UNIVERSITY of WASHINGTON

PIONEER a next generation Rare Pion Decay Experiment

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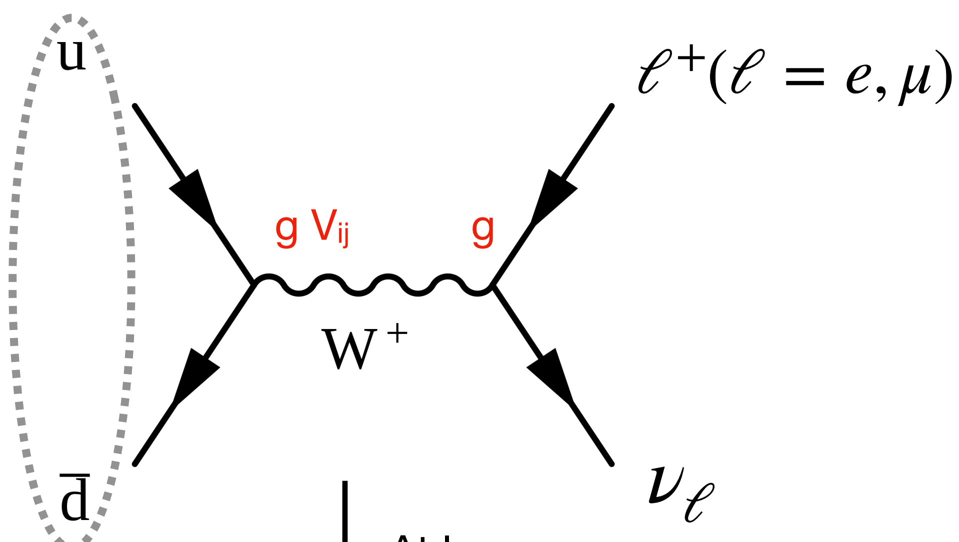
INSTITUTE for NUCLEAR THEORY

Testing the SM in Charged-Weak Decays - Jan 12-16, 2026

PIONEER

Tests of the weak interaction in rare pion decays

Charged pion
(quark model)



At low energy

$$G_F^{(\beta)} \sim \frac{g^2 V_{ij}}{M_W^2}$$

Weak (β) Decay

Lepton Flavour Universality

$$\left[G_F^{(\beta)}\right]_e / \left[G_F^{(\beta)}\right]_\mu = 1$$

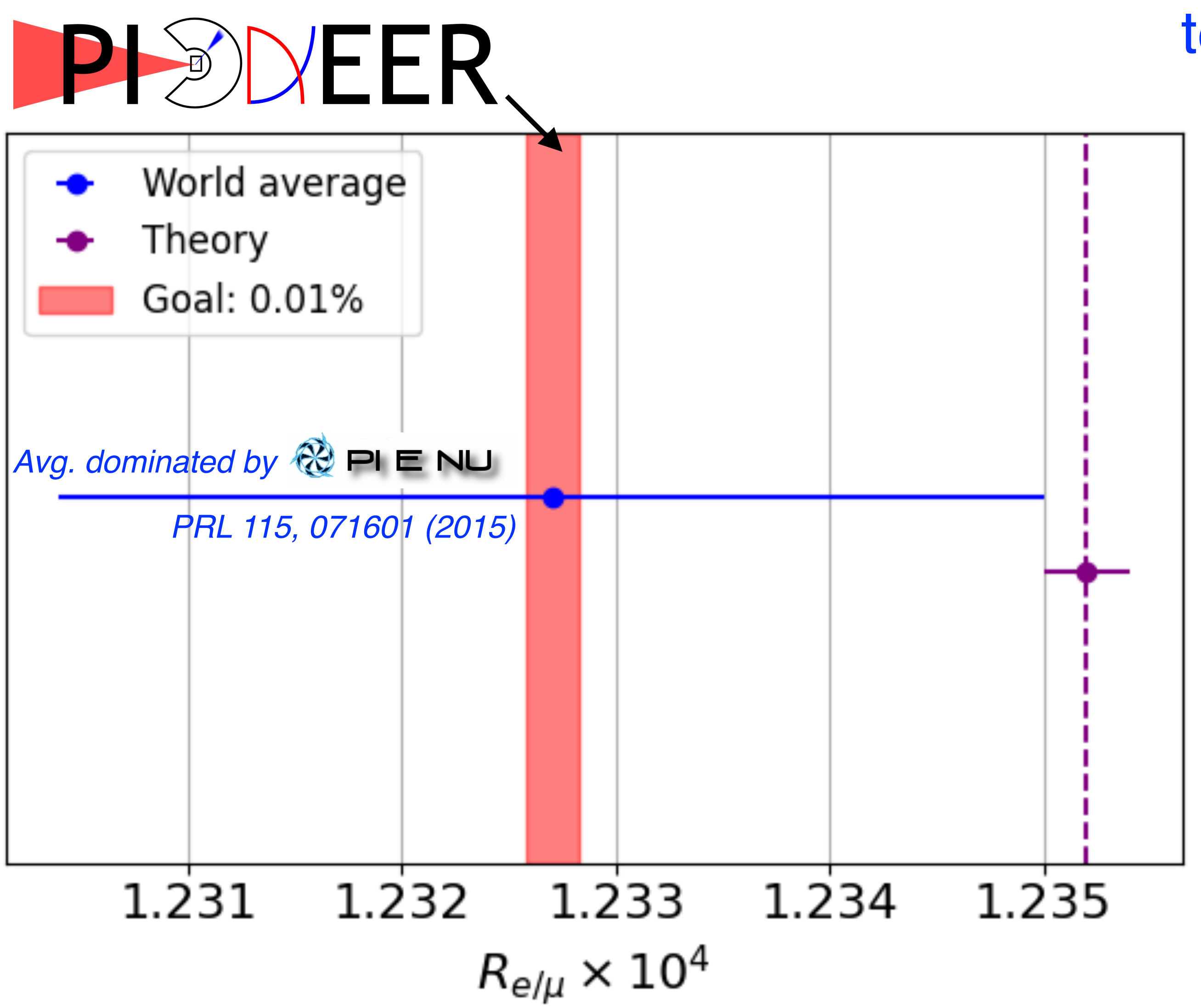
Cabbibo Universality

$$|V_{ud}|^2 + |V_{us}|^2 + |V_{ub}|^2 = 1$$

PIONEER Physics Case I

Lepton Flavor Universality

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



Best measurement from PIENU at TRIUMF tested Lepton Flavour Universality at $O\left(10^{-3}\right)$

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

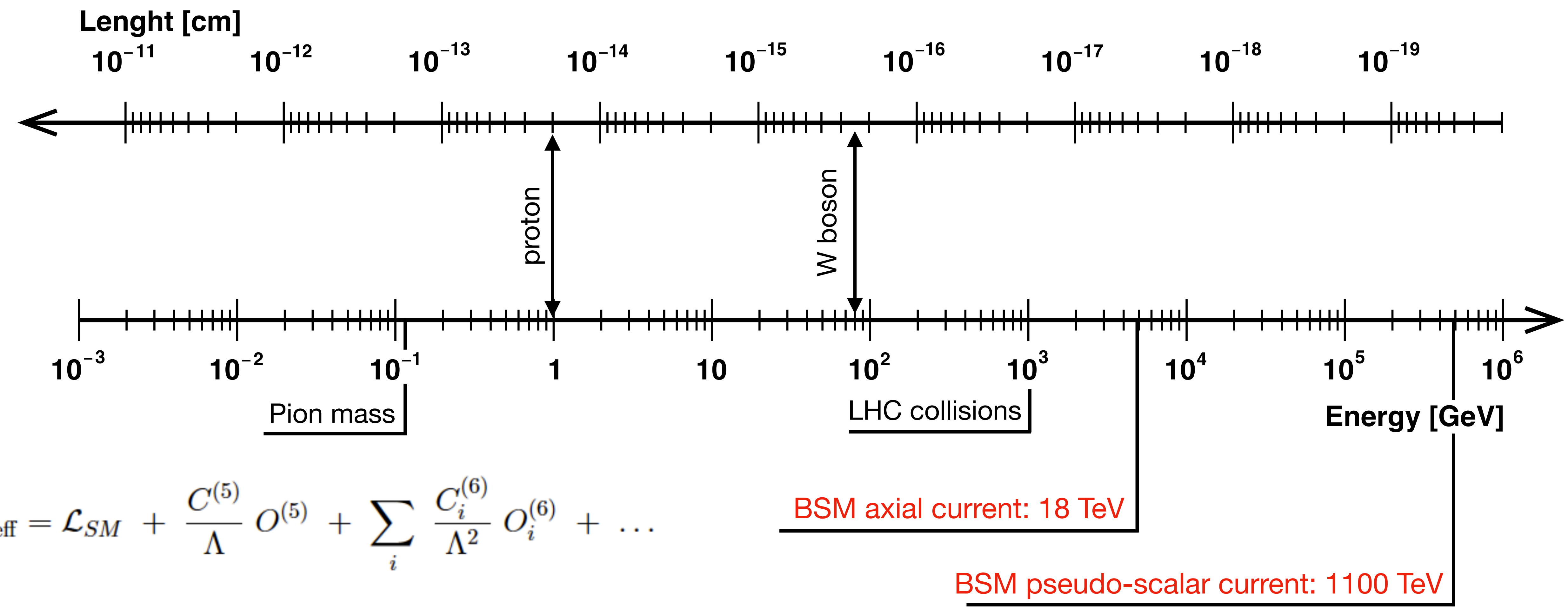
To match the precision of the SM prediction:

➡ PIONEER aims to measure $R_{e/\mu}$ to 0.01% precision

➡ 15-fold improvement over the current world best

PIONEER Physics Case I

BSM Reach of LFU test



$$\mathcal{L}_{\text{eff}} = \mathcal{L}_{SM} + \frac{C^{(5)}}{\Lambda} O^{(5)} + \sum_i \frac{C_i^{(6)}}{\Lambda^2} O_i^{(6)} + \ldots$$

Systematic analysis of all possible operators

Sensitivity up to the ~ PeV scale!

V. Cirigliano et al., JHEP02(2013)046
V Cirigliano et al., NPB2009.12.020

PIONEER Physics Case I

Side note: EFT formalism(s)

PIONEER submission to the European strategy for Particle Physics Update: arXiv:2504.06375

Conversion of the ϵ formalism from Bhattacharya et al. (PRD85.054512) to SMEFT operators

$$r = \frac{R_{e/\mu}}{R_{e/\mu}^{\mathrm{SM}}} = 1 + 2\left(\epsilon_L^{ee} - \epsilon_L^{\mu\mu}\right) - 2B_0\left(\frac{\epsilon_P^{ee}}{m_e} - \frac{\epsilon_P^{\mu\mu}}{m_\mu}\right)$$

with $B_0(\mu_{\mathrm{ren}}) = M_\pi^2/(m_u(\mu_{\mathrm{ren}}) + m_d(\mu_{\mathrm{ren}}))$

Axial current

$$\epsilon_L^{ee} - \epsilon_L^{\mu\mu} = \left[C_{Hl}^{(3)}\right]^{ee} - \left[C_{Hl}^{(3)}\right]^{\mu\mu} - \frac{1}{V_{ud}}\left(\left[C_{lq}^{(3)}\right]^{ee11} - \left[C_{lq}^{(3)}\right]^{\mu\mu11}\right)$$

Pseudo-scalar current

$$\epsilon_P^{\alpha\alpha} = \frac{1}{2V_{ud}}\left[C_{ledq}^{\dagger} - C_{lequ}^{(1)\dagger}V\right]^{\alpha\alpha11}$$

PIONEER Physics Case I

Comparison with other LFU probes

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

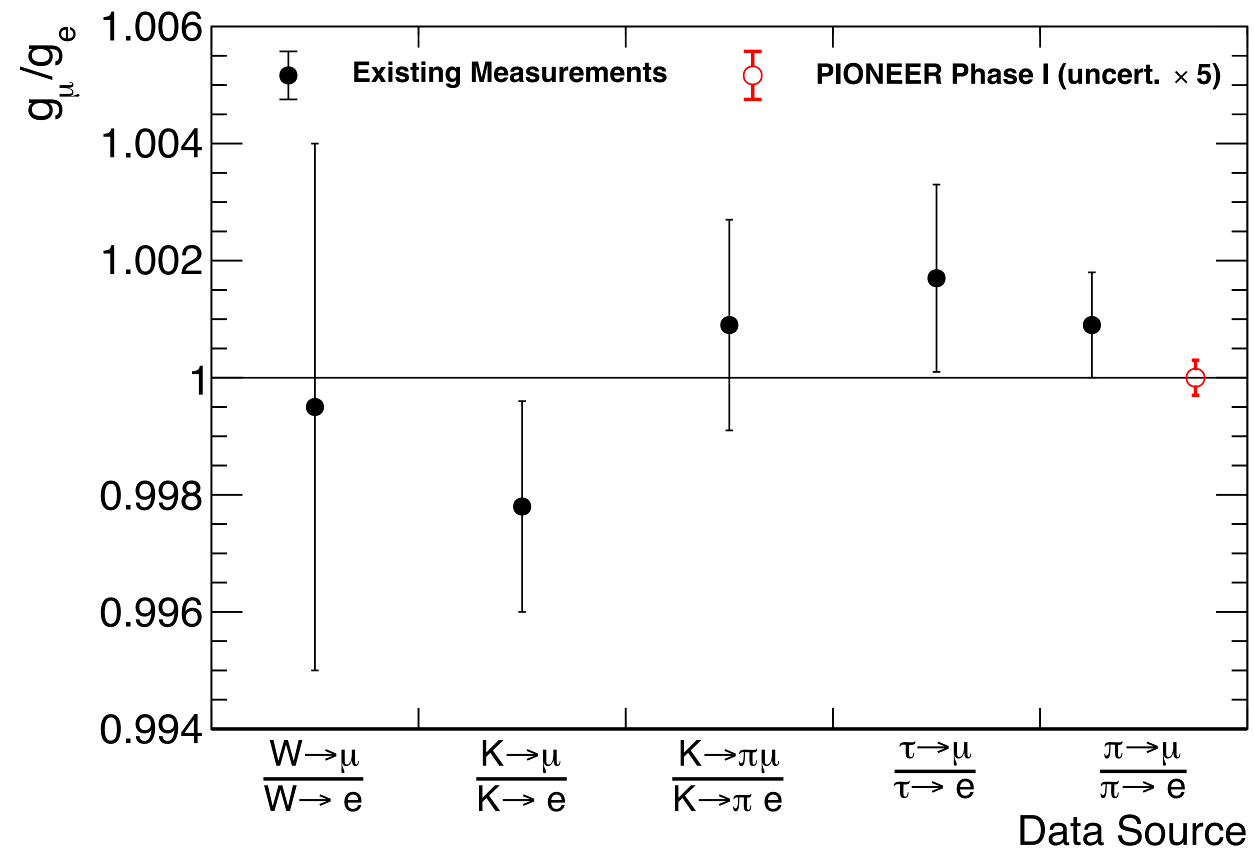
Formalism from Pich, 2012.07099
and Bryman et al, 2111.05338, ARNPS

Neglecting flavour-changing terms

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

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

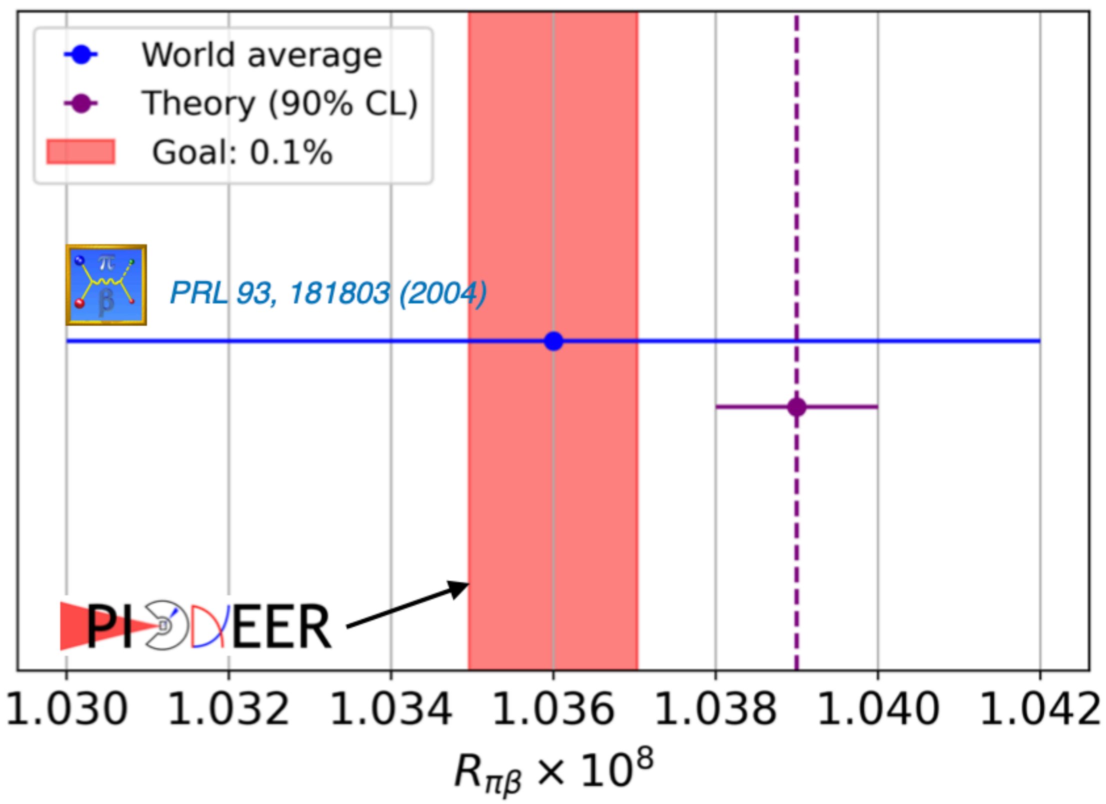
Charged pions are the most powerful probe of $\epsilon_{\mu\mu} - \epsilon_{ee}$



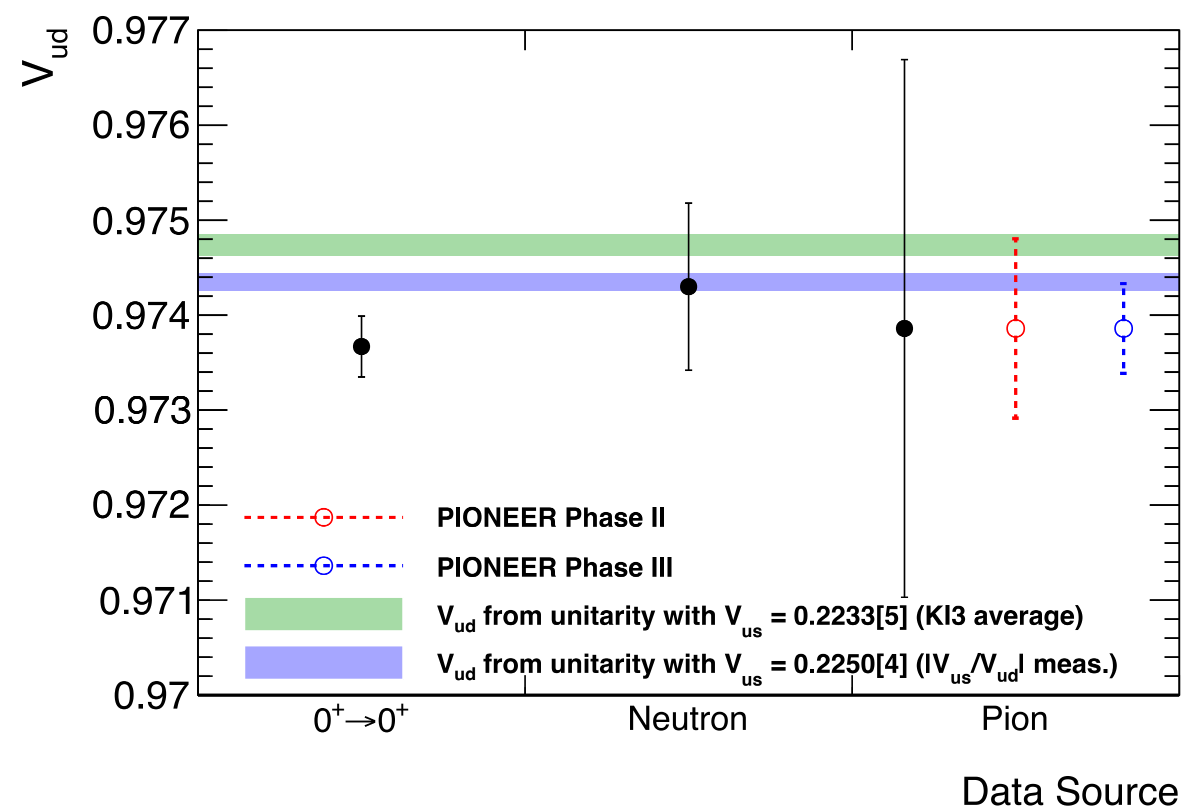
PIONEER Physics Case II

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



Phase II-III of the project

PIONEER Physics Case III

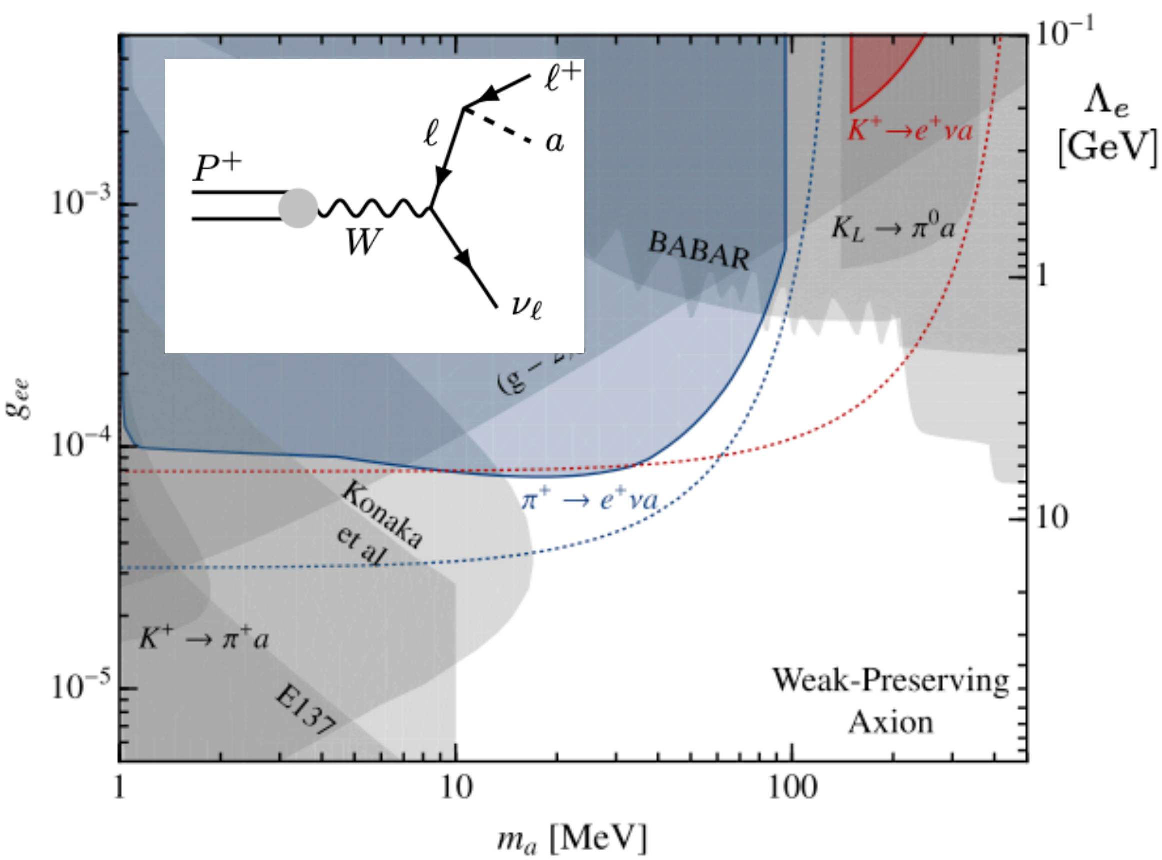
Exotic decays of the charged pion

Goal of PIONEER

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

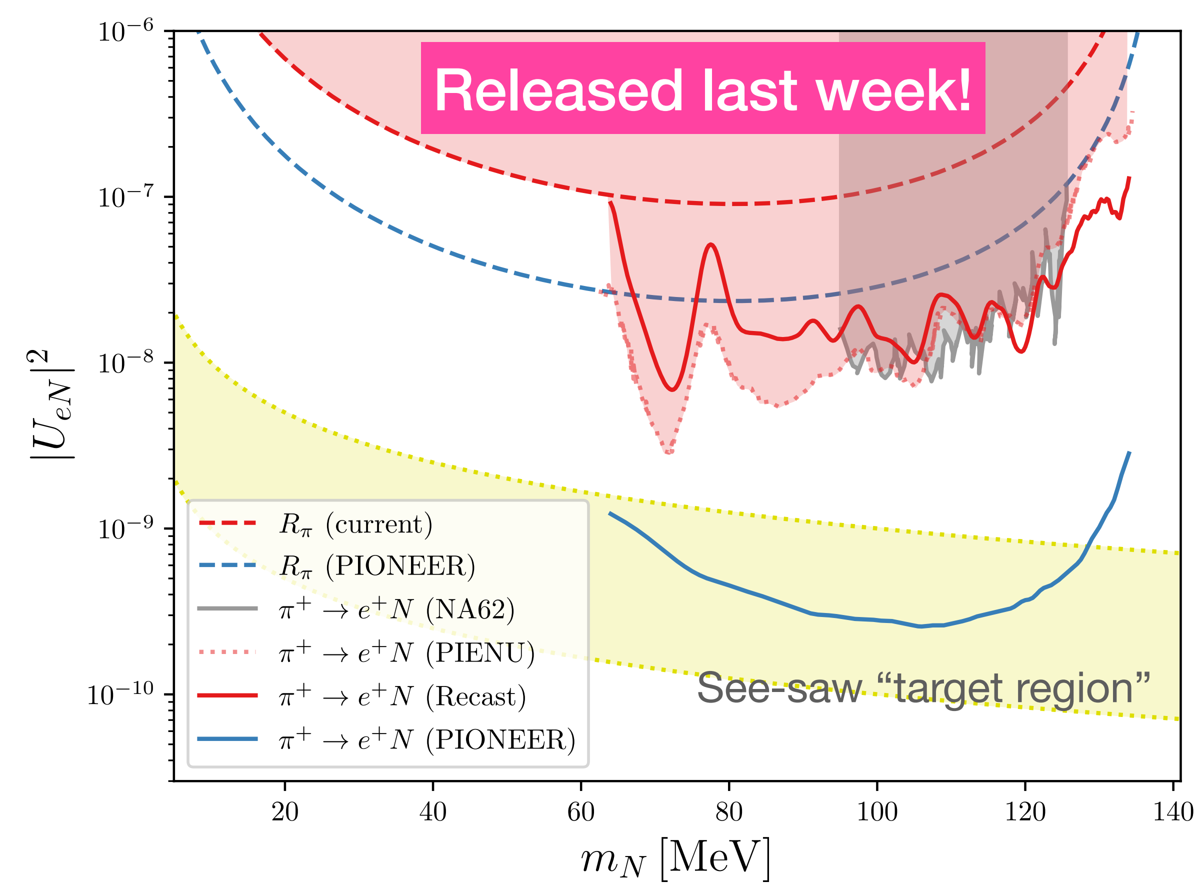
Searches profit from the very large datasets
needed for $R_{e/\mu}$ measurement

Lepto-philic axion



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

Sterile neutrino



W. Altmannshofer, J. Dror, et al.
arXiv:2601.06254

Outline

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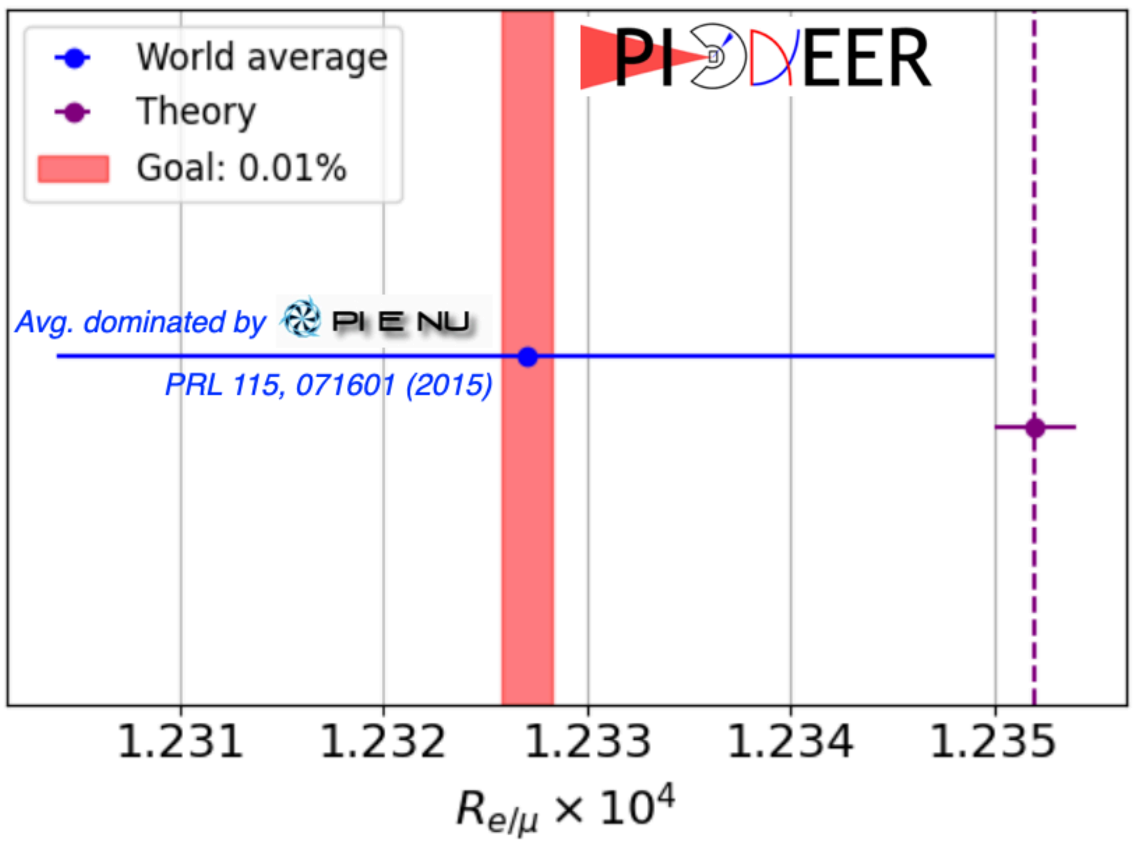


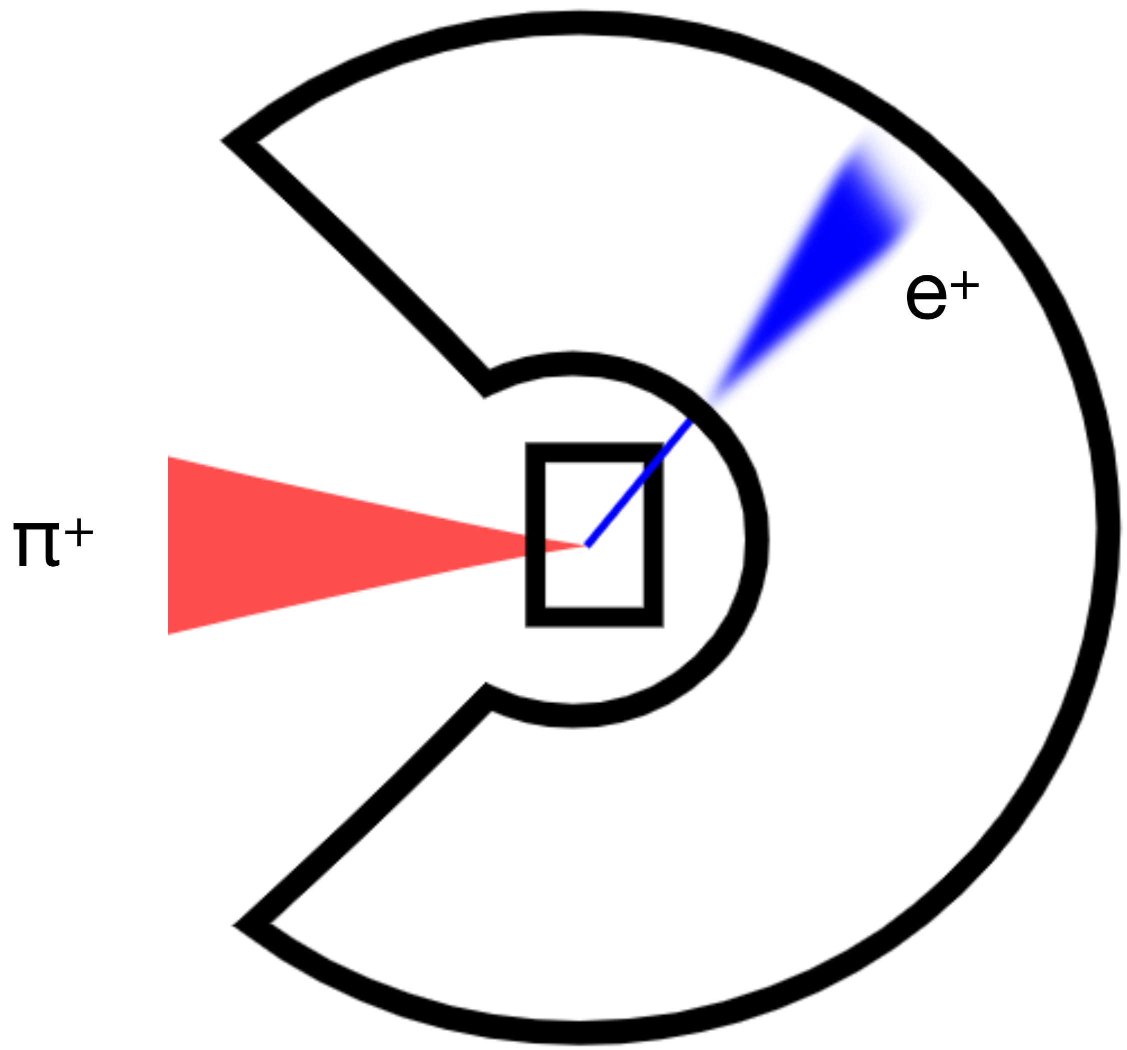
Focus of this talk:

LFU measurement strategy and PIONEER design guiding principles

Update on R&D and simulation efforts

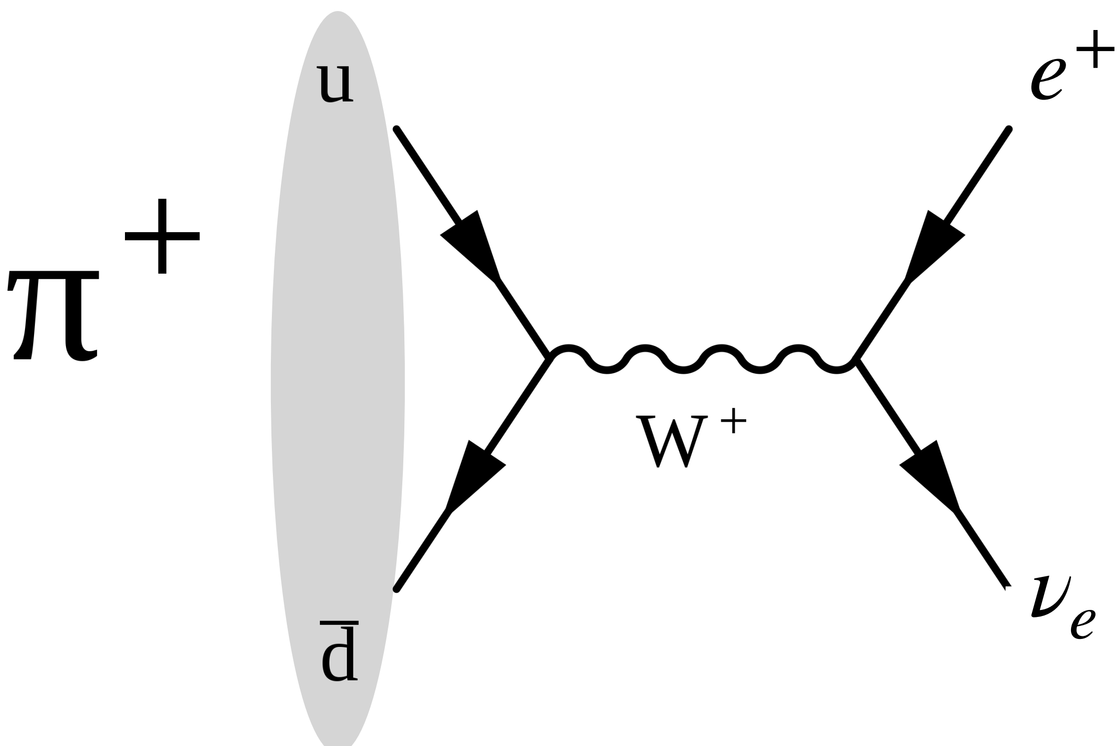
Thoughts and (very) preliminary results on piBeta

Introducing PIONEER



Introducing PIONEER

$R_{e/\mu}$ measurement strategy



$m_{\pi^+} = 139.6\,\text{MeV}$
$\tau_{\pi^+} \approx 26\,\text{ns}$

The pion stops in the target and decays

Introducing PIONEER

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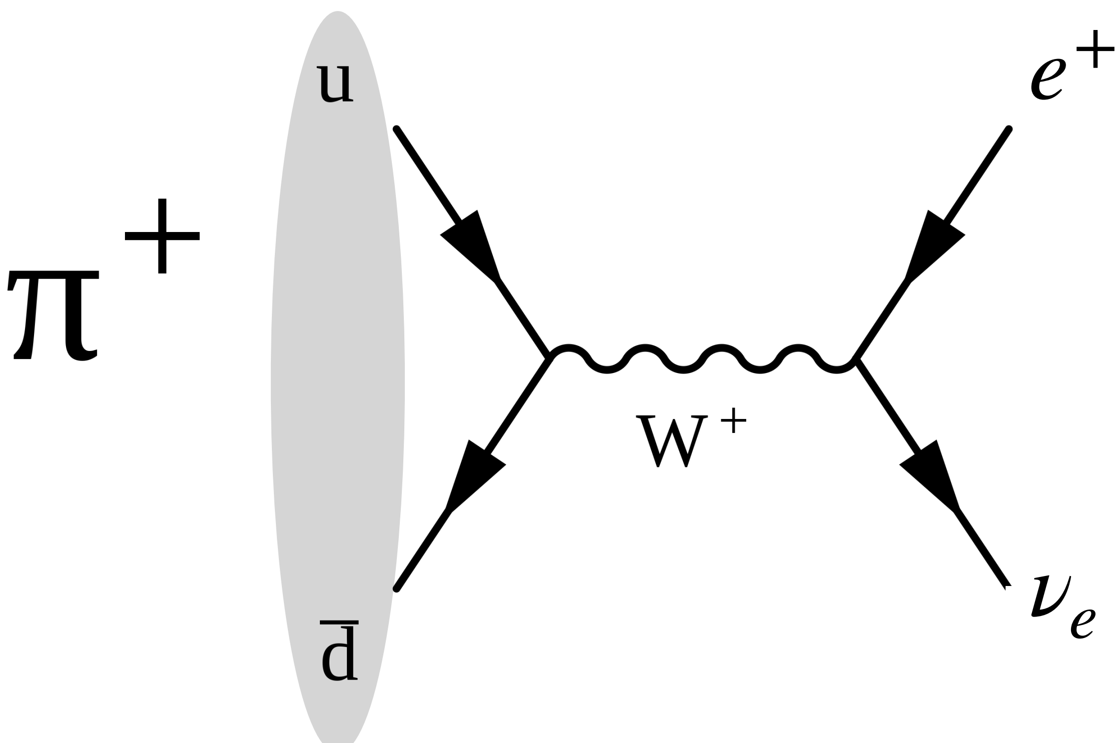

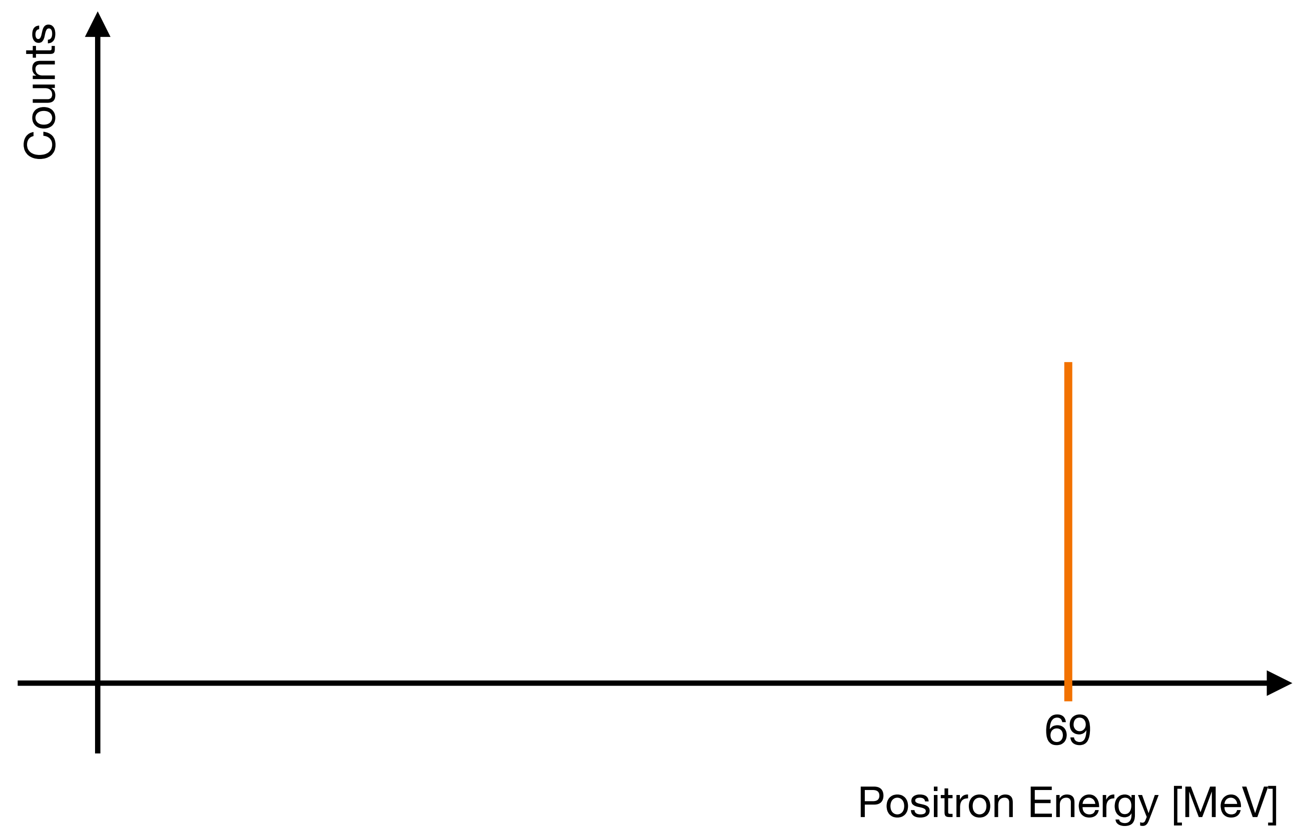

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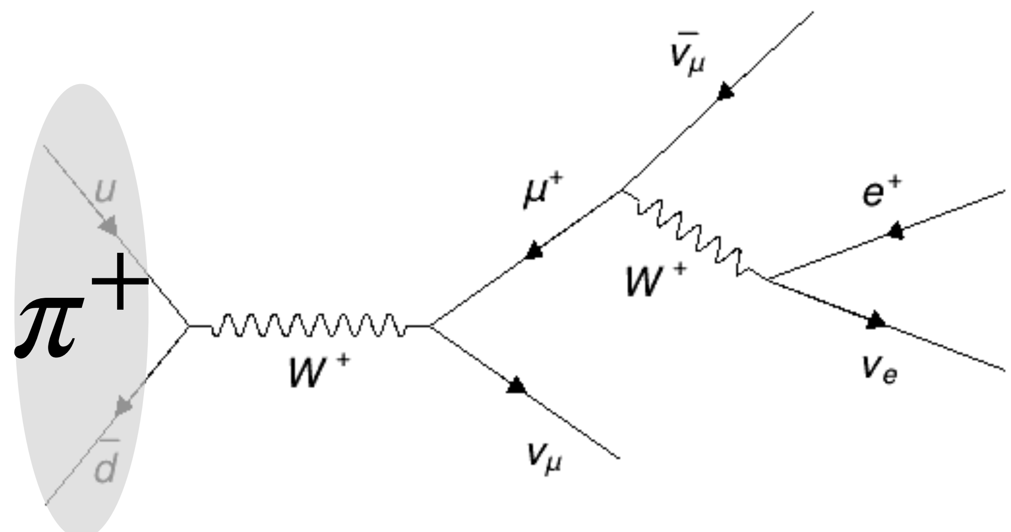


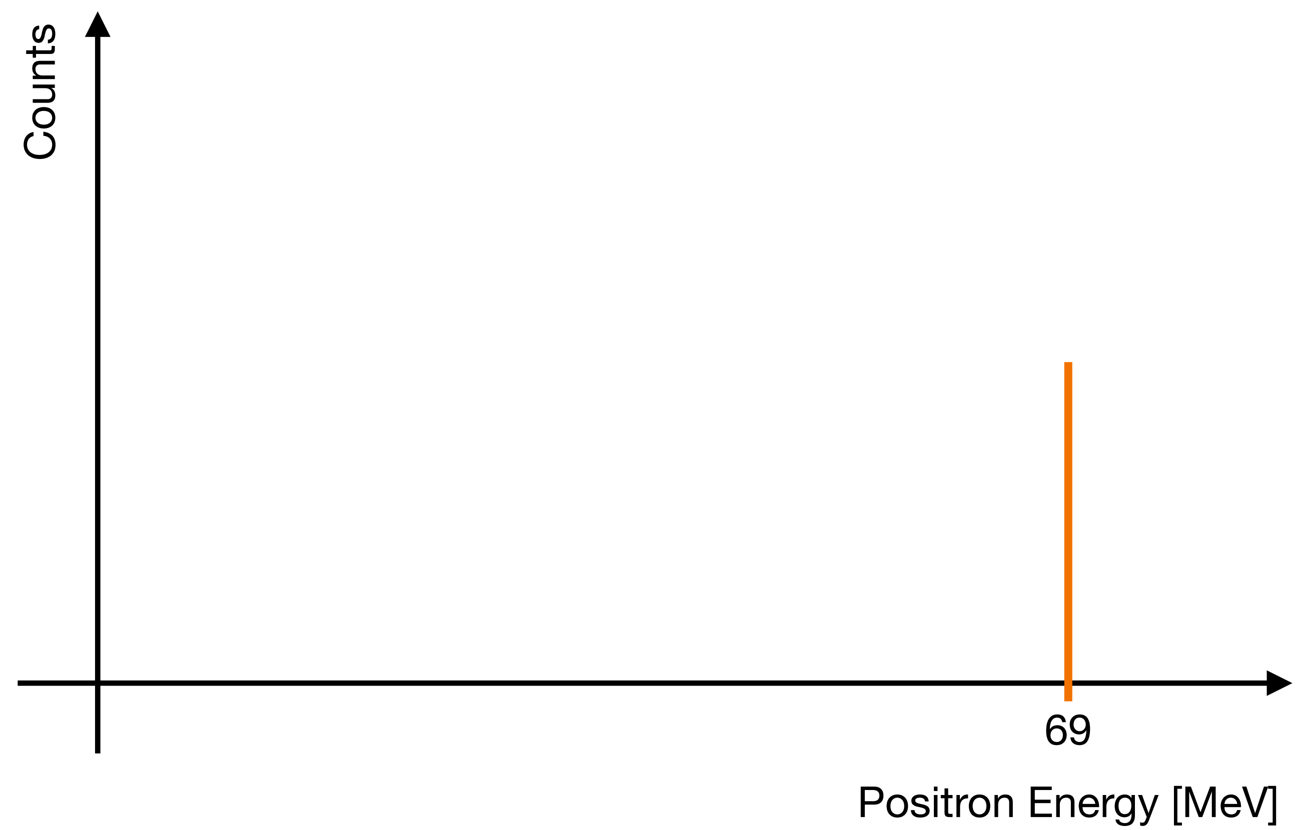
$m_{\pi^+} = 139.6$ MeV

$m_{\mu^+} = 105.7$ 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



Introducing PIONEER

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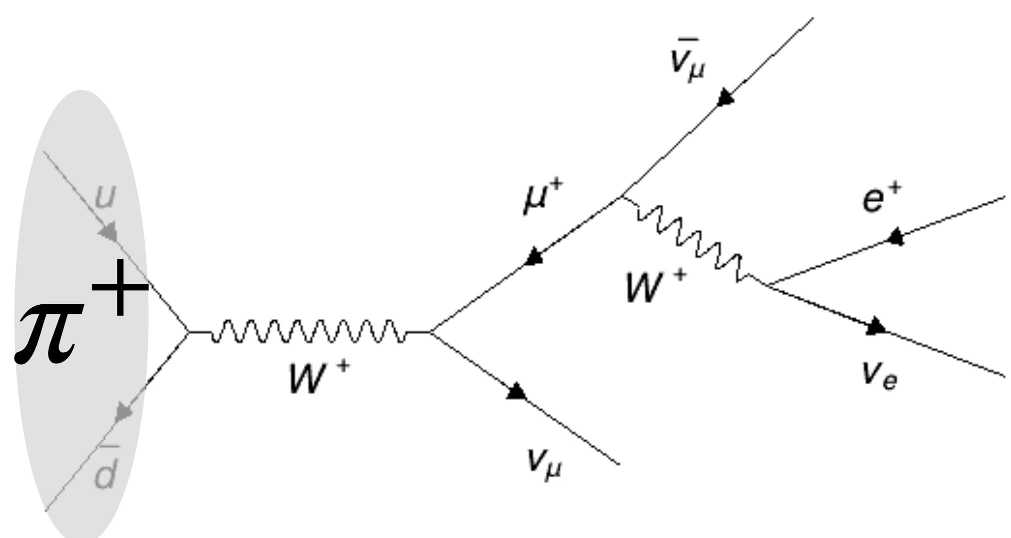

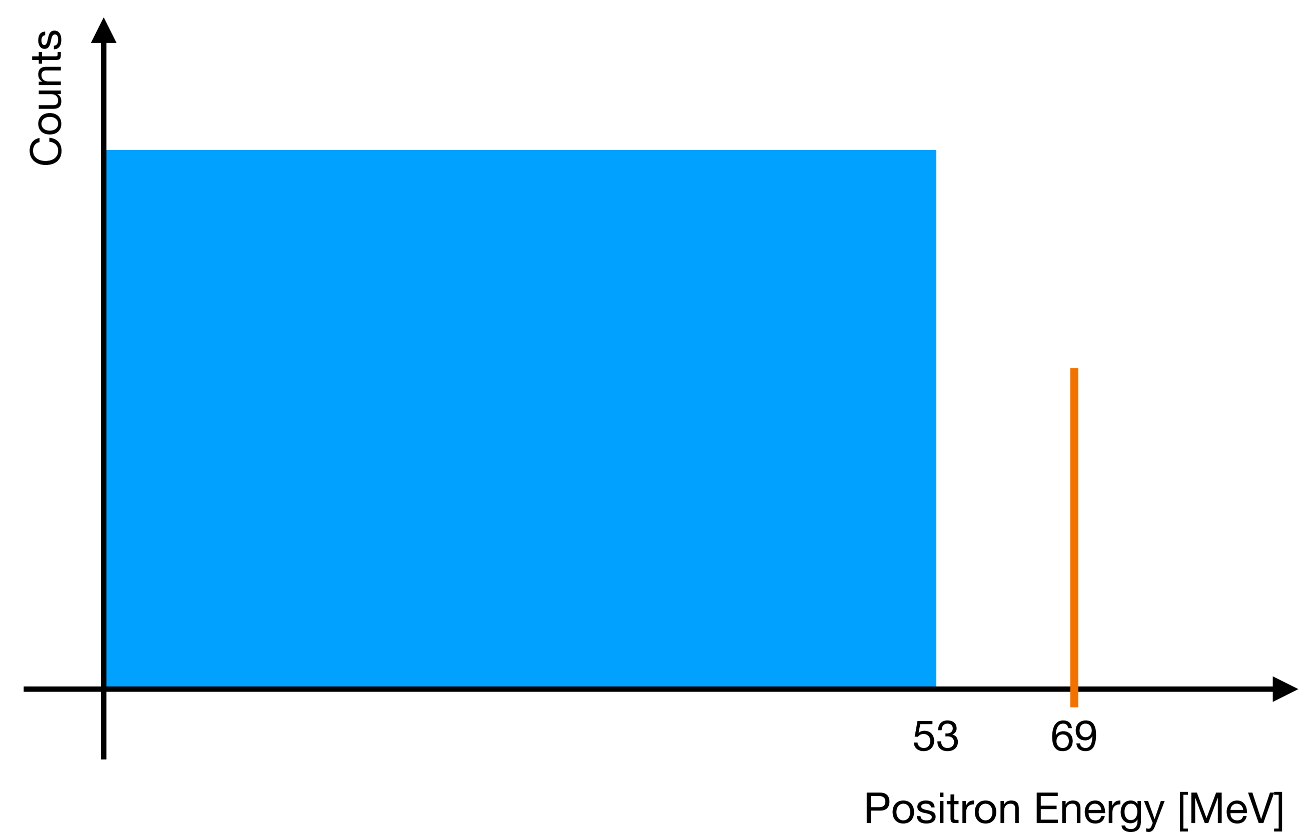

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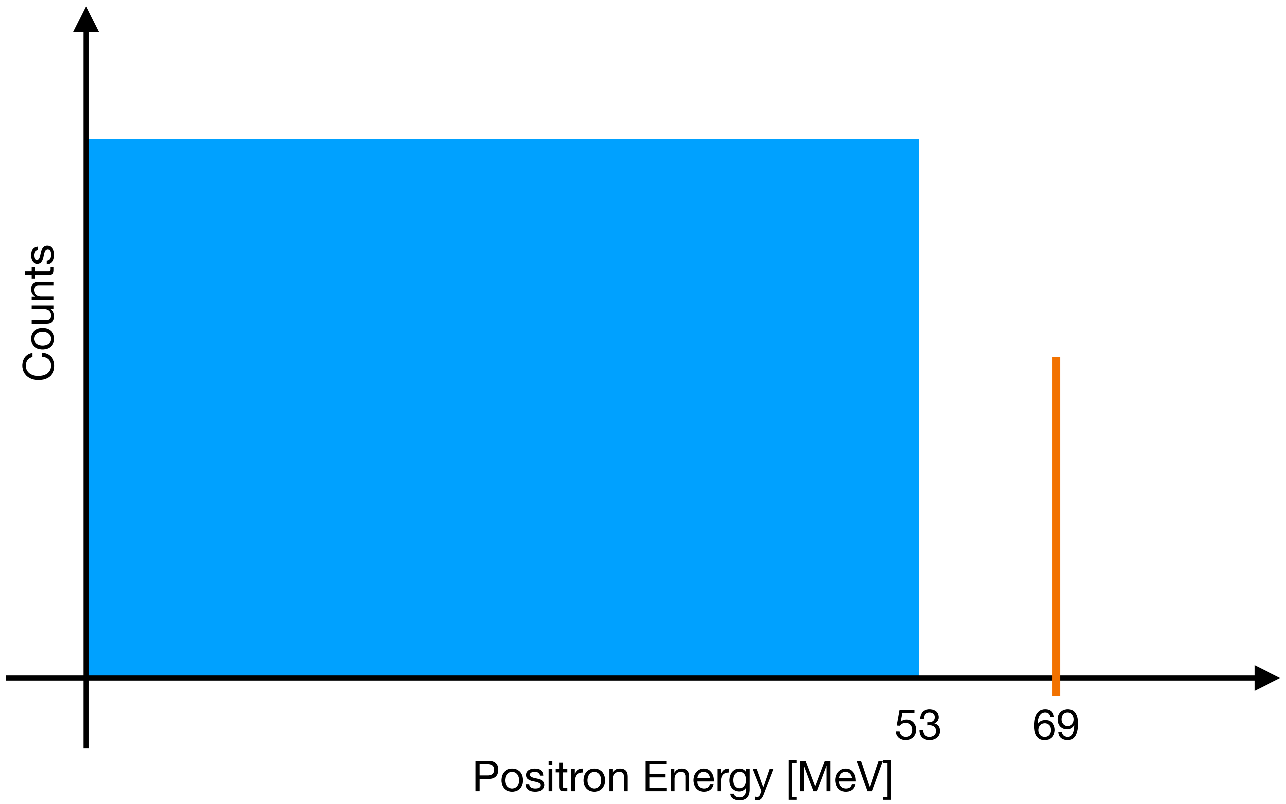
The pion stops in the target and decays

Then the muon stops in the target and decays

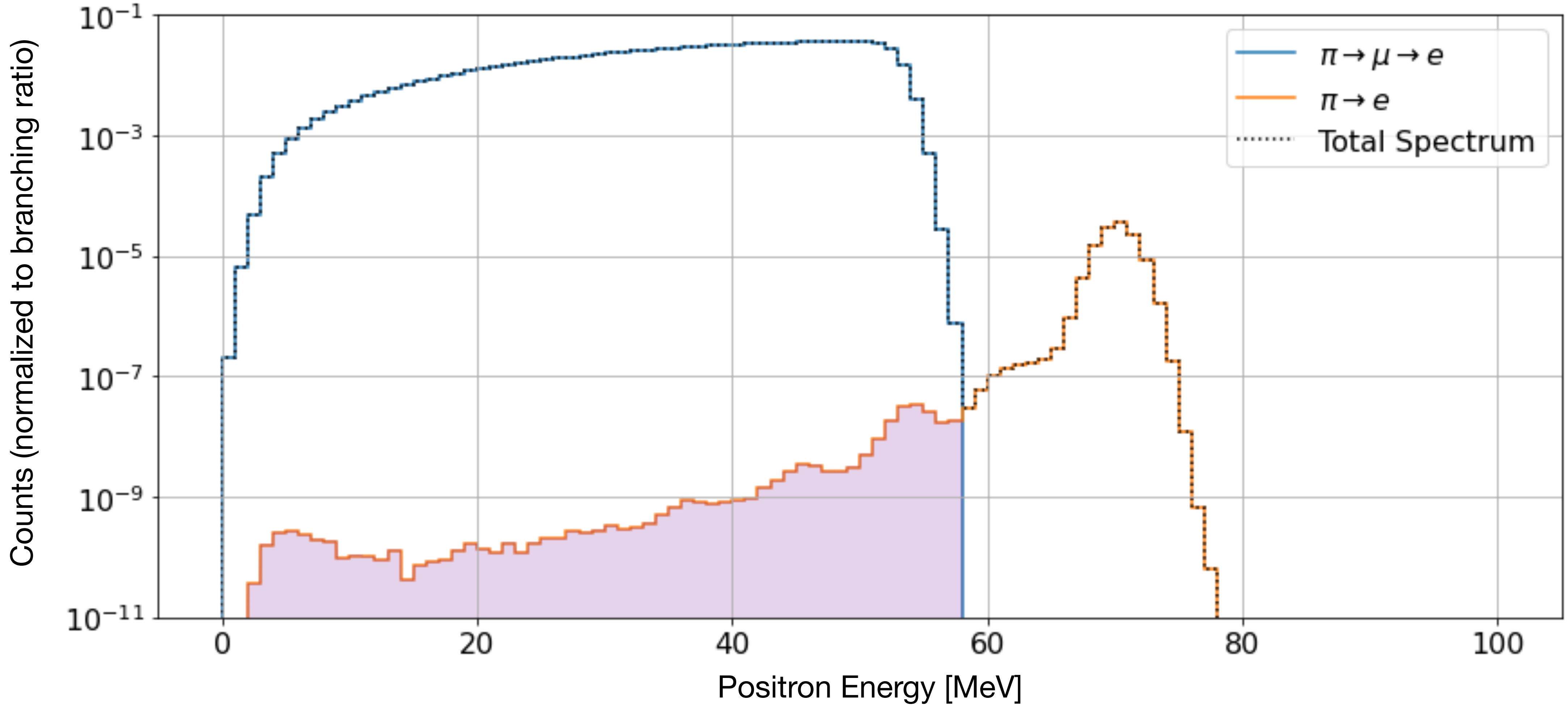
Introducing PIONEER

Facing experimental reality



Introducing PIONEER

Facing experimental reality



$$R_{e/\mu} = \frac{N_{right}}{N_{left}} \times \left[1 + C_{tail}\right] \times R_{\epsilon}$$

Introducing PIONEER

Let’s do some simple error propagation…

$$R_{e/\mu} = \frac{N_{right}}{N_{left}} \times \left[1 + C_{tail}\right] \times R_{\epsilon}$$

$$\frac{\Delta R_{e/\mu}}{R_{e/\mu}} \text{goal} = 0.01\,\%$$

Introducing PIONEER

Let's do some simple error propagation…

$$\frac{\Delta N_{right}}{N_{right}} = \frac{1}{\sqrt{N_{right}}} \rightarrow N_{right} \sim 2 \times 10^{8}$$

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$$N_{left} \sim 2 \times 10^8$$

Easy to achieve
since $N_{left} \sim 10^4 \times N_{right}$

$$\frac{\Delta R_{e/\mu}}{R_{e/\mu}} \text{goal} = 0.01\ \%$$

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If $C_{tail} \sim 1\,\%$ then $\frac{\Delta C_{tail}}{C_{tail}} \sim 1\,\%$

$$\frac{\Delta R_{e/\mu}}{R_{e/\mu}} \text{goal} = 0.01\,\%$$

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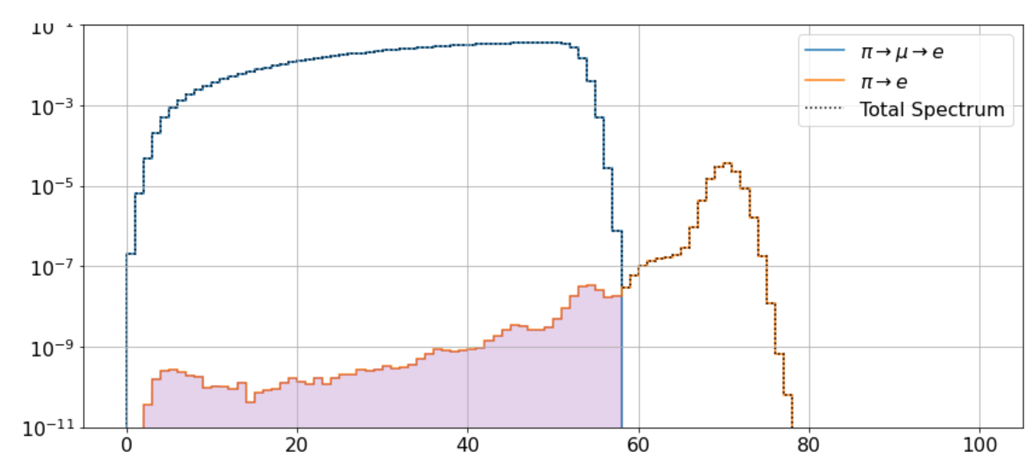
If $C_{tail} \sim 1\,\%$ then $\frac{\Delta C_{tail}}{C_{tail}} \sim 1\,\%$

"Measuring a value of 1% with a precision of 1%"

$$\frac{\Delta R_{e/\mu}}{R_{e/\mu}}\text{goal} = 0.01\,\%$$



Introducing PIONEER

Let’s do some simple error propagation…

$$\frac{\Delta N_{right}}{N_{right}} = \frac{1}{\sqrt{N_{right}}} \rightarrow N_{right} \sim 2 \times 10^8$$

$$R_\epsilon = \frac{\text{How many } \pi \rightarrow e \text{ events are collected}}{\text{How many } \pi \rightarrow \mu \rightarrow e \text{ events are collected}}$$

$$R_{e/\mu} = \frac{N_{right}}{N_{left}} \times \left[1 + C_{tail} \times R_\epsilon\right]$$

$R_\epsilon \rightarrow \frac{\Delta R_\epsilon}{R_\epsilon} \sim 0.01\,\%$

$C_{tail} \rightarrow \Delta C_{tail} \sim 0.01\,\%$

If $C_{tail} \sim 1\,\%$ then $\frac{\Delta C_{tail}}{C_{tail}} \sim 1\,\%$

“Measuring a value of 1% with a precision of 1%”

$N_{left} \sim 2 \times 10^8$

Easy to achieve
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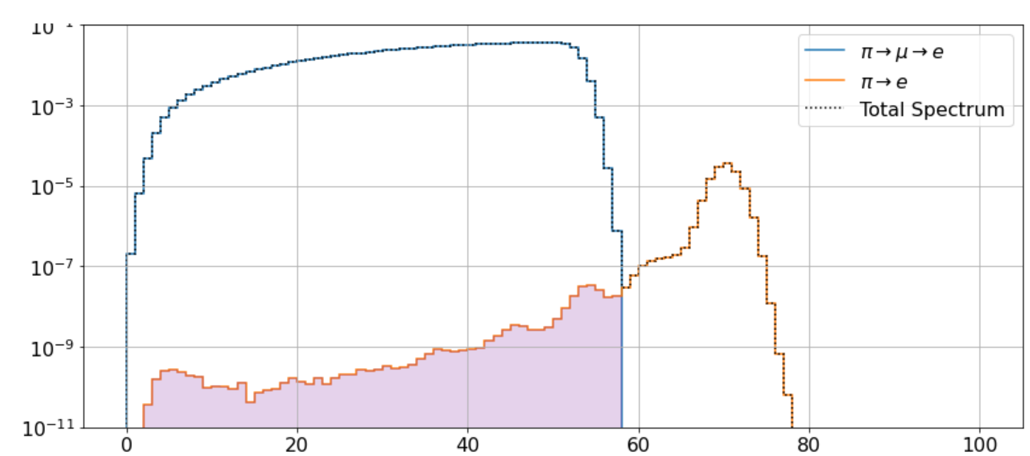
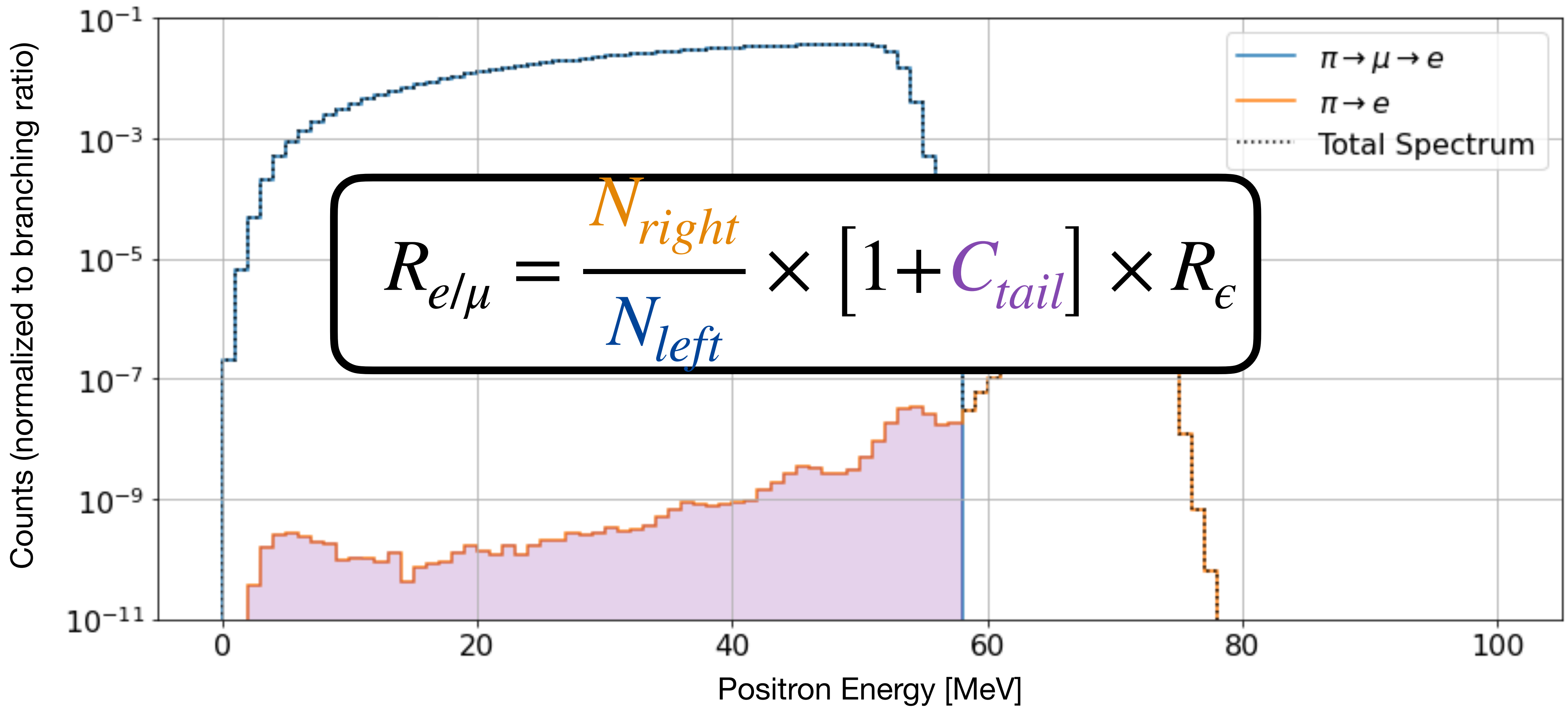


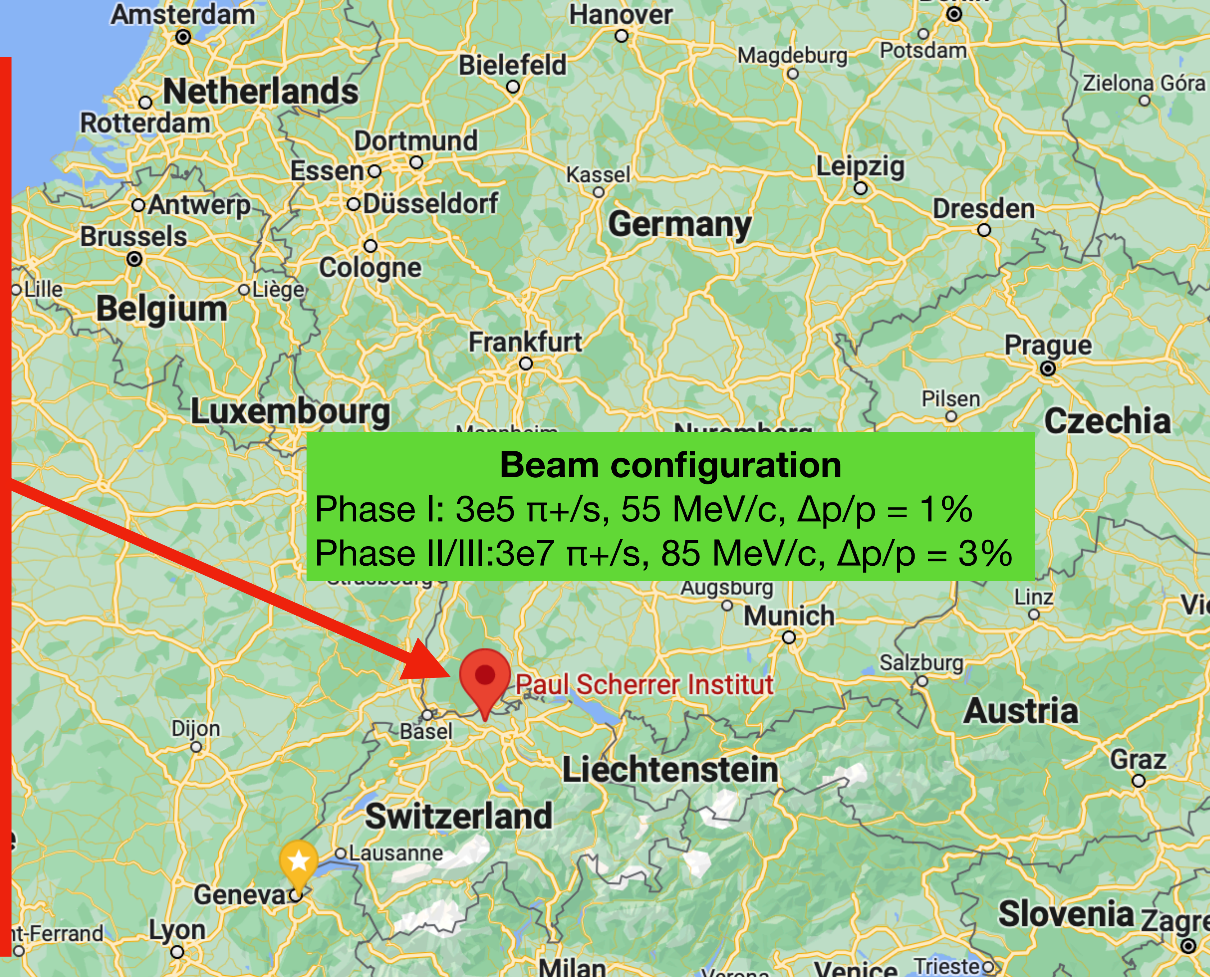
Introducing PIONEER



$$R_{e/\mu} = \frac{N_{right}}{N_{left}} \times \left[1 + C_{tail}\right] \times R_{\epsilon}$$

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
3. Tail must be measured with a precision of 1%
4. Acceptance must be understood with a precision of 0.01%



PAUL SCHERRER INSTITUT

PSI

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

Beam configuration
Phase I: 3e5 π+/s, 55 MeV/c, $\Delta p/p$ = 1%
Phase II/III:3e7 π+/s, 85 MeV/c, $\Delta p/p$ = 3%

Guiding principles to the design of the experiment:

1. **Collect very large datasets of rare pion decays**
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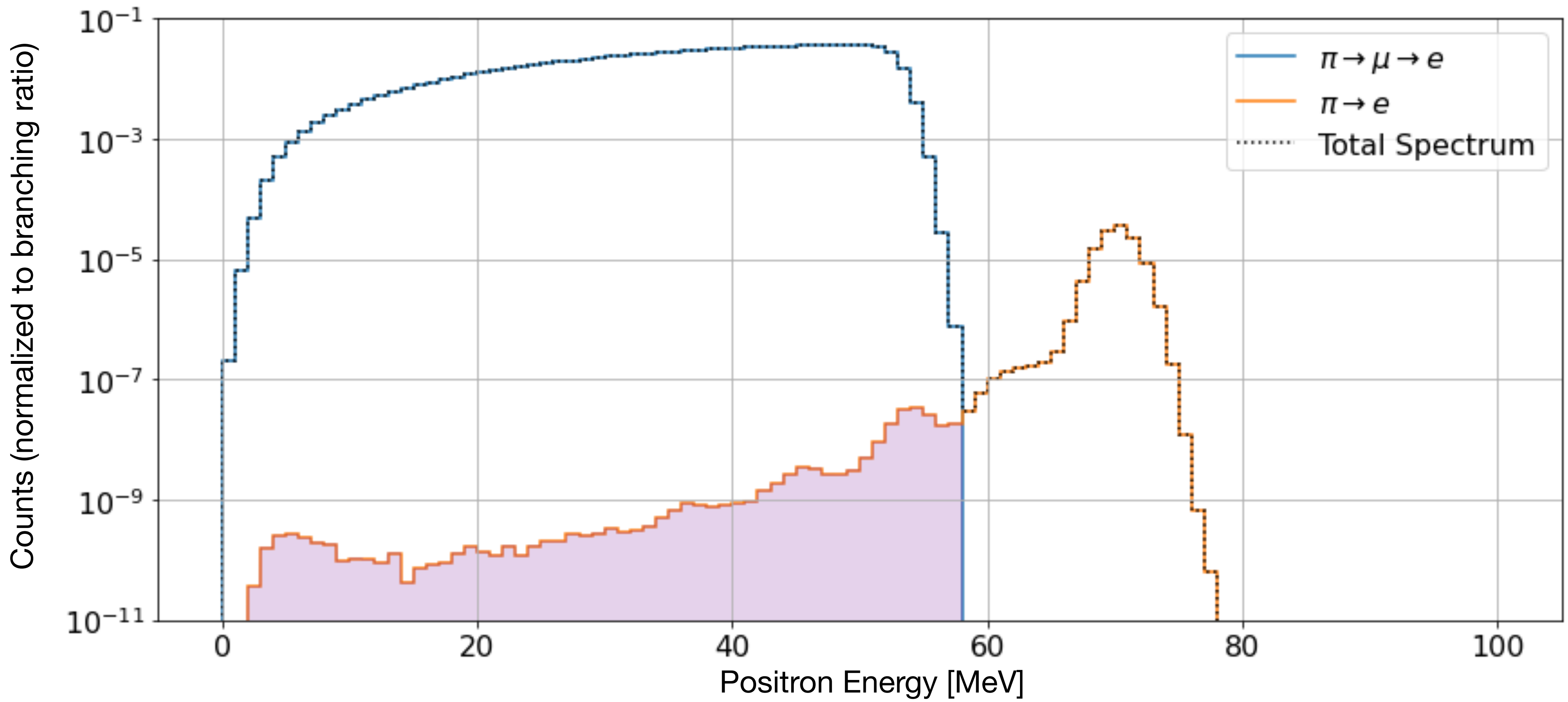
Calorimeter design



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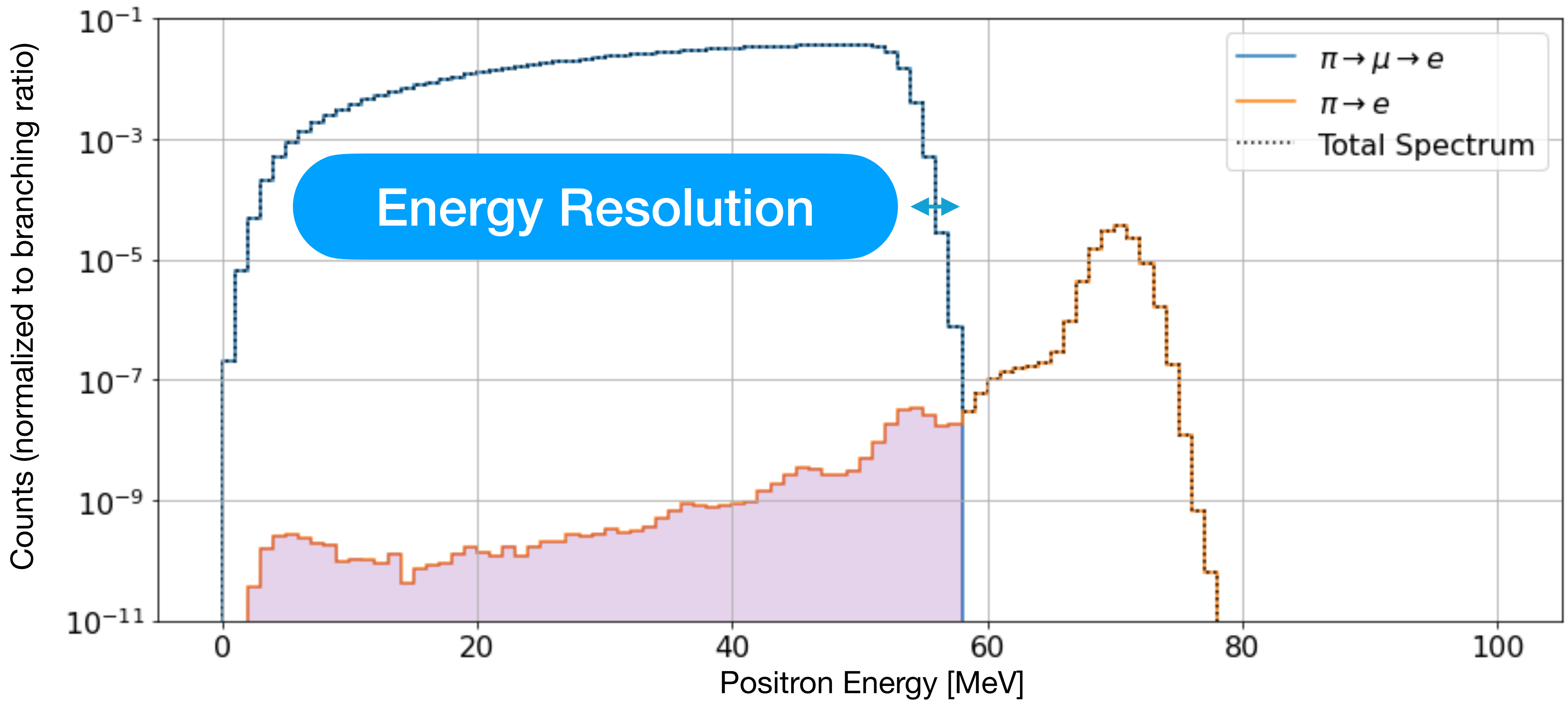

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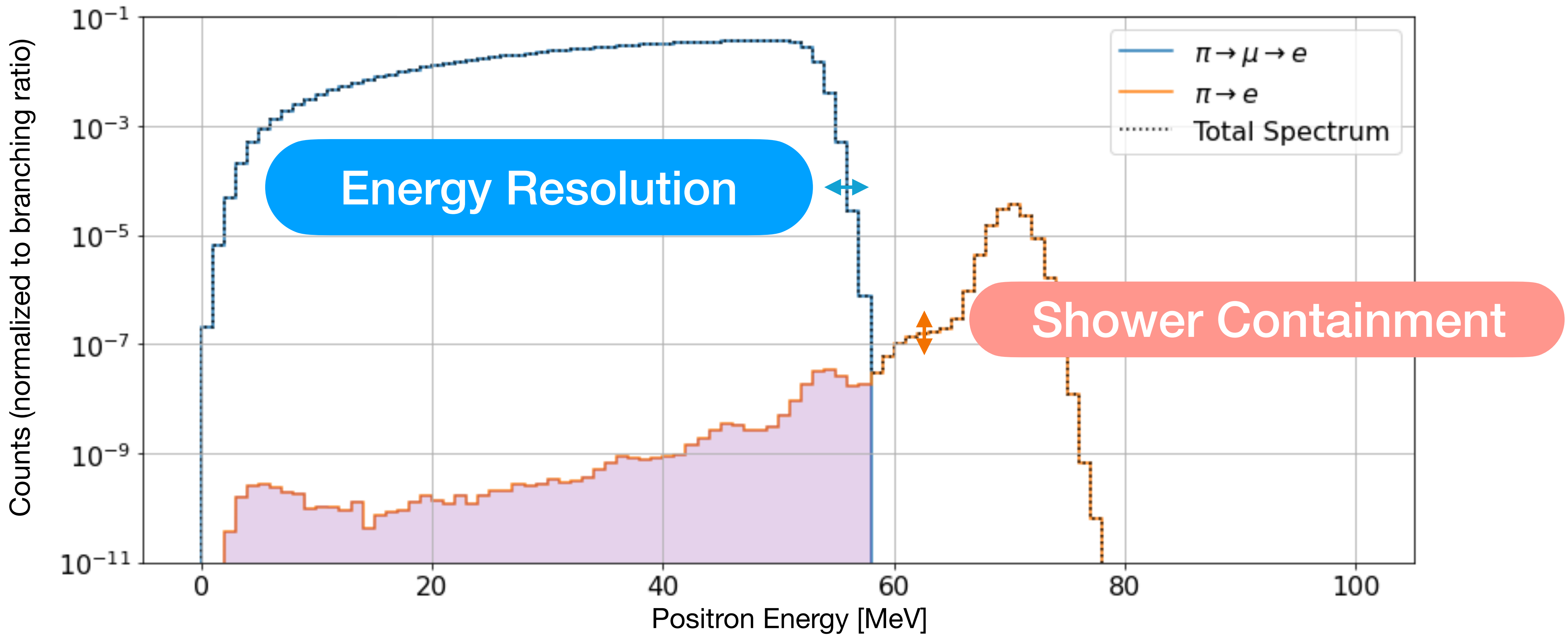

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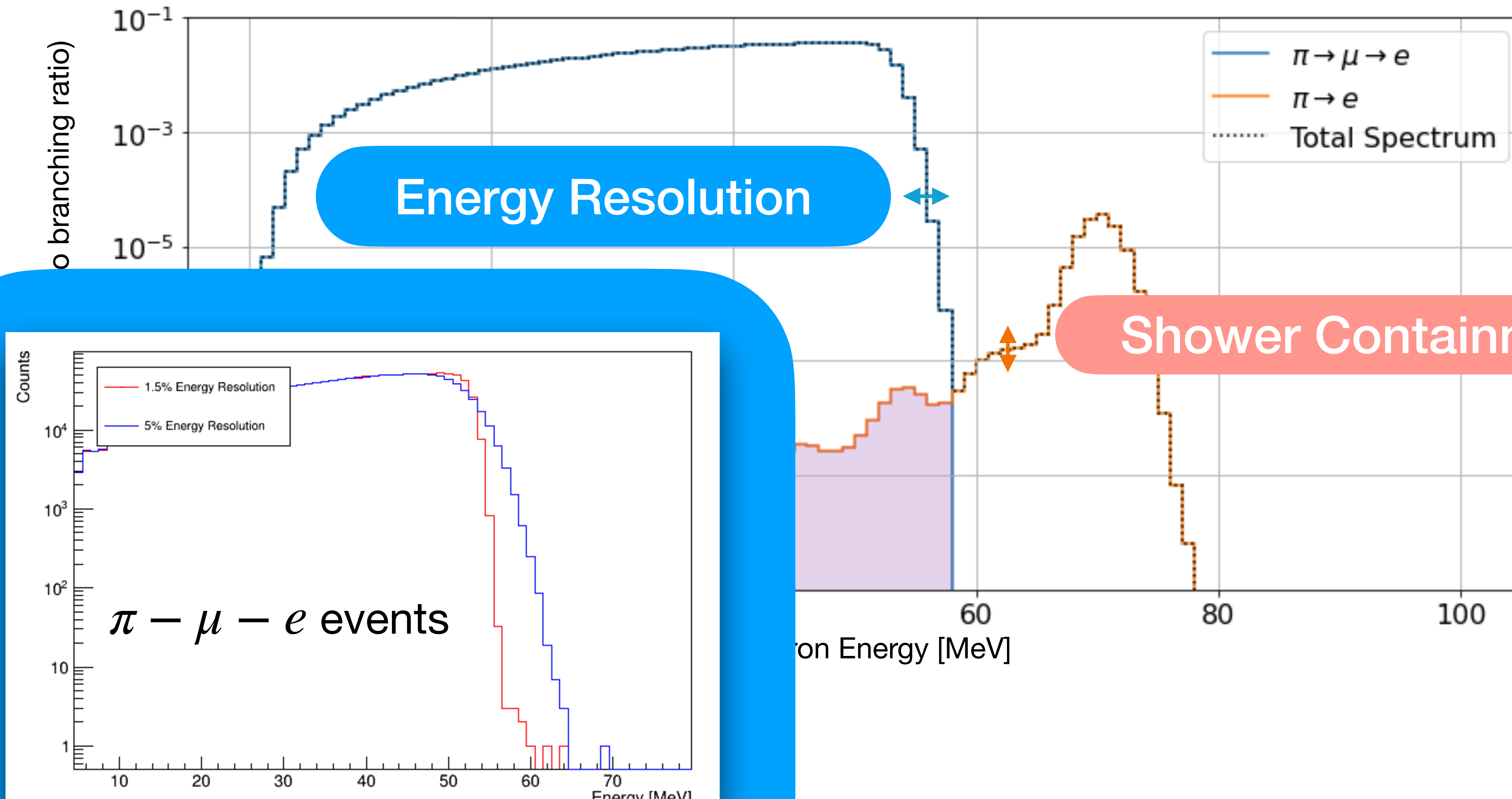


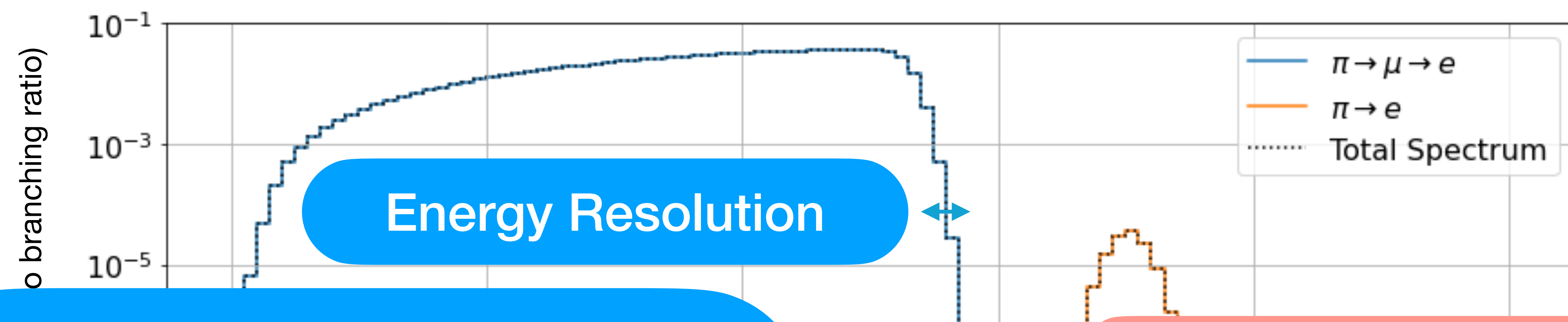
Energy Resolution

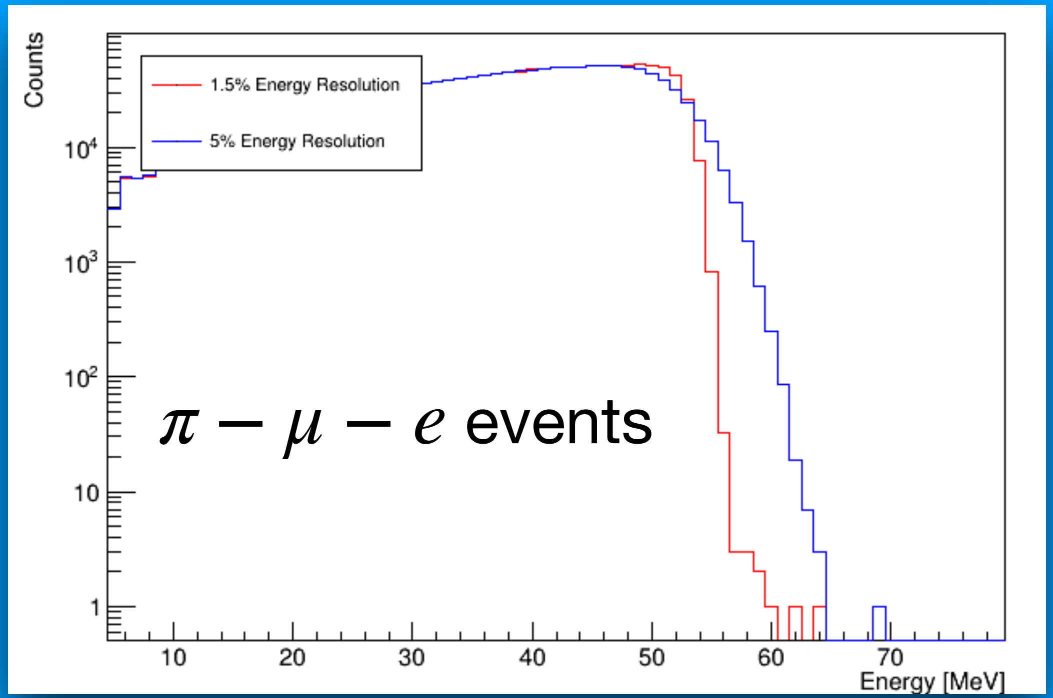
Shower Containment

$\pi - \mu - e$ events

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

Calorimeter design





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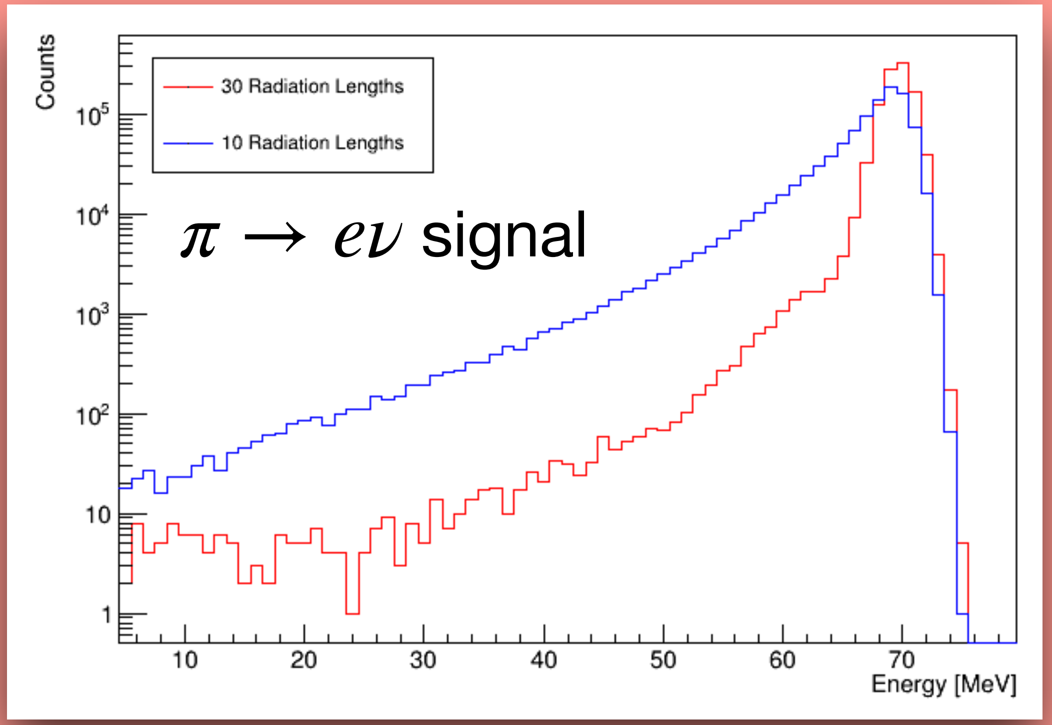
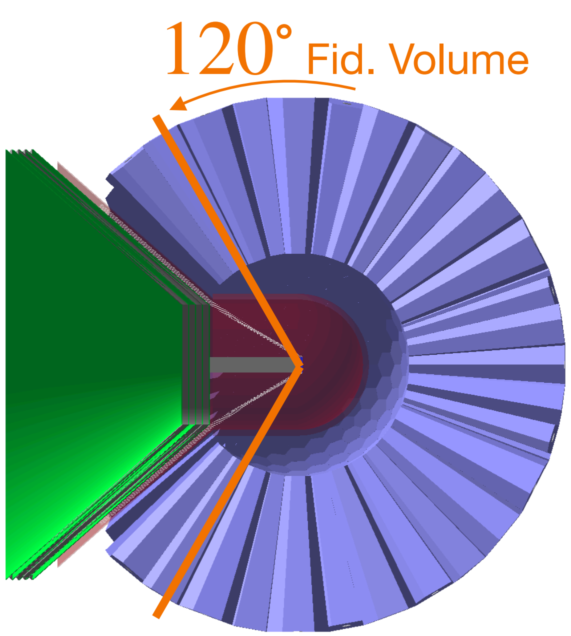


At least 19 radiation length (X_0),
Large solid angle (~3π steradians)

Calorimeter design

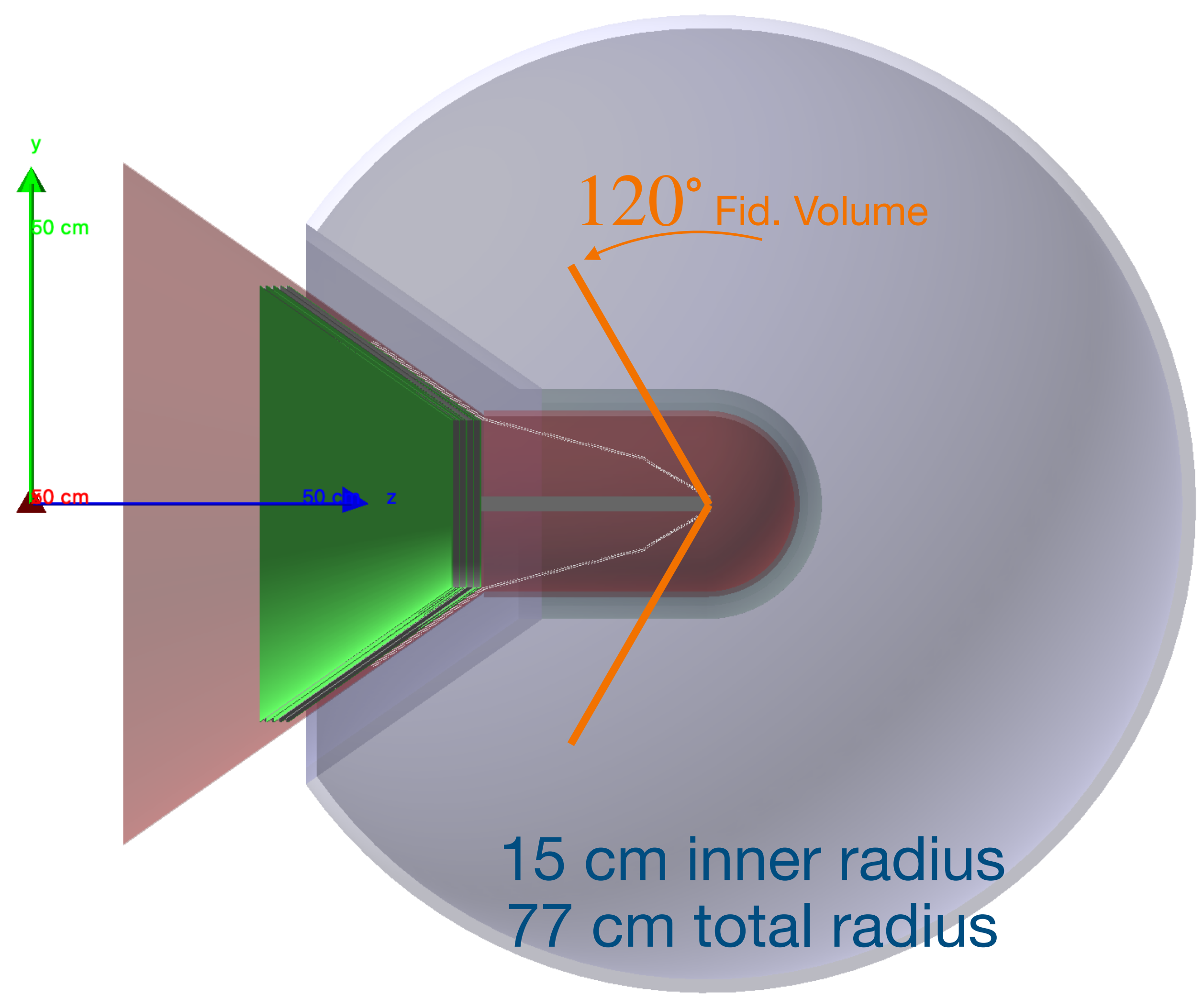
LYSO Crystals

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



15 cm inner radius
42 cm total radius

Liquid Xenon

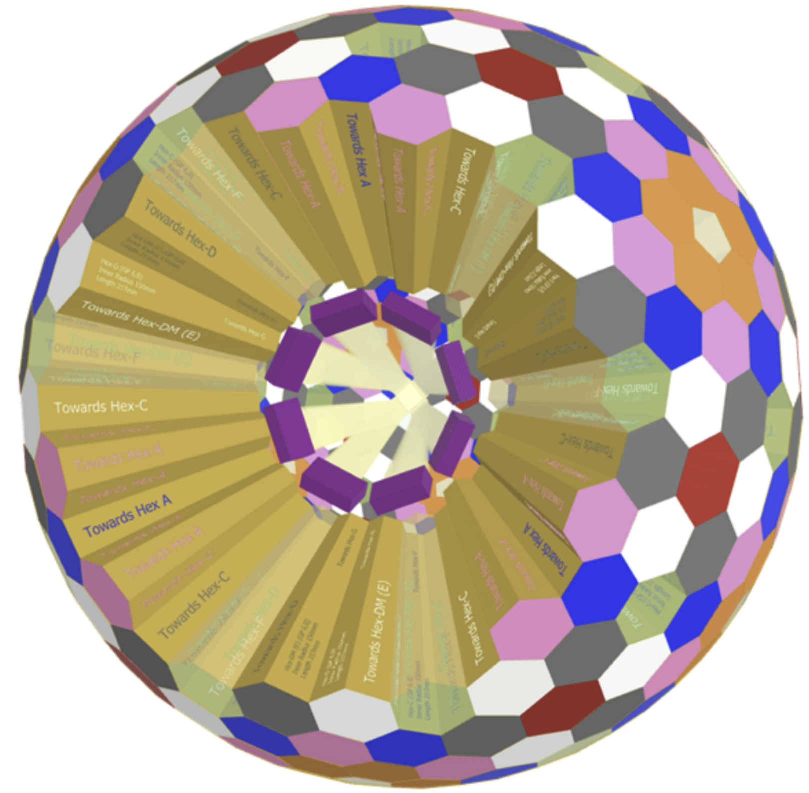


15 cm inner radius
77 cm total radius

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

Calorimeter design

Technology down select



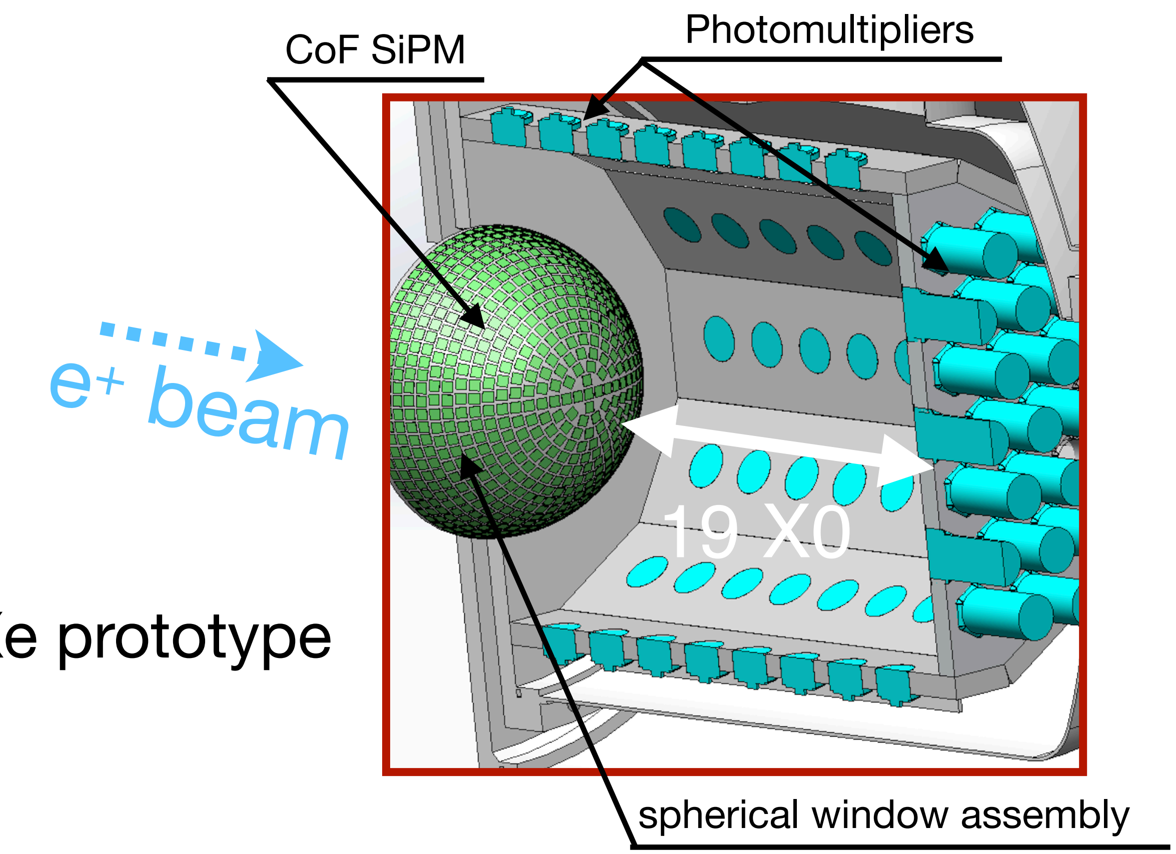
LYSO Array

- **LYSO crystals — baseline option for PIONEER**
  Conclusion of a 3y R&D program

- **LXe single volume**

  Well established technology
  from the MEG experiment

  200L Prototype planned in 2026/2027 at PSI



LXe prototype

LYSO Calorimeter R&D Program

LYSO is a fast, bright, and dense crystal scintillator that is typically used in small (~1cm^2) sizes for triggering in HEP

The PIONEER calorimeter will be composed of the 311 largest LYSO crystals ever grown (21.3 cm / 19X_0)

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2023 Test Beam

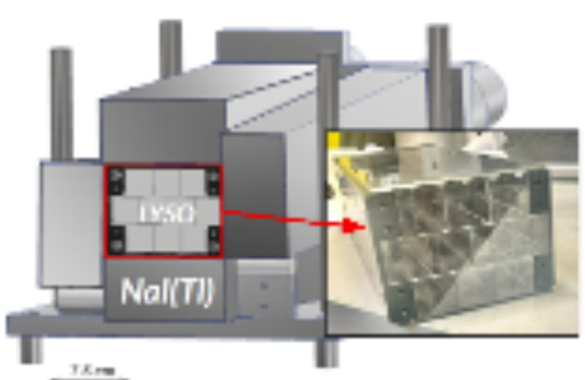
Characterized an array of 10 rectilinear LYSO crystals (2.5 x 2.5 x 18 cm^3)

Main findings

1) 1.52% energy resolution for 70 MeV e^+. ~3x better than previous LYSO arrays at this energy

2) 100 ps time resolution for pulses larger than 30 MeV

3) 6 mm spatial resolution at 70 MeV



Beesley, et al,
NIM A 1075 (2025) 170320

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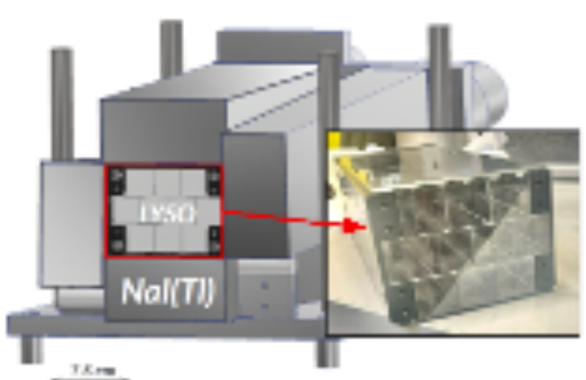

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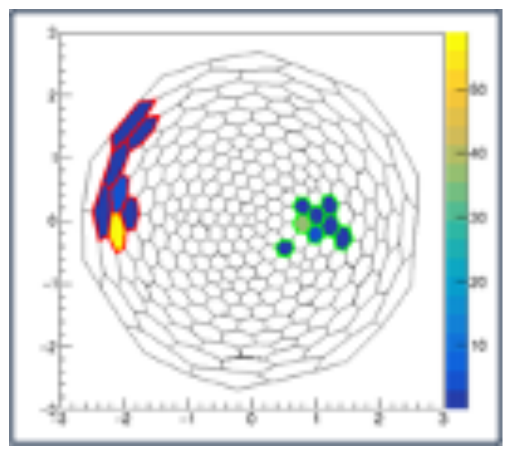
Simulation efforts



Using 2023 test beam data, a **realistic detector response** was integrated into the the PIONEER simulation framework.

Developed clustering algorithms capable of **order of magnitude improvements** in pileup suppression in the presence of intrinsic radioactivity.

LYSO Calorimeter R&D Program

LYSO is a fast, bright, and dense crystal scintillator that is typically used in small (~1cm^2) sizes for triggering in HEP

The PIONEER calorimeter will be composed of the 311 largest LYSO crystals ever grown (21.3 cm / 19X_0)

2023 Test Beam

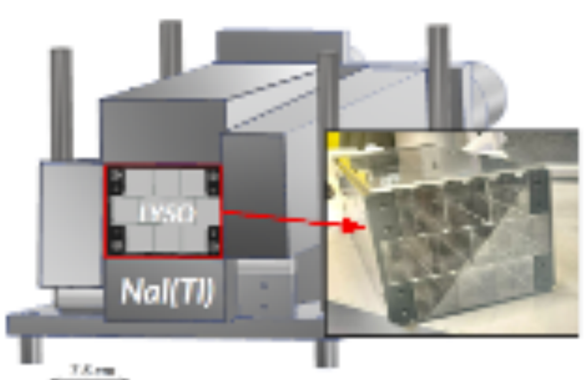
Characterized an array of 10 rectilinear LYSO crystals (2.5 x 2.5 x 18 cm^3)

Main findings

1) 1.52% energy resolution for 70 MeV e^+. ~3x better than previous LYSO arrays at this energy

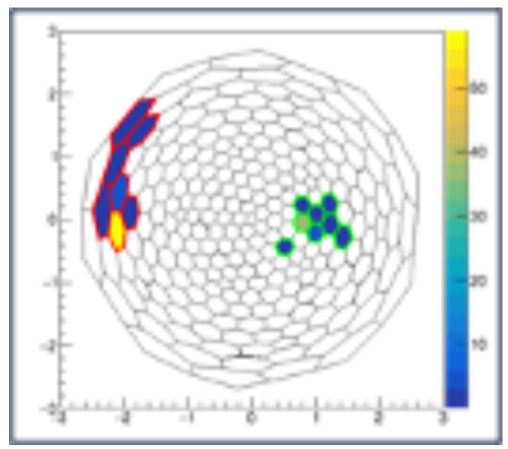
2) 100 ps time resolution for pulses larger than 30 MeV

3) 6 mm spatial resolution at 70 MeV



Beesley, et al,
NIM A 1075 (2025) 170320

Simulation efforts



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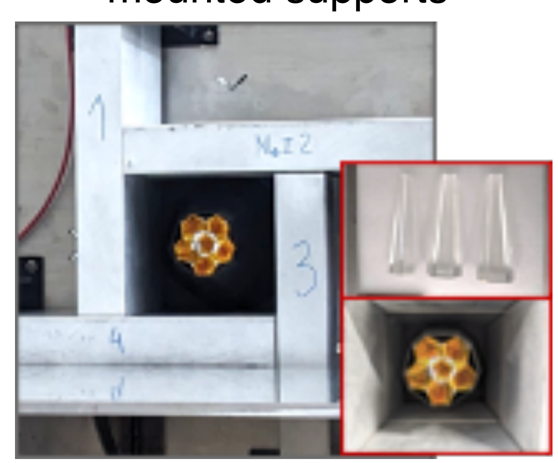
2025 Test Beam

small array of six LYSO crystals in the exact sizes/ shapes of the final calorimeter design

Main findings
LYSO meets PIONEER specifications

1) 2% energy resolution for 70 MeV e^+ despite significant lateral leakage due to the small size of the array
2) 100 ps time resolution for pulses larger than 30 MeV

3) Successful test of rear-mounted supports



Paper in preparation

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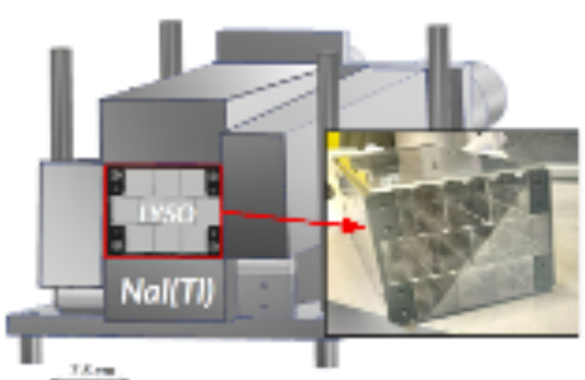

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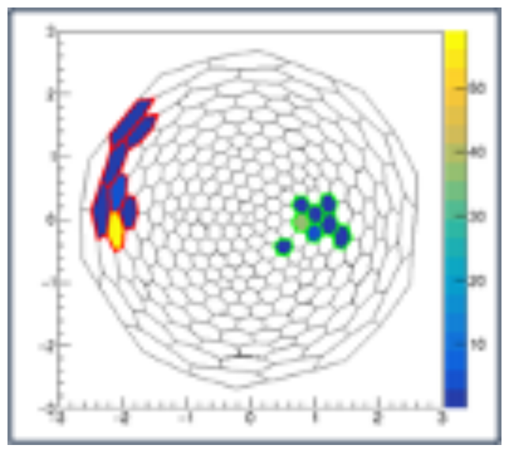

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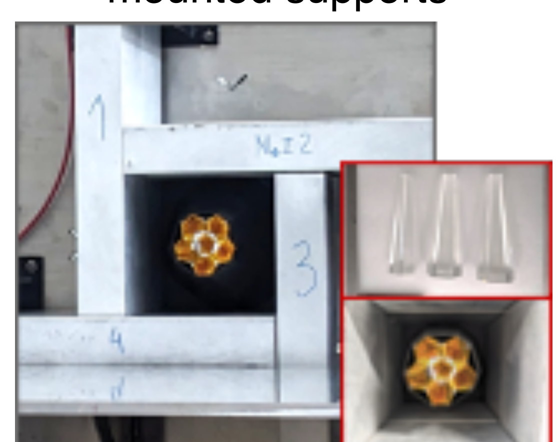
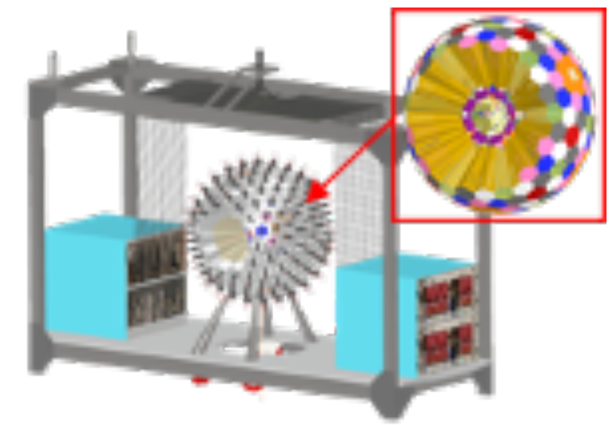


Paper in preparation

Next steps



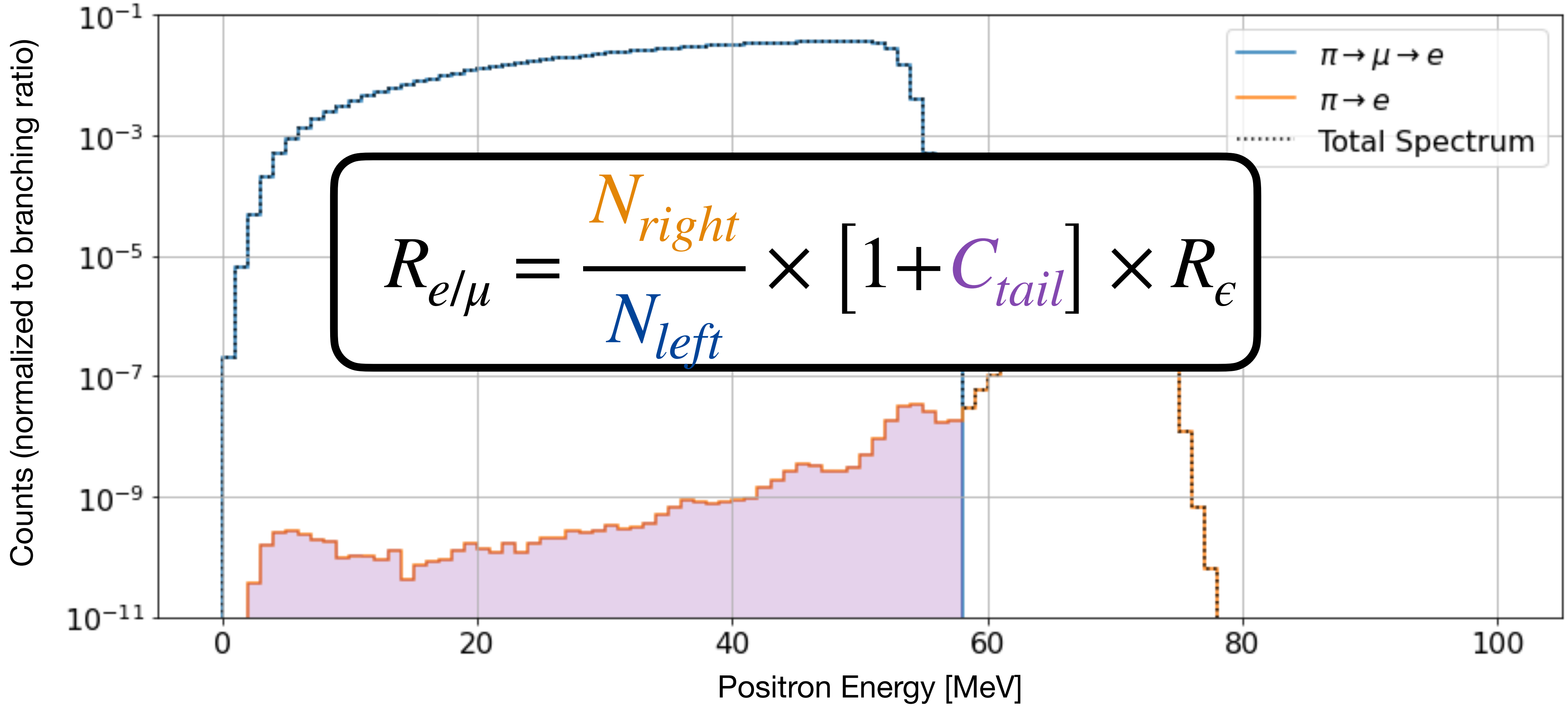
Remaining work is focused on:

1) Optimization of crystal surface roughening for maximal longitudinal response uniformity.

2) Optimization of PMT voltage dividers for fast rise times, high linearity, and constant pulse shape across 0.1 – 100 MeV range.

3) Integration of calorimeter information within our current AI ATAR reconstruction to create a global PIONEER AI reconstruction.

Back to the guiding principles



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1. Collect very large datasets of rare pion decays
2. Tail must be less than 1% of total signal
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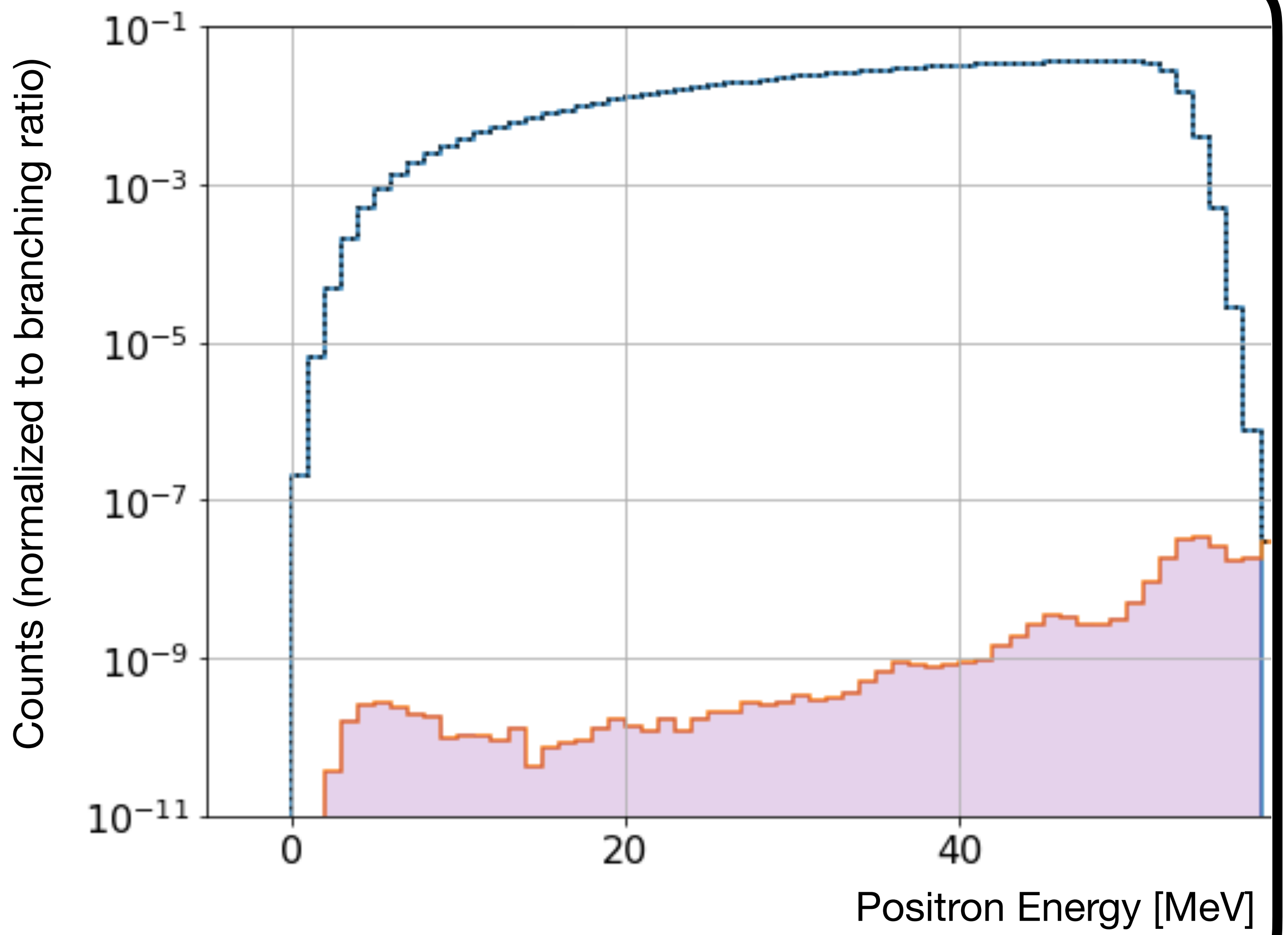
4. Acceptance must be understood with a precision of 0.01%

A challenging S/B problem



Sig / Bkg requirements

$\pi \to e$ **selection efficiency ~ 1%**

$\pi \to \mu \to e$ **rejection rate ~ 10^7**

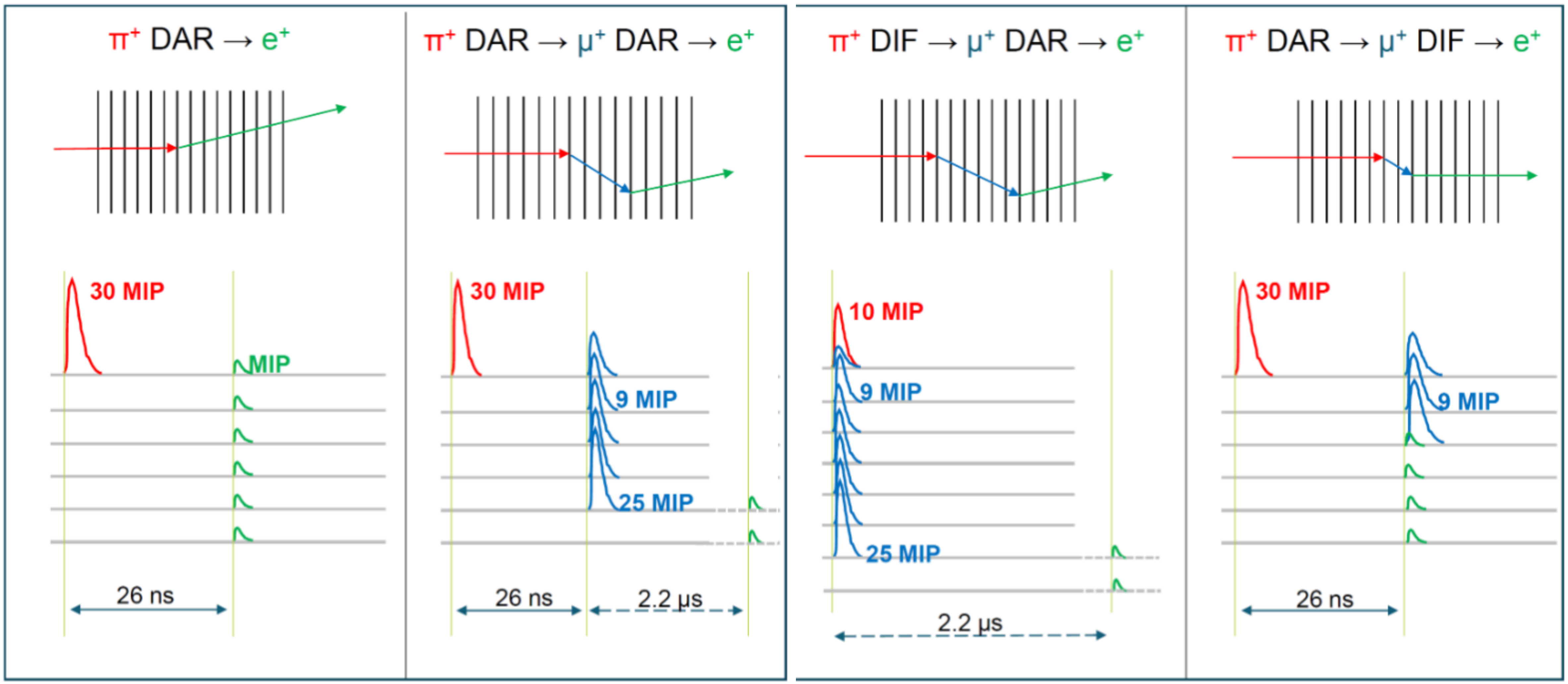
$$N_{tail}(\pi \to e) \sim C_{tail} \times R_{e/\mu} \times N(\pi \to \mu \to e)$$

With $C_{tail} \sim 1\,\%$, we expect the $\pi \to \mu \to e$ process to occur at a rate **10^6 larger** than the $\pi \to e$ process in the low energy region

PIONEER's Active TARget (ATAR)

Design Requirements Summary

Timing, Energy, Topology



DAR = Decay At Rest
MIP = Minimum Ionizing Particle

DIF = Decay In Flight

PIONEER's Active TARget (ATAR)

Design Requirements Summary

Timing

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

Nanosecond precision, micro-second length signal

Energy

Positrons are MIPs
Muons / pions are ~100 MIPS

Large dynamic range (1000) to see all particles

Topology

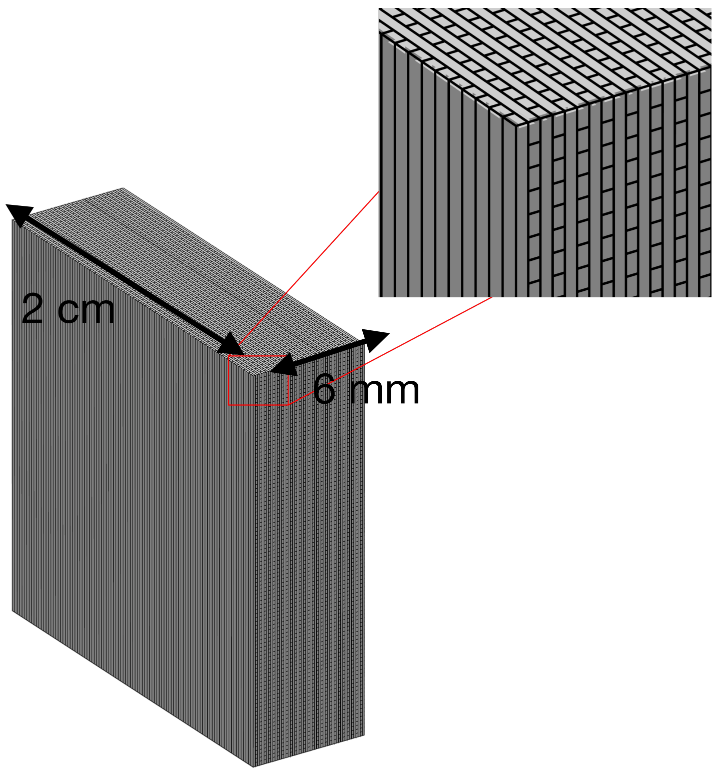
Muon from stopped pion

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

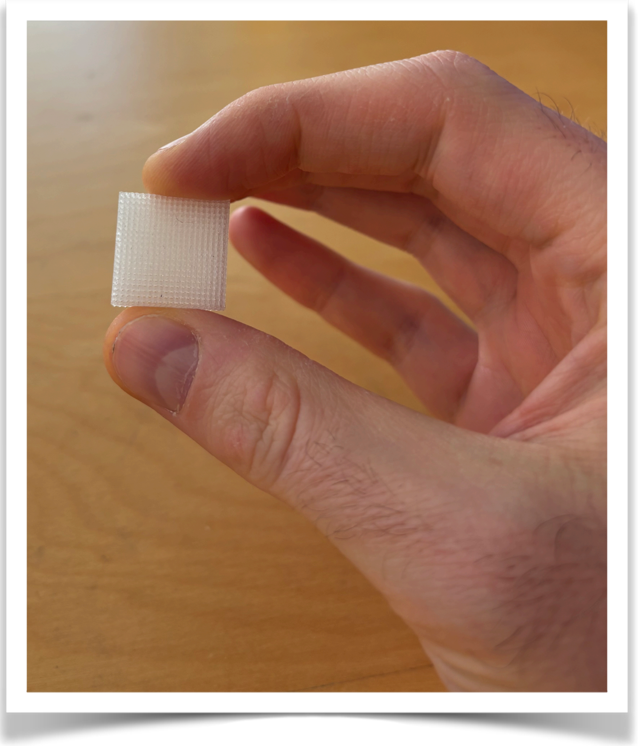
Sub-millimeter position resolution

PIONEER's Active TARget (ATAR)

The heart of the experiment



3D printed model to scale



Silicon sensors

6mm thick (48 layers of 120um)

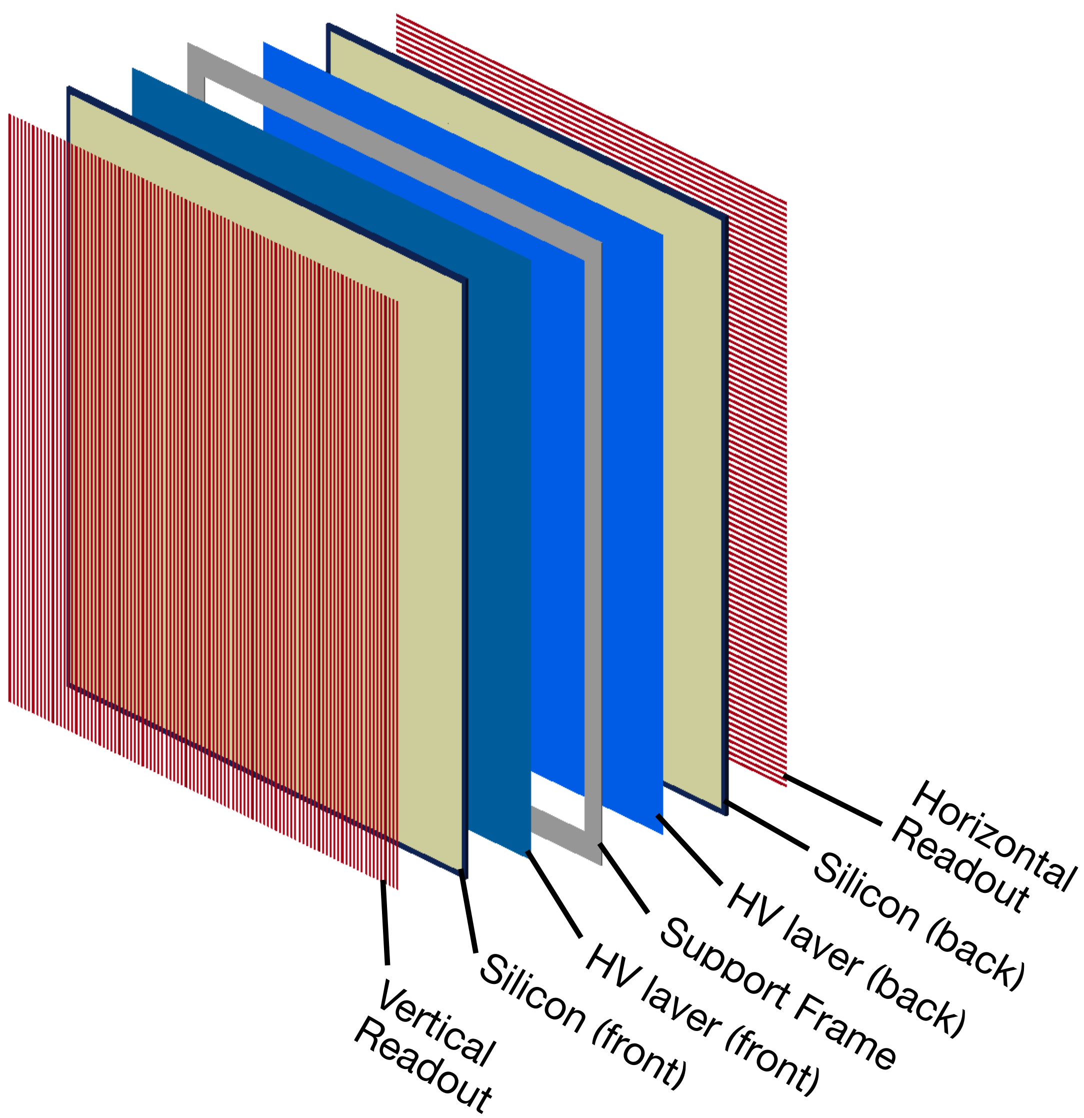
100 strips per layer covering 2x2 cm^2 area

5000 readout channels

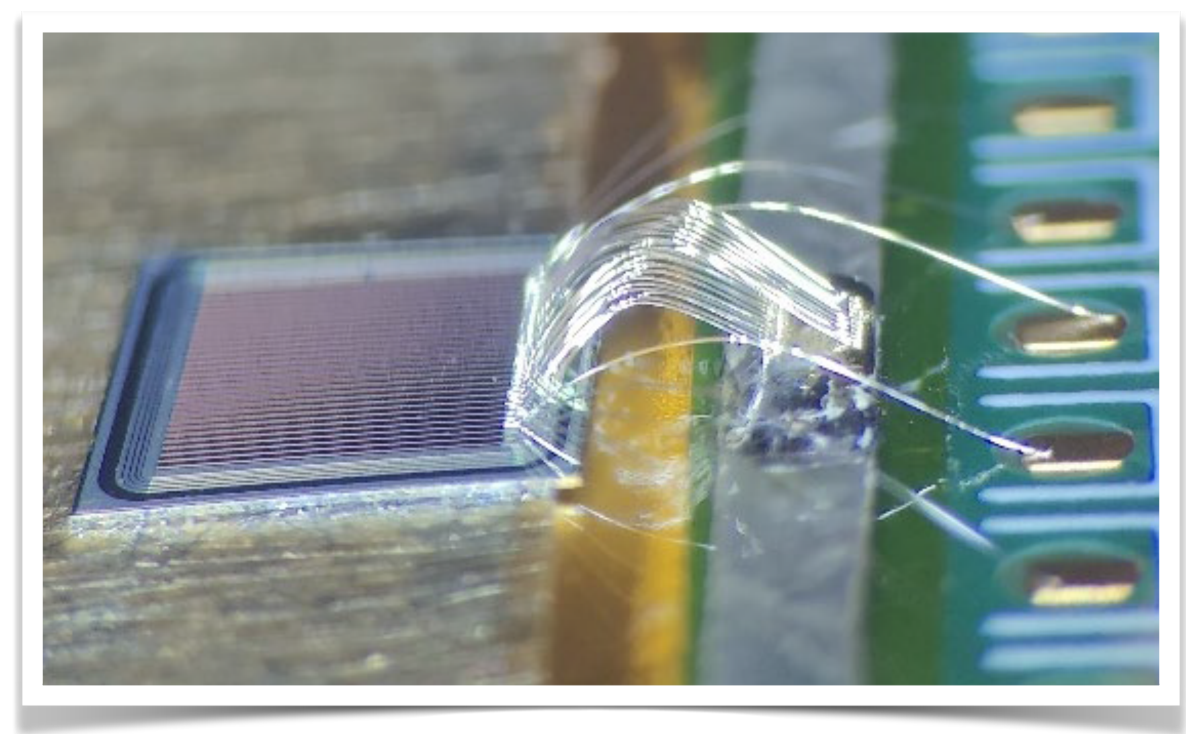
PIONEER's Active TARget (ATAR)

The heart of the experiment

Schematic of one layer

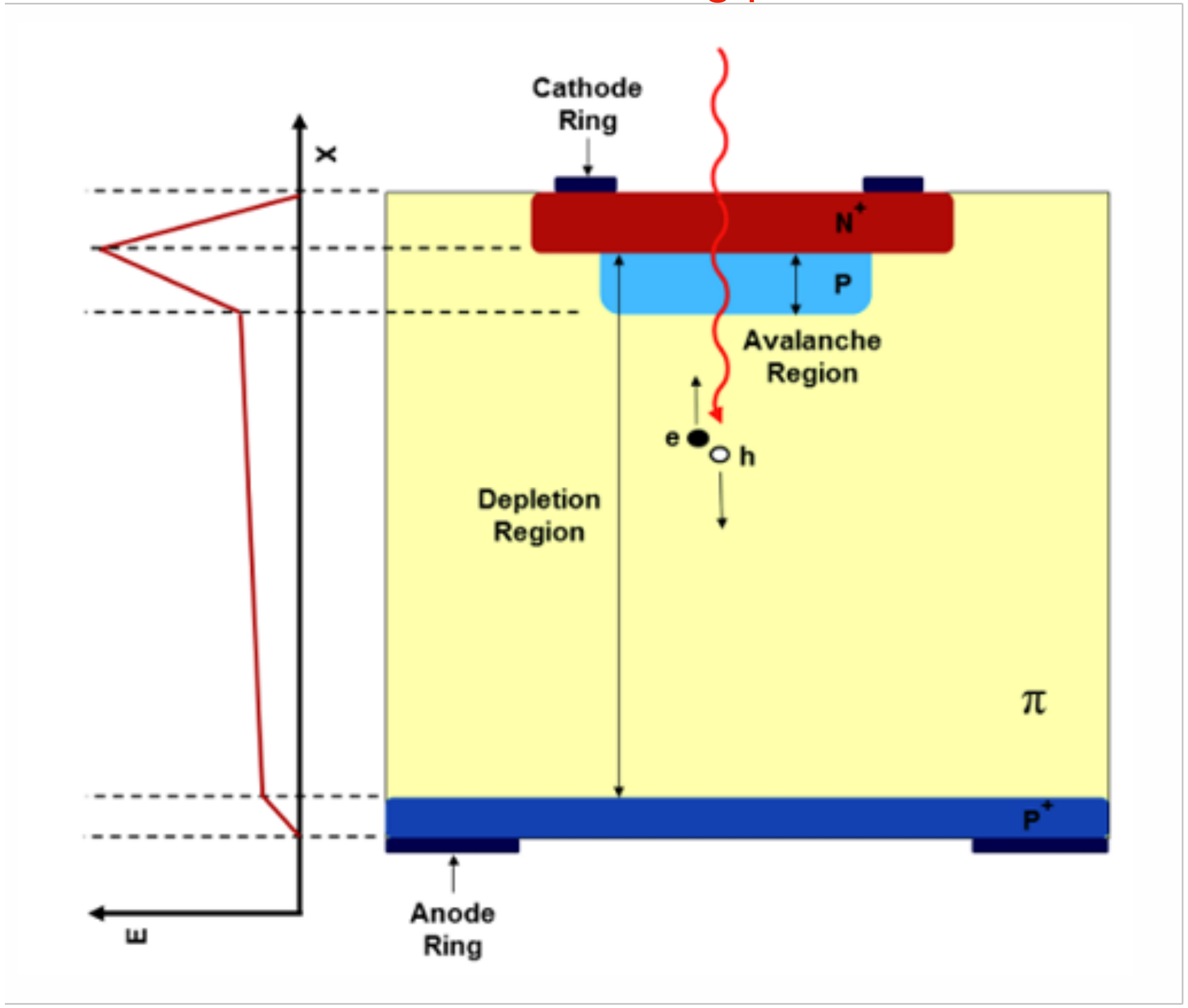


Test sensor from FBK



Low Gain Avalanche Diodes (LGADs)

Incoming particle



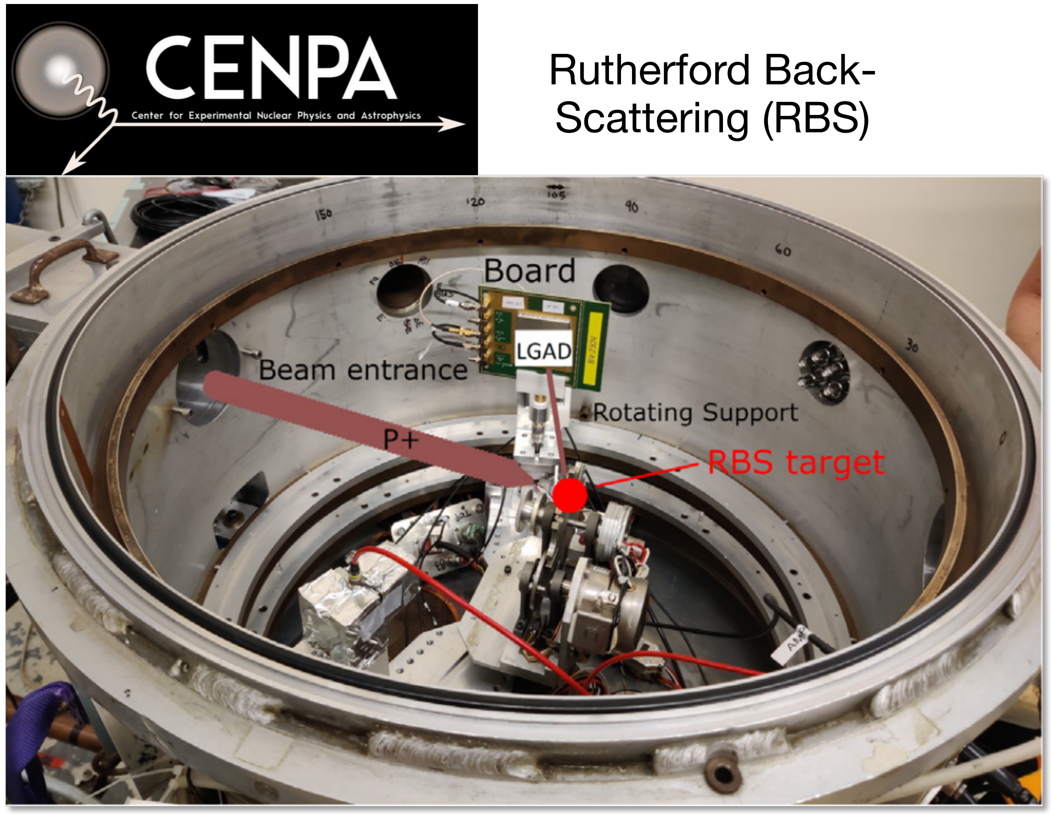
Silicon Diodes:
p-n junction separated by
an intrinsic layer (undoped)

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

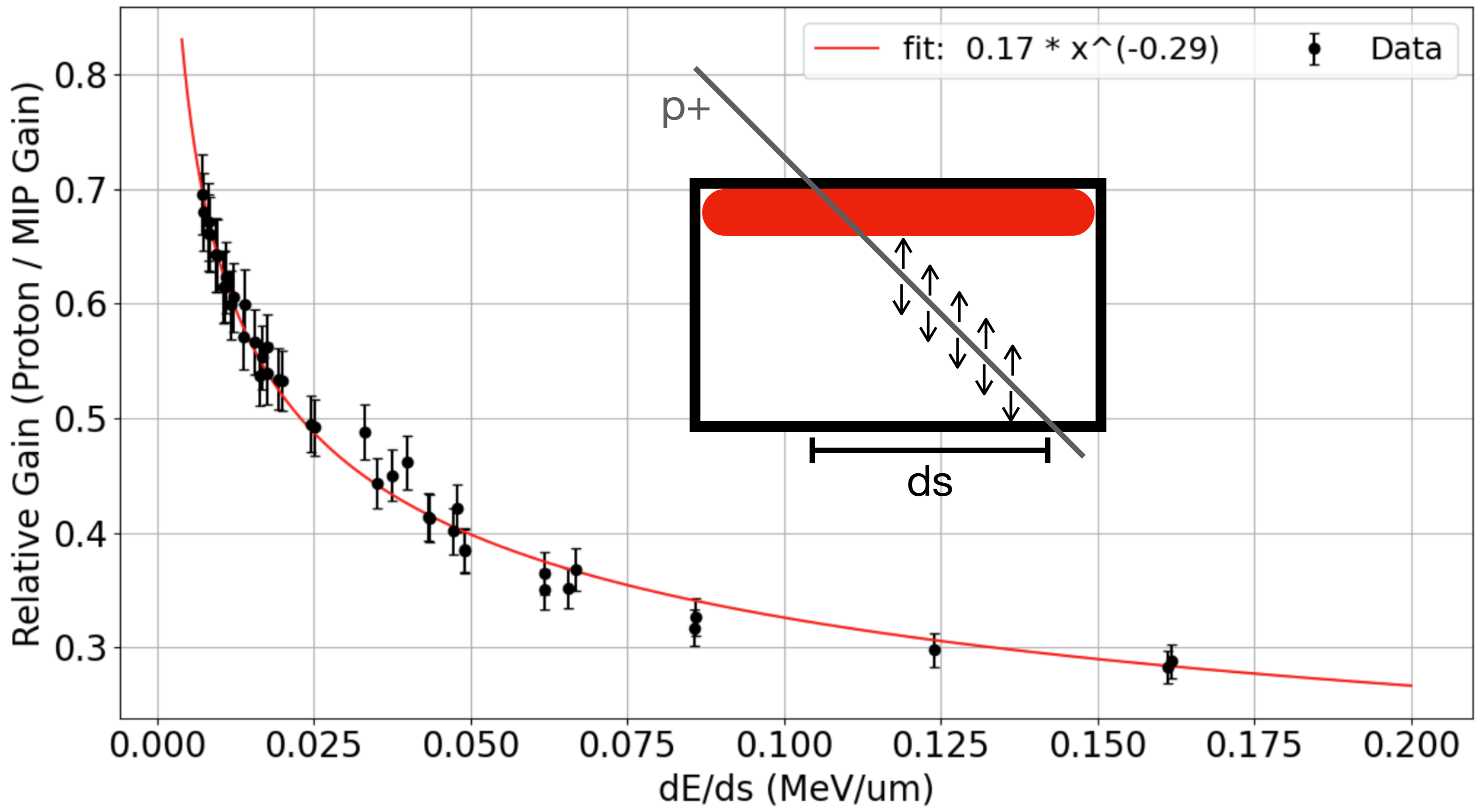
The gain mechanism saturates for **large energy deposit** and introduces an angle dependency

Sensor characterisation



Rutherford Back-Scattering (RBS)

2025 Gain Saturation Measurement — paper in preparation



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

Preparing a parametric model of the gain saturation
that we can extrapolate from protons to pions/muons

Plan to do the measurements with muons at PSI in 2026

The ATAR

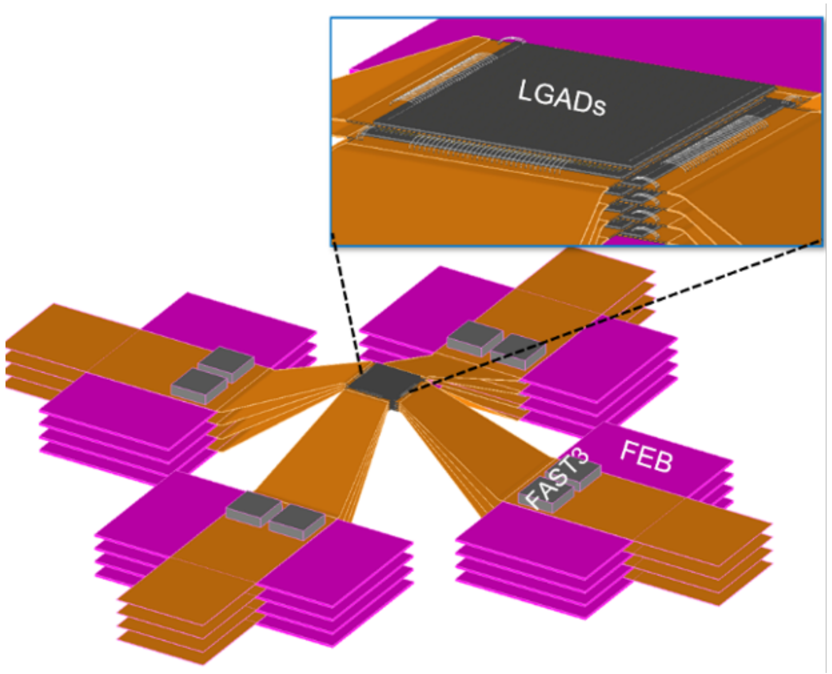
Toward first prototype

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

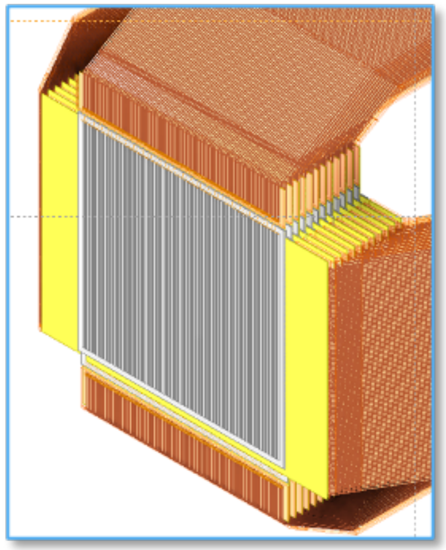
Limited prototype
10 layers, 32-to-64 channels per layers
(full system has 48 layers with 100 channels per layer)

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

Prototype

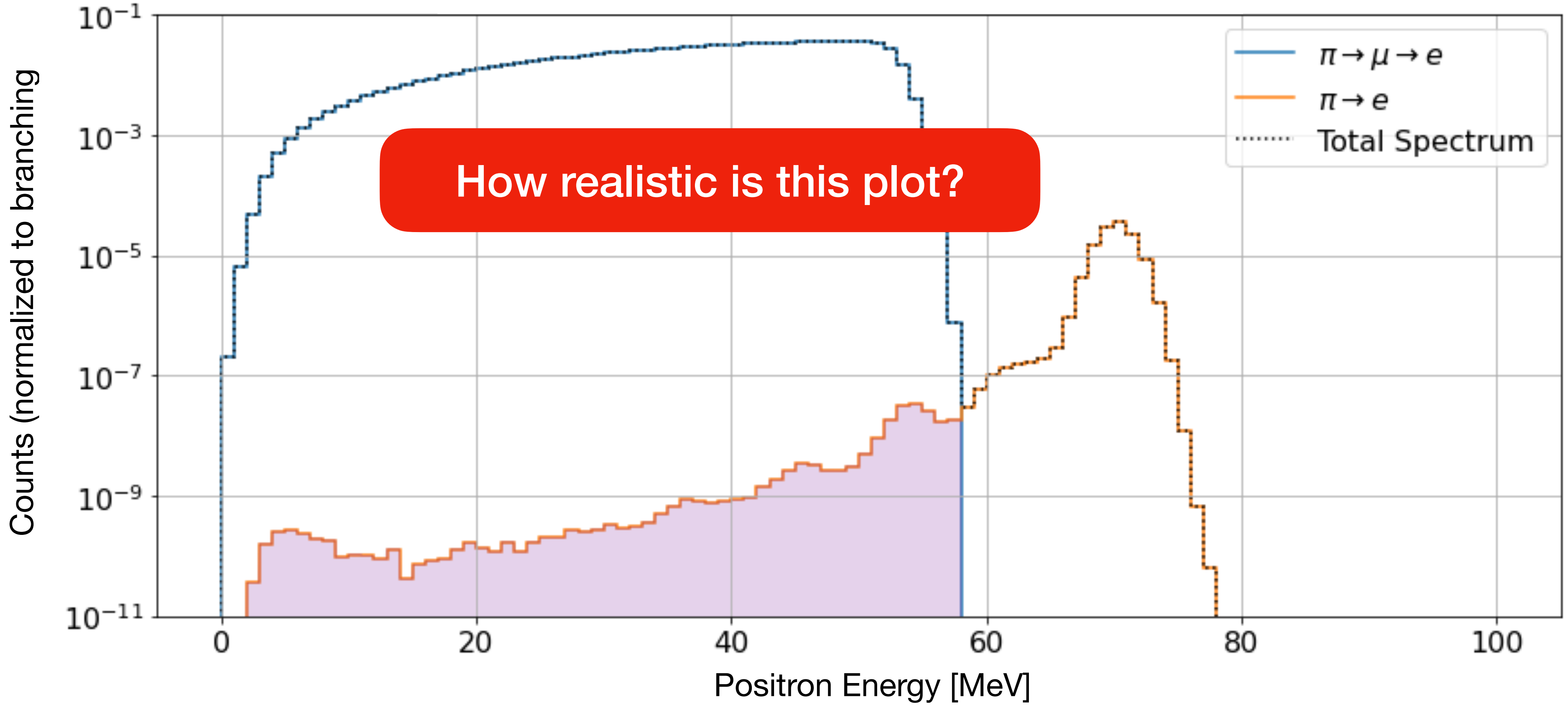


Final Target



Back to the guiding principles

Simulating the experiment



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Back to the guiding principles

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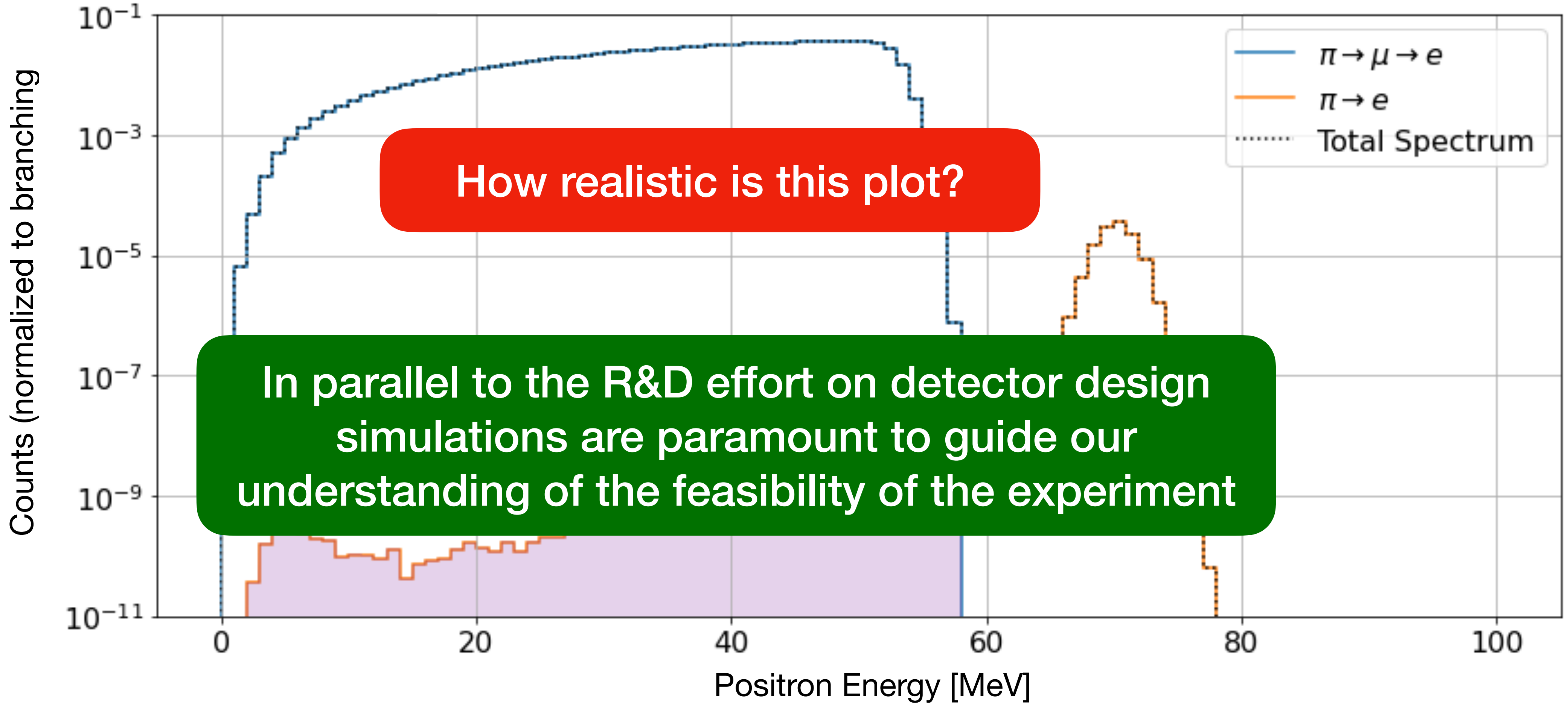

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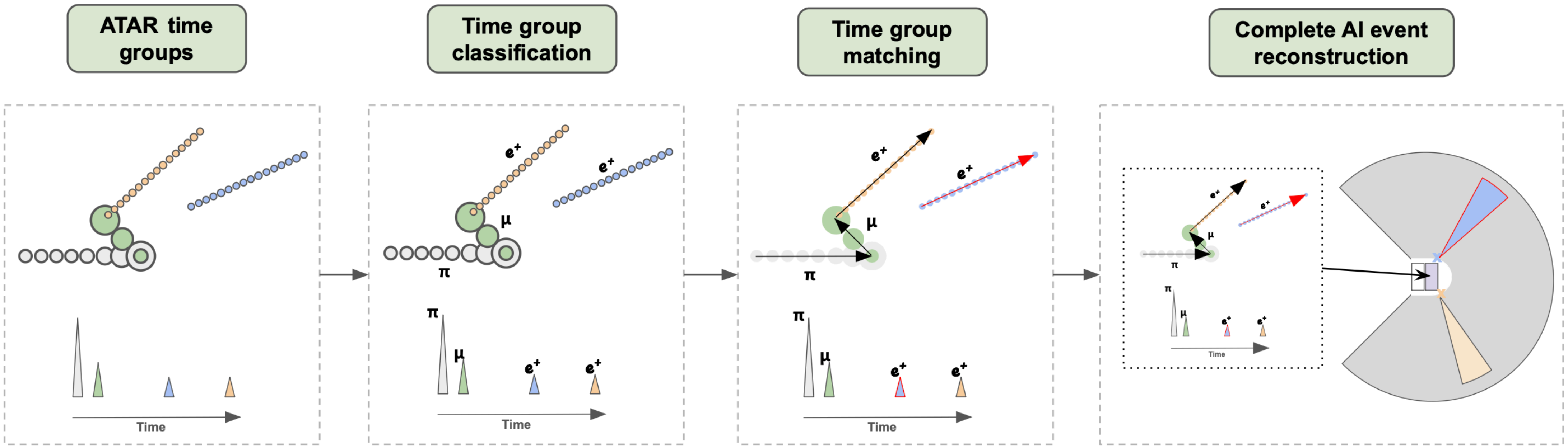
PIONEER Event Reconstruction Pipeline(s)



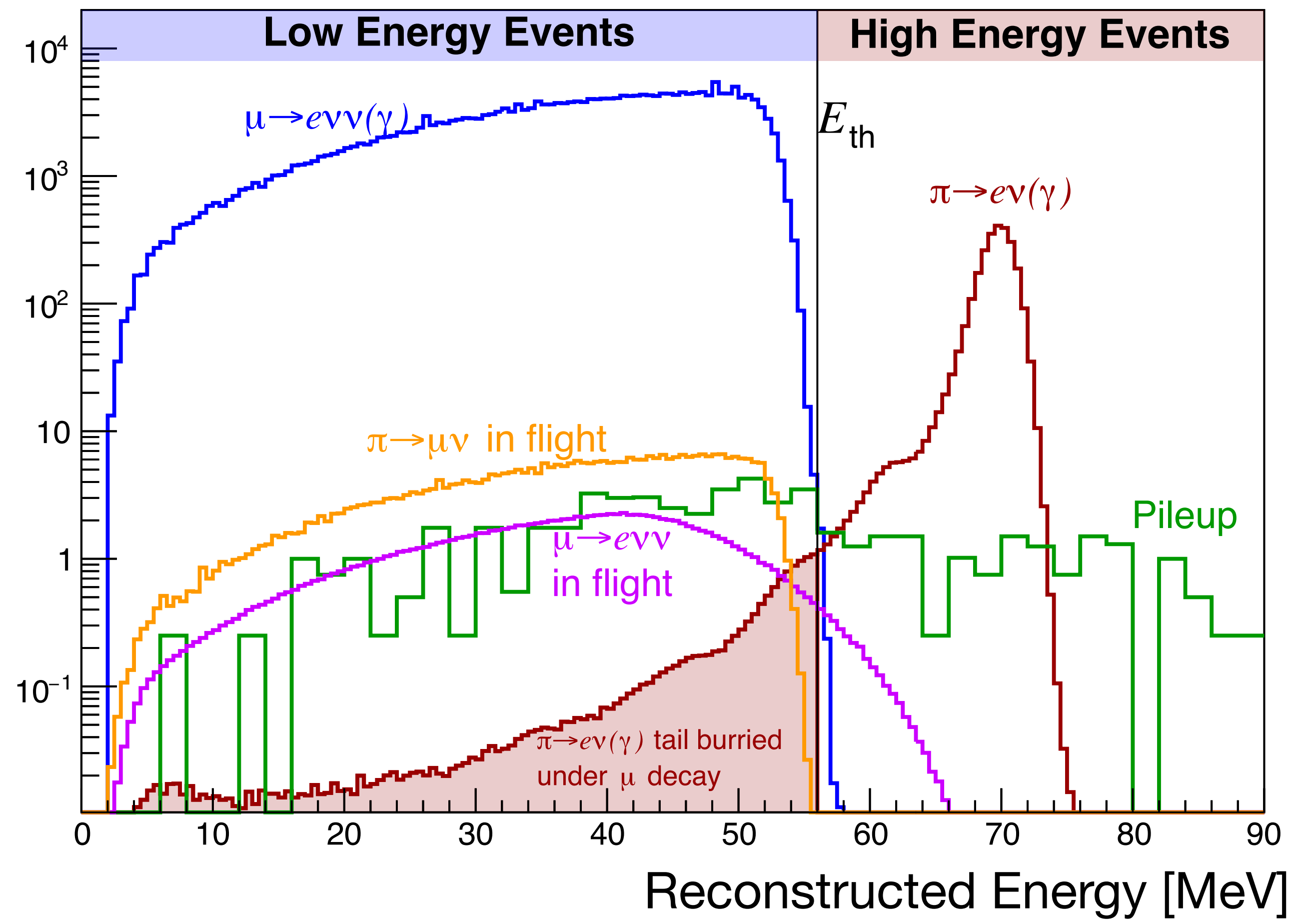
Two reconstruction pipeline in development
AI/ML employing Transformers
Traditional algorithmic "rule-based"

See P. Schwendimann slides at ACTS4NP and the
public material of PIONEER first reconstruction workshop

Nascent effort critical to support sensitivity estimates and test beam data reconstruction

Back to the guiding principles

Simulating the experiment



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

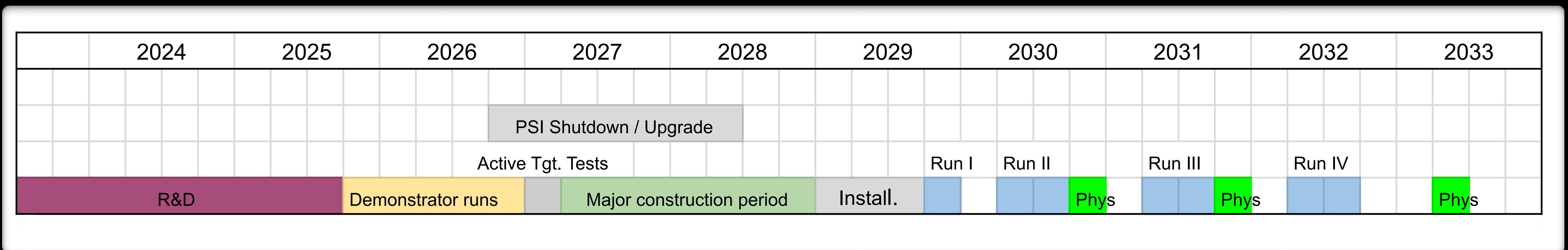
Using simulation, we validate each term of the master formula and its required precision

So far, everything indicates we can reach our targeted precision!

Timeline of the project

Timeline of the project

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



Quentin Buat (UW)

Timeline of the project

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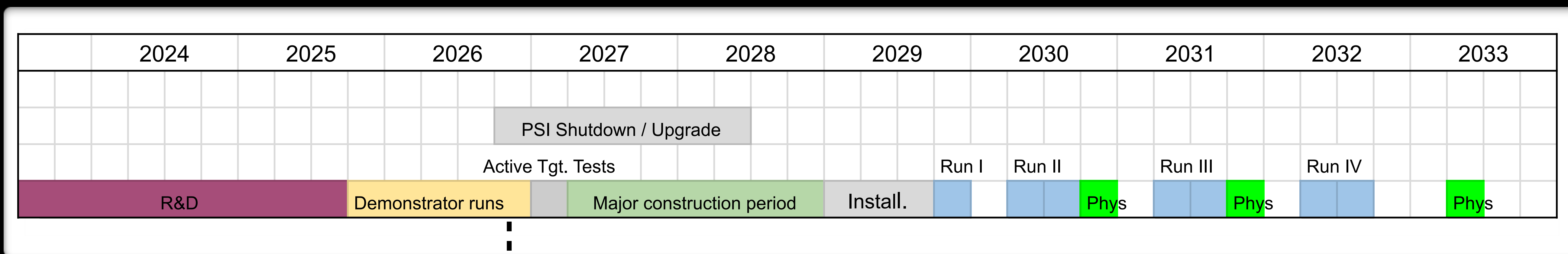
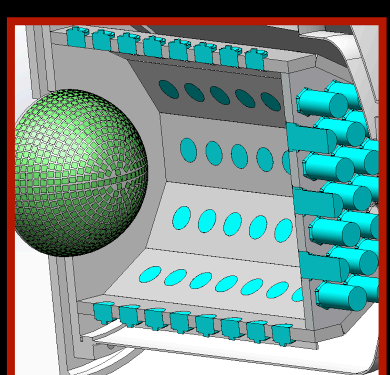
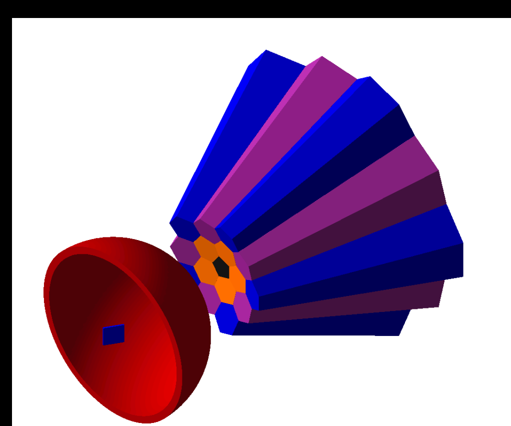


Fall 2026: demonstrator runs



LXe prototype



Demonstrator
6-array LYSO
10 layers ATAR

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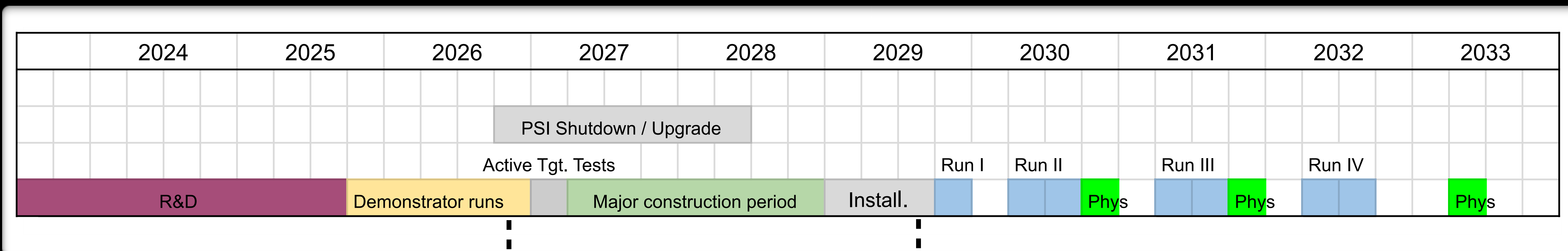
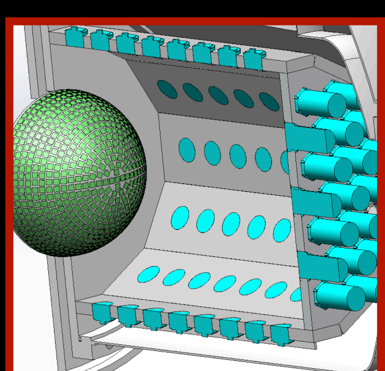


Fall 2026: demonstrator runs

Assembly
Commissioning



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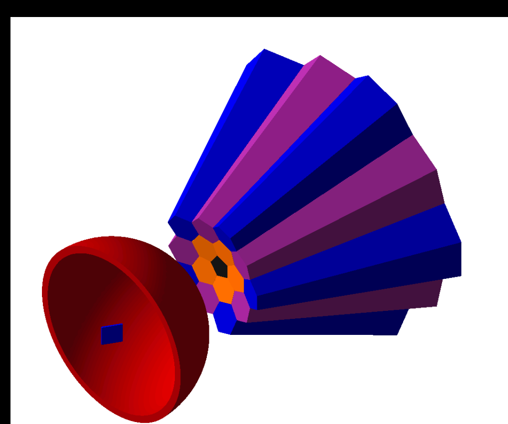

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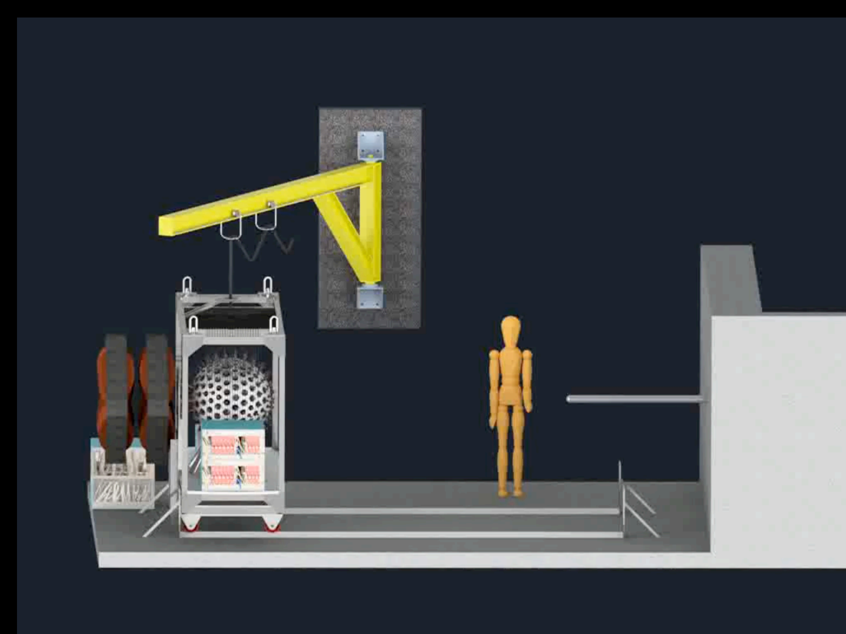

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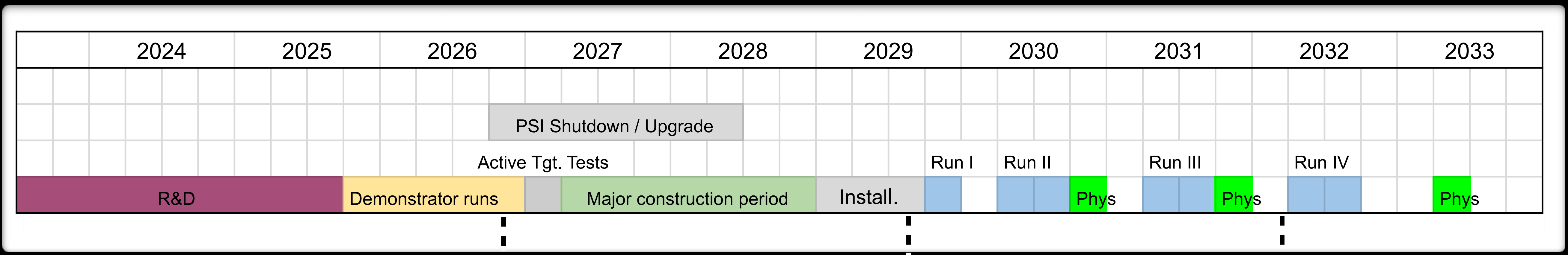

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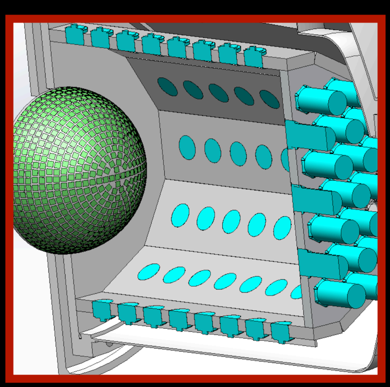

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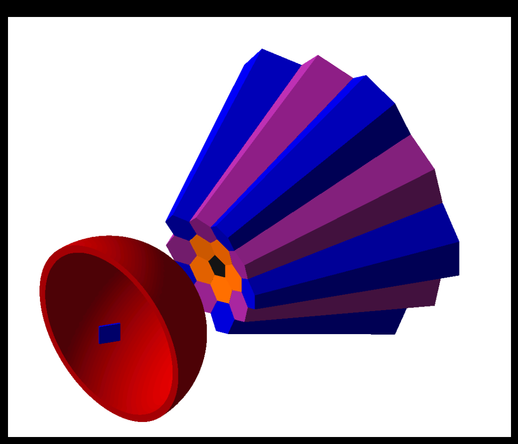

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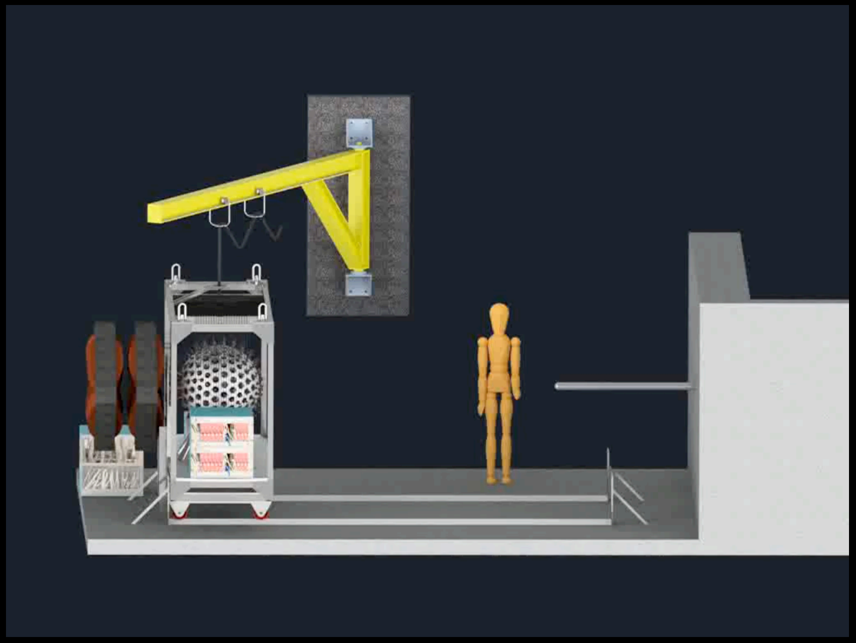
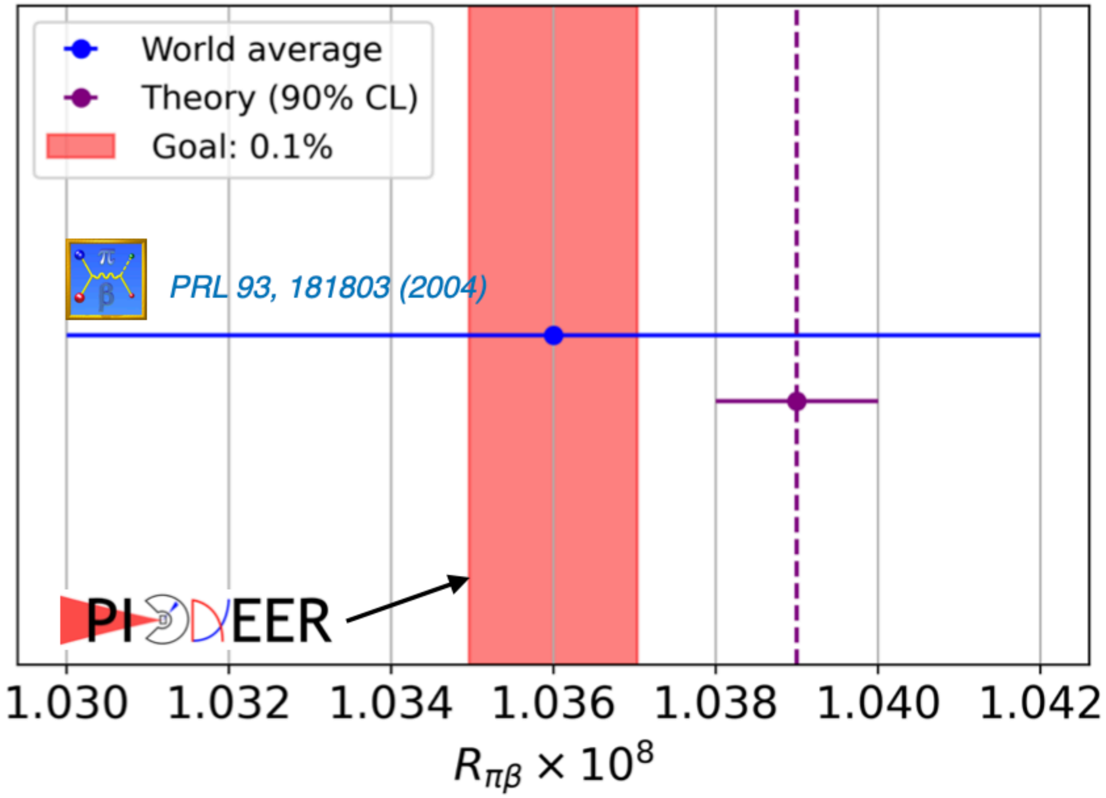


$R_{e/\mu}$ measurement

Outline

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



Focus of this talk:

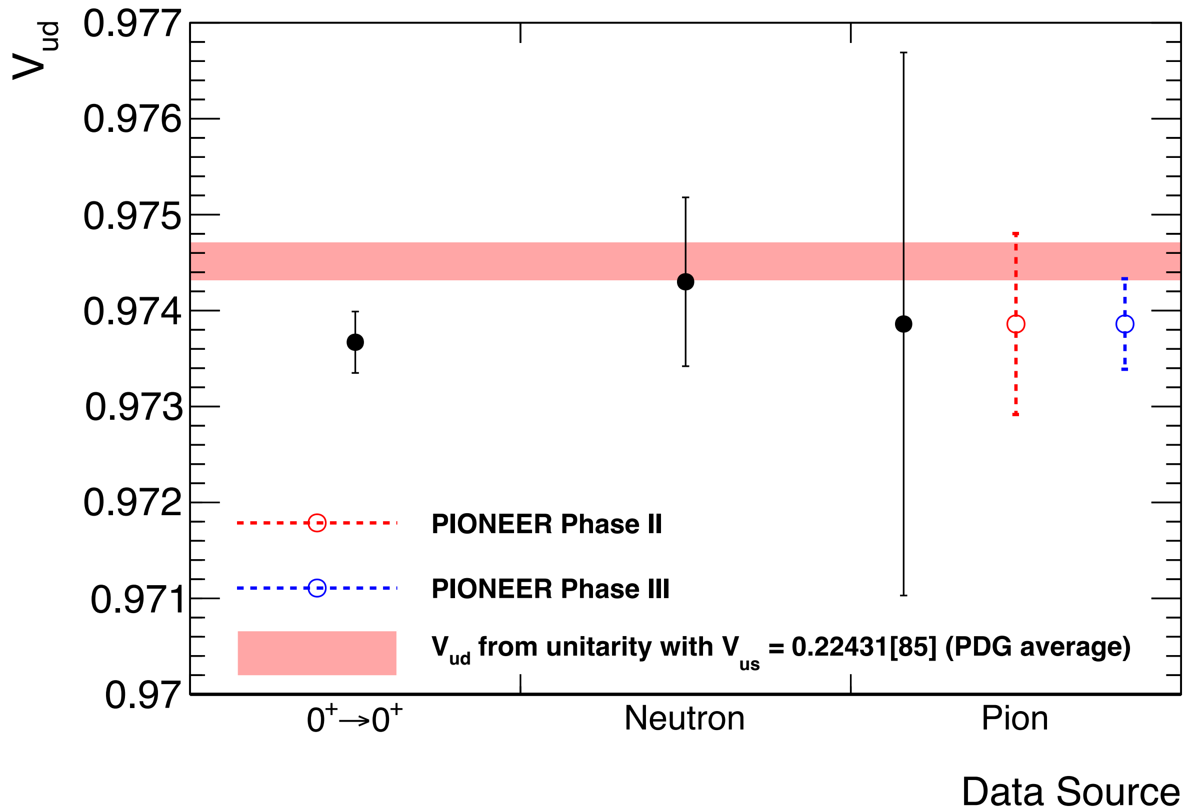
LFU measurement strategy and PIONEER design guiding principles

Update on R&D and simulation efforts

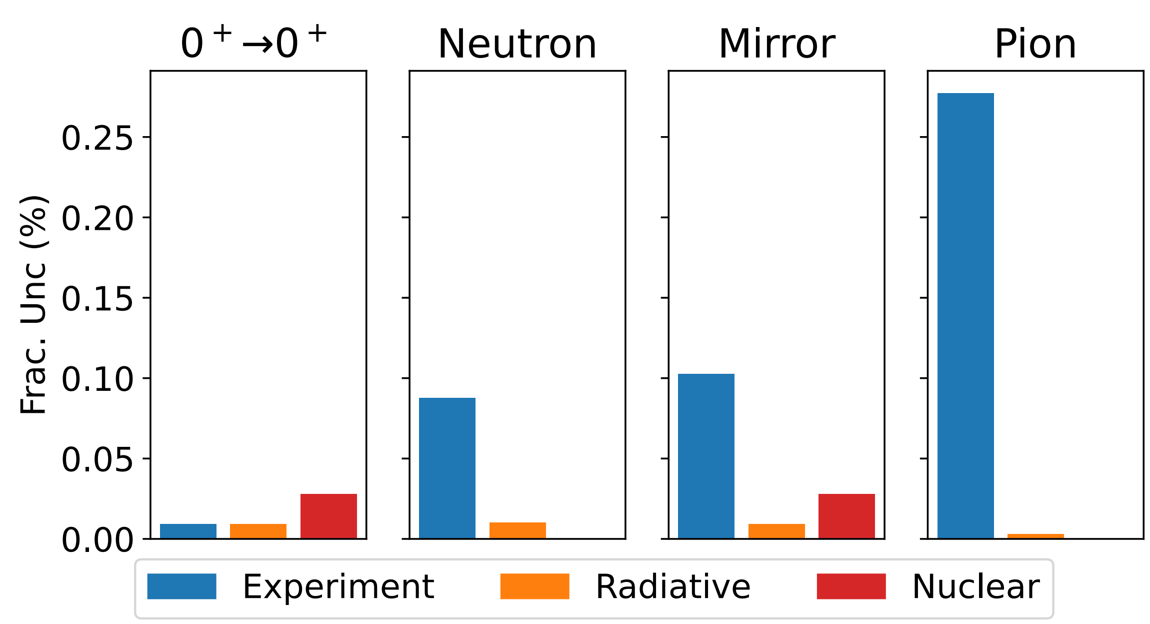
Thoughts and (very) preliminary results on piBeta

See this talk for a lengthier presentation

Landscape of V_{ud} measurements



arXiv:2301.03975



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

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

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

Pion lifetime

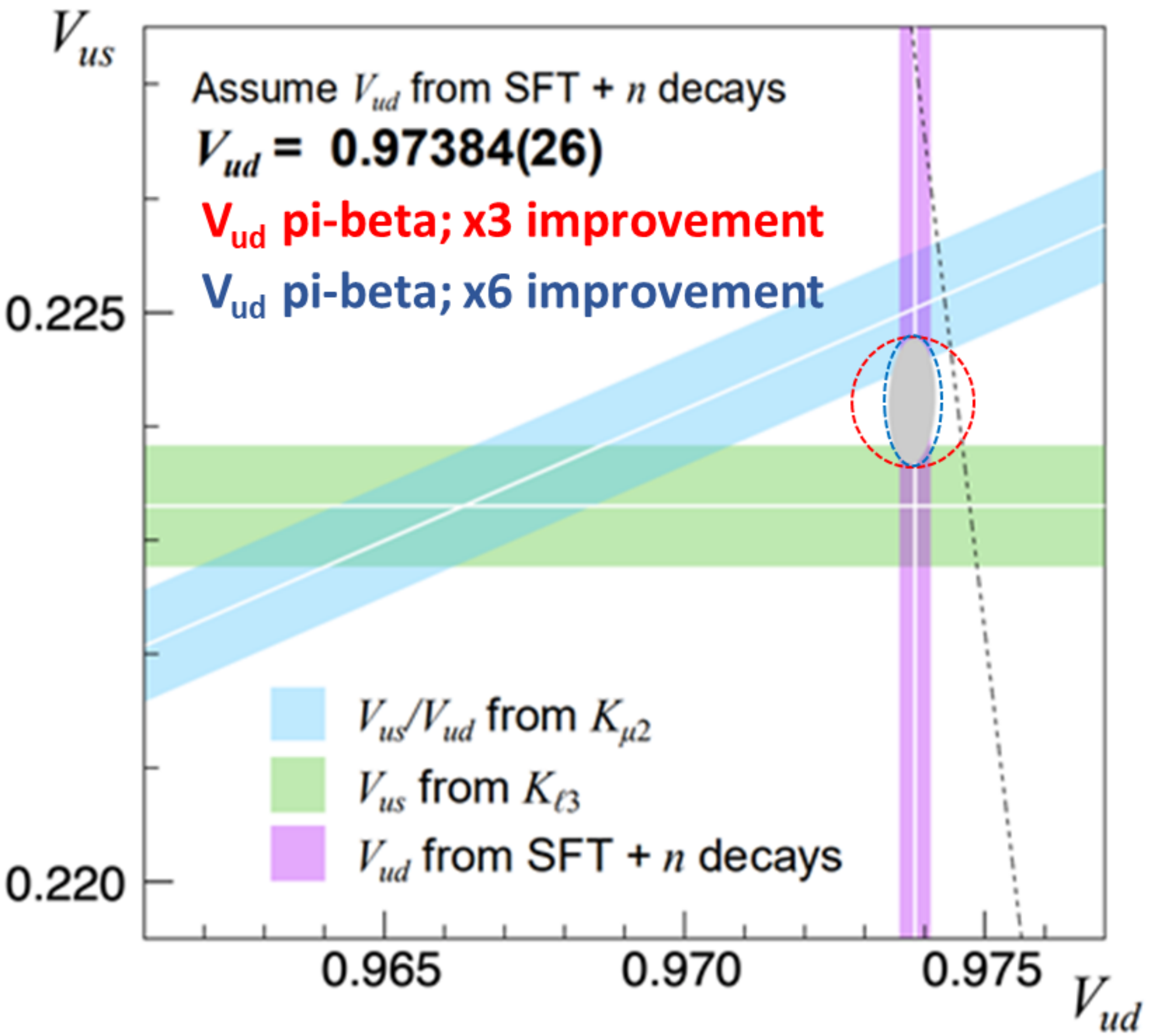
Radiative corrections

Phase space dominated
by exp. uncertainty
on pion mass splitting

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 $R_{\pi\beta}$

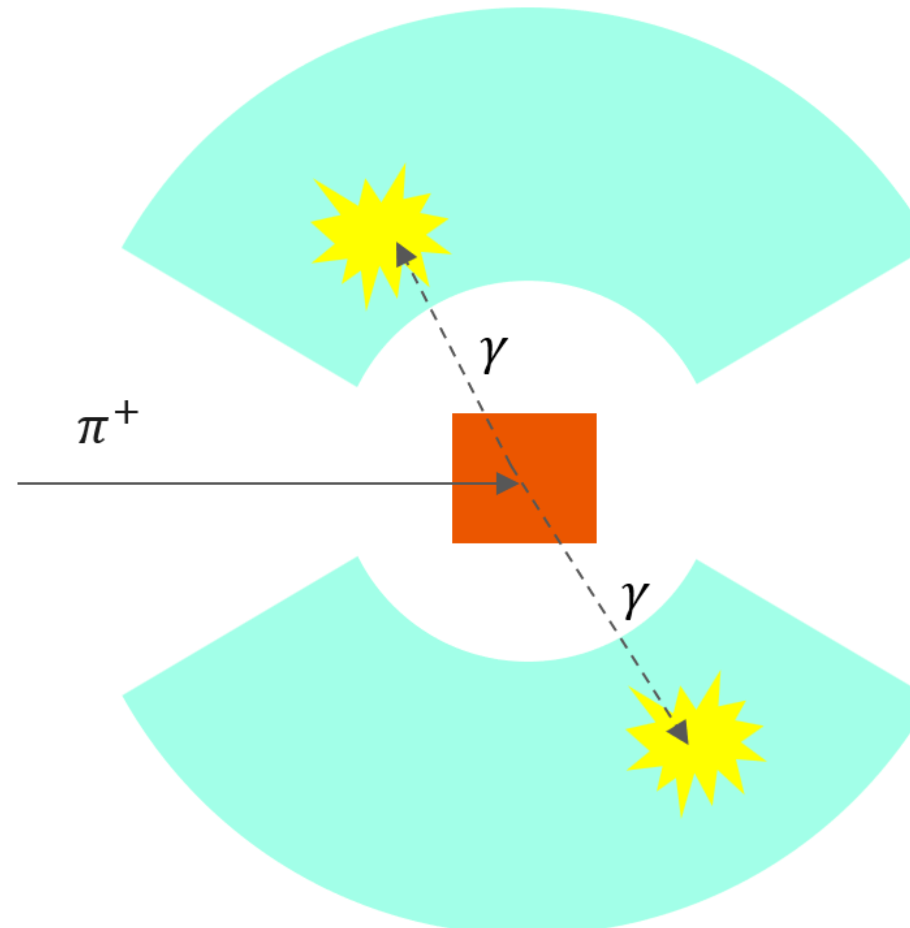
Event Topology

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

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

Two back-to-back photons

Very low energy positron



PiBeta Experiment

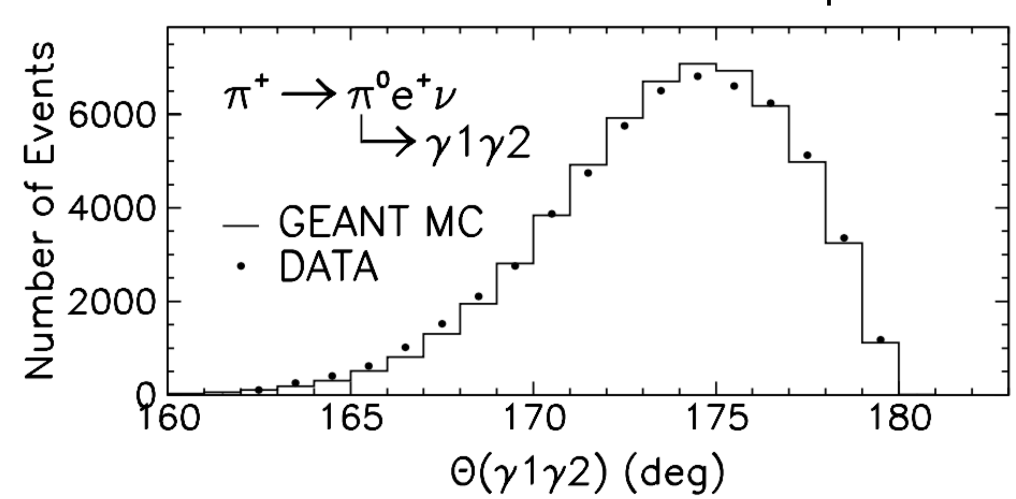
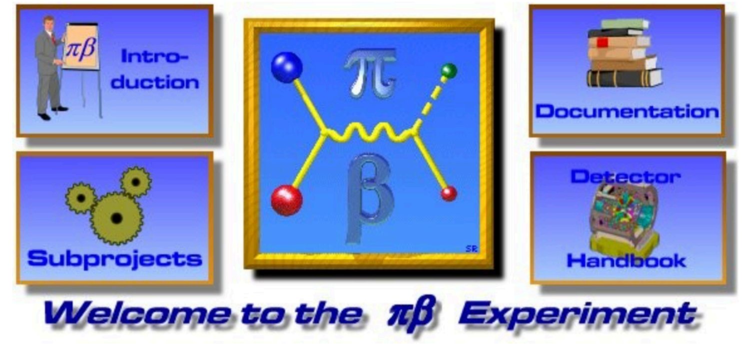


FIG. 5. Histogram of the γ-γ opening angle in π_β decay.



$R_{\pi\beta}$ 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

Uncertainty budget

Phys. Rev. Lett. 93, 181803

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

The piBeta experiment

Uncertainty budget

Phys. Rev. Lett. 93, 181803

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

Uncertainty budget

Phys. Rev. Lett. 93, 181803

Uncertainty type	Quantity	Value	$\Delta R_{\pi\beta}$ (%)
External	$R_{\pi e2}^{\mathrm{exp}}$	1.230×10^{-4}	0.33
	$R_{\pi^0 \to \gamma\gamma}^{\mathrm{exp}}$	0.9880	0.03
	π^+ lifetime	26.033 ns	0.02
Combined external			0.33
Internal	$N_{\pi e2}^{\mathrm{tot}}$ (syst)	6.779×10^8	0.19
	$A_{\pi\beta}^{\mathrm{HT}}/A_{\pi e2}^{\mathrm{HT}}$	0.9432	0.12
	$r_{\pi G} = f_{\pi G}^{\pi\beta}/f_{\pi G}^{\pi e2}$	1.130	0.26
	$N_{\pi\beta}^{\mathrm{accid}}$	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

The piBeta experiment

Uncertainty budget

Phys. Rev. Lett. 93, 181803

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0.04%

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

The piBeta experiment

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Phys. Rev. Lett. 93, 181803

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The piBeta experiment

Uncertainty budget

Phys. Rev. Lett. 93, 181803

Uncertainty type	Quantity	Value	$\Delta R_{\pi\beta}$ (%)	PIONEER Phase I
External	$R_{\pi e2}^{\mathrm{exp}}$	1.230×10^{-4}	0✗3	0.01%
	$R_{\pi^0\to\gamma\gamma}^{\mathrm{exp}}$	0.9880	0.03	
	π^+ lifetime	26.033 ns	0.02	
Combined external			0.33	
Internal	$N_{\pi e2}^{\mathrm{tot}}$ (syst)	6.779×10^8	0.19	
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Combined internal			0.38	
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Phys. Rev. Lett. 93, 181803

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	$r_{\pi\text{G}} = f^{\pi\beta}_{\pi\text{G}}/f^{\pi e2}_{\pi\text{G}}$	1.130	0.26	LYSO timing resolution
	$N^{\text{accid}}_{\pi\beta}$	0	<0.1	
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PIONEER will be able to collect $\pi^+ \to \pi^0 e^+ \nu$ efficiently

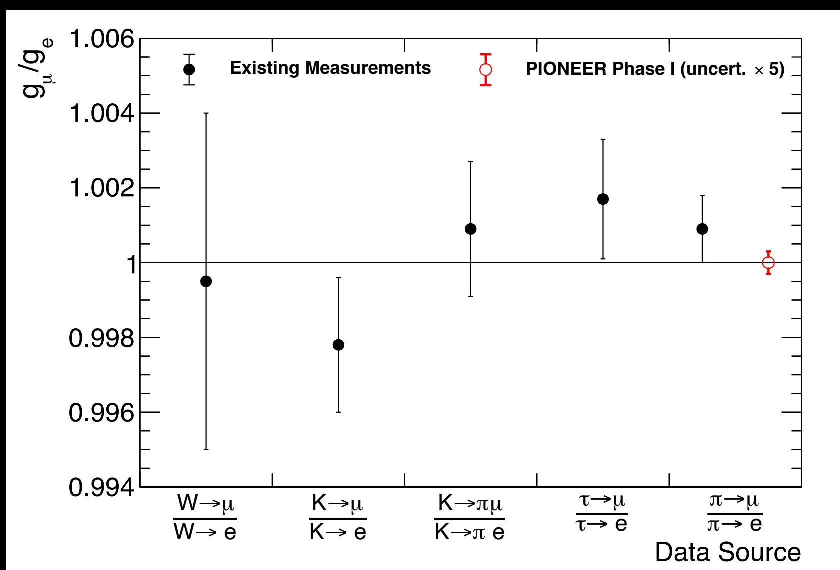
The main challenge: measuring pi-e insitu and controlling the relative acceptance of pi-e and piBeta events

The ATAR will be an invaluable asset — Need more studies for quantitative estimates

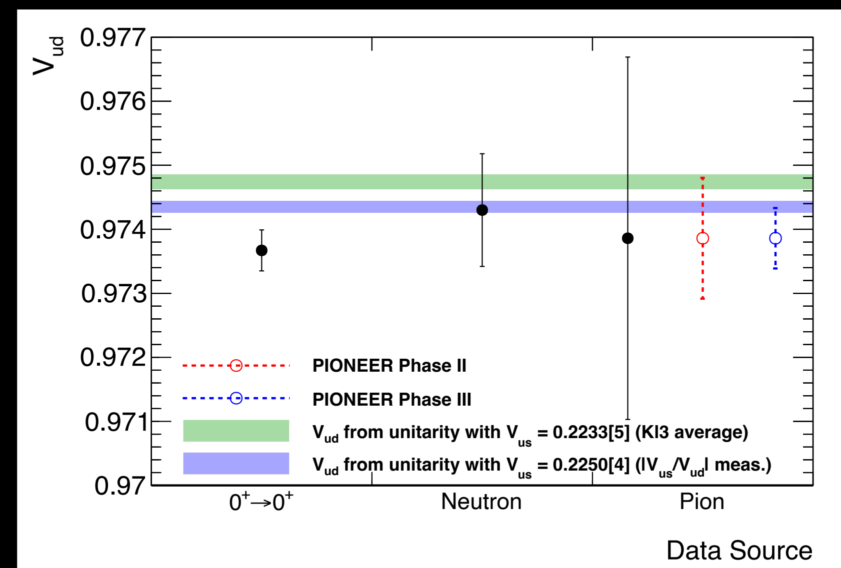
PIONEER

A next generation rare pion decay experiment

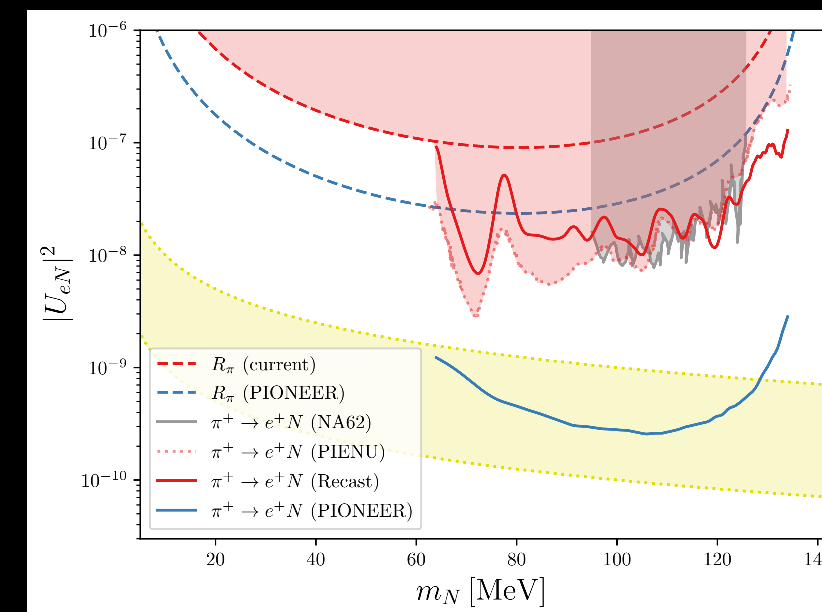
Lepton Flavor Universality

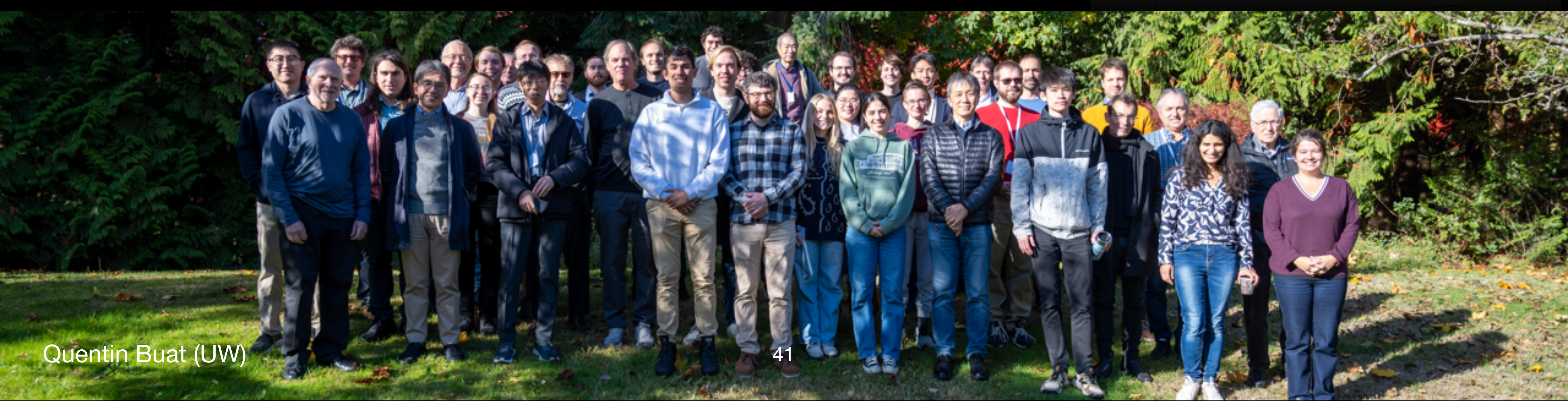


Cabbibo Angle Anomaly



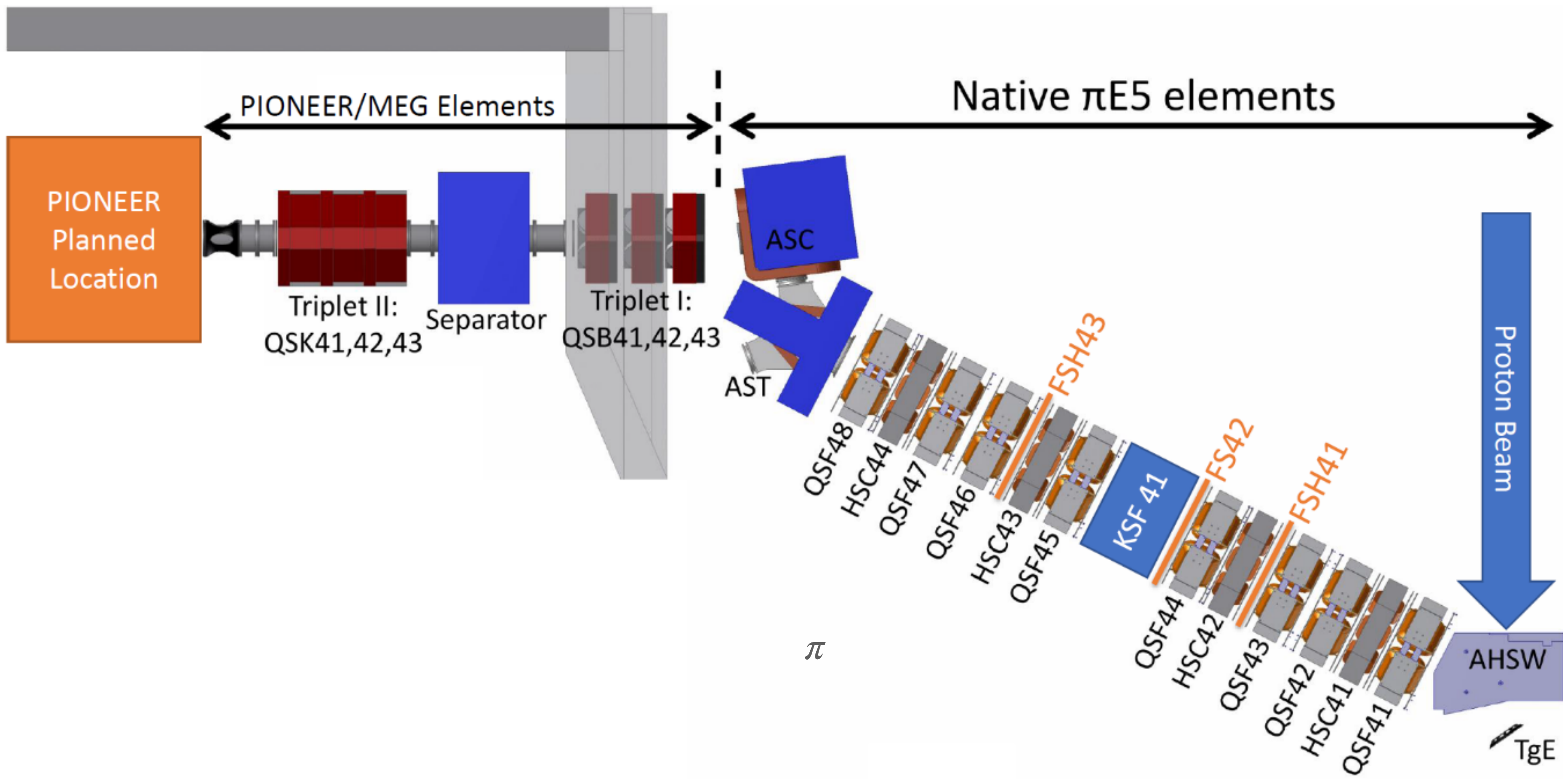
Exotic decays





Additional material

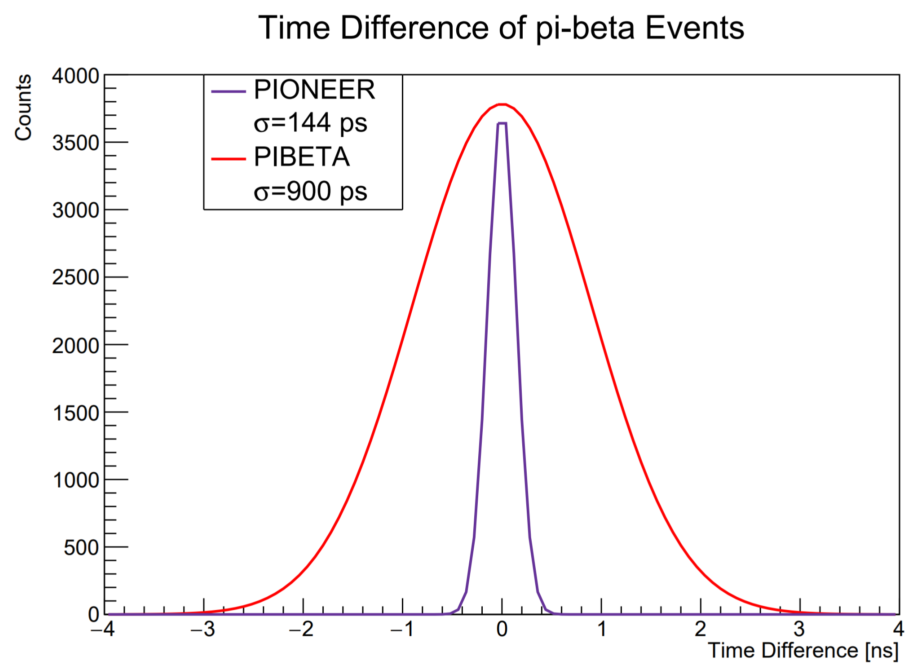
Pion Beamline at PSI



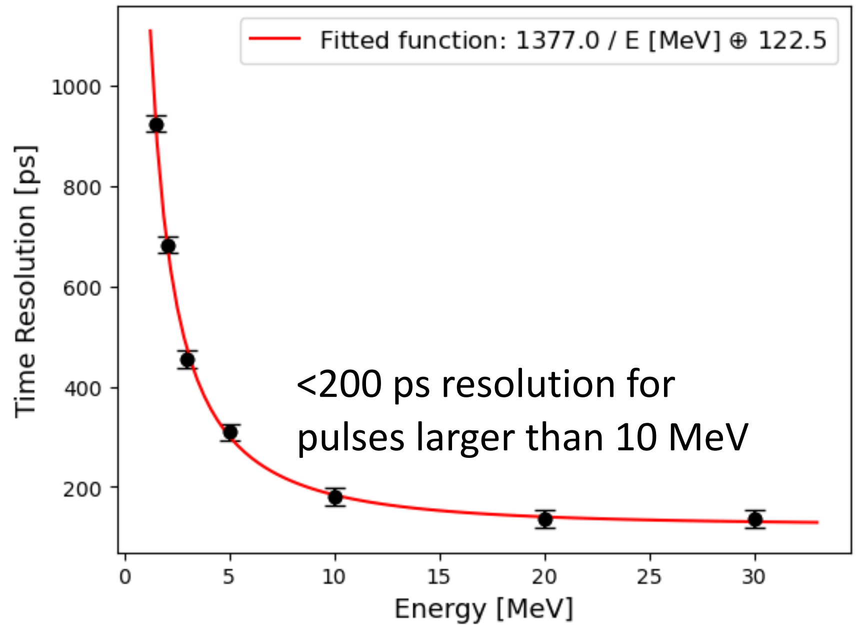
	Phase 1	Phase 2
Pion Decay of Interest	$\pi^+ \to e^+ \nu_e$	$\pi^+ \to \pi^0 e^+ \nu_e$
Rate (Hz - pion/s)	$3\ .10^5$	$3\ .10^7$
Momentum bite	dp/p=1%	dp/p=3%
Statistics/yr	10^8	10^6
Measurement precision	0.015%	0.1%

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

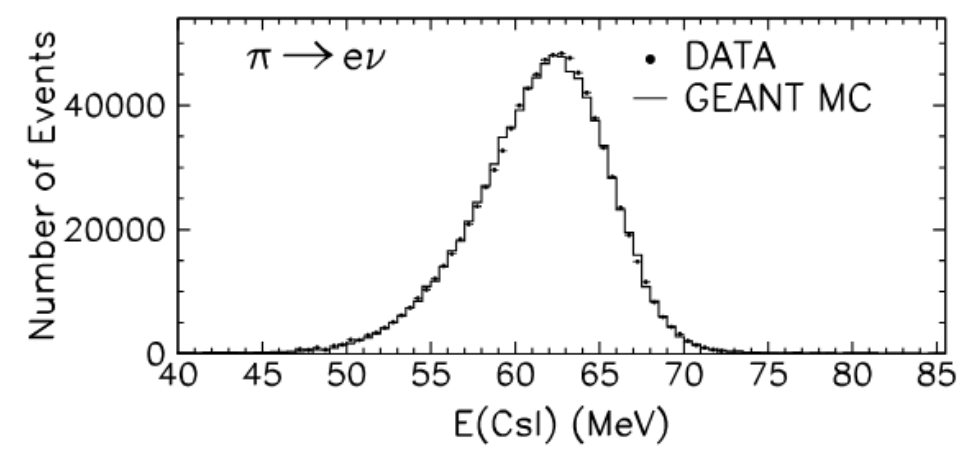


$\pi^+ \rightarrow e^+\nu_e$ Count ($N_{\pi e2}^{tot}$)

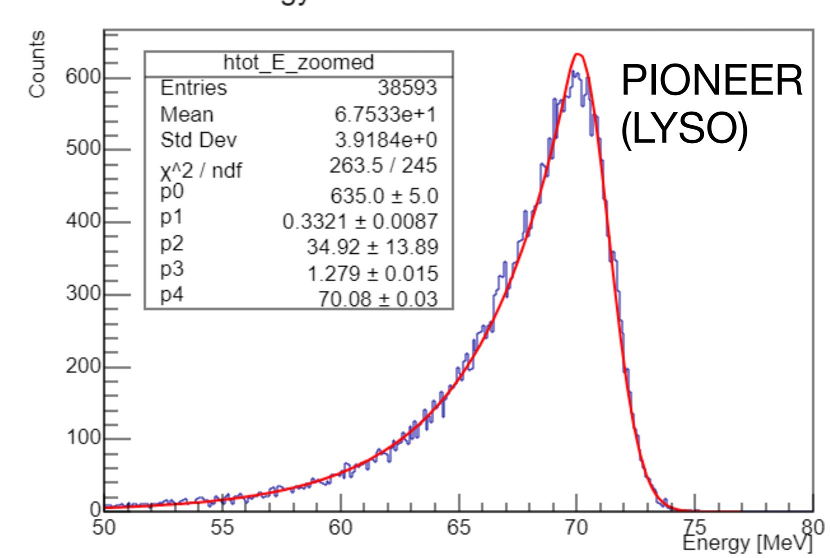
- 0.19% Uncertainty in PiBeta Experiment
- Uncertainty primarily from measuring the tail of $\pi^+ \rightarrow e^+\nu_e$ — The PiBeta experiment used Monte Carlo estimates
  - PIONEER should have a better understanding of the tail fraction from Phase I — the fraction will change if the target is changed 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



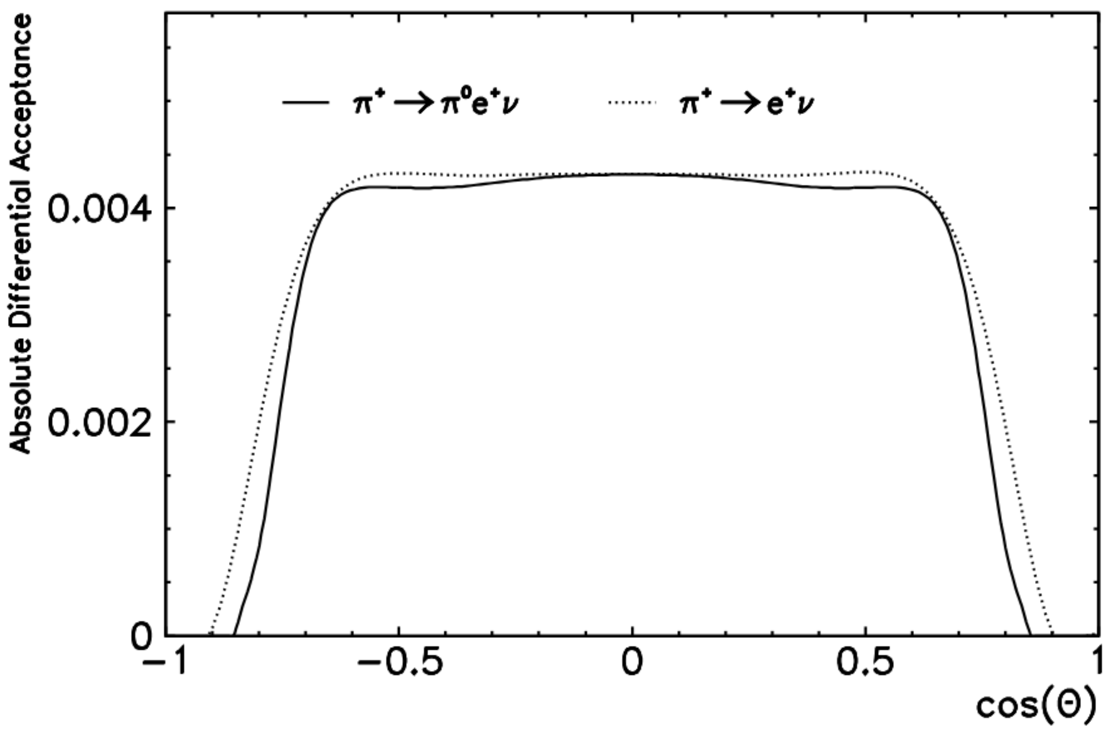
Energy Resolution 70 MeV -- 1.82%



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

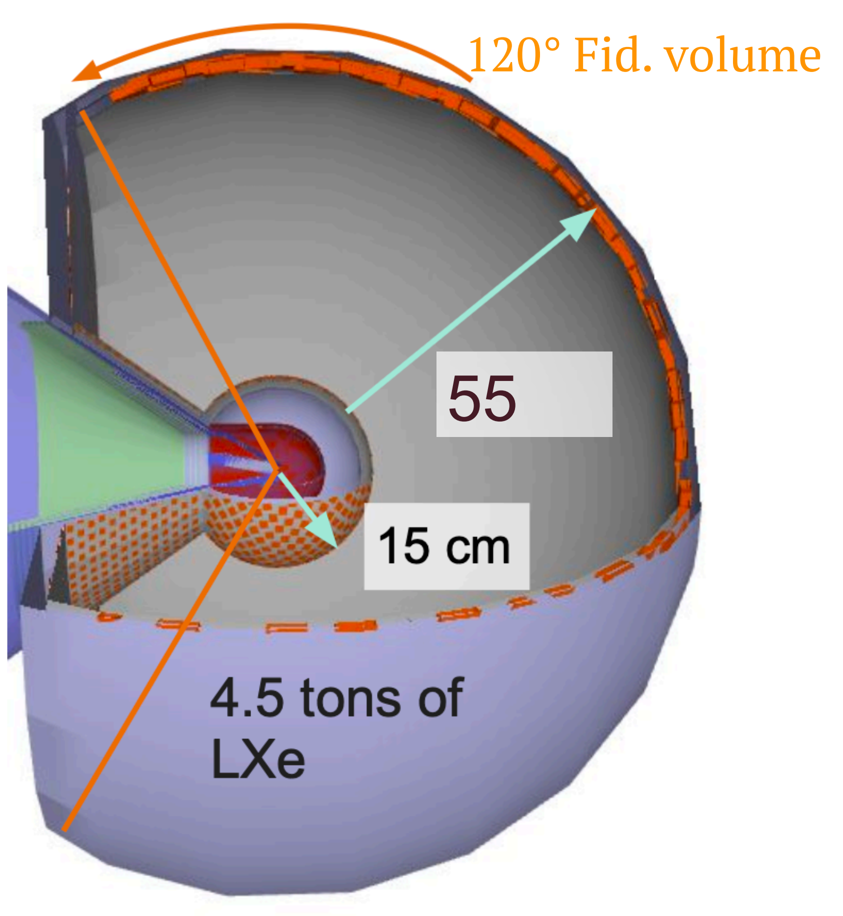
➡ **More quantitative estimates needed**

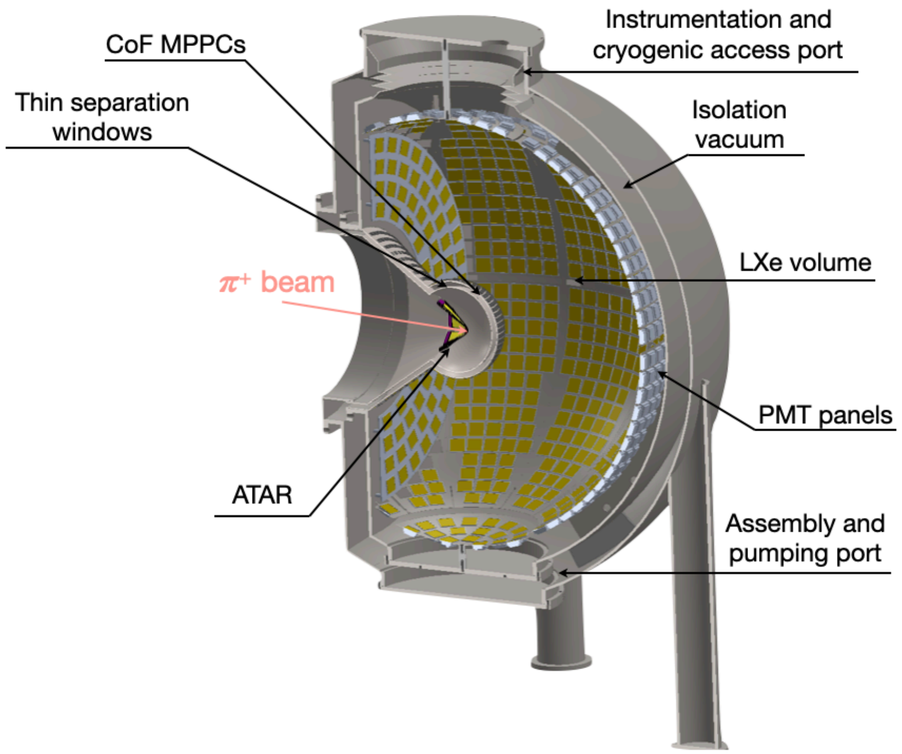


Liquid Xenon (LXe)

+ fast response
+ dense
+ highly homogeneous response
+ very bright
+ proven excellent energy resolution at ~70 MeV with γ (MEG)
+ detector can be reshaped

- pileup suppression capabilities
- cost



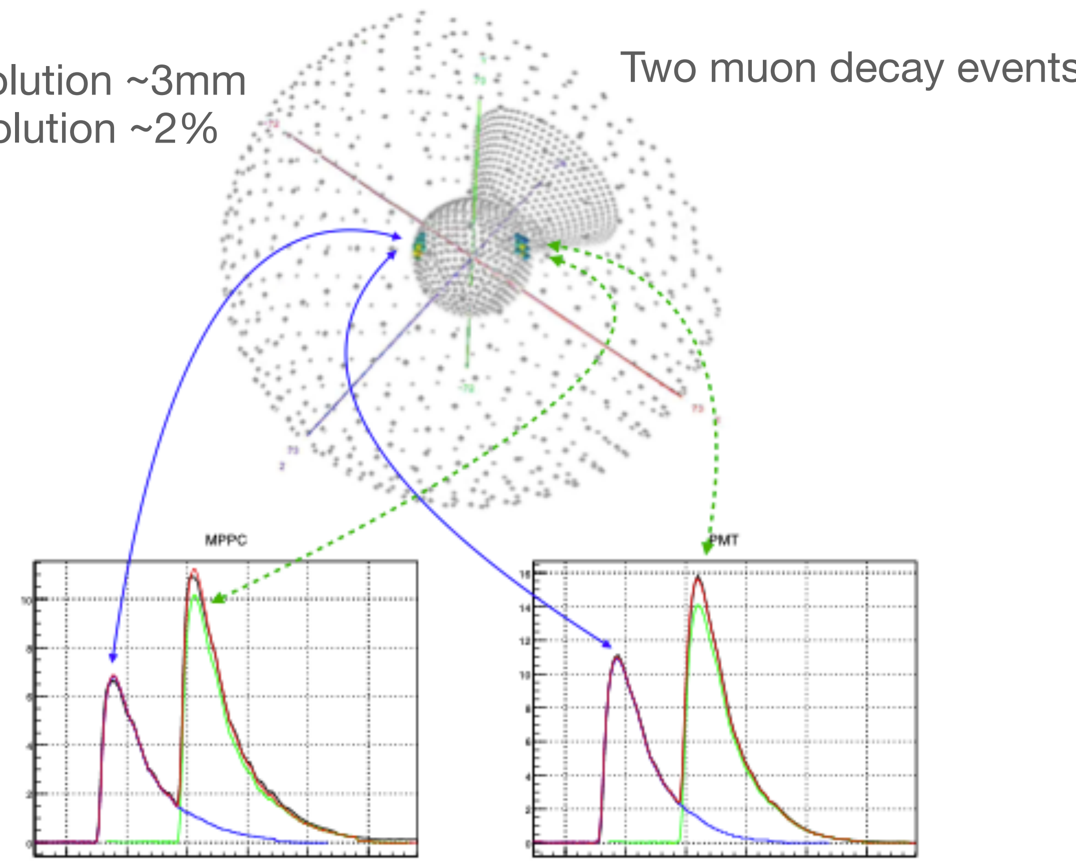


- Full optical simulation & waveform reconstruction based on data
- Cluster reconstruction for incoming particle identification
- Coverage on entrance cone provides pileup identification
- Pileup unfolding based on waveform fit
- >97% pileup reconstruction efficiency for delta t >10ns (WIP)
- Machine Learning algorithms being developed for γ/e^+ identification based on light distribution between inner and outer photosensors

Key detector components:

- thin entrance windows (200 µm of Ti-6Al-4V and 500 µm of Al-Si10Mg)
- Chip on film SiPM on inner entrance window
- Homogeneous coverage of photosensors
- Leads to high response homogeneity as a function of angle & minimal amount of dead material

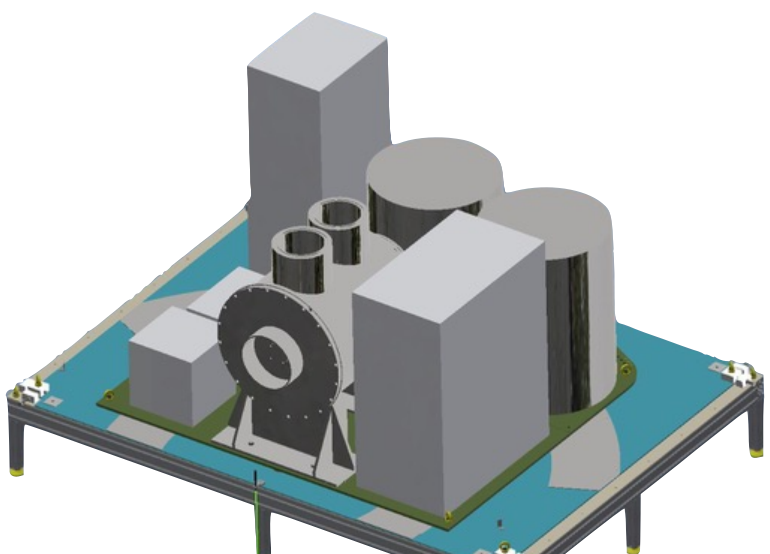
Position resolution ~3mm
Energy resolution ~2%

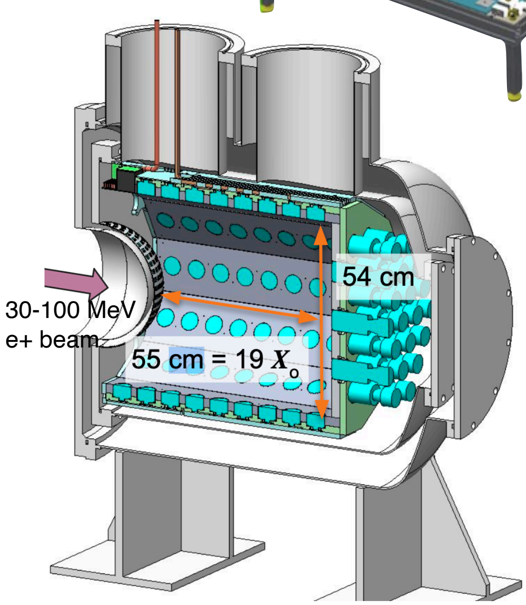


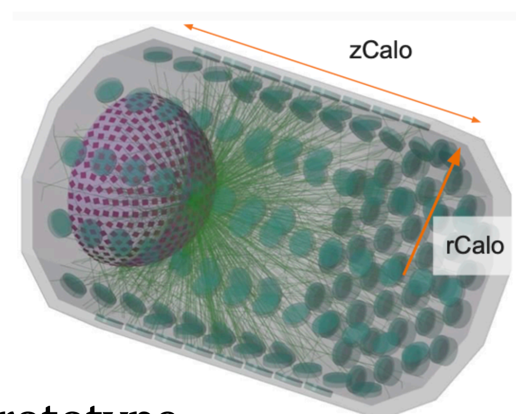
Prototype

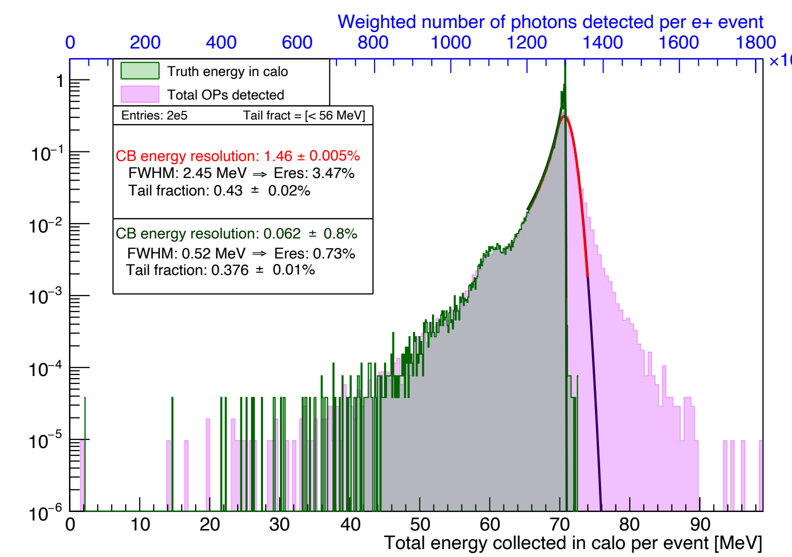
LXe

- dimension of the 1/2 sphere identical to PIONEER Calo
- SiPM coverage ~30% - same as in the full calorimeter
- 19 X0 in the forward direction
- ~5 R_M radial : tail is ~0.5 % - allows measurement of photo nuclear events

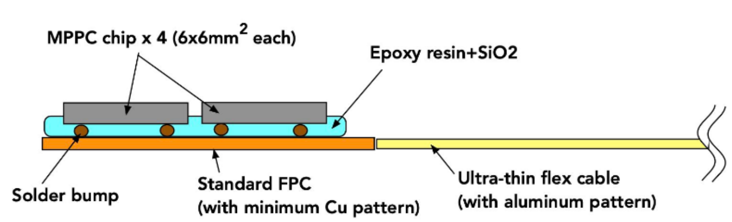


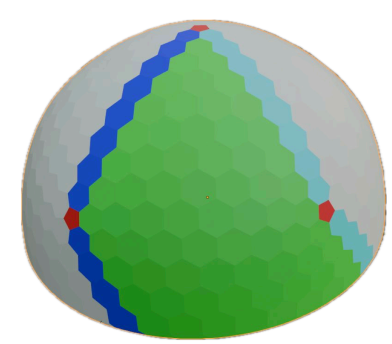


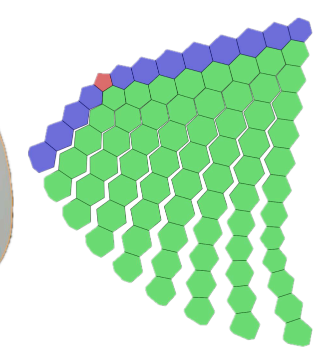




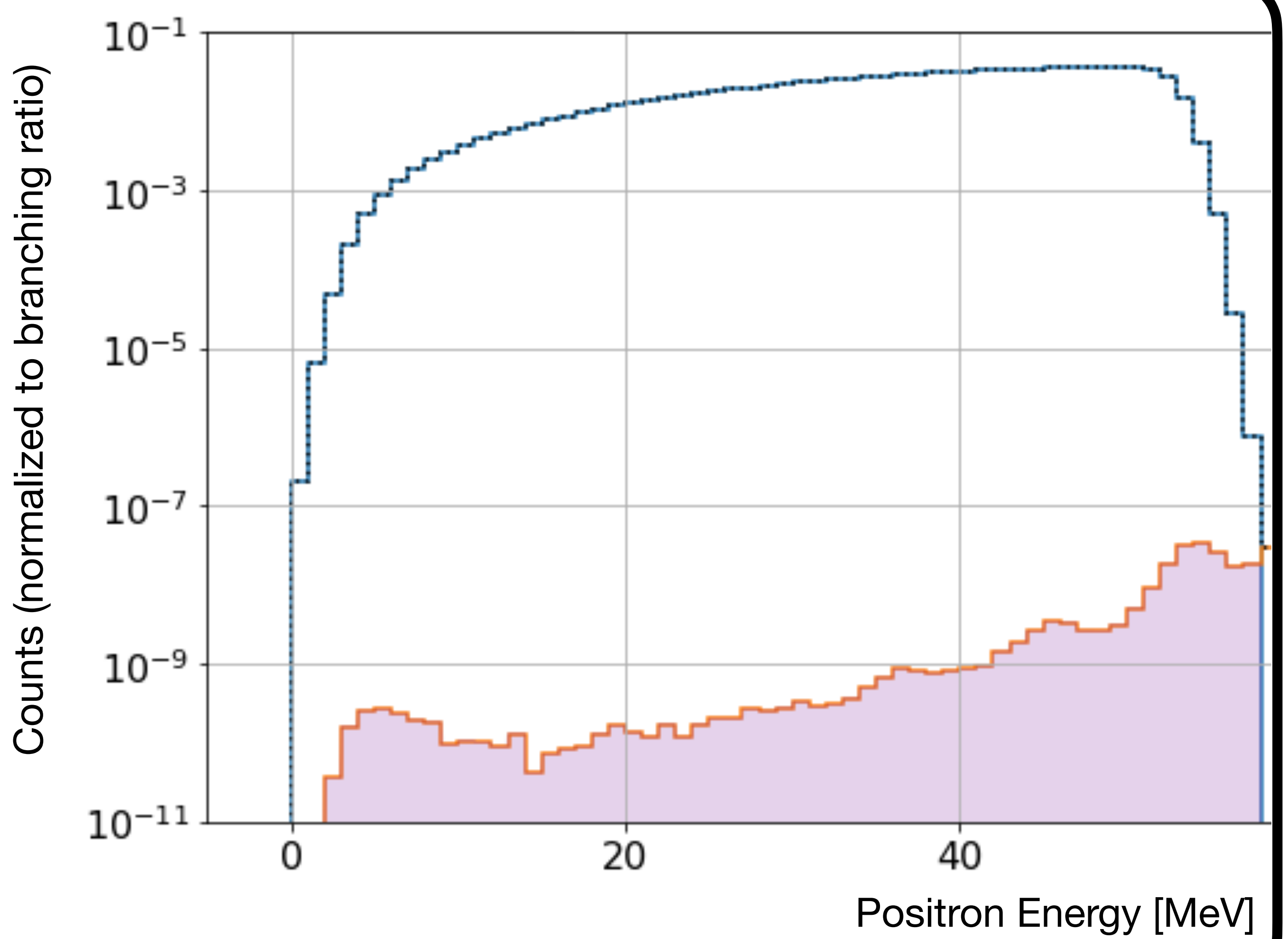
~ 200L LXe prototype
~20% available now within the collaboration, remainder needs to be funded







A challenging S/B problem

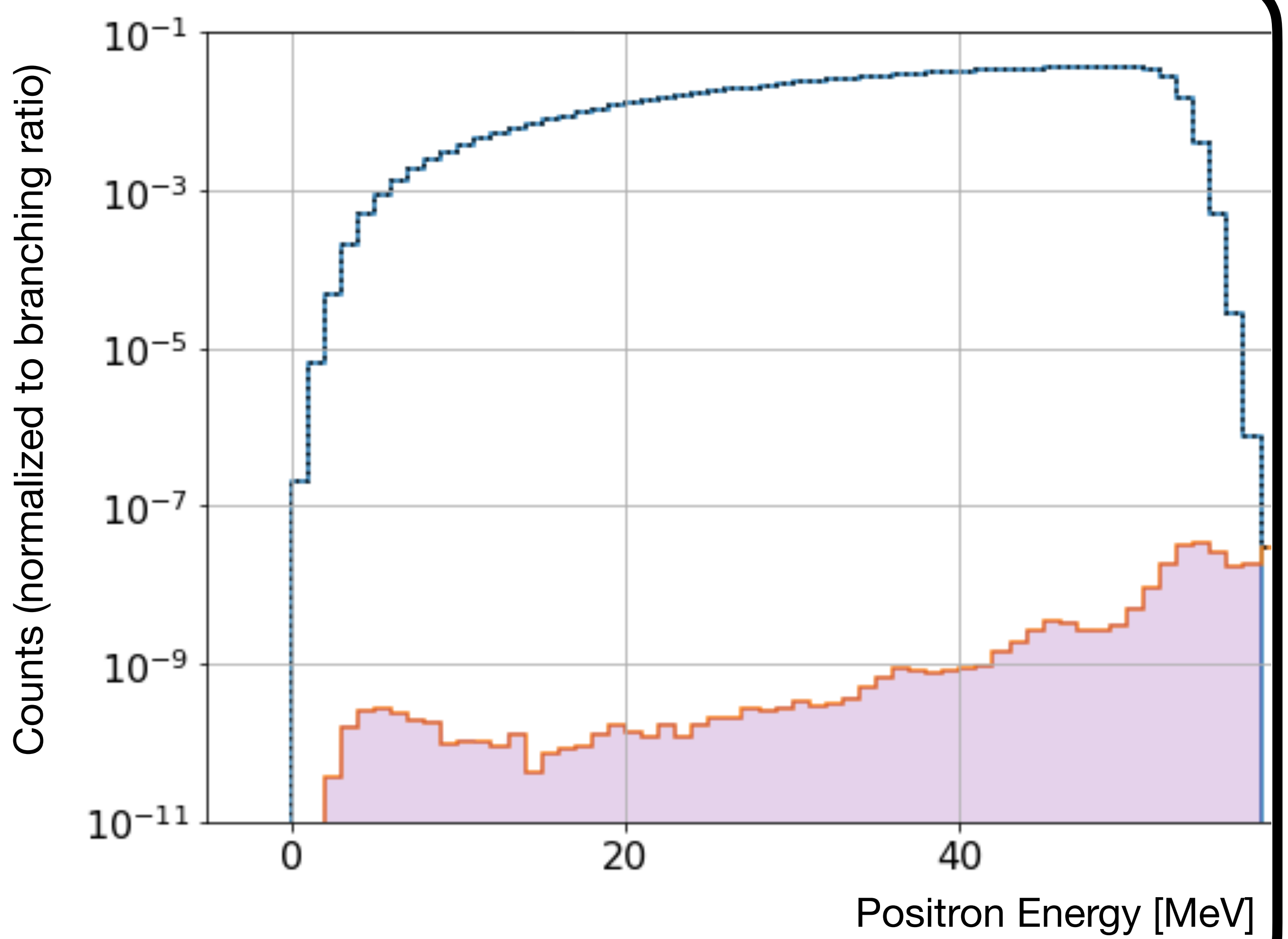


Sig / Bkg requirements

$\pi \to e$ selection efficiency ~ 1%

$\pi \to \mu \to e$ rejection rate ~ 10^7

A challenging S/B problem



Sig / Bkg requirements

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$$N_{tail}(\pi \rightarrow e) \sim C_{tail} \times R_{e/\mu} \times N(\pi \rightarrow \mu \rightarrow e)$$

With $C_{tail} \sim 1\ \%$, we expect the $\pi \rightarrow \mu \rightarrow e$ process to occur at a rate **10^6 larger** than the $\pi \rightarrow e$ process in the low energy region

The approach

PIONEER is a **fixed target** experiment

Can we instrument the target
to our advantage?

Sig / Bkg requirements

$\pi \rightarrow e$ selection efficiency ~ 1%

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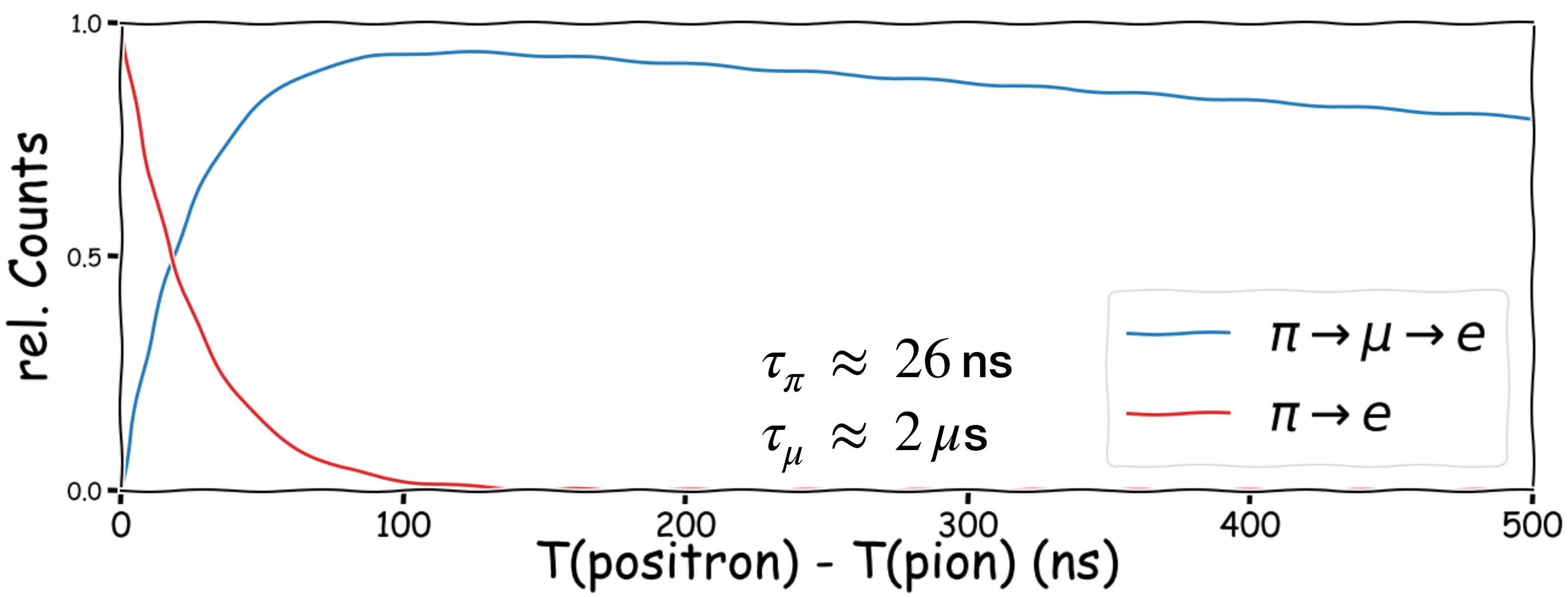
Timing measurement



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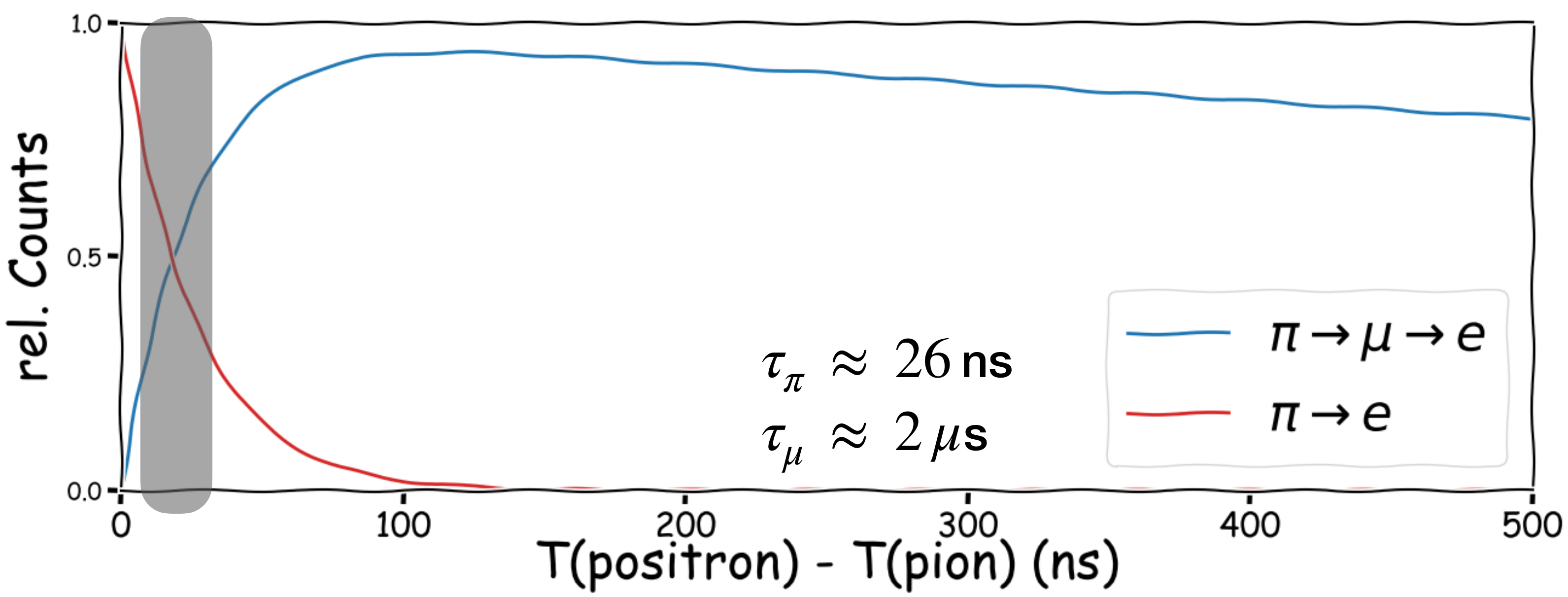

Fraction of events in [2, 32]ns

$\pi \to e : 63\,\%$

$\pi \to \mu \to e : 0.6\,\%$

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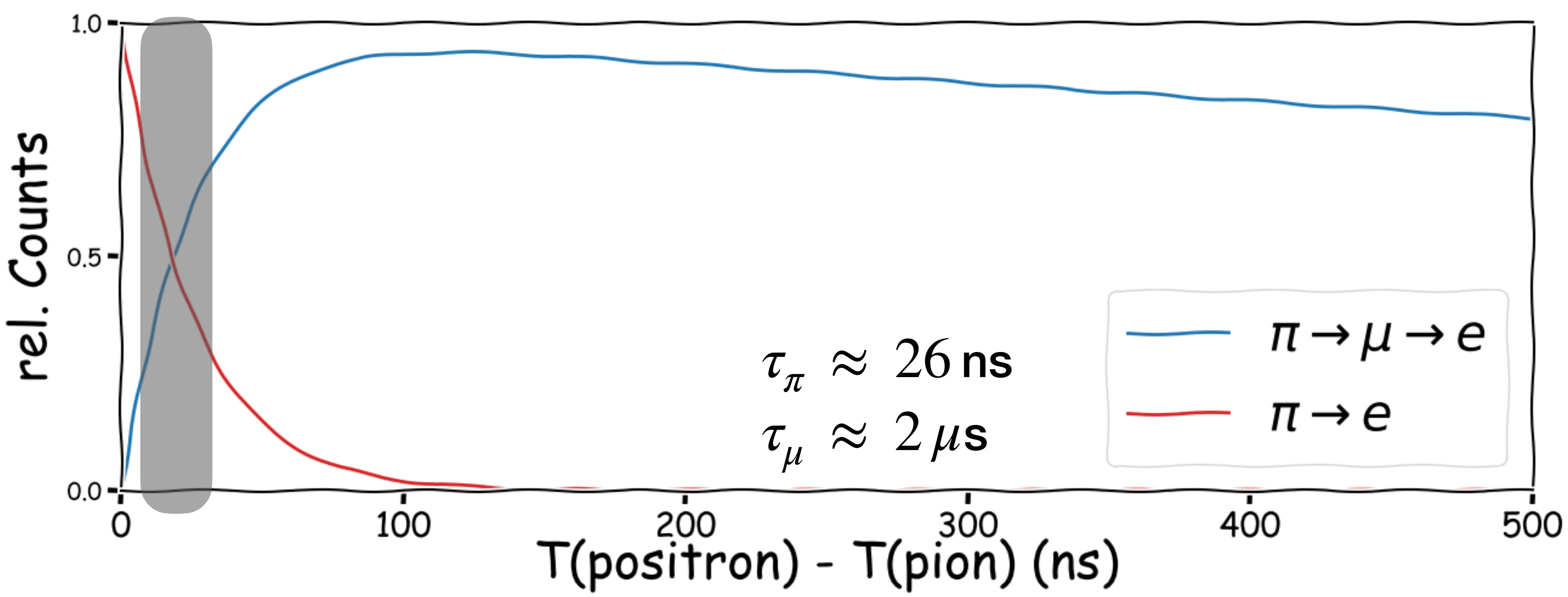

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$\pi \to \mu \to e : 0.6\,\%$

Rejection rate of ~ 150

Sig / Bkg requirements

$\pi \to e$ selection efficiency ~ 1%

$\pi \to \mu \to e$ rejection rate ~ 10^7

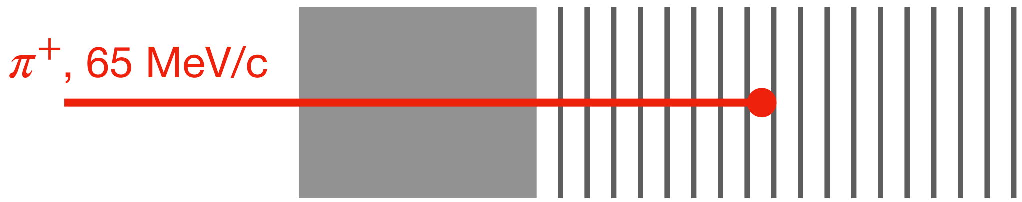
Timing

$\pi \to e$ selection efficiency ~ 60%

$\pi \to \mu \to e$ rejection rate ~ 150

The approach

Energy measurement



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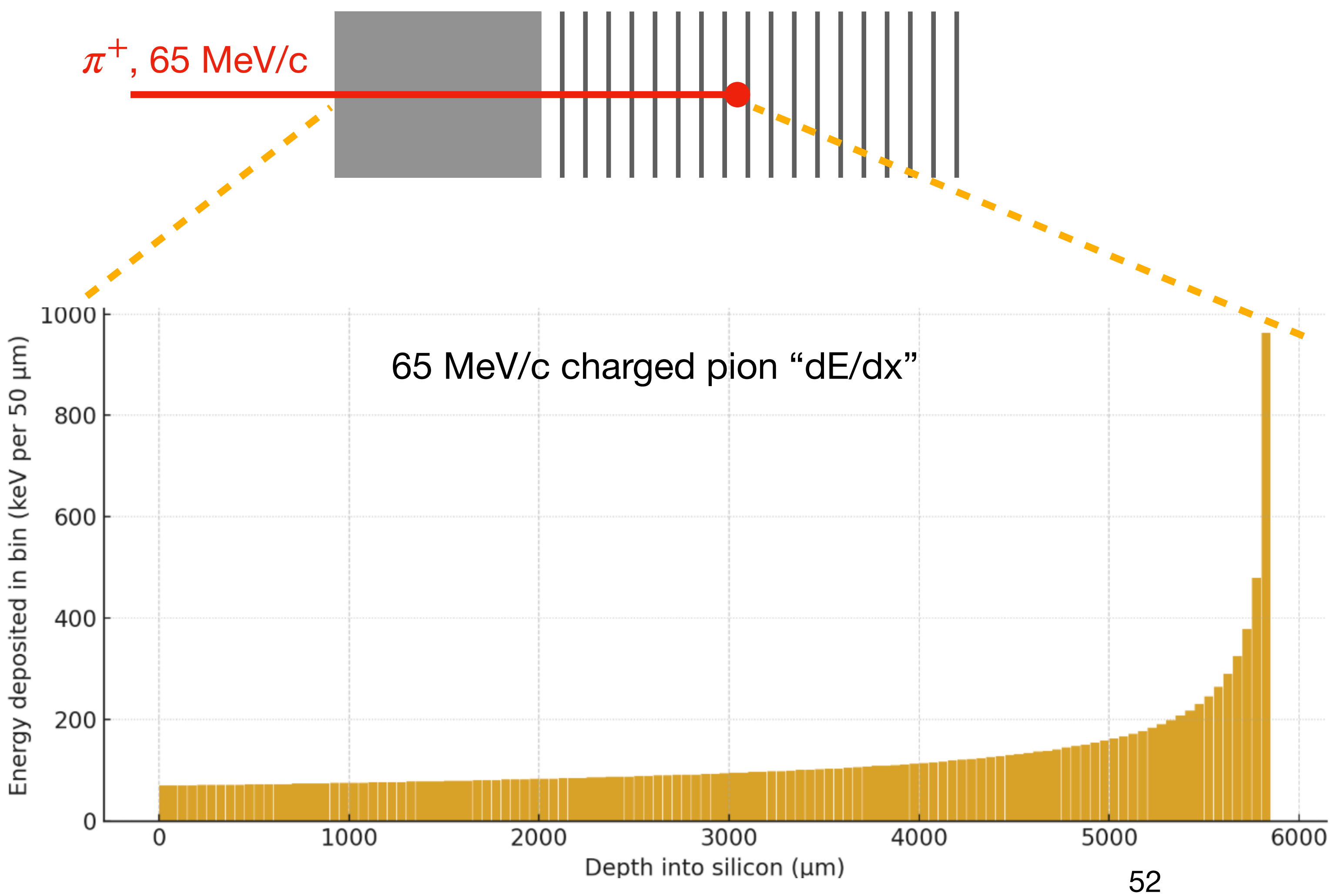
Energy measurement



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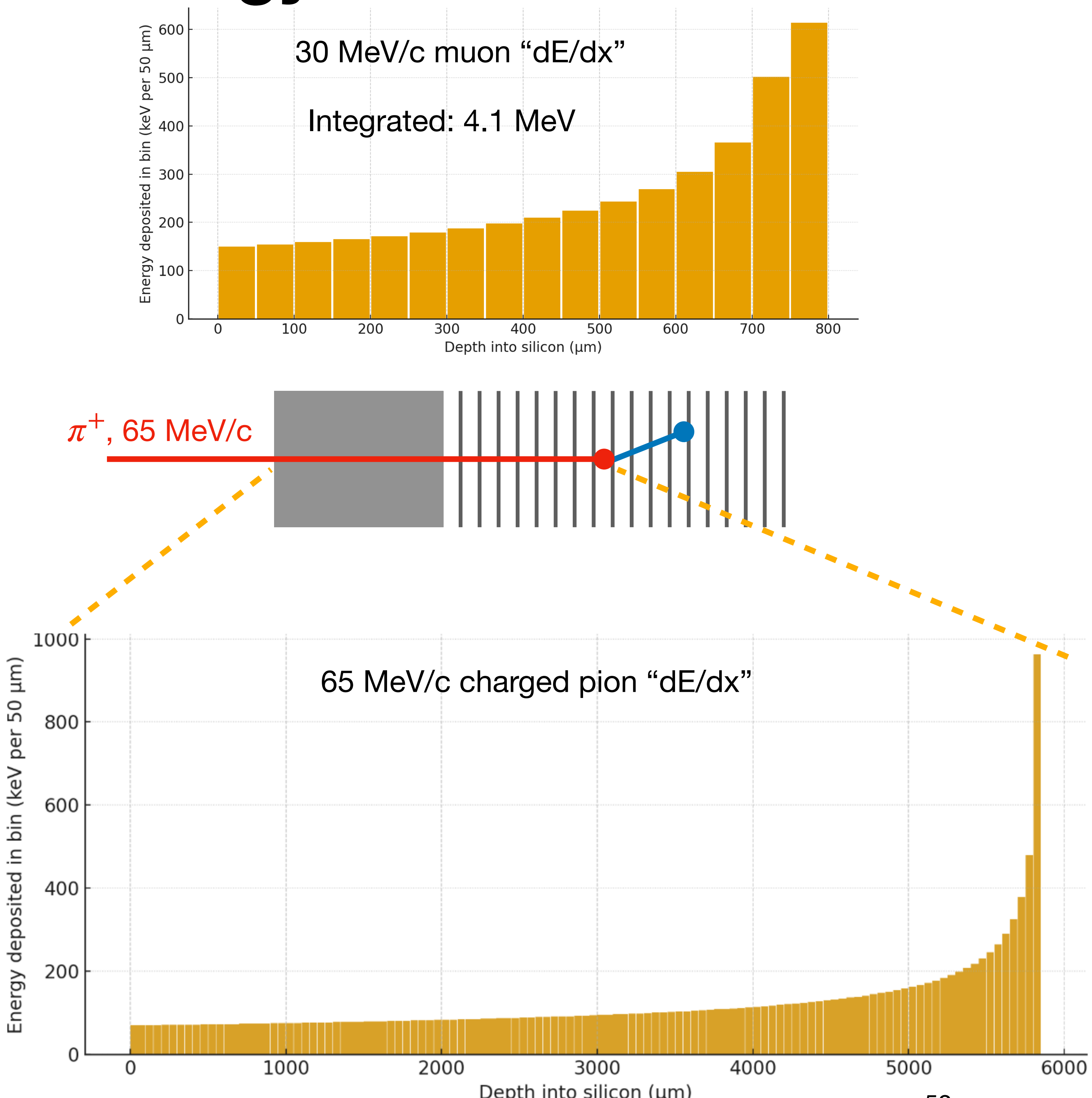

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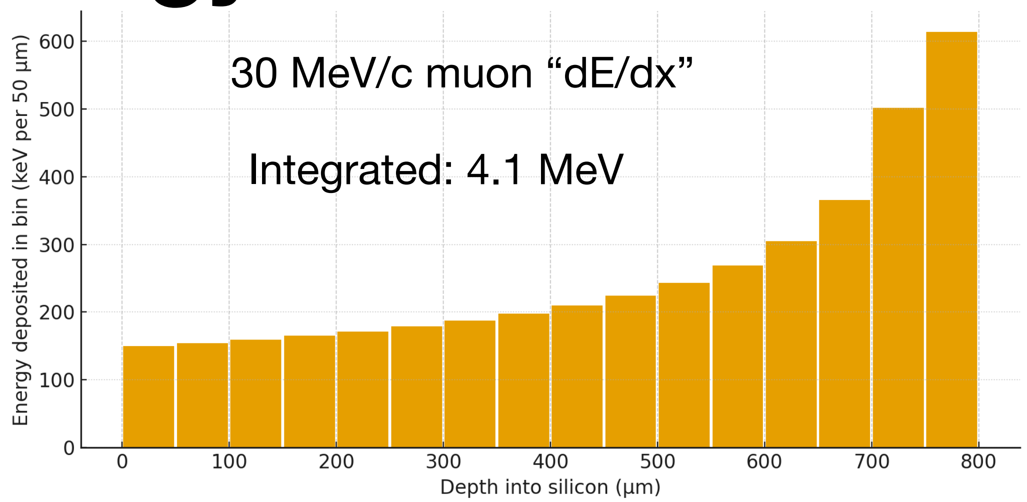
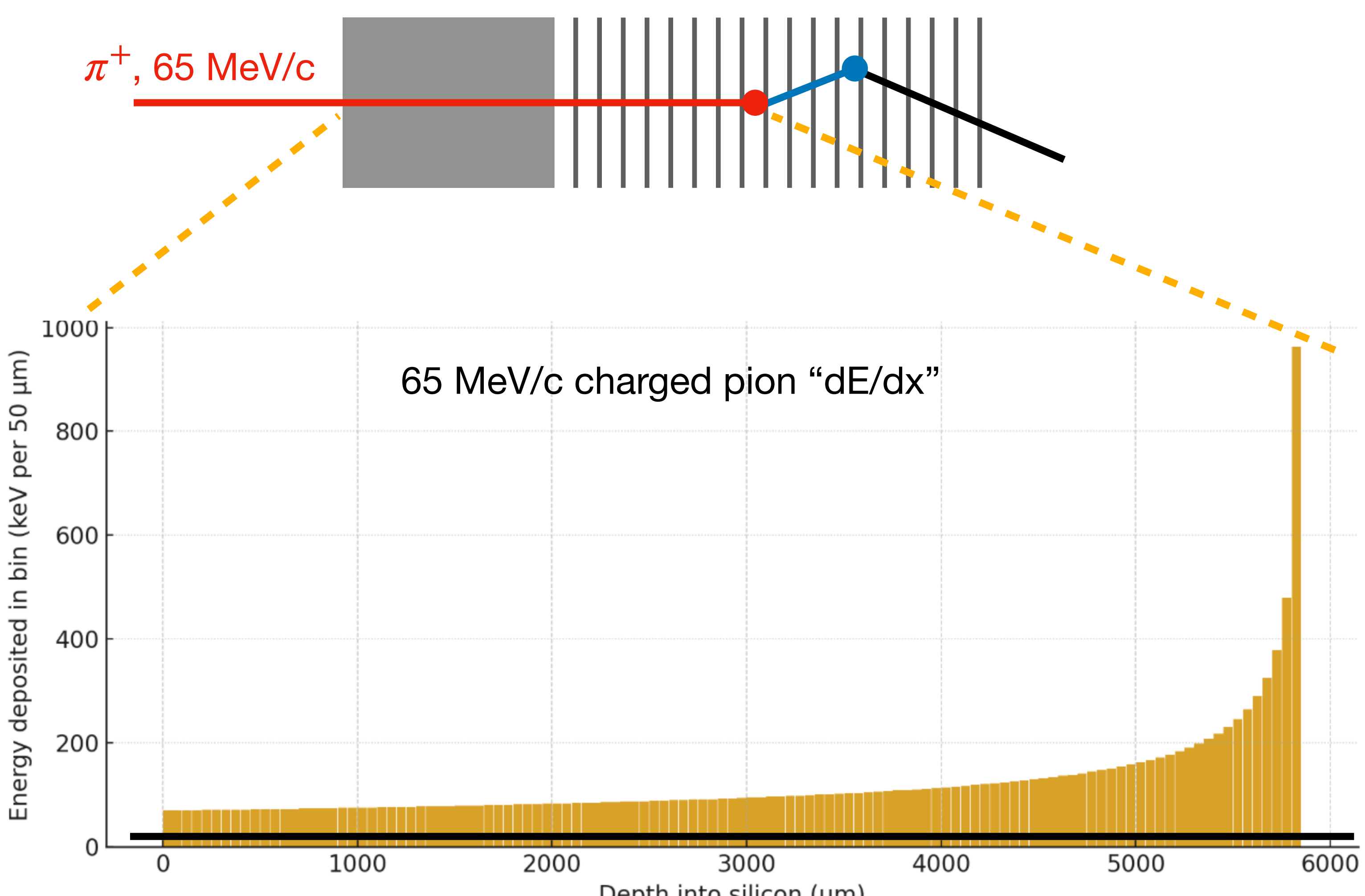
The approach

Energy measurement





Sig / Bkg requirements

$\pi \to e$ selection efficiency ~ 1%

$\pi \to \mu \to e$ rejection rate ~ 10^7

Timing

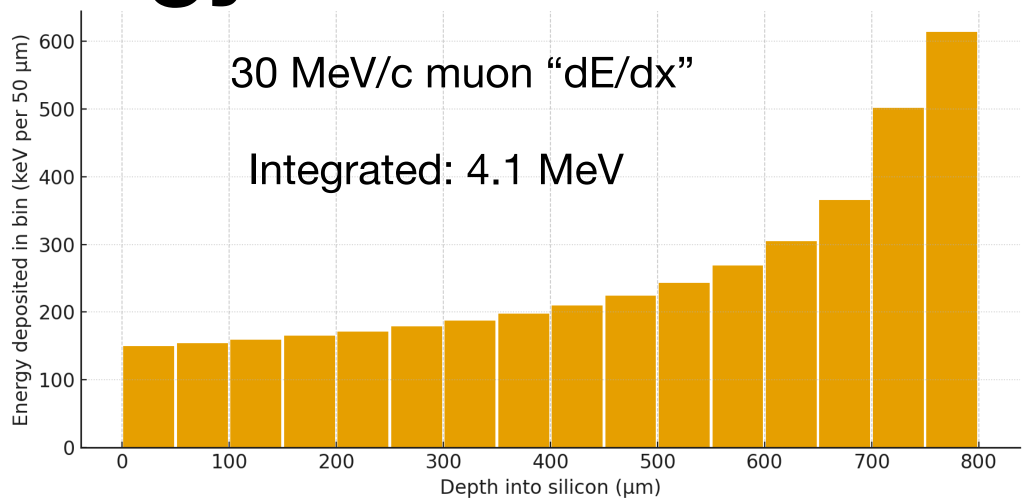
$\pi \to e$ selection efficiency ~ 60%

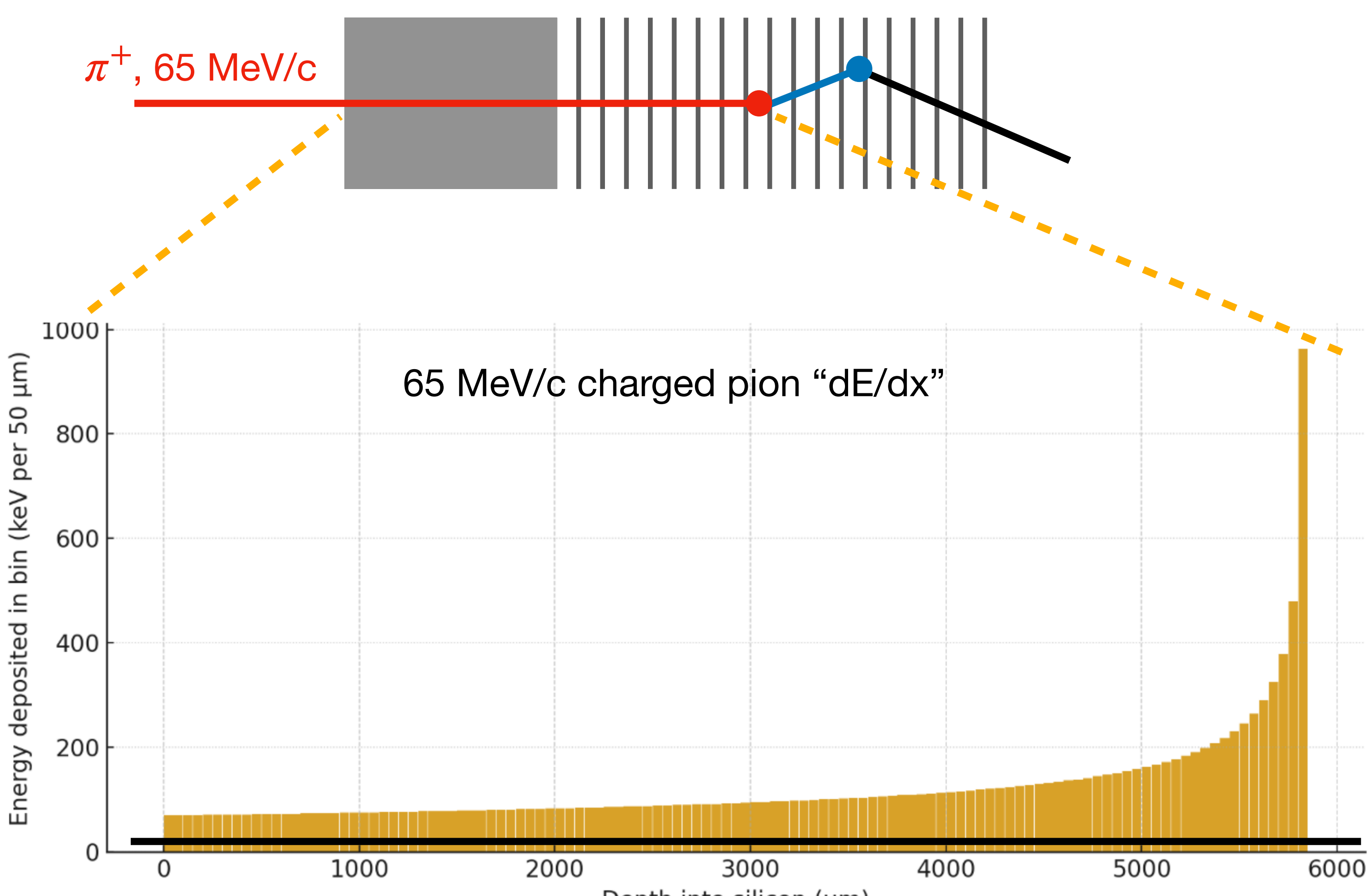
$\pi \to \mu \to e$ rejection rate ~ 150

In this regime, the positron is a Minimum Ionising Particle (MIP) energy for 120μm of silicon: ~50 keV

The approach

Energy measurement





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Sig / Bkg requirements

$\pi \to e$ **selection efficiency ~ 1%**

$\pi \to \mu \to e$ **rejection rate ~ 10^7**

Timing

$\pi \to e$ **selection efficiency ~ 60%**

$\pi \to \mu \to e$ **rejection rate ~ 150**

Energy

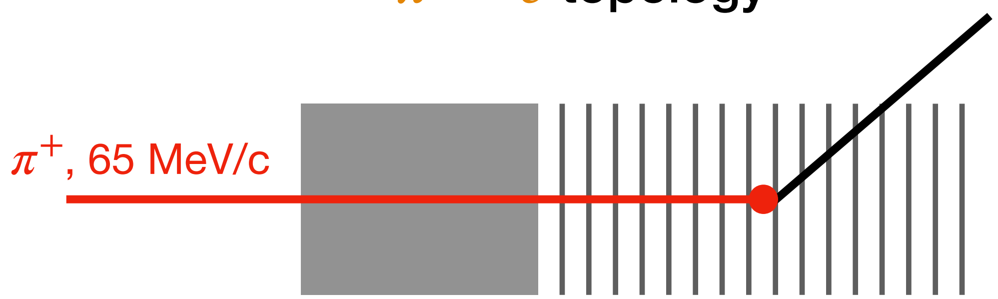
$\pi \to e$ **selection efficiency ~ 85%**

$\pi \to \mu \to e$ **rejection rate ~ 10^3**

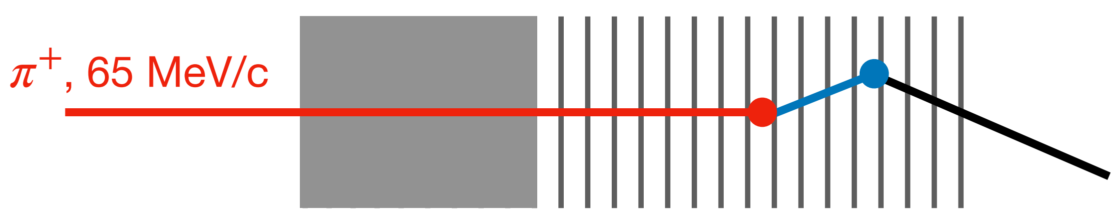
The approach

Topology

$\pi \to e$ topology



$\pi \to \mu \to e$ topology



Need for a segmented device to reconstruct trajectory of charged particles

Sig / Bkg requirements

$\pi \to e$ selection efficiency ~ 1%

$\pi \to \mu \to e$ rejection rate ~ 10^7

Energy

$\pi \to e$ selection efficiency ~ 85%

$\pi \to \mu \to e$ rejection rate ~ 10^3

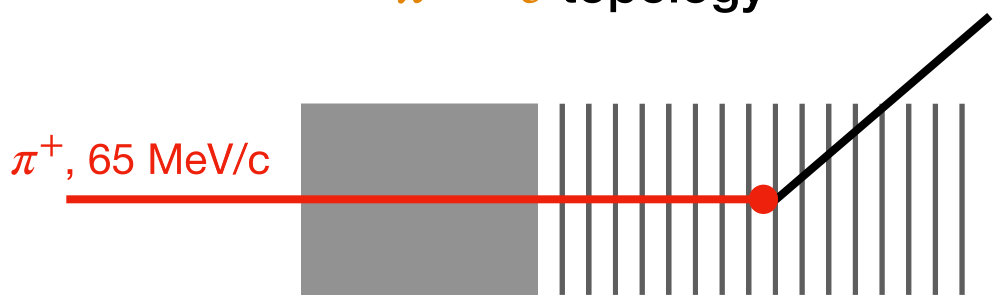
Topology

$\pi \to e$ selection efficiency ~50%

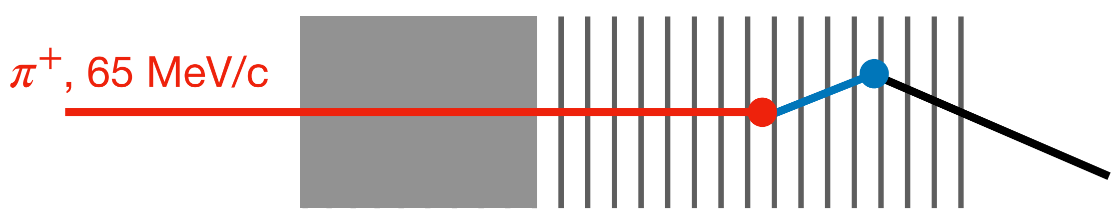
$\pi \to \mu \to e$ rejection rate ~ 500

The approach
Topology

$\pi \to e$ topology



$\pi \to \mu \to e$ topology



Need for a segmented device to
reconstruct trajectory of charged particles

Sig / Bkg requirements

$\pi \to e$ selection efficiency ~ 1%
$\pi \to \mu \to e$ rejection rate ~ 10^7

Timing

$\pi \to e$ selection efficiency ~ 60%
$\pi \to \mu \to e$ rejection rate ~ 150

Energy

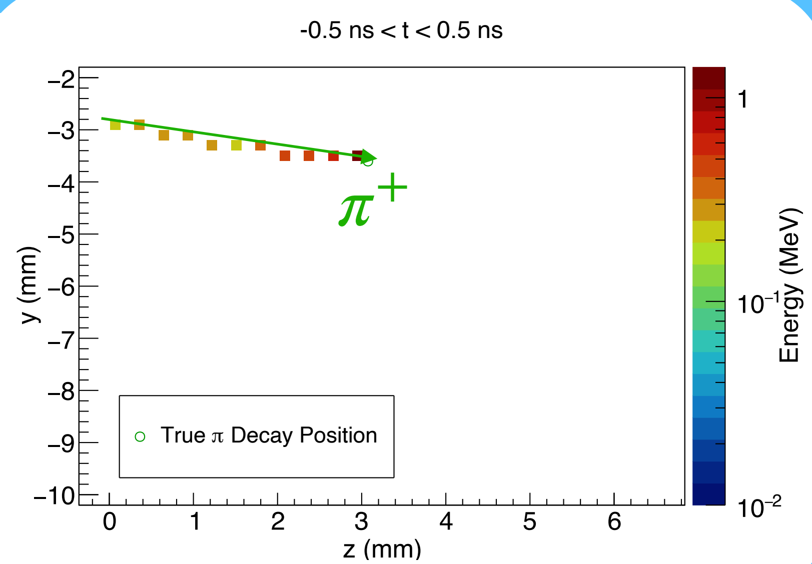
$\pi \to e$ selection efficiency ~ 85%
$\pi \to \mu \to e$ rejection rate ~ 10^3

Topology

$\pi \to e$ selection efficiency ~50%
$\pi \to \mu \to e$ rejection rate ~ 500

ATAR Tracking: main tasks

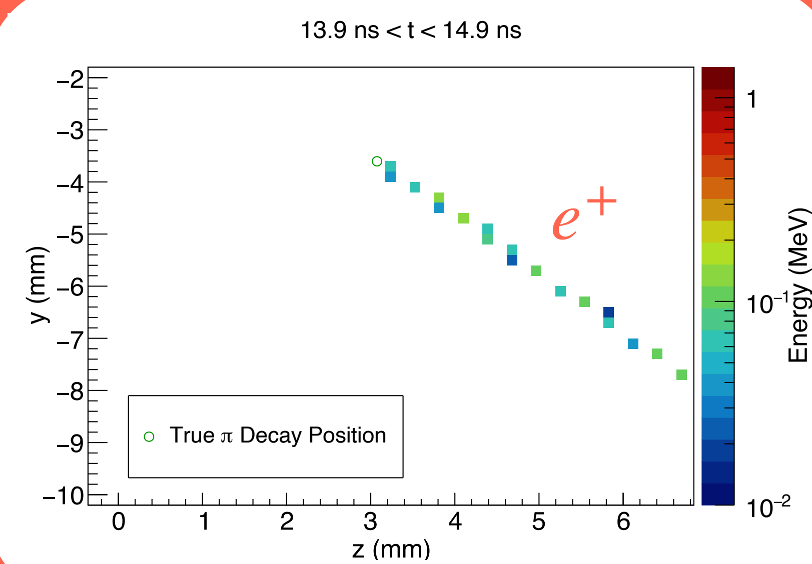
Pion Stop Location



Find the end point of the pion track.

$r_\pi(x_\pi, y_\pi, z_\pi)$

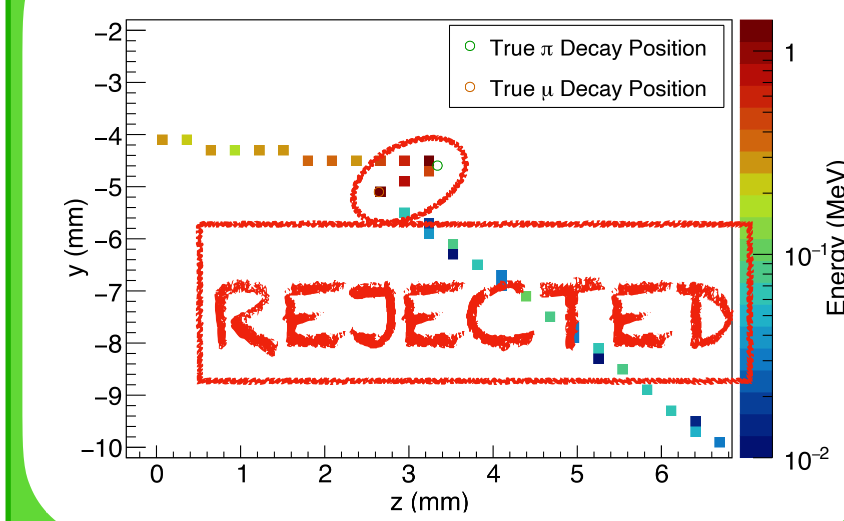
Positron Direction



Determine direction of emitted positron

θ_e, ϕ_e

Tail Analysis



Tag $\pi \to \mu \to e$ events. Provide 7 orders of magnitude suppression

P. Schwendimann's talk at ACTS4NP: https://indico.cern.ch/event/1501989/contributions/6495343/

$R_{e/\mu}$ measurement strategy

The master formula

Required precision: 0.01%

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

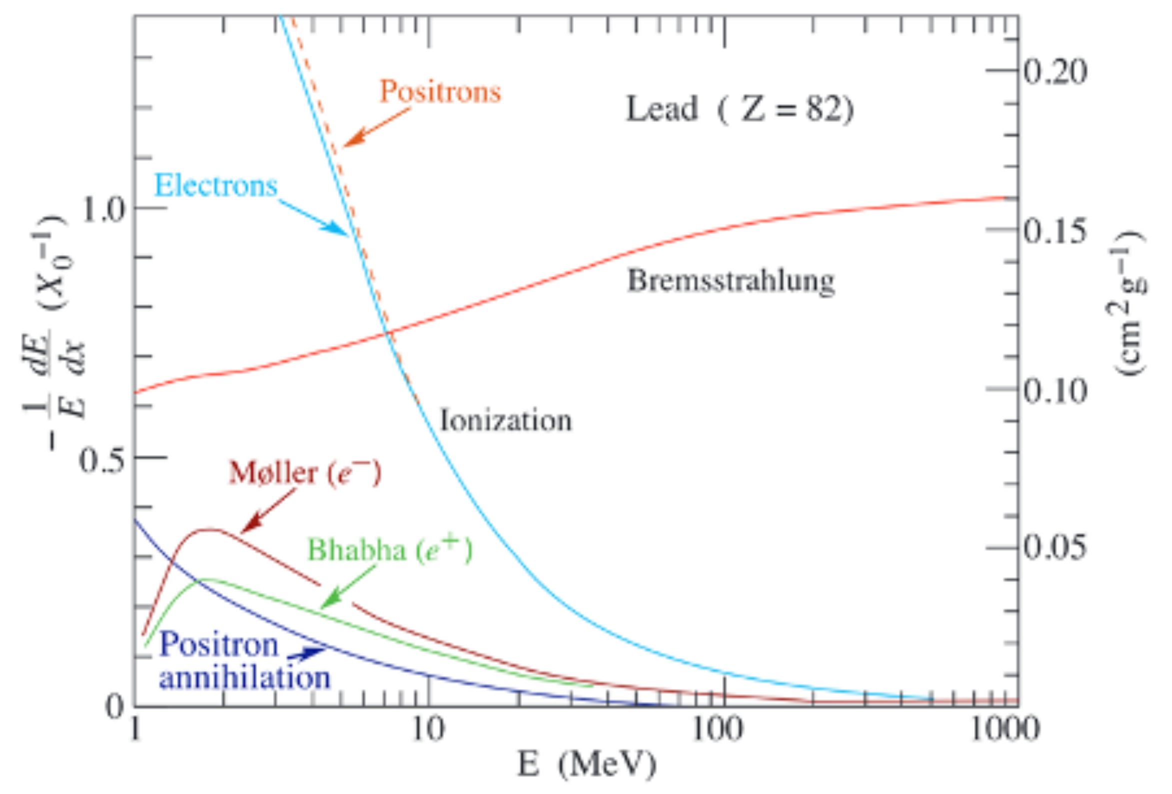
Ratio of detector acceptance for $\pi - e$ and $\pi - \mu - e$ processes

$\rightarrow \Delta R_{e/\mu}/R_{e/\mu} < 0.01\ \%$

Physics processes are energy dependent
→ bias can be introduced at the trigger/fiducial definition level.

Contributions to bias from:

- Annihilation
- Scattering (Bhabha, multiple Coulomb)
- Detector reconstruction



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**	**≤ 0.01**	

*Pion lifetime uncertainty not included
Newly proposed measurement at TRIUMF

	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%**	

To be verified by simulations and prototype measurements.

	PIENU 2015	PIONEER Estimate	
Error Source	%	%	
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