Particle tracking in the PEN experiment

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(for the PEN Collaboration)

The PEN Collaboration

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- **Motivation**

- **Experiment**

- **Particle tracking**

- **Conclusion**

Nuclear Capture of Mesons and the Meson Decay

B. PONTECORVO
National Research Council, Chalk River Laboratory, Chalk River, Ontario, Canada
June 21, 1947

THE experiment of Conversi, Pancini, and Piccioni[1] indicates that the probability of capture of a meson by nuclei is much smaller than would be expected on the basis of the Yukawa theory.[2,3] Gamow[4] has suggested that the nuclear forces are due exclusively to the exchange of neutral mesons, the processes involving charged mesons and the β-processes having probabilities which are smaller by a factor of about 10^{12}.

We notice that the probability ($\sim 10^6$ sec.$^{-1}$) of capture of a bound negative meson is of the order of the probability of ordinary K-capture processes, when allowance is made for the difference in the disintegration energy and the difference in the volumes of the K-shell and of the meson orbit. We assume that this is significant and wish to discuss the possibility of a fundamental analogy between β-processes and processes of emission or absorption of charged mesons.

An immediate consequence of the experiments of the Rome group[1] is that the usual interpretation of the β-process as a "two-step" process ("probable" production of virtual meson and subsequent β-decay of the meson) completely loses its validity, since it would predict too long β-lifetimes: the meson is no longer the particle responsible for nuclear β-processes, which are to be described according to the original Fermi picture (without mesons). Consequently there is no need to assume that charged mesons have integral spin, as the Yukawa explanation of β-processes required. Once we believe that the ordinary β-process is not connected in any way with the meson, it is difficult to see strong reasons for the usual assumption that the meson decays with emission of a β-particle and a neutrino. We shall consider then the hypothesis that the meson has spin $\frac{1}{2}\hbar$ and that its instability is not a β-process, in the sense that it does not involve the emission of one neutrino. The meson decay must then be described in a different way: it might consist of the emission of an electron and a photon or of an electron and 2 neutrinos[5] or some other process.

In the hypothesis that the meson decay is not a β-process (meson of spin $\frac{1}{2}$) *the process of nuclear absorption or production of a single meson would be accompanied by the emission of a neutrino.* This analogy between β-particles and mesons suggests, in addition, that just as the production of single β-particles is extremely unlikely, while the production of electron pairs is a very likely phenomenon, so the production of a single charged meson would be very unlikely, while the production of pairs of mesons would be quite probable. The experimental evidence is, in fact,[6] that most, if not all, of the meson showers are created in connection with large Auger showers.

The assumption that the emission or absorption of one meson is accompanied by the emission of a neutrino would explain in a natural way a somewhat puzzling experimental result. Among the few pictures of a meson stopping in the gas of a cloud chamber, no "star" has been observed at the end of the meson track.[7] The absence of a star must be due to a process leaving the capturing nucleus in a not too excited state: the mechanism proposed here would explain that the capture of a negative meson from a nucleus Z results in a nucleus $Z-1$ close to its ground level, since the excess energy could be carried away by the neutrino. Actually, in such a process we should expect that the emission of a neutrino of high energy with consequent production of the nucleus $Z-1$ in a state of low excitation would be more likely than the emission of a neutrino of low energy with the production of the nucleus $Z-1$ in a state of high excitation (cf. K-capture process).

The hypothesis that the meson decay is not a β-process, while the meson absorption is a β-process, does not require that hypothetical particles such as neutral mesons are invoked to account for nuclear forces. In fact, a heavy electron *pair* theory of nuclear forces was successfully developed by Marshak.[8] Moreover, a pair theory is capable of accounting, at least in principle, for the existence of processes in which several pairs of mesons are produced in a single act, as suggested by Heisenberg in connection with a different problem.[9]

Returning to the actual decay of the meson, an experiment suggests itself which might answer the following question: Is the electron emitted by the meson with a mean life of about 2.2 microseconds accompanied by a photon of about 50 Mev? This experiment is being attempted at the present time, since it is felt that the available analysis[10] of the soft component in equilibrium with its primary meson component is probably insufficient to decide definitely whether the meson decays into either an electron plus neutral particle(s) or electron plus photon.

[1] M. Conversi, E. Pancini, and O. Piccioni, Phys. Rev. **71**, 209 (1947). See also T. Sigurgeirson and A. Yamakawa, Phys. Rev. **71**, 319 (1947).
[2] E. Fermi, E. Teller, and V. Weisskopf, Phys. Rev. **71**, 314 (1947).
[3] J. A. Wheeler, Phys. Rev. **71**, 320 (1947).
[4] G. Gamow, Phys. Rev. **71**, 550 (1947). See also G. Gamow and E. Teller, Phys. Rev. **51**, 289 (1937).
[5] W. Nordheim, Phys. Rev. **59**, 544 (1941).
[6] G. Cocconi, A. Loveredo, and V. Tongiorgi, Phys. Rev. **70**, 852 (1946).
[7] See for a critical survey: T. H. Johnson and R. P. Shutt, Phys. Rev. **61**, 380 (1942).
[8] R. E. Marshak, Phys. Rev. **57**, 1101 (1940).
[9] References can be found in *Cosmic Radiation*, edited by W. Heisenberg (Dover Publications, New York, 1946), p. 127.
[10] See reference 9, pp. 84–97.

Бруно Понтекорво

B. Pontecorvo
μ-e universality, 1947.

"We assume that this is significant and wish to discuss the possibility of a fundamental analogy between β- processes and processes of emission or absorption of charged mesons" (muons)

Phys.Rev., v72(1947)246.

Physics Motivation / Theory

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

Modern SM calculations:

$1.2352(5) \times 10^{-4}$ Marciano and Sirlin, Phys.Rev.Lett. **71** (1993)3629

$1.2354(2) \times 10^{-4}$ Decker and Finkemeier, Nucl.Phys. **B438** (1995)17

Chiral PerturbationTheory:

$1.2356(1) \times 10^{-4}$ Cirigliano and Rosell, Phys.Rev.Lett. **99** (2007) 231801

Experiment

(1.2344±0.0023(stat)±0.0019(syst))x 10^{-4}

***TRIUMF**, Phys.Rev.Lett. 115 (2015) 071601*

(1.2265±0.0034(stat)±0.0044(syst))x 10^{-4}

***TRIUMF**, Phys.Rev D49 (1994) 28*

(1.2346±0.0035(stat)±0.0036(syst))x 10^{-4}

***PSI,** Phys.Rev.Lett. 70 (1993) 17*

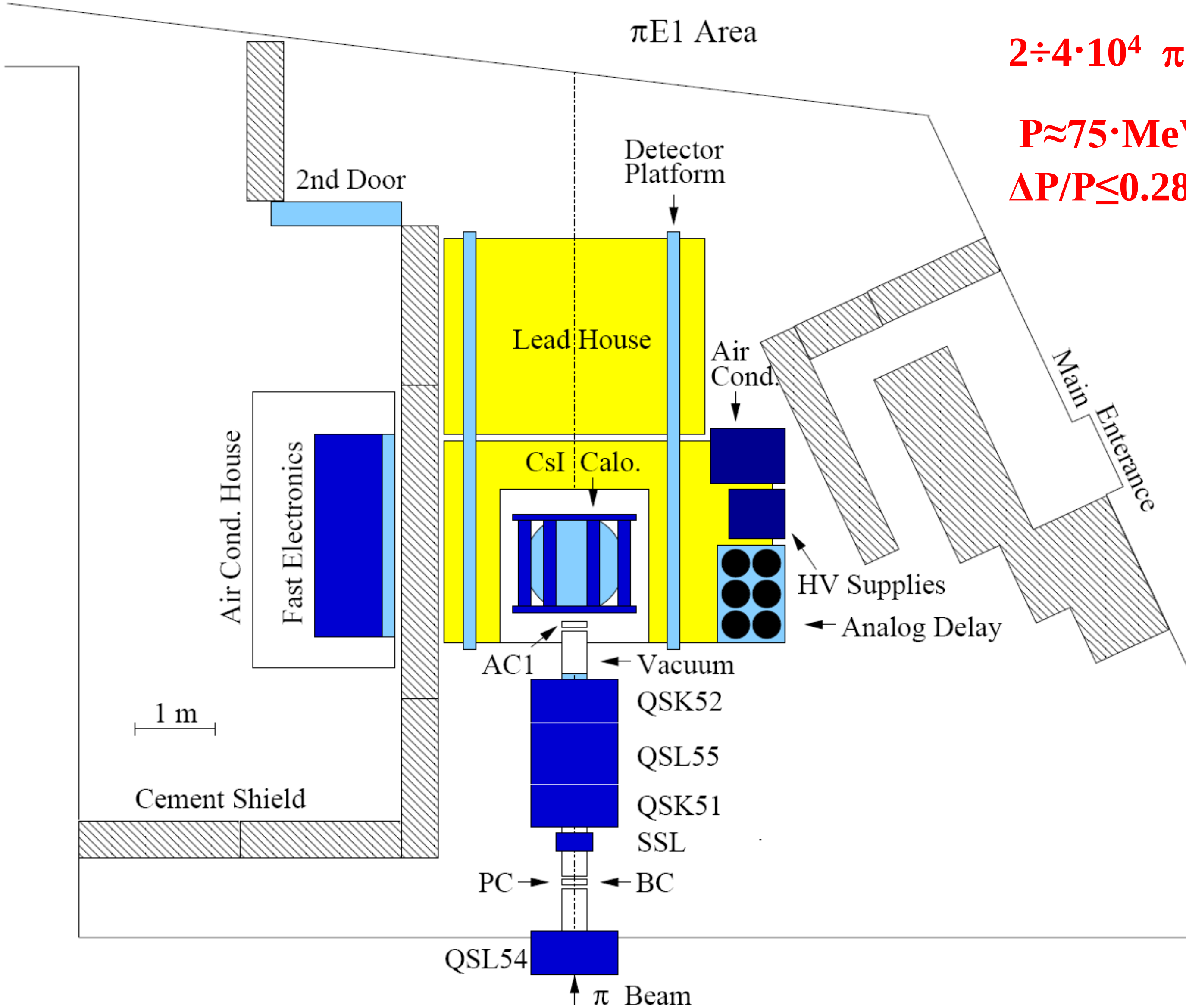
New average:

(1.2327±0.0023)x10^{-4}

$$\frac{\Delta B_{e/\mu}^{Theor}}{B_{e/\mu}^{Theor}} \approx \mathbf{1x10^{-4}}$$

$$\frac{\Delta B_{e/\mu}^{Exp}}{B_{e/\mu}^{Exp}} \approx \mathbf{1.8x10^{-3}}$$

PEN $\rightarrow \frac{\Delta B_{e/\mu}^{Exp}}{B_{e/\mu}^{Exp}} \leq \mathbf{5x10^{-4}}$



$2 \div 4 \cdot 10^4$ π^+/s,

$P \approx 75 \cdot MeV/c$,

$\Delta P/P \leq 0.28\%$[FWHM]

A layout of the PSI πE1 experimental area for the PEN experiment (top view)

PEN apparatus (2009)

Main components:

BC – Beam Counter

AD – Active Degrader

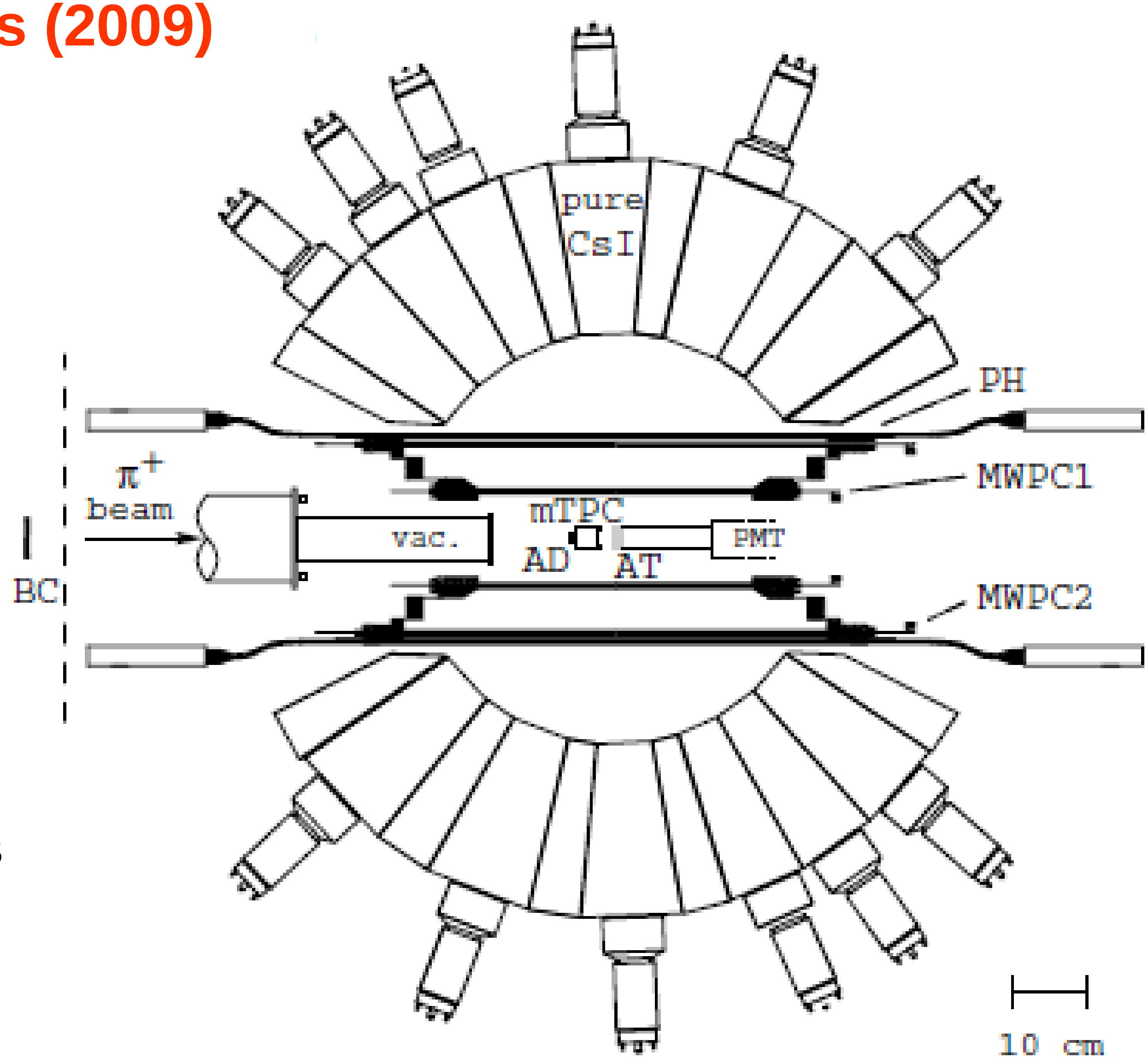
mTPC – mini
Time-Projection Chamber

AT – Active Target

MWPC1, MWPC2 – Multi-Wire Proportional Chambers

PH – Plastic Hodoscope

pure CsI - calorimeter and PMTs



CsI Calorimeter

The PEN calorimeter consists of 240 pure CsI crystals.
The inner radius of the calorimeter is 26 cm, and the module axial length is 22 cm; corresponding to 12 CsI radiation lengths (X_0 = 1.85cm)

Weight is 1.6 t.

Fast component decay time 7 ns

Slow component decay time 35 ns

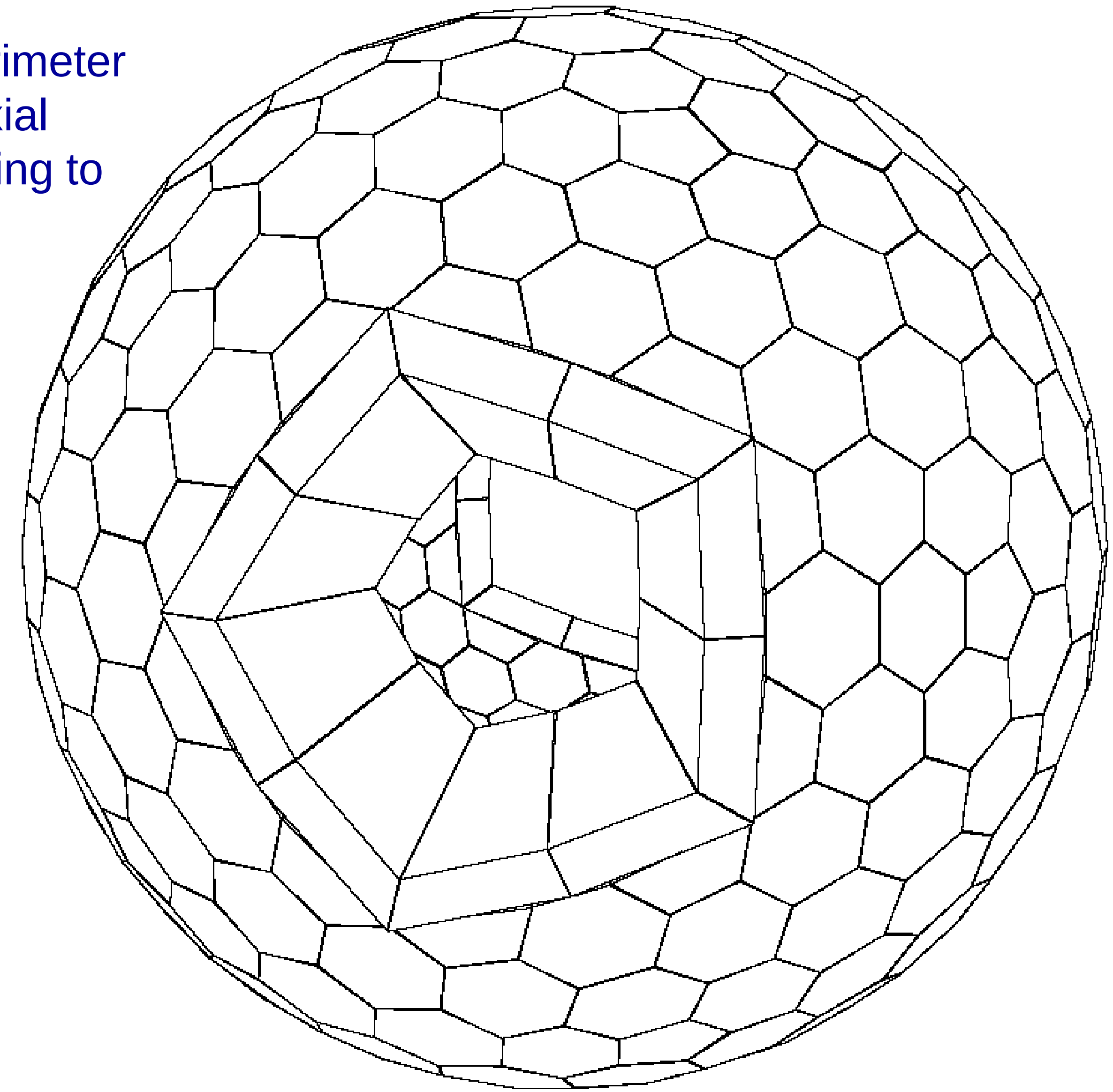
Fast/Total >0.76

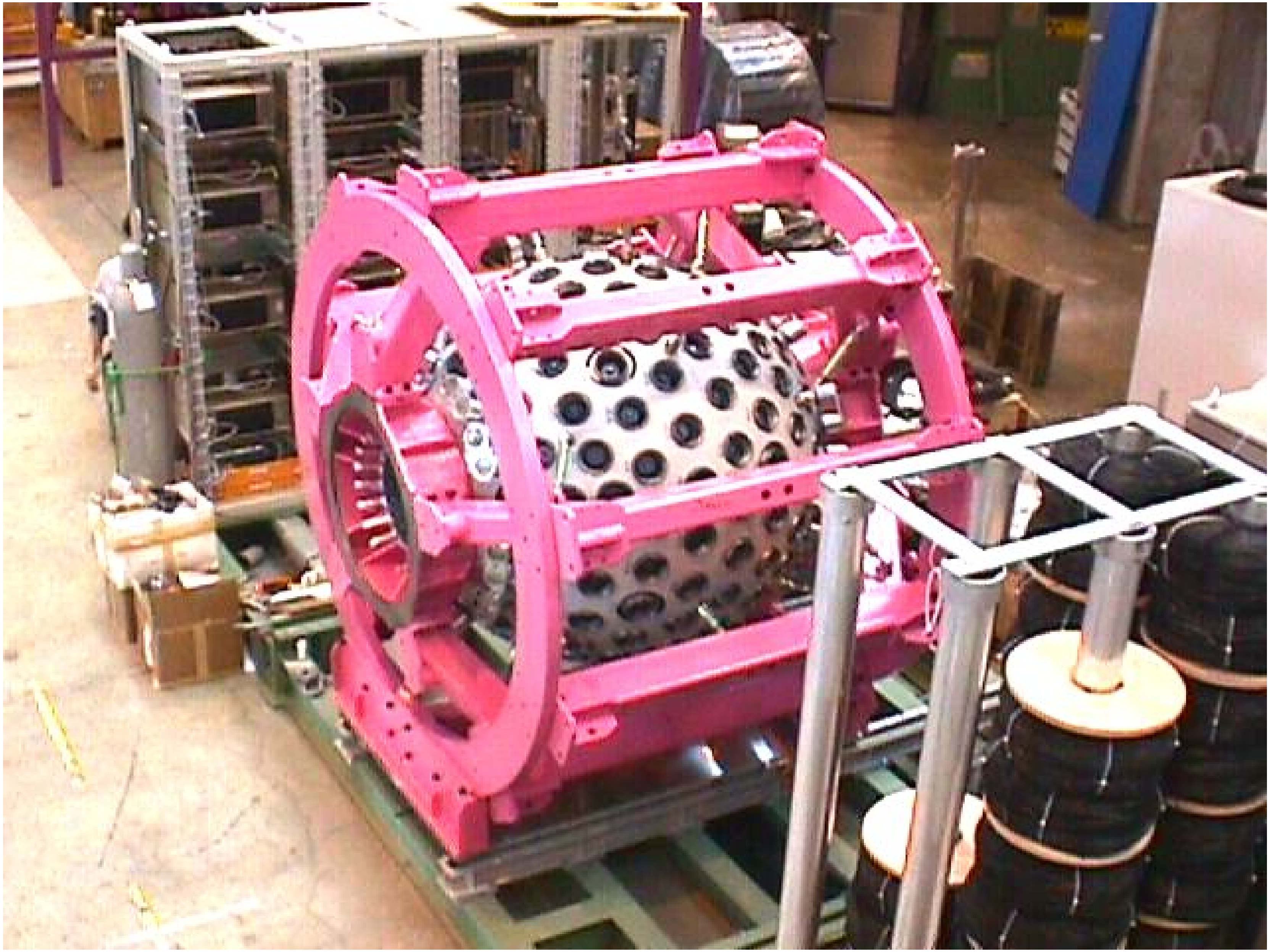
total solid angle ~0.77·4π

Angle resolution ~2°

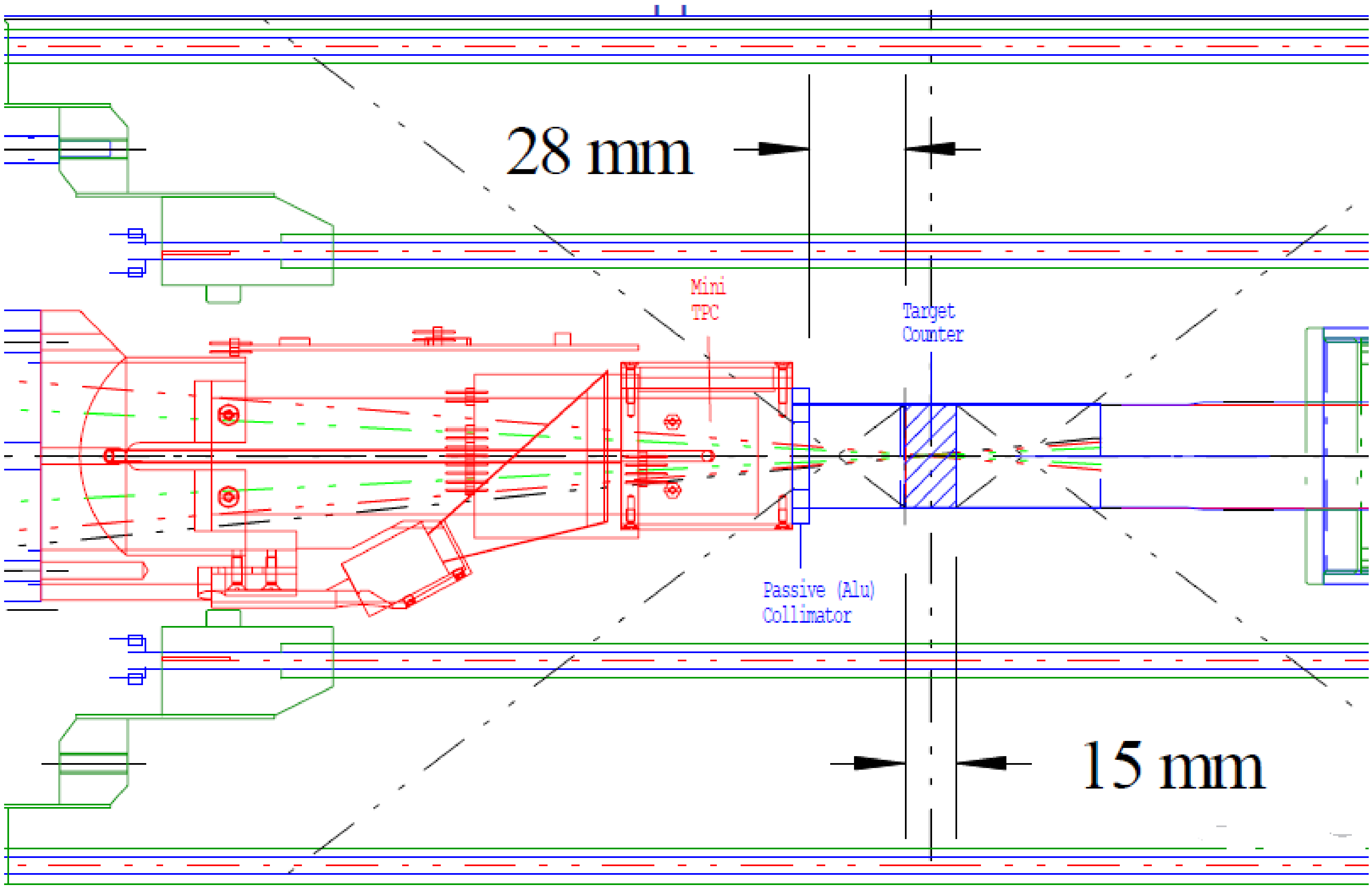
ΔE/E ~ 4-5%

Time resolution ~ 0.68 ns





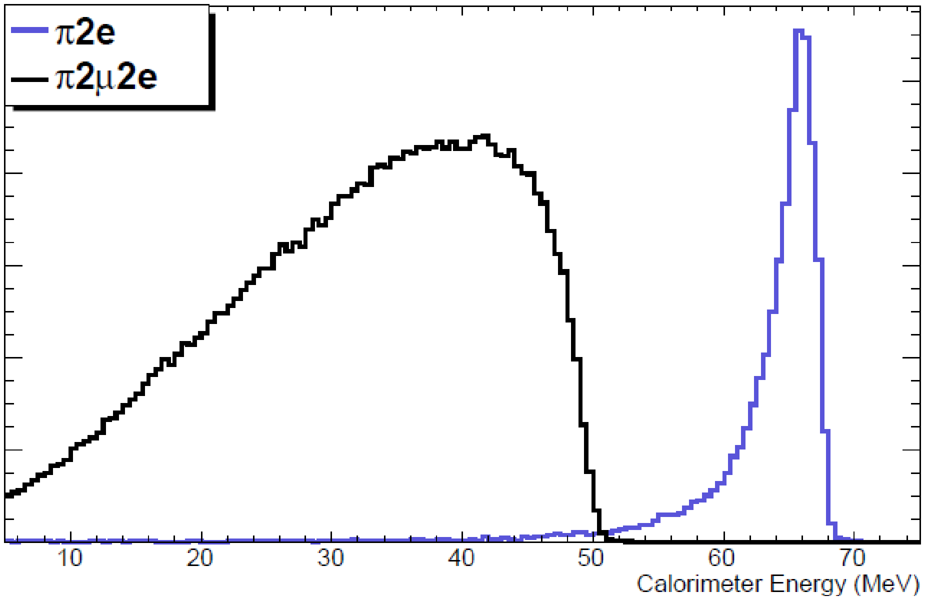
The PEN Apparatus 2009



PEN Event Trigger

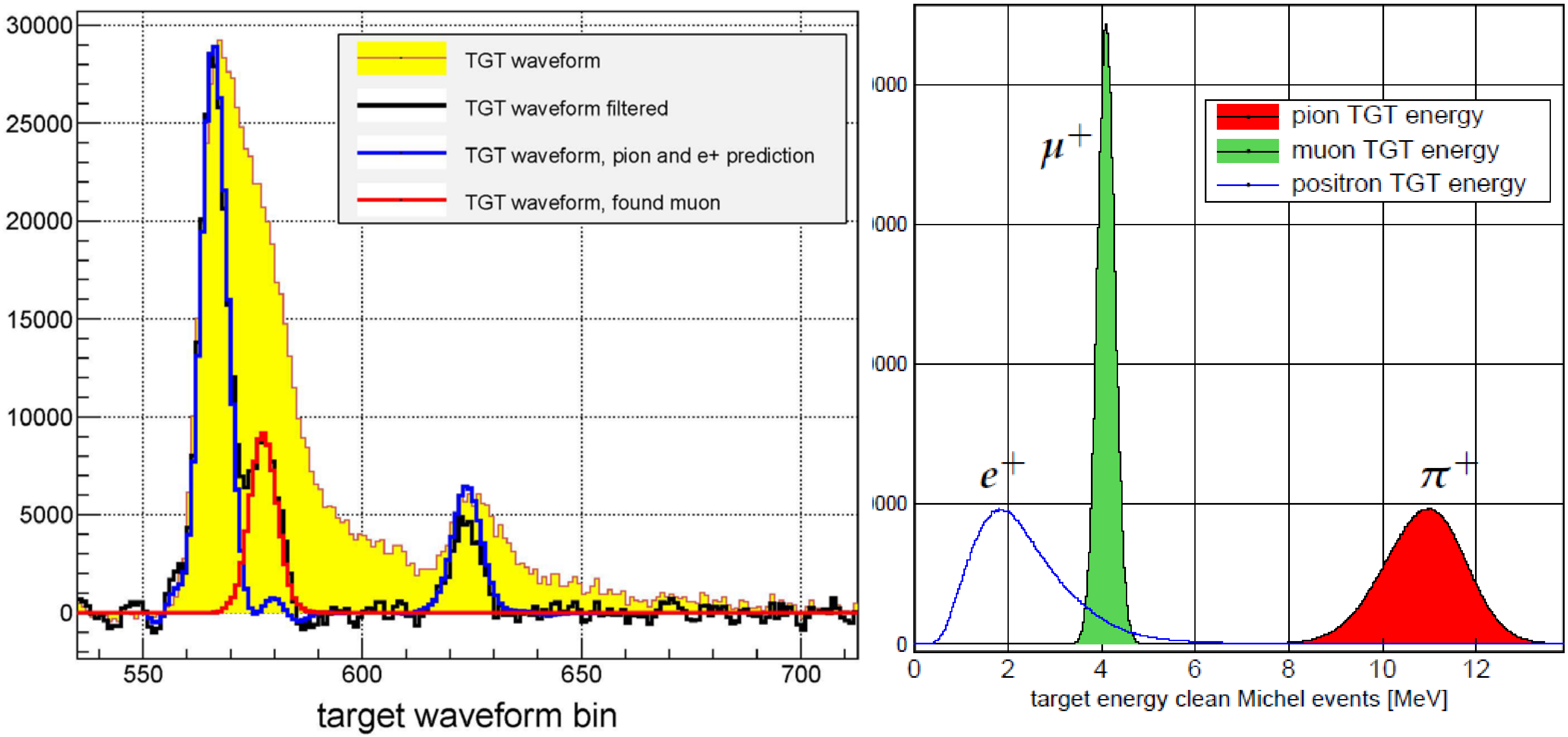
Process to Observe

- 75 MeV/c pion beam
- Active target with stopped pions, $E_{\pi AT}$=11 MeV
- $\pi \rightarrow e\nu$ (π2e), $E_e \approx 0.5 m_\pi$=69.79MeV, τ_π~26 ns
- $\pi \rightarrow \mu\nu$ (norm), E_μ=4.12 MeV
- $\mu \rightarrow e\nu\nu$, $E_{emax} \approx 0.5 m_\mu$=52.83 MeV, τ_μ~2197 ns



Acqiris High Speed 10-bit PXI Compact Digitizer, Model DC282,running at 2GS/s

Signals from beam detectors
BC – Beam Counter
AD – Active Degrader
AT – Active Target
 are sent to digitizers for waveform analysis for $\pi \rightarrow \mu \rightarrow e$ and $\pi \rightarrow e$ decay chains.



Target waveform analysis for π→μ→e decay chains in which the three signals are well separated. Removal of the predicted pion and positron signals leaves a clean 4MeV muon signal.

Beam detector mTPC

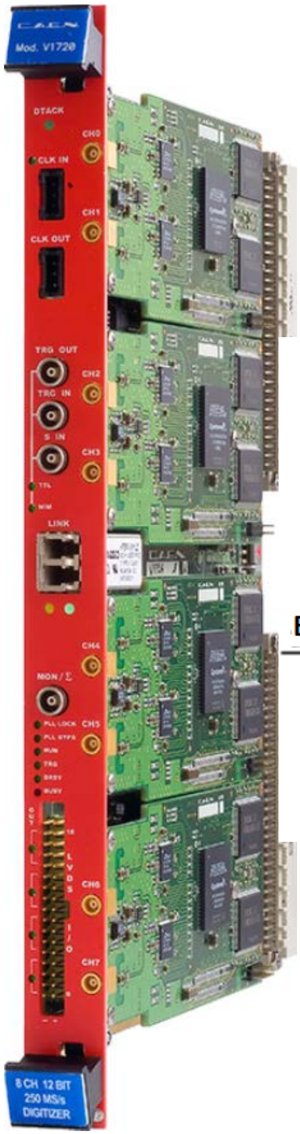
—To monitor the distribution of π^+ and μ^+ stops in the target, which is necessary for calculating the detector acceptance.

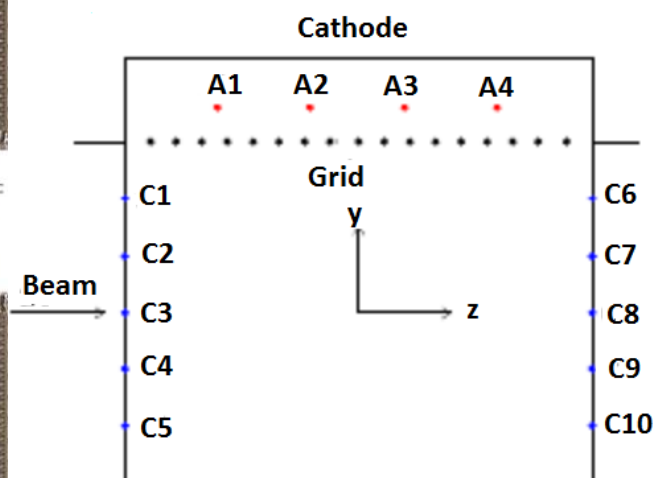
—To reconstruct the vertices of the pion decay in the active target and correct the π^+, μ^+, and e^+ energy loss with allowance for inhomogeneity of light collection in the active target.

—To reconstruct the length of e^+ tracks in the target for finding e^+ energy loss for each individual event.

—To reject events with π^+ and μ^+ that decayed in flight.

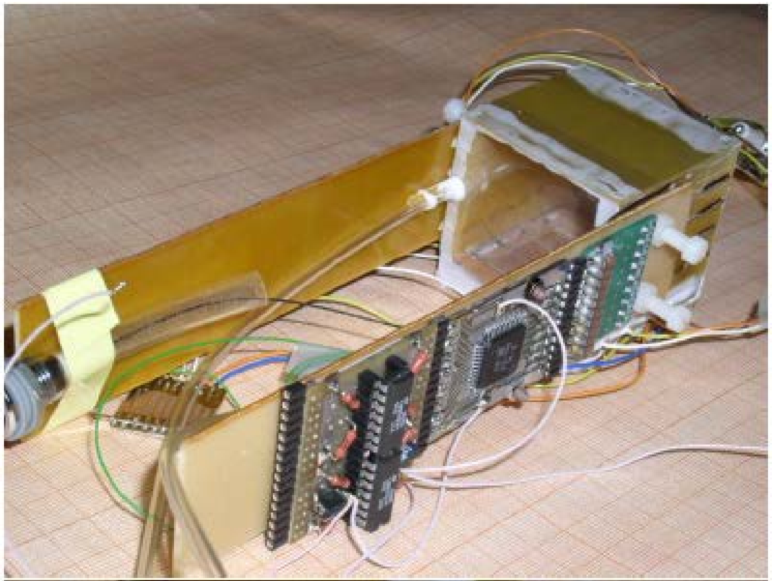
mTPC Technical Specifications

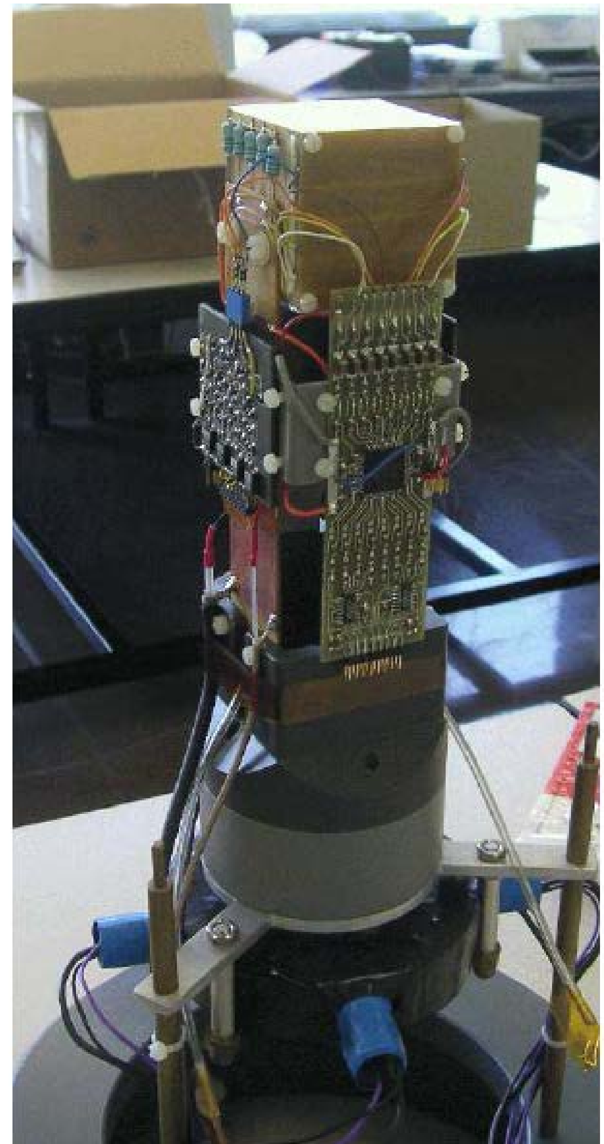




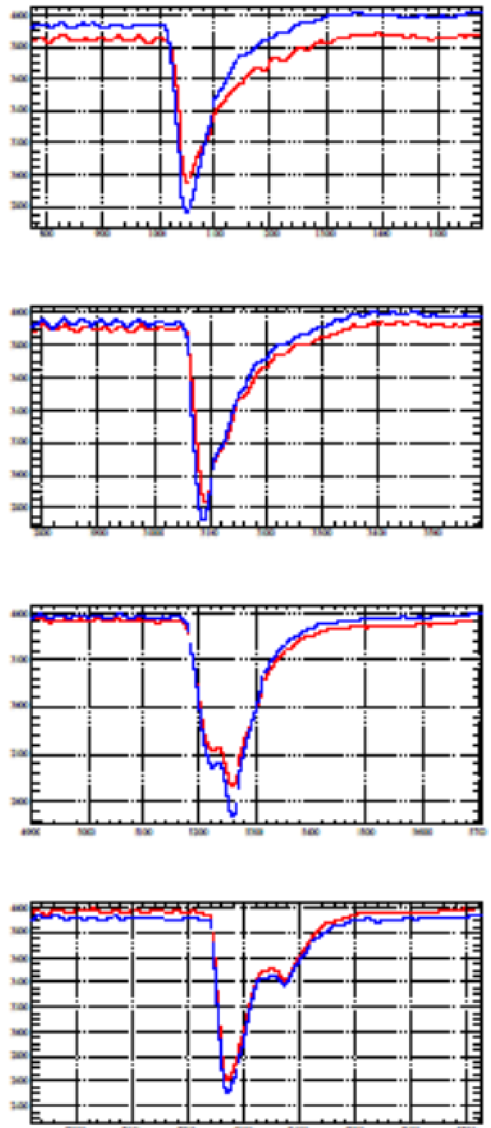
- Proportional Region: 40x6x40 mm^3
- Drift Region: 40x40x50 mm^3
- Drift Gas: 90% Ar and 10% CH_4
- 4000 V across drift region
- Grid: 50 µm wires with 1 mm spacing
- Nichrome Anode Wires
  - 40 mm length
  - 20 µm diameter
  - 10 mm spacing
  - 235 Ω resistance
- CAEN VME digitizer V170

mTPC 2009





WaveForm Digitization



- **Red**: Left
- **Blue**: Right

Pion Tracking:

- x: charge division

  Relative amp. left : right

  $\sigma_x < 0.97$ mm
- y: drift time

  Time of rising edge

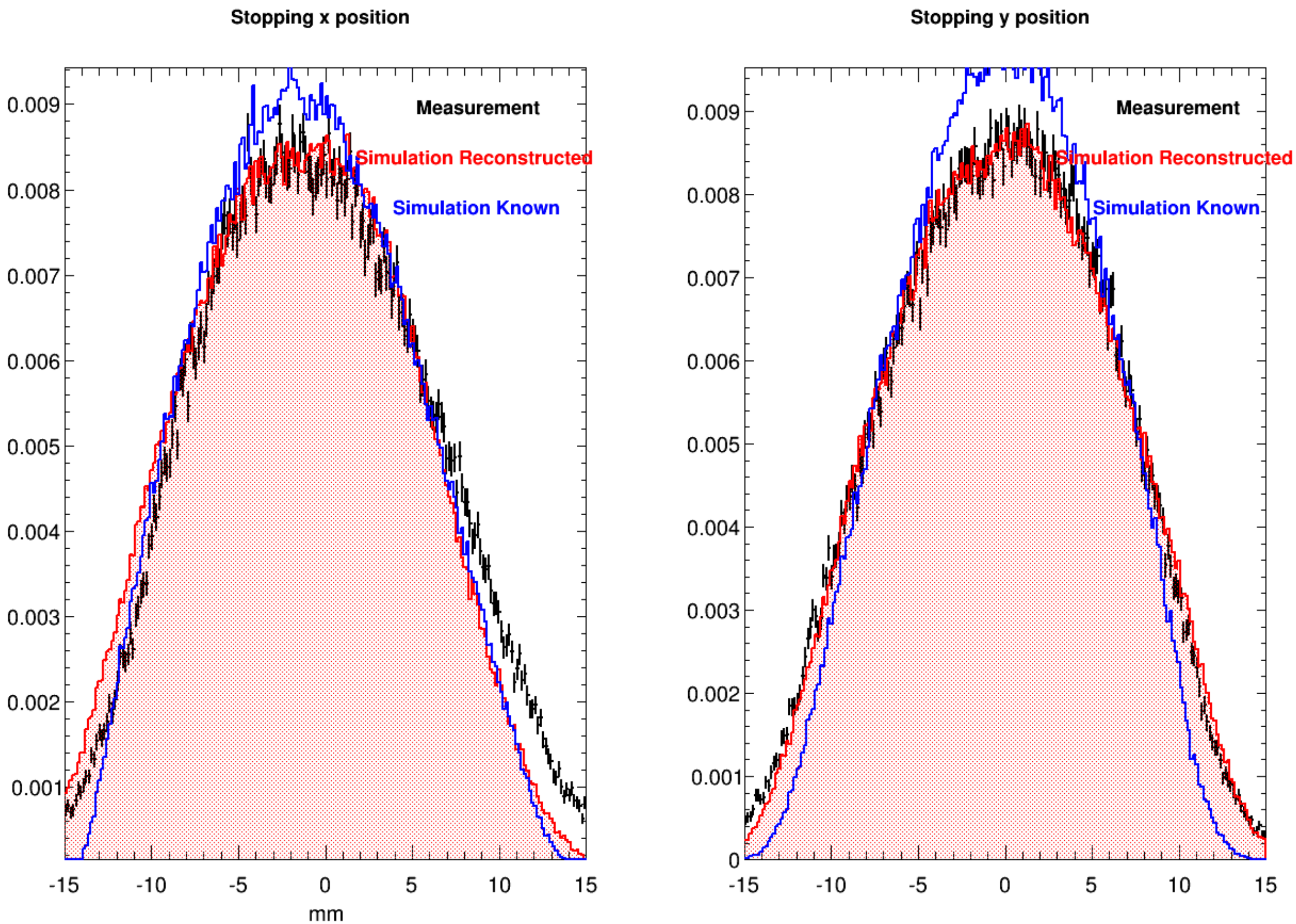
  $\sigma_y < 0.35$ mm
- z: wire location

  Physical mounting

Nydegger R. Bechelor Thesis (2012)

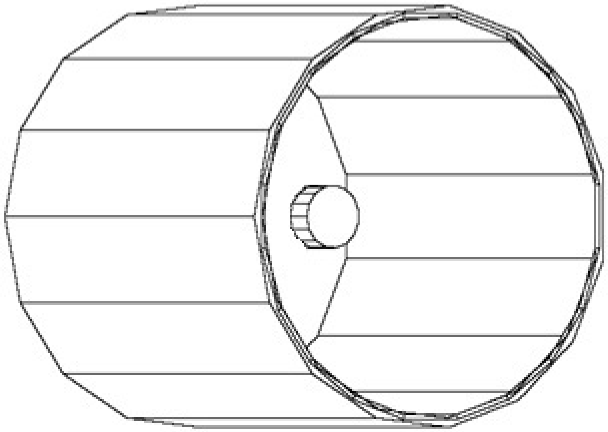
Sokolov A. et al., NIM A574 (2007) 50.

Reconstructed Stopping Distributions

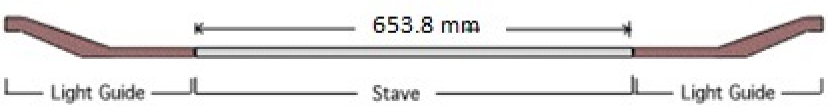


PH – PEN Plastic Hodoscope

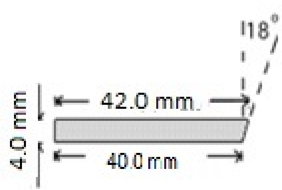
(i)



(ii)



(iii)

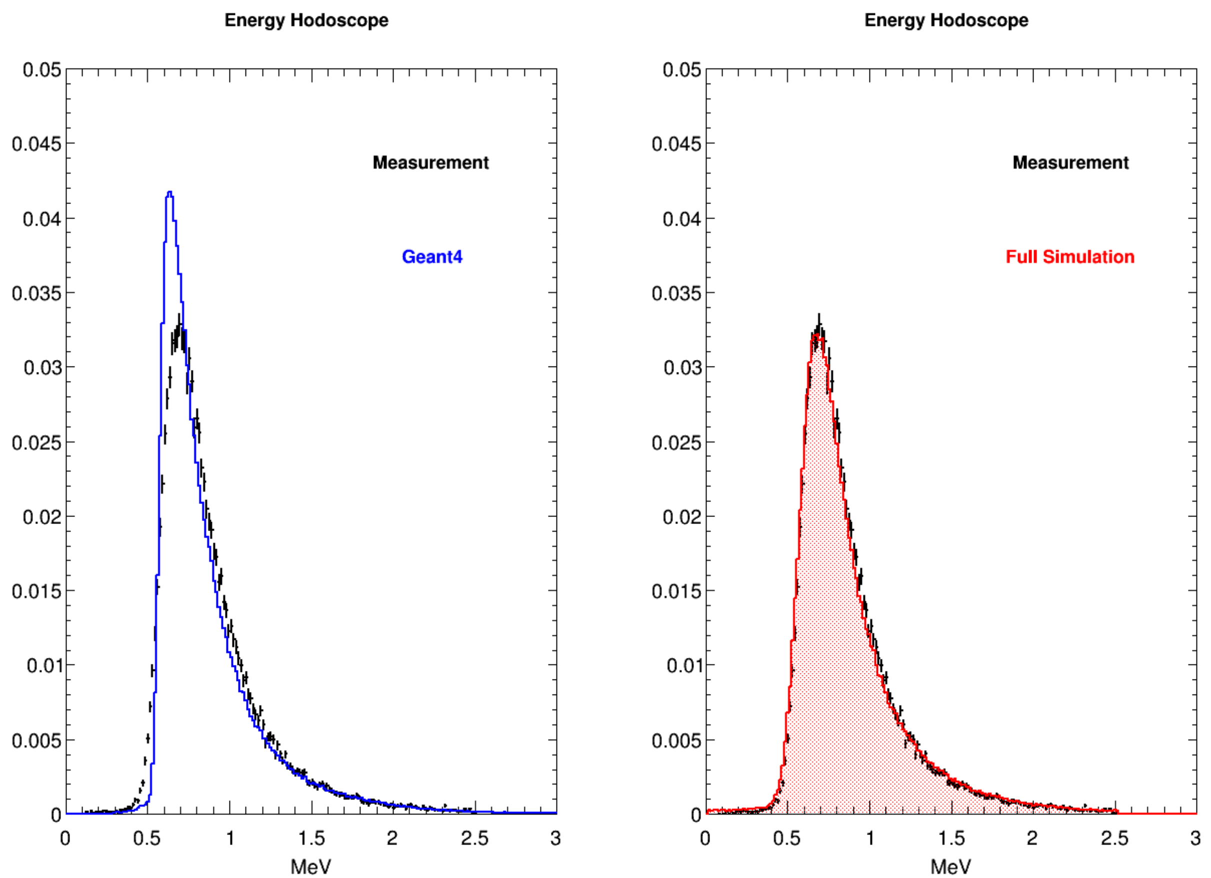


The hodoscope array consists of 20 independent BC-408 plastic scintillator staves arranged to form a complete cylinder 653.8 mm long with a 129 mm radius and 4.0 mm thickness.

The light attenuation length is 210 mm.

The scintillator light is viewed at both detector ends by two Burle Industries S83062E photomultiplier tubes. The energy resolution measured for minimum ionizing particles is $\sigma_E/E=26\%$.

PH – measurement and simulation



Left: Intrinsic response of simulation compared to measurement.

Right: Full detector response on measurement

The constraints on MWPC design for the tracking detector:

(1) low mass, in order to minimize the γ's converting into e^+ e^- pairs;

(2) high efficiency—better than 99.9%;

(3) high rate capability—up to 10^7 minimum ionizing particles (MIP) per second;

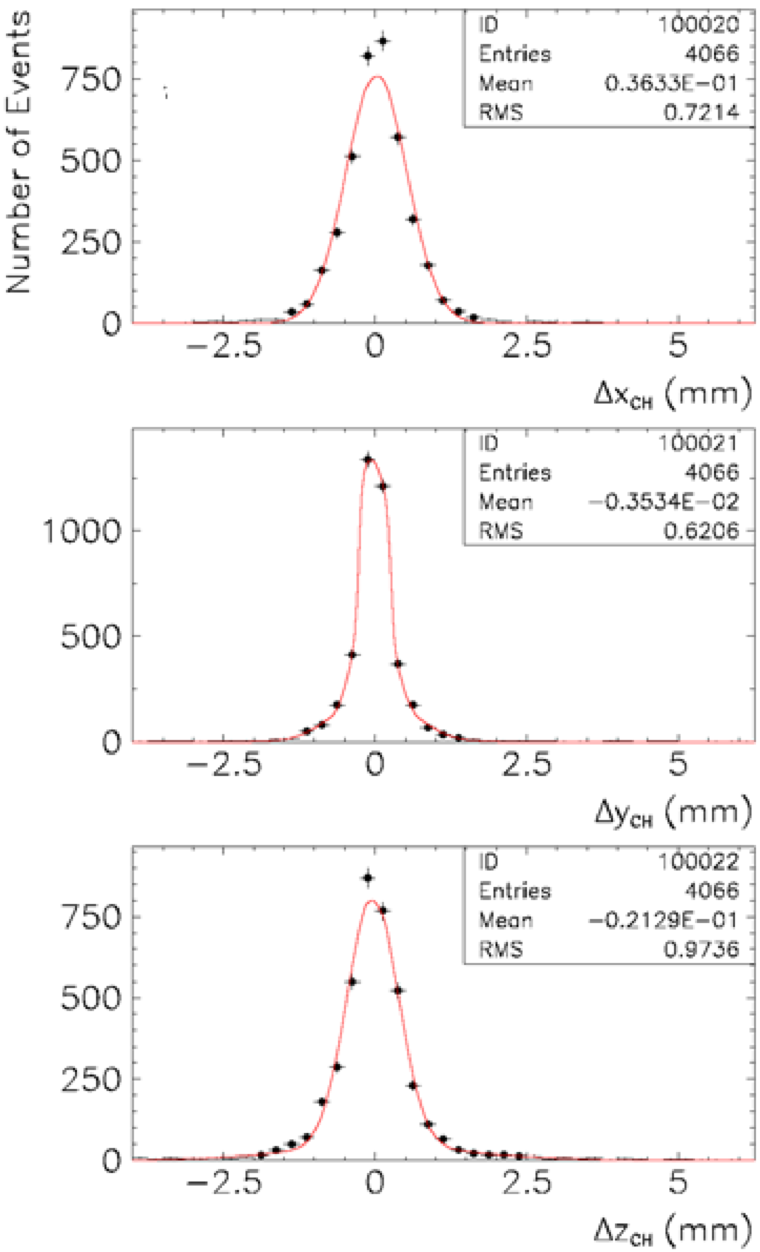
(4) stable operation and good radiation hardness;

(5) cylindrical geometry.

MWPC specification

	$MWPC_1$	$MWPC_2$
• Active length (mm)	350	540
• Diameter anode (mm)	120.3	240.2
• Number of anode wires	192	384
• Number of inner cathode strips	2x64	192
• Number of outer cathode strips	2x64	192
• Total chamber thickness (mg/cm^{2})	53.9	74.8
• Total chamber thickness (rad. length)	$1.4 \cdot 10^{-3}$	$2.0 \cdot 10^{-3}$
• Detection efficiency	>0.96	>0.97

Experimental x, y and z resolutions.

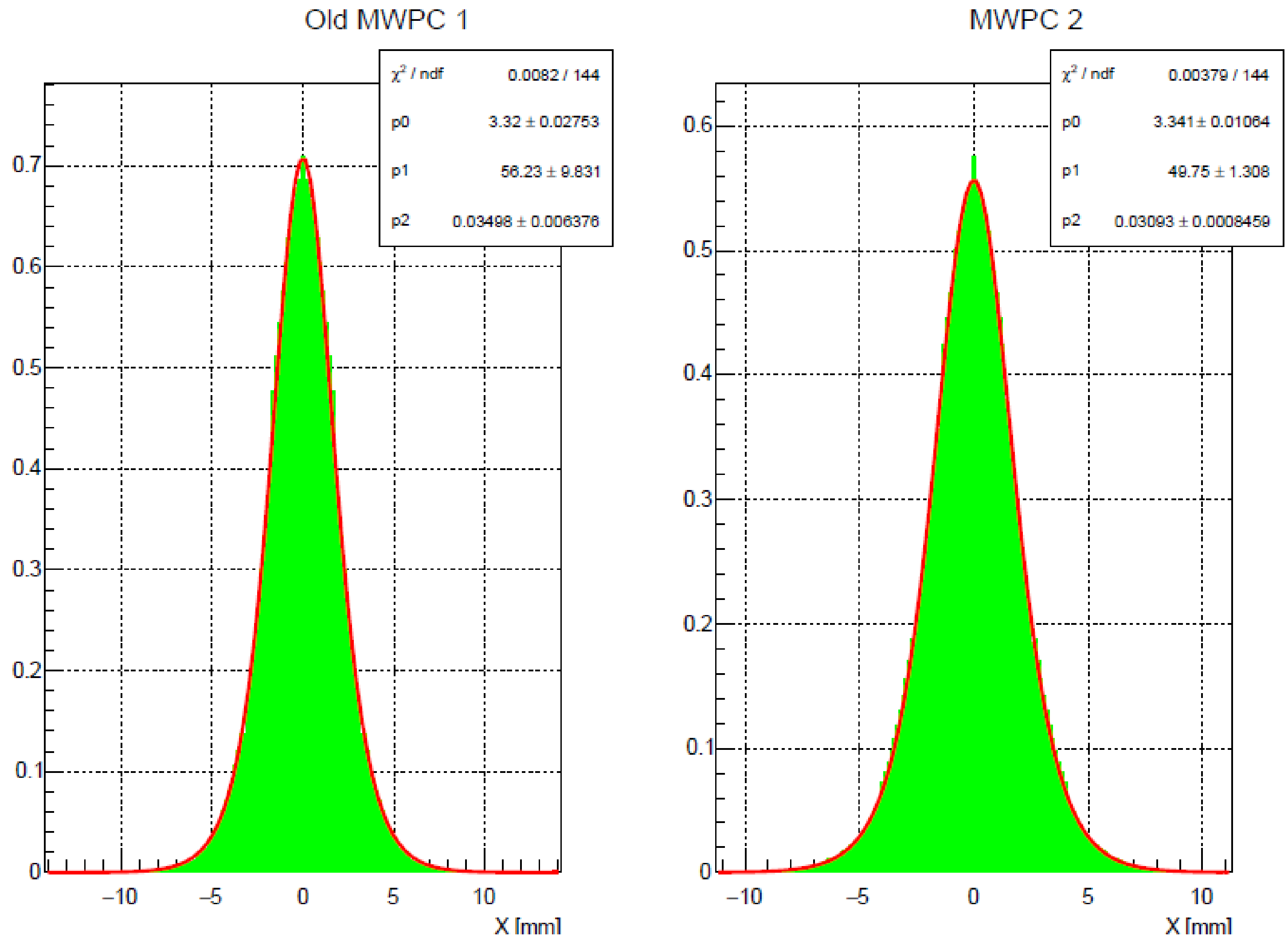


chambers' angular rms resolution at $\varphi \approx 0.75^{O}$

spatial resolution z ~0.97мм

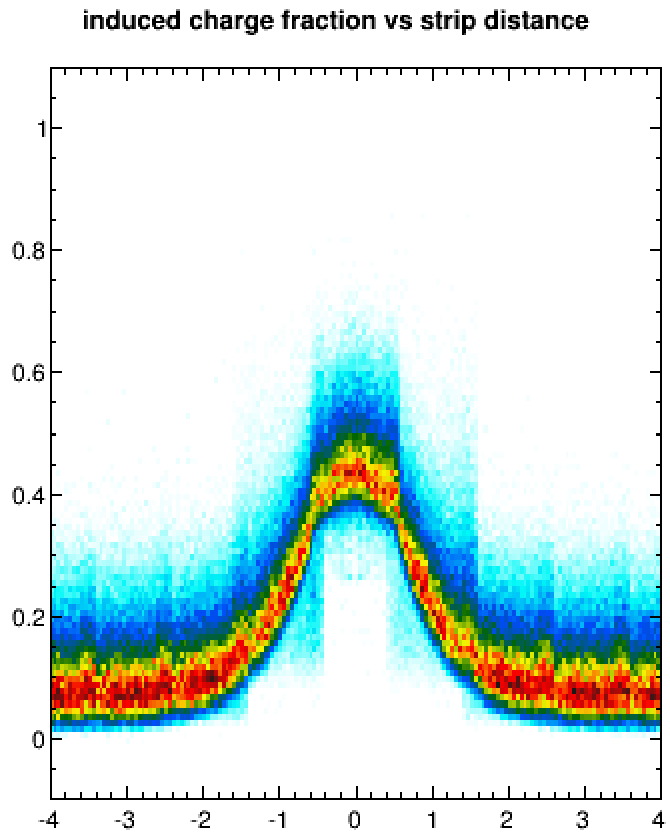
spatial resolution x,y ~0.6-0.7мм

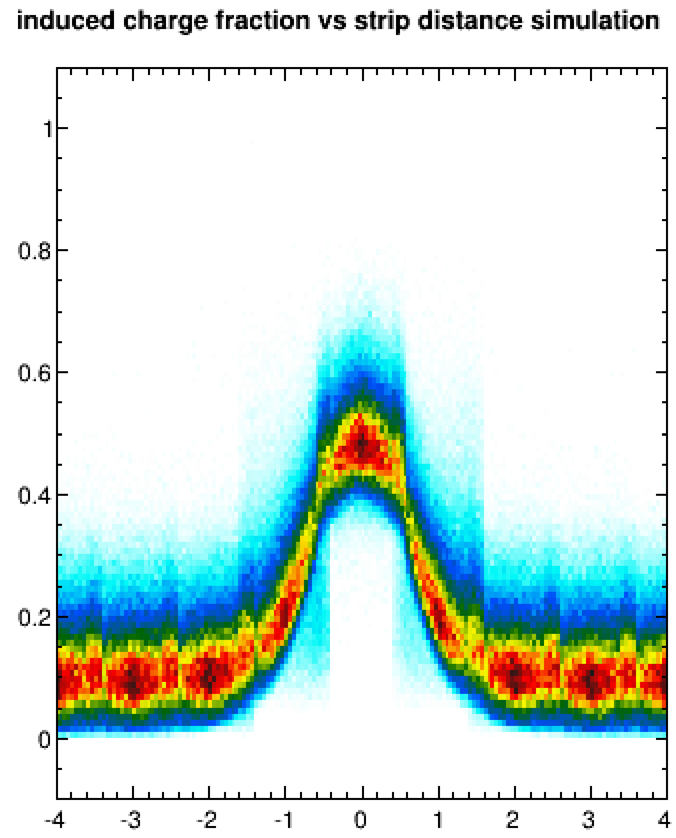
Cathode Charge Distributions in MWPCs



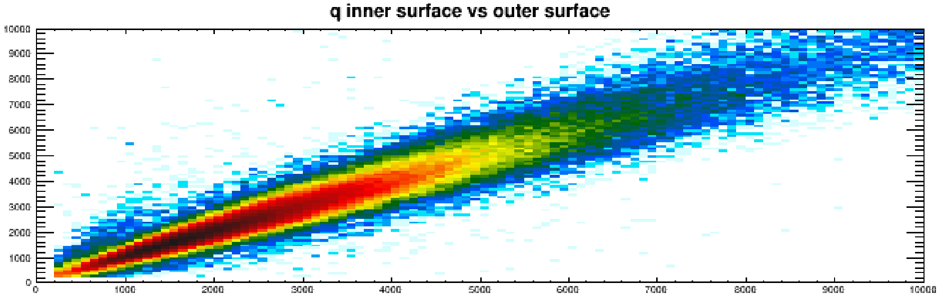
Experimental and E. Mathieson (NIM A270 (1988) 602) single parameter formula.

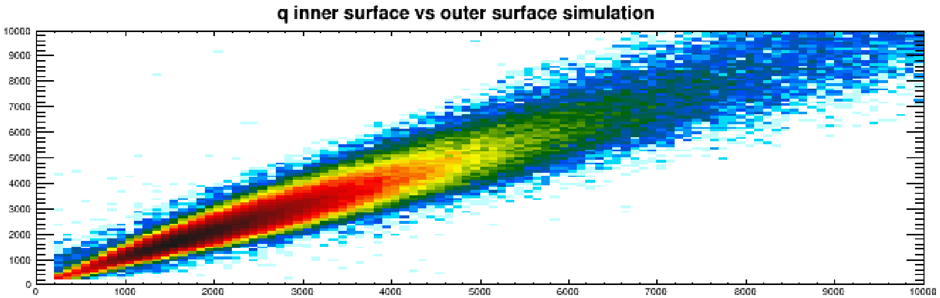
MWPC induced cathode charge Measurement and Simulation



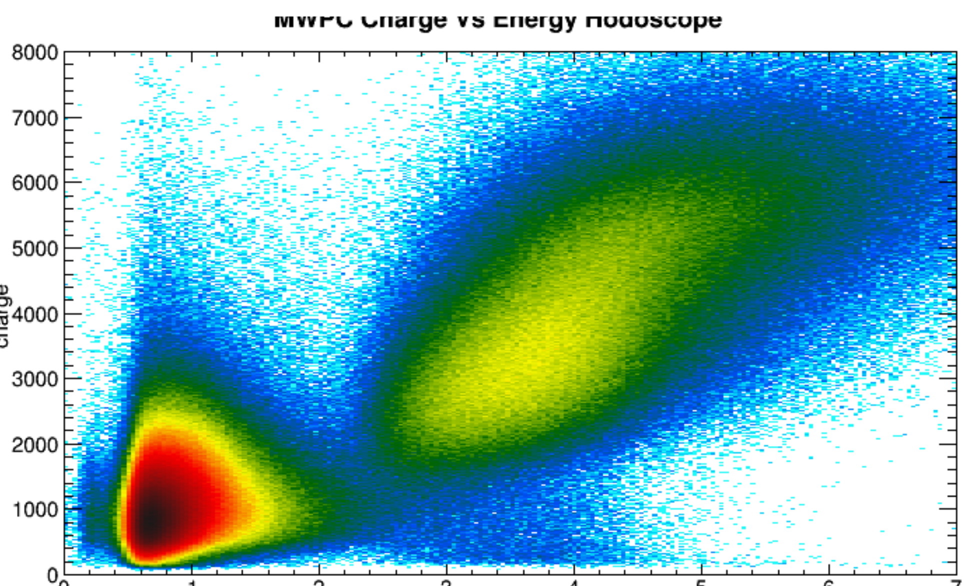


Cathode Charge Distributions



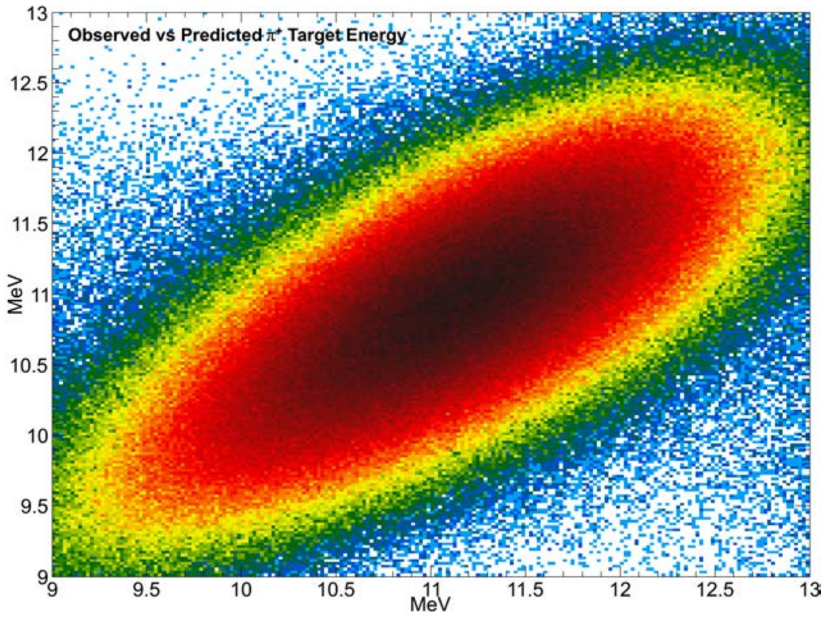


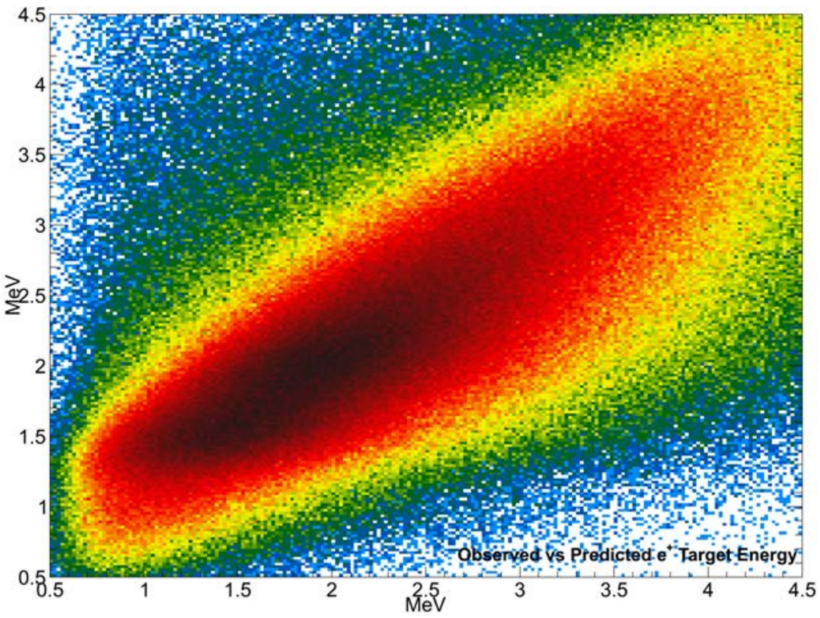
Comparison of inner and outer cathode charges for measurement and simulation.



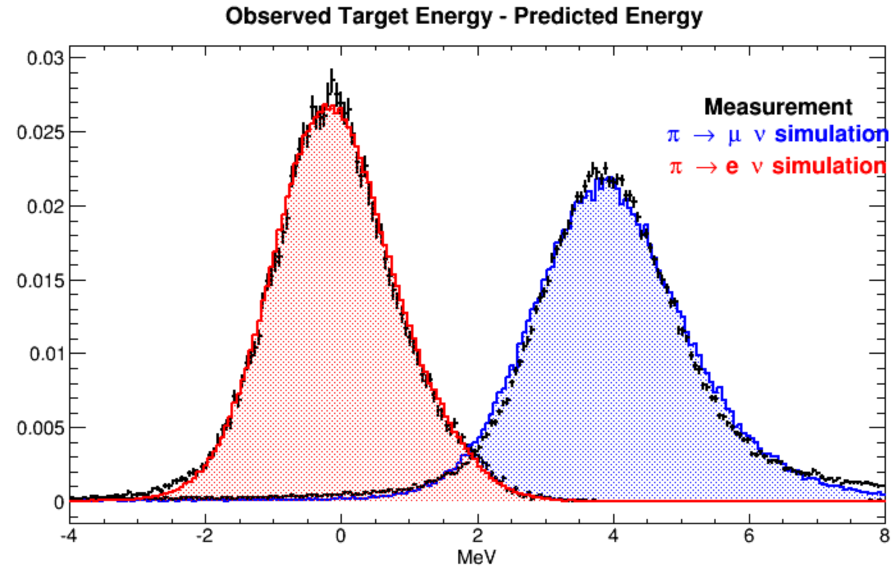
Cathode charge of MWPC (arbitrary units) vs energy deposited in plastic hodoscope PH.

Target Energy.





Observed energies are obtained from the target waveform and predicted energies are obtained from mTPC, MWPC, and beam counters for the pion and positron.



Conclusion

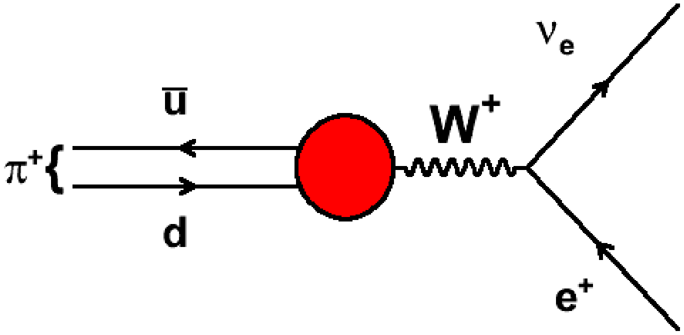
Particle tracking plays an integral part in the analysis of the PEN experiment for the precision measurement of the pion electronic decay ratio.

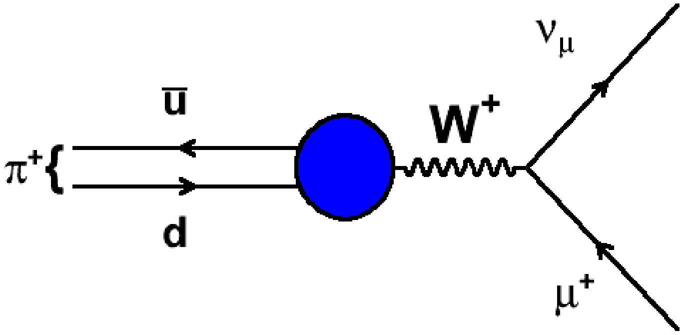
In the 2009-2010 runs the mTPC and MWPC chambers successfully operated for more then eight months.

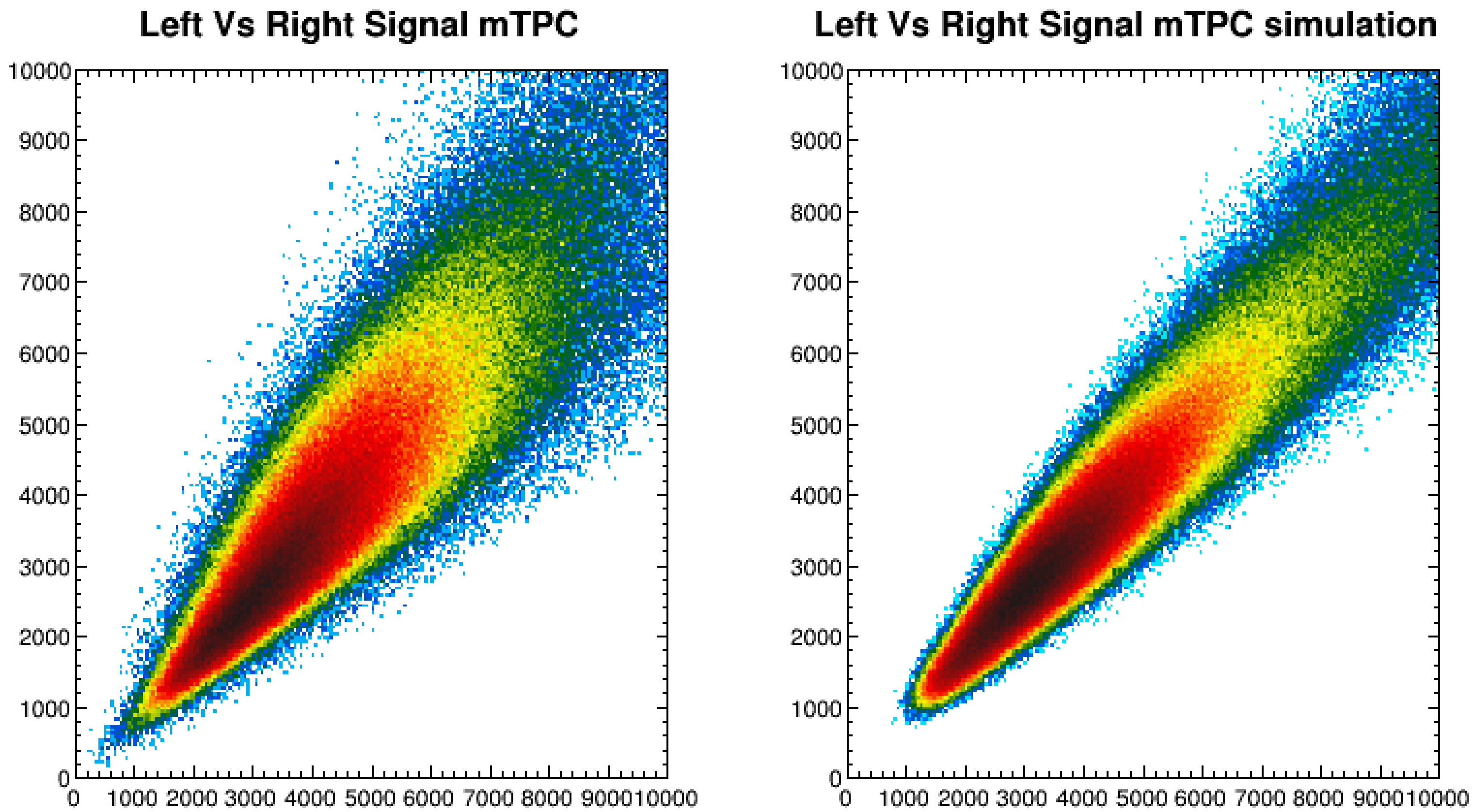
The aforementioned detectors are utilized in the calculation of vital observables that are used to discriminate between background and signal events. Proper Monte Carlo simulation, necessary for determining the acceptances, has been successfully developed, thus clearing the way for the evaluation of a precise branching ratio.

Thank you!

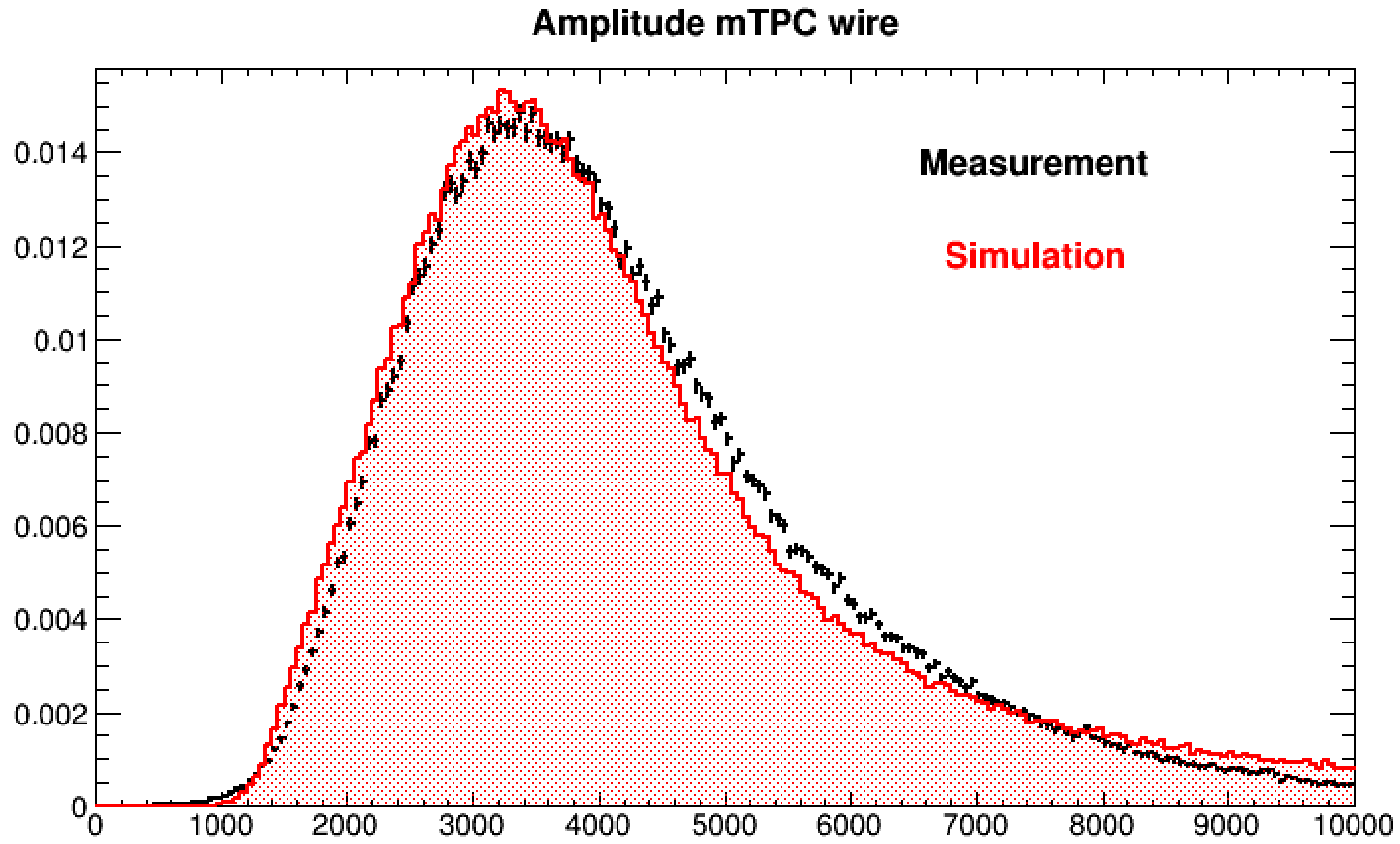
Pion decay, lepton universality





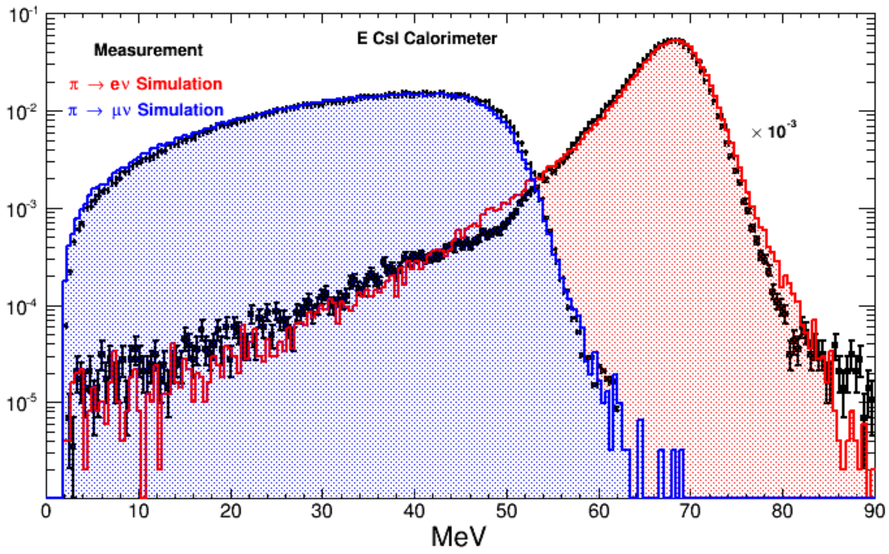


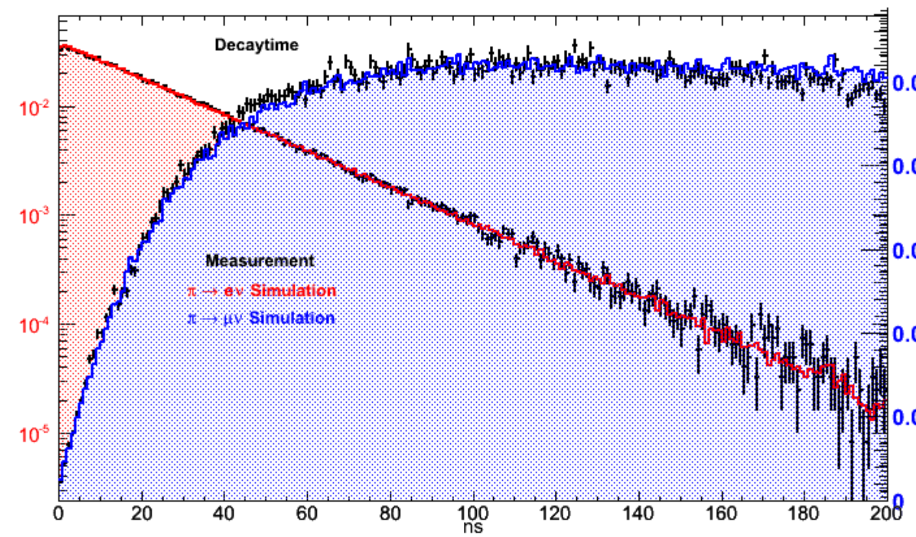
Left and Right signal correlation in the mTPC wires



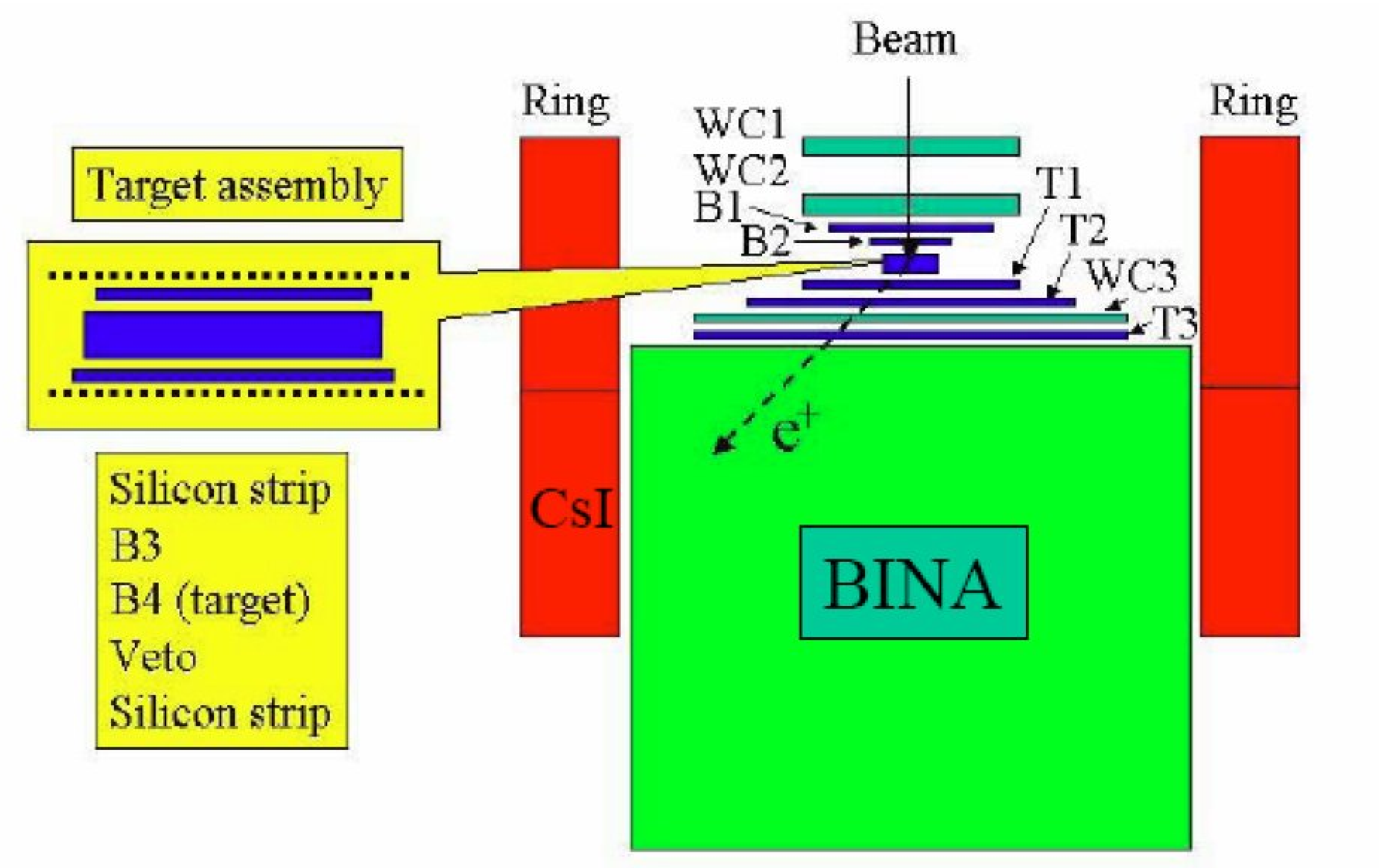
mTPC amplitude of a wire

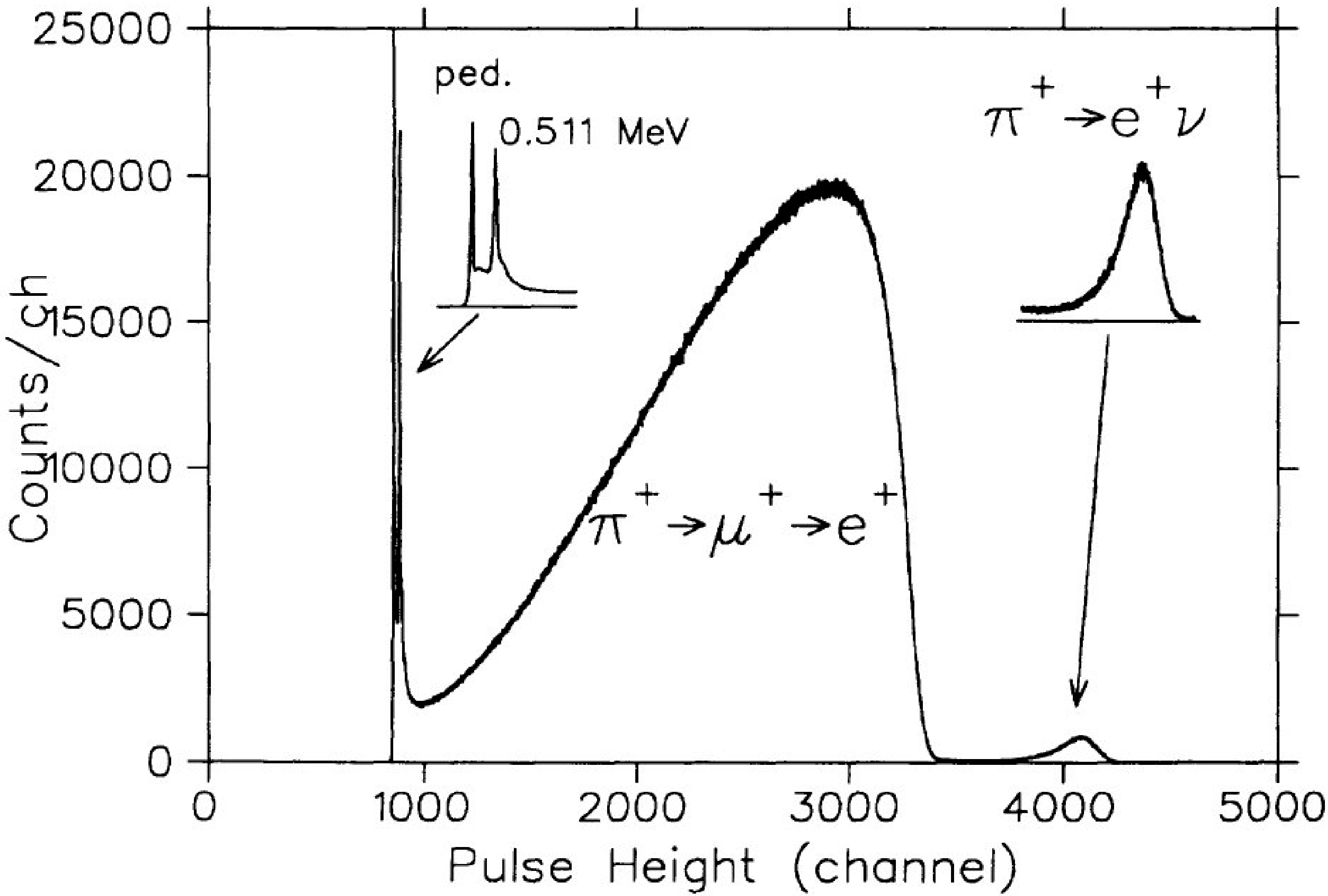
Simulation and measurements: Energy and timing





PIENU (TRIUMF)





25000
20000
15000
10000
5000
0
Counts/ch
0
1000
2000
3000
4000
5000
Pulse Height (channel)
ped.
0.511 MeV
$\pi^+ \rightarrow e^+ \nu$
$\pi^+ \rightarrow \mu^+ \rightarrow e^+$