overall uncertainties ranging from 12% to 56% (7; 8; 9; 10; 11; 12). None of these measurements considered the dependence of the form factors on the invariant mass of the $e^+\nu$ pair.

During the years 1999 - 2001 a first data set with a 16 fold pre-scaled trigger was collected as a byproduct of the PIBETA $\pi^+ \rightarrow \pi^0 e^+\nu$ branching ratio measurement (13). The analysis of the data resulted in a significant improvement in the accuracy of γ=0.443(15) (14) but also noted a substantial deficit of observed events in the high-E_γ/low-E_{e^+} kinematic region. For this reason a dedicated experiment was performed during 2004 after Zürich joined the new PEN collaboration. During these measurements the pion stop rate was reduced by almost an order of magnitude to $\sim 10^5$ /s. The reduced stop rate resulted in a dramatic reduction of accidental $e\gamma$ coincidences which allowed us to observe the decays in a much larger region of phase space.

In order to keep accidental background under control the trigger for data readout required at least one cluster of CsI crystals with a total energy above 52 MeV, the endpoint energy in muon decay. Candidate events exhibit one neutral shower in the calorimeter coincident in time with a positron track. Three kinematic regions were investigated:

region	E_{e^+} (MeV)	E_γ (MeV)	events
I	52 - 70	52 - 70	36k
II	10 - 52	52 - 70	16k
III	52 - 70	10 - 52	13k

with relative angle $\theta_{e\gamma}$ >40° for all regions. Under these conditions the decay is completely dominated by the SD$^+$ structure-dependent term proportional to $(F_V + F_A)^2$ (3).

The values of F_V, F_A, and a (defined by $F_V(q^2) = F_V(0)(1 + a \cdot q^2)$, $F_A(q^2) = F_A(0)$, and $q^2 = 1 - (2E_\gamma/m_\pi)$) were fit to the measured data by χ^2 minimization:

$$F_A = +0.0117(17)$$
$$F_V = +0.0258(17)$$
$$a = +0.095(58)$$

which represent a fourteen-fold improvement over previous measurements. The excellent agreement between the measured and calculated distributions for the best-fit parameter values (see

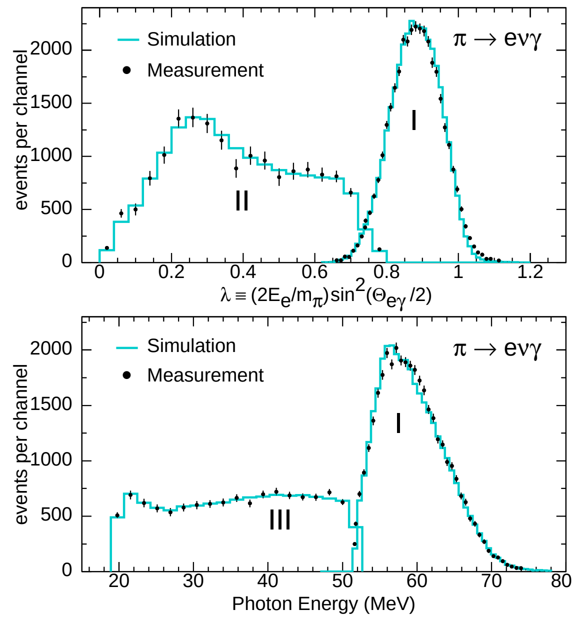

Figure 5.1: Background-subtracted $\pi^+ \rightarrow e^+\nu\gamma$ distribution of the kinematic variable $\lambda \equiv (2E_e/m_\pi)\sin^2(\theta_{e\gamma}/2)$ for regions I and II (top panel), and of the photon energy for regions I and III (bottom panel). For the simulation the best-fit values of F_V, F_A, and a were used.

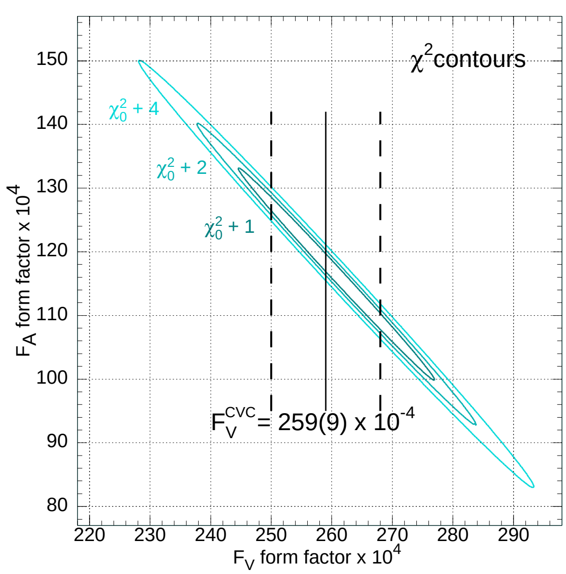

Figure 5.2: Contour plot of loci of constant χ^2 for the minimum value χ^2_0 plus 1, 2, and 4 units, respectively, in the $F_V \times F_A$ parameter plane, keeping the parameter a=0.041. The range of the CVC prediction, F_V = 0.0259(9) is indicated.

Fig. 5.1) reflects the perfect description of the data by CVC and standard $V-A$ theory in all regions of phase space. As discussed above the data are most sensitive to the combination $F_A + F_V$ which is illustrated in Fig. 5.2.

Conclusions

- The best-fit value of F_A agrees well with ChPT calculations, tending to the middle of the reported range (4; 5; 6).
- A more precise measurement of $\tau_{\pi 0}$ is needed to make full use of our data in determining F_A.
- The deficit of observed events in the high-E_γ/low-E_{e^+} has not been confirmed.
- The branching ratio for $E_\gamma > 10$ MeV and $\theta_{e\gamma} > 40^o$ is measured to be 73.9(5)$\times 10^{-8}$.
- The pion polarizability can be determined as follows: using the one-parameter fit we obtain $\alpha_E = -\beta_M$ =(2.78 $\pm$ 0.02$_{exp}$$\pm$0.10$_{Fv}$)$\times 10^{-4}$ fm^3, where the first uncertainty comes from the fit and the second from the current CVC-derived value of F_V; alternatively, one obtains $2.7^{+0.6}_{-0.5} \times 10^{-4}$ fm^3 based on our unconstrained fit of F_A and F_V.
- In addition, we use the latter fit result and CVC to make an independent determination of the neutral pion lifetime: $\tau_{\pi 0}$=(8.5 $\pm$ 1.1) $\times$ 10^{-17} s.

[1] M. Bychkov et al., **New Precise Measurement of the Pion Weak Form Factors in the $\pi^+ \rightarrow e^+\nu\gamma$ Decay**, submitted to Phys. Rev. Lett., arXiv:0804.1815 [hep-ex].

[2] PEN Collaboration, PSI experiment R-05-01, D. Pocanic and A. van der Schaaf, spokespersons.

[3] D. A. Bryman et al., Phys. Rep. 88, 151 (1982).

[4] B. R Holstein, Phys. Rev. D 33, 3316 (1986).

[5] J Bijnens and P. Talavera, Nucl. Phys. B 489, 387 (1997).

[6] C. Q Geng et al., Nucl. Phys. B 648, 281 (2004).

[7] P. Depommier et al., Phys. Lett. 7, 285 (1963).

[8] A. Stetz et al., Nucl. Phys. B 138, 285 (1978).

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

[10] L. E Piilonen et al., Phys. Rev. Lett. 57, 1402 (1986).

[11] C. A Dominguez and J. Solc, Phys. Lett. B 208, 131 (1988).

[12] V. N Bolotov et al., Phys. Lett. B 243, 308 (1990).

[13] D. Počanić et al. (PIBETA Collaboration), Phys. Rev. Lett. 93, 181803 (2004).

[14] E. Frlež et al. (PIBETA Collaboration), Phys. Rev. Lett. 93, 181804 (2004).