The PEN Experiment at PSI: Testing Lepton Universality

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Theory of π^+ Decay

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

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

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

Decay Mode	B_{exp}	
$\pi^+ \to \mu^+\nu_\mu(\gamma)$	$0.9998770(4)$	
$\pi^+ \to \mu^+\nu_\mu\gamma_{(E_\gamma > 1\text{MeV})}$	$2.00(25) \times 10^{-4}$	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. '86
$\pi^+ \to e^+\nu_e\gamma_{(E_\gamma > 10\text{MeV})}$	$7.386(54) \times 10^{-7}$	Bychkov et al. '09
$\pi^+ \to \pi^0 e^+\nu_e$	$1.036(6) \times 10^{-8}$	Pocanic 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 $\pi^+ \rightarrow e^+\nu_e$ 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,**

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

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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, $v_e > v_\mu \Rightarrow e$ is 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 $\pi^+ \to e^+\nu_e$ decay has a larger phase space than the $\pi^+ \to \mu^+\nu_\mu$ decay. $\Rightarrow$ gives a factor ~ 3.3

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

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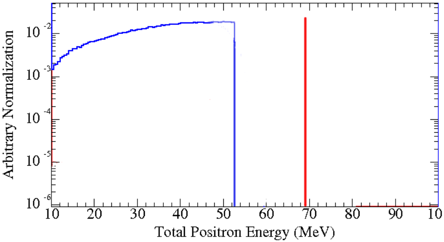
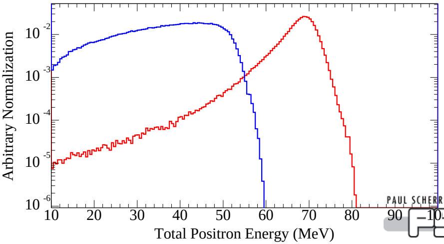
Theory of π^+ Decay

$\pi^+ \rightarrow e^+\nu_e$
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 $\pi^+ \to e^+\nu$ branching ratio.

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

$$B_{\text{calc}} = \begin{cases} (1.2352 \pm 0.0005) \times 10^{-4} \\ (1.2354 \pm 0.0002) \times 10^{-4} \\ (1.2352 \pm 0.0001) \times 10^{-4} \end{cases}$$

Marciano & Sirlin, [PRL **71**, 3629 (1993)]
Finkemeier, [Phys. Lett. B **387**, 391 (1996)]
Cirigliano & Rosel, [PRL **99**, 231801 (2007)]

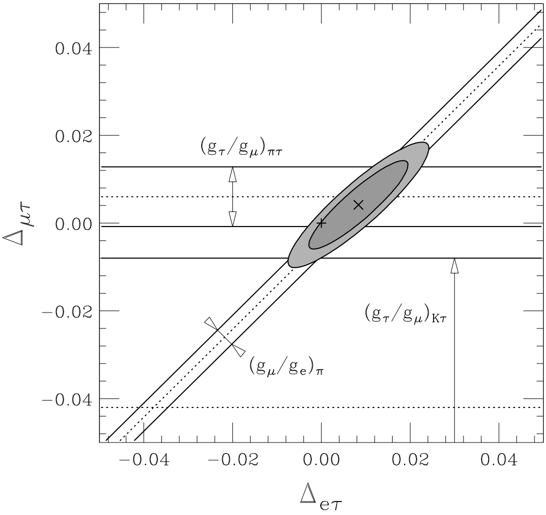
$$B_{\text{exp}} = (1.230 \pm 0.004) \times 10^{-4}$$ Experiment World Average (Current PDG)

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

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

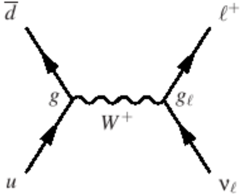
Our Goal: $\frac{\Delta B_{exp}}{B_{exp}} \leq 5 \times 10^{-4}$	PDG: $\frac{\Delta B_{exp}}{B_{exp}} \sim 3.3 \times 10^{-3}$

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:

- lepton non-universality,
- 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.

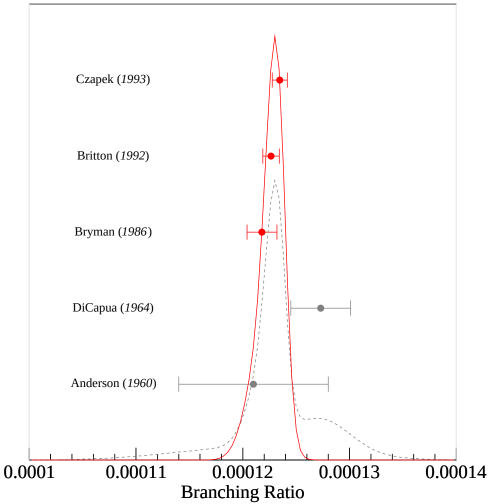
Mass Limits on Leptoquark and Supersymmetric Particles

A measurable deviation in B 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



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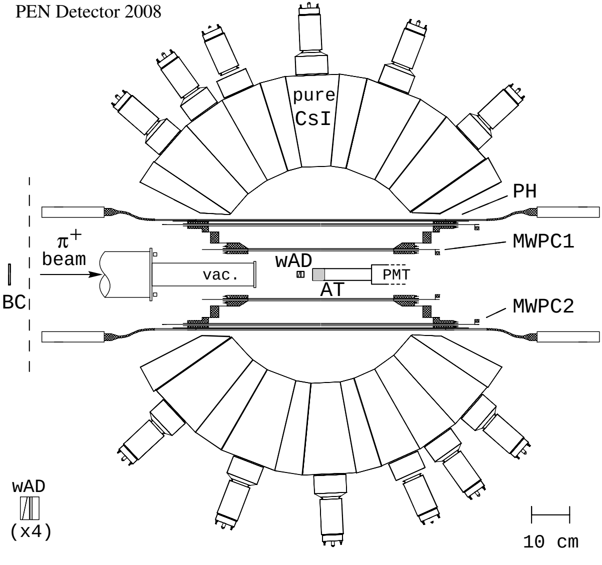
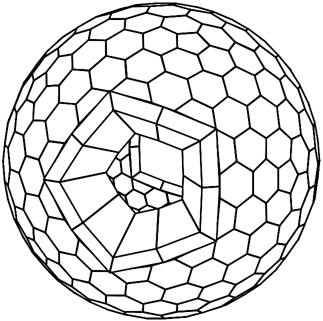
The PEN Apparatus

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

PEN Detector 2008





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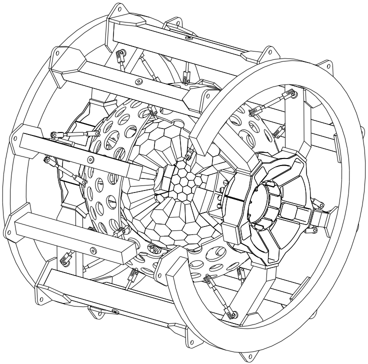
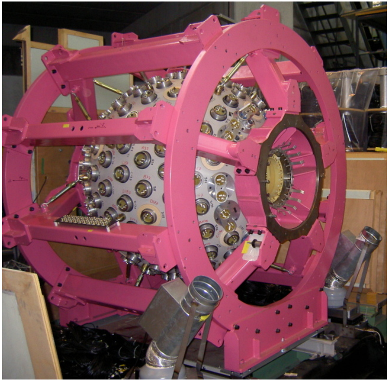
PEN Detector





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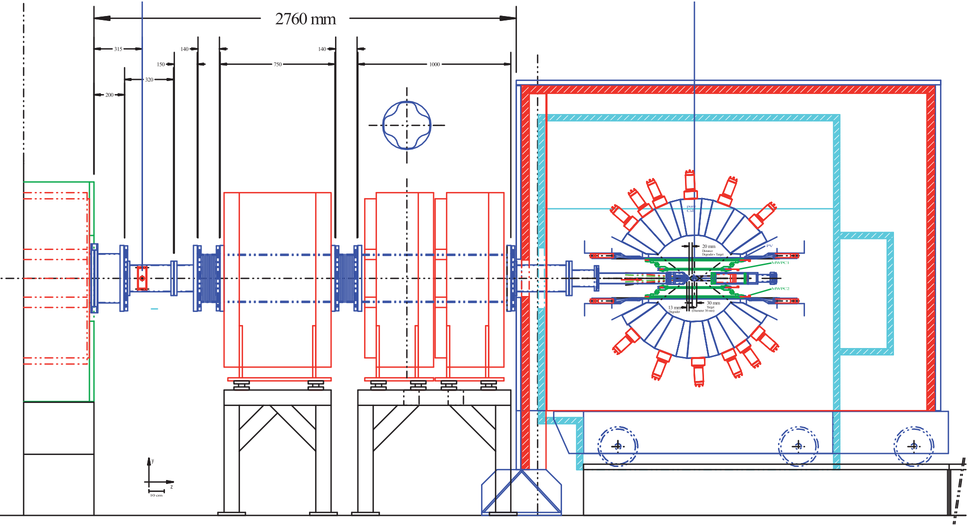
Beam Counter, Focusing Magnets, and Detectors



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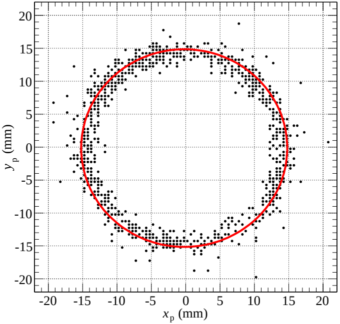
Example Calibration/Stabilization

- Checking the stability of the TGT position over time.



PEN Data Analysis

Strategy:

Determine the most likely value of the $\pi^+ \rightarrow e^+\nu_e$ 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 p.d.f.'s
- Use as much data as possible to determine B; loose cuts.

Complication:

- Critical dependence on p.d.f.

Maximum Likelihood Analysis

One likelihood function encompassing many observables and processes.

$$\mathcal{L}\left(\mathbf{x};\overrightarrow{N}\right)=\prod_{i=1}^{\mathcal{N}}\left[\sum_{m=1}^{M} f_m\left(\overrightarrow{x}_i;N_m\right)\right]$$

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

$(\overrightarrow{x}_i)$ 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.

(N_m) normalization of process m

- N_{p2e}, $\pi^+\to e^+$ (p2e)
- N_{mich}, $\pi^+\to\mu^+\to e^+$ (Michel)
- N_{acc}, Accidentals / Pile-up
- N_{dif}, Pion Decays-in-flight
- N_{P}, Proton
- $N_{?}$, etc.

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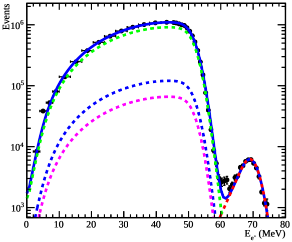
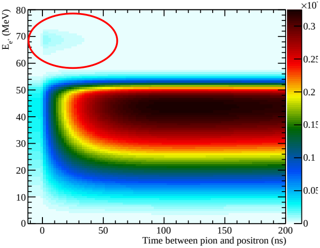
Model: Probability Density Functions

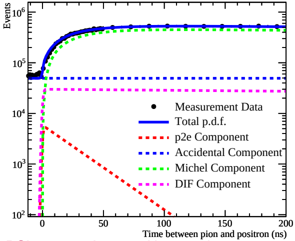
$$\mathcal{L}\left(\overrightarrow{E}, \overrightarrow{t}; N_{p2e}, N_{mich}, N_{acc}, N_{dif}\right)$$





Maximization Techniques:

- Binned vs. Unbinned
- Maximum Likelihood Fit
- χ^2 Fit
- Negative Log Likelihood, $\ell = -\ln\mathcal{L}$



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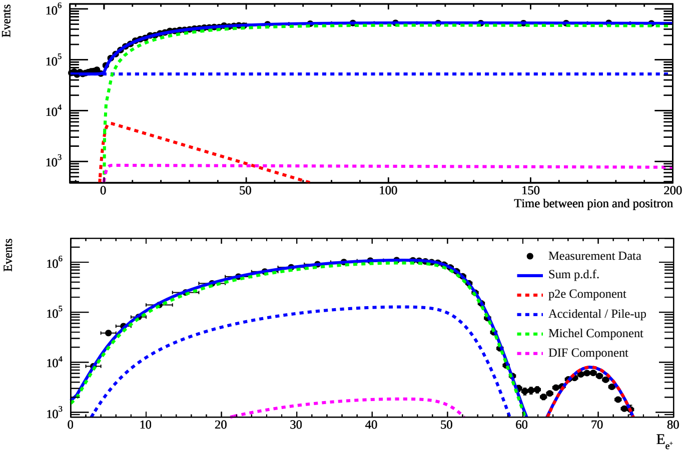
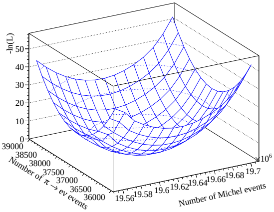
Measurement: Data



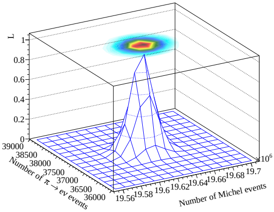
Variable Binning → Improvement in calculation speed.

Techniques: Negative Log Likelihood

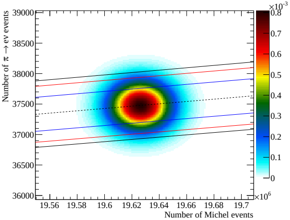
$\ell = -\ln\mathcal{L}$



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



N_{p2e} vs. N_{michel}



Use of standard software libraries MINUIT, MIGRAD, HESSE, and MINOS on ℓ. Use of ROOFIT and ROOSTATS to set up model p.d.f.

Maximum Likelihood Analysis

- Still in very early stages
- Critical dependence on p.d.f.'s

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Maximum Likelihood Analysis

- Still in very early stages
- Critical dependence on p.d.f.'s

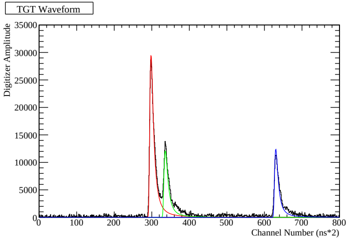
How do we determine the p.d.f's?

- Obtain guidance from GEANT4 simulation
- Use the measurement data itself
  - Make cuts to isolate each process
  - Use a target waveform analysis

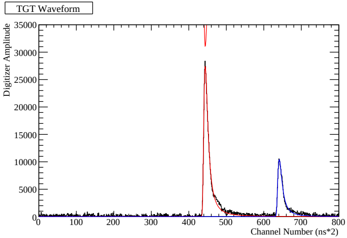
Target Waveform Analysis

Why?

- To provide cuts useful for distinguishing the various processes
- Potential new observables for likelihood analysis



Michel Event



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

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

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Response Functions

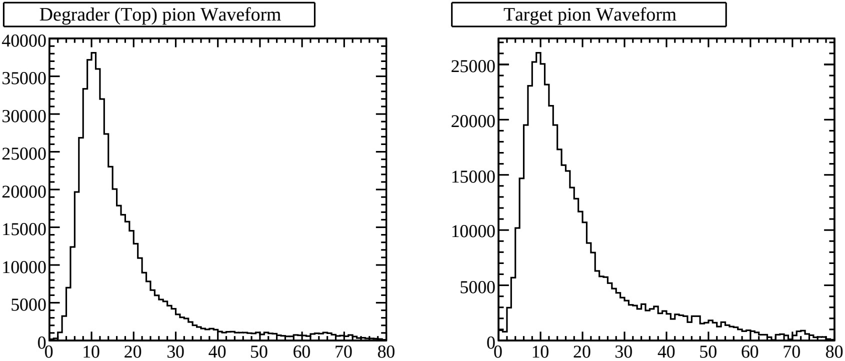


Figure: System Response Functions (Waveforms).

Pulse Shaping

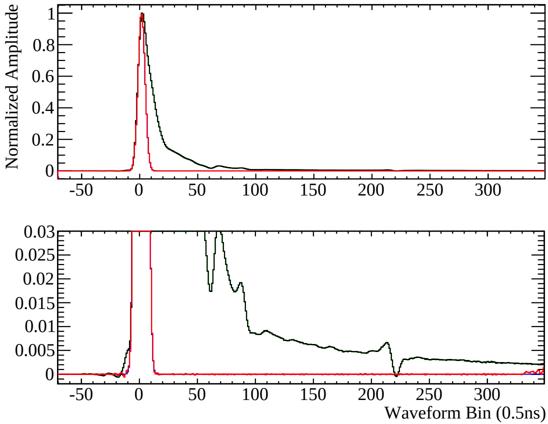
Developed an iterative program to create a digital adaptive filter.

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 $k \equiv i - j$

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Pulse Shaping

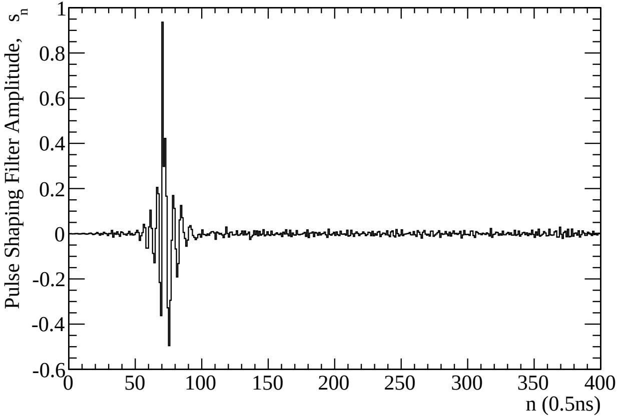


Figure: Pulse Shaping Filter.

Target Waveform Fit Parameters

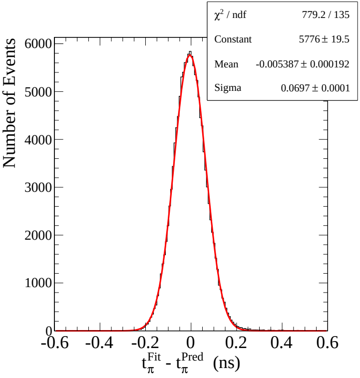
Pulse	Position in time (bin)	Amplitude
π^+	Known (from Degrader)	Known (from TOF and $E_{B0} + \sum E_{deg}$)
μ^+	Unknown	Known
e^+	Known (from Plastic Hod.)	Known (from tracking)

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$_{ee}$

π^+ Time

Determined from timing of π in degrader.

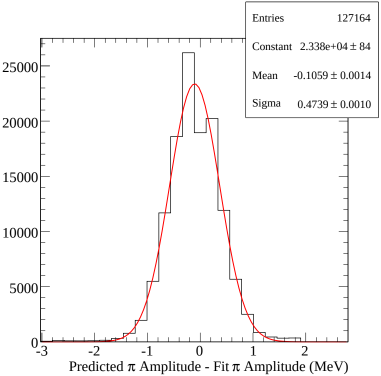
$\sigma \sim 69.7$ ps



π^+ Amplitude

Determined from TOF and the energy deposited in the degrader.

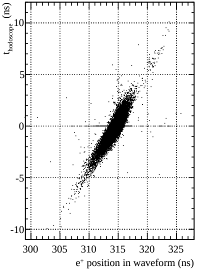
$\sigma \sim 0.47\ \mathrm{MeV}_{ee}$

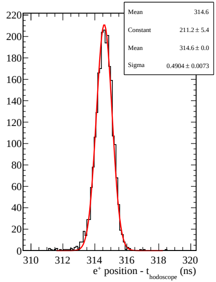


e^+ Time

Determined from the time of the Plastic Hodoscope.

$\sigma < 250$ ps





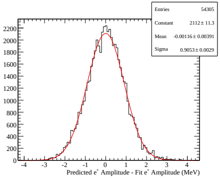
e^+ Amplitude

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

Requires knowledge of the positron decay vertex.

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

$\sigma \sim 0.9$ MeV



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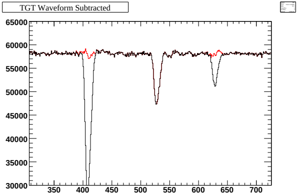
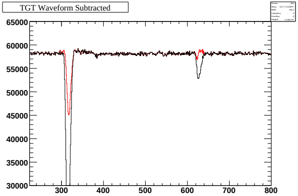
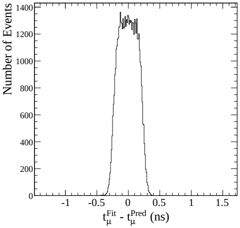
μ^+ Time

Determined by the subtracting the predicted π^+ and e^+ pulses.



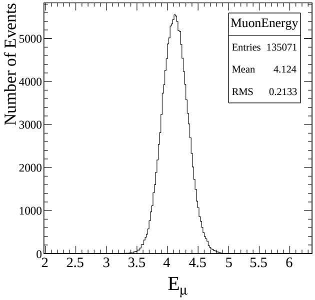


Results in non-gaussian prediction resolution:



μ^+ Amplitude

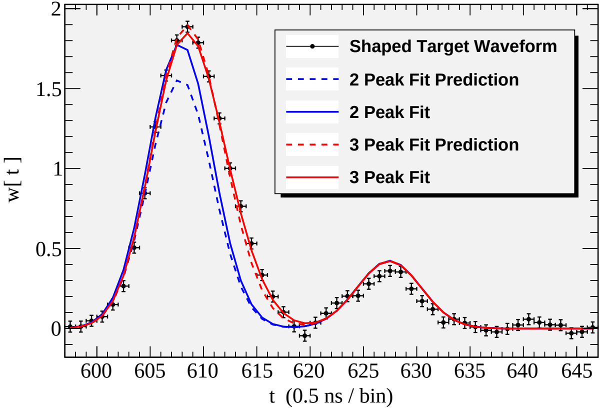
Known precisely since it is a two body decay.
$\sigma \sim 200\ \text{keV}_{ee}$
RMS/mean = 5.1%



Waveform Fitting

Modified χ^2 Function:

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



Waveform Fitting

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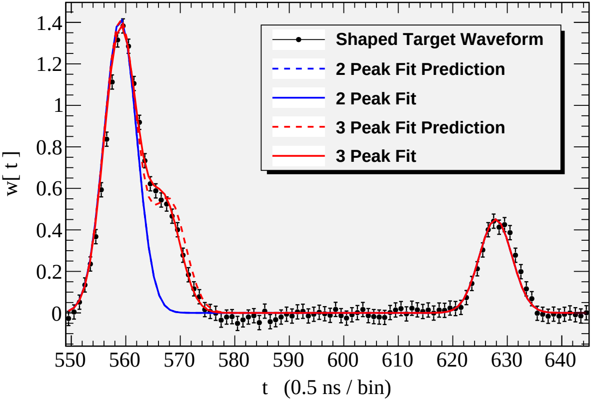
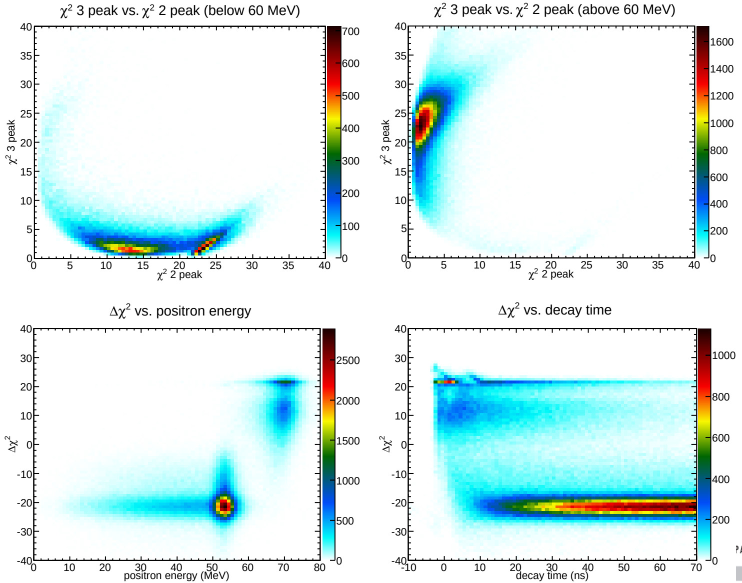


Waveform Fitting Results



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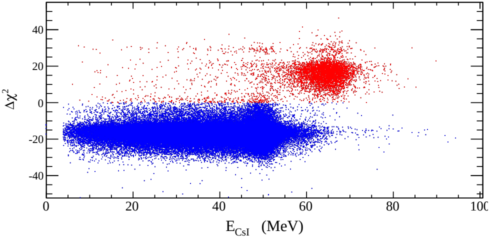
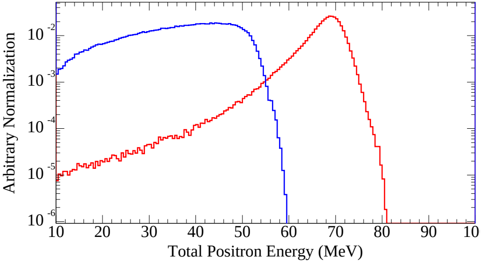
PSI

Waveform Fitting Results





Waveform Fitting Results

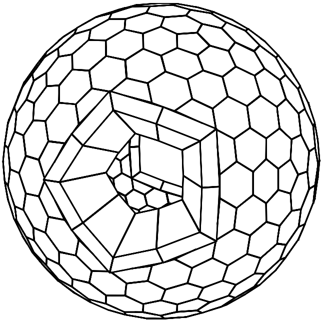
A source of systematic uncertainties:

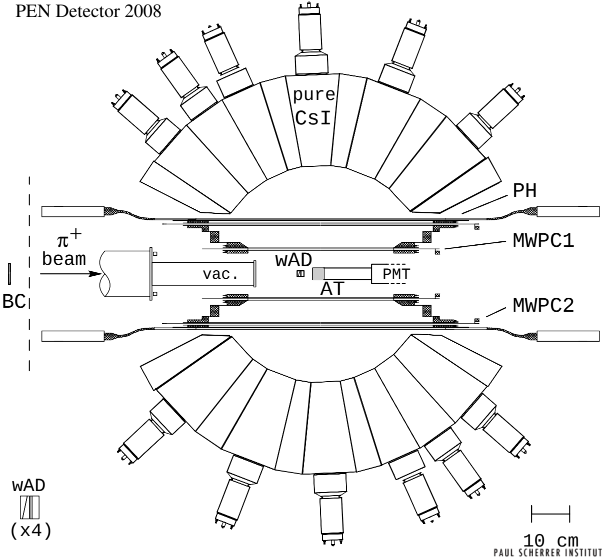
- Positron Energy in the target

Let's revisit the detector...

The PEN Apparatus: 2008

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





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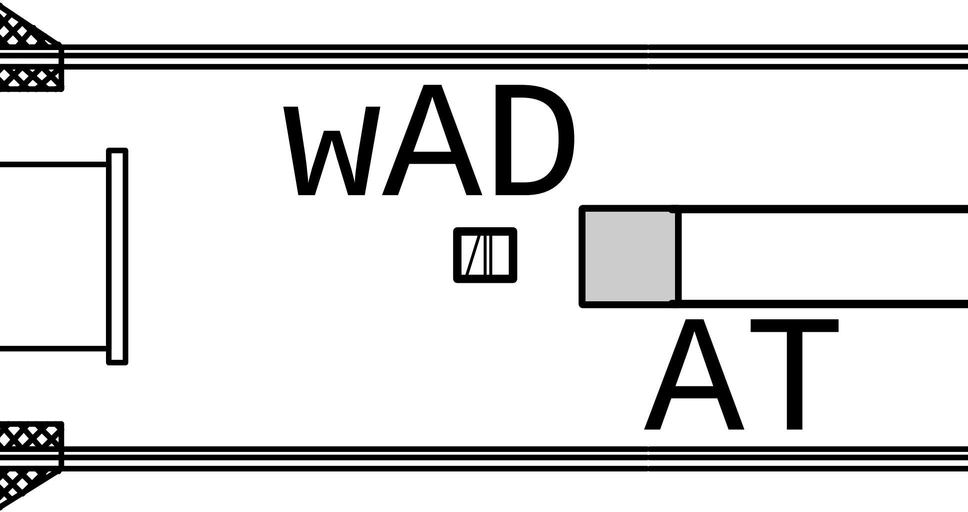
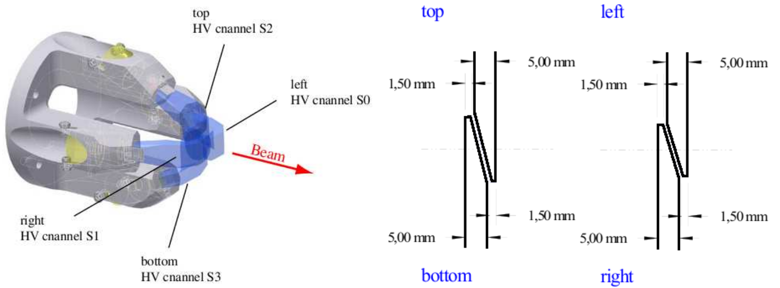
The PEN Apparatus: 2008



The PEN Apparatus: 2008

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



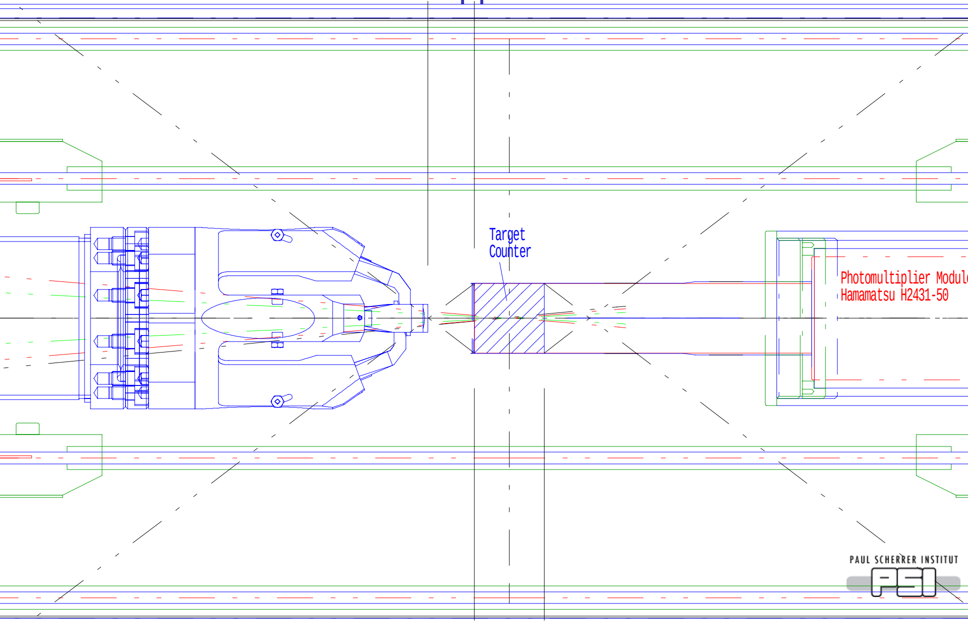
Pros:

- x,y position sensitivity of beam π^+

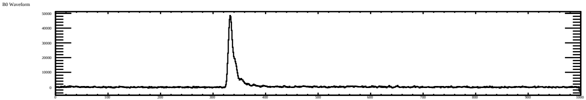
Cons due to thicker degrader (13mm as opposed to 5mm):

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

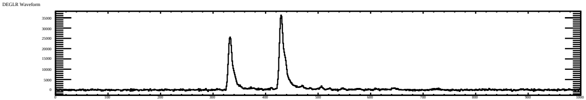
The PEN Apparatus: 2008



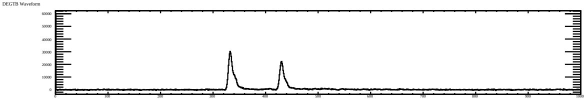
Fwd Beam Counter



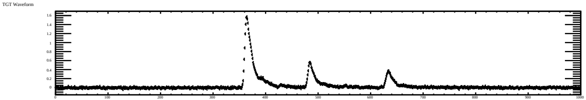
Degrader Top & Bottom



Degrader Left & Right

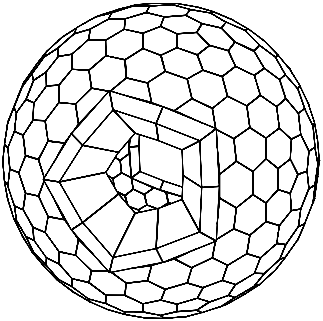


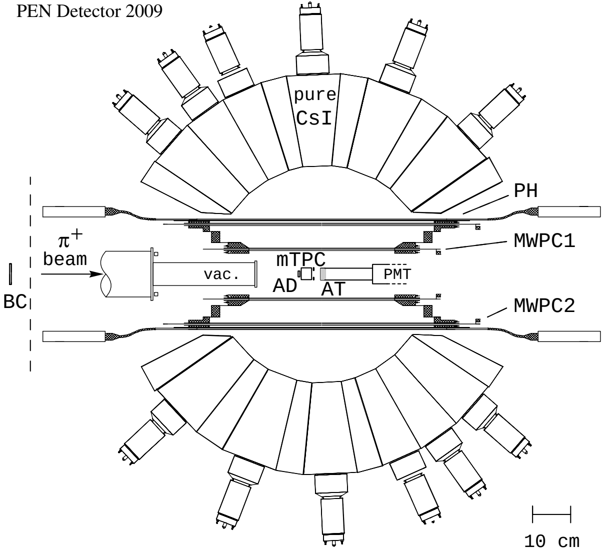
Target



The PEN Apparatus: 2009

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





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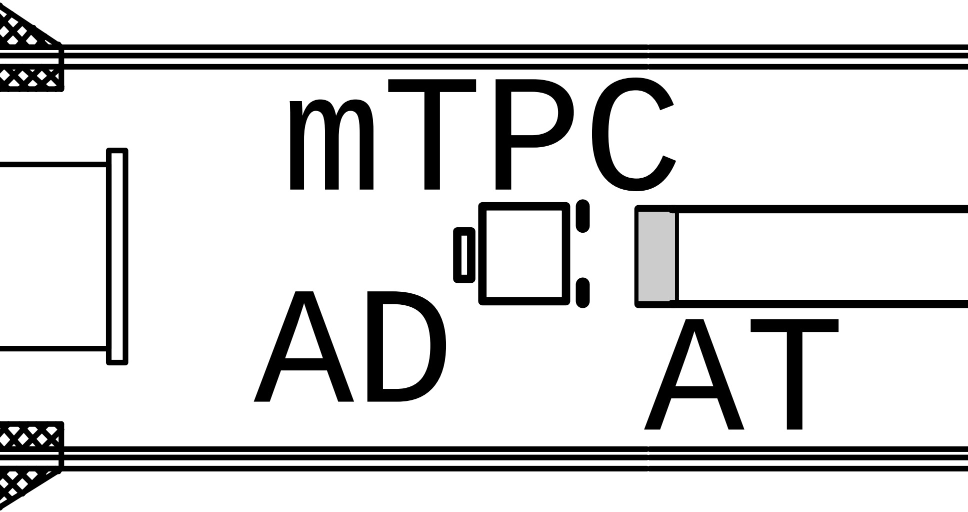
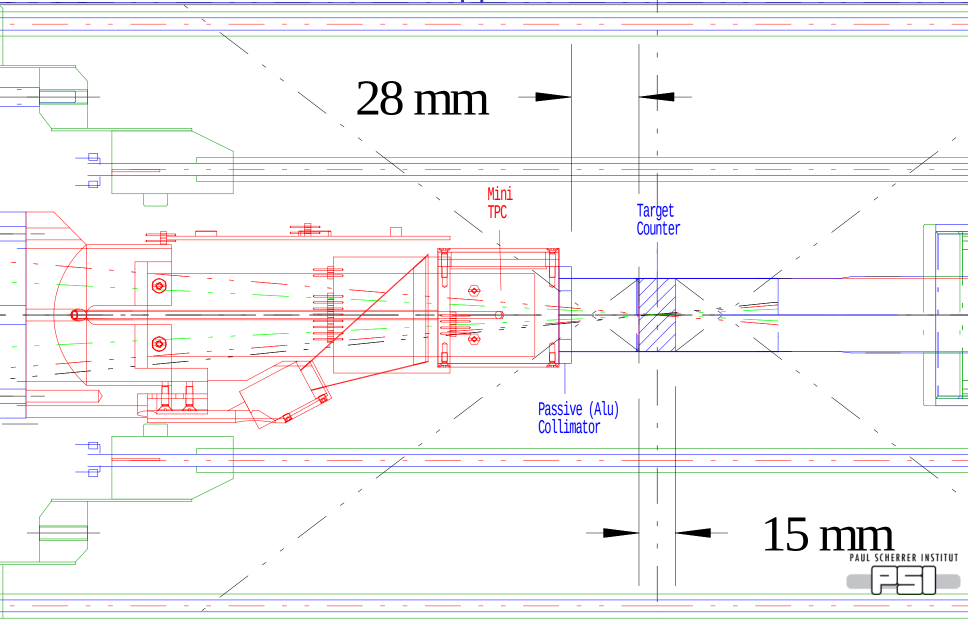
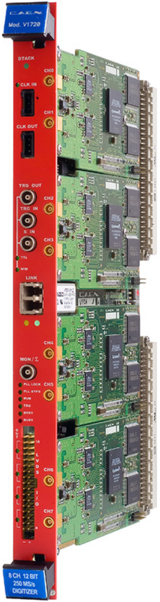
The PEN Apparatus: 2009

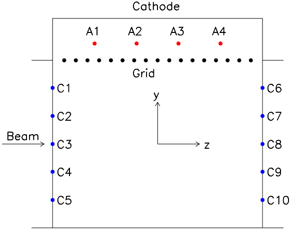


The PEN Apparatus: 2009



mTPC Technical Specifications





- Proportional Region: 40x6x40 mm
- Drift Region: 40x40x50 mm
- Drift Gas: 90% He and 10% C_2H_6
- 4000 V across drift region
- Grid: 50 μm wires with 1 mm spacing
- Nichrome Anode Wires
  - 40 mm length
  - 20 μm diameter
  - 10 mm spacing
  - 235 Ω resistance
- CAEN VME digitizer V1720

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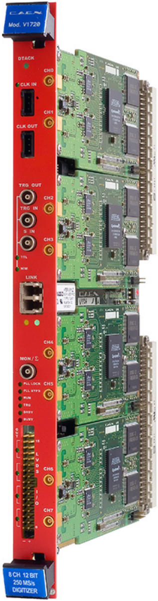
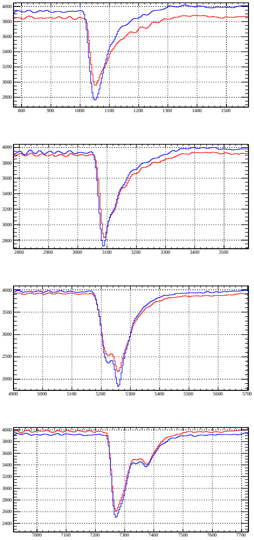
Waveform Digitization





- Red: Left
- Blue: Right

Pion Tracking:

- x: charge division
  Relative amp. left : right
- y: drift time
  Time of rising edge
- z: wire location
  Physical mounting

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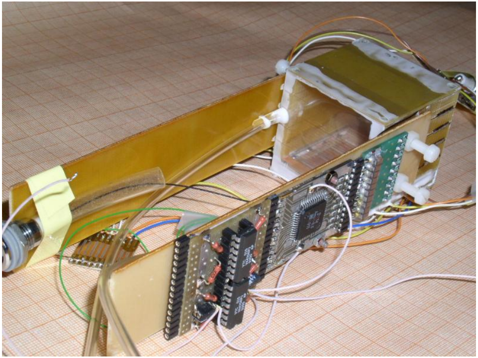
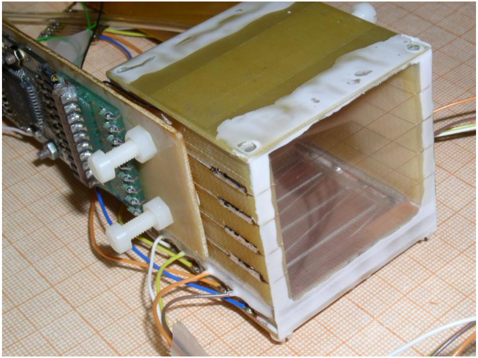
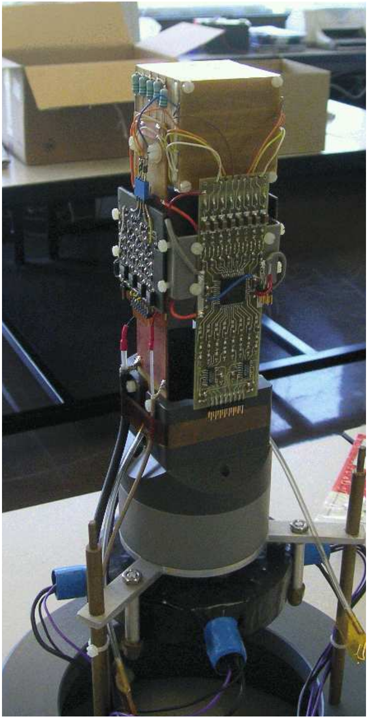
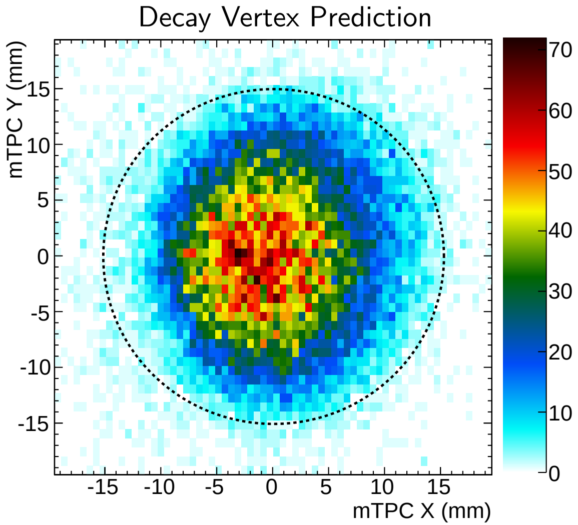






Results from 2009 Data Run



- X Position
  - charge division
  - $\sigma_x < 1.3\,\mathrm{mm}$
- Y Position
  - drift time
  - $\sigma_y < 0.35\,\mathrm{mm}$

Another systematic uncert.: Decays in Flight (DIF)

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

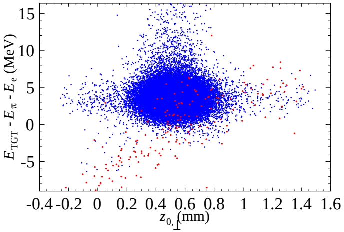
What happens if the π^+ decays before it stops?

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

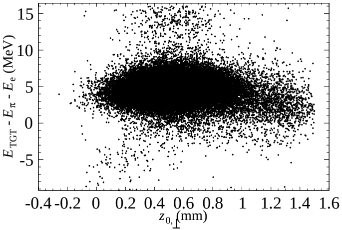
- forward DIF μ^+ go through the target
- backward DIF μ^+ don't have enough energy to appear as a π^+.
- it turns out that μ^+ traveling at $\theta \gtrsim 24^\circ$ mimic π^+ in terms of energy deposition.

π Decays-in-flight

GEANT4 Simulation (M. Bychkov)



PEN Measurement



Decays-in-flight shown in red.

Conclusion

Year 2006 (Beam Development Phase):

- Detector Refurbishment (Same detector from PiBeta Experiment).

Year 2007 (Experiment Development Phase):

- Many new components and upgrades.
- Recorded $\sim 3 \times 10^5 \pi^+ \to e^+ \nu_e$ decays

Year 2008 (1st Production Phase):

- Use of wedged degrader for π tracking.

Year 2009 (2nd Production Phase):

- Use of mini-TPC for improved π tracking.

2008 & 2009 runs resulted in $\gtrsim 1.24 \times 10^7$ recorded $\pi^+ \to e^+ \nu_e$ decays

$$\Rightarrow \ (\delta B/B)_{stat} < 2.84 \times 10^{-4}$$

(Recall Goal: $(\delta B/B)_{stat} + (\delta B/B)_{sys} < 5 \times 10^{-4}$)

Year 2010 (3rd Production Phase):

- Goal of $\sim 25 \times 10^6$ more $\pi^+ \to e^+ \nu_e$ decays

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⋆ = Spokesperson

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