UNIVERSITY *of* WASHINGTON

PIONEER a next generation Rare Pion Decay Experiment

Quentin Buat (University of Washington)

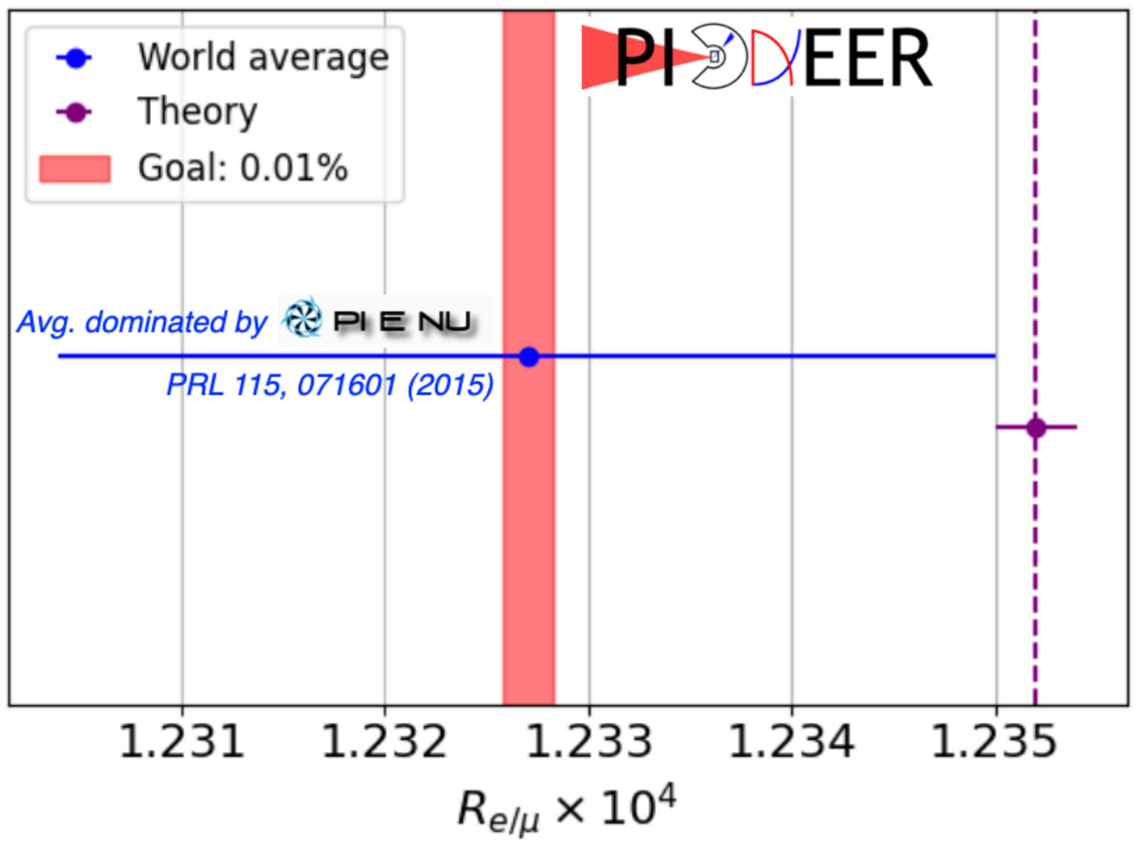
INTENSITY frontier GDR-InF

Annual GDR-InF Workshop Nov 6-8, 2024 — GANIL, Caen, France

PIONEER Physics Case

Lepton Flavor Universality

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



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

Goal of PIONEER
15-fold improvement over the current world best

BSM constraints:
- EFT analysis (JHEP. **2013**, 46 (2013))
  - ~330 TeV (pseudo scalar)
  - ~5.5 TeV (axial currents)

Phase I of the project

PIONEER Physics case

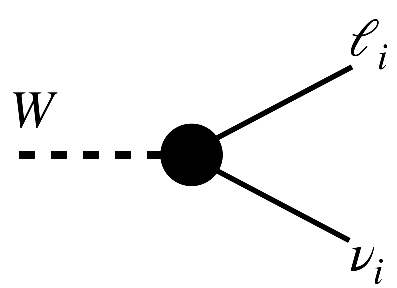
Comparing LFUV probes with EFT analysis

$$\mathcal{L} \supset -i\frac{g_2}{\sqrt{2}}\bar{\ell}_i\gamma^\mu P_L \nu_j W_\mu \left(\delta_{ij} + \varepsilon_{ij}\right)$$

Neglecting flavour-changing terms

LFUV observables depend at LO on $\epsilon_{ii} - \epsilon_{jj}$ with $(i \neq j)$

$$\frac{g_\mu}{g_e} = 1 + \epsilon_{\mu\mu} - \epsilon_{ee}$$



Modified $W\ell\nu$ couplings appear in many extensions of the SM

W', Vector-like leptons, charged Higgs, …
See review in arXiv:2111.05338

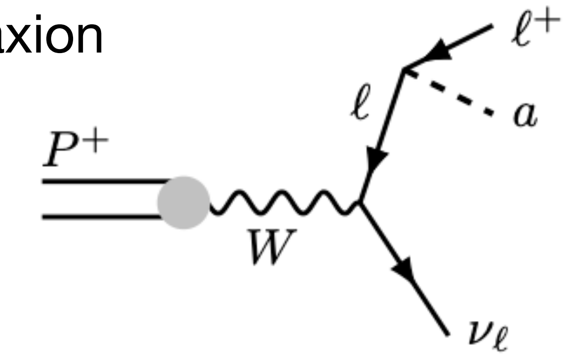
Probes of g_μ/g_e	Measurements
$B_{\tau\to\mu}/B_{\tau\to e}$	1.0017 ± 0.0016
$B_{\pi\to\mu}/B_{\pi\to e}$	**1.0010 ± 0.0009**
$B_{K\to\mu}/B_{K\to e}$	0.9978 ± 0.0018
$B_{K\to\pi\mu}/B_{K\to\pi e}$	1.0009 ± 0.0018
$B_{W\to\mu}/B_{W\to e}$	1.001 ± 0.003

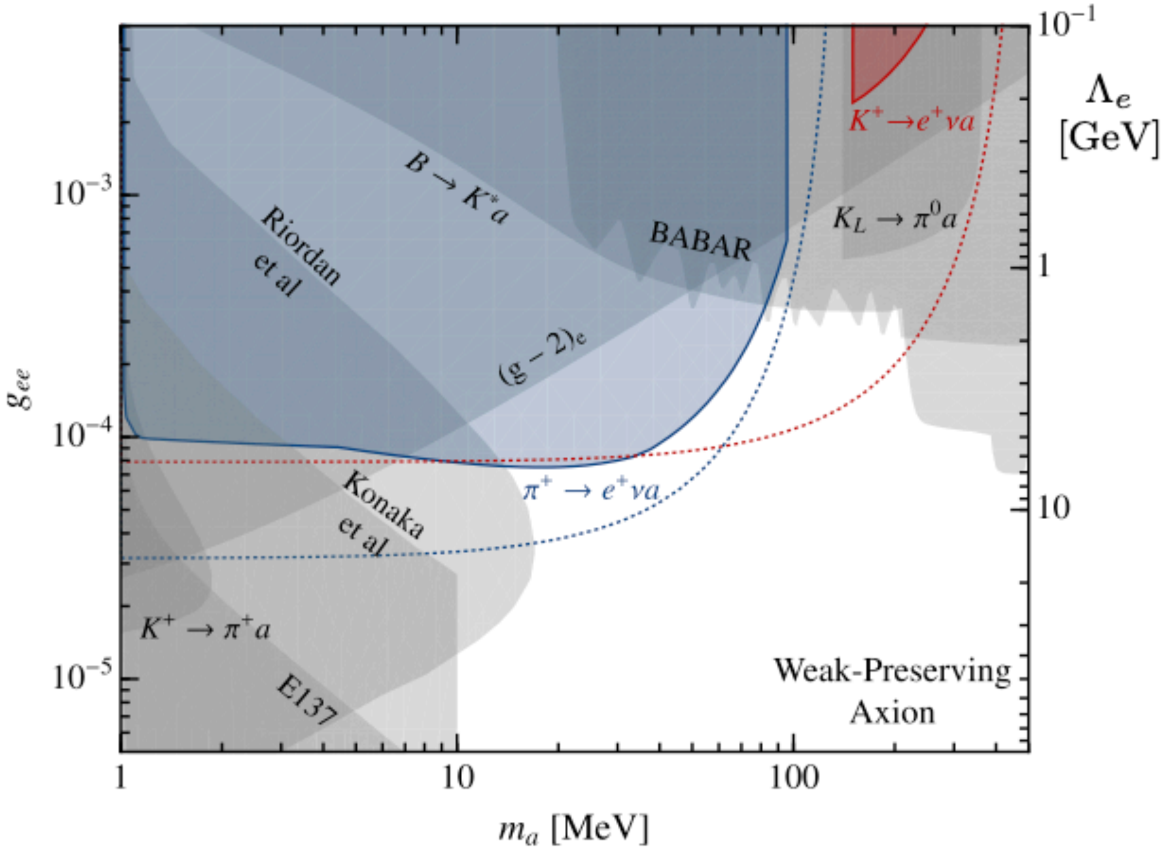
Charged pions are the most powerful probe of $\epsilon_{\mu\mu} - \epsilon_{ee}$

PIONEER Physics Case

Exotic decays of the charged pion

Lepto-philic axion





W. Altmannshofer, J. Dror, and S. Gori
Phys. Rev. Lett. **130**, 241801

Example signatures explored by TRIUMF PIENU

$\pi \to e\nu_H$	Physical Review D 97(7) 072012 (2018)
$\pi \to \mu\nu_H$	Physics Letters B 798 134980 (2019)
$\pi \to \ell\nu_\ell\nu\bar{\nu}$	Phys. Rev. D 102, 012001 (2020)
$\mu \to eX$	Phys. Rev. D 101, 052014 (2020)
$\pi \to e\nu X$	Phys. Rev. D 103, 052006 (2021)

Goal of PIONEER
Increase reach of the global search program for feeble interactions (ie ALPs, heavy neutrinos, …) in the 10—100 MeV range

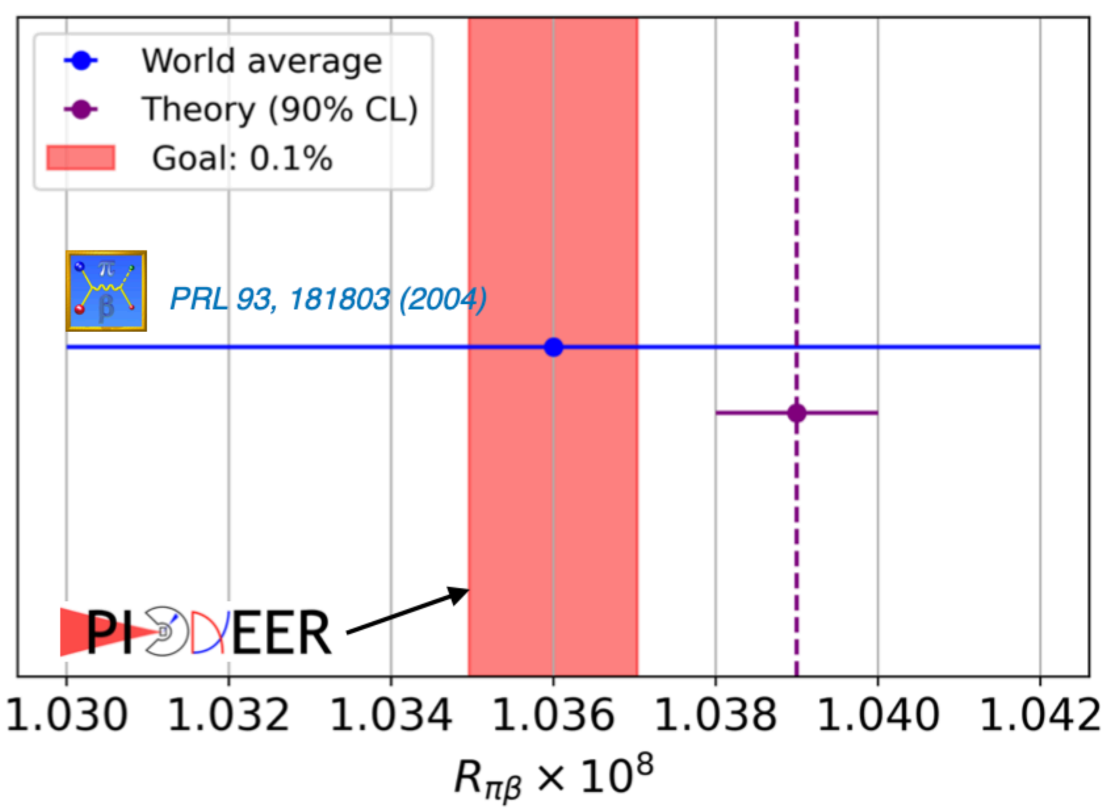
Searches profit from the very large datasets needed for $R_{e/\mu}$ measurement

Phase I of the project

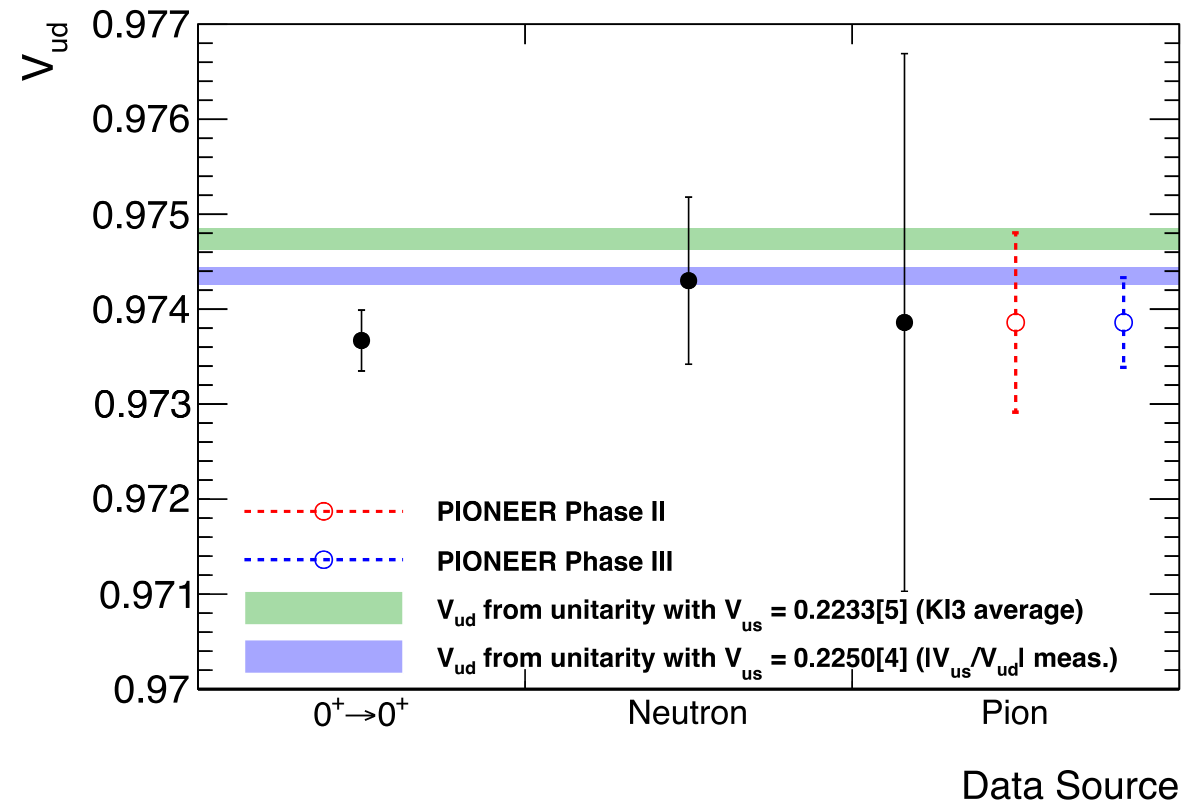
PIONEER Physics Case

piBeta measurement and V_{ud} extraction

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



Goal of PIONEER



See my talk at the Vud workshop on Tuesday!

Phase II-III of the project

PIONEER Physics Case

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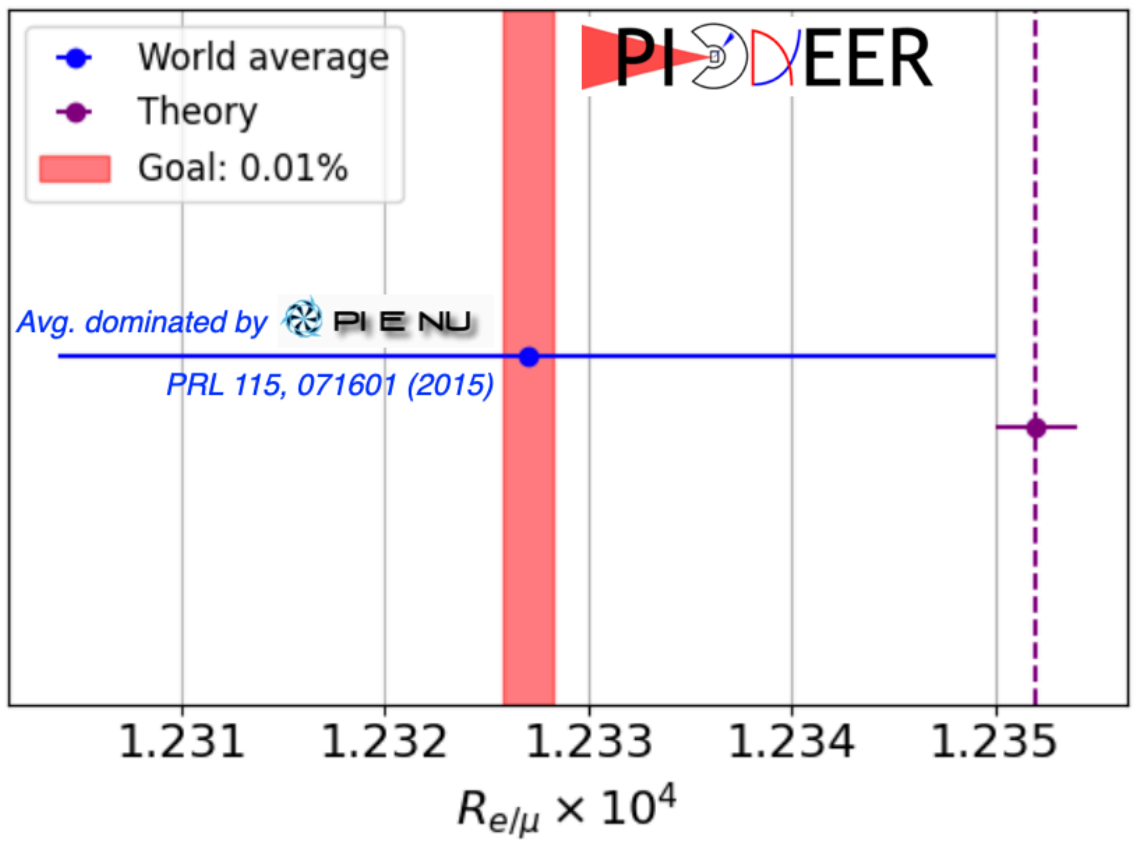


Focus of this talk:

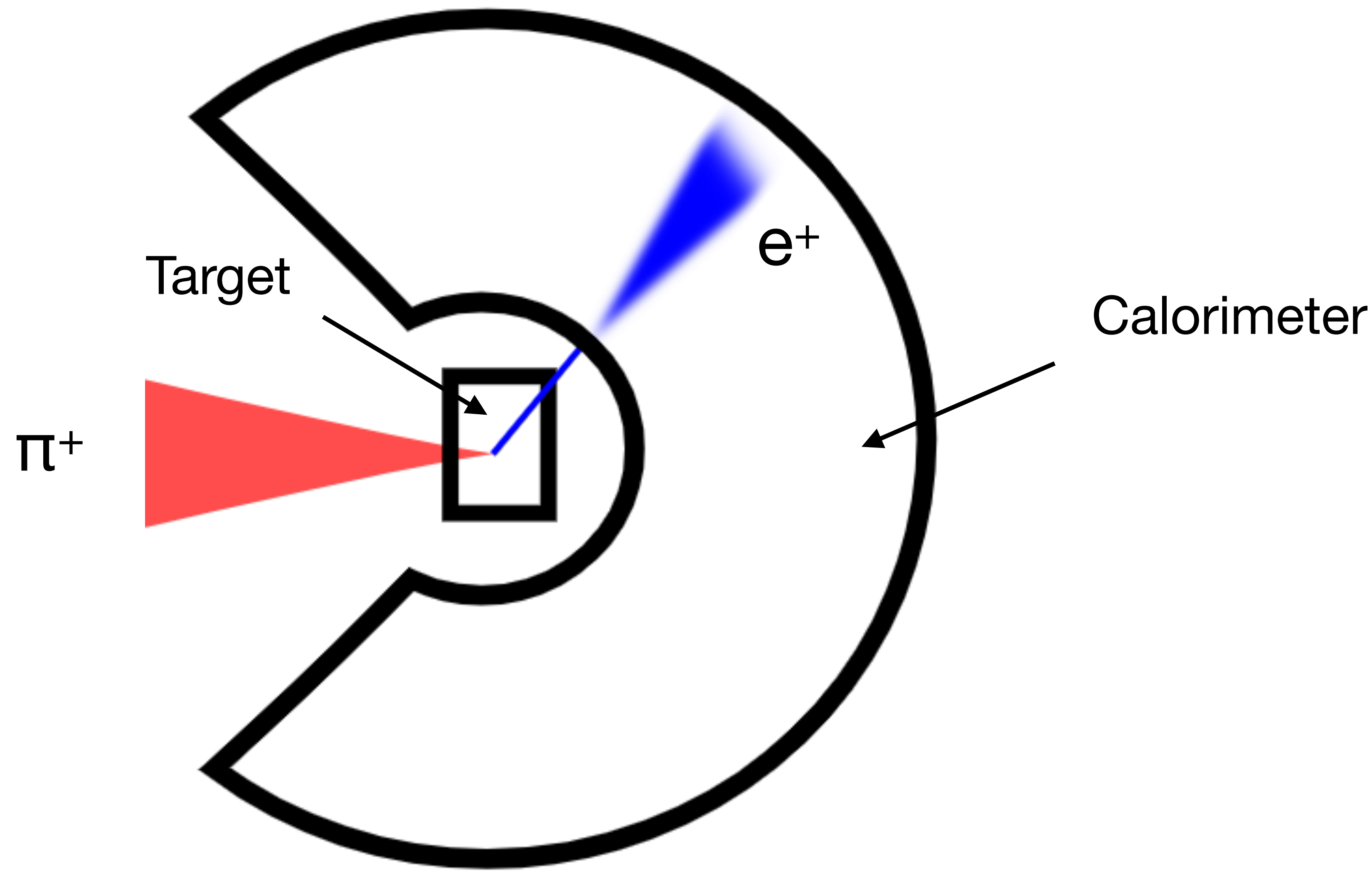
Recap of measurement strategy

Update on R&D and simulation efforts

(See my talk at GDR-InF 2023 for an historical perspective on this measurement)

Phase I of the project

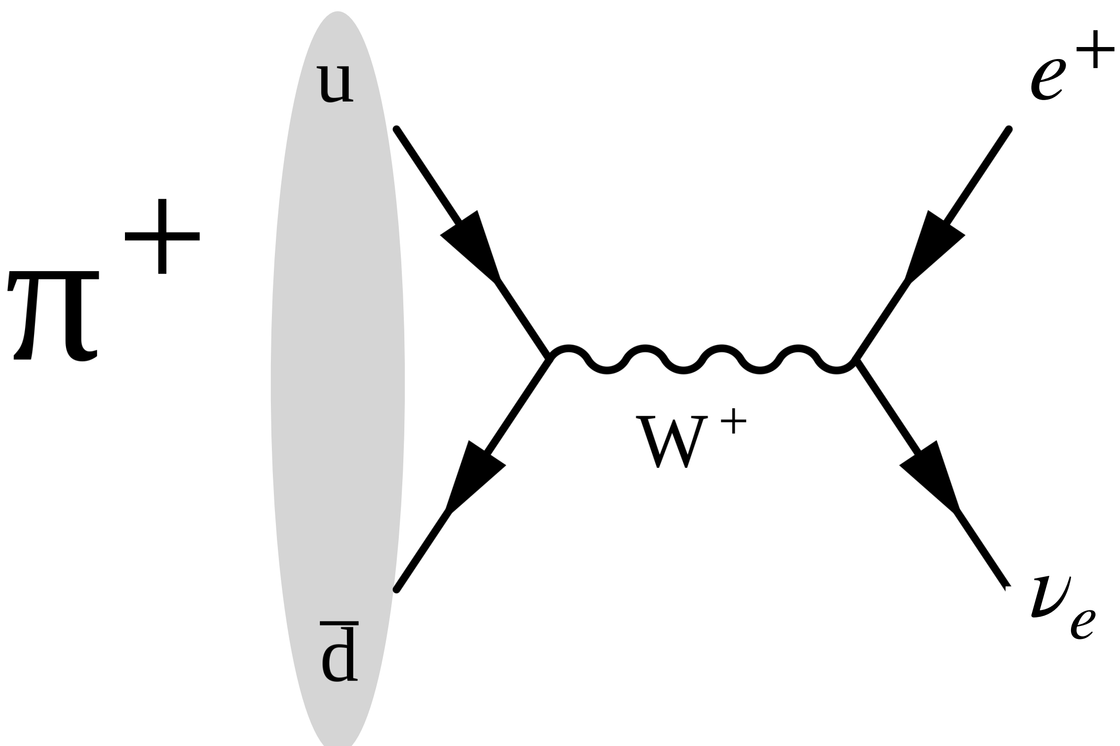
Introducing PIONEER

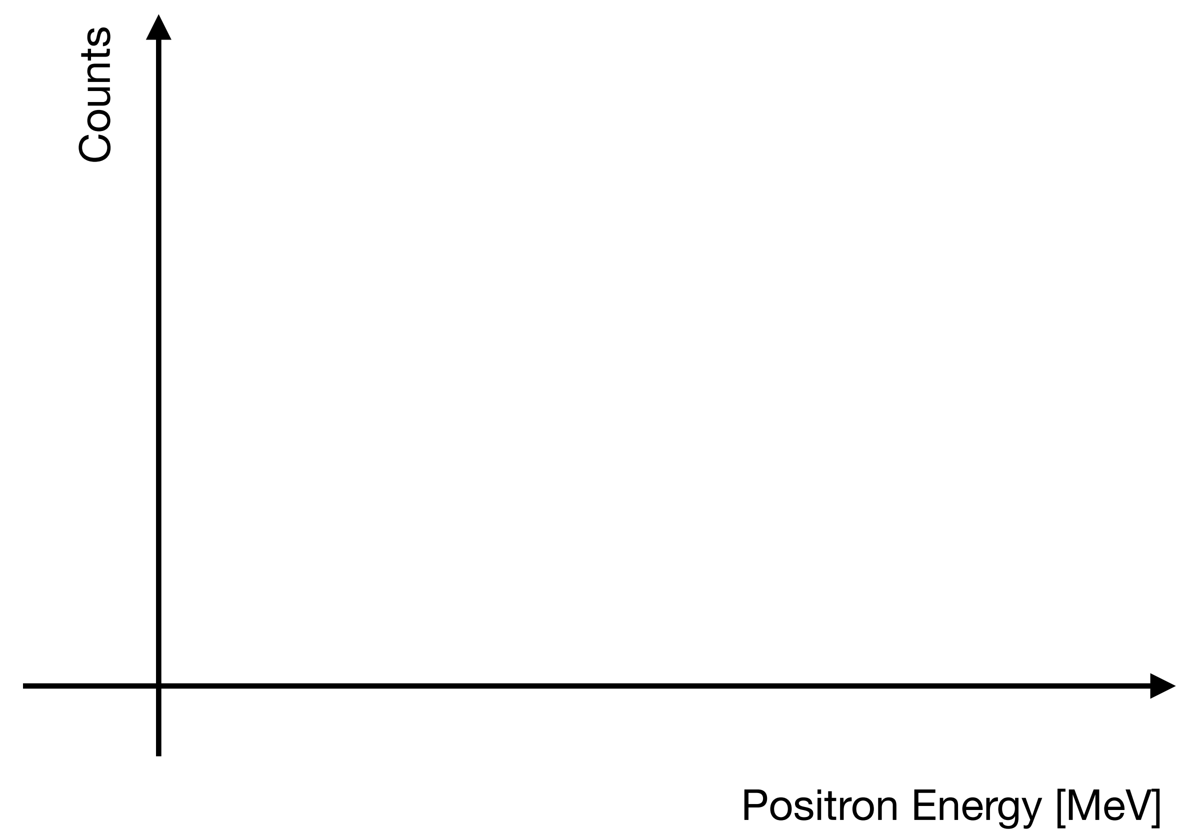


Introducing PIONEER

Phase I measurement strategy

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





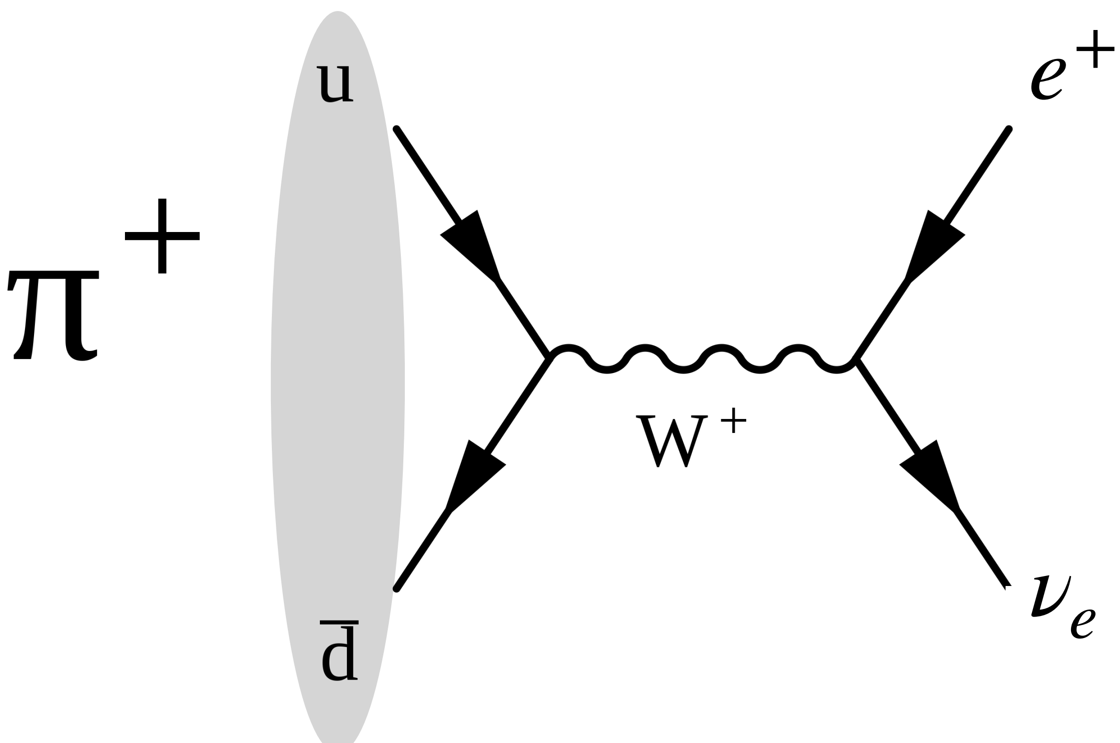
$m_{\pi^+} = 139.6\,\text{MeV}$

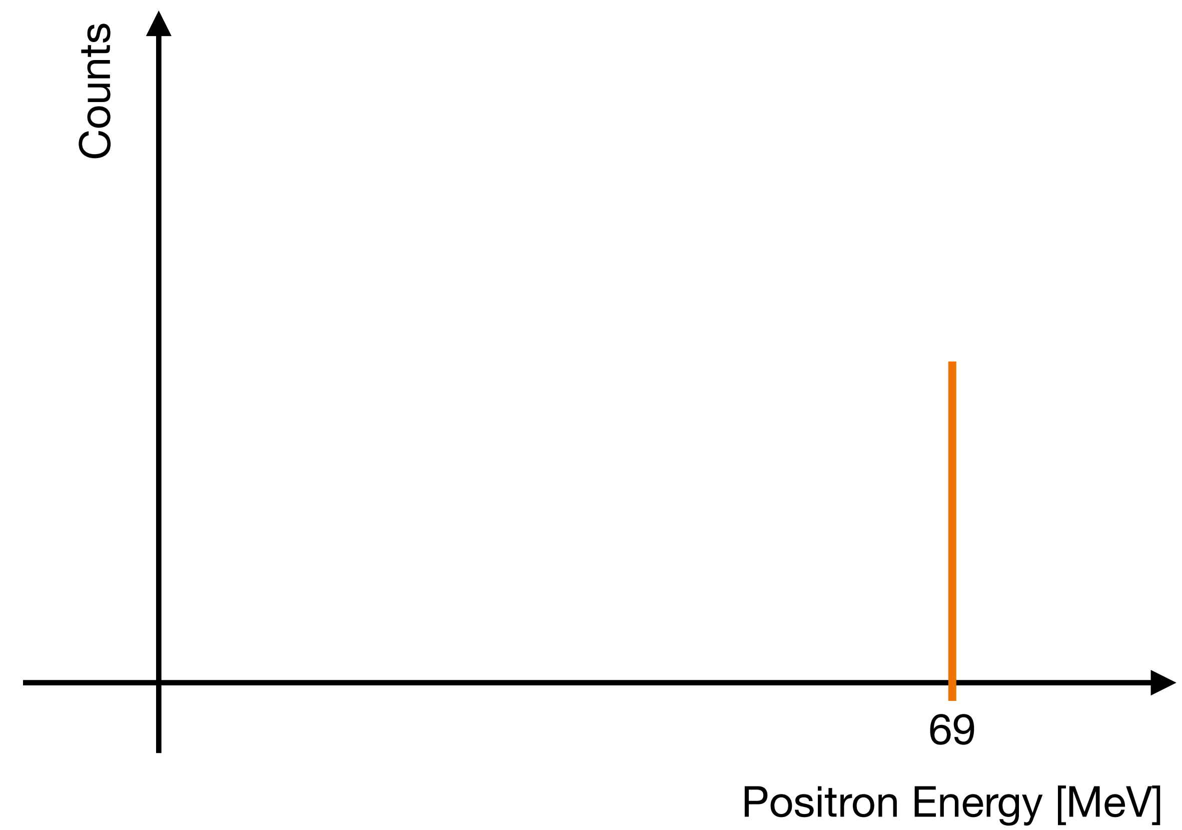
The pion stops in the target and decay

Introducing PIONEER

Phase I measurement strategy

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





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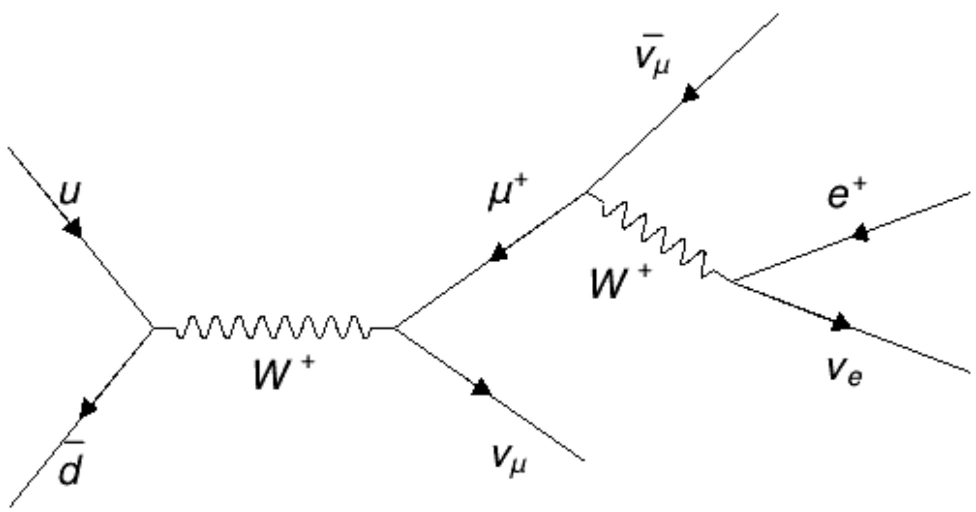
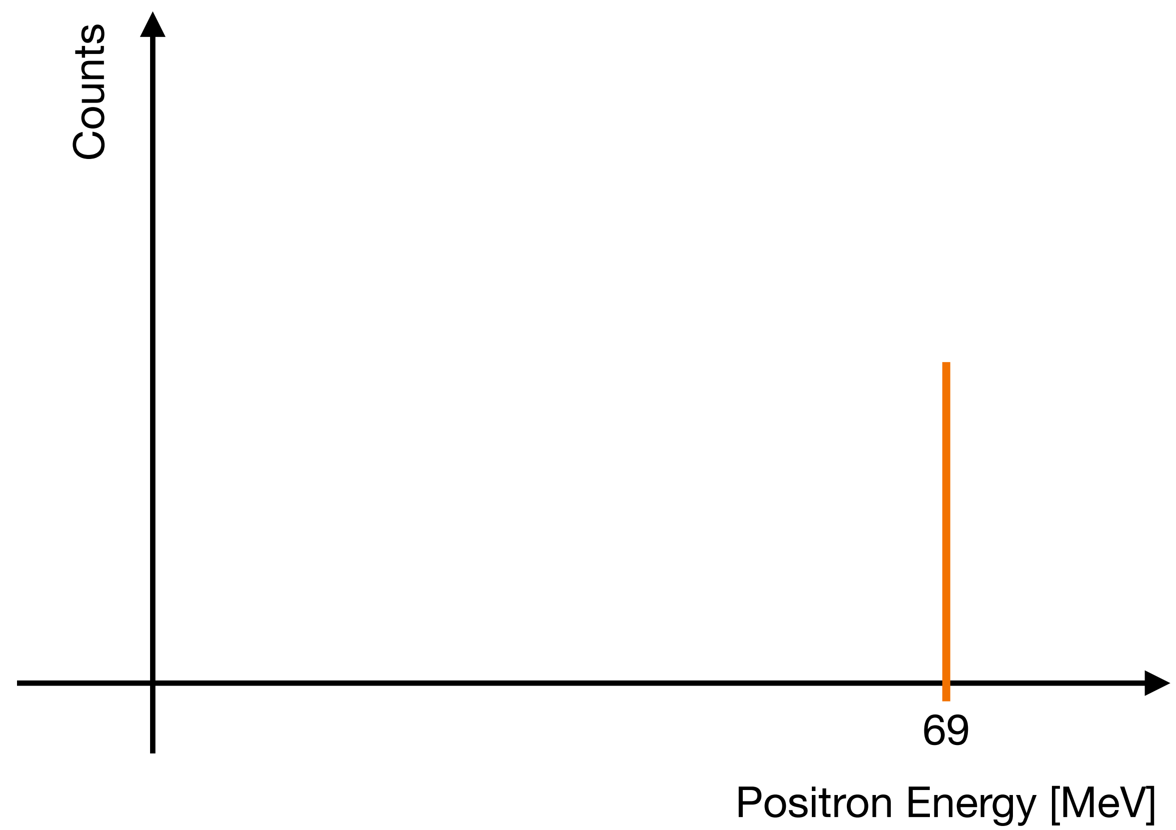




$m_{\pi^+} = 139.6$ MeV

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

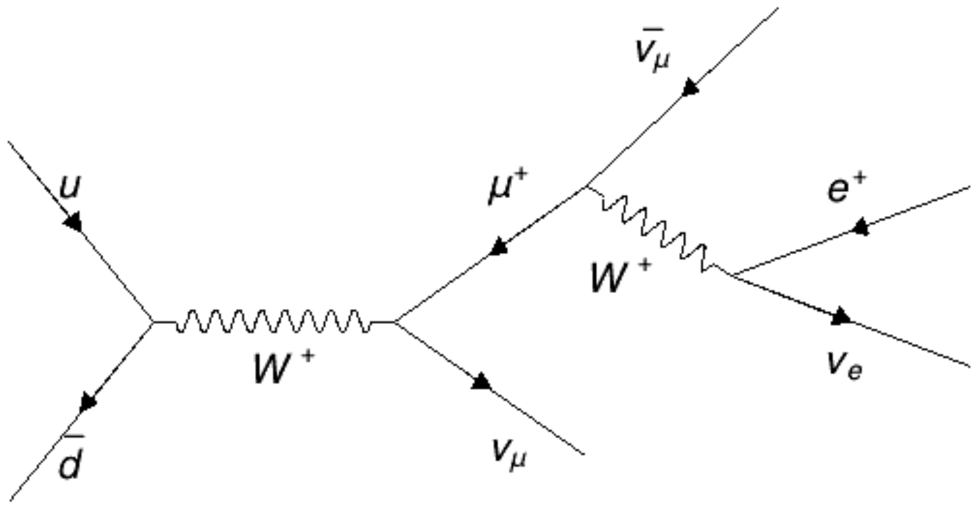
The pion stops in the target and decay

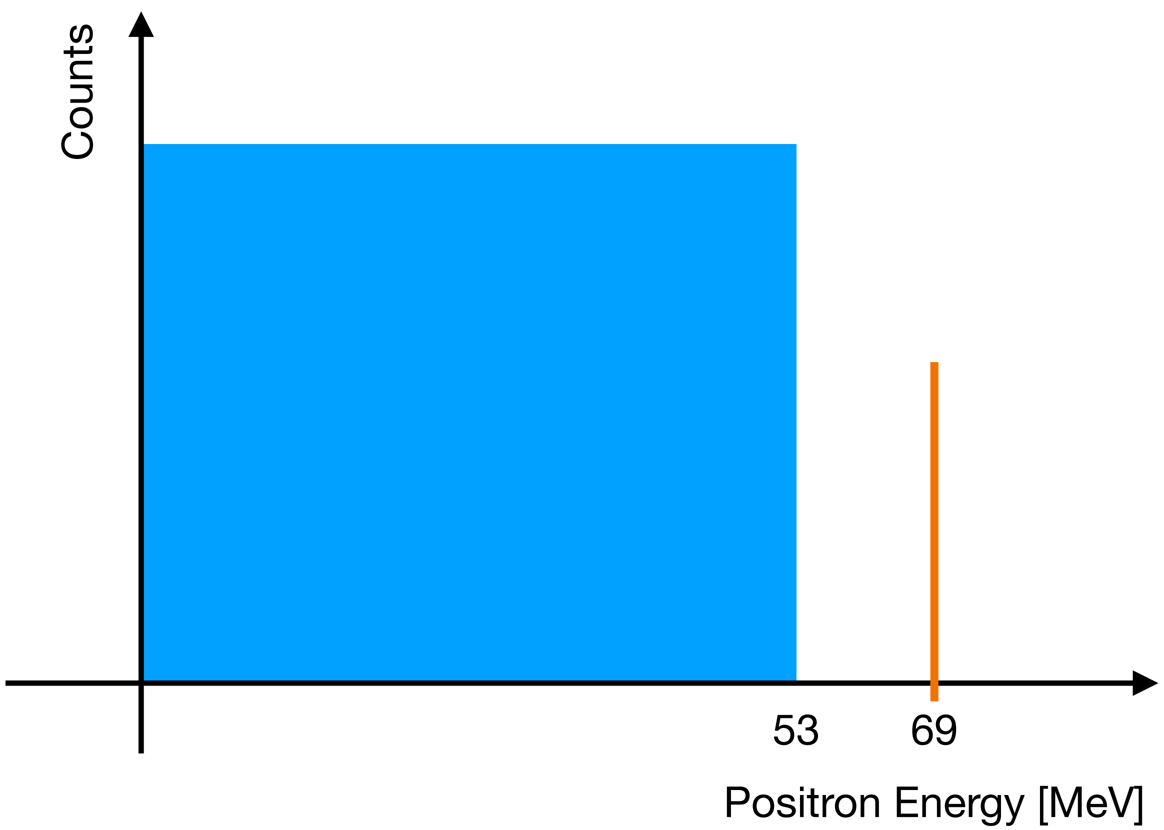
The muon acquires kinetic energy (4.1 MeV), travels in average 0.8mm, stops in the silicon target, and decay

Introducing PIONEER

Phase I measurement strategy

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





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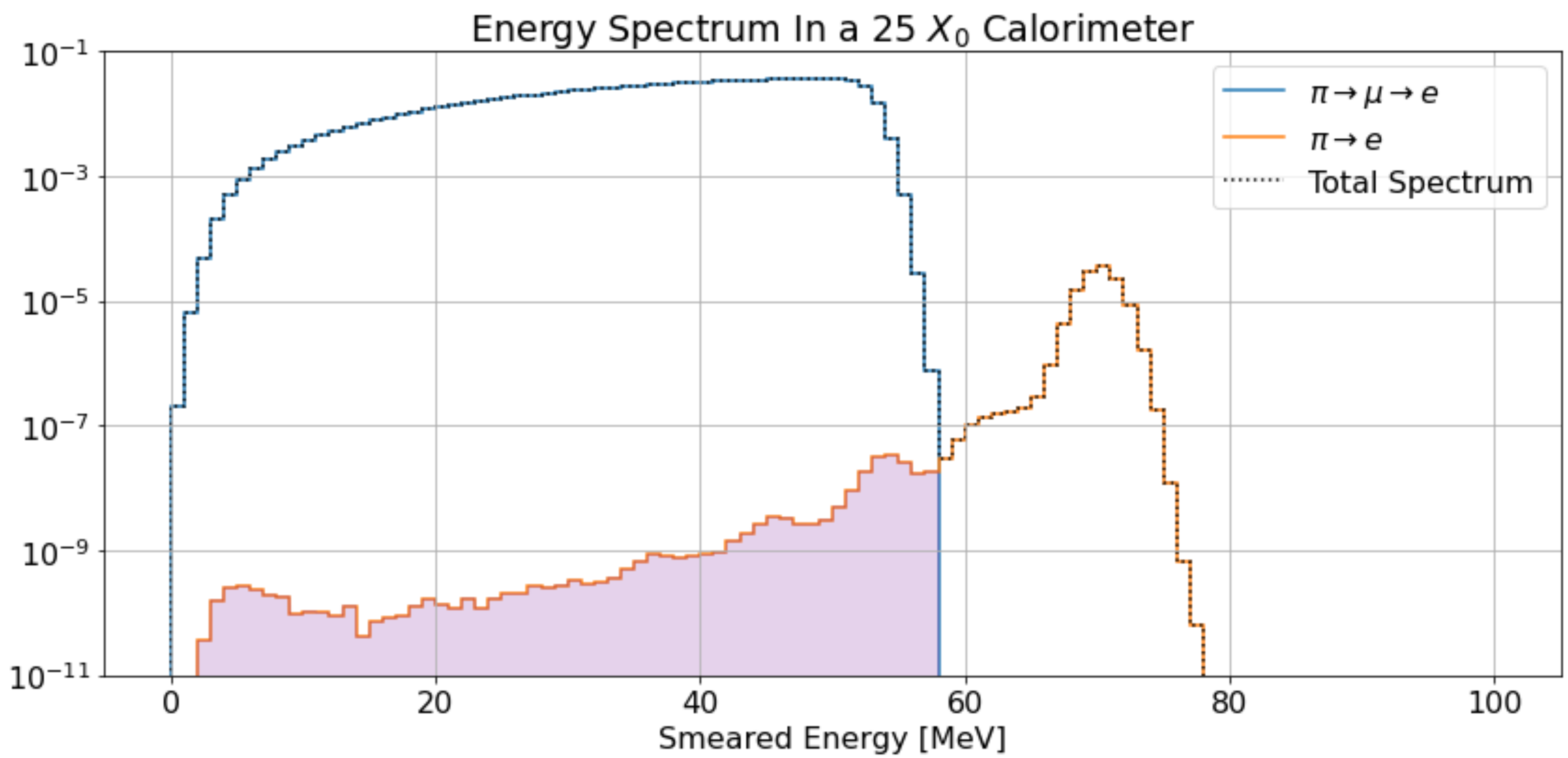
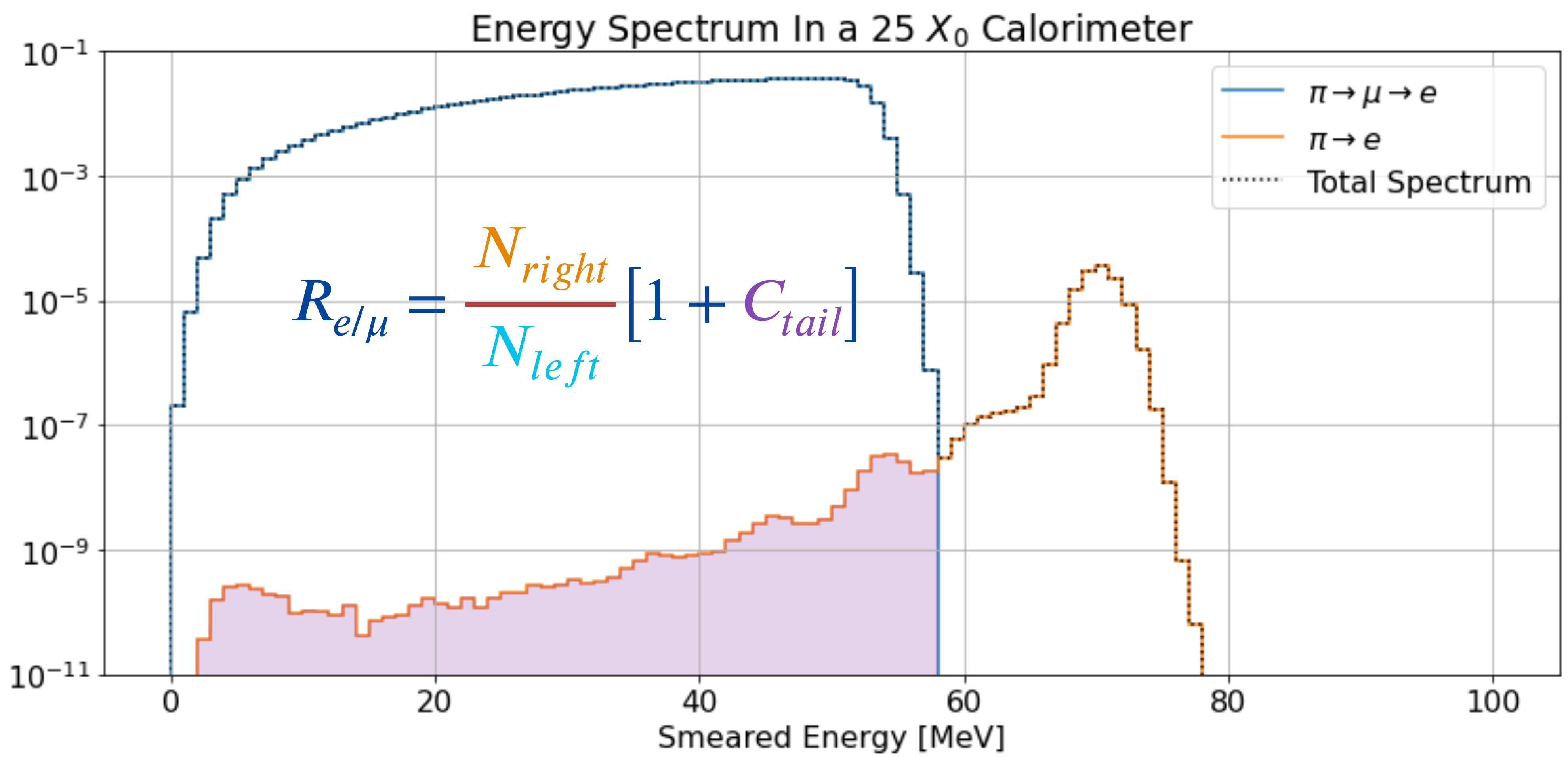
Facing experimental reality



Facing experimental reality



Guiding principles to the design of the experiment:

1. Collect very large datasets of rare pion decays (2e8 $\pi^+ \to e^+\nu_e$ during Phase I)
2. Tail must be less than 1% of total signal → Shower containment in the calorimeter
3. Tail must be measured with a precision of 1% → Event identification in the active target

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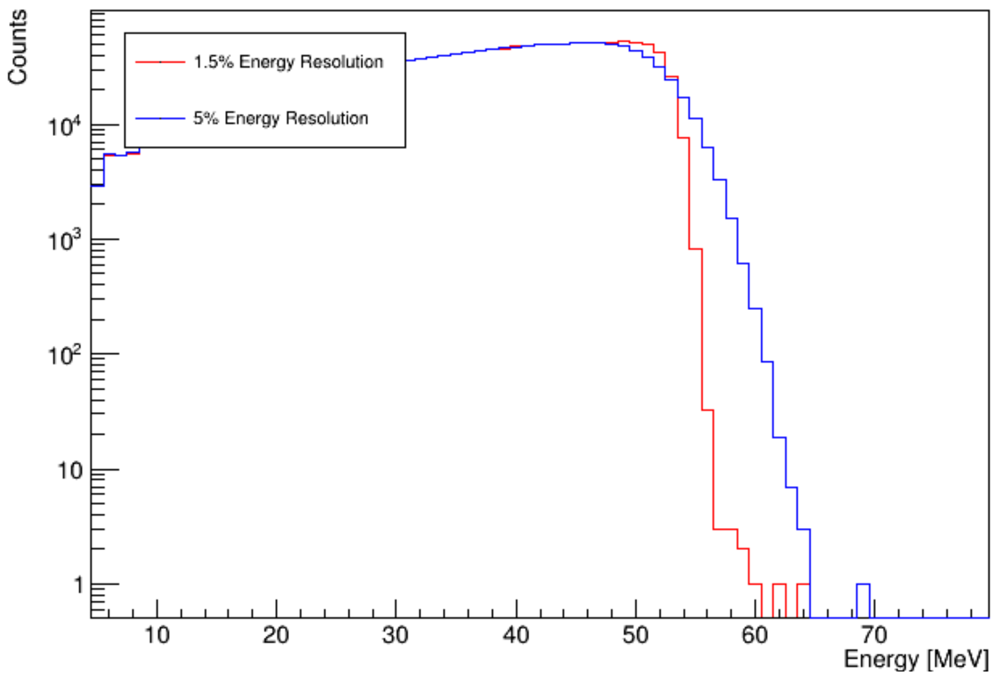
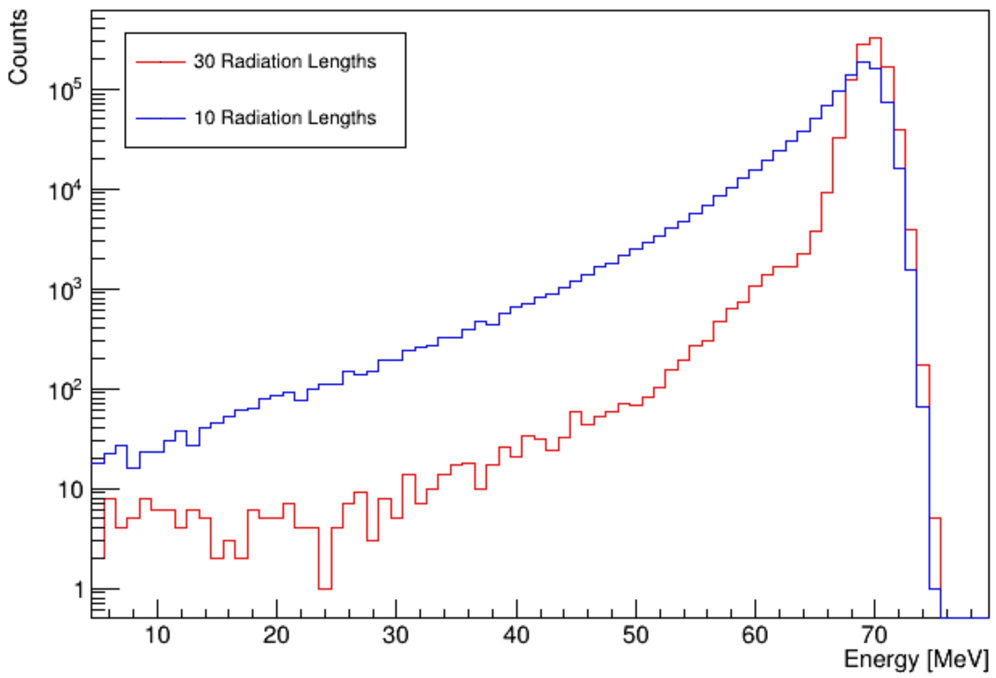
Facing experimental reality

$\pi - \mu - e$ events



Targeted resolution:
2% for positrons with 70 MeV/c

$\pi \rightarrow e\nu$ signal



At least 19 X_0

Guiding principles to the design of the experiment:

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2. **Tail must be less than 1% of total signal → Shower containment in the calorimeter**
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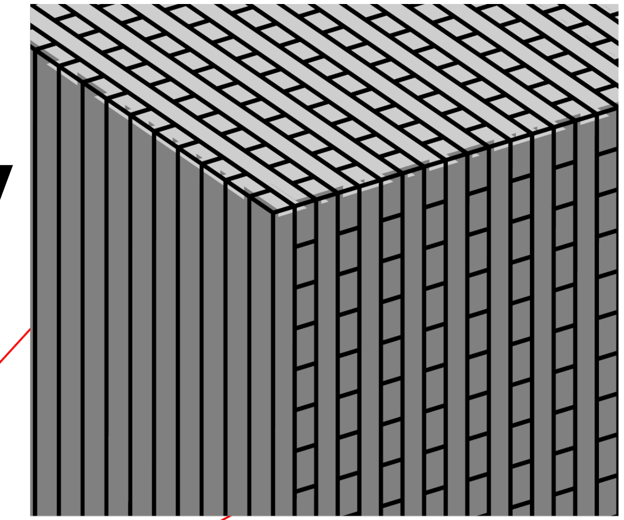
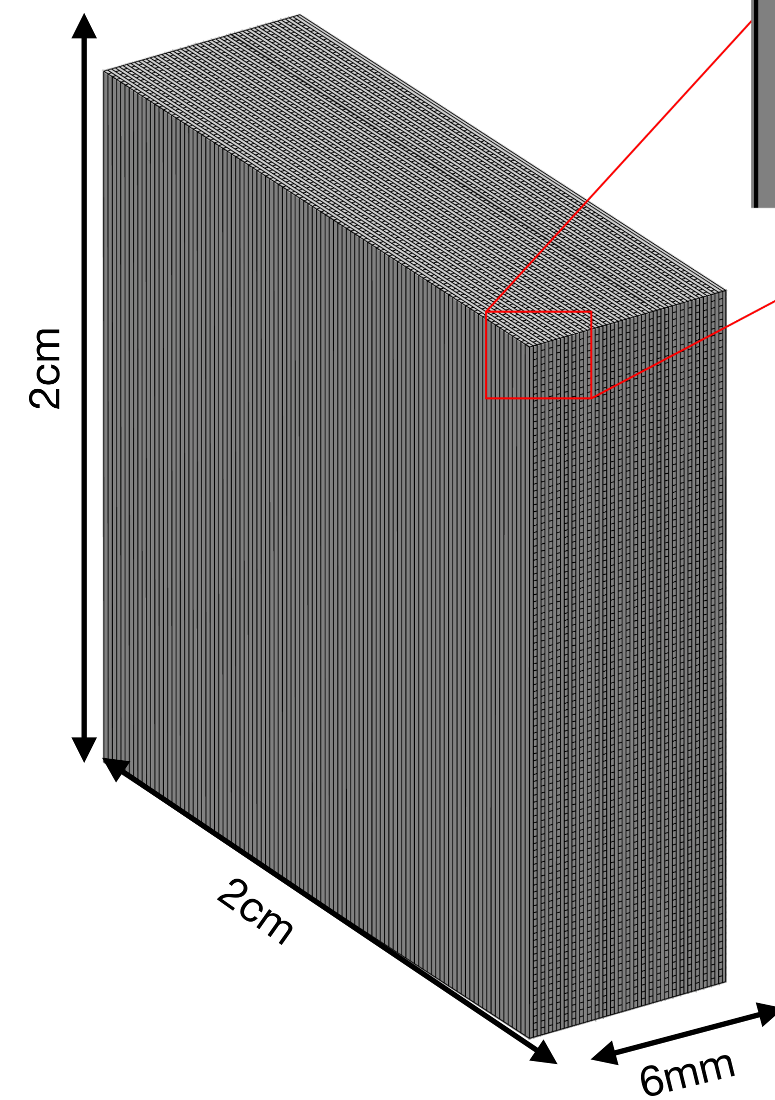
Facing experimental reality

Active target ("4D") based on low-gain avalanche diode (LGAD) technology

Tentative design

- 48 layers X/Y strips: 120 μm thick
- 100 strips with 200 μm pitch covering 2x2 cm^2 area
- Sensors are packed in stack of two with facing HV side and rotate 90





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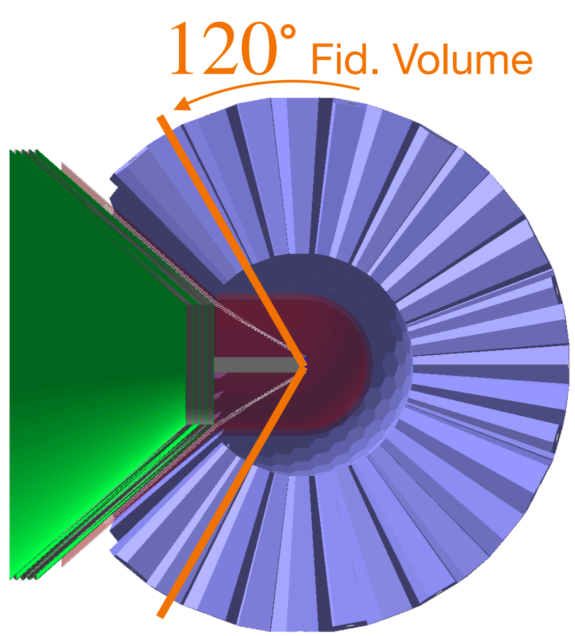
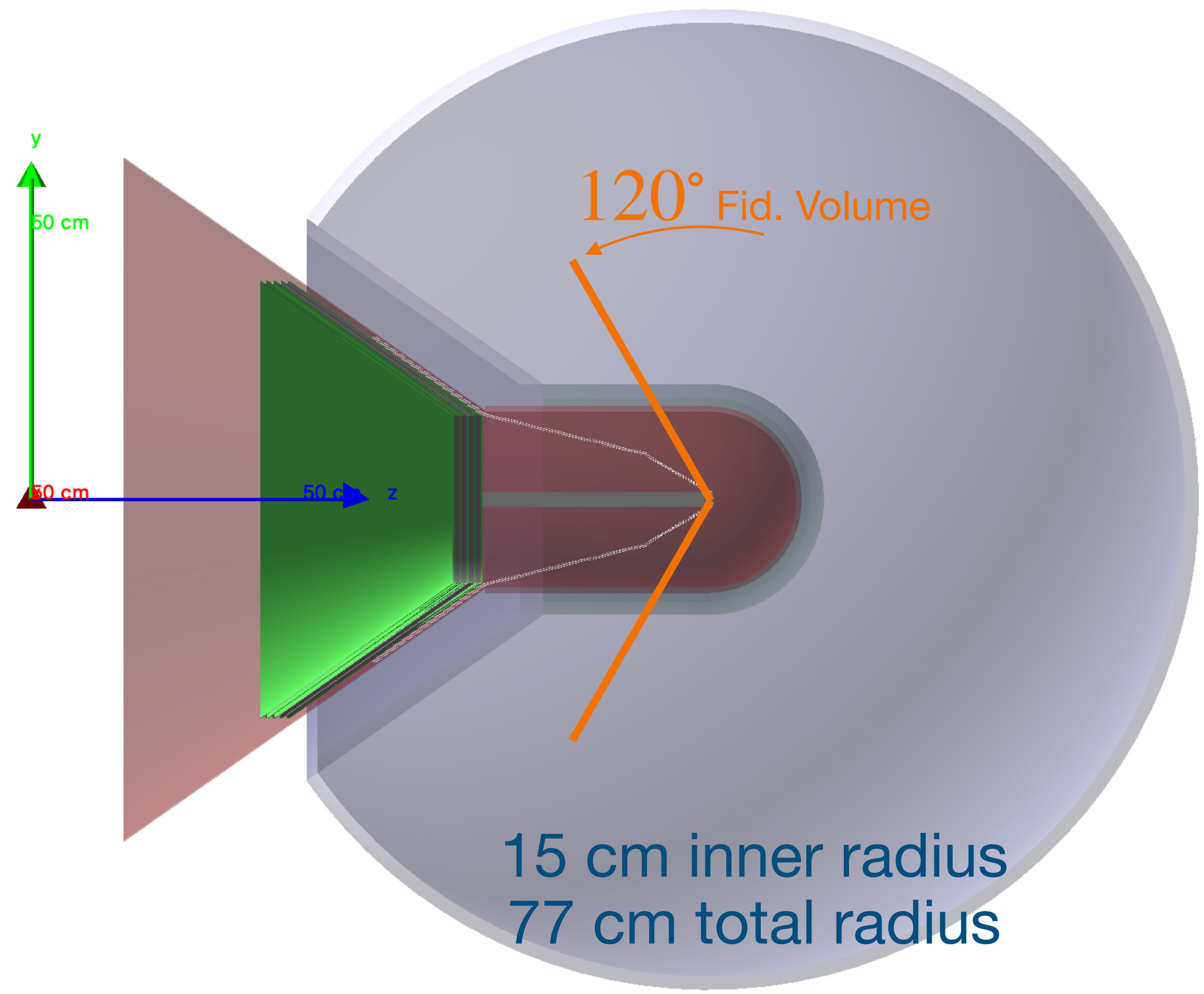
Calorimeter design

LYSO Crystals

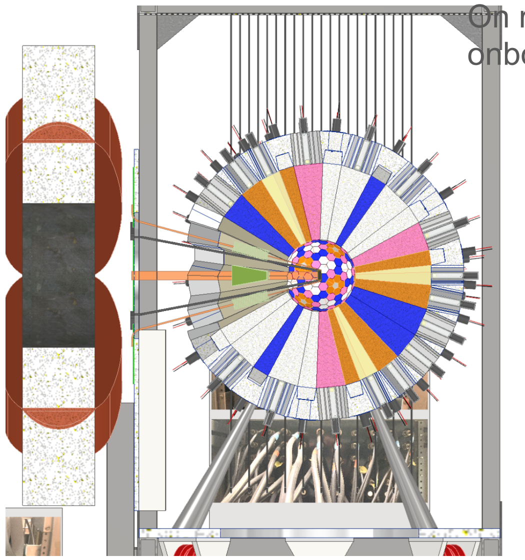


15 cm inner radius
42 cm total radius

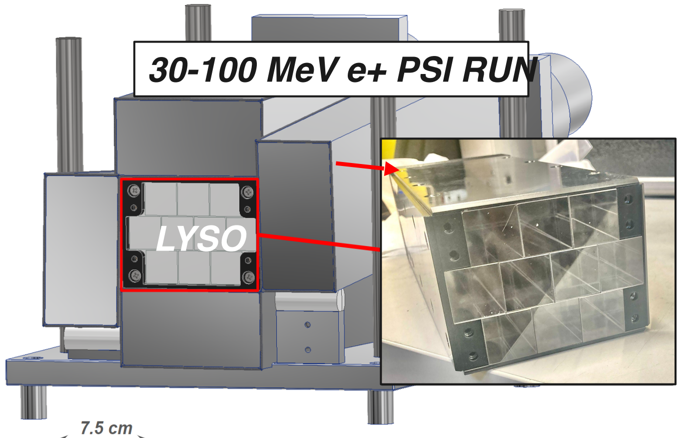
Liquid Xenon



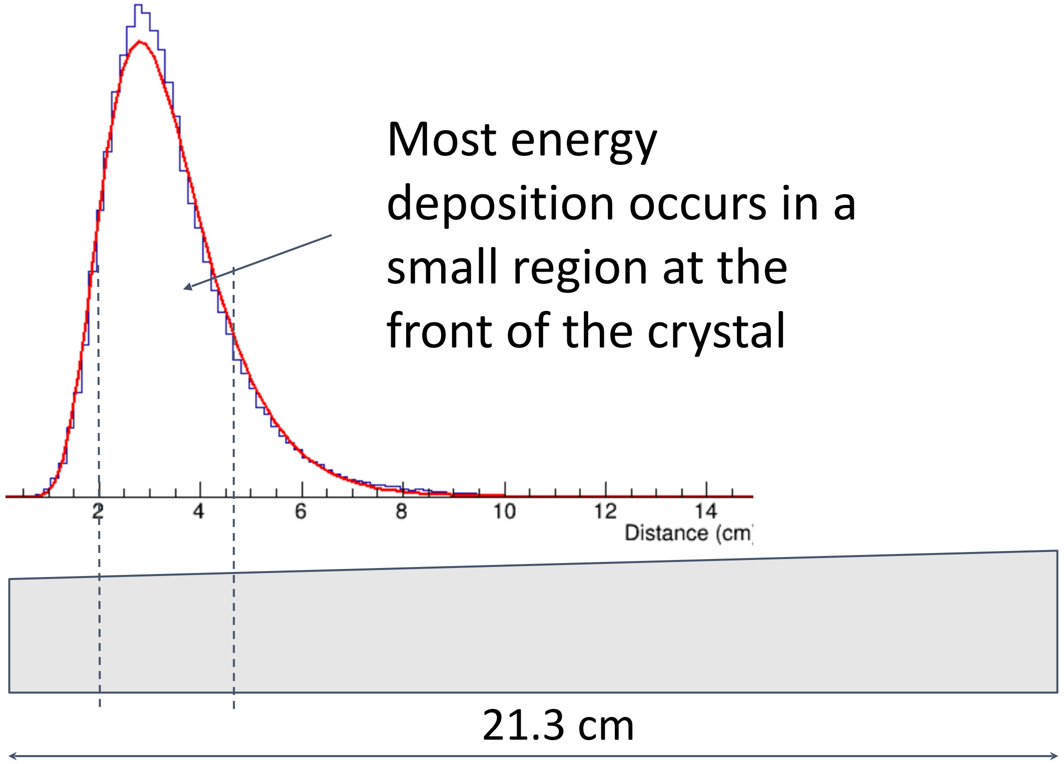
LYSO Crystal Option
R&D Program



- Calorimeter composed of 311 crystals
- LYSO is not common (yet) at PIONEER's energy scale and resolution requirements
    - Test beam studies in 2023 demonstrated 1.6% energy resolution at 70 MeV and <200ps timing resolution for pulses of 10 MeV and above
- Reconstruction studies in simulation demonstrated
    - Leverage of the segmentation for spatial separation of showers
    - Negligible impact of intrinsic radioactivity
- Next steps:
    - Study uniformity of the response with tapered crystals
    - Assemble a 16-array tapered system as a demonstrator



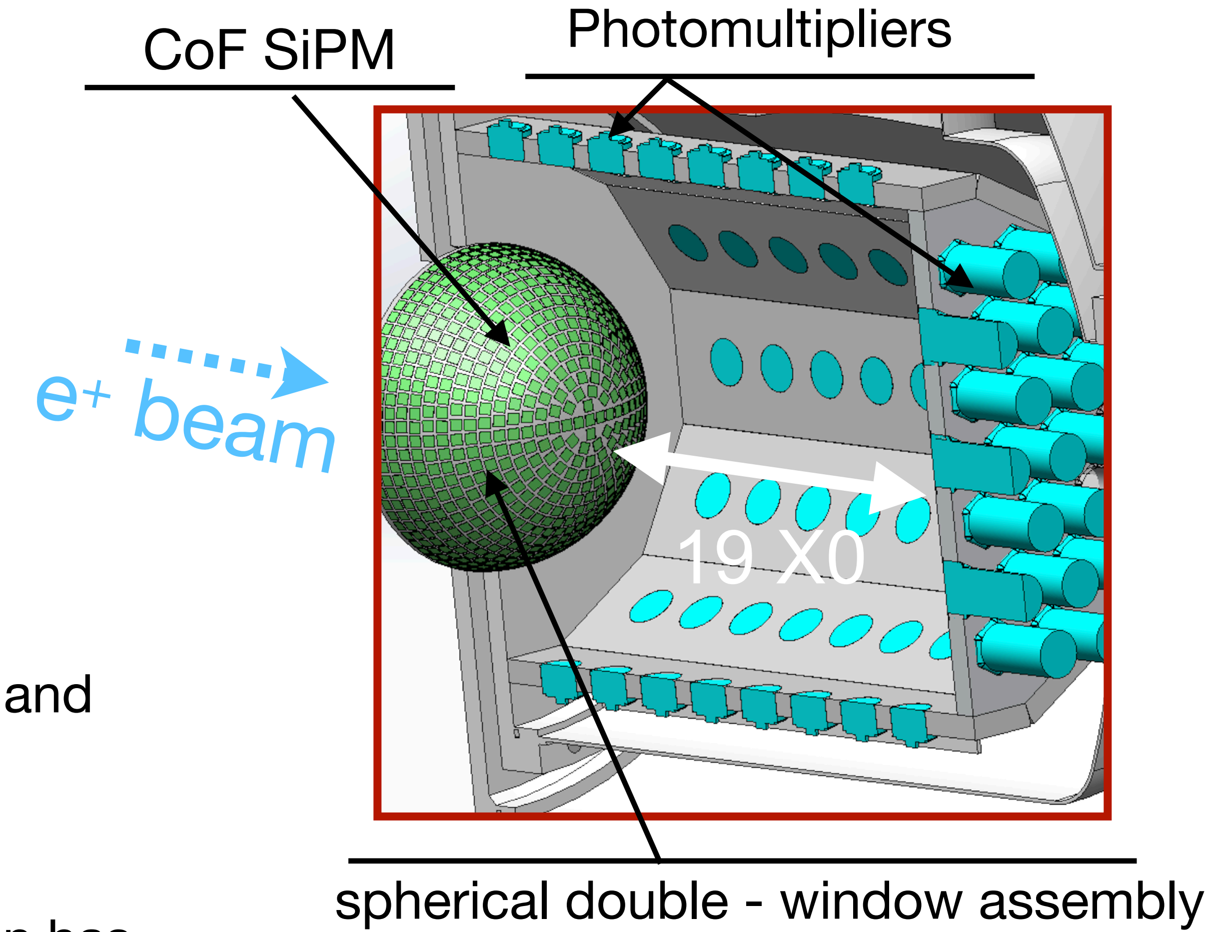
arXiv:2409.14691

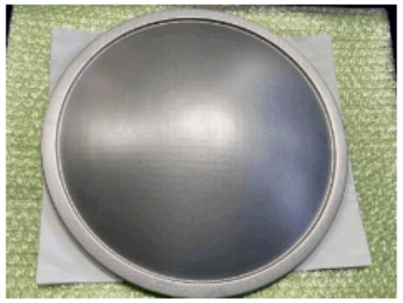


LXe Option

R&D Program

- Homogeneous single volume read by ~1300 PMTs
- Well established technology at PIONEER's energy scale and resolution requirements from MEG experiment (+ MEG collaborators in PIONEER)
- Very high energy resolution and good pileup identification has been demonstrated by MEG
- Next steps:
  - Large prototype being prepared
  - Test **structural** & **mechanical** aspects, **physics performance** (tail, energy resolution, position resolution), **technical performance** (new SiPM on film etc)
  - Simulation studies to demonstrate shower separation performance (from pulse analysis) as larger detector will likely result in sizeable beam background from upstream muons.





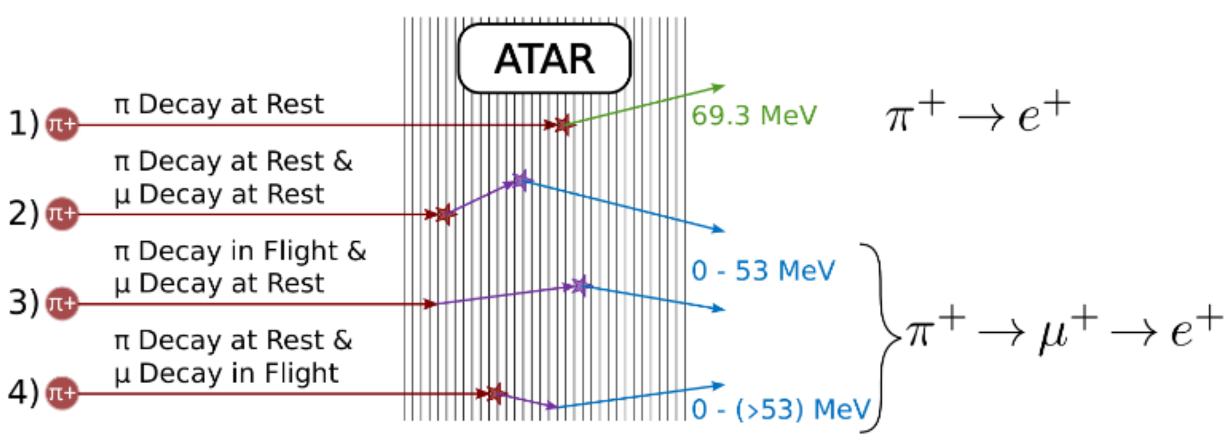
0.5mm 64Ti window

0.15mm Al Rapture disk

Active Target

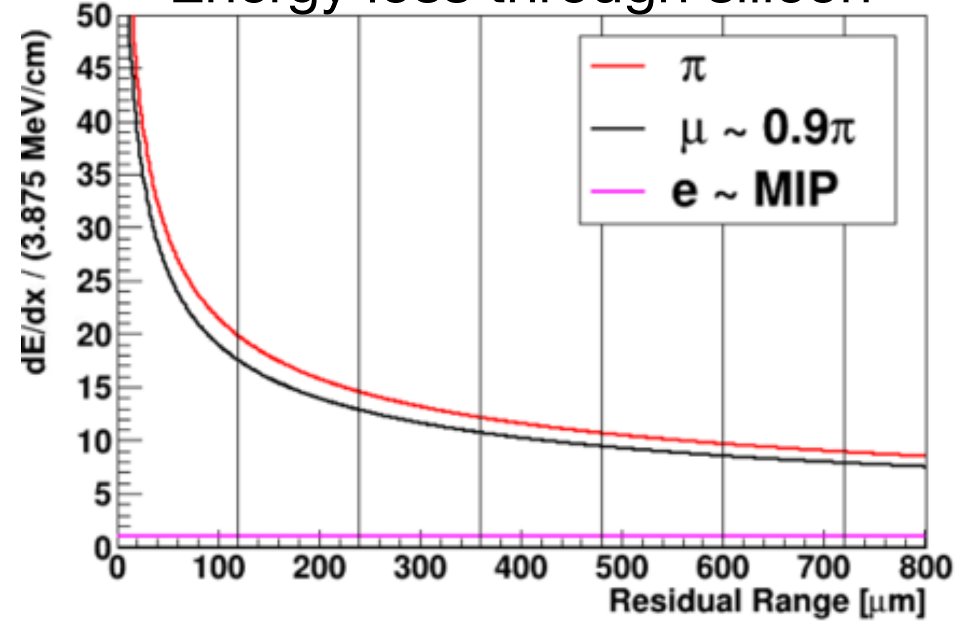
Requirements

- Thick and highly segmented target
  - stop the pion
  - tag and measure the decay chain
- Measure energy, time and position

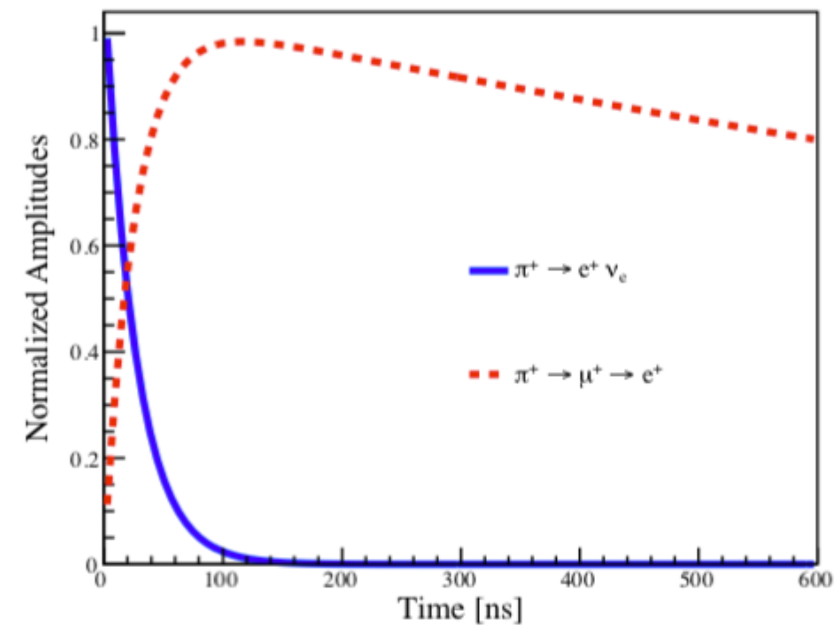


Pattern Recognition

Energy loss through silicon



Device needs to accommodate large range of energy scales



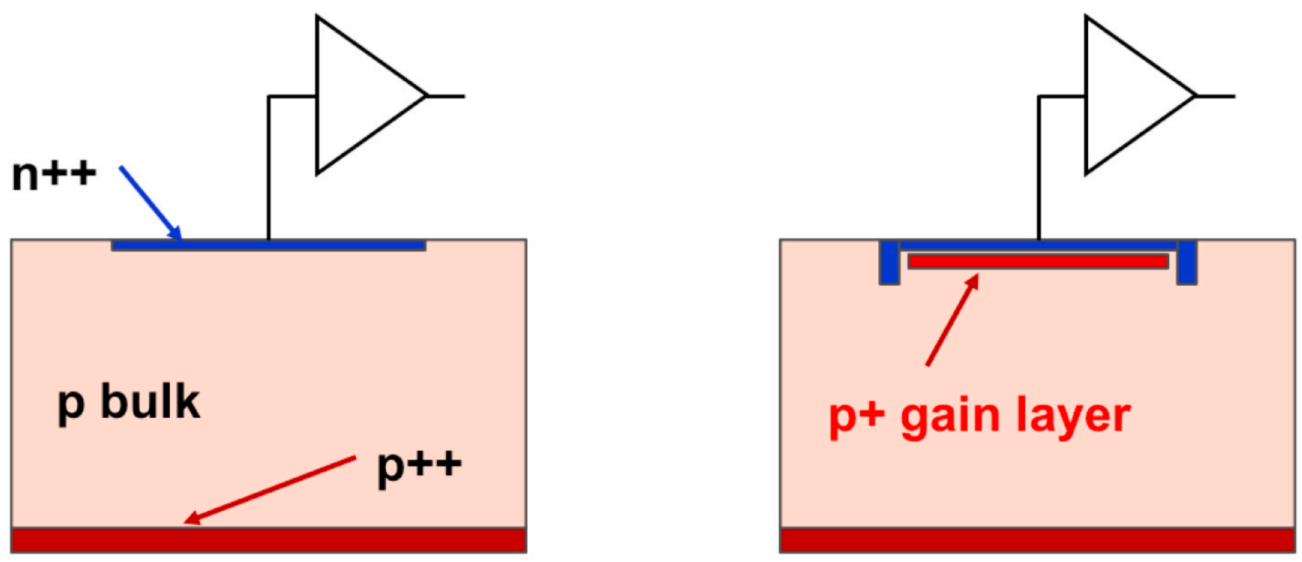
Decay chain time is very different between $\pi \to e\nu$ and $\pi - \mu - e$ events
Device needs to separate signals in a given strip with a time res of 1ns

Active Target

Low Gain Avalanche Diodes

Avalanche effect in silicon sensors

When applying a very large electric field (300 kV/cm),
electrons (and holes) acquire kinetic energy and
generate additional electron/hole pairs by impact ionisation



Traditional silicon diode **Low Gain Avalanche Diode**

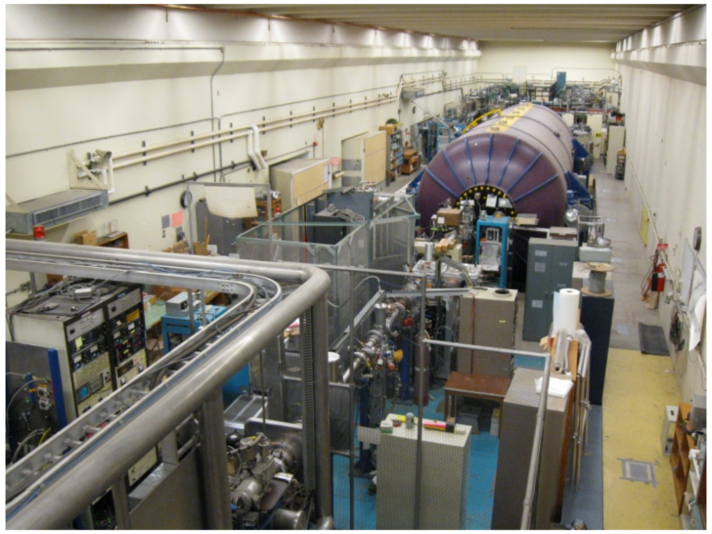
Obtained by implanting an appropriate acceptor or donor layer
when depleted, generate a very high field

The signal amplification allows for thin sensors and very good timing resolution
The gain mechanism saturates for large energy deposit

Active Target

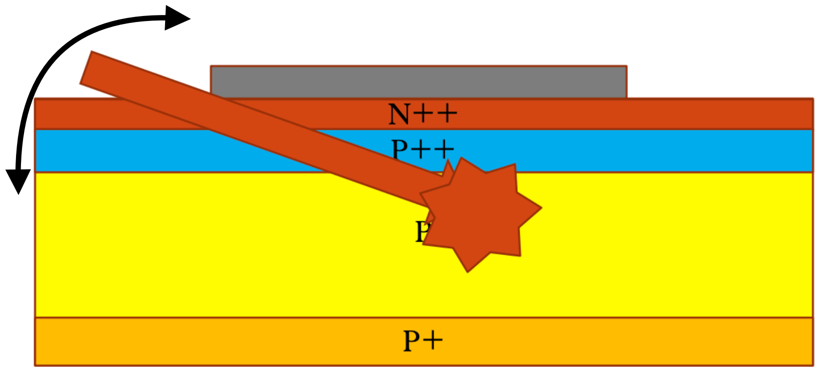
LGAD gain saturation studies

Test beam to understand LGAD response to **MeV-scale** deposits

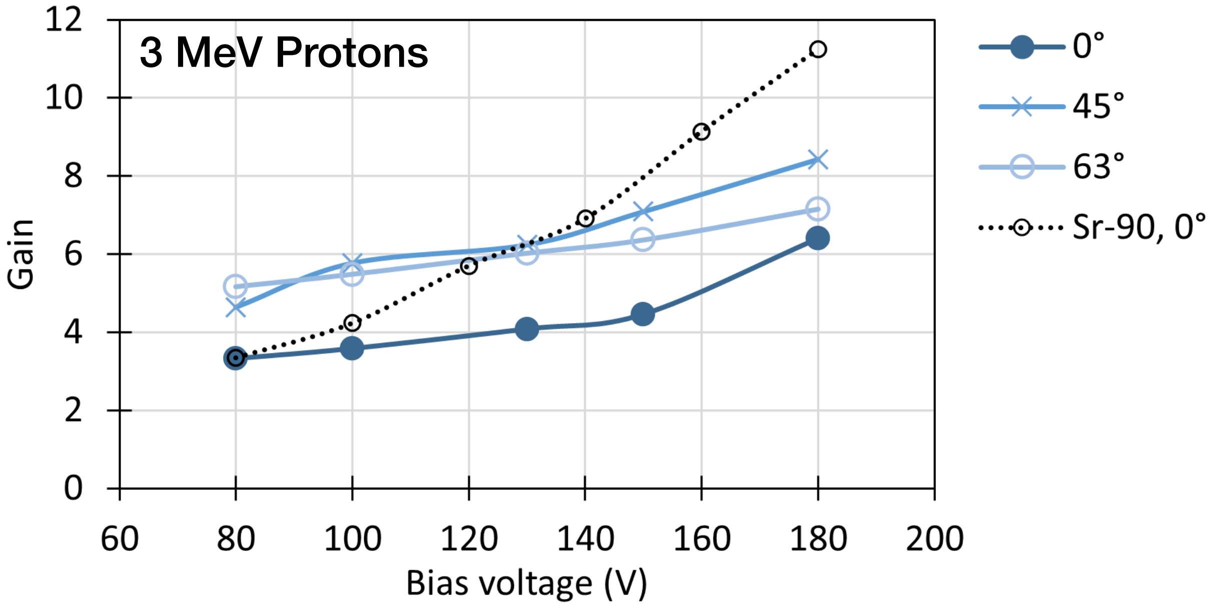


Tandem Van de Graaf Accelerator
1 to 5 MeV protons

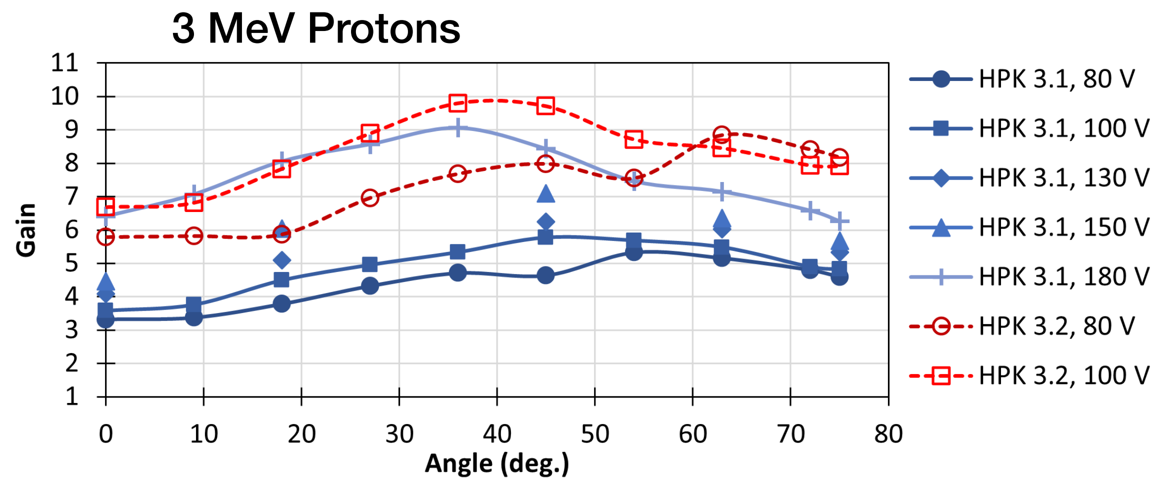
Vary the angle the protons hit the sensor



Optimise Bias Voltage to reduce saturation

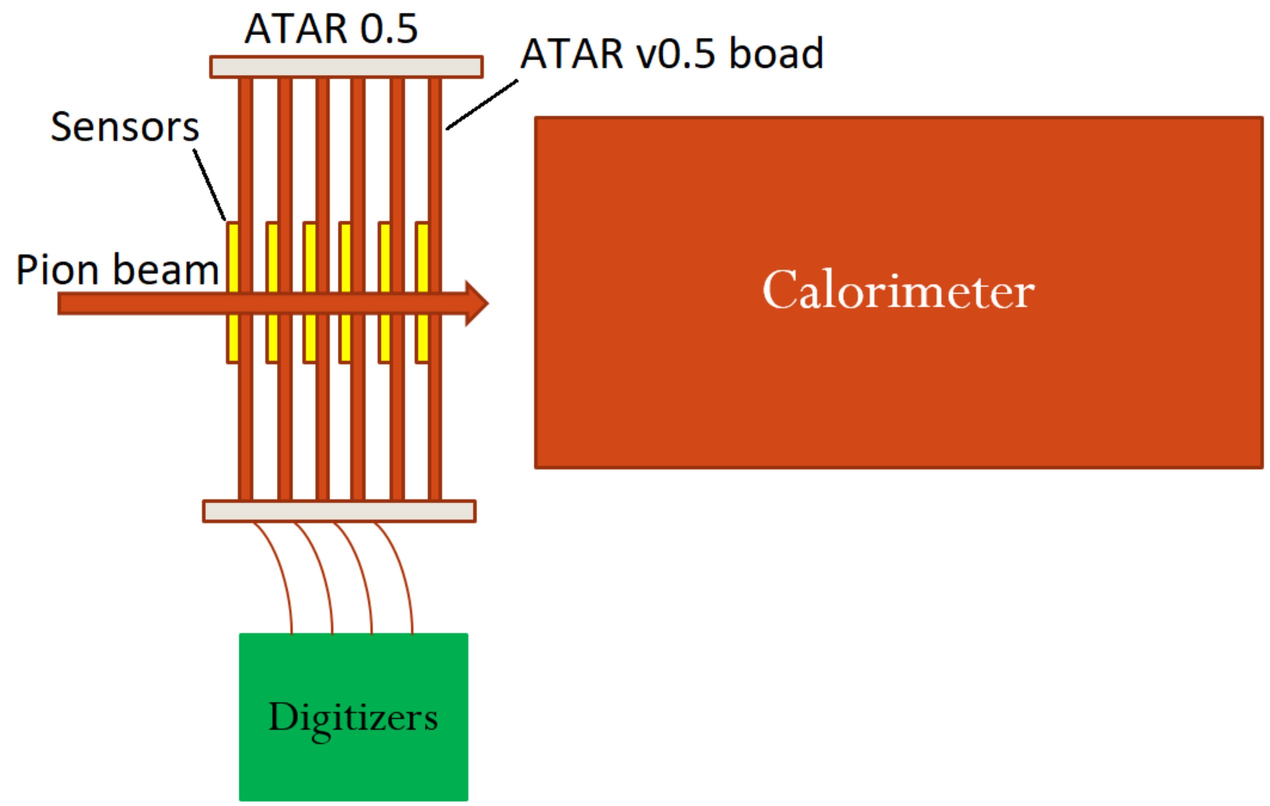


Impact of charge localisation: angular dependency of the response
→ critical input for PIONEER sensitivity studies



Active Target

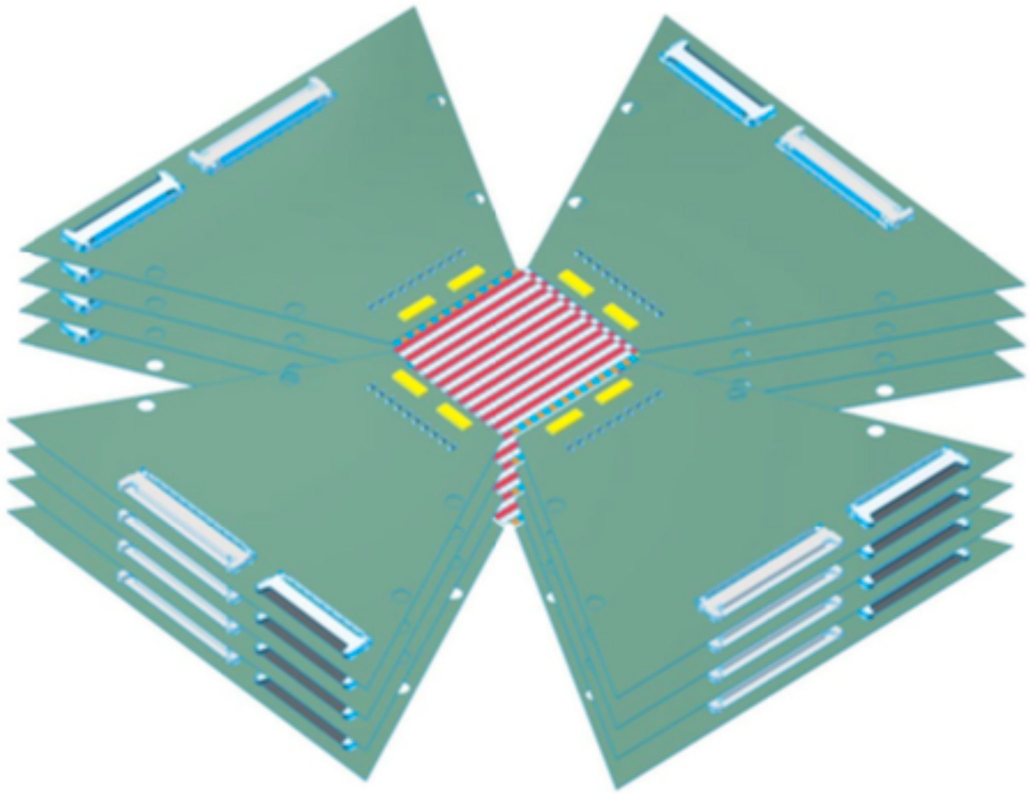
Toward first prototype



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

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

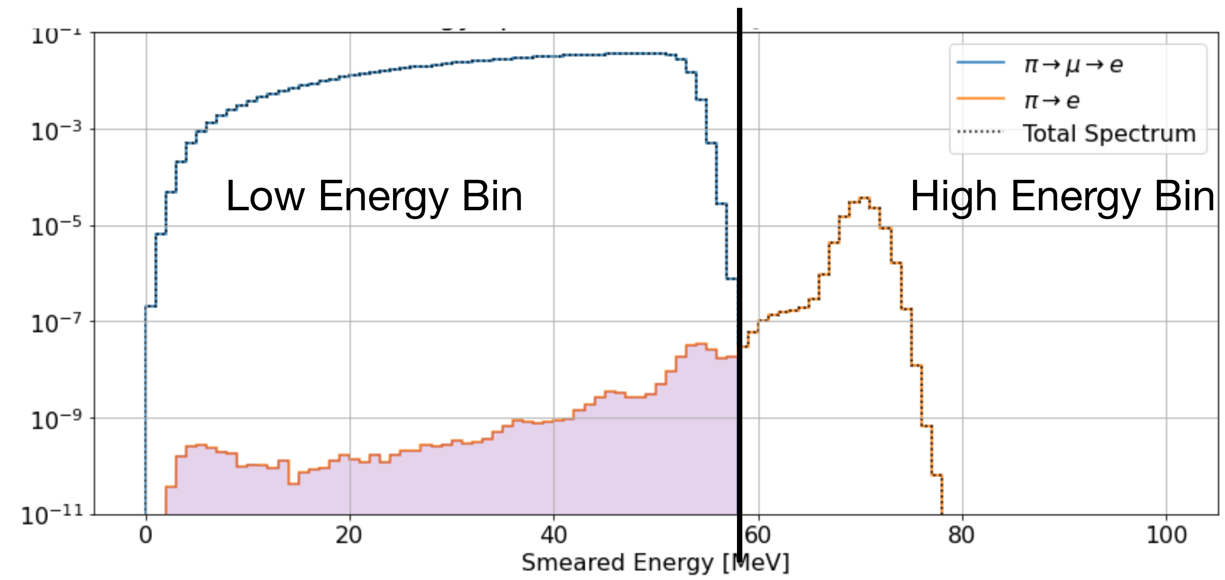
Goal is to have a first dataset of **pion or muon stopping data** before the 2027 PSI shutdown



$R_{e/\mu}$ measurement strategy

The master formula

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

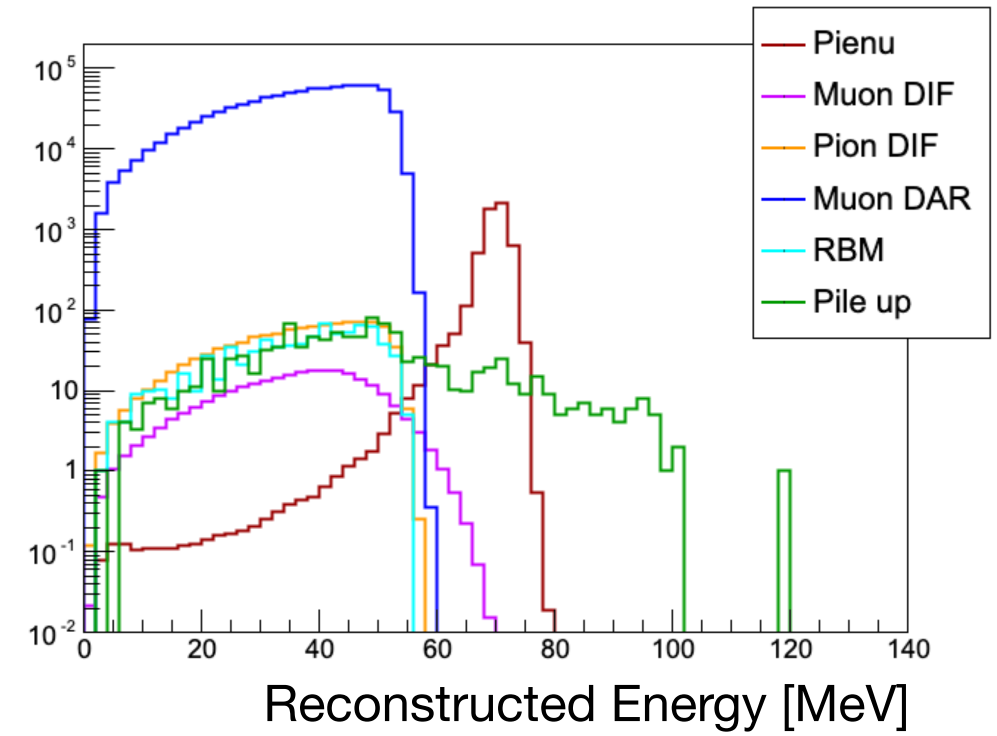


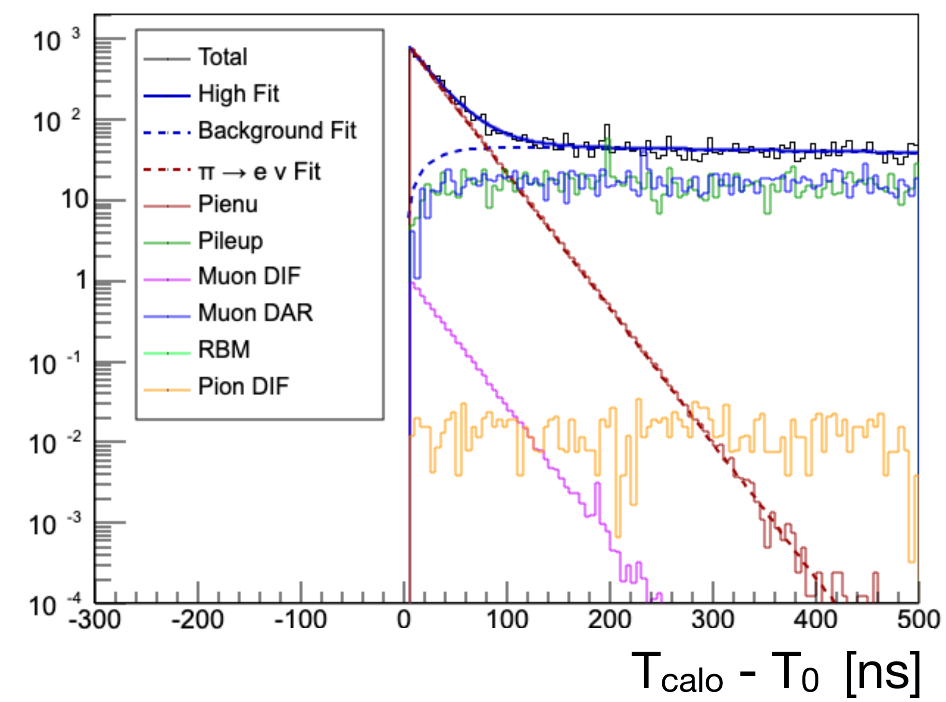
Quantity	Value	Required Precision (%)	Description
$N_{\pi-e}(E > E_{th})$	2E+08	<0.01	Number of $\pi - e$ events in the High Energy Bin
$N_{\pi-\mu-e}$	2E+10	<0.01	number of $\pi - \mu - e$ events in the Low Energy Bin
c_{tail}	1%	1	Tail fraction correction
R^{ϵ}	20%	<0.01	ratio of $\pi - e$ to $\pi - \mu - e$ decay chain acceptance

Simulation and Proto-analysis

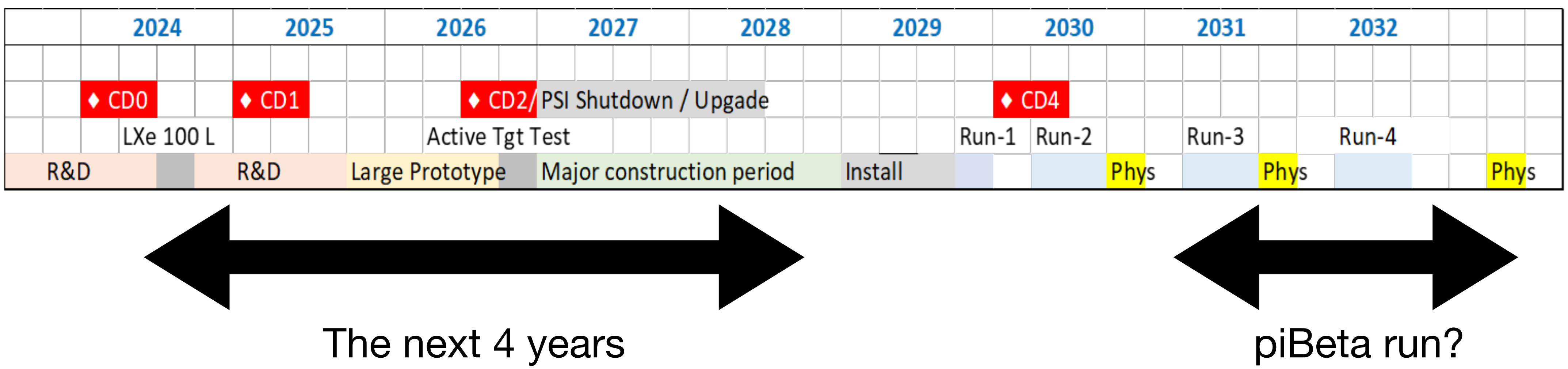
What real data could look like

- Simulate the experiment with realistic geometry, material interaction, beam dynamics, etc…
- High rate experiment → lots of beam-induced background (old muons)
- Ongoing effort to implement realistic detector response and design reconstruction algorithms
    - Use HEP tools (GEANT4, Gaudi, HistFactory/pyhf)
- So far, everything indicates the measurement can be performed at the targeted precision!





PIONEER Timeline



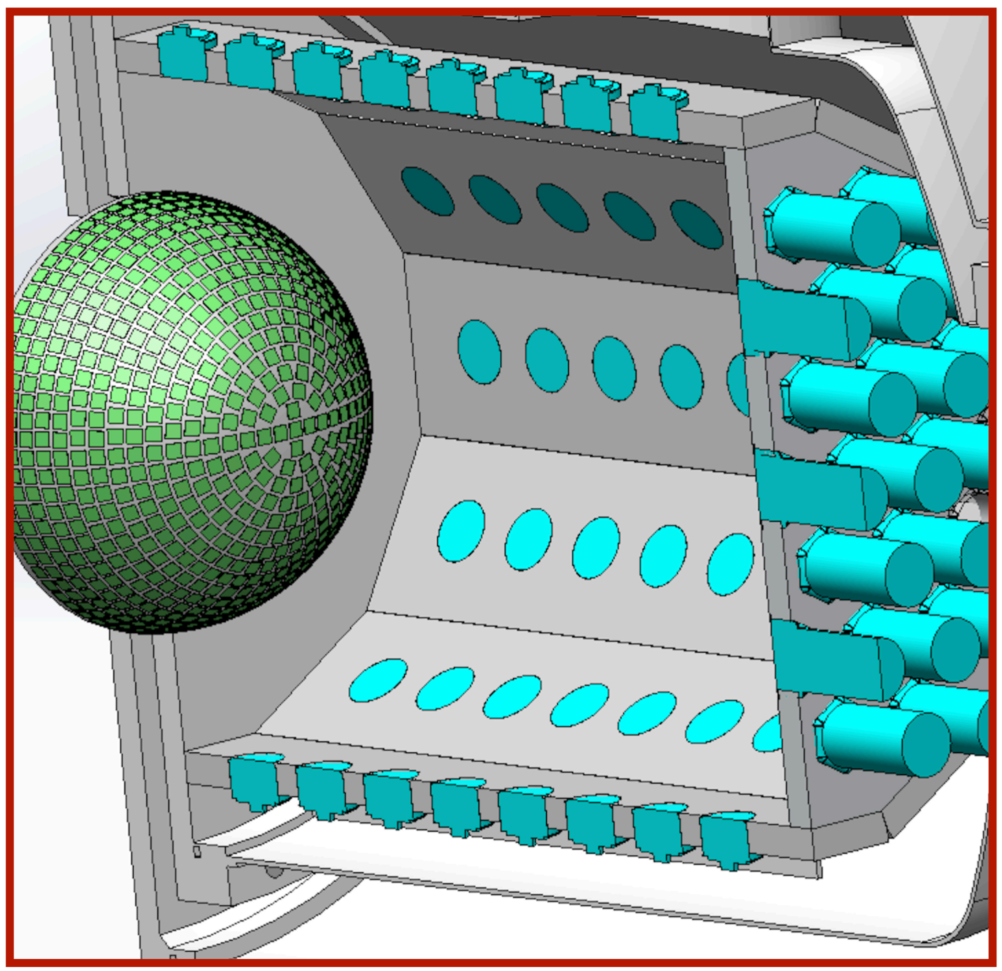
Detector R&D in calorimetry and tracking

Simulation studies to model a high precision experiment

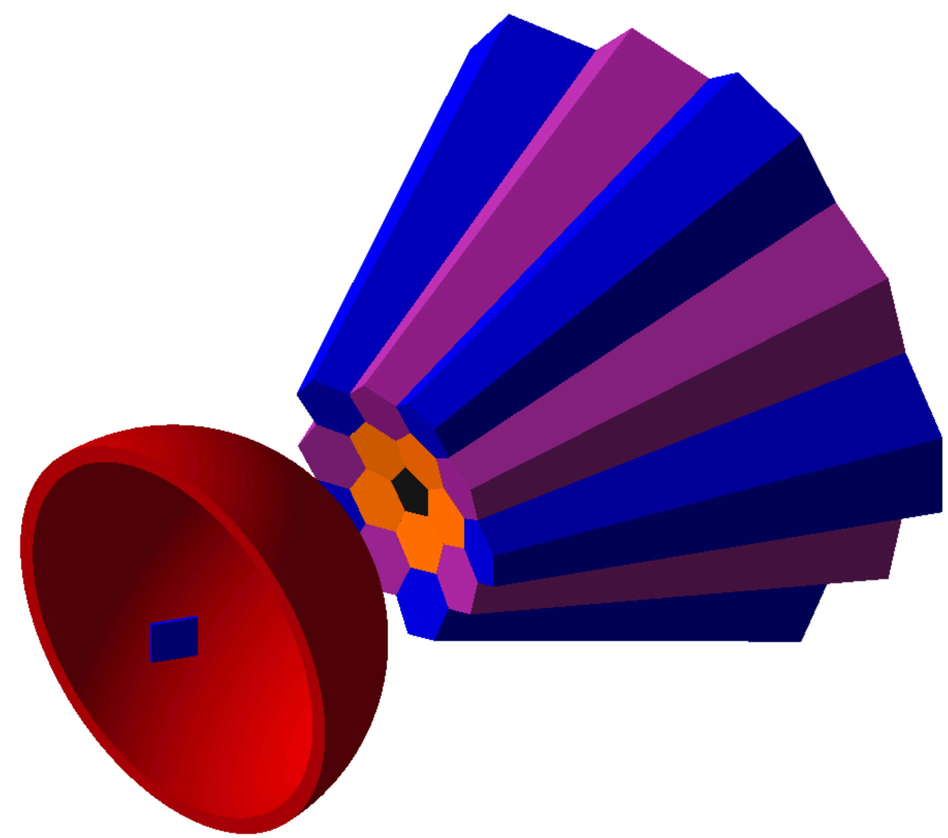
Putting an experiment together from concept to first data
Civil engineering, beam optics, detector manufacturing, LXe/LYSO acquisition, electronics, …

PIONEER R&D — the next 2 years

Prototype and demonstrator

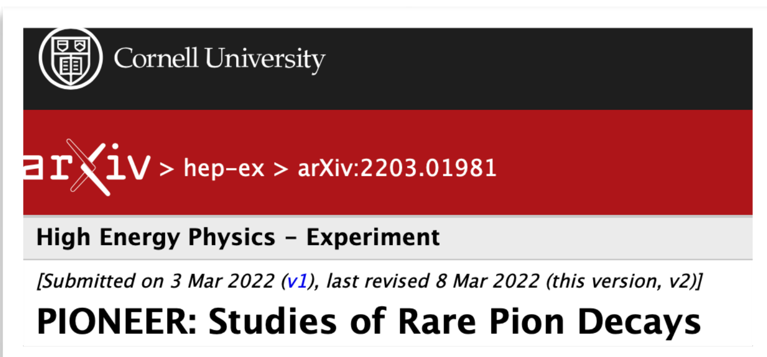


LXe prototype



Demonstrator
16-array LYSO
16 layers ATAR
Tracker?

A growing collaboration



Project approved by PSI in 2022

October 2023 collaboration meeting in Seattle

Opportunities

Exciting experiment sensitive to very high scale BSM physics

Many opportunities to get involved!

Simulations
Measurement strategy
Detector drawing (CAD, …)
Beam design
…

Get in touch:
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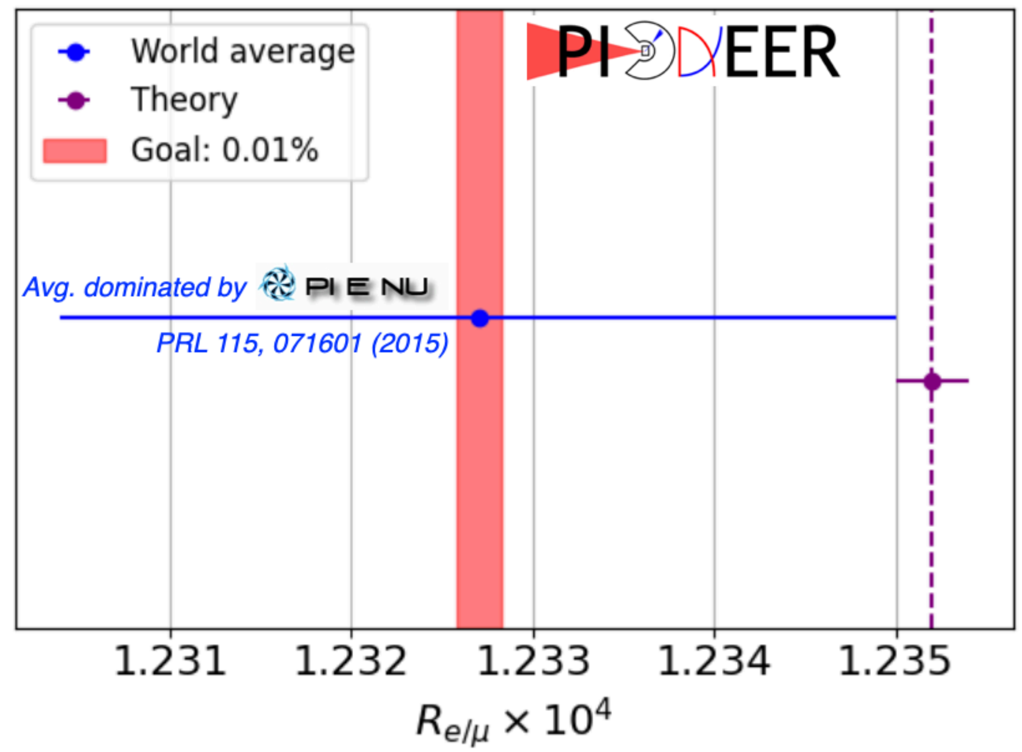
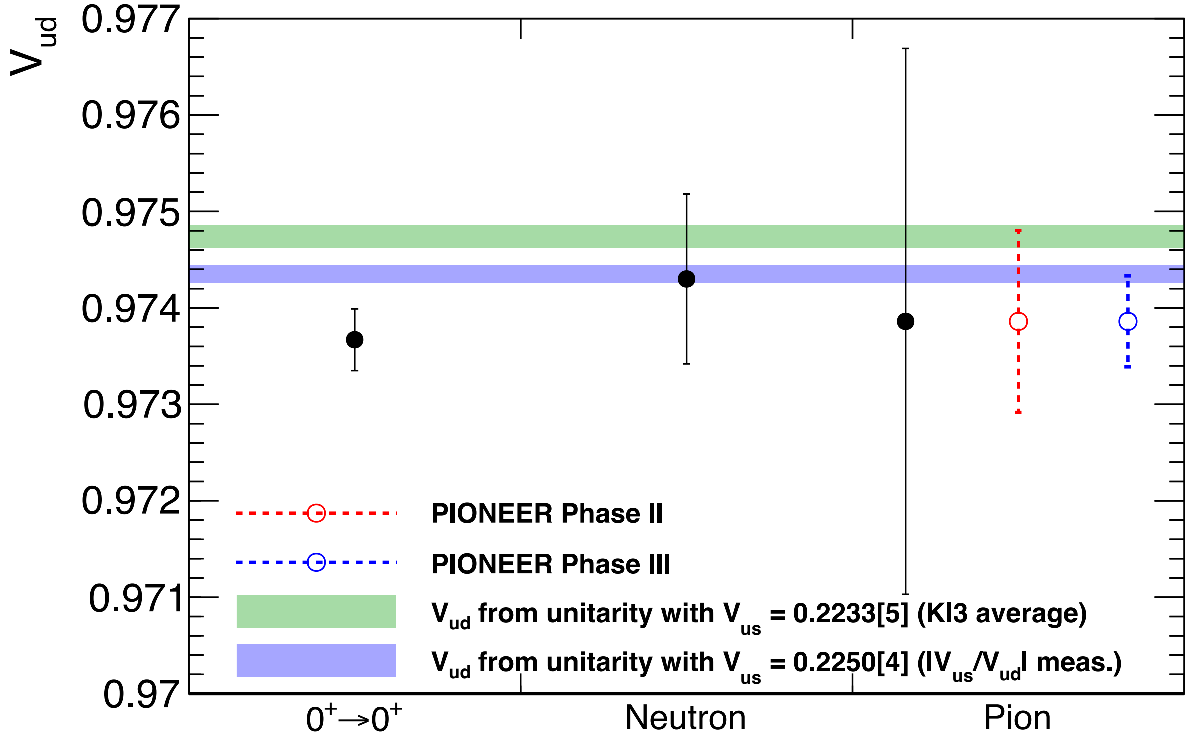
David Hertzog: hertzog@uw.edu,
Doug Bryman: doug@triumf.ca





Data Source