Probing the Foundations of the Standard Model: From Precision Pion Decays to Large-Scale Neutrino Detectors

by Dr. Saul Cuen-Rochin (Tecnologico de Monterrey)

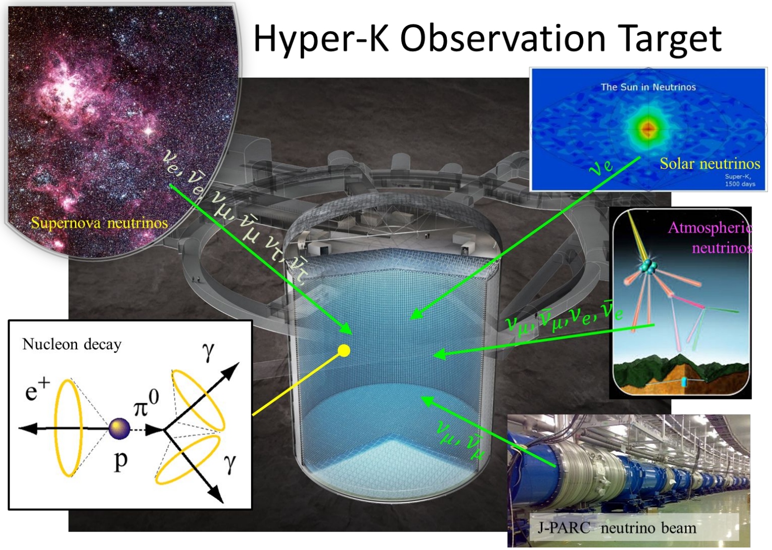
Tuesday, 29 April 2025 from 11:00 to 12:00
at Cinvestav, CDMX (Auditorio José Adem)

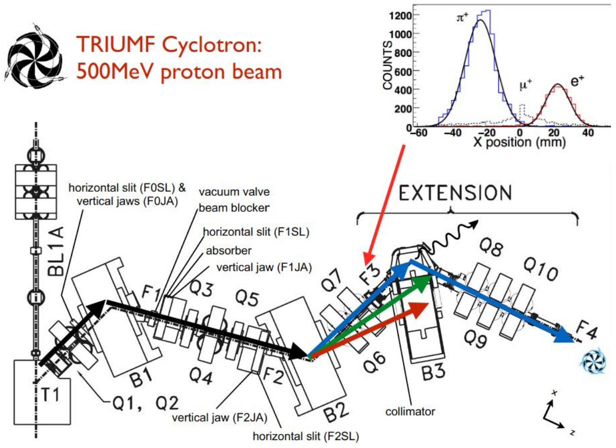
Wednesday, 30 April 2025 from 13:00 to 14:00
at ICN-UNAM (Salón de Seminarios de Gravitación y Física de Altas Energías, A225)

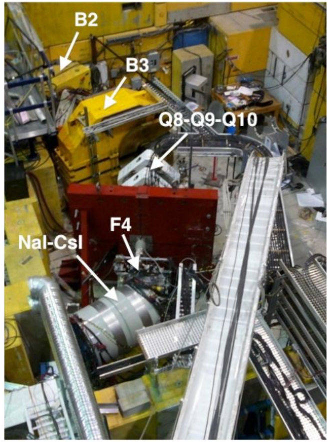
Probing the Foundations of the Standard Model

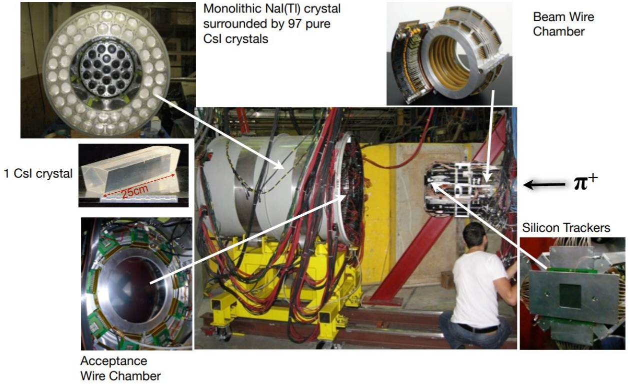
- One big question: Where will the Standard Model first crack?

- Two complementary approaches: precision pion decays & gigaton-scale neutrino detection.



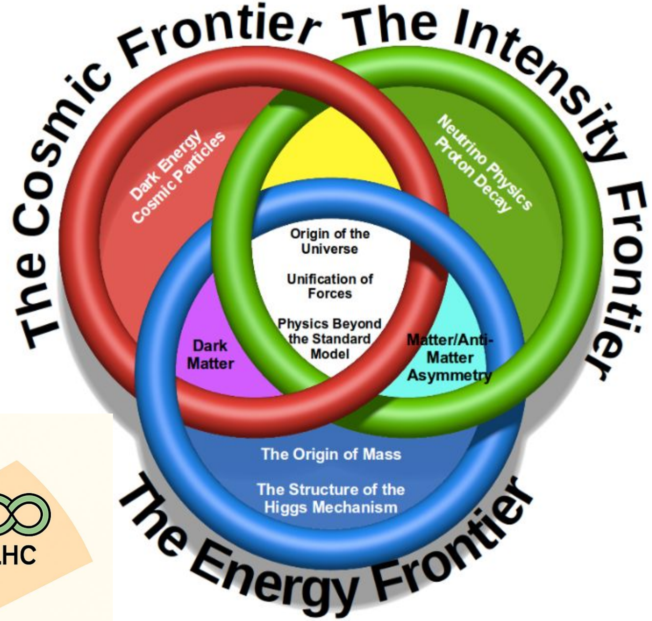




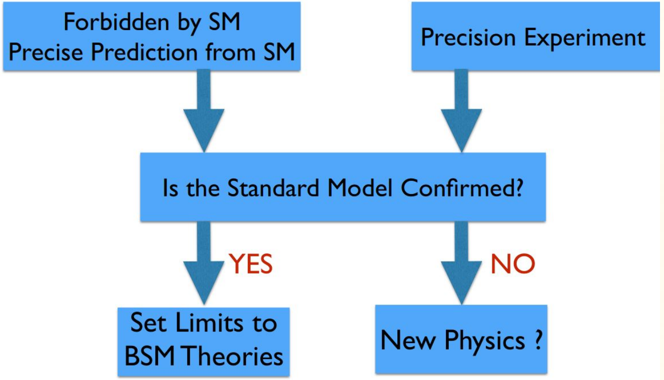


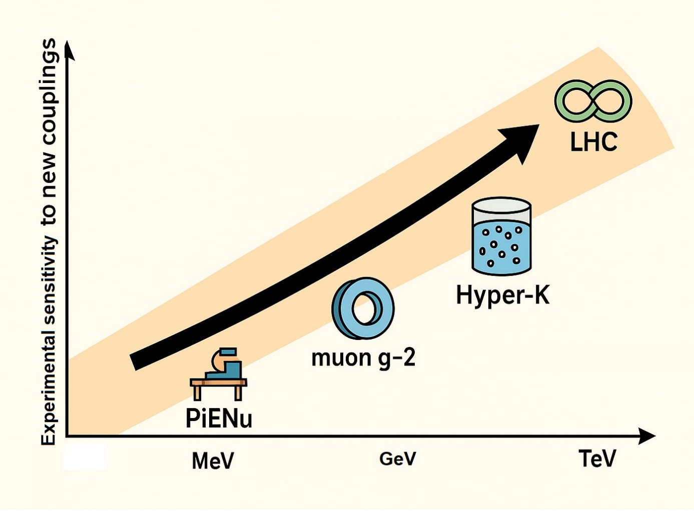
Why Look Beyond the Standard Model?

- Neutrino mass, dark matter, matter-antimatter asymmetry → SM incomplete.
- Need both high precision and high mass experiments.
- Experimental sensitivity to new couplings rises with accessible energy scale, while pinpointing where PiENu (and Pioneer), muon g-2, Hyper-K, and the LHC sit along that frontier



Precision Frontier





Experimental Dialectic

- Tabletop precision ⇄ monumental scale.
- Each tests different couplings & energy regimes.
- Combined, they constrain a wider slice of parameter space.

Experiment	Physical Scale	Typical Detector Mass / Footprint	Sensitivity Lever	Flagship Observables	Example New-Physics Handles
PiENu and PIONEER	Bench-top spectrometer (≈ 3 m long, 1 m³)	~1 t of scintillator + NaI/CsI calorimetry	**Fractional-percent precision** ΔR_e/μ ≈ 0.1 % for PIENU and 0.01 % for PIONEER (theory level)	π → e ν vs π → μ ν branching ratio	Scalar / tensor couplings, charged-Higgs or leptoquarks that violate lepton universality
Hyper-Kamiokande	Mountain-scale cavern (71 m × 68 m)	260 kt ultrapure water, 40 k PMTs	**Rare-event reach** ($p \to e^+\pi^0 > 10^{35}$ y; δ_CP at 5 σ)	ν_μ→ν_e oscillations, proton decay, super-nova ν burst	Leptonic CP violation, baryon-number violation, minimal SUSY-GUT, sterile-ν models

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.

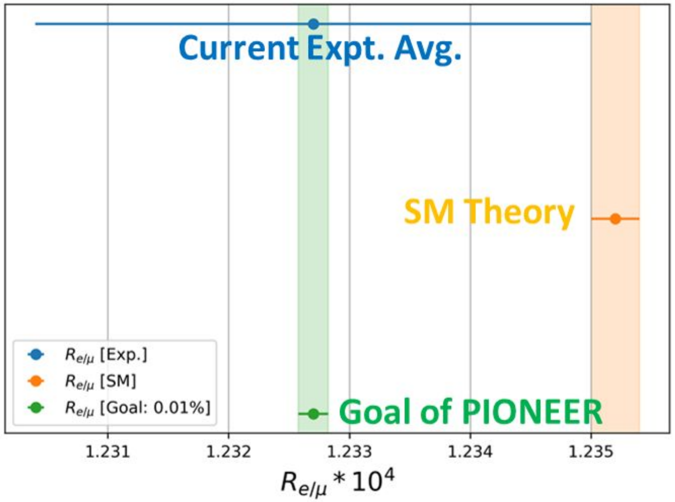
Improved Measurement of the $\pi \to e\nu$ Branching Ratio

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.

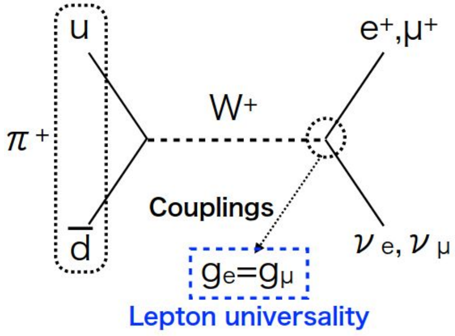
Heavy neutrinos lighter than the pion: R. E. Shrock. *General Theory of Weak Leptonic and Semileptonic Decays. 1. Leptonic Pseudoscalar Meson Decays, with Associated Tests For, and Bounds on, Neutrino Masses and Lepton Mixing*. Phys. Rev., D24:1232, 1981;

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

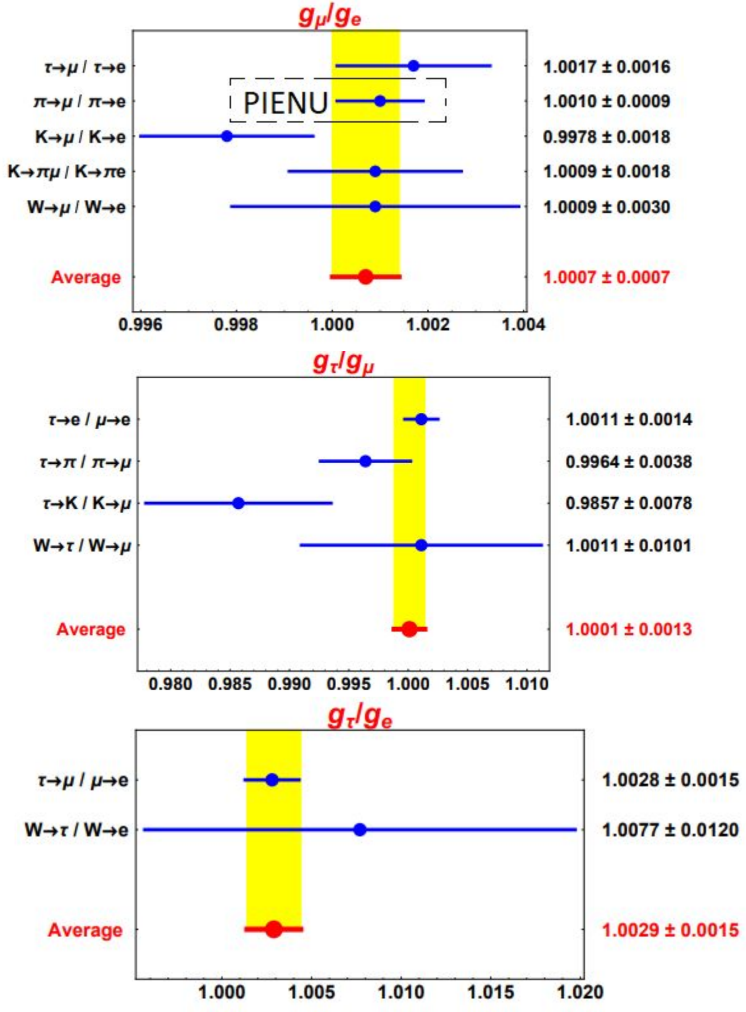
$$R_\pi = R_\pi^0\left[1 + \Delta_{e^2p^2} + \Delta_{e^2p^4} + \Delta_{e^2p^6} + ...\right]\left[1 + \Delta_{LL}\right] . \qquad (2.12)$$

- 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

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

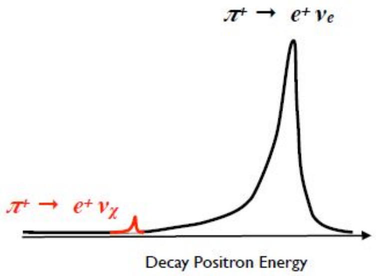
$$\frac{g_\mu}{g_e} = 1.0010 \pm 0.0009 \quad (\pm 0.09\%)$$

- **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

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

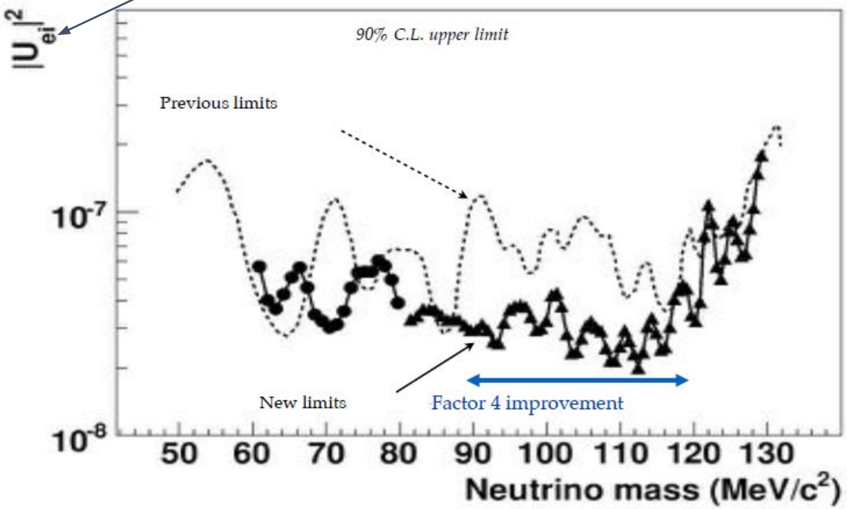
$$R_{ei} = \frac{\Gamma(\pi \rightarrow e\nu_i)}{\Gamma(\pi \rightarrow e\nu_l)} = |U_{ei}|^2 \rho_{ei}$$

Conventional υ

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

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

Neutrino mixing matrix element

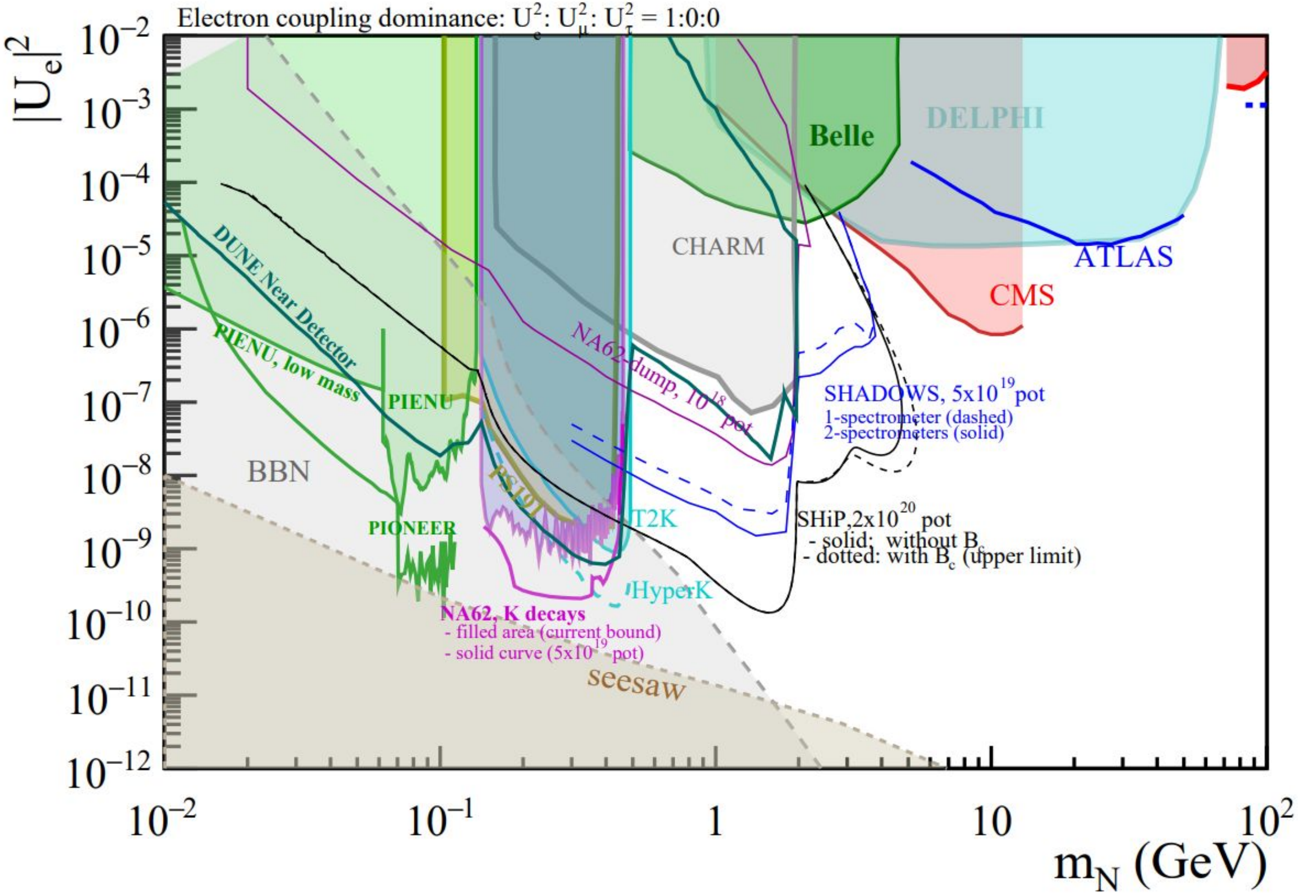


M.Aoki et al., Phys. Rev. D 84, 052002 (2011)

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

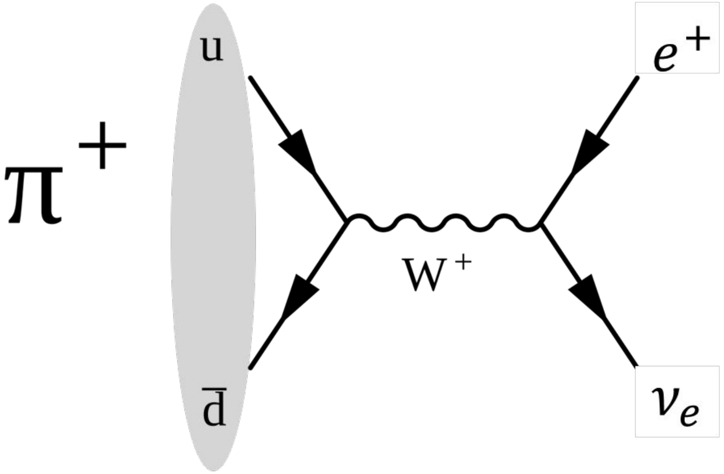
Comprehensive constraints on sterile neutrinos in the MeV to GeV mass range
D. A. Bryman and R. Shrock, Phys. Rev. D 100, 073011

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]

$R_{e/\mu}$ measurement strategy

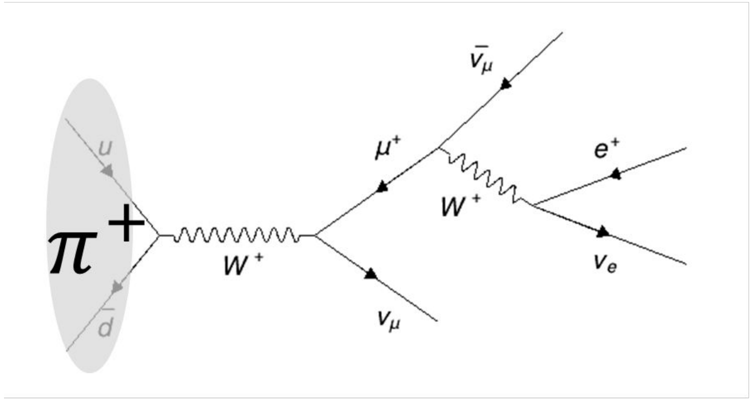


$m_{\pi^+} = 139.6 MeV$

$\tau_{\pi^+} \approx 26 ns$

The pion stops in the target and decays

$R_{e/\mu}$ measurement strategy



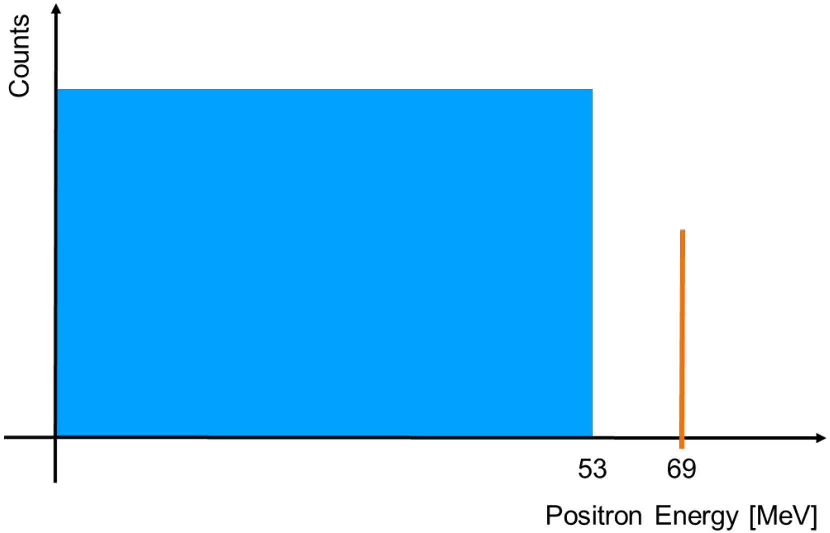
$m_{\pi^+} = 139.6 MeV$

$m_{\mu^+} = 105.7 MeV$

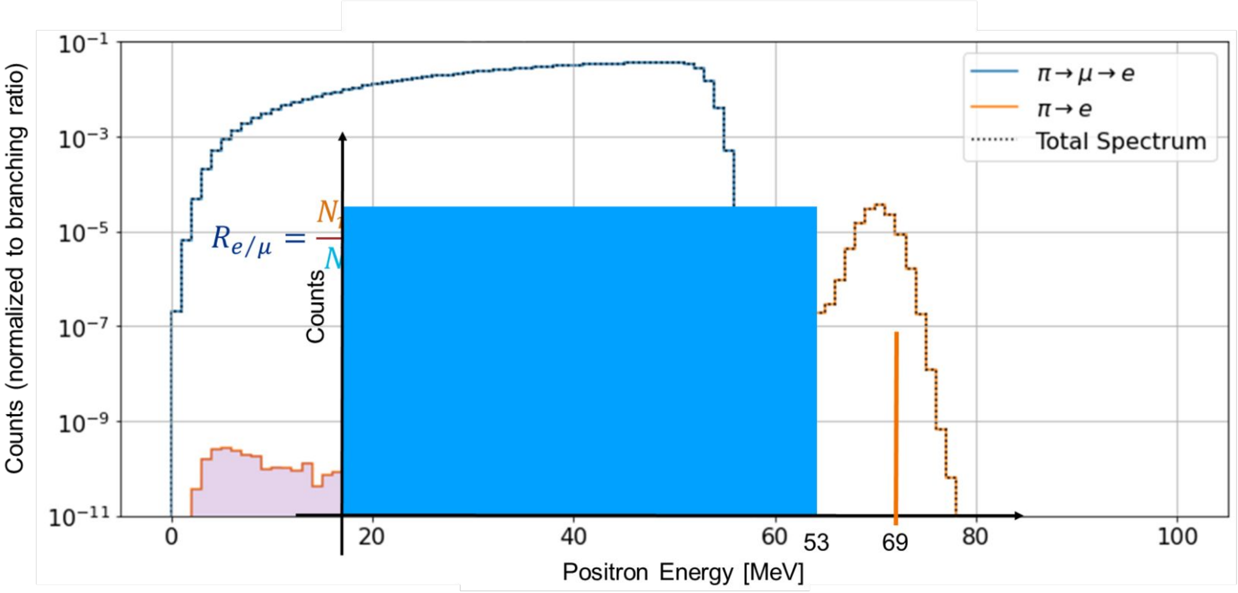
$\tau_{\mu^+} \approx 2.2 \mu s$

The pion stops in the target and decays

Then the muon stops in the target and decays



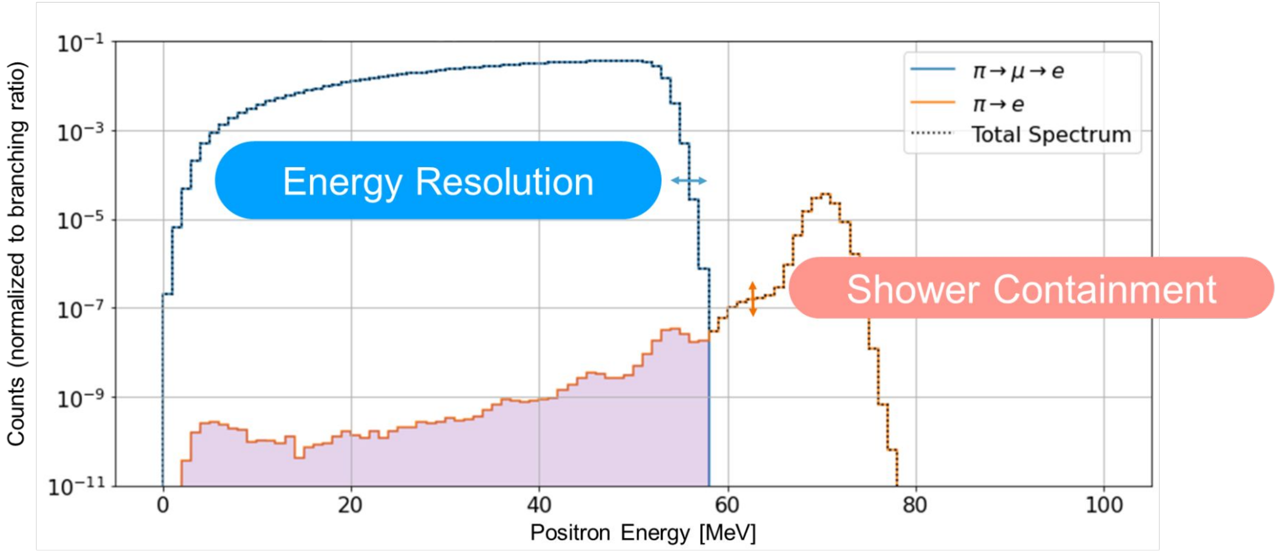
Facing experimental reality



Guiding principles to the design of the experiment:

1. Collect very large datasets of rare pion decays
2. Tail must be less than 1% of total signal
3. Tail must be measured with a precision of 1%

Calorimeter design



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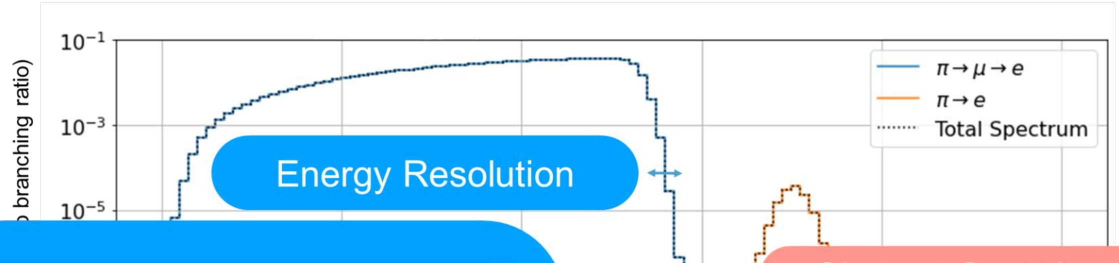
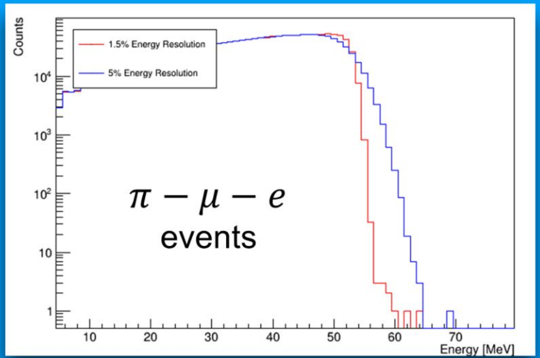
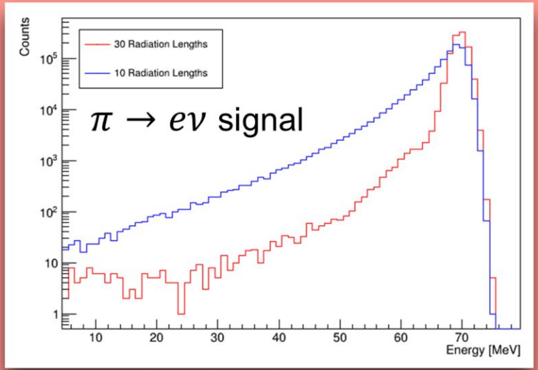




At least 2% for positrons
with 70 MeV/c momentum

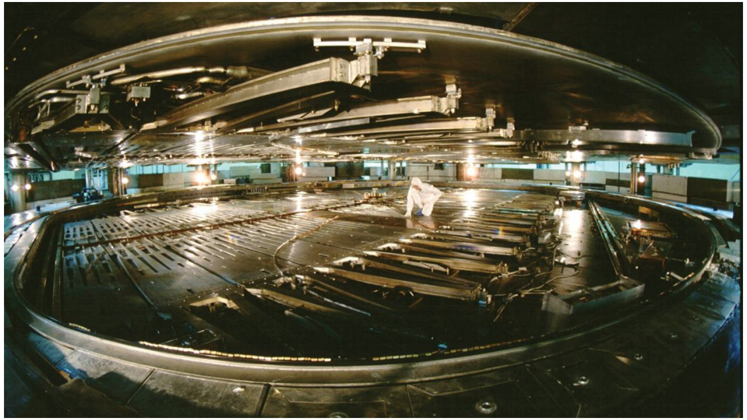


At least 19 radiation length (X_0),
Large solid angle (~3π steradians)

Gui… nt:

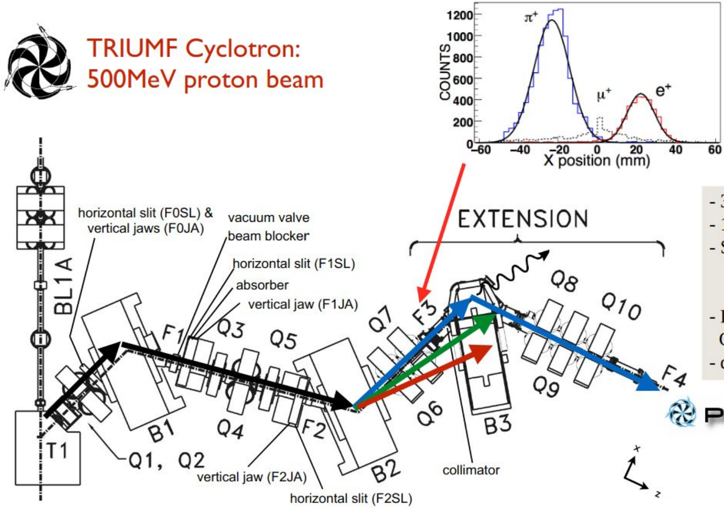
1. … ays
2. … →
3. Tail must be measured with a precision of 1%

PIENU at TRIUMF



TRIUMF's M13 beamline

TRIUMF Cyclotron:
500MeV proton beam



- 3-Dipoles Beamline
- 10 Quadrupoles
- Separation:
  Energy-loss
  Collimator
- Positron
  Contamination <1%
- dp/p ~ 1.5% FWHM

PI E NU

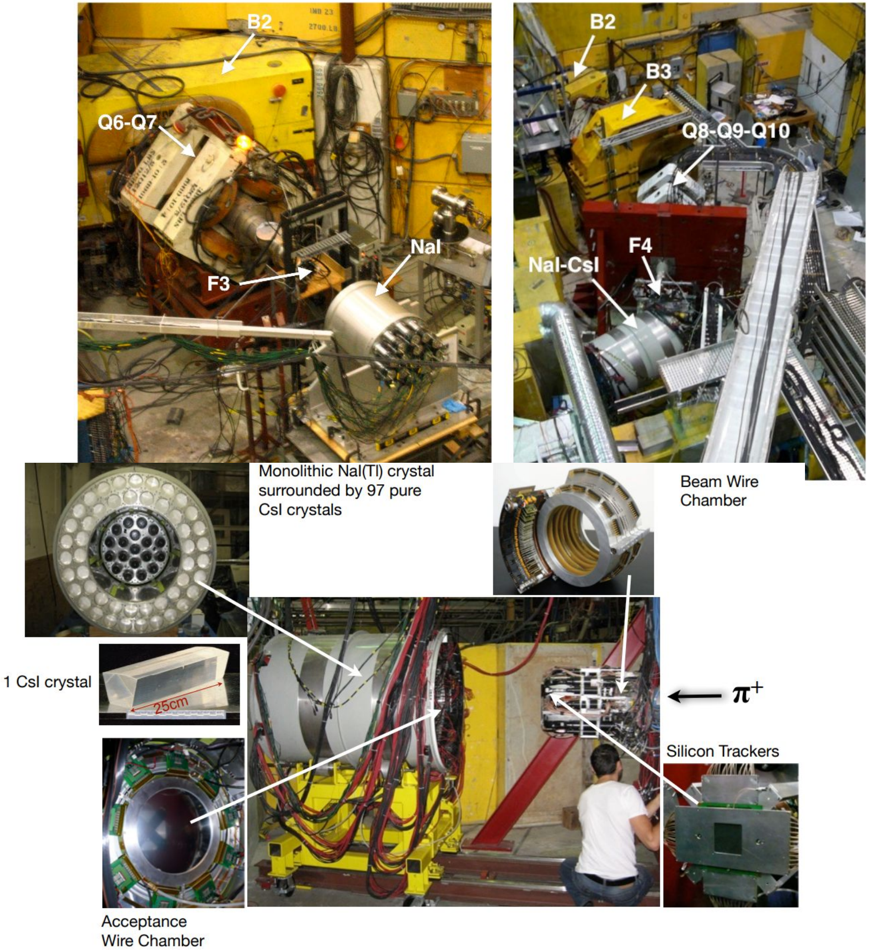
A.Aguilar-Arevalo *et al.*: Nucl. Instr. Meth. A621, 188 (2010)

60 kHz pions @ 75 MeV/c
π : μ : e = 85 : 14 : 1

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]



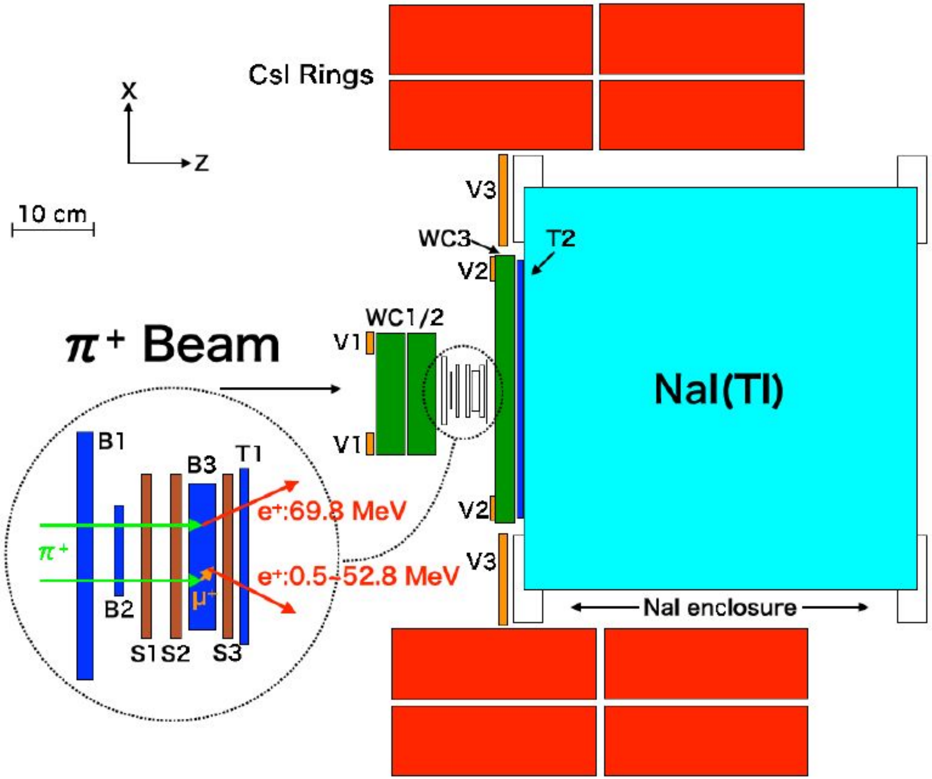
The PIENU Detector

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

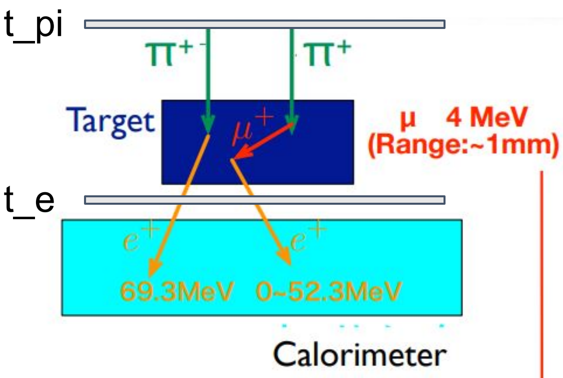
CsI ring shower collector
- tail suppression
- gamma from radiative decay

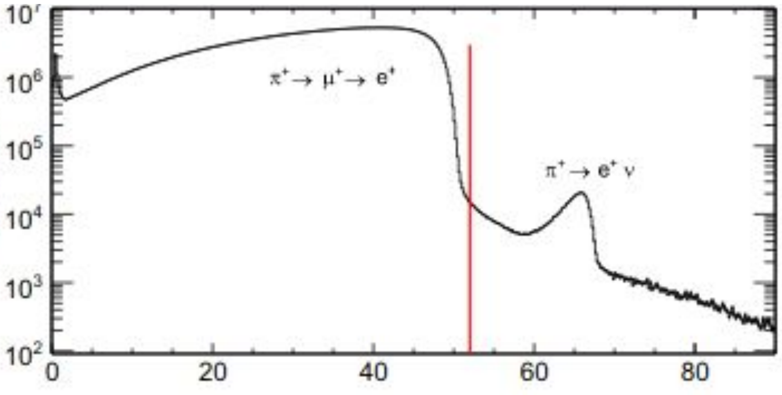
SSD and WC for particle tracking
- Identify π-DIF events in the πe2 tail region

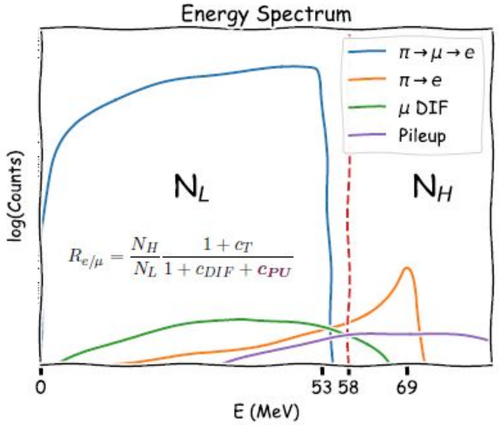
Flash-ADC readout for all counters
- Plastic Scintillator: 500MHz FADC
- NaI(Tl) and CsI: 60MHz FADC
- Pile-up tagging

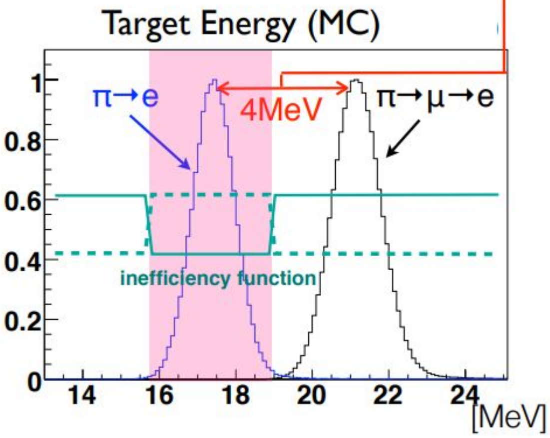


PIENU Exp. Technique

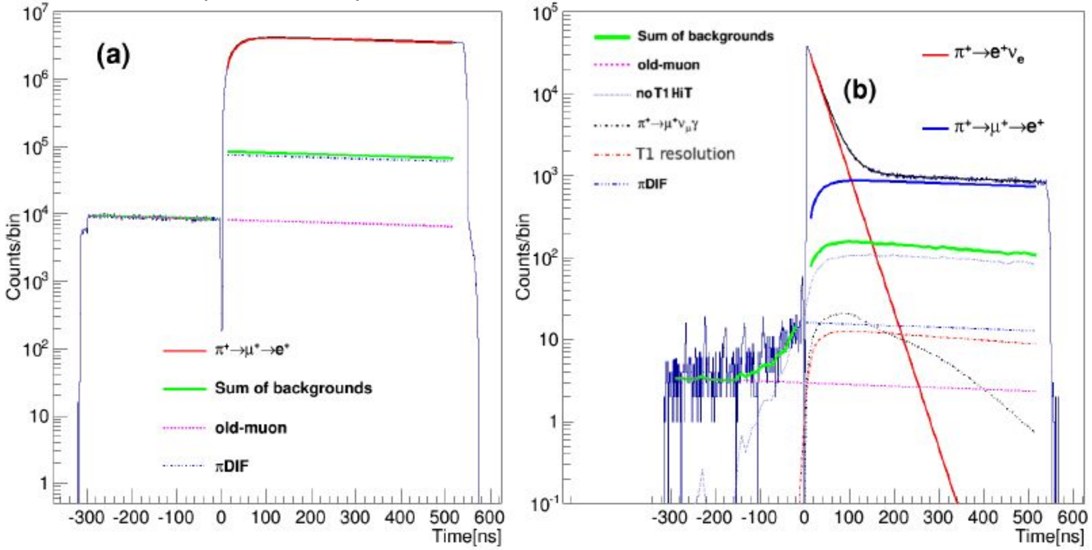








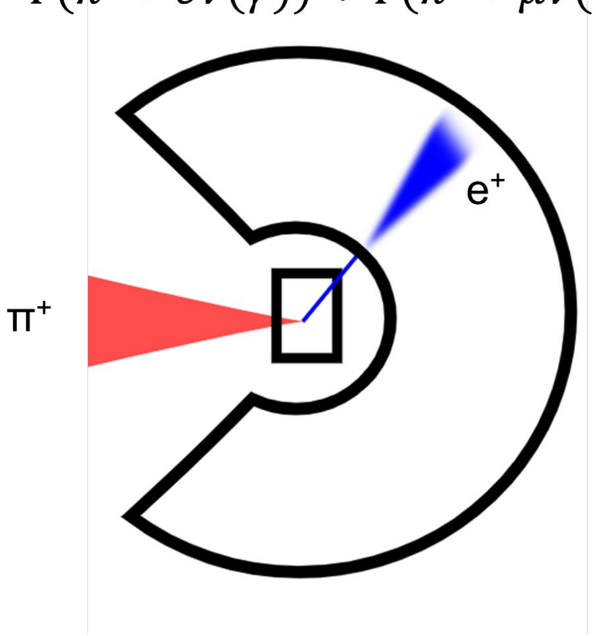
(t_e - t_pi) to build Time Spectra



Quentin Buat (University of Washington) — Jan 9, 2025

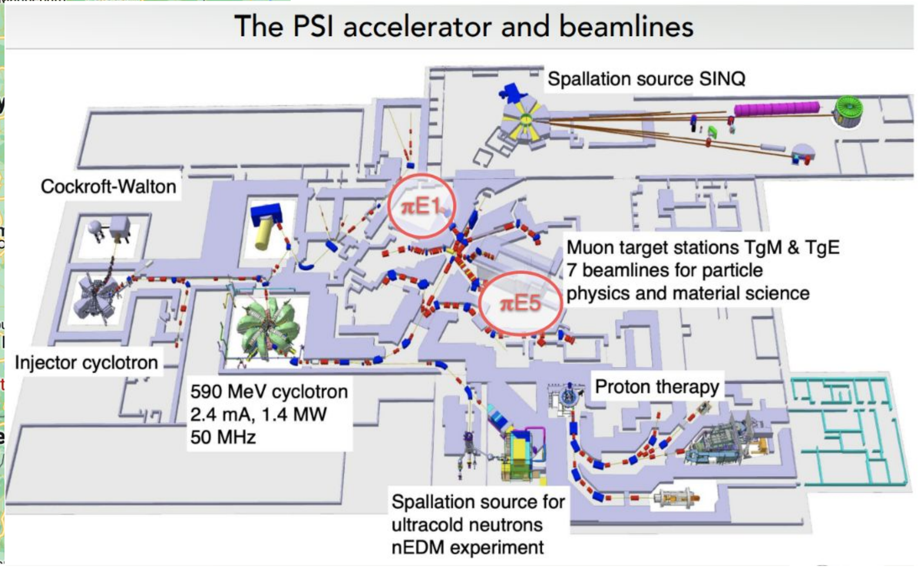
Introducing PIONEER

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



Pioneer at PSI

Quentin Buat (University of Washington) — Jan 9, 2025

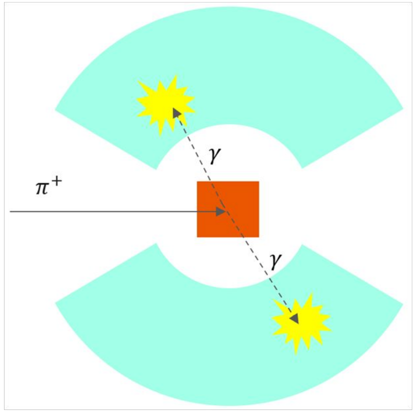


Guiding principles to the design of the experiment:

1. **Collect very large datasets of rare pion decays (2e8 $\pi^+ \rightarrow e^+\nu_e$ during Phase I)**
2. Tail must be less than 1% of total signal
3. Tail must be measured with a precision of 1%

V_{ud} extraction from pion decays

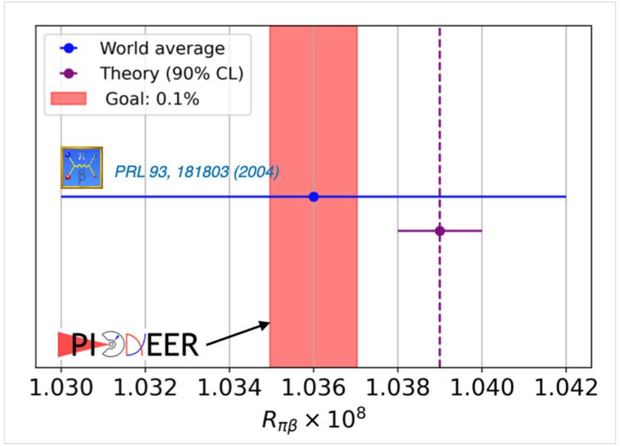
$\pi^+ \to \pi^0 e^+ \nu_e$ measurement



$$m_{\pi^+} = 139.6 MeV$$
$$m_{\pi^0} = 135.0 MeV$$
$$\tau_{\pi^0} = 0.084 fs$$

Two back-to-back photons
Very low energy positron

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

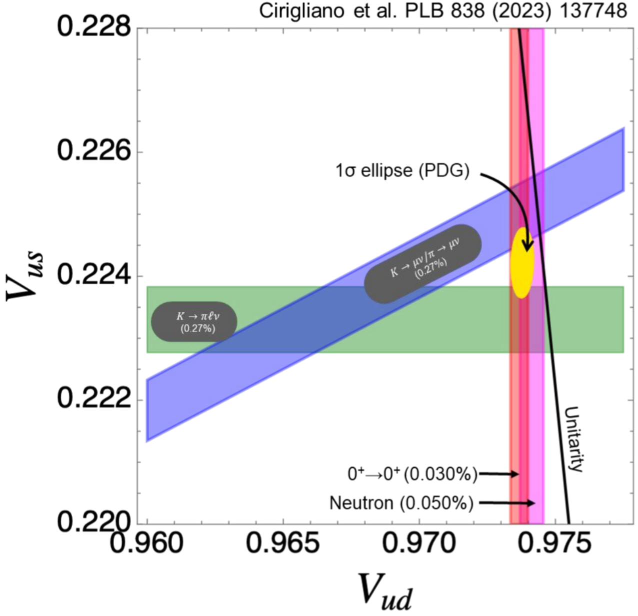


$$R_{\pi\beta}[Exp.] = 1.036(0.006) \times 10^{-8}$$

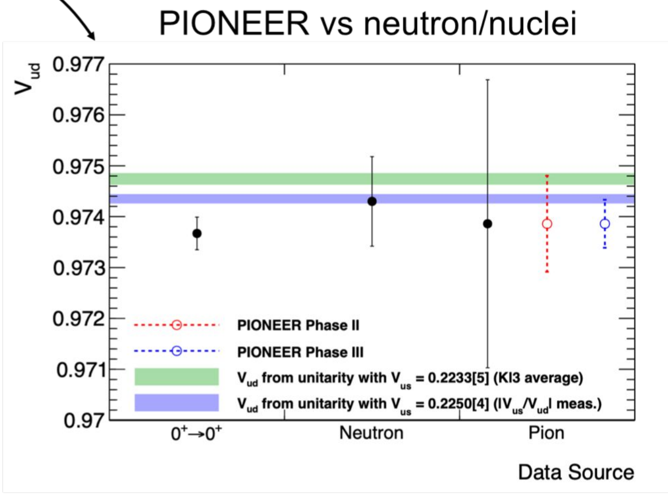
$$V_{ud}^{\pi} = 0.97386(283)$$

V_{ud} extraction from pion decays

PIONEER vs other probes



1D projection



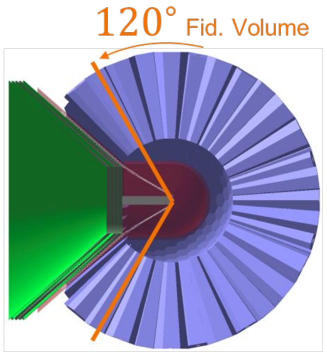
Competitive probe with a completely different error budget

Great potential to verify the observed discrepancy!

Calorimeter design

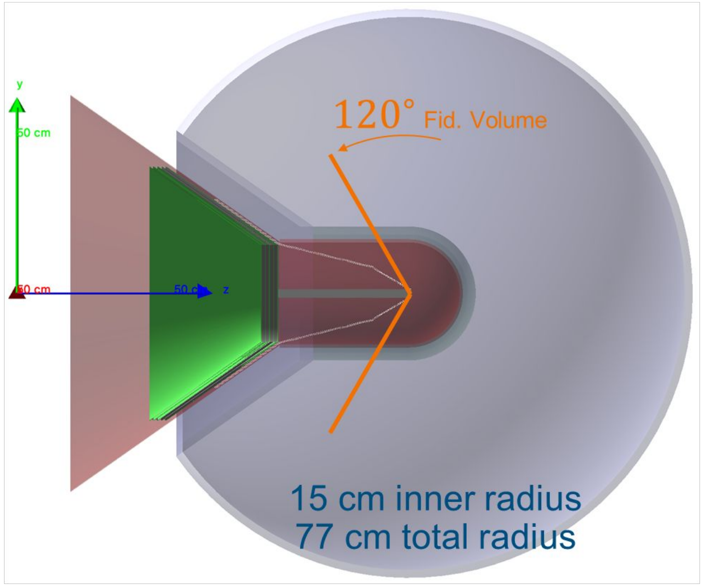
LYSO Crystals

Lutetium-yttrium oxyorthosilicate, $Lu_{2(1-x)}Y_{2x}SiO_5$



15 cm inner radius
42 cm total radius

Liquid Xenon



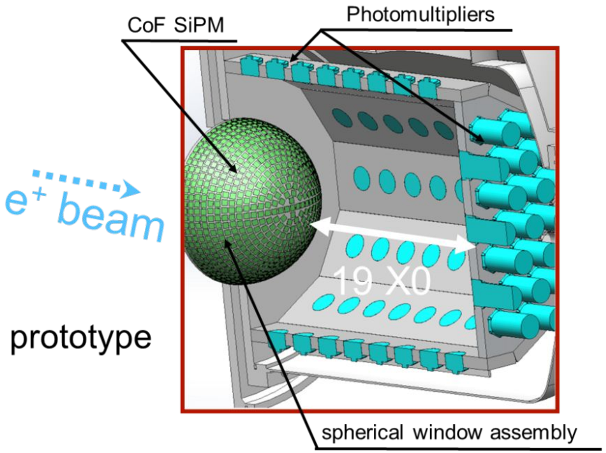
With a high-rate π^+ beam, fast (~50ns) light collection is critical

Calorimeter design

Technology down select

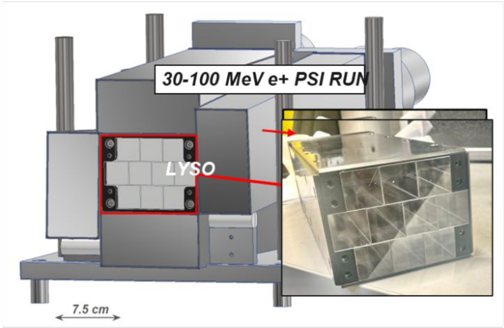
- **LXe single volume**
  Well established technology
  from the MEG experiment
  TRIUMF group leading the effort!

LXe prototype



- **LYSO crystals**
  Test beam studies demonstrated 1.6% resolution
  Simulations show segmentation is an asset

Beesley, et al, arXiv:2409.14691
(submitted to NIMA)

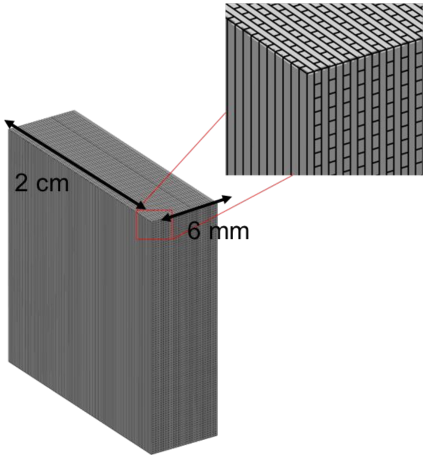


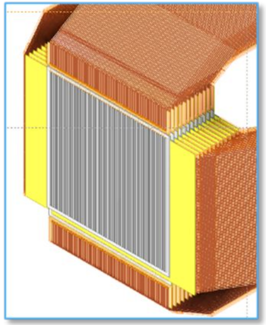
LYSO test beam meas.

- Prototypes in preparation for both options

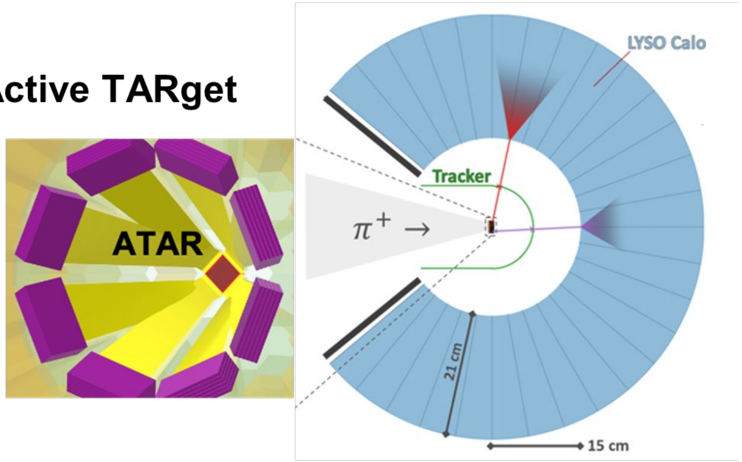
The ATAR

PIONEER’s heart





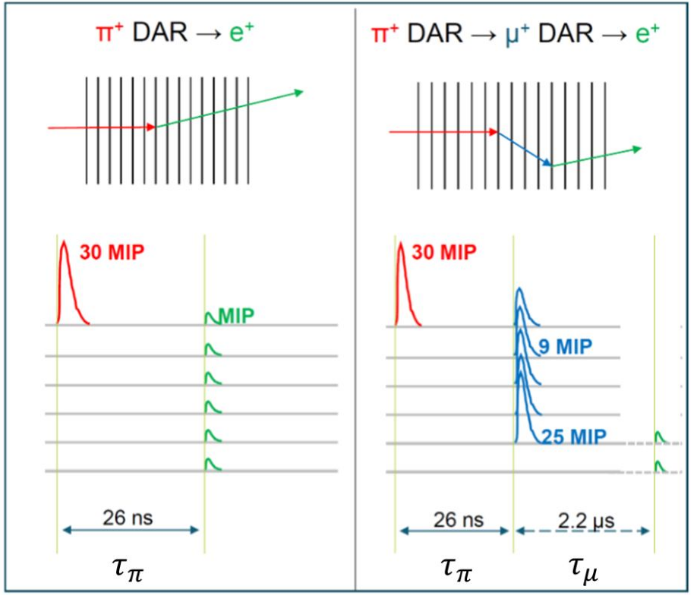
Active TARget



The ATAR

Requirements

Thick and highly segmented target to stop the pion and measure the decay chain



DAR = Decay At Rest
MIP = Minimum Ionizing Particle

Measure time, position, and energy

The ATAR

Requirements

Timing

$\tau_\pi \approx 26ns$
$\tau_\mu \approx 2\mu s$

Nanosecond precision, micro-second length signal

Position

Muon from stopped pion

E_{kin} = 4.1 MeV
Travel in Silicon ~ 0.8 mm

Sub-millimeter position resolution

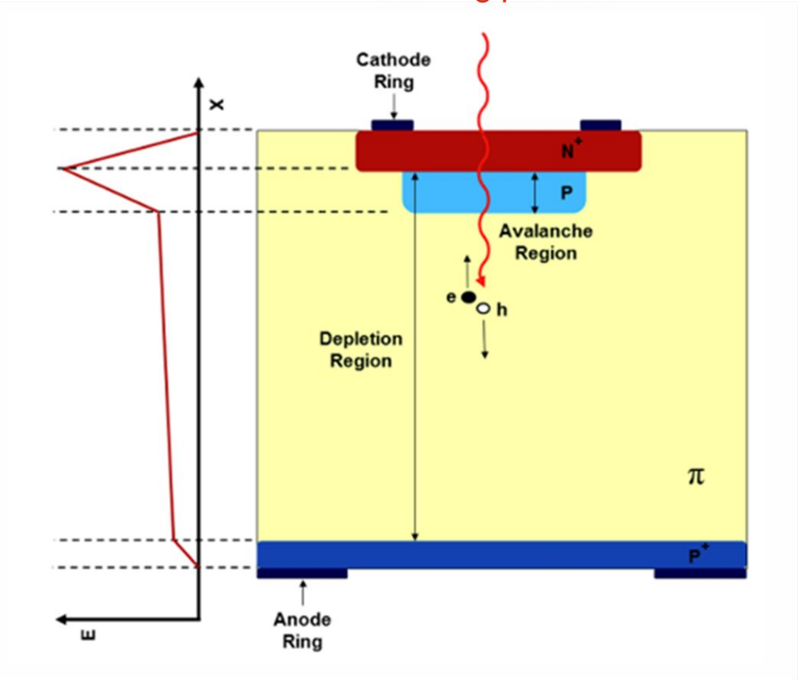
Energy

Positrons are MIPs
Muons / pions are ~100 MIPS

Large dynamic range (1000) to see all particles

Low Gain Avalanche Diodes (LGADs)

Incoming particle



Silicon Diodes:
p-n junction separated by an intrinsic layer (undoped)

LGADs:
additional highly doped layer generates a very high electric field → avalanche effect

The signal amplification allows for thin sensors and very good timing resolution

The gain mechanism saturates for **large energy deposit** and introduces an angle dependency

Quentin Buat (University of Washington) — Jan 9, 2025

Sensor characterisation

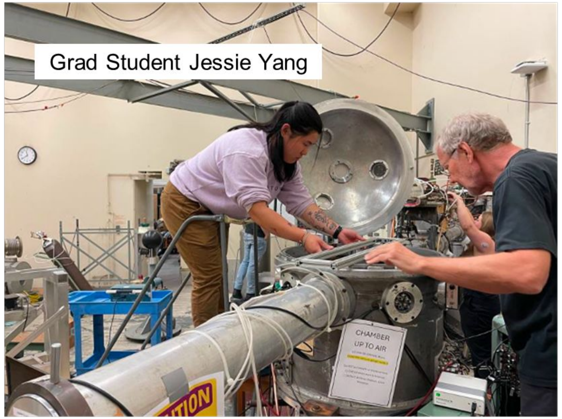
Test beam campaigns in 2023 and 2024 at the University of Washington using the CENPA tandem Van De Graaf Accelerator

Goal: gain measurement with highly ionising particles

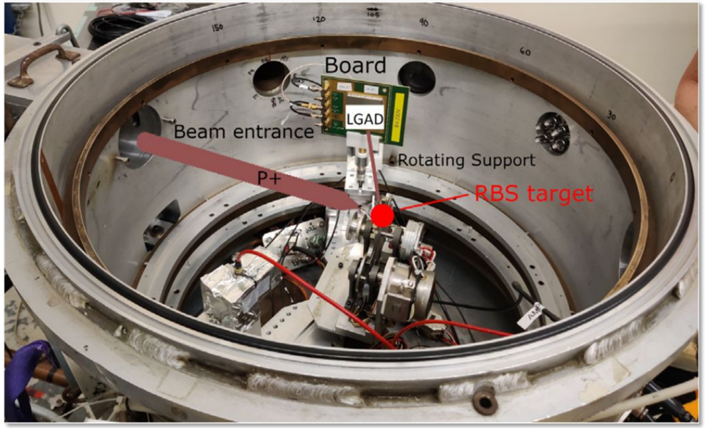
Critical for PIONEER to understand precisely the energy response saturation for π^+ and μ^+

Sensor characterisation

Gain measurements



Rutherford Back-Scattering (RBS) technique to control the rates



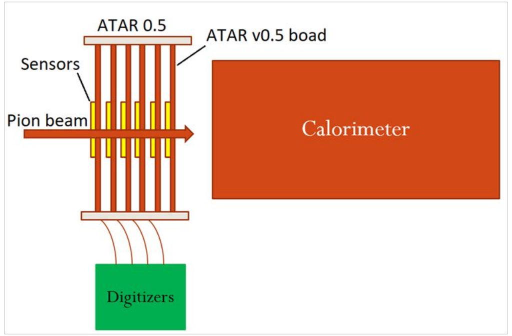
Sensors provided by multiple vendors (HPK, FBK and BNL)
selected to have low doping concentration (hence low gain) and/or shallow gain layer

2023 analysis (HPK) published (Braun et al., *NIM A 1064 (2024) 169395)*,
2024 (FBK and BNL) analysis ongoing

Next milestone: select the optimal doping for PIONEER

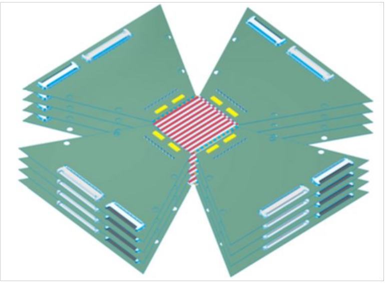
The ATAR

Toward first prototype



Current plan
Build first prototype
to take data at PSI in Fall 2026

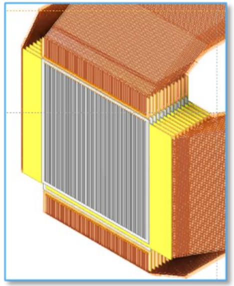
Prototype



Limited prototype
16 layers, 32 channels per layers
(full system has 48 layers with 100 channels per layer)

Goal is to have a first dataset of
pion or muon stopping data
before the 2027 PSI shutdown

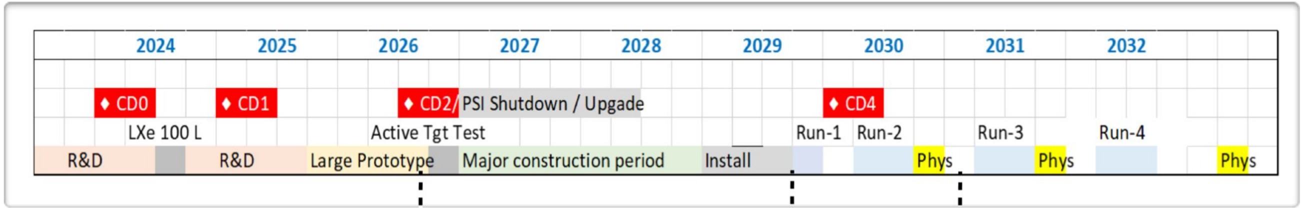
Final Target



Quentin Buat (University of Washington) — Jan 9, 2025

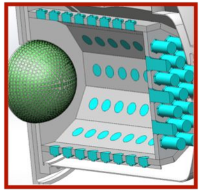
PIONEER Detector Prototyping

Very active R&D effort supported by simulations to aim for data-taking circa ~2030

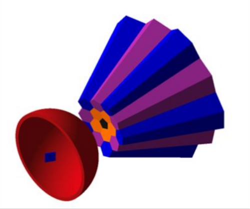


Fall 2026: demonstrator runs

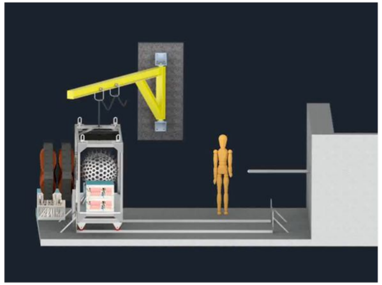
Assembly
Commissioning



LXe prototype



Demonstrator
16-array LYSO
16 layers ATAR
Tracker?



$R_{e/\mu}$ measurement

PIONEER: Beam Requirements Consistent with πE5
Beam measurements proposed.

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

- 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"* $\to$ $R_{e/\mu} \pm 0.01\%$

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

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

* 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)

$\pi \to e\nu$: 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

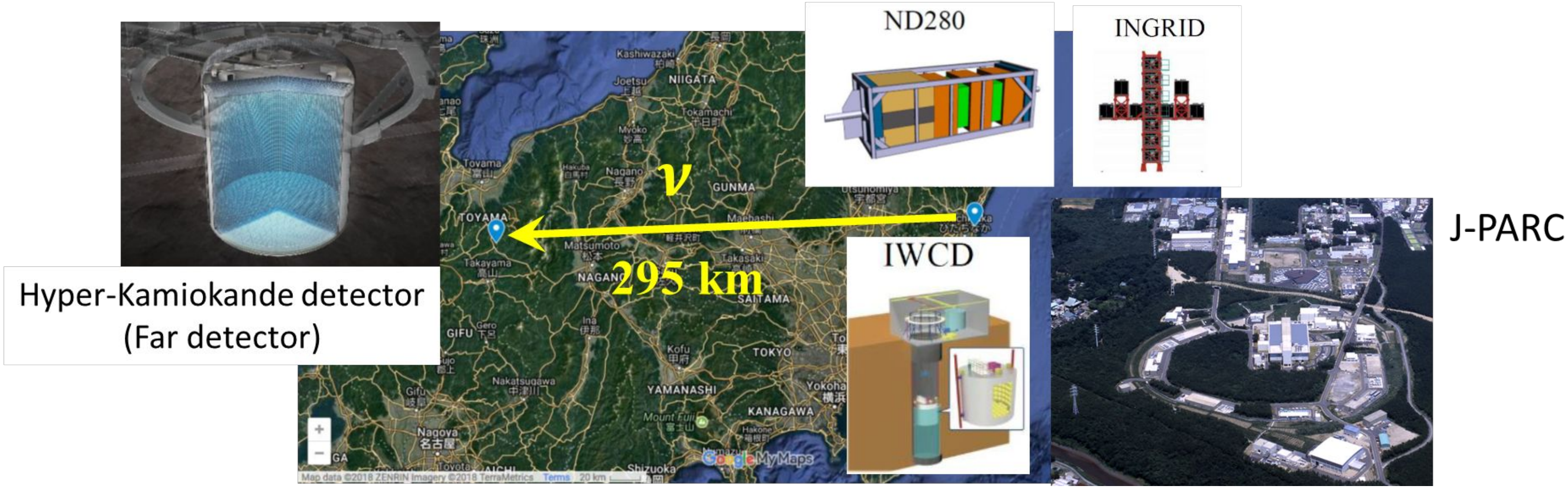
$\pi^+ \to \pi^0 e^+ \nu$: Estimated Uncertainties

	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)

Hyper-Kamiokande Project

- The Hyper-Kamiokande project includes a far detector, a neutrino beam, and a neutrino near detector complex
  - Construct the Hyper-Kamiokande detector at Kamioka
  - Upgrade the J-PARC neutrino beam
  - Construct the Intermediate Water Cherenkov Detector (IWCD) at Tokai



- **Kamiokande (1983 - 1996)**
  - Atmospheric and solar neutrino “anomaly”
  - Supernova 1987A

  Birth of neutrino astrophysics

- **Super-Kamiokande (1996 - ongoing)**
  - Proton decay: world best-limit
  - Neutrino oscillation (atm/solar/LBL)
    - All mixing angles and Δm^2s

  Discovery of neutrino oscillations

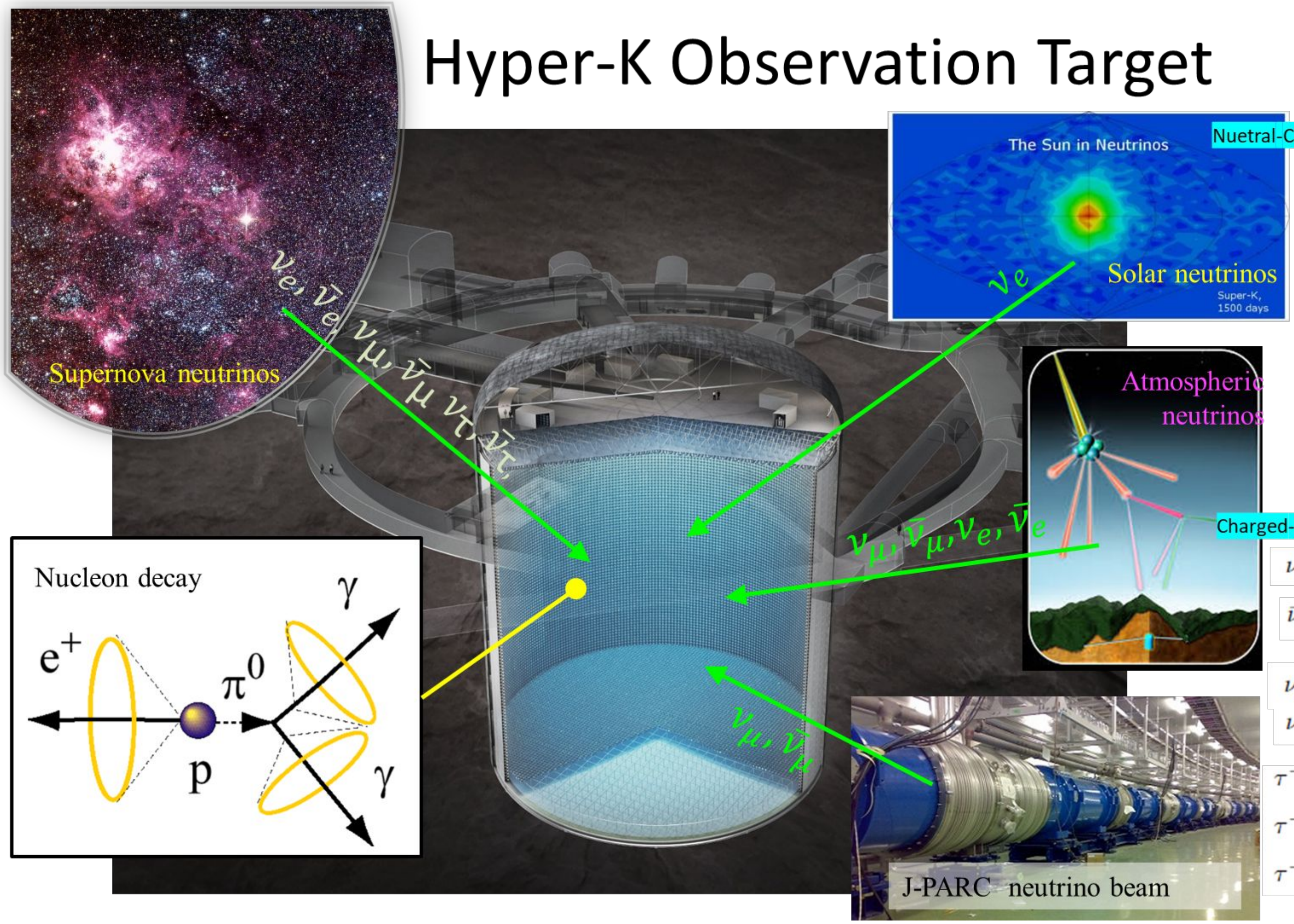
- **Hyper-Kamiokande (2027 -)**
  - Extended search for proton decay
  - Precision measurement of neutrino oscillation including CPV and MO
  - Neutrino astrophysics

  Explore new physics

Hyper-K Observation Target

$\nu_e + n \rightarrow e^- + p$

$\bar{\nu}_e + p \rightarrow e^+ + n$



Nuetral-Current Interactions (NC)

$\nu_e + e^- \rightarrow \nu_e + e^-$

$\nu + N \rightarrow \nu + N'$

$p \rightarrow e^+ + \pi^0$

$p \rightarrow \mu^+ + \pi^0$

$\pi^0 \rightarrow \gamma + \gamma$

Charged-Current Interactions (CC)

$\nu_e + n \rightarrow e^- + p$

$\bar{\nu}_e + p \rightarrow e^+ + n$

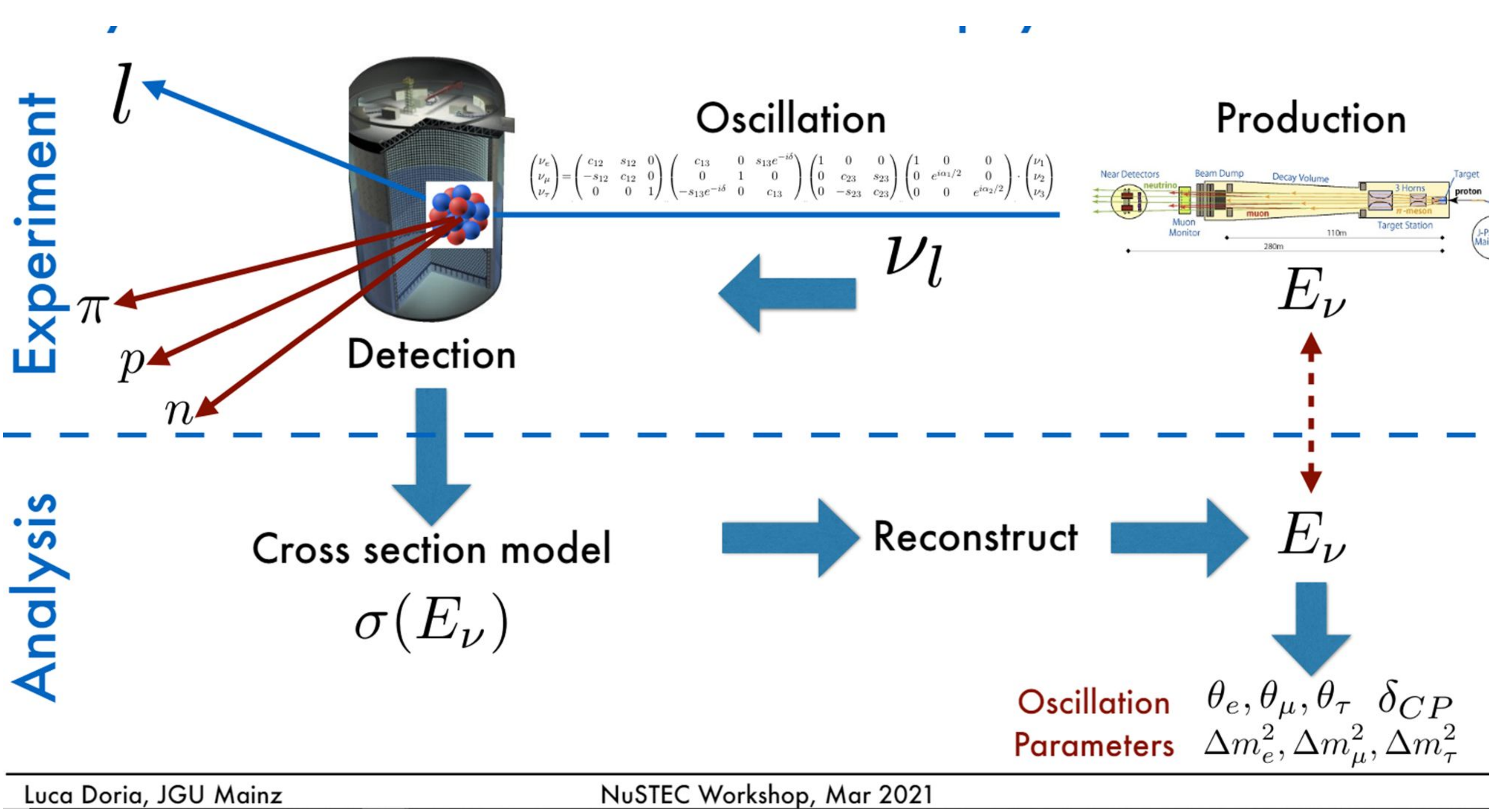
$\nu_\mu + n \rightarrow \mu^- + p$

$\nu_\tau + n \rightarrow \tau^- + p$

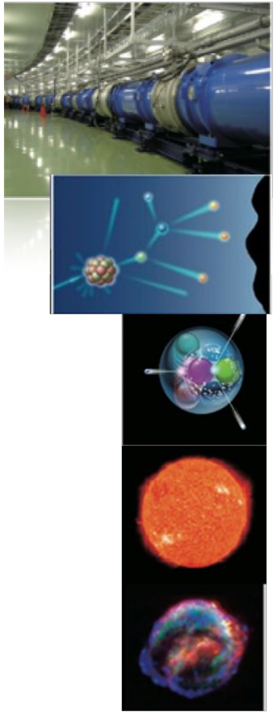
$\tau^- \rightarrow e^- + \bar{\nu}_e + \nu_\tau$

$\tau^- \rightarrow \mu^- + \bar{\nu}_\mu + \nu_\tau$

$\tau^- \rightarrow \text{hadrons} + \nu_\tau$


Experiment
Analysis
Detection
Oscillation
Production
l
π
p
n
ν_l
E_ν
Near Detectors
Beam Dump
Decay Volume
Target
proton
3 Horns
neutrino
muon
Muon Monitor
Target Station
110m
280m
Cross section model
$\sigma(E_\nu)$
Reconstruct
E_ν
Oscillation Parameters
$\theta_e, \theta_\mu, \theta_\tau \quad \delta_{CP}$
$\Delta m^2_e, \Delta m^2_\mu, \Delta m^2_\tau$
Luca Doria, JGU Mainz
NuSTEC Workshop, Mar 2021

Hyper-K Target sensitivity

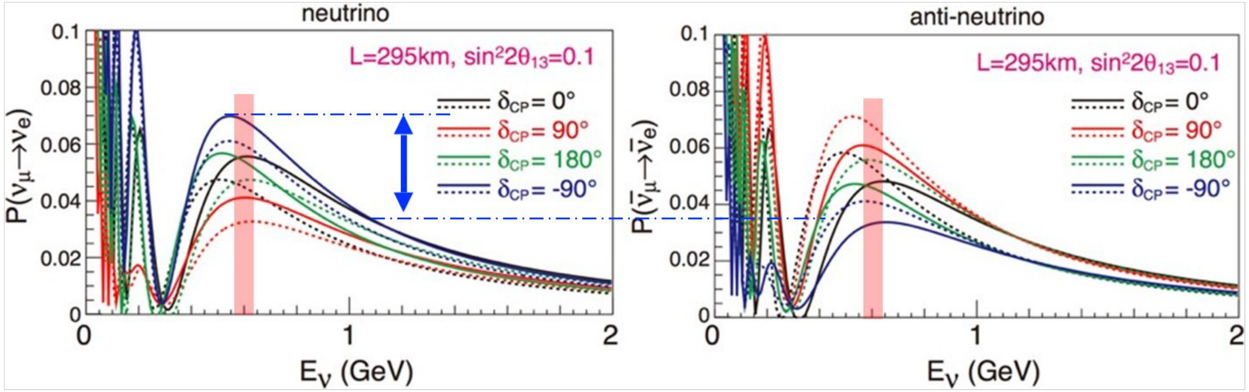


Physics category	Parameters	Sensitivity
LBL (1.3MW×10years)	δ precision	7°-20°
	CPV coverage (3/5σ)	76% / 58%
	$\sin^2\theta_{23}$ error (for 0.5)	±0.017
ATM+LBL (10 years)	MO determination	>3.8σ
	Octant determination (3σ)	$\lvert\theta_{23}$-45°$\rvert$>2°
Proton Decay (20 years)	τ for $e^+\pi^0$ (3σ)	1×10^{35} years
	τ for νK (3σ)	3×10^{34} years
Solar (10 years)	Day/Night (from 0/from KL)	8σ/4σ
	Upturn	>3σ
Supernova	Burst (10kpc)	54k-90k
	Relic	70ν's / 10 years

Long-baseline program with the J-PARC neutrino beam

Experimental setup

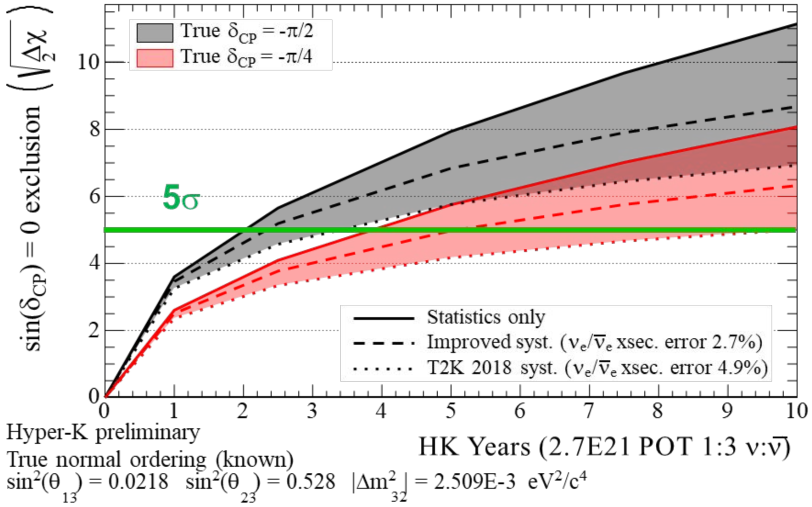
- 2.5° off-axis ν_μ and $\bar{\nu}_\mu$ beam peaked at 0.6 GeV (oscillation maximum at 295km)
  - Major interaction is QE: E_ν determined from (p, θ) of charged lepton
- Measures CP violation in neutrinos by comparing $P(\nu_\mu \rightarrow \nu_e)$ and $P(\bar{\nu}_\mu \rightarrow \bar{\nu}_e)$

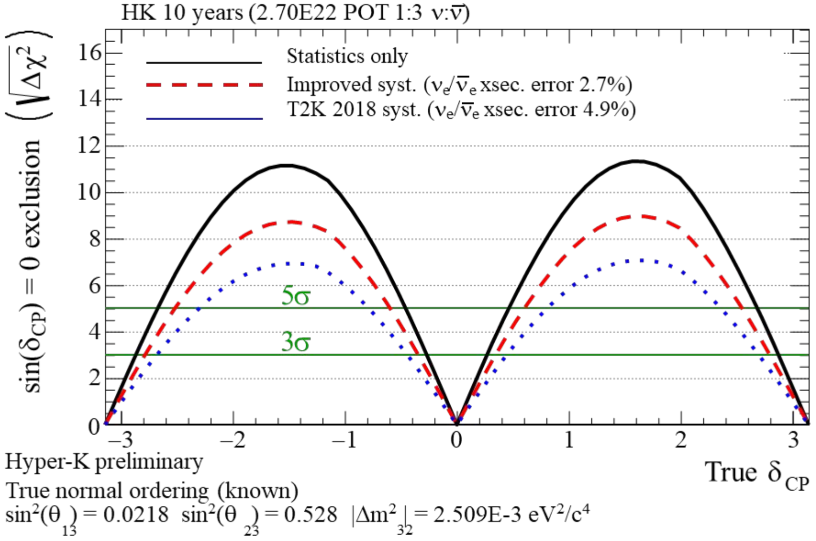


- A few % statistical uncertainties after 10 years operation with >1000 ν_e and $\bar{\nu}_e$ signals

CP violation sensitivity

- Sensitivity CP violation with 1:3 $\nu : \bar{\nu}$ beam





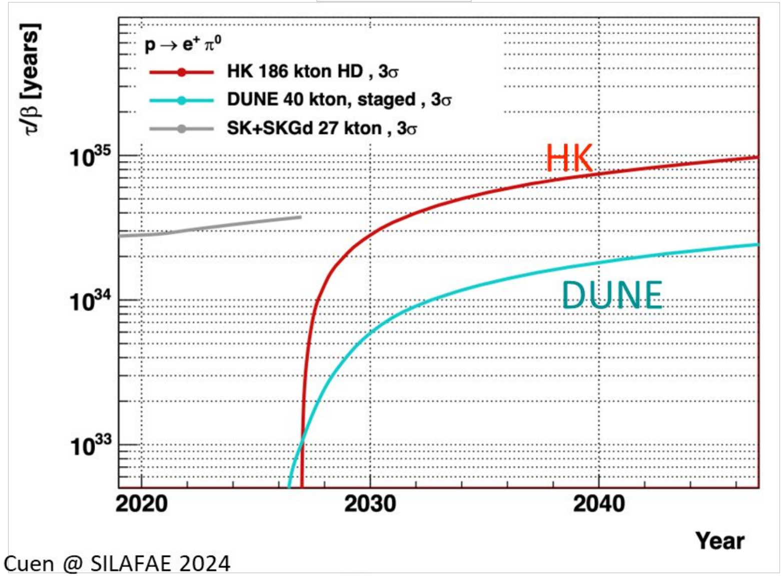
- With systematics and known mass ordering (MO): 2-3 years for 5σ sensitivity to exclude CP conservation for true $\delta\_CP = -\pi/2$.
- After 10 years of operation, 60% of δ_CP values excluded at > 5σ

Nucleon decay search

- Nucleon decay is evidence of Beyond Standard Model (BSM) and Grand Unified Theories (GUT)
- Examples of proton decay sensitivity in two modes:

[HK] arXiv:1805 04163
[DUNE] arXiv:2002.03005
[JUNO] arXiv:1508.07166

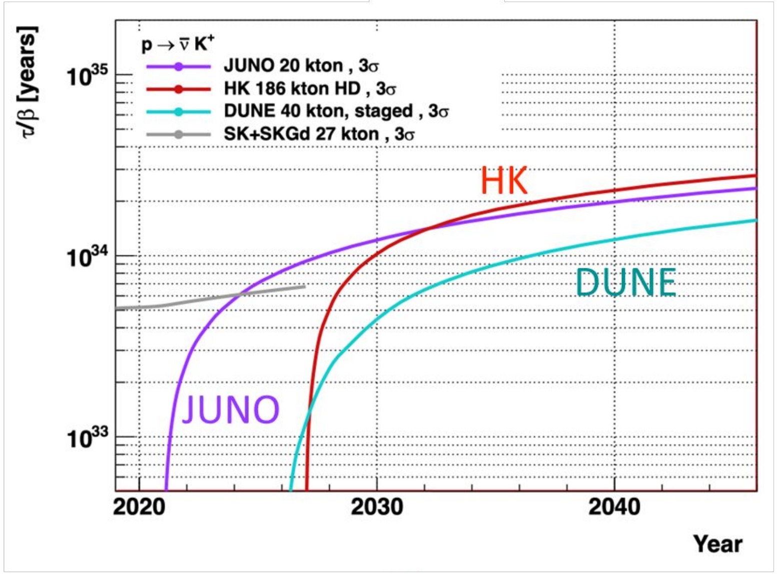
$p \rightarrow e^{+}\pi^{0}$



Saul Cuen @ SILAFAE 2024

$\tau \sim 10^{35}$ years (3σ)

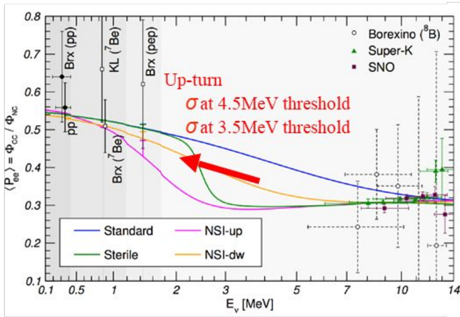
$p \rightarrow \bar{\nu}K^{+}$



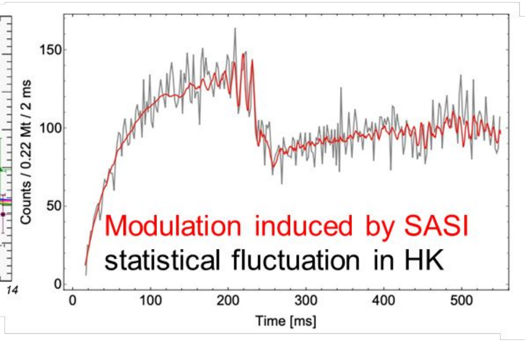
$\tau \sim 3\text{x}10^{34}$ years (3σ)

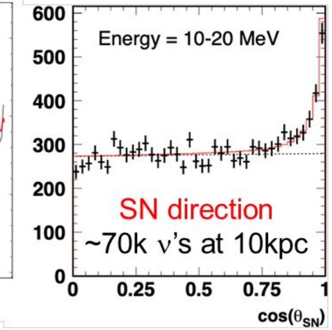
Neutrino astrophysics

- Hyper-K is designed to be sensitive to neutrinos with energies starting from a few MeV, including time, energy and direction information. Unique role in multi-messenger observation
- **Solar neutrinos:** up-turn at vacuum-MSW transition, Day/Night asymmetry, hep neutrino observation
- **Supernova burst neutrinos:** explosion mechanism, BH/NS formation, alert with ~1^{o} pointing
- **Supernova Relic Neutrinos (SRN):** stellar collapse, nucleosynthesis and history of the universe



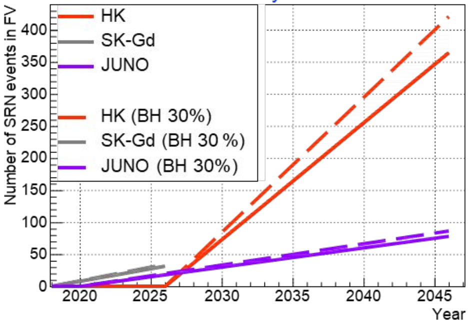
M. Maltoni et al., Phys. Eur. Phys. J. A52, 87 (2016)





SRN rate

Calculation from FV and E_{th}
Efficiency is not accounted

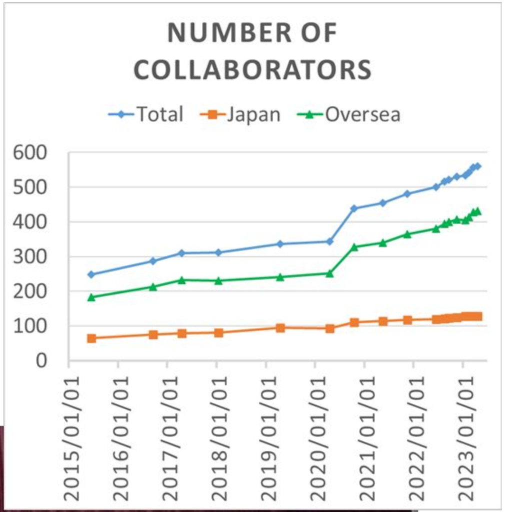


Katsuki Hiraide @ NNN23

Hyper-Kamiokande Collaboration

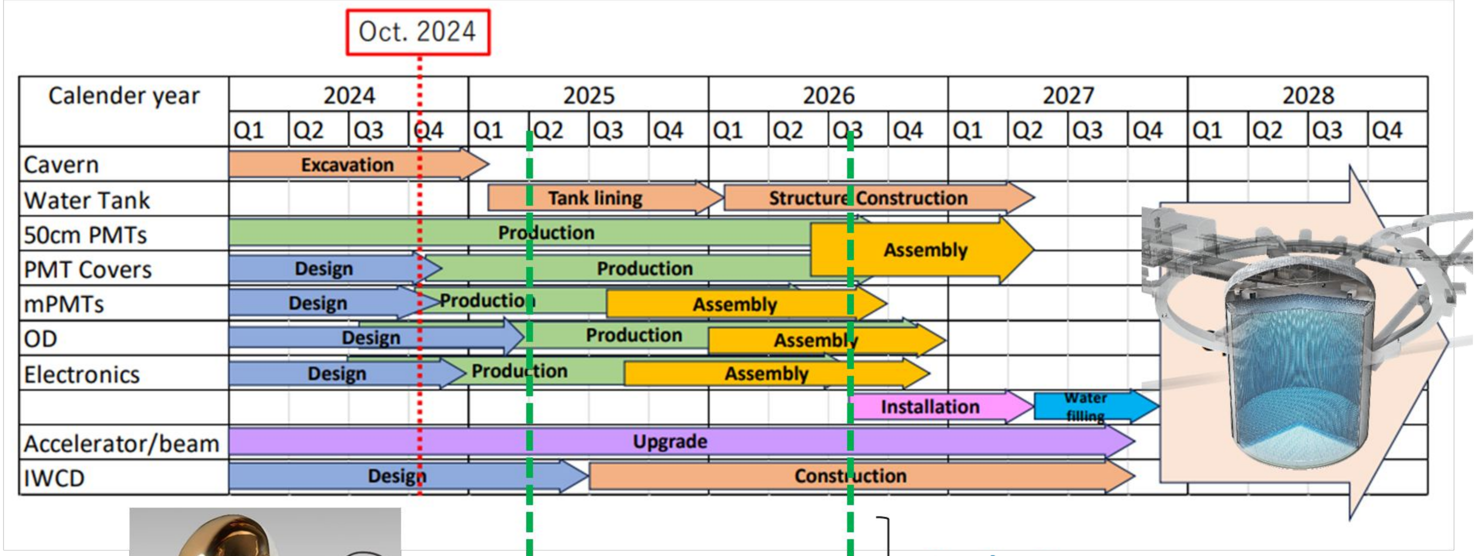
- ~600 members located in 102 institutes from 22 countries
  - 25% Japanese / 75% non-Japanese
- Recently approved as a recognized experiment (RE45) at CERN

- <u>Latest collaboration meeting October 2024 in Toyama:</u>



Hyper-K construction schedule

- The Hyper-K construction started in 2020 and will start operation in 2027.



Now

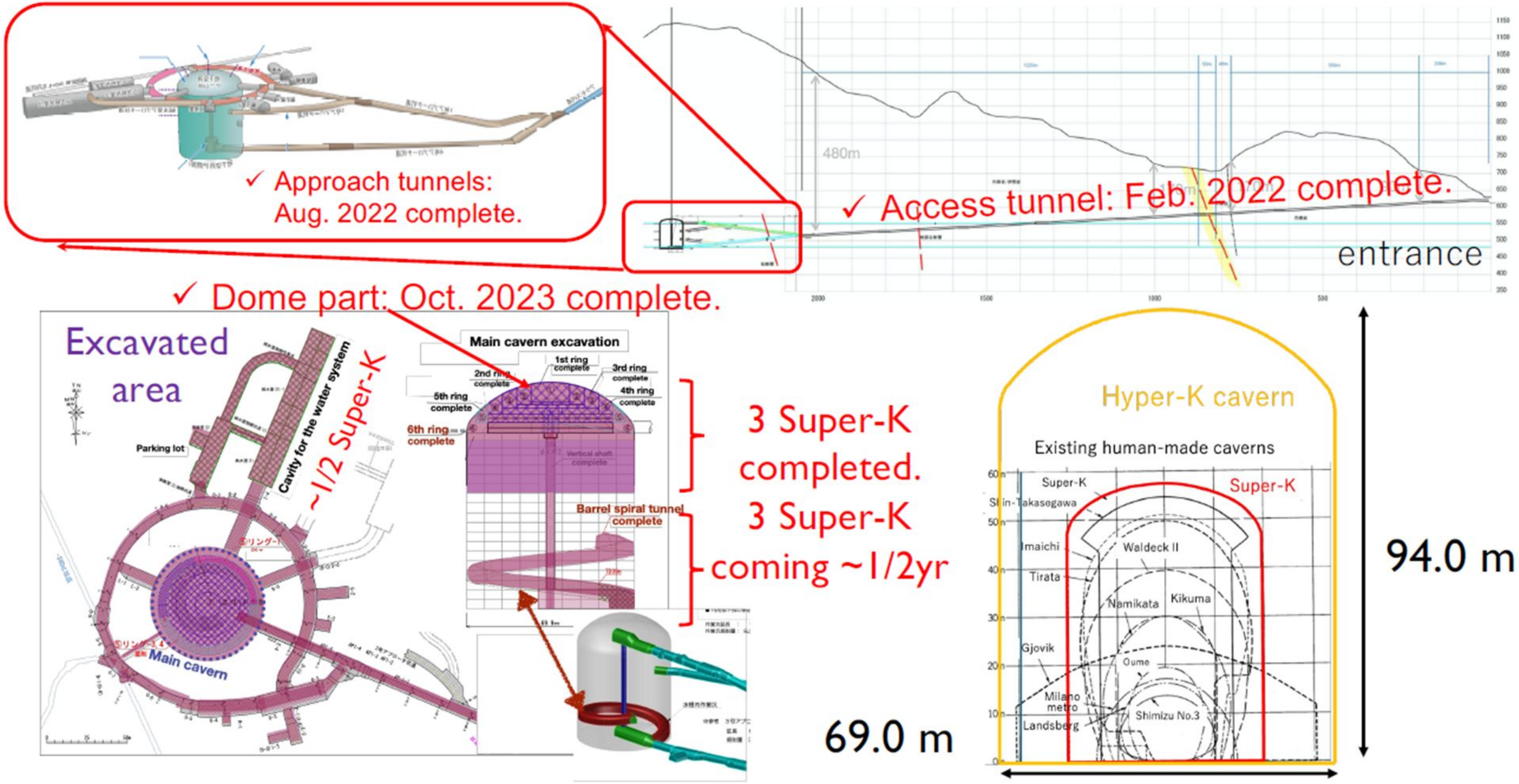
Accelerator upgrade

~2 years from now!!

Saul Cuen @ SILAFAE 2024

13

Excavating the world's largest human-made cavern



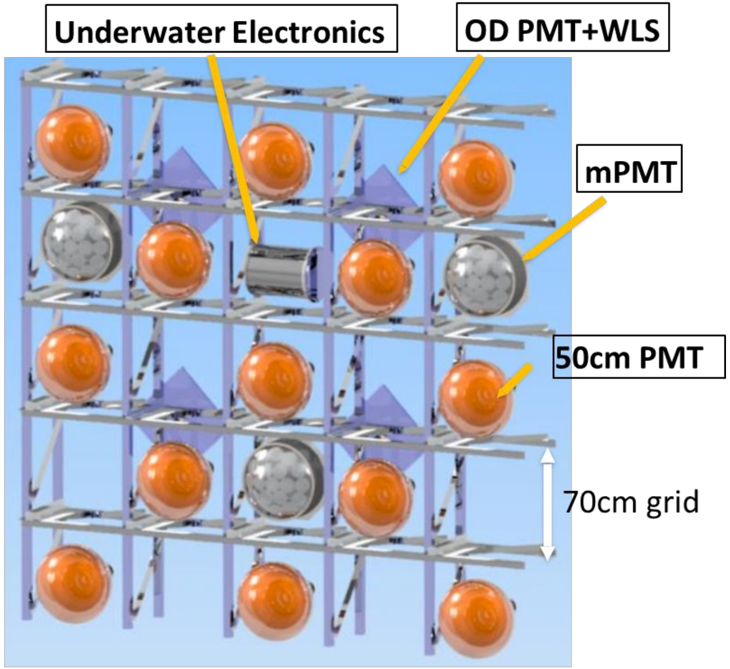
Hyper-K main cavern excavation

- **<u>October 3, 2023:</u>** Excavation of the dome section completed.
  - 69m diameter, 21m height
  - One of the largest human-made underground space.
- Now, the excavation of the barrel section is ongoing.


Excavation of the HK cavern will be completed by the end of this year!

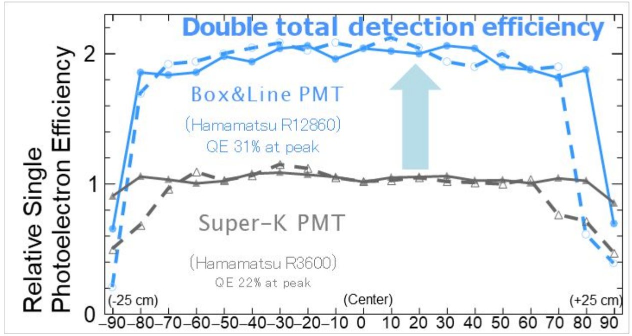
Hyper-K detector configuration

- **Inner Detector (ID)**
  - 20,000 – 20’’ PMT
  - 64.8m diameter, 65.8m height
  - 50cm PMTs will be installed
  - 800 multi-PMT modules (19 3’’ PMT each) will be integrated as hybrid configuration
- **Outer Detector (OD)**
  - 3,600 – 3’’ PMT
  - 1m (barrel) or 2m (top/bottom) thick
  - 3-inch PMT + WLS plate
  - Walls are covered with high-reflectivity Tyvek sheets
- **Under-water electronics**
  - Mitigate disadvantage of long cables



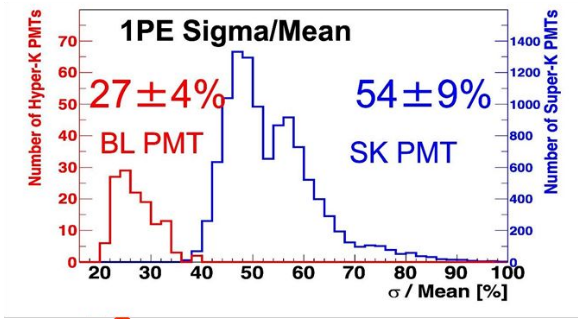
Hyper-K 50cm PMT performance

×2 better photodetection efficiency (QE×CE)

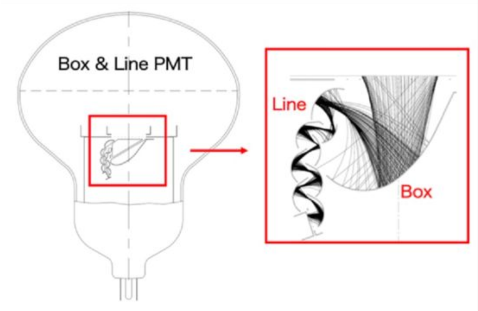


(Performance in SK tank, 1.7e7 gain)

×2 better charge resolution



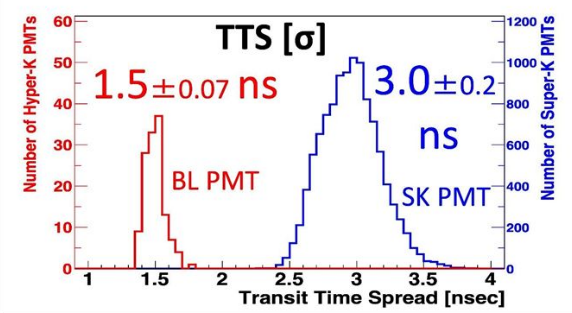
Box&Line dynode



×2 better pressure tolerance
→ enable deeper tank design, project cost reduction

Low dark rate (4kHz) and RI

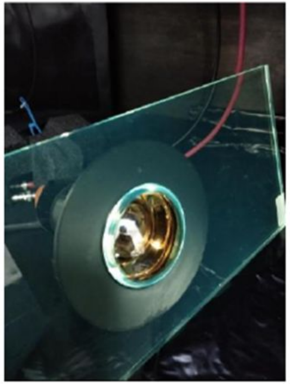
×2 better timing resolution



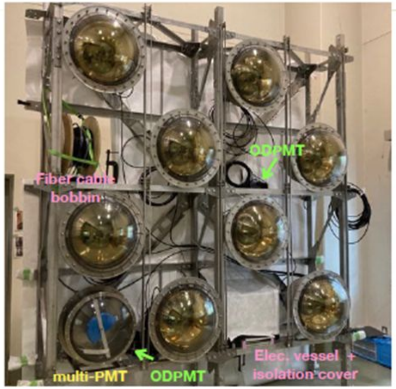

PMT production ongoing, >10,000 delivered.
Screening both at Hamamatsu and Kamioka

Photosensors and underwater electronics

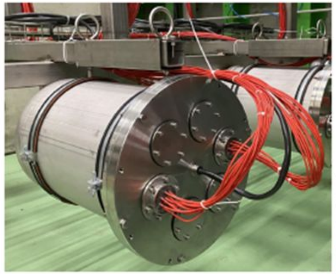
Outer detector: PMT+WLS plate

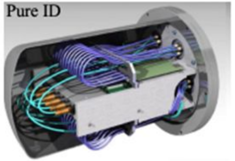


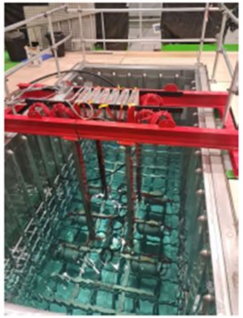
Photosensors/elec. mockup



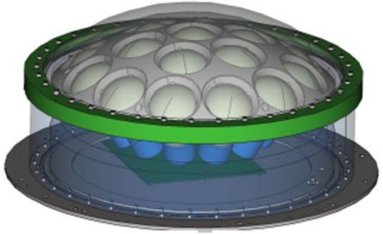
Underwater electronics: Case design and feedthrough



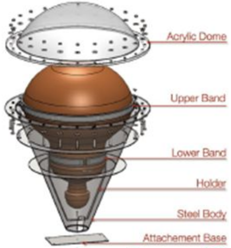


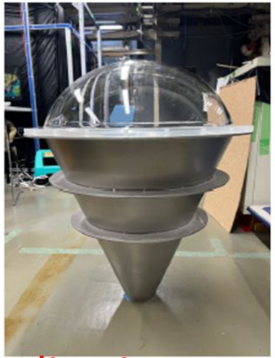


Multi-PMT module:



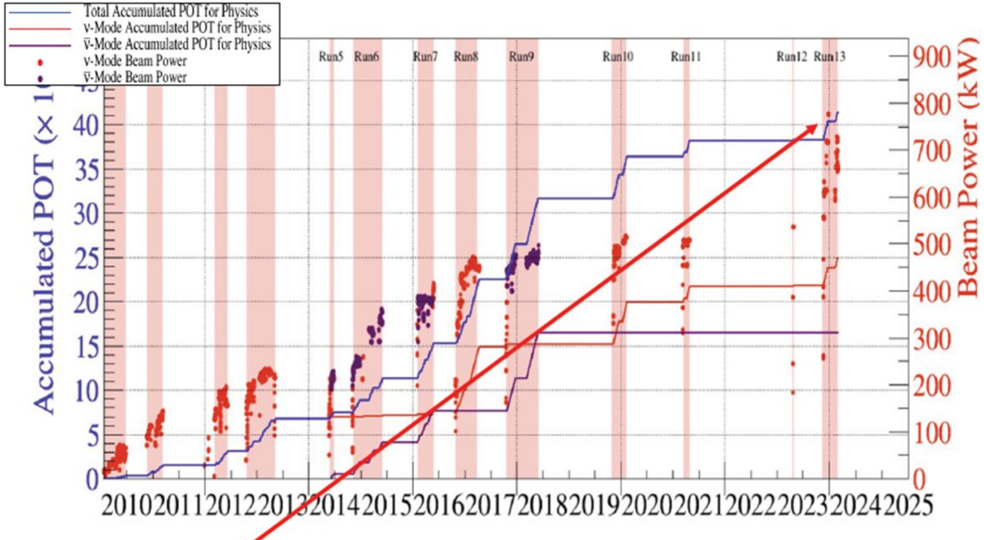
PMT cover

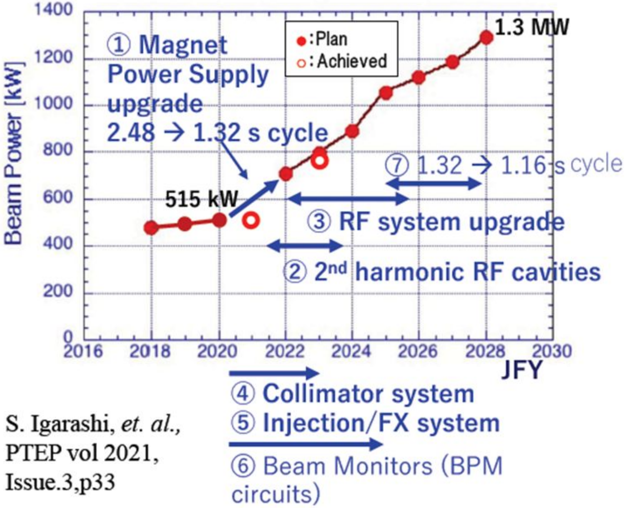




Design finalization ongoing

Beam: status and plan of power increase





S. Igarashi, *et. al.*, PTEP vol 2021, Issue.3,p33

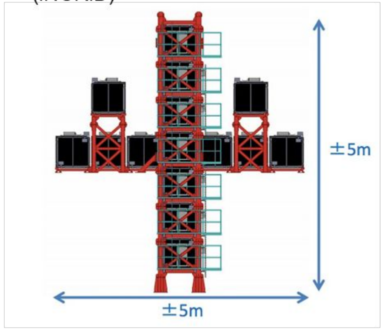
760 kW achieved already and 800 kW last week!

Further beam power increase requires:

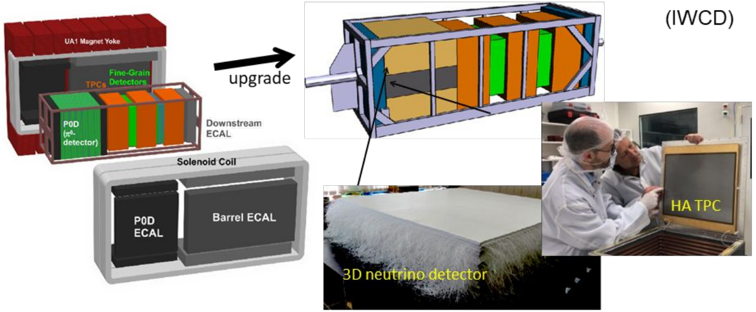
- Seeking beam loss with optics improvements
- More protons/pulse by upgrading RF system
- Further beam intensity increase will be done by 1.36 → 1.16 sec cycle

Neutrino detectors at J-PARC

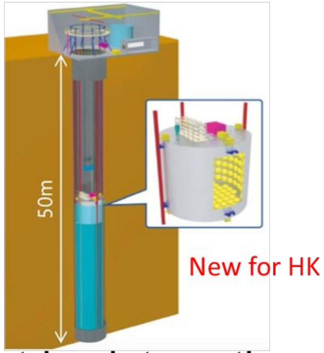
On-axis Detector
(INGRID)



Off-axis Magnetized Tracker
(ND280→Upgrade for T2K →Upgrade for HK)



Off-axis spanning Intermediate water Cherenkov detector
(IWCD)

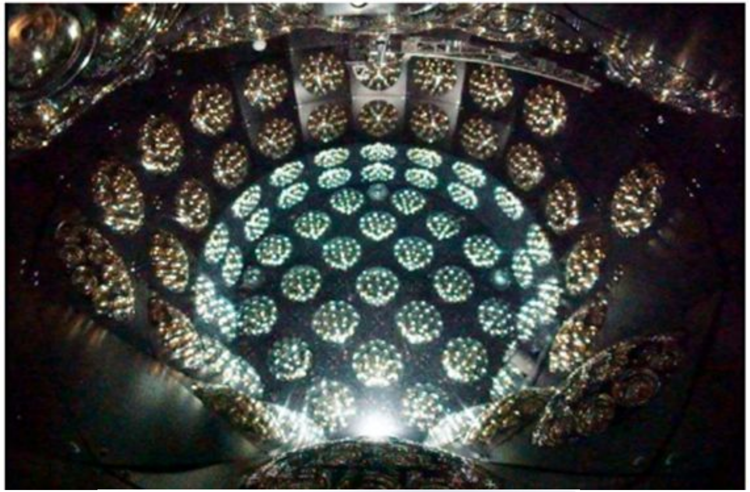


Critical components to precisely understand J-PARC beam and neutrino interactions:

- **On-axis detector:** Measure beam direction and event rate
- **Off-axis magnetized tracker:** Measure primary (anti)neutrino interaction rates, spectrum, and properties. Charge separation to measure wrong-sign background
  → Upgrade by T2K experiment and intensive discussion for further upgrade in HK-era is ongoing.
- **Intermediate WC detector:** H_2O target with off-axis angle spanning orientation.
  → Detector site investigation and conceptual facility design are ongoing.

WCTE at CERN

https://arxiv.org/pdf/2504.07216

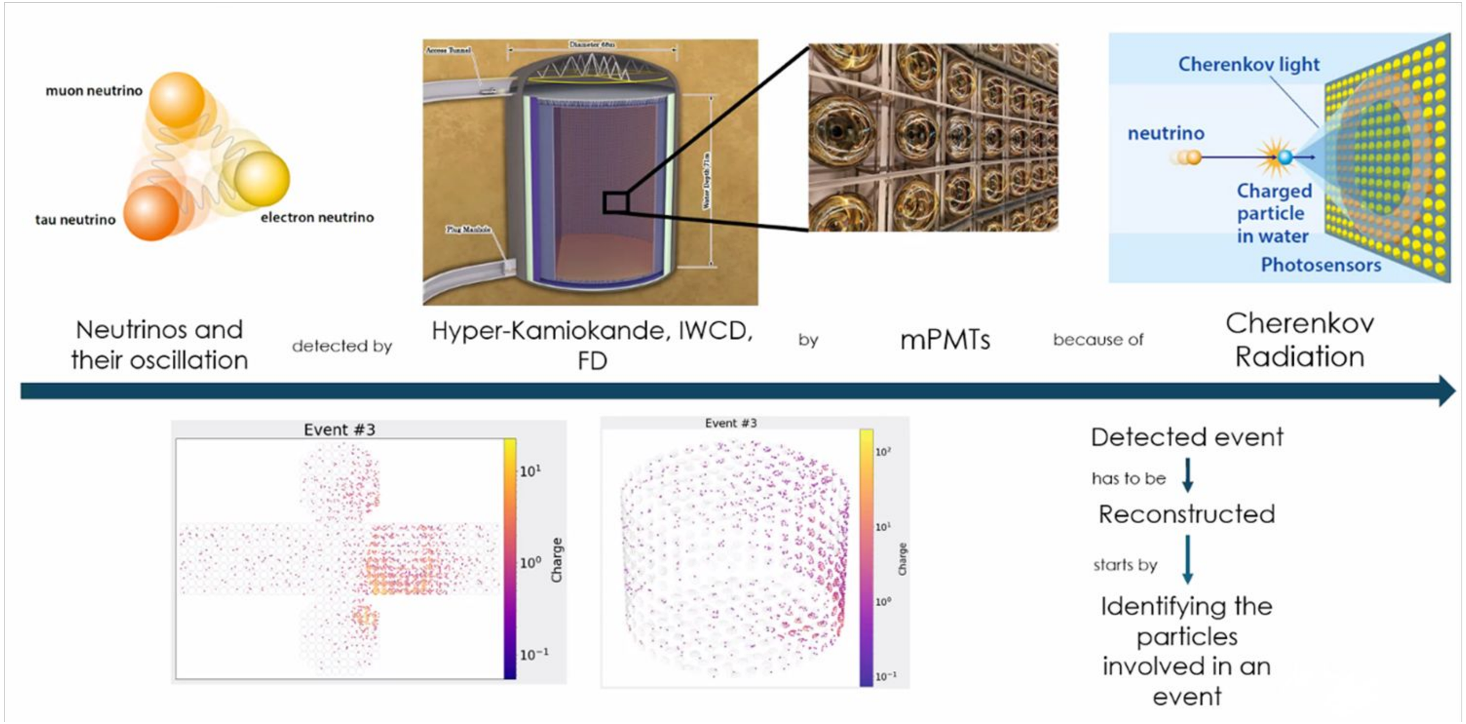


Mexican funds awarded for Hyper-K

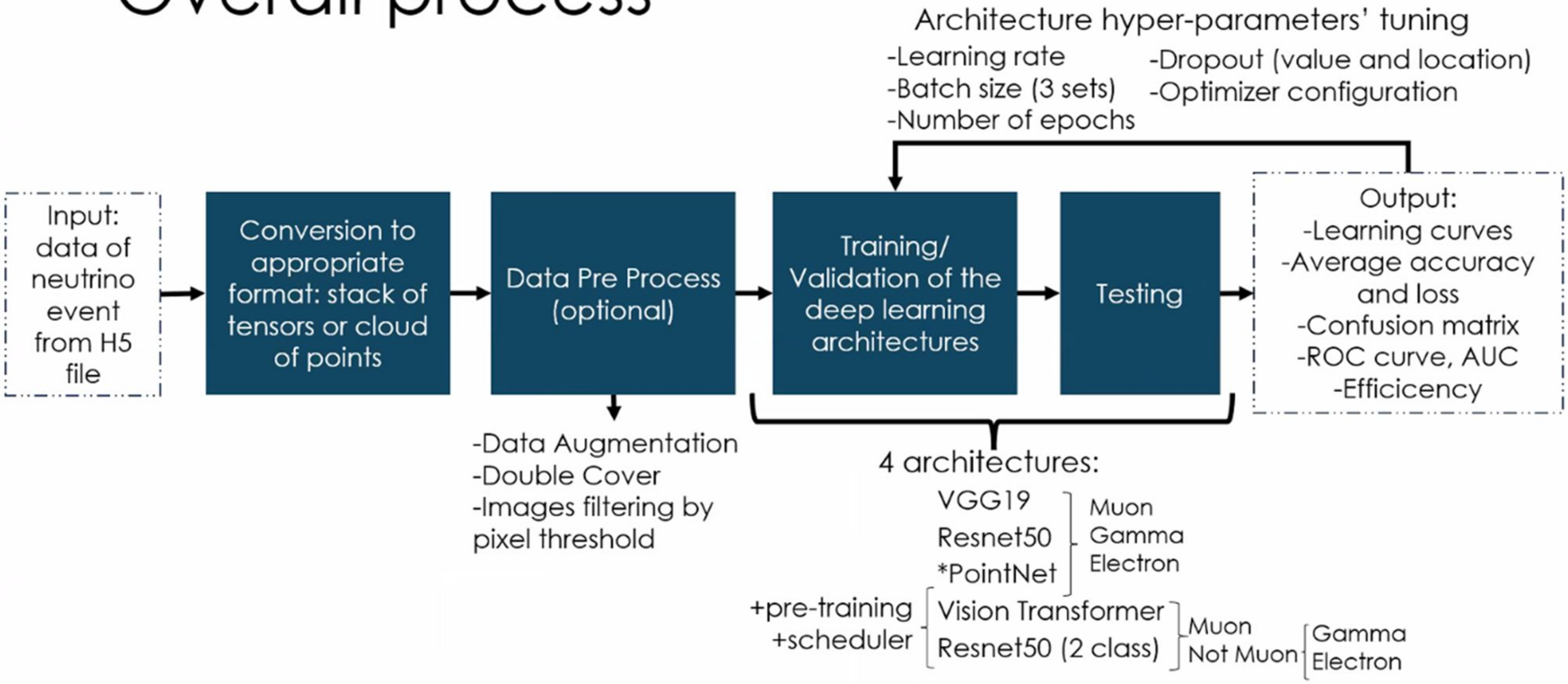
- CF-2023-G-643 "Construcción y comisionado de sensores de ciencia frontera para la detección de supernovas, materia oscura, y medición de la asimetría bariónica en el Universo, en experimentos de Neutrinos de nueva generación" (2023)
    - Grant holder: Eduardo de la Fuente Acosta (UdeG)
    - Institutions involved:
        - KAREN SALOME CABALLERO MORA (UNACH)
        - GIANNINA DALLE MESE ZAVALA (UAS)
        - ALEJANDRO KADSUMI TOMATANI SANCHEZ (TEC-GDL)
        - Saul Cuen Rochin (TEC-SIN)
- CBF2023-2024-427 "Deep Learning y Fabricación de Sensores de Ciencia de Frontera para Experimentos de Neutrinos de Próxima Generación" (2024)
    - Grant holder : Saul Cuen Rochin (TEC-SIN)
    - Institutions involved :
        - GIANNINA DALLE MESE ZAVALA (UAS)

CONAHCYT
Consejo Nacional de Humanidades Ciencias y Tecnologías

Neutrino classification

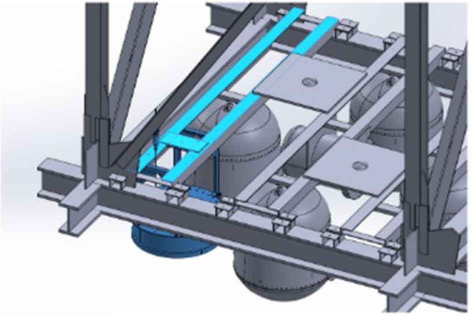


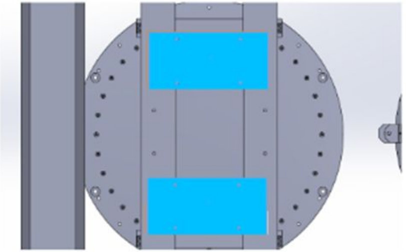
Overall process

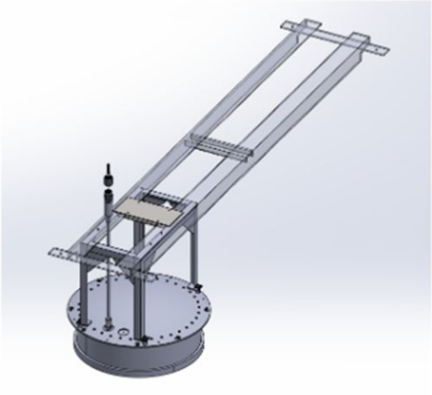


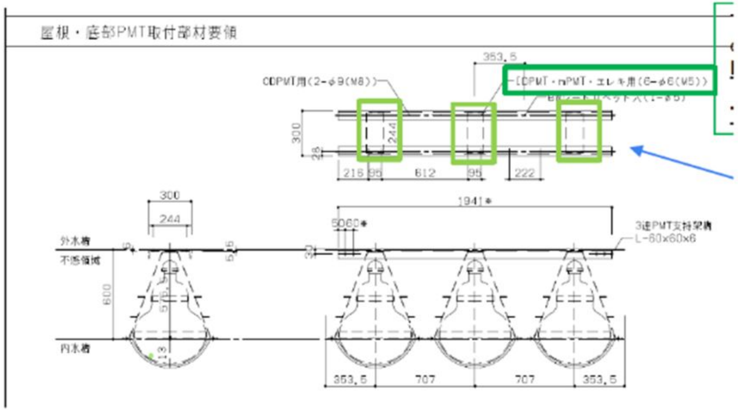
top & bottom mPMT support

Currently working on requirements from the integration group.









Tecnológico de Monterrey

mPMT mechanical stress test

Top/bottom configuration
Barrel configuration
Transportation studies, and box design
-Compression
-Temperate
-Vibrations







周辺地図 Area Map
至 富山
To Toyama
宿泊棟
Kamioka Dormitory
茂住バス停
Mozumi Bus Stop
Kavli IPMU サテライトオフィス
Kavli IPMU Satellite Office
東京大学宇宙線研究所
神岡宇宙素粒子研究施設
Kamioka Observatory
計算機棟
KEISANKITO
研究棟
KENKYUTO
現在地
You Are Here
東北大学 カムランドオフィス
Tohoku University, KamLAND Office
茂住郵便局
Mozumi Post Office
神岡総合研究棟
Kamioka Research Complex
(SOGOTO)
高原川
Takahara River
重力波観測研究施設
KAGRA Observatory
茂住パーキング
Mozumi Parking Lot
国道41号
Route 41
至 神岡市街地・高山市
To Center of Kamioka, Takayama
スーパーカミオカンデ
Super-Kamiokande
大型低温重力波望遠鏡 かぐら
KAGRA
カムランド
KamLAND
至 富山
To Toyama
現在地
You Are Here
池ノ山
Mt. Ikeno
1369
新猪谷ダム
Shininotani Dam
地下実験施設
Underground Facilities
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国道41号
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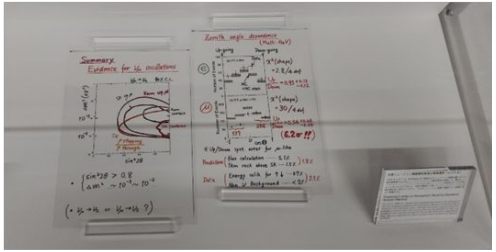
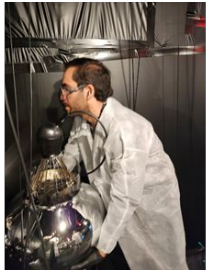
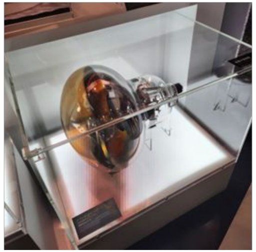
東京
Tokyo
大阪
Osaka
名古屋
Nagoya







Conclusions

- Hyper-Kamiokande is 3rd generation water Cherenkov detector in Kamioka
- Important physics targets
  - Neutrino CP violation: Discovery with 5 σ for ~60% parameter regions
  - Nucleon Decay Search for testing GUT: $\tau > 10^{35}$ years for $p \rightarrow e^+\pi^0$
  - Neutrino Astrophysics: Supernova neutrinos
- Hyper-Kamiokande construction on schedule
  - World's largest underground facility: 260 kton water Cherenkov detector
  - Access tunnel and cavern construction on track
  - 50cm PMT production underway
  - Other detector component designs being finalized
  - Neutrino beam upgrade to 1.3 MW
  - Near detector upgrade and design of intermediate detector being finalized
- Hyper-Kamiokande will start operation in 2027.

We are looking for you!

- Undergraduate, master, phd thesis, and postdocs available for PIONEER and Hyper-K… Get in contact :)
- Collaboration institutes for PIONEER:
    - Cinvestav with Pablo Roig
    - Tec de Mty with Saul Cuen <saulcuen@tec.mx>
- Collaboration institutes for Hyper-K:
    - UAS with Giannina Dalle Mese
    - UNACH with Karen Caballero
    - UdeG with Eduardo de la Fuente
    - Tec de Mty with Saul Cuen <saulcuen@tec.mx>