Searching for new physics with low-energy pions

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Flavour physics with pions

STANDARD MODEL FERMIONS

QUARKS

$u$, $c$, $t$ (2.3 MeV/c², 1.275 GeV/c², 173.1 GeV/c²)

$d$, $s$, $b$ (4.8 MeV/c², 95 MeV/c², 4.18 GeV/c²)

LEPTONS

$\nu_e$, $\nu_\mu$, $\nu_\tau$ (< 2.2 eV/c², < 0.17 MeV/c², < 15 MeV/c²)

$e$, $\mu$, $\tau$ (0.511 MeV/c², 105.7 MeV/c², 1.777 GeV/c²)

I, II, III

Three Generations of Matter
Flavour physics with pions
\[ R^\pi = \frac{\pi \rightarrow e\nu(\gamma)}{\pi \rightarrow \mu\nu(\gamma)} \]
\[
R^\pi = \frac{\pi \rightarrow e\nu(\gamma)}{\pi \rightarrow \mu\nu(\gamma)}
\]

one of the most precisely known observable involving quarks in the SM

\[
= (1.23534 \pm 0.00015) \times 10^{-4} \quad (\pm 0.012\%) \quad (\text{SM})
\]

\[
= (1.2327 \pm 0.0023) \times 10^{-4} \quad (\pm 0.187\%) \quad (\text{exp.})
\]

Precision low energy experiment on observables that can be very accurately calculated in the SM: highly sensitive tests of NP
PDG average dominated by the PIENU @ TRIUMF result blind analysis based on partial data set (~10% of full statistics)

**PIONEER: closing the precision gap**

- $R^\pi_{e\mu}$ PDG average
- $R^\pi_{e\mu}$ SM
- $R^\pi_{e\mu}$ PIONEER goal

![](chart.png)
75 years of $R^\pi_{e/\mu}$

$$R^\pi_{e/\mu} = \frac{\Gamma(\pi \to e\nu)}{\Gamma(\pi \to \mu\nu)} \sim \frac{m_e^2}{m_\mu^2} \left( \frac{m^2_\pi - m_e^2}{m^2_\pi - m^2_\mu} \right)^2 \sim 1.3 \times 10^{-4}$$

1940/50’s : Development of V-A structure of weak interaction

1950’s: Many experimental confirmation of the V-A theory
75 years of $R_{e/\mu}^{\pi}$

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Weak Interaction

Neutrinos: left-handed helicity
= directions of spin and motion are opposite
Positron is forced into the wrong helicity
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\textbf{Note on the Decay of the $\pi$-Meson}

M. Ruderman and R. Finkelstein
California Institute of Technology, Pasadena, California
(Received July 25, 1949)

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1950’s: Many experimental confirmation of the V-A theory

1956-1957: Negative experimental results BR<10^{-5}

\[ \text{Weak Interaction} \]

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= directions of spin and motion are opposite  
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<td>Scalar</td>
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<tr>
<td>Mean</td>
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<tr>
<td>P-scalar</td>
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The $\pi \to e\nu$ puzzle...

$$R_{e/\mu}^\pi = \frac{\Gamma(\pi \to e\nu)}{\Gamma(\pi \to \mu\nu)} \sim \frac{m_e^2}{m_\mu^2} \left(\frac{m_\pi^2 - m_e^2}{m_\pi^2 - m_\mu^2}\right)^2 \sim 1.3 \times 10^{-4}$$

Search for the $\beta$-Decay of the Pion. (*)

S. LOKANATHAN and J. STEINBERGER (**)  
Nevis Cyclotron Laboratories, Columbia University  
Department of Physics - New York

$$\frac{\pi \to e}{\pi \to \mu} = f = (-.3 \pm .9) \cdot 10^{-4}\ .$$

The quoted error is the standard deviation and includes the statistical uncertainty as well as an estimate of the error in the subtraction for the inverse photomeson production.

It is therefore not likely that the actual $\pi \to e$ decay fraction is greater than $0.6 \cdot 10^{-4}$ or one in $17,000$. The experiment is approximately twenty

It is not likely that the $\pi \to e$ decay is greater than $0.6 \times 10^{-4}$ is coupled symmetrically to the muon.

The non-occurrence of any kind of electronic decay of the pion is now established...
January 22nd 1957

Letter of W. Pauli to V. Telegdy

2) I still don't know why the reaction \( \pi \rightarrow e + \nu \) doesn't occur. Was anybody some new ideas about it?
The $\pi \rightarrow e\nu$ puzzle ... resolved in 1958

At a small lab that opened 4 years prior on the outskirts of Geneva, Switzerland

CERN circa 1958

~ 40 $\pi \rightarrow e\nu$ events

https://home.cern/fr/news/series/cern70/cern70-first-discovery
Discovery of Pion
1947 Nature 159:694-697

Search for the $\pi^+$ Decay of the Pion
S. Loganathan and J. Steinberger
Columbia University, Department of Physics, New York

Il Nuovo Cimento VI, 6
1958 First experimental observation of the electronic decay at CERN about 65 years ago!

No electronic decay observed
PUZZLE!

“Particle rush”
Development of SM

and “simultaneously” at Columbia University
Phys. Rev. Lett. 1, 249

... and confirmed at Univ. of Chicago
Phys. Rev. Lett. 2, 64

First precise measurement (~5%)

“Precision area”
Search for BSM

TRIUMF by Bryman et al.

TRIUMF by Britton et al.

TRIUMF by Aguilar Arevalo et al.
Phys. Rev. Lett. 115:071801 Most precise measurement (~0.2%)

1955 Supl. Nuovo cimento 2:151

1957 Il Nuovo Cimento VI, 6

PIONEER

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Physics case 1: Testing Lepton Flavor Universality

$$R^\pi = \frac{\pi^+ \to e^+ \nu(\gamma)}{\pi^+ \to \mu^+ \nu(\gamma)}$$

Weak interaction is the same for $e/\mu/\tau$ leptons
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\[ R^{\pi} = \frac{\pi^+ \rightarrow e^+ \nu(\gamma)}{\pi^+ \rightarrow \mu^+ \nu(\gamma)} \]

provides the best test of universality in charged current weak interaction

PDG value, mostly constrained by PIENU (@ TRIUMF) results:

\[ \frac{g_e}{g_\mu} = 0.9989 \pm 0.0009 \ (\pm 0.09\%) \]
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\[ \frac{g_e}{g_\mu} = 0.9989 \pm 0.0009 \quad (\pm 0.09\%) \]

BUT

Several tensions in the flavour sector, potentially hinting toward LFU

- B decays O(10%) deviations from universality.
  Both heavy quarks and leptons involved.
- Muon g-2
  Deviation (4.2 \( \sigma \)) from theory - new physics?
- CKM unitarity tests from \( \beta \) and K decays (2 - 3 \( \sigma \))
  Maybe related to LFUV?

Precise measurements of 1\textsuperscript{st} and 2\textsuperscript{nd} generation decays could be used to distinguish between models explaining 3\textsuperscript{rd} generation effects...
Physics case 2: Sensitivity to new coupling and NP at very high mass scales $\Rightarrow$ possible interpretation of universality violation

$$R_{SM}^\pi = \frac{\pi^+ \to e^+\nu(\gamma)}{\pi^+ \to \mu^+\nu(\gamma)}$$

calculated at the 0.01% level

$$\pi^+ \to e^+\nu$$ is helicity-suppressed (V-A)

$\Rightarrow R^\pi$ is extremely sensitive to presence of new pseudoscalar or scalar couplings

Pseudoscalar interactions

Charged Higgs (non-SM coupling)

$1 - \frac{R_{e/\mu}^{New}}{R_{e/\mu}^{SM}} \sim \frac{\sqrt{2}\pi}{G_\mu} \frac{1}{\Lambda_{eP}^2} \frac{m^2}{m_e(m_d + m_u)} \sim (\frac{1 TeV}{\Lambda_{eP}})^2 \times 10^3$

Marciano...

PIioneer PHASE 1 goal:
0.01 % measurement $\Rightarrow \Lambda_{eP} \sim 3000$ TeV
Physics case 2: Sensitivity to new coupling and NP at very high mass scales

- Sensitive to many other new physics scenarios
  - Leptoquarks
  - Induced scalar currents
  - Hidden sector
  - ...

- Exotic searches performed by the PIENU collaboration:
  e.g. sterile neutrinos which have implications for leptogenesis

• Recent searches performed by the PIENU collaboration:
  PIONEER will improve on all those searches
Physics case 3: Exotics decays. Example of first sterile massive neutrino search

If the heavy neutrino mass is $M_\nu = 60 \sim 130$ MeV/c$^2$

**additional low energy positron peak** can be detected in the $\pi^+ \to e^+$ spectrum


More recent and stronger bounds provided by PIENU :

PRD 97.072012 (2018)

PLB 798 (2019) 134980 [in $\pi \to \mu \nu$ decay]

Comprehensive constraints on sterile neutrinos in the MeV to GeV mass range

D. A. Bryman and R. Shrock, Phys. Rev. D 100, 073011

C. Malbrunot
Physics case 4: Testing CKM unitarity

CKM matrix: mixing of quarks of different generations through weak force

\[ V_{CKM} = \begin{pmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{pmatrix} \]

\[ |V_{ud}|^2 + |V_{us}|^2 + |V_{ub}|^2 = 1 \]

Tensions in the first row CKM unitarity test

\[ 3\sigma \text{ (or even more...)} \]

Since \(|V_{ub}| \ll |V_{us}|\), the third term can be neglected and the first row can be studied in a 2D plane

\~3\sigma tension in the first-row of CKM unitarity test

Often referred to as the Cabbibo Angle Anomaly (or CAA)
Physics case 4: Testing CKM unitarity

PIONEER Phase II goal:
Improve $B(\pi^+ \to \pi^0 e^+\nu)$ precision by $>3 \frac{V_{us}}{V_{ud}} < \pm 0.2\%$

Offers a new complementary constraint in the $V_{us} - V_{ud}$ plane

PIONEER Phase III goal:
Improve $B(\pi^+ \to \pi^0 e^+\nu)$ precision by an order of magnitude

$\pi^+ \to \pi^0 e^+\nu$ is the theoretically cleanest method to obtain $V_{ud}$

PIBETA exp. ($\pm 0.6\%$)

$B(\pi^+ \to \pi^0 e^+\nu) = (1.038 \pm 0.004_{\text{stat}} \pm 0.004_{\text{syst}} \pm 0.002_{\pi e2}) \times 10^{-8}$

Presently not competitive precision for $V_{ud}$ but would be with an order of magnitude improvement (same precision as $\beta$ decays)


[Diagram showing tensions in the first row CKM unitarity test]
Physics case 4: Testing CKM unitarity $V_{ud}$

 Courtesy of Leendert Hayen, talk at ELECTRO2022
Physics case 4: Testing CKM unitarity $V_{ud}$

Current best measurement from PIBETA at PSI

$$R_{\pi\beta}^{Exp} = 1.036(0.006) \times 10^8$$

PIioneer goal is to measure $R_{\pi\beta}$ to 0.06% precision

Ten-fold improvement over current world best

Constraint on $|V_{ud}|$ comparable to super-allowed beta decay
\[
R^\pi = \frac{\pi \rightarrow e^+ \nu(\gamma)}{\pi \rightarrow \mu^+ \nu(\gamma)} : \text{how is it measured?}
\]

\[\mu \rightarrow e^+ \bar{\nu} \]

What \( \pi \) decay to “normally”:
\[B(\pi^+ \rightarrow \mu^+ \nu(\gamma)) = 0.999877 \pm 0.0000004\]

Helicity suppressed decay:
\[B(\pi^+ \rightarrow e^+ \nu(\gamma)) = (1.2327 \pm 0.00023) \times 10^{-4}\]

Pion \( \beta \) decay:
\[B(\pi^+ \rightarrow e^+ \nu e^0) = (1.036 \pm 0.006) \times 10^{-8}\]

Measure precisely \( e^+ \) energy spectrum and \( t_{e^+} - t_{\pi^+} \)

\( \Rightarrow \) different time and energy spectra - discrimination between the two decays

Reminders:
- Pion lifetime: 26 ns
- Muon lifetime: 2197 ns
- Pion mass: 139.6 MeV
- Muon mass: 105.7 MeV
\[ R^\pi = \frac{\pi \rightarrow e\nu(\gamma)}{\pi \rightarrow (\mu\nu(\gamma))} \] : how is it measured?

\[ \mu \rightarrow e\nu\bar{\nu} \]
\[ R^\pi = \frac{\pi \rightarrow e\nu(\gamma)}{\pi \rightarrow \mu\nu(\gamma)} \]: main systematic in the PIENU experiment

Low energy tail buried under the Michel spectrum caused by:

- finite energy resolution of the calorimeter
- photo-nuclear interactions \((^{127}\text{I}(\gamma,n))\)
- shower leakage
- geometrical acceptance
- radiative decays
- etc

Main source of systematics: estimated using data (suppression of \(\pi \rightarrow \mu \rightarrow e\) decays)
Monolithic NaI(Tl) crystal surrounded by 97 pure CsI crystals

Csl crystal

Acceptance Wire Chamber

Beam Wire Chamber

Silicon Trackers

$\pi^+$
PIONEER: building on previous experiences - PIENU and PEN

**PIENU @ TRIUMF**

- Single crystal NaI(Tl) right behind the target
  - Geometrical Acceptance: 20% of $4\pi$
  - $\Delta E = 2.2\%$ (FWHM)
- CsI ring shower collector
  - $\pi_0$ tail suppression
  - Gamma from radiative decay
- SSD and WC for particle tracking
  - Identify $\pi$-DIF events in the $\pi_0$ tail region
- Flash-ADC readout for all counters
  - Plastic Scintillator: 500MHz FADC
  - NaI(Tl) and CsI: 60MHz FADC
  - Pile-up tagging
- TRIUMF M13 beamline

### CsI ring

- Geometrical Acceptance: 19 $X_0$
- NaI slow but excellent resolution (1% $\sigma$ at 70 MeV)
- Slow, small solid angle

**PEN @ PSI**

- $\pi E1$ beamline at PSI
- Stopped $\pi^+$ beam
- Active target counter
- 240 module spherical pure CsI calorimeter
- Central tracking
- Beam tracking
- Digitized waveforms

### The PEN/PIBETA apparatus

- 3 $\pi$ CsI - 12 $X_0$

- Large acceptance
- Calorimeter depth small, large tail
**PIioneer Detector Concept - Best of Both Worlds**

- Building on previous experiences (PIENU and PEN/PIBETA): use of emerging technologies (LXe, LGADs)
- Guiding principles to the design of the experiment

1. **Collect very large datasets** of rare pion decays
   \(2 \times 10^8 \pi \rightarrow e\nu\) during Phase I
   \(\rightarrow 3\pi\) sr calorimeter, intense pion beam at PSI

2. **Tail must be less than 1% of total signal**
   \(\rightarrow\) Shower containment in the calorimeter
   \(\rightarrow 25 X_0\) calorimeter, high energy resolution
   (improve uniformity), reduce pile-up (fast detectors)

3. **Tail must be measured with a precision of 1%**
   \(\rightarrow\) Event identification in the active target
   \(\rightarrow\) highly segmented and fast target (5D detector)
Guiding principles to the design of the experiment:

1. Collect very large datasets of rare pion decays \((2e8 \pi^+ \rightarrow e^+\nu_e\) during Phase I)
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Main Contender

**Liquid Xenon**

- fast response
- dense
- highly homogeneous response
- very bright
- proven high energy resolution
- Detector can be reshaped

**Main question:**

how well can a large homogeneous LXe volume handle pile-up in a high rate environment?

**Target:** ~25 $X_0$, 2% energy resolution at 70 MeV
LXe R&D and PROTOTYPING

LoLX: 2L LXe cryostat at McGill
- Test and characterize photosensor technologies (PDE, response after high irradiation, stability etc)
- Benchmark simulations (G4 with and w/o NEST and optical simulations (Chroma))
- LXe scintillation properties (IR emission, Cerenkov)
- Measure energy resolution at low energies (compare to simulations)
- Data input to NEST at zero-field
- Material test (reflectivity, different coatings, WLS) etc

~100 L cryostat at PSI (former MEG large cryostat)
- Benchmark/Validate simulations at PIONEER energy scales (0-70 MeV) to allow scaling to PIONEER final calorimeter.
- Measure detector lineshape including contribution of photonuclear reactions
- Measure energy resolution

Synergy with developments for nEXO, see talks by David Gallacher & Xiang Li both in (PPD) M2-1
This is what real data could look like

Guiding principles to the design of the experiment:

1. Collect very large datasets of rare pion decays ($2\pi^+ \rightarrow e^+\nu_e$ during Phase I)
2. Tail must be less than 1% of total signal → Shower containment in the calorimeter
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Measuring the tail fraction tag events with minimal bias while maintaining a decent (>1%) efficiency.

Guiding principles to the design of the experiment:

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PIONEER DETECTOR CONCEPT - THE ACTIVE TARGET

Active target ("4D - 5D!") based on low-gain avalanche diode (LGAD) technology

**Requirements**
- Different energy loss of particles through silicon -> needs to accommodate large range of energy scales
- Different time properties: needs to separate signal within 1 ns apart

**Tentative design**
- 48 layers X/Y strips: 120 µm thick
- 100 strips with 200 µm pitch covering 2x2 cm² area
- Sensors are packed in stack of two with facing HV side and rotate by 90 deg
\( \pi^+ \) beam

Target (ATAR) 70 cm

\[ \pi^+ \rightarrow \mu \rightarrow e^+ \]
\[ \sim 0 - 52 \text{ MeV in CALO} \]

\[ \pi^+ \rightarrow e^+ \nu \]
\[ \sim 70 \text{ MeV in CALO} \]

48 120 \( \mu \)m thick silicon layers

ATAR capability to suppress decays in flights and pileup

NOT TO SCALE
NOT TO SCALE

\( \pi^+ \) beam

Tracker

Target (ATAR)

70 cm

2 cm

48 120 \( \mu \)m thick silicon layers

\( \pi^+ \rightarrow \mu \rightarrow e^+ \)

\( e^+ \rightarrow 0-52 \text{ MeV in CALO} \)

\( \pi^+ 

\( e^+ \rightarrow e^+\nu \)

\( \sim 70 \text{ MeV in CALO} \)

ATAR capability to suppress decays in flights and pileup
Conclusions and opportunities!

- High precision rare decays provide very promising windows into NP

- PIONEER: new experiment addressing emerging SM anomalies in flavor physics

- Staged goals
  - $R^\tau$ at 0.01% matching theoretical precision
  - Pion $\beta$ decay at 0.03% (in two steps) matching super-allowed $\beta$ decay experiments

- Time-scale: 10-15 years

- Approved to run at PSI. Expected start of data taking ~ 5 years timescale.

- Supported by an international collaboration: experts from previous PIENU and PEN experiments as well as a wide range of collaborators from NA62, MEG, muon g-2, ATLAS, PSI scientists and theorists: JOIN US!

Snowmass PIONEER white paper: https://arxiv.org/abs/2203.05505
The PIONEER Collaboration

https://pioneer.triumf.ca

PIONEER first collaboration meeting Oct 2023, CENPA University of Washington