Investigating Lepton Universality via a Measurement of the Positronic Pion Decay Branching Ratio

Anthony Palladino

Advisor: Dinko Počanić

University of Virginia

Ph.D. Dissertation Defense

Charlottesville, Virginia, USA

06 December 2011

Theory of π^+ Decay

Quark Content: $\pi^+ = u\overline{d}$

Mass: $m_{\pi^+} = 139.6$ MeV

Lifetime: $\tau_{\pi^+} = 26.03$ ns

Decay Mode	Branching Fraction	
$\pi^+ \to \mu^+\nu_\mu(\gamma)$	$0.9998770(4)$	
$\pi^+ \to \mu^+\nu_\mu\gamma_{(E_\gamma > 1\mathrm{MeV})}$	$2.00(25) \times 10^{-4}$	Bressi et al. '98
$\pi^+ \to e^+\nu_e(\gamma)$	$1.230(4) \times 10^{-4}$	Czapek et al. '93, Britton et al. '92, Bryman et al. '8
$\pi^+ \to e^+\nu_e\gamma_{(E_\gamma > 10\mathrm{MeV})}$	$7.386(54) \times 10^{-7}$	Bychkov et al. '09
$\pi^+ \to \pi^0 e^+\nu_e$	$1.036(6) \times 10^{-8}$	Počanić et al. '04
$\pi^+ \to e^+\nu_e e^+ e^-$	$3.2(5) \times 10^{-9}$	Egli et al. '89

Theory of π^+ Decay

Why is $\pi^+ \to e^+\nu_e$ a rare decay? Helicity Suppression

Conservation of Angular Momentum:
In π rest frame, the π has $S = 0$.
The outgoing lepton pair (each spin 1/2) must combine to give $S = 0$

- *both* Right-Handed (Positive Helicity), or
- *both* Left-Handed (Negative Helicity)

Property that if $m = 0$:

- All $S = 1/2$ particles are Left-Handed (Negative Helicity)
- All $S = 1/2$ *anti*particles are Right-Handed (Positive Helicity)

$\Rightarrow$ **The negative helicity ν_e (ν_μ) forces the e^+ (μ^+) into a negative helicity state. But,**

$$m_{e^+} \ll m_{\mu^+} \qquad (m_{\mu^+} \simeq 200 m_{e^+})$$

Theory of π^+ Decay

Helicity: For $v = c$, fraction "violating" $= 0$.

For a given E, $v_e > v_\mu \Rightarrow e$ is less likely to have wrong helicity.

$$\text{"Helicity Conservation"} \iff \frac{1}{2} + \frac{1}{2}\frac{v}{c}$$

$$\text{"Helicity Violation"} \iff \frac{1}{2} - \frac{1}{2}\frac{v}{c}$$

$$\boxed{\frac{\text{"HelicityViolation"}(e^+)}{\text{"HelicityViolation"}(\mu^+)} \approx 3.2 \times 10^{-5}}$$

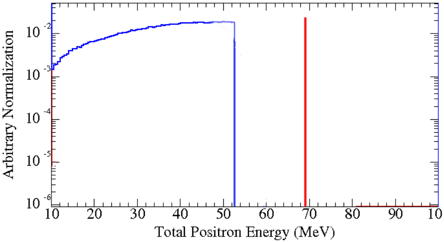
π Decay Phase Space:

Since the e^+ is lighter, the $\pi^+ \to e^+\nu_e$ decay has a larger phase space than the $\pi^+ \to \mu^+\nu_\mu$ decay. $\Rightarrow$ gives a factor $\boxed{\sim 3.3}$

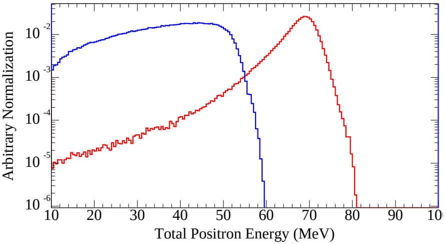
$$\boxed{\frac{\Gamma(\pi^+ \to e^+\nu_e)}{\Gamma(\pi^+ \to \mu^+\nu_\mu)} \approx 3.3 \times (3.2 \times 10^{-5}) \approx 10^{-4}}$$

Theory of π^+ Decay

$\pi^+ \rightarrow e^+\nu_e$
2-body decay
$\Rightarrow E_{e^+} = 69.8$ MeV



$\pi^+ \rightarrow \mu^+\nu_\mu$ followed by
$\mu^+ \rightarrow e^+\nu_e\bar{\nu}_\mu$
sequential decay
$\Rightarrow E_{e^+}^{\max} = 52.5$ MeV



The PEN Experiment

- Precision Measurement of the $\pi^+ \to e^+\nu_e$ branching ratio.

$$R_{\pi_{e2}} = \frac{\Gamma(\pi^+ \to e^+\nu_e(\gamma))}{\Gamma(\pi^+ \to \mu^+\nu_\mu(\gamma))} = \left(\frac{g_e}{g_\mu}\right)^2 \left(\frac{m_e}{m_\mu}\right)^2 \frac{\left(1 - m_e^2/m_\mu^2\right)^2}{\left(1 - m_\mu^2/m_\pi^2\right)^2} \left(1 + \delta R_{\pi_{e2}}\right)$$

$$R_{\pi_{e2}}^{\text{calc}} = \begin{cases} (1.2352 \pm 0.0005) \times 10^{-4} & \text{Marciano \& Sirlin, [PRL } \mathbf{71}\text{, 3629 (1993)]} \\ (1.2354 \pm 0.0002) \times 10^{-4} & \text{Finkemeier, [Phys. Lett. B } \mathbf{387}\text{, 391 (1996)]} \\ (1.2352 \pm 0.0001) \times 10^{-4} & \text{Cirigliano \& Rosel, [PRL } \mathbf{99}\text{, 231801 (2007)]} \end{cases}$$

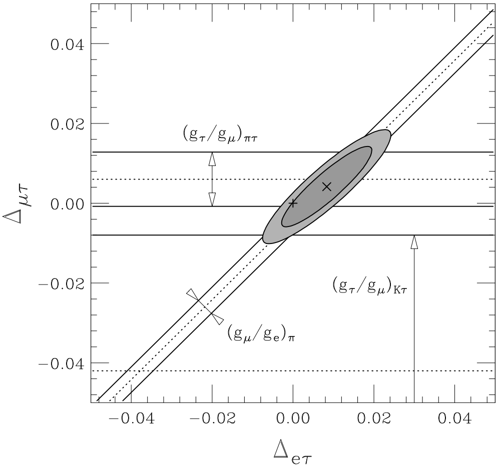
$$R_{\pi_{e2}}^{\text{exp}} = (1.230 \pm 0.004) \times 10^{-4}$$ Experiment World Average (Current PDG)

Our Goal: $\frac{\Delta R^{exp}}{R^{exp}} \leq 5 \times 10^{-4}$	PDG: $\frac{\Delta R^{exp}}{R^{exp}} \sim 3.3 \times 10^{-3}$

Lepton Universality: W. Loinaz, et. al., Phys. Rev. D **65**, 113004 (2004) [hep-ph/0403306]

$$\left(\frac{g_e}{g_\mu}\right)_\pi = 1.0021 \pm 0.0016$$

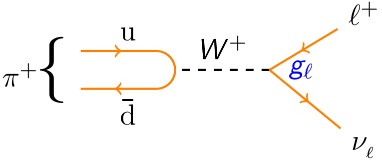
Lepton Universality



From Loinaz et al.,PRD 70 (2004) 113004

$$\Delta_{\ell\,\ell'} = \varepsilon_\ell - \varepsilon_{\ell'}$$

where $\frac{g_\ell}{g_{\ell'}} = 1 + \frac{\varepsilon_\ell - \varepsilon_{\ell'}}{2}$



Deviations from SM Prediction

A Branching Ratio that is different from the SM prediction could be caused by:

- lepton non-universality,
- charged Higgs particles in theories with more Higgs than SM,
- pseudoscalar leptoquarks in theories with dynamical symmetry breaking,
- vector leptoquarks in GUTs,
- SUSY partner particles appearing in loop diagrams,
- non-zero neutrino masses,
- Majorons.

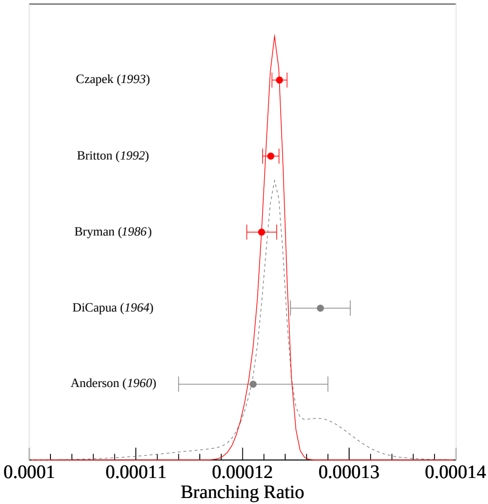
Mass Limits on Leptoquark and Supersymmetric Particles

A measurable deviation in $R_{\pi_{e2}}$ from the SM prediction is clear evidence of physics beyond the SM, sensitive to mass scales of many TeV.

Particle		Current Bounds	Projected Mass Sensitivity
Charged Higgs Boson	m_H	> 2 TeV	> 6.9 TeV
Pseudoscalar Leptoquark	m_p	> 1.3 TeV	> 3.8 TeV
Vector Leptoquark	M_G	> 220 TeV	> 630 TeV

Following the calculations in Shanker, NP B204 (82) 375

History of the Measurement

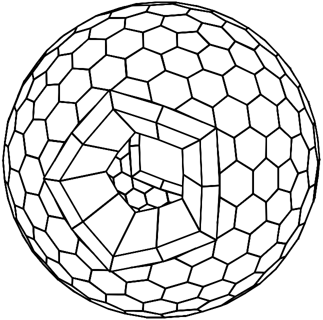


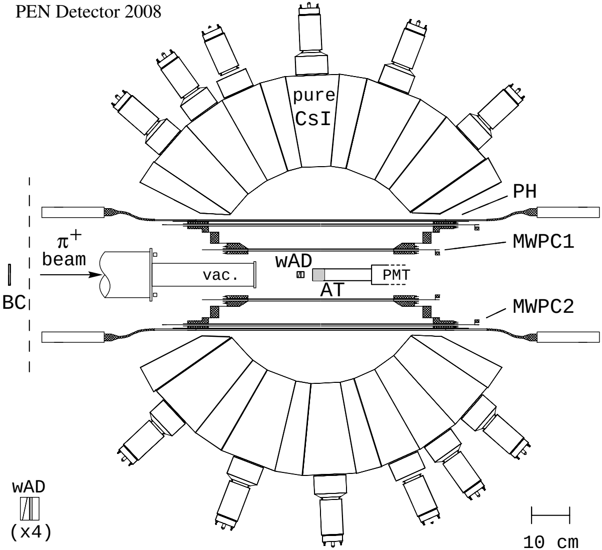
Paul Scherrer Institute

Villigen, Aargau, Switzerland

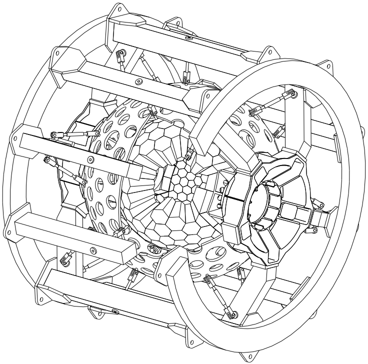
The PEN Apparatus

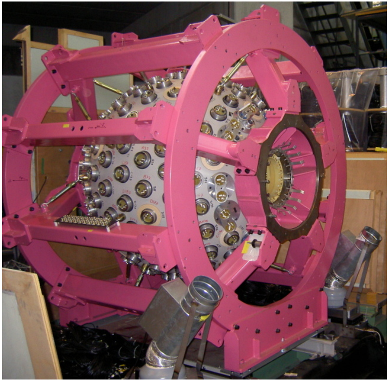
- stopped π^+ beam
- active target counter
- 240-det. pure CsI calo.
- central tracking
- digitized PMT signals
- stable temp./humidity



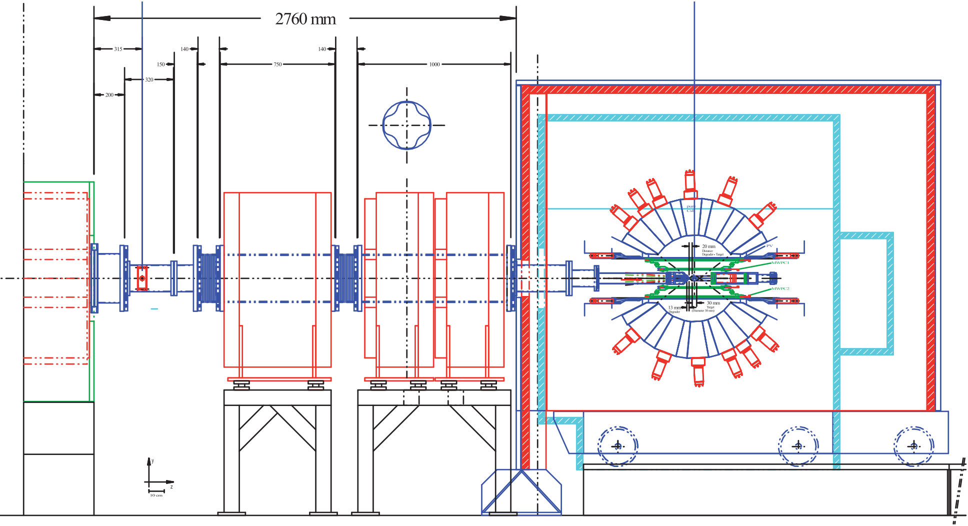


PEN Detector



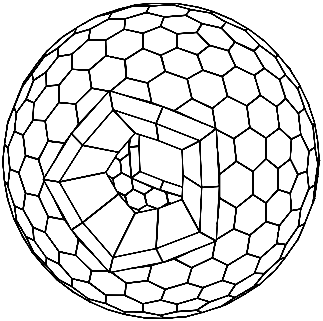


Beam Counter, Focusing Magnets, and Detectors

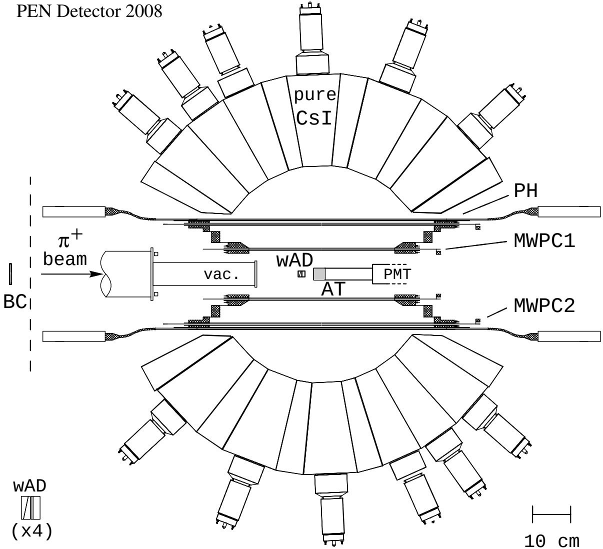


The PEN Apparatus: 2008

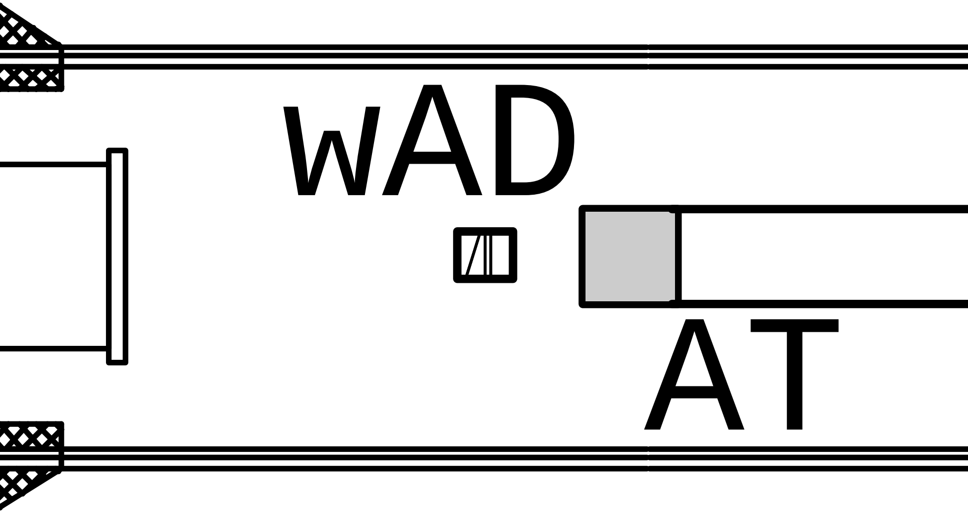
- ◦ stopped π^+ beam
- ◦ active target counter
- ◦ 240-det. pure CsI calo.
- ◦ central tracking
- ◦ digitized PMT signals
- ◦ stable temp./humidity



PEN Detector 2008

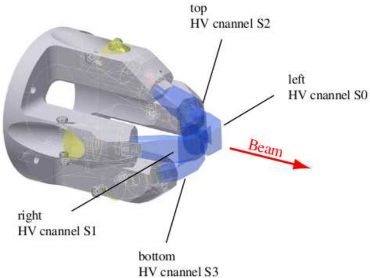


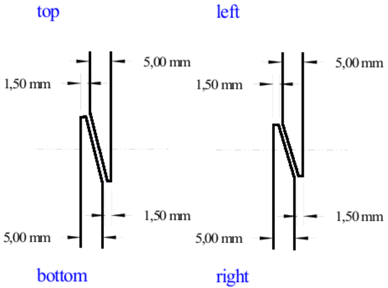
The PEN Apparatus: 2008



The PEN Apparatus: 2008

Novel, low cost, four-piece, Wedged Degrader. (UZh: P. Robmann)





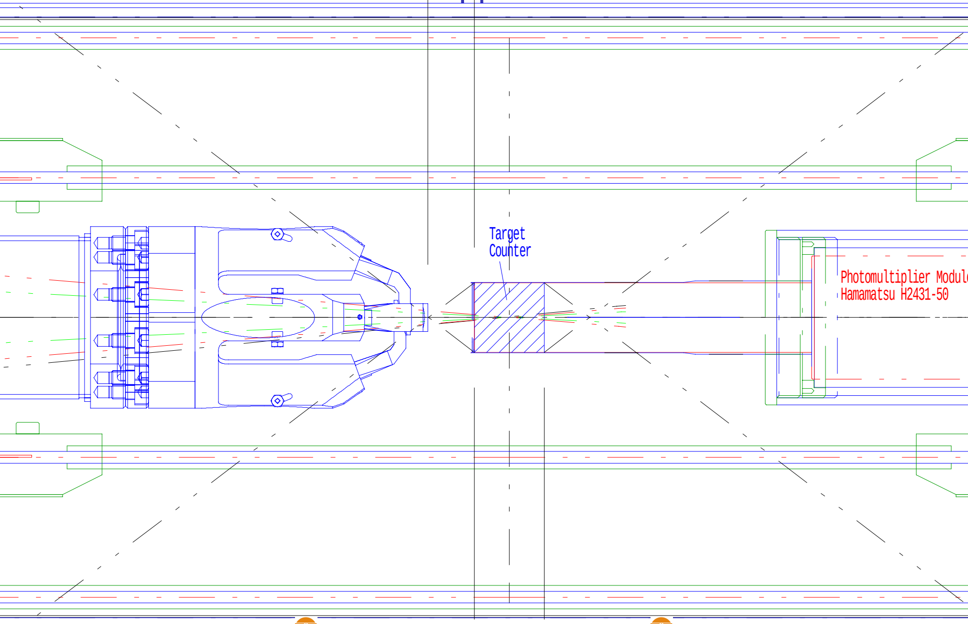
Pros:

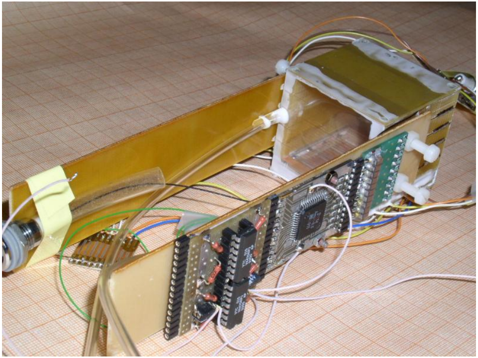
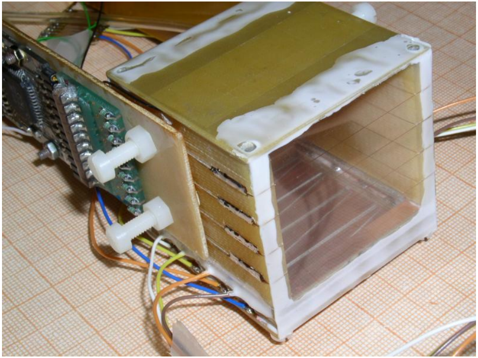
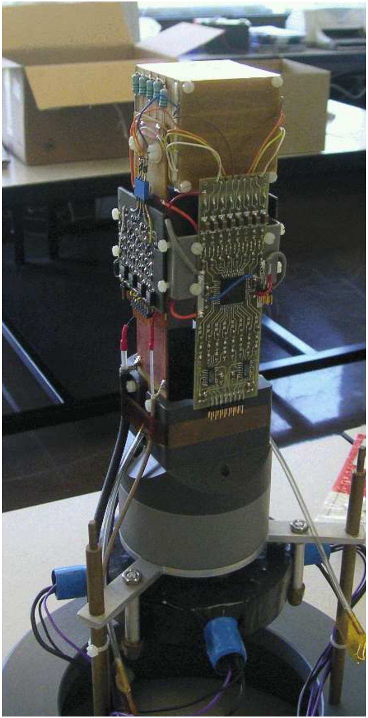
- x,y position sensitivity of beam π^+

Cons due to thicker degrader (13mm as opposed to 5mm):

- higher beam momentum required $\Rightarrow$ more nuclear reactions in target.
- more material increases multiple scattering $\Rightarrow$ π position resolution suffers.

The PEN Apparatus: 2008



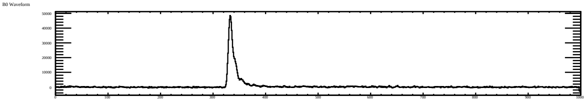
Acqiris Digitizer

Acqiris High Speed 10-bit PXI/CompactPCI Digitizer, Model DC282
4 Channels, each with 2 GS/s

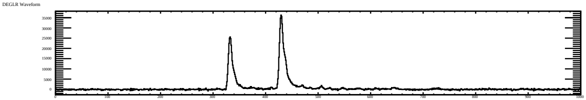
Digitized PMT waveforms from three beamline detectors:

- Upstream Beam Counter
- Active Degrader
- Active Target

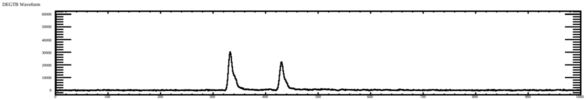
Fwd Beam Counter



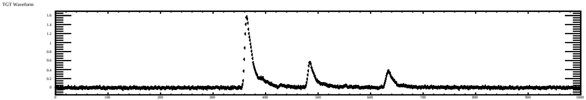
Degrader Top & Bottom



Degrader Left & Right

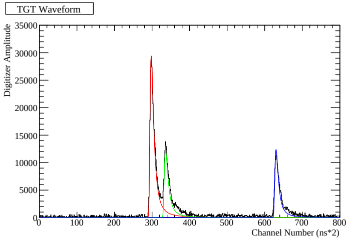


Target

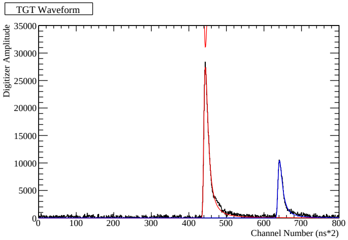


Target Waveform Analysis

- Calibrate target energy to monoenergetic muon.
- Provide cuts, useful for distinguishing the various processes.



$\pi^+ \rightarrow \mu^+ \rightarrow e^+$ Event.



$\pi^+ \rightarrow e^+$ Event.

Pulse Shaping

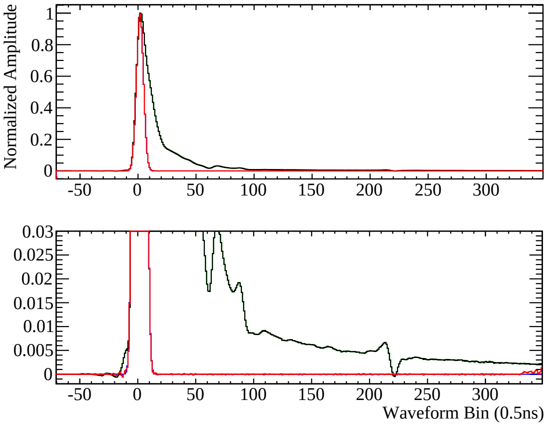
Developed an iterative program to create a digital adaptive filter.

Input:

- Averaged system response waveform array, w_i
- Desired waveform array, $\tilde{w}_i$

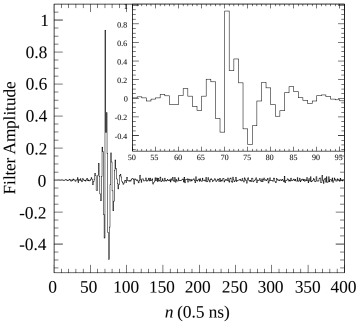
Output:

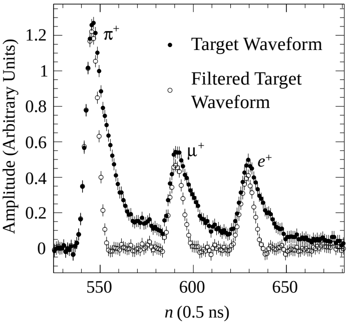
- Shaping array ("Filter"), s_i



Pulse Shaping: $\tilde{w}_i = \sum_{k=k_{\min}}^{k_{\max}} s_k w_j$ where $k \equiv i - j$

Pulse Shaping





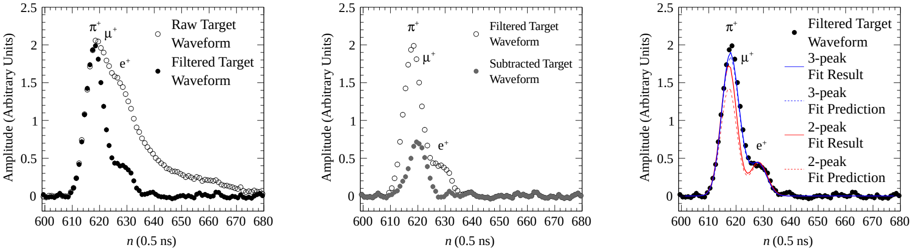
- Filtering (Shaping) isolates the monoenergetic muon for energy calibration.

★ A. Palladino, A. van der Schaaf, D. Počanić, "*Reconstructing Detector Waveforms with Overlapping Pulses*", to be submitted 2011.

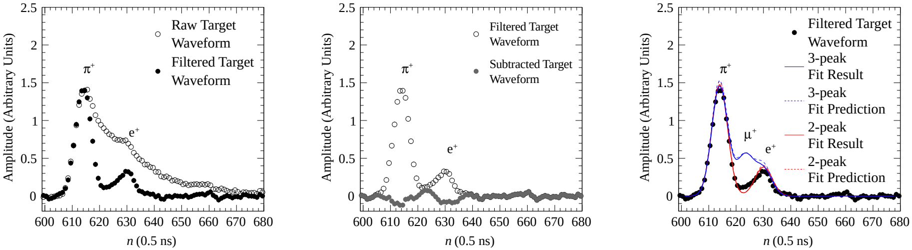
Target Waveform Fit Parameters

Pulse	Position in time	Amplitude
π^+	Known (from Degrader) $\sigma \sim$ 65 ps	Known (from TOF and $E_{B0} + \sum E_{deg}$) $\sigma \sim$ 716 keV (5.5%)
μ^+	Unknown	Known (monoenergetic) $\sigma \sim$ 200 keV (4.8%)
e^+	Known (from Plastic Hod.) $\sigma \sim$ 492 ps	Known (from tracking) $\sigma \sim$ 878 keV (29.2%)

$\pi^+ \to \mu^+ \to e^+$ Event Fit



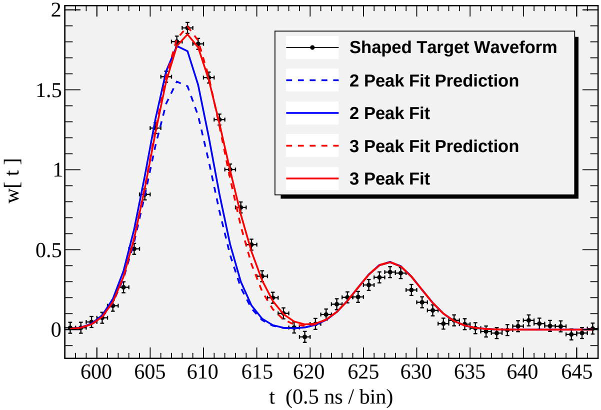
$\pi^+ \to e^+$ Event Fit



Waveform Fitting

Modified χ^2 Function:

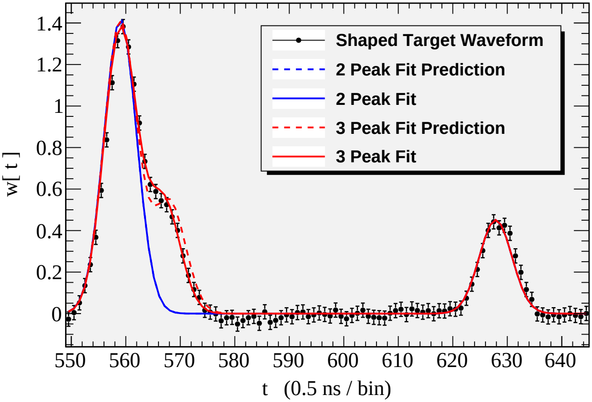
$$\chi^2 = \frac{1}{n_{\mathrm{d.o.f.}}} \sum_{i=1}^{n} \left(\frac{\tilde{w}_i^{\mathrm{Fit}} - \tilde{w}_i}{\sigma_{\tilde{w}}} \right)^2 + \lambda_1 \left(\frac{E_{\pi^+}^{\mathrm{Fit}} - E_{\pi^+}^{\mathrm{Pred}}}{\sigma_{E_{\pi^+}}} \right)^2 + \lambda_2 \left(\frac{E_{e^+}^{\mathrm{Fit}} - E_{e^+}^{\mathrm{Pred}}}{\sigma_{E_{e^+}}} \right)^2$$



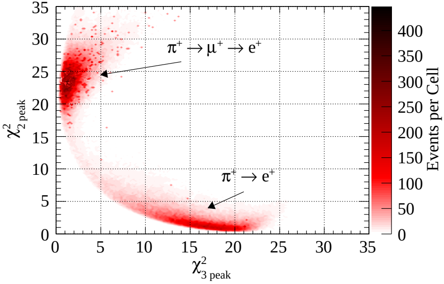
Waveform Fitting

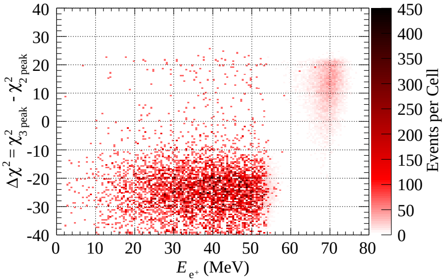
Modified χ^2 Function:

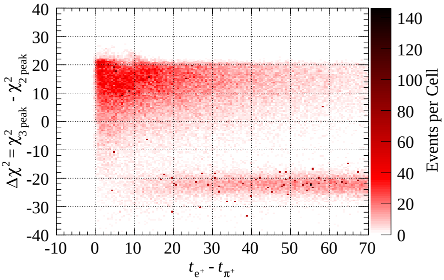
$$\chi^2 = \frac{1}{n_{\mathrm{d.o.f.}}} \sum_{i=1}^{n} \left(\frac{\tilde{w}_i^{\mathrm{Fit}} - \tilde{w}_i}{\sigma_{\tilde{w}}} \right)^2 + \lambda_1 \left(\frac{E_{\pi^+}^{\mathrm{Fit}} - E_{\pi^+}^{\mathrm{Pred}}}{\sigma_{E_{\pi^+}}} \right)^2 + \lambda_2 \left(\frac{E_{e^+}^{\mathrm{Fit}} - E_{e^+}^{\mathrm{Pred}}}{\sigma_{E_{e^+}}} \right)^2$$



Waveform Fitting Results







PEN Data Analysis

Strategy:

Determine the most likely value of the $\pi^+ \to e^+\nu_e$ branching ratio using a Maximum Likelihood Analysis.

Benefits:

- Provides a unique, unbiased, minimum variance estimate (for a large enough sample).
- Practical, tractable approach via product PDFs
- Use as much data as possible to determine $R_{\pi_{e2}}$; loose cuts.

Complication:

- Critical dependence on PDF

Maximum Likelihood Analysis

One likelihood function encompassing many observables and processes.

$$\mathcal{L}\left(\overrightarrow{x}_e\ ;\ f_m\right) = \prod_{e=1}^{\mathcal{N}} \left[\sum_{m=1}^{M} f_m\, P_m(\overrightarrow{x}_e)\right]$$

where $\mathcal{N}$ is the number of events, and

$(\overrightarrow{x}_e)$ are the observables

- Time between π^+ and e^+
- Total Positron Energy
- "Probability" of Pile-up

$$\text{“}P\text{“}_{\text{pile-up}} = \ln\left[\sum_{k=1}^{\ell} e^{-|dt_k|/\tau_\mu}\right]$$

- Pion Decay Vertex
- etc.

(f_m) fraction of process m

- $f_{\pi_{e2}}$, $\pi^+ \to e^+$
- $f_{\pi_{\mu 2}}$, $\pi^+ \to \mu^+ \to e^+$
- f_{Acc}, Accidentals / Pile-up
- f_{DIF}, Pion Decays-in-flight
- f_{Had}, Proton
- $f_?$, etc.

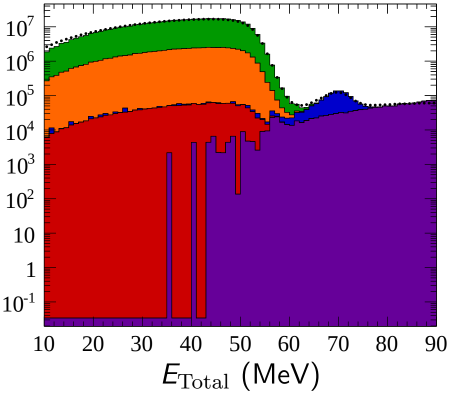
Model: Probability Distribution Functions, P_m

$$\mathcal{L}\left(\vec{E}_{\text{Total}}\ ;\ f_{\pi_{e2}}, f_{\pi_{\mu2}}, f_{\text{Acc}}, f_{\text{DIF}}, f_{\text{Had}}\right)$$

- $\pi_{\mu 2}$
- π_{e2}
- Accidental Coincidence
- π Decay-in-flight
- Hadronic (proton)

$\chi^2 / N_{\text{dof}} = 3.8$

Energy Histograms stacked on top of each other

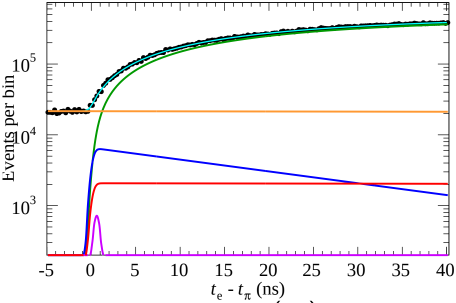


Model: Probability Distribution Functions, P_m

$$\mathcal{L}\left(\overrightarrow{\Delta t}\ ;\ f_{\pi_{e2}}, f_{\pi_{\mu 2}}, f_{\mathrm{Acc}}, f_{\mathrm{DIF}}, f_{\mathrm{Had}}\right)$$

- $\pi_{\mu 2}$
- π_{e2}
- Accidental Coincidence
- π Decay-in-flight
- Hadronic (proton)

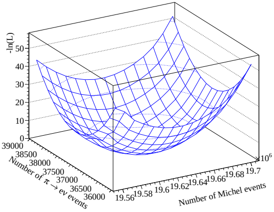
$$\chi^2/N_{\mathrm{dof}} = 1.3$$



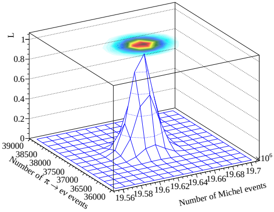
$t_e - t_\pi$ (ns)

Practicality: Negative Log Likelihood

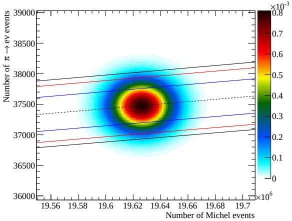
$\ell = -\ln\mathcal{L}$



$\mathcal{L} = e^{-\ell}$



N_{p2e} vs. N_{michel}



C++ code written specifically for this analysis.

Maximum Likelihood Analysis

- Framework complete
  - Flexible: can add/remove processes and observables
  - Error analysis correct (weighted events)
- Errors comparable to χ^2 fit
  - $\frac{\Delta R}{R} = 0.16\%$ (statistical)
  - $\frac{\Delta R}{R} \sim 2\%$ (systematic) $\rightarrow \frac{\Delta R}{R} < 0.02\%$

Conclusion

Year 2006 (Beam Development Phase):

- Detector Refurbishment (Same detector from PiBeta Experiment).

Year 2007 (Experiment Development Phase):

- More refurbishments / Many new components and upgrades.

Year 2008 (1^{st} Production Phase):

- Use of wedged degrader for π tracking.
- Recorded $\sim 5 \times 10^6\ \pi^+ \to e^+\nu_e$ decays

Years 2009 and 2010 (2^{nd} and 3^{rd} Production Phases):

- Use of mini-TPC for improved π tracking.
- Recorded $\sim 20 \times 10^6$ more $\pi^+ \to e^+\nu_e$ decays

Year 2011 (Data Analysis Phase):

- Finalized target waveform analysis
- Developed Maximum Likelihood analysis framework

PEN Experiment Collaboration Members:

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

[a] *Dept of Physics, Univ 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] *IHEP, Tbilisi, State University, GUS-380086 Tbilisi, Georgia*
[f] *Rudjer Bošković Institute, HR-10000 Zagreb, Croatia*
[g] *Physik Institut der Universität Zürich, CH-8057 Zürich, Switzerland*

blue = Ph.D. Candidate

⋆ = Spokesperson

PEN Web page: http://pen.phys.virginia.edu