PSI Experiment R-05-01 (PEN)

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

Progress Report and Beam Request

L. P. Alonzi[a], V. A. Baranov[b], W. Bertl[c], M. Bychkov[a], Yu.M. Bystritsky[b], E. Frlež[a], V.A. Kalinnikov[b], N.V. Khomutov[b], A.S. Korenchenko[b], S.M. Korenchenko[b], M. Korolija[d], T. Kozlowski[e], N.P. Kravchuk[b], N.A. Kuchinsky[b], M.C. Lehman[a], D. Mekterović[d], D. Mzhavia[b,f], A. Palladino[a,c], D. Počanić[a*], P. Robmann[g], A.M. Rozhdestvensky[b], S.N Shkarovskiy[b], U. Straumann[g], I. Supek[d], P. Truöl[g], Z. Tsamalaidze[f], A. van der Schaaf[g*], E.P. Velicheva[b], and V.P. Volnykh[b]

[a]*Department of Physics, University of Virginia, Charlottesville, VA 22904-4714, USA*
[b]*Joint Institute for Nuclear Research, RU-141980 Dubna, Russia*
[c]*Paul Scherrer Institut, CH-5232 Villigen PSI, Switzerland*
[d]*Institut "Rudjer Bošković," HR-10000 Zagreb, Croatia*
[e]*Instytut Problemów Jądrowych im. Andrzeja Sołtana, PL-05-400 Świerk, Poland*
[f]*IHEP, Tbilisi, State University, GUS-380086 Tbilisi, Georgia*
[g]*Physik Institut der Universität Zürich, CH-8057 Zürich, Switzerland*

(The PEN Collaboration)

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1. Summary of activities in 2009

The past year's PEN activities followed the goals and priorities stated in our 2009 beam request:

1. Continue work on the analysis of the PEN data set acquired during the 2008 beam period. This activity alone consumed about half of the manpower effort in the reporting period.
2. Implement a compact rectangular time projection chamber (mini-TPC) in the beamline between the degrader and target detectors in order to improve the position resolution of the beam particle tracking with respect to the wedged degraders used in 2008. The mini-TPC was documented in our Jan. 2009 progress report [2]; its placement in the 2009 apparatus is shown schematically in Fig. 1.
3. Comprehensively overhaul the electronics and DAQ by implementing these changes:
    (a) Replace the 0.5 ns least significant bit LRS 1877 FastBus multihit TDC's with newly acquired 100 ps LSB CAEN V1190A VME multihit units in order to realize the full potential of the plastic hodoscope (PH) detector intrinsic timing resolution. PH timing determines

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[*] Co-Spokesmen

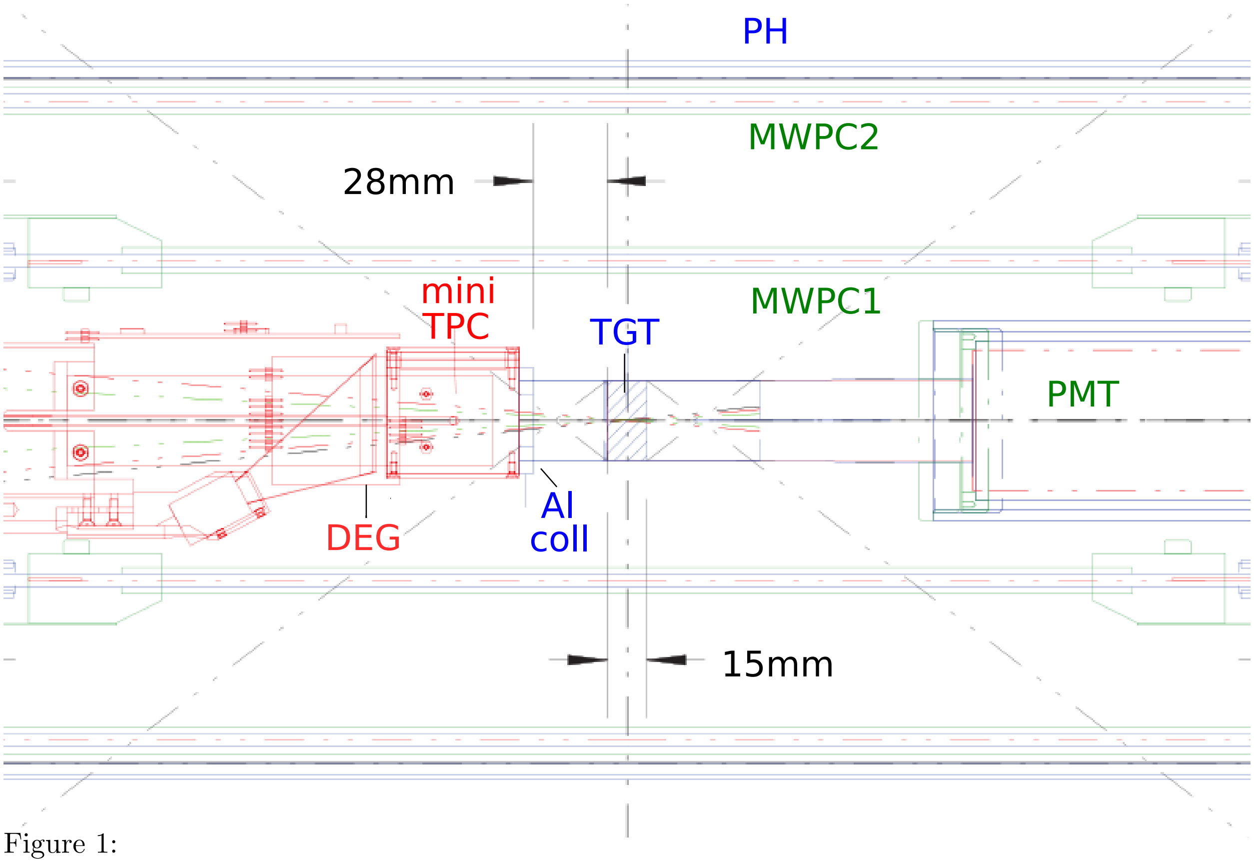

Figure 1:
Schematic drawing of the central-region beam detectors deployed in the 2009 PEN run: the thin ($t = 5$ mm) active degrader, the new mini-TPC with a passive aluminum collimator, and the stopping target counter. All of them are surrounded by the cylindrical multiwire proportional chambers MWPC-1,2 and the 20-bar thin plastic hodoscope detector array.

the resolution of the measured decay time (the time elapsed between the pion stop and positron emission). Furthermore, it directly affects the reliability of the target waveform fits of the positron track emerging from both pion and muon decays because the PH positron signal is used to predict the time of the target positron signal. The latter can be quite small for events in which the pion stops near the surface of the target counter.

(b) Implement newly acquired CAEN V1720 waveform digitizers for the readout of the new mini-TPC in order to extract the maximum of information from this counter.

(c) Incorporate the additional VME crate into the DAQ scheme along with a "user datagram protocol" (UDP) software-based system for providing proper event synchronization of the frontends. The hardware-based event synchronization of the FastBus frontend used in 2008 was retained.

(d) Simplify and redesign the fast trigger electronics so as to (i) provide triggers based on the full sum of energy deposited in all CsI calorimeter modules in place of the existing 9-module cluster sums (required and optimized for much higher rate running conditions), and (ii) eliminate the LB-102 fast logic units from the trigger in the wake of persistent problems with their reliability experienced during the 2008 beam period. A part of the trigger redesign was to implement a very low threshold CsI energy trigger for the purpose of the $\pi \to e\nu$ energy response "tail" measurement (in addition to the plastic hodoscope trigger). The combination of a reduced time window width to about four pion lifetimes, and a veto of the muon pulse in the $\pi \to \mu \to e$ chain, enabled us to reduce the prescaling ratio for this trigger to 1/10, and thus to accumulate π_{e2} "tail" events at the required rate without unduly increasing the DAQ dead time.

5. Study and optimize additional beam shielding in the new constellation of the central beam detectors.
6. Record over 5×10^6 clean $\pi \to e\nu$ events with well controlled systematics.

All of these goals were met. The period between 16 Aug. and 23 Dec. was allotted to the PEN experiment in 2009. The run started with a catastrophic accident: on 16 August 2009, during the final movement of the calorimeter assembly to its operating position with the active target, mini-TPC and degrader in close proximity, a misaligned beam pipe flange damaged MWPC-1, the inner proportional chamber, beyond repair. The recovery from this loss took almost one month, until 15 September, by which time the spare MWPC-1 had been overhauled, tested, installed and conditioned for use in beam. This down time was used as much as was possible to implement changes in the DAQ system and the trigger electronics.

Nevertheless, another four weeks were required to fully implement and debug the new electronics, trigger modules, DAQ system, and to stabilize and gain-match the calorimeter. Providing reliable event synchronization among four branches of the fast DAQ system posed a particular challenge. Upgrades to the DAQ system also included (a) switching all online PCs to Gigabit Ethernet, and (b) successfully programming the FASTBUS controller to use 64-bit block transfer mode. These improvements allowed us to almost double the DAQ speed for the 2009 data taking.

Quality data taking commenced on 16 October 2009. The data collection lasted until 22 December, one day before the scheduled end of beam time (a power failure in the Experimental Hall brought about a premature end to the 2009 PSI proton beam time).

During the 66 calendar days from 16 October to 22 December, the PEN apparatus was ready and functioning essentially at all times when the proton beam was available. In that period, the apparatus observed about 1.33×10^{11} tagged pion stops in the target detector, and recorded a total of $10 - 11 \times 10^6$ $\pi \to e\nu$ decays before cuts, thus exceeding our original goal by a factor of two.

During a break in proton beam delivery we introduced a strong AmBe source with the characteristic 4.4 MeV photon line from the $^{9}\mathrm{Be}(\alpha, \mathrm{n})^{12}\mathrm{C}^*$ reaction (along with the associated single- and double photon escape peaks). We used these data to check the threshold behavior and check the absolute energy calibration of the CsI calorimeter near threshold. Results of that measurement are summarized in Sec. 2.

2. Select results of the data analysis

We have reported extensively on the initial results of the PEN data analysis in previous progress reports, particularly in the January 2009 report [2]. This document therefore includes only those results not previously reported.

As emphasized in the PEN experiment proposal [1], and in our previous progress reports, one of the key benchmarks of the analysis involves efficient suppression of the Michel positron events so that the the low-end "tail" of the energy response function of the calorimeter may be accurately determined. Among other factors, this analysis critically depends on our ability to distinguish between 2-peak π_{2e} and 3-peak $\pi \to \mu \to e$ events in the target, primarily based on the target signal waveform fits. The ensuing waveform fit χ^2 distributions are shown in Fig. 2. There is very good separation of the classes of events best described by a 2-peak fit from those conforming to a 3-peak fit. As expected, the 2-peak events are strongly present for positron energies above 60 MeV, while being virtually absent below 60 MeV. Similarly, excellent separation in the variable $\Delta\chi = \chi_{3\ \mathrm{peak}} - \chi_{2\ \mathrm{peak}}$ is observed as a function of positron energy and time of decay following pion stop time.

Figure 3 shows a preliminary result for the "tail" of the calorimeter energy response function analyzed from the last two weeks of our 2008 beam time. This analysis relies strongly on the above

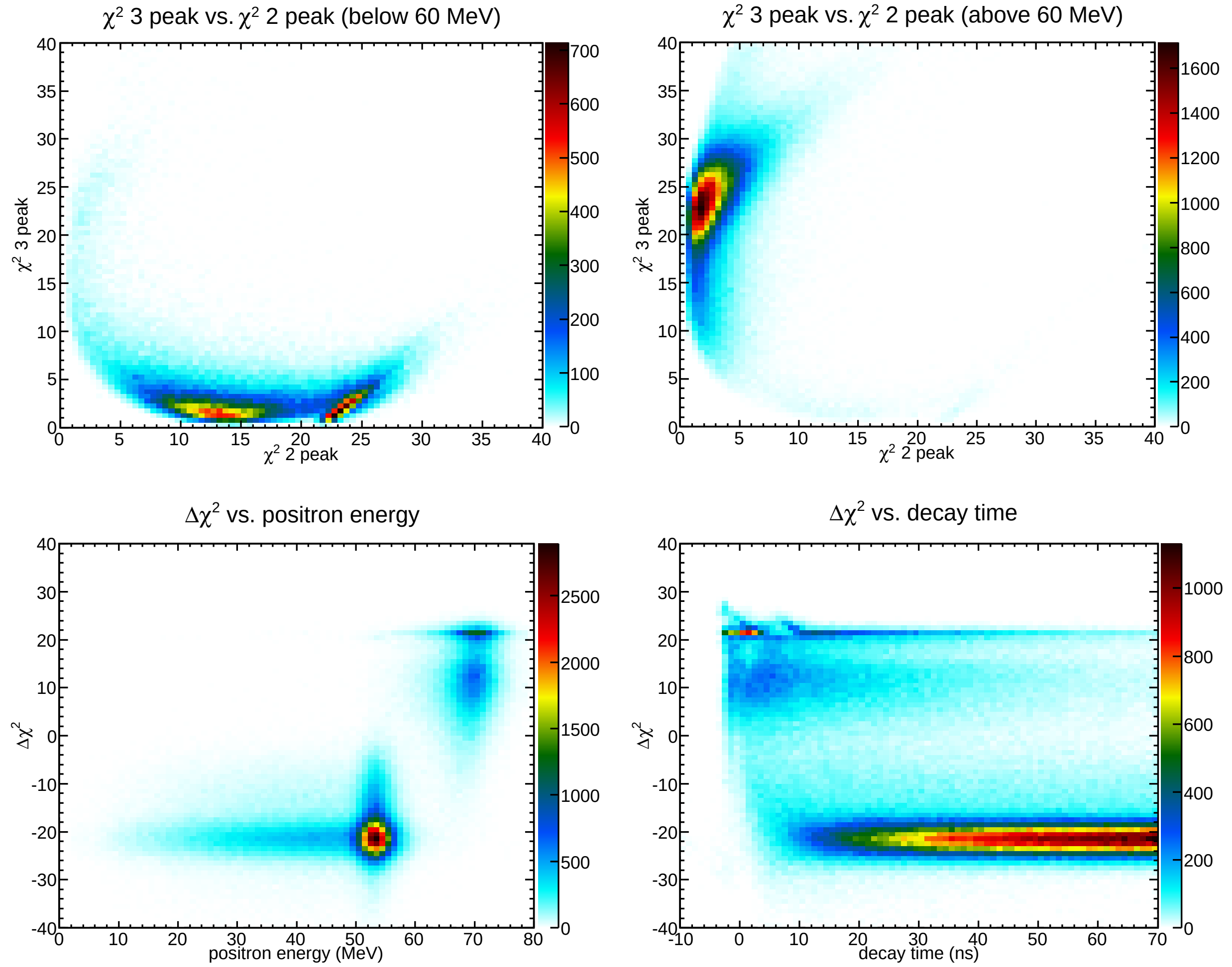

Figure 2:
Top panels: distributions of values of goodness of fit χ^2 for 2 peaks against χ^2 for 3 peaks for events with total positron energy above 60 MeV (left) and below 60 MeV (right). Bottom panels: values of $\Delta\chi^2 = \chi^2_{3\ peak} - \chi^2_{2\ peak}$ plotted as a function of total positron energy and decay time (the time elapsed between the pion stop and positron emission).

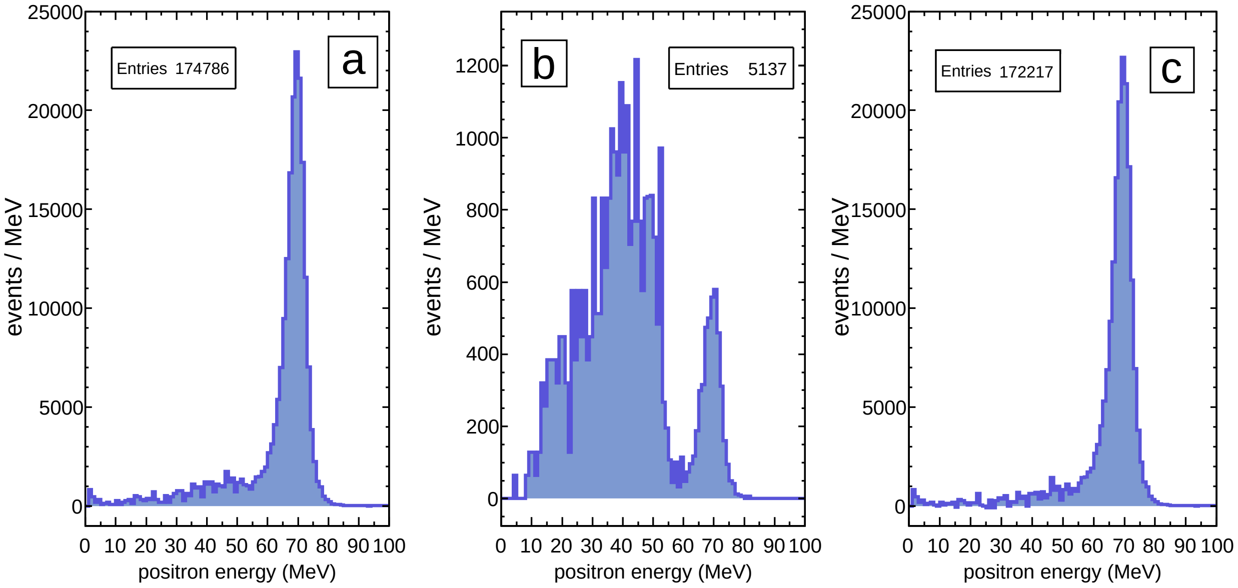

Figure 3:
Energy spectra of the decay positrons: for decay times below 25 ns (histogram ***a****), and for decay times between 100 and 150 ns (histogram* ***b****). Histogram* ***c*** *shows the net positron energy spectrum obtained after subtraction of appropriately scaled histogram* ***b*** *from histogram* ***a****. As expected based on Monte Carlo simulations, the "tail" fraction below 52 MeV constitutes approximately 3 % of the total yield. The small peak near the origin corresponds to residual protons from incompletely suppressed prompt events. This work is in progress.*

target waveform fits, as well as other appropriate physics cuts.

A further indication of the active target intrinsic resolution is given by the energy spectra recorded in parallel in the target ADC channels. Fig. 4 presents a typical 4.1 MeV muon energy spectrum obtained from the target signal waveform analysis (top plot), as well as the relative separation of the target energy peaks with and without the 4.1 MeV muon occurring within the ADC gate (bottom plots); all are from the 2009 beam period.

Time resolution of the beam counters and the plastic hodoscope array is critical for accurate time predictions of the pion stop and decay positron pulses in the target signal waveforms. Accurate predictions of these quantities greatly improve the reliability of the waveform fits, and thus facilitate the maximum likelihood analysis. One of the improvements implemented for the 2009 beam period involved the replacement of relatively low resolution 0.5 ns least significant bit LRS 1877 FastBus multihit TDC's with 100 ps LSB CAEN V1190A VME multihit TDC's. The resulting improvement in plastic hodoscope timing is illustrated in Fig. 5. The rms resolution of $\sim$ 250 ps per bar end reported for prompt proton events translates into $<$ 180 ps resolution for the PH mean time. However, the analogous time resolution for the (smaller) positron pulses, the principal factor in the target decay positron track time prediction, will not be quite as good. These results will receive a small improvement from better offline timing alignment of the 20 hodoscope bars than was available online.

A major new piece of equipment introduced for 2009 was the mini-TPC, placed along the beam

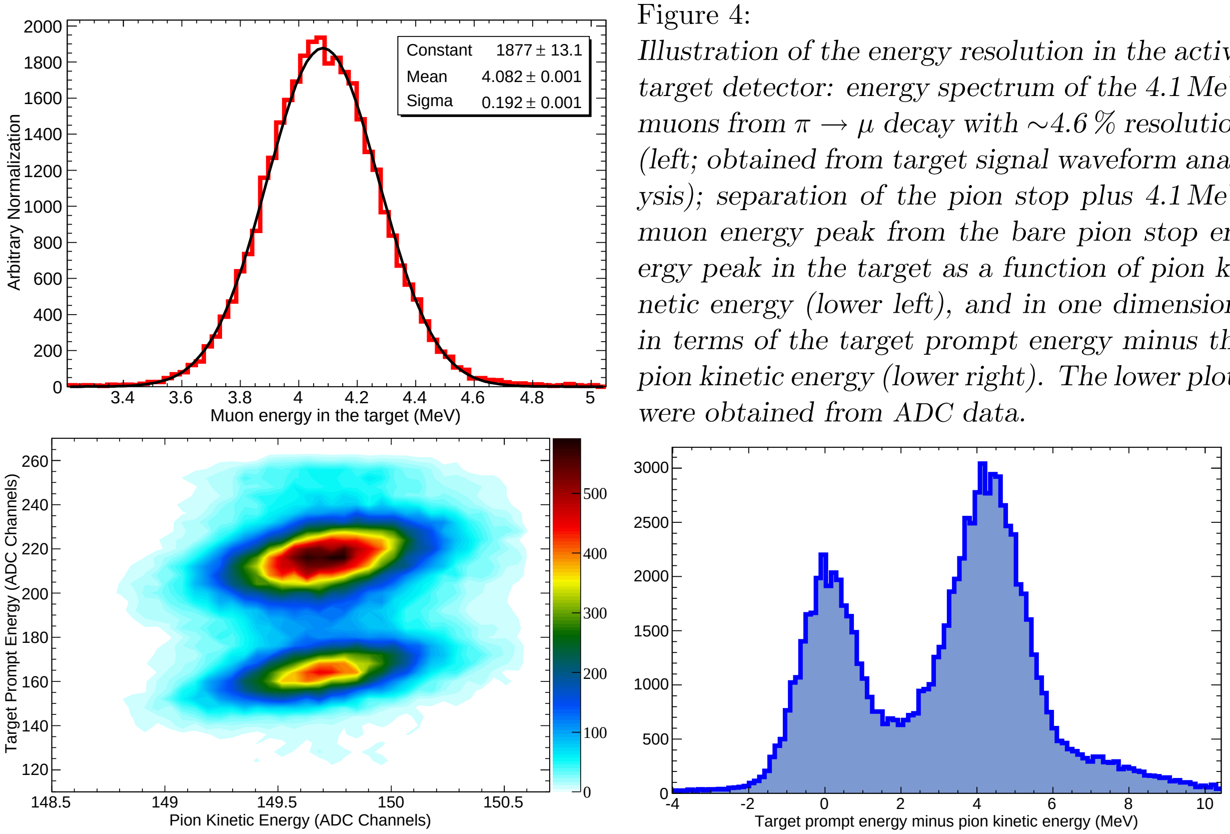

Figure 4:
Illustration of the energy resolution in the active target detector: energy spectrum of the 4.1 MeV muons from $\pi \to \mu$ decay with ~4.6 % resolution (left; obtained from target signal waveform analysis); separation of the pion stop plus 4.1 MeV muon energy peak from the bare pion stop energy peak in the target as a function of pion kinetic energy (lower left), and in one dimension, in terms of the target prompt energy minus the pion kinetic energy (lower right). The lower plots were obtained from ADC data.

axis between the active degrader and target detectors. We briefly illustrate its performance in Figs. 6, 7 and 8. We only used the anode wire readout of the TPC whose waveforms on both ends (beam left and right) were digitized in CAEN V1720 waveform digitizers. Track coordinates were determined based on the charge division between the left and right ends (x), drift time (y), and wire number (z). The detector performed very well, with excellent separation of signal and noise, and it easily handled beam particle pileup at ~26,000 fiducial pion stops/s in the target. The per-wire position resolution obtained by analyzing pairwise differences of coordinates was approximately 0.5 mm in y and ~1 mm in x, a result subject to slight improvement in further analysis. The

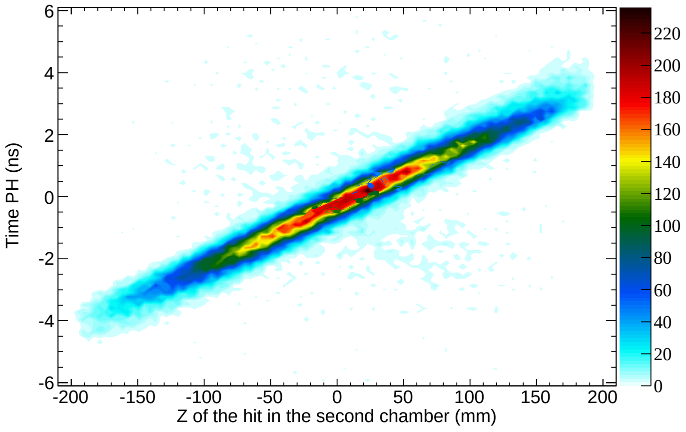

Figure 5:
Illustration of the time resolution of the plastic hodoscope detector array in the 2009 PEN data. Plotted are the time differences between the upstream and downstream detector bar ends, summed over all 20 bars, for prompt events, against the z coordinate of the track in MWPC-2. The corresponding intrinsic rms time resolution is about 0.25 ns (data recorded with the new 100 ps LSB TDC's). For comparison, the resolution obtained in 2008 using the old 0.5 ns LSB TDC's was ~0.35 ns.

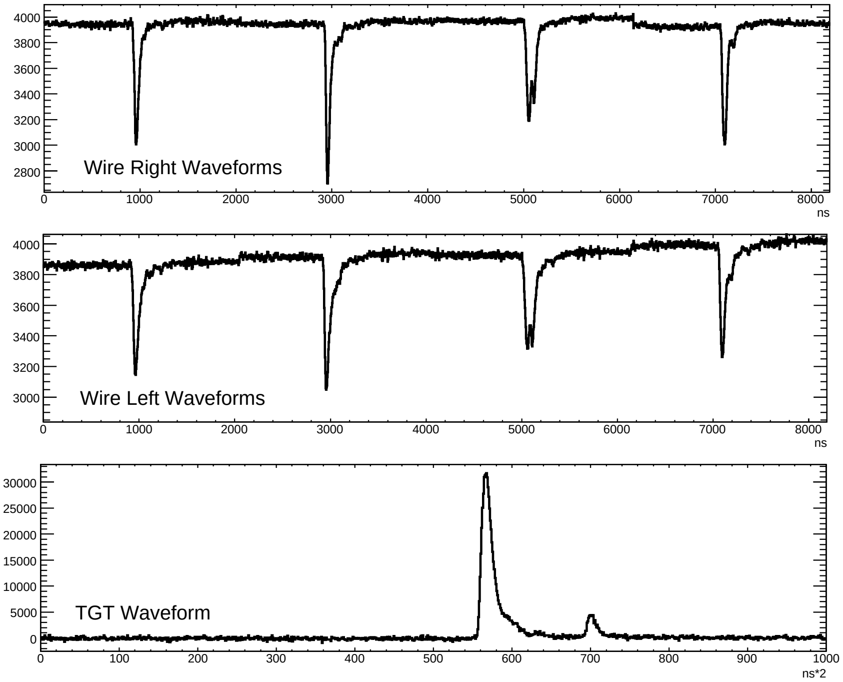

Figure 6:
Mini-TPC and active target signal waveforms for a typical event with a single pion track in the mini-TPC. Top and middle traces are from the mini-TPC wire-right and wire-left readout, respectively. The four TPC wire waveforms are concatenated with each signal spanning 2048 ns. Bottom trace: the corresponding target waveform showing the pion stop and decay positron signals.

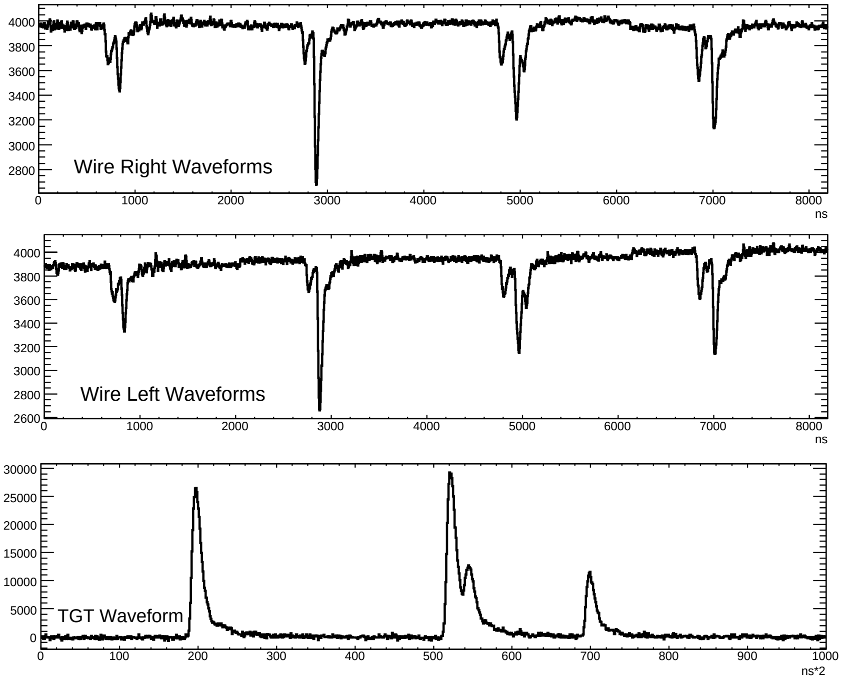

Figure 7:
Same as Fig. 6 but for a typical event with two beam particles in the mini-TPC waveform. The pileup particle preceding the second pion stop by about 150 ns is clearly observable in the target waveform as well.

mini-TPC has met our expectations in all respects.

The low energy performance of the CsI calorimeter was explored during a proton beam maintenance period with an AmBe source emitting about 2×10^5 4.4 MeV photons per second. The results of that measurement are summarized in Fig. 9. The 4.4 MeV photon line is measured with approximately 12 % relative energy resolution. This result is in good agreement with the observed energy resolution of about 4 % at 65 MeV, and it provides additional input in the Monte Carlo description of the calorimeter response function. Another significant result of this measurement

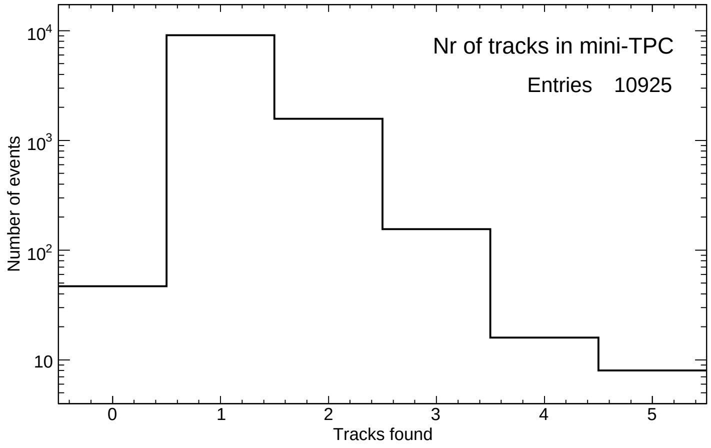

Figure 8:
A representative histogram of multiplicity of tracks reconstructed in the mini-TPC. The $n = 5$ *bin of the histogram was incremented for events with five or more tracks. The track inefficiency is approximately* 5×10^{-3}. *Work in progress.*

is the clear separation of the single-escape 511 keV peak in the near neighbors of the CsI module receiving the bulk of the 4.4 MeV photon's energy, clearly demonstrating our ability to detect sub-MeV events with adequate resolution. In fact, we set the threshold of our low-energy ("tail") CsI calorimeter trigger well below 0.5 MeV, at approximately 0.2 MeV.

Towards the end of the 2009 beam time, we reduced the operating temperature of the CsI from 22°C to 18°C, observing an average increase in CsI scintillation light collection of 7.6 %, in excellent agreement with our earlier observations [3, 4]. Running with lower CsI operating temperature was a success. The change in temperature was not introduced earlier because of the relatively frequent detector accesses early in the beam time, and the desire to keep the data set uniform. Opening the detector to external air requires prior gradual warming of the CsI modules to close to outside ambient temperature in order to prevent condensation of moisture on CsI surfaces.

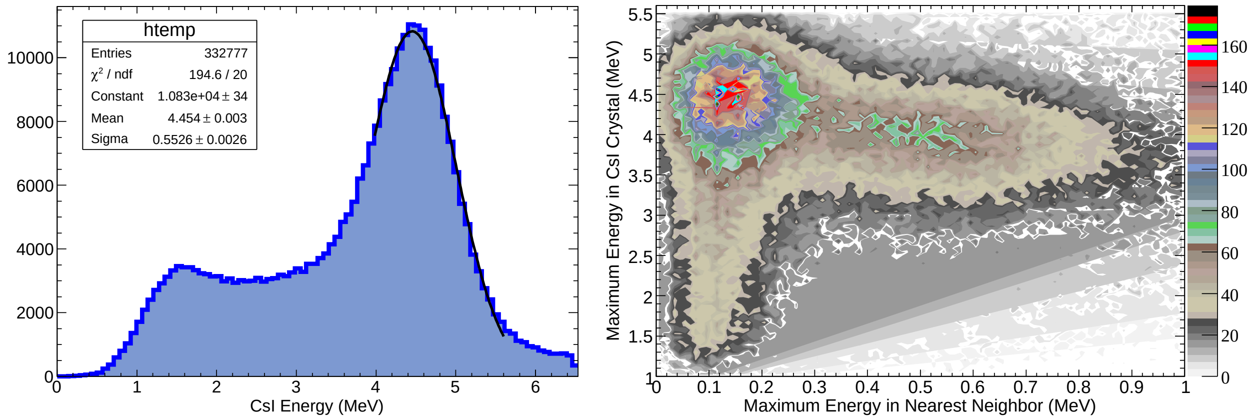

Figure 9:
Illustration of the CsI calorimeter performance with the AmBe source. Left panel: response of the CsI calorimeter to the 4.4 MeV $^{12}\mathrm{C}^*$ *photons summed over all 220 CsI fiducial modules. The relative energy resolution at 4.4 MeV is approximately 12 %. Right panel: Two-dimensional contour plot of the energy in the peak CsI module against the maximum energy recorded in its nearest neighbors, summed for all 220 CsI fiducial modules. There is a clear separation of the full 4.4 MeV peak and the single-escape peak deposting 511 keV in a nearest neighbor.*

Although our modules are sealed by a protective layer of lacquer, this step is a necessary precaution due to the moderately hygroscopic nature of CsI. Additionally, the relatively large thermal inertia of the calorimeter results in temperature equilibrating times of about two days, during which the calorimeter's energy resolution is not optimized. However, since we anticipate few detector access breaks in 2010, an even lower calorimeter operating temperature is planned for 2010 data taking, with the accompanying improvement in energy resolution. The practical limit in how low in temperature we can go is set by the cooling power of the temperature control system, and the external heat load on the detector. The combination of these two factors determine the achievable dew point of the controlled air inside the thermal enclosure. The operating temperature must be sufficiently above the dew point to ensure that the relative humidity inside remains acceptable.

3. Improvements for 2010

For the requested 2010 beam time we plan modest improvements, as follows.

(a) Run at a slightly higher pion momentum and double the present signal rates. The DAQ system implemented in 2009 is capable of handling double the 2009 signal physics rates with a slightly more selective trigger.

(b) Replace the current active degrader detector with a slightly thicker one in order to accommodate the planned increase in the pion beam momentum.

(c) Implement a new lower-mass mini-TPC, also produced by the Dubna collaborators, with significantly thinner walls, enabling us to position the TPC against the target, and resulting in a tighter beam spot.

(d) Further improve the shielding around the beam pipe by implementing custom-shaped lead elements, in order to reduce the beam-related background even further.

(e) Implement a completely new and more robust event synchronization system for the various DAQ frontend computers.

(f) Lower the CsI operating temperature in steady state running, in order to improve the calorimeter energy resolution.

We also note with great pleasure the addition of Martin Lehman, a new graduate student from UVa, to the collaboration.

4. Resources and beam request

We request 18 weeks of beam time in the πE1 beam area, which includes three weeks for setup and calibration, and 15 weeks of data taking.

Under our planned running condition, this amount of beam time would let us acquire some 25×10^6 π_{e2} decay events, which, combined with earlier data, would allow us to comfortably reach our target statistical uncertainty of $\delta B/B \simeq 2\times10^{-4}$. In view of the current placement of the PEN detector in the πE1 area, we request that our beam time be allocated in the first half of the Ring Accelerator 2010 beam delivery period, i.e., from its start at end of April until the end of August.

There are no major costs associated with the requested beam time. The main expenditures are the material costs of operating the detector (wire chamber gas, supplies, consumables), and modest amounts to support certain local expenses at PSI for collaborators from former socialist countries, similar to the 2009 budget.

References

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