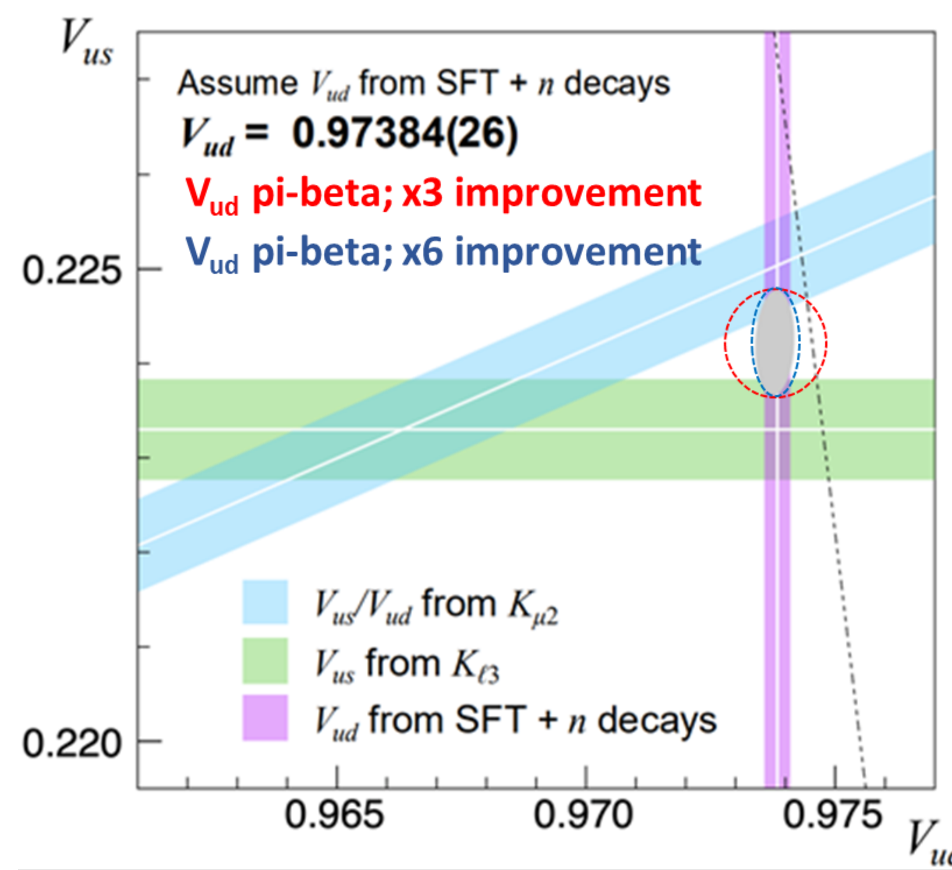
Prospects for a V_{ud} measurement with the PIONEER Experiment

Quentin Buat (University of Washington)

Workshop on Vud from pion, neutron and nuclear beta decay
Nov 5-6, 2024 — GANIL, Caen, France

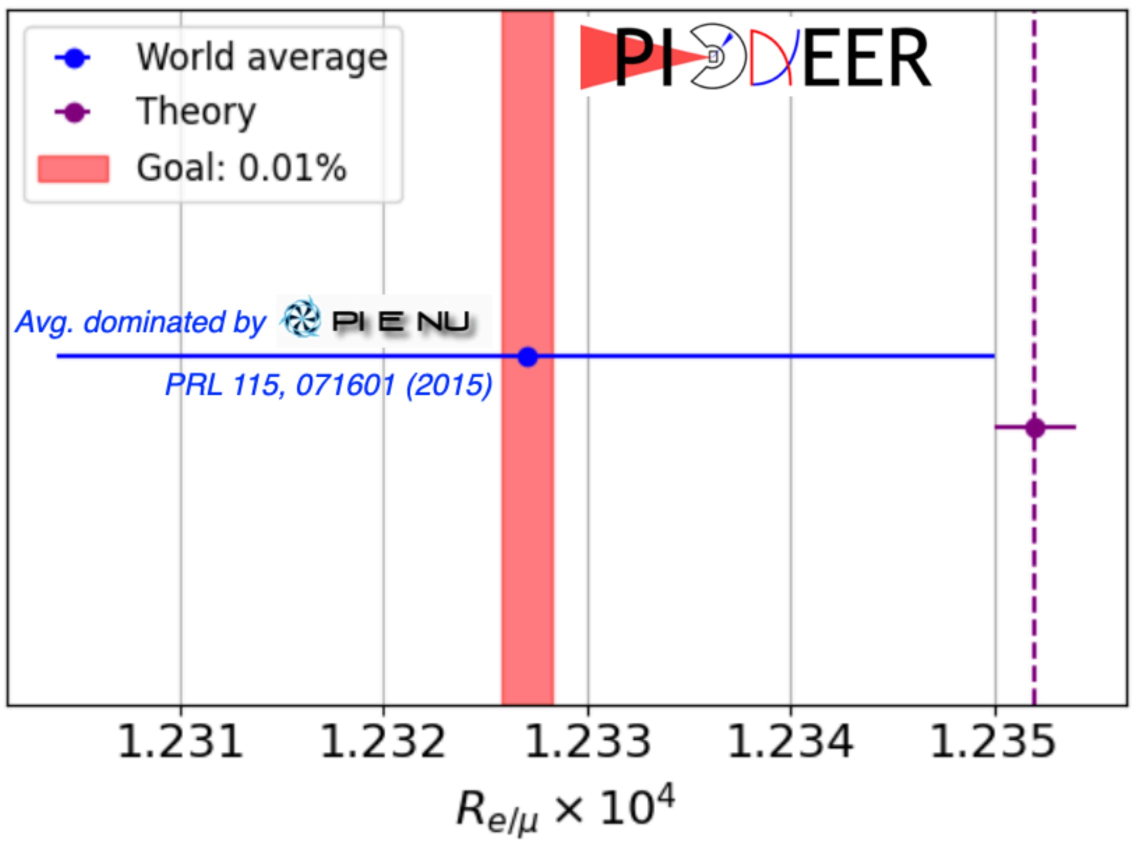


Courtesy Matt Moulsen

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

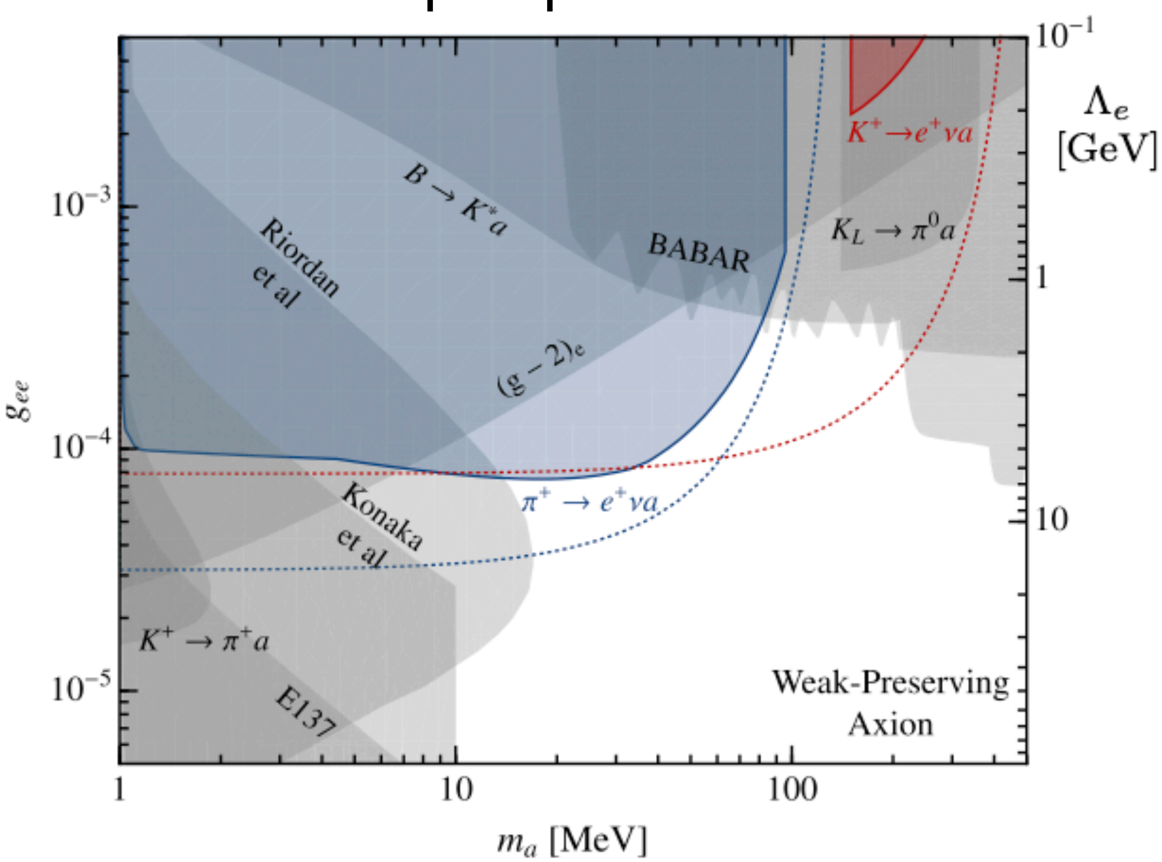
BSM constraints:
EFT analysis (JHEP. **2013**, 46 (2013))
~330 TeV (pseudo scalar)
~5.5 TeV (axial currents)

Phase I of the project

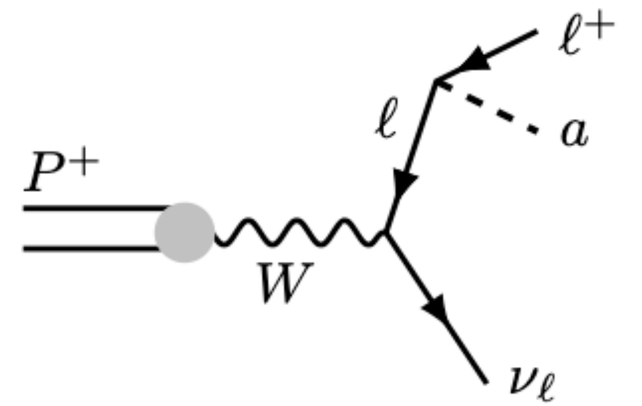
PIONEER Physics Case

Exotic decays of the charged pion

Lepto-philic axion



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



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

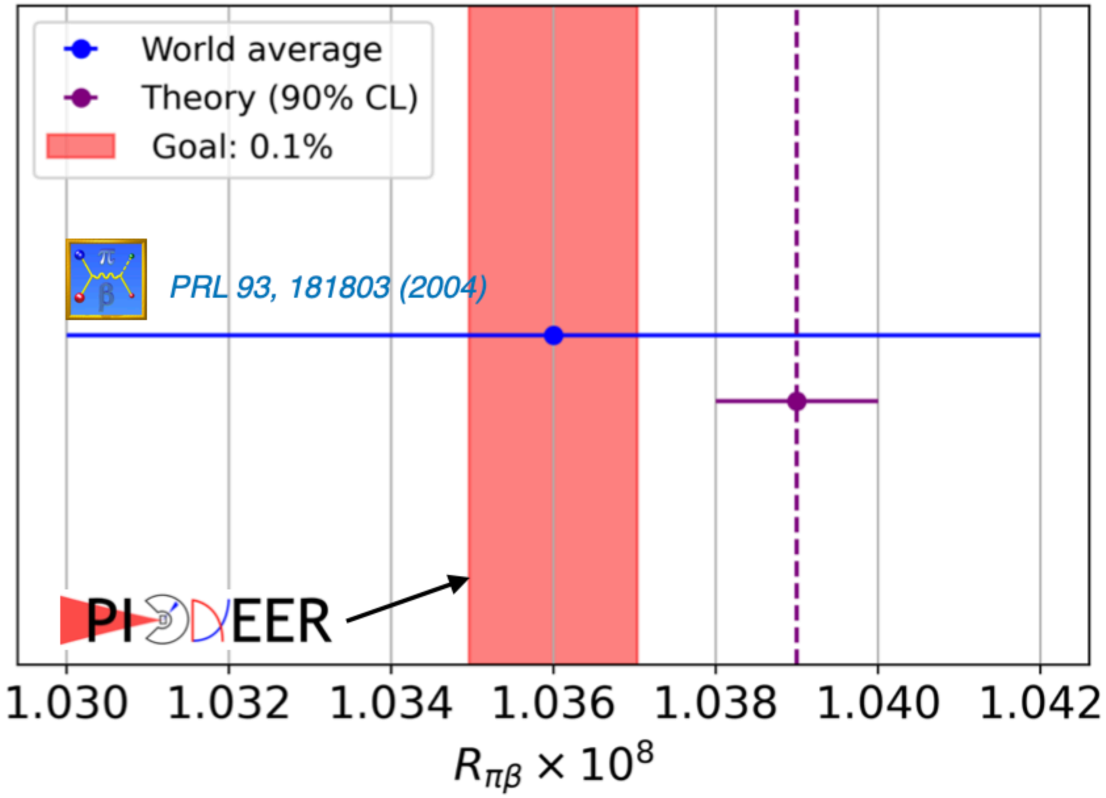
Searches profit from the very large datasets needed for $R_{e/\mu}$ measurement

Phase I of the project

PIONEER Physics Case

piBeta measurement and V_{ud} extraction

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



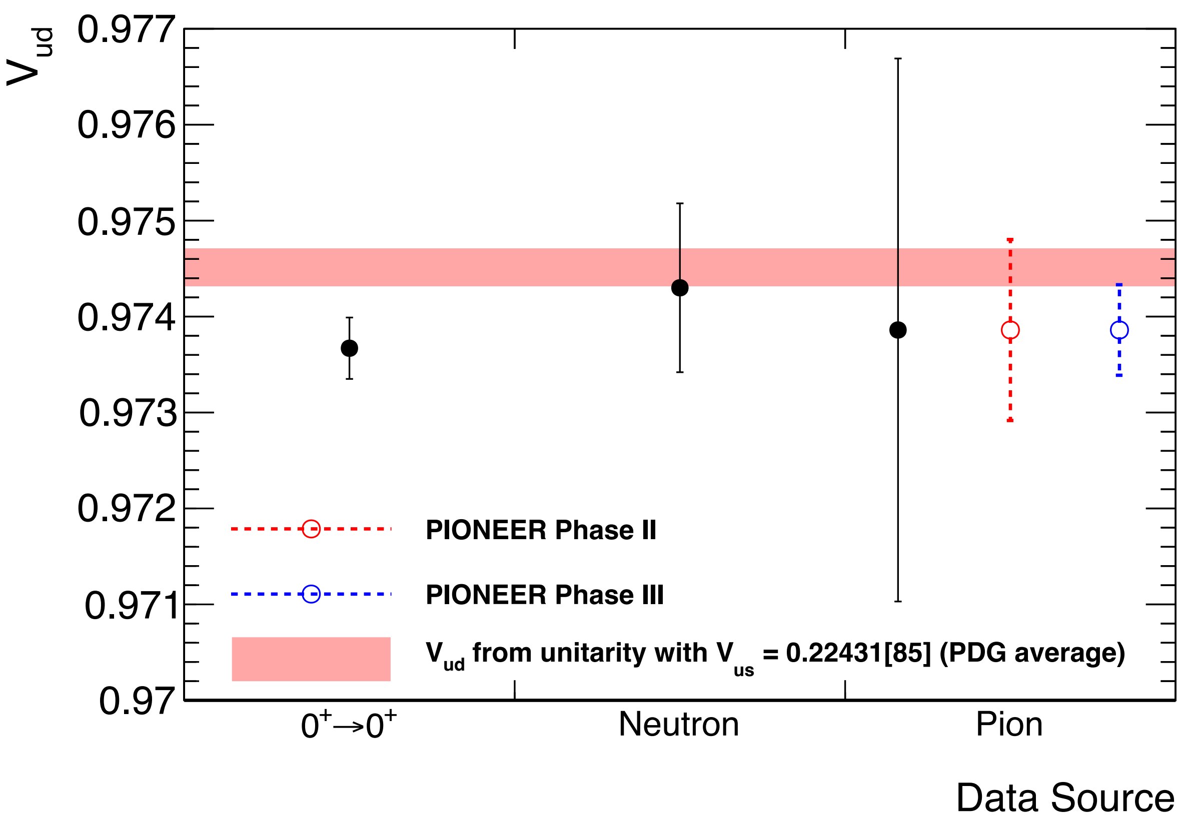
$$R_{\pi\beta}[\text{Exp.}] = 1.036(0.006) \times 10^{-8}$$

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

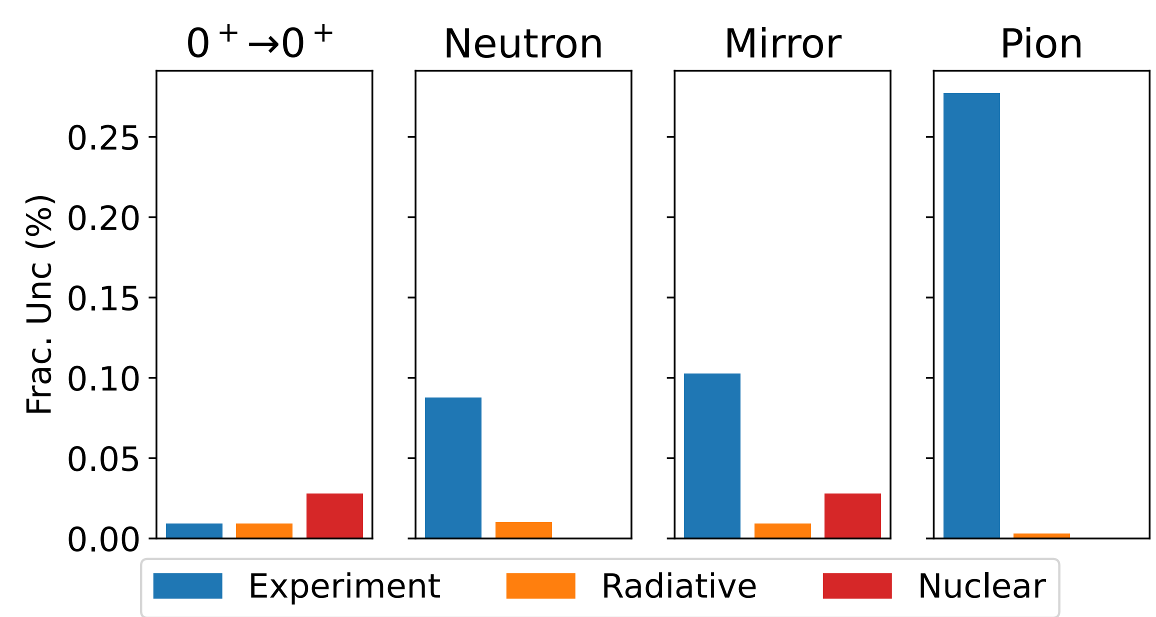
Goal of PIONEER
Reduce the uncertainty as much as possible to be relevant in comparison to super-allowed beta decays and neutron measurements

Phase II-III of the project

Landscape of V_{ud} measurements



arXiv:2301.03975



$$V_{ud}^{0^+\to0^+} = 0.97367\,(11)_{\text{exp}}\,(13)_{\Delta_V^R}\,(27)_{NS}\,[32]_{\text{total}}$$

$$V_{ud}^{n,\text{PDG}} = 0.97430\,(2)_{\Delta_f}\,(13)_{\Delta_R}\,(82)_{\lambda}\,(28)_{\tau_n}[88]_{\text{total}}$$

$$V_{ud}^{\pi} = 0.97386\,(281)_{\text{BR}}\,(9)_{\tau_\pi}\,(14)_{\Delta_R^\pi}\,(28)_{\Delta_f}\,[283]_{\text{total}}$$

Pion lifetime

Radiative corrections

Phase space dominated by exp. uncertainty on pion mass splitting

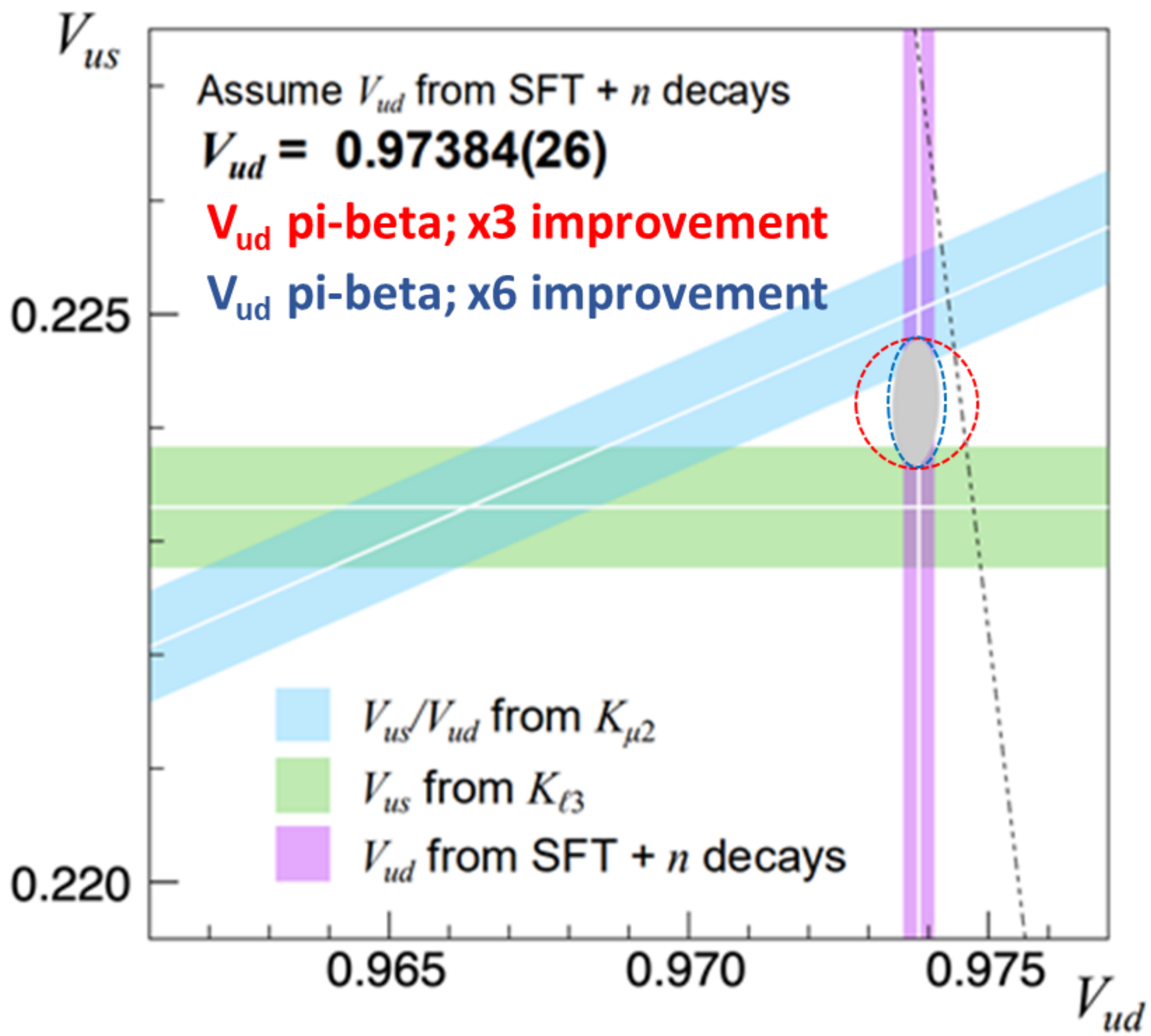
3:20 PM | **The pion beta decay: Theory**

Speaker: Marc KNECHT (CNRS)

Role of piBeta measurement

V_{us} vs V_{ud} Representation

- Now: not competitive
- x3 improvement: nice, maybe it gets added to the plot
- x6 improvement: competitive with neutron estimates, useful cross-check
- x10 improvement: become the reference



Courtesy Matt Moulsen

Measuring $R_{\pi\beta}$

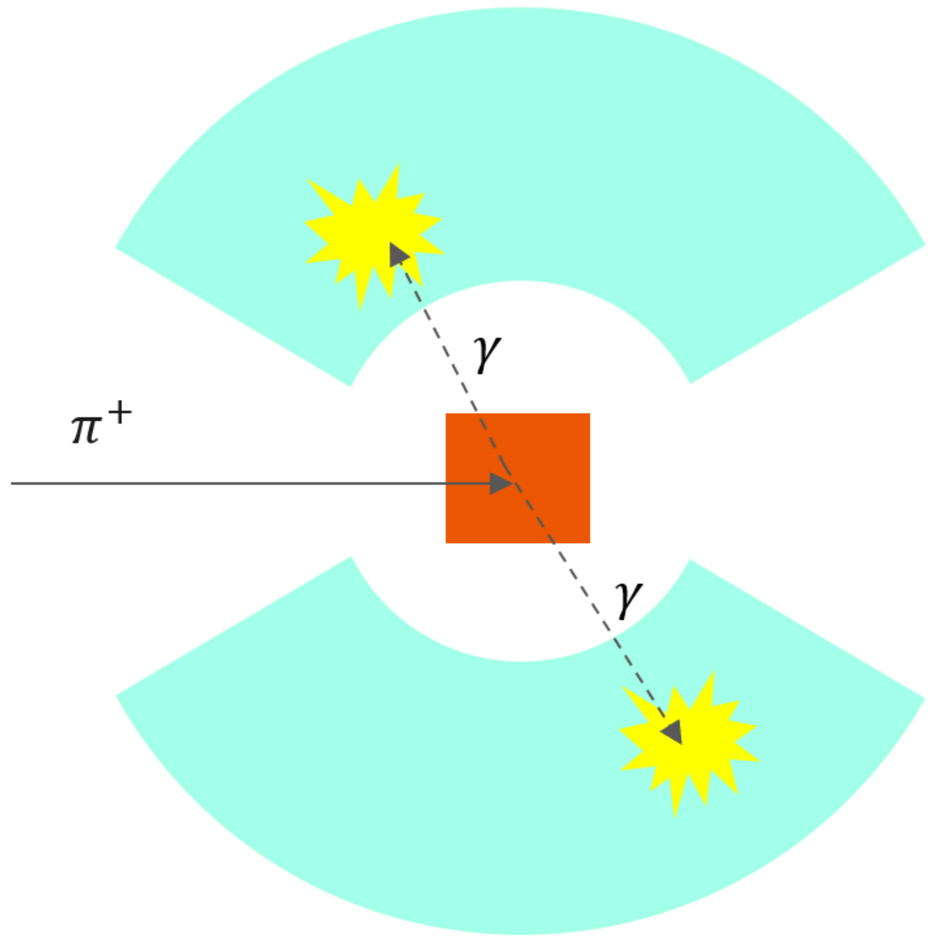
Event Topology

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

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

Two back-to-back photons

Very low energy positron



PiBeta Experiment

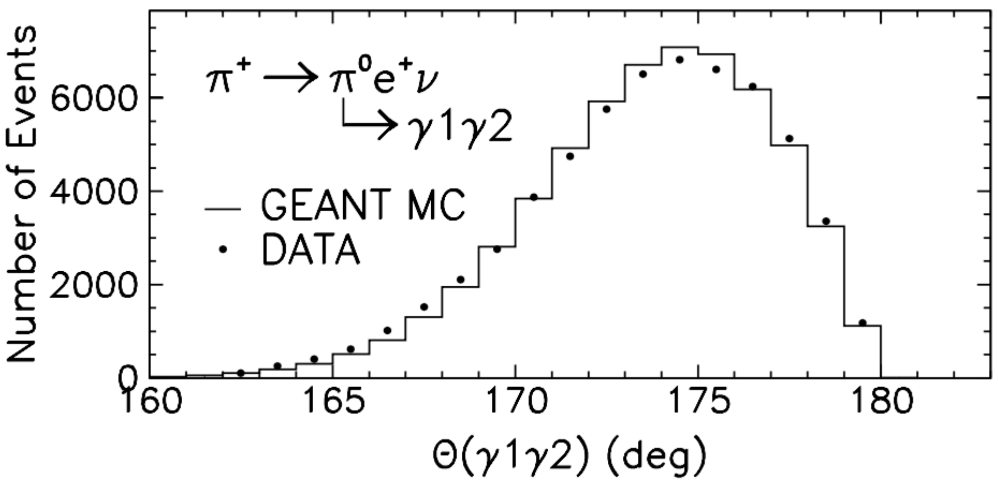


FIG. 5. Histogram of the γ-γ opening angle in π_β decay.

$R_{\pi\beta}$ measurement

The PiBeta Experiment Approach

Measure ratio to $\pi^+ \to e^+\nu_e$ BR

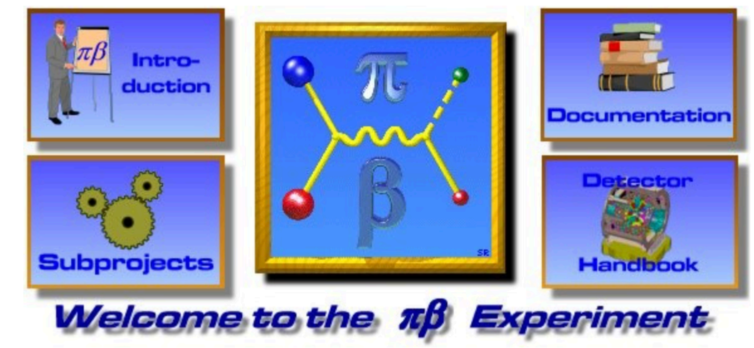
Alleviates the need to count every pion (difficult in high rate experiment)

Requires to control relative acceptance of $\pi^+ \to \pi^0 e^+\nu_e$ and $\pi^+ \to e^+\nu_e$ events in the piBeta run

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

The piBeta experiment

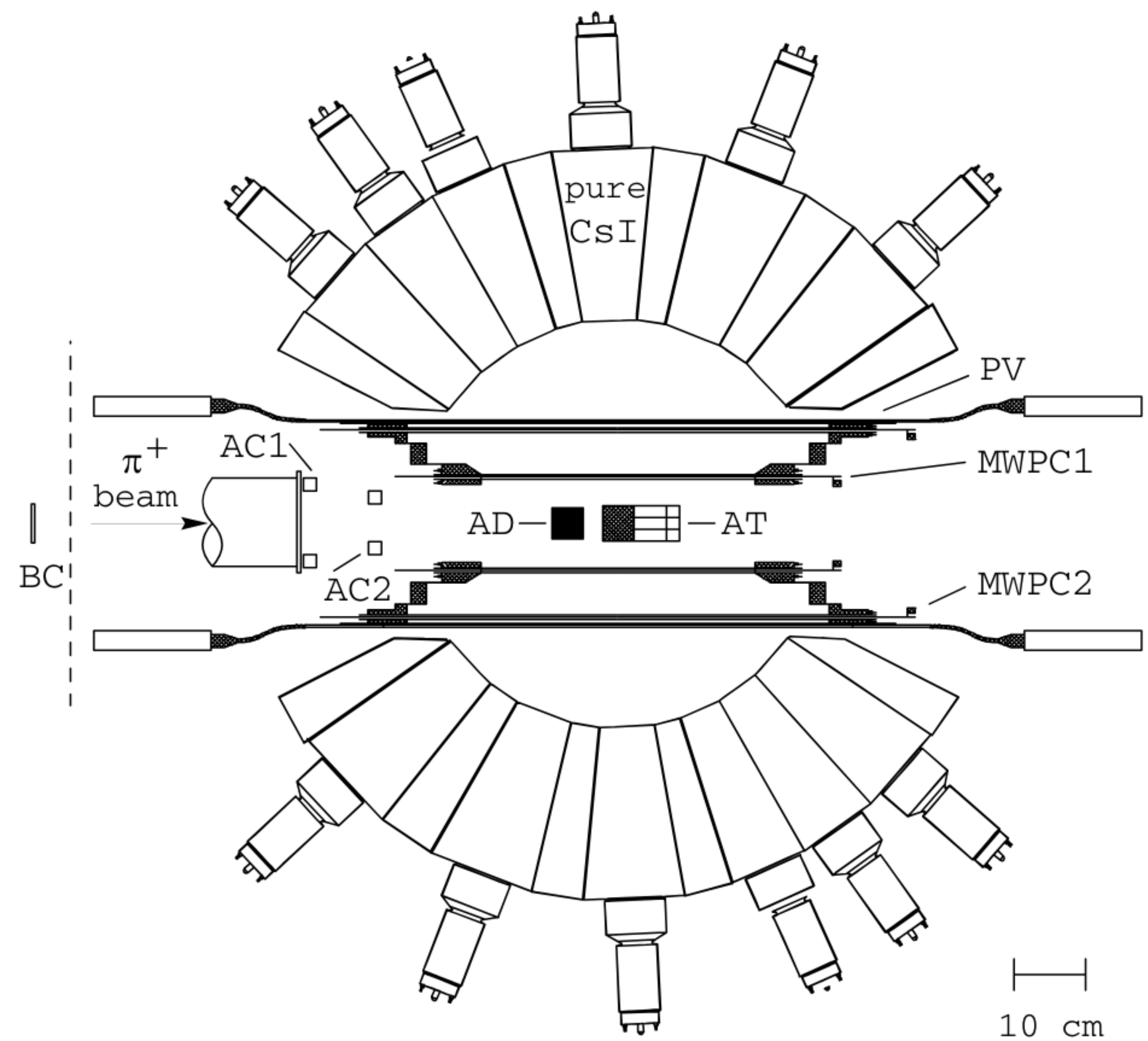
http://pibeta.phys.virginia.edu/



PSI πE1 Beam Line at **110 MeV/c**
10^6 **pions/s** stopped in active target

Gamma and positron energy measured by CsI calorimeter

Plastic Scintillator Hodoscope (PV) and Multi-Wire Proportional Chambers (MWPC) for tracking and particle identification



The piBeta experiment

Uncertainty budget

Phys. Rev. Lett. 93, 181803

Uncertainty type	Quantity	Value	$\Delta R_{\pi\beta}$ (%)	
External	$R^{\text{exp}}_{\pi e2}$	1.230×10^{-4}	0.33	External input
	$R^{\text{exp}}_{\pi^0 \to \gamma\gamma}$	0.9880	0.03	
	π^+ lifetime	26.033 ns	0.02	
Combined external			0.33	
Internal	$N^{\text{tot}}_{\pi e2}$ (syst)	6.779×10^8	0.19	Relative acceptance of $\pi^+ \to \pi^0 e^+ \nu_e$ and $\pi^+ \to e^+ \nu_e$
	$A^{\text{HT}}_{\pi\beta}/A^{\text{HT}}_{\pi e2}$	0.9432	0.12	
	$r_{\pi\text{G}} = f^{\pi\beta}_{\pi\text{G}}/f^{\pi e2}_{\pi\text{G}}$	1.130	0.26	
	$N^{\text{accid}}_{\pi\beta}$	0	<0.1	
	f_{CPP} correction	0.9951	0.10	
	f_{ph} correction	0.9980	0.10	
Combined internal			0.38	
Statistical	$N_{\pi\beta}$	64 047	0.395	Statistical uncertainties

Equal contributions from statistical uncertainty (size of the piBeta decay sample) and systematic uncertainties (acceptance effects)

The piBeta experiment

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Can we collect enough $\pi^+ \to \pi^0 e^+ \nu_e$ events?

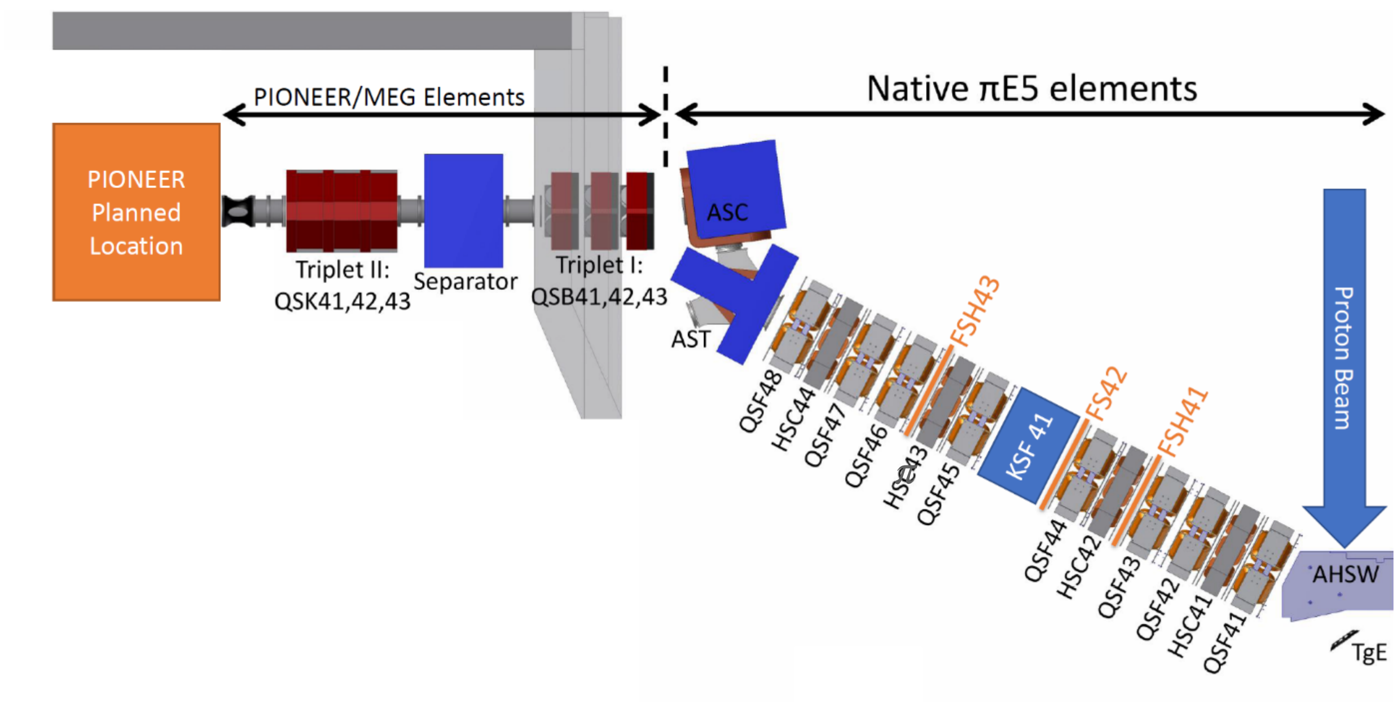
PAUL SCHERRER INSTITUT

PSI

Located near Zurich, Switzerland
World most intense low-energy pion beamline

The world's brightest pion beam line

Pion Beamline at PSI



Beam properties	Phase I	Phase II-III
Pion Decay of Interest	$\pi^+ \to e^+ \nu_e$	$\pi^+ \to \pi^0 e^+ \nu_e$
Rate (pions/s)	$3 \,.10^5$	$3 \,.10^7$
Momentum (MeV/c)	65	85
Momentum bite —Δp/p (%)	1	3
Statistics (events/year)	10^8	10^6

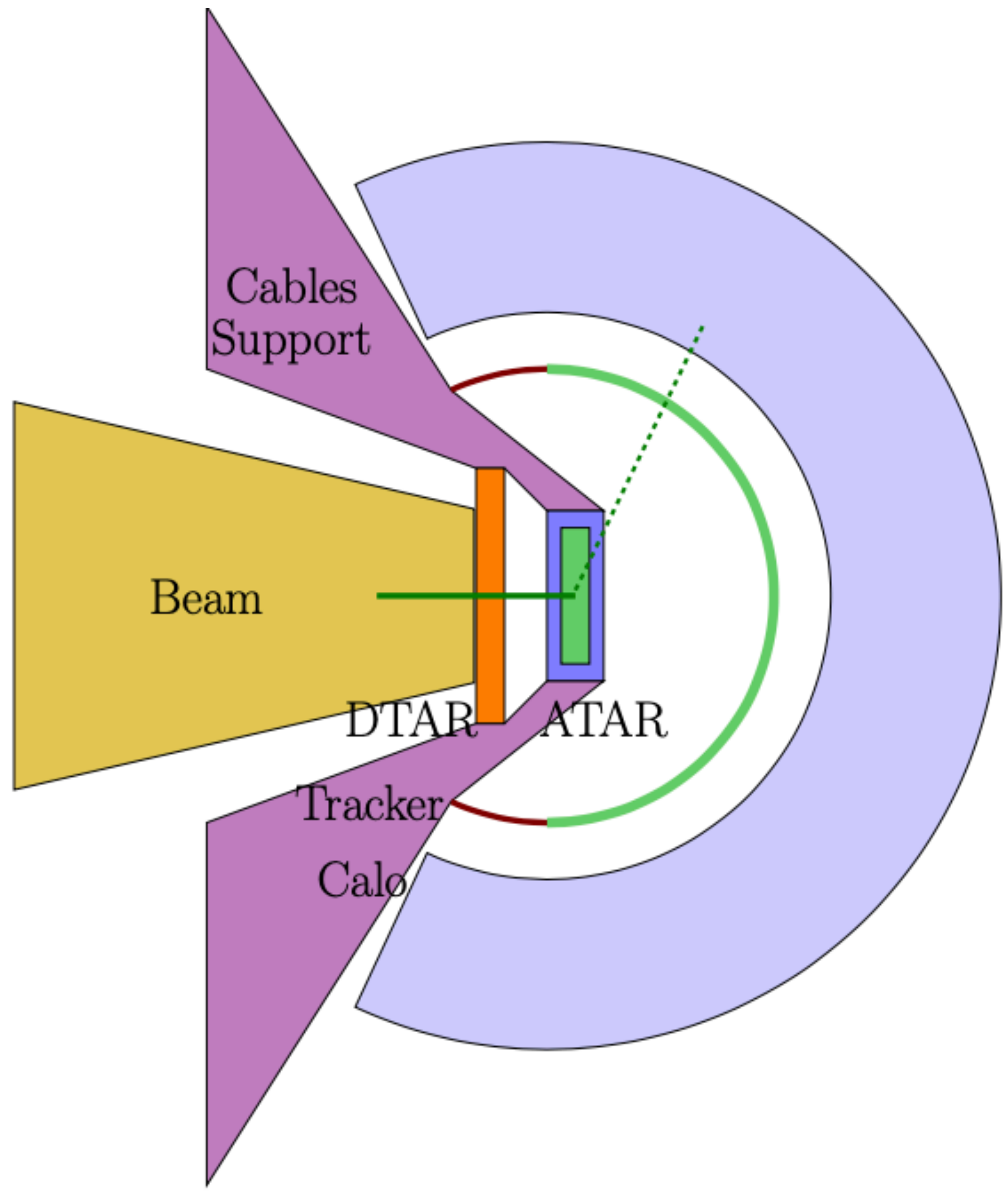
Collecting $\pi^+ \rightarrow \pi^0 e^+ \nu_e$ events

Assumes detector efficiency of 20% and typical PSI experiment runtime

Improvement over piBeta	Targeted statistical	Required number of	Number of years
Baseline	0.4	64047	N/A
x3	0.1	10^6	1
x6	0.05	4.10^6	4
x10	0.01	10^7	10

But this requires handling the beam at a rate of 3.10^7 pions / s

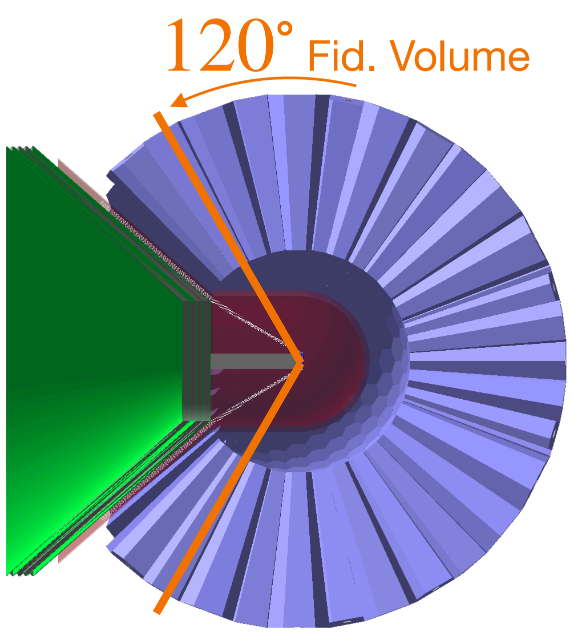
PIONEER Detector concept



PIONEER Detector conceptS

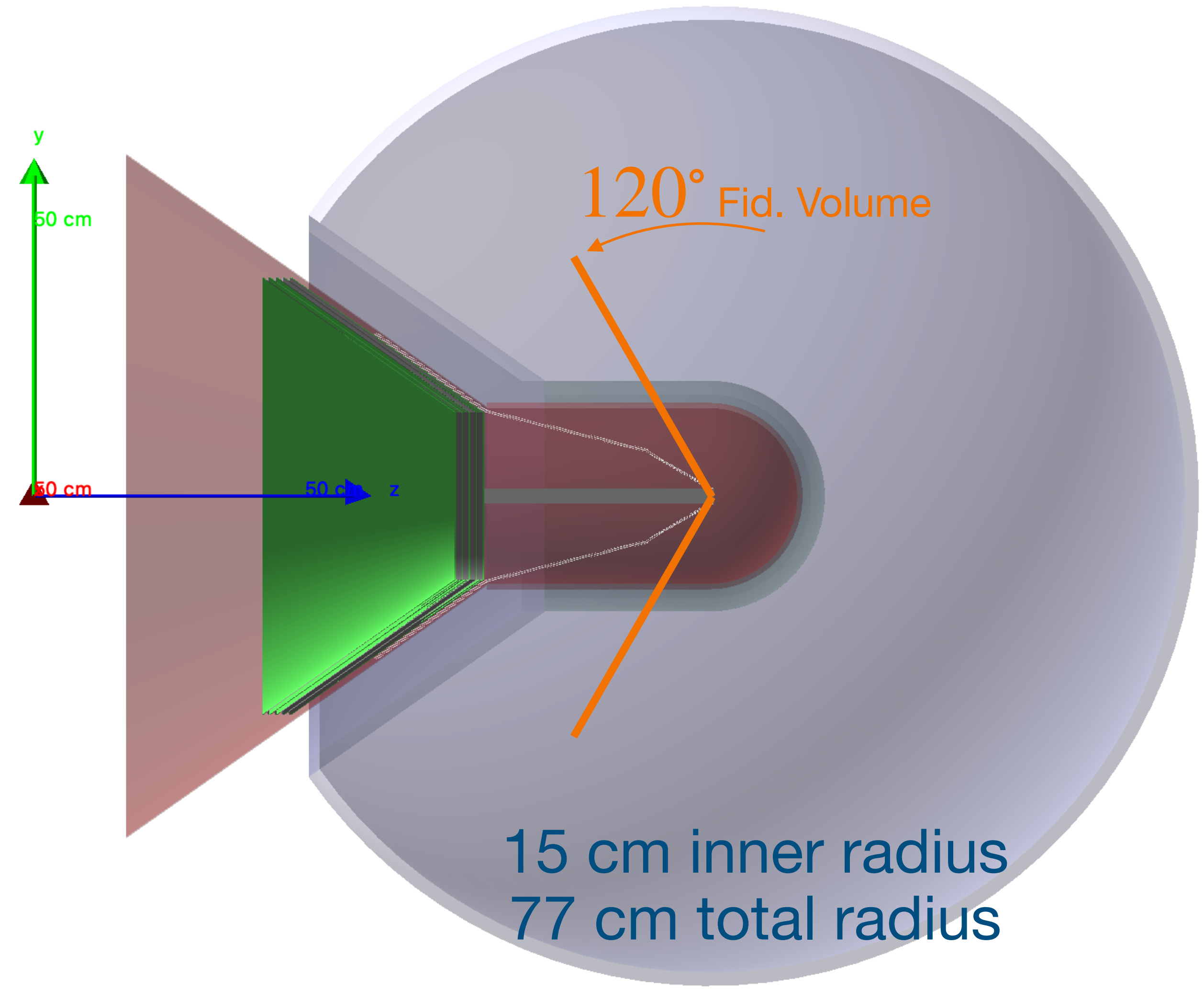
Two calorimeter options

LYSO Crystals



15 cm inner radius
42 cm total radius

Liquid Xenon

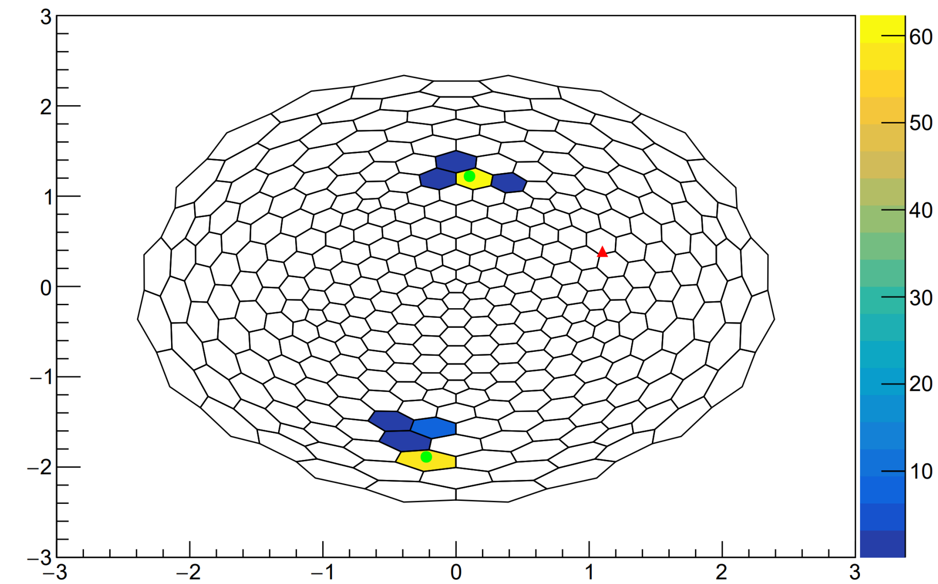


Size driven by shower containment
By far the priciest component of the system
Will build **one** for the entire life of the experiment (PHASE I-III)

Detecting $\pi^+ \to \pi^0 e^+ \nu_e$ events

The importance of segmentation

- Segmentation is necessary to distinguish gammas from each other and coincident particles
- A high density is necessary to limit pileup events that cannot be distinguished from the gammas
- Given the high probability of spatial overlap, a Liquid Xenon calorimeter is not favoured*



Calorimeter	Inner Radius	Molière Radius	Calo Surface Area*	pi-beta Area	Overlap Probability
PIBETA CsI	26 cm	3.5 cm	8495 cm^2	308 cm^2	3.6%
PIONEER LYSO	15 cm	2.07 cm	2827 cm^2	108 cm^2	3.8%
PIONEER LXe	15 cm	5.22 cm	2827 cm^2	685 cm^2	24.2%

* without making some significant changes to the design (add a magnet?)

Detecting $\pi^+ \rightarrow \pi^0 e^+ \nu_e$ events

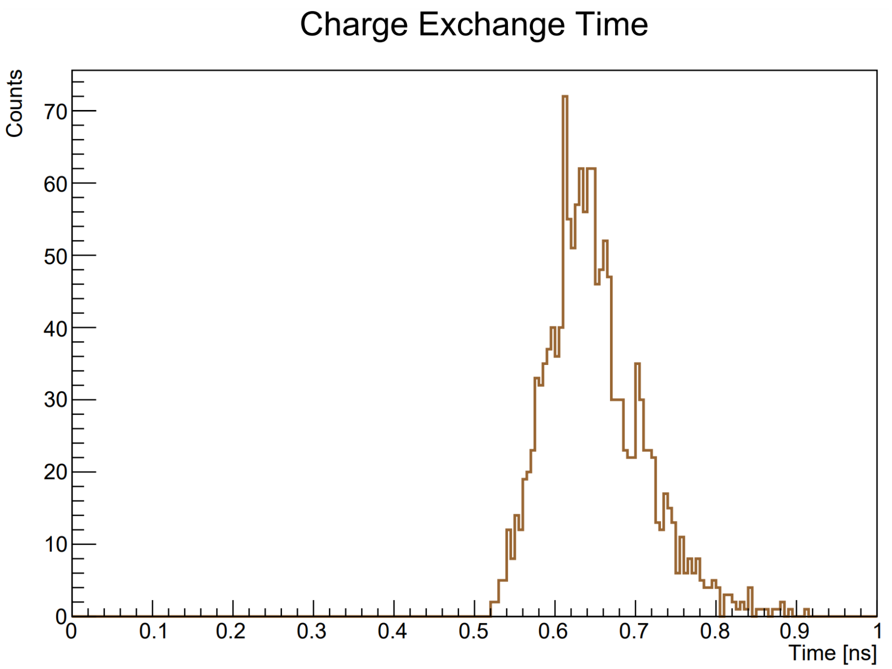
Charge exchange process

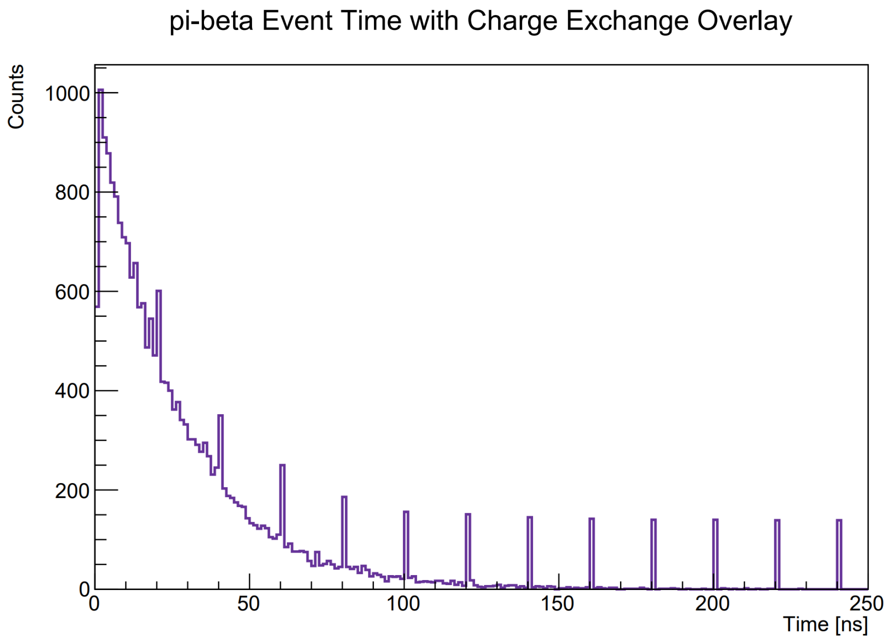
Pion charge exchange $\pi^+ + n \rightarrow \pi^0 + p$
looks like the pion beta decay in the calorimeter

These charge exchange events occur promptly

A 1 (2) ns cut around RF times would remove
100% of charge exchange events

Such a cut would retain
77 (95)% of the pion beta decay events

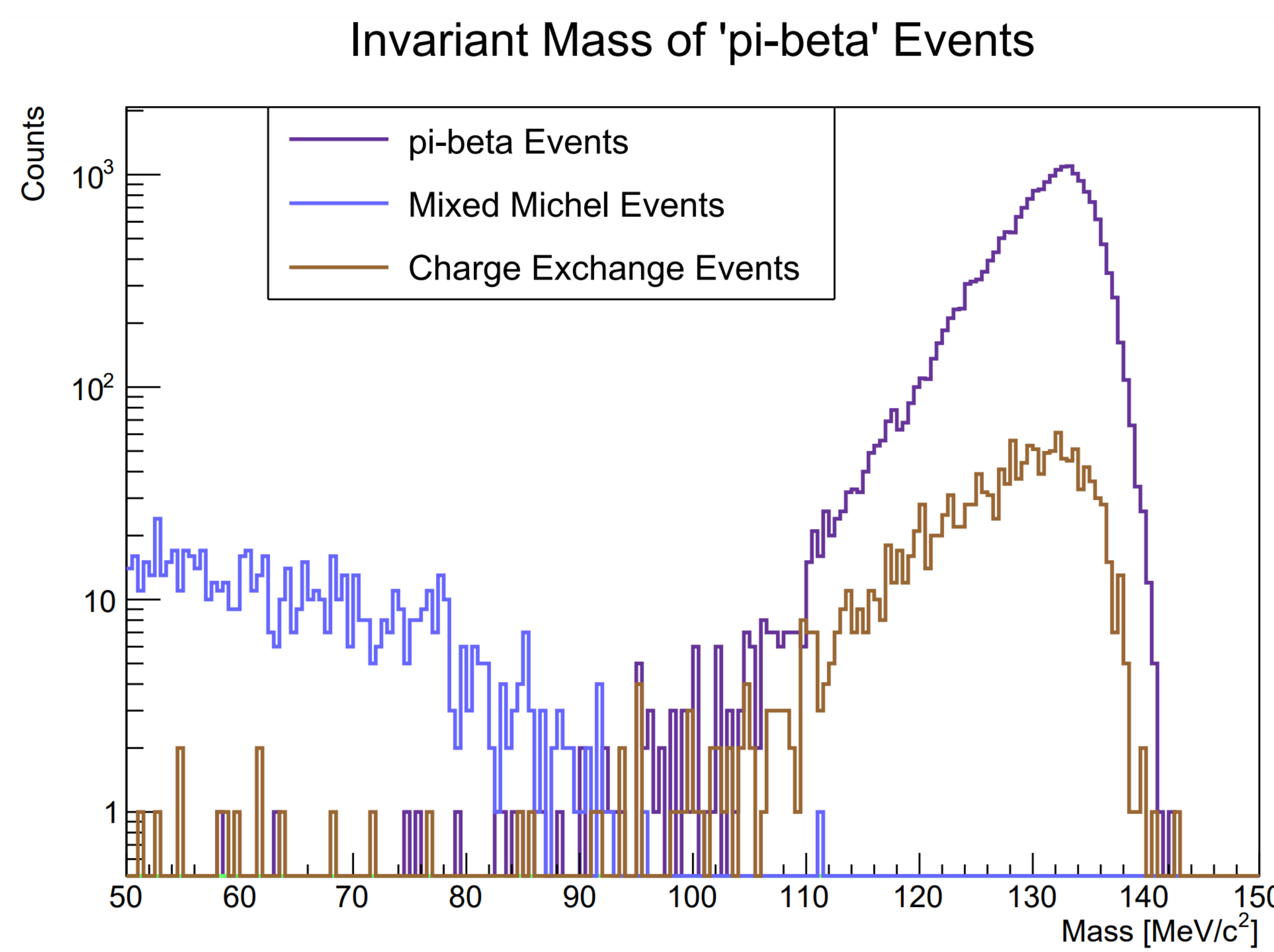




Detecting $\pi^+ \rightarrow \pi^0 e^+ \nu_e$ events

Mass reconstruction

- Mixed Michel events:
  - $\pi \rightarrow \mu(\rightarrow e\nu\nu)\nu$ is 10^8 more frequent than $\pi^+ \rightarrow \pi^0 e^+ \nu$
  - Muon life time is 2.2 μs while the pion lifetime is 26 ns
  - We expect a continuum of positron (ranging from 0 to 53 MeV) in the detector
  - Many will happen in time coincidence
- Ability to reconstruct the photon pair invariant mass alleviate the issue for collecting $\pi^+ \rightarrow \pi^0 e^+ \nu$ events



Relative rates of Michel Pileup and Charge Exchange to pi-beta are not to scale

The piBeta experiment

Uncertainty budget

Phys. Rev. Lett. 93, 181803

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	$N^{accid}_{\pi\beta}$	0	<0.1
	f_{CPP} correction	0.9951	0.10
	f_{ph} correction	0.9980	0.10
Combined internal			0.38
Statistical	$N_{\pi\beta}$	64 047	0.395

0.01%

PIONEER Phase I

0.04%

PIONEER will be able to collect $\pi^+ \to \pi^0 e^+ \nu$ efficiently

The piBeta experiment

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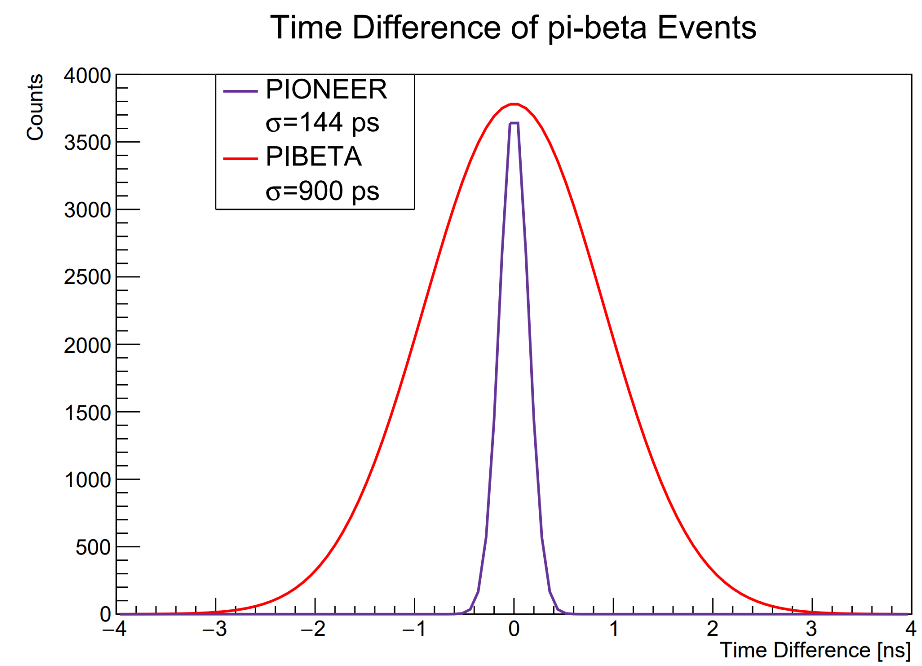
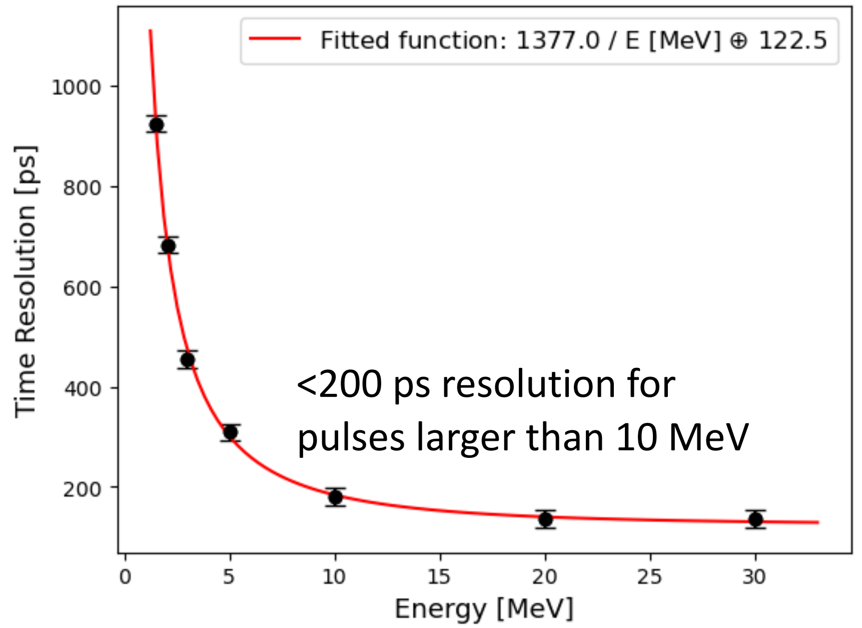
Gate Fraction Ratio $(r_{\pi G} = f_{\pi G}^{\pi\beta} / f_{\pi G}^{\pi e2})$

- 0.26% Uncertainty in PiBeta Experiment
- This is the probability the decay occurs in some data collection window
- The uncertainty is primarily from determining window opening
    - PiBeta triggered on the beam and the calorimeter and used a 10ns hardware veto
    - Some delay is needed to remove charge exchange events
    - Thus, the gate opening time needed to be determined from experimental data
    - This method includes more $\pi\beta$ events, maximising useful statistics
- PIONEER timing resolution should be much better and alleviate this issue



LYSO Test beam result: https://arxiv.org/abs/2409.14691



The piBeta experiment

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0.01%

0.04%

The piBeta experiment

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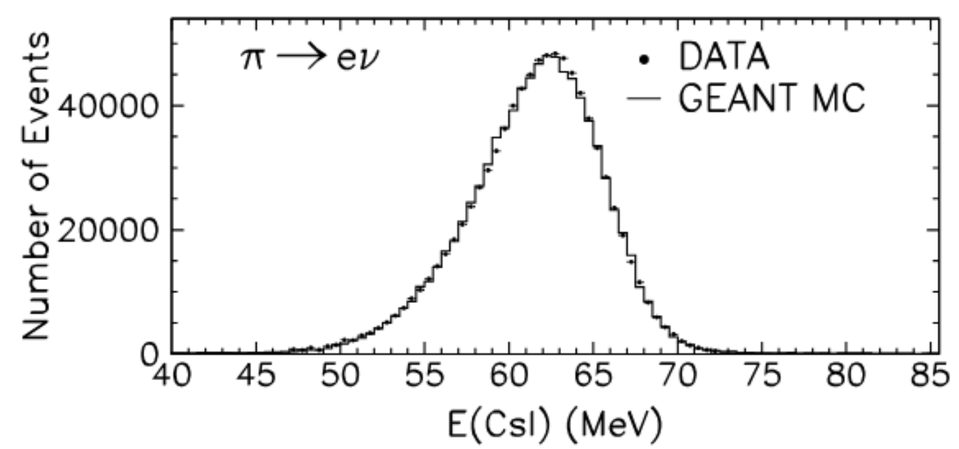
	f_{ph} correction	0.9980	0.10	
Combined internal			0.38	
Statistical	$N_{\pi\beta}$	64 047	~~0.505~~	0.04%

$\pi^+ \rightarrow e^+\nu_e$ Count ($N^{tot}_{\pi e2}$)

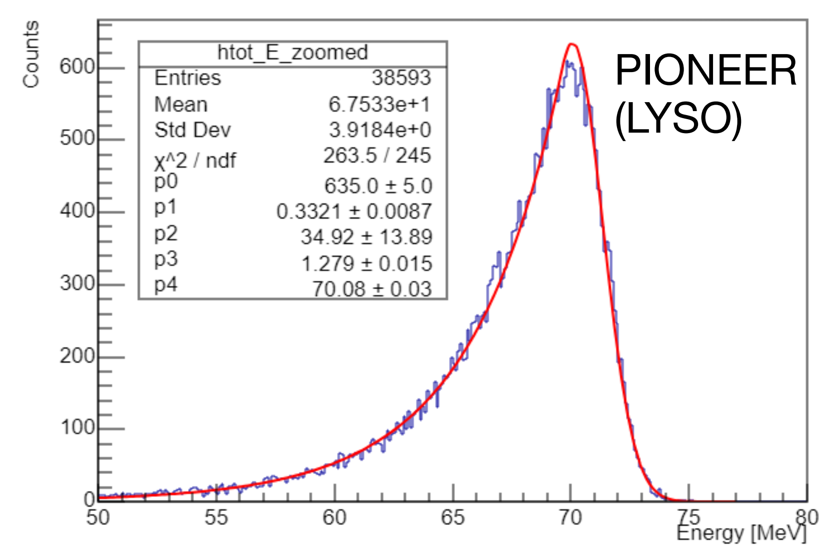
- 0.19% Uncertainty in PiBeta Experiment
- Uncertainty primarily from measuring the tail of $\pi^+ \rightarrow e^+\nu_e$ — The PiBeta experiment used Monte Carlo estimates
    - PIONEER should have a better understanding of the tail fraction from Phase I — the fraction will change if the target is changed for phase II
    - PIONEER's increased calorimeter depth will greatly decrease the tail size compared to PiBeta (20 RL vs 12 RL)
- The **PIONEER ATAR** will provide a huge performance boost to reveal the tail

➡ **More quantitative estimates needed**

PiBeta Experiment



Energy Resolution 70 MeV -- 1.82%

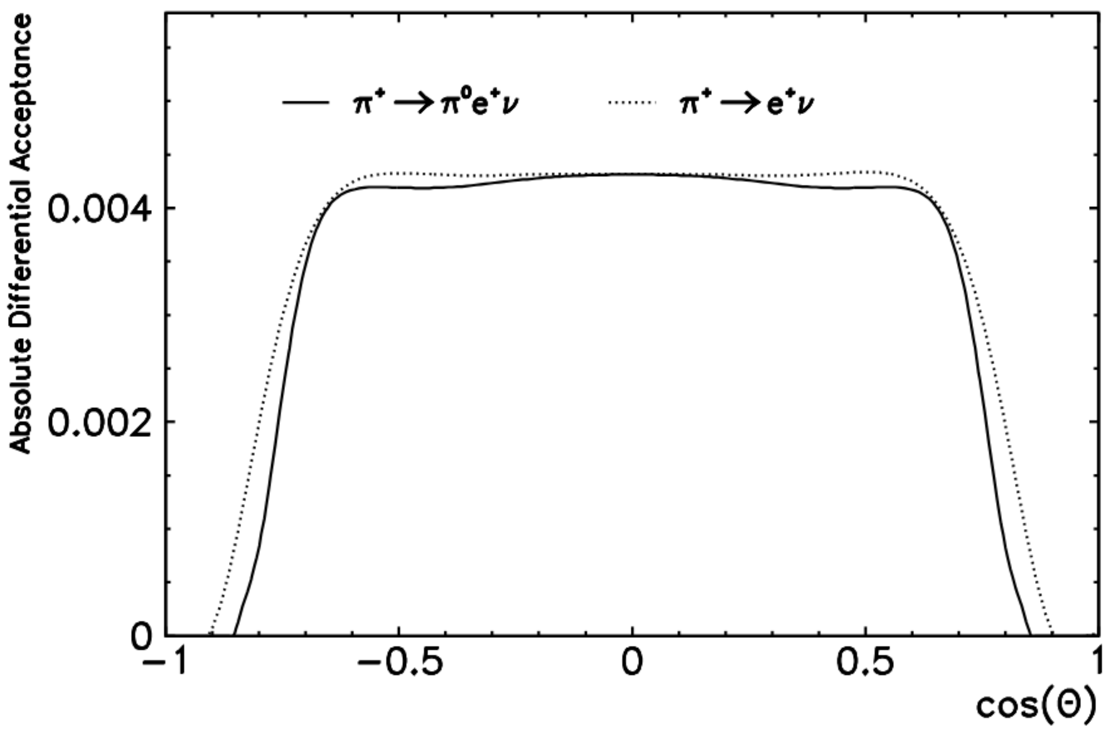


PIONEER (LYSO)

Acceptance Ratio ($A_{\pi\beta}^{HT} / A_{\pi e2}^{HT}$)

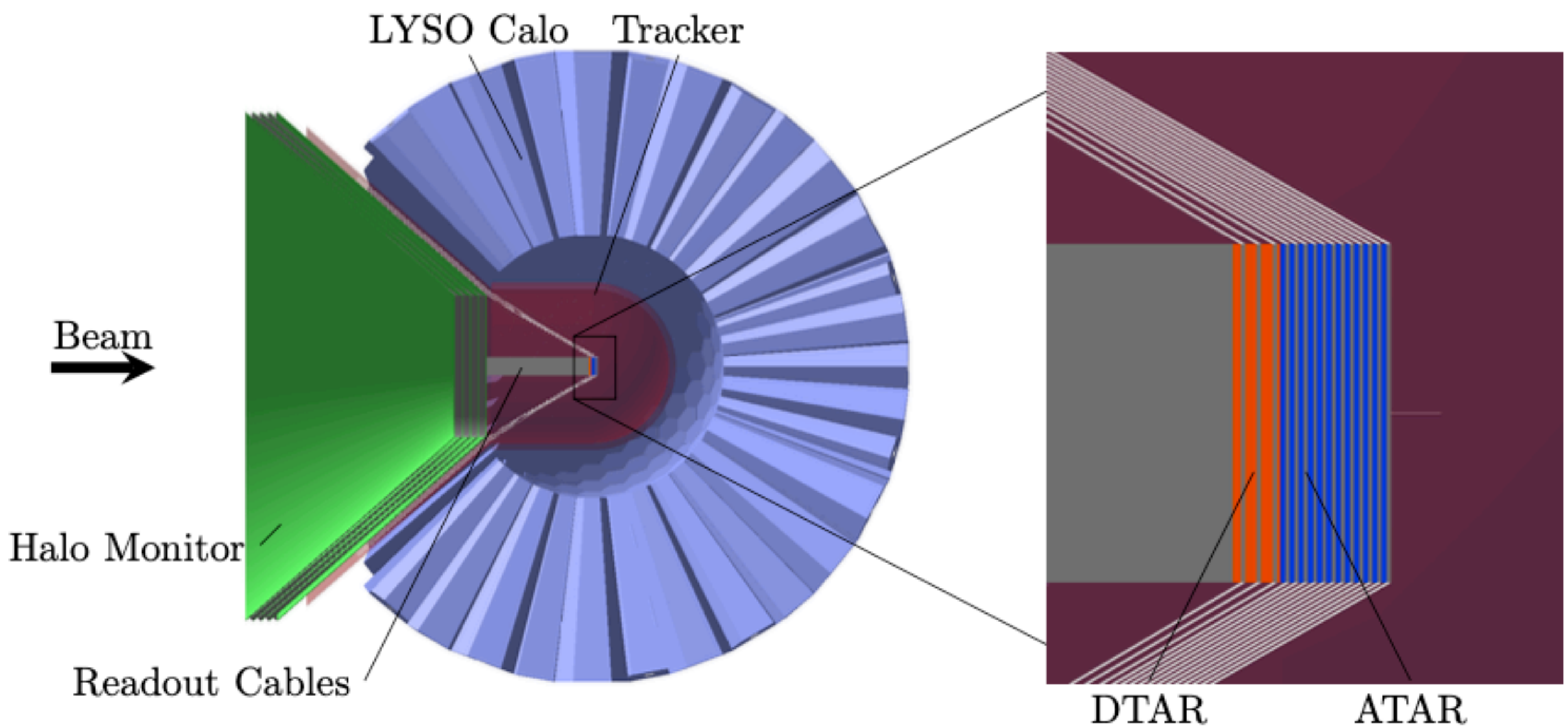
- 0.12% Uncertainty in PiBeta Experiment
- Acceptance uncertainty dominated by uncertainty in **pion stop distribution**
- PiBeta backtracked charged particles from their trackers to the target to determine the pion stop distribution (50 micron uncertainty)
- The **PIONEER ATAR** and tracker should be able to improve this precision

➡ **More quantitative estimates needed**



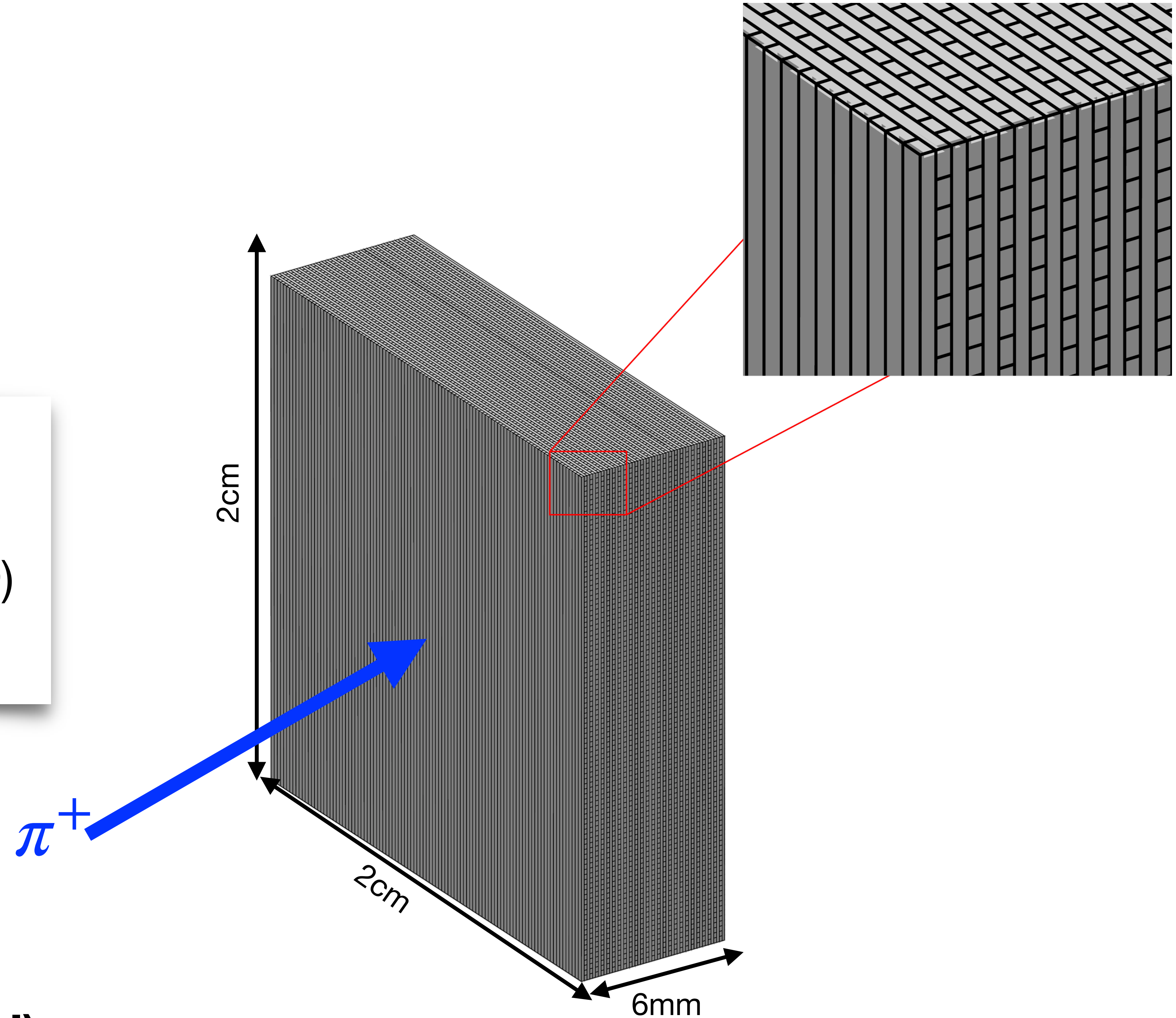
PIONEER's Active Target (ATAR)

The heart of the experiment



ATAR Design

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



Thickness must be increased to 1.1cm for PHASE II-III (for a pion momentum of 85 MeV/c)

Tentative design (PHASE I)

48 layers: 120 μm thick

100 strips per layer with 200 μm pitch covering 2x2 cm^2 area

Layers packed by 2 with rotating orientation for 3D position determination

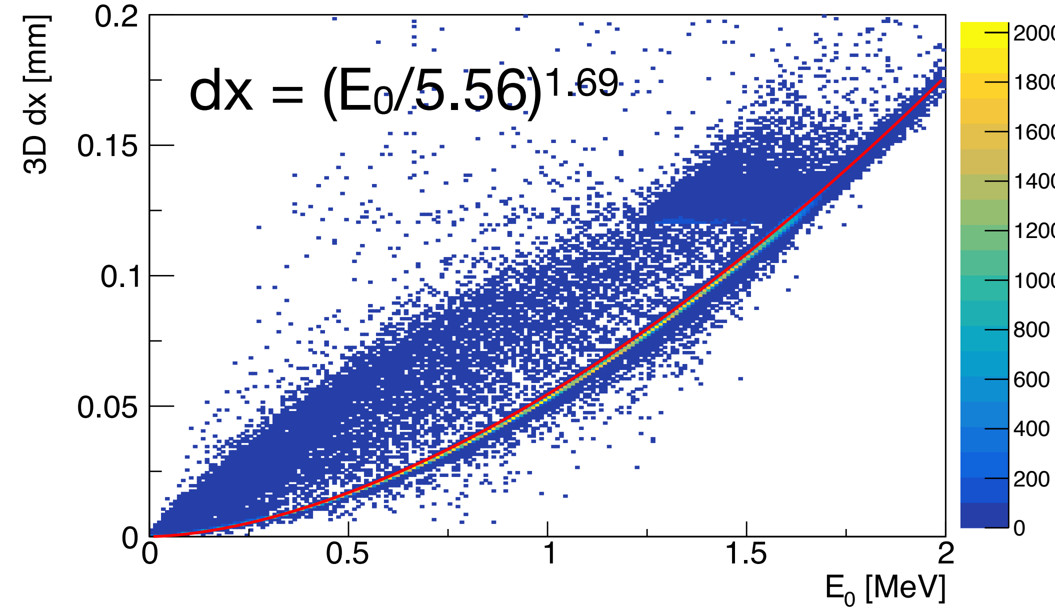
Active Target

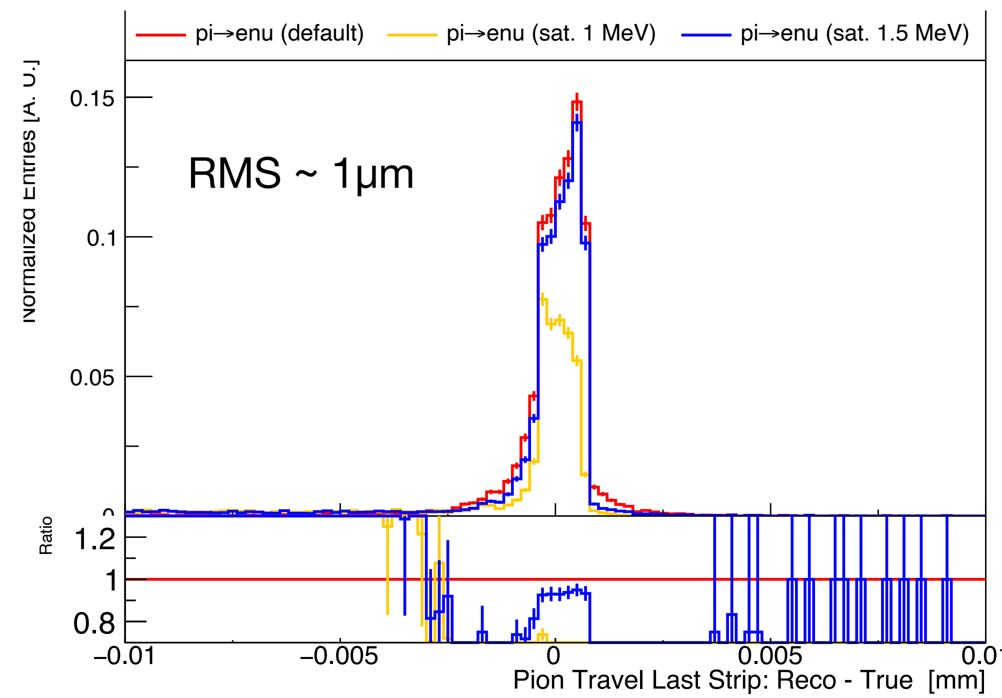
Deliverables

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

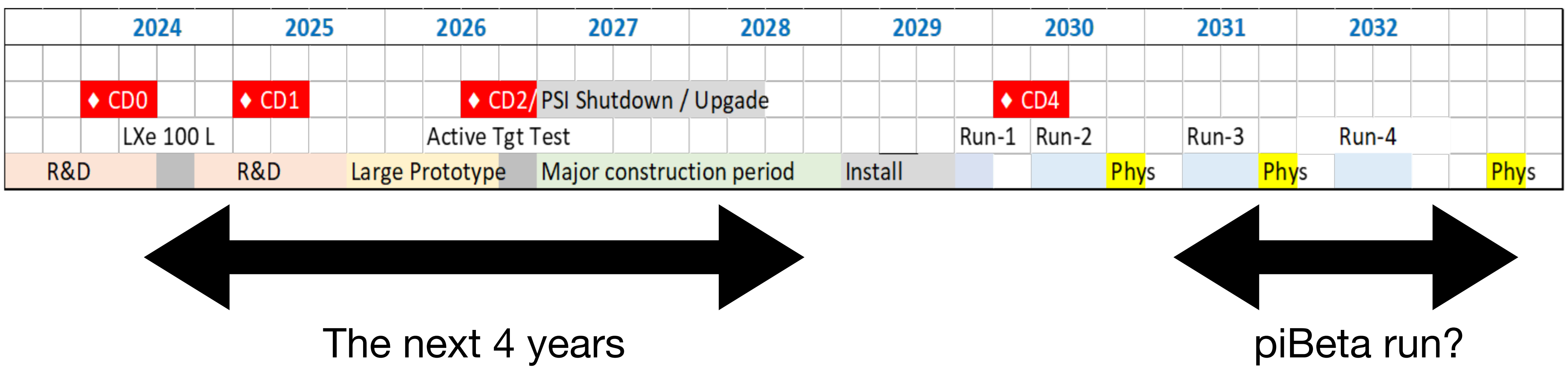
Pion stop determined with 1 μm precision
piBeta had a precision of 50 μm

Opportunities to redesign the measurement strategy and count all the stopping pions?





PIONEER Timeline

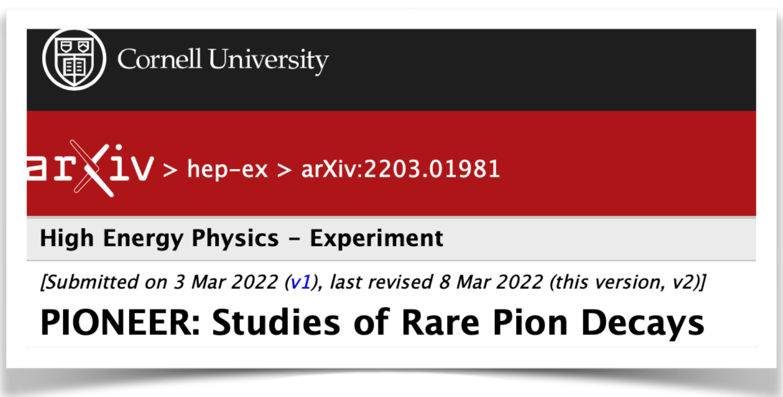


Detector R&D in calorimetry and tracking

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, …

A growing collaboration


Cornell University

arXiv > hep-ex > arXiv:2203.01981

High Energy Physics – Experiment

[Submitted on 3 Mar 2022 (v1), last revised 8 Mar 2022 (this version, v2)]

PIONEER: Studies of Rare Pion Decays

Project approved by PSI in 2022

October 2023 collaboration meeting in Seattle

Opportunities for $R_{\pi\beta}$

Presented preliminary studies on piBeta

> Most of them carried by Bradley Taylor, a junior PhD student at UW

Many opportunities to get involved!

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

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PIONEER