TRIUMF

PIONEER @ PSI
Precision Measurement of Rare Pion Decays

Bob Velghe* on behalf of the PIONEER collaboration

Marseille – June 12, 2023

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University of California, Santa Cruz, University of Washington, University of Chicago, University of British Columbia, TRIUMF, Paul Scherrer Institute, Tsinghua University, Argonne National Laboratory, University of Zurich, CERN, Tecnológico de Monterrey, Stony Brook University, Brookhaven National Laboratory, Johannes Gutenberg University Mainz, Fermilab, Cornell University, University of Virginia, ETH Zurich, University of Kentucky, University of Bern, KEK, University of Tokyo, University of Victoria

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PIONEER is the next generation rare pion decay experiment.

The program will address important questions connected to possible new physics scenarios:

- Lepton Flavor Universality (LFU) ●
- CKM matrix unitarity ●
- Exotic Physics Searches ●

Primary objective:

$$R_{e/\mu} = \frac{\Gamma\left(\pi^+ \to e^+\nu(\gamma)\right)}{\Gamma\left(\pi^+ \to \mu^+\nu(\gamma)\right)} \quad ; \quad \frac{\delta R}{R} \approx 0.01\ \%$$

Sensitive to new physics up to $\mathcal{O}\left(1000\right)$ TeV in some scenarios.

Annu. Rev. Nucl. Part. Sci. 61 (2011) 331

Approved to run at Paul Scherrer Institut (PSI), starting in ≈ 5 years.

An intense detector R&D effort is needed:

- Active "4D" target, with **LGAD** sensors,
- A high resolution **LXe** calorimeter*,
- And much more ...

Still in the early days, exciting physics and growing collaboration, **join us!**

Outline of the Talk

Introduction

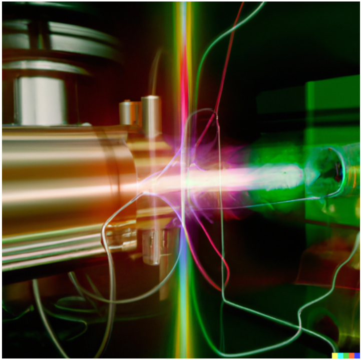
Rare Pion Decays

Past Experiments

PIONEER @ PSI

Summary & Outlook

I asked OpenAI DALL·E 2 for a detector concept ...



... not yet up to the task!

$\pi^{\pm}$ Decays – A Short (and incomplete) History

No. 4047 May 24, 1947 NATURE 695

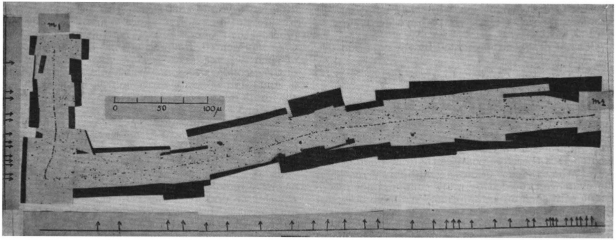


Fig. 1. OBSERVATION BY MRS. I. ROBERTS. PHOTOMICROGRAPH WITH COOKE × 45 'FLUORITE' OBJECTIVE. ILFORD 'NUCLEAR RESEARCH', BORON-LOADED C2 EMULSION. m_1 IS THE PRIMARY AND m_2 THE SECONDARY MESON. THE ARROWS, IN THIS AND THE FOLLOWING PHOTOGRAPHS, INDICATE POINTS WHERE CHANGES IN DIRECTION GREATER THAN 2° OCCUR, AS OBSERVED UNDER THE MICROSCOPE. ALL THE PHOTOGRAPHS ARE COMPLETELY UNRETOUCHED

- 1947, Lattes et al. → Discovery of the charged pion
- 1949, Ruderman & Finkelstein → First prediction of $R_{e/\mu}$

$R_{e/\mu} = \frac{\Gamma(\pi^+ \to e^+ \nu)}{\Gamma(\pi^+ \to \mu^+ \nu)} \approx 10^{-4}$, assuming pseudoscalar π^+ and axial-vector interaction.

- 1957, Anderson & Lattes → Measured $\mathcal{B}(\pi^+ \to e^+ \nu) < 2.1 \times 10^{-5}$

Nat. 159 (1947) 694, Phys Rev. 76 (1949) 1458, Nuovo Cim. 6 (1957) 1356

$\pi^{\pm}$ Decays – A Short (and incomplete) History

Feynman & Gell-Mann, Theory of the Fermi Interaction (1958)

> The ratio of the rates of the two processes can be calculated without knowledge of the character of the closed loops. It is $(m_e/m_\mu)^2(1-m_\mu{}^2/m_\pi{}^2)^{-2}=13.6\times10^{-5}$. 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.

- 1958, Fazzini et al. → $\mathcal{B}(\pi^+ \to e^+\nu) > 4 \times 10^{-5}$
- 1960, Anderson et al. → $\mathcal{B}(\pi^+ \to e^+\nu) = (1.21 \pm 0.07) \times 10^{-4}$

“[...] strong confirmation of the hypothesis of a **universal V-A interaction** of Fermi couplings.”

- 1964, Di Capua et al. → $\mathcal{B}(\pi^+ \to e^+\nu) = (1.247 \pm 0.028) \times 10^{-4}$

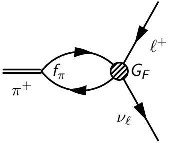
“[...] in agreement with **universal theory for** $(e\nu)$ **and** $(\mu\nu)$ **weak couplings**”

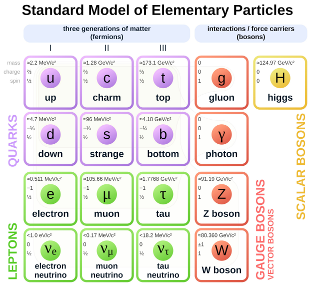
Phys. Rev. 109 (1958) 193, [Phys. Rev. Lett. 1 (1958) 247], [Phys. Rev. 119 (1960) 2050], [Phys. Rev. 133 (1964) B1333]

$\pi^{\pm}$ Decays – Lepton Flavor Universality

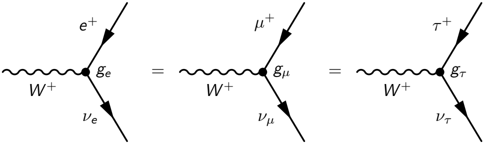
1950s view, Fermi Interaction → Universal G_F

$$\Gamma\left(\pi^+ \to \ell^+ \nu\right) = \frac{G_F^2 f_\pi^2 m_\pi m_\ell^2}{8\pi}\left(1 - \frac{m_\ell^2}{m_\pi^2}\right)^2$$





Standard Model → All leptons couple to the $W^{\pm}$ bosons with the same strength



Bare coupings are identical, $g_e = g_\mu = g_\tau$. **New interaction if disproved!**

Lepton Flavor Universality – Experimental Landscape

So far, observations are consistent with the SM ...
$\rightarrow \pi$, K, τ decays:

$$\frac{g_\mu}{g_e} = 1.0009 \pm 0.0006\ , \quad \frac{g_\tau}{g_\mu} = 1.0013 \pm 0.0013\ , \quad \frac{g_\tau}{g_e} = 1.0022 \pm 0.0013$$

(also tested in Z and W decays)

... but some anomalies are pointing to a possible violation of the lepton flavour universality (arXiv:2204.12175)

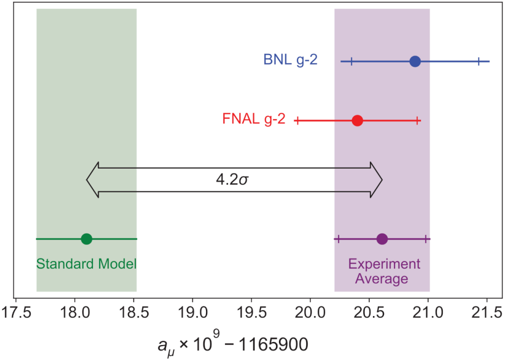
- ~~R_K and R_{K^*} ($b \rightarrow s\mu\mu$)~~ [LHCb arXiv:2212.09153]
- R_D and R_{D^*} ($b \rightarrow c\tau\nu$) [BABAR, Belle, LHCb arXiv:2302.02886]
- $g - 2$ (a_μ) [Phys. Rev. Lett. 126 (2021) 141801]
- CKM first row unitarity ("Cabibbo angle") [Phys. Rev. Lett. 125 (2020) 071802]
- and more.

Fundamental aspect of the Standard Model, more efforts needed to bring clarity!

Annu. Rev. Nucl. Part. Sci. 72 (2022) 69, Phys. Rev. D 105 (2022) 072008, Nat. Phys. 17 (2021) 813, Phys. Rep. 427 (2006) 257

Anomalies (I)

The anomalous magnetic moment of the muon "$(g-2)$" quantifies the departure from the Dirac prediction, it is precisely calculated in the SM.



Phys. Rev. Lett. 126 (2021) 141801

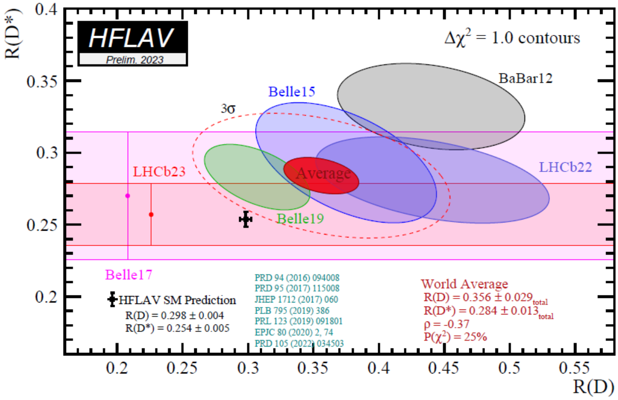
The "Hadronic Vacuum Polarization" term dominates the SM uncertainties.

The lattice-QCD-based prediction is compatible with the SM Nat. 593 (2021) 51

Semileptonic B decays

$$\mathcal{R}(D^0) \equiv \mathcal{B}(B^- \to D^0 \tau^- \bar{\nu}_\tau)/\mathcal{B}(B^- \to D^0 \mu^- \bar{\nu}_\mu)$$

$$\mathcal{R}(D^*) \equiv \mathcal{B}(\bar{B} \to D^* \tau^- \bar{\nu}_\tau)/\mathcal{B}(\bar{B} \to D^* \mu^- \bar{\nu}_\mu)$$



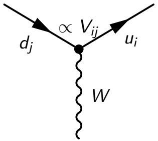
Excess of semitauonic decays over the SM predictions (3.2σ)

CKM Matrix – First Row Unitarity & Cabibbo Angle

Cabibbo–Kobayashi–Maskawa matrix → Fundamental parameters of the SM.

Probability of transition from a flavor j quark to a flavor i quark.

$$\underbrace{\begin{pmatrix} d' \\ s' \\ b' \end{pmatrix}}_{\text{weak interaction basis}} = \underbrace{\begin{pmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{pmatrix}}_{V_{\mathrm{CKM}}} \underbrace{\begin{pmatrix} d \\ s \\ b \end{pmatrix}}_{\text{mass basis}}$$



Focusing on the 1st row, **unitary condition**:

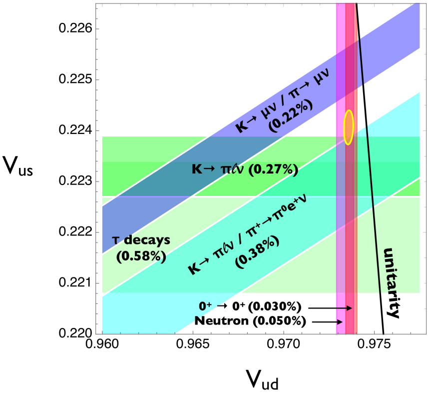
$$|V_{ud}|^2 + |V_{us}|^2 + \cancel{|V_{ub}|^2} = 1 \qquad [V_{ub} \ll V_{ud} \ \& \ V_{us}]$$

Can be written in term of the *Cabibbo* angle: $\cos^2\theta_C + \sin^2\theta_C = 1$, hence the name.

Nicola Cabibbo, Phys. Rev. Lett. 10 (1963) 531

CKM Matrix – First Row Unitarity

V_{us} (and/or V_{us}/V_{ud}) can be extracted from multiple processes:



arXiv:2111.05338

Tension in the measurement: $\Delta_{\mathrm{CKM}} = (-19.5 \pm 5.3) \times 10^{-4} \neq 0$

Connection with LFU violation → Modified $W\ell\nu$ couplings Phys. Rev. Lett. 125 (2020) 111801

PIONEER – Physics Goals

Phase 1: $R_{e/\mu} = \frac{\Gamma\left(\pi^+ \to e^+ \nu(\gamma)\right)}{\Gamma(\pi^+ \to \mu^+ \nu(\gamma))}$

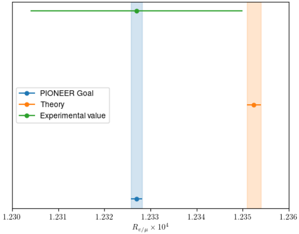
Powerful lepton flavor universality test → Aim for 0.01% rel. uncertainty.

Phase 2: $R_{\pi\beta} = \frac{\Gamma\left(\pi^+ \to \pi^0 e^+ \nu\right)}{\Gamma(\mathrm{total})}$

Theoretically clean extraction of $|V_{ud}|$, CKM unitarity test (V_{us}/V_{ud})
→ Aim for 0.2% rel. uncertainty (3-fold improvement).

Byproduct of the main searches: Exotic searches e.g. heavy neutrinos, dark sector, etc.

Uncertainty on $R_{e/\mu}^{\mathrm{SM}}$ is 0.01%, a **factor** $15\times$ **lower** than the experimental value.



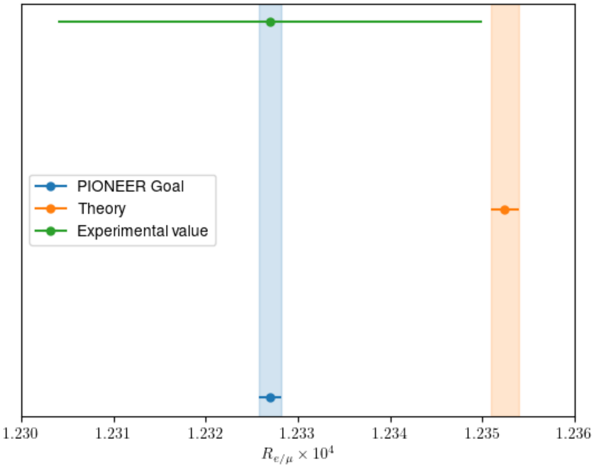
$R_{e/\mu}$	$1.23524(15) \times 10^{-4}$	(SM)
	$1.2327(23) \times 10^{-4}$	(World average)

Best measurement by PIENU, Phys. Rev. Lett. 115 (2015) 071801.
Consistent with the SM prediction $\rightarrow g_e/g_\mu = 1.0010(9)$.

Annu. Rev. Nucl. Part. Sci 72 (2022) 69

Phys. Rev. Lett. 2 (1959) 477, Phys. Rev. D 8 (1973) 3612, Phys. Rev. Lett. 71 (1993) 3629, Phys. Rev. Lett. 99 (2007) 231801

$R_{e/\mu}$ – State of the Art



$R_{\pi\beta}$ – State of the Art

$R_{\pi\beta} = 1.036(6) \times 10^{-8}$ (PIBETA @ PSI) PRL 93, 181803 (2004)

$\lvert V_{ud}\rvert$	$0.97373(31)$	(Superallowed β decays) PRC 102, 045501 (2020)
	$0.9740(28)_{\mathrm{exp}}(1)_{\mathrm{th}}$	($R_{\pi\beta}$) PRL 124, 192002 (2020)

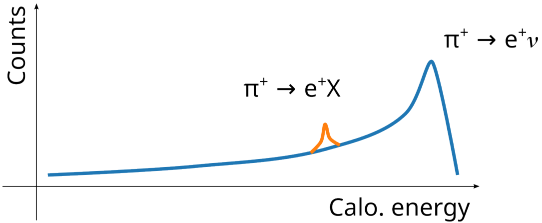
The V_{ud} extraction from $R_{\pi\beta}$ is theoretically clean (0.3%) but not competitive with the superallowed β decays (0.03%, dominated by theoretical correction)

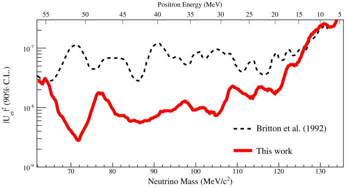
But, $3\times$ improvement in $R_{\pi\beta} \rightarrow \delta 0.2\%$ on $V_{us}/V_{ud} \rightarrow$ competitive!

$$\frac{V_{us}}{V_{ud}} \propto \frac{\Gamma\left(K^+ \to \pi^+ \ell \nu\right)}{\Gamma\left(\pi^+ \to \pi^0 e^+ \nu\right)}$$

Phys. Rev. D 101 (2020) 091301(R)

Peak searches in the energy spectrum → Heavy Neutrinos and other Dark Sector physics e.g. $\pi^+ \to e^+\nu_h$





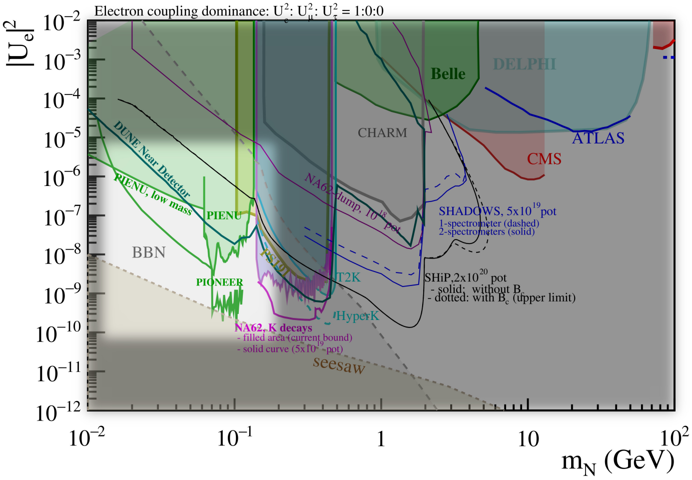
PIENU, Phys. Rev. D 97 (2018) 072012

$$R_{ei} = \frac{\Gamma\left(\pi \to e\nu_i\right)}{\Gamma\left(\pi \to e\nu_e\right)} = \left|U_{ei}\right|^2 \rho_{ei}\ ;\ m\left(\nu_i\right) \neq 0$$

where U_{ei} is a mixing factor and ρ_{ei} a kinematic factor.

Phys. Lett. B 96 (1980) 159

Exotic Searches – State of the Art



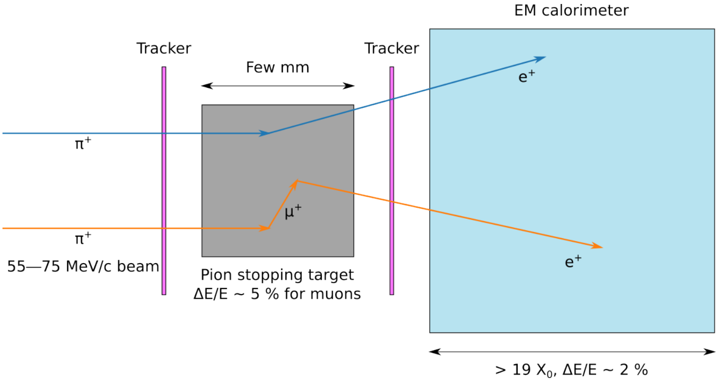
arXiv:2203.08039

PIONEER will improve PIENU limites by an order of magnitude.

$R_{e/\mu}$ Measurement – Basic Principles (I)

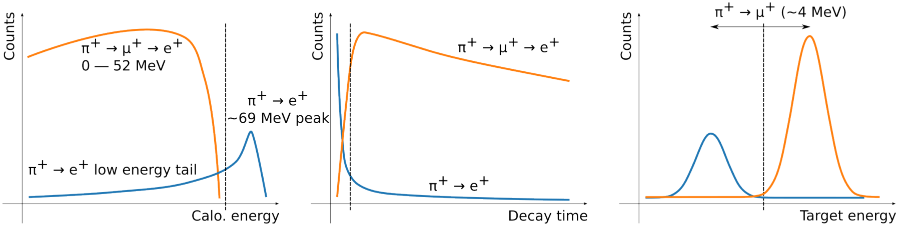
Focus on **positrons** ($\pi \to e\nu$) and ($\pi \to \mu\nu \to e\nu\overline{\nu}$)

“Count and sort” the positrons coming from the stopped pions
→ Many systematics cancel



Trackers allow to tag π-decays-in-flight (πDIF) upstream of the target, detect pile-up, reconstruct π-decay vertices and define the e^+ acceptance

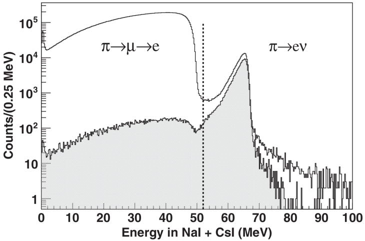
$R_{e/\mu}$ Measurement – Basic Principles (II)

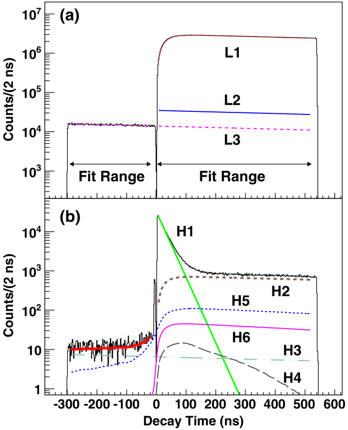


Understanding the $\pi^+ \to e^+\nu$ low-energy tail is key! Calorimeter is imperfect: finite resolution, energy leakages, photonuclear interactions, ...

$R_{e/\mu}$ Extraction – Example from PIENU

Fit two time spectra, one for $E_e^+ < 52$ MeV (L) and one for $E_e^+ > 52$ MeV (H):





PIENU – main contributions:

- L1: $\pi^+ \to \mu^+ \to e^+$,
- L2: πDIF, followed by $\mu^+ \to e^+ \nu \overline{\nu}$,
- H1: $\pi^+ \to e^+ \nu$,
- H2: Energy resolution ($\pi^+ \to \mu^+ \to e^+$), radiative μ decays & pile-up.

$\to$ See PRL 115 (2015) 071801 for more details.

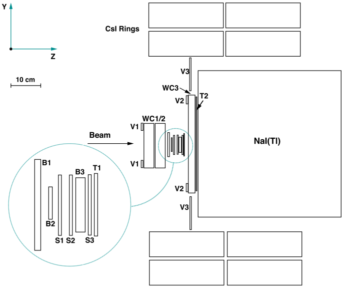
PIENU @ TRIUMF

Installed on the M13 beamline at TRIUMF, 60 kHz pions at 75 MeV/c.

Geometrical acceptance was about 20%.

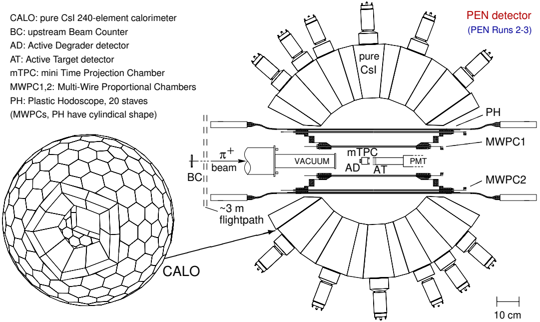
Main elements:

- Target: Plastic scintillator counters (B3),
- Beam π^+ and e^+ tracking: Multiwire proportional chambers (WC) and silicon strip detectors (S),
- EM Calo: Monolithic NaI(Tl) crystal (19 X_0, $\Delta E = 2.2\%$ at 70 MeV) surrounded by CsI crystals,
- B1 and T1 give the pion time and positron time, respectively.



NIMA 791, 38 (2015)

PIBETA detector (1999–2001) designed for the precision measurement of pion beta decay ($\pi^+ \to \pi^0 e^+ \nu$). Repurposed in 2008—2010 (PEN) for $R_{e/\mu}$.



PIBETA: Nucl. Instrum. Meth. A 526 (2004) 300

EM Calo: Segmented CsI crystal (12 X_0, $\Delta E = 12.8\%$ at 62.55 MeV)

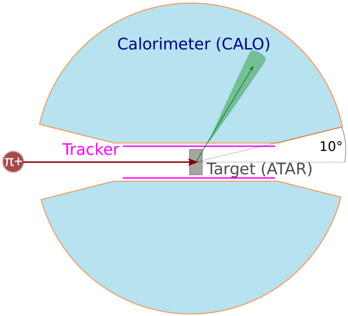
Phys. Rev. Lett. 93 (2004) 181803

New! PIONEER @ PSI

Build upon the legacy of PIENU, PEN, and PIBETA.

Key Improvements:

- Segmented active target (ATAR)
  $\rightarrow$ 4D tracking, LGAD technology,
- 3π, 25 X_0 EM calorimeter (CALO)
  $\rightarrow$ Baseline option: LXe, $\Delta E/E < 2\%$.



Proposal approved by PSI in 2022. arXiv:2203.01981, PSI website

Uncertainties Estimate

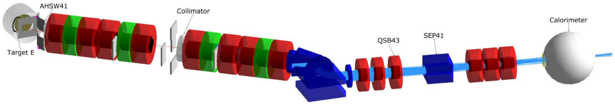
	PIENU	PEN	PIONEER
π^+ stopping rate (Hz)	5×10^4	2×10^4	3×10^5
Calo rad. length (X_0)	19	12	25
Calo $\delta E/E$ (%)	2.2	12.8	1.5%

Table based on 2×10^8 $\pi \to e\nu$ events (3 5-month-runs)

Error Source	PIENU 2015 %	PIONEER Estimate %
Statistics	0.19	0.007
Tail Correction	0.12	<0.01
t_0 Correction	0.05	<0.01
Muon DIF	0.05	0.005
Parameter Fitting	0.05	<0.01
Selection Cuts	0.04	<0.01
Acceptance Correction	0.03	0.003
Total Uncertainty	**0.24**	$\leq$ **0.01**

PIENU: NIM A 791 (2015) 38, PEN: hep-ex/0312017

High intensity pion beam at PSI (πE5).

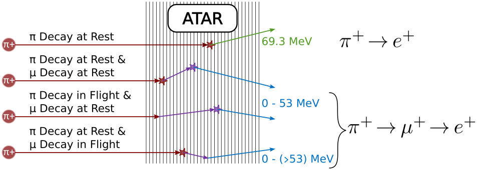


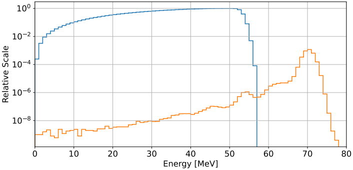
PIONEER PSI proposal

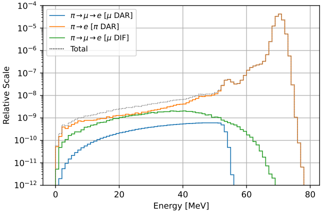
	Phase 1 ($R_{e/\mu}$) 🔴	Phase 2 ($\pi^+ \to \pi^0 e^+ \nu$) 🟢
P	55–70 MeV/c	$\approx$ 85 MeV/c
$\Delta X, \Delta Y$	< 10 mm	< 15 mm
$\delta p/p$	$<$ 2%	$<$ 5%
Pion rate	300 kHz	20 MHz

Separation of π / μ / e in beamline (Wien "$E \times B$" filter).

Stop the 55–70 MeV/c pion beam, active area $\approx 20 \times 20 \times 6$ mm^3





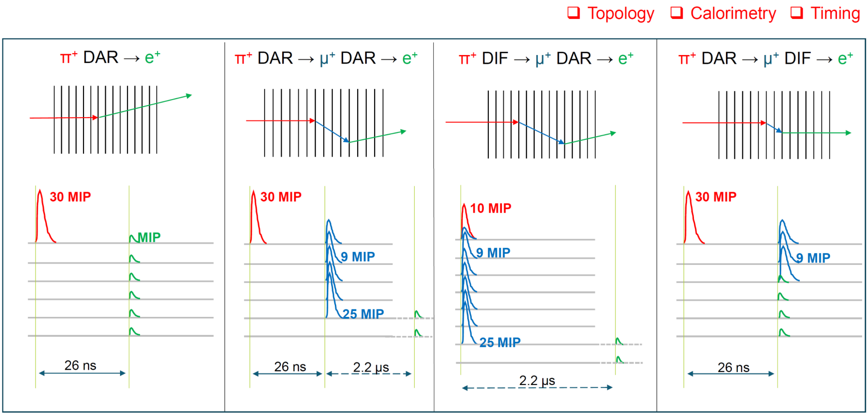


Requirements:

- Large dynamic range,
  (MIPs $\to \pi^+/\mu^+$ decays),
- Good time resolution,
  (pulse separation down to < 1.5 ns),
- Compact,
  (dead material is detrimental),
- Sufficient granularity,
  (detect πs decay-in-flight).

Active Target – $\pi^+ \to \mu^+ \to e^+$ Tagging

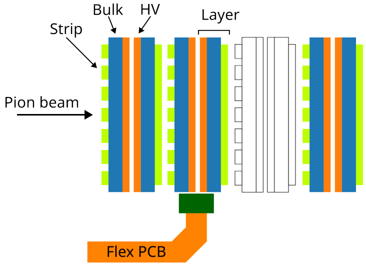
Identify (and suppress) $\pi^+ \to \mu^+ \to e^+$ events → Reveals the tail such that it can be corrected for.



ATAR – Silicon-based Detector

Baseline design is $\approx 50\times$ alternating silicon strips planes (120 µm thick).

- Low Gain Avalanche Detectors (LGAD), silicon with a thin gain layer,
- 100 strips, 2 cm length, with 200 µm pitch (2×2 cm^2 area),
- Sensors are packed in stack of 2 with facing HV side and rotated by 90°.

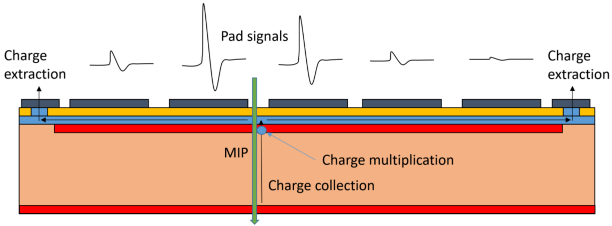


Strips are wire-bonded to a flex PCB, signals are routed to fast analog amplifiers ($d < 5$ cm), digitizers installed outside of the main detector volume.

ATAR – Current R&D Efforts

LGADs are Si detectors with a thin multiplication layer (gain $\times 10 - 50$).

Multiple segmentation techniques have been developed, focus on **AC-LGADs**:



S. Mazza

Readout pads are AC-coupled, no dead regions in the active area. Charge sharing between pixels makes the reconstruction more complex (but allow for fine position reconstruction).

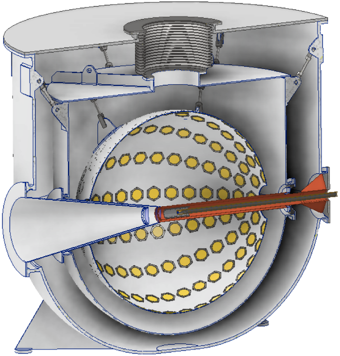
DC-LGADs are another option (no charge sharing), e.g. Trench Insulated LGADs.

PIONEER – EM Calorimeter

The $\pi^+ \to e^+\nu$ low energy tail is the dominant systematic uncertainty.
Fast and high resolution calorimetry is paramount!

Requirements:

- 25 X_0, 3π sr geometric acceptance,
- Aim at $\Delta E/E = 1.5$ %,
- Fast response ($\tau_d < 45$) for pile-up.



Liquid Xenon Calorimeter

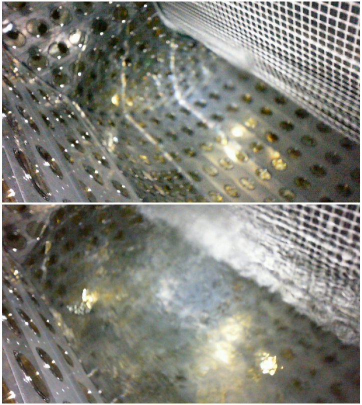
Baseline option! Draw from MEG experience.

LXe strong points:

- Good energy resolution, $\Delta E/E \approx 1.8\%$ (MEG),
- Good time resolution, $\tau_d \approx 45$ ns,
- High light yield, comparable to NaI(Tl), $\lambda = 171$ nm,
- Uniform response and high density, (2.95 g cm^{-3}, $X_0 = 2.77$ cm).

But ...

- Cost (9 t of LXe ...),
- Complex cryogenic systems.



MEG2 LXe calo, Toshiyuki Iwamoto

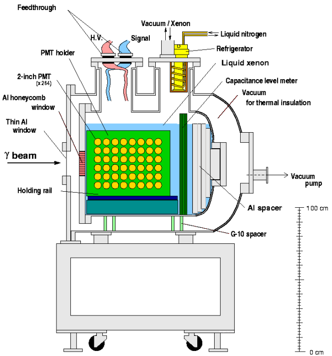
LXe Prototype

Work has started to repurpose the MEG large prototype for beam testing. (70 – 120 L capacity)

Test beam to study

- Pile-up rejection,
- Optical segmentation,
- Reflecting material.

Also useful to validate Geant4 simulation, including NEST package.

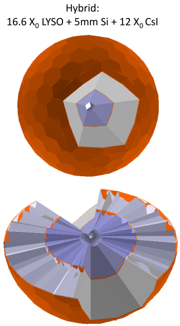


MEG collaboration

A smaller test setup (McGill) will be used to study SiPMs responses.

A LYSO crystal calorimeter is being investigated as an alternative to LXe.

- $\Delta E/E$ not very well know, 4% have been reported,
- Good time resolution, $\tau_d \approx 40$ ns,
- High light yield, comparable to NaI(Tl), $\lambda > 350$ nm,
- High density, (7.1 g cm^{-3}, $X_0 = 1.2$ cm).



Lars Borchert

3×3 array of $2.5 \times 2.5 \times 18$ cm^3 LYSO crystals will be tested at PSI in November.

IEEE Transactions on Nuclear Science 63 (2016) 596

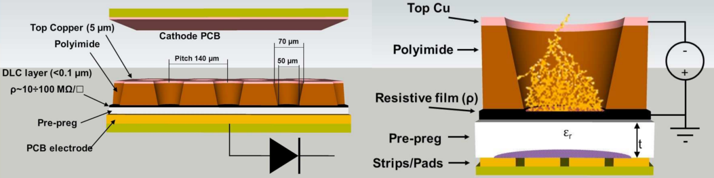
PIONEER – Positron Tracker

Tracker installed between the active target and the calorimeter
→ connect the EM-shower to the pion stopping position.

- Low mass not to degrade the positron energy,
- Position resolution $\mathcal{O}\,(1\ \mathrm{mm})$,
- Time resolution $\mathcal{O}\,(1\ \mathrm{ns})$.

Possible options:

- μ-RWELL (a type of micro-pattern gas detector),
- HV-MAPS (High Voltage Monolithic Active Pixel Sensors),
- Silicon strips.

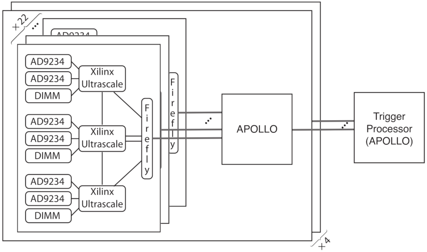


μ-RWELL – JINST 14 (2019) P05014

M. Poli Lener et al. The micro-RWELL detector. Proc. Sci., MPGD2017:019, 2019, I.Perić, P. Fischer et al., NIM A 582 (2007) 876

Based on the Apollo Platform (CMS Pixel Readout), modular ATCA blades.

- Powerful FPGAs,
- 25 Gbps optical inputs,
- Rely on the PCIe protocol for data transfers.



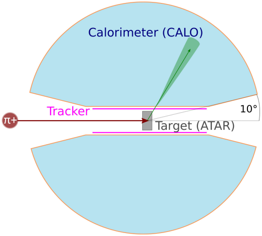
Proposed calorimeter read-out.

The acquisition will run on networked PC's.

PIONEER objectives:

- Lepton flavor violation → $R_{e/\mu} = \frac{\Gamma\left(\pi^+ \to e^+ \nu(\gamma)\right)}{\Gamma(\pi^+ \to \mu^+ \nu(\gamma))}$ at 0.01%
- CKM matrix unitarity → $R_{\pi\beta} = \frac{\Gamma\left(\pi^+ \to \pi^0 e^+ \nu\right)}{\Gamma(\text{total})}$ at 0.2%
- Exotic searches e.g. heavy neutrinos, dark sector, etc.

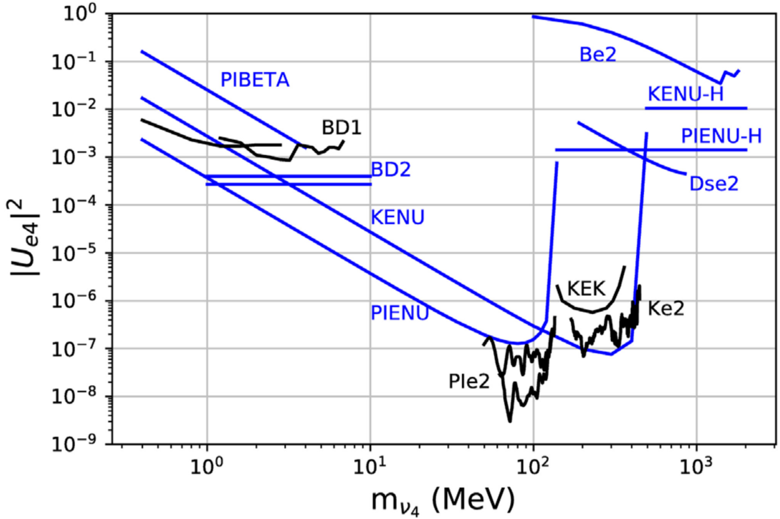
- Approved to run at PSI,
- State-of-the-art technologies:
  - Active target (LGADs),
  - Fast and high resolution calorimetry,
  - Low mass tracker.



Large and diverse group, collaborators from PIENU, PEN, NA62, MEG, $g-2$, leading theorists, ... → **JOIN US!**

Backup Slides

Constrains on Sterile Neutrinos – $R_{e/\mu}$

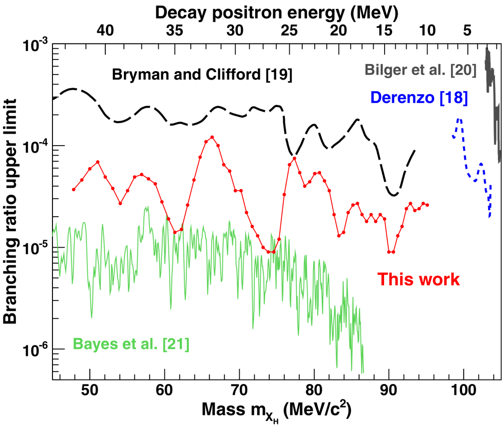


Phys. Rev. D 100, 053006 (2019)

Search for $\mu^+ \to e^+ X_H$ – PIENU

Charged lepton flavour violating decay, X_H is a massive neutral boson.

Peak search in the background-suppressed positron energy spectrum:



Limit on the $\mathcal{BR}$ in neutral boson mass region 47.8 – 95.1 MeV/c^2.

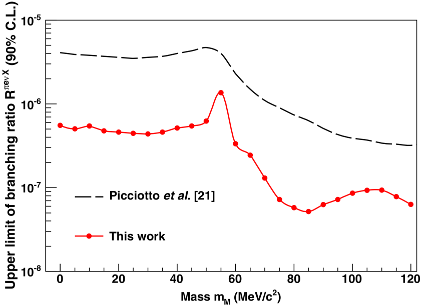
Phys. Rev. D 101, 052014 (2020)

Searches for $\pi^+ \to l^+\nu X$ – PIENU

Search for 3 body π decays where X is a weakly interacting neutral particle.

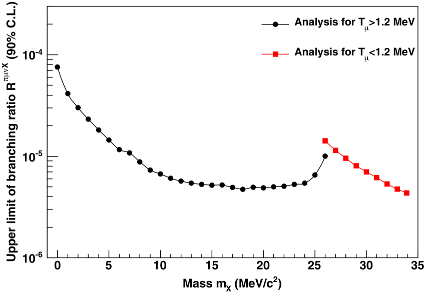
$\pi^+ \to e^+\nu X$

Fit the background-suppressed positron energy spectrum:



$\pi^+ \to \mu^+\nu X$

Two regimes, depending on the muon kinematic energy deposited in the target:



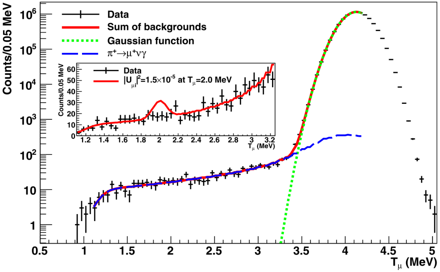
Phys. Rev. D 103, 052006 (2021)

Limit on $|U_{\mu 4}|^2$ – $\pi^+ \to \mu^+ \nu_H$ – PIENU

Two regimes, depending on the muon kinematic energy deposited in the target:

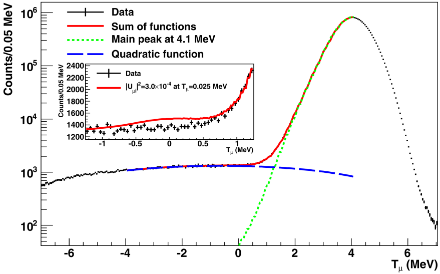
$T_\mu > 1.2$ MeV

Identify a second pulse in the target due to the μ^+ kinematic energy.



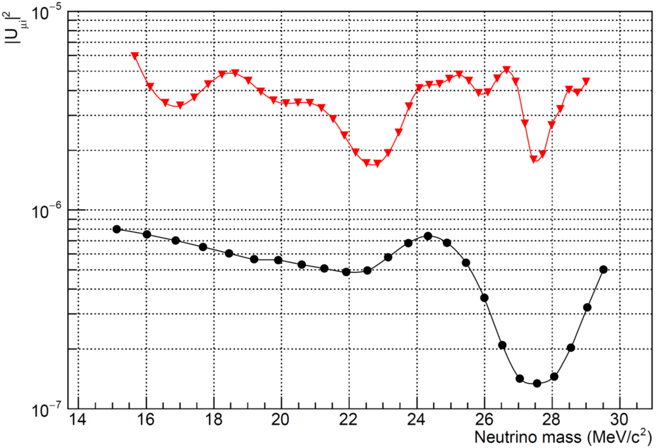
$T_\mu < 1.2$ MeV

Integrate the energy in the target to capture the whole $\pi^+ \to \mu^+ \to e^+$. Subtract the pion and positron kinematic energy.



Phys. Lett. B 798, 134980 (2019)

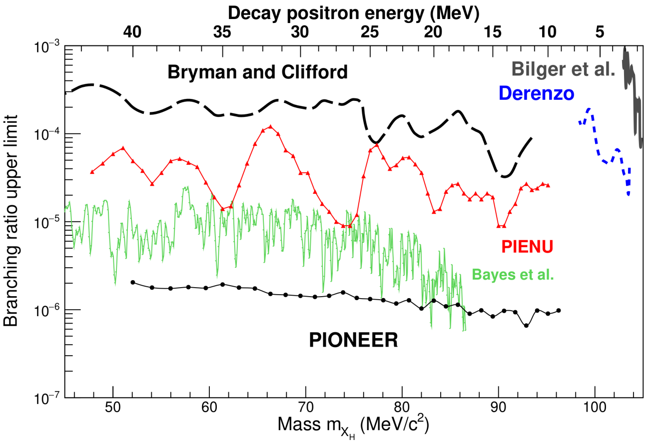
Limit on the Mixing Matrix Element $|U_{\mu 4}|^2$ – $\pi^+ \to \mu^+ \nu_H$



Solid red: PIENU limit, peak search in the μ^+ kinematic energy spectrum (target). Black: PIONEER projections.

Charged lepton flavor violating decay where X_H is a massive boson.

Phys. Rev. Lett. 49, 1549 (1986)



Assumes $\tau_X > 10^{-9}$ s, peak search in the background-suppressed positron energy spectrum.

Phys. Rev. D 97 (2018) 072012