

STUDY OF THE $\pi^+ \rightarrow e^+ \nu \gamma$ DECAY ANOMALY

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Summary:

The proposed work is an extension of a program of precise studies of rare pion and muon decays using the PIBETA detector. In the first phase, 1999–2001, the collaboration completed a set of measurements of the $\pi^+ \rightarrow \pi^0 e^+ \nu$, $\pi^+ \rightarrow e^+ \nu$, $\pi^+ \rightarrow e^+ \nu \gamma$, and $\mu^+ \rightarrow e^+ \nu \bar{\nu} \gamma$ decays. Data for all of the decays except $\pi \rightarrow e \nu \gamma$ ($\pi_{e2\gamma}$) are in excellent agreement with predictions of the Standard Model, with better than 1% accuracy. While the bulk of the measured $\pi_{e2\gamma}$ data are compatible with the standard (V–A) form of the weak interaction, we have found significant ($\sim 20\%$) deviations in the kinematic region corresponding to high E_γ /low E_{e^+} , not explained by instrumental or analysis inefficiencies. In 1990 a similar anomaly was observed in the ISTR A experiment using a radically different technique, albeit with a much lower statistical significance. The anomaly has remained unexplained; some authors have tentatively attributed it to a small tensor component in the interaction whose main contribution occurs in this kinematic region. Our original run was optimized for hard two-shower kinematics. This proposal revisits the $\pi_{e2\gamma}$ decay in a dedicated, lower rate experiment, with the aim to produce one-arm $\pi_{e2\gamma}$ data matching the high precision of our two-arm data. This should decisively clarify the experimental situation, and provide an optimal basis for further theoretical study of the problem.

*Co-spokesmen

BEAM REQUIREMENTS:

Beam line: $\pi E1$

Beam properties:

particle type: π^+

intensity: $0.1 - 2 \times 10^5 \pi^+/\text{s}$ stopped in target

momentum: $\sim 114 \text{ MeV}/c$

Detector: the PIBETA detector system

Special conditions: Setup of the PIBETA DAQ shack inside the area, as during the 1999–2001 run, including the special shielding wall.

Original beam request: 15 weeks, starting in mid-May 2004

Subsequent beam requests: Not foreseen, barring unexpected developments or equipment failure during the 2004 beam period.

SPECIAL SAFETY CONSIDERATIONS: none

Note: The running conditions will be exactly the same as during the 1999–2001 PIBETA run, with the pion beam intensity reduced approximately five-fold.

1. Background and motivation: summary of previous results

The work proposed here continues a program of precise measurements of the rare pion and muon decays using the PIBETA detector system. In the first run, 1999–2001 the chief subject of study was the pion beta decay, $\pi^+ \rightarrow \pi^0 e^+ \nu$, with the goal to achieve a $\sim 0.5\%$ accuracy in the $\pi\beta$ branching ratio. We use $\pi^+ \rightarrow e^+ \nu$ decay events (π_{e2}) for normalization. However, all rare pion and muon decays, as well as the main decay of the muon, have been studied extensively. This is due not only to the physics interest that each process carries, but also as a necessary and powerful consistency check of the overall systematics and control of signal backgrounds. The acquired data set comprises 2.2×10^{13} beam pion stops, and has been analyzed in several passes.

The first results of our analysis, already reported at several meetings and conferences, are now prepared for publication, and are available as preprints. These results provide the motivation for the present proposal. We will refer to the following three papers:

- I: “Design, Commissioning and Performance of the PIBETA Detector at PSI”, E. Frlež et al., hep-ex/0312017, submitted to Nucl. Inst. Meth. A.
- II. “Precise Measurement of the $\pi^+ \rightarrow \pi^0 e^+ \nu$ Branching Ratio”, D. Počanić et al., hep-ex/0312030, submitted to Phys. Rev. Lett.
- III. “Precise Measurement of the Pion Axial Form Factor in the $\pi^+ \rightarrow e^+ \nu \gamma$ Decay”, E. Frlež et al., hep-ex/0312029, submitted to Phys. Rev. Lett.

Preprint I gives a detailed account of the detector system design and performance, as well as of our experimental method and procedures. Preprints II and III report our physics results for the $\pi\beta$ and $\pi_{e2\gamma}$ channels. Preprint III will be followed soon by a paper, currently in preparation, focusing on the departures in our data from the Standard Model (SM) predictions. To avoid duplication of material, papers II and III are appended to this document.

We can summarize the results presented in preprints I–III as follows.

Pion Beta Decay

The experimental signal for pion beta decay events in our data is very clean. The analysis has proceeded smoothly. Our current result for the branching ratio

$$R_{\pi\beta}^{\text{exp}} = [1.034 \pm 0.004 (\text{stat}) \pm 0.007 (\text{syst})] \times 10^{-8}, \quad (1)$$

or, alternatively, for the decay rate,

$$\Gamma_{\pi\beta}^{\text{exp}} = [0.3972 \pm 0.0015 (\text{stat}) \pm 0.0025 (\text{syst})] \text{ s}^{-1}, \quad (2)$$

represents a five-fold improvement in precision over the most recent previous measurement [1], and is in excellent agreement with the Standard Model prediction using the currently accepted Particle Data Group (PDG) recommended value for V_{ud} [2].

We are continuing to refine the analysis and simulation, and see no obstacles in reaching the stated goal of $\sim 0.5\%$ accuracy. We note that our statistical uncertainty is somewhat

larger than originally planned, due to excessive down time in 2001, our last year of running. In our next analysis pass we will include $\pi\beta$ decay events occurring closer in time to the beam π^+ stop than the current 10 ns cut, yielding several thousand more events. The measurements proposed here would add $\gtrsim 5000$ $\pi\beta$ events. All told, our $\pi\beta$ statistical uncertainty should end up below 0.4%.

Finally, a thorough understanding of the $\pi\beta$ channel and how it influences the backgrounds to the $\pi_{e2\gamma}$ signal is essential for a precise measurement of the latter decay.

The π_{e2} decay

This is the process we have used to normalize our $\pi\beta$ and $\pi_{e2\gamma}$ results. We have also performed independent normalizations to the number of stopped beam pions and have found the results consistent with the π_{e2} normalization at the level of 1% or better. We have, furthermore, investigated evaluating $\Gamma(\pi_{e2})/\Gamma(\text{total})$ on the same basis, using two different approaches. Both methods agree with the PDG recommended value [2] (as well as with the SM prediction [3]) at the sub-1% level. One has to keep in mind that the 1999–2001 run was optimized for $\pi\beta$ decay measurement, and therefore is not indicative of the ultimate accuracy of π_{e2} detection achievable with the PIBETA detector. We therefore see our π_{e2} analysis as encouraging in terms of a dedicated precise measurement of the π_{e2} branching ratio.

There has been a great deal of interest for some time in an accurate experimental test of lepton universality, which is preserved in the Standard Model. Decay $\pi \rightarrow e\nu$ is unique in being accessible both theoretically and experimentally at $\lesssim 10^{-3}$ accuracy, thus presenting the possibility for setting stringent limits on non-SM physics which could lead to violations of lepton universality. Mindful of this opportunity, we intend to use the proposed 2004 beam time to perform several tests of π_{e2} detection systematics. A dedicated π_{e2} measurement will, however, require a new experimental proposal, and is outside the scope of this document.

The $\pi_{e2\gamma}$ decay

Decay $\pi \rightarrow e\nu\gamma$ proceeds via a combination of QED (inner bremsstrahlung) and structure-dependent amplitudes [4]. The latter make it a textbook process for determining the pion form factors, which, in turn, provide important input for effective QCD calculations, such as chiral perturbation theory.

As we have reported previously, the radiative pion decay $\pi^+ \rightarrow e^+\nu\gamma$, has turned out to be the great surprise of our experiment. Our measurements of the branching ratio for this decay are presented in detail in Preprint III. To summarize, we have evaluated the $R(\pi_{e2\gamma})$ for three kinematic regions, which we have labeled as *A*, *B*, and *C*. Data in regions *A* and *C* are mutually compatible within the framework of the Standard Model (including the CVC-mandated value of $F_V = 0.0259(5)$, the pion vector form factor [2]). Data from region *B* are in disagreement; their inclusion into the SM fit lowers the extracted value of F_A , the pion axial-vector form factor, such that

$$F_A/F_V \equiv \gamma = 0.443(15) \text{ for all three regions, but} \quad (3)$$

$$\gamma = 0.480(16) \text{ for region } A \text{ only, or for } A \text{ and } C. \quad (4)$$

Naturally, we cannot ignore data in region B . We have spent a great deal of time and effort to track down any possible sources of detection and/or analysis inefficiency which would manifest itself only in the low- E_{e^+} /high- E_γ kinematics of region B . We can report that our analysis yields differential and integral branching ratios in agreement with the SM predictions for all measured rare decays at the 1% level or better. Most importantly this is true for the $\mu \rightarrow e\nu\bar{\nu}\gamma$ decay, which features its own version of “region B ”. An inefficiency amounting to $\sim 20\%$ would show up in these analyses, yet it has not [5].

Turning to theory, we have investigated the possibility of unusually large radiative corrections affecting primarily the kinematic region B . Dubna theorists Kuraev and Bystritsky have recently revisited [6] the radiative corrections to the $\pi e 2\gamma$ decay originally calculated by Nikitin [7]. E. Velicheva has taken the expressions obtained by Kuraev and Bystritsky, and calculated the corrections that apply to our kinematic regions. The corrections range from -1.1% to -3.3% , depending on the region, and were included in our analysis presented in paper III, leaving us with the 19% shortfall in region B discussed above.

Another possible theoretical explanation for the anomaly involves the destructive interference of the QED internal bremsstrahlung amplitude (IB) with a small tensor amplitude, normally assumed absent in the Standard Model and its supersymmetric extensions [16]. As unlikely as this may seem, the subject has been seriously considered over the past fifteen years. A deficit similar to the one we found, was noted in the $\pi e 2\gamma$ measurement of the ISTRA experiment [8, 9]. Using these data Poblaguev extracted a pion tensor form factor of $F_T = -0.0056(17)$ [10, 11]. In a subsequent careful analysis, Herczeg could not rule out this possibility on the basis of all the known constraints from beta decay [12]. On the other hand, Chizhov has proposed a new intermediate chiral boson with an anomalous interaction with matter, in order to account for the apparent non-(V-A) behavior in radiative pion decay [13]. Furthermore, the same author has recently pointed out that the detected anomaly may also be responsible for the discrepancy in the spectral functions extracted from e^+e^- and τ data [14]. Poblaguev has recently revisited the problem, suggesting the possibility of an even bigger tensor form factor, $F_T = -0.0115(33)$ [15]. There have been other papers during the 1990’s addressing the same question, e.g., Refs. [17, 18, 19].

The possibility that F_V may actually differ from the CVC value is normally not considered. Scadron and coworkers, however, point out that F_V is experimentally poorly determined [the PDG world average is $F_V = 0.017(8)$]. They use the experimental value to support the linear sigma model prediction of $\gamma = 2/3$ [20]. A lower value of F_V would tend to improve the fits in region B , although the overall agreement would still not be satisfactory. We have not given serious consideration to this possibility.

Our purpose here is not to speculate about the possible theoretical explanation for the anomaly we have observed. We instead wish to produce the most precise set of experimental data to serve as a solid basis for critical comparisons of theoretical predictions. With that in mind, we note that our data are least precise in region B , the one kinematic region where the putative tensor interaction makes the greatest difference (adding $F_T \neq 0$ in our fits produces a negligible change in the differential yields in regions A and C). In particular, we note that the accidental background in region B is highest, with S/B of 3.8, compared with 7.6 and > 300 for regions C and A , respectively. This is understandable since the data were acquired with a one-arm trigger at a high pion stopping rate in the target, in the presence

of an intense Michel background.

We illustrate this point quantitatively in Fig. 1 where we show our data and two recent fits for region B . In order to compare with previous work, we use the standard decay amplitude parametrization including F_T [19], and plot the differential decay rate against the kinematic variable λ , which can be calculated in two ways. First, we evaluate λ on the basis of the measured positron energy E_e and opening angle $\theta_{e\gamma}$, i.e.,

$$\lambda_1 = \frac{2E_e}{m_\pi} \sin^2 \frac{\theta_{e\gamma}}{2}, \quad (5)$$

shown in the top panel of the figure. Second, we evaluate λ based on the measured photon and positron energies, such that

$$\lambda_2 = 1 + \frac{y-1}{x}, \quad \text{where} \quad x = \frac{2E_\gamma}{m_\pi} \quad \text{and} \quad y = \frac{2E_e}{m_\pi}. \quad (6)$$

The two plots are evaluated completely independently, and demonstrate the consistency of our method. However, the event sets in both plots are identical. For this reason we do not average λ_1 and λ_2 , but instead show them separately.

The effect of the destructive interference of the tensor term with the IB amplitude is clearly visible in both plots. The present error bars on our data points, as well as their scatter in the central region where the Michel background subtraction was maximal, compromise the quality of the data, and impede a decisive and unambiguous discrimination between theoretical predictions. We will present a more detailed account of the observed effect in a forthcoming preprint. Data analysis and simulation of the $\pi e 2\gamma$ and $\mu \rightarrow e\nu\bar{\nu}\gamma$ decays is continuing.

Fig. 1 also illustrates another potential experimental source of the observed anomaly, other than the instrumental/analysis inefficiency mentioned above. Erroneously reconstructed energy of the positron showers at lower energies, i.e., a pronounced nonlinearity in the energy response of the detector well below 70 MeV could conceivably deplete the low- E_e part of the energy spectrum significantly. Our primary energy gain calibration is performed by matching the $\pi e 2$ monoenergetic peak to the Monte Carlo (MC) response (cf. Fig. 3 in Preprint III). It is important to note here that the absolute energy scale is not of essential importance for the physics analysis (our MC simulation is realistic and includes modeling of the photomultiplier response, detector inhomogeneity, pile-up and noise, and thus reports observables removed from the primary energy deposition). On the other hand, simultaneous precise matching of all kinematical variable spectra to the MC predictions in *all* decay processes without separate adjustments is essential.

The most sensitive cross-check of the $\pi e 2$ energy calibration in the radiative decay channel is provided by evaluating the difference histogram between λ_1 and λ_2 of Eqs. (5) and (6), respectively. We show one such histogram in Fig. 2. Clearly, the effect of a 1% gain shift is unmistakable, and the procedure confirms the validity of the original gain calibration. Furthermore, gain linearity at lower energies is tested by comparing data and simulation of the Michel positron energy spectrum which extends down to our experimental lower threshold. Results of an earlier such comparison are shown in Fig. 3 (a new pass in the muon decay analysis is currently under way). There is no indication of any significant deviations or depletions at low energies. The same conclusion is confirmed by the integral branching

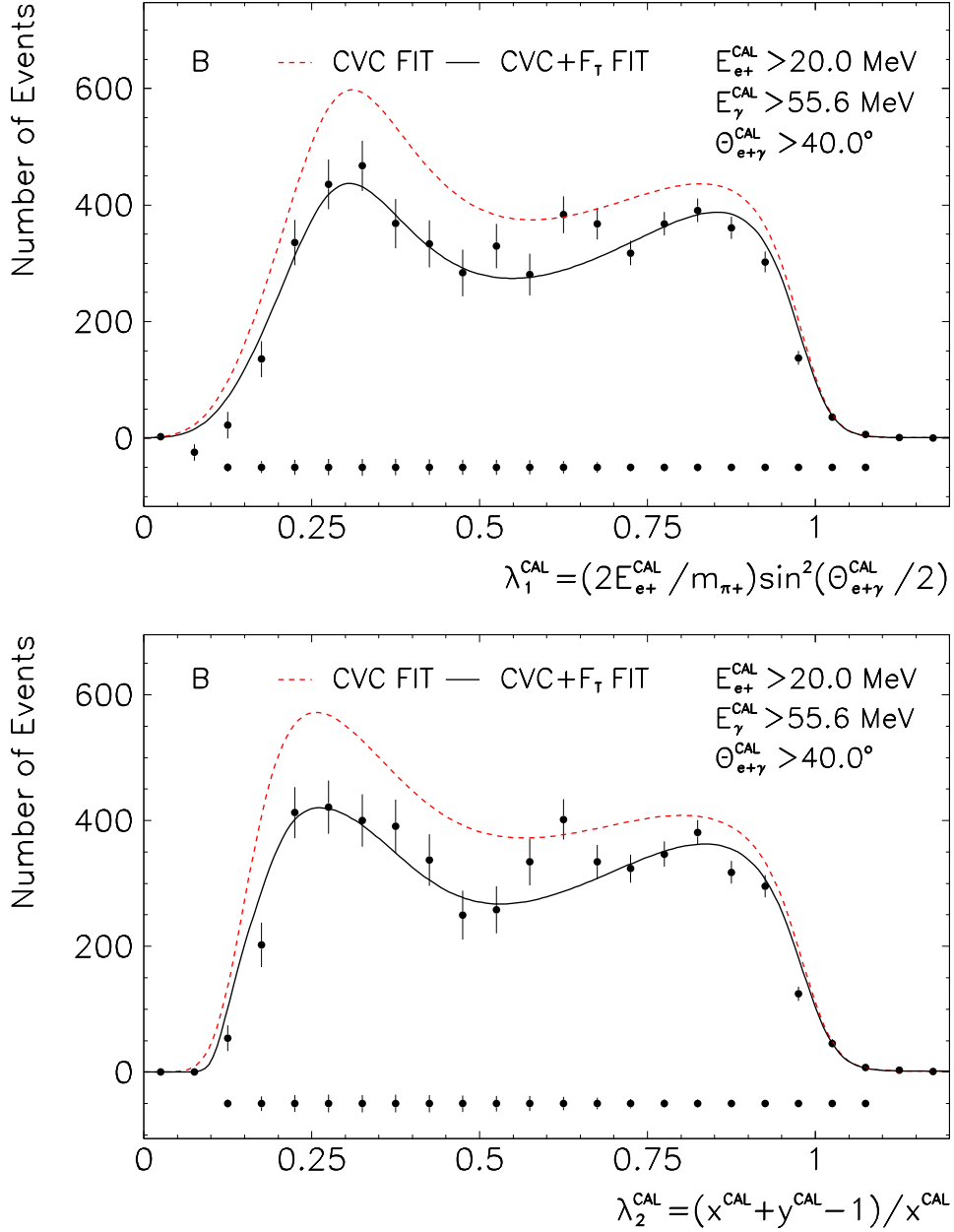


Figure 1: Top panel: measured spectrum of $\lambda_1 = (2E_e/m_\pi) \sin^2(\theta_{e\gamma}/2)$ in $\pi e 2\gamma$ decay for the kinematic region B , with limits noted in the figure. Dashed curve: three-region global best fit with the pion form factor $F_V = 0.0259$ fixed by the CVC hypothesis, $F_T = 0$, and F_A free. Solid curve: $F_V = 0.0259$ and $F_A = 0.0115$ from the first fit, this time with F_T released to vary freely, resulting in $F_T = -0.0018(3)$. Error bars on the points at bottom of graph reflect the expected uncertainties in the proposed dedicated measurement. Bottom panel: same as above, but plotting the variable λ evaluated purely on the basis of photon and positron energies: $\lambda_2 = (x + y - 1)/x$, where $x = 2E_\gamma/m_\pi$, and $y = 2E_e/m_\pi$. The agreement between the two methods is very good; the slight differences are due to the detector response functions for the measured observables.

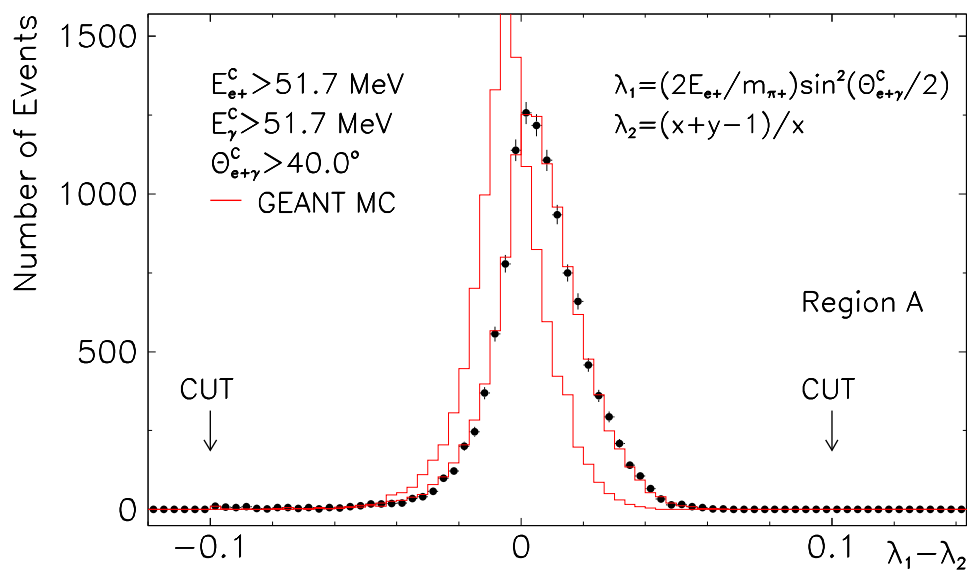


Figure 2: Mis-match between the experimental and simulated $\lambda_1 - \lambda_2$ distributions in the radiative pion decay. Two different GEANT simulations, differing by 1% in gain factor are superimposed to the experimental data.

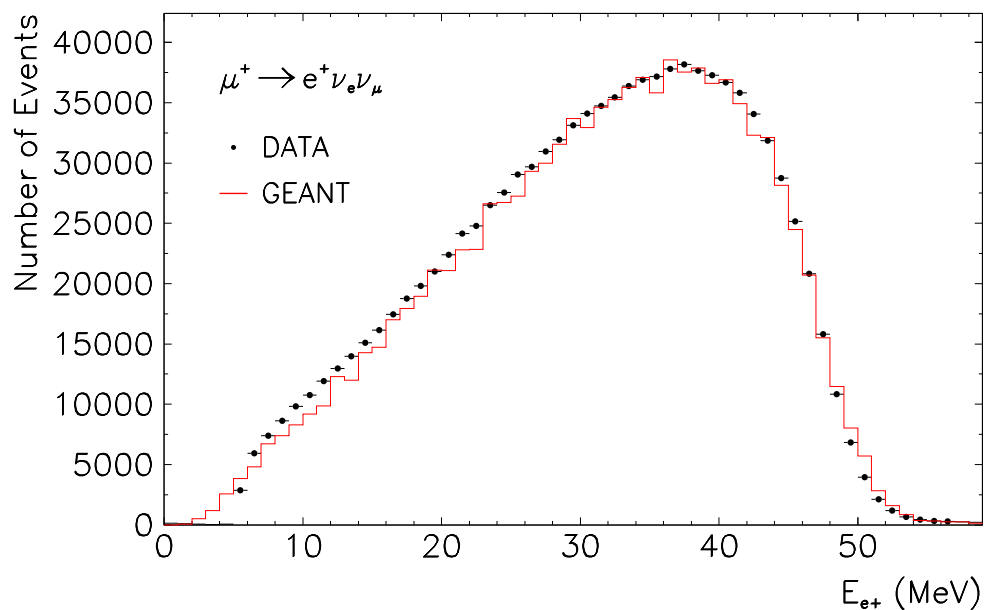


Figure 3: Energy spectrum of the positron in Michel decay. Points: data. Solid histogram: Monte Carlo simulation. Preliminary; further analysis is under way.

ratio evaluation, and by the spectra and differential branching ratios in our muon radiative decay data. In summary, our analysis confirms the validity of our gain calibration well within 0.2 MeV across the energy range of interest.

We finally note that we have studied the linearity of the CsI crystal response in detail (a) for each individual module after delivery, using a tomography setup, and (b) directly with monoenergetic positron beams of varying energy for several partial detector setups ranging from 12 to 44 modules. These results have given us an excellent understanding of the fundamental linearity of the calorimeter detectors; they are published in several papers [21, 22]. The measured response functions were used to fix the relevant GEANT parameters in our Monte Carlo simulation.

2. The proposed measurements

Given our anomalous branching ratio result in region B , the unique sensitivity of region B to the putative tensor interaction, the longstanding interest in this open question, and the less than optimal quality of our data in region B , we propose to revisit the $\pi_{e2\gamma}$ decay with a dedicated run optimized for regions B and C .

The first phase of the PIBETA experiment was run with $\sim 8 - 9 \times 10^5$ pion stops/s in the target. The optimal stopping rate for one-arm trigger acquisition of radiative pion decay data with our detector is somewhere between 100 and 200 kHz, depending on the reduction of data acquisition (DAQ) dead time. One of the unknown parameters is the amount of improvement of DAQ live time fraction following the planned replacement of the front-end DAQ computer with a new faster model. In the absence of empirical information, we have used the conservative lower number for event rate estimates. Turning off the DSC digitizer for all but the beam detectors restores $\sim 10\%$ to the live time fraction. This is justified given the lower event rates in the other detectors.

The main modification of the detector consists of substituting a simpler one-piece active target in place of the nine-piece target detector used in the main PIBETA run.

The breakdown of the counting statistics in the first-phase $\pi_{e2\gamma}$ data set is $N_A : (N_B + N_C) = 31\text{ k} : 12\text{ k}$. Running for three months with a reduced pion stopping rate and suitably modified trigger, we can collect up to 20k clean events with $S/B > 40$ in regions B and C . The expected error limits for the planned new data in region B are shown in Fig. 1 on the line of data points at the bottom of each plot. The measurement will also add some $\gtrsim 3000$ region A events, leading to a further improvement in the precision of the F_A/F_V ratio determination.

Just as important as the proposed $\pi_{e2\gamma}$ measurement will be the new data on the radiative muon decay, $\mu \rightarrow e\nu\bar{\nu}\gamma$. We project adding some 300k new radiative muon decay events to our data set by appropriately adjusting the prescaling factor on the low-threshold two-arm trigger. This will approximately double the number of events in this channel recorded so far. However, the new data set will be much cleaner than the old, with $S/B \geq 15$, i.e., comparable to the new $\pi_{e2\gamma}$ data. This is significant as a possibly more stringent test of a small tensor term in the weak Lagrangian. In other words, while hadronic structure effects may well be responsible for the anomalies we have observed in radiative pion decay, such effects are absent in muon decay. Thus, a clean high-statistics set of radiative muon decay data should provide a basis for tests of non-(V-A) interaction terms. Before this can be

fully accomplished, though, more theoretical work is needed. An important task will be to update the calculation of radiative corrections for $\mu \rightarrow e\nu\bar{\nu}\gamma$ decay; there are indications that a theory group at Dubna may soon take up this job. Furthermore, M. Chizhov has undertaken to investigate the possible signature of a tensor term in the radiative muon decay observables. We therefore expect that our radiative muon decay data will be valuable in clearing up the current controversy.

Finally, the measurement will add $\gtrsim 5000$ $\pi\beta$ decay events to our data set.

3. Resources and beam request

We request three months of data acquisition beam time plus three weeks for set-up and calibration in the $\pi E1$ beam area, i.e., a total of 15 weeks. Given the detector and personnel readiness requirements, we request that this period begin in mid-May and run through August 2004.

There are no major costs associated with the requested run. The main expenditures are the material costs of operating the detector (MWPC gas, supplies). The cost of replacing the front-end computer is modest, on the order of 1–2 kCHF. We estimate the overall material and supply costs of the proposed run to be about 20 kCHF.

While several original collaboration members will not be available for the run proposed here (Crawford, Daum, Ritt), new members have joined: the University of Zürich group (P. Robmann, U. Straumann, P. Truöl, A. van der Schaaf, possibly with a student), T. Sakhelashvili (PSI), M. Korolija, plus a possible student (IRB, Zagreb). On the theoretical side we are joined by E. Velicheva (Dubna) and M. Chizhov (Univ. of Sofia and CERN).

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