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

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PEN [1] measures the branching ratio $B \equiv \Gamma_{\pi\to e\overline{\nu}(\gamma)}/\Gamma_{\pi\to\mu\overline{\nu}(\gamma)}$ with an accuracy <0.05%. The present world average is B=1.230(4)$\cdot 10^{-4}$ [2]. In the Standard Model charged pion decays are mediated at tree level by (virtual) W exchange $\pi \to W \to \ell\overline{\nu}_\ell$. By measuring a ratio potentially large hadronic uncertainties in the initial pion state cancel resulting in a theoretical uncertainty <0.01%. The theoretical prediction is based on the universality (flavour independence) of the $W \to \ell\overline{\nu}_\ell$ coupling strength and the notion that W couples to lefthanded fermions only which leads to "helicity suppression" (Γ vanishes in the limit $m_\ell \to 0$) and the present experimental result for B is the best of all available tests of these two concepts.

PEN uses a CsI crystal ball as main detector. Positron tracking is achieved with cylindrical MWPC's. Beam counters include a mini-TPC and an active scintillating target which is also used to record the decay signals [3].

The twobody decay $\pi \to e\overline{\nu}$ results in a monoenergetic positron (E $\sim \frac{1}{2}m_\pi c^2$) with an exponential decaytime distribution ($\tau_\pi \sim 26$ ns). The decay chain $\pi \to \mu\overline{\nu}$ followed by the threebody decay $\mu \to e\nu\overline{\nu}$ results in a continuous positron energy distribution (E $< \frac{1}{2}m_\mu c^2$) with a decay time first rising with τ_π and then falling with $\tau_\mu \sim 2197$ ns. For the two signal processes these energy and time probability density functions (pdf's) are uncorrelated and thus enter as onedimensional components in the total pdf. The main complication in separating these two contributions always was and still is the radiative tail of the positron energy in $\pi \to e\overline{\nu}$ decay which results in a $\sim 2\%$ overlap of the two processes. Figure 7.1 shows a cartoon of the situation.

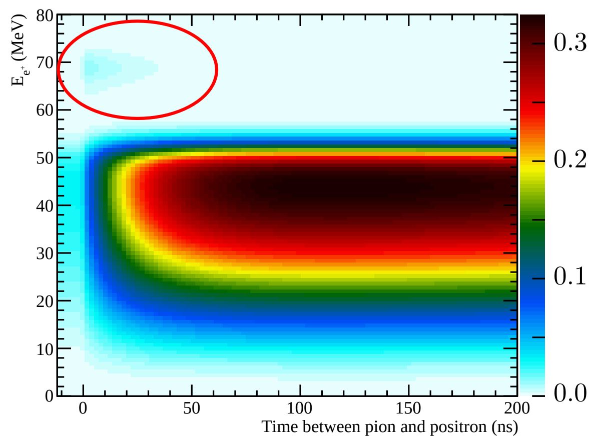

Fig. 7.1 – Distribution of the main observables distinguishing the decay modes $\pi \to eX$ and $\pi \to \mu X$. About 2% of the $\pi \to eX$ events are located in the region below 50 MeV dominated by $\pi \to \mu X$. The red contour indicates the main $\pi \to eX$ region.

If one wishes to keep the systematic uncertainty associated with this overlap below the envisaged few 10^{-4} level one has to know the yield of the lowenergy tail with a *relative* uncertainty better than 1%. At this level simulation can not be trusted so the distribution had to be measured in parallel.

Data taking

Data taking finished in 2010. Table 7.1 lists the vital information during the three years of data taking and the resulting statistical error in the branching ratio. Various readout triggers were implemented based primarily on the energy observed in the electromagnetic calorimeter. All but the main trigger (with energy threshold around 48 MeV) were prescaled.

Tab. 7.1 – PEN vital statistics during three years of data taking. The total *statistical* error in the branching ratio $\Delta B/B^{\text{stat.}}$ is well below the goal accuracy. Footnotes indicate the main trigger conditions.

	2008	2009	2010	total	
measuring period	111	98	68	277	days
π stops	0.746	1.33	1.64	3.7	10^{11}
$\pi \to e\nu$ decays[a]	4.1	7.8	10.1	22.0	10^6
$\pi \to e\nu$ decays[b]	–	0.48	0.86	1.34	10^6
$\pi \to \mu \to e$ decays[c]	50	86	71	207	10^6
$\Delta B/B^{\text{stat.}}$	0.07	0.04	0.03	0.02	%

[a] e^+ energy above 48 MeV
[b] full energy distribution, needed for low-energy tail, 1:10 - 1:16 prescaled
[c] $\Delta t(\pi - e^+) < 200$ ns, 1:64 prescaled

Data analysis

The analysis of a precision measurement such as PEN requires painstaking care and will take many (wo)man years. To remove any bias caused by theoretical prejudice a blind analysis is performed by training the reconstruction algorithms on small subsets of the data. To keep systematic errors under control the multidimensional maximum likelihood analysis uses pdf's straight from the measurement wherever possible. Only in regions where processes overlap GEANT4 simulations will take over from the observed pdf's.

Pushing systematic errors to the 10^{-4} region opens a can of worms (others would call the task challenging). Pions can scatter into the acceptance of the decay detectors, react with the target nuclei (producing energetic protons), decay during the ∼0.1 ns of travel inside the target, to name a few sources of background. Half a dozen processes will be included in the likelihood analysis and to cope with these event types a variety of additional observables will enter the pdf's: target waveform variables, preceding beam signals (affecting accidental coincidences), dE/dx information (to discriminate against protons), vertex location (to identify pion decays in flight) and probably more.

It is our intention to not only find the location of maximum likelihood in the multidimensional parameter space but to determine the full likelihood distribution for the branching ratio which has the advantage that the error distribution comes out for free. An unbinned likelihood analysis over 10^8 events in a parameter space with six or more dimensions is indeed “challenging” at least. A smart scan should avoid regions with low likelihood and will have to keep the required CPU power under control.

In the spirit of a blind analysis we are not able to show any results at this instant. Next year's report should show more!

[1] PEN Collaboration, PSI experiment R-05-01, D. Pocanic and A. van der Schaaf, spokespersons.

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

[3] see previous annual reports for details: `http://www.physik.unizh.ch/reports.html`