PIONEER: A next-generation rare pion decay experiment

David Hertzog; University of Washington

On behalf of the 74 current Collaborators:

W. Altmannshofer,[1] O. Beesley,[2] E. Blucher,[3] A. Bolotnikov,[4] S. Braun,[2] D. Bryman,[5,6] Q. Buat,[2] L. Caminada,[7] S. Chen,[8] M. Chiu,[4] V. Cirigliano,[2] S. Corrodi,[9] A. Crivellin,[7,10] S. Cuen-Rochin,[11] J. Datta,[12] K. Dehmelt,[12] A. Deshpande,[12,4] A. Di Canto,[4] L. Doria,[13] J. Dror,[1] M. Escobar Godoy,[1] A. Gaponenko,[14] P. Garg,[12] G. Giacomini,[4] L. Gibbons,[15] C. Glaser,[16] D. Göldi,[17] S. Gori,[1] T. Gorringe,[18] C. Hempel,[6] D. Hertzog,[2] S. Hochrein,[17] M. Hoferichter,[19] S. Ito,[20] T. Iwamoto,[21] P. Kammel,[2] B. Kiburg,[14] K. Labe,[15] J. Labounty,[2] U. Langenegger,[7] C. Malbrunot,[6] A. Matsushita,[21] S. Mazza,[1] S. Mehrotra,[12] S. Mihara,[20] R. Mischke,[6] A. Molnar,[1] T. Mori,[21] J. Mott,[14] T. Numao,[6] W. Ootani,[21] J. Ott,[1] K. Pachal,[6] D. Pocanic,[16] C. Polly,[14] X. Qian,[4] D. Ries,[13] R. Roehnelt,[2] B. Schumm,[1] P. Schwendimann,[2] A. Seiden,[1] A. Sher,[6] R. Shrock,[12] A. Soter,[17] T. Sullivan,[22] E. Swanson,[2] V. Tishchenko,[4] A. Tricoli,[4] T. Tsang,[4] B. Velghe,[6] V. Wong,[6] E. Worcester,[4] M. Worcester,[4] and C. Zhang[4]

[1] University of California Santa Cruz
[2] University of Washington
[3] University of Chicago
[4] Brookhaven National Laboratory
[5] University of British Columbia
[6] TRIUMF
[7] Paul Scherrer Institute
[8] Tsinghua Universtiy
[9] Argonne National Laboratory
[10] University Zurich
[11] Tecnologico de Monterrey
[12] Stony Brook University
[13] Johannes Gutenberg University
[14] Fermilab
[15] Cornell University
[16] University of Virginia
[17] ETH Zurich
[18] University of Kentucky
[19] University of Bern
[20] KEK
[21] The University of Tokyo
[22] University of Victoria

U.S. Institutes

The Collaboration has extensive experience in

- Rare π & K Decays; Muon g-2, Muon Lifetime, MEG CLFV, & many PSI experiments
- We have STRONG, YOUNG Leadership at many institutions who will drive this program forward

Closed Caption

PIONEER approved at PSI addressing 3 Physics Questions

10 x Improvements in precision

- **Lepton Flavor Universality**
- **Cabibbo Angle Anomaly**
- **Sterile neutrinos and exotic decays**

Jan. 2022 ***Approved with high priority @ PSI***

arXiv:2203.01981v2 [hep-ex] 8 Mar 2022

PSI Ring Cyclotron Proposal R-22-01.1
PIONEER: Studies of Rare Pion Decays

W. Altmannshofer,[1] H. Binney,[2] E. Blucher,[3] D. Bryman,[4,5] L. Caminada,[6] S. Chen,[7] V. Cirigliano,[8] S. Corrodi,[9] A. Crivellin,[6,10,11] S. Cuen-Rochin,[12] A. DiCanto,[13] L. Doria,[14] A. Gaponenko,[15] A. Garcia,[2] L. Gibbons,[16] C. Glaser,[17] M. Escobar Godoy,[1] D. Göldi,[18] S. Gori,[1] T. Gorringe,[19] D. Hertzog,[2] Z. Hodge,[2] M. Hoferichter,[20] S. Ito,[21] T. Iwamoto,[22] P. Kammel,[2] B. Kiburg,[15] K. Labe,[16] J. LaBounty,[2] U. Langenegger,[6] C. Malbrunot,[5] S.M. Mazza,[1] S. Mihara,[21] R. Mischke,[5] T. Mori,[22] J. Mott,[15] T. Numao,[5] W. Ootani,[22] J. Ott,[1] K. Pachal,[5] C. Polly,[15] D. Počanić,[17] X. Qian,[13] D. Ries,[23] R. Roehnelt,[2] B. Schumm,[1] P. Schwendimann,[2] A. Seiden,[1] A. Sher,[5] R. Shrock,[24] A. Soter,[18] T. Sullivan,[25] M. Tarka,[1] V. Tischenko,[13] A. Tricoli,[13] B. Velghe,[5] V. Wong,[5] E. Worcester,[13] M. Worcester,[26] and C. Zhang[13]

[1] Santa Cruz Institute for Particle Physics (SCIPP), University of California Santa Cruz, 1156 High street, Santa Cruz (CA) 95064 USA
[2] Department of Physics, University of Washington, Box 351560, Seattle, Washington 98195 USA
[3] Enrico Fermi Institute and Department of Physics, University of Chicago, 5720 South Ellis Avenue, Chicago, IL 60637 USA
[4] Department of Physics & Astronomy, University of British Columbia 6224 Agricultural Road, Vancouver V6T 1Z1 Canada
[5] TRIUMF, 4004 Wesbrook Mall, Vancouver V6T 2A3 Canada
[6] Paul Scherrer Institute, 5232 Villigen PSI Switzerland
[7] Department of Engineering Physics, Tsinghua University, 30 Shuangqing Road, Haidian District, Beijing, 100084 P. R. China
[8] Institute for Nuclear Theory, University of Washington, Seattle WA 98195-1550 USA
[9] Argonne National Laboratory, High Energy Physics Division, 9700 S Cass Ave, Lemont, IL 60439 USA
[10] Physik-Institut University of Zurich Winterthurerstrasse 190 CH-8057 Zurich Switzerland
[11] Division of Theoretical Physics, CERN, Espl. des Particules 1, 1211 Meyrin Switzerland
[12] Tecnológico de Monterrey, School of Engineering and Sciences, Blvd. Pedro Infante 3773 Pte, Culiacan 80100 Mexico
[13] Physics Department, Brookhaven National Laboratory, Upton, NY, 11973 USA
[14] PRISMA+ Cluster of Excellence and Johannes Gutenberg Universität Mainz, Institut für Kernphysik, J.-J.-Becher-Weg 45, 55128 Mainz Germany
[15] Fermi National Accelerator Laboratory (FNAL),

https://arxiv.org/abs/2203.01981

Snowmass 2022 White Paper

arXiv:2203.05505v1 [hep-ex] 10 Mar 2022

Testing Lepton Flavor Universality and CKM Unitarity with Rare Pion Decays in the PIONEER experiment

W. Altmannshofer,[1] H. Binney,[2] E. Blucher,[3] D. Bryman,[4,5] L. Caminada,[6] S. Chen,[7] V. Cirigliano,[8] S. Corrodi,[9] A. Crivellin,[6,10,11] S. Cuen-Rochin,[12] A. Di Canto,[13] L. Doria,[14] A. Gaponenko,[15] A. Garcia,[2] L. Gibbons,[16] C. Glaser,[17] M. Escobar Godoy,[1] D. Göldi,[18] S. Gori,[1] T. Gorringe,[19] D. Hertzog,[2] Z. Hodge,[2] M. Hoferichter,[20] S. Ito,[21] T. Iwamoto,[22] P. Kammel,[2] B. Kiburg,[15] K. Labe,[16] J. LaBounty,[2] U. Langenegger,[6] C. Malbrunot,[5] S.M. Mazza,[1] S. Mihara,[21] R. Mischke,[5] T. Mori,[22] J. Mott,[15] T. Numao,[5] W. Ootani,[22] J. Ott,[1] K. Pachal,[5] C. Polly,[15] D. Počanić,[17] X. Qian,[13] D. Ries,[23] R. Roehnelt,[2] B. Schumm,[1] P. Schwendimann,[2] A. Seiden,[1] A. Sher,[5] R. Shrock,[24] A. Soter,[18] T. Sullivan,[25] M. Tarka,[1] V. Tischenko,[13] A. Tricoli,[13] B. Velghe,[5] V. Wong,[5] E. Worcester,[13] M. Worcester,[26] and C. Zhang[13]

[1] Santa Cruz Institute for Particle Physics (SCIPP), University of California Santa Cruz, 1156 High street, Santa Cruz (CA) 95064 USA
[2] Department of Physics, University of Washington, Box 351560, Seattle, Washington 98195 USA
[3] Enrico Fermi Institute and Department of Physics, University of Chicago, 5720 South Ellis Avenue, Chicago, IL 60637 USA
[4] Department of Physics & Astronomy, University of British Columbia 6224 Agricultural Road, Vancouver V6T 1Z1 Canada
[5] TRIUMF, 4004 Wesbrook Mall, Vancouver V6T 2A3 Canada
[6] Paul Scherrer Institute, 5232 Villigen PSI Switzerland
[7] Department of Engineering Physics, Tsinghua University, 30 Shuangqing Road, Haidian District, Beijing, 100084 P. R. China
[8] Institute for Nuclear Theory, University of Washington, Seattle WA 98195-1550 USA
[9] Argonne National Laboratory, High Energy Physics Division, 9700 S Cass Ave, Lemont, IL 60439 USA
[10] Physik-Institut University of Zurich Winterthurerstrasse 190 CH-8057 Zurich Switzerland
[11] Division of Theoretical Physics, CERN, Espl. des Particules 1, 1211 Meyrin Switzerland
[12] Tecnológico de Monterrey, School of Engineering and Sciences, Blvd. Pedro Infante 3773 Pte, Culiacan 80100 Mexico
[13] Physics Department, Brookhaven National Laboratory, Upton, NY, 11973 USA
[14] PRISMA+ Cluster of Excellence and Johannes Gutenberg Universität Mainz, Institut für Kernphysik, J.-J.-Becher-Weg 45, 55128 Mainz Germany
[15] Fermi National Accelerator Laboratory (FNAL), P.O. Box 500, Batavia IL 60510-5011 USA

First Beam Request-May 2022

Paul Scherrer Institut PSI | PSI Research, Labs & User Services

Research at PSI | Research Divisions and Labs | Facilities and Instruments | PSI User Servi

PSI Home > Labs & User Services > NUM > LTP > PIONEER Experiment

PIONEER Experiment
Documents

PIONEER Experiment

The PIONEER experiment is a next generation experiment to measure the charged-pion branching ratio to electrons vs. muons. This measurement, which is highly sensitive to new physics at high mass scales, has broad implications for the universality of lepton interactions. Using state-of-the-art instrumentation - learning from the previous generation PEN and PIENu measurements - and a new high-intensity beam, measurements of the pion decay to electrons vs. muons and pion beta decay will im-prove on pre... agreement w... able precisio... SM. Further r... lepton flavor... trinos and ax...

Simulations ... apparatus, w... beampipe an... Germany, Jap...

The best refe...

The collabora... the PIE5 bear...

PSI Progress Report 2023

R-22-01.1 PIONEER Progress Report

W. Altmannshofer,[1] O. Beesley,[2] E. Blucher,[3] S. Braun,[2] D. Bryman,[4,5] Q. Buat,[2] L. Caminada,[6] S. Chen,[7] V. Cirigliano,[2] S. Corrodi,[8] A. Crivellin,[6,9] S. Cuen-Rochin,[10] J. Datta,[11] K. Dehmelt,[11] A. Deshpande,[11,12] A. Di Canto,[12] L. Doria,[13] J. Dror,[1] M. Escobar Godoy,[1] A. Gaponenko,[14] A. Garcia,[2] P. Garg,[11] L. Gibbons,[15] C. Glaser,[16] D. Göldi,[17] S. Gori,[1] T. Gorringe,[18] D. Hertzog,[2] M. Hoferichter,[19] S. Ito,[20] T. Iwamoto,[21] P. Kammel,[2] B. Kiburg,[14] K. Labe,[15] J. Labounty,[2] U. Langenegger,[6] C. Malbrunot,[5] A. Matsushita,[21] S.M. Mazza,[1] S. Mehrotra,[11] S. Mihara,[20] R. Mischke,[5] A. Molnar,[1] T. Mori,[21] J. Mott,[14] T. Numao,[5] W. Ootani,[21] J. Ott,[1] K. Pachal,[5] D. Pocanic,[16] C. Polly,[14] X. Qian,[12] D. Ries,[13] R. Roehnelt,[2] B. Schumm,[1] P. Schwendimann,[2] A. Seiden,[1] A. Sher,[5] R. Shrock,[11] A. Soter,[17] T. Sullivan,[22] E. Swanson,[2] V. Tishchenko,[12] A. Tricoli,[12] B. Velghe,[5] V. Wong,[5] E. Worcester,[12] M. Worcester,[12] and C. Zhang[12]

[1] University of California Santa Cruz [2] University of Washington [3] University of Chicago [4] University of British Columbia [5] TRIUMF [6] Paul Scherrer Institute [7] Tsinghua University [8] Argonne National Laboratory [9] University Zurich [10] Tecnologico de Monterrey [11] Stony Brook University [12] Brookhaven National Laboratory [13] Johannes Gutenberg University [14] Fermilab [15] Cornell University [16] University of Virginia [17] ETH Zurich [18] University of Kentucky [19] University of Bern [20] KEK [21] The University of Tokyo [22] University of Victoria

(Dated: January 9, 2023)

ABSTRACT: During the past year the PIONEER collaboration has continued to develop the experiment by performing simulations and detector design work. In addition, initial investigations of the $\pi E5$ beam line were made. The status of the work will be discussed.

I. INTRODUCTION

The PIONEER proposal was approved at BV54 in January, 2021 and since then the PIONEER Collaboration has been developing aspects of the experiment. Two weeks of test beam allotted in $\pi E5$ offered a first chance for in-person collaboration, and the launching of the experimental campaign. In October 2022, a Rare Pion Decay

Physics Case 1: Best Test of Lepton Flavor Universality

- **Lepton Flavor Universality test:** $$R^{theory}_{e/\mu} = \frac{\Gamma(\pi \rightarrow e\nu(\gamma))}{\Gamma(\pi \rightarrow \mu\nu(\gamma))}$$

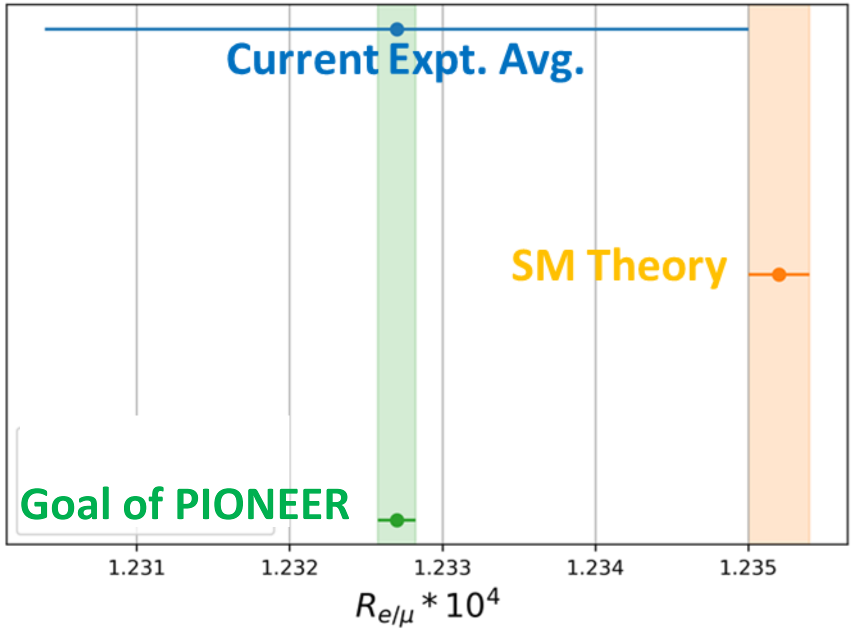
Theory: Marciano/Sirlin
→ Cirigliano/Rosell

$$R_{e/\mu}(\text{SM}) = 1.23524(015) \times 10^{-4}$$

$$R_{e/\mu}(\text{Exp}) = 1.23270(230) \times 10^{-4}$$

15 x worse than theory

(PIENU / the **best** test of LFU)



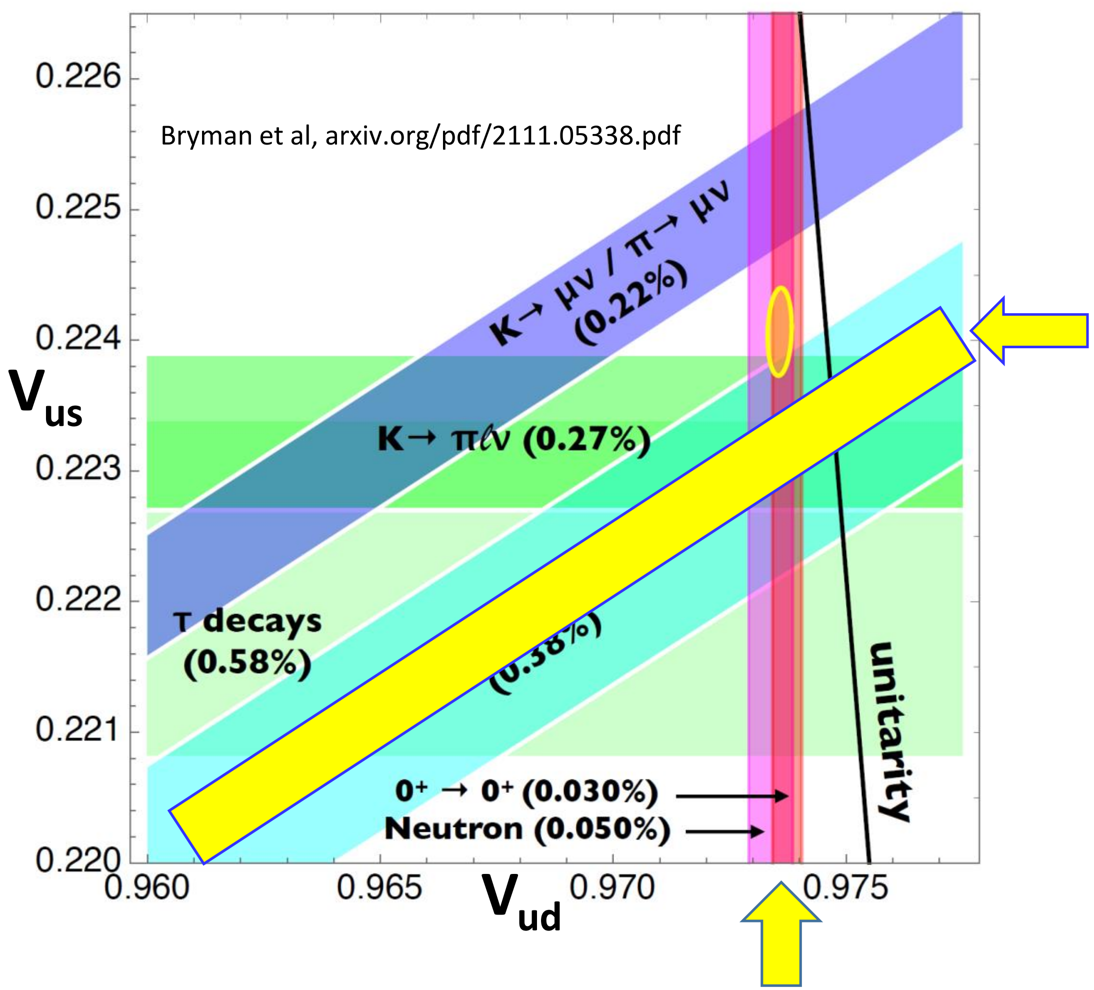
Current $$\frac{g_e}{g_\mu} = 0.9990 \pm 0.0009 \quad (\pm 0.09\%)$$

Goal: $$\frac{g_e}{g_\mu} \sim \pm 0.005\%$$

Unprecedented precision.
Sensitive to New Physics mass scales >10^3 TeV

Physics Case 2: High Precision unitarity test with pion beta decay

Tensions in the first-row CKM unitarity test



Pion beta decay, $\pi^+ \to \pi^0 e^+ \nu(\gamma)$ **provides the theoretically cleanest determination of** $|V_{ud}|$

Dominant uncertainty in $\delta|V_{ud}|$ associated with hadronic and nuclear corrections

3-fold improvement → improved V_{us}/V_{ud}

10-fold improvement to determine V_{ud} at the level of 0^{++}, but without nuclear corrections

Pion beta decay offers unique precision to determine V_{ud}

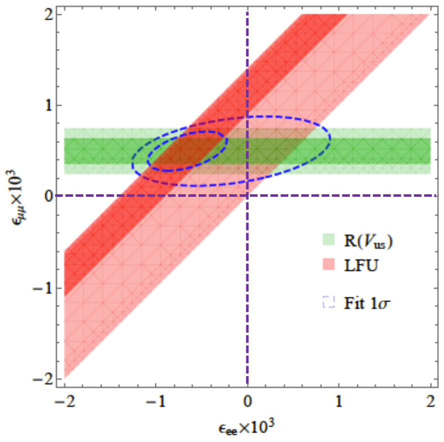
LFUV may be impacting the CAA?

Assuming unitarity, V_{ud} deduced from $K_{\ell 2}$ and $K_{\ell 3}$ and nuclear beta decay is *inconsistent*

Is this tension a sign of LFUV ??

Modifies Fermi constant in **muon decay**

$$\frac{1}{\tau_\mu} = \frac{(G_F^{\mathcal{L}})^2 m_\mu^5}{192\pi^3}(1+\Delta q)(1+\varepsilon_{ee}+\varepsilon_{\mu\mu})^2$$

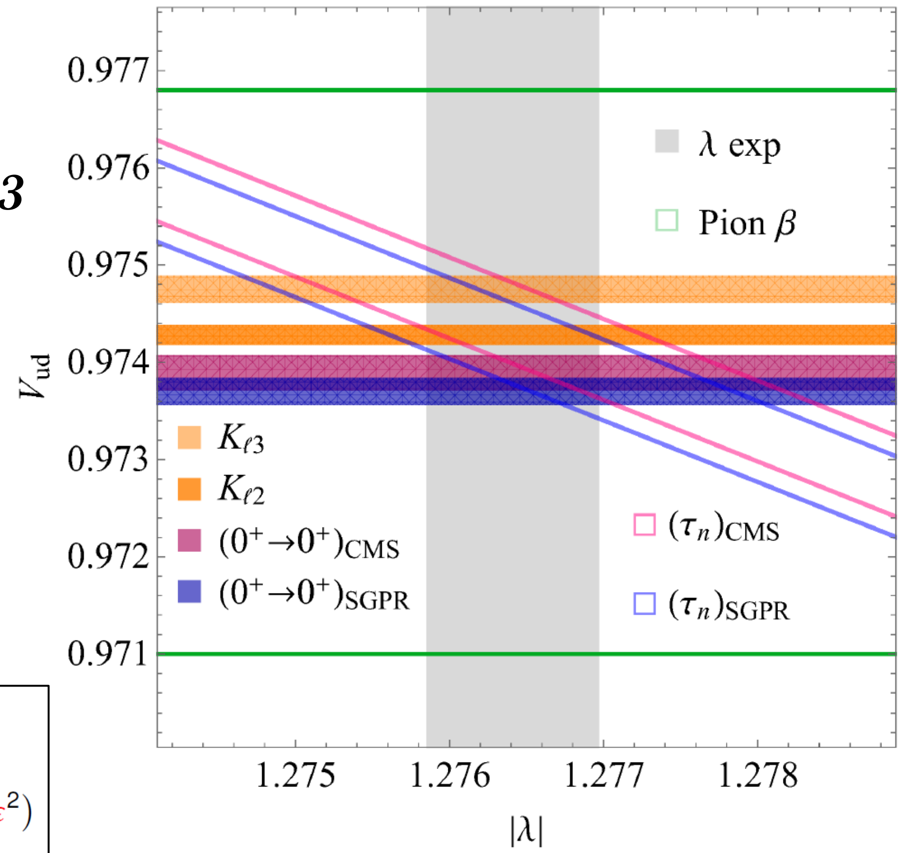


Construct ratio Crivellin, MH 2020

$$R(V_{us}) \equiv \frac{V_{us}^{K_{\mu 2}}}{V_{us}^{\beta}} \equiv \frac{V_{us}^{K_{\mu 2}}}{\sqrt{1-(V_{ud}^{\beta})^2-|V_{ub}|^2}} = 1-\left(\frac{V_{ud}}{V_{us}}\right)^2 \varepsilon_{\mu\mu} + \mathcal{O}(\varepsilon^2)$$

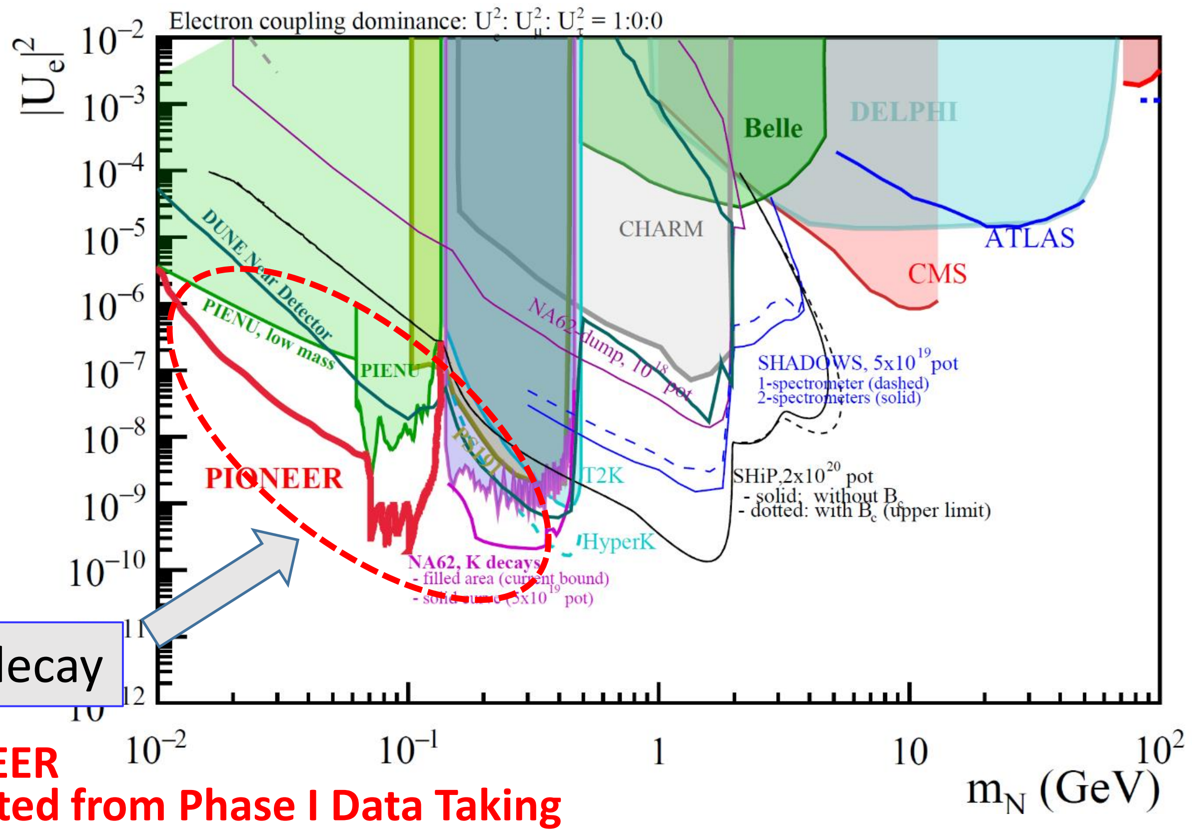
$\hookrightarrow$ LFUV effect enhanced by $(V_{ud}/V_{us})^2 \sim 20$!

Crivellin-Hoferichter 2002.07184, PRL



ε_{ij} are possible small corrections to the charged W-ℓ-ν couplings,

Physics Case 3: Sterile neutrinos and exotic decays



Pion decay

PIONEER
Expected from Phase I Data Taking

Snowmass paper: The Present and Future Status of Heavy Neutral Leptons; Abdullahi et al
https://arxiv.org/pdf/2203.08039.pdf

Uniquely sensitivity in the low mass region 1-120 MeV

Heavy sterile neutrino and hidden sector searches improved by factor of 10

$$\pi \to e\nu_H$$

$$\pi \to \mu\nu_H$$

$$\pi \to e\nu X$$

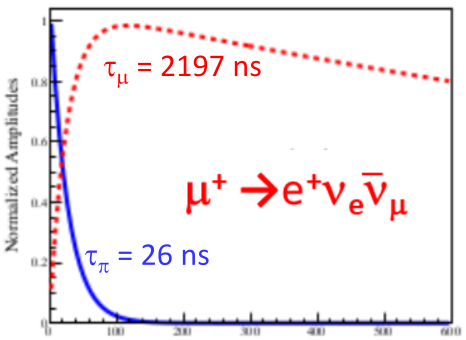
Example papers published by PIENU

A. Aguilar-Arevalo et al. Physical Review D 97(7) 072012 (2018)
A. Aguilar-Arevalo et al. Physics Letters B 798 (2019) 134980
A. Aguilar-Arevalo et al. Phys. Rev. D 102, 012001 (2020)
A. Aguilar-Arevalo et al. Phys. Rev. D 101, 052014 (2020)
A. Aguilar-Arevalo et al. Phys. Rev. D 103, 052006 (2021)

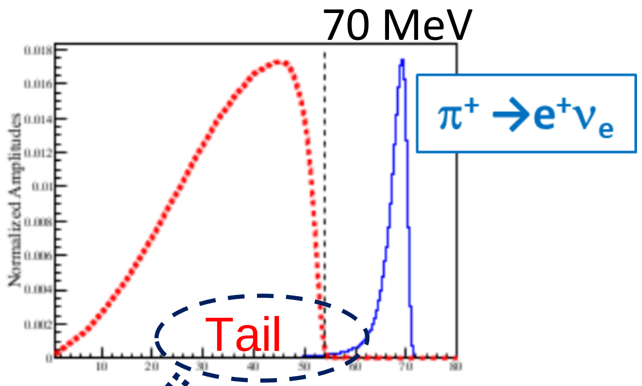
Our strategy for a next-gen pi-e-nu experiment

$$BR\left(\pi^+ \to \mu^+\nu_\mu(\gamma)\right) = 0.999877 = \pm 0.0000004$$

$$BR\left(\pi^+ \to e^+\nu_e(\gamma)\right) = (1.2327 \pm 0.0023) \times 10^{-4}$$

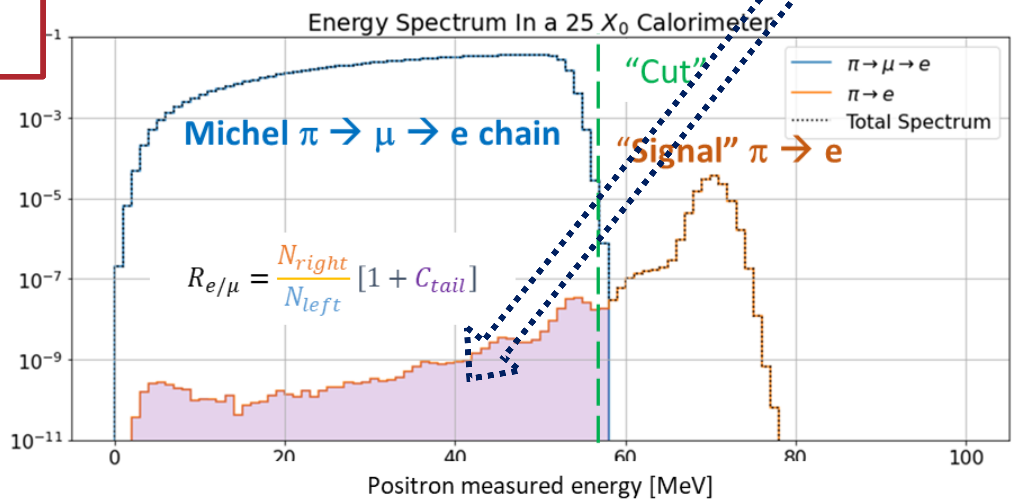


Timing



e^+ Energy

The key to major improvements over current state-of-the-art experiments (PIENU, PEN) is to accurately determine fraction of $\pi \to$ e events that hide below the Michel spectrum: "The Tail"



25 X_0 deep calorimeter: ***Tail fraction <1%***

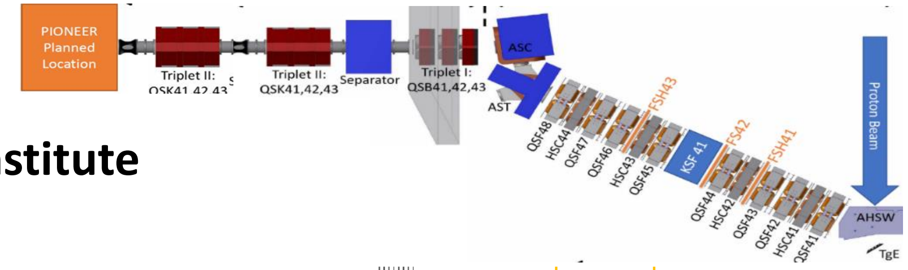
Highly segmented, active target with energy, timing, and topology information to identify events:

Tail fraction uncertainty <0.01%

Overall uncertainty goal:

$$R_{e/\mu} = \frac{\Gamma(\pi \to e\nu(\gamma))}{\Gamma(\pi \to \mu\nu(\gamma))} = \pm 0.01\%$$

Technical approach (scope) requires

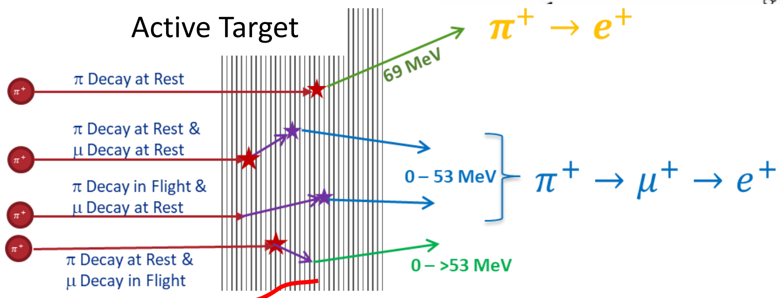


- Most intense **low-energy pion beamline is at the Paul Scherrer Institute**
  - PSI fully supports experiments, installation, etc.

KEY Development

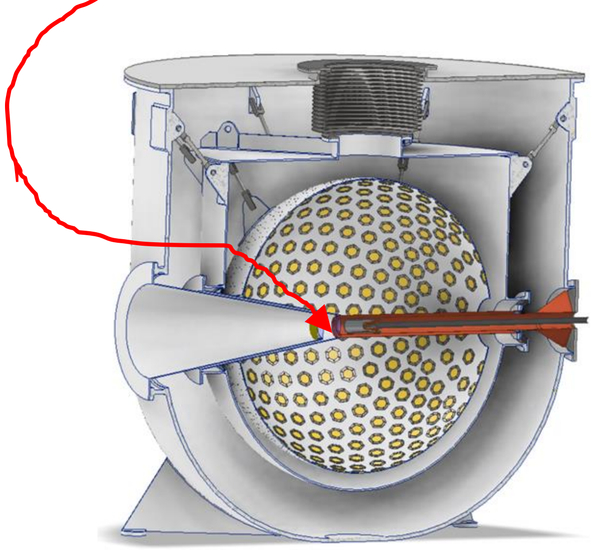
- **LGAD 5D-Tracking target (low-gain, avalanche diode)**

  High precision tracking Si strip target (Active Target)
  - Distinguishes events types (unique feature)
  - 5000 channels with time, energy, and position in 2x2x0.6 cm^3



KEY Development

- **25 X0 LXe Scintillating Calorimeter**
  - High-resolution, uniform, fast
  - Following MEG II ; <1.5% resolution at 70 MeV



- **State-of-the-art** additional instrumentation
  - + µRWell Tracker; fast triggering; high speed digitization and DAQ
  - Many following LHC developments

PIONEER Project Costing … being drawn from full WBS exercise that is in progress

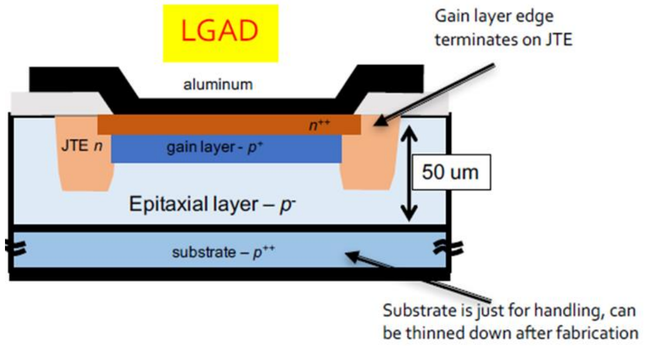
- Total project cost $26 M + 50% contingency = $39 M
  - Includes U.S. and International "new-money" contributions
  - Does not include $10 M worth of *existing* 3 ton LXe and its infrastructure from MEG II
  - Does not include evaluating the value of PSI's full support of beamline, installation, data storage, and general support
- 60% U.S.
- 40% International (Japan / Canada / Swiss)

- Net US Cost: $16 + $8 contingency = $24 M

FYI: We use LXe @ $2.56 M/ton as quoted to P5 by the XLZD "70 T"

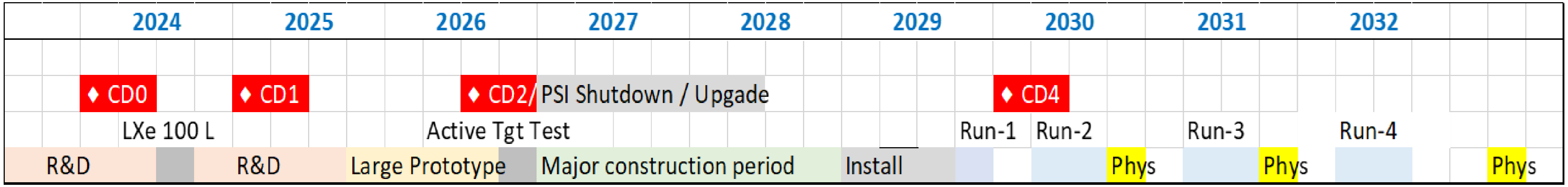
Needed R&D / Agencies

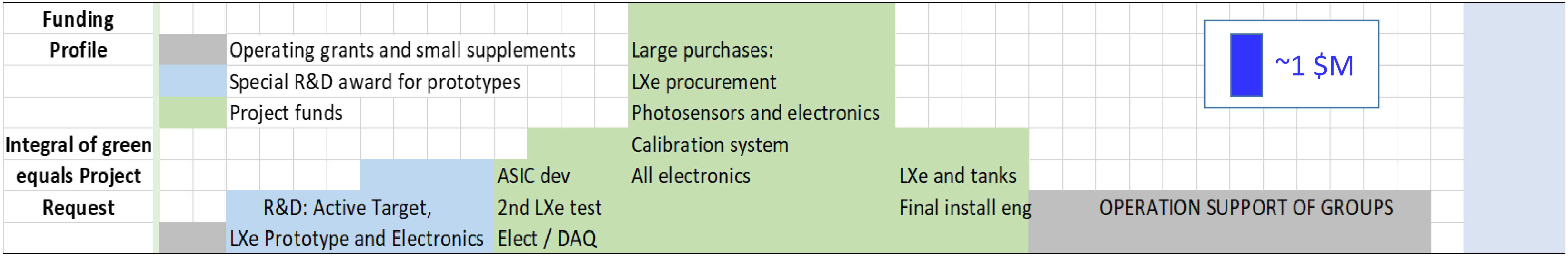
- R&D funds critically needed for next 2 years
  - Priorities: 5D Active Target development, custom electronics designs, 100 L LXe prototype (10% of TPC is target)



- Multi-Agency support?
  - DOE-HEP is viewed as funding source with BNL as Lead Lab
  - DOE and NSF Nuclear-funded groups have relatively smaller scope (by $) projects and are assumed to be supported by NP agencies

Timeline and budget. See backups for finer detail





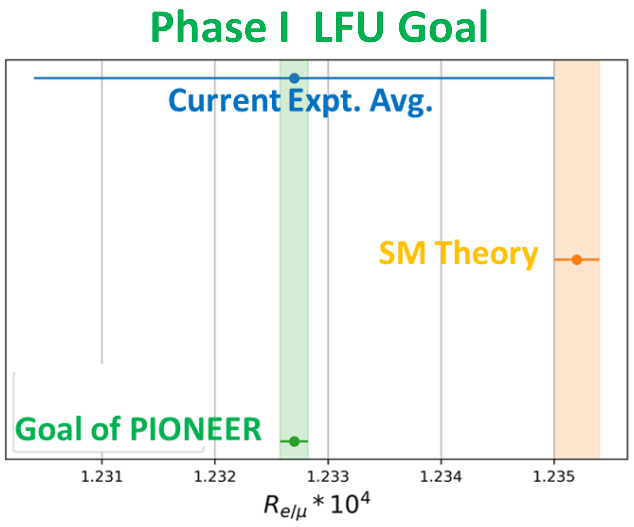
Physics* FTEs needed (i.e.; Scientific effort)

- R&D Phase
  - **~10 FTEs** presently on Calorimeter, Active Target, Simulations, Electronics, DAQ
    - This will rapidly grow with influx of R&D funding
- Construction Phase
  - **~30 FTEs** for testing, building, analyzing, simulations, pre-installations
    - Expect 5-10 graduate students and 5-10 postdocs and more senior scientists who are rolling off present commitments that will have ended
- Commissioning and Running Phase and Online Analysis
  - **~30 FTEs** (out of larger 100 person collaboration)
    - Expect more graduate students and postdocs here given the many physics channels and topics that serve thesis and other projects

*Engineering and technicians are included in R&D, Project, and Operating Grant support, but not counted here

PIONEER Summary and Request to P5

- A Unique Precision Test of Lepton Flavor Universality in a Next-Gen Pion Decay Experiment
  - Unprecedented 0.005% precision on LFU
  - Pion Beta Decay to obtain highest precision on V_{ud}
  - 10-fold improvements in sterile neutrino search

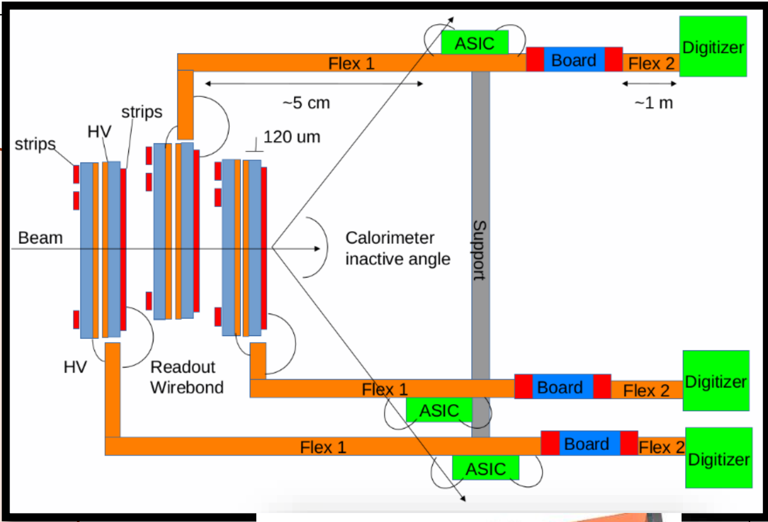


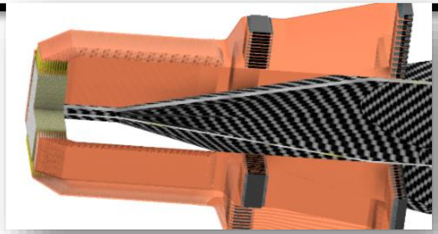
- PIONEER is approved at PSI where it will be strongly supported
  - While it is a US HEP-Led project, there is a significant international component
  - BNL is Lead Lab with very strong young leadership

- P5 Requests
  - Strong support of our physics program and a priority message to Agencies to initiate funding
  - We are “small” but our Physics Reach is large

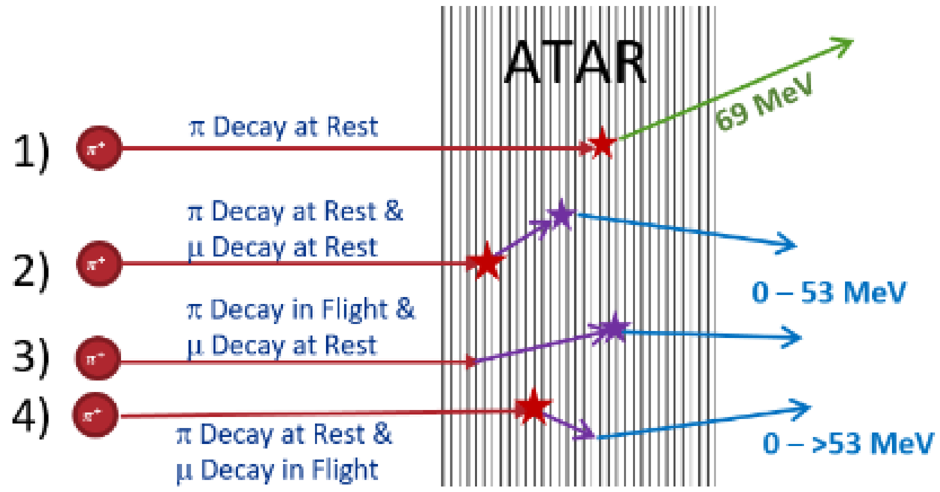
Active Target (ATAR)

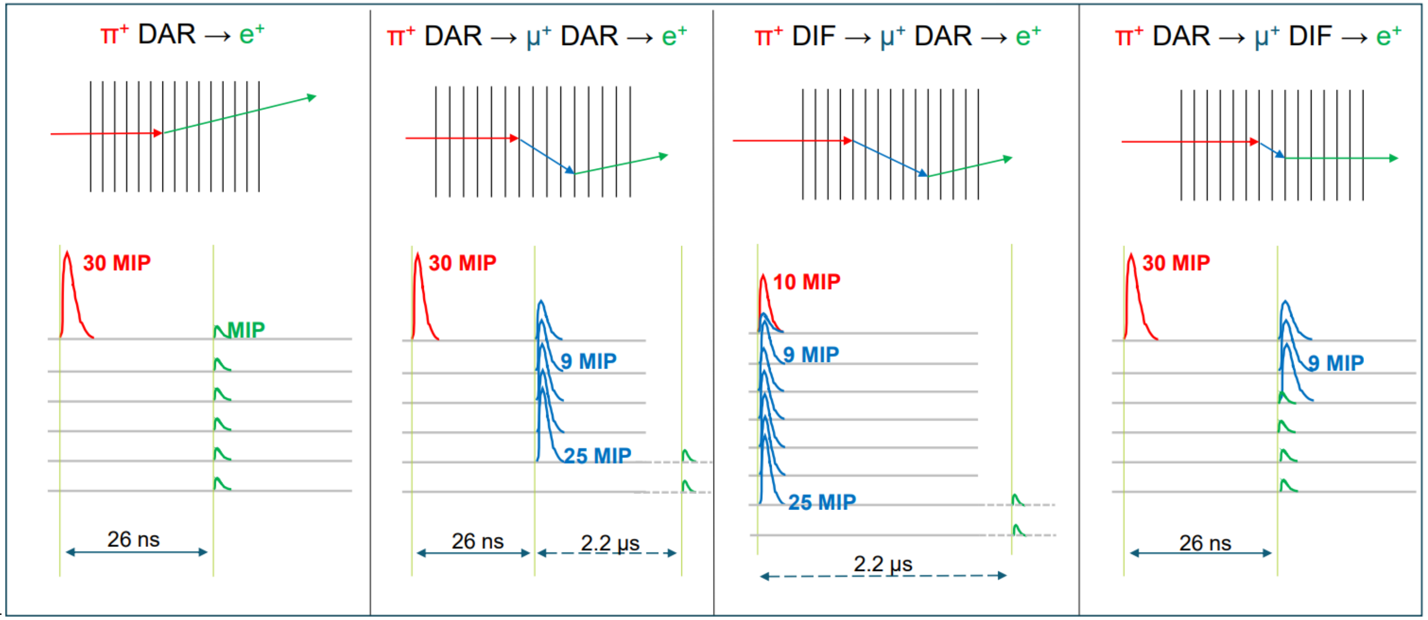
- **Full silicon active target (ATAR)**:
  - **High granularity** in (X,Y, Z), fast full collection time, good energy response, high dynamic range
  - Crucial to recognize decay chains that cannot be separated with the positron energy only
- The **chosen sensor for the ATAR is a high granularity Low Gain Avalanche Diode (LGAD) technology**
  - **Why LGADs? High S/N, full fast collection time, great time resolution**
  - Alternative design with standard Silicon being studied as well
- 48 compact layers of LGAD strip sensors, 2x2 cm wide, 6 mm thick
  - Complex event reconstruction to detect all types of pion decays
- **Fast electronic readout and fully digitized for each event**



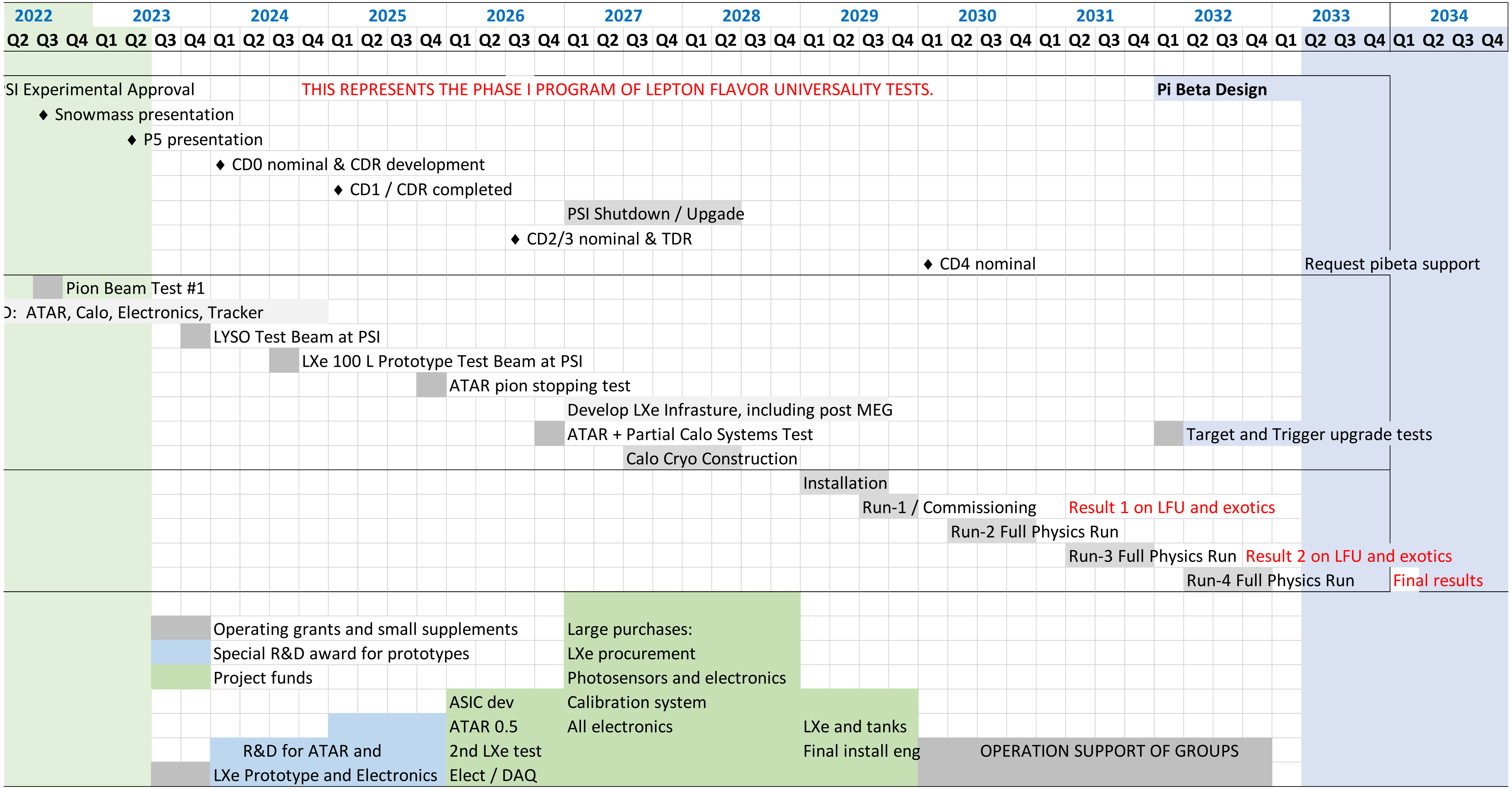


What happens ⟷ **What is measured**





Detailed Notional timeline & funding profile



U.S. and International approximate Scope division

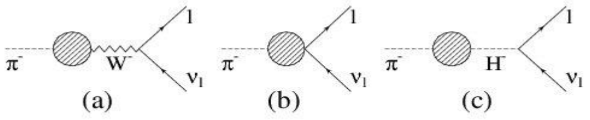
- **U.S. Scope**
  - Management, project costs
  - Active Target development and readout electronics
  - Calorimeter digital electronics
  - Trigger and DAQ
  - Calibration system for calorimeter
  - Tracker system
- **International Scope (Japan, Canada, Switzerland)**
  - Custom beamline elements
  - Fraction of new LXe purchase
  - Calorimeter photosensors, cabling, and power supplies
  - Cryo-vessel design and construction
  - Cryo infrastructure expansion beyond MEG II
  - Beamline detectors and LH_2 charge-exchange calibration infrastructure
  - Local installation support at PSI
  - Data storage at PSI

~ 60%

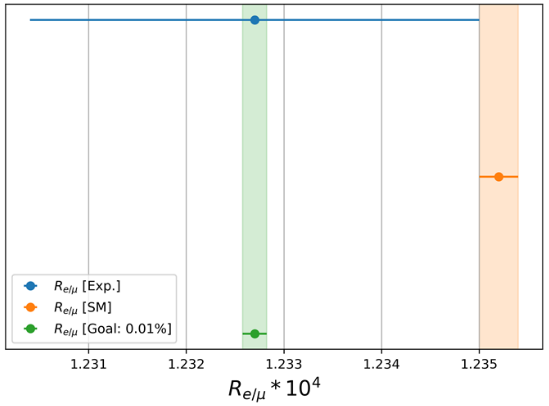
~40%

$\pi^+ \to e^+ \nu$ *LFU* Tests: Sensitivity to High Mass Scales

Pseudoscalar interactions



Charged Higgs (non-SM coupling)



$$1 - \frac{R^{New}_{e/\mu}}{R^{SM}_{e/\mu}} \sim \mp \frac{\sqrt{2}\pi}{G_\mu} \frac{1}{\Lambda^2_{eP}} \frac{m_\pi^2}{m_e(m_d + m_u)} \sim \left(\frac{1TeV}{\Lambda_{eP}}\right)^2 \times 10^3$$

Marciano…

Phase I PIONEER Goal: 0.01 % measurement→Λ~3000 TeV

Many others:

- **Leptoquarks**
- **Excited gauge bosons**
- **Compositeness**
- **SU(2)xSU(2)xSU(2)xU(1)**
- **Hidden sector ….**

Induced Scalar Currents

Campbell and Maybury (2005), Marciano

$R_{e/\mu}(0.01\%)$: $\Lambda_S > 180\, TeV\, (!)$

Apparent LFUV could also appear via massive sterile neutrinos (e.g. in $\pi^+ \to l^+ \nu_H$ with implications for leptogenesis (Elahi et al. 2109.09751).

Exotic Searches in PIONEER Phase I

Searches for
Sterile Neutrinos

$\pi \to e\nu_H$

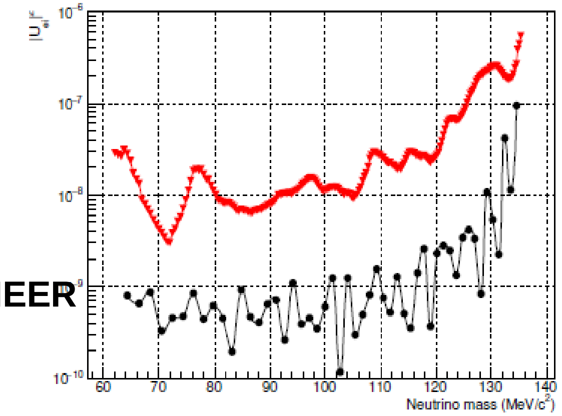
$\left|U_{e4}^2\right| vs\, m_H$

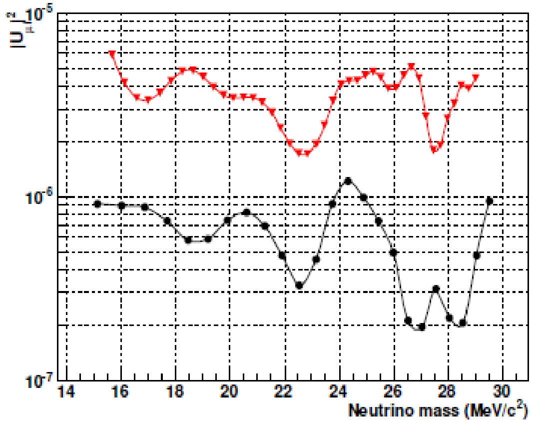
$\pi \to \mu\nu_H$

$\left|U_{\mu 4}^2\right| vs\, m_H$

PIENU

PIONEER





Also to be improved by an order of magnitude:

$$\pi \to \mathrm{e}/\mu\nu \mathrm{X};\ \pi \to \mathrm{e}/\mu\nu\nu\bar{\nu}$$

Strategy for 10^{-4} precision experiment

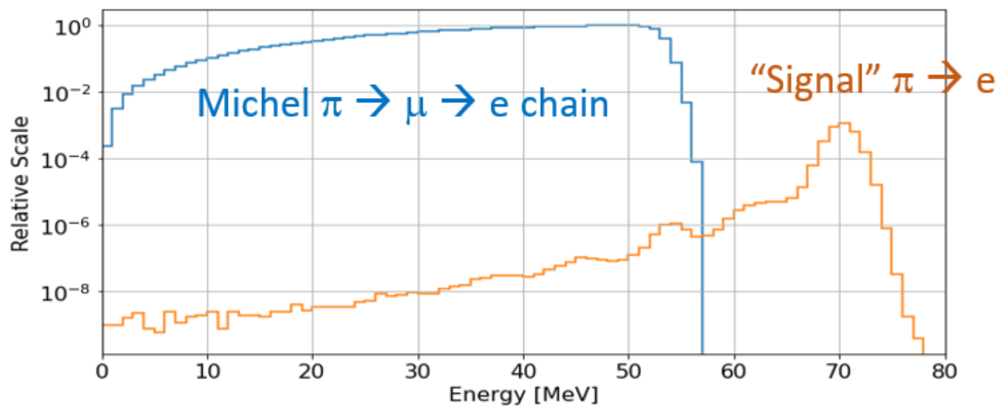
$$\sigma_{stat} = \sigma_{sys} = 0.7 \times 10^{-4}$$

- Analysis

$$\boxed{R_{e/\mu} = \frac{\pi \to e\nu(\gamma)}{\pi \to \mu\nu(\gamma)}}$$

  - fit high/low energy e^+ time distributions
    - $\pi - e$
    - $\pi - \mu - e$
    - background, pileup, etc

normalization & background

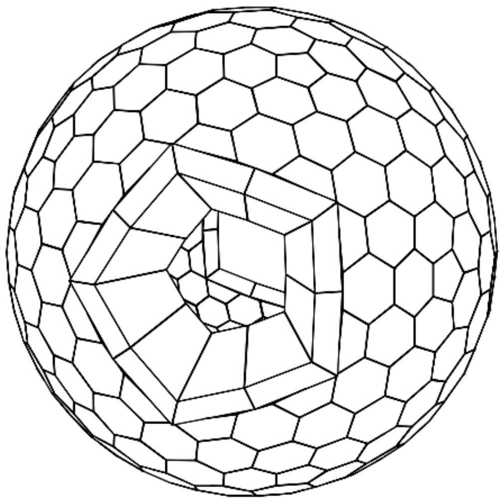


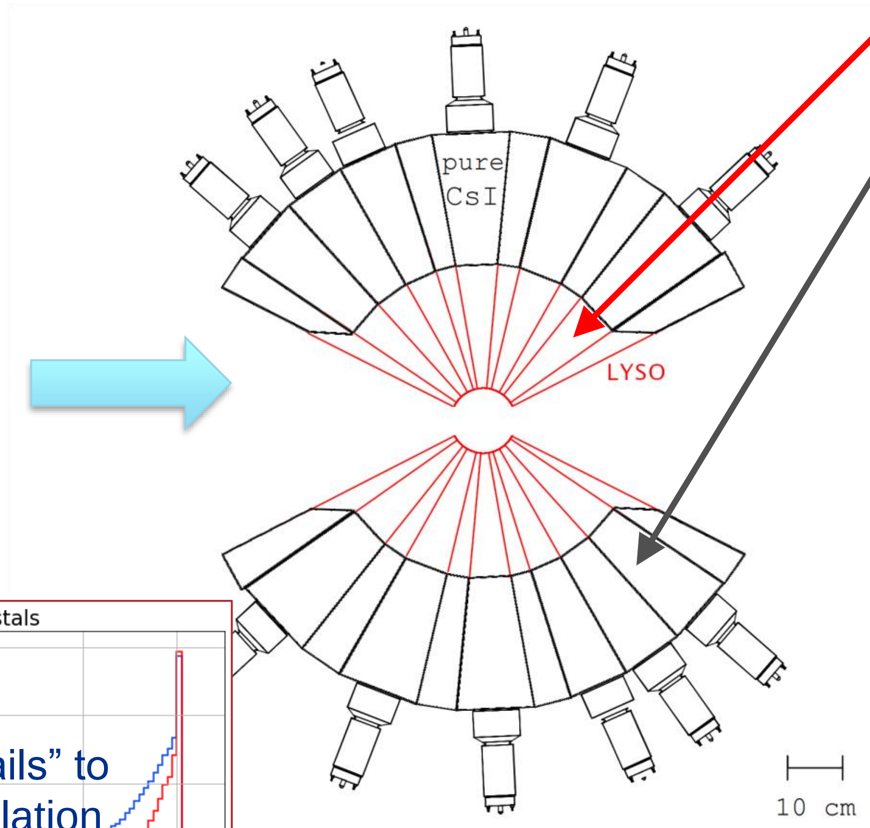
- Statistics
  - 2×10^8 $\pi \to e\nu$ events
    in 2-3 years with 3×10^5 π/s beam

- Systematic improvements
  - intense, high quality π^+ beam
  - active target with key new ideas and technology
  - calorimeter: 3π, $25X_0$, high res., fast

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**

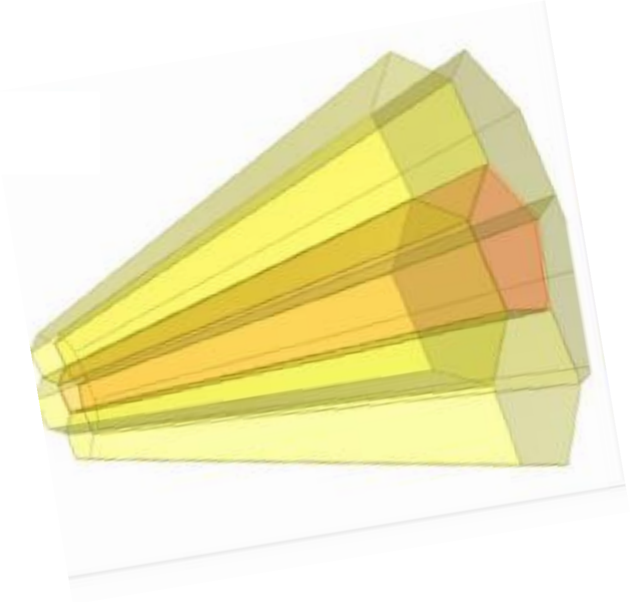
A LYSO based crystal CALO is being investigated to provide a comparison with LXe. To date, no LYSO test array has met our required precision goal but we are testing new crystals to see if improvements have been achieved.

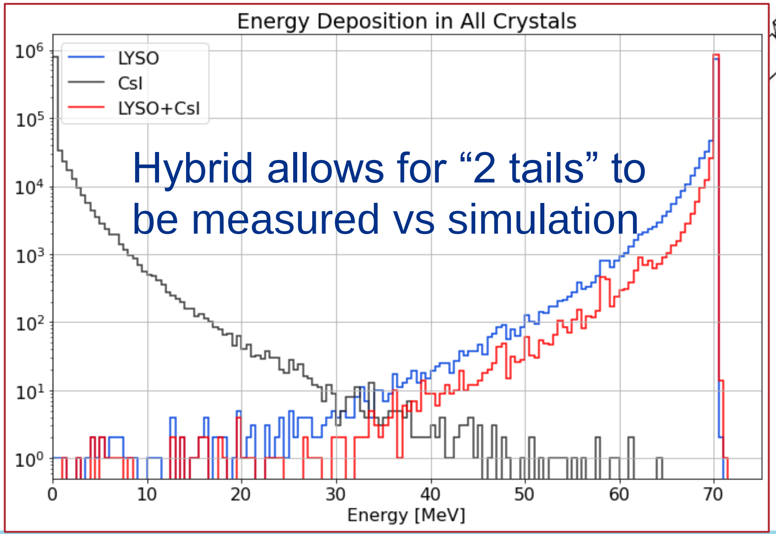




New LYSO $(16\ X_0)$

+ PEN CsI xtals $(12\ X_0)$

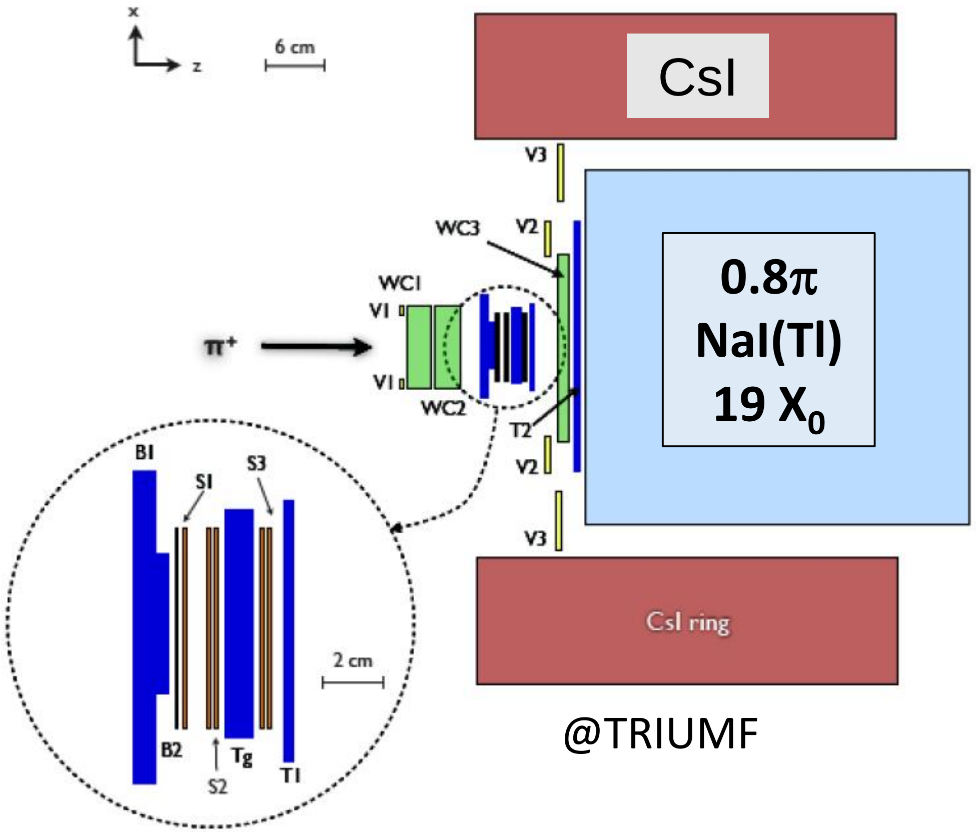




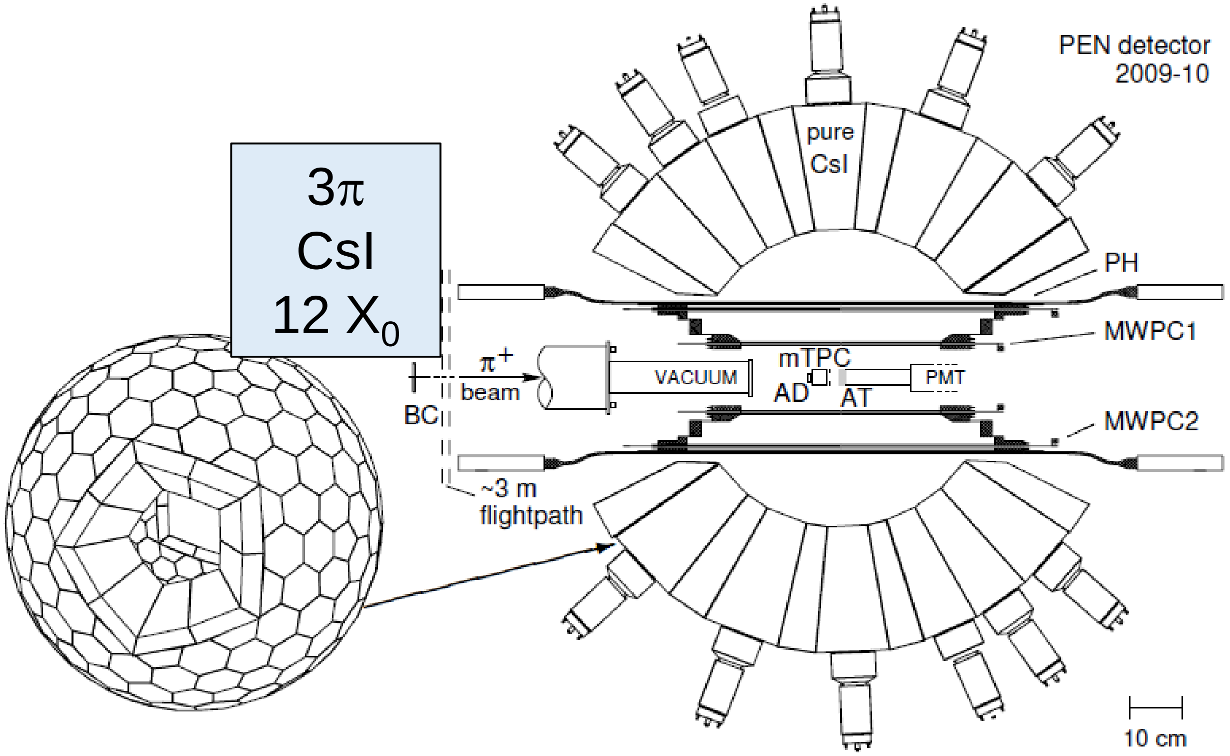
- Fast, segmented, compact
- Is resolution good enough?
- LYSO for HEP not yet demonstrated, given its promise and extensive use in PET

Two (rather different) Pion Decay Experiments: PIENU and PEN/PIBETA

Both took data a long ago but have (known) challenges to overcome before final results



@TRIUMF



@PSI

- NaI slow, but excellent resolution
- Single large crystal but shower leakage depends on angle changing resolution and tail fraction
- Small solid angle

- Good geometry but calorimeter depth of $12X_0$ too small to resolve tail under muon spectrum.

WBS Examples

1	Project Management	
	1.1	Project Manager/CAM
	1.2	Deputy PM
	1.3	Controls
	1.4	Project ME/EE
	1.5	Reviews/travel
2	Beamline	
	2.1	Management and conceptual design
	2.2	Instrumentation
	2.3	Entrance Counters and Readout
	2.4	Separator
3	Active Target (ATAR)	
	3.1	Management and conceptual design
	3.2	LGAD sensors
	3.3	Frontends, readout, and cabling
	3.3.1	Frontend
	3.3.2	Cabling
	3.4	Power supplies
	3.5	Calibration
	3.6	Mechanical support
4	Tracker	
	4.1	Management and conceptual design
	4.2	Detector
	4.3	Frontends, readout, and cabling
	4.4	Power supplies
	4.5	Calibration
	4.6	Mechanical support
5	Calorimeter (LXe)	
	5.1	Management and conceptual design
	5.2	Xenon procurement
	5.3	Cryogenic plant
	5.3.1	Liquid storage
	5.3.2	Gas storage
	5.3.3	Purification
	5.3.4	Purity monitor
	5.4	Cryo Control/UPS
	5.5	Photosensors
	5.6	Frontends, readout, and cabling
	5.7	Power supplies
	5.8	Calibration
	5.9	Mechanical Support

5a	Calorimeter (LYSO)	
	5a.1	Management and conceptual design
	5a.2	Crystals & Mechanical Support
	5a.3	Photosensors and frontend
	5a.4	Power supplies and cables
	5a.5	Calibration
6	Electronics	
	6.1	Management and conceptual design
	6.2	Clock and control
	6.3	Hardware Trigger
	6.4	Calo WFDs
	6.5	LGAD WFDs
	6.6	Tracker TDCs
	6.7	Other backend electronics
	6.8	UPS
7	DAQ and Computing	
	7.1	Management and conceptual design
	7.2	Control Room
	7.3	Computing (Midas level)
	7.4	Online (DQM / DB / Nearline)
	7.5	Data storage (PSI provide?)
	7.6	Offline
	7.7	Slow controls
8	Installation	
	8.1	Management and conceptual design
	8.2	Beamline
	8.3	Calorimeter and tracker
	8.4	ATAR
	8.5	Alignment
	8.6	Counting House (physical)
	8.7	Power and grounds

WBS Examples (WBS 3.1&3.2 ATAR related …

The Conceptual design costs are those to go from the CD-0 Mission Need Approval in Jan 2024 to the CD-1 Review in Jan 2025. Pre-CD0 accom

Conceptual Design (~1 year): Covers cost to produce conceptual design needed for CD-1 review, 1st pass at engi

Labor table -

Activity Name	Labor Type	Hours	Labor Source	Funding Type	Estimate Unc.	
New FAST board design	Electric…	40	Univer…	DOE P…	Rough…	UW
New FAST board design	Electric…	40	Univer…	DOE P…	Rough…	UCSC
FAST board assembly	Electric…	40	Univer…	DOE P…	Rough…	UW-UCSC
TCAD simulation	Electron…	320	Univer…	Base (…	Rough…	UCSC
BNL sensor design	Scientist	120	US Lab	DOE P…	Rough…	BNL
BNL sensor production testing	Scientist	40	Univer…	Base (…	Rough…	UCSC-UW
BNL sensor production testing	Student…	160	Univer…	Base (…	Rough…	UCSC-UW
Sensor-board assembly	Mechan…	20	Univer…	Base (…	Rough…	UCSC
Characterization of board	Scientist	40	Univer…	DOE P…	Rough…	UCSC-UW
FAST on flex design studies	Electric…	100	Univer…	DOE P…	Rough…	UCSC-UW
FAST on flex prototype	Electric…	60	Univer…	DOE P…	Rough…	
Thermal demonstrator assembly	Mechan…	40	Univer…	DOE P…	Rough…	UW
Thermal demonstrator testing	Scientist	80	Univer…	Base (…	Rough…	UW
PiN readout design	Electric…	60	Univer…	Base (…	Rough…	UCSC
HD-SoC characterization	Scientist	160	Univer…	Base (…	Rough…	UCSC
Mechanical structure design	Mechan…	60	Univer…	DOE P…	Rough…	UW
Mechanical support design	Mechan…	60	Univer…	DOE P…	Rough…	UW
Assembly jig design & documentation	Mechan…	40	Univer…	DOE P…	Rough…	UW
Assembly jig fabrication	Mechan…	40	Univer…	DOE P…	Rough…	UW
Assembly process development	Mechan…	24	Univer…	DOE P…	Rough…	UW
Assembly process development	Mechan…	24	Univer…	DOE P…	Rough…	UW
Assembly process documentation	Mechan…	24	Univer…	DOE P…	Rough…	UW
Mechanical structure assembly	Mechan…	40	Univer…	DOE P…	Rough…	UW
Mechanical structure assembly	Mechan…	80	Univer…	DOE P…	Rough…	UW
Mechanical structure assembly	Electric…	40	Univer…	DOE P…	Rough…	UW

M&S and Contracted Labor table -

Item Descriptions	Direct Cost ($k)	Funding Type	Estimate Unc.			
FAST board production	6	Base (…	Rough…			
Flex board production	3	Base (…	Conc …			
BNL sensor production	100	DOE P…	Vendo…		BNL LDRD	right number?
Thermal demosntrator parts	1	Base (…	Rough…			
TI-LGAD shared production	20	Base (…	Rough…			
Mechanical parts	2	Base (…	Rough…			
Cables	1	Base (…	Rough…			
Travel	5	Base (…	Rough…			

Preliminary Design (~1 year): Covers cost from CD-1 to producing CD-2 level preliminary design, 3d drawings, improved estimates

Labor table -

Activity Name	Labor Type	Hours	Labor Source	Funding Type	Estimate Unc.	Hourly Rate	Activity Cost
Mask design	Scientist	80	US Lab	DOE …	Rough…	$269.75	$21,580.00
Electrical testing	Student…	40	Univer…	Base (…	Rough…		$0.00
Dynamic/TB testing	Scientist	40	Univer…	Base (…	Rough…		$0.00
Dynamic/TB testing	Student…	160	Univer…	Base (…	Rough…		$0.00
TCAD simulation	Scientist	160	Univer…	Base (…	Rough…		$0.00
Sensor assembly	Mechan…	20	Univer…	Base (…	Rough…	$60.00	$1,200.00

M&S and Contracted Labor table -

Item Descriptions	Direct Cost ($k)	Funding Type	Estimate Unc.	O/H Rate	Total Cost
AC-LGAD-pin prototype production	100	DOE …	Rough…	#N/A	
Readout board production	5	DOE …	Rough…		
TI-LGAD (alternative tech) prototype produc	100	DOE …	Rough…		
Sensor coating or special assembly	2	DOE …	Rough…		
Travel	5	Base (…	Rough…		

Final Design (~1 year): Covers cost to produce CD-3 level final design, final shop drawings, final prototypes)

Labor table -

Activity Name	Labor Type	Hours	Labor Source	Funding Type	Estimate Unc.	
Mask design	Scientist	80	US Lab	DOE …	Rough…	Updated by Volodya
Electrical testing	Student…	40	Univer…	Base (…	Rough…	
Dynamic/TB testing supervise	Scientist	40	Univer…	Base (…	Rough…	
Dynamic/TB testing	Student…	160	Univer…	Base (…	Rough…	
QC supervise	Scientist	40	Univer…	Base (…	Rough…	
QC	Student…	160	Univer…	Base (…	Rough…	
TCAD simulation	Scientist	80	Univer…	Base (…	Rough…	
Sensor assembly	Mechan…	40	Univer…	Base (…	Rough…	

M&S and Contracted Labor table -

Item Descriptions	Direct Cost ($k)	Funding Type	Estimate Unc.
Sensor prototype production with full size	100	DOE …	Rough…
Readout board production	5	DOE …	Rough…
Sensor coating or special assembly	2	DOE …	Rough…
Travel	5	Base (…	Rough…

Implemenation (1-2 years): Covers cost to build experiment (installation covered in separate WBS)

Labor table -

Activity Name	Labor Type	Hours	Labor Source	Funding Type	Estimate Unc.
Mask design	Scientist	80	US Lab	DOE …	Rough…
QC supervise	Scientist	40	Univer…	Base (…	Rough…
QC	Student…	160	Univer…	Base (…	Rough…
Dynamic/TB testing	Student…	320	Univer…	Base (…	Rough…
TCAD simulation	Scientist	80	Univer…	Base (…	Rough…

M&S and Contracted Labor table -

Item Descriptions	Direct Cost ($k)	Funding Type	Estimate Unc.
Sensor production	100	NSF …	Rough…
Handling devices and supports	10	NSF …	Rough…
Sensor coating or special assembly	10	DOE …	Rough…
Travel	10	Base (…	Rough…

Assumptions: (Document assumptions that went into these estimates, see examples)

Assuming AC-LGAD technology, a final PIN-only production costs less (no GL implantation) but prototypes will likely all be on shared wafers

TI-LGAD is more expensive, double sided is more expensive

AC-LGAD charge sharing can be contained to first neighbor, very small long range sharing

Gain saturation is limited to a reasonable level

2 prototype productions are enough for the final design

WBS Examples
(WBS 6.4; Calo digitizers)

Preliminary Design (~1 year): Covers cost from CD-1 to producing CD-2 level preliminary design, 3d drawings, improved estimates, prototypes, advanced

Labor table -

Activity Name	Labor Type	Hours	Labor Source	Funding Type	Estimate Unc.	
1 FPGA (4 channel) prototype WFD	Electron...	640	Univer...	Other	Rough...	includes schematics and board design
1 FPGA prototype firmware	Electron...	400	Univer...	Other	Rough...	
Experimental interface Firmware, prototype	Student...	900	Univer...	Base (...	Rough...	

M&S and Contracted Labor table -

Item Descriptions	Direct Cost ($k)	Funding Type	Estimate Unc.	
PCB fabrication	4.5	Other	Conc ...	
XCKU025-2 FPGAs	6.3	Other	Catalo...	This price will come down when I get price break i
AD9234 digitizers	7.3	Other	Catalo...	See L. Gibbons' WFD_pioneer spreadsheet
Other IC components (specified)	2.0	Other	Catalo...	
Non IC components (estimated)	0.3	Other	Conc ...	
Board assembly	3.0	Other	Conc ...	Based on g-2 WFD5 costs -- similar complexity
Power mezzanine	1.5	Other	Conc ...	Based on g-2 WFD5 costs -- similar complexity
Analog Front End (AFE) mezzanine	2.5	Other	Conc ...	Based on g-2 WFD5 costs -- similar complexity
Firefly assemblies	3.8	Other	Vendo...	
Crate	1.5	Other	Conc ...	

Final Design (~1 year): Covers cost to produce CD-3 level final design, final shop drawings, final prototypes)

Labor table -

Activity Name	Labor Type	Hours	Labor Source	Funding Type	Estimate Unc.
Revisions / full 12 channel prototype WFD	Electron...	320	Univer...	NSF ...	Rough...
Full 12 channel WFD firmware	Electron...	160	Univer...	NSF ...	Rough...
Experimental interface firmware, revisions	Student...	500	Univer...	Base (...	Rough...

M&S and Contracted Labor table -

Item Descriptions	Direct Cost ($k)	Funding Type	Estimate Unc.	
PCB fabrication	5.0	NSF ...	Conc ...	
XCKU025-2 FPGAs	18.9	NSF ...	Catalo...	This price will come down when I get price break i
AD9234 digitizers	21.8	NSF ...	Catalo...	See L. Gibbons' WFD_pioneer spreadsheet
Other IC components (specified)	2.0	NSF ...	Catalo...	
Non IC components (estimated)	0.5	NSF ...	Conc ...	
Board assembly	3.0	NSF ...	Conc ...	Based on g-2 WFD5 costs -- similar complexity
Power mezzanine	1.5	NSF ...	Conc ...	Based on g-2 WFD5 costs -- similar complexity
Analog Front End (AFE) mezzanine	2.5	NSF ...	Conc ...	Based on g-2 WFD5 costs -- similar complexity
Firefly assemblies	3.8	NSF ...	Vendo...	
Crate	1.5	NSF ...	Conc ...	

Implemenation (1-2 years): Covers cost to build experiment (installation covered in separate WBS)

Labor table -

Activity Name	Labor Type	Hours	Labor Source	Funding Type	Estimate Unc.
Revisions / production package	Electron...	160	Univer...	NSF ...	Rough...
Final firmware revisions, testing and installa	Electron...	80	Univer...	NSF ...	Rough...
Final experimental firmware revisions	Student...	160	Univer...	Base (...	Rough...
Assembly / testing / installation	Student...	300	Univer...	Base (...	Rough...

M&S and Contracted Labor table -

Item Descriptions	Direct Cost ($k)	Funding Type	Estimate Unc.
PCB fabrication	17.0	NSF ...	Conc ...
XCKU025-2 FPGAs	247.6	NSF ...	Catalo...
AD9234 digitizers	371.3	NSF ...	Catalo...
Other IC components (specified)	45.4	NSF ...	Catalo...
Non IC components (estimated)	8.5	NSF ...	Conc ...
Board assembly	17.0	NSF ...	Conc ...
Power mezzanine	9.4	NSF ...	Conc ...
Analog Front End (AFE) mezzanine	17.0	NSF ...	Conc ...
Firefly assemblies	59.5	NSF ...	Vendo...
Crates	18.0	NSF ...	Conc ...