PEN Experiment

Charles Glaser

University of Virginia

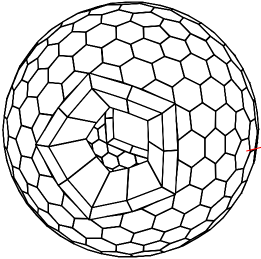
PEN Collaboration

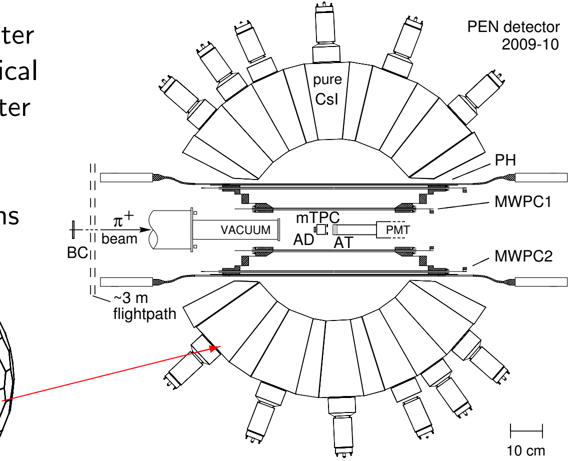
Overview

- Detector
- PEN approach
- Simulation
- Tools
- Where we are

Detector Setup

- πE1 beamline at PSI
- stopped π^+ beam
- active target counter
- 240 module spherical pure CsI calorimeter
- central tracking
- beam tracking
- digitized waveforms



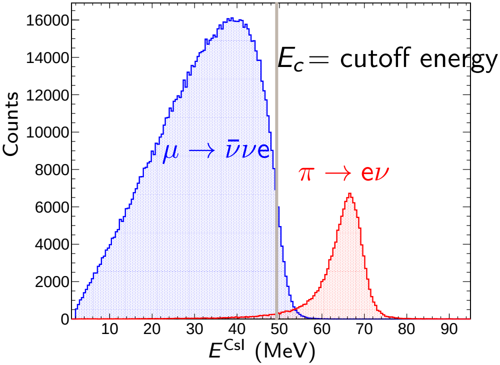


BC: Beam Counter
AD: Active Degrader
AT: Active Target

PH: Plastic Hodoscope (20 stave cylindrical)
MWPC: Multi-Wire Proportional Chamber (cylindrical)
mTPC: mini-Time Projection Chamber

PEN analysis approach

$$R^{exp}_{\pi 2e} = \frac{N_{peak}}{N_{\pi\to\mu\nu(\gamma)}} \times (1 + \epsilon_{tail}) \times \text{corrections}$$



PEN analysis approach

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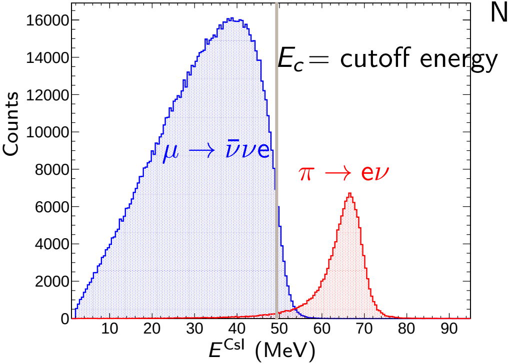
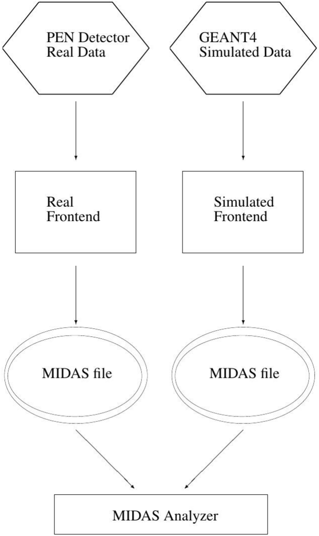


Need:

- $N_{\pi\to\mu\nu(\gamma)}$ (Data)
- N_{peak} (Data)
- Tail fraction (Simulation)
- Time window (Data/theory)
- Cut efficiencies/acceptances
- etc. (Simulation)

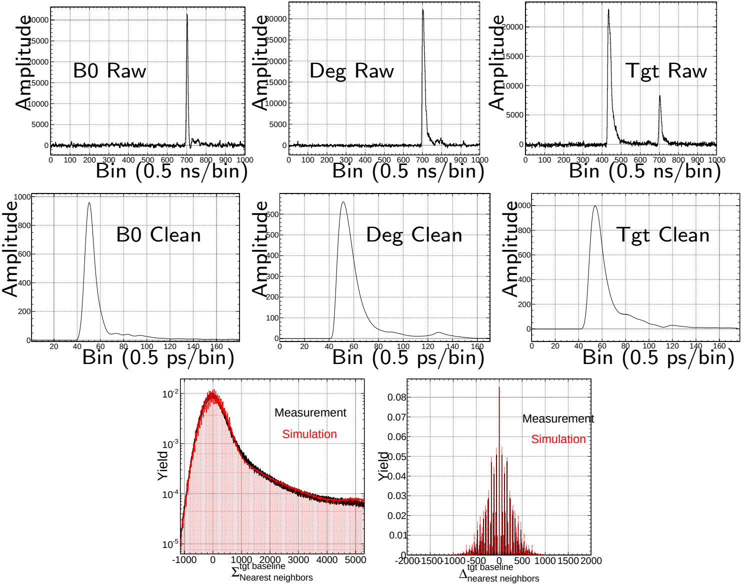
Used to determine tail fraction, acceptances, systematics etc ...
Ultra-realistic simulation required!



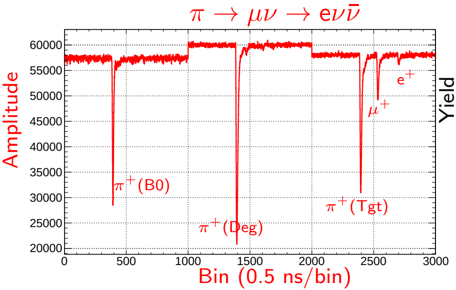
- Synthetic waveforms and baseline
- Detector responses
- Electron equivalent energies
- Correct beam profile and detector r
- Pedestals
- Attenuation of signals
- Correct CsI responses

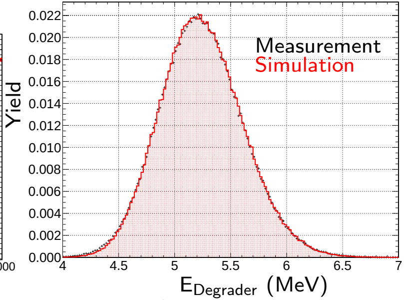
Output of analyzer indistinguishable

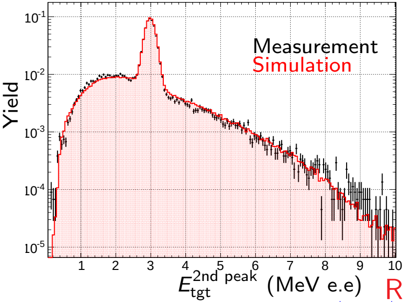
Responses


B0 Raw
Deg Raw
Tgt Raw
Amplitude
Bin (0.5 ns/bin)
B0 Clean
Deg Clean
Tgt Clean
Bin (0.5 ps/bin)
Measurement
Simulation
Yield
$\Sigma^{\text{tgt baseline}}_{\text{Nearest neighbors}}$
$\Delta^{\text{tgt baseline}}_{\text{nearest neighbors}}$

Outputs







Synthetic waveforms are constructed

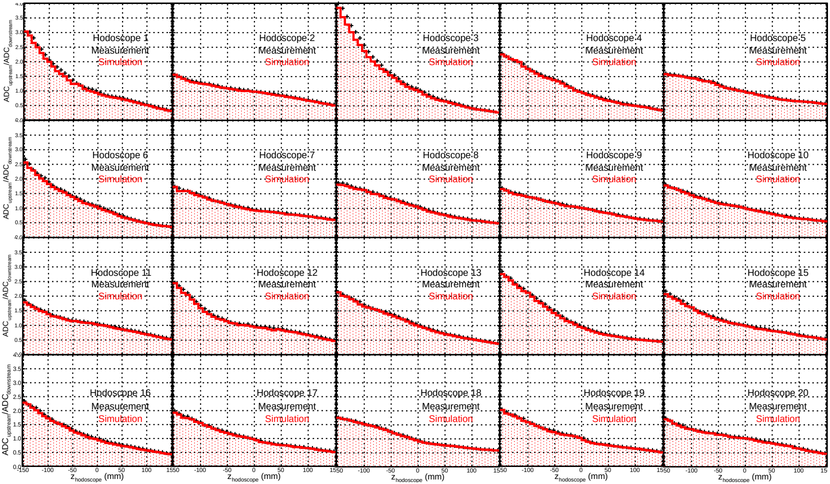
Electron equivalent energies used for ampl

Timing for position

Photo electron statistics/ "smearing"

Reconstructed observables indistinguishable

Hodoscopes

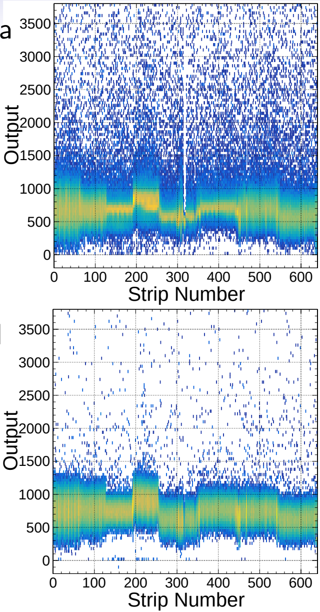


Attenuation of signal is simulated for all 20 staves

MWPCS

Data

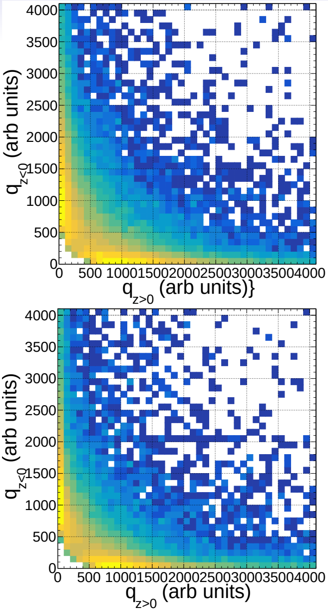
SIM



MWPC pedestals

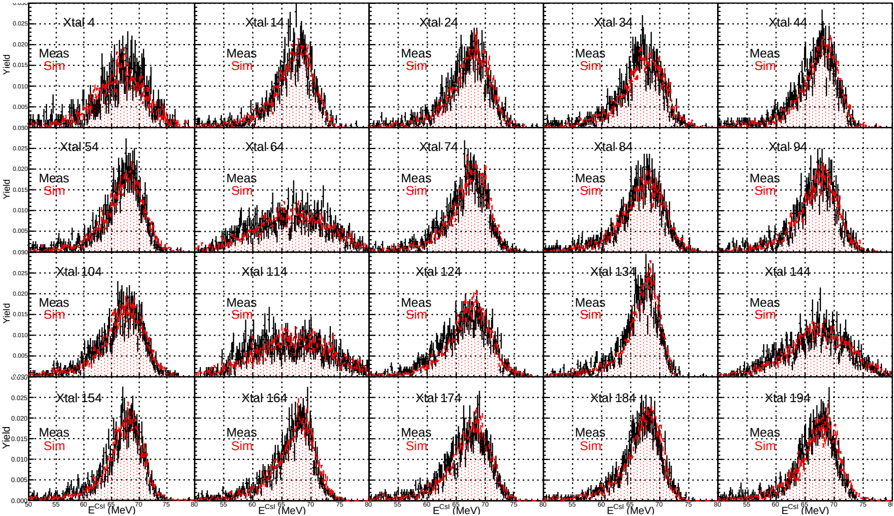
Data

SIM



Charge up vs down z around 0

CsI



Non-uniformities, efficiencies, etc all unique to each crystal

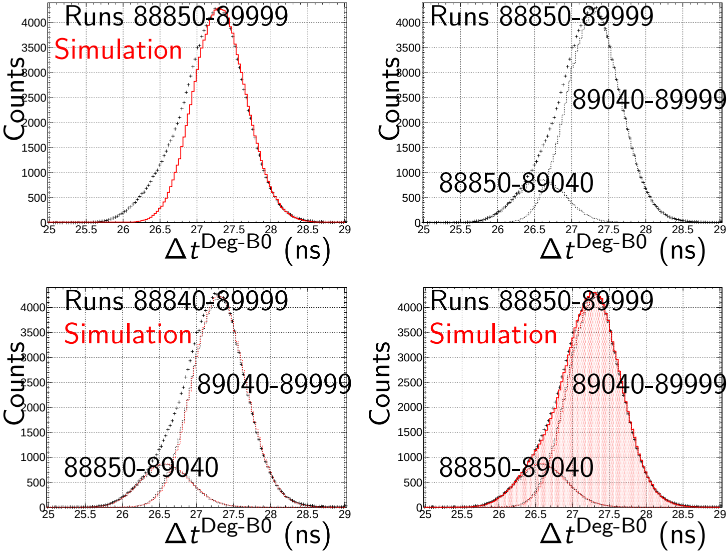
Run changes

run 1	run 2	run 3
1 geometry	7 geometries	4 geometries
2 momenta	8 momenta	4 momenta
4 wedged deg	5 mm deg	7 mm deg
No mtpc	mtcp 10mm sep	mtcp 12.5mm sep
Supercluster trig	Simple trig	Simple trig
1232 runs	6427 runs	6606 runs

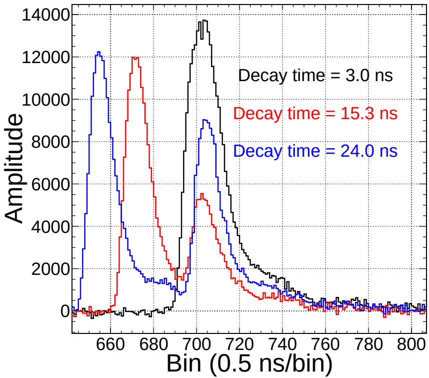
12 simulation configurations needed to fully simulate PEN

Debugging/blinding uses one simulation each for runs 2 and 3

One geometry, different momentum



Target responses



Decay time $= t_e^{\text{birth}} - t_\pi^{\text{stop}}$

As few as 1 peak

$$\pi \xrightarrow[\text{fast}]{} e\nu$$

$$\pi \xrightarrow[\text{fast}]{} \mu\nu \xrightarrow[\text{fast}]{} e\nu\bar{\nu}$$

At most 3 peaks

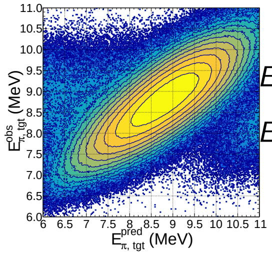
$$\pi \xrightarrow[\text{slow}]{} \mu\nu \xrightarrow[\text{slow}]{} e\nu\bar{\nu}$$

Different decays produce different target responses

Peak pileup complicates energy and timing extraction

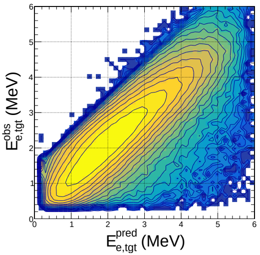
Need more than just target responses

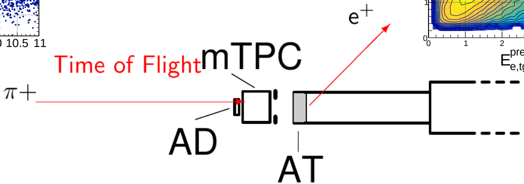
Predicting times and energies

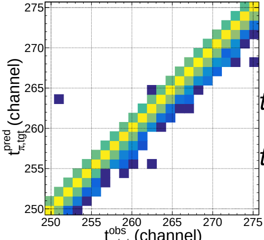


E_π : TOF + AD

E_e : MWPC + mTPC

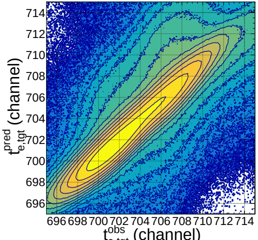




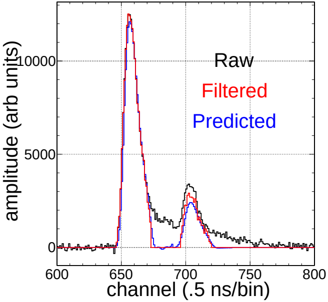


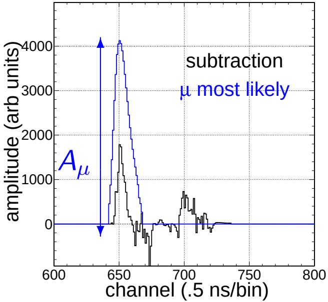
t_π : TOF + AD

t_e : MWPC + mTPC +HOD



Predict the tgt waveform





Create a predicted waveform

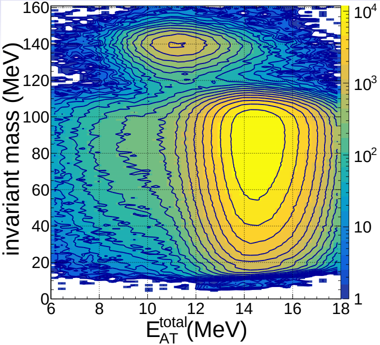
Compare predicted and filtered, $\chi^2_{\text{2-peak}}$

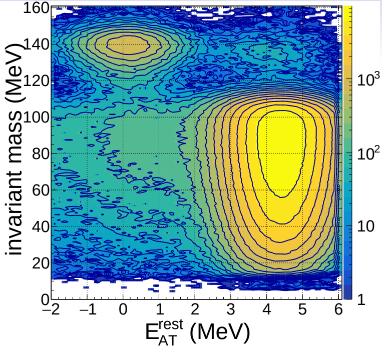
Subtract predicted and filtered

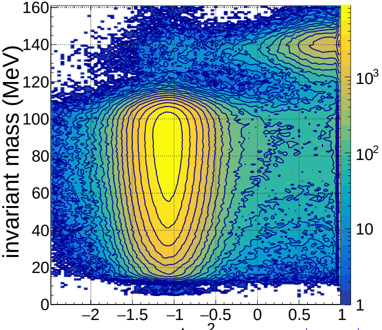
Muon placed at each bin between π and e

Peform comparison at each bin $\chi^2_{\text{3-peak}}$

Take $\chi^2_{\text{3-peak,min}}$



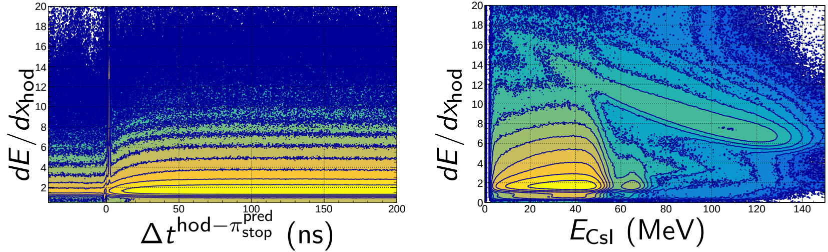




$$\Delta\chi^2 = \frac{\left(\chi^2_{\text{2-peak}} - \chi^2_{\text{3-peak,min}}\right)}{(A_\mu)^2}$$

Hadronic/prompts

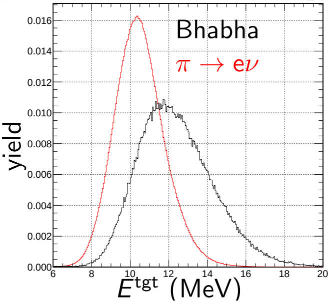
Pions can be absorbed by nuclei (Carbon) producing proton or deuteron, $^{12}C(\pi^+, p)X$.

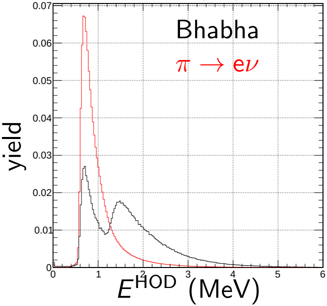


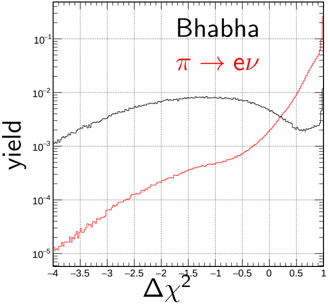
Proton makes its way to the calorimeter at the pion predicted stopping time

dE/dx selection in the hodoscope is preferable to time selection

Bhabha scattering from $\pi \to e\nu(\gamma)$ decays



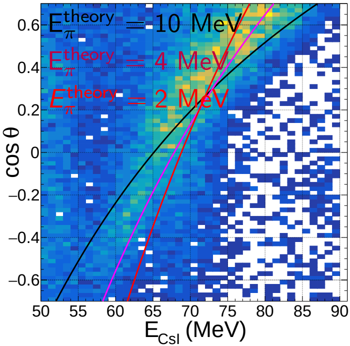




Stringent $\pi \to e\nu$ selection isolates $> 99\%$ Bhabha

MWPCs tracking

$$\pi \xrightarrow[\text{DIF}]{} e\nu$$



$-3 <$ decay time < 3 ns

Target energy deficit

$$\cos\theta = \frac{E_\pi}{\sqrt{E_\pi^2 - m_\pi^2}} - \frac{m_\pi^2}{2E_e\sqrt{E_\pi^2 - m_\pi^2}}$$

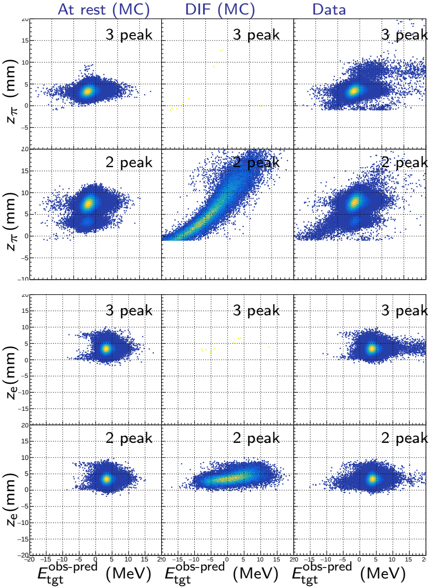
$N_{\text{Peak}} \sim 10^{-3}$

$\epsilon_{\text{Tail}} \sim 10^{-4}$ contribution (built in to MC)

Inclusion requires selection:

decay time > -4 ns (actually a good thing!)

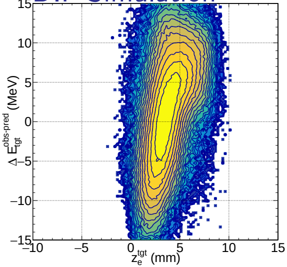
$\pi \xrightarrow[\text{DIF}]{} \mu\nu \to e\nu\bar{\nu}$



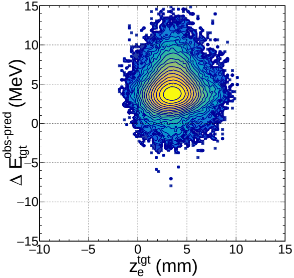
- 30-50 MeV selection
- 3 target peaks:
  Well separated $\pi \to \mu\nu \to e\nu\bar{\nu}$
- 2 target peaks:
  Expected in decays in flight
- z_e starting position of e^+
  along beam line (from MWPCs)
- z_π stopping position of π^+
  from target energy in first peak
- $E_{tgt}^{obs\text{-}pred}$ (MeV) target energy balance
  total energy minus predictions

$\pi \xrightarrow[\text{DIF}]{} \mu\nu \rightarrow e\nu\bar{\nu}$

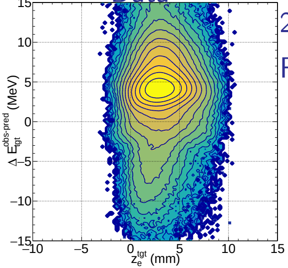
DIF Simulation



At rest simulation



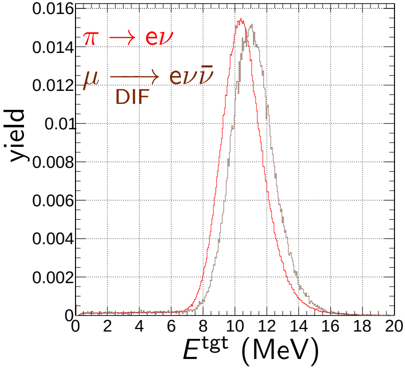
Data

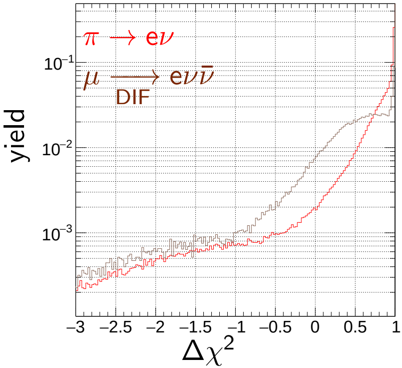


2D cuts can help isolate/eliminate DIF

Rigorous cuts used in exp tail

$\pi \to \mu\nu \xrightarrow[\text{DIF}]{} e\nu\bar{\nu}$





Identical decay time spectra

Nearly identical target energy

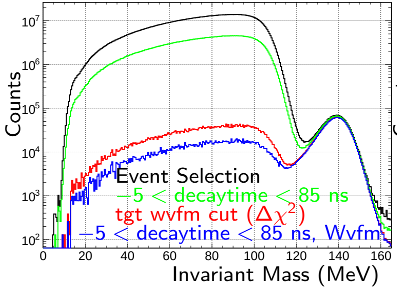
Nearly all $\mu \xrightarrow[\text{DIF}]{} e\nu\bar{\nu}$ in low energy tail

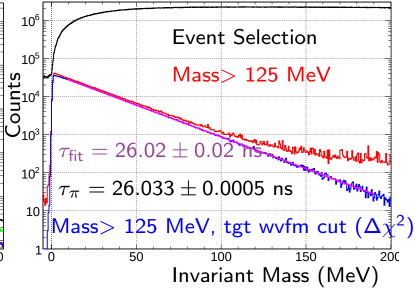
$\Delta\chi^2 \sim 0.5$

Eliminate $\sim 40\%$ $\mu \xrightarrow[\text{DIF}]{} e\nu\bar{\nu}$

At expense $\sim 18\%$ of $\pi \to e\nu$

Number of $\pi \to e\nu$

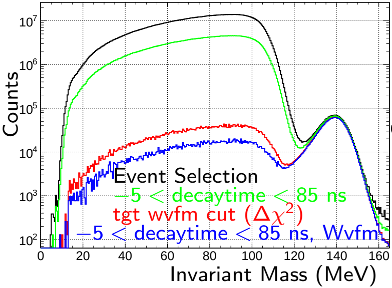


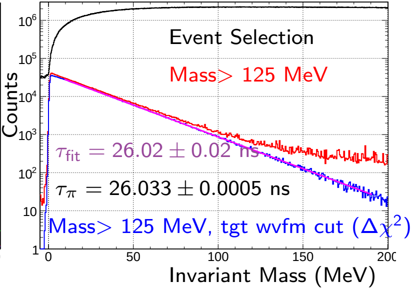


tgt wvfm cut is needed ($\Delta\chi^2$).

$$N_{\pi\to e\nu(\gamma),\text{run 2}} = (1409.33 \pm 1.18) \times 10^3$$
$$N_{\pi\to e\nu(\gamma),\text{run 2}} = (2413.81 \pm 1.63) \times 10^3$$
$$\delta N_{\pi\to e\nu(\gamma),\text{run 2}} / N_{\pi\to e\nu(\gamma),\text{run 2}} = 8.50 \times 10^{-4}$$
$$\delta N_{\pi\to e\nu(\gamma),\text{run 3}} / N_{\pi\to e\nu(\gamma),\text{run 3}} = 6.49 \times 10^{-4}$$

Number of $\pi \to e\nu$





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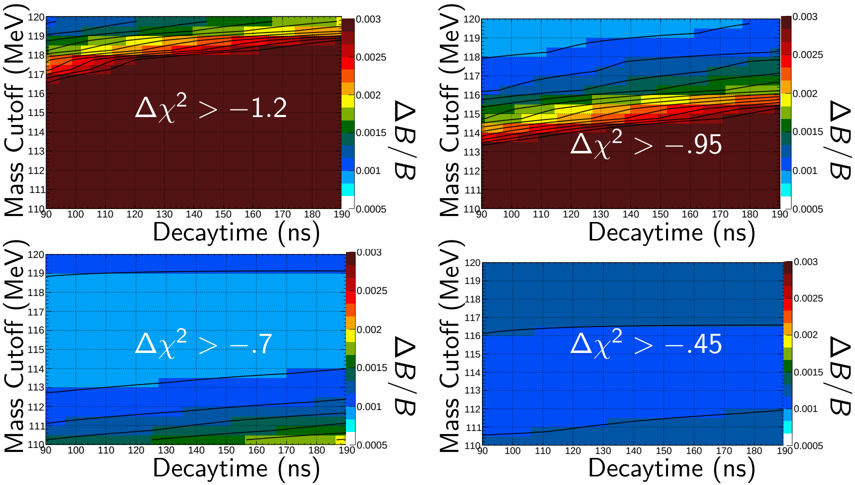
$$\delta N_{\pi\to e\nu(\gamma)} / N_{\pi\to e\nu(\gamma)} = 5.26 \times 10^{-4} \text{ (GOAL: } 5 \times 10^{-4})$$

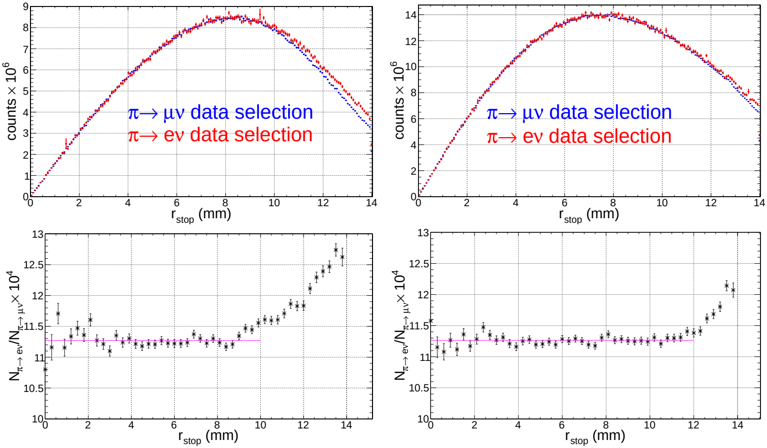
Minimizing Error for $\pi \rightarrow e\nu(\gamma)$



Time window, cutoff, waveform cut ... etc

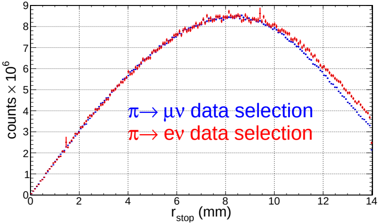
Energy requirement at positron birth

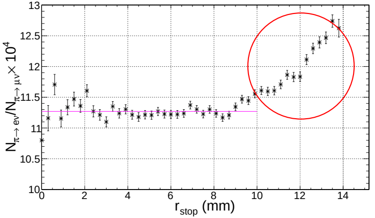
Run 2 Run 3



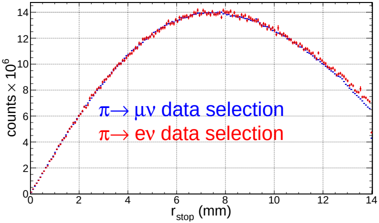
Energy requirement at positron birth

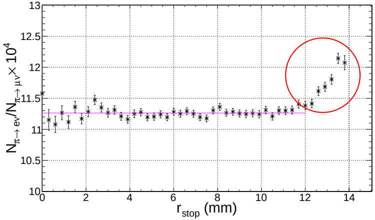
Run 2





Run 3





run 2 data $\sim 50\%$ run 3 data $\sim 30\%$

$\delta N/N \sim 4.13 \times 10^{-4}$

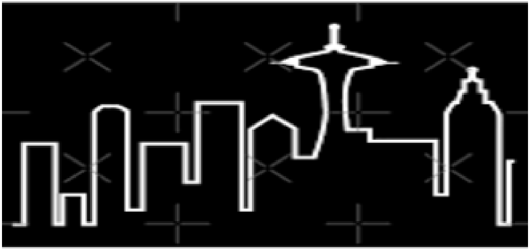
Key take aways

- All detectors are active in both time and energy
- Almost no dead material
- Detectors serve muliple purpose
- Double up detectors (redundant use)
- Geometry changes accounted for in simulation
- Correct stopping distribution is needed
- Different tools to “isolate” decay modes

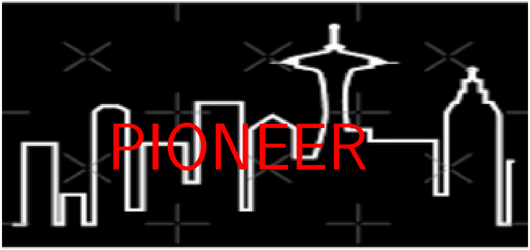
Continuing tasks

- Improvements on $\Delta\chi^2$ via predictions
- Ultra-realistic radiative muon decay generator
- Correction for r-stop trigger threshold
- Final check on calibrations
- Finalizing the various simulation configs
- Improving statistics on experimental tail
- Improving understanding of $\delta\epsilon_{\text{tail}}$

Thanks for listening



Thanks for listening



And ... Goodnight Seattle!

Family

Active and former PIBETA and PEN collaborators

L. P. Alonzi, K. Assamagan, V. A. Baranov, W. Bertl, C. Broennimann, S. Bruch, M. Bychkov, Yu.M. Bystritsky, M. Daum, T. Fl "ugel, E. Frlež, C. Glaser, R. Frosch, K. Keeter, V.A. Kalinnikov, N.V. Khomutov, J. Koglin, A.S. Korenchenko , S.M. Korenchenko , M. Korolija, T. Kozlowski, N.P. Kravchuk , N.A. Kuchinsky, D. Lawrence, M. Lehman, W. Li, J. S. McCarthy, R. C. Minehart, D. Mzhavia , E. Munyangabe, A. Palladino , D. Počanić *, B. Ritchie, S. Ritt , P. Robmann, O.A. Rondon-Aramayo, A.M. Rozhdestvensky, T. Sakhelashvili , P. L. Slocum, L. C. Smith, N. Soić RB, U. Straumann, I. Supek, P. Truöl, Z. Tsamalaidze, A. van der Schaaf *, E.P. Velicheva, M. Vitz, V.P. Volnykh, Y. Wang, C. Wigger, H.-P. Wirtz, K. Ziock.

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