7 Testing lepton universality: the $\pi \to e\overline{\nu}$ / $\pi \to \mu\overline{\nu}$ branching ratio

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(PEN Collaboration)

The measured value of the $\pi \to e\overline{\nu}$ / $\pi \to \mu\overline{\nu}$ branching ratio ($1.2312(37) \times 10^{-4}$ [1]), even if 20 years old by now, still gives the best constraint on deviations from the SM assumption of a universal (flavour independent) coupling of W bosons to leptons. Two new experiments [2] are underway which aim at improvements in accuracy by almost one order of magnitude.

Precision measurements of this kind require great care in proper handling of systematic errors. Precise knowledge of the probability density functions (pdf's) of the various observables entering the likelihood analysis has to be based primarily on the measured data with minimal support by simulation in regions where processes can't be isolated sufficiently well. Of particular importance in this respect is the low-energy tail of the $\pi \to e\overline{\nu}$ positron energy pdf.

Detection efficiencies depend slightly on positron energy, mainly since the mean energy deposited in the MWPC tracking detectors rises with energy in combination with the fixed thresholds of the readout electronics.

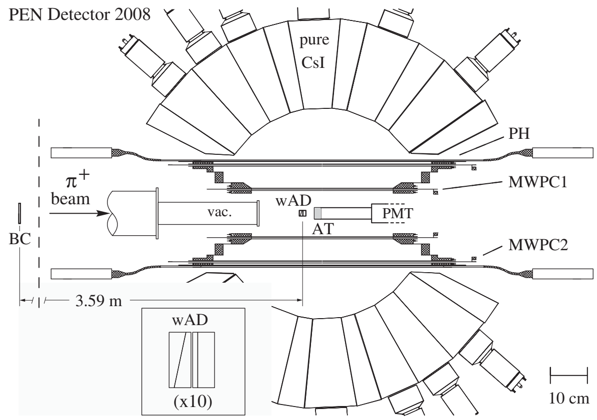

FIG. 7.1 – *PEN as used in the year 2008. The pion beam is focused on beam counter BC and then again 3.59 m further downstream on the active degrader wAD (see inset) which consists of two pairs of wedge-shaped plastic scintillators for a rough position measurement.*
Decay e^+'s emitted from the active target AT are detected in a 240 element 3π Sr CsI calorimeter preceded by two MWPCs and a plastic hodoscope PH consisting of twenty slabs.

Pion beam

PEN took data during the years 2008 – 2010 at the πE1 beam line at PSI and has been working on the analysis ever since [3]. Charged particles produced in the E target by 590 MeV protons are transported to the experimental area by a series of quadrupole and dipole magnets. The beam line can be thought of as two magnetic spectrometers in a row followed by a focusing magnet triplet. The first spectrometer directs particles in the selected momentum band to a 2 mm thick carbon degrader. Heavier particles lose more momentum than lighter particles so in the focal plane of the second spectrometer the beam is split up depending on the particle mass and with the help of a collimator pions are separated from muons and positrons.

Figure 7.1 shows a cross-section through the PEN setup as used in 2008. For the chosen beam momentum around 75 MeV/c the pions stop 8 ± 1 mm deep inside the active target AT. All beam counters are read out both with high-performance (2 GHz bandwidth and sampling frequency) waveform digitizers and with long-range multi-hit TDC's which are useful to find extra beam signals in the preceding few μs which give an enhanced probability for accidental coincidences.

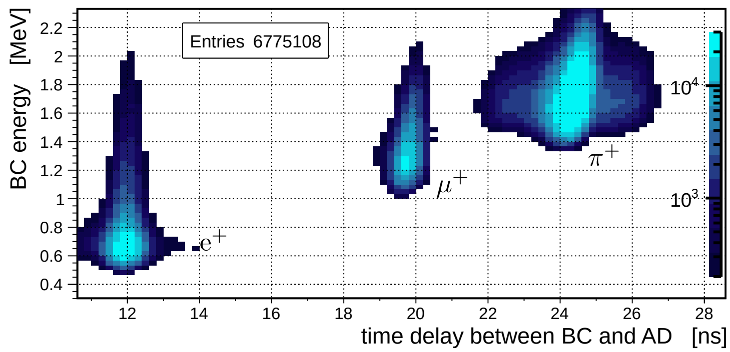

FIG. 7.2 – *Distribution of energy loss in the first beam counter (BC) versus time delay between BC and the degrader/tracker (wAD) situated 3.59 m downstream.*

With the help of BC and wAD remaining beam contaminations can be removed (see Fig. 7.2) [9].

Pions are not only well separated from remaining positrons and muons but the pion velocity (and thus its energy) at the wAD entrance can be determined for each individual event. The trigger for data readout required a delay of 22 – 26 ns characteristic for pions. In order to show all beam contaminations events were selected with at least one additional beam particle. The observed tails in the pion distribution (cut by the trigger) result from pion decay shortly before wAD (see discussion below). Note that (i) larger π or μ energy loss gives slower particles, (ii) pions move with half the speed of light and (iii) about half of the π's reaching BC decay before reaching wAD.

Pion reactions

In the past year the emphasis has shifted from merely isolating the two signal processes to understanding all recorded events. About one third of the data are explained by pion reactions in the target which result mostly in the prompt emission of protons and deuterons with relatively high energies. These events are easily recognized (see Fig. 7.3) and very few enter the final samples.

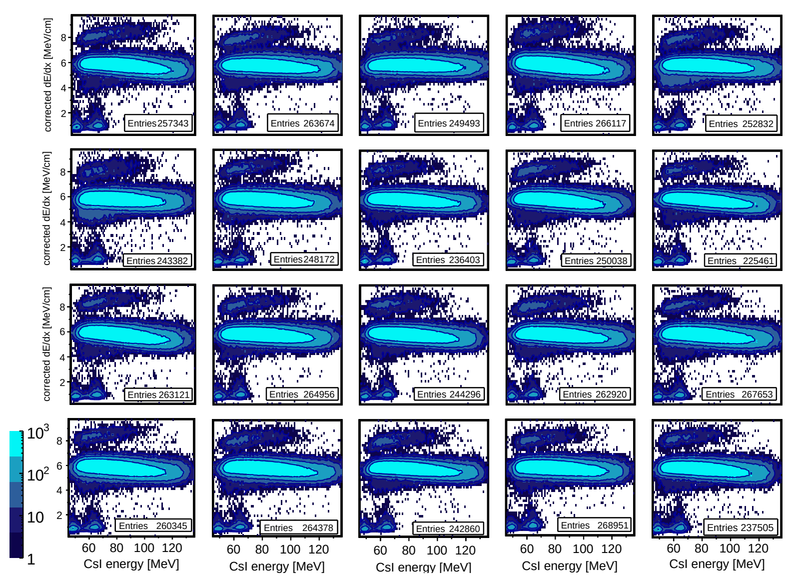

FIG. 7.3 – *Distributions of dE/dx versus E of prompt processes for the twenty individual PH plastic scintillators. The energy loss has been corrected to result in "horizontal" distributions for protons (the dominant contribution). The correction factor is equal to 1 at 100 MeV kinetic energy. Note at larger dE/dx the deuteron bands and at the low end the $\mu \to e\nu\overline{\nu}$ and $\pi \to e\overline{\nu}$ positrons.*

[9] results presented in this report are from the full 2008 data set only

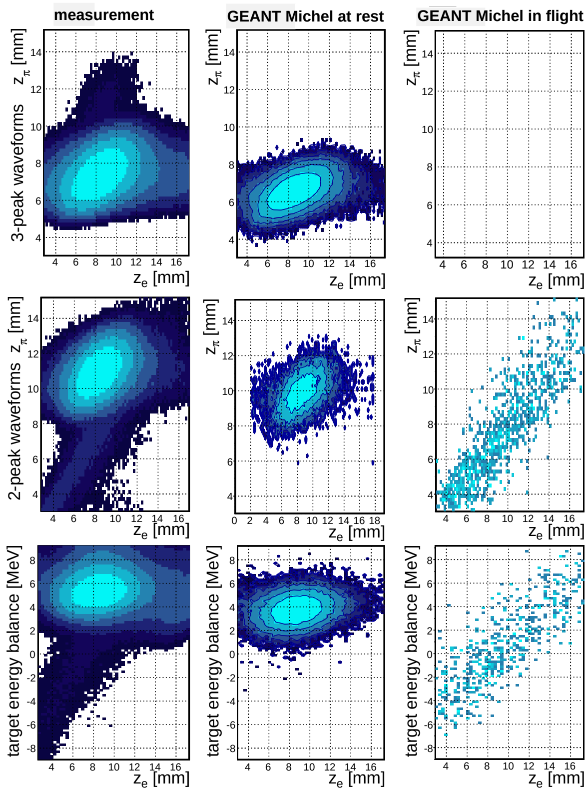

Fig. 7.4 – *Evidence for $\pi \rightarrow \mu\overline{\nu}$ decay shortly before the pion would have come to rest. Measured distributions (left) for e^+ final states between 30 and 50 MeV are compared with the corresponding results for simulated $\pi - \mu - e$ sequences (Michel events). The latter are separated in two groups depending on the μ^+ energy at decay (known to the SIMULATOR). Events with muons decaying at rest are shown in the middle, decays in flight in the right panels.*

The top two rows show events with well separated signals in the target waveform, either three (typical for $\pi - \mu - e$) or just two (as expected for decay in flight). The bottom row shows all events.

z_e: starting position coordinate of the e^+ along the beam line (from MWPCs).

z_π: final position coordinate of the π^+ along the beam line (from π^+ energy deposited in the target).

The target energy balance is the total target energy minus the predicted energies of π^+ and e^+. See the text for further explanations.

Pion decay before stopping

Much more problematic are events in which the pion decays shortly before it would have stopped. Such processes can not always be distinguished, in particular when the pion energy at decay time approaches zero, and are thus included in the likelihood analysis. It takes $O(0.1)$ ns for a pion to stop in the active target so a few permille of them decay before stopping. When the resulting muon stops in the target the event may become a $\pi \rightarrow \mu\overline{\nu}$ candidate but no $\pi \rightarrow e\overline{\nu}$. As illustrated in Fig. 7.4 such events show two peaks rather than three in the target waveform and also exhibit a characteristic tail in the distribution of the target energy balance versus decay location along the beam line. The target energy balance is the observed total target energy corrected for the contributions expected for the incoming pion and the outgoing positron. The energy deposited by the pion can be predicted event by event based on the observed pion velocity over the final 3.59 m and the energy loss observed in the preceding beam tracker wAD. The expected positron signal is based on the path length in the target deduced from the positron trajectory. For $\pi \rightarrow e\overline{\nu}$ the energy balance peaks at zero, for $\pi - \mu - e$ it peaks at the 4 MeV muon energy. With the help of the simulation $\pi \rightarrow \mu\overline{\nu}$ in flight can be accounted for with minimal systematic uncertainties.

As shown in Fig. 7.5 $\pi \rightarrow e\overline{\nu}$ in flight was observed too which came as a surprise since we hadn't given it much thought. The process has a weird distribution in the two main observables since energy is Doppler broadened and decaytime is quasi-prompt.

Conclusions

In conclusion we can say that progress has been slow but steady. As so often many complications were "forgotten" in the proposal but so far no real show stopper has been found.

Unfortunately for PEN two key collaborators from Virginia have finished their PhD projects [4, 5] and will move on to post-doc positions elsewhere. This means that the load on the few remaining workers

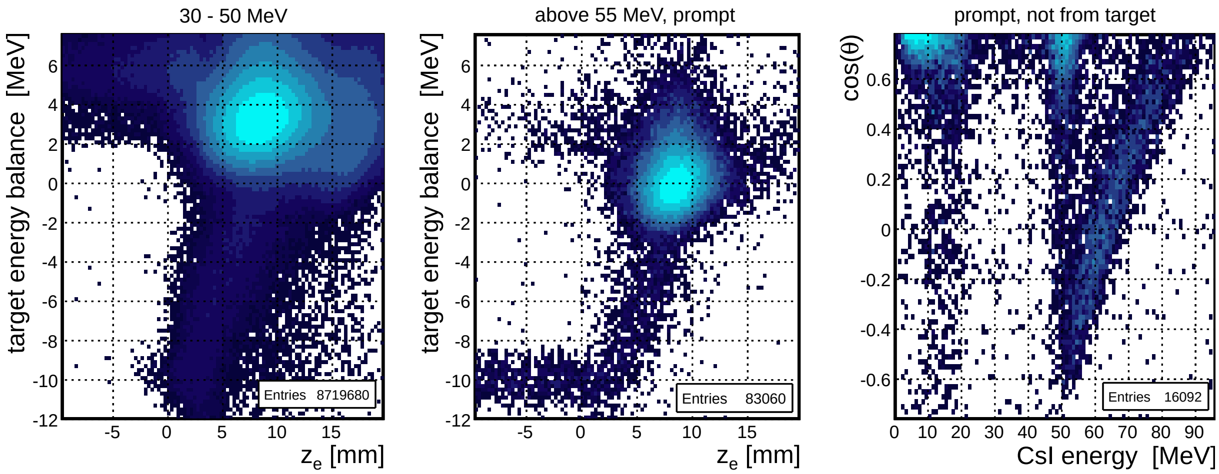

FIG. 7.5 – *Evidence for $\pi \to e\overline{\nu}$ decay in flight. The left panel shows the $\pi \to \mu\overline{\nu}$ distribution from Fig. 7.4 for comparison. The energy offset has been corrected in this figure. $\pi \to e\overline{\nu}$ in flight requires no stopping material and may thus lead to decay vertices in front of the target without any target signal (horizontal band around -10 MeV in the middle panel populated by events without the expected ≈10 MeV pion signal). The right panel shows a clean signal of such events for which the e^+ energy shows a dependence on polar emission angle θ characteristic for Lorentz broadening. Additional, mostly forward contributions are from scattered beam (below 20 MeV) and decays of μ^+ stops in the degrader system. The energy region below 50 MeV was pre-scaled 1:64 in the trigger for data readout.*

will increase even further. In this respect we are extremely happy to mention the bachelor work of Raphael Nydegger who optimized the reconstruction routines of the mini TPC used as beam tracker after 2008 and managed to improve the position resolution by a factor 2.

[1] G. Czapek *et al.*, Phys. Rev. Lett. **70** (1993) 17; D. I. Britton *et al.*, Phys. Rev. Lett. **68** (1992) 3000.

[2] PEN Collaboration, PSI experiment R-05-01 (2005), D. Pocanic and A. van der Schaaf, spokespersons; PIENU Collaboration, TRIUMF proposal 1072 (2006), D. Bryman and T. Numao, spokespersons.

[3] see previous annual reports for details: `www.physik.uzh.ch/reports.shtml`

[4] Anthony Palladino Jr., *Investigating Lepton Universality via a Measurement of the Positronic Pion Decay Branching Ratio*, PhD Dissertation (2012), The University of Virginia. `http://pen.phys.virginia.edu/references/palladino_dissertation.pdf`

[5] Loreto Peter Alonzi III, *Measuring the Pion Substructure with Radiative Positronic Pion Decays*, PhD Dissertation (2012), The University of Virginia. `http://pen.phys.virginia.edu/references/alonzi_dissertation.pdf`