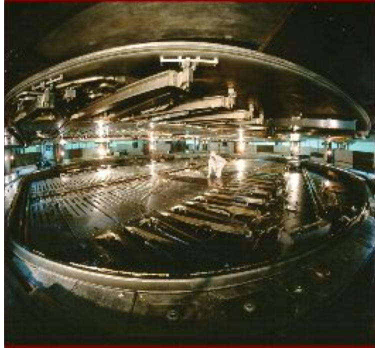
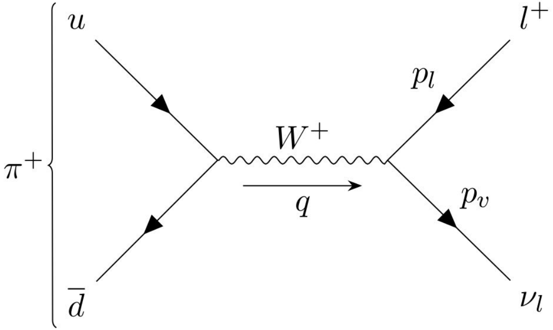
TRIUMF
Canada’s national laboratory for particle and nuclear physics
Laboratoire national canadien pour la recherche en physique nucléaire et en physique des particules



Testing Lepton Flavor Universality with Rare Pion Decays

$$\pi^+ \rightarrow e^+\nu_e$$



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Seminario Virtual Física de Altas Energías, ICN-IF-UNAM

2020-Nov-04

Agenda

- General Context, Motivation, and Status
- Experimental Technique
- Results so far
- Summary and Future Plans

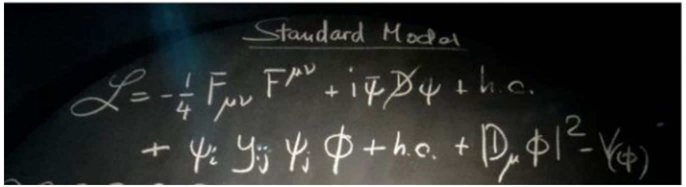
*All references are from: http://hdl.handle.net/2429/69938

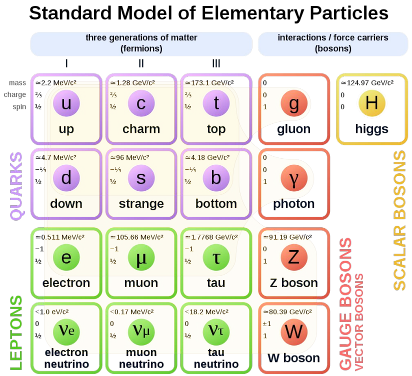
The Standard Model (SM) and its flaws...

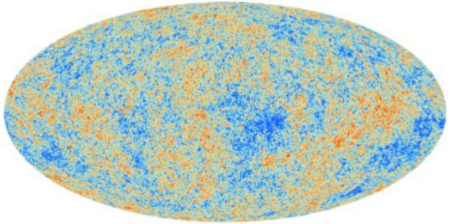
- The best description of matter/anti-matter interactions so far.

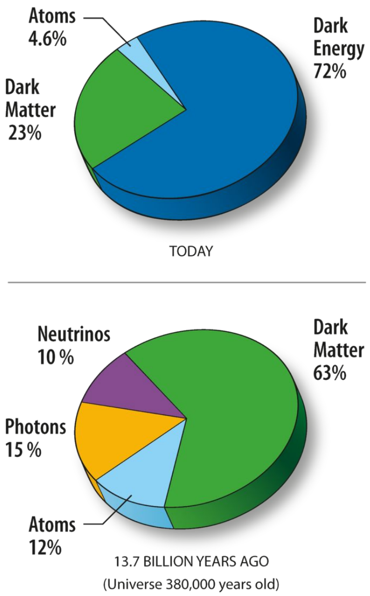
- Theoretical Issues:
  - Gravity (not included)
  - Neutrino masses (not included)
  - Hierarchy problem (Weak >> Grav)
  - Flavor problem (3 families)

- Cosmological Issues:
  - Dark Energy/Matter
  - Inflation
  - Matter/Antimatter Asymmetry
  - CP violation



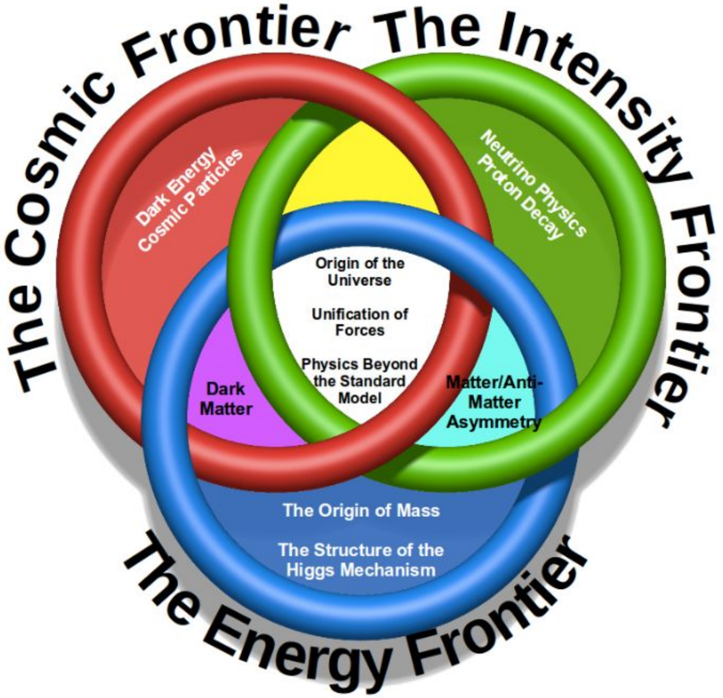




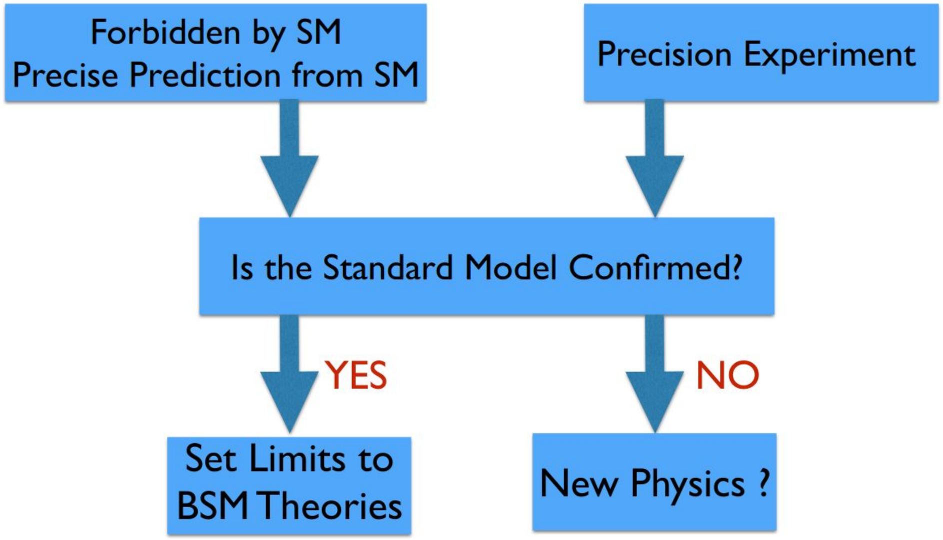


Wilkinson Microwave Anisotropy Probe (WMAP)

Frontiers of Particle Physics



Precision Frontier



Pion prediction and discovery

- 1935: The pion is the lightest meson (quark-anti-quark bound state) with a mass of 139 MeV/c^2, and it was first predicted by Yukawa, when he published his theory of mesons in 1935 [33], as the carrier of a strong and short-range force that can bind nucleons in nuclei.

- 1936: Another light particle, the muon has a mass of 105.7 MeV/c^2 ; it was discovered in 1936 by Anderson and Neddermeyer, 10 years before the pion, and as it was in the same mass range, it was initially thought to be Yukawa's particle.

- 1947: Powell and his collaborators discovered the pion [34] by exposing photographic plates to cosmic rays at a high altitude, i.e., at the tops of mountains.

- 1949 and 1950: Yukawa and Powell received the Nobel Prize in Physics, respectively [35].

  Yukawa reflected years later…

  "*I felt like a traveler who rests himself at a small tea shop at the top of a mountain slope. At that time I was not thinking about whether there were any more mountains ahead.*" Tabibito [36].

Pion Puzzles

- The first puzzle was the observation of the π+ → μ+ v_μ → e+ v_e v̄_μ (PIMUE) decay chain, but never the direct π + → e + v_e (PIENU) decay.
- From pure phase space considerations, if the electron at 0.511 MeV/c^2 is two orders of magnitude smaller in mass than the muon, why do pions not decay directly into positrons or electrons?
- In 1955 and 1957, two experiments, one at Columbia University [37] and the other at the E. Fermi Institute [38], reported no direct electronic decay from pions, setting an upper limit on the branching ratio defined as the relative rate of decay of pions into electrons over muons (including associated neutrinos and radiative components):

$$R_\pi = \frac{\Gamma(\pi^+ \to e^+\nu_e + \pi^+ \to e^+\nu_e\gamma)}{\Gamma(\pi^+ \to \mu^+\nu_\mu + \pi^+ \to \mu^+\nu_\mu\gamma)}. \quad (1.1)$$

- The upper limit was set to **R^exp_1957 ~ 10^−6** . Another puzzle at the time was the evidence for parity violation in weak interactions; C. Wu et al. confirmed it with their beta-decay experiment in 1956 [39].
- At the time, parity violation could only be explained by the contemporary vector-axial-vector (V-A) theory of weak interactions proposed by E.C.G. Sudarshan and R.E. Marshak [40].
- In 1958, parity violation and the concept of a universal form of weak interaction were combined into one theory by R.P. Feynman and M. Gell-Mann [41]. The approach predicted a branching ratio of pions decaying directly to positrons over muons of the order of **R^(V-A)_1958 ~ 10^−4** in contradiction with the experimental upper limit at that time. The V-A theory explains how the mass dependent helicity suppression favors the muonic decay over the positron by four orders of magnitude.

  “*These theoretical arguments seem to the authors to be strong enough to suggest that the disagreement with the He 6 recoil (a double focusing magnetic spectrometer used by Anderson et. al.) experiment and with some other less accurate experiments indicates that these experiments are wrong. The π → e+ v problem may have a more subtle solution.*” - Feynman and Gell-Mann [41].

Pion Answers

- <u>Later in 1958</u>, the $\pi^+ \rightarrow e + v_e$ (PIENU) decay mode was finally discovered at CERN [42] and Columbia University [43].

- <u>Later, in 1960</u>, H.L. Anderson et al. obtained the first precise measurement [44] with $\mathbf{R^{exp}_{1960} = (1.21 \pm 0.07) \times 10^{-4}}$, cementing and establishing the new V-A theory as the correct description of the weak interaction, which was subsequently adopted into the Standard Model (SM) of particle physics.

- Since pions were used to establish the SM, we can now use them to challenge it, measuring its properties with high precision and trying to detect deviations from predictions.

- <u>In 2011:</u> Bryman et al. reported the latest theoretical ratio update in 2011 at $\mathbf{R^{SM} = (1.2352 \pm 0.0002) \times 10^{-4}}$ which represents one of the most precisely calculated SM observable involving quarks.

- <u>In 2015</u>: By contrast, the current experimental value reported in 2015 by the PIENU experiment at TRIUMF is $\mathbf{R^{exp}_{2015} = (1.2344 \pm 0.0023(stat.) \pm 0.0019(syst.)) \times 10^{-4}}$ [5], representing only about a tenth of our data, which is less precise than the theory by an order of magnitude. Therefore, further precision is required. The PIENU experiment at TRIUMF was planned with the aim of improving the precision level to 0.1%.

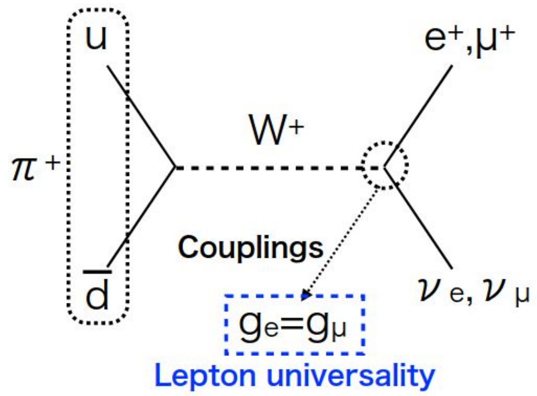
Improved Measurement of the $\pi \rightarrow e\nu$ Branching Ratio

A. Aguilar-Arevalo *et al.* (PIENU Collaboration)
Phys. Rev. Lett. **115**, 071801 – Published 13 August 2015

DOI:https://doi.org/10.1103/PhysRevLett.115.071801

Motivation and status

- Deviations from the SM prediction may imply:
    - a violation of lepton universality, the SM hypothesis that electrons and muons have the same weak interactions;
    - heavy neutrinos lighter than the pion [45];
    - and the presence of new physics beyond the SM,
        - such as new pseudo-scalar interactions, i.e., R-parity violating supersymmetry pseudo scalars [28], leptoquarks [46],
        - and charged Higgs bosons [24].
- In some instances, these indirect constraints can far exceed the reach of direct searches at colliders. Most remarkably, a deviation from SM could imply the existence of a new pseudo-scalar interaction with an energy scale up to O(1000 TeV), which would enhance the branching ratio by O(0.1%) [47].
- This talks represents the latest experimental measurement effort by the PIENU collaboration.
    - The PIENU datasets contain four years of data, taken between 2009 and 2012, with 6.5 million (M) π + → e + v_e events.
    - The current analysis presented is blinded, but includes the highest quality data portion available, 3 M, π + → e + v_e events.
    - Moreover, major experimental systematic problems have been solved recently, allowing for increased precision up to 0.12% in R_π^exp from the 2015 published measurement.



http://hdl.handle.net/2429/69938

Access to Lepton Universality test

- Vector-Axial (helicity suppression) gives the first order R

$$R_\pi^0 = \frac{\Gamma_{\pi\to e}}{\Gamma_{\pi\to\mu}} = \frac{g_e^2}{g_\mu^2}\frac{m_e^2}{m_\mu^2}\left(\frac{m_\pi^2 - m_e^2}{m_\pi^2 - m_\mu^2}\right)^2 . \qquad (2.10)$$

- In 2007, Cirigliano and Rosell [47] recalculated the corrections using Chiral Perturbation Theory (ChPT). ChPT uses a low-energy effective field theory for QCD, allowing for strong interaction calculations. ChPT enabled a power series solution for the radiative corrections

$$R_\pi = R_\pi^0 \left[1 + \Delta_{e^2p^2} + \Delta_{e^2p^4} + \Delta_{e^2p^6} + ...\right]\left[1 + \Delta_{LL}\right] . \qquad (2.12)$$

- Going back to Eq. 2.10, we could introduce the hypothesis that the coupling constants are different for each generation (g = g_e = g_μ = g_τ) and then the branching ratio expression becomes

$$R_\pi^{\mathrm{SM}} = \left(\frac{g_\mu}{g_e}\right)^2 R_\pi^{\mathrm{exp}} . \qquad (2.14)$$

Table 2.6: Experimental results on lepton universality (LU) tests from studies of π, K, τ, μ and W decay. In some cases, μ and τ's lifetime (τ_μ, and τ_τ) measurements were used in combination for LU tests. Here, $\mathcal{B}$ represents the branching fraction of a particular decay mode.

Decay mode, and lifetimes	g_μ/g_e
$\Gamma_{\pi\to\mu}/\Gamma_{\pi\to e}$	1.0004 ± 0.0012 [5]
$\mathcal{B}_{\tau\to\mu}/\mathcal{B}_{\tau\to e}$	1.0018 ± 0.0014 [68]
$\mathcal{B}_{K\to\mu}/\mathcal{B}_{K\to e}$	0.996 ± 0.005 [69]
$\mathcal{B}_{K\to\pi\mu}/\mathcal{B}_{K\to\pi e}$	1.002 ± 0.002 [70]
$\mathcal{B}_{W\to\mu}/\mathcal{B}_{W\to e}$	0.997 ± 0.010 [70]
	g_τ/g_μ
$\mathcal{B}_{\tau\to e}$, τ_μ, τ_τ	1.0011 ± 0.0015 [68]
$\mathcal{B}_{\tau\to\pi}/\mathcal{B}_{\pi\to\mu}$	0.9963 ± 0.0027 [68]
$\mathcal{B}_{\tau\to K}/\mathcal{B}_{K\to\mu}$	0.9858 ± 0.0071 [68]
$\mathcal{B}_{W\to\tau}/\mathcal{B}_{W\to\mu}$	1.039 ± 0.013 [70]
	g_τ/g_e
$\mathcal{B}_{\tau\to\mu}$, τ_μ, τ_τ	1.0029 ± 0.0015 [68]
$\mathcal{B}_{W\to\tau}/\mathcal{B}_{W\to e}$	1.036 ± 0.014 [70]

Tensions in Lepton Universality

- Recently, charged current (CC) second-order weak interactions have been measured, pointing towards lepton universality violation. LHCb reported flavour-changing neutral-current processes… [71], [72]

- The LHCb and BaBar second-order weak interaction deviations from universality, required to explain these measurements, are extensive compared to the uncertainties stated in Table 2.6.

- To interpret these results concerning new physics, while remaining consistent with other measurements, generally requires the new physics to couple preferentially to the third generation of particles [77].

PIENU measurements so far...

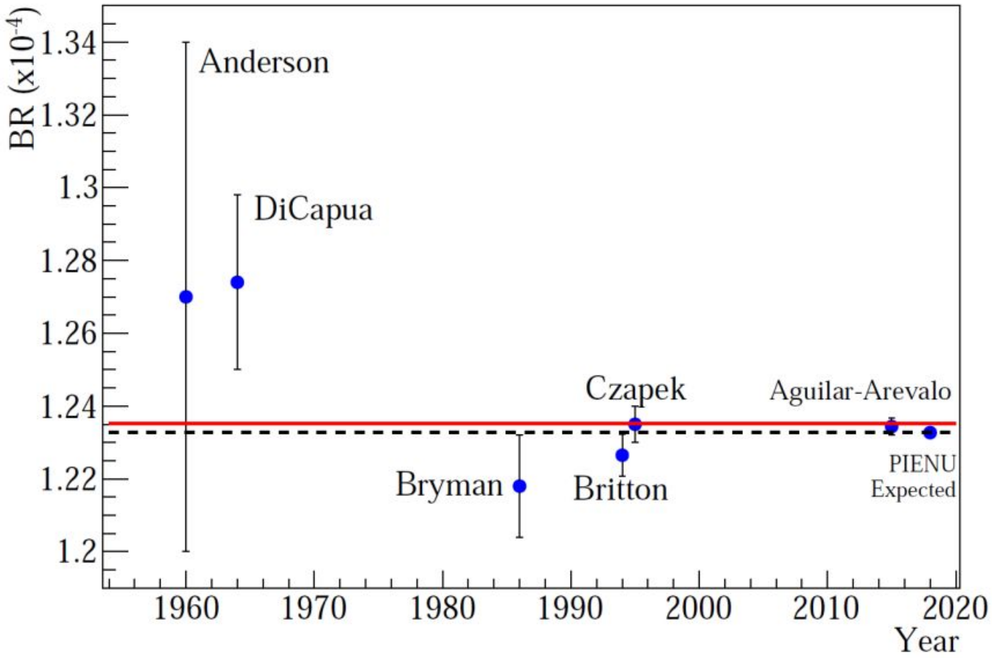


Figure 1.1: History of the R_π^{exp} branching ratio measurements. Red line: SM calculation [24]. Black dashed line: PDG experimental average [21].

Experimental Technique

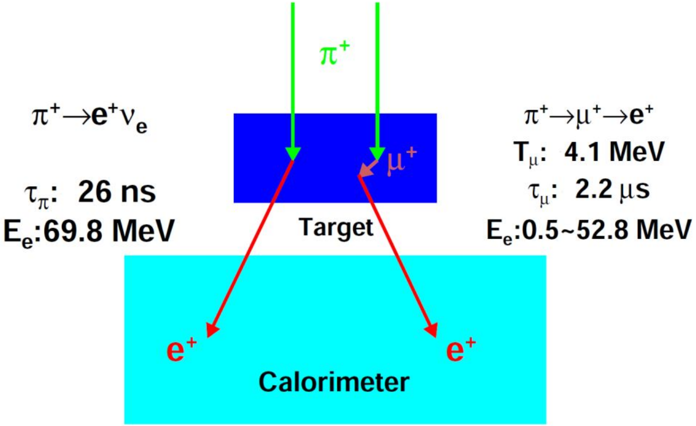


Figure 1.2: Schematic illustration of experimental technique: two pionic decays in a scintillator target; and decay positrons collected by the calorimeter.

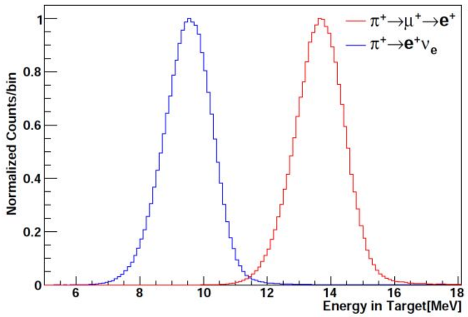


Figure 1.4: Energy deposited in the target B3 for $\pi^+ \to e^+\nu_e$ (blue line) and $\pi^+ \to \mu^+\nu_\mu \to e^+\nu_e\bar{\nu}_\mu$ (red line) events from GEANT4.

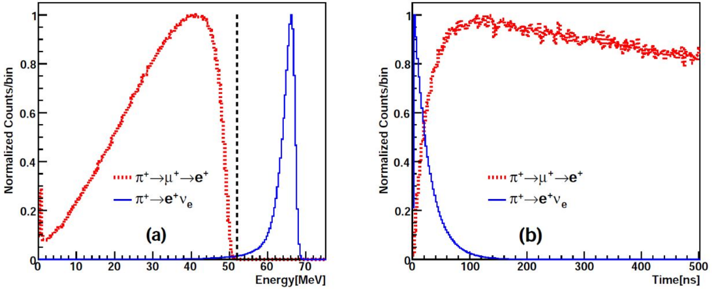
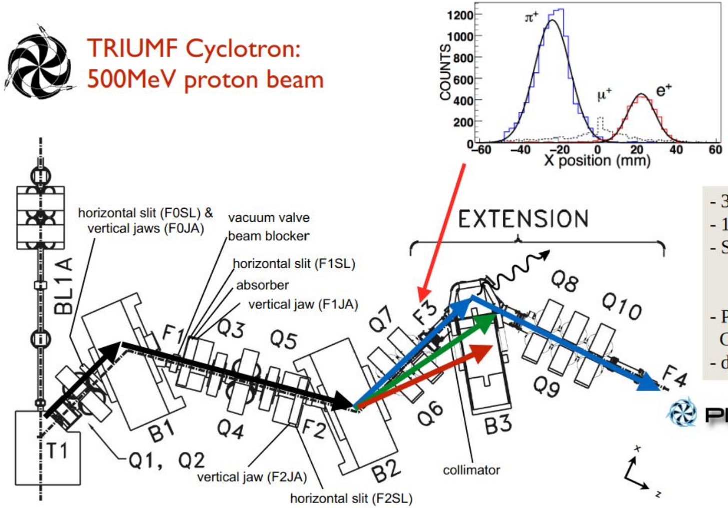


Figure 1.5: (Left) Time spectra and (right) energy spectra in the calorimeters of $\pi^+ \to e^+\nu_e$ and $\pi^+ \to \mu^+\nu_\mu \to e^+\nu_e\bar{\nu}_\mu$ decays obtained from simulations. The spectra are normalized to the same amplitude. Using an

The PIENU Pion beam

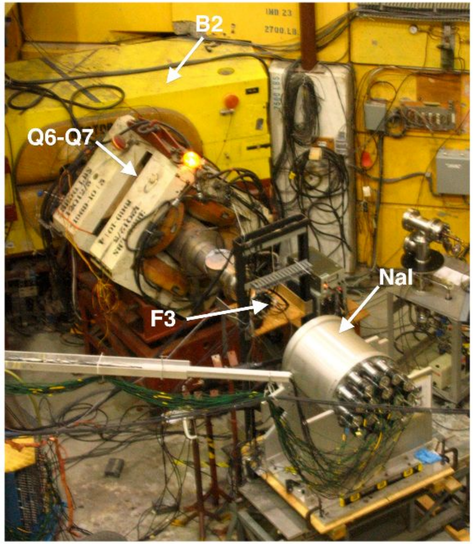
TRIUMF Cyclotron:
500MeV proton beam

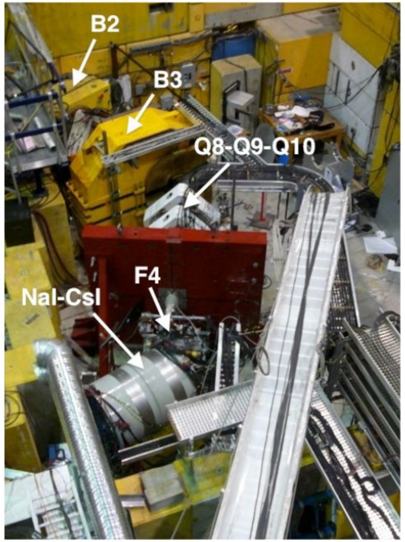


- 3-Dipoles Beamline
- 10 Quadrupoles
- Separation:
  Energy-loss
  Collimator
- Positron Contamination <1%
- dp/p ~ 1.5% FWHM

PIENU

A.Aguilar-Arevalo *et al.*: Nucl. Instr. Meth. A621, 188 (2010)





The PIENU detector

Beam:

60kHz pions @ 75 MeV/c

$\pi : \mu : e = 85 : 14 : 1$

Detector:

Acceptance: 20%

Plastic Scintillators

NaI(Tl) + CsI Calorimeter

Wire Chambers

Silicon Strips

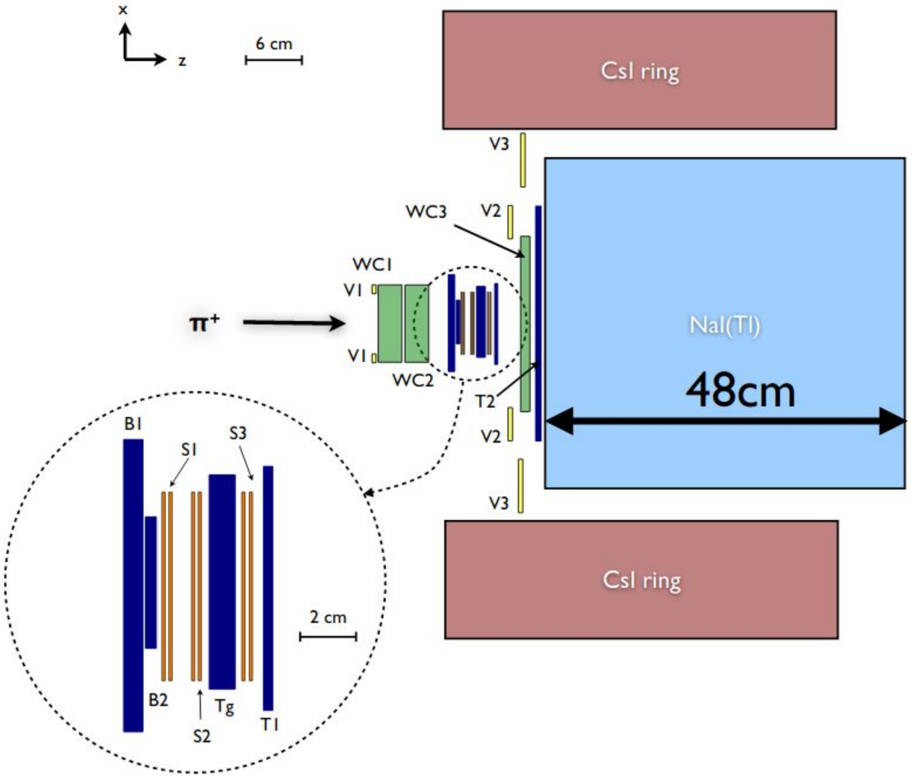
Energy resolution:

2.2% FWHM @ 70MeV

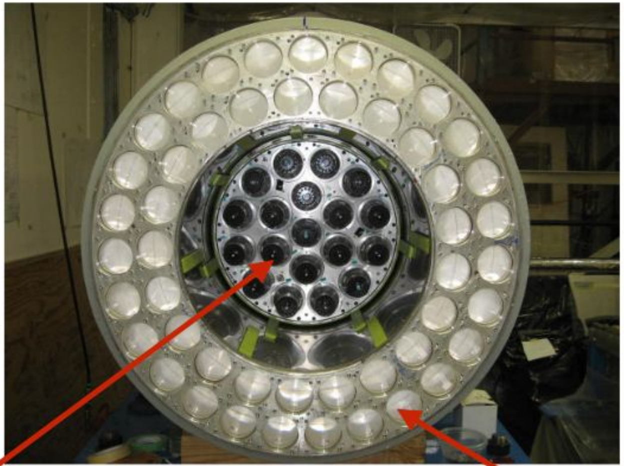
Temperature Stabilization

Data taking:

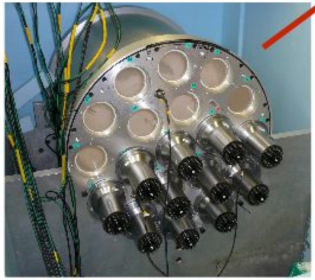
2009-2012



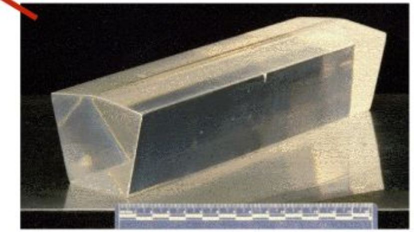
Calorimeter



"BiNa":
Monolithic 48x48cm
NaI(Tl) crystal
19-PMTs readout

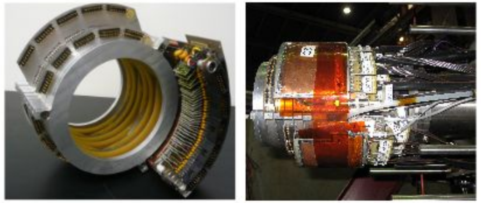


97 pure CsI crystals
single PMT readout

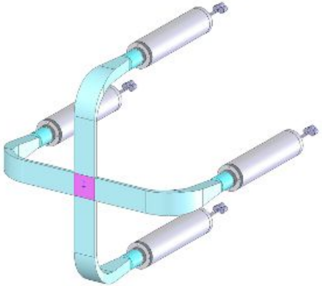


Tracking and Time/Energy Detectors

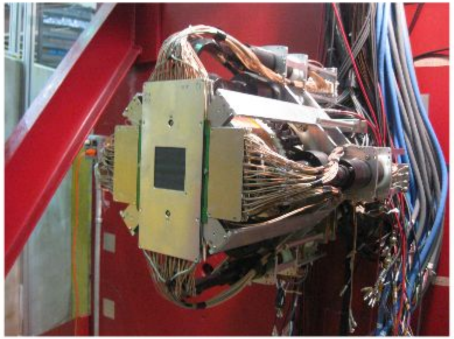
Beam Wire Chambers



Scintillators (4-PMT / 500MHz readout)

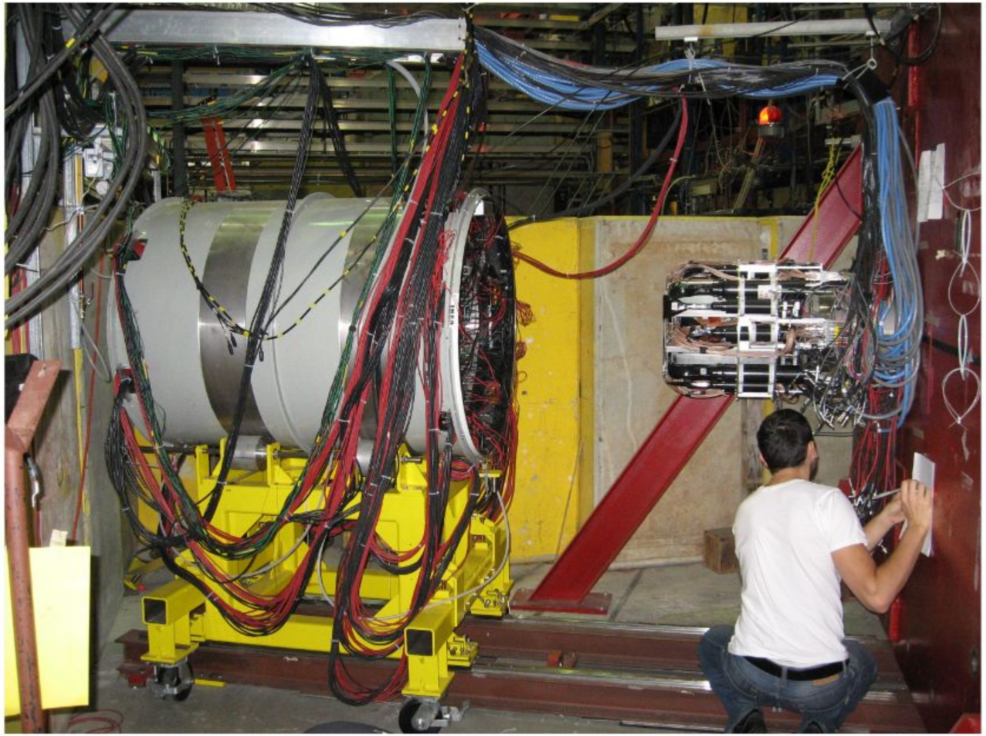


Silicon Microstrip Detectors



Positrons Wire Chambers

Experimental setup



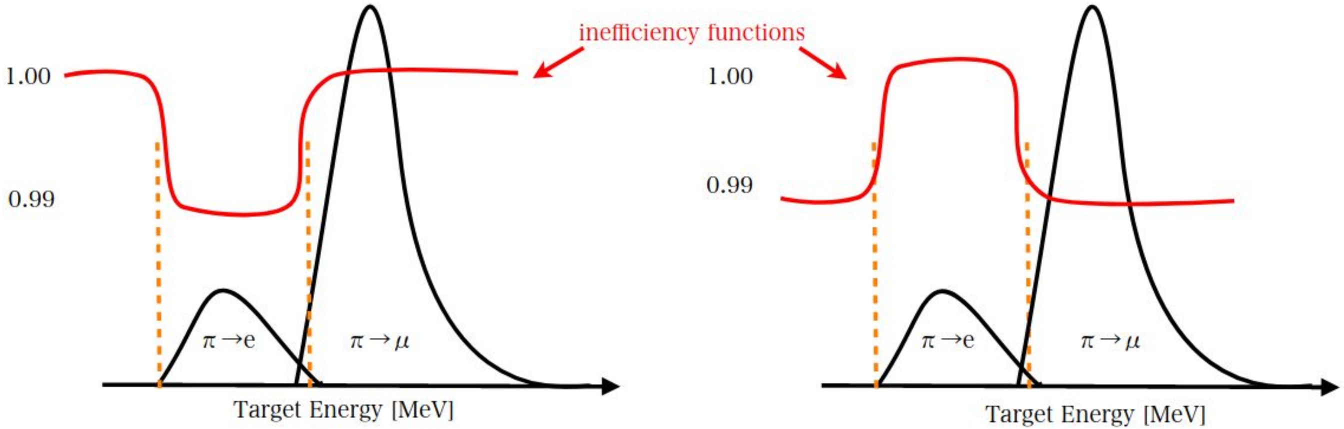
π^+

Beam

A.Aguilar-Arevalo *et al*: Nucl. Instr. Meth. A79, 38-46 (2015)

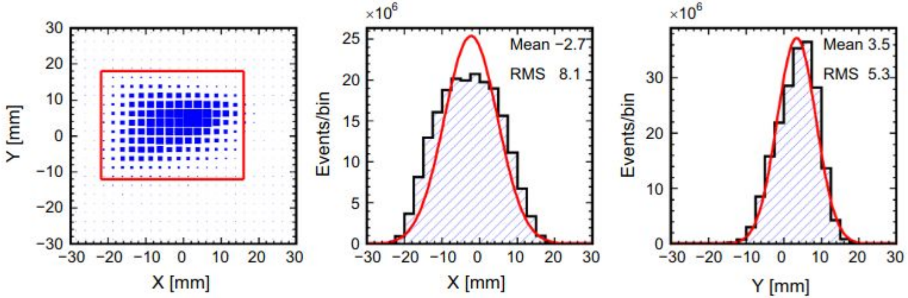
"Blind" Analysis

- **Avoid biases in precision experiments!**
- Blinding procedure done before starting the analysis.
- One of the two decays is slightly suppressed: BR changes.
- Random and unknown inefficiency factor
- "Unblinding" only when the Collaboration agrees on the analysis procedure and systematic error estimates.

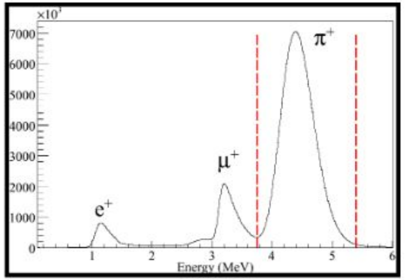


Event Selection

Beam Wire Chambers



Pion Selection with B1/2 Scintillators



Other selection cuts:

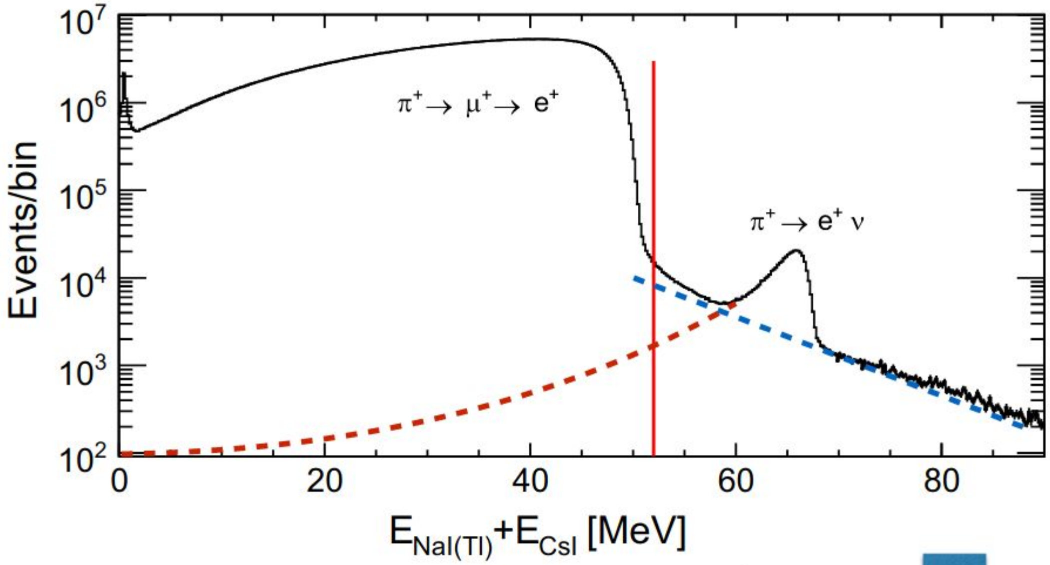
Pileup, Protons rejection, Timings, Positron Acceptance (R = 60mm)

Triggers:

Physics:	Calibration:
Prescaled (x16)	Beam Positrons
Early Time (6-46ns)	Beam Muons
High Energy (Ecal > 46MeV)	Cosmic Rays

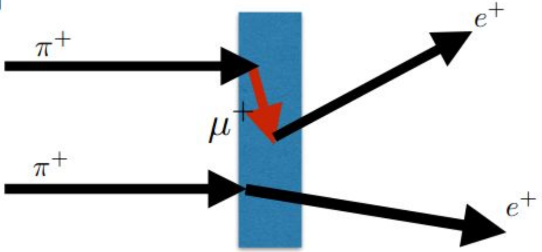
Trigger Rate: 600Hz

Energy spectrum



Low Energy Tail

Pileup



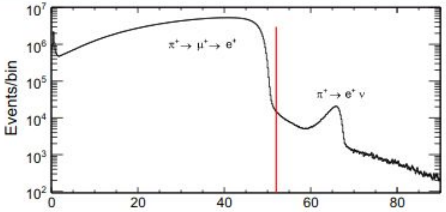
Analysis Strategy

- Measure the Energy Spectrum
- Consider the Low- and High-Energy Time Spectra.
- Fit the spectra with signal and background shapes.

- Correct the BR from the fit for:
  - Low Energy Tail (largest correction)
  - Acceptance Correction
  - Muon Decays in Flight Correction

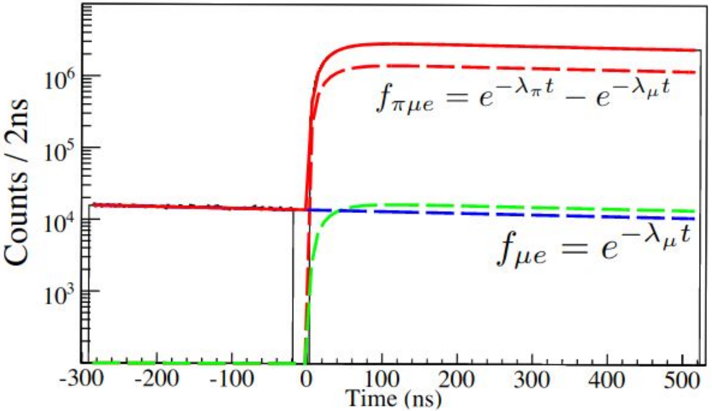
- Do systematic checks, branching ratio R vs:
  - Low/High energy cut
  - Acceptance

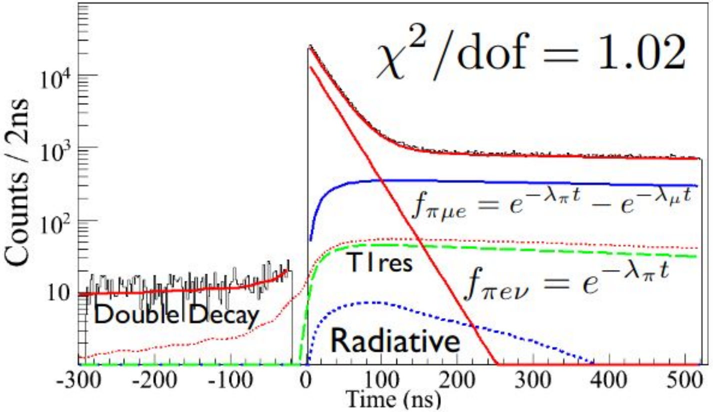
Time Spectrum Fit



E<52MeV

E>52MeV





Systematic checks

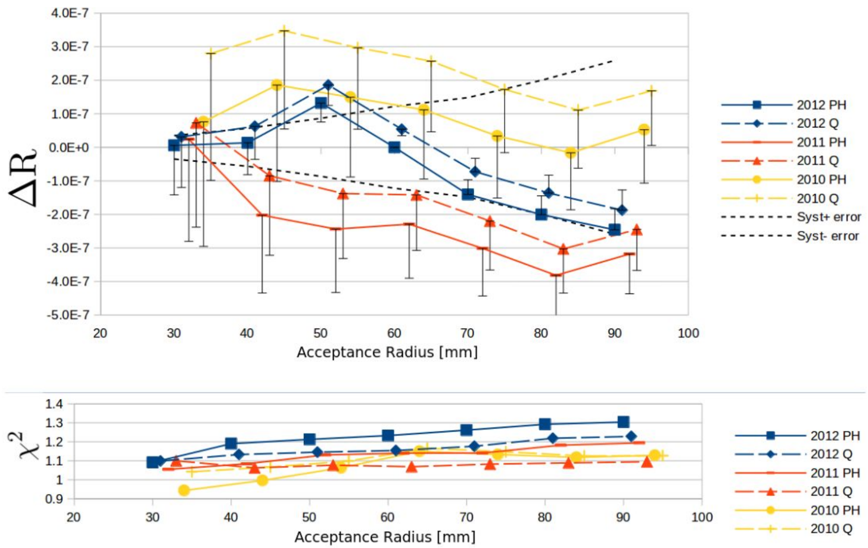


Figure 7.4: $\Delta R \pm \Delta e$ (Eq. 7.1) vs. A_R, Charge Integration and Pulse-height: The x-axis is the A_R value in mm units. The y-axis is in ΔR (corrected) units, with zero change representing 2012(PH)'s analysis using anchor point with cuts $A_R = 60$ mm and $E_{\text{cut}} = 52$ MeV, the error bars (Δe) on each point represent the uncorrelated statistical error between the point in question and the anchor point with the error bars going up when there is an statistical increase and down otherwise. The horizontal dashed black lines both at the same distance from anchor represent the calorimeter's LET systematic error. The bottom part shows the total χ^2 from the fitting function for each point.

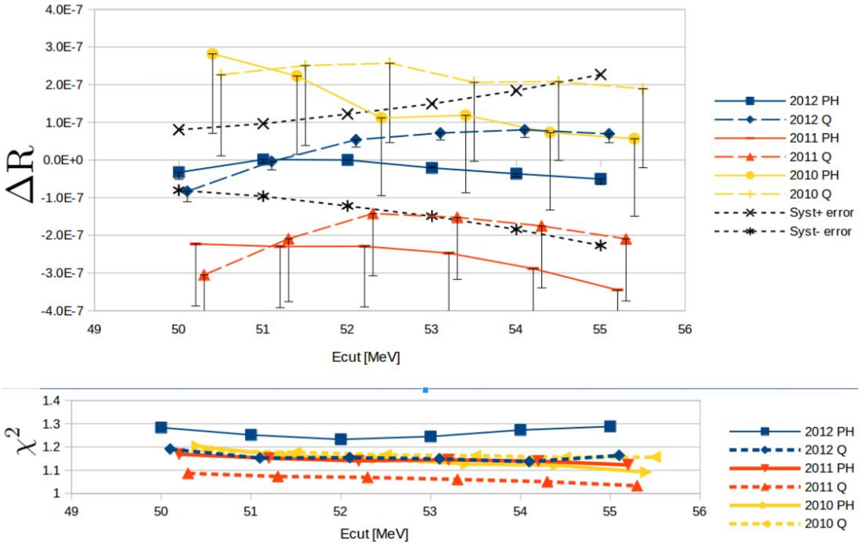


Figure 7.5: $\Delta R \pm \Delta e$ (Eq. 7.1) vs. E_{cut}, Charge Integration and Pulse-height: The x-axis is the E_{cut} value in MeV units. The y-axis is in ΔR units, with zero change representing 2012(PH)'s analysis using anchor point with cuts $A_R = 60$ mm and $E_{\text{cut}} = 52$ MeV, the error bars (Δe) on each point represent the uncorrelated statistical error between the point in question and the anchor point with the error bars going up when there is an statistical increase and down otherwise. The horizontal dashed black lines both at the same distance from anchor represent the calorimeter's LET systematic error. The bottom part shows the total χ^2 from the fitting function for each point.

Combining datasets...

Table 7.3: Combination of 2010, 2011, and 2012 datasets for $A_R = 40$ mm. The branching ratios for all datasets are still blinded. See Section 7.3 and Table 7.2 for nomenclature. The PH version was chosen over the Q based branching ratio since the global systematic error is (marginally) better.

	Value	Stat. error	Syst. error
$R^{\text{raw}}[10^{-4}]$ §5.3.4	Y_i	$\delta Y_i^{\text{st.}}$	$\delta Y_i^{\text{sy.}} = \sqrt{\Sigma_\alpha^2}$
2012 (PH)	1.2***	0.0014	0.0003
(Q)	1.2***	0.0014	0.0003
2011 (PH)	1.2***	0.0025	0.0006
(Q)	1.2***	0.0025	0.0007
2010 (PH)	1.2***	0.0030	0.0008
(Q)	1.2***	0.0031	0.0008
Common Corrections	C_k	$\delta C_k^{\text{st.}}$	$\delta C_k^{\text{sy.}}$
LET §6.1.1	1.0261	0.0002	0.0005
Acceptance §6.2	0.9978	0.0002	
t_0 §6.4	1.0006	0.0003	
Common systematics			S_l
$\sqrt{\Sigma_\beta^2}$ (PH)			0.0005
(Q)			0.0006
$R^{\text{final}}[10^{-4}]$			
2012 (PH)	1.2***	0.0015	0.0008
(Q)	1.2***	0.0015	0.0009
2011 (PH)	1.2***	0.0026	0.0010
(Q)	1.2***	0.0026	0.0011
2010 (PH)	1.2***	0.0030	0.0011
(Q)	1.2***	0.0031	0.0012
Weighted avg.	R_f	$\delta R_f^{\text{st.}}$	$\delta R_f^{\text{sy.}}$
(PH)	1.2***	0.0013	0.0008
(Q)	1.2***	0.0013	0.0009

Results

The *blinded*[39] branching ratio $R_\pi = \frac{\Gamma(\pi^+\to e^+\nu_e + \pi^+\to e^+\nu_e\gamma)}{\Gamma(\pi^+\to\mu^+\nu_\mu + \pi^+\to\mu^+\nu_\mu\gamma)}$ calculated for this thesis regarding the highest quality data available from PIENU's datasets (Run IV, V and VI) with about 3 million $\pi^+ \to e^+\nu_e$ events[40] collected between 2010 and 2012 is

$$R_\pi^{blind} = (1.2^{***} \pm 0.0013(\text{stat.}) \pm 0.0008(\text{syst.})) \times 10^{-4}. \qquad (8.1)$$

represents a *0.12% precision measurement*, a factor of 30 improvement from previous generation experiments [12] [13] and a factor 2 from a subset of data (Run IV) published [5] in 2015 as

$$R_\pi^{2015} = (1.2344 \pm 0.0023(\text{stat.}) \pm 0.0019(\text{syst.})) \times 10^{-4}. \qquad (8.2)$$

Using the published result of R_π^{2015}, a 0.24% precision measurement, the following result was obtained,

$$g_e/g_\mu = 0.9996 \pm 0.0012, \qquad (8.4)$$

translating into a 0.12% precision of the lepton universality test. Using the current estimates for the errors from R_π^{blind} (0.12% precision) would improve the errors of the ratio of the coupling constants to ± 0.0006, thus reaching a 0.06% precision test of LU.

This would make pion decay the most sensitive test of lepton universality, and improve the already stringent constraints on models attempting to explain the hints of possible lepton non-universality seen by the LHCb [71] [72] and BaBar [73] experiments. Essentially, the models must include the property that the mechanism that couples differently to the different generations be greatly enhanced for the third generation [77].

Future PIENU-Xe experiment (Snowmass 2020)

- Access theory level PIENU measurement!
- How?
  - Deep, uniform calorimeter. High acceptance. Reconstruction of pileup. To improve statistics and systematics by a factor of 10.

https://www.snowmass21.org/docs/files/summaries/RF/SNOWMASS21-RF2_RF3-048.pdf

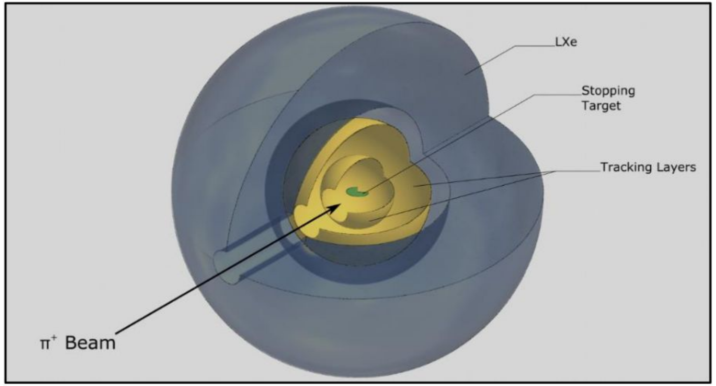


Figure 1. Schematic of a conceptual PIENUXe setup. The beam is stopped in a pixelated, active stopping target surrounded by two thin silicon tracking layers. The entire experiment is enveloped by a liquid xenon electromagnetic calorimeter readout by silicon photo-multipliers.

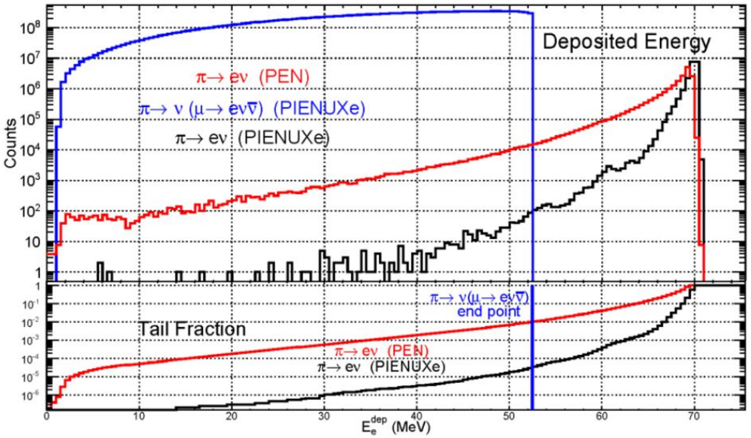


Figure 2. Upper plot: histogram of E_e^{dep}, the π_{e2} positron energy deposited in active components for a proposed 28 X_0 thick spherical LXe concept detector (black), compared with the same for the 12 X_0 pure CsI PEN apparatus (red), along with energy deposition for the background $\pi \to \mu \to e$ decay chain events (blue). Lower plot: comparison of the corresponding "tail" fractions as a function of E_e^{dep}; the LXe concept detector improves on the PEN fraction by two orders of magnitude in the region of interest.