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PIONEER

Precision Measurements of Rare Pion Decays

P. Schwendimann on behalf of the PIONEER collaboration

W. Altmannshofer, O. Beesley, H. Binney, E. Blucher, D. Bryman, L. Caminada, S. Chen, V. Cirigliano, S. Corrodi, A. Crivellin, S. Cuen-Rochin, K. Dehmelt, A. Deshpande, A. DiCanto, L. Doria, A. Gaponenko, P. Garg, A. Garcia, L. Gibbons, C. Glaser, M. Escobar Godoy, D. Göldi, S. Gori, T. Gorringe, D. Hertzog, Z. Hodge, M. Hoferichter, S. Ito, T. Iwamoto, P. Kammel, B. Kiburg, K. Labe, J. LaBounty, U. Langenegger, C. Malbrunot, S.M. Mazza, S. Mihara, R. Mischke, A. Molnar, T. Mori, J. Mott, T. Numao, W. Ootani, J. Ott, K. Pachal, C. Polly, D. Počanić, X. Qian, D. Ries, R. Roehnelt, B. Schumm, P. Schwendimann, A. Seiden, A. Sher, R. Shrock, A. Soter, T. Sullivan, M. Tarka, V. Tischenko, A. Tricoli, B. Velghe, V. Wong, E. Worcester, M. Worcester, C. Zhang

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14th Conference on the Intersections of Particle and Nuclear Physics

Primary Goals of PIONEER

Precision Measurements of Rare Pion Decays [1]

Phase I: e/μ Decay Branching Ratio

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

with a precision $< 0.01\,\%$

Phase II: PiBeta Decay

$$R_{\pi\beta} = \frac{\Gamma(\pi^+ \to \pi^0 e^+\nu)}{\Gamma(\text{all})}$$

with a precision $< 0.2\,\%$

Pioneer Experiment approved by Paul Scherrer Institute

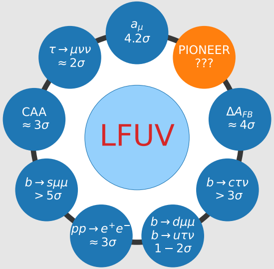
- Proposal: https://arxiv.org/abs/2203.01981
- PSI Website: https://www.psi.ch/en/pioneer

Lepton Flavour Universality Violation?

Lepton Flavour Universality (LFU)

(Bare) coupling for all leptons is given by the Fermi Constant G_F.

Hints to new physics [2]



PIONEER Physics Cases

Phase I: $R_{e/\mu}$

- Test $G_F^{(\mu)} \stackrel{?}{=} G_F^{(e)} \stackrel{?}{=} G_F$

Phase II: $R_{\pi\beta}$

- Measure $|V_{us}/V_{ud}|$ to 0.2 %
- CKM-Matrix unitarity check

Exotic Searches

- e.g. Heavy Neutral Lepton

Improving Experimental Precision for $R_{e/\mu}$

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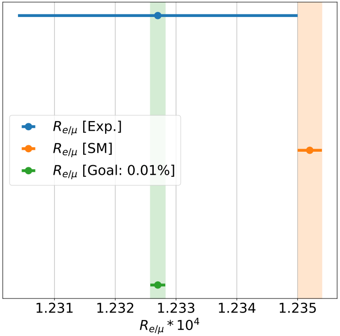
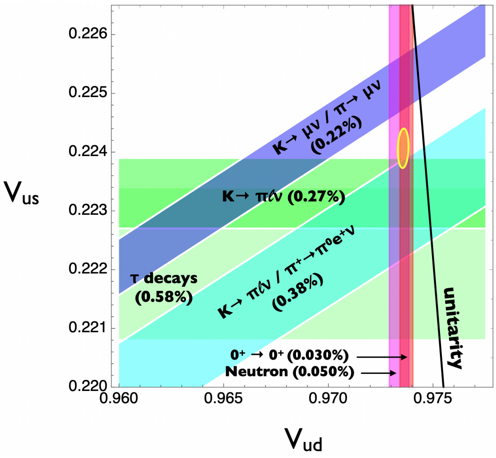


$$R_{e/\mu}(\text{SM}) = 1.23\mathbf{524(015)} \times 10^{-4} \quad [3]$$
$$R_{e/\mu}(\text{EXP}) = 1.23\mathbf{270(230)} \times 10^{-4} \quad [4]$$

Excellent channel to probe the SM and most precise test of Lepton Flavour Universality Violation (LFUV).

Implications of an improved $R_{\pi\beta}$



D. Bryman et al. [3]

CKM Unitarity Test, $|V_{us}/V_{ud}|$

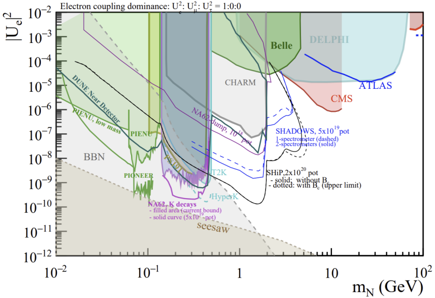
- $K \to \pi l \nu \quad / \quad \pi^+ \to \pi^0 e^+ \nu$ dominated by PiBeta decay uncertainties.
- PIONEER Phase II:

$$0.38\,\% \to 0.2\,\%$$

Determining $|V_{ud}|$ by $\pi^+ \to \pi^0 e^+ \nu$

- Cleanest theory determination
- Experimental uncertainty too large for now.

Exotic Searches with PIONEER



A. M. Abdullahi et al. [5]

Heavy Neutral Lepton

$$\pi^+ \to l^+ N$$

Other Dark Sector Decays

- $\pi^+ \to l^+ \nu X$
- $\pi^+ \to l^+ X Y$
- $\mu^+ \to e^+ X$

The Basics of Pion Decays

Reminders

π^+	Lifetime:	26 ns
π^+	Mass:	139 MeV
μ^+	Lifetime:	2197 ns
μ^+	Mass:	106 MeV

Pion Decays

$\pi^+ \rightarrow \mu^+\nu(\gamma),\ \mu^+ \rightarrow e^+\nu\nu$	99.9877 %
$\pi^+ \rightarrow e^+\nu(\gamma)$	1.2327×10^{-4}
$\pi^+ \rightarrow \pi^0 e^+\nu,\ \pi^0 \rightarrow \gamma\gamma$	1.036×10^{-8}

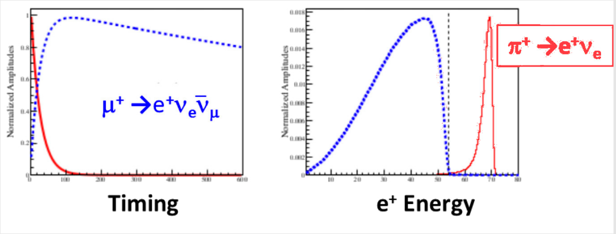
Signatures

$\pi \rightarrow \mu\nu$ $\quad E_e < m_\mu/2$

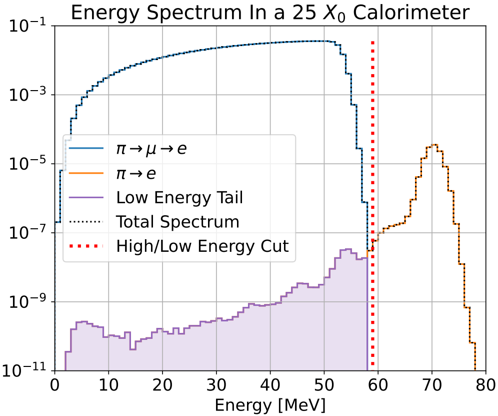
$\boldsymbol{E_e}$ < 53 MeV

$\pi \rightarrow e\nu$ $\quad E_e = m_\pi/2$

$\boldsymbol{E_e}$ ≈ 69 MeV



The Devil in the (de)Tail



Calorimeter Effects

No calorimeter is perfect ...

- Finite resolution
- Tail due to energy leakage
- Photonuclear effects
- Interaction details matter

Need to reveal and characterise the tail to reach the desired precision!

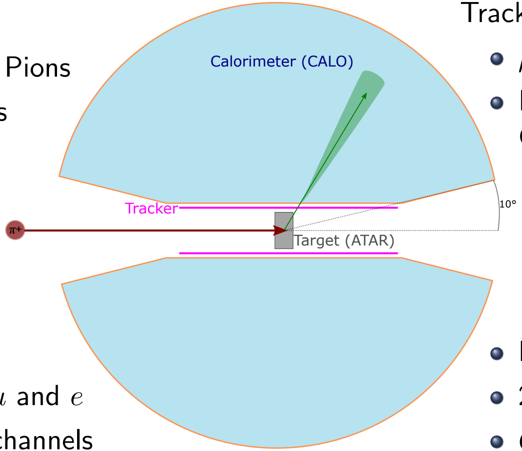
The Basic Detector Concept

Beam

- 65 MeV/c Pions
- 3×10^5 π/s

Tracker

- μRWELL?
- Match ATAR hits to Calo hits



Active Target

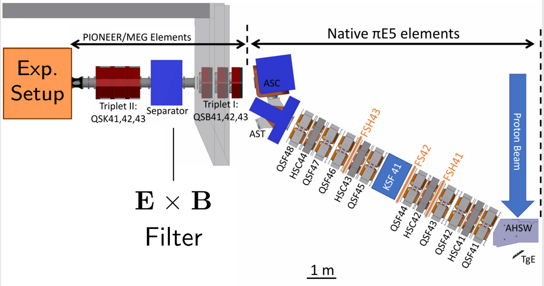
- LGADs
- Track π, μ and e
- $\mathcal{O}(5000)$ channels

Calorimeter

- LXe vs LYSO/CsI
- 25 X_0
- $\mathcal{O}(1000)$ channels

Requiring the World's Brightest Stopped Pion Beam

PiE5 Secondary Beamline at PSI

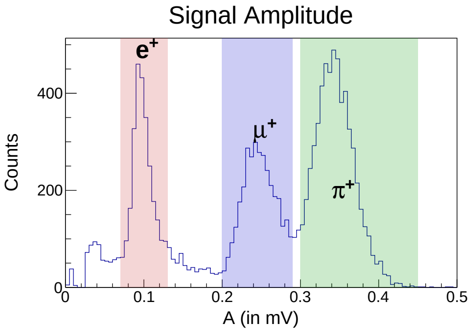


Requirements

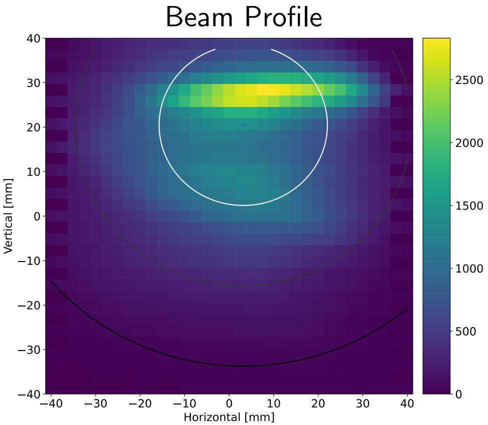
- Momentum: 65 MeV/c ✅
- Rate: $> 300\,000\ \pi^+/s$ ✅
- Beam Size: $\sigma_x, \sigma_y < 10$ mm ✅
- Momentum Bite: $dp/p < 2\,\%$ ✅
- Contamination: $< 10\,\%\ e, \mu$ 🚧

Learning beamline properties in test beams and improve to reach our goals.

Test Beam at PSI: Characterising the Beam Properties

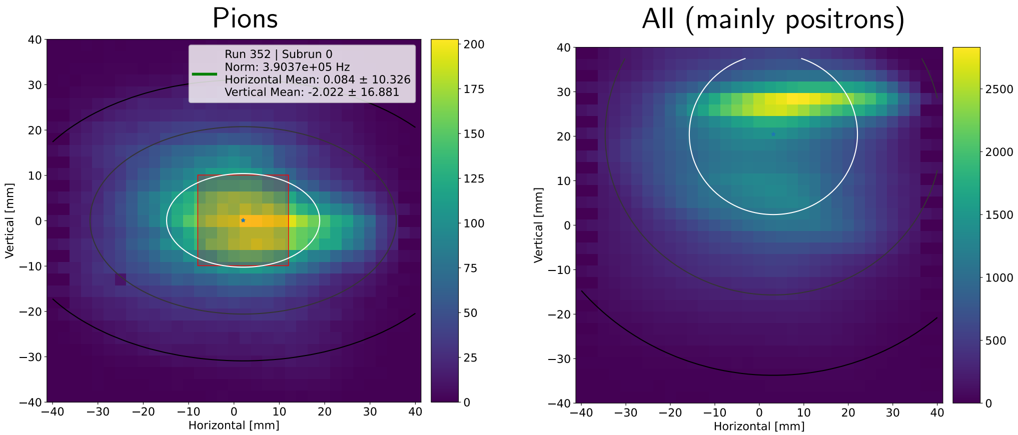


Single 2×2 mm Scintillator



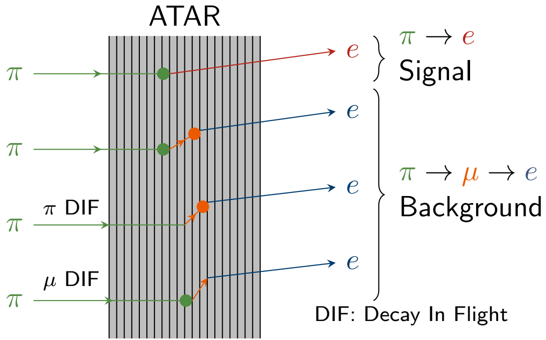
Reject e, μ by adjusting trigger threshold to count only π^+

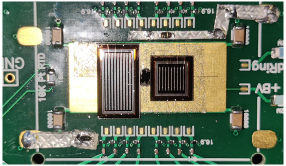
Partially Successful Beamline Optimisation



Only partial separation of pions. Beamline modifications required.

To Measure the Tail: Active Target for 4D tracking





Design Concept

- Size: 20 mm $\times$ 20 mm $\times$ 6 mm
- 48 alternating Layers
- 100 Channels per Layer

Low Gain Avalance Detector

LGADs with 120 µm active thickness

- Modest Gain $(10 - 50)$
- Time Resolution $<$ 100 ps
- Full Charge Collection $\approx$ 2 ns
- Intense R&D at UCSC

Dedicated Trigger to See the Tail

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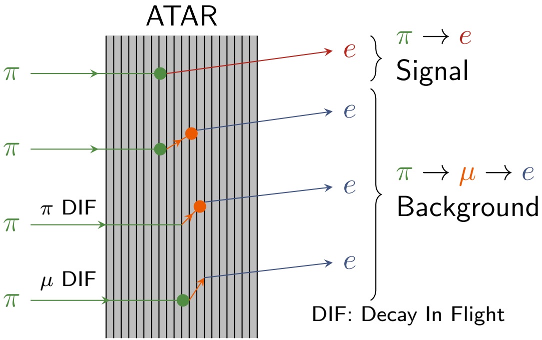
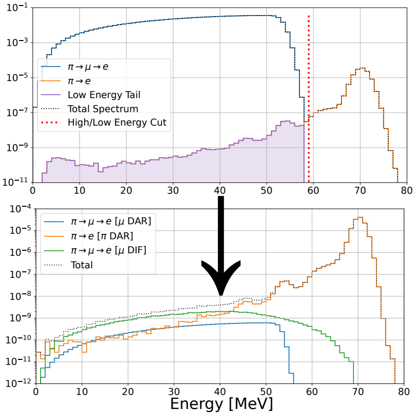
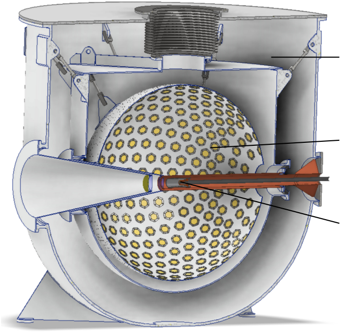




Background suppression reveals the tail such that it can be corrected for.

To Suppress the Tail: $25\ X_0$ Calorimeter

Baseline Design



Conceptual Design

- 9 t LXe sphere in insulation vacuum
- $\approx$ 1000 channel readout.

Experience from MEG II [6]

- Fast: sub-ns timing, $\approx$ 40 ns decay
- 1.7 % peak resolution for 55 MeV γ

Liquid Xenon Challenges

- 9 t Liquid Xenon
- VUV Photosensors

R&D for Crystal Calorimeter Alternative

Recycle PEN Calorimenter

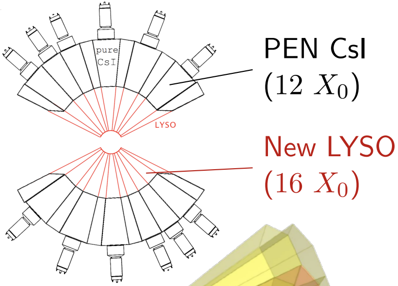
Use existing PEN Calorimeter (already at PSI) and match an inner LYSO layer.

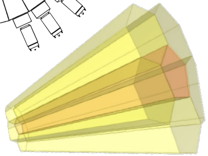
LYSO Benefits

- Fast (Competitive with LXe)
- Compact ($16\ X_0 \approx 20\,\mathrm{cm}$)
- Segmented

LYSO Challenges

- Is energy resolution good enough?
- LYSO not yet demonstrated in HEP.





Characterisation of LYSO crystals ongoing at UW.

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PIONEER is approved by PSI and supported by a growing international collaboration of physicists from broad communities.

Exciting Physics to be explored

- $R_{e/\mu}$: Lepton Flavour Universality Violation
- $R_{\pi\beta}$: important implication for CKM unitarity.
- Exotic physics searches follow automatically from these precision measurements.

Required for Success

- State of the art active target with 4D tracking
- High resolution, fast and deep calorimeter
- The world's most intense stopping pion beamline
- State of the art electronics

Institutes Involved

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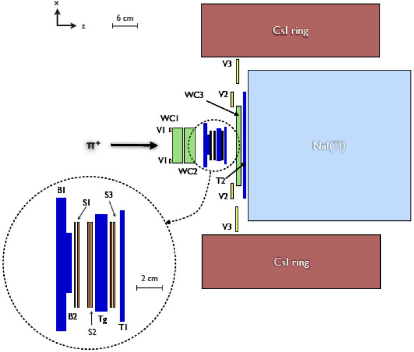
Further Reading

Santa Cruz Institute for Particle Physics (SCIPP), University of California Santa Cruz
Department of Physics, University of Washington
Institute for Nuclear Theory, University of Washingtons
Enrico Fermi Institute and Department of Physics, University of Chicago
Department of Physics & Astronomy, University of British Columbia
TRIUMF
Paul Scherrer Institute
Department of Engineering Physics, Tsinghua University
Argonne National Laboratory
Physik-Institut, University of Zurich
Division of Theoretical Physics, CERN
Tecnológico de Monterrey, School of Engineering and Sciences
Department of Physics and Astronomy, Stony Brook University
C. N. Yang Institute for Theoretical Physics, Stony Brook University
Physics Department, Brookhaven National Laboratory
Instrumentation Division, Brookhaven National Laboratory
PRISMA^{+} Cluster of Excellence and Johannes Gutenberg University Mainz
Department of Chemistry – TRIGA site, Johannes Gutenberg University Mainz
Fermi National Accelerator Laboratory
Department of Physics, Cornell University
Department of Physics, University of Virginia
ETH Zurich
Department of Physics and Astronomy, University of Kentucky
Albert Einstein Center for Fundamental Physics, Institute for Theoretical Physics, University of Bern
KEK, High Energy Accelerator Research Organization
International Center for Elementary Particle Physics (ICEPP), The University of Tokyo
Department of Physics and Astronomy, University of Victoria

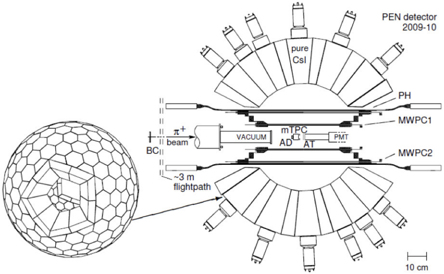
Previous Pion Decay Experiments: PIENU and PEN/PiBeta

PIENU @ TRIUMF [7]



$0.8\pi, 19X_0$ NaI

PEN/PiBeta @ PSI [8]



$3\pi, 12X_0$ CsI

Exotic Searches

e.g. Heavy Neutral Lepton

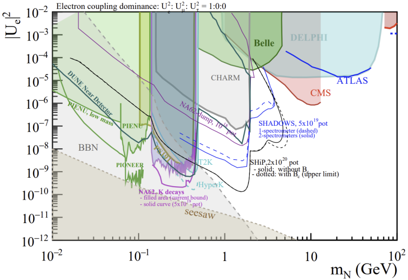


Figure 26: Heavy Neutral Leptons with coupling to the first lepton generation. Filled areas are existing bounds from: PS191 [31], CHARM [576], PIENU (peak searches [24] and bounds at low masses [38, 39, 566]), NA62 (K_{eN}) [28], T2K [36], Belle [577]; DELPHI [544], ATLAS [327] and CMS [340]. Colored curves are projections from: NA62-dump [405], NA62 K^+ decays (extrapolation obtained by the Collaboration based on [28]), PIONEER [565], SHADOWS [519], DarkQuest [561], SHiP [448], DUNE near detector (projections based on methods developed in [539]), and Hyper-K (projections based on [36]). The BBN bounds are from [445] and heavily depend on the model assumptions (hence they should be considered indicative). The seesaw bound is computed under the hypothesis of two HNLs mixing with active neutrinos.

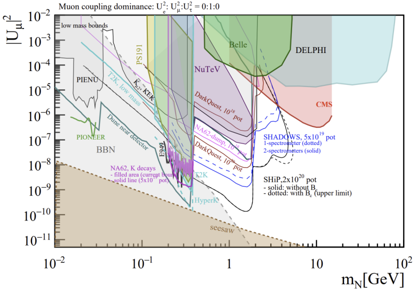
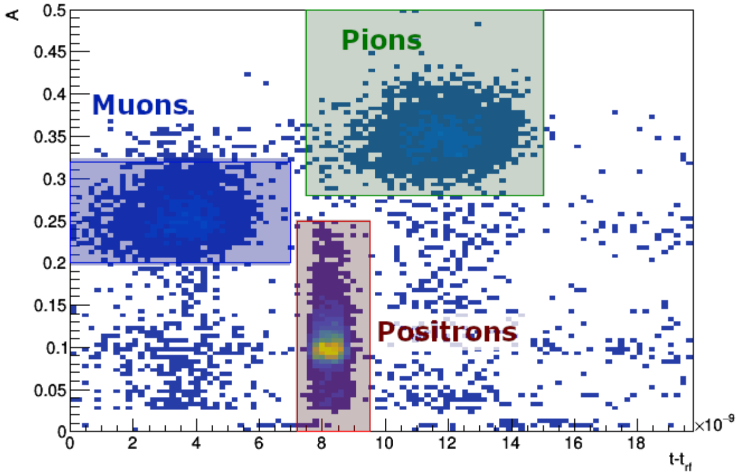


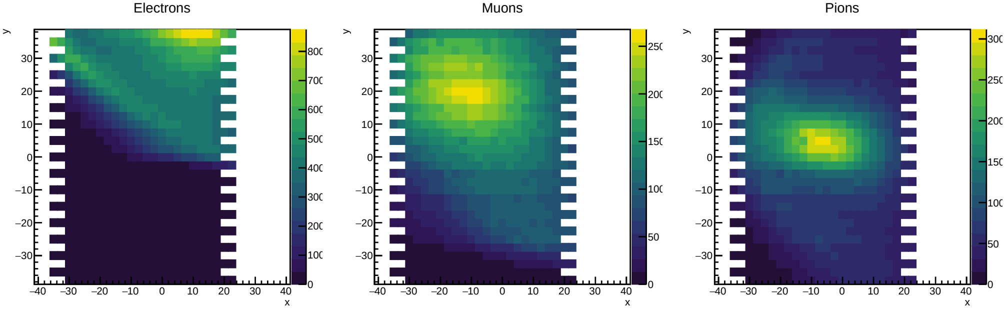
Figure 27: Heavy Neutral Leptons with coupling to the second lepton generation. Filled areas are existing bounds from: PS191 [31], CHARM [576], NA62 ($K_{\mu N}$) [29], T2K [36], E949 [23], Belle [577]; DELPHI [544], and CMS [340]. The "low mass bounds" label refers to a set of results obtained from π and K decays, as detailed in Ref. [39], namely a PIENU result [25] and $K_{\mu 2}$ results at KEK [22, 578]. Colored curves are projections from: NA62-dump [405], NA62 K^+ decays (projections obtained by the Collaboration based on [29]), SHADOWS [519], DarkQuest [561], PIONEER [565], SHiP [448], DUNE near detector (projections based on methods developed in [539]), Hyper-K (projections based on [36]), T2K low mass [514]. The BBN bounds are from [445] and heavily depend on the model assumptions (hence should be considered only indicative). The seesaw bounds are computed under the hypothesis of two HNLs mixing with active neutrinos.

https://arxiv.org/pdf/2203.08039.pdf

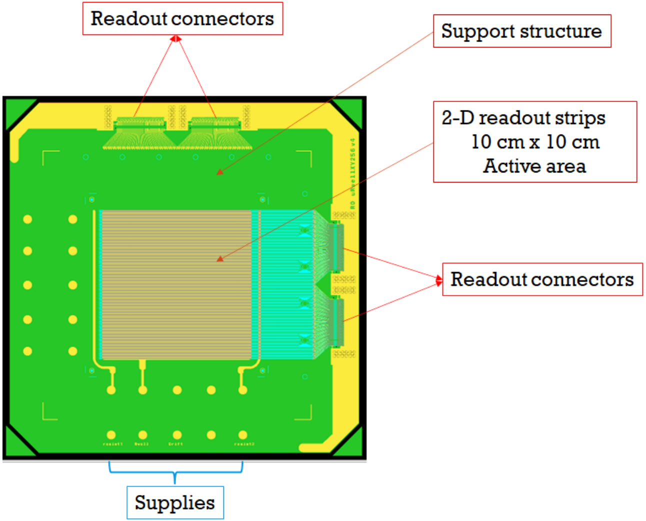
Amplitude and Time of Flight for Particle Species



Amplitude and Time of Flight Separation



Tracker Technology: μRWELL [9]



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[1] W. Altmannshofer et al. (PIONEER Collaboration).
PSI Ring Cyclotron Proposal R-22-01.1.
arXiv:2203.01981 [hep-ex], 2022.

[2] A. Crivellin, J. Matias.
Beyond the standard model with lepton flavor universality violation.
arXiv:2204.12175 [hep-ph], 2022.

[3] D. Bryman, V. Cirigliano, A. Crivellin, G. Inguglia.
Testing lepton flavor universality with pion, kaon, tau, and beta decays.
arXiv:2111.05338 [hep-ph], 2021.

Further Reading II

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Further Reading

[4] Particle Data Group: R.L. Workman et al.
Review of Particle Physics.
Progr. Theor. Exp. Phys., 2022(8):083C01, 2022.

[5] A. M. Abdullahi et al.
The present and future status of heavy neutral leptons.
arXiv:2203.08039 [hep-ph], 2022.

[6] A. M. Baldini et al. (MEG II Collaboration).
The Search for $\mu^+ \to e^+\gamma$ with 10^{-14} Sensitivity: The Upgrade of the MEG Experiment.
Symmetry, 13(9):1591, 2021.

Further Reading III

[7] A. Aguilar-Arevalo et al. (PIENU Collaboration).
Improved measurement of the $\pi \to e\nu$ branching ratio.
Phys. Rev. Lett., 115:071801, 2015.

[8] D. Počanić et al.
Precise measurement of the $\pi^+ \to \pi^0 e^+ \nu$ branching ratio.
Phys. Rev. Lett., 93:181803, 2004.

[9] M. Poli Lener et al.
The micro-RWELL detector.
Proc. Sci., MPGD2017:019, 2019.