PIONEER: a next-generation pion decay experiment

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On behalf of PIONEER Collaboration

PIONEER Proposal: arXiv:2203.01981

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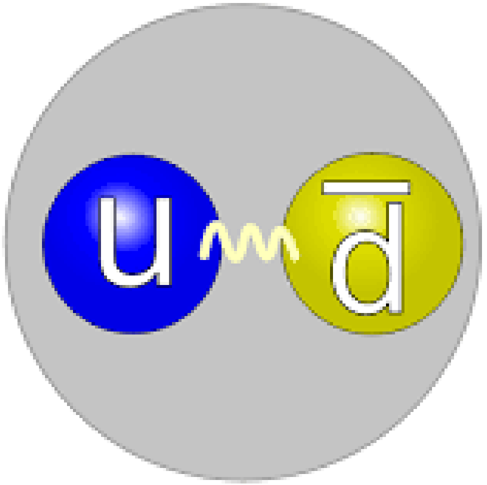
[14] Johannes Gulenberg University
[15] ETH Zurich
[16] Fermilab
[17] Cornell University
[18] University of Virginia
[19] University of Kentucky
[20] University of Bern
[21] Kilakyshu College
[22] University of Tokyo
[23] KEK
[24] University of Victoria

Charged PION ($\pi^{\pm}$)



Quark model

- Spin-0 pseudoscalar meson ($J^P=0^-$)
- Mass = 139.57039 $\pm$ 0.00018 MeV [ppm]
- Lifetime = 26.033 $\pm$ 0.005 ns [~0.02%]
- Decay Modes:
  - $\pi^+ \rightarrow \mu^+ \nu_\mu$ **B**ranching **R**atio 99.98770 $\pm$ 0.00004 %
  - $\pi^+ \rightarrow e^+ \nu_e$ **B. R.** $(1.230 \pm 0.004) \times 10^{-4}$ [~0.3%]
  - $\pi^+ \rightarrow \pi^0 \nu_e e^+$ **B. R.** $(1.036 \pm 0.006) \times 10^{-8}$ [~0.6%]
  - $\pi^+ \rightarrow e^+ \nu_e e^+ e^-$ **B. R.** $(3.2 \pm 0.9) \times 10^{-9}$

Taken from PDG

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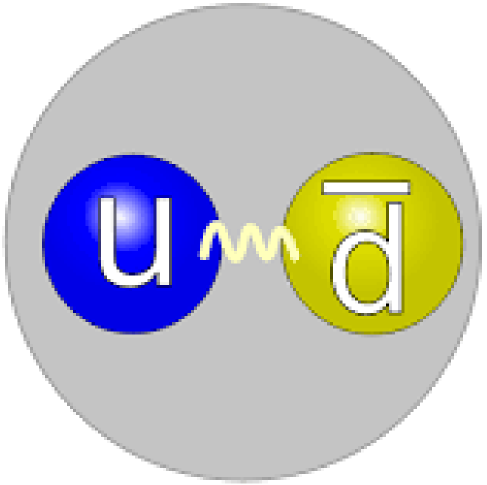


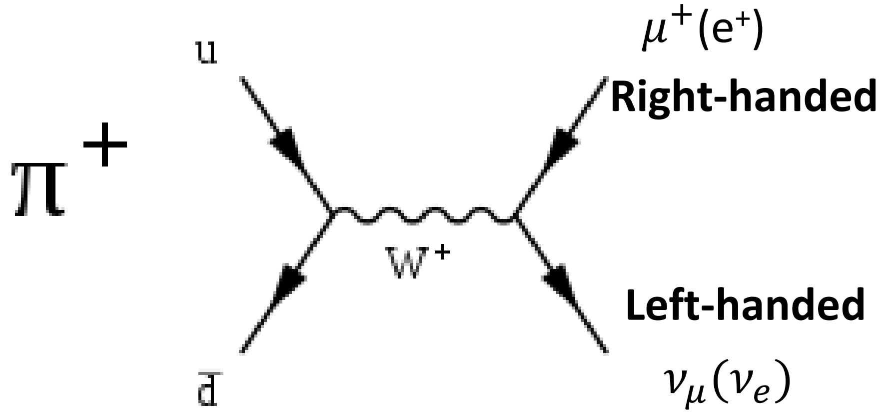
Quark model

Relevant for this talk

Taken from PDG

Pion Leptonic Decays ($\pi e\nu/\pi\mu\nu$)

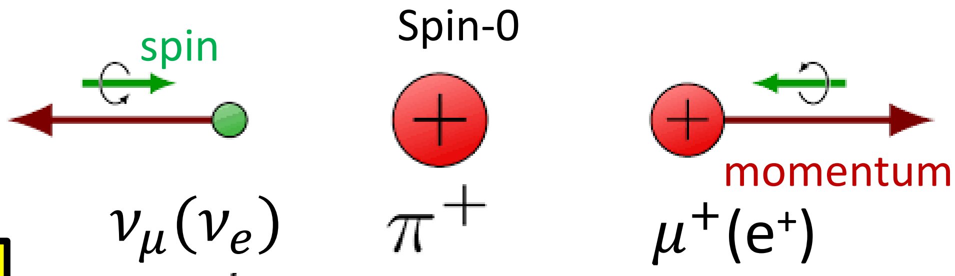
- Weak decay only involves left-handed (LH) leptons & right-handed (RH) anti-leptons
  - LH: negative helicity at massless limit
  - RH: positive helicity at massless limit
- Standard Model **assumes** lepton flavor universality
  - Coupling is blind of flavor



$$R^\pi := \frac{\Gamma(\pi\to e\nu)}{\Gamma(\pi\to\mu\nu)} \approx \frac{m_e^2}{m_\mu^2}\left(\frac{m_\pi^2-m_e^2}{m_\pi^2-m_\mu^2}\right)^2 = 1.233\times10^{-4}$$

Helicity suppression

Phase space factors



Left-handed
Negative helicity

Right-handed, but
Negative helicity

History of R^{π}

- 1940/50's: Development of V-A structure of weak interaction
- 1950's: Many experimental confirmation of the V-A theory
- 1956/1957: Negative experimental result $R^{\pi} < 10^{-5}$

Note on the Decay of the π-Meson

M. RUDERMAN AND R. FINKELSTEIN
California Institute of Technology, Pasadena, California
(Received July 25, 1949)

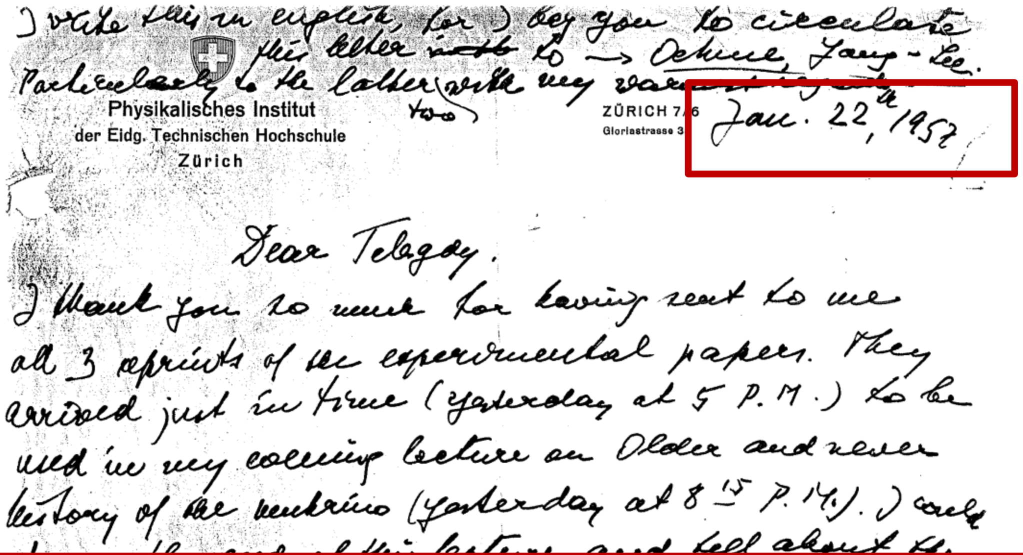
TABLE I. Ratio of $\pi \rightarrow (e, \nu)$ to $\pi \rightarrow (\mu, \nu)$-decay for couplings (1) and (7).

Meson	Type of β-decay: Scalar	P-scalar[a]	Vector	P-vector	Tensor
Scalar	5.1	f	f	f	f
P-scalar	f	5.1	f	1.0×10^{-4}	f
Vector	f	f	4.0	f	2.4
P-vector	f	f	f	4.0	f

Theory of the Fermi Interaction

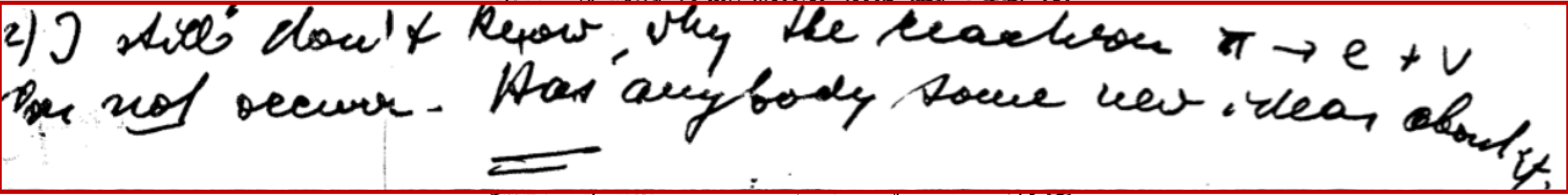
R. P. FEYNMAN AND M. GELL-MANN
California Institute of Technology, Pasadena, California
(Received September 16, 1957)

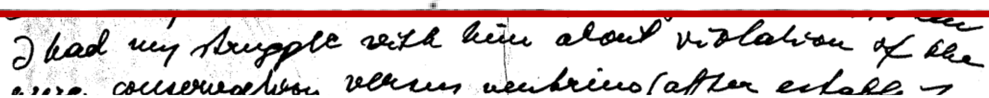
Experimentally[16] no $\pi \rightarrow e + \nu$ have been found, indicating that the ratio is less than 10^{-5}. This is a very serious discrepancy. The authors have no idea on how it can be resolved.



Jan 22nd, 1957

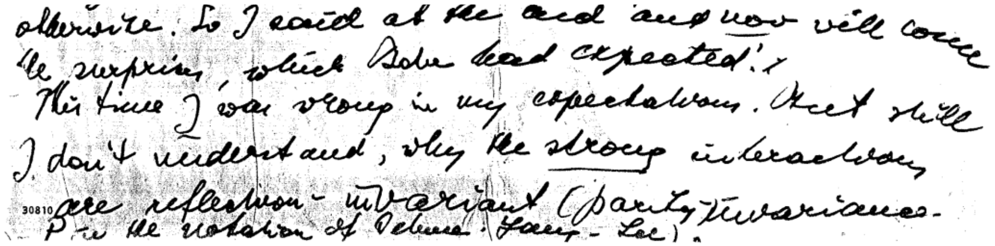
Letter of W. Pauli to V. Telegdy





I still don't know, why the reaction $\pi \rightarrow e + \nu$ does not occur.

Has anybody some new ideas about it?



"Particle rush"
Development of SM

Discovery of Pion — 1947 — *Nature* 159:694-697

No electronic decay observed
PUZZLE!

1955 — *Supl. Nuovo cimento* 2:151

Search for the β-Decay of the Pion. (*)
S. LOKANATHAN and J. STEINBERGER (**)
Nevis Cyclotron Laboratories, Columbia University
Department of Physics - New York

1957 — *Il Nuovo Cimento* VI, 6

IL NUOVO CIMENTO — VOL. VI, N. 6 — 1° Dicembre 1957
Search for the Electronic Decay of the Positive Pion (*)
H. L. ANDERSON (+)
Scuola di Perfezionamento in Fisica Nucleare dell'Università - Roma
C. M. G. LATTES (×)
Enrico Fermi Institute for Nuclear Studies
The University of Chicago - Chicago

1958 — First experimental observation of the **electronic decay** at CERN **more than 60 years ago!**

VOLUME 1, NUMBER 7 — PHYSICAL REVIEW LETTERS — OCTOBER 1, 1958
ELECTRON DECAY OF THE PION
T. Fazzini, G. Fidecaro, A. W. Merrison, H. Paul, and A. V. Tollestrup*
CERN, Geneva, Switzerland
(Received September 12, 1958)
Phys. Rev. Lett. 1, 7

"put CERN on the map of high energy physics!"

... and "simultaneously" at Columbia University — *Phys. Rev. Lett.* 1, 249

1959 — ... and confirmed at Univ. of Chicago — *Phys. Rev. Lett.* 2, 64

x3

First precise measurement (~5%)

1964 — Di Capua et al. — *Phys. Rev.* 133(5B):B1333–B1340

~x2

"Precision area"
Search for BSM

1986 — TRIUMF by Bryman et al. — *Phys. Rev. D* 3(5):1211–1221

x2.5

1992 — TRIUMF by Britton et al. — *Phys. Rev. Lett.* 68:3000–3003

1993 — PSI by Czapek et al. — *Phys. Rev. Lett.* 70 (1) 17-20

~x2

2015 — TRIUMF by Aguilar Arevalo et al. — *Phys. Rev. Lett.* 115:071801 — Most precise measurement (~0.2%)

PIONEER — x20

Curtesy of C. Malbrunot

Previous R^π Experiments

- PIENU @ TRIUMF
- PEN @ PSI
- Several previous experiments

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		

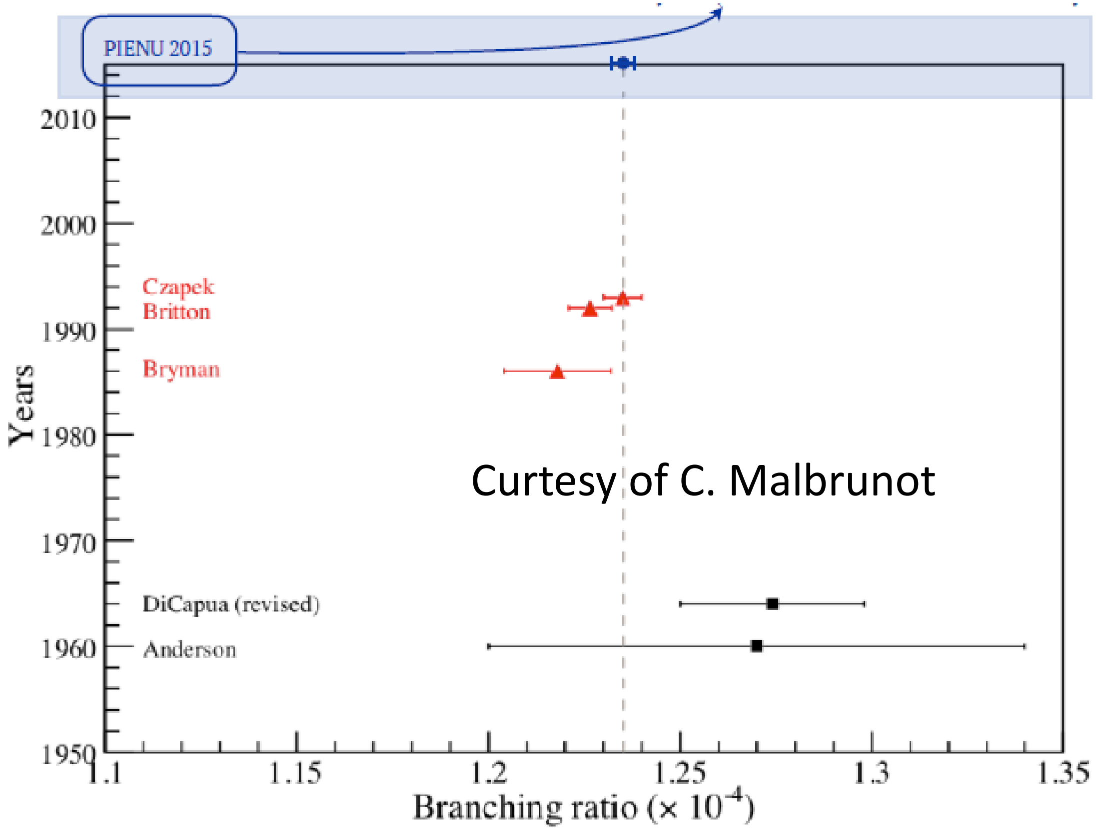
[1] DICAPUA 64 has been updated using the current mean life.

PDG 2018: R^π ~ 0.19%

PIENU and PEN aims at 0.1% for their final measurements

PIONEER Goal x20 improvement

First PINEU result @ 0.2% based on 10% of Data



Curtesy of C. Malbrunot

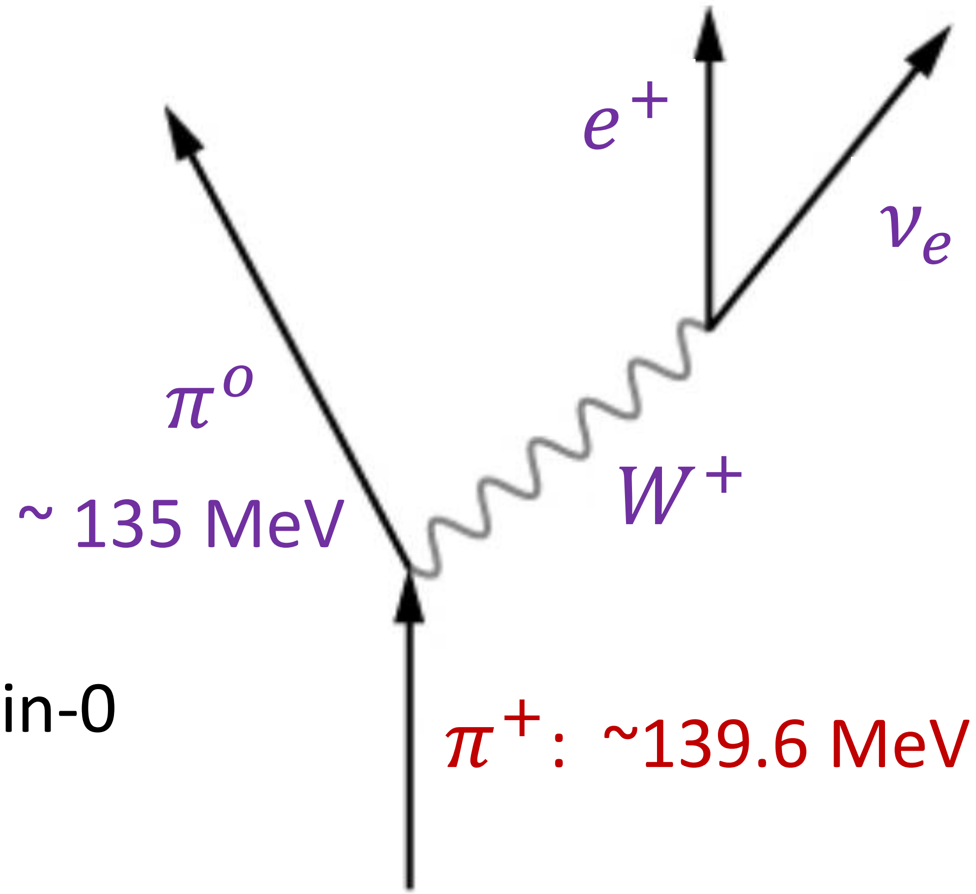
Pion Beta Decay B. R. $(1.036 \pm 0.006) \times 10^{-8}$

Phase Space Suppression

$$\Gamma_{\pi\beta} = \frac{G_\mu^2 |V_{ud}|^2}{30\pi^3}\left(1 - \frac{\Delta}{2M_{\pi^+}}\right)^3 \Delta^5 \, f(\epsilon, \Delta)(1+\delta)$$

$$\Delta = M_{\pi^+} - M_{\pi^o};\ \epsilon = \left(\frac{m_e}{\Delta}\right)^2$$

f: Fermi function; δ: loop correction

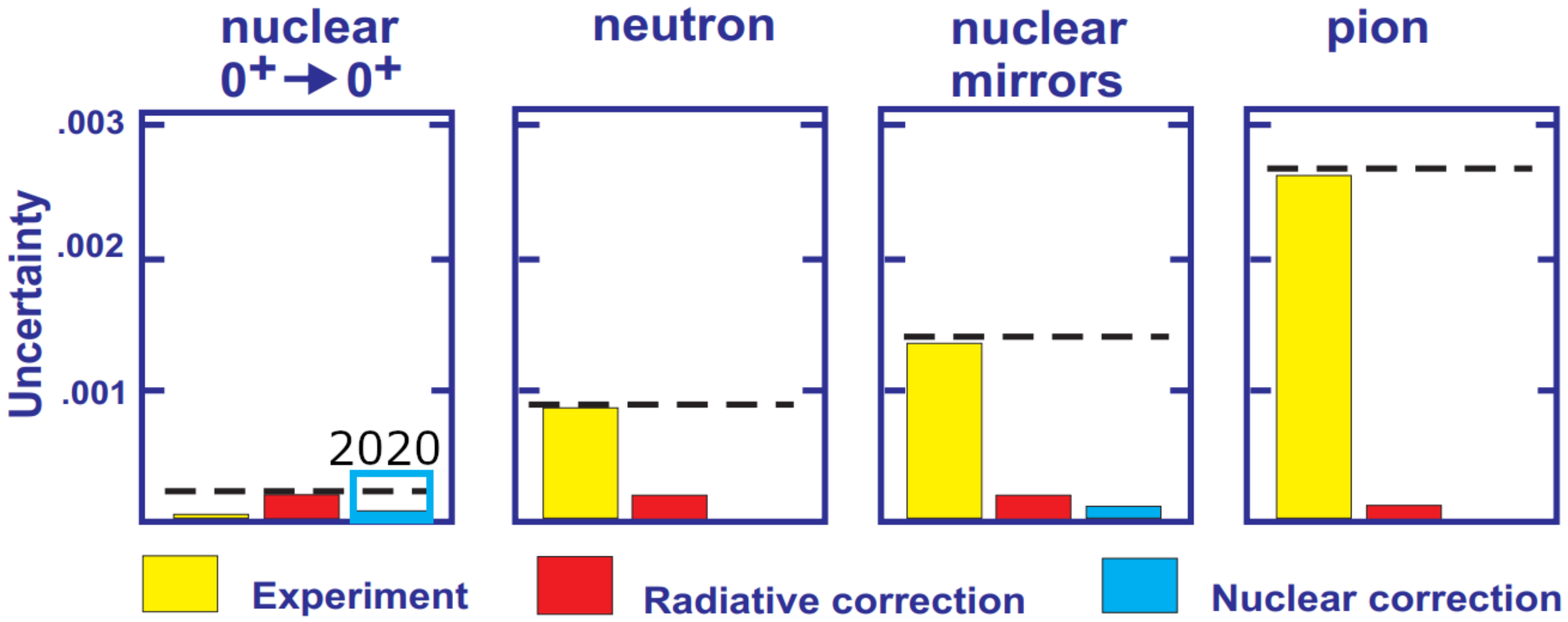


- Analogous to neutron beta decay, but with spin-0 (much simpler hadronic contributions)

- The theoretically cleanest way of measuring V_{ud}

Measurement of V_{ud}

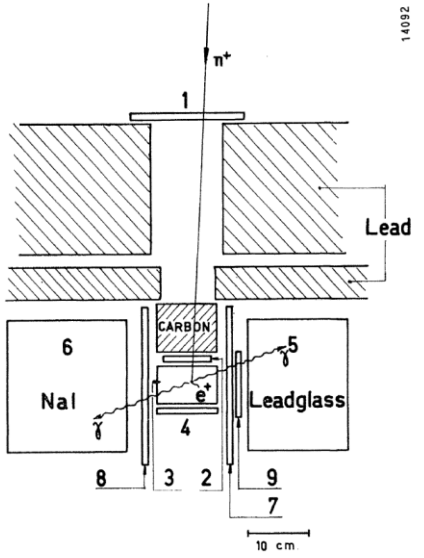
- Pion (cleanest but hard BR~10^{-8})
- Neutron (also need g_A)
- Super allowed $0^+ \rightarrow 0^+$
- T=1/2 mirrors (e.g. ^3H & ^3He)

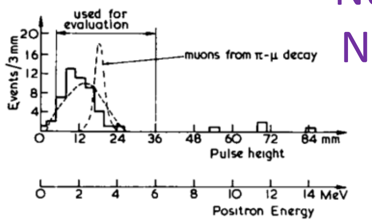


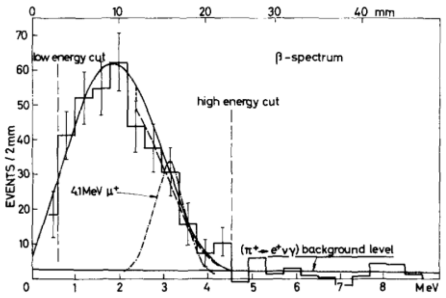
Courtesy of Leendert Hayen

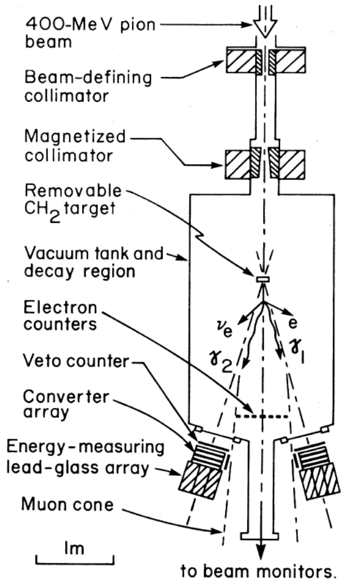
Pion Beta Decay Measurements

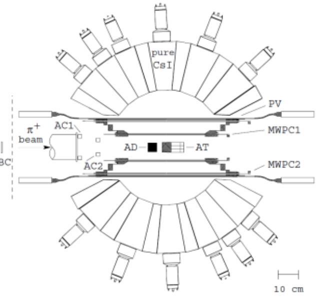
1947	1958	1962	1963	1968	1985	2004	
Discovery of pion	Discovery of $\pi e \nu$	**Discovery of $\pi\beta$ decay**	$(1.15 \pm 0.22) \times 10^{-8}$	$(1 \pm 0.1) \times 10^{-8}$	$(1.026 \pm 0.039) \times 10^{-8}$	$(1.036 \pm 0.006) \times 10^{-8}$	**PIONEER Goals**
Nature 159,674	PRL 1, 247	Phys. Lett. 2, 23 O(10) events	Phys. Lett. 5, 61 O(30) events	Nucl. Phys. B4, 189; Nucl. Phys. B4, 432 O(100) events	Phys. Rev. D 32, 547 O(700) events	PRL93,181803 O(70k) events	II: O(0.6M) events III: O(7M) events

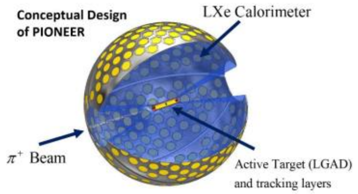








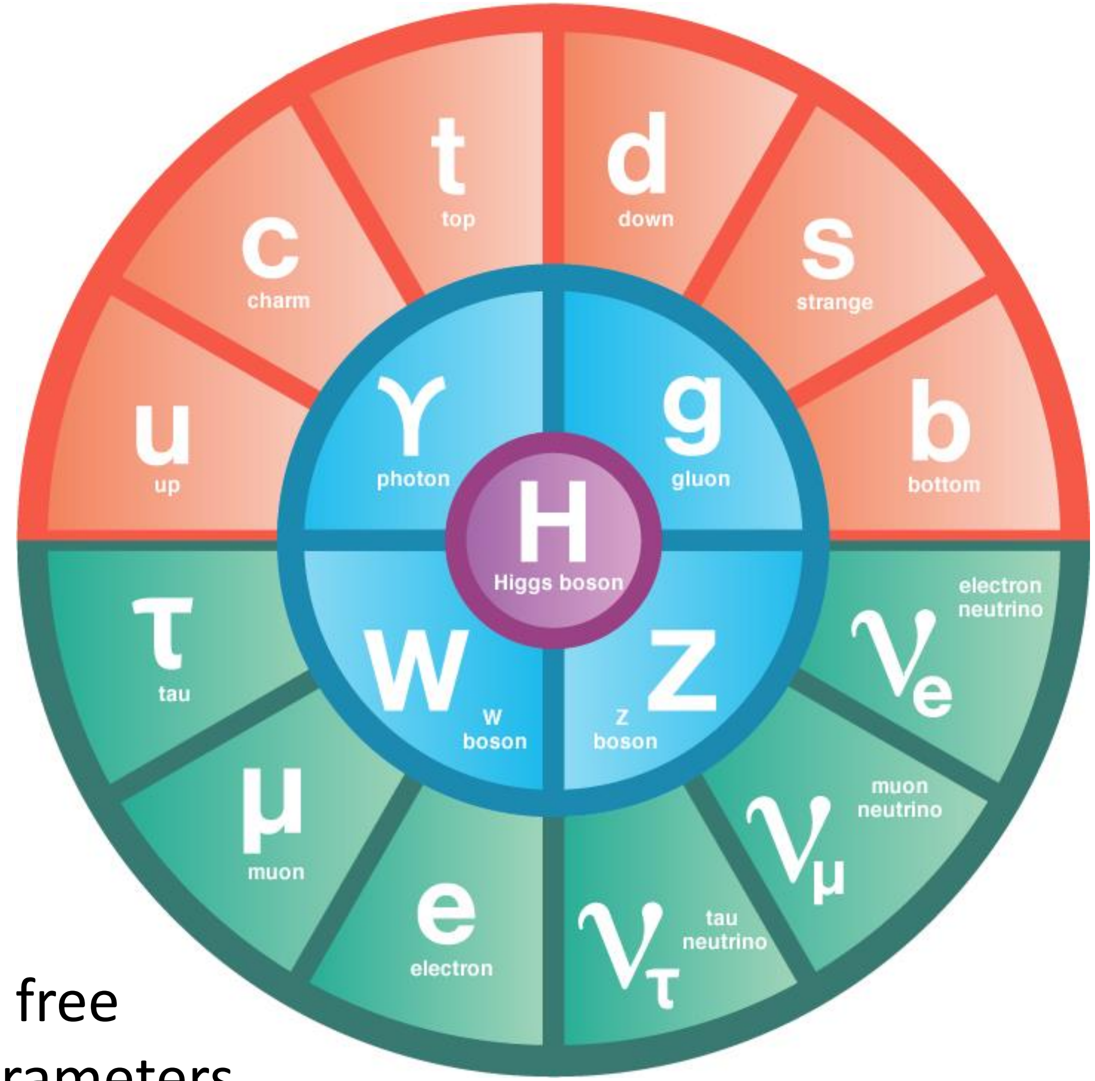




Why PIONEER?

non official logo!

Standard Model of Particle Physics



19 free parameters

- Direct evidence of physics beyond standard model
  - Neutrino oscillation → non-zero neutrino mass and mixing (19→26-28 parameters)
- Additional evidence of physics beyond standard model
  - Existence of Dark Matter and Dark Energy

The main technique: Aim Collider at the Standard Model and try to crack it

Warning: evidence of the unbreachable castle …

Direct approach

Coming up empty

Curtesy of D. Hertzog

What else can we do?

Direct approach

The Next Step is High Luminosity

But, there is also an indirect approach: "Quantum tunneling"

Curtesy of D. Hertzog

Physics Motivation I: Testing **L**epton **F**lavor **U**niversality

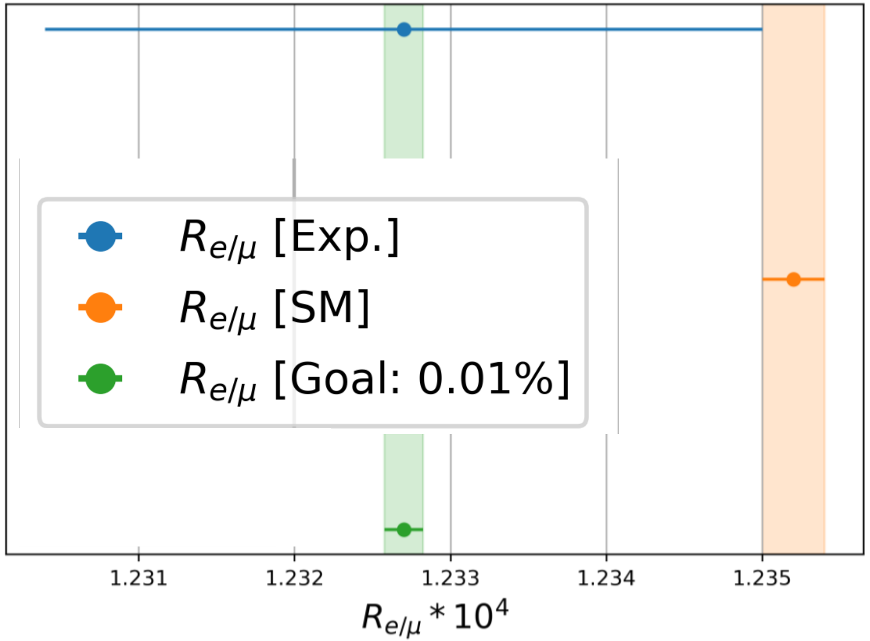
- **LFU in SM: the weak coupling "g" is the same for $e/\mu/\tau$ leptons**
- $R_{e/\mu} = \frac{\Gamma(\pi\to e\nu(\gamma))}{\Gamma(\pi\to\mu\nu(\gamma))}$, currently best, tested charged LFU at $O(10^{-3})$

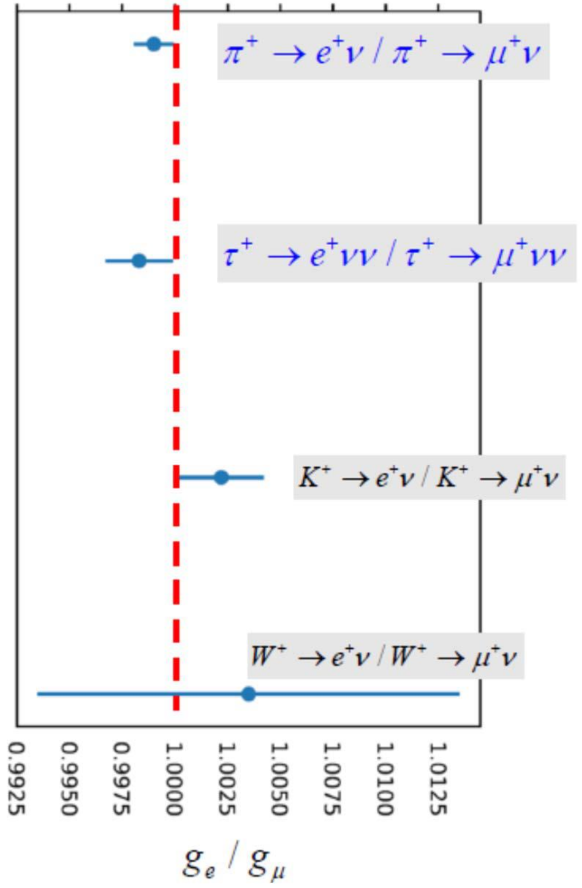
$$R_{e/\mu}^{\rm SM} = 1.23524(015)\times 10^{-4}$$
$$R_{e/\mu}^{\rm Exp} = 1.23270(230)\times 10^{-4}$$

possibly the most accurately calculated decay process involving hadrons

→ $$\frac{g_e}{g_\mu} = 0.9989 \pm 0.0009$$

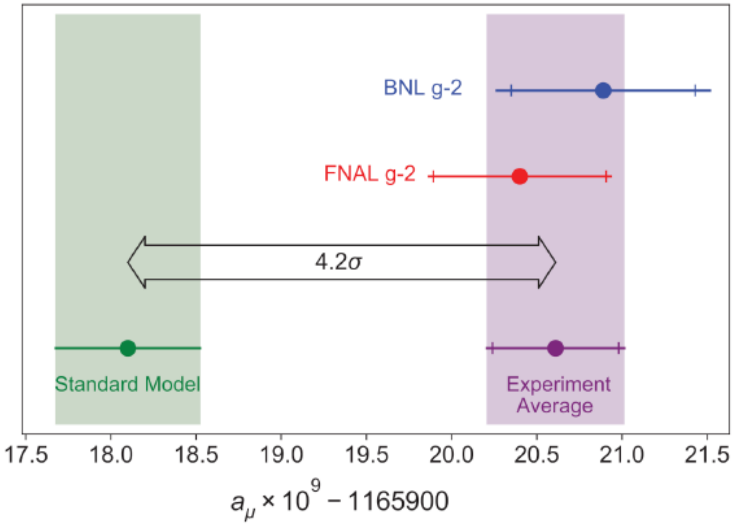
PIONEER aims to measure $R_{e/\mu}$ to ~0.01%, x20 improvement over the current world best, matching the SM precision to test lepton flavor universality



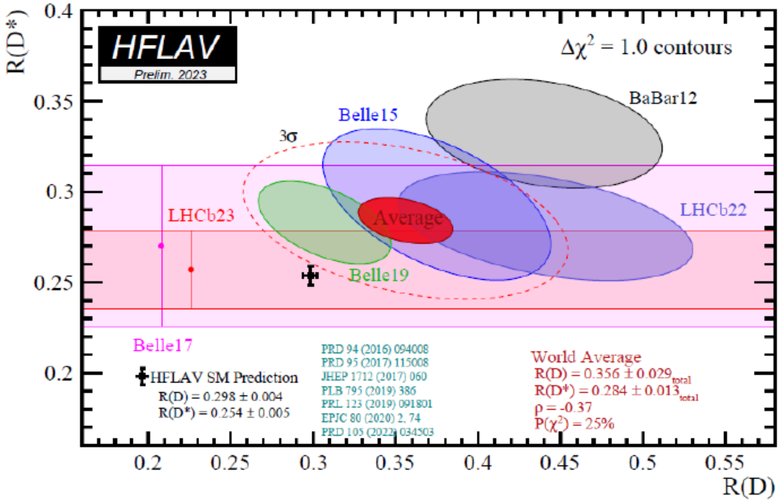


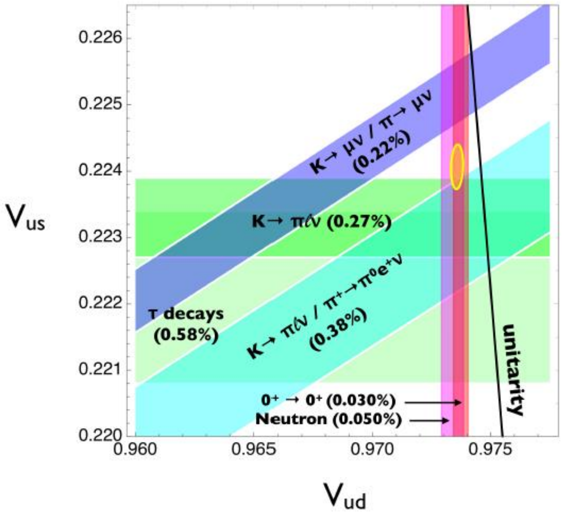
Some anomalies pointing LFU Violation

- Several new tensions in the flavor sector, hinting toward lepton flavor universality violation (LFUV)
  - ~~B decays: $R(K^*) = \frac{B\to K^*\mu\mu}{B\to K^*ee}$, and R(K)~~ (LHCb arXiv:2212.09153)
  - B decays: $R(D^*) = \frac{B\to D^*\tau\nu}{B\to D^* l\nu}$, O(10%) deviations at 3-4σ from LFU
  - Muon g-2: 4.2σ deviation from SM prediction, hint of LFUV compared to electron g-2
  - Cabibbo Angle Anomaly: 2-3σ tension from CKM unitarity from β and K decays, hint of LFUV with modified $Wl\nu$ couplings



Phys. Rev. Lett. 126 (2021) 141801



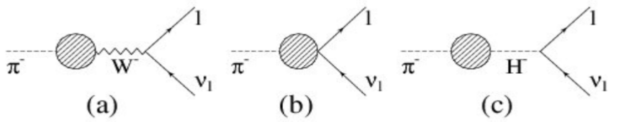


arXiv:2111.05338

Test BSM Explanations of LFUV Anomalies

- Precision measurement of $R^{\pi}_{e/\mu}$ is extremely sensitive to presence of new pseudoscalar or scalar couplings

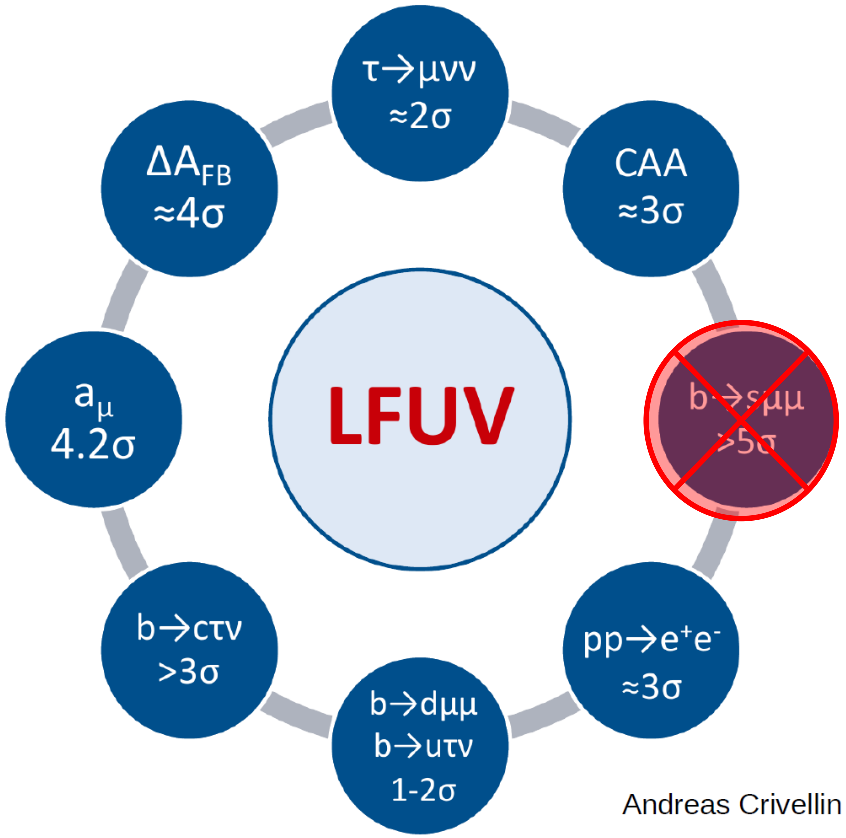
Pseudoscalar interactions



Charged Higgs (non-SM coupling)

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

Marciano…

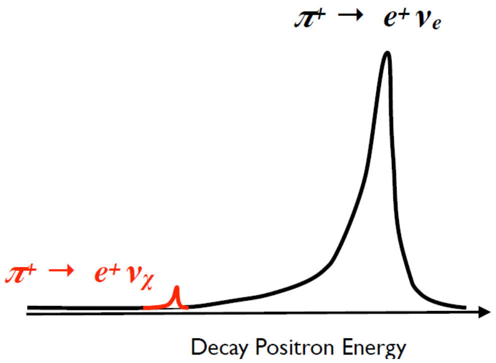


Andreas Crivellin

Test beyond SM physics explanations of LFUV anomalies through sensitivity to quantum effects of new particles up to PeV mass scale

Physics Motivation II: Sensitivity to New Physics

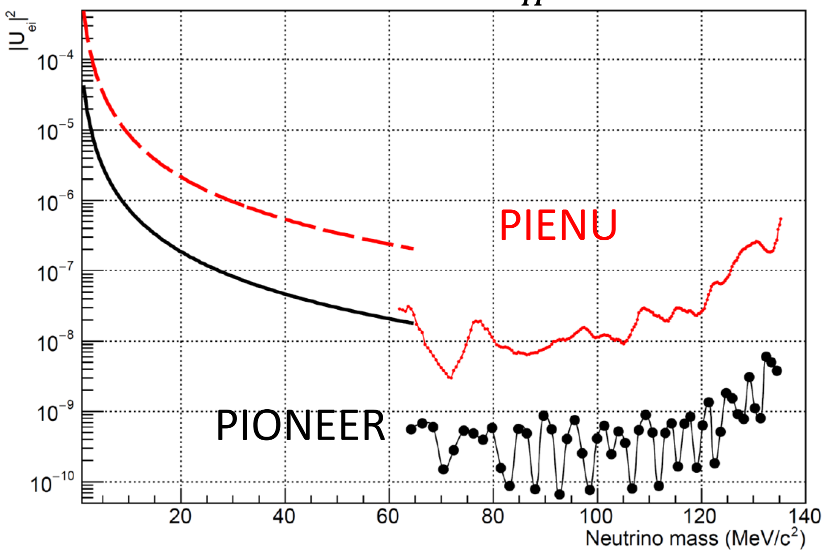
- PIONEER will improve sensitivity by **about one order of magnitude** to a host of exotic decays, including heavy sterile neutrinos, various light dark sector particles, LFUV decays of muon into light NP particles



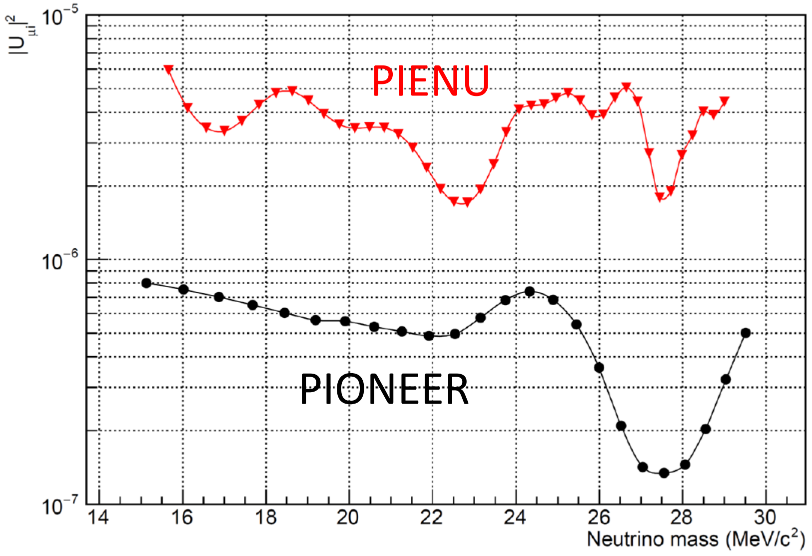
If the mass of heavy neutrinos, which have implications for leptogenesis, are $M_\nu = 60{\sim}130\ MeV/c^2$, additional low energy positron peak can be detected in the $\pi^+ \rightarrow e^+$ energy spectrum

R. E. Shrock

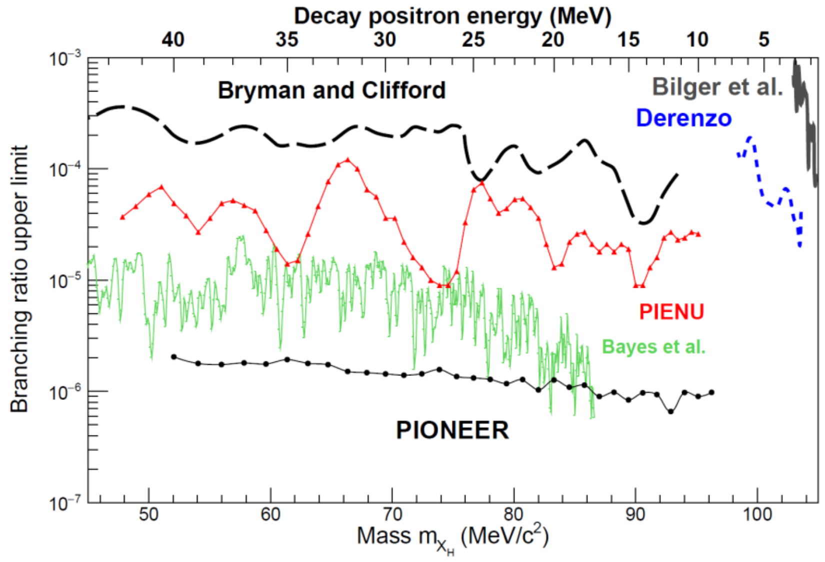
$\pi^+ \rightarrow e^+ \nu_H$



$\pi^+ \rightarrow \mu^+ \nu_H$

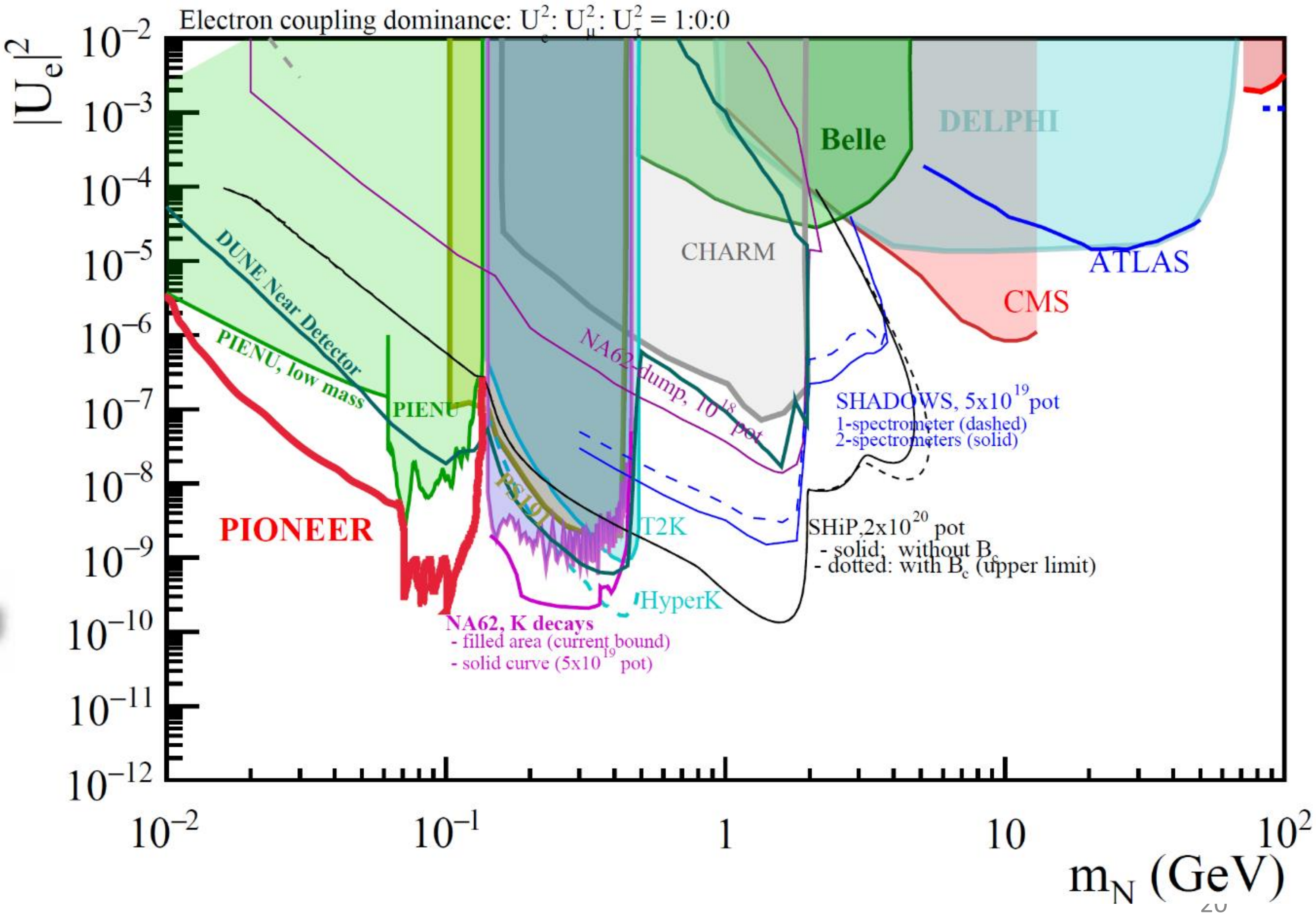


$\mu^+ \rightarrow e^+ X_H$



Exotic Searches – Global Experimental Context

- PIONEER will improve previous limits by **about one order of magnitude** to a host of exotic decays in the low mass region 1-120 MeV



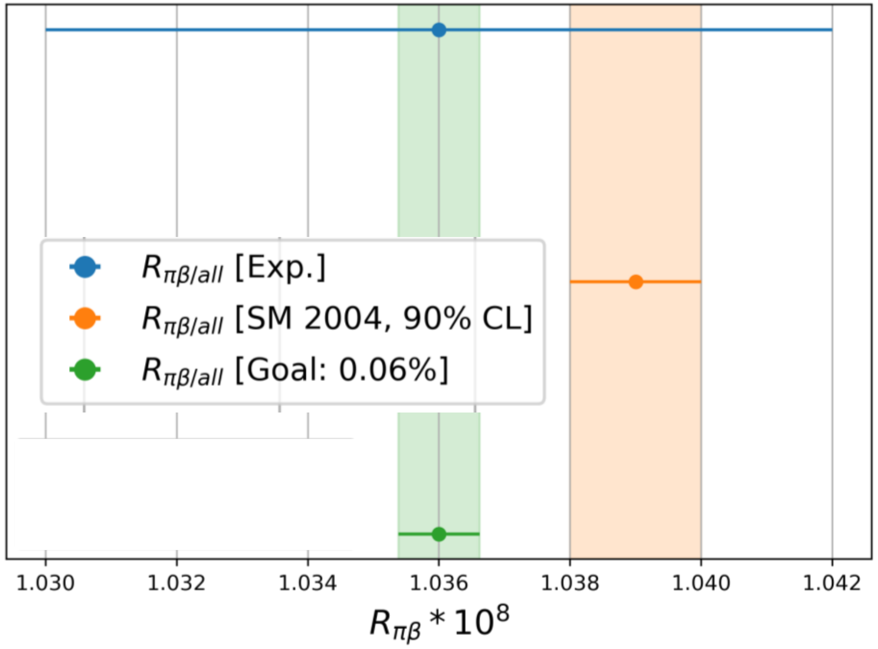
Example papers published by PIENU

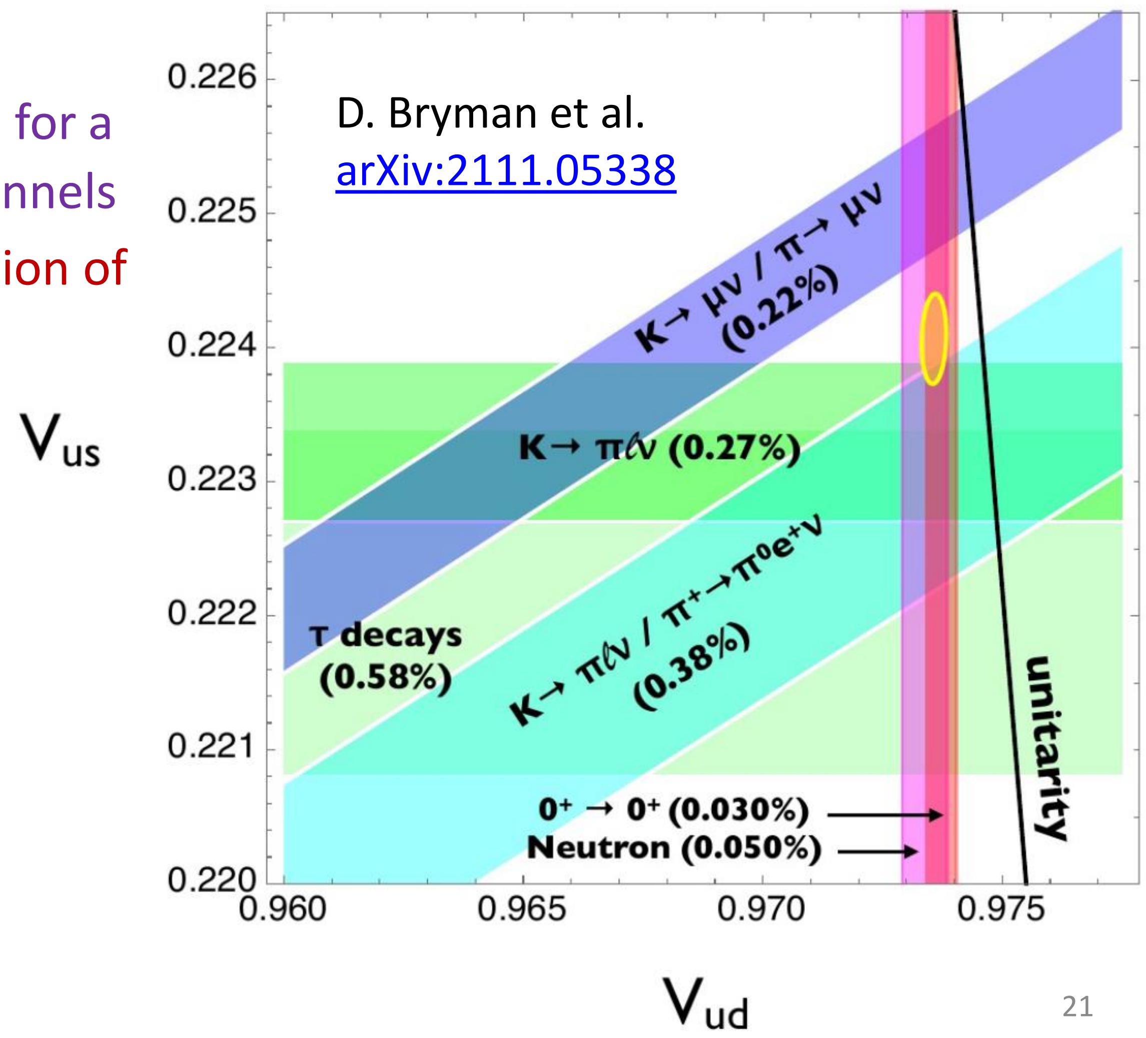
A. Aguilar-Arevalo et al. Physical Review D 97(7) 072012 (2018)
A. Aguilar-Arevalo et al. Physics Letters B 798 (2019) 134980
A. Aguilar-Arevalo et al. Phys. Rev. D 102, 012001 (2020)
A. Aguilar-Arevalo et al. Phys. Rev. D 101, 052014 (2020)
A. Aguilar-Arevalo et al. Phys. Rev. D 103, 052006 (2021)

Physics Motivation III: Testing CKM Unitarity

- Pion beta decay provides the theoretically cleanest determination of $|V_{ud}|$
  - $R_{\pi\beta}^{Exp} = \frac{\Gamma(\pi^+ \to \pi^0 e\nu(\gamma))}{\Gamma(all)} = (1.036 \pm 0.006) \times 10^{-8}$
  - 3-fold improvement in $R_{\pi\beta}$ with $K \to \pi l\nu(\gamma)$ allows for a 0.2% determination of $|V_{us}/V_{ud}|$ matching axial channels
  - 10-fold improvement allows for a 0.02% determination of $|V_{ud}|$, comparable to super-allowed beta decay

~3σ tension in the first-row of CKM unitarity test (CAA: Cabibbo Angle Anomaly)



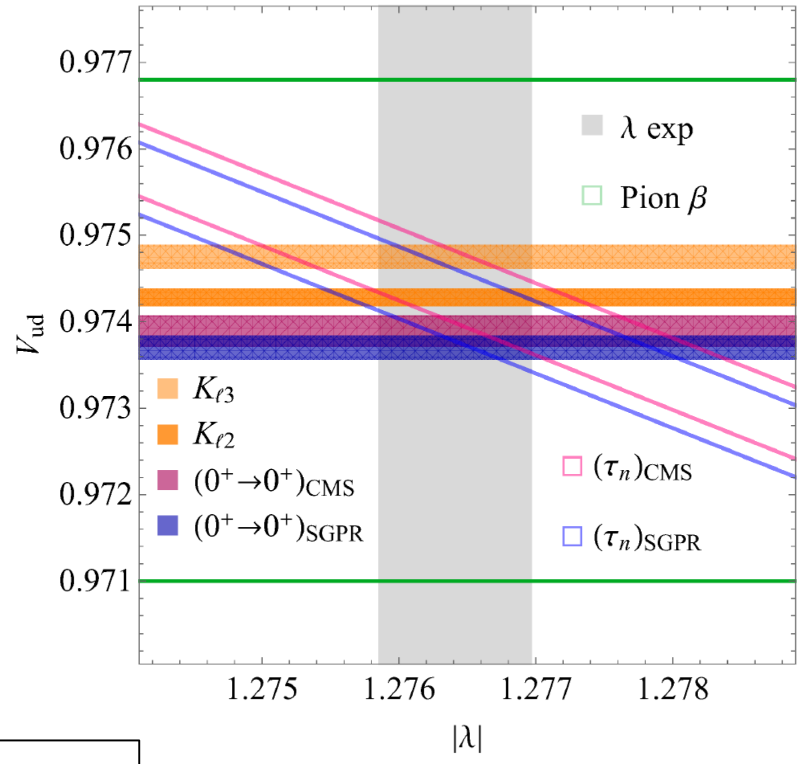


Connection between LFUV and CAA?

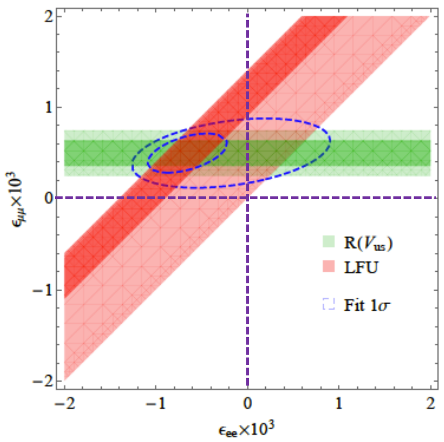
- Assuming CKM unitarity, V_{ud} (or V_{us}) deduced from K_{l2} and K_{l3} and nuclear beta decay is inconsistent

Is this tension a sign of LFUV ??

- Modified 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 $(V_{ud}/V_{us})^2 \sim 20$!

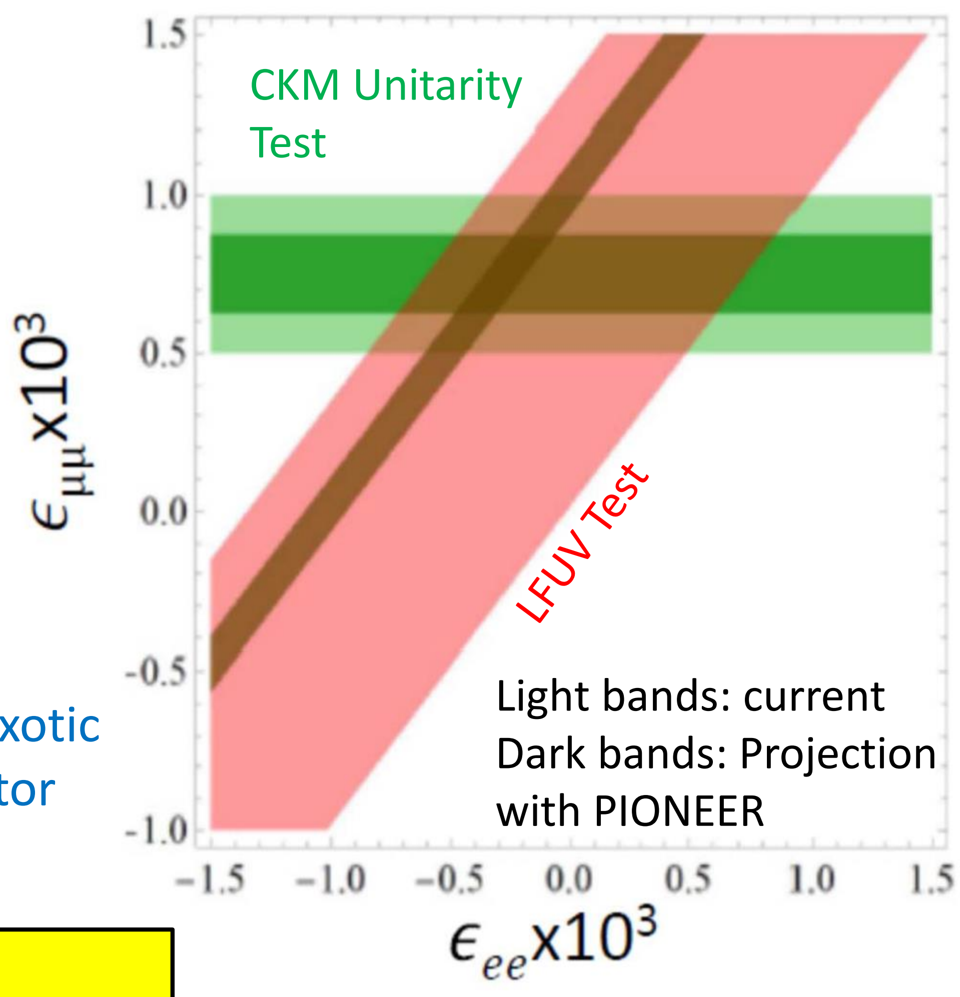
ε_{ij} are possible small corrections to the charged W-ℓ-ν couplings

Crivellin-Hoferichter 2002.07184, PRL

Summary of PIONEER Physics Goals

- Phase I Goals:
  - Measure $R_{e/\mu} = \frac{\Gamma(\pi \to e\nu(\gamma))}{\Gamma(\pi \to \mu\nu(\gamma))}$ to 0.015, matching SM prediction precision
  - Improve e/μ universality test by an order of magnitude
- Phase II (III) Goals:
  - Measure $R_{\pi\beta} = \frac{\Gamma(\pi^+ \to \pi^0 e\nu(\gamma))}{\Gamma(all)}$ to 0.05%
  - Improve CKM unitarity tests by an order of magnitude with $\left|\frac{V_{us}}{V_{ud}}\right| < 0.1\%$ and $|V_{ud}| \sim 0.02\%$
- Parasitic Goals:
  - One order of magnitude improvement in search for a host of exotic decays including heavy sterile neutrinos, various light dark sector particles, LFUV decays of muon into light NP particles

Modified $Wl\nu$ couplings

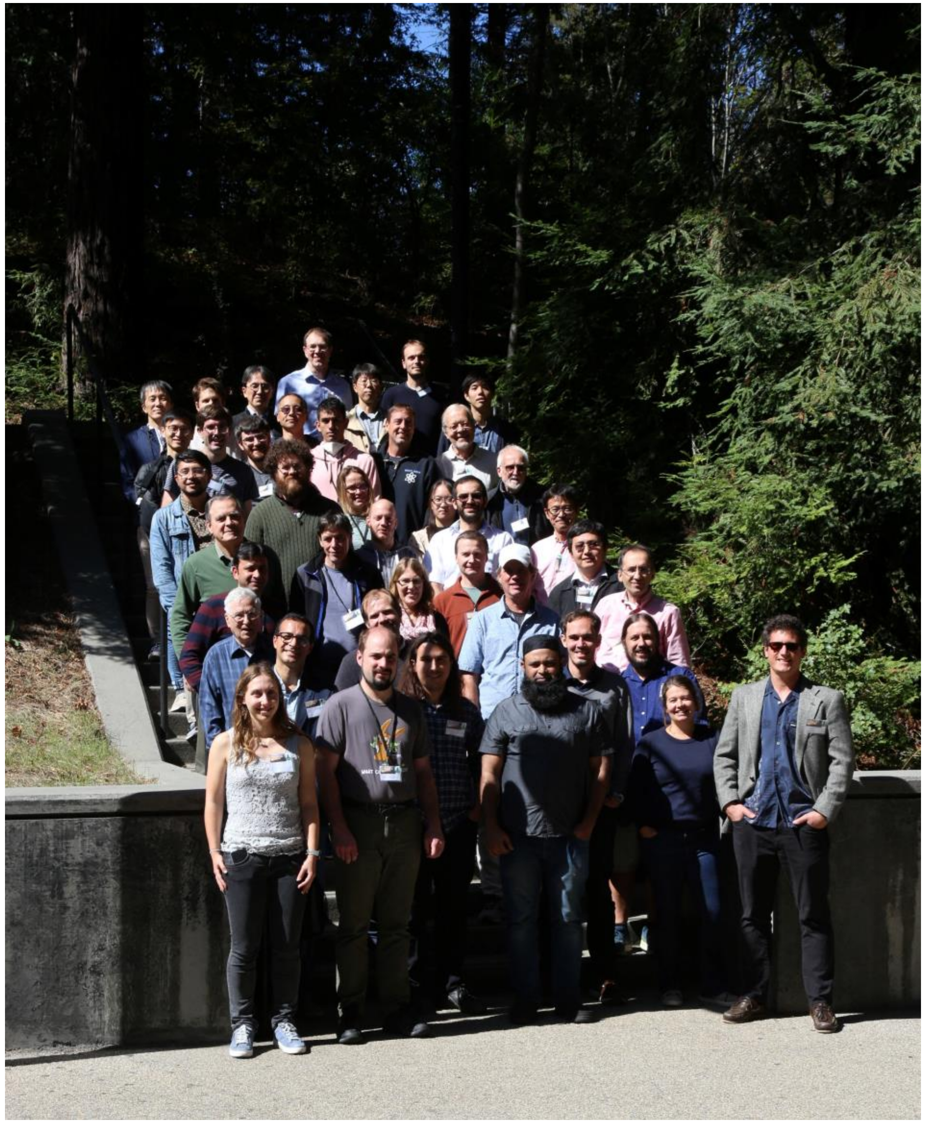


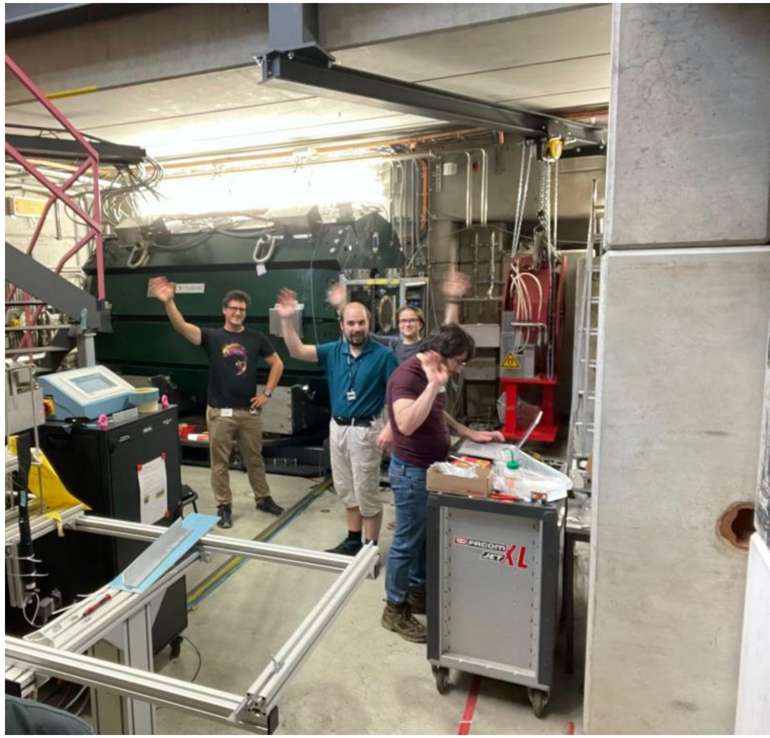
A. Crivellin and M. Hoferichter

We will focus on phase I, which is already a major challenge;
however, the core of the apparatus is designed to accommodate later phases

What is PIONEER?

non official logo!





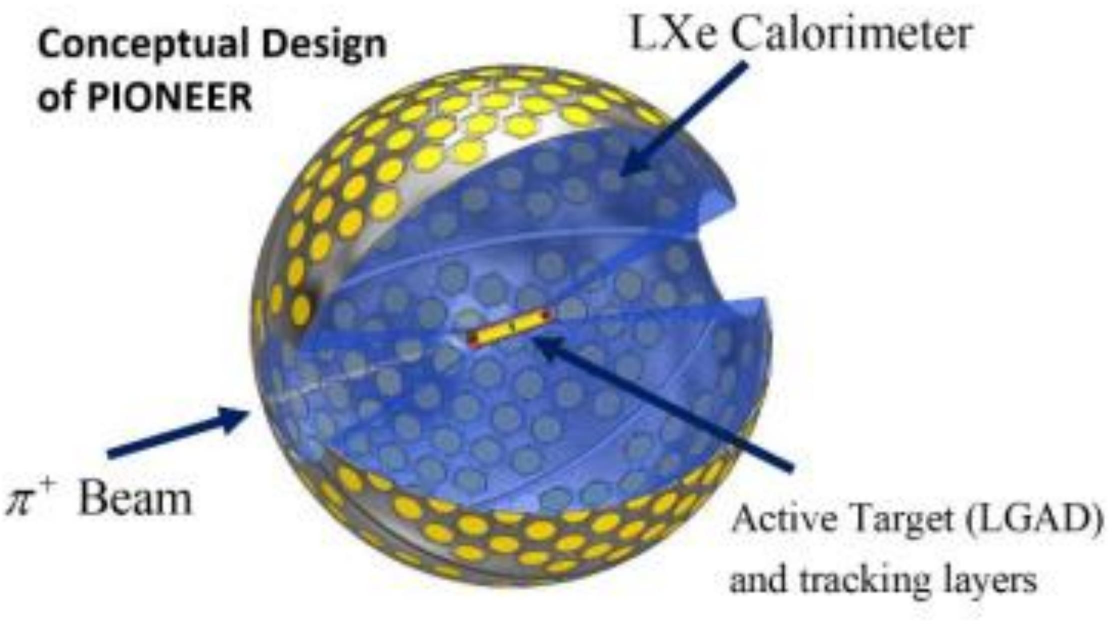
Currently over 80 collaborators from 24 institutions

Conceptual Design of PIONEER Phase I

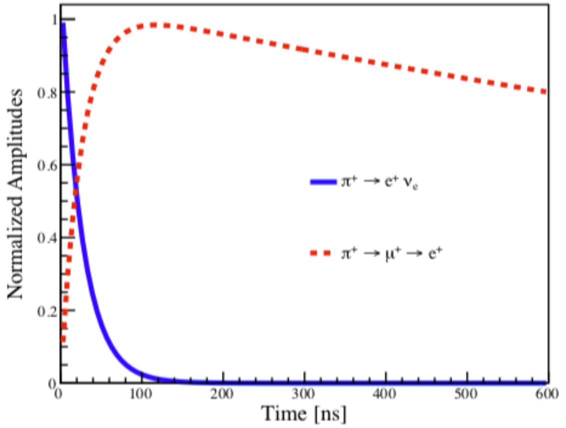
- Aims to collect $2 \times 10^8\ \pi^+ \rightarrow e^+\nu$ events at Paul Scherrer Institute (PSI) to measure $R_{e/\mu}$ to 0.01%

Features of stopped π decay	$\pi \rightarrow e\nu(\gamma)$	$\pi \rightarrow \mu\, \nu(\gamma)$ $\boldsymbol{\mu \rightarrow e\nu\nu(\gamma)}$	Detector technology
Decay Time	26 ns (π)	26 ns + 2197 ns (μ)	
$E_{e+\gamma}$	69.3 MeV*	0 MeV -- 52.3 MeV	(Fast) LXe calo.
Pattern recognition	Two tracks (π + e)	Three tracks (π + μ + e)	Active target (LGAD tech.)

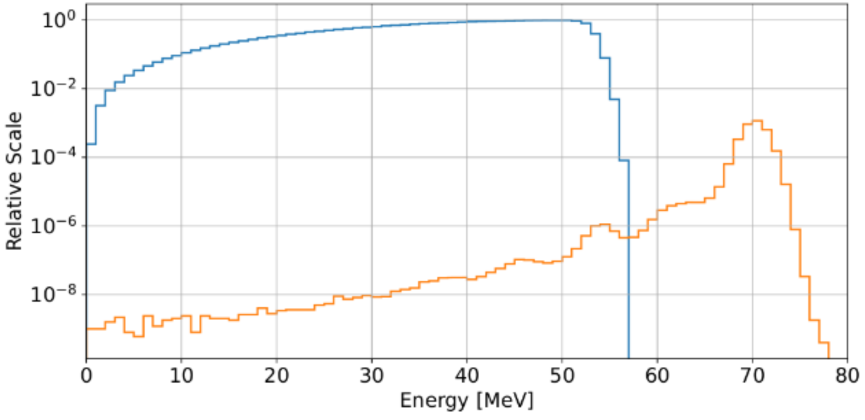
*: there is a long tail at lower energy region



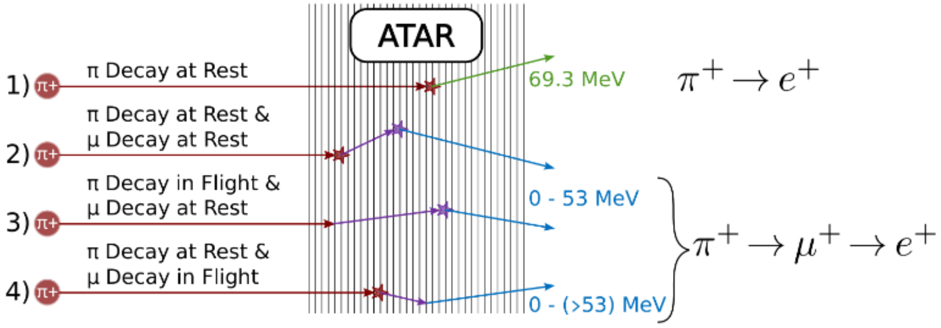
Time Information



Energy Information



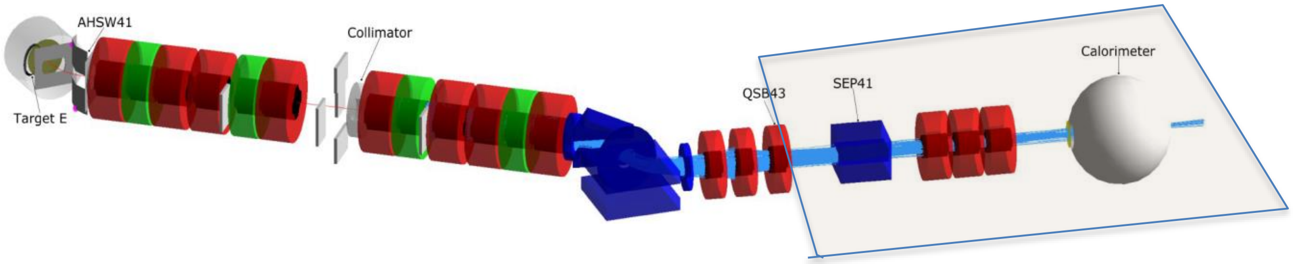
Pattern Recognition Information



Also, π/μ separation with dE/dx

Pion Beamline @ PSI

piE5



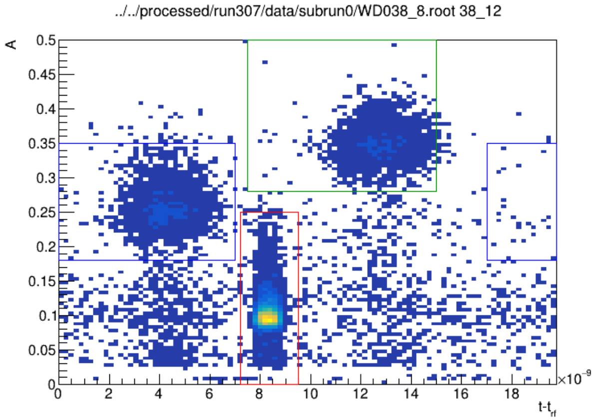
- Specifications:
  - Momentum p=55-70 MeV/c allowing for $E \times B$ separation of π from μ and e
  - Tight beam spot (< 2 cm^2) and small divergence
  - Narrow momentum bin (2%) for well defined π stopping location in active target

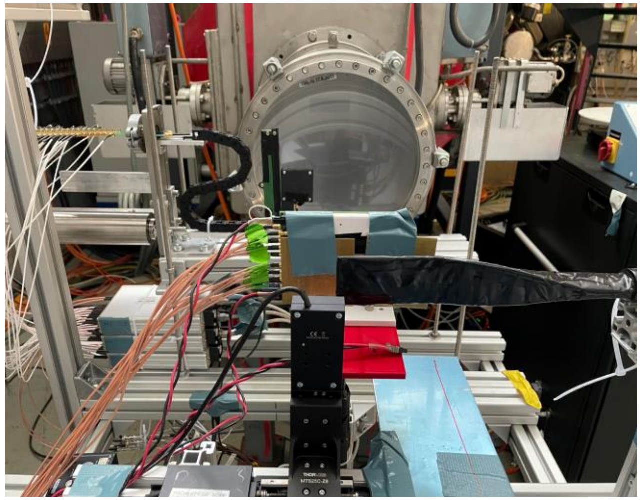
Phase I $\pi \rightarrow e\nu$:

- π^+Beam: 55 MeV/c ; $\frac{\Delta p}{p}$~2%; 3x10^5 Hz
- 2 x10^8 events in 3 "yrs"* $\rightarrow$ $R_{e/\mu}$±0.01%

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





Beam test @ 2022

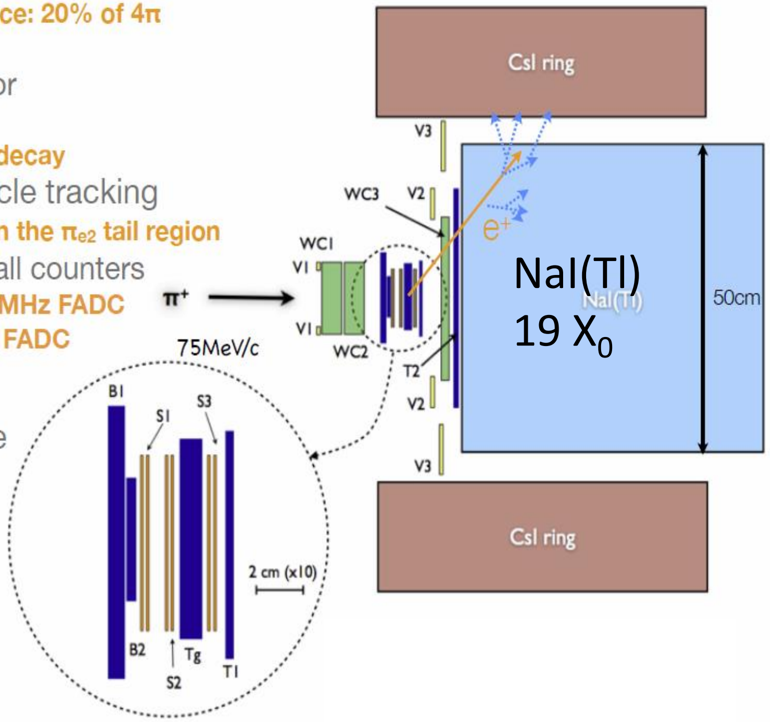
Two Recent Pion Decay Experiments: PIENU and PEN

PIENU

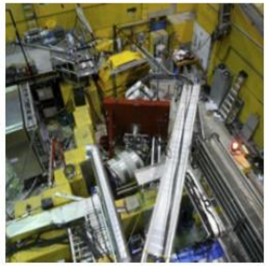
$$\frac{\pi^+ \to e^+\nu}{\pi^+ \to \mu^+\nu} \;\&\; \pi^+ \to e/\mu^+ \nu_H$$

& 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

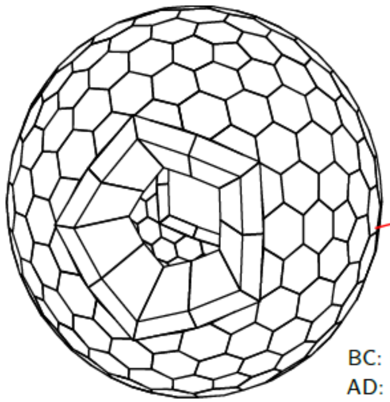


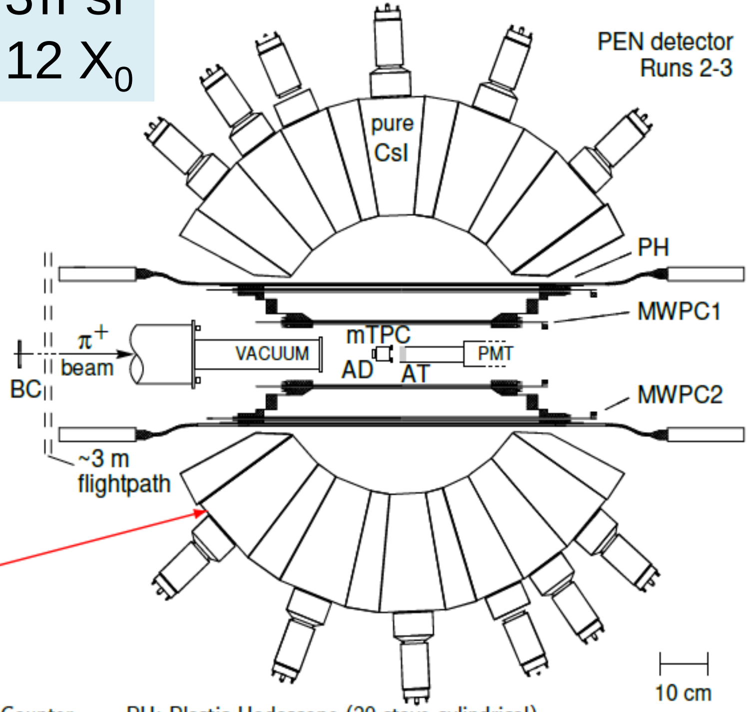
The PEN/PIBETA apparatus

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

- 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

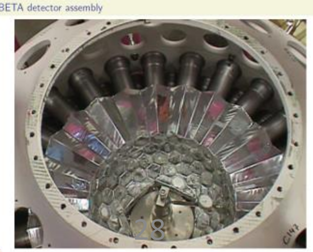




BC: Beam Counter
AD: Active Degrader
AT: Active Target

PH: Plastic Hodoscope (20 stave cylindrical)
MWPC: Multi-Wire Proportional Chamber (cylin
mTPC: mini-Time Projection Chamber

PIBETA detector assembly



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

PIONEER will be clearer, larger, deeper, and faster!

PIONEER Detector Concept – best of both worlds $\pi^+ \rightarrow e^+ \nu$

- Building on PIENU and PEN/PIBETA experiences: use emerging technologies (LXe, LGAD)

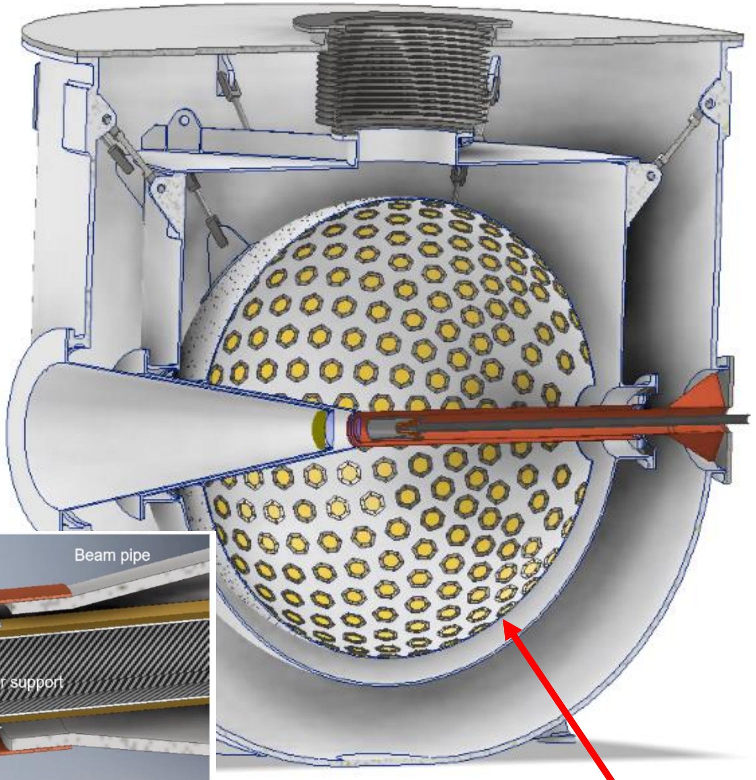
(→ Improvements Compared to PIENU)

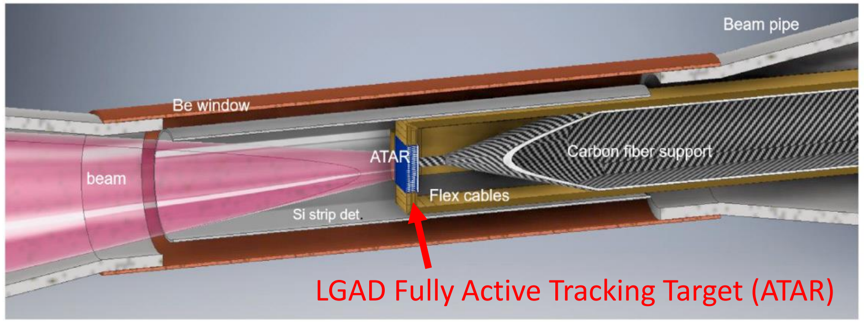
- 25 X_0, 3π sr calorimeter → Improve uniformity (x5) → reduce tail correction (x5)
  Fast scintillator response (LXe) → reduce pile-up uncertainties (x5)

- Active target (“4D”) based on LGAD technology
  → reduce tail correction uncertainty (x10)
  Fast pulse shape → allow π → μ → e decay chain observation

- **State-of-the-art** additional instrumentation
  - + μRWell Tracker; fast triggering; high speed digitization; and pipline DAQ → improve efficiency

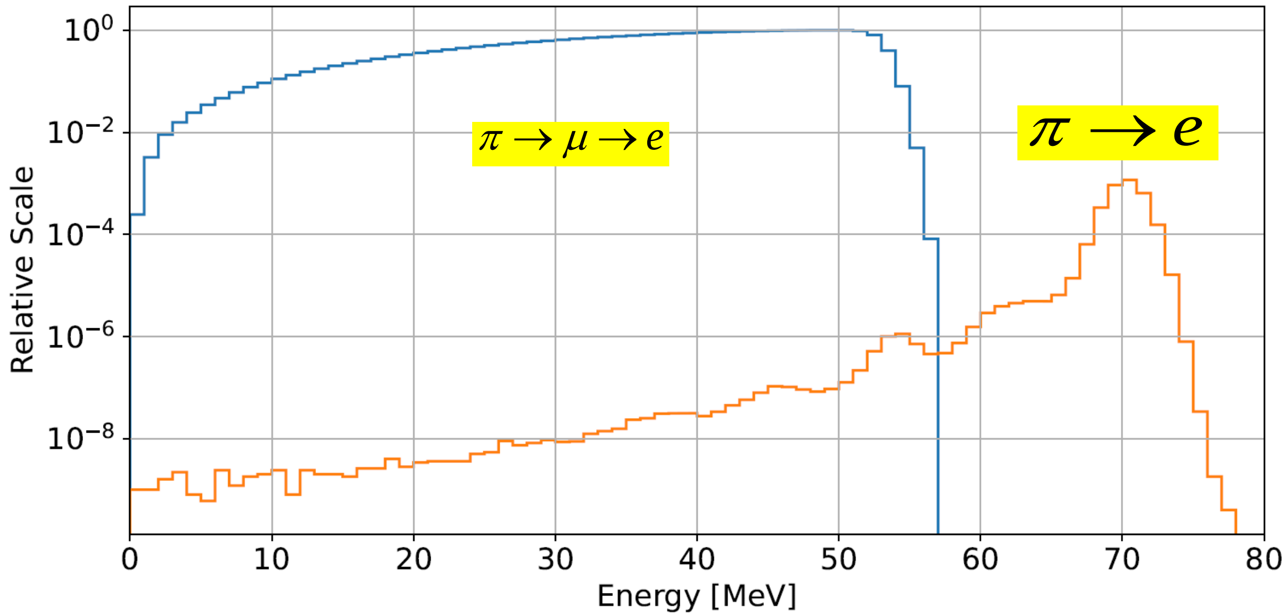
- Intense Pion beam at PSI



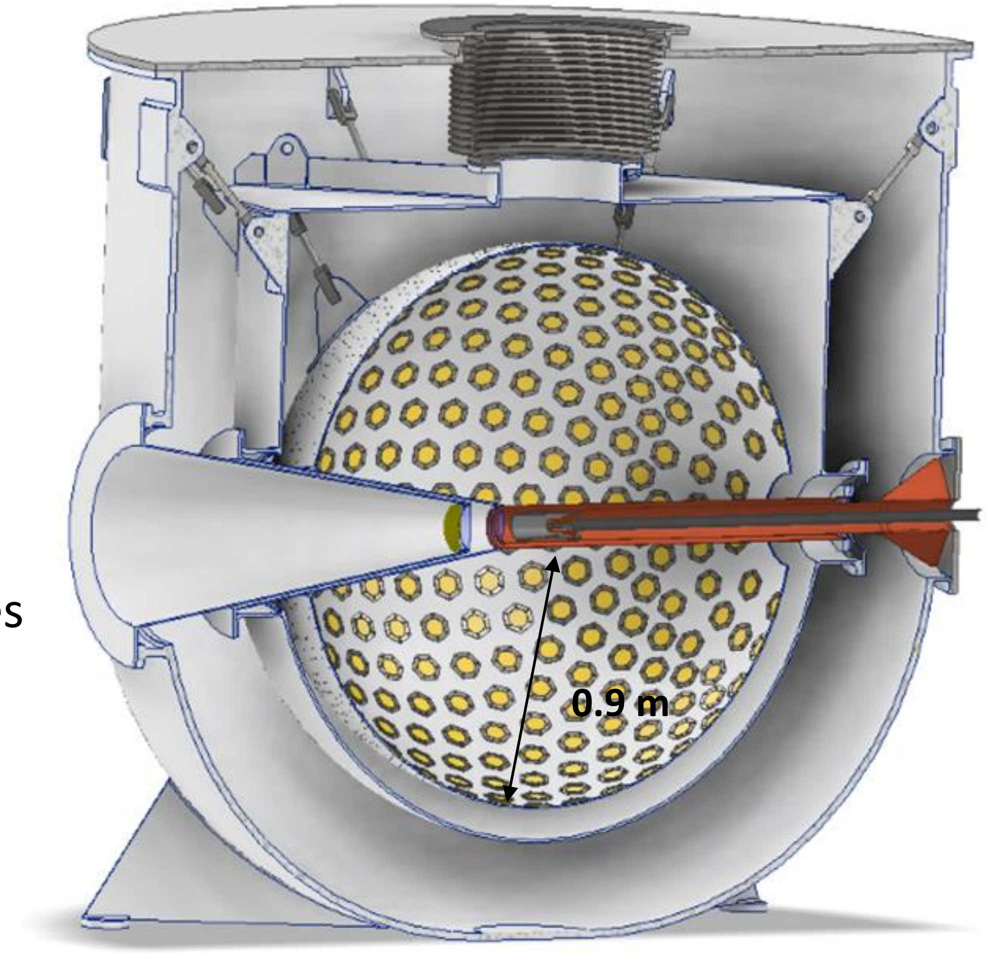


PIONEER Detector Concept: LXe Calorimeter

- 25 X_0, 3π sr calorimeter → reduce tail correction (x5) → Improve uniformity (x5)
  Fast scintillator response (LXe) → reduce pile-up uncertainties (x5)



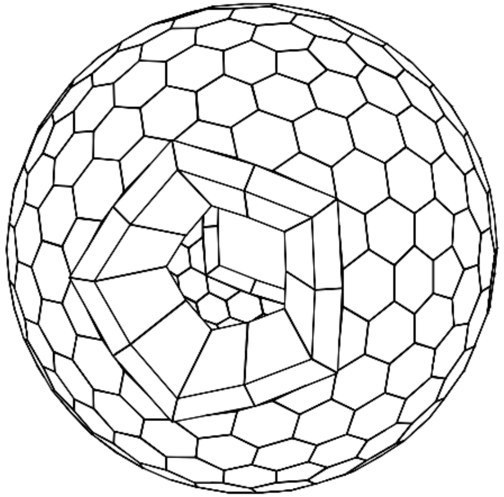
Experience from MEG



Low energy tail of $\pi \to e\nu$ is the dominated systematic uncertainties to reach the physics goal of Uncertainty on $R_{e/\mu}$< 0.01%;

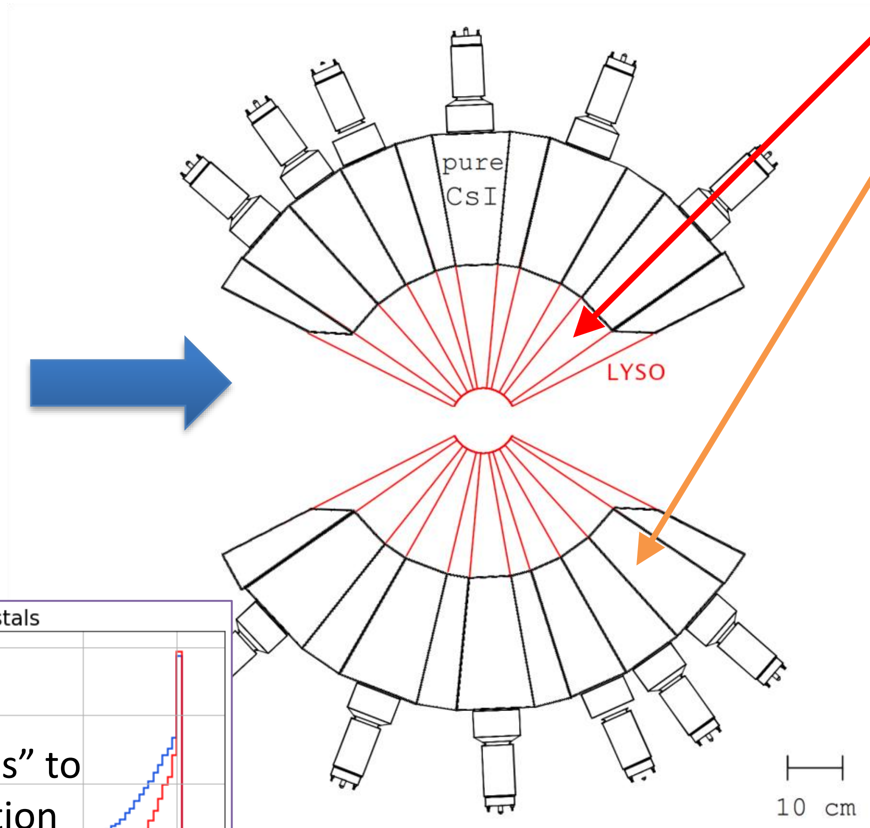
- *Excellent energy resolution of calorimeter → minimize the tail fraction*
- Fast detector response → more resistance to pile-up, and allows for high statistics

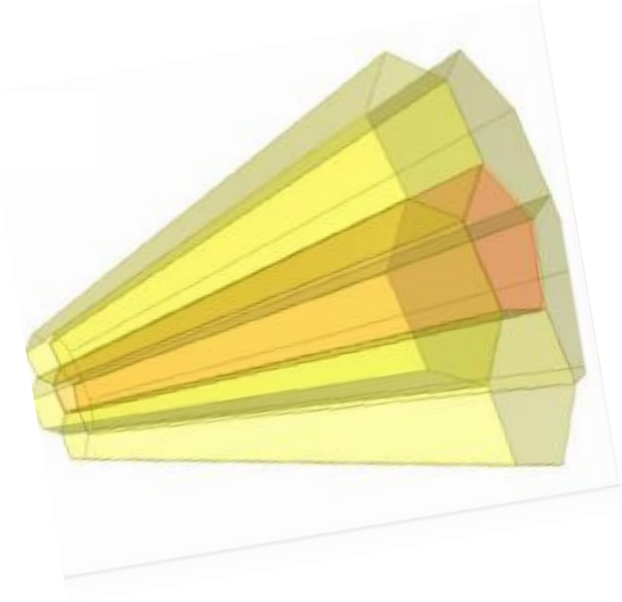
An alternative LYSO based crystal CALO is being investigated to provide a comparison with LXe. To date, no LYSO test array has met our required precision goal, but we are testing new crystals to see if improvements have been achieved

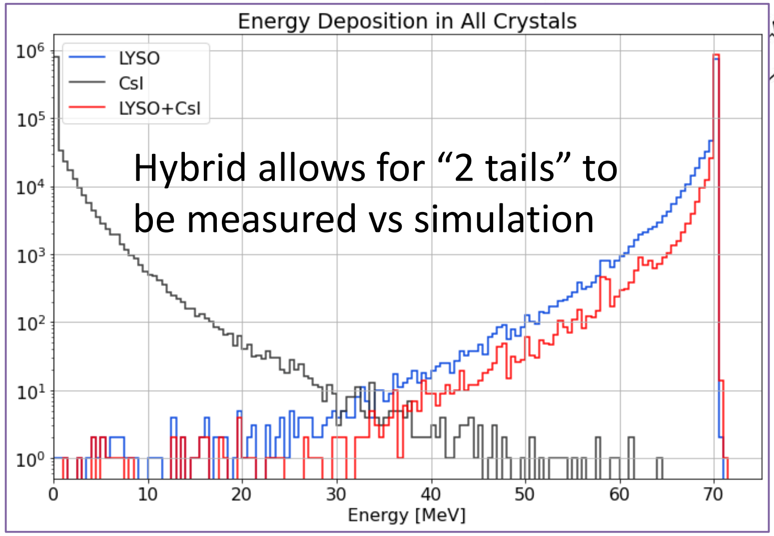


New LYSO ($16\ X_0$)

+ PEN CsI xtals ($12\ X_0$)



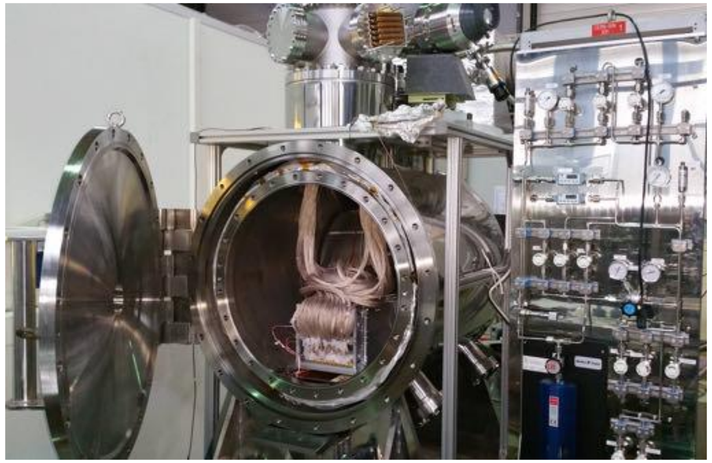


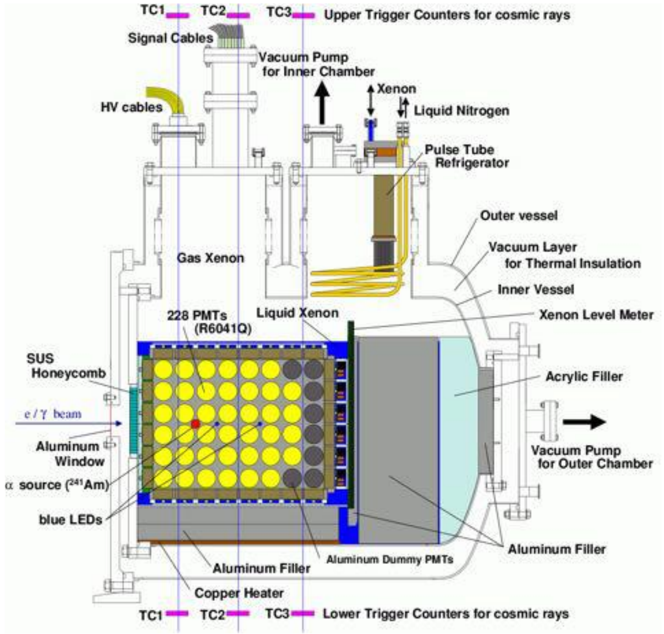


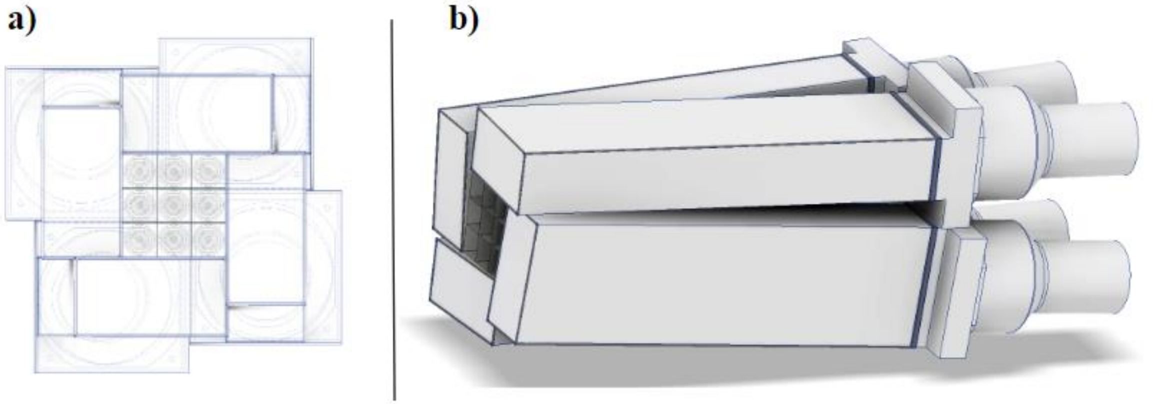
- Fast, segmented, compact
- Is resolution good enough?
- LYSO for HEP not yet demonstrated, given its promise and extensive use in PET

Prototype Detectors (to be tested @ PSI)

- 3x3 LYSO surrounded by NaI(TI)
  - Understanding the energy response
- LYSO made by SICCAS in Shanghai
  - 2 weeks beam test in Nov./2023 in collaborating with STJTU team

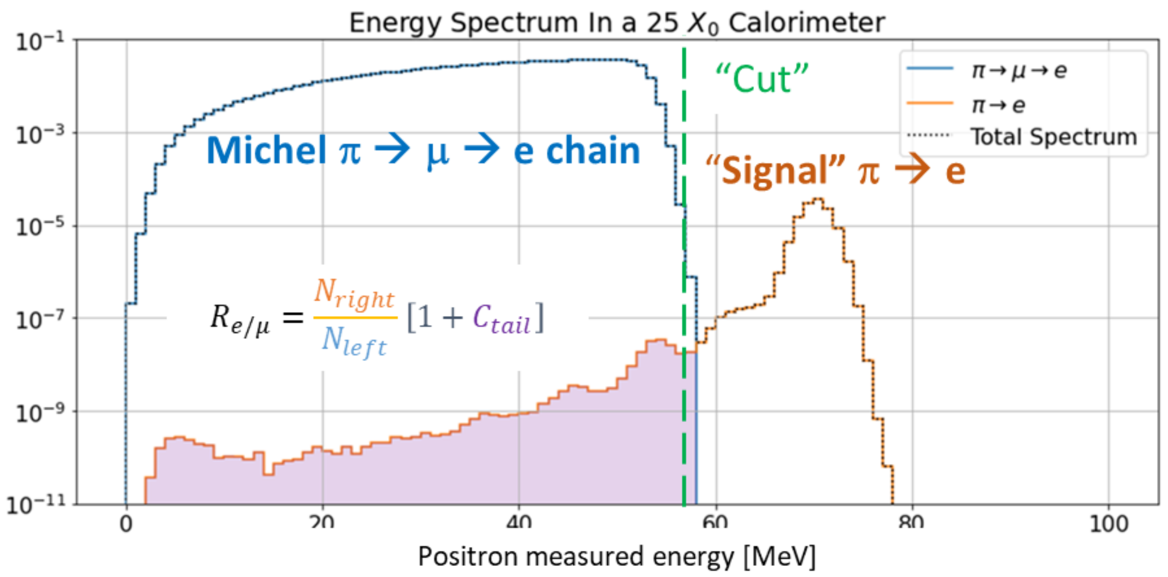




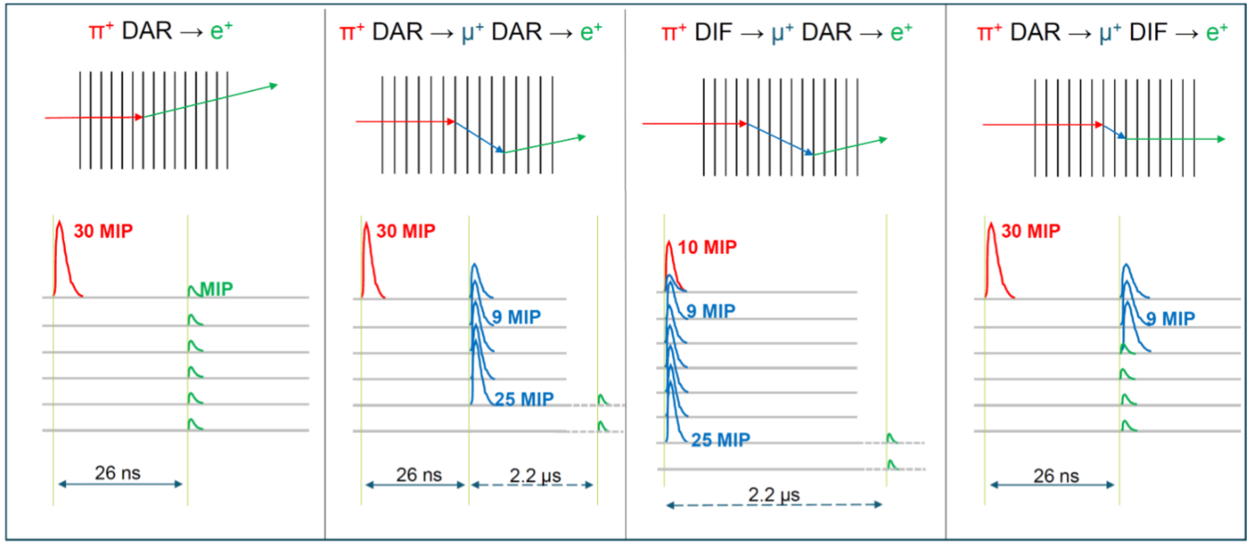


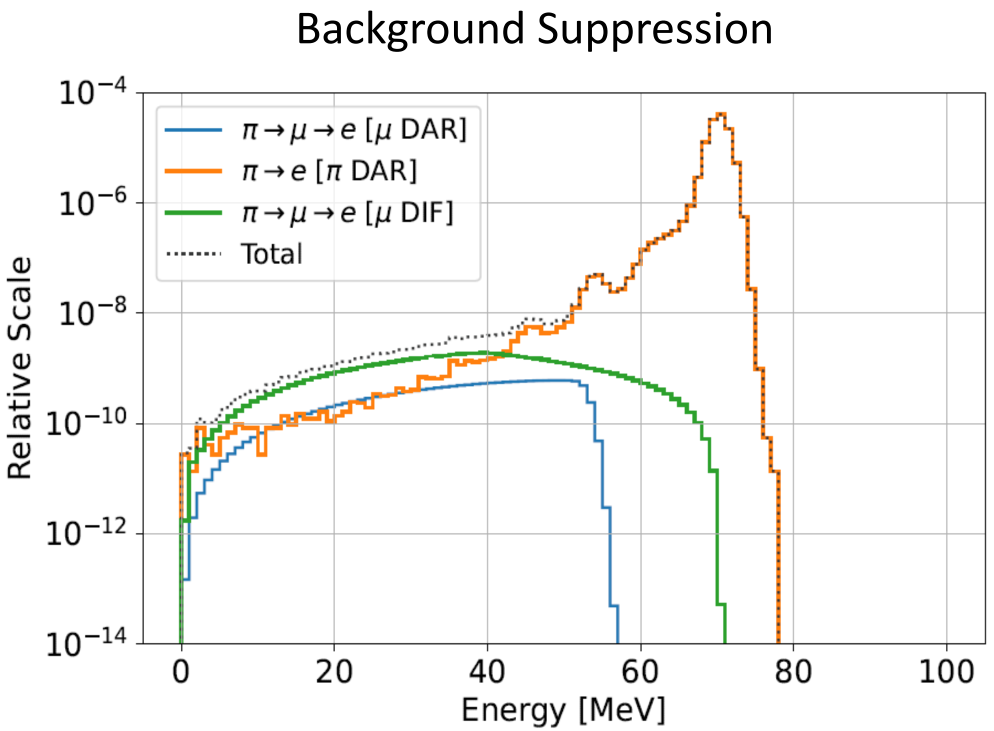
- LXe prototype
  - Based on MEGII prototype
  - Test of window for positron
  - Understanding the energy resolution

In-situ Measurement of the Low-energy Tail



❑ Topology ❑ Calorimetry ❑ Timing



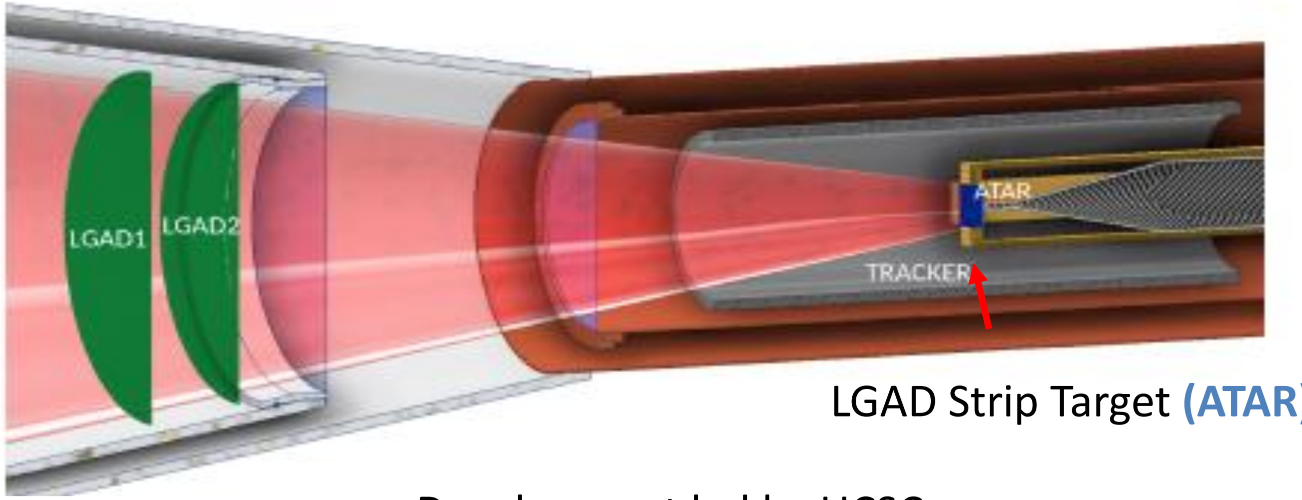


Low energy tail to be measured in situ using ATAR suppression of decay-in-flight backgrounds

- *High segmentation allows for pattern recognition and dE/dx information for pion and muon*

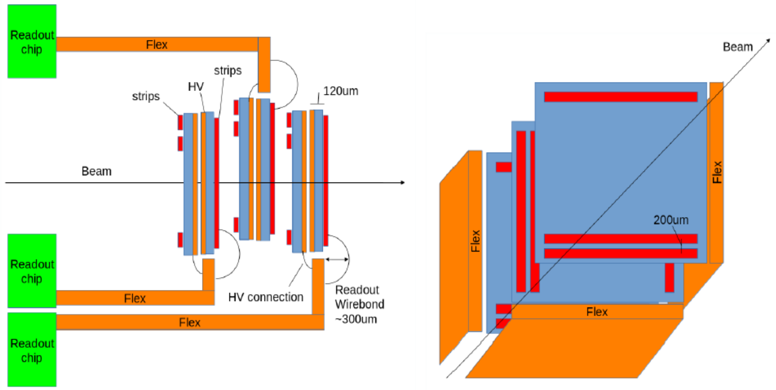
PIONEER Detector Concept: Active Target (ATAR)

- Active target ("4D") based on low-gain avalanche diode (LGAD) technology
- Requirements:
  - High segmentation, compact with less dead materials, fast collection pion decay chain
  - Large dynamic range for electron (MIP) and stopping pions/muons (x100 MIP)
- Tentative design:
  - 48 layers X/Y strips: 120 um thick
  - 100 strips with 200 um pitch covering 2x2 cm^2 area
  - Sensors are packed in stack of two with facing HV side and rotate 90^o

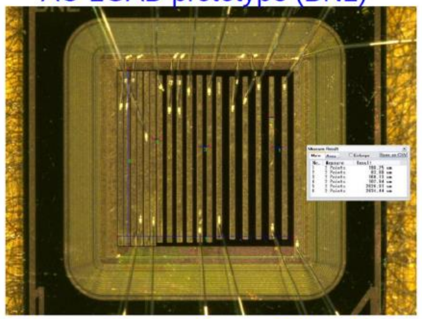


LGAD Strip Target **(ATAR)**

Development led by UCSC



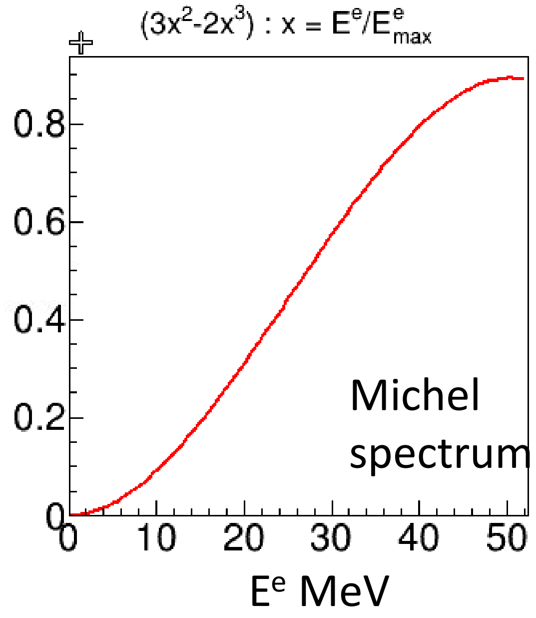
AC-LGAD prototype (BNL)

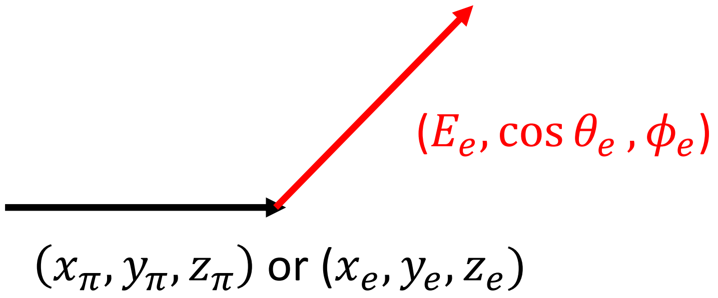


80 µm-wide strips, 100, 150, 200 µm pitch; 5-15µm resolution

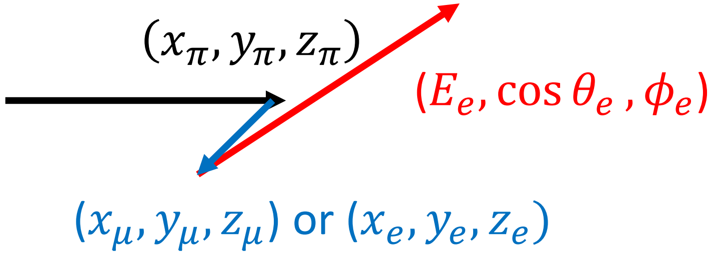
Acceptance Difference between πeν and πμν

- Good position resolution (~100 um) of ATAR leads to smaller acceptance difference between πeν and πμν
  - Requiring 5 positron hits in ATAR will enable an energy threshold of 0.5 MeV (2×10^{-6} positrons below this energy for Michel spectrum)
  - Chance for large-angle (15°) Bhabha scattering within 1000 um in ATAR → **Difference of acceptance ~ 2 e-4**

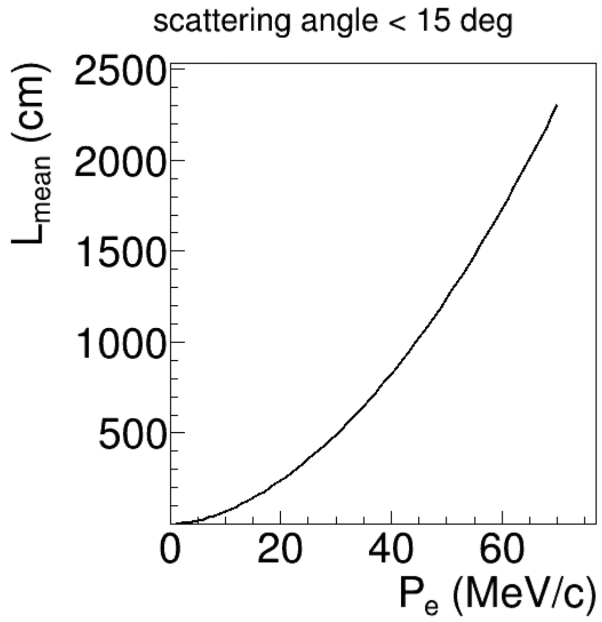




πeν @ 70 MeV

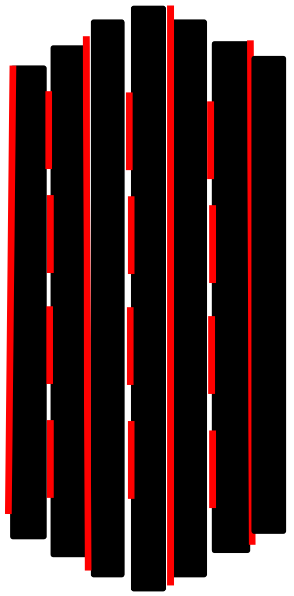


πμe @ 0-52 MeV



Alternative Designs Under Development

- 2-sided readout with X-Y strips
- Shared strip readout to minimize dead materials
- PiN + slow low-noise electronics (e.g. 5 ns) can be an alternative to the LGAD + fast electronics (< 1 ns)



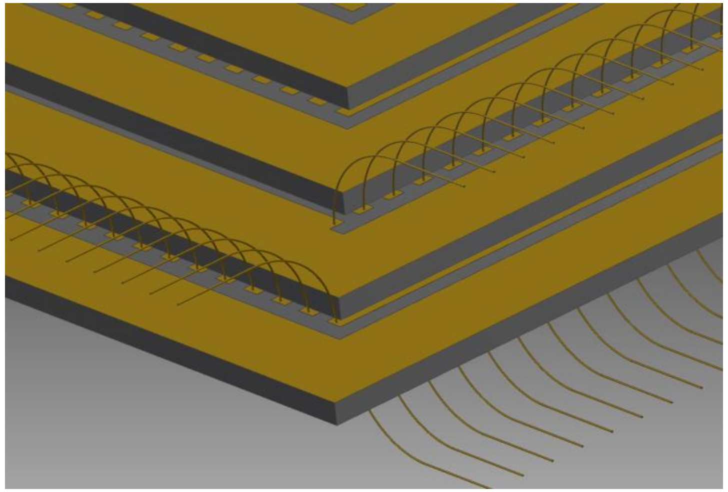
Bulk (120 um)

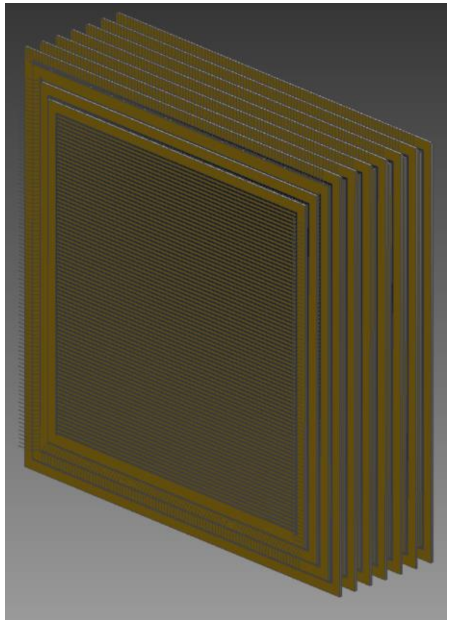
Readout strip (200 um pitch, 100 width)

Layers are gradually increased/decreased, so that we can readout from the sides

	MIP hit	MIP track (50 hits assumed with 2-sided readout)	10xMIP hit	30xMIP hit
T0 resolution	408 ps	408/sqrt(50) = 58 ps	103 ps	74 ps
Charge resolution (1024 e in 7 ns)	<13.1%	13.1%/sqrt(50) = 1.9%	<1.31 %	<0.44%
2-peak separation @ 3D point of the decay layer	N/A	N/A	Good with 1.5 ns separation, when delayed hit charge is not too small	

Example performance for a 5-ns electronics shaping time





$\pi \rightarrow e\nu$: 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
Newly proposed measurement at TRIUMF

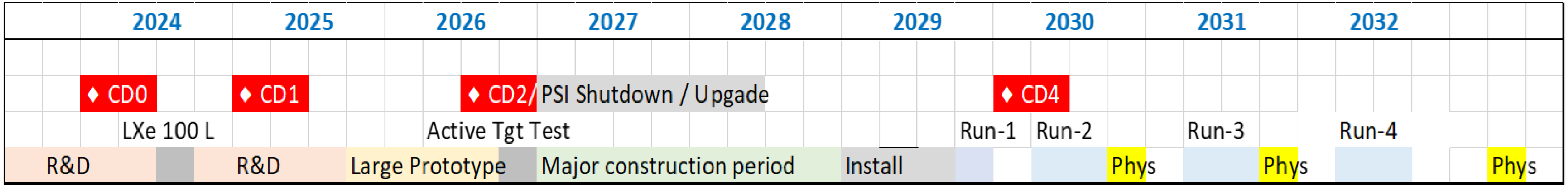
$\pi^+ \rightarrow \pi^0 e^+ \nu$: Estimated Uncertainties

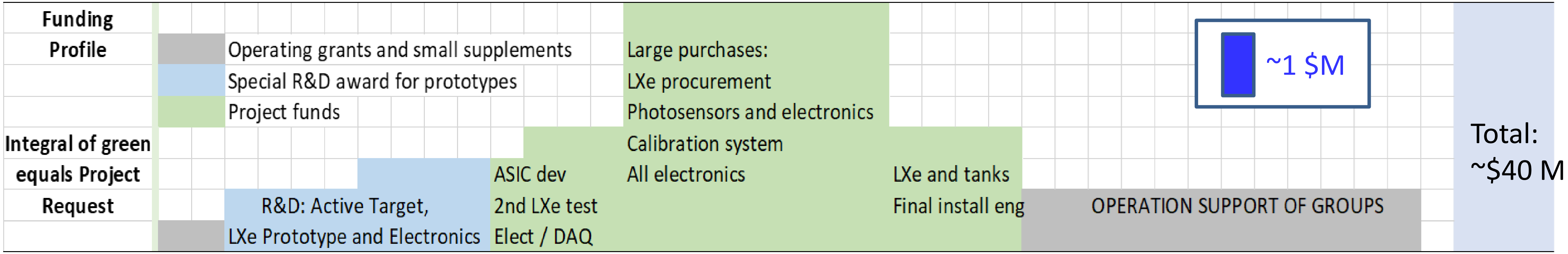
	PiBeta	PIONEER (Phase II)	
Statistics	0.4%	0.1%	
Systematics	0.4%	<0.1%	(ATAR (β), MC, Photonuclear, π→e ν)
Total	0.64%	**0.2%**	

Status of PIONEER Experiment

- PIONEER Phase I approved by PSI PAC
  - 2 weeks beam time was allocated for 2022
    - Establish the tune needed in piE5 beam line: categorization/optimization of beam intensity, quality, spot size, momentum bite, background
  - 2 weeks beam time was allocated for 2023 for CALO test
  - Dedicated beam tests for ATAR/CALO in 2024
- Currently over 80 collaborators from 24 institutions
  - Diverse research background: both nuclear and particle physics (U.S and international) communities including PIENU, PEN/beta, MEG/MEGII experiments, as well as experts in rare kaon decay, muon experiments, high-energy collider physics, neutrino physics, PSI scientists, and leading theorists
  - *There is much work to do and many open topics: Tracker design, Calorimeter choices, Trigger scheme, simulation efforts,* **JOIN US!**

Timeline and budget





Aims at physics data taking by the end of this decade

Phase-II and Phase III will follow (15+ years program)

$\pi^+ \to e^+\nu$

Summary

$\pi^+ \to \pi^0 e^+\nu$

- PIONEER, a next-generation rare pion decay experiment, aims at testing lepton flavor universality and unitarity of CKM matrix
  - Good discovery potential with emerging anomalies in flavor physics

- PIONEER employs state-of-art detector technologies (LGAD, Noble Liquid calorimetry)
  - Phase I approved at PSI with beam time in 2022 and 2023
  - Rare Pion Decay Workshop (6-October 8, 2022): Overview · Indico (cern.ch)
  - Expected start of data taking in ~5 years time scale with an overall time scale of 15+ years

- JOIN us in this exciting experiment with excellent discovery potential and cutting-edge instrumentations

Crystals with Mass Production Capability

Crystal	NaI:Tl	CsI:Tl	CsI	BaF_2	CeF_3	PbF_2	BGO	BSO	$PbWO_4$	LYSO:Ce	AFO Glasses	Sapphire:Ti
Density (g/cm^3)	3.67	4.51	4.51	4.89	6.16	7.77	7.13	6.8	8.3	7.40	4.6	3.98
Melting points (^oC)	651	621	621	1280	1460	824	1050	1030	1123	2050	\	2040
X_0 (cm)	2.59	1.86	1.86	2.03	1.65	0.94	1.12	1.15	0.89	1.14	2.96	7.02
R_M (cm)	4.13	3.57	3.57	3.10	2.39	2.18	2.23	2.33	2.00	2.07	2.89	2.88
λ_I (cm)	42.9	39.3	39.3	30.7	23.2	22.4	22.7	23.4	20.7	20.9	26.4	24.2
Z_{eff}	50.1	54.0	54.0	51.6	51.7	77.4	72.9	75.3	74.5	64.8	42.8	11.2
dE/dX (MeV/cm)	4.79	5.56	5.56	6.52	8.40	9.42	8.99	8.59	10.1	9.55	6.84	6.75
λ_{peak} [a] (nm)	410	560	420 310	300 220	340 300	\	480	470	425 420	420	365	750
Refractive Index[b]	1.85	1.79	1.95	1.50	1.62	1.82	2.15	2.68	2.20	1.82	\	1.76
Normalized Light Yield[a,c]	120	190	4.2 1.3	42 4.8	8.6	\	25	5	0.4 0.1	100	1.5	\
Total Light yield (ph/MeV)	35,000	58,000	1700	13,000	2,600	\	7,400	1,500	130	30,000	450	\
Decay time[a] (ns)	245	1220	30 6	600 0.5	30	\	300	100	30 10	40	40	3200
Hygroscopic	Yes	Slight	Slight	No	No	No	No	No	No	No	No	No
Experiment	Crystal Ball	CLEO BaBar BELLE BES III	KTeV Mu2e S. BELLE	TAPS Mu2e-II	\	A4 g-2	L3 BELLE CalVision	\	CMS ALICE PrimEx Panda	COMET HERD CMS BTL RADiCAL	HHCAL	HHCAL