UNIVERSITY *of* WASHINGTON

PIONEER

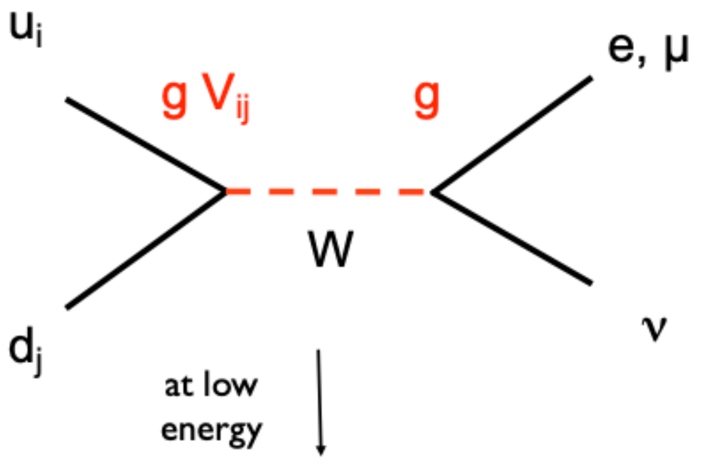
A next generation rare pion decay experiment

Quentin Buat (University of Washington) — Nov 7, 2023 - GdR INF 2023

Rare Pion Decays

Probing weak universality

- Charged currents in the SM are mediated by the exchange of a W boson between left-handed fermions
    - The coupling is the same for all fermions



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

Lepton Flavour Universality

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

Cabbibo Universality

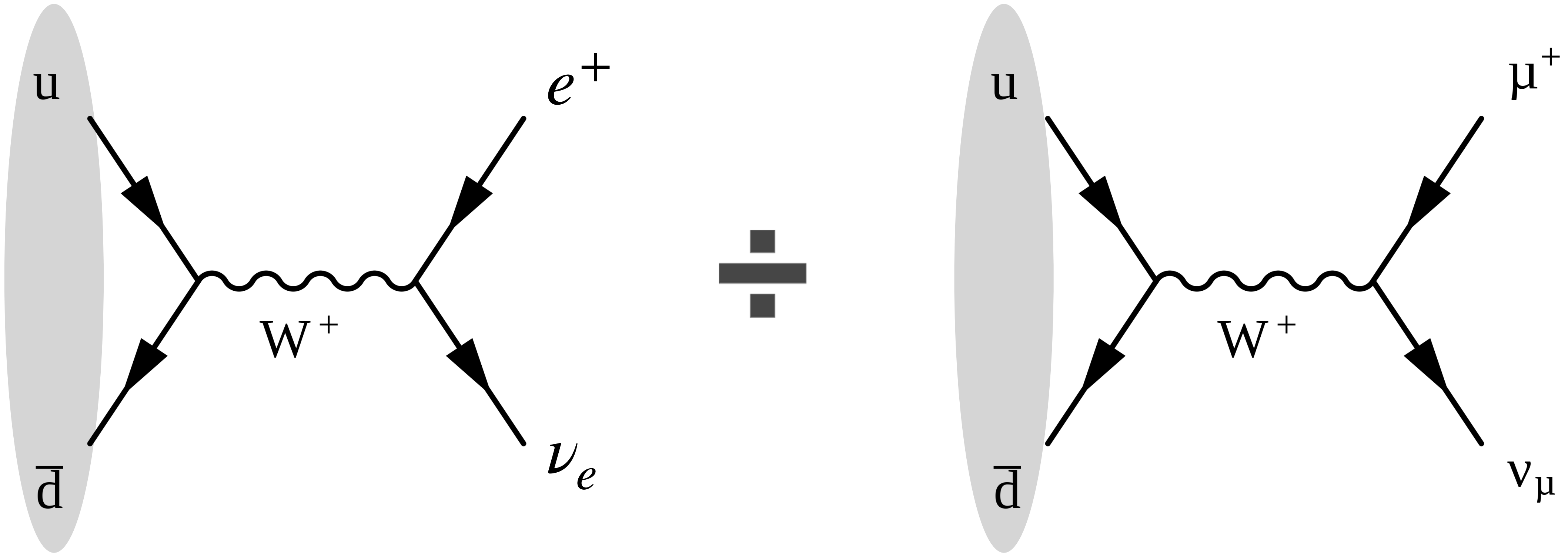
$$|V_{ud}|^2 + |V_{us}|^2 + |V_{ub}|^2 = 1$$

PIONEER will test both!

Rare Pion Decays

Lepton Flavour Universality

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



$$R_{e/\mu} = \underline{\frac{m_e^2}{m_\mu^2}} \times \underline{\left(\frac{m_\pi^2 - m_e^2}{m_\pi^2 - m_\mu^2}\right)^2} \times \left[1 + \underline{\text{EW corrections}}\right] = 1.23524(015) \times 10^{-4}$$

'Helicity suppression' term: ~2.3 x10^{-5}

Phase space term: ~ 5.5

Fully computed at NLO
O(10^{-4}) uncertainties at NNLO

Rare Pion Decays

Lepton Flavour Universality

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

$$R_{e/\mu} = \frac{m_e^2}{m_\mu^2}\left(\frac{m_\pi^2 - m_e^2}{m_\pi^2 - m_\mu^2}\right)^2 \times \left[1 + \text{EW} \quad \text{corrections}\right] = 1.23524(015) \times 10^{-4}$$

The π→eν branching ratio is so small that for a while it was excluded

Lokanathan and Steinberger (1955):
Range telescope at Columbia Nevis cyclotron: $R_{e/\mu} < 1.2 \times 10^{-4}$ (90% CL)

Anderson and Lattes (1957):
Magnetic spectrometer at Chicago cyclotron: $R_{e/\mu} < 1.3 \times 10^{-4}$ (90% CL)

Rare Pion Decays

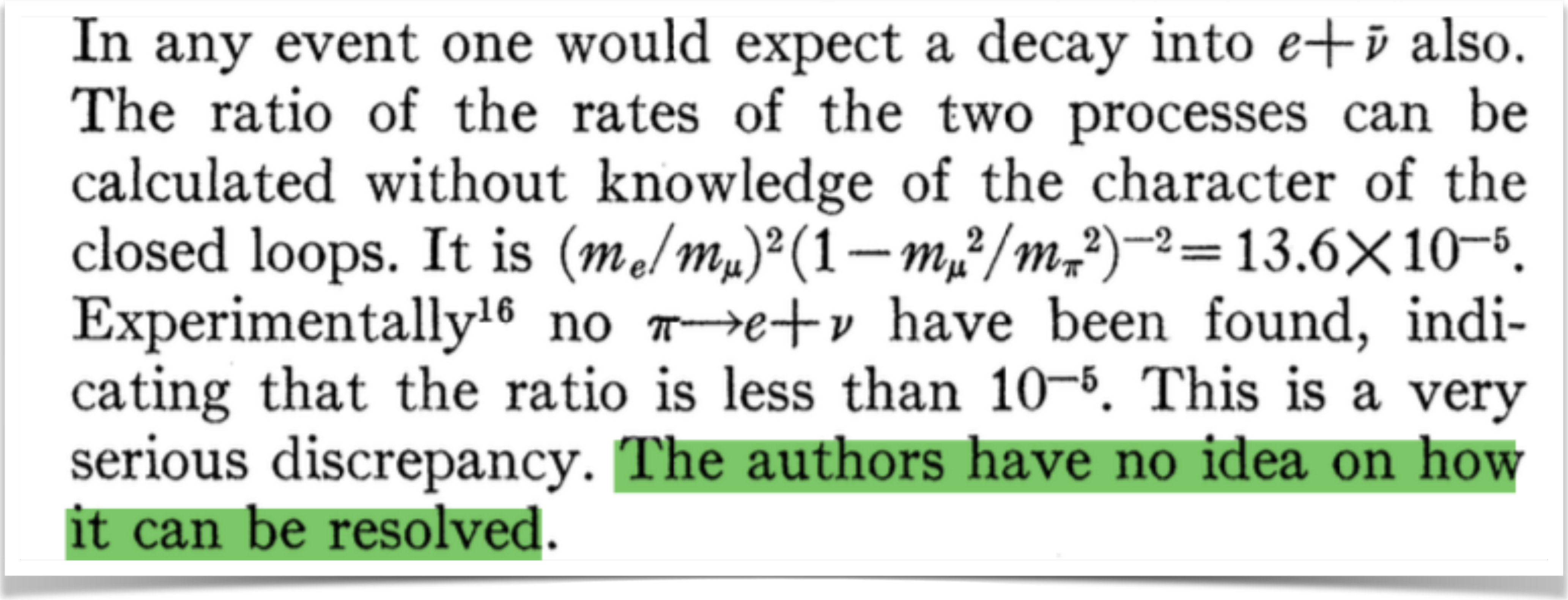
Lepton Flavour Universality

$$R_{e/\mu} = \frac{\Gamma(\pi \rightarrow e\nu(\gamma))}{\Gamma(\pi \rightarrow \mu\nu(\gamma))}$$

$$R_{e/\mu} = \frac{m_e^2}{m_\mu^2}\left(\frac{m_\pi^2 - m_e^2}{m_\pi^2 - m_\mu^2}\right)^2 \times \left[1 + \text{EW corrections}\right] = 1.23524(015) \times 10^{-4}$$

Causing a lot of confusion…

Feynman and Gell-Mann, PR 109, 193 (1958)



In any event one would expect a decay into $e+\bar{\nu}$ also. The ratio of the rates of the two processes can be calculated without knowledge of the character of the closed loops. It is $(m_e/m_\mu)^2(1-m_\mu{}^2/m_\pi{}^2)^{-2}=13.6\times10^{-5}$. Experimentally[16] no $\pi\rightarrow e+\nu$ have been found, indicating that the ratio is less than 10^{-5}. This is a very serious discrepancy. The authors have no idea on how it can be resolved.

Rare Pion Decays

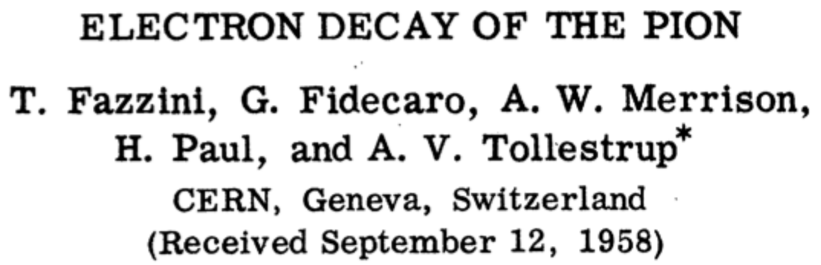
Lepton Flavour Universality

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

DISCOVERY!

At a small lab that opened 4 years prior on the outskirts of Geneva, Switzerland

CERN circa 1958



ELECTRON DECAY OF THE PION

T. Fazzini, G. Fidecaro, A. W. Merrison,
H. Paul, and A. V. Tollestrup*
CERN, Geneva, Switzerland
(Received September 12, 1958)

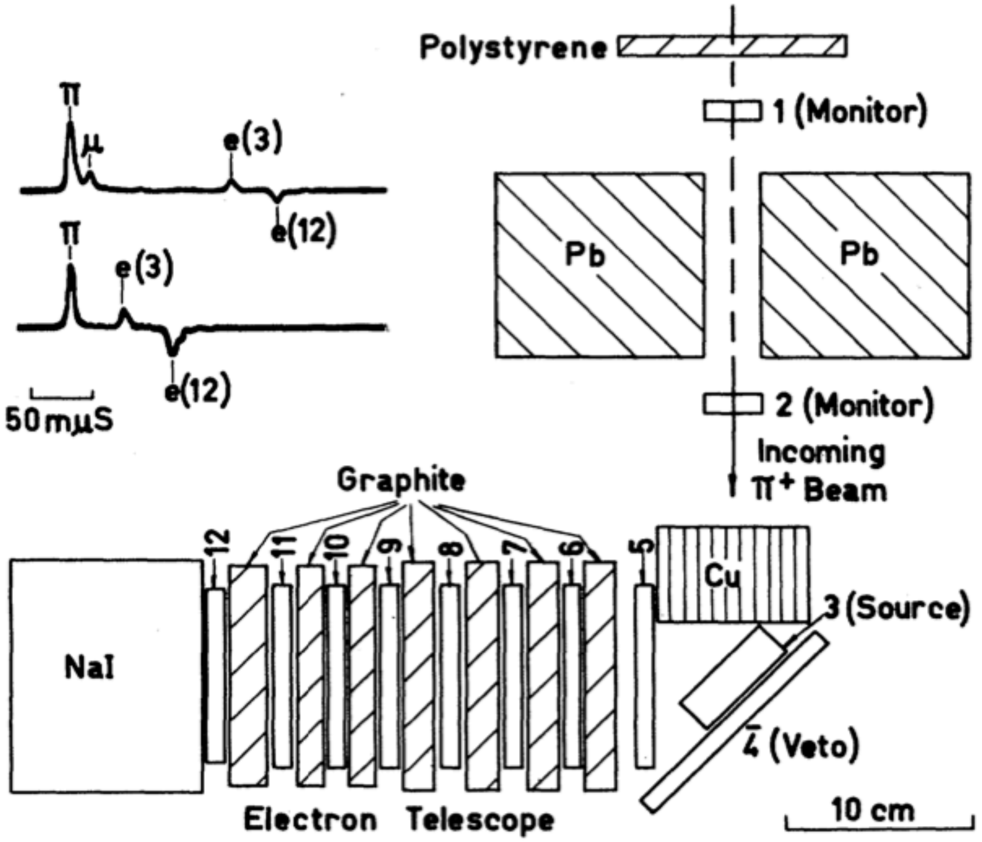


FIG. 1. Experimental layout, and (inset) typical π-μ-e and π-e pulse.

~ 40 $\pi \to e\nu$ events

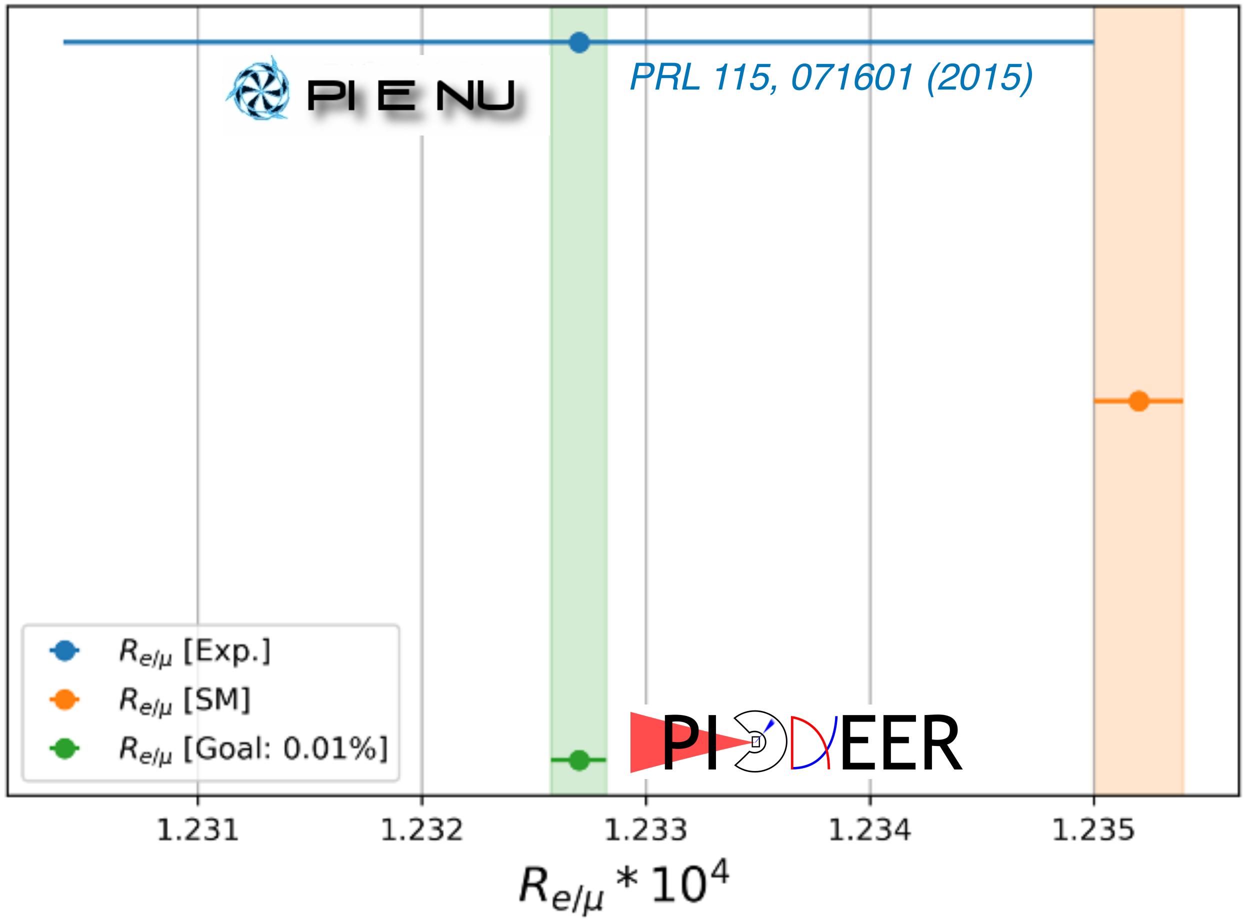
Rare Pion Decays

Lepton Flavour Universality

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

We call this measurement PHASE I

$R_{e/\mu}$[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

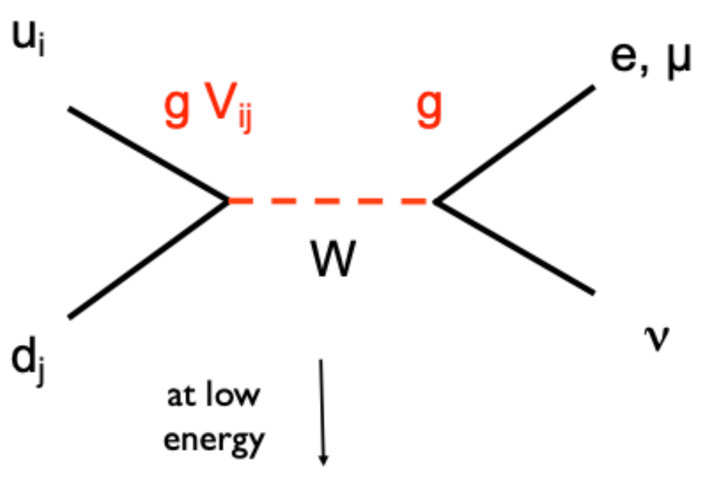
15-fold improvement over the current world best

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

Rare Pion Decays

Probing weak universality

- Charged currents in the SM are mediated by the exchange of a W boson between left-handed fermions
  - The coupling is the same for all fermions



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

Lepton Flavour Universality

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

Cabbibo Universality

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

Rare Pion Decays

Testing CKM Unitarity

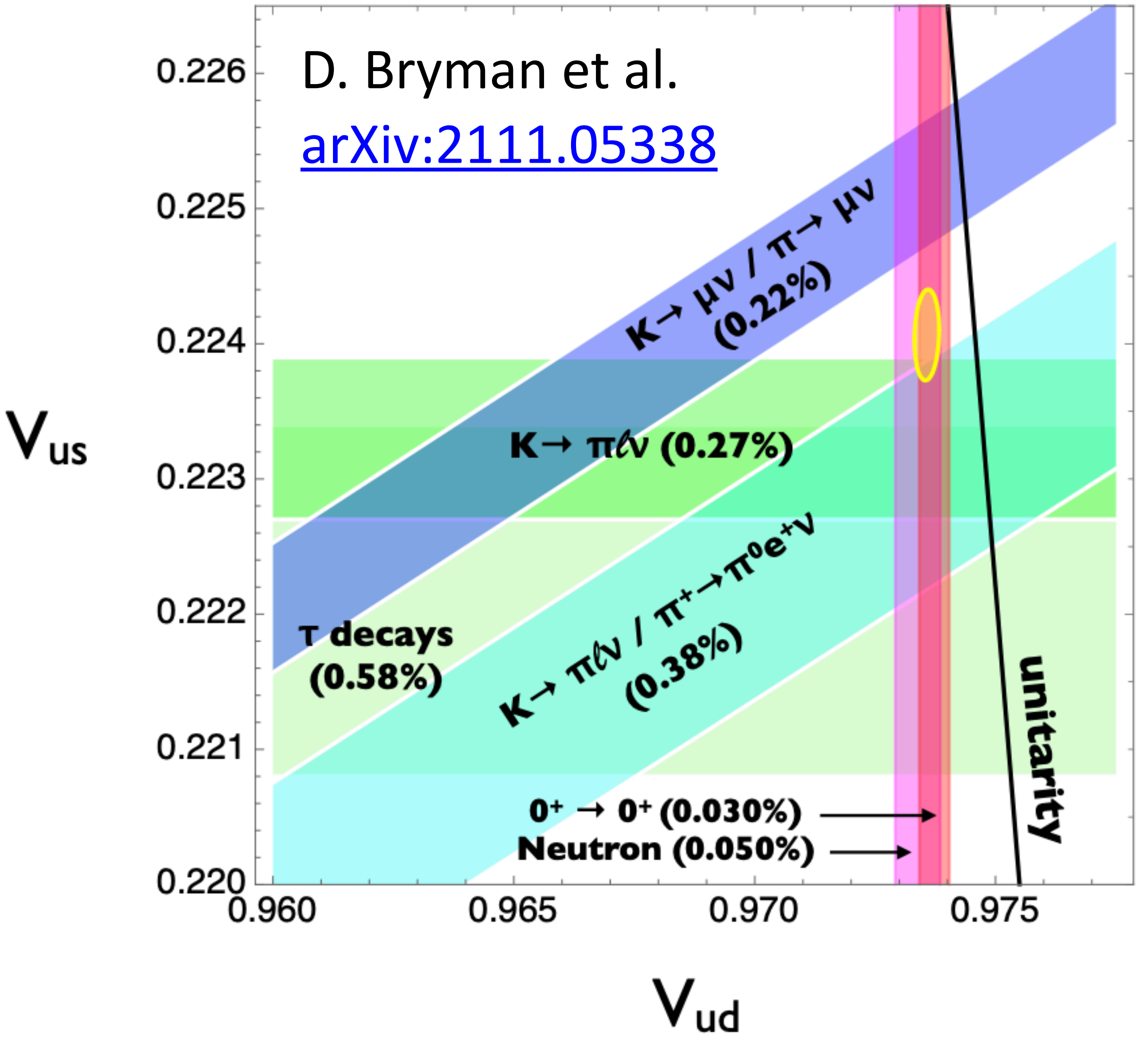
$$\begin{bmatrix} |V_{ud}| & |V_{us}| & |V_{ub}| \\ |V_{cd}| & |V_{cs}| & |V_{cb}| \\ |V_{td}| & |V_{ts}| & |V_{tb}| \end{bmatrix} = \begin{bmatrix} 0.97370 \pm 0.00014 & 0.2245 \pm 0.0008 & 0.00382 \pm 0.00024 \\ 0.221 \pm 0.004 & 0.987 \pm 0.011 & 0.0410 \pm 0.0014 \\ 0.0080 \pm 0.0003 & 0.0388 \pm 0.0011 & 1.013 \pm 0.030 \end{bmatrix}.$$

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

Since $|V_{ub}| \ll |V_{us}|$, the third term can be neglected and the first row can be studied in a 2D plane

~3σ tension in the first-row of CKM unitarity test

Often referred to as the Cabbibo Angle Anomaly (or CAA)



D. Bryman et al.
arXiv:2111.05338

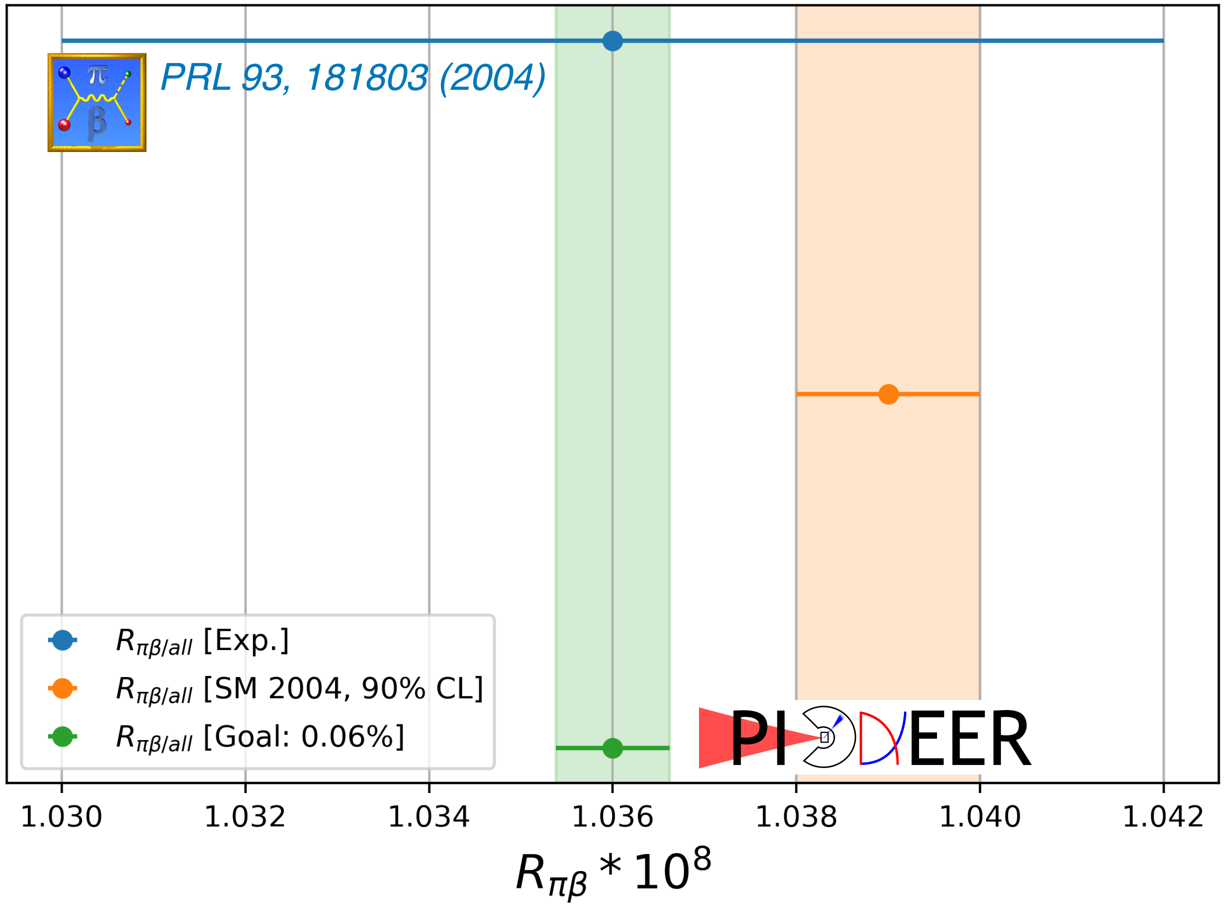
Rare Pion Decays

Testing CKM Unitarity

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

We call this measurement
PHASE II

Pion beta decay provides the theoretically cleanest determination of $|V_{ud}|$



Current best measurement from PIBETA at PSI

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

PIONEER goal is to measure $R_{\pi\beta}$ to 0.06% precision

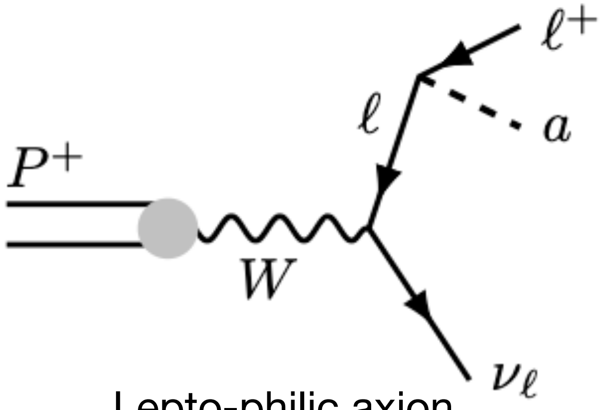
Ten-fold improvement over current world best

Constraint on $|V_{ud}|$ comparable to super-allowed beta decay

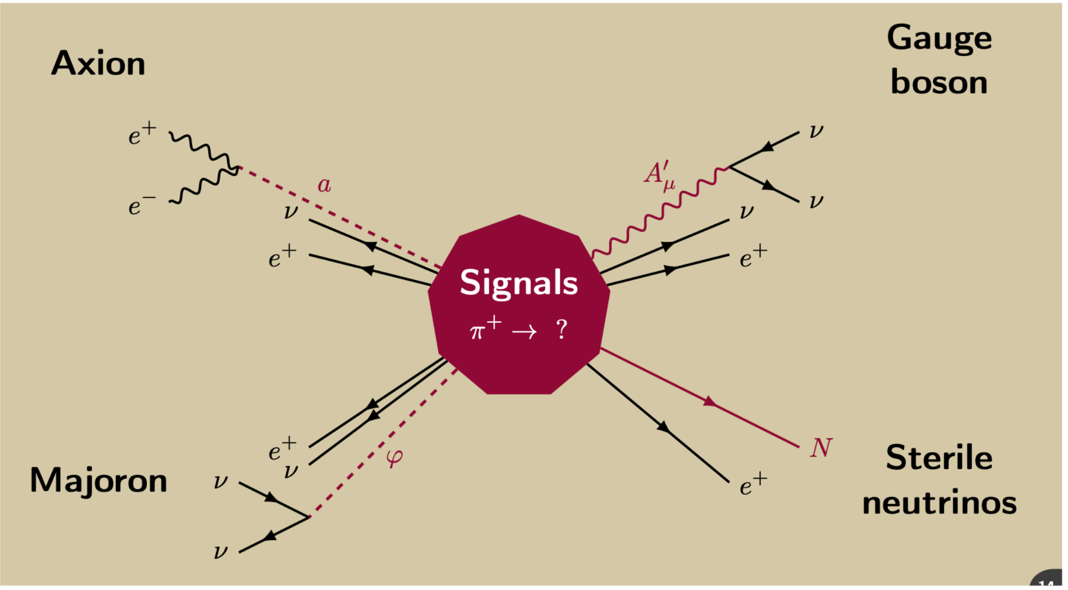
Rare Pion Decays

Direct searches for new physics

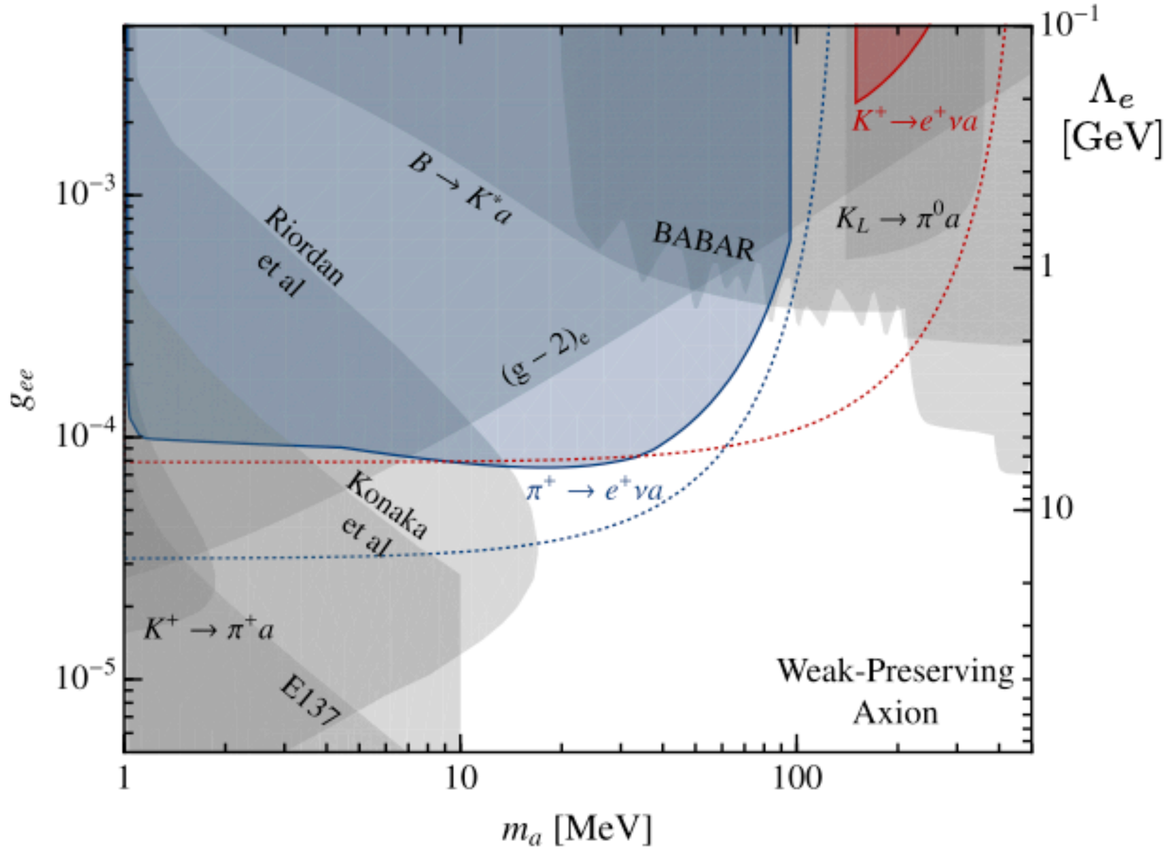
- Collecting very large samples of rare pion decay
  - Search for new weakly coupled particle in the MeV range
  - Popular models involve sterile neutrinos or axion-like particles



Lepto-philic axion

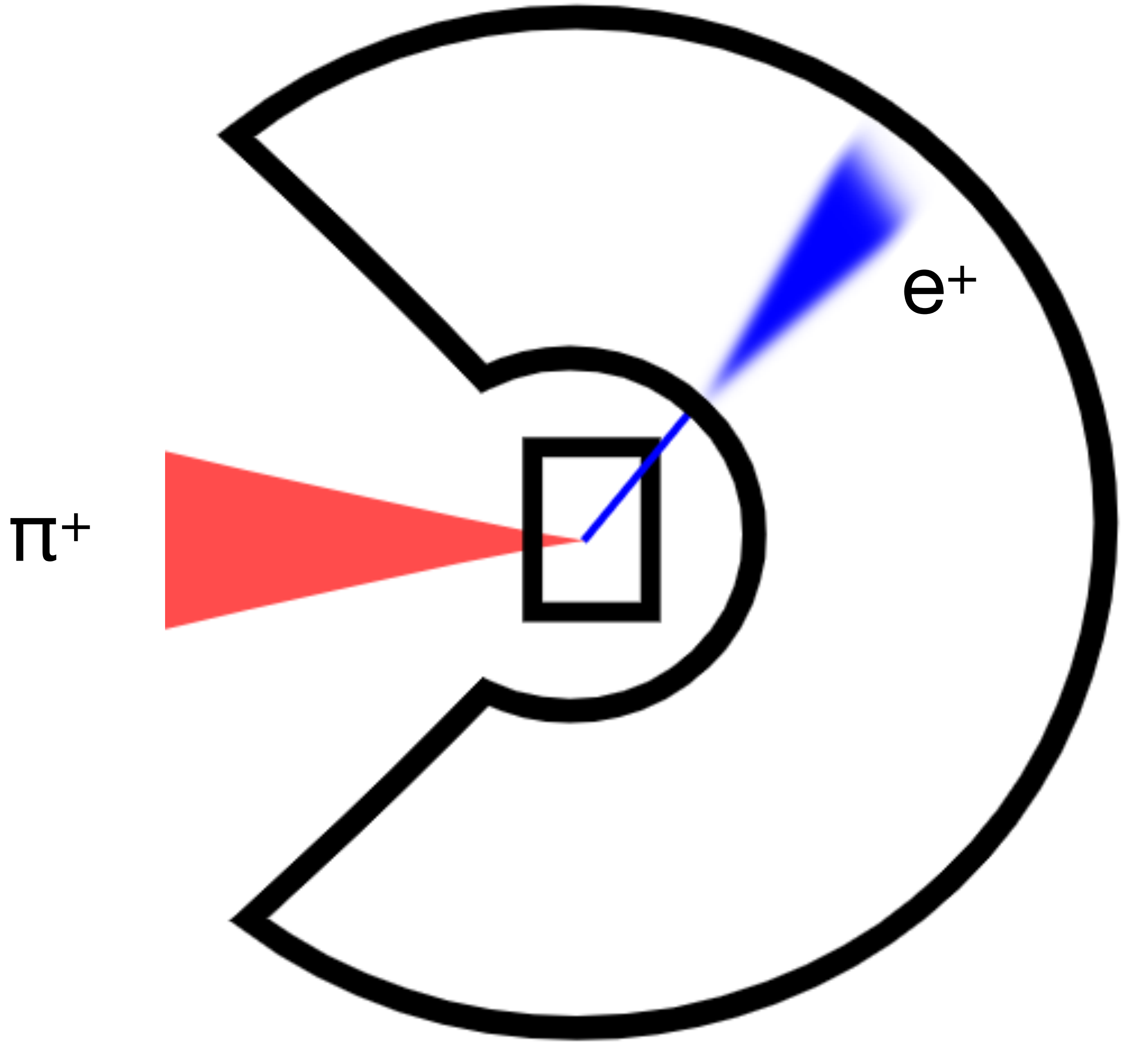


J. Dror review at 2022 Rare Pion Decays Workshop
indico contribution



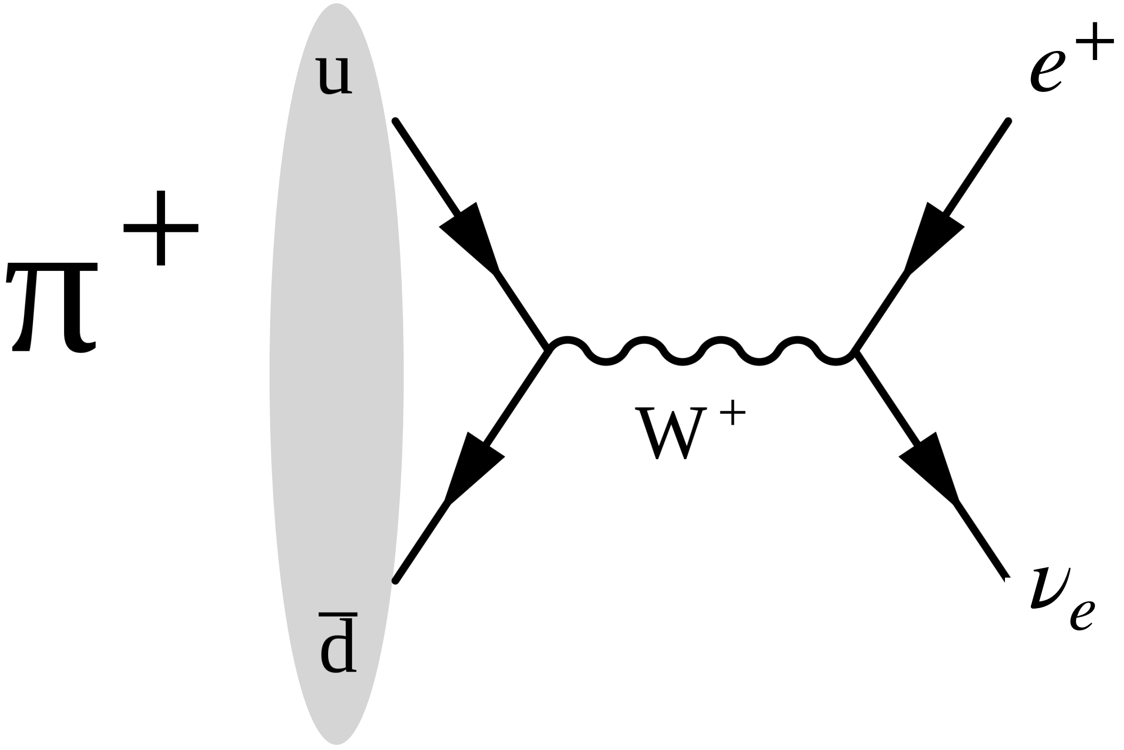
W. Altmannshofer, J. Dror, and S. Gori
Phys. Rev. Lett. **130**, 241801

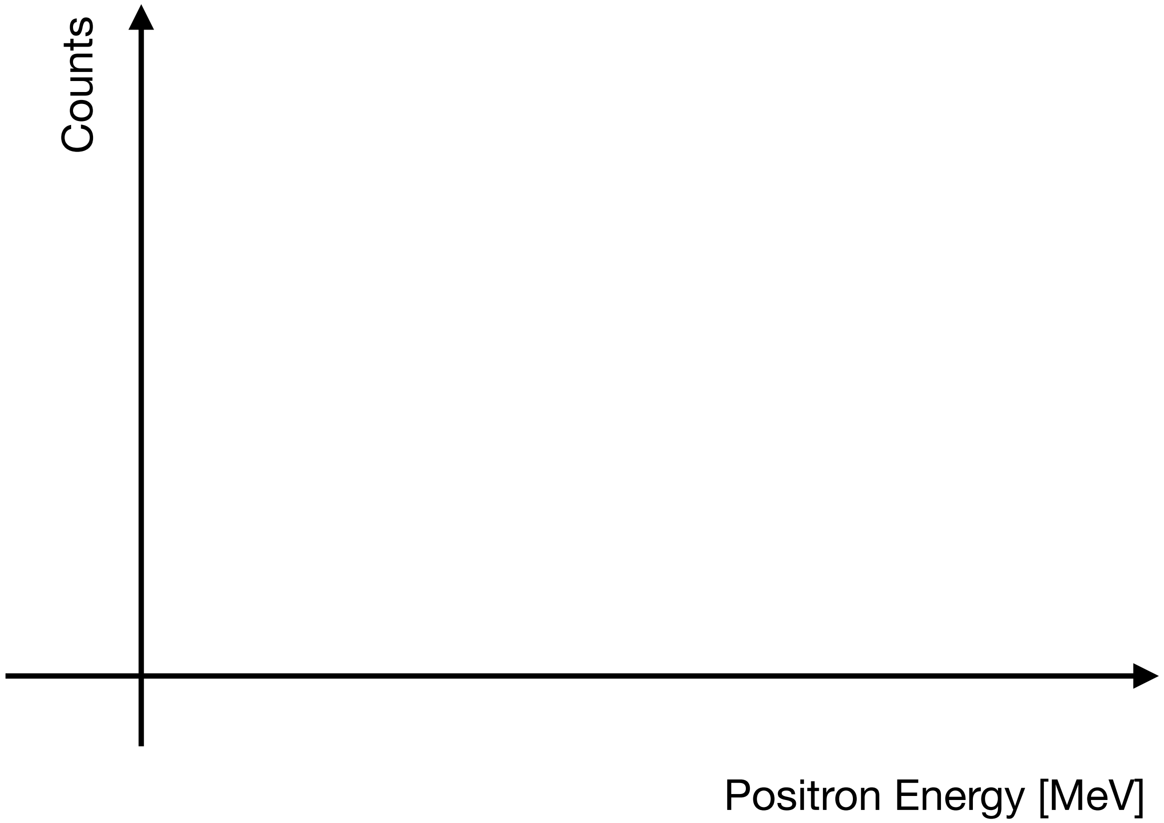
Introducing PIONEER



Introducing PIONEER

Phase I measurement strategy



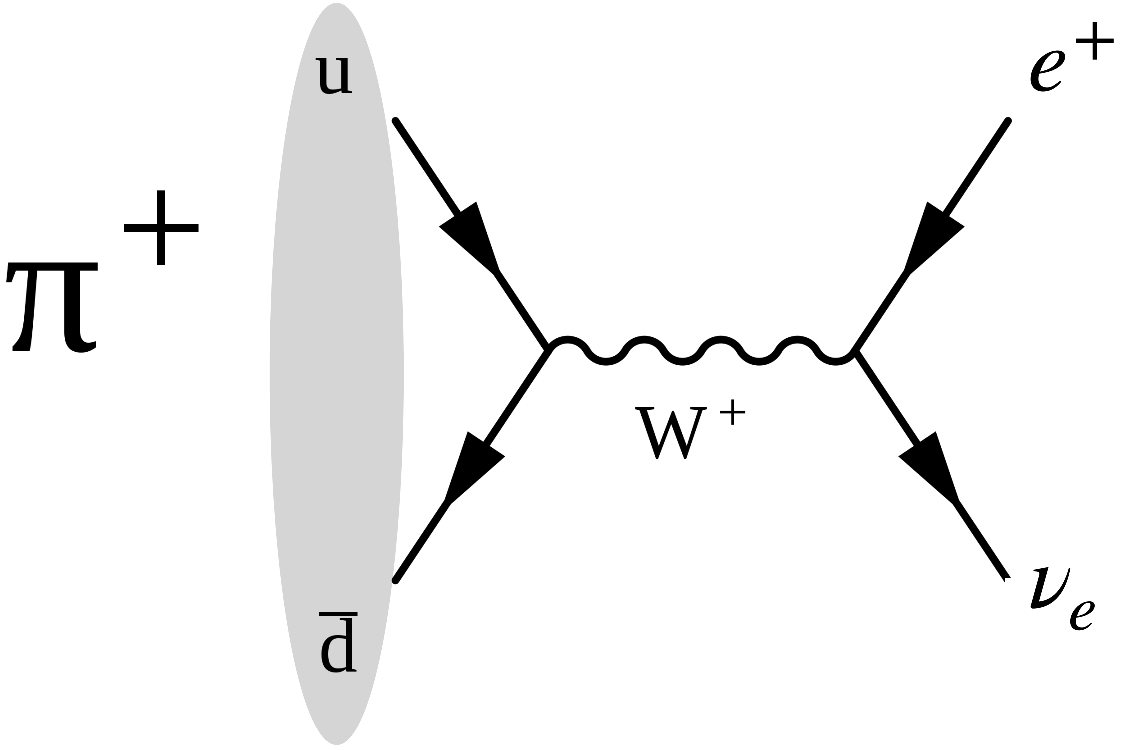


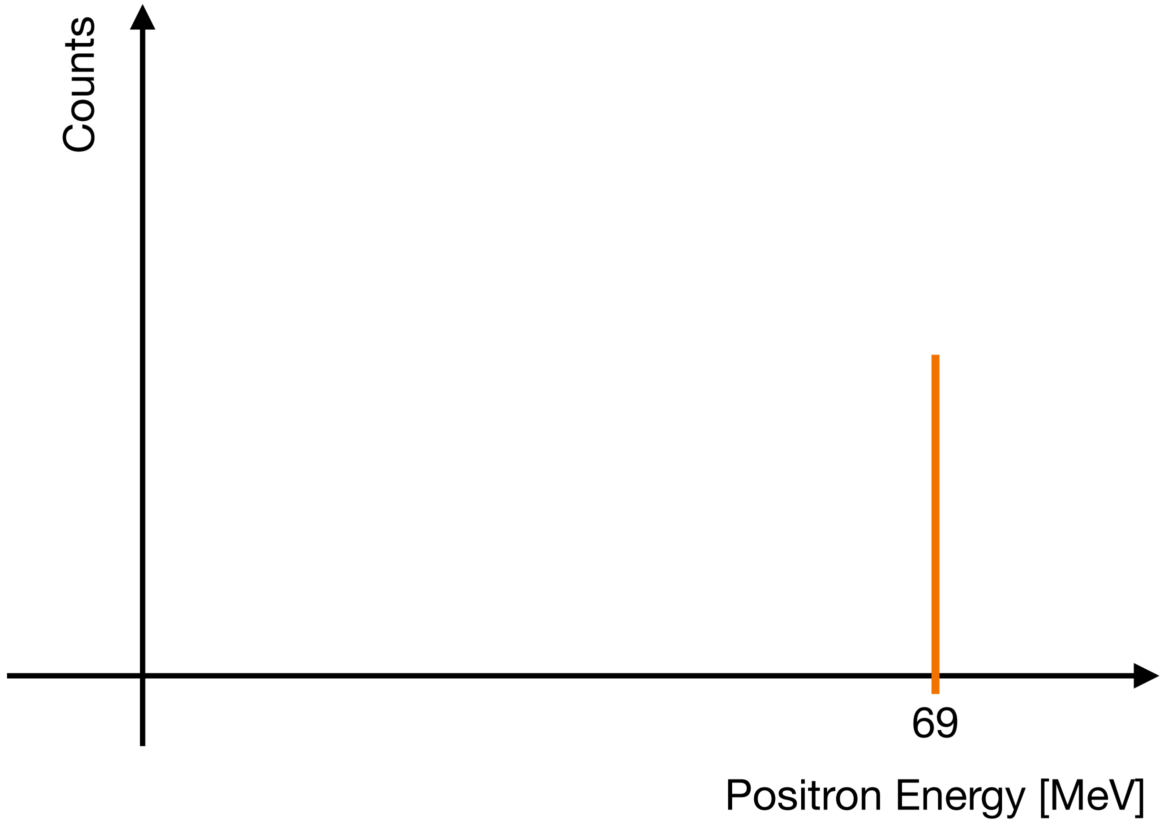
$m_{\pi^+} = 139.6\,\text{MeV}$

The pion stops in the target and decay

Introducing PIONEER

Phase I measurement strategy



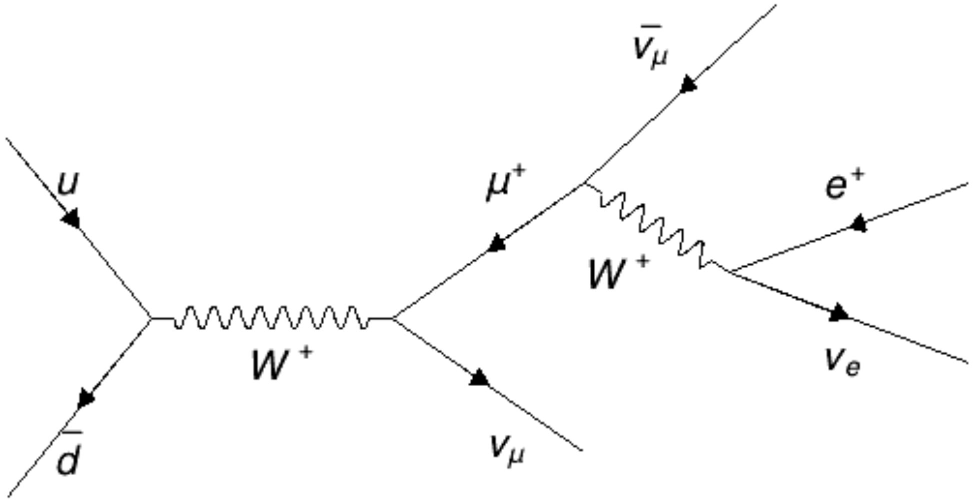


$m_{\pi^+} = 139.6\,\text{MeV}$

The pion stops in the target and decay

Introducing PIONEER

Phase I measurement strategy

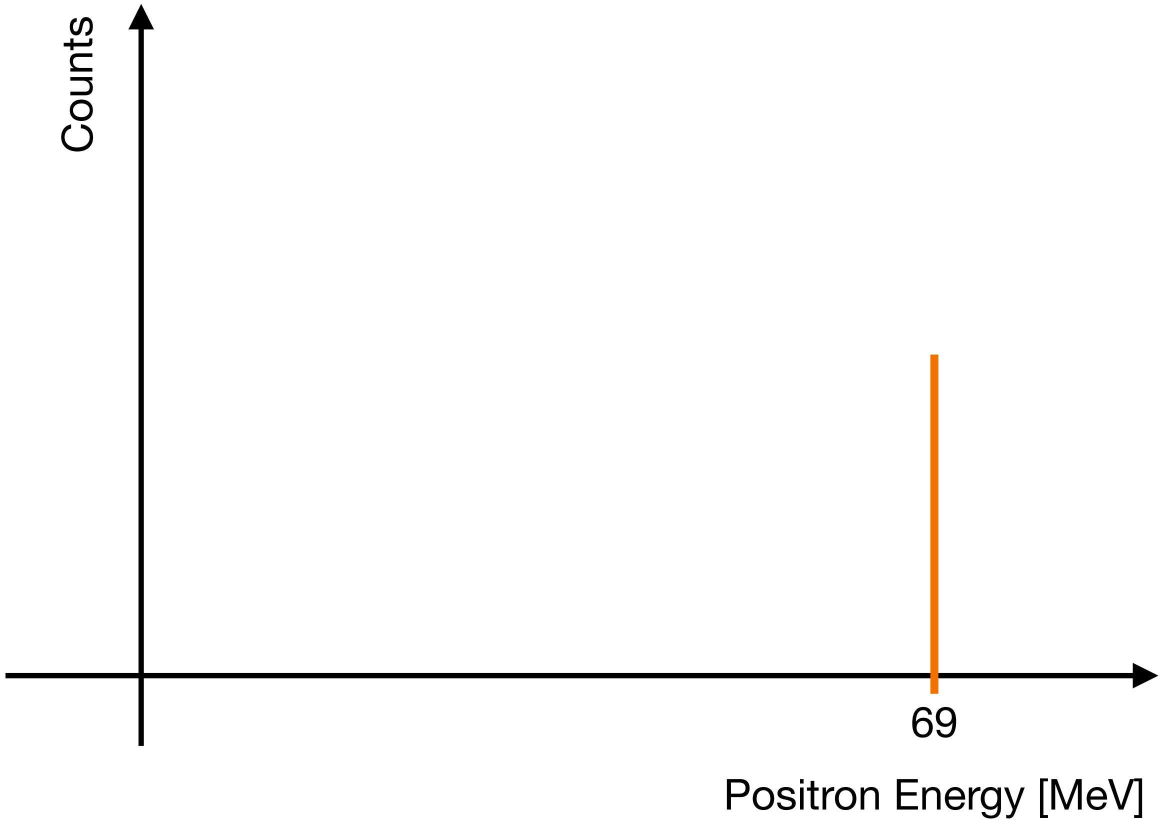


$m_{\pi^+} = 139.6\,\text{MeV}$

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

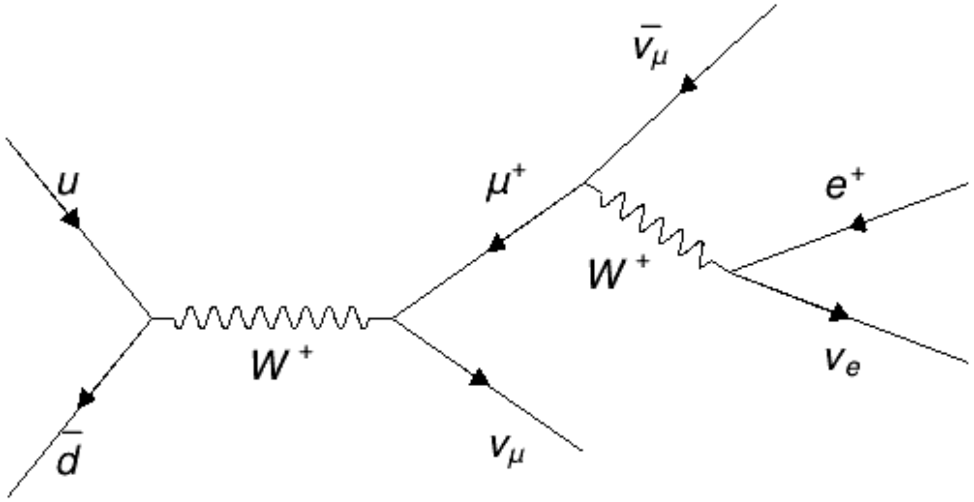
The pion stops in the target and decay

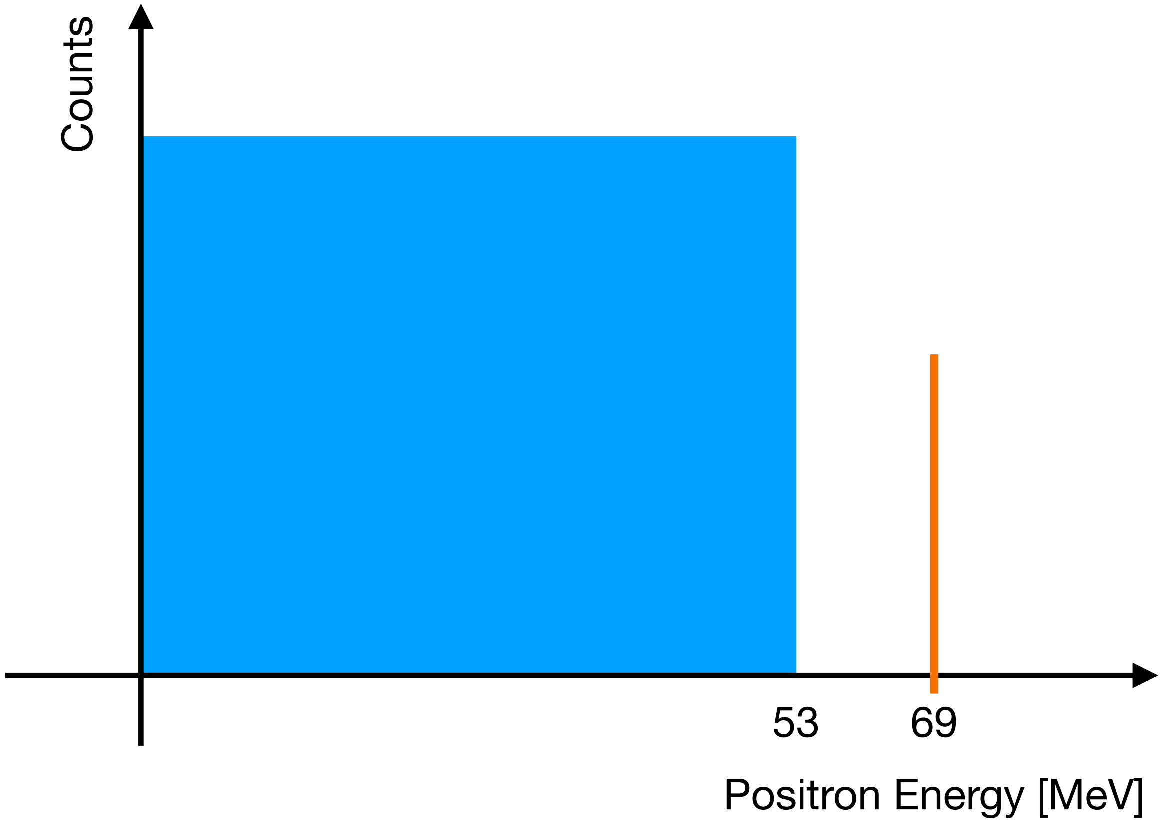
Then the muon stops in the target and decay



Introducing PIONEER

Phase I measurement strategy





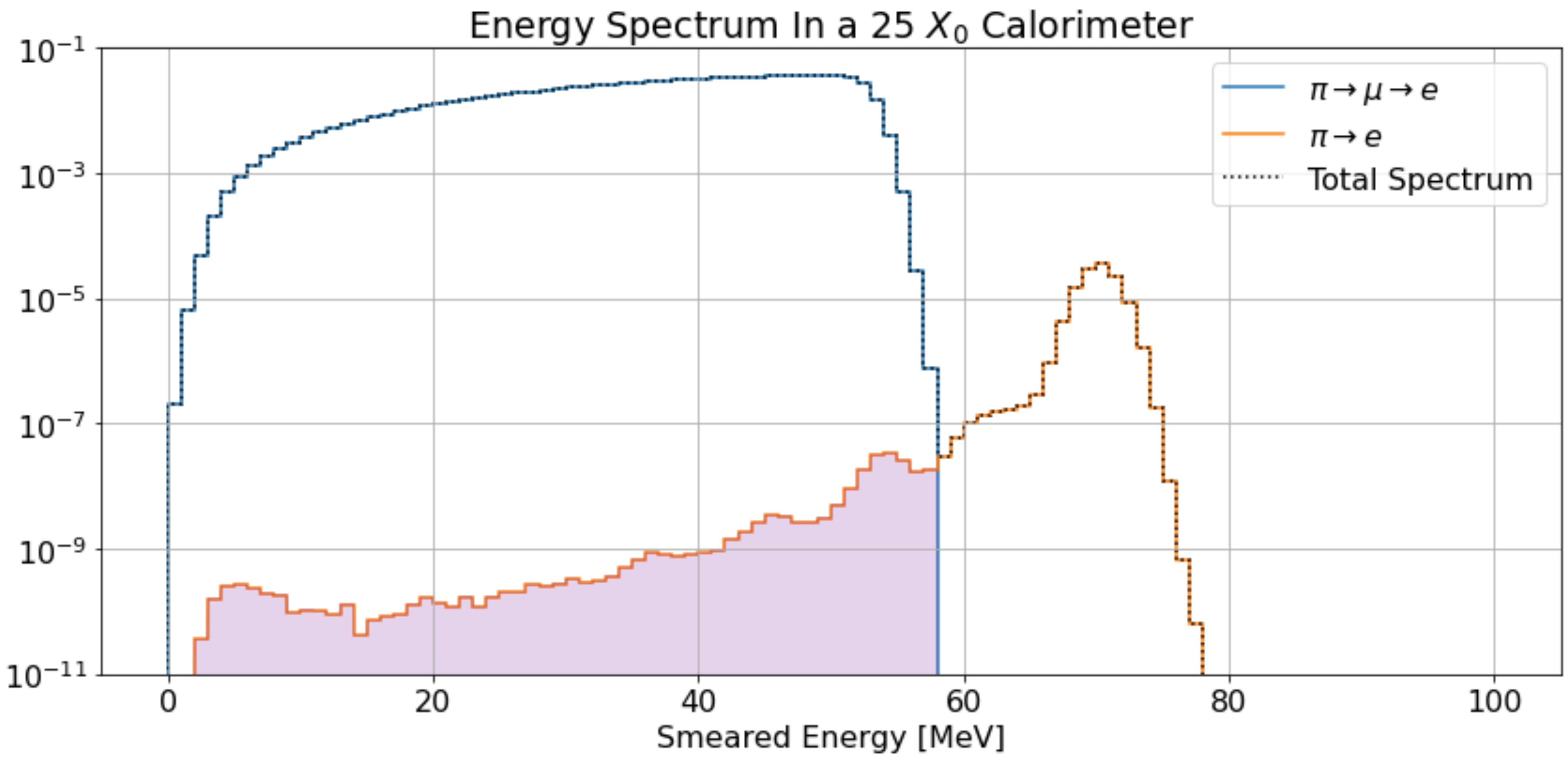
$m_{\pi^+} = 139.6$ MeV

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

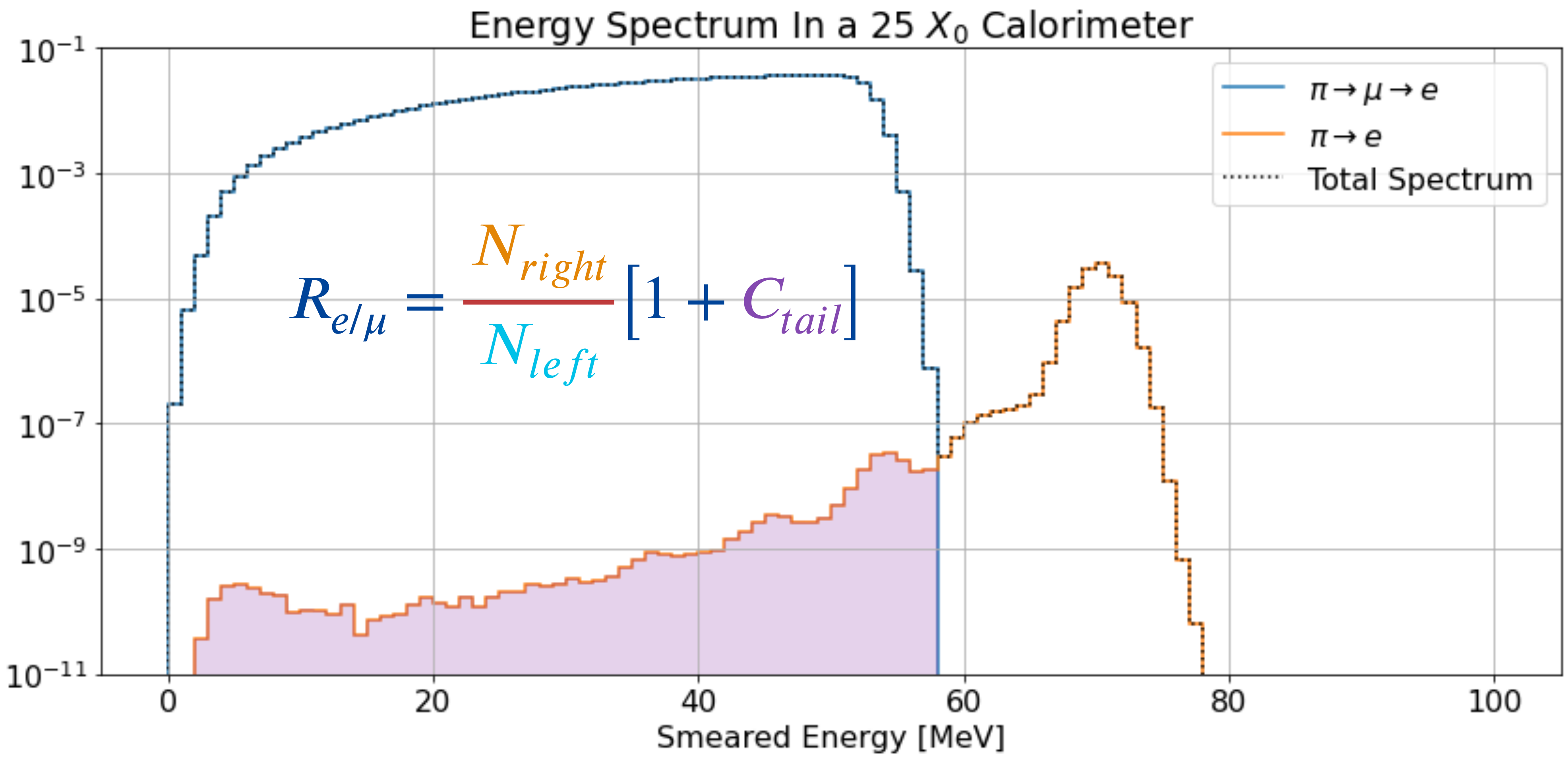
The pion stops in the target and decay

Then the muon stops in the target and decay

Facing experimental reality



Facing experimental reality



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

Guiding principles to the design of the experiment:

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

PAUL SCHERRER INSTITUT

PSI

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

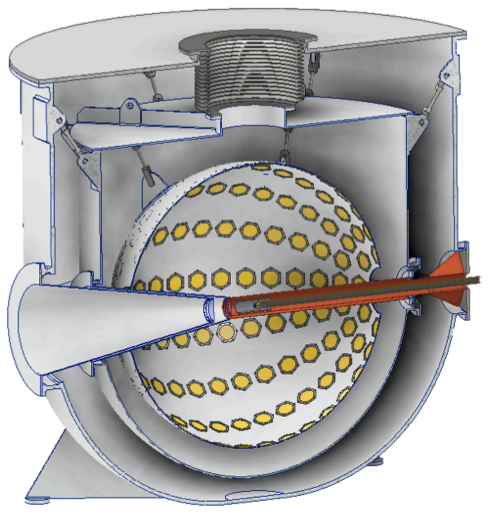
300x10^5 pions/s at 65 MeV/c

Guiding principles to the design of the experiment:

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

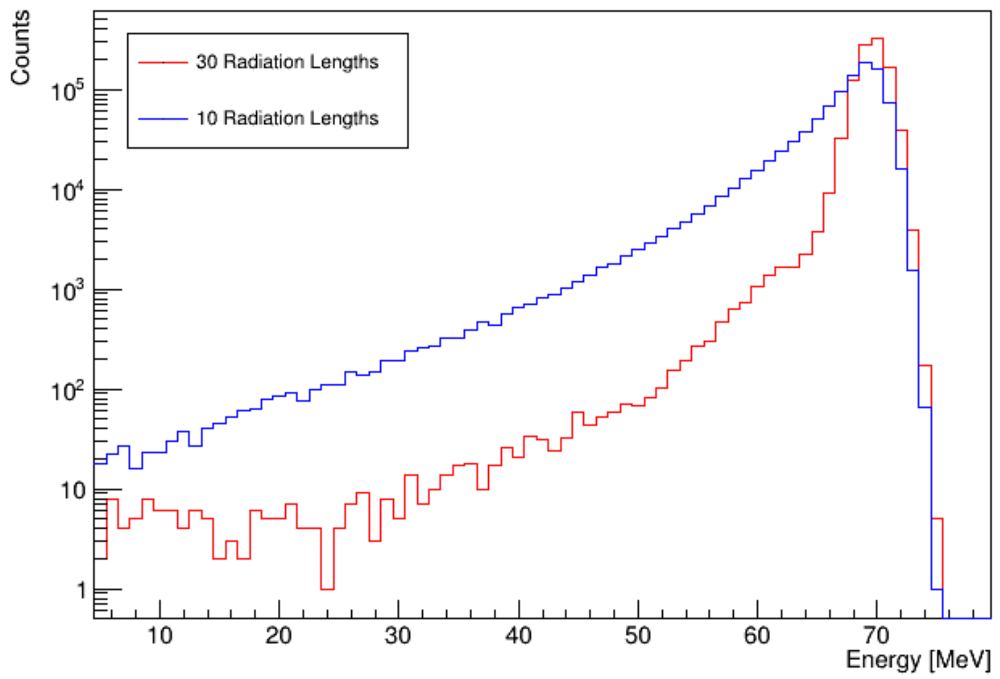
Facing experimental reality

Liquid Xenon



Fast response
Highly homogeneous response
Detector can be reshaped

$\pi \rightarrow e\nu$ signal



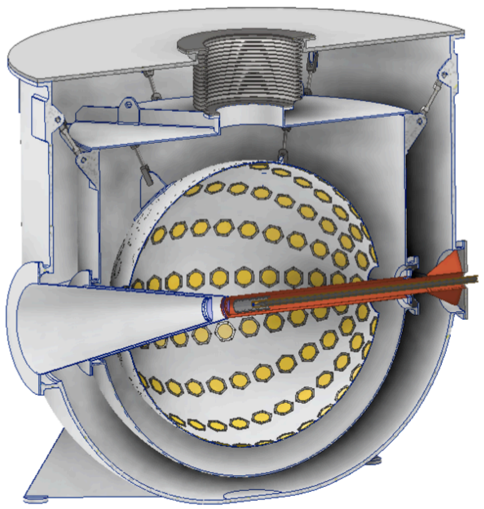
At least 25 X_0

Guiding principles to the design of the experiment:

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

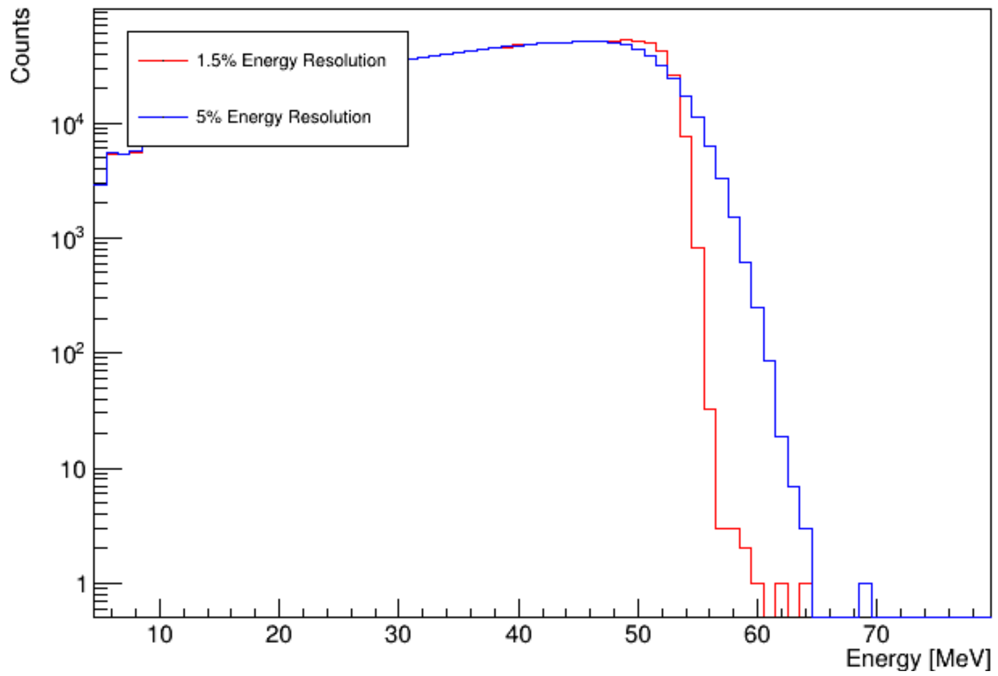
Facing experimental reality

Liquid Xenon



Fast response
Highly homogeneous response
Detector can be reshaped

$\pi - \mu - e$ background



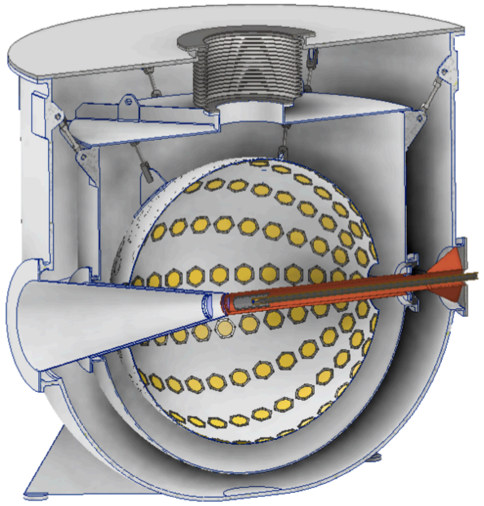
Targeted resolution:
2% for positrons with 70 MeV/c

Guiding principles to the design of the experiment:

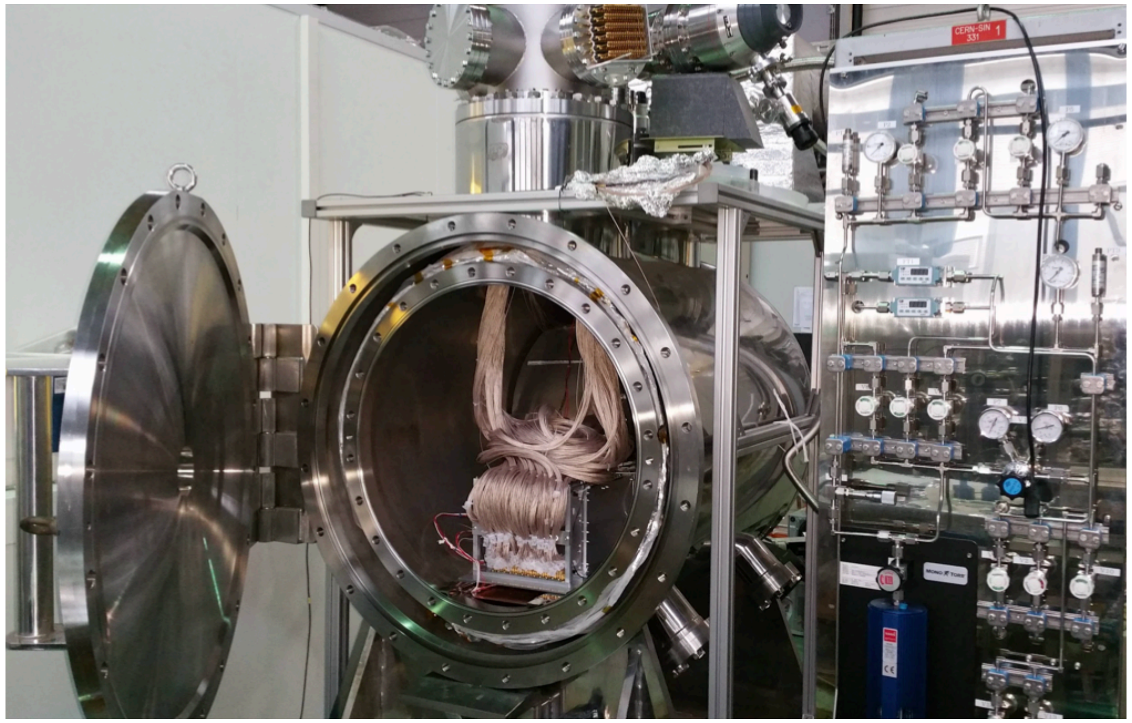
1. Collect very large datasets of rare pion decays (2e8 $\pi^+ \rightarrow e^+\nu_e$ during Phase I)
2. **Tail must be less than 1% of total signal → Shower containment in the calorimeter**
3. Tail must be measured with a precision of 1% → Event identification in the active target

Facing experimental reality

Liquid Xenon



Fast response
Highly homogeneous response
Detector can be reshaped



Building a 100L prototype
28 X_0 cylinder

Guiding principles to the design of the experiment:

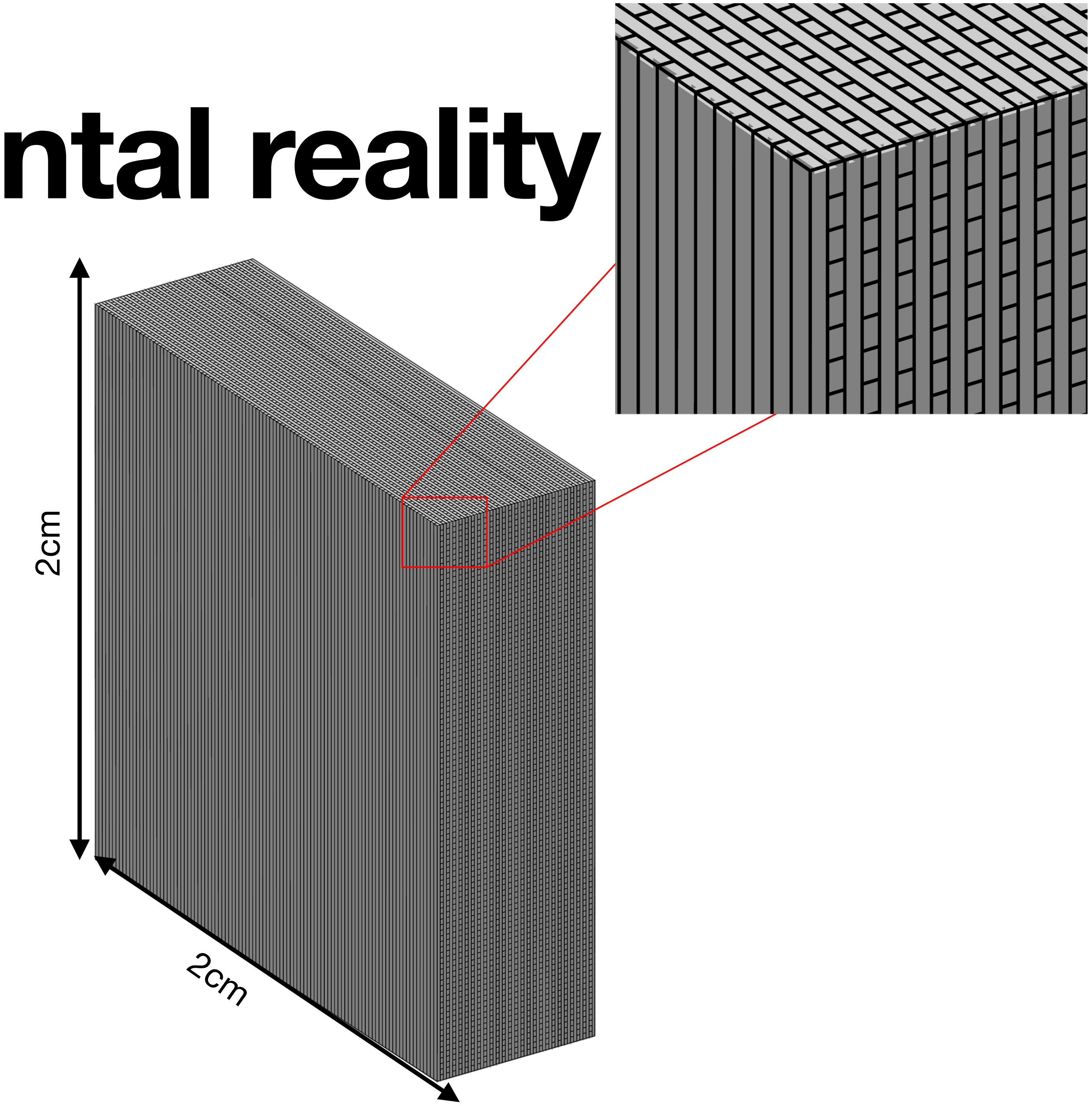
1. Collect very large datasets of rare pion decays (2e8 $\pi^+ \rightarrow e^+\nu_e$ during Phase I)
2. **Tail must be less than 1% of total signal → Shower containment in the calorimeter**
3. Tail must be measured with a precision of 1% → Event identification in the active target

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



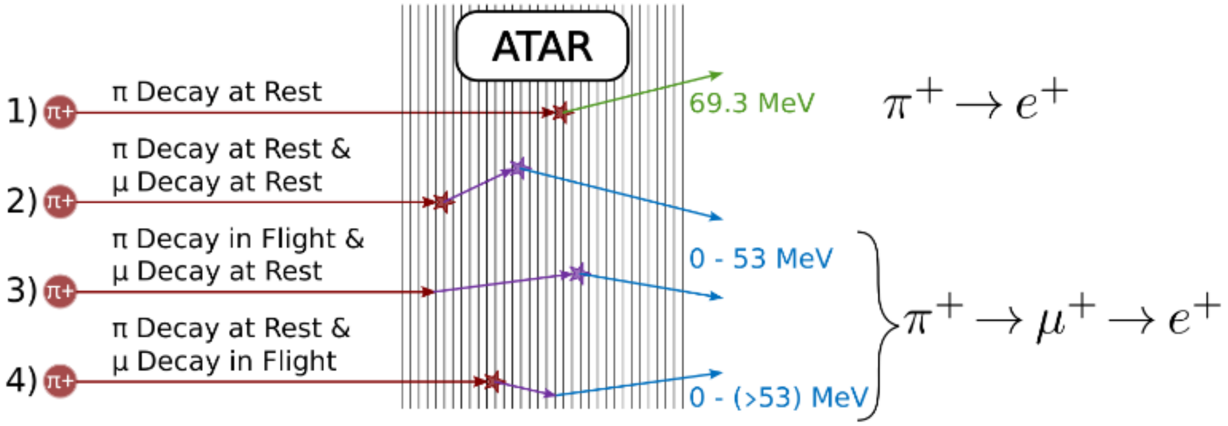
Guiding principles to the design of the experiment:

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**

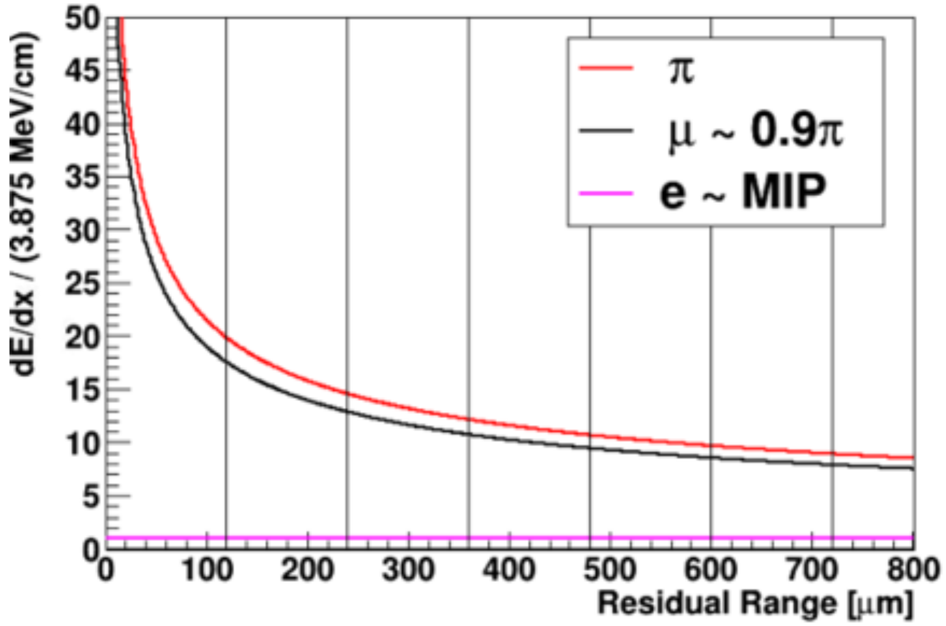
Active Target

Requirements

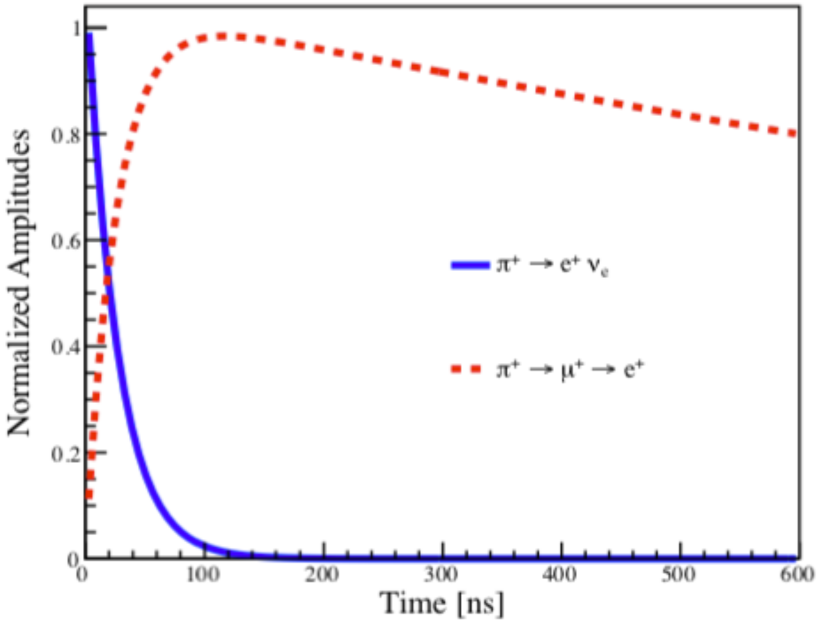
- Thick and highly segmented target to
  - stop the pion
  - tag and measure the decay chain
- Measure energy, time and position



Pattern Recognition



Energy loss of particles through silicon
Device needs to accommodate
large range of energy scales

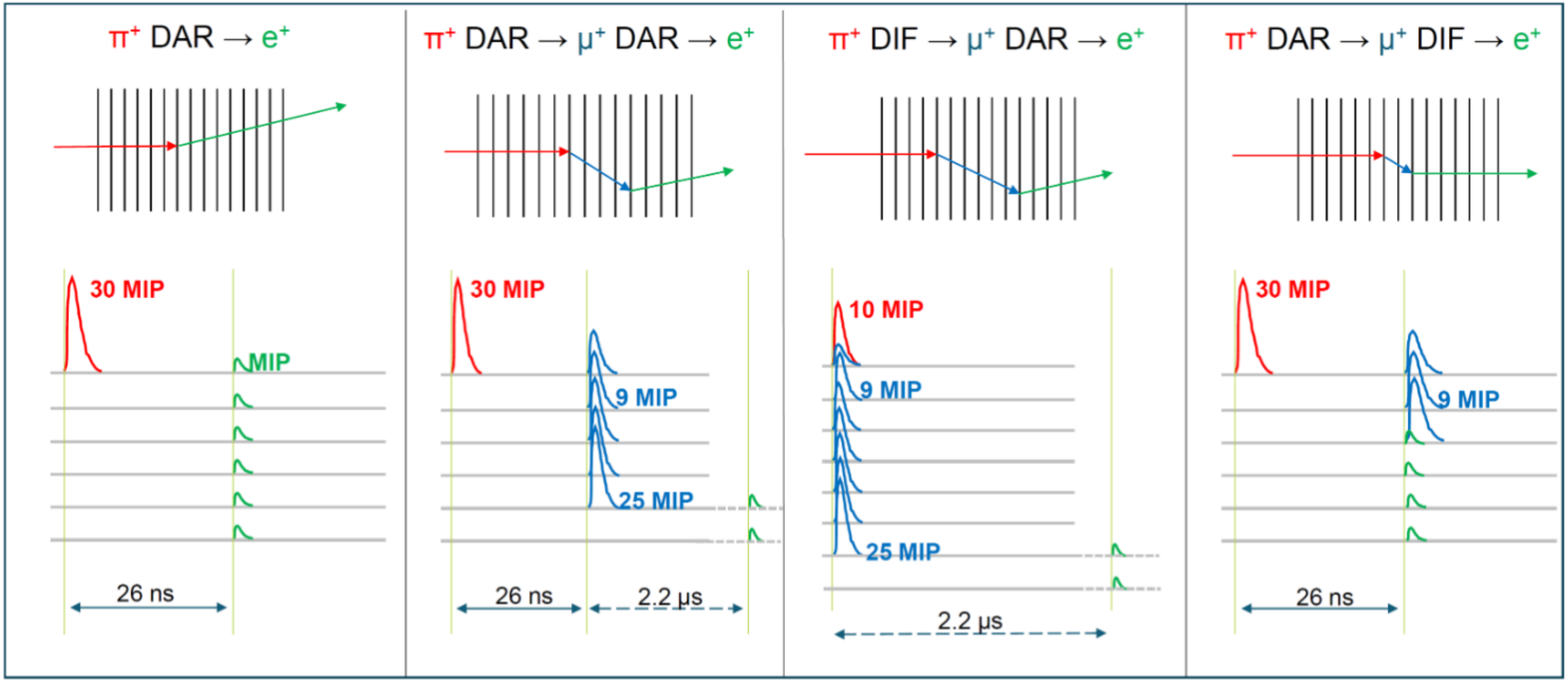


Decay chain time is very different
between $\pi \to e\nu$ and $\pi - \mu - e$ events
Device needs to separate
signal within 1 ns apart

Active Target

Pion Decay tagging

☐ Topology ☐ Calorimetry ☐ Timing



Glossary:

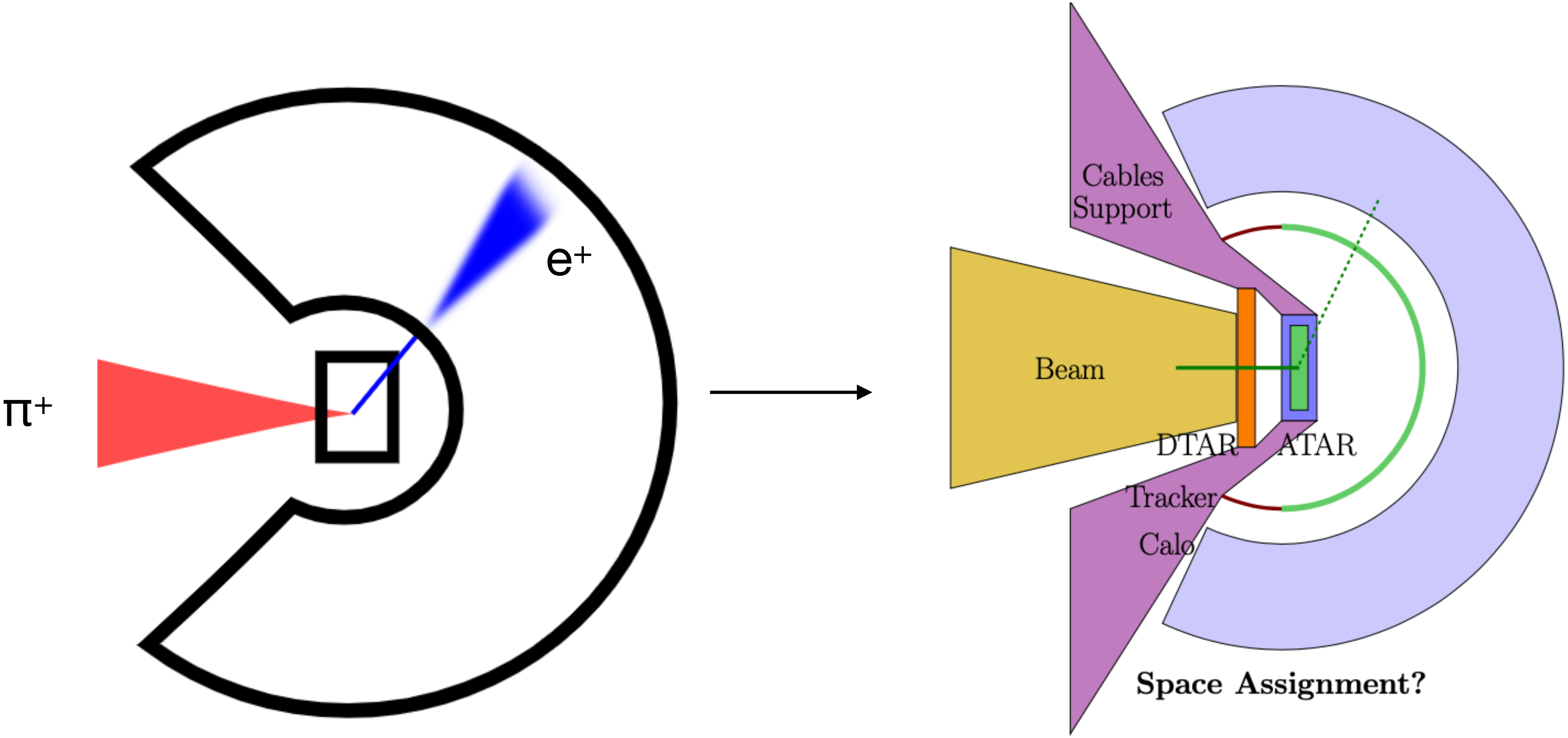
DAR: Decay At Rest — particle stops in material before decaying

DIF: Decay In Flight — particle decays before depositing all its kinetic energy

MIP: Minimum Ionizing Particle — particle at the threshold of being detectable through ionisation (i.e. a positron through silicon)

Simulation studies

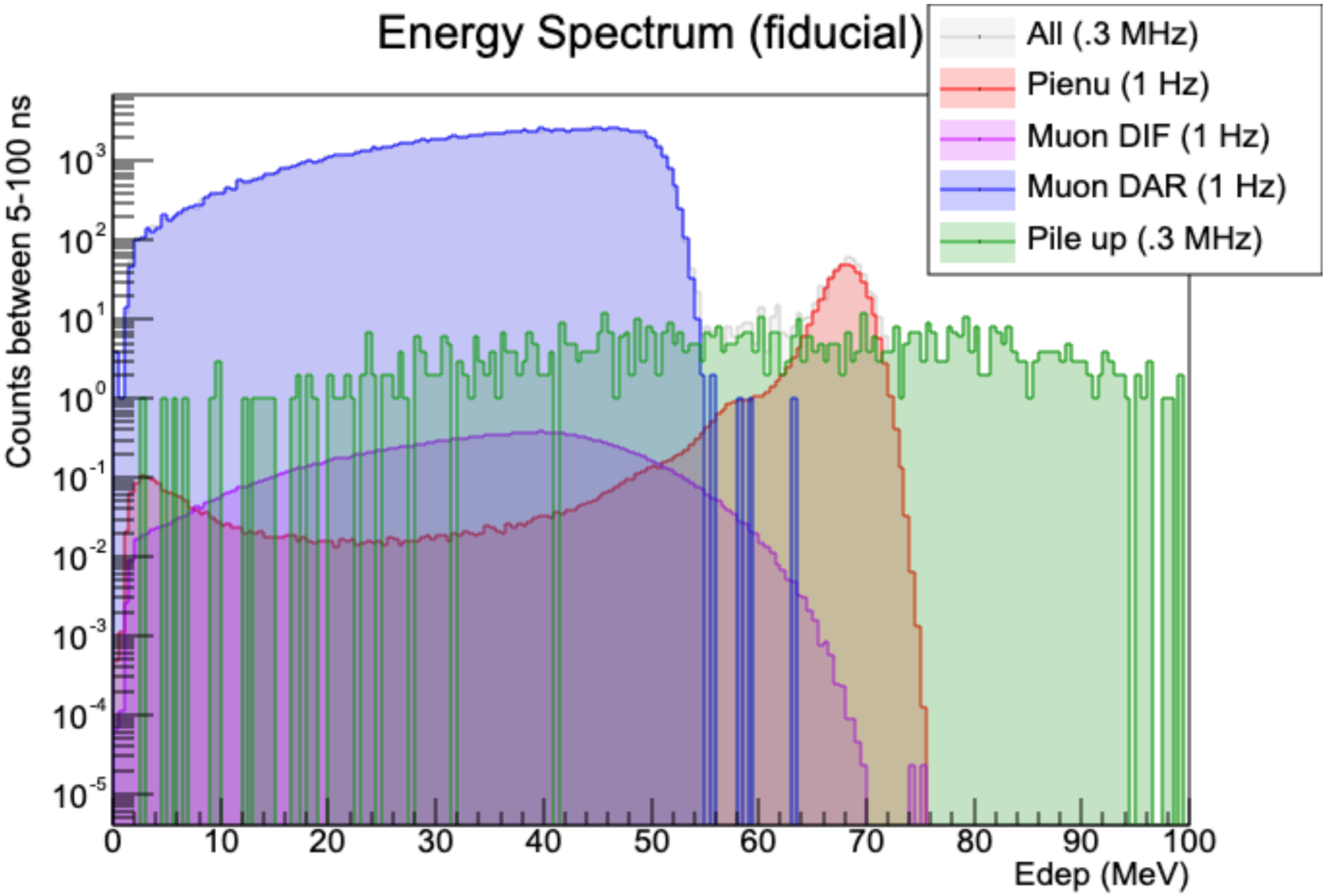
Realistic detector geometry



GEANT4
A SIMULATION TOOLKIT

Simulation studies

Prototyping the data analysis

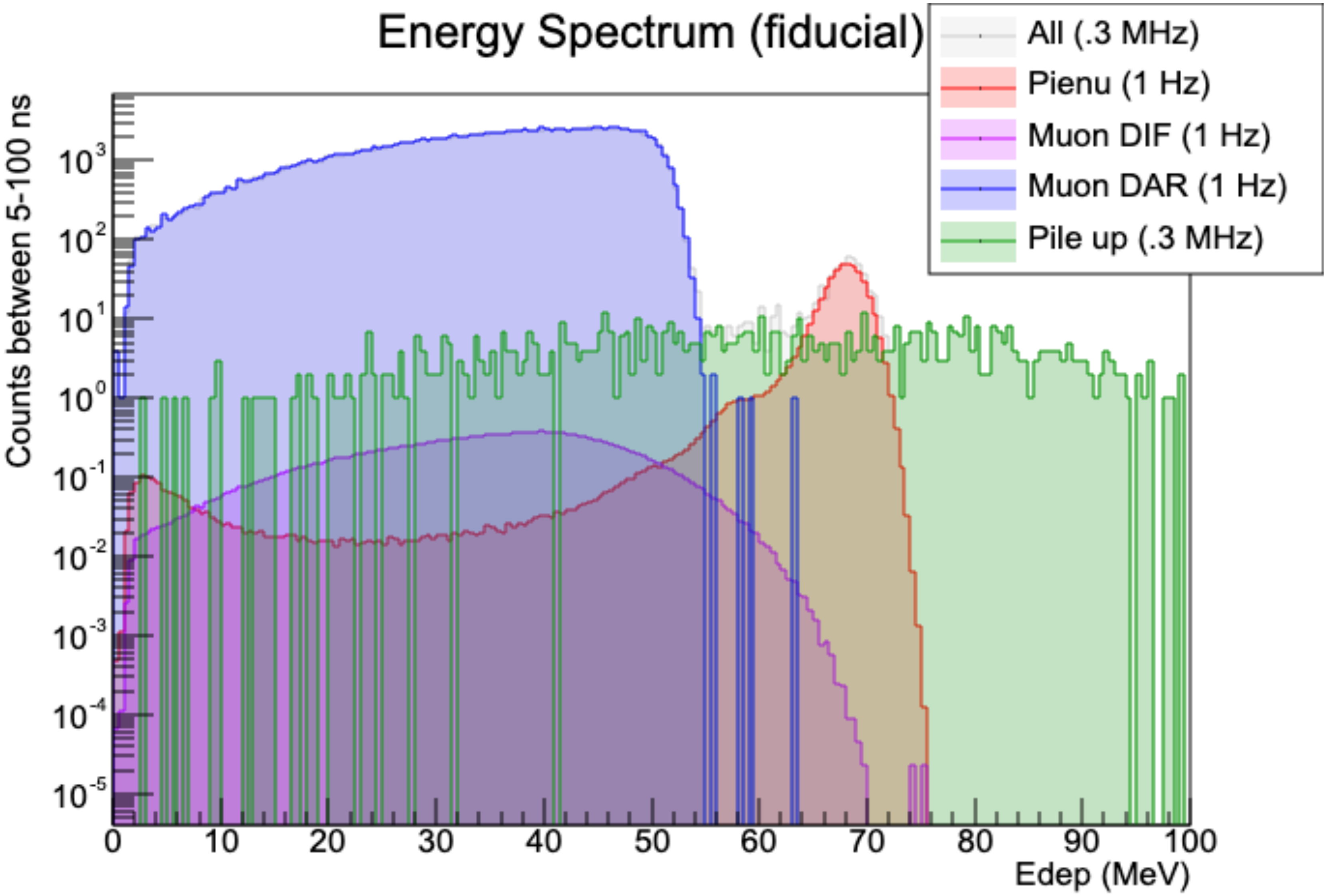


This is what real data could look like

Finding the signal in a ‘sea’ of backgrounds

Simulation studies

Prototyping the data analysis



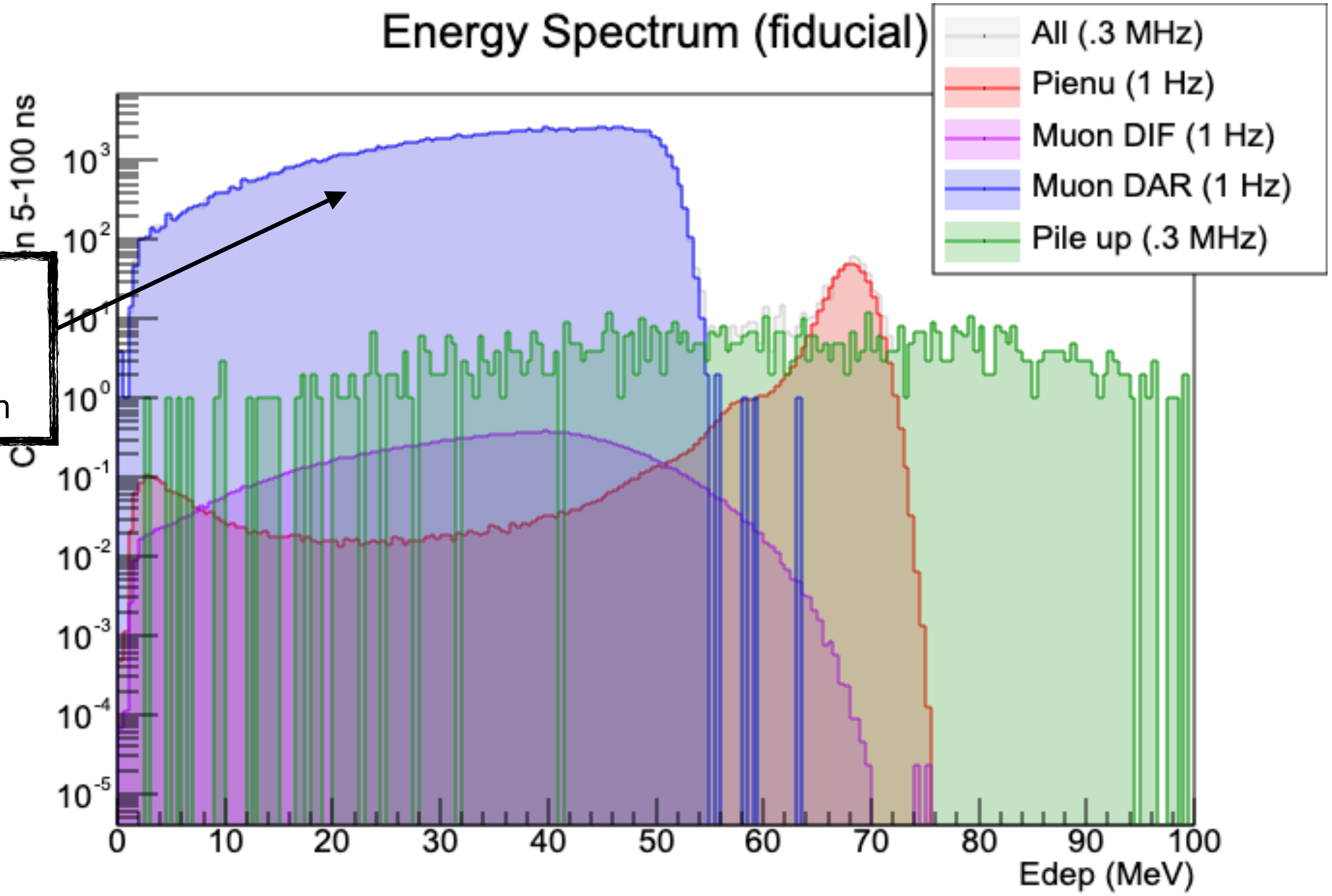
This is what real data could look like

Measuring the tail fraction

tag events with minimal bias while maintaining a decent (>1%) efficiency

Simulation studies

Prototyping the data analysis



Muon Decay At Rest
Excellent pulse shape separation should provide O(10-7) rejection

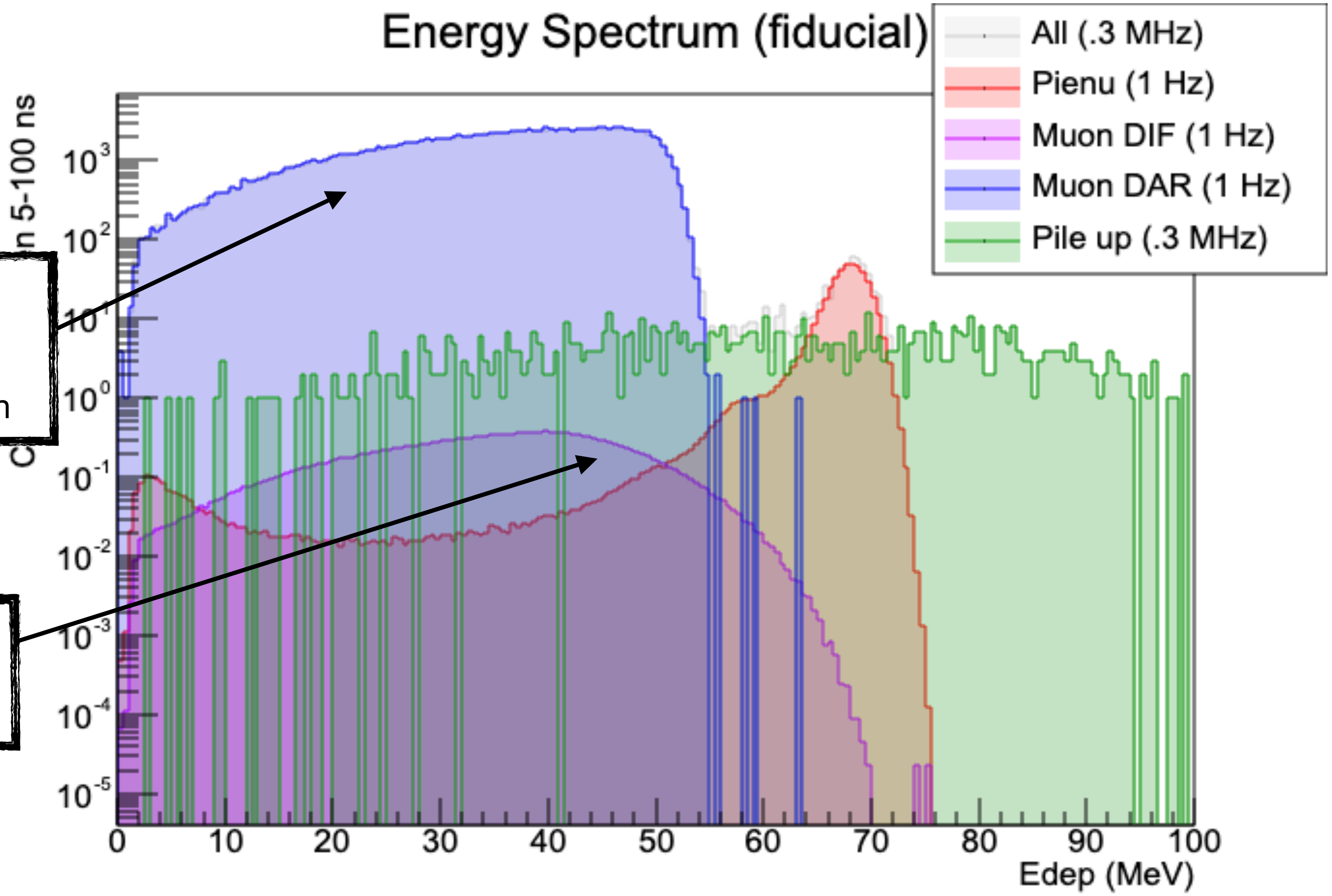
This is what real data could look like

Measuring the tail fraction

tag events with minimal bias while maintaining a decent (>1%) efficiency

Simulation studies

Prototyping the data analysis



Muon Decay At Rest
Excellent pulse shape
separation should
provide O(10-7) rejection

Muon Decay In Flight
Pion stop determination
dE/dx discrimination

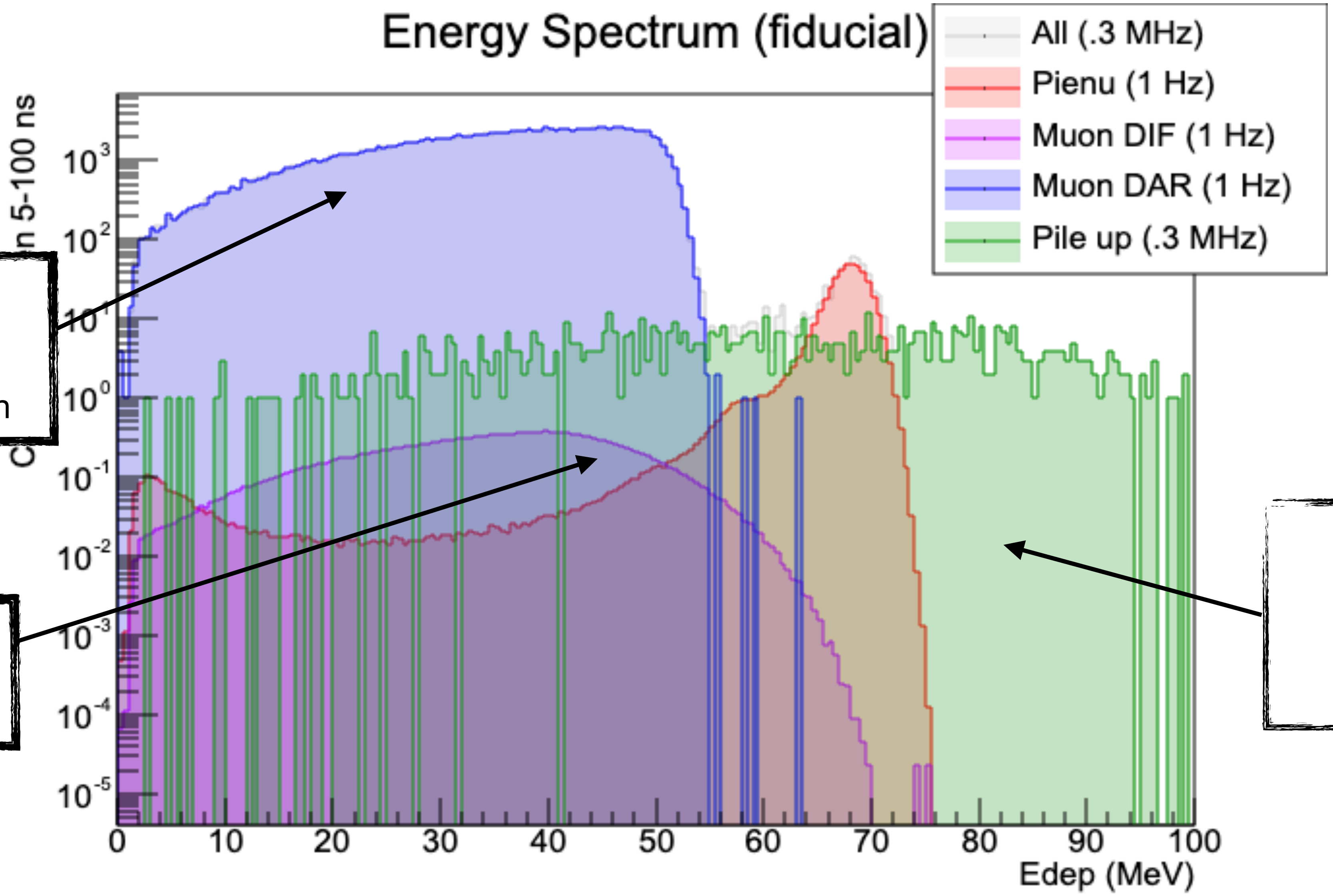
This is what real data could look like

Measuring the tail fraction

tag events with minimal bias while maintaining a decent (>1%) efficiency

Simulation studies

Prototyping the data analysis



Muon Decay At Rest
Excellent pulse shape separation should provide O(10-7) rejection

Muon Decay In Flight
Pion stop determination
dE/dx discrimination

Pileup
Spatial resolution in the target
Time separation from the pion stop

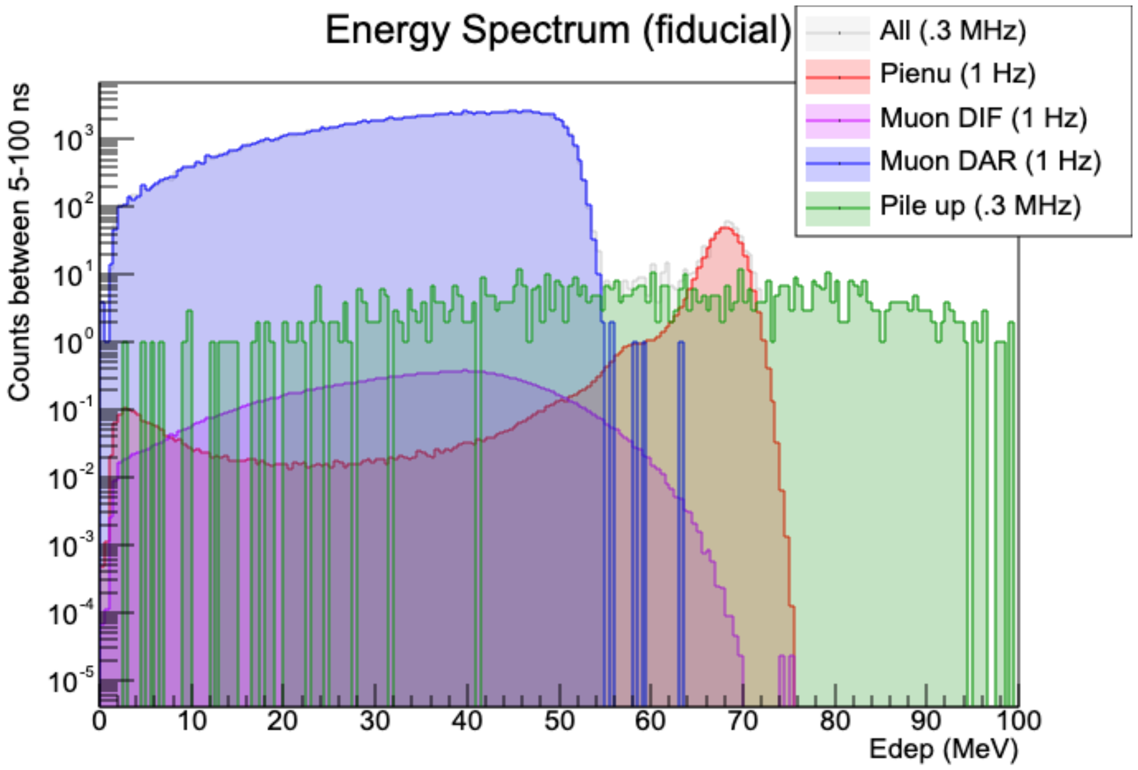
This is what real data could look like

Measuring the tail fraction

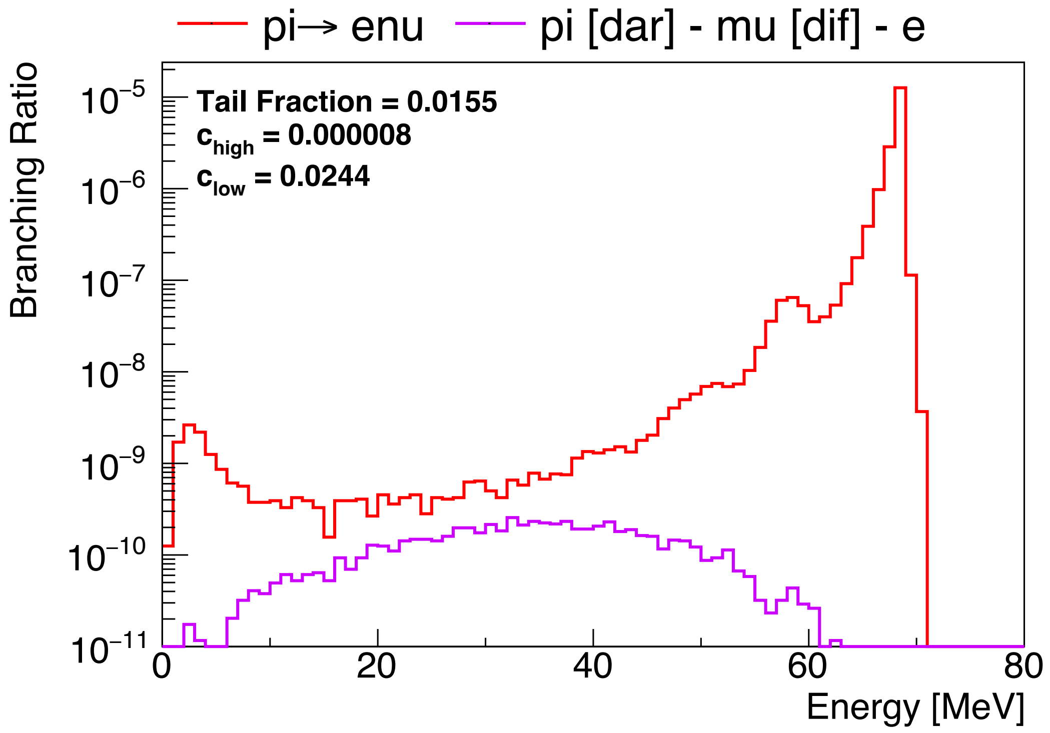
tag events with minimal bias while maintaining a decent (>1%) efficiency

Simulation studies

Revealing the tail

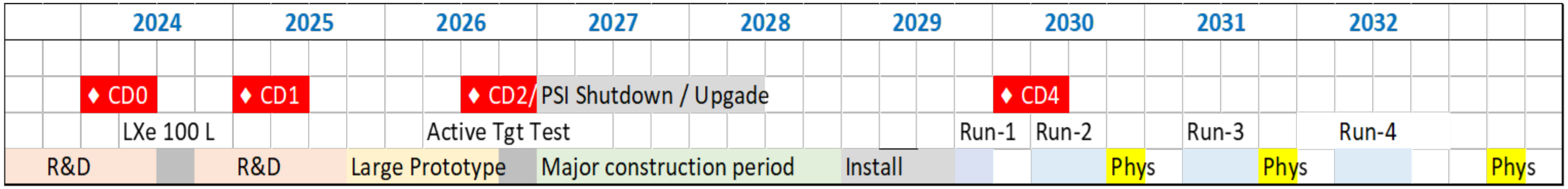


→

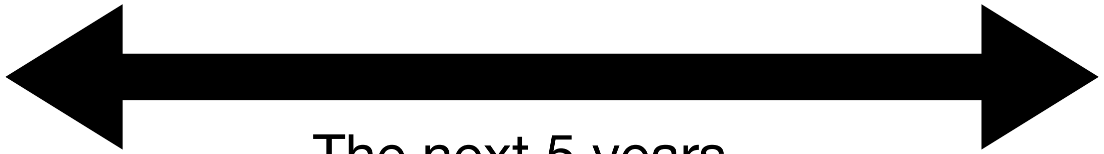


The instrumented active target is a fantastic tool to understand the backgrounds and achieve our target sensitivity

Timeline of the project



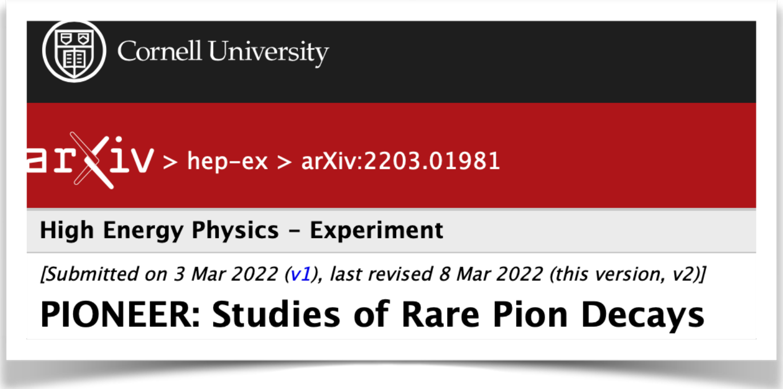
	2024	2025	2026	2027	2028	2029	2030	2031	2032	
	♦ CD0	♦ CD1	♦ CD2/	PSI Shutdown / Upgade			♦ CD4			
	LXe 100 L		Active Tgt Test			Run-1	Run-2	Run-3	Run-4	
R&D		R&D	Large Prototype	Major construction period		Install	Phys	Phys		Phys



The next 5 years

- Detector R&D in calorimetry and tracking
- Simulation studies to model a high precision experiment
  - We need to understand π→eν and π→μν acceptance difference to 10^{-4}…
- Putting an experiment together from concept to first data:
  - Civil engineering, beam optics, detector manufacturing, LXe 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

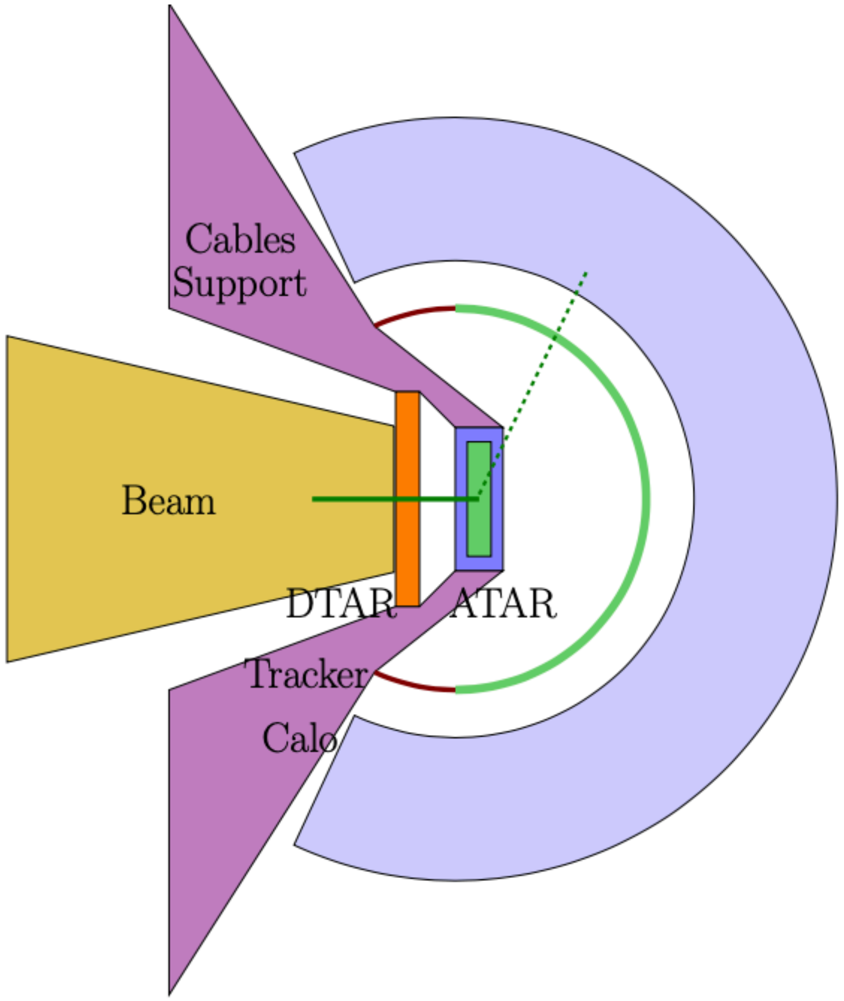
Proposal submitted last year at PSI

First collaboration meeting mid October at CENPA

Conclusion

- PIONEER is a **new proposal** for a rare pion decays experiment at PSI
  - Stringent tests of flavour universality
  - Up to PeV scale sensitivity to BSM effects
- Concept of the experiment has been established and is very promising
- Ongoing effort to move from concept to serious prototype
  - Lots of opportunities for new collaborators to get involved!
  - Get in touch:
    Quentin Buat: qbuat@uw.edu ,
    Chloé Malbrunot: cmalbrunot@triumf.ca,
    David Hertzog: hertzog@uw.edu,
    Doug Bryman: doug@triumf.ca

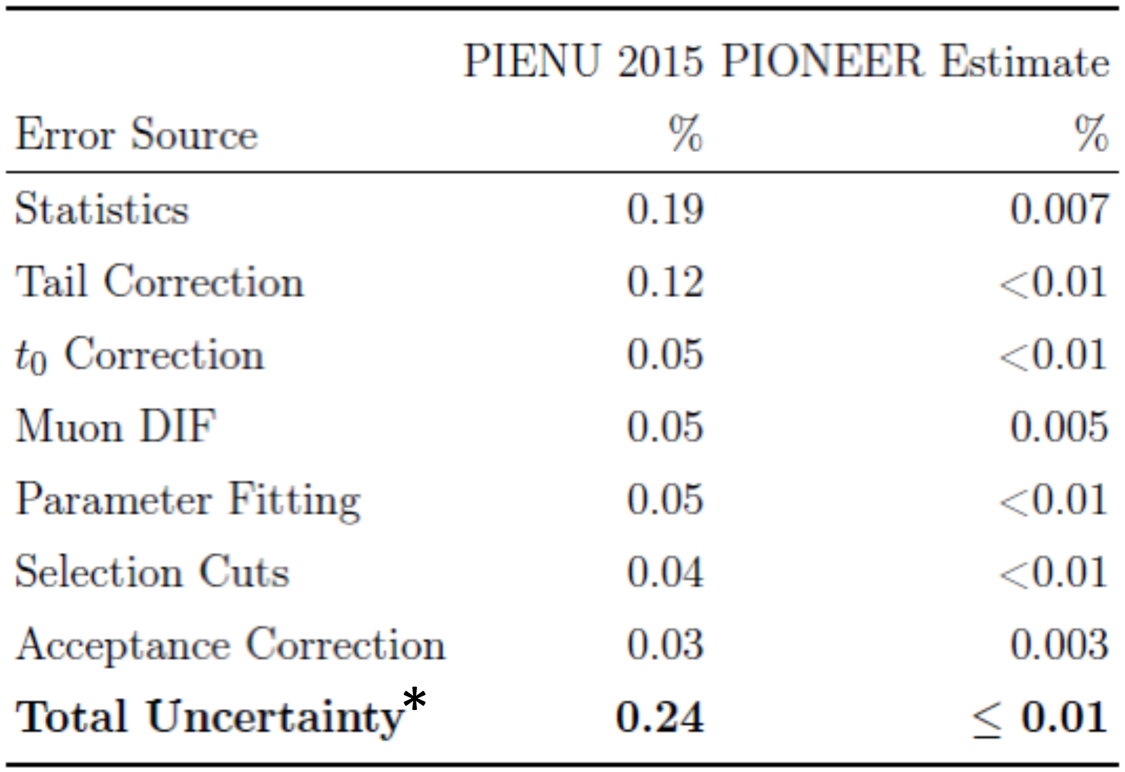
Unofficial logo, ongoing contest



Uncovered in this talk:
Degrader
Tracker
Trigger/DAQ
…

Additional slides

To be verified by simulations and prototype measurements.



Error Source	PIENU 2015 %	PIONEER Estimate %
Statistics	0.19	0.007
Tail Correction	0.12	<0.01
t_0 Correction	0.05	<0.01
Muon DIF	0.05	0.005
Parameter Fitting	0.05	<0.01
Selection Cuts	0.04	<0.01
Acceptance Correction	0.03	0.003
Total Uncertainty*	**0.24**	**$\leq$ 0.01**

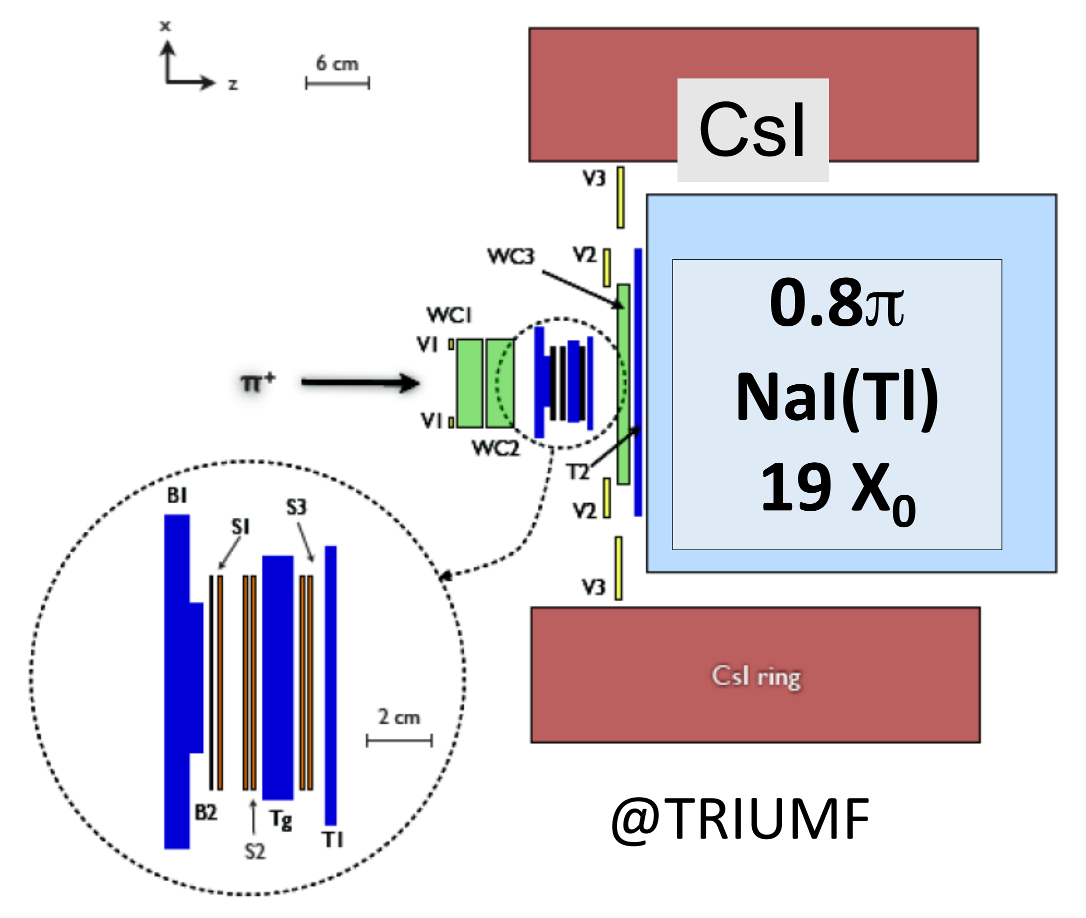
(Calorimeter/ATAR)
(ATAR timing/dE/dx)
(ATAR)
(Calorimeter/ATAR)
(Calorimeter/ATAR)
(Calorimeter)

*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%**	

Two recent Pion Decay Experiments

PIENU



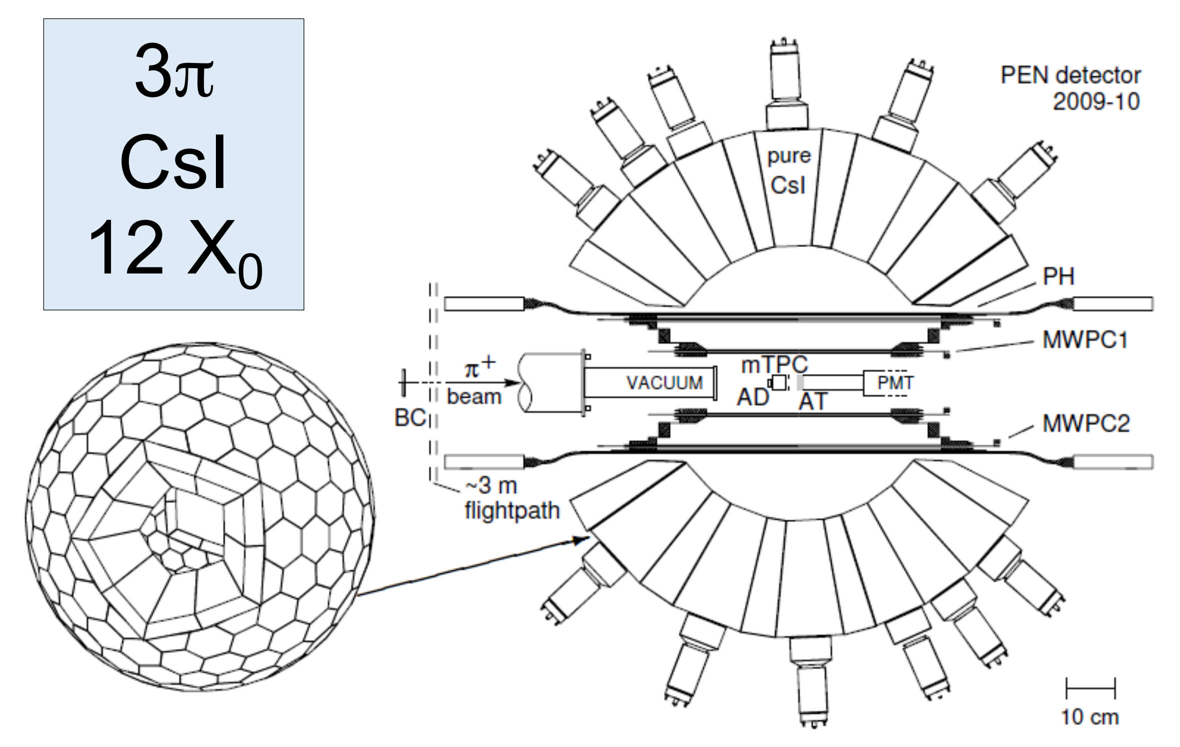
CsI

0.8π
NaI(Tl)
19 X_0

@TRIUMF

- Experiment at TRIUMF
- NaI slow, but excellent resolution
- Single large crystal not uniform enough (material and effective “depth”)
- Small solid angle

PEN/PIBETA



3π
CsI
12 X_0

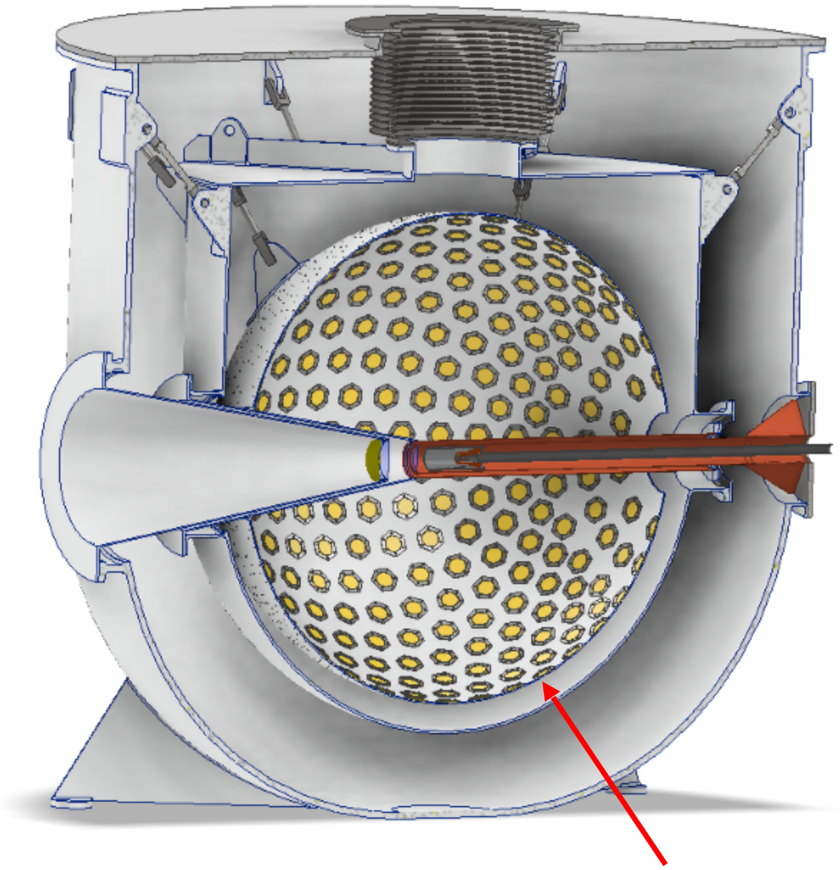
- Experiment at PSI
- Large acceptance but calorimeter depth of 12X_0 too small to resolve tail under the π-μ-e spectrum.

Both experiments took data a while ago but have (known) challenges to overcome before final results

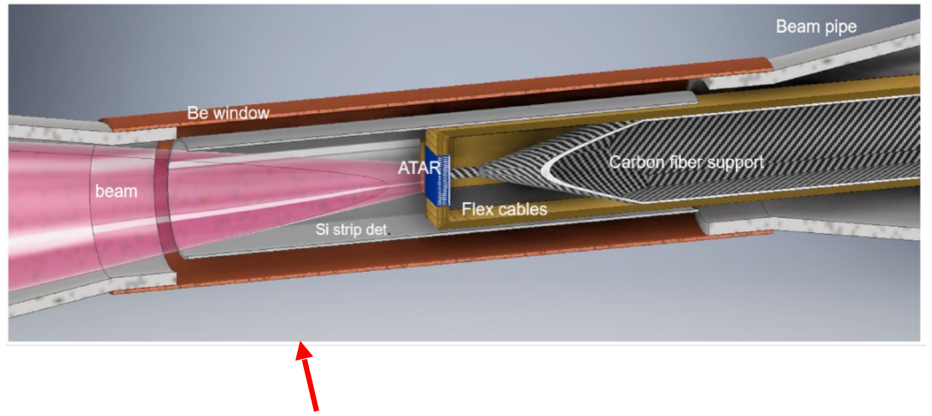
PIONEER Detector

best of both worlds

- Building on PIENU and PEN/PIBETA experiences and use emerging technologies (LXe, LGAD)
- Intense Pion beam at PSI
- Calorimeter: 25 X_0, 3π sr calorimeter
  - Improve uniformity (x5)
  - reduce tail correction (x5)
  - reduce pile-up uncertainties with fast scintillator response (x5)
- Active target ("4D") based on LGAD technology
  - reduce tail correction uncertainty (x10)
  - Fast pulse shape: allow $\pi \rightarrow \mu \rightarrow e$ decay chain observation
- State-of-the-art additional instrumentation:
  - μRWell Tracker
  - Fast triggering
  - High speed digitization



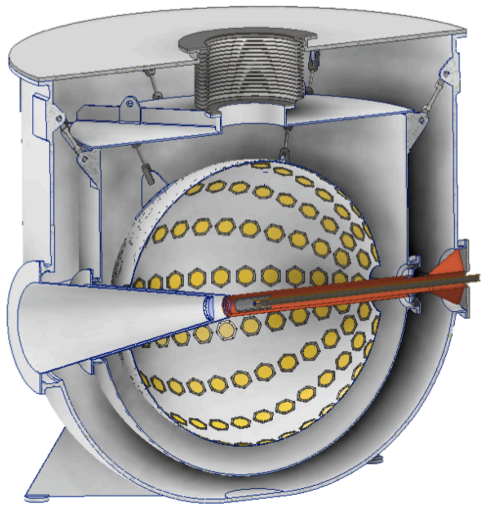
LXe calorimeter



LGAD Fully Active Tracking Target (ATAR)

Calorimeter Technologies

Liquid Xenon

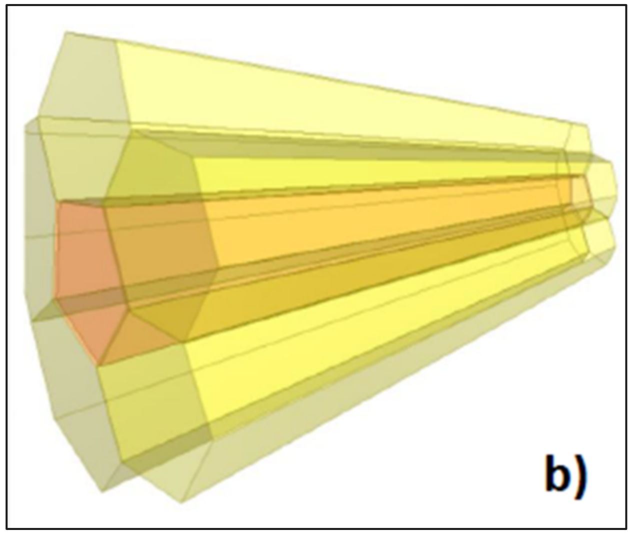


Fast response
Highly homogeneous response
Detector can be reshaped

BUT

Expensive?
Unsegmented calorimeter
impacts pileup rejection

LYSO Crystals



Fast response
High stopping power
Intrinsically segmented

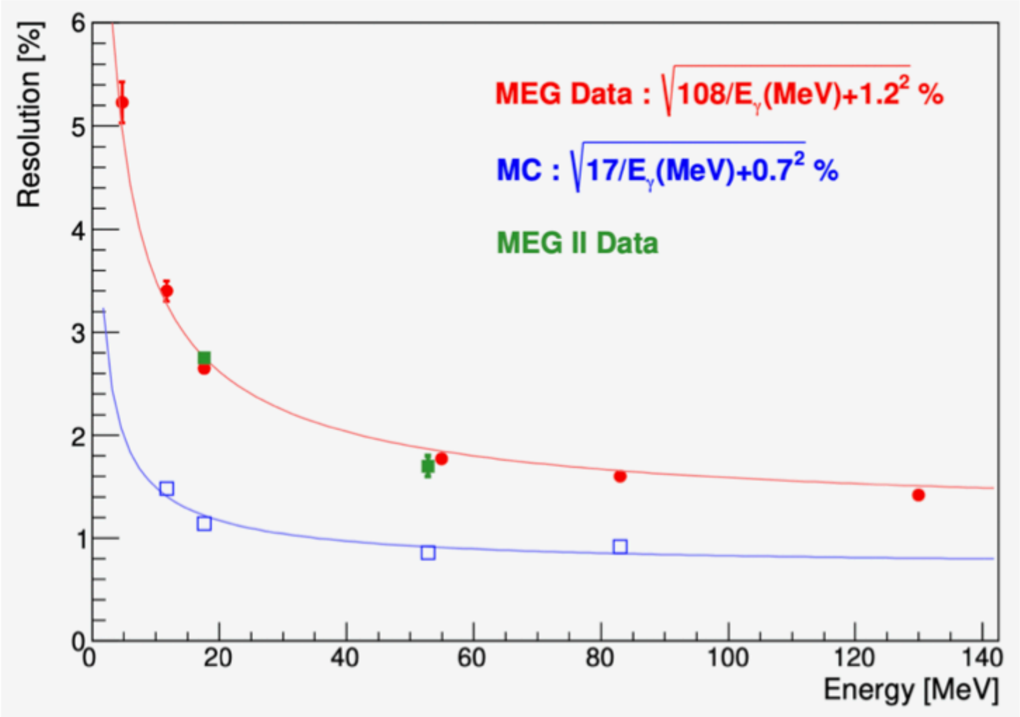
BUT

Resolution better than 4% has not
been demonstrated for an array of
LYSO crystals at 70 MeV

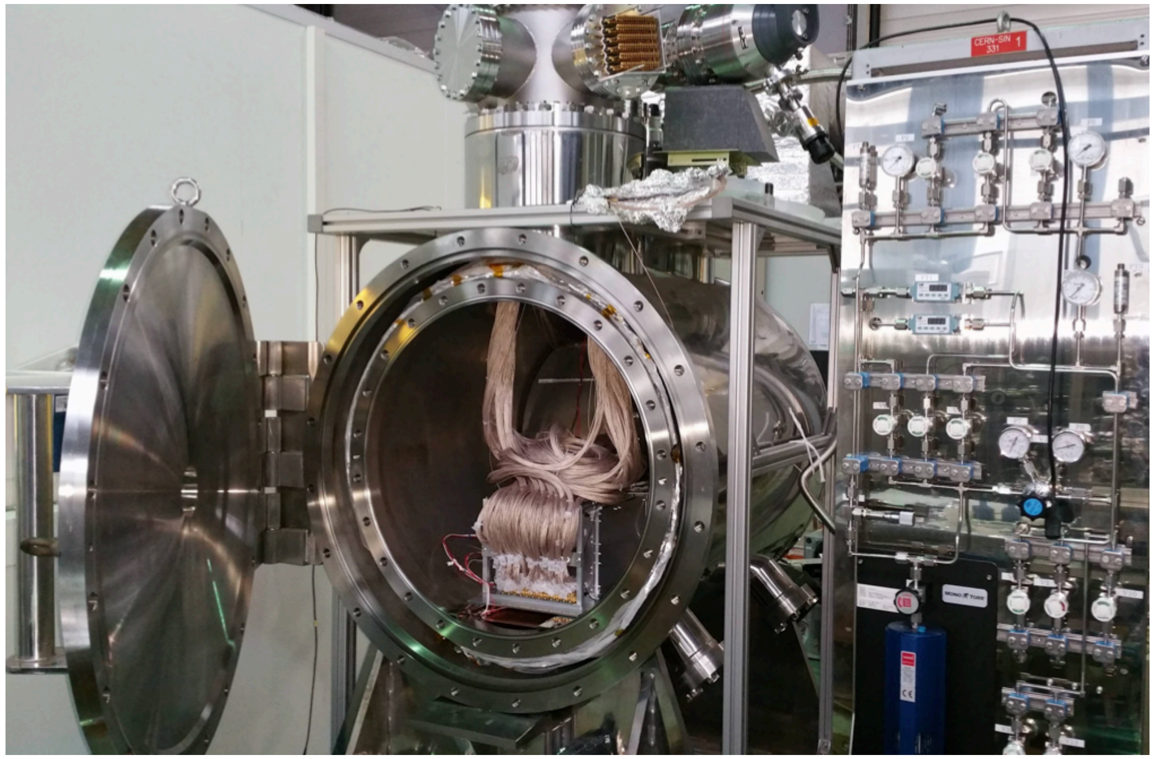
Growing long homogeneous
crystals is a challenge

Calorimeter Developments

Liquid Xenon Prototype

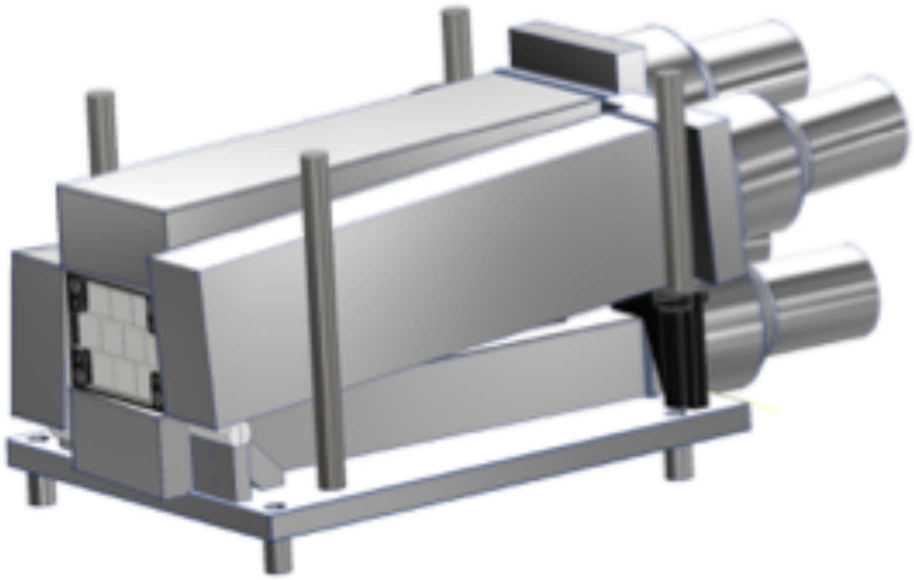


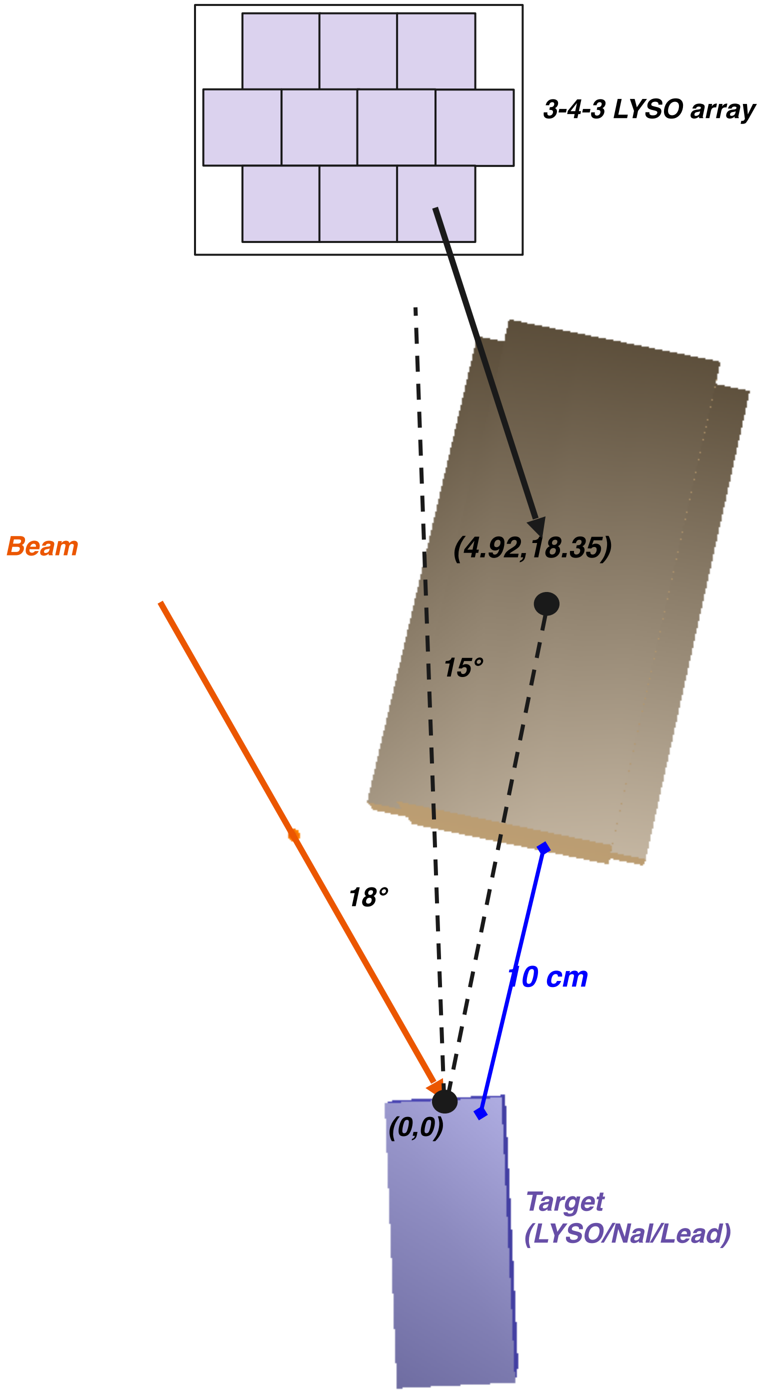
- Series of prototypes leading to a large 100L, 28X_0 cylinder
    - Measure resolution for 70 MeV positrons
    - Check and correct simulations
- Build expertise with LXe handling
- Bonus: prototype could set stringent limits on μ→eeeee (arXiv:2306.15631)



Calorimeter Developments

LYSO Test Beam studies

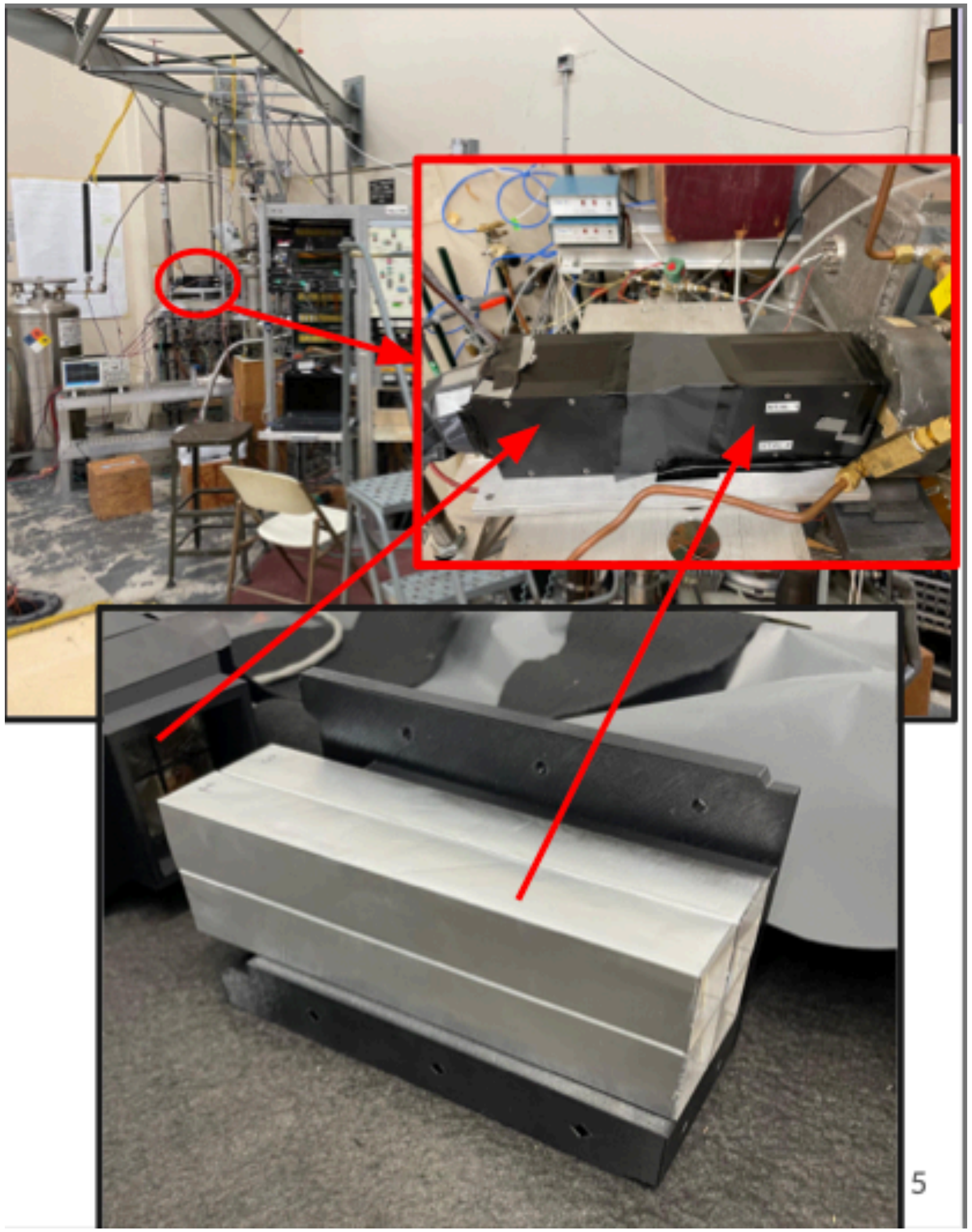




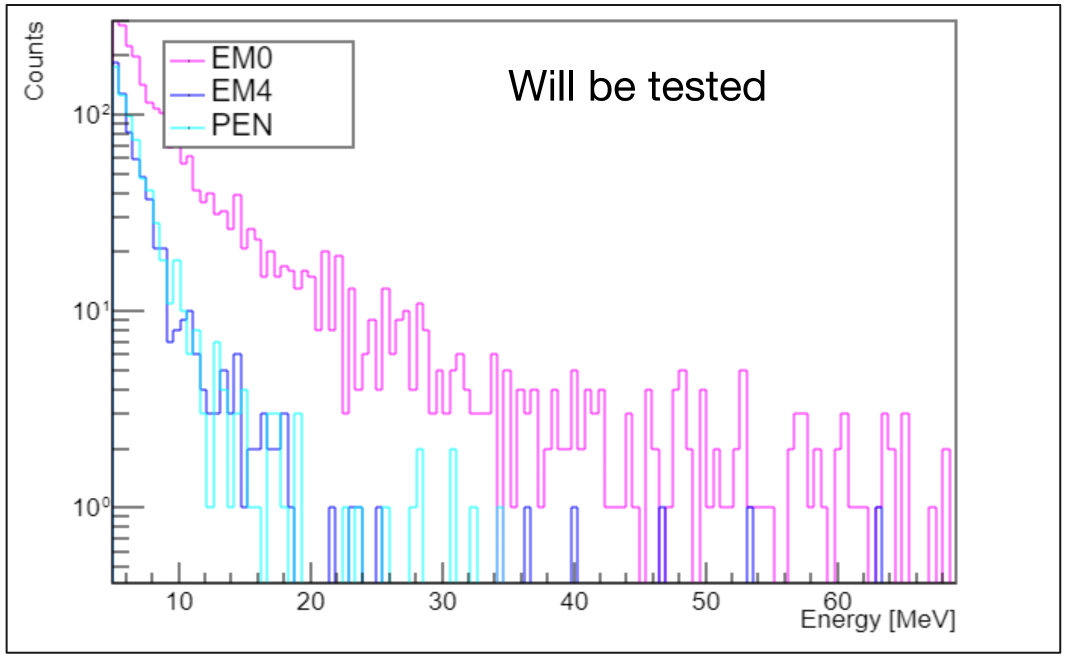
- Goals:
  - LYSO resolution for 70 MeV positrons
  - Albedo modelling validation
- Ongoing prep work at UW with the in-house accelerator
  - Testing with a sharp 17.6 MeV gamma from a Li-7 source
  - Moving setup at PSI for test beam at the end of November

Calorimeter Developments

LYSO Test Beam studies



Large discrepancies of the albedo effect between different simulation models


Will be tested

Quotes for 70 L (220kg) LXe

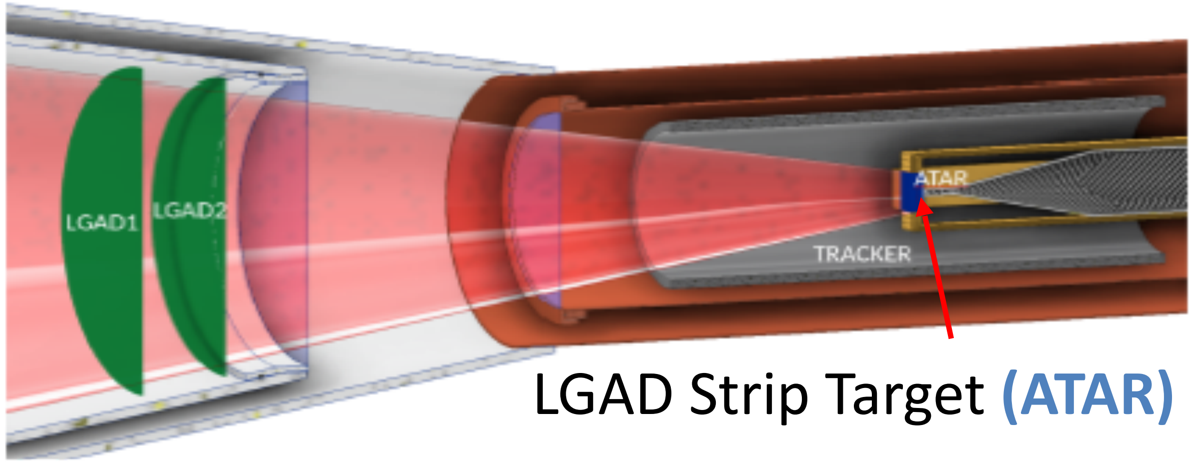
- Quote from CERN in June (20 kg each cylinder, 3.3m^3 at STP)
  - **$2.7 per gram,** *high quality with certified content of SF$_6$ below 0.01 ppm*
- Xenon pricing from China (10 m^3 each cylinder, 4 pieces in total)
  - Xenon price is 10 times less than the same time last year and at a historically low level
  - Wuhan Iron and Steel Corporation can offer **$1.8 per gram***. They have supplied Xenon to SJTU, Columbia, and UCSD. They have sufficient Xenon in stock for shipping right now.
  - Fuhaicryo offered **$1.62 per gram***. They have also sold to the US previously. They have sufficient Xenon in stock for shipping right now.
  - Price slightly increased from the last time we reported to the collaboration (Wuhan $1.62/g, Fuhaicryo $1.38/g)
- Xenon pricing from domestic suppliers
  - Praxair/Linde (US) **$12.35 per gram*** 2023, **$16.15 per gram*** in 2024
  - Airgas/Air Liquide can't even provide a quote for Xenon due to being in Force Majeure with Xenon supply in the next 4-5 months, the previous informal quote was **$18 per gram***

*Shipping and custom duties excluded. Estimated cost of shipping is in the order $10k-20k

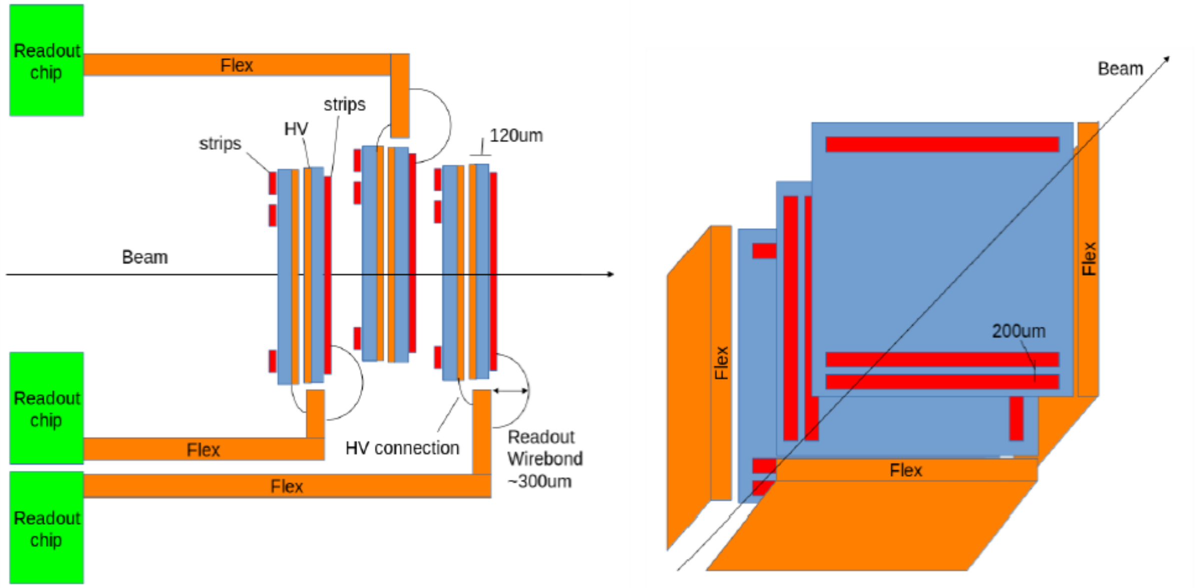
PIONEER Detector Concept:

Active Target (ATAR)

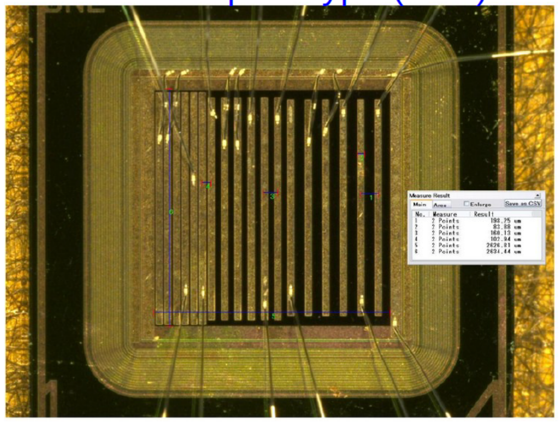
- Active target ("4D") based on low-gain avalanche diode (LGAD) technology
- Requirements:
  - High segmentation, compact with less dead materials, fast collection time to reconstruct pion decay chain
  - Large dynamic range for electron (MIP) and stopping pions/muons (x100 MIP)
- Tentative design:
  - 48 layers X/Y strips: 120 um thick
  - 100 strips with 200 um pitch covering 2x2 cm^2 area
  - Sensors are packed in stack of two with facing HV side and rotate 90^o



LGAD Strip Target **(ATAR)**



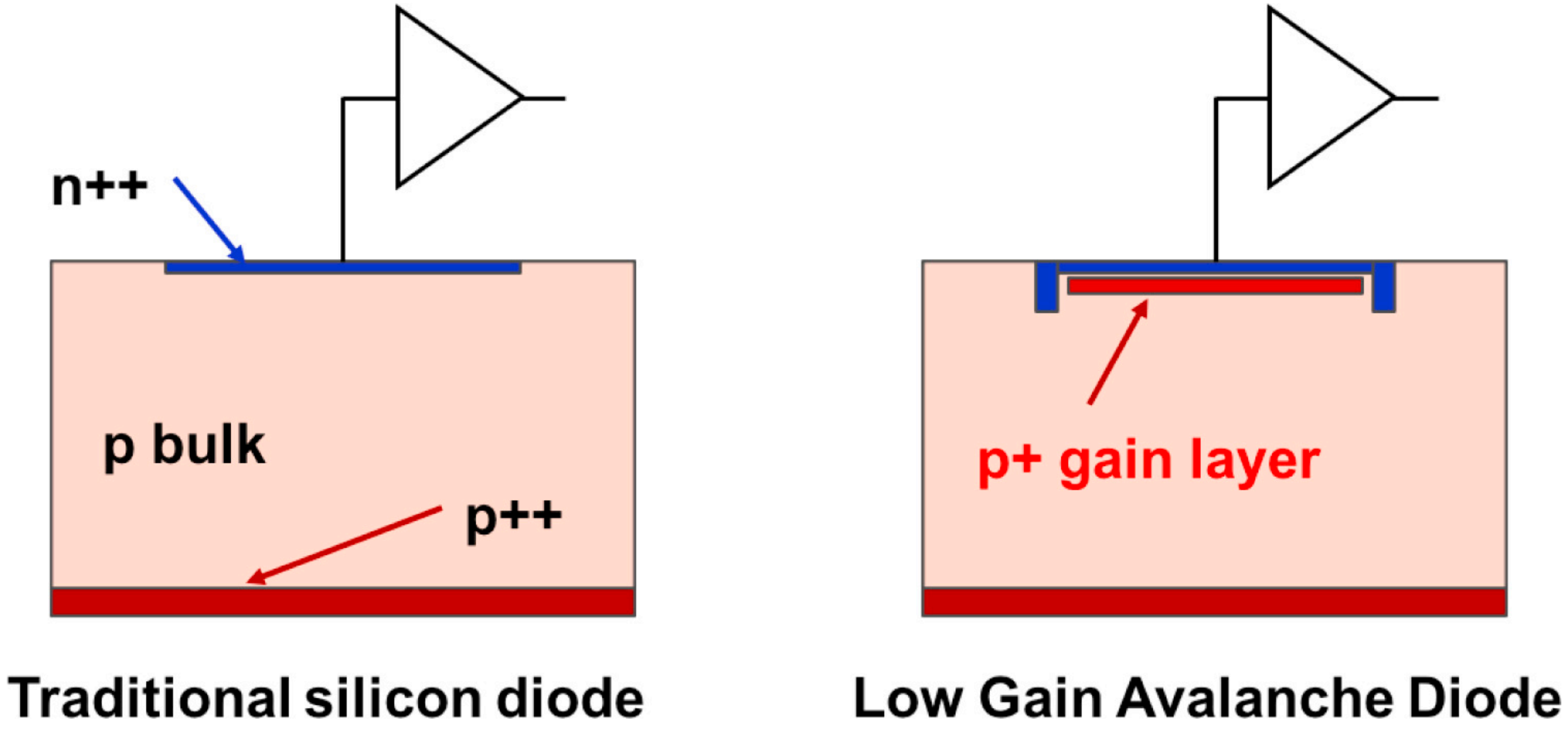
AC-LGAD prototype (BNL)



80 µm-wide strips, 100, 150, 200 µm pitch; 5-15µm resolution

Active Target

Low Gain Avalanche Diodes



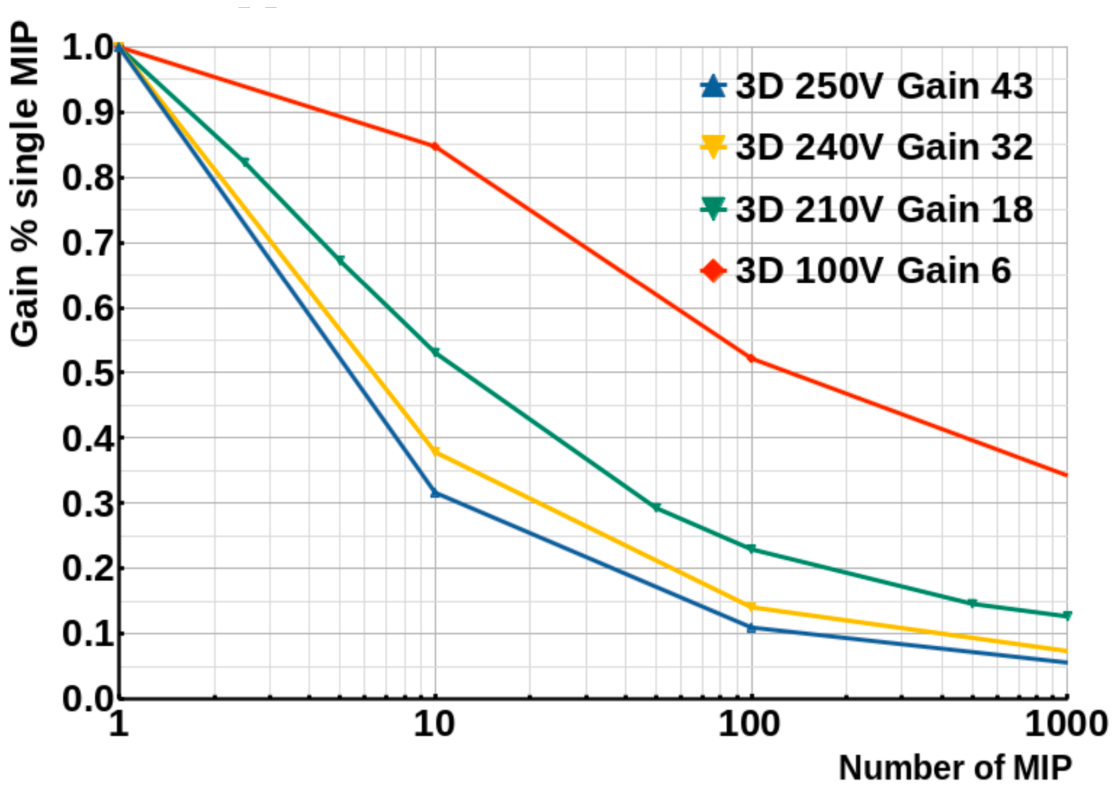
In silicon sensors, when applying a very large electric field (300 kV/cm), electrons (and holes) acquire kinetic energy and can generate additional e/h pairs by impact ionisation → ‘avalanche’ effect

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 high timing resolution
The gain mechanism saturates for large energy deposit

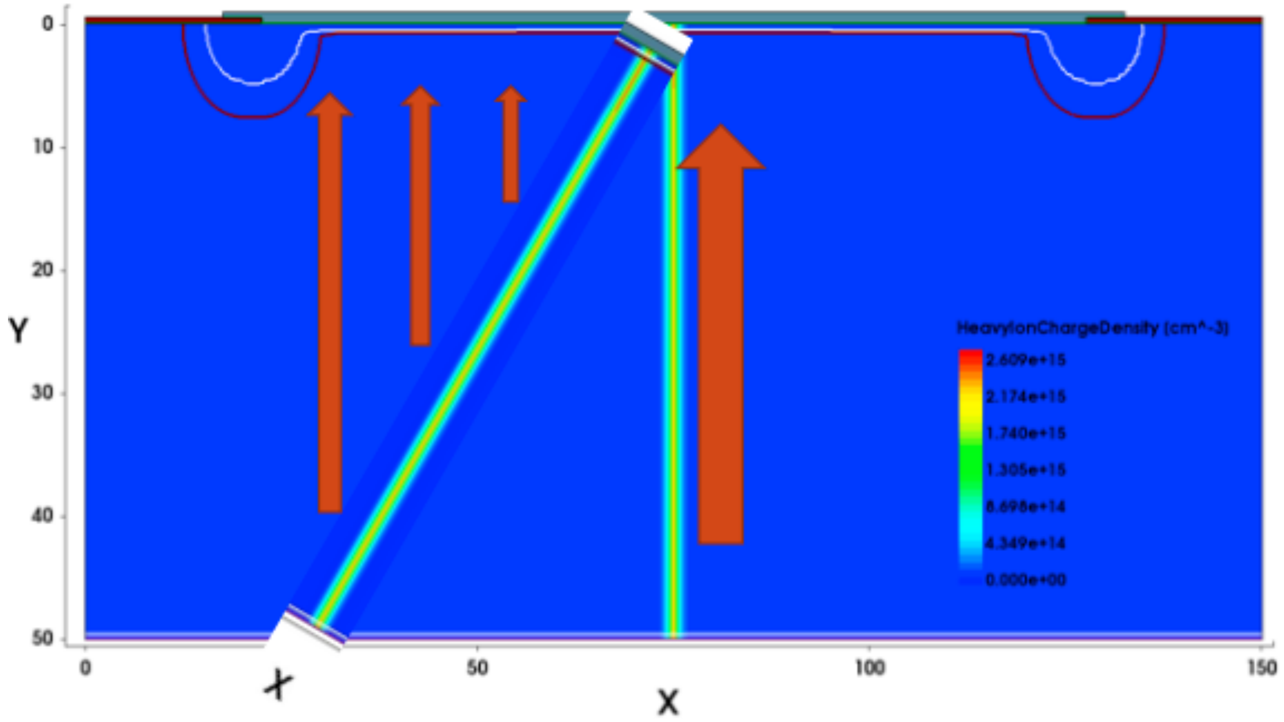
Active Target

Low Gain Avalanche Diodes



TCAD Simulations:

- Large gain suppression effect with high input charge density
- Gain suppression reduced if input charges are spread more evenly
- Gain of LGAD produced by impact ionization in high field region of gain layer
  - Very sensitive to electric field magnitude



Critical for PIONEER's feasibility to understand the MeV-scale response of LGADs

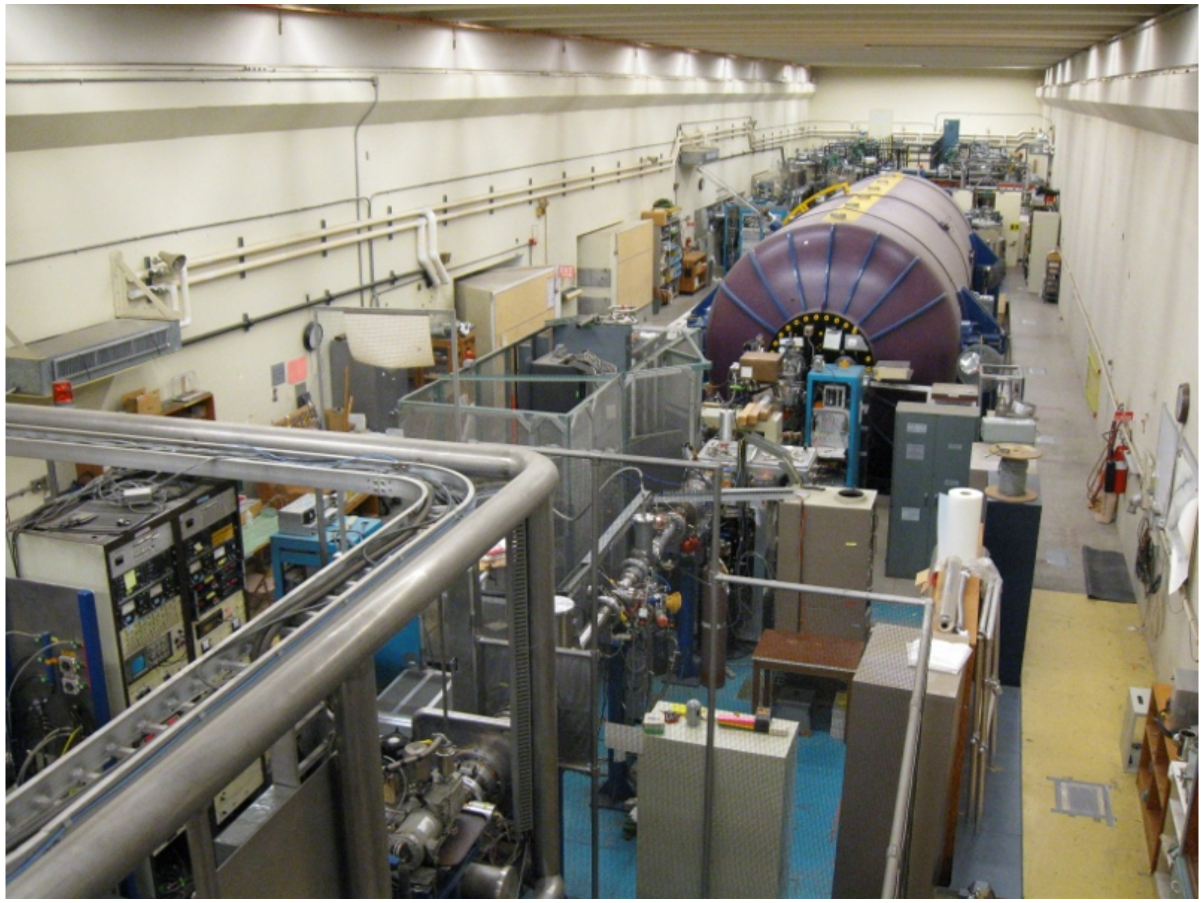
Performing our own tests

Active Target

Tandem Accelerator at the University of Washington

CENPA

Center for Experimental Nuclear Physics and Astrophysics

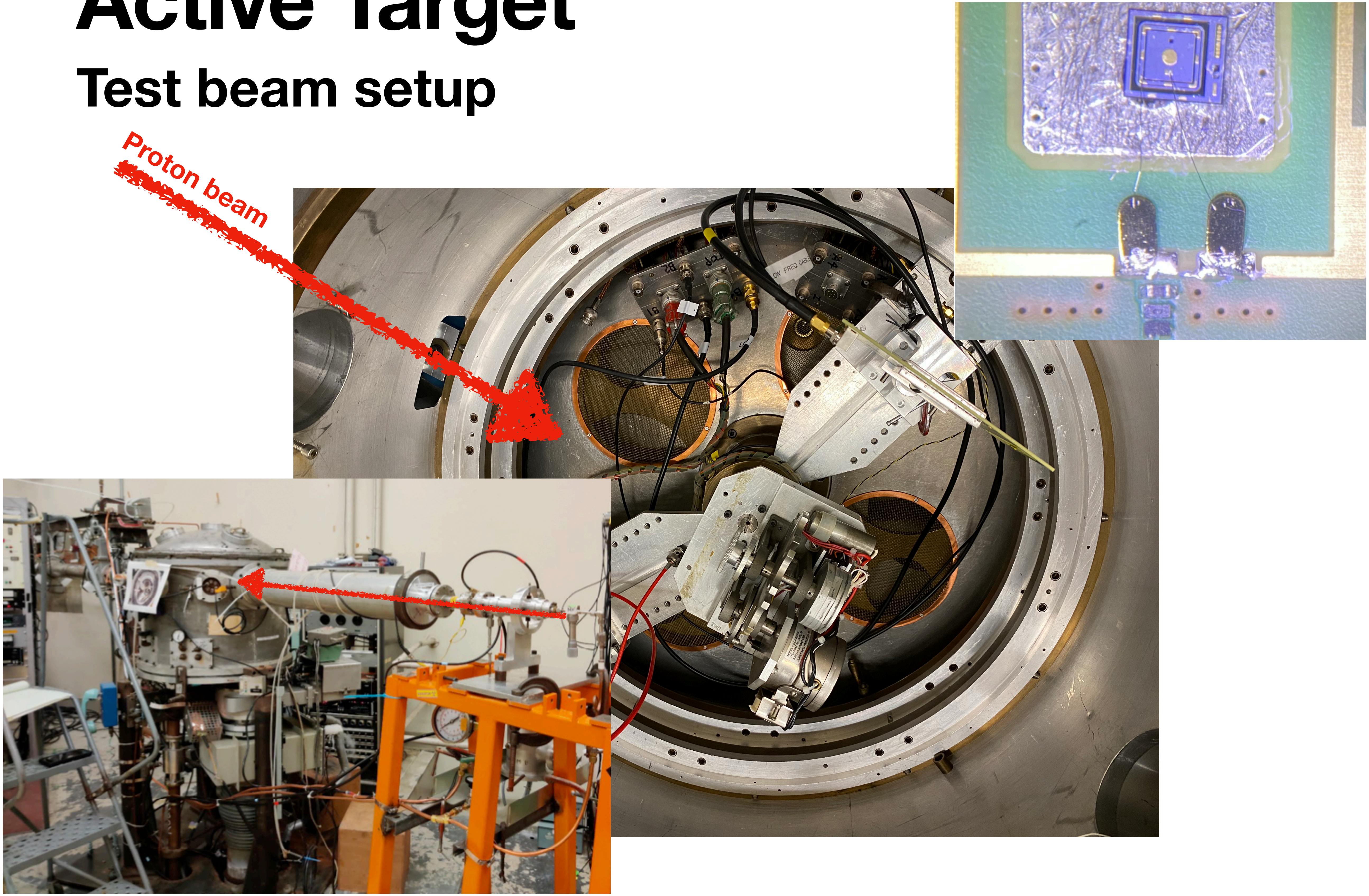


Tandem Van de Graaf Accelerator

Test beam this summer at CENPA to understand LGAD response of **MeV-scale** deposit

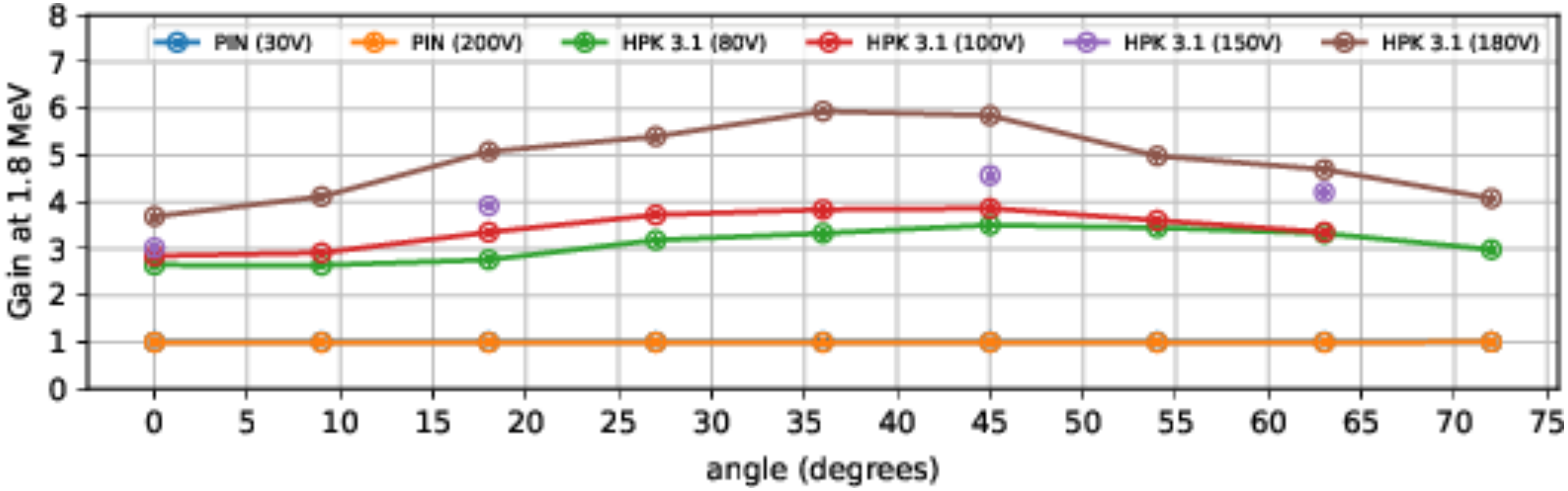
Active Target

Test beam setup


1mmx1mm sensor with 50µm thickness

Active Target

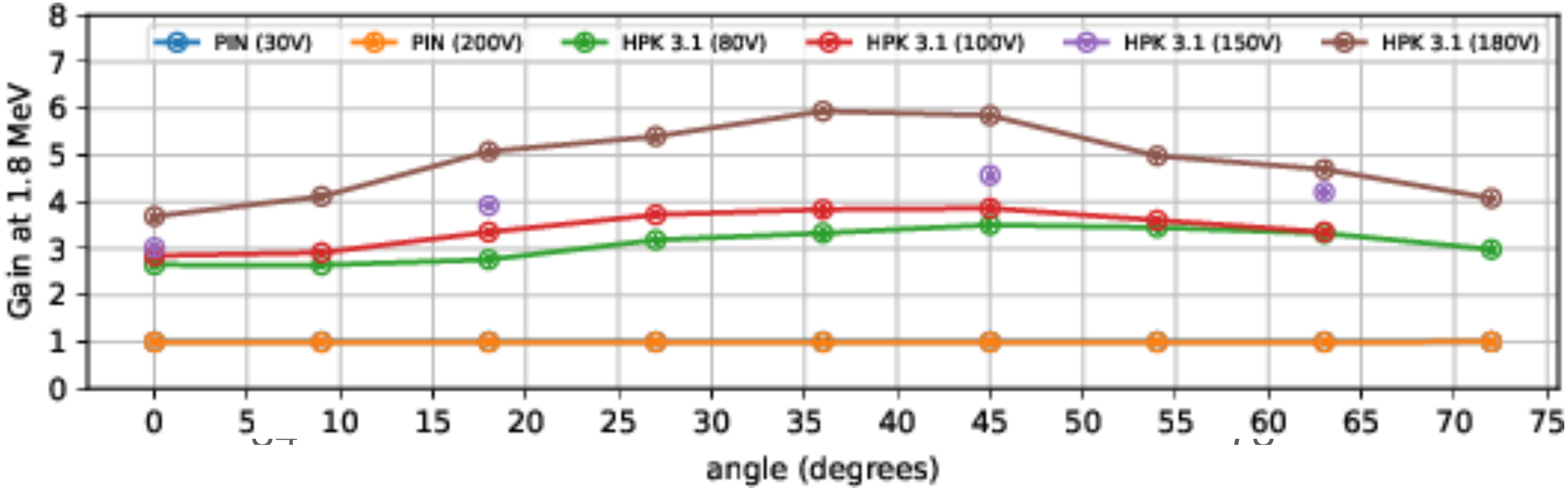
LGAD gain saturation studies

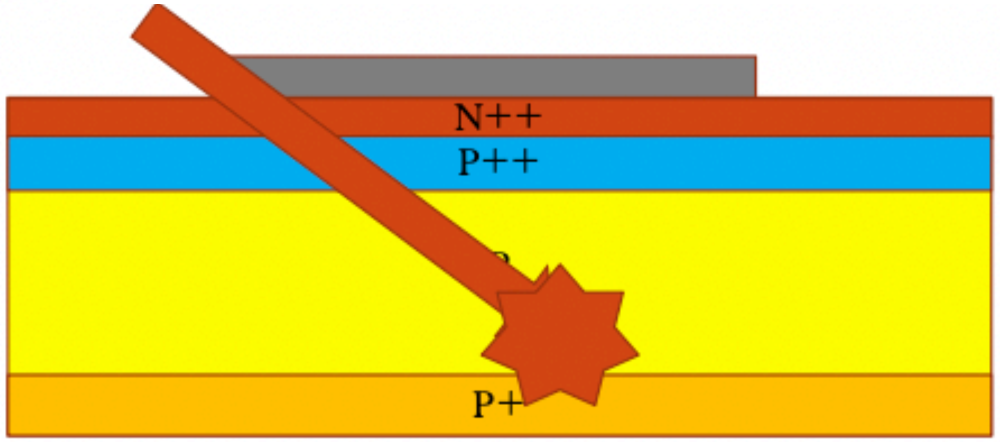


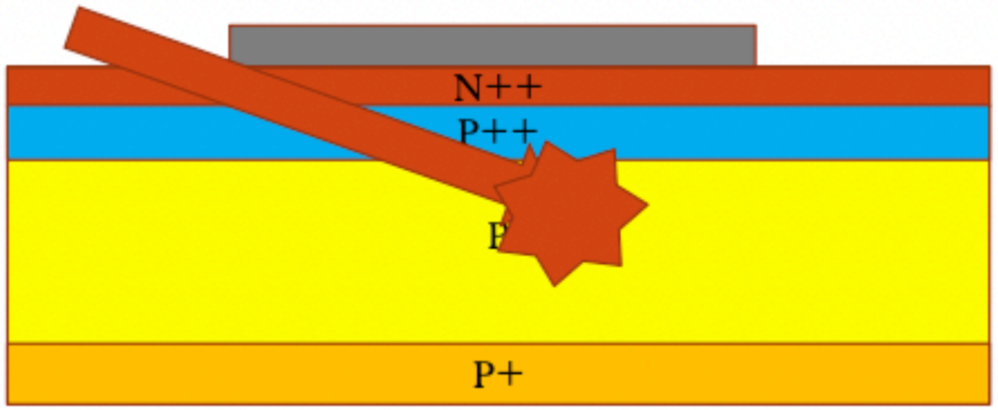
- Studied sensor response at various energy from 1.8 to 5 MeV
- Expected gain increase with increasing bias voltage
- Observed large gain reduction compared to the response from a beta source
- Impact of charge localisation: angular dependency of the response

Active Target

LGAD gain saturation studies



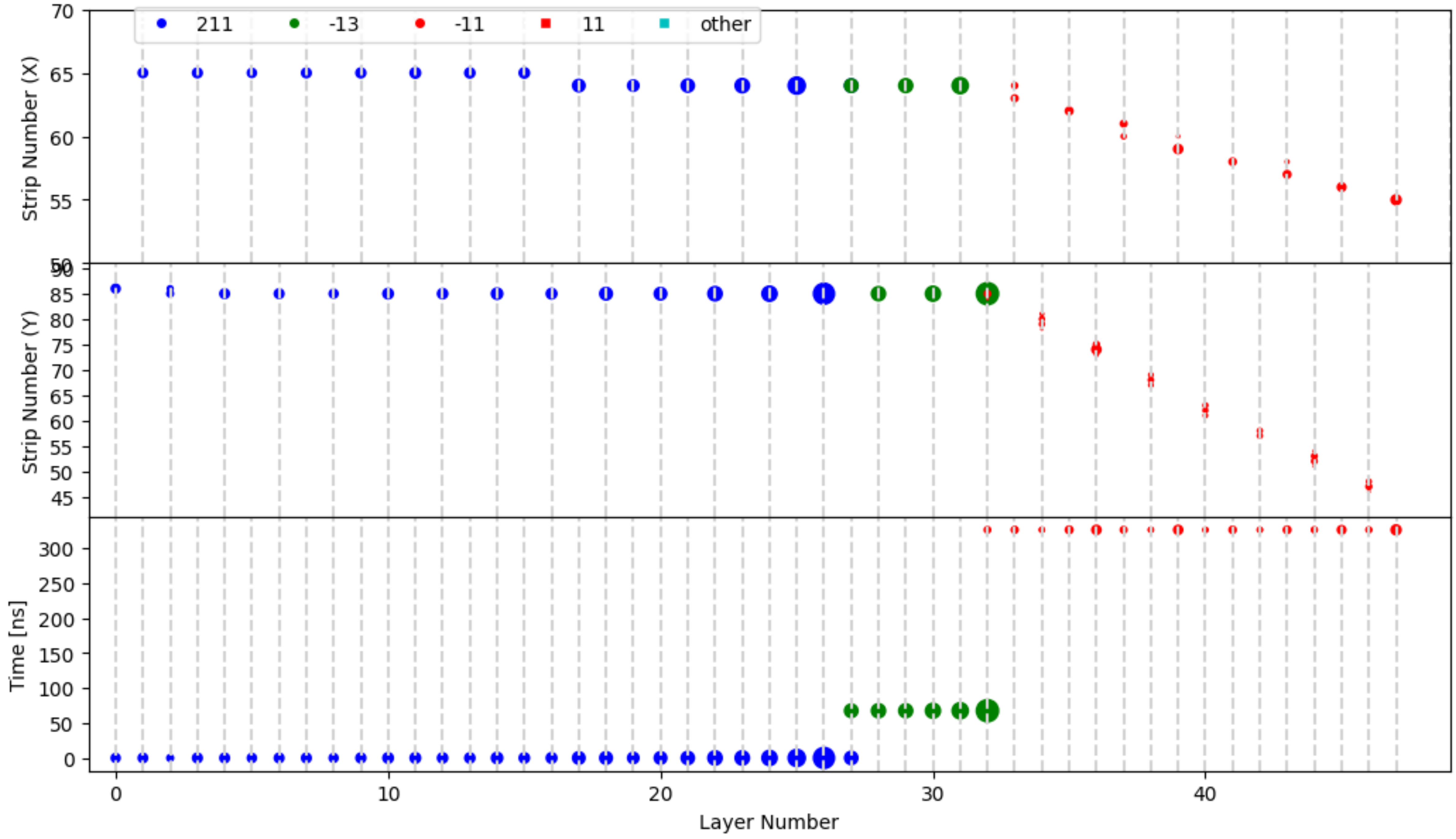




Trying to reproduce observed behaviour in simulations

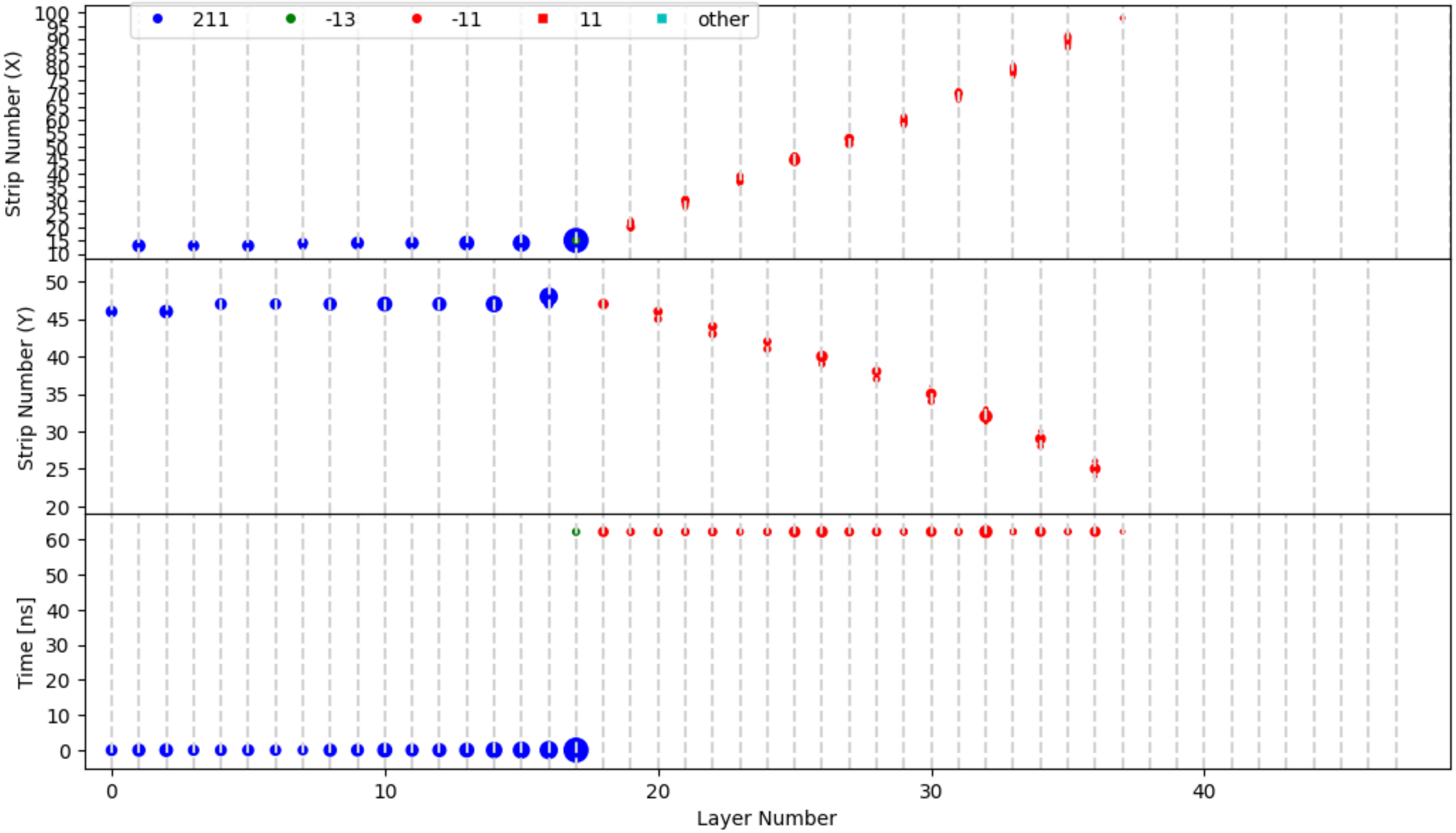
Simulation studies

An easy case: pion and muon decay at rest



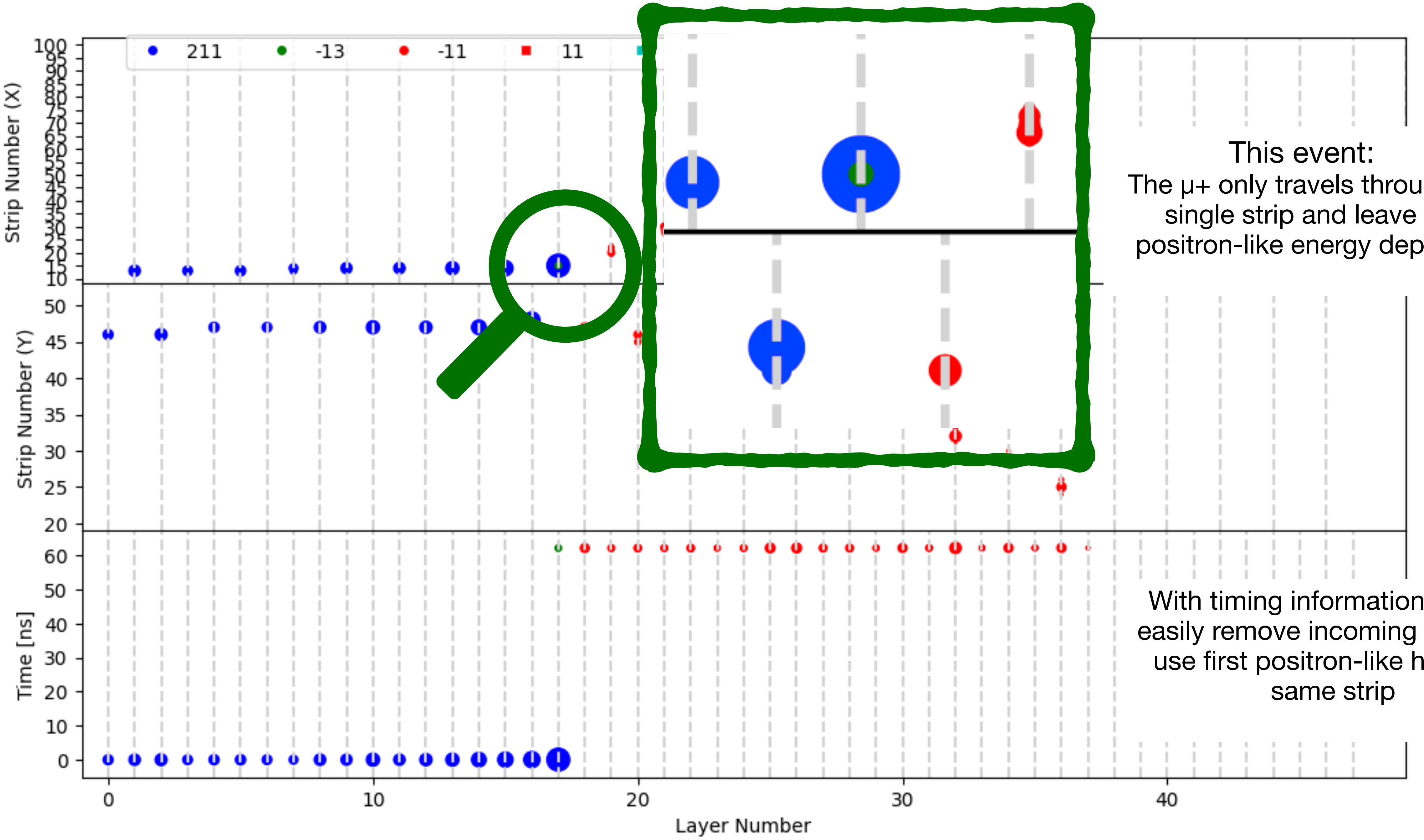
Simulation studies

A difficult case: muon decaying in flight



Simulation studies

A difficult case: muon decaying in flight

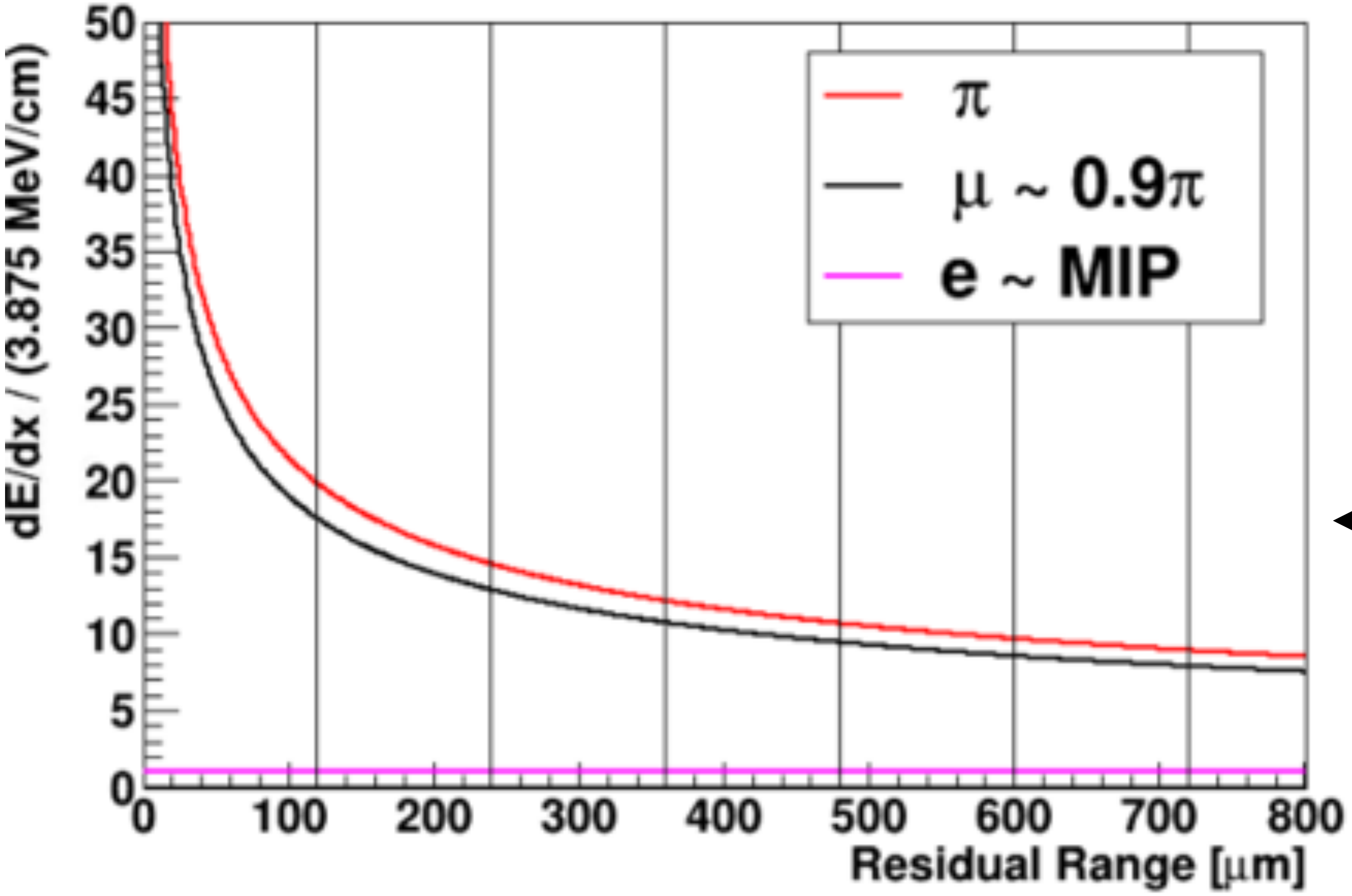


This event:
The μ+ only travels through a single strip and leave a positron-like energy deposit

With timing information we can easily remove incoming pion and use first positron-like hit in the same strip

Simulation studies

A difficult case: muon decaying in flight



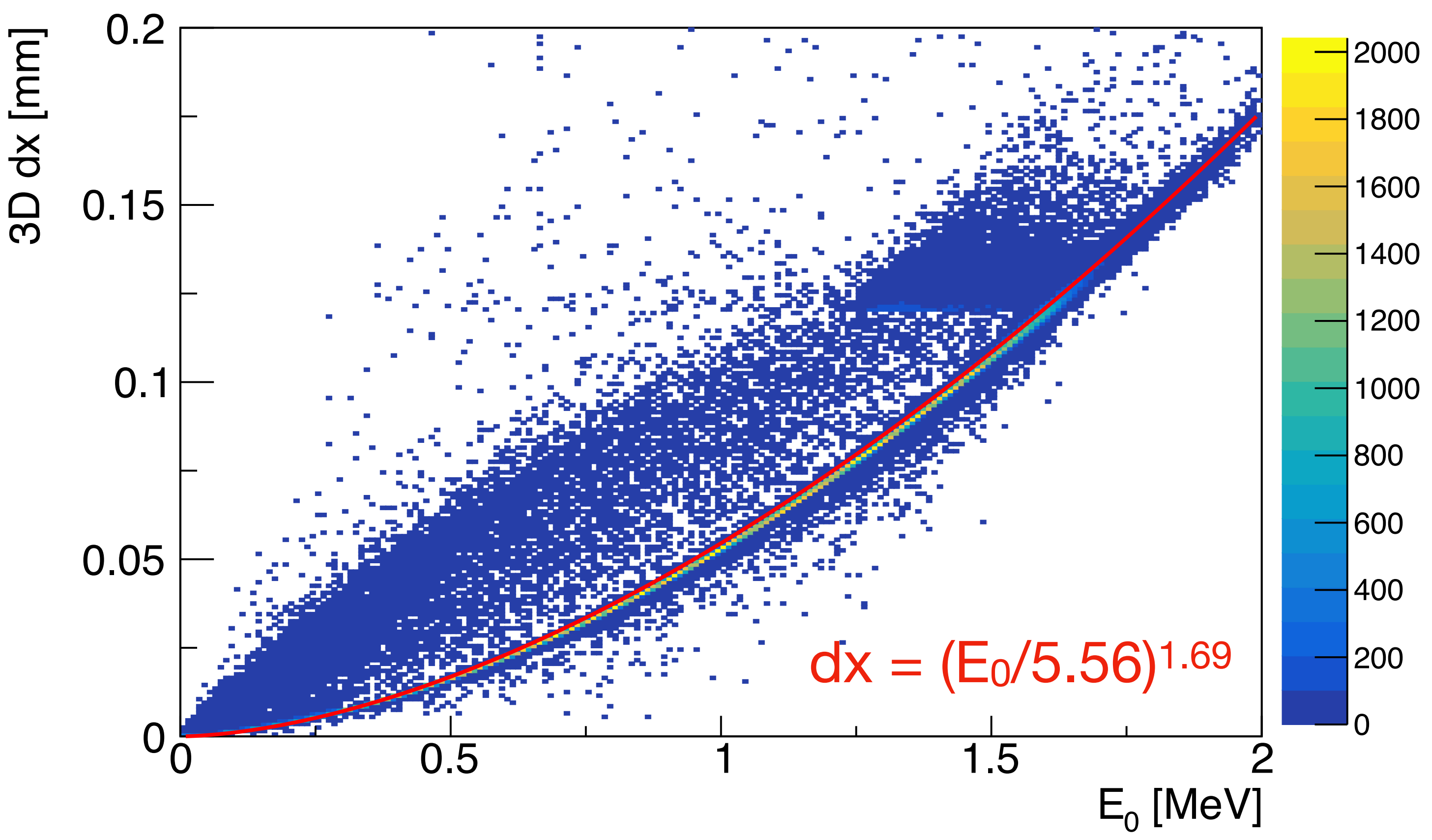
A Particle enters ATAR here

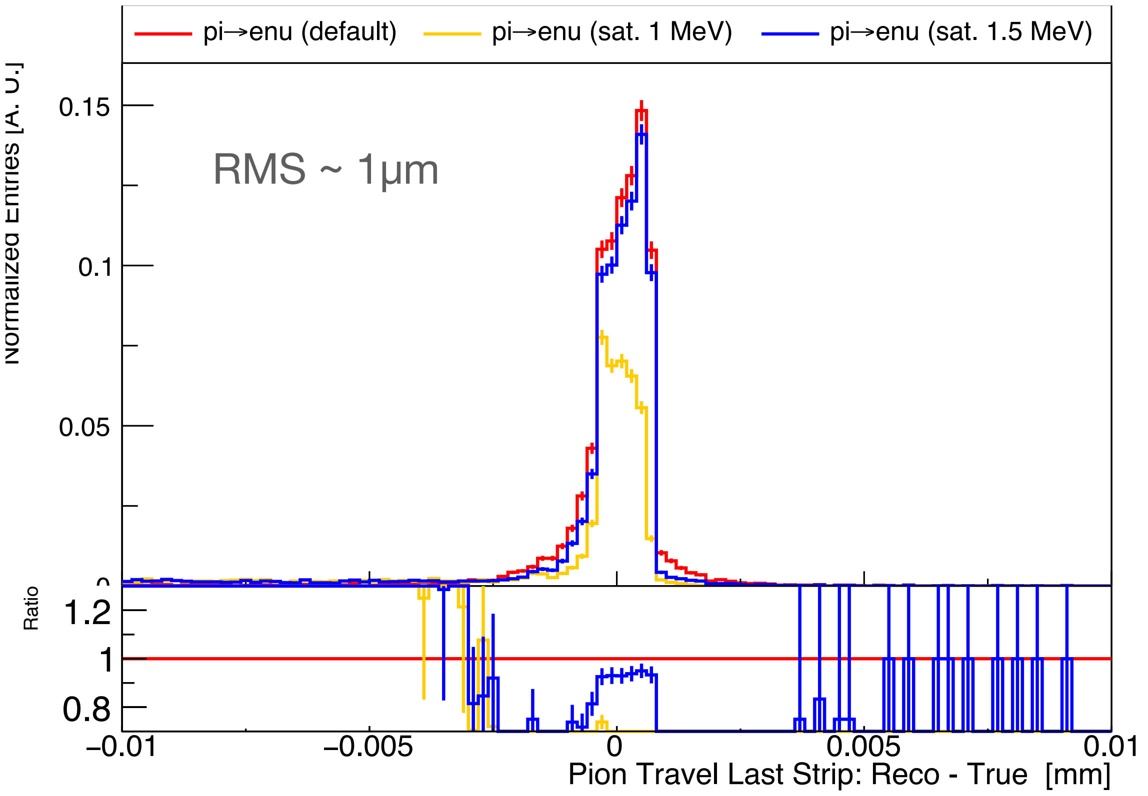
We can learn a lot about a particle travel through material from measuring its energy!

Simulation studies

A difficult case: muon decaying in flight

Step 1: Precisely determining the pion stopping position

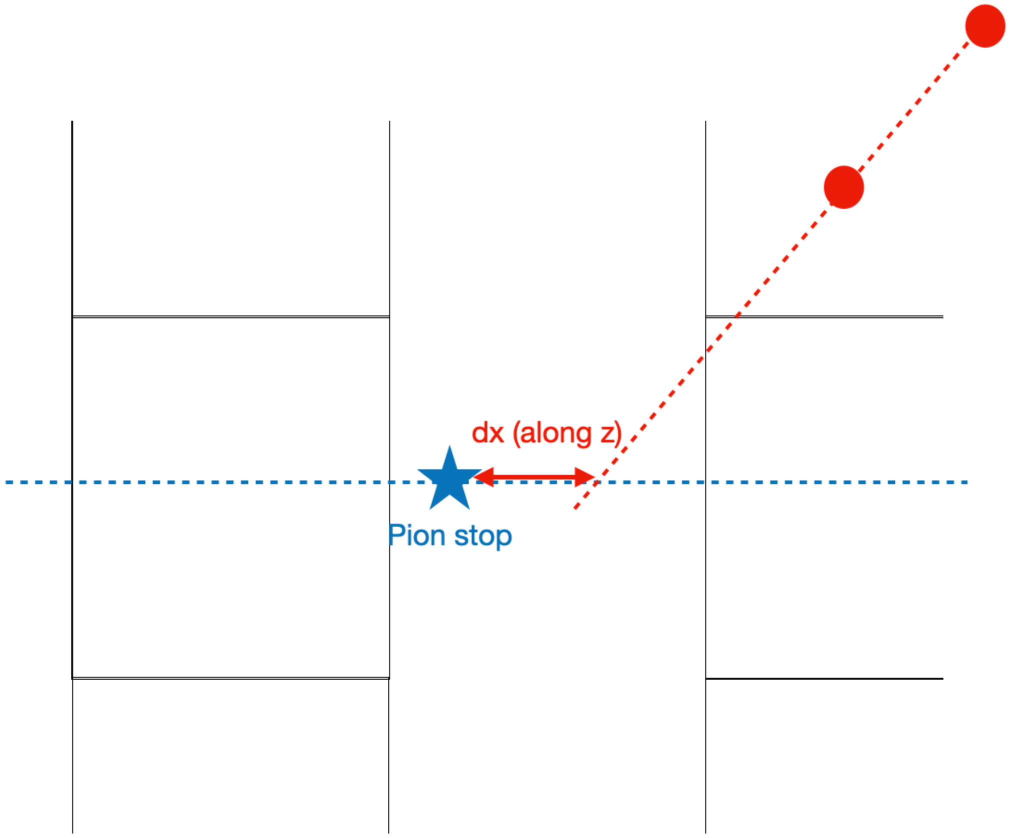


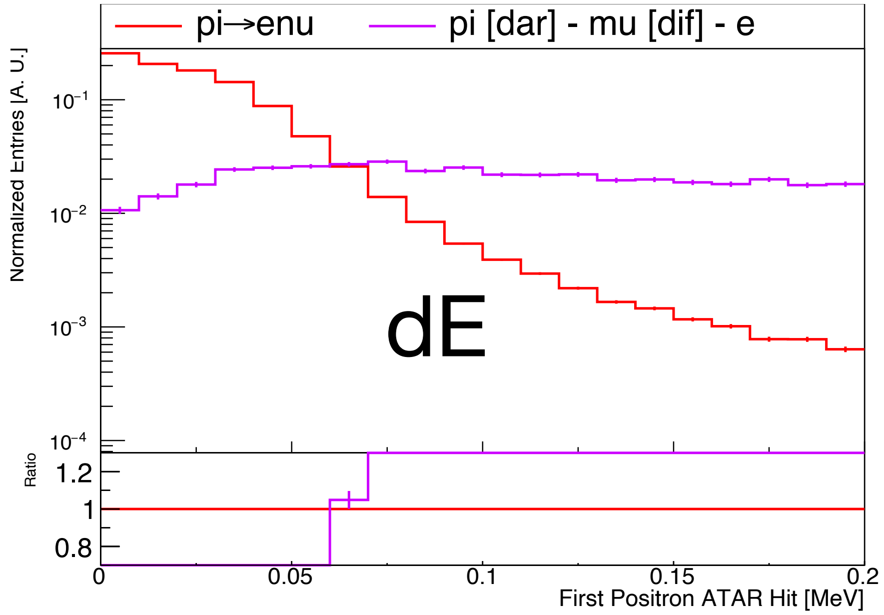


Simulation studies

A difficult case: muon decaying in flight

Step 2: measuring the dE/dx of the outgoing particle





÷