PIONEER:
A Next-Generation Rare Pion Decay Experiment

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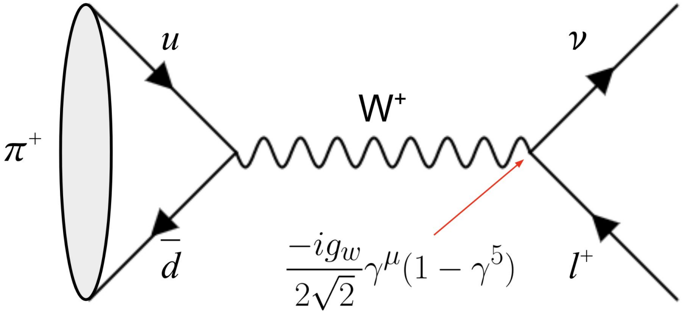
Leukerbad, 19.01.2023

Why study Pion decays?

The charged Pion (here π+) decay:

- lightest meson, consisting of u & d quarks
- Predominantly decays via weak force into μ due to helicity suppression of decay into e



Current situation:

- SM: $$R_{e/\mu} = \frac{\Gamma(\pi \to e\nu(\gamma))}{\Gamma(\pi \to \mu\nu(\gamma))} = 1.23524(15) \times 10^{-4}$$
- Exp.: $$R_{e/\mu} = \frac{\Gamma(\pi \to e\nu(\gamma))}{\Gamma(\pi \to \mu\nu(\gamma))} = 1.2327(23) \times 10^{-4}$$

Phase I measurement:

PIONEER goals:

- Improve current experimental sensitivity by a factor 15
- Directly test lepton flavour (e-μ) universality since $R_{e/\mu} \propto g_e/g_\mu$
- Probe SM extensions affecting $R_{e/\mu}$

Motivation:

- Hints for lepton flavour universality violation in $B \to D^{(*)}$ decays
- Anomalous μ magnetic moment measurement
- Observed forward-backward asymmetry in $B \to D^{(*)}$ decays to e/μ

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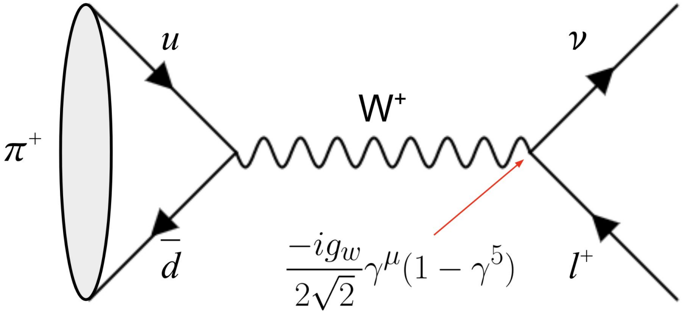

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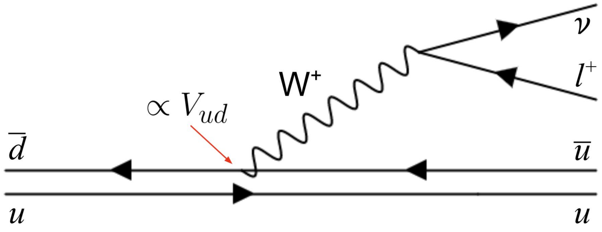
Phase II & III measurement:

PIONEER goals:

- Further improve experimental sensitivity for $R_{e/\mu}$
- Additionally measure pion beta-decay for a direct measurement of V_{ud} :



Motivation:

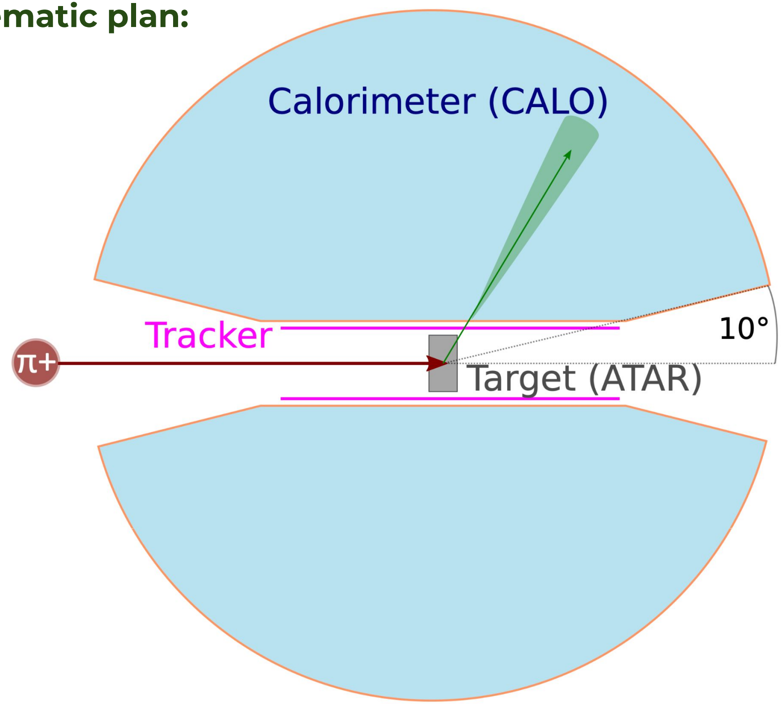
- Hints for Cabibbo angle anomaly combining results of various experiments (Non unitarity of the CKM matrix first row)

Experimental setup

PIONEER will need:

- High intensity, low momentum pion beam
- Highly segmented active target (ATAR) with good time resolution
- Cylindrical tracker to link ATAR and calorimeter signal
- Fast calorimeter with excellent energy resolution, 25 radiation lengths deep and covering 3π sr solid angle
- Fast electronics, DAQ,..

Schematic plan:



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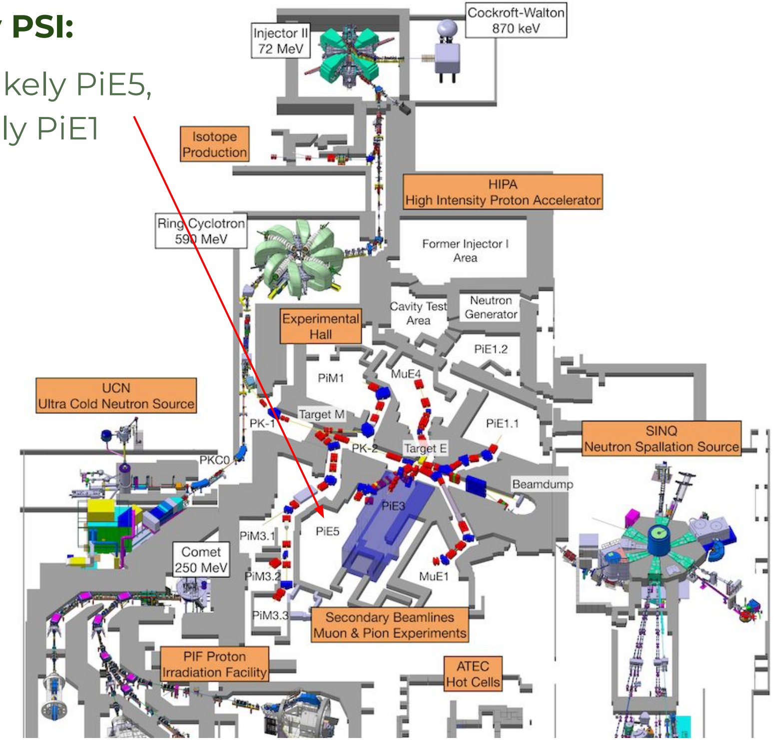
Provided by PSI:

- Most likely PiE5, possibly PiE1



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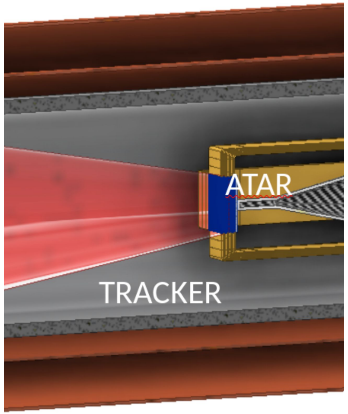
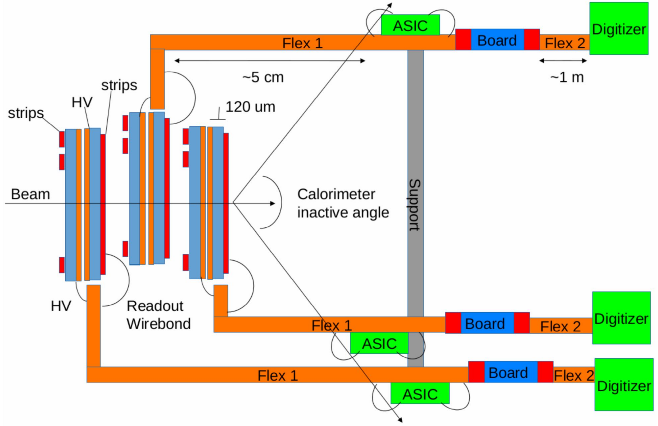
Low Gain Avalanche Diode detector (LGAD):

- Silicon detector with moderate internal gain
- Provides high position and time resolution

Tracker:

- Silicon strip detector
- Measures position in z, φ and t





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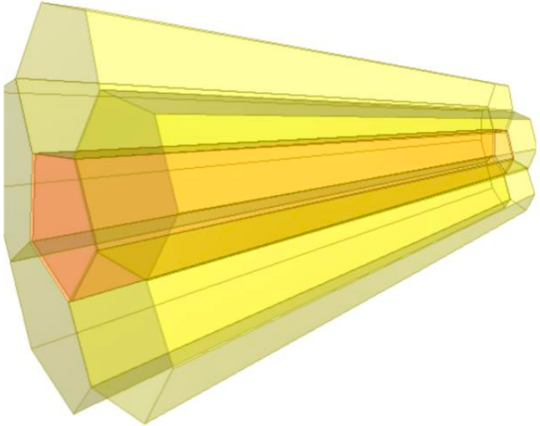
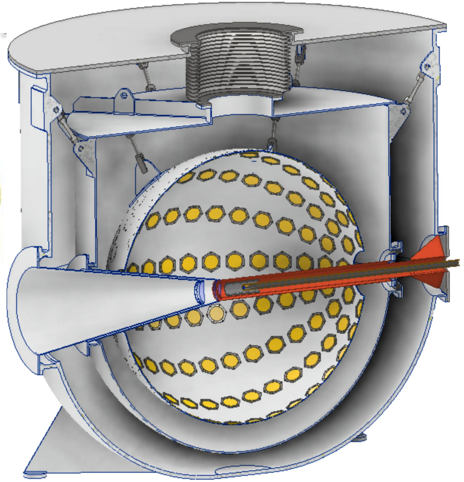
Most likely LXe scintillation calorimeter:

- Fast scintillation light signal
- Good light yield and energy resolution

Alternatively LYSO crystals:

- High density and good light yield

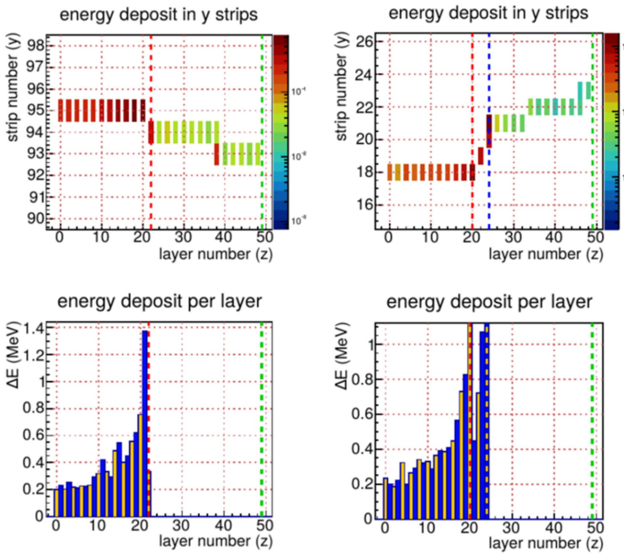




Expected signal

ATAR:

- Measures energy deposition of stopping π^+ (and μ^+)

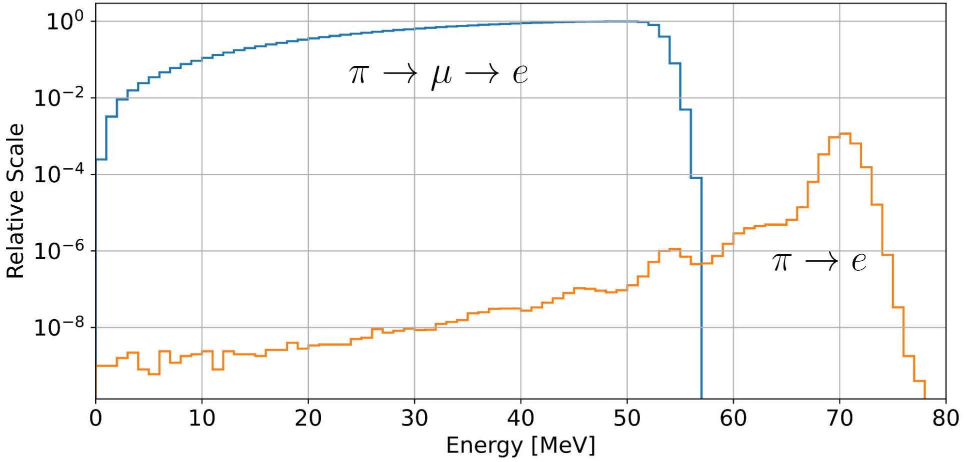


Calorimeter:

- Measures e^+ energy deposition

Expected signal:

- Monoenergetic peak at $m_\pi/2$ for $\pi \to e$
- Michel spectrum with endpoint at $m_\mu/2$ for $\pi \to \mu \to e$



Thank you for listening!

Do you have questions?

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Links & References:

PIONEER experiment proposal:

https://pioneer.npl.washington.edu/pub/Internal/WebHome/R-22-01.1_PIONEER.pdf

Experiment overview on the PSI website:

https://www.psi.ch/en/pioneer/documents

Figures from:

https://pioneer.npl.washington.edu/pub/Internal/WebHome/R-22-01.1_PIONEER.pdf

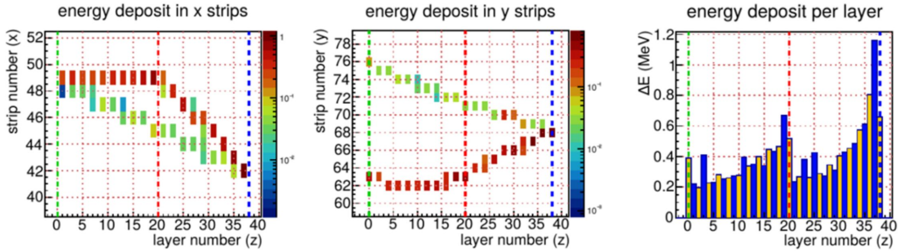
Main challenges and backgrounds

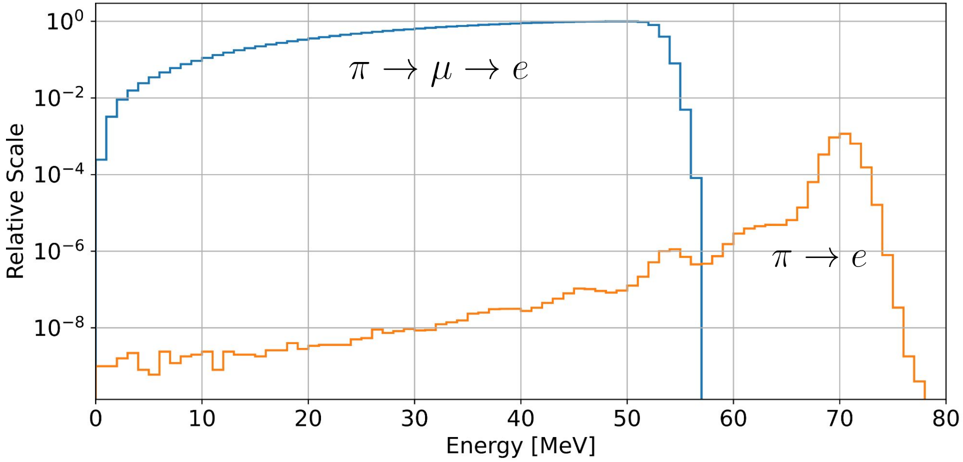
Challenges:

- Suppress sources of systematic uncertainties
- Handling increased pion rates (pulse pileup)

Backgrounds:

- Beamline muons and positrons
- Old muons decaying in the ATAR in accidental coincidence
- Muons and pions decaying in flight (μDIF / πDIF)
- Low energy tail of $\pi \to e$ signal due to geometrical acceptance, shower leakage and photonuclear interactions





Charged Pion decay

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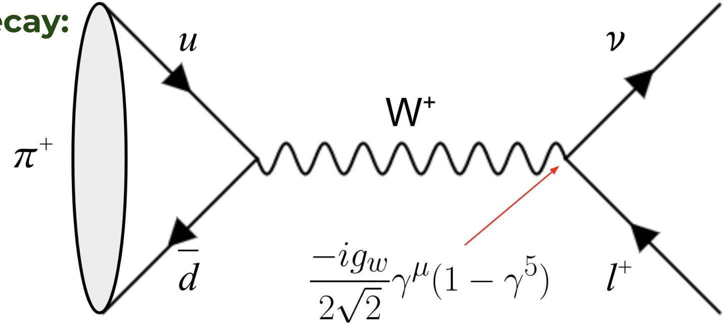
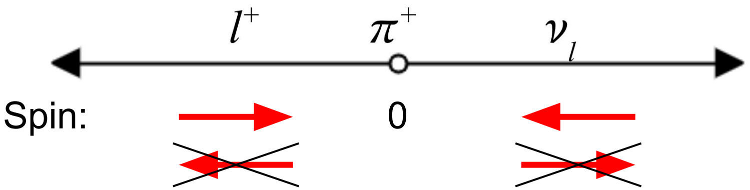
Decay:





The decay of charged pions is "helicity suppressed":

- Pion is a **spin 0** particle
- Because the spin is conserved in the decay, the products need to either have **both helicity +1 or -1**.
- Because of its (V-A) structure, the weak force **only** couples to **left handed** chirality **particles** and **right handed** chirality **anti-particles**
- The neutrino is (almost) massless so it is **ultrarelativistic** and **helicity ≃ chirality**
- This means that the **anti-lepton** needs to have **helicity -1** and **right handed chirality**
- Therefore, the **lighter** the **anti-lepton**, the more relativistic it is and the stronger the **helicity suppression**