Letter of Intent for an Experiment at PSI

Precise Measurement of the $\pi^+ \to e^+\nu$ Branching Ratio

V. A. Baranov,[c] W. Bertl,[b] M. Bychkov,[a] Yu. M. Bystritsky,[c] E. Frlež,[a] V. A. Kalinnikov,[c] N. V. Khomutov,[c] A. S. Korenchenko,[c] S. M. Korenchenko,[c] M. Korolija,[g] T. Kozlowski,[d] N. P. Kravchuk,[c] N. A. Kuchinsky,[c] R. C. Minehart,[a] D. Mzhavia,[c,e] D. Počanić,[a] B. G. Ritchie,[f] P. Robmann,[h] O. A. Rondon-Aramayo,[a] A. M. Rozhdestvensky,[c] T. Sakhelashvili,[h*] S. Scheu,[h] V. V. Sidorkin,[c] L. C. Smith,[a] U. Straumann,[h] I. Supek,[g] Z. Tsamalaidze,[e] A. van der Schaaf,[h] B. A. VanDevender,[a] E. P. Velicheva,[c] V. V. Volnykh,[c] and Y. Wang[a]

[a]*Department of Physics, University of Virginia, Charlottesville, VA 22904-4714, USA*

[b]*Paul Scherrer Institut, CH-5232 Villigen PSI, Switzerland*

[c]*Joint Institute for Nuclear Research, RU-141980 Dubna, Russia*

[d]*Institute for Nuclear Studies, PL-05-400 Swierk, Poland*

[e]*Institute for High Energy Physics, Tbilisi, State University, GUS-380086 Tbilisi, Georgia*

[f]*Dept. of Physics and Astronomy, Arizona State University, Tempe, AZ 85287-1504, USA*

[g]*Rudjer Bošković Institute, HR-10000 Zagreb, Croatia*

[h]*Physik Institut der Universität Zürich, CH-8057 Zürich, Switzerland*

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Summary: We intend to propose a new measurement of the $\pi^+ \to e^+\nu(\gamma)$ (π_{e2} decay) branching ratio with a precision of $\sim 0.1\,\%$ at PSI, using the PIBETA detector system. This letter of intent addresses the beam and detector development work required before a full experiment proposal can be put forward. Well controlled theoretical uncertainties for the π_{e2} decay render this process the most accurate experimental test of lepton universality available. At present, accuracy of the π_{e2} decay measurements lags behind the theoretical precision by an order of magnitude. A number of exotic physics scenarios outside the standard model may lead to a violation of lepton universality. While such scenarios may be (highly) speculative, lepton universality, as well as all lepton properties in general, have attained added significance in the light of recent developments in the neutrino sector. A stringent experimental test of e–μ universality, however, will remain relevant regardless of the path that future theoretical and experimental developments may take.

*On leave from Institute for High Energy Physics, Tbilisi, Georgia.

BEAM REQUIREMENTS:

Beam line: πE1

Beam properties:

particle type: π^+

intensity: $\sim 1\,000 - 10\,000$ π^+/s stopped in target

momentum: < 110 MeV/c

Detector: the PIBETA detector system

Special conditions: Setup of the PIBETA DAQ shack inside the area, as during the 1999–2001 and 2004 runs, including the special shielding wall.

Original beam request: Four weeks, possibly split in two periods of two weeks each.

Subsequent beam requests: Several months of beam time in the πE1 area in 2006 and 2007, subject to submission and approval of a full experiment proposal.

SPECIAL SAFETY CONSIDERATIONS: none

Note: The running conditions will be the same as during the 1999–2001 and 2004 PIBETA runs, with a significantly reduced pion beam intensity.

1. Physics motivation

Historically, the ratio of decay rates $\Gamma(\pi \to e\bar{\nu}(\gamma))/\Gamma(\pi \to \mu\bar{\nu}(\gamma))$ provided one of the key confirmations of the $V-A$ nature of the electroweak interaction.† It is therefore not surprising that practically all modern textbooks on subatomic physics continue to treat the $\pi \to \ell\bar{\nu}_\ell$ decay in detail at the tree level. Furthermore, higher-order contributions to the process are so well controlled that the ratio can be calculated with the highest accuracy of any allowed meson decay. The two most recent standard model (SM) calculations are by Marciano and Sirlin [1] and Decker and Finkemeier [2]. They give, respectively,

$$R^{\rm SM}_{e/\mu} = \left.\frac{\Gamma(\pi \to e\bar{\nu}(\gamma))}{\Gamma(\pi \to \mu\bar{\nu}(\gamma))}\right|_{\rm calc} = \begin{cases} (1.2352 \pm 0.0005) \times 10^{-4}, & \text{Ref. [1], and} \\ (1.2356 \pm 0.0001) \times 10^{-4}, & \text{Ref. [2].} \end{cases}$$

These authors have demonstrated that the π_{e2} branching ratio is theoretically understood at the level of a few parts in 10^4, i.e., $(\Delta R/R)^{\rm SM}_{e/\mu} \leq 4 \times 10^{-4}$.

On the other hand, experimental results lag in precision behind the SM calculations by about an order of magnitude. The current world average, unchanged for a decade, gives the ratio [3]

$$R^{\rm exp}_{e/\mu} = \left.\frac{\Gamma(\pi \to e\bar{\nu}(\gamma))}{\Gamma(\pi \to \mu\bar{\nu}(\gamma))}\right|_{\rm exp} \equiv B(\pi \to e\bar{\nu}(\gamma))_{\rm exp} = (1.230 \pm 0.004) \times 10^{-4}\,,$$

i.e., $(\Delta R/R)^{\rm exp} \simeq 33 \times 10^{-4}$, or about an order of magnitude less accurate than the standard model calculation. The above value of $R^{\rm exp}$ is dominated by two measurements, one made at TRIUMF [4],

$$R^{\rm exp}_{e/\mu} = [1.2265 \pm 0.0034({\rm stat}) \pm 0.0044({\rm syst})] \times 10^{-4}\,,$$

and the other at PSI [5],

$$R^{\rm exp}_{e/\mu} = [1.2346 \pm 0.0035({\rm stat}) \pm 0.0036({\rm syst})] \times 10^{-4}\,.$$

The π_{e2} branching ratio world average presently provides the best test of μ–e universality.

Broader implications of μ–e universality and of the above value for $R^{\rm exp}_{e/\mu}$ were discussed in detail in Ref. [6] and will not be reproduced here. It suffices to say that experimental tests of lepton universality provide a useful crosscheck of SM predictions, as well as potentially useful independent limits on masses and couplings of certain particles outside of the SM.

Rapid developments in the neutrino sector in recent years have renewed the interest in lepton universality. Comprehensive reviews of the subject were made by Pich [7] and Loinaz et al. [8]. In all such analyses the μ–e universality limit from the branching ratio of $\pi_{e2(\gamma)}$ decay emerges as the most stringent limit available. This is well illustrated in Fig. 1 which shows a set of four summary plots of the experimental limits on lepton universality from Loinaz et al. [8]. The authors have parametrized possible flavor non-universal suppressions of the SM lepton coupling constants g_ℓ in $W\ell\nu_\ell$ coupling ($\ell = e, \mu, \tau$) as follows:

$$g_\ell \quad \longrightarrow \quad g_\ell\left(1 - \frac{\epsilon_\ell}{2}\right)\,.$$

†The "(γ)" appearing in the decay designations implies that the radiative decays $\pi \to \ell\bar{\nu}\gamma$ are not resolved or subtracted from the $\pi \to \ell\bar{\nu}$ yield.

The linear combinations of ϵ_ℓ's constrained by W, τ, π, K decays are:

$$\frac{g_\mu}{g_e} = 1 + \frac{\epsilon_e - \epsilon_\mu}{2}, \qquad \frac{g_\tau}{g_\mu} = 1 + \frac{\epsilon_\mu - \epsilon_\tau}{2}, \qquad \text{and} \qquad \frac{g_\tau}{g_e} = 1 + \frac{\epsilon_e - \epsilon_\tau}{2}.$$

Two of the three combinations are independent. Experimental constraints can be evaluated on $\Delta_{e\mu} \equiv \epsilon_e - \epsilon_\mu$, $\Delta_{\mu\tau} \equiv \epsilon_\mu - \epsilon_\tau$, and $\Delta_{e\tau} \equiv \epsilon_e - \epsilon_\tau$; Loinaz et al. have chosen the latter two. The corresponding plots are shown in Fig. 1. Improving the π decay limit on g_μ/g_e would have the effect of reducing the allowed region to a narrower strip in the $\Delta_{\mu\tau}$–$\Delta_{e\tau}$ plane.

It is interesting to examine the absolute size of the experimental limits on lepton universality. We start with the ratio of the $\pi_{\ell 2}$ decay rates

$$R_{e/\mu} = \frac{\Gamma(\pi \to e\bar{\nu}(\gamma))}{\Gamma(\pi \to \mu\bar{\nu}(\gamma))} = \frac{g_e^2}{g_\mu^2}\frac{m_e^2}{m_\mu^2}\frac{(1 - m_e^2/m_\pi^2)^2}{(1 - m_\mu^2/m_\pi^2)^2}\left(1 + \delta R_{e/\mu}\right) , \tag{1}$$

where $\delta R_{e/\mu}$ denotes the radiative corrections to the processes, amounting to almost four percent. Similarly, the ratio of the relevant τ and π decay rates yields

$$R_{\tau/\pi} = \frac{\Gamma(\tau \to \pi\nu_\tau(\gamma))}{\Gamma(\pi \to \mu\bar{\nu}(\gamma))} = \frac{g_\tau^2}{g_\mu^2}\frac{m_\tau^3}{2m_\mu^2 m_\pi}\frac{(1 - m_\pi^2/m_\tau^2)^2}{(1 - m_\mu^2/m_\pi^2)^2}\left(1 + \delta R_{\tau/\pi}\right) , \tag{2}$$

this time with smaller radiative corrections ($\delta R_{\tau/\pi} \simeq 0.0016$). Using the above equations and the available experimental data, one can evaluate [8]

$$\left(\frac{g_e}{g_\mu}\right)_\pi = 1.0021 \pm 0.0016 \quad \text{and} \quad \left(\frac{g_\tau}{g_\mu}\right)_{\pi\tau} = 1.0030 \pm 0.0034\,.$$

For comparison, W decays yield limits that are almost an order of magnitude less stringent [8]:

$$\left(\frac{g_e}{g_\mu}\right)_W = 0.999 \pm 0.011 \quad \text{and} \quad \left(\frac{g_\tau}{g_e}\right)_W = 1.029 \pm 0.014\,.$$

It bears noting that a flavor non-universal coupling suppression of the order of a few times 10^{-3} would suffice to account for the NuTeV anomaly [9], provided, of course, that the latter is real [8]. In time, the present NuTeV controversy may come to be resolved otherwise; however, an accurate determination of $R_{e/\mu}$ in pion decay will remain valuable regardless of the future developments in theory and experiment.

2. Experimental method

The measurement discussed in this letter of intent is a continuation of a program of precise measurements of 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 (π_β) decay, $\pi^+ \to \pi^0 e^+\nu$, with the goal to achieve $\sim 0.5\,\%$ accuracy in the π_β branching ratio. We used $\pi^+ \to e^+\nu$ decay events for normalization. The first result of this work, recently published in Ref. [10], has improved the accuracy of the pion beta decay sixfold over the previous most accurate measurement. The π_β decay analysis continues, and an improved final result will be forthcoming. We have also reported a fourfold improved result on the $\pi^+ \to e^+\nu\gamma$ radiative pion decay branching

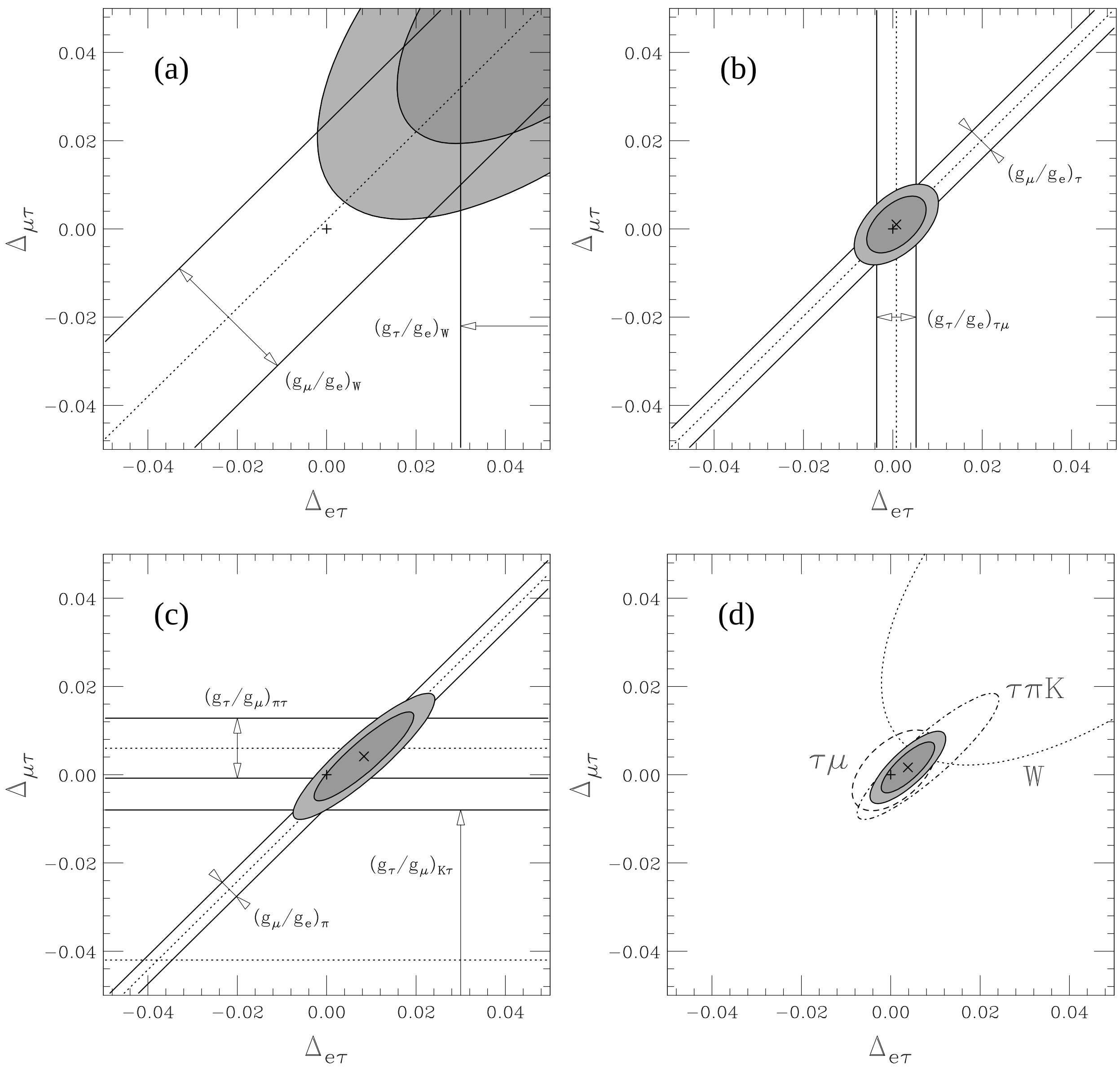


Figure 1: Experimental constraints on possible violations of lepton universality plotted in the $\Delta_{\mu\tau}$ vs. $\Delta_{e\tau}$ (from Loinaz et al., Ref. [8]). Limits in panel (a) are derived from W decay, from τ decay in panel (b), from π and K decay in panel (c). Panel (d) depicts the combined limits. Improving the π decay limits on g_μ/g_e would have the effect of reducing the allowed region to a narrower strip in panels (c) and (d).

ratio, and F_A, the pion axial vector form factor [11]. The latter work has revealed a significant anomaly in the data corresponding to the high-E_γ/low-E_{e^+} kinematic region, which led to a dedicated run in 2004, PSI experiment R-04-01. The 2004 run data are being analyzed as of this writing.

The experimental method considered for the proposed π_{e2} measurements builds strongly on that used in the π_β runs, with important modifications. Details of the PIBETA detector architecture and the π_β measurement technique are given in Refs. [12, 10, 11]. In this letter of intent we reproduce only the most relevant points. Figures 2–4 schematically depict the components and the geometry of the PIBETA detector system.

More to the point, Figure 5 shows the π_{e2} signal definition in the 1999–2001 PIBETA run. The time signature of the $\pi \to e\nu$ events was critical in separating them from the background dominated by muon decays. This method is adequate for counting π_{e2} relative to π_β events with approximately 0.3 % accuracy due to many shared systematic uncertainties. In particular, the undetected low energy "tail" of the π_{e2} calorimeter response was largely correlated with the similar "tail" for the π_β photon showers. The low-energy events in both channels were primarily caused by shower leakage in the back of the CsI calorimeter.

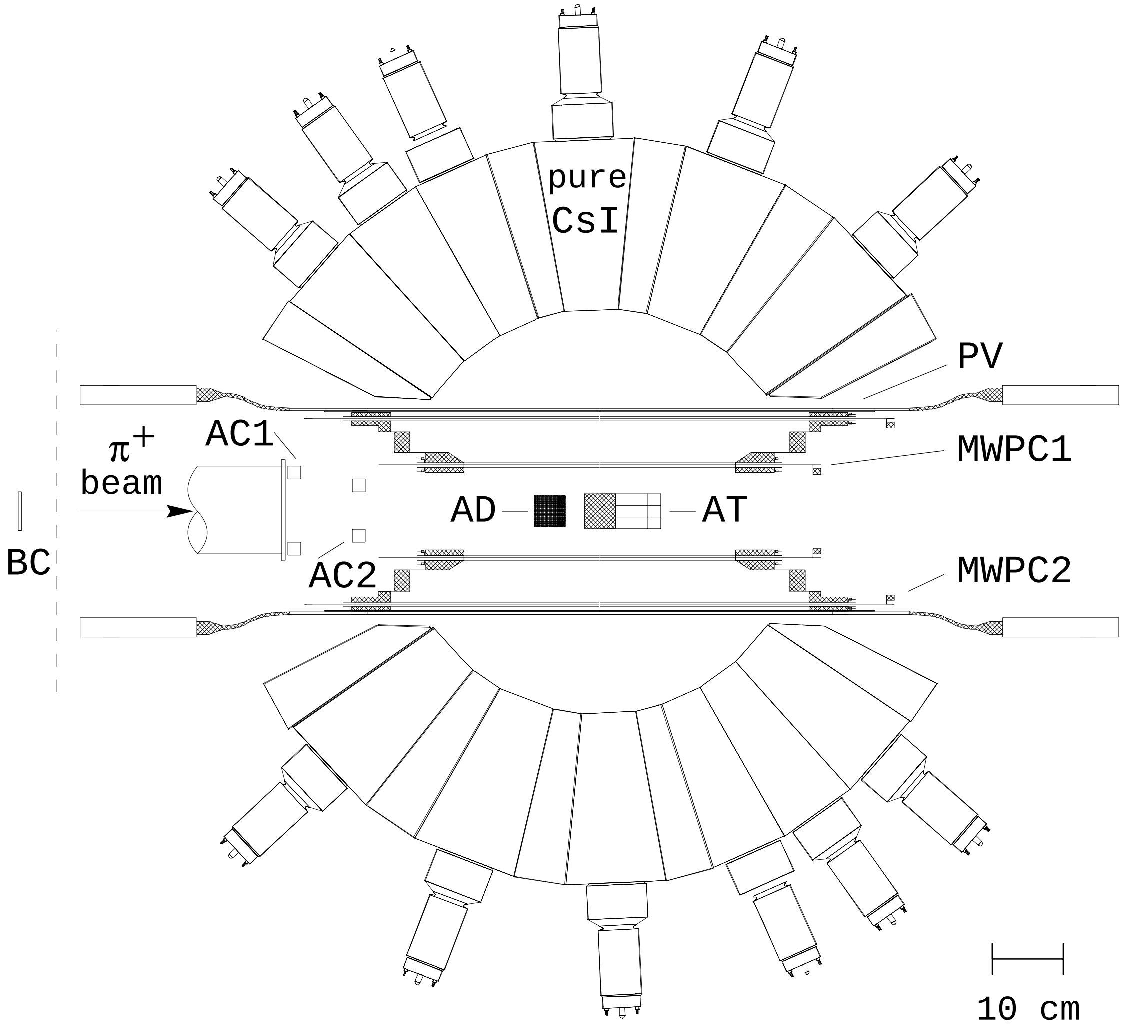
For an absolute measurement of the π_{e2} decay branching ratio we need to implement two improvements over the previous method:

(i) A reliable way to identify and count the beam pions stopped in the target, and the portion of their lifetime for which the experiment is ready to accept events, and

(ii) A sufficiently accurate measurement of the entire energy dependence of the calorimeter response to the decay positrons.

The only reliable way of accomplishing both objectives is by making use of fast digitization of the target, degrader and forward beam counter pulses, in addition to the information supplied by the CsI shower calorimeter. In 2000 we implemented and subsequently used a pulse digitizing system on all applicable PIBETA detector systems. The domino sampling chip (DSC) with its supporting electronics was a prototype system developed at PSI [13]. While this system provided valuable data in the 1999–2001 and 2004 runs, it has been clear from the start that it would need to be significantly improved in several aspects in order to meet the more demanding π_{e2} application. Furthermore, the DSC system proved unreliable in the long run. Thus, in the 2004 run we had to limit its application to the beam counters only due to the failure of a number of boards.

Figure 6 presents digitized target signal lineshapes for four typical events, two each of the $\pi \to \mu \to e$ and $\pi \to e$ variety. In this 2004 lower-rate run ($\sim 10^5\,\pi$stops/s) we used a one-piece target in place of the default nine-piece target designed for the high-rate π_β running. While the DSC performed its task well for the beam counters in 2004, providing good efficiency as well as timing and energy resolution, it was inadequate in several ways: (a) readout dead time limited the event rate to about 100/s or less, (b) its implementation after a considerable length of delay cable compromised the timing and double pulse resolution, and (c) the reliability of the prototype system is clearly unacceptable for a new lengthy and precise measurement.



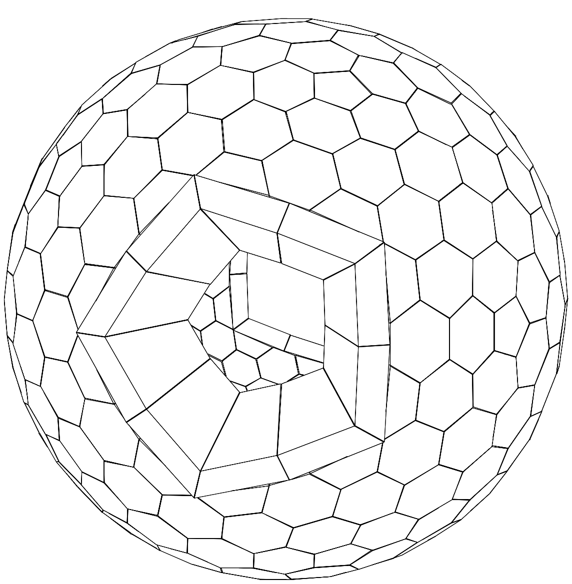


Figure 2: (above) Schematic cross section of the PIBETA apparatus showing the main components: beam entry, active degrader and target, MWPC's and support, plastic veto detectors and PMT's, pure CsI calorimeter and PMT's.

Figure 3: (left) A view showing the geometry of the pure CsI shower calorimeter. The sphere is made up of 240 elements, truncated hexagonal, pentagonal, and trapezoidal pyramids; it covers about 80 % of 4π in solid angle.

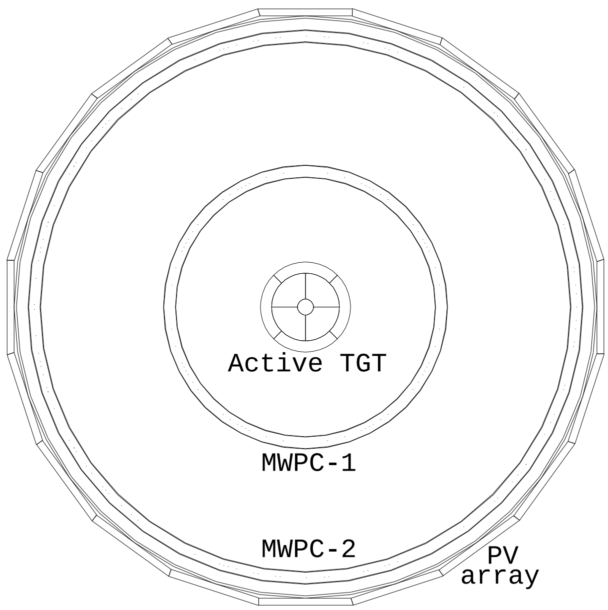


Figure 4: Axial view of the central detector region showing the nine-element target detector, the two thin concentric MWPC's, and the twenty-element thin plastic scintillator barrel veto detector. The nine-element target will be replaced by a single-piece detector for the proposed $\pi \to e\nu$ runs. (Beam is perpendicular to the page.)

3. Detector upgrade

Several improvements to the present PIBETA detector will be required. Despite the largely reduced stop rate, the number of $\pi \to e\nu$ events recorded will be limited by the readout dead time. For this reason we are studying various means of increasing the data acquisition event rate, as well as modifications of the trigger logic.

As can be seen from the waveforms shown in Fig. 6, the digitized target signals have rise and fall times of ~ 5 ns and ~ 15 ns, respectively. These values result in a double pulse resolution of 5–8 ns, depending on the relative amplitudes of the signals, i.e., non-negligible on the scale of the pion life time. It is our intention to increase the bandwidth of the target readout by an order of magnitude by the following means:

(i) *Faster scintillating material*
Table 1 lists the characteristics of some typical examples of plastic scintillating materials produced by the Bicron Corp. With a decay time of 0.7 ns BC-422Q is 2–3 times faster than most other materials at the price of a factor five loss in light yield.

(ii) *Faster light collection*
A compact detector geometry without light guides and with non-reflective wrapping at one side will keep the light paths below a couple of centimeters.

(iii) *Faster light sensor*
Ultra-fast microchannel plate PMT's (photomultipliers using microchannel plates in stead of discrete dynodes) have response times around 0.1 ns compared to 1–2 ns for a classical PMT.

(iv) *Faster waveform digitizer*
In the proposed development run we intend to use a waveform digitizer with an analog bandwidth of 1 GHz and sampling rates of 5–10 GHz.

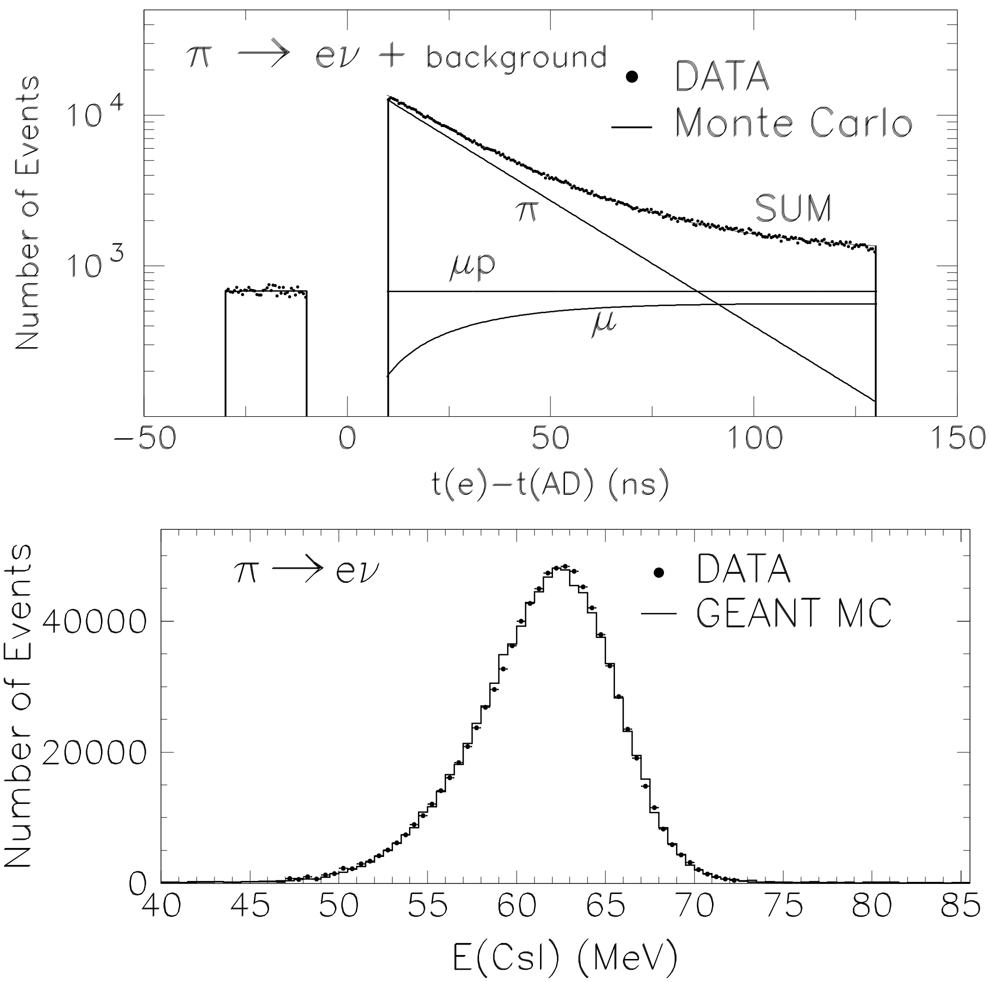


Figure 5: Top panel: A typical histogram (dots) of differences between the positron track time, $t(e)$, and beam pion stop time, $t(\text{AD})$, for one-arm trigger events, compared with a sum of the Monte Carlo-simulated responses for π_{e2} decay (π), muon decay (μ), and muon pile-up events (μp). The π_{e2} pile-up background, being much lower, is off scale in the plot. Prompt events are suppressed. Bottom panel: CsI calorimeter energy spectrum for the π_{e2} decay events, after background subtraction.

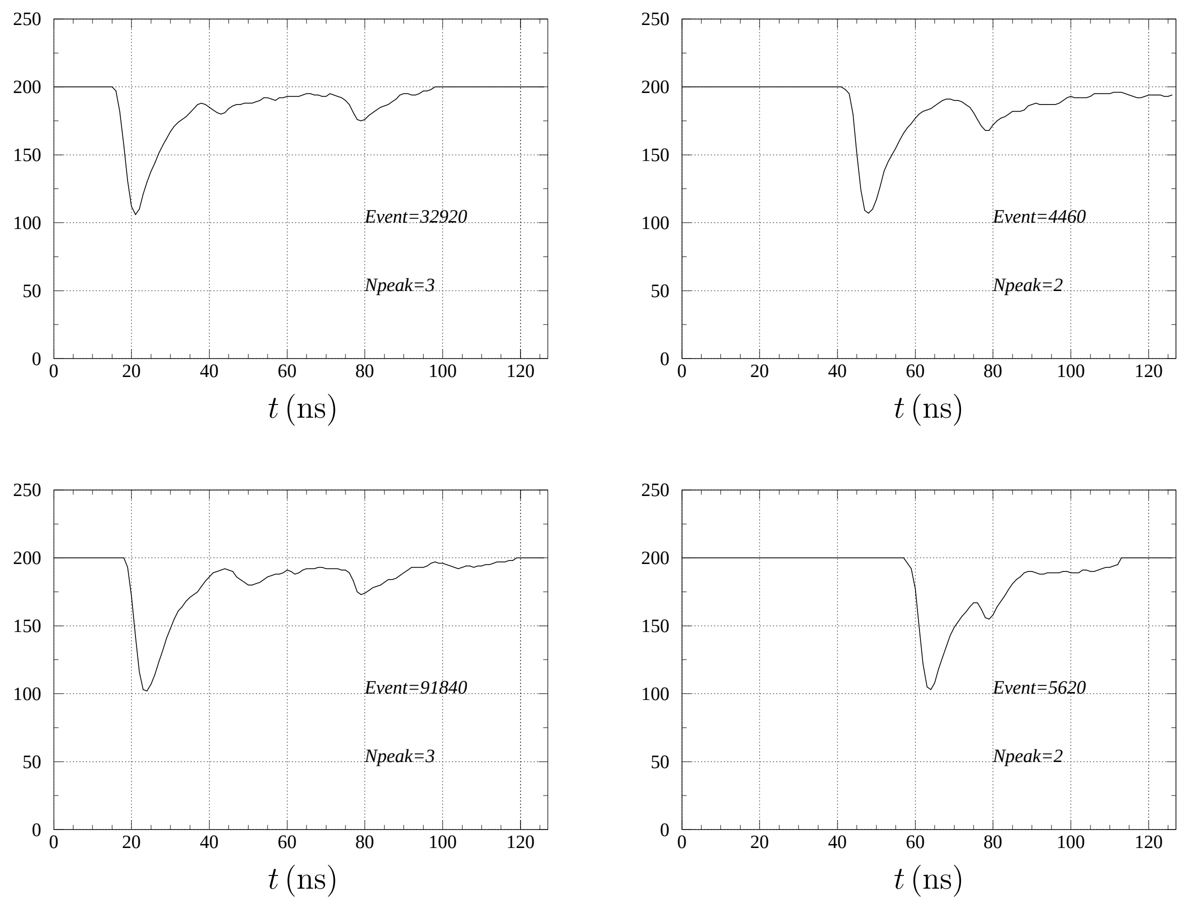


Figure 6: Plots of digitized signal amplitude (arbitrary units) against time (ns) for four typical events in the target detector. Lineshapes in the left-hand panels are for $\pi \to \mu \to e$ events ("Npeak = 3"), while the right-hand panels display $\pi \to e$ events ("Npeak = 2"). All were obtained during a 2004 run with a single-piece target. The event time, determined by the CsI calorimeter, falls at $t \approx 80$ ns. Note that the zero-suppression electronics removes all signal bins below a preset threshold, e.g., all bins before the large leading pulse corresponding to the energy deposited in the target by the stopping pion. The events shown have passed all cuts required for good "Michel" and π_{e2} events, respectively, imposed on the tracking, time and energy signals in the wire chambers, thin veto counters and the CsI calorimeter.

Table 1: Comparison of Bicron plastic scintillating material properties.

Type	Light yield rel. to anthracene	Peak wavelength (nm)	decay time (ns)	Attenuation length (m)
BC-404	0.68	408	1.8	1.6
BC-408	0.64	425	2.1	3.8
BC-416	0.38	434	4.0	4.0
BC-418	0.67	391	1.4	1.0
BC-420	0.64	391	1.5	1.1
BC-422	0.55	370	1.6	0.08
BC-422Q	0.11	370	0.7	< 0.8
BC-428	0.36	480	12.5	1.5

Another improvement in the signature of the events would be brought about by precise tracking of the beam particles. Given the relatively low beam intensity low-mass drift chambers could be used in the beam which would help to identify pile-up events and events induced by muons in the beam.

4. Resources and beam request

We request four weeks of beam and detector development time in the πE1 beam area, with the option of using it in two separate two-week periods, subject to reconciling potential scheduling conflicts.

There are no major costs associated with the requested run. The main expenditures would be minor material costs and incidental expenses, such as gas for wire chambers, estimated at no more than 10 kCHF.

The current collaboration consists of the collaborators who were active participants in the 2004 run of experiment R-04-01. We are open to new collaborators from outside institutions, as well as PSI. Due to funding realities, it may be necessary to provide modest support for the Swierk and Zagreb collaborators while at PSI. Thanks to improved funding at JINR, the Dubna collaborators would not require similar support.

In the longer term there will likely be non-negligible equipment upgrade costs, to be determined more accurately subsequent to the presently requested development run(s). At this time we plan to seek to fund the bulk of these costs from sources outside PSI.

Looking beyond the proposed test run, we are aware of a major manpower requirement on the collaboration. During the 2004 run four CsI detectors stopped operating over the course of the first two months. Unfortunately, the four failed detectors were not accessible for repair during the run. Accessing them will require a major effort at disassembly and reassembly; equipment repair costs (PMT dividers, replacement PMTs) would be borne by the collaboration, leaving nil or minimal cost demands on PSI. While not required for the 2005 development beam time, this inspection and repair will be necessary before the full π_{e2} run, and would only be justified after a full experiment proposal is approved.

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