PIONEER

Development of the Large Prototype LXe calorimeter for PIONEER

Emma Klemets (she/her)
PhD student at UBC & TRIUMF
Supervisor: Chloé Malbrunot

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PIONEER (unofficial logo)

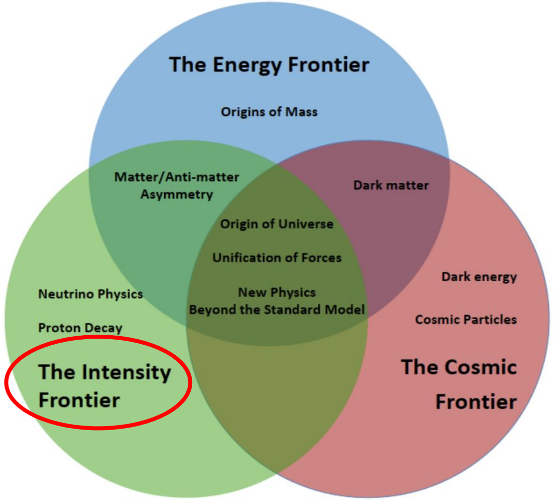
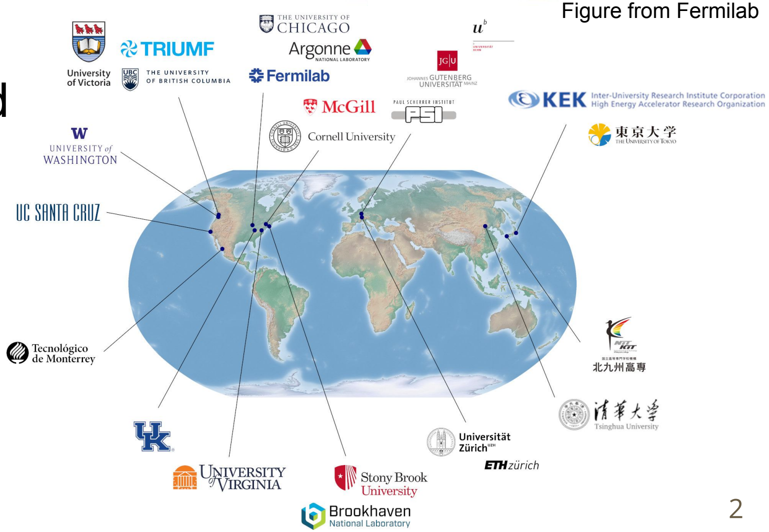


Figure from Fermilab

- A rare pion decay experiment in the intensity frontier
  - A high precision measurement to probe new physics at high energies
- Currently being designed and prototyped
- At PSI (The Paul Scherrer Institute), Switzerland
  → The highest intensity pion beam
- Our collaboration is ~ 80 scientists from 25 universities & national labs in Canada, the US, Japan and Switzerland



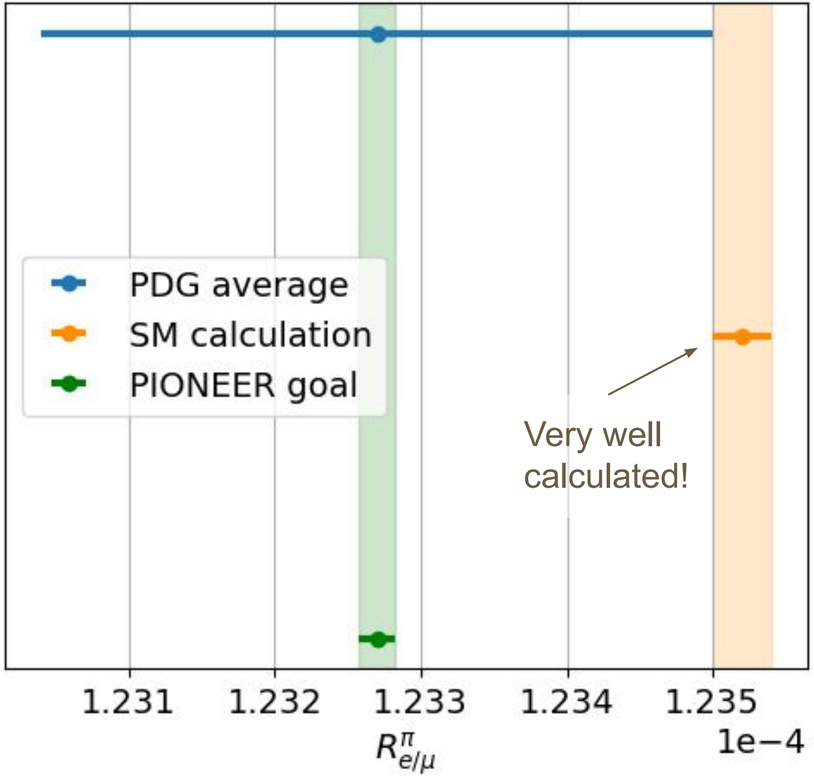
PIONEER phase 1 goal: lepton flavour universality

Measure the pion decay ratio:

$$R^{\pi}_{e/\mu} = \frac{\pi^+ \to e^+ \nu_e(\gamma)}{\pi^+ \to \mu^+ \nu_\mu(\gamma)}$$

Best test of the hypothesis that leptons have identical weak interaction strengths

- Known very precisely theoretically in the Standard Model (SM) [1]
- Current measurement (PIENU experiment at TRIUMF [2]) has 15x larger error bars than theory
- PIONEER goal is a 0.01% measurement



[1] Cirigliano & Rosell, https://doi.org/10.1103/PhysRevLett.99.231801
[2] Aguilar-Arevalo, et al. https://doi.org/10.1103/PhysRevLett.115.071801

What we measure

$$R^{\pi}_{e/\mu} = \frac{\pi^+ \to e^+ \nu_e(\gamma)}{\pi^+ \to \mu^+ \nu_\mu(\gamma)}$$

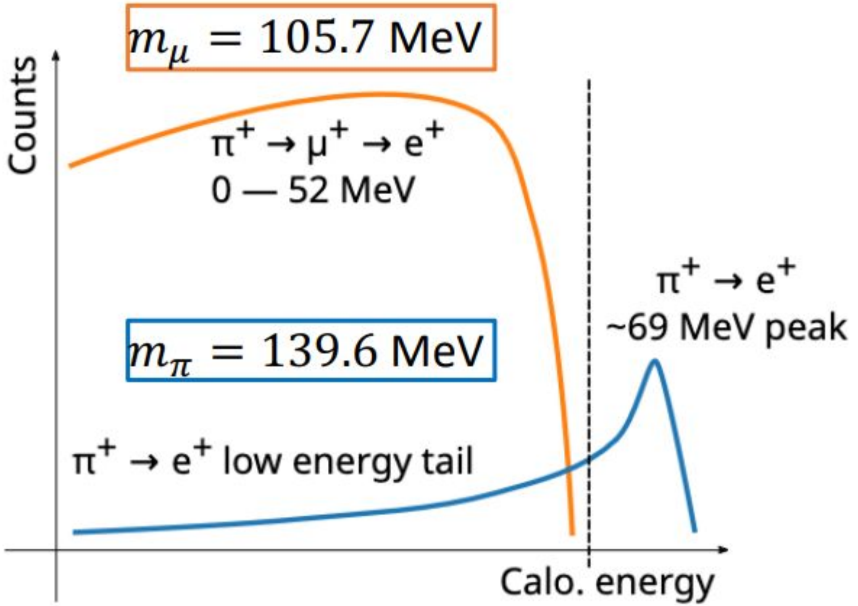
We measure the positron energy & time spectra to discriminate between the decays. Here looking just at energy.

Pion to positron: π → e

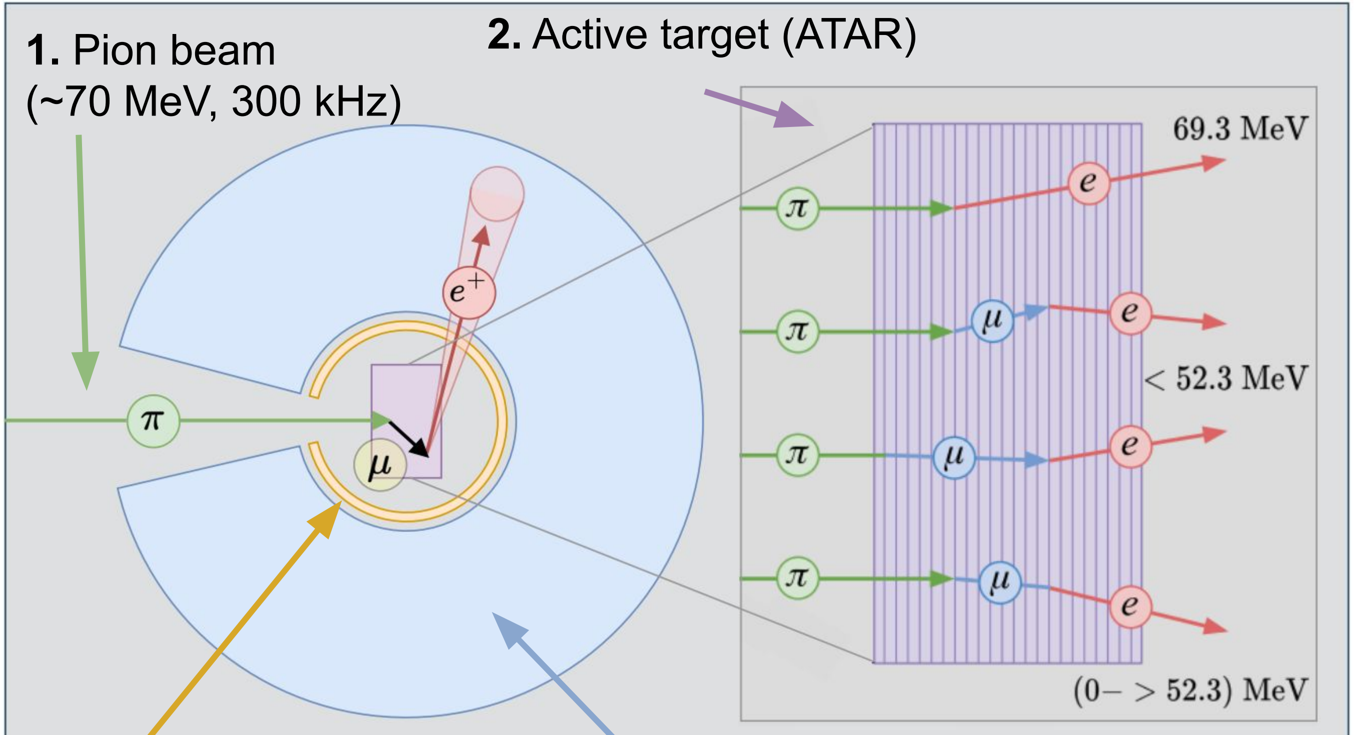
- Two body decay
- Positron energy ~ 69 MeV
- Timing based on τ_π ~ 26 ns

Pion to muon: π → μ → e

- Three body decay
- Positron energy in [0, 52] MeV
- Timing based on τ_μ ~ 2200 ns



Overview of the experimental setup

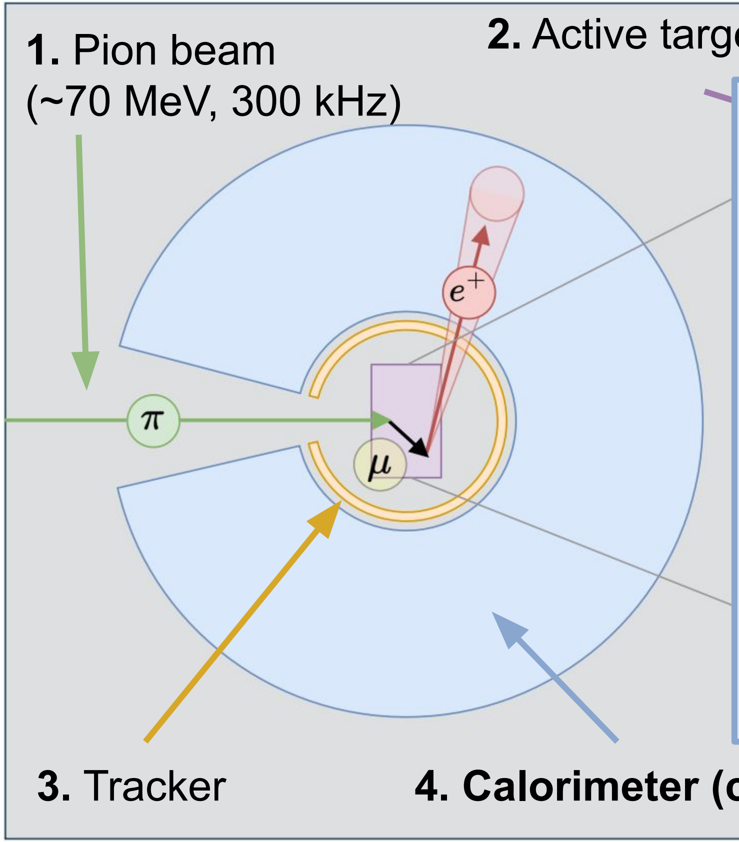


ATAR figure from Stefan Hochrein

π → e

π → μ → e

Overview of the experimental setup



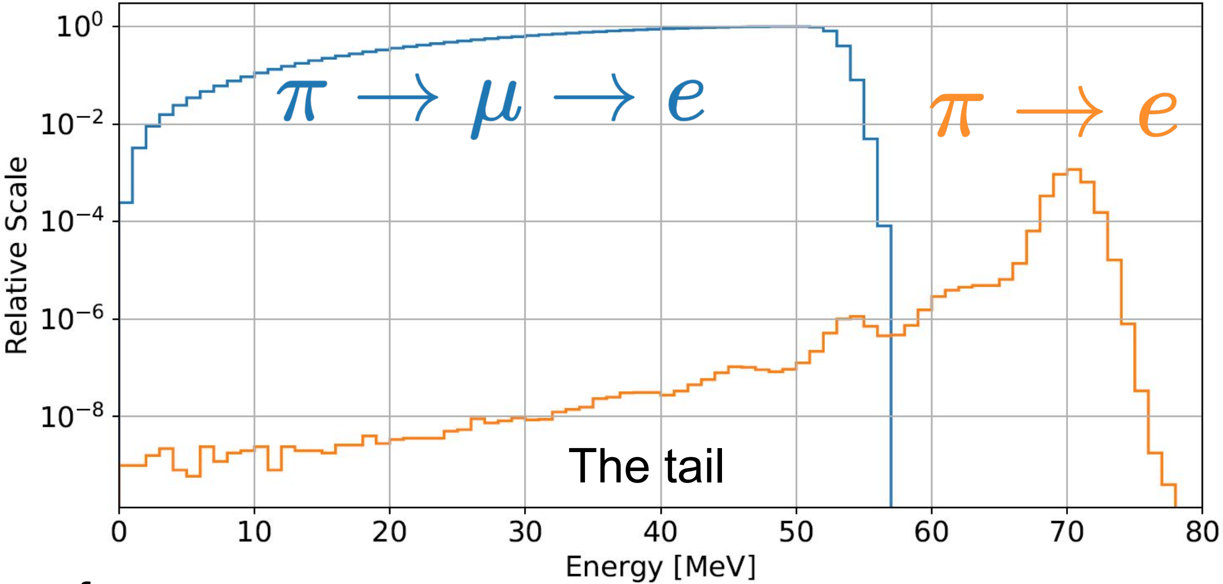
The calorimeter

To be made of liquid xenon (LXe) or LYSO crystals – both are fast, with large light yield.

My focus is the **LXe** option:

- Energy deposits create EM showers
- We detect vacuum ultraviolet (VUV) scintillation light
- Excellent energy resolution and very uniform light response

What makes this so difficult: the low energy tail is buried under the Michel spectrum



This tail comes from:

- Finite energy and time resolution of the detector
- Electromagnetic shower leakages through the front & sides
- Photo-nuclear interactions
- Radiative decays …

Minimizing the tail fraction ⇒ the job of a good calorimeter

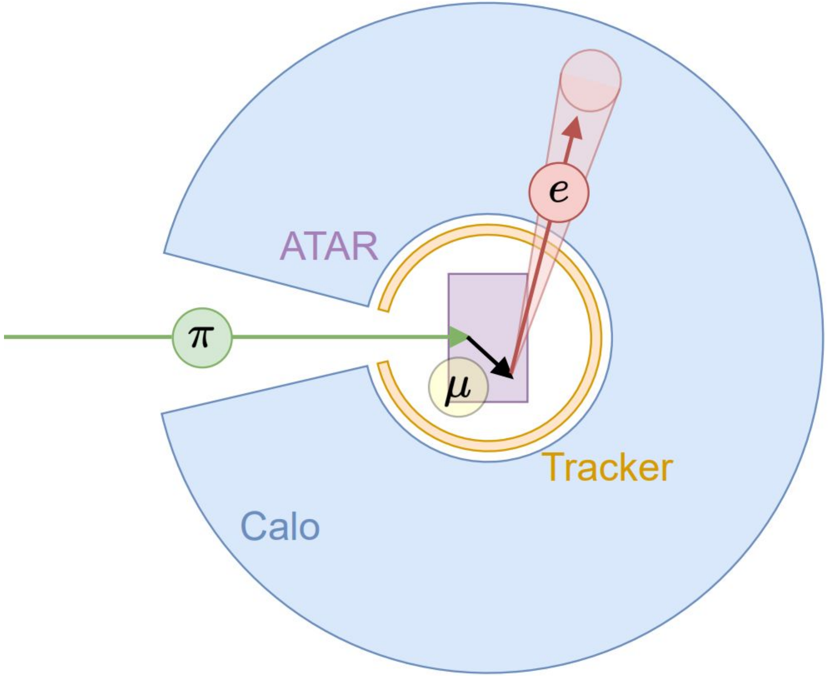
The calorimeter

Designed to precisely determine the energy deposited by incoming particles.

- Discrimination criterion between $\pi \rightarrow e$ and $\pi \rightarrow \mu \rightarrow e$ events

What we need from the calorimeter is:

I. High angular coverage and uniformity
II. Fast, sub-ns timing: ~40 ns decay
III. Resolution: 1.5 - 2% peak resolution
IV. Pile-up separation ability



General PIONEER experiment diagram

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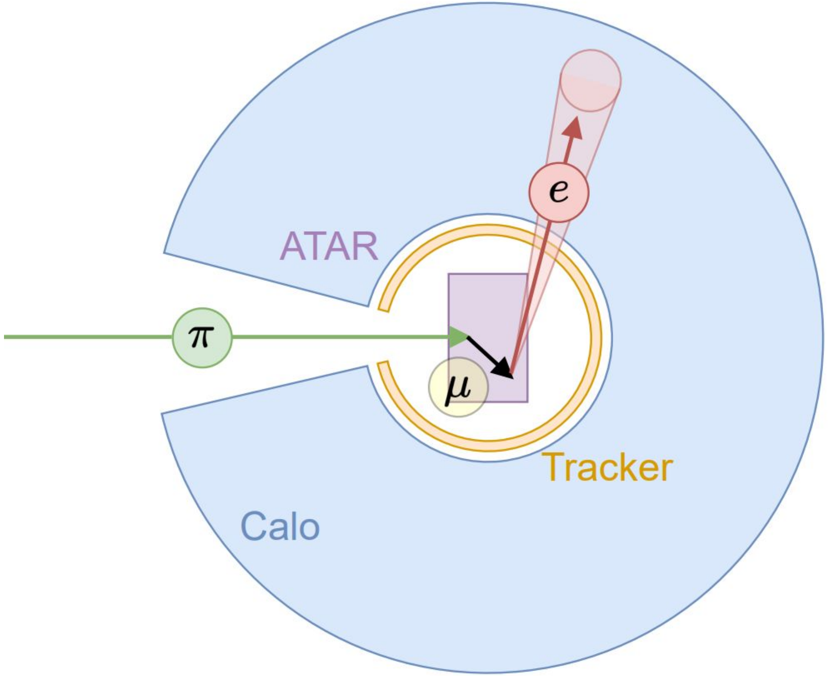


General PIONEER experiment diagram

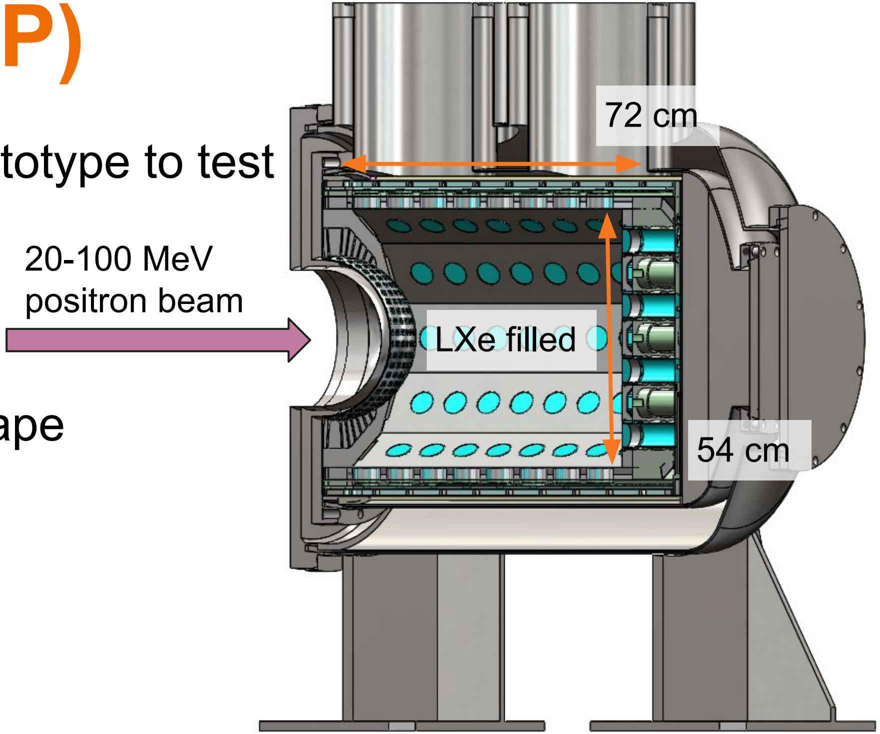
A technology choice for the calorimeter will be made between LXe or LYSO crystals

The Large Prototype (LP)

We are building a large LXe calorimeter prototype to test the LXe calorimeter option.

Goals:

- Measure energy resolution and line shape
  - Compare to simulations
- Study shower leakages
- Study pileup suppression
- Practical training on building and running a LXe cryogenics system



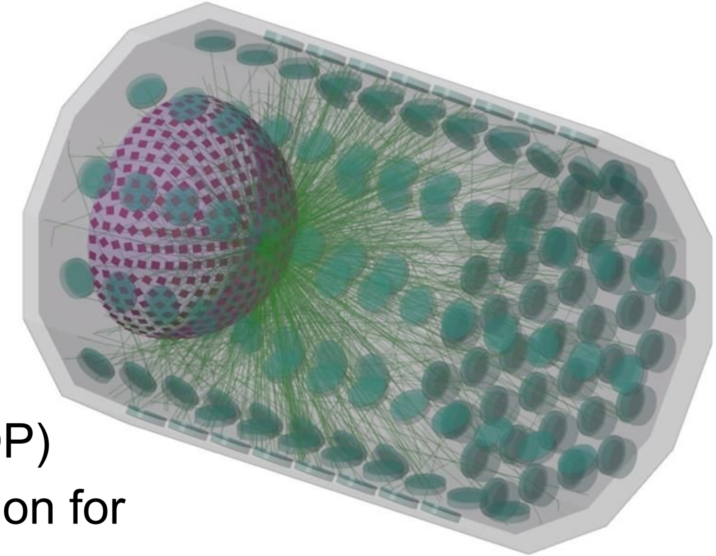
Current large prototype design using ~650 kg of LXe. Nominal design has 133 photomultiplier tubes (PMTs) and 400 silicon photomultipliers (SiPM) quads.

My simulation development for the LP

We have a PIONEER simulation framework:

- Written using Geant4, ROOT
- A Monte Carlo (MC) simulation of our experiment, along with detector response, event mixing and reconstruction algorithms

Visualization of photon paths in the LP simulation.



I've been working on developing the optical photon (OP) processing in our simulation as I build the MC simulation for the Large Prototype.

- Results are used for design choices
- The simulation will also be validated with prototype data

Simulation analysis

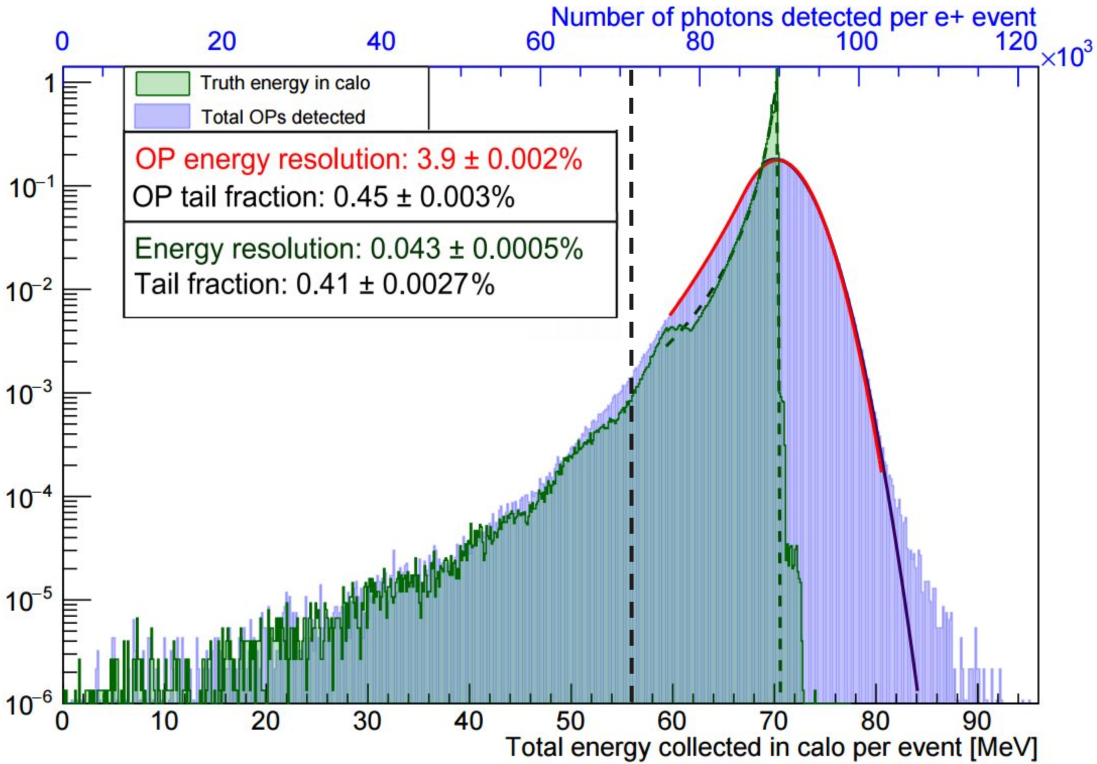
Green: Truth energy deposits in calo
→ MC only

Blue: Optical photons detected scaled to match energy peak
→ Still oversimplified compared to real data

Red: Crystal Ball function fit to peak region, resulting in σ & μ values

Energy resolution = σ/μ

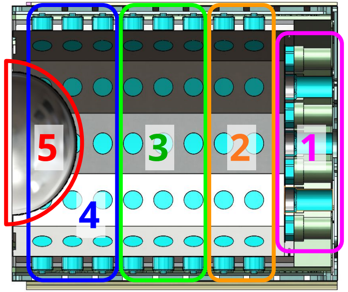
$$\text{Tail fraction} = \frac{\sum(\text{events with energy} < 56\ \text{MeV})}{\sum(\text{all events})}$$



LP simulation results for 5×10^{6} positron events

Weighting performance

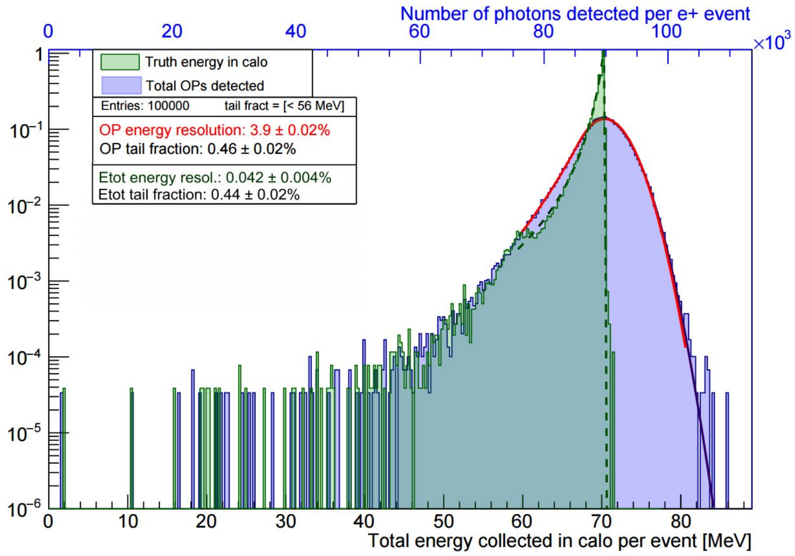
Beam is a forward 70 MeV positron with beam spot of ~1 cm^2, no divergence



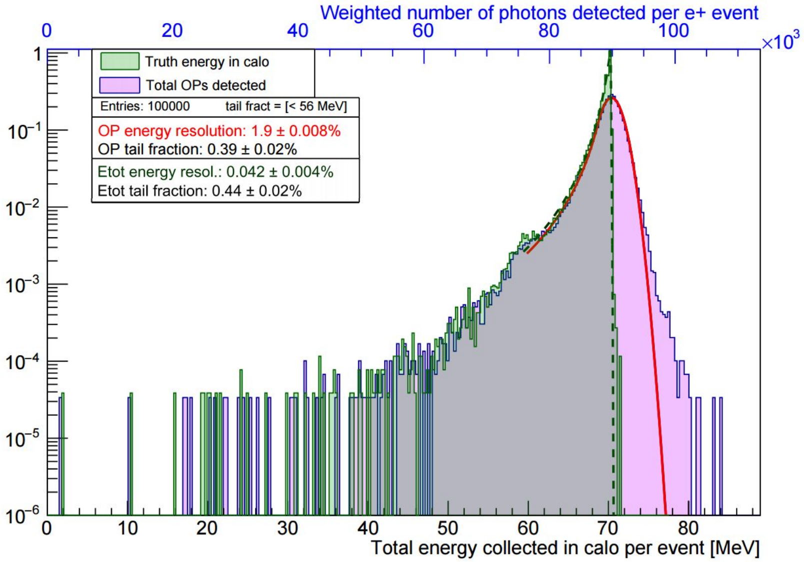
The weighting of photon hits is needed because of the different PMT/SiPM coverage on each surface.

After weighting: energy resolution goes from 3.9% to 1.9%

Before weighting



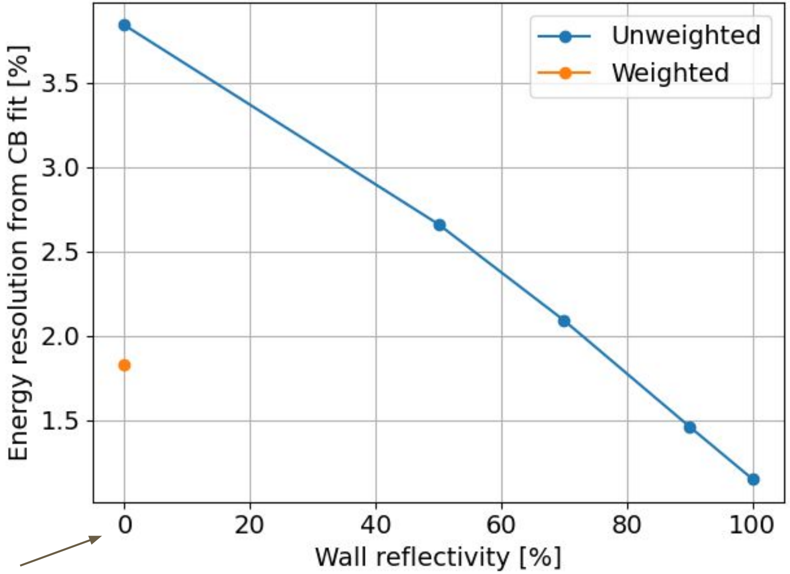
After simple 5 surface weighting



Design parameters studies

Internal reflectivity

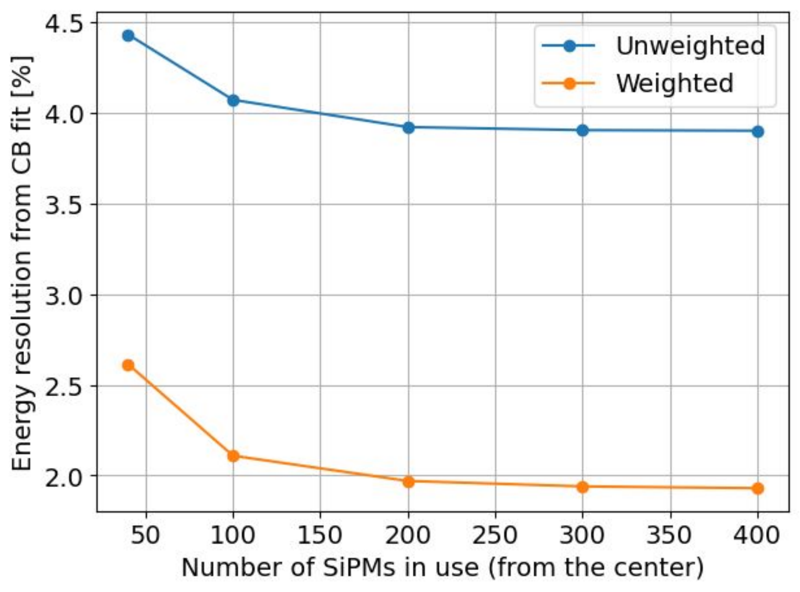
More reflective → more uniform light detection, but timing will be smeared out



100% absorbing

Number of window photosensors

More silicon photomultipliers → more complicated DAQ system needed

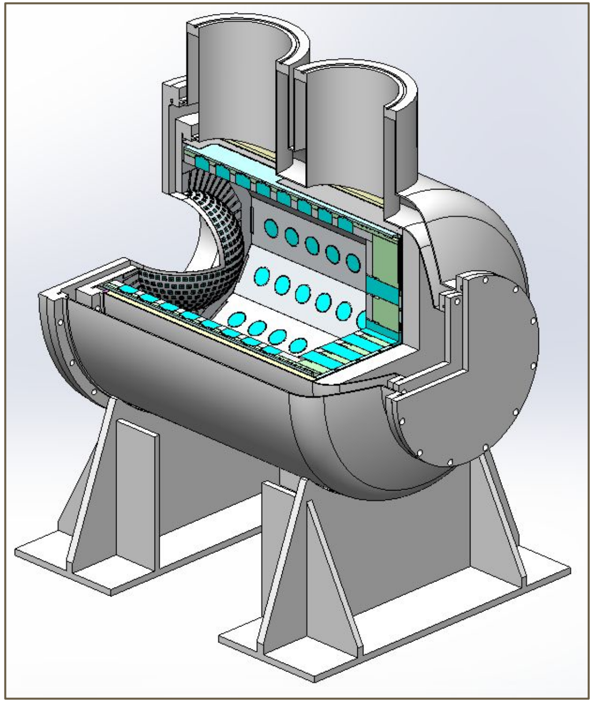


Conclusions

The PIONEER Experiment at PSI is under development.

The LXe Large Prototype is one part of this work:

- Simulations design choices and preliminary results are almost complete.
- More specific simulations planned include an angled beam and calibration studies.
- Lots of hardware development ongoing at TRIUMF, PSI, KEK, and at the University of Tokyo.
- We're expecting to test the LP during beamtime at PSI in 2026!



TRIUMF

PIONEER

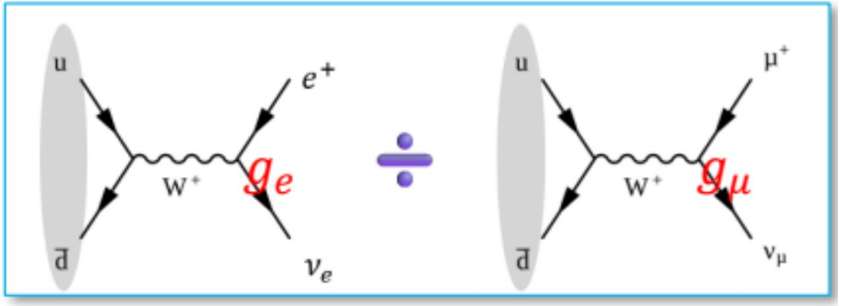
A next generation rare pion decay experiment

NSERC CRSNG

Backups

Why this ratio?

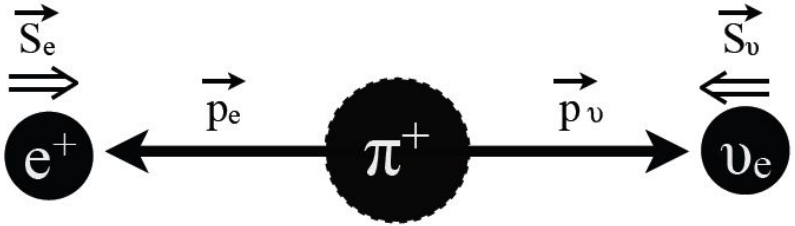
$$R^{\pi}_{e/\mu} = \frac{\Gamma\Big((\pi^+ \to e^+\nu_e) + (\pi^+ \to e^+\nu_e\gamma)\Big)}{\Gamma\Big((\pi^+ \to \mu^+\nu_\mu) + (\pi^+ \to \mu^+\nu_\mu\gamma)\Big)}$$



Strong helicity-suppressed in π → eν :

$$R^{\pi}_{e/\mu} \sim \frac{m_e^2}{m_\mu^2}\left(\frac{m_\pi^2 - m_e^2}{m_\pi^2 - m_\mu^2}\right)^2 \sim 10^{-4}$$

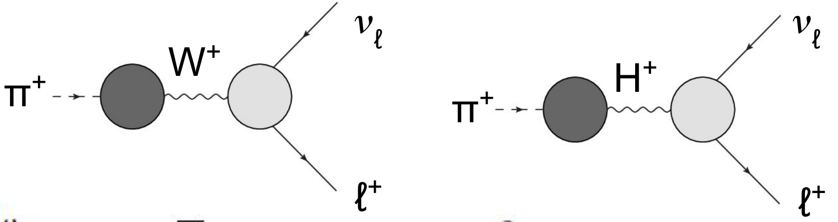
~ 10^{-5} × ~ 5.5



Beyond the Standard model (BSM)

Our goal precision will make us sensitive to high mass scale BSM physics

ex. new pseudoscalars couplings: charged Higgs



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

$(P = \pi^{+/-})$

Our 0.01% measurement → energy scale (Λ_{eP}) ~ 3000 TeV

And many others:

- New scalar couplings
- Leptoquarks
- Induced scalar currents…

Campbell, https://doi.org/10.1016/j.nuclphysb.2004.12.015

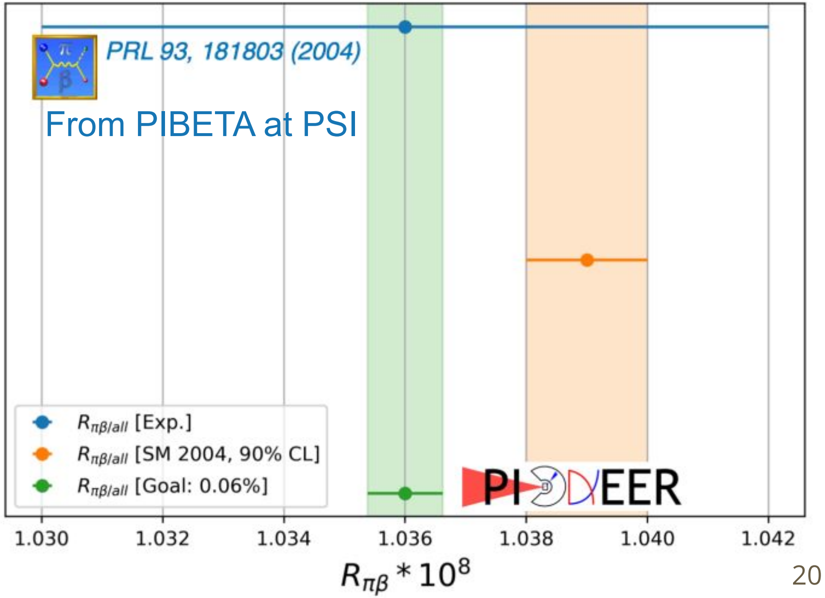
Later phases of PIONEER

Other physics

- New couplings and physics at very high mass
- Exotics decays: sterile massive neutrino search

Phase 2 & 3 - CKM unitarity

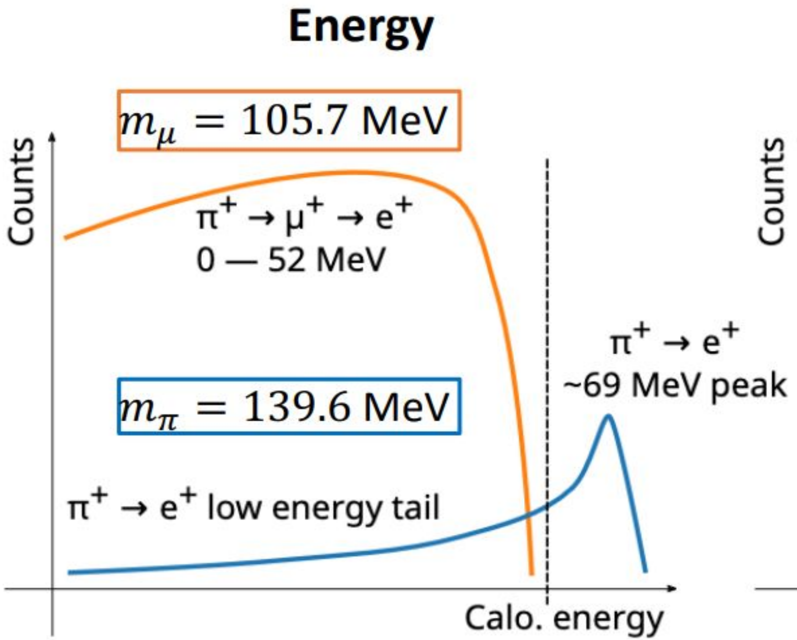
- Using Pion Beta decays, to improve the precision of: $B(\pi^+ \to \pi^0 e^+ \nu)$
- To measure the quark mixing parameters: $|V_{us}|/|V_{ud}|$ and $|V_{ud}|$

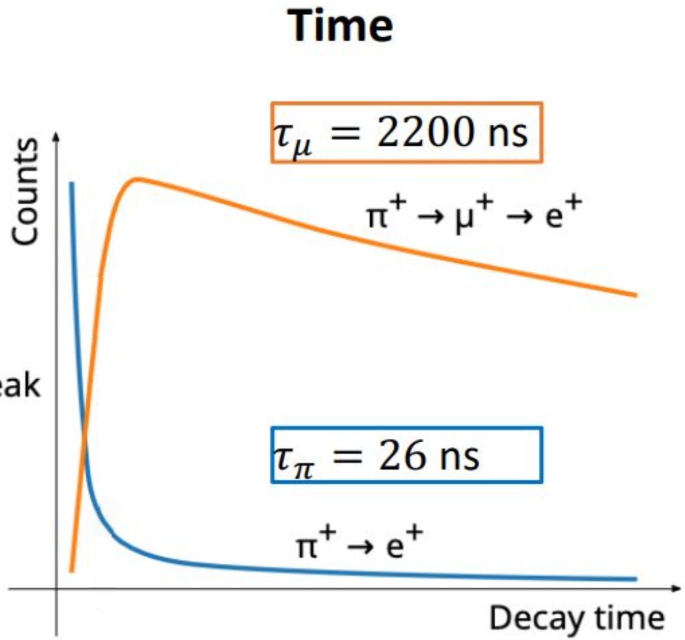


Energy & time

$$R_{e/\mu} = \frac{N_{\pi-e}(E > E_{th})}{N_{\pi-\mu-e}} \times (1 + c_{tail}) \times R^{\epsilon}$$

We measure the positron energy & time spectra to discriminate between the decays. After fits are performed, there are also corrections (c_{tail}, R^{ϵ})

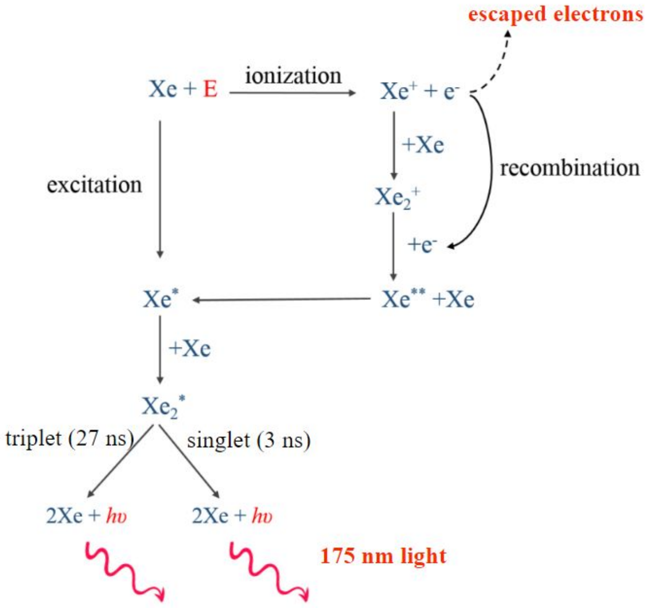




Liquid xenon for calorimetry

Liquid xenon (LXe) - a nobel liquid with good characteristics for use in a calorimeter

- High atomic number & density → high stopping power for radiation
- Very good uniformity & fast response
- Produces both charge carriers & scintillation light → we will use only the light signal



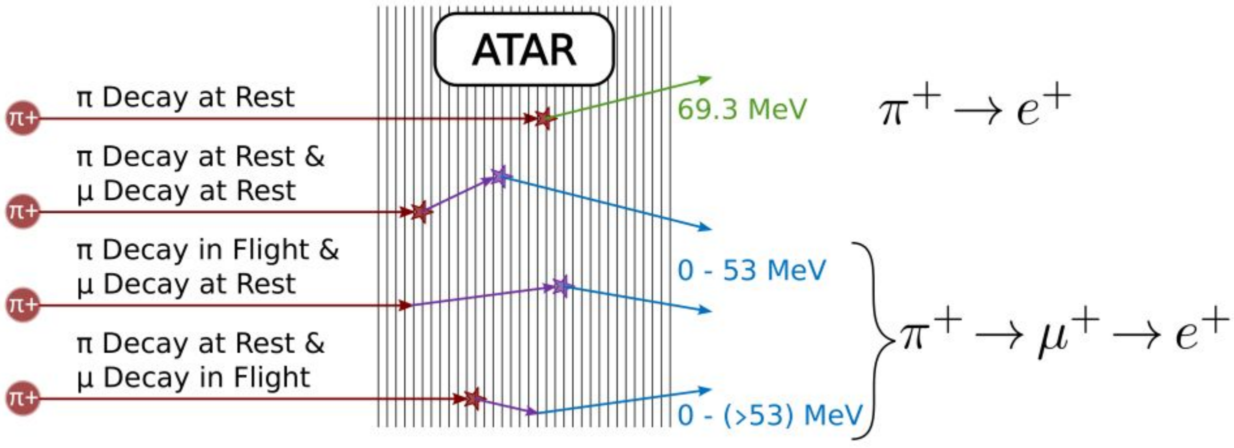
Optical properties of the light signal:

Scintillation yield: ~ 50 000 photons / MeV of deposited energy from a beta particle
→ lots of light produced!

Wavelength: ~ 175 nm → vacuum ultraviolet (VUV) light

LXe overview: Aprile et al.https://journals.aps.org/rmp/abstract/10.1103/RevModPhys.82.2053

ATAR details

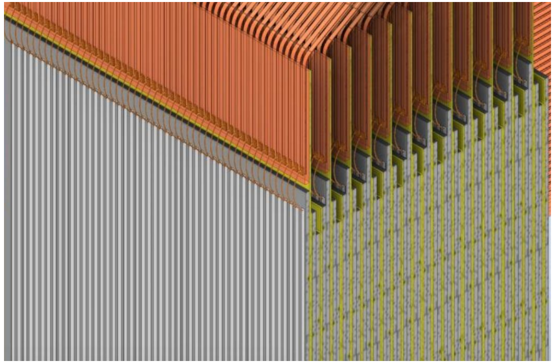


A 5D tracking system that will:

- Define the pion stopping region
- Provide high resolution timing information

Design requirements:

- Large dynamic range: minimum-ionizing particles (MIPs) to π/μ stopping
- Good time resolution: < 100 ps
- Sufficient granularity: < 200 μm
- Minimal dead material



Design baseline: 48 stacked planes of 120 μm thick AC-LGAD strips

New technology: LGADs (AC-coupled low gain avalanche diodes)

From Jennifer Ott

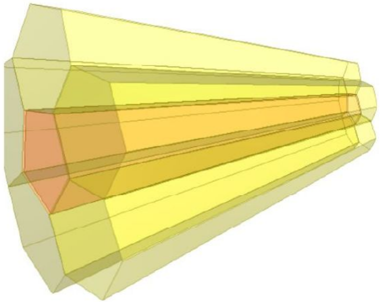
LYSO details

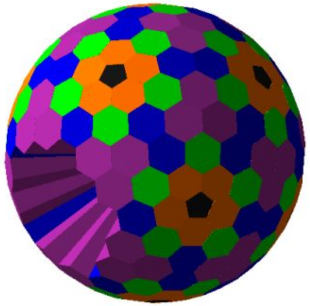
- Energy resolution is not very well known, 4.5% has been reported at 70 MeV
- Our colleagues primarily at the University of Washington are testing a small simpler crystal array at the moment, with currently promising results
- Getting an array of 300+ tapered crystals manufactured is currently possible, by a single company

Lutetium–yttrium oxyorthosilicate (LYSO):

- By weight: 72% Lutetium, 17% Oxygen, 6% Silicon, **3% Cerium (dopant)**, 2% Yttrium
- **X_0 = 1.14 cm** , R_M = 2.07 cm
- Decay time = **40 ns**
- Light yield **30,000 γ/MeV**
- λ_{peak} 420 nm -> conventional PMTs
- Radioactive (< 1 MeV constant rumble)
- Non hygroscopic
- No Temp dependence
- n = 1.82
- Not so cheap … ☹

From David Hertzog





Lightmap output from simulation