Brookhaven National Laboratory

U.S. DEPARTMENT OF ENERGY

PIONEER experiment

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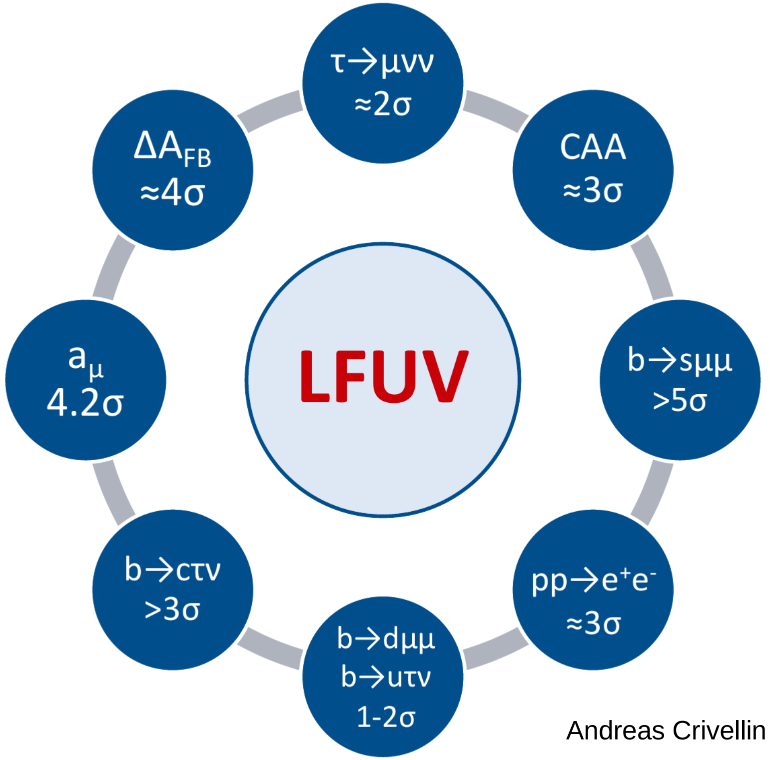
Hints of Lepton Flavor Universality Violation

Several high precision measurements of accurately predicted SM processes show possible indications of violating Lepton Flavor Universality and CKM unitarity

- Muon $g-2$ (4.2σ)
- B Decays: $R(D^*) = \dfrac{B \to D^* \tau\nu}{B \to D^* \mu\nu}$; $R(K^*) = \dfrac{B \to K^* \mu\mu}{B \to K^* ee}$
  $R(D^*)$, $R(K^*)$, $R(K)$ (3-4σ)
  $\mathcal{O}(10\%)$ deviation from universality
- CKM unitarity tests (2-3σ): β and K decays
  May be related to LFUV (Crivellin, Hoferichter)



Andreas Crivellin

Motivation I: Stringent Test of Lepton Flavor Universality

$$R_{e/\mu}^{\mathrm{SM}} = \frac{\Gamma\left(\pi \to e\nu(\gamma)\right)}{\Gamma\left(\pi \to \mu\nu(\gamma)\right)} = (1.2352 \pm 0.0002) \times 10^{-4}$$ $(\pm 0.02\%)$

Marciano, Sirlin; Cirigliano, Rosell

Possibly the most accurately calculated decay process involving hadrons

$$R_{e/\mu}^{\mathrm{exp}} = (1.2327 \pm 0.0023) \times 10^{-4}$$ $(\pm 0.19\%)$

PEN, PIENU goals: $(\leq \pm 0.1\%)$

$$\frac{g_e}{g_\mu} = 0.9989 \pm 0.0009$$ $(\pm 0.09\%)$

Experiments are an order of magnitude less precise than theory

PIONEER goals: $(\pm 0.01\%)$ measurement of $R_{e/\mu}$

measurement of $\pi^+ \to \pi^0 e^+ \nu(\gamma)$ with 3 to 10-fold improvement

$R_{e/\mu}$ measurement

- provides the best test of electron-muon universality in charged-current weak interactions
- $R_{e/\mu}$ is one of the most precisely known observables involving quarks within the SM and NP can even have (chirally) enhanced effects, making it an extremely sensitive probe of NP.
- 0.01% measurement of $R_{e/\mu}$ will probe mass scale up to PeV range
- Possible sources of deviation include new interactions involving
  - scalar particles like Majorons
  - charged Higgs particles
  - leptoquarks
  - supersymmetry with and without R-parity violation
  - massive sterile neutrinos
  - dark sector processes

Motivation II: CKM unitarity

$\pi^+ \to \pi^0 e^+ \nu(\gamma)$ measurement

- 3σ tension in the first-row CKM unitarity test (Cabibbo anomaly)
- Pion beta decay is the cleanest (theoretically) way to measure $|V_{ud}|$ (Czarnecki, Marciano)
- measurement by PIBETA

  $$B(\pi^+ \to \pi^0 e^+ \nu(\gamma)) = (1.036 \pm 0.004(\text{stat}) \pm 0.004(\text{syst}) \pm 0.003(\pi \to e\nu)) \times 10^{-8}$$

  leads to

  $$|V_{ud}| = 0.9739(28)_{\text{exp}}(1)_{\text{th}} \; (\pm 0.3\%)$$

  not presently competitive with super-allowed nuclear beta decays
- an order of magnitude improvement in precision of BRPB measurement is needed
- pion beta decay measurement was added to the PIONEER scietific program per suggestion of Bill Marciano

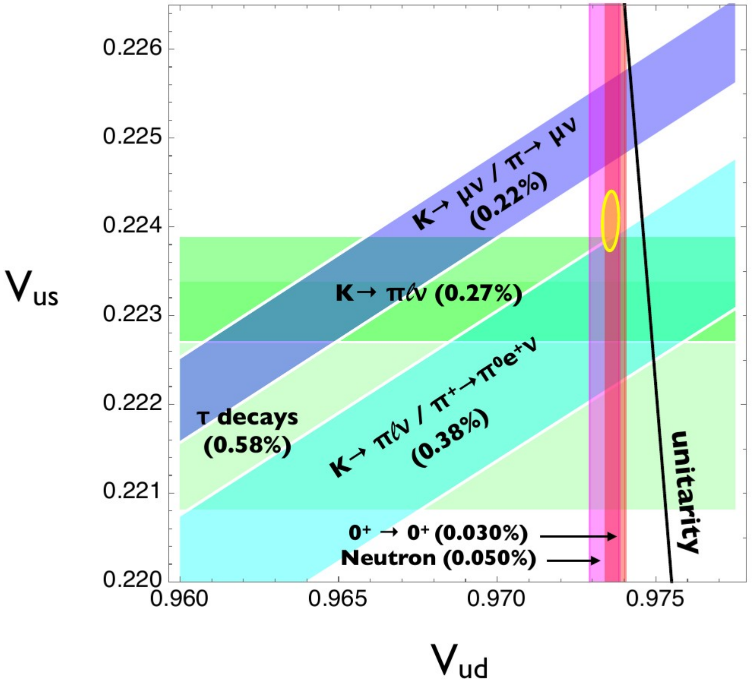


FIG. 1. Summary of constraints on V_{ud} and V_{us} (assuming the Standard Model hypothesis) from nuclear, nucleon, meson, and τ lepton decays. For each constraint, the one-sigma uncertainty on V_{us} or V_{ud} is given in parenthesis (see text for details). The one-sigma ellipse from a global fit (with $\chi^2/\text{d.o.f.} = 2.8$), depicted in yellow, corresponds to $V_{ud} = 0.97357(27)$ and $V_{us} = 0.22406(34)$, implying $\Delta_{\text{CKM}} = |V_{ud}|^2 + |V_{us}|^2 - 1 = (-19.5 \pm 5.3) \times 10^{-4}$.

arXiv:2111.05338 [hep-ph]

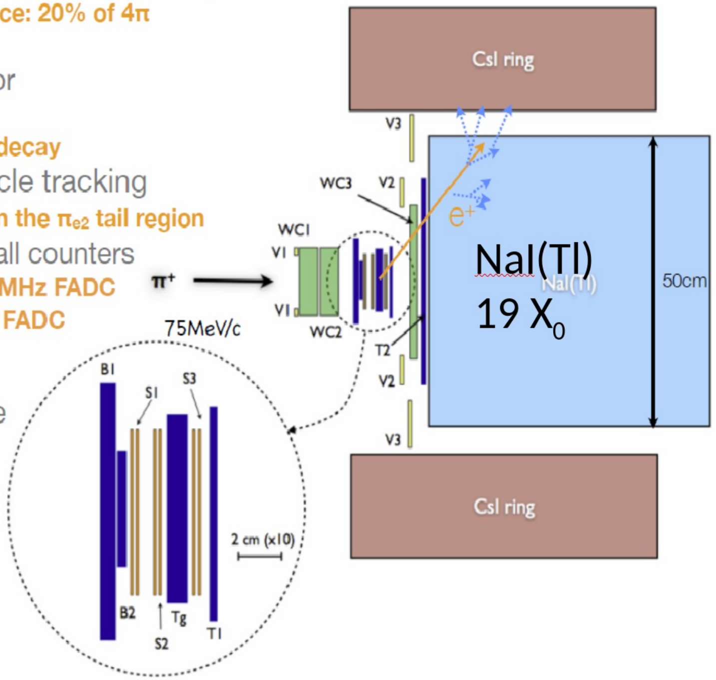
Recent Pion Decay Experiments: PIENU and PEN

PI E NU

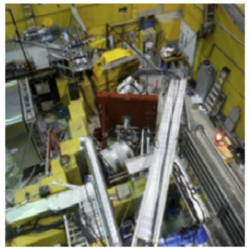
$$\frac{\pi^+ \to e^+ \nu}{\pi^+ \to \mu^+ \nu} \;\&\; \pi^+ \to e/\mu^+ \nu_H$$

& exotics

- Single crystal NaI(Tl) right behind the target
  - Geometrical Acceptance: 20% of 4π
  - ΔE = 2.2%(FWHM)
- CsI ring shower collector
  - π_{e2} tail suppression
  - gamma from radiative decay
- SSD and WC for particle tracking
  - Identify π-DIF events in the π_{e2} tail region
- Flash-ADC readout for all counters
  - Plastic Scintillator: 500MHz FADC
  - NaI(Tl) and CsI: 60MHz FADC
  - Pile-up tagging



- TRIUMF M13 beamline



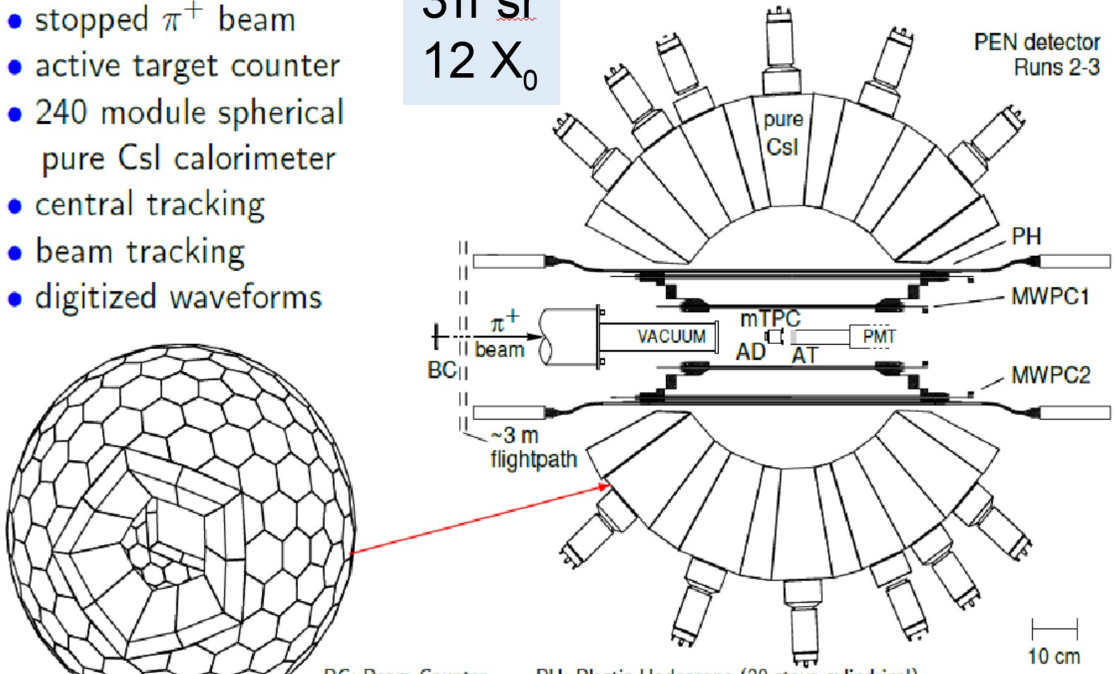
BNL role: CsI and NaI calorimeter

19/01/2022 Doug Bryman PSI PIONEER

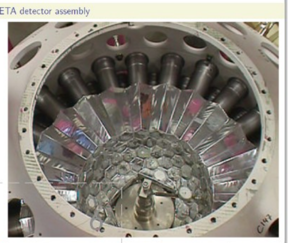
The PEN/PIBETA apparatus $\pi^+ \to \pi^0 e^+ \nu \;\&\; \pi^+ \to e^+ \nu(\gamma)$

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

3π sr
$12\ X_0$



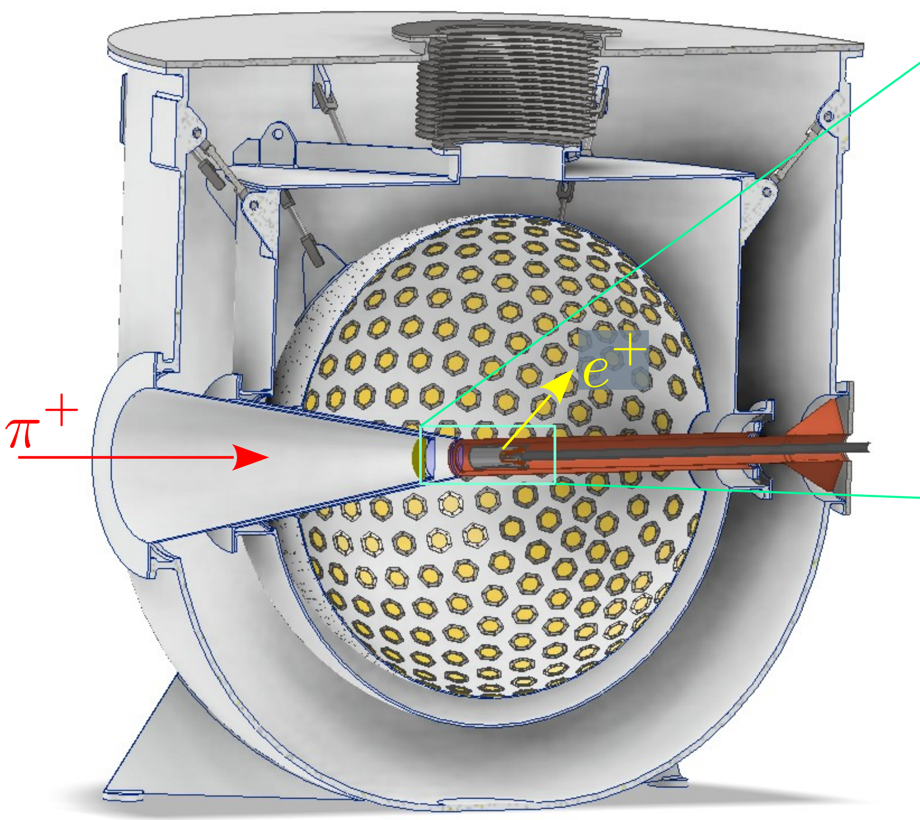
BC: Beam Counter
AD: Active Degrader
AT: Active Target
PH: Plastic Hodoscope (20 stave cylindrical)
MWPC: Multi-Wire Proportional Chamber (cylir
mTPC: mini-Time Projection Chamber

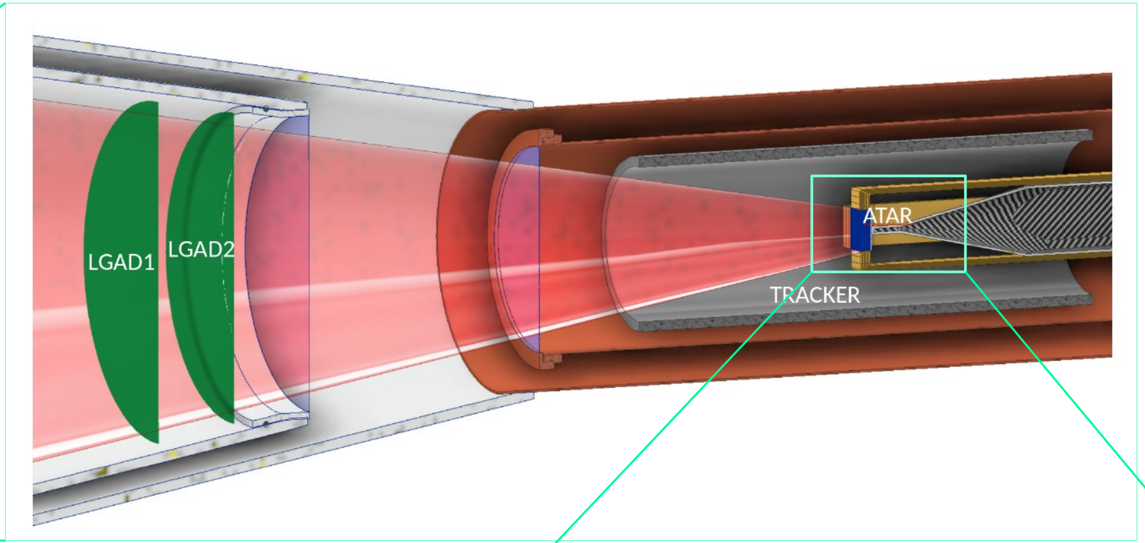


PIBETA signal: $\pi^0 \to \gamma\gamma$

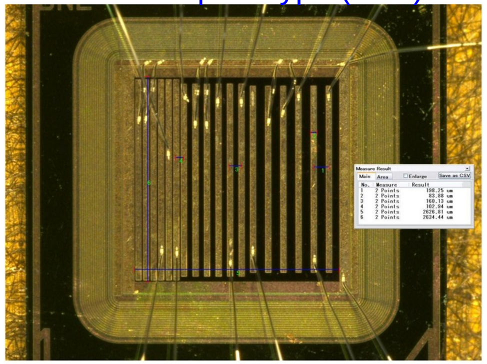
The new measurement of Re/μ would build on the techniques refined in the previous experiments with high energy resolution like TRIUMF PIENU and high acceptance for positrons and gammas like PSI PEN.

PIONEER experimental method

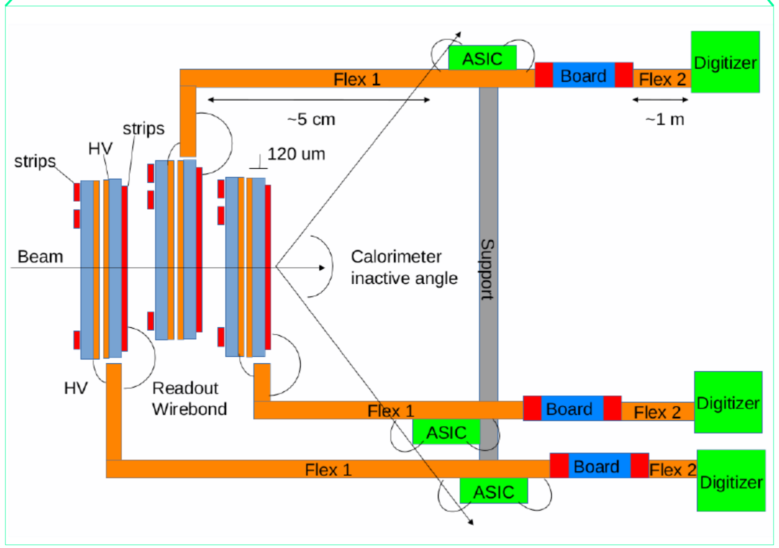




AC-LGAD prototype (BNL)

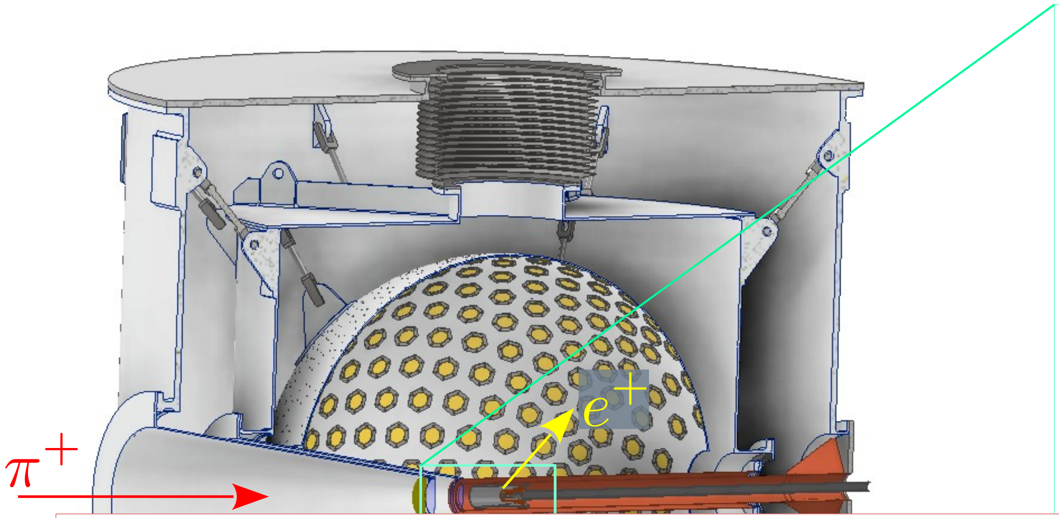


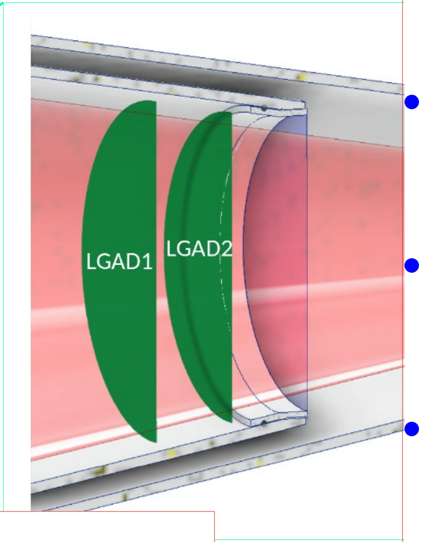
80 µm-wide strips, 100, 150, 200 µm pitch; 5-15µm resolution



- Low-energy (~55-85 MeV/c) pions stopped in an active target (~10 MHz)
- Positrons tracked and energy measured in a “4π” calorimeter (LXe, $25X_0$)
- Decays tagged in target and by energy and timing

PIONEER experimental method

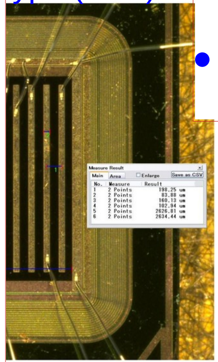




BNL interests / leadreship

- Choice of LXe calorimeter matches with BNL's long history of noble liquid calorimeter research and development.
- The pattern recognition and event reconstruction required in ATAR and LXe matches with BNL's physics analysis expertise.
- Technology choice of ATAR matches with BNL's LGAD expertise. BNL is leading the development of LGADs and AC-coupled LGADs for 4D detectors (time+space).
- Synergy between the development of LGADs for PIONEER and the work done on LGADs and AC-LGADs at BNL for an ECA two LDRDs, a US-Japan RD collaboration and for EIC.
- Synergy between the energy frontier, neutrino and rare processes groups, as well as with instrumentation.

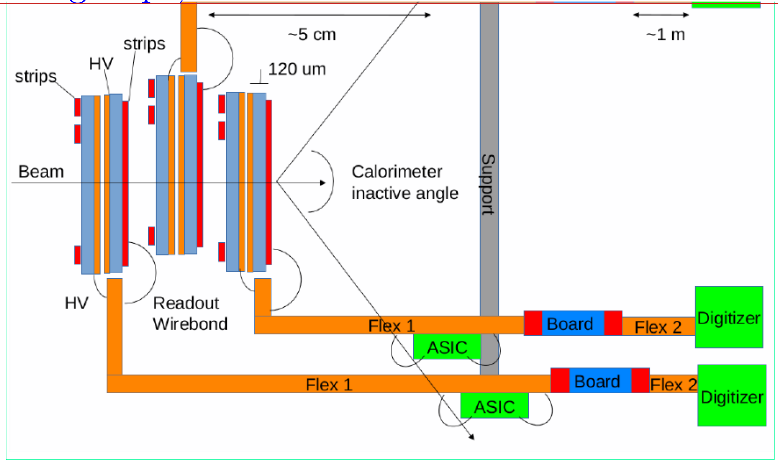
type (BNL)



100, 150,

m resolution

Xe)



E. Cost Estimate

Table V indicates the estimated costs of the PIONEER experiment assuming that the MEG 1000 l LXe supply (estimated value CHF 7.5M) will be used.

PIONEEER Cost Estimate	M ChF
R&D	2.0
ATAR	1.3
Trackers/Beam instr.	0.5
Calorimeter	20.3
Trigger/DAQ	1.0
Other	1.0
Total	**26.1**

TABLE V – PIONEER preliminary cost estimate.

R&D plans

In 2022-23, we anticipate performing detector R&D in several areas including the following:

- Beam studies. We will carry out beam studies in $\pi E5$ (and possibly $\pi E1$) to establish the required beam conditions. A beam request for 2022 tests will be submitted.
- ATAR (see next section).
- Cylindrical positron tracker. Designs with standard 300μm thick Si strips and with LGADs are being considered. We expect to construct and test prototypes of various geometries.
- LXe prototype. The objectives of this R&D work include determination of the properties of photo-sensors and optical properties of materials for use in the LXe calorimeter. We also want to benchmark the photon transport simulations. We are considering the development of a medium scale calorimeter prototype that would enable measurements of properties like energy resolution and photonuclear effects for validation of simulations.
- LXe calorimeter optical segmentation. Small prototypes will be used initially and UV compatible materials will be evaluated. Some of these studies may be done using a LXe cryostat at McGill university containing ~2 l of LXe developed for SiPM tests for nEXO. An assembly hosting SiPMs, reflective material and a retractable radioactive source will be prepared at TRIUMF and brought to McGill for measurements.
- SiPMs. SiPM degradation at high rates will be studied. We will test available photosensors using small LXe prototypes in association with the McGill setup mentioned above.
- Crystal alternatives to LXe. Arrays of LYSO crystals with varying levels of doping will be evaluated from various manufacturers. See the Appendix for more details.
- DAQ. Rate testing of FPGA-to-CPU/GPU and CPU-to-CPU communication via optical PCI-express links will be done along with performance testing of data compression algorithms for CALO data.
- Trigger prototyping. We will use a prototype APOLLO Command Module that the Cornell CMS group will share with PIONEER, and build a 4-channel prototype of the digitizer board for evaluation and communications development.

ATAR R&D

- After initial sensor characterization and design optimization a PIONEER specific prototype production should happen by the end of 2023. The characterization includes studies on LGAD energy resolution and gain suppression mechanism.
- Building of a first ATAR demonstrator (ATAR0) with a few planes of available sensor prototypes (BNL strip LGADs, 2.5 cm with 500 μm pitch). An electronics board with suitable characteristics needs to be designed and produced. The prototype would be then tested in a pion/muon beamline either at TRIUMF or PSI. This prototype may be produced by the end of 2023.
- Identification of a suitable chips for the analog amplification and digitization by 2024. The effect of a short flex between sensor and chip will be studied within 2022.
- The support mechanics and thermal load needs to be studied well with mock-up prototypes and silicon heaters. These details needs to be fully understood by 2025.
- Full production of sensors and readout ASIC, once identified, should take less than a year given the modest area of the ATAR. Therefore final production and subsequent assembly can start in 2025.

Summary

- Exciting physics.
- The measurement has a strong potential of making significant impact in the field.
- PIONEER is a very active and quickly growing collaboration:
  - A proposal has been submitted to PSI (7 co-authors from BNL – 6xPO+1xIO)
  - White paper is being written

PSI Ring Cyclotron Proposal

PIONEER: Studies of Rare Pion Decays

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