レプトン普遍性の破れを精密検証する PIONEER 実験のための測定器の開発

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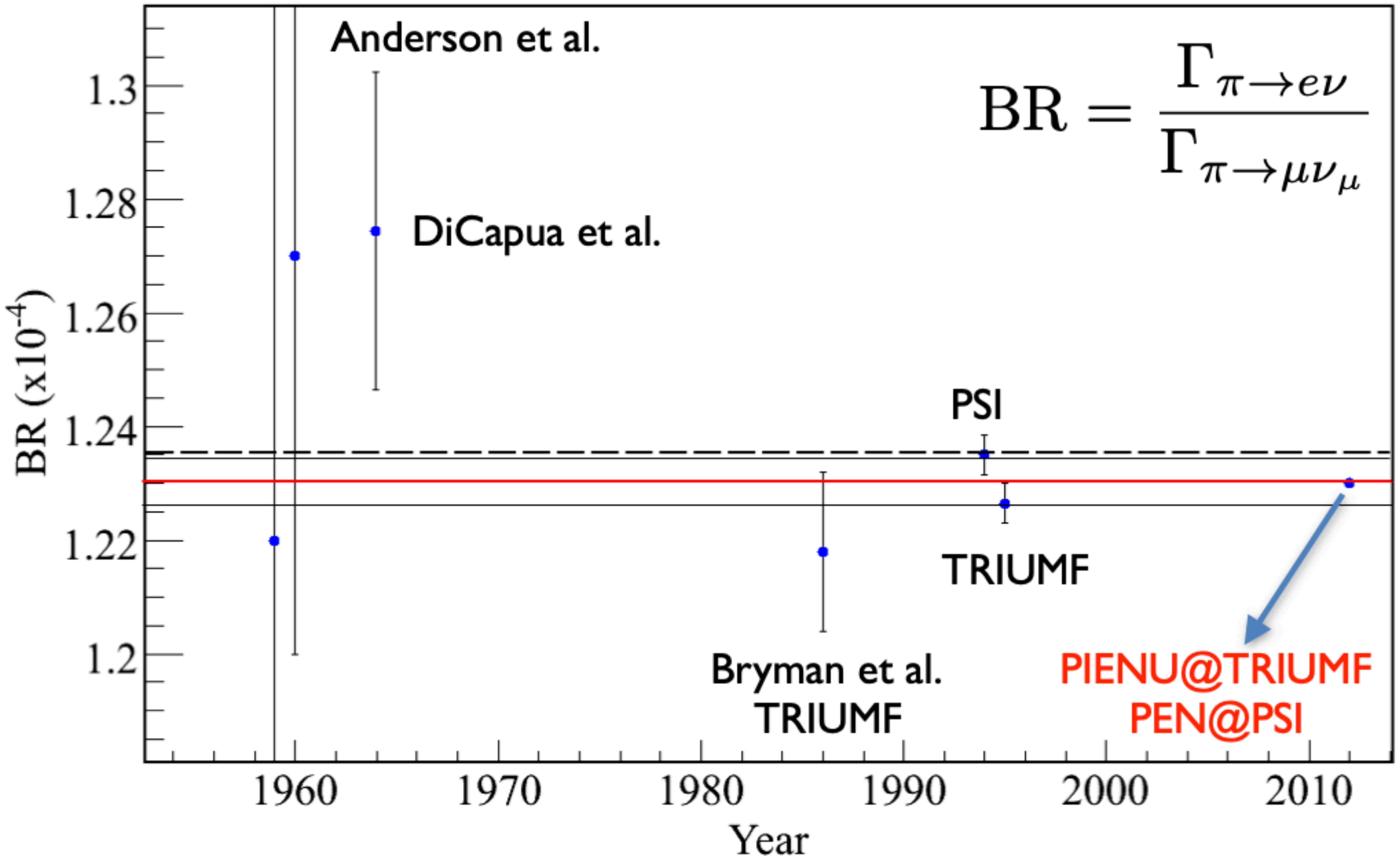
JSPS Core-to-Core Program

Lepton universality test with pion

The ratios of the decay rates $R^{\pi}_{e/\mu} = \Gamma(\pi \to e\bar{\nu}_e(\gamma)/\Gamma(\pi \to \mu\bar{\nu}_\mu(\gamma))$ provide some of the most stringent tests of LFU of the SM gauge interactions

- $\Gamma(\pi \to e\bar{\nu}_e(\gamma))$ are helicity-suppressed due to the V-A structure of the charged current
- Sensitive probes of all SM extensions that induce non-universal corrections to W-lepton couplings



Theoretical uncertainty

- 10^{-4} level

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

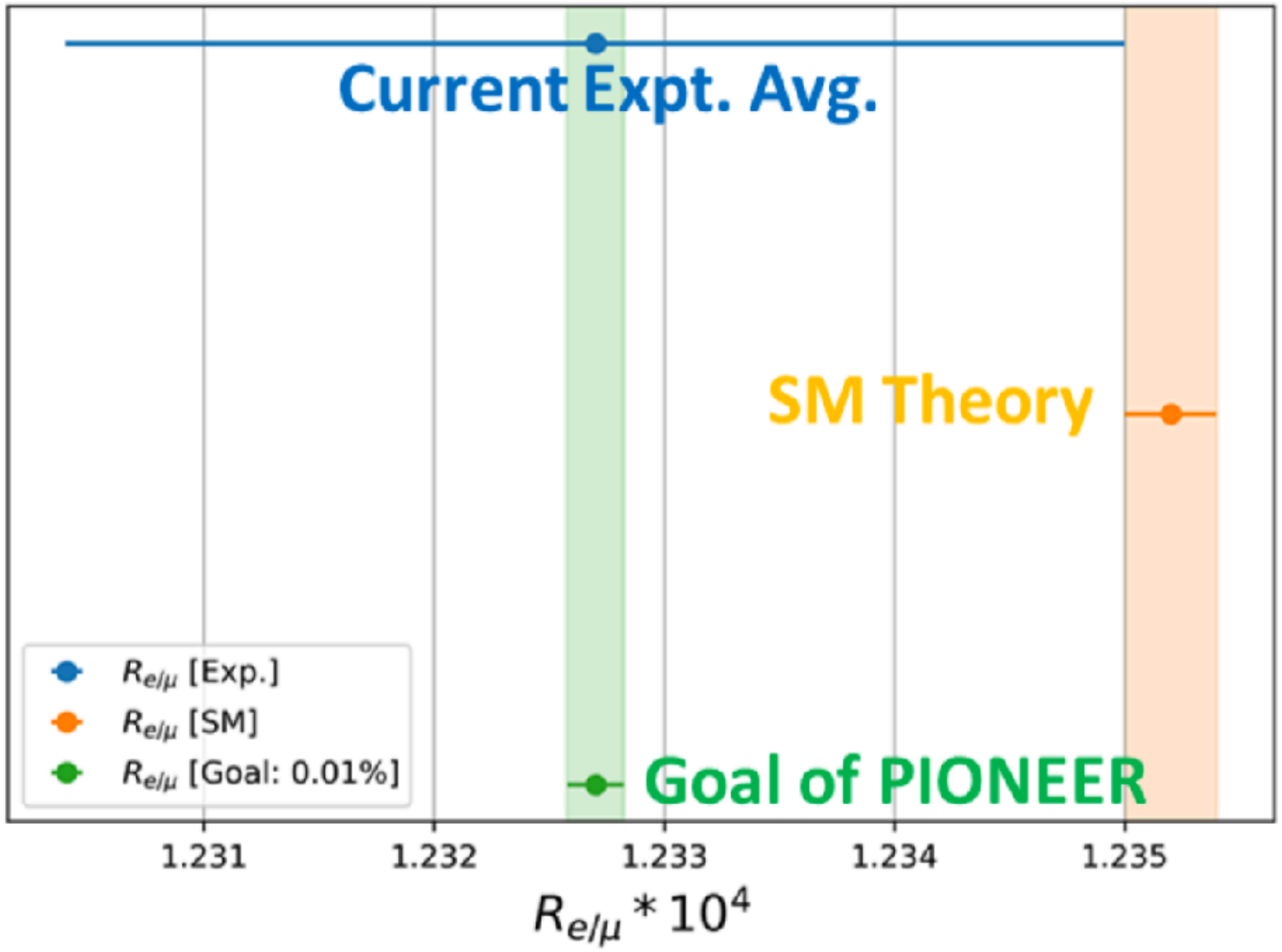
Experimental uncertainty

- 10^{-3} level: 10 times worse than that of theoretical calculation

$$R(\mathrm{Exp})^{\pi}_{e/\mu} = 1.23270(230) \times 10^{-4}$$

PIONEER goals

- Phase I
  - Improving $R^{\pi}_{e/\mu}$ experimental precision by a factor of 15 to 0.01% level
  - NP at the PeV scale can be probed
- Phase II
  - $\dfrac{\Gamma(\pi^+ \to \pi^0 e^+ \nu)}{\Gamma(\text{Total})}$ with a precision < 0.2%
  - Improve the precision by three times
  - CKM matrix unitary check → 10 times improvement in Phase III
- Exotic searches
  - Heavy neutral lepton



Basics of pion decays

Measurements:

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 → $BR\left(\pi^+ \to e^+\nu_e(\gamma)\right) = 1.2327 \pm 0.0023) \times 10^{-4}$

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

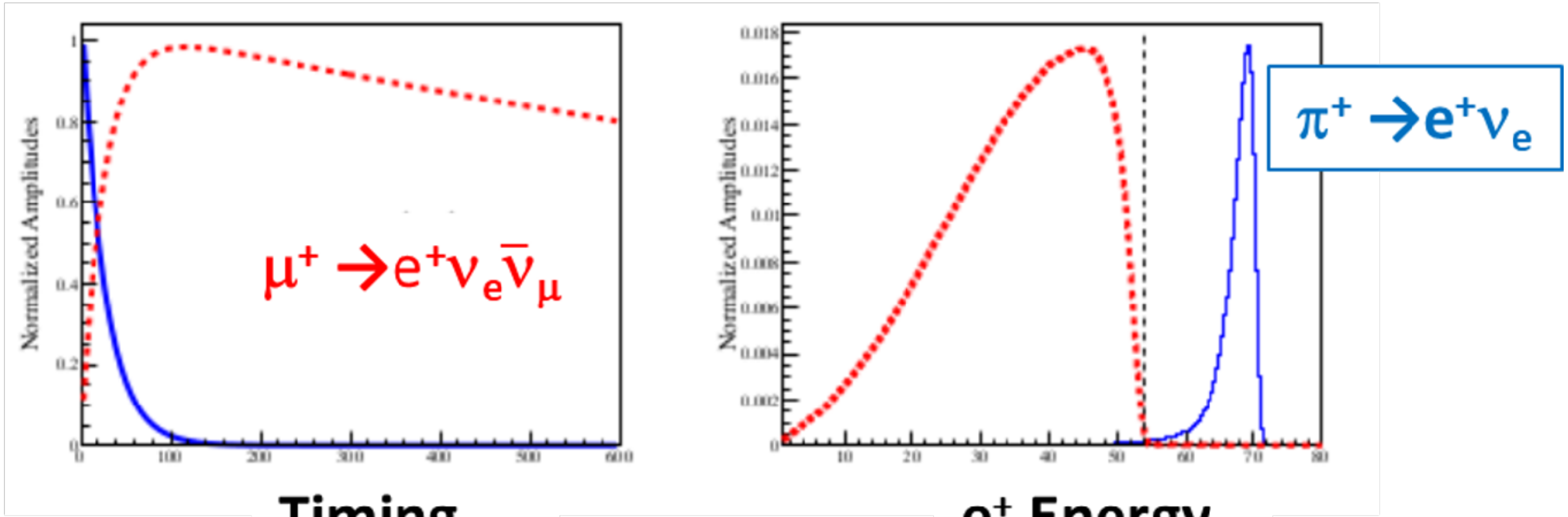
Reminders:

Pion lifetime: 26 ns

Muon lifetime: 2197 ns

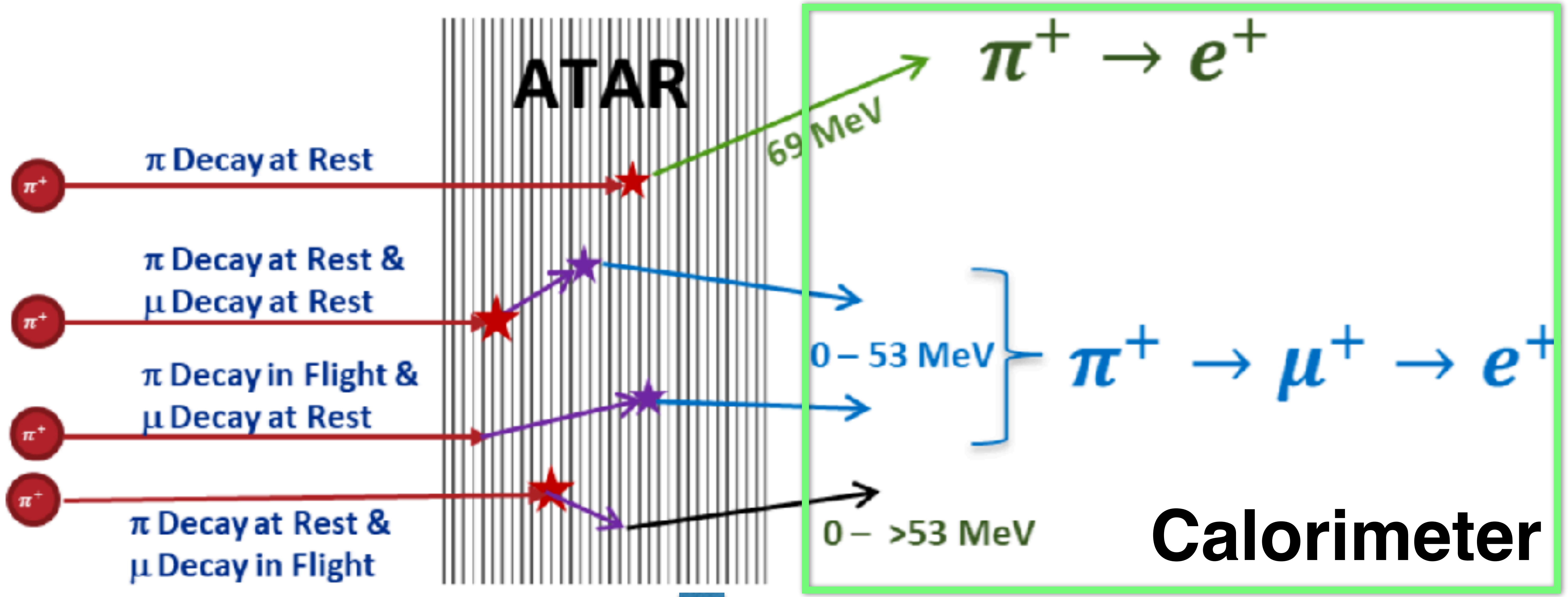
Pion mass: 139.6 MeV

Muon mass: 105.7 MeV



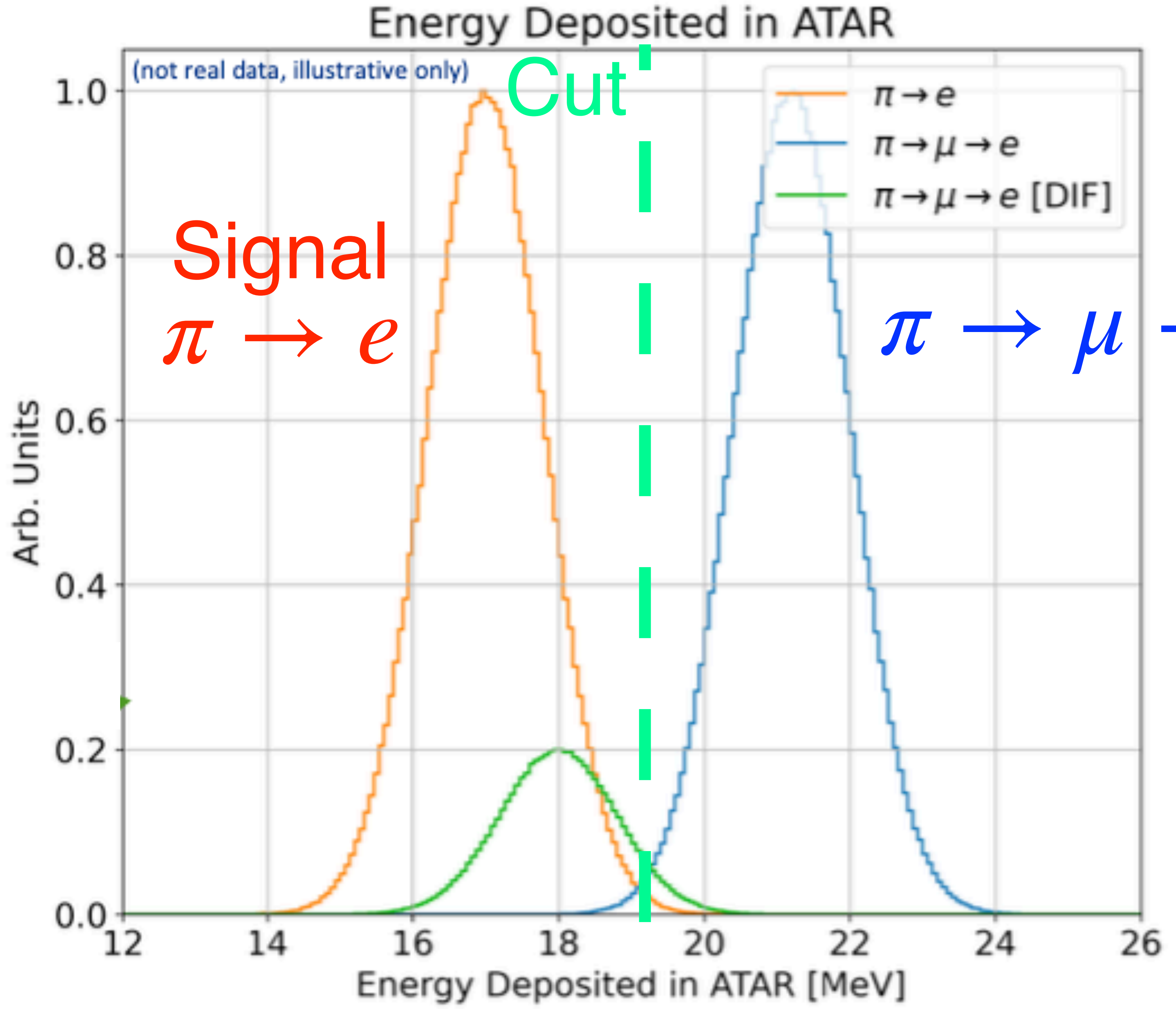
Timing   e⁺ Energy

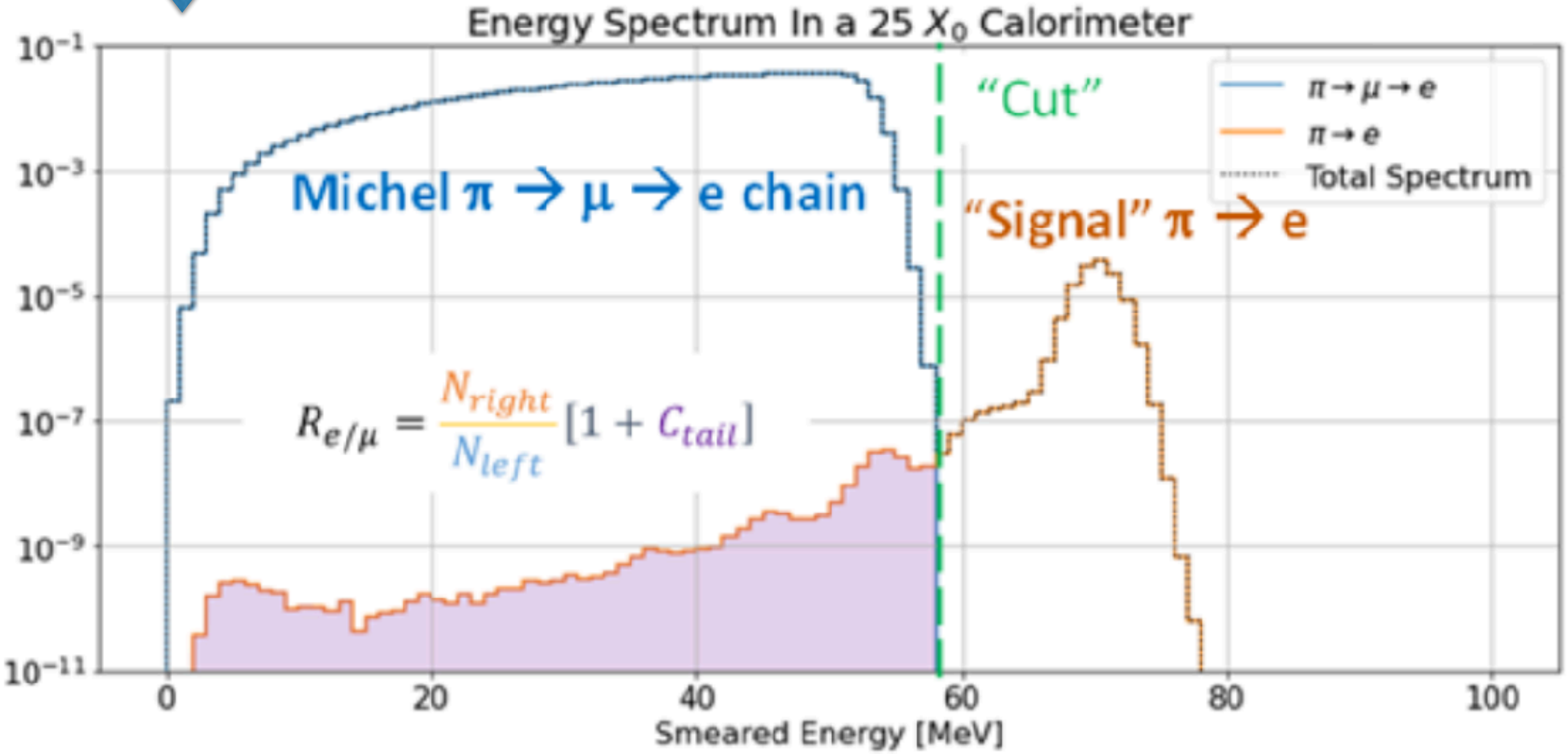
Signal & Background



ATAR energy deposit

Calorimeter energy deposit

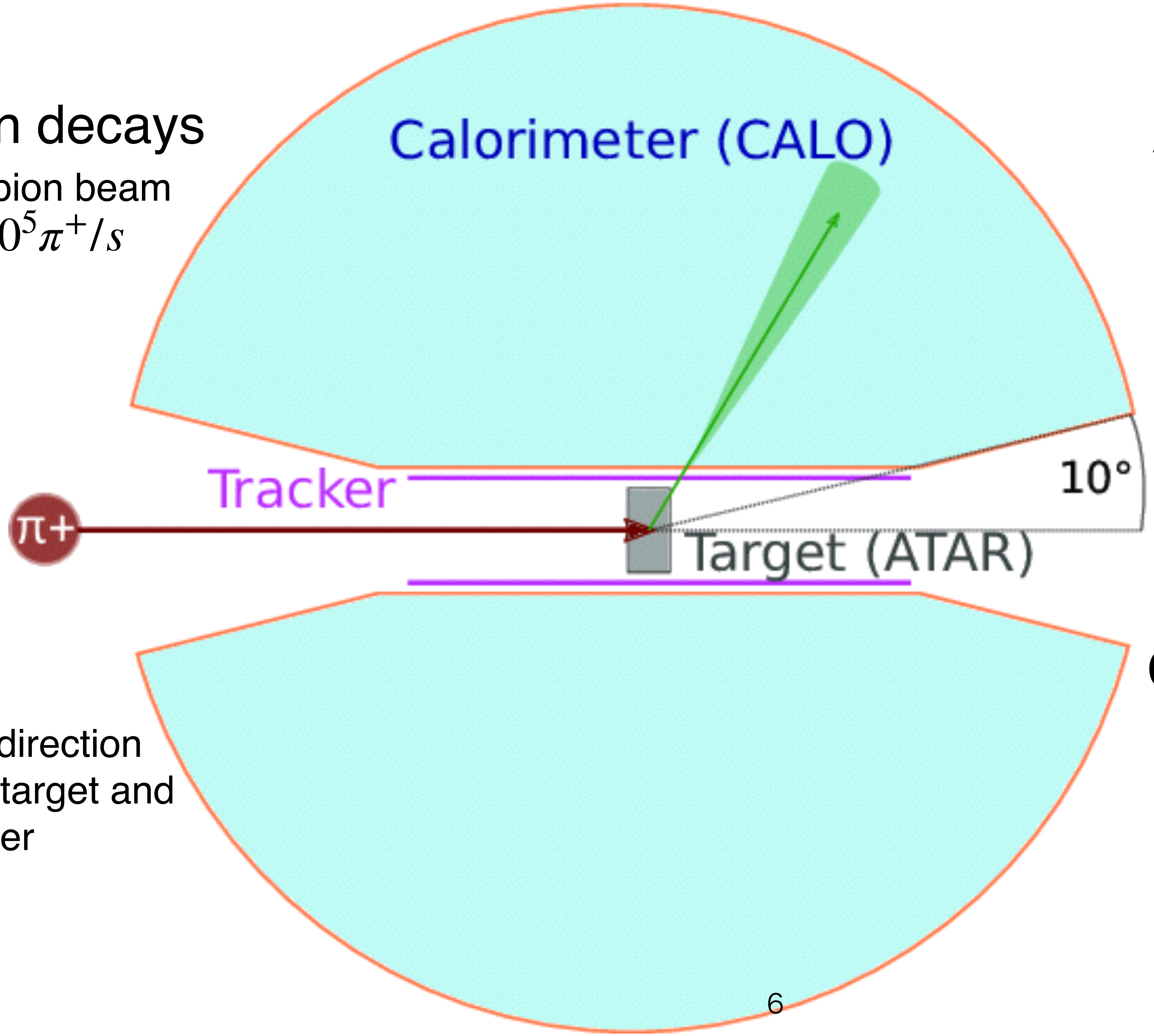




PIONEER Concept

A lot of pion decays

- intense pion beam $> 3 \times 10^5 \pi^+/s$



Active Target

- Tracking $\pi \rightarrow e$ / $\pi \rightarrow \mu \rightarrow e$ events
- energy, timing, particle direction
- position resolution ~ 100μm
- timing resolution ~ 1ns
- Tolerant to high event rate

Tracker

- Positron direction between target and calorimeter

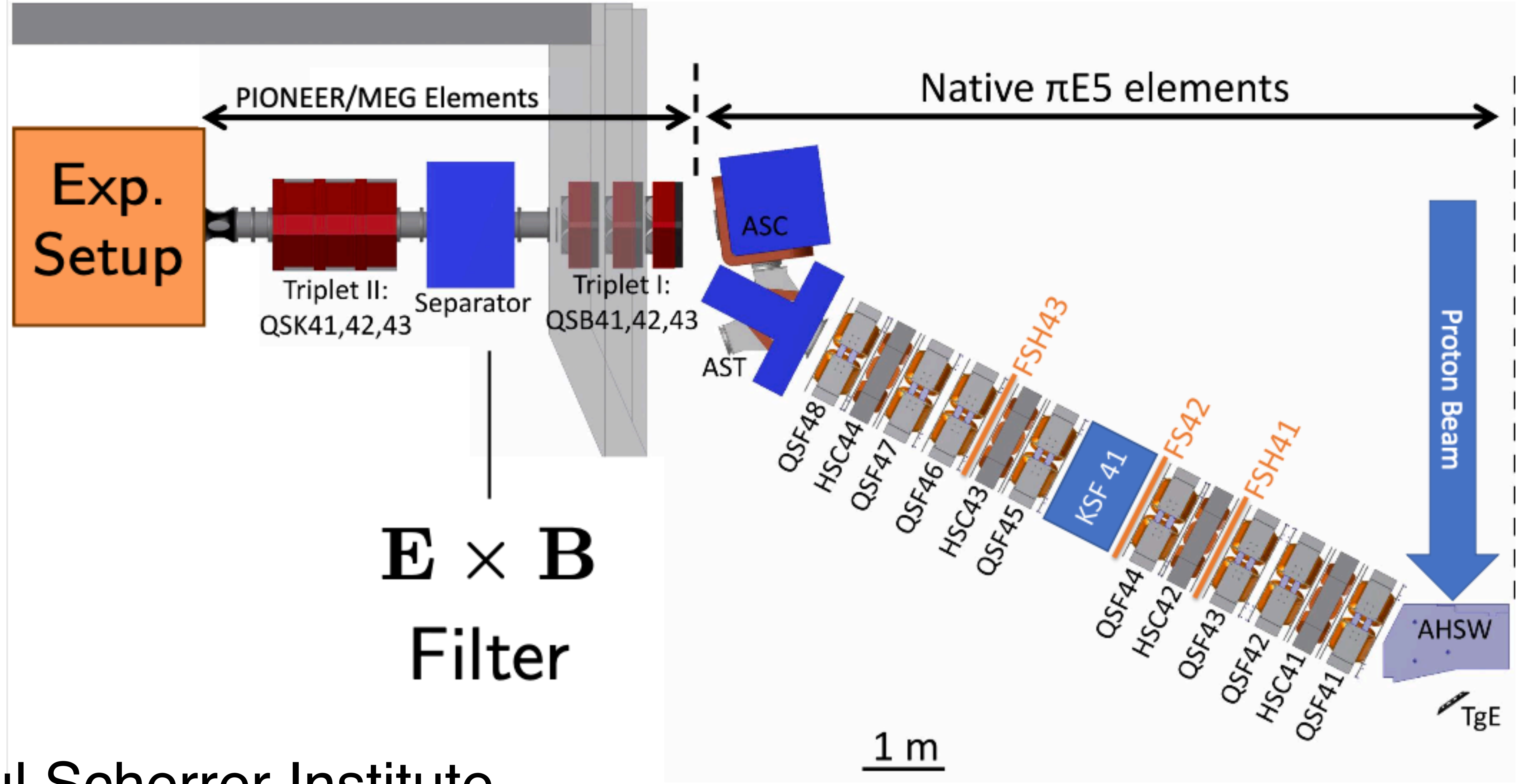
Calorimeter

- Positron energy, and time
- 25 X_0 to reduce low energy tail region
- 3π sr calorimeter
- Tolerant to high event rate

World most intense pion beam

Requirements

- Momentum : 65 MeV/c
- Rate : $> 3 \times 10^5$ π+/s
- Beam size : σ_x, $\sigma_y < 10$ mm
- Momentum bite : dp/p < 2%
- Contamination : < 10% e, μ

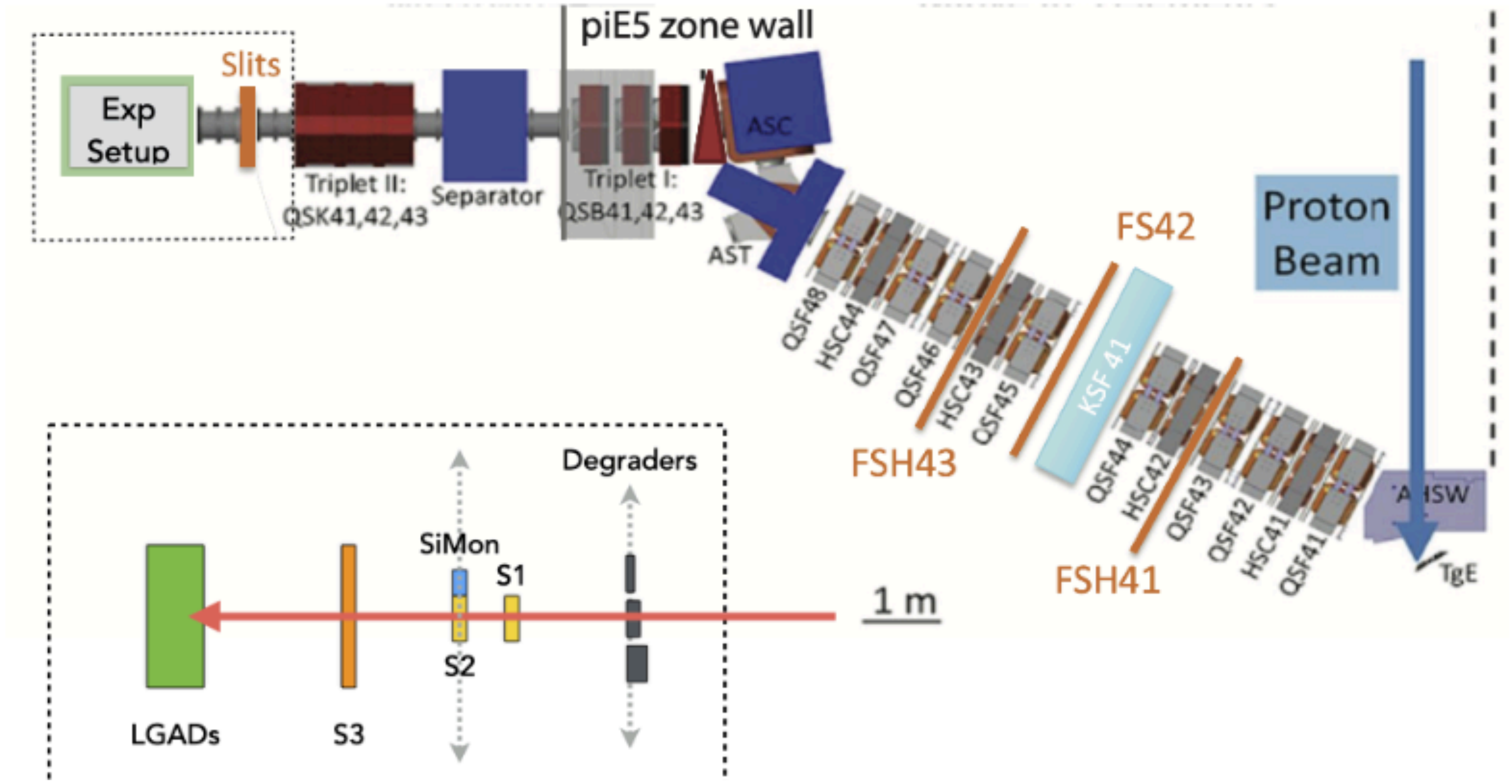


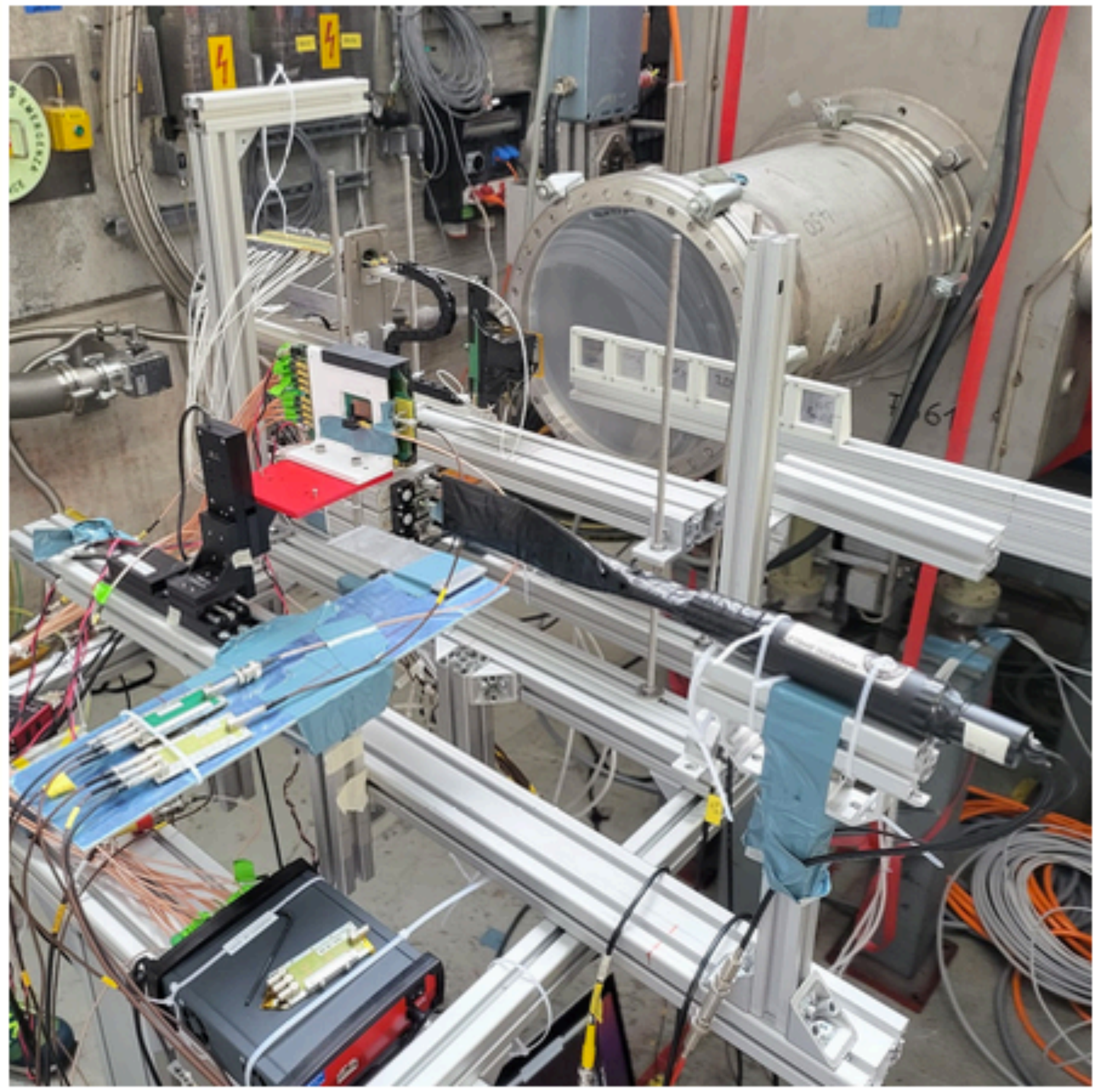
1.4 MW 590 MeV proton accelerator

Paul Scherrer Institute

- PiE5 beam line would be the only candidate.
- The beam profile should be tested
- The possibility of other beamlines like PiE1 will be tested too
  - MEG, Mu3e will occupy the PiE5 at least until 2026

Beam test in 2022

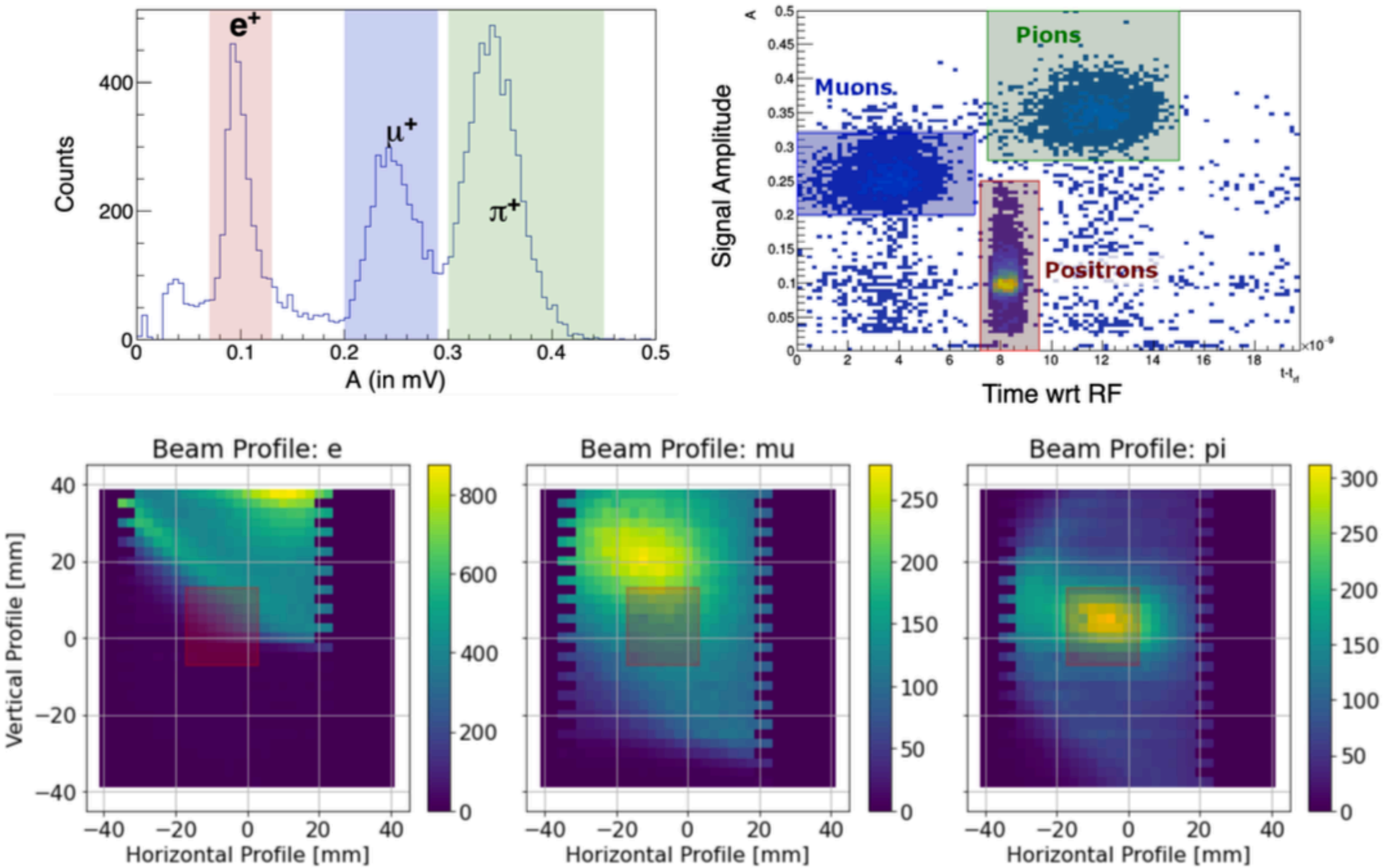




Property	Beam test	PIONEER specs
π^+/s stopped in ATAR (kHz)	300 @ 65 MeV/c	300 @ 60 MeV/c
beam size $\sigma_x \times \sigma_y$ (mm^2)	23 x 10	8 x 8
particle separation $e : \mu : \pi$	25 : 32 : 43	10 : 10 : 80
$\frac{dP}{P}$ FWHM (%)	~ 3	<2

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

Beam test 2022



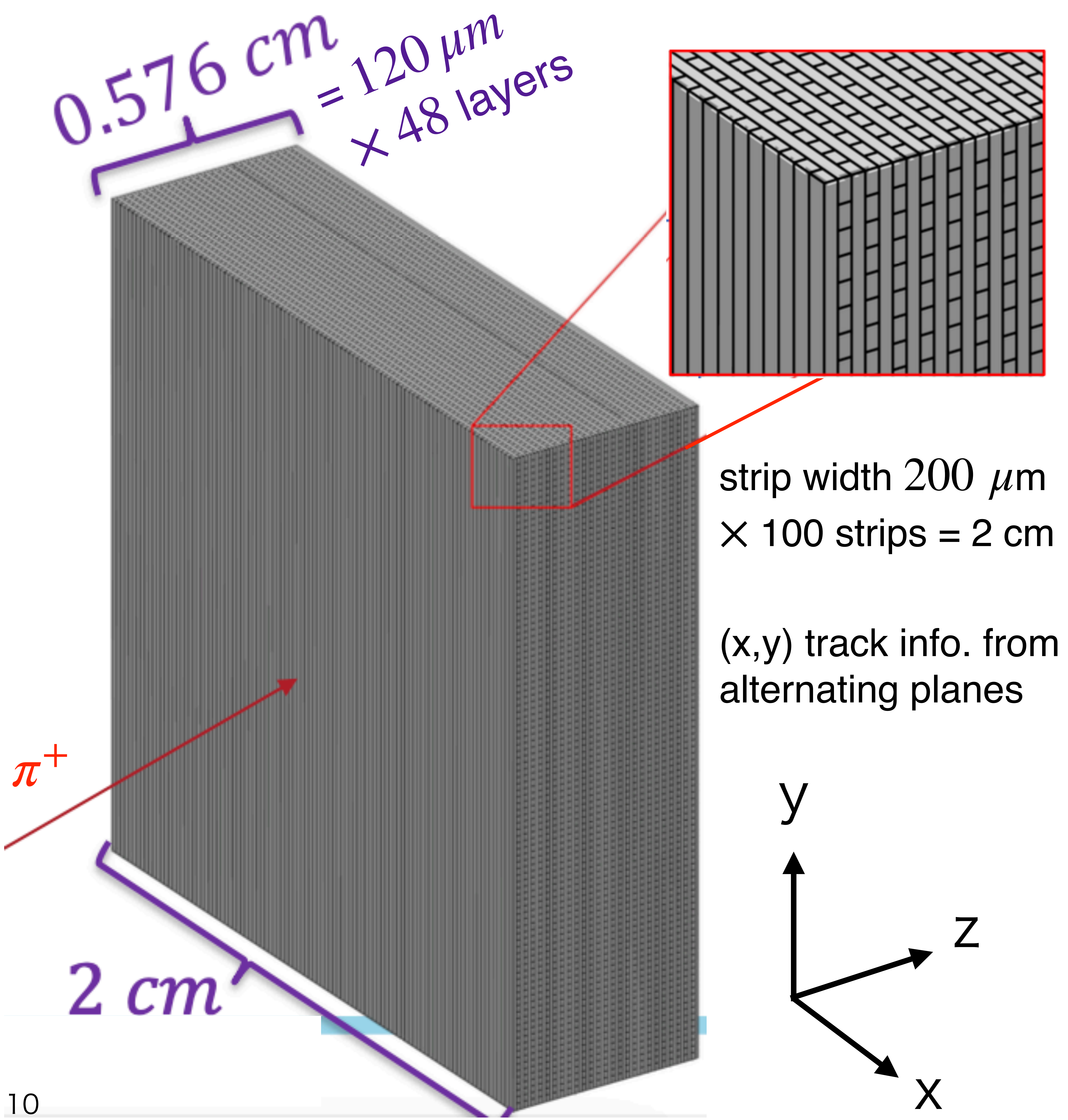
Active Target (ATAR)

ATAR requirements

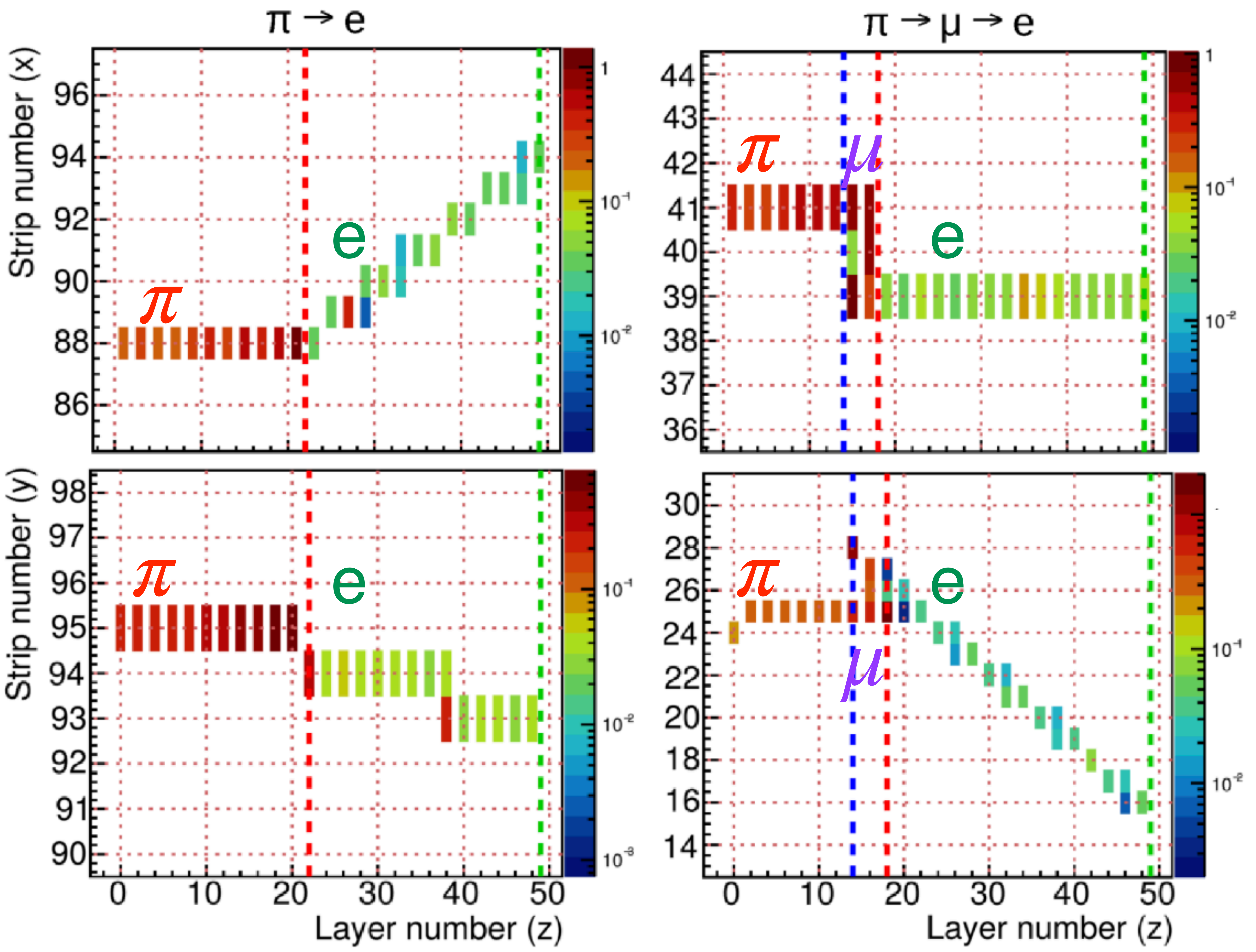
- Energy
  - 30 keV MIP ~ 4 MeV μ^+ Bragg peak range
  - Energy resolution, large dynamic range
- Tracking ($\pi/\mu/e$)
  - High granularity in (X, Y, Z)
  - 4 MeV μ^+ travels 0.8 mm in Si
- Timing
  - π/μ hit separation by 1.5ns for 300 kHz

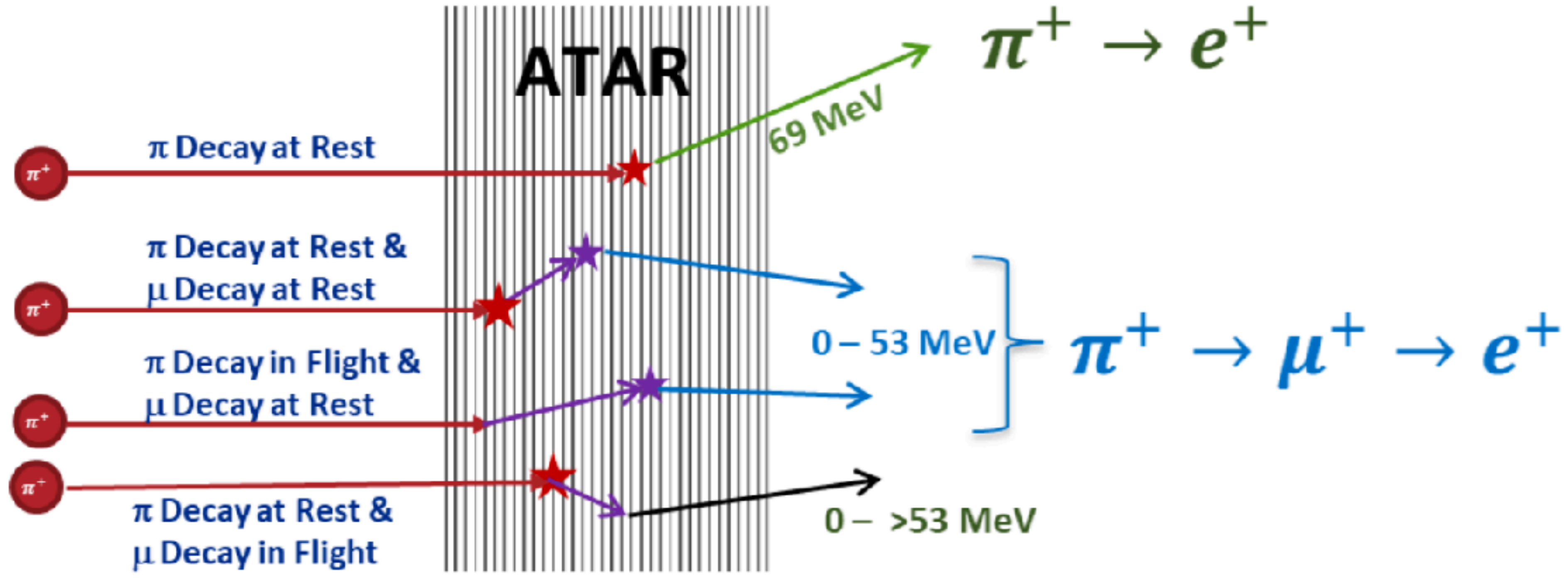
Chosen sensor for ATAR

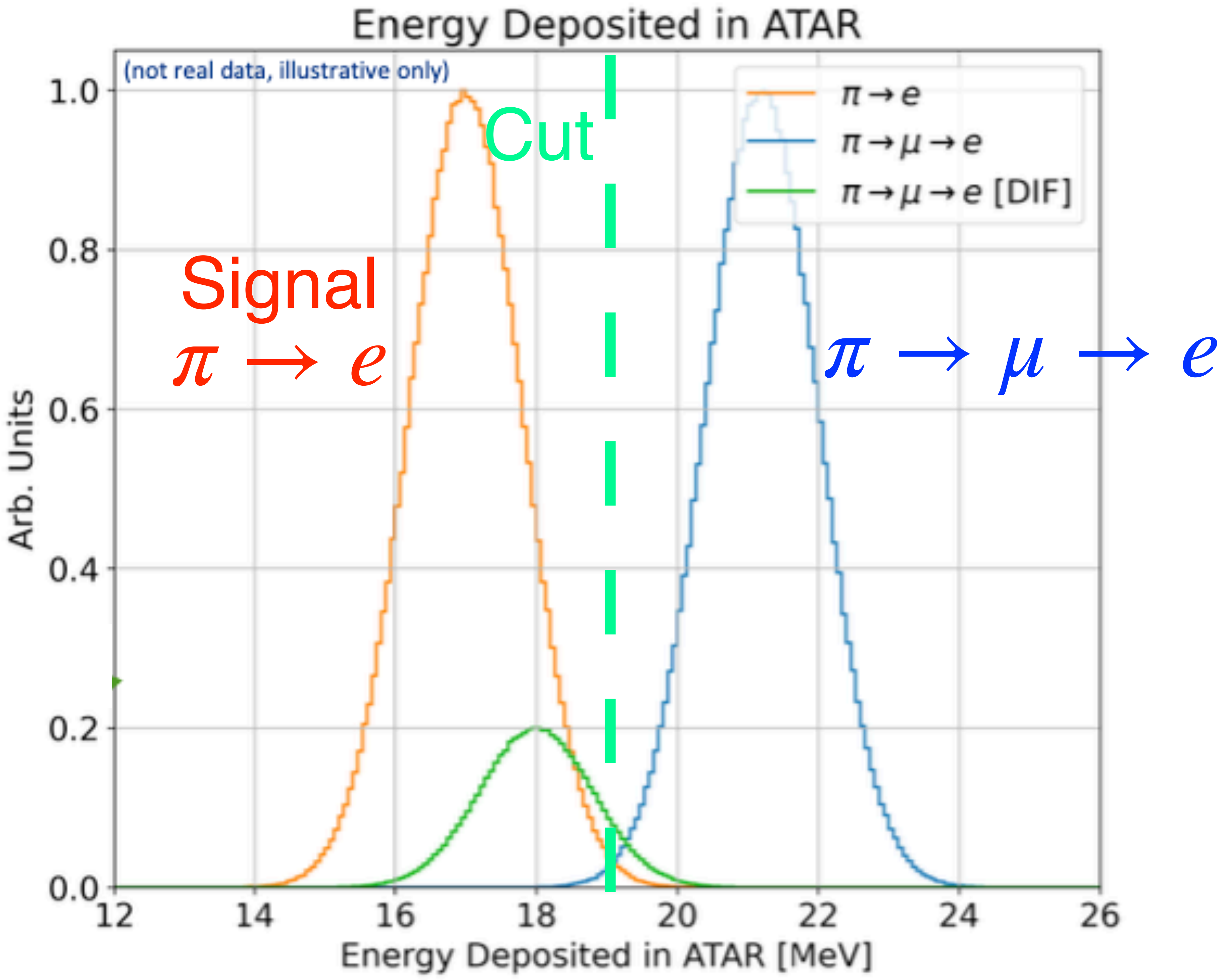
- High granularity Low Gain Avalanche Diode (LGAD)
- High S/N, full fast collection time, great time resolution



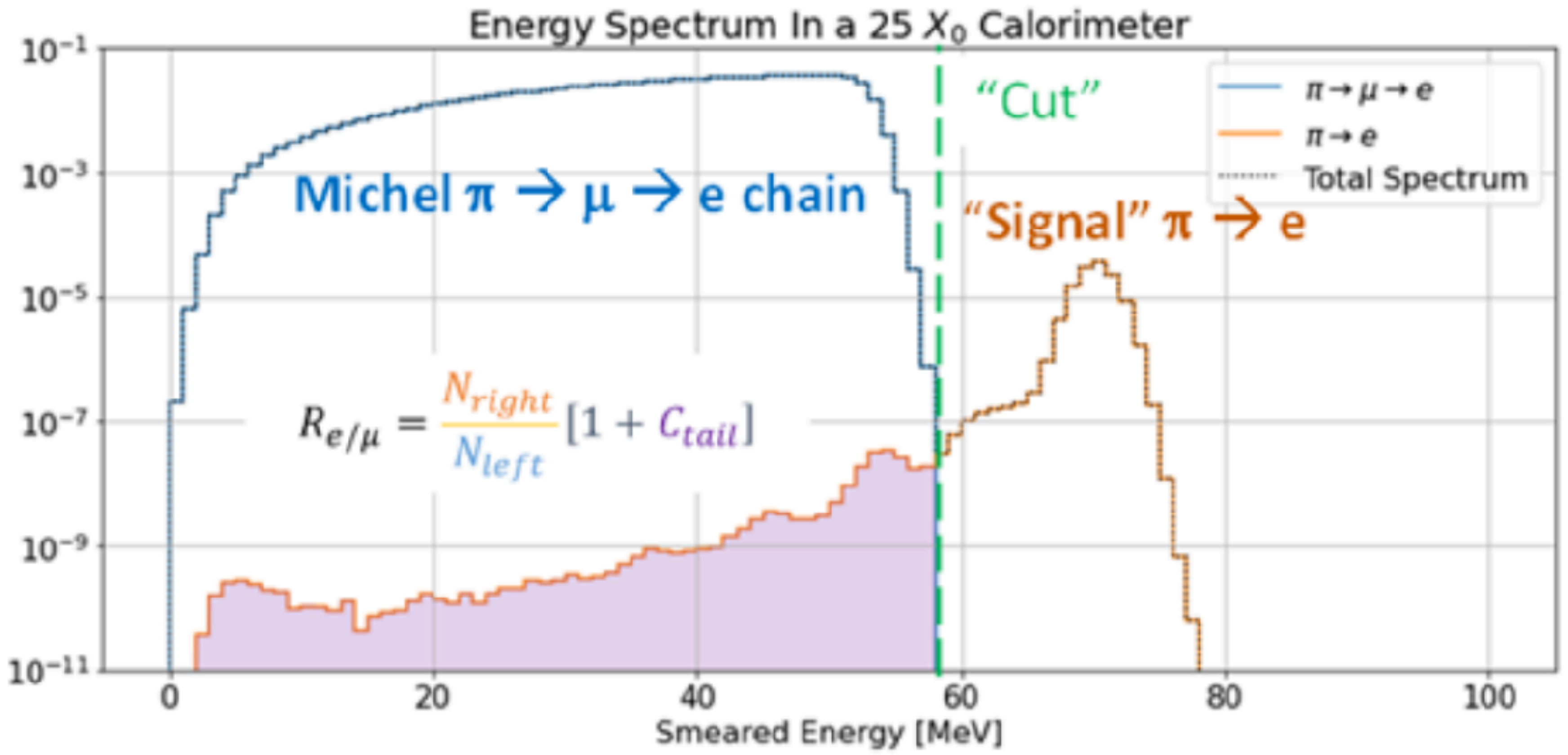
ATAR tracking





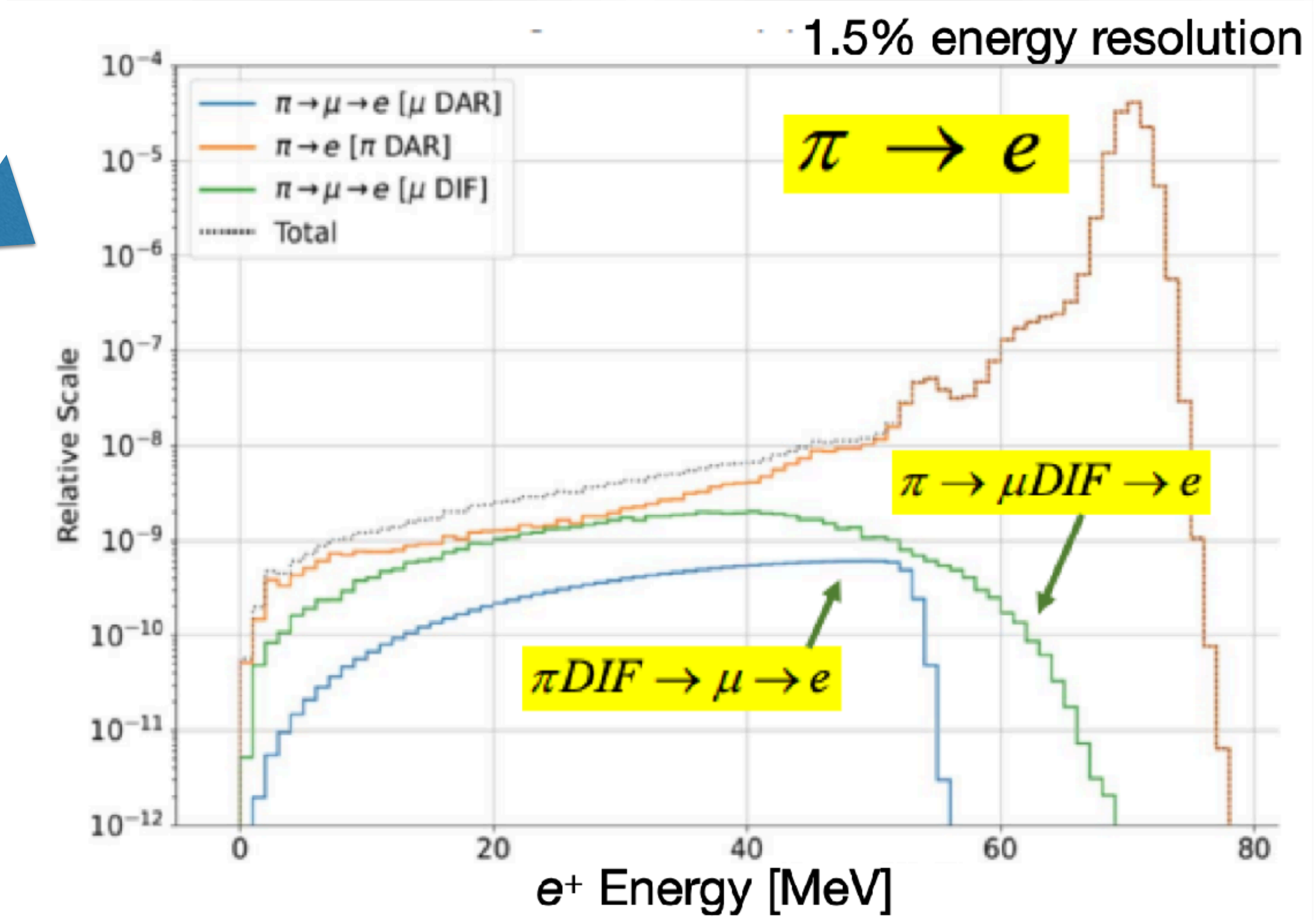


ATAR background rejection



Combined information of tracking, timing, and energy deposit

- reduces the Michel $\pi \rightarrow \mu \rightarrow e$ chain "background"



Tracker

Connect positron tracks between ATAR and Calo.

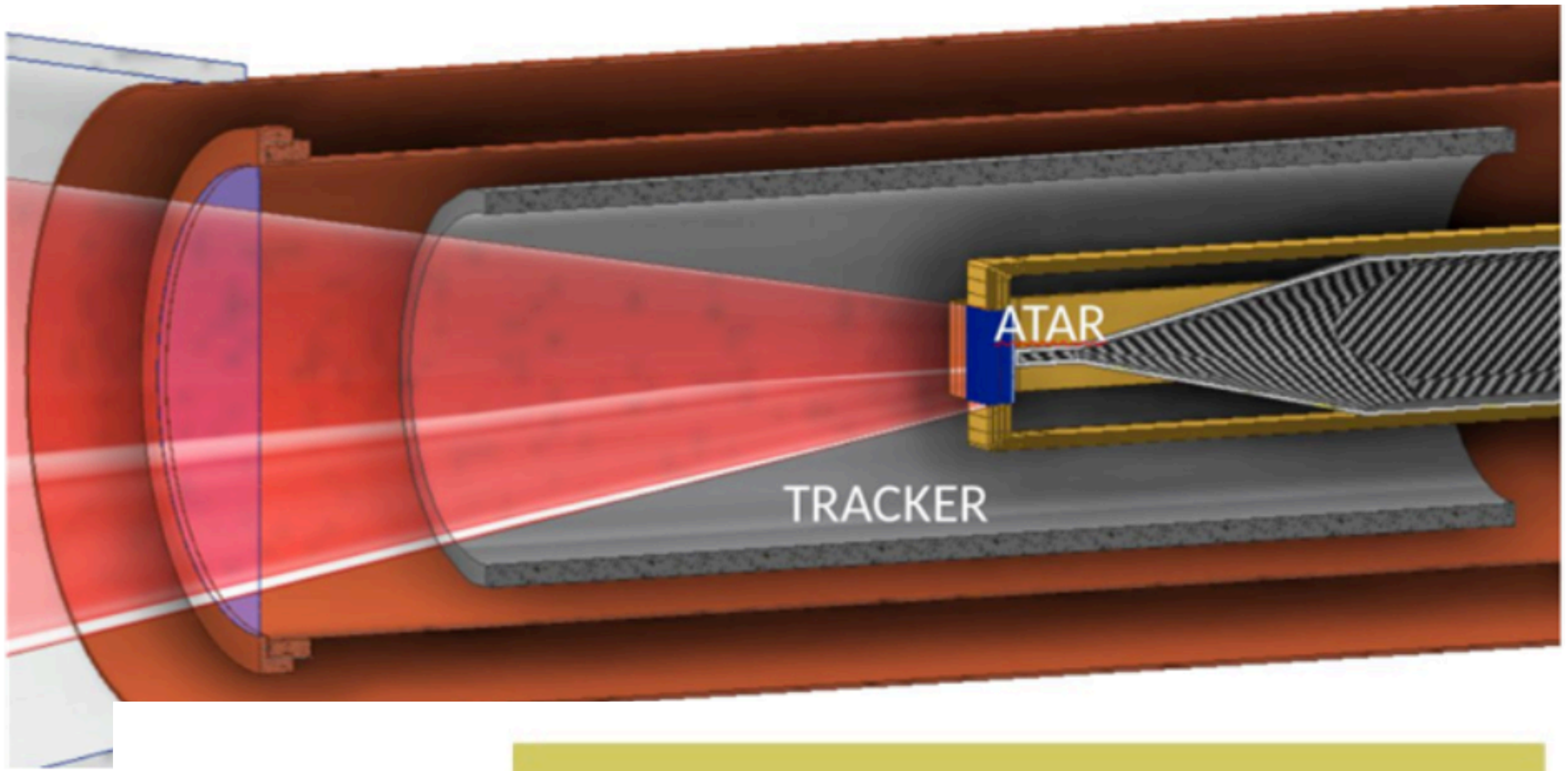
- Low material budget is required
- z, ϕ, and time

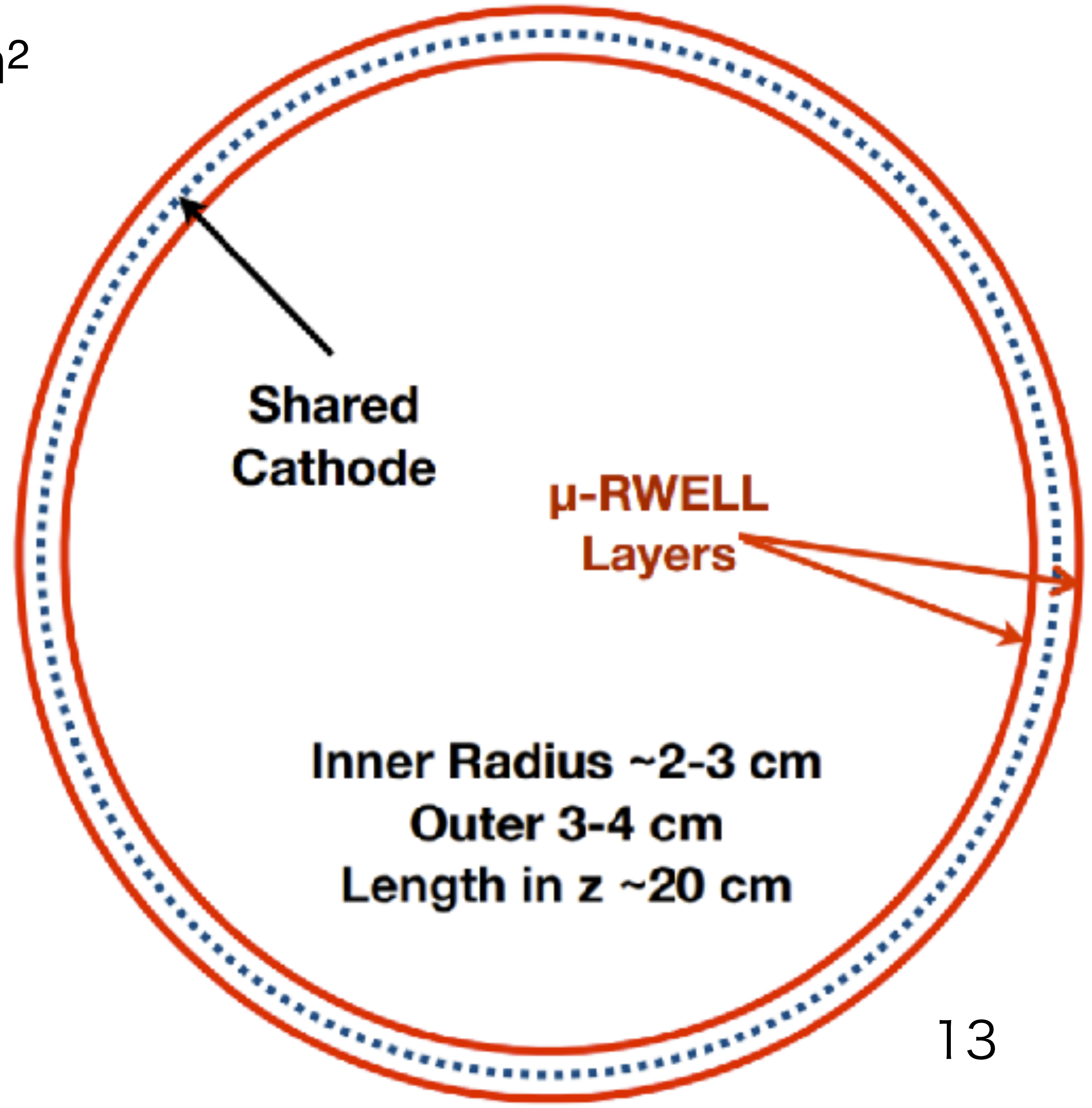
The μ-RWELL is a very promising technology in harsh environment

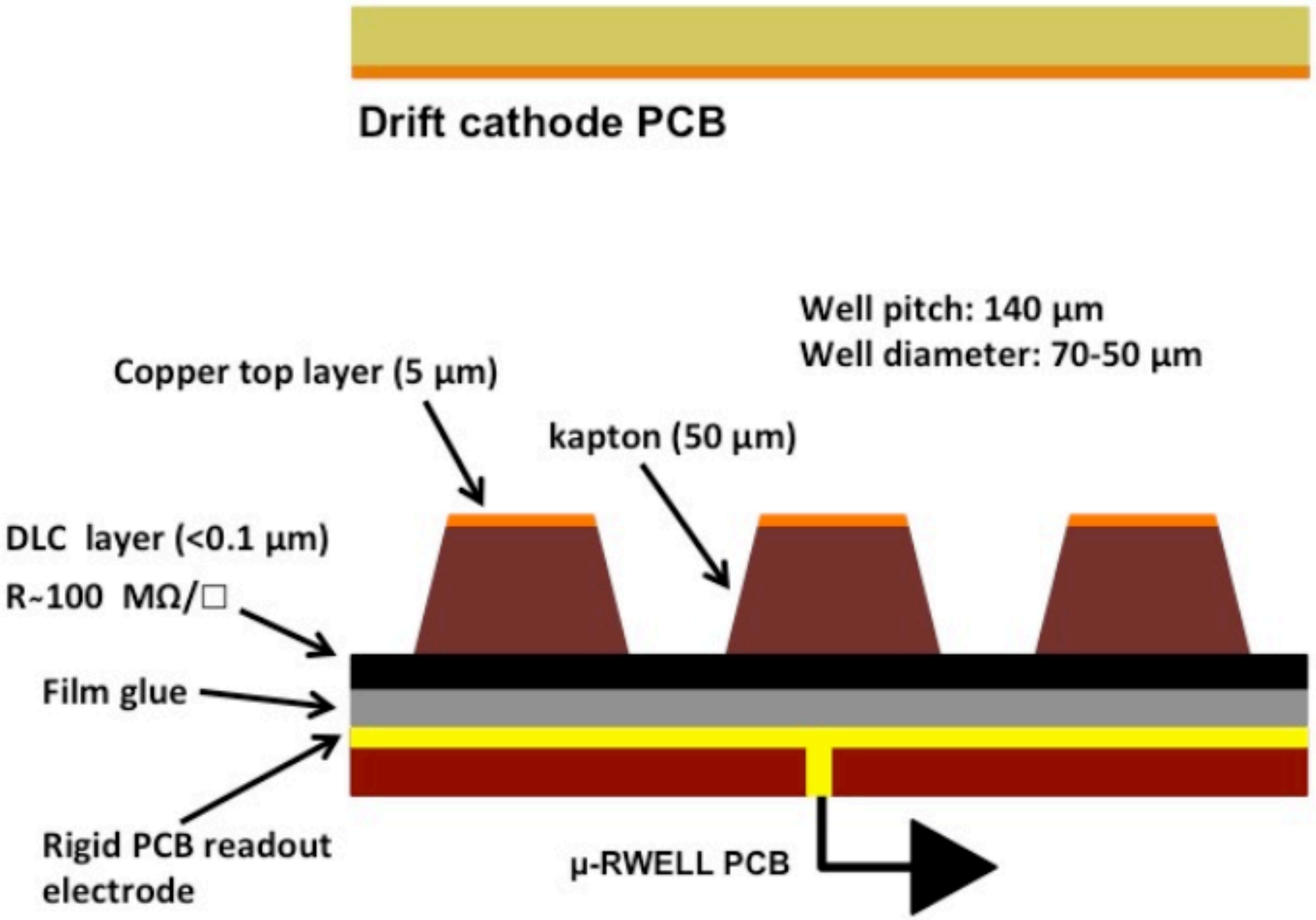
- compact, simple to assemble and intrinsically spark-protected

Performance

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







Calorimeter

Calorimeter requirements

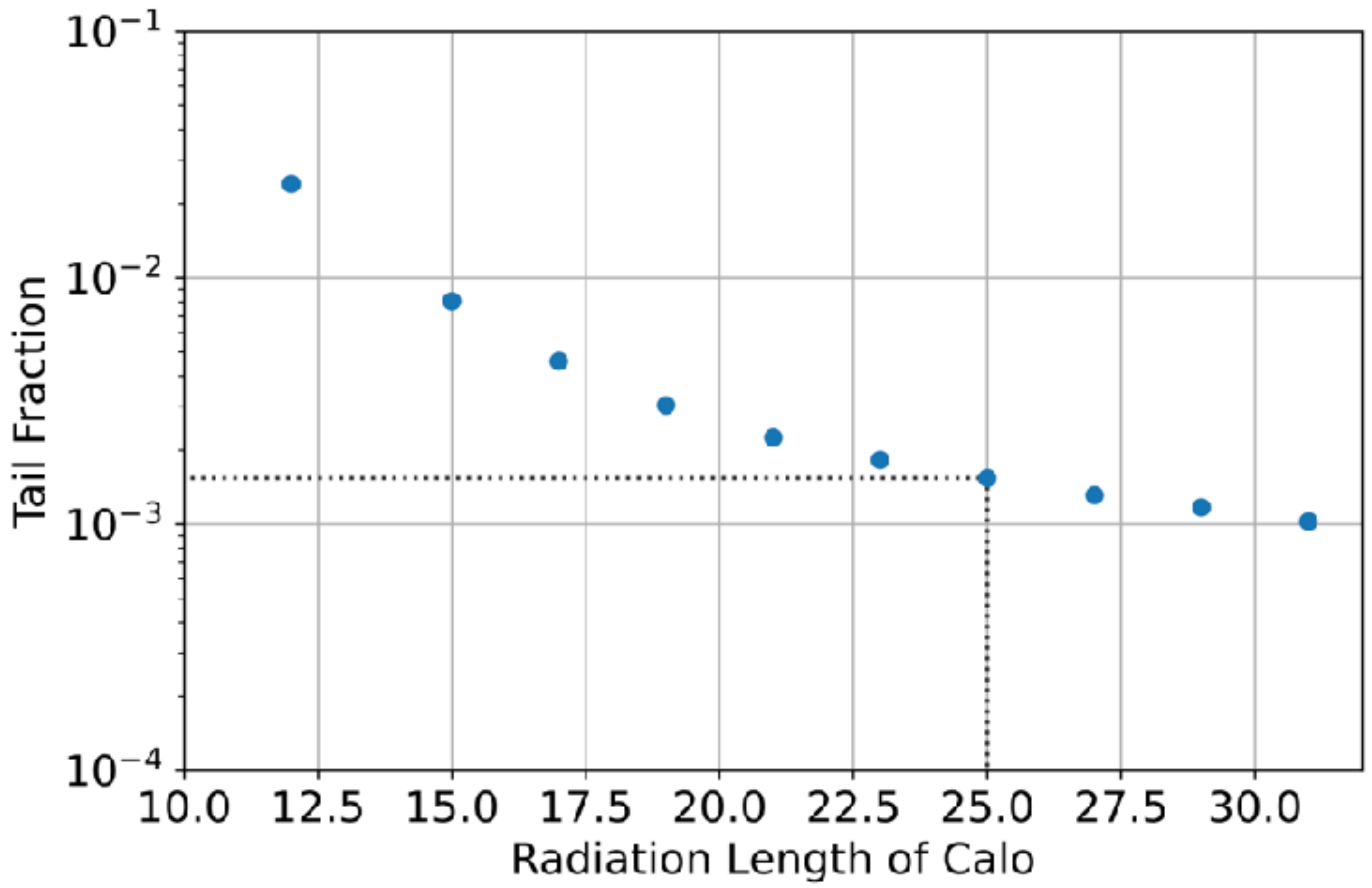
- 3π coverage, high uniformity, sub-ns timing
- Energy Resolution 1.5–2.0%
- $25X_0$ for tail suppression
- High rate tolerant, pileup separation

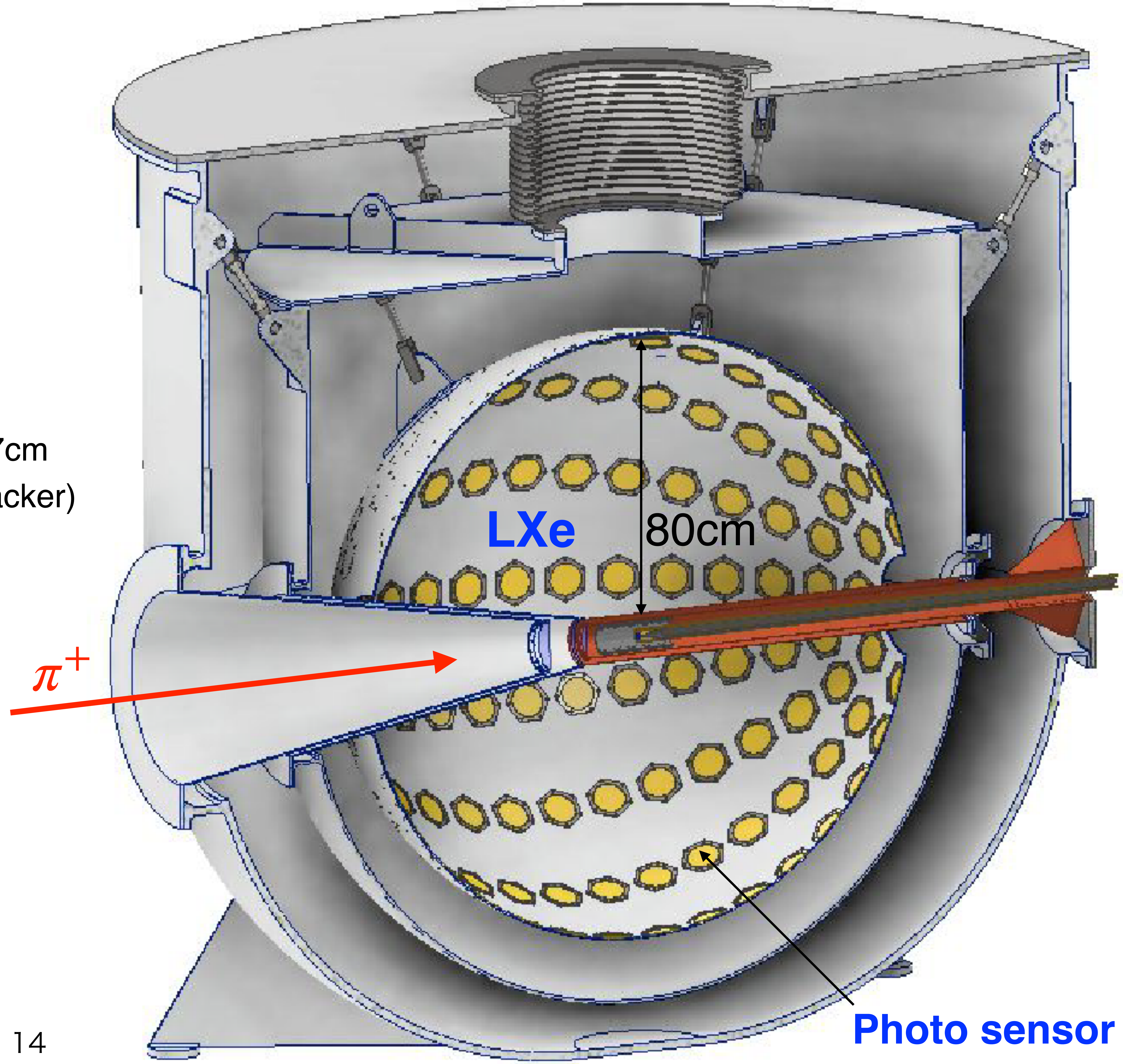
LXe calorimeter is the baseline design

- Technology well proven by MEG II LXe detector

Conceptual design

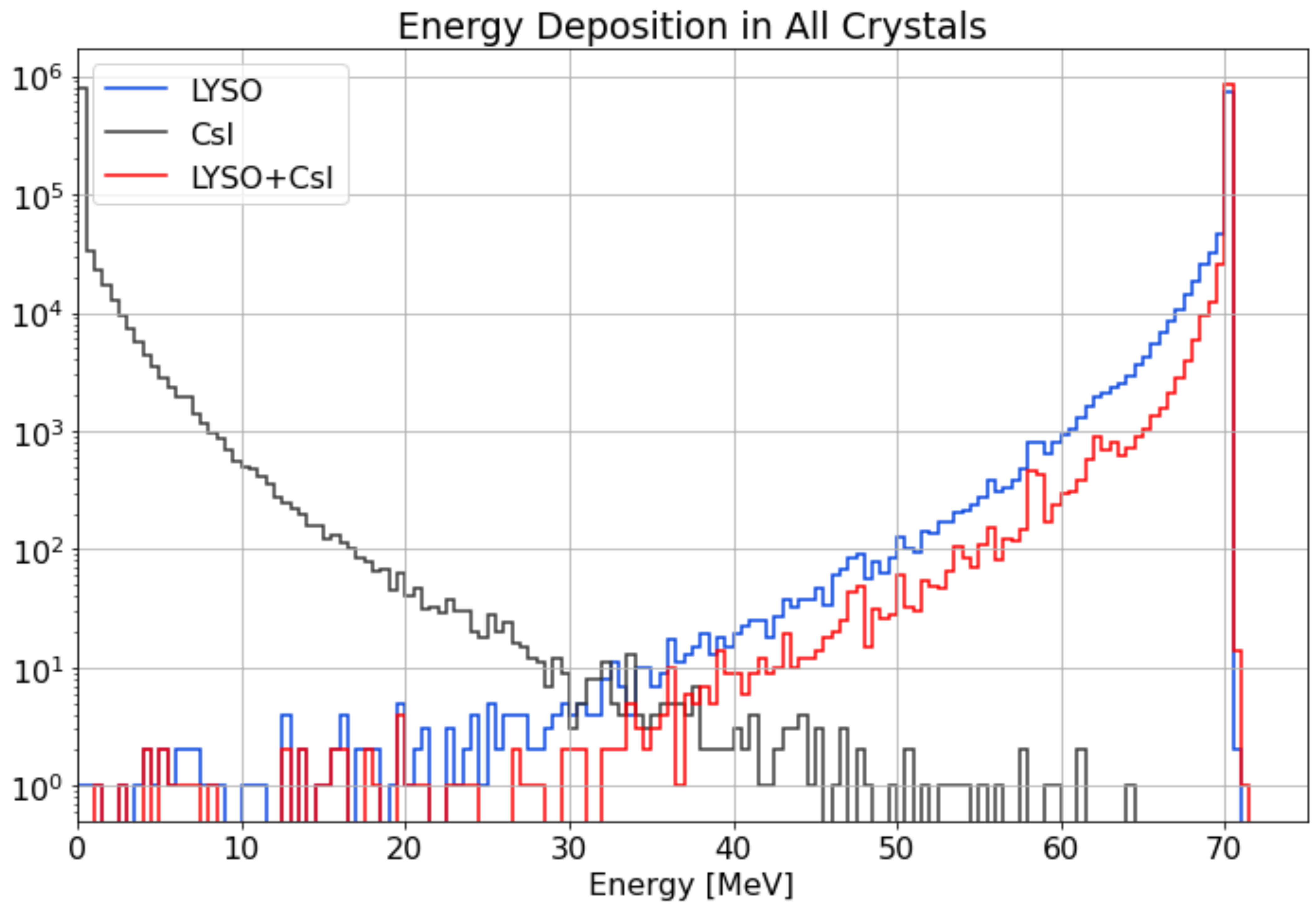
- 9t LXe in vacuum isolated cryostat, r_{out} = 80cm, $r_{in\text{-}cyl}$ = 7cm
- Photo sensors only outer face (incident position from tracker)

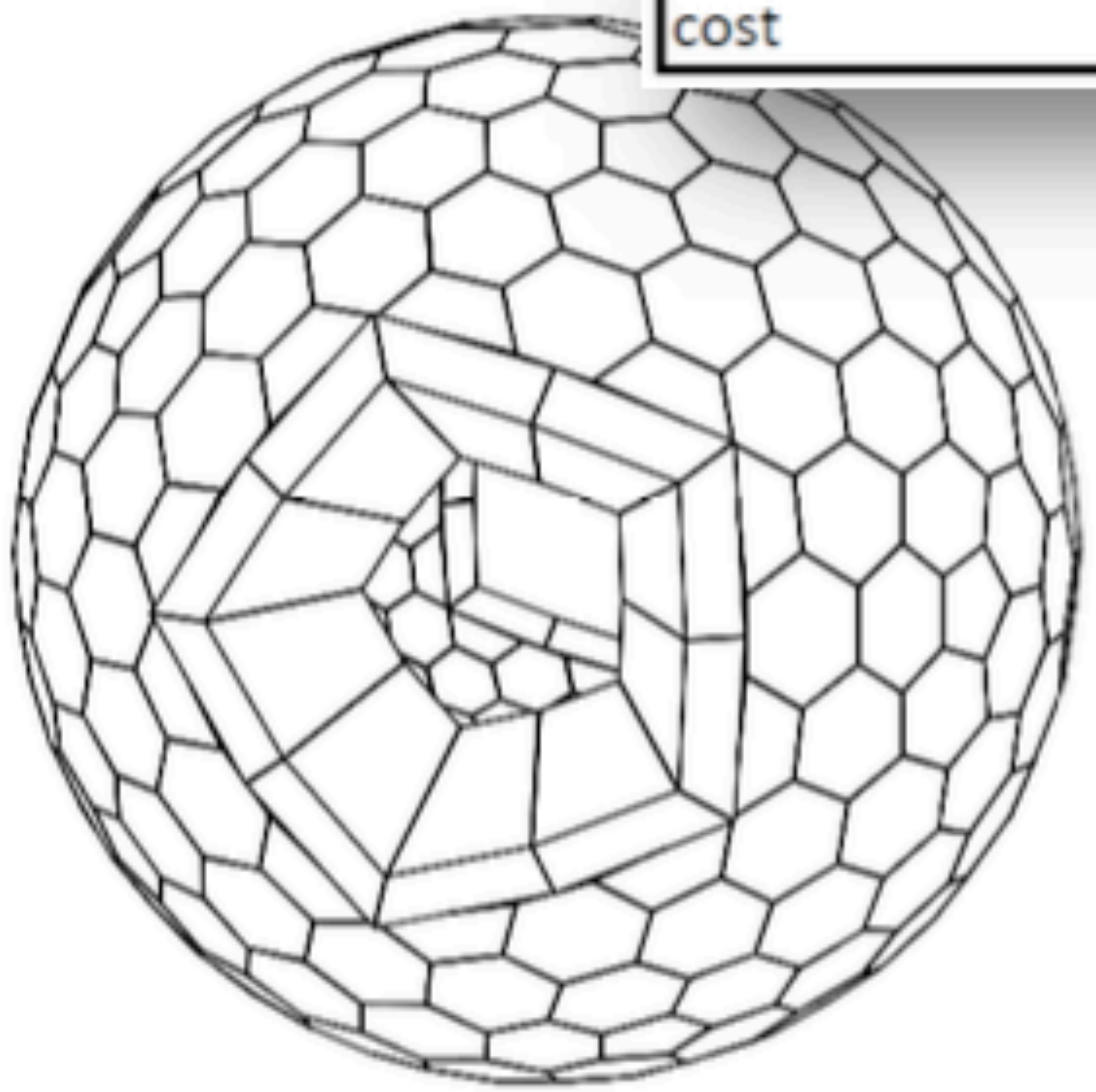


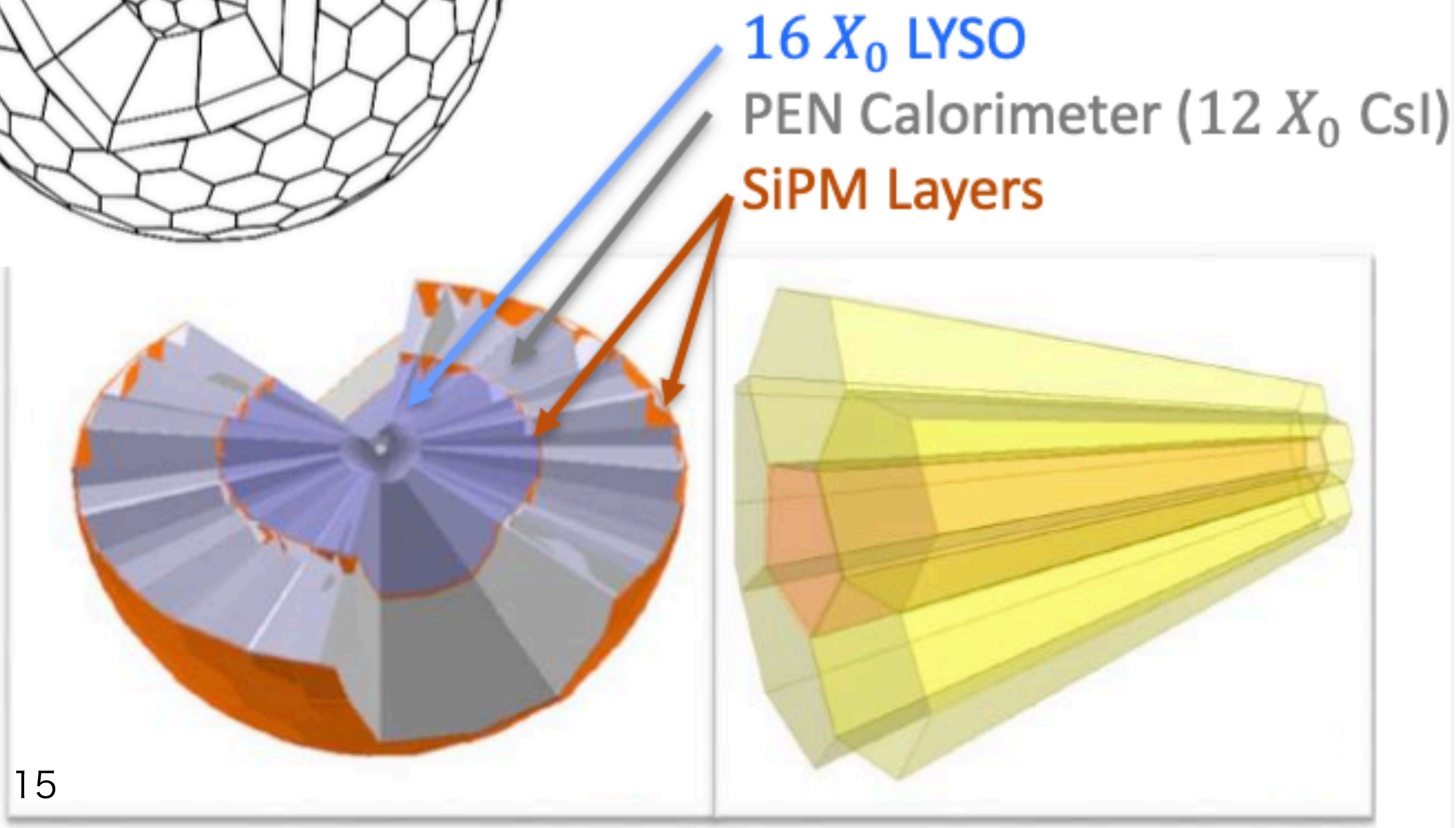


Calorimeter: Competing design

property	LXe	LYSO+CsI
timing and decay const	similar	similar
X0	25	28
resolution	1.50%	4%, not fully optimized
segmentation, pileup	R&D	standard
compactness		15x smaller volume
production/experience	MEG, DM, 0v2β	mostly short crystals, PET
photo sensors	VUV SiPM issues	standard SiPMs
cost		potentially lower



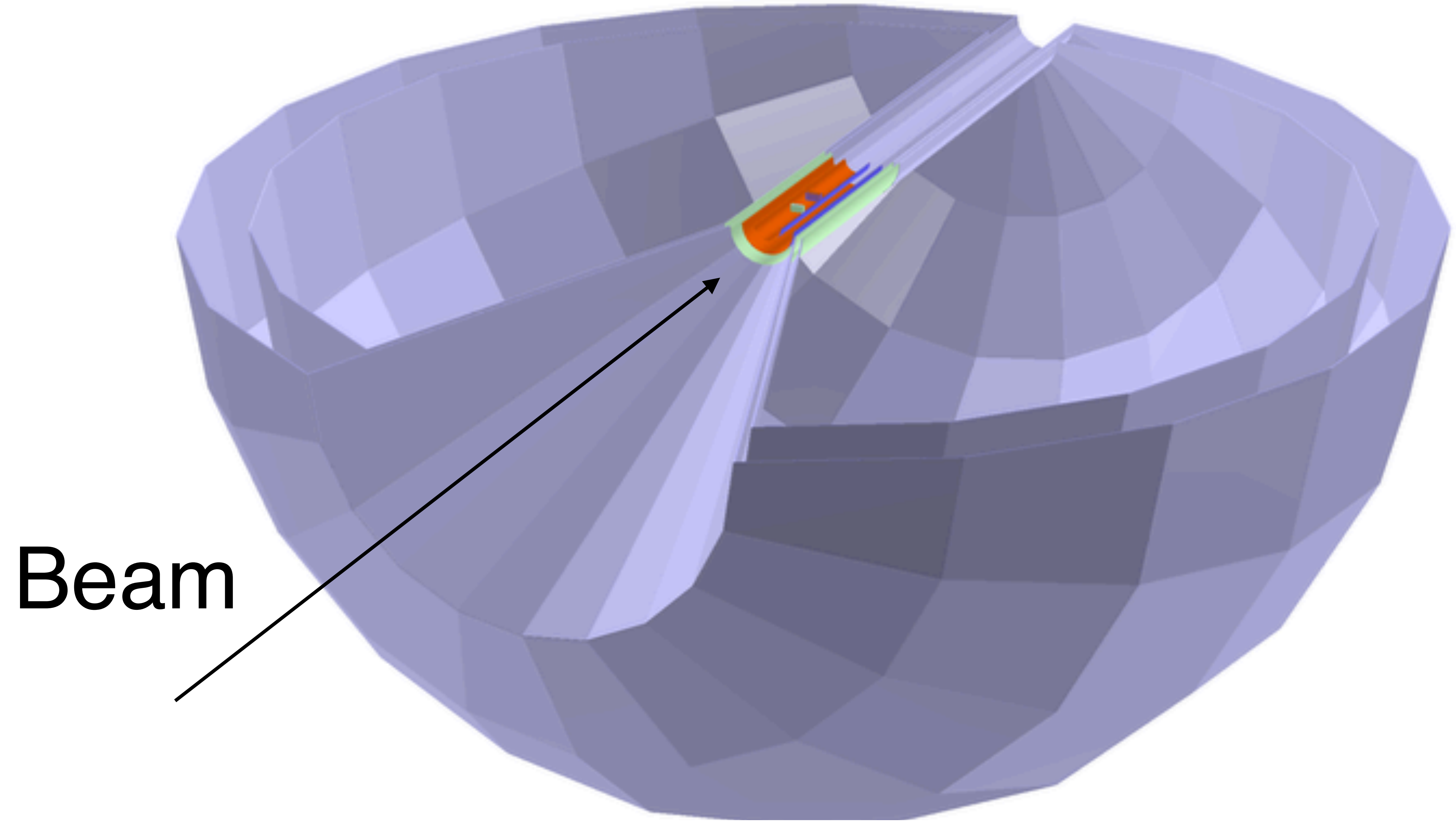




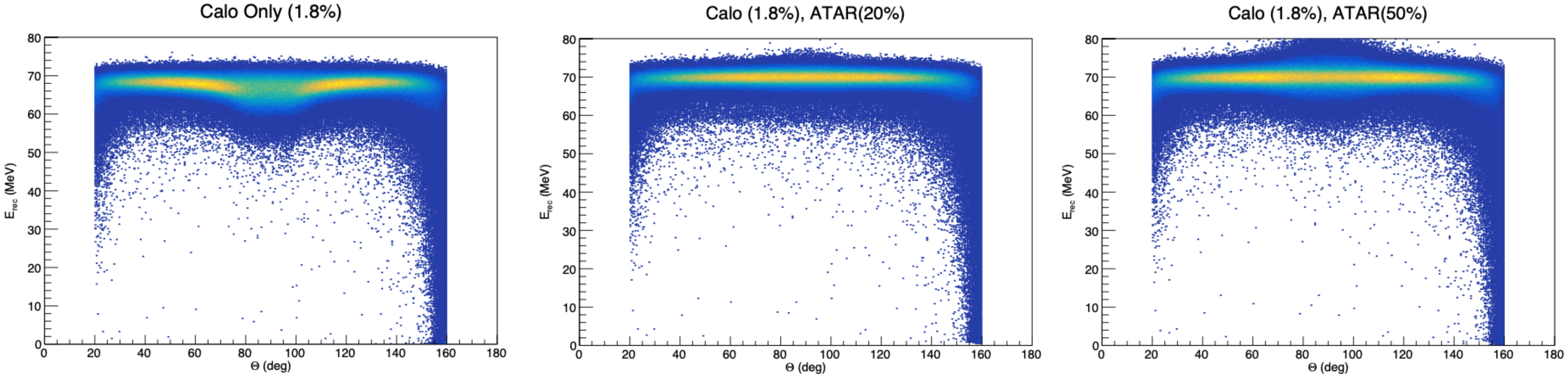
LYSO + CsI

- Effectively measuring with 2 calorimeters at the same time (16X_0 LYSO + 12X_0 CsI) gives us a unique handle on the low energy tail
- Energy resolution can be an issue

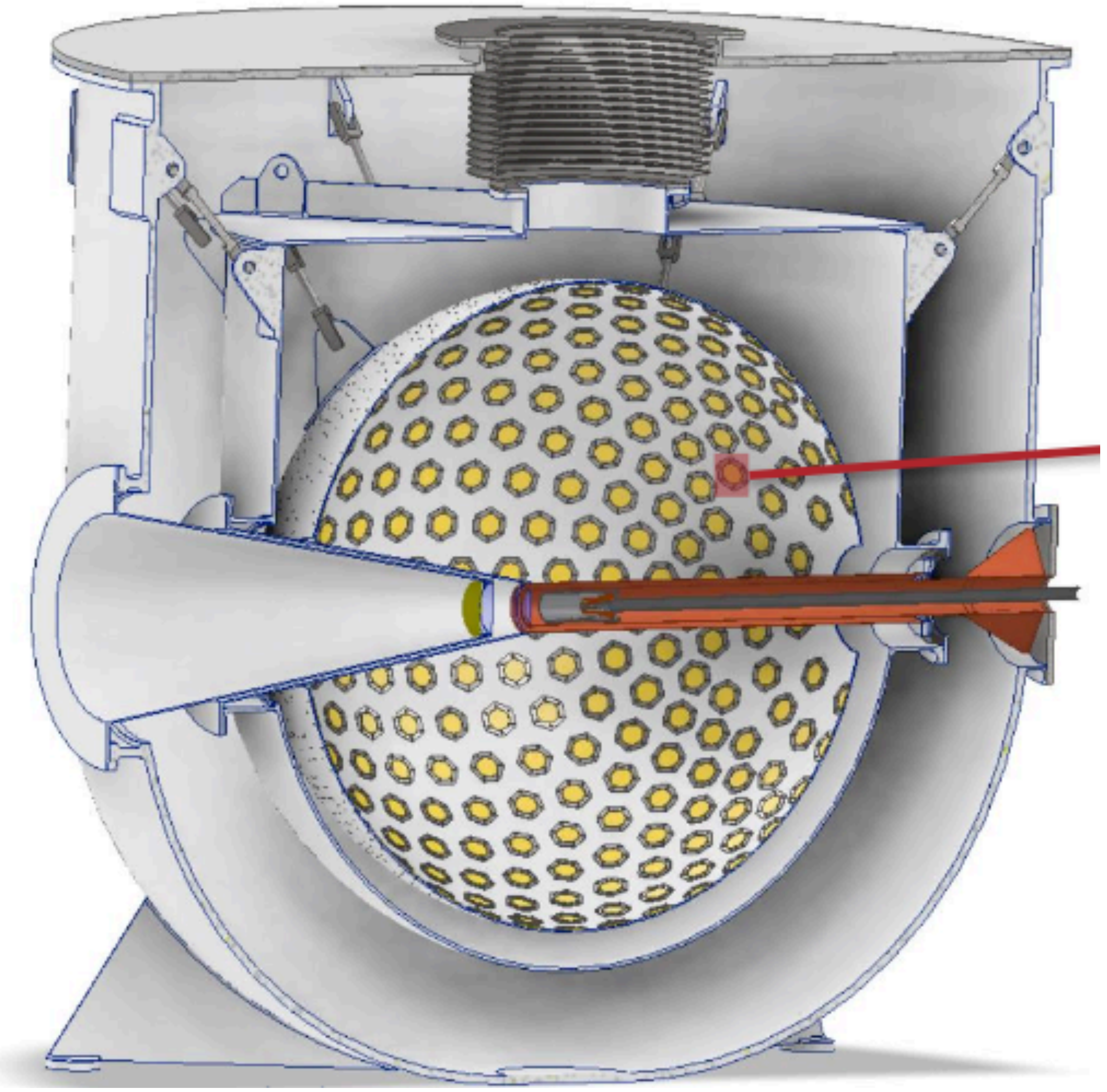
Simulating the whole detector

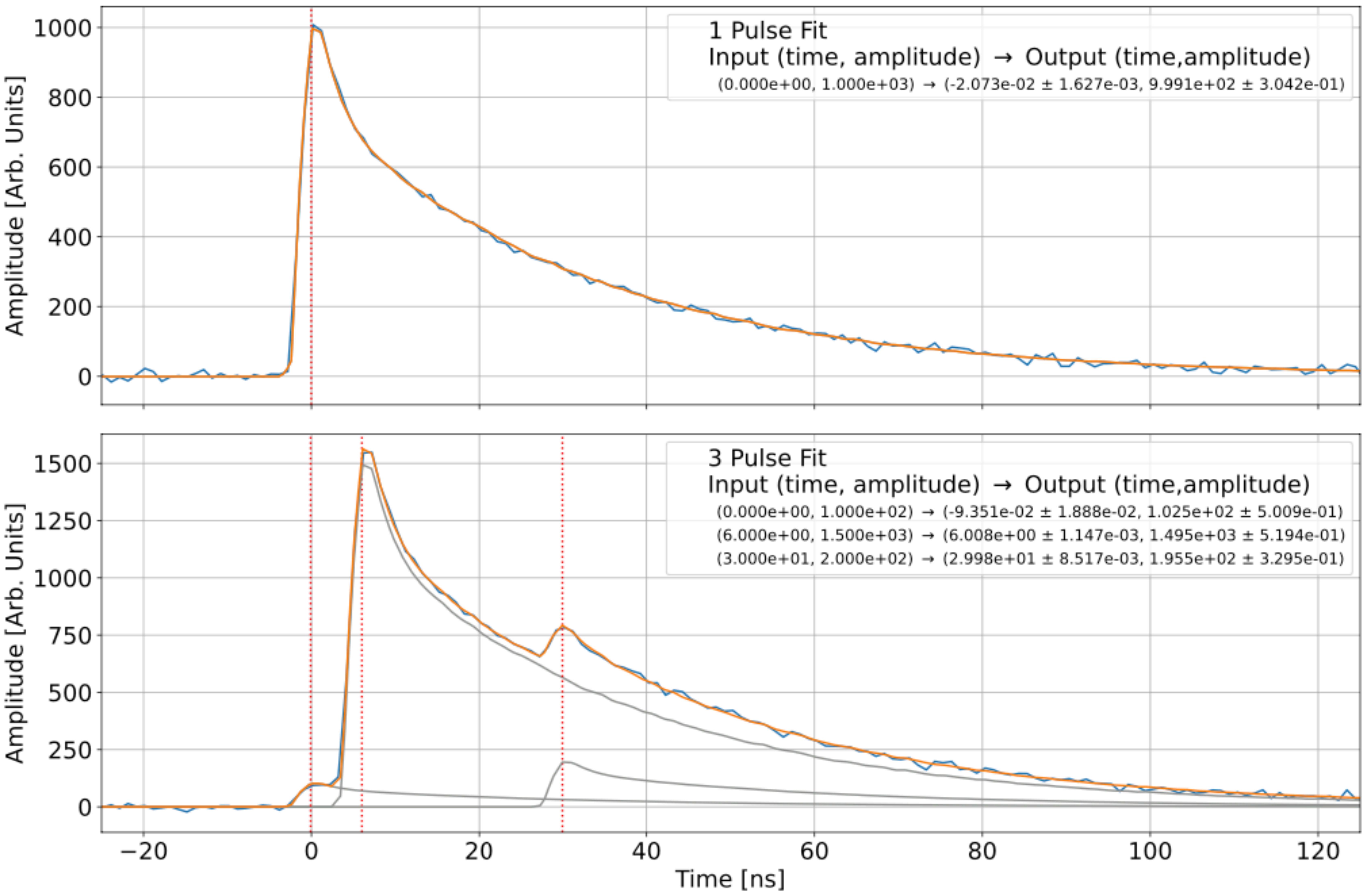


- Example of geometry study
  - Asymmetric shape between US/DS
  - Calo only
  - Calo + ATAR (20% energy resolution)
  - Calo + ATAR (50% energy resolution)
- Fiducial volume
  - It is important to take into account the ATAR energy deposits at $80^\circ < \Theta < 100^\circ$ because this is the direction of the largest ATAR dimension



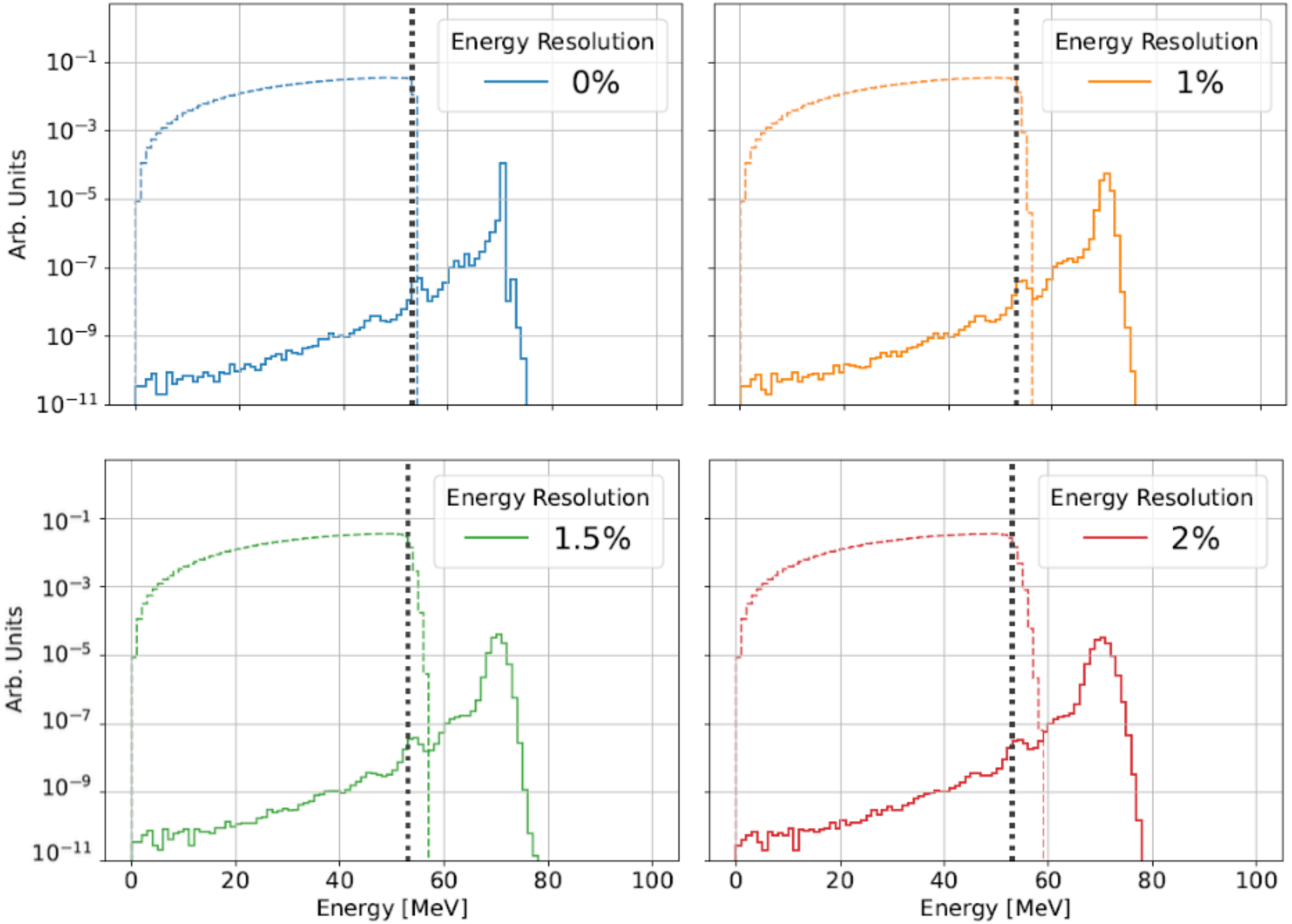
Pulse Fitting Studies





Pileup identification with waveform analysis seems working well

Calorimeter energy resolution effects



Tail correction is relatively insensitive to resolution

$\pi \to \mu \to e$ events will contaminate the $\pi \to e$ signal region

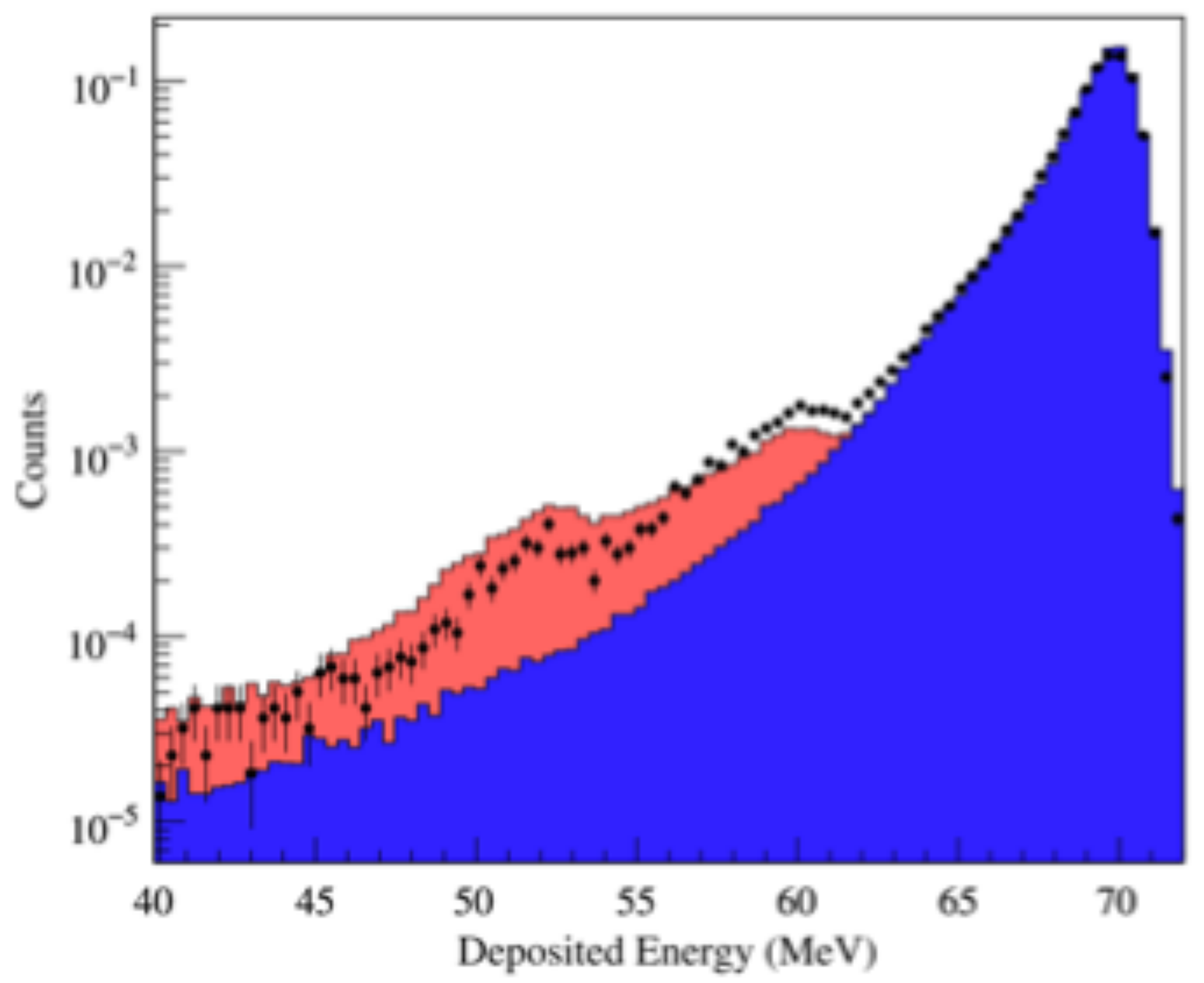
Photo-nuclear reaction

Photonuclear reactions in NaI detector

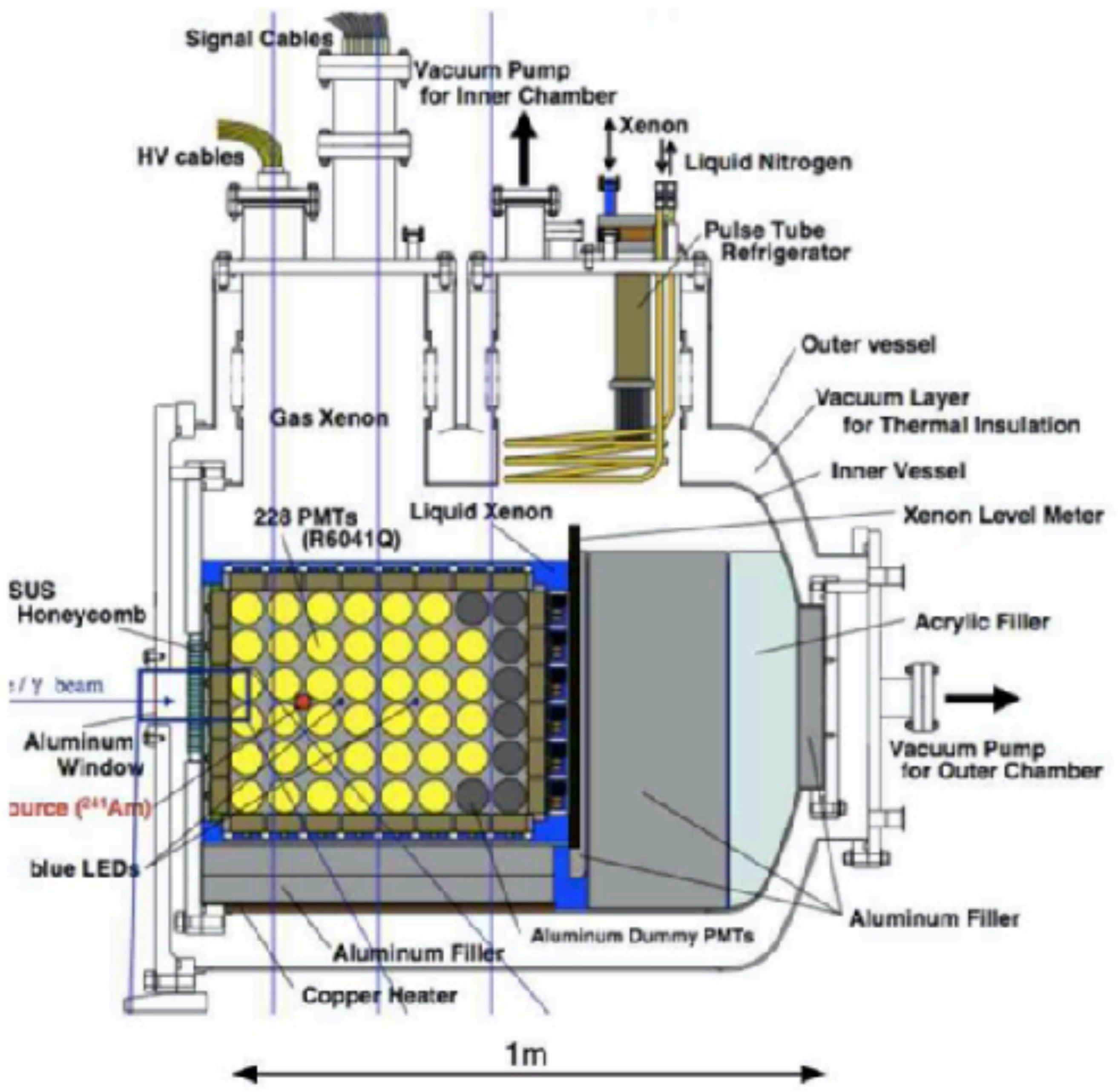
- ^{127}I captures γ(electromagnetic shower)
  → n(94%), p(4%), α(2%) emission
  → 1n, or 2n escape from NaI
  → peaks in low energy region
- This energy region is buried in π→μ→e decays, and Geant4 simulation should be tuned by data

Beam test was performed with NaI in the previous experiment

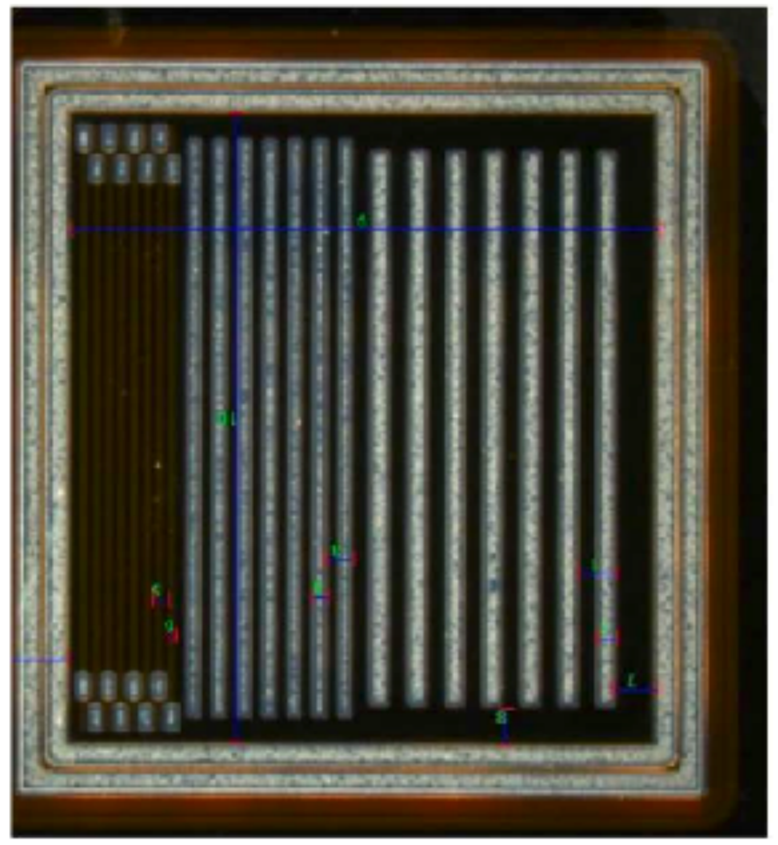
Beam test with LXe prototype (~100l LXe) will be performed for that



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



Prospects 2023 and beyond



- ATAR components
  - Several AC-LGAD sensors of 50 μm thickness produced in 2022
  - 120 μm thickness and fully active w/o an inactive support wafer in 2023
- Tracker components
  - A two layer sandwich of $10 \times 10\, cm^2$ in a 2-D planar scheme
- Crystal calorimeter tests
  - 3 × 3 array of LYSO rectangular crystals will tell us the effects of measuring 70 MeV/c positron energies from the combined pulses of up to 9 participating crystals
- Beam test in November 2023 in PiM1 at PSI
- LXe calorimeter tests
  - Evaluate the LXe performance for 70 MeV positrons using a prototype (70 l of LXe)
  - This is a major project with a time-scale of two years, aiming at being ready in 2024
- TDR will be prepared within 3 years

Conclusion

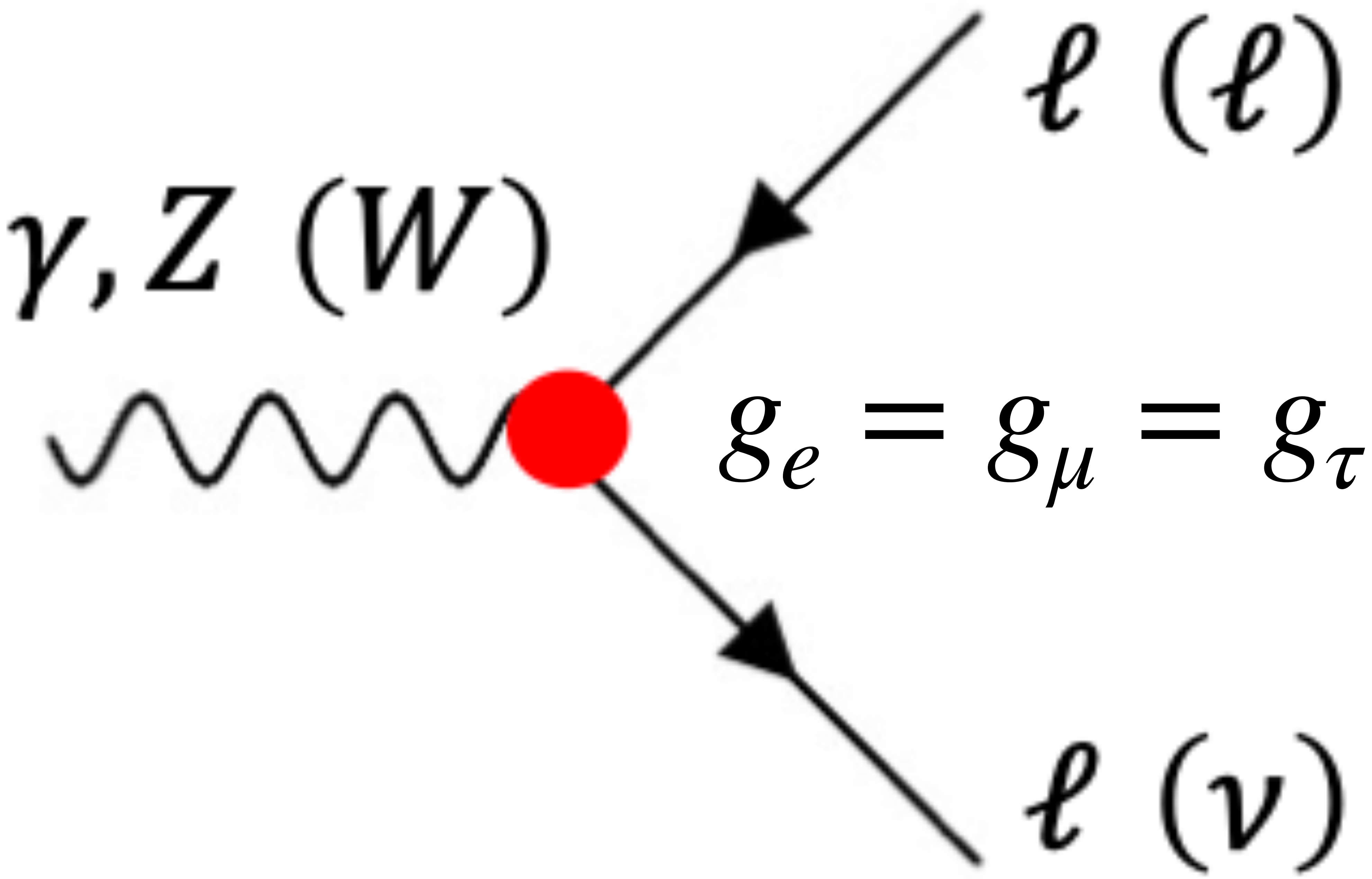
- There are three key points for the PIONEER experiment to improve the sensitivity, intense pion beam, active target, and calorimeter.
- The detector R&D is underway to prepare the TDR in 3 years.
- The liquid xenon detector is the baseline design for the PIONEER calorimeter. The Japanese group will lead the R&D based on the experience on the MEG II LXe detector.
- We would like you to join us!

Uncertainty Estimates

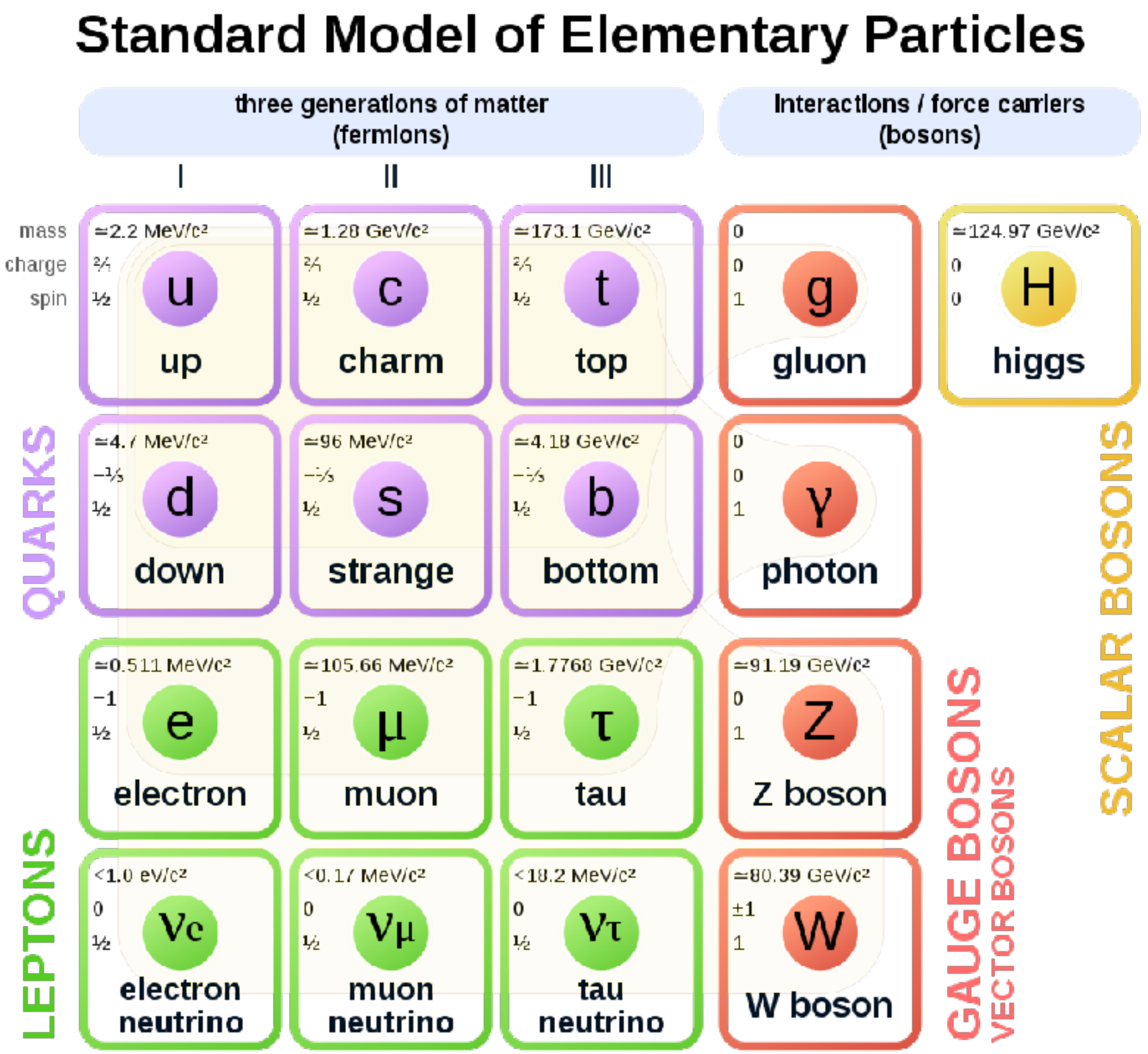
	PIENU 2015	PIONEER Estimate
Error Source	%	%
Statistics	0.19	0.007
Tail Correction	0.12	<0.01
t_0 Correction	0.05	<0.01
Muon DIF	0.05	0.005
Parameter Fitting	0.05	<0.01
Selection Cuts	0.04	<0.01
Acceptance Correction	0.03	0.003
Total Uncertainty	**0.24**	$\leq$ **0.01**

Lepton Flavor Universality

- The weak interaction in the Standard Model is the same for $e/\mu/\tau$
  - Gauge interactions are lepton flavor universal



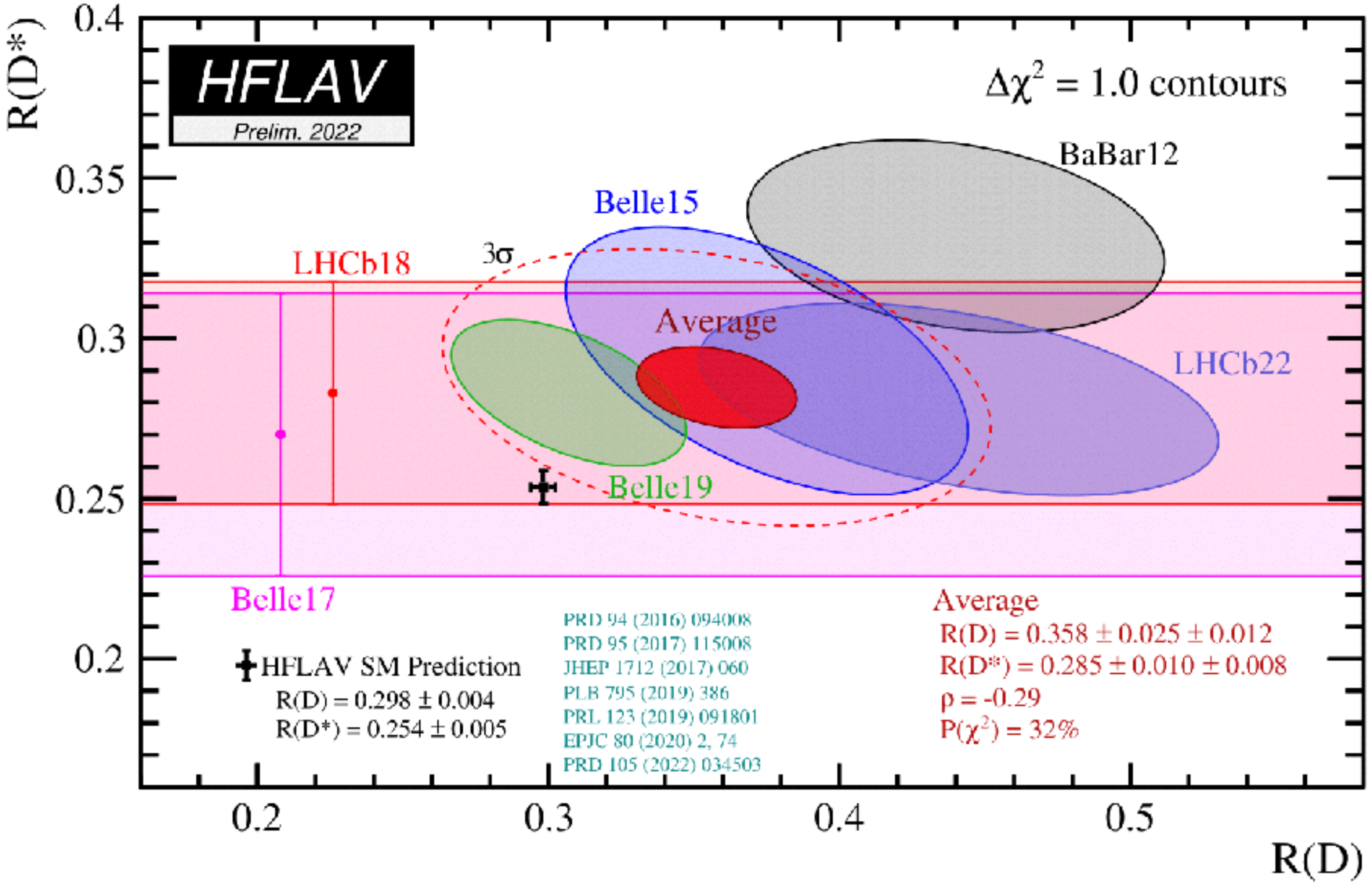
$$g_e = g_\mu = g_\tau$$



Test of Lepton Flavor Universality

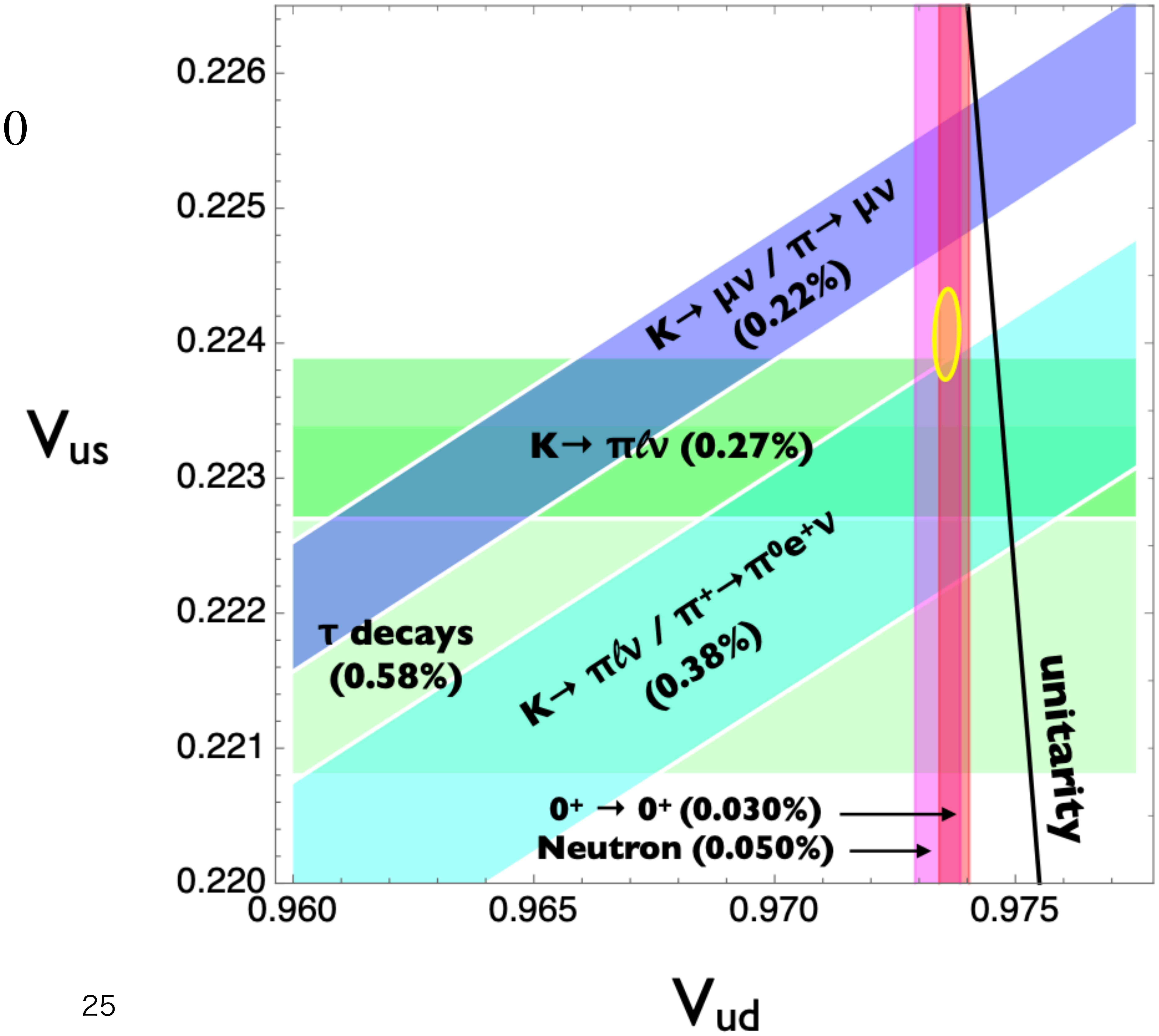
$$R(D^*) = \frac{\mathcal{B}(\overline{B}^0 \to D^{*+}\tau^-\overline{\nu}_\tau)}{\mathcal{B}(\overline{B}^0 \to D^{*+}\mu^-\overline{\nu}_\mu)}$$

- R(D), R(D*) deviate from the SM expectation by more than 3σ
  - Can be a hint of LFUV between τ and μ
- $(g-2)_l$ $(l = e, \mu, \tau)$ of charged leptons are sensitive probes of LFUV
  - longstanding $(g-2)_\mu$ can be considered as another hint of LFUV when compared to $(g-2)_e$

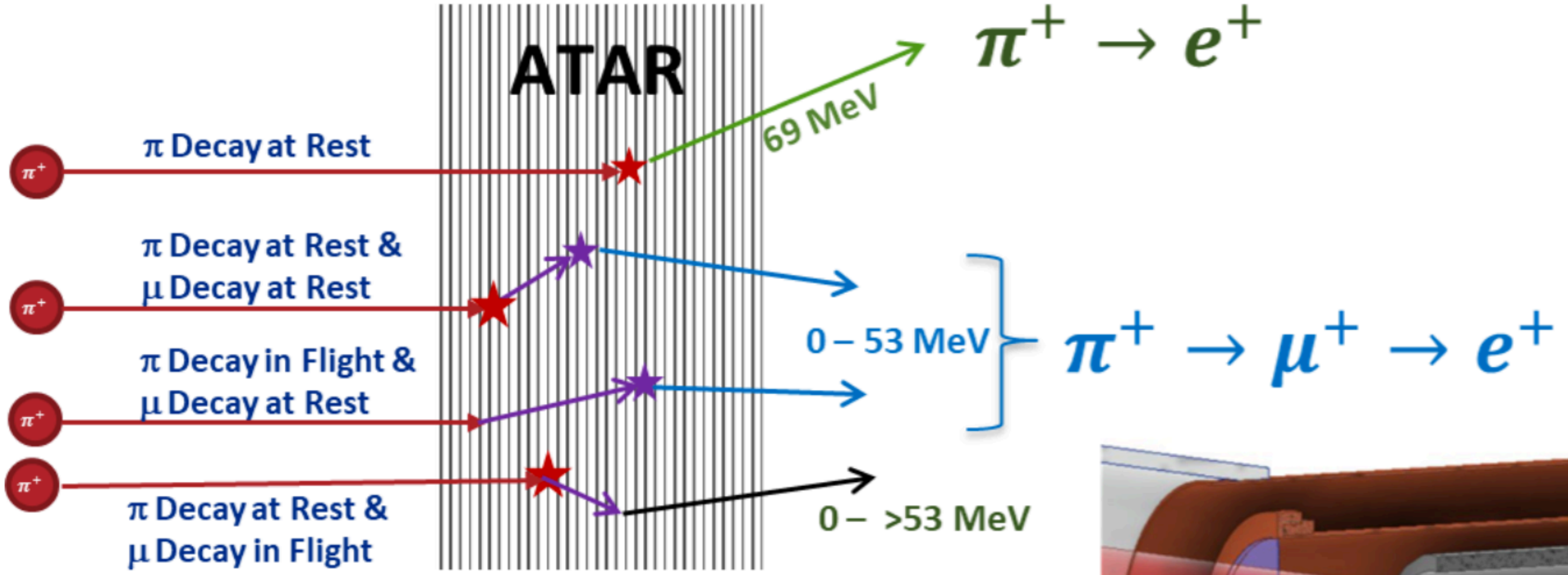


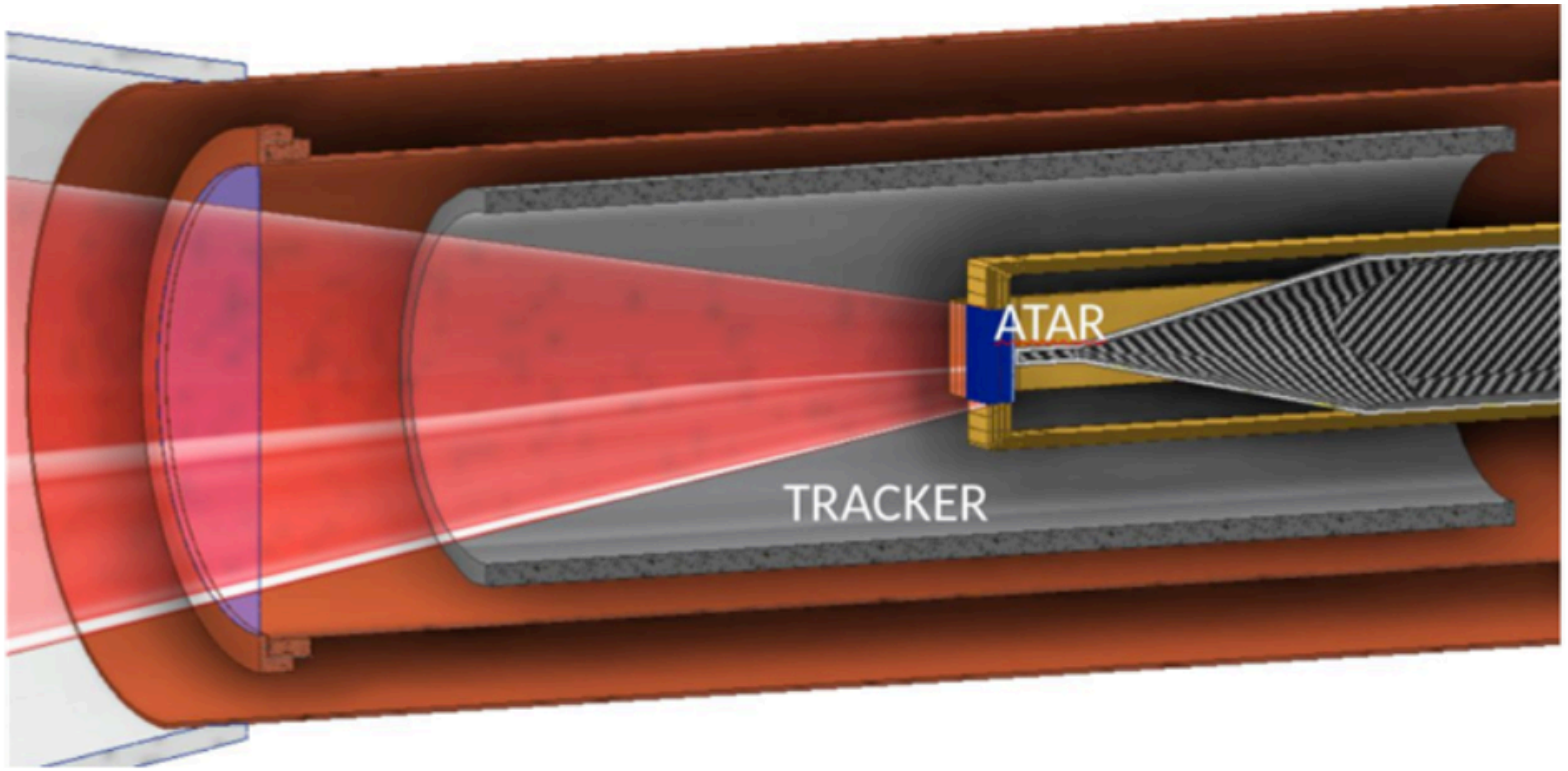
Beta Decays and CKM Unitarity

- Unitarity of the CKM matrix
  $\Delta_{\text{CKM}} \equiv |V_{ud}|^2 + |V_{us}|^2 + |V_{ub}|^2 - 1 = 0$
- In practice, $|V_{ub}|^2 < 10^{-5}$, only V_{ud} and V_{us} are concerned
- $\Delta_{\text{CKM}} = (-19.5 \pm 5.3) \times 10^{-4}$, 3.7σ effect
- This can be interpreted as a LFUV
  - V_{ud} dominant from electron meas.
  - V_{us} dominant from muon meas.

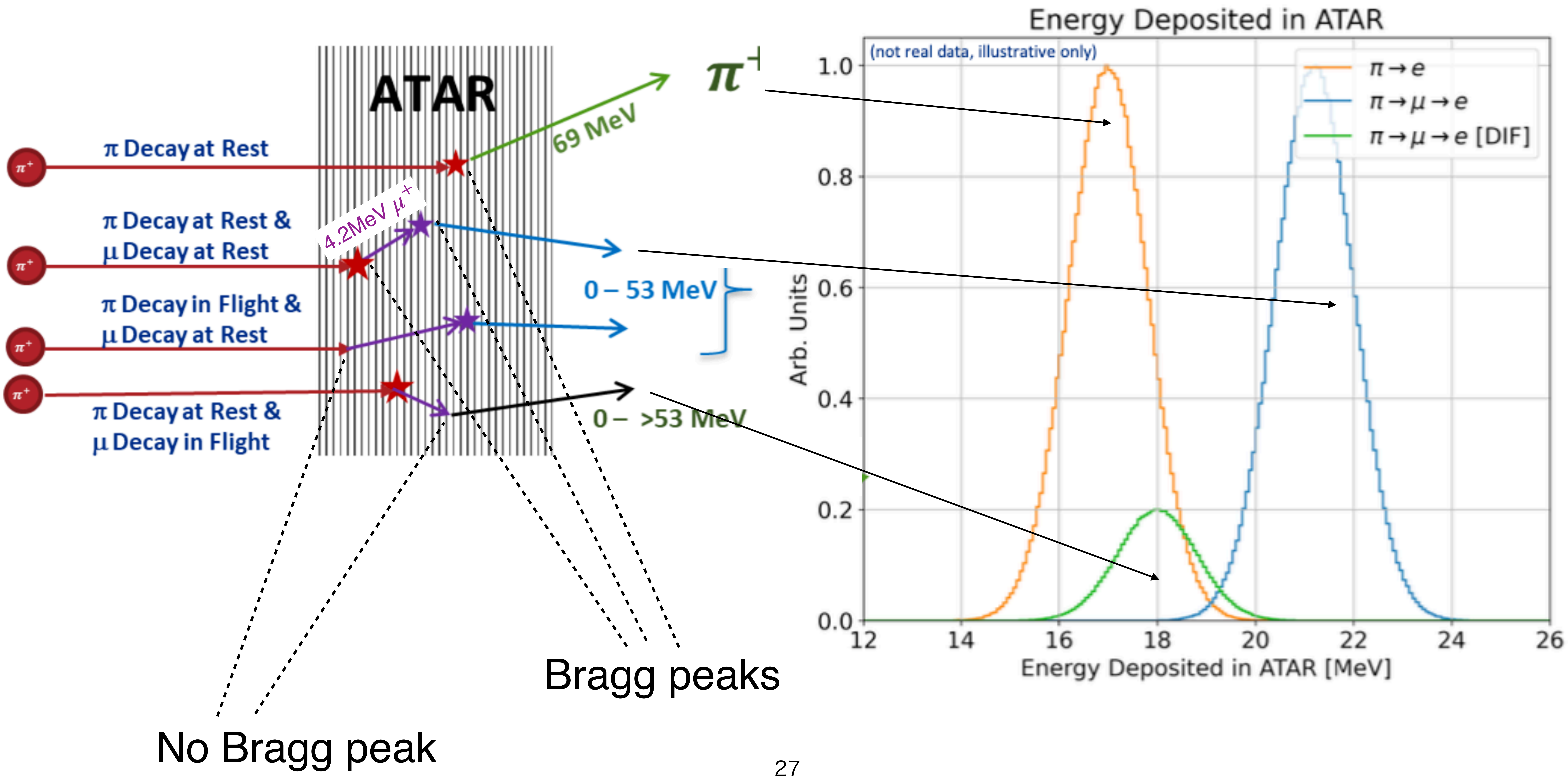


Signal and background

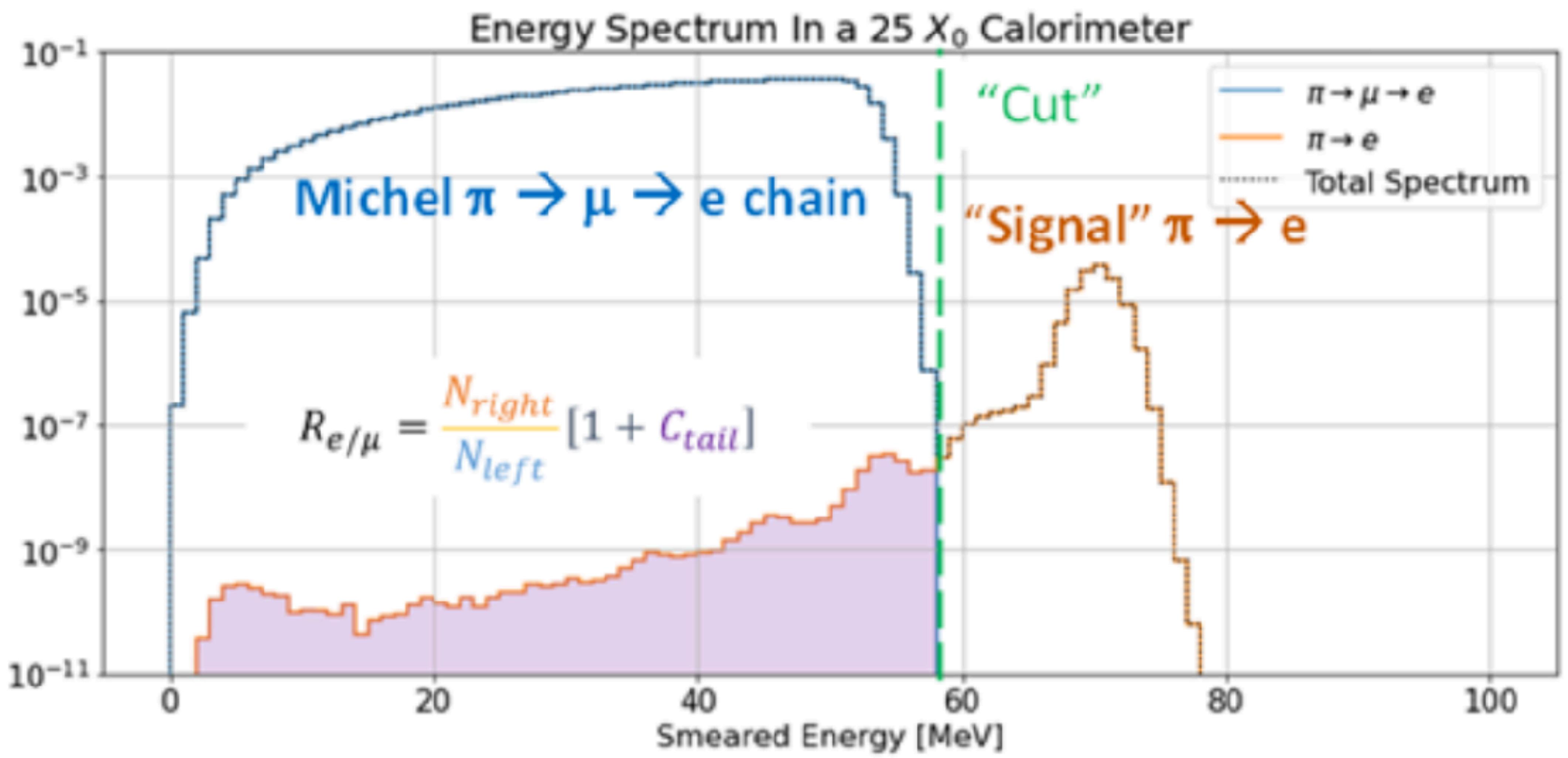


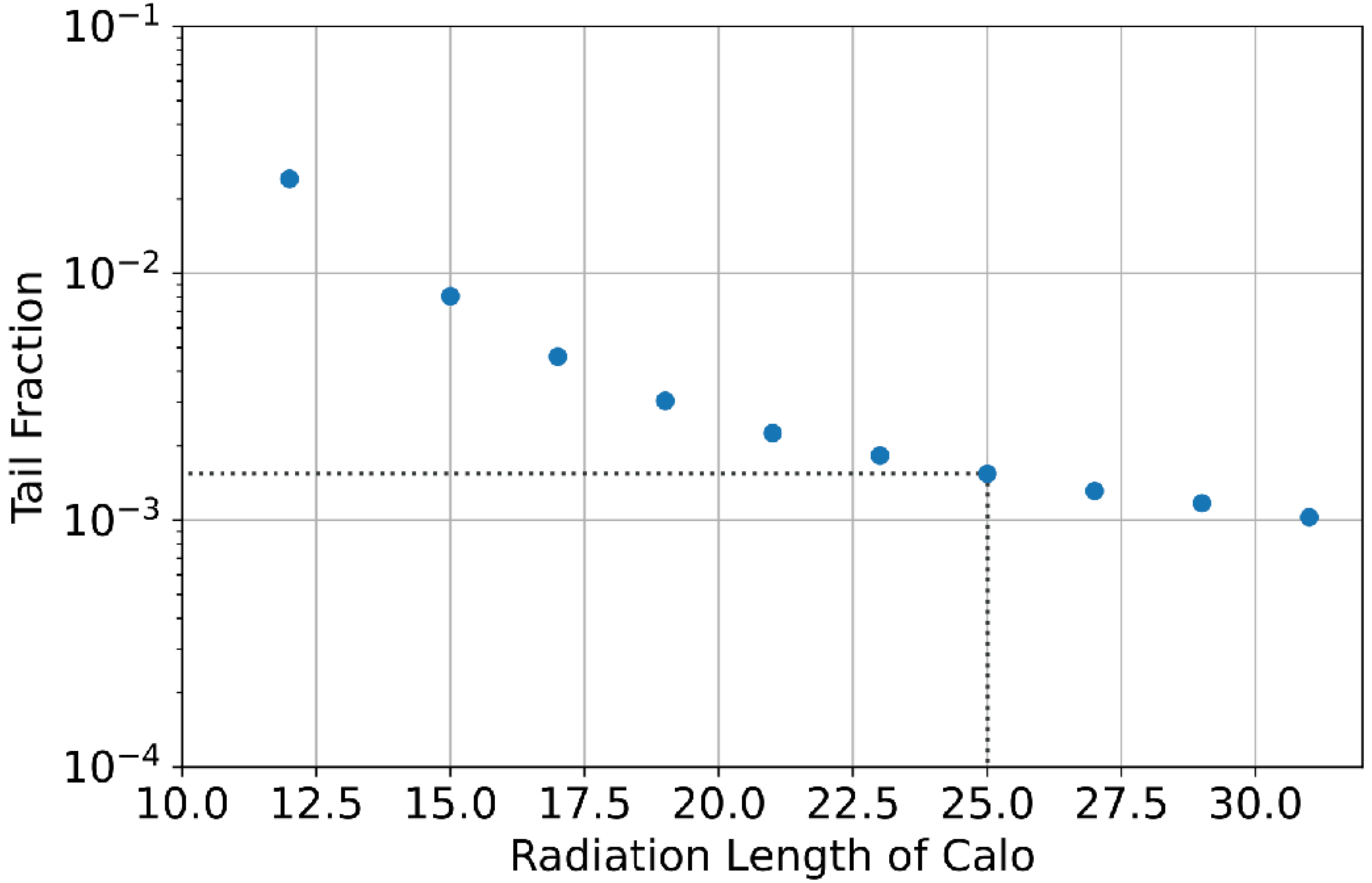


ATAR

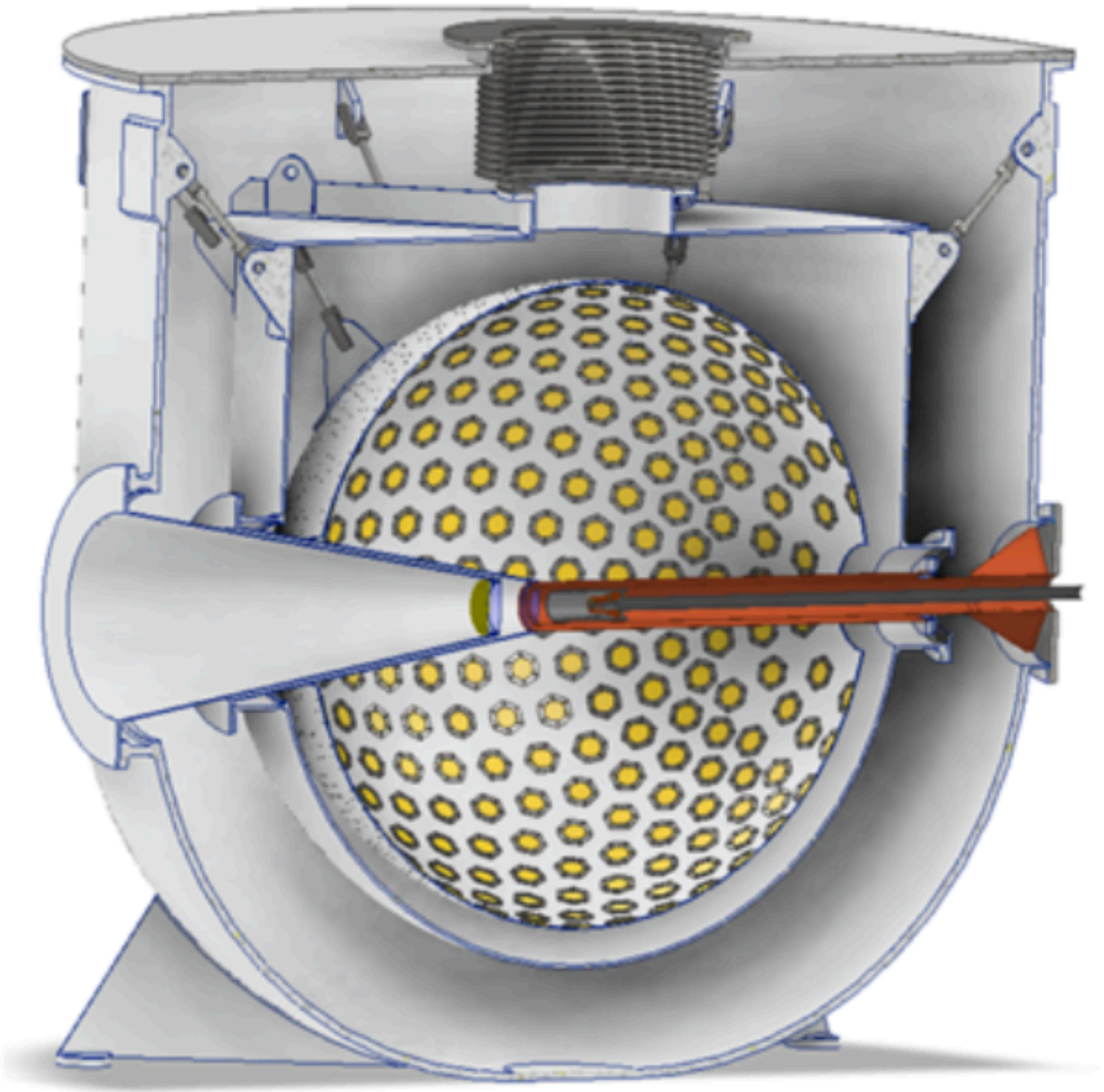

ATAR
π Decay at Rest
π Decay at Rest &
μ Decay at Rest
π Decay in Flight &
μ Decay at Rest
π Decay at Rest &
μ Decay in Flight
4.2MeV μ+
69 MeV
π+
0 – 53 MeV
0 – >53 MeV
Energy Deposited in ATAR
(not real data, illustrative only)
π→e
π→μ→e
π→μ→e [DIF]
Arb. Units
Energy Deposited in ATAR [MeV]
Bragg peaks
No Bragg peak

Role of Calorimeter

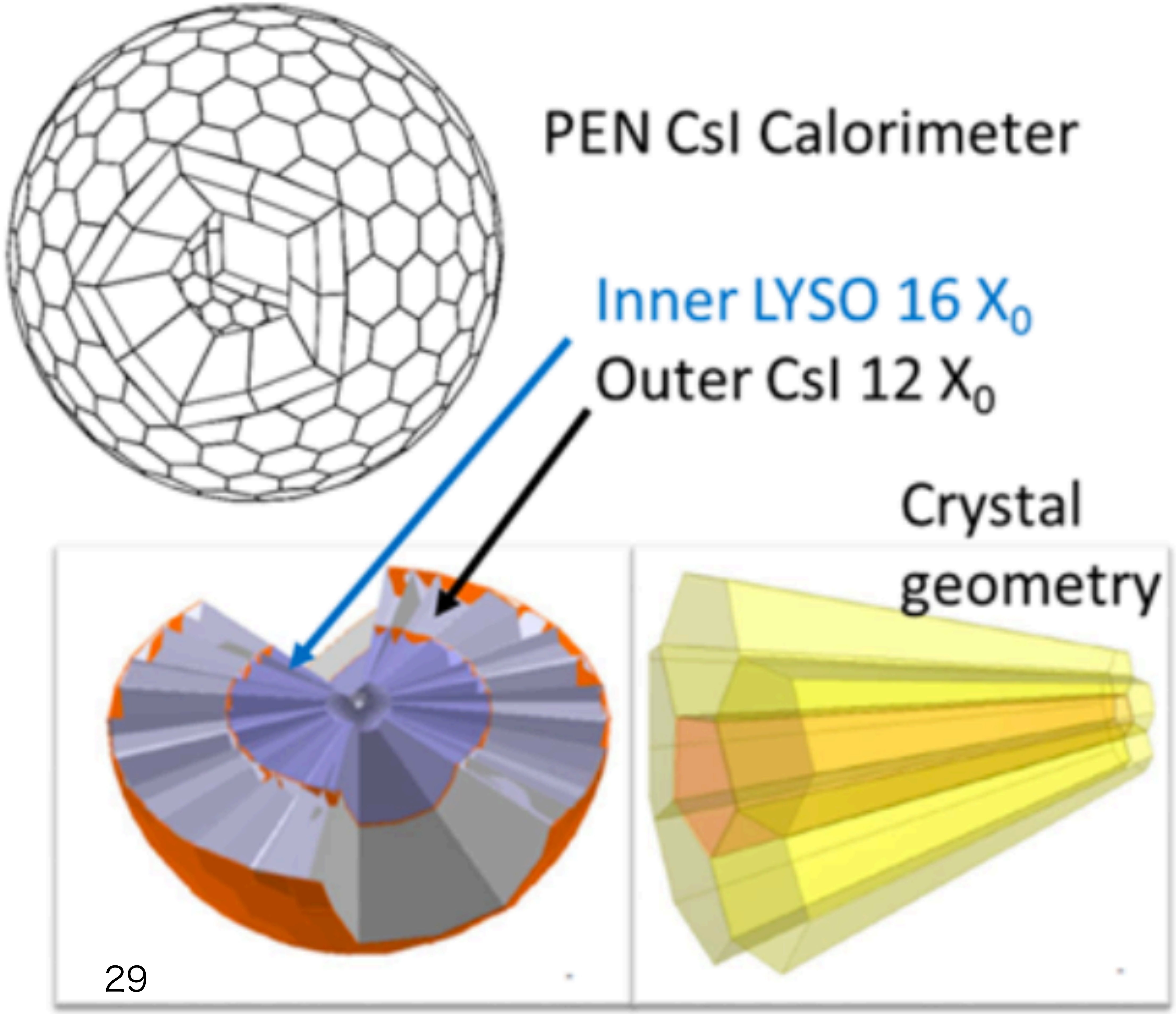




Calorimeter

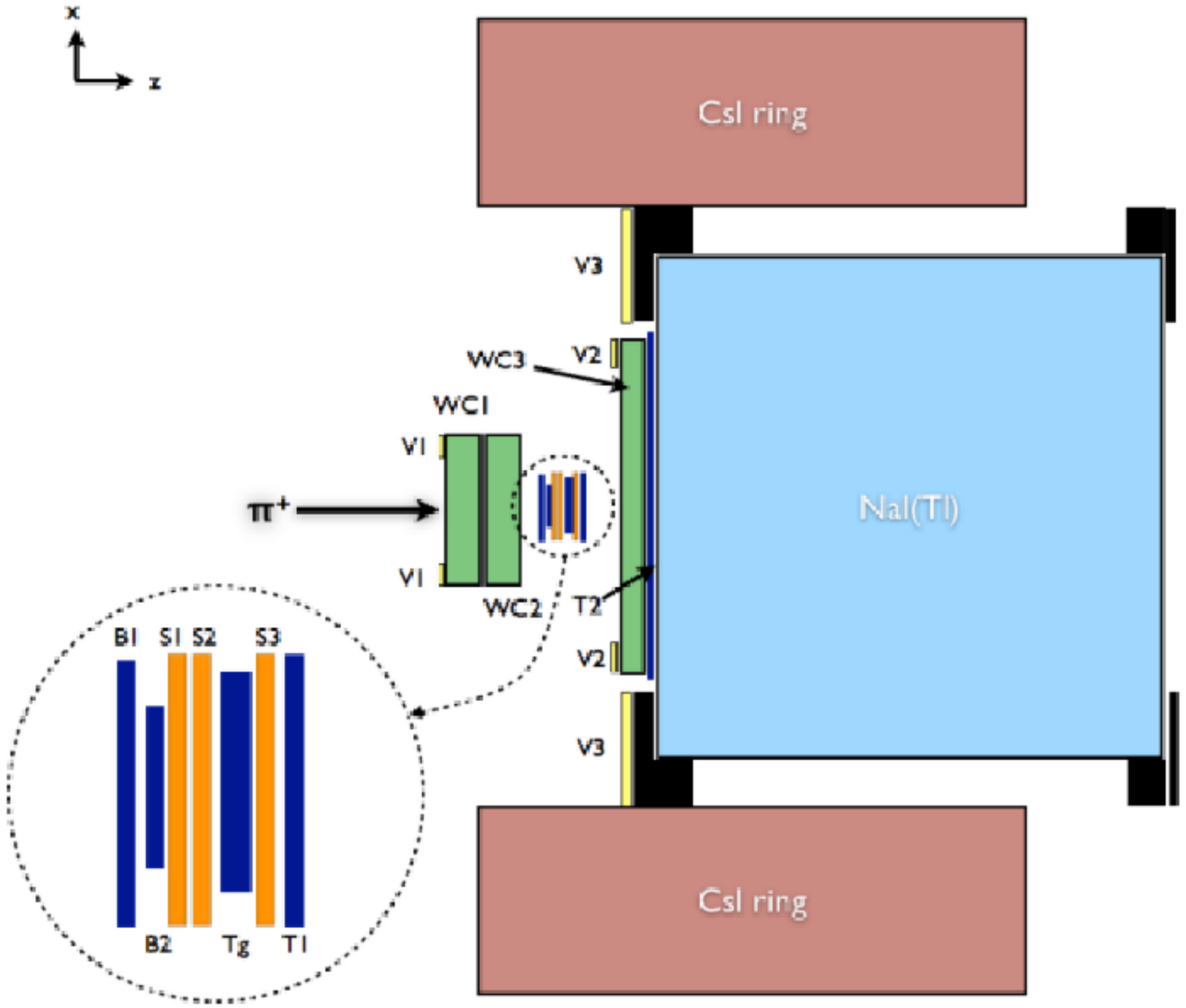


Detector	Density g/cm^3	dE/dx MeV/cm	X_0 cm	R_M cm	Decay time ns	λ_{max} nm	Light output %
LXe	2.953	3.707	2.872	5.224	3, 27, 45	178	100
LSO(Ce)	7.40	9.6	1.14	2.07	40	402	85

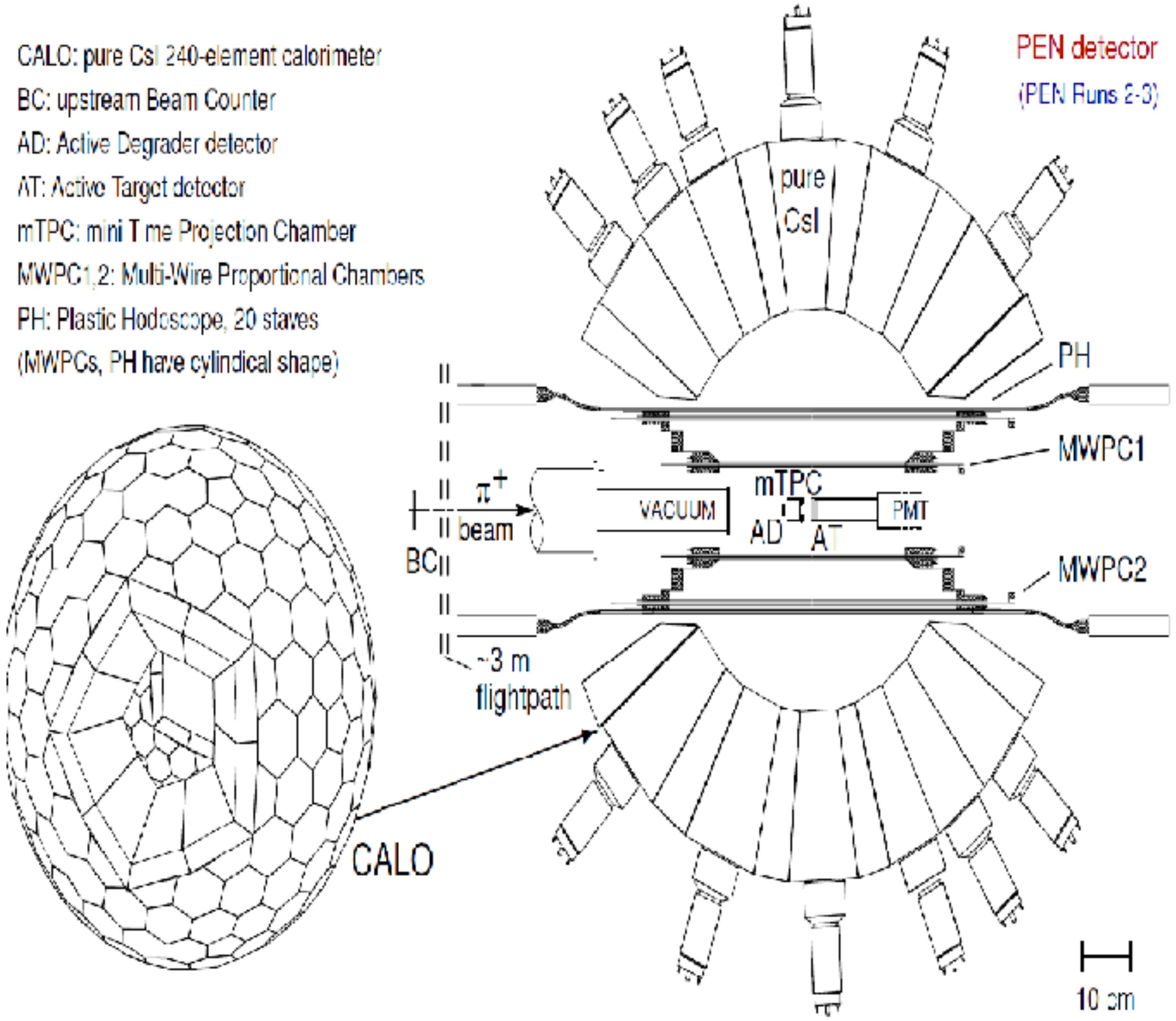


Lessons learned

PIENU @ TRIUMF



PEN & PiBeta @ PSI

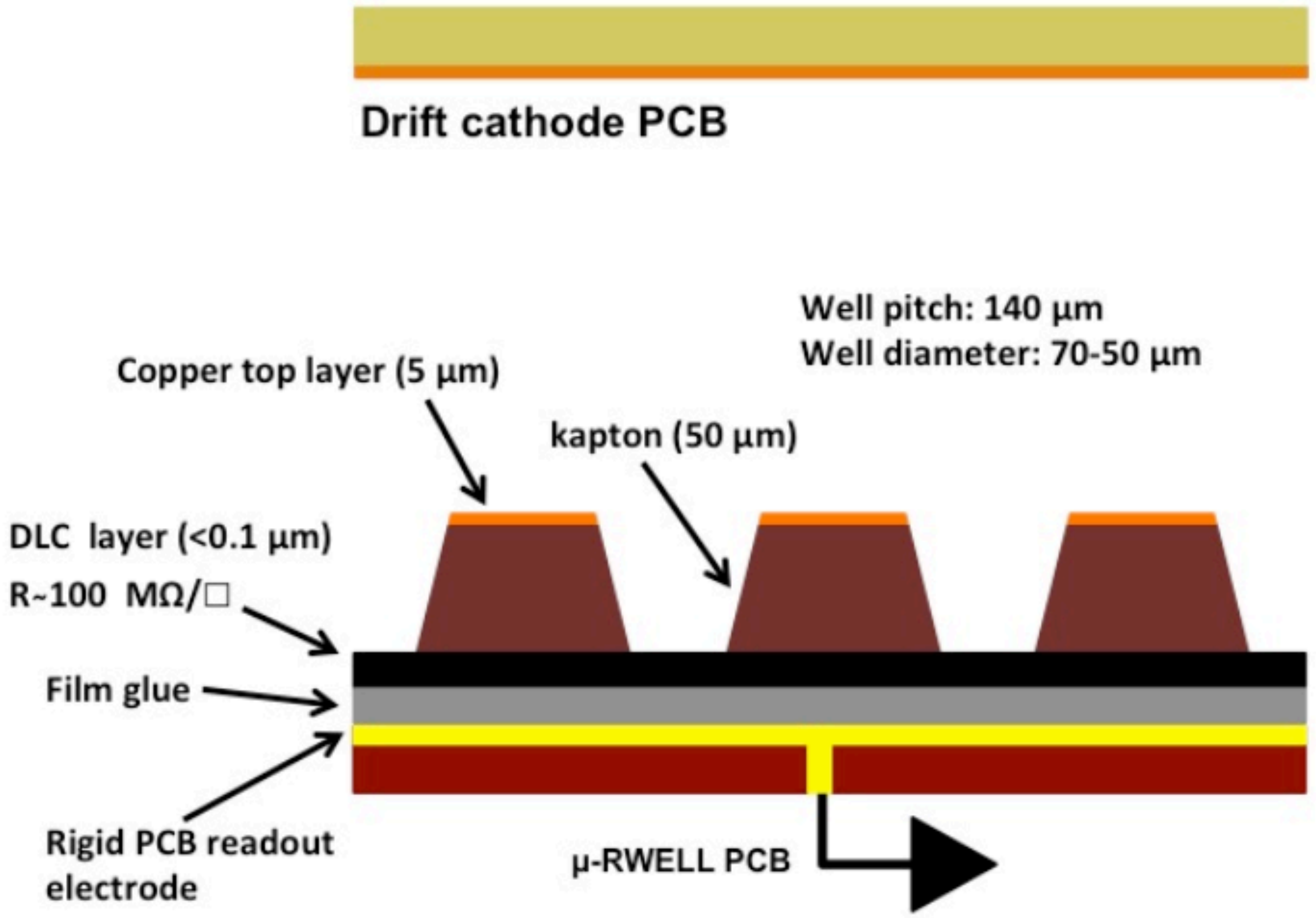


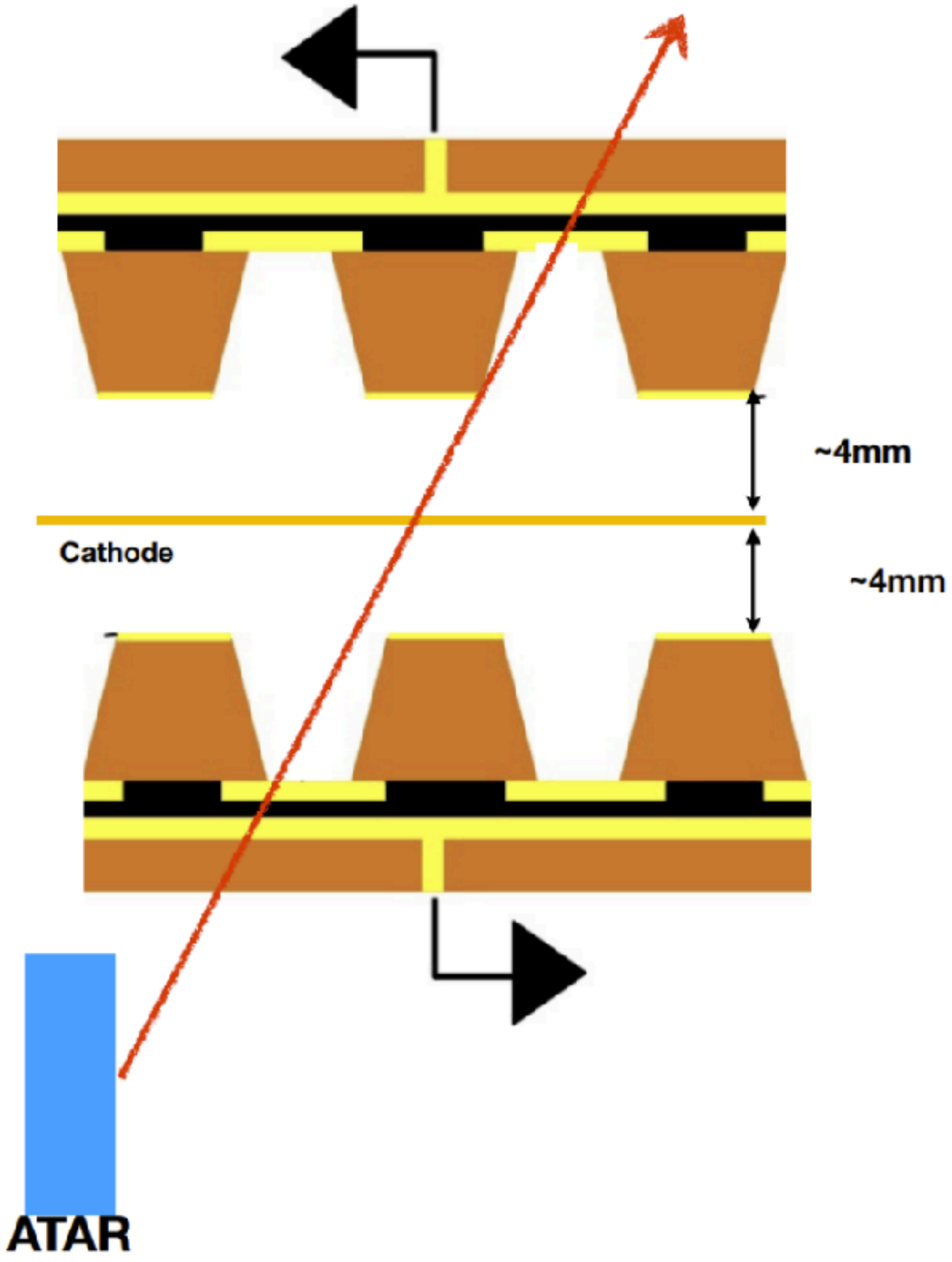
- Slow … NaI, but good resolution
- Single large crystal not uniform enough (material and effective “depth”)
- Small solid angle

- Good geometry but CsI calorimeter was only 12 X_0;
- Can’t get tail under control
- Resolution never published

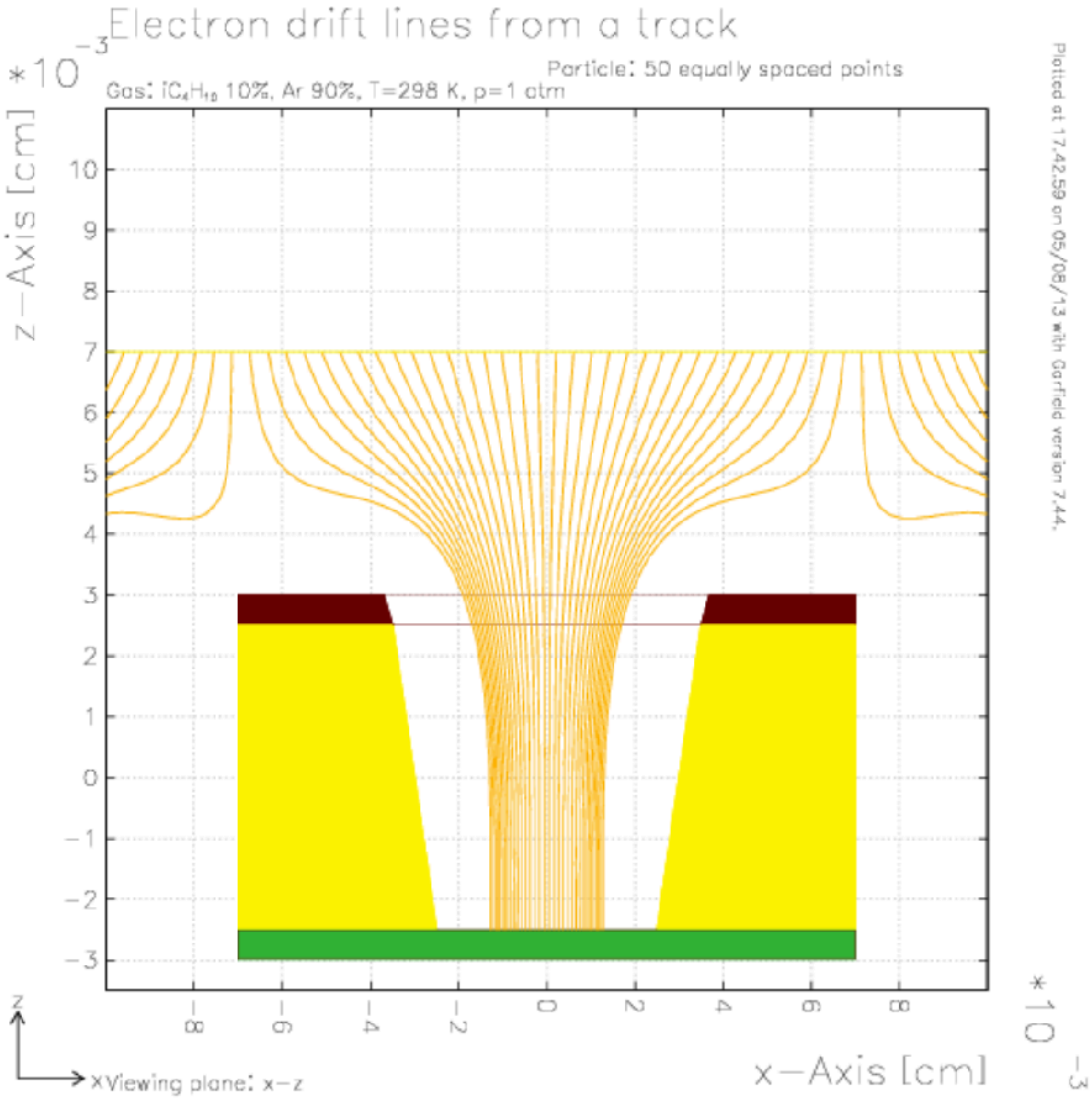
Resistive Micro WELL (µ-RWELL) detector

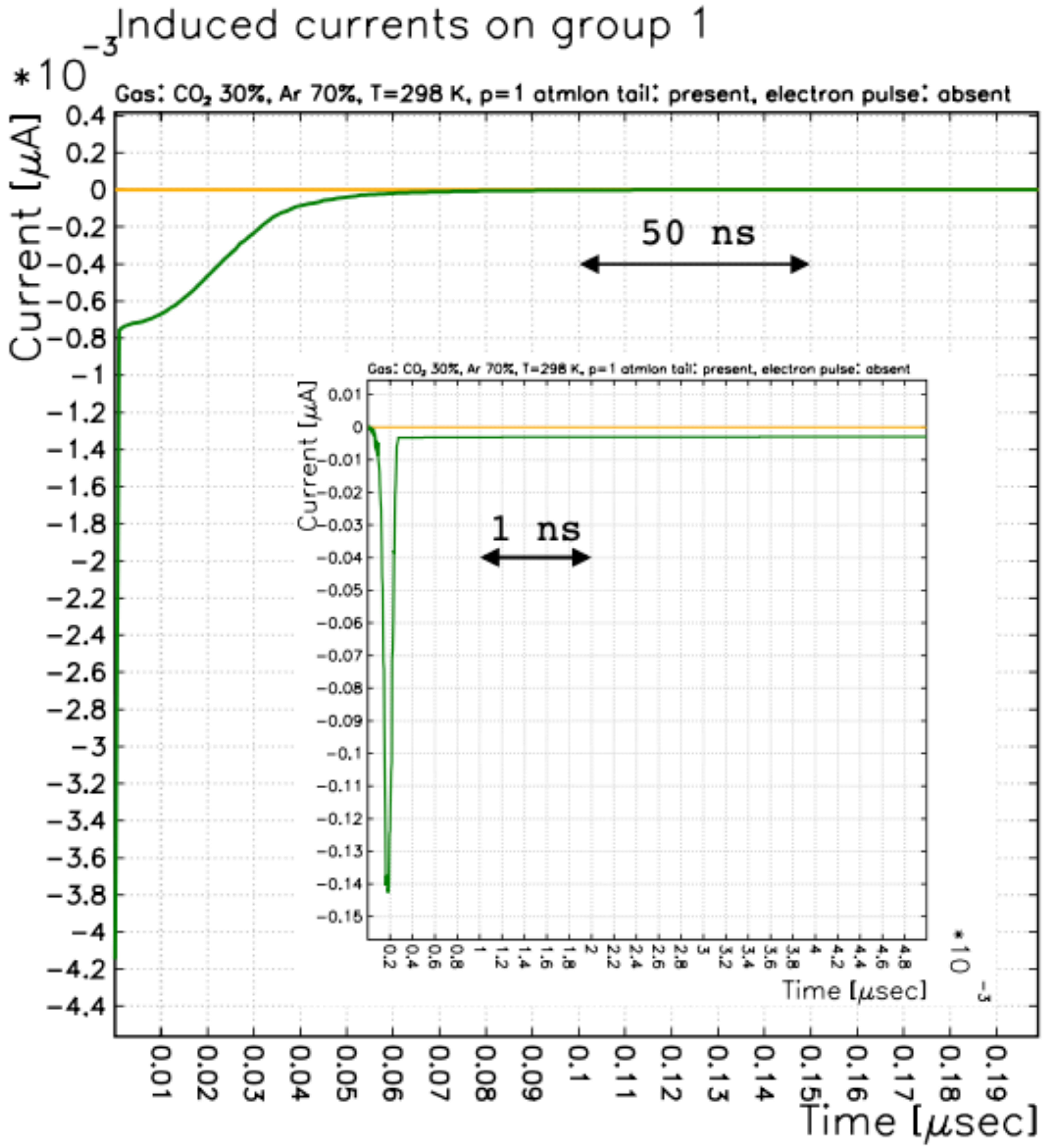
- The µ-RWELL is a very promising technology in harsh environment
  - compact, simple to assemble and intrinsically spark-protected
- Performance
  - Gas gain > 104
  - Rate capability > 1MHz/cm2
  - Space resolution < 100µm
  - Time resolution ~ 6ns





GARFIELD simulation for μ-RWELL

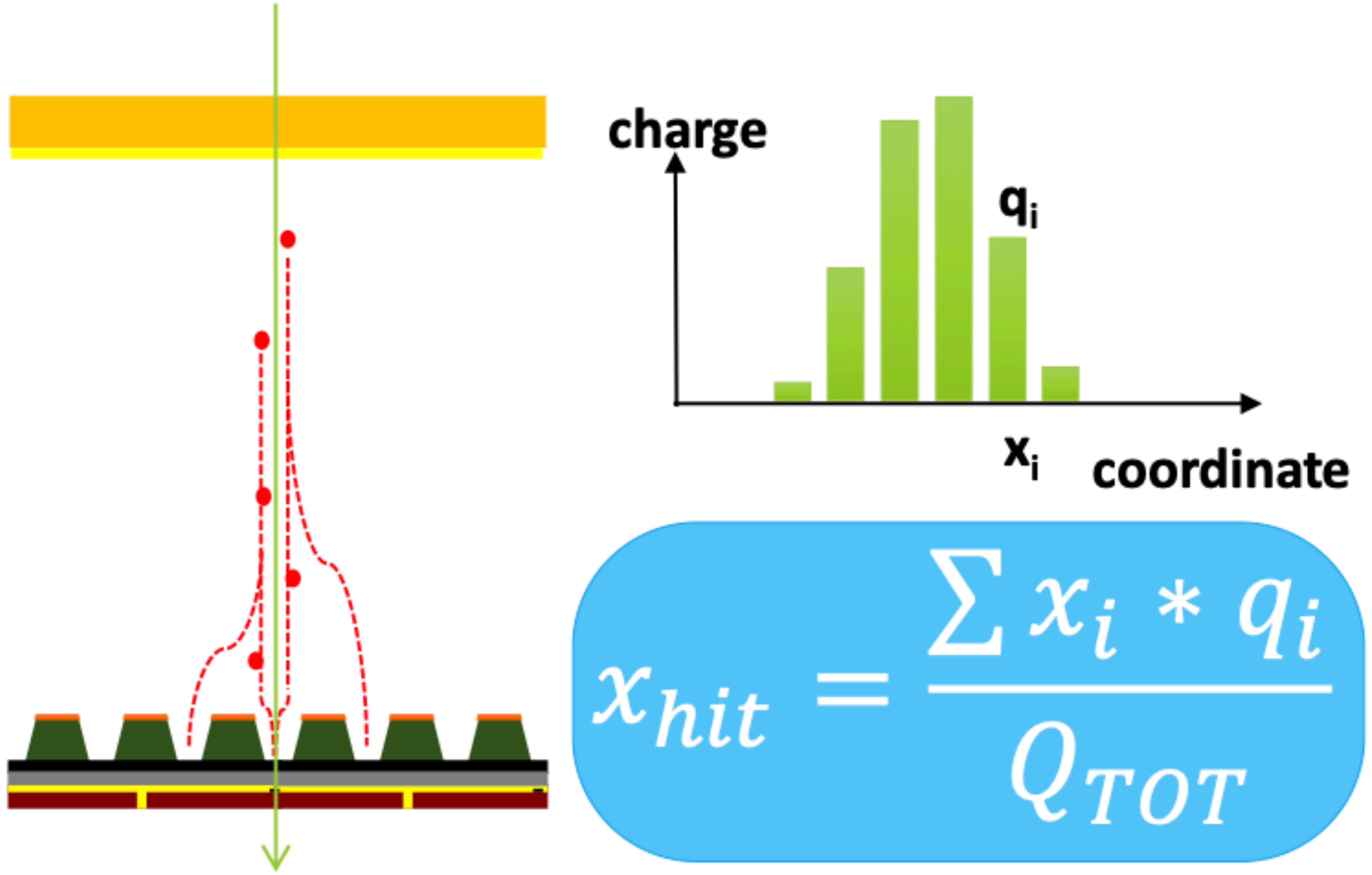




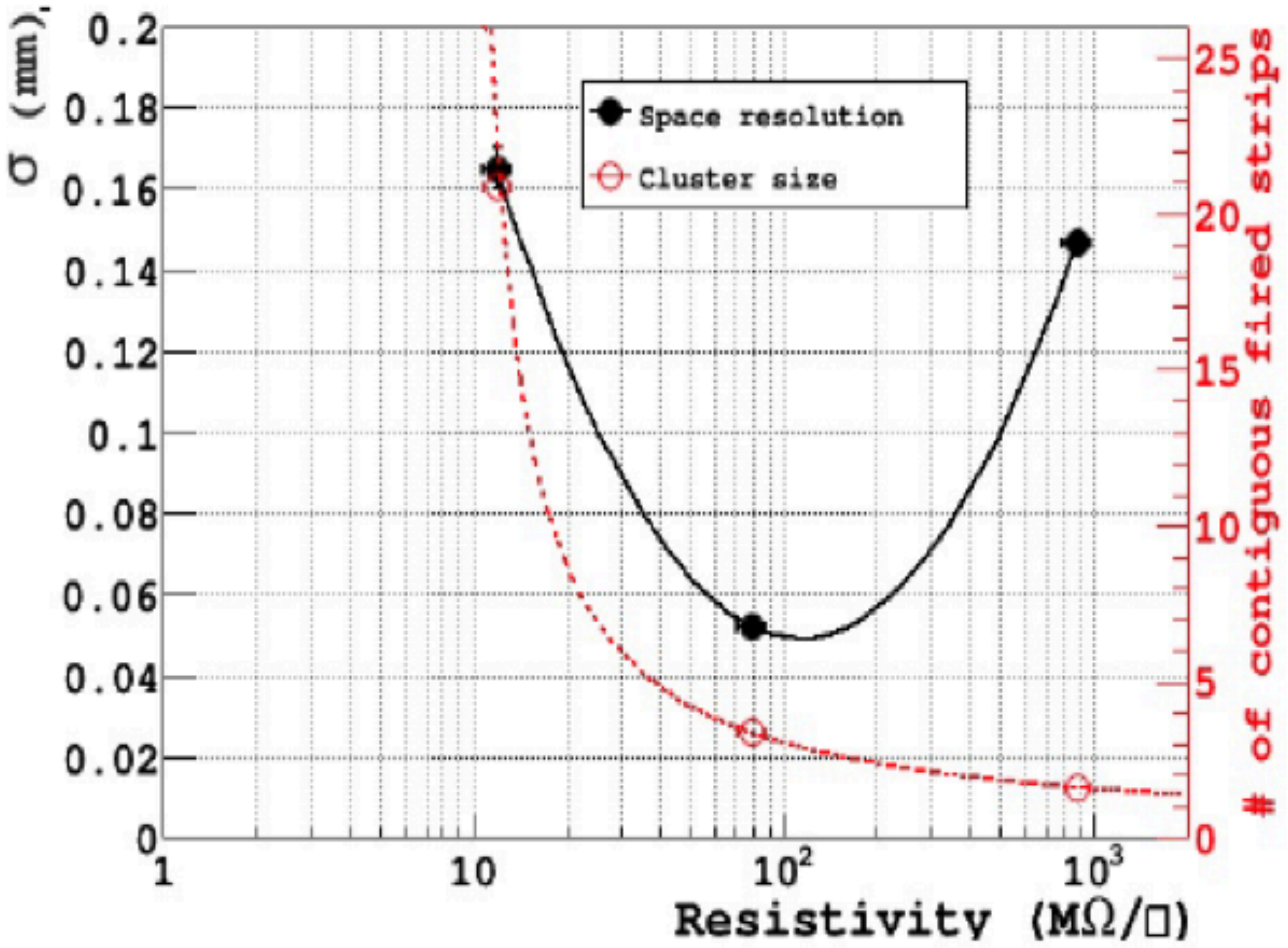
Spatial resolution vs DLC resistivity

1D STRIP READOUT

With the charge centroid analysis (for orthogonal tracks) the track position is determined as a weighted average of fired strips.



$$x_{hit} = \frac{\sum x_i * q_i}{Q_{TOT}}$$

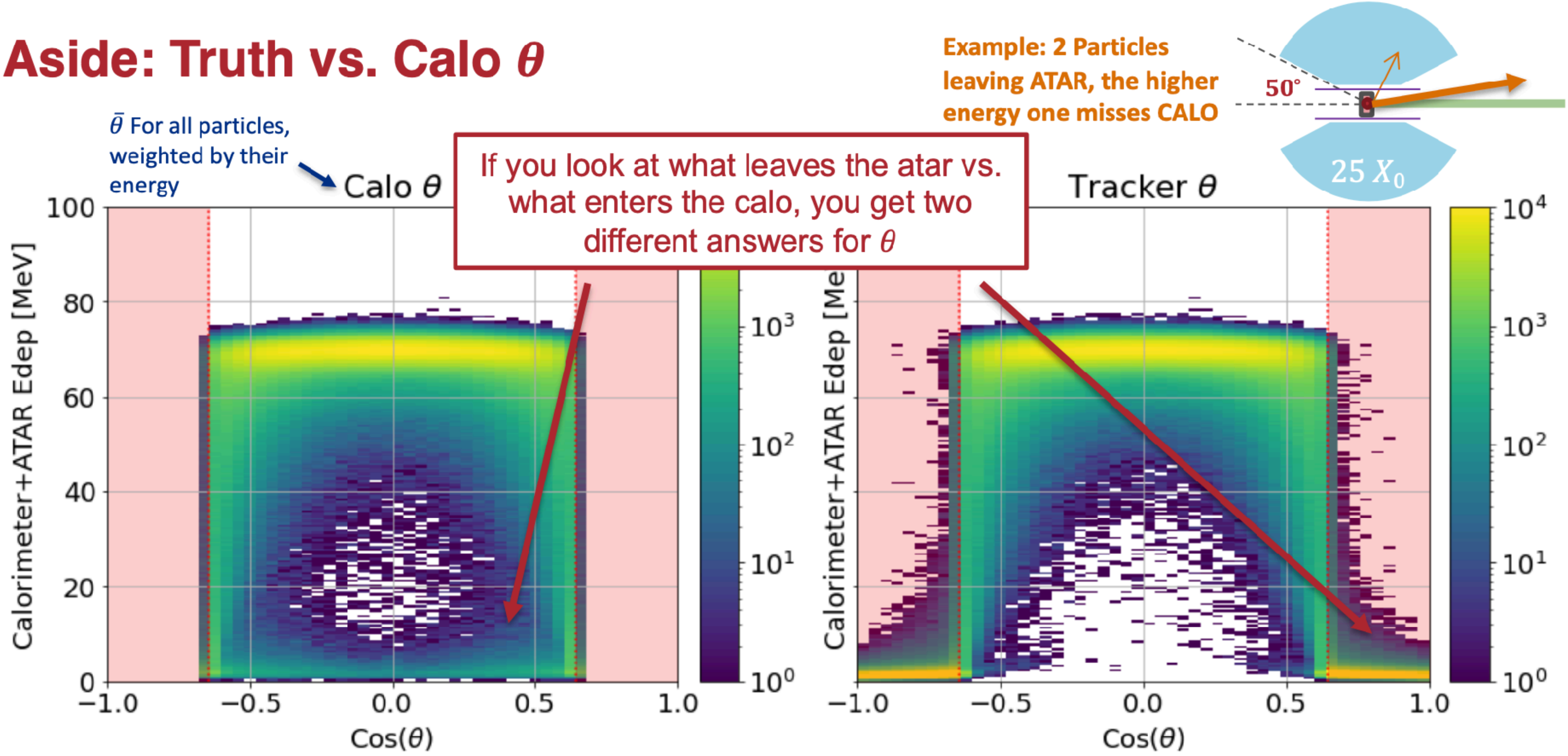


The space resolution exhibits a minimum around 100 MΩ/☐:

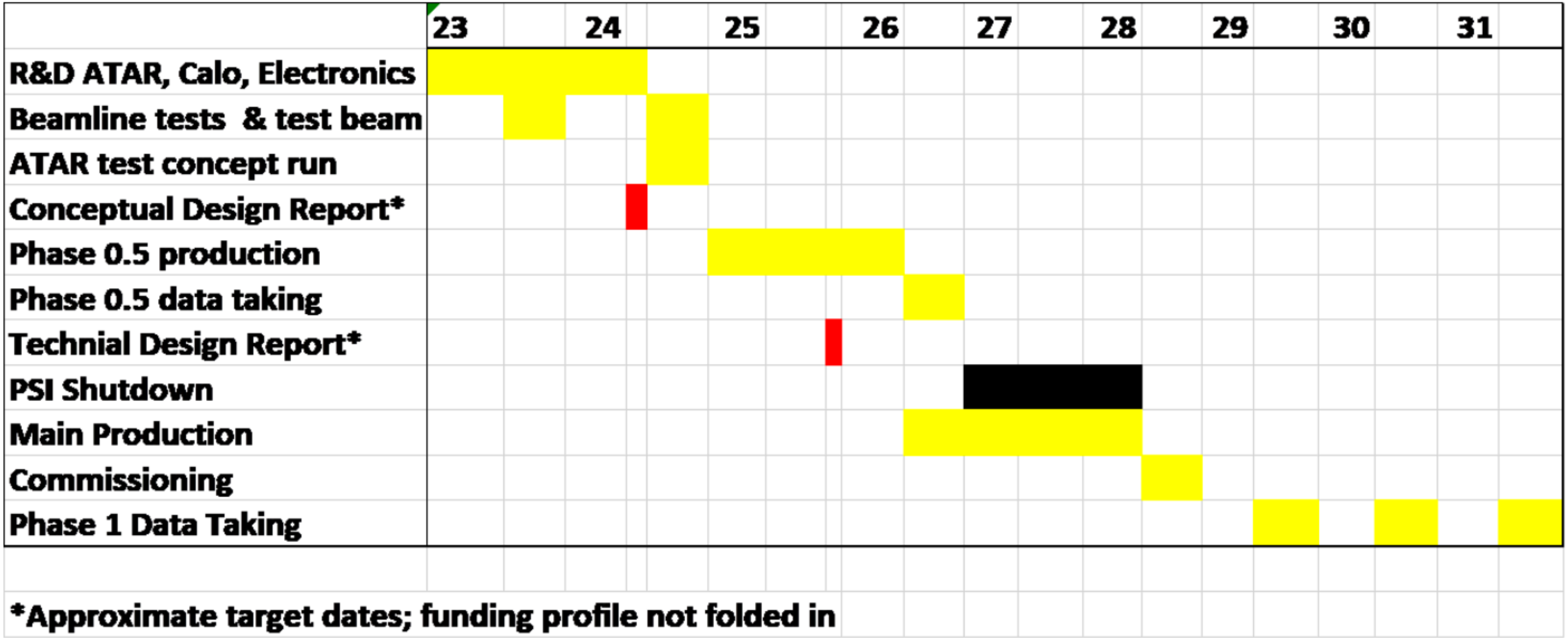
- at low resistivity the charge spread increases and then σ is worsening
- at high resistivity the charge spread is too small (Cluster-size → 1 fired strip) then the Charge Centroid method becomes no more effective (σ → pitch/√12)

Tracker

Aside: Truth vs. Calo θ

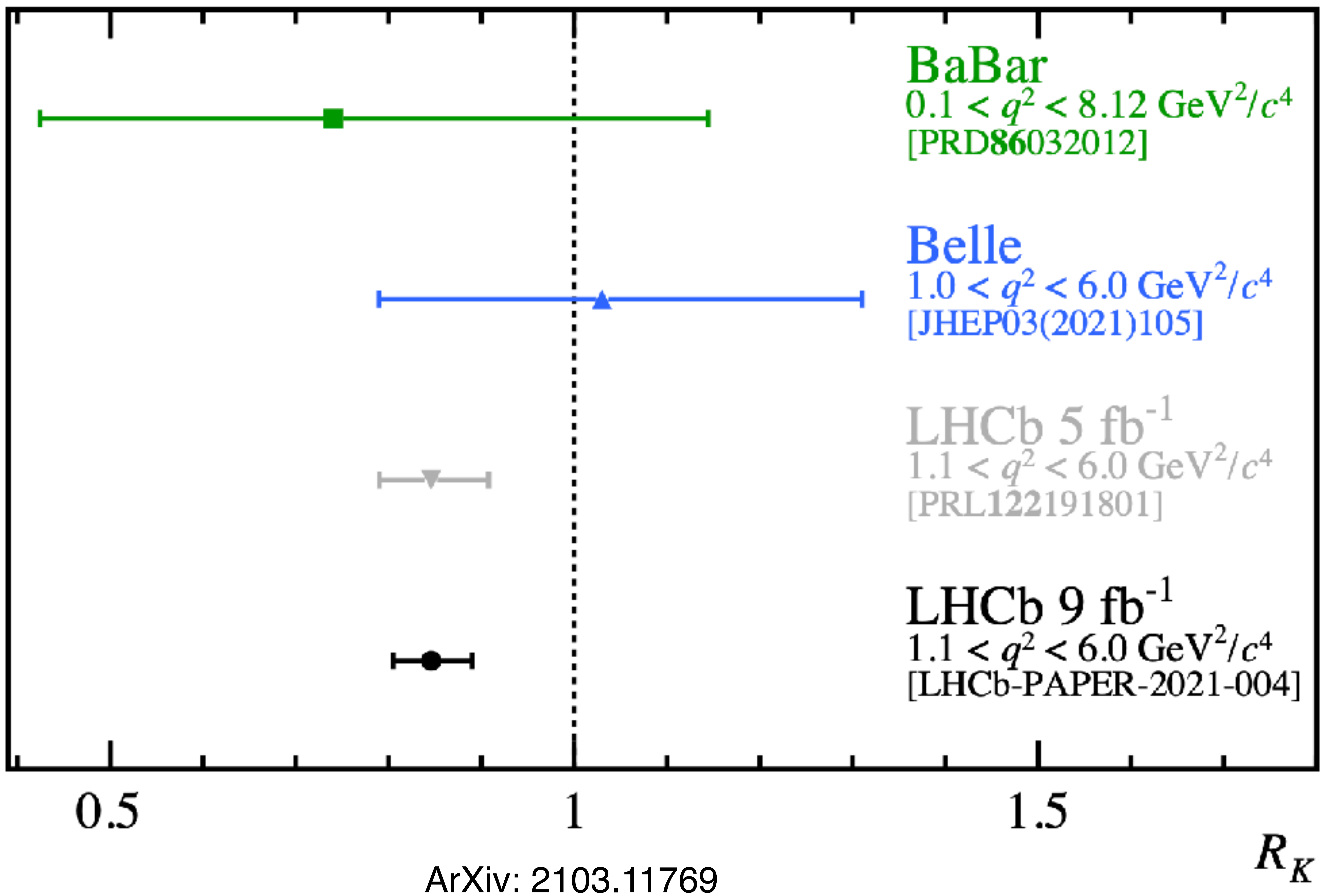


Schedule



23
24
25
26
27
28
29
30
31
R&D ATAR, Calo, Electronics
Beamline tests & test beam
ATAR test concept run
Conceptual Design Report*
Phase 0.5 production
Phase 0.5 data taking
Technial Design Report*
PSI Shutdown
Main Production
Commissioning
Phase 1 Data Taking
*Approximate target dates; funding profile not folded in

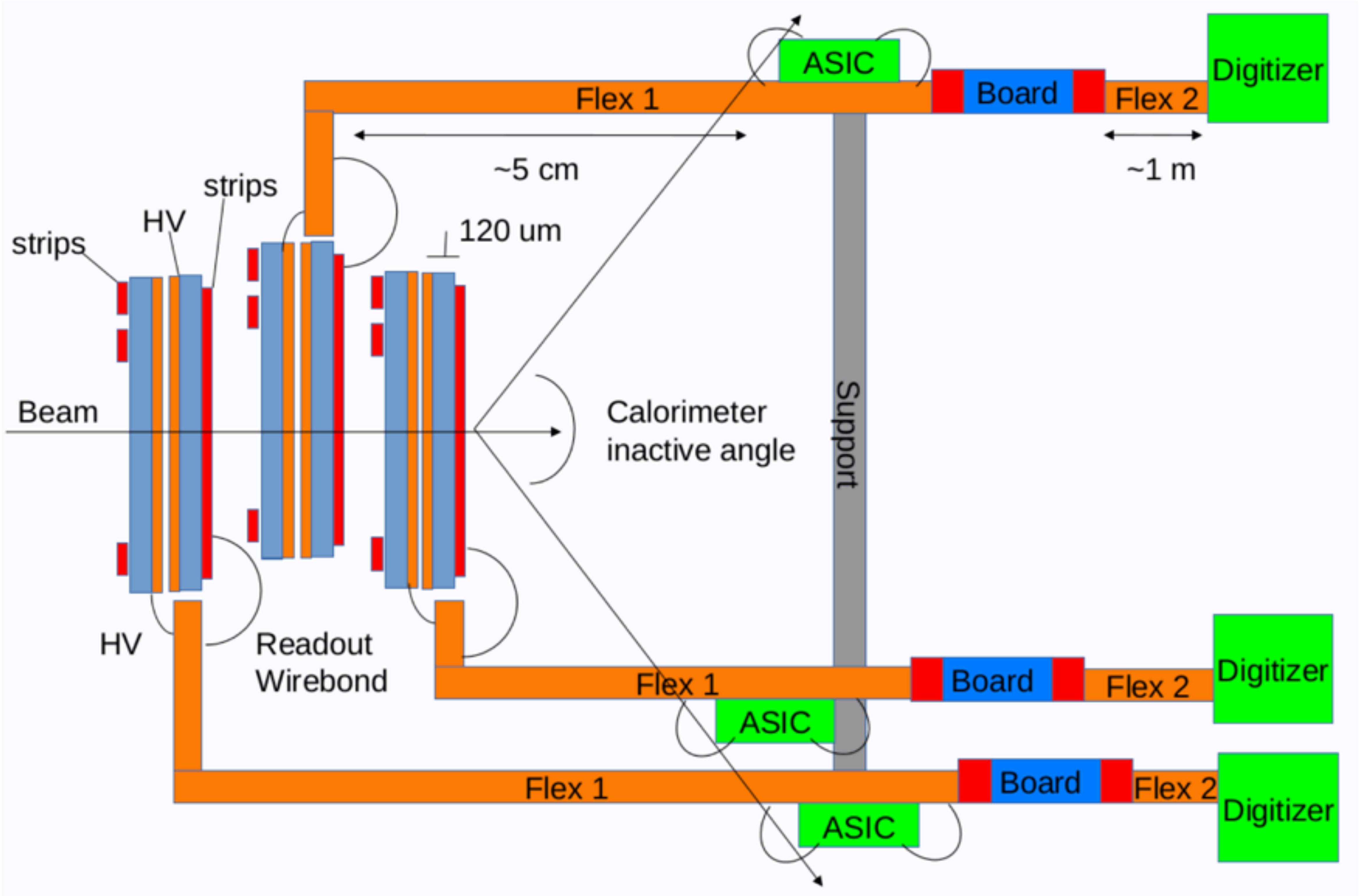
R_K



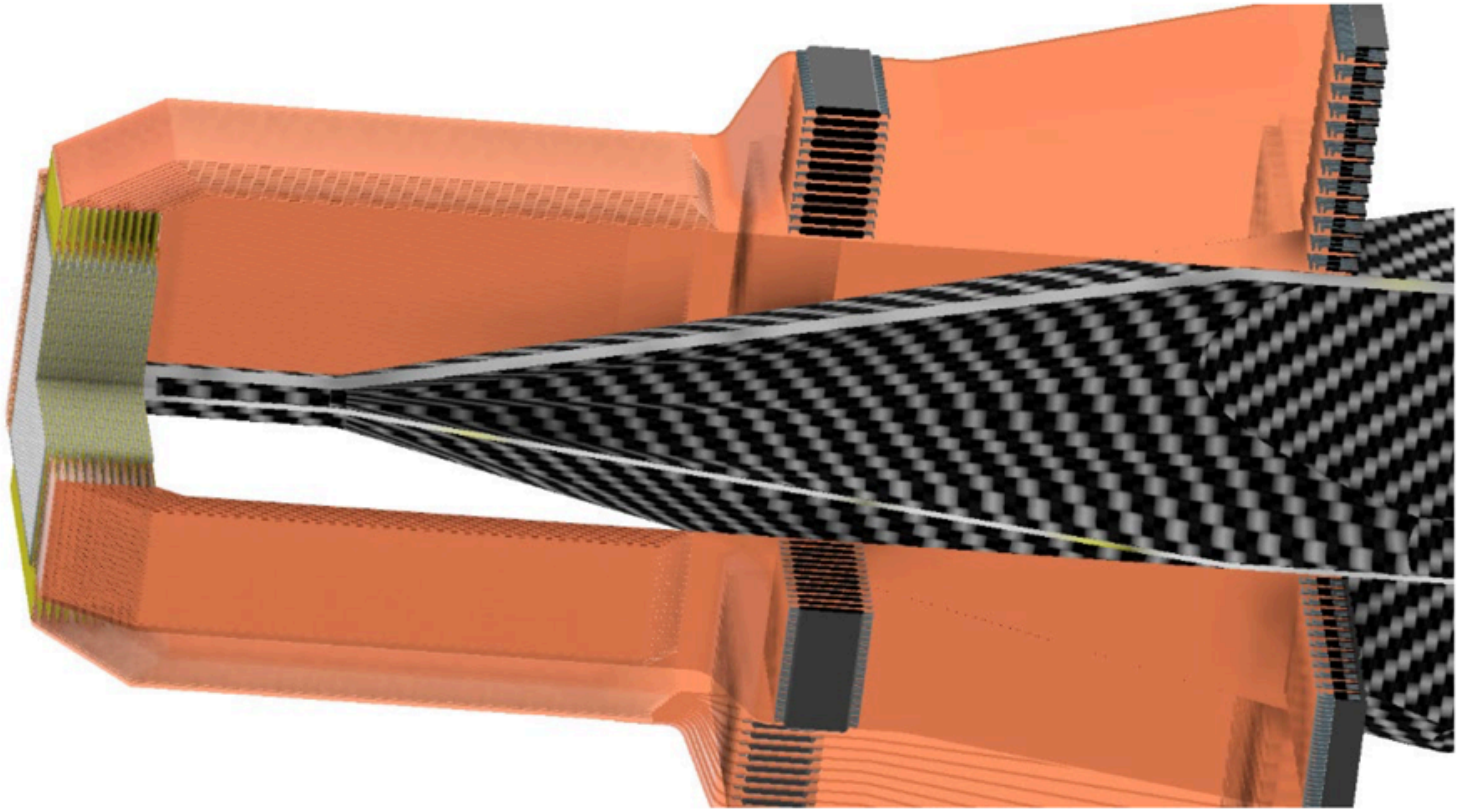
ArXiv: 2103.11769

ATAR

ATAR concept

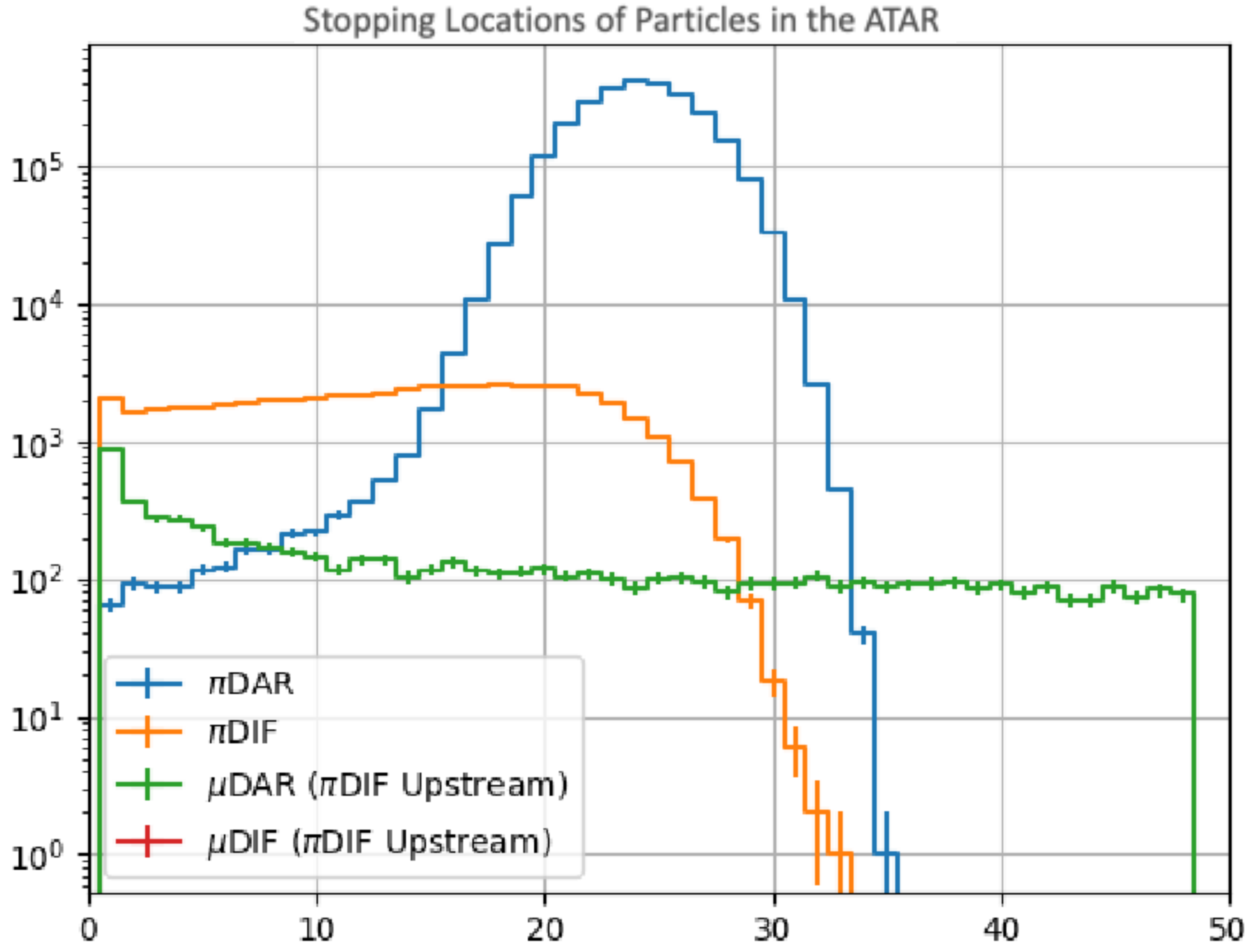


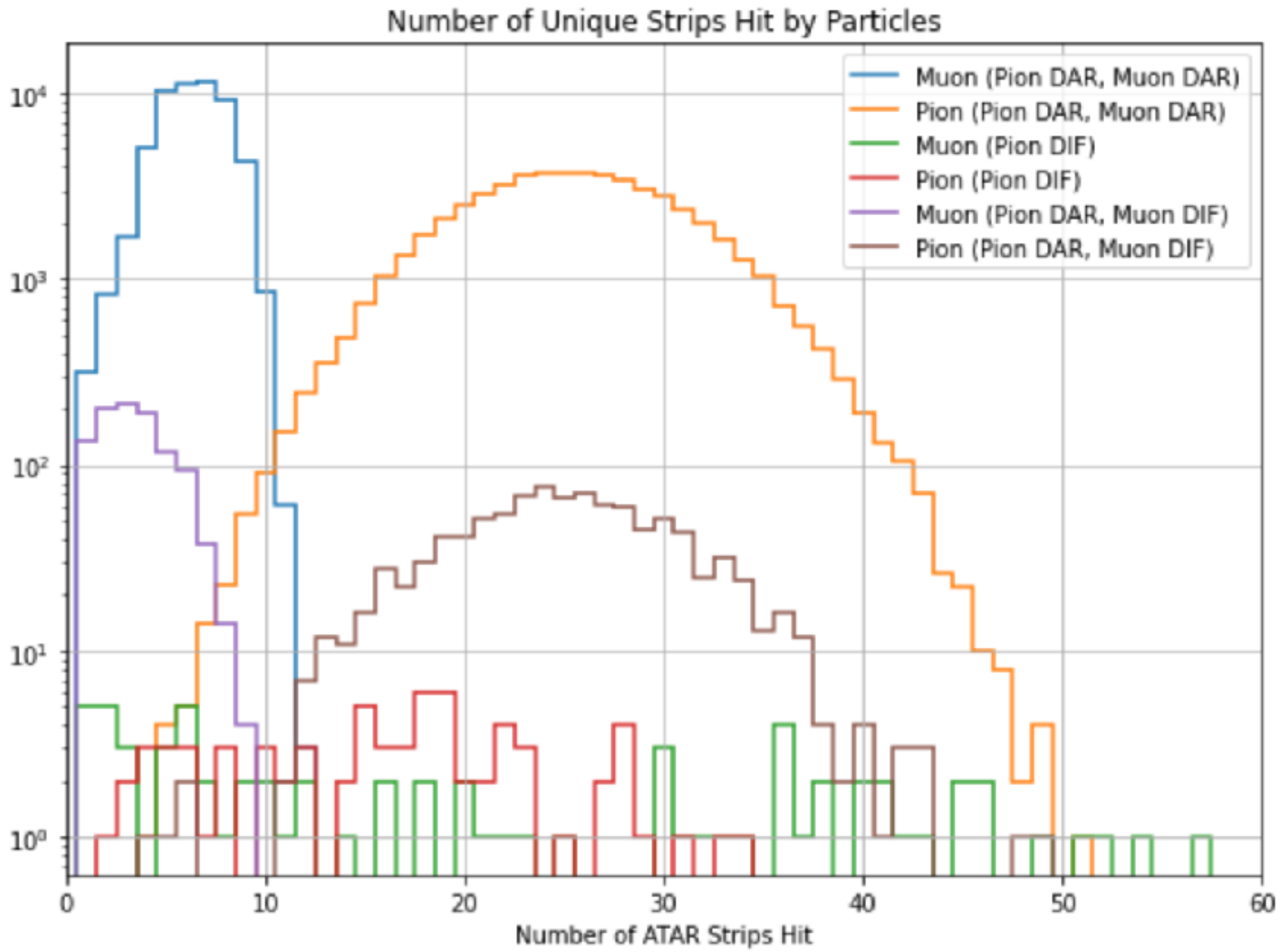
ATAR mechanical drawing



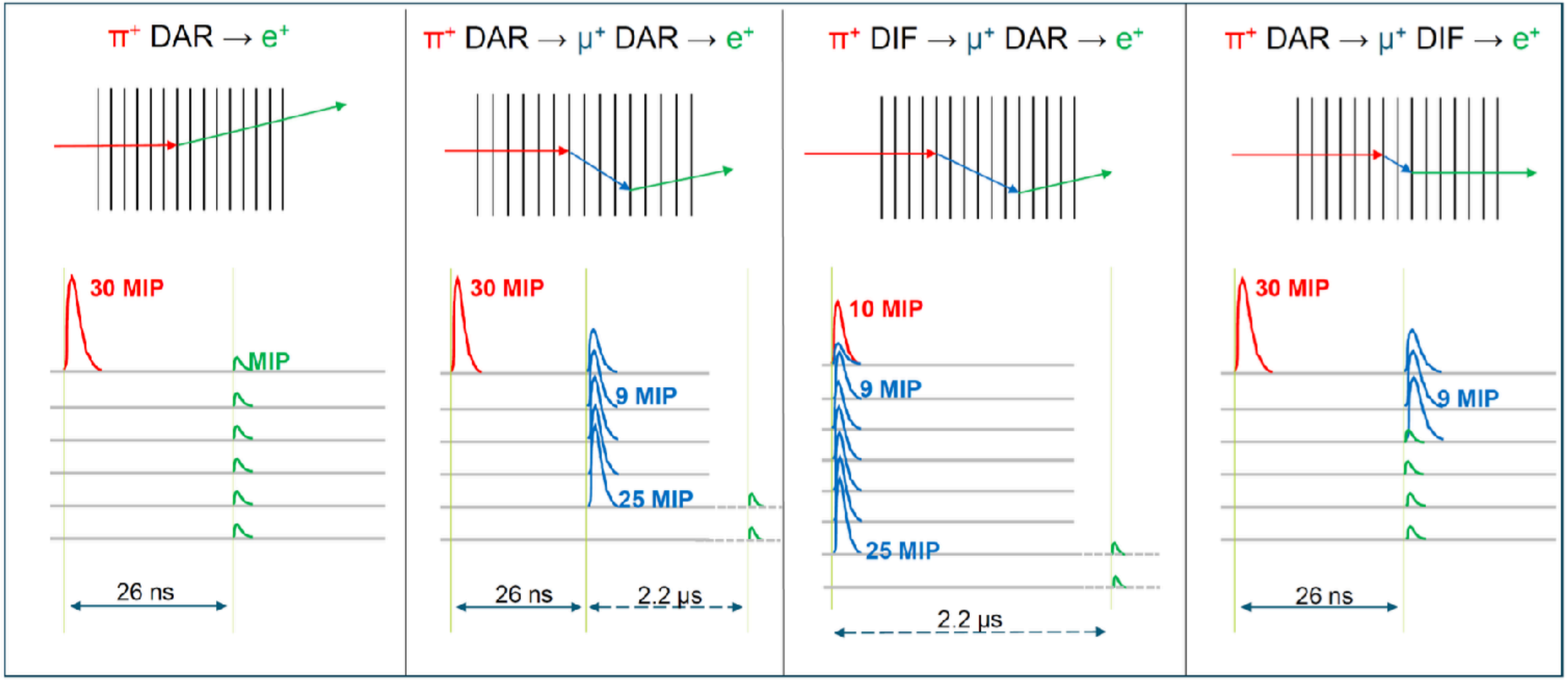
ATAR

- Suppresses backgrounds that severely impacted previous experiments
  - $\pi \to e\nu$ decay in flight (~1/5000)
  - $\mu \to e$ decay in flight (1/20 × ~1/10)



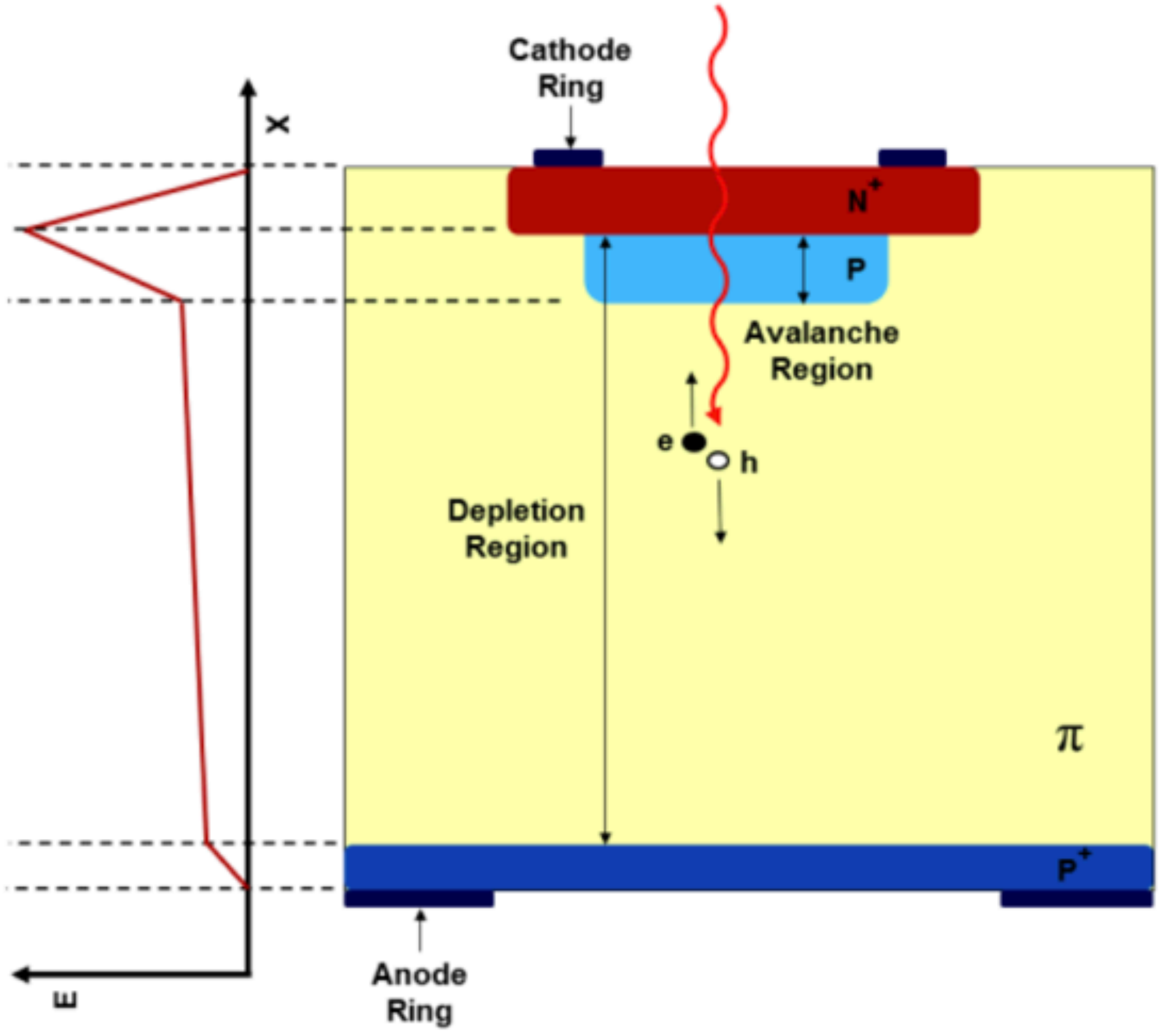


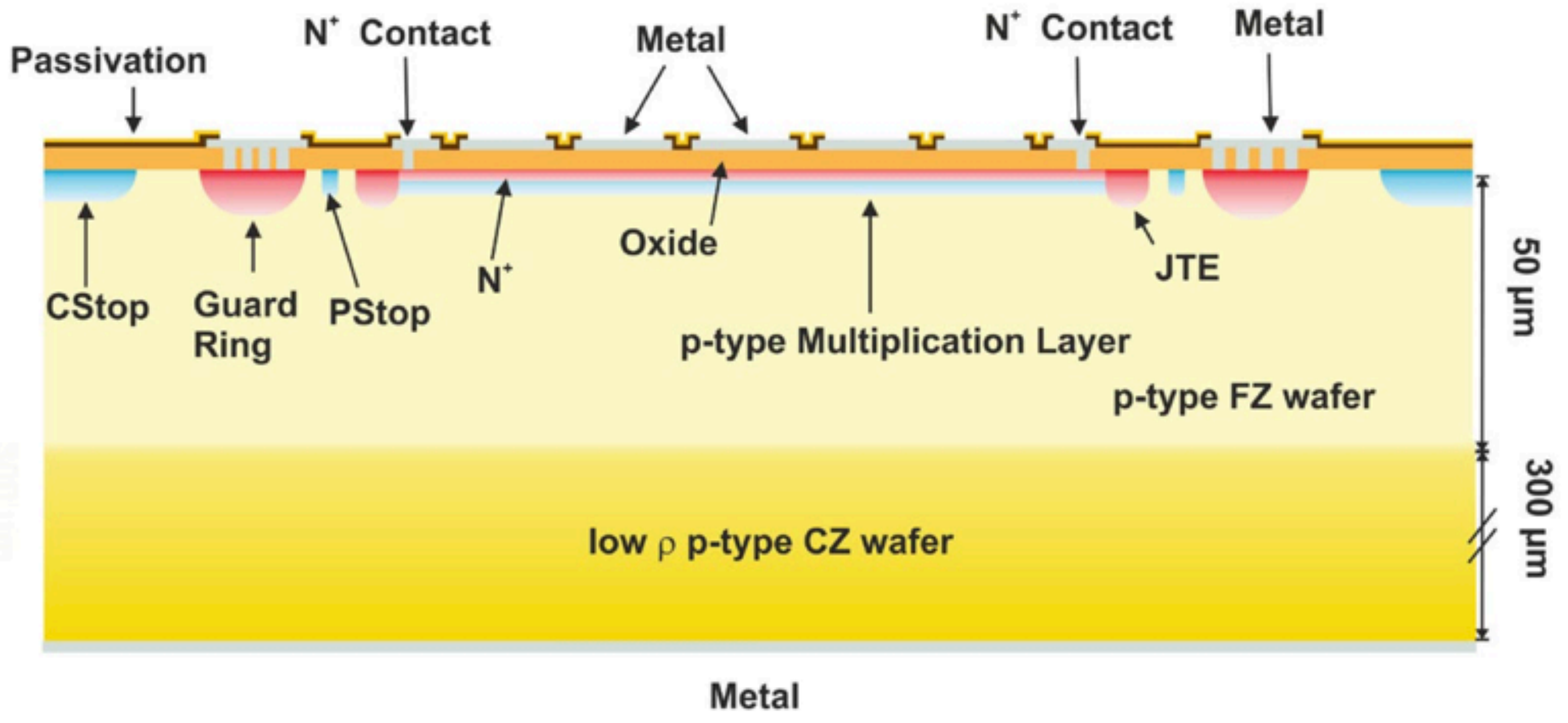
ATAR



- Topology information : 2 vs. 3 tracks
- Timing information : 26ns vs. 26ns + 2.2μs
- Energy information : 10% difference in the energy deposition per unit length between μ and π

AC-LGAD





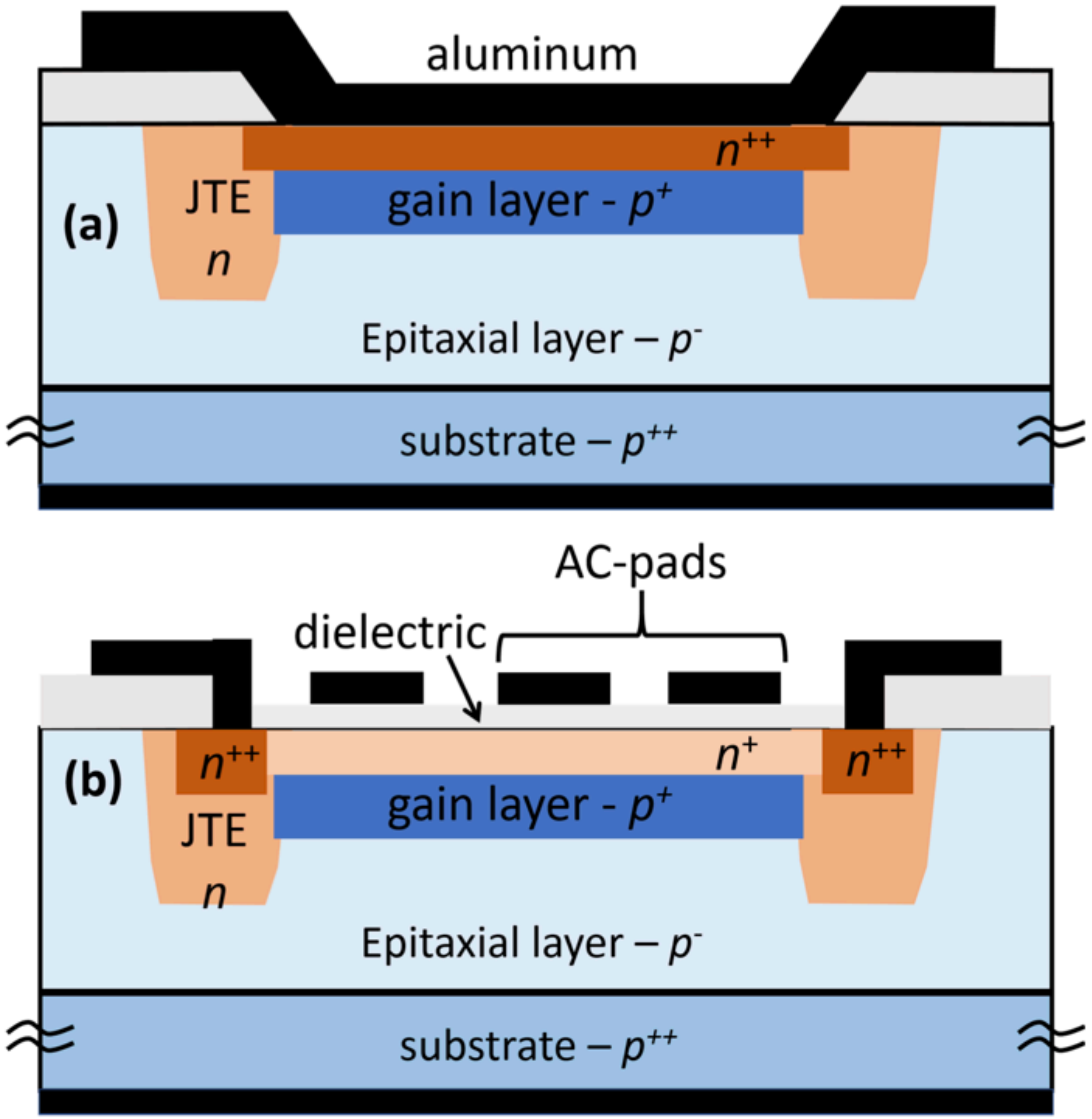
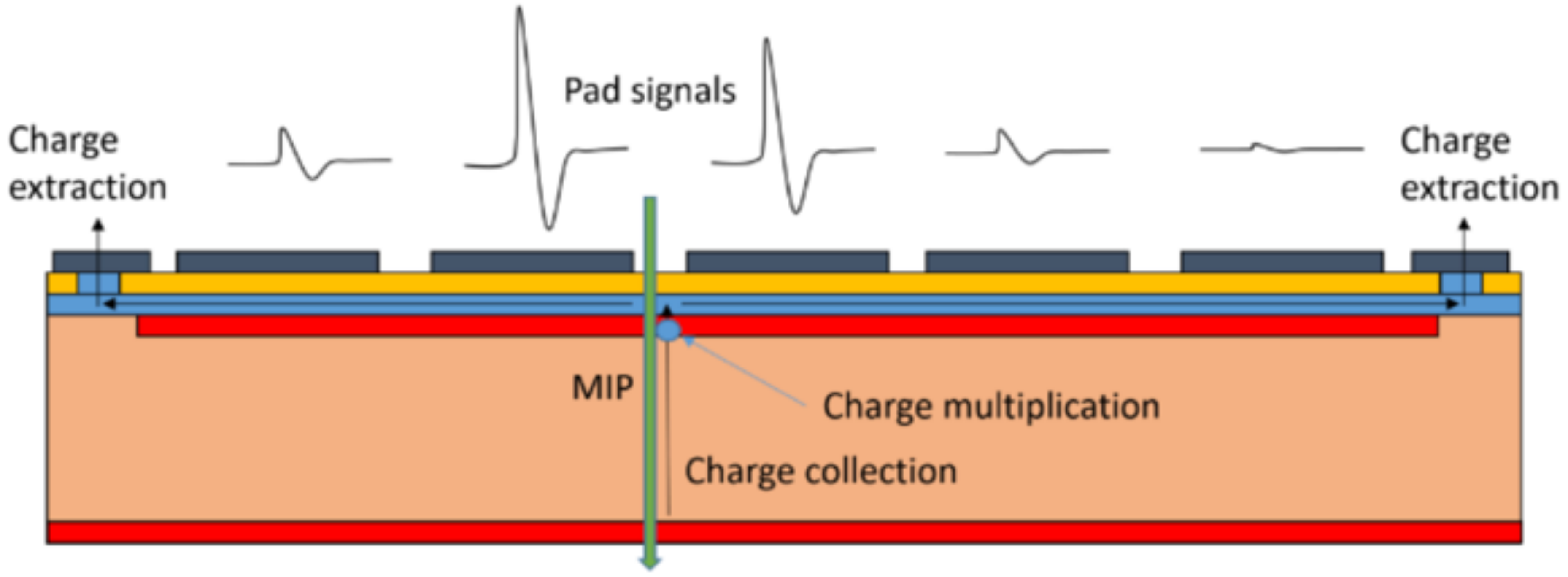


Figure 1. (a) Sketch of a section of a single-pad standard LGAD; (b) sketch of a section of a segmented AC-LGAD (not to scale).

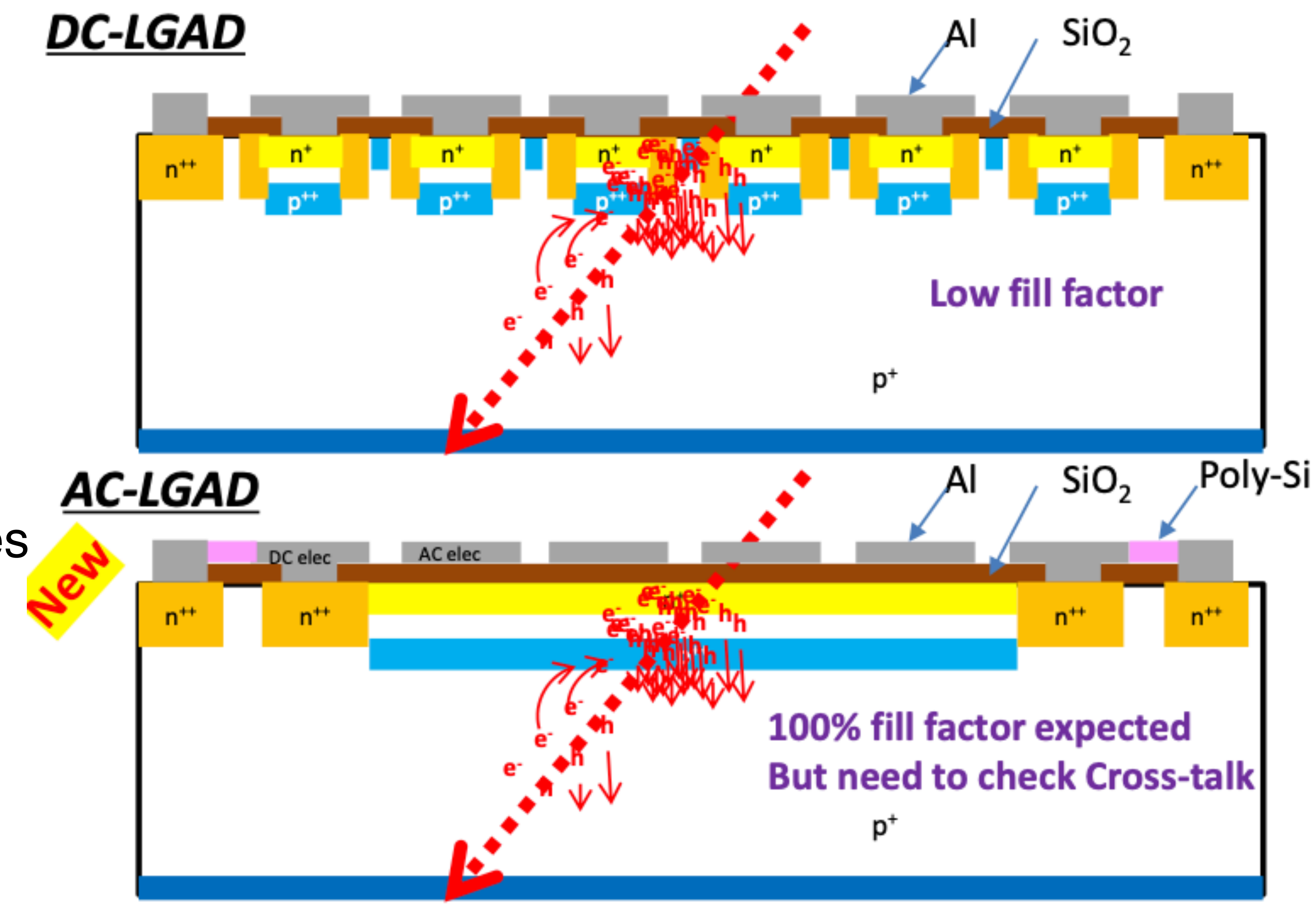
arXiv:1906.11542

AC-LGAD


Pad signals
Charge extraction
Charge extraction
MIP
Charge multiplication
Charge collection

LGAD

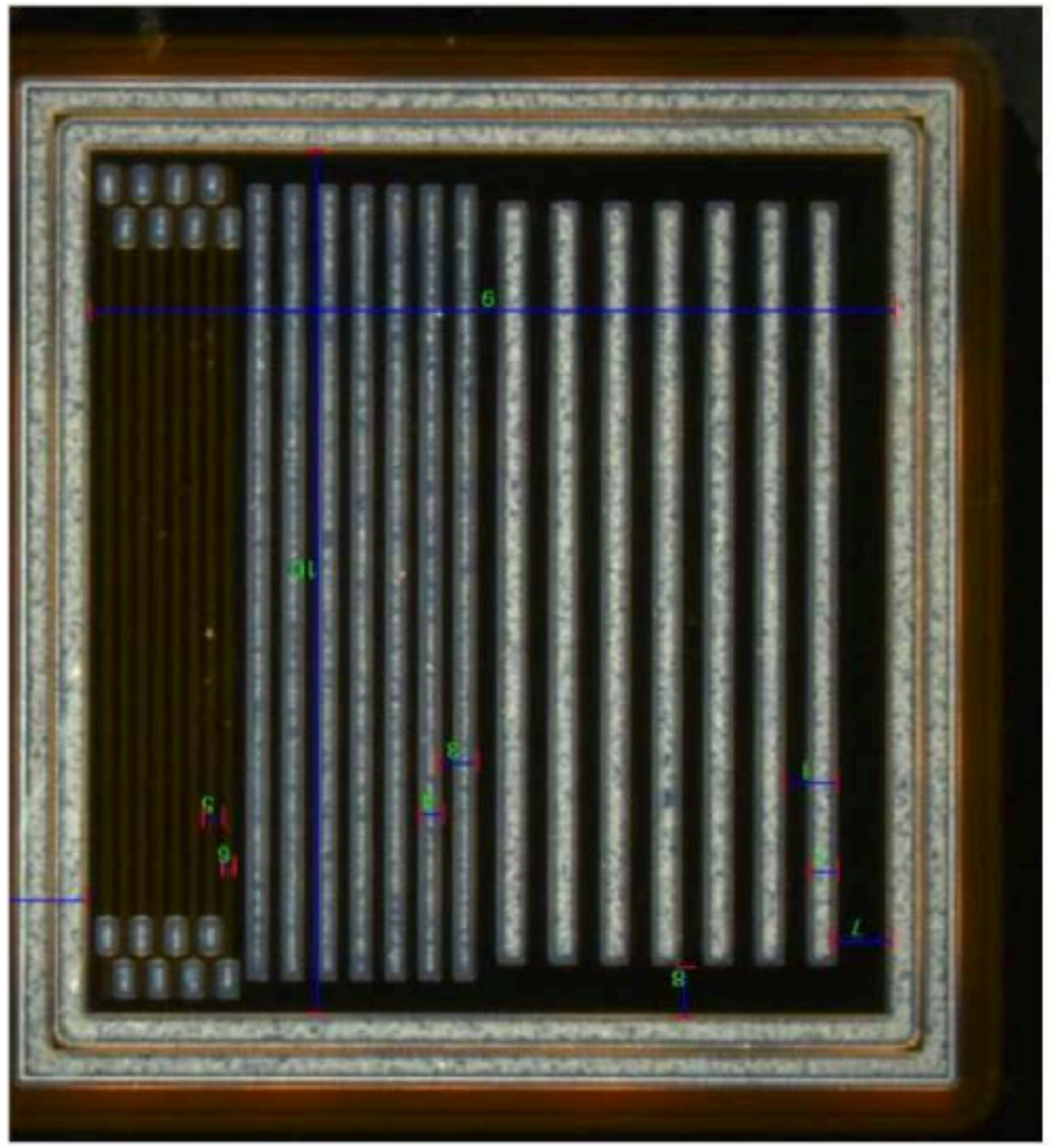
- Low Gain Avalanche Detector
  - General n^+-in-p type sensor with p^+ gain layer under n^+ implant to make higher Electric Field
  - thin detector, modest internal gain (10–50) for better S/N ratio, sharp rise edge
  - → Good time resolution ~ 30ps has been achieved
  - Finer electrode for the good position resolution
    - DC-LGAD has only 20% of active area
- AC-LGAD
  - Common gain layer with AC-coupled readout
    - to reach 100% fill factor
  - Cross-talk expected in the n+ implant
    → Increase resistivity of n+ implant
    referred to as Resistive Silicon Detectors (RSD)
  - Intrinsic charge sharing between metal electrodes
    - allows for hit precision better than $\sqrt{12}$
  - Gain suppression should be studied

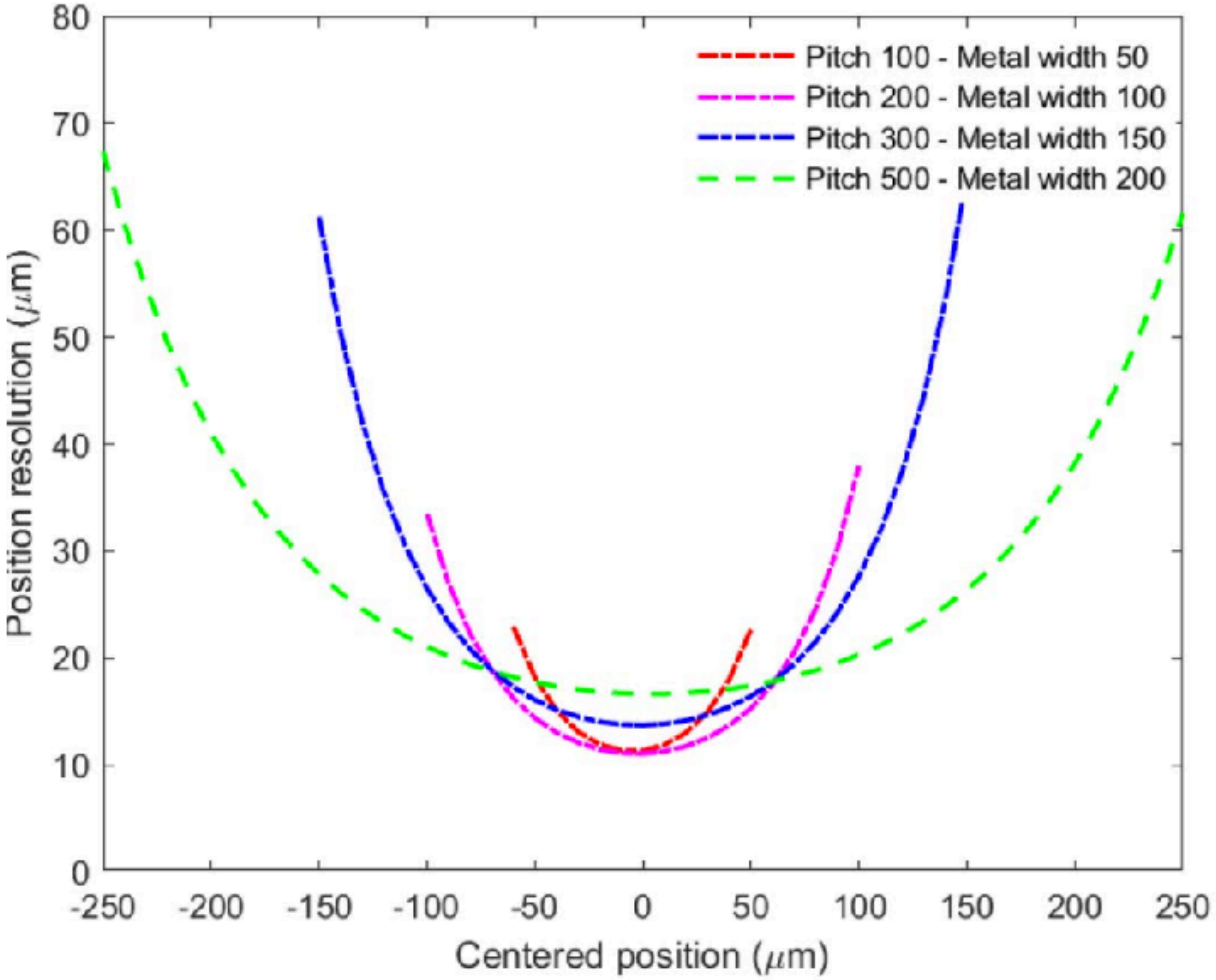


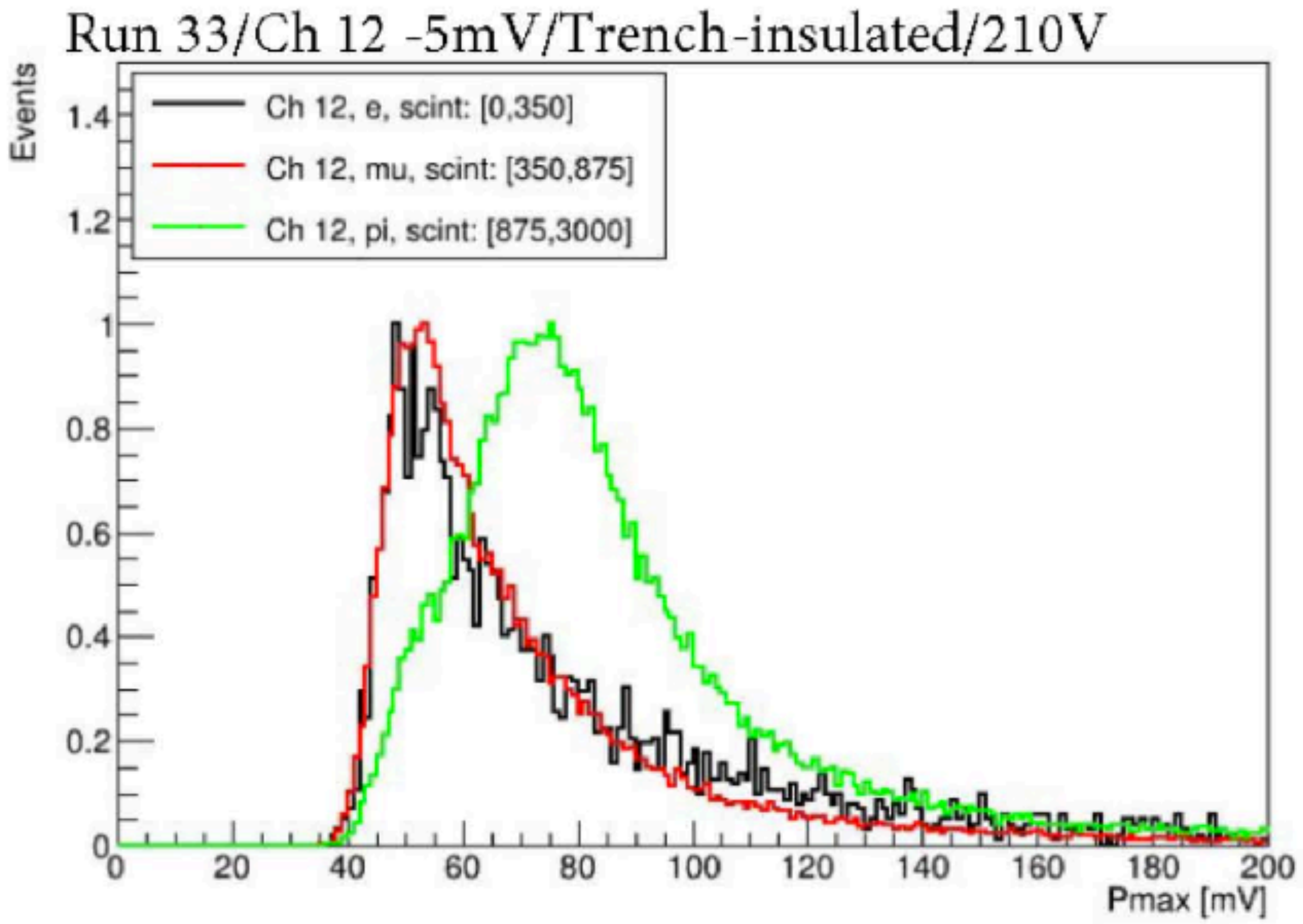
ATAR R&D

- Test device of 50 μm at BNL for different pitches, widths, and lengths
- The PIONEER baseline of 200 μm pitch was proven to be the best solution

BNL strip AC-LGAD

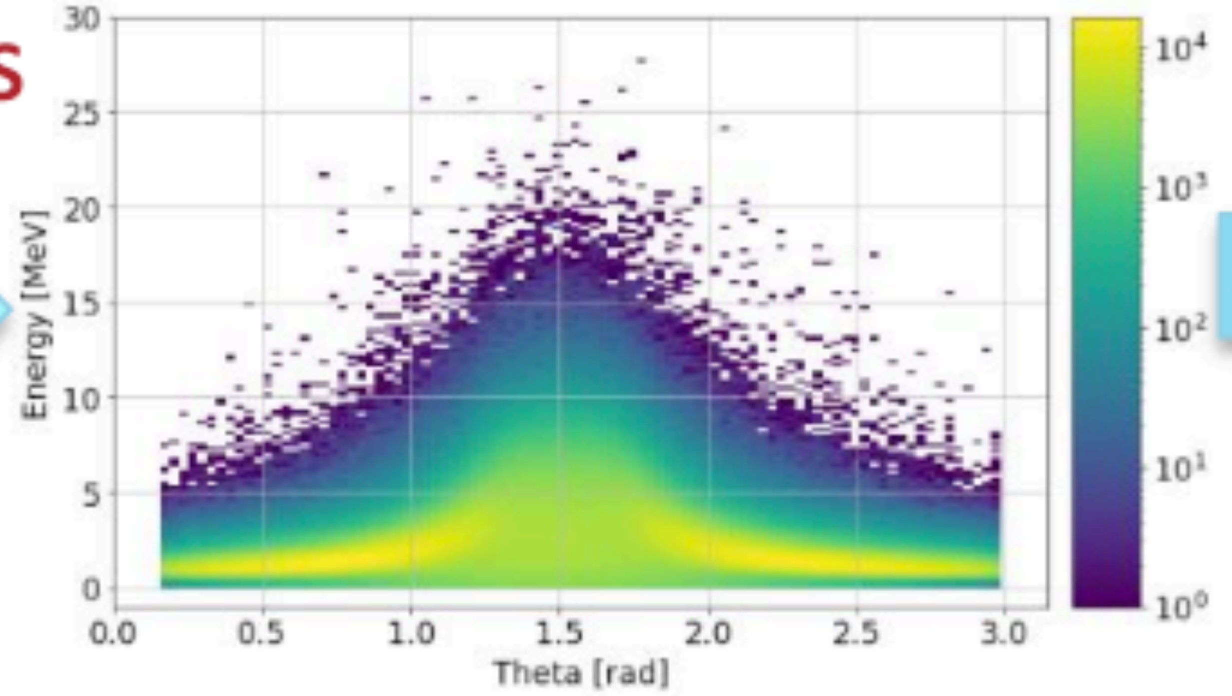


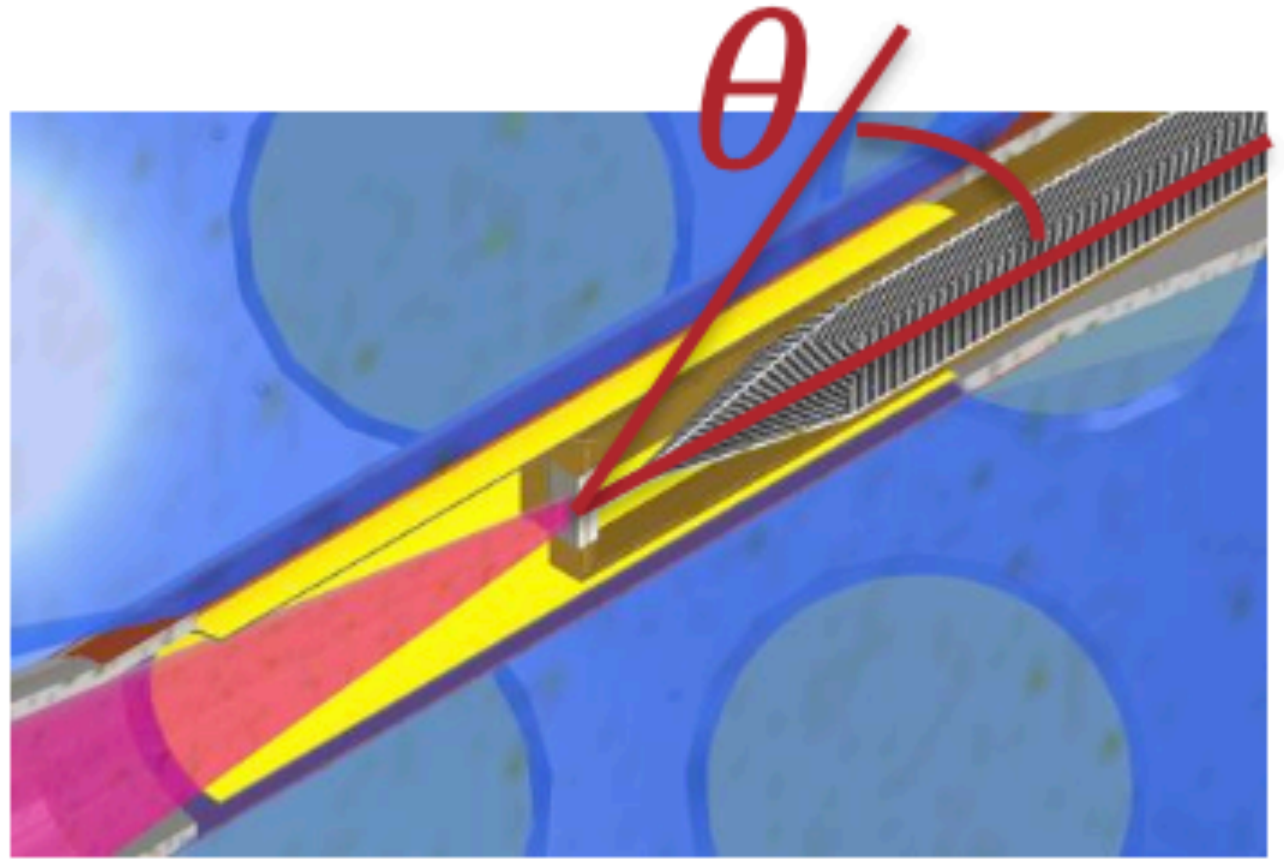


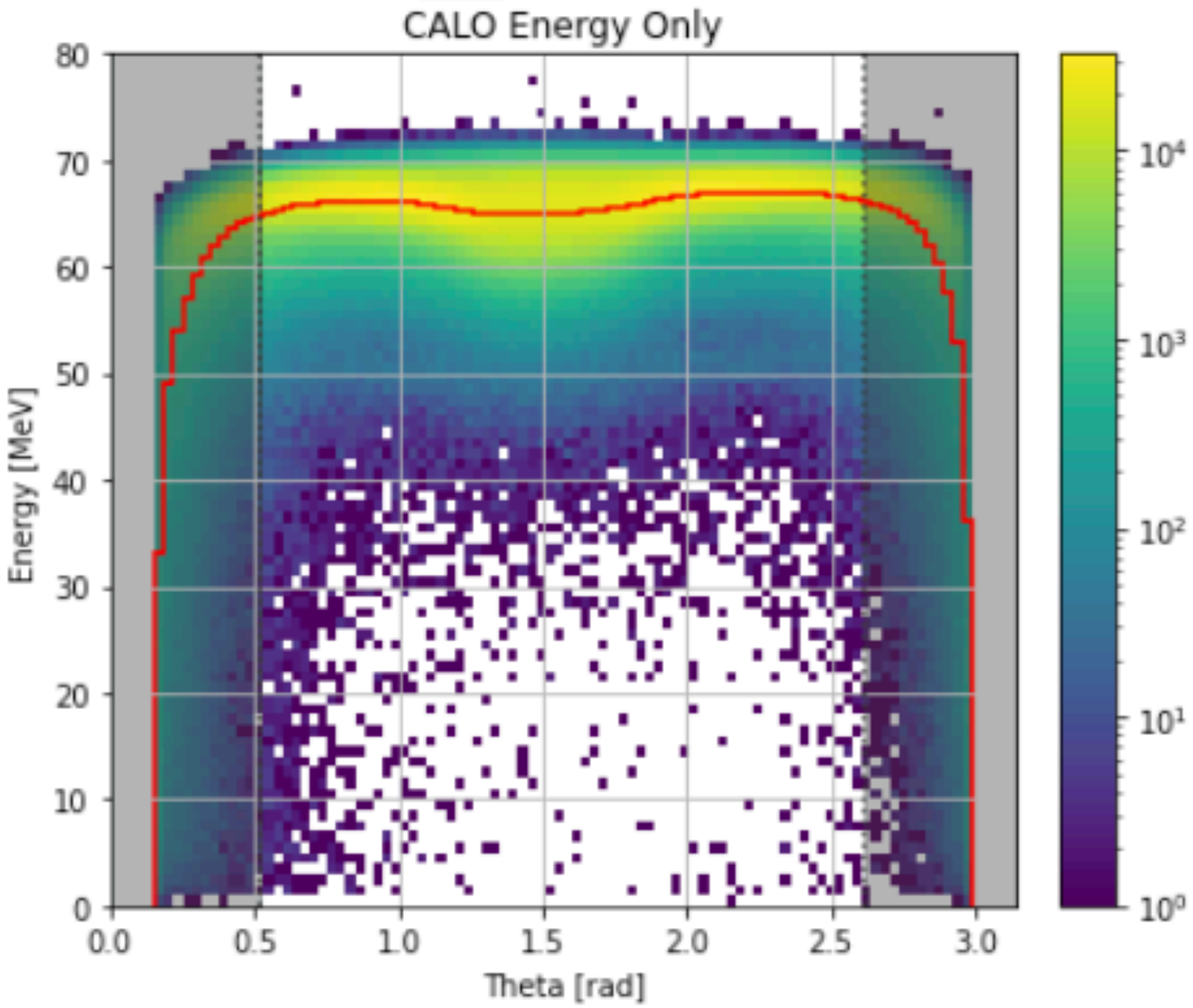


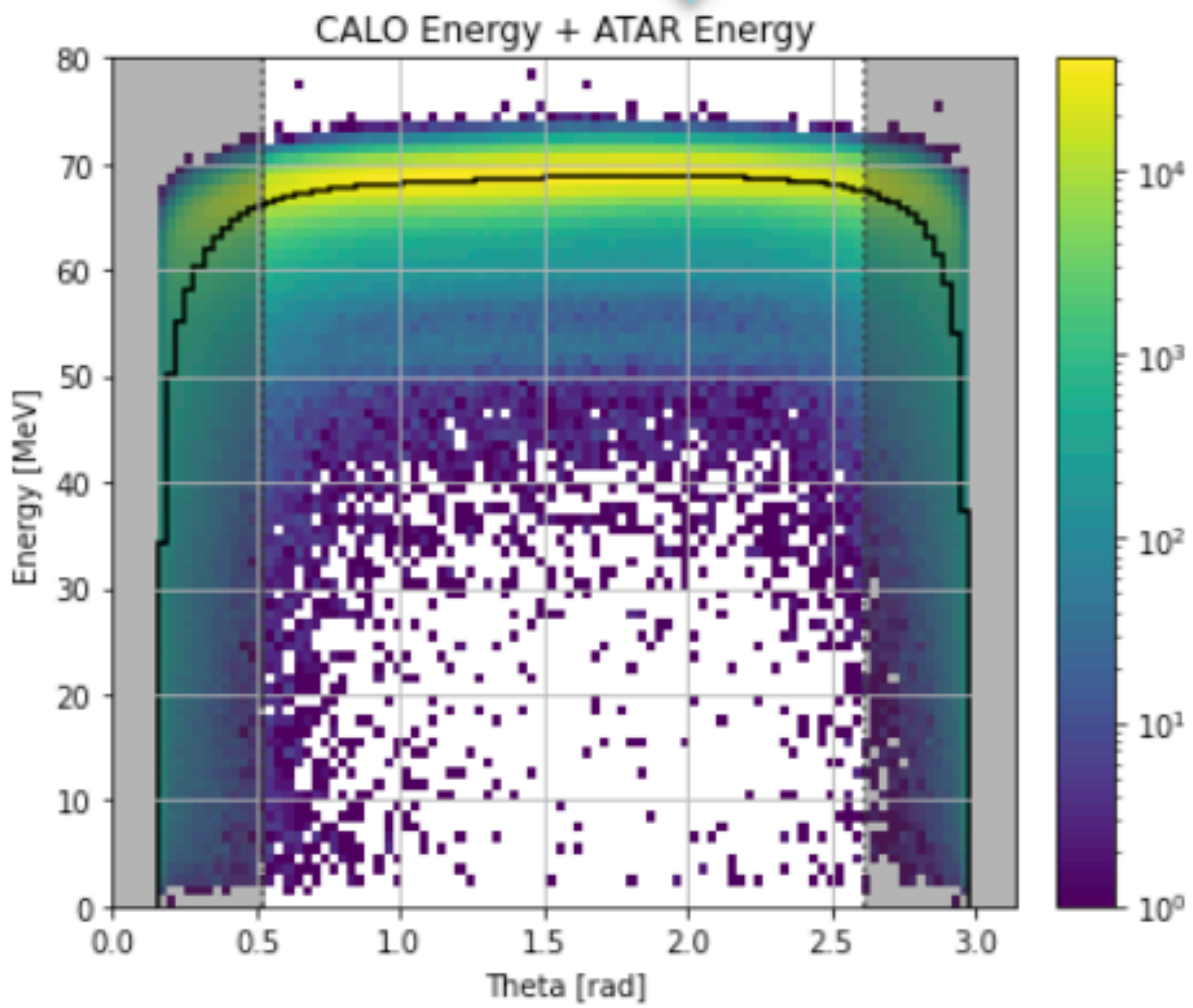
Dead material studies

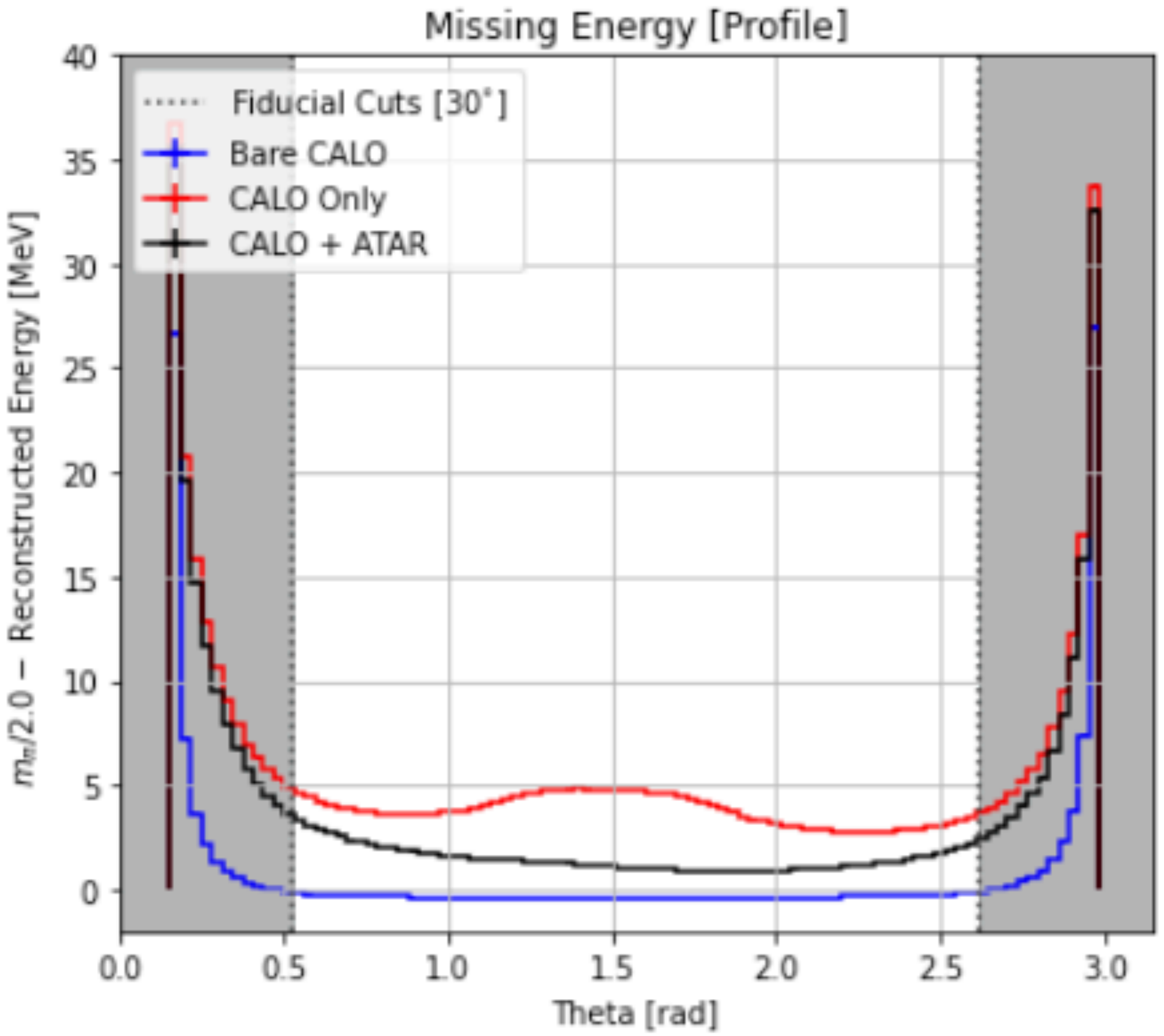
Add ATAR Energy on an event-by-event basis











Current Status

- Proposal presented to PSI review committee in 2022
  - The PSI committee’s report: We enthusiastically support this proposal with high priority
- Snowmass report

Beam test 2023

- Study whether $\pi E1$ can function as an alternative beam line during the development phase of PIONEER
  - Ultimately only $\pi E5$ beam line will deliver sufficient rate for the full experiment
  - Need development work and beam dynamics simulations
  - $\pi E5$ is currently overbooked by MEG II and Mu3e, and we need short test beam times
  - $\pi M1$ is assigned to PIONEER in 2023.

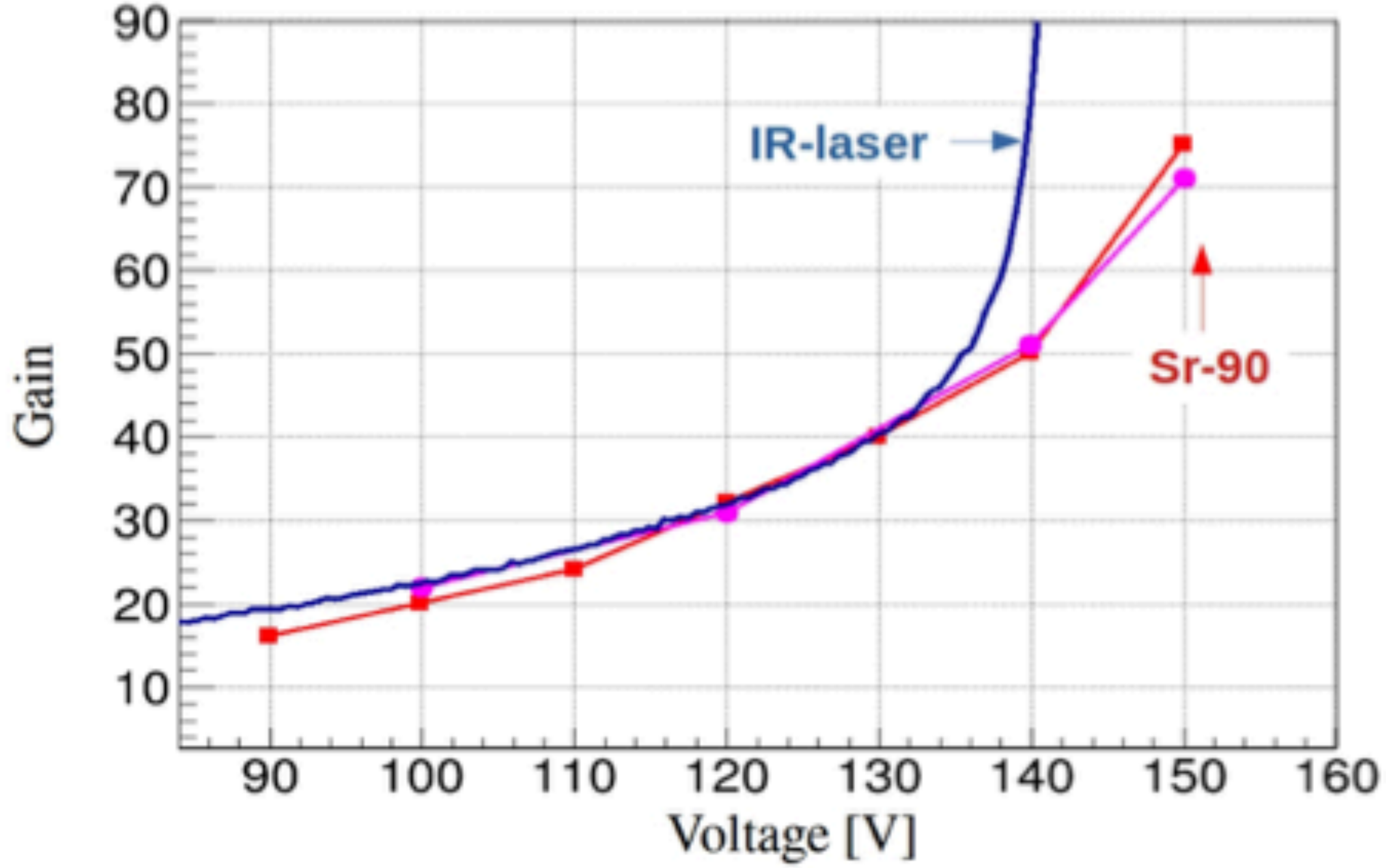
- Development and test critical detector components
  - New ATAR sensors, a prototype for the tracker, a compact crystal calorimeter with electrons

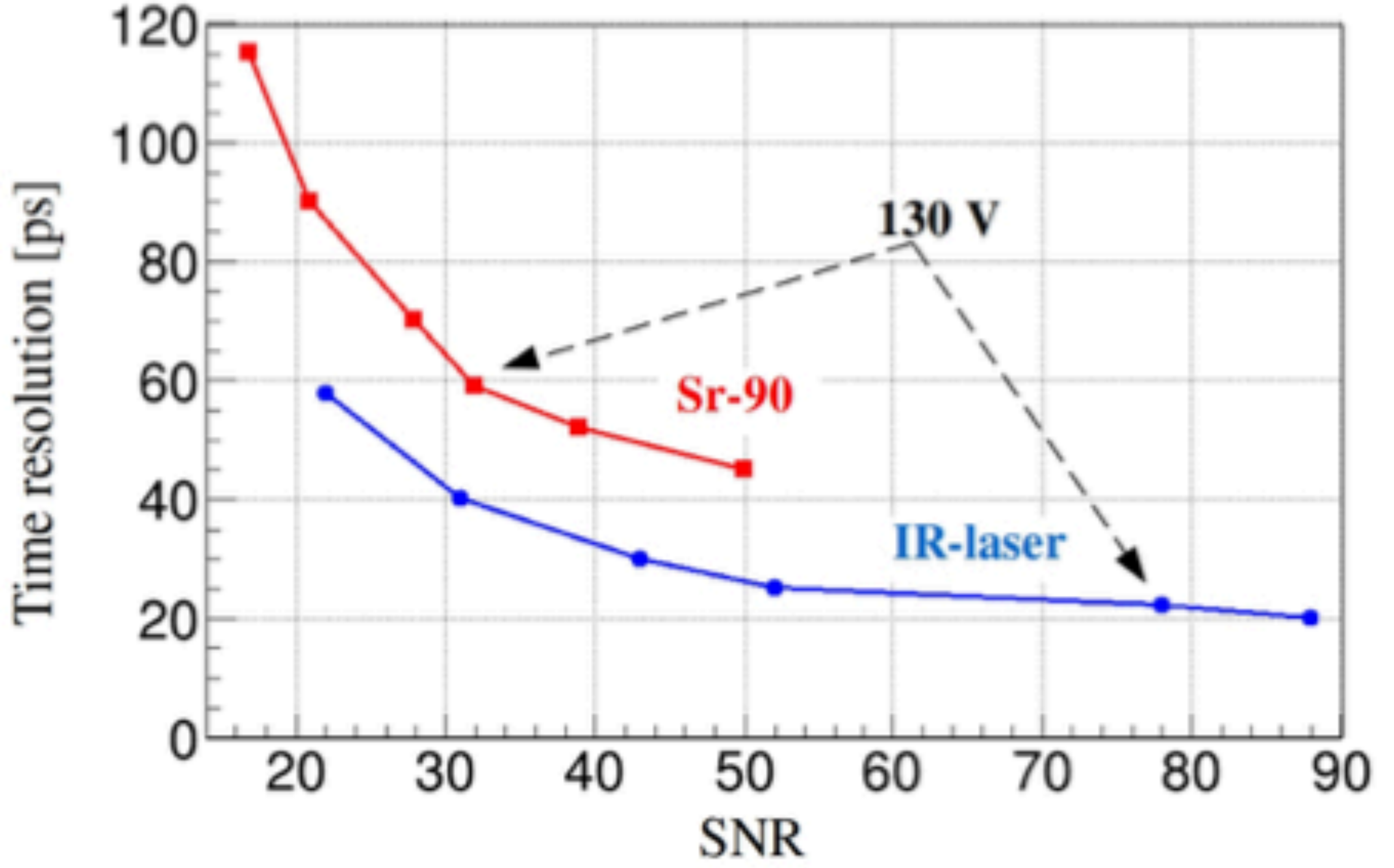
- November - December 2023 for two weeks
  - $\pi E1$, momentum 60–80 MeV/c, $\Delta p/p \leq 2\,\%$ FWHM
  - stopping rate $10^5 \pi^+/s$ around a momentum P=65MeV/c

- If these requirements are met, $\pi E1$ would be suitable not only for detector development, but might allow a limited production run at the precision level of current experiments (PIENU, PEN) before the 2027 shutdown

LGAD gain suppression

ArXiv: 2107.10022





- Gain depends on the charge density projected into the gain layer, generated by a laser (lower charge density) or a charged particle (higher charge density) in the bulk
- Too many charge carriers inside a small gain layer volume will produce a local reduction in the electric field, a screening effect, resulting in a lower gain

$R^{\pi}_{e/\mu}$ Calculation

- Chiral perturbation theory (ChPT)
  - low energy effective field theory (EFT) of QCD

$$R^P_{e/\mu} = \bar{R}^P_{e/\mu}\left[1 + \Delta^P_{e^2Q^0} + \Delta^P_{e^2Q^2} + \Delta^P_{e^2Q^4} + \ldots + \Delta^P_{e^4Q^0} + \ldots\right]$$

$$\bar{R}^P_{e/\mu} = \frac{m_e^2}{m_\mu^2}\left(\frac{m_P^2 - m_e^2}{m_P^2 - m_\mu^2}\right)^2$$

$\Delta^P_{e^2Q^0}$: electromagnetic correction point-like approximation for pions

$$\Delta^P_{e^2Q^2} \sim (\alpha/\pi)(m_P/\Lambda_\chi)^2$$

$$\Delta^P_{e^2Q^4} \sim (\alpha/\pi)(m_P/\Lambda_\chi)^4 (m_P/m_e)^2$$

$$\Delta^P_{e^4Q^0,LL} = (7/2)(\alpha/\pi \log m_\mu/m_e)^2$$

- $Q \sim m_\pi/\Lambda_\chi, \Lambda_\chi \sim 4\pi F_\pi \sim 1.2$ GeV
- $F_\pi \simeq 92.4$ MeV: pion decay constant
- e: electromagnetic coupling

$$R(\mathrm{SM})^\pi_{e/\mu} = 1.23524(15) \times 10^{-4}$$

$$\Delta^\pi_{e^2Q^0} = -3.929\%$$

$$\Delta^\pi_{e^2Q^2} = 0.053(11)\%$$

$$\Delta^\pi_{e^2Q^4} = 0.073(3)\%$$

$$\Delta^{(\pi)}_{e^4Q^0} = 0.055(3)\%$$

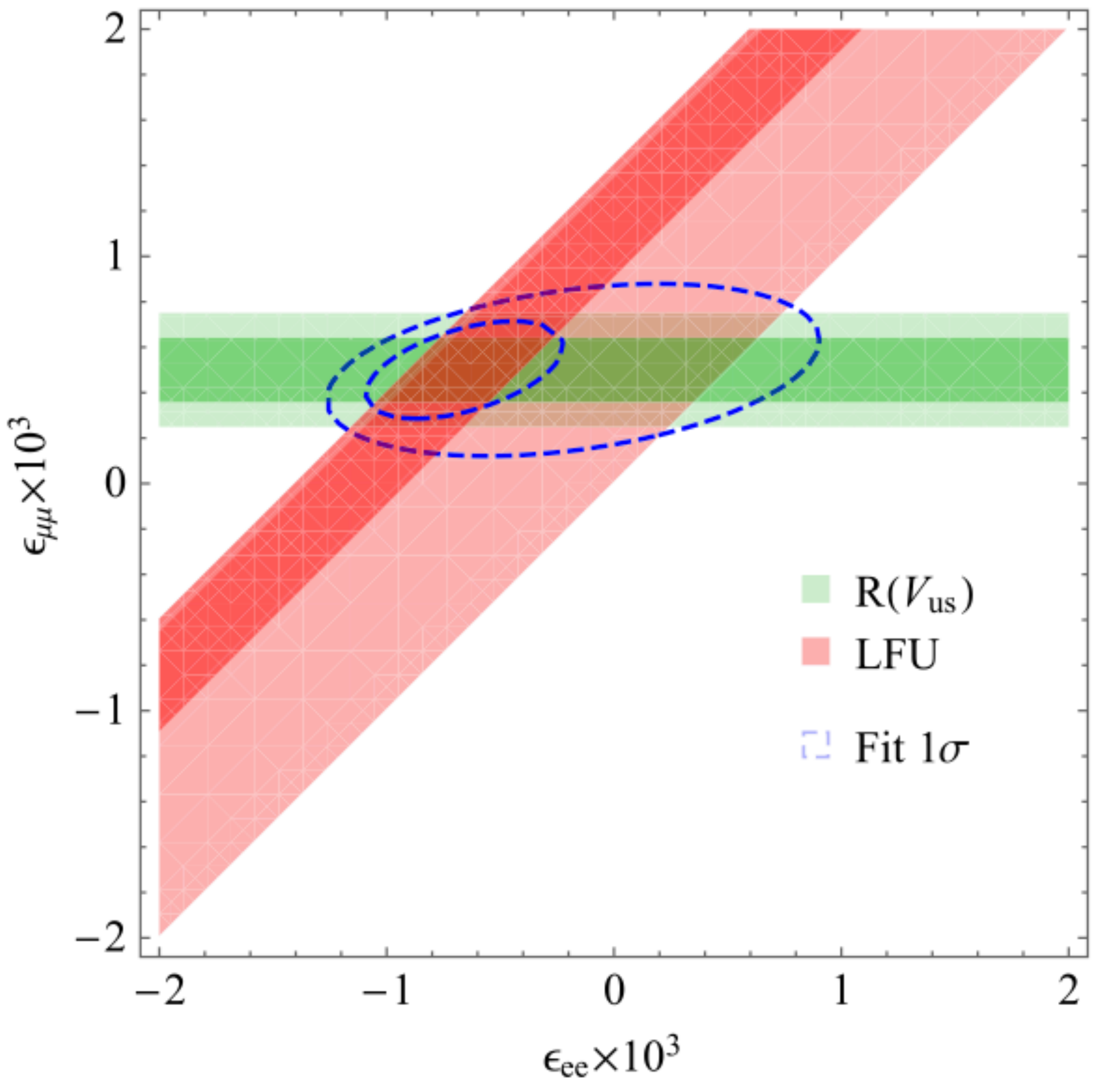
New physics interpretation

- Effective field theory approach (Modified $Wl\nu$ couplings)

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

  - g_2 : SM SU(2)$_L$ gauge coupling recovered in the limit $\epsilon_{ij} \to 0$

- Global fit of $\epsilon_{ee}, \epsilon_{\mu\mu}$ indicates deviation of $\mathrm{R}^{\pi}_{e\mu}$ from the SM (smaller value is preferred)
  - which data are used?



New physics models

- W’ boson
- Vector-like Leptons
- Singly charged SU(2)L singlet scalar
- Scalar SU(2)L Triplet
- SU(2)L Neutral Vector Bosons (Z’)
- Leptoquarks
- Charged Higgs

PIONEER phase II

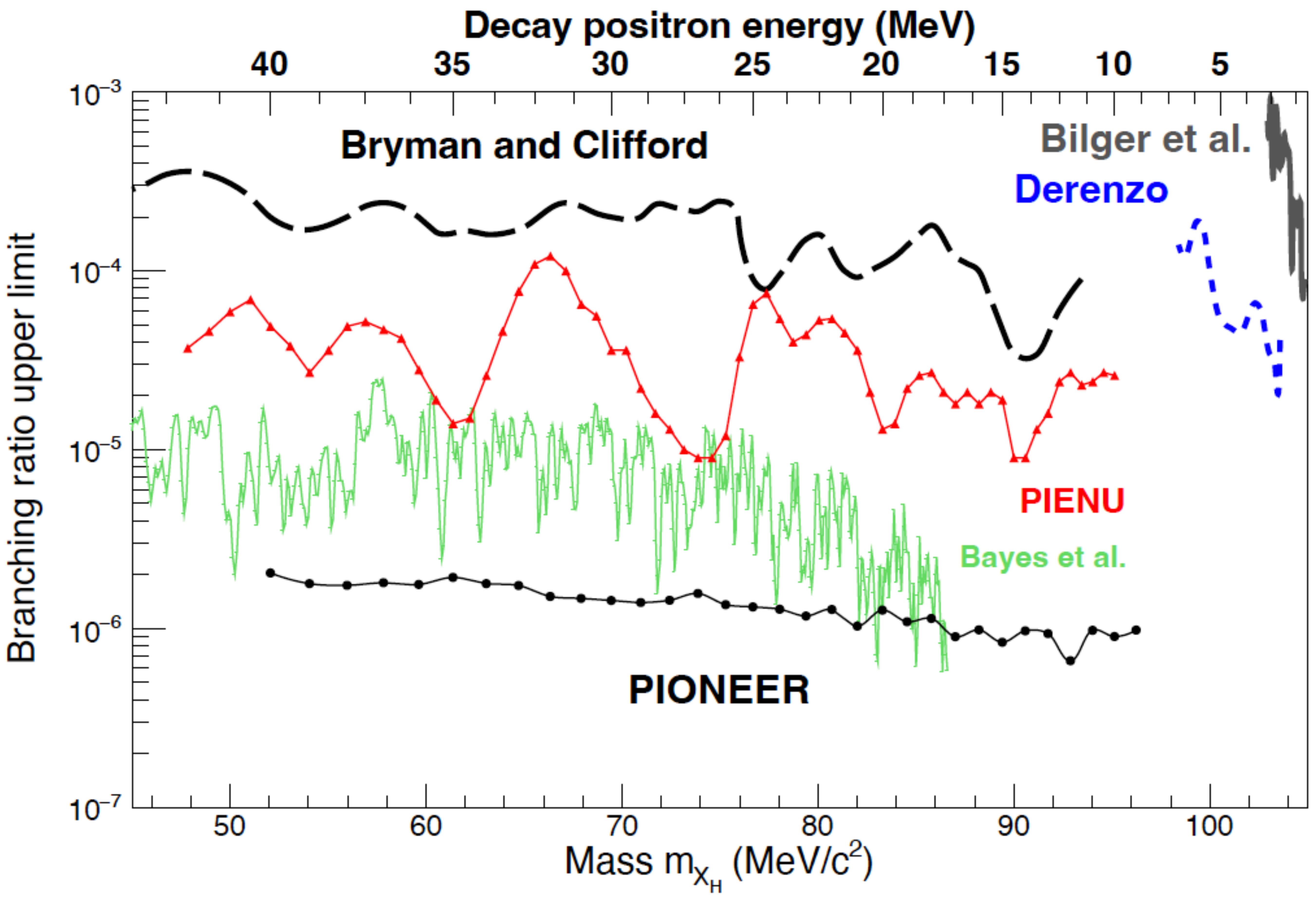
- The detector optimized for next-generation $R^{\pi}_{e/\mu}$ experiment also be ideally suited for a high-precision measurement of pion beta decay
  - to extract $|V_{ud}|$ in a theoretically pristine manner
  - The most accurate branching ratio for pion beta decay by PiBeta experiment at PSI

$$\frac{\Gamma(\pi^+ \to \pi^0 e^+ \nu)}{\Gamma(\text{Total})} = 1.036 \pm 0.004\ (\text{stat}) \pm 0.004\ (\text{syst}) \pm 0.003\ (\pi \to e\nu) \times 10^{-8}$$

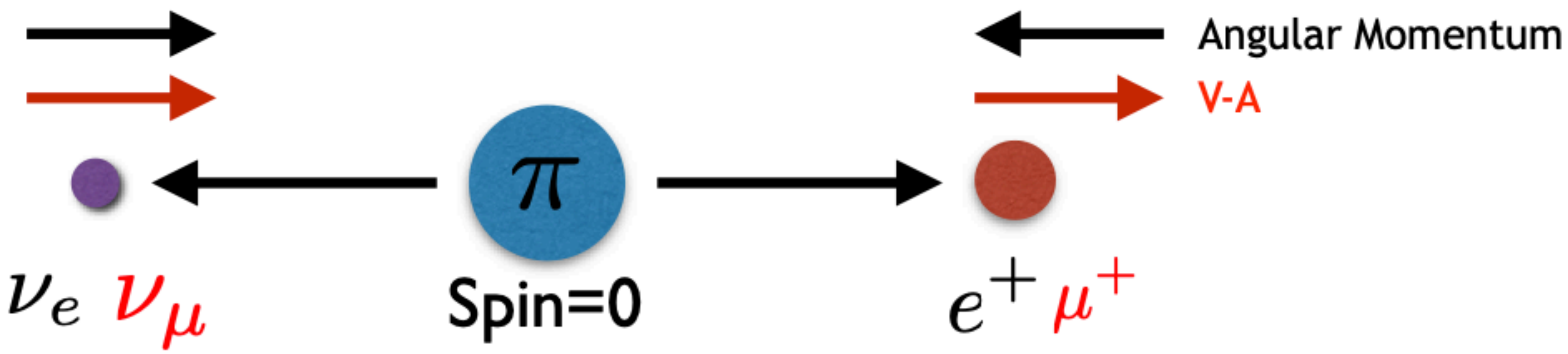
  - $|V_{ud}| = 0.9739(28)_{exp}(1)_{th}$ at 0.3% is not relevant for the CKM unitarity tests
  - super allowed nuclear beta decays with a precision of 0.03%
- First step (phase II)
  - Determination of $|V_{us}/V_{ud}|$ at 0.2% by $R_V = \frac{\Gamma(K \to \pi l \nu(\gamma))}{\Gamma(\pi^+ \to \pi^0 e^+ \nu(\gamma))} = 1.9884(115)_\pi(93)_K \times 10^7$
  - This can be competitive constraint in $|V_{us}| - |V_{ud}|$ plane $R_A = \frac{\Gamma(K \to \mu\nu(\gamma))}{\Gamma(\pi \to \mu\nu(\gamma))} = 1.3367(25)$
- Second step (phase III)
  - theoretically cleanest extraction of $|V_{ud}|$ at the 0.02% level

PIONEER exotic decay

- Improve sensitivity of exotic decays
  - 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 $\mu^+ \to e^+X_H$



Helicity Suppression



Neutrinos produced only by weak interactions:

Neutrinos: left-handed helicity

Antineutrinos: right-handed helicity

Weak interaction forces the electron into the “wrong” helicity state

The V-A structure of the weak interactions explains why the muon decay mode is favoured!