PIONs, MUONs and the occasional KAON

David Hertzog / Peter Kammel

CENPA
Center for Experimental Nuclear Physics and Astrophysics

- Plenary:
  - Martin Hoferichter: *Tests of lepton flavor universality and CKM unitarity*
  - Doug Bryman: *Exploring Flavor Physics with Pions and Kaons*
- Breakout Session:
  - Vincenzo Cirigliano: *The physics of lepton flavor universality and CKM unitarity*
  - Toshiyuki Iwamoto: *The MEG II experiment and a new idea for the precision test on LUV with the LXe detector*
  - Simone Mazza: *Fast silicon detector technologies for 4D tracking in future HEP experiments*
  - Dinko Pocanic: *Lessons learned from the PiBeta and PEN experiments*
  - Tristan Sullivan: *Lessons learned from PIENU*
  - Andreas Knecht: *Pion and muon beams at PSI, performance and plans*

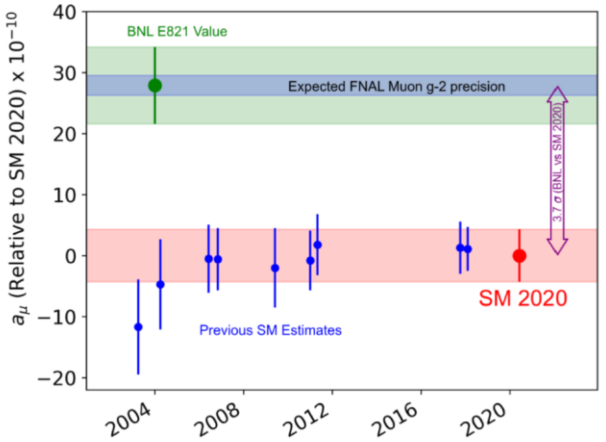
Prompts from organizers – (we return to this at the end)

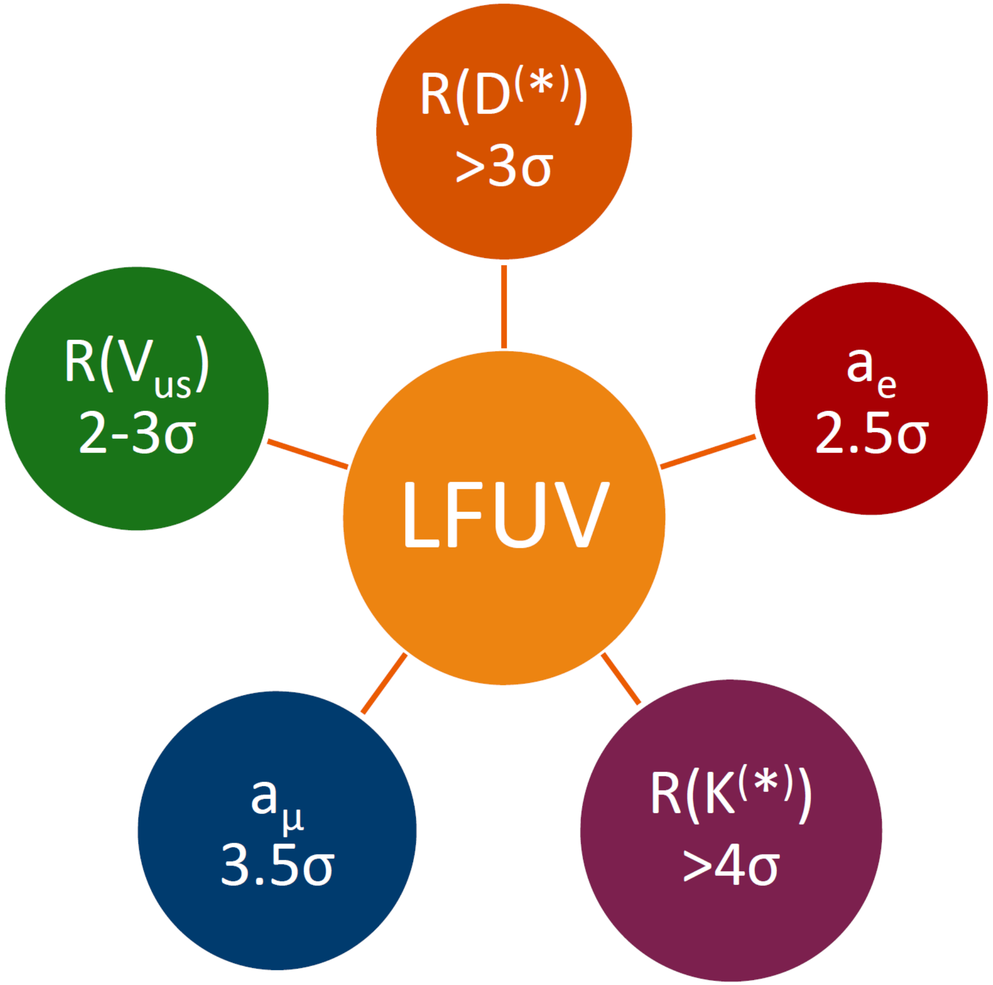
- **What ideas could (or could not) be turned into actual experiments at TRIUMF/CENPA?**
  - **A next-generation Rare Pion Decay seems to be our clear focus**: Nicknamed (for now) PIENUXe
- **What homework do we need to do to figure this out?**
  - **Beamlines investigations;**
    - We know demands from prior efforts. We made good progress in a review of the capabilities and specific options at PSI, and on the limitations and conflicting demands. PSI would "welcome" this.
    - The situation at TRIUMF is less clear. There is no "ready to go/borrow/steal" beamline, but there are options with existing areas/lines, or new ones to be considered dedicated to this effort.
  - **Calorimeter concept.**
    - Expertise in this group from MEG's development of LXe and SiPMs. There success is based on a significant R&D efforts and real use of the detector. A huge advantage to draw from.
    - We did not discuss crystal calorimeter ideas, but in the bigger picture we will need to address options, even if to simply provide needed comparisons related to funding.
    - There are many challenges with windows, readout, cost, geometry, calibrations, installation, …
  - **Stopper/Tracker "combination"**
    - Strong case made to track the stop and track the decay positrons from that vertex. Can this be done with modern developments?
    - Learned of a candidate new technology that would be great, but made of XY strip geometry. Might be okay ? But have to begin thinking
  - **Monte Carlo Simulations**
    - A modified PEN GEANT code has been extracted and readied for use with "toy" detector ideas. Some runs done with LXe calo to demonstrate the importance of a deep calorimeter to address the "tail" systematic in pi e nu, the leading problem.
- **Should we form a working group to answer such questions? Who are key people to target for this working group?**
  - The group said "**Yes**". The work naturally falls in various divisions related to technological expertise, theory, simulation, beams, …
  - We will assemble (softly) with the aim of real homework prior to DND 2021 / Snowmass. Lively email exchanges started.
  - We want to, and need to, enlarge the interested parties prior to developing any "formal organizational structure"

The Physics Motivation(s)

Some things anomalous in the Flavor Sector?

Unconfirmed flavor-related anomalies :
- Muon g-2 (3+ σ)
- B decays – LFU violation (CC, NC) (2.5-3 σ)
- Unitarity of CKM matrix 1st row (2-3 + σ)





Something wrong with Unitarity?

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

Andreas Crivellin

The Physics Case: what we might do about it

- Lepton Flavor Universality test in $R_{e/\mu}^{theory} = \dfrac{\Gamma\left(\pi \to e\nu(\gamma)\right)}{\Gamma\left(\pi \to \mu\nu(\gamma)\right)}$

Theory

$$R_{e/\mu}^{(\pi)} = 1.2352(1) \times 10^{-4}$$

Experiment

$$R_{e/\mu}^{(\pi)} = 1.2327(23) \times 10^{-4}$$

This just demands to be tested better! A clean generic way to look for new physics. Theory vs Experiment in high precision test

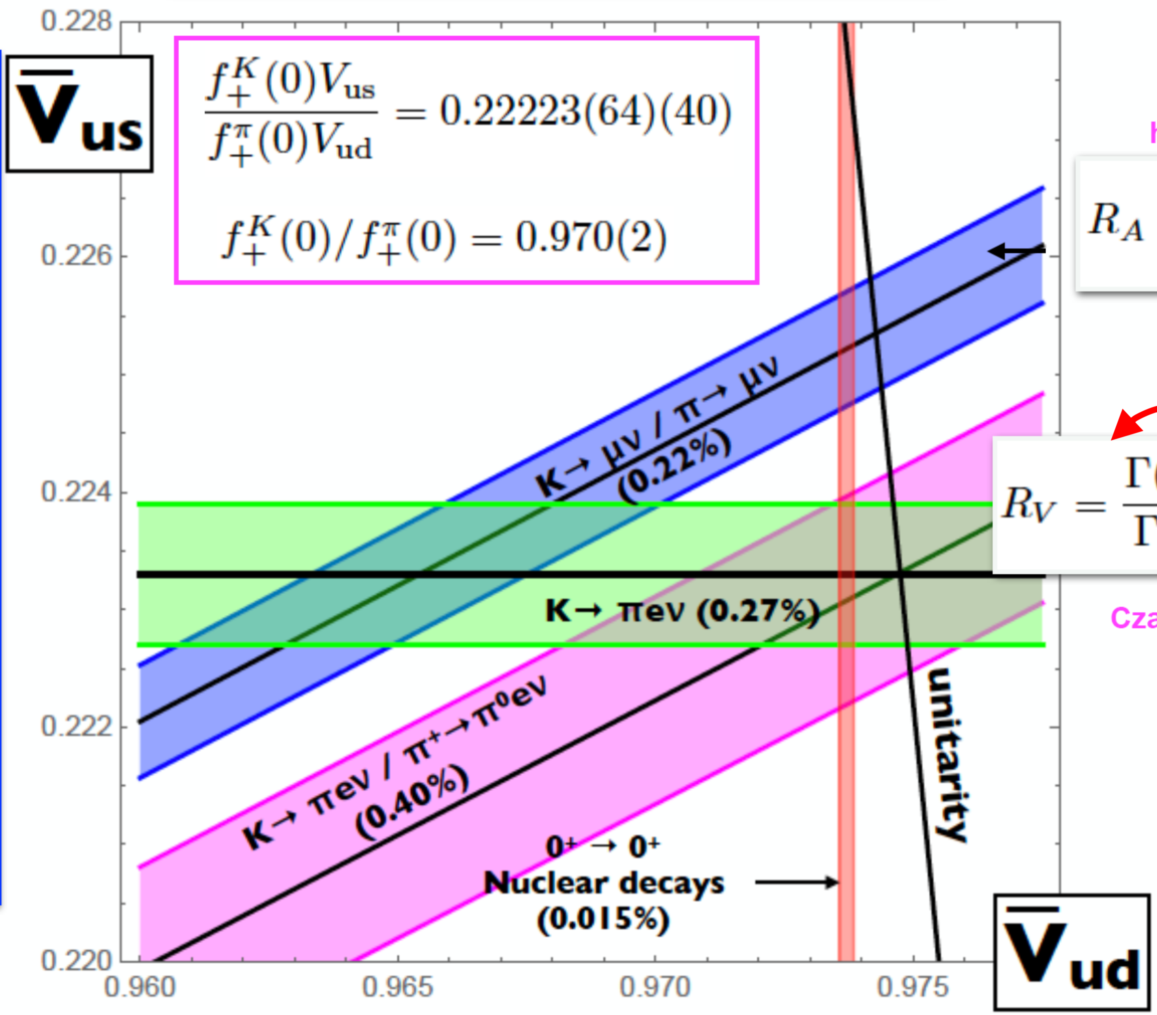
The Physics Case: what else we might do

- 3 x improved Pion Beta Decay → new ratio R_V

R_V is nearly competitive with R_A. Hints to yet another tension!

3x improvement in PIBETA BR, along with modest improvement in K form factor and BRs, would lead to competitive V_{us}/V_{ud} @ 0.2%.

Realistic short term goal?



Marciano, hep-ph/0402299, PRL

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

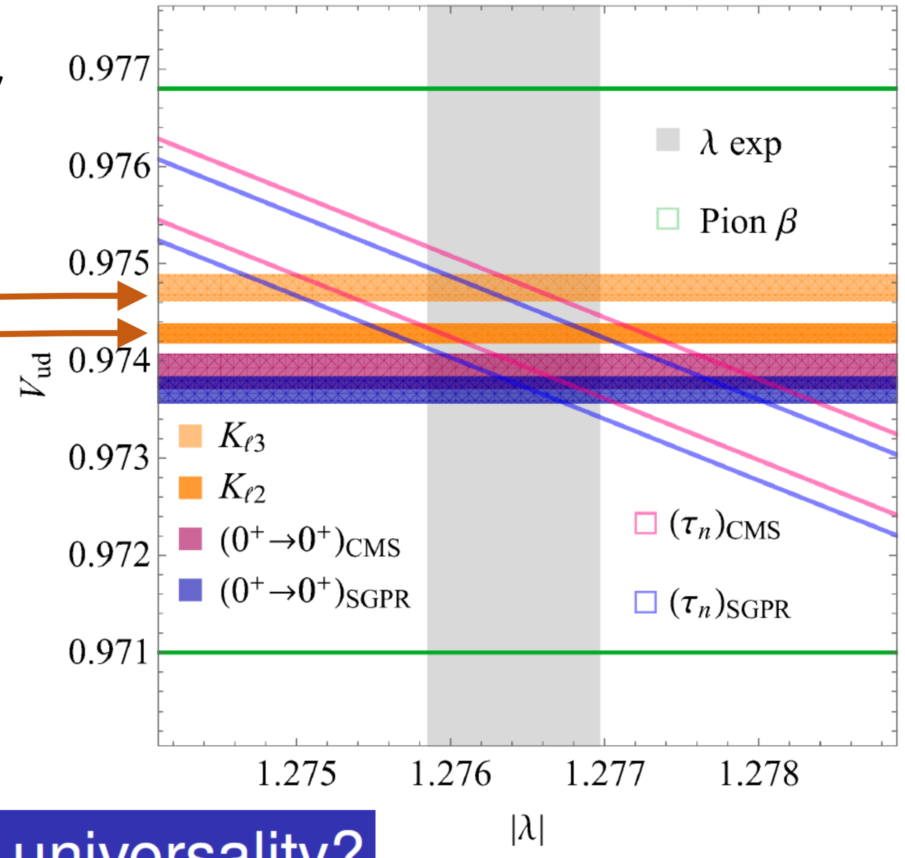
$$R_V = \frac{\Gamma(K_L \to \pi^\pm e^\mp \nu(\gamma))}{\Gamma(\pi^+ \to \pi^0 e^+ \nu(\gamma))}$$

Czarnecki, Marciano, Sirlin 1911.04685, PRD

Vincenzo Cirigliano

The Physics Case II. They might be related

- CKM 1st Row Unitarity. Start by *assuming* it's true. But then …The V_{ud} you get by taking: $|V_{ud}|^2 = 1 - |V_{us}|^2$
- Is different than the one you get from beta decay



Modifies Fermi constant in **muon decay**

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

***V_{ud}* tension as a sign for the violation of lepton flavor universality?**

Martin Hoferichter

We already wrote a LOI for SNOWMASS … but as an aim for DND 2020

Testing Lepton Flavor Universality and CKM Unitarity with Rare Pion Decays

LOI for Snowmass 2020 Discussion

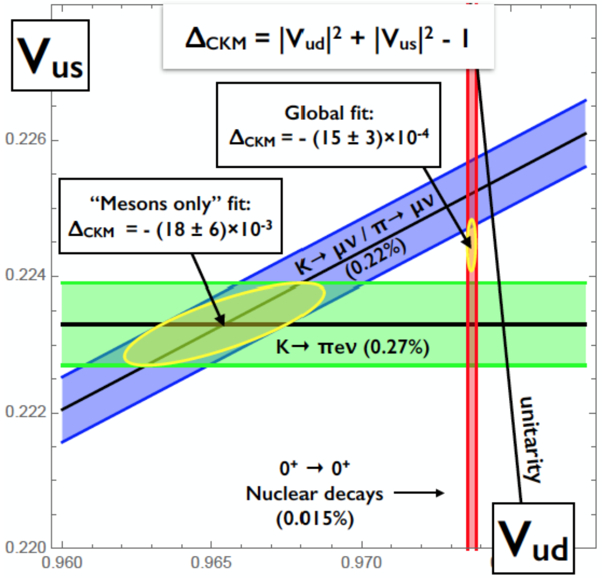
August 27, 2020

A. Aguilar-Arevalo[1], D. Bryman[2,3], S. Chen[4], V. Cirigliano[5], A. Crivellin[6,7,8], S. Cuen-Rochin[9], A. Czarnecki[10], L. Doria[11], A. Garcia[12], L. Gibbons[13], C. Glaser[14], M. Gorchtein[11], T. Gorringe[15], D. Hertzog[12], Z. Hodge[12], M. Hoferichter[16], P. Kammel[12], J. Kaspar[12], K. Labe[13], J. Labounty[12], S. Ito[17], W. Marciano[18], S. Mihara[19], R. Mischke[3], T. Numao[3], C. Ortega Hernandez[1], D. Pocanic[14], T. Sullivan[20]

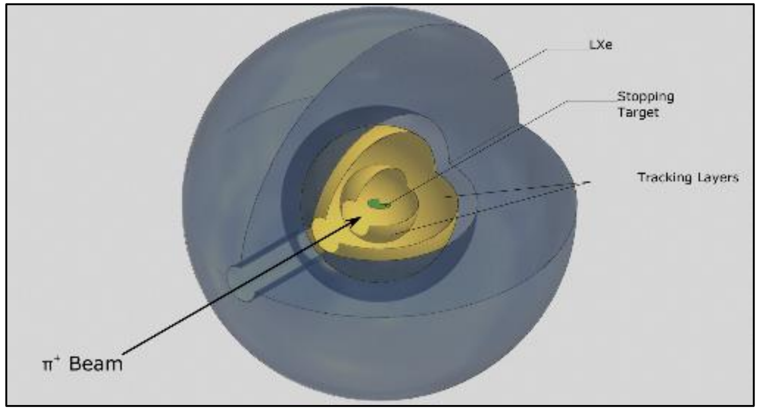
[1]Universidad Nacional Autonoma de Mexico, [2]University of British Columbia, [3]TRIUMF, [4]Tsinghua University, [5]Los Alamos National Laboratory, [6]Paul Scherrer Institute, [7]University of Zurich, [8]CERN, [9]Universidad Autonoma de Sinaloa, [10]University of Alberta, [11]University of Mainz, [12]University of Washington, [13]Cornell University, [14]University of Virginia, [15]University of Kentucky, [16]University of Bern, [17]Okayama University, [18]Brookhaven National Laboratory, [19]KEK, [20]University of Victoria,

PiENuXE: Testing *Lepton Flavor Universality* and *CKM Unitarity* with Rare (stopped) Pion Decays

- Goals
  - Improve e/μ universality and CKM unitarity tests by an order of magnitude
  - Measure π→eν/π→μν to ±0.015%, matching SM theory precision
  - Measure pion beta decay rate to ±0.06%
    - Leads to V_{us}/V_{ud} constraint to < 0.1%



- Motivation drawn from
  - Possibly related tensions from $(g\text{-}2)_{\mu,e}$, CKM unitarity, and *B* decays
  - Possibility that the apparent violation of CKM unitarity is a manifestation of Lepton Flavor Universality Violation (LFUV). (PhysRevLett.125.111801, Sept 2020)
  - Precise theory, experiments far behind in comparable precision



- How
  - Next-gen design based on real-world lessons from PEN and PiENu
  - $28X_0$ LXe/SiPM – fast, high resolution, x10 smaller low-energy tail
  - Mu3e style silicon trackers – event reconstruction at high rates
  - Pixelated target, customized for LFUV or PiBeta (separate) runs

Please contact us (hertzog@uw.edu) or others on LOI signatory list. 22 Institutes, (27 experimentalist; 5 theorists).

Toward a new experiment involves …

- Starting the group … LOI and actively recruiting
- Studying the history … talks: “lessons learned”
- Learning about new technologies you might use … talks LXe, LGADs,
- Exploring where you might do it … talks PSI, TRIUMF
- Figuring out how to pay for it … ***JENS !!!!!!!!!!***
- Some new simulations
- Some prototypes
- And then the fun begins.

Lessons for a next generation experiment

Dinko Pocanic (PEN/PiBeta)

- One can never know too much about an event. **Redundancy** in the measured observables is essential.
- **Precision tracking** of beam and decay product particles is critically important.
- There is no substitute for **resolution (E, t, spatial)**, especially in the calorimeter. Calorimeter thickness, though expensive, is essential.
- Calorimeter must be **separable** so that its response can be studied directly with beam in a controlled manner.
- **Calorimeter segmentation** is critical. The PiBeta calorimeter was designed to provide sufficient angular resolution for photon-induced showers, and delivered. Calorimeter segmentation enables use of high beam stopping rates with ease.
- **Low mass** everywhere in the path of particles (beam and decay products) is essential.
- Highly realistic **simulation** of the apparatus and processes is a given.
- Handling the **high target rate** for an ultimate $R^{\pi}_{e3(\gamma)}$ measurement is a **challenge**.

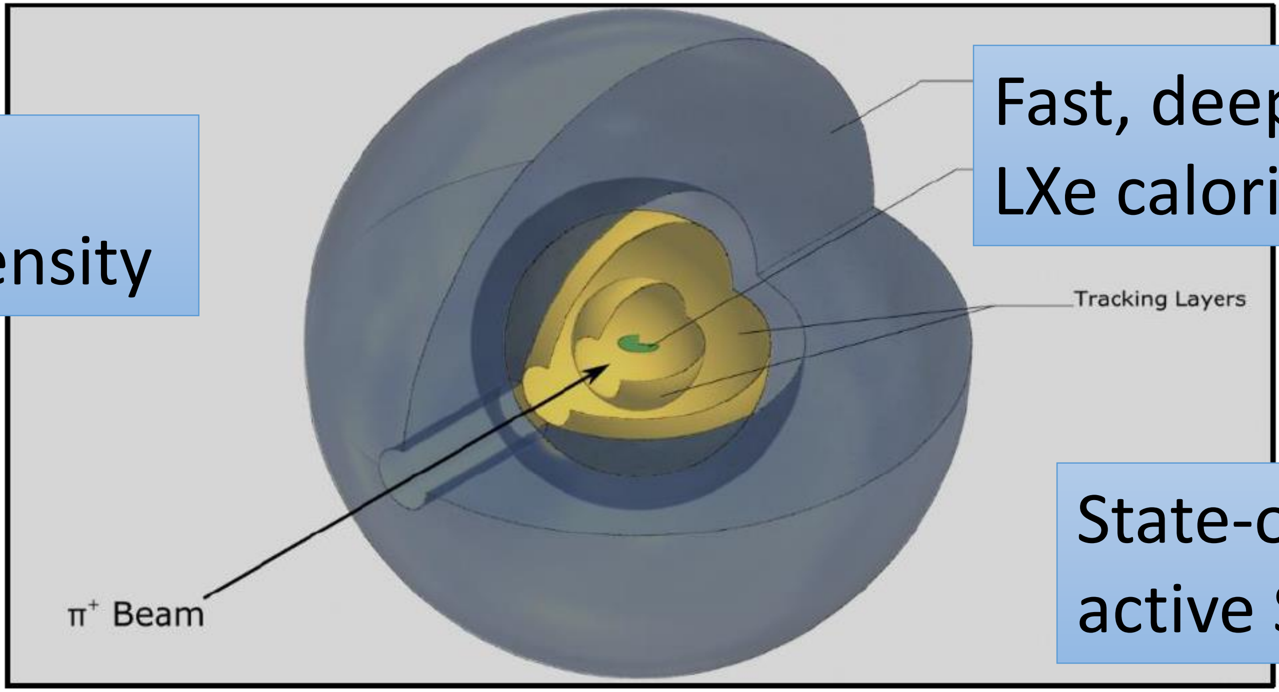
Tristsan Sullivan
(PiENu)

Obstacles

- Physical design of detector, including cryo and cabling
- Very accurate knowledge of real detector geometry
- Pion beam with low contamination from other particles, narrow momentum bite, high flux
- Proper characterization of beamline
- Thorough measurement of detector response, both initially and ongoing
- Proper characterization of electronic noise, both initially and ongoing
- Version-controlled, unit-tested software, for both DAQ and analysis
- Robust checks of incoming physics data
- Other than that it’s easy

PIENUXE: New Rare π Decay Experiment with LXe

π^+ beam
10x higher intensity



Fast, deep, homogenous LXe calorimeter

State-of-the-art active Si target

Overall
- >20x higher statistics
- >10x reduction systematics

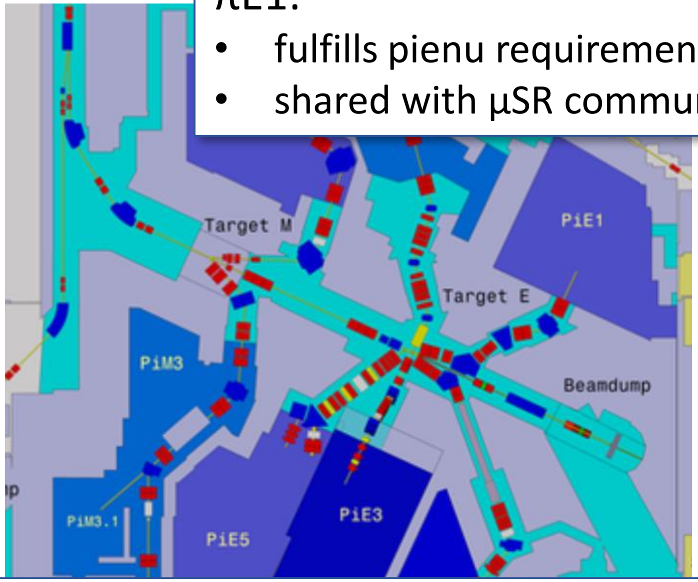
Lessons learned @ TRIUMF and PSI
Dinko (UVa), Tristan (TRIUMF)

Beam

	$\pi^+ \to e^+ \nu$	$\pi^+ \to \pi^0 e^+ \nu$
momentum	75 MeV/c, 2x10^5 Hz, dp/p=1%	75 MeV/c, 3x10^7 Hz, dp/p=3%
Statistics/yr	10^8	10^6
precision	0.015%	0.1%

- PSI

Andreas (PSI)



πE1:
- fulfills pienu requirements
- shared with μSR community

πE5:
- fulfills piBeta requirements
- world's highest intensity beamline likely available in a few year's when MEG finished

experiment welcome at PSI

- TRIUMF

Doug (TRIUMF)

some possibilities, at least for pienu
development studies required !

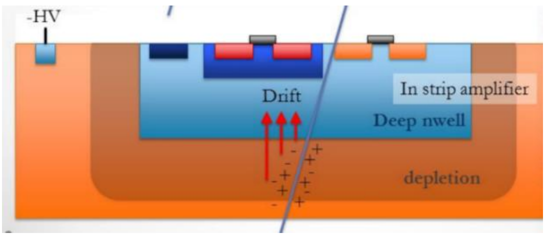
Can TRIUMF assemble a Study Group to look into this?

Figure 1: Layout of T2 and M9 beamlines

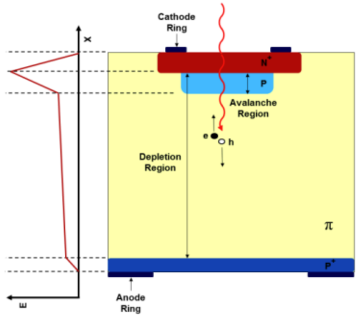
Active target and tracker

- main issues
  - vertex reconstruction, pile-up
  - separation $\pi \to e\nu$ from $\pi \to \mu \to e$
- Not fully utilized for pienu and piBeta
- Breakthrough in fast Si detector technology

  LGADs: 50 µm thick, pixel, 30 ps, fast pulses
- Concept aligned with highly active detector research, HL-LHC
- First concepts during workshop
  - active target replaces tracker
  - narrow beampipe into calo

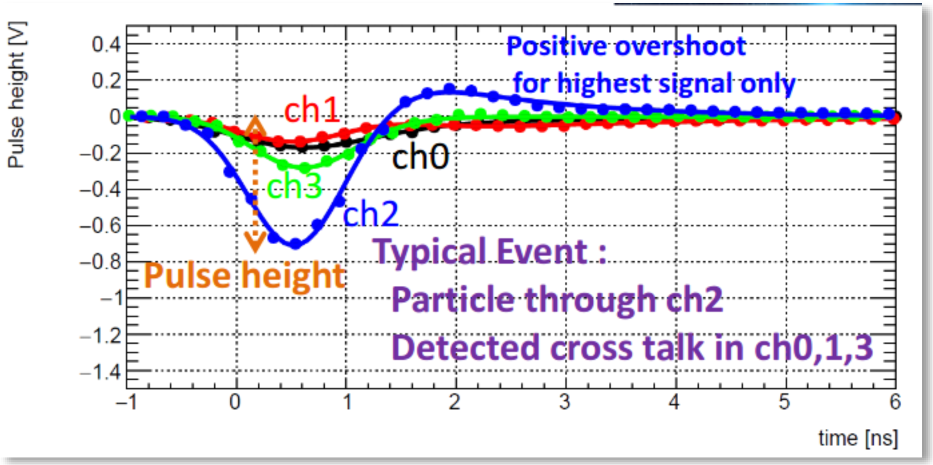


HV-CMOS, high granularity, 0.1-10 ns



LGADs, mm granularity, **30 ps**

Simone (UC Santa Cruz)



Tristan (TRIUMF)

LXe calorimeter

Toshiyuko (Univ Tokyo)

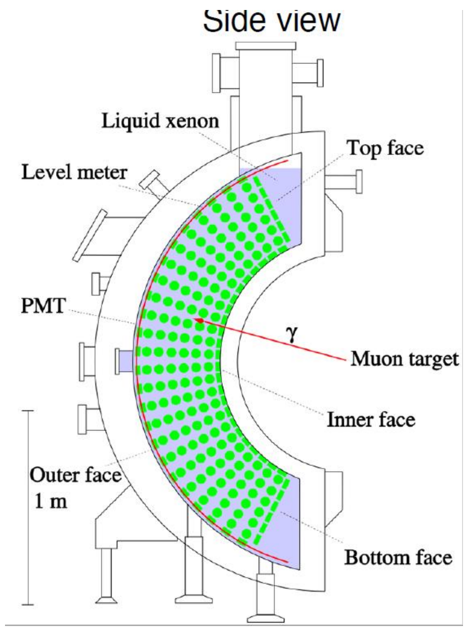
- State of the art

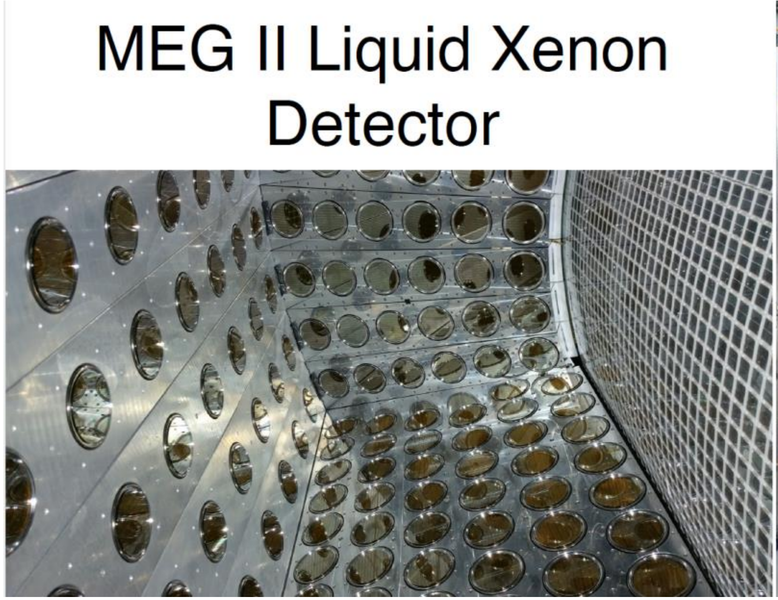
  Detector medium : 900 l LXe
  - Homogeneous
  - Heavy (3 g/cm^3)
  - High light yield
  - decay time : 45ns (γ)
  - Depth 38.5cm (~13X_0)
- Resolution
  - ~2.5 mm position
  - ~55 ps timing
  - ~1.7% energy
- Tokyo group

  interested in testing pienu experiment with MEGII, related detector characterization

  100 l prototype detector exists

  received R&D funding for new pienu



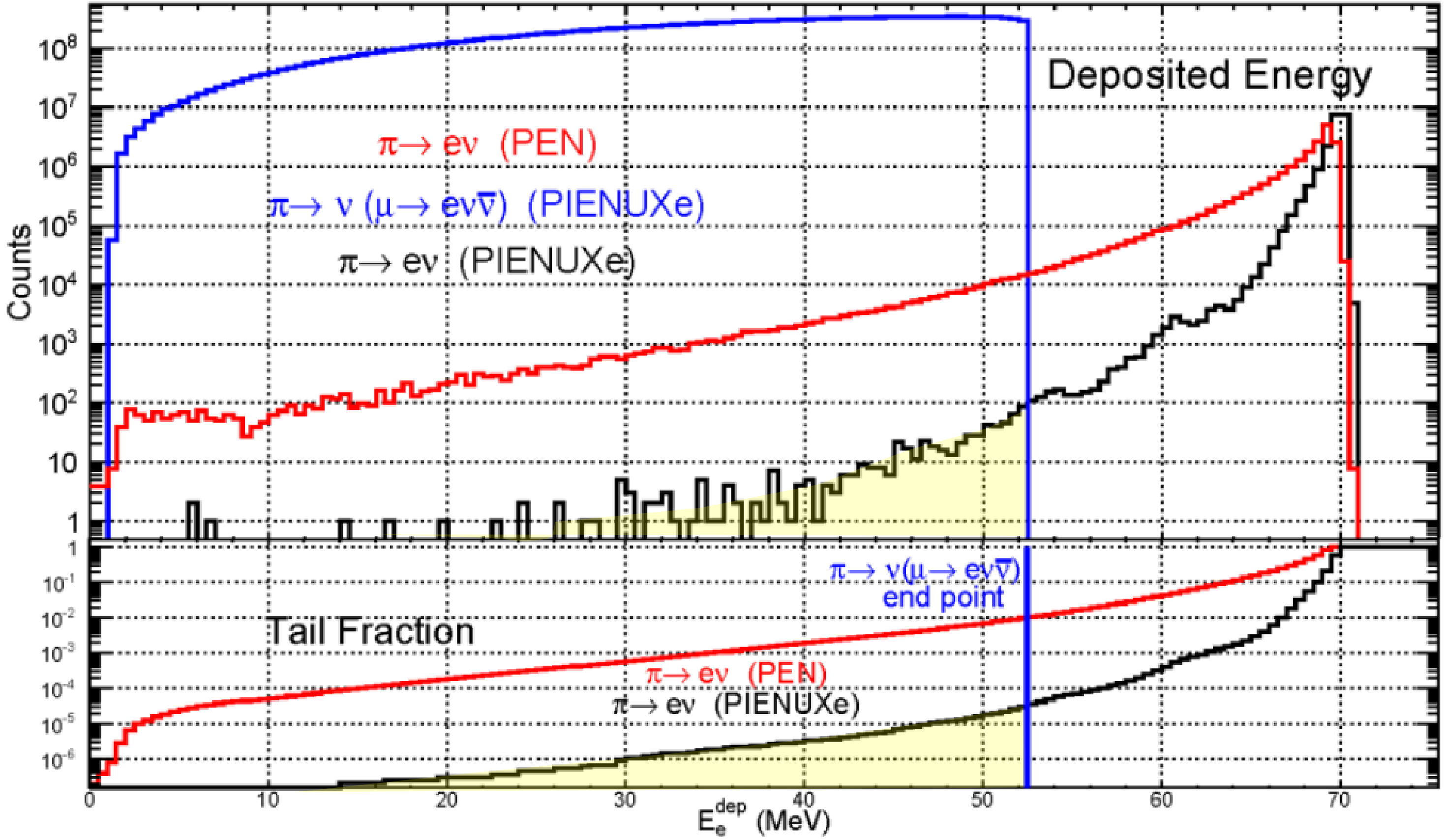


LXe calorimeter for PIENUXe

- 28 X_0
- symmetric
- ~ 50% efficiency

➢ 200 better $\pi \to e\nu$ tail suppression than PEN @ PSI

Dinko (UVa)



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