The PIONEER experiment at PSI

- Lepton flavor universality test with pion -

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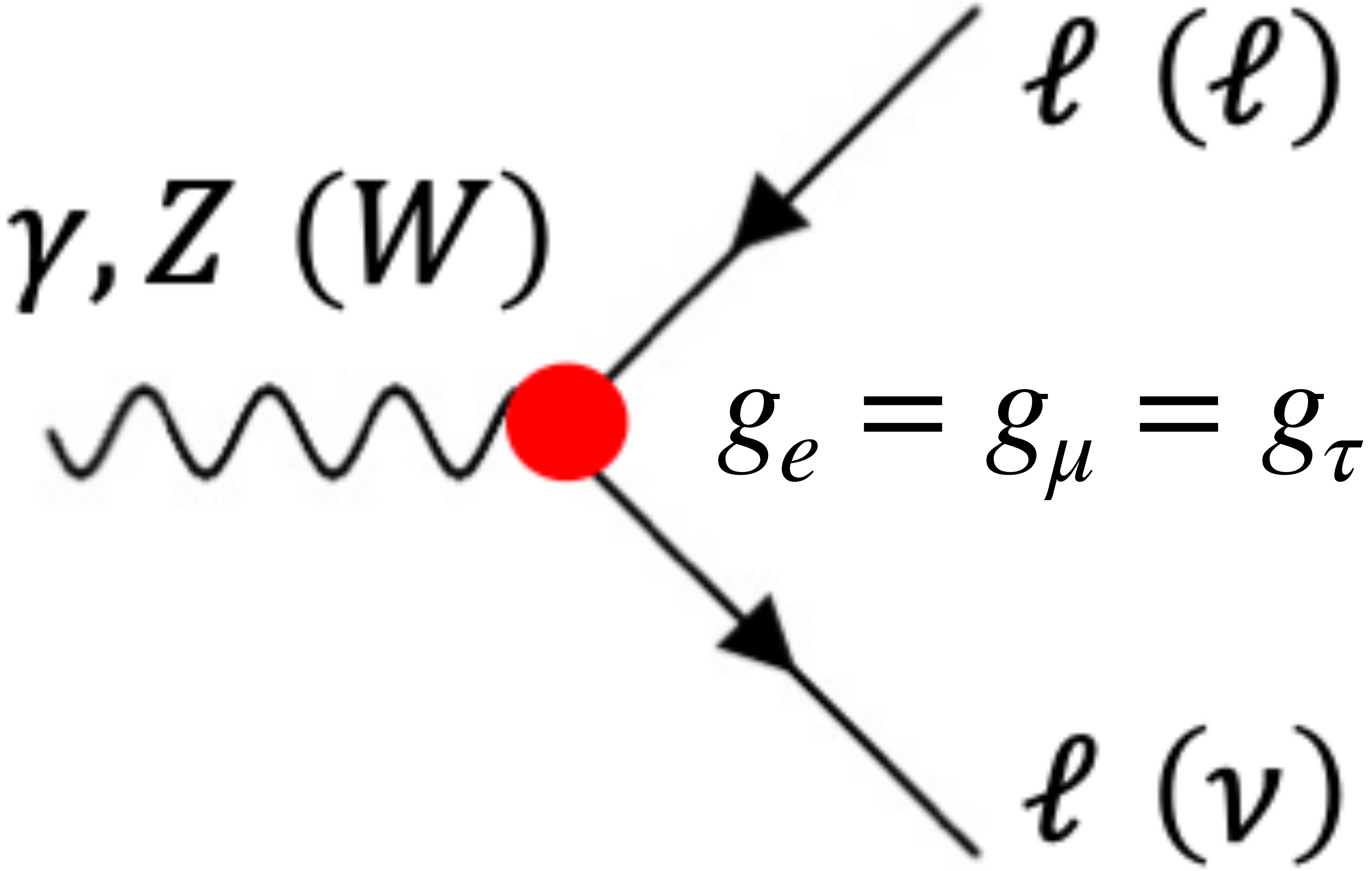
JSPS Core-to-Core Program

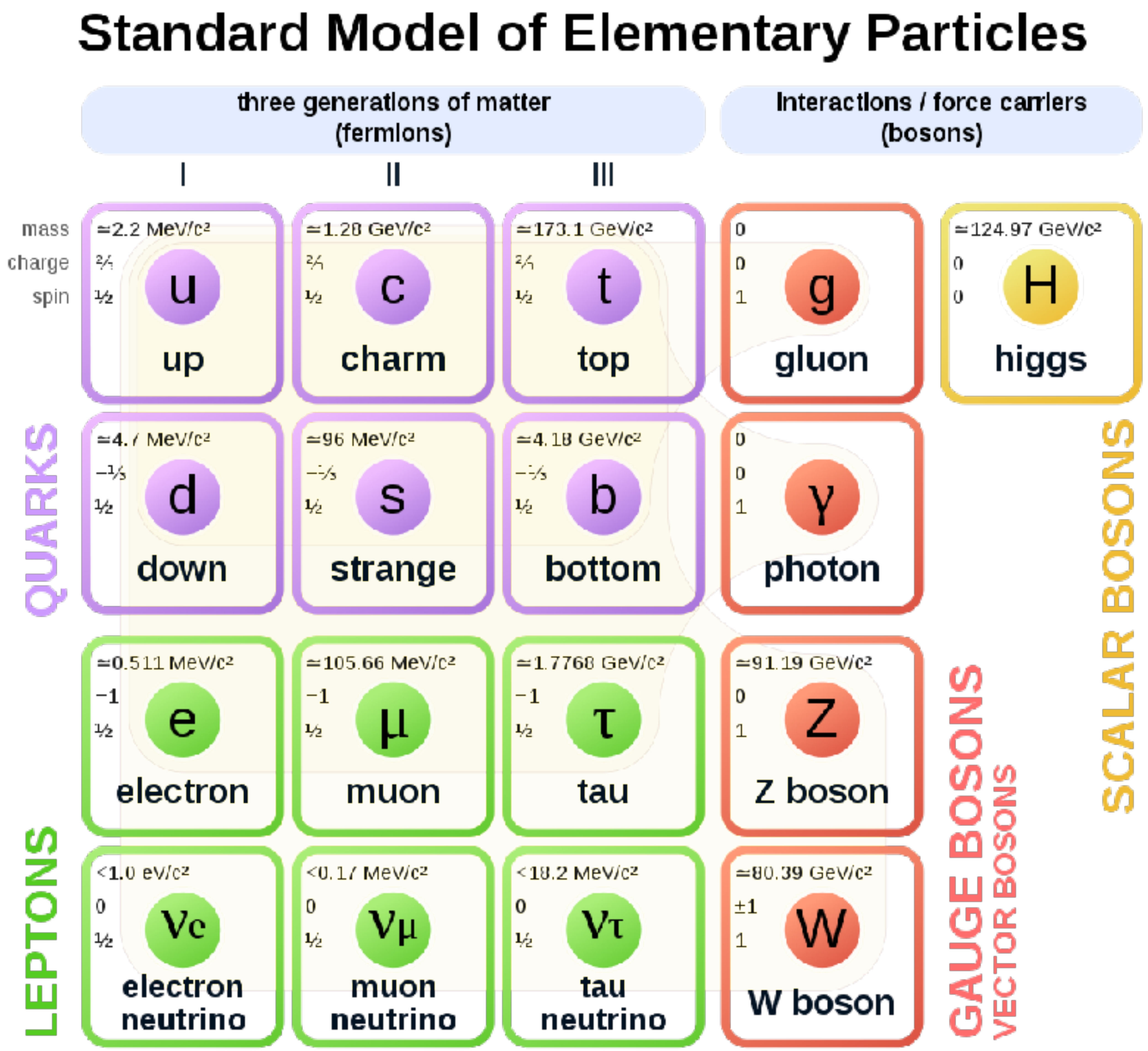
Introduction

Gauge interactions are lepton flavor universal in the standard model

- Precise evaluation of lepton flavor universality is important to look for new physics



$$g_e = g_\mu = g_\tau$$



Question: Any deviations from the universality?

Lepton universality test with pion

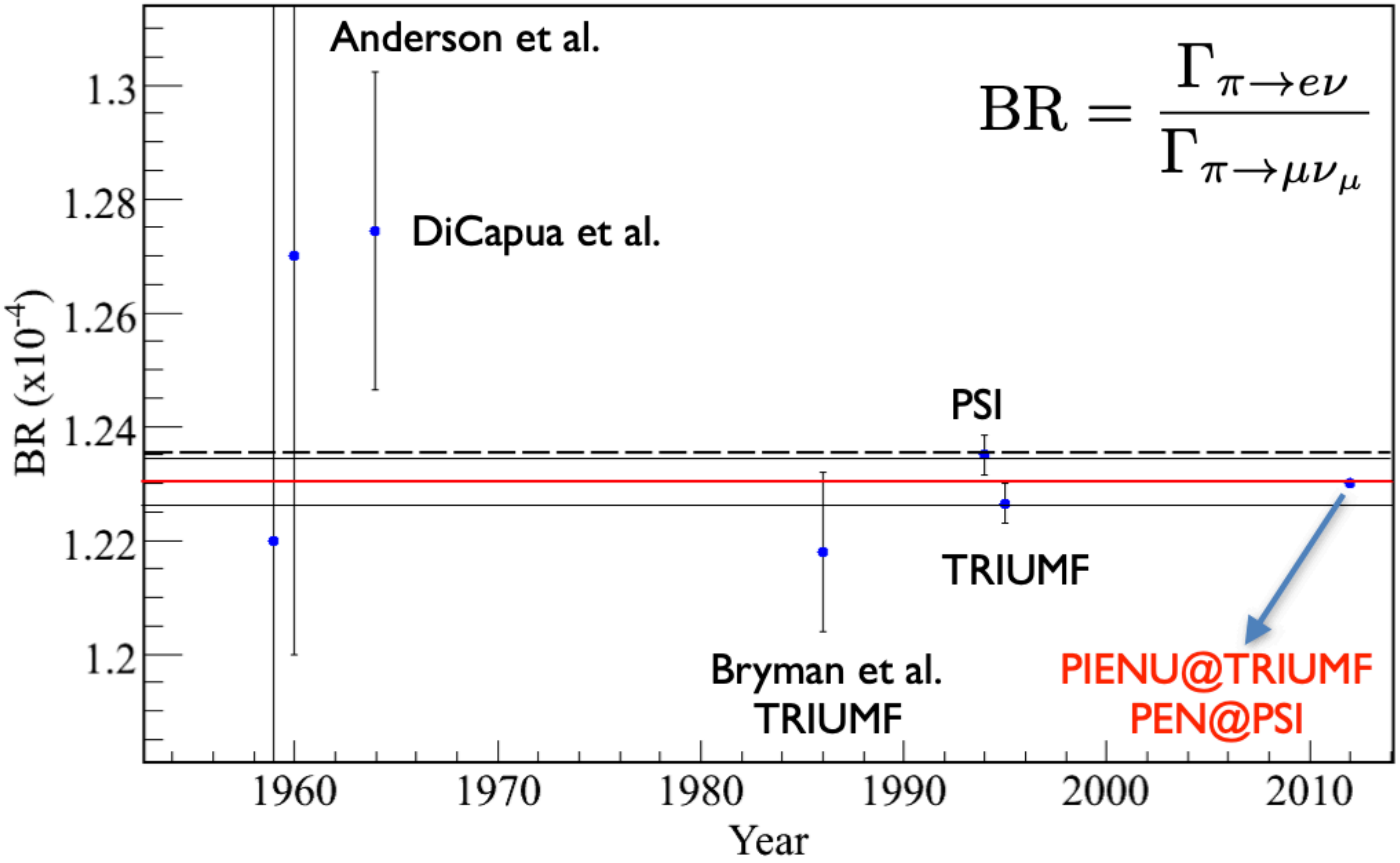
$$R^{\pi}_{e/\mu} = \frac{\Gamma(\pi \to e\bar{\nu}_e(\gamma))}{\Gamma(\pi \to \mu\bar{\nu}_\mu(\gamma))}$$

provides unique opportunity to test LFU

$R(\mathrm{SM})^{\pi}_{e/\mu}$ (SM)
$= 1.23524(015) \times 10^{-4}$
(0.01%)

$R(\mathrm{E\bar{x}p})^{\pi}_{e/\mu}$ (Exp)
$= 1.23270(230) \times 10^{-4}$
(0.18%)

Theory 15x more precise than experiment



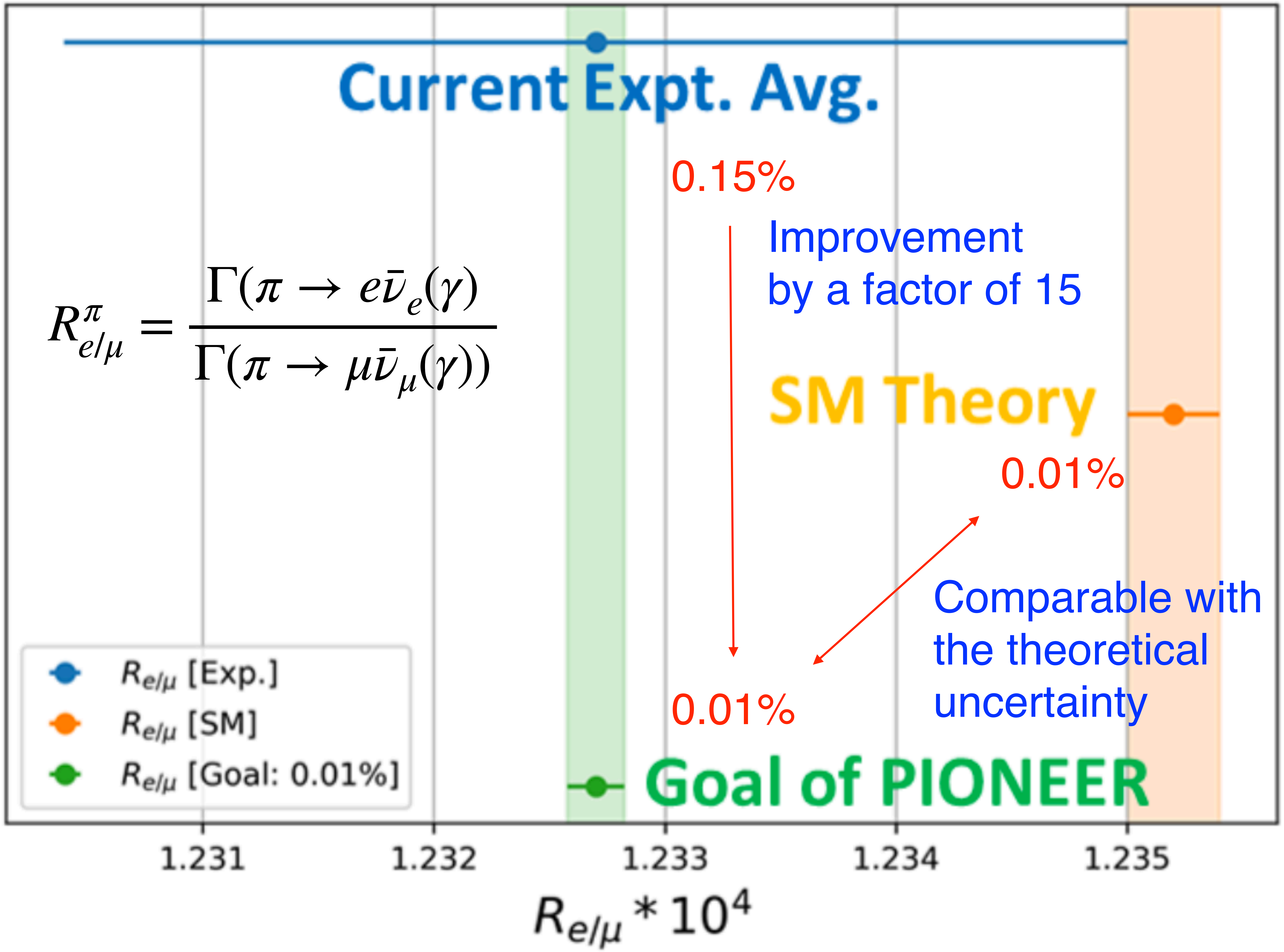
PIONEER goal (I)

Phase I

$$R^{\pi}_{e/\mu} = \frac{\Gamma(\pi \to e\bar{\nu}_e(\gamma))}{\Gamma(\pi \to \mu\bar{\nu}_\mu(\gamma))}$$

NP at the PeV scale can be probed

PIONEER experiment is approved by Paul Scherrer Institute in Switzerland in 2022

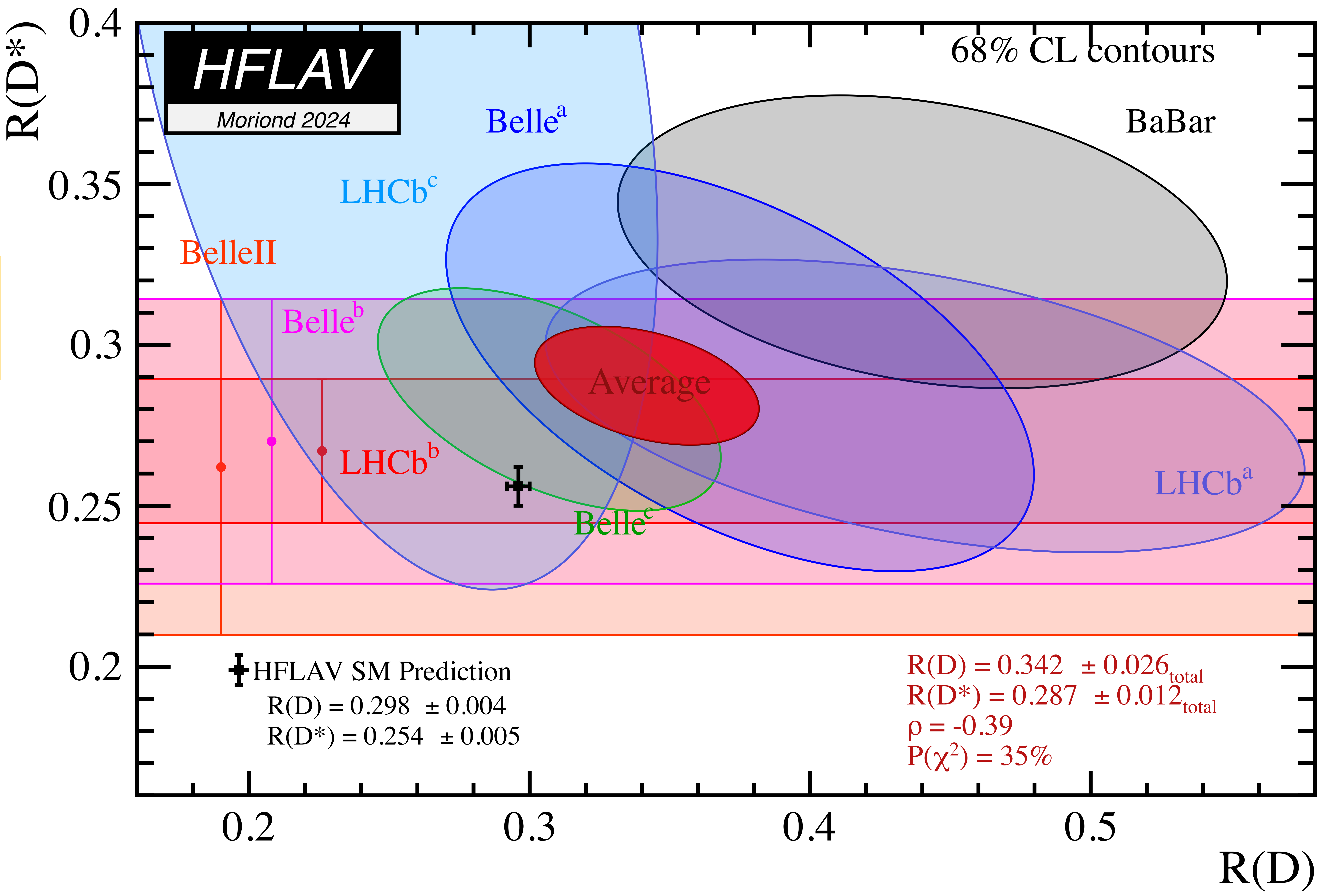


Hints of lepton flavor universality violation ?

$$R(D^*) = \frac{\mathcal{B}(\overline{B}^0 \to D^{*+}\tau^-\overline{\nu}_\tau)}{\mathcal{B}(\overline{B}^0 \to D^{*+}\mu^-\overline{\nu}_\mu)}$$

R(D), R(D*) deviate from the SM expectation by ~3σ

- Can be a hint of LFUV between τ and μ



Basics of pion decays

PIONEER measures

<u>Measurements:</u>

What a pion decays to "normally" → $BR\left(\pi^{+} \to \mu^{+}\nu_{\mu}(\gamma)\right) = 0.999877 = \pm 0.0000004$

The helicity suppressed "e" branch → $BR\left(\pi^{+} \to e^{+}\nu_{e}(\gamma)\right) = 1.2327 \pm 0.0023) \times 10^{-4}$

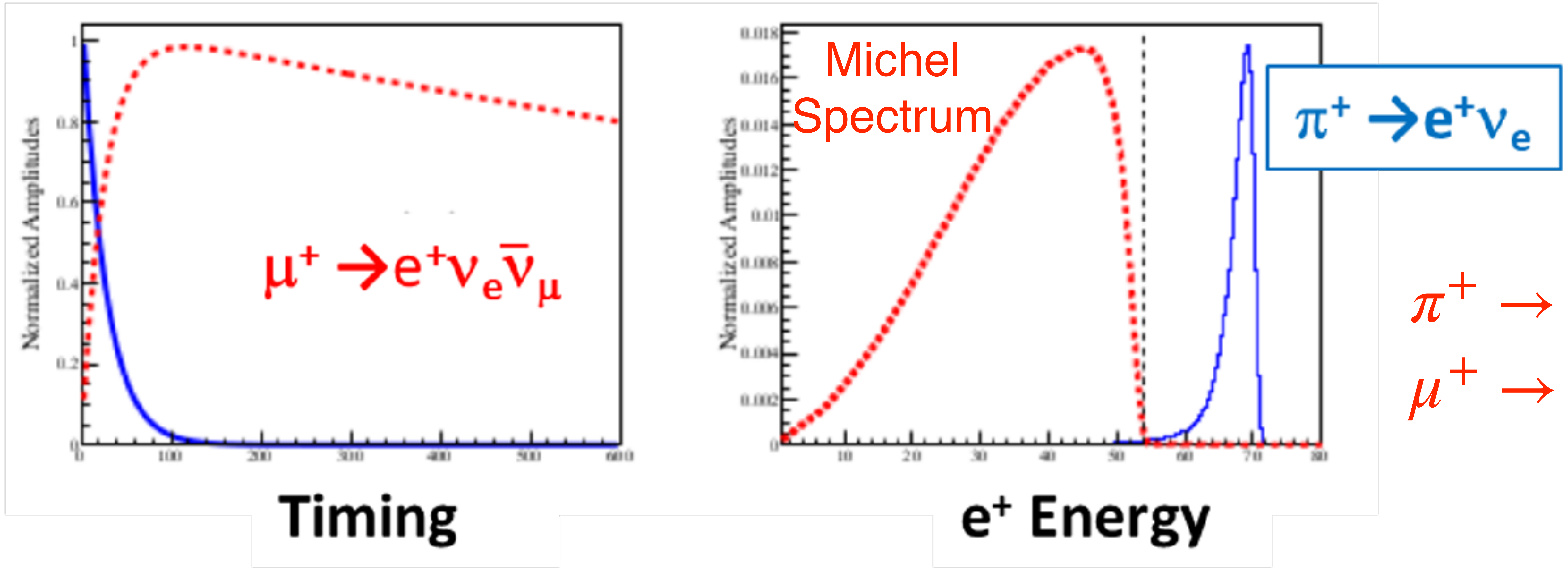
} → Phase I

The "beta decay" branch → $BR\left(\pi^{+} \to e^{+}\nu_{e}\pi^{0}\right) = 1.036 \pm 0.006) \times 10^{-8}$ → Phase II

<u>Reminders:</u>

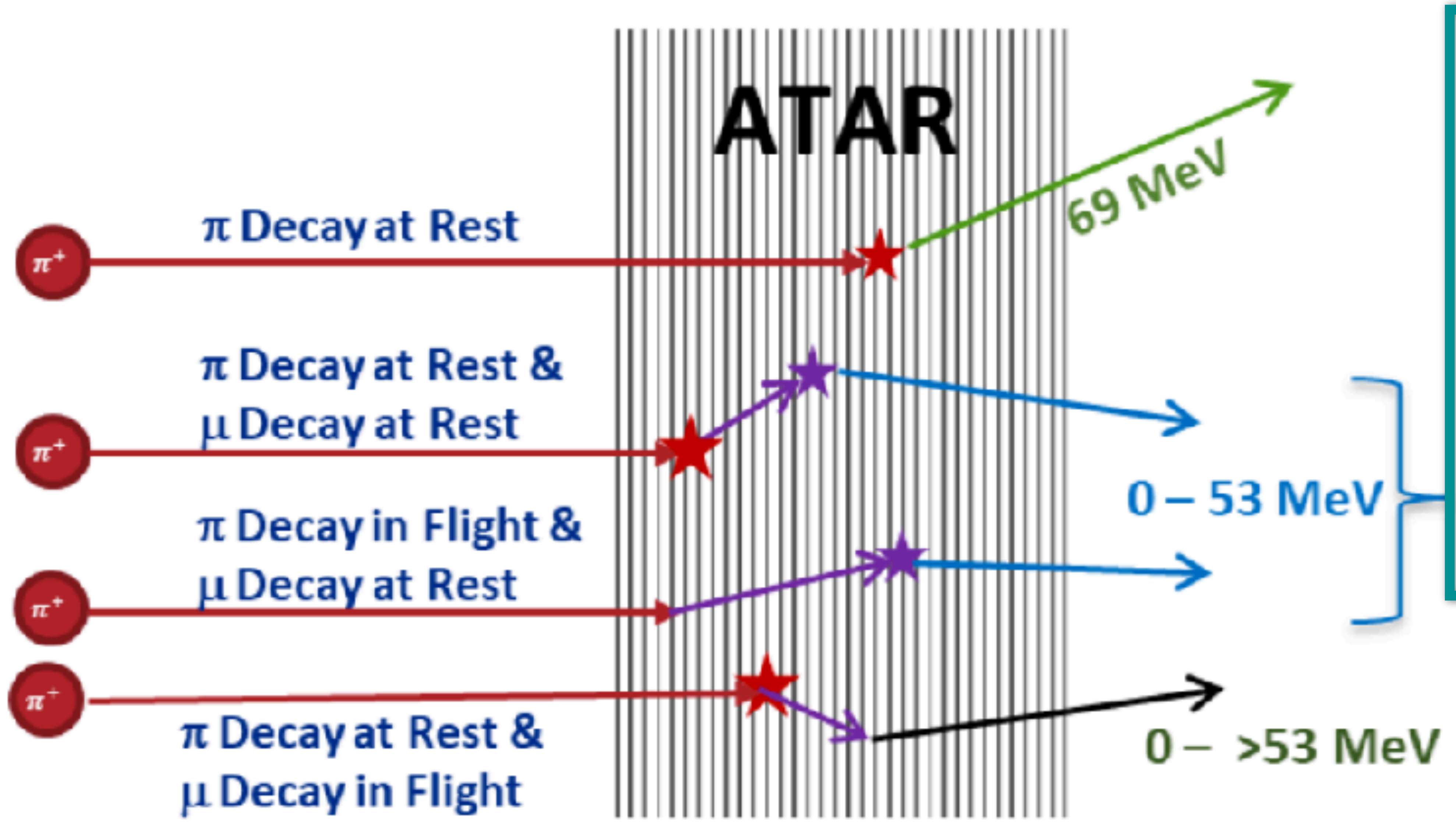
Pion lifetime: 26 ns
Muon lifetime: 2197 ns

Pion mass: 139.6 MeV
Muon mass: 105.7 MeV



$\pi^{+} \to \mu^{+}\nu(\gamma)$
$\mu^{+} \to e^{+}\nu\bar{\nu}(\gamma)$

Measurement principle

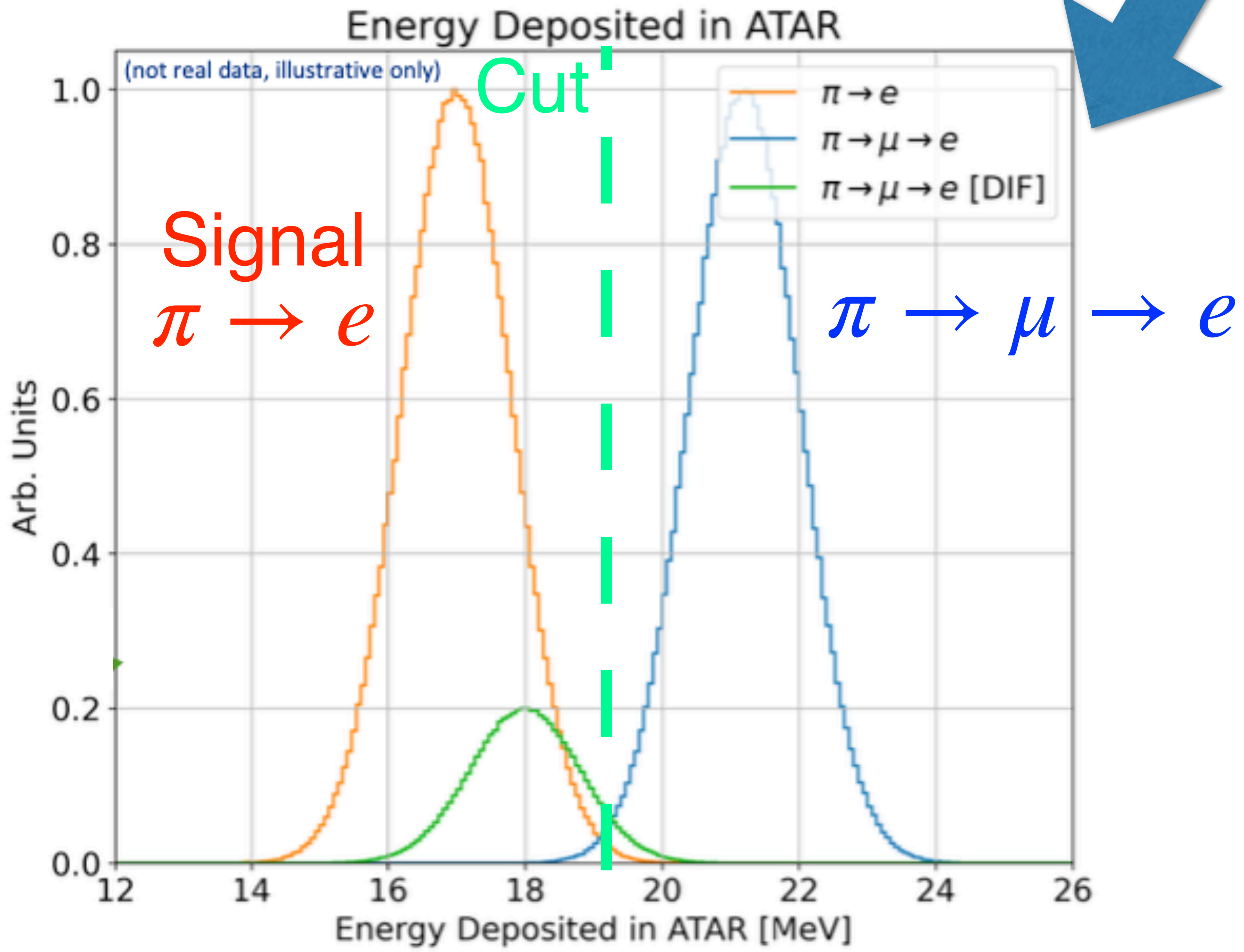


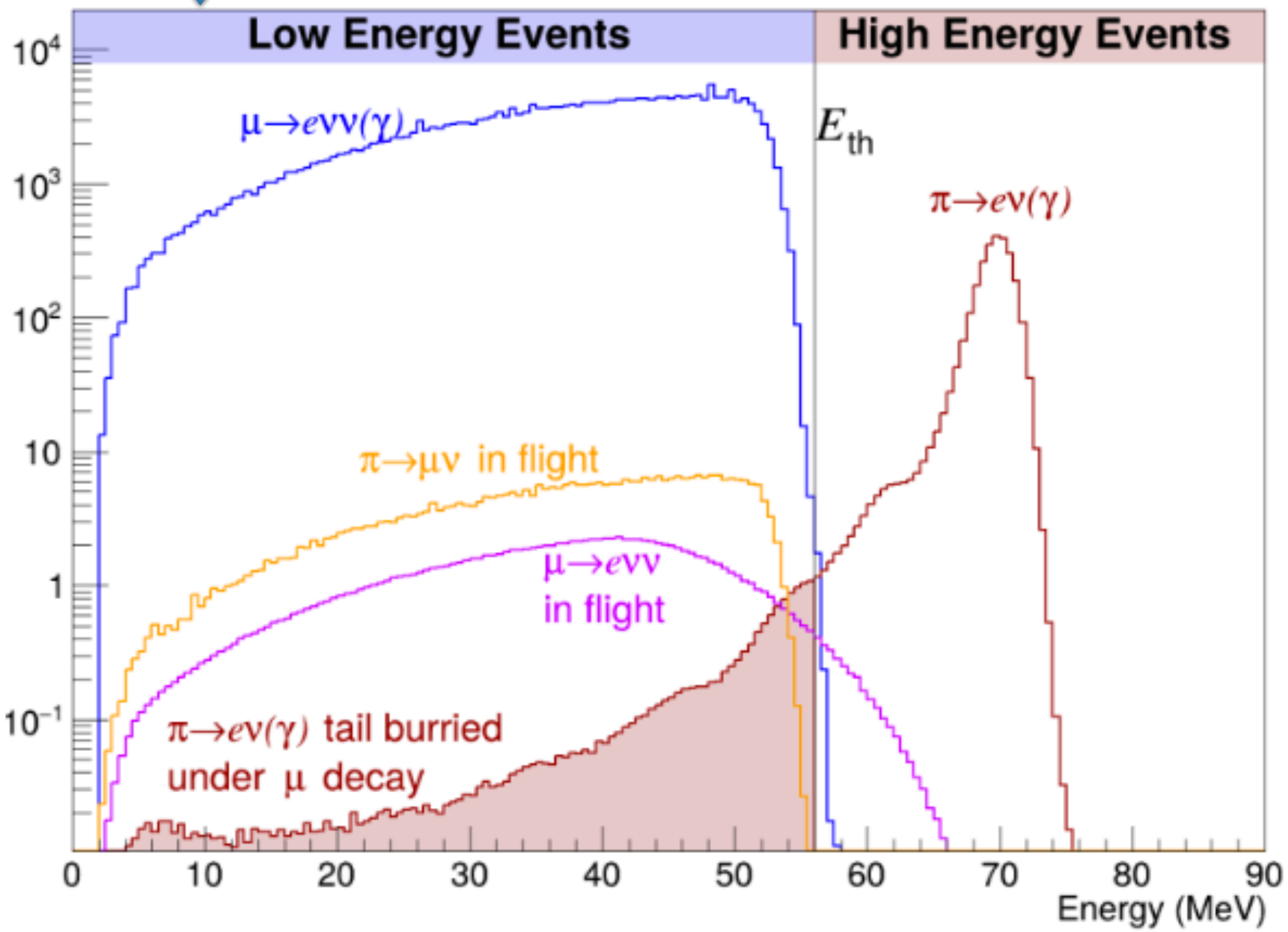
$\pi^+ \rightarrow e^+$

$\pi^+ \rightarrow \mu^+ \rightarrow e^+$

Calorimeter energy deposit

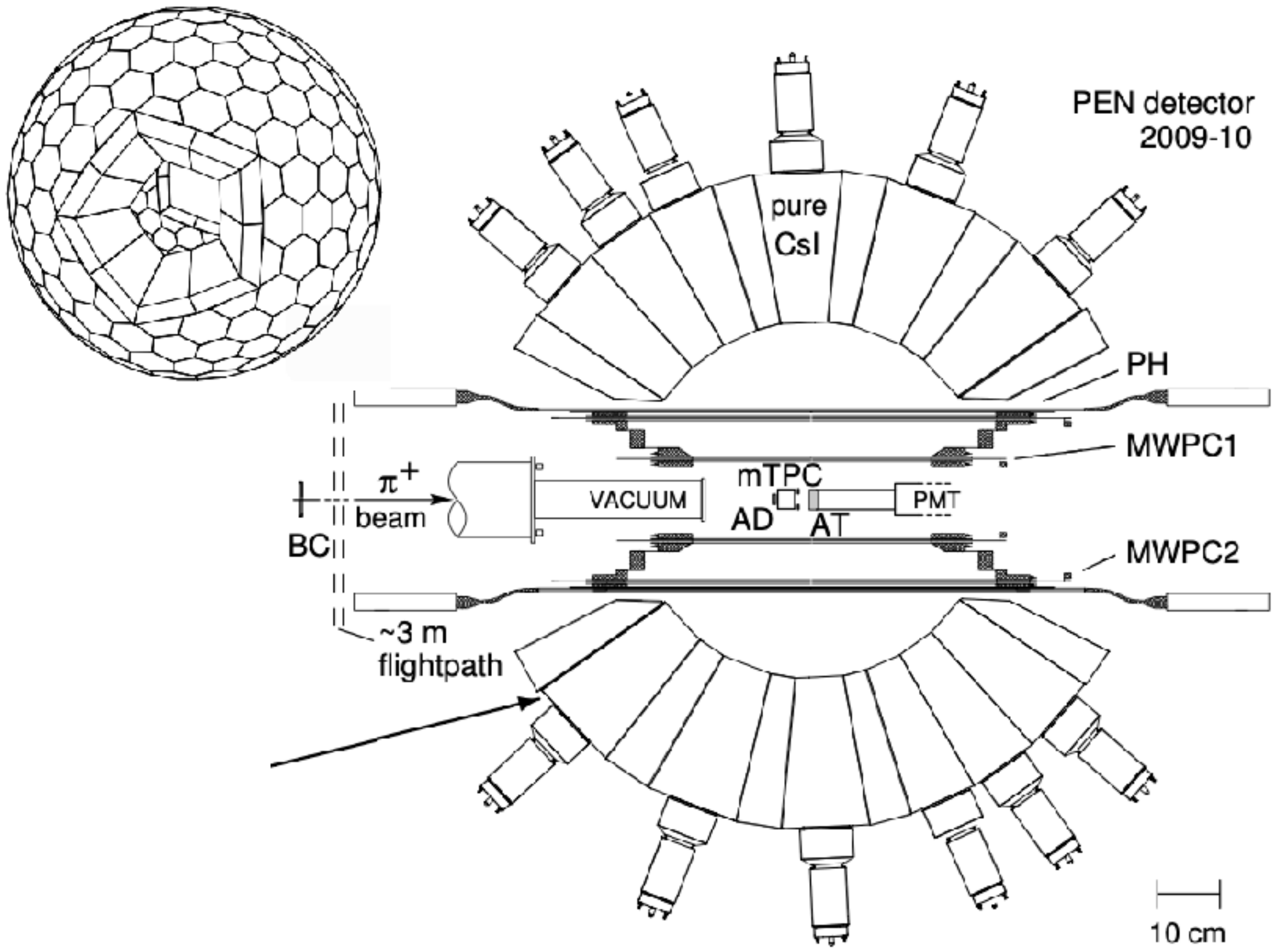
ATAR energy deposit



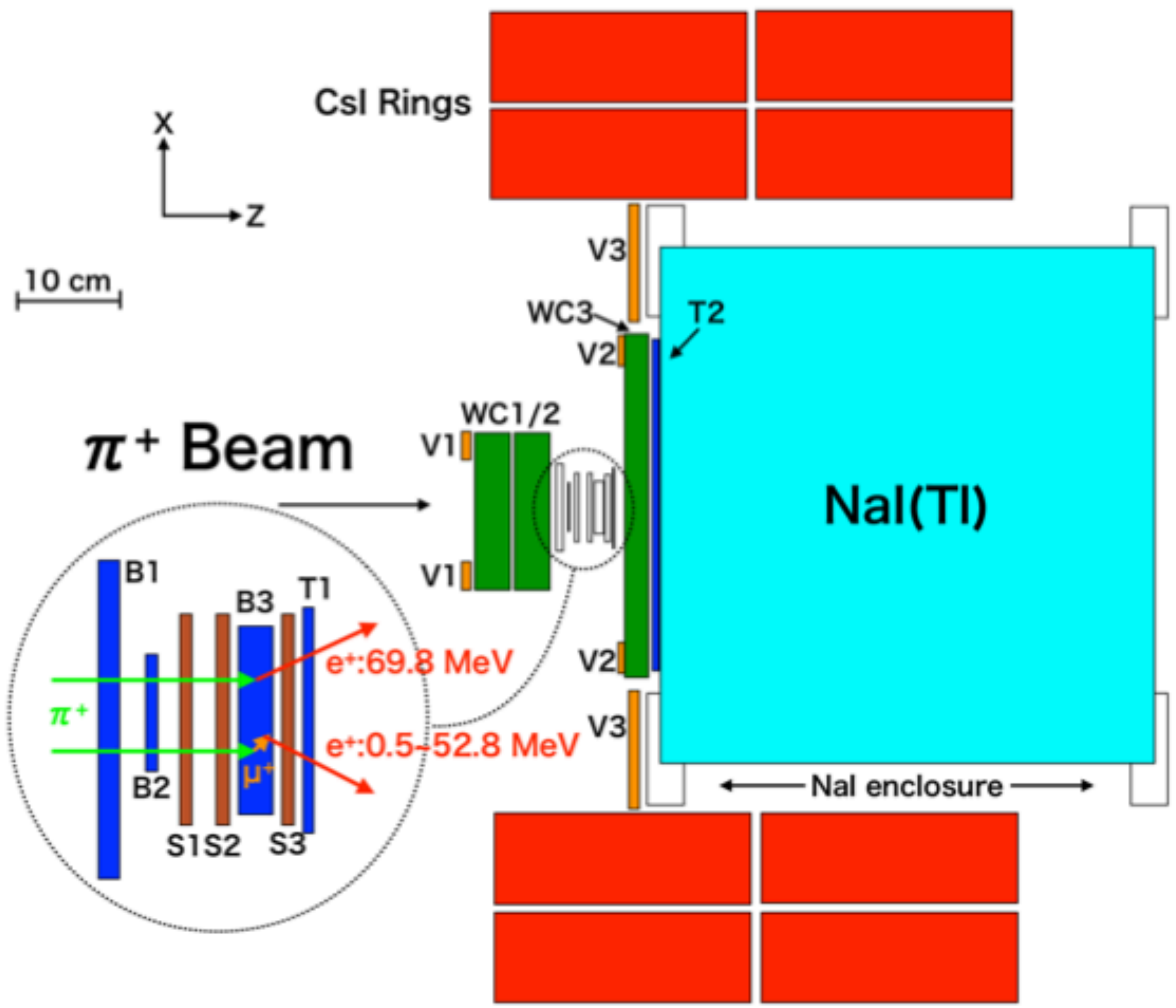


Previous experiments

PEN experiment @ PSI



PIENU experiment @ TRIUMF



Scintillator active target (measures time and energy deposit of $\pi^+, (\mu^+), e^+$)

240 segmented CsI ($\Delta E = 12.8\,\%$)
Good geometry, but only $12X_0$

Single crystal NaI(Tl) ($\Delta E = 2.2\,\%$)
Slow, small solid angle

PIONEER concept

Intense π+ beam at 65 MeV/c

- > 3×10^5 π^+/s
- Available at PSI πE5

Segmented Active Target

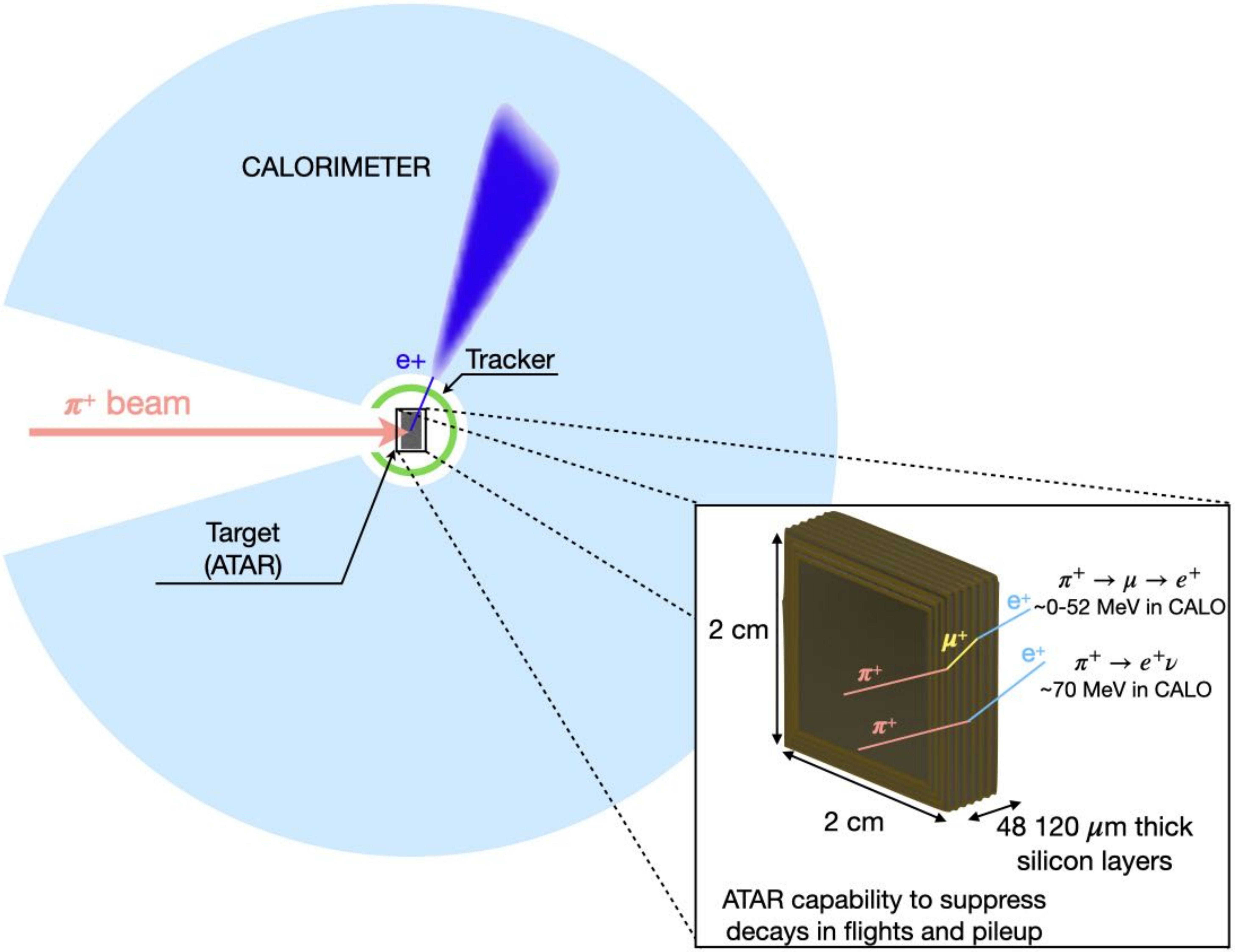
- Tracking π→e/π→μ→e events
- Energy, timing, particle direction
- Position resolution ~ 100μm
- Timing resolution ~ 1 ns

Calorimeter

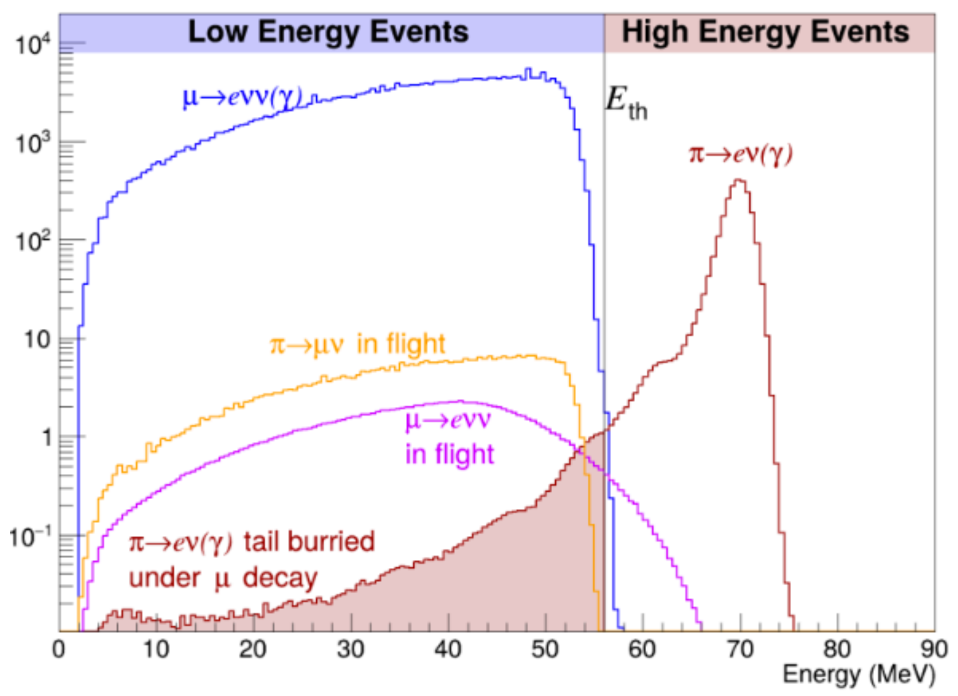
- Positron energy, time
- Depth of ~19 X_0 to reduce low energy events
- Large area acceptance

Tracker

- Positron direction between target and calorimeter

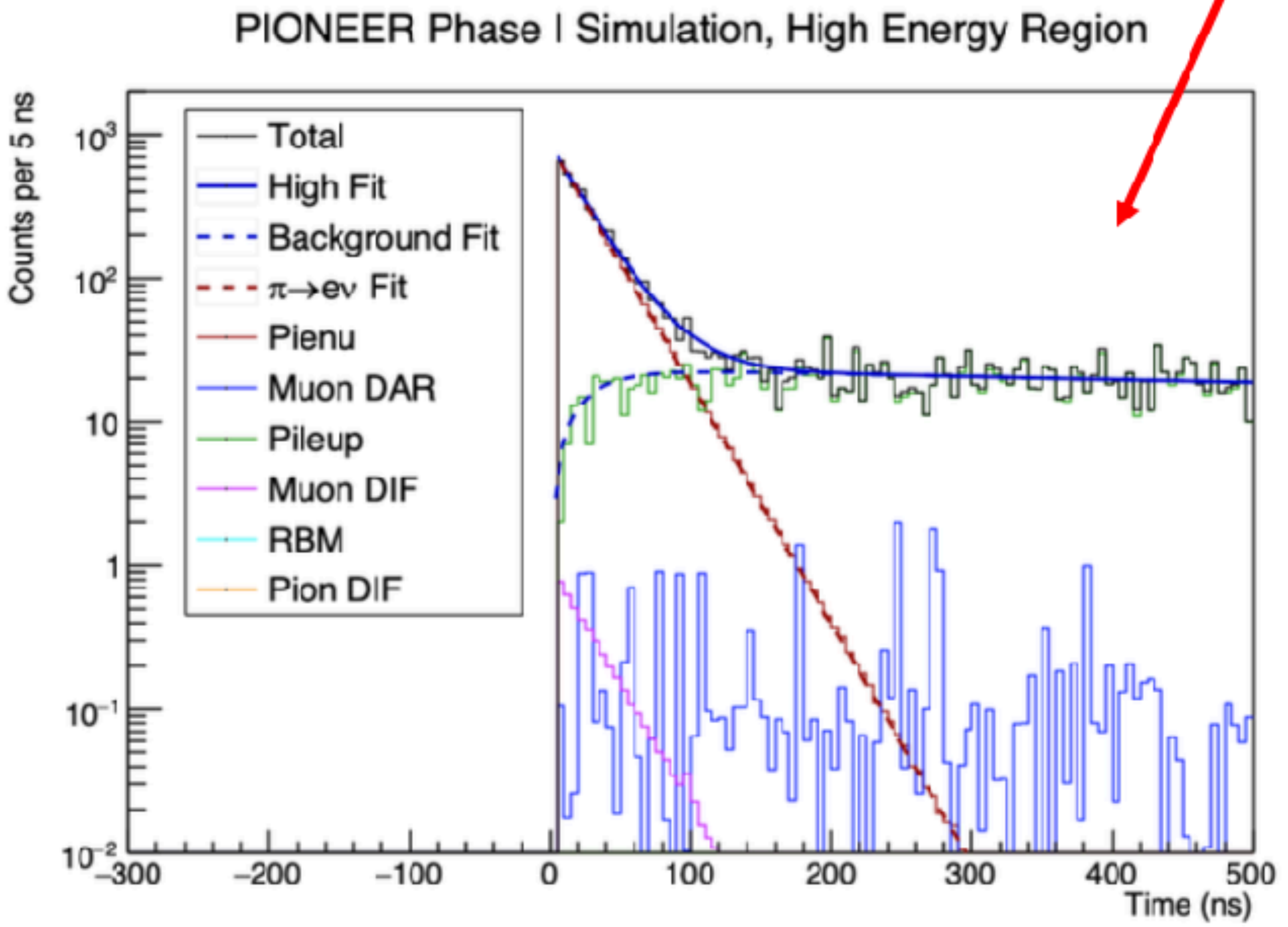


Basic analysis strategy to extract $R_{e/\mu}$

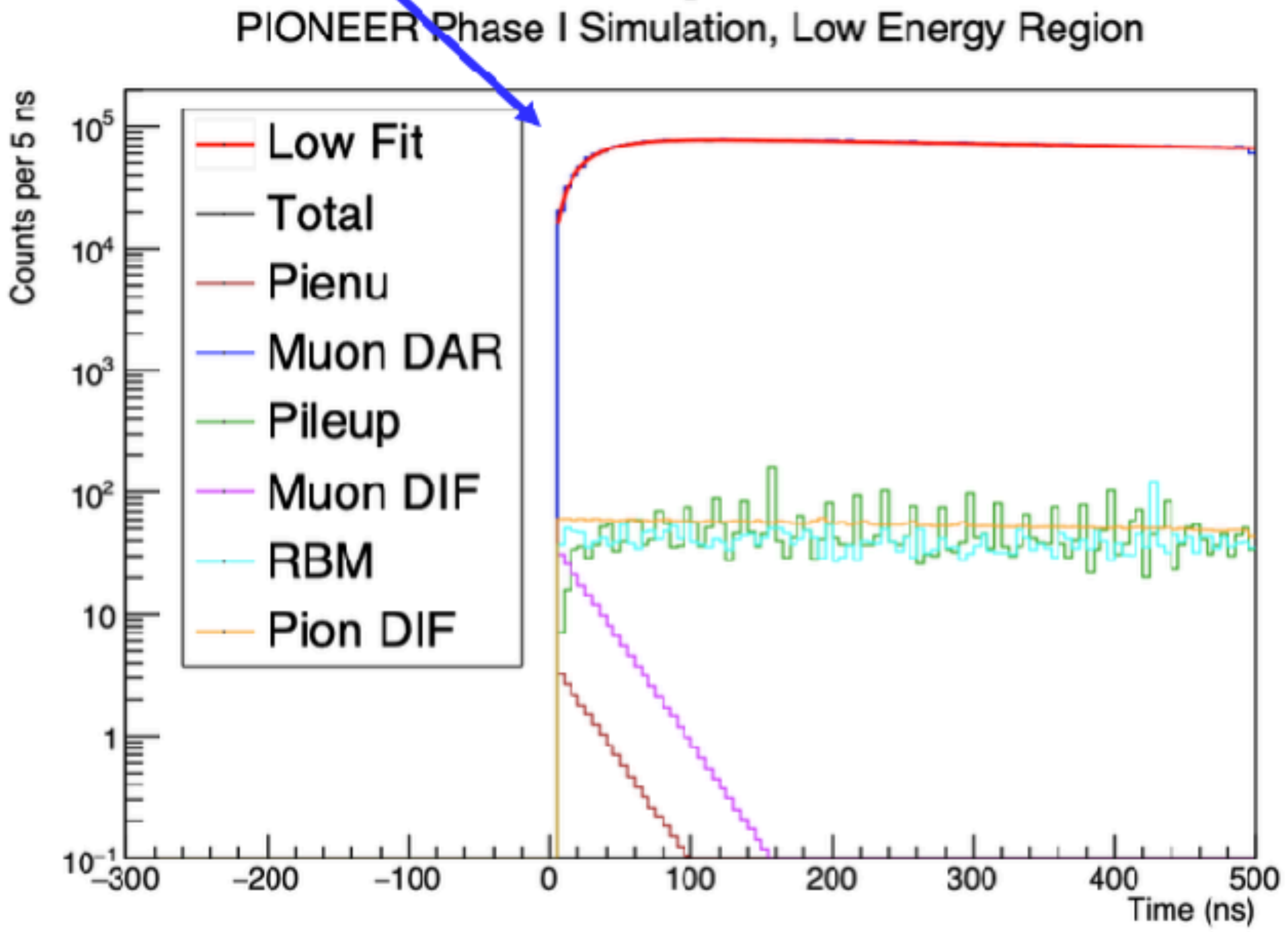


$$R_{e/\mu} = \frac{N_{\pi-e}(E > E_{th})}{N_{\pi-\mu-e}} \times (1 + c_{tail}) \times R^{\epsilon}$$

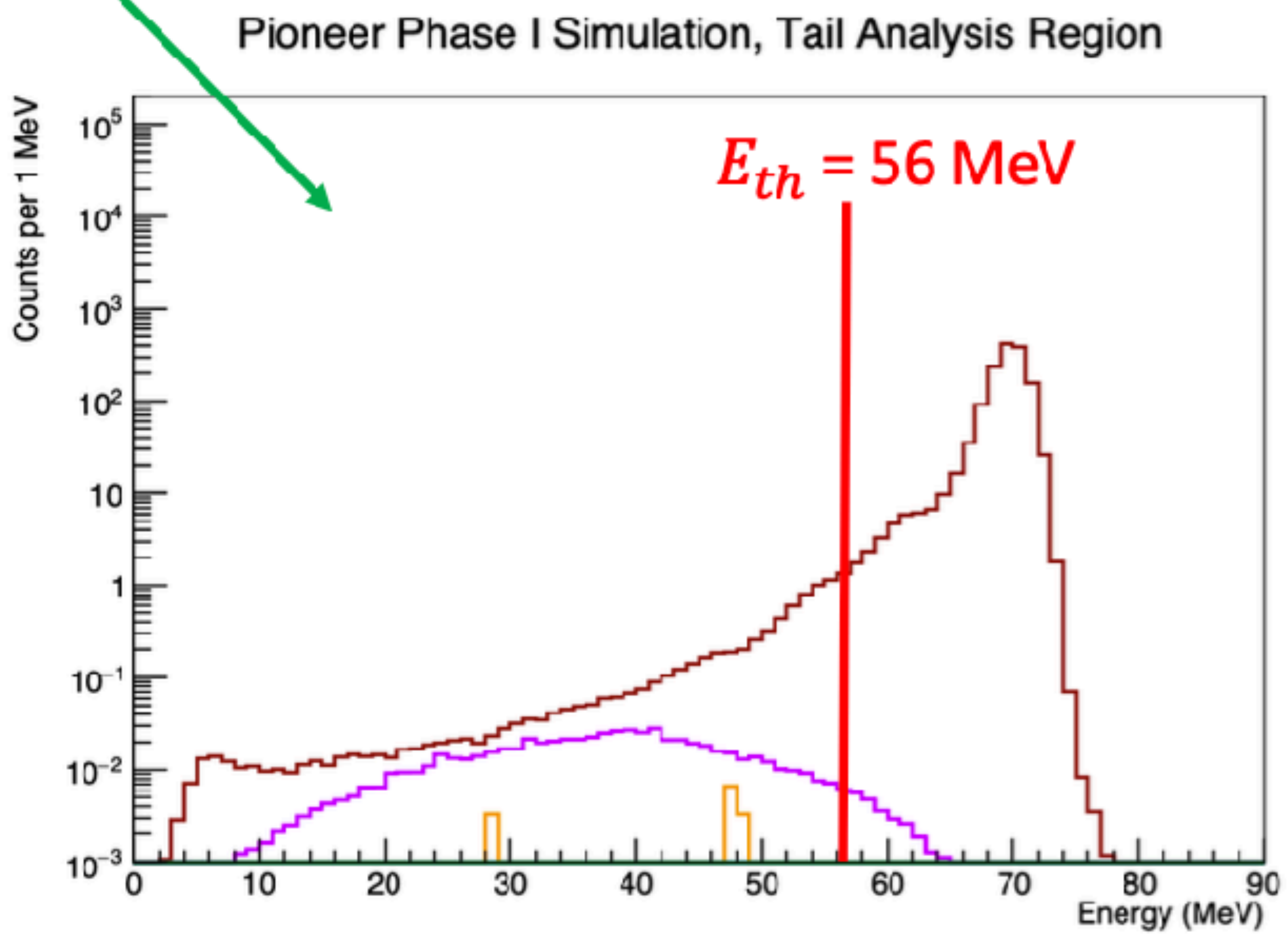
Acceptance ratio



Counts in "high bin" above ~56MeV

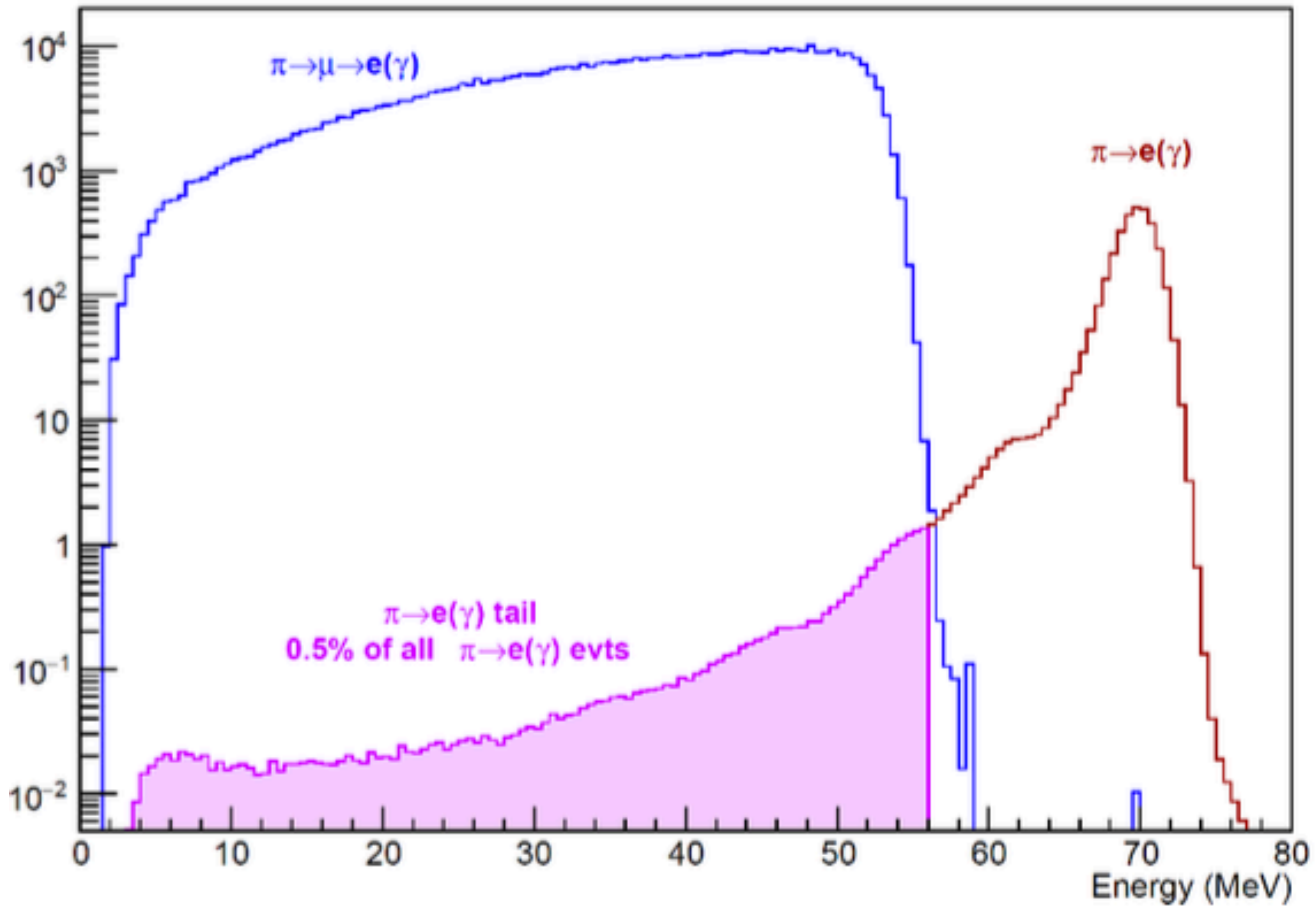


Counts in "low bin" below ~56MeV



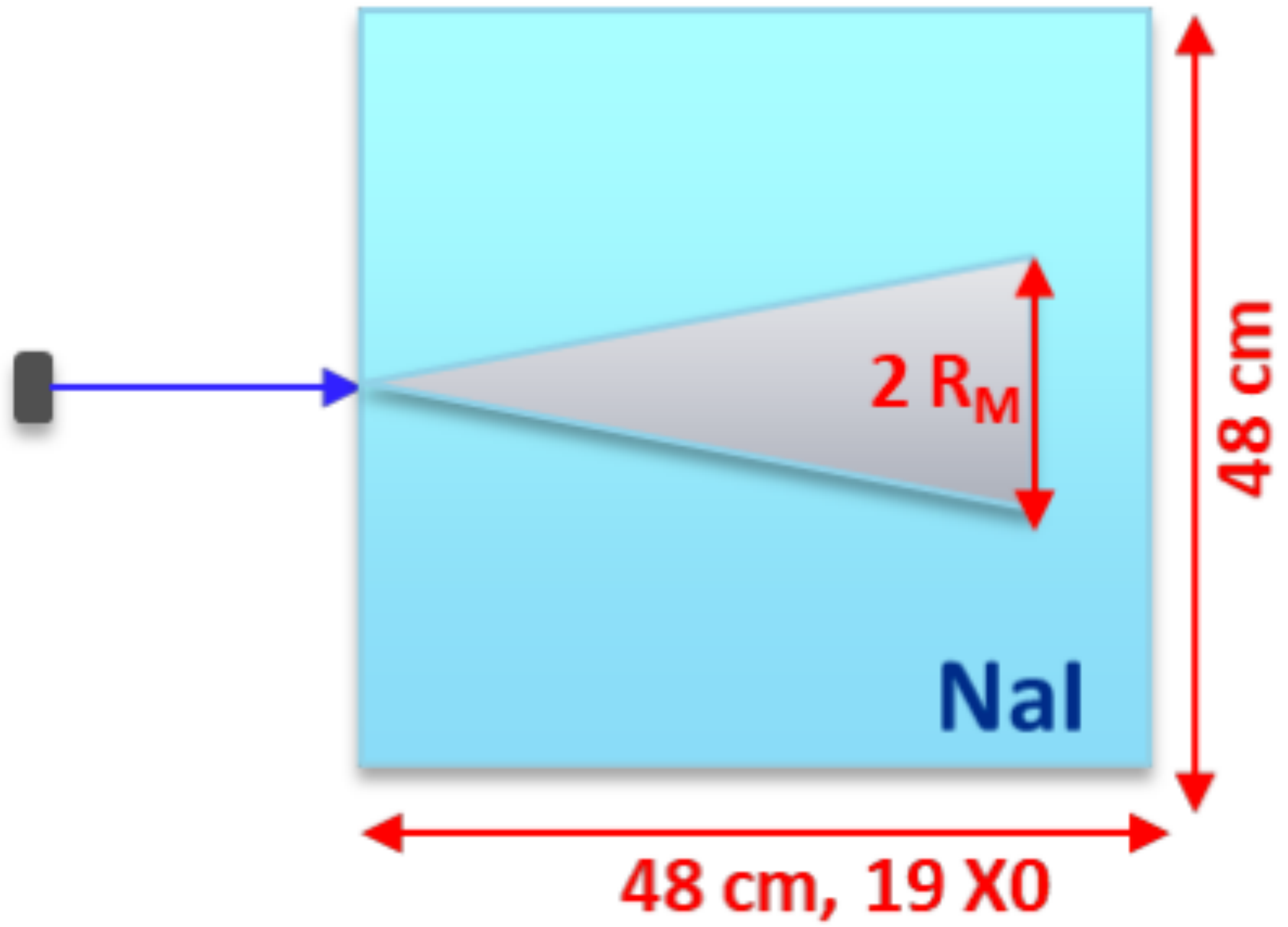
$\pi^+ \to e^+$ events that deposit < 56MeV in the Calo

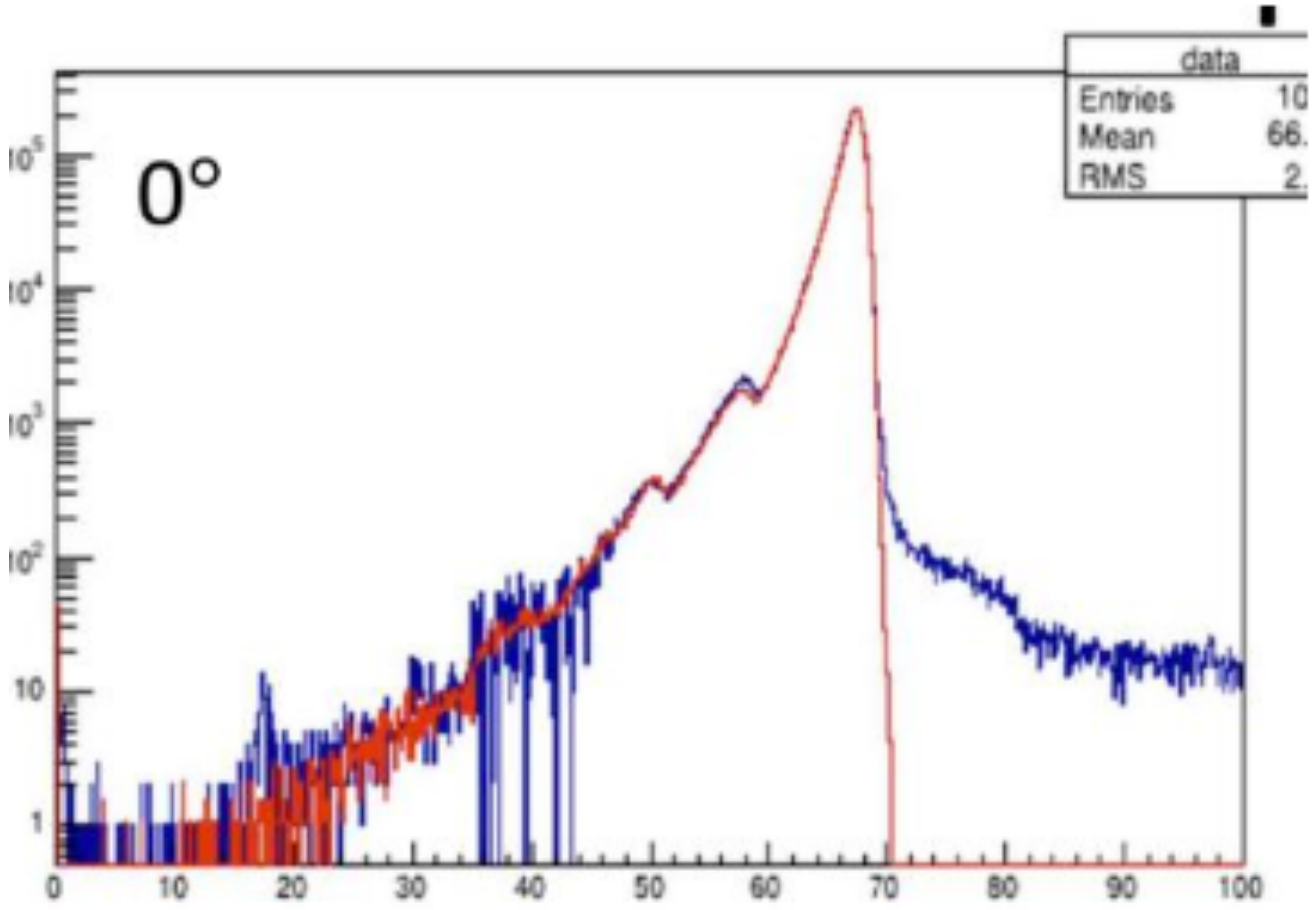
The size of the tail correction



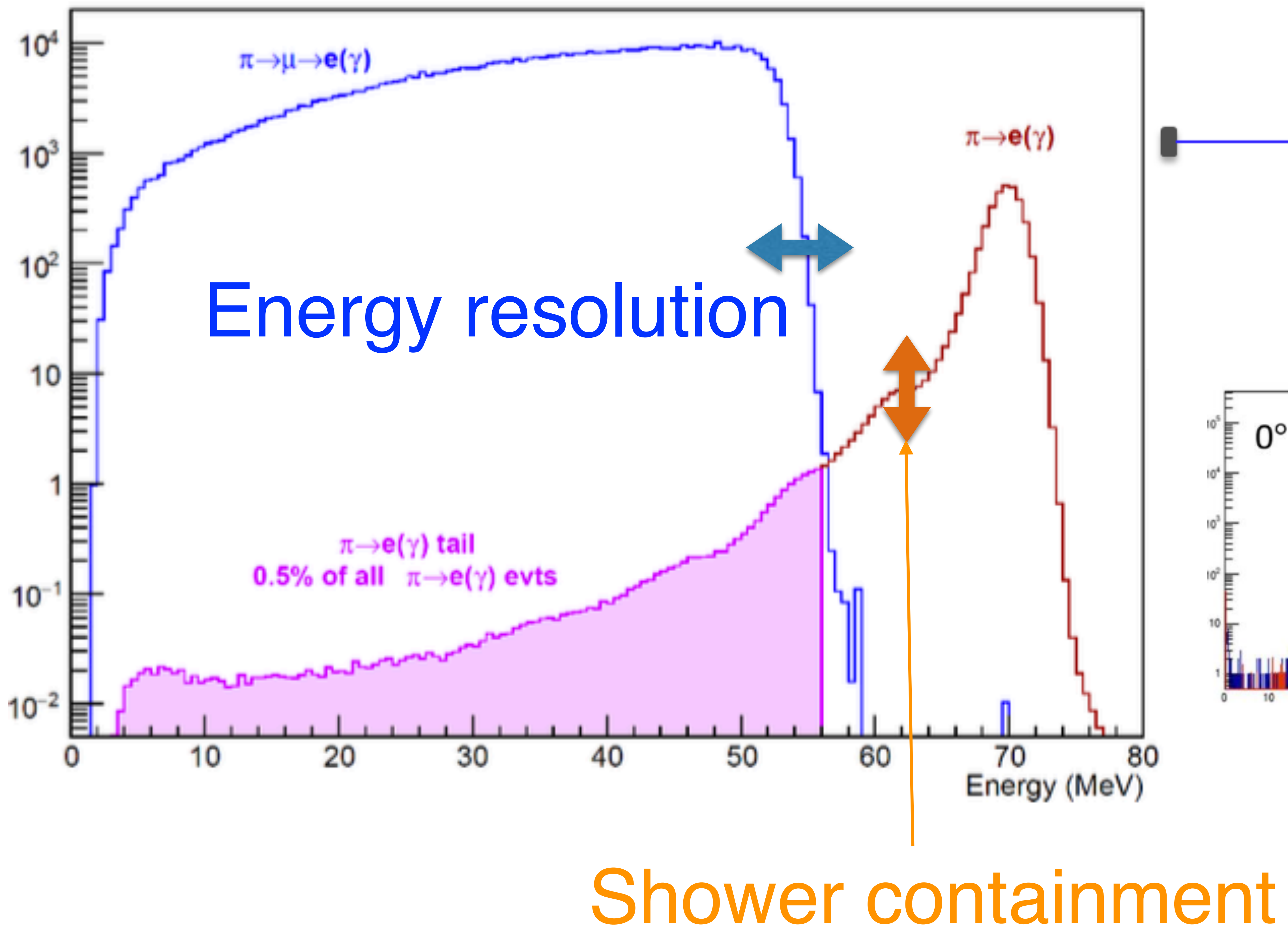
- Depth and inner radius optimized in Simulations

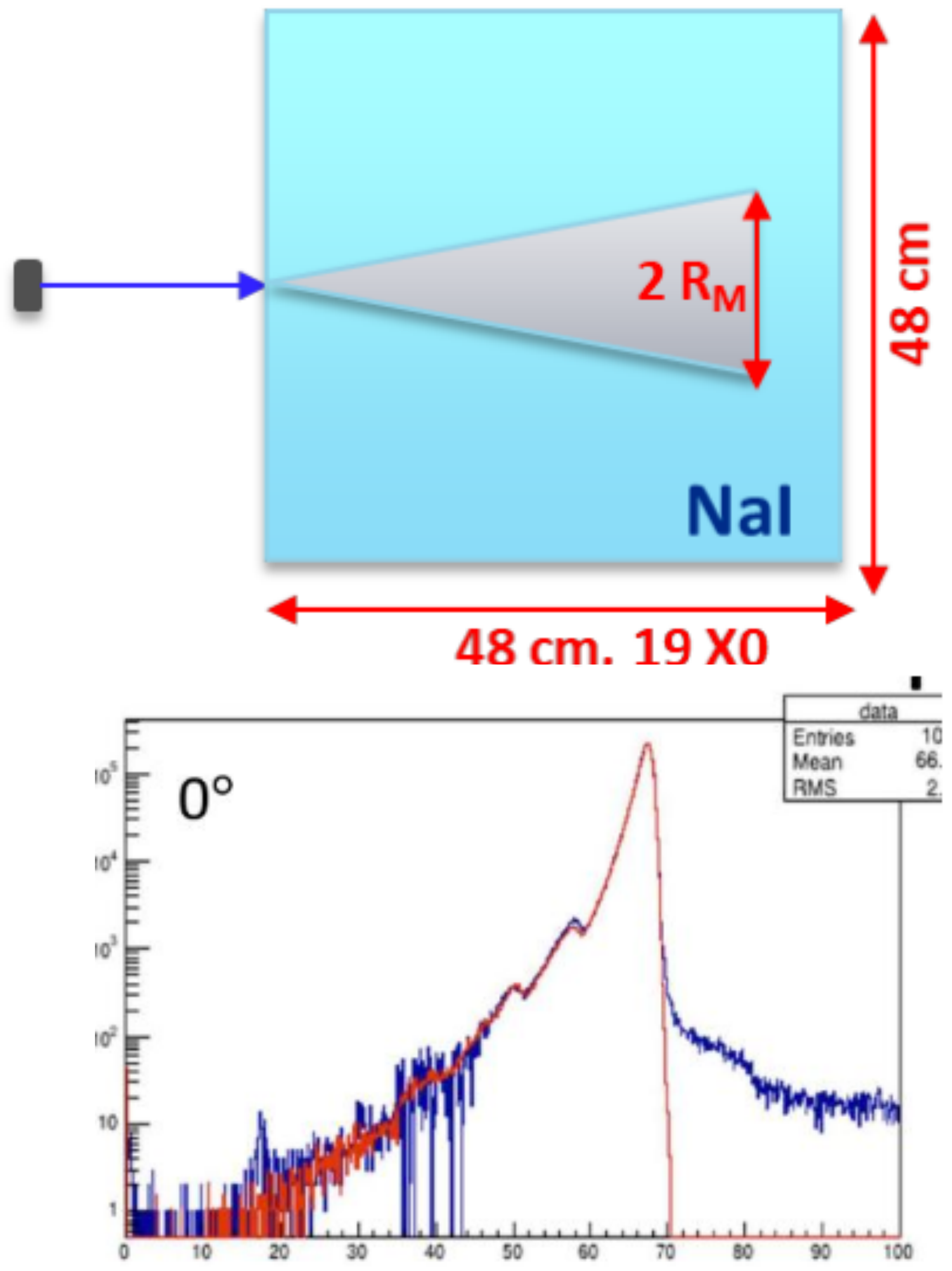
- PIENU obtained excellent resolution and a minimal tail fraction @small angles
- But not at larger angels



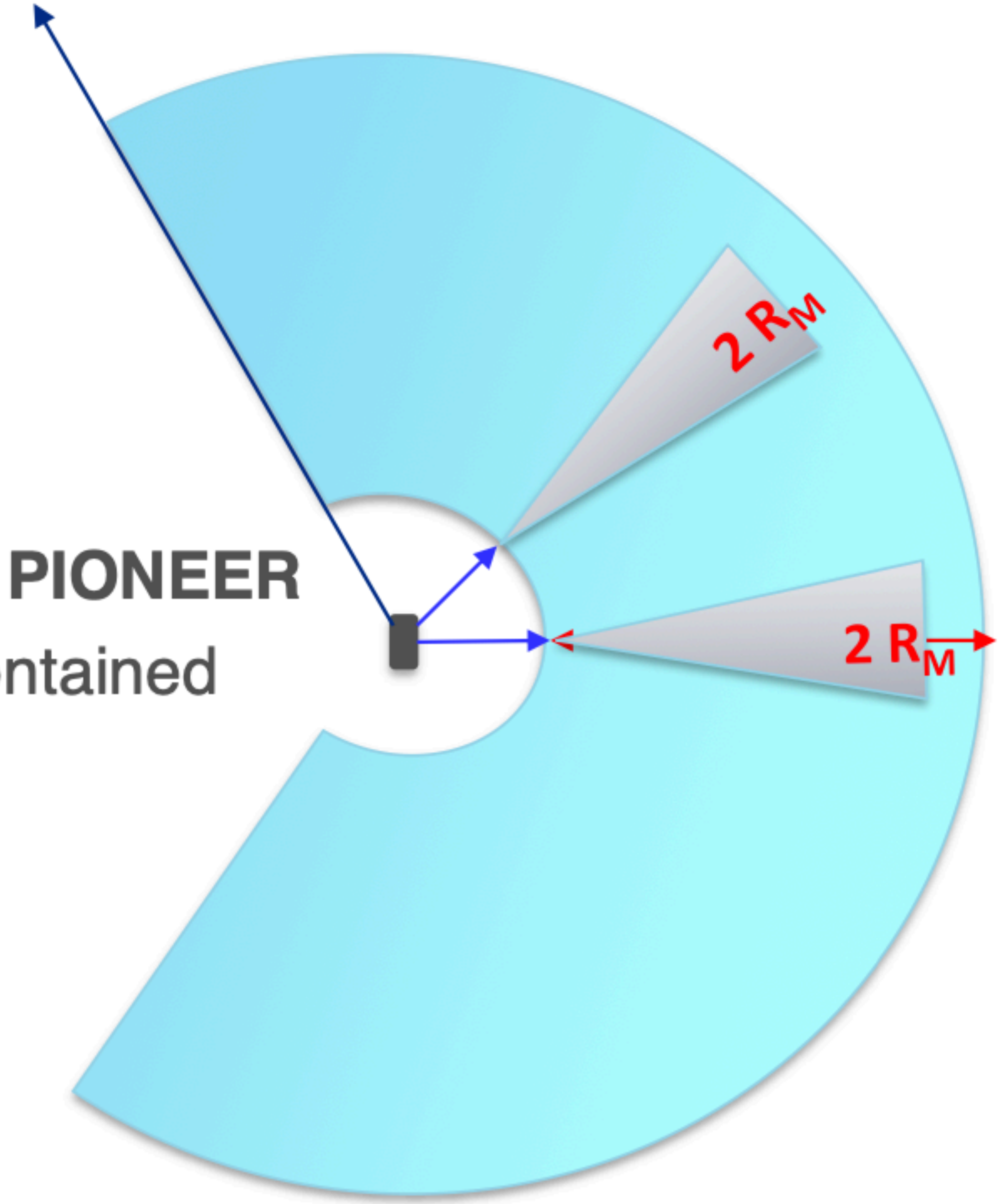


The size of the tail correction





PIONEER geometry works
for all angles

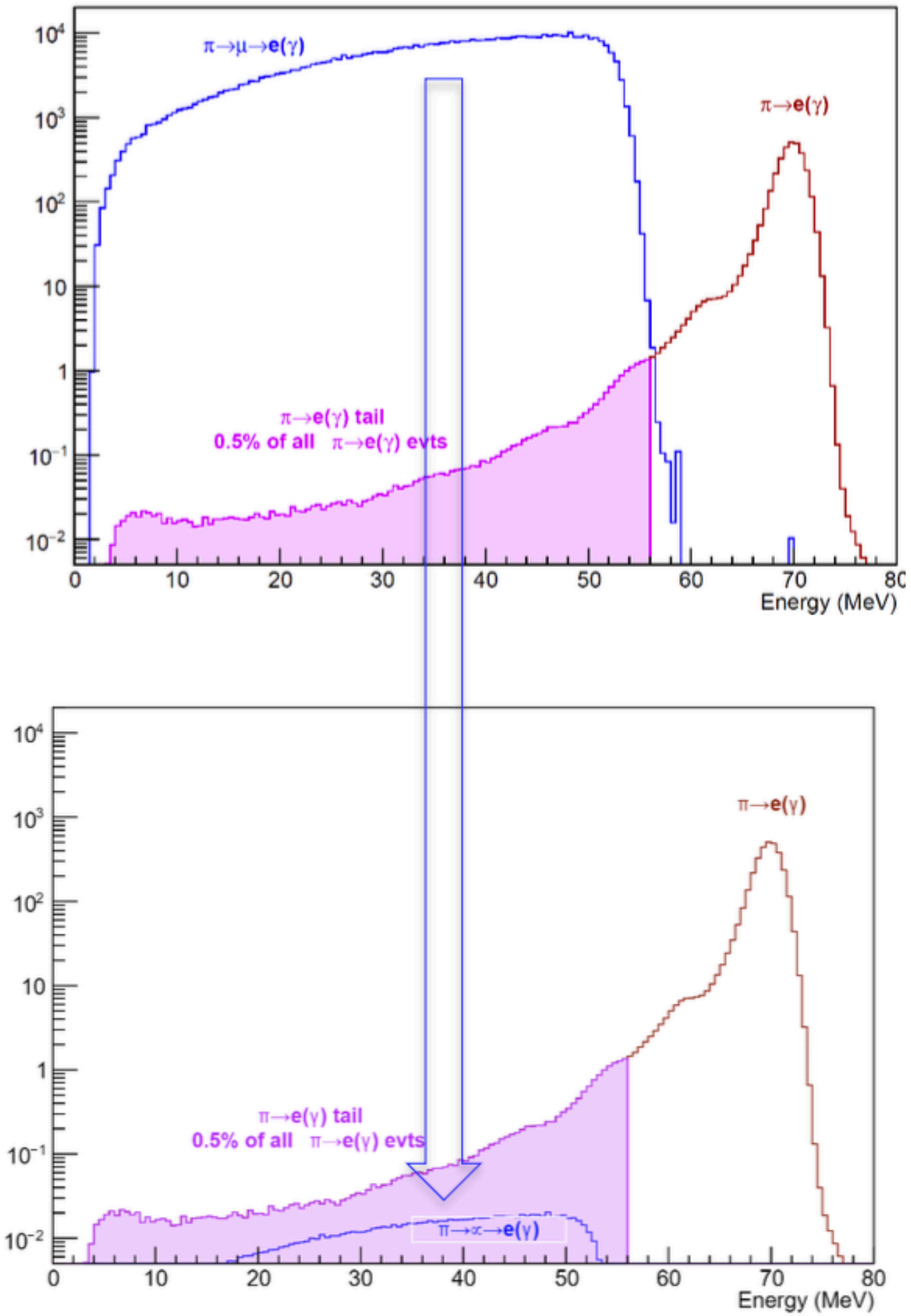


Spherical 19 X0 PIONEER

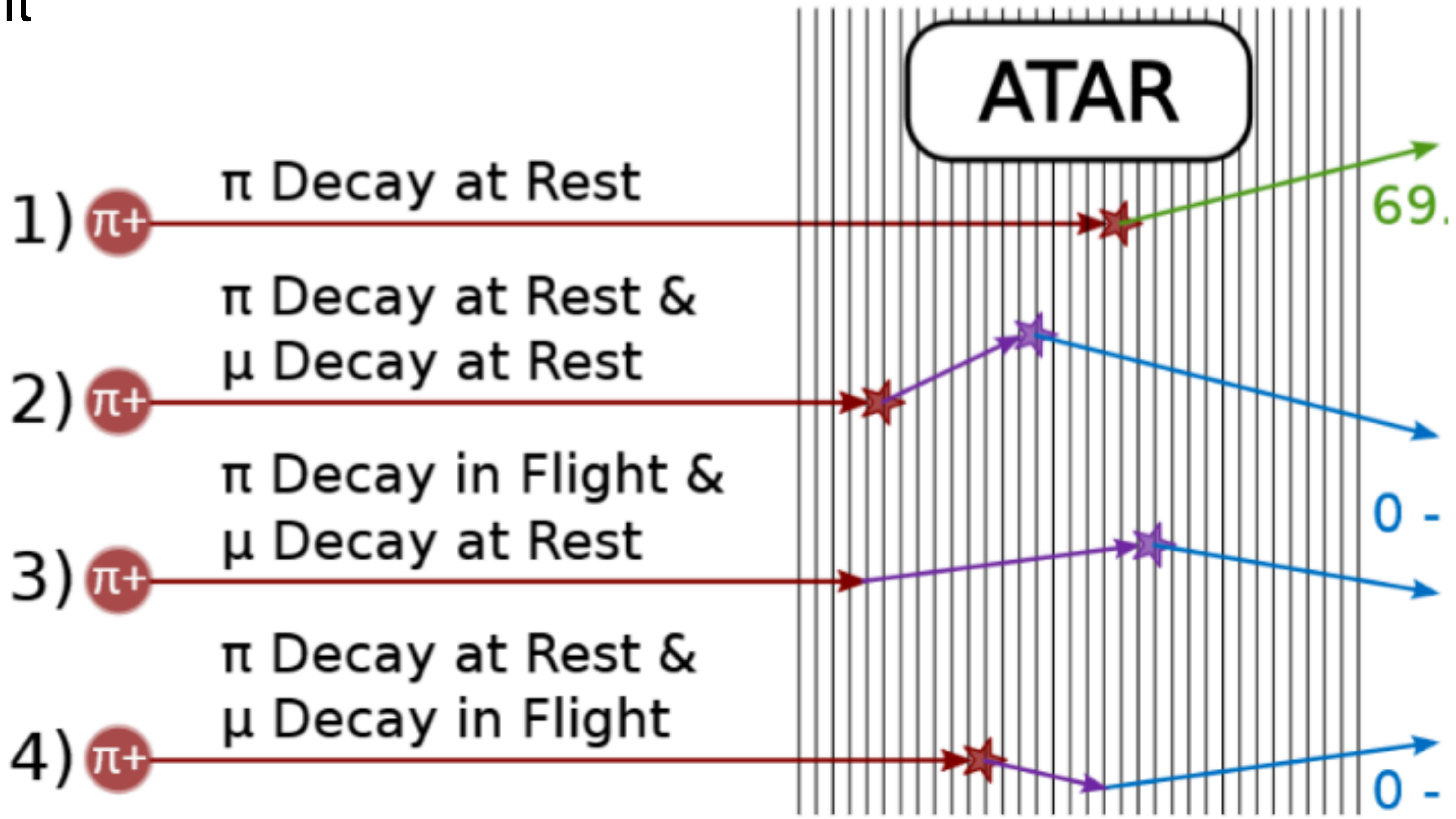
Uniform in θ & contained

- Depth and inner radius optimized in Simulations

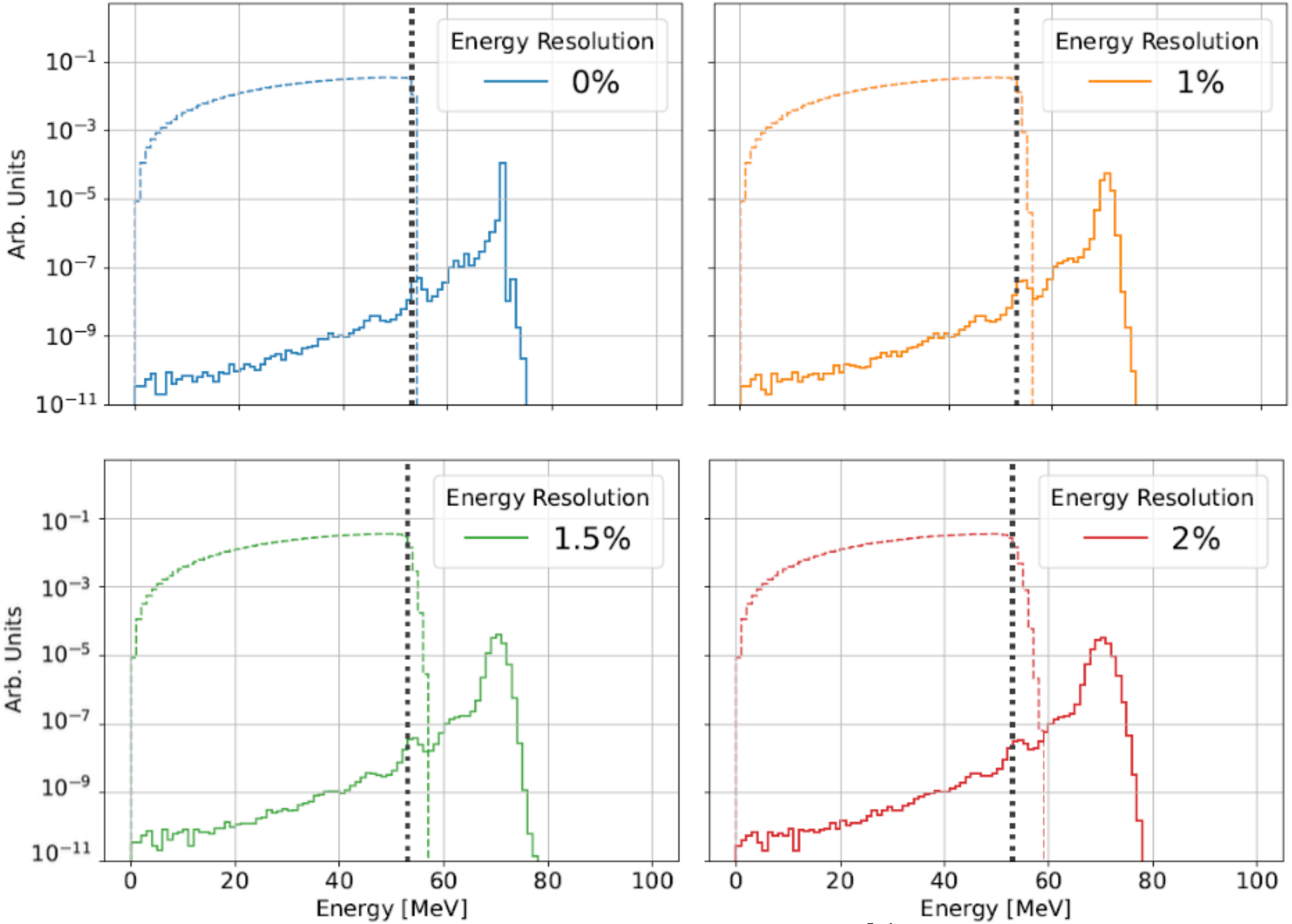
To reveal the Tail



- Suppress $\pi \to \mu \to e$ chain on a subset of events
- Use ATAR pattern recognition and energy measurements properties
  - 2 tracks with energetic Bragg peak termination
  - 1 escaping MIP track
  - Veto the event



Energy resolution of calorimeter



- $\pi \to \mu \to e$ events contaminate signal region of $\pi \to e$

World most intense pion beam

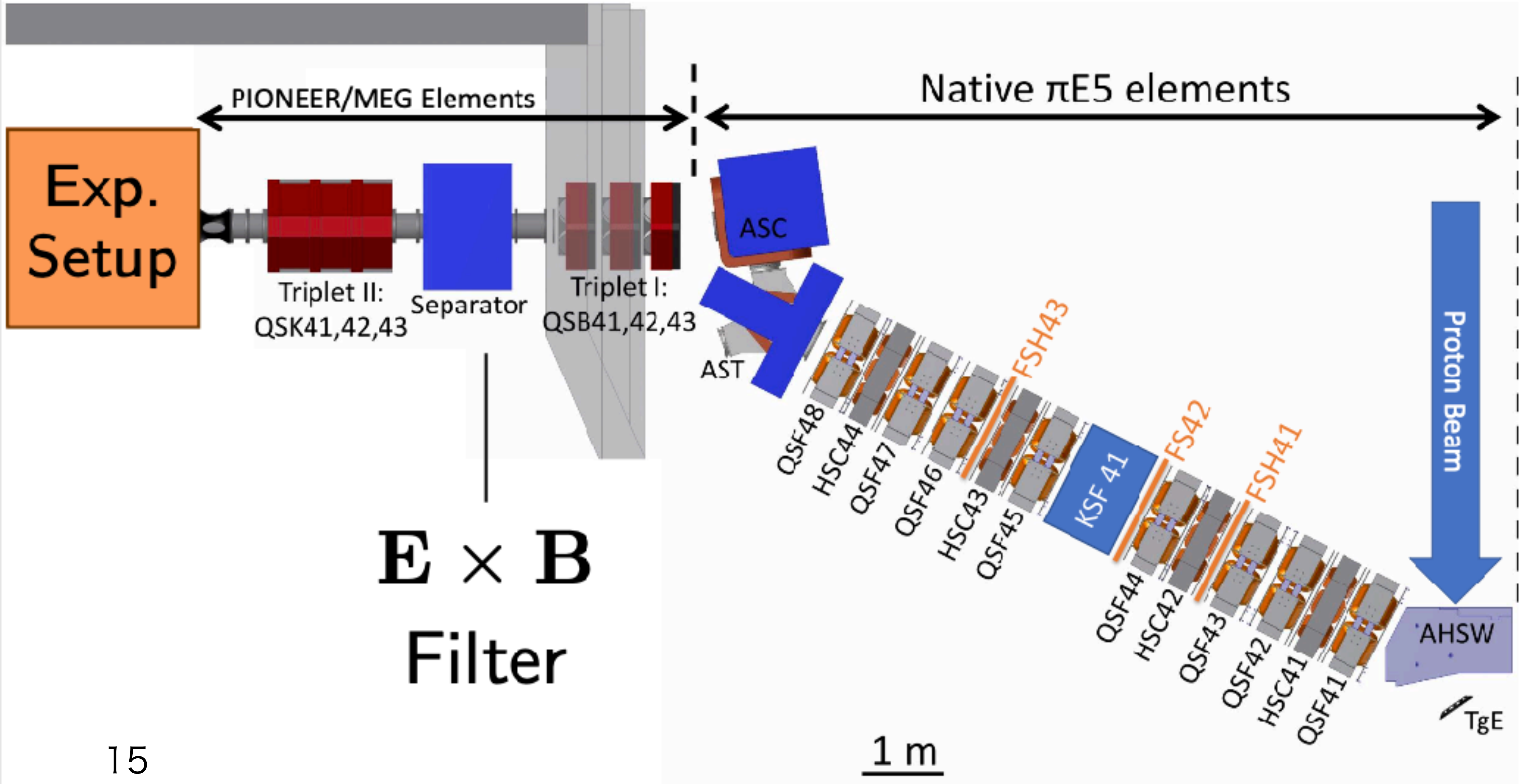
Requirements

- Rate : > 3×10^5 π^+/s at 65MeV/c
- Beam size : σ_x, σ_y < 2x2 cm^2
- Momentum bite : dp/p < 2%
- Particle μ/e < 10%

1.4 MW 590 MeV proton accelerator in Paul Scherrer Institute in Switzerland

Paul Scherrer Institute

- PiE5 beam line would be the only candidate in terms of rate.
- MEG, Mu3e will occupy the PiE5 at least until 2026 (and Mu3e even after)



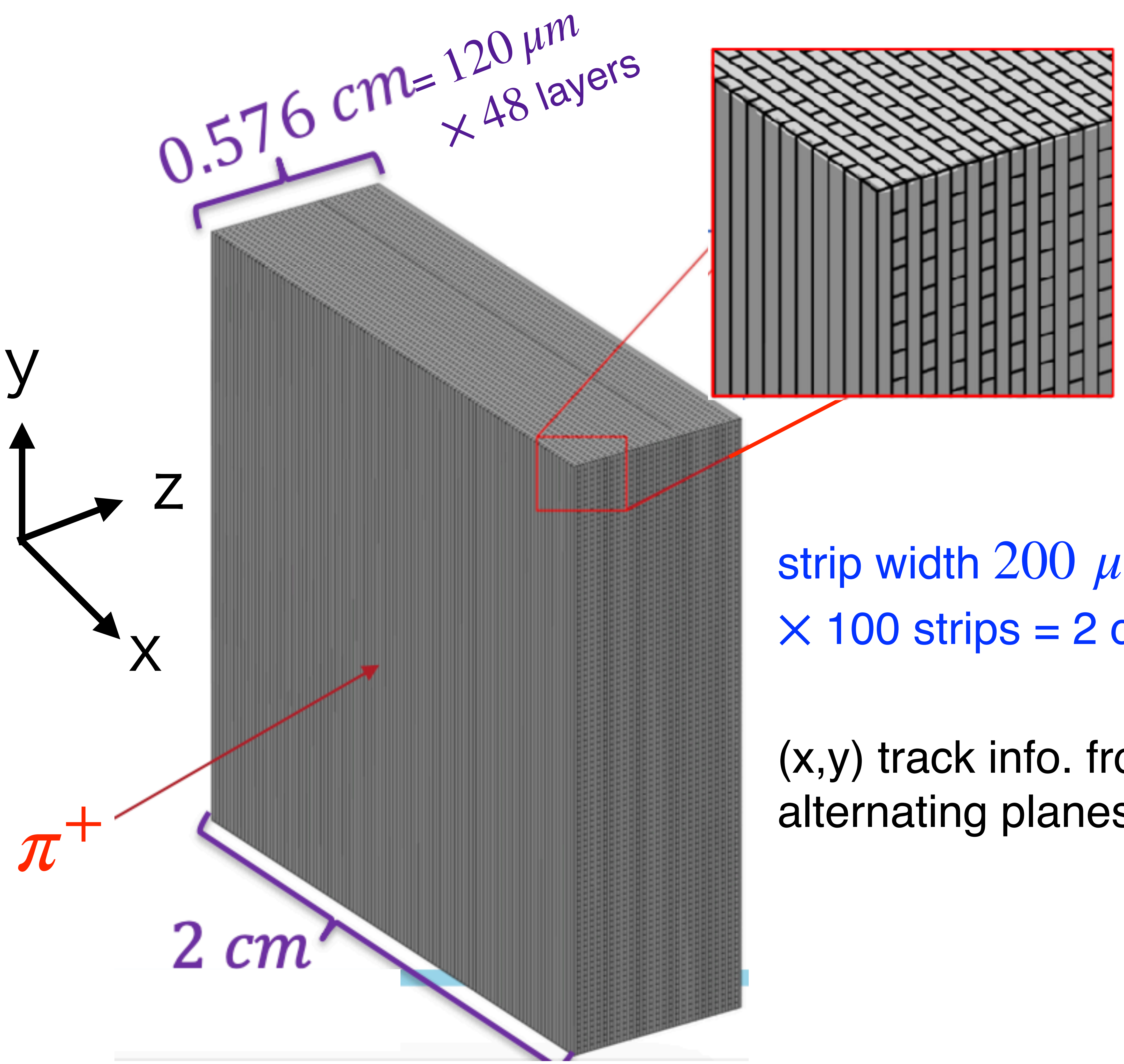
Status

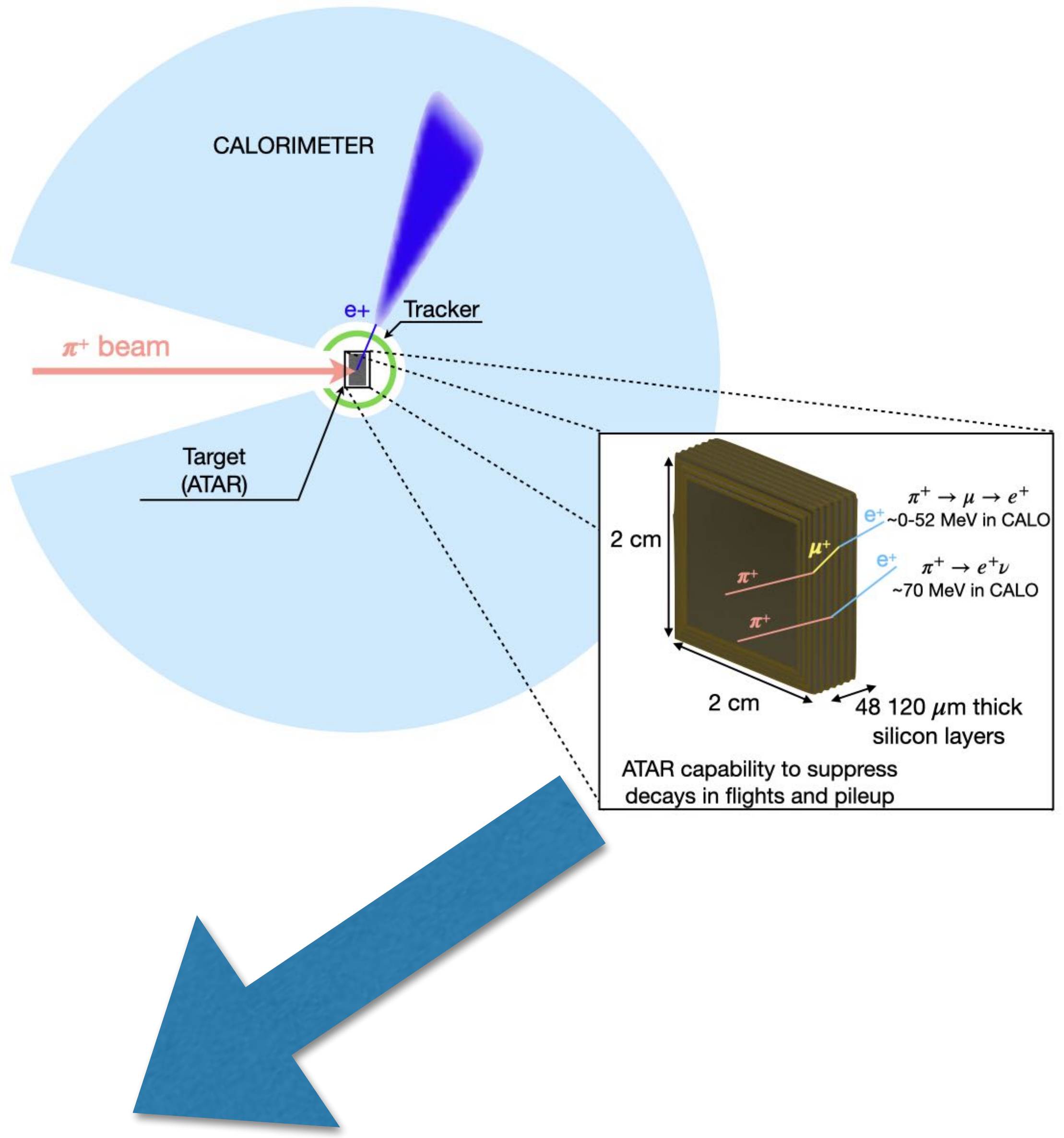
- Phase space measurement for detector design for a week is requested to PSI

Active target

Requirements

- Energy response
  - 40 keV MIP ~ 4 MeV μ^+ Bragg peak
  - $\sigma_E < 10\%$, large dynamic range
- Tracking (π/μ/e)
  - High granularity in (X,Y,Z)
  - R_π(65MeV/c) ~ 4mm, R_μ(4.1MeV) ~ 0.8mm in Si
- Timing
  - π/μ hit separation by 2ns for 300kHz

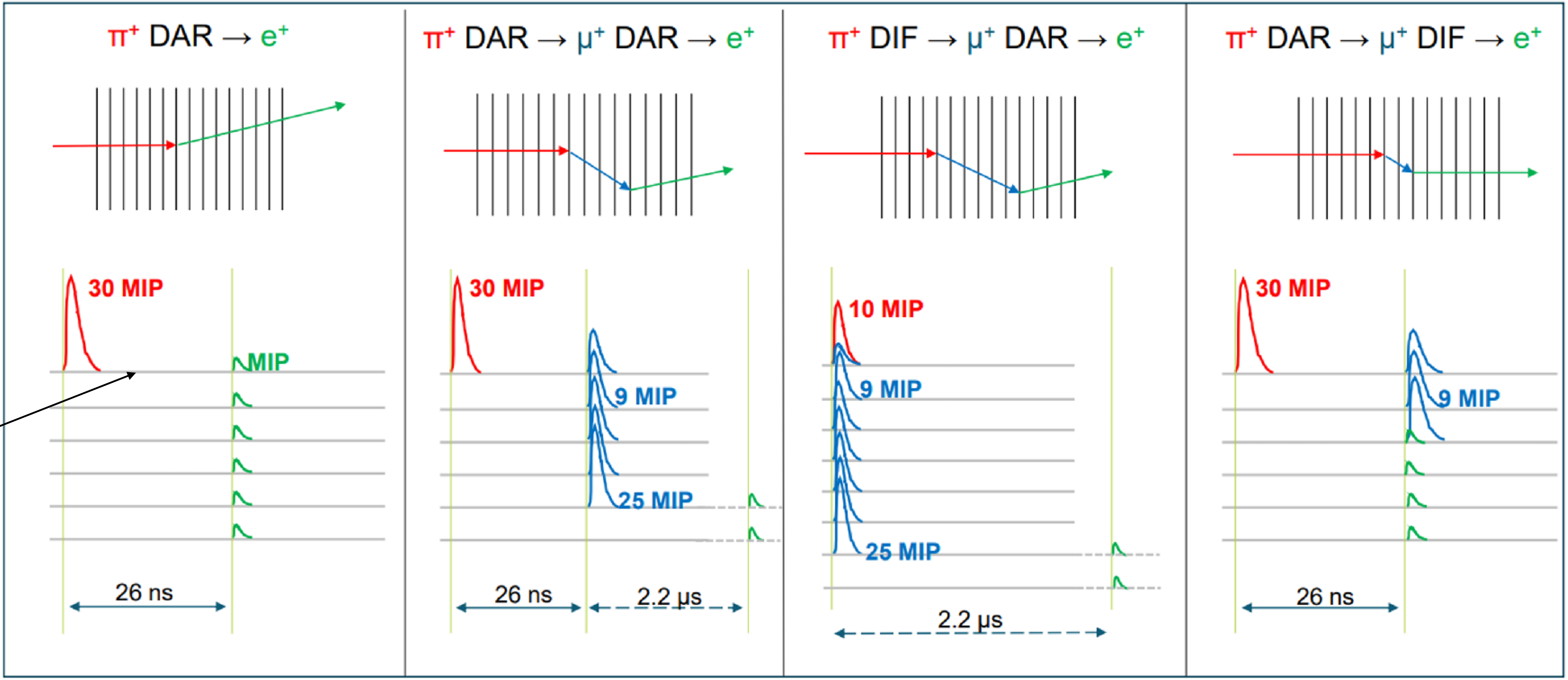




strip width $200\ \mu m$
× 100 strips = 2 cm

(x,y) track info. from alternating planes

What is measured in ATAR



Time separated pulses on a single strip

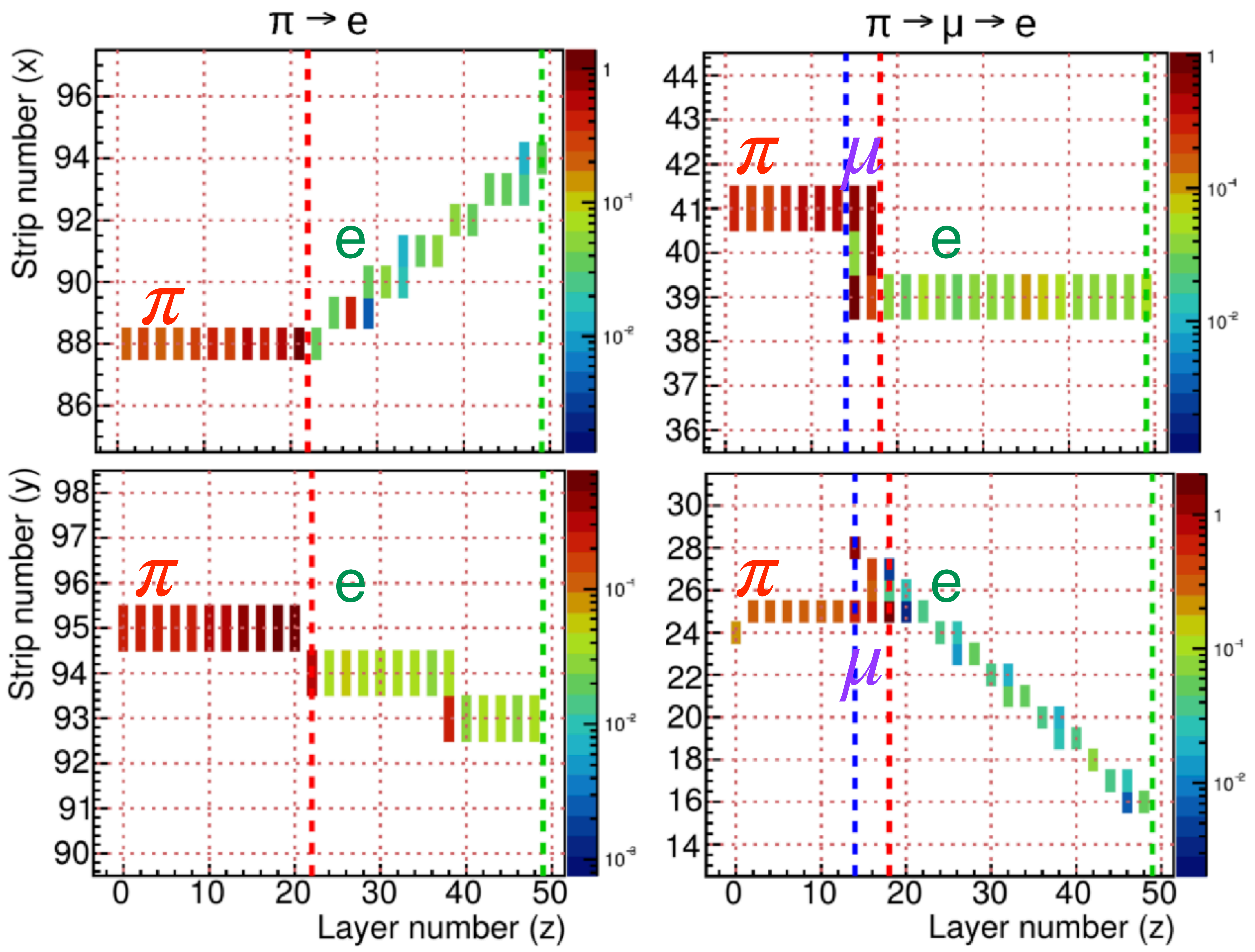
$R_\pi(65MeV/c) \sim 4mm$

$R_\mu(4.1MeV) \sim 0.8mm$

ATAR tracking

Combined information of tracking, timing, and energy deposit

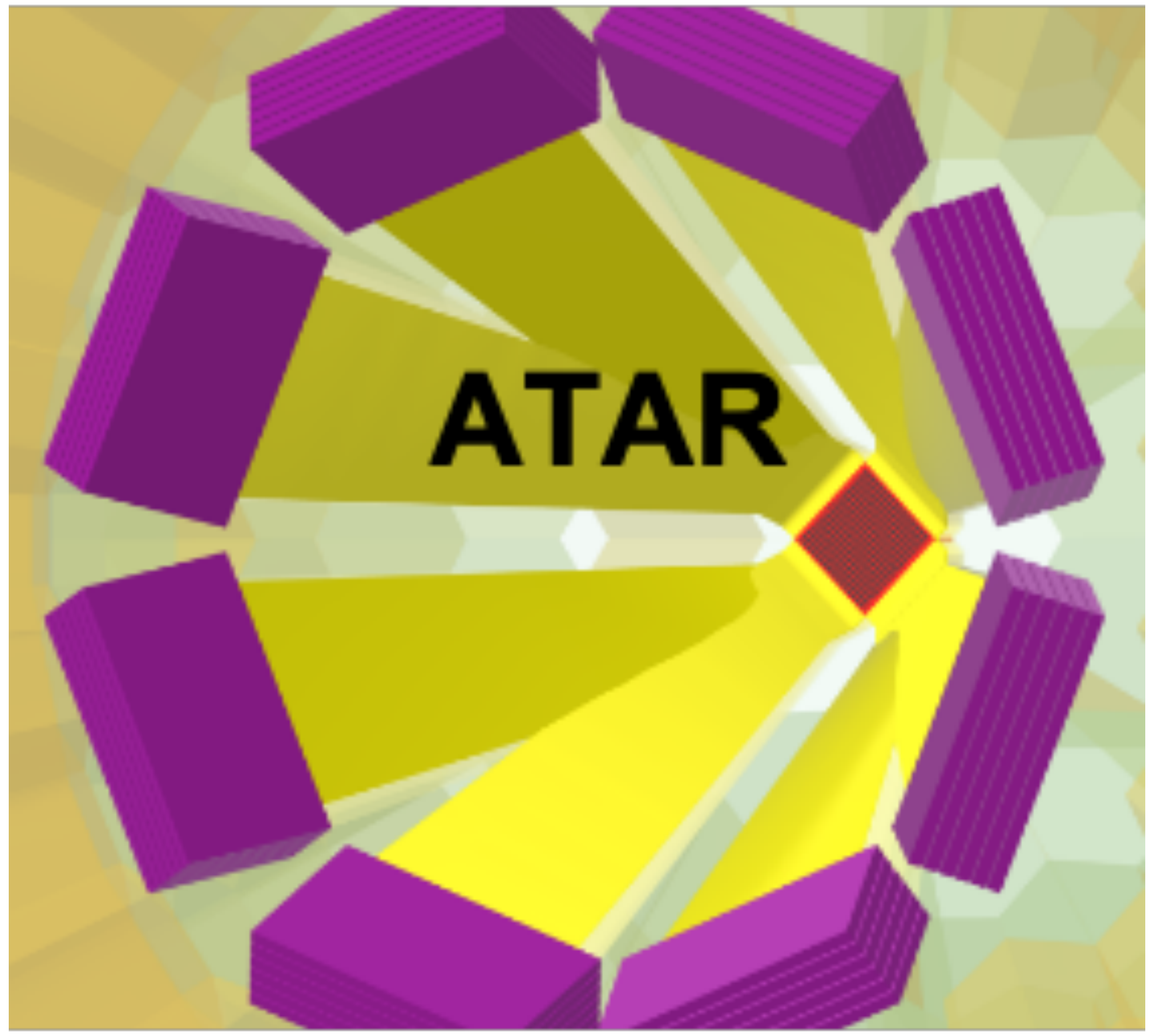
- reduces the Michel $\pi \to \mu \to e$ chain “background” for tail correction

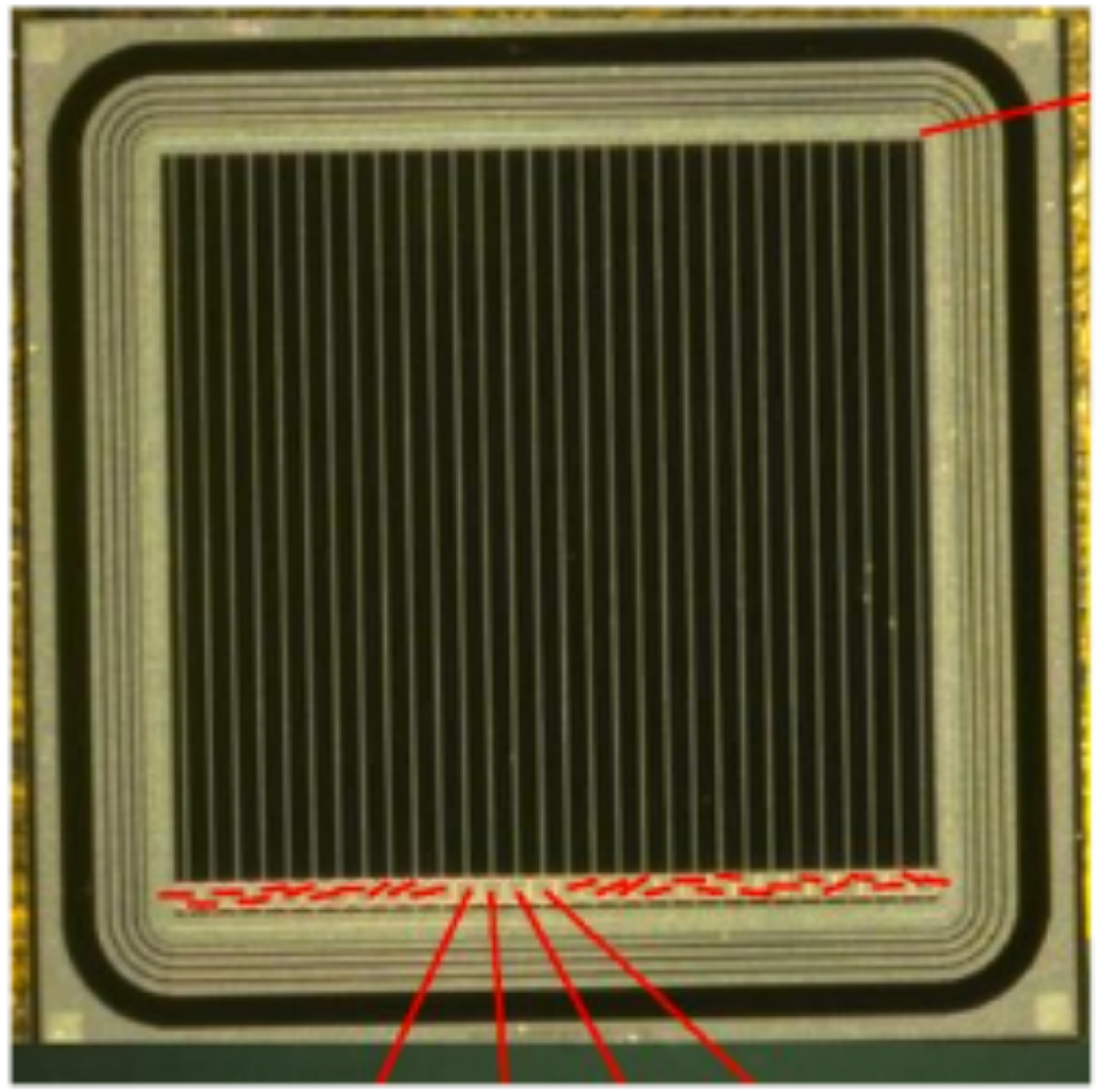


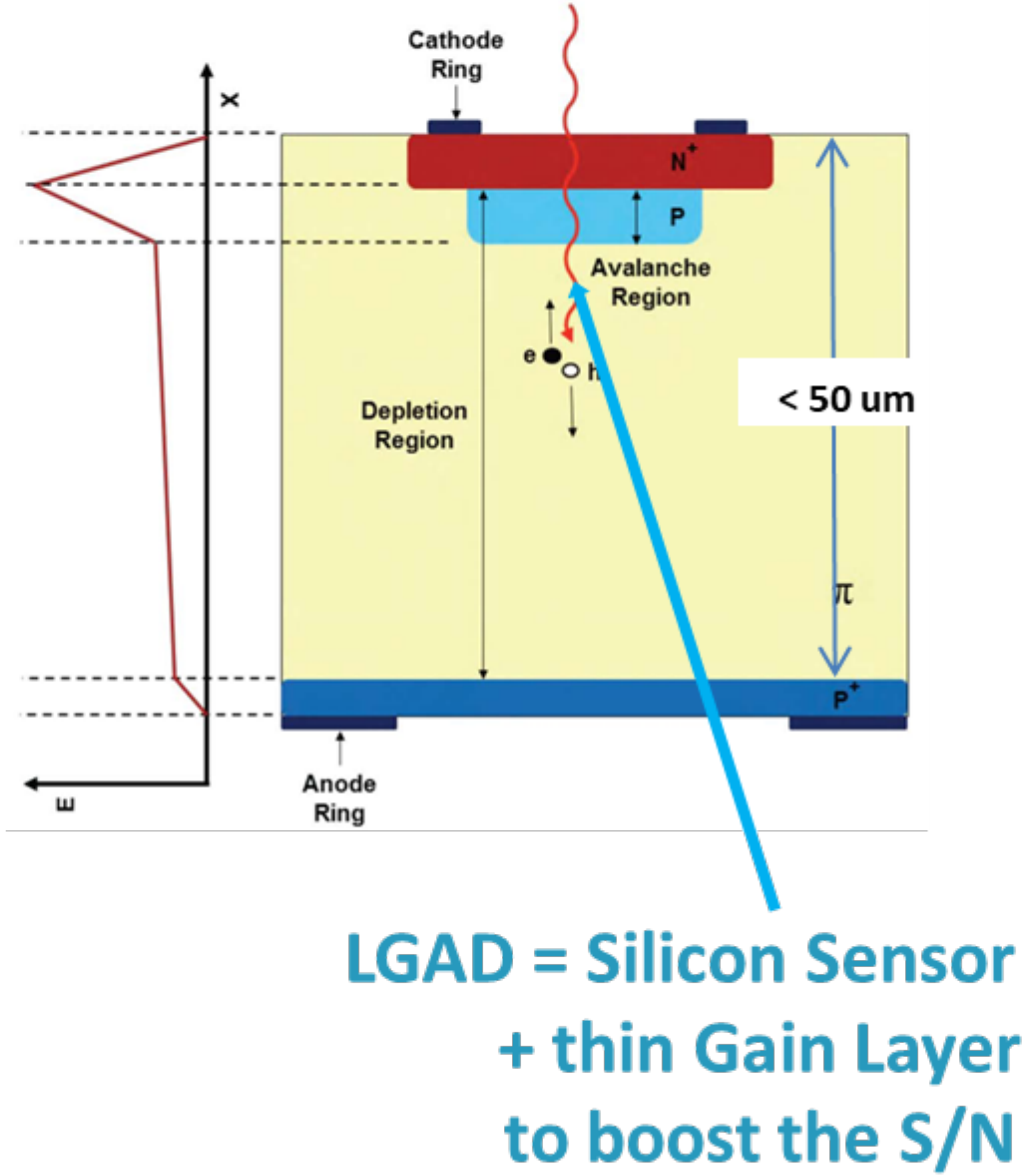
ATAR current design

- Current baseline design for ATAR
  - LGADs high granularity technology (TI-LGADs)
    - Additional highly doped layer generates high electric field → avalanche effect
    - Signal amplification allows for thin sensors and good timing resolution

LGAD, Silicon sensor with thin gain layer to boost S/N

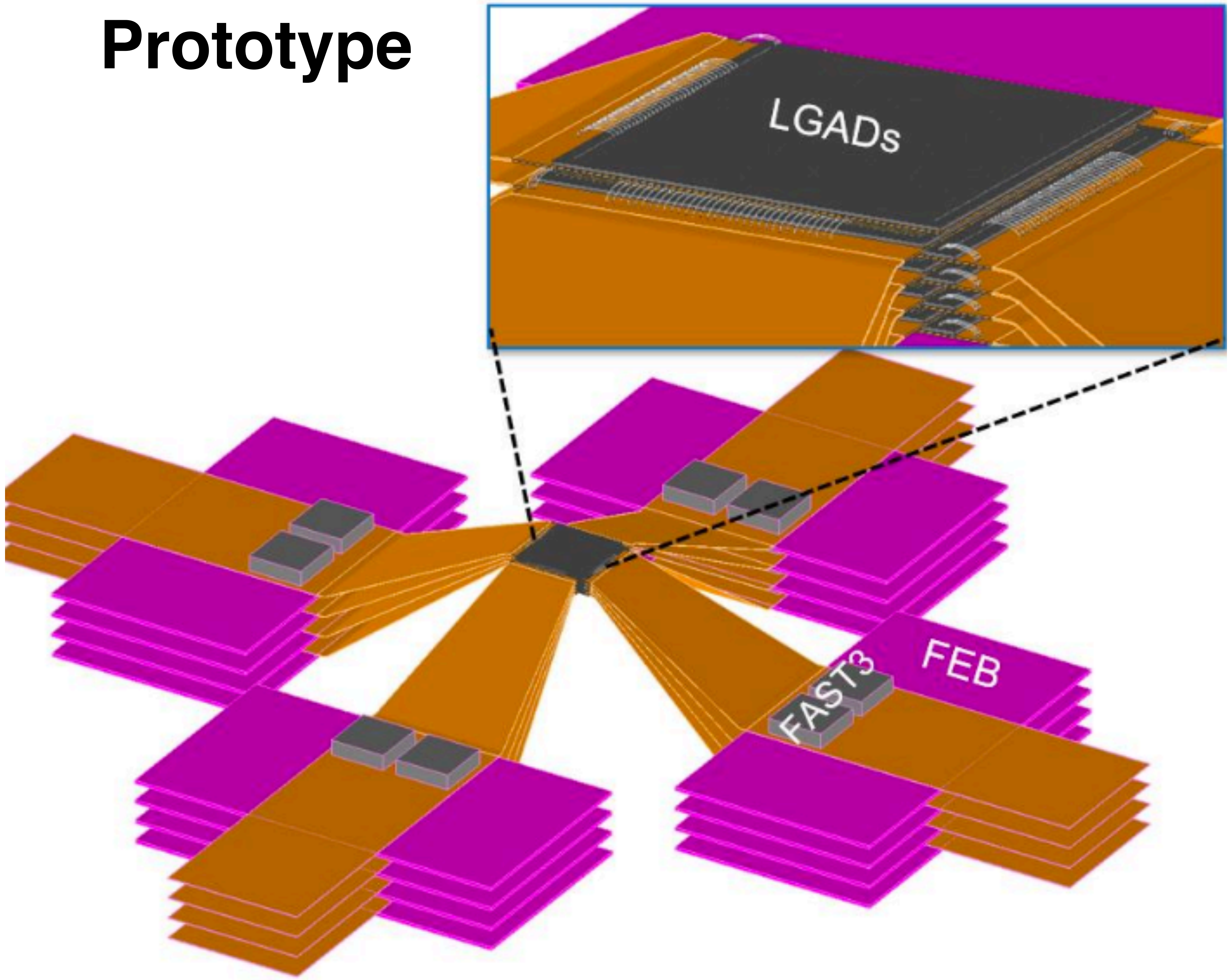






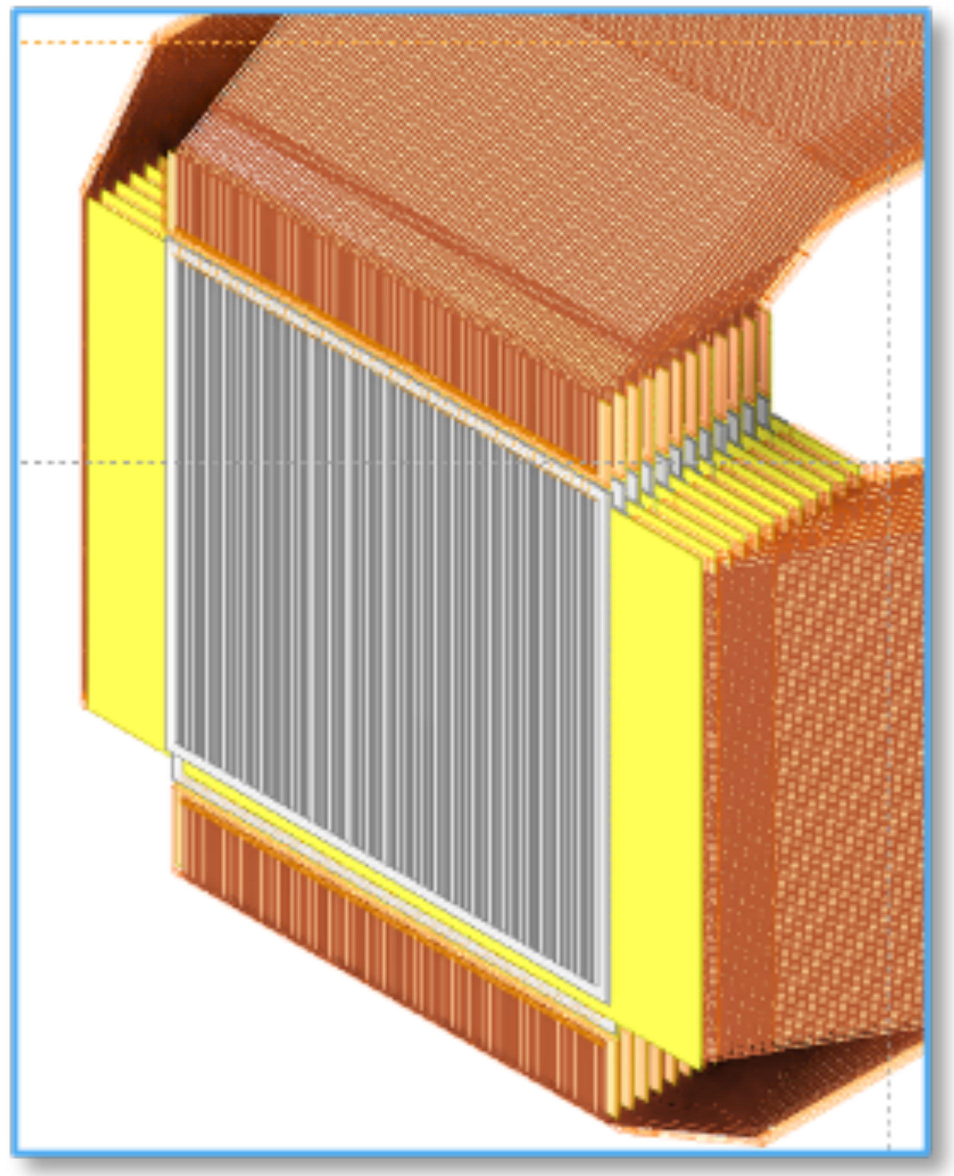
ATAR’s demonstrator

Prototype



- Production of 16-plane ATAR in 2026
  - To take data at PSI in 2026
- Limited prototype
  - 16 layers, 32 channels per layers (full system has 48 layers with 100 channels per layer)

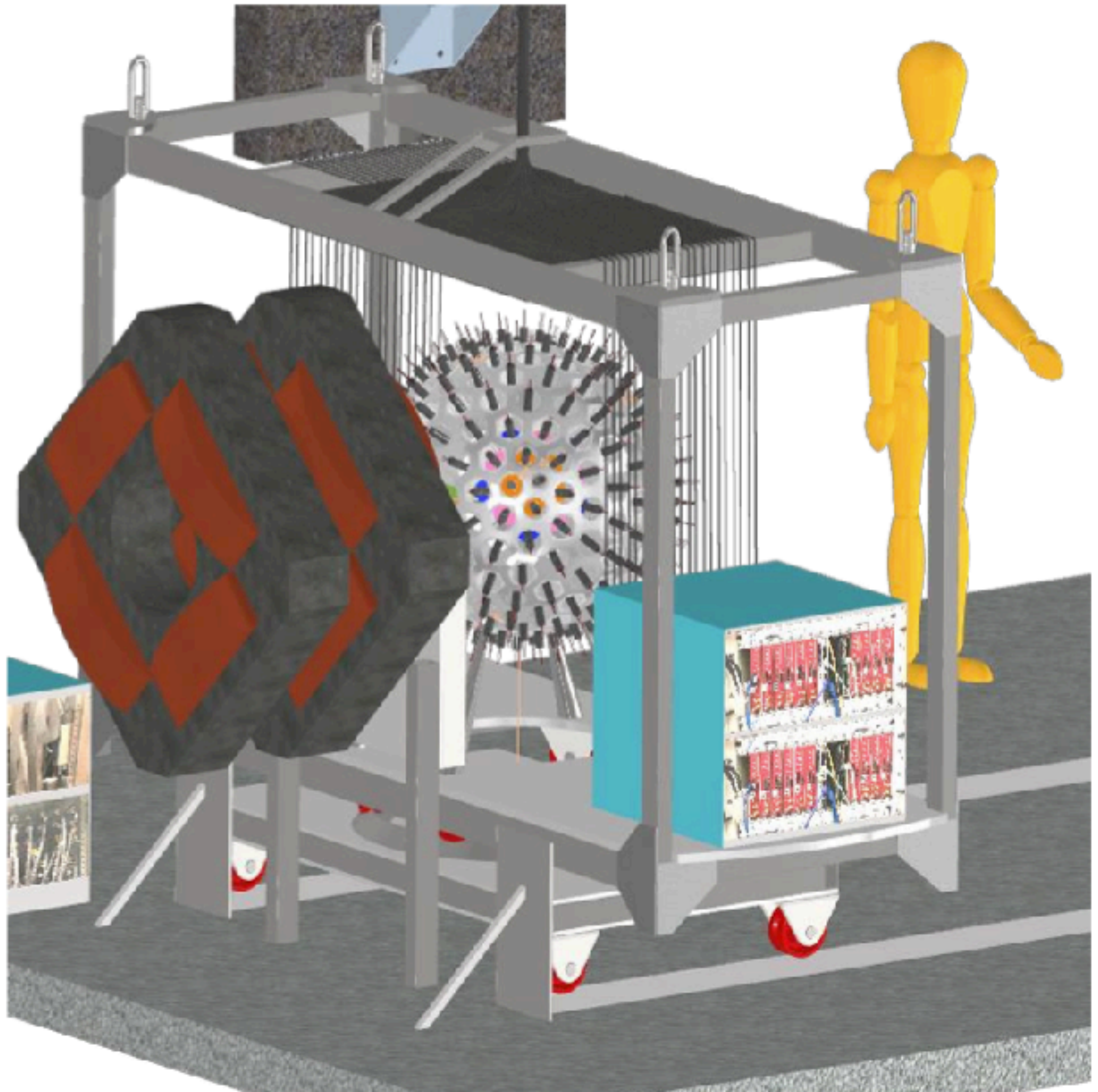
Final Target

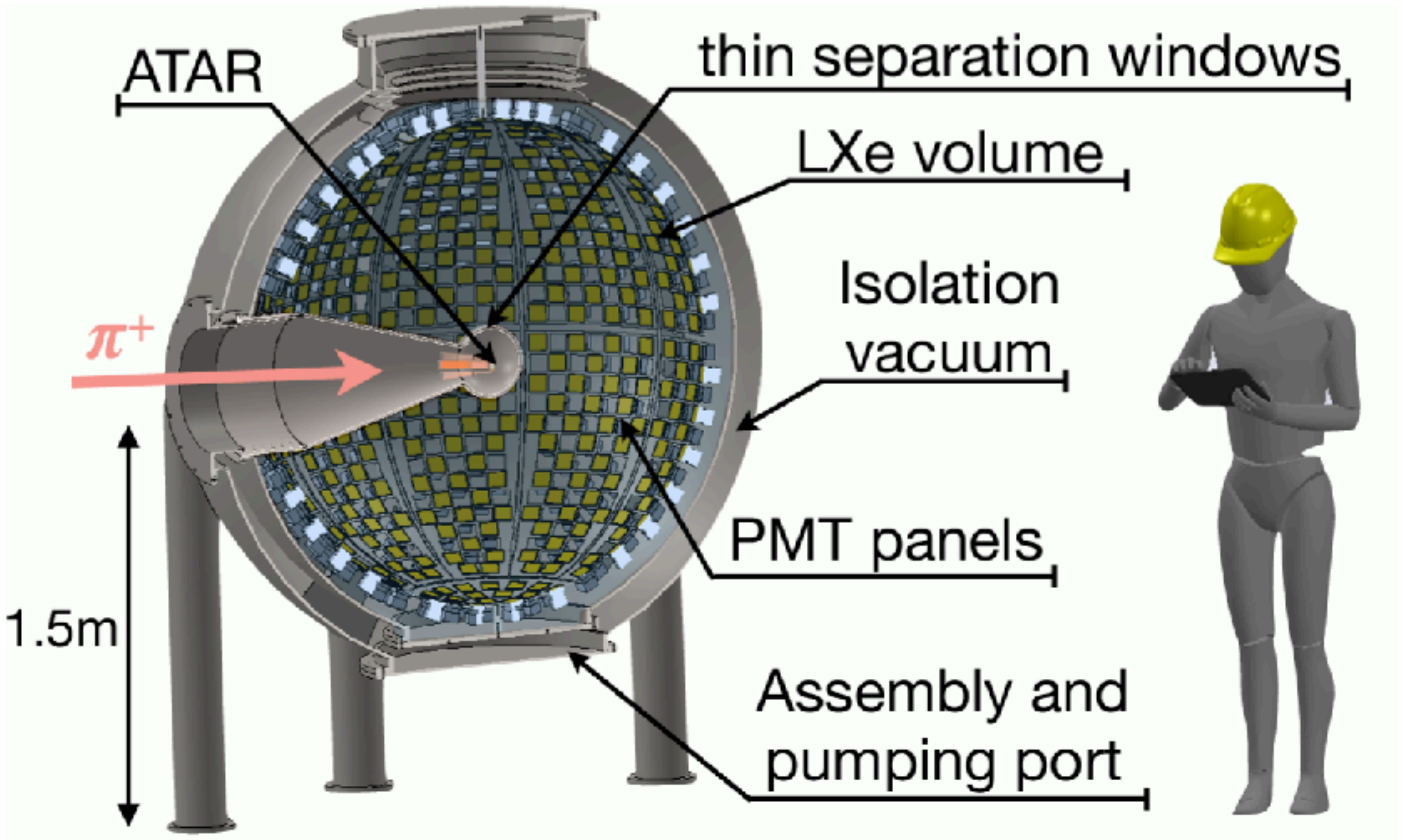


Two calorimeter options

Common features

- High light yield (>30,000 γ/MeV)
- "Fast" 40ns decay time
- $\sigma_E < 2\%$, good timing
- 120° fiducial volume

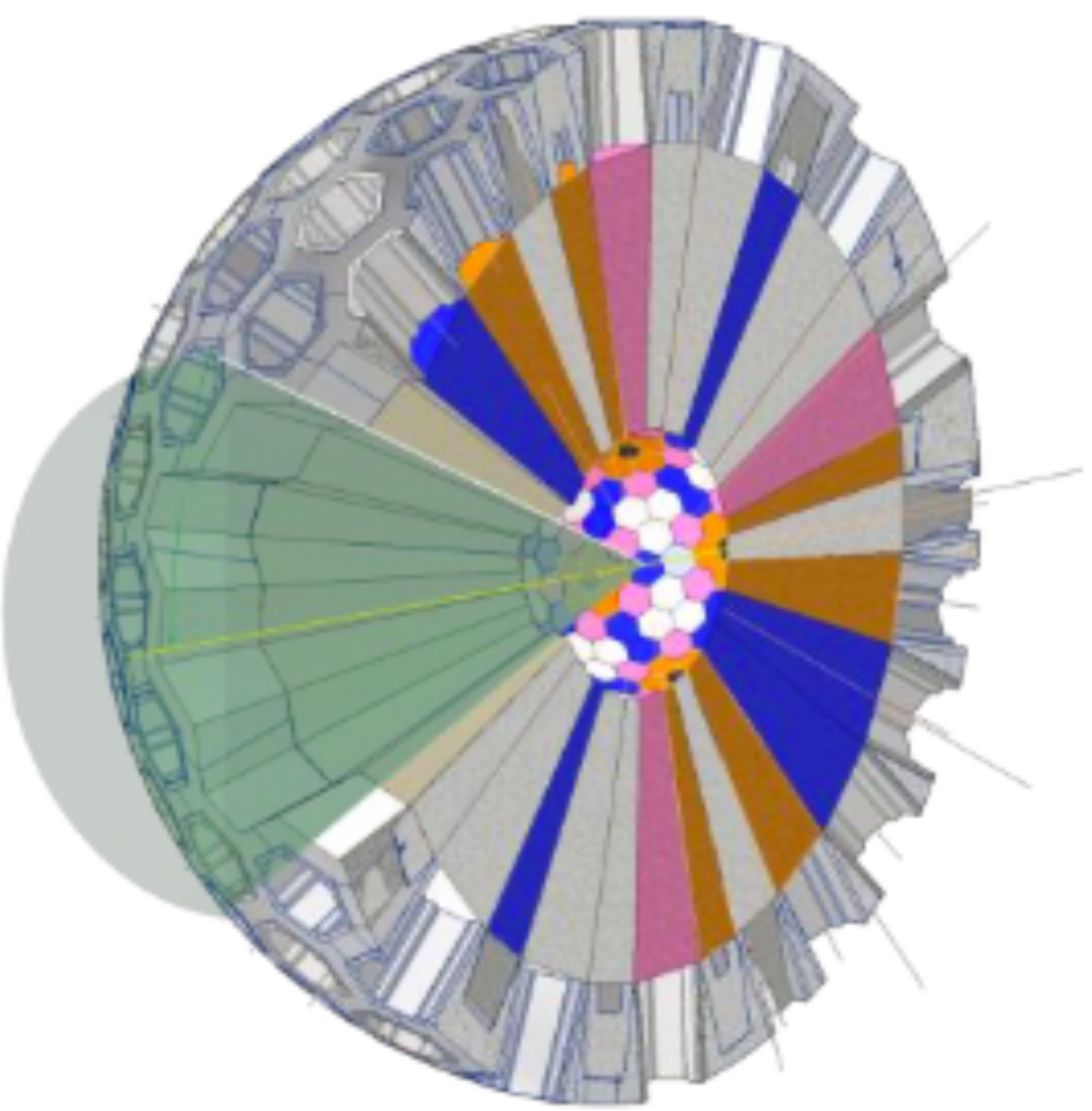


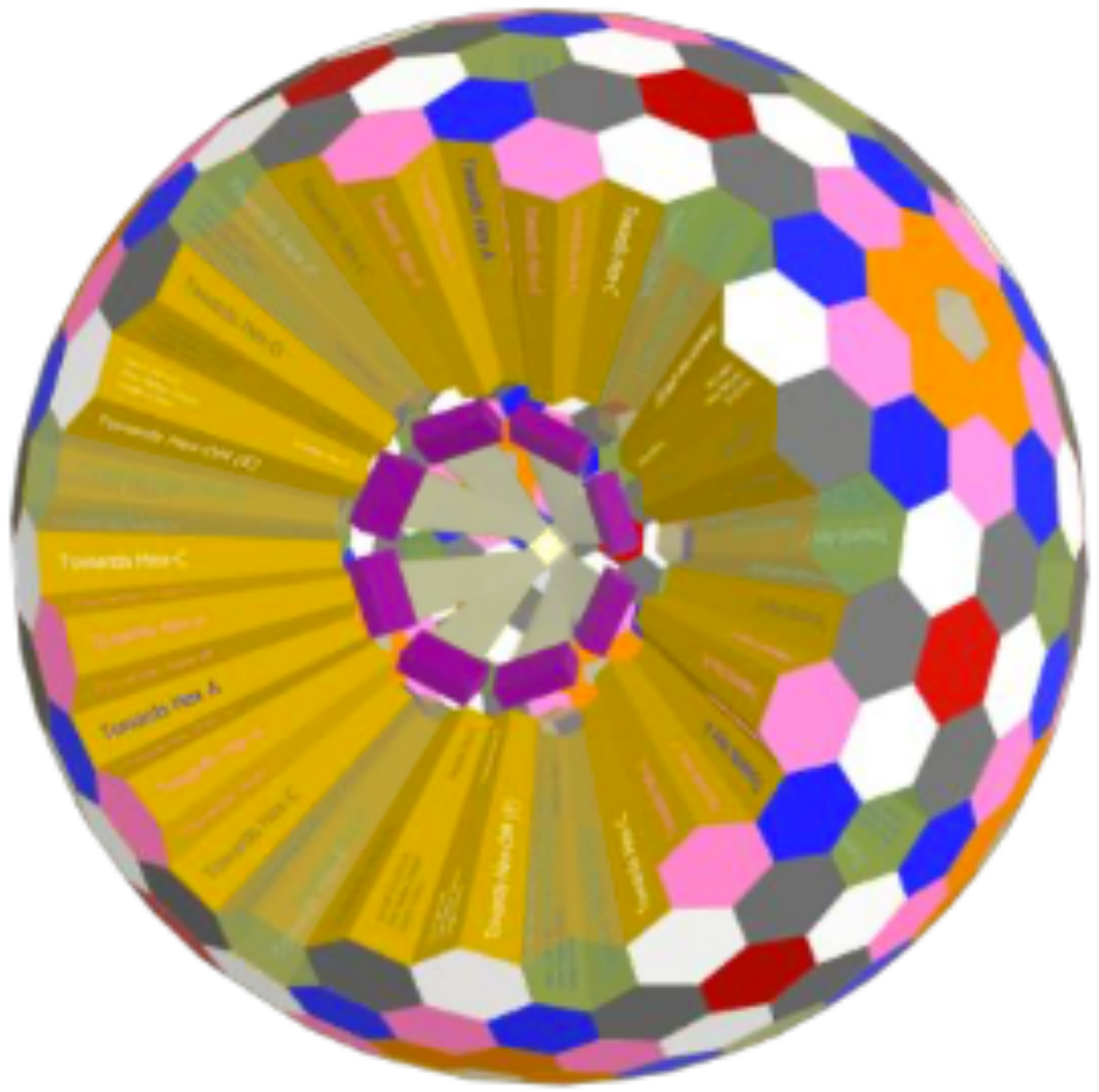


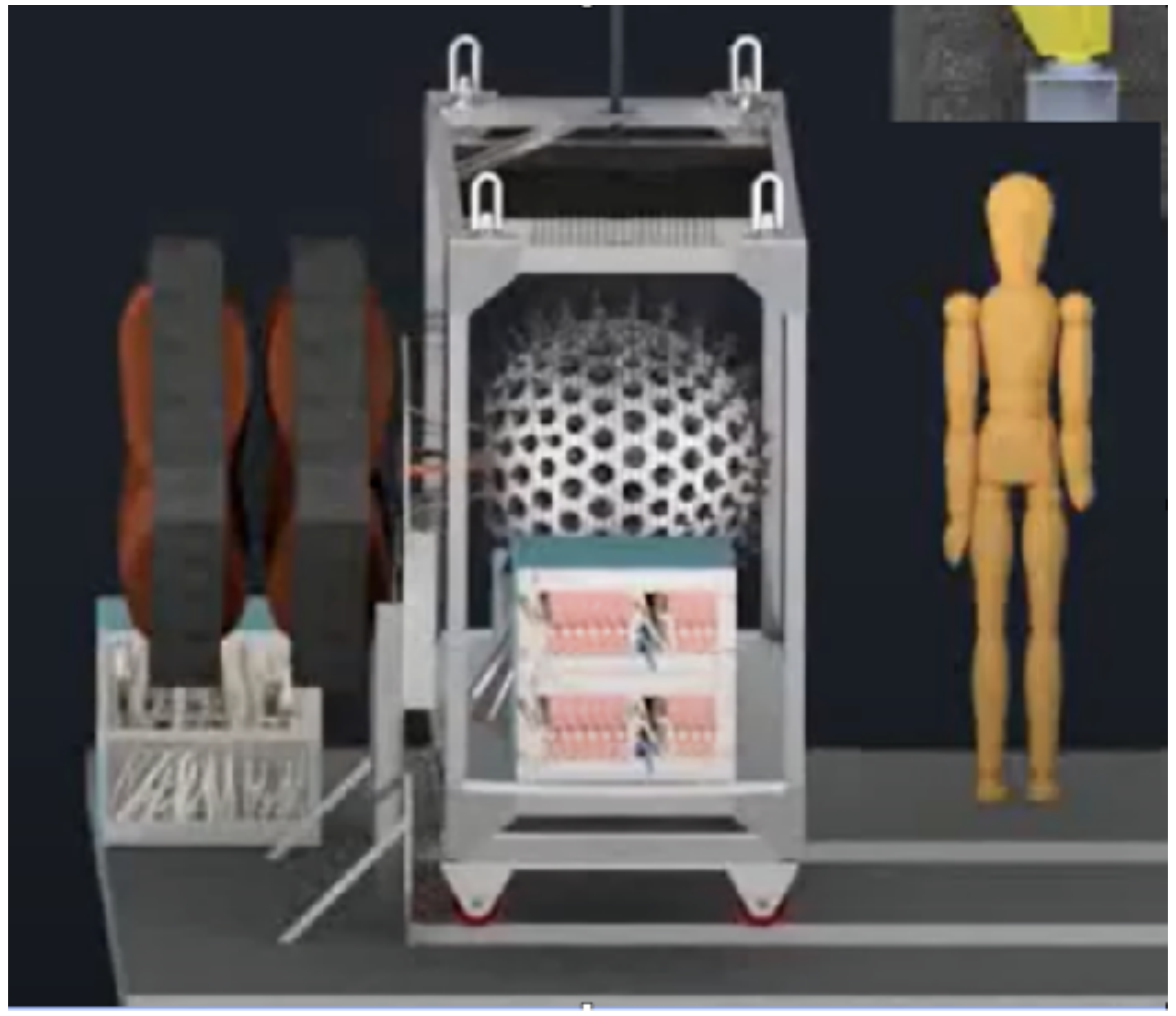
Two options

- LXe ~ single volume (4t)
  - 1650 VUV sensors
  - 15cm inner, 77cm total radius
- LYSO ~ segmented
  - 311 blue PMTs ~ 420nm
  - 15cm inner, 42 cm total radius

LYSO crystal calorimeter





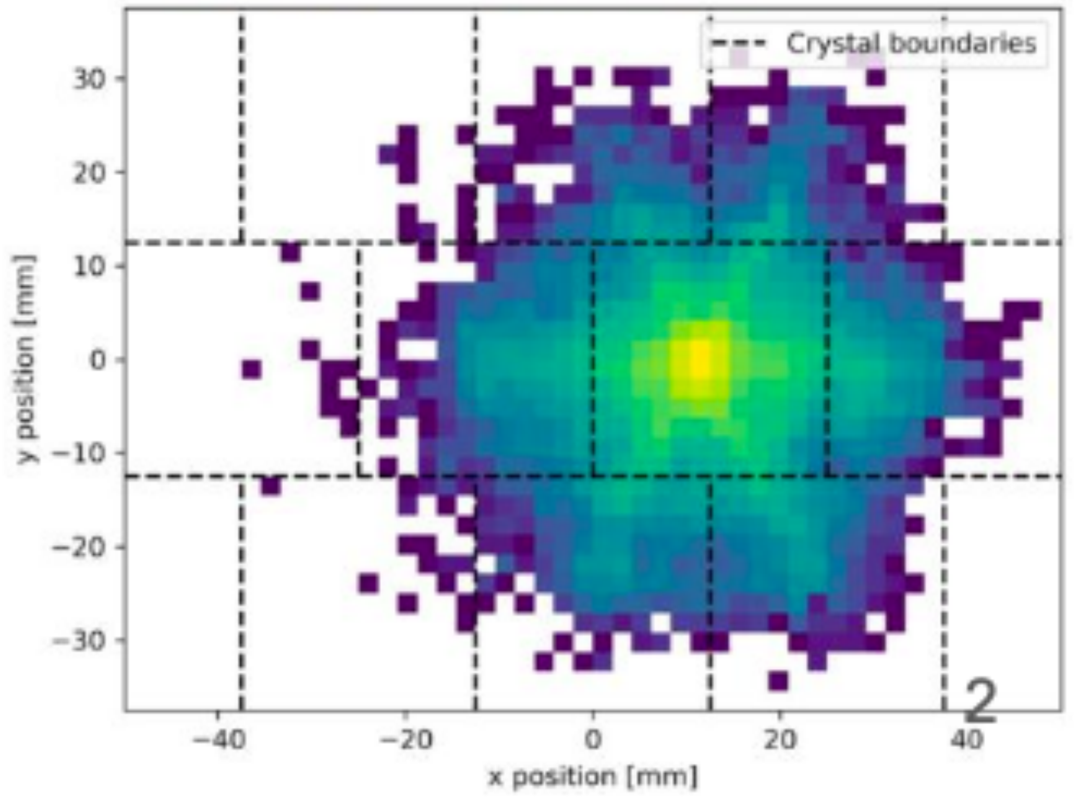


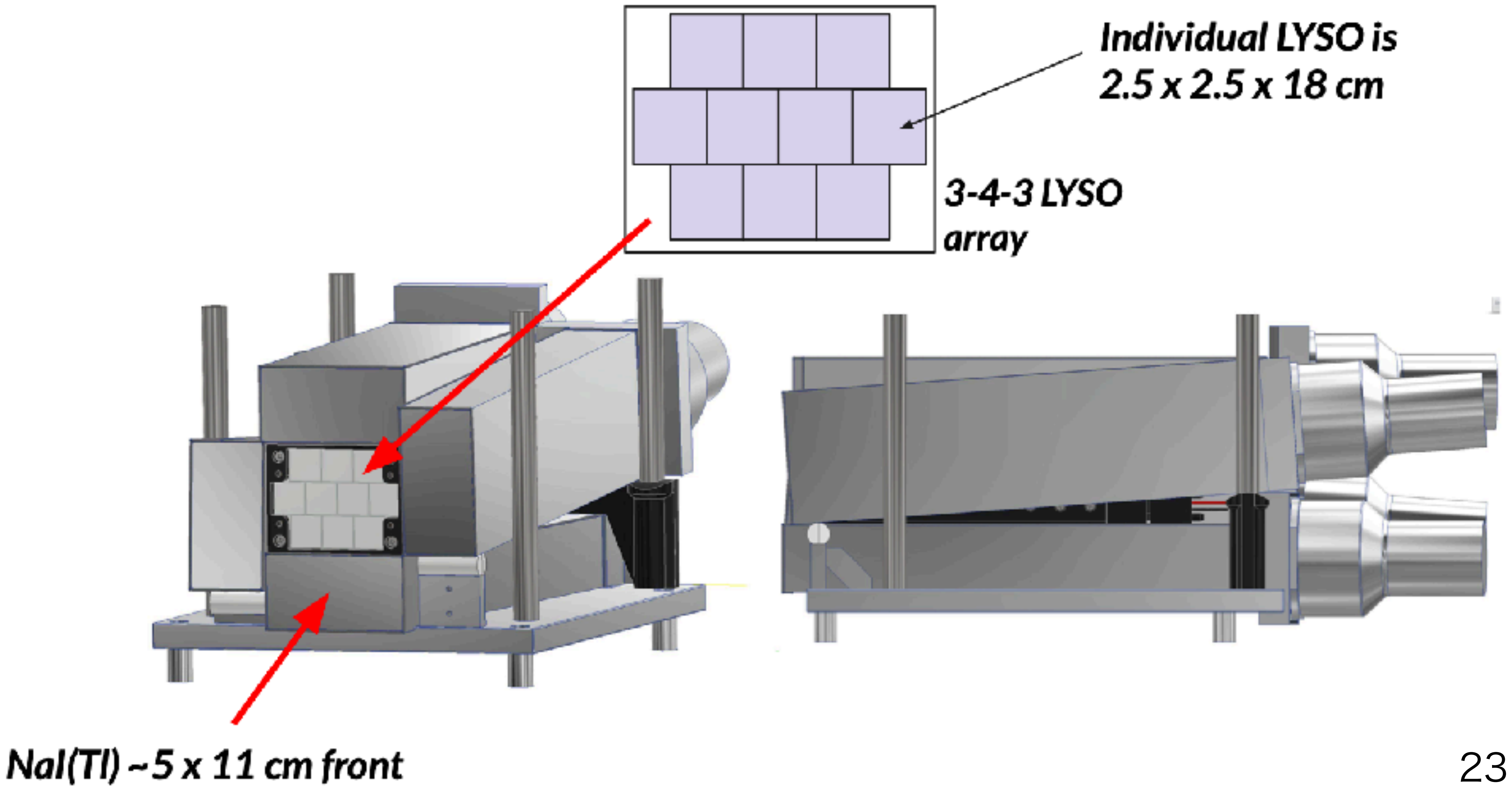
- Design based on simulations & input from measurements
  - 311 crystals, 8 different shapes, 40° opening on sphere
  - 19 X_0 (21.3cm), 15cm inner radius
- Features
  - Prototype 10 LYSO crystal array demonstrated σ_E=1.52% @ 70 MeV
  - SICCAS demonstrated to grow largest Hex crystal: ~1% uniformity
- Risk factors
  - Natural radioactivity, performance at low energies
  - LYSO production consistency

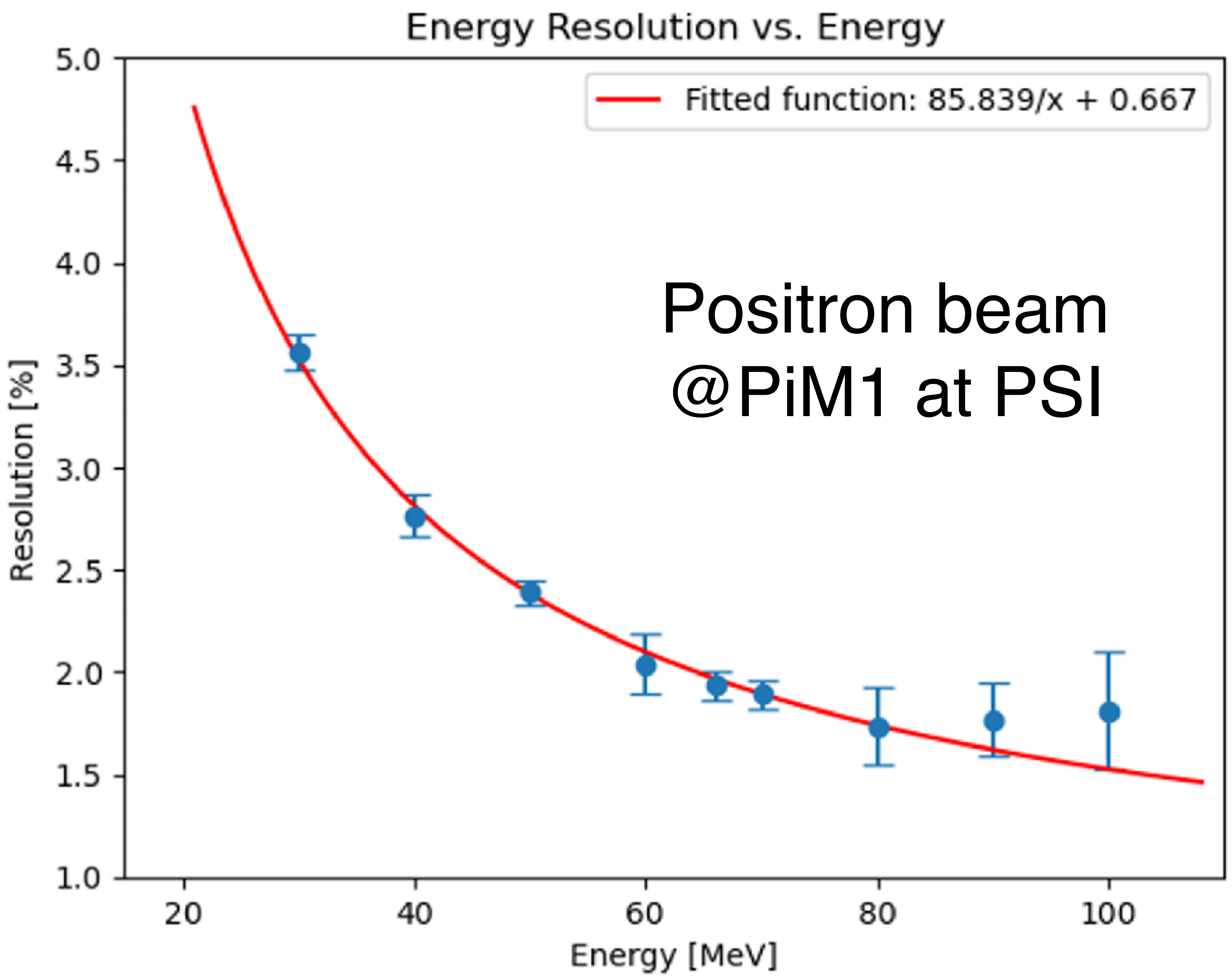
LYSO calorimeter R&D

- Ten 2.5 x 2.5 x 18 cm^3 LYSO crystals wrapped in ESR
  - Spatial resolution (6mm@70MeV)
  - Time resolution (~100ps)
  - Energy resolution (1.52% at 70MeV)

Position resolution



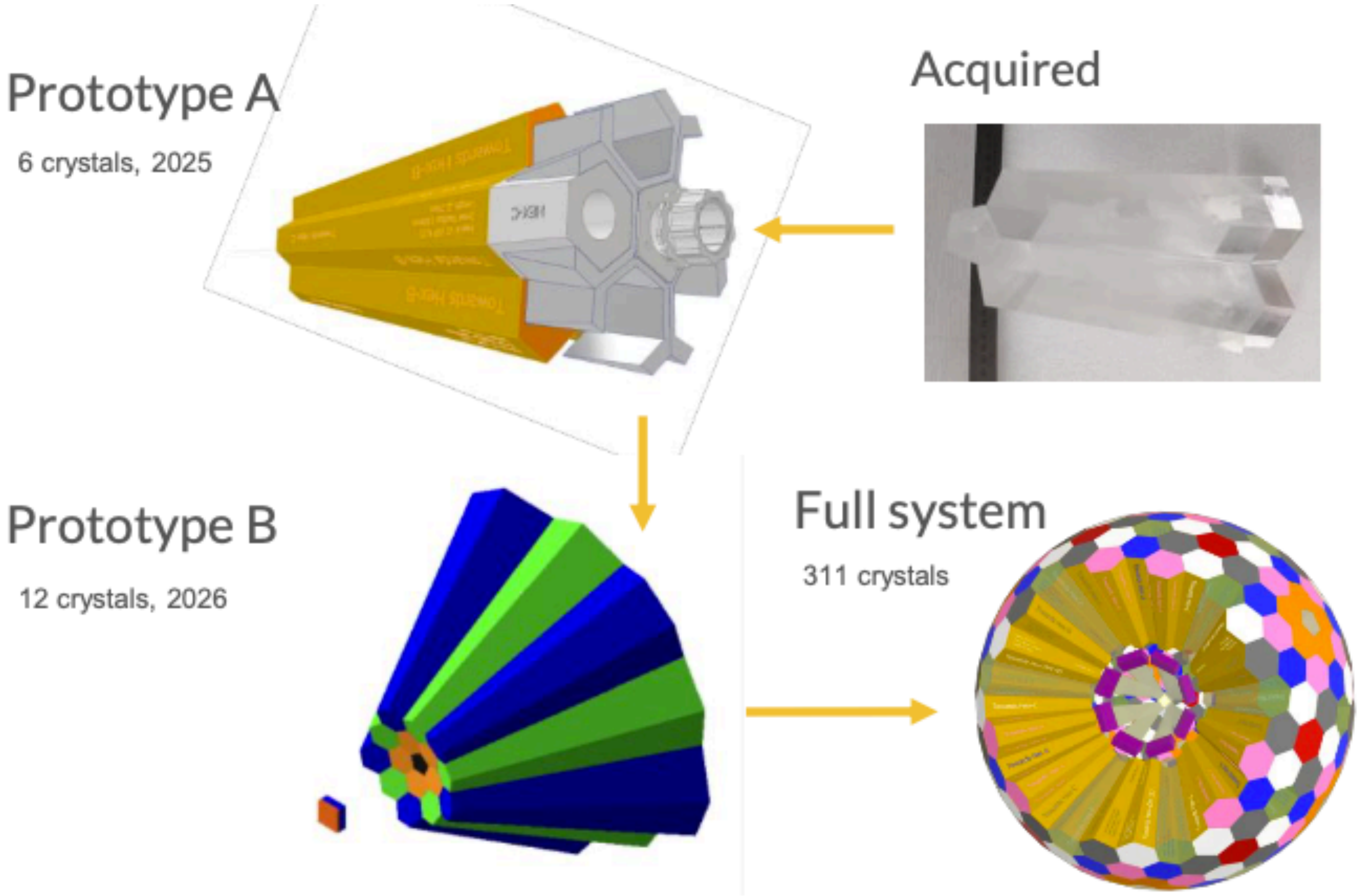




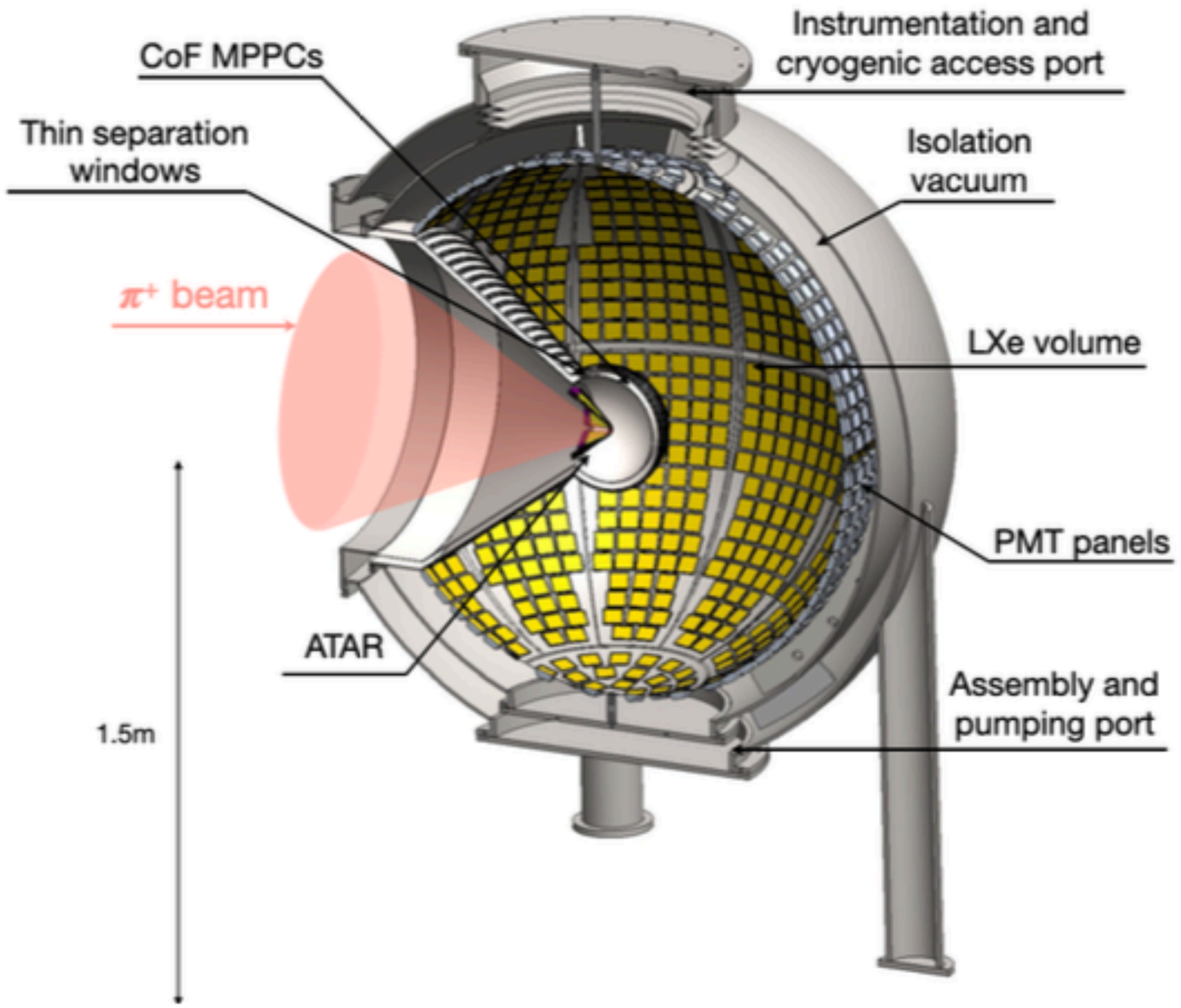
LYSO tapered crystal prototypes

- Prototype A : 6-array
  - Consistent quality in large sized crystals
  - 3 crystals ready, rest in 2-3 months, beam test @PSI
- Prototype B: 16-array
  - Demonstration of production consistency and quality

- The two prototypes are part of the full sphere, and conclusive on performance for PIONEER



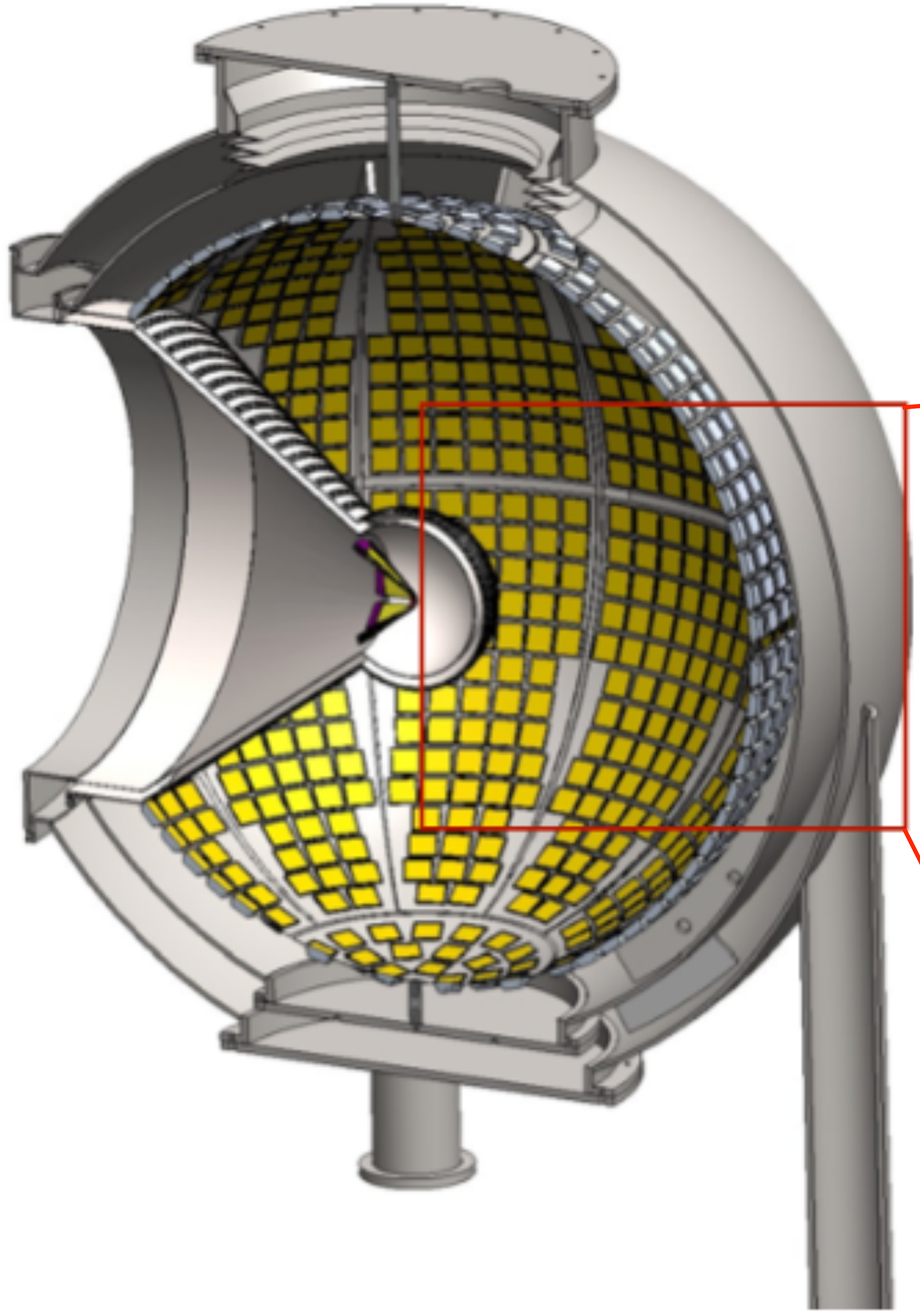
LXe calorimeter



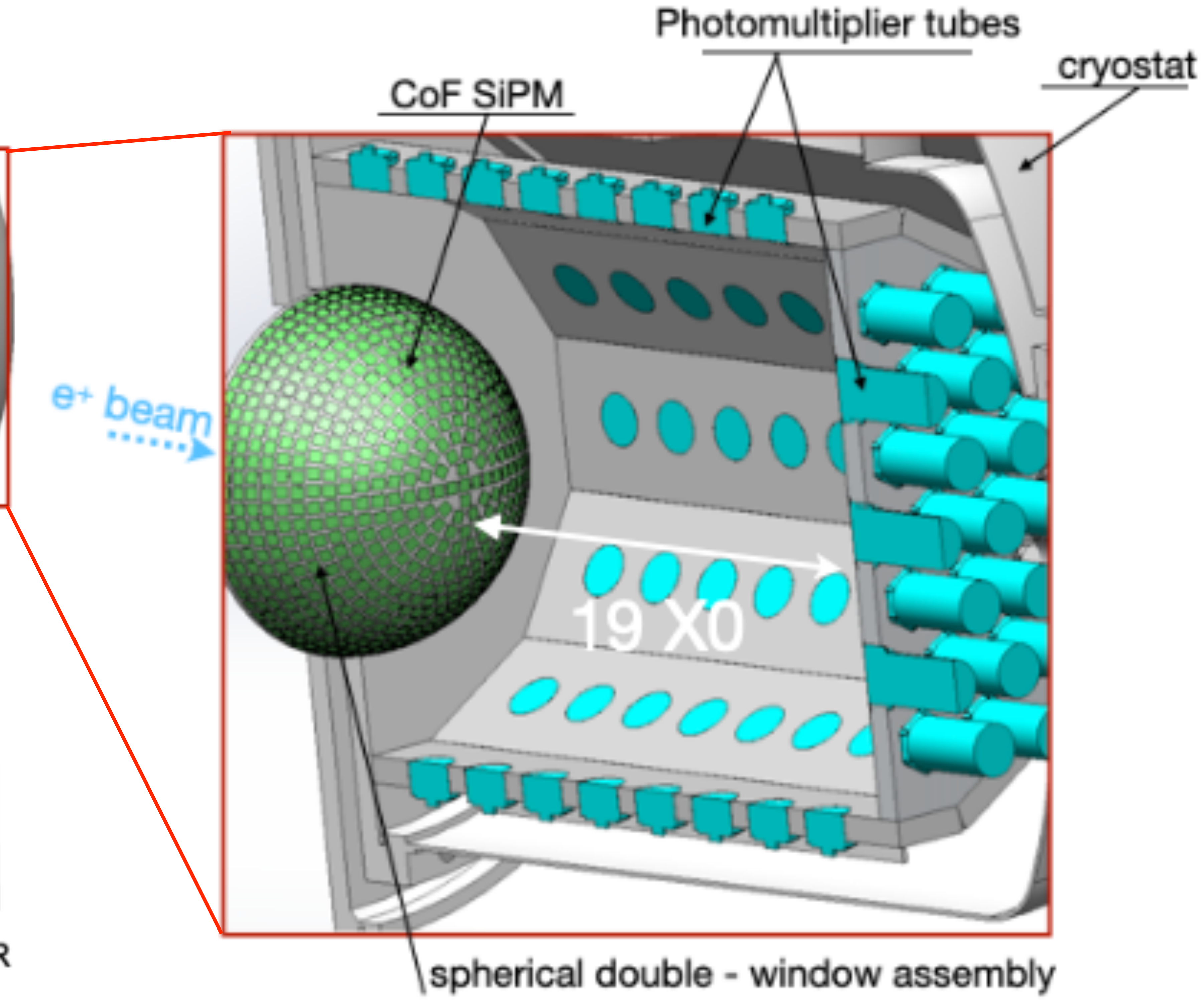
- Homogeneous photosensor coverage
  - SiPM on entrance window and cone
  - PMTs on outer shell
- 4.5t of LXe (3t in MEG)
- <1500 readout channels (SiPM & PMTs
- Optimization of the geometry in progress

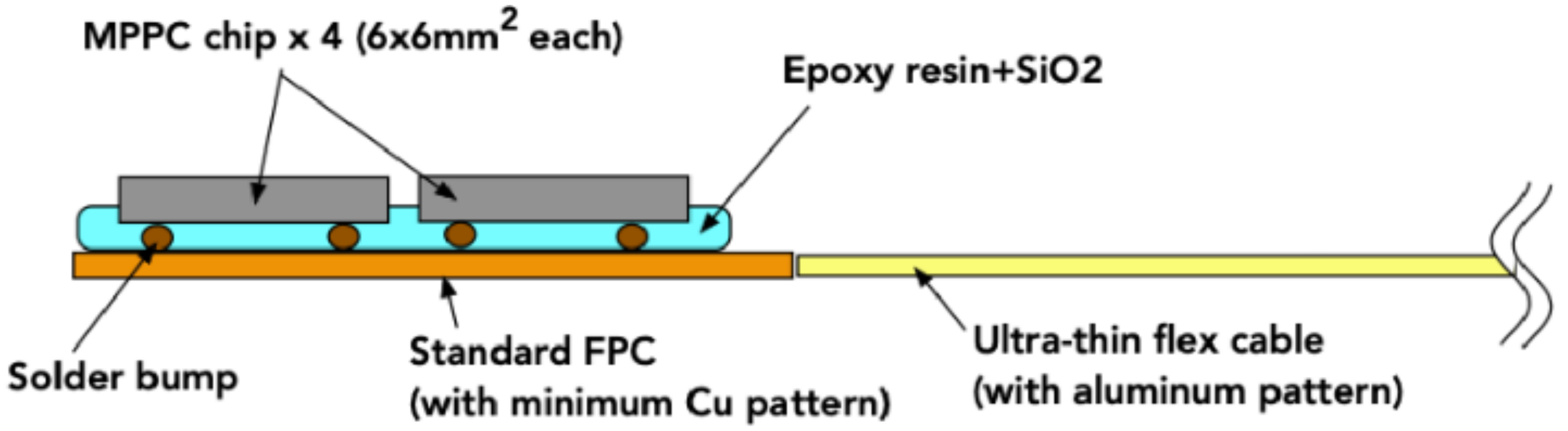
LXe calorimeter R&D

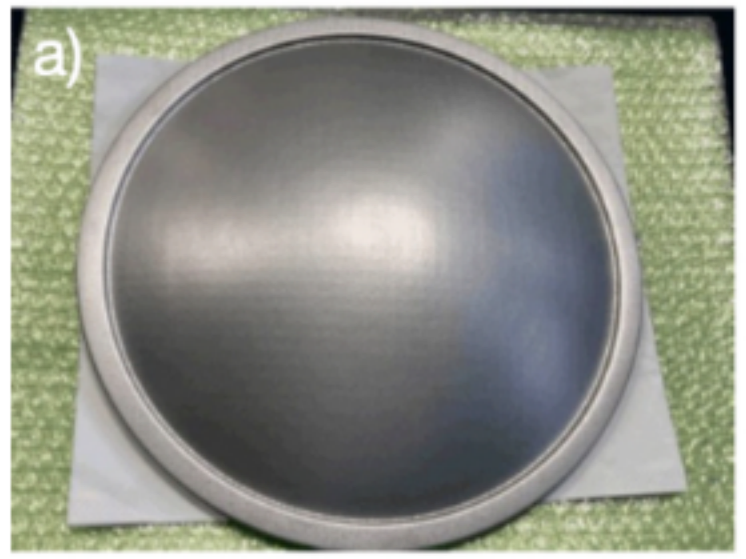
- LXe large prototype to confirm
  - Physics performance
    - Energy resolution, tail
  - Photosensor performance & mechanical assembly
    - CoF design and assembly on sphere
    - SiPM aging
    - New version of VUV-MPPCs developed by HPK
    - Dome shaped 0.5mm Ti-6Al-4V windows
- MEG prototype cryostat dimensions well suited
- Beam test in PiM1 at PSI in 2026



Conceptual Design for the LXe PIONEER Calorimeter (~ 5 tons)



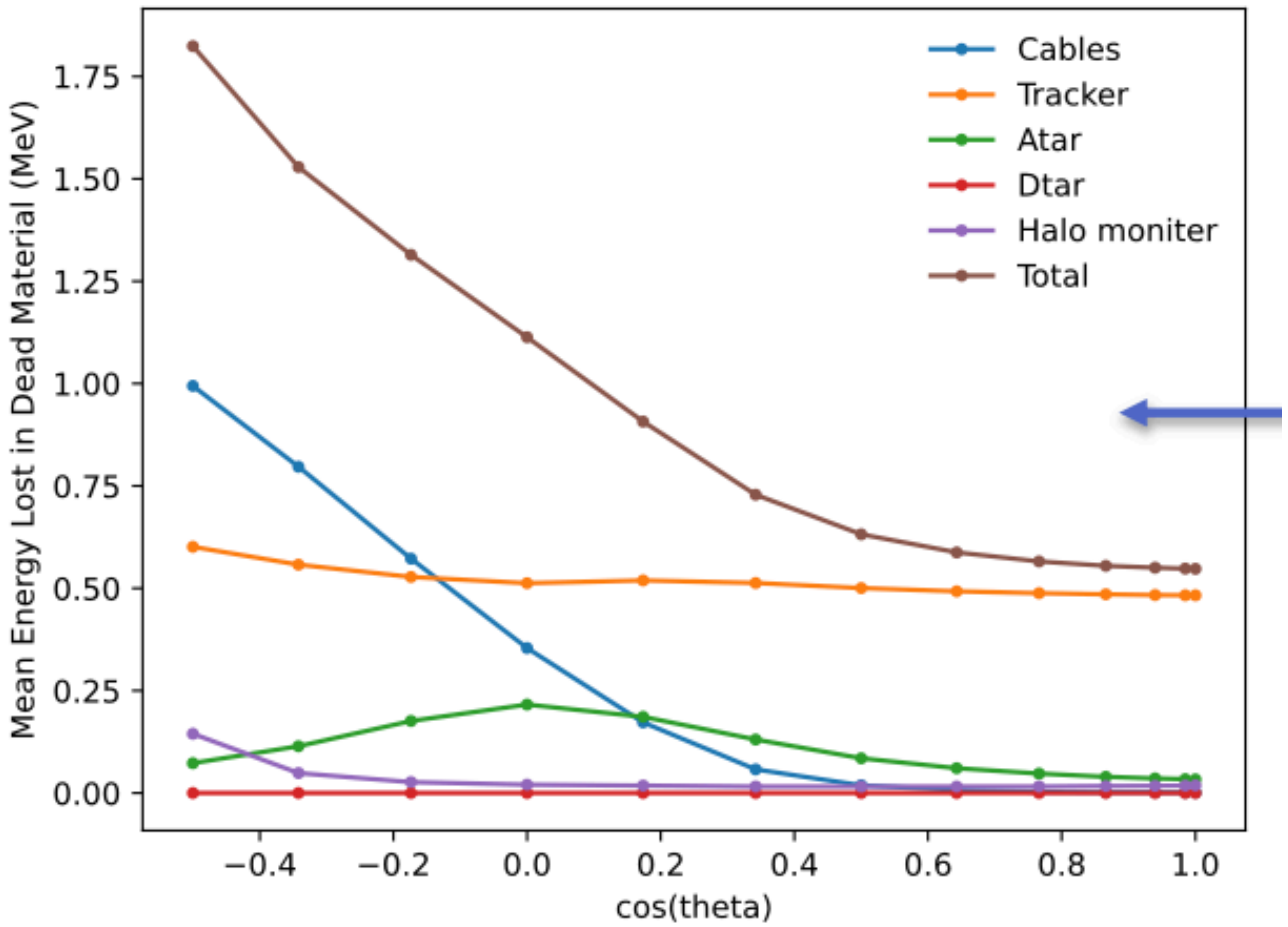




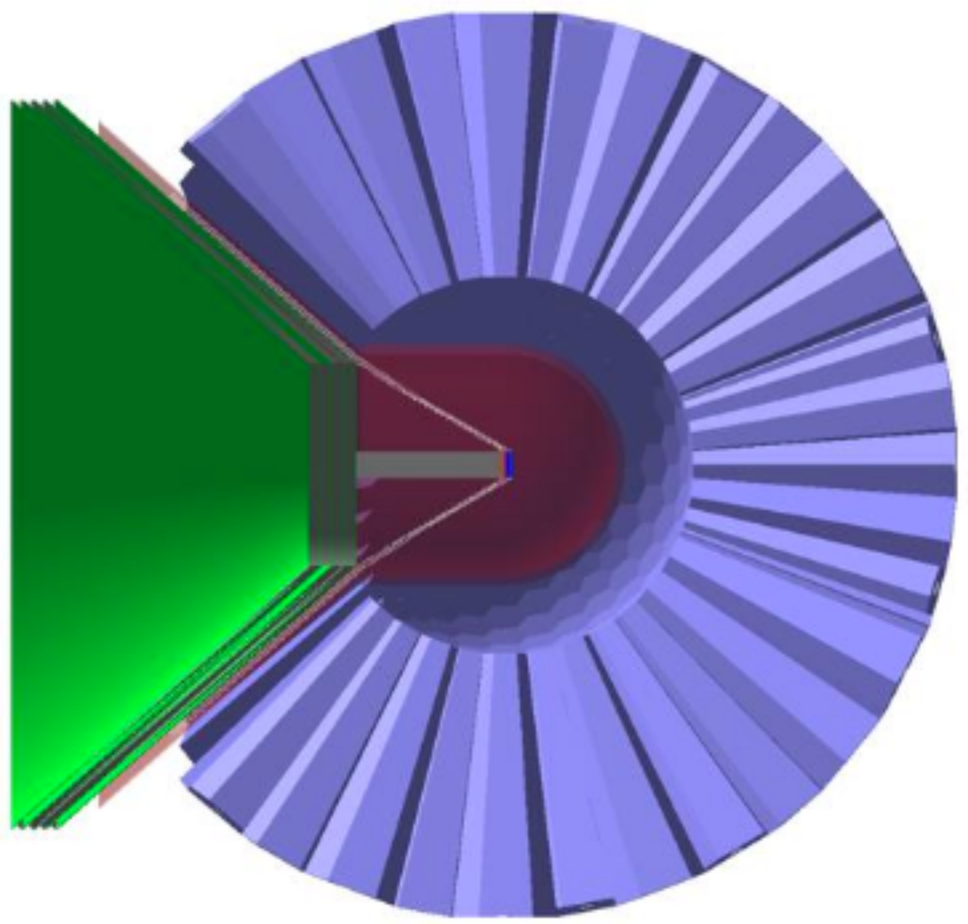
Conceptual Design for the large prototype (~ 650 kg)

Simulation and analysis

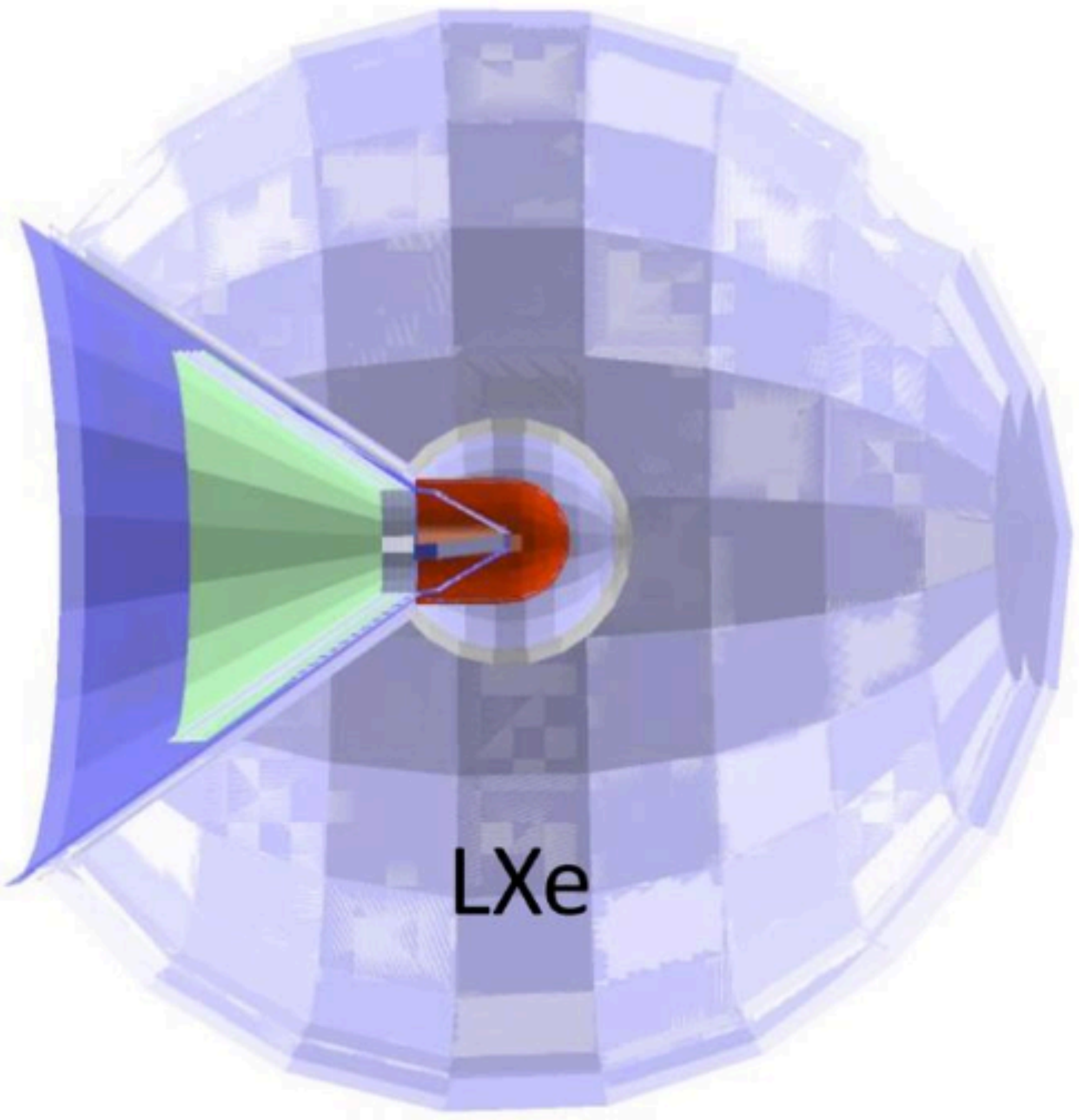
- Simulation in the Geant4 framework
- Detailed accounting of dead material in and around the target (cables and support structure)



Energy losses for a 70 MeV e+ In PIONEER's fiducial volume (0°<θ<120°)

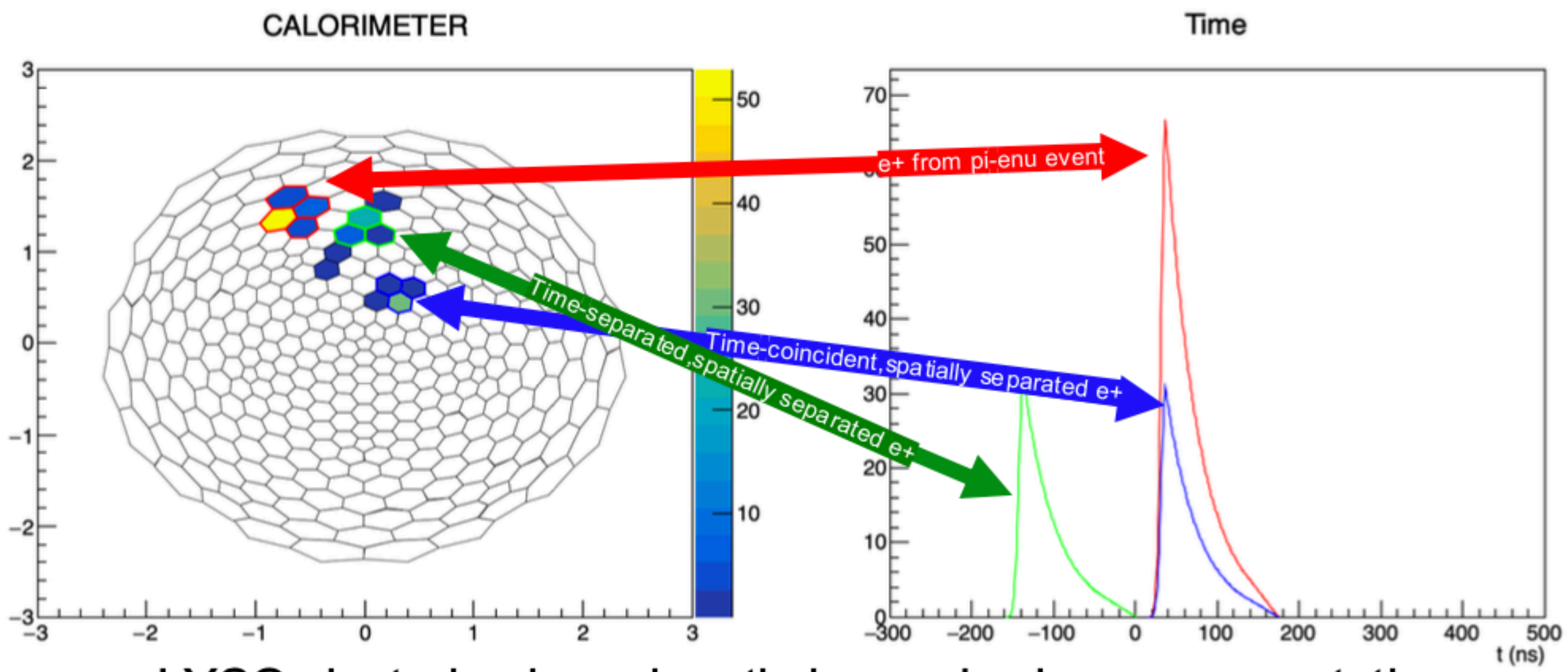


LYSO

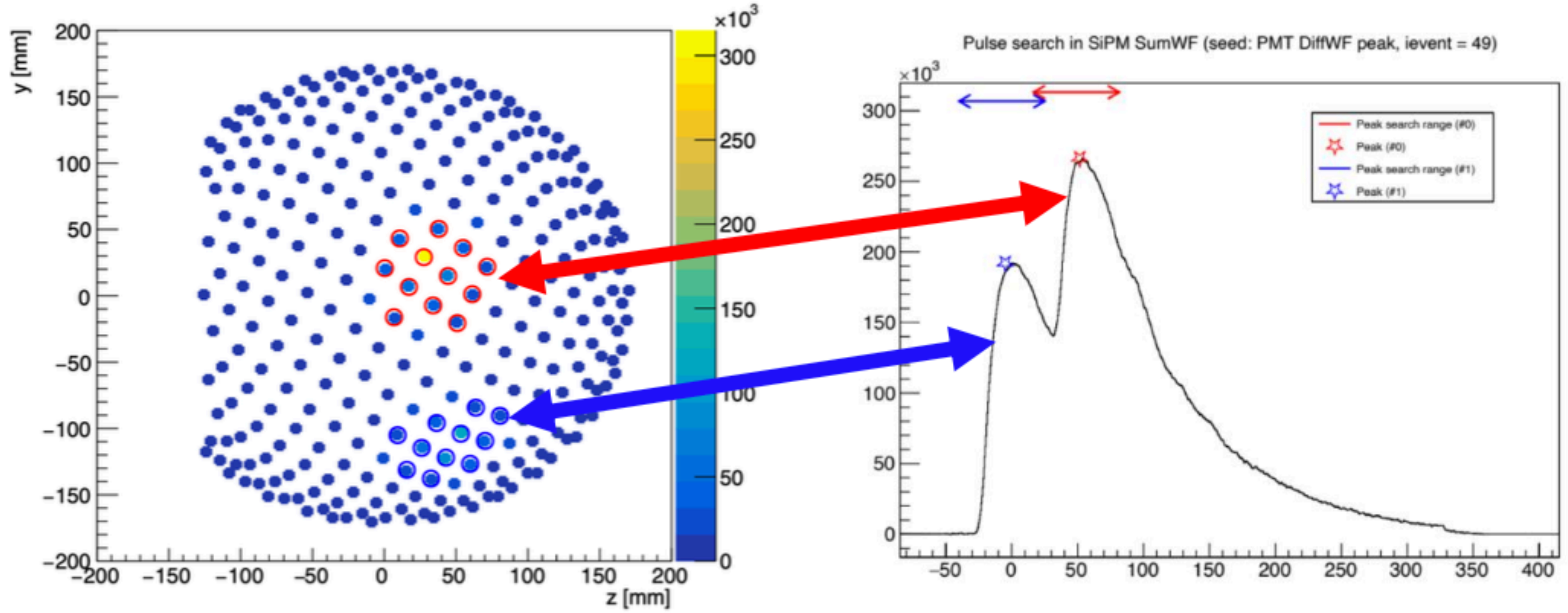


Event reconstruction (CALO)

- Energy clusters formation in the calorimeter
  - Digitized hits → Clustering → Tracklet and pattern recognition in the imaging device (ATAR+tracker)



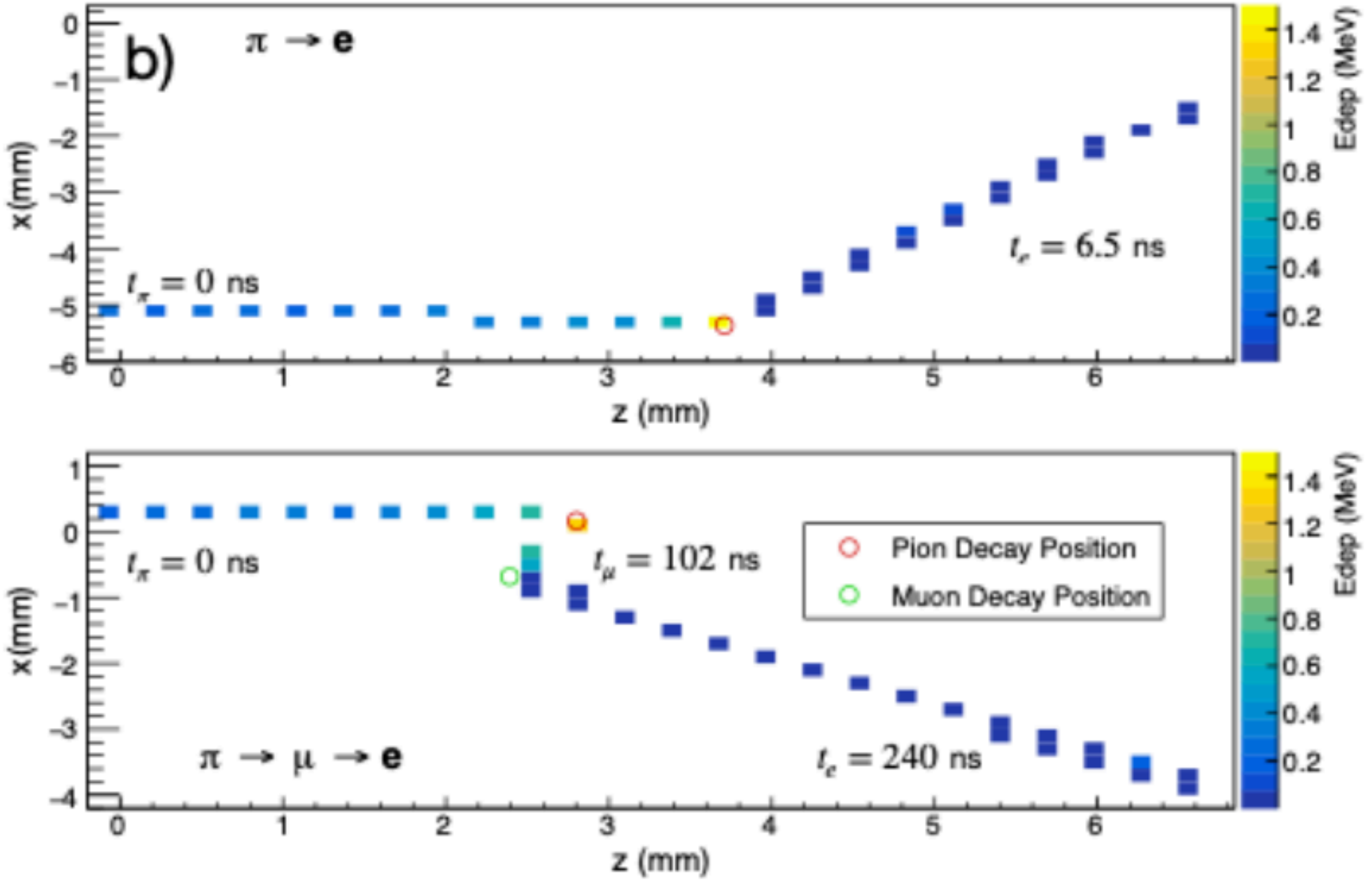
LYSO clustering based on timing and volume segmentation



LXe clustering based on timing and energy profile in neighboring SiPMs

Event reconstruction (ATAR)

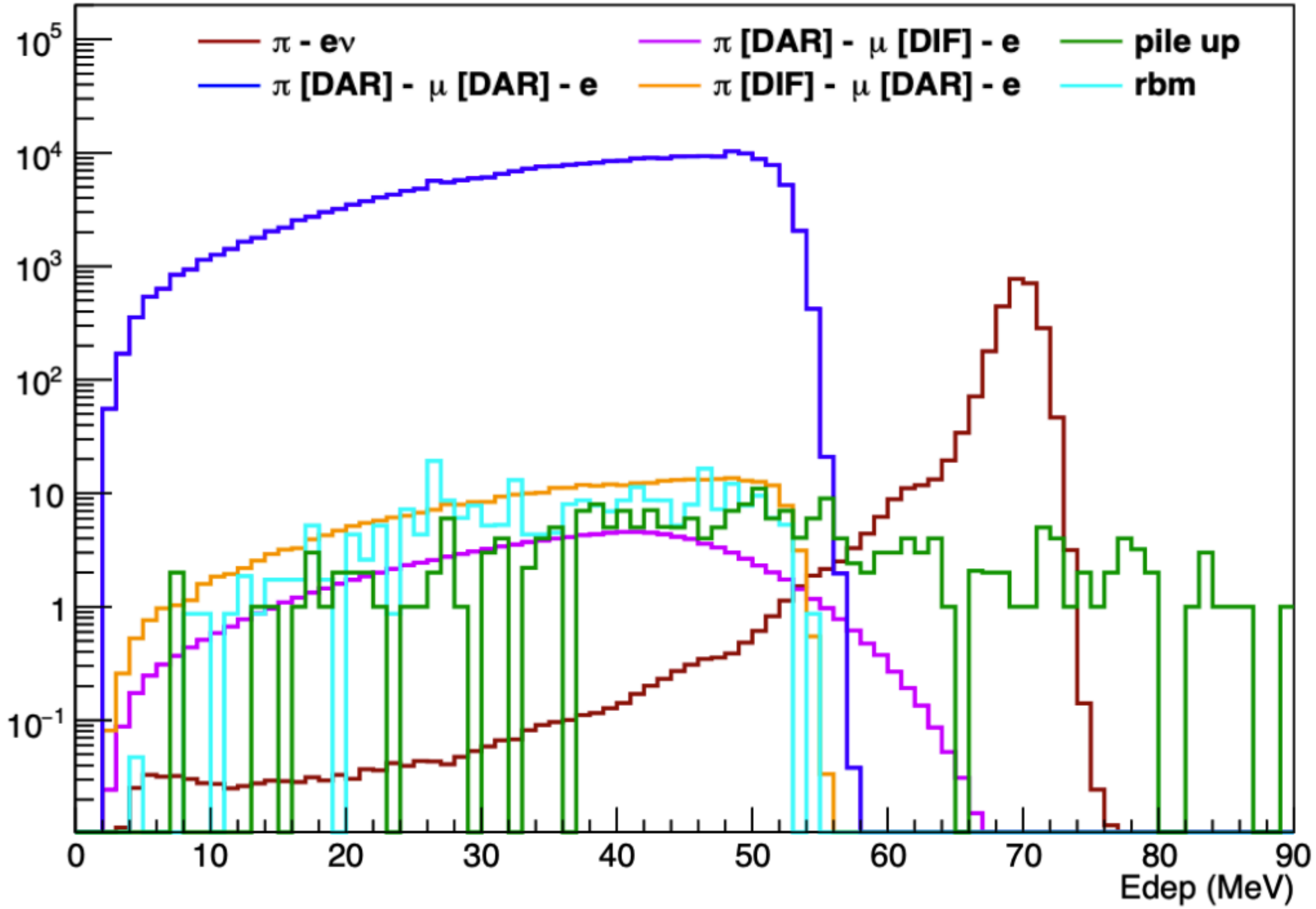
- Critical for the measurement
  - Tail reveal, pile-up suppression, acceptance, …
  - Iterative process
  - Opportunity for AI/ML tool to shine



Reconstructed energy spectrum (MC)

Legend Description

- **π-ev**: Single π-ev events.
- **π [DAR]- μ [DAR] - e**: Single pion at rest, muon at rest events
- π [DAR]- μ [DIF] - e: Muon decay in flight events in target region.
- π [DIF] - μ[DAR] - e: Pion decay in flight events in target region
- RBM: Recent beam muons. Pion decays in beam and the muon stops on target.
- **Pile up**: Hits from several time-coincident events



Reconstructed energy spectrum for events collected within [5, 35] ns after the T0 (from degrader)

Target precision to extract $R_{e/\mu}$

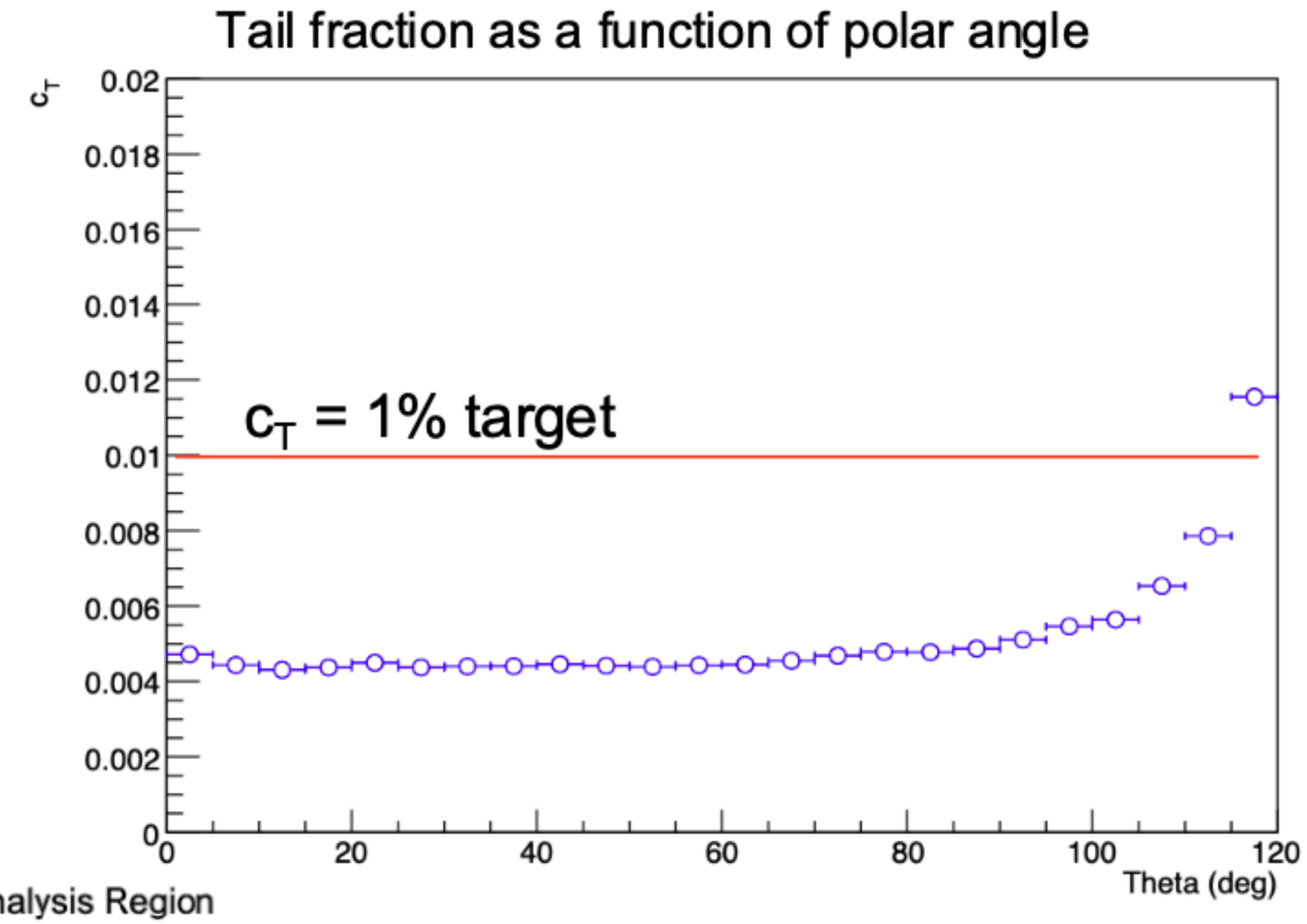
$$R_{e/\mu} = \frac{N_{\pi-e}(E > E_{th})}{N_{\pi-\mu-e}} \times (1 + c_{tail}) \times R^{\epsilon}$$

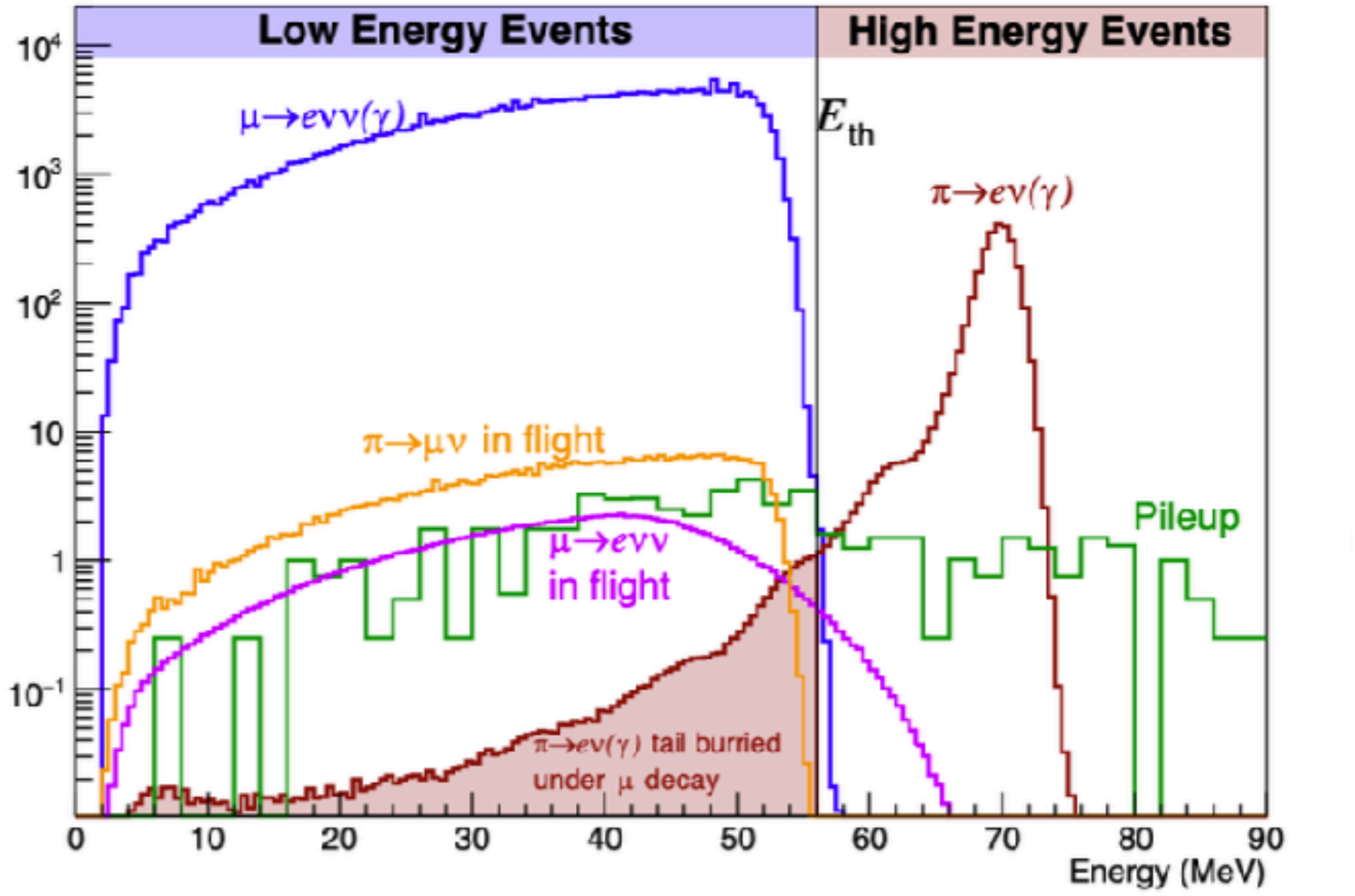
$$\frac{\Delta R_{e/\mu}}{R_{e/\mu}} = 0.01\%$$

	Quantity	Target Value	Required Precision (%)	Description
	$N_{\pi-e}(E > E_{th})$	2x10^{8}	<0.01	Number of $\pi - e$ events in the High Energy Bin
	$N_{\pi-\mu-e}$	2x10^{10}	<0.01	Number of $\pi - \mu - e$ events in the Low Energy Bin
Most challenging	c_{tail}	0.01	1	Tail fraction correction
Most challenging	R^{ϵ}	1	<0.01	Ratio of $\pi - e$ to $\pi - \mu - e$ acceptance

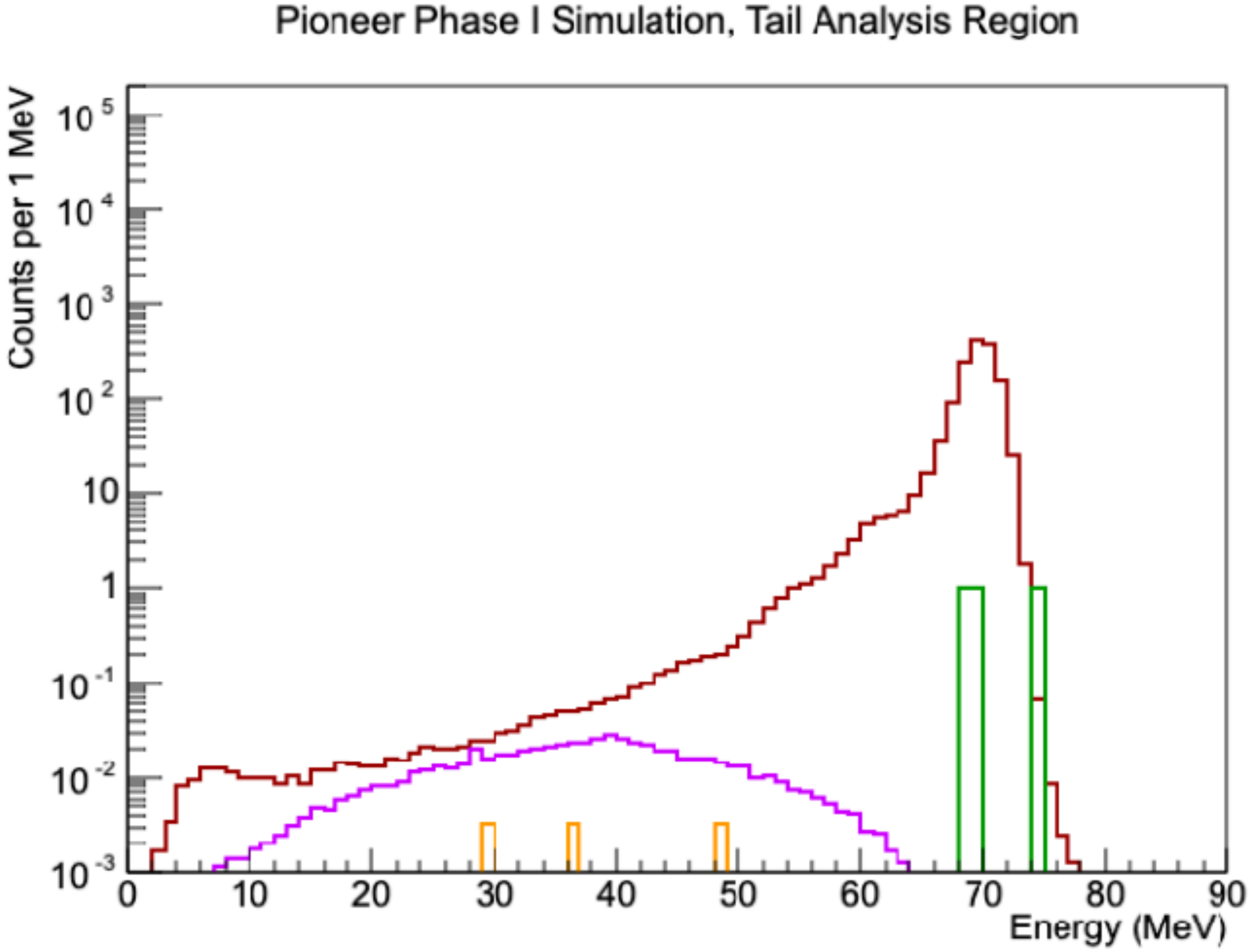
Tail Fraction c_{tail}

- Tail fraction is currently estimated to be ~0.5%
  - Well below the 1% target





Reconstructed energy spectrum for events collected within [5, 35]ns after the T0 (from degrader)



Reconstructed energy spectrum for events selected for the Tail Fraction measurement

PIONEER Goal (II) : Beta Decays and CKM Unitarity

Unitarity of the CKM matrix

$$\Delta_{\rm CKM} \equiv |V_{ud}|^2 + |V_{us}|^2 + |V_{ub}|^2 - 1 = 0$$

$(|V_{ub}|^2 < 10^{-5})$

only V_{ud} and V_{us} are concerned

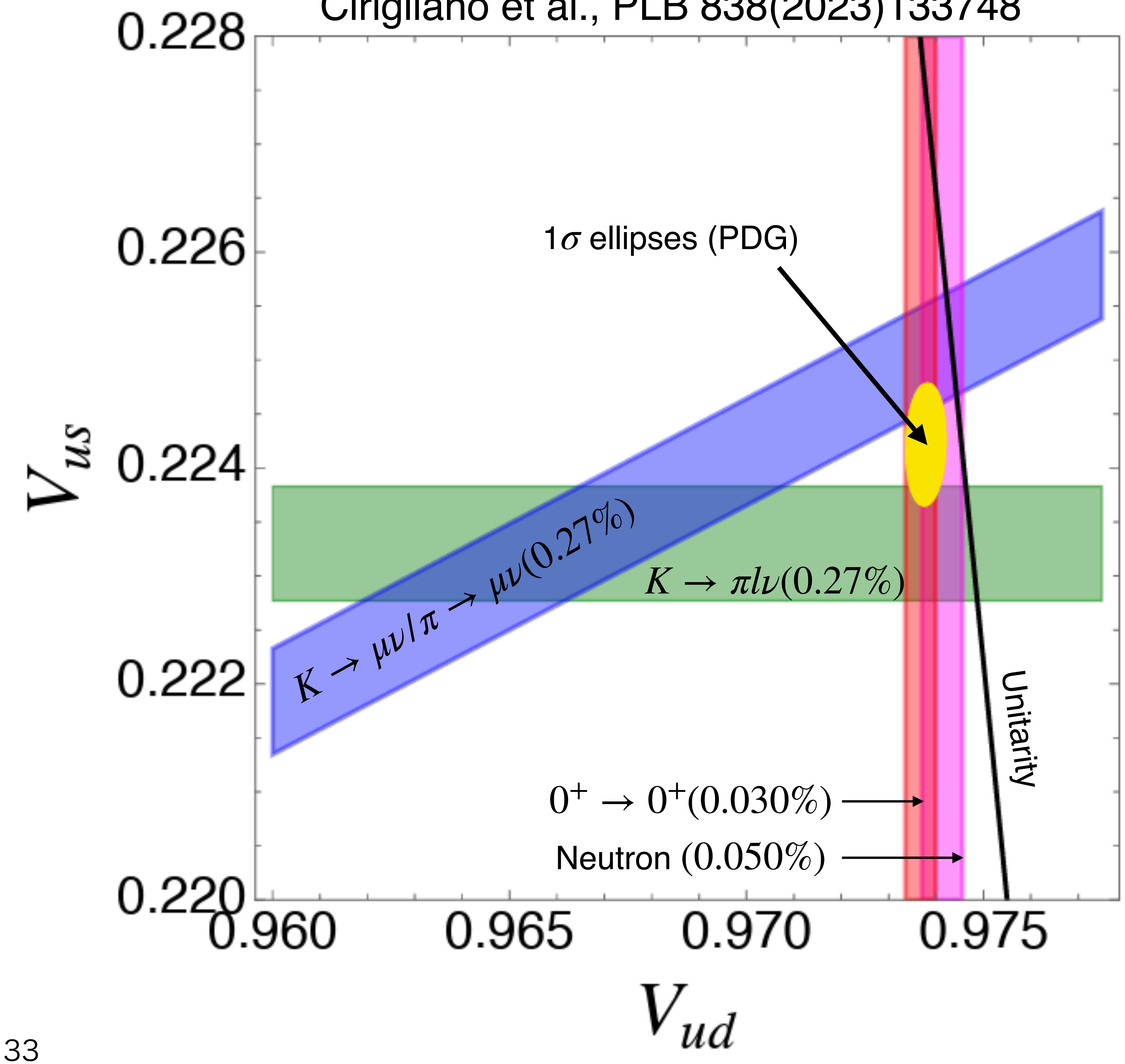
$$\Delta_{\rm CKM} = (-19.5 \pm 5.3) \times 10^{-4},$$

2-3σ effect (Cabbibo Angle Anomaly)

This can also be interpreted as a LFUV

- V_{ud} dominant from electron meas.
- V_{us} dominant from muon meas.

Cirigliano et al., PLB 838(2023)133748



PIONEER goal (II)

Current measurements

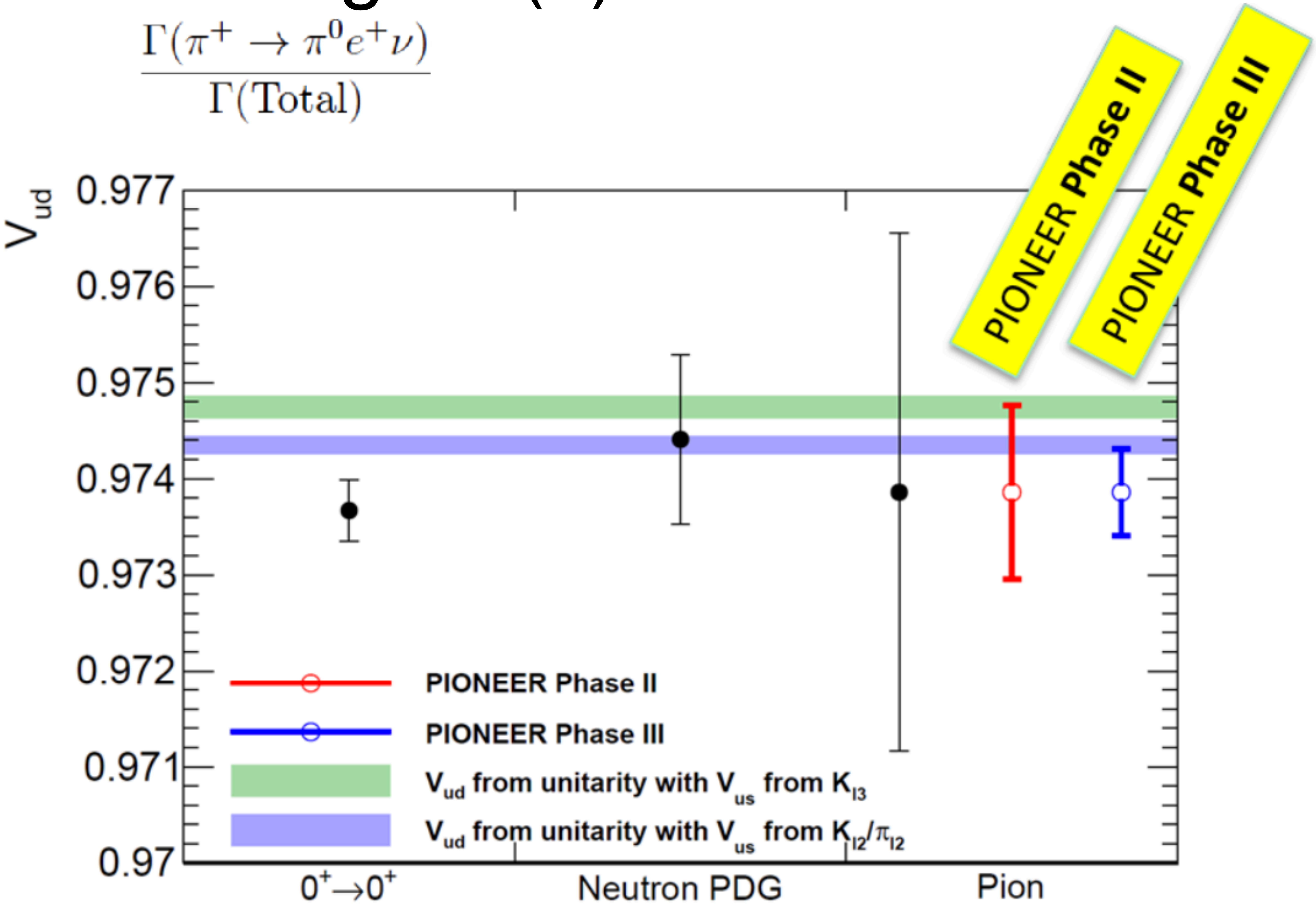
$$R_{\pi\beta} = \frac{\Gamma[\pi^+ \to \pi^0 e^+ \nu(\gamma)]}{\Gamma[\pi^+ \to \mu^+ \nu(\gamma)]}$$

$= 1.038(6) \times 10^{-8}$ (0.56%)

Phase II & III

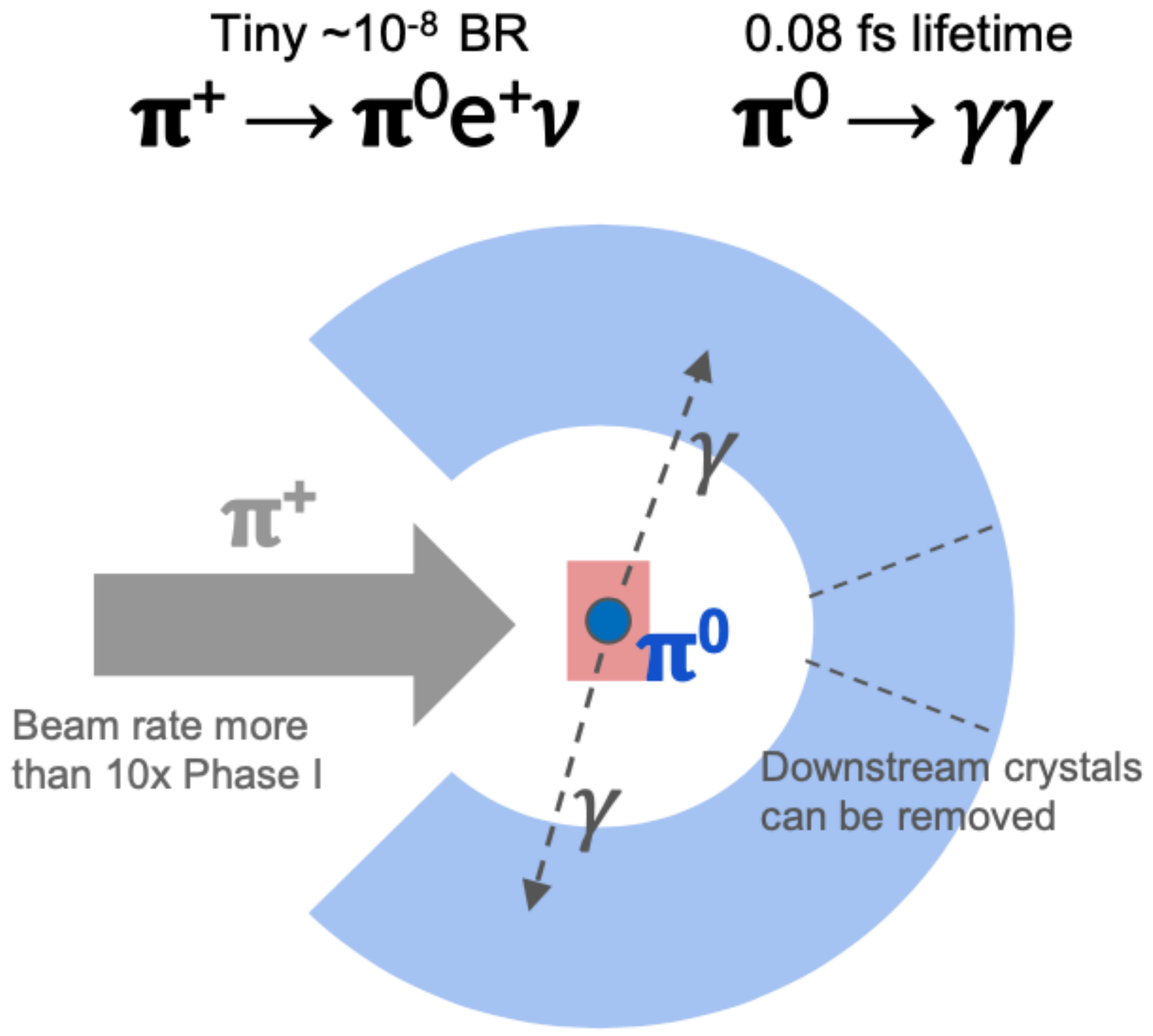
- Improvement by a factor of 3 (Phase II) / 10(Phase III)
- CKM unitarity check by theoretically cleanest $|V_{ud}|$

$$\frac{\Gamma(\pi^+ \to \pi^0 e^+ \nu)}{\Gamma(\text{Total})}$$



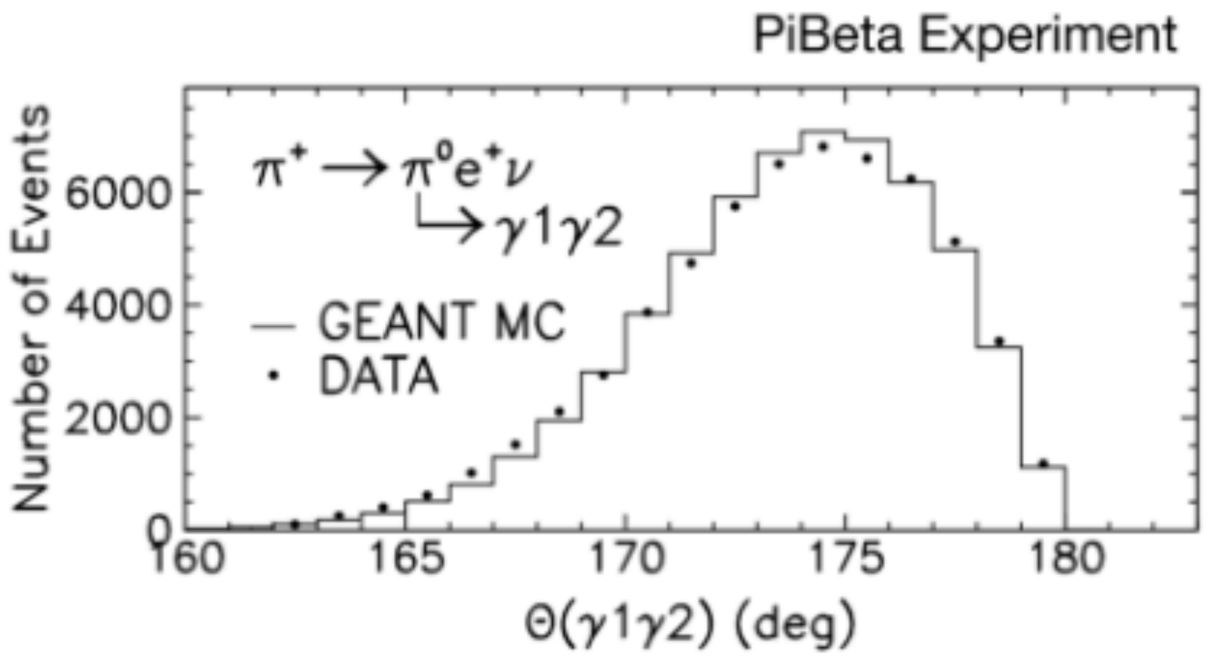
PDG24

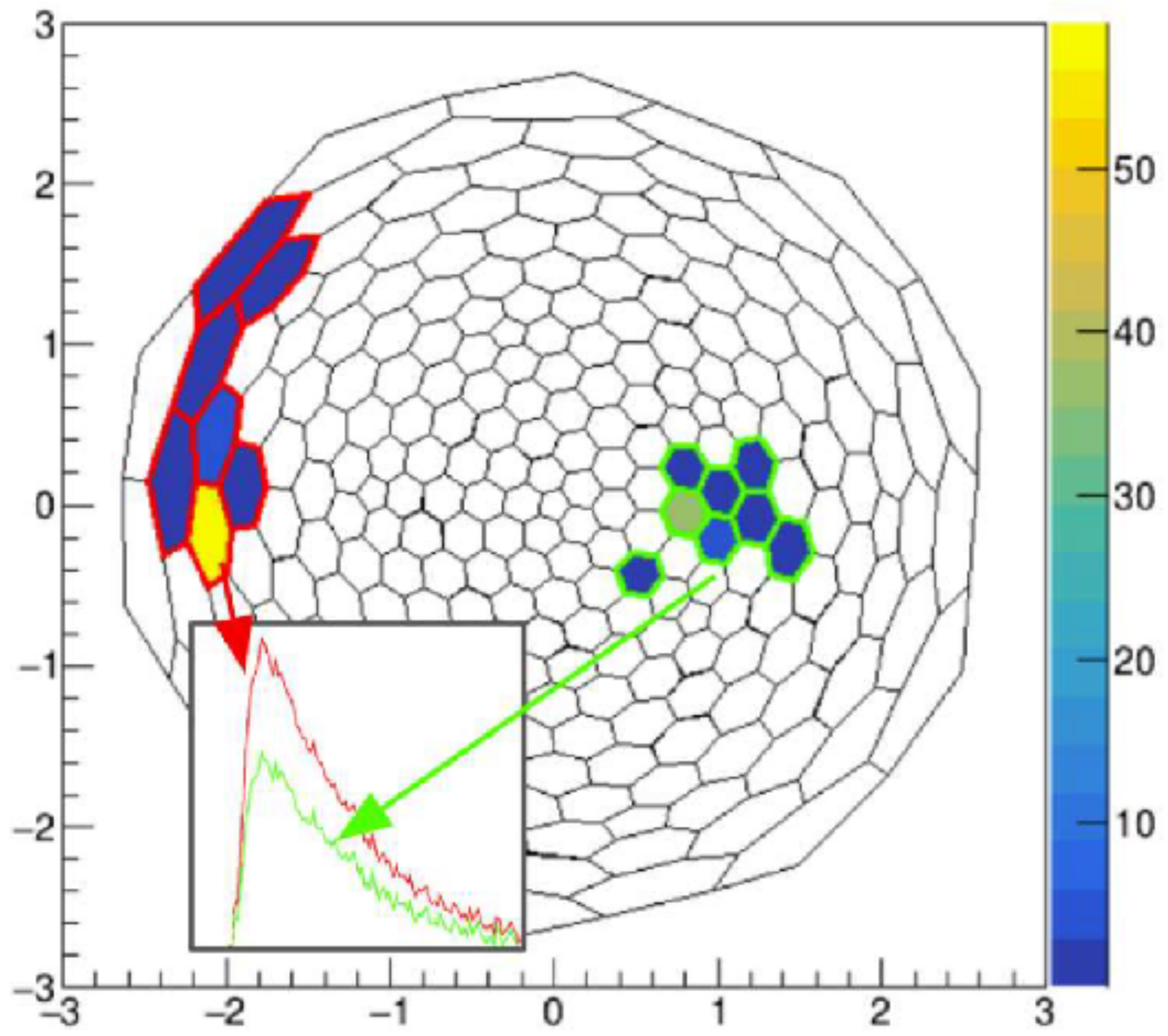
PIONEER PiBeta measurement in Phase II/III

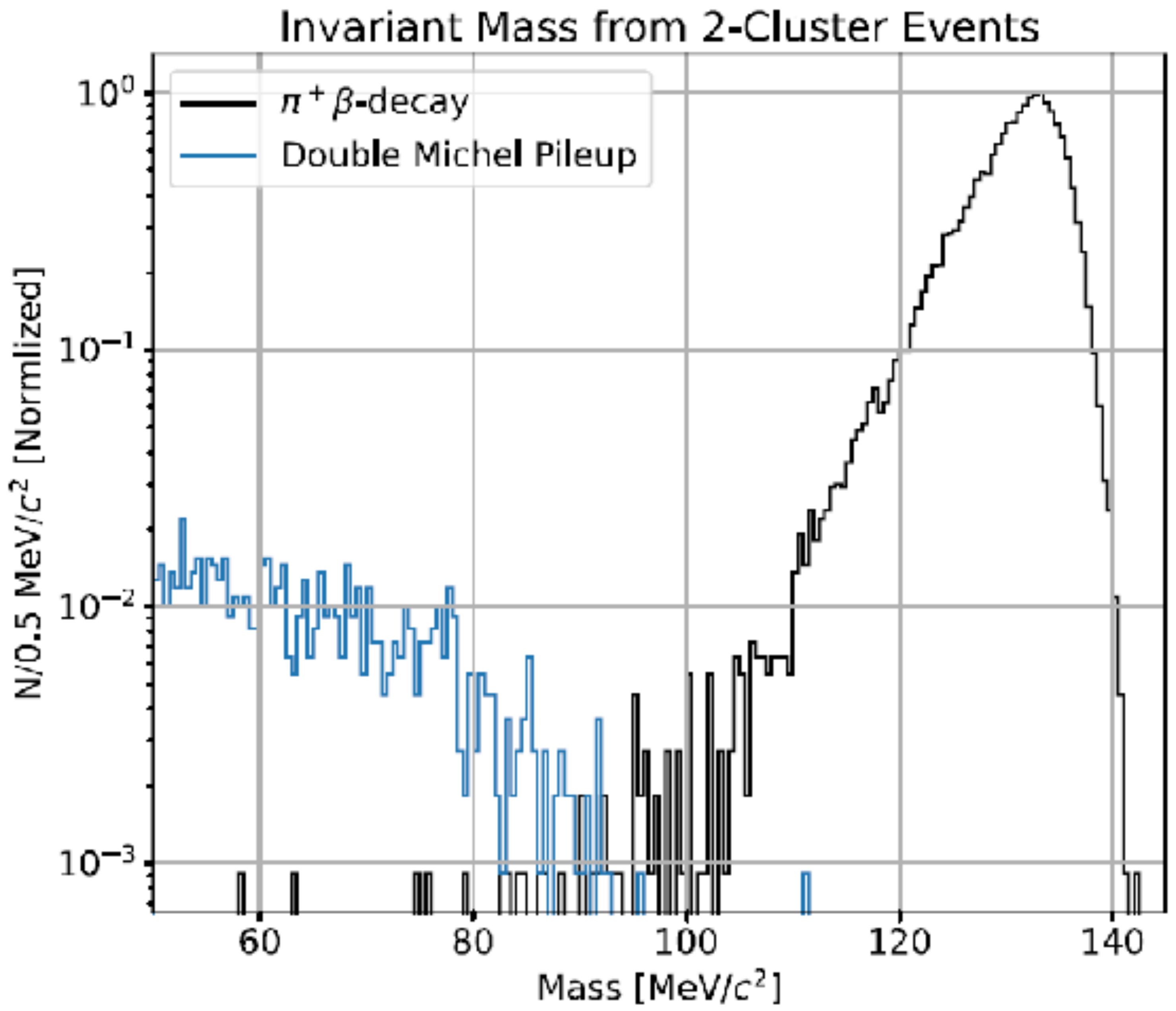


- Segmentation is critical to the reconstruction of PiBeta events in a high rate environment

Clusters are back-to-back







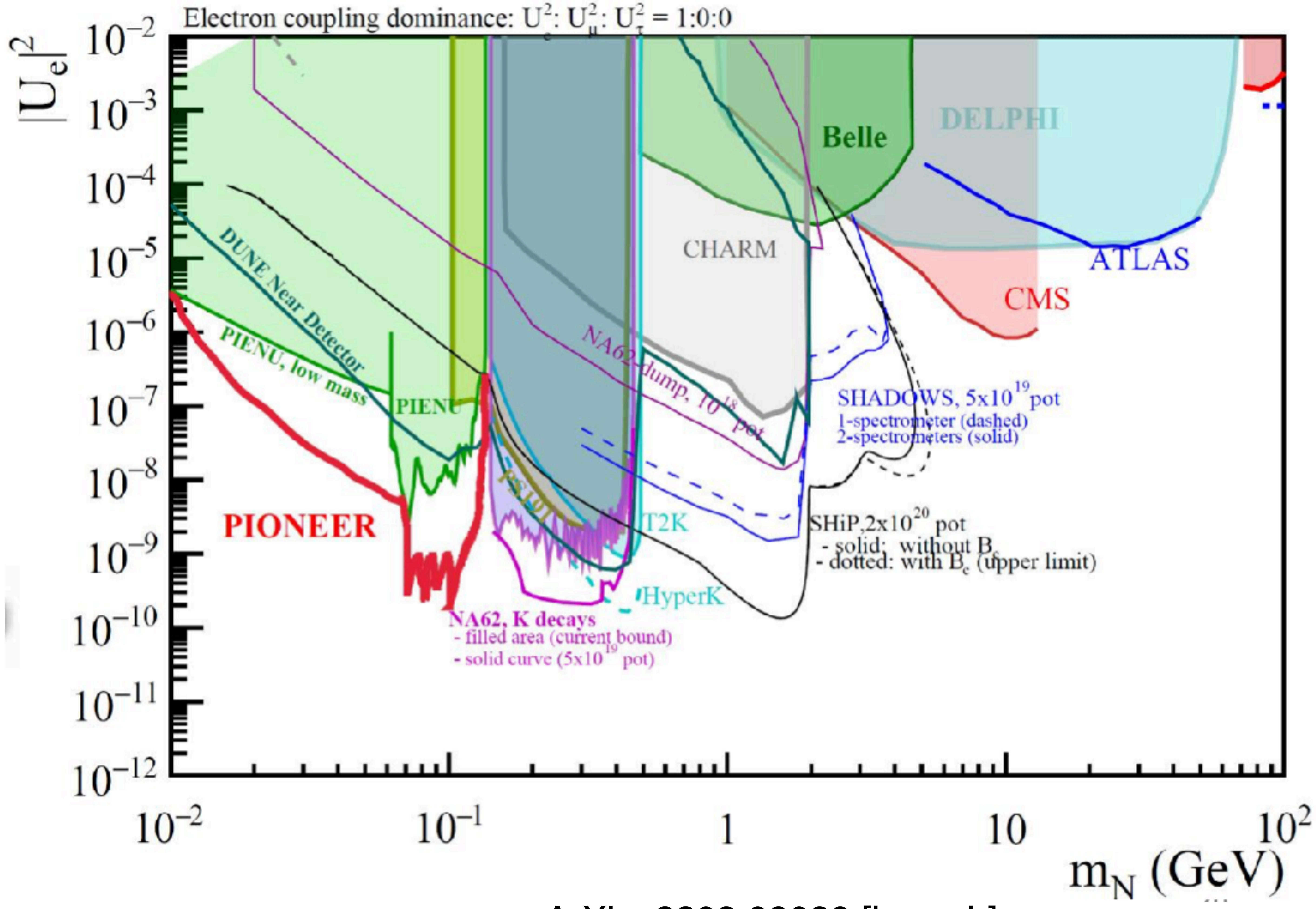
PIONEER Goal (III) : Exotic decay search

Search for exotic decays
beyond previous limits

- Heavy neutrinos $\pi^+ \to l^+\nu_H$
- pion decays to various light dark sector particles
- lepton-flavor violating decays of the muon into light NP particles $\mu^+ \to e^+X_H$

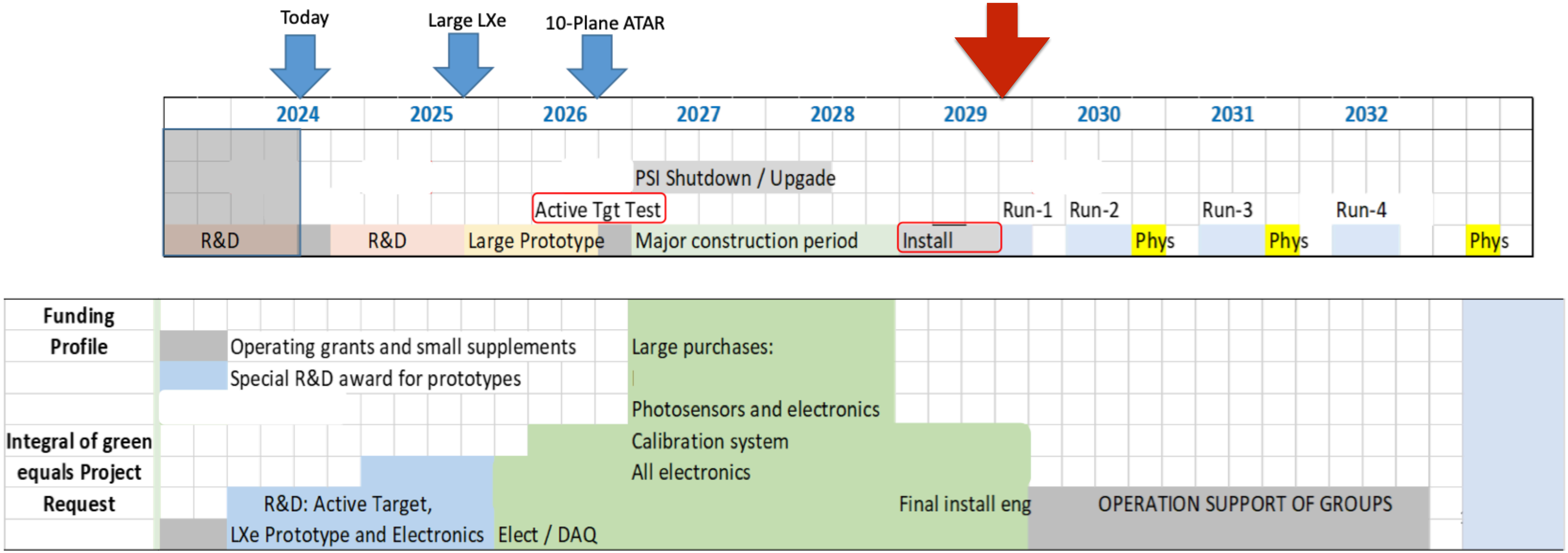
About one order of magnitude for exotic decays in the low mass region 10-120MeV

Heavy Neutral Lepton search



ArXiv: 2203.08039 [hep-ph]

PIONEER timelines



- PSI has a long shutdown between 2027 and 2028
- The PIONEER experiment will aim at the detector construction during that, and start the run from 2029

Conclusion

- The PIONEER experiment is approved by PSI scientific committees
- The lepton flavor universality violation will be explored by the measurements on $R^{\pi}_{e/\mu}$
- The measurements on pion beta decay ($\pi^+ \rightarrow \pi^0 e^+ \nu$) can be important inputs for CKM unitarity
- There are three key points for the PIONEER experiment to improve the sensitivity, intense pion beam, active target, and calorimeter.
- The PIONEER collaboration grows internationally. New ideas, expertise, and new collaborators are welcome.

PIONEER collaboration

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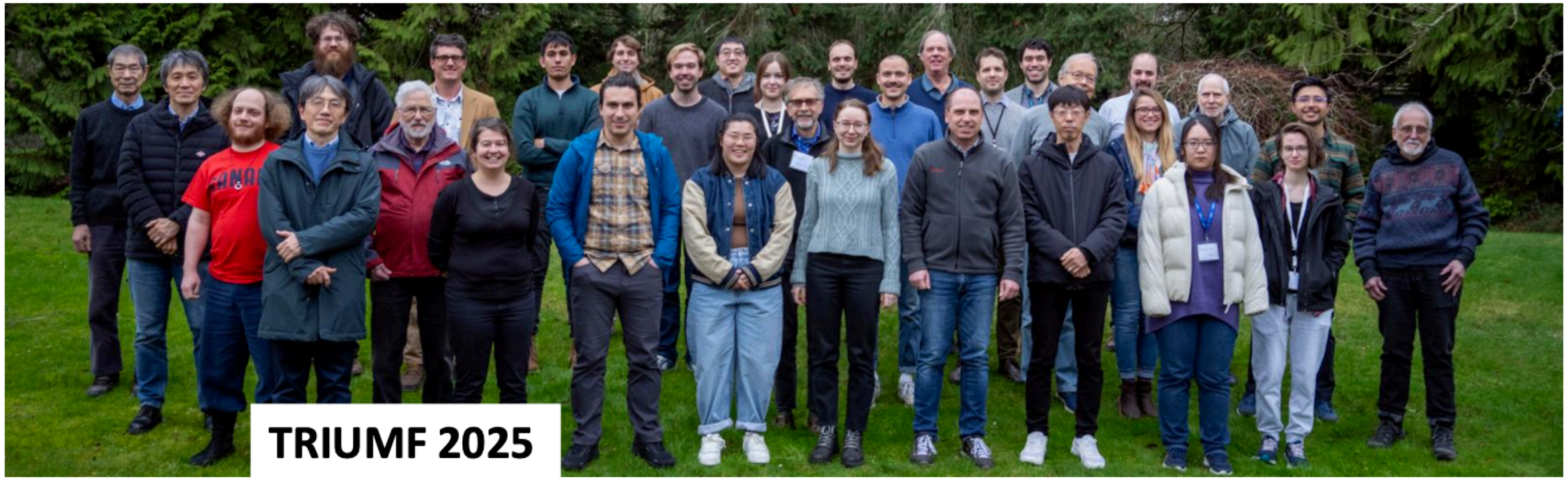

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[2] *University of Washington*
[3] *University of Chicago*
[4] *University of British Columbia*
[5] *TRIUMF*
[6] *Tsinghua University*
[7] *Theoretical Division, Los Alamos National Laboratory*
[8] *Argonne National Laboratory*
[9] *Paul Scherrer Institute*
[10] *University of Zurich*
[11] *CERN*
[12] *Tec de Monterrey*
[13] *Brookhaven National Laboratory*
[14] *Johannes Gutenberg University Mainz*
[15] *Fermilab*
[16] *Cornell University*
[17] *University of Virginia*
[18] *ETH Zurich*
[19] *University of Kentucky*
[20] *University of Bern*
[21] *KEK*
[22] *University of Tokyo*
[23] *Stony Brook University*
[24] *University of Victoria*

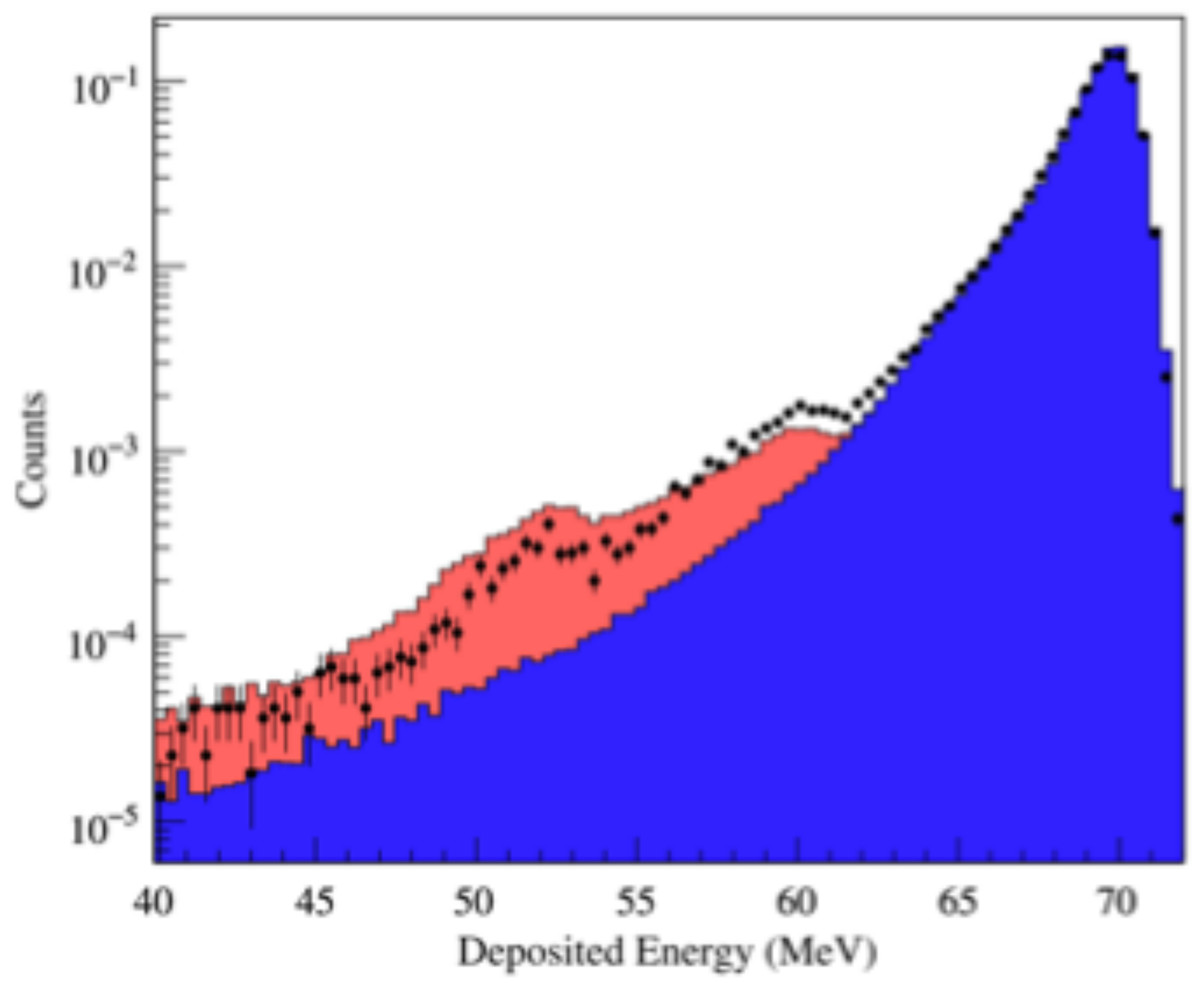
Photo-nuclear reaction

Photonuclear reactions in NaI detector

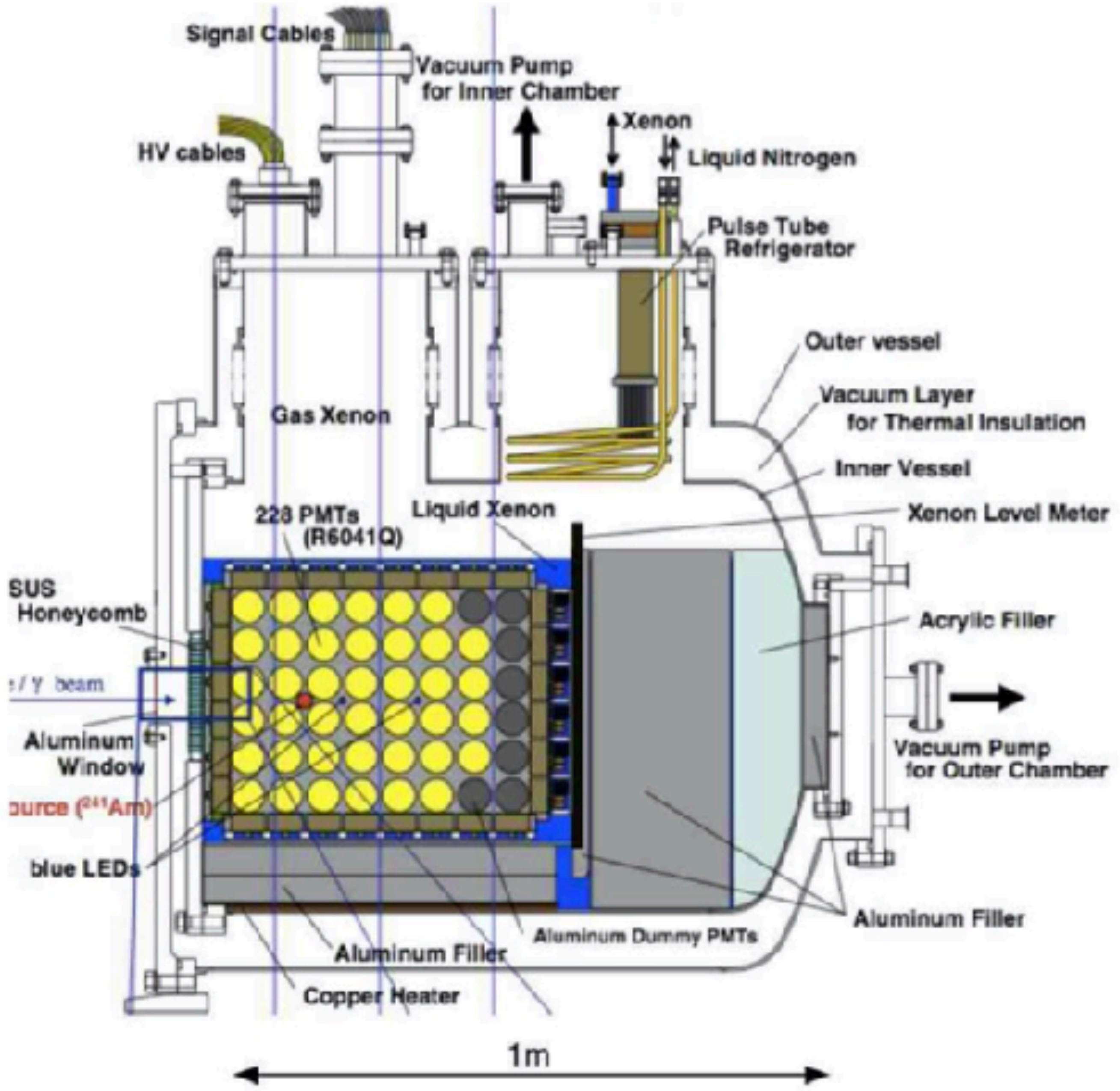
- ^{127}I captures γ(electromagnetic shower)
  → n(94%), p(4%), α(2%) emission
  → 1n, or 2n escape from NaI
  → peaks in low energy region
- This energy region is buried in π→μ→e decays, and Geant4 simulation should be tuned by data

Beam test was performed with NaI in the previous experiment

Beam test with LXe prototype (~100l LXe) will be performed for that

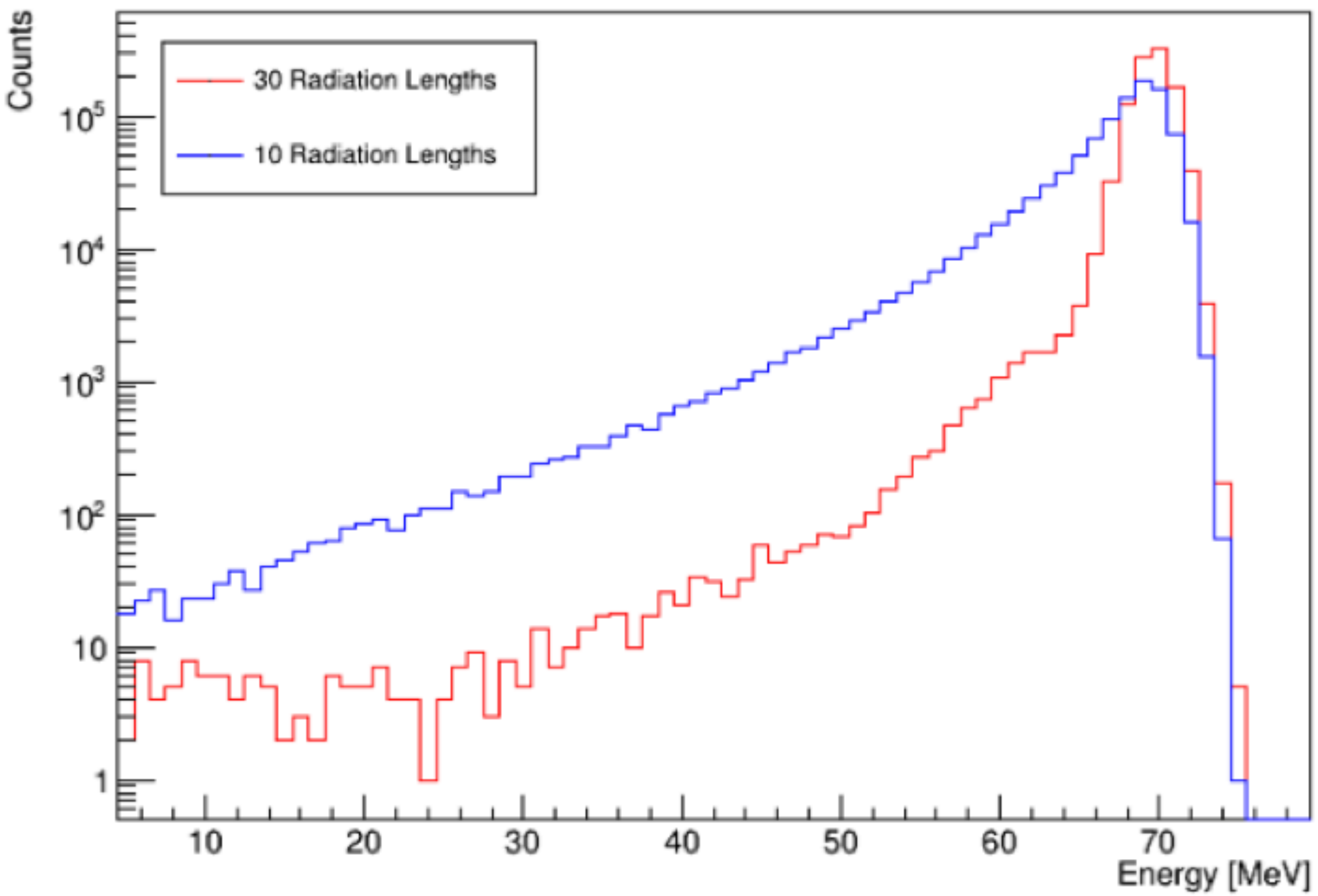


Nucl. Instrum.Meth.A621(2010)188-191

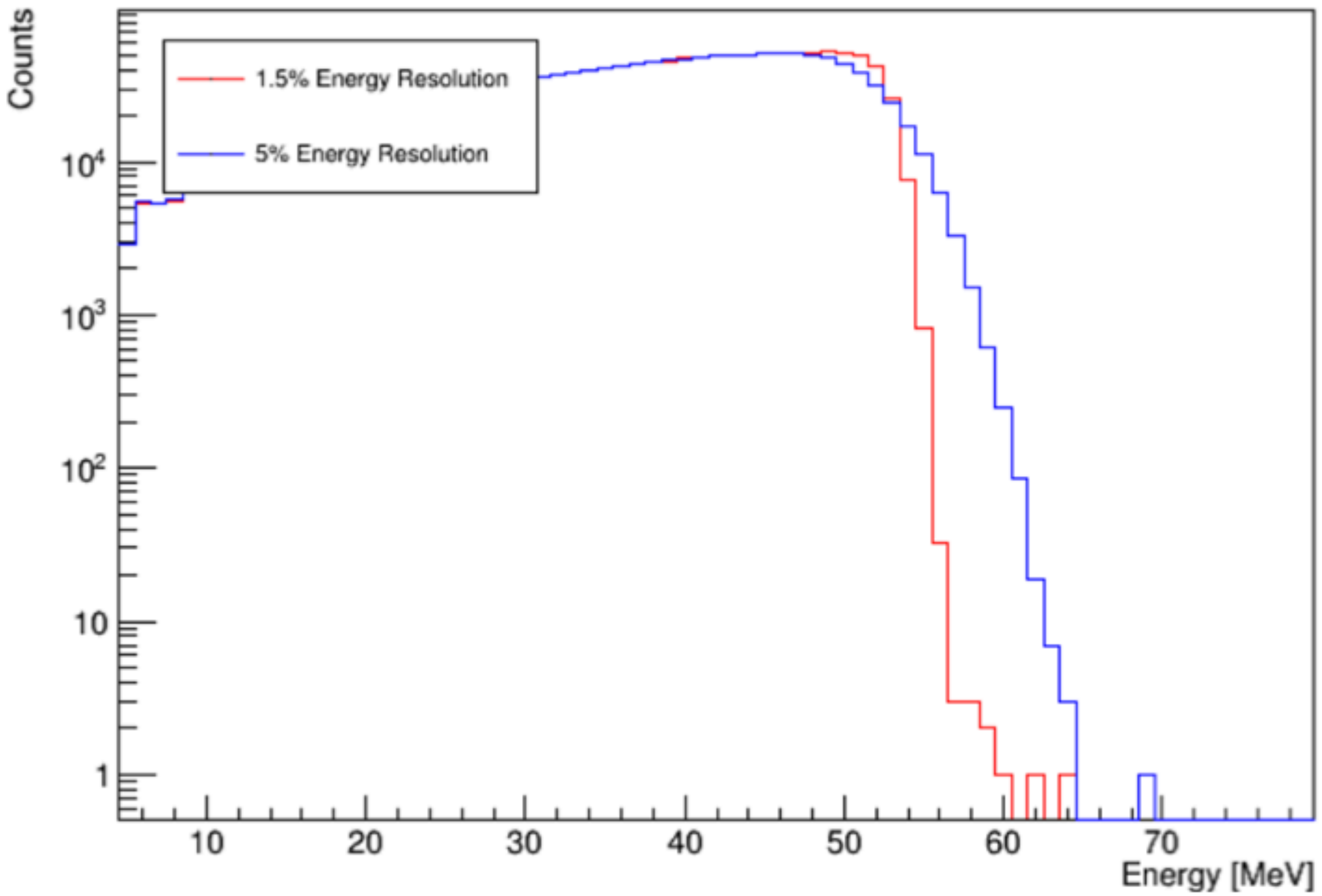


Calorimeter concept

$\pi \rightarrow e\nu$ signal

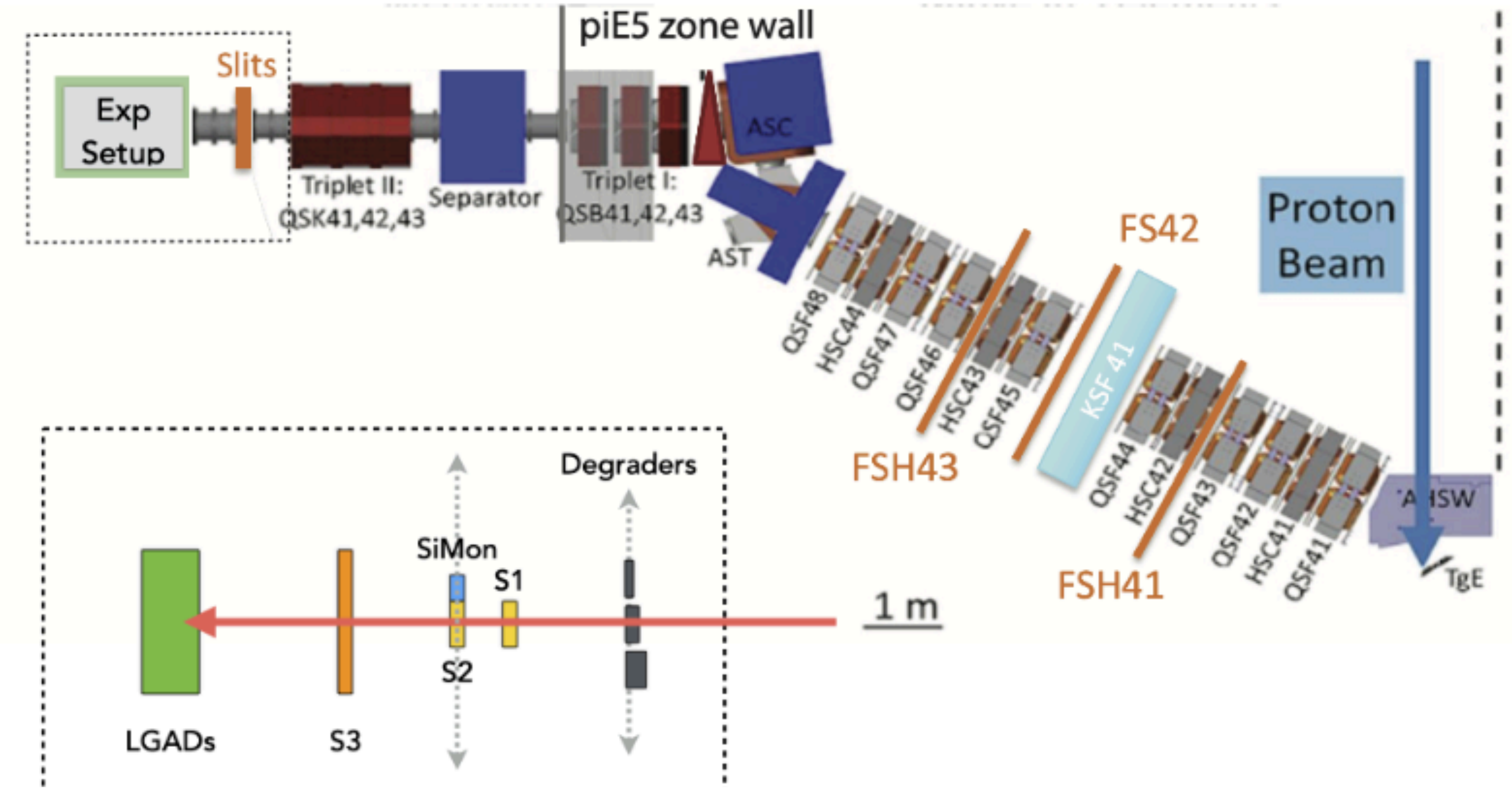


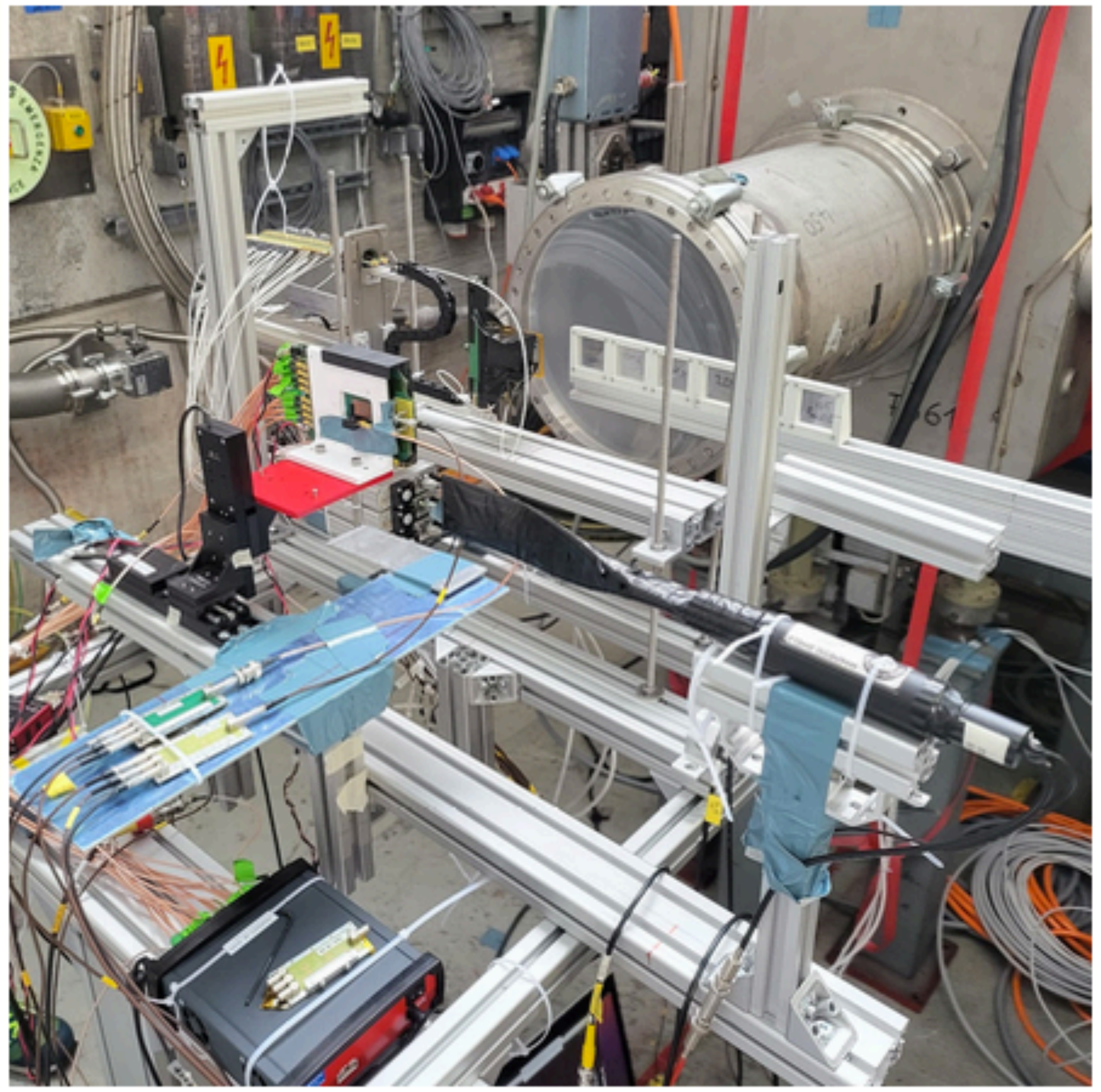
$\pi - \mu - e$ background



Target: ~25 X_0, 2% energy resolution at 70 MeV

Beam test in 2022

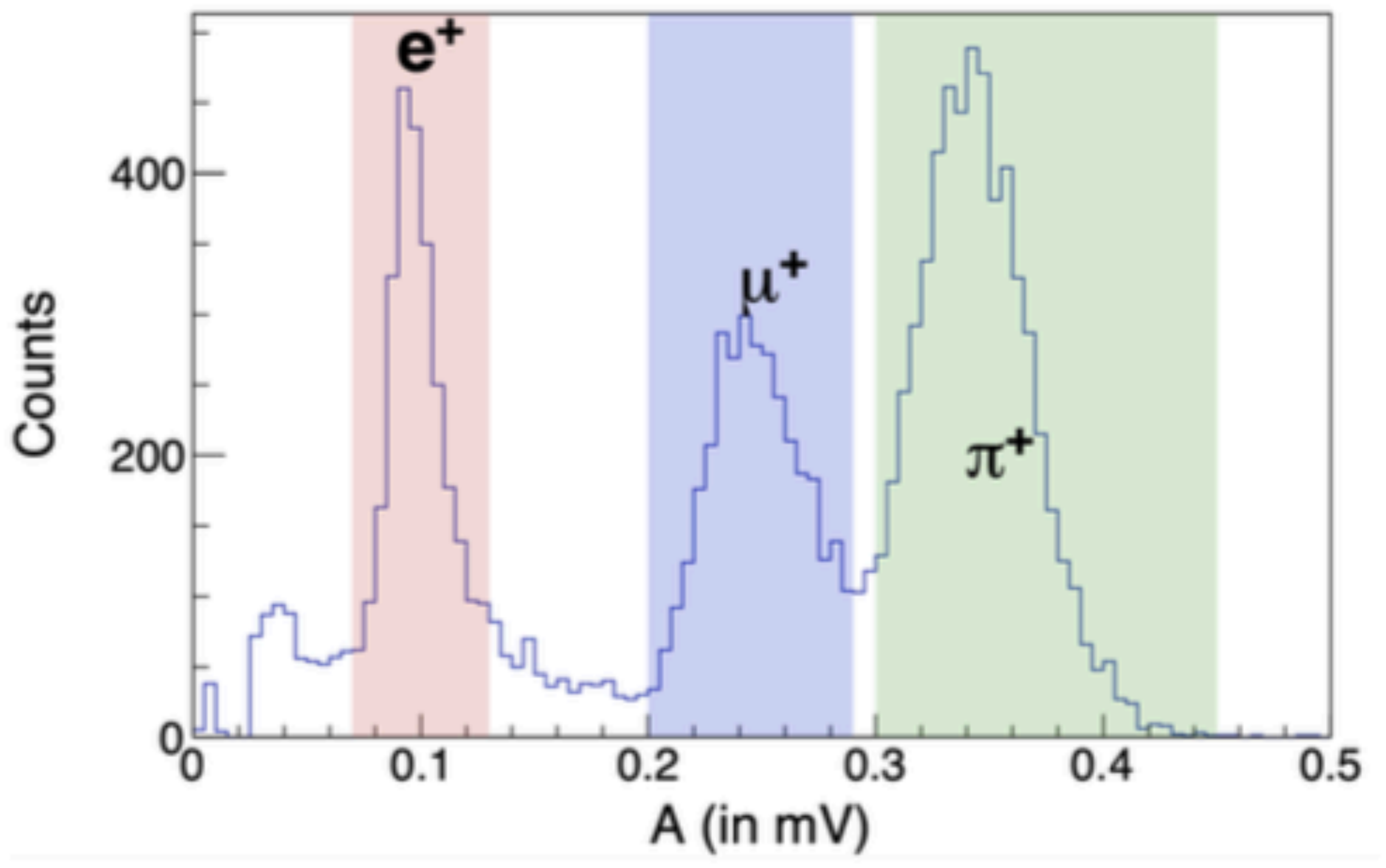


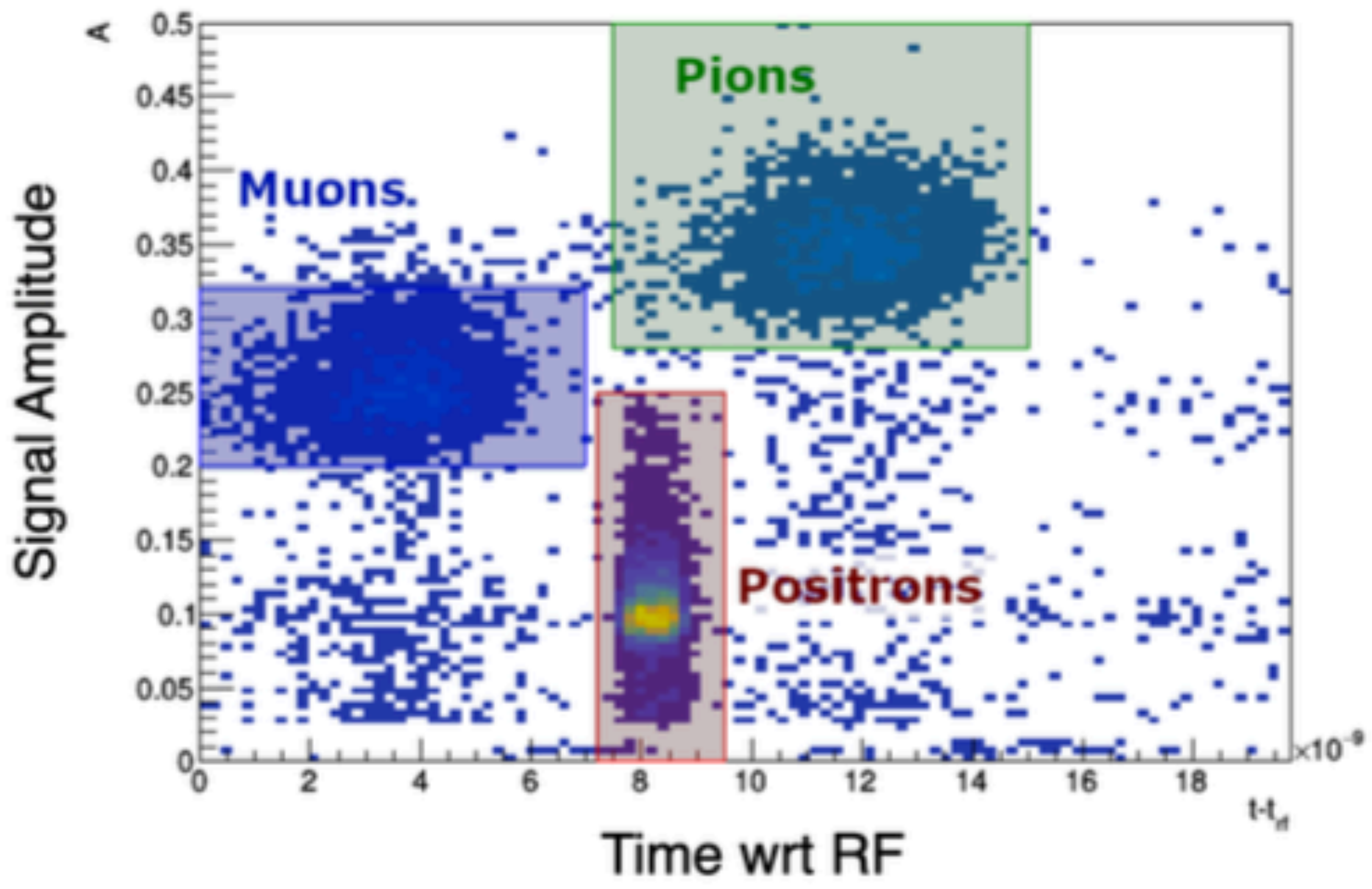


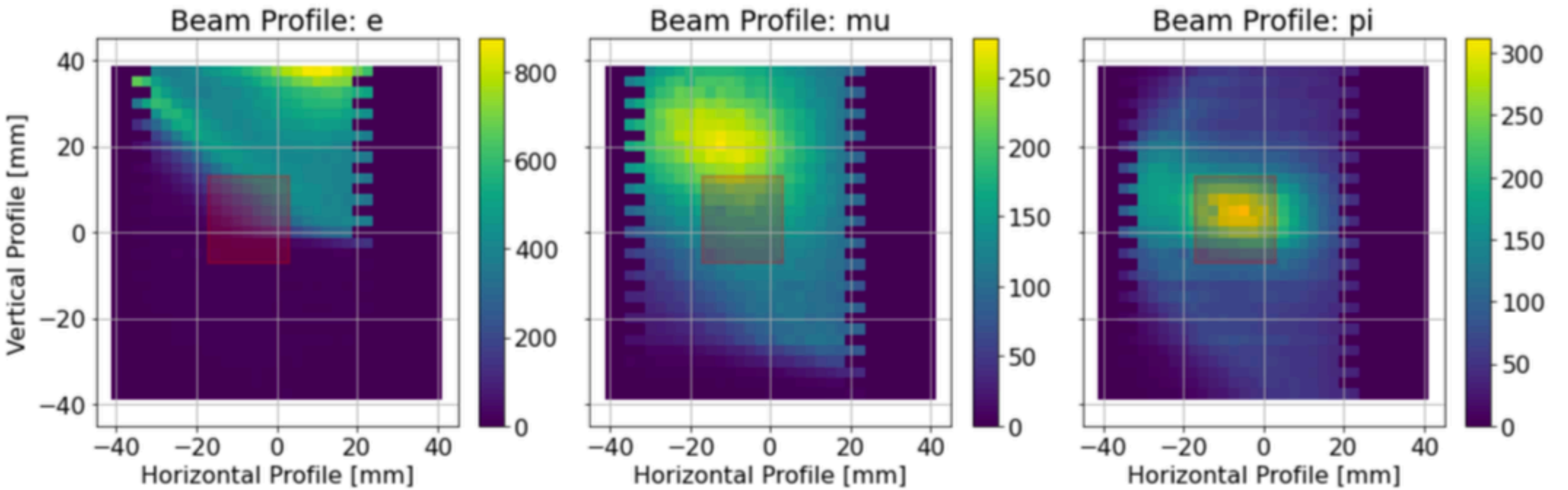
Property	Beam test	PIONEER specs
π^+/s stopped in ATAR (kHz)	300 @ 65 MeV/c	300 @ 60 MeV/c
beam size $\sigma_x \times \sigma_y$ (mm^2)	23 x 10	8 x 8
particle separation $e : \mu : \pi$	25 : 32 : 43	10 : 10 : 80
$\frac{dP}{P}$ FWHM (%)	~ 3	<2

- Sufficient beam rate was already confirmed. Further tuning for the beam profiles are necessary in the coming years

Beam test 2022







Tracker

Connect positron tracks between ATAR and Calo.

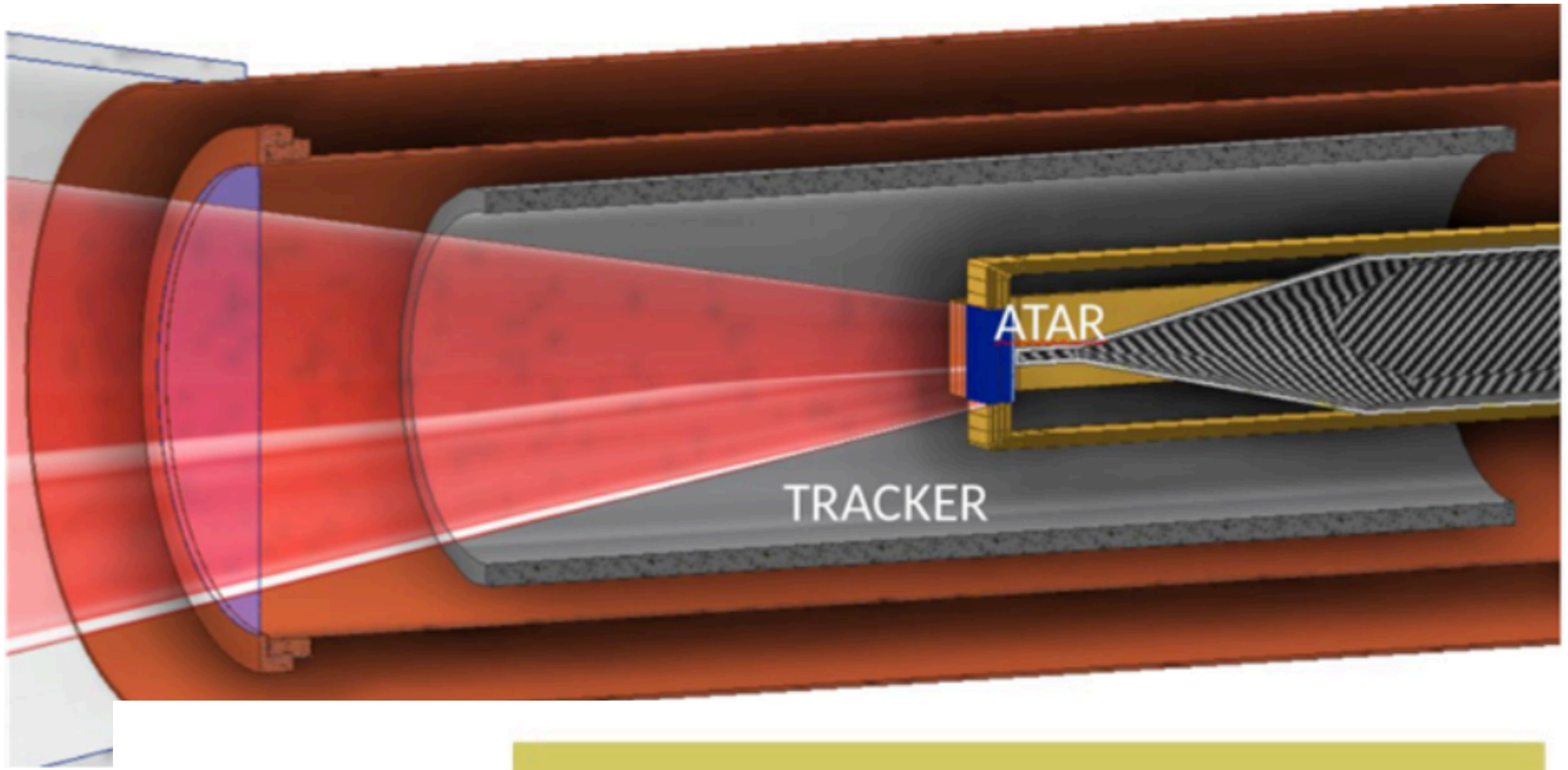
- Low material budget is required
- z, ϕ, and time

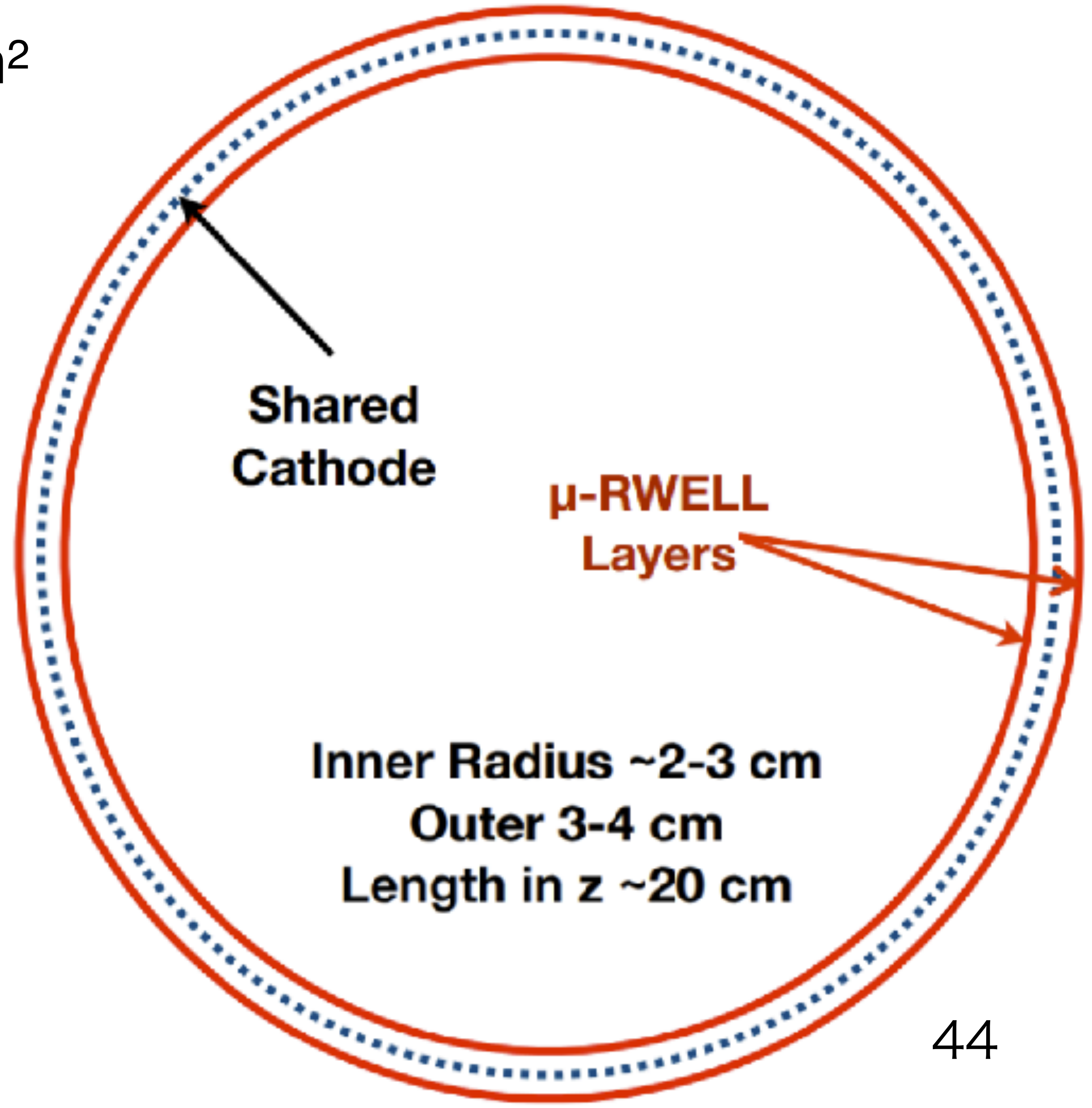
The µ-RWELL is a very promising technology in harsh environment

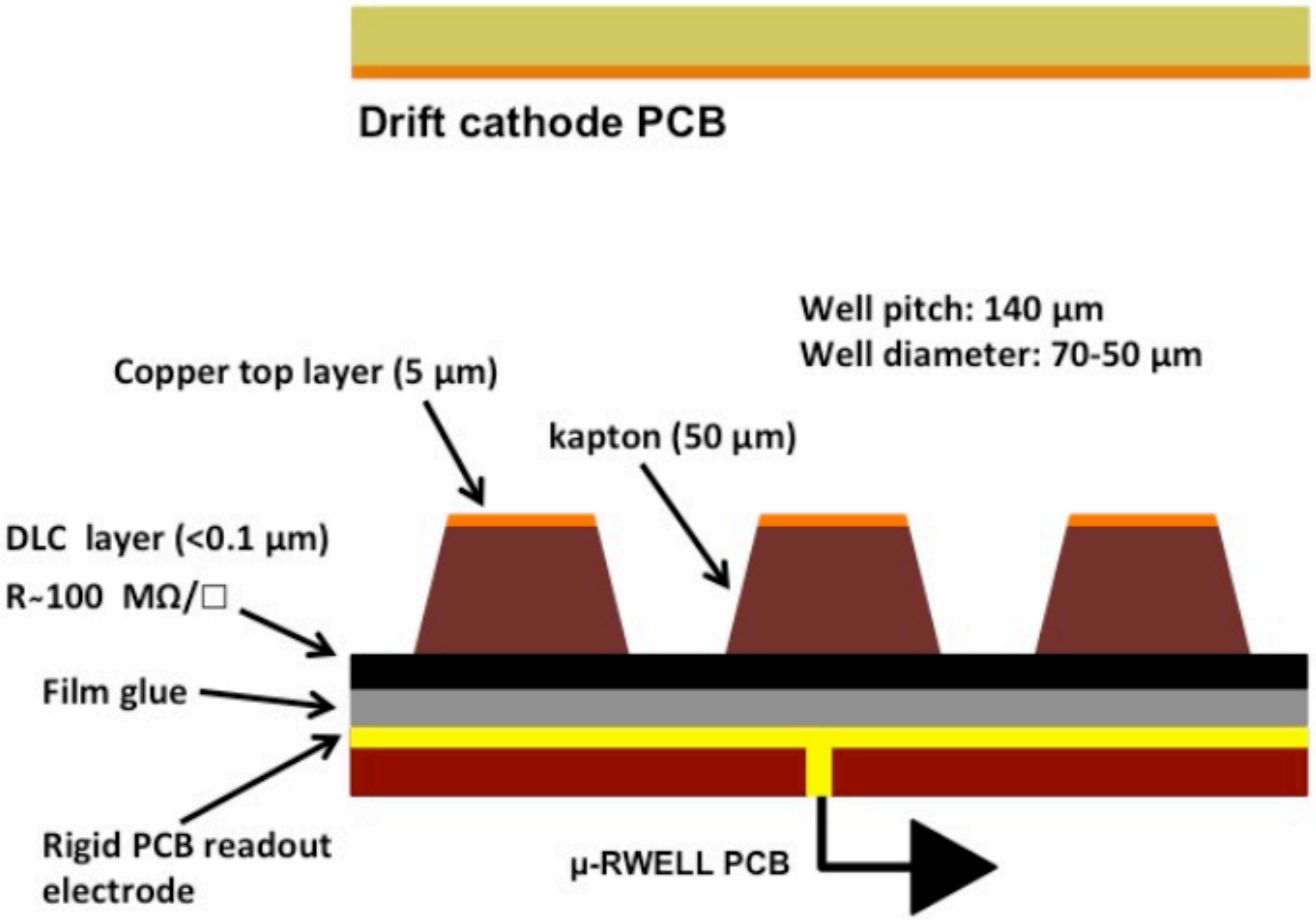
- compact, simple to assemble and intrinsically spark-protected

Performance

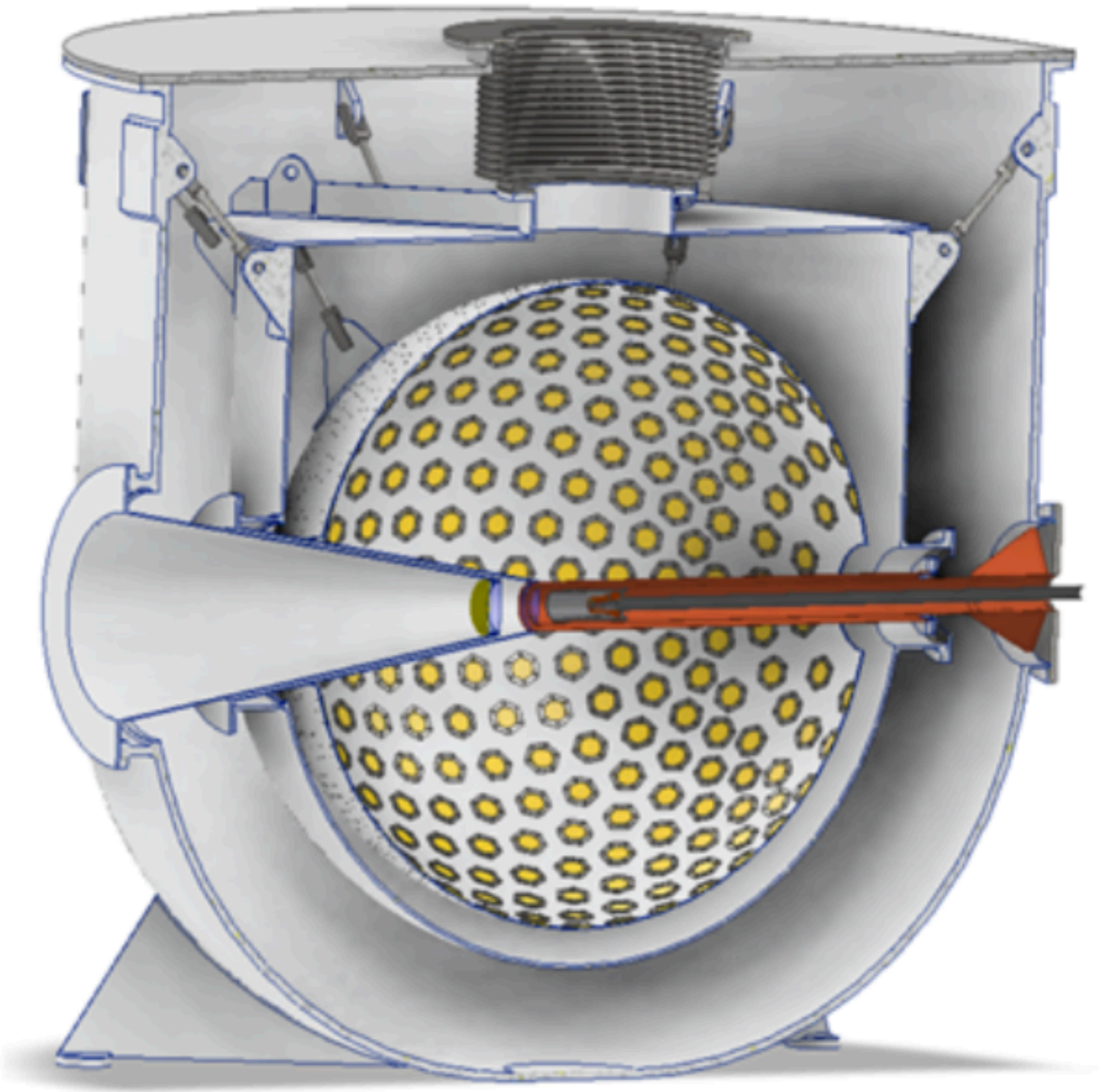
- Gas gain > 10^4
- Rate capability > $1 MHz/cm^2$
- Space resolution < 100µm
- Time resolution ~ 6ns



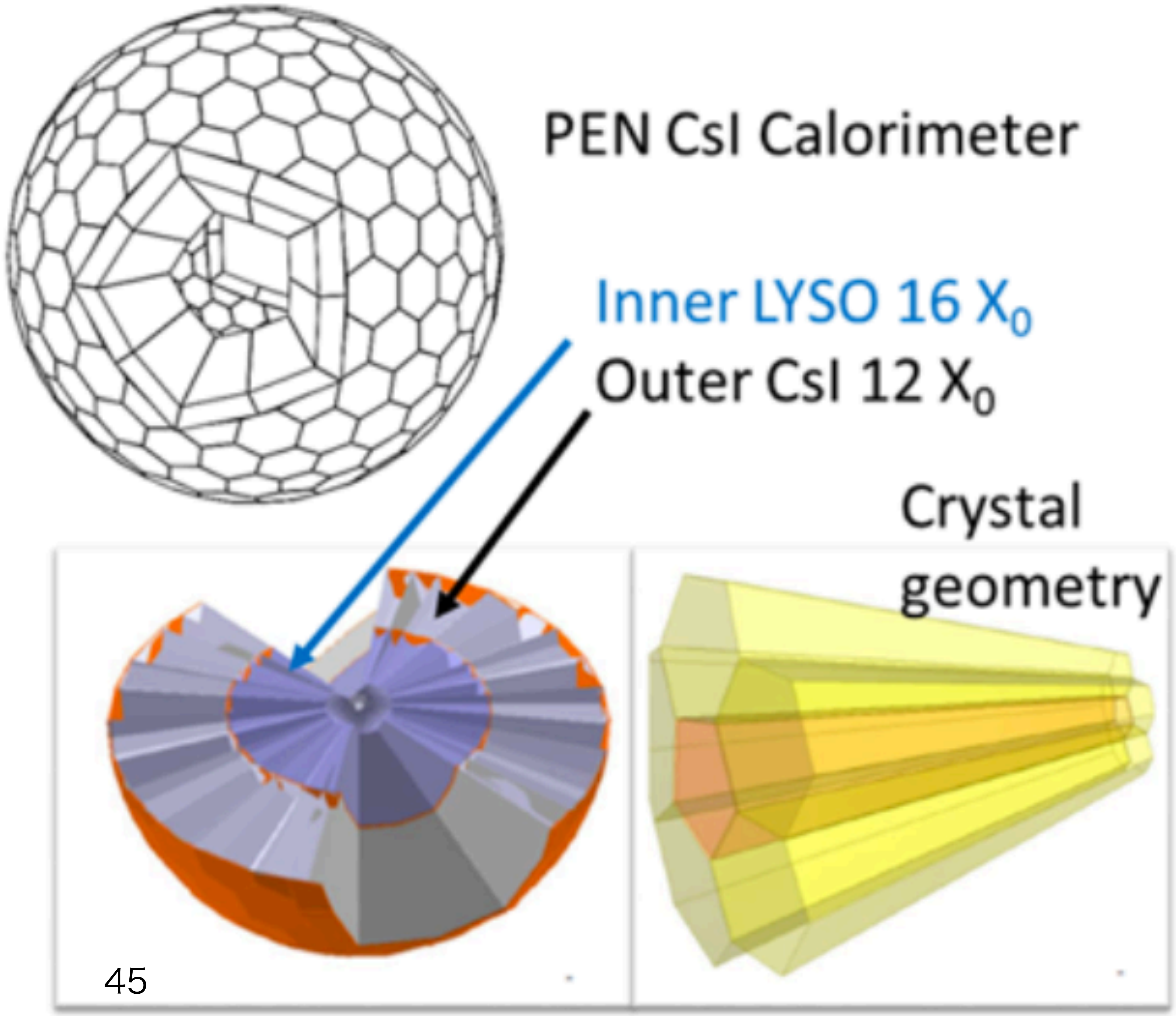




Calorimeter



Detector	Density g/cm^3	dE/dx MeV/cm	X_0 cm	R_M cm	Decay time ns	λ_{max} nm	Light output %
LXe	2.953	3.707	2.872	5.224	3, 27, 45	178	100
LSO(Ce)	7.40	9.6	1.14	2.07	40	402	85



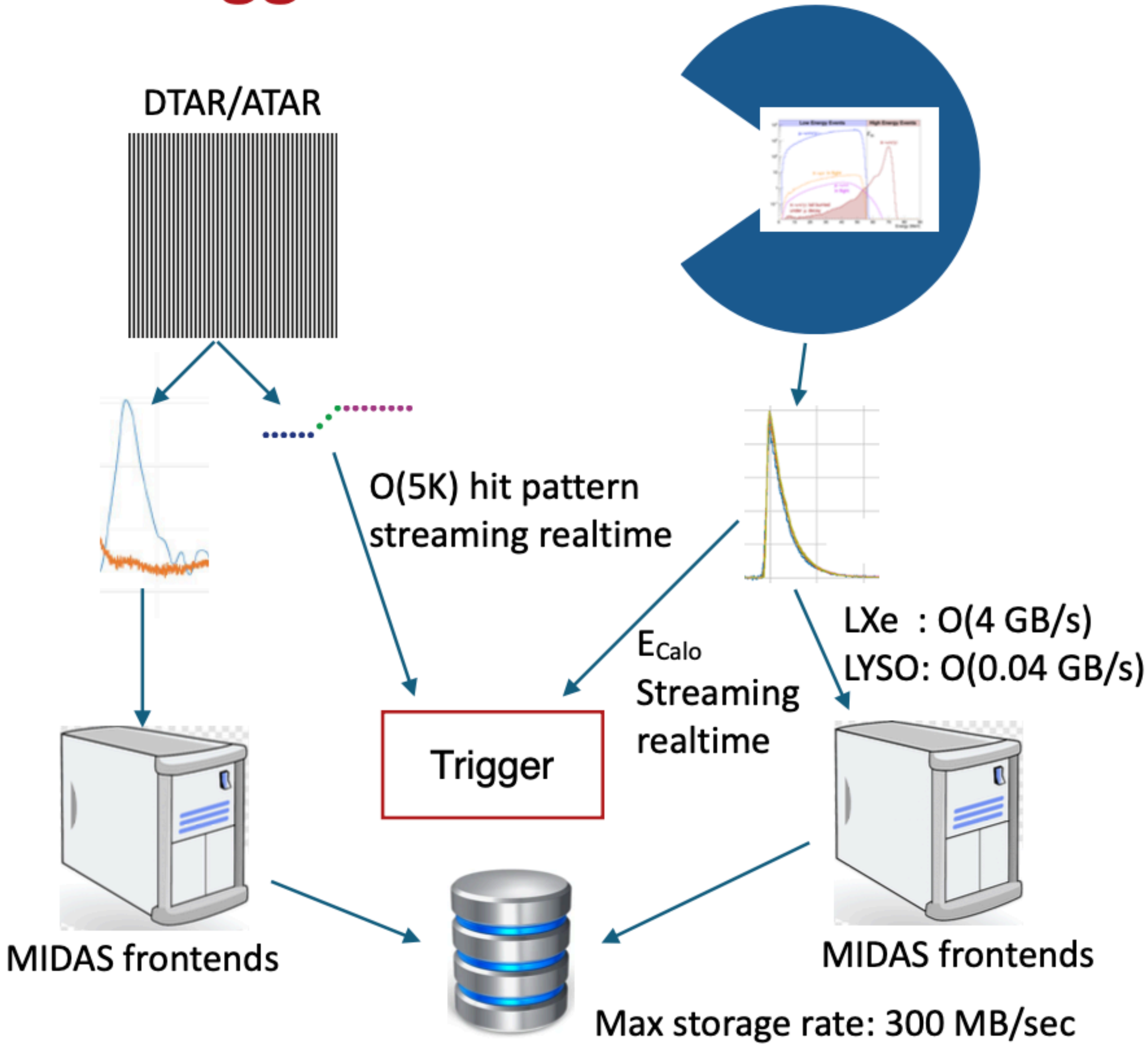
DAQ and Trigger Electronics: Triggers and Rates

Key Physics Triggers

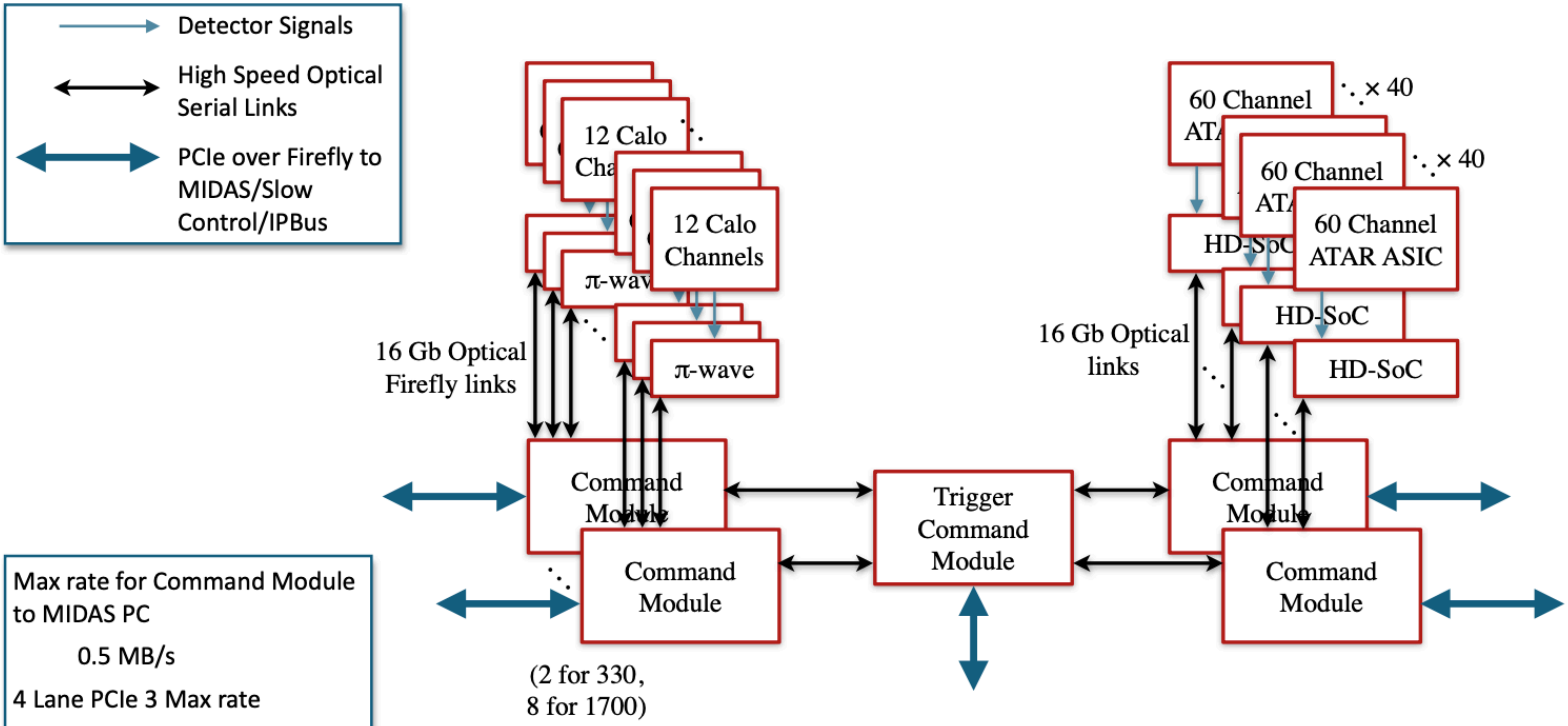
- Minimum bias (π stops): 3 kHz
  - defines T_0
  - prescaled by 100
- E_{Calo} > 50 MeV: 0.1 kHz
  - within [-300,700] ns of T_0
- ATAR (Tracker) hit: 3.4 kHz
  - within [-300,700] ns of T_0
  - prescaled by 50
- PROMPT ATAR (Tracker) hit: 5 kHz
  - within [-5,40] ns of T_0

Some challenges

- ATAR digitizer analog buffering ⇒ O(few hundred ns) trigger decisions
- LXe event size vs data storage rate ⇒ lossy compression (eg., MEG II)



A Coherent DAQ



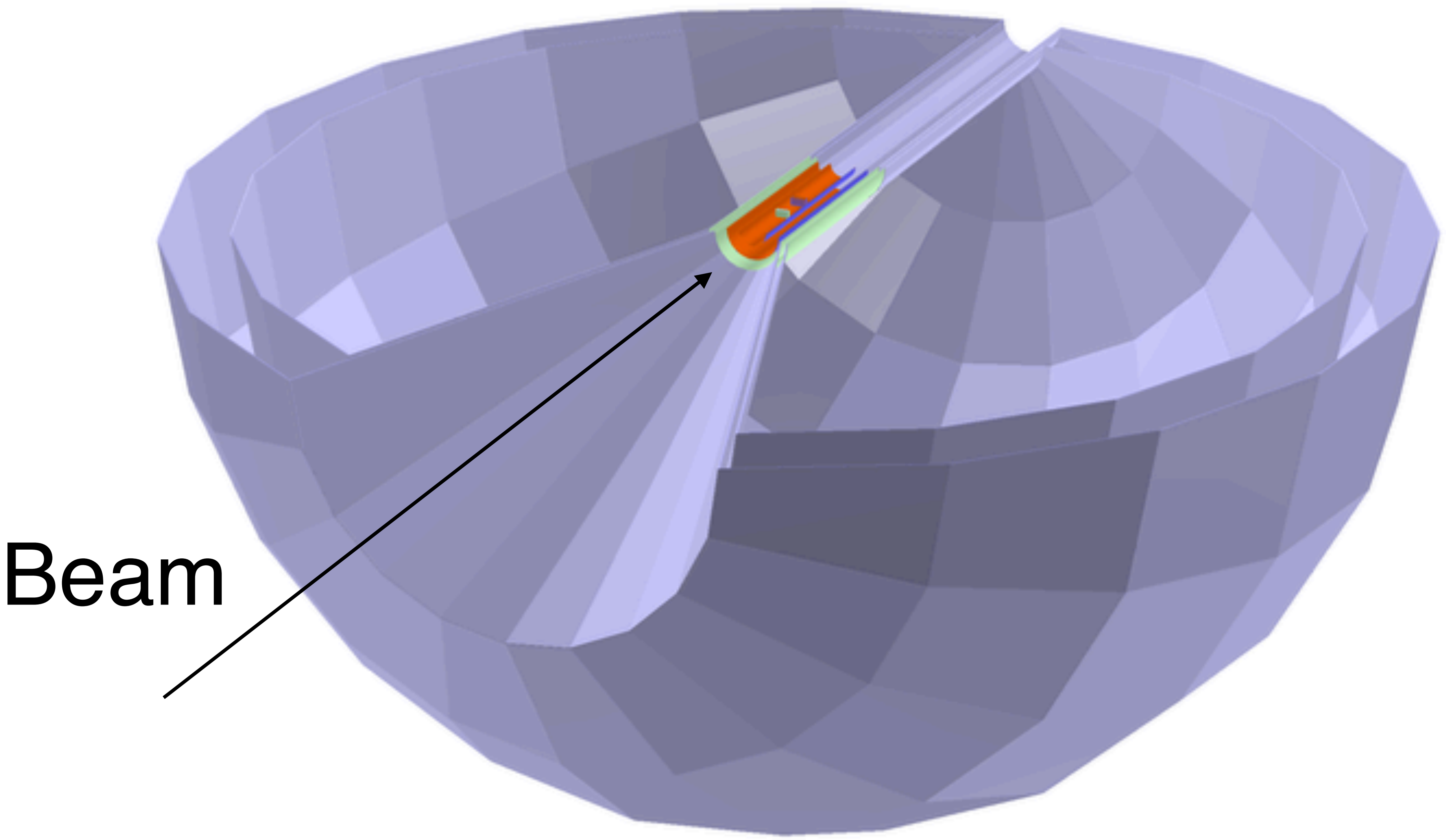
Max rate for Command Module to MIDAS PC

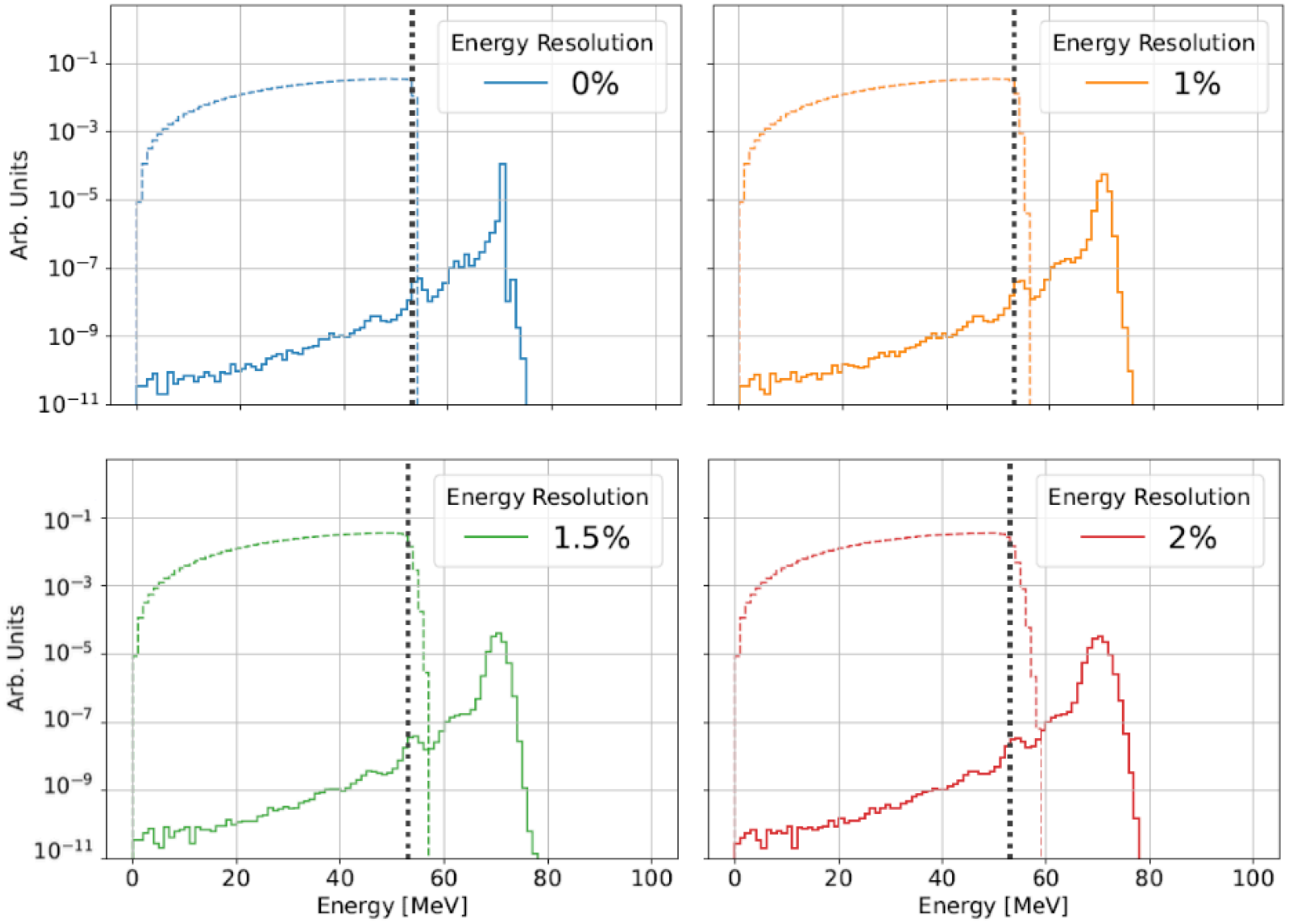
0.5 MB/s

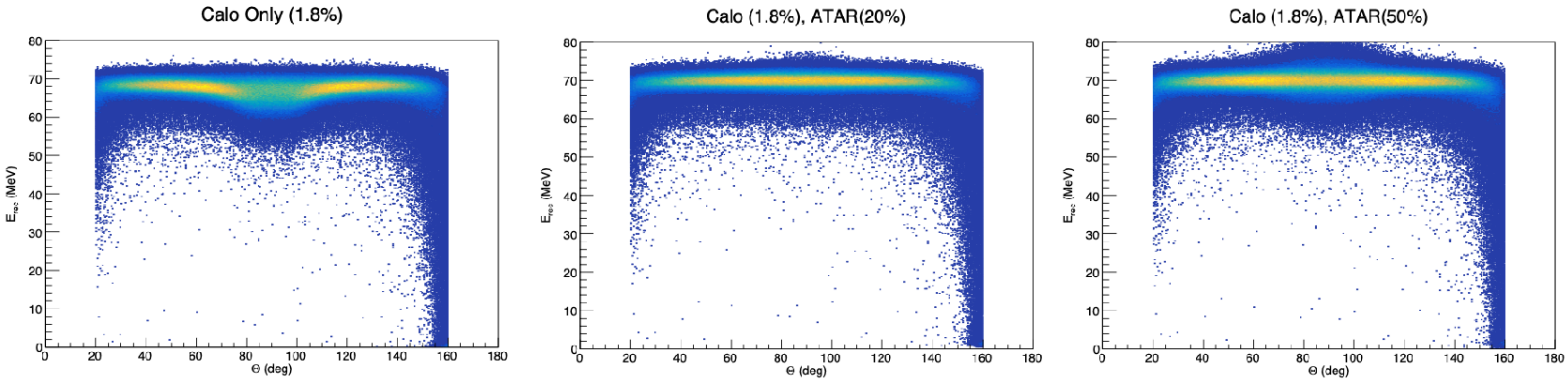
4 Lane PCIe 3 Max rate

4 GB / s

Simulating the whole detector





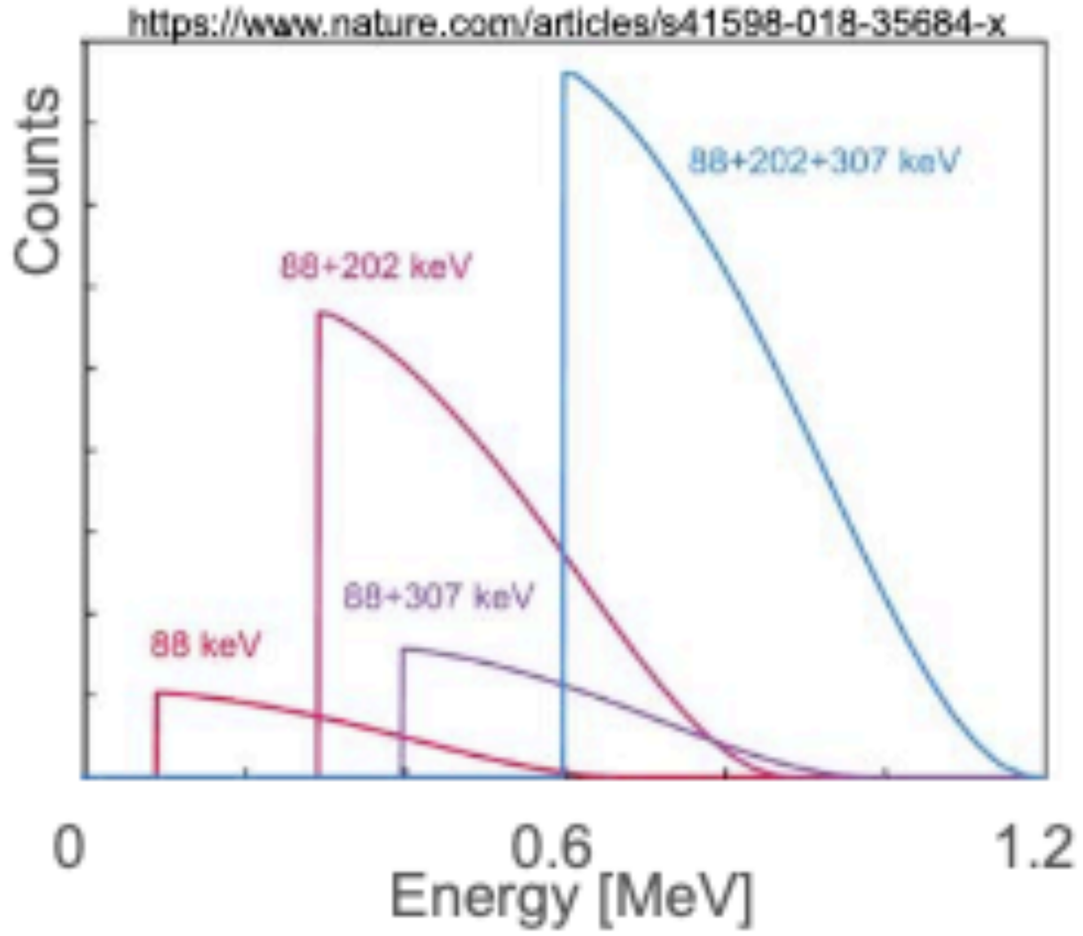


Effects of natural radioactivity

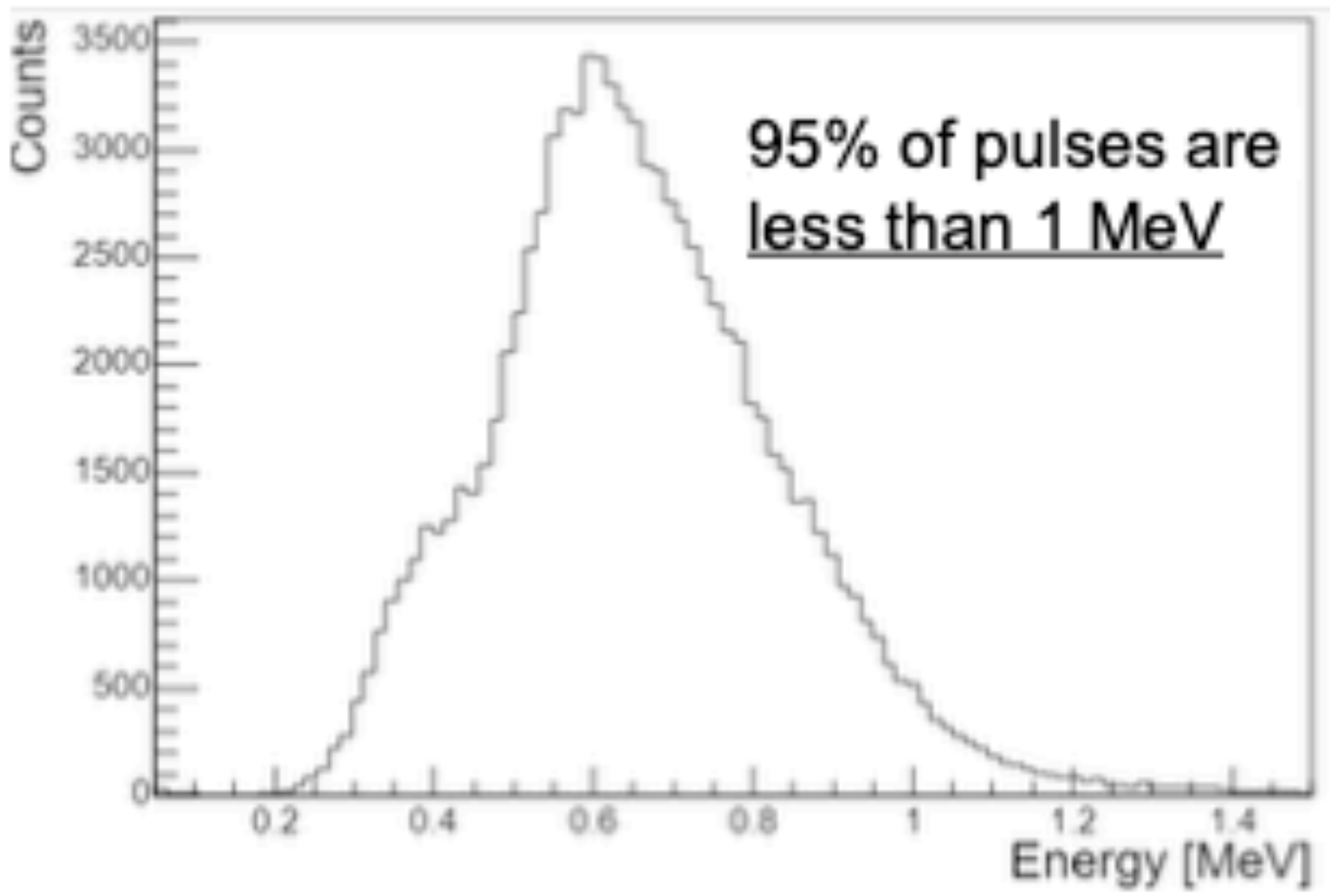
Lutetium (Lu-176) is the most abundant radoactive element in LYSO by weight (2.5%)

- 150 kHz in 10 crystal PiM1 test beam array → ca. 20 MHz in full PIONEER calo, 20% chance of a radioactive event within a 10 ns window
- Typical event cluster size (6 crystals) gives more than order of magnitude geometric suppression

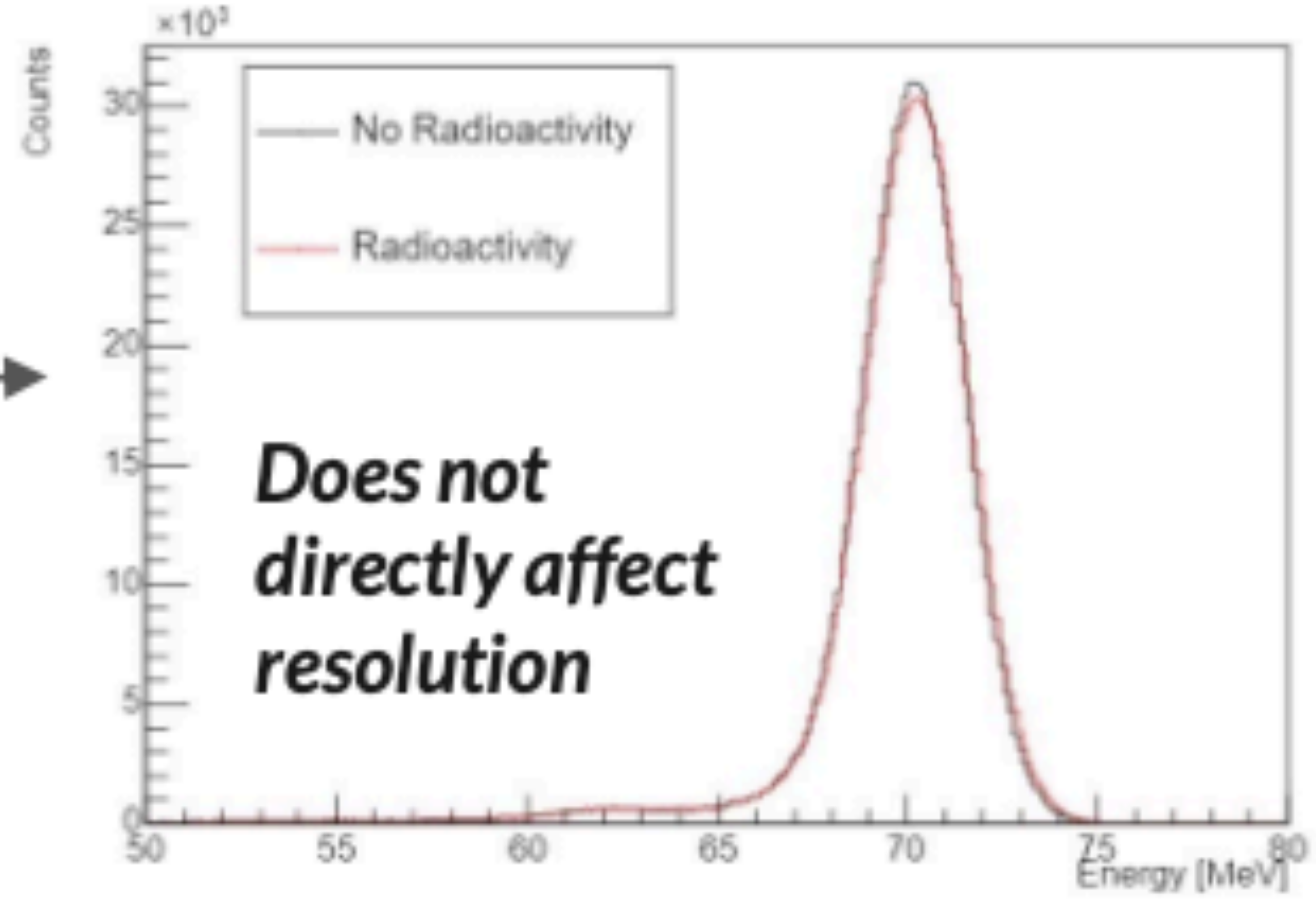
Theoretical spectrum: 88, 202, 307 keV γs + β spectrum



Measured spectrum for one of our 2.5 x 2.5 x 18 cm³ crystals



Simulation of radioactivity in full PIONEER calorimeter



If calorimeter hit requirement is imposed in analysis:

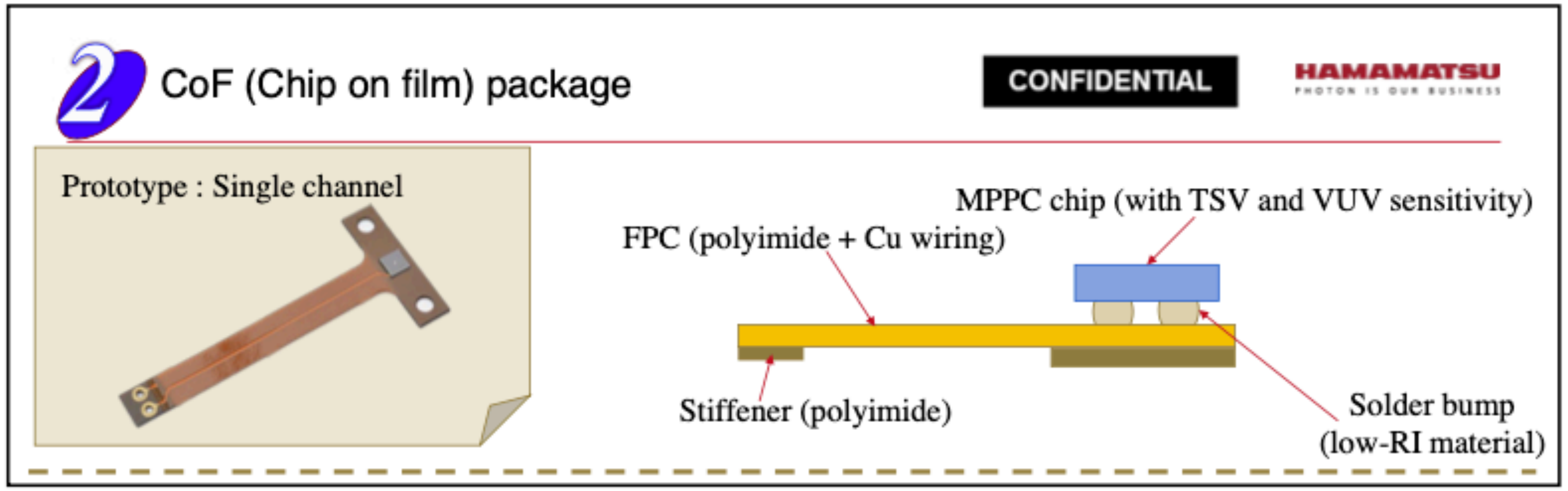
- More difficult to reconstruct events w/ less than 1.5 MeV in calo due to radioactivity
- ~1% of Michel events don't have clusters above 1.5 MeV, correction must be known to ~1%

Correction strategies are investigated from the ATAR side. The present analysis strategy does not rely on calorimeter hits

SiPM with Chip-on-Film (CoF) Package

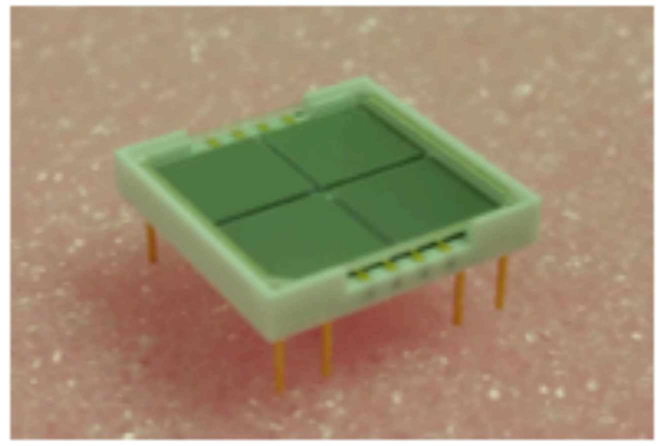
- Under development by Hamamatsu
- Lower mass compared to the standard package (à la MEG-II VUV-MPPC)
- TSV VUV-MPPC (no wire bonding)

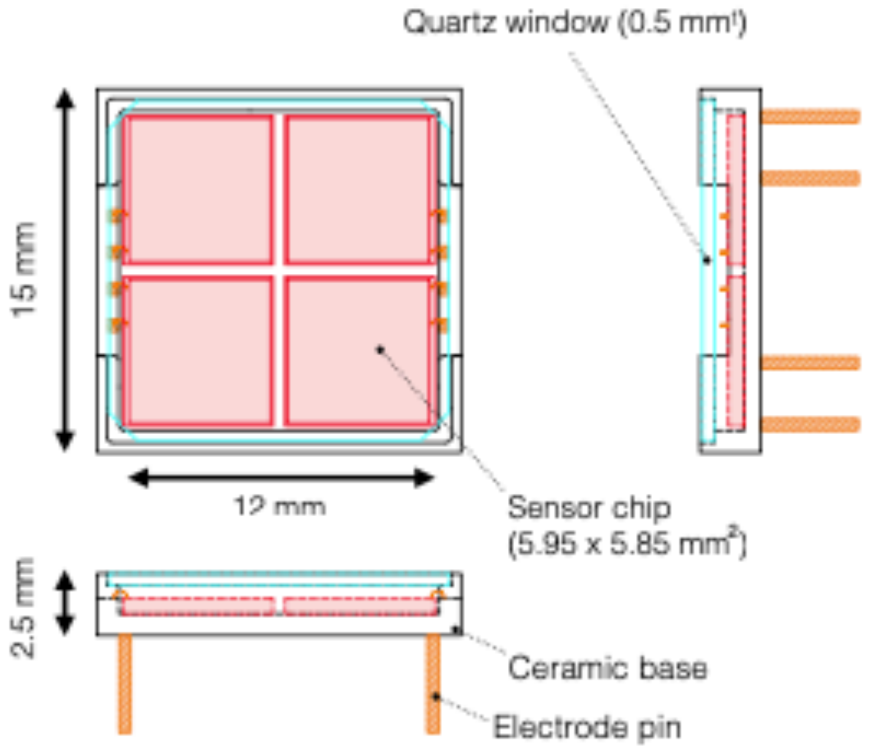
SiPM with CoF package



	Thickness	X_0	
Si	0.2mm	0.21%	
Solder bump	0.15mm (2% area)	2×10^{-5}%	
Filler	0.15mm	0.08%	
FPC	0.2mm	Al trace	Cu trace
		0.02%	0.14%
	Total	**0.29-0.43%**	

MEG II VUV-MPPC





	Thickness	X_0
Quartz window	0.5mm	0.41%
Si	0.2mm	0.21%
Ceramic	1mm	5 %
	Total	**5.6%**

LXe cryostat windows

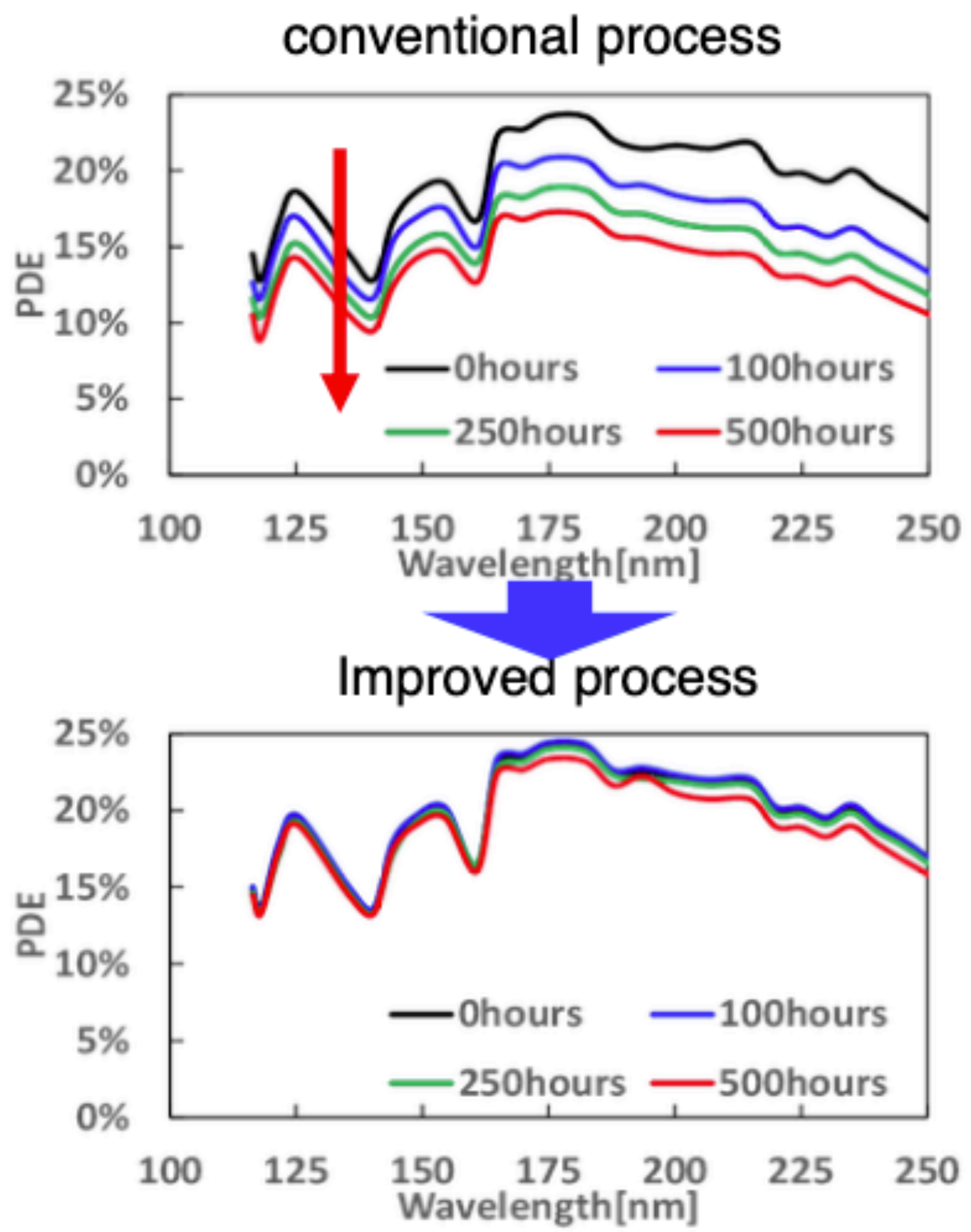
	Thickness	X_0
Ti window	0.2mm	0.56%
Al window	0.5mm	0.56%

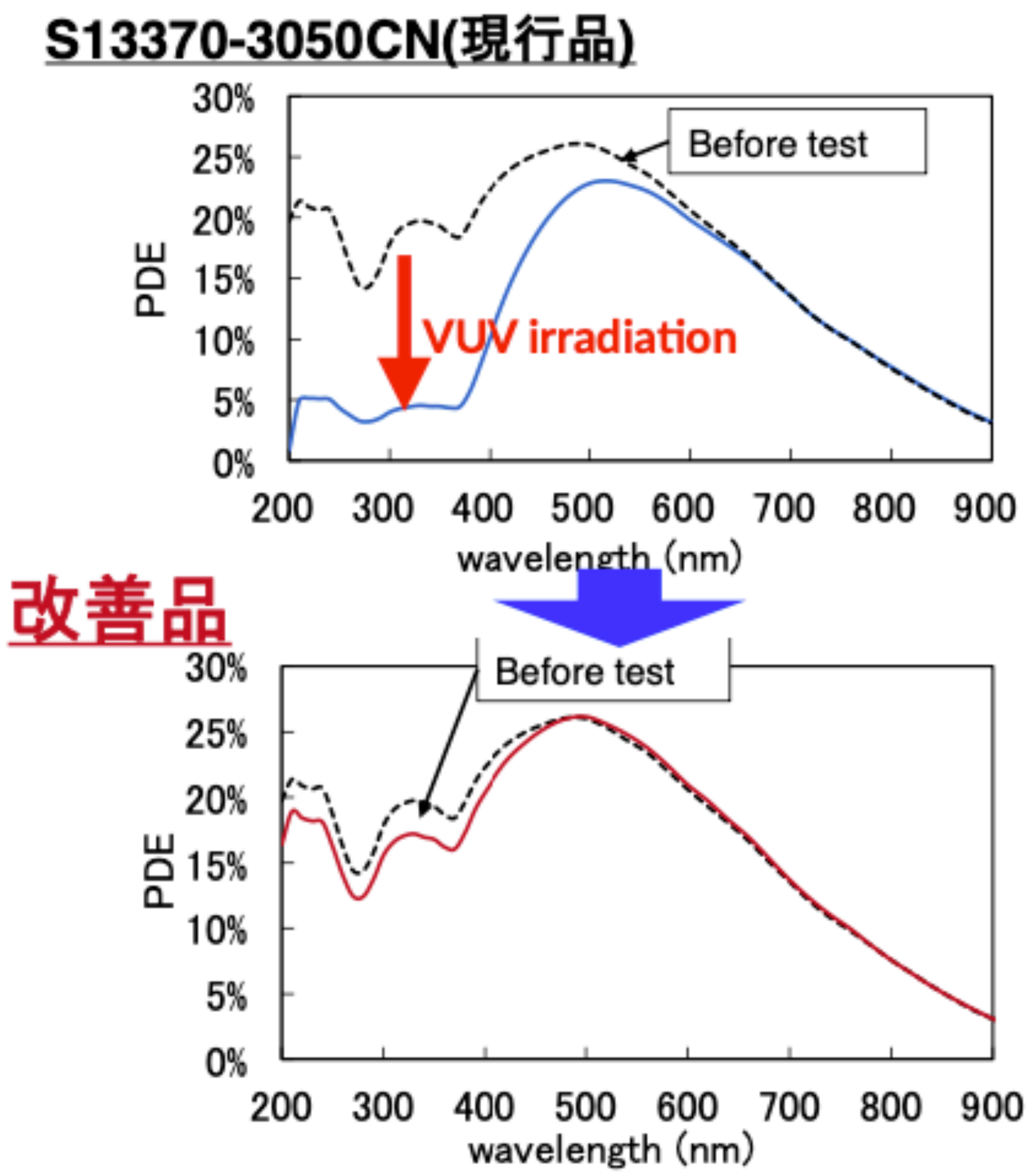
LXe as dead material

LXe	0.2mm	0.7%

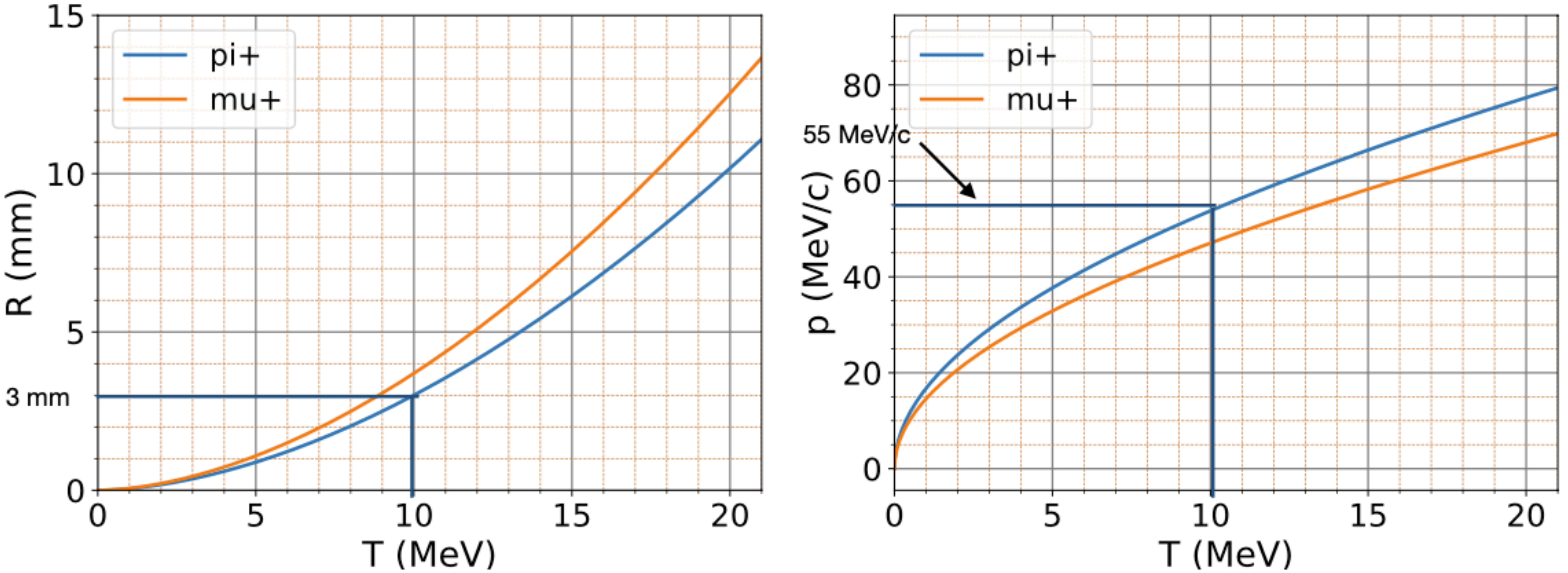
SiPM Ageing

- New version of VUV-MPPC developed by Hamamatsu
  - Improved immunity to humidity and VUV irradiation
  - Not sure if it can mitigate the ageing observed in MEG II LXe detector
  - To be tested in lab with the CoF-MPPC prototypes and in beam with the large prototype





ATAR Design motivations



Pion: p=55 MeV/c, Edep = 10 MeV, range = 3mm
Muon: Edep=4.1 MeV (kinetic energy of a muon from a pion decaying at rest)
range = 0.8mm

Total thickness of 6mm, sensor thickness of ~120μm to get 0(5) hits for a muon track
X, Y dimensions: ‘as big as possible’ — 2 cm x 2 cm