Basic Theory
Lepton Universality
Massive Neutrinos
Experiment
Geant4 Simulation
Digitizer
MWPC
mTPC
CsI

Precise Determination of the Pion Electronic Decay Branching Ratio

Charles Glaser

University of Virginia

PEN Collaboration

Overview

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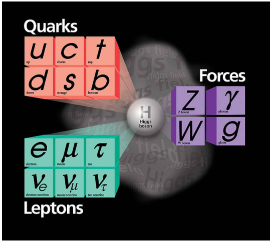
- Basic Theory/PEN
- Motivations
  - Lepton Universality
  - Massive Neutrinos
- Experiment
- Geant4 Simulation
  - Waveform Digitizer
  - Multi-Wire Proportional Chamber
  - Mini-Time Projection Chamber
  - CsI EM Calorimeter
  - Putting it together

Standard Model



- expected particles of nature
- spontaneous symmetry breaking- mass
- local gauge invariance- gauge bosons (force mediators)

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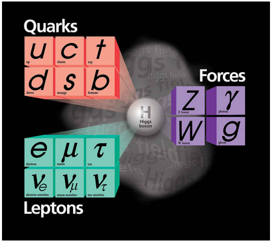

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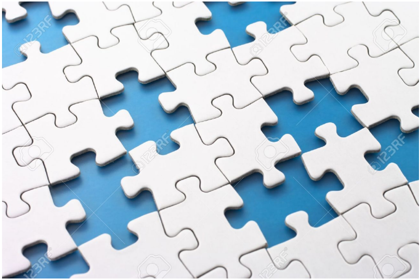

Not complete:

- why 3 generations?
- dark matter?
- massive/sterile neutrinos?
- supersymmetry?

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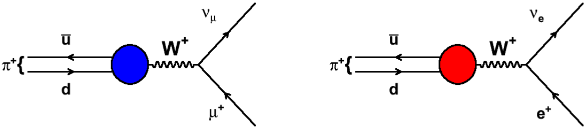
Explore the (V−A) interaction through a precision measurement



$$\frac{\Gamma(\pi^+ \to e^+ \nu_e(\gamma))}{\Gamma(\pi^+ \to \mu^+ \nu_\mu(\gamma) \to e^+ \nu_e \bar{\nu}_\mu)} = \left(\frac{g_e}{g_\mu}\right)^2 \left(\frac{m_e}{m_\mu}\right)^2 \frac{\left(1-\left(\frac{m_e}{m_\mu}\right)^2\right)^2}{\left(1-\left(\frac{m_\mu}{m_\pi}\right)^2\right)^2}(1+\delta_R)$$

Theoretical BR: $(1.2352 \pm 0.0001) \times 10^{-4}$ *

Experimental BR: $(1.230 \pm 0.004) \times 10^{-4}$

δ_R rad/loop corrections in SM, non V−A extensions

$(\frac{g_e}{g_\mu})^2 = 1.0021 \pm 0.0016$ (experimental)

Goal: relative uncertainty 5×10^{-4} or better

* D.Počanić et al J. Physics G 2014 **41** 11

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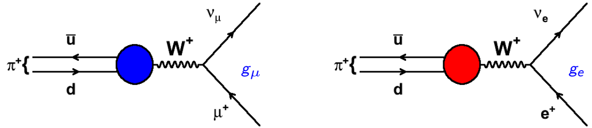

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Theory/PEN

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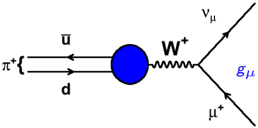

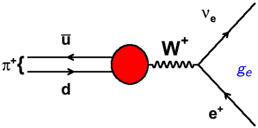

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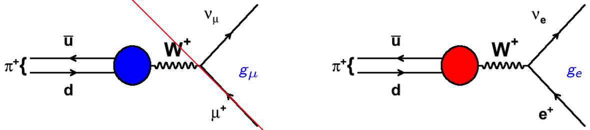

$\sim 2.5 \times 10^{-5}$

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Reach of π_{e2} decay beyond the SM (New Physics)

$$\mathcal{L}_{NP} = \left[\pm\frac{\pi}{2\Lambda_V^2}\bar{u}\gamma_\alpha d \pm \frac{\pi}{2\Lambda_A^2}\bar{u}\gamma_\alpha\gamma_5 d\right]\bar{e}\gamma^\alpha(1-\gamma_5)\nu + \left[\pm\frac{\pi}{2\Lambda_S^2}\bar{u}d \pm \frac{\pi}{2\Lambda_P^2}\bar{u}\gamma_5 d\right]\bar{e}(1-\gamma_5)\nu\,,$$

(Λ_i ...scale of NP)

CKM unitarity and superallowed Fermi nuclear decays currently limit:

$$\Lambda_V \geq 20\,\text{TeV}, \qquad \text{and} \qquad \Lambda_S \geq 10\,\text{TeV}\,.$$

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At $\Delta R^\pi_{e/\mu}/R^\pi_{e/\mu} = 10^{-3}$, π_{e2} decay is directly sensitive to:

$$\boxed{\Lambda_P \leq 1000\,\text{TeV}} \qquad \text{and} \qquad \boxed{\Lambda_A \leq 20\,\text{TeV}},$$

and indirectly, through loop effects to $\boxed{\Lambda_S \leq 60\,\text{TeV}}$.

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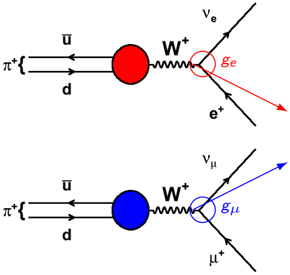
In general multi-Higgs models with charged-Higgs couplings

$\lambda_{e\nu} \approx \lambda_{\mu\nu} \approx \lambda_{\tau\nu}$, at 0.1 % precision, $R^\pi_{e\mu}$ probes $\boxed{m_{H^\pm} \leq 400\,\text{GeV}}$.

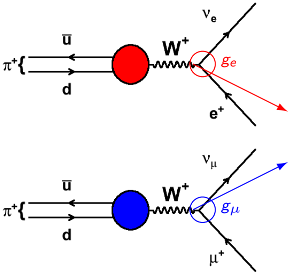
Lepton universality



$$\frac{g_e}{g_\mu} \stackrel{?}{=} 1$$

In SM, e, μ, and τ differ by Higgs couplings only

Lepton universality



$$\frac{g_e}{g_\mu} \stackrel{?}{=} 1$$

Redefining $g_l \rightarrow g_l(1 - \frac{\epsilon_l}{2})$

$$\frac{g_i}{g_j} = 1 + \frac{\epsilon_j - \epsilon_i}{2}$$

$$\Delta_{ij} = \epsilon_i - \epsilon_j \quad *$$

Δ_{ij} is constrained by current experimental data

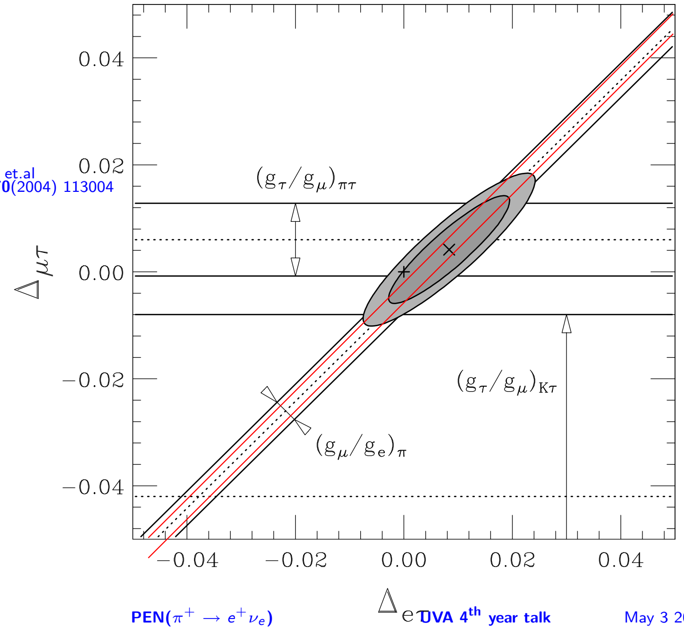
and can be be further constrained.

In SM, e, μ, and τ differ by Higgs couplings only

* Will Loinaz, et al. Nutev anomaly, lepton universality, and nonuniversal neutrino-gauge couplings. Phys.Rev. D, 70(11):113004, 2004

Lepton universality

Loinaz et.al
PRD **70**(2004) 113004



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Suppose, ν: $(\nu_e, \nu_\mu, \nu_\tau, \nu_1, ...)$

- $\nu_\alpha = \Sigma U_{\alpha i} \nu_i$
- $\pi \rightarrow e\nu_e = \Sigma \pi \rightarrow e\nu_i$ (incoherent)
- normally, $\pi \rightarrow e\nu_e$ e has 70 MeV
- with $\pi \rightarrow e\nu_x$ e has $<$ 70 MeV-monoenergetic
- isolated signal below normal peak

relaxes helicity supression of $\pi \rightarrow e\nu$

$$V - A \sim \frac{(1 - \frac{v_e}{c})}{(1 - \frac{v_\mu}{c})} \sim \frac{m_e^2}{m_\mu^2}$$

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Experiment
Geant4 Simulation
Digitizer
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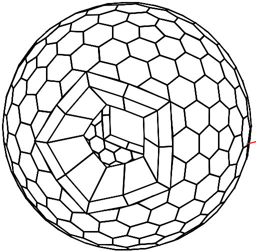
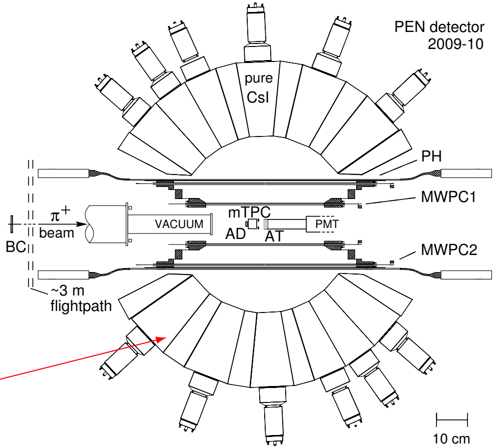
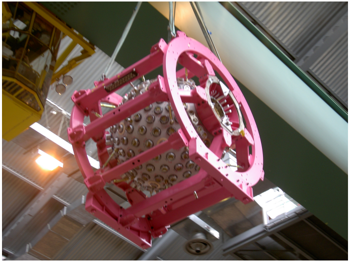
Paul Scherrer Institude (PSI)
2008-2010

Detector Setup

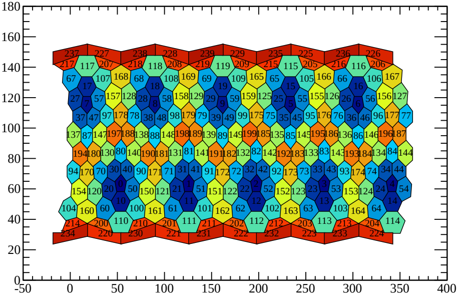
- πE1 beamline at PSI
- stopped π^+ beam
- active target counter
- 240 spherical pure CsI calorimeter
- central tracking
- beam tracking
- digitized waveforms







Mercator Projection of CsI Crystals



Basic Theory
Lepton Universality
Massive Neutrinos
Experiment
Geant4 Simulation
Digitizer
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Triggers

2 Process for final e:

$\mu \to e\nu\bar{\nu}$

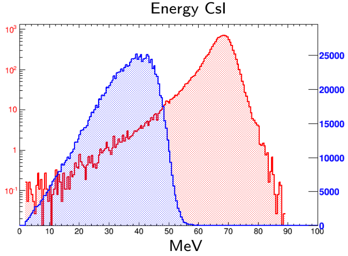
$\tau_\mu = 2.2\,\mu s$

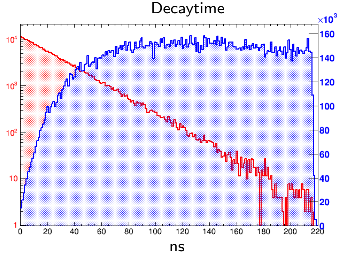
$E_{e\ max} = \frac{1}{2} m_\mu = 52.5\,\text{MeV}$

$\pi \to e\nu$

$\tau_\pi = 26.03\,\text{ns}$

$E_{e\ max} = \frac{1}{2} m_\pi = 69.5\,\text{MeV}$





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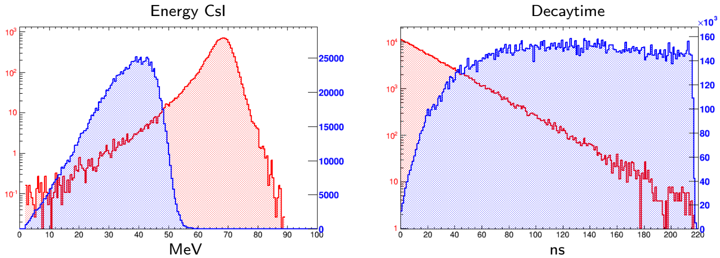
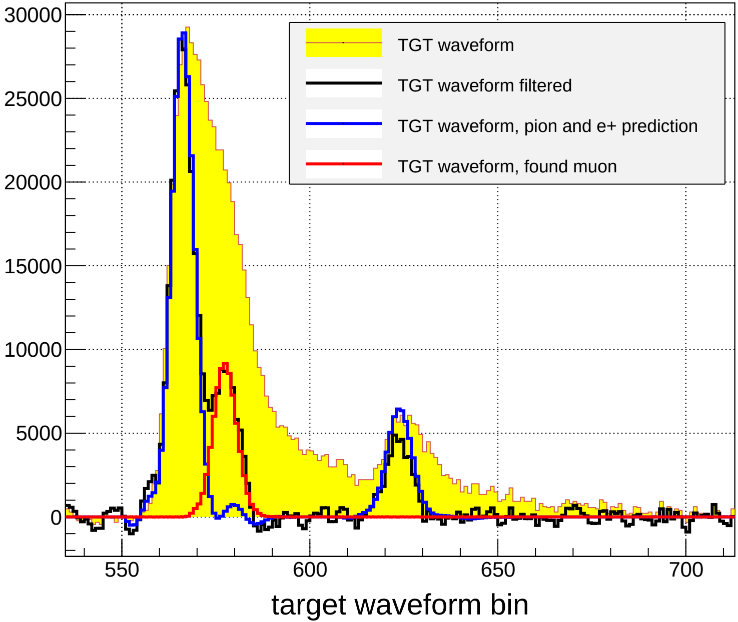


e^+ within 250 ns of the stopping time

anything above 48 MeV is recorded

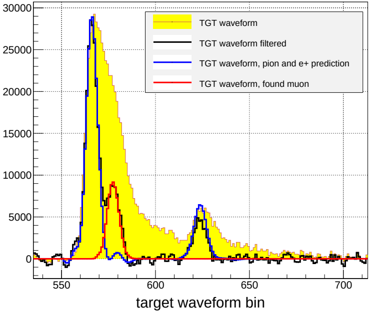
if below 48 MeV, prescaled by 64

A closer look at waveforms



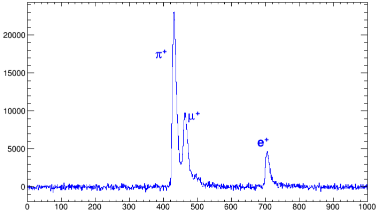
A closer look at waveforms

2 GS/s digitized waveforms predicted π energy and time

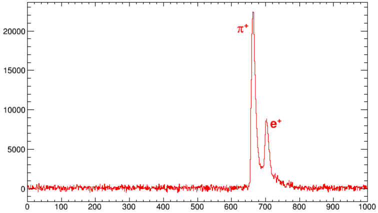


MWPC 250 Ms/s TPC digitizer PH predict e^+ energy and time

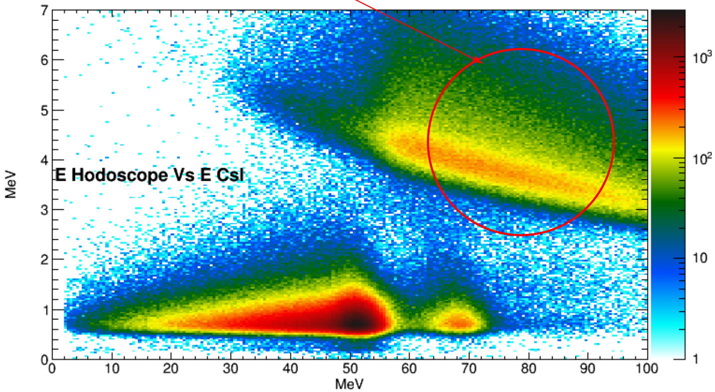
μ found



no μ found



π absorption produces **protons** through hadronic interactions



Experimental Branching Ratio

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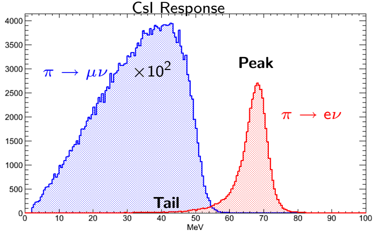
$$\text{Branching ratio} = \frac{\text{Number of } \pi \rightarrow e\nu \text{ Events}}{\text{Number of } \pi \rightarrow \mu\nu \text{ Events}}$$

$$\text{Rate}(\pi^+ \rightarrow e^+\nu_e) = \frac{N_{Tail} + N_{Peak}}{A_e N_\pi}$$

$$\text{Rate}(\pi^+ \rightarrow \mu^+\nu_\mu \rightarrow e^+\nu_e\bar{\nu}_\mu) = \frac{N_\mu}{A_\mu N_\pi}$$

$$\frac{\text{Rate}(\pi^+ \rightarrow e^+\nu_e)}{\text{Rate}(\pi^+ \rightarrow \mu^+\nu_\mu \rightarrow e^+\nu_e\bar{\nu}_\mu)} = \frac{N_{Peak}\left(1 + \frac{N_{Tail}}{N_{Peak}}\right) A_\mu}{N_\mu A_e}$$



A = Acceptances

Geant4 Monte Carlo Simulation

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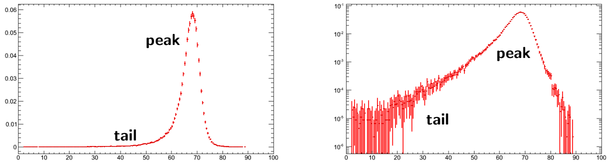
- particle tracking
- energy deposition
- decaying particles
- acceptances by studying **pure processes**

CsI Response $\pi \to e\nu$



Will give us $\frac{\mathbf{N_{tail}}}{\mathbf{N_{peak}}}$

Problems

Basic Theory
Lepton Universality
Massive Neutrinos
Experiment
Geant4 Simulation
Digitizer
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Geant gives energies and timings and positions
does not simulate full detector response

In the Experiment:

- digitized energies and timings
- signals/waveforms
- photoelectron statistics smear signal

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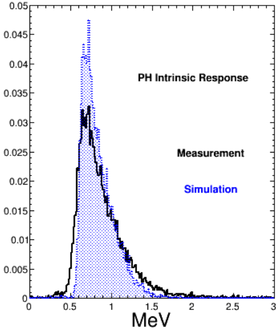

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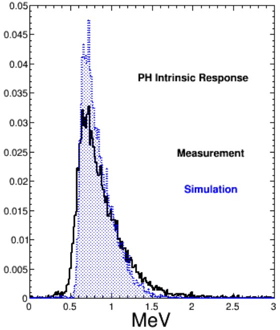

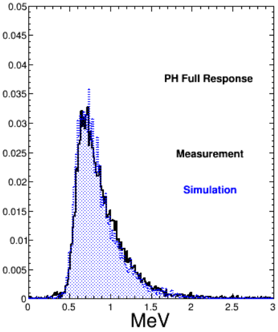

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Full detector responses that are simulated :

- waveform digitizer with beam counters (B0, DEG, TGT)
- mini-time projection chamber (mTPC)
- multi-wire proportional chamber (MWPC)
- plastic hodoscope (PH)
- CsI calorimeter

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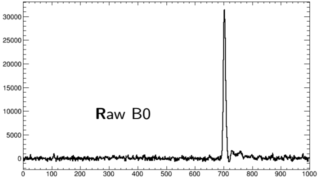
- beam counter, degrader, target



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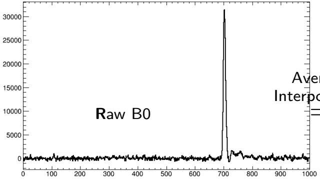

Average
Interpolate
$\Longrightarrow$

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Geant4 Simulation
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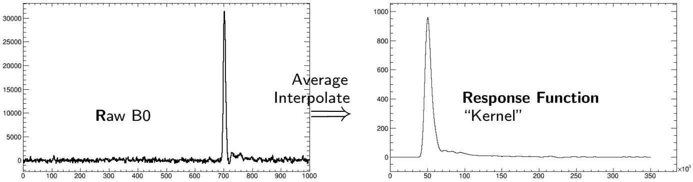
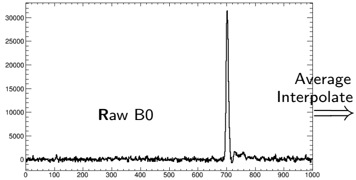
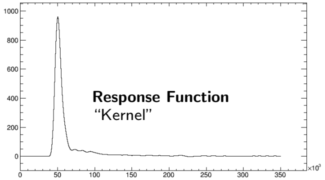
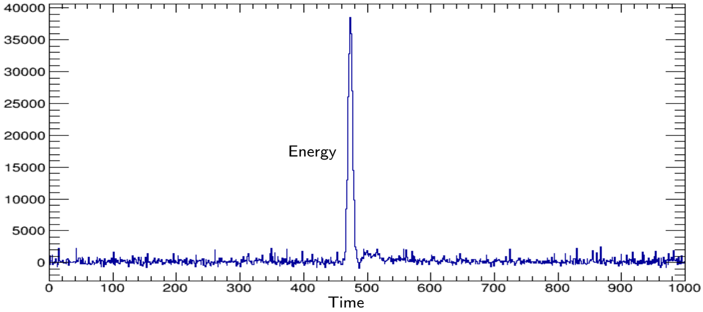


Waveform digitizer

- beam counter, degrader, target







Not that simple!

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Lepton Universality
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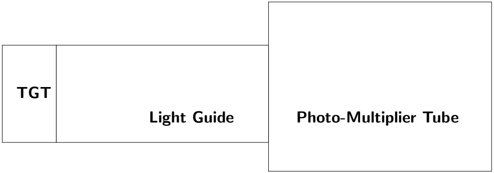
The "energy"- deduced from number of photoelectrons



Basic Theory
Lepton Universality
Massive Neutrinos
Experiment
Geant4 Simulation
Digitizer
MWPC
mTPC
CsI

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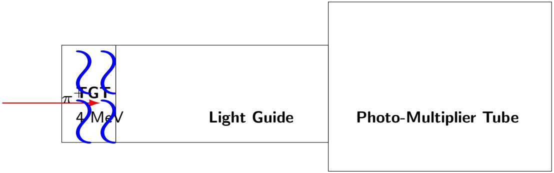
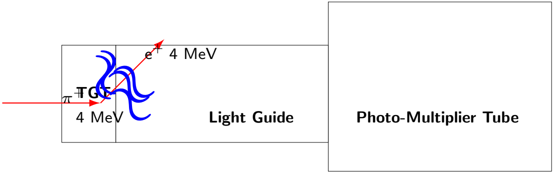


Not that simple!

The “energy”- deduced from number of photoelectrons



Basic Theory
Lepton Universality
Massive Neutrinos
Experiment
Geant4 Simulation
Digitizer
MWPC
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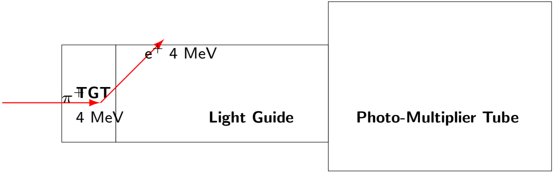
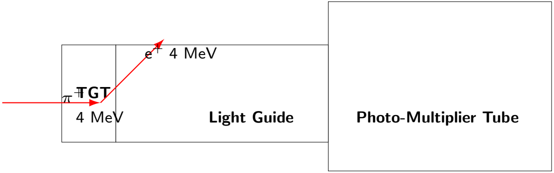


Is the light output the same?

Not that simple!

Basic Theory
Lepton Universality
Massive Neutrinos
Experiment
Geant4 Simulation
Digitizer
MWPC
mTPC
CsI

The "energy"- deduced from number of photoelectrons



Is the light output the same?

NO!

To the Literature!

Basic Theory
Lepton Universality
Massive Neutrinos
Experiment
Geant4 Simulation
Digitizer
MWPC
mTPC
CsI

The light intensity $\propto$ E$_{\text{deposited}}$ for E$_e$ >100 keV

heavy particles- nonlinear response! ie $\not\propto$E

$\alpha = 0.025 \pm 0.002$ g cm^{-2}MeV^{-1} *

$$E_{ee} = \frac{(\mathrm{d}E/\mathrm{d}x)_{\mathrm{min}}}{\ln\left[1+\alpha(\mathrm{d}E/\mathrm{d}x)_{\mathrm{min}}\right]} \int_0^{\mathrm{L}} \ln\left[1+\alpha(\mathrm{d}E/\mathrm{d}x)_{\mathrm{p}}\right] \mathrm{d}x$$

To the Literature!

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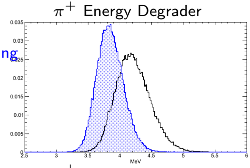
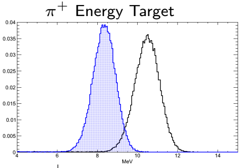
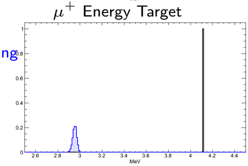
Simulation
Light Quenching

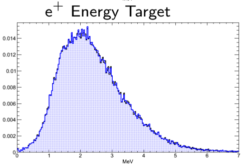




Simulation
Light Quenching

Simulation
Light Quenching



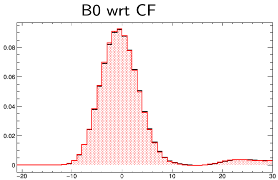


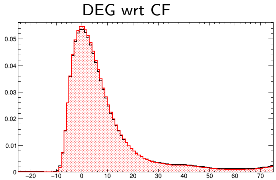
Simulation
Light Quenching

* G. V. O'Reilly, N.R. Kolb, R.E. Pywell, NIM A (1996)

Beam counters

Basic Theory
Lepton Universality
Massive Neutrinos
Experiment
Geant4 Simulation
Digitizer
MWPC
mTPC
CsI

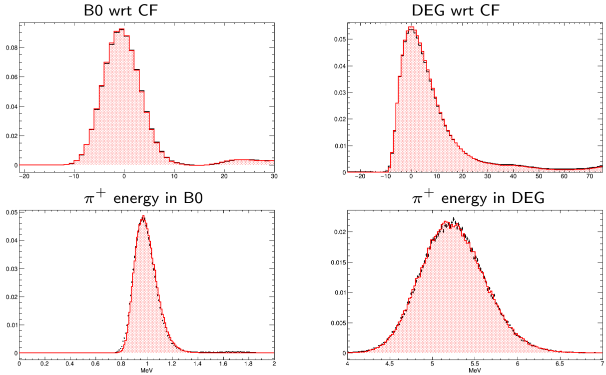




measurement
simulation

Basic Theory
Lepton Universality
Massive Neutrinos
Experiment
Geant4 Simulation
Digitizer
MWPC
mTPC
CsI

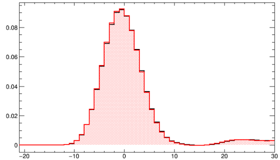
Beam counters



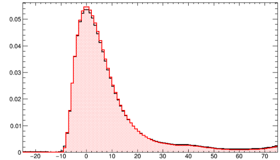
measurement
simulation

Basic Theory
Lepton Universality
Massive Neutrinos
Experiment
Geant4 Simulation
Digitizer
MWPC
mTPC
CsI

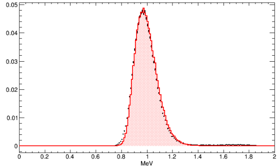
B0 wrt CF



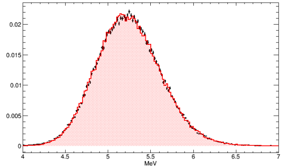
DEG wrt CF



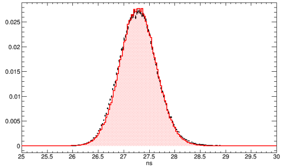
π^+ energy in B0



π^+ energy in DEG



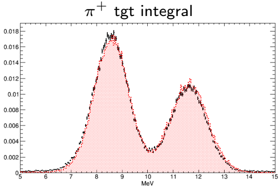
π^+ time of flight B0-DEG

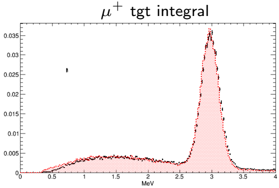


measurement
simulation

Raw tgt response:

measurement
simulation



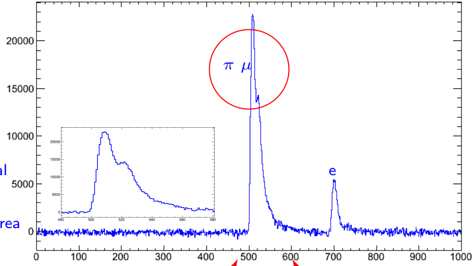


Raw tgt response:

π decays quickly

μ on top of π signal

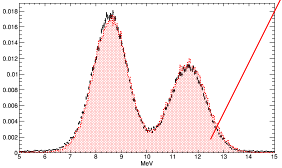
π picks up higher area



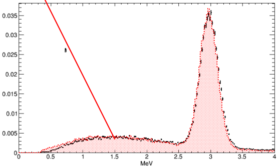
measurement

simulation

π^+ tgt integral



μ^+ tgt integral



Multi-Wire Proportional Chamber (MWPC)

Basic Theory
Lepton Universality
Massive Neutrinos
Experiment
Geant4 Simulation
Digitizer
MWPC
mTPC
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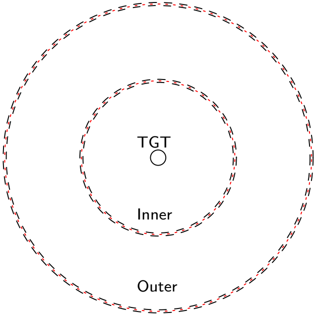
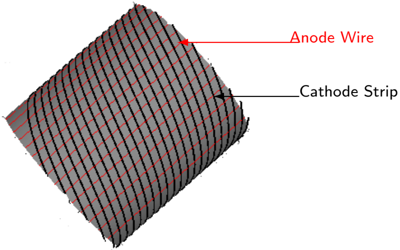
Decay Particle Tracking

- Inner Chamber
  - 192 Anode Wires
  - 256 Cathode Strips
- Outer Chamber
  - 384 Anode Wires
  - 384 Cathode Strips





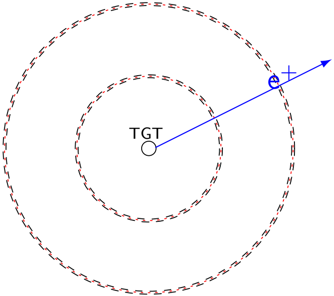
Basic Theory
Lepton Universality
Massive Neutrinos
Experiment
Geant4 Simulation
Digitizer
MWPC
mTPC
CsI

e^+ approaches chamber

ion pairs are formed

drawn toward the anode

induced charge on neighboring cathodes



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Lepton Universality
Massive Neutrinos
Experiment
Geant4 Simulation
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MWPC
mTPC
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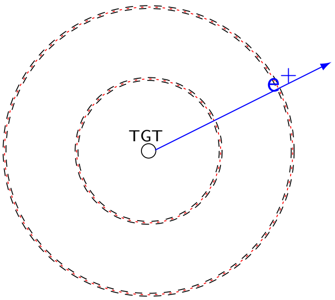

the wire fired gives us ϕ ie (x,y)
the strips fired gives us z

Problem: How much charge is induced on cathode strips?

Multi-Wire Proportional Chamber (MWPC)

It has been shown E. Mathieson NIM 270 (1988)

$$\frac{\rho(\lambda)}{q_a} = K_1 \frac{1 - \tanh^2(K_2\lambda)}{1 + K_3 \tanh^2(K_2\lambda)} \quad \text{where } K_1 = \frac{K_2\sqrt{K_3}}{4\arctan(\sqrt{K_3})}$$

$$\text{and } K_2 = \frac{\pi}{2}\left(1 - \frac{\sqrt{K_3}}{2}\right)$$

Multi-Wire Proportional Chamber (MWPC)

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Geant4 Simulation
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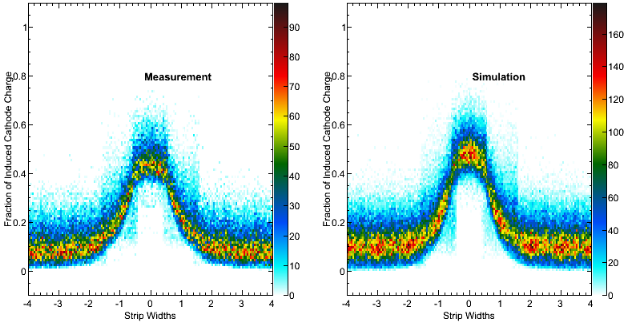
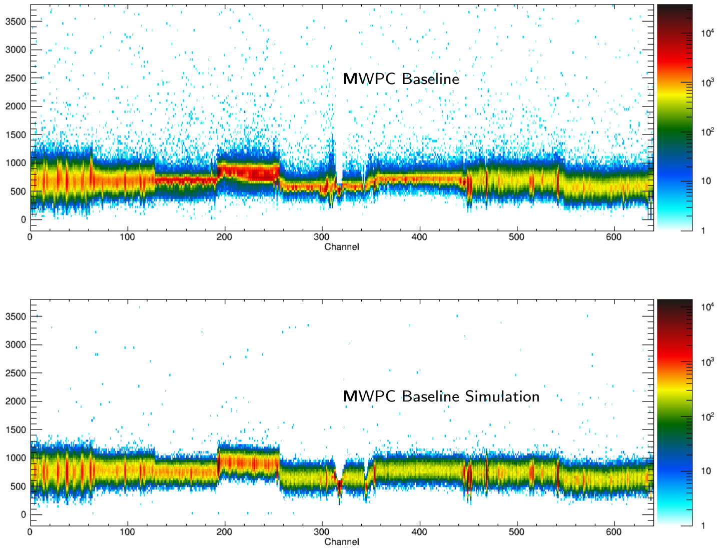
$$\text{and } K_2 = \frac{\pi}{2}\left(1 - \frac{\sqrt{K_3}}{2}\right)$$

λ: $\frac{z}{\text{Anode-Cathode separation}}$

q_a: Anode Charge

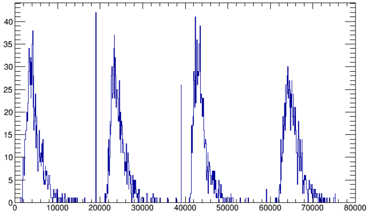



MWPC Baseline
MWPC Baseline Simulation
Channel
Channel

MTPC

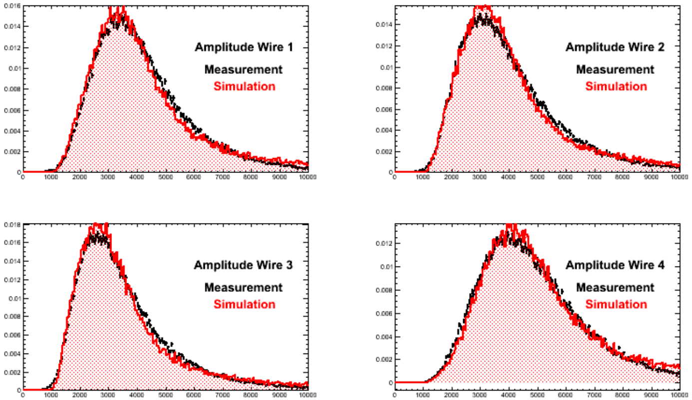
Wire Chamber + Drift Chamber

- beam tracking
- π produces ion pairs
- charges drawn to wires
- charge collected related to energy deposited
- relative charge on each pair of wires determines 1 coordinate
- drift time determines the other coordinate
- output is digitized signal

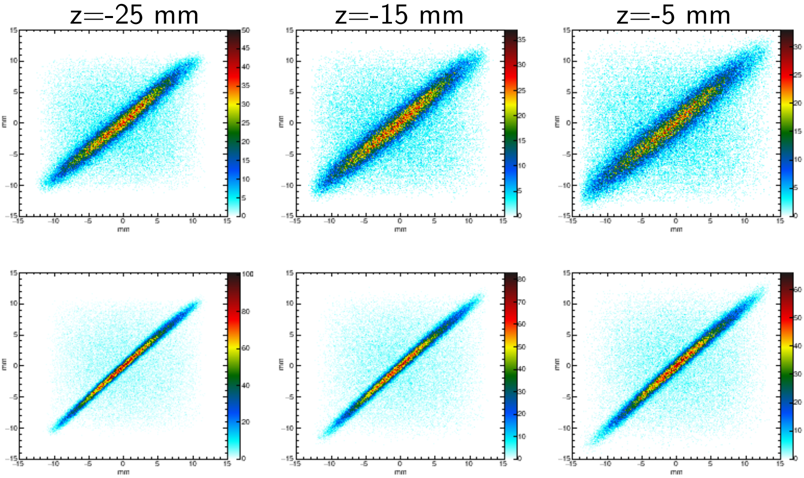


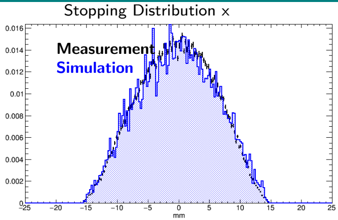
MTPC

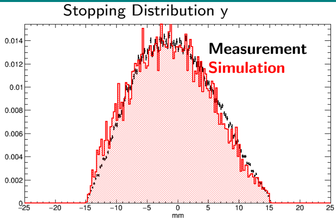
- response function
- place according to drift time (y-coordinate)
- scale according to energy and x-coordinate



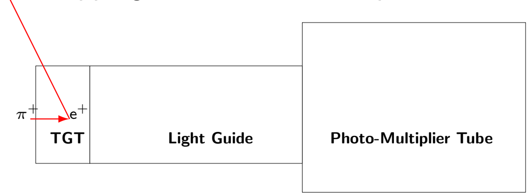
Top: Known x (geant) vs reconstructed x (waveforms)
Bottom: Known y (geant) vs reconstructed y (waveforms)







stopping distribution + mwpc = vertex

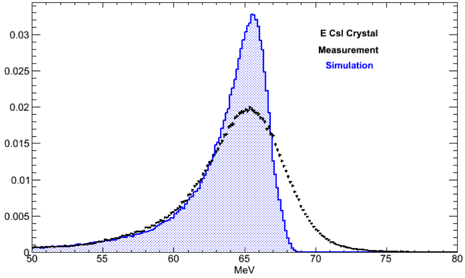


Vertex allows for predicted e^+ energy $\Rightarrow$

Prediction in TGT waveform

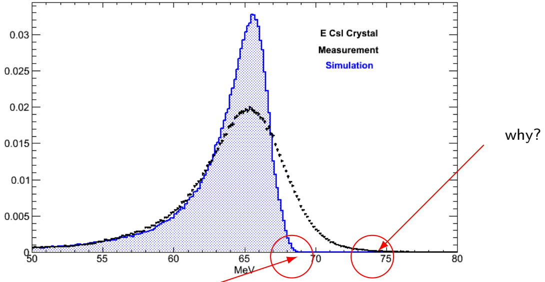
CsI EM Calorimeter

Consider $\pi \rightarrow e\nu$



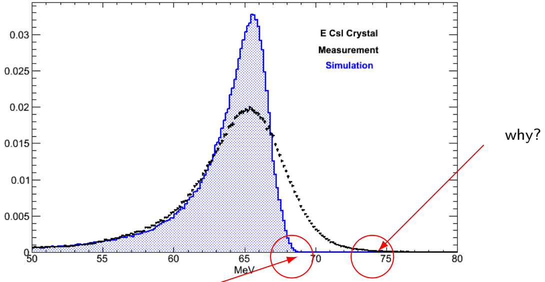
CsI EM Calorimeter

Consider $\pi \to e\nu$



expected end point $\sim \frac{m_\pi}{2} \approx 69.5\text{MeV}$

Consider $\pi \rightarrow e\nu$



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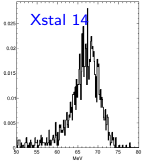
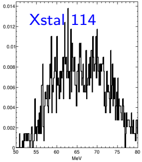
1. Crystals are not all the same





CsI EM Calorimeter

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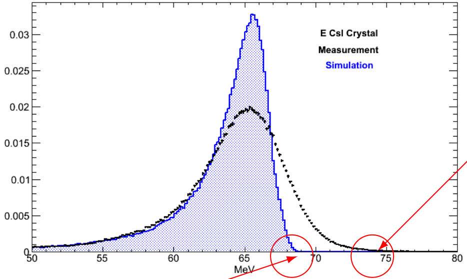
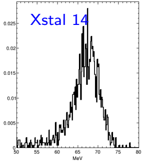
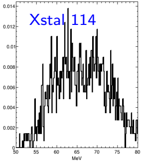


why?

expected end point $\sim \frac{m_\pi}{2} \approx 69.5\text{MeV}$

1. Crystals are not all the same





2. Photoelectron statistics

- shower $\rightarrow$ photons
- photons $\rightarrow$ PMT
- PMT $\rightarrow$ photoelectrons
- photoelectrons $\rightarrow$signal

Photoelectron Statistics?

It has been shown that the number of photelectrons produced is a Poisson distribution assuming: *

1. $P(1, t, \mathrm{d}t + t) \propto \gamma I(t)$
2. $\mathrm{d}t$ can be chosen very small
3. P does not change based off previous events occuring.

Photoelectron Statistics?

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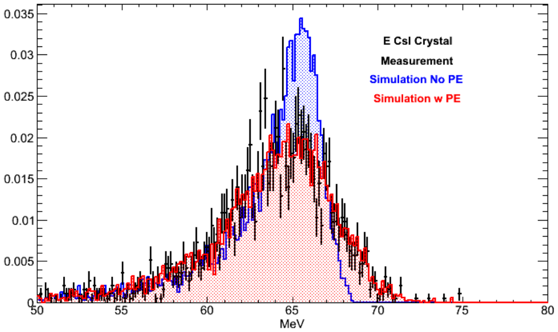
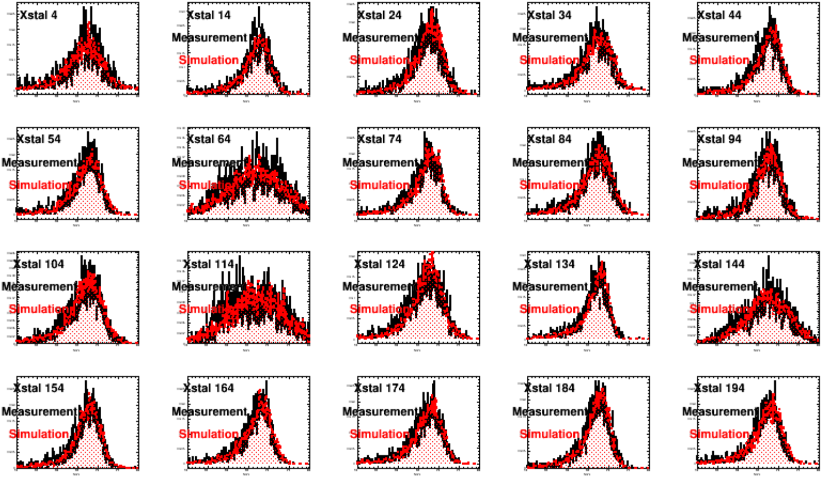
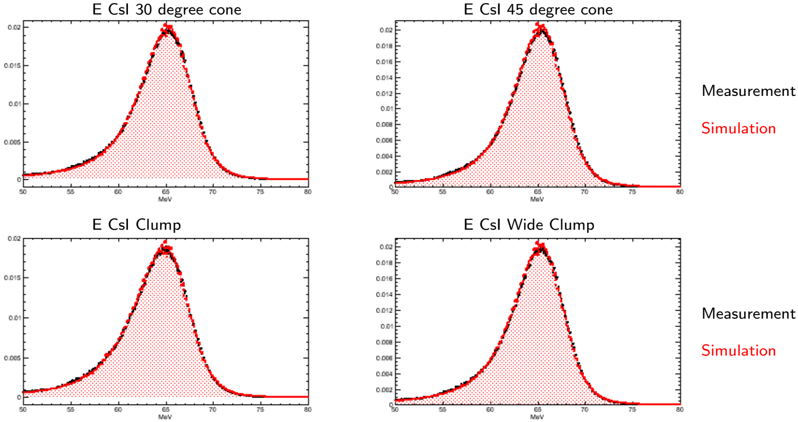


* L. Mandel, Procs. Phys. Soc. (London) **74** 233 (1959)

Do this to all 240 Crystals

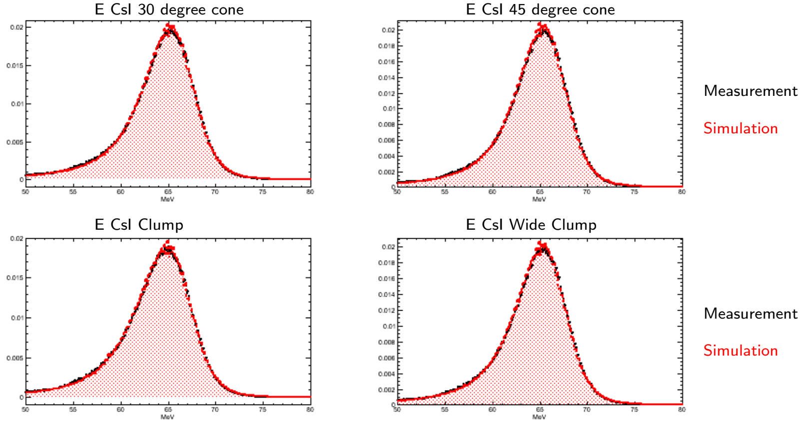


CsI



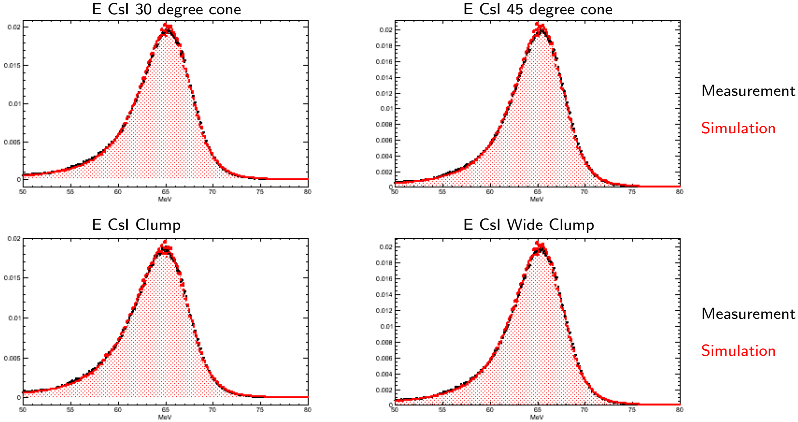
E CsI 30 degree cone
E CsI 45 degree cone
E CsI Clump
E CsI Wide Clump
MeV
Measurement
Simulation
Measurement
Simulation

CsI



If all is good above 50 MeV, the tail should follow:

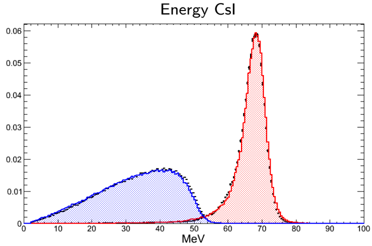
CsI

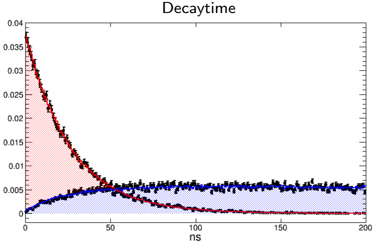


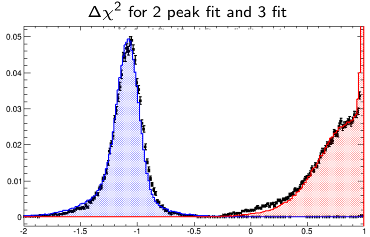
If all is good above 50 MeV, the tail should follow:

tail-to-peak ratio may be obtained

Basic Theory
Lepton Universality
Massive Neutrinos
Experiment
Geant4 Simulation
Digitizer
MWPC
mTPC
CsI







Measurement

$\pi \to e\nu$ Simulation

$\pi \to \mu\nu$ Simulation

If All this Works...

Basic Theory
Lepton Universality
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CsI

Then

- get acceptances
- study false positive signals
- get tail-to-peak ratio
- get branching ratio
- put limits on beyond Standard Model physics

Currently working on

- obtaining tail-to-peak ratio
  - **Issue: Giant Dipole Resonances of ^{127}I**
- mwpc efficiencies
  - **Issue: Based on “seen” energy**
- positron lineshape
  - **aids in search of massive ν ’s**

Current 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 uva , , 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 .

Home pages: http://pibeta.phys.virginia.edu
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Basic Theory
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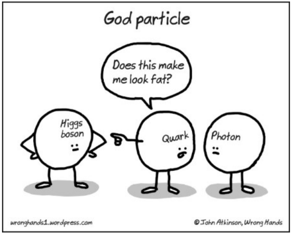
Digitizer
MWPC
mTPC
CsI

Thanks For Listening!



References

1. D.Počanić et al J. Physics G 2014 **41** 11

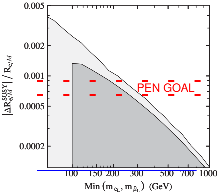
2. Will Loinaz, Naotoshi Okamura, Saifuddin Rayyan, Tatsu Takeuchi, and L. C. R. Wijeward- hana. Nutev anomaly, lepton universality, and nonuniversal neutrino-gauge couplings. Phys. Rev. D, 70(11):113004, 2004

3. G. V. O'Reilly, N.R. Kolb, R.E. Pywell, Nucl. Instr. and Meth. in Res. A 368(1996)745-749

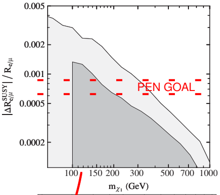
4. L. Mandel, "Fluctuations of photon boeams: the distribution of photo-electrons", Procs. Phys. Soc. (London) **74** 233 243 (1959)

Basic Theory
Lepton Universality
Massive Neutrinos
Experiment
Geant4 Simulation
Digitizer
MWPC
mTPC
CsI

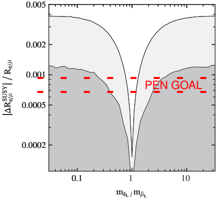
minimal selec-tron, smuon masses:



lowest mass chargino:



slepton mass degen-eracy:



Higgsino mass param's. μ, $m_{\tilde{u}_L}$: