The PIONEER experiment for precise measurements of lepton flavor universality

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on behalf of PIONEER collaboration
ICEPP, the University of Tokyo

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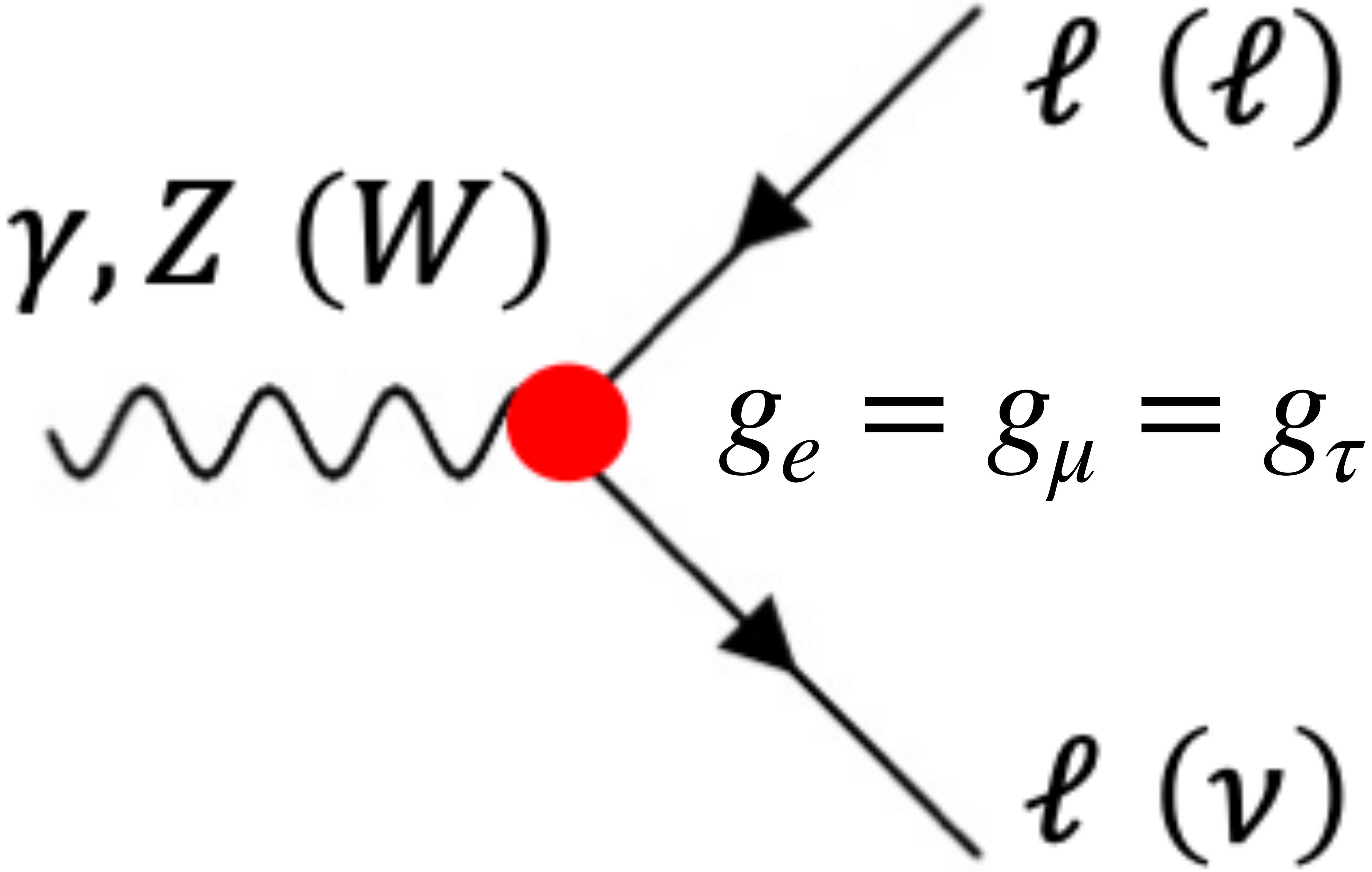
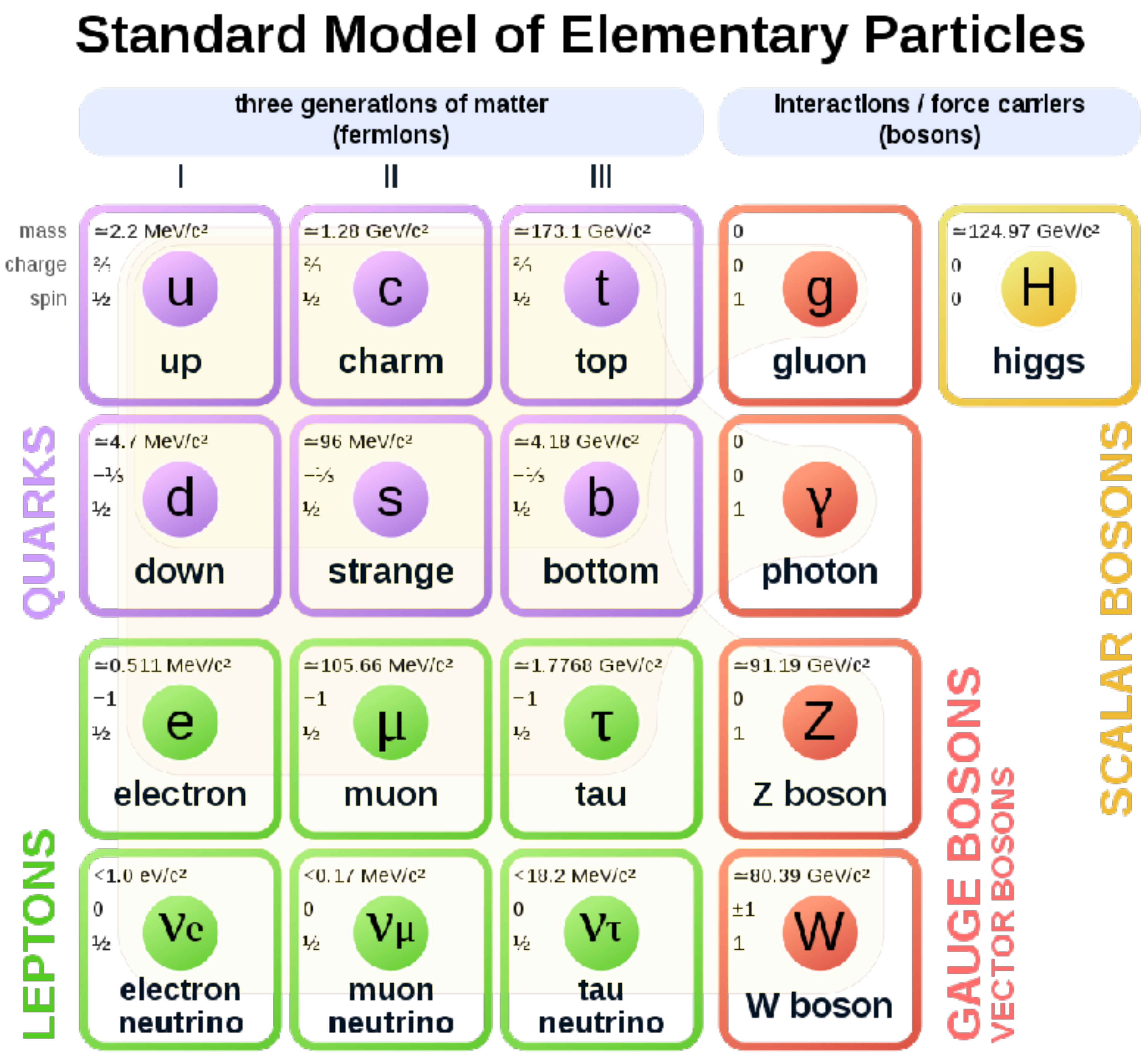
JSPS Core-to-Core Program

Lepton Flavor Universality

The weak interaction in the Standard Model is the same for $e/\mu/\tau$

- Gauge interactions are lepton flavor universal

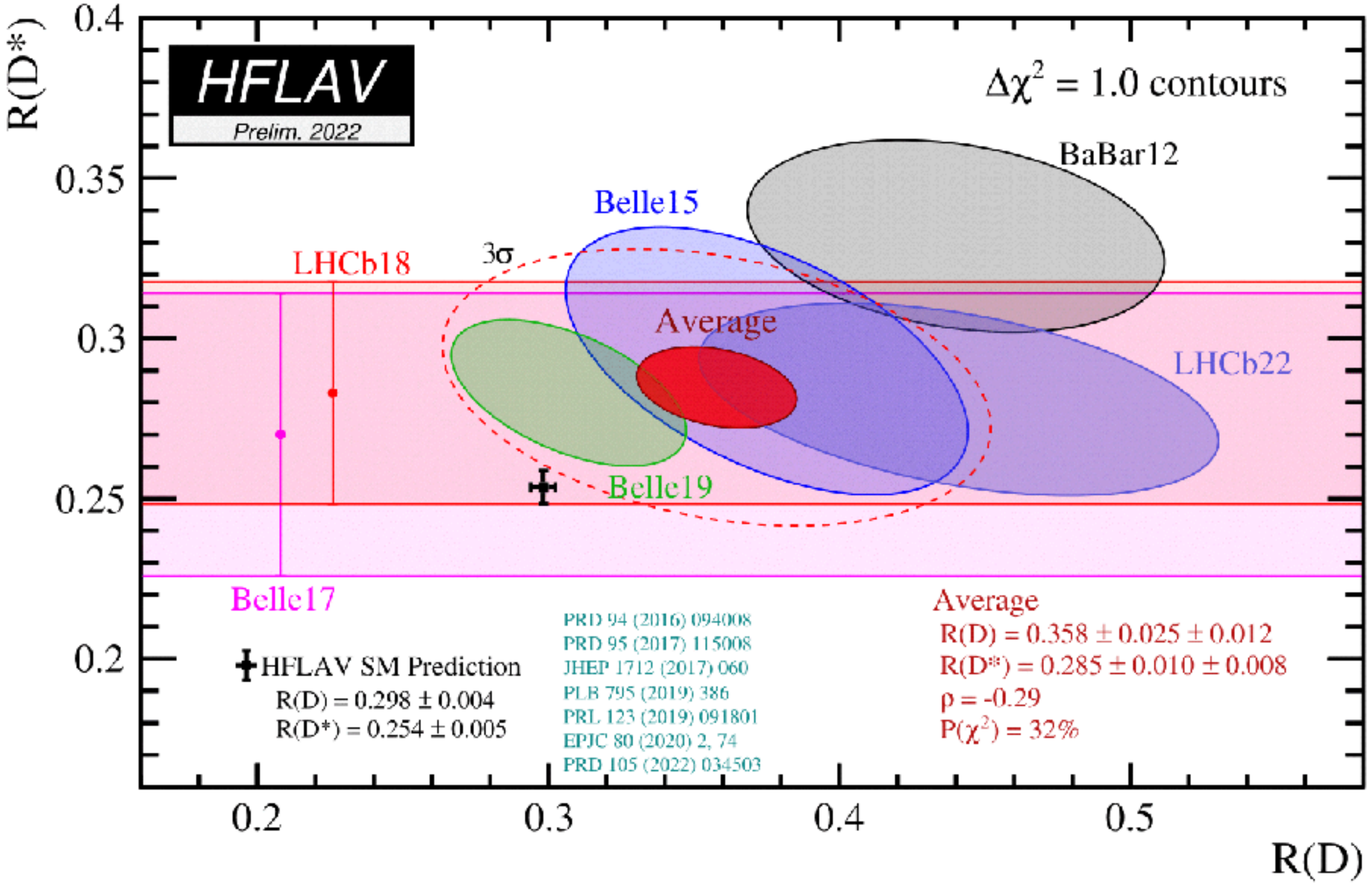




Deviation from Lepton Flavor Universality?

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

- 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 $(g-2)_\mu$ deviation can be considered as another hint of LFUV when compared to $(g-2)_e$



Beta Decays and CKM Unitarity

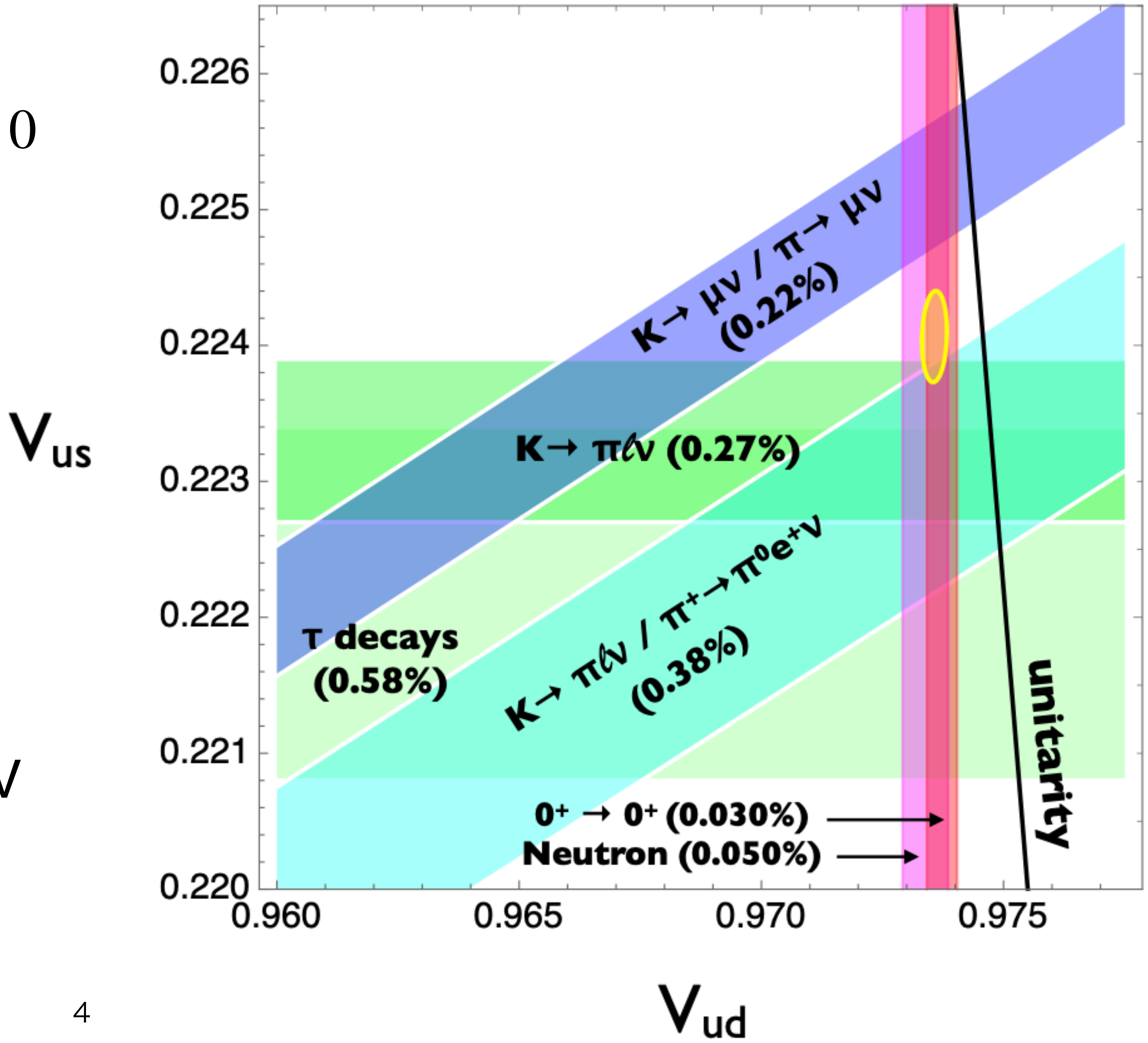
Unitarity of the CKM matrix
$\Delta_{CKM} \equiv |V_{ud}|^2 + |V_{us}|^2 + |V_{ub}|^2 - 1 = 0$

In practice, $|V_{ub}|^2 < 10^{-5}$, only V_{ud} and V_{us} are concerned

$\Delta_{CKM} = (-19.5 \pm 5.3) \times 10^{-4}$,
3.7σ effect

This can also be interpreted as a LFUV

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



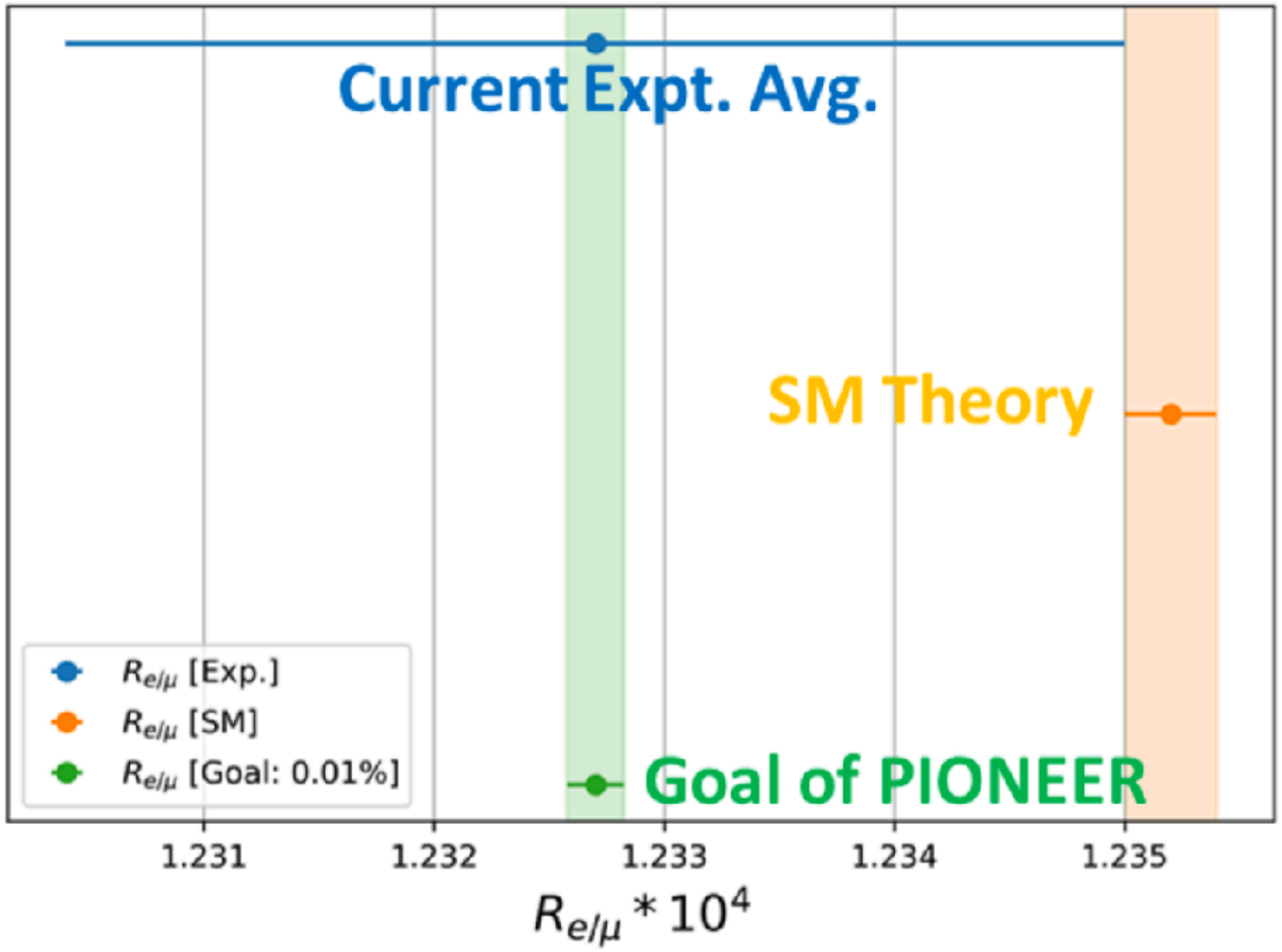
PIONEER goals

Phase I

- $R^{\pi}_{e/\mu} = \Gamma(\pi \to e\bar{\nu}_e(\gamma)/\Gamma(\pi \to \mu\bar{\nu}_\mu(\gamma))$ Experimental precision improvement
  by a factor of 15 to 0.01% level
- NP at the PeV scale can be probed

Phase II

- $\frac{\Gamma(\pi^+ \to \pi^0 e^+ \nu)}{\Gamma(\text{Total})}$ with a precision < 0.2%
- Improve the precision by three times
- CKM matrix unitary check → 10 times improvement in Phase III (theoretically cleanest $|V_{ud}|$ test)



Exotic searches

- Heavy neutral lepton

PIONEER experiment is approved by Paul Scherrer Institute in Switzerland

Basics of pion decays

Measurements:

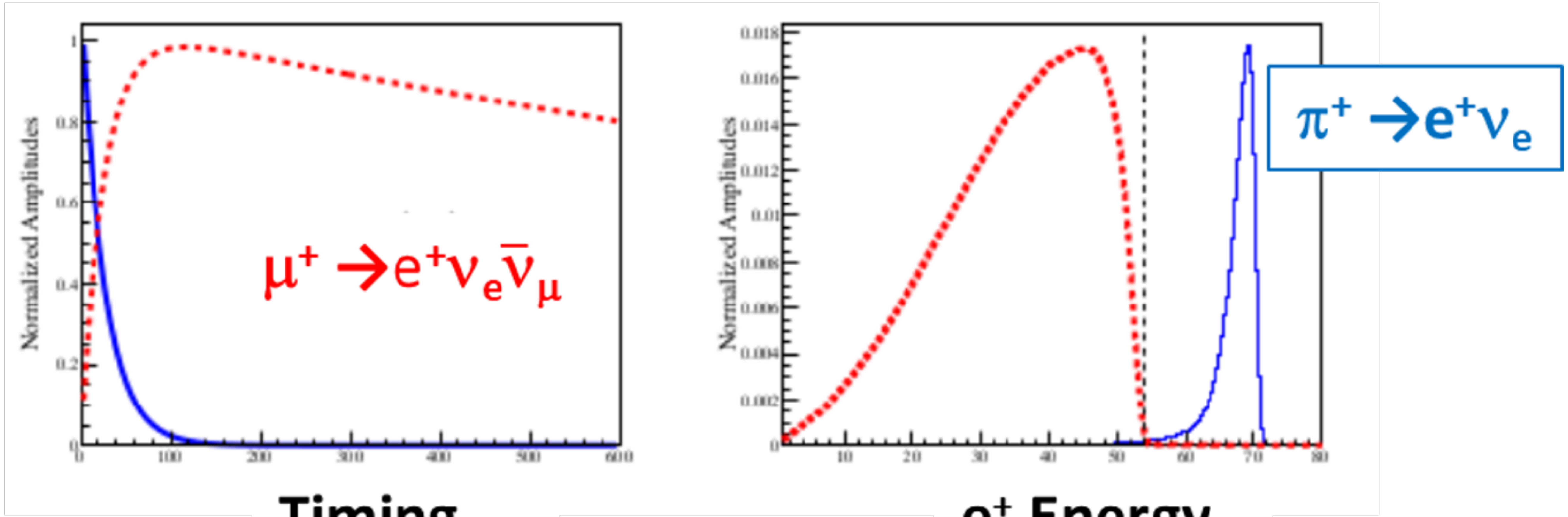
What a pion decays to "normally" → $BR\left(\pi^+ \rightarrow \mu^+\nu_\mu(\gamma)\right) = 0.999877 = \pm 0.0000004$

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

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

Reminders:

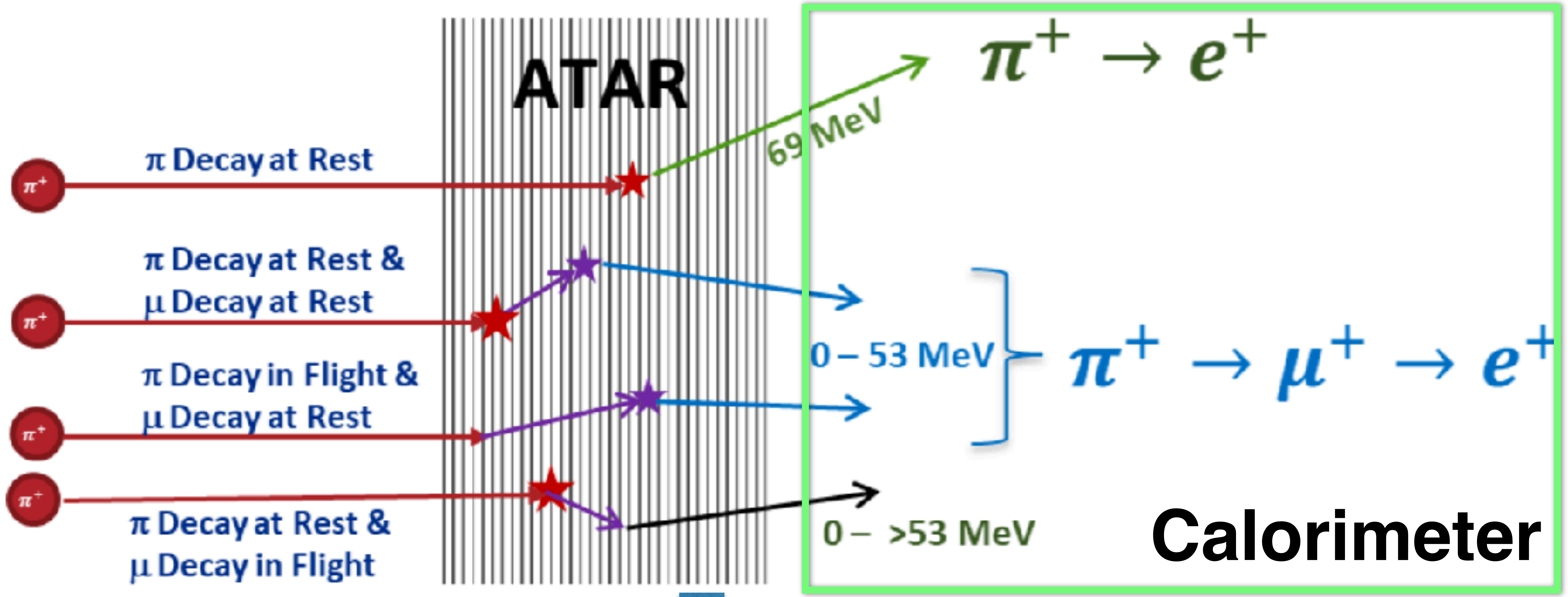
Pion lifetime:	26 ns
Muon lifetime:	2197 ns
Pion mass:	139.6 MeV
Muon mass:	105.7 MeV



Timing

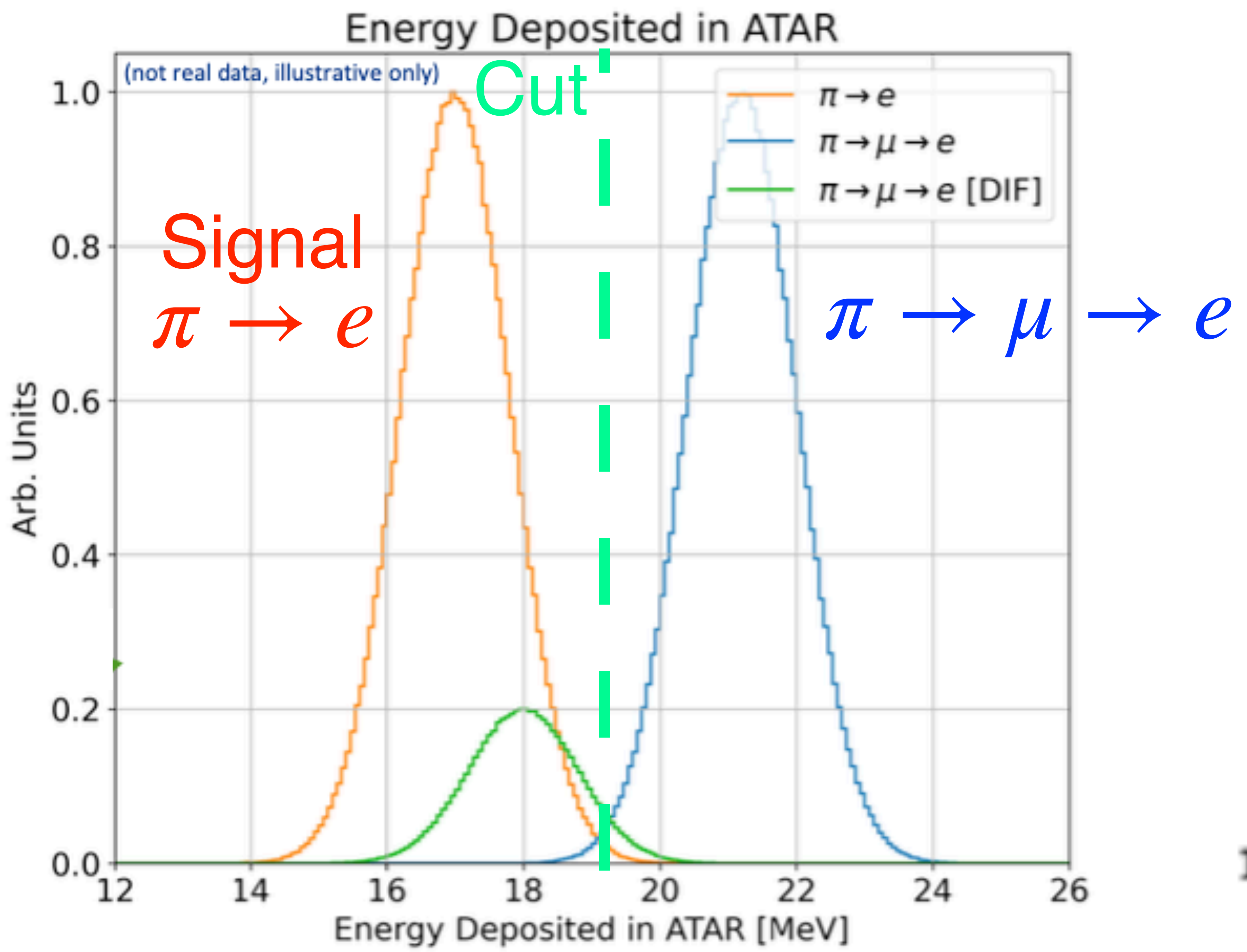
e^+ Energy

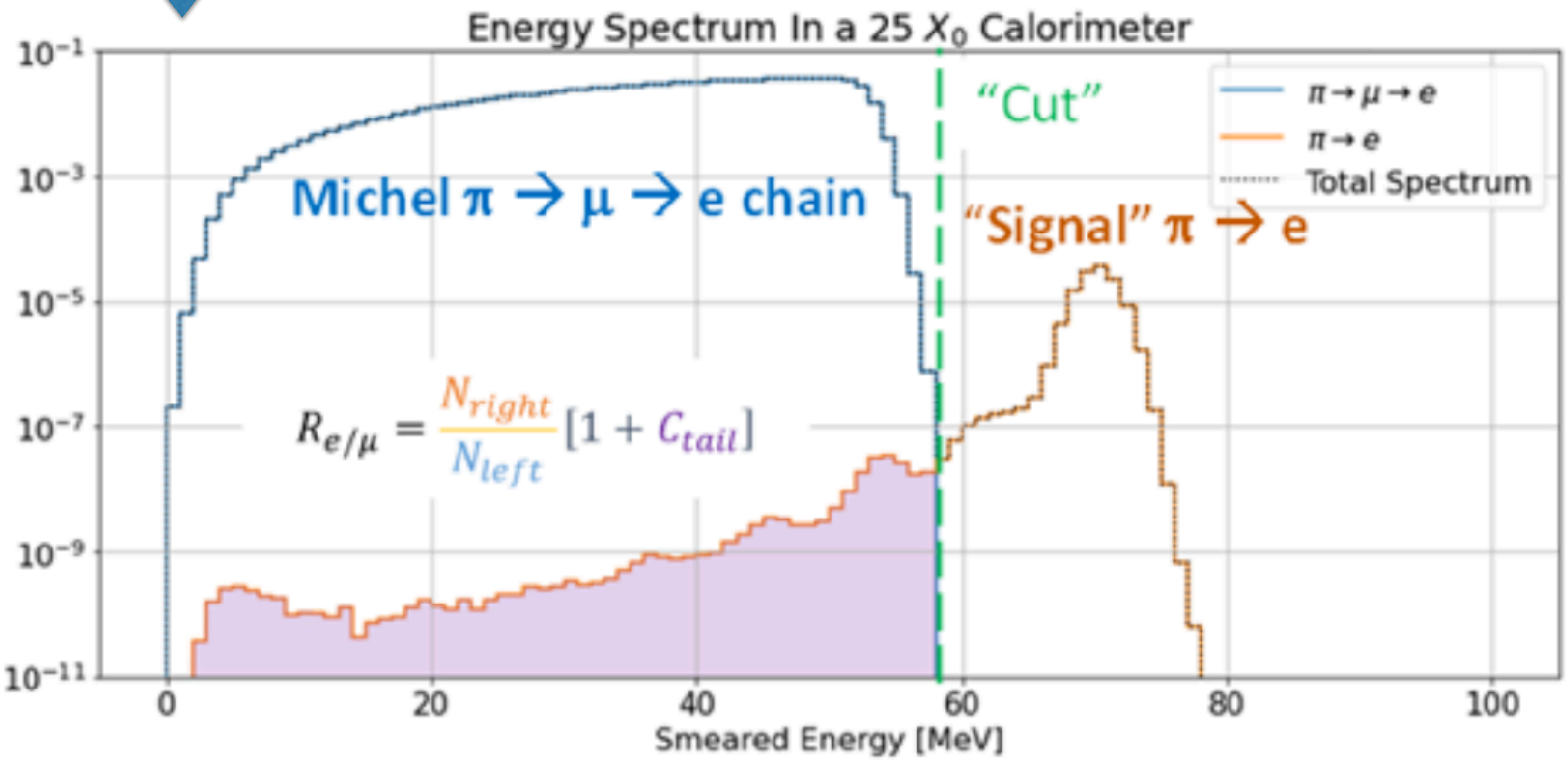
Signal & Background



ATAR energy deposit

Calorimeter energy deposit





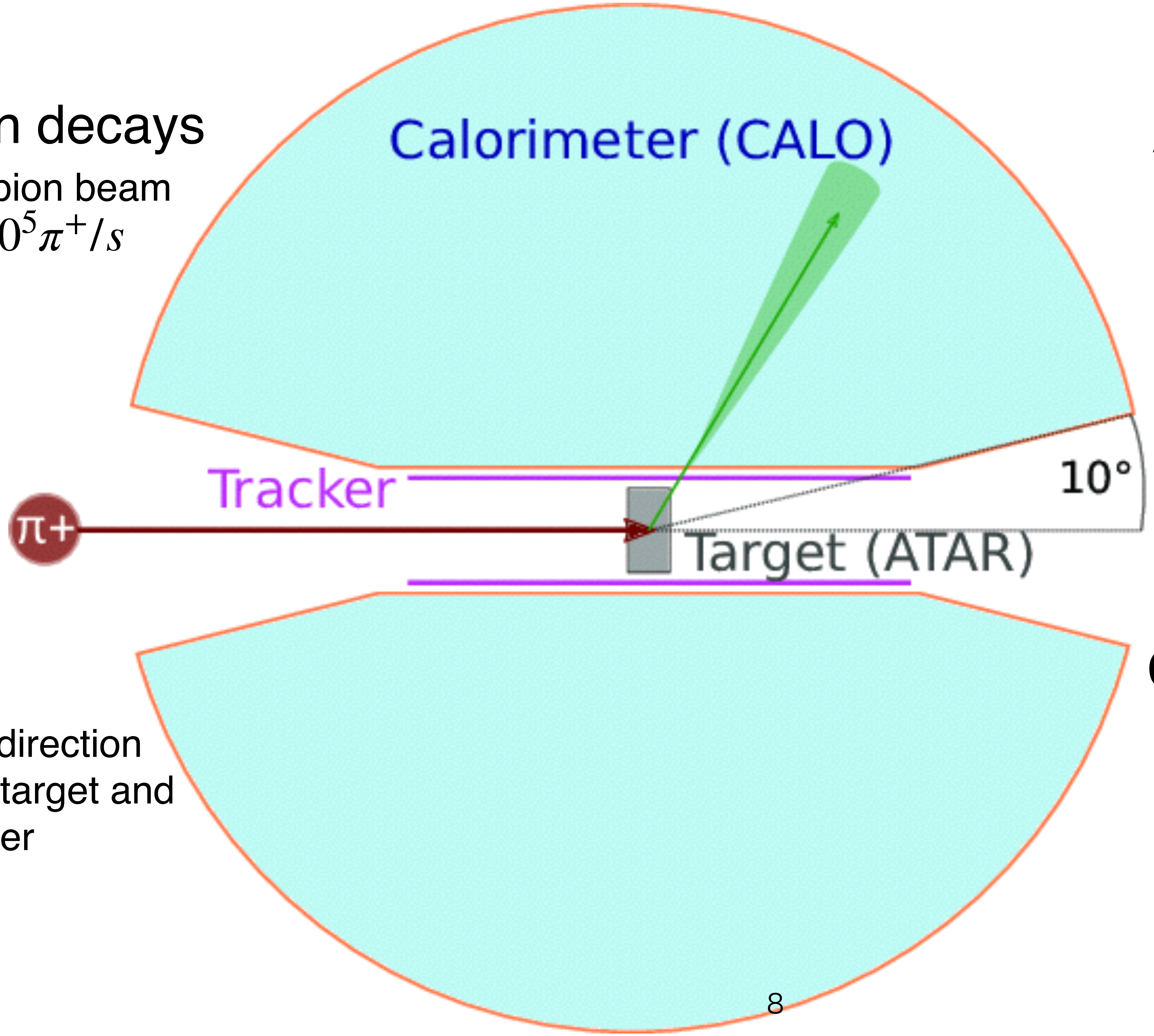
PIONEER Concept

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

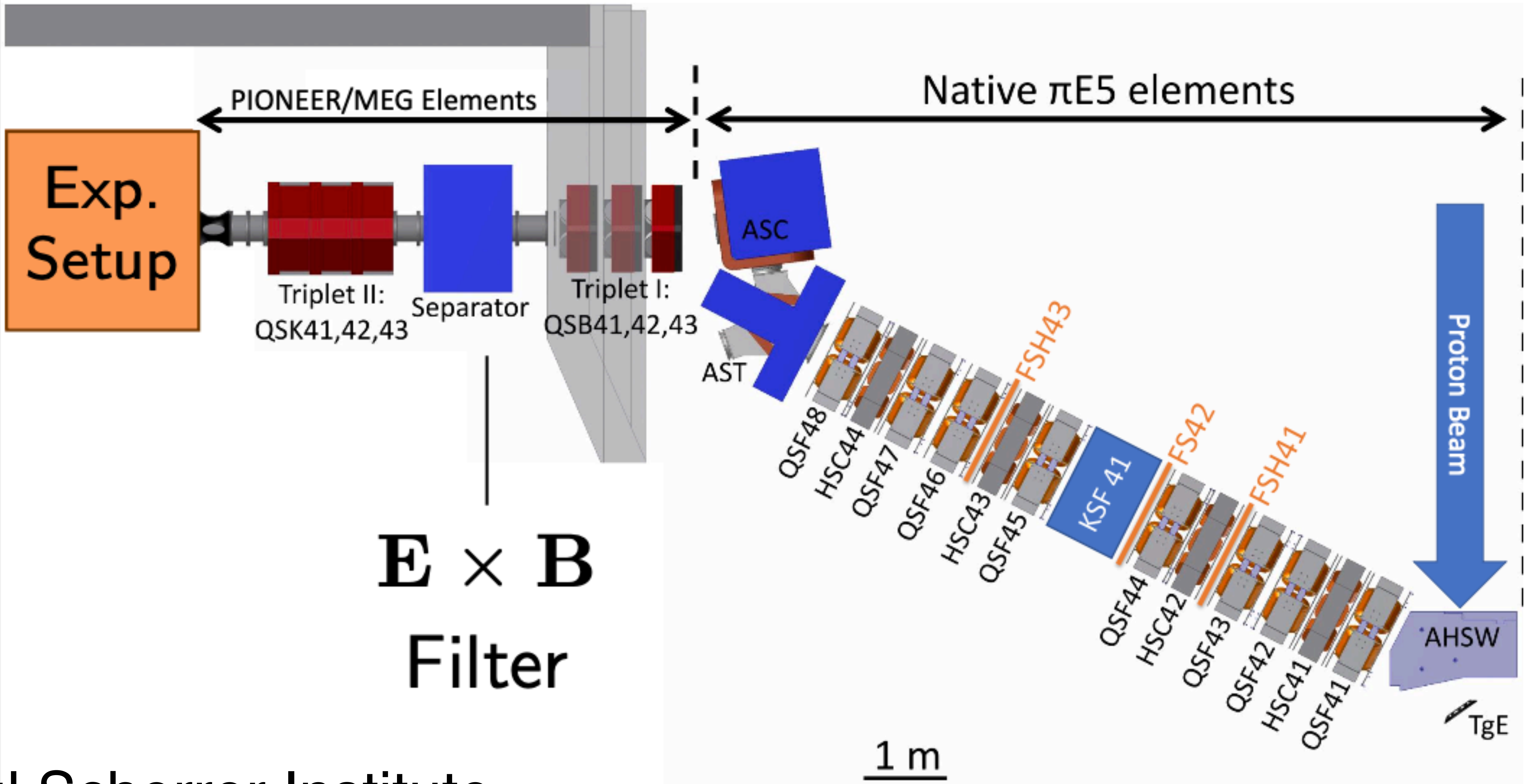
- Positron energy, and time
- 25 X_0 to reduce low energy tail region
- 3π sr calorimeter
- Tolerant to high event rate

World most intense pion beam

Requirements

- Momentum : 65 MeV/c
- Rate : > 3×10^5 π^+/s
- Beam size : σ_x, σ_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

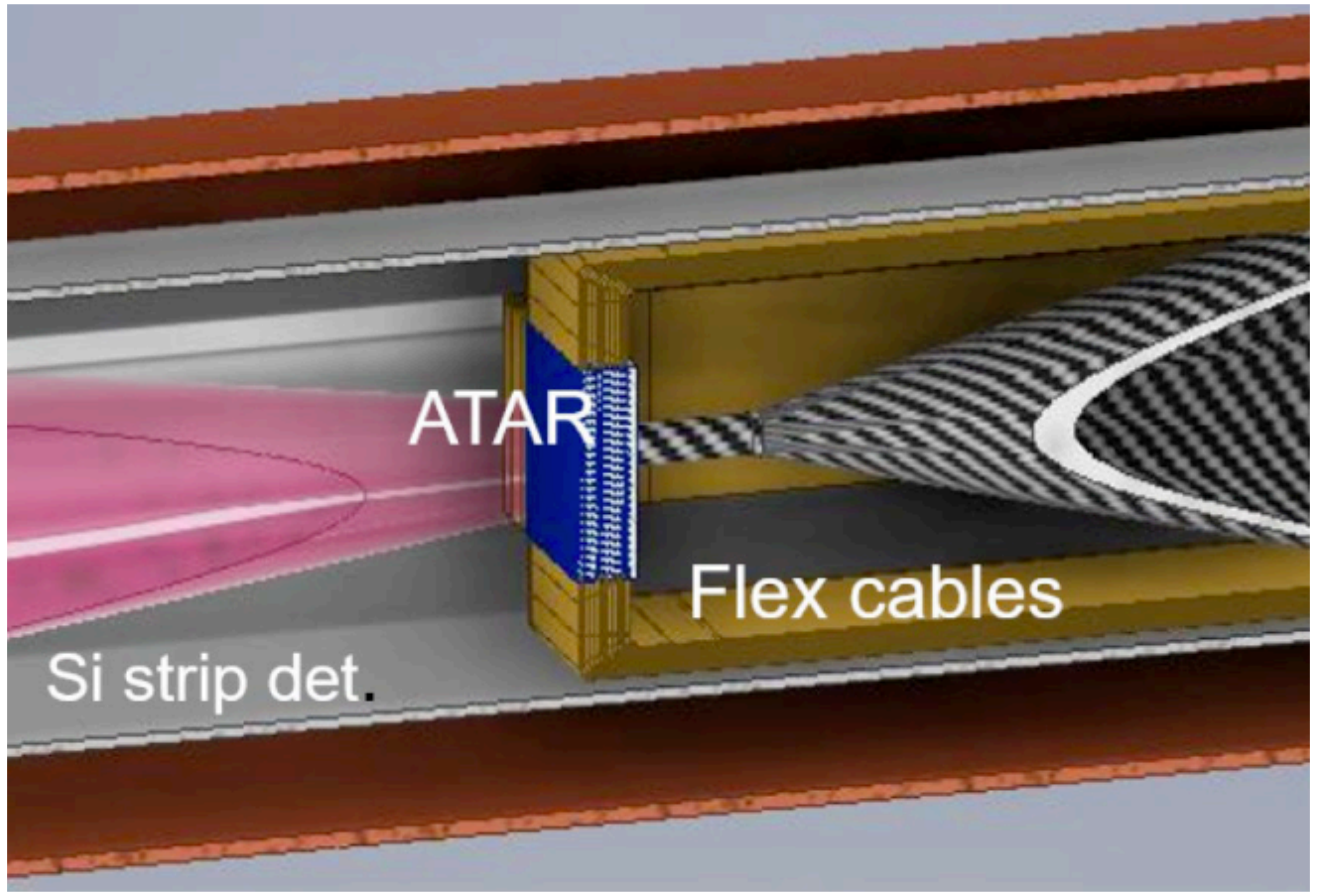
Active Target (ATAR)

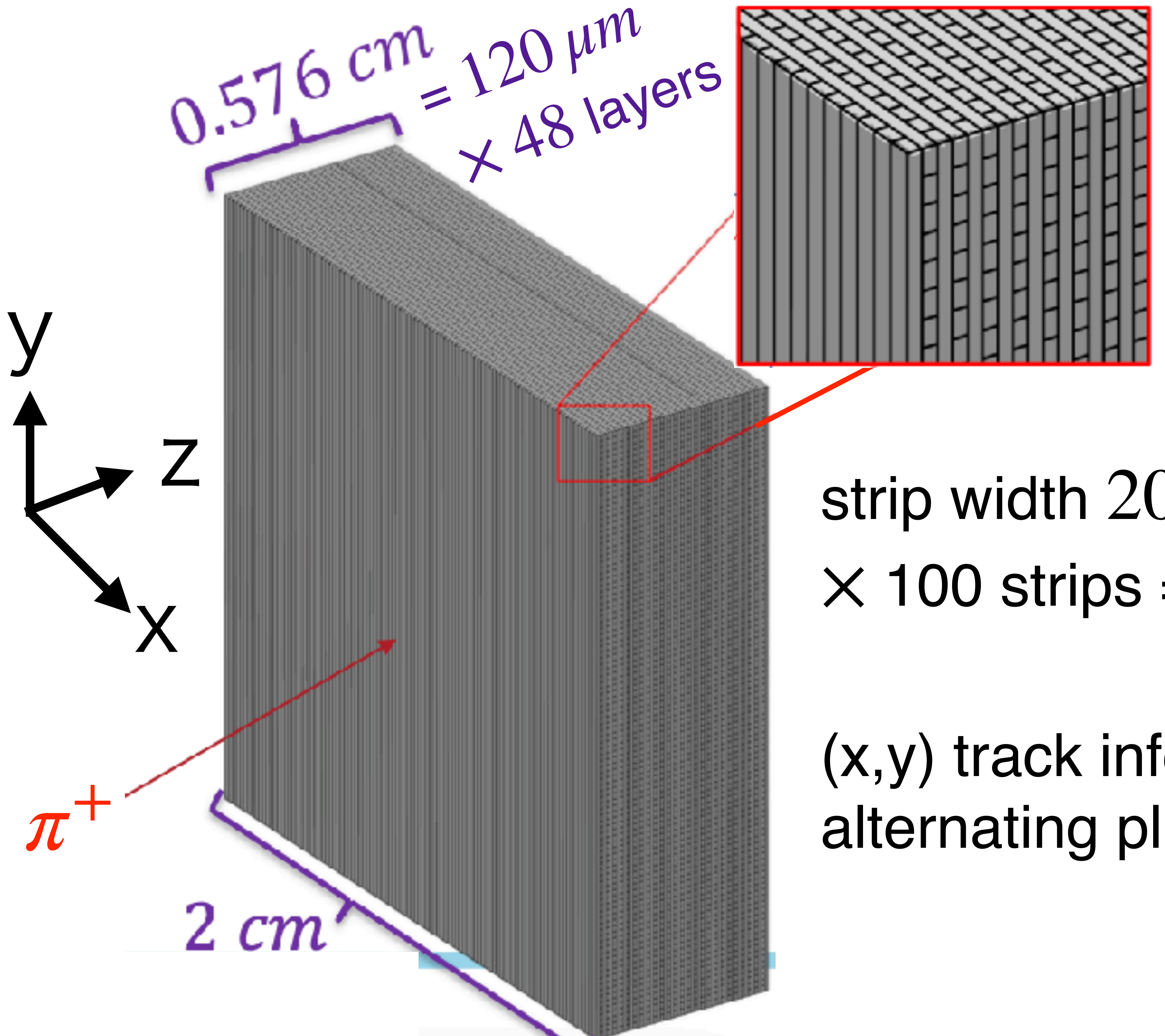
ATAR requirements

- 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

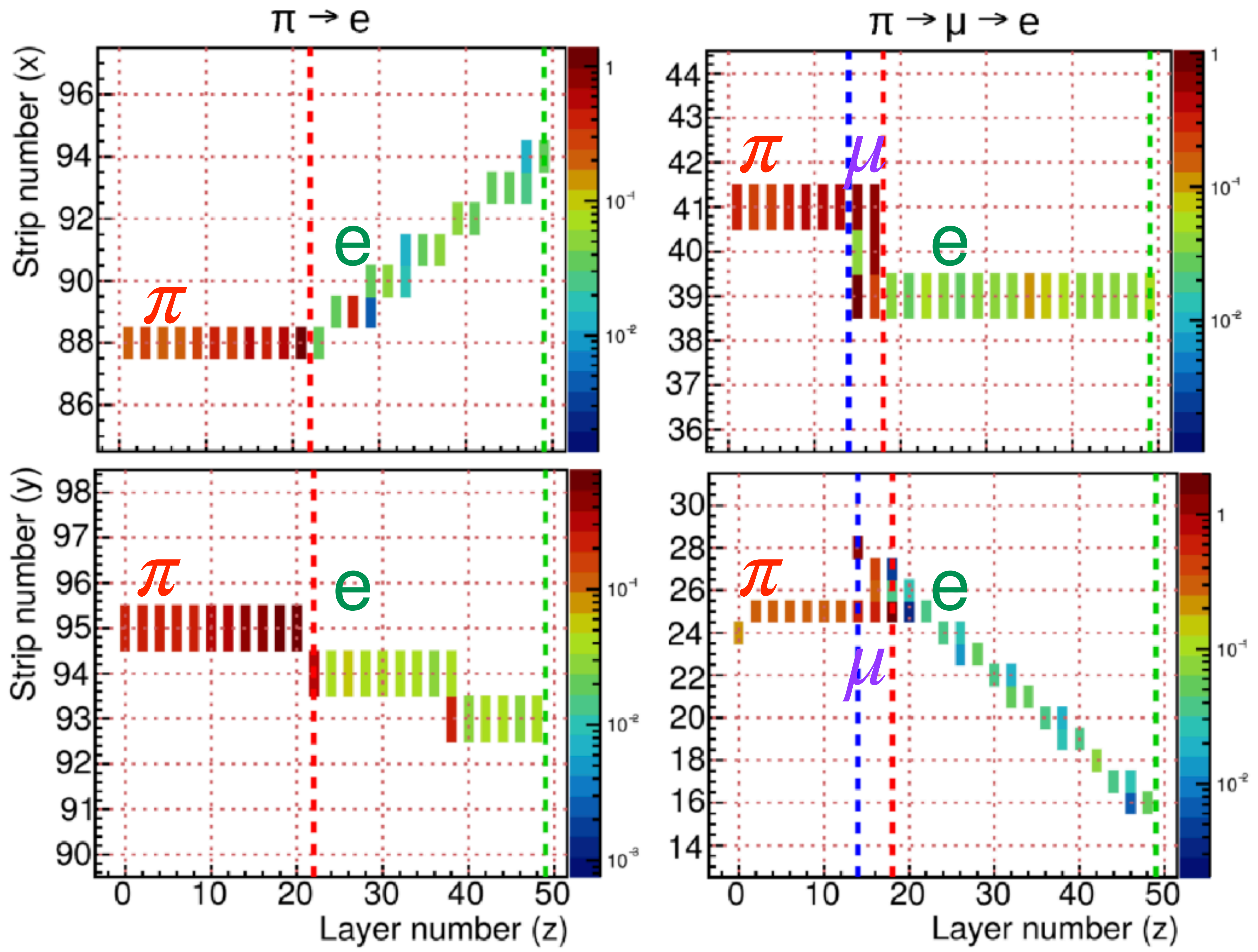


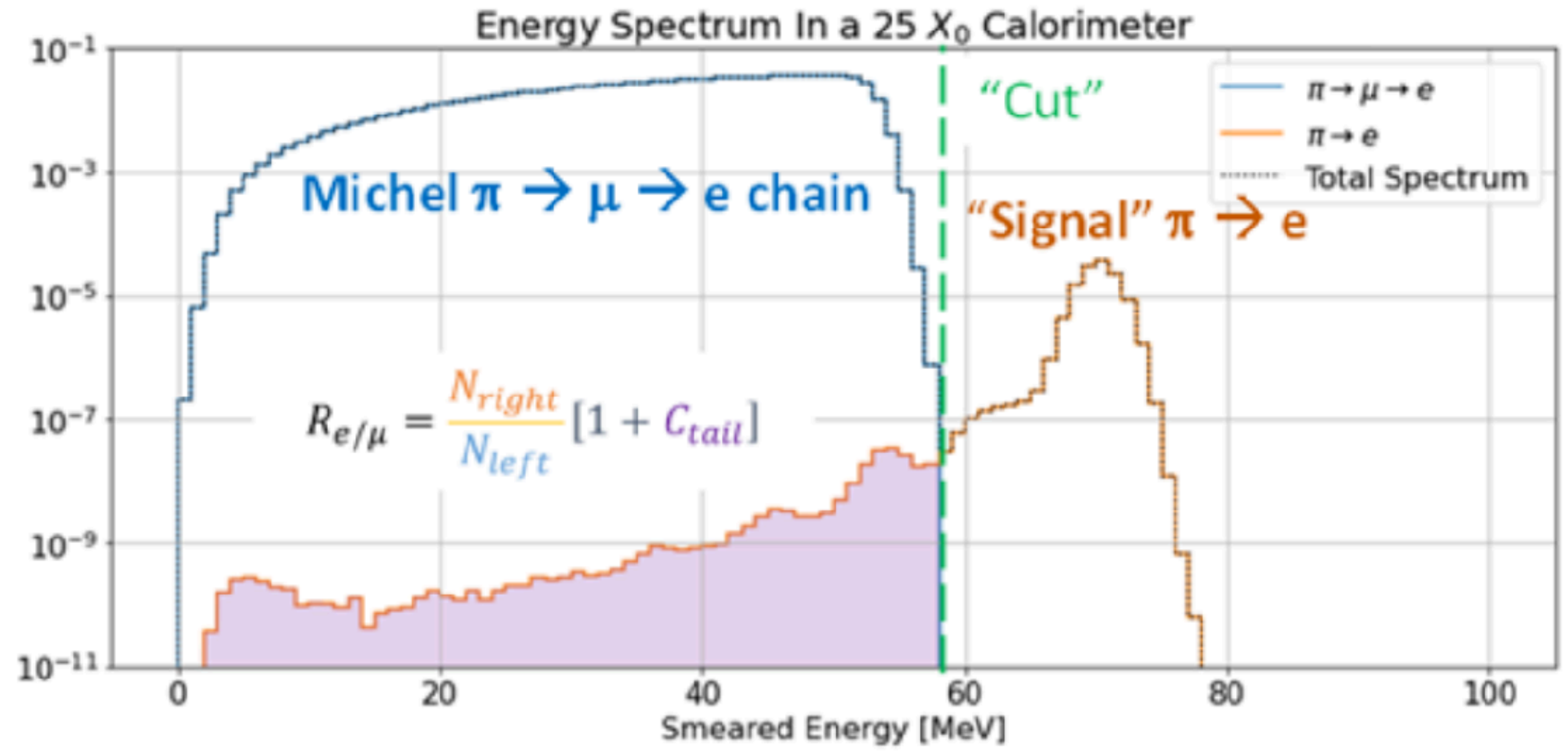


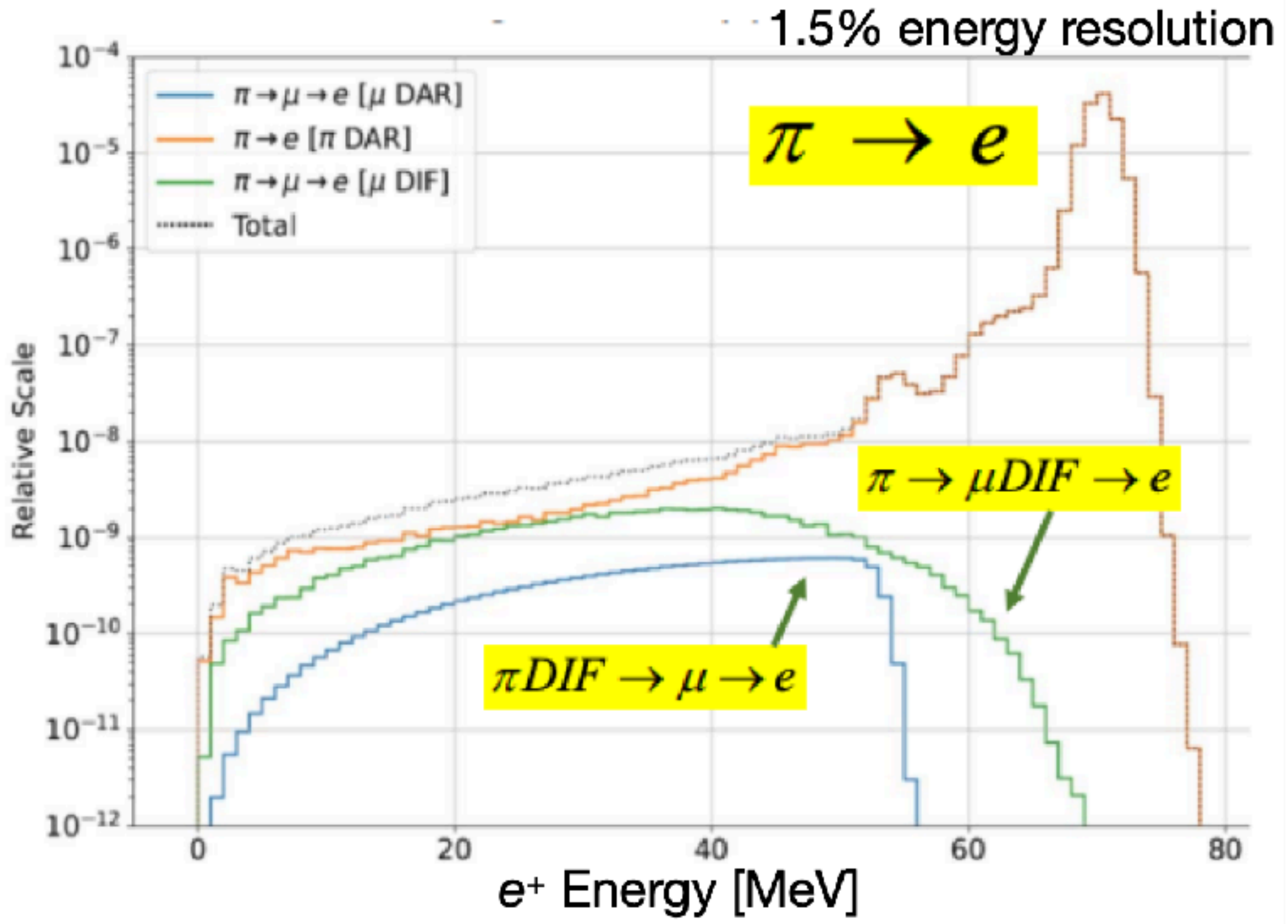
strip width 200 μm × 100 strips = 2 cm

(x,y) track info. from alternating planes

ATAR tracking







Combined information of tracking, timing, and energy deposit

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

Calorimeter

Calorimeter requirements

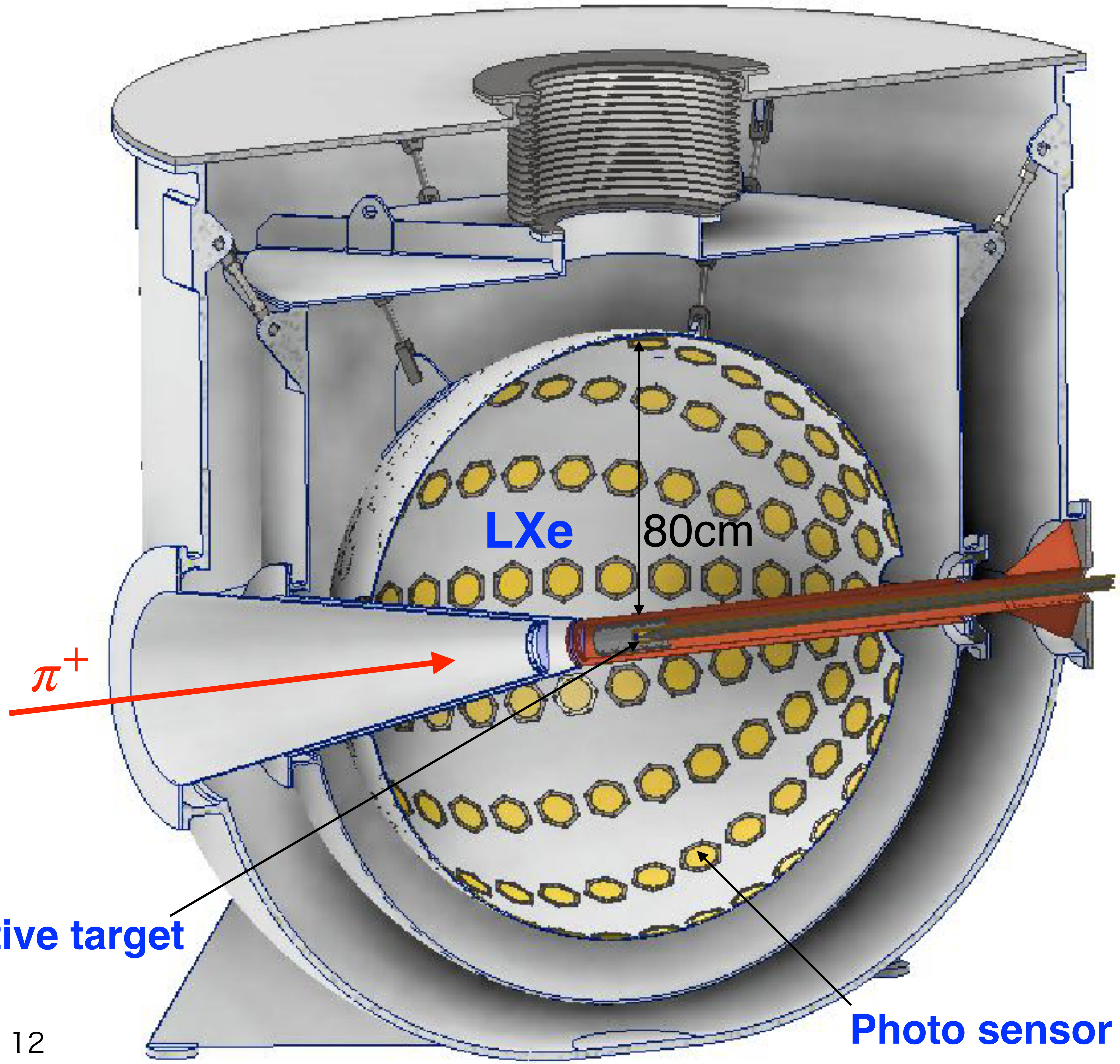
- 3π coverage, high uniformity, sub-ns timing
- Energy Resolution 1.5–2.0%
- $25X_0$ for tail suppression
- High rate tolerant, pileup separation

LXe calorimeter is the baseline design

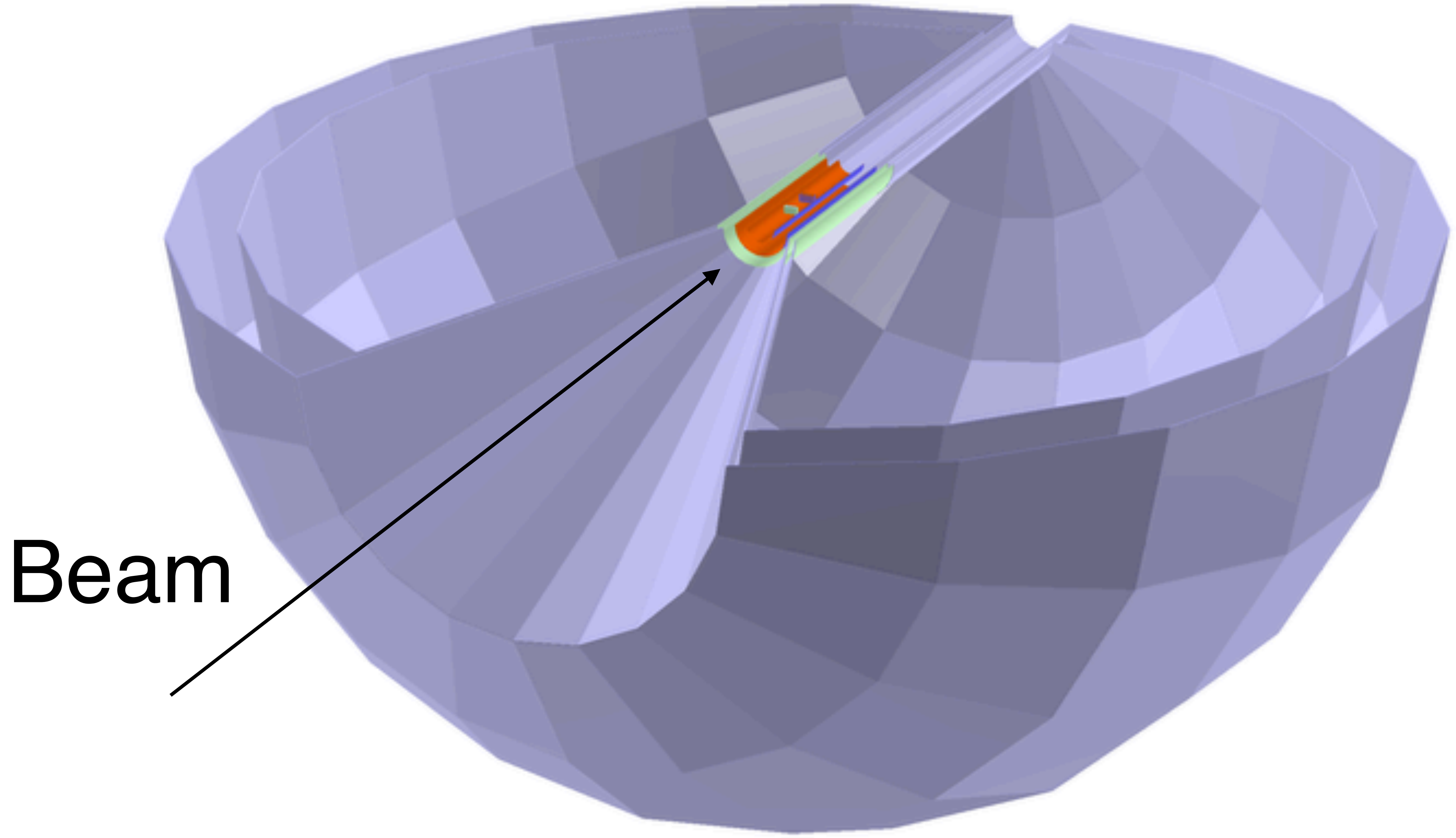
- Technology well proven by MEG II LXe detector

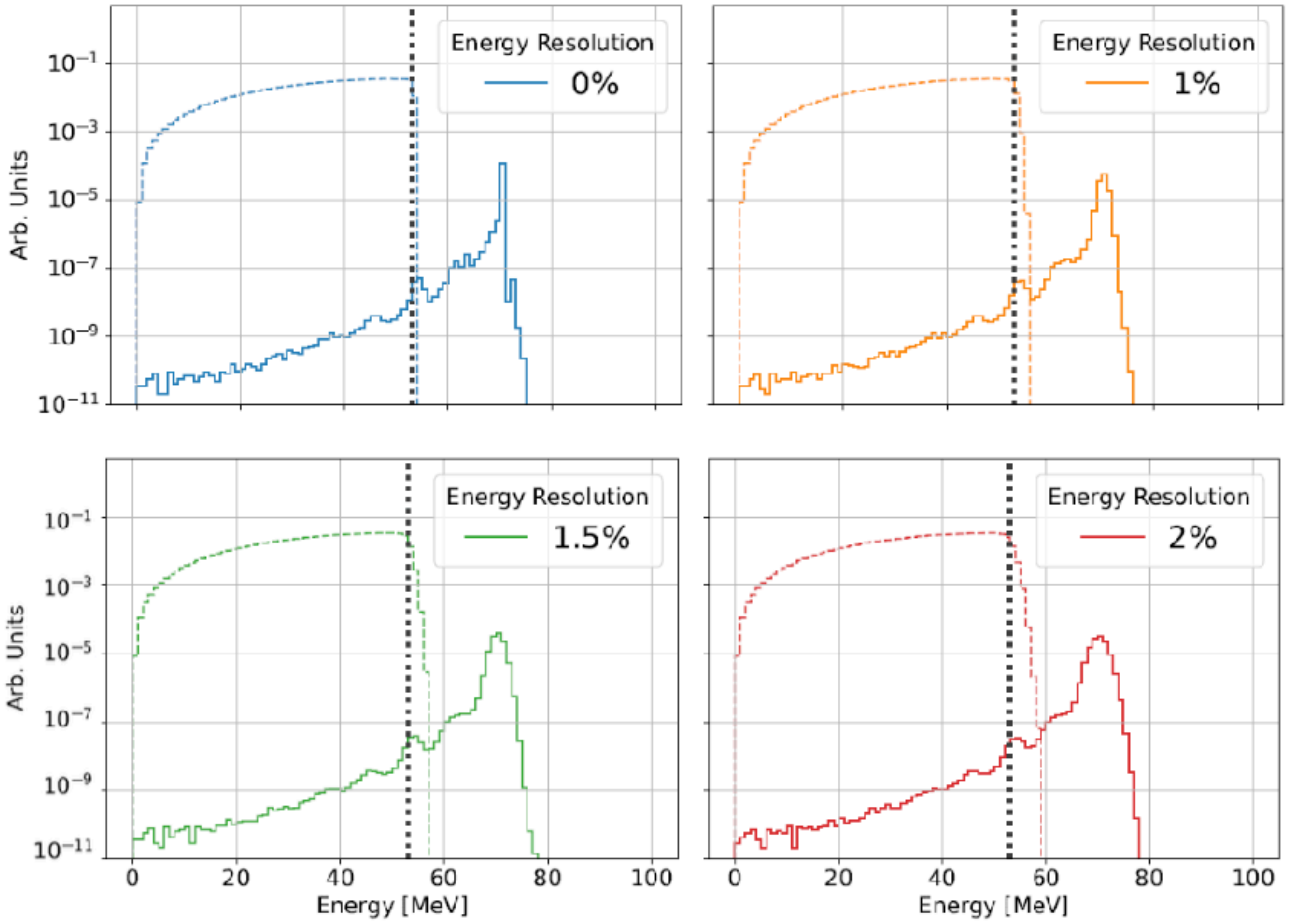
Conceptual design

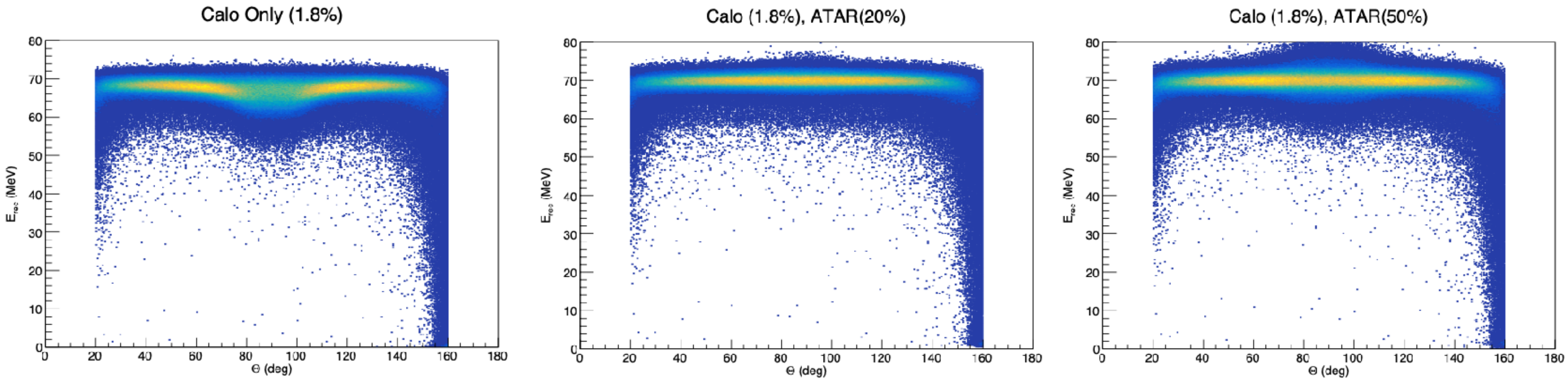
- 7t LXe in vacuum isolated cryostat, r_{out} = 80cm, $r_{in\text{-}cyl}$ = 7cm
- Photo sensors only outer face (incident position from tracker)



Simulating the whole detector







Statistics & Systematic improvements

Intense, high quality π^+ beam

2×10^8 $\pi \rightarrow e\nu$ events in 2–3 years

with 3×10^5 π^+/s beam

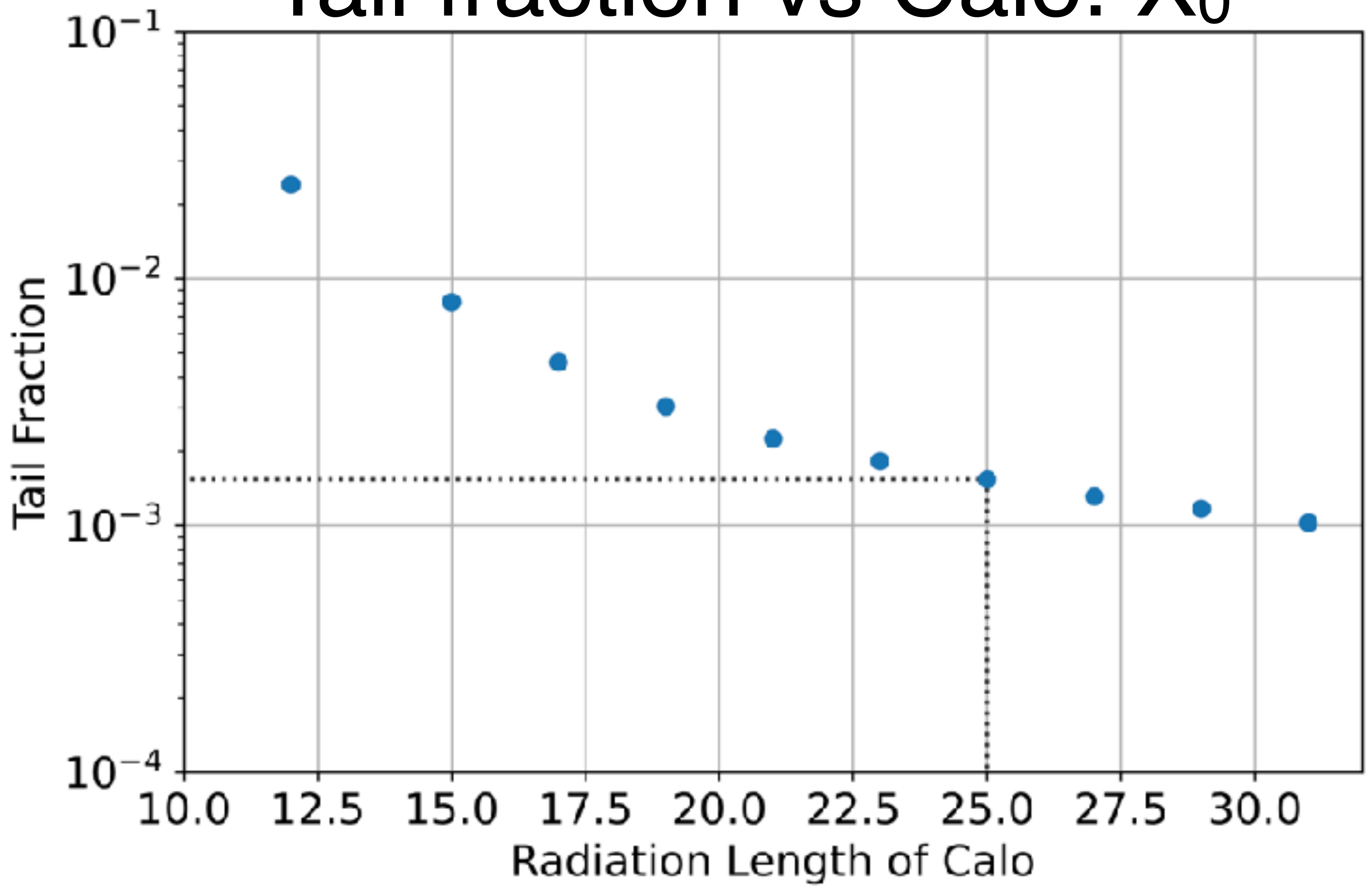
Active target with new new technology

Calorimeter 3π, 25X_0, high res., fast

Dominant systematics from tail correction

	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**

Tail fraction vs Calo. X_0



- Detector R&D with prototypes to demonstrate the above uncertainties in three years

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 experiment will aim at preparing the TDR in 3 years, construction in 2 years, and starting the run from ~2028.

PIONEER collaboration

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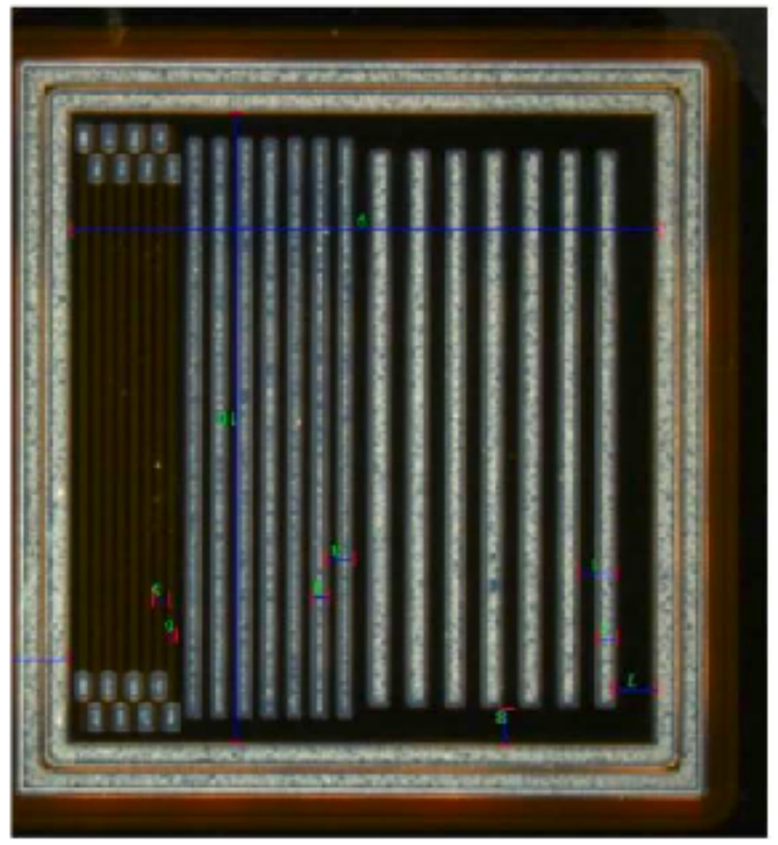
Prospects 2023 and beyond



- 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

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 $\mu^+ \to e^+X_H$

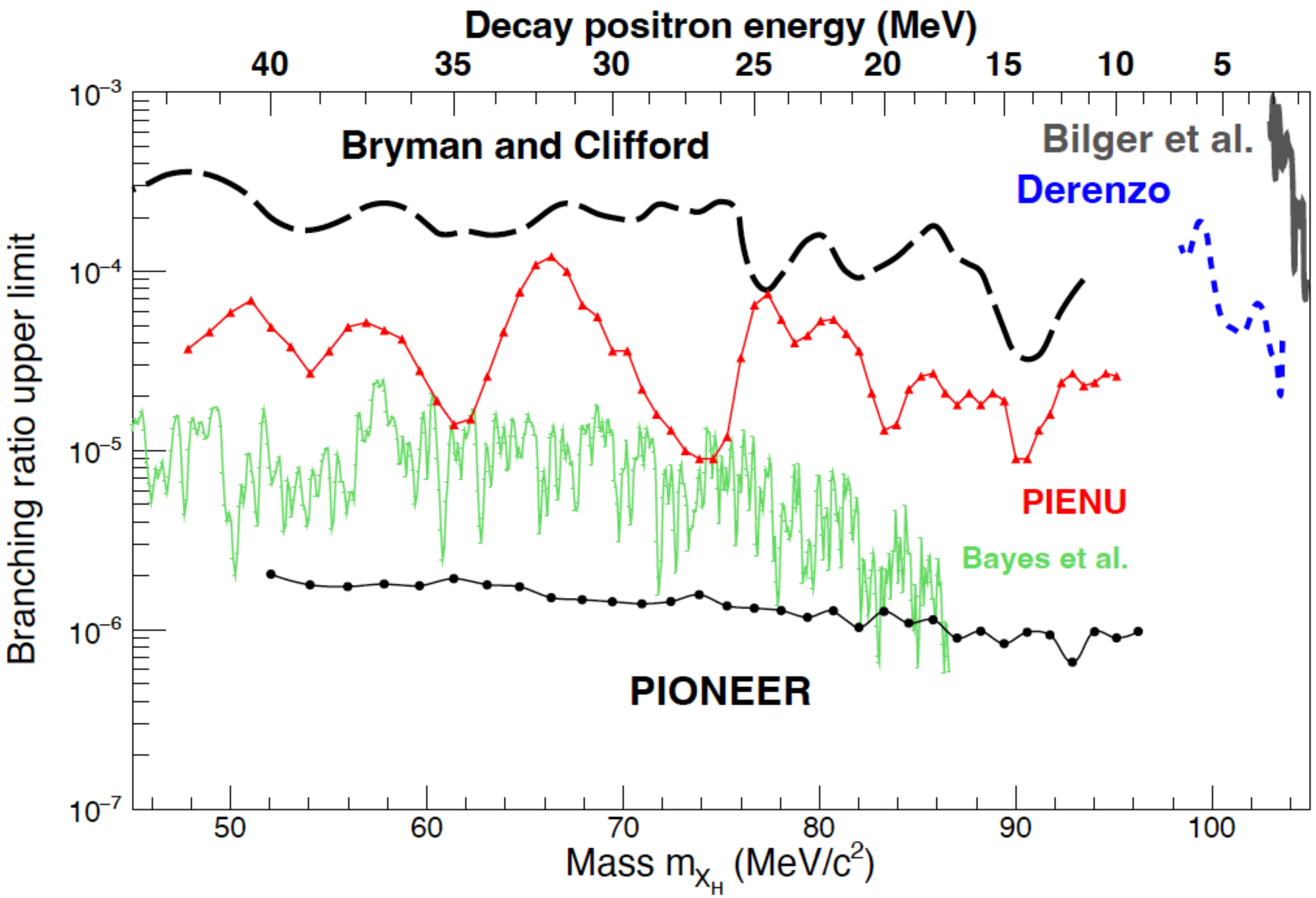
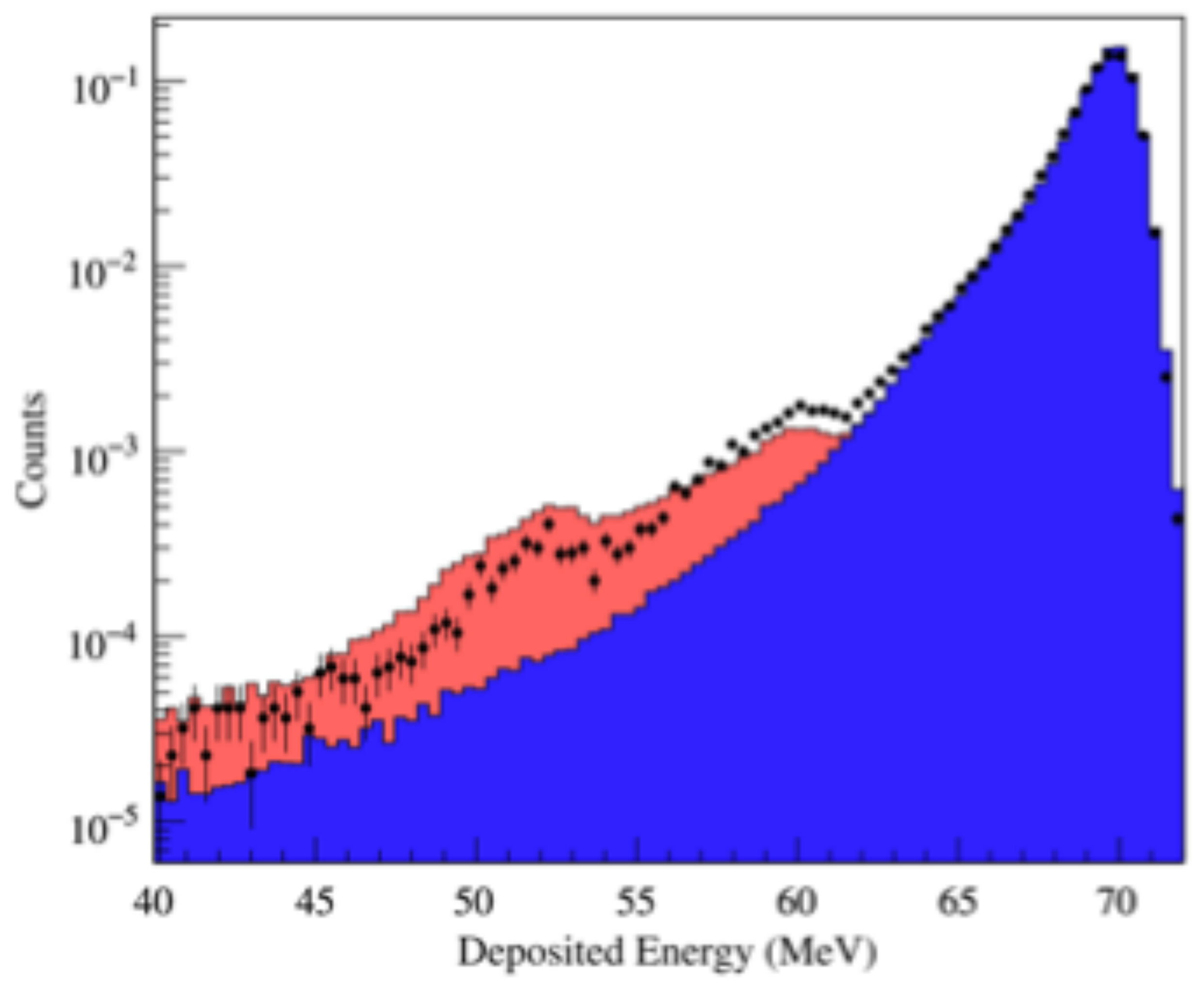


Photo-nuclear reaction

Photonuclear reactions in NaI detector

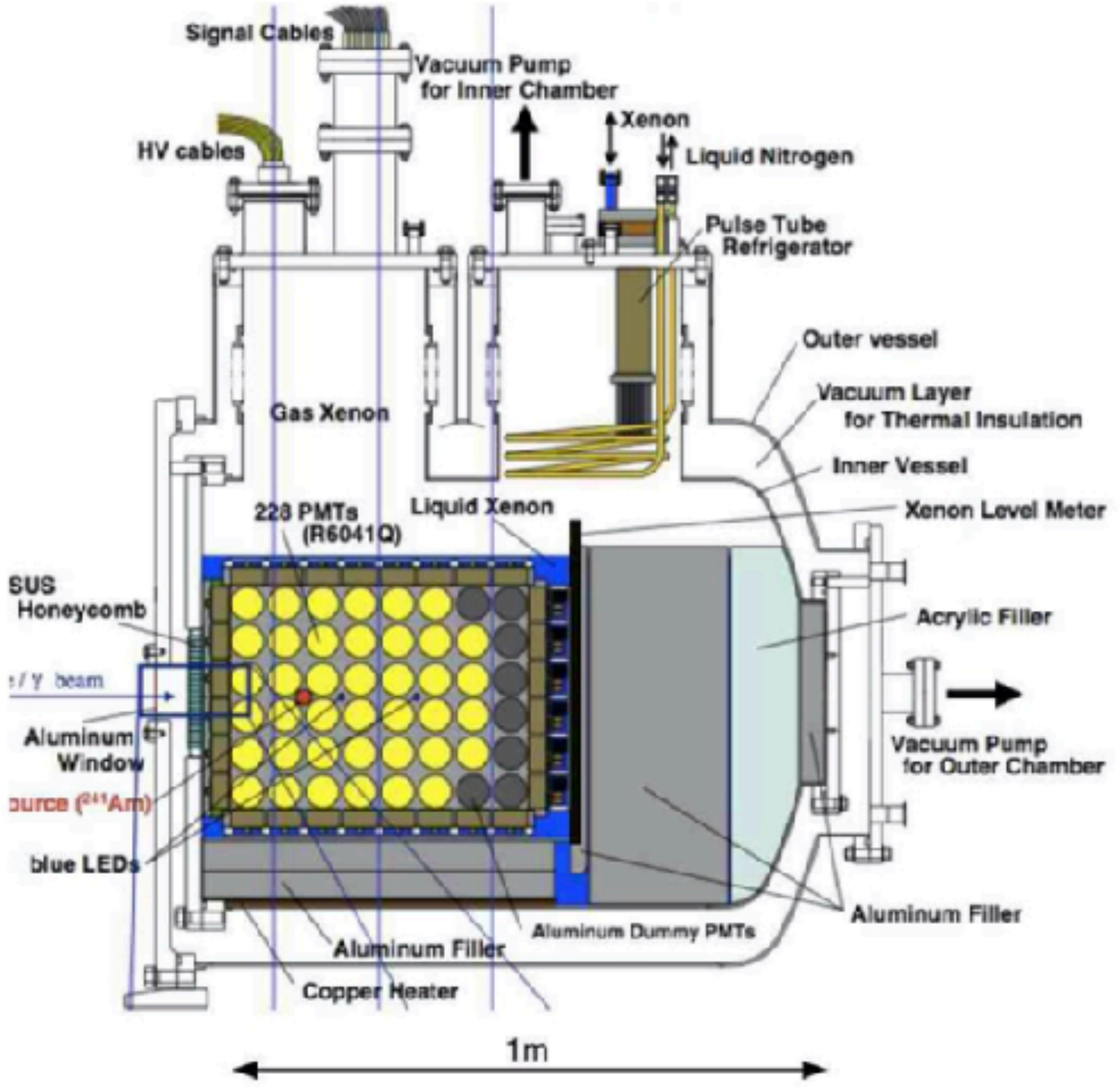
- ^{127}I captures γ(electromagnetic shower)
  → n(94%), p(4%), α(2%) emission
  → 1n, or 2n escape from NaI
  → peaks in low energy region
- This energy region is buried in π→μ→e decays, and Geant4 simulation should be tuned by data



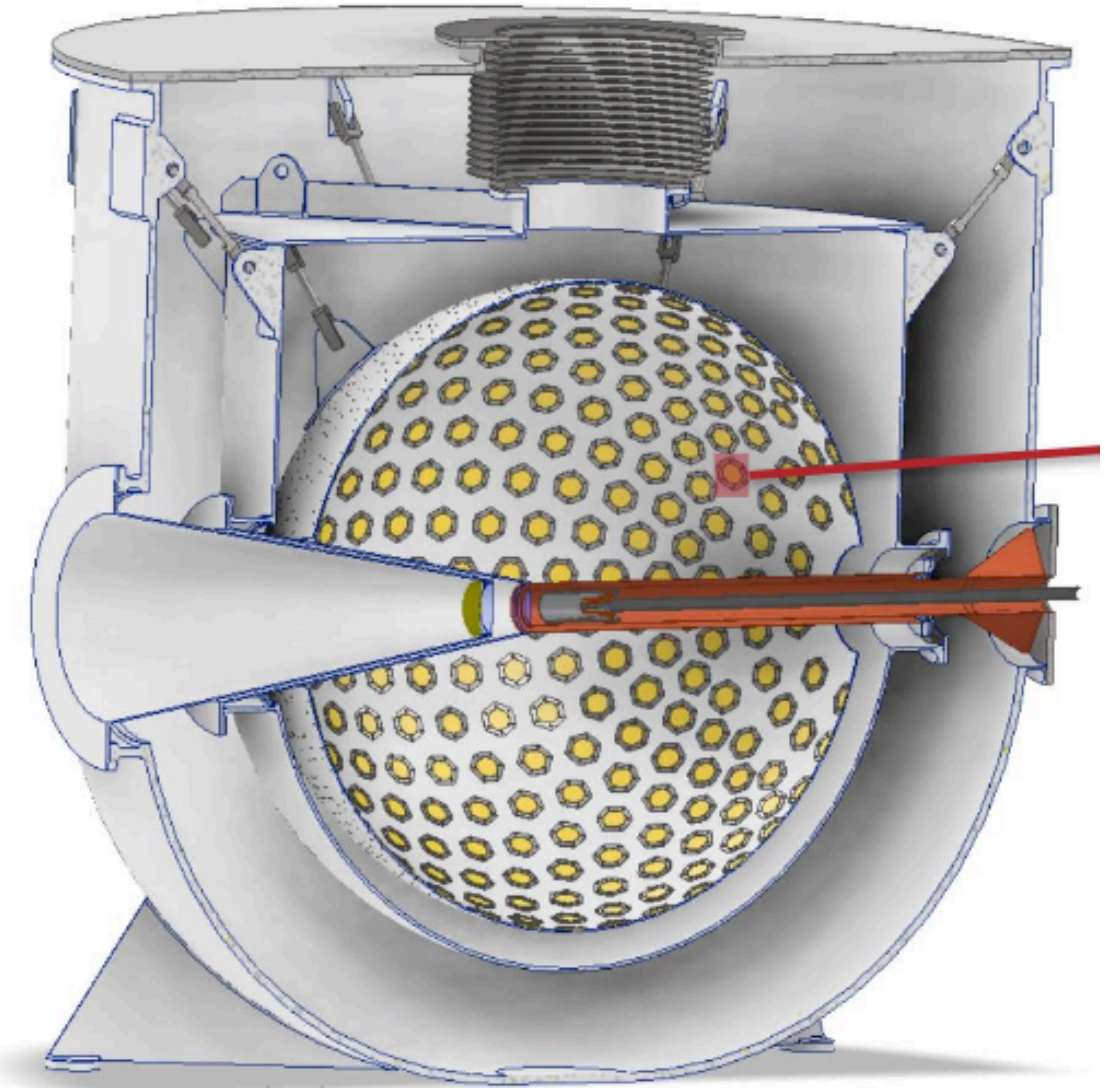
Nucl. Instrum.Meth.A621(2010)188-191

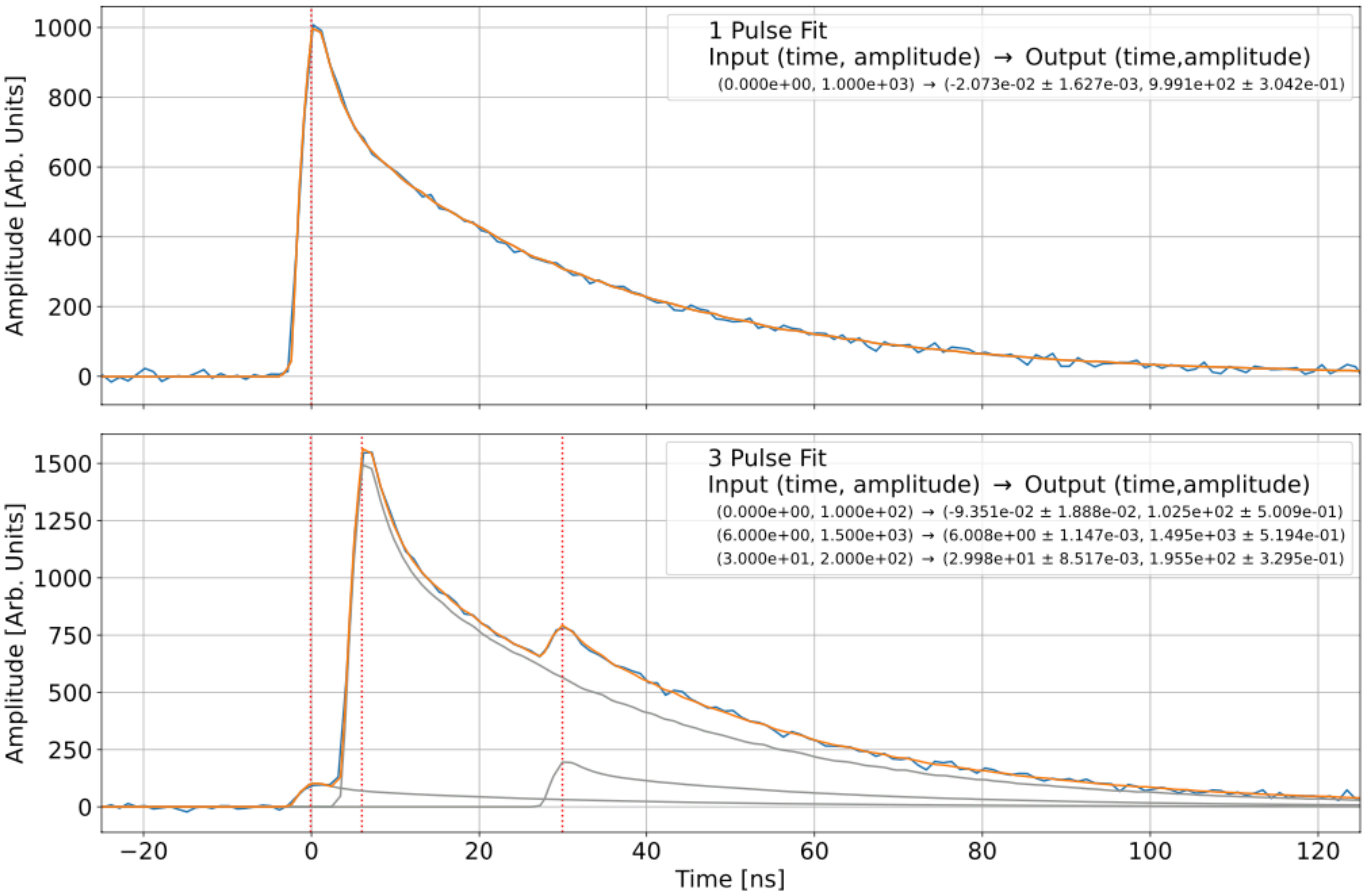
Beam test was performed with NaI in the previous experiment

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



Pulse Fitting Studies

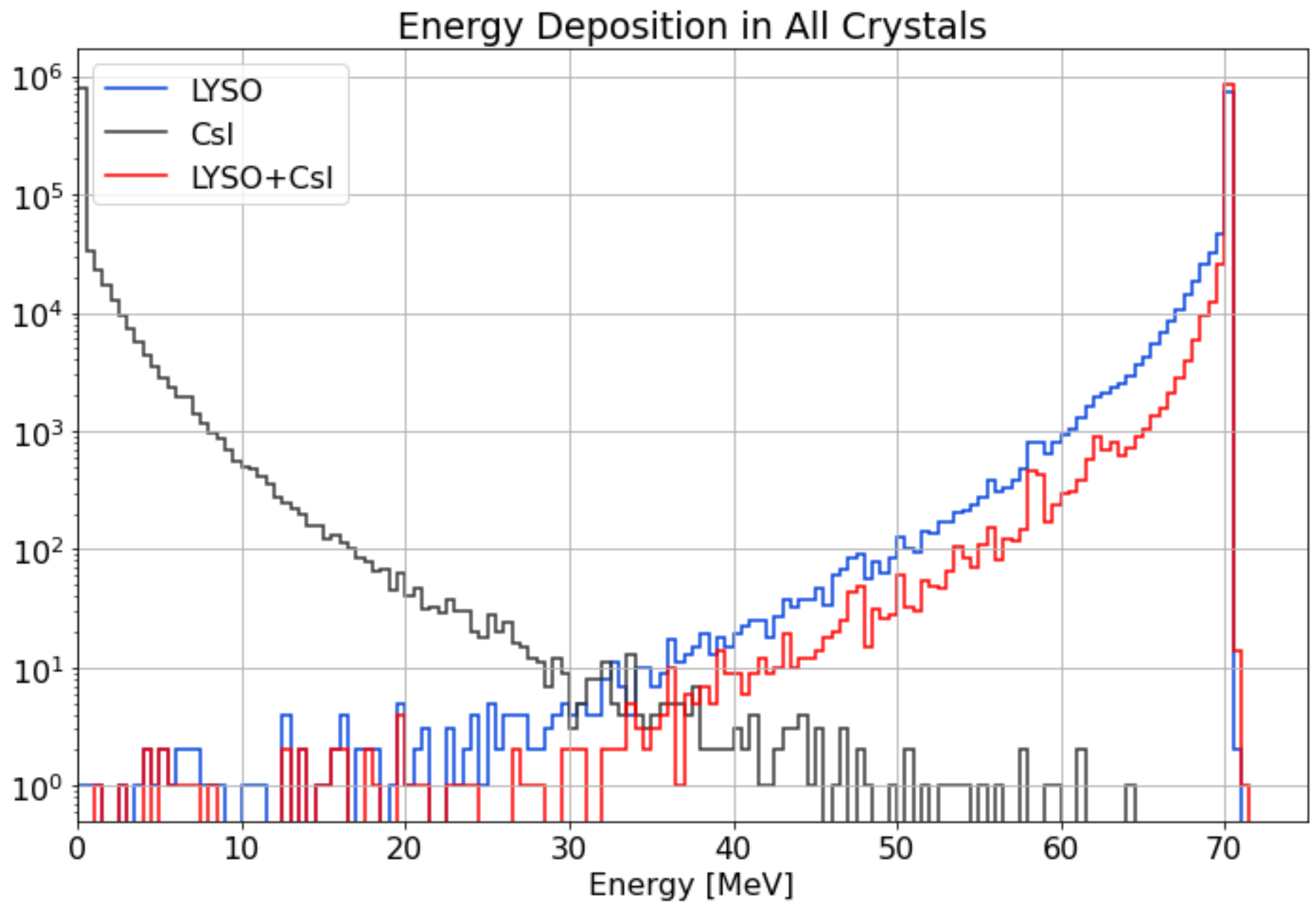


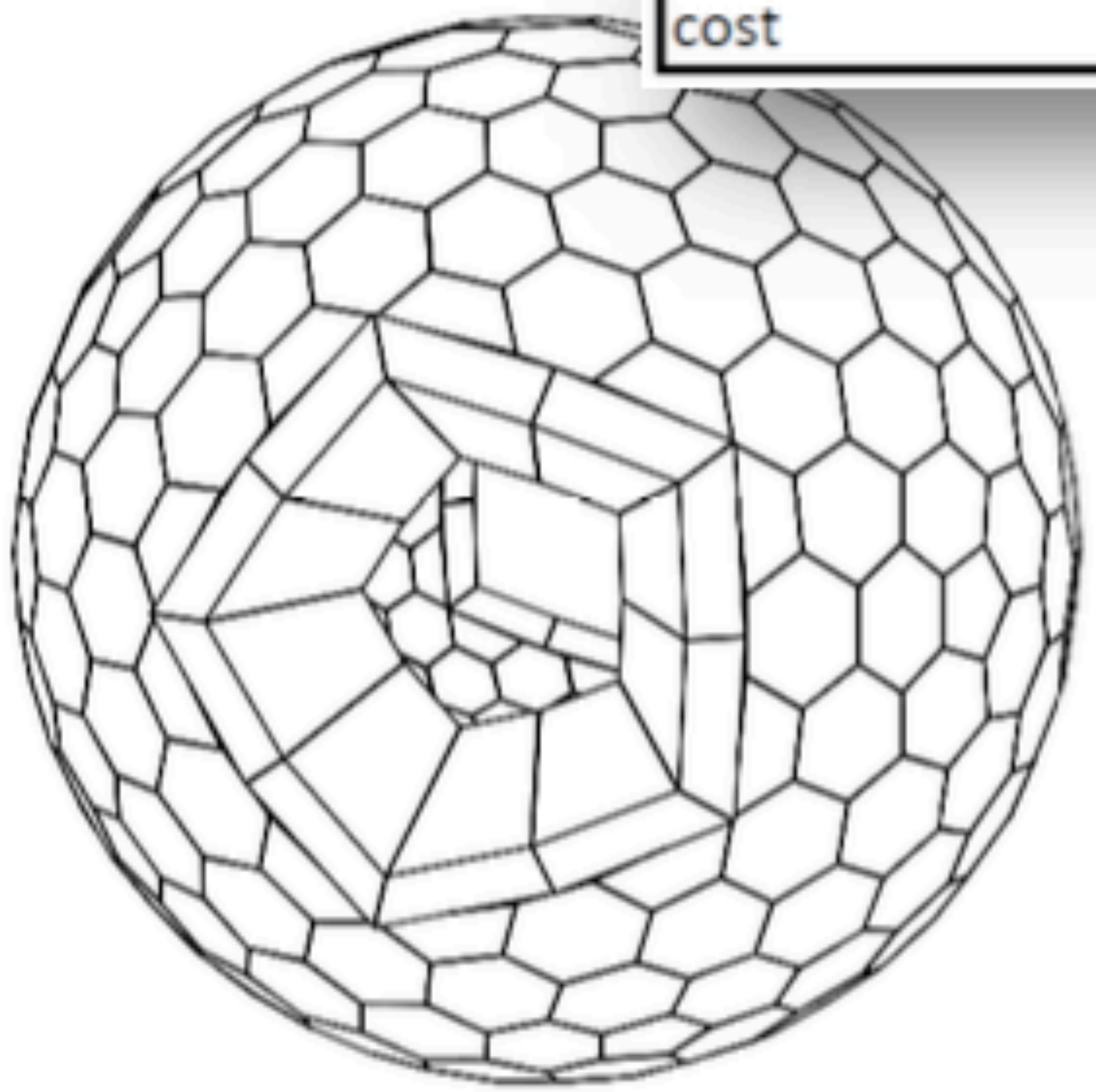


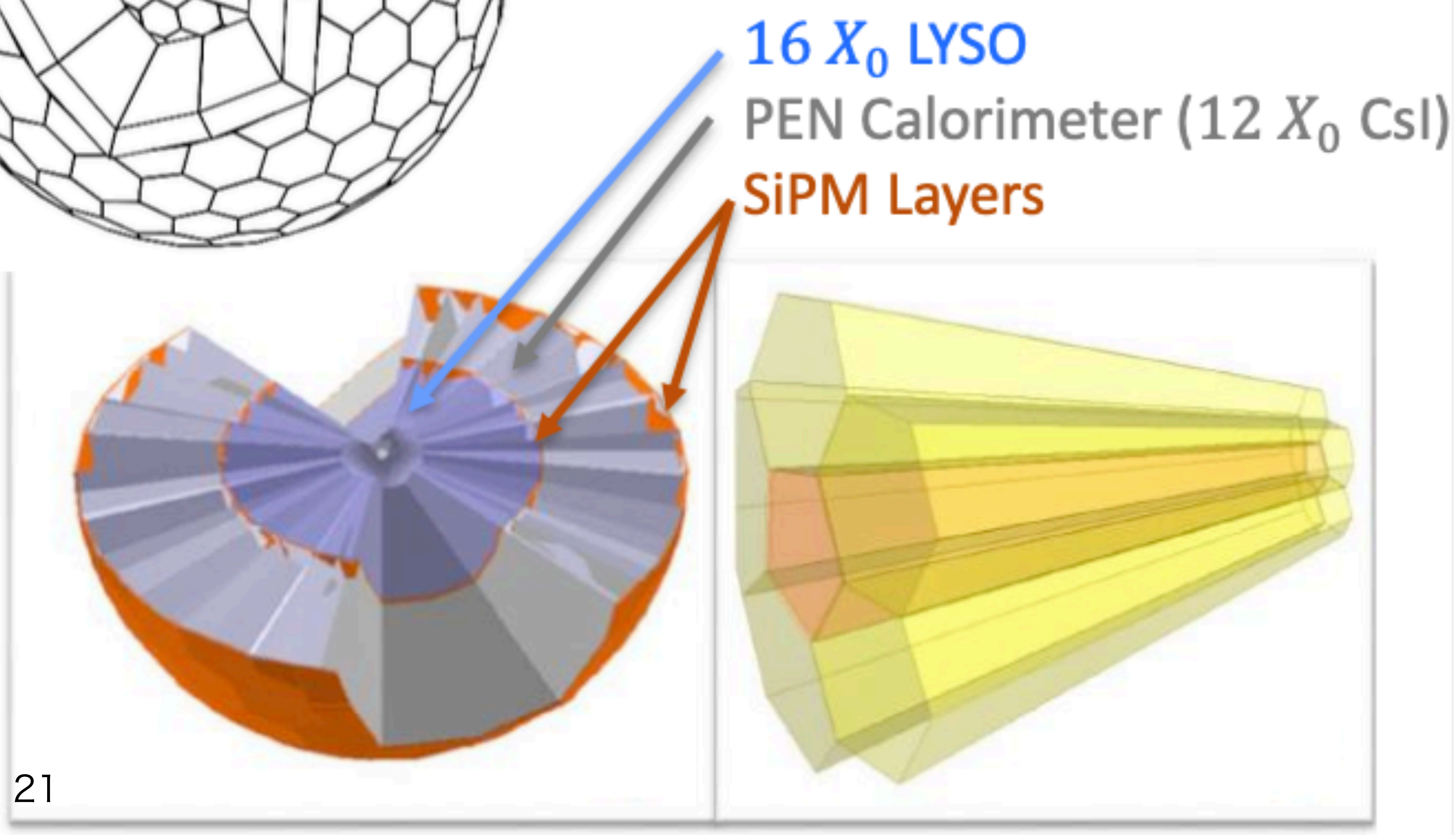
Pileup identification with waveform analysis seems working well

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



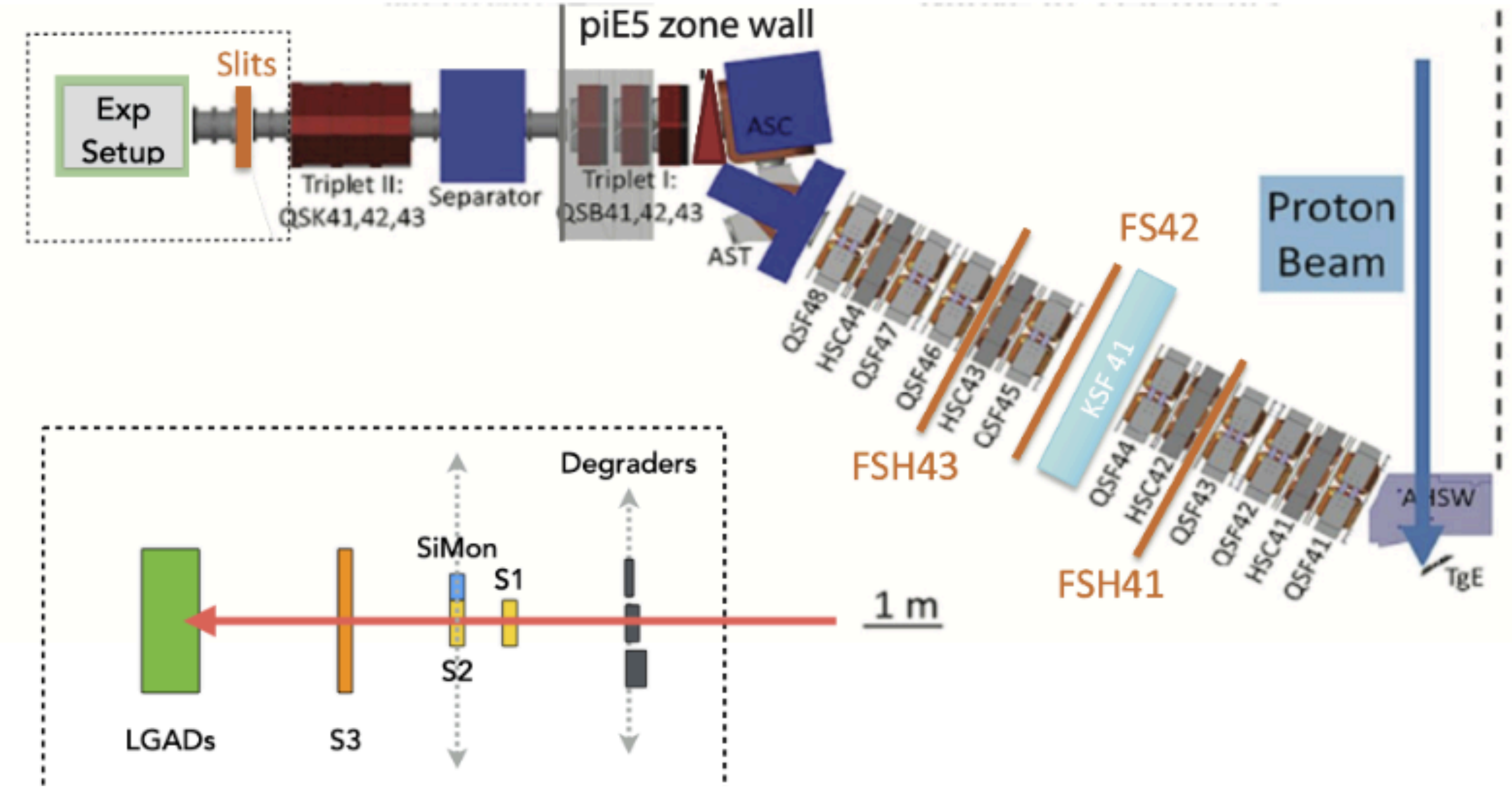


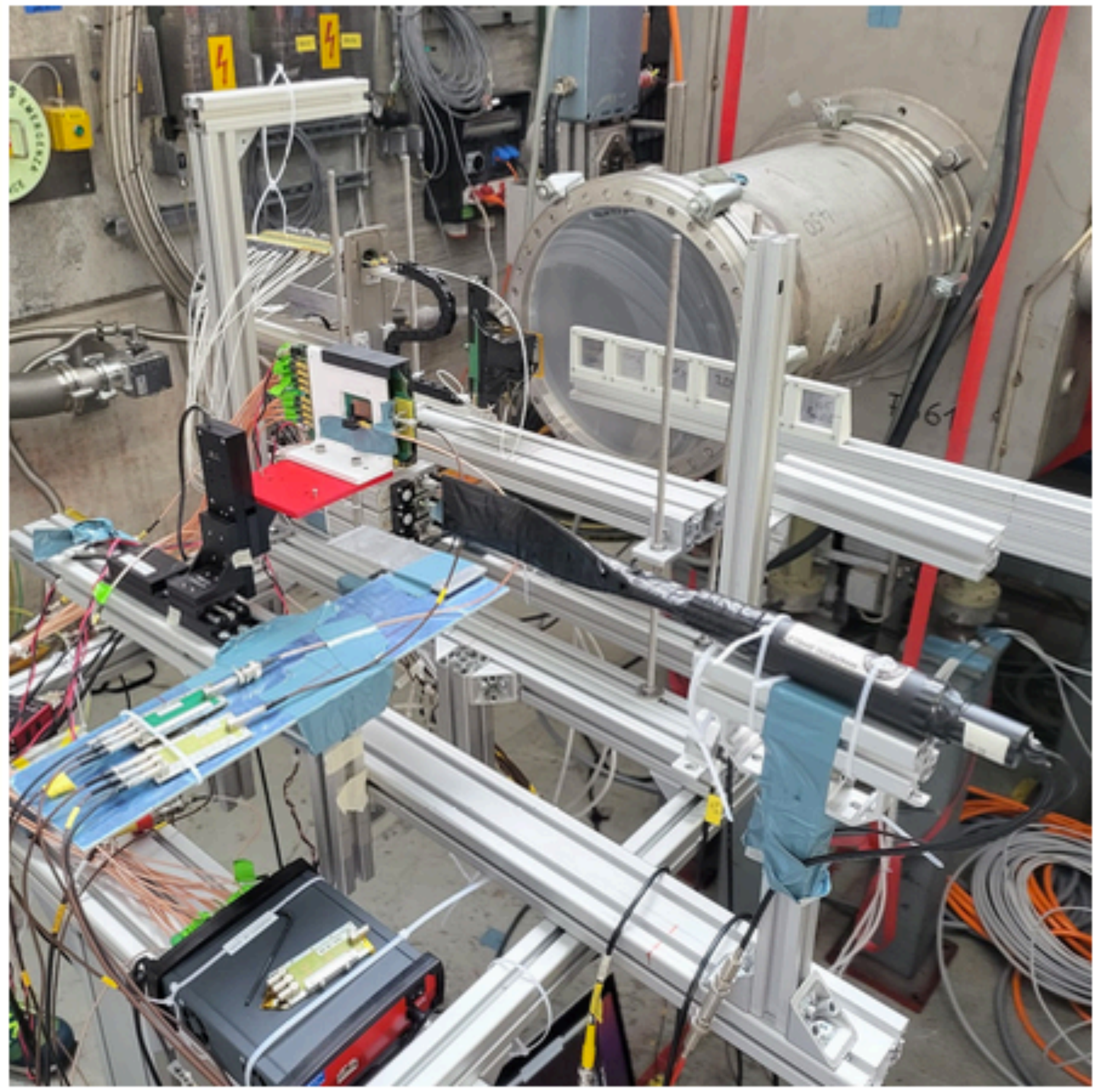


LYSO + CsI

- 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

Beam test in 2022

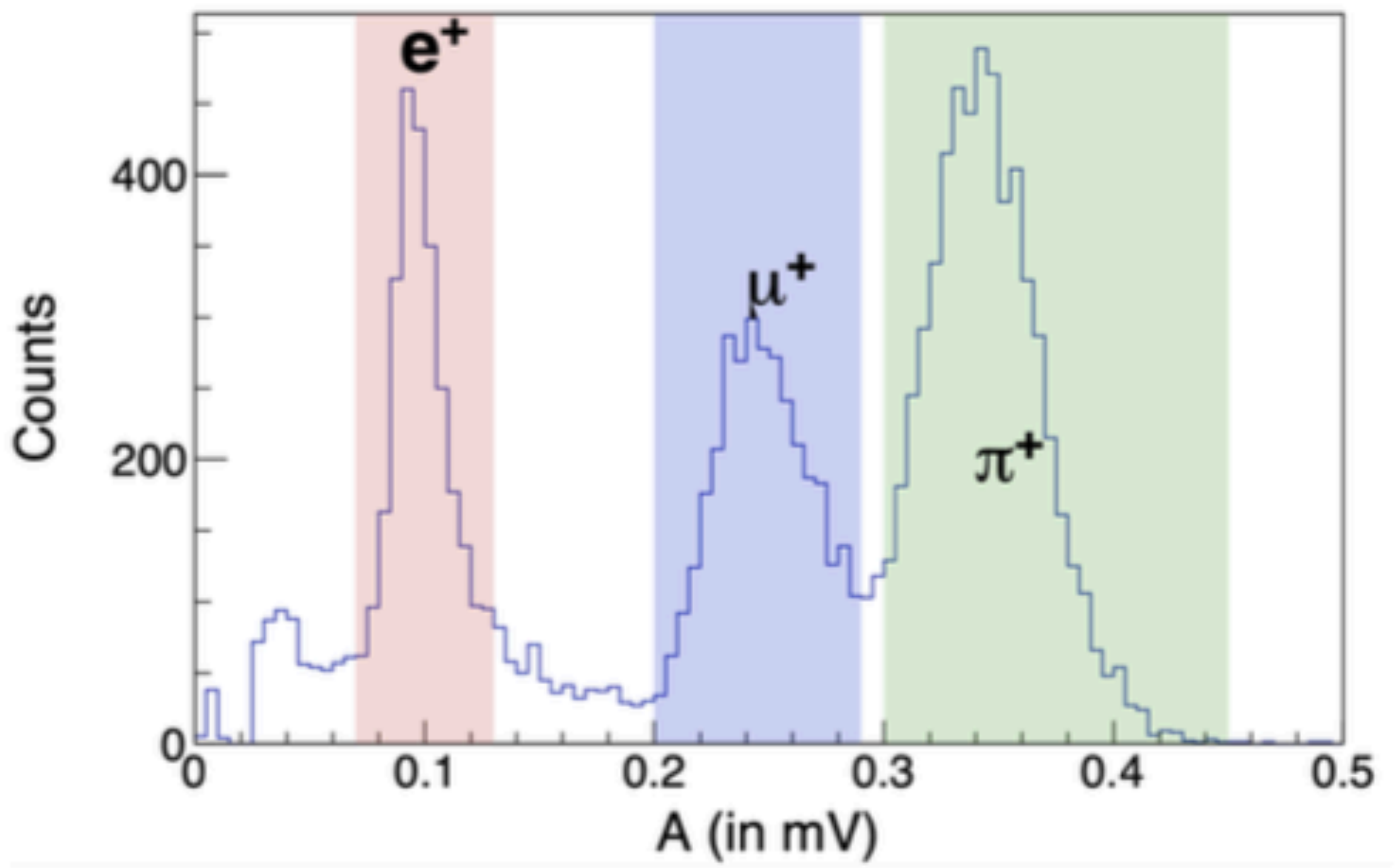


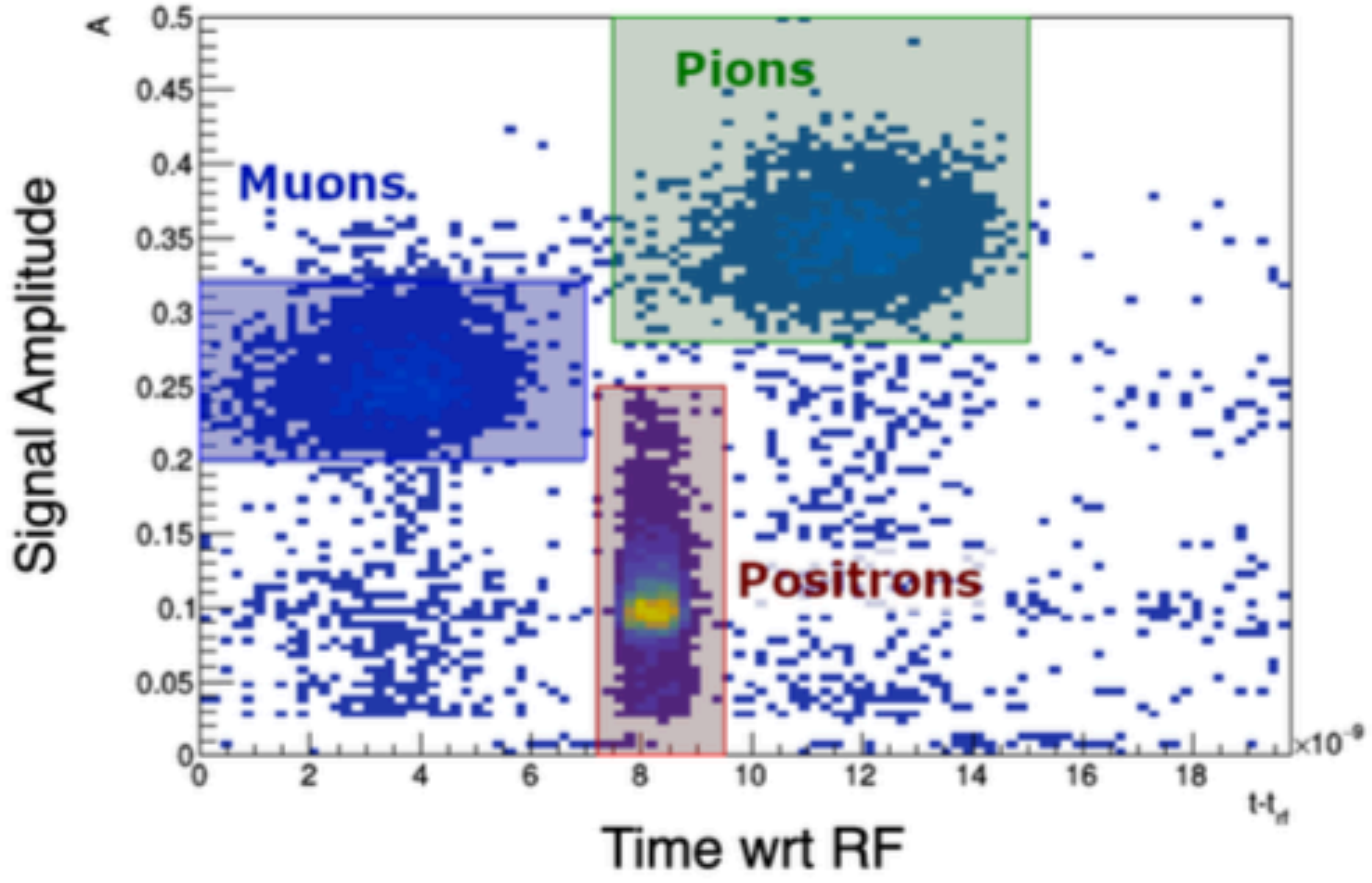


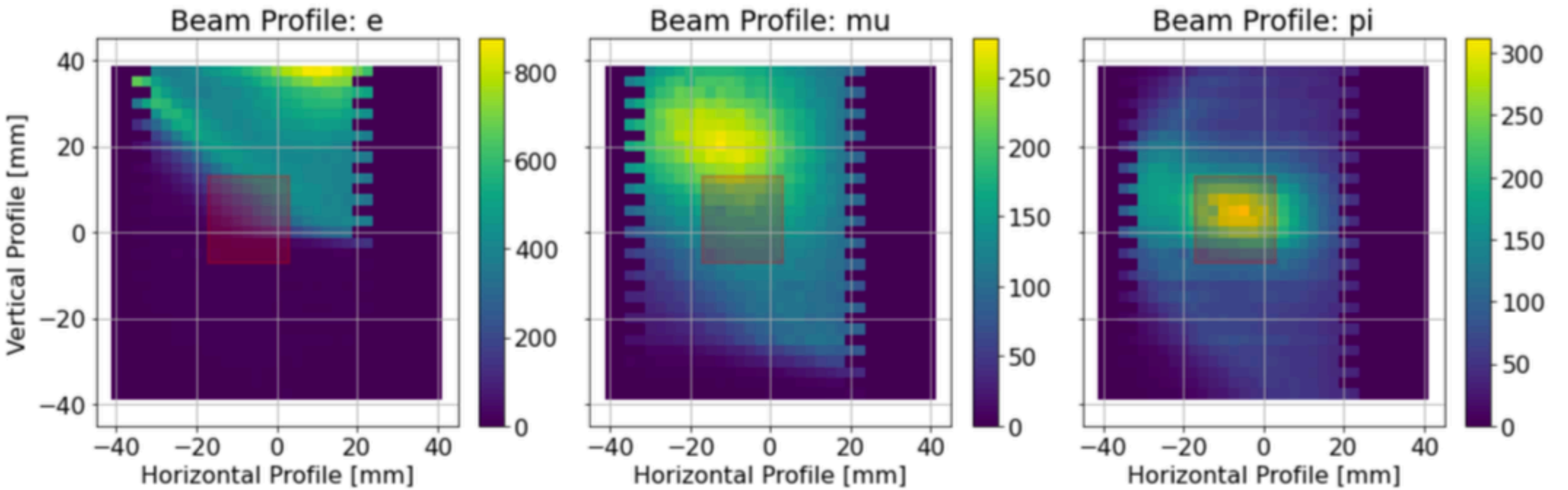
Property	Beam test	PIONEER specs
π^+/s stopped in ATAR (kHz)	300 @ 65 MeV/c	300 @ 60 MeV/c
beam size $\sigma_x \times \sigma_y$ (mm^2)	23 x 10	8 x 8
particle separation $e : \mu : \pi$	25 : 32 : 43	10 : 10 : 80
$\frac{dP}{P}$ FWHM (%)	~ 3	<2

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

Beam test 2022







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

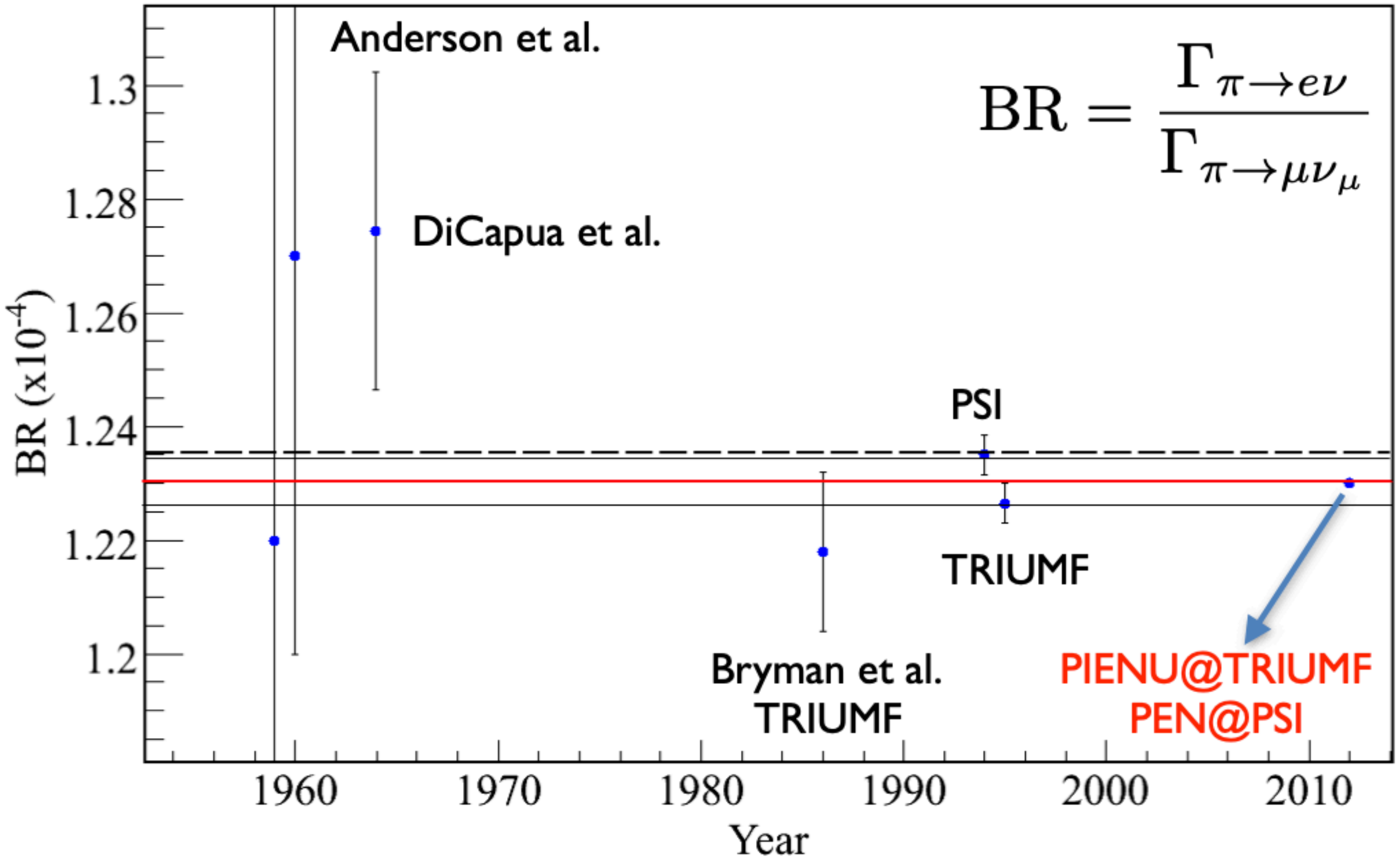
- 10^{-4} level

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

Experimental uncertainty

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

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



Tracker

Connect positron tracks between ATAR and Calo.

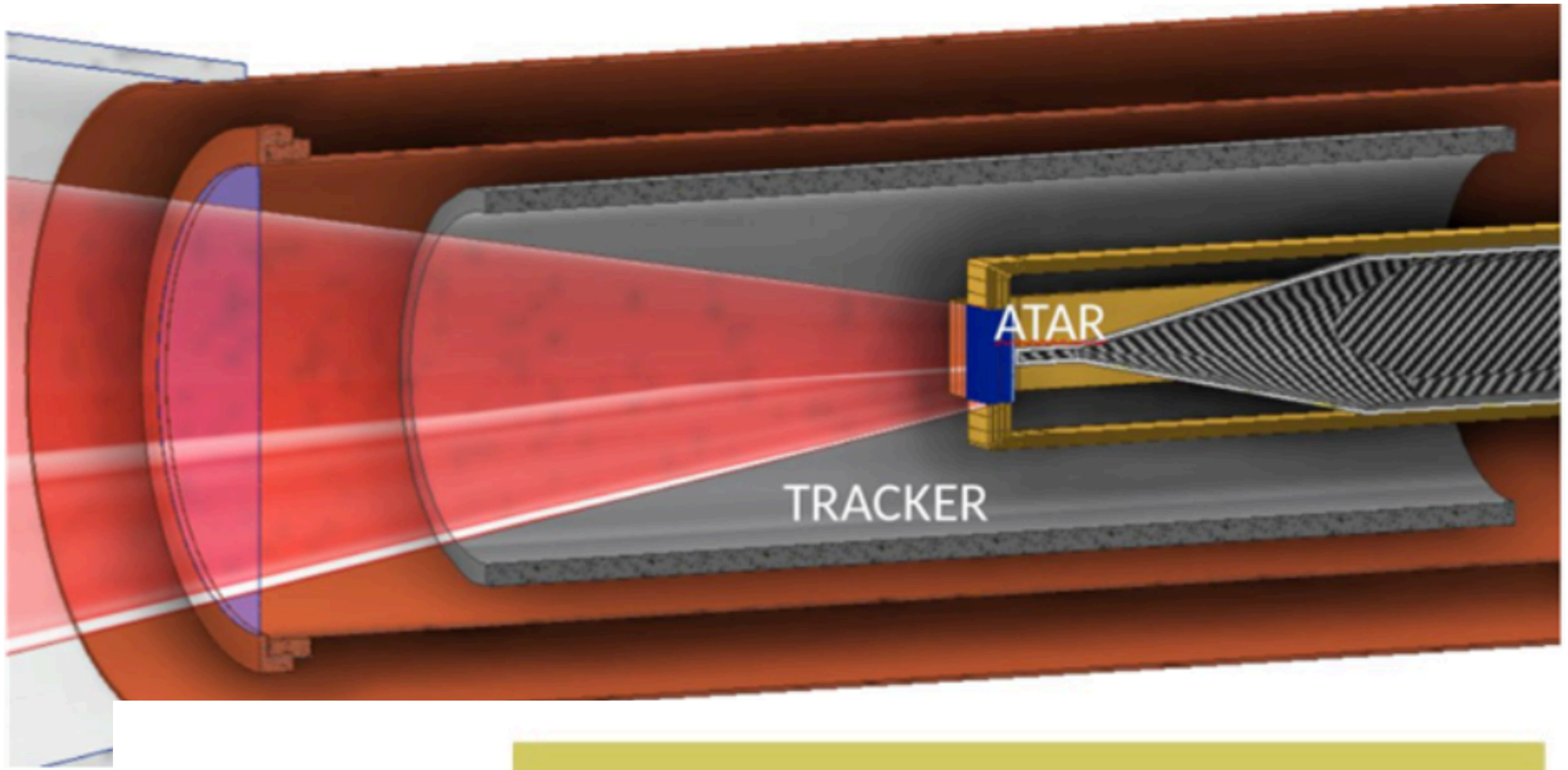
- Low material budget is required
- z, ϕ, and time

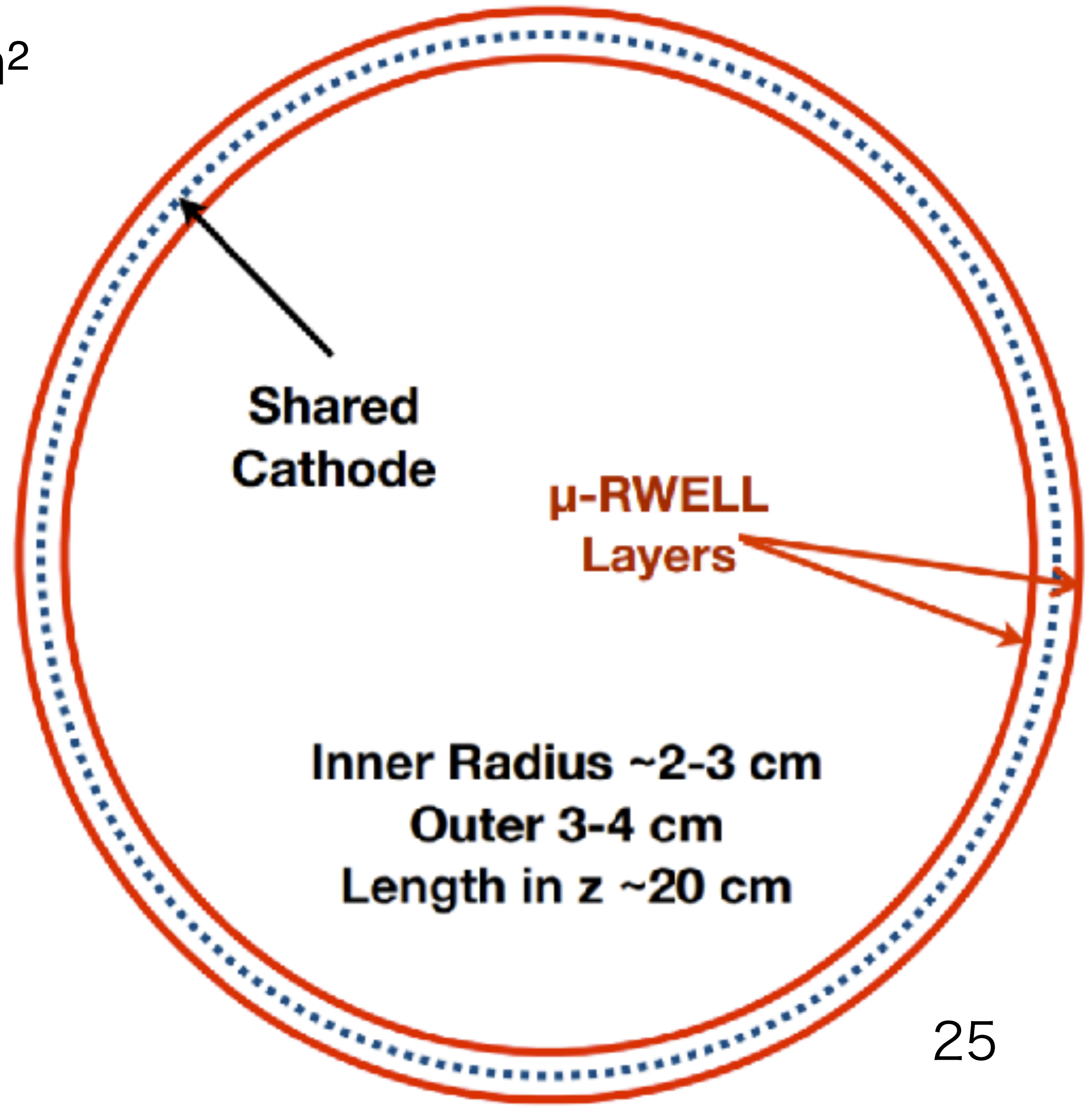
The μ-RWELL is a very promising technology in harsh environment

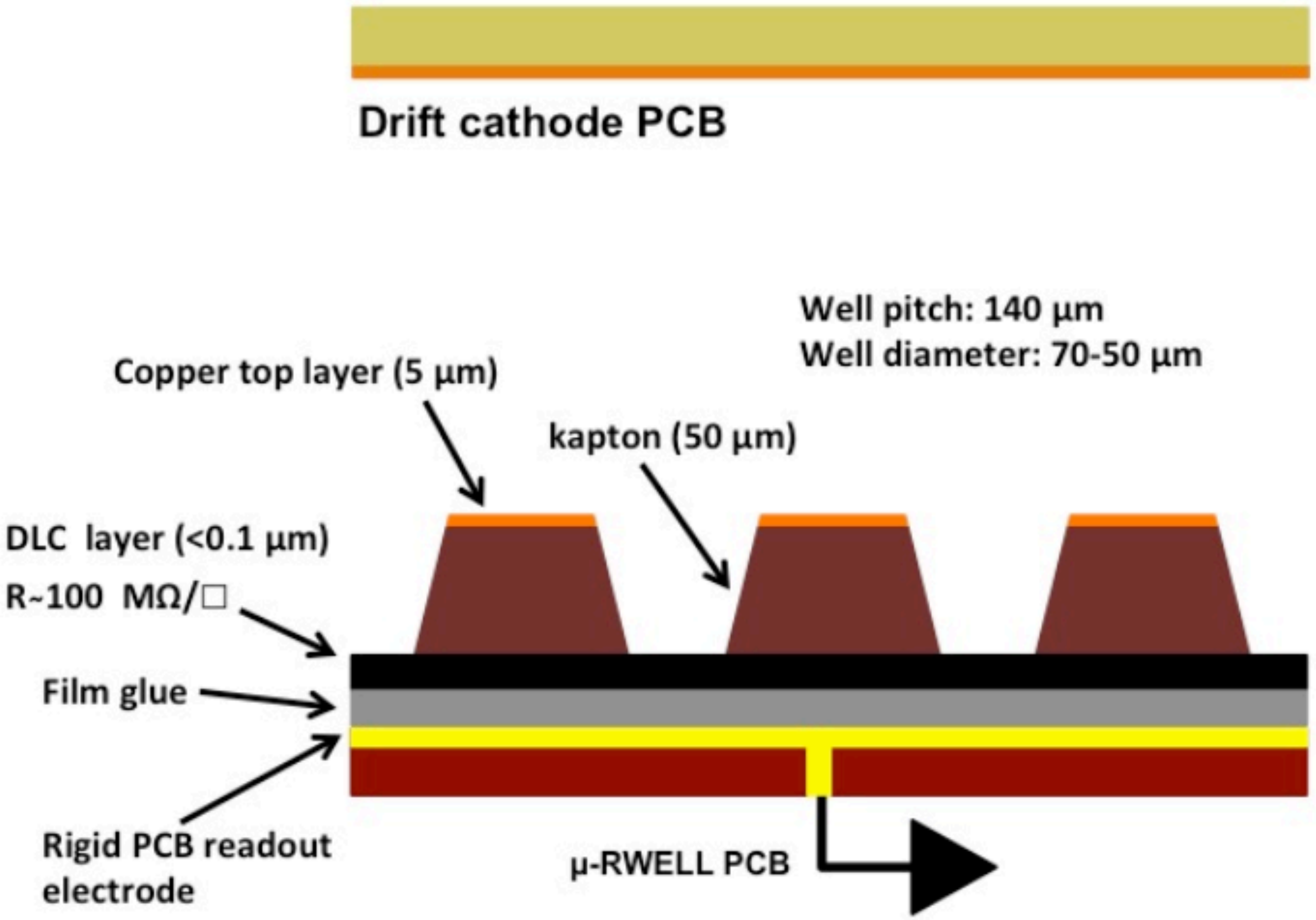
- compact, simple to assemble and intrinsically spark-protected

Performance

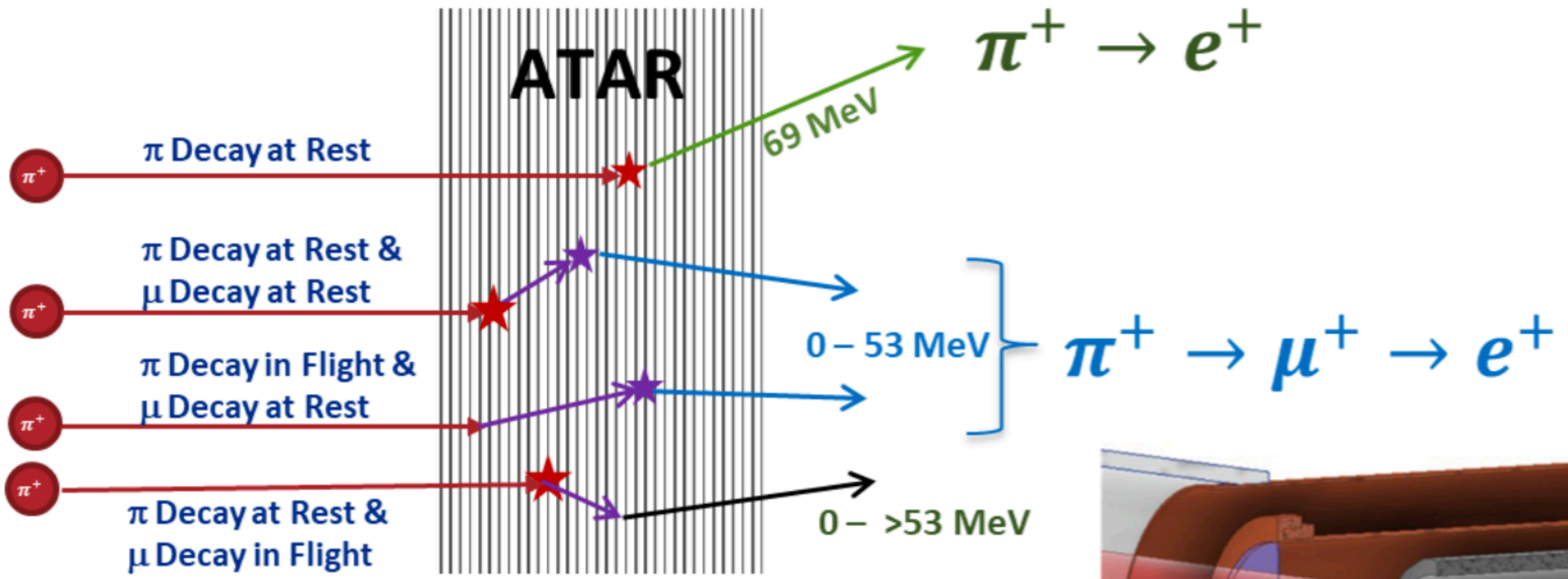
- Gas gain > 10^4
- Rate capability > $1 MHz/cm^2$
- Space resolution < 100μm
- Time resolution ~ 6ns

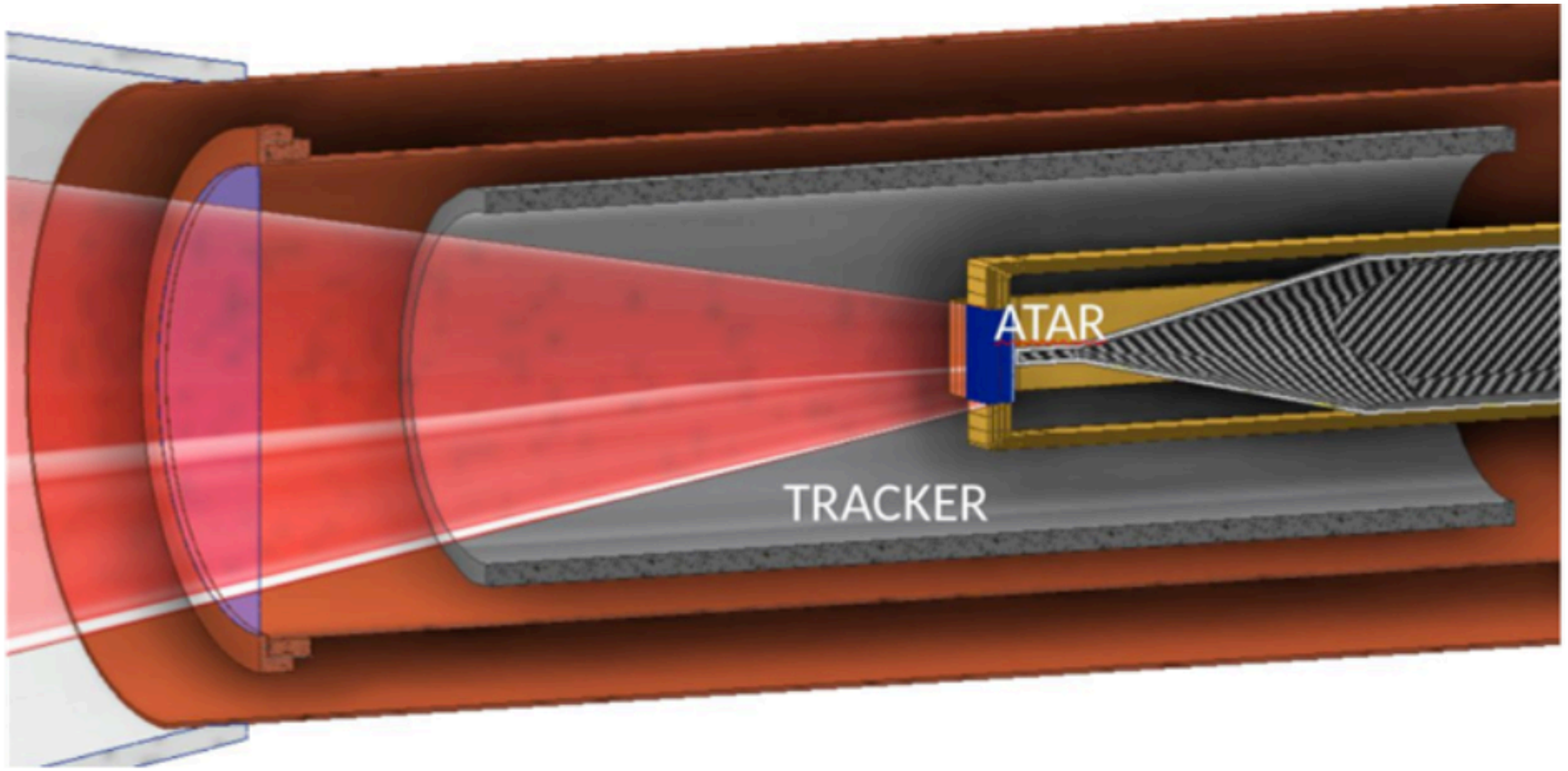




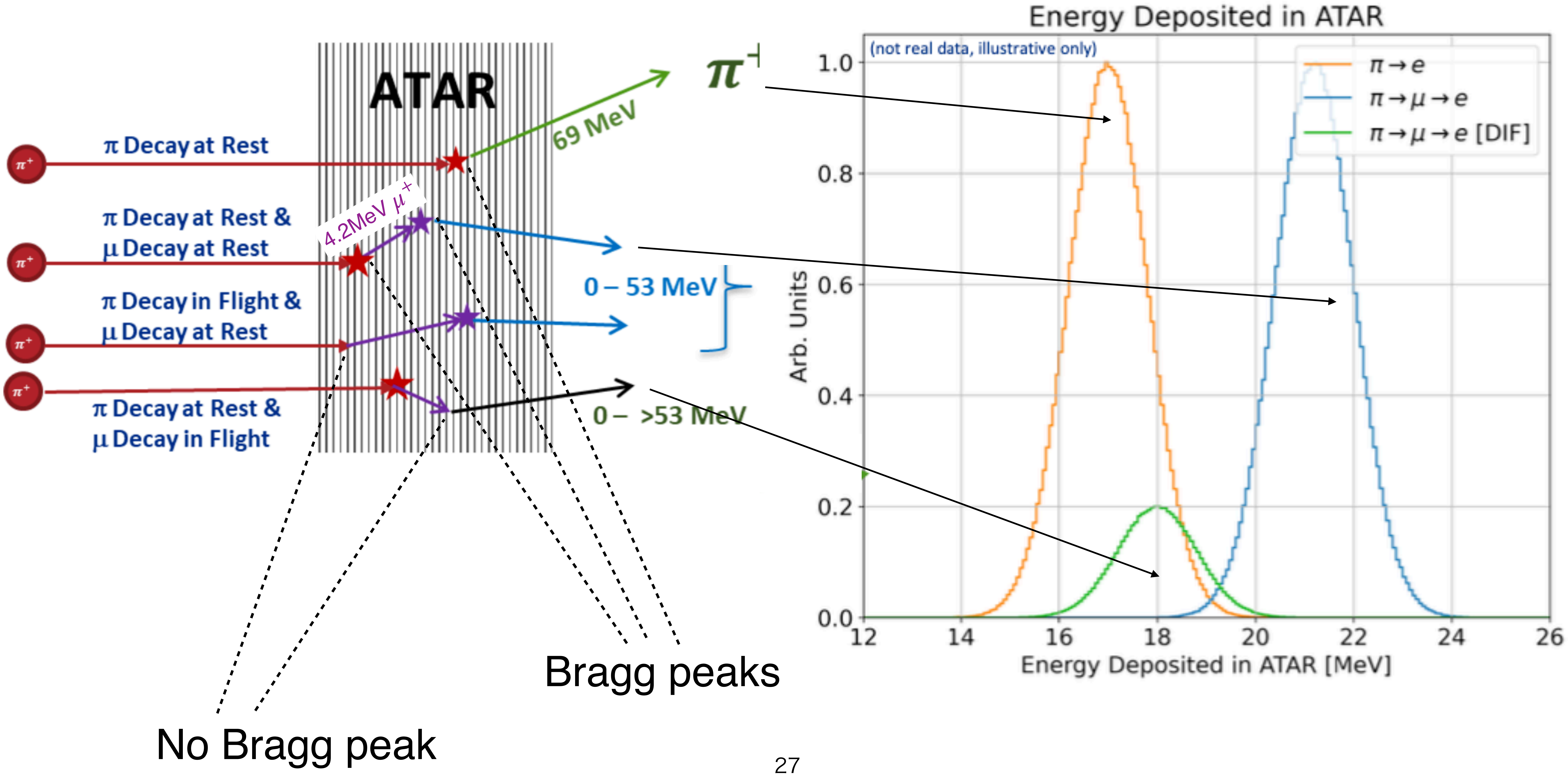


Signal and background

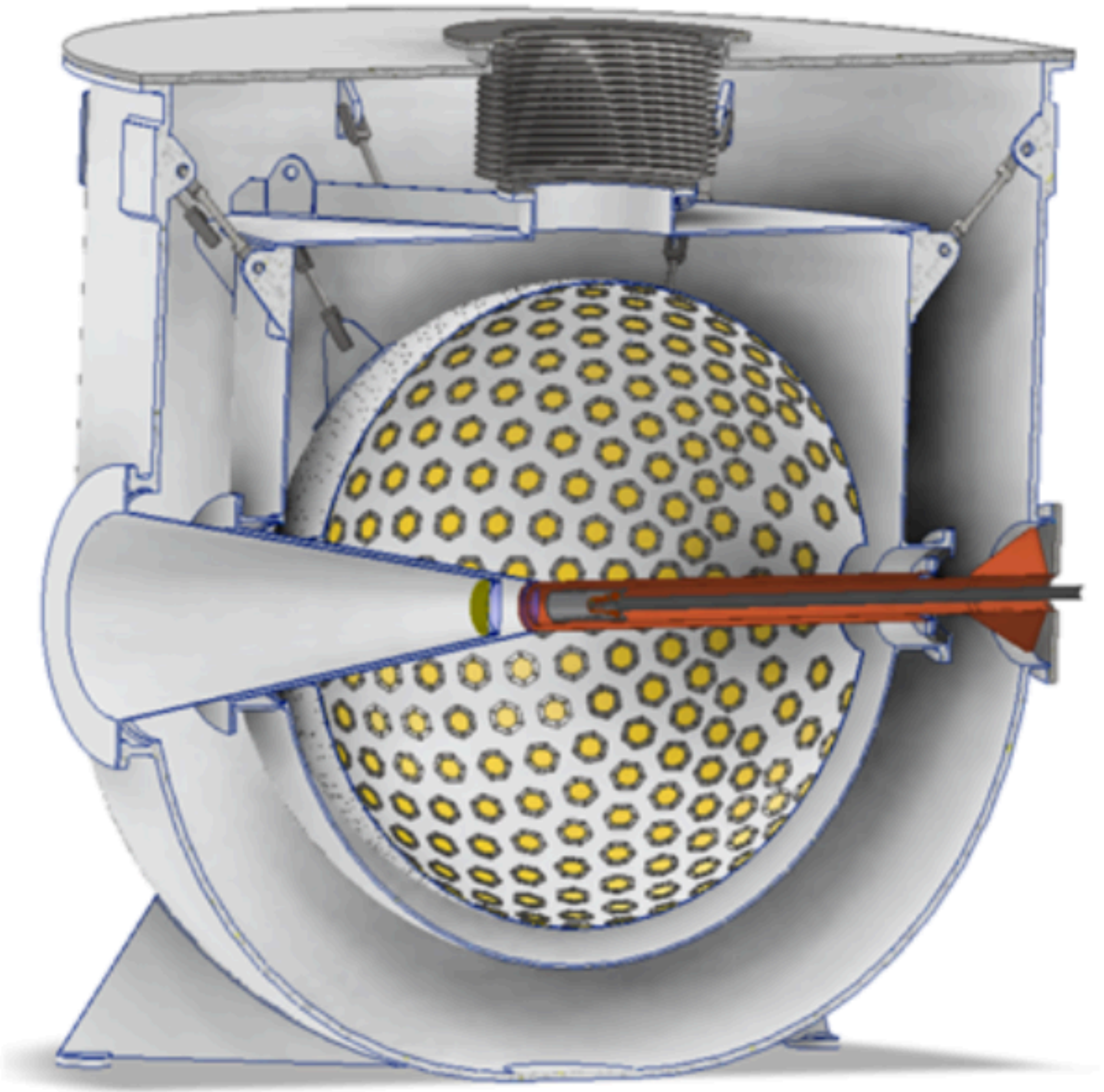




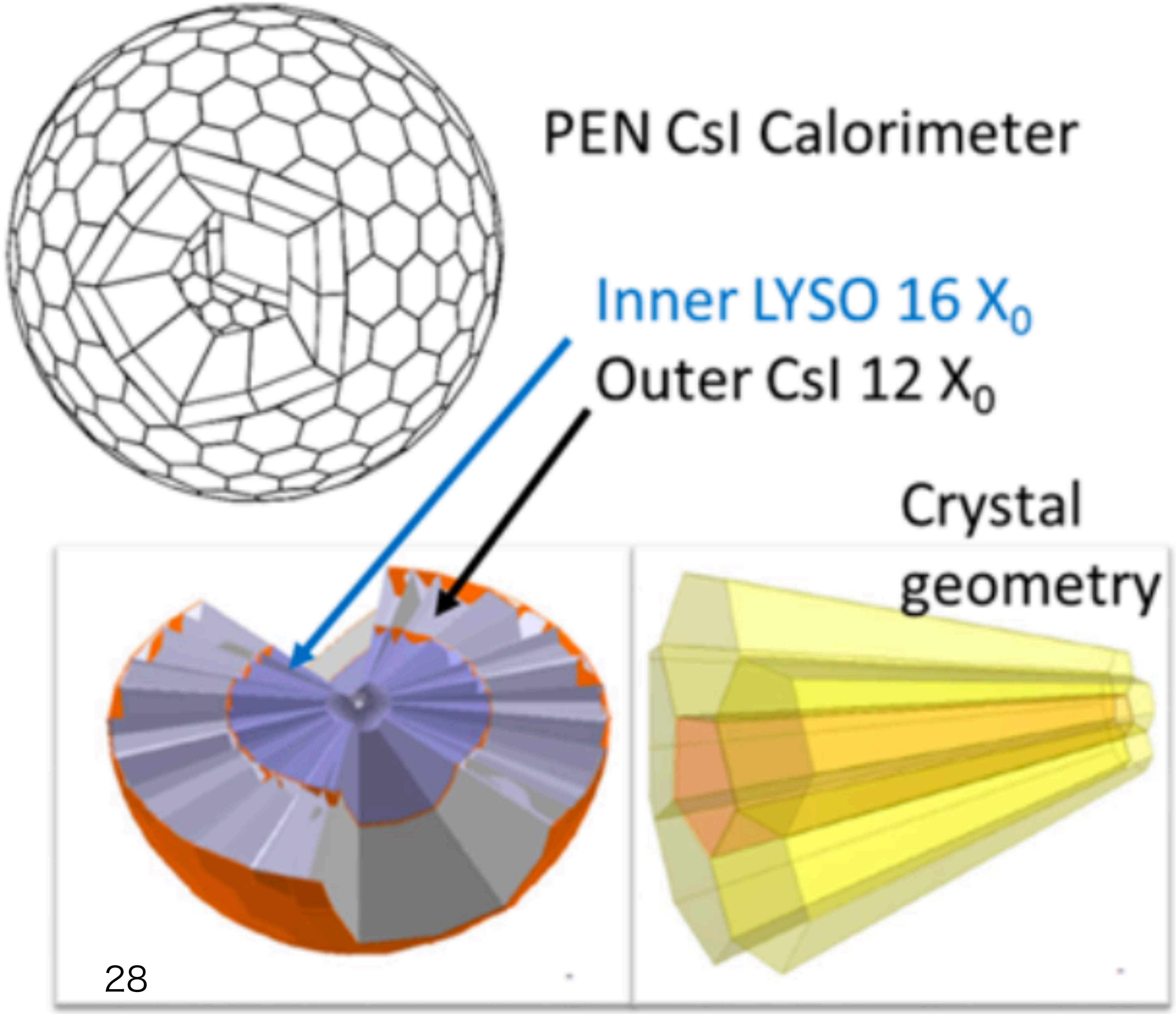
ATAR


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
Bragg peaks
No Bragg peak
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]

Calorimeter

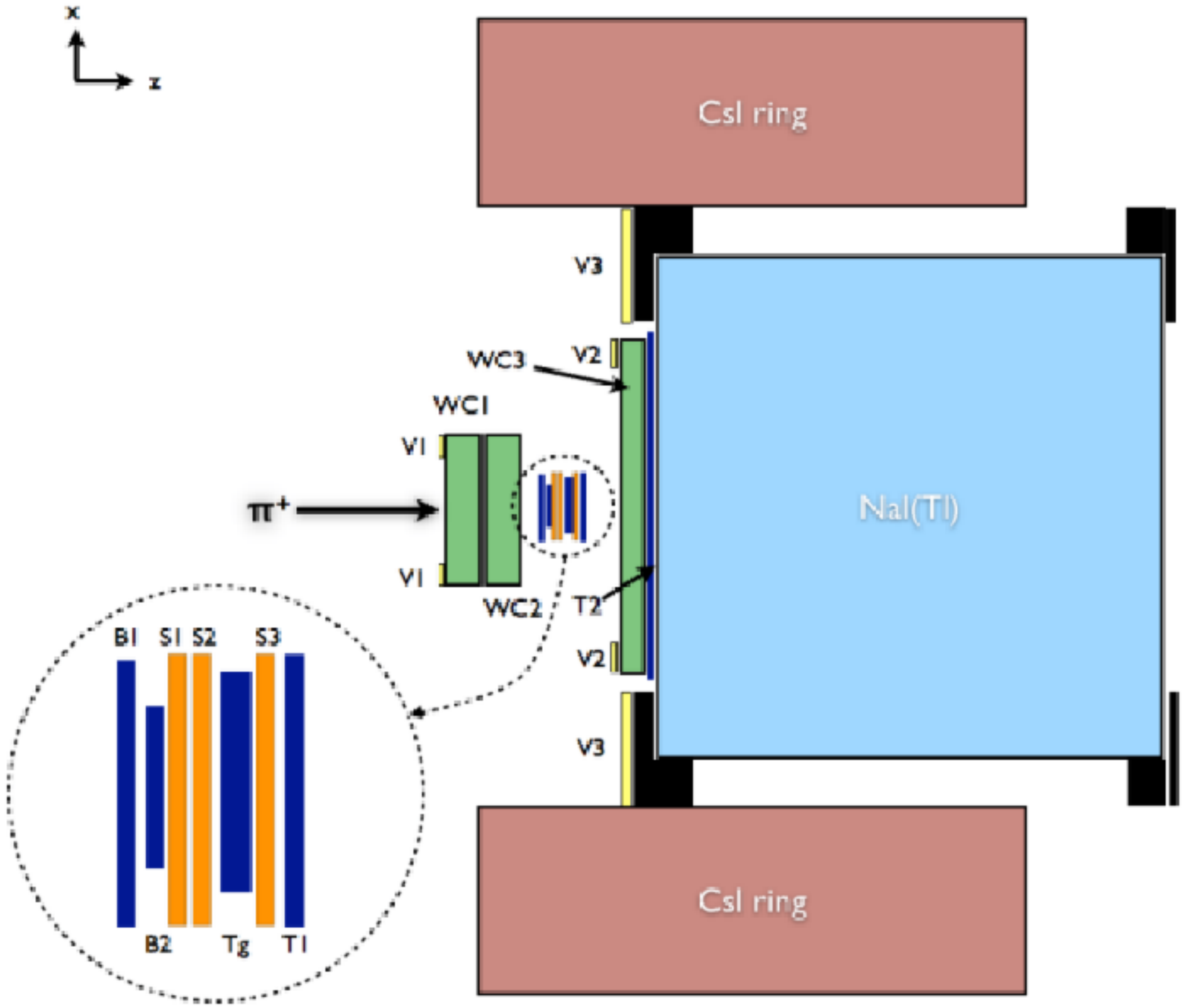


Detector	Density g/cm^3	dE/dx MeV/cm	X_0 cm	R_M cm	Decay time ns	λ_{max} nm	Light output %
LXe	2.953	3.707	2.872	5.224	3, 27, 45	178	100
LSO(Ce)	7.40	9.6	1.14	2.07	40	402	85

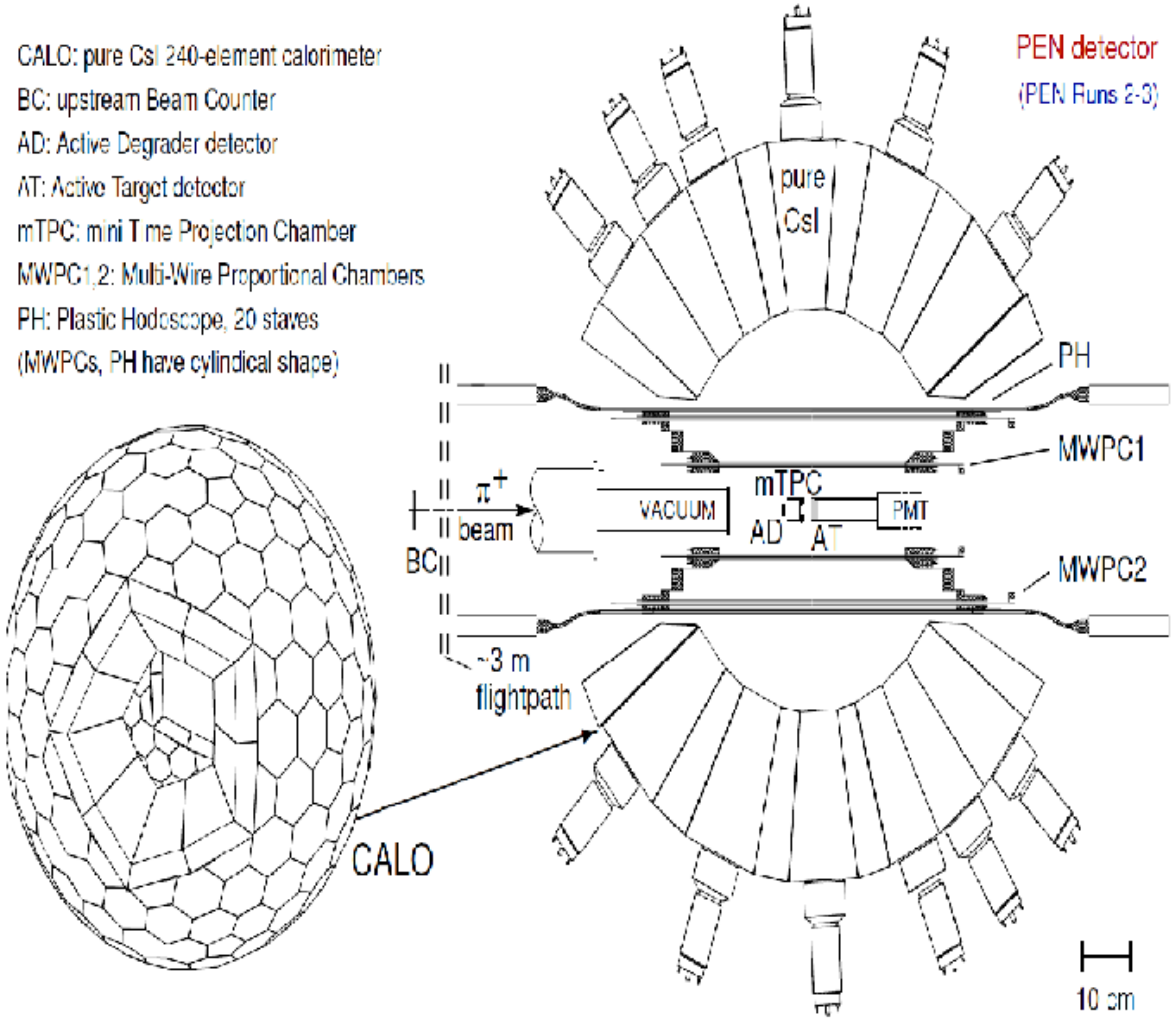


Lessons learned

PIENU @ TRIUMF



PEN & PiBeta @ PSI

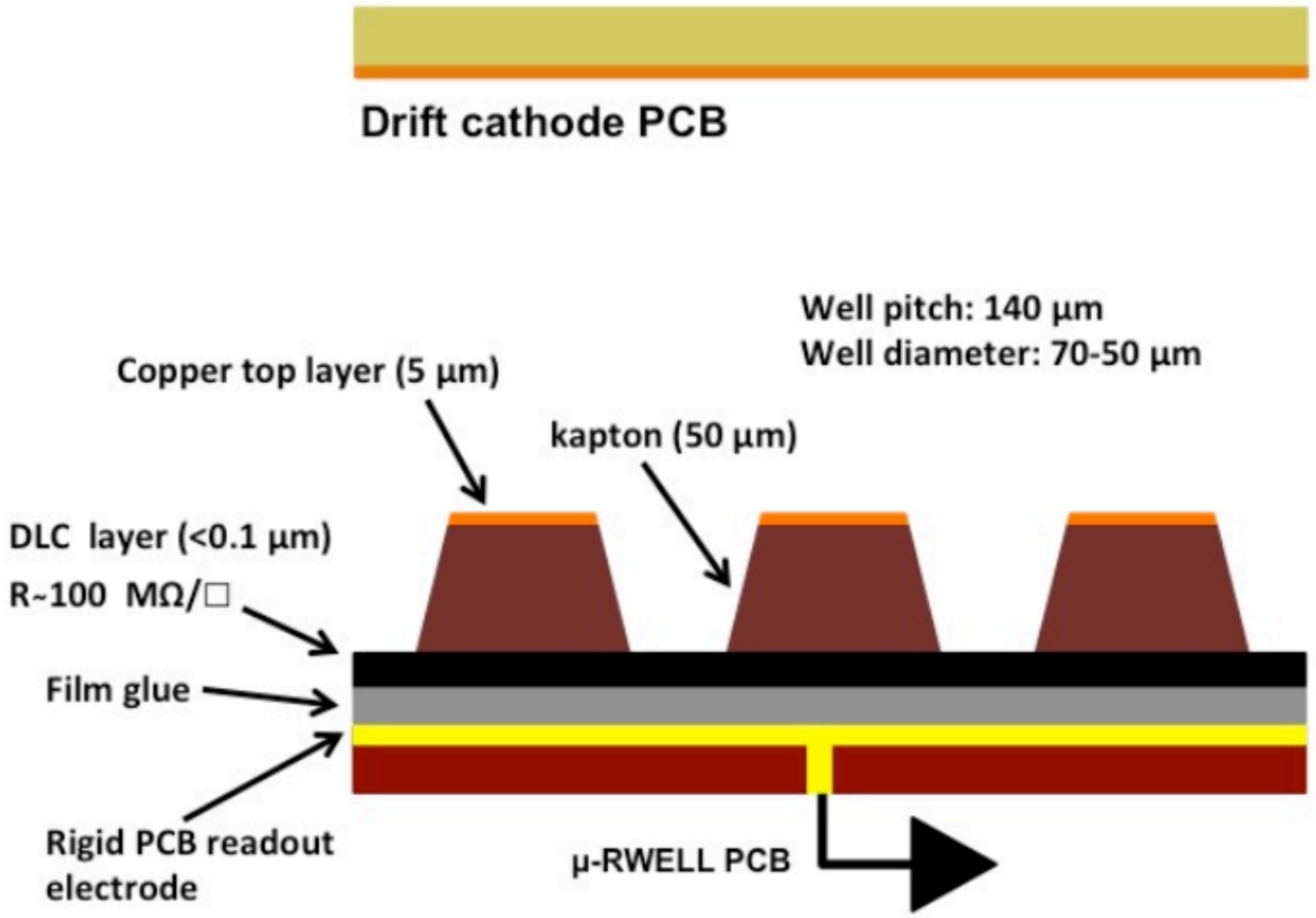


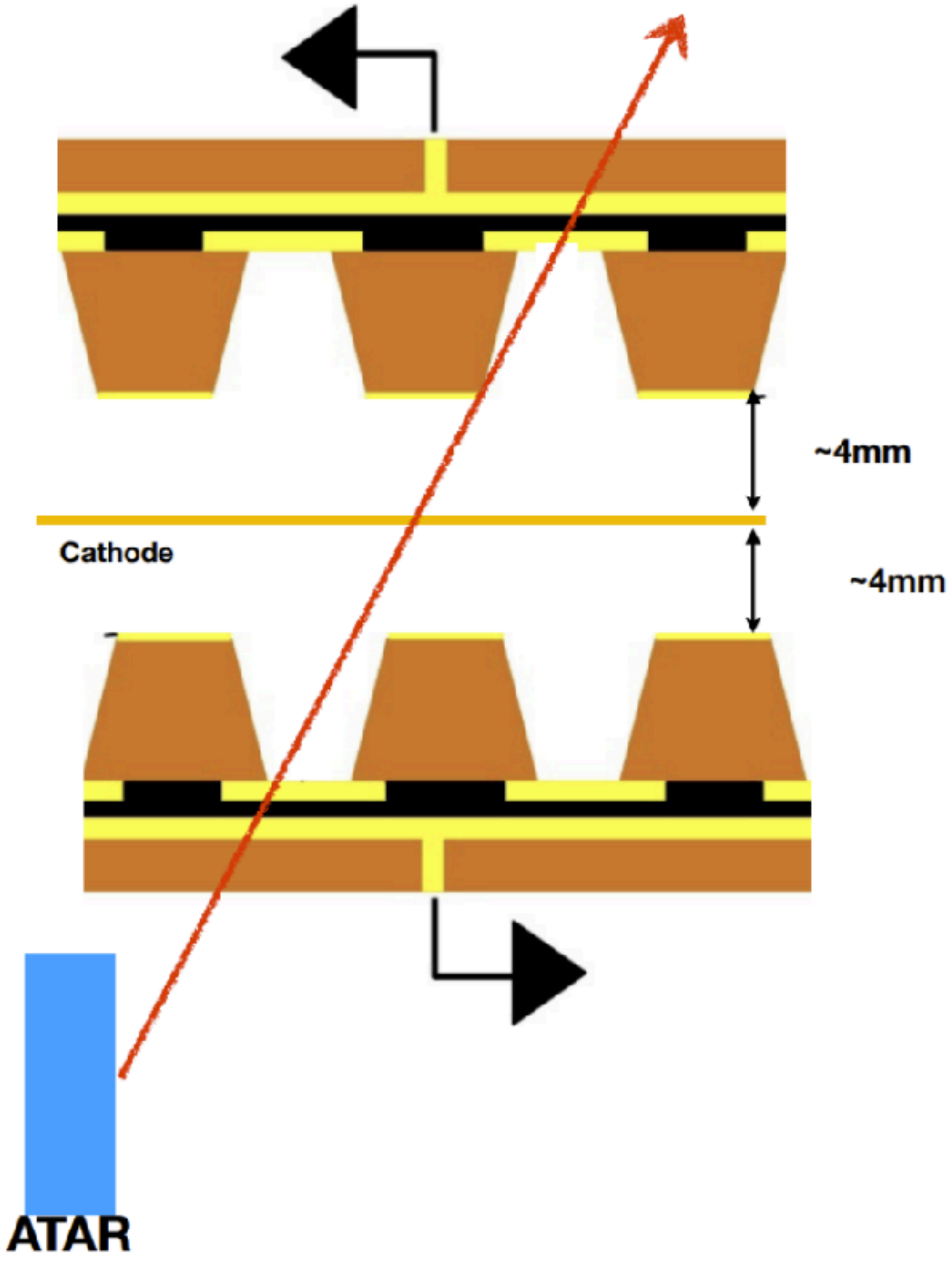
- Slow … NaI, but good resolution
- Single large crystal not uniform enough (material and effective “depth”)
- Small solid angle

- 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

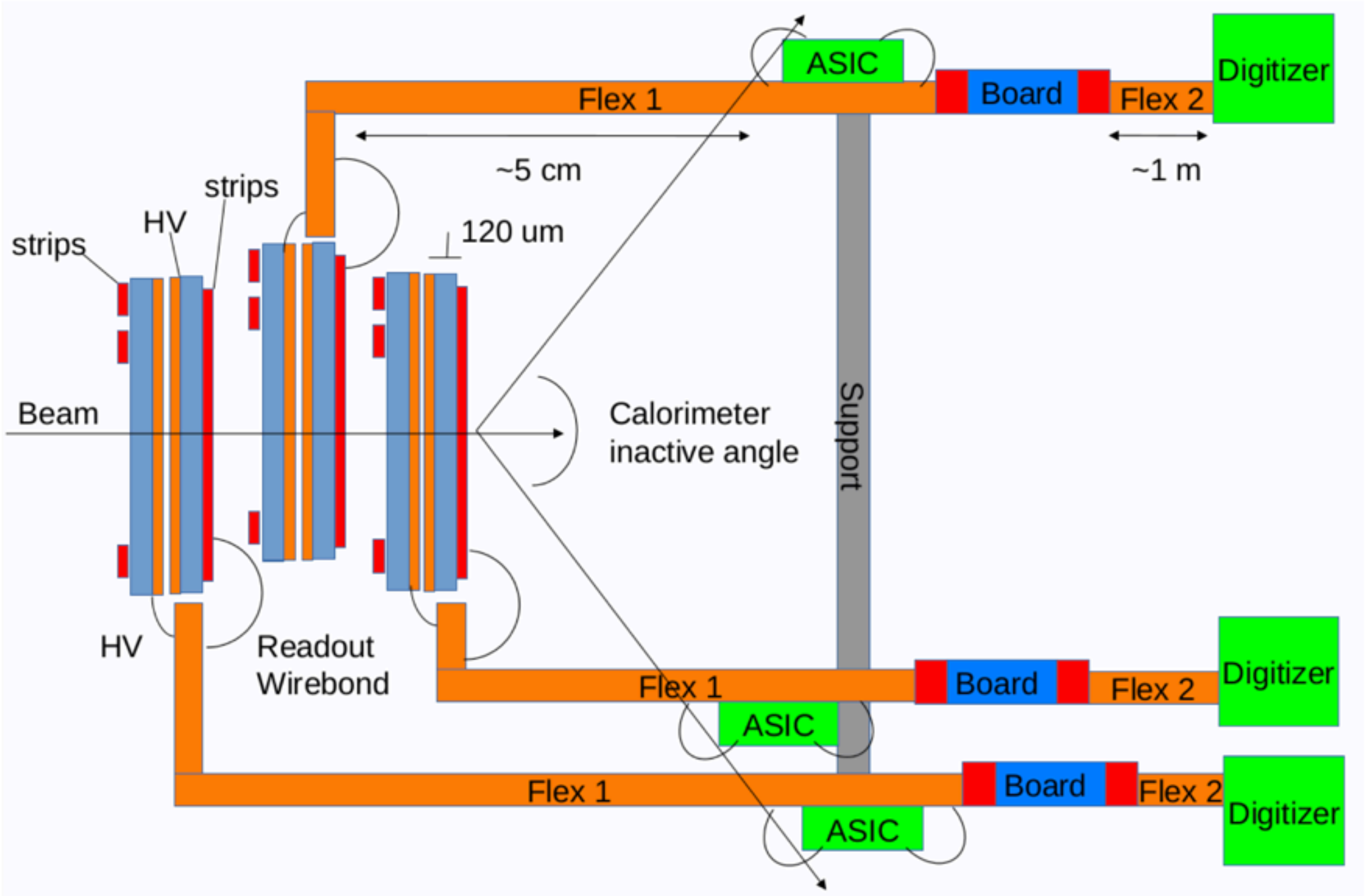
- The μ-RWELL is a very promising technology in harsh environment
  - compact, simple to assemble and intrinsically spark-protected
- Performance
  - Gas gain > 104
  - Rate capability > 1MHz/cm2
  - Space resolution < 100μm
  - Time resolution ~ 6ns



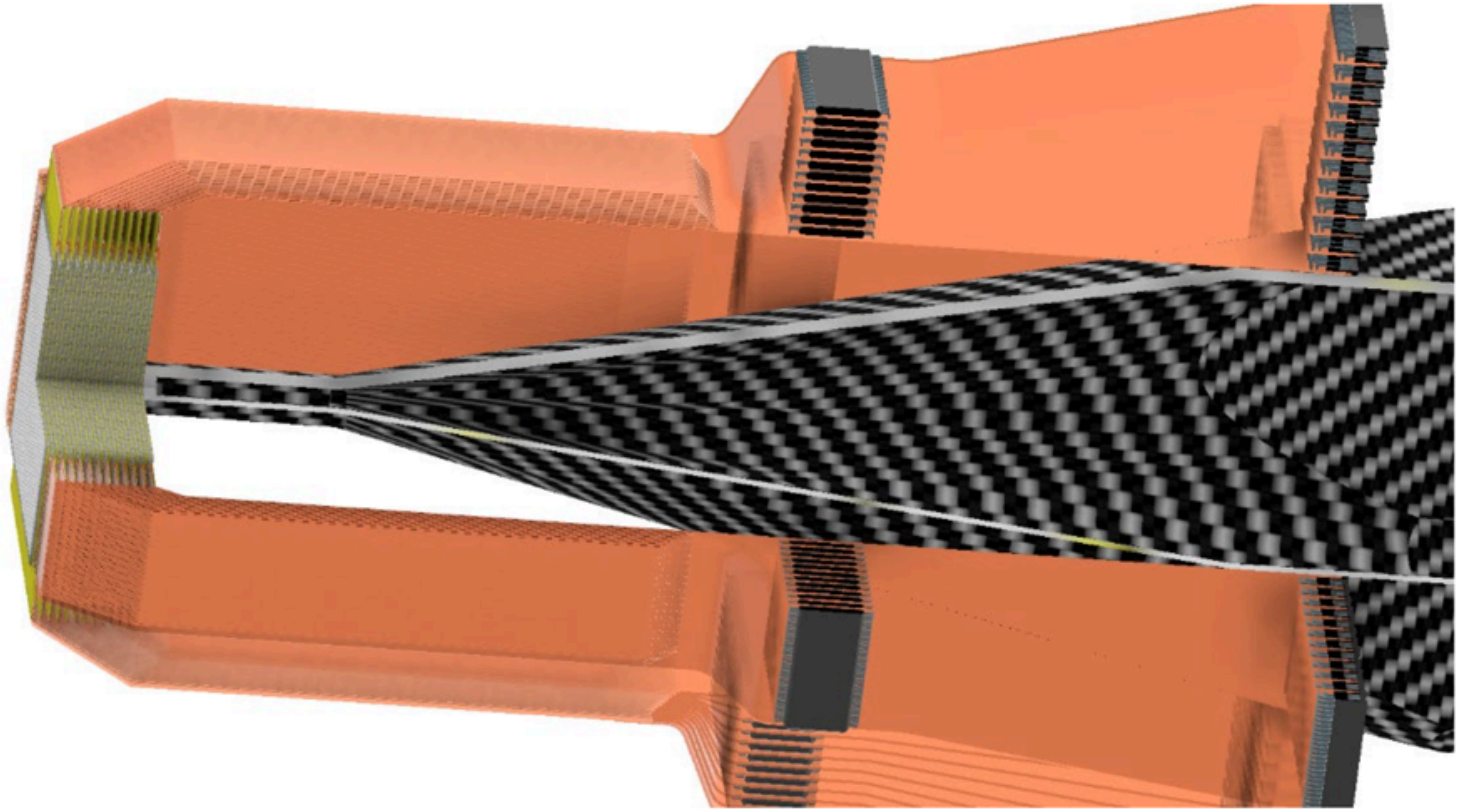


ATAR

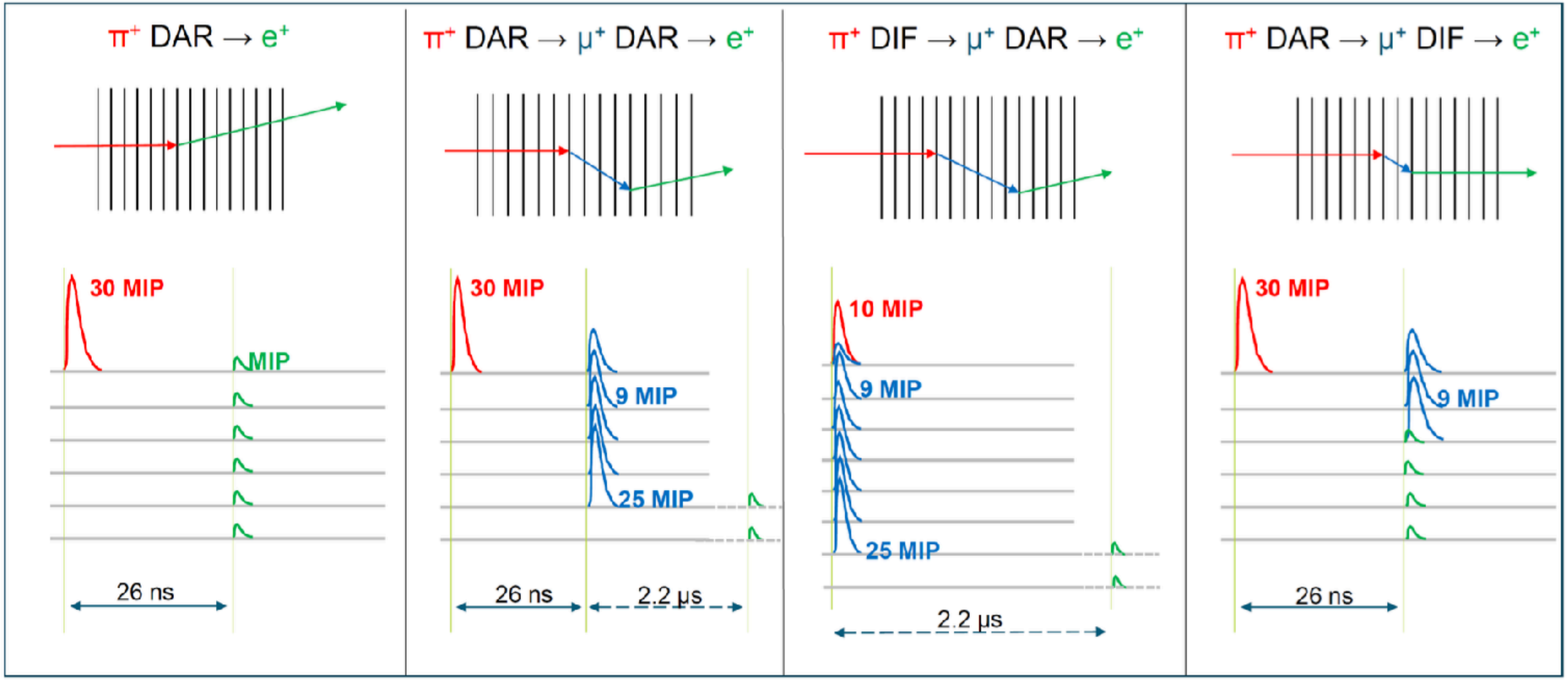
ATAR concept



ATAR mechanical drawing



ATAR

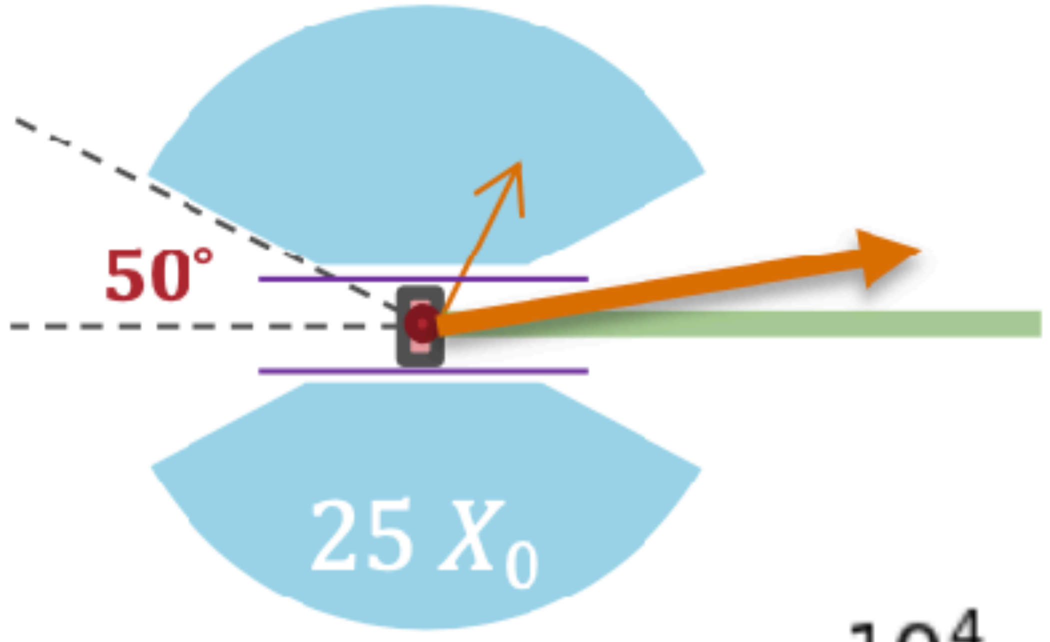


- Topology information : 2 vs. 3 tracks
- Timing information : 26ns vs. 26ns + 2.2μs
- Energy information : 10% difference in the energy deposition per unit length between μ and π

Tracker

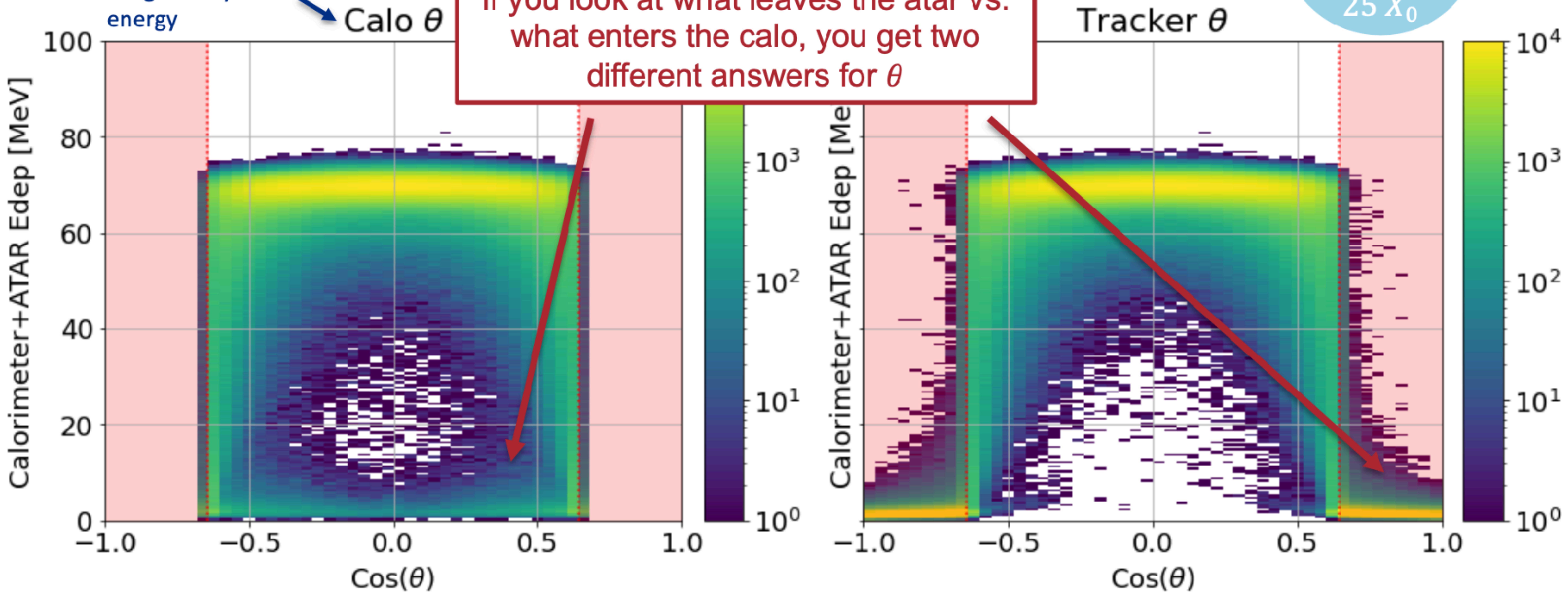
Aside: Truth vs. Calo θ

Example: 2 Particles leaving ATAR, the higher energy one misses CALO



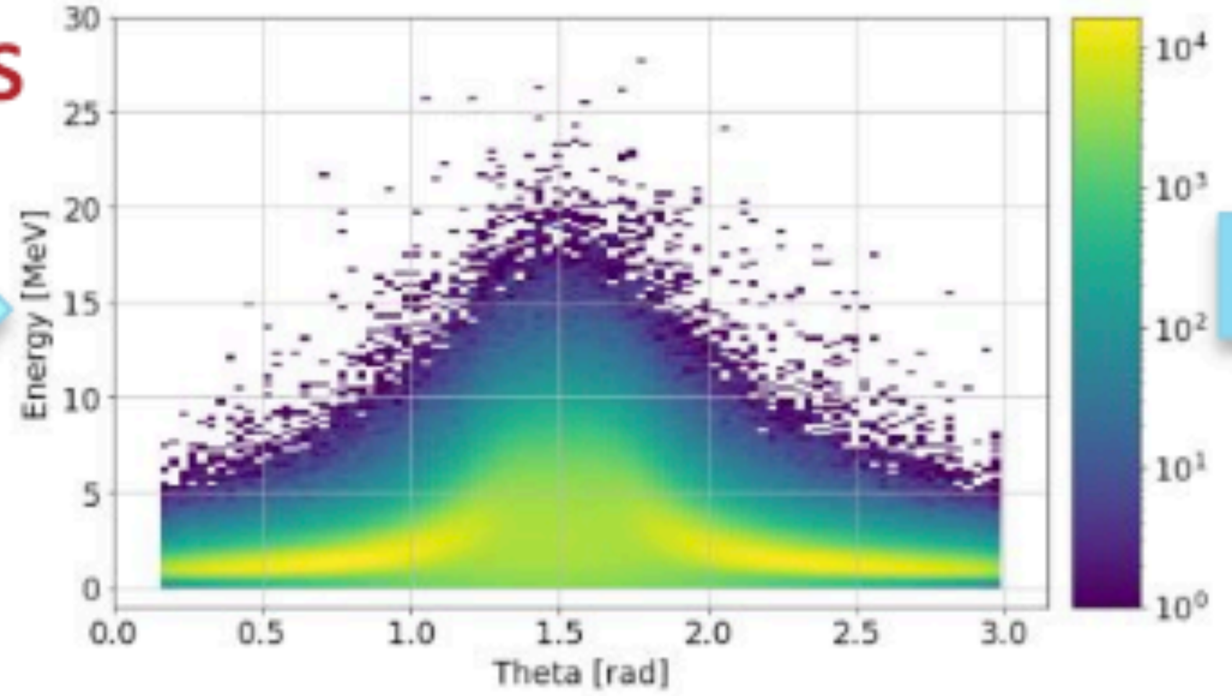
$\bar{\theta}$ For all particles, weighted by their energy

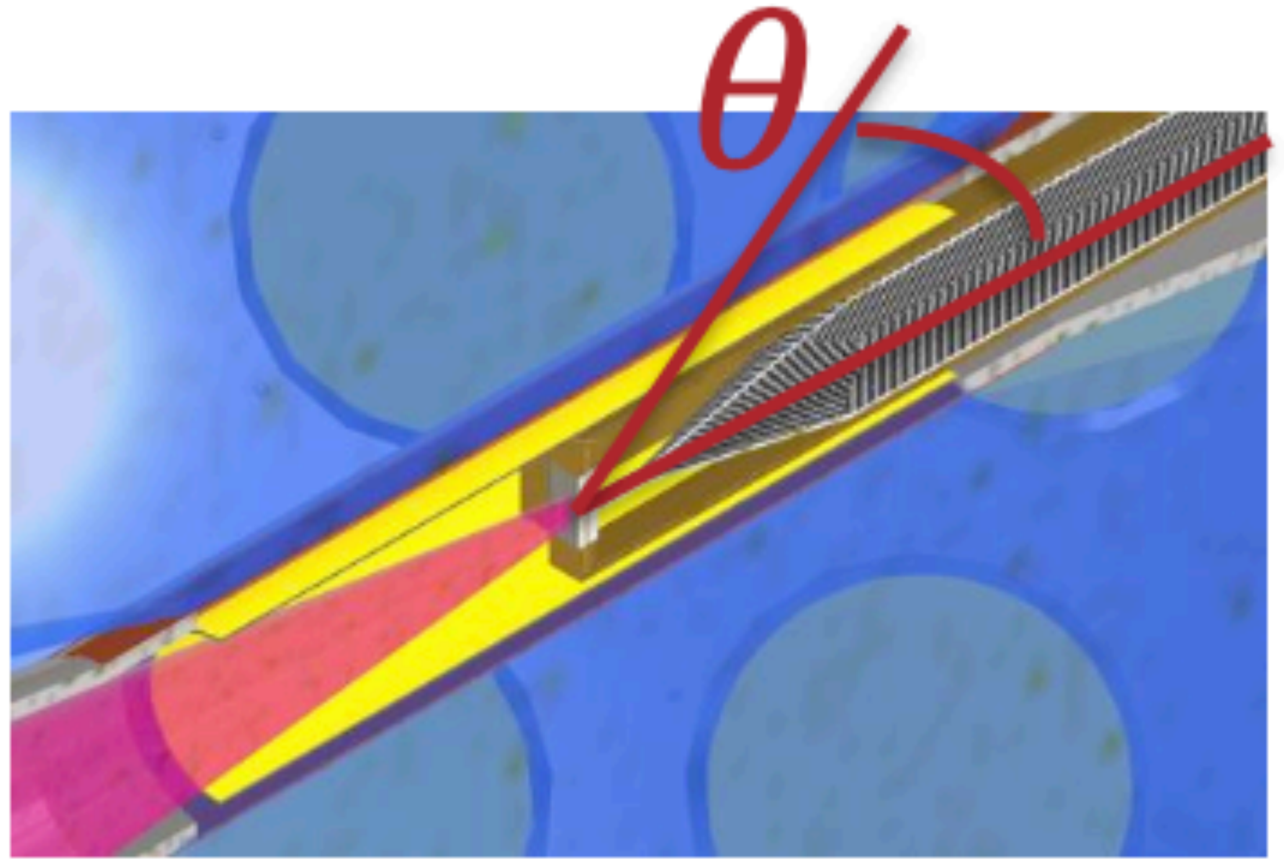
If you look at what leaves the atar vs. what enters the calo, you get two different answers for θ

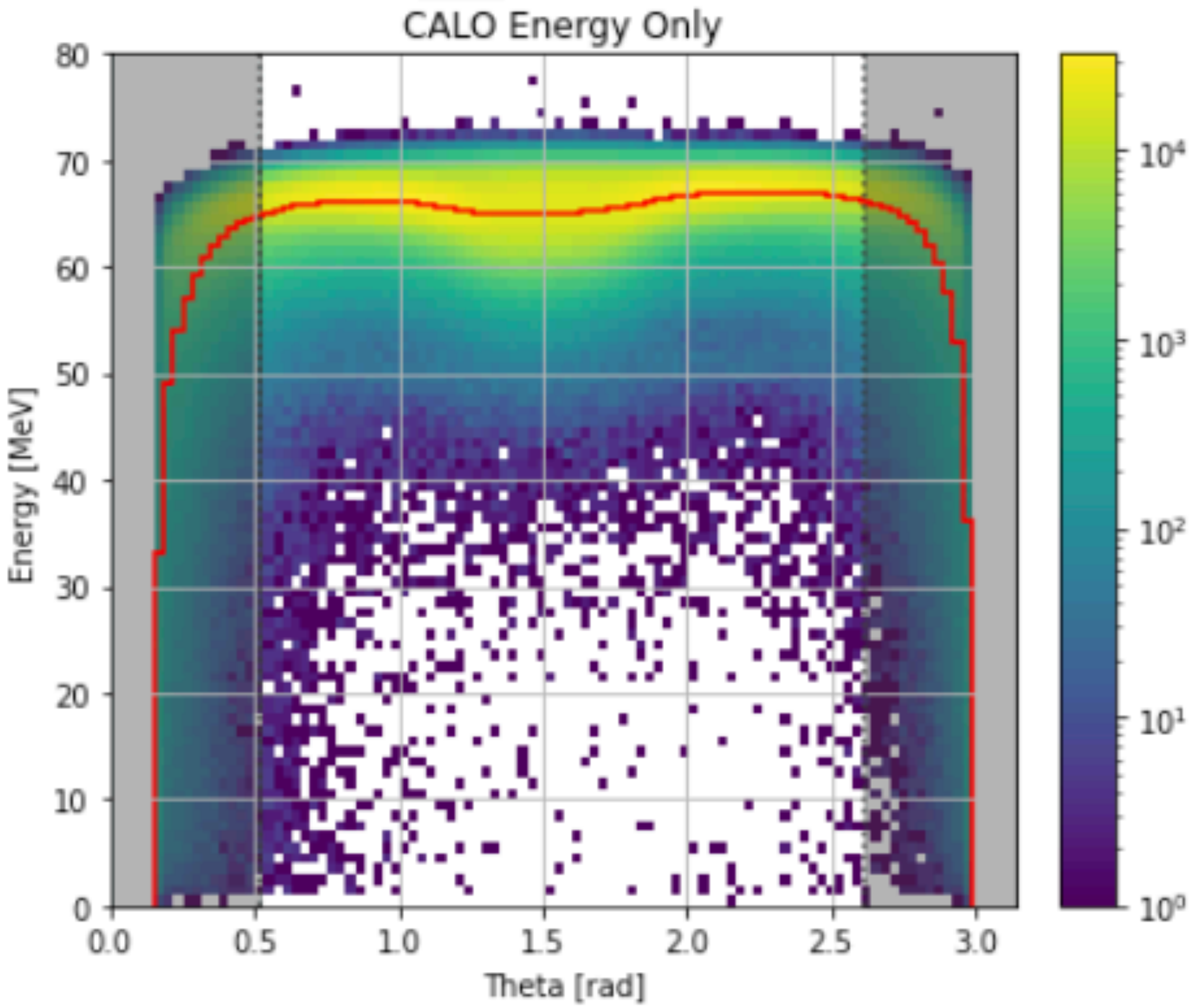


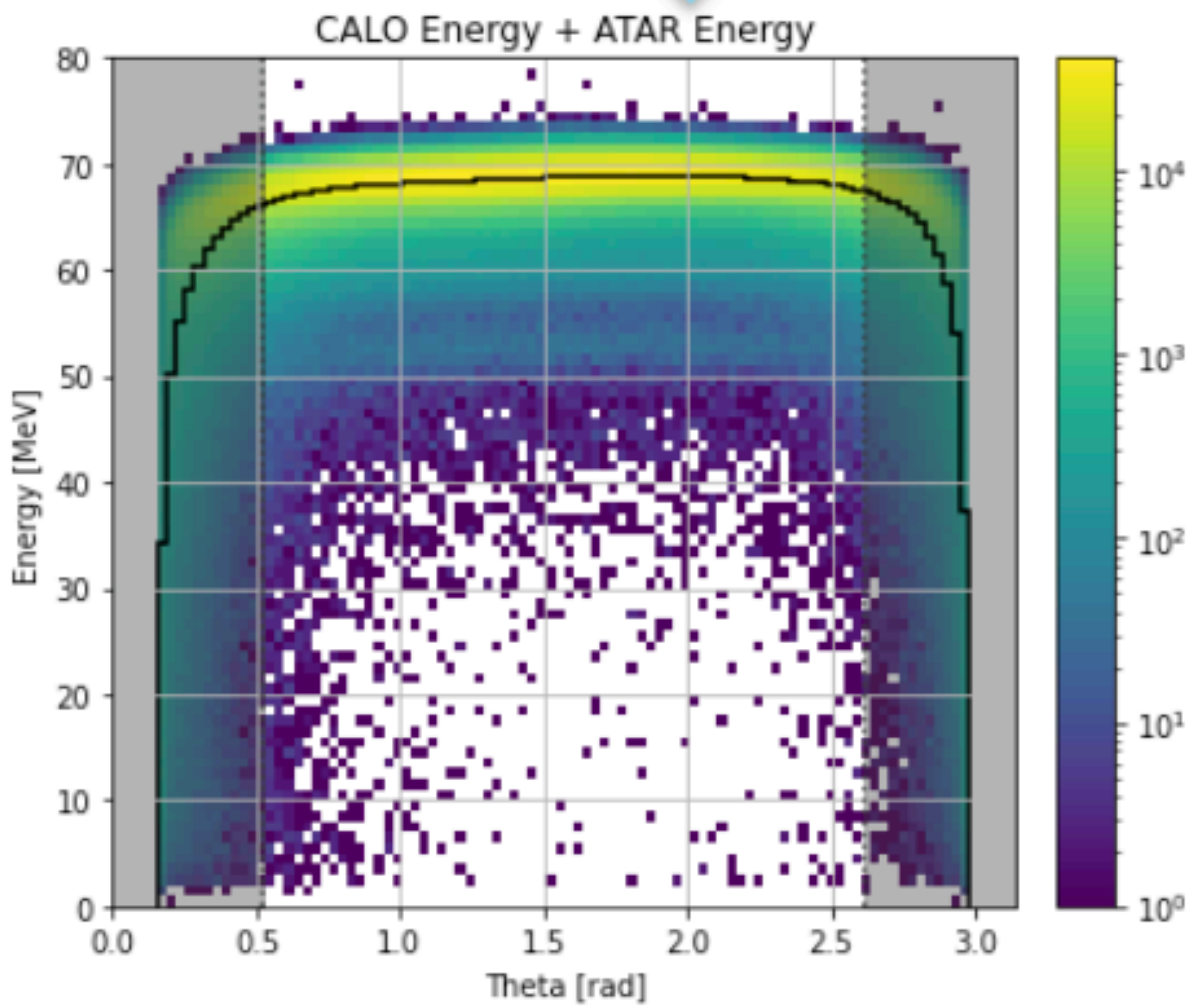
Dead material studies

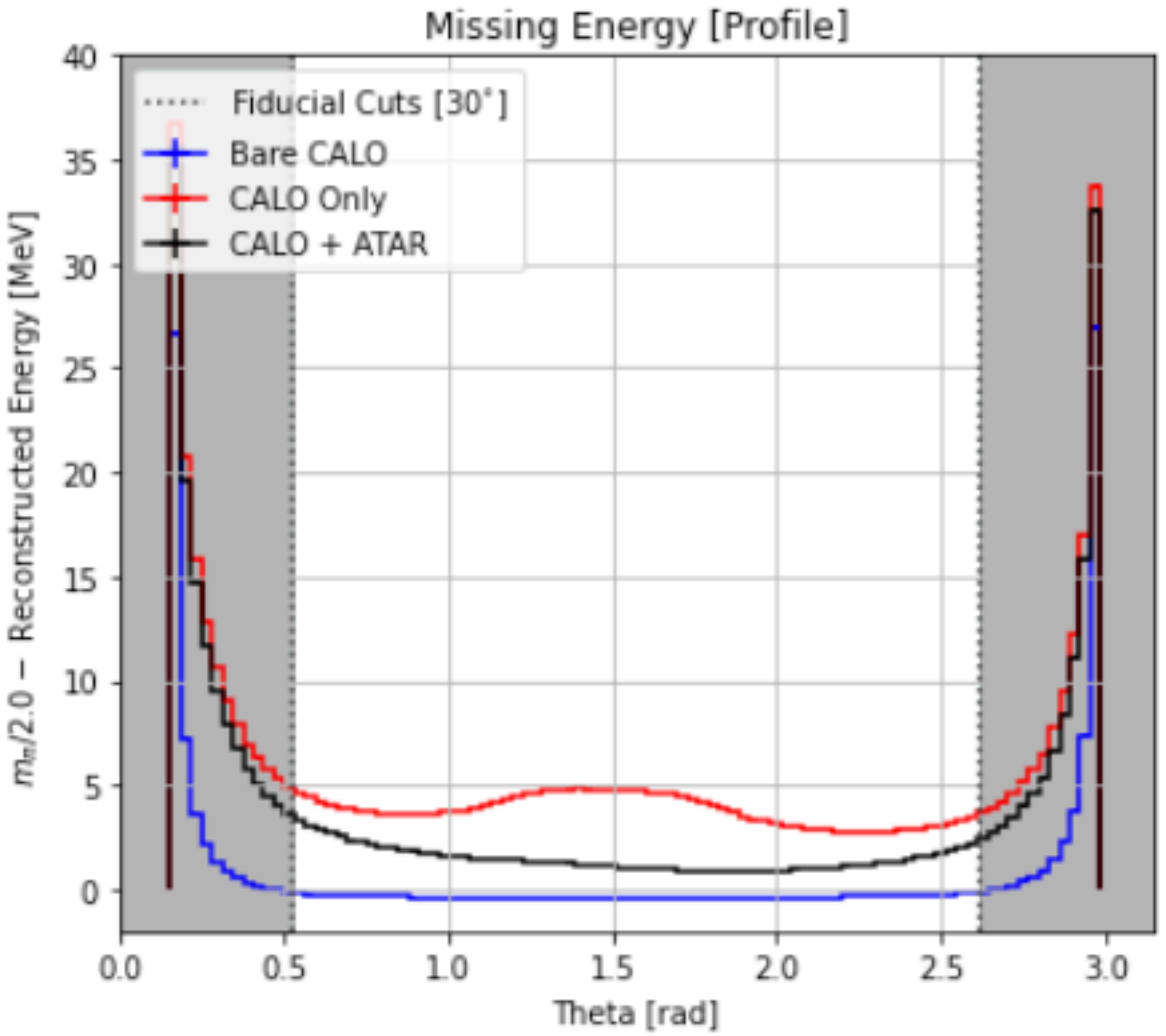
Add ATAR Energy on an event-by-event basis





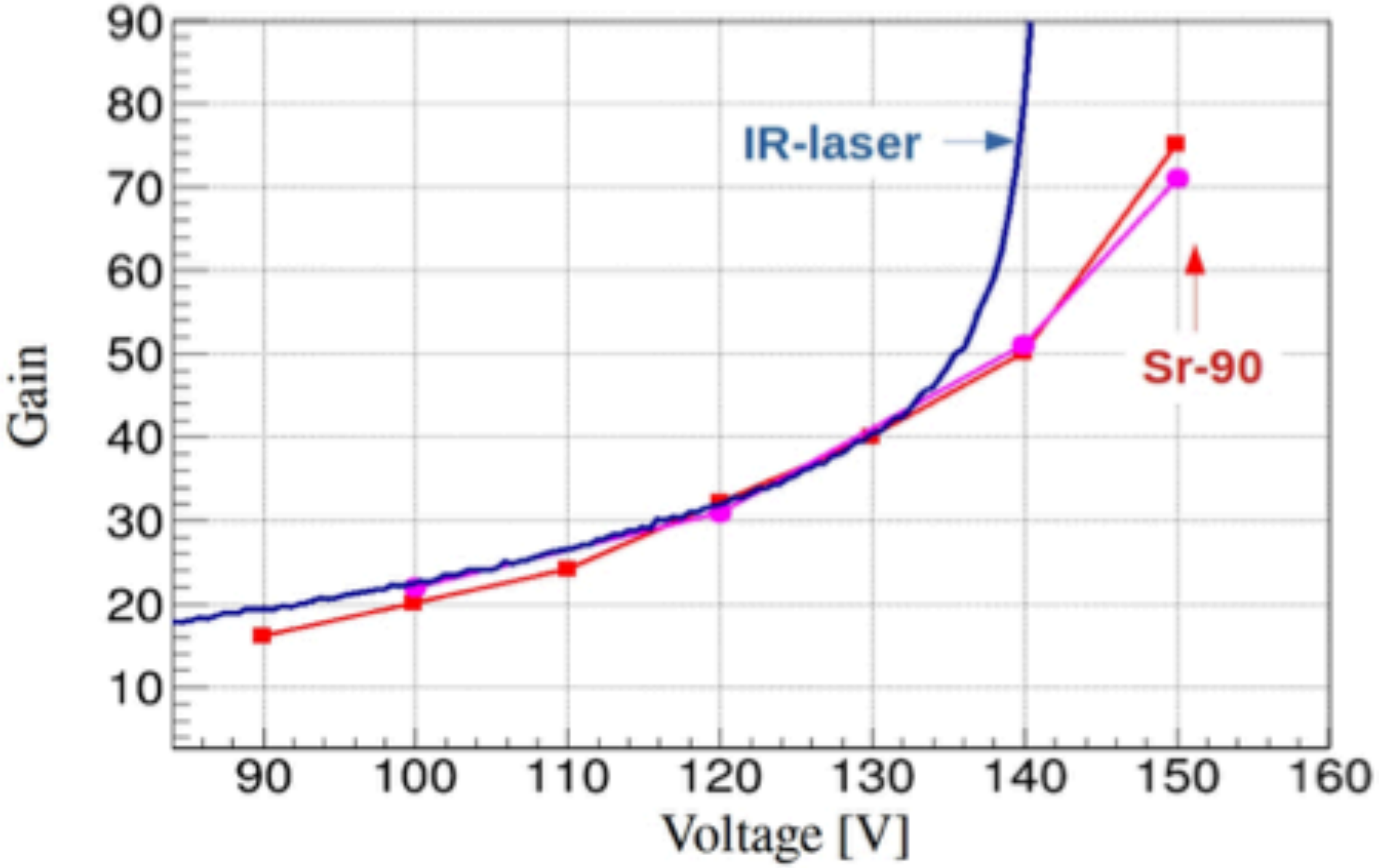


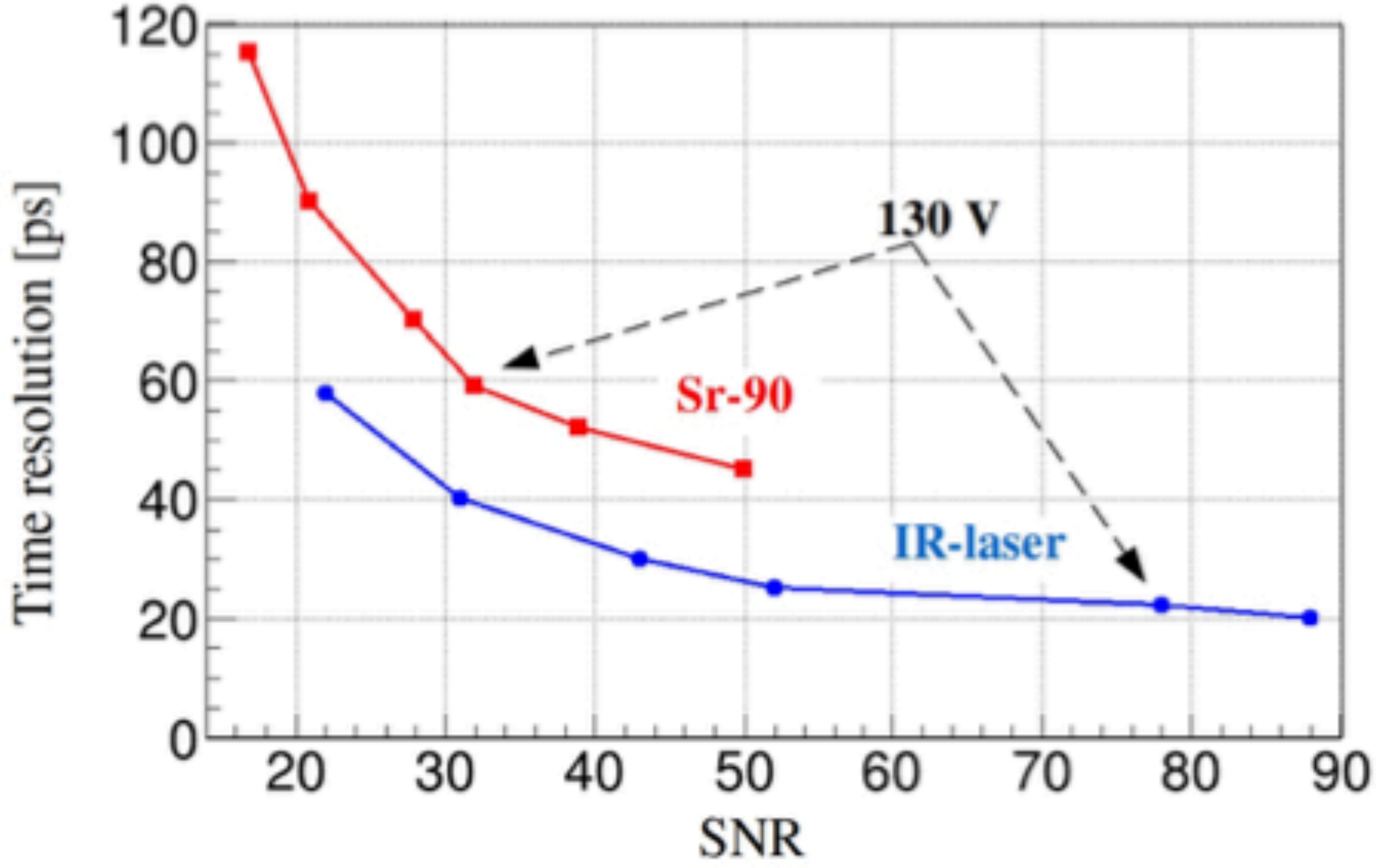




LGAD gain suppression

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