Pioneer: A next generation rare pion decay experiment

Quentin Buat (UW) - REU Monday Meeting - July 24, 2023

But first, a few slides about me

- Joined UW as a faculty a 2 years ago
- Research interests:
  - Higgs physics at the LHC
  - Machine learning for particle physics event reconstruction
  - Rare pion decay experiments

Quentin Buat

But first, a few slides about me

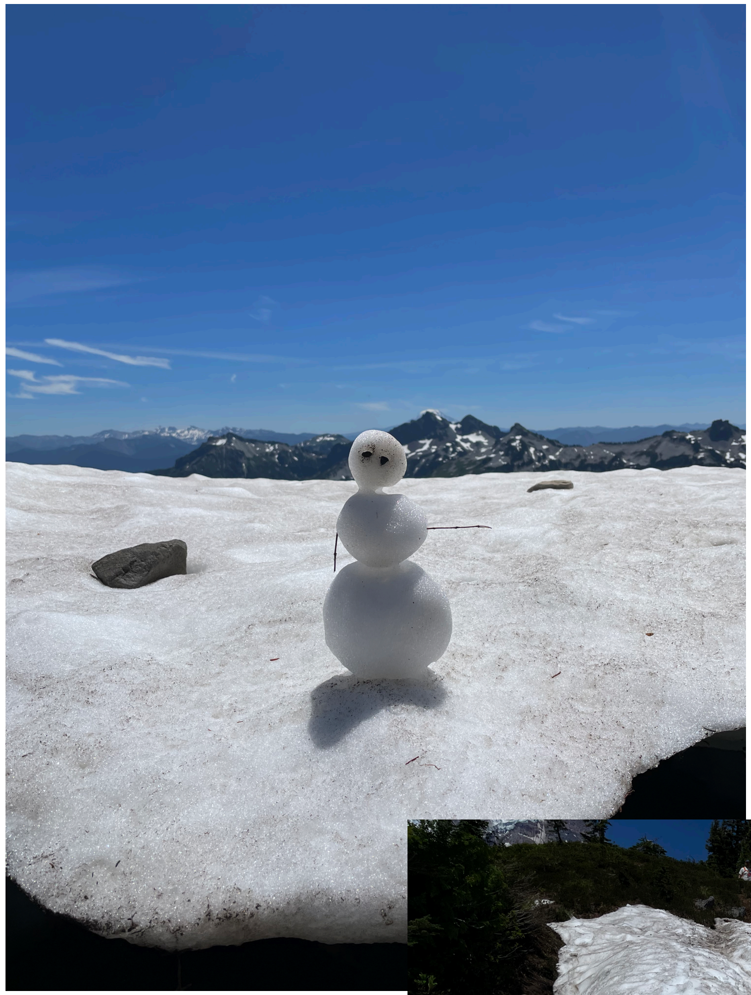
2010 - 2013 - PhD in Grenoble, France

2014 - PostDoc in Vancouver (SFU)

2015 - And in Geneva, Switzerland (CERN)

Which prepared me perfectly for …

Leading the REU trip to Mt Rainier



The SM of Particle Physics

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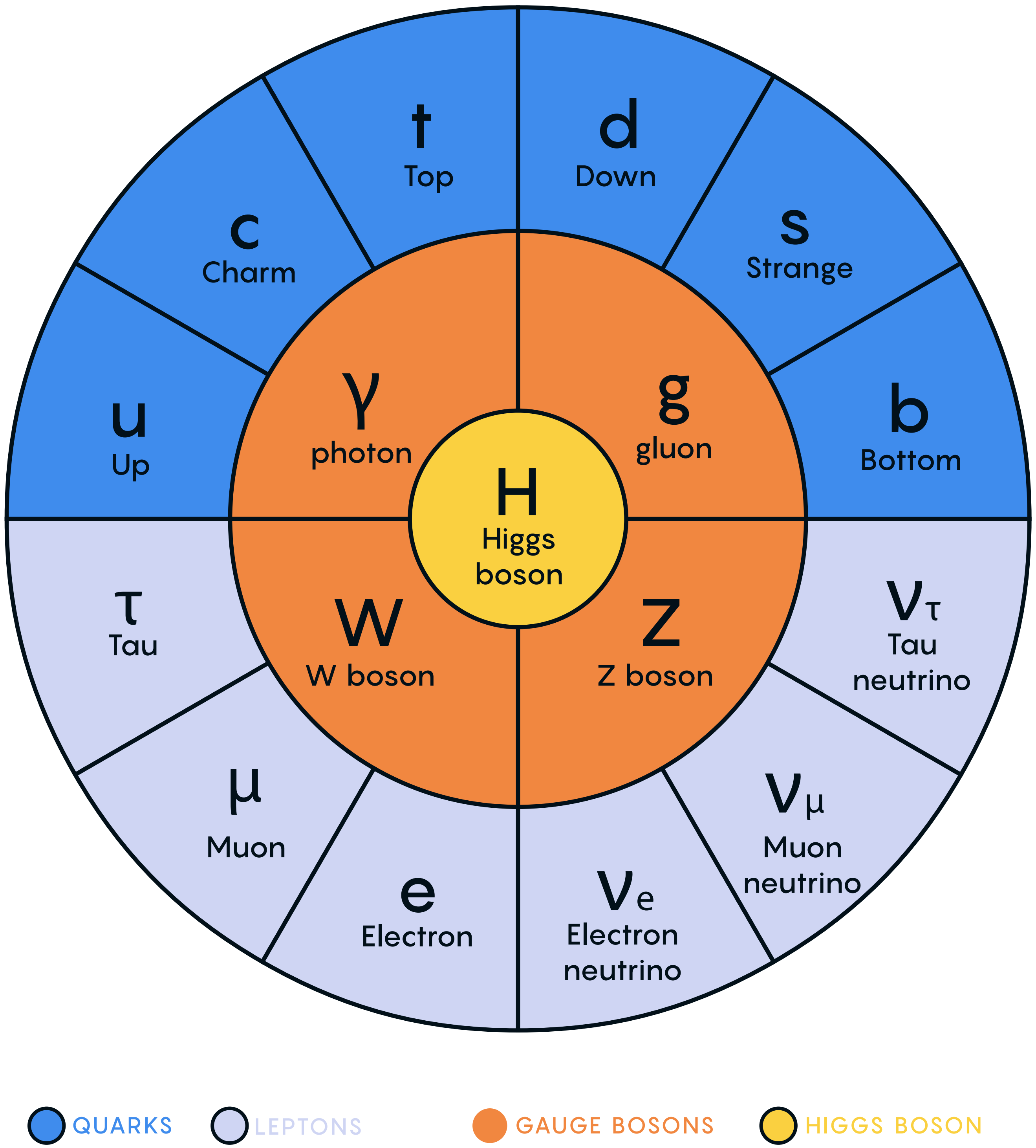
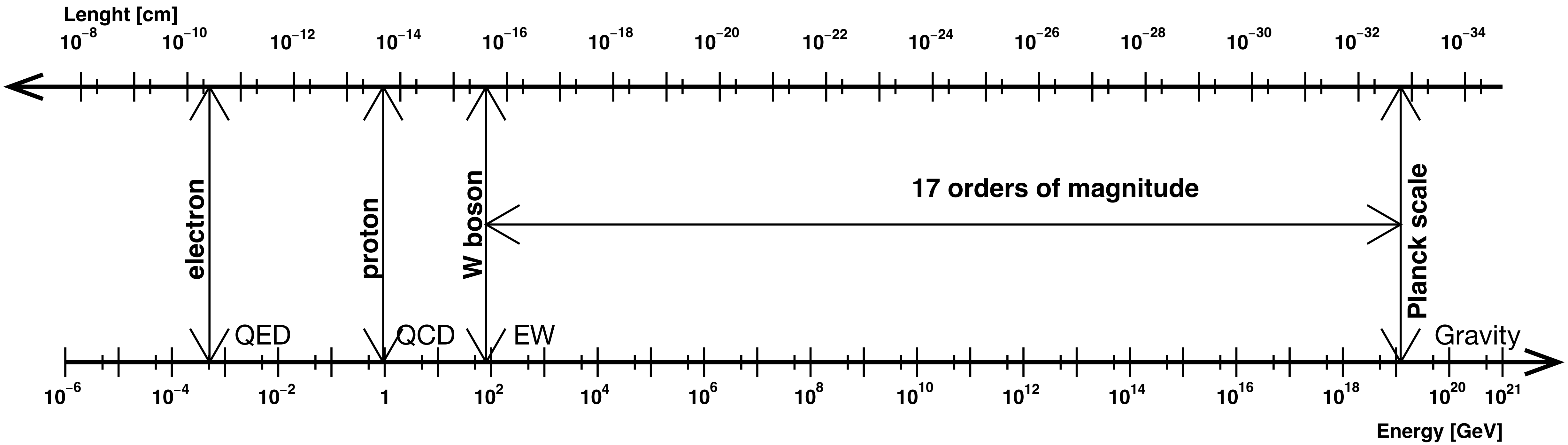


Fundamental interactions



Known forces in Nature and their associated energy scale

Particle Physics in the XXI century: explore the gap between EW and Gravity scales

The direct approach

Collide particles at the highest possible energy

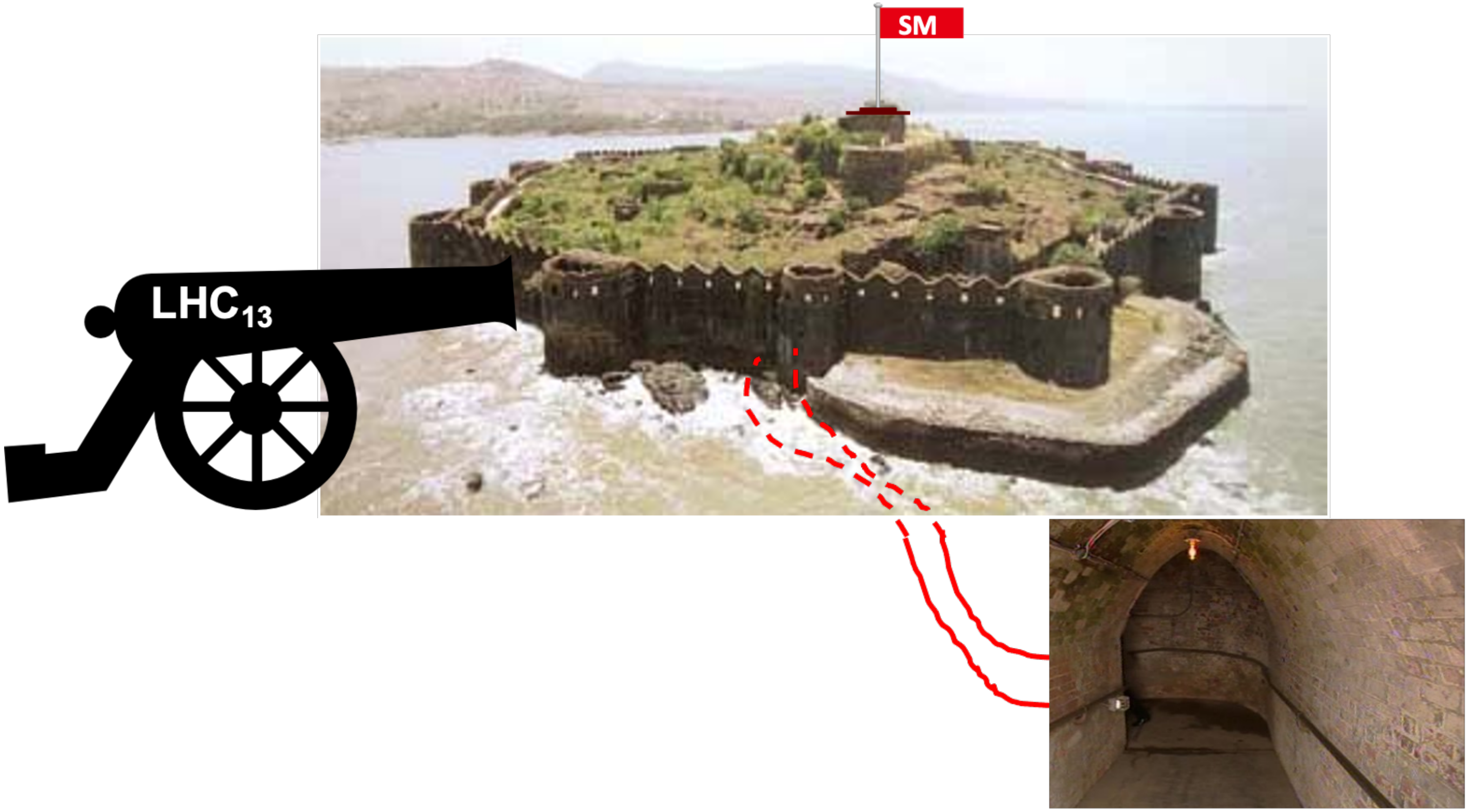
The LHC: 27km circular collider near Geneva, Switzerland

Most powerful collider in the world: collision at a centre-of-mass energy of 13.6 TeV

Discovered the Higgs boson and deploy a comprehensive measurement program to understand the Higgs sector

However, no sign of deviations from the SM and no large collision energy increase foreseen anytime soon

What else can we do?

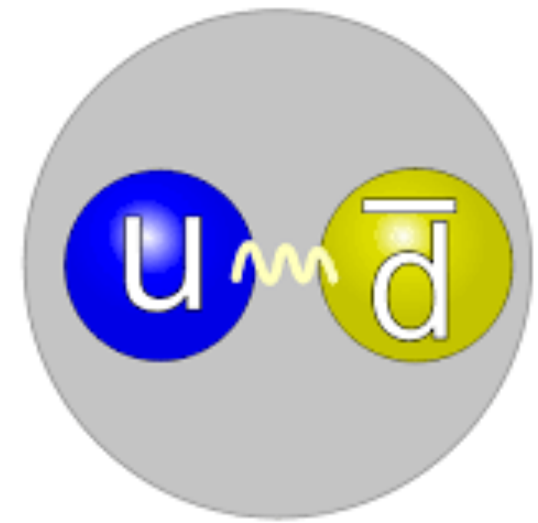


High energy particles can have an impact at lower energy through quantum effects

PIONEER Studies charged pions

π^+

- Mass = 139.57039 ± 0.00018 MeV [ppm]
- Lifetime = 26.033 ± 0.005 ns [~0.02%]
- Decay Modes:
  - $\pi^+ \rightarrow \mu^+\nu_\mu$ **B**ranching **R**atio 99.98770 ± 0.00004 %
  - $\pi^+ \rightarrow e^+\nu_e$ **B. R.** $(1.230 \pm 0.004) \times 10^{-4}$ [~0.3%]
  - $\pi^+ \rightarrow \pi^0\nu_e e^+$ **B. R.** (1.036 ± 0.006) $\times 10^{-8}$ [~0.6%]
  - $\pi^+ \rightarrow e^+\nu_e e^+ e^-$ **B. R.** $(3.2 \pm 0.9) \times 10^{-9}$

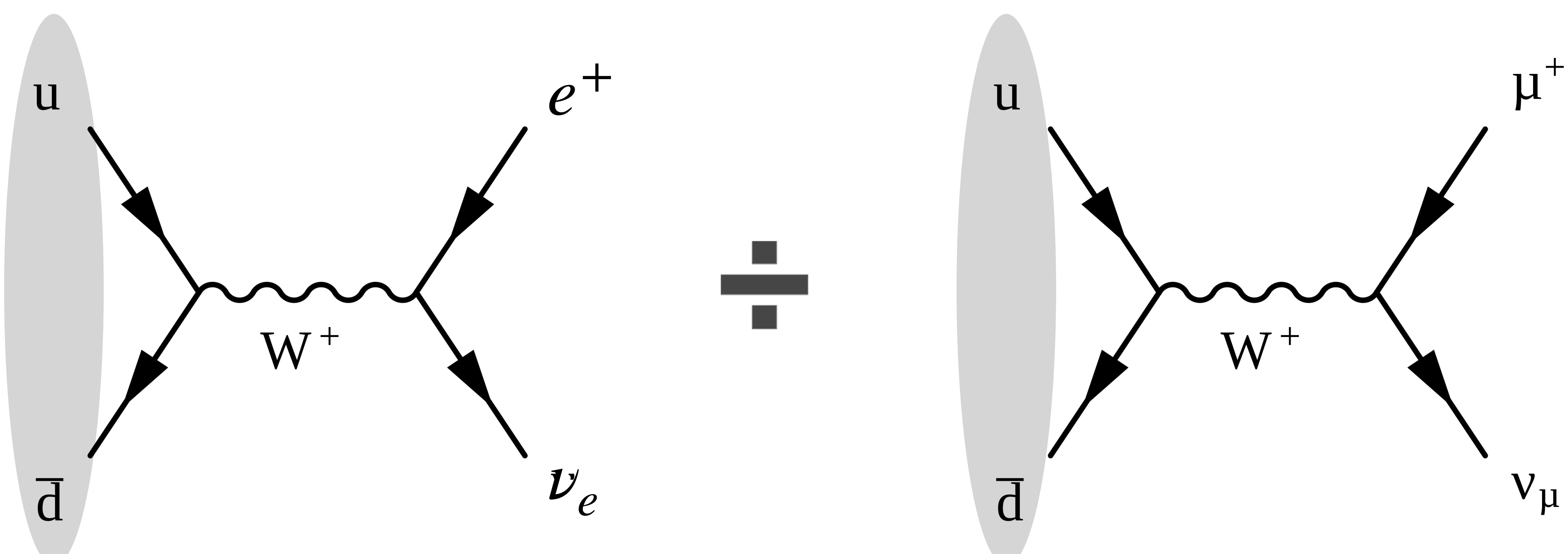


Quark model

Rare pion decays

- Probe Some interesting features of the weak interaction:
  - Same coupling for three generations of leptons: lepton flavour universality

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



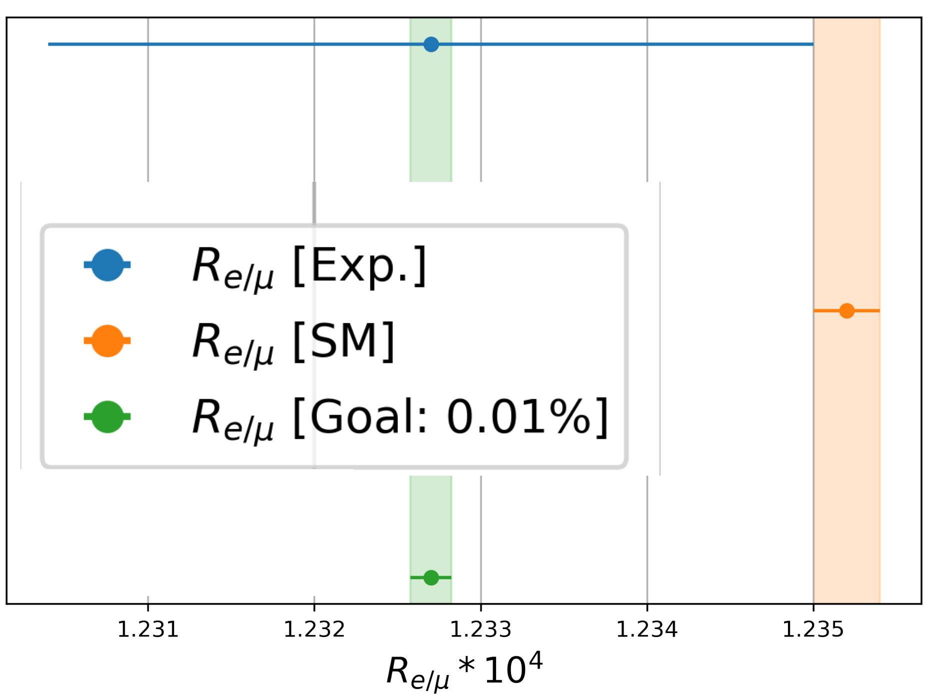
Physics Motivation I:

Testing Lepton Flavor Universality

- **LFU in SM: the weak coupling "g" is the same for $e/\mu/\tau$ leptons**
- $R_{e/\mu} = \dfrac{\Gamma(\pi \to e\nu(\gamma))}{\Gamma\left(\pi \to \mu\nu\left(\gamma\right)\right)}$, currently best, tested charged LFU at $O(10^{-3})$

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

→ possibly the most accurately calculated decay process involving hadrons



PIONEER aims to measure $R_{e/\mu}$ to ~0.015%, x15 improvement over the current world best, matching the SM precision to test lepton flavor universality

Rare pion decays

- Probe Some interesting features of the weak interaction:
  - Same coupling for three generations of leptons: lepton flavour universality
  - Mismatch of quantum states between freely propagating quarks (and neutrinos) and weakly-interacting ones:
    - This leads to a mixing matrix (called CKM for quarks)

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

- PIONEER: Looking for violation of LFU and unitarity of the CKM matrix with charged pions decay

Physics Motivation II:

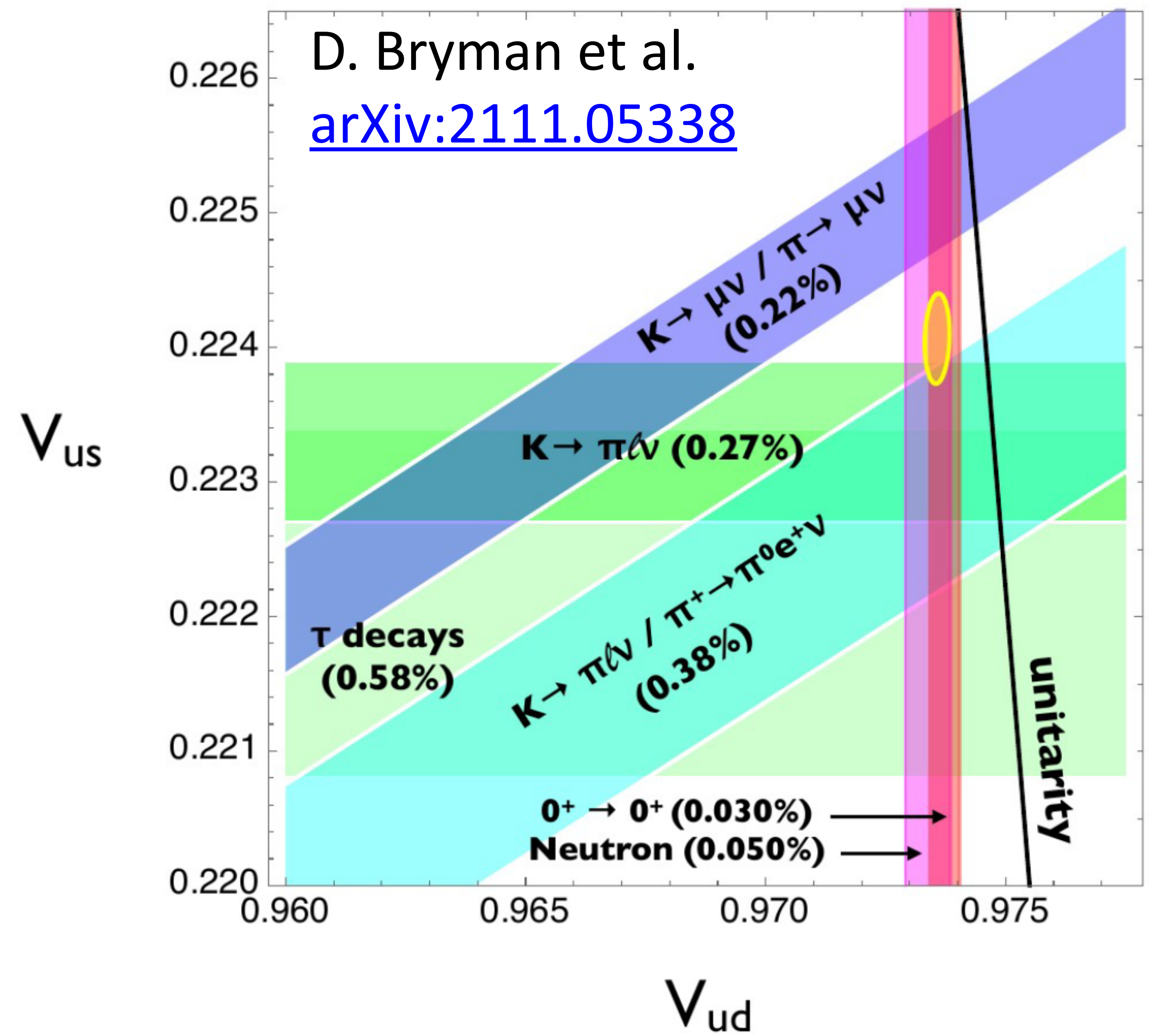
Testing CKM Unitarity

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

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

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

~3σ tension in the first-row of CKM unitarity test
Also referred to as Cabibbo Angle Anomaly or CAA

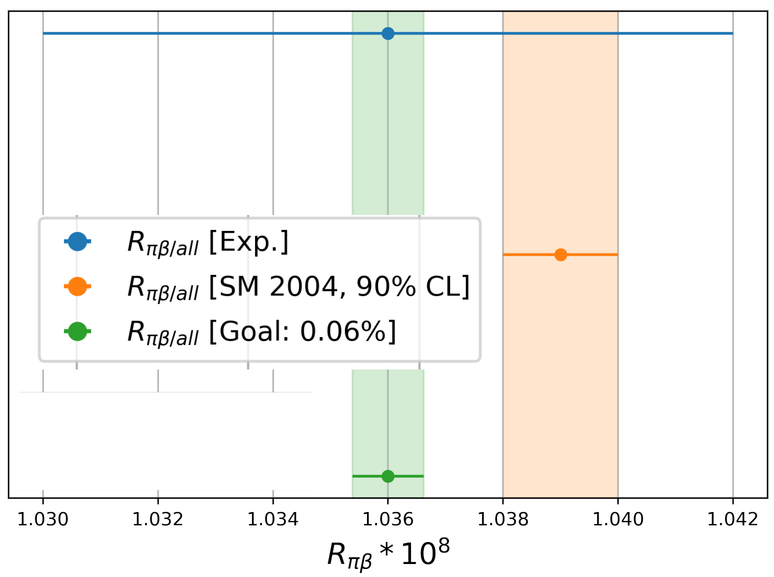


Physics Motivation II:

Testing CKM Unitarity

- Pion beta decay provides the theoretically cleanest determination of $|V_{ud}|$
- $R_{\pi\beta}^{Exp} = \frac{\Gamma(\pi^+ \rightarrow \pi^0 e\nu(\gamma))}{\Gamma(all)} = (1.036 \pm 0.006) \times 10^{-8}$

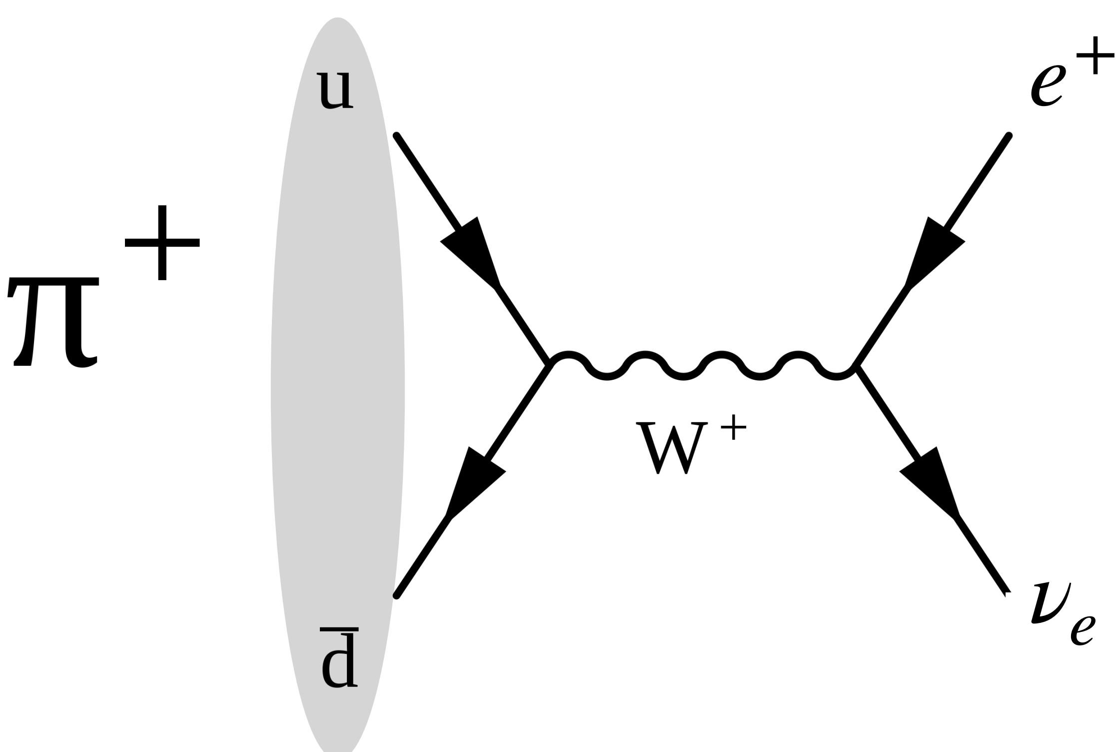
- 10-fold improvement allows for a 0.02% determination of $|V_{ud}|$, comparable to super-allowed beta decay



Introducing Pioneer

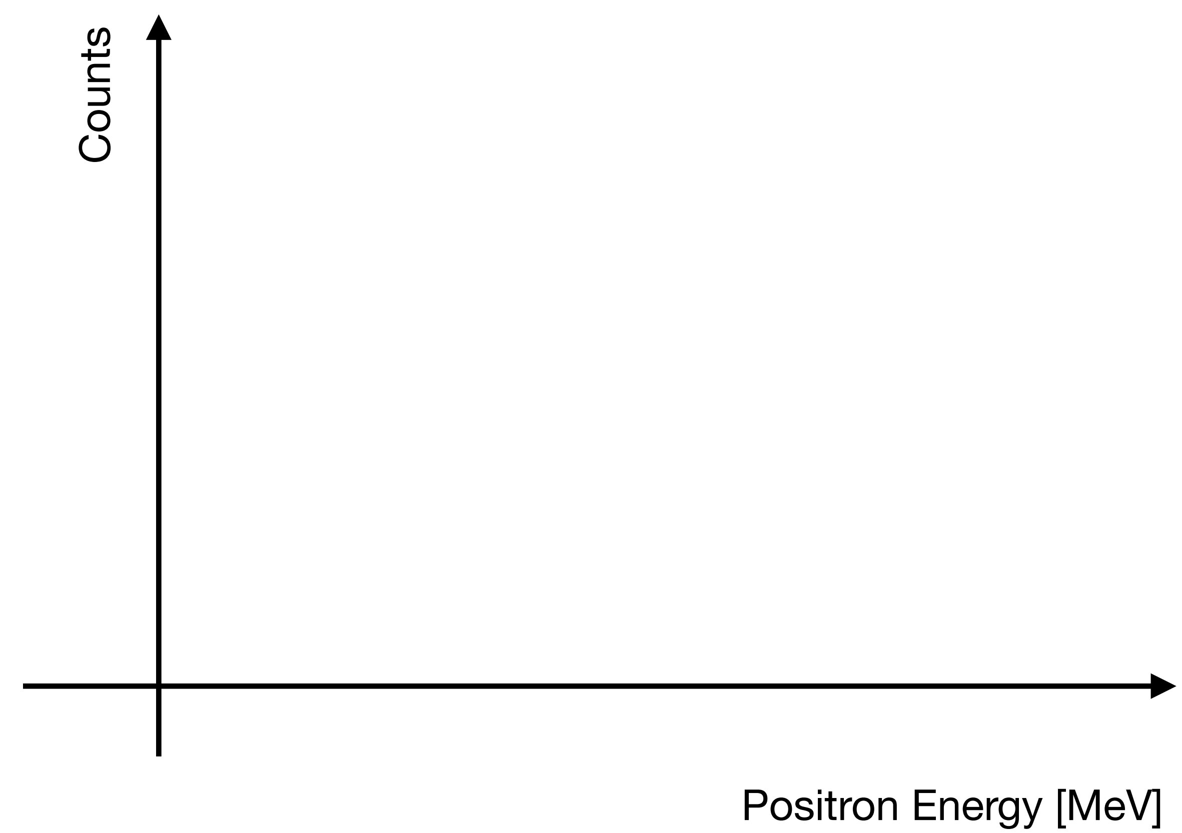
Concept of the Phase I measurement

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



$m_{\pi^+} = 139.57039 \pm 0.00018$ MeV

Pions stop in the target and decay



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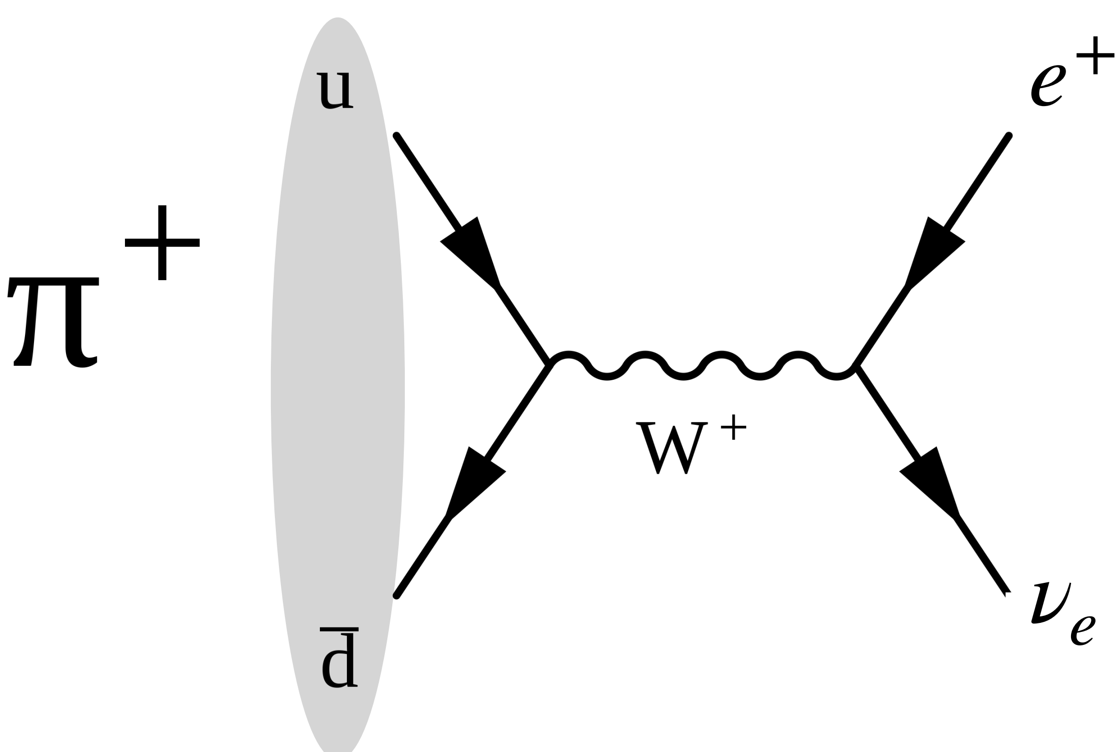

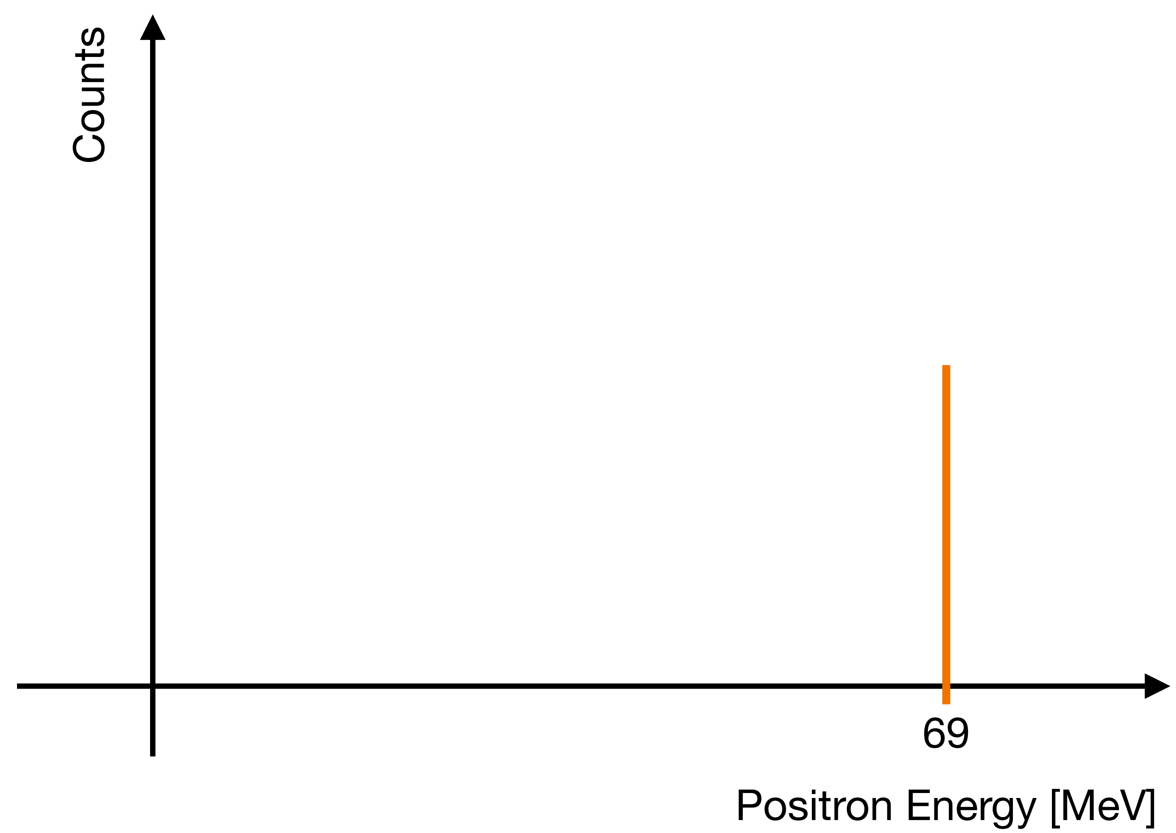

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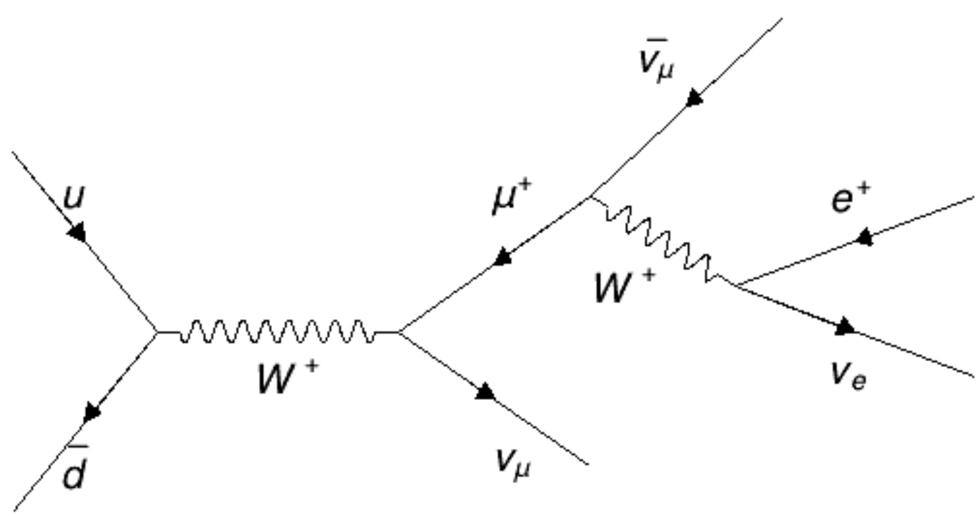
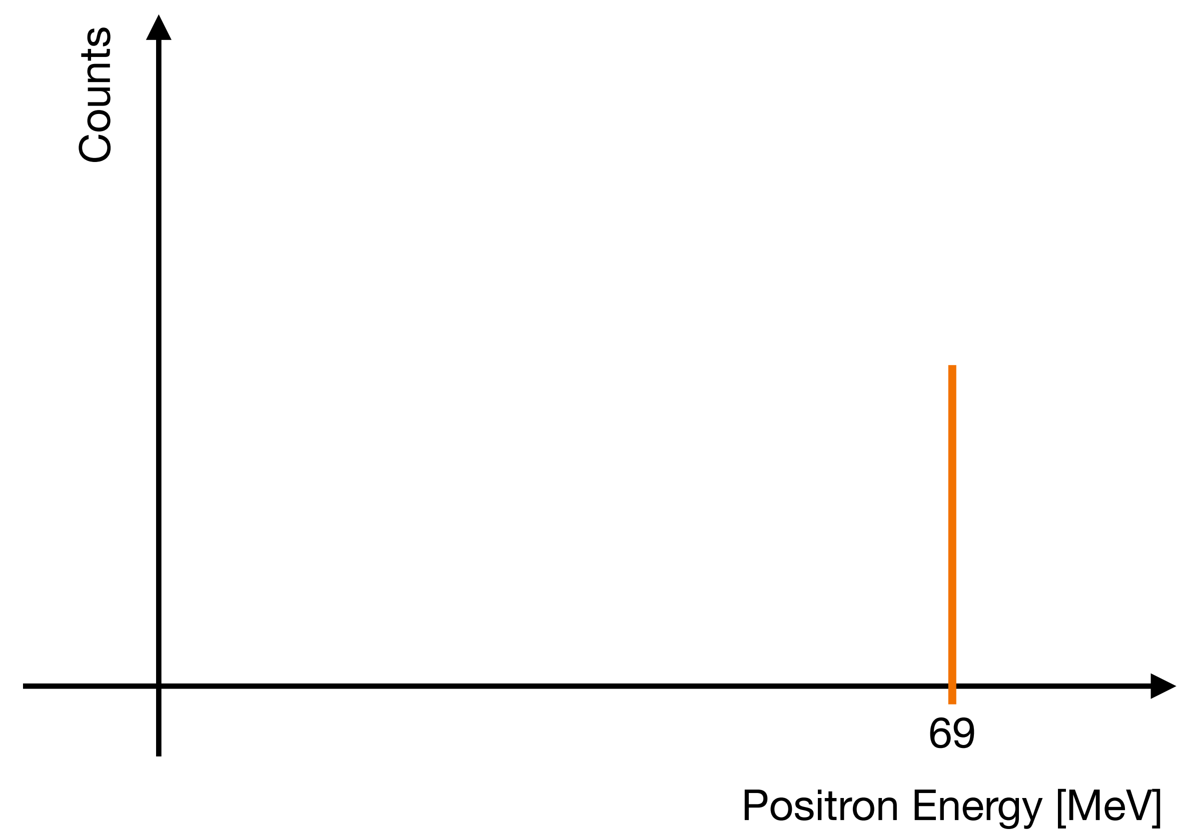


$m_{\pi^+} = 139.6\,\text{MeV}$

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

Pions stop in the target and decay

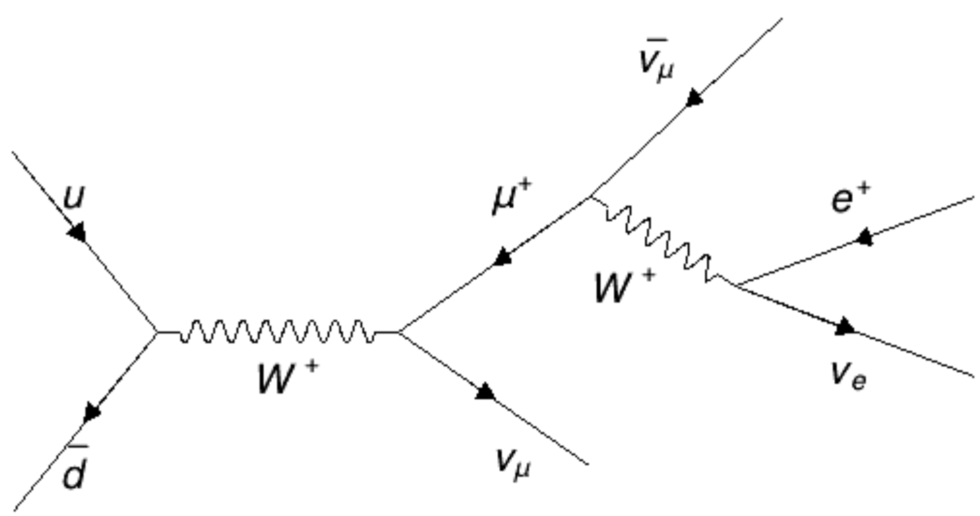
Muons stop in the target and decay

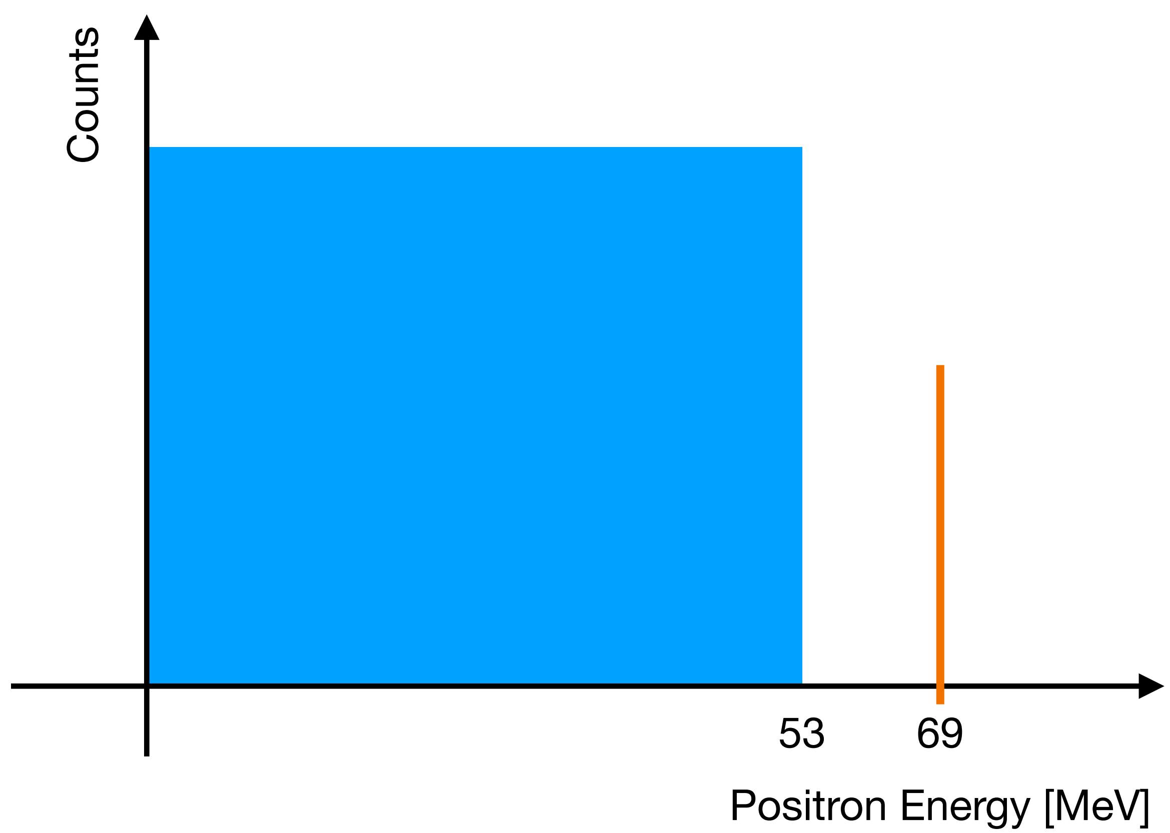


Introducing Pioneer

Concept of the Phase I measurement

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





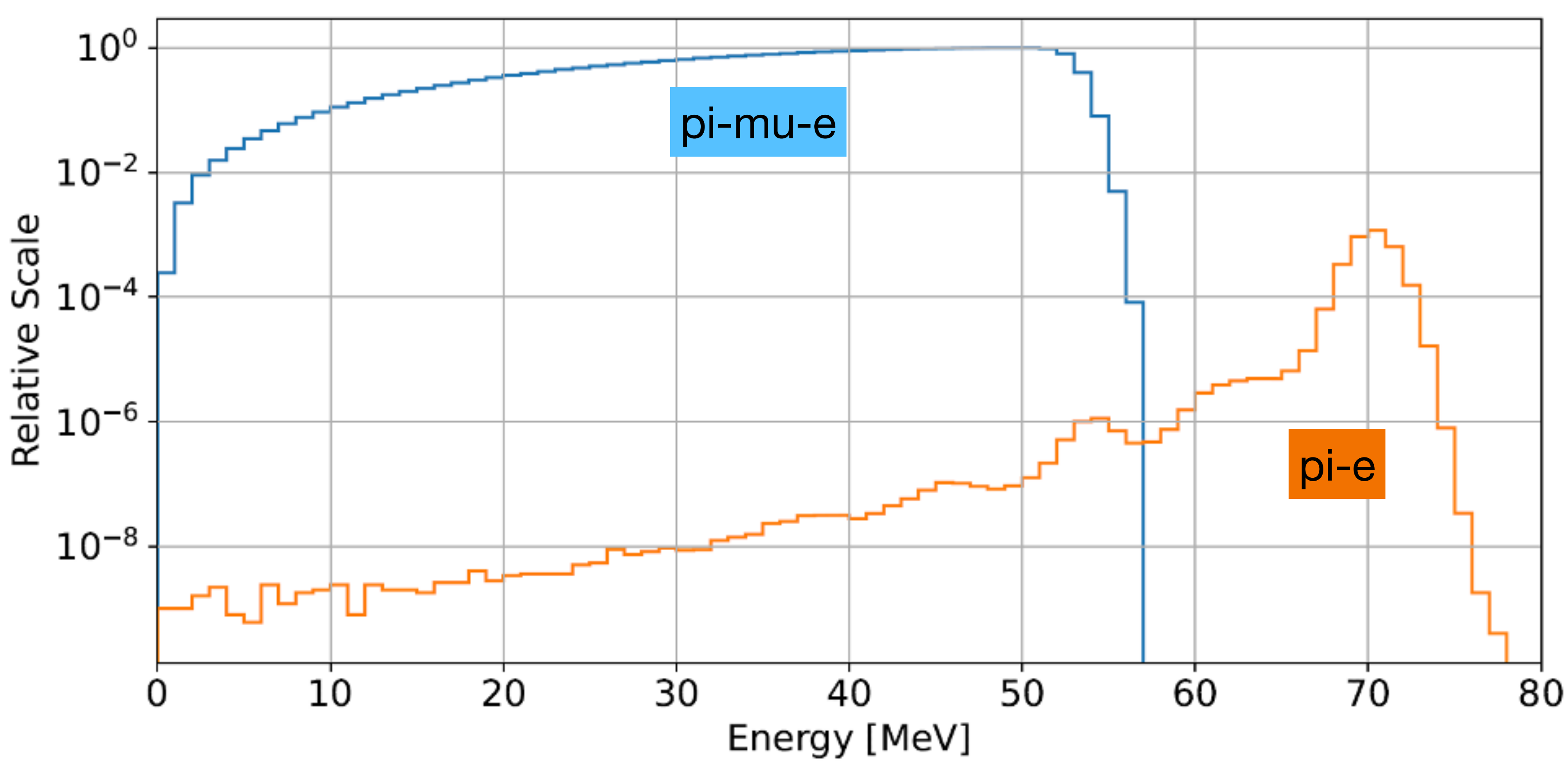
$m_{\pi^+} = 139.6$ MeV

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

Pions stop in the target and decay

Muons stop in the target and decay

Facing experimental reality



Guiding principles to the design of the experiment:

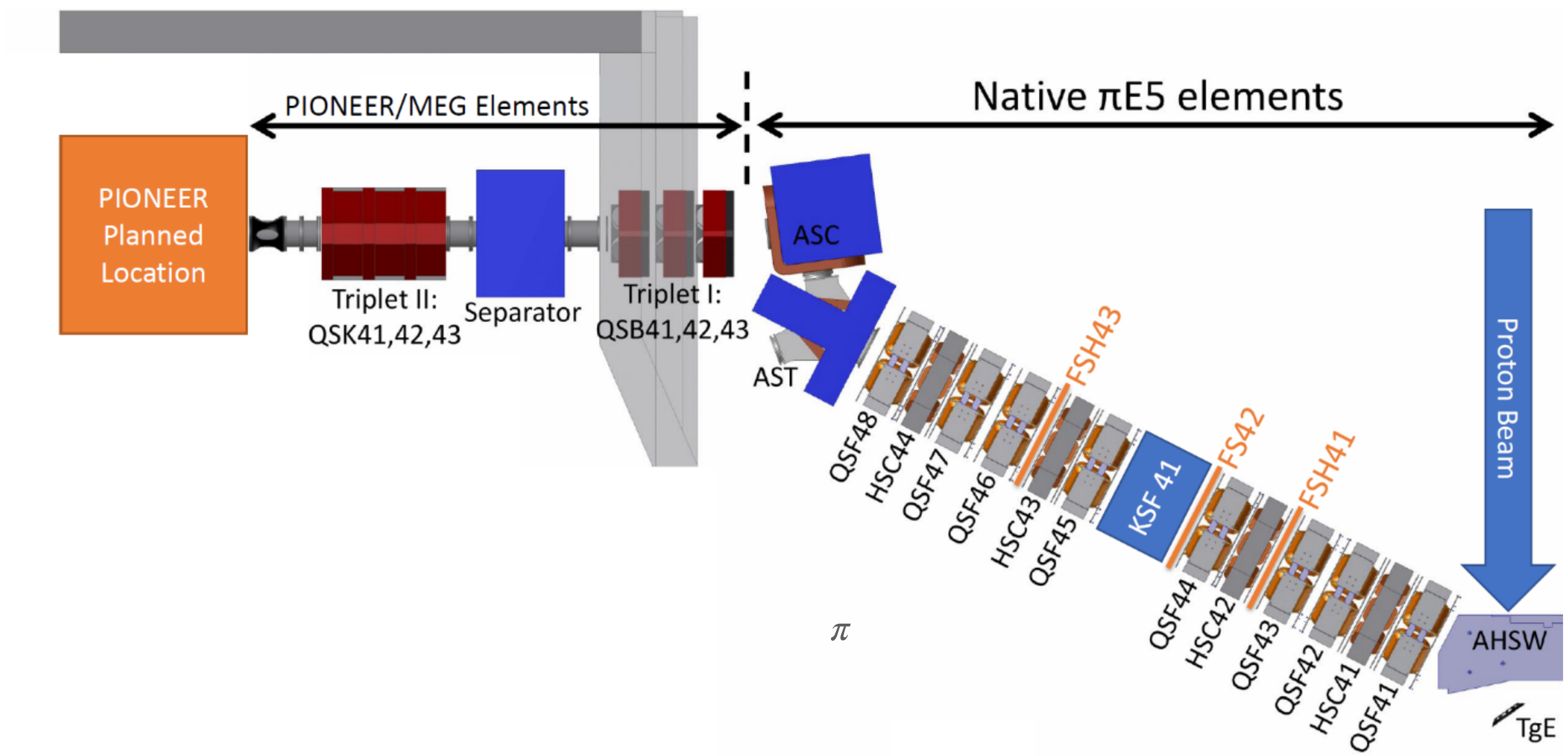
- Collect very large datasets of rare pion decays (2e8 $\pi^+ \to e^+\nu_e$ during Phase I)
- Tail must be less than 1% of total signal —> Shower containment, energy resolution
- Tail must be measured with a precision of 1% —> Event identification

PAUL SCHERRER INSTITUT

PSI

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

Pion Beamline @ PSI



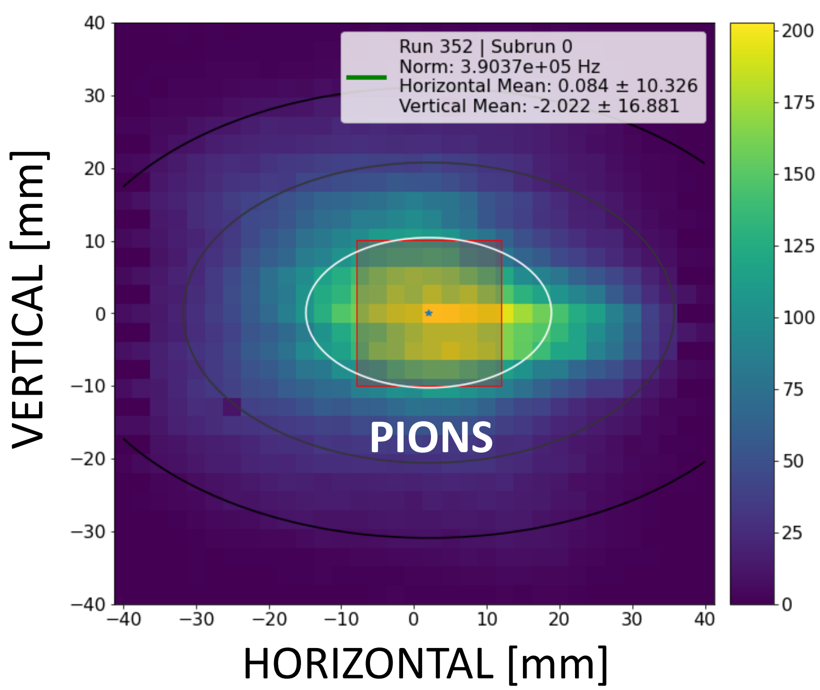
	Phase 1	Phase 2
Pion Decay of Interest	$\pi^+ \to e^+\nu_e$	$\pi^+ \to \pi^0 e^+\nu_e$
Rate (Hz - pion/s)	$3 .10^5$	$3 .10^7$
Momentum bite	dp/p=1%	dp/p=3%
Statistics/yr	10^8	10^6
Measurement precision	0.015%	0.1%

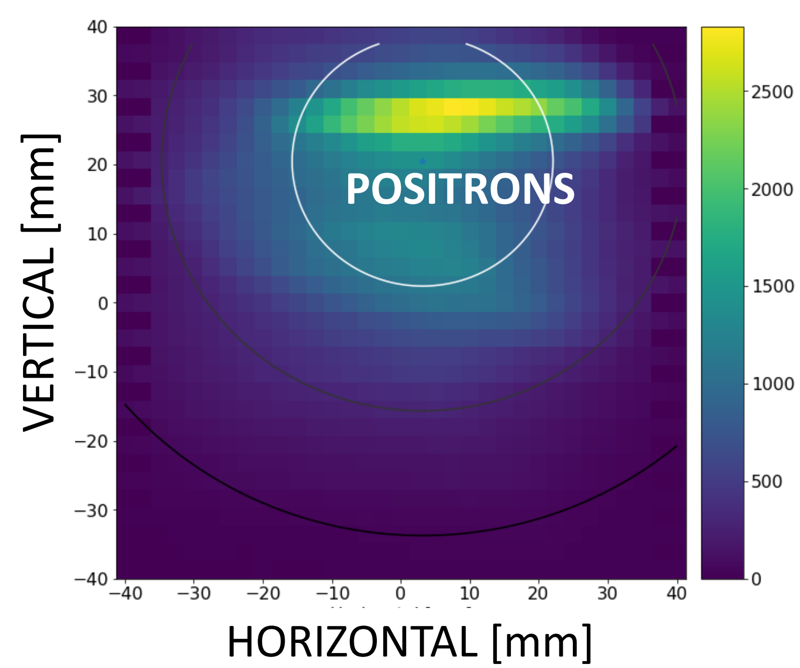
Pion Beamline @ PSI

- Specifications:
  - Rate: O(10^7 Hz)
  - Momentum p=55-70 MeV/c
  - $E \times B$ separation of π from μ and e
  - Tight beam spot (< 2 cm^2) and small divergence
  - Narrow momentum bite (dp/p <2%) to stop π+ in 3±0.5mm silicon target

2022 test beam study

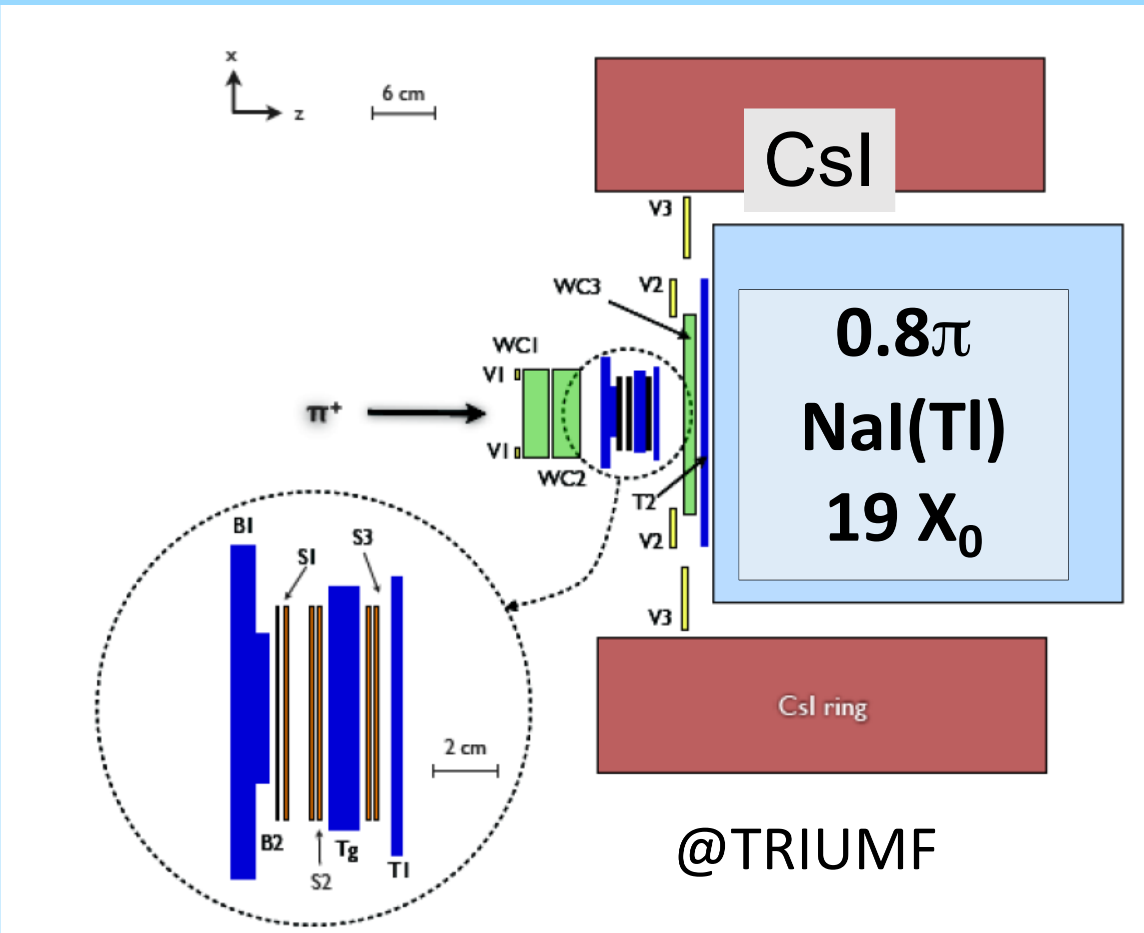
Beamline Position	p_π (MeV/c)	π^+ Rate X 10^6 Hz
QSB43	55	6.3
CALO Center	55	1.0
QSB43	75	61.5
CALO Center	75	11.1





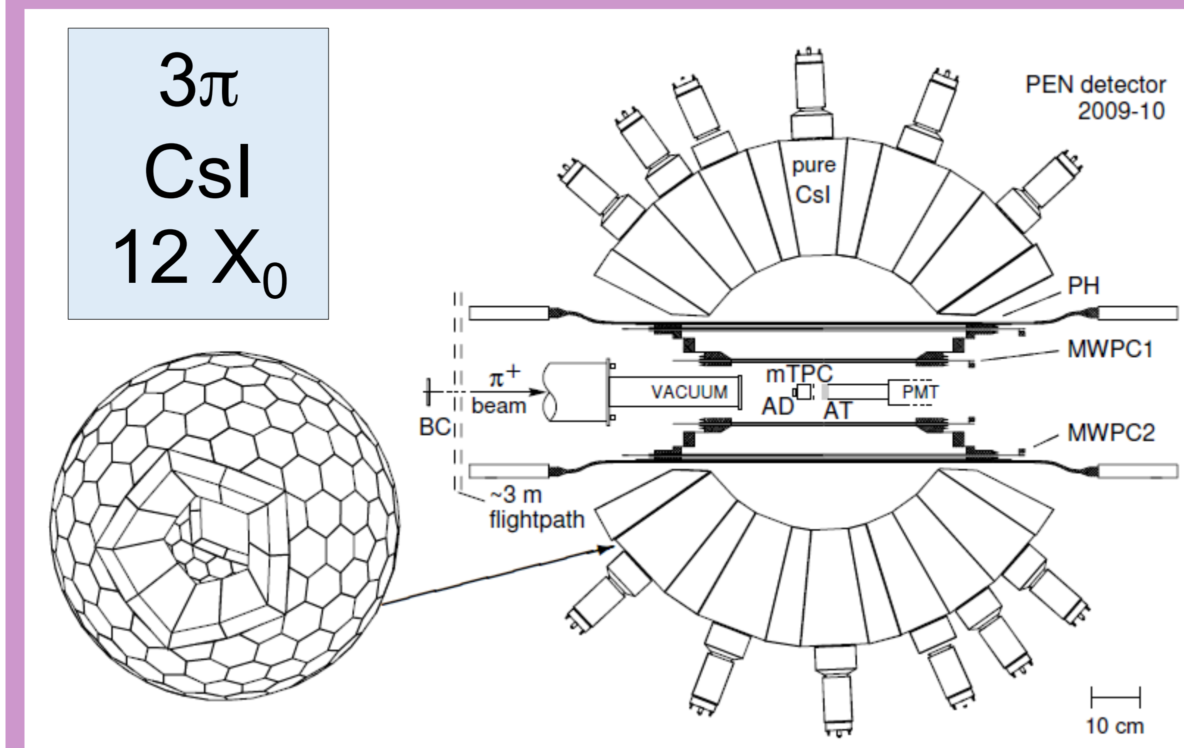
Two recent Pion Decay Experiments

PIENU



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

PEN/PIBETA

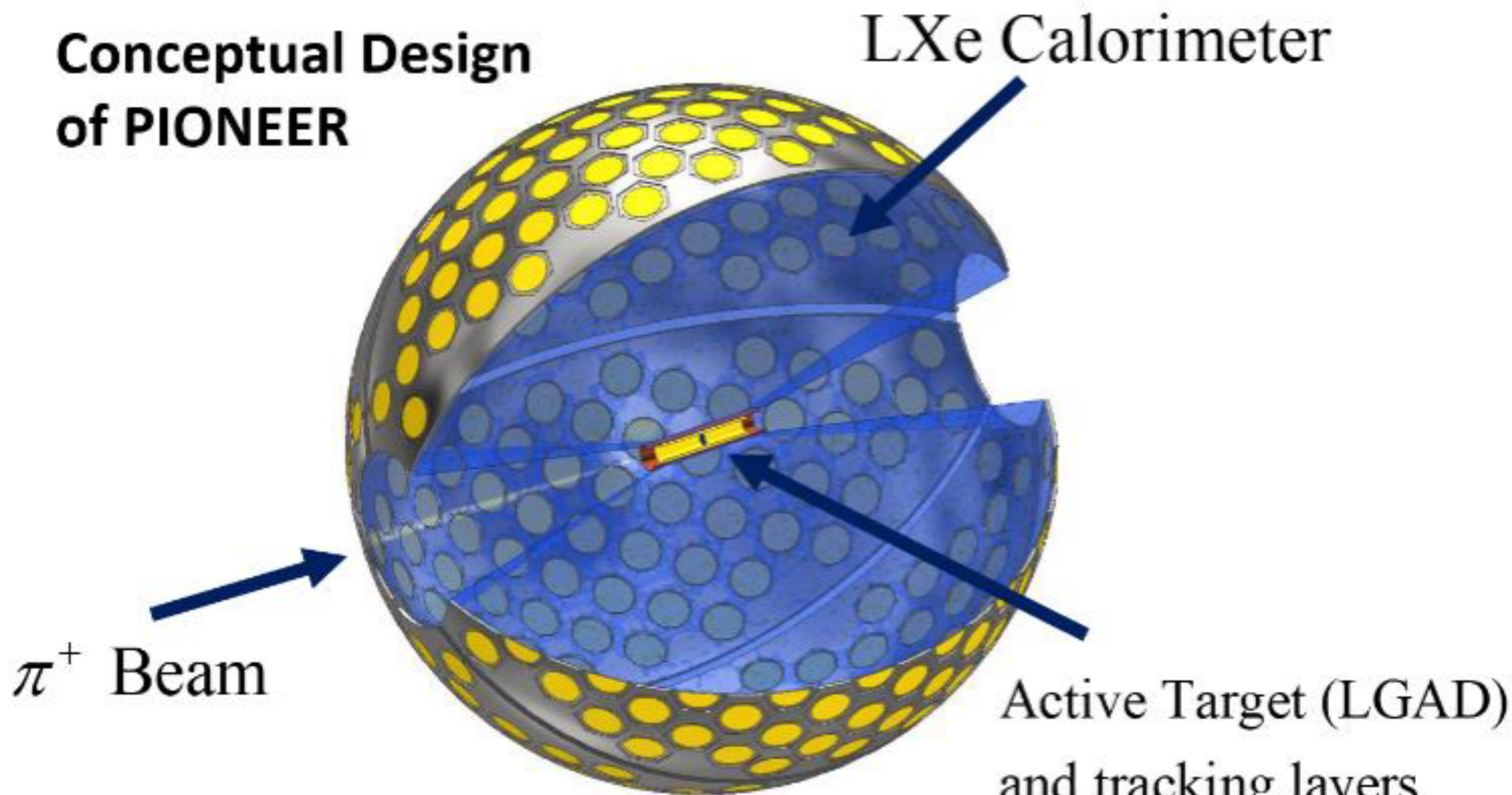


- Experiment at PSI
- geometry but calorimeter depth of $12X_0$ too small to resolve tail under muon spectrum.

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

Detector Design

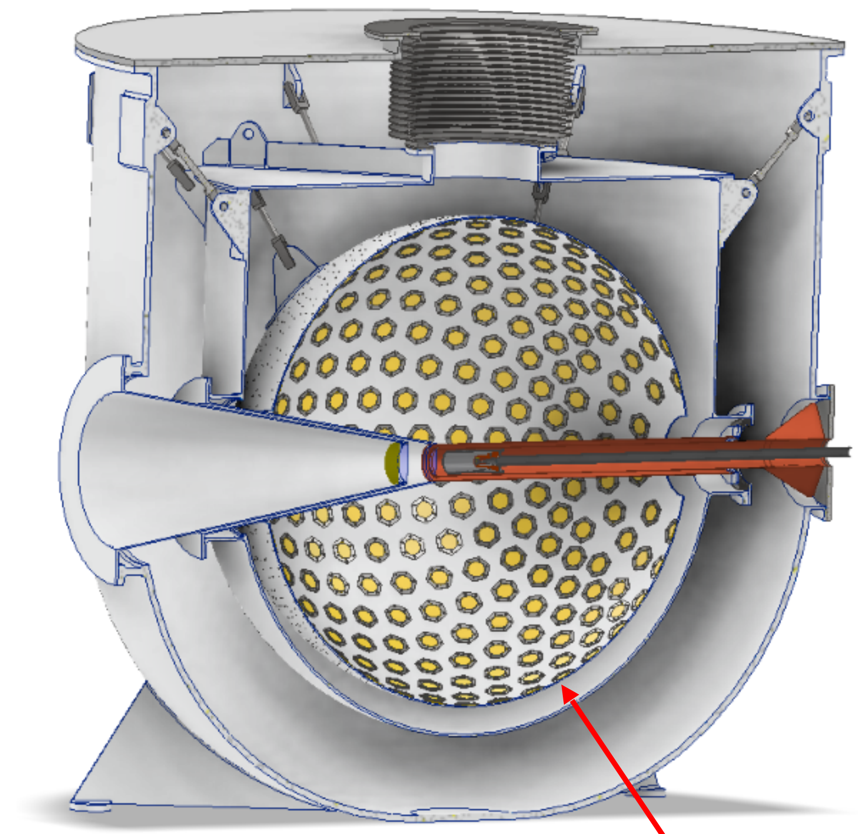
Build from lesson learned at PIENU and PEN/PIBETA



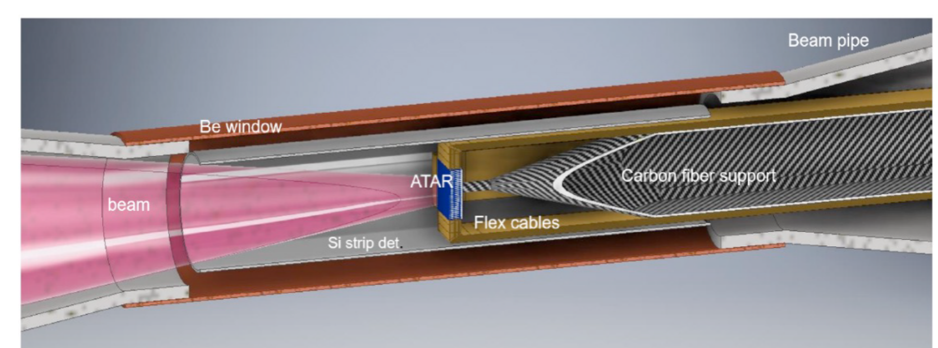
PIONEER Detector

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)

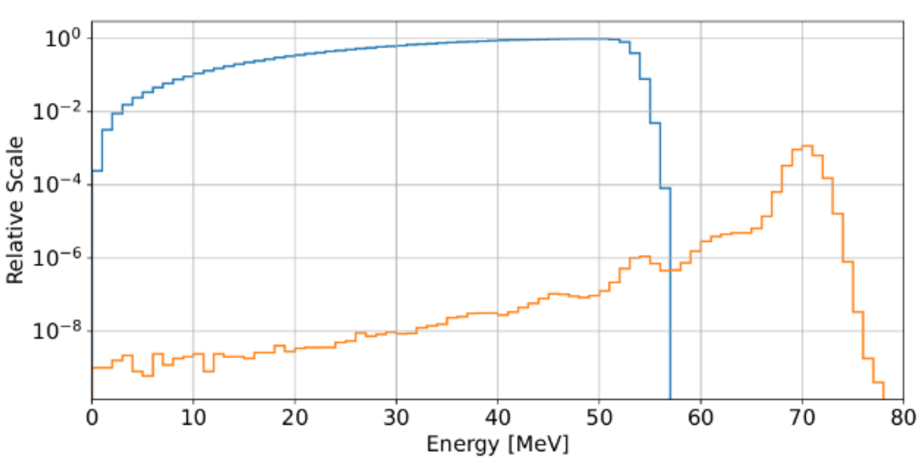
Conceptual Design of PIONEER Phase I

Key features

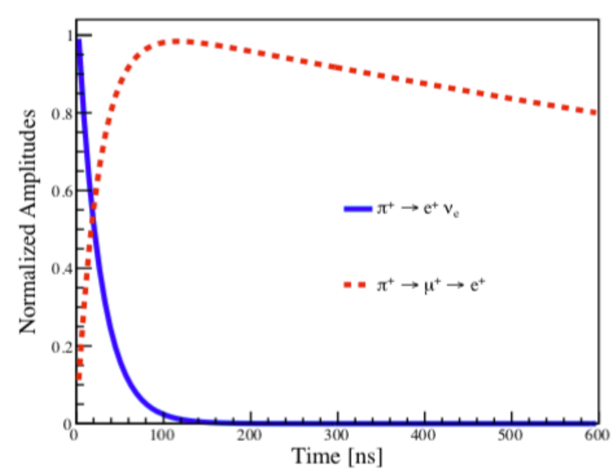
Features of stopped π decay	$\pi \to e\nu(\gamma)$	$\pi \to \mu\,\nu(\gamma)$ $\mu \to e\nu\nu(\gamma)$	Detector technology
Decay Time	26 ns (π)	26 ns + 2197 ns (μ)	
$E_{e+\gamma}$	69.3 MeV*	0 MeV -- 52.3 MeV	(Fast) LXe calo.
Pattern recognition	Two tracks (π + e)	Three tracks (π + μ + e)	Active target (LGAD tech.)

*: there is a long tail at lower energy region

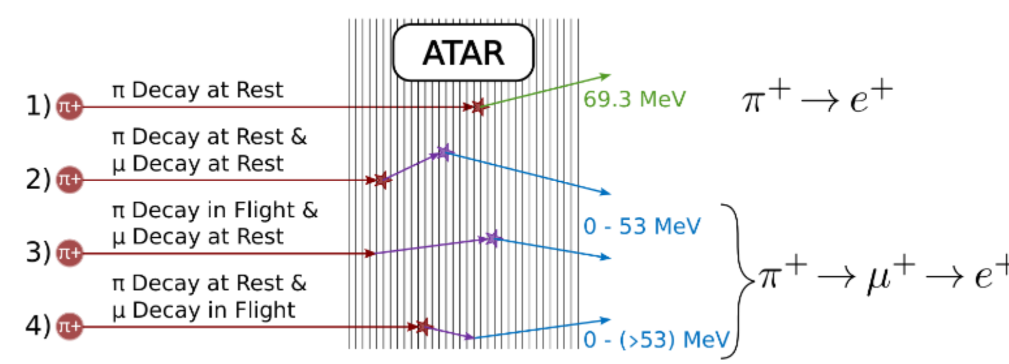
Energy Information



Time Information



Pattern Recognition

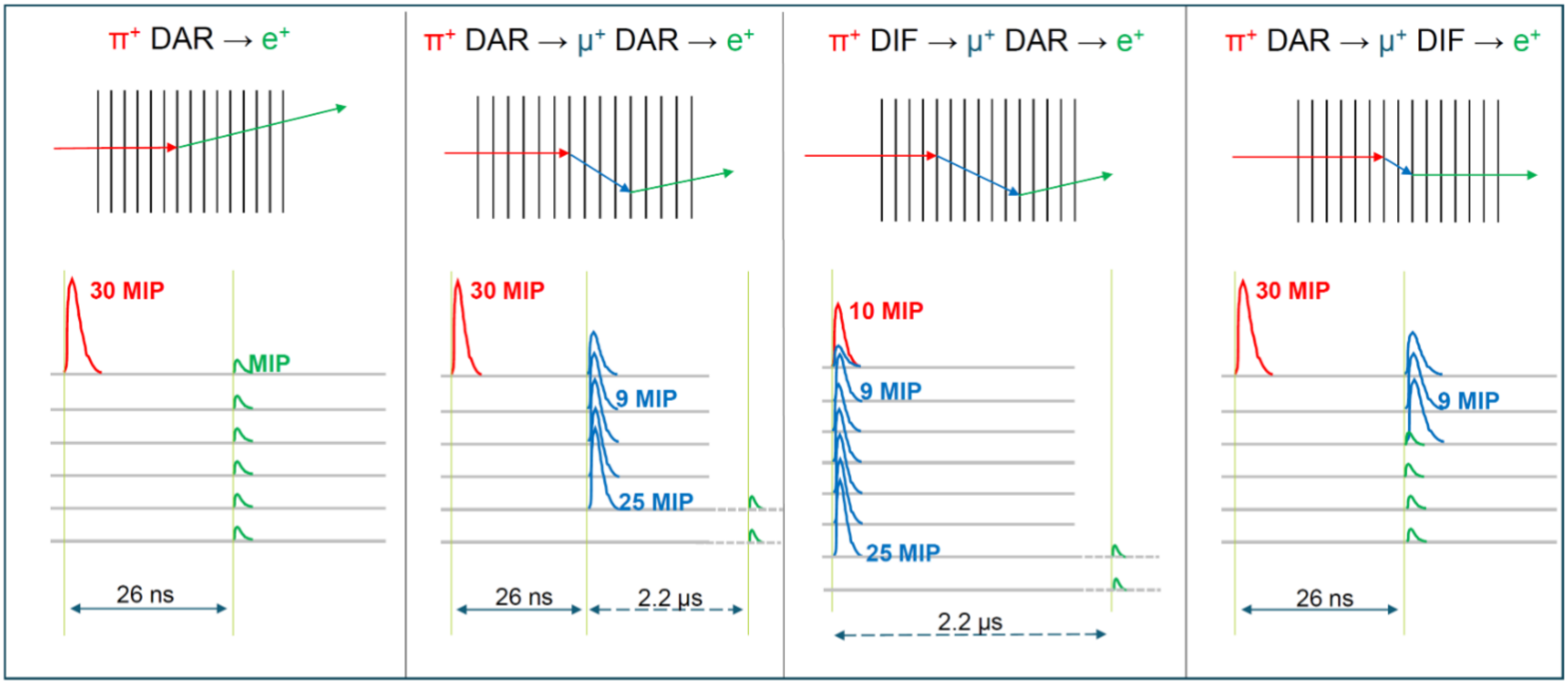


Also, π/μ separation with dE/dx

Pion Decay tagging

- 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 (for example with a Si. det.)

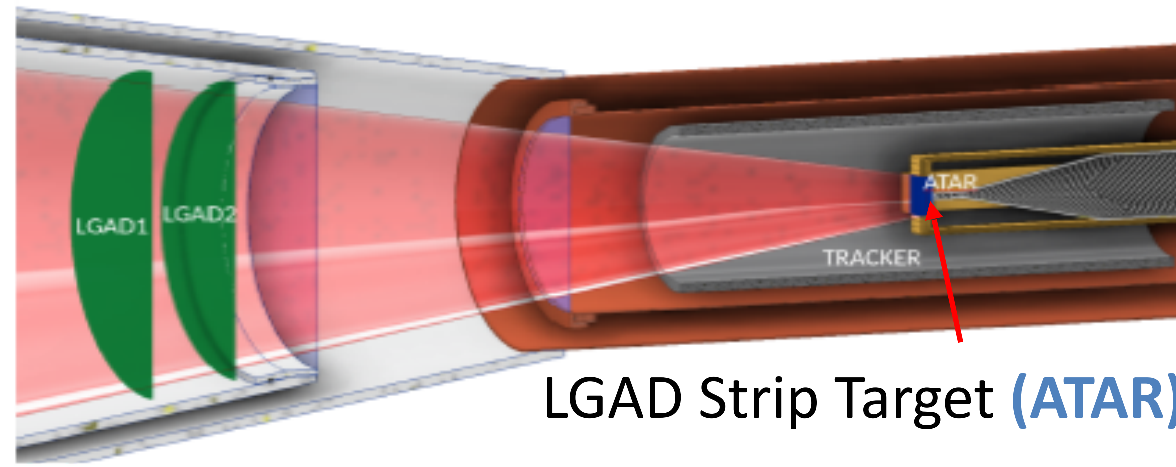
❑ Topology ❑ Calorimetry ❑ Timing



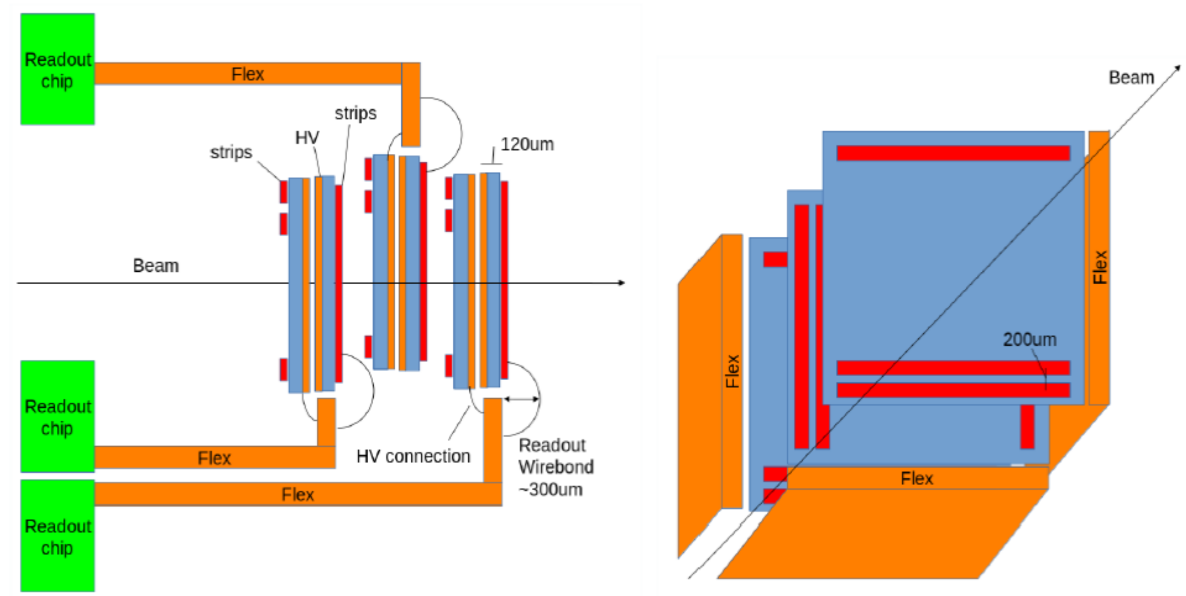
PIONEER Detector Concept:

Active Target (ATAR)

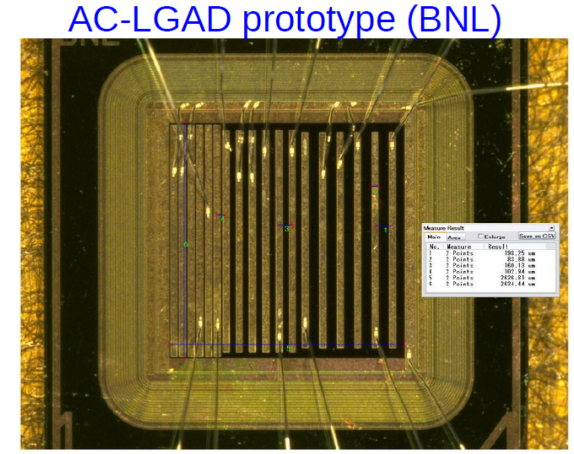
- Active target ("4D") based on low-gain avalanche diode (LGAD) technology
- Requirements:
  - High segmentation, compact with less dead materials, fast collection time to reconstruct pion decay chain
  - Large dynamic range for electron (MIP) and stopping pions/muons (x100 MIP)
- Tentative design:
  - 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)**



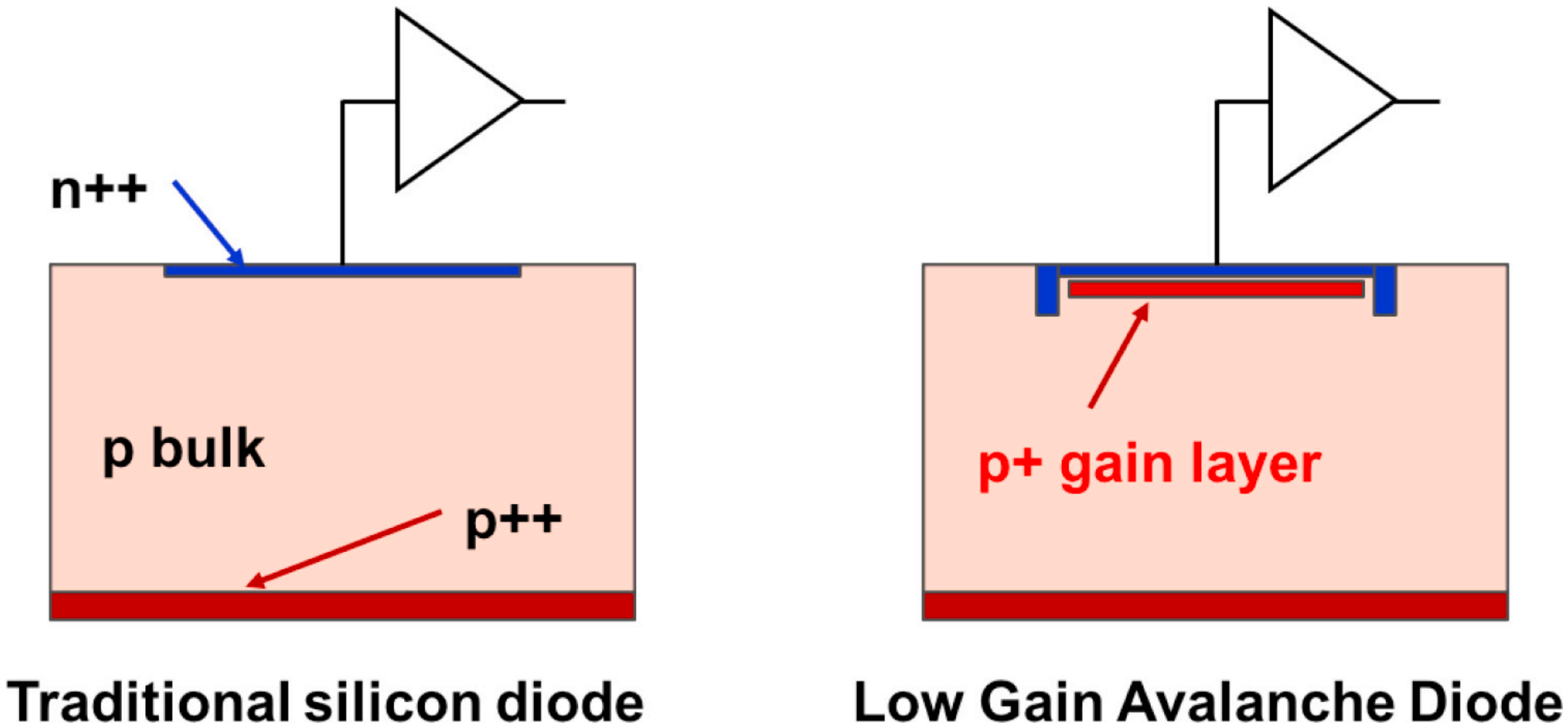
AC-LGAD prototype (BNL)



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

PIONEER Detector Concept:

Traditional Silicon Diode vs LGAD



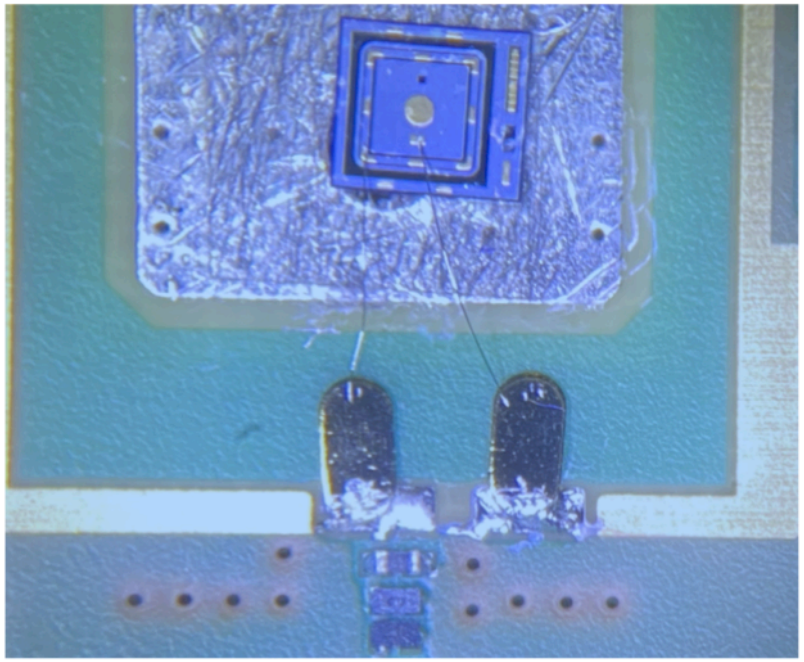
- In silicon sensors, when applying a very large electric field (300 kV/cm), electrons (and holes) acquire kinetic energy and can generate additional e/h pairs by impact ionisation —> ‘avalanche’ effect
  - Can be obtained by implanting an appropriate acceptor or donor that, when depleted, generate a very high field
- The signal amplification enables very high timing resolution —> good for PIONEER, we need O(1ns)
- The gain mechanism saturates for large energy deposit —> bad for PIONEER

PIONEER Detector Concept:

X-Rays studies

Study low energy deposits with X-rays with the Stanford Synchrotron Radiation Lightsource (SSRL) at SLAC
5-70 keV with a repetition rate of 500 MHz

1 mm^2 sensor



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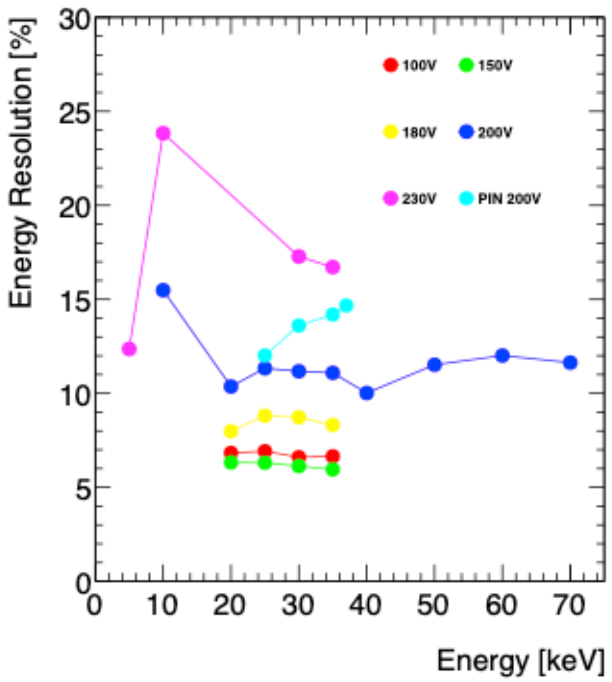
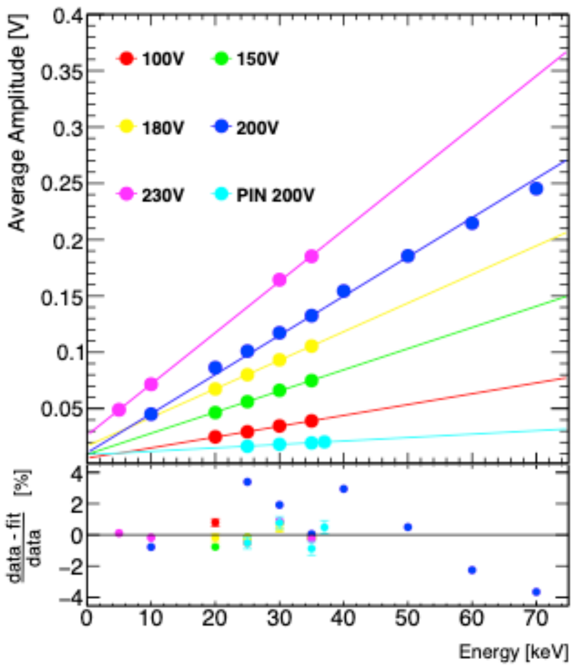
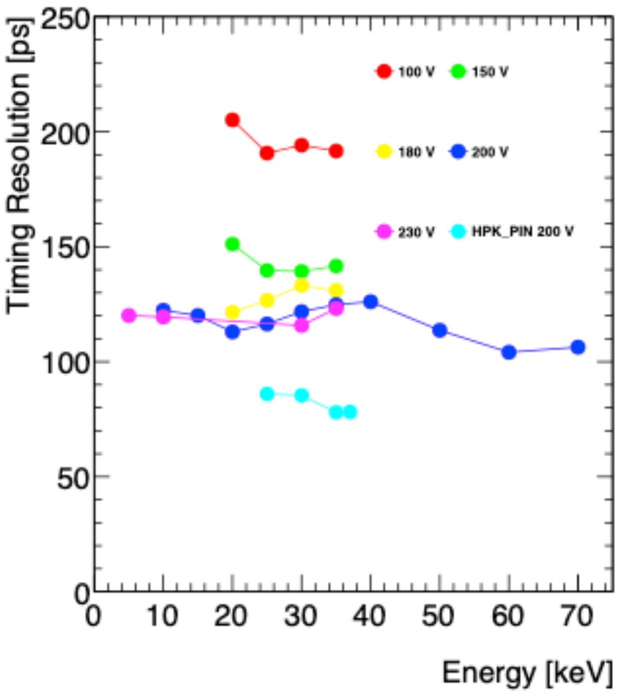






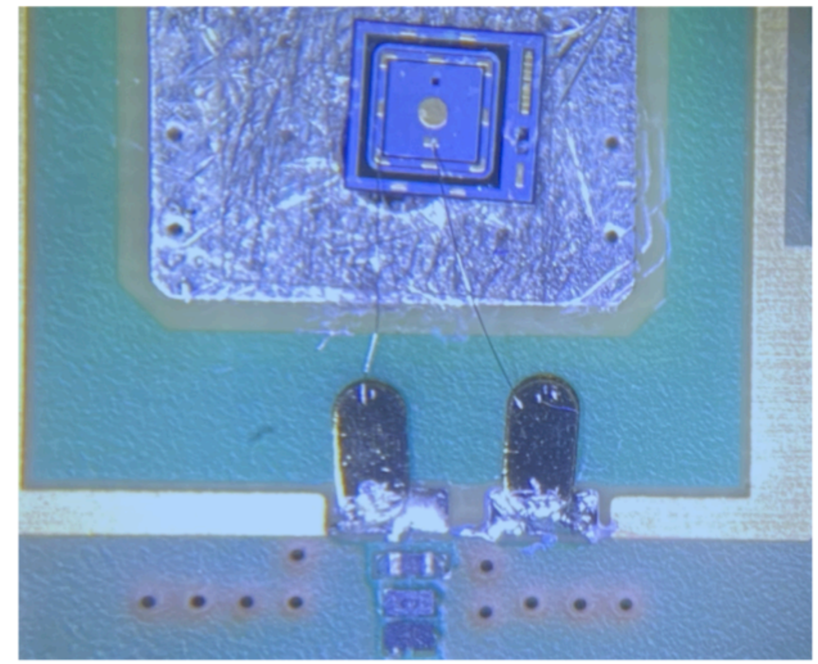
PIONEER Detector Concept:

CENPA Test-beam studies

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

Tandem Van de Graaf Accelerator

1 mm^2 sensor



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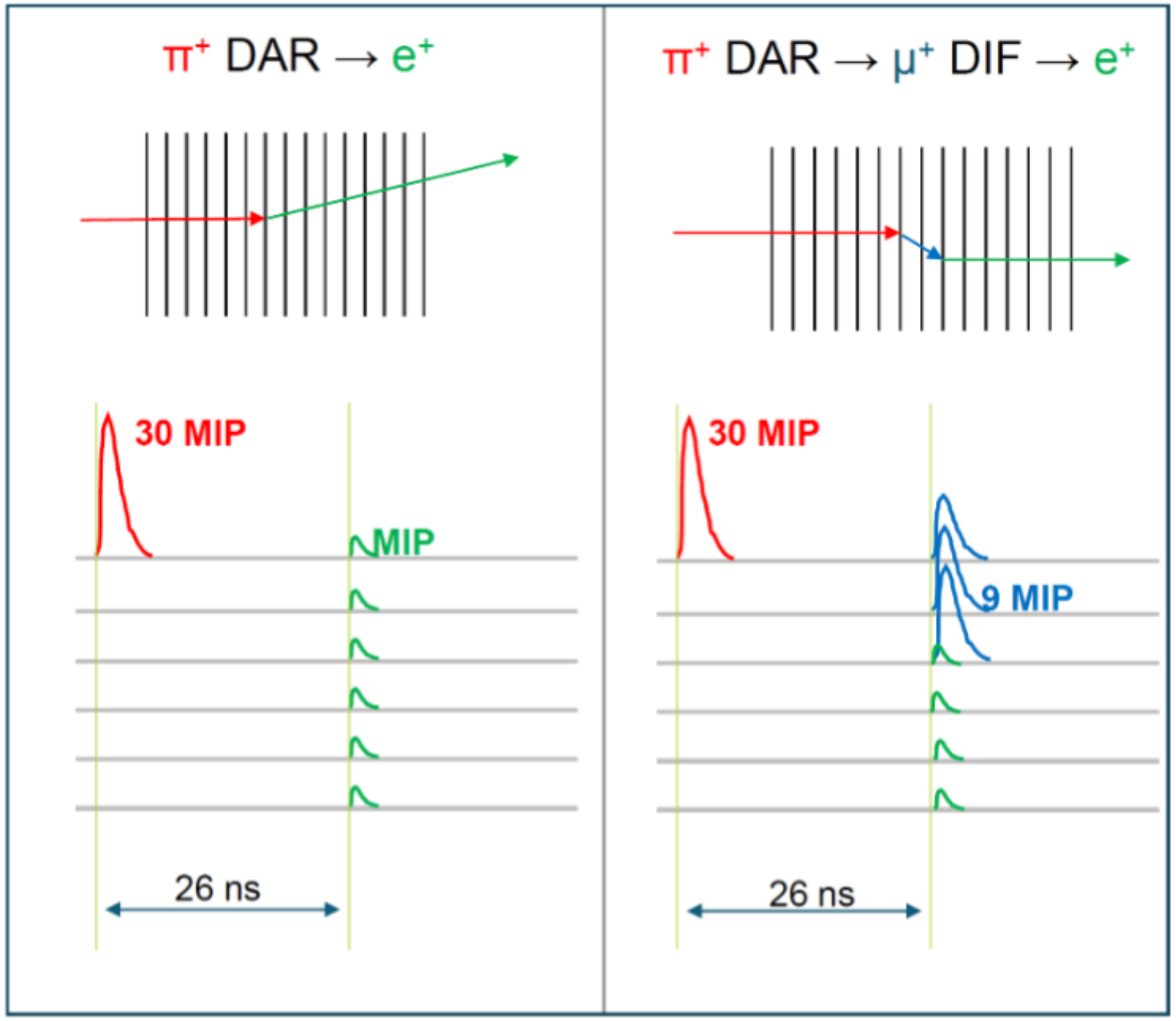
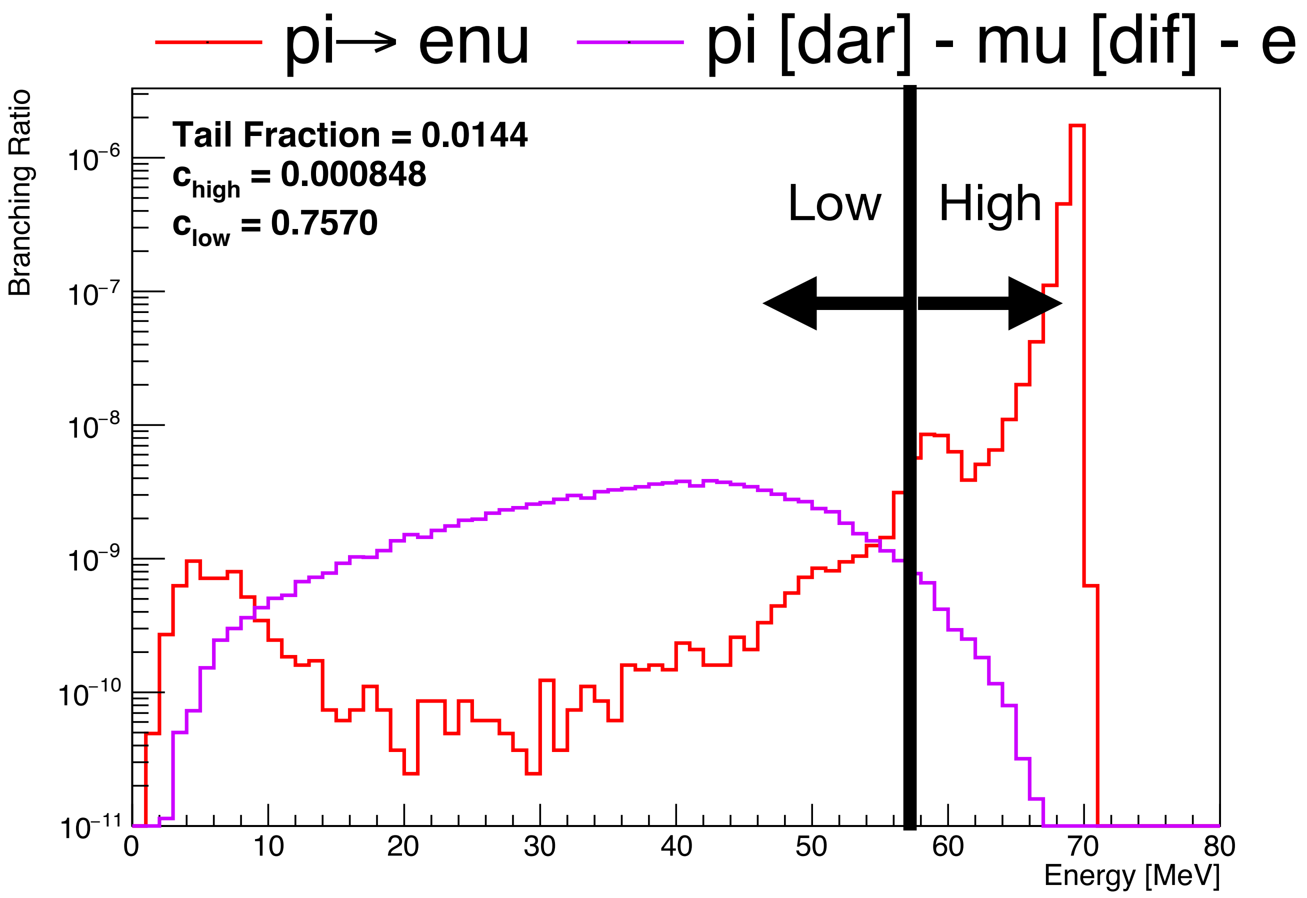
More in Caleb’s talk in a couple weeks

Simulation studies

Tagging Decay-in-Flight (DIF) muon events

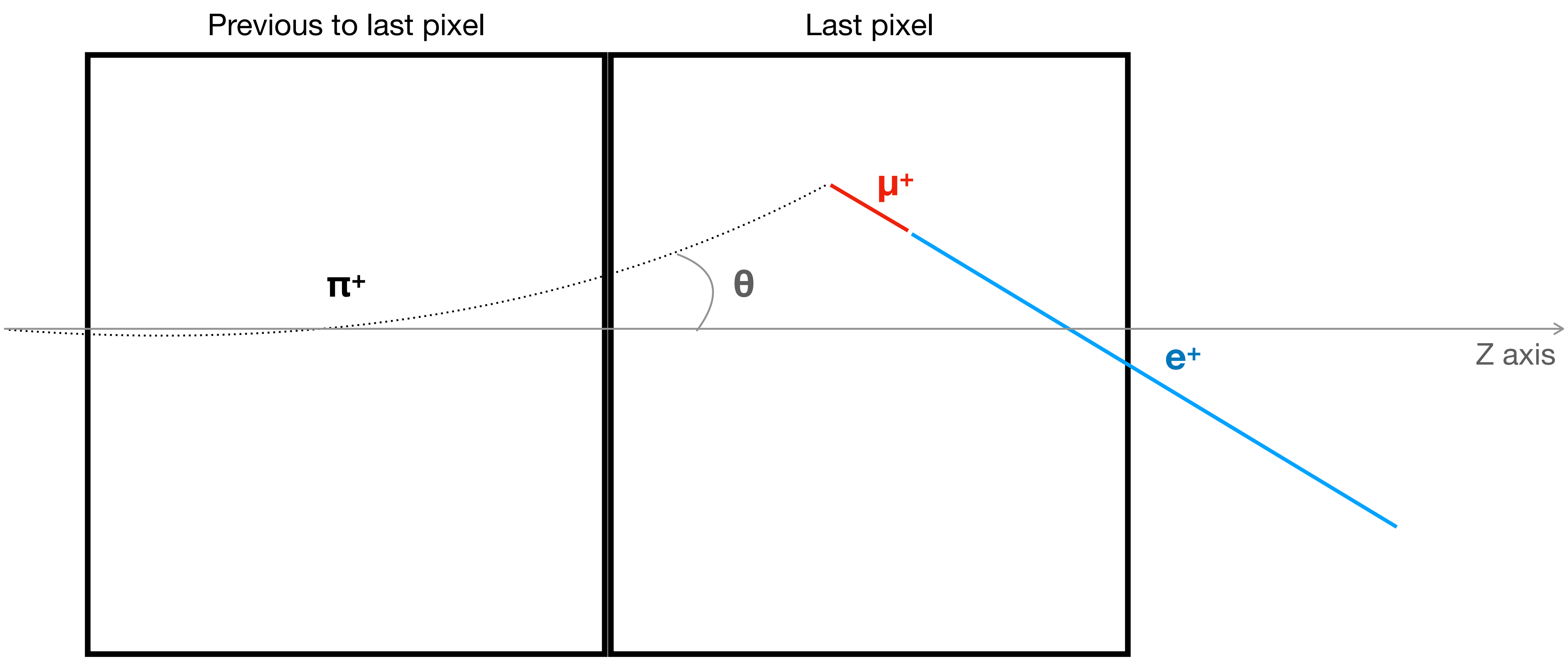




- Sizeable contamination in the high bin
  - $\frac{N^H_{\pi-\mu-e}}{N^H_{\pi-\mu-e} + N^H_{\pi-e}}$ ~ 0.08%
- Tail fraction of 1.4%
- Low bin contamination
  - $\frac{N^L_{\pi-\mu-e}}{N^L_{\pi-\mu-e} + N^L_{\pi-e}} = 76\%$
- **How can the ATAR detector help us?**

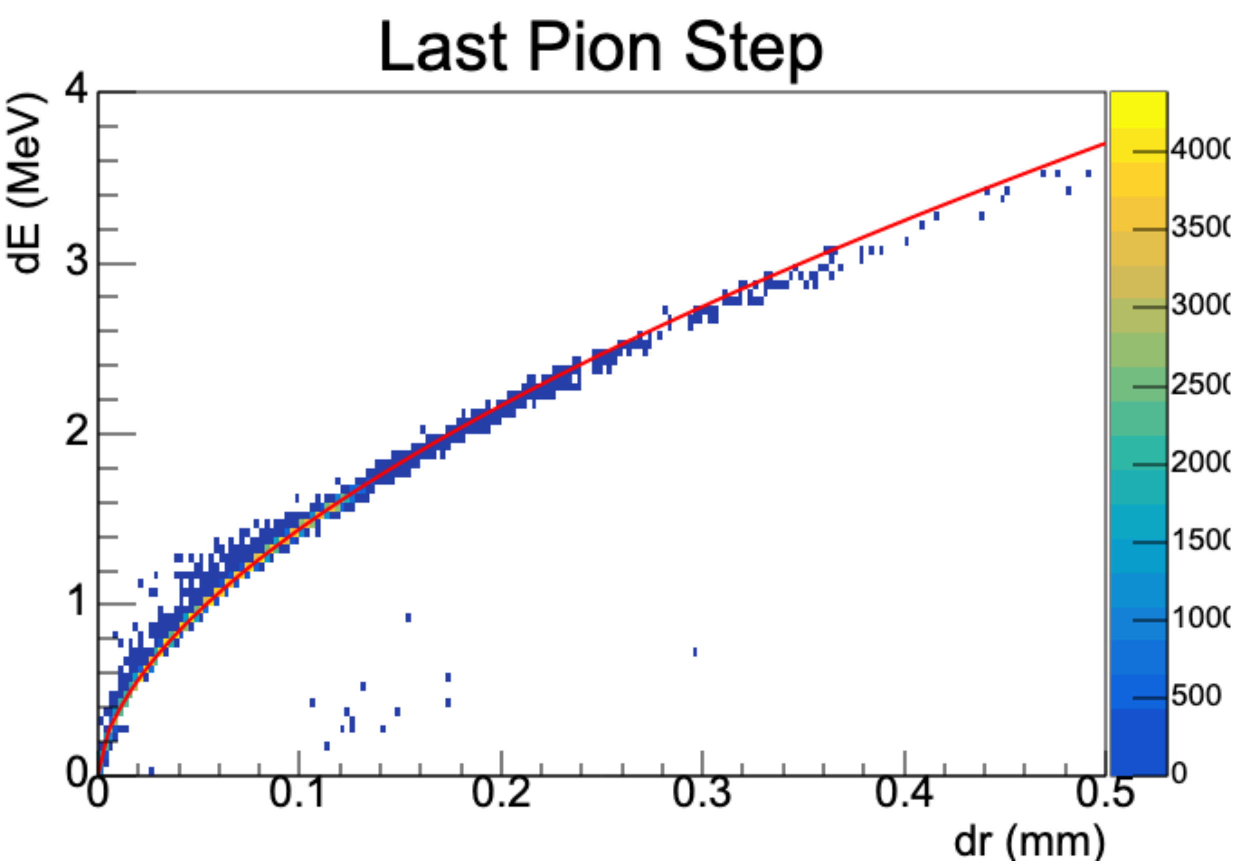
Tagging Decay-in-Flight (DIF) muon events

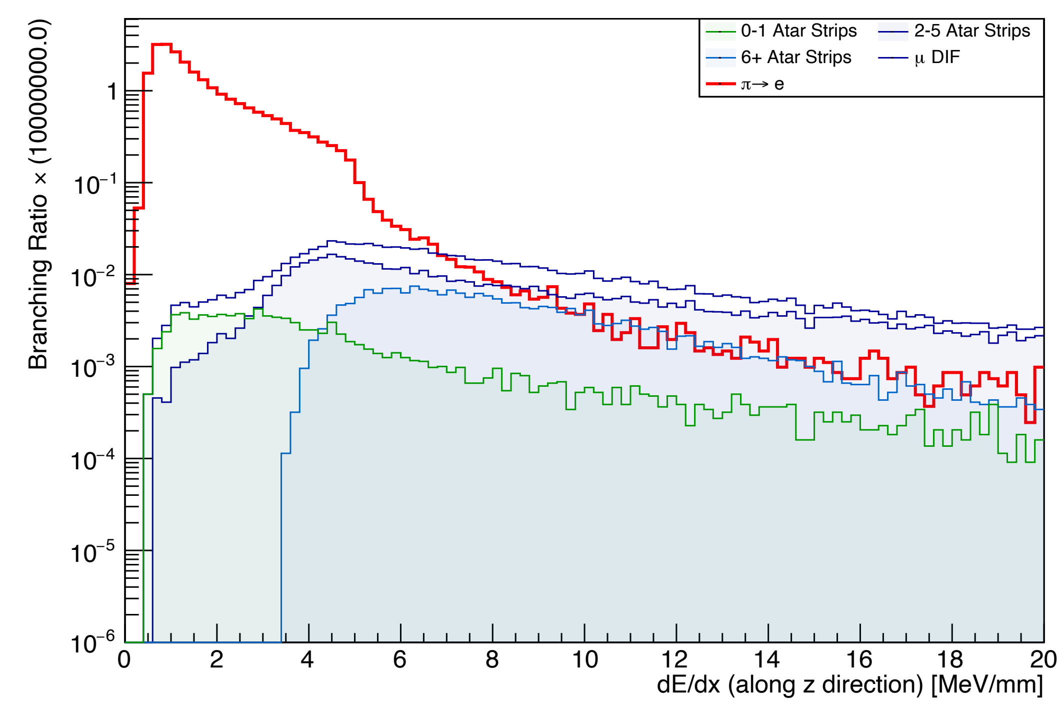
Decay in the last pion pixel (aka the really difficult one)



Tagging Decay-in-Flight (DIF) muon events

Using Energy deposit - path traveled relationship





Determine pion travel in last strip from energy deposited
Infer distance travelled by pion decay (either muon or positron) from geometrical consideration

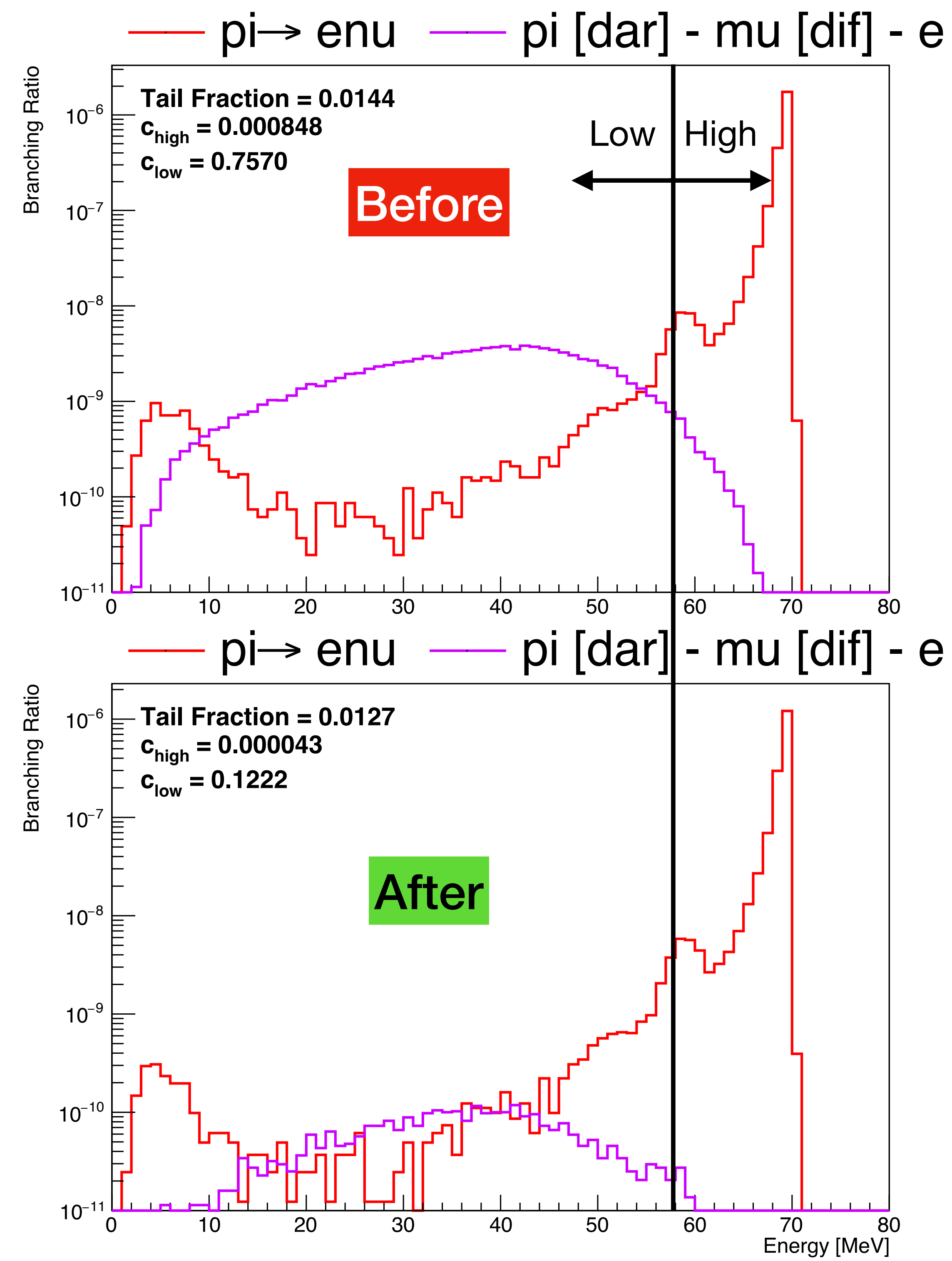
→

Compute dE/dx of the muon candidate

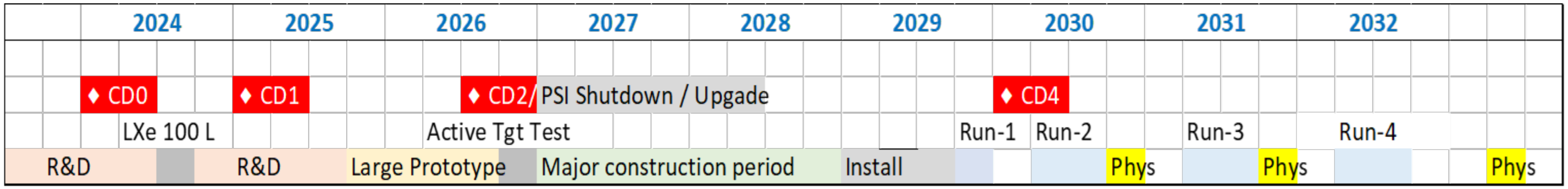
Tagging Decay-in-Flight (DIF) muon events

How well does it work?

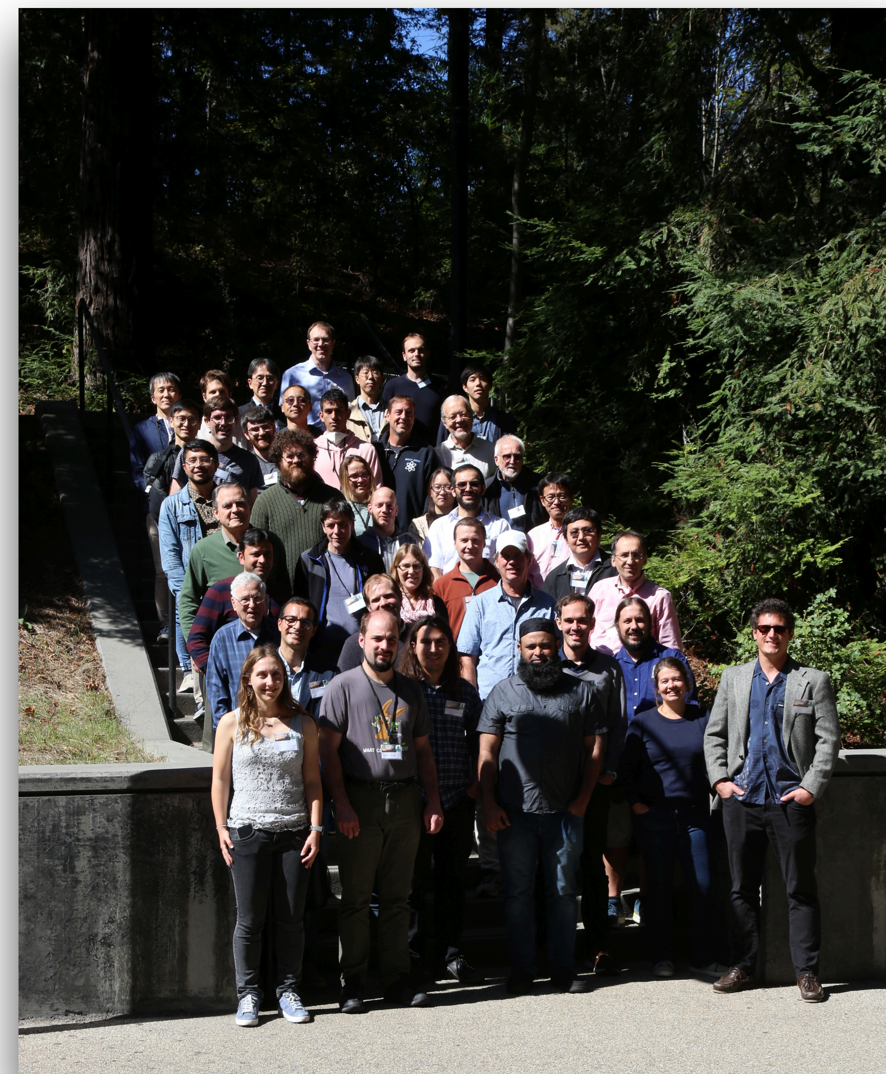
- dE/dx criteria reduces the background by a factor 7 for same signal efficiency
- Some room for improvement:
  - Include more geometry information
  - Harvest correlation of pion stopping point to previous to last energy deposit (in addition to the last one)



Putting PIONEER together



- Presented simulation studies and hardware characterisation for the target
- Many other ongoing activities
    - Beam dynamics
    - Calorimeter design
    - Tracker
    - DAQ, …
- CENPA Team (8 people):
  David Hertzog, Peter Kammel, Q.B.,
  Patrick Schwendimann, Svende Braun,
  Josh Labounty, Omar Beesley,
  Caleb Landsdell



First Collaboration Meeting Last October at UCSC

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	(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%**	