The PIBETA Experiment:

Annual Progress Report

The PIBETA Collaboration

7 November 2002

Pion beta decay, $\pi^+ \to \pi^0 e^+ \nu$, provides the most direct and theoretically interpretable means to study weak u-d quark mixing. Precise knowledge of V_{ud} tests quark-lepton universality, and thus constrains certain aspects of physics beyond the minimal Standard Model (SM).

The PIBETA experiment, proposed by an international collaboration of seven institutions led by UVa, was approved by the PSI Program Committee in 1992. Our experimental goal is to match the experimental accuracy of pure Fermi nuclear β decays in several stages of measurement. We use $\pi^+ \to e^+ \nu$ decay events for normalization. More information on the project and its status is available online at *http://pibeta.phys.virginia.edu/* and mirrored as well at *http://pibeta.web.psi.ch/*.

The detector construction was completed in 1998/99, and data acquisition started in the second half of 1999. Since then we have reached the design operating conditions for the detector system and have run the experiment during the 2000 and 2001 beam periods at PSI.

In all important respects the detector has met its design specifications. The quality of our data is best illustrated in Figures 1 to 3, which show results of a partial analysis of our 1999 and 2000 data. For both $\pi\beta$ and $\pi \to e\nu$ events the energy and timing spectra are clean and free of background. The $\pi \to e\nu$ decay, used for normalization in determining the pion beta decay branching ratio, is of paramount importance to the experiment, and is shown first. The γ–γ opening angle in pion beta decay, a critical quantity in reducing the systematic uncertainties of the experiment, is histogrammed in Figure 3. The good agreement with Monte Carlo simulations evident in the figure is a consequence of our detailed study of the geometry of the pion stopping distribution. The latter is the leading source of systematic uncertainty in our acceptance. It is presently well under control, and we are further improving its accuracy.

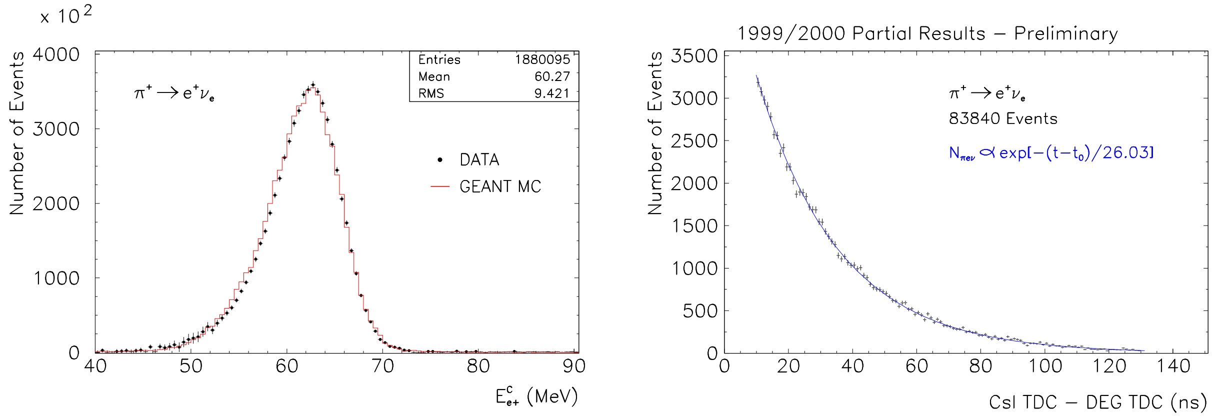

Figure 1: Energy (left panel) and timing distribution (right panel) of the measured $\pi \to e\nu$ events for a subset of acquired data. Solid curves: GEANT simulation. Preliminary.

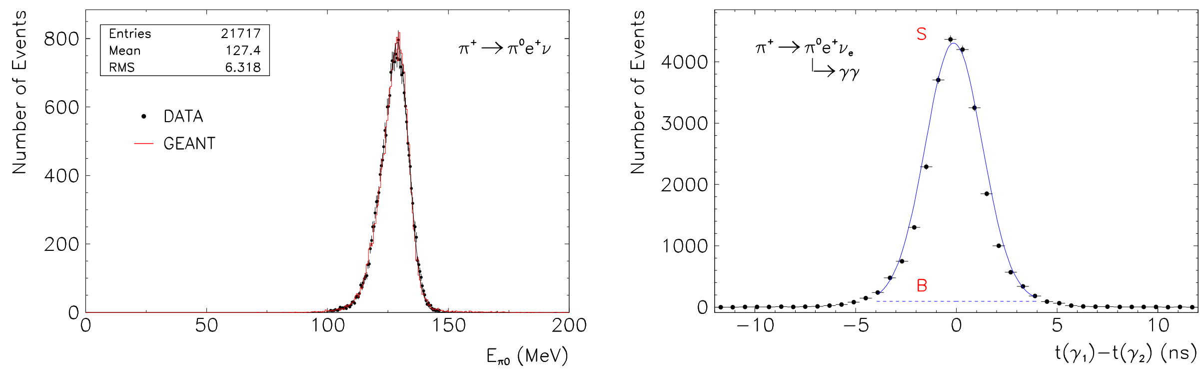

Figure 2: Left: energy spectrum of the measured pion beta decay events ($\pi^+ \to \pi^0 e^+ \nu$) for a subset of data; solid curve: GEANT simulation (preliminary). Right: γ-γ time difference for the same set of $\pi\beta$ data events (dots); curve: fit. Signal to background ratio exceeds 250. Preliminary.

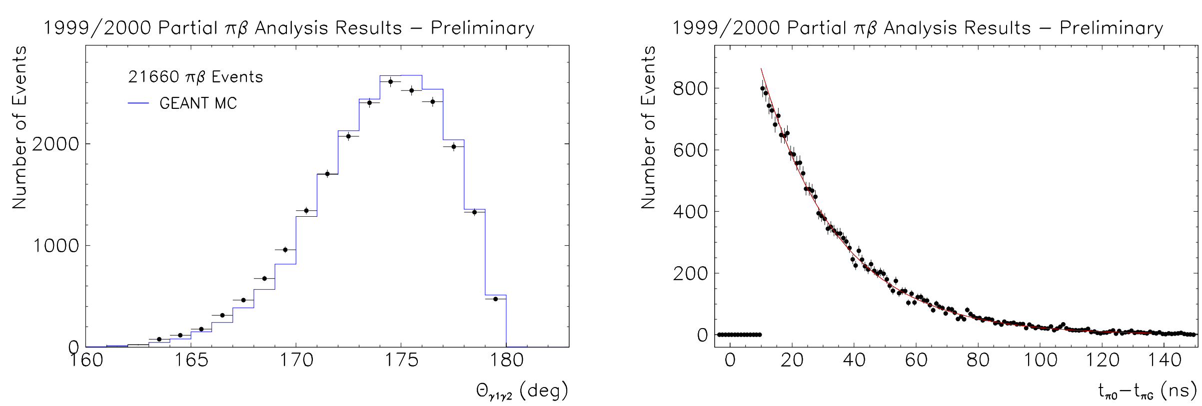

Figure 3: Left: measured γ-γ opening angle in pion beta decay events ($\pi^+ \to \pi^0 e^+ \nu$) for a subset of acquired data; solid curve: GEANT simulation (preliminary). Right: time difference between the beam pion stop and the $\pi\beta$ decay events (dots); curve: pion lifetime exponential curve. Preliminary.

The pion beta decay branching ratio

Even before finishing our measurements we started analyzing the data set acquired in 1999 and 2000. Our current ***preliminary working*** result for the pion beta decay branching ratio is

$$BR \simeq 1.044 \pm 0.007(\text{stat.}) \pm 0.009(\text{syst.}) \times 10^{-8} \ .$$

We have enlarged the quoted systematic uncertainty because, as of this writing, we have not finished cross-checking all of the corrections applied in the current analysis pass. Our result is to be compared with the previous most accurate measurement of McFarlane et al.[1]:

$$BR = 1.026 \pm 0.039 \times 10^{-8} \ ,$$

as well as with the SM Prediction (Particle Data Group, 2002[2]):

$$\begin{aligned} BR &= 1.038 - 1.041 \times 10^{-8} \quad (90\%\text{C.L.}) \\ & \quad\ (1.005 - 1.008 \times 10^{-8} \quad \text{excl. rad. corr.}). \end{aligned}$$

We see that even our working result strongly confirms the validity of the CVC hypothesis and SM radiative corrections[3, 4]. Another interesting comparison is with the prediction based on the most accurate evaluation of the CKM matrix element V_{ud} based on the CVC hypothesis and the results of measurements of superallowed Fermi nuclear decays (Particle Data Group 2002[2]):

$$BR = 1.037 \pm 0.002 \times 10^{-8} \ .$$

Thus, our current preliminary working result is in very good agreement with the predictions of the Standard Model and the CVC hypothesis. The quoted systematic uncertainties are being reduced as our analysis progresses. To put this result into broader perspective, we can compare the central value of V_{ud} extracted from our data with that listed in PDG 2002[2]:

$$\begin{aligned} \text{PDG 2002:} &\quad V_{ud} = 0.9734(8), \\ \text{PIBETA prelim:} &\quad V_{ud} = 0.9771(56). \end{aligned}$$

At this point our analysis indicates a slightly higher value of V_{ud} than the reported world average. If it persists at increased precision, our result would tend to remove the well publicized violation of CKM unitarity.

Radiative pion and muon decays

Besides pion beta decay events, we have also recorded a large data set of radiative decays: $\pi^+ \to e^+\nu\gamma$ (RPD) and $\mu^+ \to e^+\nu\bar{\nu}\gamma$ (RMD). The former are used to extract the ratio F_A/F_V of the axial-vector and vector pion form factors, a quantity of longstanding interest to low energy effective QCD theory, particularly to chiral perturbation theory. Both processes are furthermore sensitive to non-(V−A) admixtures in the electroweak lagrangian, and thus can reveal information on physics outside of the present SM.

To date we have analyzed both pion and muon radiative decays, though with more attention devoted to the former, as it is an important physics background to other decays under study. We note that the pion radiative decay analysis has given us the most surprising result to date, and that we are expending significant effort in trying to resolve the issue.

Due to the different event triggers used, our experiment covers three distinct regions in the phase space of the $\pi^+ \to e^+\nu\gamma$ decay:

- region A with e^+ and γ emitted into opposite hemispheres, each with energy exceeding that of the Michel edge ($E_M \simeq 52\,\text{MeV}$), recorded in the main two-arm trigger,
- region B with an energetic photon ($E_\gamma > E_M$), and $E_{e+} \geqslant 20\,\text{MeV}$, recorded in the one-arm trigger, and
- region C with an energetic positron ($E_{e+} > E_M$), and $E_\gamma \geqslant 20\,\text{MeV}$, also recorded in the one-arm trigger.

Fig. 4 illustrates the quality of our data by showing preliminary results of a partial analysis of the data in the pion radiative decay modes. The signals are clearly distinguishable from background in each of the three regions, and the decaying pion mass is well reconstructed.

Together, the three regions overconstrain the Standard Model parameters describing the decay, and thus allow us to examine possible new information about the pion's hadronic structure, or non-(V−A) interactions. Appropriate analysis of these data is involved and requires a detailed presentation for which there is not enough space here. We will briefly summarize the salient points of our analysis here.

The preliminary results presented below are based on the 1999 and 2000 data, and they:

◦ include only regions A and B (due to a small residual admixture of muon radiative decays; this problem is being addressed as of this writing),

◦ exclude border regions in acceptance, as we are still perfecting the Monte Carlo simulation code, though their inclusion does not alter the results significantly,

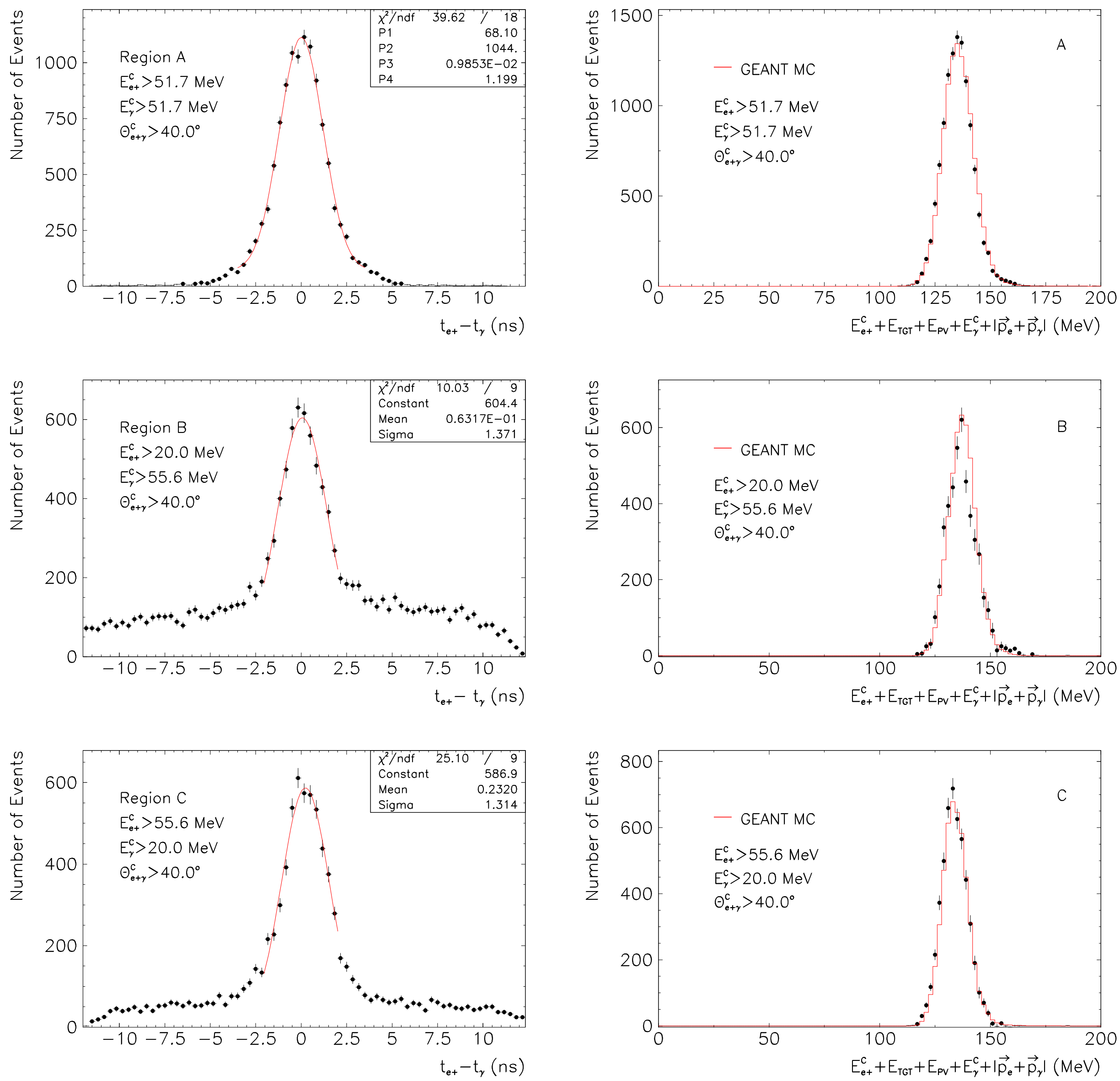

Figure 4: e-γ timing difference in the 1999/2000 subset of the $\pi \to e\nu\gamma$ radiative decay (RPD) data (left panels), indicating the signal-to-background ratios in the three kinematic regions, A, B, and C, respectively, noted on the graphs. The right-hand graphs show the "invariant π^+ mass" variable, reconstructed from the same subset of our RPD data (dots) and simulation (histogram). Preliminary results—work in progress.

◦ do not include the most recent improvement in detector resolution functions (to be implemented in the next analysis pass).

The above limitations notwithstanding, our analysis shows a strong departure from SM predictions. Standard Model with the V−A electroweak sector requires only two form factors, F_A and F_V to describe the so-called structure-dependent amplitude in RPD. The remainder of the decay amplitude is accounted for by QED in the inner-bremsstrahlung (IB) term. The pion vector form factor is strongly constrained by the CVC hypothesis, while existing data on the radiative pion decay (PDG 2002[2]) suggest that $F_A \simeq 0.5\, F_V$, yielding

$$F_V = 0.0259 \pm 0.0005 \ , \qquad \text{and} \qquad F_A \simeq 0.012 \ .$$

Simultaneous as well as separate fits of our data in regions A and B (region C is found to be substantially in agreement after the fact) show a statistically significant deficit in RPD yield compared to predictions based on the above values of the pion form factors.

An even larger deficit in RPD yield, though less statistically significant than our finding due to fewer data, was first reported by the ISTRA collaboration in Dubna[5, 6]. This first observation was interpreted by Poblaguev[7, 8] as indicative of the presence of a tensor weak interaction in the pion, giving rise to a tensor pion form factor $F_T \sim -6 \times 10^{-3}$.

Subsequently, Peter Herczeg[9] found that the existing experimental evidence on beta decays could not rule out a small nonzero value of F_T of this order of magnitude.

We illustrate the results of our two-dimensional fits by showing projected one-dimensional distributions of two kinematic variables, λ and E_γ, in Figs. 5 and 6, respectively. Here $\lambda = (2E_{e+}/m_{\pi+}) \sin^2(\theta_{e\gamma}/2)$ combines E_{e+}, the positron energy, and $\theta_{e\gamma}$, the positron-photon opening angle, in such a way that λ ranges from 0 to 1 regardless of E_γ.

These fits should be treated as merely representative of the direction in which our data are driving the pion form factor values, not as definitive results. The fits were made in two-dimensional kinematic space of $x = 2E_\gamma/m_{\pi+}$, and λ.

Fig. 5 shows three sets of curves corresponding to three sets of fit parameters:

FIT I:	F_V fixed by CVC; F_A free; $F_T \equiv 0$	dotted curve	$\chi^2/\text{ndf} = 5.6$,
FIT II:	F_V and F_A free; $F_T \equiv 0$	dashed curve	$\chi^2/\text{ndf} = 2.3$,
FIT III:	F_V fixed by CVC; F_A and F_T free	solid curve	$\chi^2/\text{ndf} = 1.1$.

Clearly, a satisfactory fit to our data requires $F_T \neq 0$. Furthermore, fits with $F_T \equiv 0$ force nonphysical values for F_A, F_V, or both. Thus, like the ISTRA data[5, 6], our data appear to call for a destructive interference between the IB term and a small negative tensor

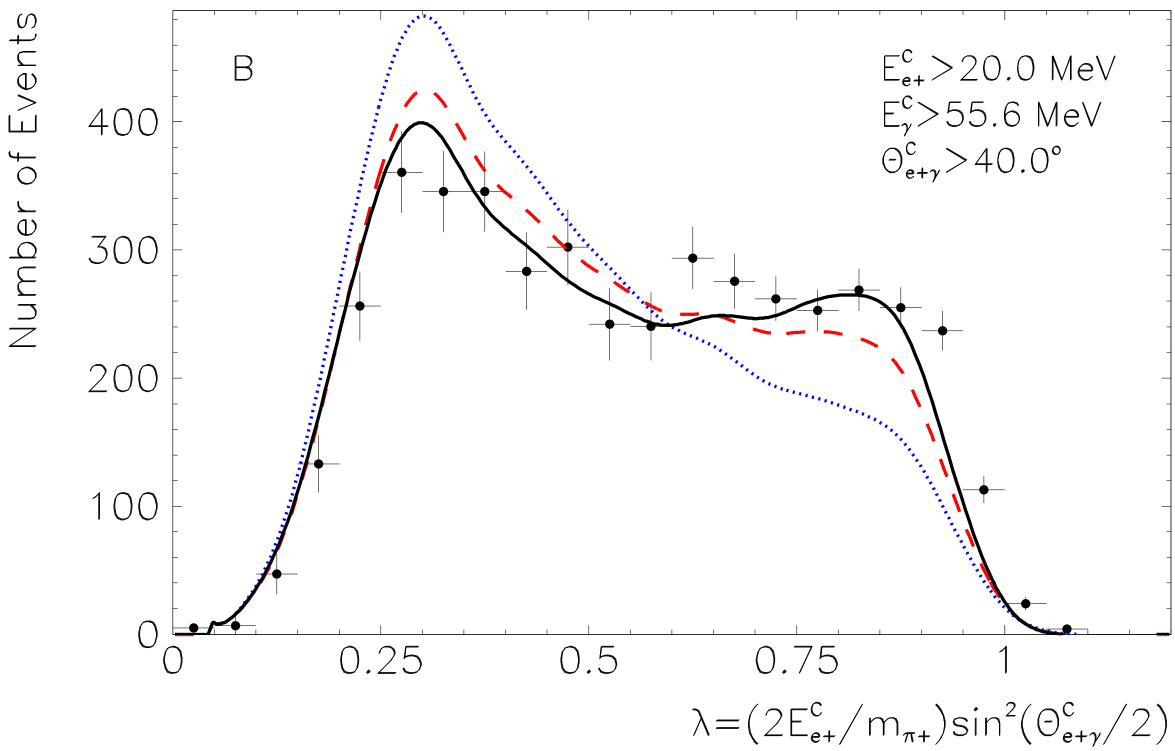

Figure 5: Measured spectrum of the kinematic variable $\lambda = (2E_{e+}/m_{\pi+})\sin^2(\theta_{e\gamma}/2)$ in $\pi^+ \to e^+\nu\gamma$ decay for the kinematic region B, with limits noted in the figure. Dotted (blue) curve: fit with the pion form factor F_V fixed by the CVC hypothesis, and F_A taken from the PDG 2002 compilation [2]. Dashed (red) curve: fit with F_V and F_A released of all constraints, and $F_T \equiv 0$. Solid (black) curve: fit with F_V constrained by CVC, and F_A and F_T unconstrained. The resulting value for F_T is -0.0017 ± 0.0001. Preliminary results—work in progress.

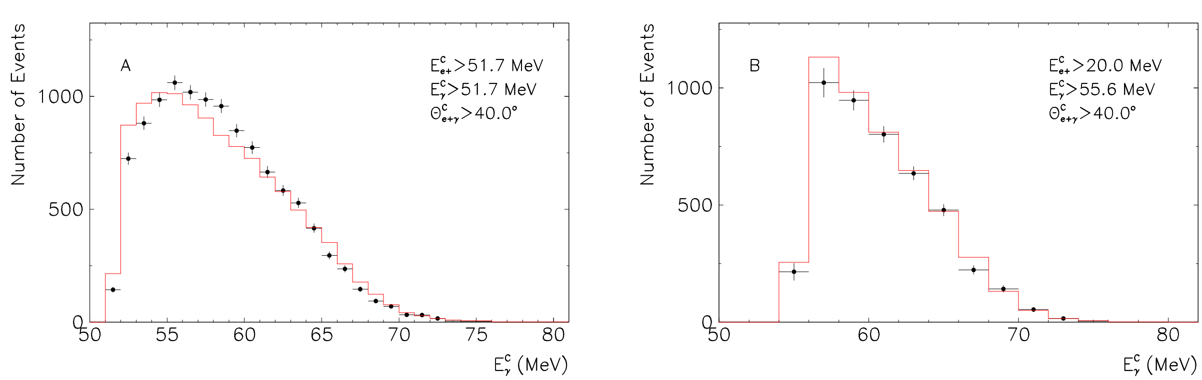

Figure 6: Results of the above best fit (with $F_T \neq 0$) shown projected in the E_γ kinematic variable for regions A and B. Preliminary results—work in progress.

amplitude:

$$F_T \simeq -0.0017 \pm 0.0001 \; .$$

This result is very preliminary, it is subject to correction due to possible systematic distortions in the analysis routines, i.e., the quoted uncertainty comes entirely from the fit minimization procedure.

Illustrating the consistency of our data, Fig. 6 shows the projected E_γ spectra from kinematic regions A and B with the superimposed theoretical histograms resulting from FIT III. Data in region C are found to be in similar agreement.

We are not accepting this result at face value, and are devoting nearly all available group resources to searching for possible errors in the analysis routines (especially charged particle tracking), or in the Monte Carlo simulations of theoretical amplitudes, that may be responsible for the observed departure from SM predictions.

While we have not yet definitively eliminated every possibility of error in our data analysis, the analysis of other pion and muon decays to date shows remarkable precision: the pion beta decay branching ratio is at $\lesssim 1\,\%$ accuracy and improving, with $\pi \to e\nu$ decays even better. This would be impossible without the excellent agreement between data and simulations observed in scores of variables and channels, which we are not presenting here due to space limitations. Thus, if an analysis error is causing the nonzero F_T result, it must be a subtle one, arising under very peculiar circumstances affecting the RPD events only.

Summary of PIBETA results to date

In the first phase of the PIBETA experiment we have recorded about two orders of magnitude more rare pion and muon decay events than was available in the entire world data sets on the $\pi^+ \to \pi^0 e^+\nu$, $\pi^+ \to e^+\nu\gamma$ and $\mu^+ \to e^+\nu\bar{\nu}\gamma$ channels. The event statistics for the main decay channels studied in the PIBETA experiment are summarized in Table 1.

Table 1: Summary of the PIBETA event statistics, compared with the world data set.

Decay	PIBETA data set	World data set
$\pi^+ \to \pi^0 e^+\nu$	$> 50\,$k events	$1.77\,$k events
$\pi^+ \to e^+\nu$	$> 580\,$M events	$0.35\,$M events
$\pi^+ \to e^+\nu\gamma$	$> 60\,$k events	$1.35\,$k events
$\mu^+ \to e^+\nu\bar{\nu}\gamma$	$> 500\,$k events	$8.5\,$k events

It is clear from the numbers in Table 1 that we will achieve significantly improved precision in the analysis of the radiative decay modes, as well as the $\pi\beta$ channel ($\sim 0.5\,\%$ in the first stage). We are currently well on our way to achieving the stated goals of this stage of the project. The second stage, however, will require a remeasurement of the $\pi \to e\nu$ decay rate, for which the PIBETA detector is ideally suited. The breakdown of the major sources of uncertainty is given in Table 2. All of the important terms represented in the table are in place as of this writing; they will be implemented in the next analysis pass through the full data set. A first look at the full data set has indicated no problems; in fact the 2001 data are of the highest quality.

Table 2: Summary of the uncertainties in the evaluation of the pion beta decay branching ratio, $BR(\pi^+ \to \pi^0 e^+ \nu)$ at the conclusion of the current analysis pass through a partial 1999/2000 data set (reported on in the preceding sections), and for the projected final result of the analysis of the entire data set, 1999–2001. The latter result also assumes a remeasurement of the $BR(\pi \to e\nu)$.

Uncertainties at end of analysis pass:		Current	Entire set
External:	pion lifetime	0.019	0.019
	$BR(\pi \to e\nu)$	0.33	~ 0.1*
	$BR(\pi^0 \to \gamma\gamma)$	0.032	0.032
Internal:	$A(\pi\beta)/A(e\nu)$	0.35	< 0.3
	$\Delta t(\gamma - e)$	0.03	0.03
	E thresh.	< 0.1	< 0.1
Statistical:		0.7	~ 0.4
Total:		0.9	$\lesssim 0.5$

* requires a new measurement.

In summary, the present preliminary stage of our analysis has yielded a pion beta branching ratio which, for the first time, confirms experimentally the validity of the CVC hypothesis in a meson, as well as the SM radiative corrections[3, 4].

We are vigorously examining our unexpected result for the $\pi \to e\nu\gamma$ decay for possible errors or inefficiencies in the analysis routines, and expect to resolve the issue in the near future. If the current result should remain standing, it would imply the first evidence of a tensor weak interaction at the tree level.

References

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