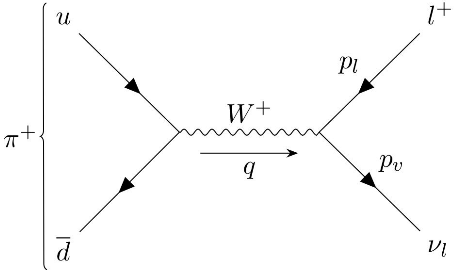
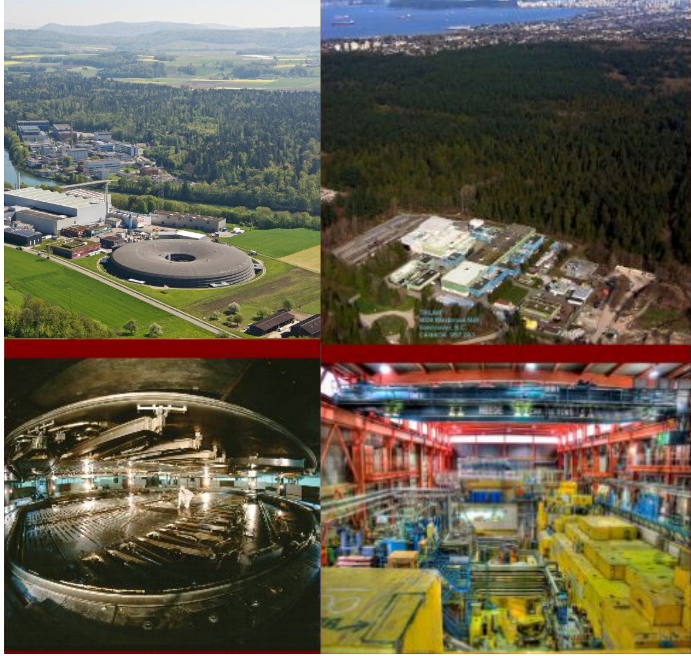
Rare pion decays at PIONEER

$$\pi^+ \rightarrow e^+ \nu_e$$





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On behalf of the collaborations: PIENU, PIONEER

TRIUMF — PAUL SCHERRER INSTITUT PSI

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TRIUMF is Canada's national laboratory for particle and nuclear physics.
The Paul Scherrer Institute (PSI) is a multi-disciplinary research institute for natural and engineering sciences in Switzerland (Suiza).

PIENU measurement status & Goal of Phase I in PIONEER (2026-2031)

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

$$= (1.23534 \pm 0.00015) \times 10^{-4} \quad (\pm 0.012\%) \quad \text{(SM)}$$

$$= (1.2327 \pm 0.0023) \times 10^{-4} \quad (\pm 0.187\%) \quad \text{(PDG exp.)}$$

x 15

R_e/u is one of the most precisely known observables involving quarks in the SM: V. Cirigliano and I. Rosell, JHEP, 0710:005, 2007

PIENU is a precision experiment on observables that can be very accurately calculated in the SM highly sensitive to New Physics and Lepton Flavor Universality (LFU)tests.

PDG average dominated by the PIENU result (0.24% precision) in 2015 based on partial data set (~10% of full statistics). Final PIENU data analysis with full data 6M pi->enu events is targeting 0.1% precision.

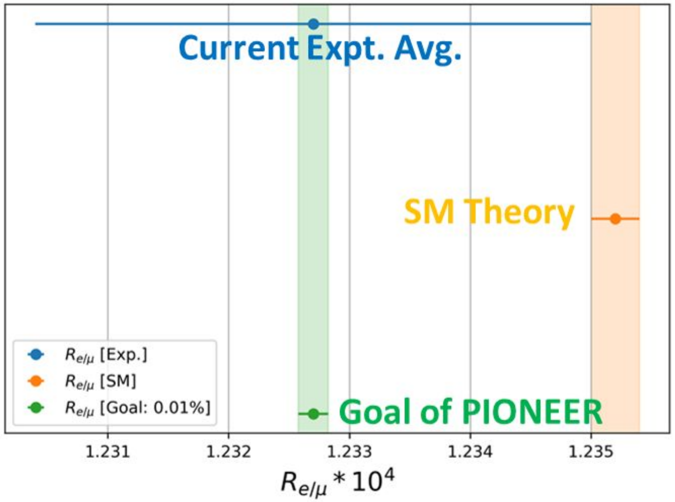
Improved Measurement of the $\pi \to e\nu$ Branching Ratio

A. Aguilar-Arevalo *et al.* (PIENU Collaboration)
Phys. Rev. Lett. **115**, 071801 – Published 13 August 2015

In 2019, a PIENU blinded result (S. Cuen PhD thesis) became available reaching 0.12% precision in R_e/u: https://dx.doi.org/10.14288/1.0378447

Currently a PhD student from UNAM (I. Ortega) is working with PIENU collaboration to unblind the full and final PIENU result.

PIONEER Phase 1 goal is to capture 200M pi->enu events to reach 0.01% precision to reach SM theory precision.



PIONEER proposal: arxiv:2203.01981

Deviations from the SM prediction may imply:

a violation of lepton universality, which is NOT a SM hypothesis, it is a consequence of gauge theory of SM (Lagrangian invariant to local transformations, i.e. Lie Groups) meaning that electrons and muons have the same weak interactions.

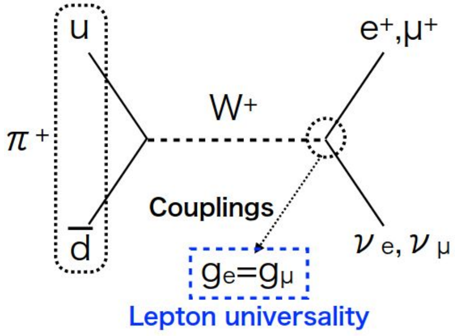
Heavy neutrinos lighter than the pion: R. E. Shrock. *General Theory of Weak Leptonic and Semileptonic Decays. 1. Leptonic Pseudoscalar Meson Decays, with Associated Tests For, and Bounds on, Neutrino Masses and Lepton Mixing*. Phys. Rev., D24:1232, 1981;

and the presence of new physics beyond the SM, such as new pseudo-scalar interactions, i.e.,

R-parity violating supersymmetry: M. J. Ramsey-Musolf, S. Su, and S. Tulin. *Pion Leptonic Decays and Supersymmetry*. Phys. Rev., D, (2007).

Leptoquarks: M. Leurer. A Comprehensive study of leptoquark bounds. Phys. Rev., D (1994)

Charged Higgs bosons & the existence of a new pseudo-scalar interaction with an energy scale up to O(1000 TeV), which would enhance the branching ratio by O(0.1%): D. A. Bryman, W. J. Marciano, R. Tschirhart and T. Yamanaka. *Rare kaon and pion decays: Incisive probes for new physics beyond the standard model*. Annual Review of Nuclear and Particle Science, 61:331-354, 2011.



How to access LFU experimentally?

- Vector-Axial (helicity suppression) gives the first order R

$$R_\pi^0 = \frac{\Gamma_{\pi\to e}}{\Gamma_{\pi\to\mu}} = \frac{g_e^2}{g_\mu^2}\frac{m_e^2}{m_\mu^2}\left(\frac{m_\pi^2 - m_e^2}{m_\pi^2 - m_\mu^2}\right)^2 . \qquad (2.10)$$

- In 2007, Cirigliano and Rosell recalculated the corrections using Chiral Perturbation Theory (ChPT). ChPT uses a low-energy effective field theory for QCD, allowing for strong interaction calculations. ChPT enabled a power series solution for the radiative corrections

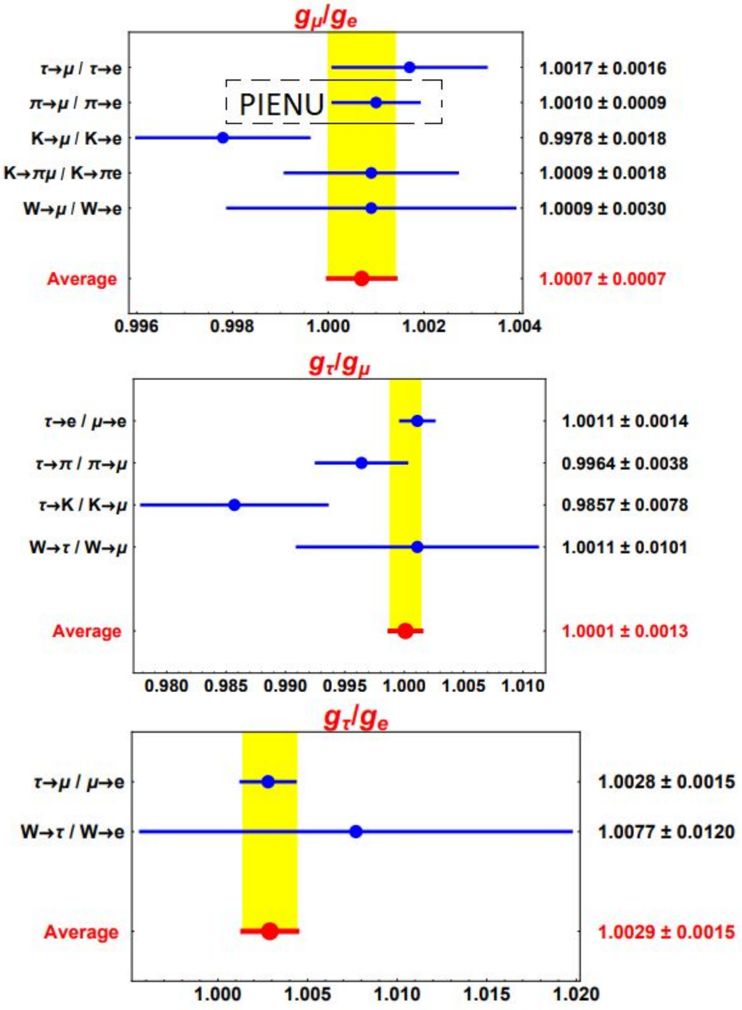
$$R_\pi = R_\pi^0 \left[1 + \Delta_{e^2p^2} + \Delta_{e^2p^4} + \Delta_{e^2p^6} + ...\right]\left[1 + \Delta_{LL}\right] . \qquad (2.12)$$

- Going back to Eq. 2.10, we could introduce the hypothesis that the coupling constants are different for each generation (g = g_e = g_μ = g_τ) and then the branching ratio expression becomes

$$R_\pi^{\mathrm{SM}} = \left(\frac{g_\mu}{g_e}\right)^2 R_\pi^{\mathrm{exp}} . \qquad (2.14)$$

$$\frac{g_\mu}{g_e} = 1.0010 \pm 0.0009 \quad (\pm 0.09\%)$$

- **PIENU has the best LFU test measurement so far…**



Images from: A. Pich's talk, Rare Pion Decay Workshop, Santa Cruz 06-08 Oct 2022

Many exotic searches performed by the PIENU collaboration: e.g. heavy and sterile neutrinos which have implications for leptogenesis

Contents lists available at ScienceDirect

Physics Letters B

www.elsevier.com/locate/physletb

ELSEVIER

Search for heavy neutrinos in $\pi \to \mu\nu$ decay

PHYSICAL REVIEW D **97**, 072012 (2018)

Suggestion

Improved search for heavy neutrinos in the decay $\pi \to e\nu$

PHYSICAL REVIEW D **102**, 012001 (2020)

Search for the rare decays $\pi^+ \to \mu^+\nu_\mu\nu\bar{\nu}$ and $\pi^+ \to e^+\nu_e\nu\bar{\nu}$

PHYSICAL REVIEW D **101**, 052014 (2020)

Improved search for two body muon decay $\mu^+ \to e^+X_H$

PHYSICAL REVIEW D **103**, 052006 (2021)

Search for three body pion decays $\pi^+ \to l^+\nu X$

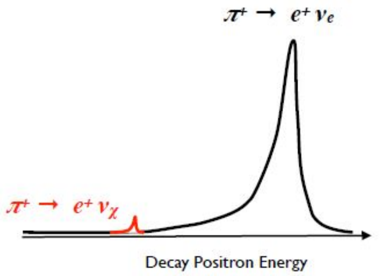
recent searches performed by the **PIENU** collaboration

⇓

PIONEER will improve on all those searches by ~1 order of magnitude

Image from C. Malbrunot (PSI Oct/2022)

Example of massive neutrino search in PIENU



If the heavy neutrino mass is M_ν= 60~130 MeV/c^2 **additional low energy positron peak** can be detected in the $\pi^+ \rightarrow e^+$ spectrum

R.E Shrock Phys.Rev.D 24, 1232 (1981),
Phys. Lett. B 96, 159 (1980)

Heavy υ

Kinematic factor

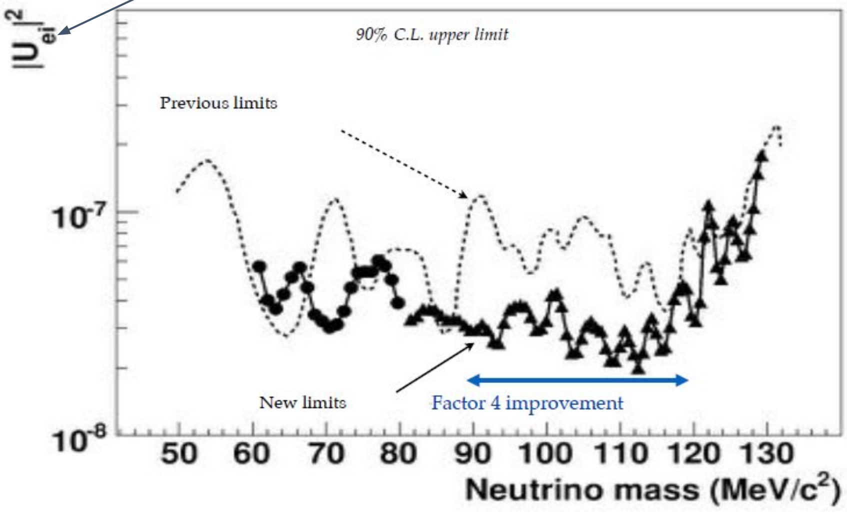
$$R_{ei} = \frac{\Gamma(\pi \rightarrow e\nu_i)}{\Gamma(\pi \rightarrow e\nu_l)} = |U_{ei}|^2 \rho_{ei}$$

Conventional υ

$$\nu_\ell = \Sigma_{i=1}^{3+k} U_{\ell i} \nu_i$$

$$\ell = e, \mu, \tau, \chi_1, \chi_2 \cdots \chi_k$$

Neutrino mixing matrix element



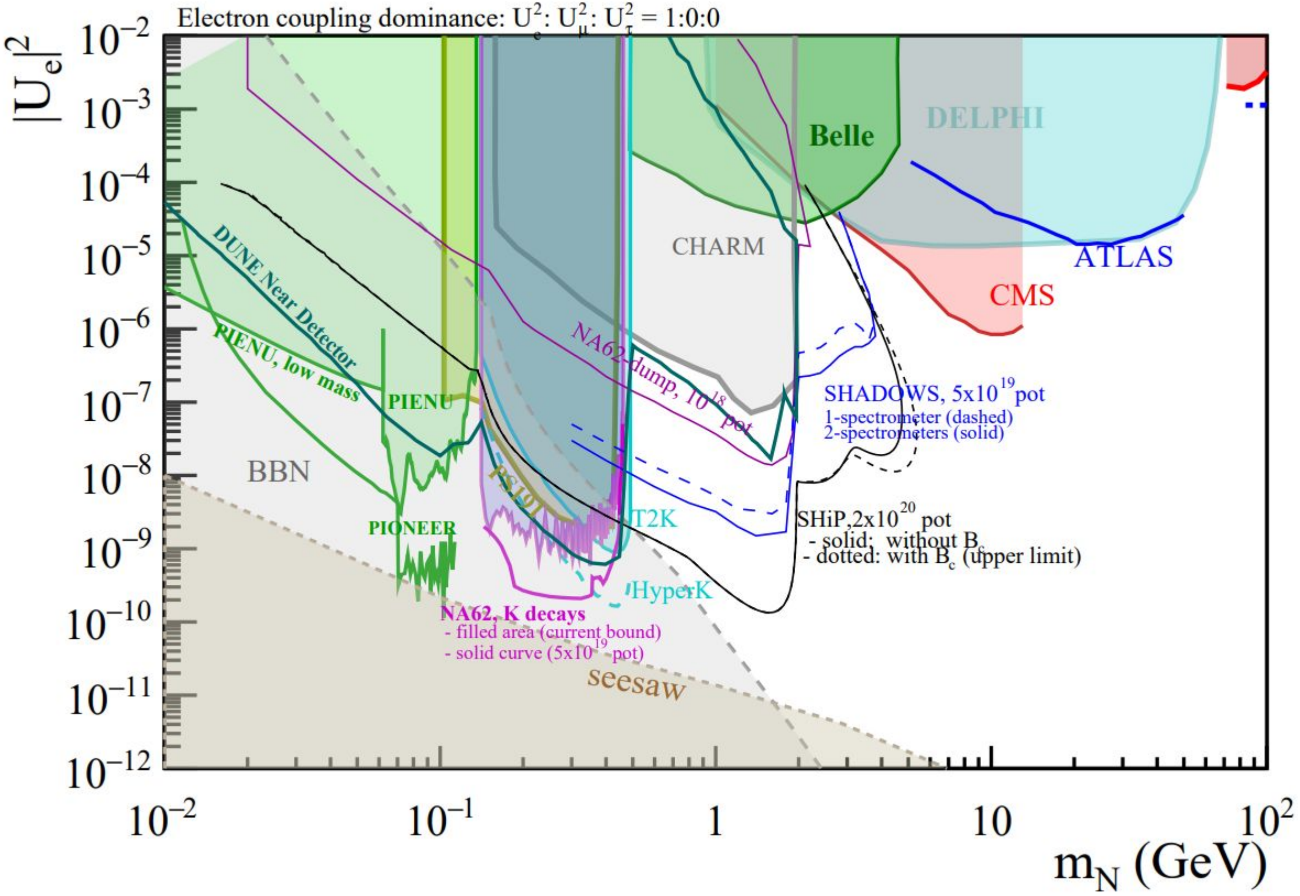
M.Aoki et al., Phys. Rev. D 84, 052002 (2011)

More recent and stronger bounds provided by PIENU :
PRD 97.072012 (2018)
PLB 798 (2019) 134980 [in $\pi \rightarrow \mu\nu$ decay]

Comprehensive constraints on sterile neutrinos in the MeV to GeV mass range
D. A. Bryman and R. Shrock, Phys. Rev. D 100, 073011

Slide from C. Malbrunot (PSI Oct/2022)

Heavy Neutral Leptons with coupling to the first lepton generation



Asli M. Abdullahi et al. “The Present and Future Status of Heavy Neutral Leptons”. 2022 Snowmass Summer Study. Mar. 2022. arXiv: 2203.08039 [hep-ph]

Previous $R^{\pi}_{e/\mu}$ experiments

1940/50's : Development of V-A structure of weak interaction

1950's: Many experimental confirmations of the V-A theory

1956-1957: Negative experimental results BR<10^{-5}

Theory of the Fermi Interaction

R. P. Feynman and M. Gell-Mann
California Institute of Technology, Pasadena, California
(Received September 16, 1957)

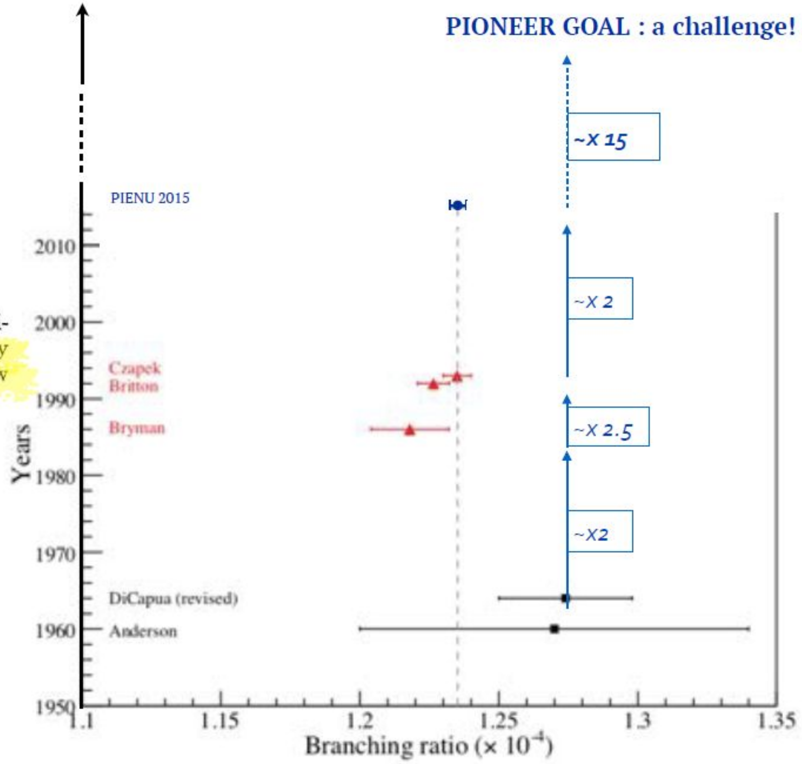
Experimentally[16] no $\pi \to e + \nu$ have been found, indicating that the ratio is less than 10^{-5}. This is a very serious discrepancy. The authors have no idea on how it can be resolved.

1958: First positive experimental result at CERN (PRL 1,7 (1958))

PDG 2018 ±0.19 %

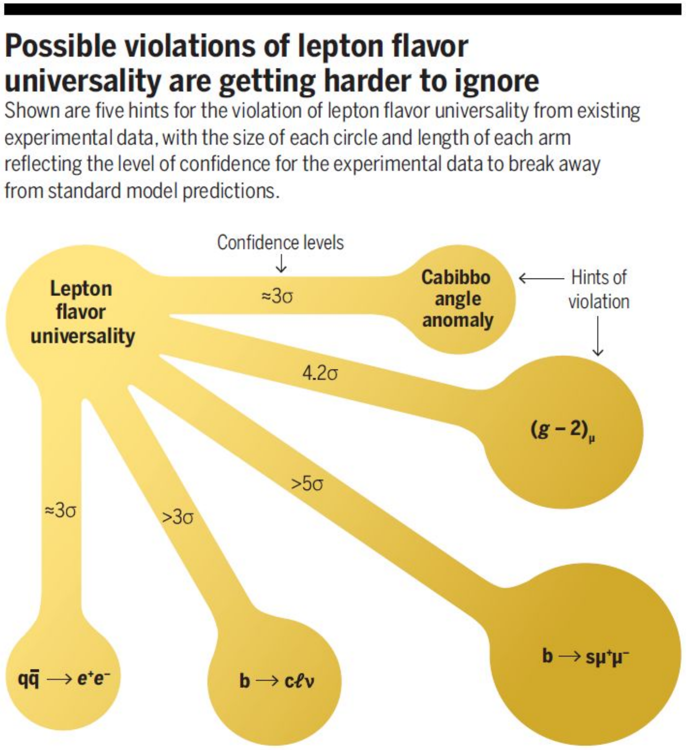
VALUE (units 10^{-4})	EVTS	DOCUMENT ID		TECN	CHG	COMMENT
1.2327±0.0023 OUR AVERAGE						
1.2344±0.0023±0.0019	400k	AGUILAR-AR...	15	CNTR	+	Stopping π^+
1.2346±0.0035±0.0036	120k	CZAPEK	93	CALO		Stopping π^+
1.2265±0.0034±0.0044	190k	BRITTON	92	CNTR		Stopping π^+
1.218 ±0.014	32k	BRYMAN	86	CNTR		Stopping π^+
• • • We do not use the following data for averages, fits, limits, etc. • • •						
1.273 ±0.028	11k	[1] DICAPUA	64	CNTR		
1.21 ±0.07		ANDERSON	60	SPEC		

[1] DICAPUA 64 has been updated using the current mean life.



Slide from C. Malbrunot (PSI Oct/2022)

Why the hype with R_e/u? -> Lepton Flavor Universality Violation (LFUV)



ANDREAS CRIVELLIN AND MARTIN HOFERICHTER
SCIENCE 25 Nov 2021 Vol 374, Issue 6571 pp. 1051-1052 DOI: 10.1126/science.abk2450

Some nuclear **Beta** and **Kaon** decays observables have **evidence of first row unitarity violation of Cabibbo-Cobayashi-Maskawa (CKM) matrix**, the tension is about **3σ**, and is called "**Cabibbo angle anomaly**". This lead to think electrons and muons behave more different than prescribed.

Anomaly appeared in the measurement of the "g-factor" (**dimensionless magnetic moment**) of the muon. **2006 at Brookhaven** National Laboratory and confirmed recently by "**muon g – 2**" experiment at **Fermilab in 2021**. Deviation of **4.2σ** from theory. This observable can be considered as a probe of LFUV.

The **LHCb** experiment did ratios of **B→Kee** over **B → Kμμ**, thus also an effective probe for LFUV. Together with other similar meson decays, the **b→see** and **b→sμμ** observables have a **5σ** deviation from the SM.

Similarly the ratios of other **B** meson decays involving **b→*clv*** report deviation of **3σ**

The Compact Muon Solenoid (**CMS**) experiment at **CERN** observed more very-high-energy electrons compared to muons in proton-proton collision, **3σ** away from SM: **qq→ee**

"Future measurements and improved theory predictions are poised to thoroughly scrutinize the currents hints for the violation of LFU. If confirmed, this could provide the longsought guidance for the construction of the fundamental theory of particle physics and for addressing phenomena outside the realm of the SM, including neutrino masses, dark matter, and the matter over antimatter dominance in the Universe"

Precise measurements of 1st and 2nd generation decays could be used to distinguish between models explaining 3rd generation effects: welcome PIENU and PIONEER experiments :)

Goal of Phase II & III in PIONEER (2033?)

Testing CKM unitarity first row: $|V_{ud}|^2 + |V_{us}|^2 + |V_{ub}|^2 = 1$

Vus/Vud tension a sign of LFUV? Crivellin & Hoferichter PRL 125,111801(2020)

What π decays to "normally": $B(\pi^+ \to \mu^+\nu(\gamma)) = 0.999877 \pm 0.0000004$

Helicity suppressed decay: $B(\pi^+ \to e^+\nu_e(\gamma)) = (1.2327 \pm 0.00023) \times 10^{-4}$

Pion β decay: $B(\pi^+ \to e^+\nu_e\pi^0) = (1.036 \pm 0.006) \times 10^{-8}$

PIONEER Phase II goal:

Improve $B(\pi^+ \to \pi^0 e^+\nu)$ precision by >3 $\frac{V_{us}}{V_{ud}} < \pm 0.2\,\%$

Offers a new complementary constraint in the $V_{us} - V_{ud}$ plane

A. Czarnecki et al. *Phys.Rev.D* 101 (2020) 9, 091301

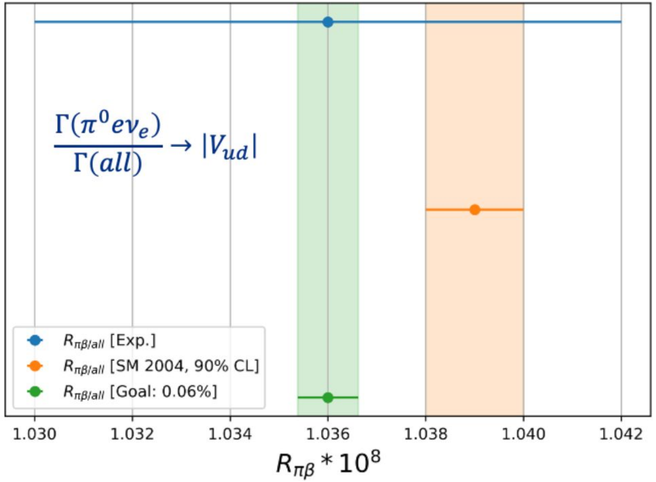
PIONEER Phase III goal: ← Needed to test CKM first row unitarity

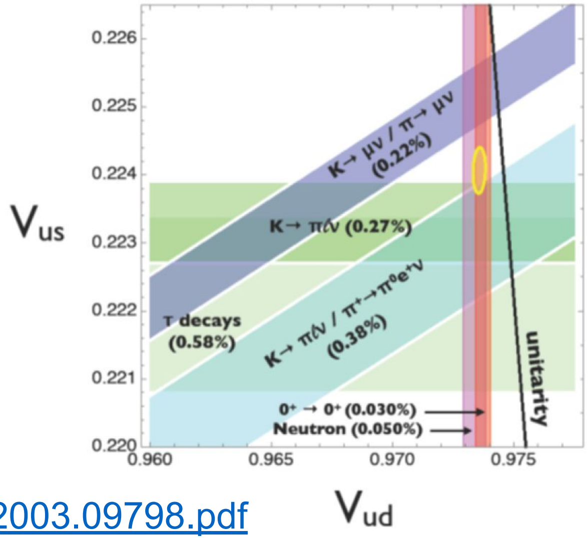
Improve $B(\pi^+ \to \pi^0 e^+\nu)$ precision by an order of magnitude

$\pi^+ \to \pi^0 e^+\nu$ is the theoretically cleanest method to obtain V_{ud}

PIBETA exp. (±0.6%)

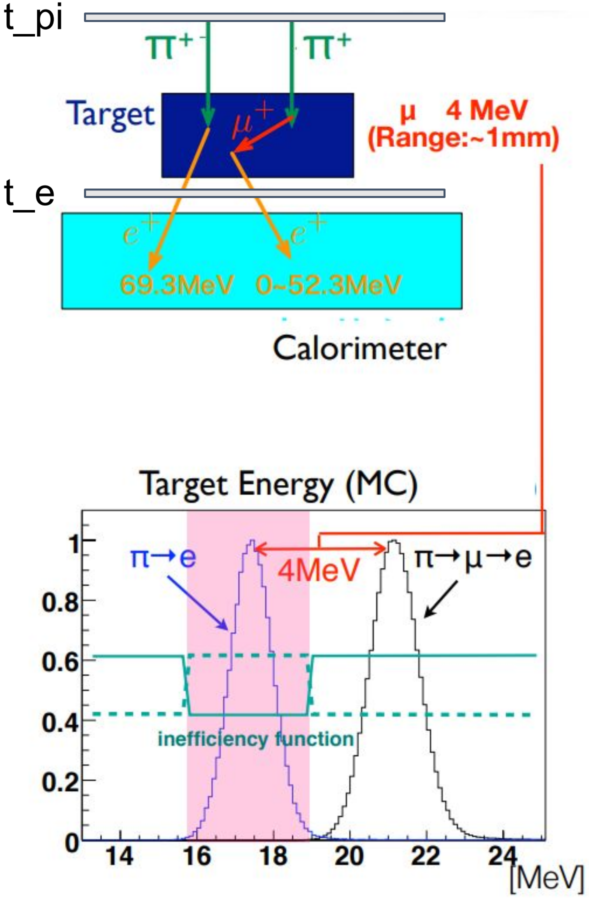
$$B(\pi^+ \to \pi^0 e^+\nu) = (1.038 \pm 0.004_{stat} \pm 0.004_{syst} \pm 0.002_{\pi e2}) \times 10^{-8}$$

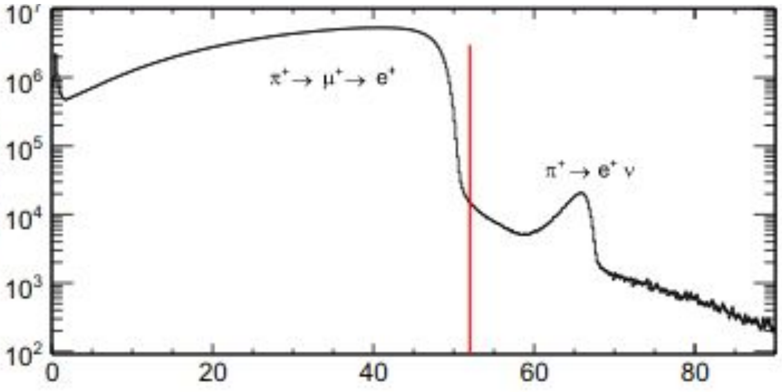


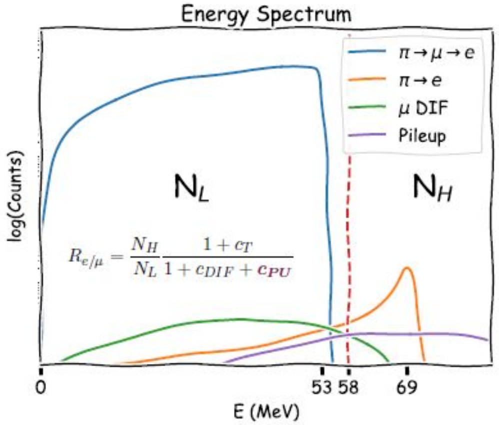


Latest theoretical calculation, Feng and others: https://arxiv.org/pdf/2003.09798.pdf

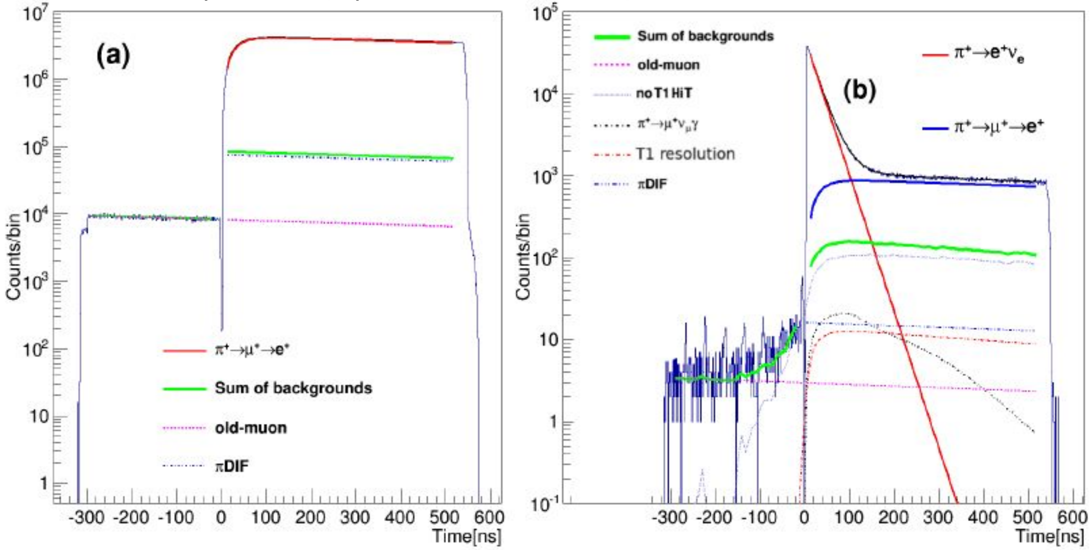
PIENU Exp. Technique







(t_e - t_pi) to build Time Spectra



PIENU Exp. Technique

https://dx.doi.org/10.14288/1.0378447

- Measure the Energy Spectrum
- Consider the Low- and High-Energy Time Spectra
- Fit the spectra with signal and background shapes.
- Correct the R_e/u from the fit for:
  - Low Energy Tail (largest correction)
  - Acceptance Correction
  - Muon Decays in Flight Correction
- Do systematic checks, branching ratio R vs:
  - Low/High energy cut
  - Acceptance

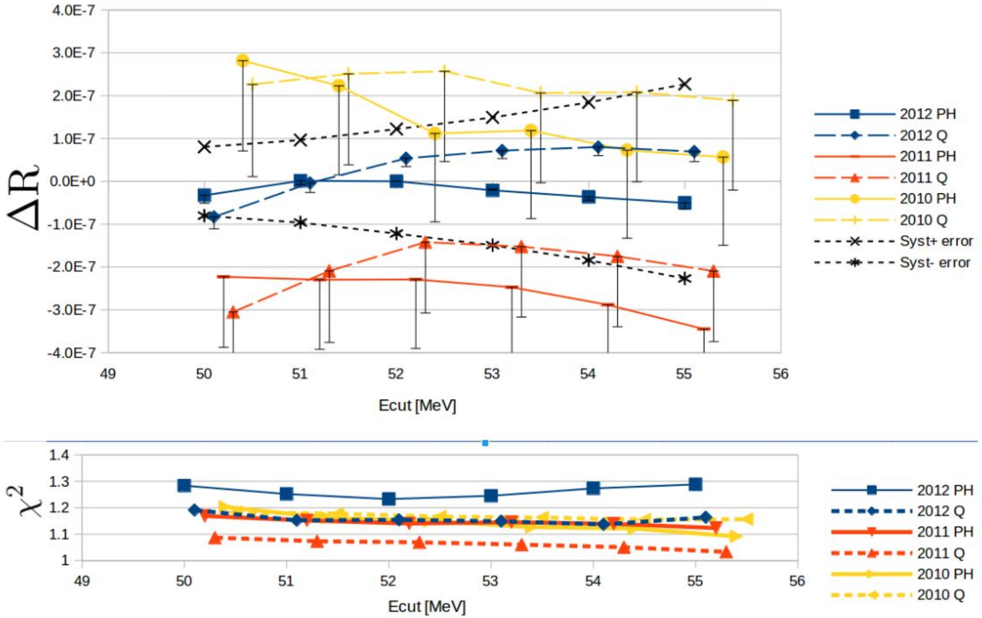
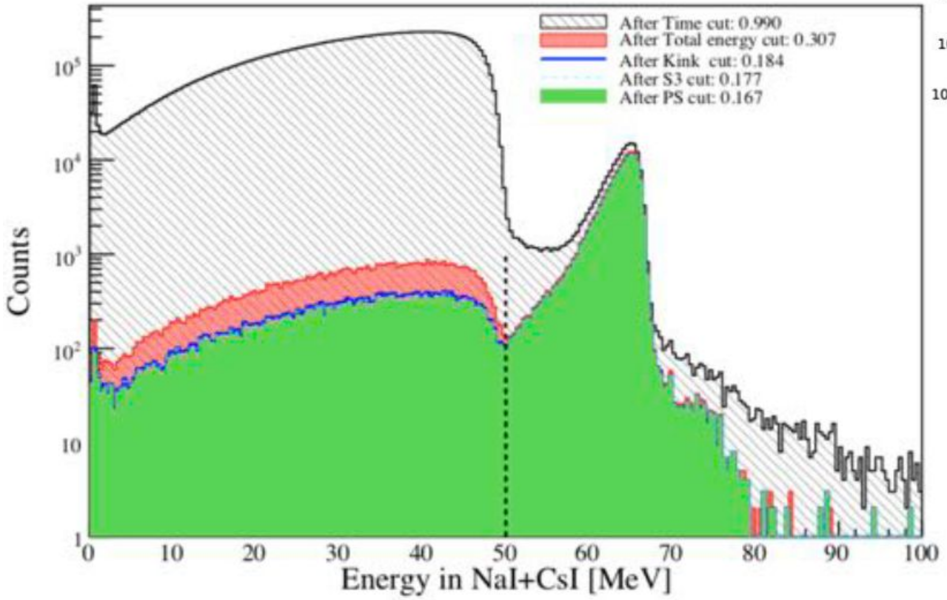
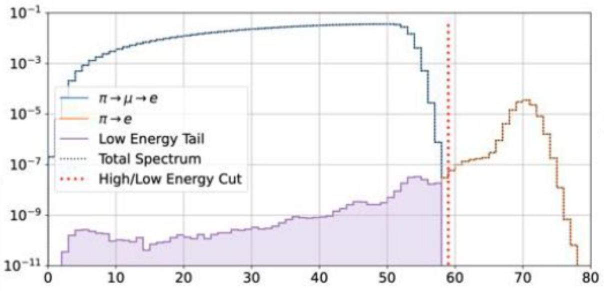
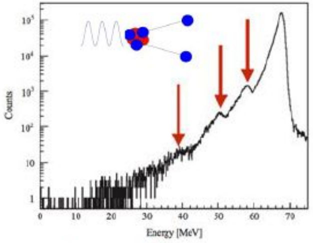


Figure 7.5: $\Delta R \pm \Delta e$ (Eq. 7.1) vs. E_{cut}, Charge Integration and Pulse-height: The x-axis is the E_{cut} value in MeV units. The y-axis is in ΔR units, with zero change representing 2012(PH)'s analysis using anchor point with cuts $A_R = 60$ mm and $E_{\text{cut}} = 52$ MeV, the error bars (Δe) on each point represent the uncorrelated statistical error between the point in question and the anchor point with the error bars going up when there is an statistical increase and down otherwise. The horizontal dashed black lines both at the same distance from anchor represent the calorimeter's LET systematic error. The bottom part shows the total χ^2 from the fitting function for each point.

Tail correction: major uncertainty. “the devil’s in the (de)tail”







A. Aguilar-Arevalo et al., Nuclear Instruments and Methods in Physics Research A 621 (2010) 188–191

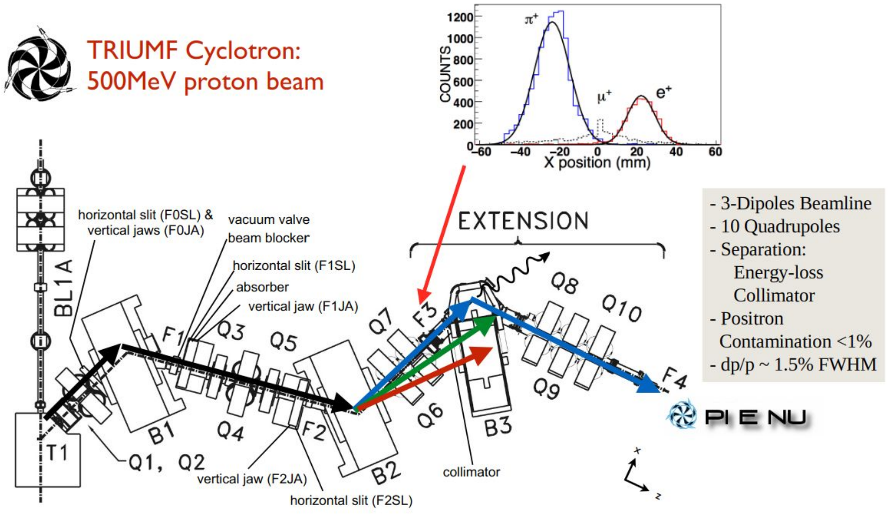
Low energy tail buried under the Michel spectrum caused by:

- finite energy resolution of the calorimeter
- photo-nuclear interactions (^{127}I(ɣ,n))
- shower leakage
- geometrical acceptance
- radiative decays
- etc

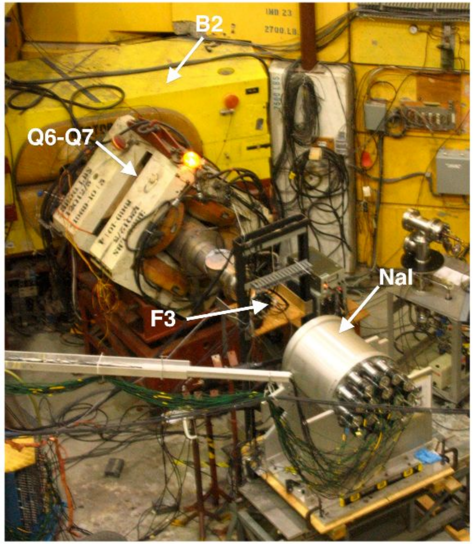
Main source of systematics : estimated using data (suppression of $\pi \rightarrow \mu \rightarrow e$ decays)

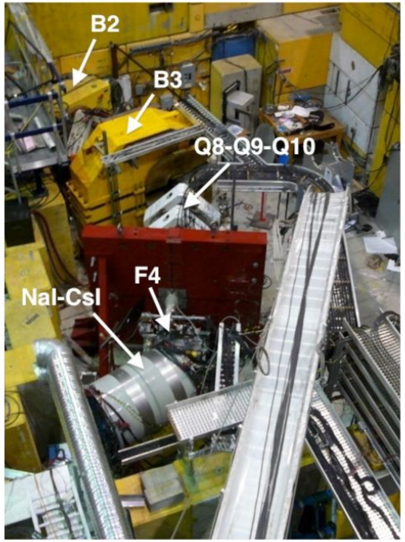
Slide from C. Malbrunot (PSI Oct/2022)

TRIUMF's M13 beamline



A.Aguilar-Arevalo *et al.*: Nucl. Instr. Meth. A621, 188 (2010)





60 kHz pions @ 75 MeV/c

π : μ : e = 85 : 14 : 1

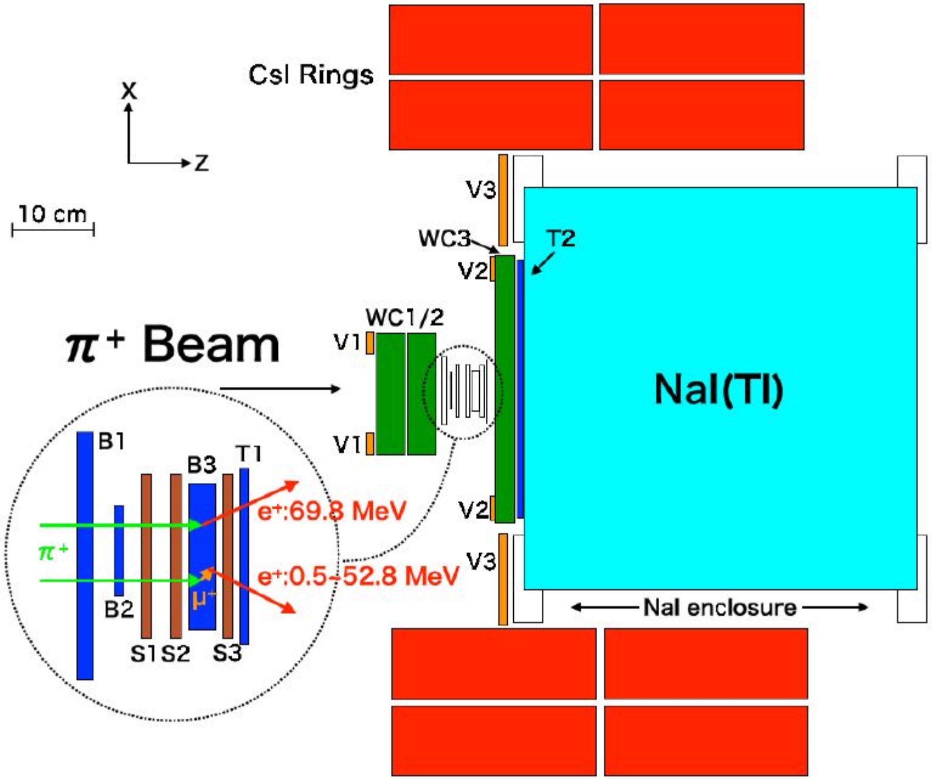
The PIENU Detector

Single crystal NaI(TI) right behind the target
    Geometrical Acceptance: 20% of 4π
    ΔE = 2.2%(FWHM)

CsI ring shower collector
    πe2 tail suppression
    gamma from radiative decay

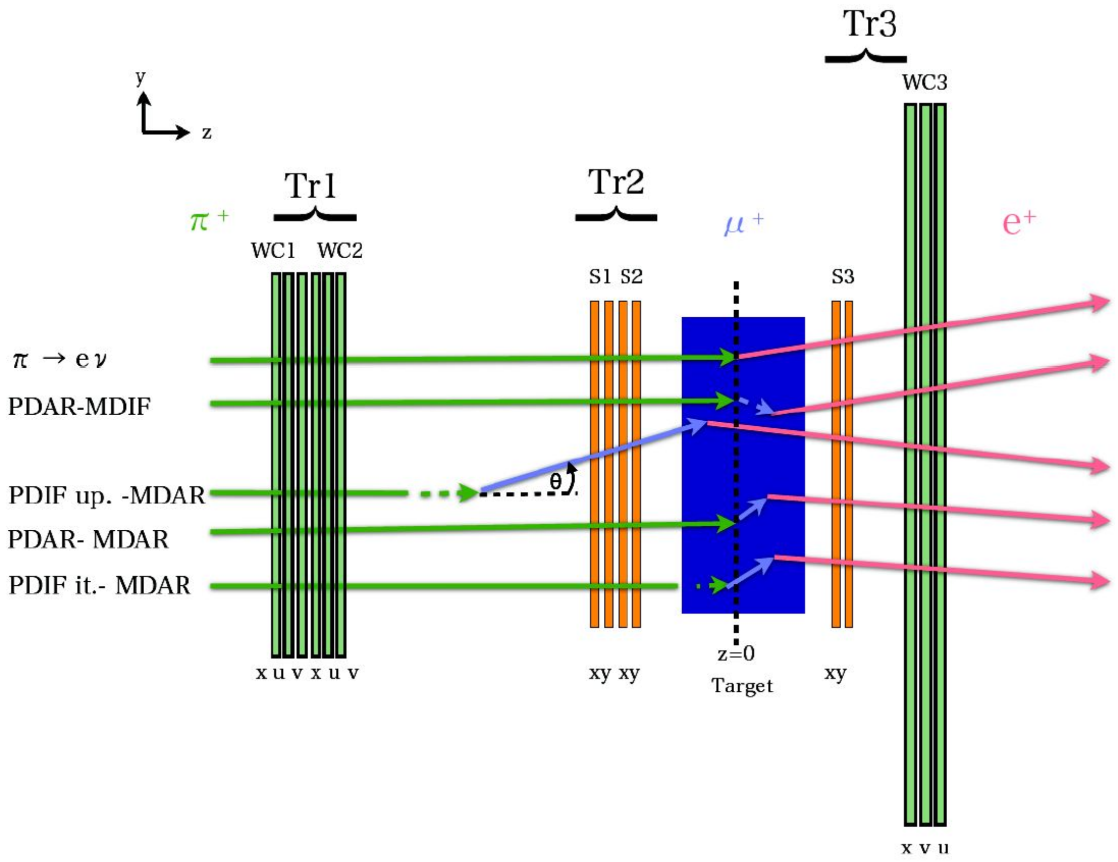
SSD and WC for particle tracking
    Identify π-DIF events in the πe2 tail region

Flash-ADC readout for all counters
    Plastic Scintillator: 500MHz FADC
    NaI(TI) and CsI: 60MHz FADC
    Pile-up tagging



The PIENU Trackers

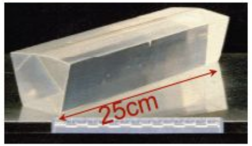
MDIF not detectable: thus a correction is needed. Area of opportunity for PIONEER?



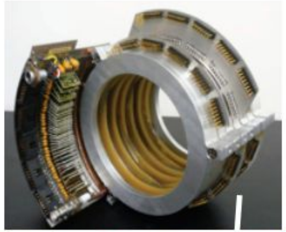
The real PIENU Detector

Monolithic NaI(Tl) crystal surrounded by 97 pure CsI crystals

1 CsI crystal



Acceptance Wire Chamber



Beam Wire Chamber

ELSEVIER

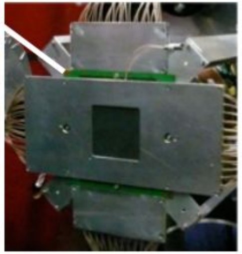
Nuclear Instruments and Methods in Physics Research Section A: Accelerators, Spectrometers, Detectors and Associated Equipment

Volume 791, 11 August 2015, Pages 38-46

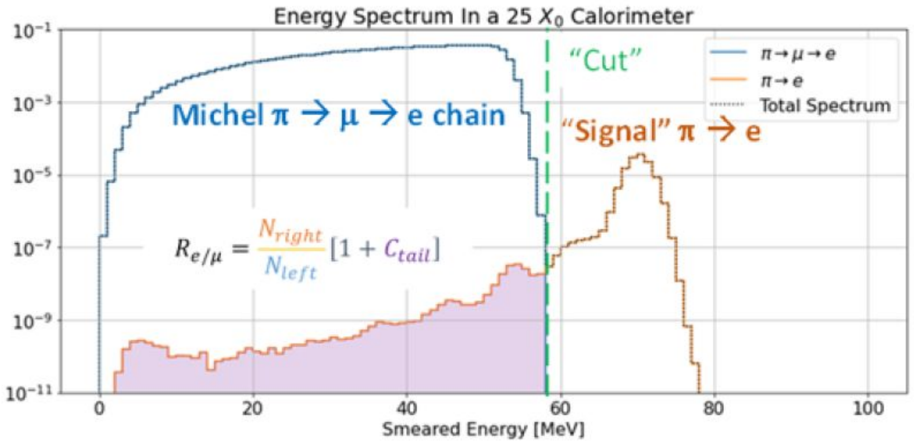
Detector for measuring the $\pi^+ \to e^+ \nu_e$ branching fraction

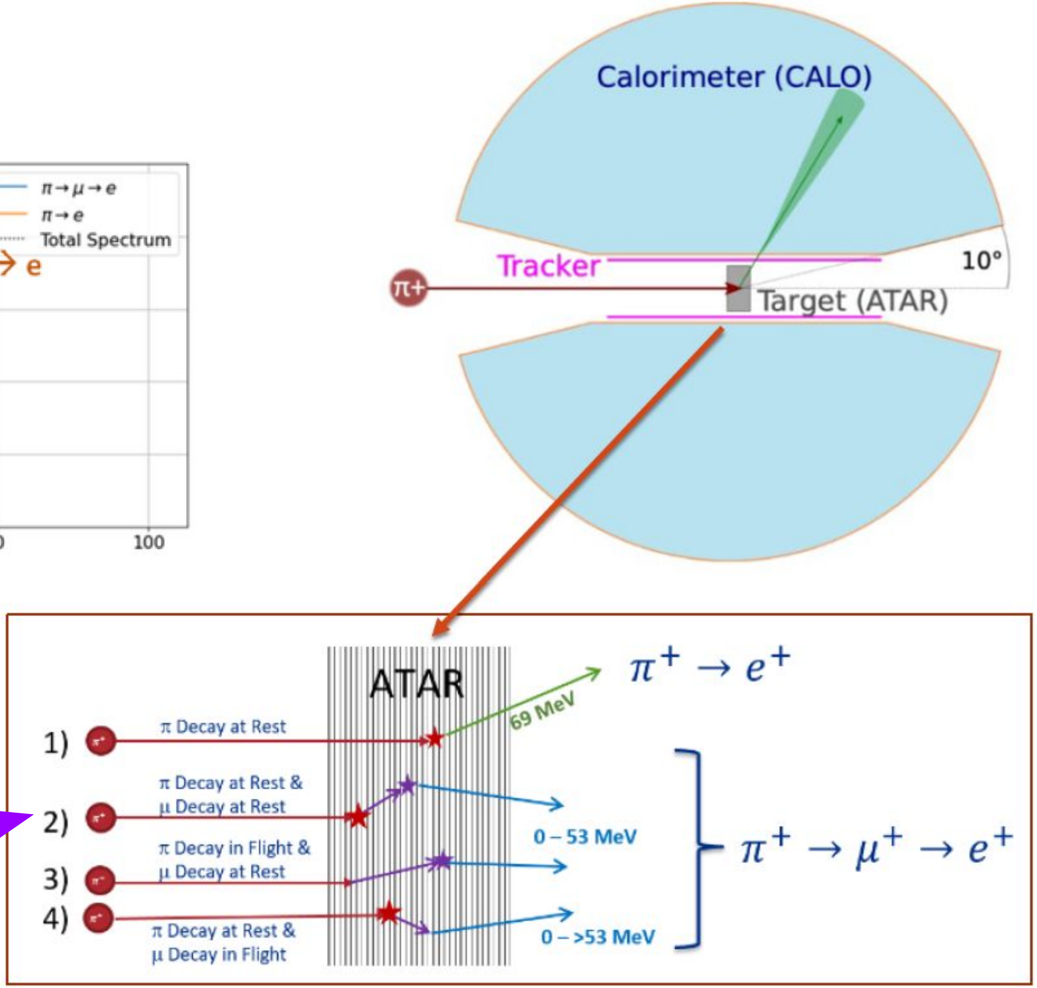
A.A. Aguilar-Arevalo [a], M. Aoki [b], M. Blecher [c], D. vom Bruch [e, 1], D. Bryman [e], J. Comfort [i], S. Cuen-Rochin [e], L. Doria [d], P. Gumplinger [d], A. Hussein [f], Y. Igarashi [g], N. Ito [b], S. Ito [b], S.H. Kettell [h], L. Kurchaninov [d], L. Littenberg [h], C. Malbrunot [e, 2], R.E. Mischke [d], A. Muroi [b], T. Numao [d] ...M. Yoshida [b, 4]

Silicon Trackers



PIONEER detector concept





MDIF IS detectable, actually all decay chains are detectable: thus systematic improvement is possible from previous experiment.

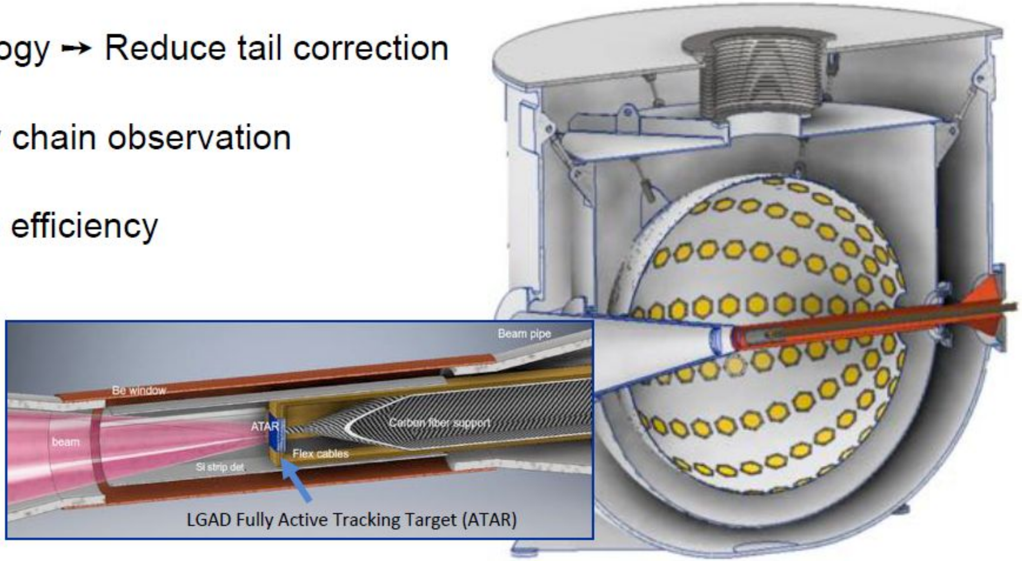
PIONEER DETECTOR CONCEPT - best of PIENU and PEN worlds

- Building on previous experiences (PIENU and PEN/PIBETA) : use of emerging technologies (LXe, LGADs)
  - 25 X_0, 3π sr calorimeter → Reduce tail corrections (x5) → Improve uniformity (x5)
    Fast scintillator response (LXe) → Reduce pile-up uncertainties (x5)
  - active target ("4D") based on LGADs technology → Reduce tail correction uncertainty (x10)
    Fast pulse shape → allow $\pi \to \mu \to e$ decay chain observation
  - Fast electronics and pipeline DAQ → Improve efficiency
  - Intense Pion beam at PSI

$$25\,X_0$$

$$\Delta t \sim 100\ \text{ps}$$

$$\frac{\Delta E}{E} \sim 1.5\%$$



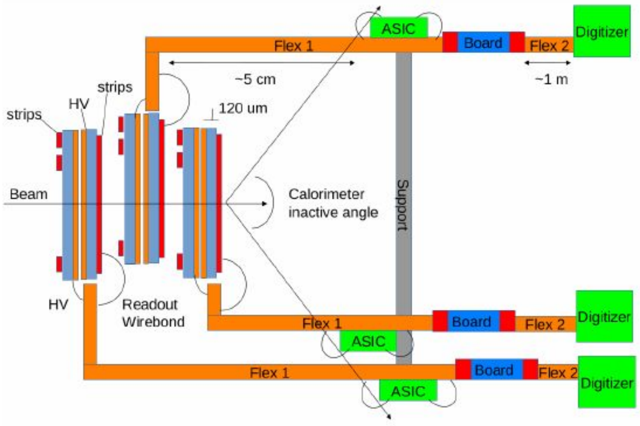
Slide from C. Malbrunot (PSI Oct/2022)

ATAR design

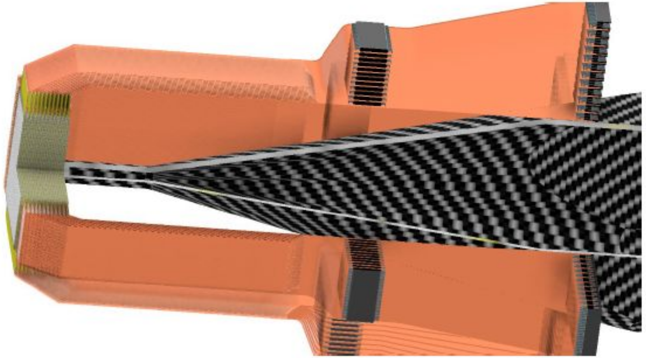
- **Full silicon active target**: compact ~2x2 cm area of silicon, ~6 mm thick
  - High granularity in (X,Y, Z), fast full collection time, good energy response, high dynamic range
- The **chosen sensor for the ATAR is an high granularity LGAD** technology (AC-LGADs or TI-LGADs)

- **ATAR initial design**
  - **48 layers of 120um thick LGADs,** 200 um pitch strips, layers have to be as close as possible
  - Compromise between granularity, total active area, timing and dead material
- Readout flexes are alternating on the four sides to allow space for the wire bonds
  - **First (5 cm) flex carries the un-amplified signal from sensor to ASIC** with fast analog amplification mounted on the flex
- The **ATAR signals will be fully digitizer** in a region of interest (ROI, temporal or spatial) for each event
  - Event reconstruction will use raw waveforms from several channels

ATAR concept



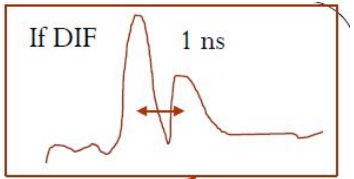
ATAR mechanical drawing



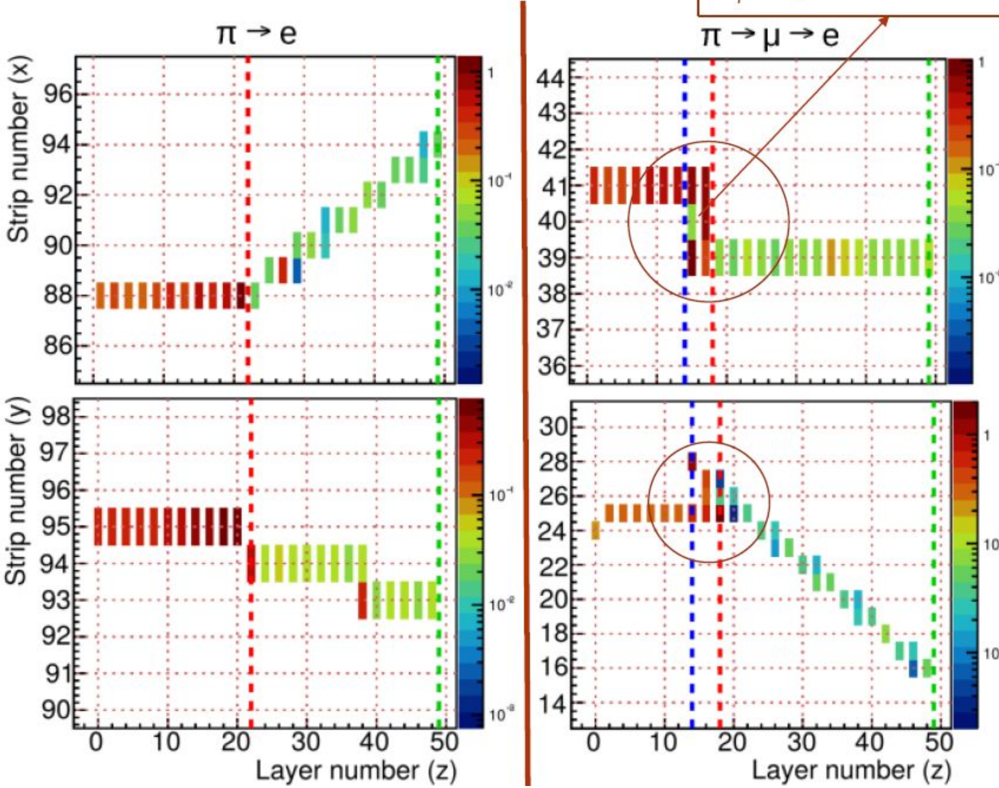
Slide from S. Mazza (Rare Pion Decay Workshop 2022)

Event reconstruction

- Event simulation for $\pi \to e$ and $\pi \to \mu \to e$
  - Plotted ATAR hits for baseline design
  - Muon life time of about 800 μm
- Pion beam entering from the left
  - Red dotted line: pion stop
  - Blue dotted line: muon stop
- **Energy deposited in each plane varies by a factor ~100**
  - Electron is a MiP, Muon and Pion are not
- Highlighted Overlap of hits in for $\pi \to \mu \to e$ can be further resolved with **pulse pair resolution in time**
- Event reconstruction using advanced **machine learning algorithms** is also being pursued

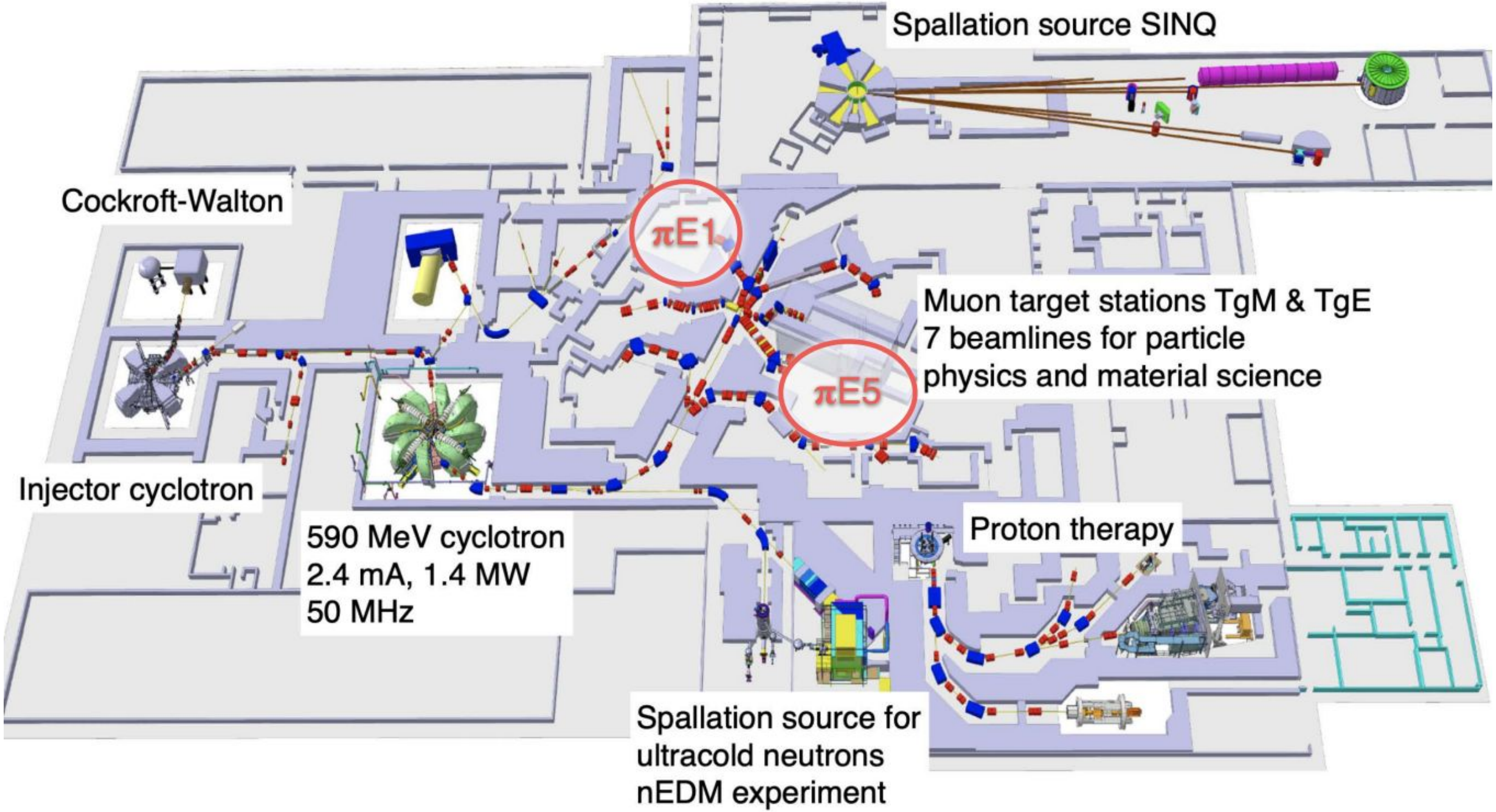


https://indico.cern.ch/event/1175216/contributions/5064175/



Slide from S. Mazza (Rare Pion Decay Workshop 2022)

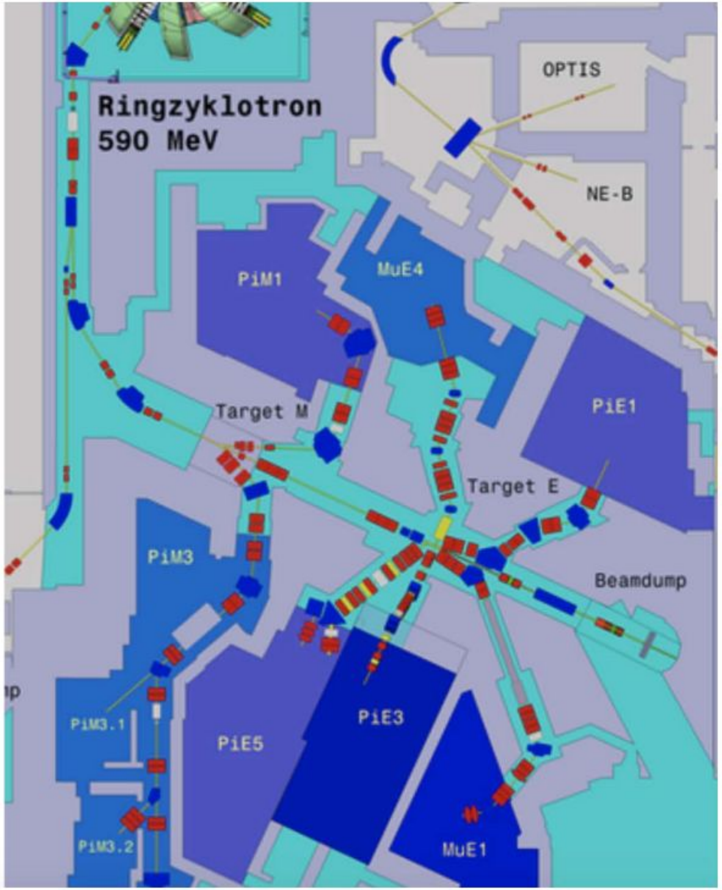
The PSI accelerator and beamlines



PIONEER

PSI Accelerators and Beamlines

- PiE5:
  - Highest-rate beamline available to particle physics
  - Home of MEG, Mu3e, Lamb Shift, piHe, …
- PiE1:
  - Shared with muSR
  - Home of MuSun, PIBETA, PEN, …



PIONEER: Beam Requirements Consistent with πE5
Beam measurements proposed.

Phase I $\pi \rightarrow e\nu$:

- π^+ Beam: 55 MeV/c ; $\frac{\Delta p}{p}$ ~2%; $3\text{x}10^5$ Hz
- 2 $\text{x}10^8$ events in 3 "yrs"* $\rightarrow$ $R_{e/\mu} \pm 0.01\%$

Phase II $\pi^+ \rightarrow \pi^0 e\nu$:

- π^+ Beam: O(85) MeV/c ; $\frac{\Delta p}{p}$ ~3%; 10^7 Hz
- 7 $\text{x}10^5$ events in 4 "yrs"* $\rightarrow$ $R_{\pi\beta} \pm 0.2\%$

* 5 months/yr

πE5 G4Beamline Model

X 10^6 Hz

Beamline Position	p_π (MeV/c)	π^+ Rate
QSB43	55	6.3
CALO Center	55	1.0
QSB43	75	61.5
CALO Center	75	11.1

Beamtime Request 2022
2 weeks for beam studies.

Slide from D Bryman (PSI 2022)

$\pi \rightarrow e\nu$: Estimated Uncertainties

To be verified by simulations and prototype measurements.

Error Source	PIENU 2015 %	PIONEER Estimate %	
Statistics	0.19	0.007	
Tail Correction	0.12	<0.01	(Calorimeter/ATAR)
t_0 Correction	0.05	<0.01	*(ATAR timing/dE/dx)*
Muon DIF	0.05	0.005	*(ATAR)*
Parameter Fitting	0.05	<0.01	(Calorimeter/ATAR)
Selection Cuts	0.04	<0.01	(Calorimeter/ATAR)
Acceptance Correction	0.03	0.003	(Calorimeter)
Total Uncertainty*	**0.24**	$\leq$ **0.01**	

*Pion lifetime uncertainty not included

$\pi^+ \rightarrow \pi^0 e^+ \nu$: Estimated Uncertainties

	PiBeta	**PIONEER (Phase II)**	
Statistics	0.4%	0.1%	
Systematics	0.4%	<0.1%	(ATAR (β), MC, Photonuclear, π→e ν)
Total	0.64%	**0.2%**	

Slide from D Bryman (PSI 2022)

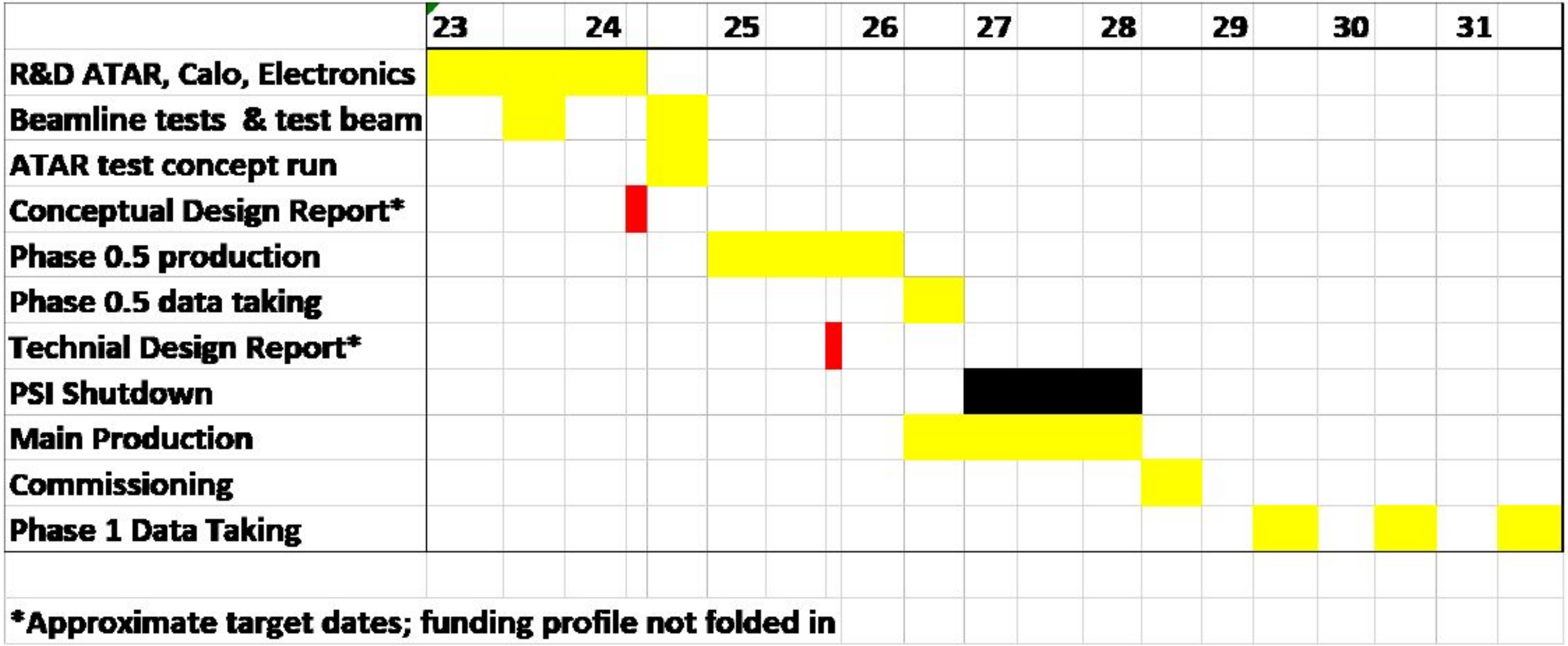
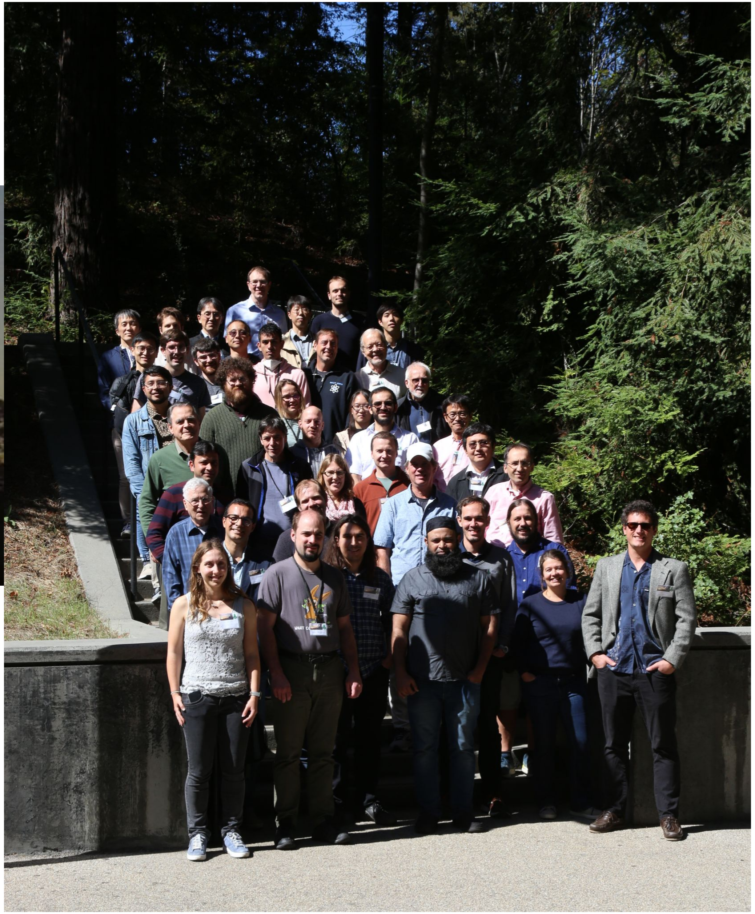


FIG. 7 – In this draft schedule, we indicate by "Phase 0.5" an intermediate milestone where a significant fraction of the hardware can be assembled to make a meaningful test of experimental strategy, including special triggers that exploit the power of the ATAR.

PIONEER collaboration



Supported by a large, experienced international collaboration: experts from previous PIENU and PEN experiments as well as a wide range of international collaborators from NA62, MEG, muon g-2, ATLAS, PSI scientists and leading theorists: JOIN US!