Perspectives on $\pi \rightarrow e\,\nu$ Measurements

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University of British Columbia &TRIUMF

Lepton Flavor

Electron *Thompson, Townsand, Wilson 1896*

Muon *Nedermeyer, Anderson 1937*

Tau *Perl et al. 1974*

$$\Delta = 40 \pm 12 \text{ yrs}$$

Lepton Flavor Universality ***Pontecorvo** 1946*

Conserved Lepton Number ***Konopinski, Mahmoud** 1953*

Conserved Lepton Flavor ***Pontecorvo** 1959*

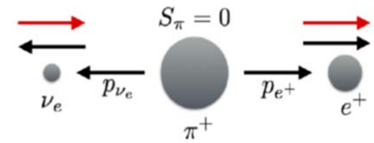
No theory of flavor:

- Three (“identical”) generations; universal interactions
- Huge mass differences between and within the generations; tiny ν mass
- CP violation accommodated
- Symmetry between lepton and quark sectors (GUT, scale?)

Charged Lepton Flavor Universality in π Decay

$$R^{SM}_{e/\mu} = \frac{\Gamma\left(\pi^+ \to e^+\nu(\gamma)\right)}{\Gamma\left(\pi^+ \to \mu^+\nu(\gamma)\right)} = \left(1.23524 \pm 0.00015\right) x10^{-4}$$

(±0.012%)



Marciano/Sirlin → Cirigliano

DB et al. 2111.05338

Possibly the most accurately calculated decay process involving hadrons.

Current Result (PDG): $R^{exp}_{e/\mu} = (1.2327 \pm 0.0023)x10^{-4}$ (±0.19%)

PI E NU

→ Relative weak interaction strength: $\frac{g_e}{g_\mu} = 0.9990 \pm 0.0009$ (±0.09%)

The most accurate test of π-μ universality but experiments are an order of magnitude less precise than theory.

$\pi^+ \rightarrow e^+\nu$ Pre-history/Beginnings

By 1949 $\pi \rightarrow \mu\nu$ was observed, but $\pi \rightarrow \mathrm{e}\nu$ was not seen (< 1/100).

- 1949: Ruderman and Finkelstein PR 76, 1458 (1949)

  If the pion is a pseudoscalar $\mathrm{R}=\dfrac{\pi \rightarrow \mathrm{e}\nu}{\pi \rightarrow \mu\nu} = 10^{-4}$.

But…

- 1955 Lokanathan and Steinberger

  Range telscope at Colunbia Nevis cyclotron; $\mathrm{R}<1.2 \times 10^{-4}$ (90% *c.l.*)

- 1957 Anderson and Lattes

  Magnetic spectrometer at Chicago cyclotron; $R < 1.3\ x\ 10^{-5}$ (90% *c.l.*)

1958 Feynman tried to understand the discrepancy but can't.

Feynman and Gell-Mann PR 109, 193 (1958):

The ratio of the rates of the two processes can be calculated without knowledge of the character of the closed loops. It is $(m_e/m_\mu)^2(1-m_\mu^2/m_\pi^2)^{-2}=13.6\times 10^{-5}$. Experimentally[16] no $\pi\rightarrow e+\nu$ have been found, indicating that the ratio is less than 10^{-5}. This is a very serious discrepancy. The authors have no idea on how it can be resolved.

Referring to another experimental discrepancy with a prediction by Feynman & Gell-Mann:

V. Telegdi says "FG? " **"NFG!"**

(Thx: M. Blecher)

DISCOVERY!

1958 T. Fazzini *et al.* PRL 1, 247 (1958)

Range telscope +NaI crystal at the CERN cyclotron

Observe $\pi \rightarrow e\nu$ events: $R > 4 \times 10^{-5}$

ELECTRON DECAY OF THE PION

T. Fazzini, G. Fidecaro, A. W. Merrison, H. Paul, and A. V. Tollestrup*
CERN, Geneva, Switzerland
(Received September 12, 1958)

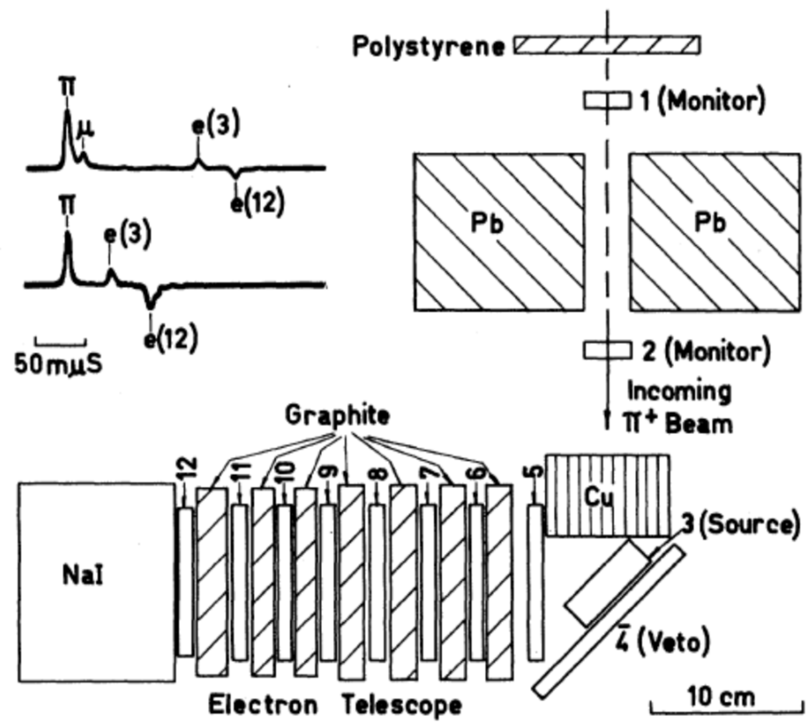


FIG. 1. Experimental layout, and (inset) typical π-μ-e and π-e pulse.

Confirmation

1958 G. Impeduglia *et al*. PRL 1,249 (1958)

H2 Bubble chamber at Columbia

Observe 6 $\pi \to e\nu$ events (no R calculated).

β DECAY OF THE PION*

G. Impeduglia, R. Plano, A. Prodell,
N. Samios, M. Schwartz, and J. Steinberger
Columbia University,
New York, New York
(Received September 15, 1958)

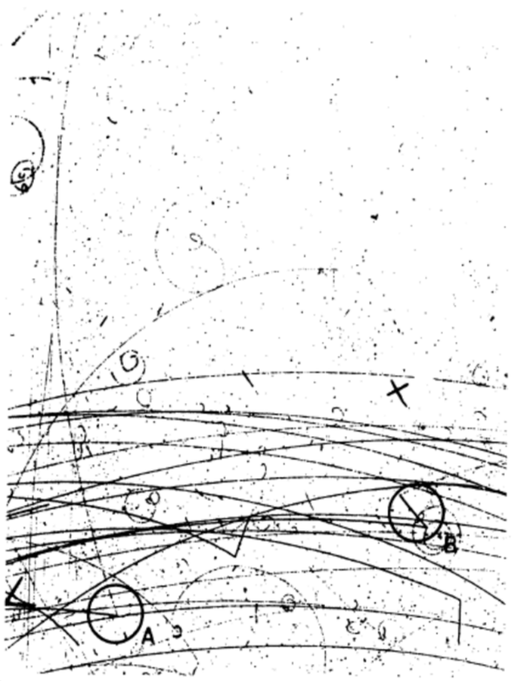


FIG. 1. Reproduction of the π-e decay with longest electron track. The event is marked "A". An example of the more common π-μ-e sequence is labeled "B".

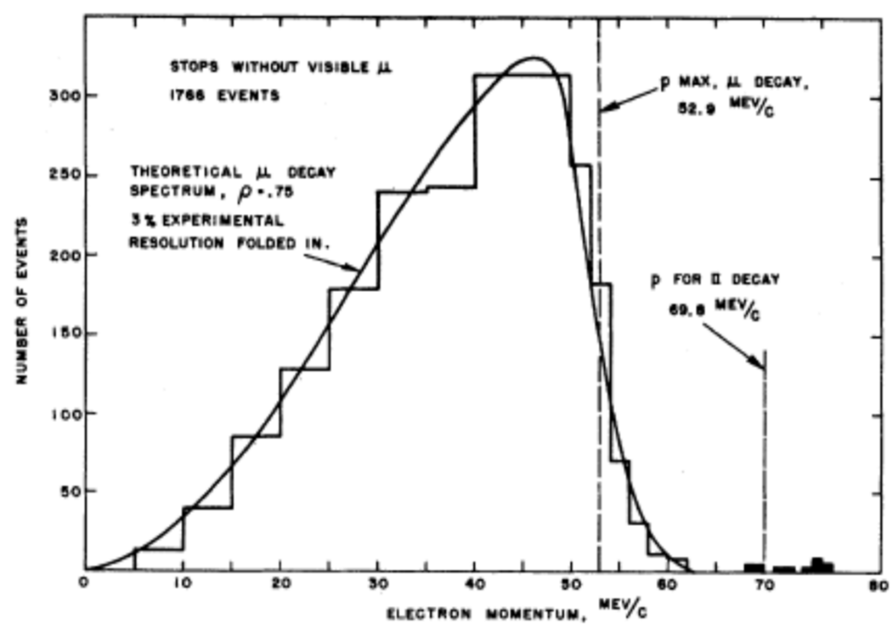


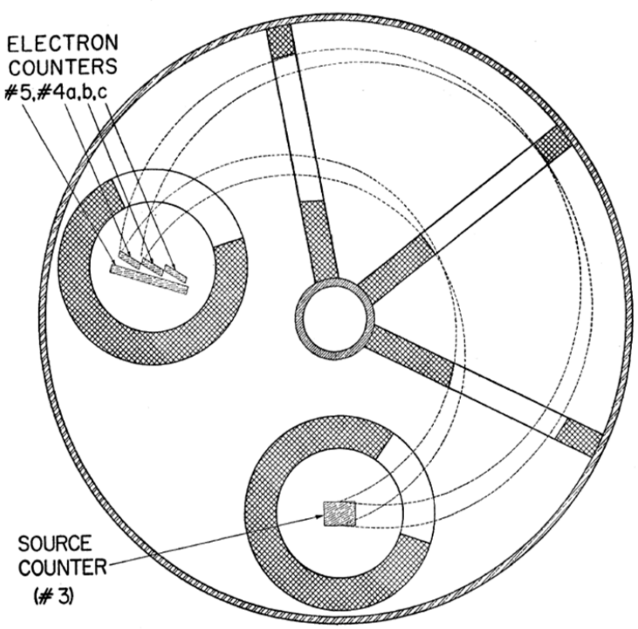
FIG. 2. Histogram of the momenta of the secondaries of all events in which the incoming stopping track apparently decays directly into an electron.

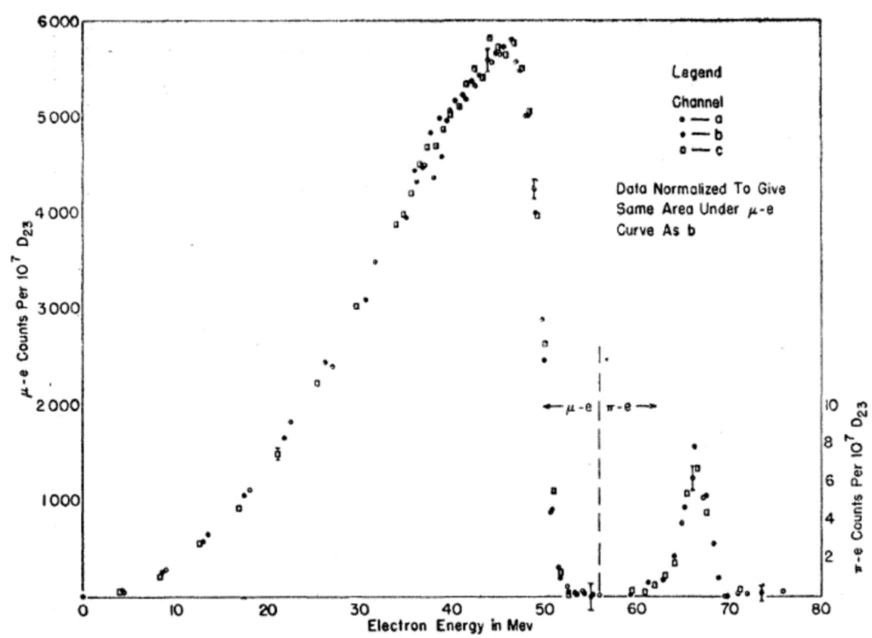
Anderson et al. 1960 (PR 119, 2050 (1960))

Magnetic Spectrometer -- first accurate measurement

1346 events (6% accidentals, 5% π-μ-e contamination)

The branching ratio $(1.21 \pm 0.07) \times 10^{-4}$.





Included a tortured explanation of why the previous experiment missed it.
Anderson: " I stubbed my professional toe on this one."
This was the impetus for developing the blind analysis for E787 $K \to \pi \nu\nu$.

Study of the Decay $\pi \rightarrow e^+\nu$

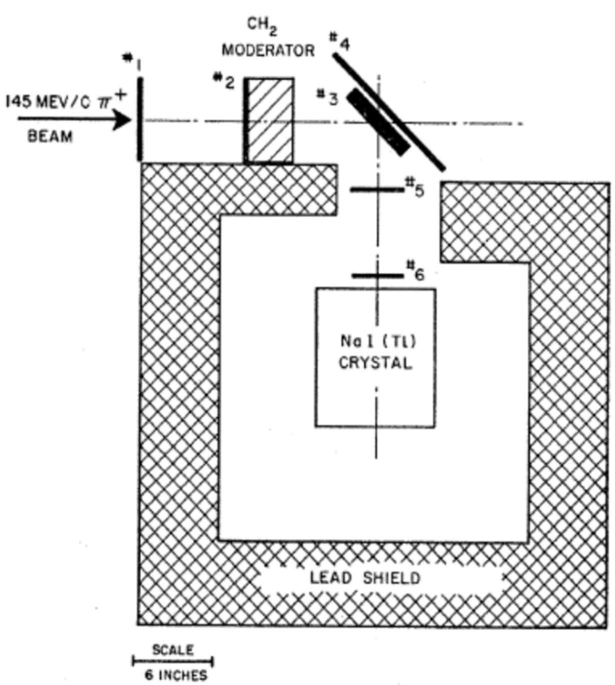
E. Di Capua, R. Garland, L. Pondrom, and A. Strelzoff

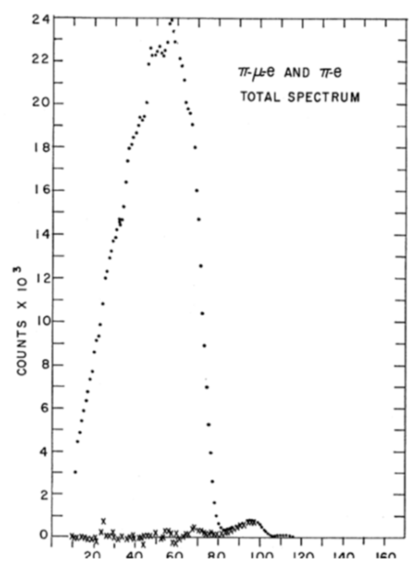
Phys. Rev. 133, B1333 (1964)

Columbia Nevis Lab

Original crystal calorimeter technique to measure the ratio

$$R=\frac{\Gamma(\pi \rightarrow e\nu + \pi \rightarrow e\nu\gamma)}{\Gamma(\pi \rightarrow \mu\nu + \pi \rightarrow \mu\nu\gamma)}$$; allowed direct comparison with theory.





x, $\pi \rightarrow e^+\nu$ after $\mu \rightarrow e$ subtraction

10800 $\pi \rightarrow e$ events

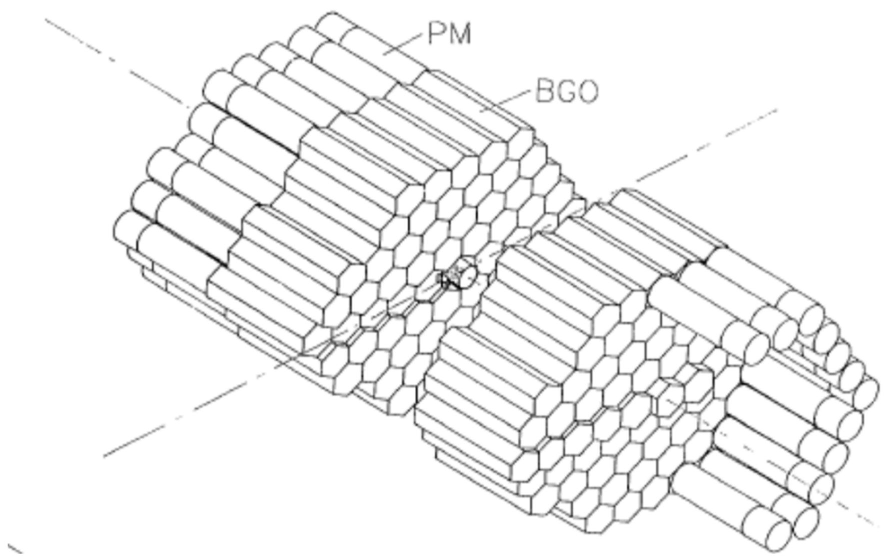
$R = 1.273 \pm 0.028 \times 10^{-4}$

(after correction for τ_π)

Branching ratio for the rare pion decay into positron and neutrino
G. Czapek…B. Hahn *et al.,* Phys. Rev. Lett. 70, 17 (1993)

Bern group at SIN (PSI)

Large Solid angle BGO calorimeter; 1.2 x10^5 events
(1.2346±0.0035±0.0036) x 10^{-4}



D.I. Britton et al. ,*Phys.Rev.D* 49 (1994) 28-39

1.9 x10^5 events

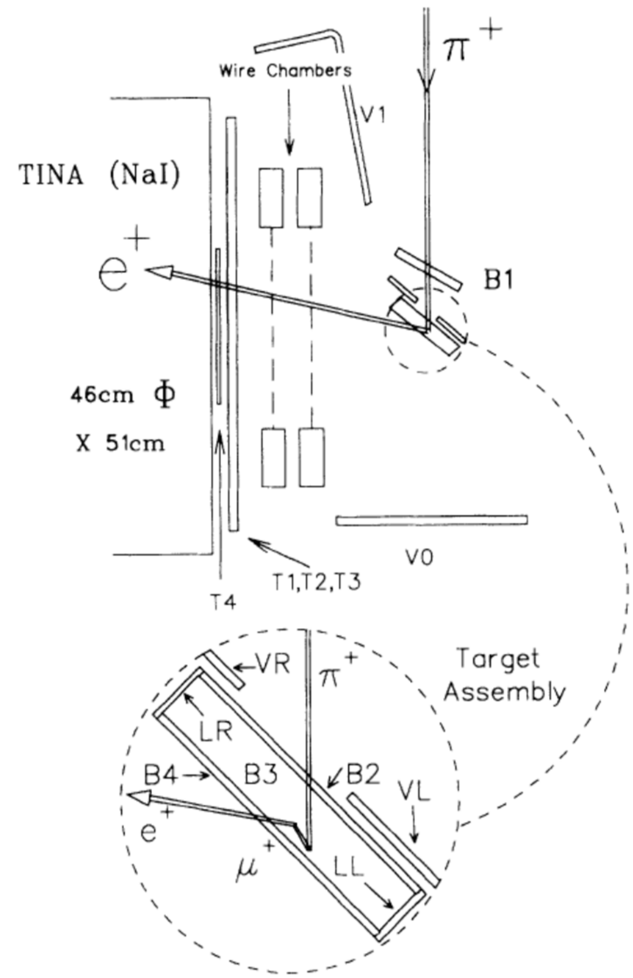
TRIUMF

TINA: 19 X_0 NaI(Tl)

Early 1980s: 1st attempts…

1986 (1.218±0.014) x 10^{-4}

1992 (1.2346±0.0035±0.0036) x 10^{-4}



Pion Beta Decay and $\pi \rightarrow e\nu\gamma_{SD}$

$R^{\pi}_{\mu/e}$ Precision Goal: <0.1%

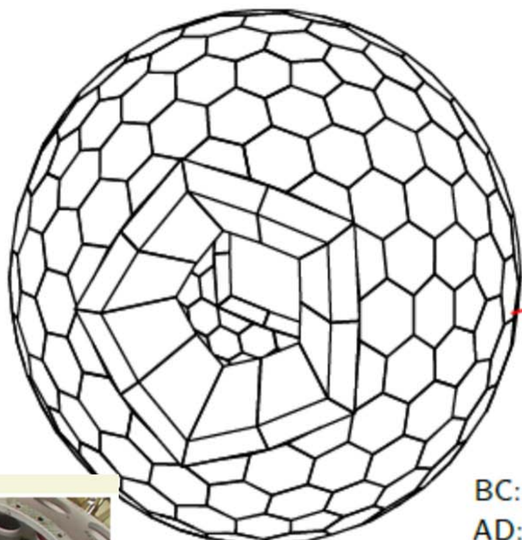
The PEN/PIBETA apparatus

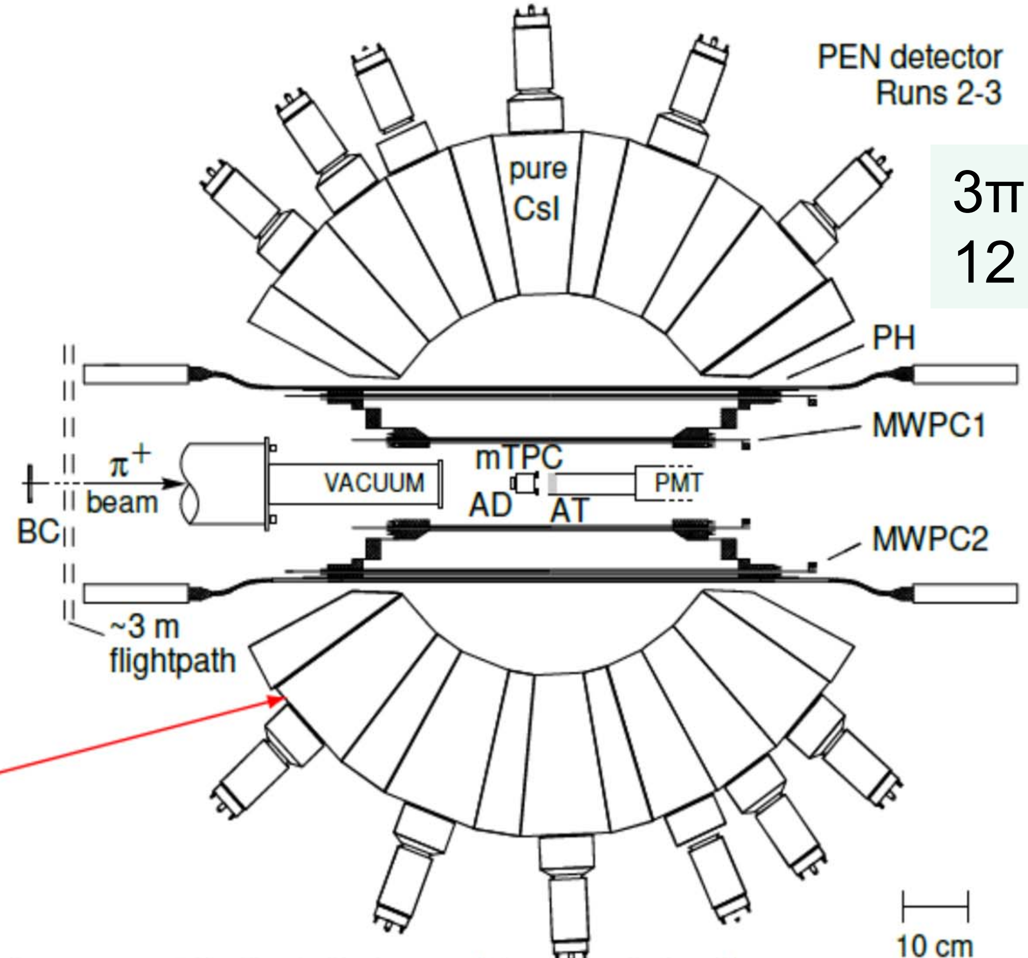
D. Počanić (UVa)

>10^7 events

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

3π
12 X_0

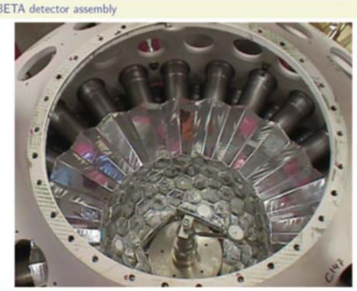




BC: Beam Counter
AD: Active Degrader
AT: Active Target

PH: Plastic Hodoscope (20 stave cylindrical)
MWPC: Multi-Wire Proportional Chamber (cylindrical)
mTPC: mini-Time Projection Chamber

PIBETA detector assembly



TRIUMF

PIENU

$R^{\pi}_{\mu/e}$ Precision Goal: 0.1%

$$\frac{\pi^+ \to e^+ \nu}{\pi^+ \to \mu^+ \nu} \ \& \ \pi^+ \to e/\mu^+ \nu_H$$

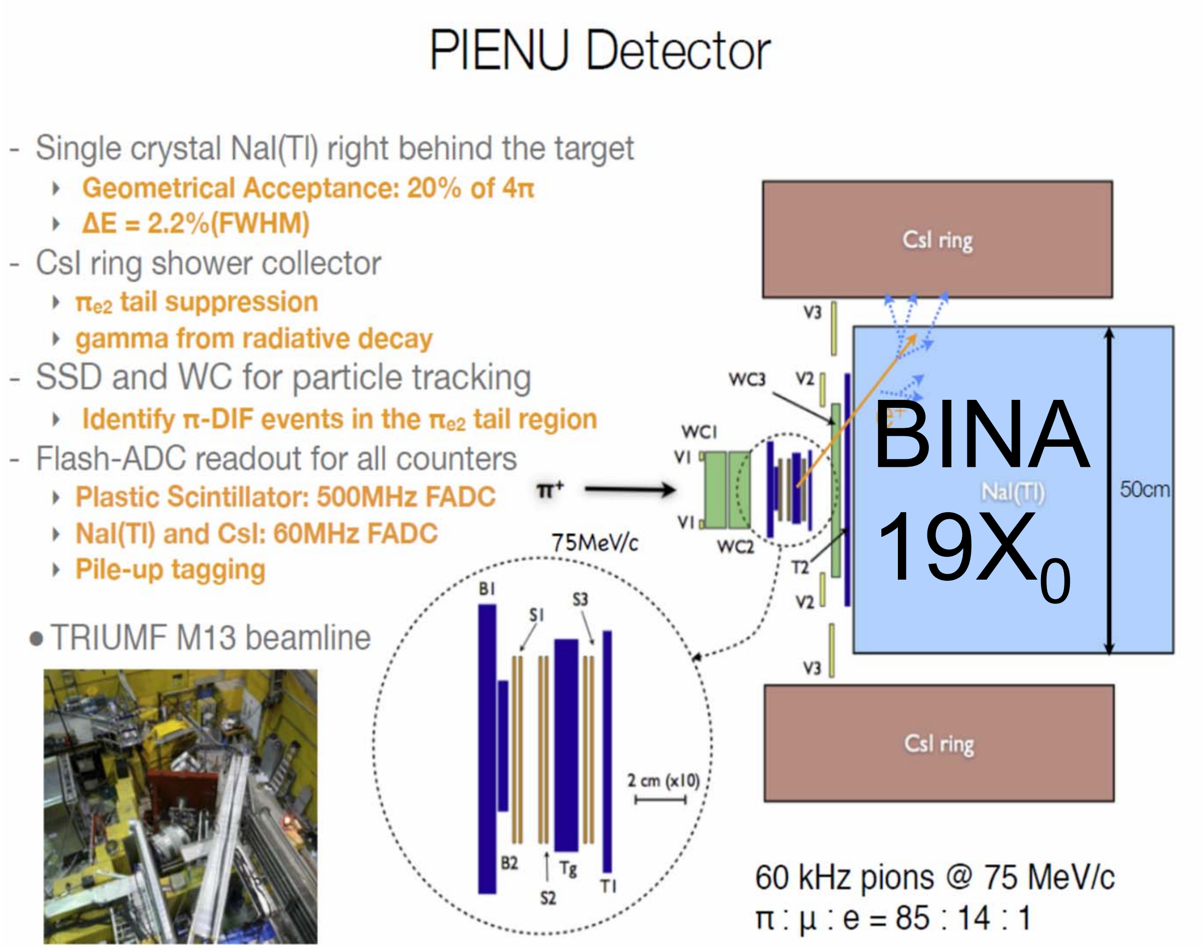
& exotics

BINA+CsI: 10^6 events ($\to 10^7$)

R= $(1.2344 \pm 0.0023 \pm 0.0019) \times 10^{-4}$

A. Aguilar-Arevalo et al., *Phys.Rev.Lett.* 115 (2015) 7, 071801

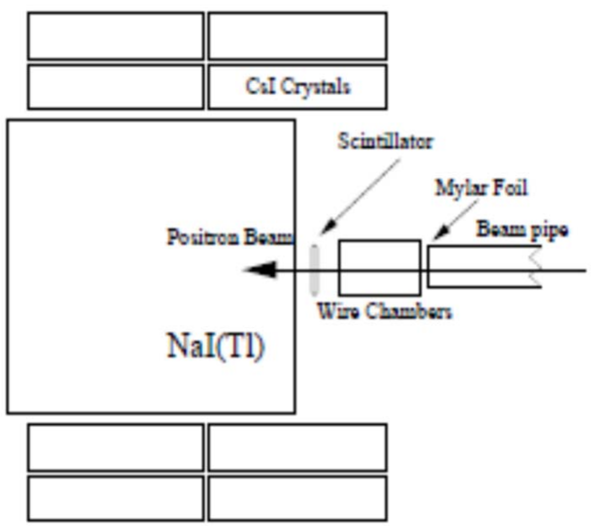
$$\frac{\Delta E}{E} \sim 1\% \text{ enabled } \nu_H \text{ searches}$$

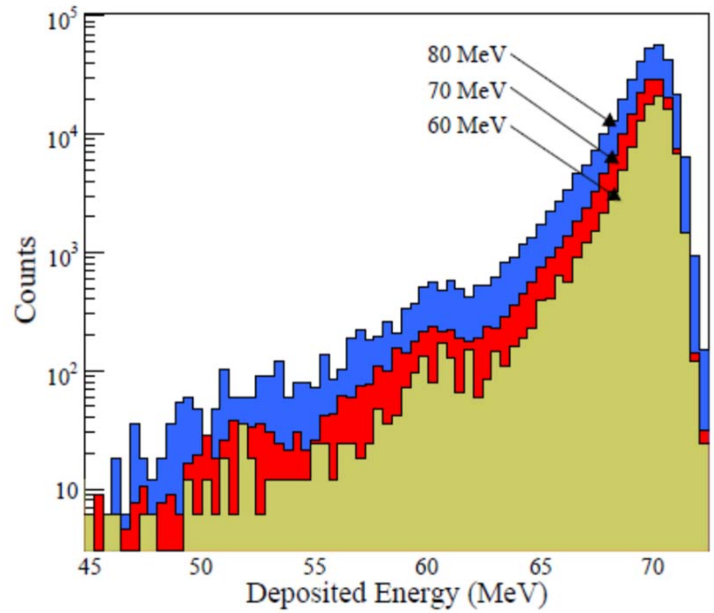


Discovery of Photonuclear Peaks in Lineshape

A. Aguilar-Arevalo et al. *Nucl.Instrum.Meth.A* 621 (2010) 188.

Direct beam measurement of the calorimeter response.



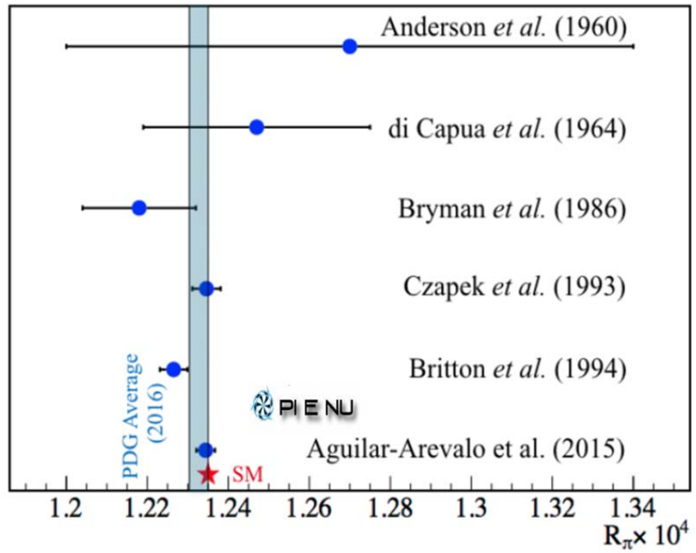


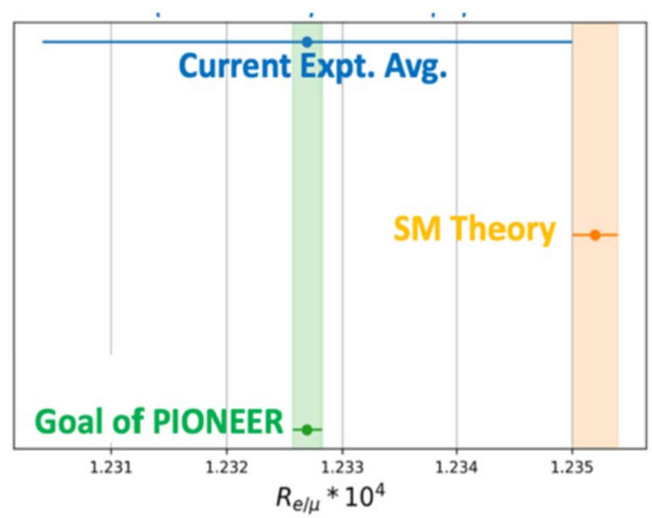
Beam $\frac{\sigma_p}{p} \sim 0.64\%$

$\pi^+ \to e^+\nu$ Experiments -- stopped pions

- Chicago (1960) – ***Magnetic spectrometer***
  1st precise measurement ±6%
- Columbia (1964) ***NaI(Tl) crystal***; ± 2%
- TRIUMF (1986, 1992, 2015 **PIENU**)
  NaI(Tl)/CsI crystals
  ± 0.24% → 0.1%? 10^7 events
- PSI (1993)
  BGO ± 0.4%
  PSI (2010) **PEN**
  CsI >10^7 events → <0.1%?

L. Doria





PDG:

R=1.2327 ± 0.0023 x 10^{-4}

Possible $\pi \rightarrow e\nu$ Experimental Techniques

Decay at rest ratio measuring positrons from $\pi \rightarrow e$ and $\pi \rightarrow \mu \rightarrow e$

Cancellation of particle ID systematics

- Non-magnetic total absorption calorimeter
  - **Includes photons for direct comparison with theory**
  - **Momentum independent efficiency**
  - **Suitable for piBeta measurement**
  - **Fair-poor energy resolution:**
    tail correction; pile-up; reduced sensitivity to ν_H
- Magnetic spectrometer
  - **Excellent energy (momentum) resolution**
    Minimal tail correction; facilitates ν_H searches
  - **Minimal pile-up issues**
  - **Radiative correction required for comparison with theory**
  - **Momentum dependent efficiency & acceptance**
  - **Momentum scale matching required**

Possible π→eν Experimental Techniques

Decay-in-flight momentum + calorimeter measurements (Like NA62 $K^+ \to e^+ \nu$)

- **High rates, acceptance possible**
- **Excellent energy/momentum resolution possible**
- **Coincident electron & gamma measurements**
- **Suitable for piBeta measurement**
- **Requires high precision e/μ particle ID**
- **Possible e/μ efficiency mismatch**
- **μ→e DIF effects; background for π→e**

PIENU and PEN: Lessons for PIONEER:

Decay at rest, non-magnetic spectrometer technique capable of reaching another order of magnitude in precision.

PIENU:

- <1% tail at central direction; 3% for all directions
  Uniformity of tail matters; Minimized tail correction with 19 X_0
- Direct measurement of the tail with e+ beam was **essential**
- High energy resolution enabled sterile ν searches

PEN (PSI/BERN):

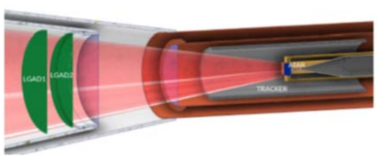
- Large, uniform solid angle allowed lower beam rates and reduced accidentals; larger acceptance for radiative processes

Take-aways:
Maximize solid angle, uniformity, thickness, resolutions

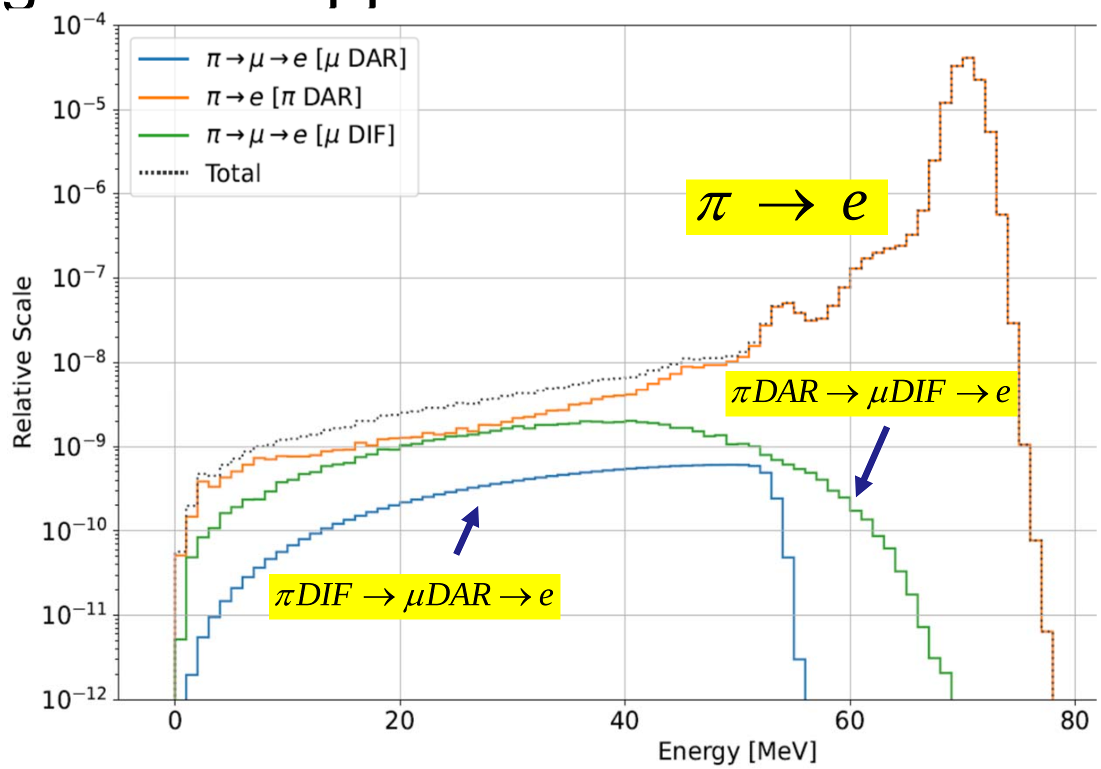
PIONEER Tail Measurement

1. **Indirect Measurement**:

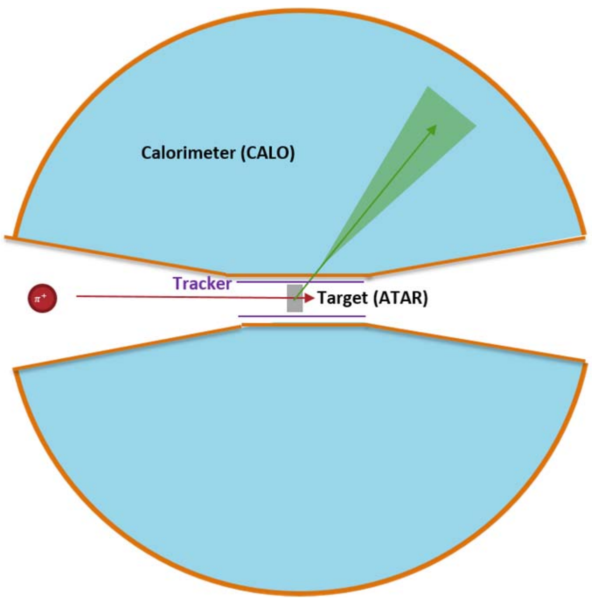
- **Low energy tail measured *in situ using* ATAR suppression of π decay-in-flight and decay-at-rest backgrounds.**
- **Must independently measure (at least) the πDAR-μDIF component.**

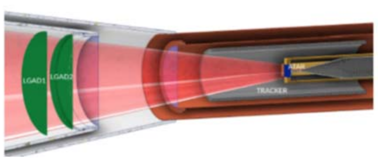


Background Suppression for Tail Measurement



Present PIONEER Concept: **No easy way to inject positron beam for direct lineshape or photonuclear measurements, MC confirmation, or calibration.**





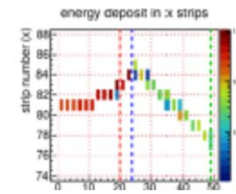
Features

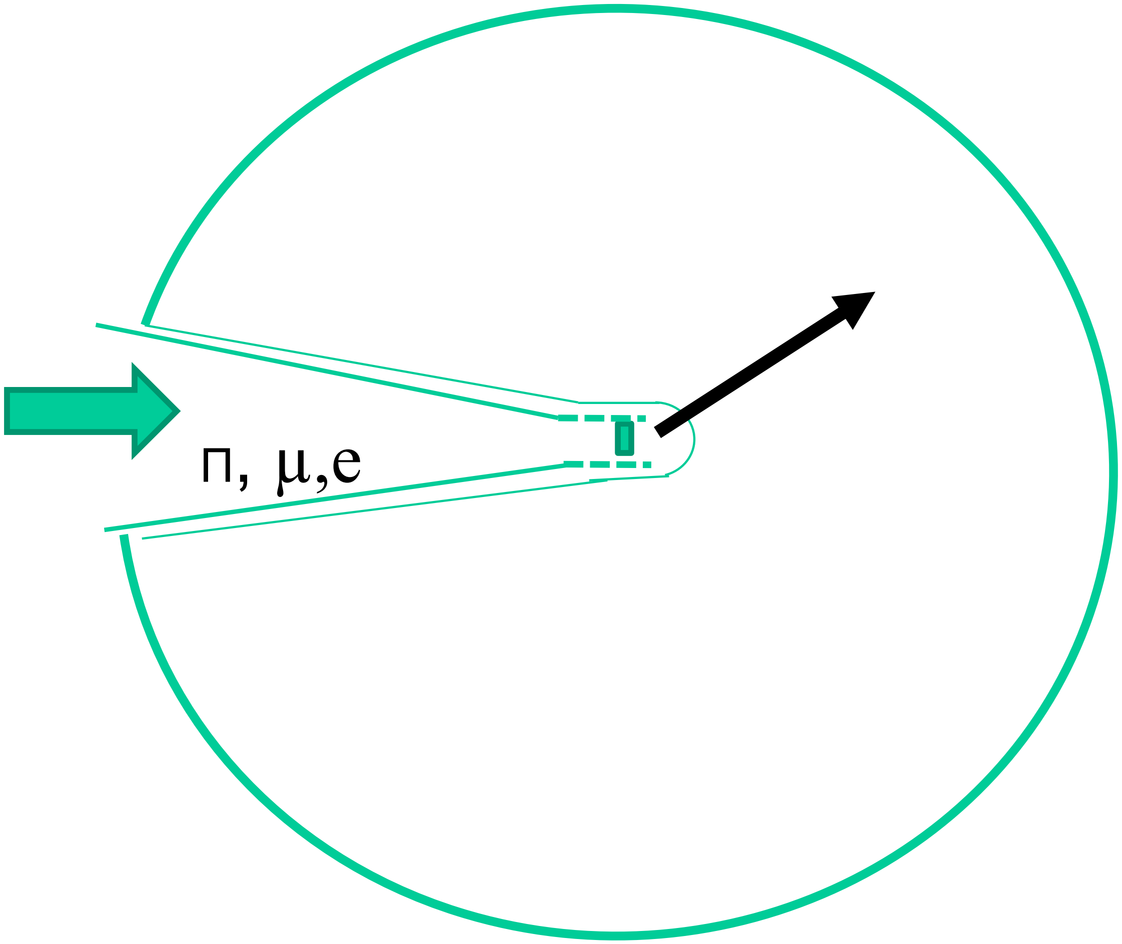
- Some beam muons (<40KHz, <15%) and most beam positrons (4KHz) escape downstream

Drawbacks

- Non-uniformities in tail due to fiducial cuts
- Main acceptance in 90 deg direction
  max. ATAR energy loss; poorest e+ tracking

Alternative "PACMAN" PIONEER Geometry





Features

- Downstream direction has clean acceptance with best ATAR tracking
- Larger unobstructed, uniform solid angle, fiducial region
- **Facilitates positron beam injection for lineshape and calibration measurements**

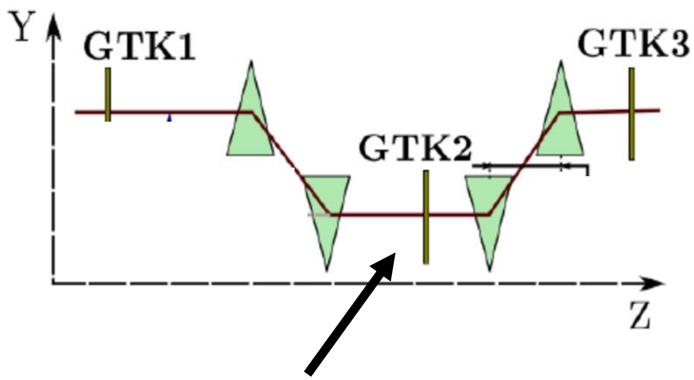
Drawbacks/Challenges

- Beam muons remain in calo area: +10%
- Beam positrons hit calo (~4K Hz) +1%
- All cables, inner region supports from upstream; possible beam constraints

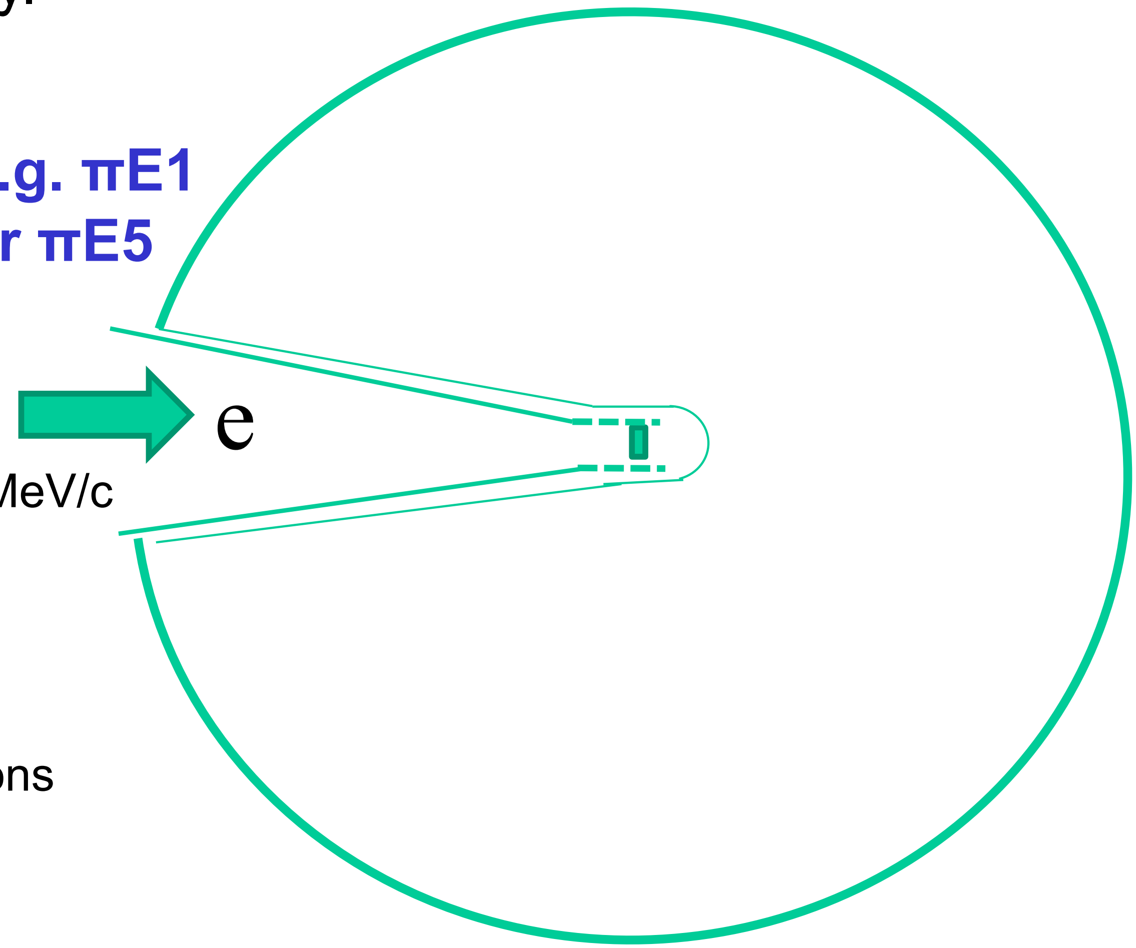
PIONEER Tail Measurement

2. **Direct Measurement**: Low energy tail measured *in situ* with positron beam in the PACMAN geometry.

Momentum analyzed beam e.g. πE1 or Achromat (à la NA62) for πE5



Thin pixel/strip or gas tracking stations



Conclusions:

PIONEER aims at order of magnitude improvements in precision for measurements of $\pi \rightarrow e\nu$ and pion beta decay to provide unique new information on Lepton Flavor Universality and CKM unitarity.

PIONEER extends the technique using stopped low energy pions and a non-magnetic spectrometer with increased thickness calorimetry and an advanced active segmented target to reduce statistical and systematic uncertainties.

- **Several lessons were learned from PIENU and PEN:**
  - **Increase thickness (X_0) of calorimeter to minimize tail correction**
  - **Measure the lineshape tail**
  - **Use large solid angle, fast detectors; minimize pile-up effects**
  - **Optimize the uniformity of the acceptance**