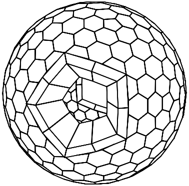
Measuring the Pion Substructre with Radiative Positronic Pion Decays

Dissertation Committee Meeting

L. Peter Alonzi III

University of Virginia – PEN Collaboration

17^{th} of April, 2012



Outline

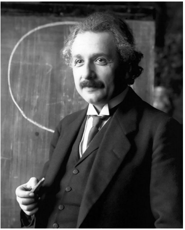
- The Physics of Pions
- The contribution of the PEN collaboration
  - $\pi^+ \to e^+ \nu_e \gamma$
  - Simulation

Feynman's Analogy

Imagine you are watching a game of chess; except you do not know the rules, and cannot see the whole board.

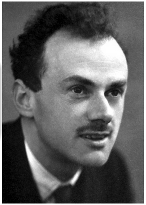
Street Chess by Petr Kratochvil

All of Physics



1905: Relativity

$$E = m$$



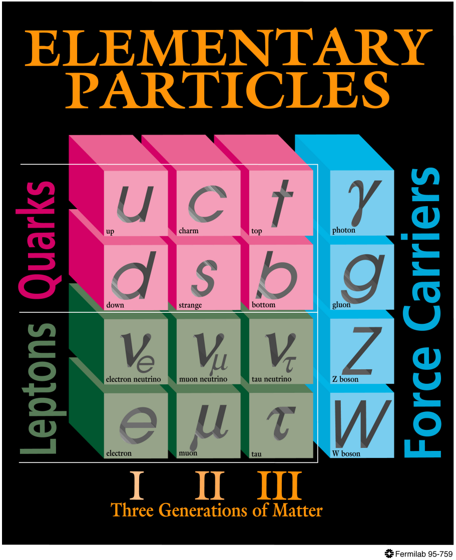
1928: Quantization

$$i\gamma^{\mu}\partial_{\mu}\psi = m\psi$$

1915 – 1967: Symmetries

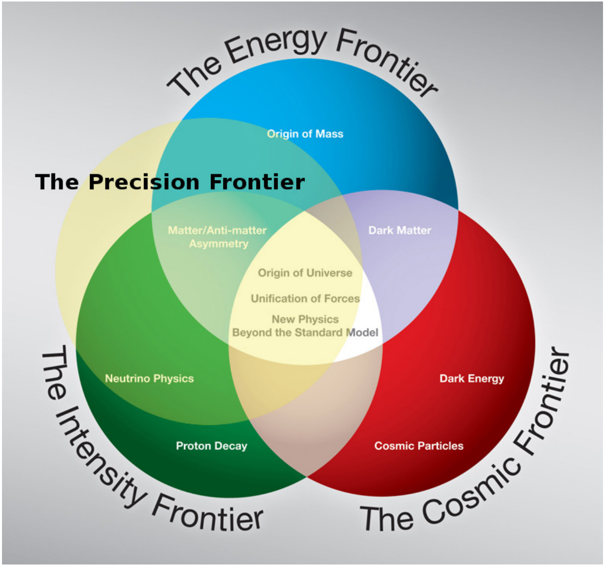
$$\mathrm{SU}(3)_C \otimes \mathrm{SU}(2)_L \otimes \mathrm{U}(1)_Y$$

The Actors

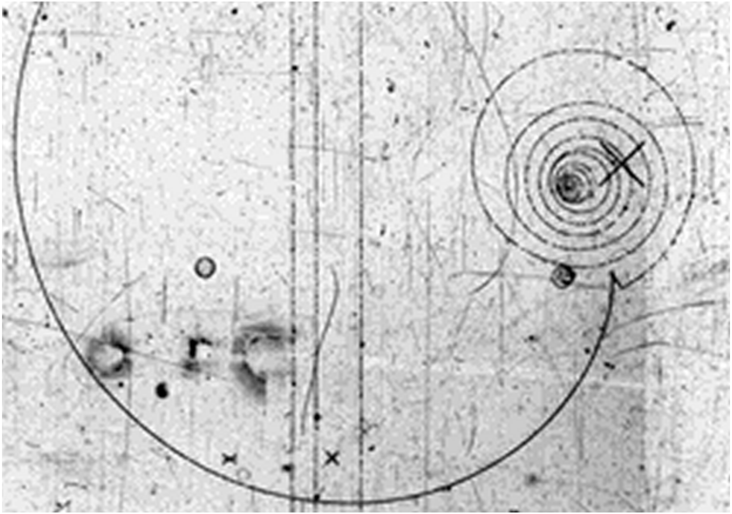


ELEMENTARY PARTICLES
Quarks
Leptons
Force Carriers
u
up
c
charm
t
top
d
down
s
strange
b
bottom
ν_e
electron neutrino
ν_μ
muon neutrino
ν_τ
tau neutrino
e
electron
μ
muon
τ
tau
γ
photon
g
gluon
Z
Z boson
W
W boson
I II III
Three Generations of Matter
Fermilab 95-759

What's Next?

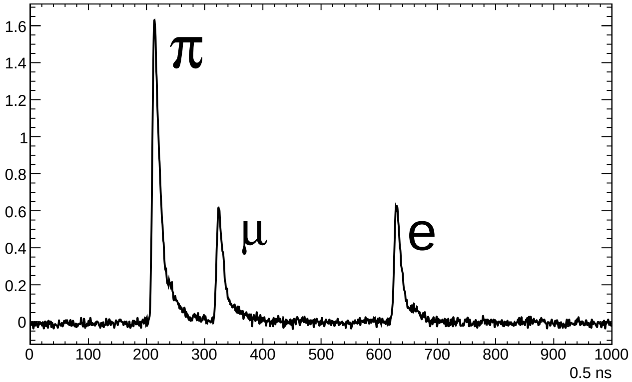

The Energy Frontier
The Precision Frontier
Origin of Mass
Matter/Anti-matter Asymmetry
Dark Matter
Origin of Universe
Unification of Forces
New Physics Beyond the Standard Model
Neutrino Physics
Dark Energy
Proton Decay
Cosmic Particles
The Intensity Frontier
The Cosmic Frontier

What Does a Pion Look Like?

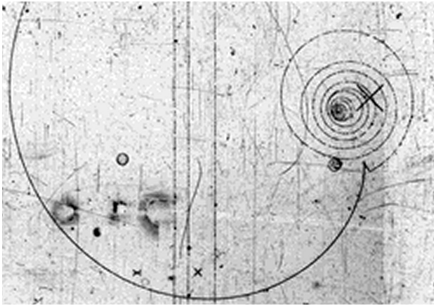


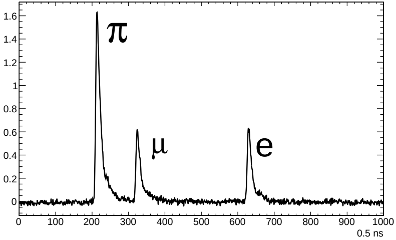
http://teachers.web.cern.ch/teachers/archiv/HST2006/bubble_chambers/BCWebIntro.htm

What Does a Pion Look Like?



The Pion Frontier





- Testing Yukawa's hypothesis
- Mass of the W boson
- Weak Symmetry (V-A)
- Weak Lepton Universality
- Pion Structure (F_A/F_V)
- Standard Model Tests

Global Context $\pi \to e\nu$

THEORY: $BR = \dfrac{\Gamma(\pi \to e\nu(\gamma))}{\Gamma(\pi \to \mu\nu(\gamma))} = \dfrac{g_e}{g_\mu} \dfrac{m_e^2(m_\pi^2 - m_e^2)}{m_\pi^2(m_\pi^2 - m_\mu^2)} =$

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

EXPERIMENT [PDG]: $BR = (1.230 \pm 0.004) \times 10^{-4}$; $\dfrac{\delta BR}{BR} \approx 3.3 \times 10^{-3}$

$$\boxed{\text{PEN GOAL: } \frac{\delta BR}{BR} < 5 \times 10^{-4}}$$

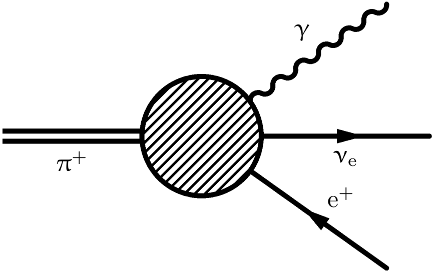
Branching Ratio Analysis: $\pi^+ \to e^+\nu\gamma$

$$BR_{\pi\to e\nu_e\gamma} = BR_{\pi\to e\nu_e}\left(\frac{N_{\pi\to e\nu_e\gamma}}{A_{\pi\to e\nu_e\gamma}}\right)\left(\frac{A_{\pi\to e\nu_e}}{N_{\pi\to e\nu_e}}\right)$$

- $BR_{\pi\to e\nu_e}$
- $N_{\pi\to e\nu_e}$
- $A_{\pi\to e\nu_e}$
- $N_{\pi\to e\nu_e\gamma}$
- $A_{\pi\to e\nu_e\gamma}$

The BR only makes sense for given kinematic regions!

Kinematics of $\pi^+ \to e^+ \nu_e \gamma$



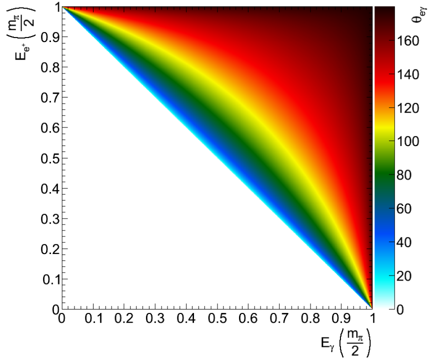
12 free parameters:

- Momentum Conservation (3)
- Energy Conservation (1)
- Particles (3)
- Arbitrary Rotation (3)
- 2 DOF remain

We measure 3 observables:

- photon energy (E_γ, x)
- positron energy (E_e, y)
- opening angle ($\cos\Theta_{e\gamma}$)

Kinematics of $\pi^+ \to e^+\nu_e\gamma$



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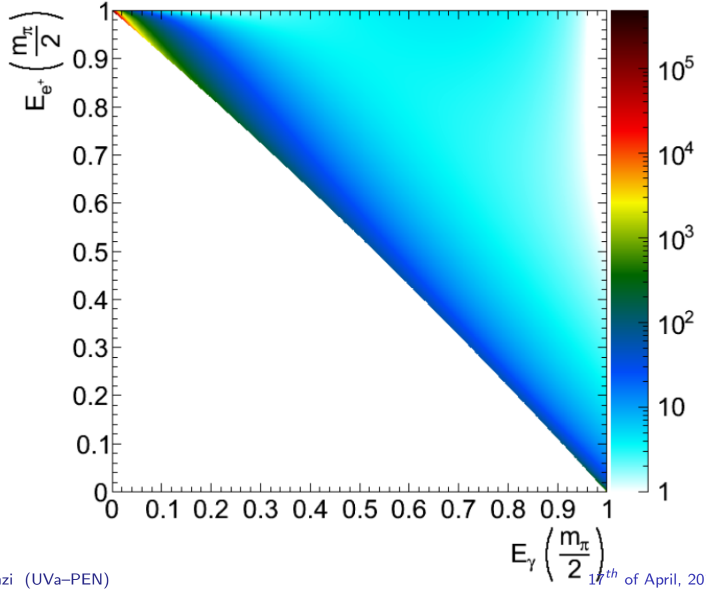
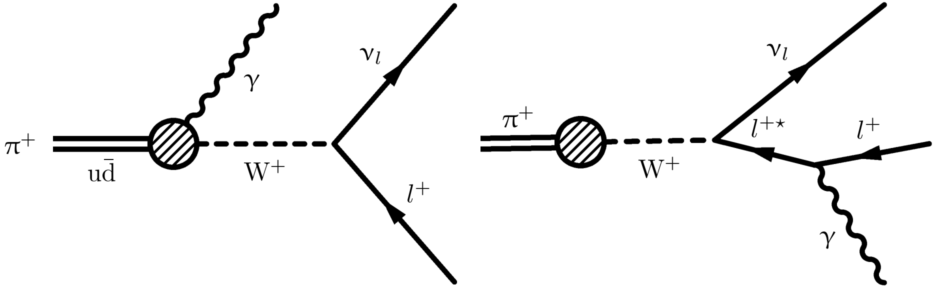
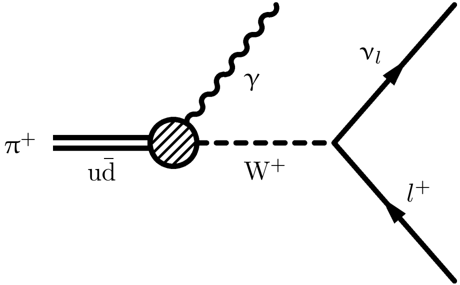
Total Differential Decay Rate for $\pi^+ \to e^+\nu_e\gamma$

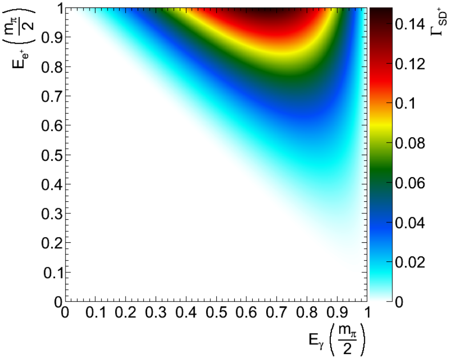


$\mathcal{M}(\pi \to e^+ \nu_e \gamma) = \mathcal{M}_{SD} + \mathcal{M}_{IB}$



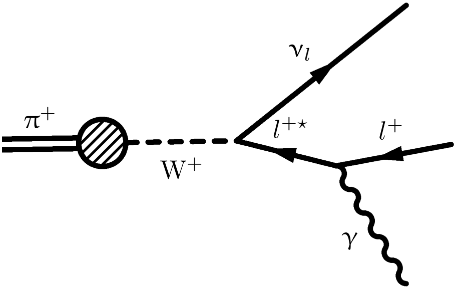
Structure Dependent Component

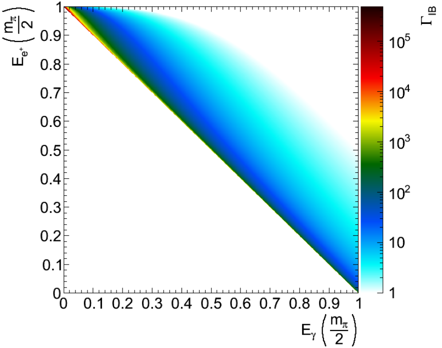




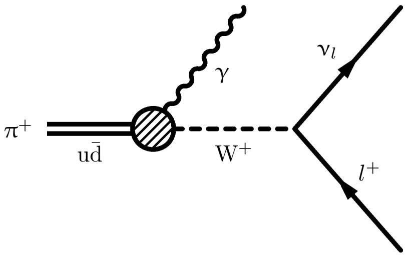
$$\boxed{\frac{d^2\Gamma_{SD}}{dxdy} = \frac{\alpha}{8\pi}\Gamma_{\pi\to e\nu}\left(\frac{m_\pi}{m_e}\right)^2\left(\frac{1}{f_\pi}\right)^2\left[(F_V+F_A)^2 SD^+(x,y)+(F_V-F_A)^2 SD^-(x,y)\right]}$$

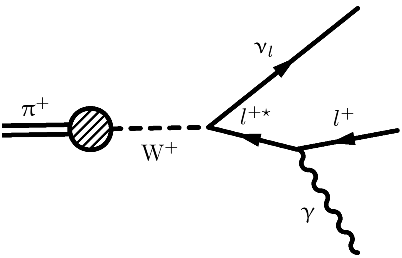
Inner Bremsstrahlung Component

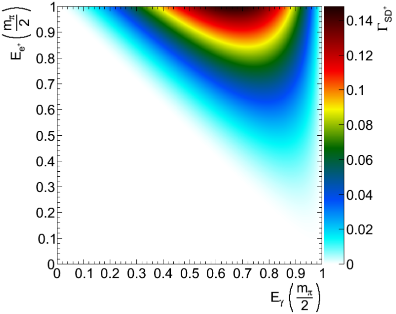


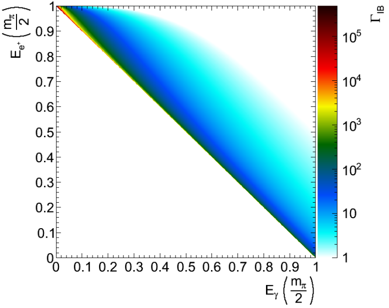


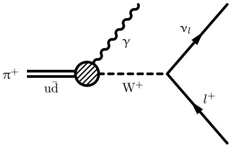
$$\boxed{\frac{d^2\Gamma_{IB}}{dxdy} = \frac{\alpha}{2\pi}\Gamma_{\pi\to e\nu} IB(x,y)}$$

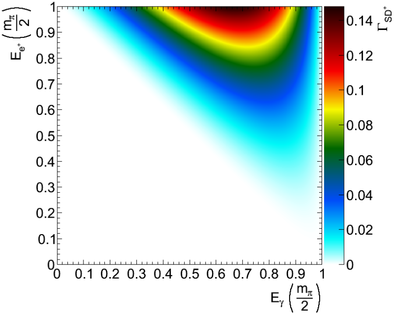

π+
ud̄
γ
W+
νl
l+

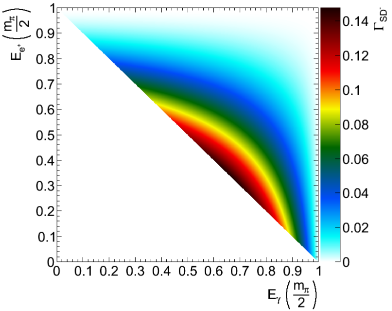

π+
W+
νl
l+⋆
l+
γ


E_{e+} (m_π/2)
E_γ (m_π/2)
Γ_{SD+}
0
0.1
0.2
0.3
0.4
0.5
0.6
0.7
0.8
0.9
1
0.02
0.04
0.06
0.08
0.1
0.12
0.14


E_{e+} (m_π/2)
E_γ (m_π/2)
Γ_IB
0
0.1
0.2
0.3
0.4
0.5
0.6
0.7
0.8
0.9
1
10
10^2
10^3
10^4
10^5







$$\frac{d^2\Gamma_{SD}}{dxdy} = \frac{\alpha}{8\pi}\Gamma_{\pi\to e\nu}\left(\frac{m_\pi}{m_e}\right)^2\left(\frac{1}{f_\pi}\right)^2\left[(F_V+F_A)^2 SD^+(x,y) + (F_V-F_A)^2 SD^-(x,y)\right]$$

Measuring F_V and F_A

$$\boxed{\chi^2 = \sum_{i=\mathrm{A,B,C}} \frac{(B_i^{\mathrm{the}} - B_i^{\mathrm{exp}})^2}{\sigma_i^2}}$$

Measurement (MeV_{exp})			BR Evaluation (MeV)		
Reg.	$E_{\mathrm{e}^+}^{exp}$	E_γ^{exp}	Reg.	E_{e^+}	E_γ
I	> 51.7	> 51.7	A	> 50	> 50
II	$20 - 51.7$	55.6	B	> 10	> 50
III	> 55.6	$20 - 51.7$	C	> 50	> 10

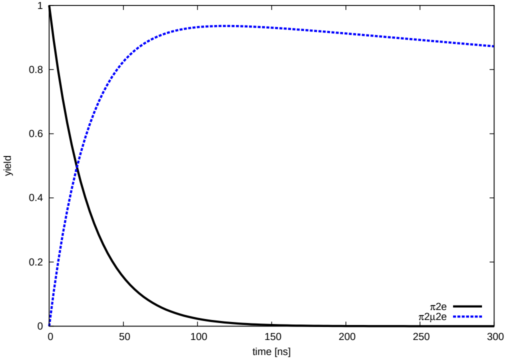
PEN Event Trigger

Processes to Observe

- $\pi \to e\nu$
- $\pi \to e\nu\gamma$
- $\pi \to \mu\nu \ (\to e\nu)$ (norm)

Traits to Prefer

- Stopped Pion
- Early Pion decay times
- Large secondary energies



To understand the trigger is to understand the experiment.

PEN Event Trigger

Processes to Observe

- $\pi \to e\nu$
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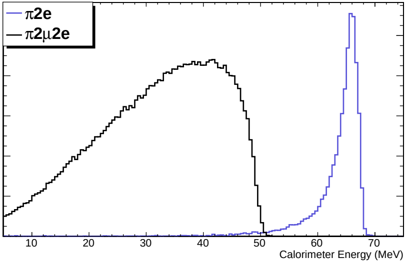
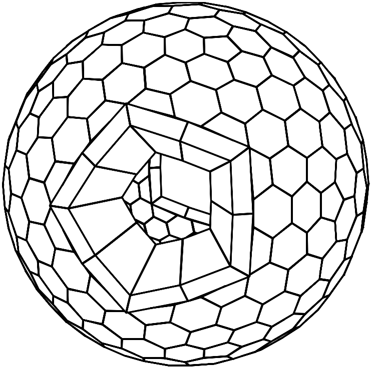
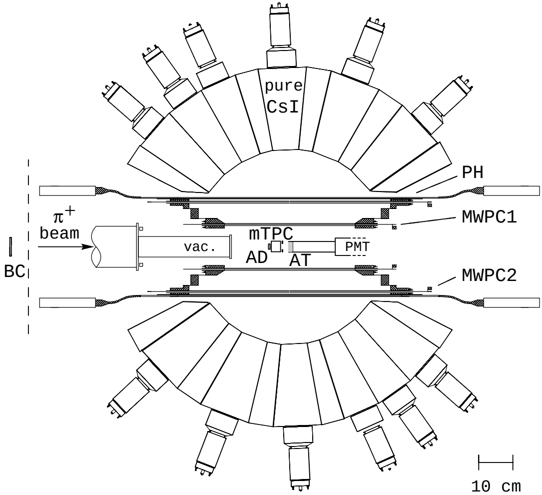


To understand the trigger is to understand the experiment.

PEN Detector Overview

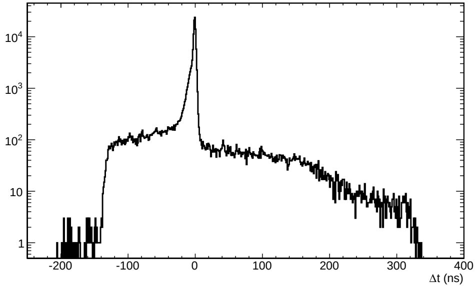


PEN Detector Overview



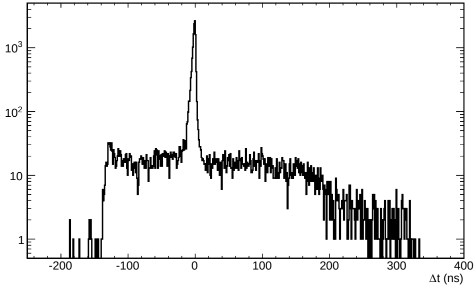
Extracting $N_{\pi \to e \nu_e \gamma}$

- Raw Data ($\Delta t \equiv t_e - t_\gamma$)



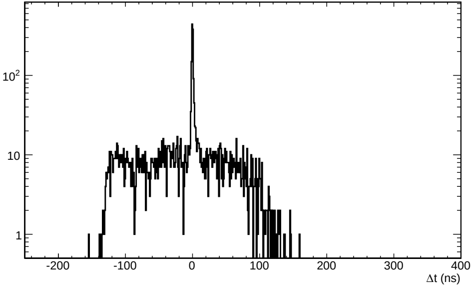
Extracting $N_{\pi\to e\nu_e\gamma}$

- Raw Data ($\Delta t \equiv t_e - t_\gamma$)
- Particle ID



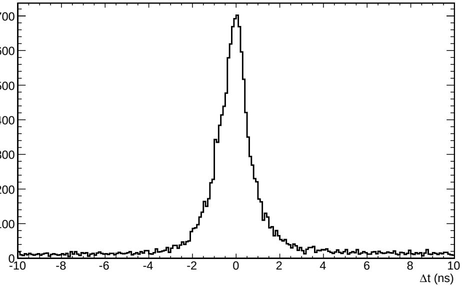
Extracting $N_{\pi\to e\nu_e\gamma}$

- Raw Data ($\Delta t \equiv t_e - t_\gamma$)
- Particle ID
- Hard Photons



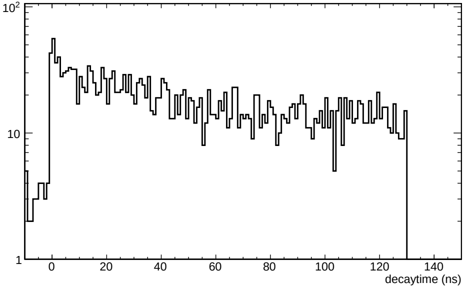
Extracting $N_{\pi\to e\nu_e\gamma}$

- Raw Data ($\Delta t \equiv t_e - t_\gamma$)
- Particle ID
- Hard Photons
- Signal Region



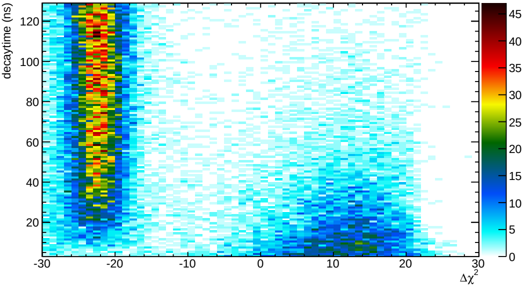
Extracting $N_{\pi \to e\nu_e\gamma}$

- Raw Data ($\Delta t \equiv t_e - t_\gamma$)
- Particle ID
- Hard Photons
- Signal Region
- Cross Check ($t_e - t_\pi$)



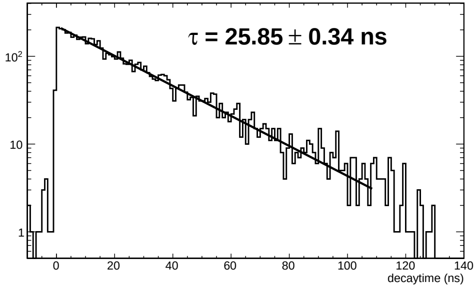
Extracting $N_{\pi \to e \nu_e \gamma}$

- Raw Data ($\Delta t \equiv t_e - t_\gamma$)
- Particle ID
- Hard Photons
- Signal Region
- Cross Check ($t_e - t_\pi$)
- Waveform Cut



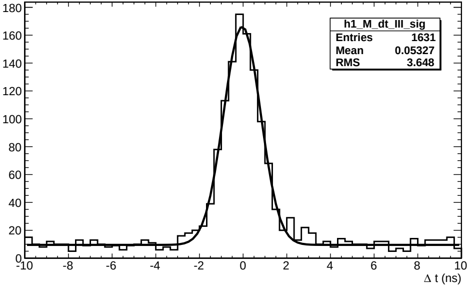
Extracting $N_{\pi\to e\nu_e\gamma}$

- Raw Data ($\Delta t \equiv t_e - t_\gamma$)
- Particle ID
- Hard Photons
- Signal Region
- Cross Check ($t_e - t_\pi$)
- Waveform Cut
- Cross Check Again



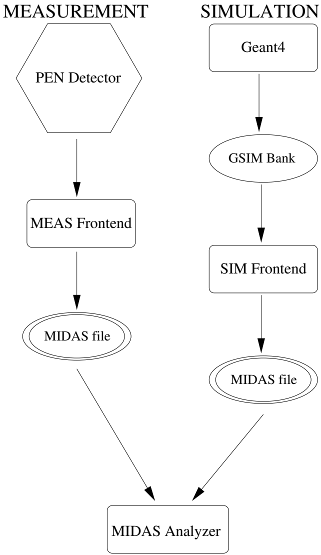
Extracting $N_{\pi \to e \nu_e \gamma}$

- Raw Data ($\Delta t \equiv t_\mathrm{e} - t_\gamma$)
- Particle ID
- Hard Photons
- Signal Region
- Cross Check ($t_\mathrm{e} - t_\pi$)
- Waveform Cut
- Cross Check Again
- Final Data (Reg. A,B,C)



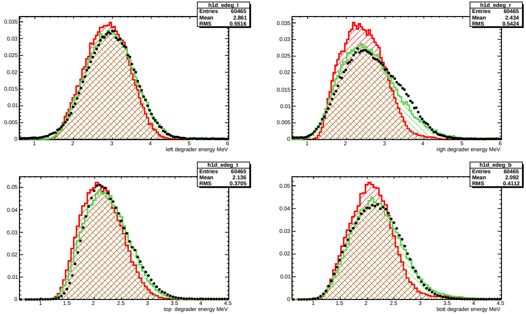
Determining $A_{\pi \to e \nu_e \gamma}$

- Simulation Technique



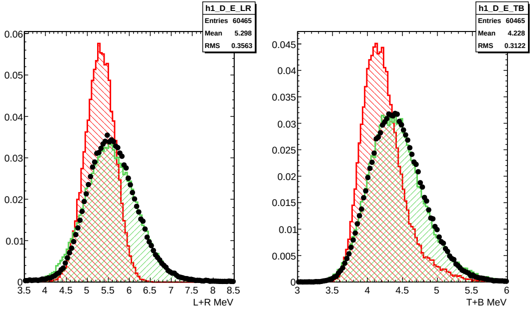
Determining $A_{\pi\to e\nu_e\gamma}$

- Simulation Technique
- Degrader Wedges

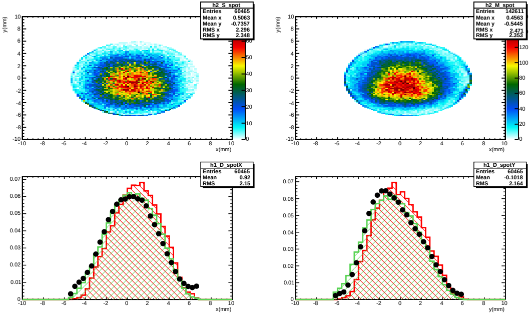


Determining $A_{\pi \to e \nu_e \gamma}$

- Simulation Technique
- Degrader Wedges
- Degrader Pairs

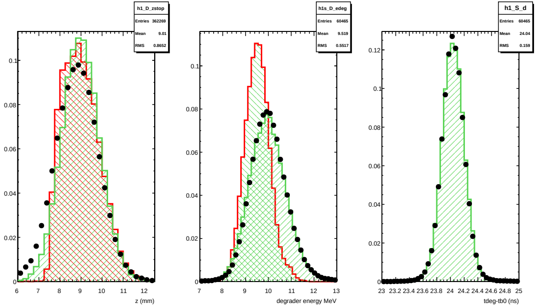


- Simulation Technique
- Degrader Wedges
- Degrader Pairs
- Beam Profile



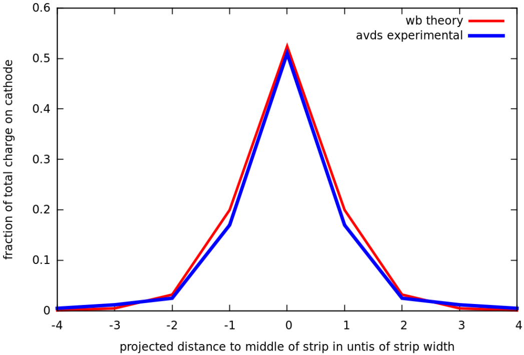
Determining $A_{\pi\to e\nu_e\gamma}$

- Simulation Technique
- Degrader Wedges
- Degrader Pairs
- Beam Profile
- Beam Momentum



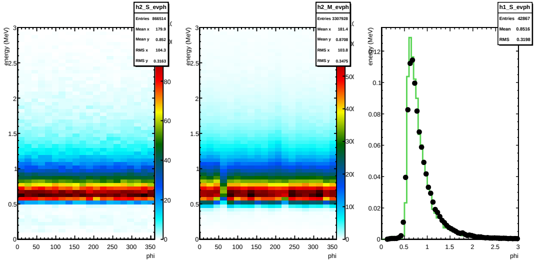
Determining $A_{\pi \to e\nu_e\gamma}$

- Simulation Technique
- Degrader Wedges
- Degrader Pairs
- Beam Profile
- Beam Momentum
- Wire Chambers



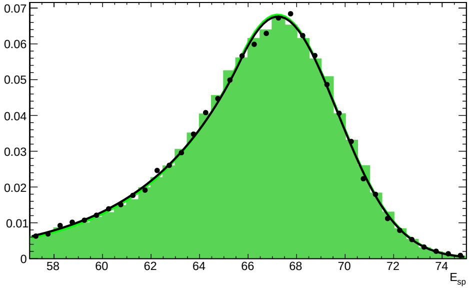
Determining $A_{\pi \to e \nu_e \gamma}$

- Simulation Technique
- Degrader Wedges
- Degrader Pairs
- Beam Profile
- Beam Momentum
- Wire Chambers
- Plastic Hodoscope



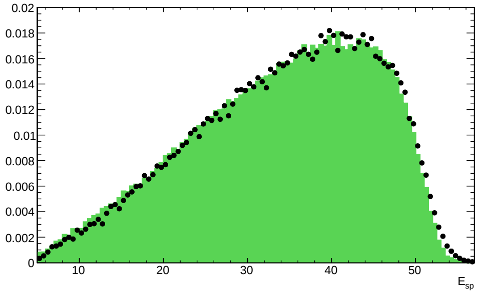
Determining $A_{\pi \to e \nu_e \gamma}$

- Simulation Technique
- Degrader Wedges
- Degrader Pairs
- Beam Profile
- Beam Momentum
- Wire Chambers
- Plastic Hodoscope
- CsI Calorimeter ($\pi \to e$)



Determining $A_{\pi\to e\nu_e\gamma}$

- Simulation Technique
- Degrader Wedges
- Degrader Pairs
- Beam Profile
- Beam Momentum
- Wire Chambers
- Plastic Hodoscope
- CsI Calorimeter ($\pi \to e$)
- CsI Calorimeter ($\pi \to \mu$)



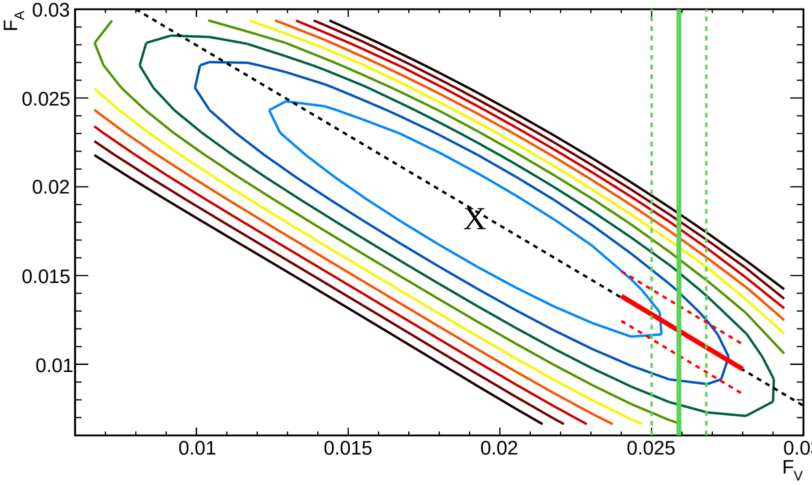
PEN Run Summary

Channel event statistics from physics goals assessment, *not published results*.

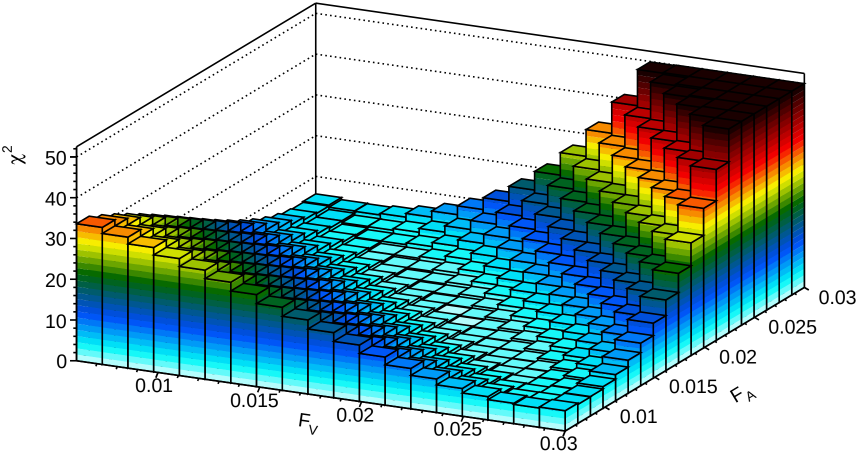
Year	Run Time (days)	π-stops (10^{10})	$\pi \to \mathrm{e}$ (10^6)	$\pi \to \mathrm{e}\gamma$ (10^3)
2008	111	7.5	4.5	5.8
2009	98	13.1	8.3	10.0
2010	68	16.4	10.3	12.5

Region	Events	P/B	σ_{stat}	σ_{sys}	σ_{tot}
I	291.9	$>$200	0.0592	0.0550	0.0808
II	421.3	100	0.0489	0.0406	0.0636
III	856.8	29	0.0344	0.0402	0.0529

Objective Function in the $F_V F_A$ – Plane (2008 data)



Objective Function in the $F_V F_A$ – Plane (2008 data)



Experiment R-05-01 (PEN) collaboration members:

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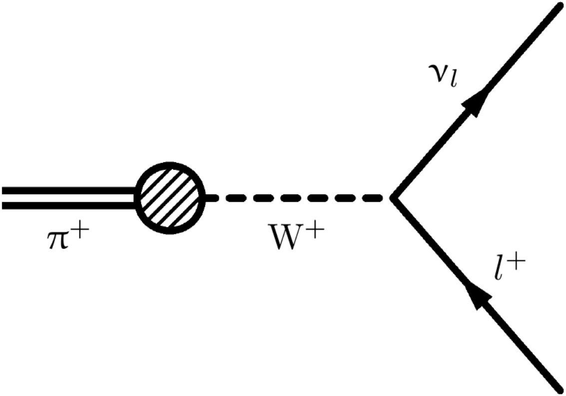
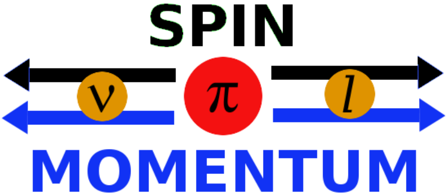
Tree Level Pion Decay

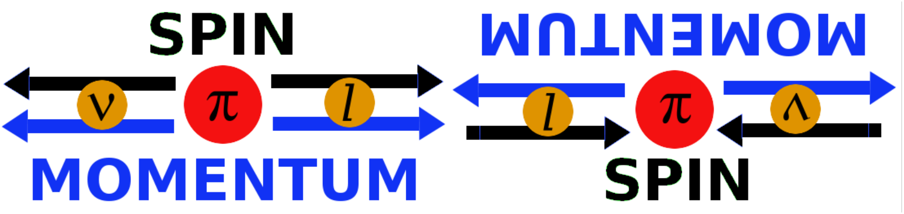


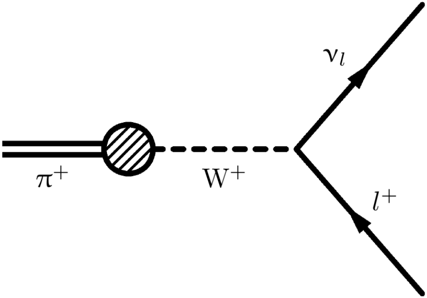
$$\boxed{\frac{\Gamma(\pi \to e\nu)}{\Gamma(\pi \to \mu\nu)} \sim 10^{-4} \qquad m_e \ll m_\mu}$$

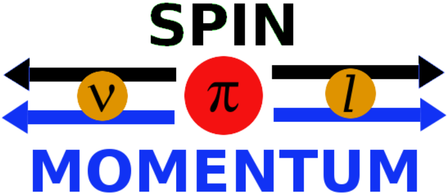
Mirror Symmetry: $(x \to -x, y \to -y, z \to -z)$



Mirror Symmetry: $(x \rightarrow -x, y \rightarrow -y, z \rightarrow -z)$





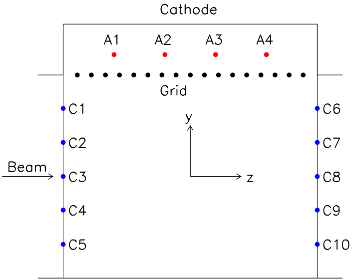


$$\mathcal{M} \sim \bar{u}(p)\gamma_\mu(1 - \gamma^5)\nu(k)$$

Helicity $\equiv \vec{S} \bullet \vec{P}$

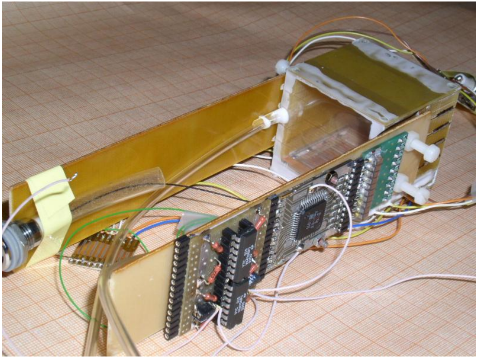
Helicity is **not** a Lorentz invariant. Violation $\sim$ mass

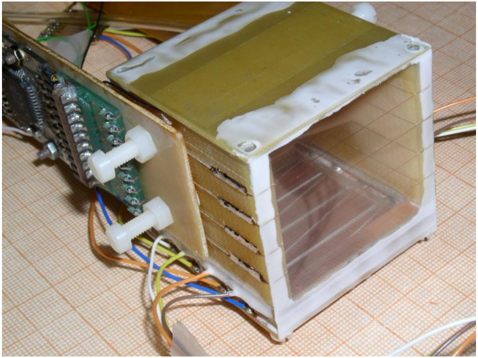
mTPC Technical Specifications

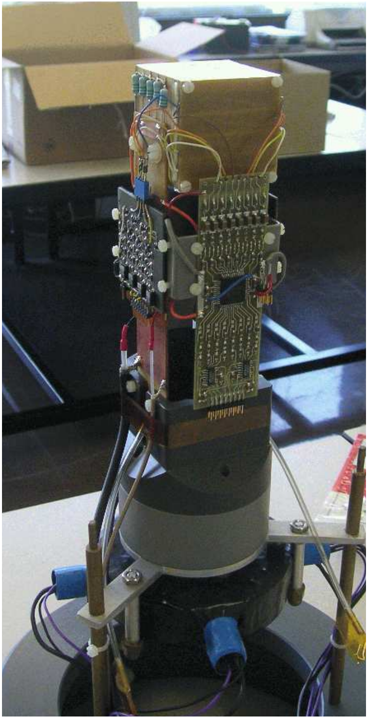


- Proportional Region: 40x6x40 mm
- Drift Region: 40x40x50 mm
- Drift Gas: 90% He and 10% C_2H_6
- 4000 V across drift region
- Grid: 50 μm wires with 1 mm spacing
- Nichrome Anode Wires
  - 40 mm length
  - 20 μm diameter
  - 10 mm spacing
  - 235 Ω resistance
- CAEN VME digitizer V1720

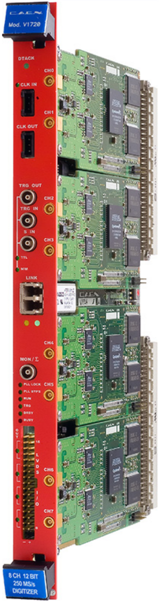
Fabricated by our collaborators from Dubna, Russia

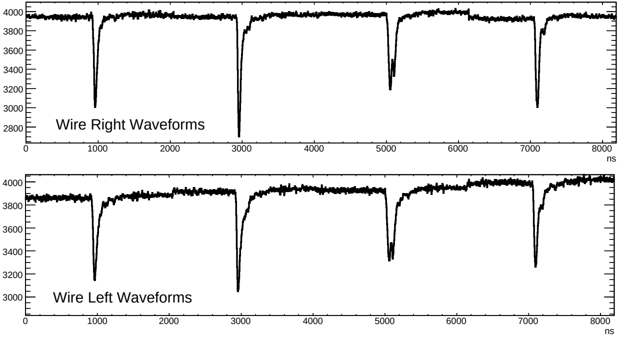






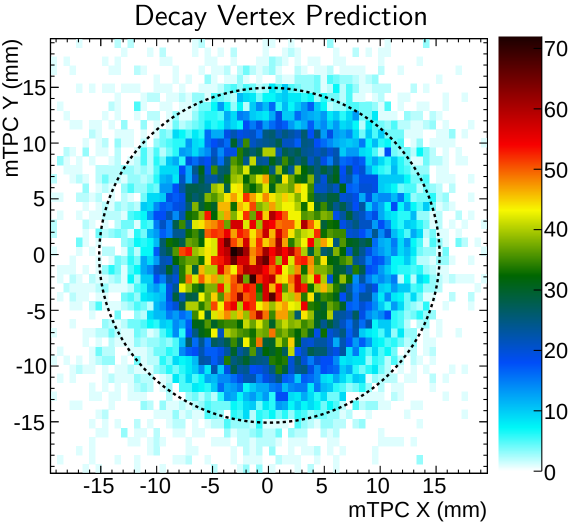
Waveform Digitization





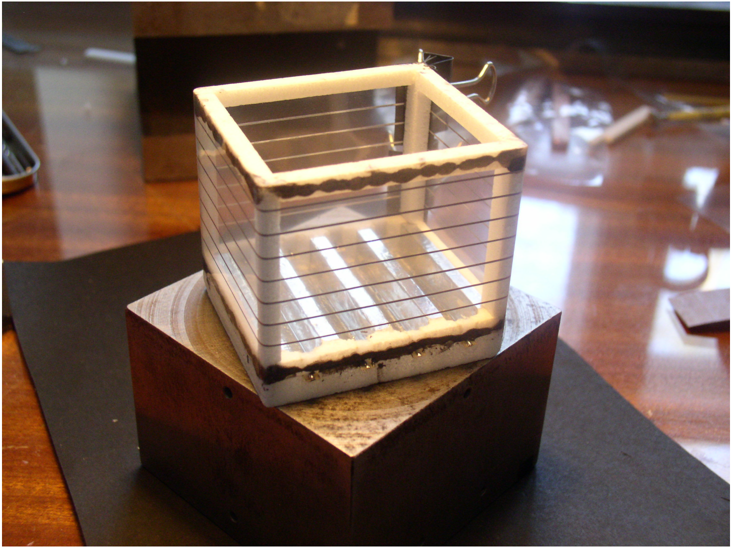
- x: charge division
- y: drift time
- z: wire location

Results from 2009 Data Run

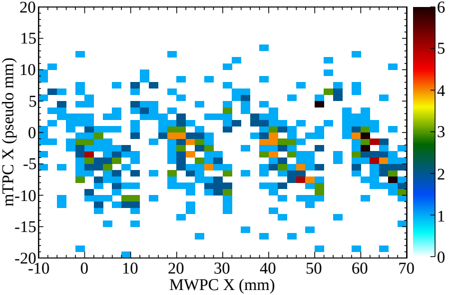


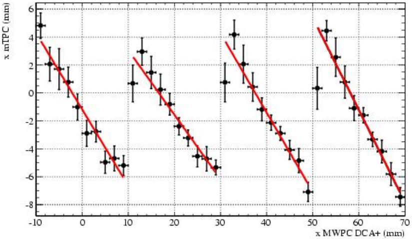
- X Position
  - charge division
  - $\sigma_x < 1.3\,\mathrm{mm}$
- Y position
  - drift time
  - $\sigma_y < 0.35\,\mathrm{mm}$

2010 mTPC (Mark II)



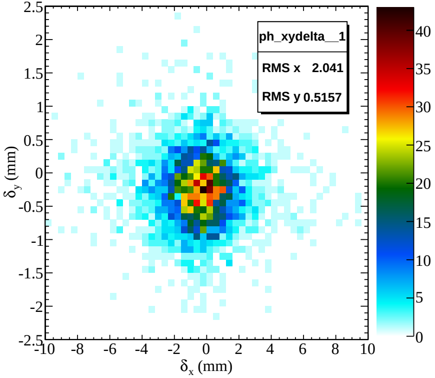
mTPC Coordinate Calibration





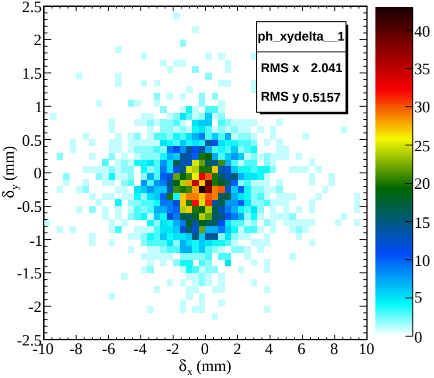
- MWPC coordinates well known
- Calibrate mTPC with MWPC

mTPC coordinate Resolution



$$\delta_i = i_2 - i_1 + \frac{(i_0 - i_3)}{3}$$

mTPC coordinate Resolution



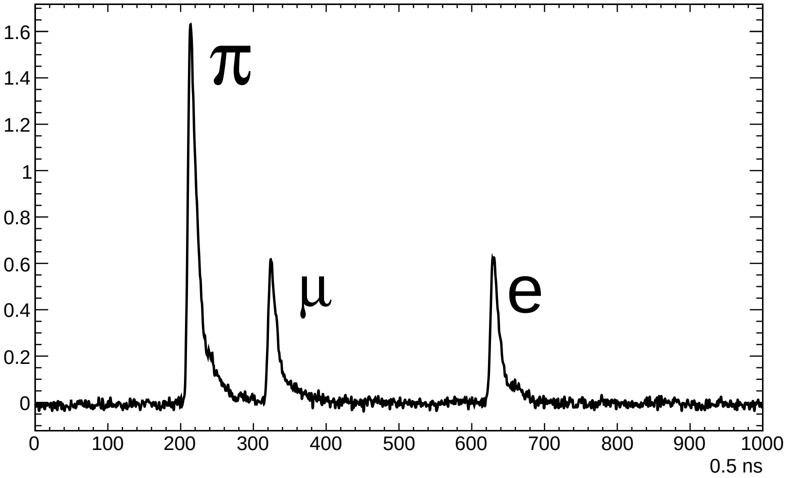
$$\delta_i = i_2 - i_1 + \frac{(i_0 - i_3)}{3}$$

$$\sigma_i = \frac{RMS_{\delta_i}}{\sqrt{1^2 + 1^2 + (1/3)^2 + (1/3)^2}}$$

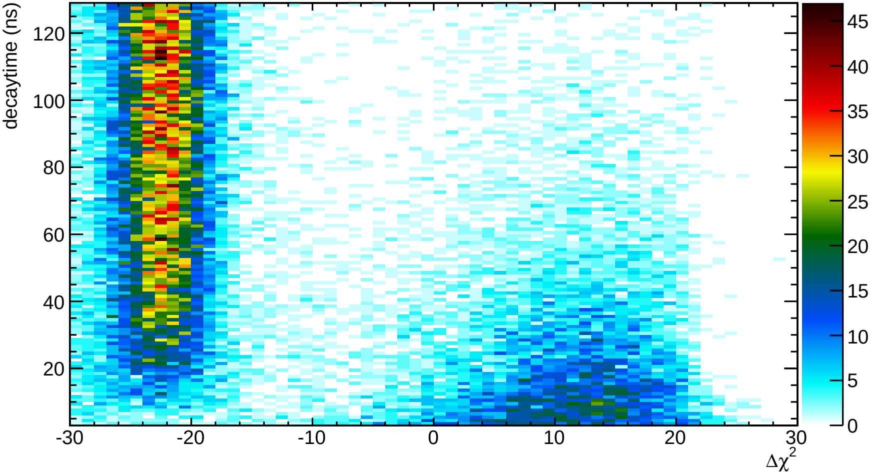
$\Rightarrow$ $\sigma_x < 1.3\,\mathrm{mm}$ (charge division)

$\Rightarrow$ $\sigma_y < 0.35\,\mathrm{mm}$ (drift time)

Target Waveform Digitization

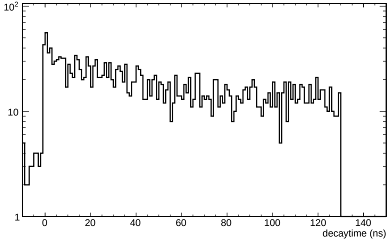


Background Suppression



Background Suppression

Before



After