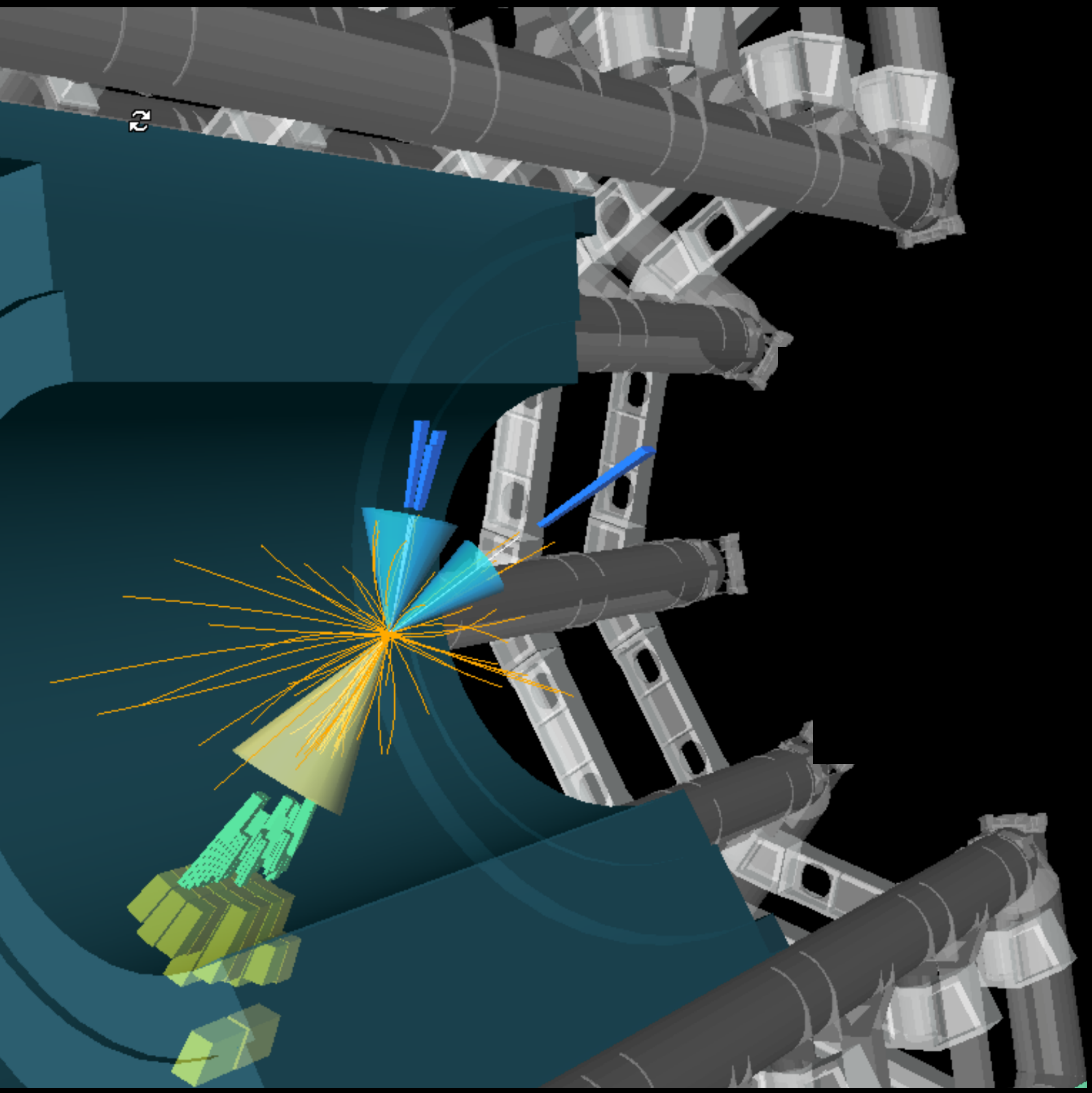


ATLAS EXPERIMENT

The origin of flavour: from the Higgs boson to rare pion decays

PIONEER

Quentin Buat (University of Washington) — July 22nd, 2024

But first, a few slides about me

- Joined UW as a faculty 3 years ago
- Research interests:
  - Higgs boson and Electroweak measurements at the LHC
  - Machine learning for particle physics event reconstruction
  - Rare pion decay experiments

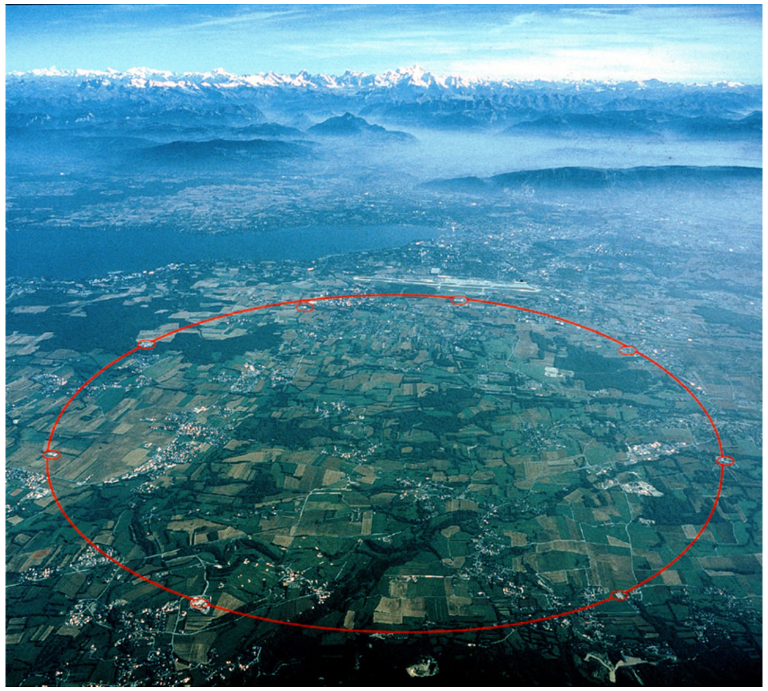
Quentin Buat

But first, a few slides about me

2010 - 2013 - PhD in Grenoble, France

2014 - PostDoc in Vancouver (SFU)

2015 - 2020 in Geneva, Switzerland (CERN)



Which prepared me perfectly for …

Leading the REU trip to Mt Rainier

August 11

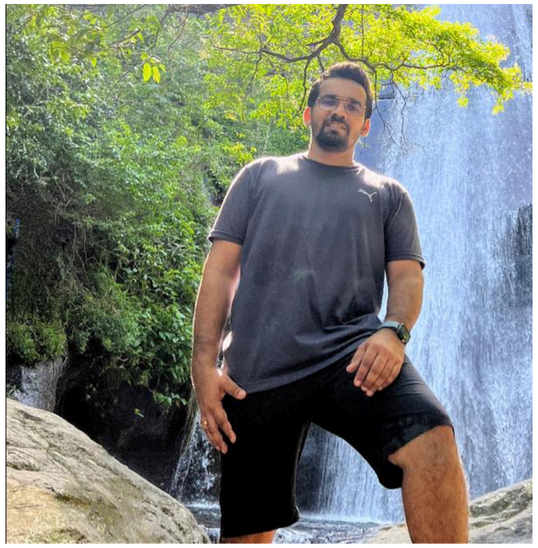
Mark your calendar!

https://forms.gle/3C4xRQhu6E99ULsR7

* Disclaimer: weather on the photo is for illustration only

REU — A first step toward grad school

Torrey Saxon
REU U. Michigan / CERN 2018
Grad student Notre Dame Univ.



Sameera Lakshan
REU CERN 2019
Grad student at North Dakota S. U.

Jeffrey Backus
REU Stony Brook Univ 2021
Grad. Student at Princeton Univ.

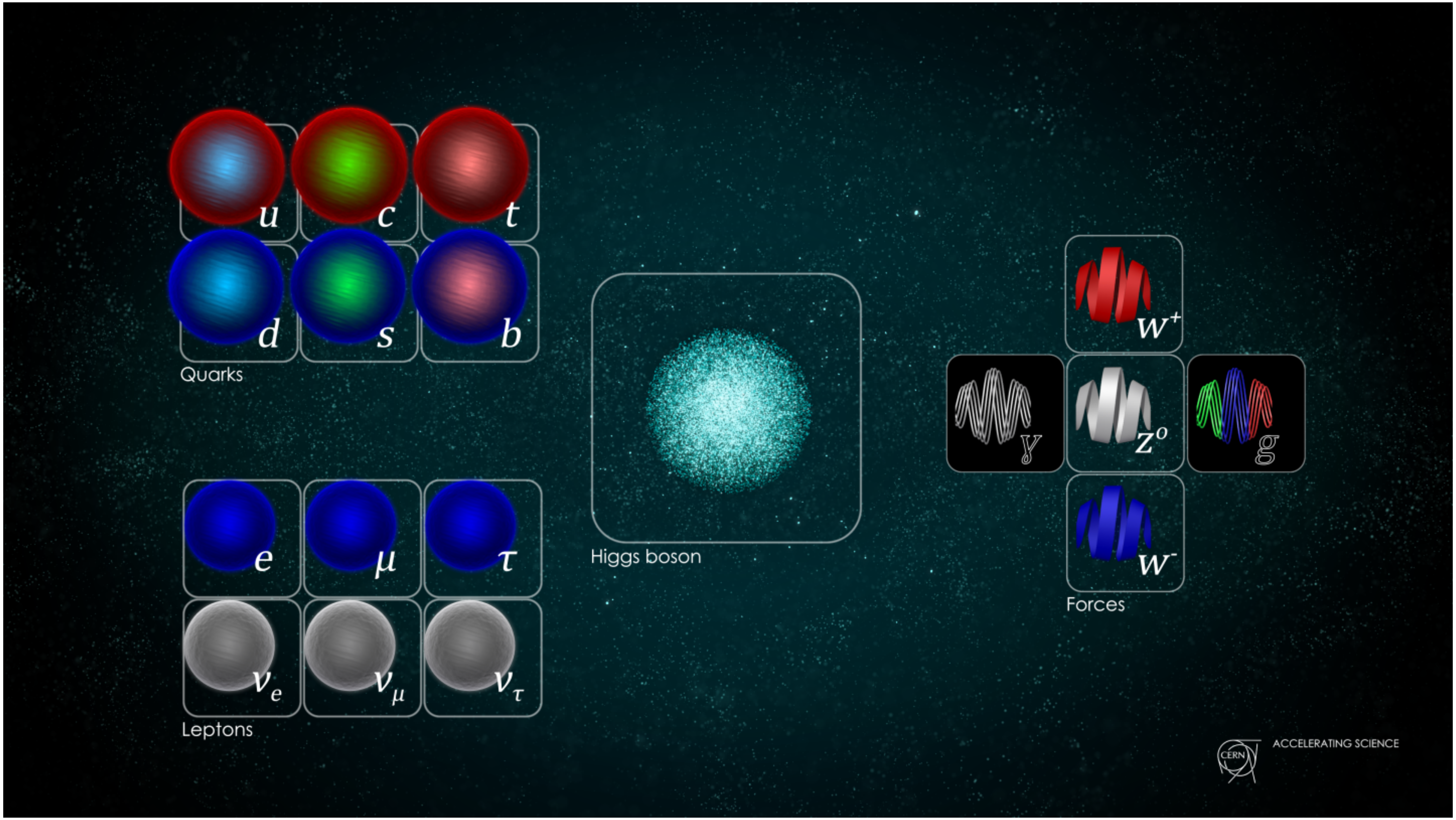
Miles Cochran-Branson
REU UW 2022
UW Grad student (Buat Group)

Caleb Lansdell
REU UW 2023
Starting grad school at OSU

Megan Harrison
REU UW 2024

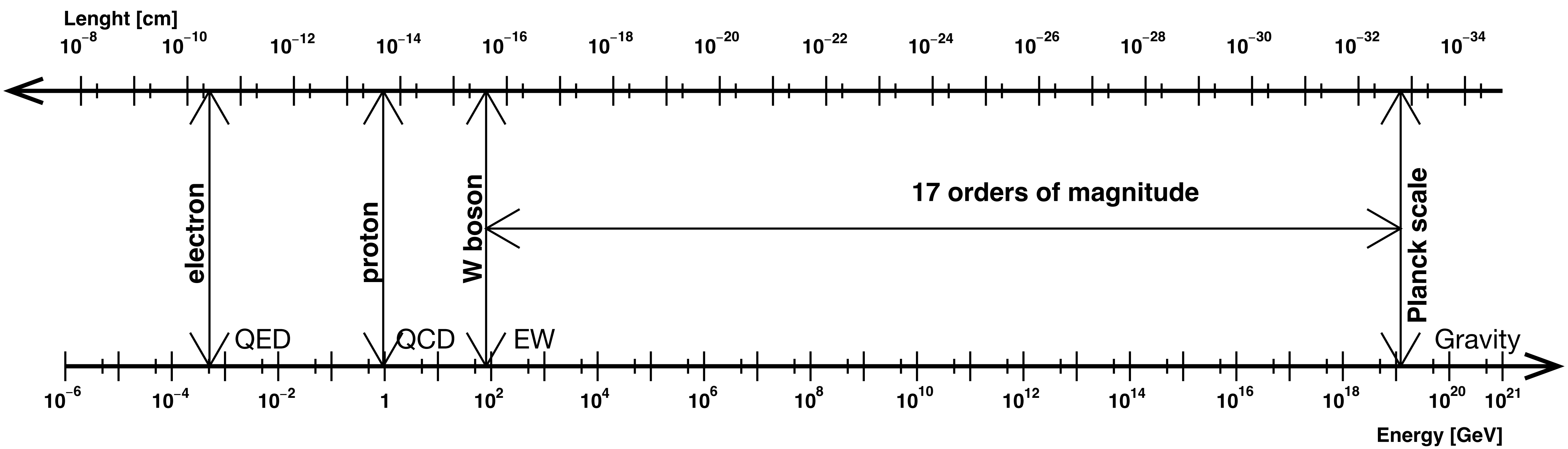
Particle Physics

Elementary Particles …



Particle Physics

And fundamental interactions



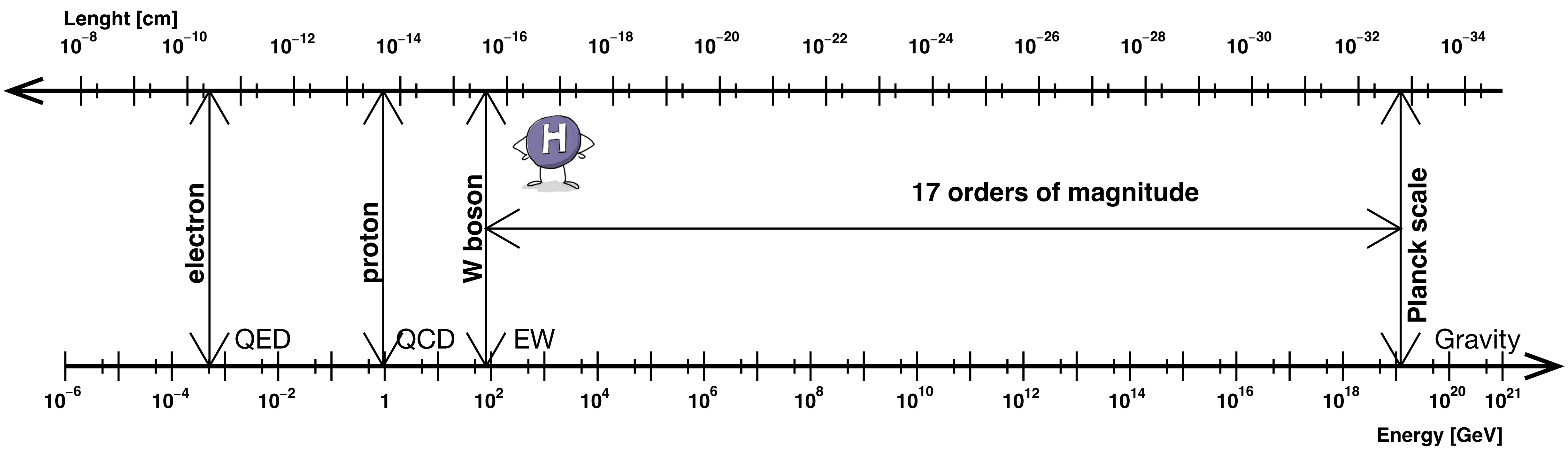
Known forces in Nature and their associated energy scales

Explore the gap between EW and Gravity scales

Look for feeble interactions below the electroweak scale

The Higgs boson

A scalar particle to complete the model



Known forces in Nature and their associated energy scales

Higgs Boson mass has been determined
→ Standard Model is a fully constrained theory

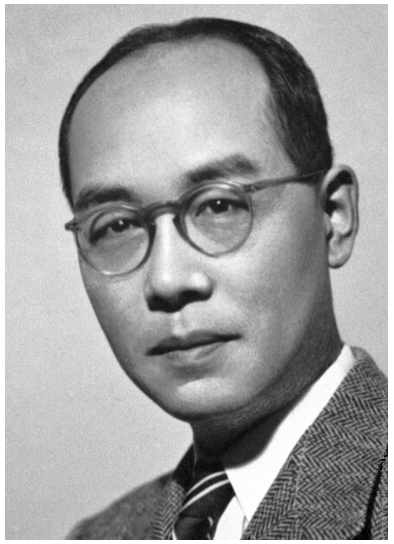
Each measurement tests the model's validity
at higher energy scales through **quantum 'imprints'**

From G.F. Guidice, arXiv:0801.2562

Quantum 'imprints'

A textbook example: Yukawa's pion model

Low energy model



Hideki Yukawa

Pions predicted in 1935 as mediators responsible for the binding of nuclei

$$m_{\pi^+} = 139.57061(24)\,\text{MeV}/c^2$$

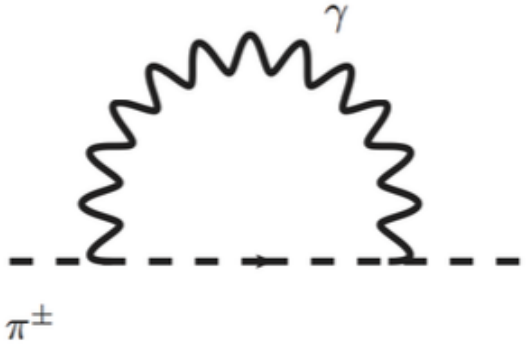
$$m_{\pi^0} = 134.9768(5)\,\text{MeV}/c^2$$

Experimental measurement

$$m^2_{\pi^+} - m^2_{\pi^0} \approx (35.5\,\text{MeV}/c^2)^2$$

Quantum 'imprints'

Quantum corrections from QED only apply to the charged pion



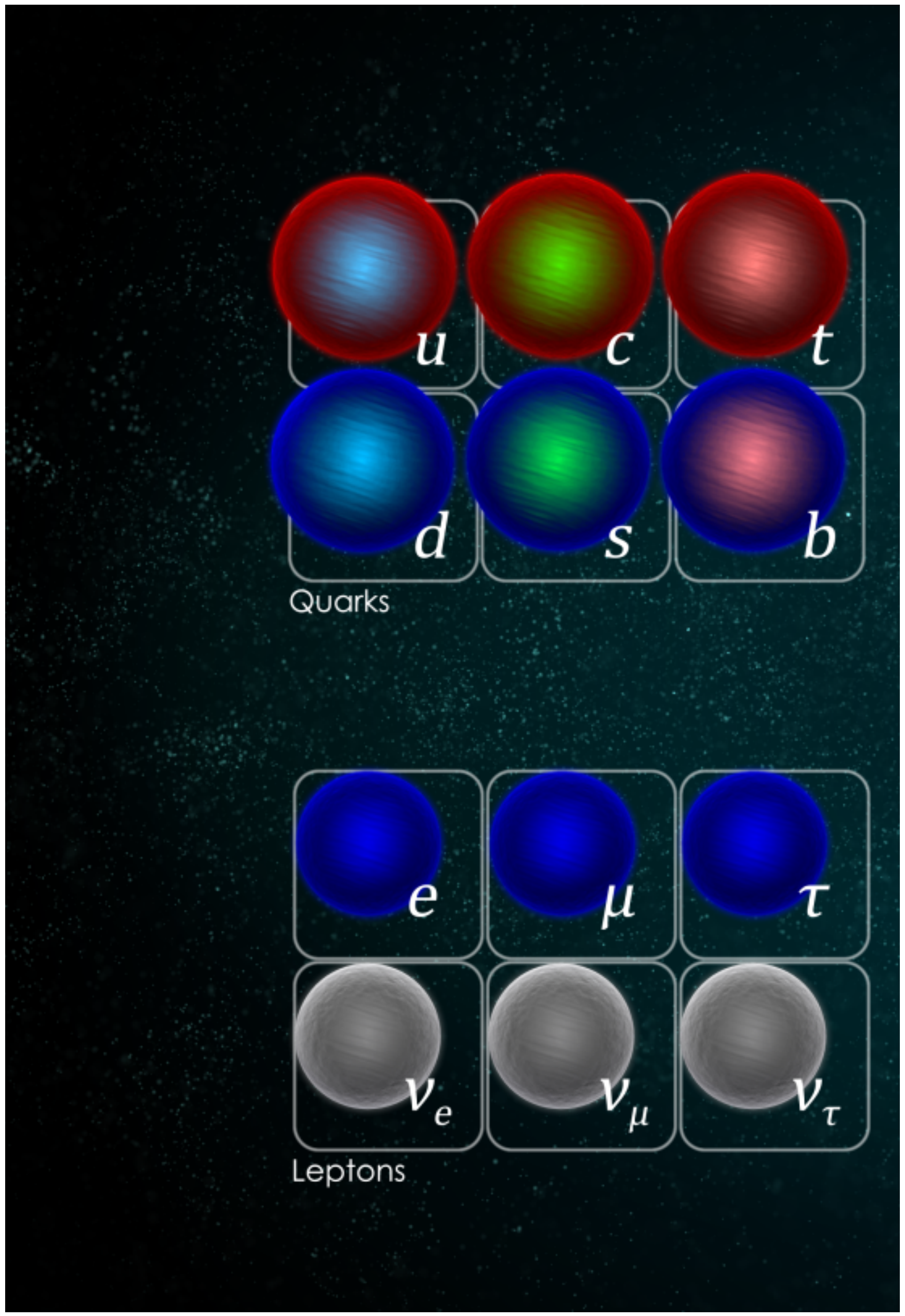
$$m^2_{\pi^+} - m^2_{\pi^0} = \frac{3\alpha}{4\pi}\Lambda^2$$

To keep quantum corrections lower than the experimental measurement leads to $\Lambda \lesssim 850\,\text{MeV}$

And indeed at ≈ 770 MeV/c^2, the rho meson appears

The Flavour Sector

… remains a mystery



Large span of fermion masses?

Why do fermions mix?

Is the weak interaction universal?

Precise measurements of SM expectations can lead us to a breakthrough on these questions

Outline

Higgs Boson couplings to leptons at the LHC with the ATLAS detector

ATLAS EXPERIMENT

Large span of fermion masses?

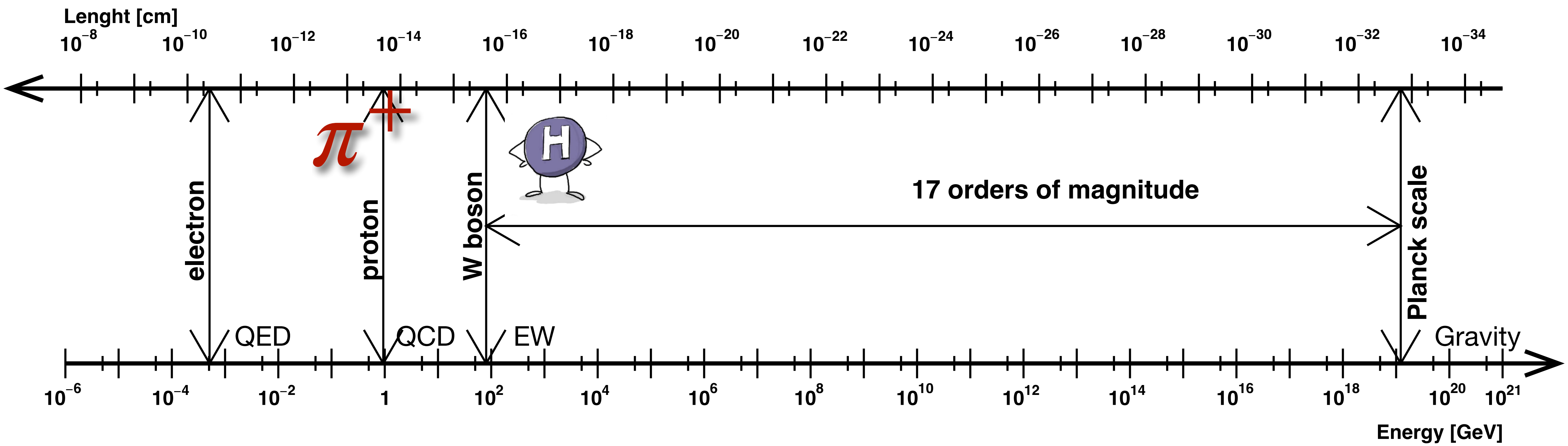
Why do fermions mix?

Is the weak interaction universal?

Tests of the weak interaction in rare pion decays

PIONEER

A scalar particle to complete the model



Known forces in Nature and their associated energy scales

Higgs Boson mass has been determined
→ Standard Model is a fully constrained theory

Each measurement tests the model's validity
at higher energy scales through **quantum 'imprints'**

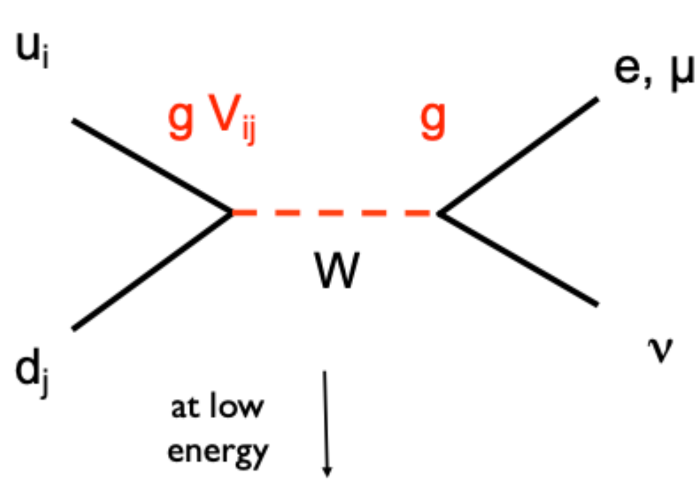
Rare pion decays: measurements at the MeV-scale

Rare Pion Decays

Tests of weak universality

Charged currents in the SM are mediated by the exchange of
a W boson between left-handed fermions
and right-handed anti-fermions

The coupling is the same for all fermions



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

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!

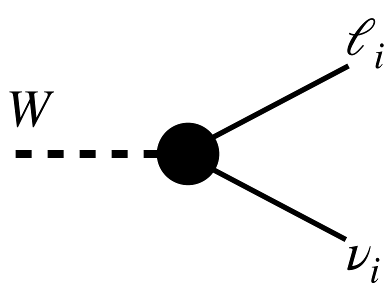
Rare Pion Decays

Tests of weak universality

Charged currents in the SM are mediated by the exchange of
a W boson between left-handed fermions
and right-handed anti-fermions

The coupling is the same for all fermions

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



Neglecting flavour-changing terms →

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

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

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

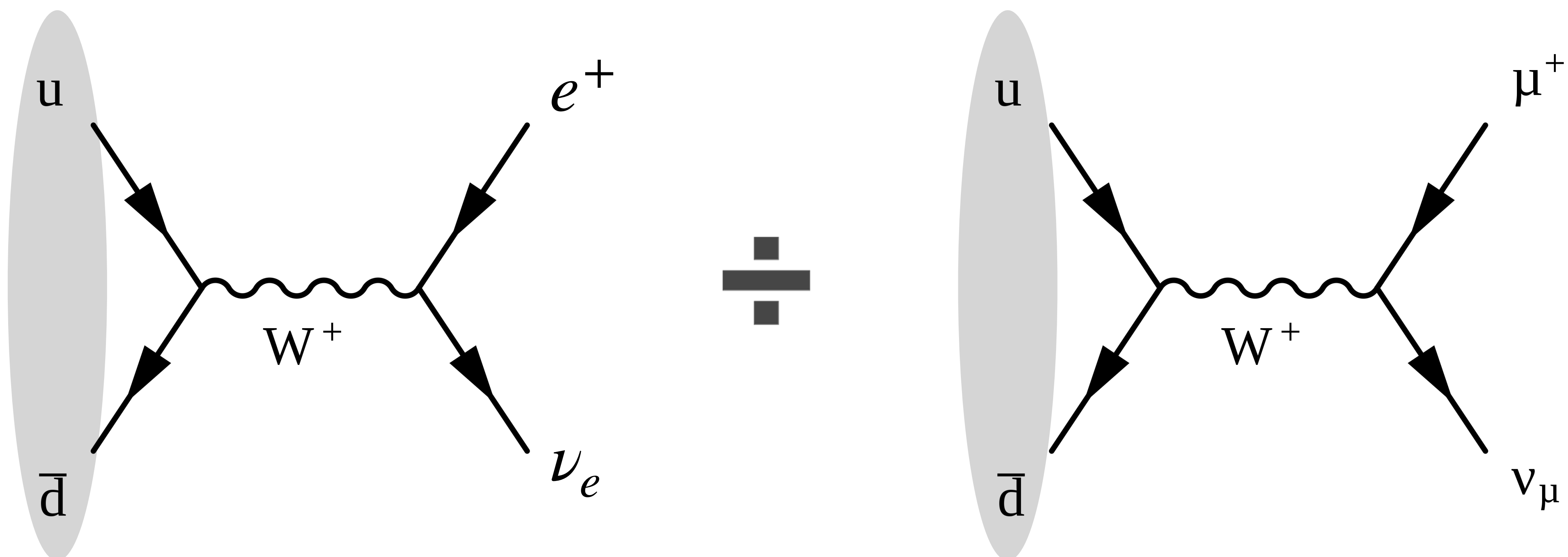
W', Vector-like leptons, charged Higgs, …
See review in arXiv:2111.05338

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

Rare Pion Decays

Lepton Flavour Universality

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



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

'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

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

The $\pi \to e\nu$ branching ratio is so small that initially the process was excluded

BR$(\pi \to \mu\nu) \approx 0.9998770$, *meaning ~1 out of every 10^4 pions decays to an electron*

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: $R_{e/\mu} < 1.3 \times 10^{-5}$ (90% CL)

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

Rare Pion Decays

Lepton Flavour Universality

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

Causing a lot of confusion…

Theory of the Fermi Interaction

R. P. Feynman and M. Gell-Mann
California Institute of Technology, Pasadena, California

(Received September 16, 1957)

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 $\pi\to e+\nu$ 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.

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

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)

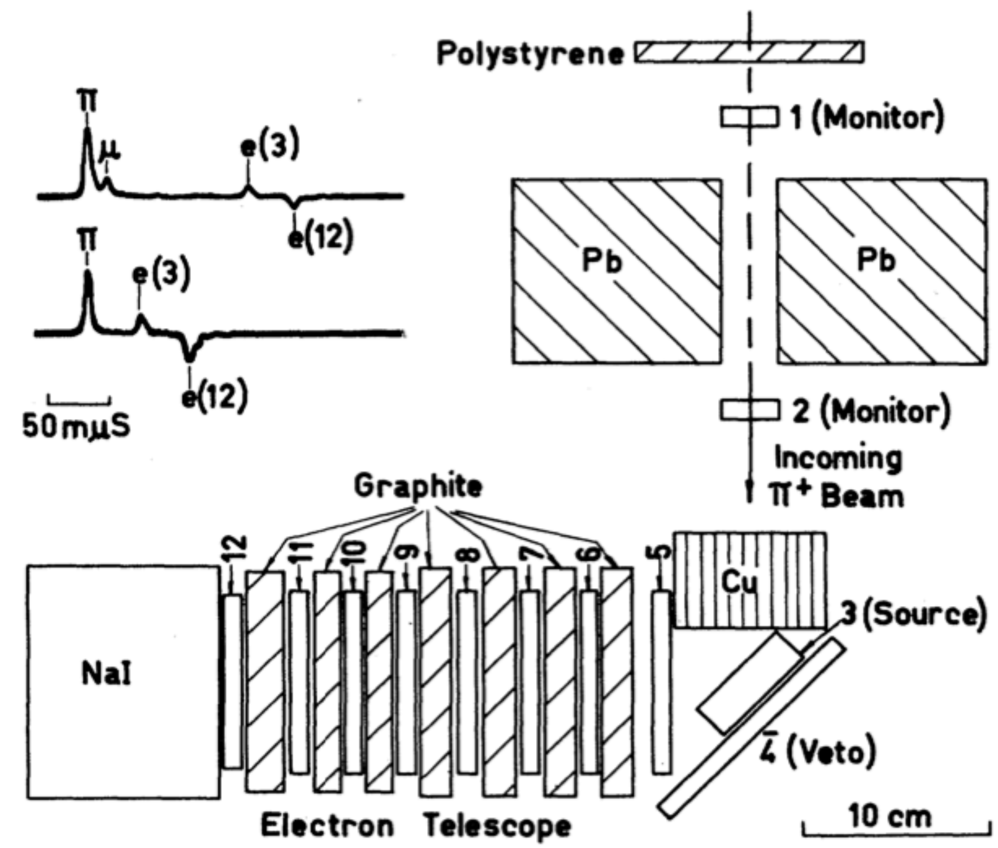
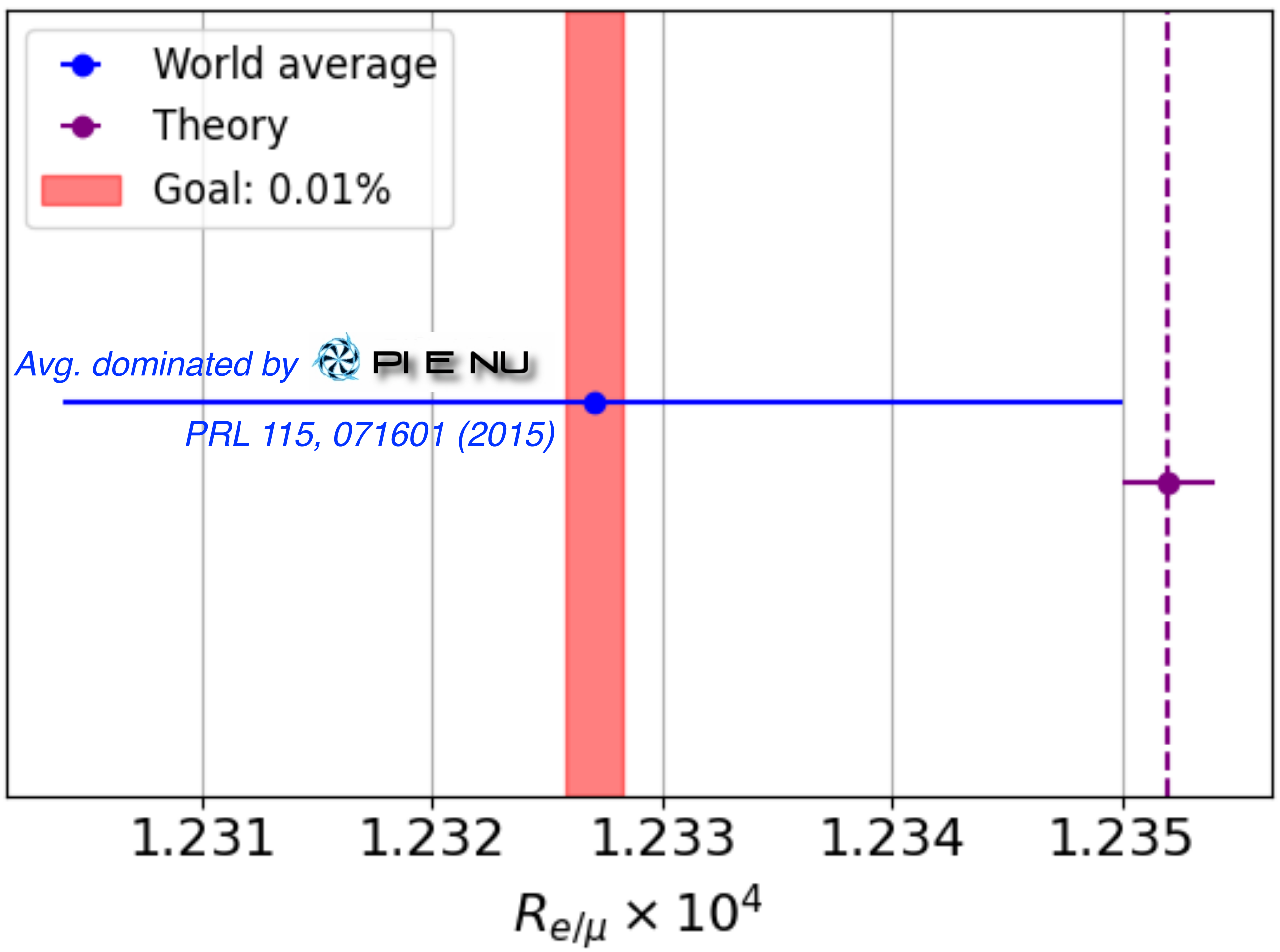


FIG. 1. Experimental layout, and (inset) typical π-μ-e and π-e pulse.

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

Rare Pion Decays

Lepton Flavour Universality



We call this measurement PHASE I

Best measurement from PIENU at TRIUMF tested charged LFU 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

EFT analysis (JHEP. **2013**, 46 (2013))
Constraints: up to ~330 TeV for a pseudo-scalar particle

Rare Pion Decays

Testing CKM Unitarity

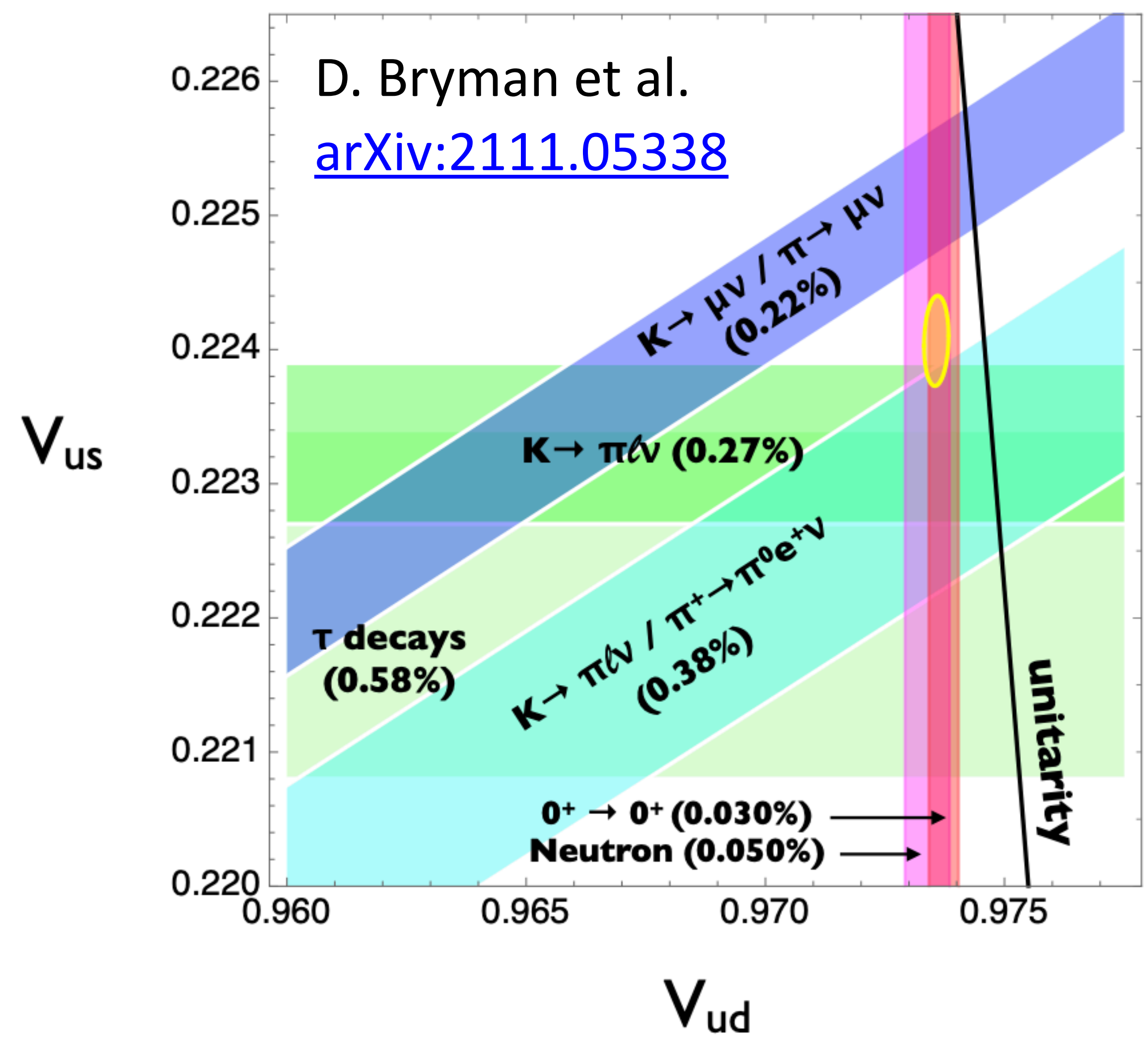
$$\begin{bmatrix} |V_{ud}| & |V_{us}| & |V_{ub}| \\ |V_{cd}| & |V_{cs}| & |V_{cb}| \\ |V_{td}| & |V_{ts}| & |V_{tb}| \end{bmatrix} = \begin{bmatrix} 0.97370 \pm 0.00014 & 0.2245 \pm 0.0008 & 0.00382 \pm 0.00024 \\ 0.221 \pm 0.004 & 0.987 \pm 0.011 & 0.0410 \pm 0.0014 \\ 0.0080 \pm 0.0003 & 0.0388 \pm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

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

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)



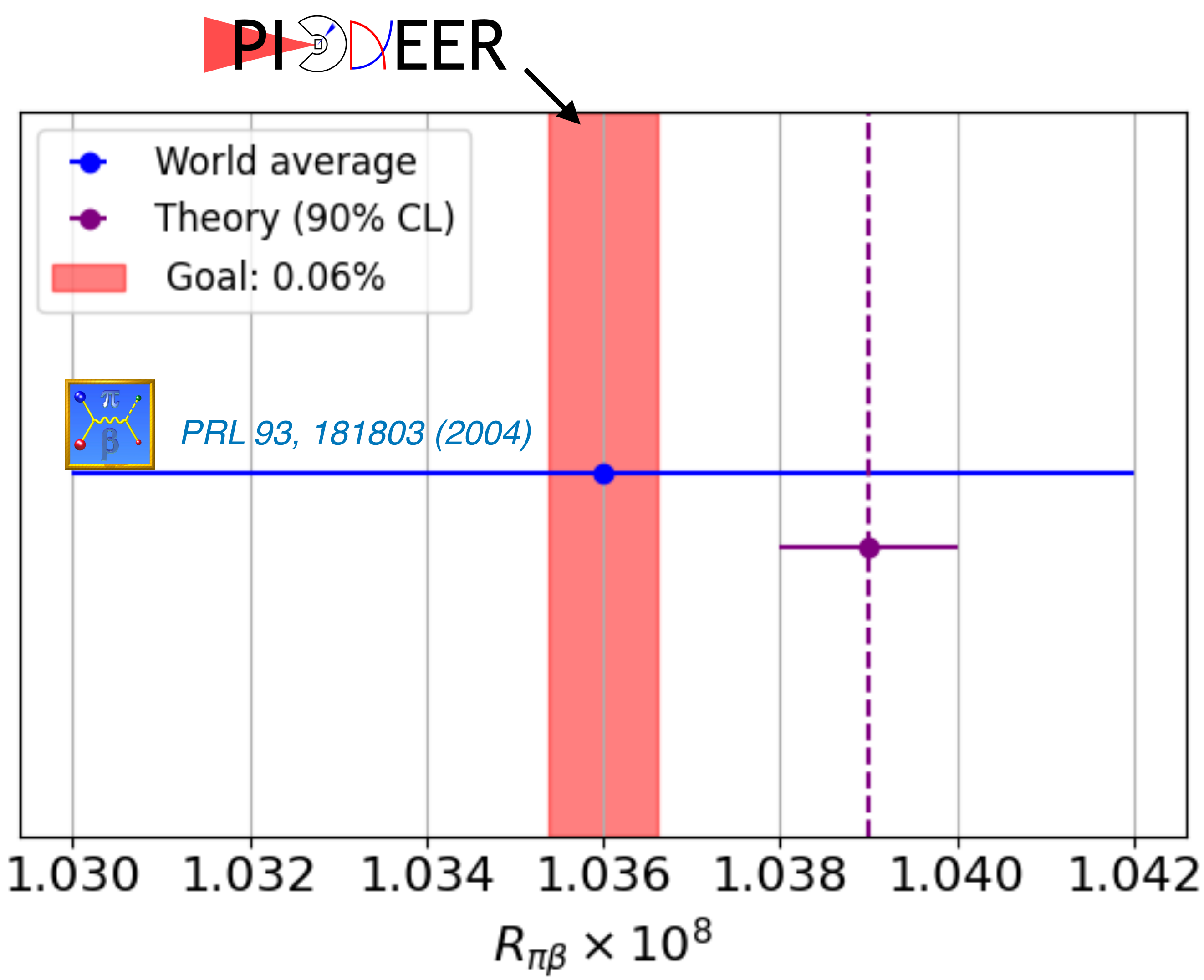
Rare Pion Decays

Testing CKM Unitarity

We call this measurement
PHASE II & III

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

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 aims to measure $R_{\pi\beta}$ to 0.06% precision

Ten-fold improvement over current world best

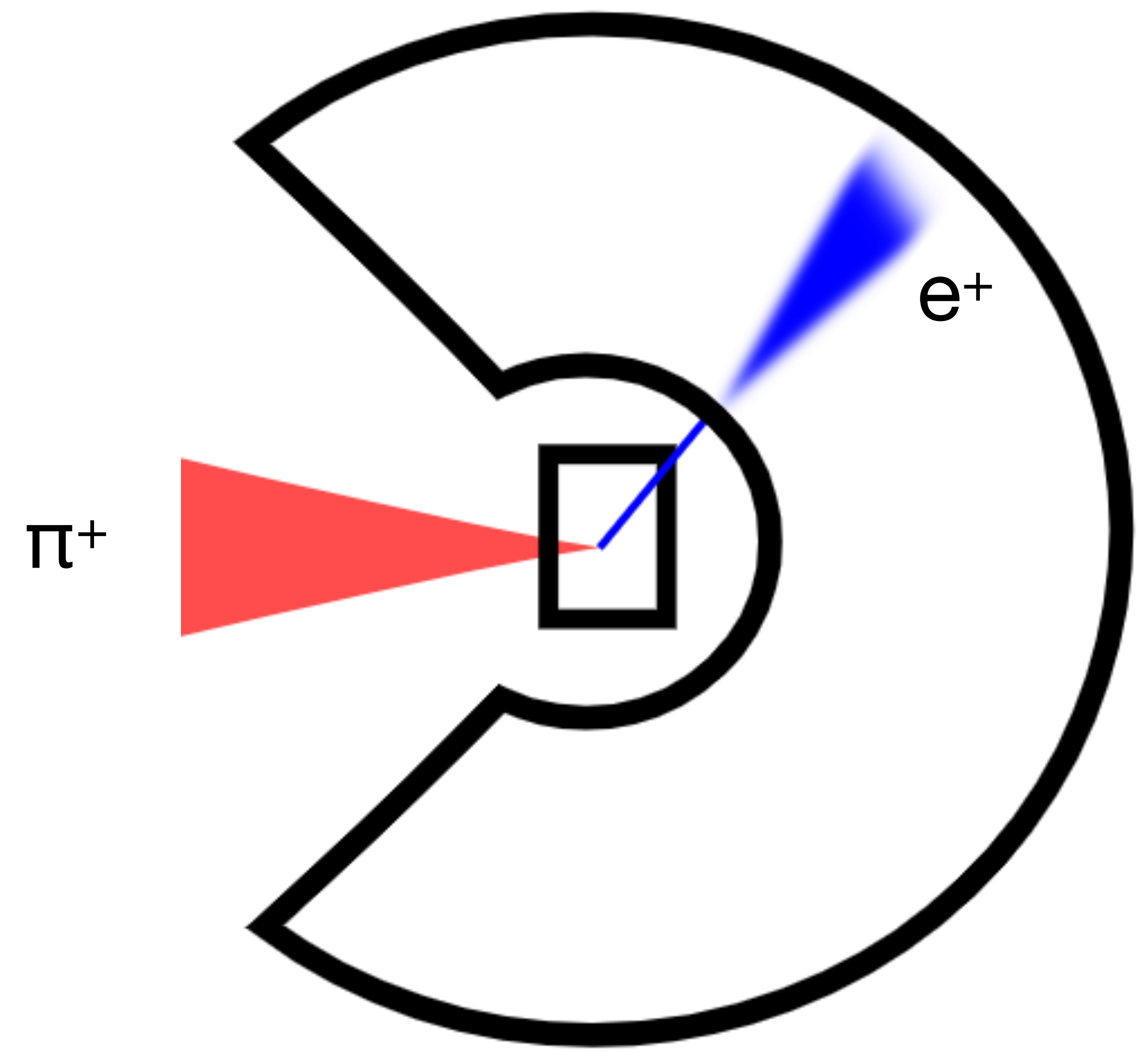
Constraint on $|V_{ud}|$ comparable to super-allowed beta decay

Introducing PIONEER

Phase I measurement strategy

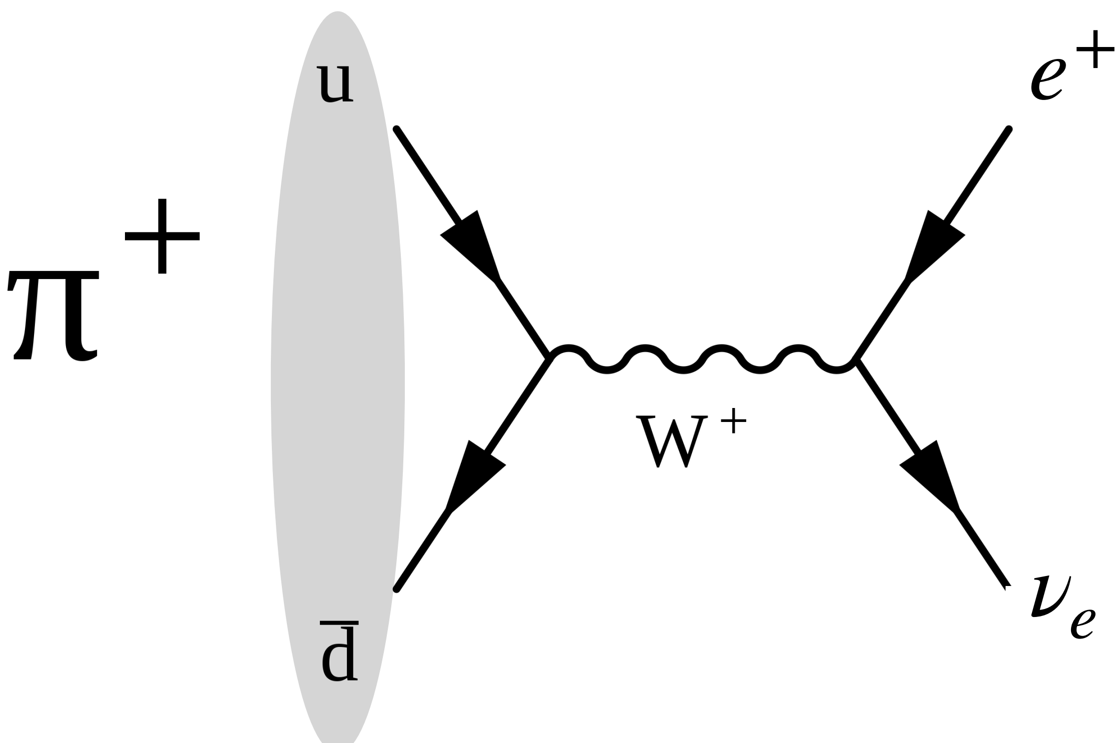
Detector developments

Simulation studies



Introducing PIONEER

Phase I measurement strategy

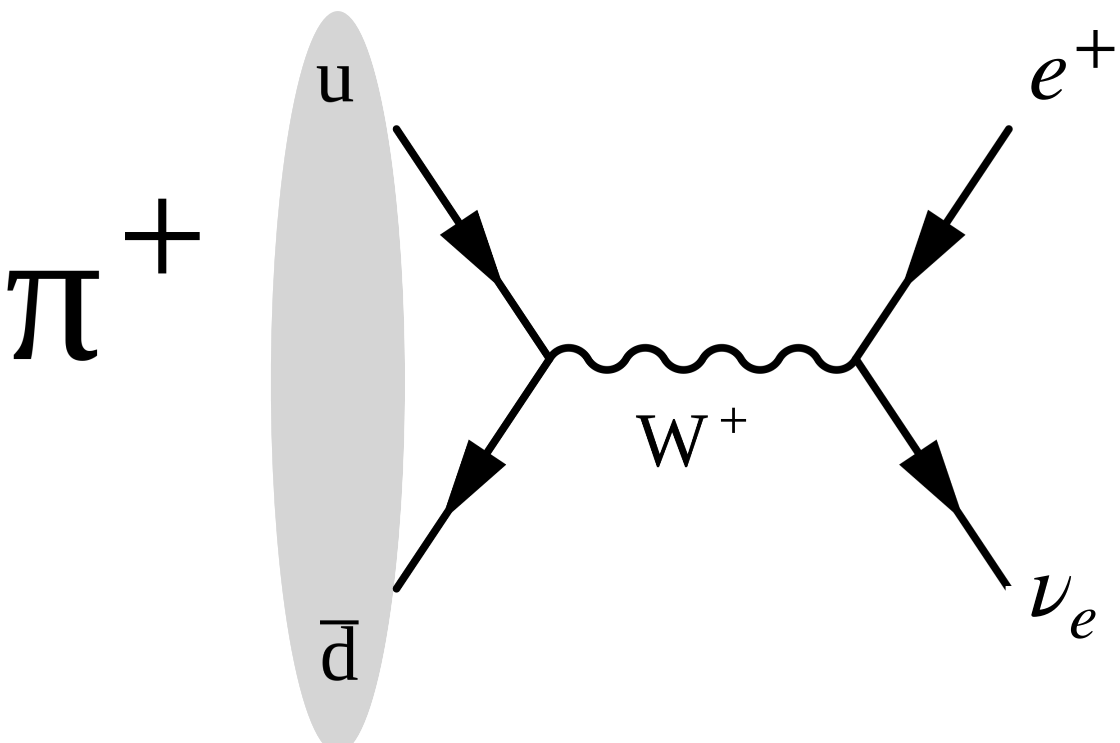


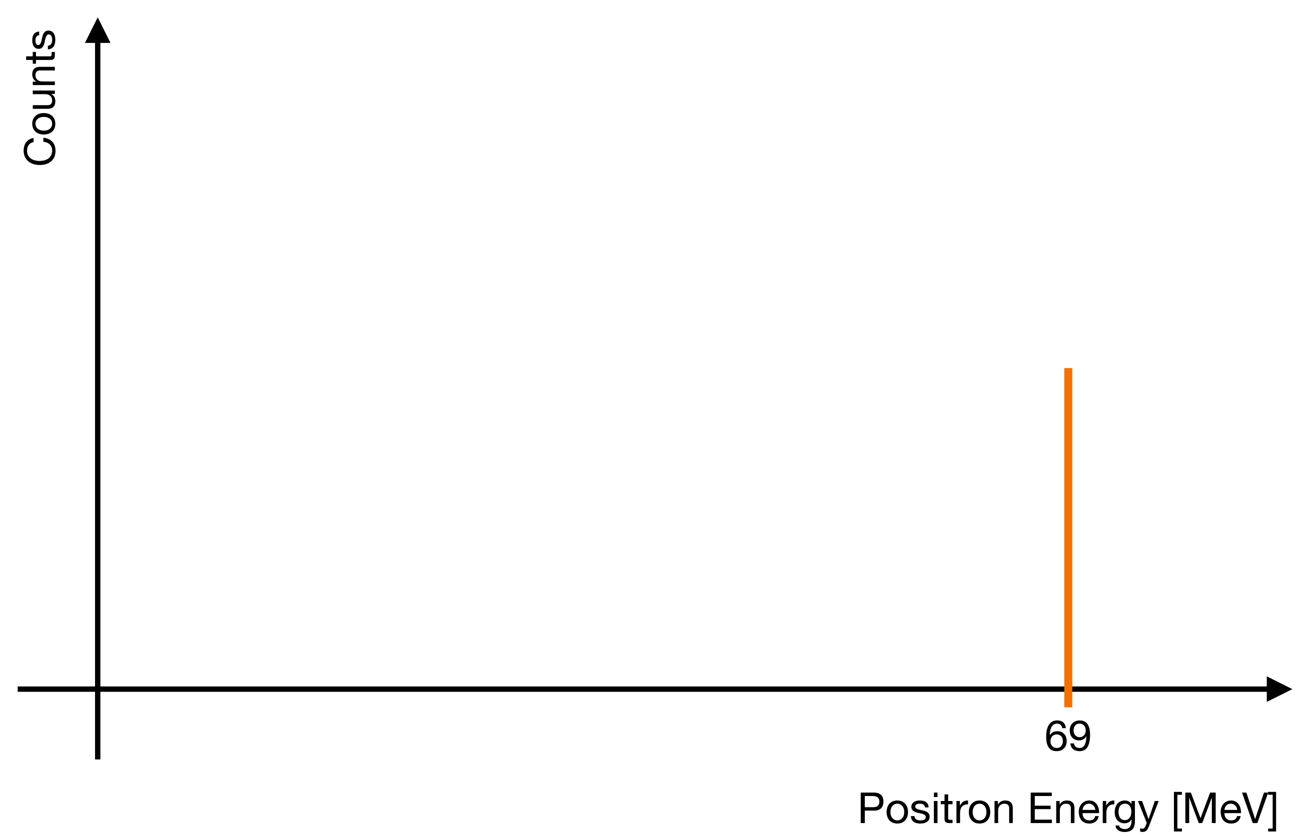
$m_{\pi^+} = 139.6\,\text{MeV}$

The pion stops in the target and decays

Introducing PIONEER

Phase I measurement strategy





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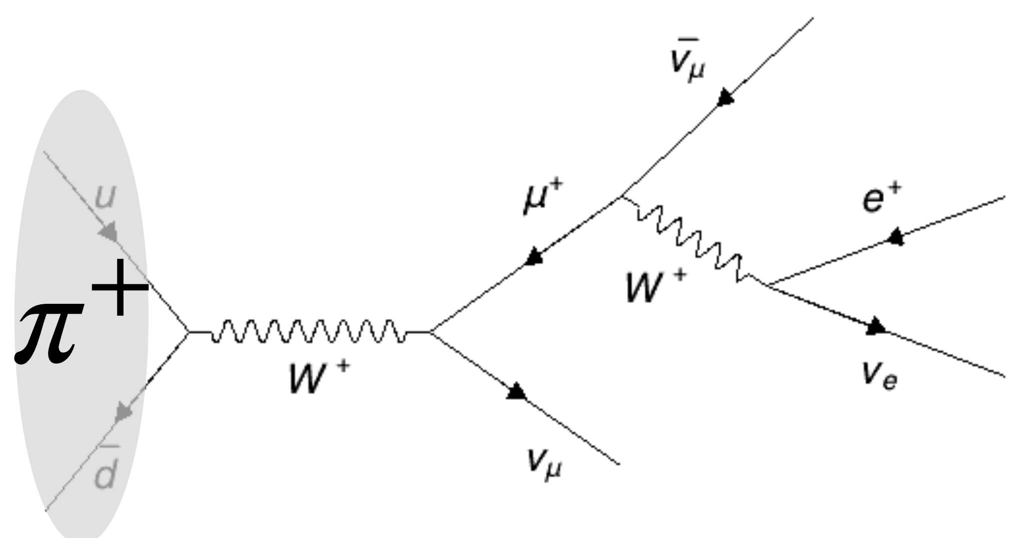
Introducing PIONEER

Phase I measurement strategy



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

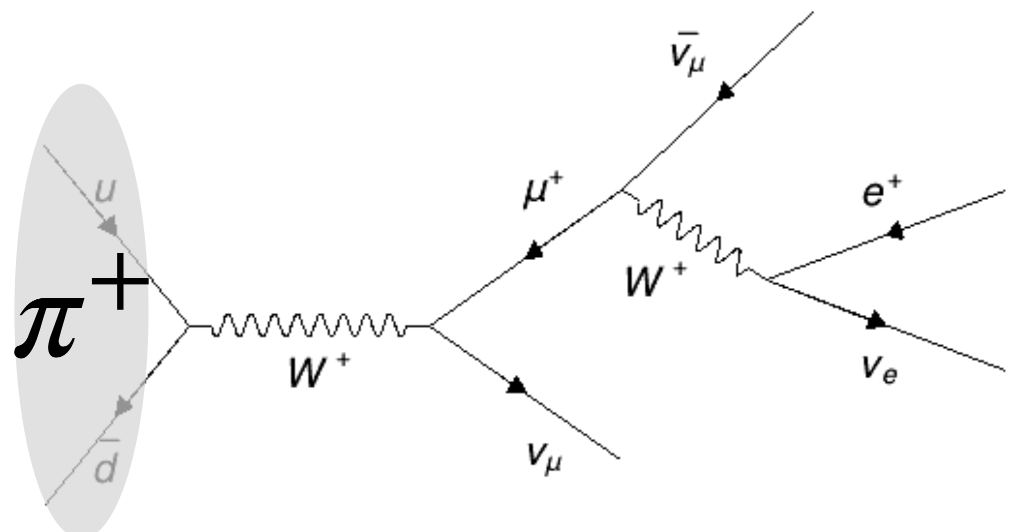
$m_{\mu^+} = 105.7$ MeV

The pion stops in the target and decays

Then the muon stops in the target and decays

Introducing PIONEER

Phase I measurement strategy



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

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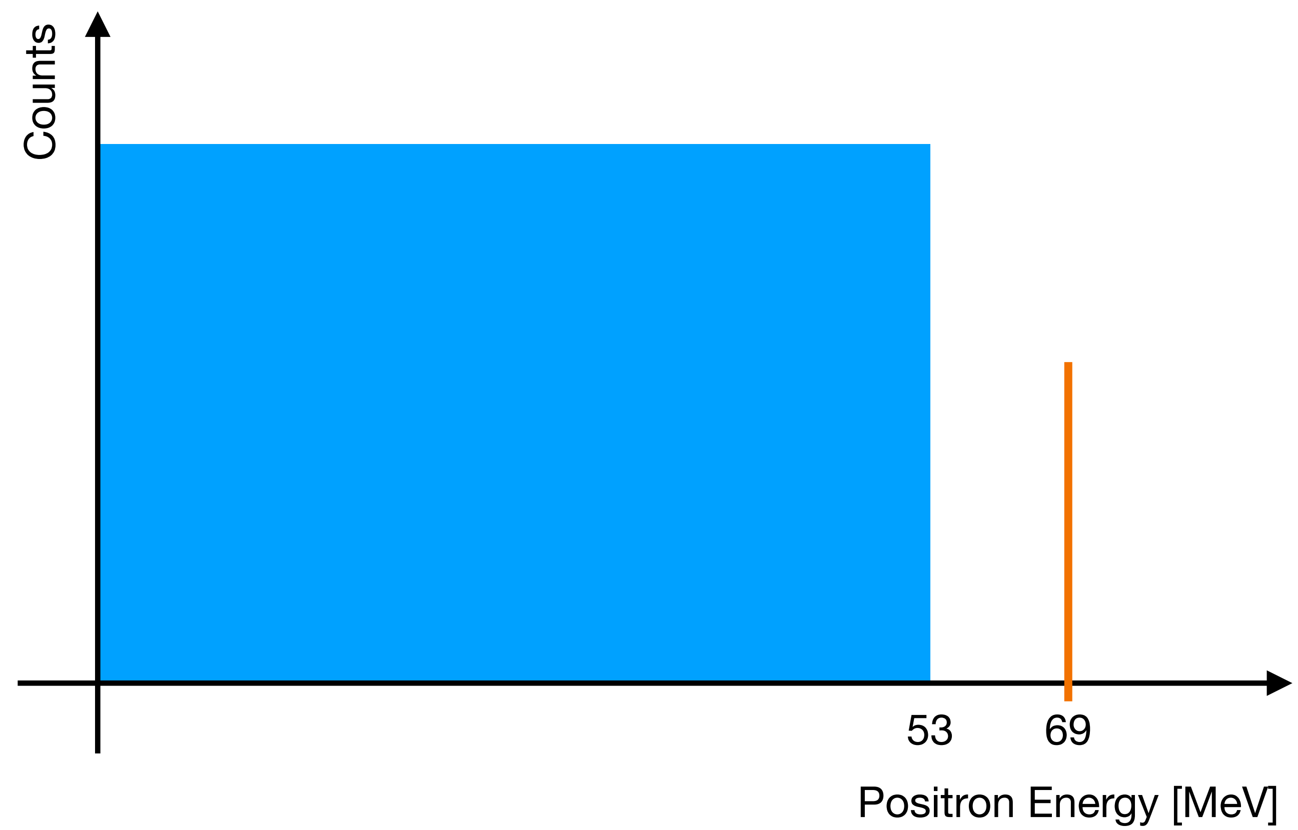
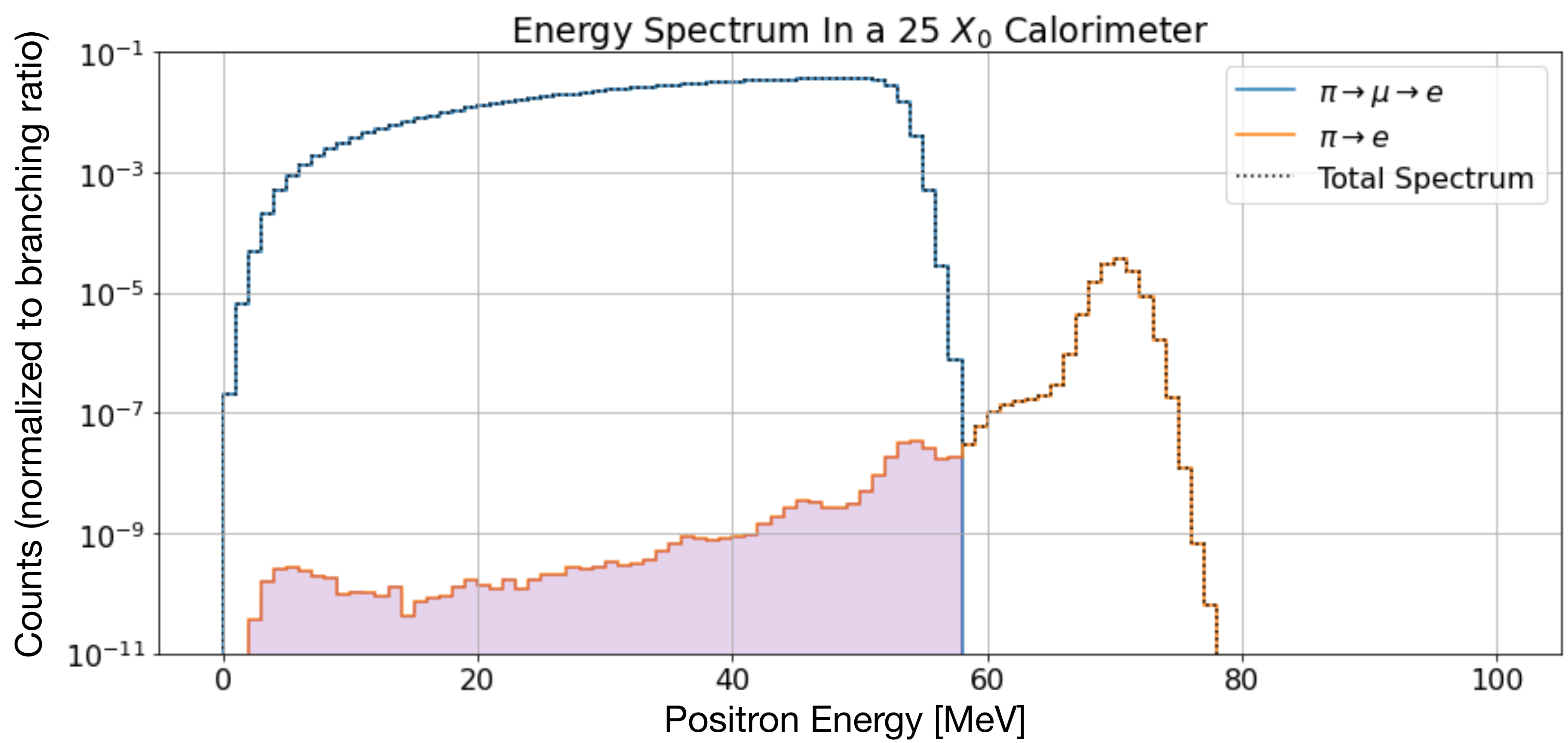
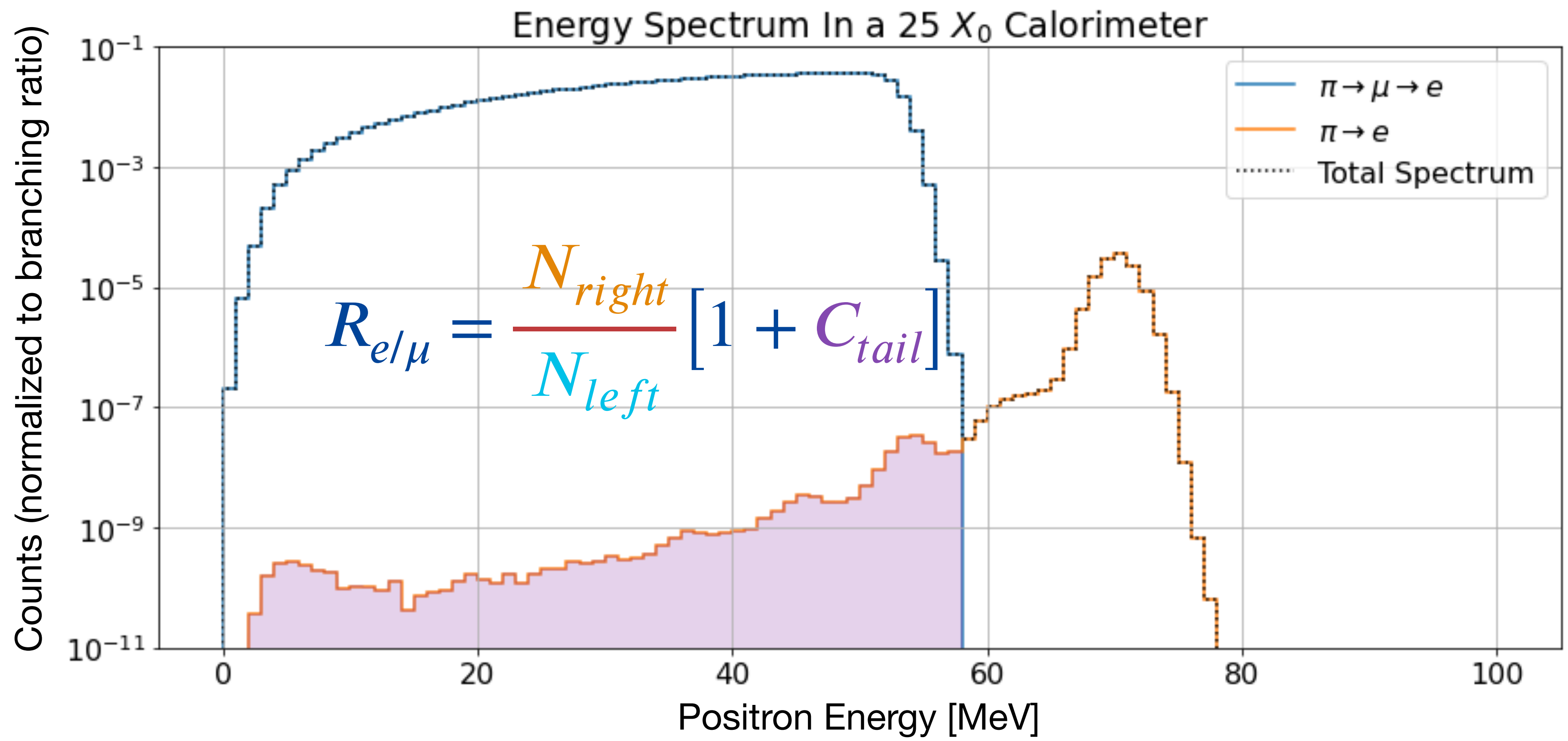


Facing experimental reality



Facing experimental reality



Guiding principles to the design of the experiment:

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

Guiding principles to the design of the experiment:

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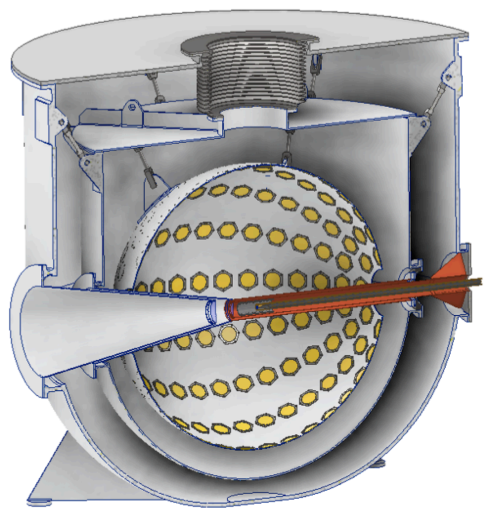
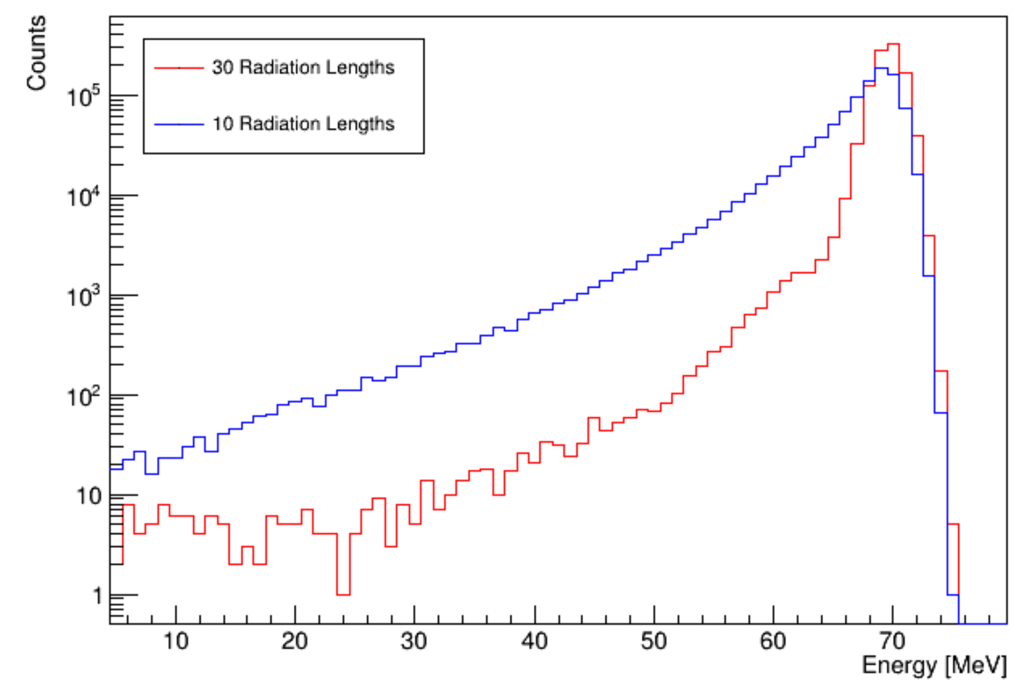
Facing experimental reality

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)
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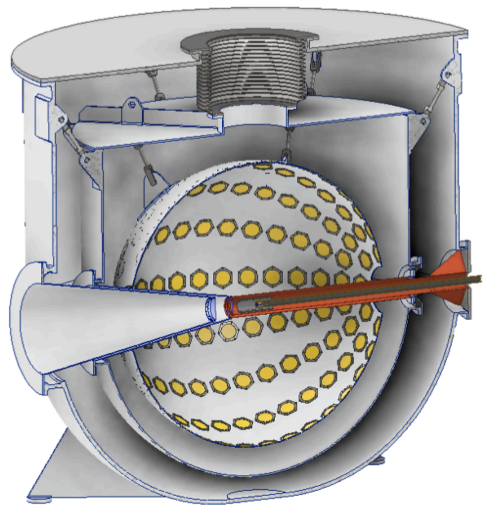
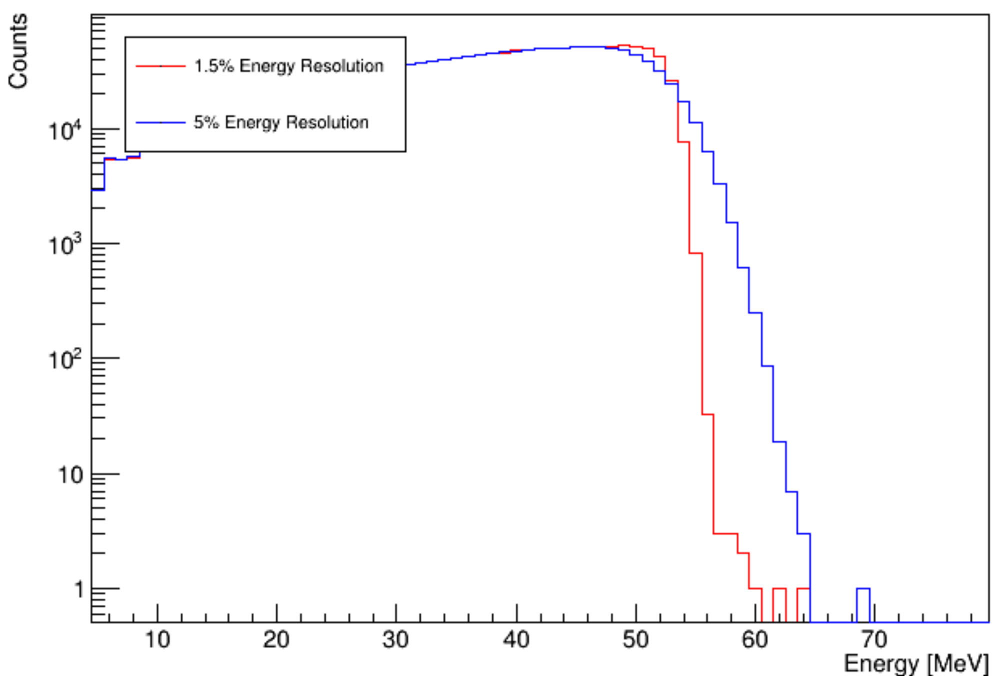
Facing experimental reality

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 $\pi^+ \to e^+\nu_e$ during Phase I)
2. **Tail must be less than 1% of total signal → Shower containment in the calorimeter**
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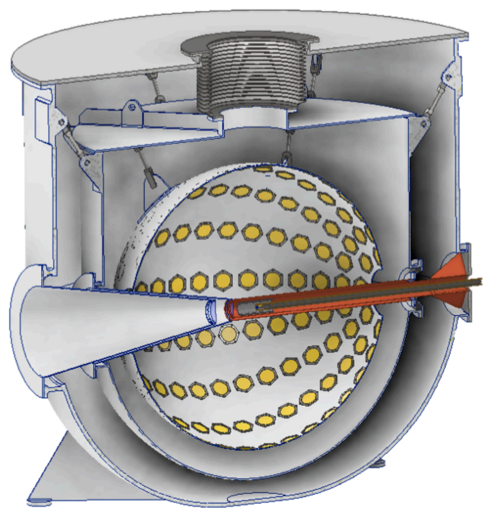
Facing experimental reality

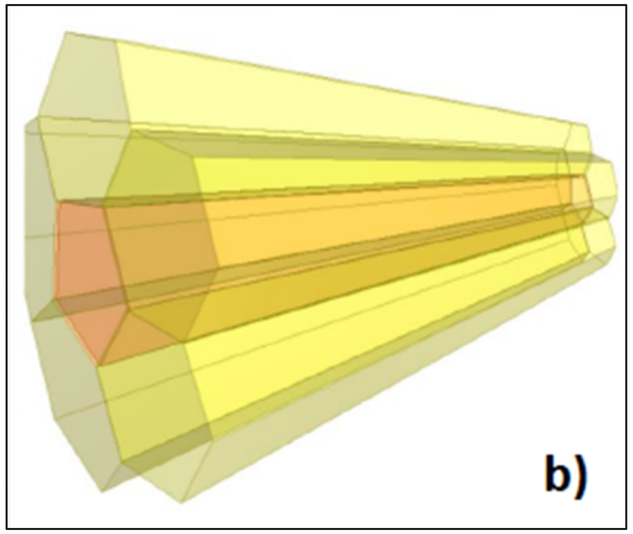
Liquid Xenon



Fast response
Highly homogeneous response
Detector can be reshaped

?

LYSO Crystals

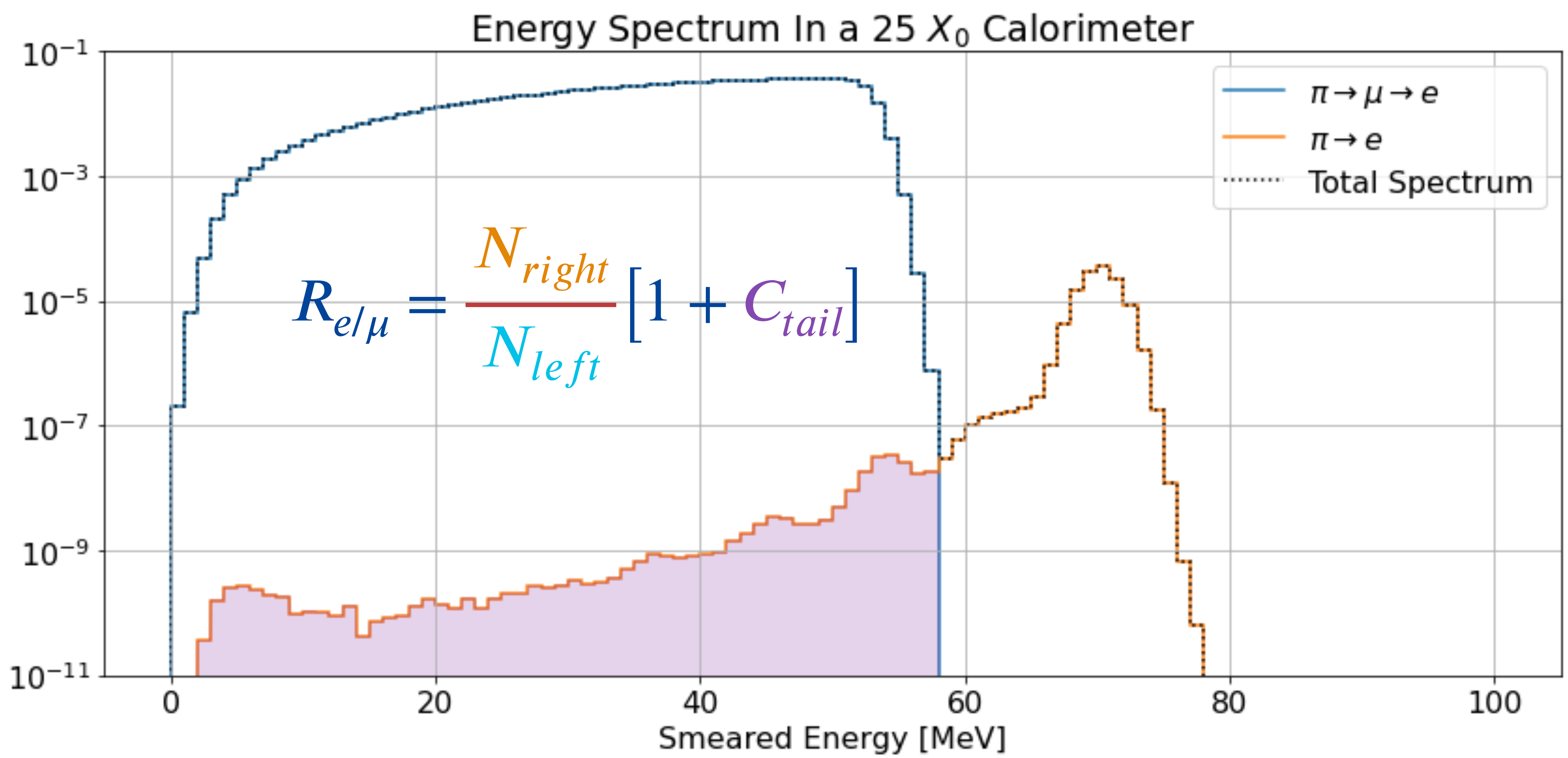


Fast response
High stopping power
Intrinsically segmented

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



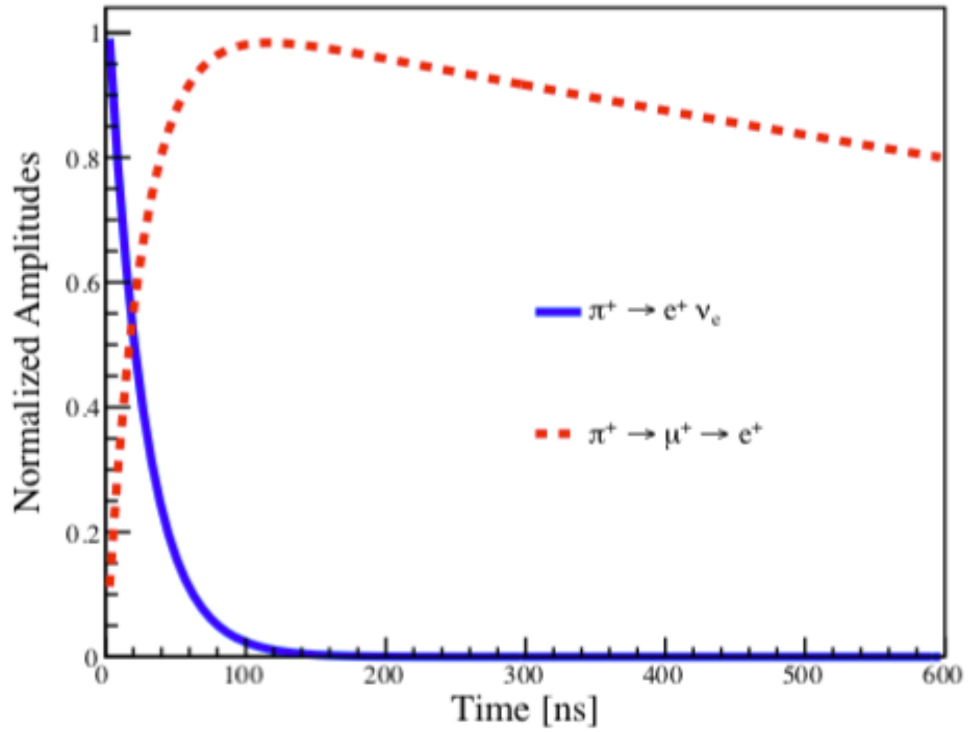
Guiding principles to the design of the experiment:

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**

Active Target

Requirements

Decay chain time is very different between $\pi \rightarrow e\nu$ and $\pi - \mu - e$ events



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

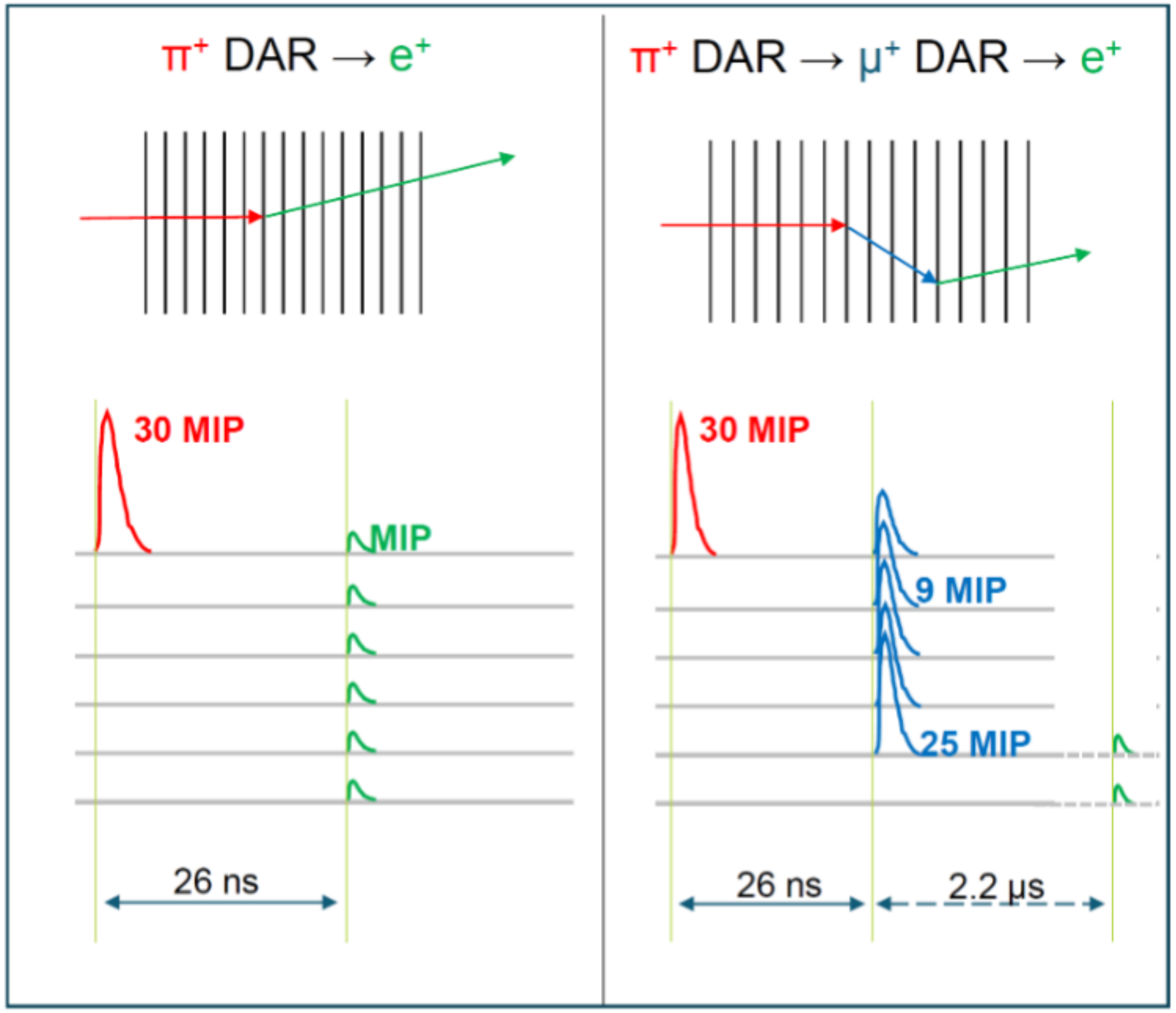
Device needs to separate single strip signals within 1 ns apart

1 μs long analog signal needs to be extracted and digitised

Active Target

Requirements

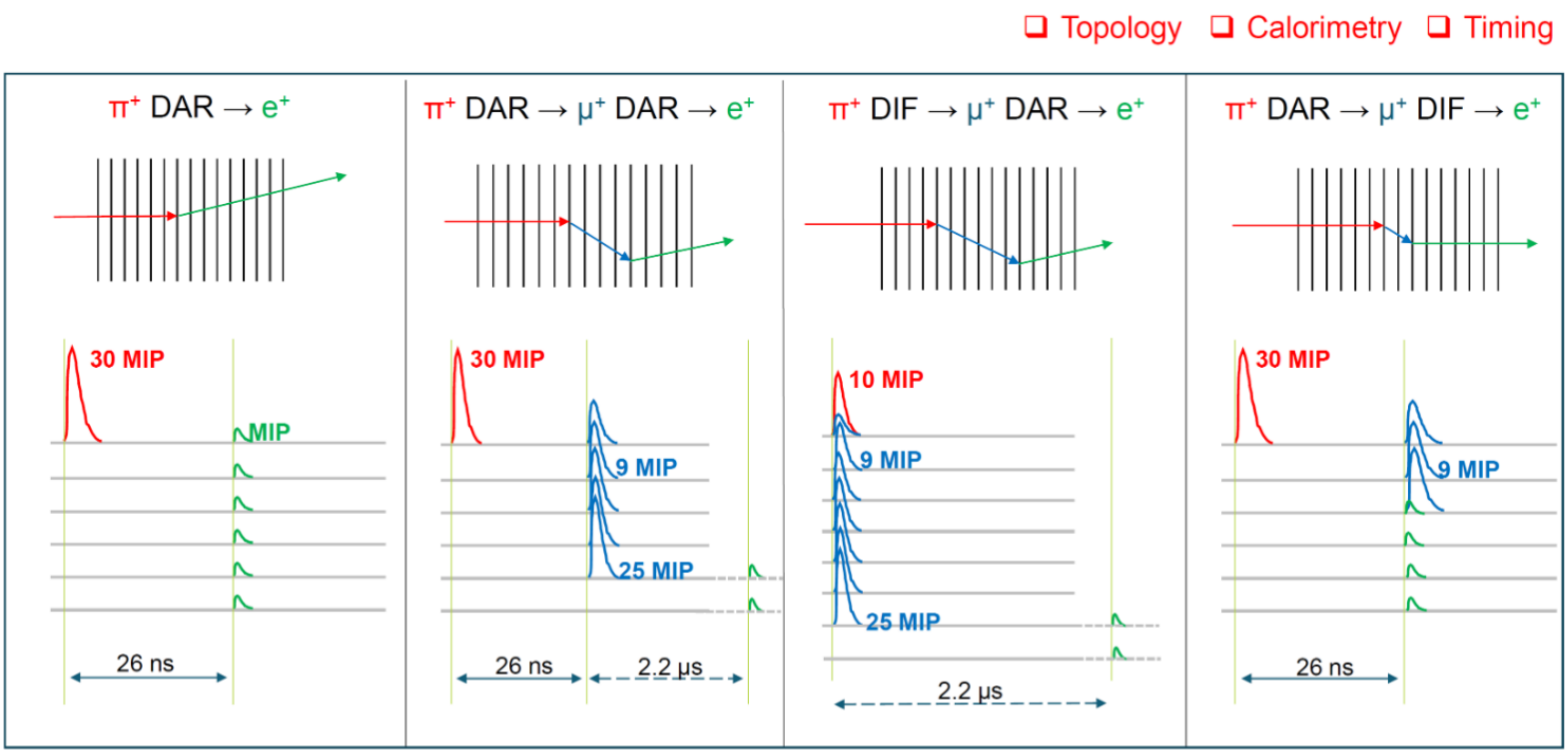
- Thick and highly segmented target to
    - stop the pion
    - tag and measure the decay chain
- Measure time, position, and energy



DAR = Decay At Rest
MIP = Minimum Ionizing Particle

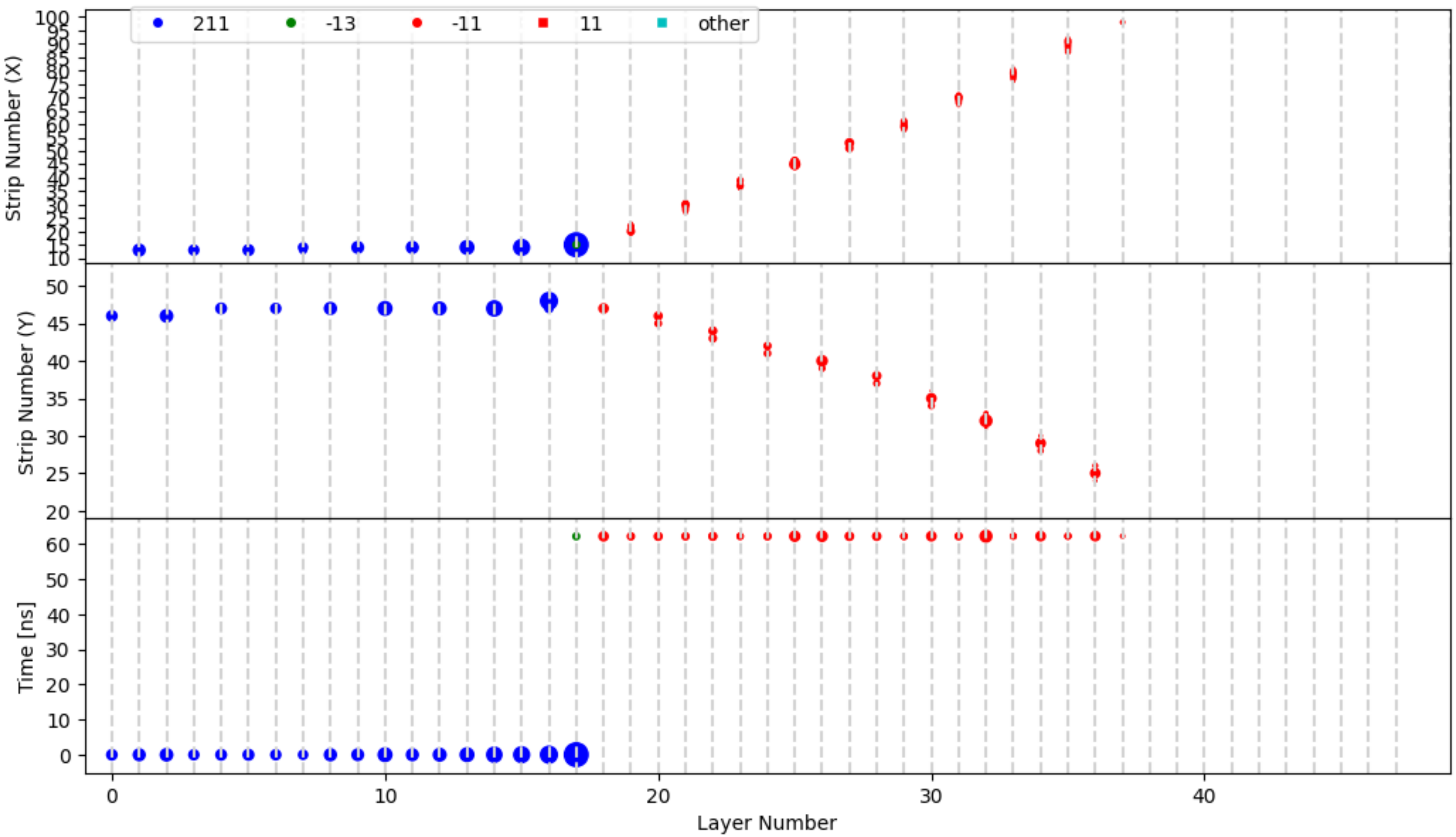
Active Target

Requirements



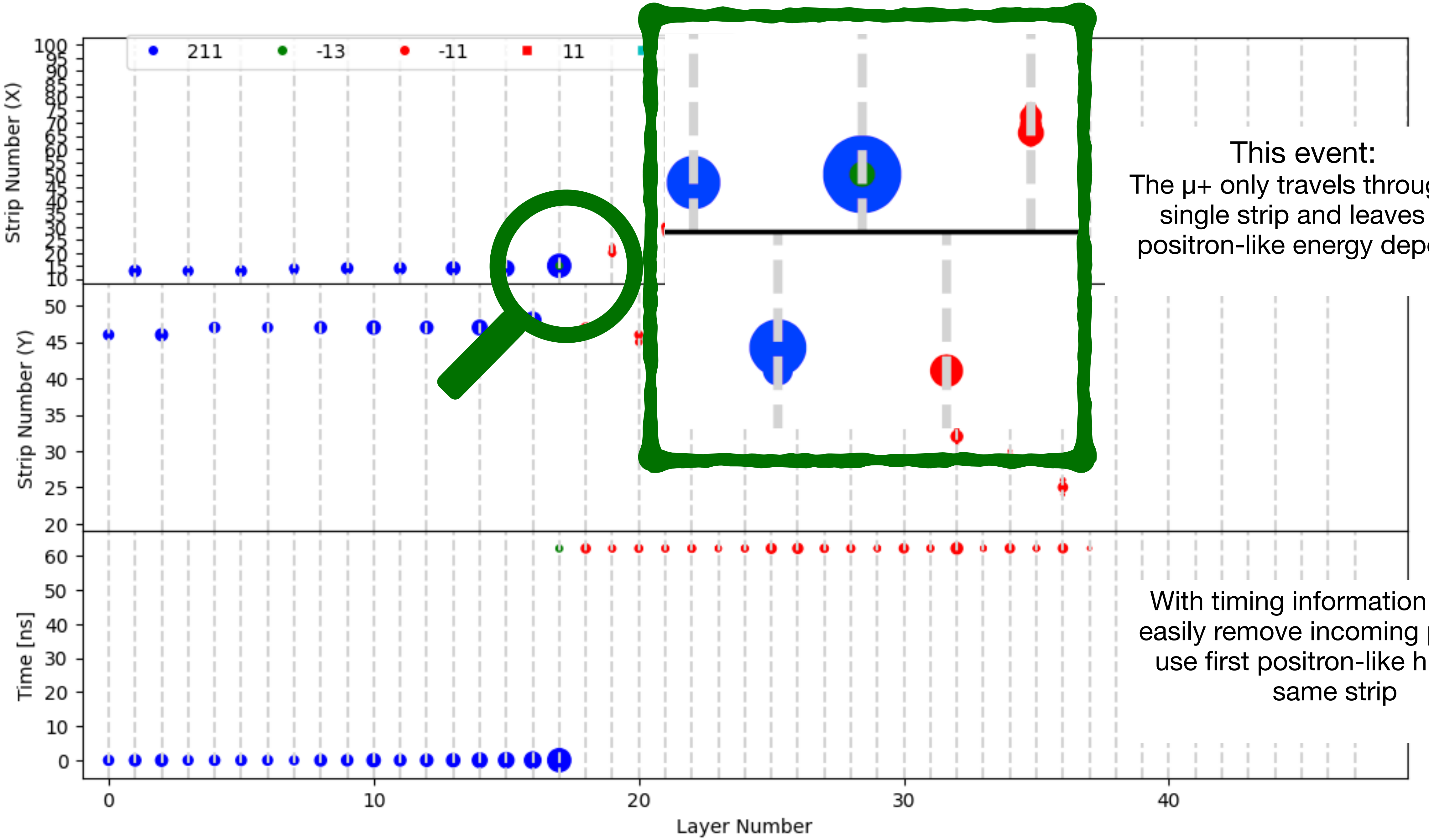
Active Target

Muon decaying in flight (DIF)



Simulation studies

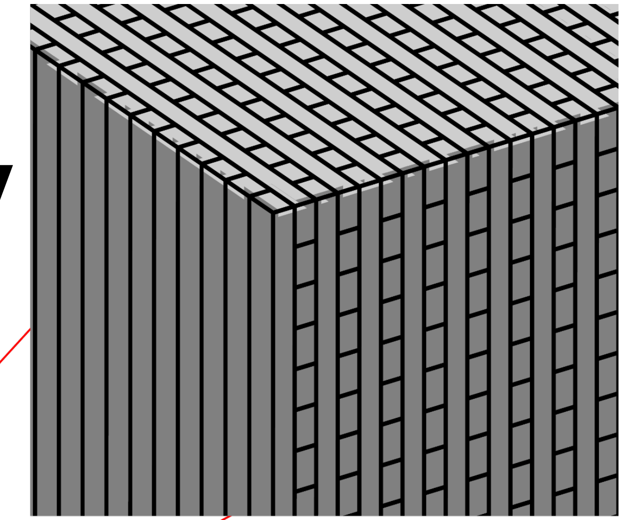
Muon decaying in flight (DIF)



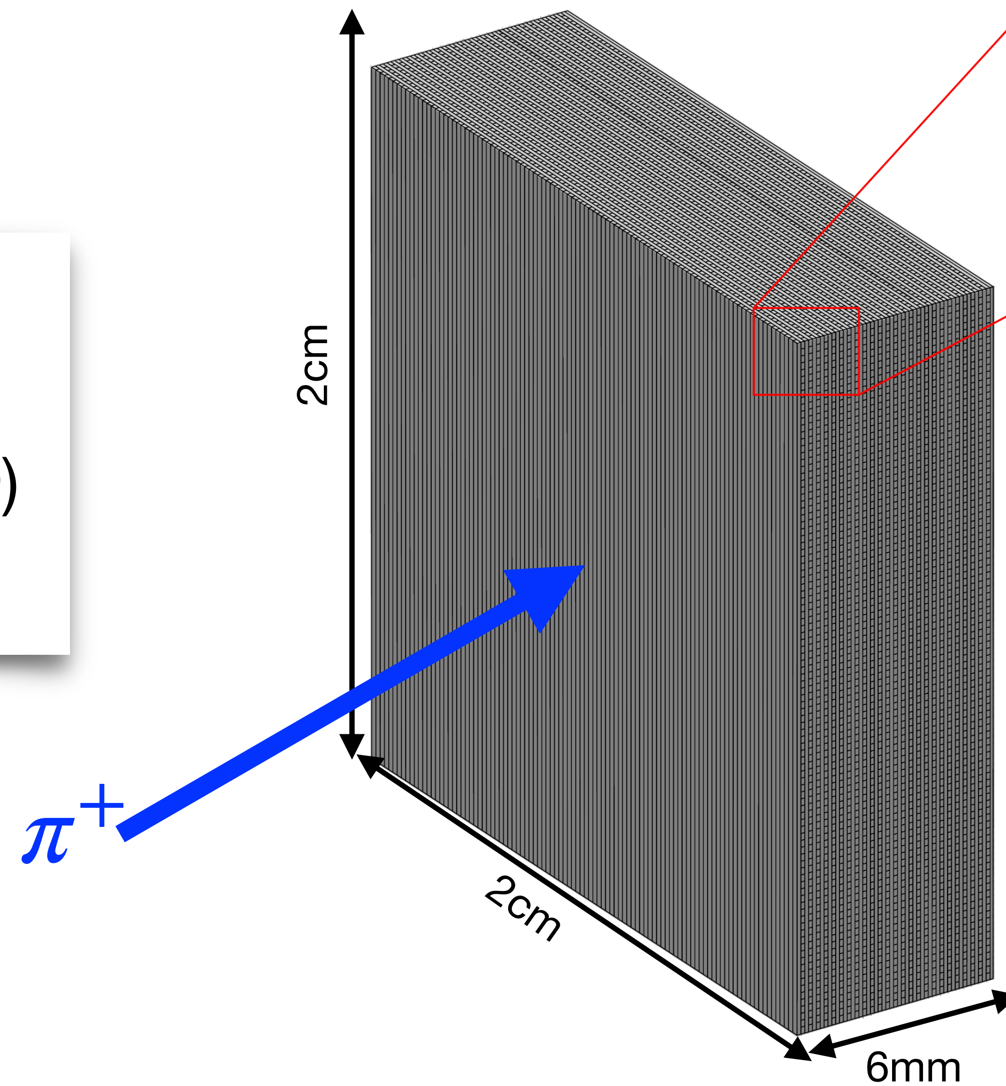
This event:
The μ+ only travels through a single strip and leaves a positron-like energy deposit

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

Facing experimental reality



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



Tentative design

48 layers: 120 μm thick

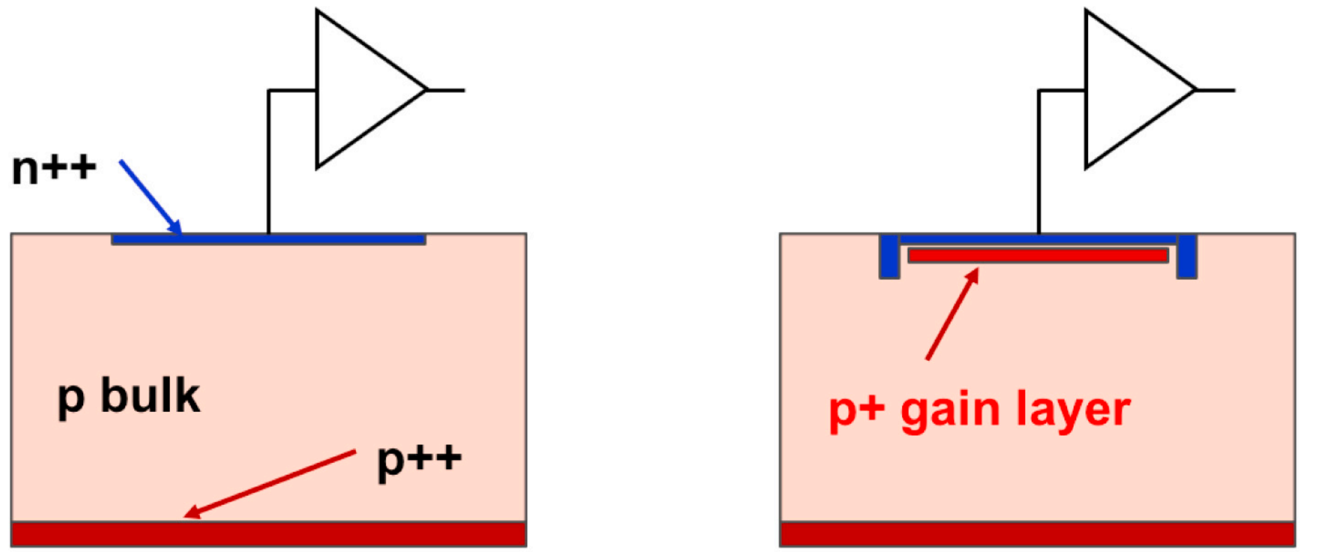
100 strips per layer with 200 μm pitch covering 2x2 cm^2 area

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

Active Target

Low Gain Avalanche Diodes

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



Traditional silicon diode

Low Gain Avalanche Diode

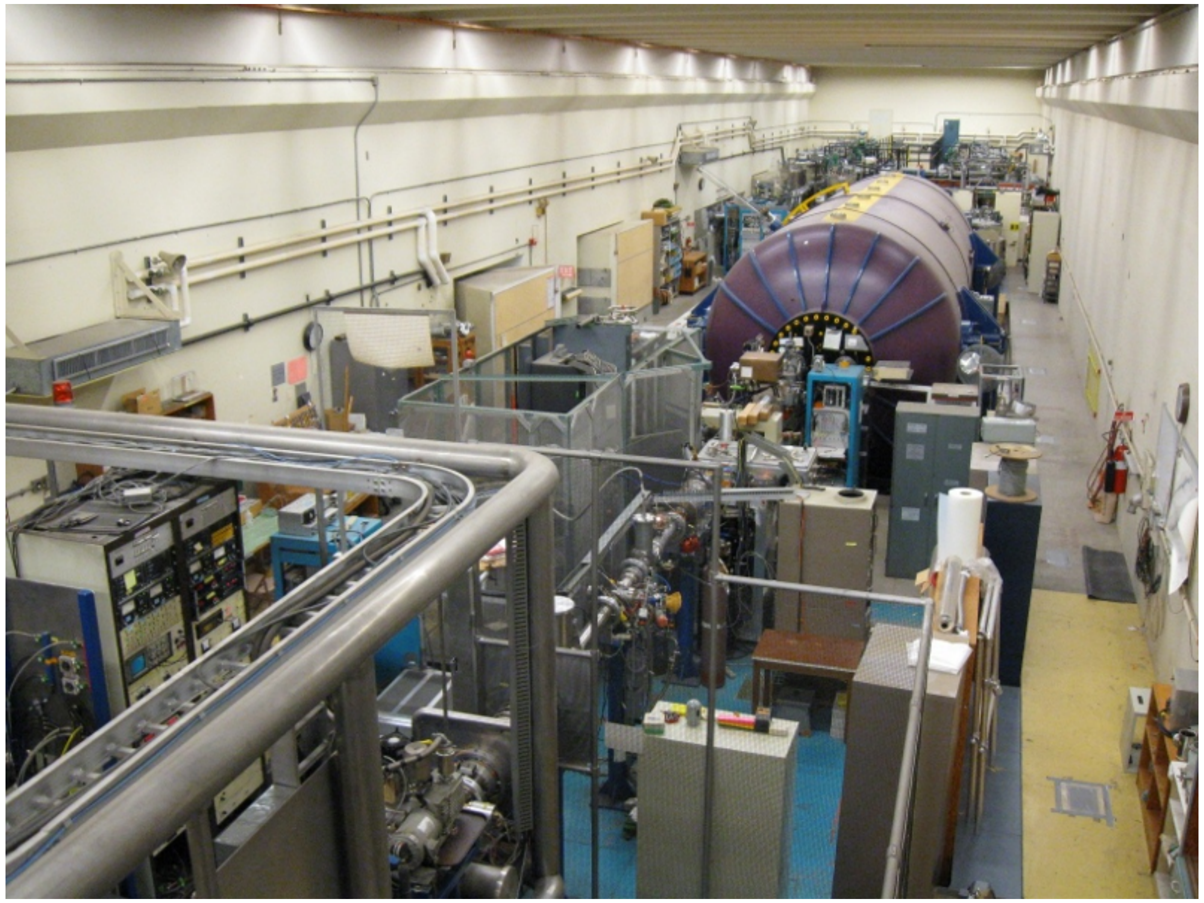
Obtained by implanting an appropriate acceptor or donor layer
when depleted, generate a very high field

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

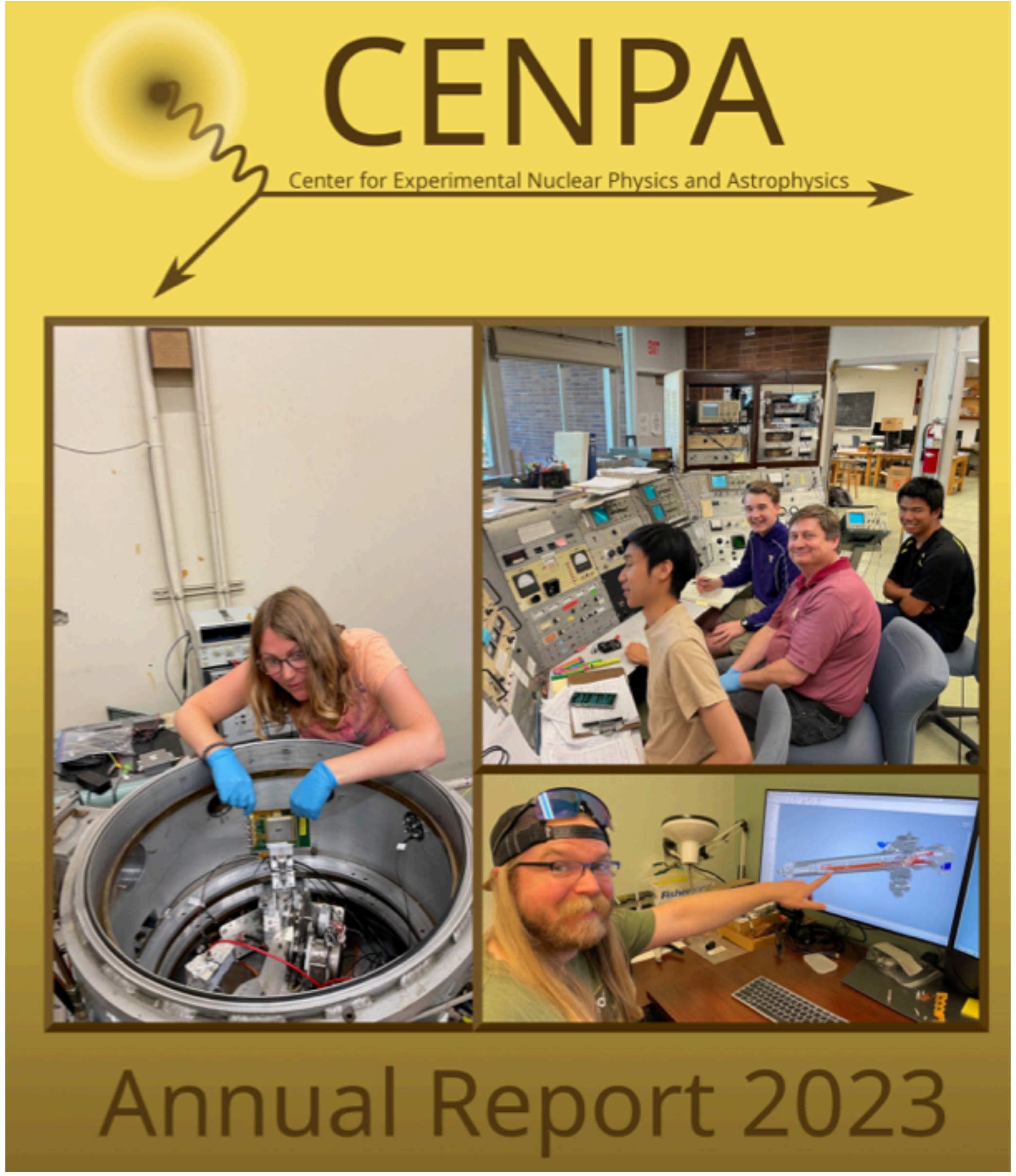
Active Target

Tandem Accelerator at the University of Washington

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



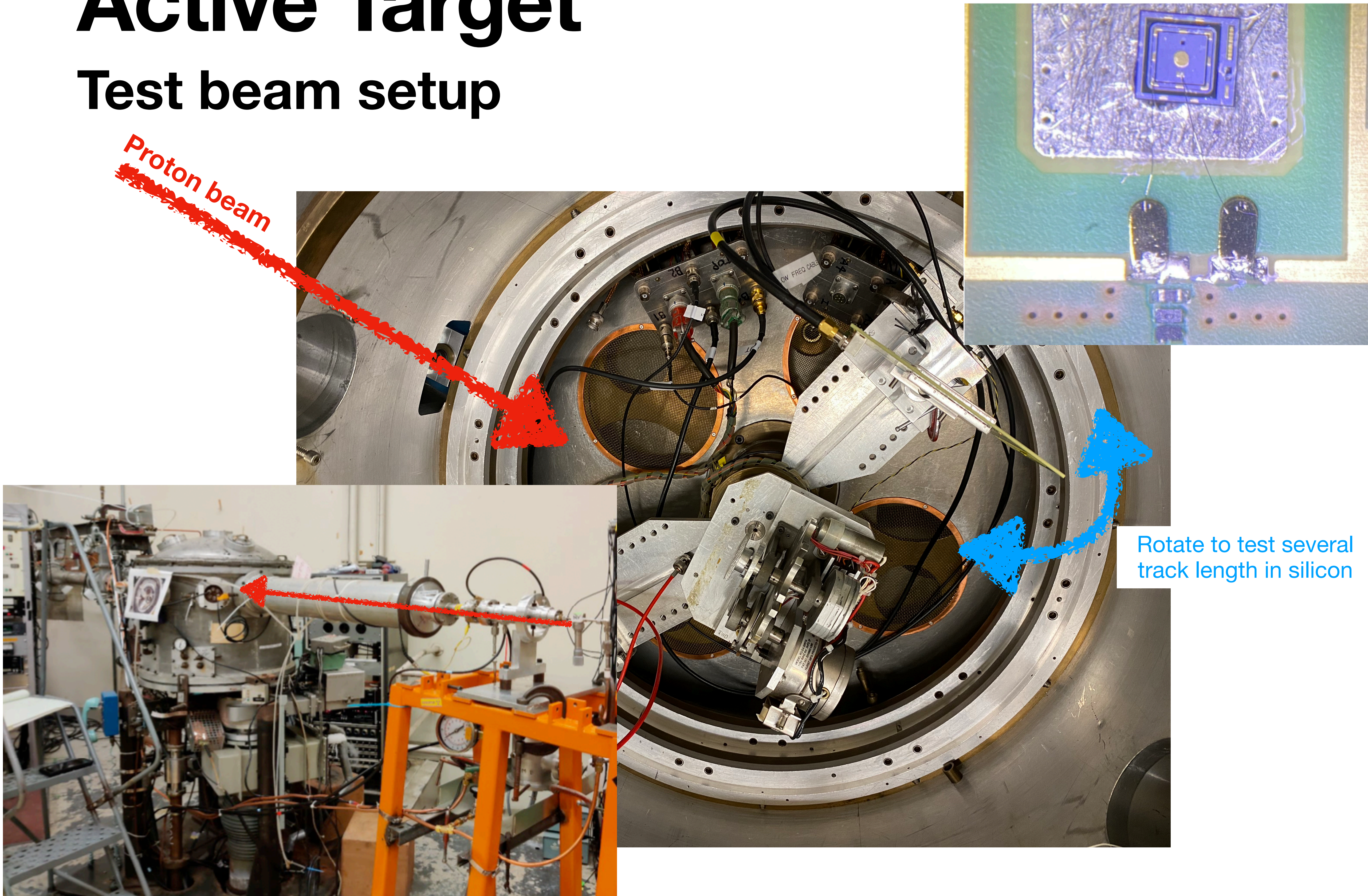
Tandem Van de Graaf Accelerator
1 to 5 MeV protons



Active Target

Test beam setup

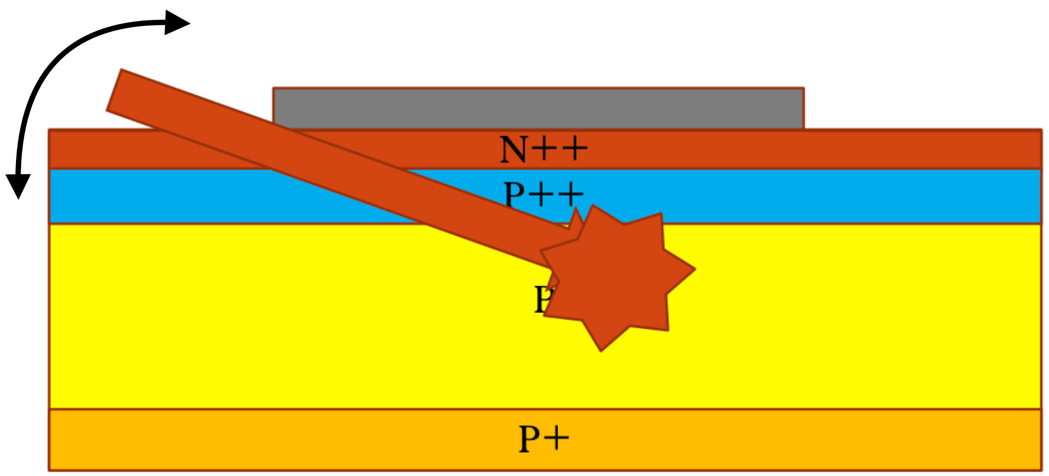
1×1 mm^2 sensor with $50\,\mu$m thickness



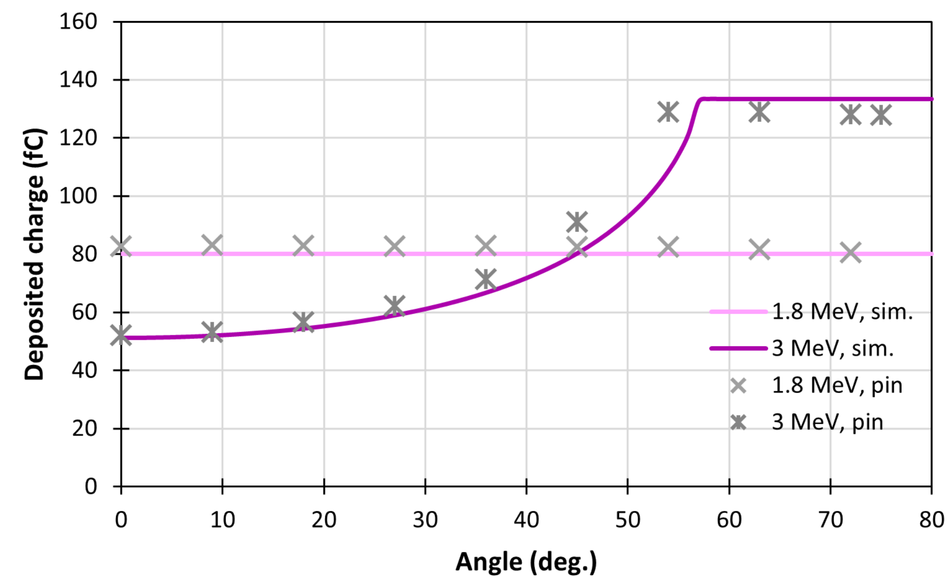
Active Target

LGAD gain saturation studies

Vary the angle the protons hit the sensor

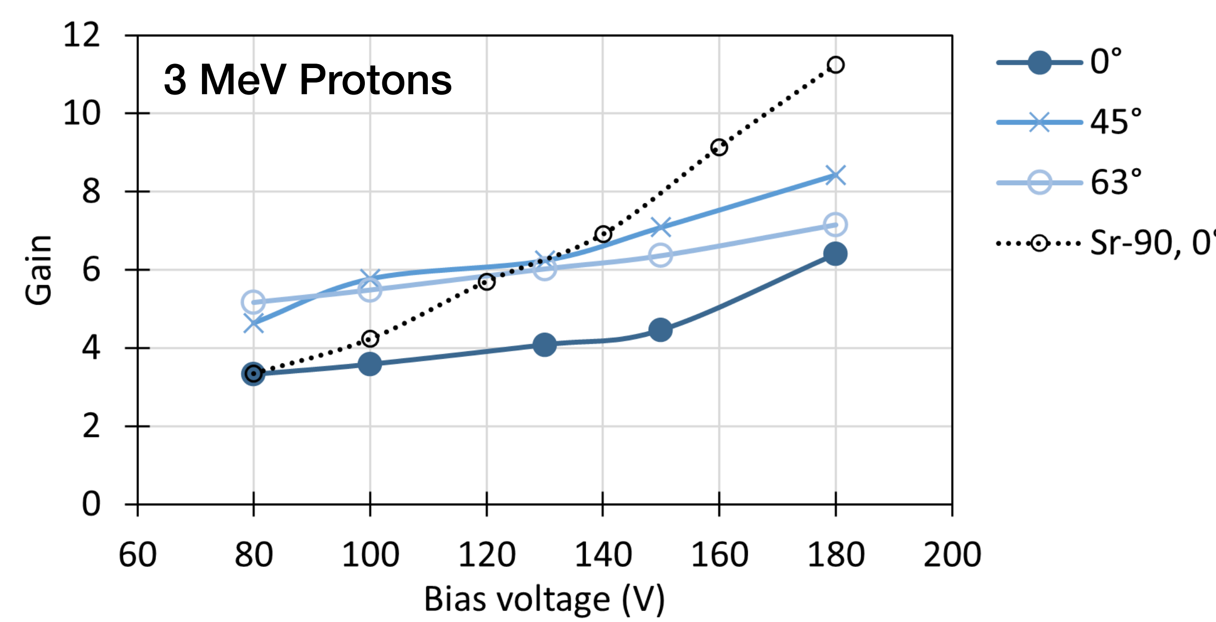


Submitted to Nuclear Inst. Meth.



Verified expected gain (and gain saturation) increase with increasing bias voltage

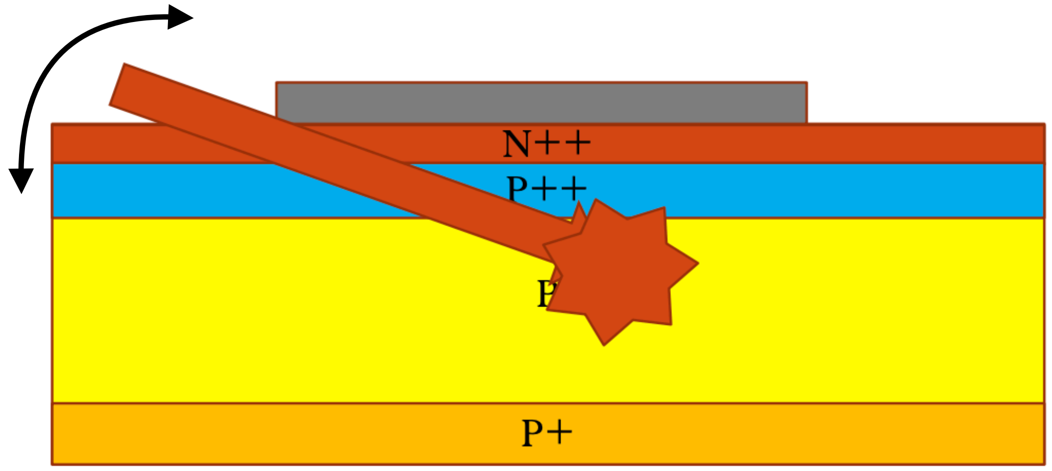
Observed some saturation for minimum ionising track (from Sr-90 beta source) at low angle

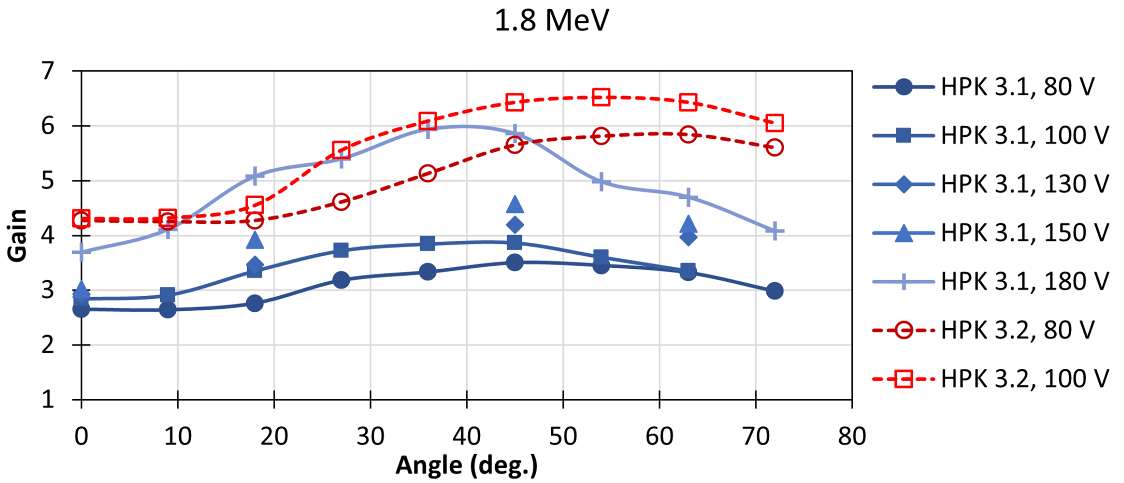


Active Target

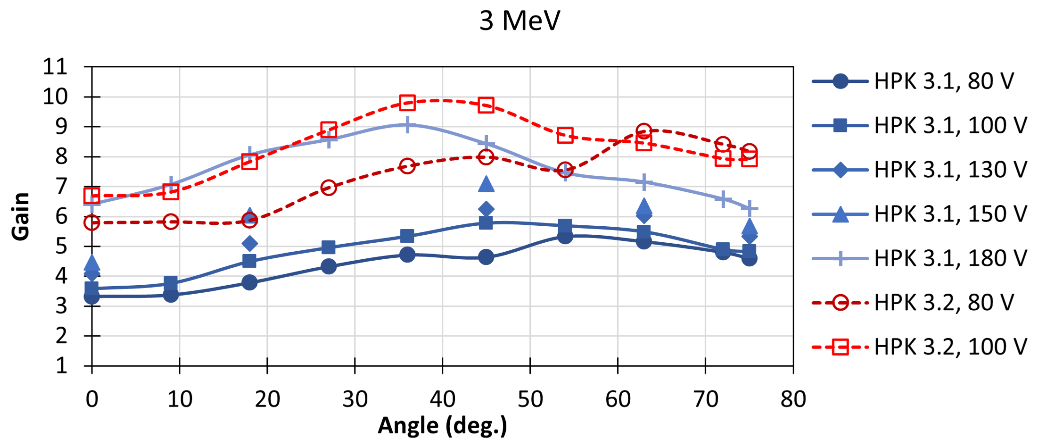
LGAD gain saturation studies

Vary the angle the protons hit the sensor





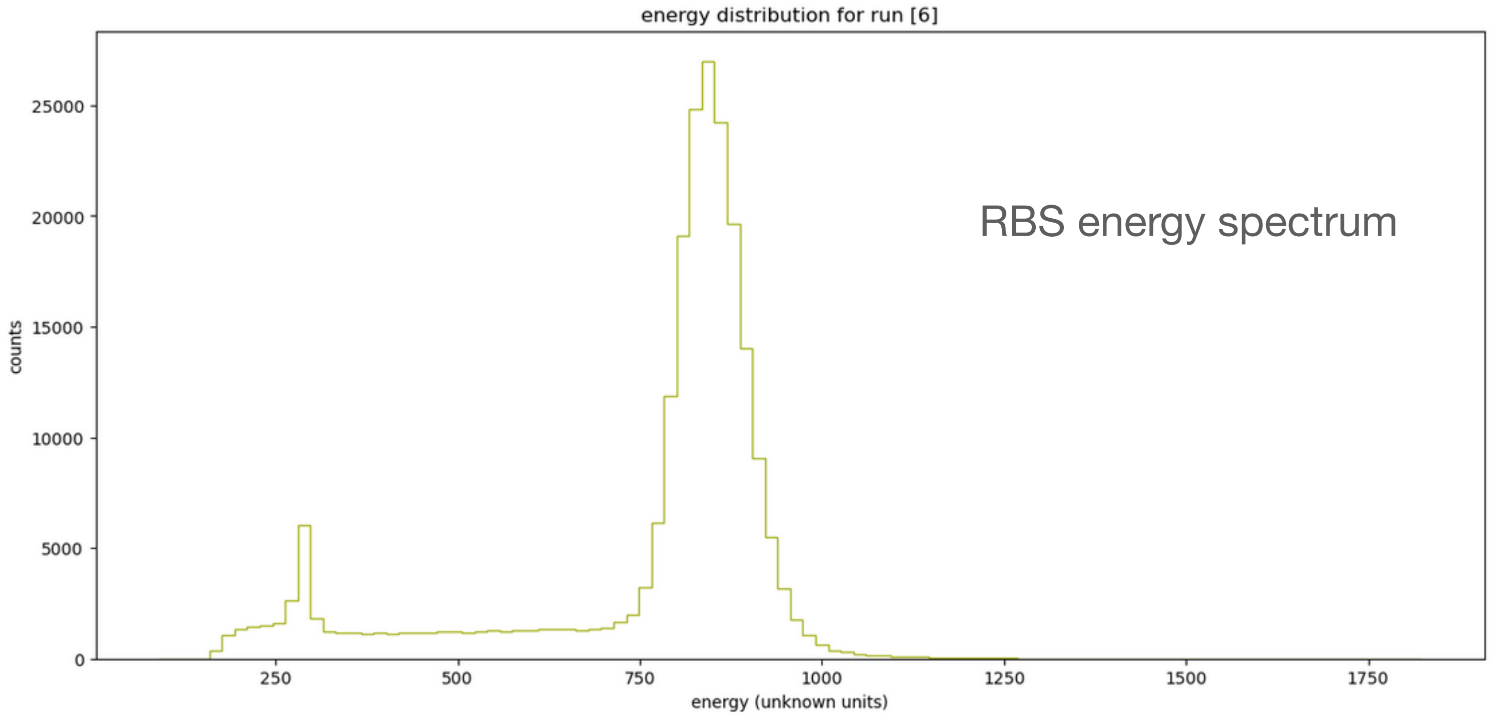
Impact of charge localisation: angular dependency of the response → critical input for PIONEER sensitivity studies

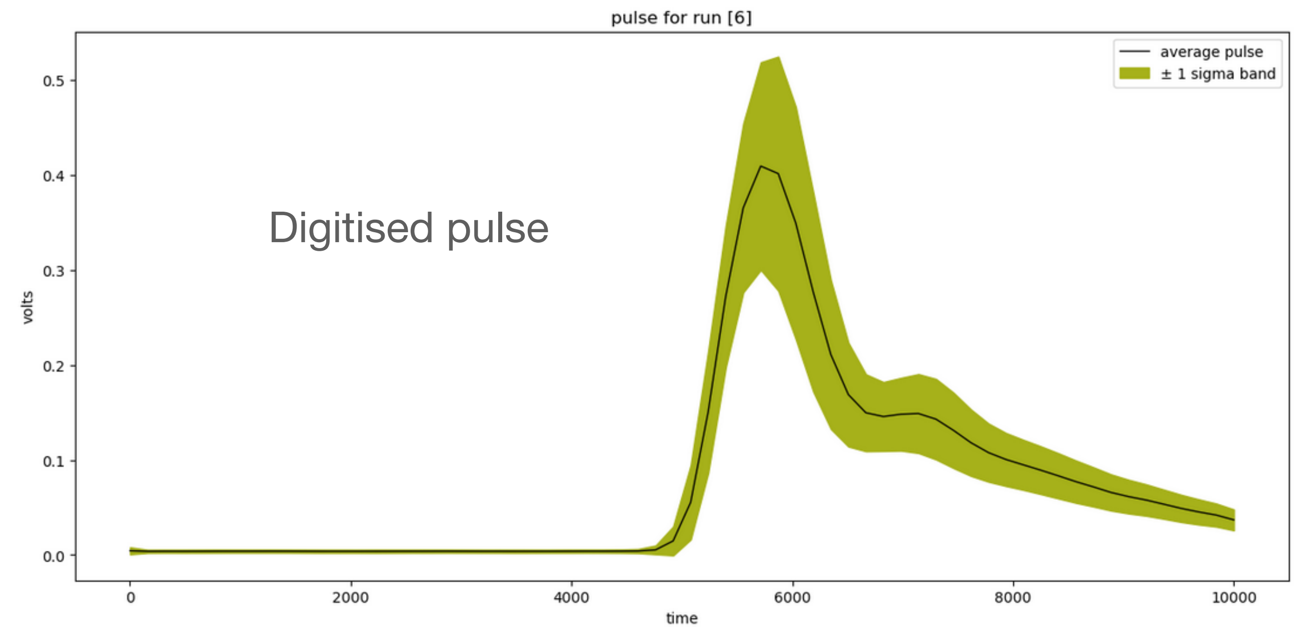


Upcoming tests this summer for shallower gain layers and multi-channels sensors

2024 Test beam campaign

Megan Harrison (REU UW 2024)





Data taking at CENPA started last Friday

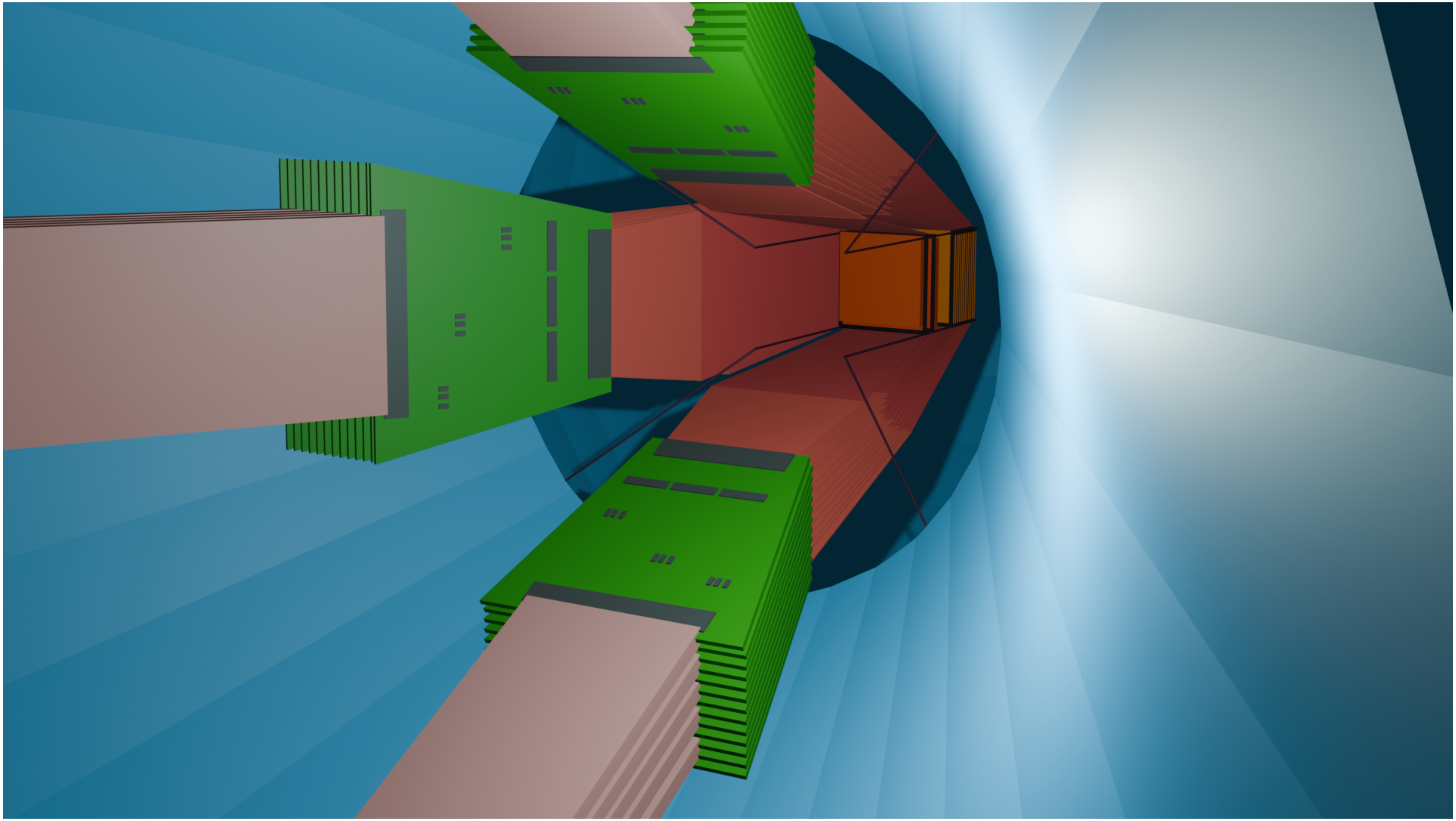
Single sensor tests

- Understand gain saturation
  - Overall amount
  - Angle dependency
- Sensors
  - FBK thick sensor (50um, 100um, 150um). Single pads of 2x2 mm2
    - Sensors have a special doping and the lowest gain we can hope for
  - FBK thick sensors (50, 100, 150), single pads of 2x2 mm2
    - This version is thinned down so we can study deposit from the back side
  - BNL 200um single pad sensors
    - Status (July 12, Yousen and Volodya): device works at BNL
  - PIN baseline:
    - For each sensor, we have a PIN equivalent

Goal: converge on the sensor of choice for PIONEER first prototype

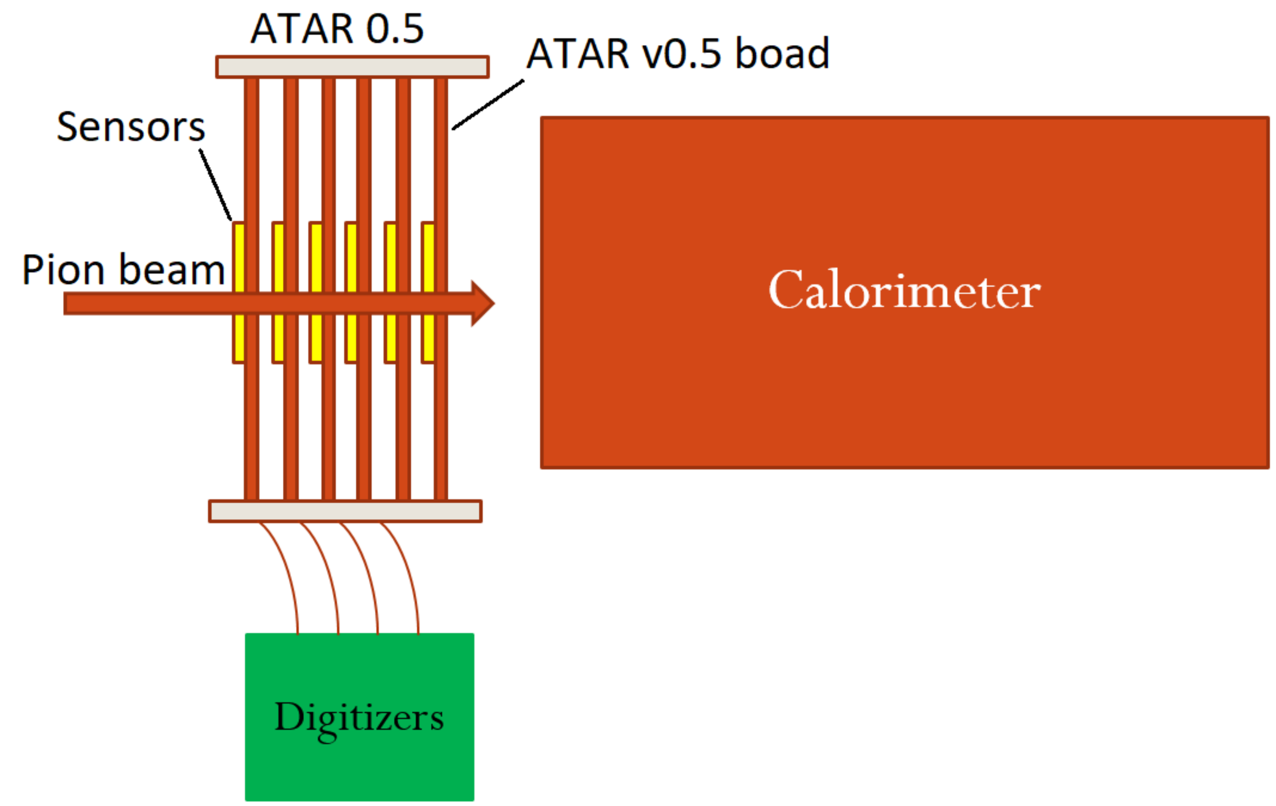
Active Target

Conceptual design



Active Target

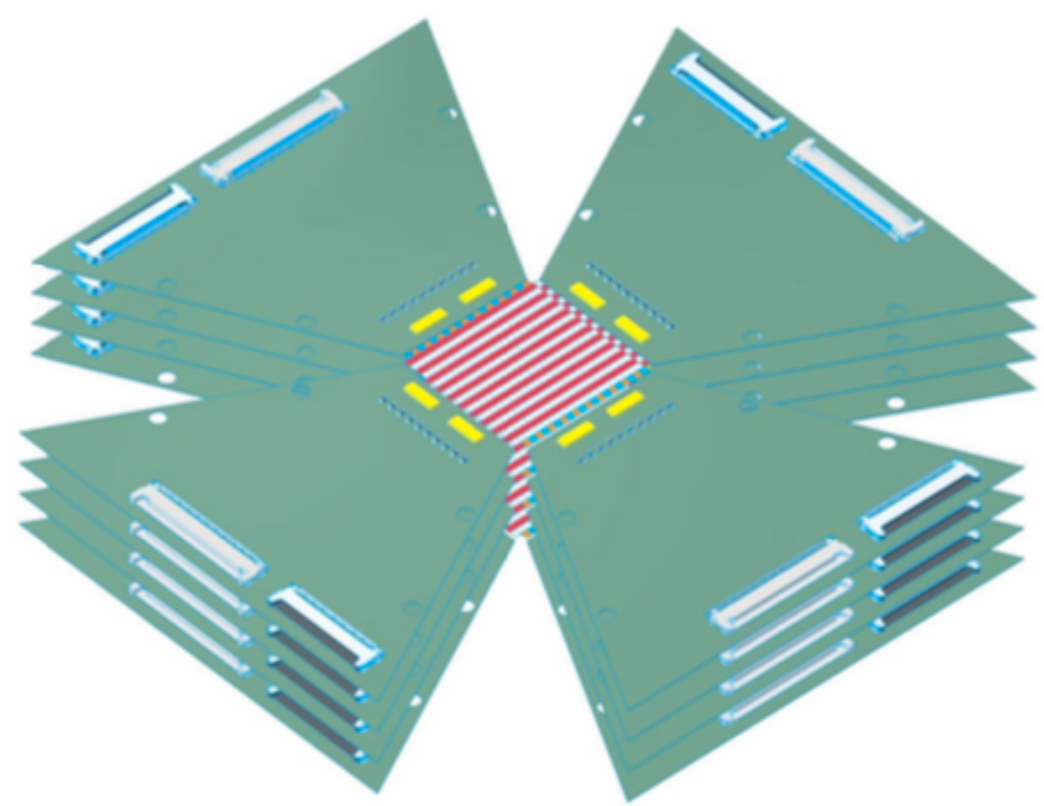
Toward first prototype



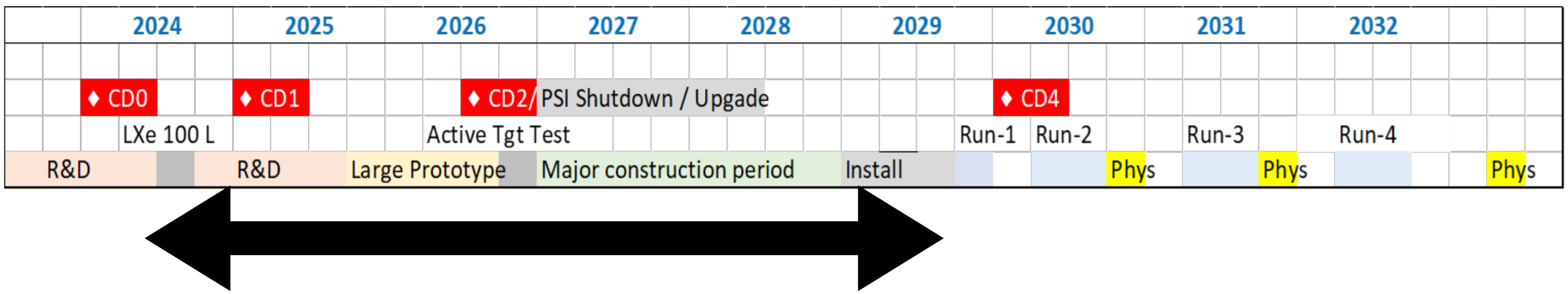
Current plan
Build first prototype
to take data at PSI before 2027

Limited prototype
10 layers, 16 channels per layers

Goal is to have a first
physics measurement
before the 2027 PSI shutdown



Timeline of the project



The next 6 years

PIONEER is a nascent collaboration
(bylaws are being written this month)

Exciting Detector R&D in **tracking** and calorimetry

Putting an experiment together from concept to first data:

Civil engineering, beam optics,
detector manufacturing,
LXe acquisition, electronics, …

Detailed simulation studies are essential

Conclusion

Exciting time to tackle the flavour puzzle of the Standard Model

Study the mass generation mechanism at the LHC
using state-of-the-art 'big data' techniques to harvest
the most out of the outstanding pp collision dataset

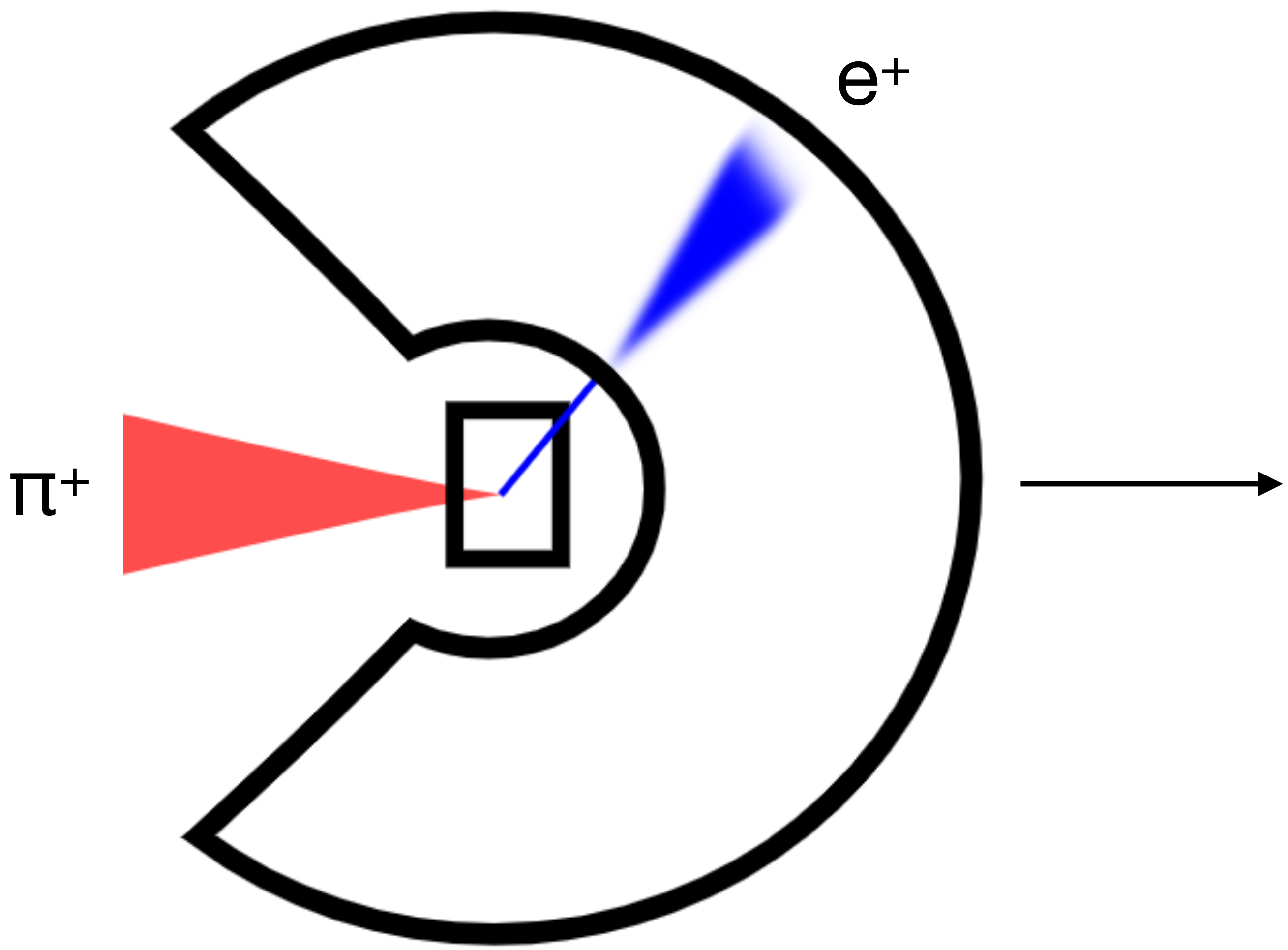
Rare pion decays are a powerful and pristine
probe of high energy scale physics

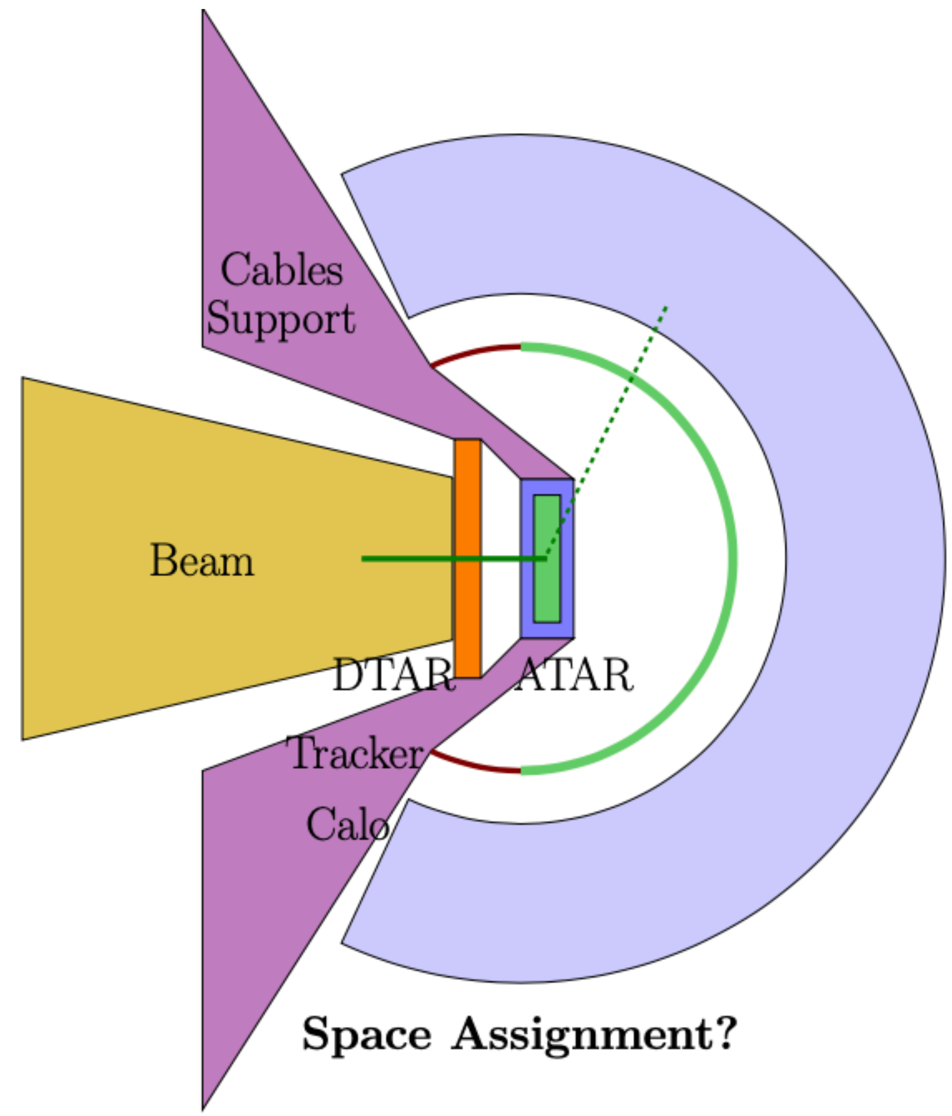
PIONEER employs emergent technology
to significantly improve over the
current generation of experiments

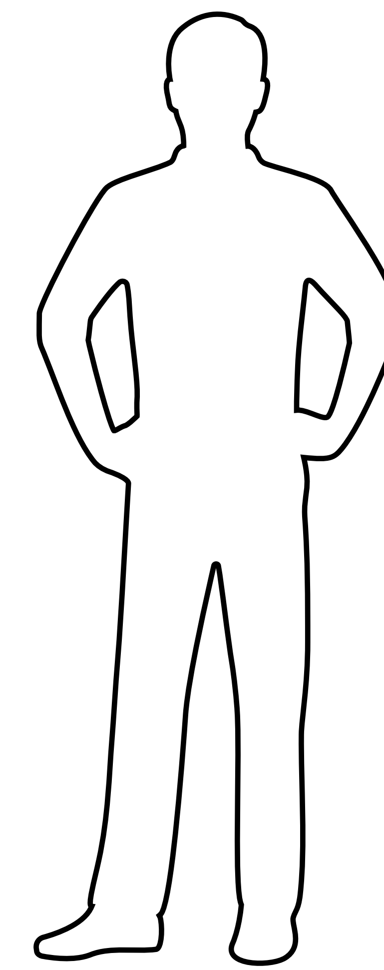
Additional material

Simulation studies

Realistic detector geometry



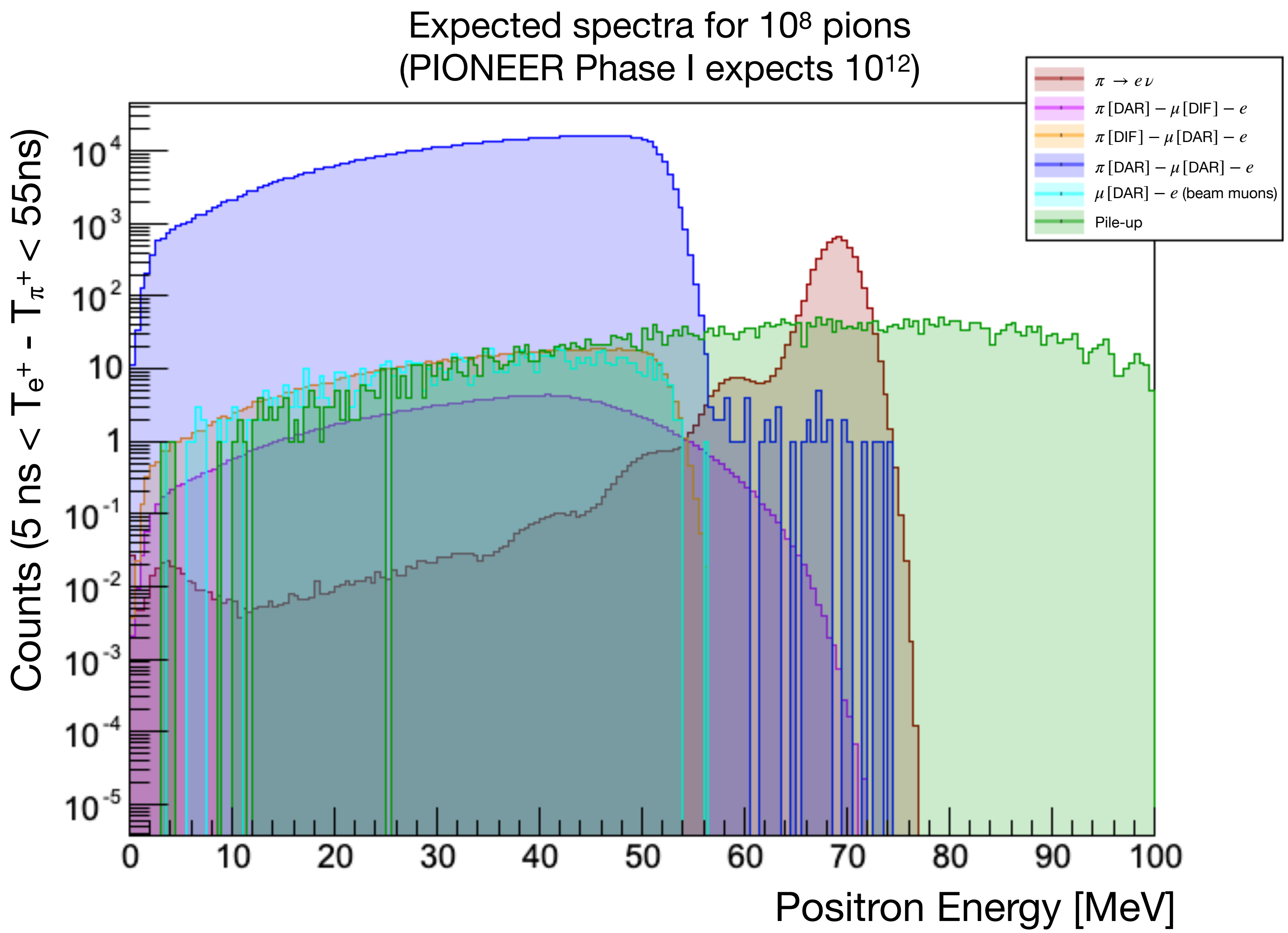




A human-scale experiment

Simulation studies

Prototyping the data analysis

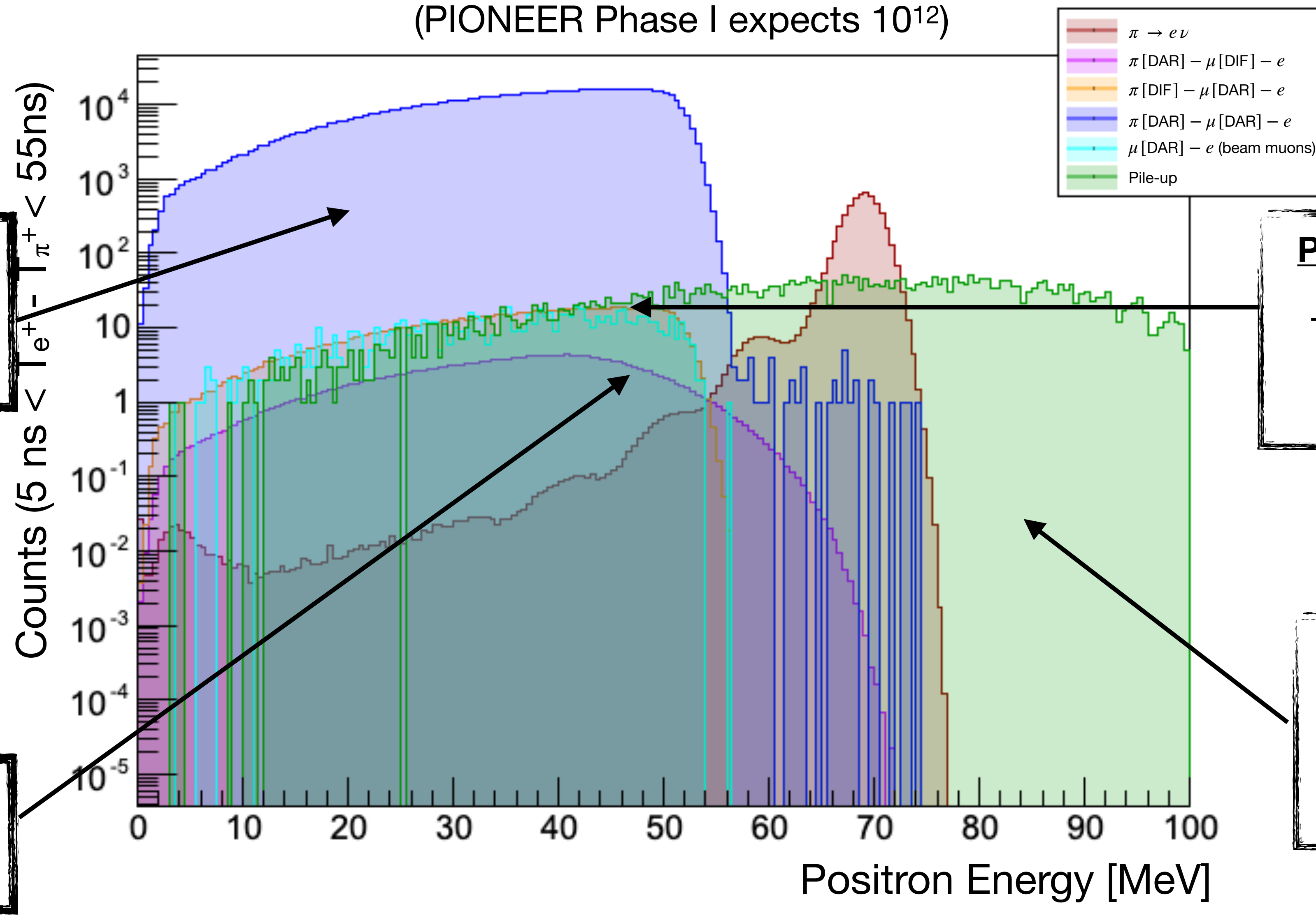


This is what real data could look like

Simulation studies

Prototyping the data analysis

Expected spectra for 10^8 pions
(PIONEER Phase I expects 10^{12})



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

Muon Decay In Flight
'The hard ones'
need O(10^2) rejection

Pion Decay In Flight and beam muons
Topology, energy-range, time spectra
need O(10^4) rejection

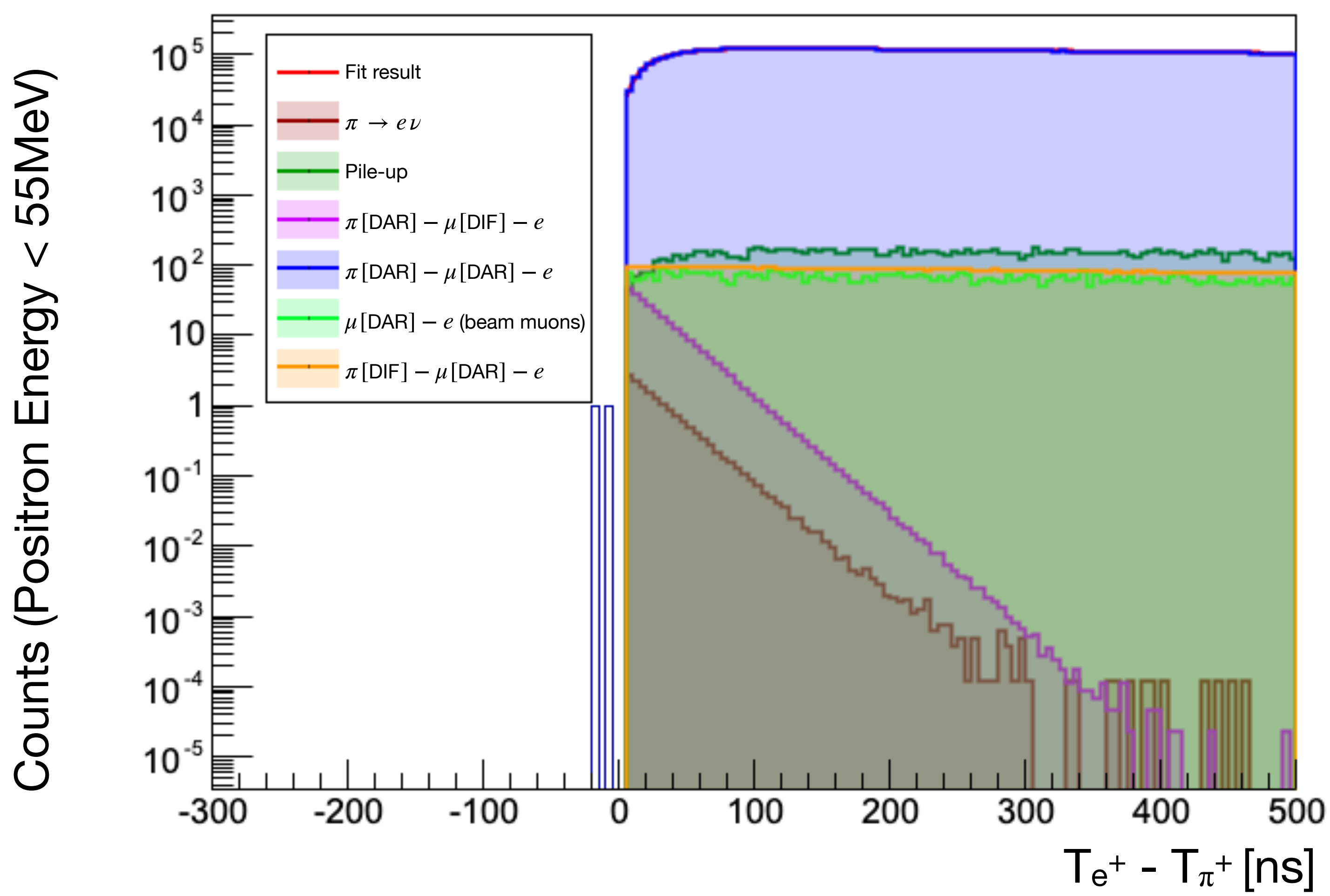
Pileup
Spatial resolution in the target
Time separation from the pion stop

Measuring the tail fraction: Select background-free sample with minimal bias while maintaining a decent (>1%) efficiency

Simulation studies

Prototyping the data analysis

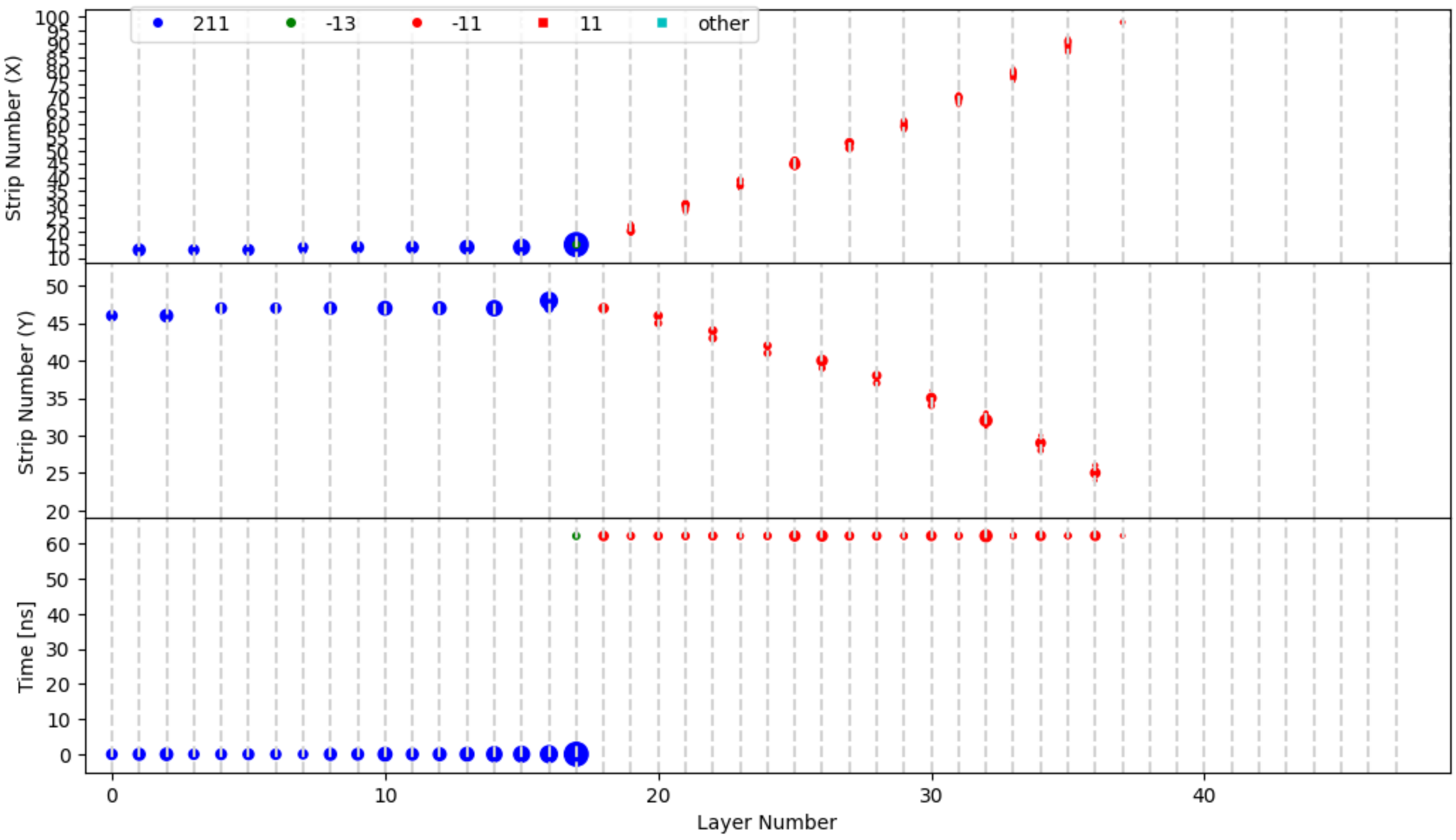
Expected spectra for 10^8 pions
(PIONEER Phase I expects 10^{12})



$\pi[DAR] - \mu[DIF] - e$ and $\pi \rightarrow e\nu$ have the same time spectrum,
suppression can only be achieve using energy and topology from the active target

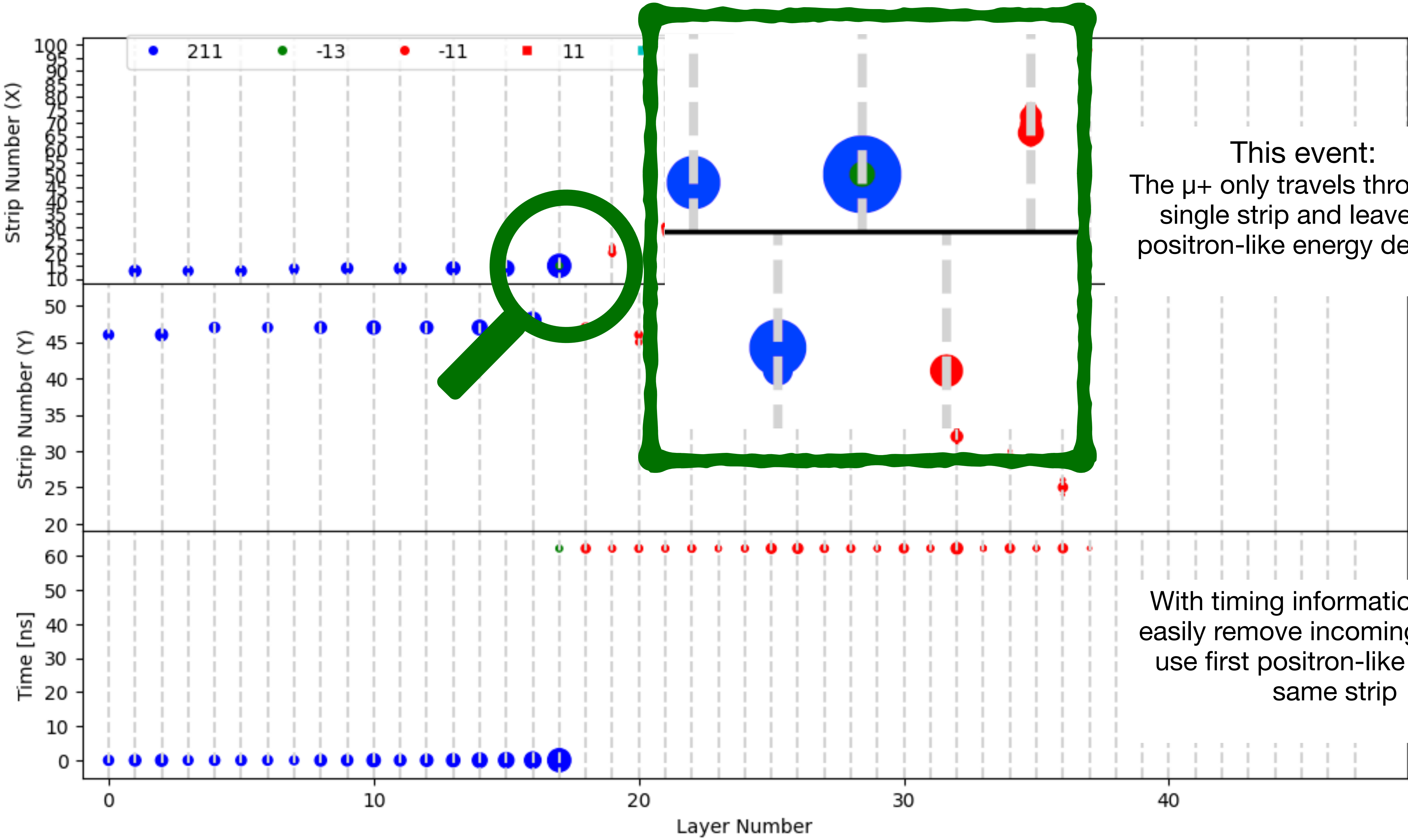
Simulation studies

Muon decaying in flight (DIF)



Simulation studies

Muon decaying in flight (DIF)



This event:
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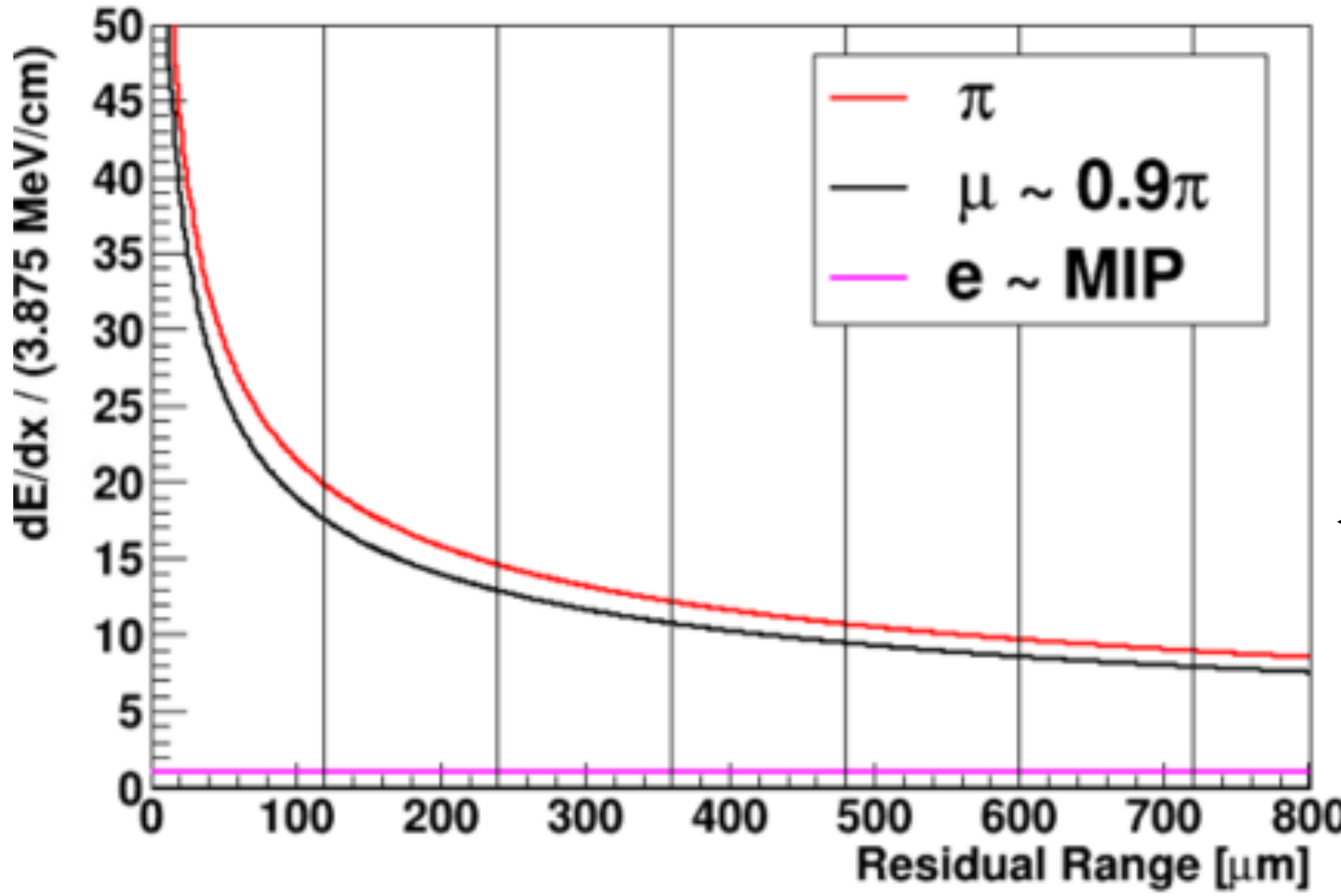
Simulation studies

Muon decaying in flight (DIF)

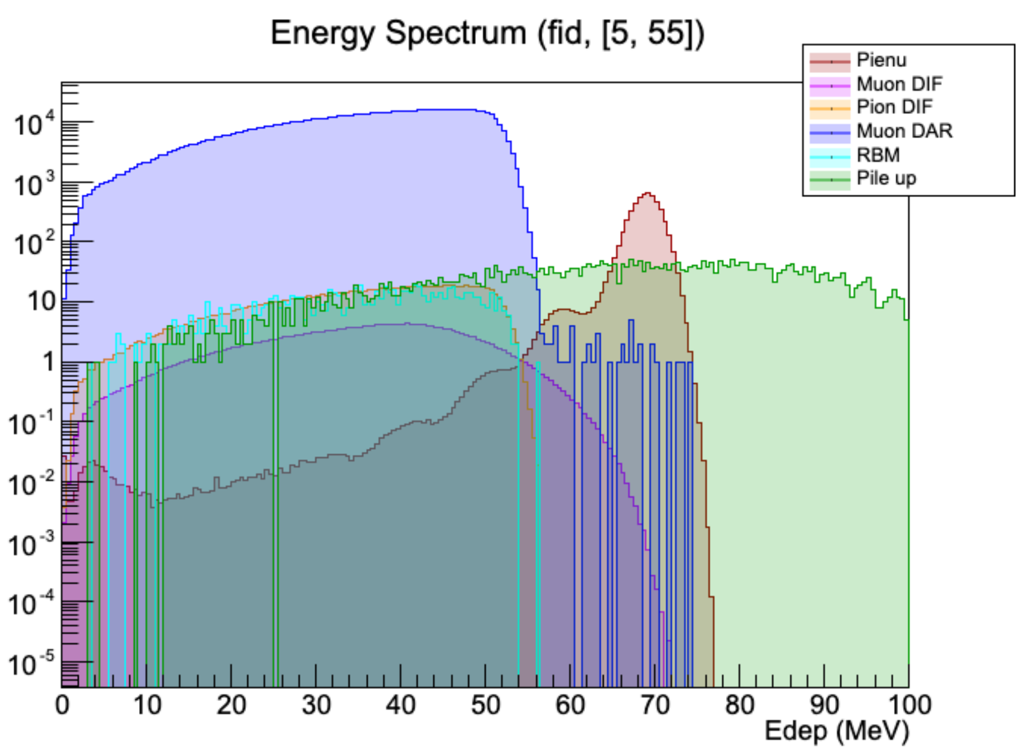


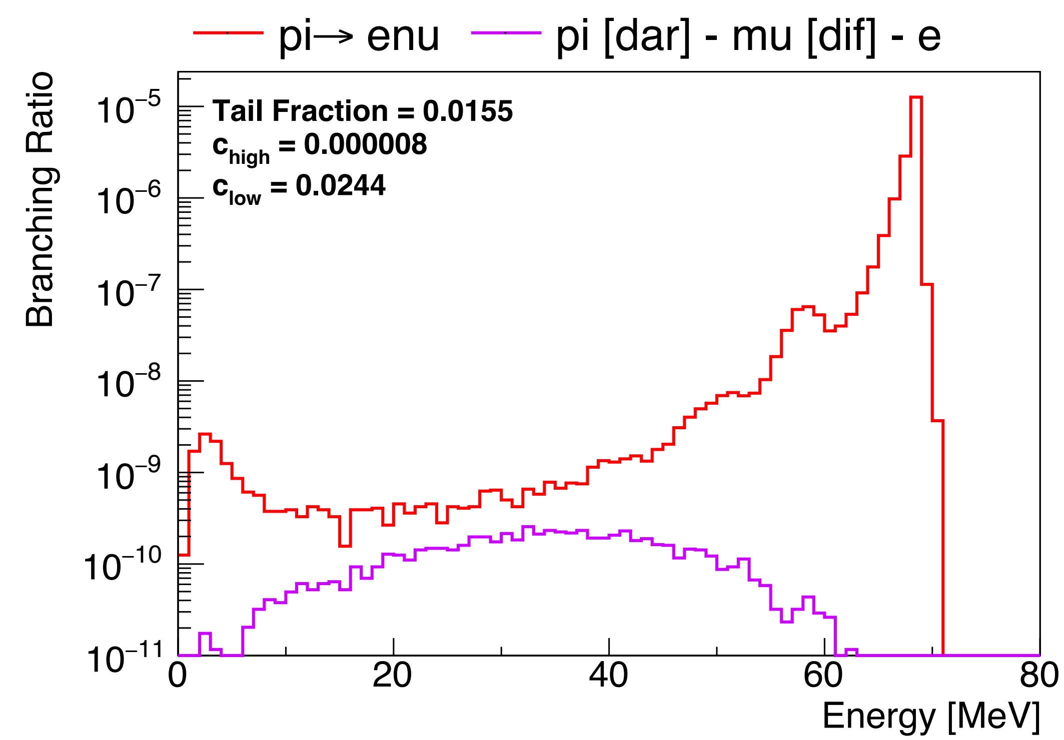
A Particle enters ATAR here

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

Simulation studies

Muon decaying in flight (DIF)

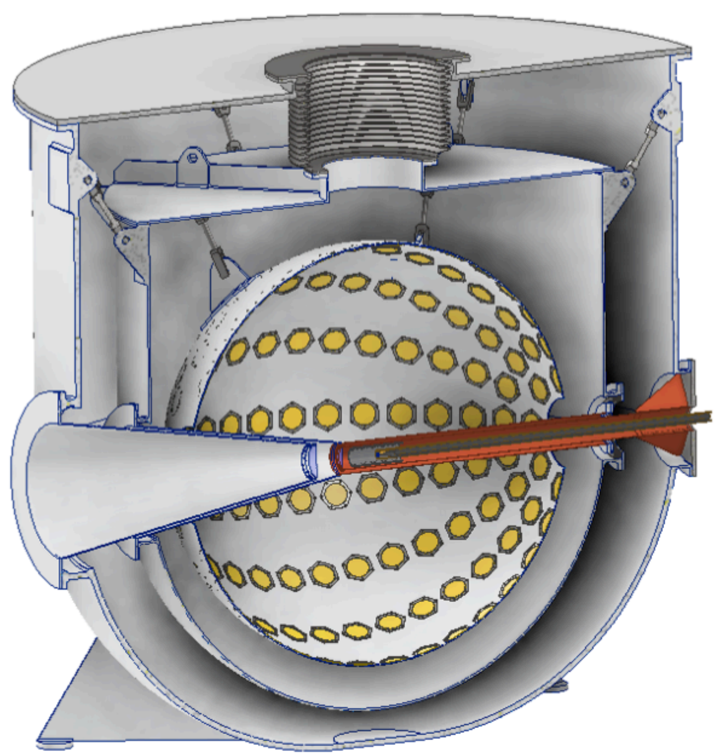




The instrumented active target is a fantastic tool to understand the backgrounds and achieve our targeted sensitivity

PIONEER

Liquid Xenon



Fast response
Highly homogeneous response
Detector can be reshaped

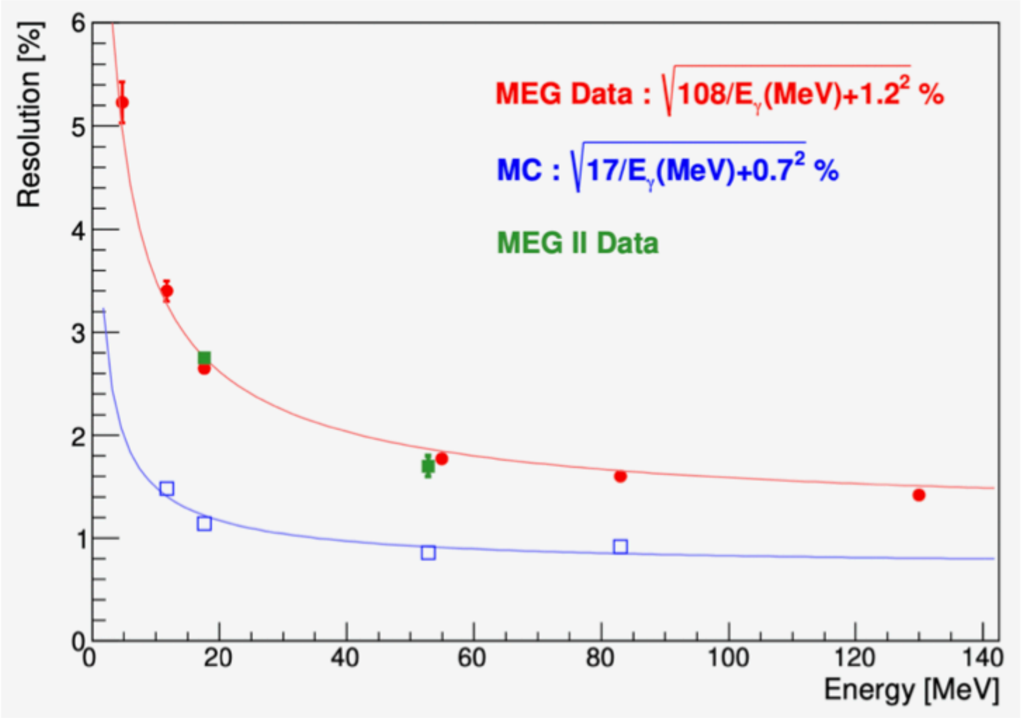
PI E NU

Uncertainty Budget

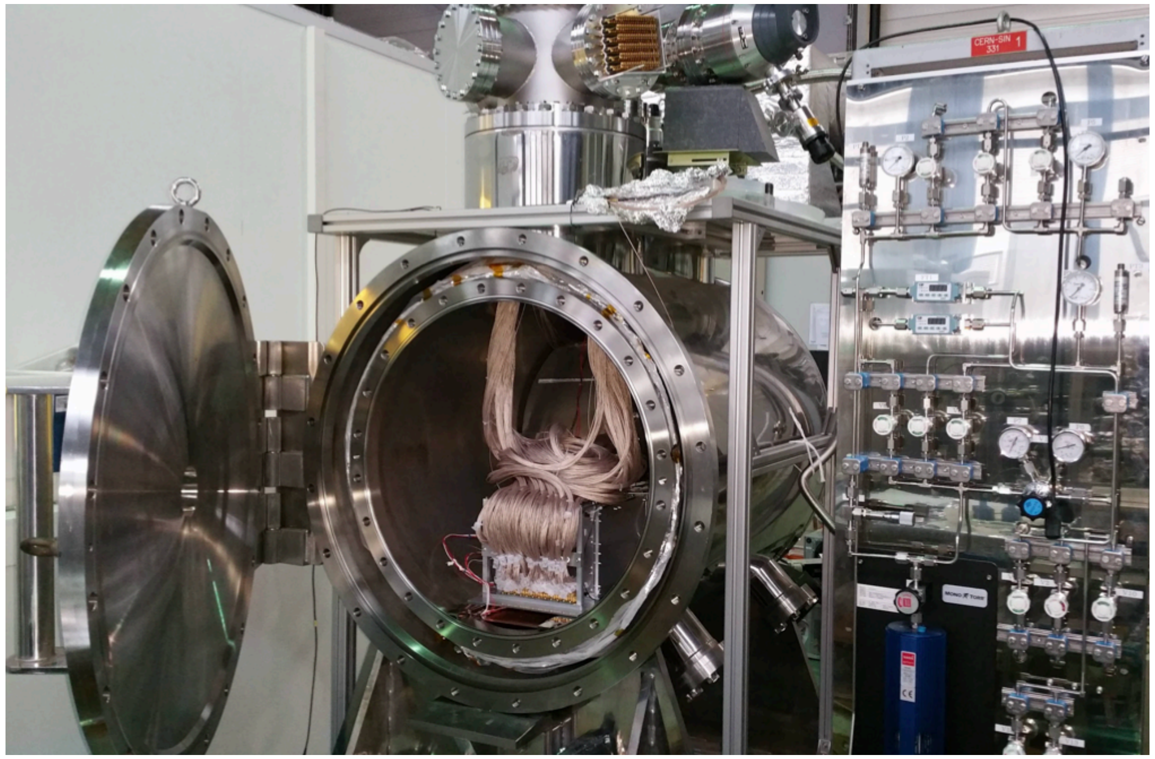
Source	%
Statistics	0.19
Tail Correction	**0.12**
Total Uncertainty	0.24

Calorimeter Developments

Liquid Xenon Prototype

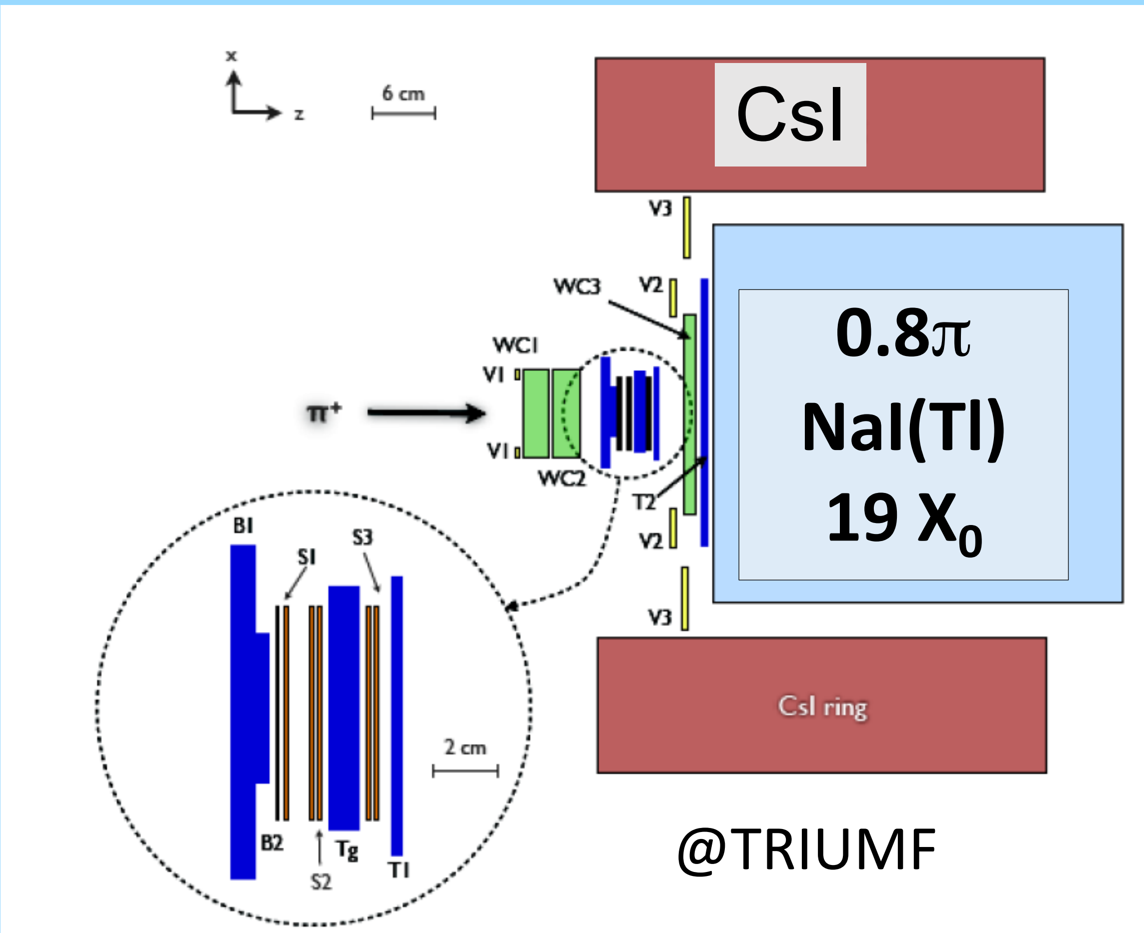


- Series of prototypes leading to a large 100L, $28X_0$ cylinder
  - Measure resolution for 70 MeV positrons
  - Check and correct simulations
- Build expertise with LXe handling
- Bonus: prototype could set stringent limits on μ→eeeee (arXiv:2306.15631)



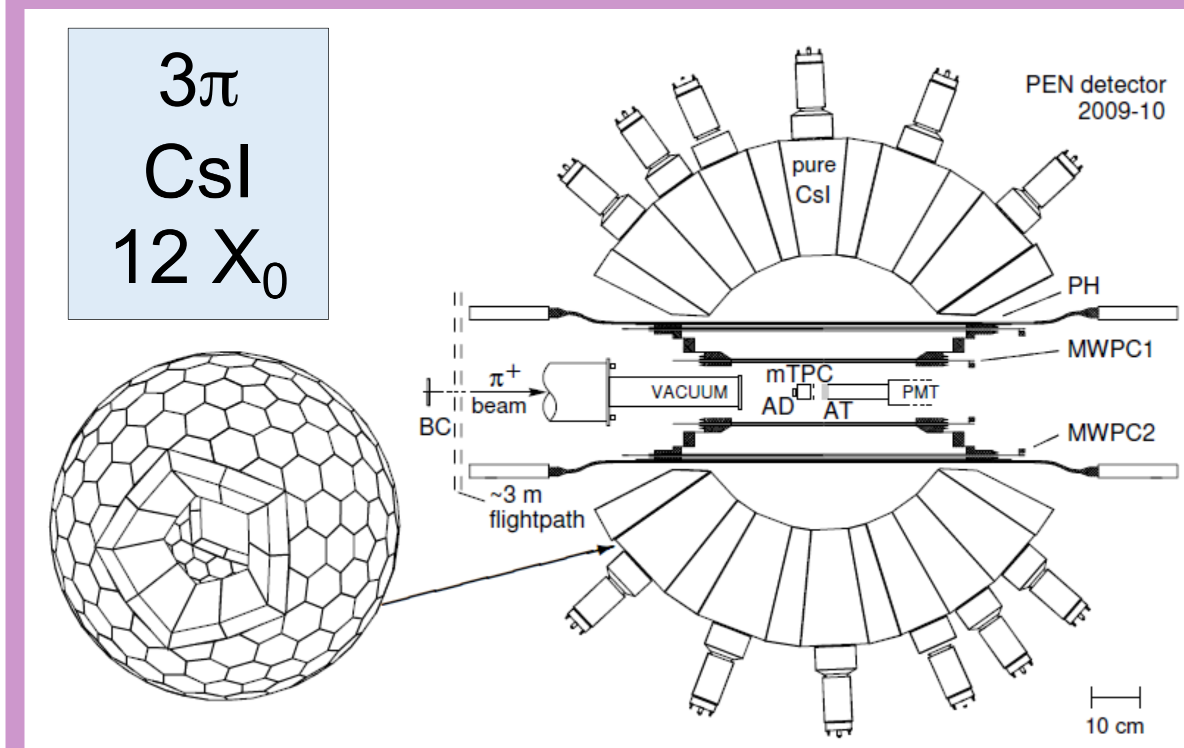
Two recent Pion Decay Experiments

PIENU



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

PEN/PIBETA



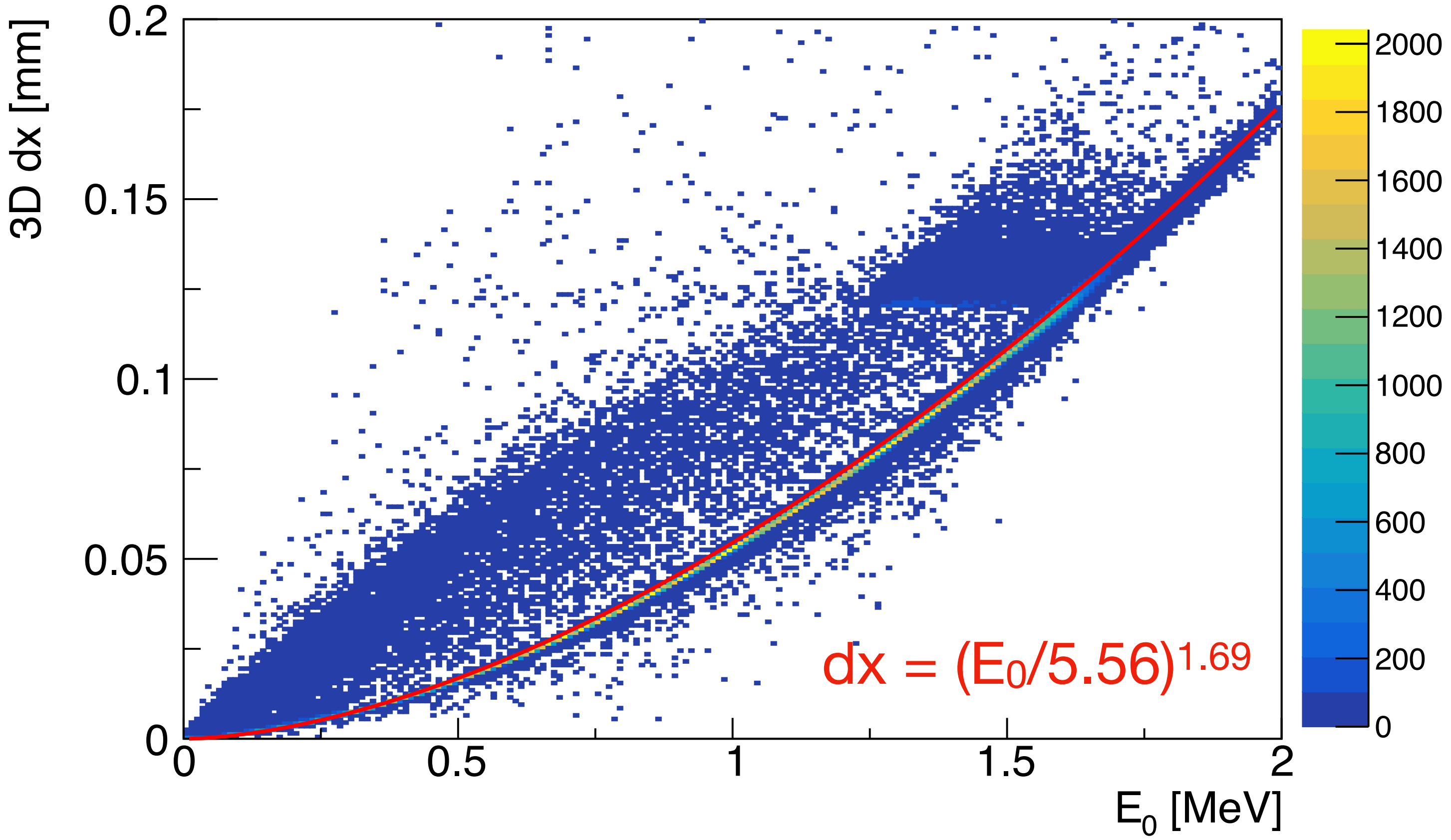
- Experiment at PSI
- Large acceptance but calorimeter depth of $12X_0$ too small to resolve tail under the π-μ-e spectrum.

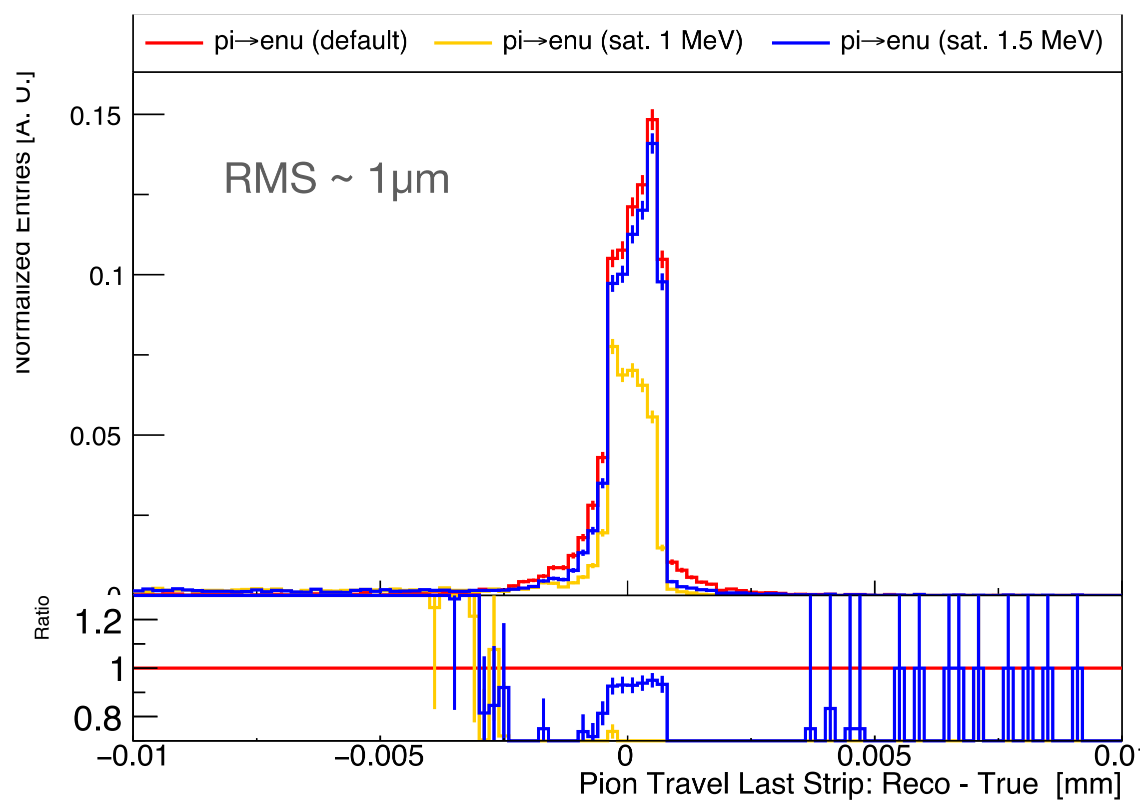
Both experiments took data a while ago but have (known) challenges to overcome before final results

Simulation studies

A difficult case: muon decaying in flight

Step 1: Precisely determining the pion stopping position

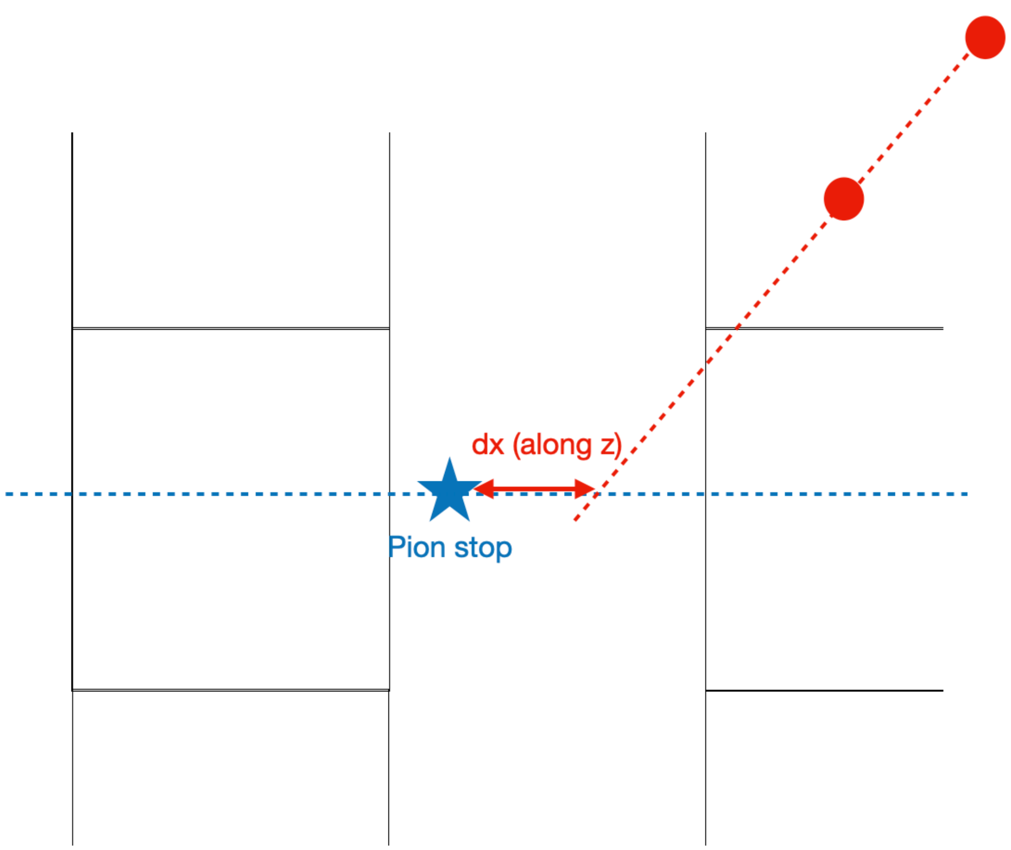


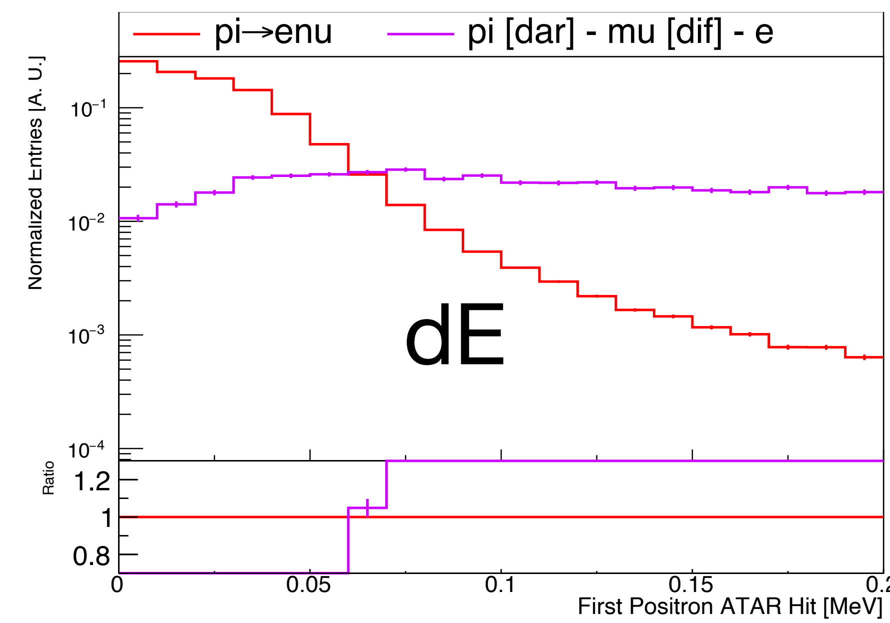


Simulation studies

A difficult case: muon decaying in flight

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





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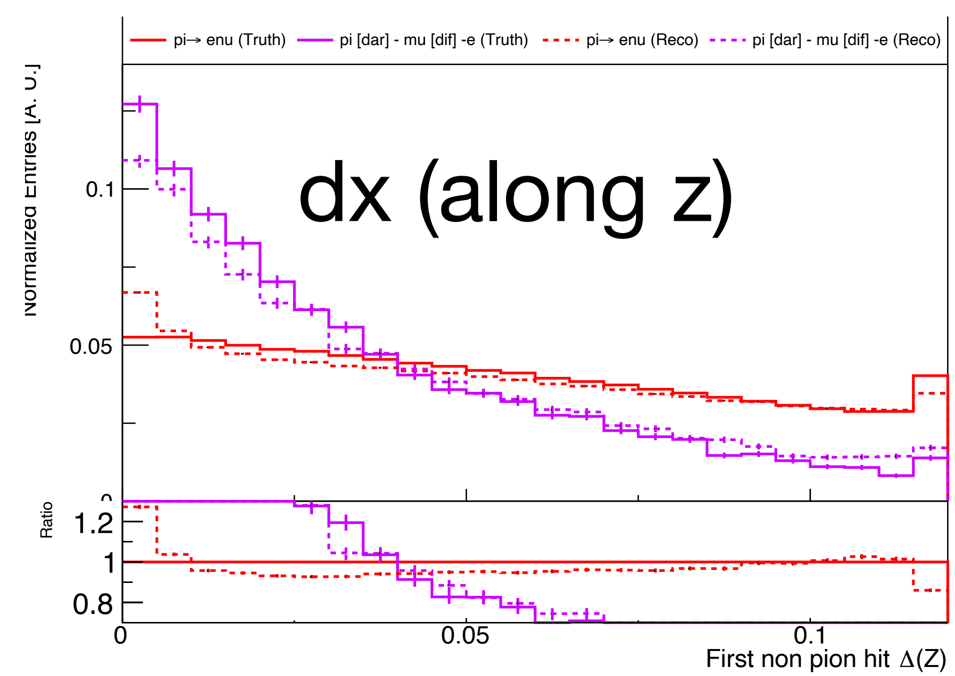
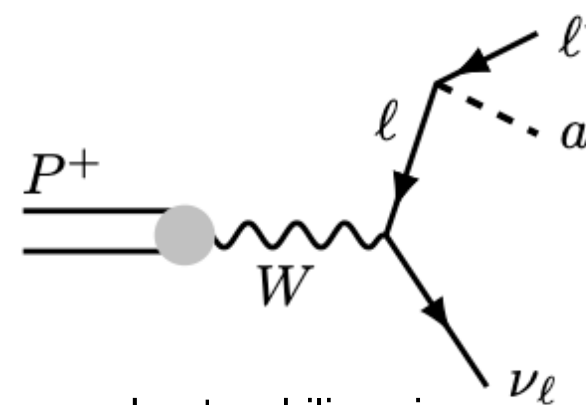


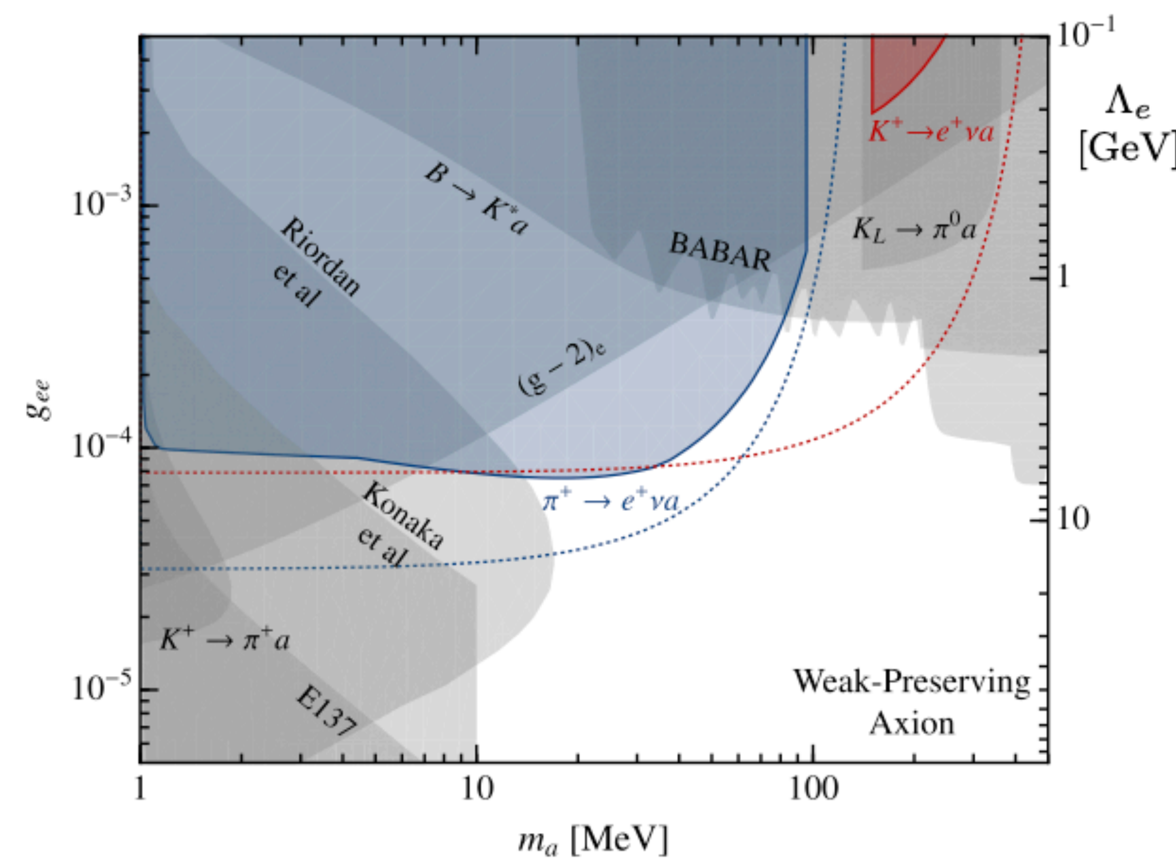
Rare Pion Decays

Direct searches for new physics

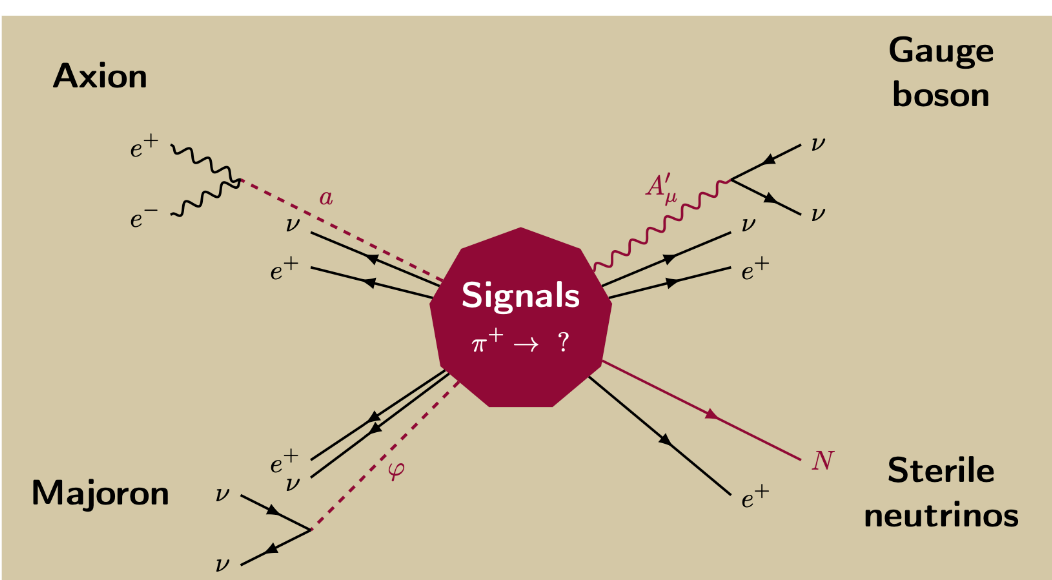
- Collecting very large samples of rare pion decay
    - Search for new weakly coupled particle in the MeV range
    - E.g. sterile neutrinos or axion-like particles



Lepto-philic axion



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



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