Precision Measurement of Rare and Ultra-Rare Pion decays, next-generation experiment PIONEER.

$$\pi^+ \to e^+ \nu_e$$
$$\pi^+ \to \pi^0 e^+ \nu_e$$

Seminar plan

1. Collaboration
2. Motivation
3. Intention
4. Previous experiments
5. Setup
6. Conclusion

Proposal → https://inspirehep.net/literature/2046439

The PIONEER collaboration consists of participants from PIENU, PEN / PiBeta, MEG($\mu^+ \rightarrow e^+ \gamma$) and g − 2

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The collaboration is still developing and welcomes new members.

LFUV have been accumulated in recent years

B anomalies

In semi-leptonic bottom quark decays ($b \to s\, \ell^+ \ell^-$ and $b \to c\tau\,\nu$).
BaBar, LHCb and Belle have reported 2-3σ deviations from the SM.
$R(K^{(*)}) = Br[B \to K^{(*)} \mu^+ \mu^-] / Br[B \to K^{(*)} e^+ e^-]$ (3.1σ LHCb)
$R(D^{(*)}) = Br[B \to D^{(*)} \tau \nu_\tau] / Br[B \to D^{(*)} (e,\mu)\nu_e]$ (3.4/3.5σ BaBar / Belle)
Global analyses of the $b \to s\, \ell^+ \ell^-$ data deviate from the SM by 7σ (arXiv:2104.08921 [hep-ph])

anomalous magnetic moments $(g-2)_\mu$

$\alpha_\mu = 116\,591\,810(43) \times 10^{-11}$ SM, 2020
$\alpha_\mu = 116\,592\,061(41) \times 10^{-11}$ 4.2σ deviation (BNL 2006), FNAL 2021)

Cabibbo angle anomaly

3σ deficit in unitarity of the Cabibbo-Kobayashi-Maskawa matrix $|V_{ud}|^2 + |V_{us}|^2 + |V_{ub}|^2 = 0.9985(5)$.

Non-resonant production of di-leptons

4σ excess in $pp \to e^+ e^-$ with an invariant mass > 1.8 TeV (CMS 2021)
ATLAS and HERA found more di-electrons than expected.

Oliver Fischer,... arXiv:2109.06065 (hep-ph), “Unveiling Hidden Physics at the LHC”

$\boldsymbol{\pi^+ \to \mu^+}$(4.2MeV) $\boldsymbol{+ \nu_\mu}$
$\boldsymbol{\pi^+ \to e^+}$(69.3 MeV) $\boldsymbol{+ \nu_e}$

Low-energy measurements can be sensitive tests of new physics (NP).
$\boldsymbol{R_{e/\mu} = \Gamma(\pi^+ \to e^+ \nu)/\Gamma(\pi^+ \to \mu^+ \nu)}$ is the most precisely calculated observable involving quarks.

The uncertainty of the SM calculation for $R_{e/\mu}$ is 1.2×10^{-4}.
0.01% measurement of $R_{e/\mu}$ can reviel NP at PeV scale and even several PeV in specific models such as leptoquarks.
The ratio is sensitive to the scalar, pseudoscalar couplings absent from the SM.
For example if there are charged Higgs which gives rise to pseudoscalar operator.

In Ref. **arXiv:1711.10391(hep-ph)** some NP contributions to pion – electron decay are computed.

However, while the uncertainty of the SM calculation for $R_{e/\mu}$ is very small,
the current experimental world average is about a factor 15 less precise, limiting the NP reach.

CKM unitarity and pion beta decay

$\boldsymbol{\pi^+ \rightarrow \pi^0 e^+ \nu_e}$

Precision measurements of beta decays of neutrons, nuclei, and mesons provide determinations of the elements $|V_{ud}|$ and $|V_{us}|$ of the CKM quark-mixing matrix.
PIONEER experiment will also be suited for a high-precision measurement of pion beta decay.
Determination of $|V_{ud}|$ from pion beta decay is very clean theoretically,
because is free from nuclear-structure uncertainties.

Current value $\boldsymbol{|V_{ud}| = 0.9739(28)_{exp}\,(1)_{th}}$ come from the PiBeta experiment at PSI:

$$\mathbf{Br(\pi^+ \rightarrow \pi^0 e^+ \nu) = 1.036 \pm 0.004(stat) \pm 0.004(syst) \pm 0.002(\pi \rightarrow e\nu) \times 10^{-8}}$$

From super-allowed nuclear beta decays (14 experimens): $\boldsymbol{|V_{ud}| = 0.97370(14)}$.

Exotic decays, direct search for NP.

$\boldsymbol{\pi^+ \rightarrow e^+ \nu_H}$

Low ν_H mass will give a monochromatic peak at the low energies of the outgoing positron.
If the ν_H mass is greater than the kinematic limit for emission,
there will be an violation of e – μ universality.

$\boldsymbol{\pi^+ \rightarrow e^+ \nu_e X}$,

X - an axion-like-particle that mixes with the neutral pion,
or X - a light gauge boson coupling to differences of lepton numbers.

$\boldsymbol{\pi^+ \rightarrow \ell^+ XY}$, where X/Y are light dark sector particles.

$\boldsymbol{\mu \rightarrow eX}$**,** where X is a neutral boson (an axion or a Majoron).

Pion to muon decays.

$\boldsymbol{\pi^+ \rightarrow \mu^+ \nu_H}$

$\boldsymbol{\pi^+ \rightarrow \mu^+ \nu_\mu X}$

$\boldsymbol{\pi^+ \rightarrow \mu^+ \nu_\mu \nu \bar{\nu}}$

PIONEER is proposed 3 phases measurements (I, II, III)
and based on the experience of the PIENU, PEN, PiBeta and MEG experiments

I $R_{e/\mu} = \Gamma(\pi^+ \rightarrow e^+ \nu_e) / \Gamma(\pi^+ \rightarrow \mu^+ \nu_\mu)$ measurement with ~ 10^{-4} precision,
2×10^8 $\pi^+ \rightarrow e^+ \nu$ events
$E(\pi^+) = 10(0.2)$ MeV flux 0.3 MHz
2.5 months.

II pion beta decay $\pi^+ \rightarrow \pi^0 e^+ \nu_e$ study with 2×10^{-3} precision
3×10^5 $\pi^+ \rightarrow \pi^0 e^+ \nu$ events
$E(\pi^+) = 22(1)$ MeV, flux 20 MHz
3 weeks.

III pion beta decay $\pi^+ \rightarrow \pi^0 e^+ \nu_e$ study with 5×10^{-4} precision,
4×10^6 $\pi^+ \rightarrow \pi^0 e^+ \nu$ events
$E(\pi^+) = 22(1)$ MeV, flux 20 MHz
7 months, 4 years of (5 months/yr)

	EXPERIMENT	THEORY
$\pi^+ \rightarrow \mu^+(4.12\ \mathrm{MeV}) + \nu_\mu$;	**0.9999**	**0.9999**
$\pi^+ \rightarrow e^+(69.3\ \mathrm{MeV}) + \nu_e$;	**$1.2327(23) \times 10^{-4}$ (PDG)**	**$1.23524(15) \times 10^{-4}$**
$\pi^+ \rightarrow \pi^0 + e^+ + \nu_e$;	**$1.036(6\ ) \times 10^{-8}$ (PiBeta, PSI)**	**$\rightarrow\ \lvert V_{ud} \rvert = 0.9739(28)(1)$**
Nuclear beta decays (14 experimens)		**$\rightarrow\ \lvert V_{ud} \rvert = 0.97370(14)$**

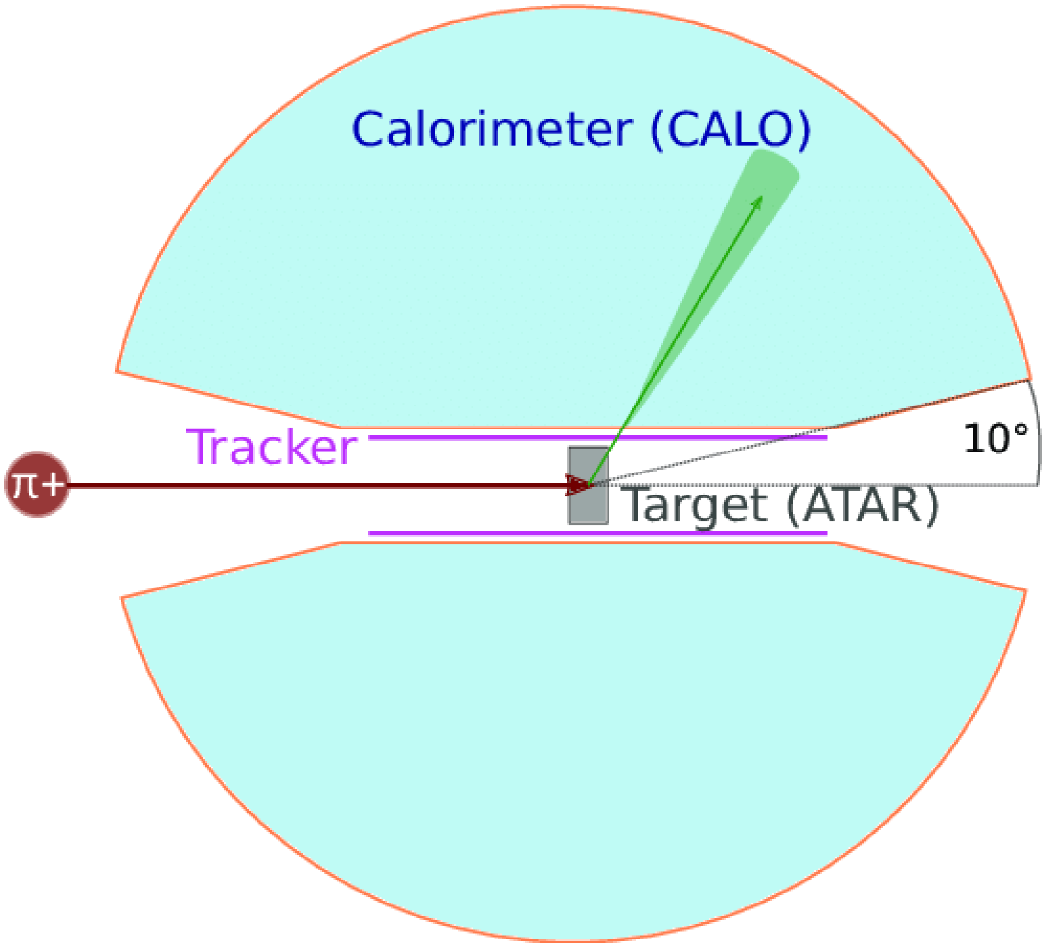
Britton...(TRIUMF, 1992) $\rightarrow$ $R_{e/\mu} = [1.2265 \pm 0.0034(\mathrm{stat}) \pm 0.0044(\mathrm{sys})] \times 10^{-4}$

PIENU(TRIUMF, 2015) $\rightarrow$ $R_{e/\mu} = (1.2344 \pm 0.0023(\mathrm{stat}) \pm 0.0019(\mathrm{syst})) \times 10^{-4}$ $\rightarrow$ $\mathrm{err}(R_{e/\mu}) = 1 \times 10^{-3}$

PiBeta(PSI, 2014) $\rightarrow$ $R_{e/\mu} = (1.2366 \pm 0.0064) \times 10^{-4}$

PEN(PSI) $\rightarrow$ $\mathrm{err}(R_{e/\mu}) = 2 \times 10^{-3}$ $\rightarrow$ 2024

Experimental Setup



ATAR - 50 planes of silicon sensors
20×20×6 mm,
5000 readout channels,
0.1 ns time resolution,
10 % energy resolution

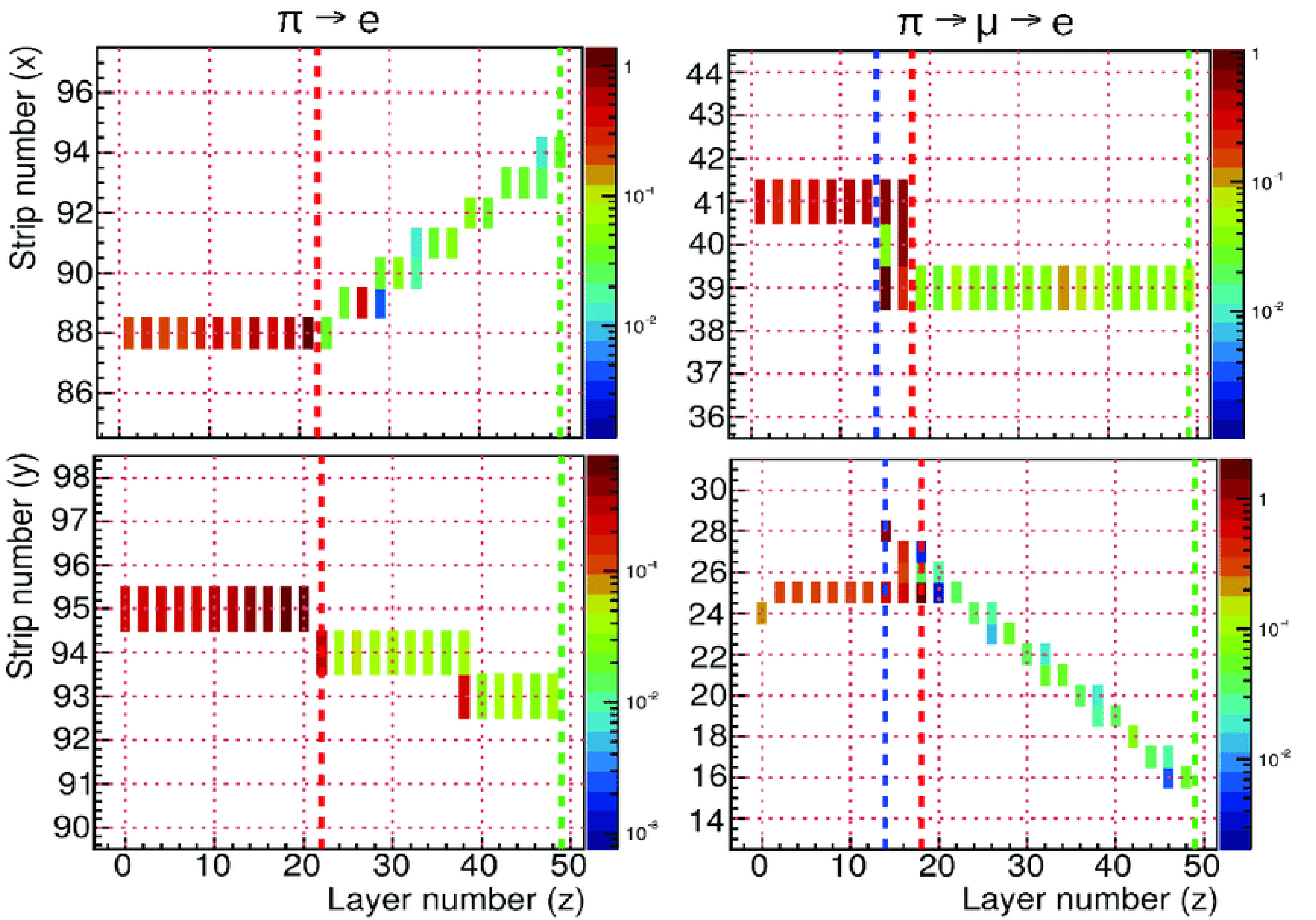
CALO - 3π (140^0 polar angle), $25X_0$,
9 tons liquid xenon (165K),
UV / VUV sensitive phototubes,
scintillation light is 175 nm,
1.5 % energy resolution,
3.5 GB/s raw data rate.

Tracker - dual layer cylindrical silicon strips,
Inner deametr 50 mm,
length 250 mm,
300 μm resolution in XY,
1-3 mm in the beam axis,
time resolution < 1 ns.

Active target ATAR

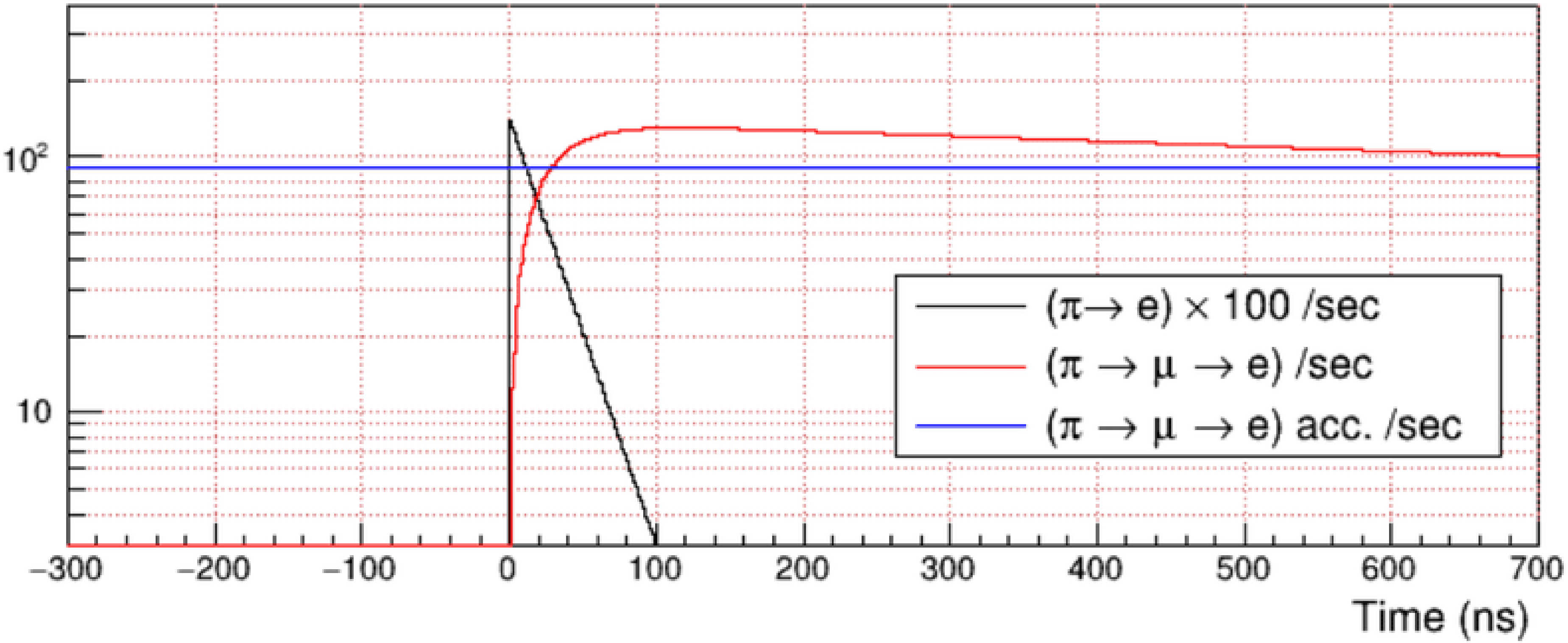
The highly segmented active target consist of 50 planes with 100 strips (200μm × 2cm).
ATAR is used to distinguish event types and can provide
4D tracking at the level of 150 μm in space and < 1 ns in time.
Energy measurements 30-4000 keV signals for positrons and Bragg peaks of stopping π^+ and μ^+.
The chosen technology for the ATAR is based on Low Gain Avalanche Detectors (LGAD),
thin silicon detectors with moderate internal gain.
Due to the internal gain and thin bulk, LGADs have fast rise time and short full charge collection time.
Simulations using optimized LGAD parameters provide confidence
that triggers can be constructed to isolate and measure all event types.

- Beam testing of a ATAR demonstrator by the end of 2024.
- Identification of a suitable chips for the analog amplification and digitization by 2024.
- The support mechanics and thermal load needs to be studied by 2025.
- Final production and subsequent assembly can start by the end of 2025.



π → e
π → μ → e
Strip number (x)
Strip number (y)
Layer number (z)
Layer number (z)

Positron rates (s^{-1}) after π^+ stop



High rate CALO detector

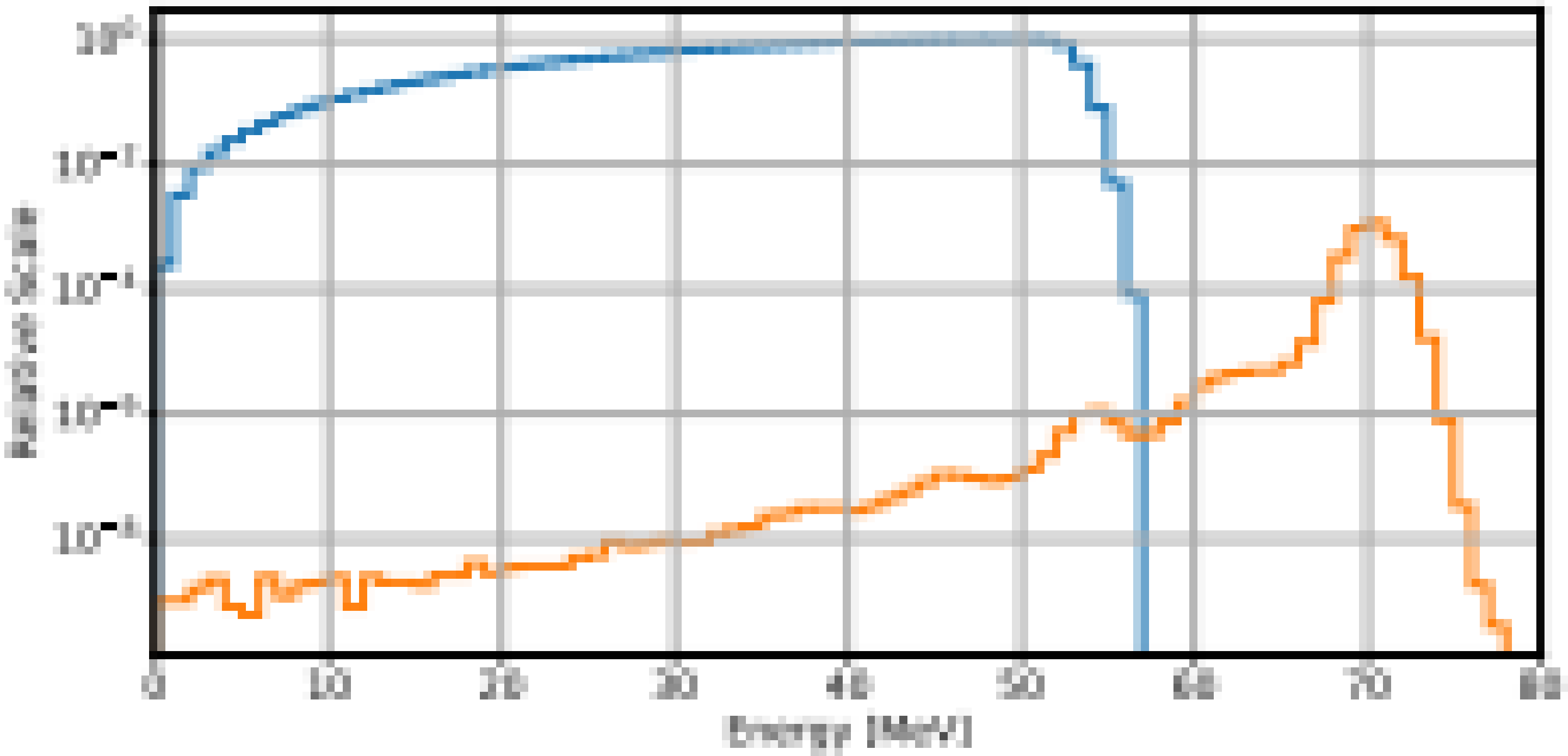
3 m diameter ball (9 tons of liquid xenon), 3π, $25X_0$.
Scintillation light is 175 nm.
Read out by fast timing UV sensitive phototubes and state-of-the-art VUV SiPMs.
High light yield with 1.5% energy resolution (at 70 MeV of e^+),
with highly uniform response.
MEG-II and Hamamatsu developed large Multi-Pixel Photon Counter (12×12 mm^2).

The experience is drawn from the MEG and MEG-II ($\mu^+ \rightarrow e^+ \gamma$) experiments
which use a large scale, high rate LXe detector.

Experiments searching for the dark matter (XENON, LUX-ZEPLIN) and
double beta decay events (KamLAND-Zen, (n)EXO)
also use detectors with similar scale liquid xenon cryos.

Positron energy spectra from CALO detector

Blue line – muon decay positron (Michel) 0 – 52.3 MeV
Yellow line – pion decay positron 69.3 MeV



The equipment is required for the CALO detector:

1. High-pressure gas tank for 9 tons xenon storage.
2. Gas/Liquid xenon purification system at the ppb level.
3. Refrigeration.
4. Temperature and pressure control system.
5. Piping for transporting xenon in the gas and liquid phase.
6. A cryostat that can temporarily hold xenon in a liquid state during emergencies or maintenance.

Cylindrical Tracker

A dual layer cylindrical silicon strip tracker measure the positron in two dimensions
Z (the beam direction), and φ (azimuthal angle), and time.
The detector has an inner diameter of 5 cm and a length of 25 cm
The wire bonded ASIC readout.
The tracker is used to link the locations of pions stopping in the ATAR target to showers in the calorimeter.

Overlapping lengths of 10 cm strips are needed to cover the entire region.
Two layers of strips will provide 1 mm Z resolution and 0.3 mm in the perpendicular direction.
The silicon strip sensors may be constructed with regular silicon or LGADs.
Regular silicon is 300 µm of thickness and 1 ns time resolution.
LGADs can be 50 µm with 50 ps time resolution.
LGAD silicon strips with 10 cm length is an additional challenge.
Silicon strips with 10 cm of length have been successfully fabricated for the ATLAS Inner Tracker Strip Detector.

PIENU vs PIONEER

	PIENU 2015	PIONEER Estimate
Error Source	%	%
Statistics	0.19	0.007
Tail Correction	0.12	<0.01
t0 Correction	0.05	<0.01
Muon decay in flight	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	≤ 0.01

Conclusion

During the next 2-3 years PIONEER setup will be created.
The main features of the PIONEER experiment include:
highly segmented active stopping target with reconstruction all types of events,
improved time and energy resolutions,
greatly increased calorimeter depth (25 X_0) with 3π angle coverage,
high-speed detector with highly uniform response,
Full beam and positron trackers.

During last 10-12 years PIONEER collaboration intend to increase the experimental precision of the rare pion decays by order of magnitude.
Comparing these data with theoretical predictions can reveal new indications of NP and allow testing physical models beyond of SM including heavy neutrinos and dark sector physics.