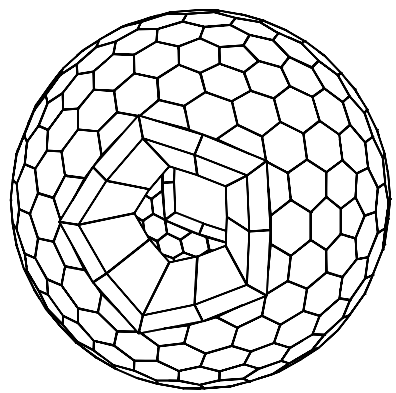
Don't Change the Channel ... Study it for a While

Precision Measurements of Rare Pion Decay Channels

L. Peter Alonzi III

University of Virginia - PEN Collaboration

27^{th} of March, 2012



Outline

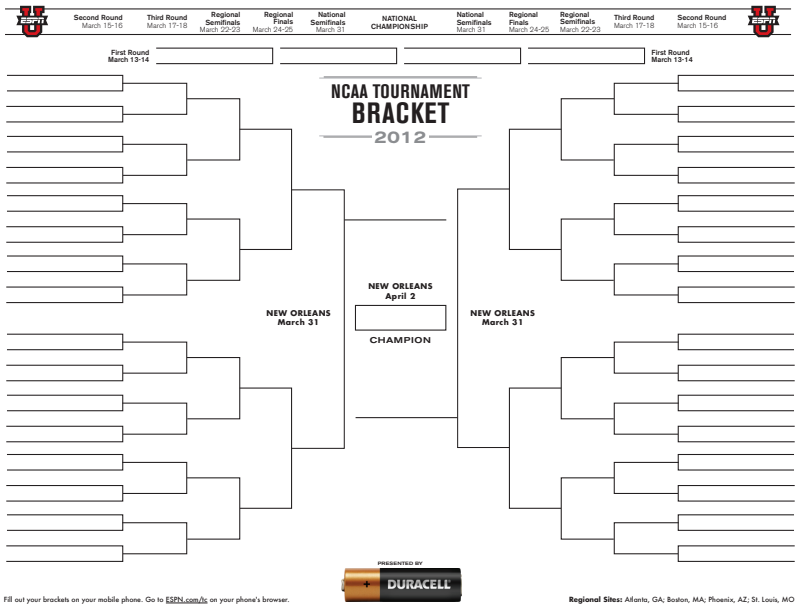
Fundamentals of Pion Decay

Experimental Techniques

Results

Warm Up

How many games are played in a single elimination tournament?



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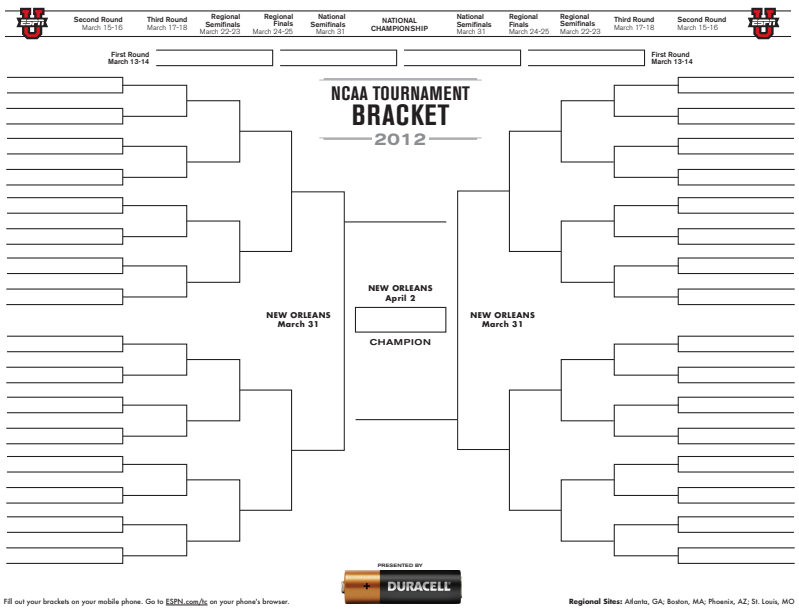

Cheat Sheet

- $32+16+8+4+2+1 = 63$ games

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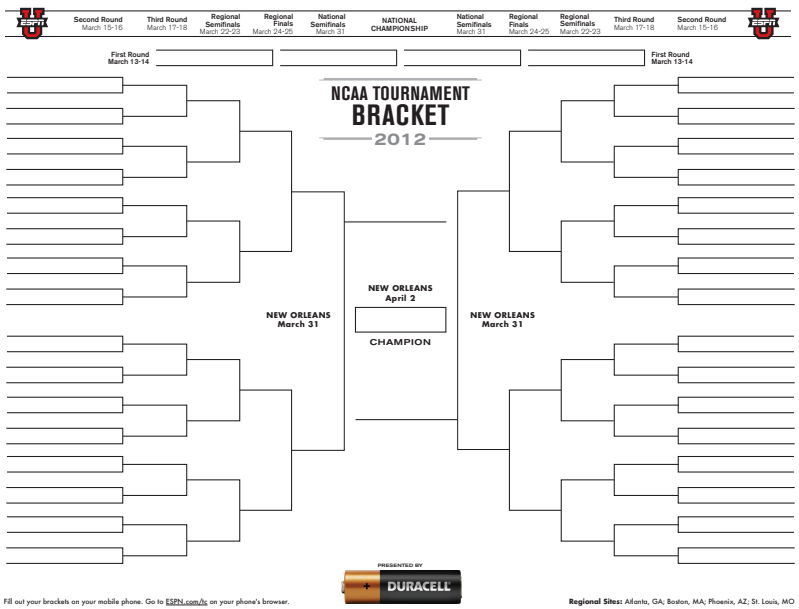

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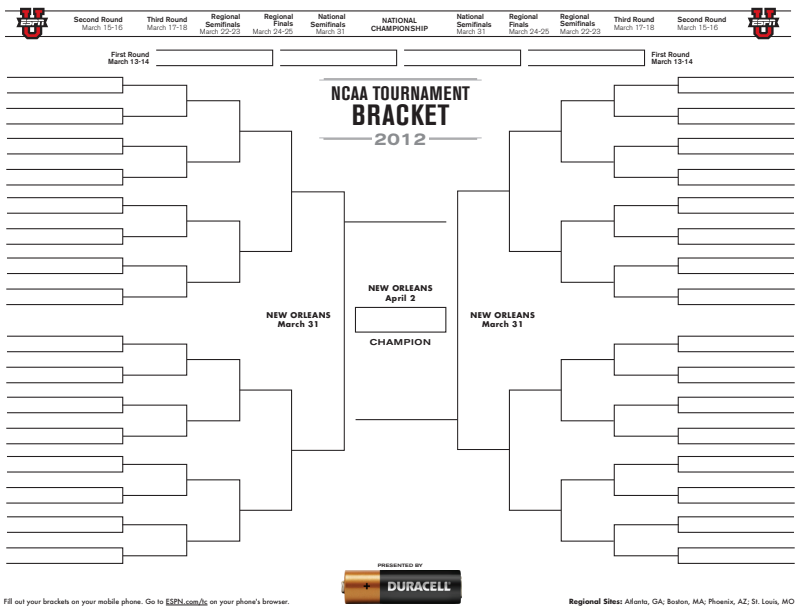

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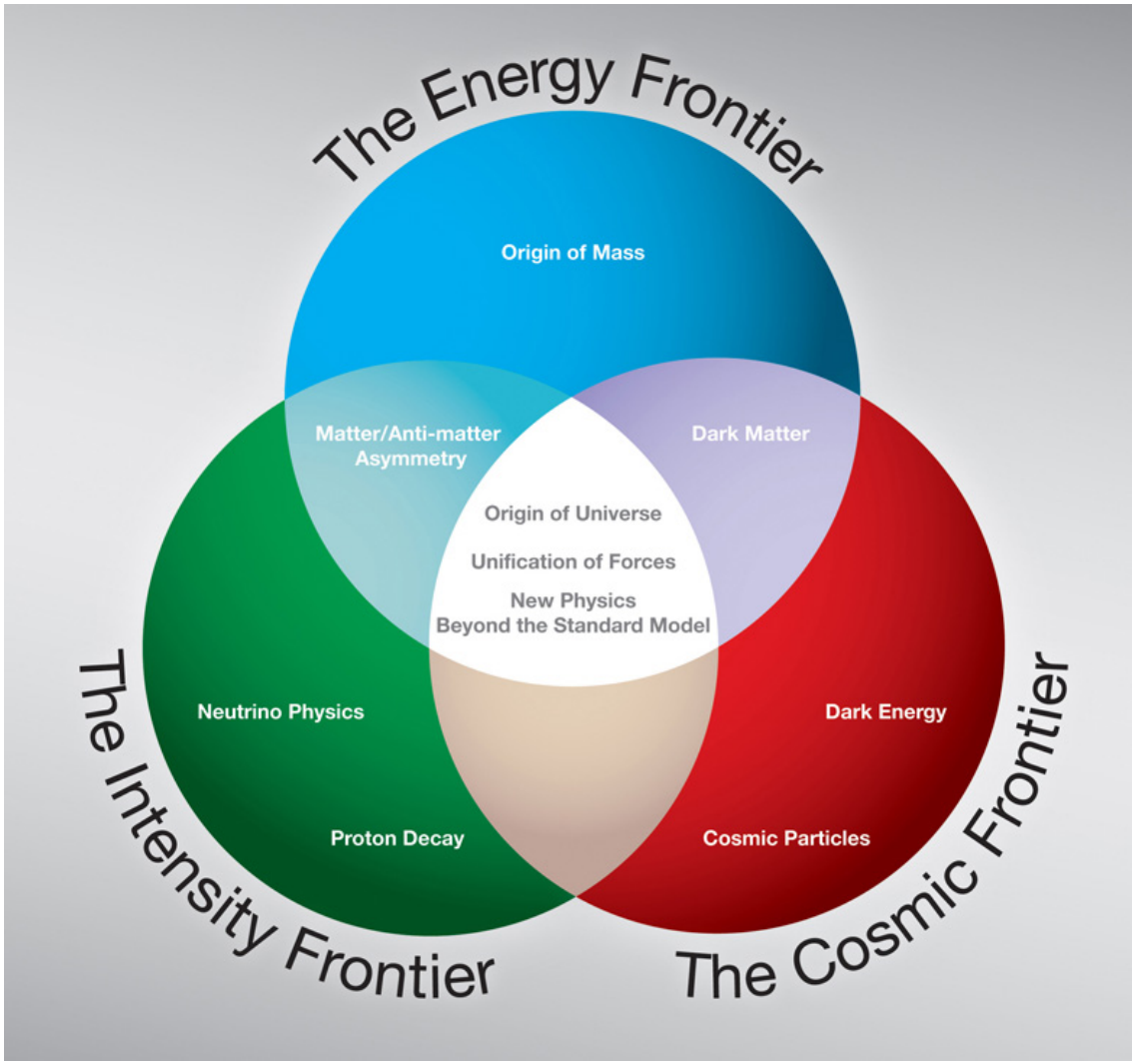
- $\sum_{i=0}^{k-1} 2^i = 63 \quad (\text{w/ } k = \#\text{rounds})$
- $N - 1 = 63 \quad (\text{w/ } N = \#\text{teams})$

Invoking the fundamental nature of a phenomena is powerful.


The Energy Frontier
Origin of Mass
Matter/Anti-matter Asymmetry
Dark Matter
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New Physics Beyond the Standard Model
Neutrino Physics
Proton Decay
Dark Energy
Cosmic Particles
The Intensity Frontier
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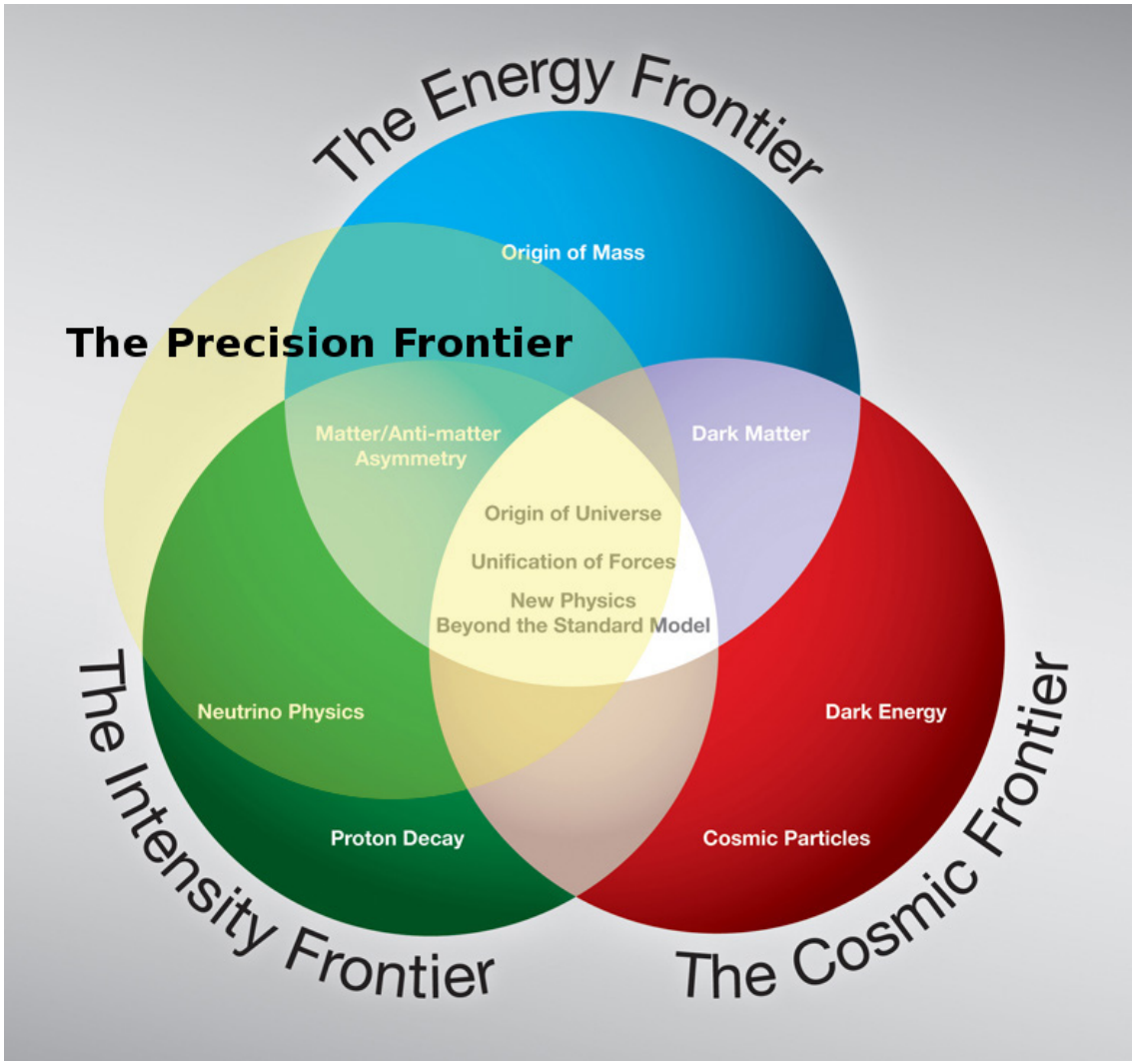
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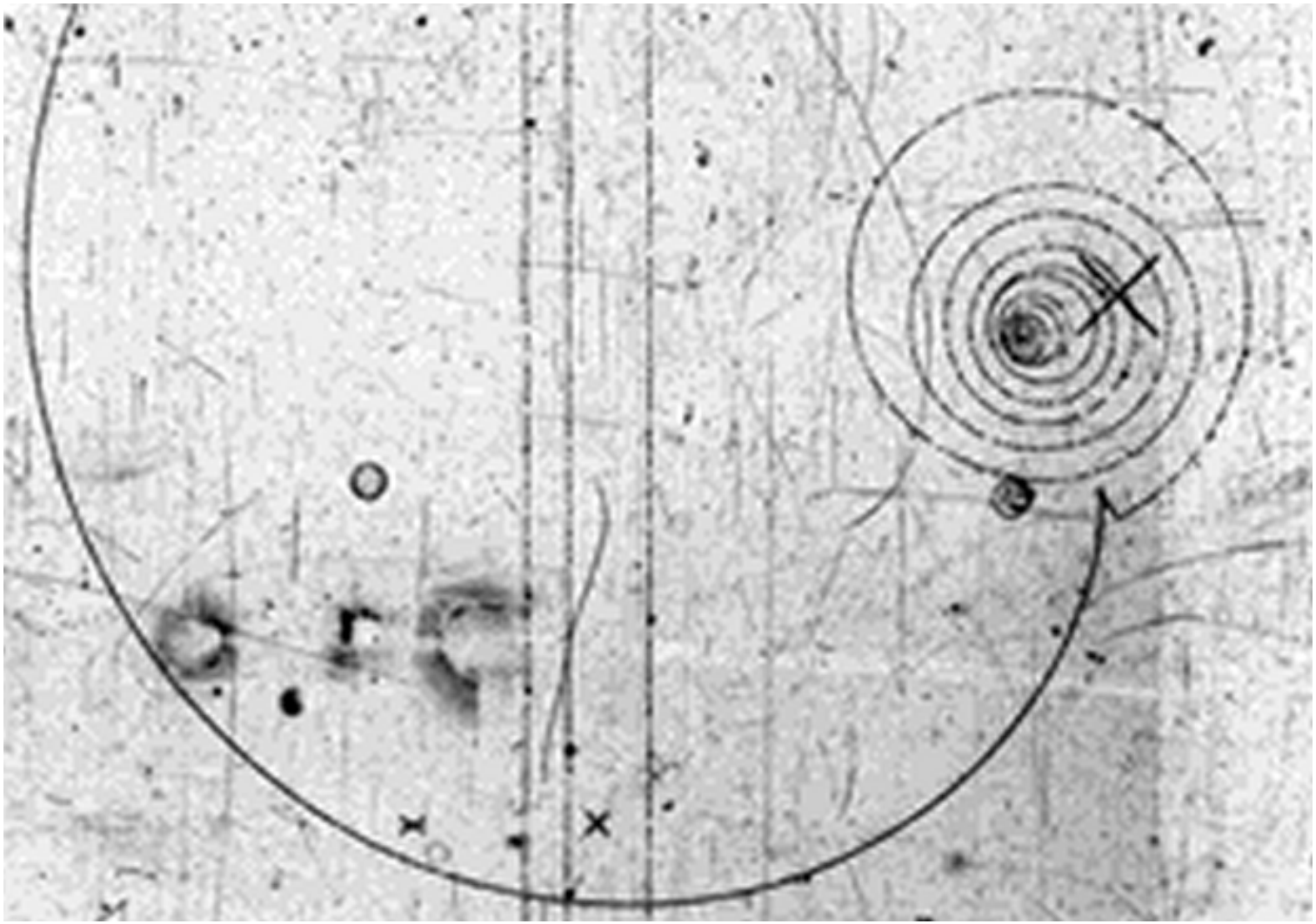
Feynman's Analogy

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

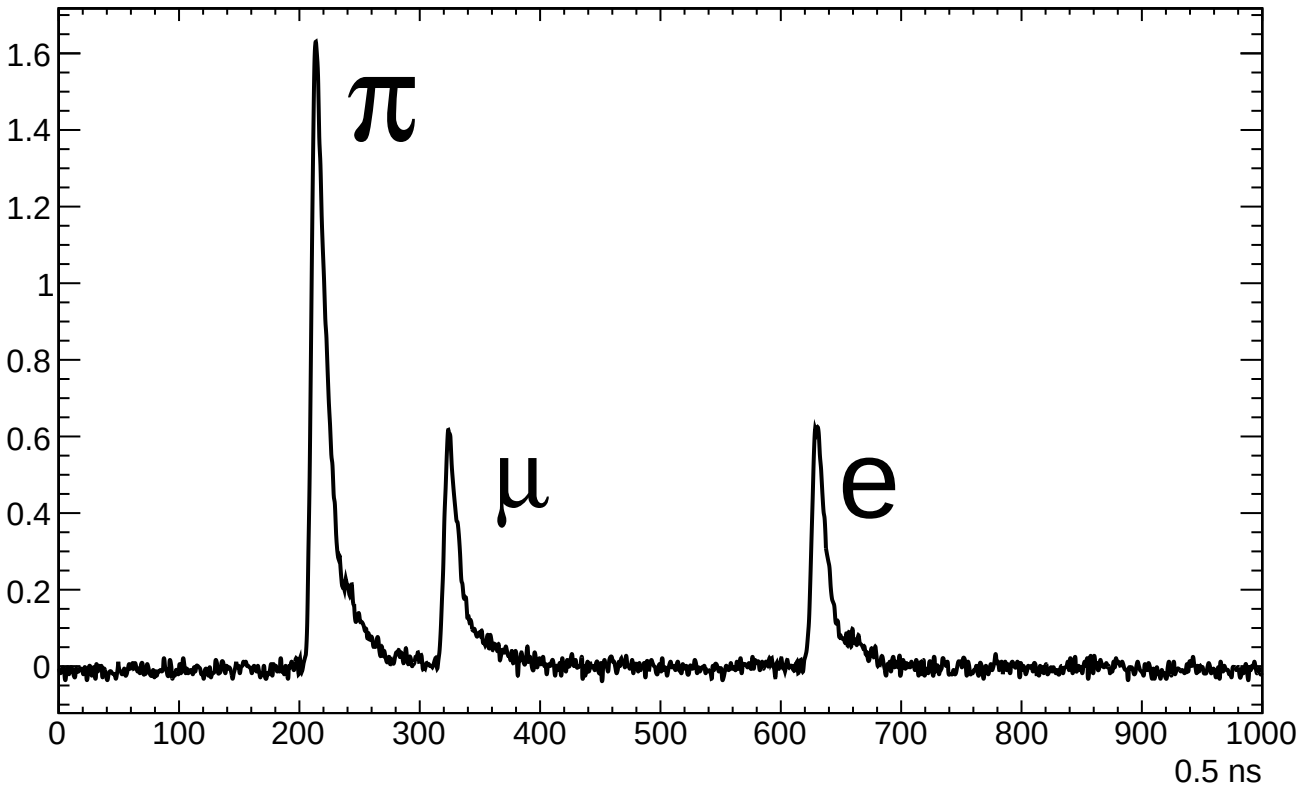
Street Chess by Petr Kratochvil

Pion Decay

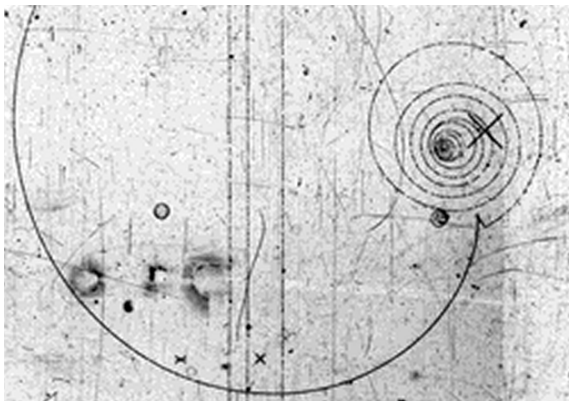


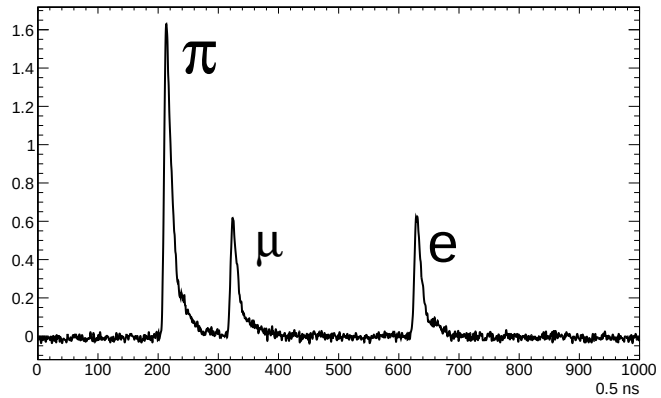
http://teachers.web.cern.ch/teachers/archiv/HST2006/bubble_chambers/BCWebIntro.htm

Pion Decay


π
μ
e
1.6
1.4
1.2
1
0.8
0.6
0.4
0.2
0
0
100
200
300
400
500
600
700
800
900
1000
0.5 ns

The Pion's Role

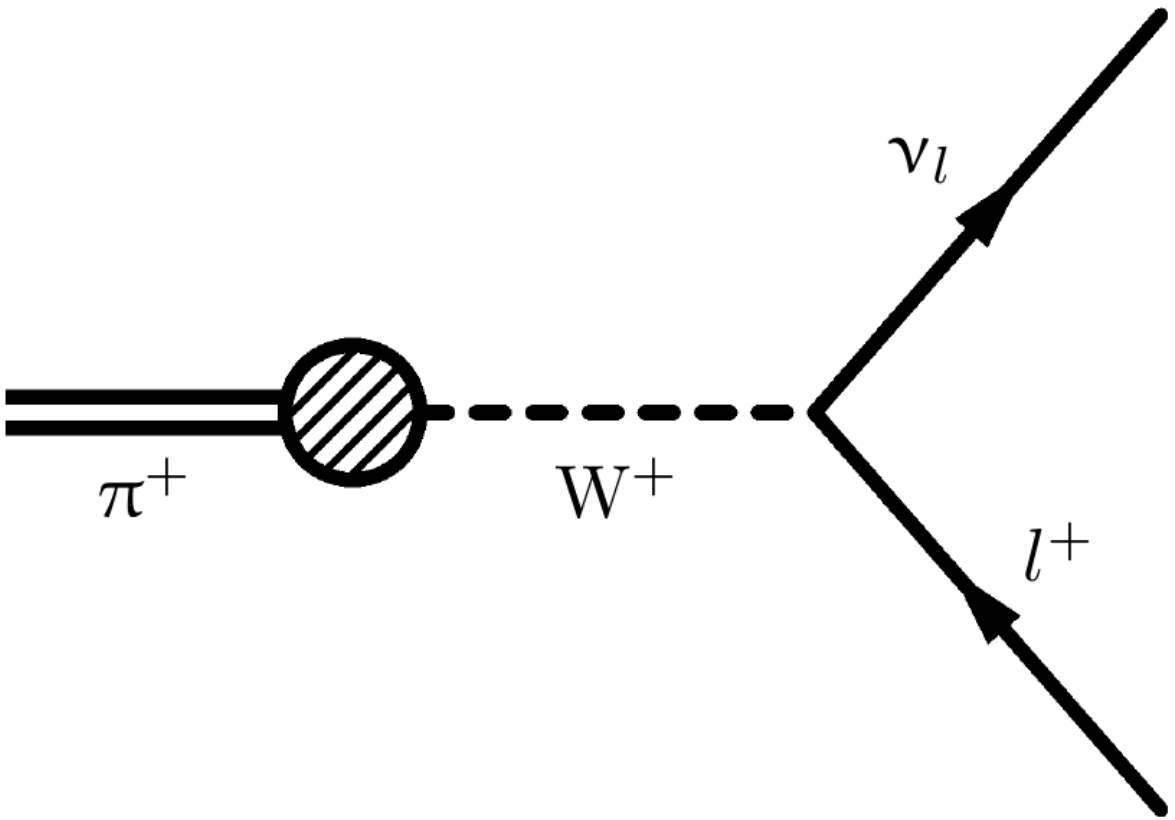




- Testing Yukawa's hypothesis
- Mass of the W boson
- Characterize Weak Force (V-A)

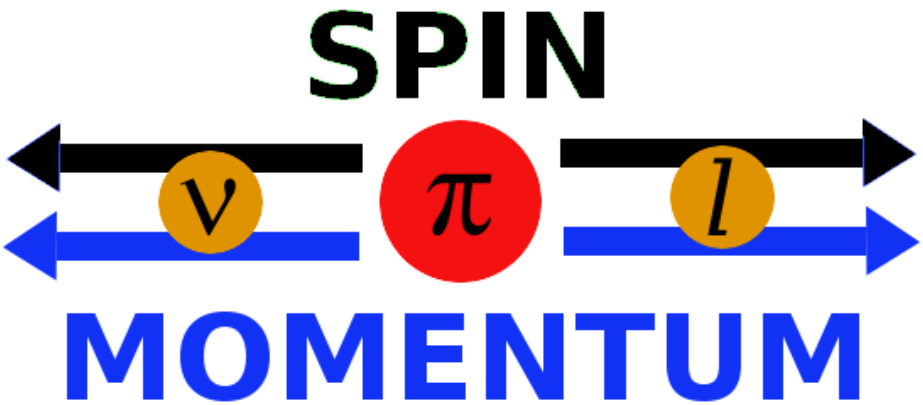
- Weak Lepton Universality
- Pion Structure (F_A/F_V)
- Beyond Standard Model Tests

Tree Level Pion Decay



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

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



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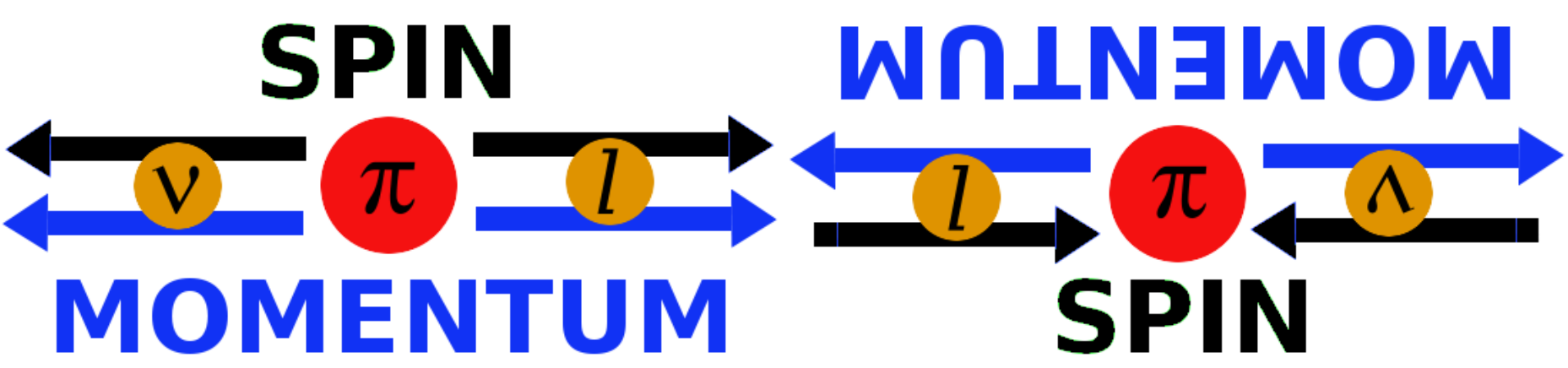
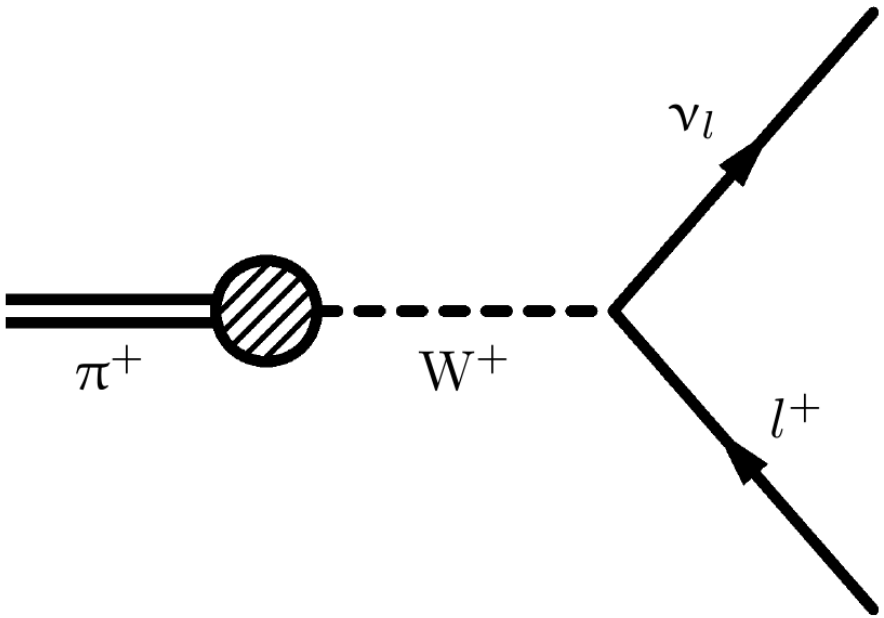
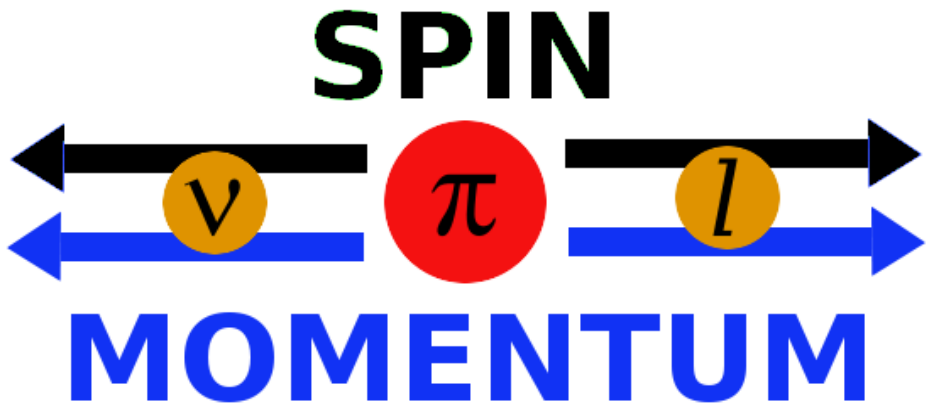


The Left-Handed Force





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

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

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

Global Context $\pi \to e\nu$

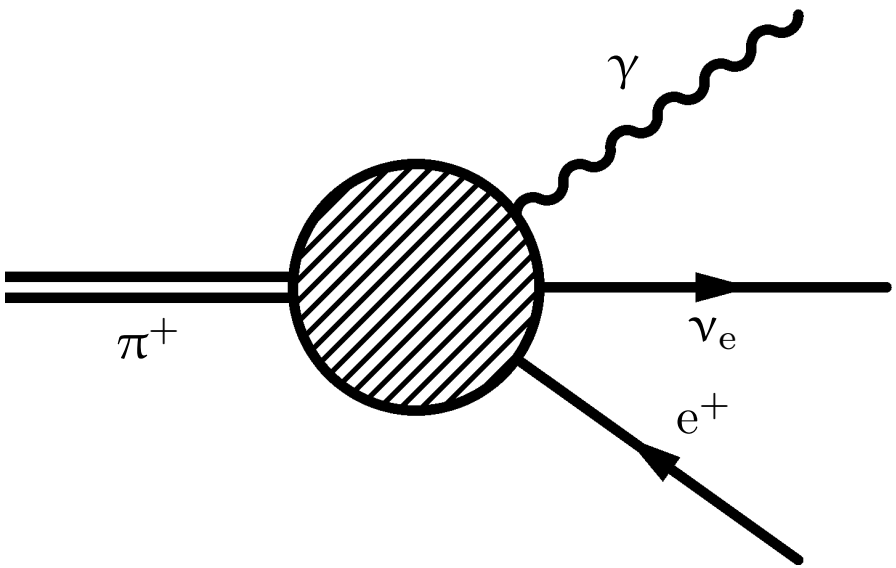
THEORY: $BR = \dfrac{\Gamma(\pi \to e\nu(\gamma))}{\Gamma(\pi \to \mu\nu(\gamma))} = \dfrac{g_e}{g_\mu}\dfrac{m_e^2(m_\pi^2 - m_e^2)}{m_\pi^2(m_\pi^2 - m_\mu^2)} =$

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

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

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

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 ($\cos\Theta_{e\gamma}$)

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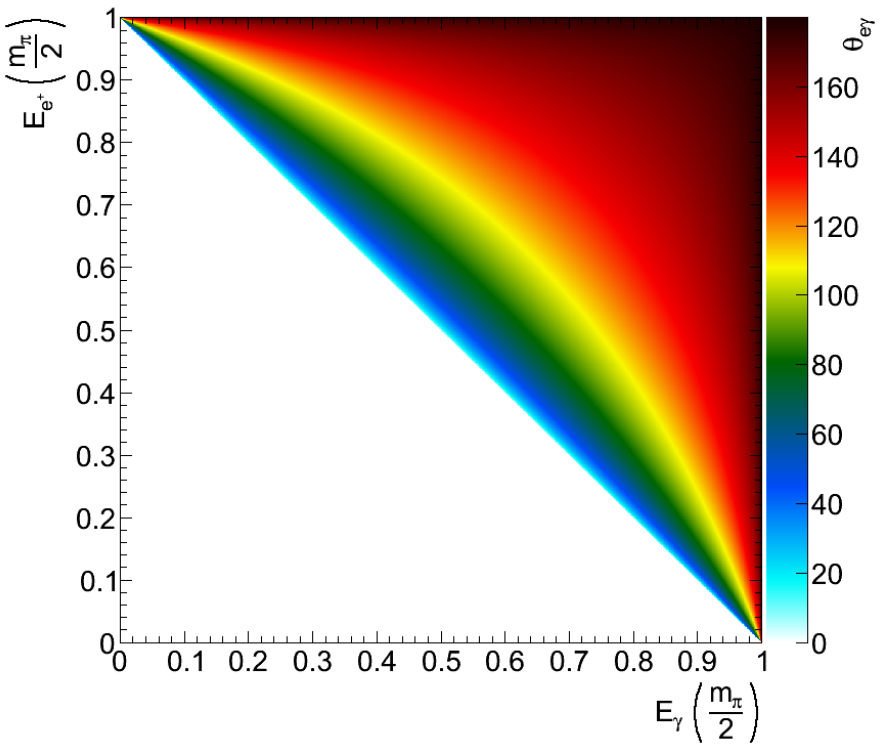

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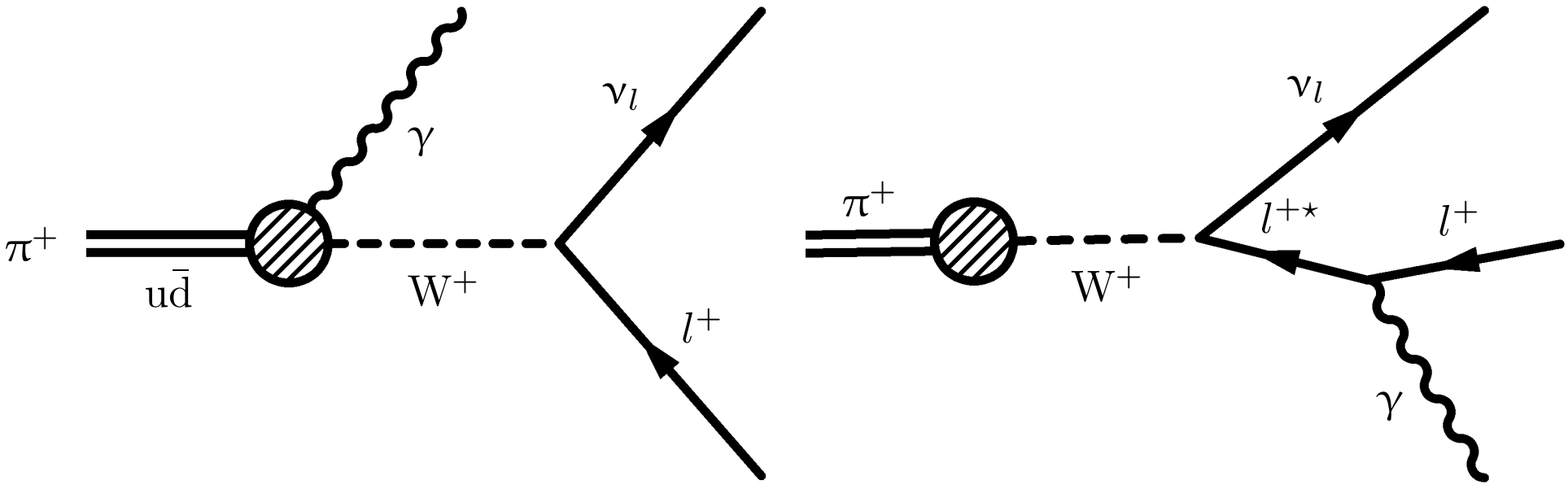
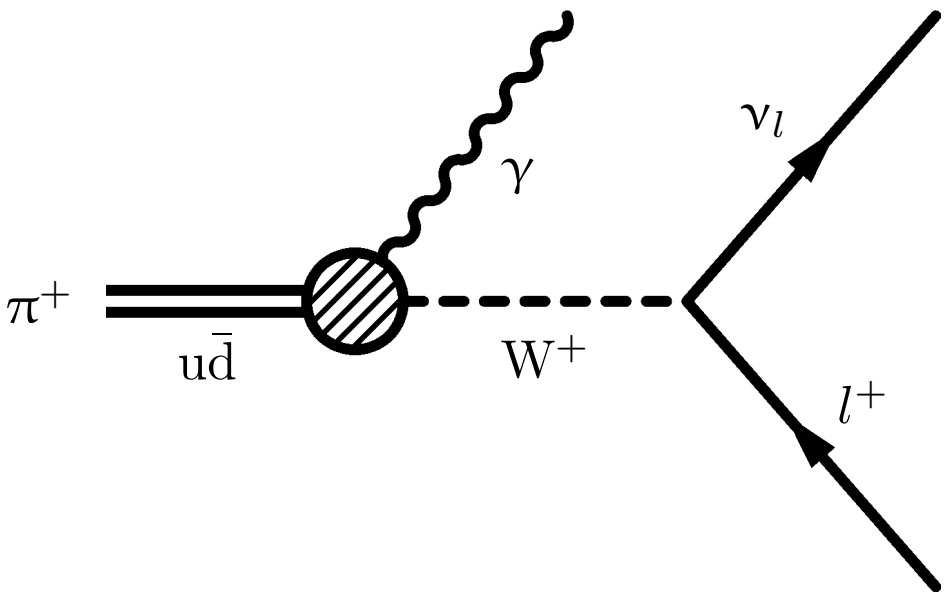
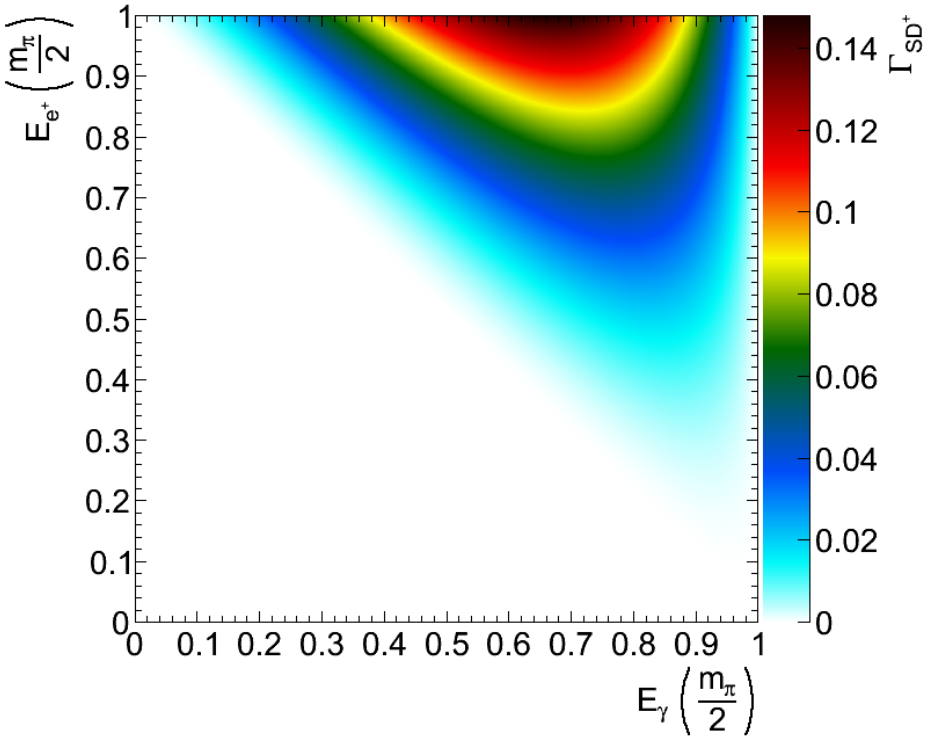
$$\mathcal{M}(\pi \to e^+ \nu_e \gamma) = \mathcal{M}_{SD} + \mathcal{M}_{IB}$$



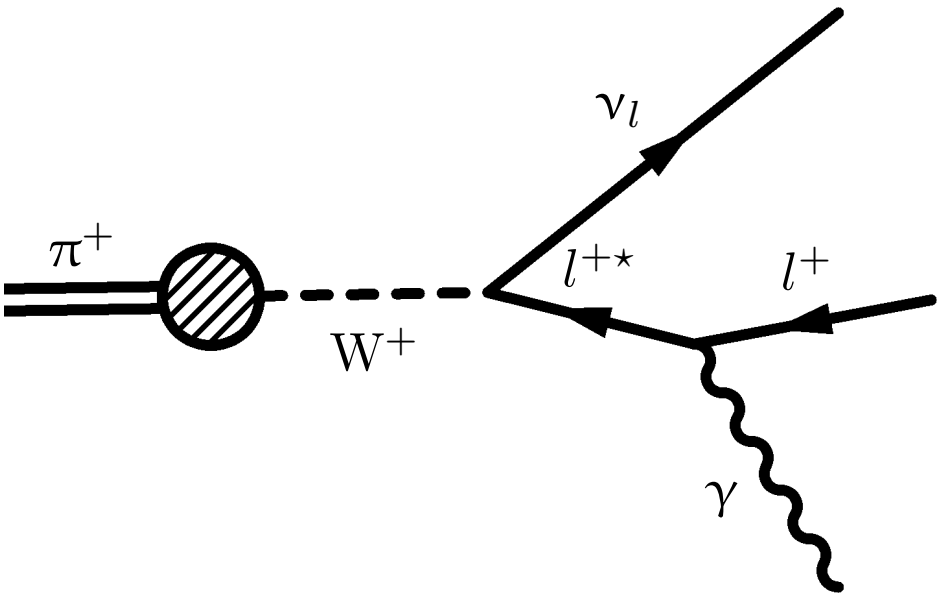
Structure Dependent Component

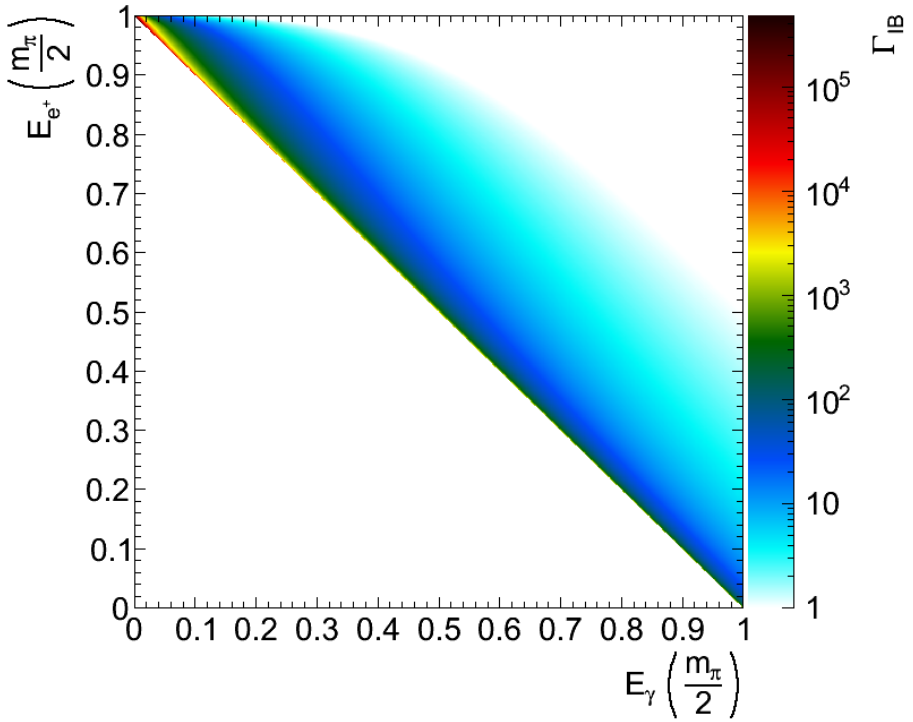




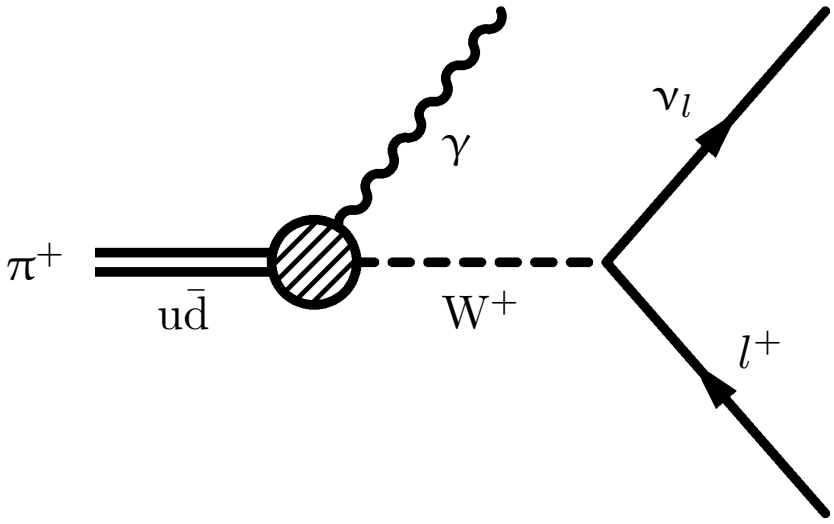
$$\frac{d^2\Gamma_{SD}}{dxdy} = \frac{\alpha}{8\pi}\Gamma_{\pi\to e\nu}\left(\frac{m_\pi}{m_e}\right)^2\left(\frac{1}{f_\pi}\right)^2\left[(F_V+F_A)^2SD^+(x,y)+(F_V-F_A)^2SD^-(x,y)\right]$$

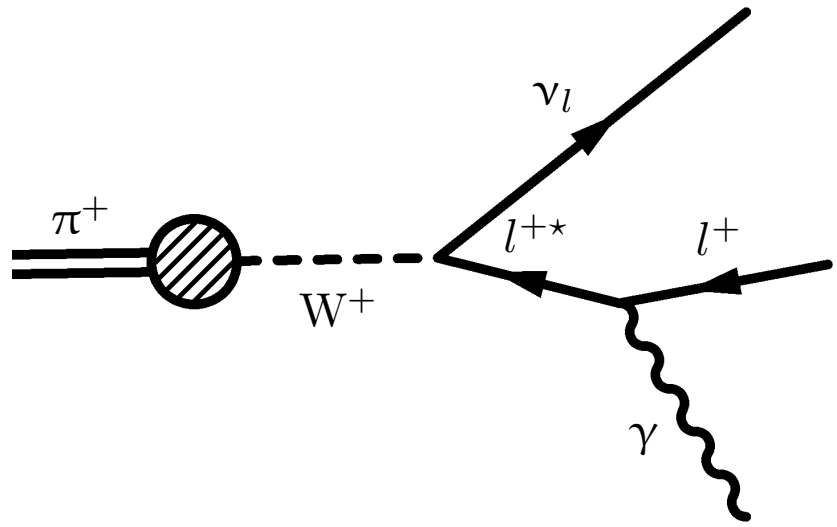
Inner Bremsstrahlung Component

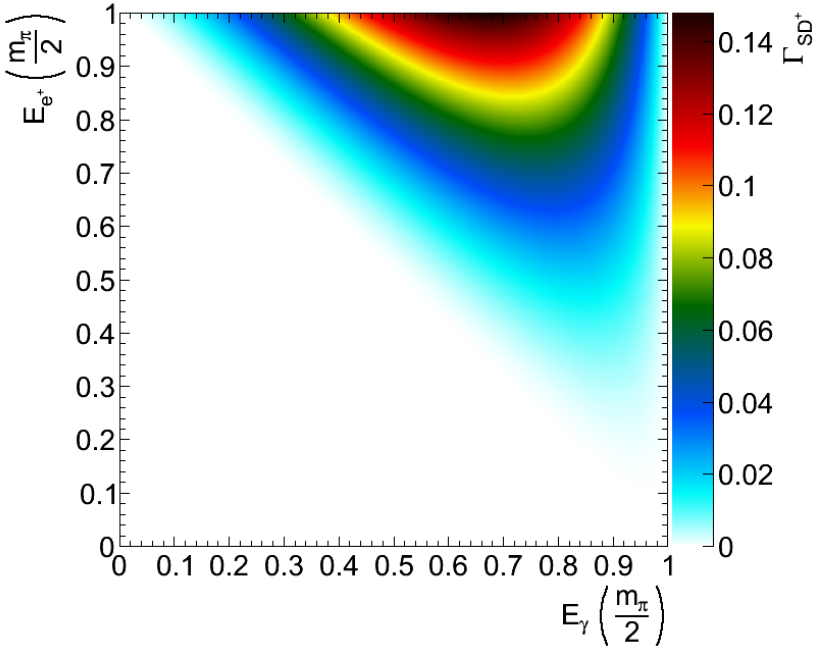


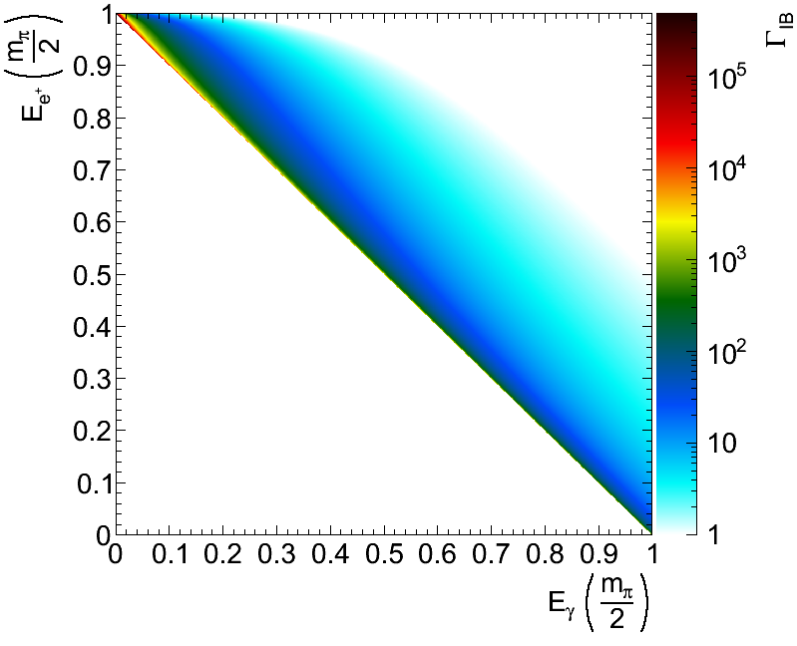


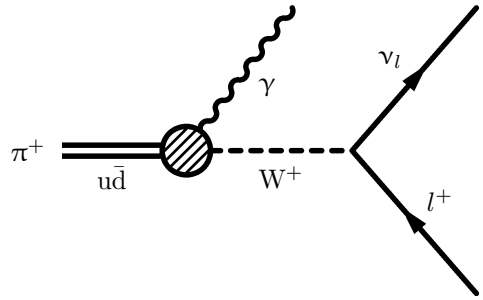
$$\frac{d^2\Gamma_{IB}}{dxdy} = \frac{\alpha}{2\pi}\Gamma_{\pi\to e\nu} IB(x,y)$$

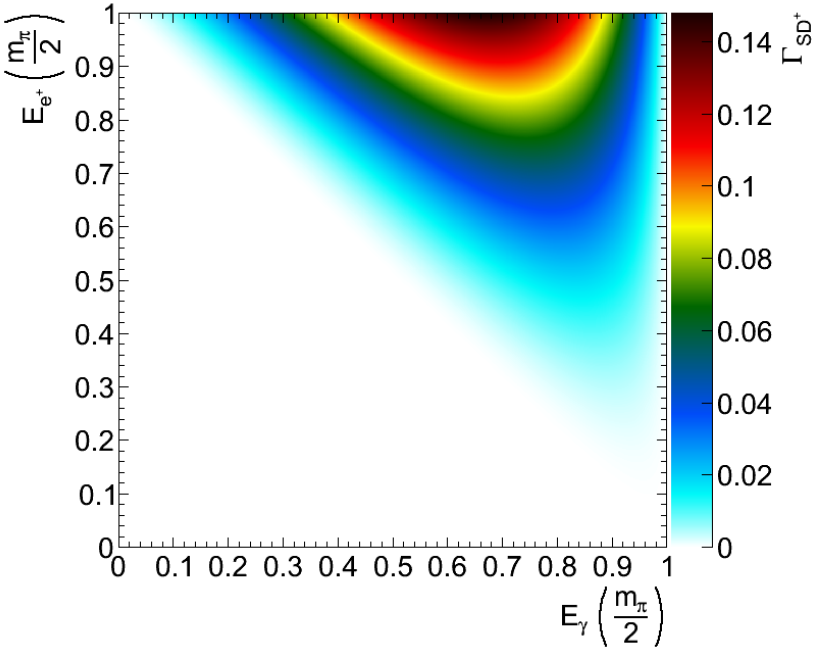

π^+
$u\bar{d}$
γ
W^+
ν_l
l^+

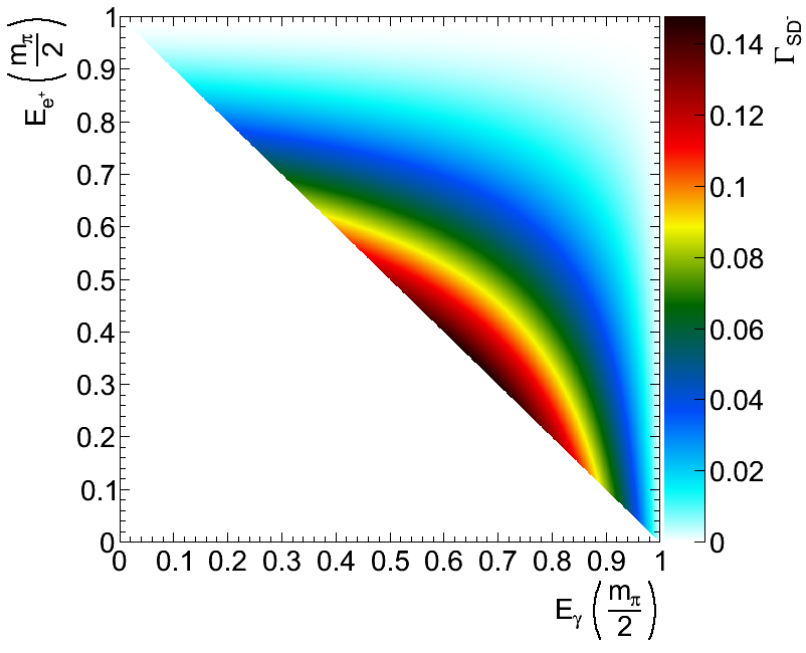

π^+
W^+
ν_l
$l^{+\star}$
l^+
γ


$E_{e^+}\left(\frac{m_\pi}{2}\right)$
$E_\gamma\left(\frac{m_\pi}{2}\right)$
Γ_{SD^+}
0 0.1 0.2 0.3 0.4 0.5 0.6 0.7 0.8 0.9 1
0 0.02 0.04 0.06 0.08 0.1 0.12 0.14


$E_{e^+}\left(\frac{m_\pi}{2}\right)$
$E_\gamma\left(\frac{m_\pi}{2}\right)$
Γ_{IB}
0 0.1 0.2 0.3 0.4 0.5 0.6 0.7 0.8 0.9 1
1 10 10^2 10^3 10^4 10^5







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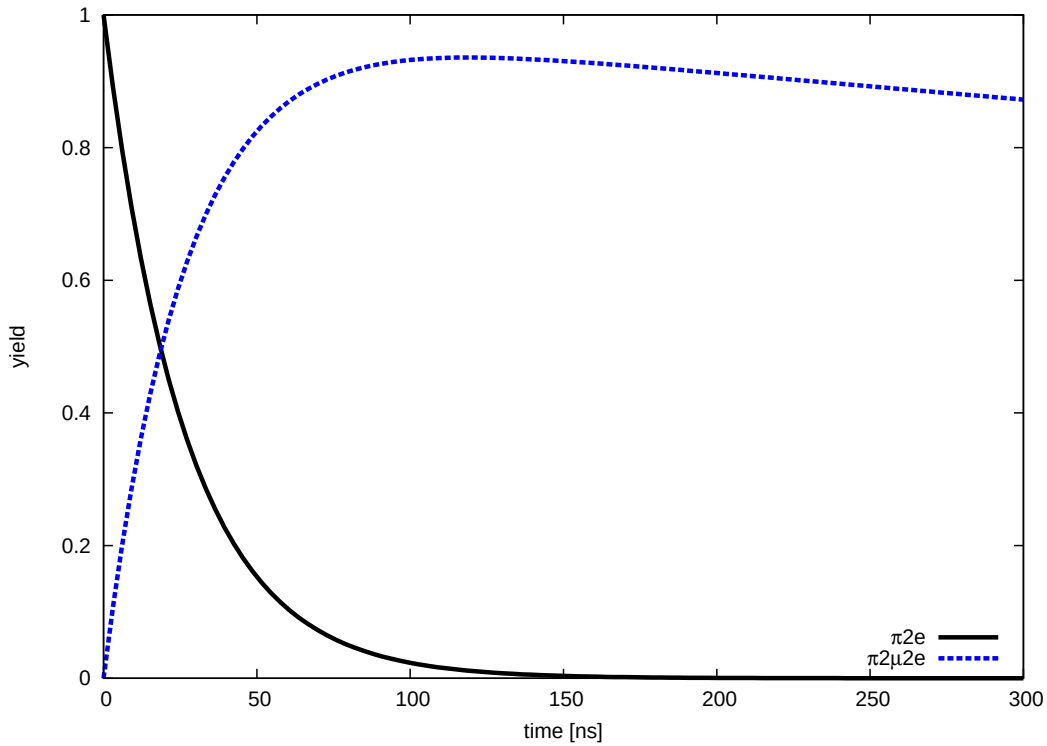
PEN Event Trigger

Processes to Observe

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

Traits to Prefer

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



To understand the trigger is to understand the experiment.

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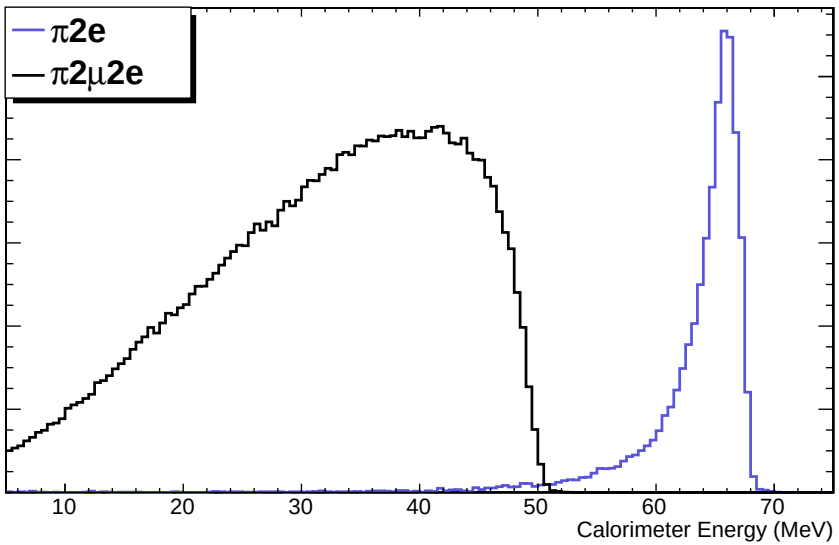

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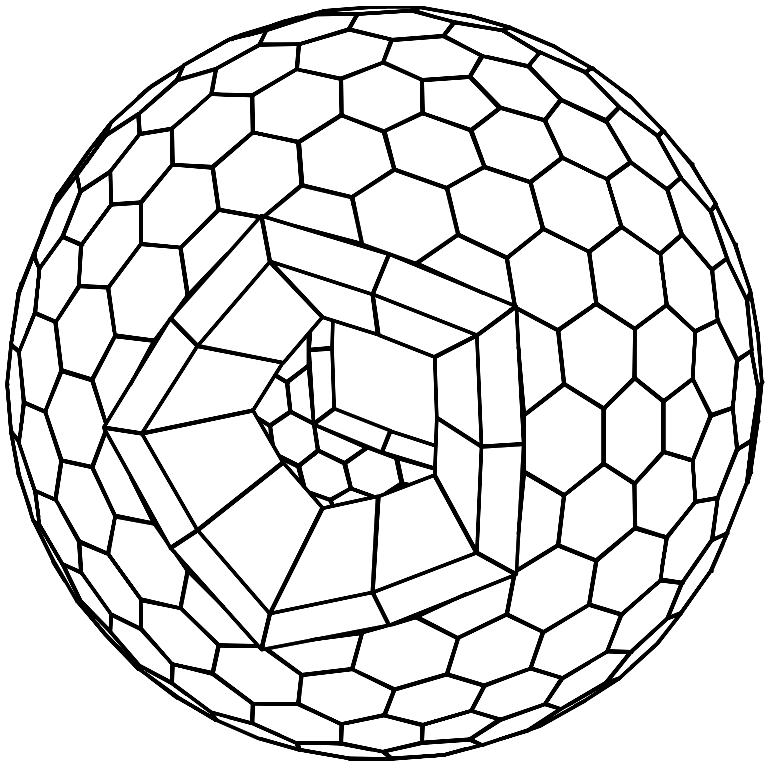
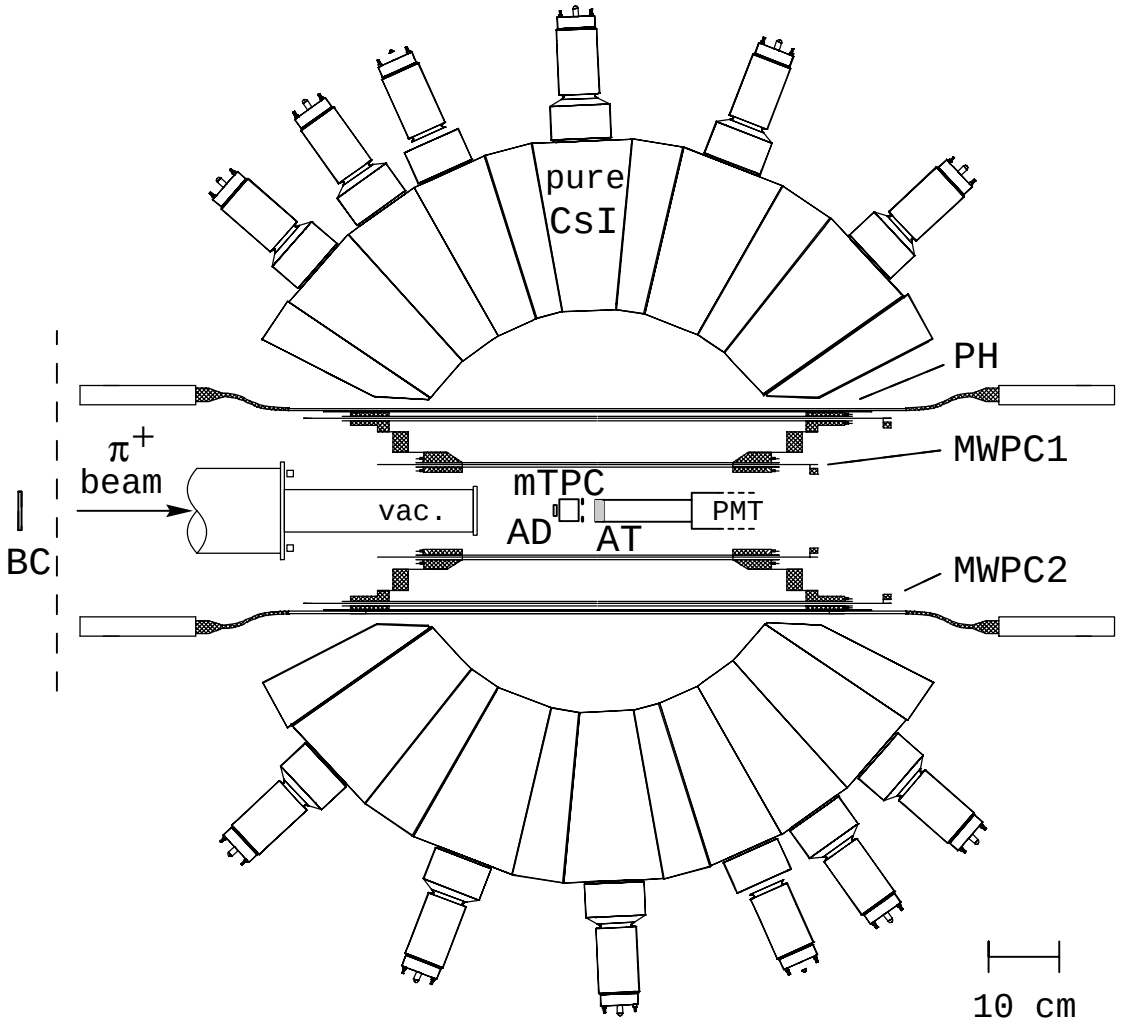
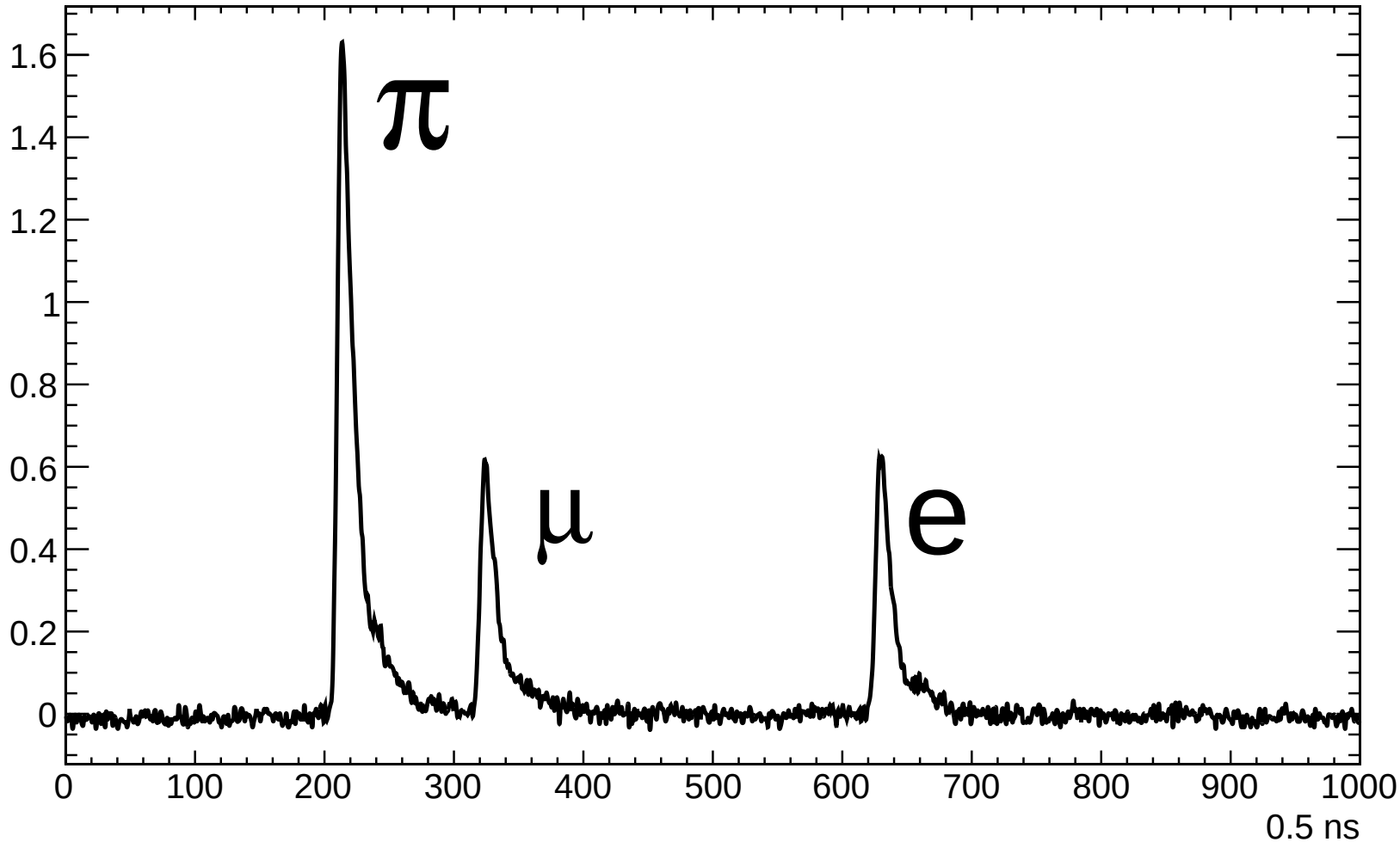
PEN Detector Overview



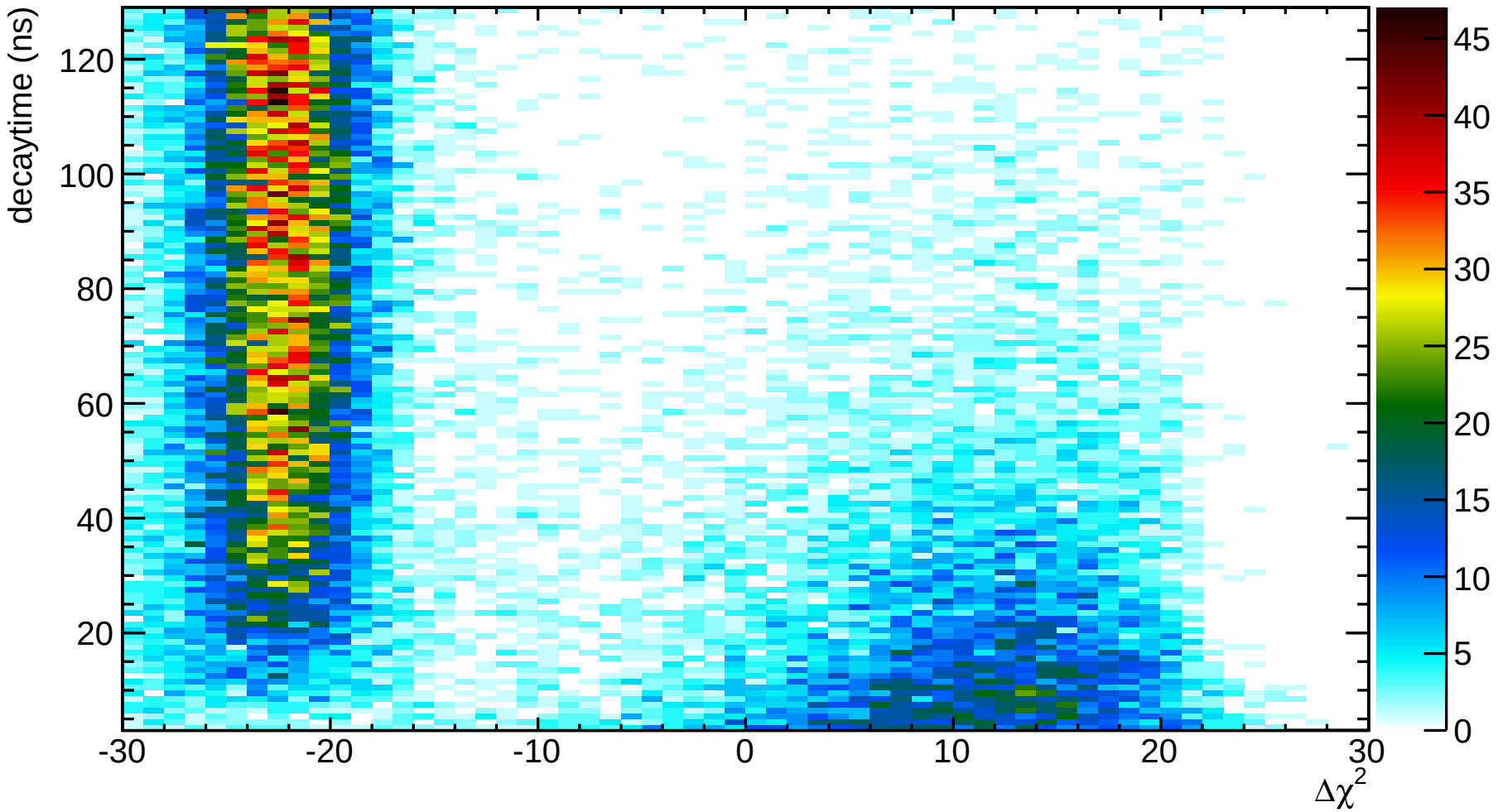
PEN Detector Overview



Target Waveform Digitization

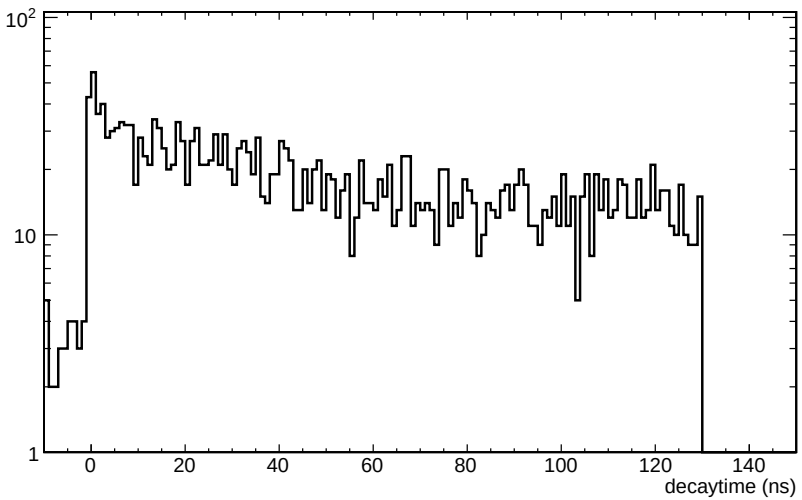


Background Suppression

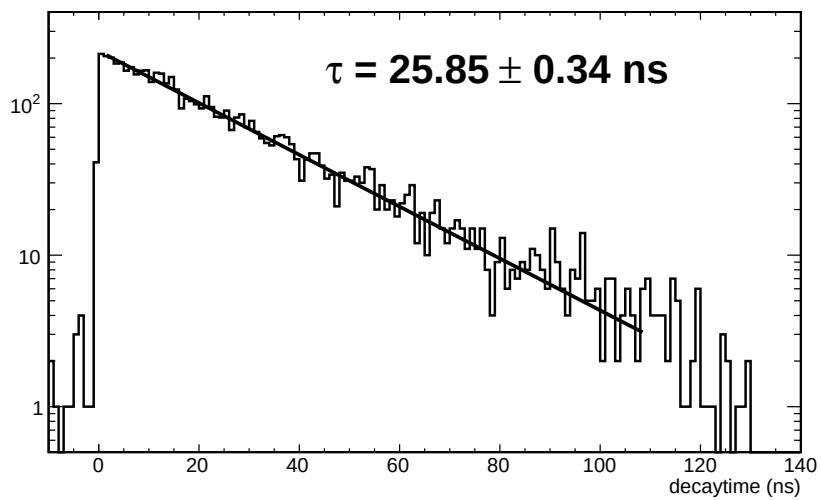


Background Suppression

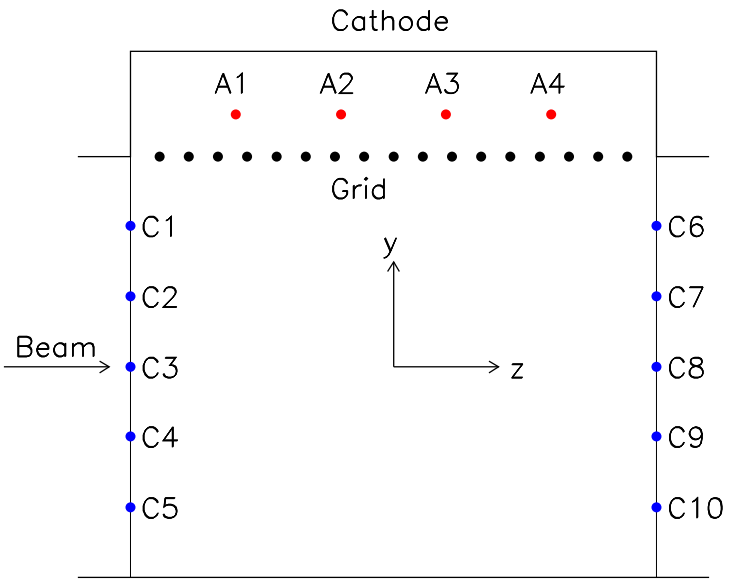
Before



After

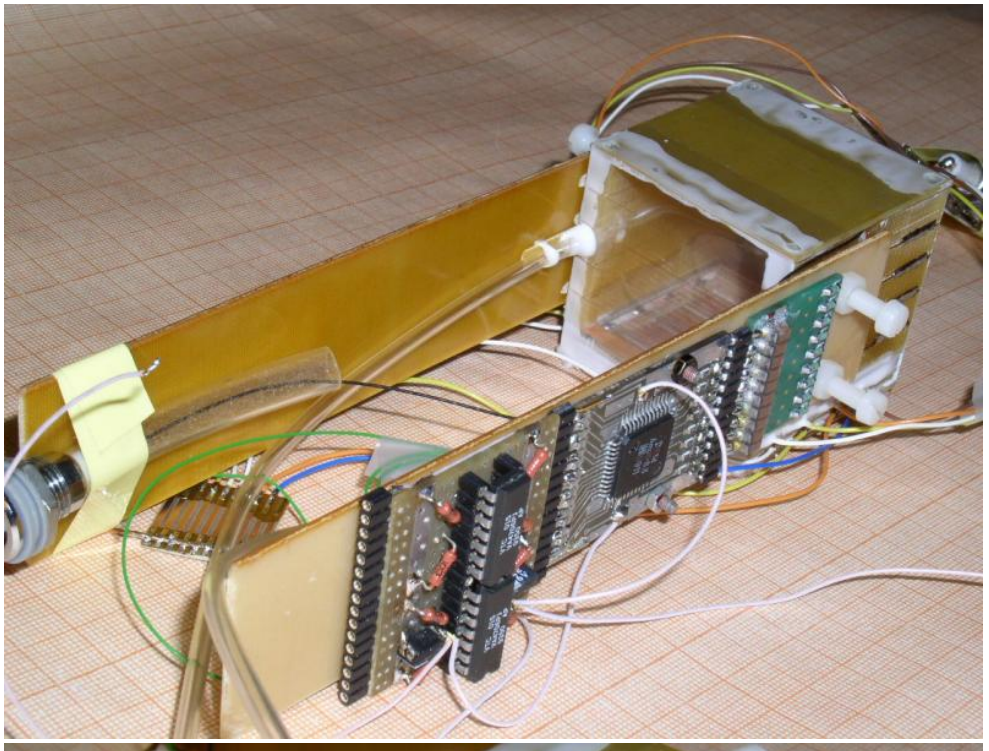


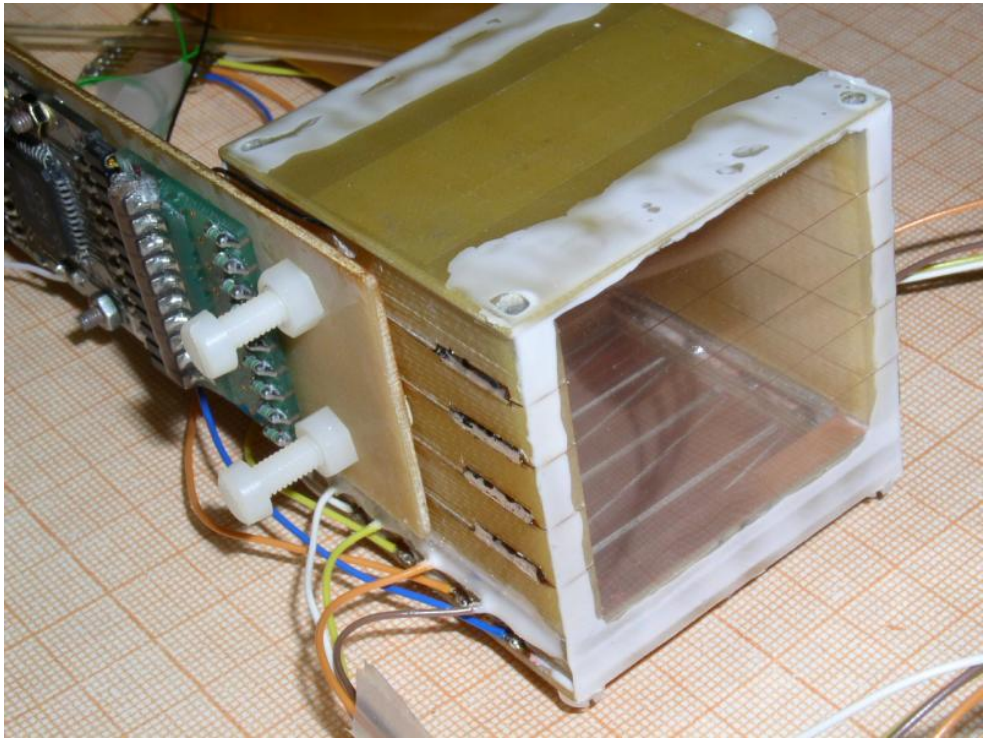
mTPC Technical Specifications

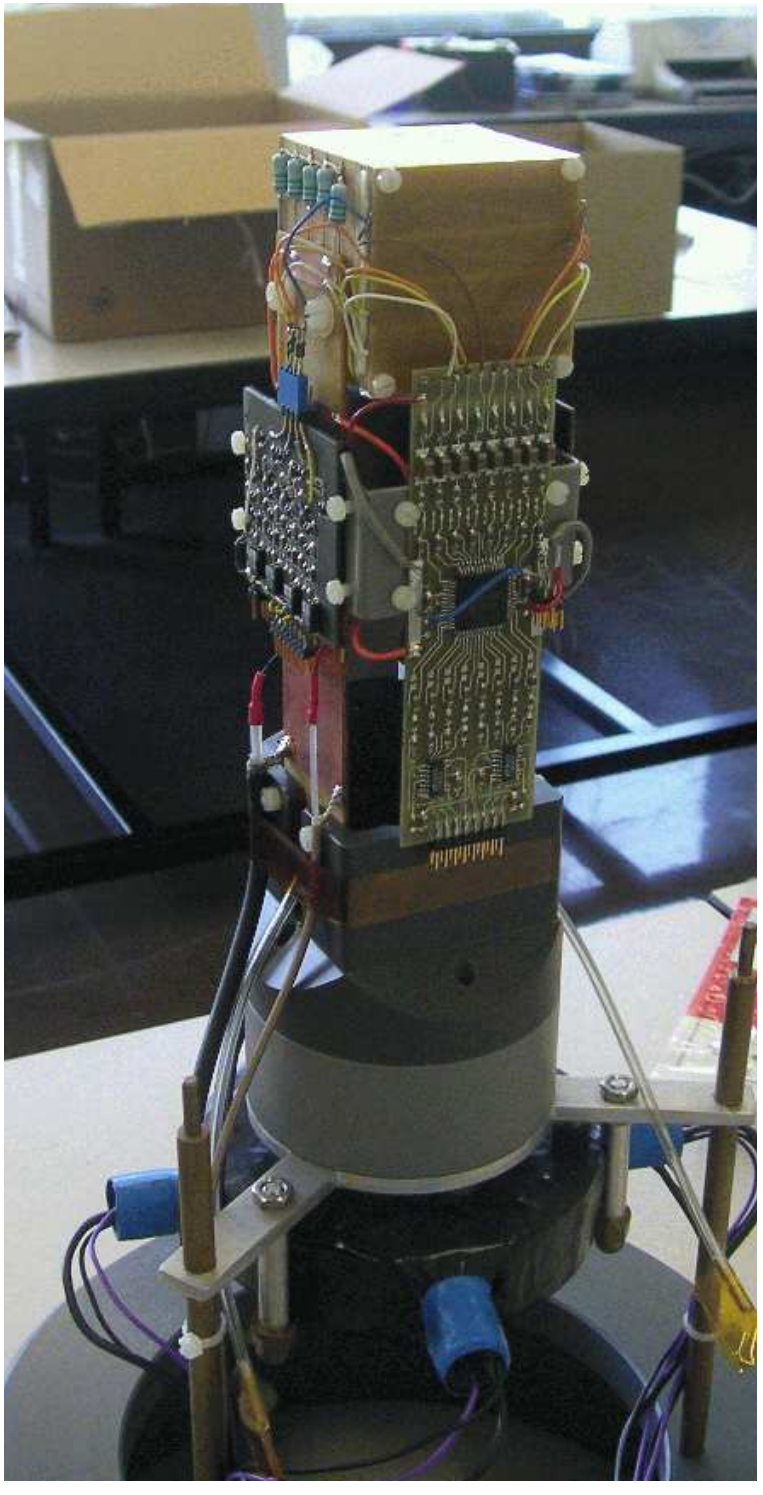


- Proportional Region: 40x6x40 mm
- Drift Region: 40x40x50 mm
- Drift Gas: 90% He and 10% C_2H_6
- 4000 V across drift region
- Grid: 50 μm wires with 1 mm spacing
- Nichrome Anode Wires
  - 40 mm length
  - 20 μm diameter
  - 10 mm spacing
  - 235 Ω resistance
- CAEN VME digitizer V1720

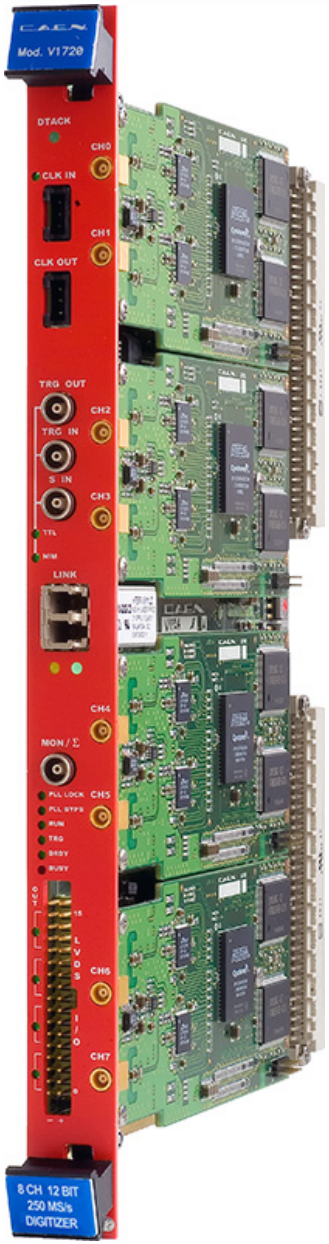
Fabricated by our collaborators from Dubna, Russia

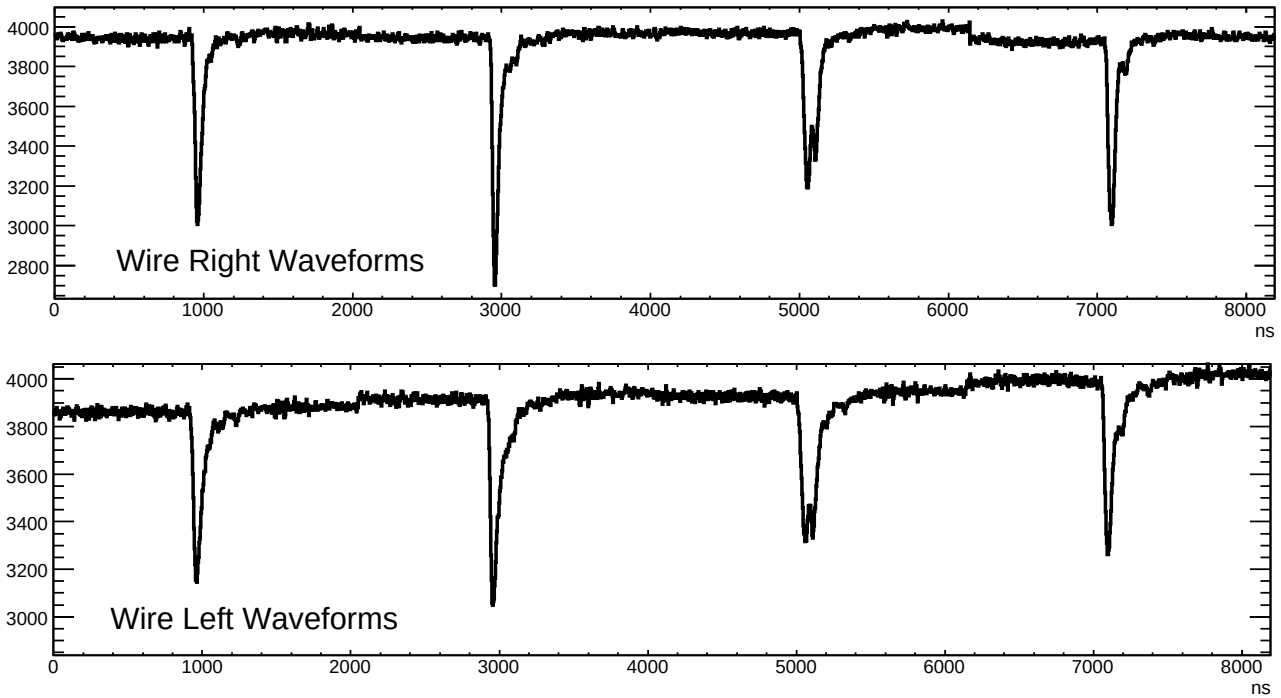






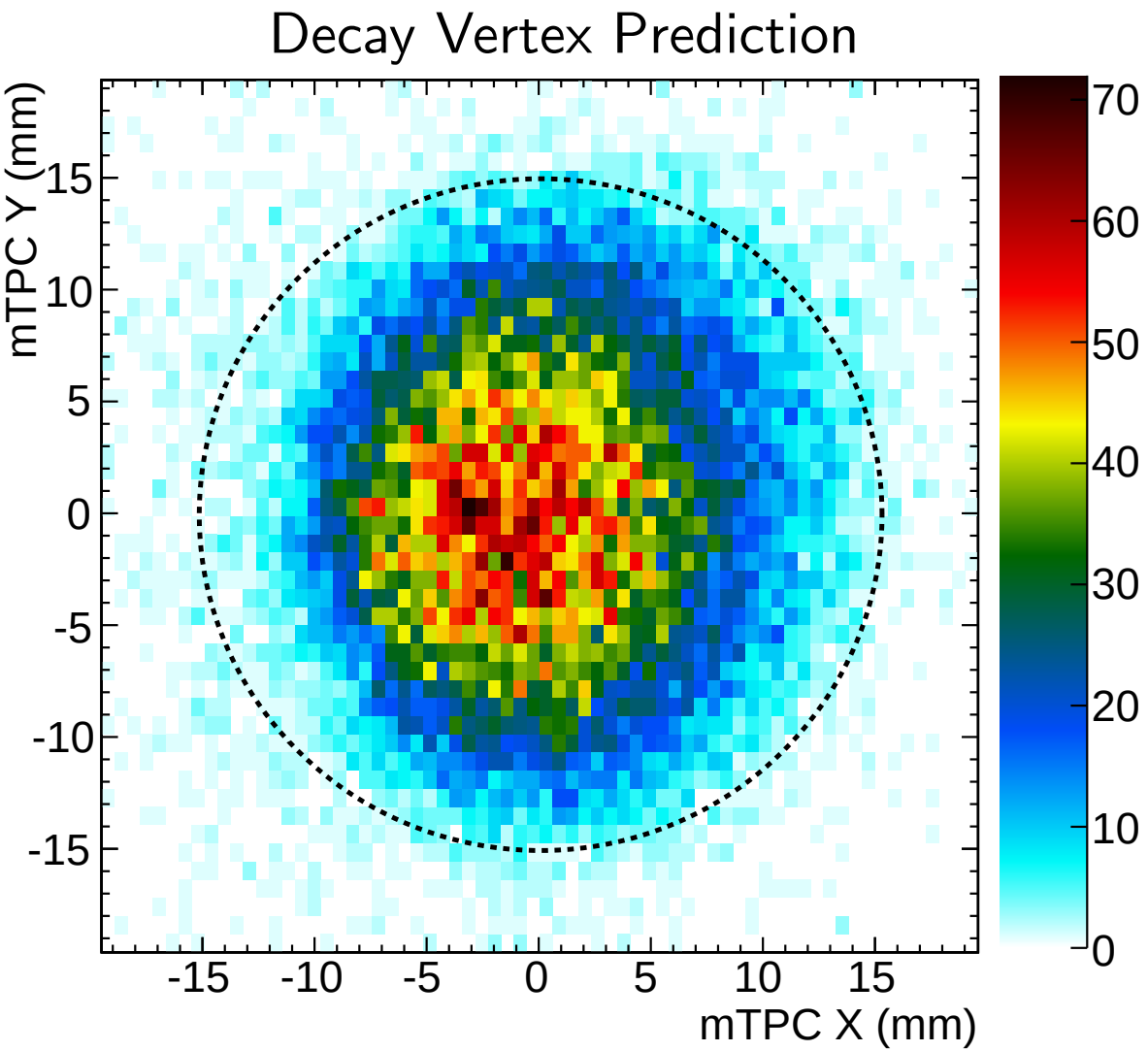
Waveform Digitization





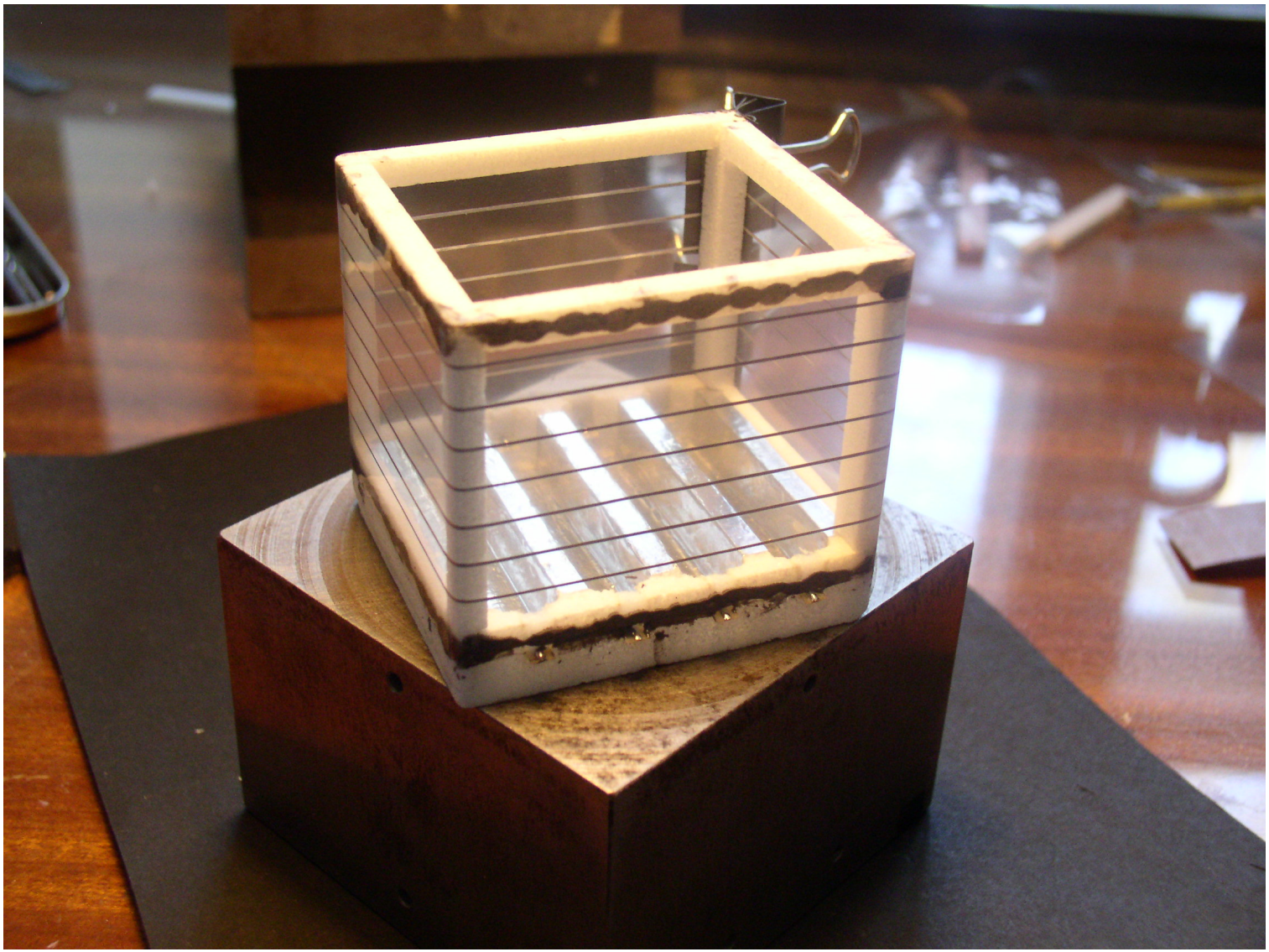
- x: charge division
- y: drift time
- z: wire location

Results from 2009 Data Run



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

2010 mTPC (Mark II)



Outline

Fundamentals of Pion Decay

Experimental Techniques

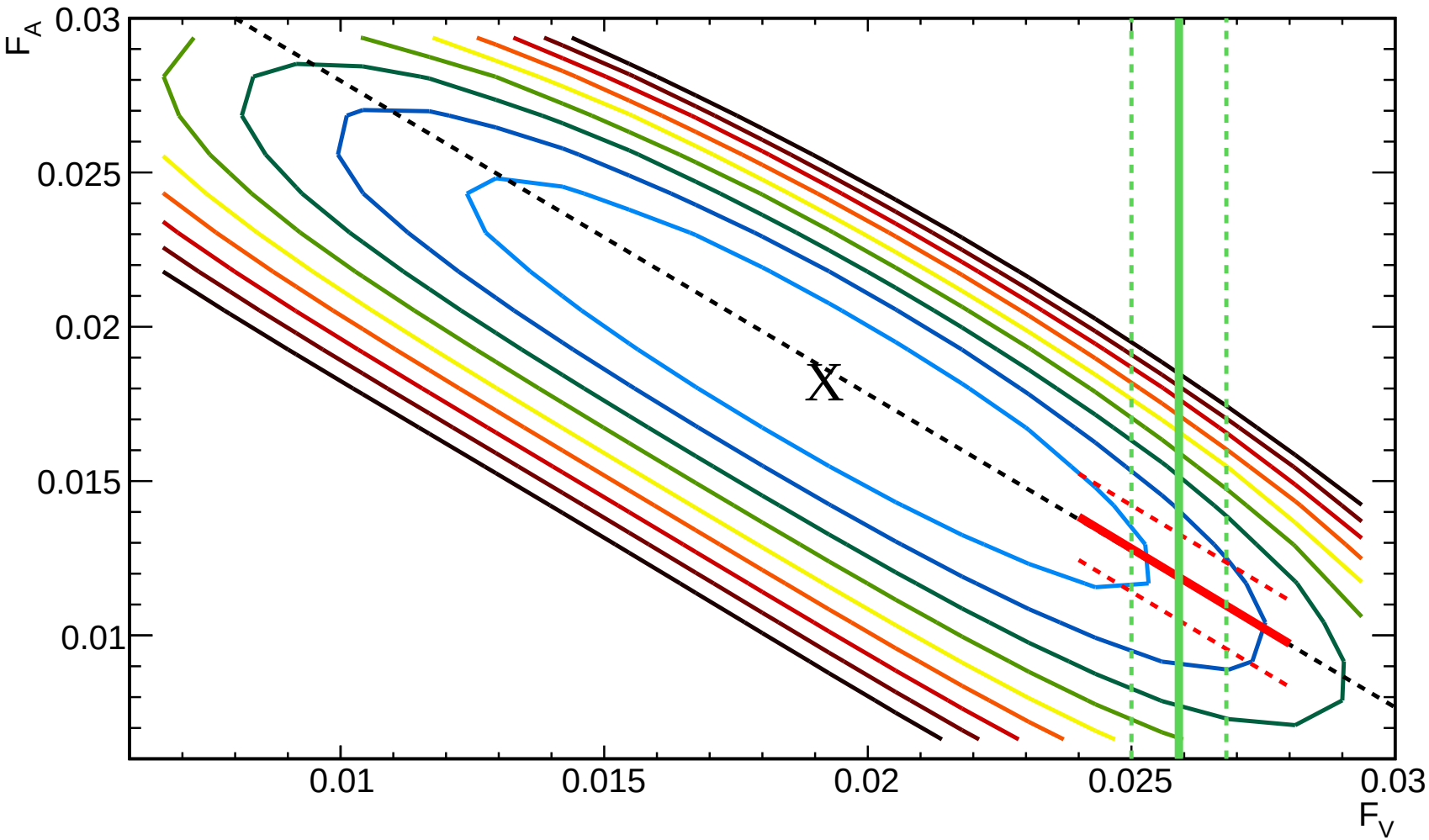
Results

PEN Run Summary

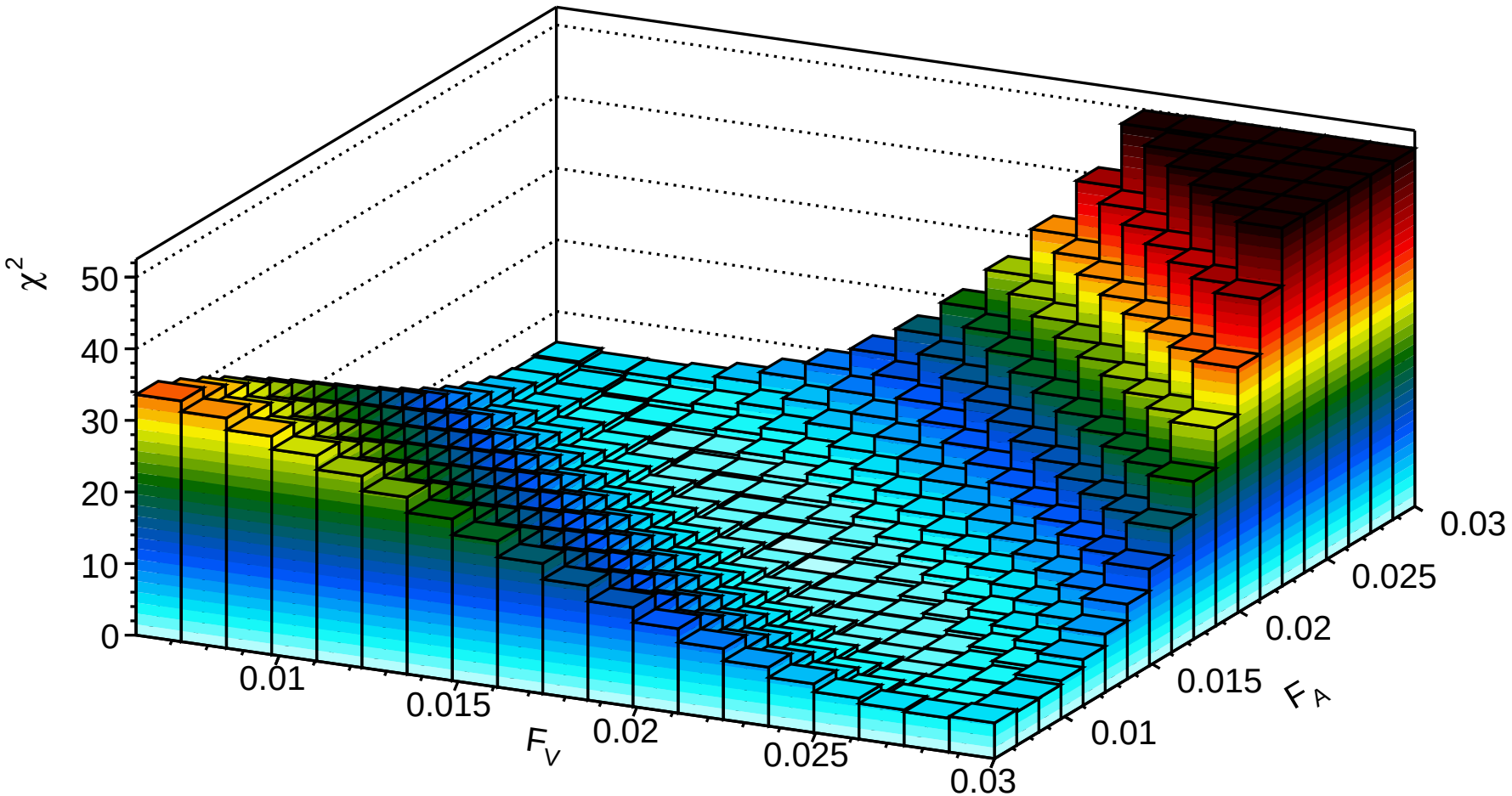
Year	Run Time (days)	π-stops (10^{10})	$\pi \to e$ (10^{6})	$\pi \to e\gamma$ (10^{3})
2008	111	7.5	4.5	5.8
2009	98	13.1	8.3	10.0
2010	68	16.4	10.3	12.5

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

Isolating F_V and F_A (2008 data)



Isolating F_V and F_A (2008 data)



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

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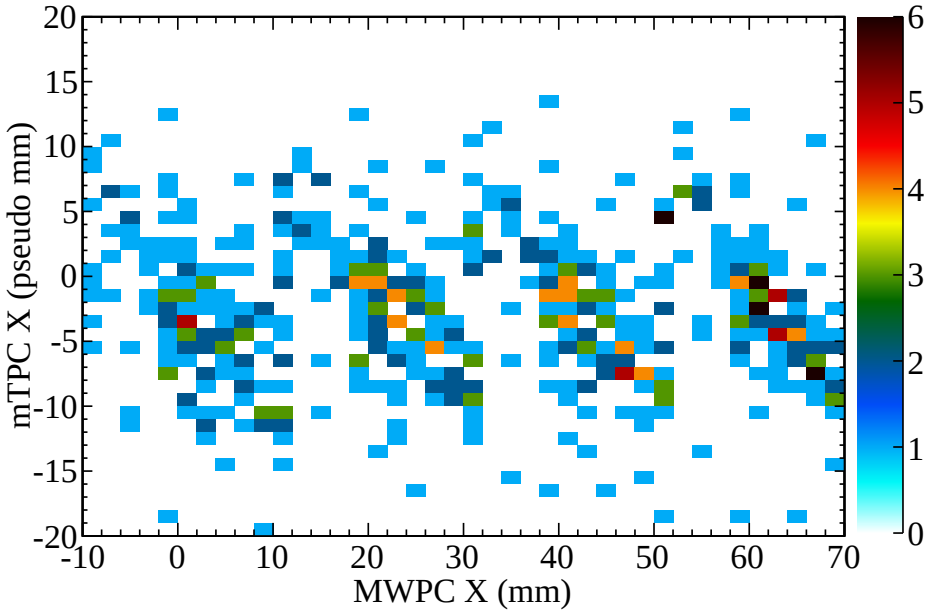
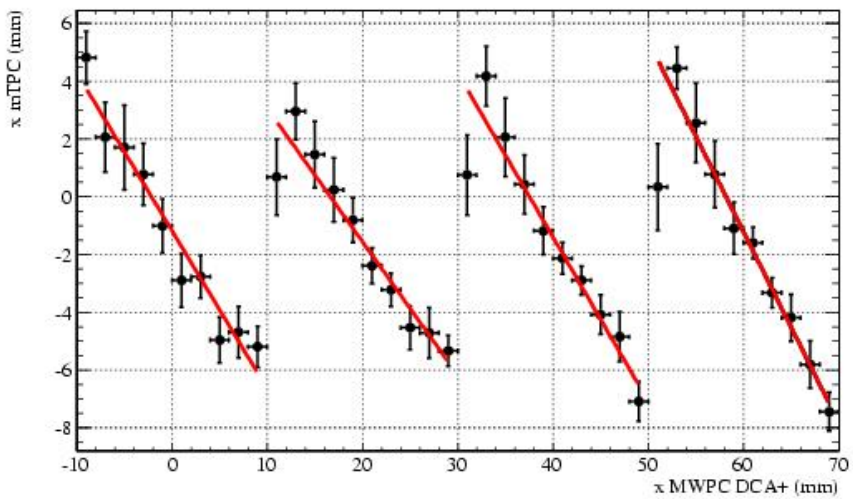
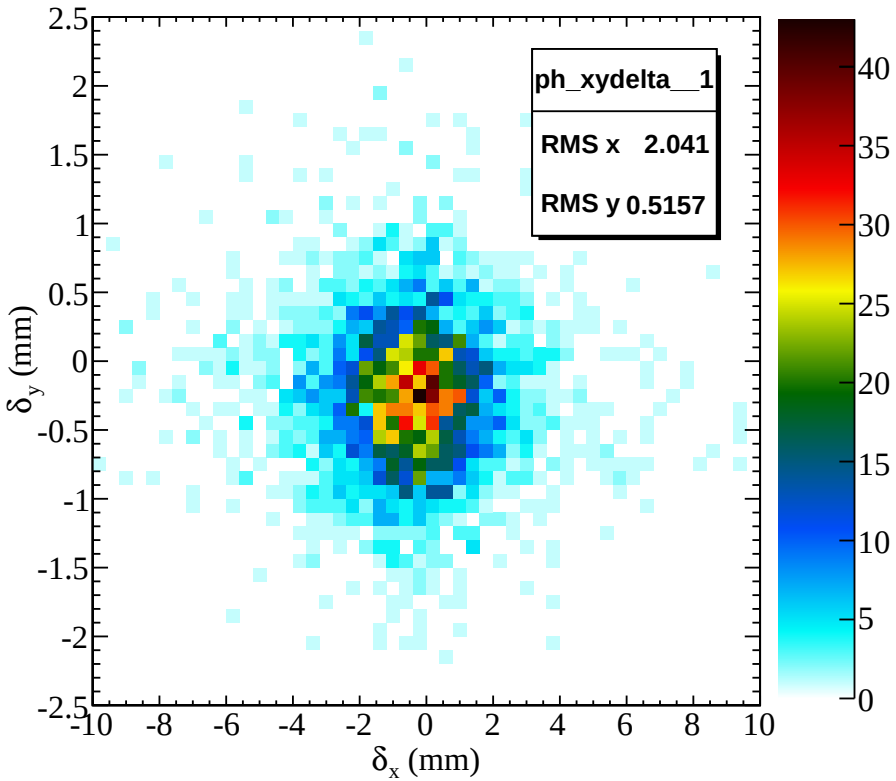
mTPC Coordinate Calibration





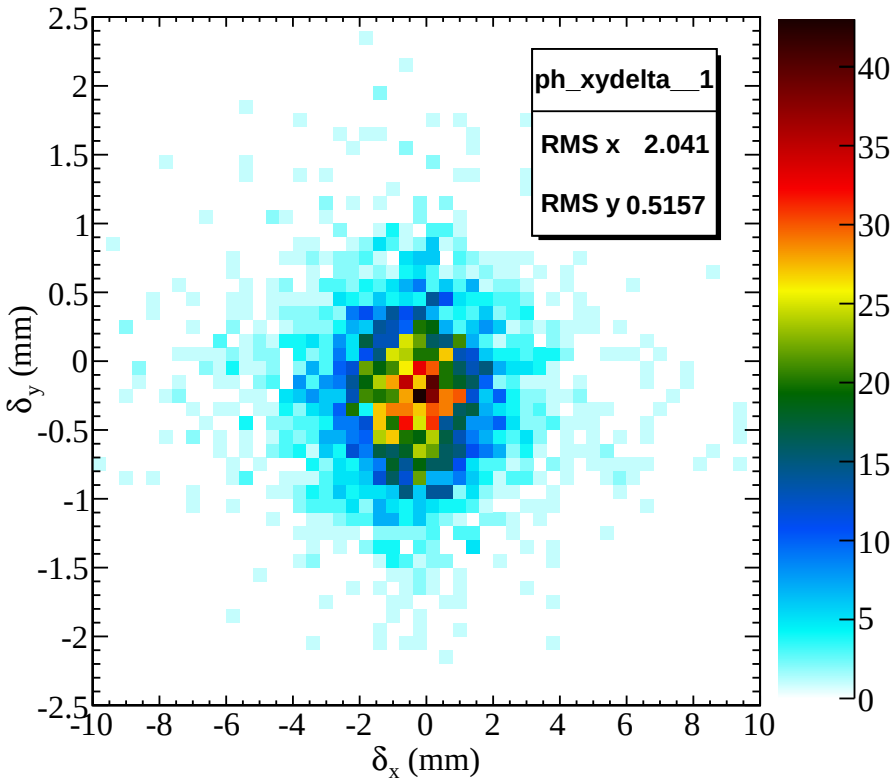
- MWPC coordinates well known
- Calibrate mTPC with MWPC

mTPC coordinate Resolution



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

mTPC coordinate Resolution



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

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

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

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