PIONEER: a next-generation rare pion decay experiment

Yousen Zhang on behalf of PIONEER collaboration

13 May 2024

Brookhaven National Laboratory

U.S. DEPARTMENT OF ENERGY

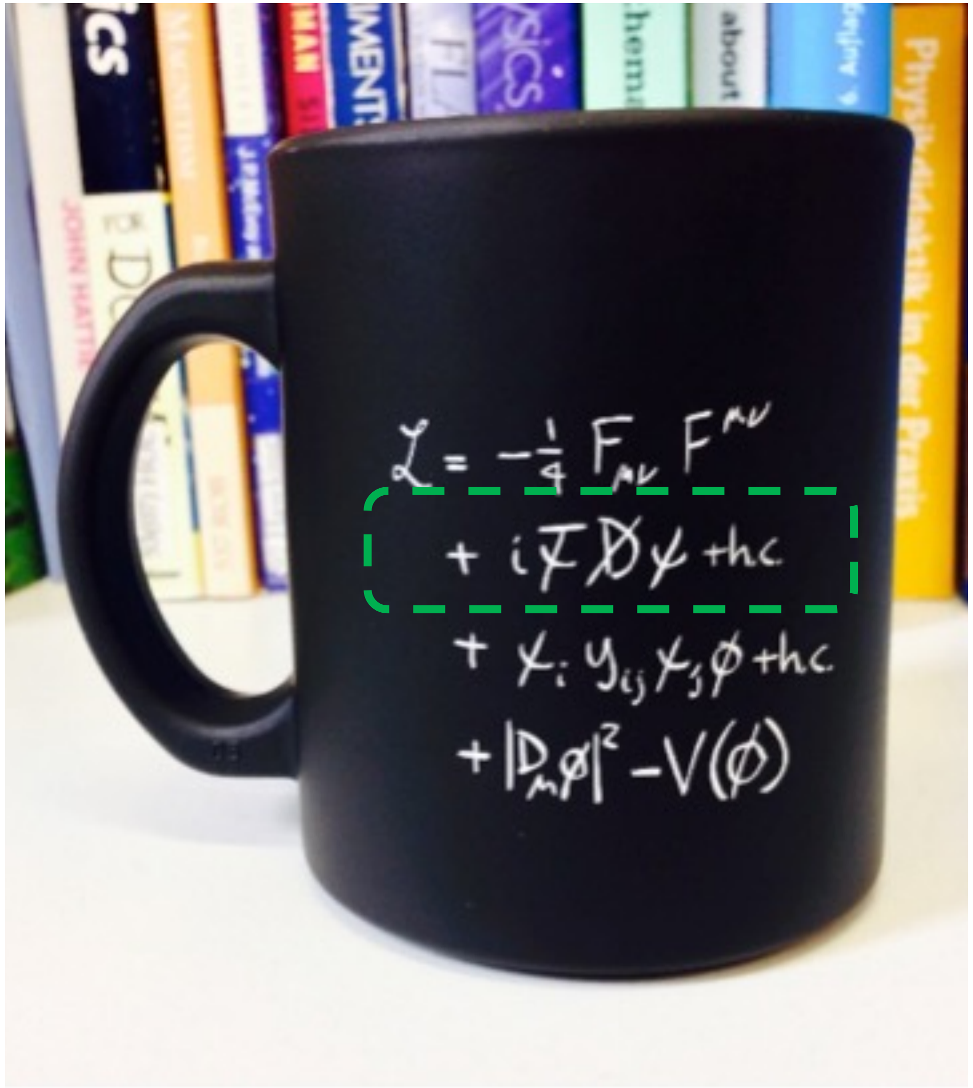
Lepton flavor symmetry and violation

Standard model (SM): not a full story

Lepton flavor universality (LFU) – an assumed symmetry in SM

- Universal coupling with gauge interaction among leptons $g_e = g_\mu = g_\tau$
- **Violations imply new physics**

Rare π^+ decay $R^{\pi}_{e/\mu} = \frac{\Gamma(\pi\to e\nu(\gamma))}{\Gamma(\pi\to\mu\nu(\gamma))}$ is key observable to LFU

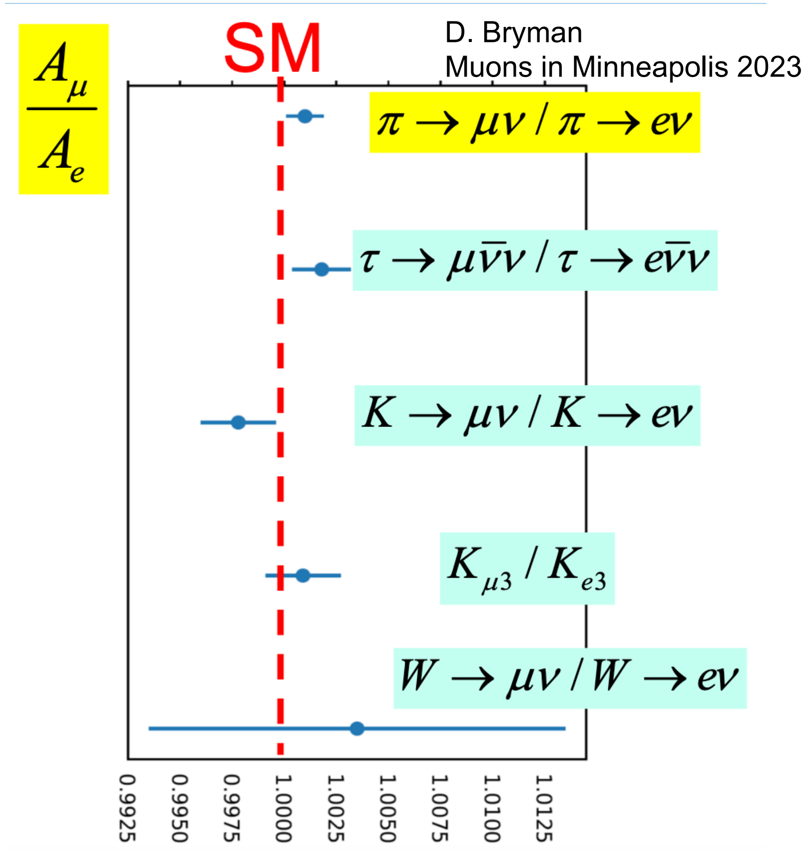


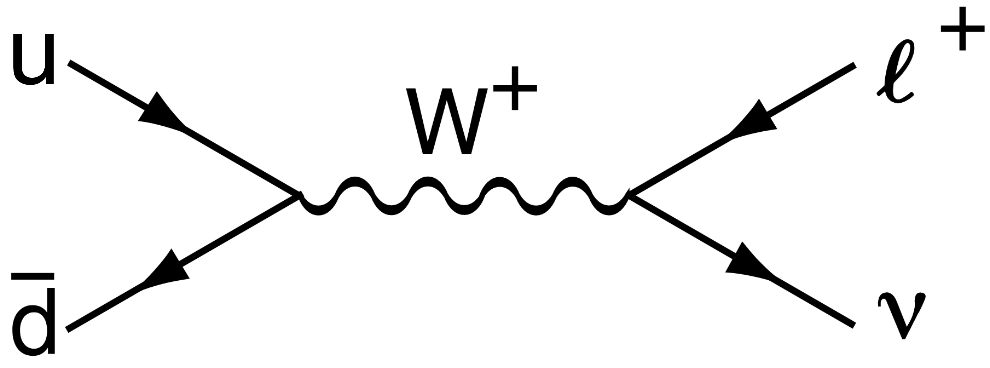
Why $\pi^+(u\bar{d}) \to l^+\nu$?

Most stringent μ/e test $\mathcal{L}_{CC} = A_\ell[\bar{u}\gamma^\mu P_L d][\bar{\nu}_\ell\gamma_\mu P_L \ell]$

$$R_{e/\mu}\,(\text{exp}) = 1.2327(23) \times 10^{-4} \qquad \left(\frac{A_\mu}{A_e}\right)_{R_{e/\mu}} = 1.0010(9)$$

- Highly helicity-suppressed, $R^\pi_{e/\mu} \propto m_e^2/m_\mu^2$
- Corrections to tree-level from high order quantum effects or high-energy new physics
  - Enhanced sensitivity to pseudo-scalar interaction $\propto \frac{M_\pi^2}{m_e(m_u+m_d)}$
  - Modified $Wl\upsilon$ coupling
  - …





10.1146/annurev-nucl-102010-130431
10.1146/annurev-nucl-110121-051223

Quark mixing and pion decays

$$\frac{-g}{\sqrt{2}}(\overline{u_L}, \overline{c_L}, \overline{t_L})\gamma^\mu W_\mu^+ V_{\rm CKM}\begin{pmatrix} d_L \\ s_L \\ b_L \end{pmatrix} + \text{h.c.}, \qquad V_{\rm CKM} \equiv V_L^u V_L^{d\dagger} = \begin{pmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{pmatrix}.$$

- Unitary implies

$$|V_{ud}|^2 + |V_{us}|^2 + |V_{ub}|^2(\sim 2\times10^{-5}) = 1$$

$$|V_{ud}|^2 + |V_{us}|^2 - 1 = (-19.5 \pm 5.3) \times 10^{-4}$$

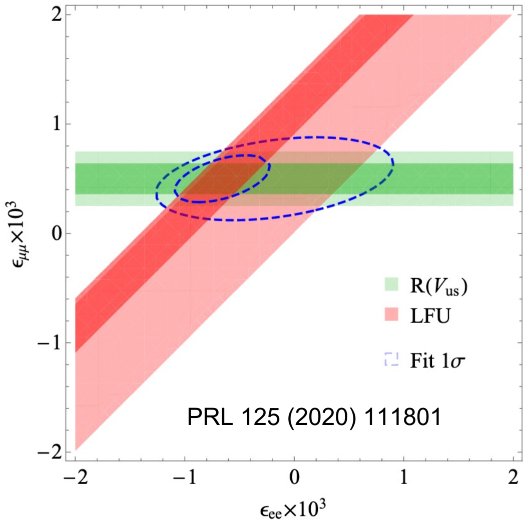
- Modified $Wl\nu$ coupling leads to $V_{ud}^{\beta} = V_{ud}^{\mathcal{L}}(1 - \epsilon_{\mu\mu})$
  (PRL 125 (2020) 111801)
  - $\boldsymbol{R^{\pi}_{e/\mu}}$ sensitive to $(\mathbf{1} - \boldsymbol{\epsilon_{\mu\mu}} + \boldsymbol{\epsilon_{ee}})$

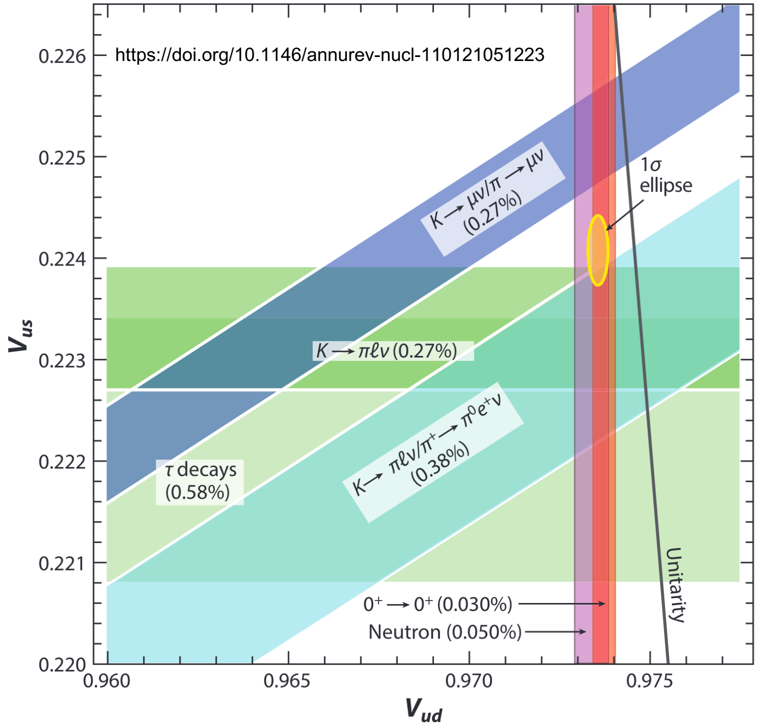
- $R_{\beta\pi} = \frac{\Gamma(\pi^+\to\pi^0 e^+\nu(\gamma))}{\Gamma(total)}$ ~(10^{-8}) theoretically cleanest for $|V_{ud}|$=0.9739(28)$_{\rm exp}$(1)$_{\rm th}$

PRD 101 (2020) 091301(R)

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

PRL 93 (2004) 181803





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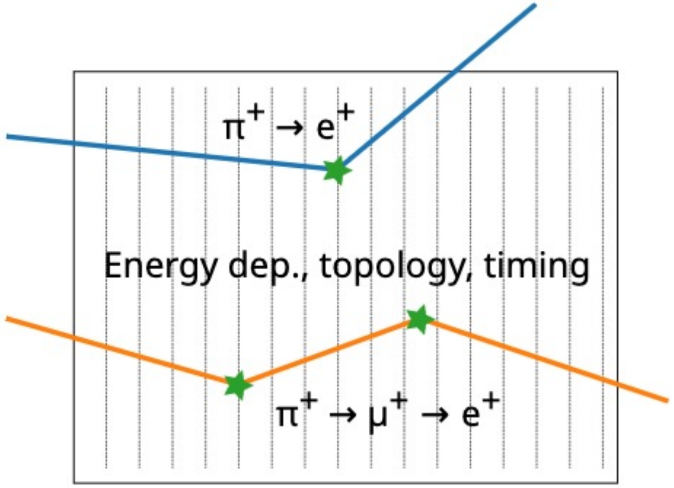
Challenges and opportunities

$$R_{e/\mu}(\mathrm{SM}) = 1.23524(015)\times10^{-4}$$

$$R_{e/\mu}(\mathrm{exp}) = 1.23270(230)\times10^{-4}$$

- For $\delta \boldsymbol{R}^{\pi}_{e/\mu} \sim O(10^{-4})$, given $\boldsymbol{R}^{\pi}_{e/\mu} \sim 1\times10^{-4}$
  - Pion beam with high intensity and rate
  - Excellent particle identification (PID)
    - Timing + position reconstruction
    - Energy deposition
  - Energy resolution for differentiating $\pi \to e$ and $\pi \to \mu \to e$

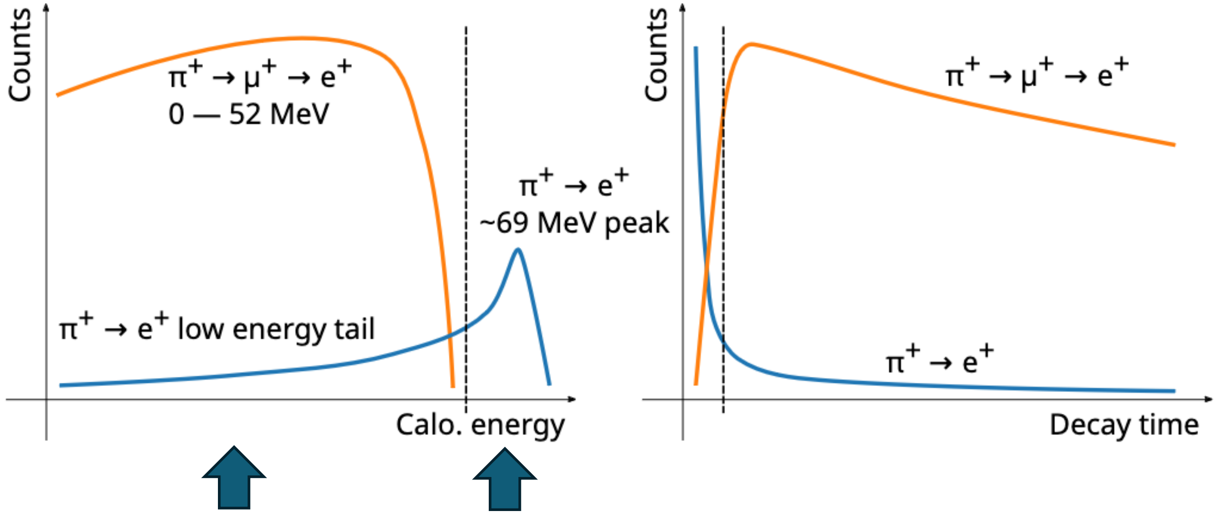


Active target

Experiment method:

- $$R_{e/\mu} = \frac{N(\pi\to e)}{N(\pi\to\mu\to e\ )} = \frac{N^{H.E.}(\pi\to e)(1+C_{tail})}{N(\pi\to\mu\to e)}$$

$$C_{tail} = \frac{N^{L.E.}(\pi \to e)}{N^{H.E.}(\pi \to e)}$$



$N^{L.E.}(\pi \to e)$ $N^{H.E.}(\pi \to e)$

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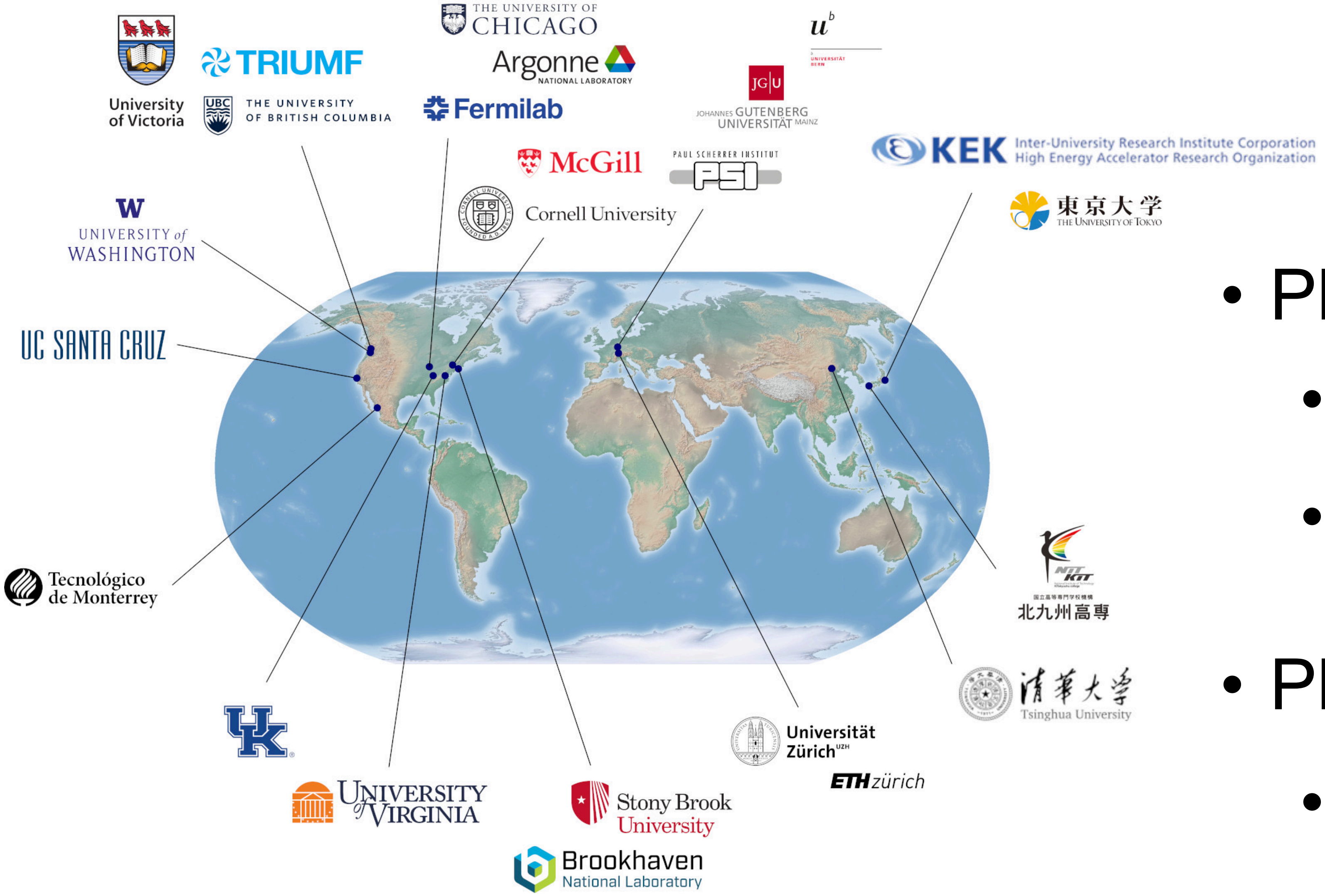


- Phase 1:
  - $R^{\pi}_{e/\mu} = \dfrac{\Gamma(\pi \to e\nu(\gamma))}{\Gamma(\pi \to \mu\nu(\gamma))}$
  - other BSM searches

- Phase 2+3
  - $R_{\beta\pi} = \dfrac{\Gamma(\pi^{+} \to \pi^{0} e^{+} \nu(\gamma))}{\Gamma(total)}$

https://pioneer.triumf.ca

arXiv:2203.01981

Concept design of PIONEER experiment

- $\pi E5$ beam – 300 kHz high intensity pion beam at PSI
- Degraded TARget – to slow pions
- Active TARget – to stop pions
- Calorimeter – to determine positron energy and timing
- Tracker – auxiliary part to determine topology of exiting positron track

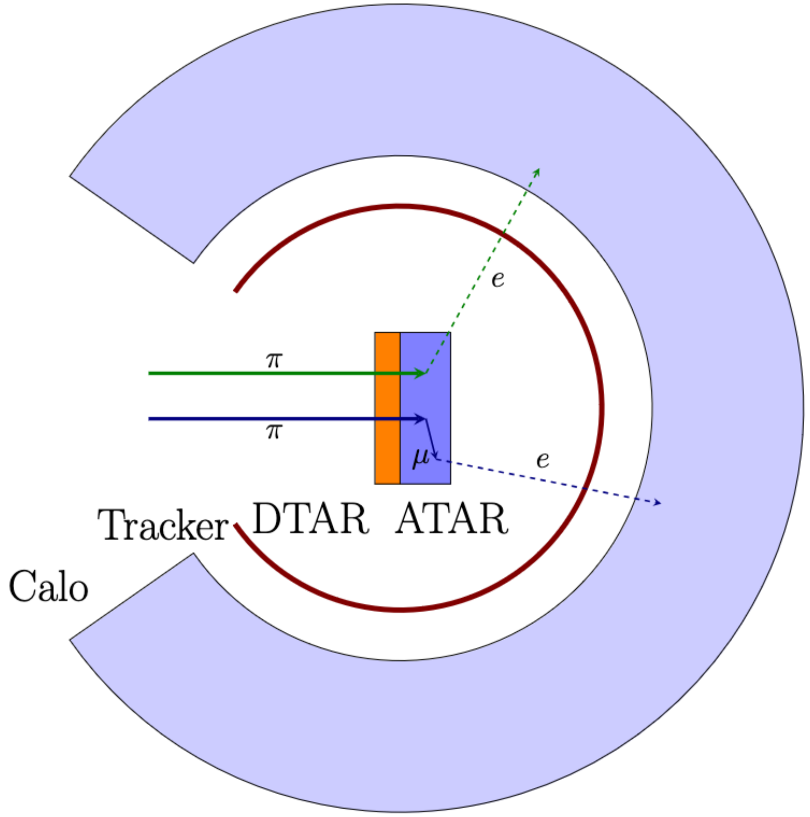
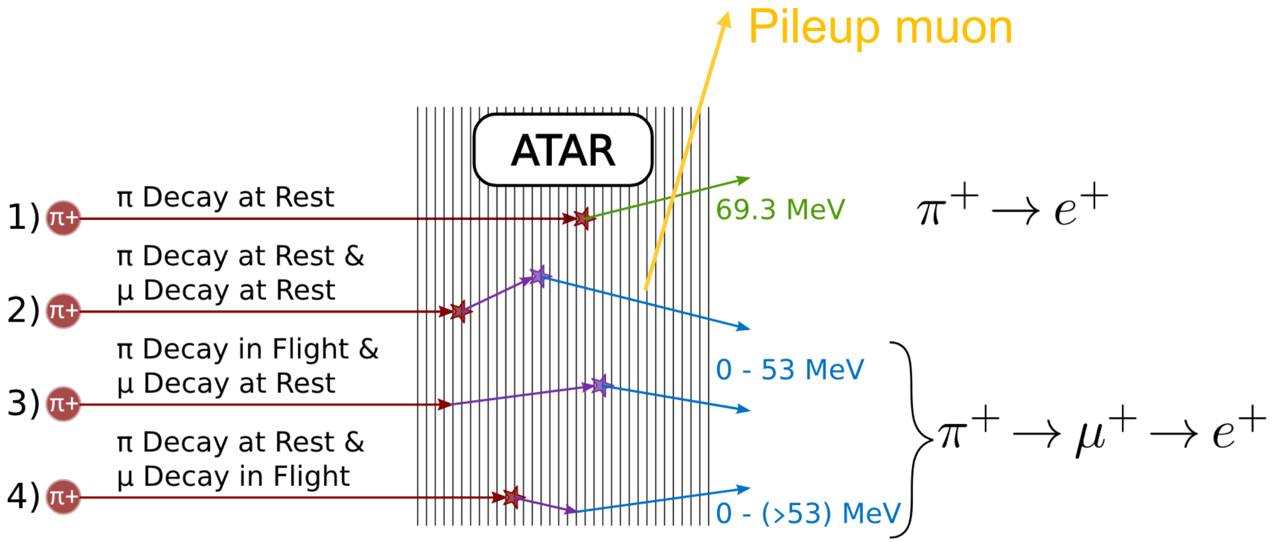
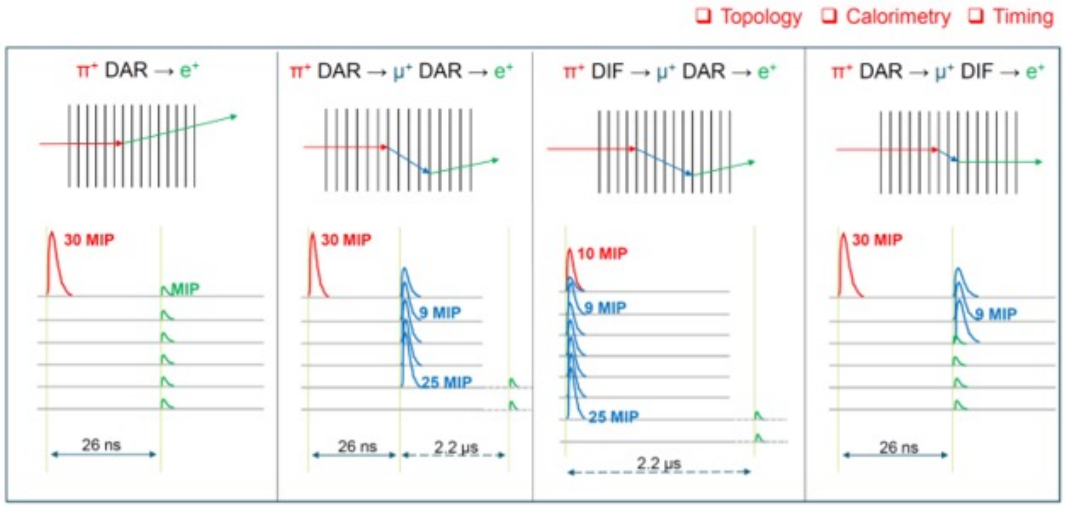


Illustration of PIONEER

ATAR – a (4+1)-D tracking calorimeter

- Challenges to ATAR
  - Signal-to-background ratio $O(10^{-4})$ require excellent $\pi \rightarrow \mu$ rejection
  - Pileup old muons
  - Impurity from beam μ/e
- Design must satisfy
  - High granularity for tracking
  - Fast response in timing
  - Good determination of energy deposition inside ATAR





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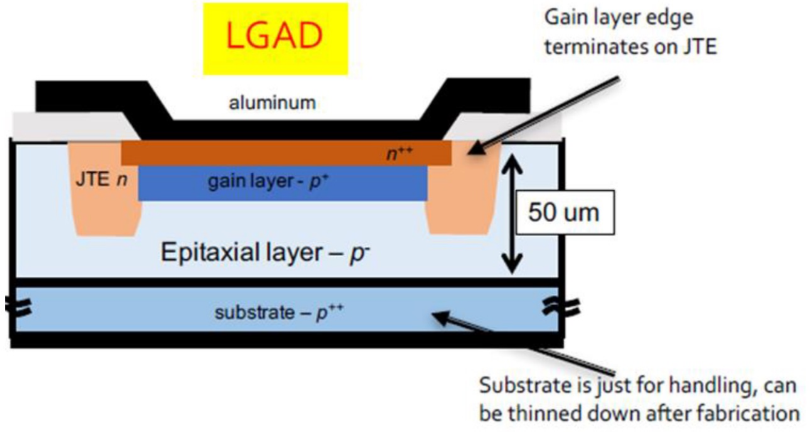
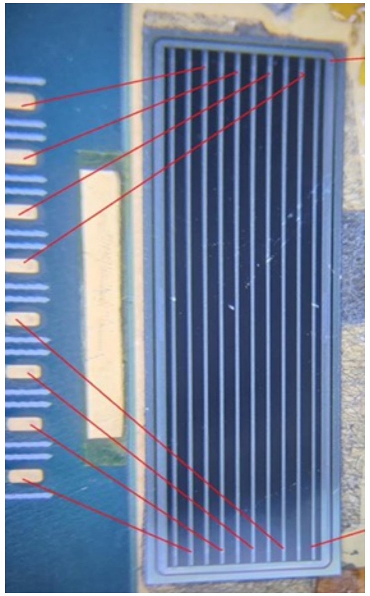
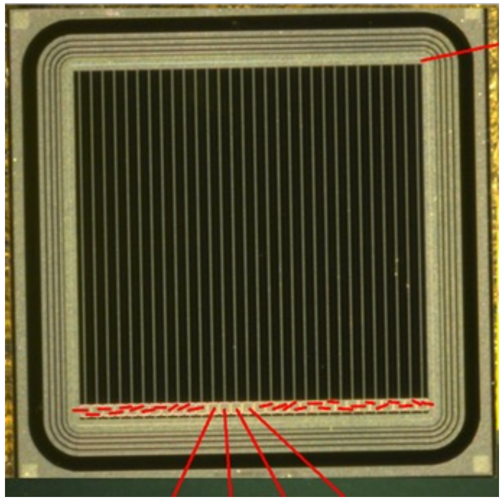
ATAR – a (4+1)-D tracking calorimeter

- Low Gain Avalanche Diode (LGAD)
  - An additional gain layer multiply signals
  - Better timing resolution down to $O(10)\ ps$
  - Widely used at particle physics, e.g. HL-LHC, EIC, etc.
- ATAR key specifications
  - 48 layers of 120um-thick LGAD plane
  - 2x2 cm^2 transverse size for each layer
  - 100 strips for each layer (200 um pitch size)





AC-LGAD



TI-LGAD

https://www.mdpi.com/2410-390X/5/4/40
https://doi.org/10.1016/j.nima.2024.169395

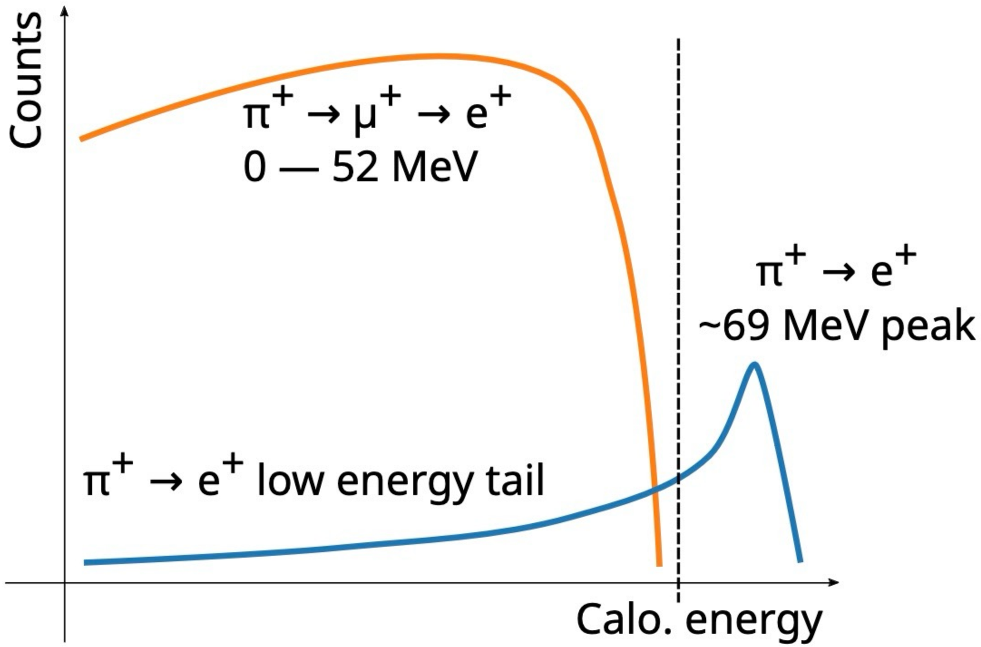
Calorimeter

Challenges to CALO

- Bhabha scattering, shower leakage, σ_E and etc. lead to a tail of $\pi \to e$ under overwhelming $\pi \to \mu \to e$
- Pileup muon accidentally produce fake $\pi \to e$

Calorimeter needs to satisfy

- Reasonable radiation length
- Excellent energy resolution
- Large solid angle coverage
- Precision timing



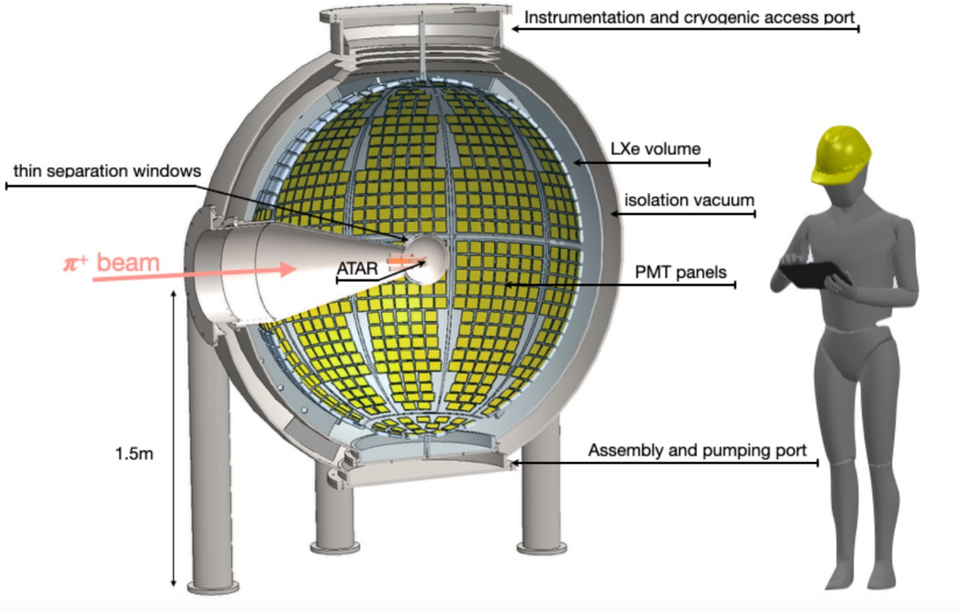
CALO options: LXe and LYSO crystal

Liquid Xenon (LXe) arxiv:2310.11902

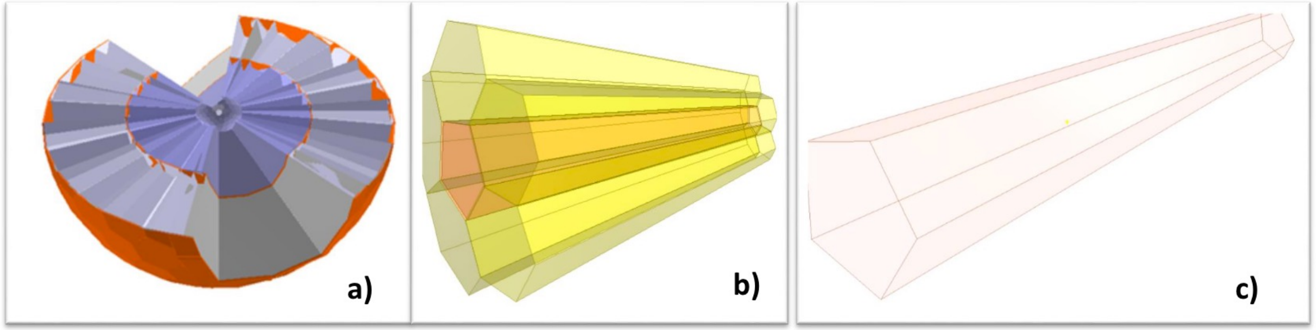
- Excellent homogeneity
- Energy resolution ~1.8% @ 50 MeV

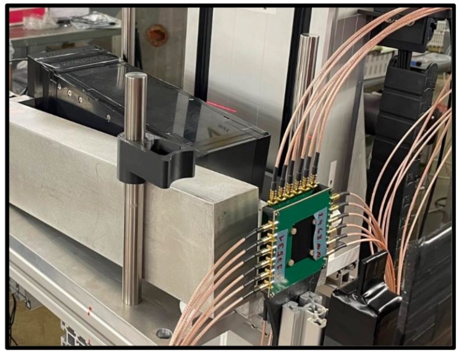
LYSO crystals NIM A 824 (2016) 684, arxiv:2203.06731

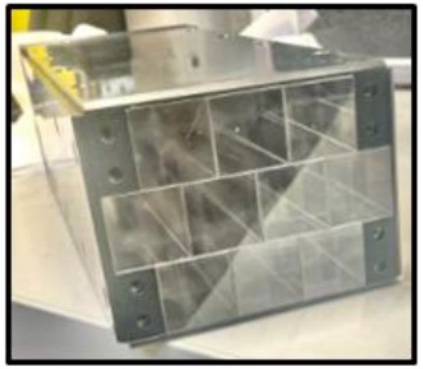
- Segmented
- Prototype studies show resolution < 2%



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







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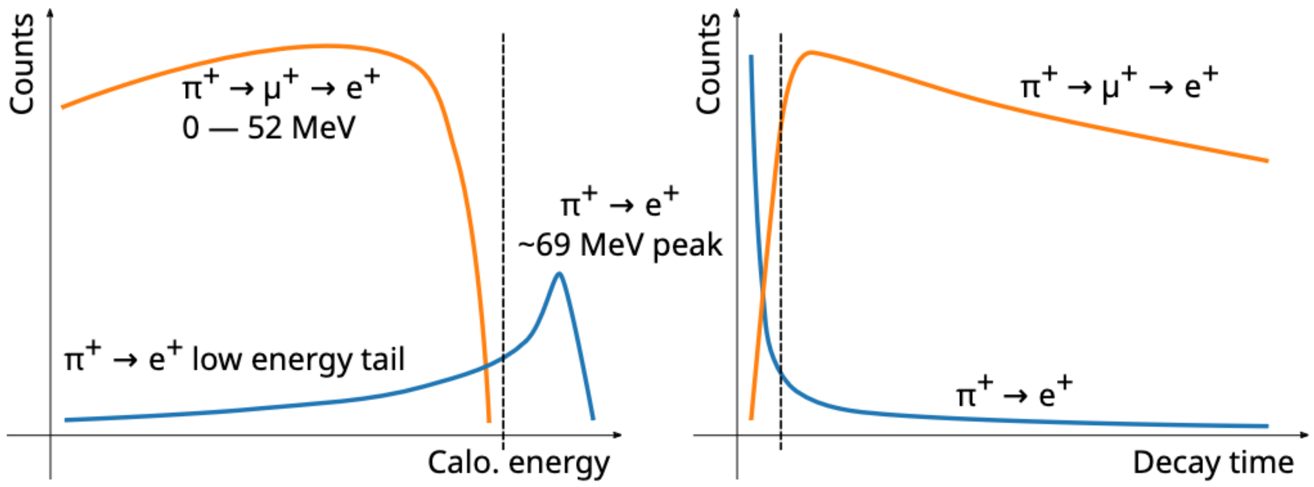
LYSO updates in talk by D. Hertzog in Instrumentation session, 13 May 2024, 14:30

Fast trigger and data acquisitions

Several key triggers

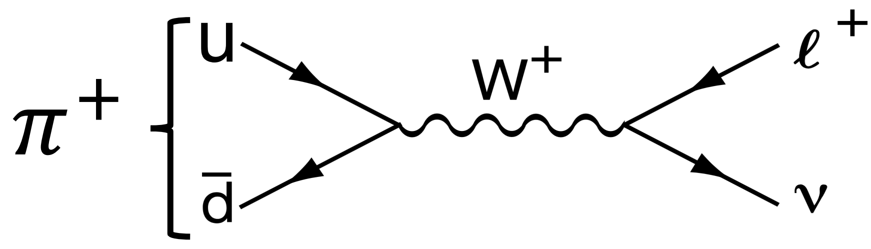
- PI – an unbiased trigger
- Prompt – suppress $\pi \to \mu$
- CALO – suppress $\pi \to \mu$
- TRACK – for redundancy

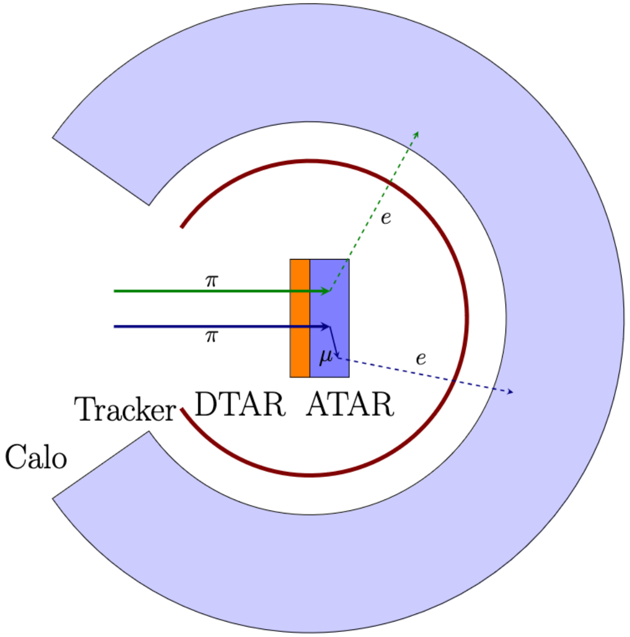
triggers	prescale	range TR(ns)	rate (kHz)
PI	1000	-300,700	0.3
CaloH	1	-300,700	0.1
TRACK	50	-300,700	3.4
PROMPT	1	2,32	5



Summary and outlook

- Unique physics opportunities to study LFUV by measuring pion rare decays
- PIONEER aims at
  - $R^{\pi}_{e/\mu} = \frac{\Gamma(\pi \to e\nu(\gamma))}{\Gamma(\pi \to \mu\nu(\gamma))}$ with uncertainty O(0.01%)
  - $R_{\beta\pi} = \frac{\Gamma(\pi^+ \to \pi^0 e^+ v(\gamma))}{\Gamma(total)}$ with uncertainty O(0.05%)
- Active developments of PIONEER design
  - (4+1)-D active silicon targets
  - Calorimeter with excellent timing and energy response
  - Fast trigger and DAQ
  - And more!





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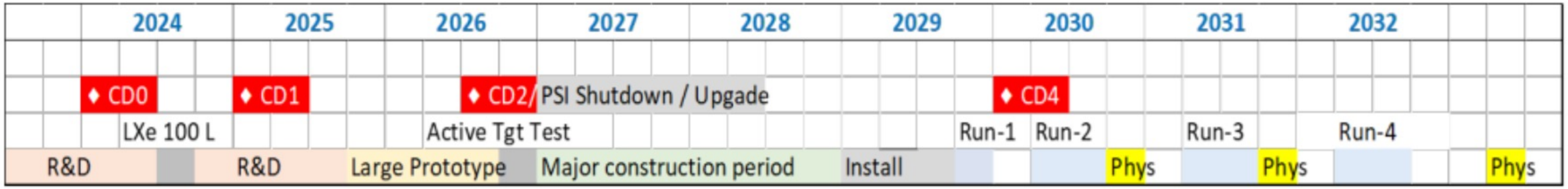
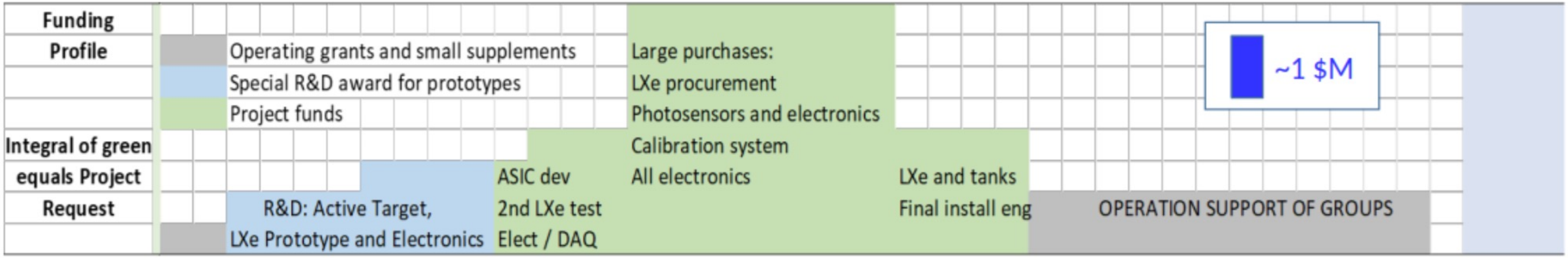
Backup

PIONEER Experiment





P5 presentation by D. Hertzog

CKM and LFUV

Redefinition of fermi constant and assume CKM in SM is unitary

$$\frac{1}{\tau_\mu} = \frac{(G_F^{\mathcal{L}})^2 m_\mu^5}{192\pi^3}(1+\Delta q)(1+\varepsilon_{ee}+\varepsilon_{\mu\mu})^2$$

$$V_{ud}^{\beta} = V_{ud}^{\mathcal{L}}(1-\varepsilon_{\mu\mu})$$

$$V_{us}^{K_{\mu 3}} = V_{us}^{\mathcal{L}}(1-\varepsilon_{ee})$$

$$V_{us}^{K_{e3}} = V_{us}^{\mathcal{L}}(1-\varepsilon_{\mu\mu})$$

$$G_F = G_F^{\mathcal{L}}(1+\varepsilon_{ee}+\varepsilon_{\mu\mu}).$$

$$V_{us}^{\beta} \equiv \sqrt{1-(V_{ud}^{\beta})^2-|V_{ub}|^2} \simeq V_{us}^{\mathcal{L}}\left[1+\left(\frac{V_{ud}^{\mathcal{L}}}{V_{us}^{\mathcal{L}}}\right)^2\varepsilon_{\mu\mu}\right]$$

$$R(V_{us}) = \frac{V_{us}^{K_{\mu 2}}}{V_{us}^{\beta}}$$

TABLE I. Ratios sensitive to LFUV in the μ-e sector, indicating the dependence on the LFU violating parameters ε_{ij}. For $R(V_{us})$ we give the values corresponding to the radiative corrections from Refs. [11,14]. The last column gives the constraints on $(\varepsilon_{\mu\mu}-\varepsilon_{ee})\times 10^3$ and $\varepsilon_{\mu\mu}\times 10^3$, respectively.

Observable	Measurement	Constraint
$K\to\pi\mu\bar\nu/K\to\pi e\bar\nu \simeq 1+\varepsilon_{\mu\mu}-\varepsilon_{ee}$	1.0010(25) [77]	1.0(2.5)
$K\to\mu\nu/K\to e\nu \simeq 1+\varepsilon_{\mu\mu}-\varepsilon_{ee}$	0.9978(18) [3,78,79]	−2.2(1.8)
$\pi\to\mu\nu/\pi\to e\nu \simeq 1+\varepsilon_{\mu\mu}-\varepsilon_{ee}$	1.0010(9) [3,80–82]	1.0(9)
$\tau\to\mu\nu\bar\nu/\tau\to e\nu\bar\nu \simeq 1+\varepsilon_{\mu\mu}-\varepsilon_{ee}$	1.0018(14) [3,32]	1.8(1.4)
$W\to\mu\bar\nu/W\to e\bar\nu \simeq 1+\varepsilon_{\mu\mu}-\varepsilon_{ee}$	0.9960(100) [83,84]	−4(10)
$B\to D^{(*)}\mu\nu/B\to D^{(*)}e\nu \simeq 1+\varepsilon_{\mu\mu}-\varepsilon_{ee}$	0.9890(120) [85]	−11(12)
$R(V_{us})\simeq 1-(V_{ud}/V_{us})^2\varepsilon_{\mu\mu}$	0.9891(33) [11]	0.58(17)
	0.9927(39) [14]	0.39(21)

(PRL 125 (2020) 111801)

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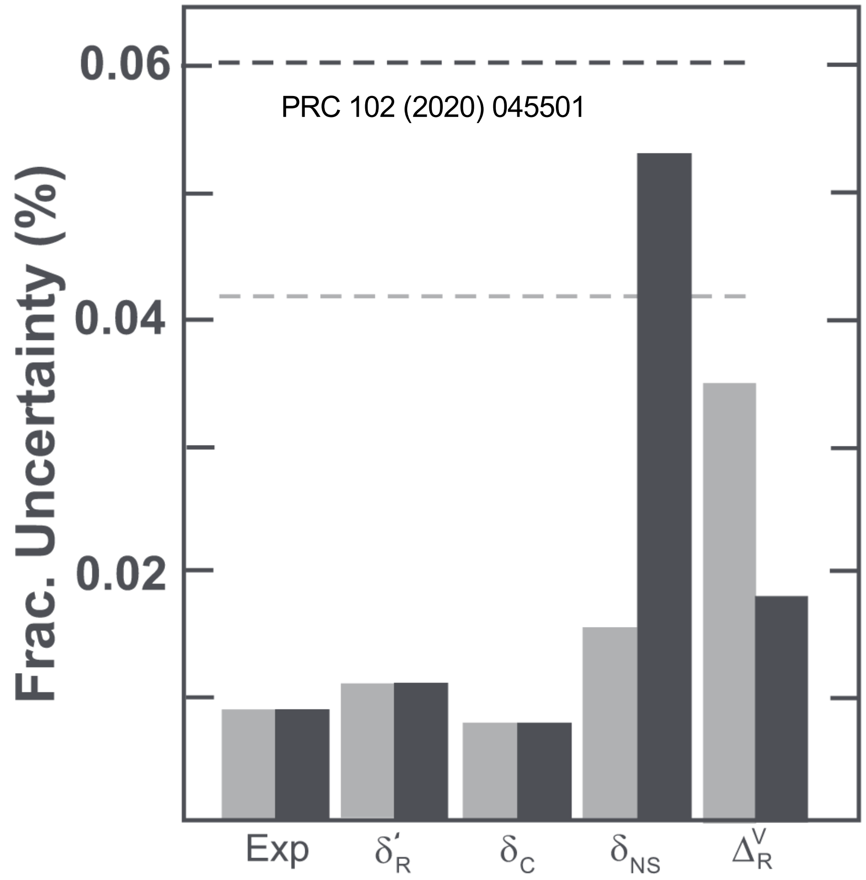
CKM elements

Superallowed beta decay

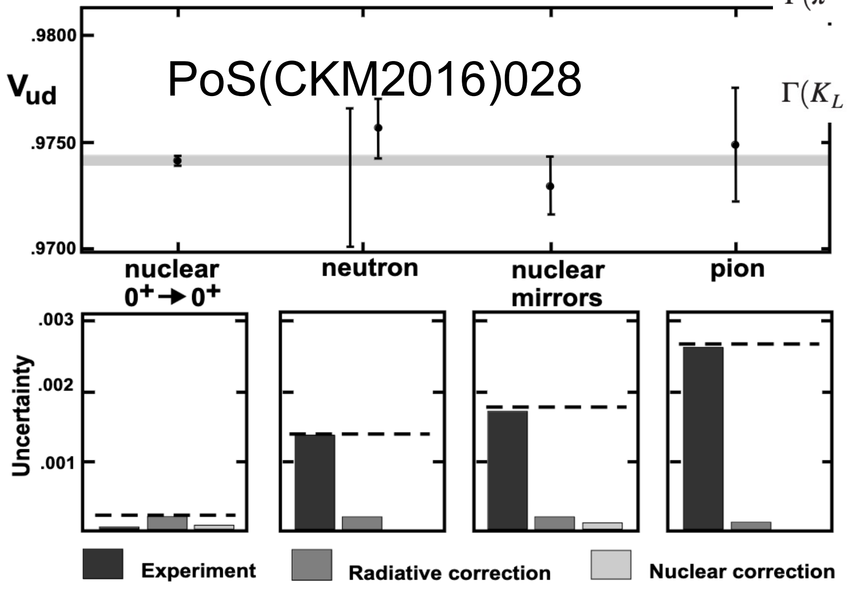


$$\frac{\Gamma(\pi^+ \to \pi^0 e^+ \nu)}{\Gamma(\mathrm{Total})} = 1.036 \pm 0.004(\mathrm{stat}) \pm 0.004(\mathrm{syst}) \pm 0.003(\pi \to e\nu) \times 10^{-8}$$

- PIONEER Phase 2: 3-fold improvement for $R_{\beta\pi}$ and a 0.2% determination for $|V_{us}/V_{ud}|$
- PIONEER Phase 3: 10-fold improvement for $R_{\beta\pi}$ and 0.02% determination for V_{ud} without nuclear structure dependence

$$\Gamma(\pi^+ \to \pi^0 e^+ \nu(\gamma)) = \frac{G_\mu^2 |V_{\mathrm{ud}}|^2 m_{\pi^+}^5 |f_+^\pi(0)|^2}{64\pi^3}(1 + \mathrm{RC}_\pi) I_\pi,$$

$$\Gamma(K_L \to \pi^\mp e^\pm \nu(\gamma)) = \frac{G_\mu^2 |V_{\mathrm{us}}|^2 m_{K_L}^5 |f_+^K(0)|^2}{192\pi^3}(1 + \mathrm{RC}_K) I_K$$



* Neutron needs corrections from lifetime and λ

$$R_V = \frac{\Gamma(K_L \to \pi^\pm e^\mp \nu(\gamma))}{\Gamma(\pi^+ \to \pi^0 e^+ \nu(\gamma))}$$

$$R_A = \frac{\Gamma(K \to \mu\nu(\gamma))}{\Gamma(\pi \to \mu\nu(\gamma))}$$

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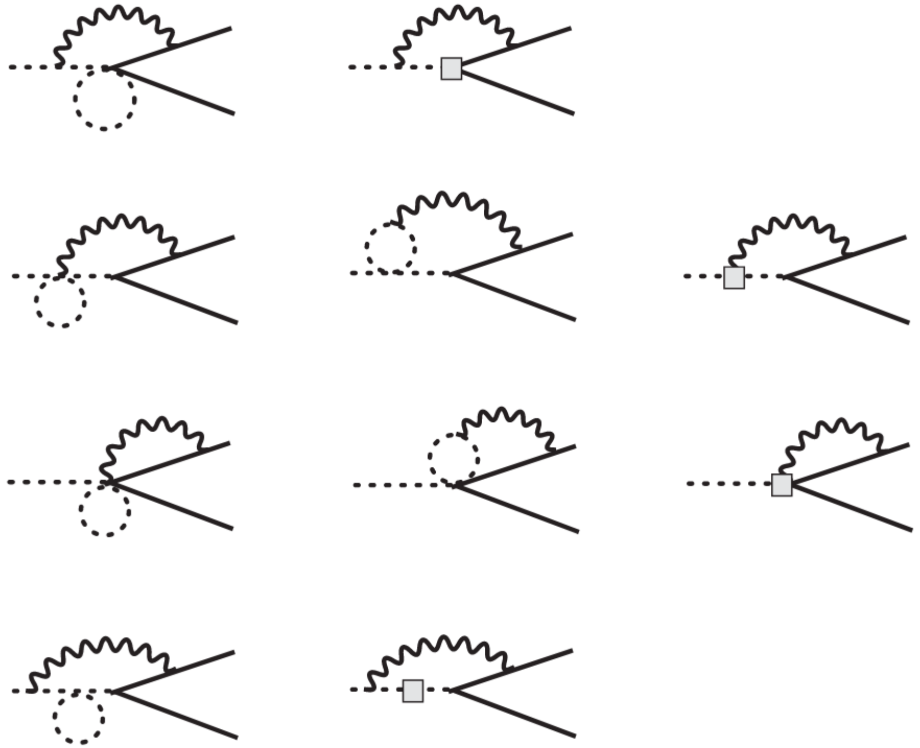
SM and charged scalar

Standard model calculation using ChPT

$$R_{e/\mu}^{(P)} = R_{e/\mu}^{(0),(P)}[1 + \Delta_{e^2p^2}^{(P)} + \Delta_{e^2p^4}^{(P)} + \Delta_{e^2p^6}^{(P)} + \ldots]$$

$$R_{e/\mu}^{(0),(P)} = \frac{m_e^2}{m_\mu^2}\left(\frac{m_P^2 - m_e^2}{m_P^2 - m_\mu^2}\right)^2.$$



PRL 99 (2007) 231801

Sensitivity to PeV scale

$$1 - \frac{R_{e/\mu}^{New}}{R_{e/\mu}^{SM}} \sim \mp \frac{\sqrt{2}\pi}{G_\mu}\frac{1}{\Lambda_{eP}^2}\frac{m_\pi^2}{m_e(m_d + m_u)}$$

From PiENu proposal $\sim (\frac{1TeV}{\Lambda_{eP}})^2 \times 10^3,$

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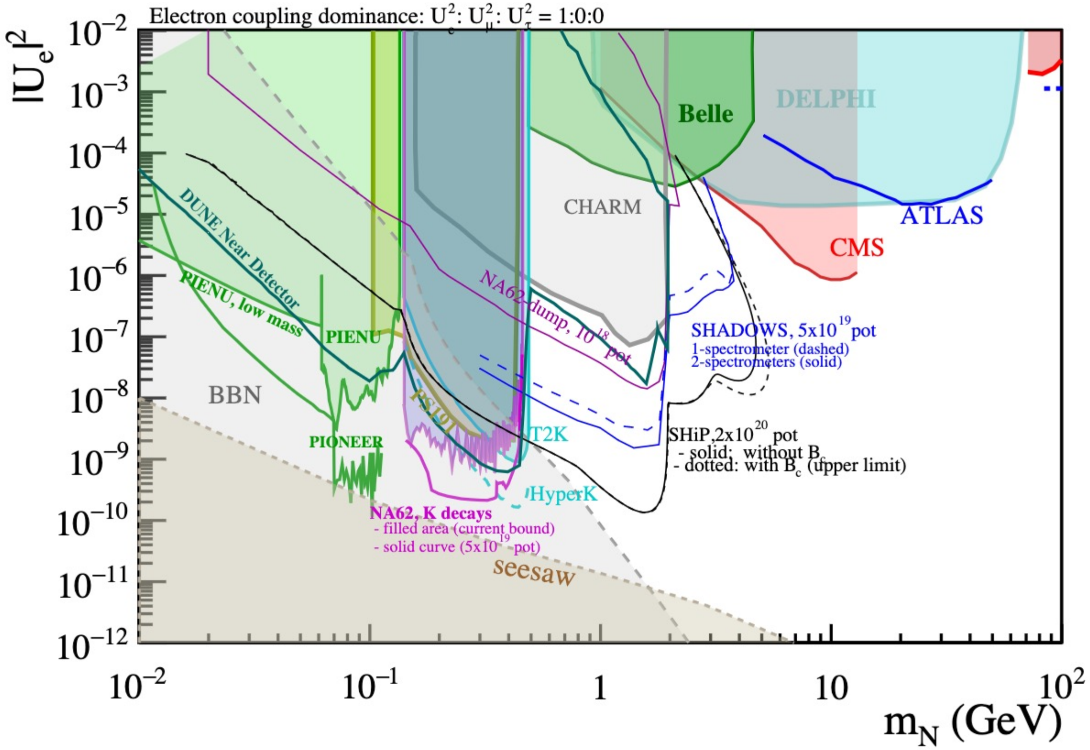
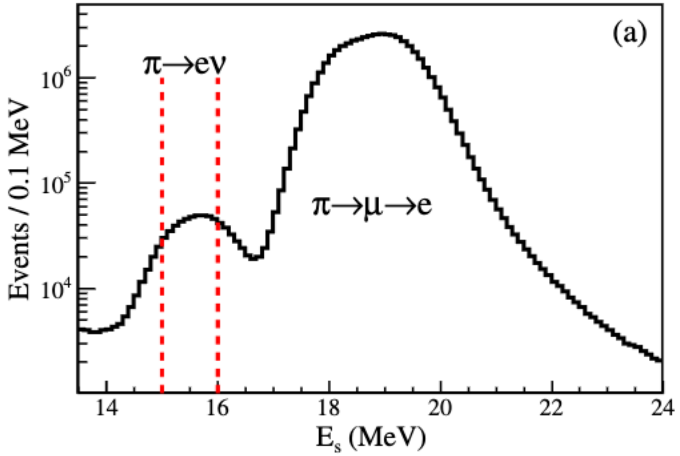
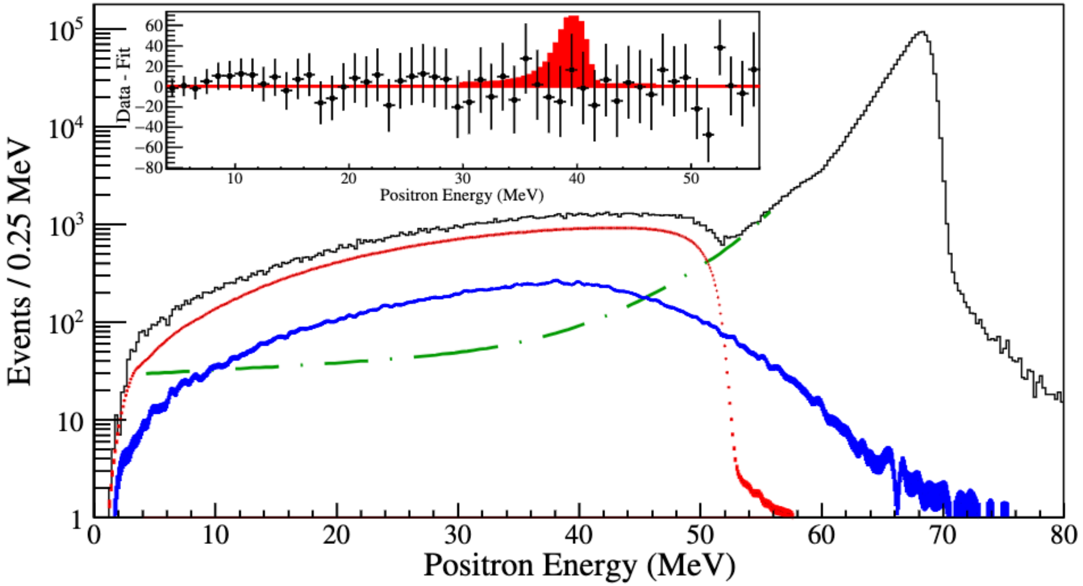
Heavy neutrino, $\pi \to e\upsilon_H$

Heavy neutrino, $\pi \to e\upsilon_H$



Arxiv:2203.08039





PRD 97 (2018) 072012

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Error budgets

From PiENu & PEN to PIONEER

$$R_{e/\mu} = \frac{N(\pi \to e)}{N(\pi \to \mu \to e\ )} = \frac{N^{H.E.}(\pi \to e)(1 + C_{tail})}{N(\pi \to \mu \to e)}$$

- Phase 1: Expected 2x10^8 $\pi \to e\nu(\gamma)$ for 3 years (5 mon/yr)
- Phase 2: Expected 7×10^5 $\pi^+ \to \pi^0 e\nu(\gamma)$ for 4 years (5 mon/yr)
- Phase 3: Expected 7×10^6 $\pi^+ \to \pi^0 e\nu(\gamma)$

	PIENU 1505.02737	PEN hep-ex/0312017	PIONEER
π^+ stopping rate (Hz)	5×10^4	2×10^4	3×10^5
CALO radiation length (X_0)	19	12	25
CALO resolution σ, $\delta E/E$ (%)	0.9	12.8	1.5

Phase	p (MeV/c)	Δp/p (%)	ΔZ (mm)	ΔX x ΔY (mm^2)	ΔX',ΔY'	R_π (10^6/s)
I	55-70	2	1	10x10	±10°	0.3
II,III	≈ 85	≤ 5	3	15x15	±10°	20

Error Source	PIENU 2015 %	PIONEER Estimate %
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**	**≤ 0.01**

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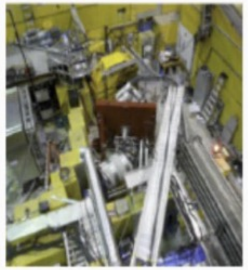
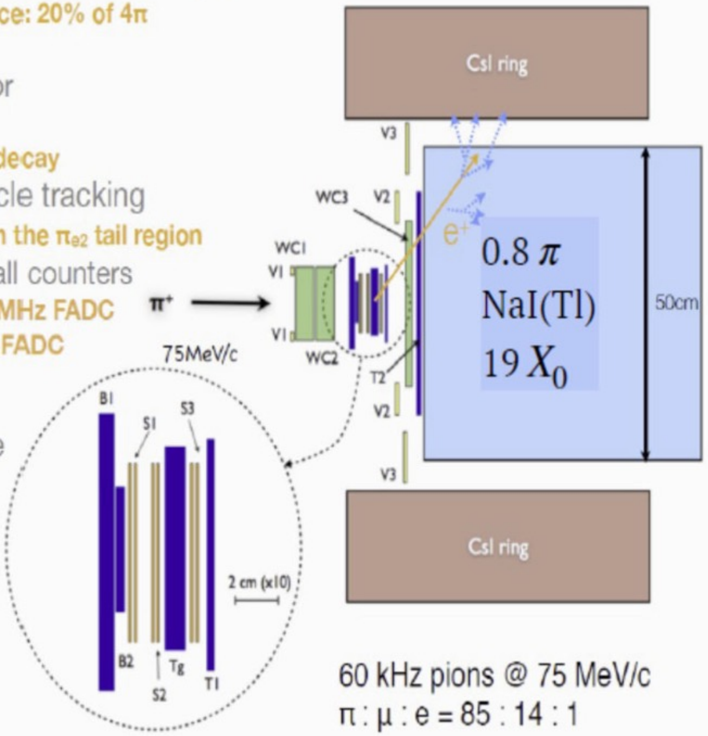
PiENu and PiBeta/PEN

PIENU @ TRIUMF

- Single crystal NaI(Tl) right behind the target
  - Geometrical Acceptance: 20% of 4π
  - ΔE = 2.2%(FWHM)
- CsI ring shower collector
  - π_{e2} tail suppression
  - gamma from radiative decay
- SSD and WC for particle tracking
  - Identify π-DIF events in the π_{e2} tail region
- Flash-ADC readout for all counters
  - Plastic Scintillator: 500MHz FADC
  - NaI(Tl) and CsI: 60MHz FADC
  - Pile-up tagging
- TRIUMF M13 beamline





60 kHz pions @ 75 MeV/c

π : μ : e = 85 : 14 : 1

NaI slow but excellent resolution (1% σ at 70 MeV)

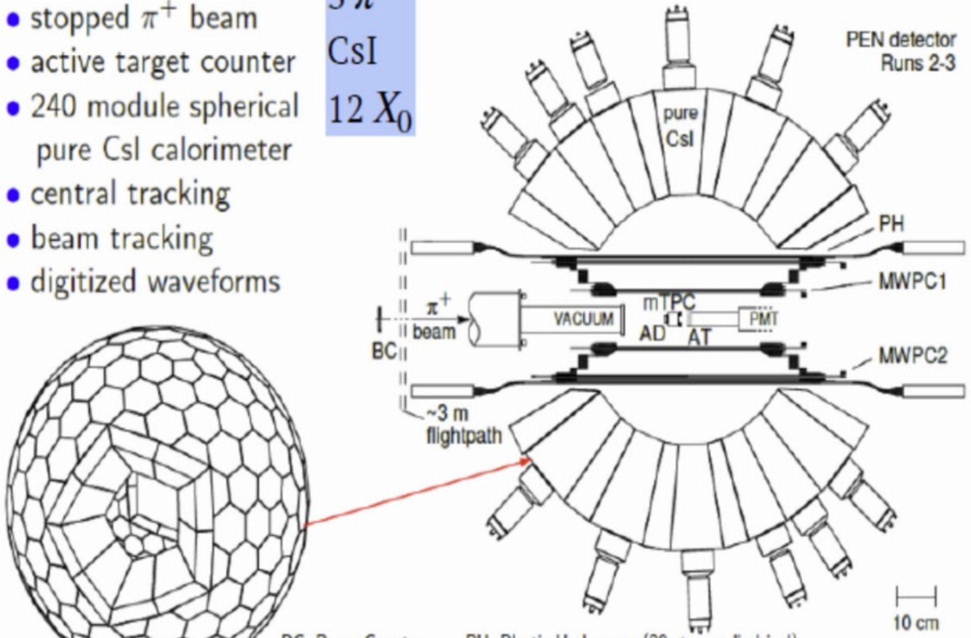
non uniformity, small solid angle

PEN @ PSI

The PEN/PIBETA apparatus

- πE1 beamline at PSI
- stopped π^+ beam
- active target counter
- 240 module spherical pure CsI calorimeter
- central tracking
- beam tracking
- digitized waveforms

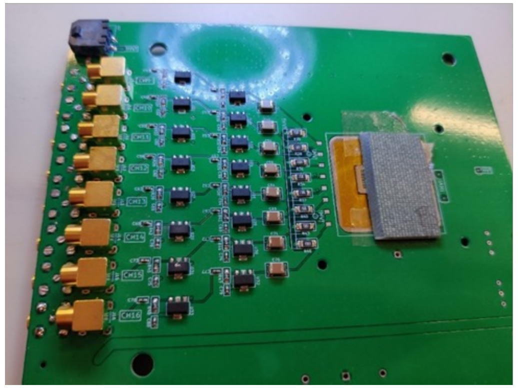
$3\,\pi$
CsI
$12\,X_0$

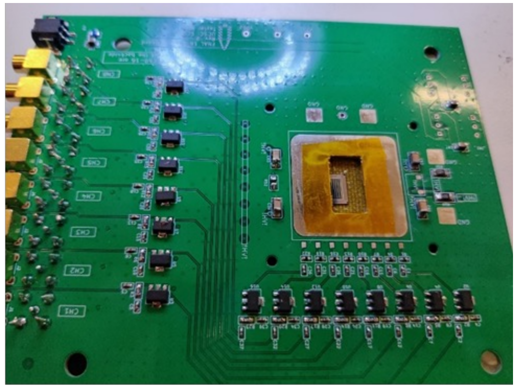


BC: Beam Counter
AD: Active Degrader
AT: Active Target
PH: Plastic Hodoscope (20 stave cylindrical)
MWPC: Multi-Wire Proportional Chamber (cylindrical)
mTPC: mini-Time Projection Chamber

Good geometry but calorimeter depth too small

Gallery of ATAR





- (a) Standard LGAD
- (b) AC-LGAD / TI-LGAD

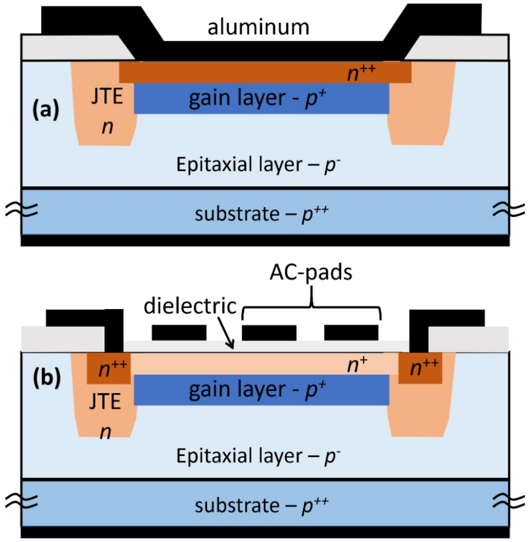


Figure 1. (a) Sketch of a section of a single-pad standard LGAD; (b) sketch of a section of a segmented AC-LGAD (not to scale).

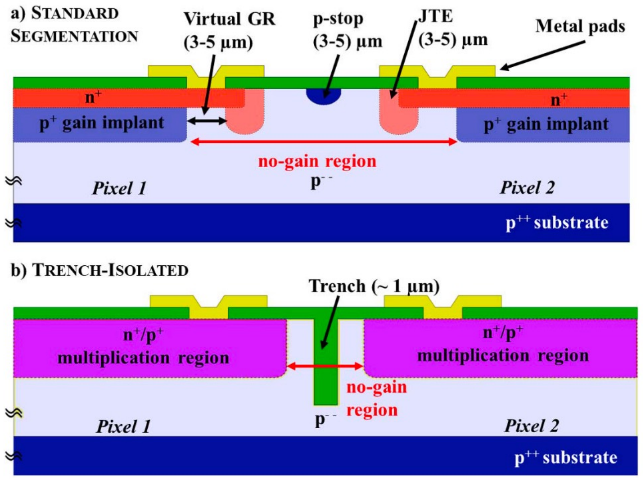


Fig. 1. Schematic drawings of a standard LGAD (a) and of the proposed trench-isolated LGAD (b).

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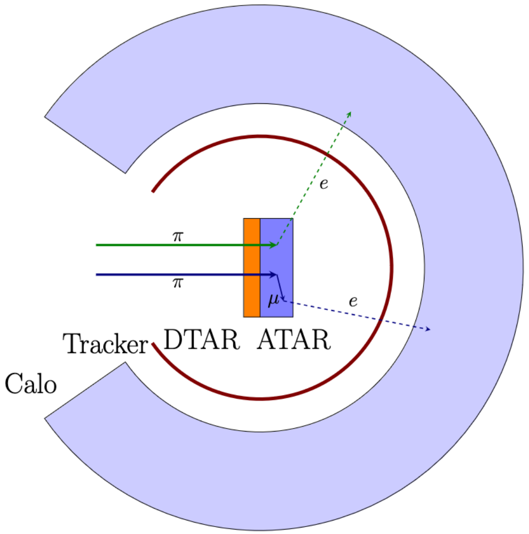
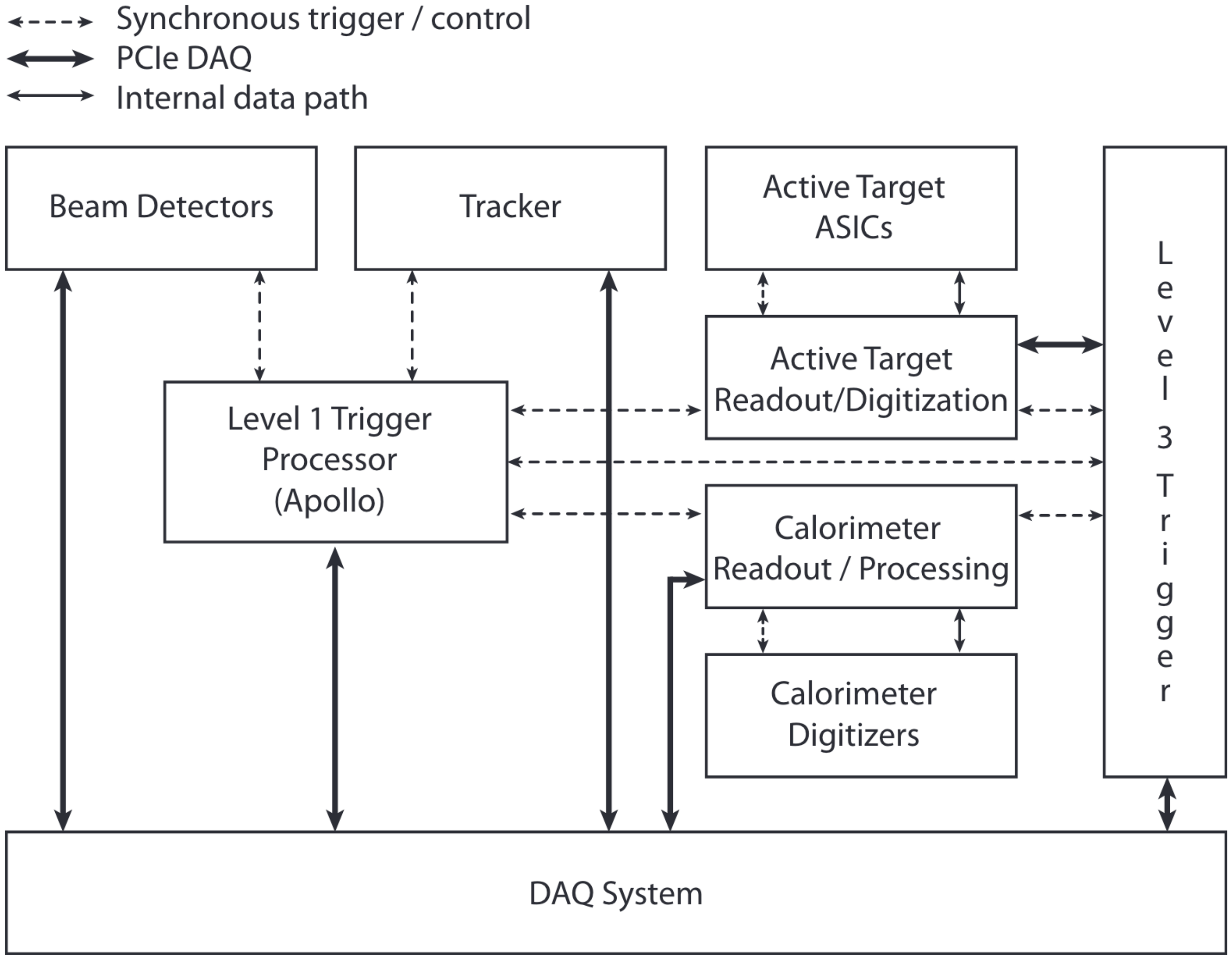
Trigger design



triggers	prescale	range TR(ns)	rate (kHz)
PI	1000	-300,700	0.3
CaloH	1	-300,700	0.1
TRACK	50	-300,700	3.4
PROMPT	1	2,32	5



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