A Precise Measurement of the $\pi^+ \longrightarrow e^+\nu_e$ Branching Ratio

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4^{th} Year Graduate Student Seminar; Charlottesville, Virginia
14 January 2009

Theory of π^+ Decay

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

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

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

Decay Mode	Expt. Branching Ratio
$\pi^+ \rightarrow \mu^+\nu_\mu$	0.9998770(4)
$\pi^+ \rightarrow \mu^+\nu_\mu\gamma$	$2.00(25) \times 10^{-4}$
$\pi^+ \rightarrow e^+\nu_e$	$1.230(4) \times 10^{-4}$
$\pi^+ \rightarrow e^+\nu_e\gamma$	$1.61(23) \times 10^{-7}$
$\pi^+ \rightarrow \pi^0 e^+\nu_e$	$1.025(34) \times 10^{-8}$
$\pi^+ \rightarrow e^+\nu_e e^+ e^-$	$3.2(5) \times 10^{-9}$

Theory of π^+ Decay

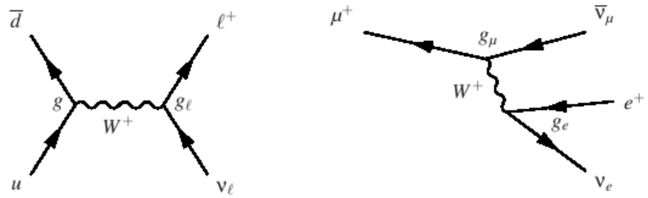

Figure: Feynman Diagrams for $\pi^+ \rightarrow l^+\nu$ and the Michel decay $\mu^+ \rightarrow e^+\nu_e\overline{\nu}_\mu$.

The $\pi^+ \rightarrow e^+\nu_e$ is a 2-body decay $\Rightarrow E_{e^+} = 69.8 MeV$
The $\pi^+ \rightarrow \mu^+ \rightarrow e^+$ sequential decay $\Rightarrow E_{e^+}^{max} = 52.5 MeV$

Theory of π^+ Decay

Radiative Corrections

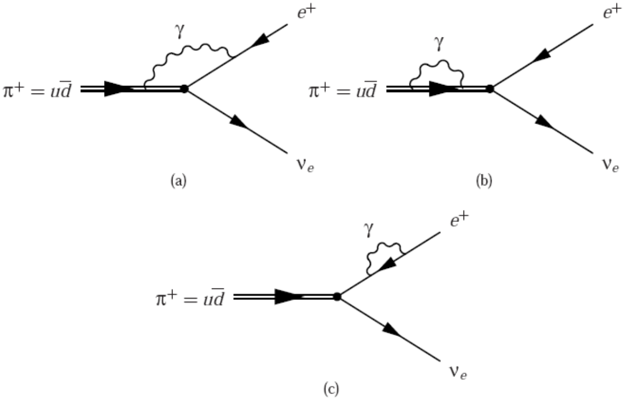

Figure: Feynman Diagrams Showing Emission and Reabsoption of Photons

Theory of π^+ Decay

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

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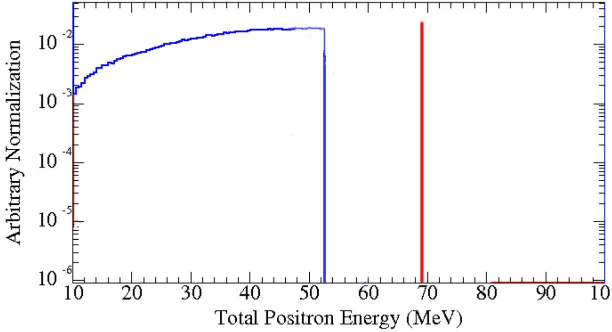


Figure: Ideal Case: Perfect Detection

Theory of π^+ Decay

Why is $\pi^+ \rightarrow e^+\nu_e$ 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 forces the e^+ into a negative helicity state. But,**

$$m_{e^+} << m_{\mu^+}$$

Theory of π^+ Decay

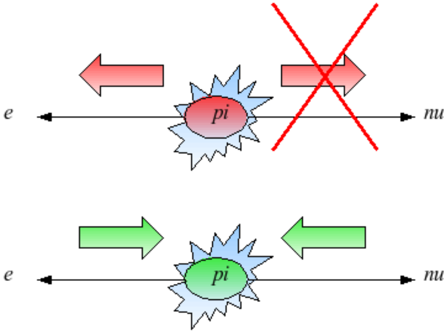
Helicity

$m_{\pi^+} = 139.56995$ MeV

$m_{\mu^+} = 106.65839$ MeV $\Rightarrow$ wants to be right-handed

$m_{e^+} = 0.51099$ MeV $\Rightarrow$ *really* wants to be right-handed

$m_\nu < 10^{-6}$ MeV $\Rightarrow$ forces both **left-handed**



Theory of π^+ Decay

Helicity

$$\text{Correct Helicity State} = \frac{1}{2} + \frac{1}{2}\frac{v}{c}$$

$$\text{Wrong Helicity State} = \frac{1}{2} - \frac{1}{2}\frac{v}{c}$$

For $v = c$, fraction "Wrong" $= 0$.

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

$\frac{LH(e^+)}{LH(\mu^+)} \approx 3.2 \times 10^{-5}$

π Decay Phase Space

Since the e^+ is lighter, the $\pi^+ \rightarrow e^+\nu_e$ decay has a larger phase space than the $\pi^+ \rightarrow \mu^+\nu_\mu$ decay. $\Rightarrow$ gives a factor ~ 3.3

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

Physics Motivation

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

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

$B_{calc} = (1.2352 \pm 0.0005) \times 10^{-4}$ Marciano & Sirlin, [PRL **71**, 3629 (1993)]

$B_{calc} = (1.2354 \pm 0.0002) \times 10^{-4}$ Decker & Finkemeier, [NP B **438**, 17 (1995)]

$B_{calc} = (1.2352 \pm 0.0001) \times 10^{-4}$ Cirigliano & Rosel, [PRL **99**, 231801 (2007)]

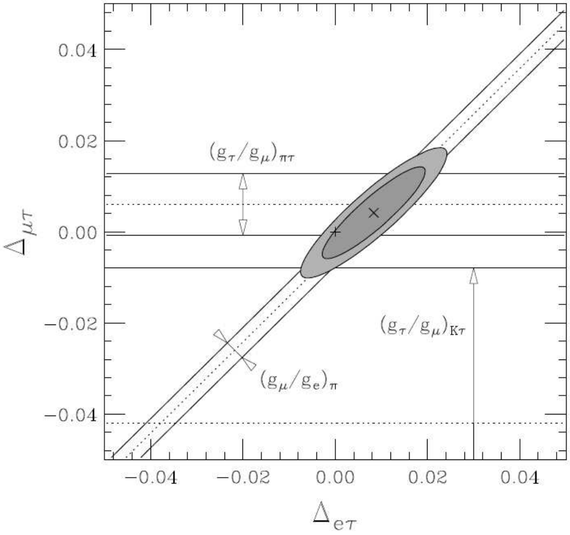
$B_{exp} = (1.230 \pm 0.004) \times 10^{-4}$ Experiment World Average (Current PDG)

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

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

Our Goal:	$\frac{\Delta B_{exp}}{B_{exp}} \leq 5 \times 10^{-4}$

Lepton Universality



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

$$\Delta_{\ell\ell'} = 2\frac{g_\ell}{g_{\ell'}}$$

Deviations from SM Prediction

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

- charged Higgs particles in theories with more Higgs than SM,
- pseudoscalar leptoquarks in theories with dynamical symmetry breaking,
- vector leptoquarks in Pati-Salam type GUT's,
- SUSY partner particles appearing in loop diagrams,
- non-zero neutrino masses,
- Majorons.

Mass Limits on Leptoquark and Supersymmetric Particles

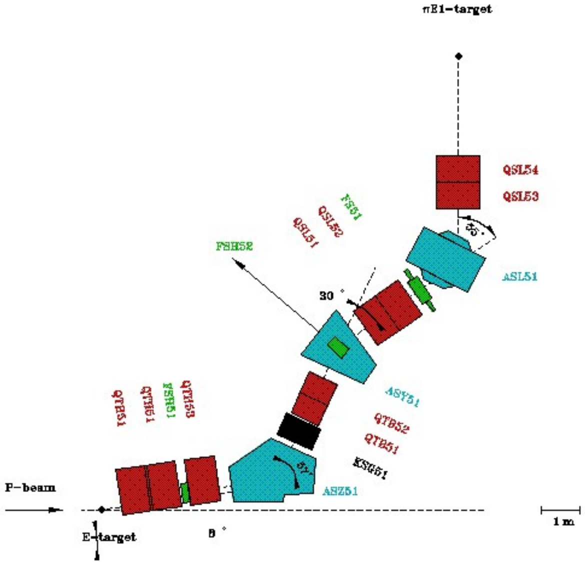
We will be able to give lower bounds on the masses of some hypothetical particles in theories beyond the standard model.
Following the calculations in Shanker, NP B204 (82) 375:

Particle	Projected Lower Bound	Current Bounds
Charged Higgs Boson:	$m_H > 6.9$ TeV	$m_H > 2$ TeV
Pseudoscalar Leptoquark:	$m_p > 3.8$ TeV	$m_p > 1.3$ TeV
Vector Leptoquark:	$M_G > 630$ TeV	$M_G > 220$ TeV

Paul Scherrer Institute

Villigen, Aargau, Switzerland

Beamline


πE1−target
QSL54
QSL53
FS51
QSL52
QSL51
FSH52
ASL51
30 °
ASY51
QTB52
QTB51
ASZ51
QTH51
FSH51
P−beam
E−target
1 m

Year 2006

- Beam Development Run.
- Detector Refurbishment (Same detector from PiBeta Experiment).
- Full detector was not in beamline.

Year 2007

- Experiment Development Run.
- Detector installed in beamline.

Year 2007

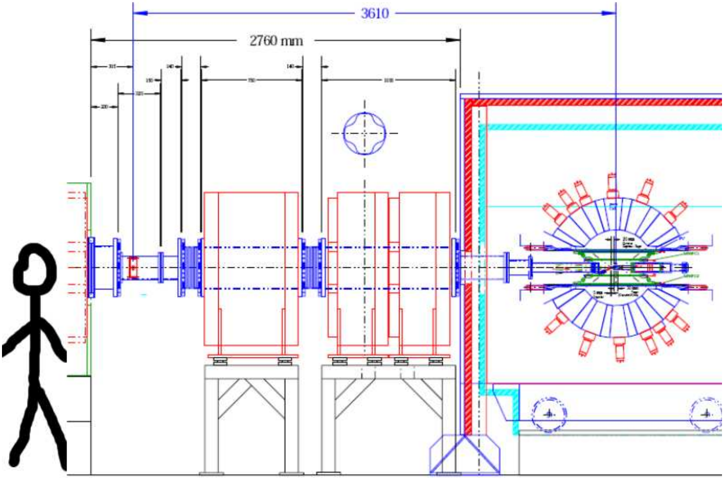
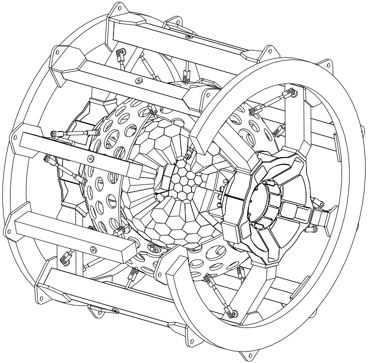
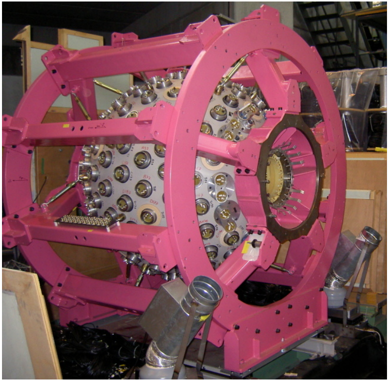


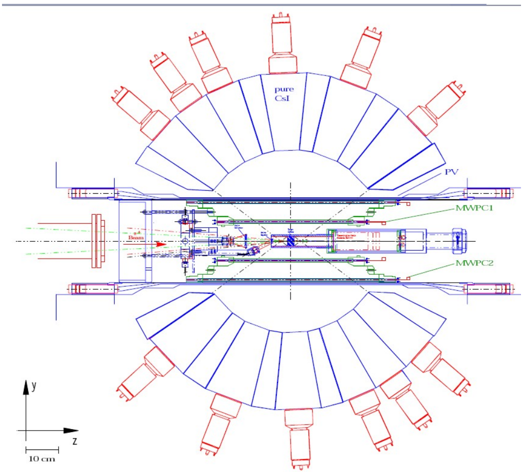
Figure: Beam Counter and Focusing Magnets.

Year 2007: PEN Detector



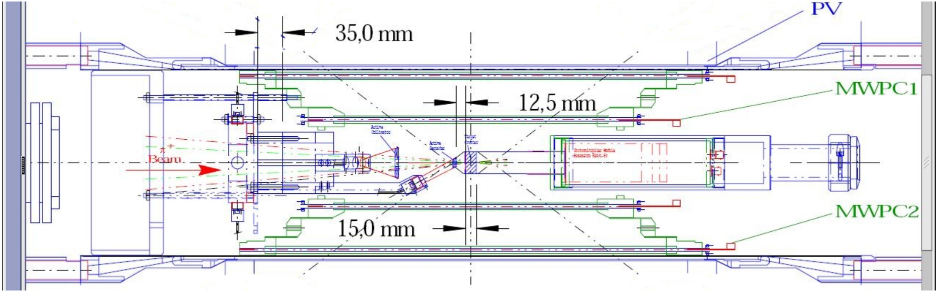


Year 2007: PEN Detector



Year 2007: PEN Detector

- Single piece active degrader.



Theory of π^+ Decay

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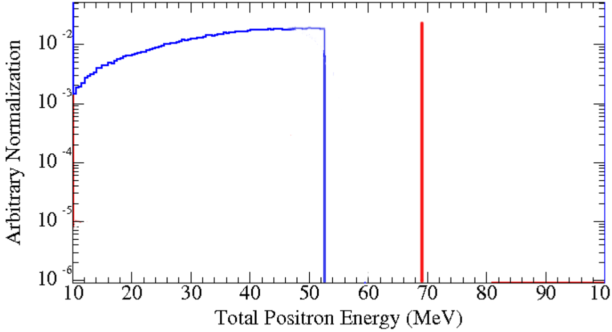
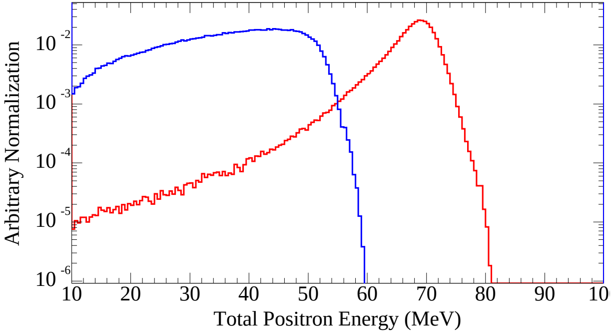


Figure: Non-realistic Case of Ideal Detectors

Simulated Tails



Must accurately distinguish the $\pi^+ \rightarrow e^+\nu_\mu$ events from the $\pi \rightarrow \mu \rightarrow e$ events.

Suppress the Michel events and recover the $\pi^+ \rightarrow e^+\nu_\mu$ tail.

Year 2007: Development Run Conclusions

- Recorded $\sim 3 \times 10^5 \pi^+ \to e^+ \nu_e$ decays
- New beamline plastic scintillator detectors
- Refurbished 20-piece cylindrical Plastic Hodoscope
- New temp. sensors
- New Slow Control System (temp., humidity, HV)
- New DAQ
- Various upgrades (FE electronics, etc.)

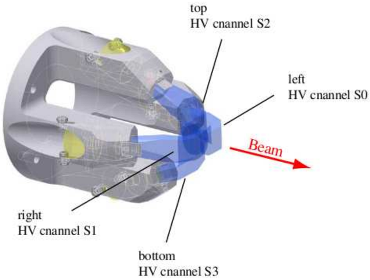
Problem:

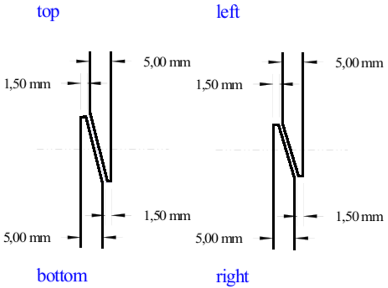
- π^+ decay vertex not known well enough $\Rightarrow$ e^+ energy resolution not good enough.

Solution for following run:
Implemented a novel, low cost, Wedged Degrader for *x*,*y* position sensitivity.

Year 2008: PEN Detector

Novel, low cost, four-piece, Wedged Degrader.





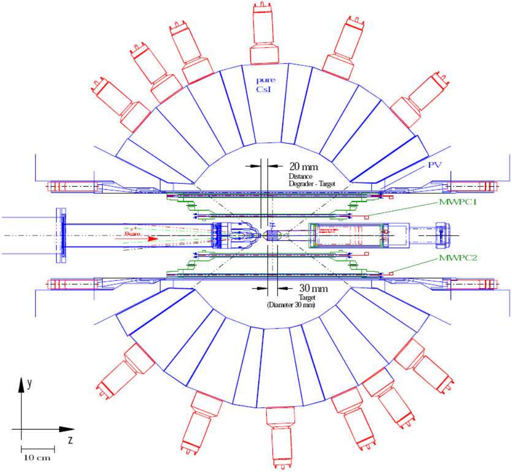
Pros:

- x,y position sensitivity

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

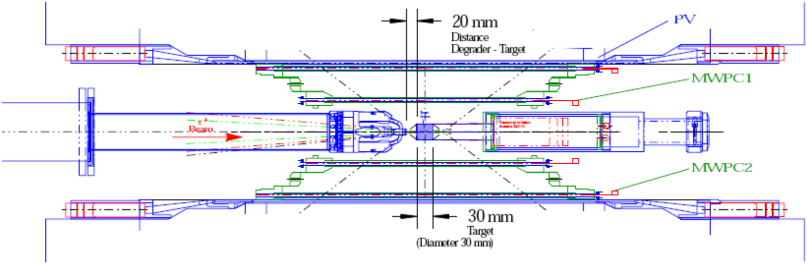
- higher beam momentum required ⇒ more nuclear reactions in target.
- more material increases multiple scattering ⇒ π position resolution suffers.

Year 2008: PEN Detector



Year 2008: PEN Detector

- Wedged four-piece active degrader.



Year 2008: PEN Detector

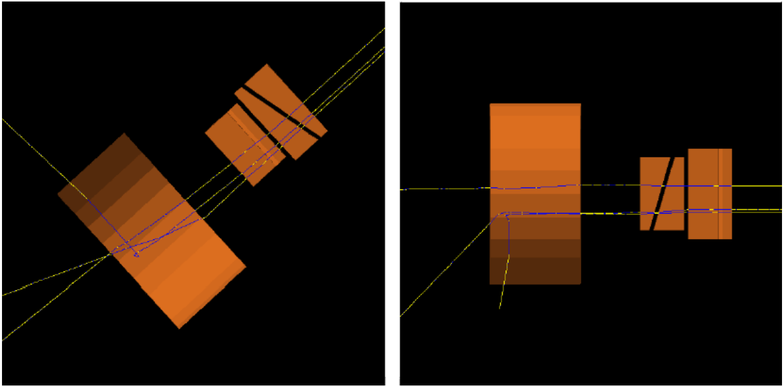


Figure: Simulation (E. Frlež) showing wedged-degrader and target.

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

Digitized PMT waveforms from three beamline detectors:

- Beam Counter
- Degrader (wedge: left,right,top,bottom)
- Target

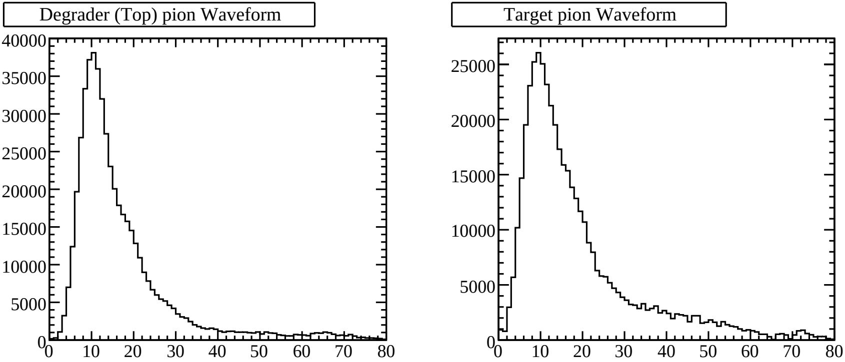


Figure: System Response Functions (Waveforms).

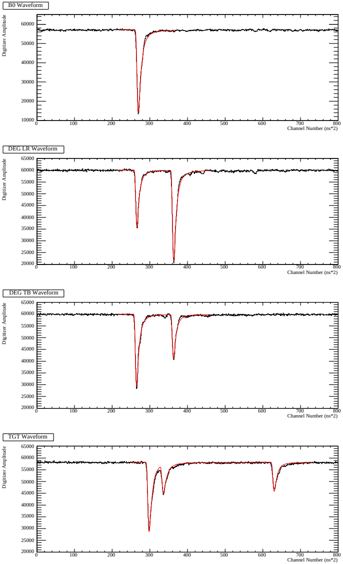


Figure: Fitted Digitizer Waveforms.

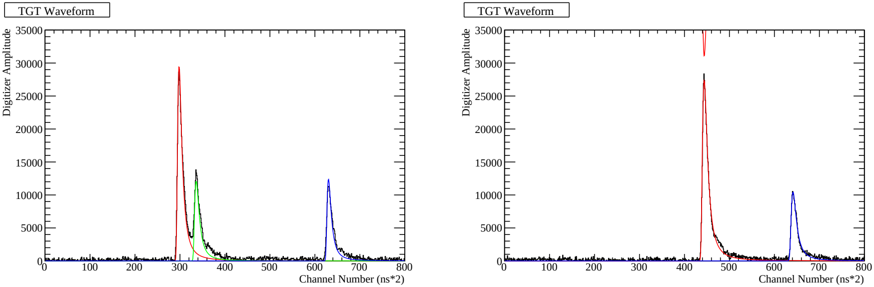


Figure: Michel vs. $\pi^+ \to e^+\nu_e$ Waveforms.

Target Waveform Fit Parameters

Pulse	Position in time (bin)	Amplitude
π^+	Known (from Degrader)	Known (from TOF and $E_{B0} + \sum E_{deg}$)
μ^+	Unknown	Known
e^+	Known (from Plastic Hod.)	Known (from tracking)

π^+ Position

Determined from bin position of π in degrader.

$\sigma \sim$ 110 ps

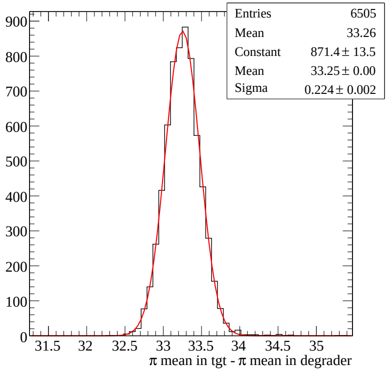


Figure: π^+ Bin Prediction Accuracy

π^+ Amplitude

Determined from TOF and the energy deposited in beam counter and degrader.

$\sigma \sim 0.47$ MeV$_{ee}$

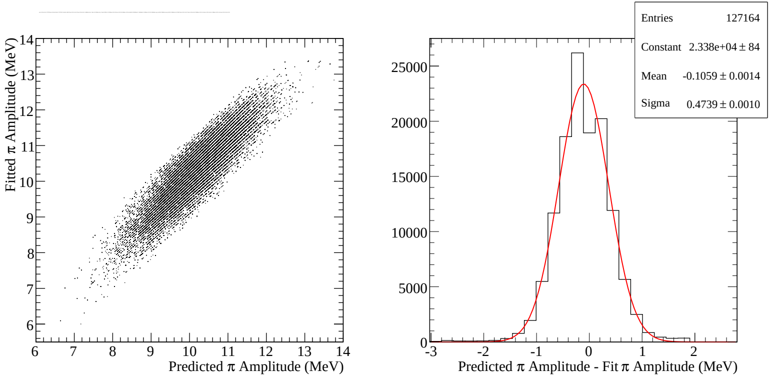


Figure: π^+ Energy Prediction Accuracy

e^+ Position

Determined from the time of the Plastic Hodoscope.
(Will improve once the 20 hodoscope staves are calibrated.)
$\sigma \sim 250$ ps

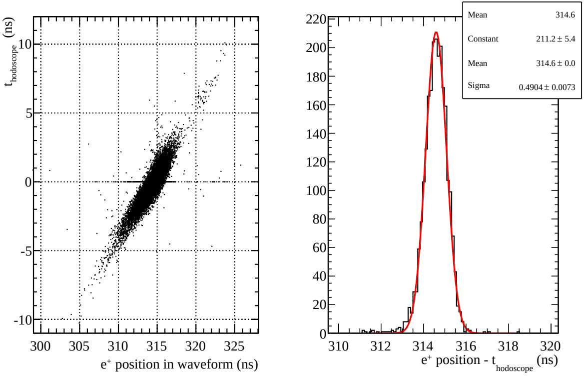


Figure: e^+ Timing Prediction Accuracy

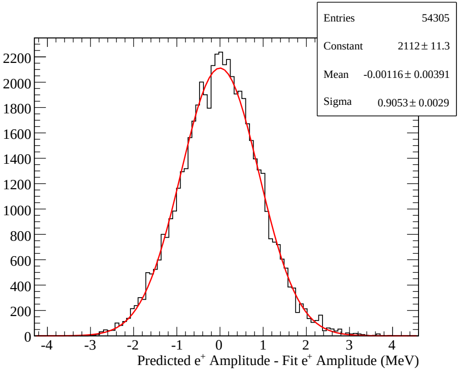
e^+ Amplitude

Determined from the distance e^+ travels in the target.

Requires knowledge of the positron decay vertex.

- π^+ entry position from wedged degraders.
- e^+ track from MWPC, Plastic Hodoscope, and CsI Calorimeter.

$\sigma \sim 0.9$ MeV$_{ee}$



μ^+ Amplitude

Known precisely since it is a two body decay.

$\sigma \sim 100$ keV$_{ee}$

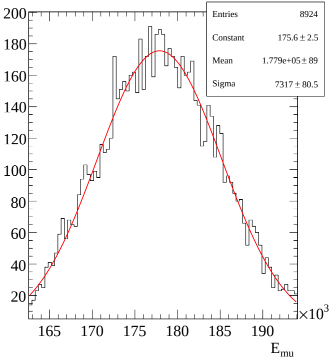


Figure: μ^+ Energy from Waveform, $\sigma/\text{mean} = 4.2\%$

Target Waveform Fit Parameters

Pulse	Position in time (bin)	Amplitude
π^+	$\sigma \sim$ 110 ps	$\sigma \sim$ 470 keV$_{ee}$
μ^+	Unknown	$\sigma \sim$ 100 keV$_{ee}$
e^+	$\sigma \sim$ 250 ps	$\sigma \sim$ 900 keV$_{ee}$

Target Waveforms

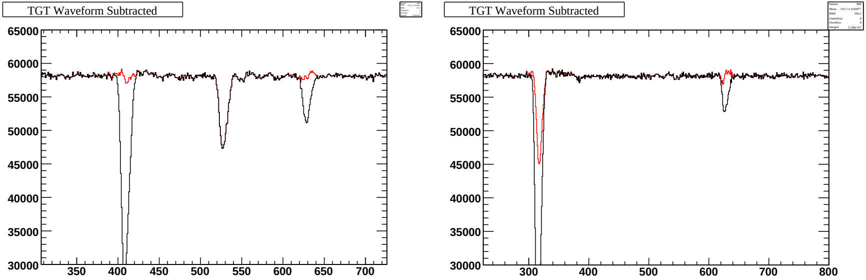


Figure: Target Waveforms before and after subtraction.

BOTH of these waveforms are $\pi^+ \rightarrow \mu^+ \rightarrow e^+$.

Waveform Analysis Result: π^+ Lifetime

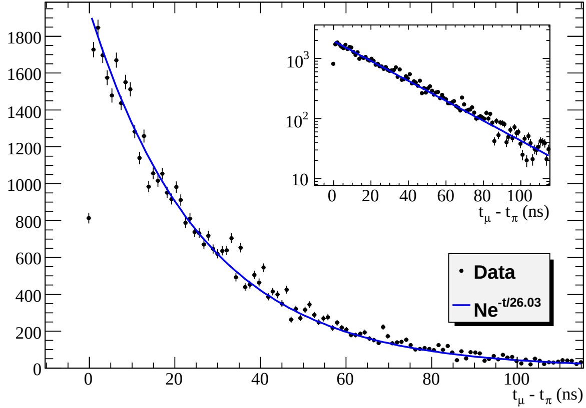


Figure: π^+ Lifetime, blue has fixed $\tau = 26.03$ ns

Another systematic uncert.: Decays in Flight (DIF)

$$\text{DIF} \sim O(10^{-4})$$

What happens if the π^+ decays before it stops?

In some cases this will cause a $\pi^+ \to \mu^+ \to e^+$ event to look like a $\pi^+ \to e^+$ event.

- forward DIF μ^+ go through the target
- backward DIF μ^+ don't have enough energy to appear as a π^+.
- it turns out that μ^+ traveling at $\theta \gtrsim 24^\circ$ mimic π^+ in terms of energy deposition.

Another systematic uncert.: Decays in Flight (DIF)

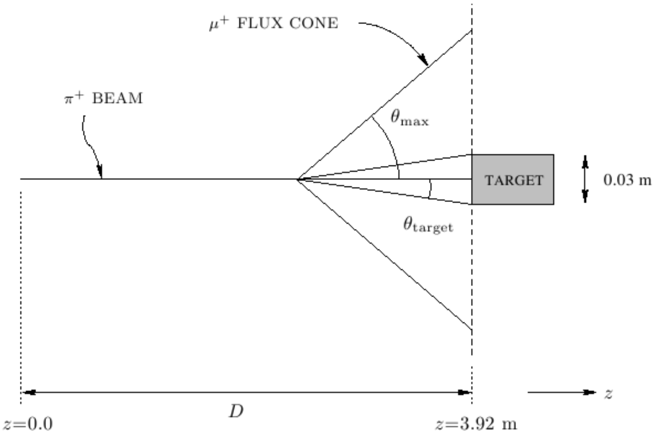


Figure: Decays in Flight

Another systematic: Decays in Flight (DIF)

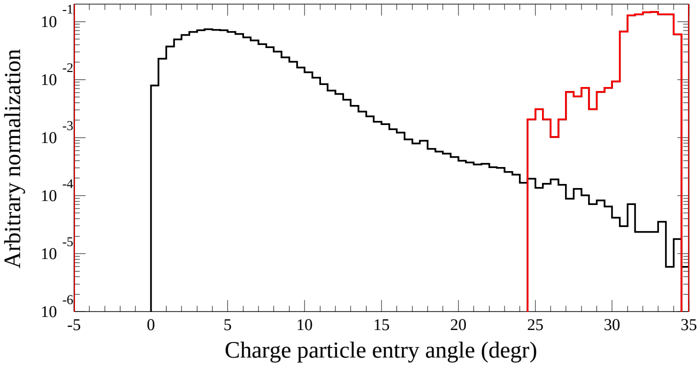


Figure: Simulated (M. Bychkov) π^+ entry angle (black), μ^+ entry angle (red)

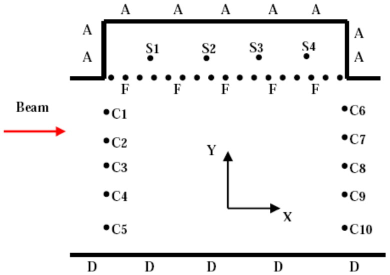
Method of Suppressing DIF

Solution for 2009 Run

Replace the Wedged Degrader with a Mini Time Projection Chamber.

- miniTPC currently under development at the Joint Institute for Nuclear Research, Dubna, Russian Federation.
- Will provide us with x,y position of particle entering the target
- Will give us the angle at which it enters the target
- Can go back to thinner single piece degrader
  $\Rightarrow$ Will reduce systematics introduced by wedged degrader while simultaneously helping us supress π decays in flight.

Mini Time Projection Chamber



A - Cathode
F - Grid
C - Potential electrodes
S - Anodes
D - U_{drift}

Figure: miniTPC

Time Fits to Obtain Branching Ratio

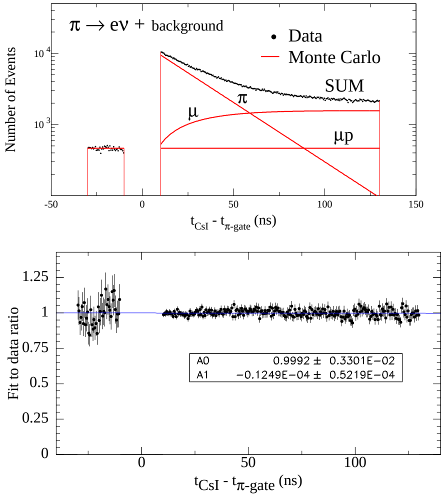


Figure: (2004 data)

Conclusion

- Two development/engineering runs completed (2007 & 2008).
- Ramped up to 30,000 stopped π^+/sec at 85 MeV/c momentum.
- Novel use of wedged degrader for position sensitivity.
- Digitized signals from active beam elements.
- 2007 & 2008 runs resulted in:
  $> 8 \times 10^{10}$ stopped pions
  $> 4.7 \times 10^{6}$ recorded $\pi^+ \to e^+ \nu_e$ decays
  $\Rightarrow \ (\delta B/B)_{stat} < 5 \times 10^{-4}$

  (Recall Goal: $(\delta B/B)_{stat} + (\delta B/B)_{sys} < 5 \times 10^{-4}$)
- Design of a miniTPC underway for the 2009 run.
- PEN Web page: http://pen.phys.virginia.edu

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