PIONEER

A next-generation rare pion decay experiment

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A *Growing* Collaboration: New members very welcome !!

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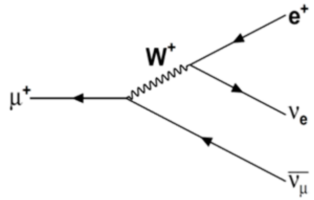
SNOWMASS 2021(2)

Lepton Flavor Universality is a simple concept:

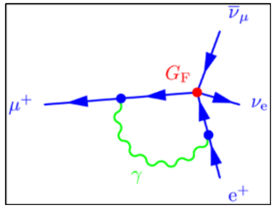
The weak interaction bare gauge couplings among leptons are the same e / μ / τ

- The weak-interaction “strength” is associated with the Fermi Constant, $\mathbf{G_F}$
- Muon decay provides the most precise measurement
  - Technically it determines $\mathbf{G_\mu}$, which is usually just called $\mathbf{G_F}$ … because we believe in LFU !



G_F(MuLan) = 1.166 378 7(6) x 10^{-5} GeV^{-2} (0.5 ppm)

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



PRL 106, 041803 (2011)
Phys. Rev. D 87, 052003 (2013)

Questioning the validity of what others took to be true…

PHYSICAL REVIEW D, VOLUME 60, 093006

Fermi constants and “new physics”

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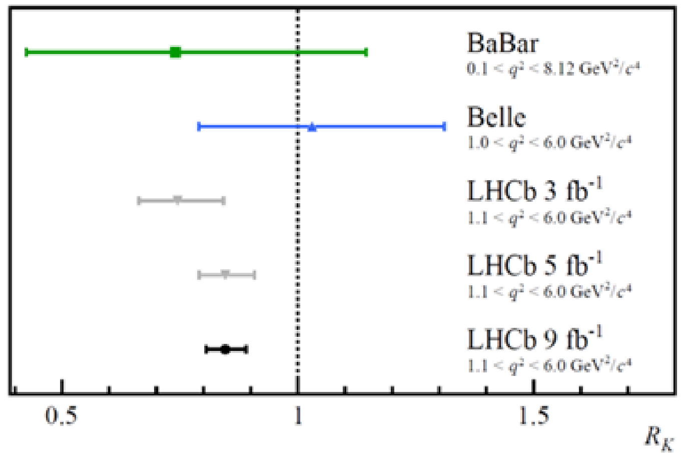
(Received 25 March 1999; published 7 October 1999)

Status now? Strong hints of problems with various *B* decay channels and leptons*

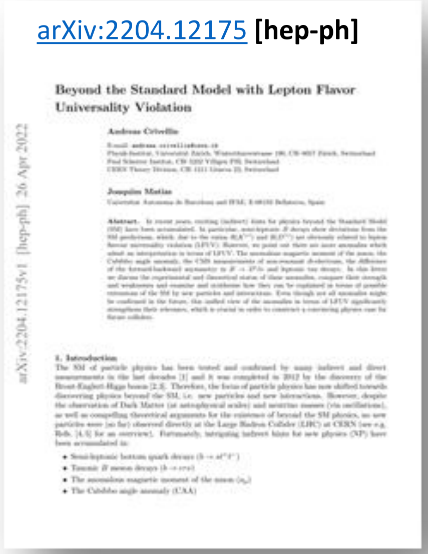
$B \to D^{(*)}\tau\nu$ / $B \to D^{(*)}\mu\nu$; charged currents

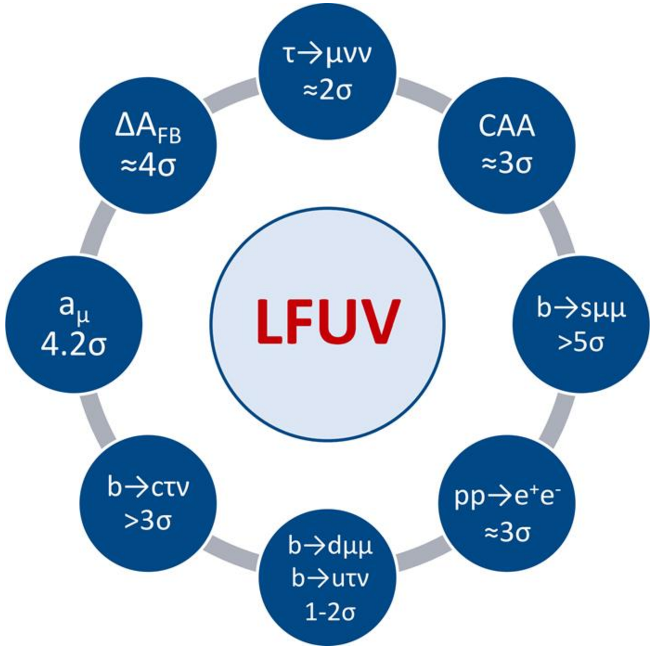
$B \to K^{(*)}\mu\mu$ / $B \to K^{(*)}ee$; neutral currents

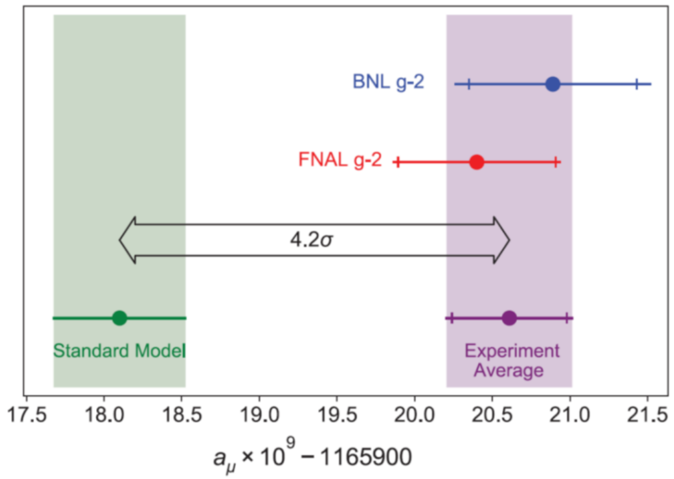


O(10%) deviations from universality !

Also, "lots" of anomalies are associated with flavor measurements







Physics Case 1: Test LFUV at precision of theory

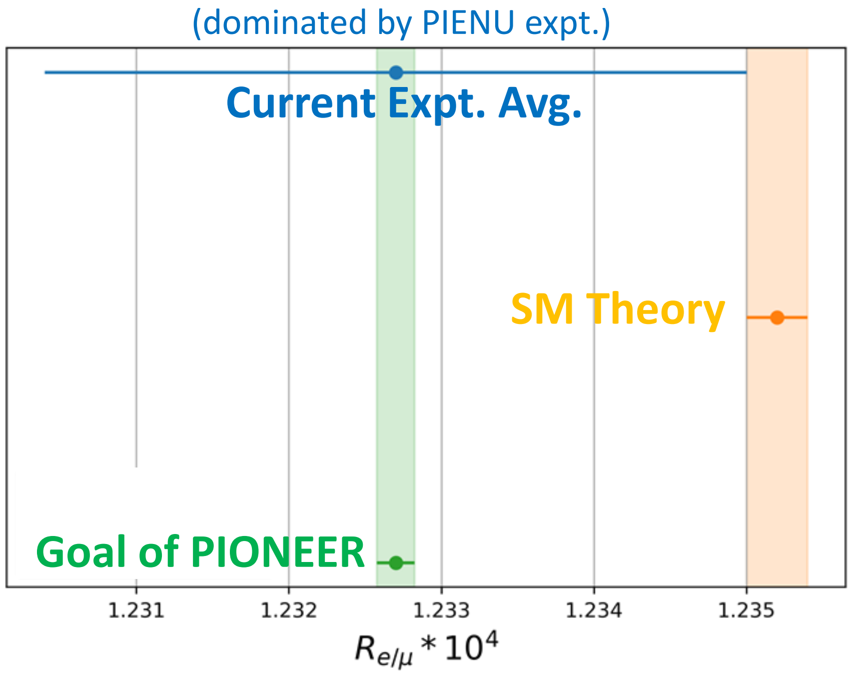
- Lepton Flavor Universality test in $R_{e/\mu}^{theory} = \frac{\Gamma(\pi \to e\nu(\gamma))}{\Gamma(\pi \to \mu\nu(\gamma))}$

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

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

15 x worse than theory

$$\frac{g_e}{g_\mu} = 0.9990 \pm 0.0009 \quad (\pm 0.09\%)$$



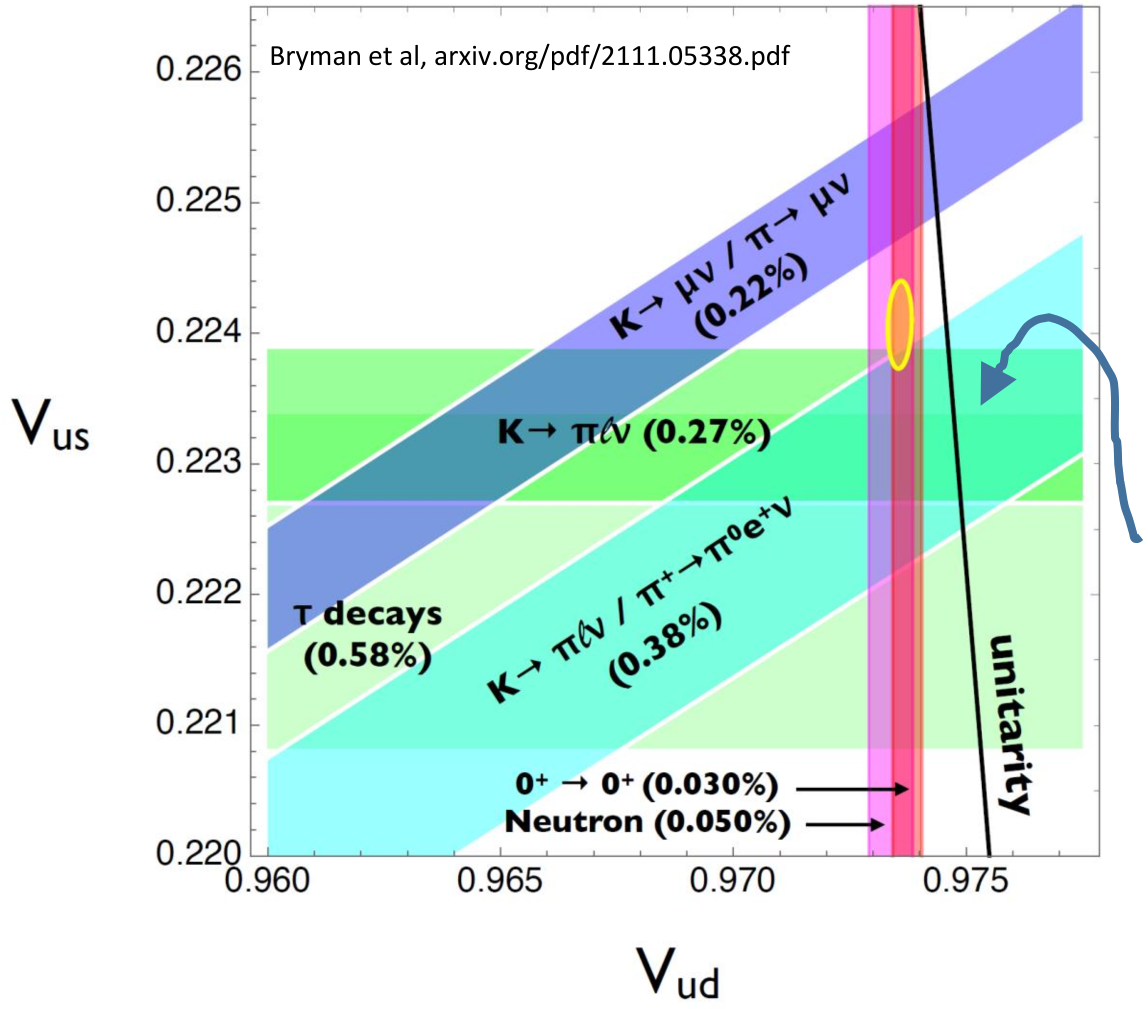
This just demands to be tested better! A clean generic way to look for new physics. Theory vs Experiment in high precision test.

Will be (by far) the most precise test of Lepton Flavor Universality

Physics Case 2: Improve pion beta decay by factor of 3
(note: This is a long term goal, representing Phase II of PIONEER)

Tensions in the first-row CKM unitarity test

Again a ~3σ problem (or even more)

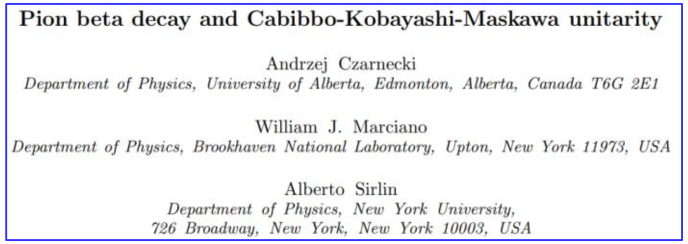


Dominant uncertainty in $\delta|V_{ud}|$ are associated with hadronic and nuclear corrections

Pion beta decay, $\pi^+ \to \pi^0 e^+ \nu(\gamma)$ provides the theoretically cleanest determination of $|V_{ud}|$

BUT, uncertainty is too large at present.

New idea* , a 3-fold improvement (~doable) in pion beta decay, together with improved $K \to \pi \ell \nu(\gamma)$ Improves R_V as shown


Pion beta decay and Cabibbo-Kobayashi-Maskawa unitarity

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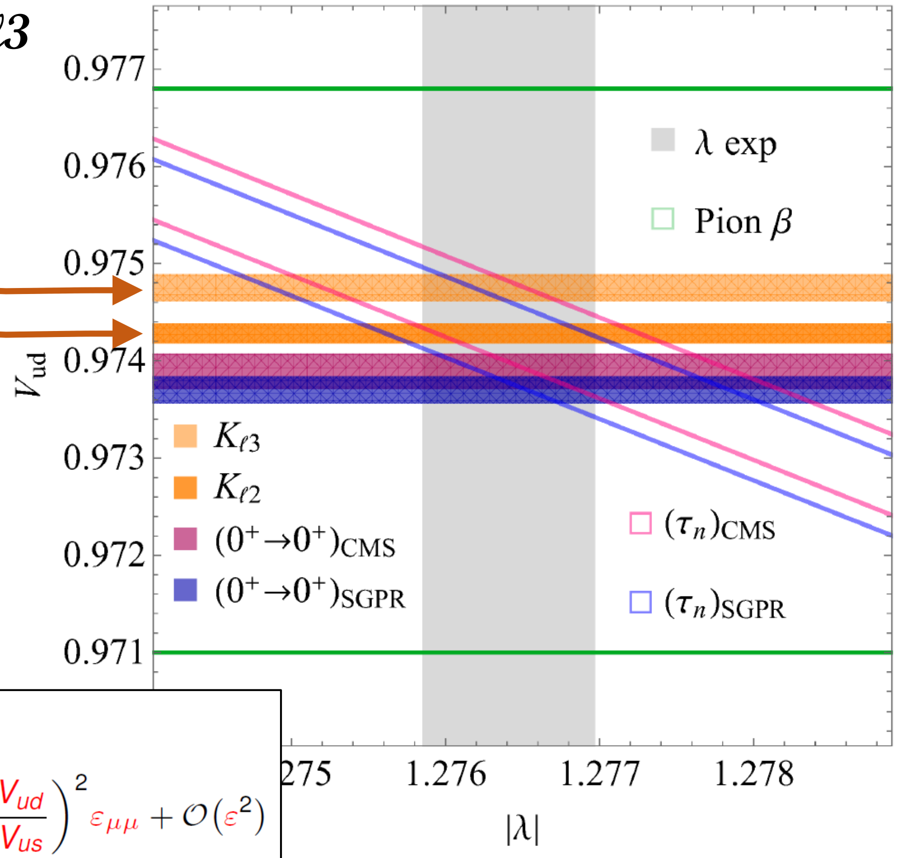
See also A. Crivellin /arxiv.org/pdf/2207.02507.pdf

A Physics Case suggesting they might be related !

Start by *assuming* unitarity. The V_{ud} you get by taking: $|V_{ud}|^2 = 1 - |V_{us}|^2$

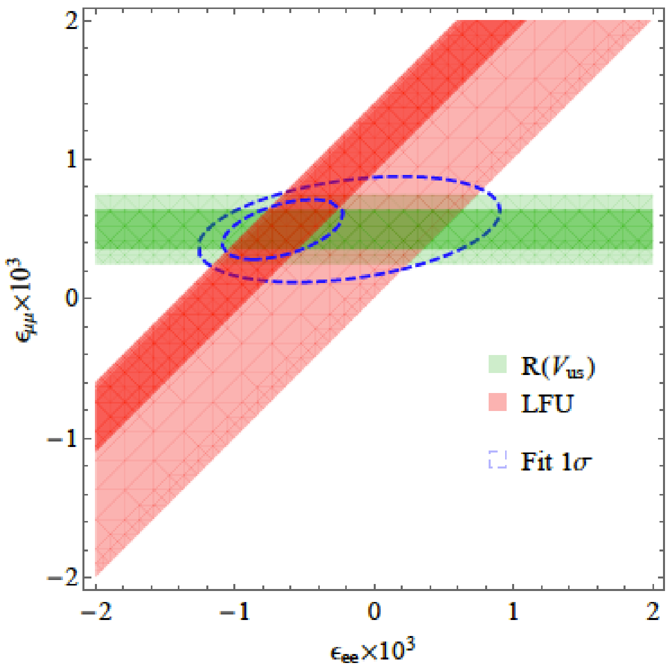
Is different for what is implied by using $K_{\ell 2}$ and $K_{\ell 3}$ than the "standard" V_{ud} from beta decay



Is this tension a sign of LFUV ??

Modifies Fermi constant in **muon decay**

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



Construct ratio Crivellin, MH 2020

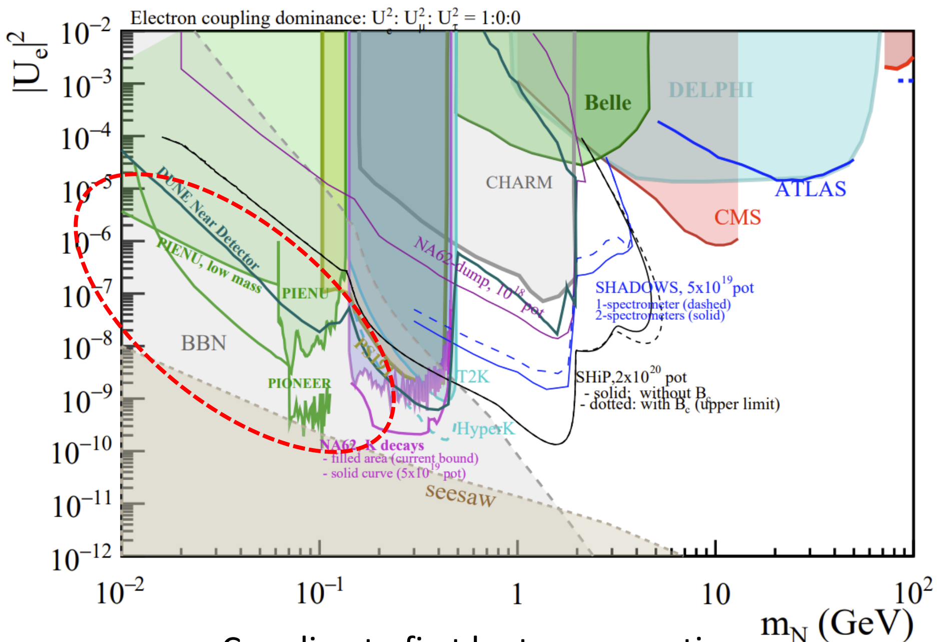
$$R(V_{us}) \equiv \frac{V_{us}^{K_{\mu 2}}}{V_{us}^{\beta}} \equiv \frac{V_{us}^{K_{\mu 2}}}{\sqrt{1-(V_{ud}^{\beta})^2-|V_{ub}|^2}} = 1 - \left(\frac{V_{ud}}{V_{us}}\right)^2 \varepsilon_{\mu\mu} + \mathcal{O}(\varepsilon^2)$$

↪ LFUV effect enhanced by $(V_{ud}/V_{us})^2 \sim 20$!

Crivellin-Hoferichter 2002.07184, PRL

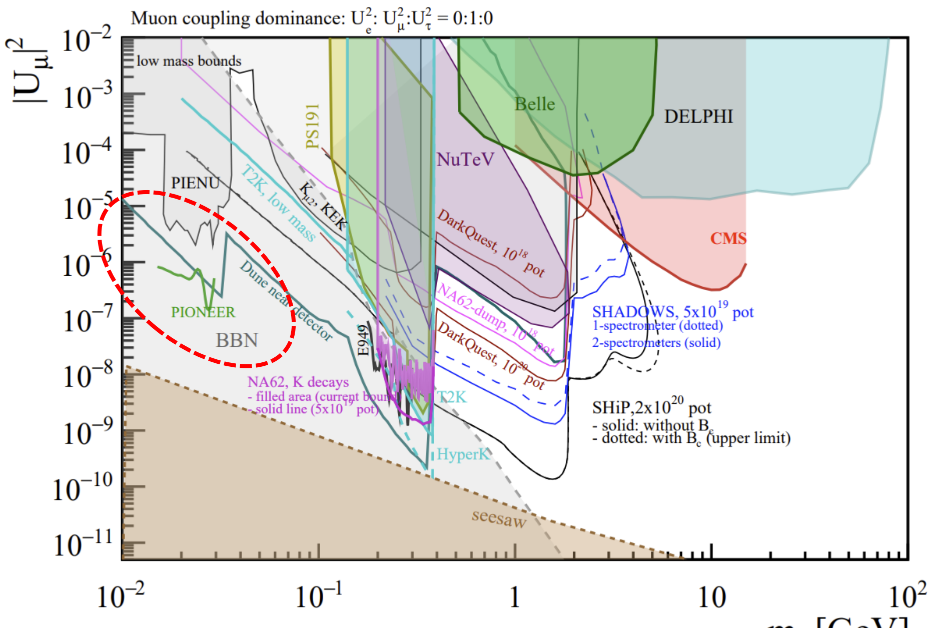
Physics Case 3: Exotic physics search:

Example: Heavy Neutral Lepton Limits (PIONEER proposal)



Coupling to first lepton generation

Figure 26: Heavy Neutral Leptons with coupling to the first lepton generation. Filled areas are existing bounds from: PS191 [31], CHARM [576], PIENU (peak searches [24] and bounds at low masses [38, 39, 566]), NA62 (K_{eN}) [28], T2K [36], Belle [577]; DELPHI [544], ATLAS [327] and CMS [340]. Colored curves are projections from: NA62-dump [405], NA62 K^+ decays (extrapolation obtained by the Collaboration based on [28]), PIONEER [565], SHADOWS [519], DarkQuest [561], SHiP [448], DUNE near detector (projections based on methods developed in [539]), and Hyper-K (projections based on [36]). The BBN bounds are from [445] and heavily depend on the model assumptions (hence they should be considered indicative). The seesaw bound is computed under the hypothesis of two HNLs mixing with active neutrinos.



Coupling to second lepton generation

Figure 27: Heavy Neutral Leptons with coupling to the second lepton generation. Filled areas are existing bounds from: PS191 [31], CHARM [576], NA62 ($K_{\mu N}$) [29], T2K [36], E949 [23], Belle [577]; DELPHI [544], and CMS [340]. The "low mass bounds" label refers to a set of results obtained from π and K decays, as detailed in Ref. [39], namely a PIENU result [25] and $K_{\mu 2}$ results at KEK [22, 578]. Colored curves are projections from: NA62-dump [405], NA62 K^+ decays (projections obtained by the Collaboration based on [29]), SHADOWS [519], DarkQuest [561], PIONEER [565], SHiP [448], DUNE near detector (projections based on methods developed in [539]), Hyper-K (projections based on [36]), T2K low mass [514]. The BBN bounds are from [445] and heavily depend on the model assumptions (hence should be considered only indicative). The seesaw bounds are computed under the hypothesis of two HNLs mixing with active neutrinos.

The Present and Future Status of Heavy Neutral Leptons
Abdullahi et al
Contribution to Snowmass

https://arxiv.org/pdf/2203.08039.pdf

A Rapidly Developing Rare Pion Decay Collaboration

Snowmass 2021

Testing Lepton Flavor Universality and CKM Unitarity with Rare Pion Decays in the PIONEER experiment

arXiv:2203.05505v1 [hep-ex] 10 Mar 2022

PSI *Approved* Proposal Jan. 2022

PSI Ring Cyclotron Proposal R-22-01.1
PIONEER: Studies of Rare Pion Decays

arXiv:2203.01981v2 [hep-ex] 8 Mar 2022

Snowmass 2022 White Paper

Testing Lepton Flavor Universality and CKM Unitarity with Rare Pion Decays in the PIONEER experiment

arXiv:2203.05505v1 [hep-ex] 10 Mar 2022

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First Beam Tests May 2022

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PIONEER Experiment
Documents

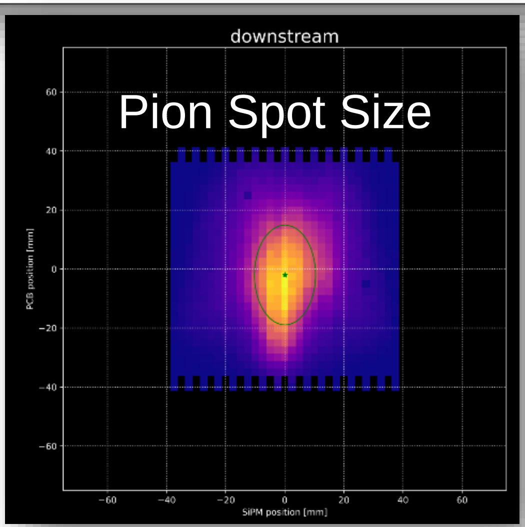
PIONEER Experiment

The PIONEER experiment is a next generation experiment to measure the charged-pion branching ratio to electrons vs. muons. This measurement, which is highly sensitive to new physics at high mass scales, has broad implications for the universality of lepton interactions. Using state-of-the-art instrumentation - learning from the previous generation PEN and PiENu measurements - and a new high-intensity beam, measurements of the pion decay to electrons vs. muons and pion beta decay will improve on previous studies by an order of magnitude to the 10^{-4} precision level. A disagreement with the theoretical Standard Model(SM) prediction, which has a remarkable precision at the same level, would unambiguously imply new physics beyond the SM. Further motivation comes from the muon g-2 discrepancy and intriguing hints for lepton flavor violation in the B-meson sector. Exotic rare decays involving sterile neutrinos and axions will also be searched for with unprecedented sensitivity.

Simulations of detector geometry are well underway. The design of the experimental apparatus, which consists of an 80 cm sphere of liquid Xenon, surrounding a beampipe and active target, is being pursued by various groups in Canada, China, Germany, Japan, Mexico, Switzerland, and the USA.

The best reference to the experiment is arxiv:2203.01981

The collaboration will have the first two weeks of beam-time in May/June 2022 at the PIE5 beamline at PSI.

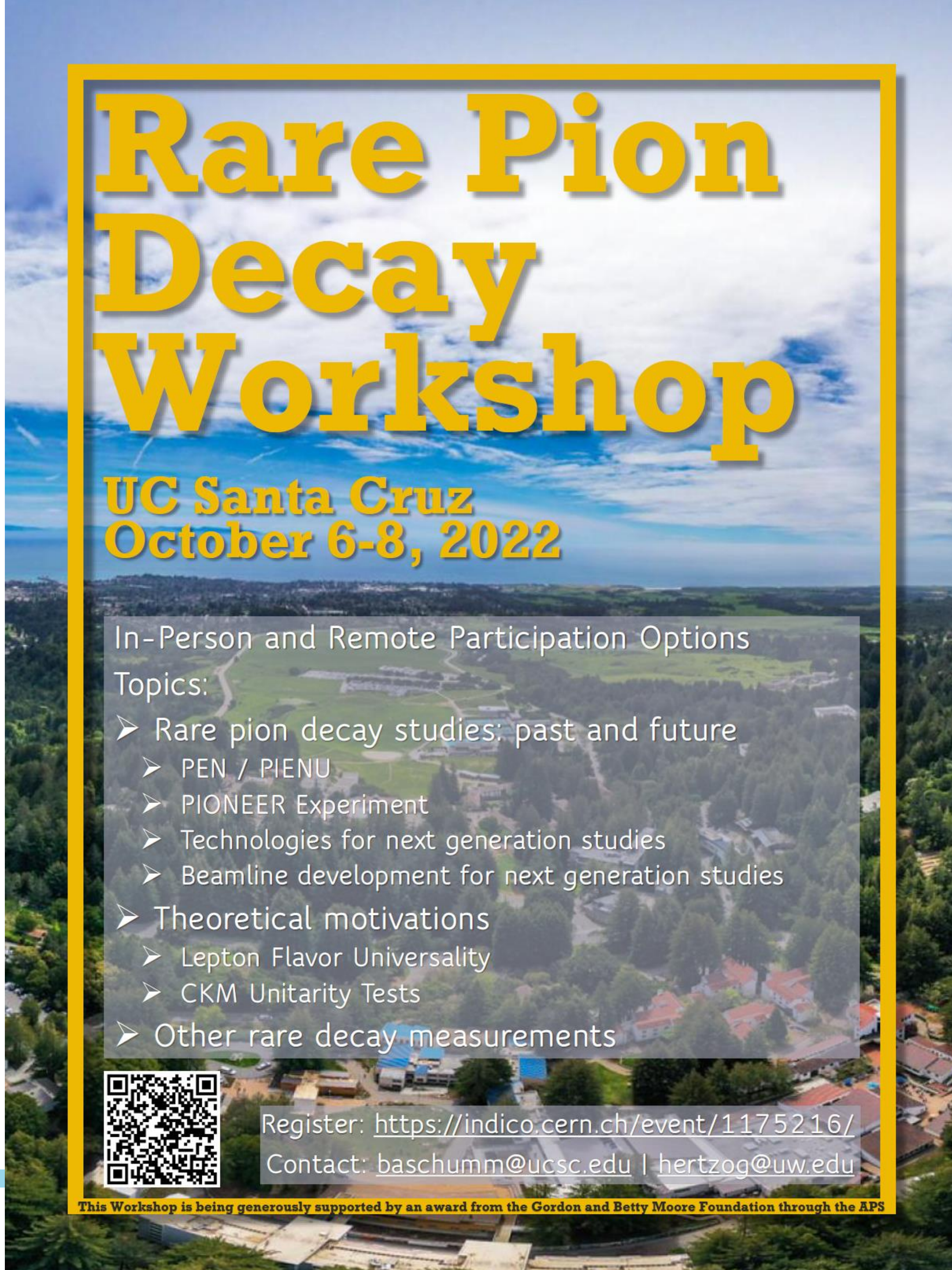


Workshop Oct 6-8, 2022

- Rare Pion Decay Workshop at UC Santa Cruz
  - Theory talks
  - Experimental talks
  - A chance to develop and design

- If you are interested in PIONEER, please reach out to me (hertzog@uw.edu)

Link to workshop →



The basics of pion decay and the challenges

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

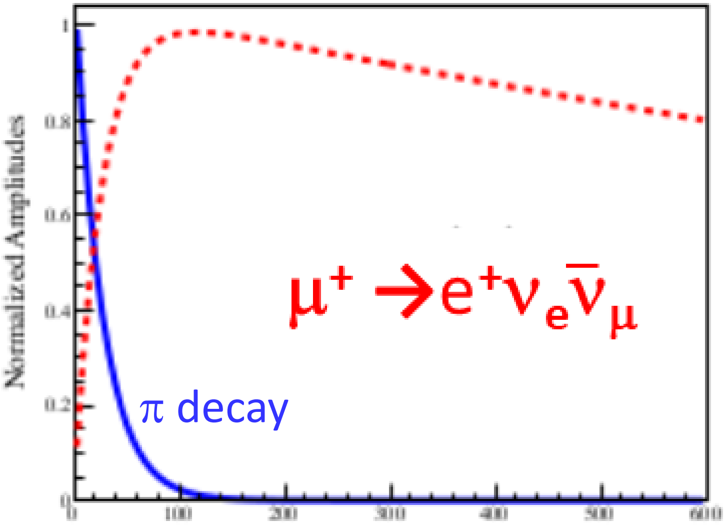
Reminders:

Pion lifetime: 26 ns

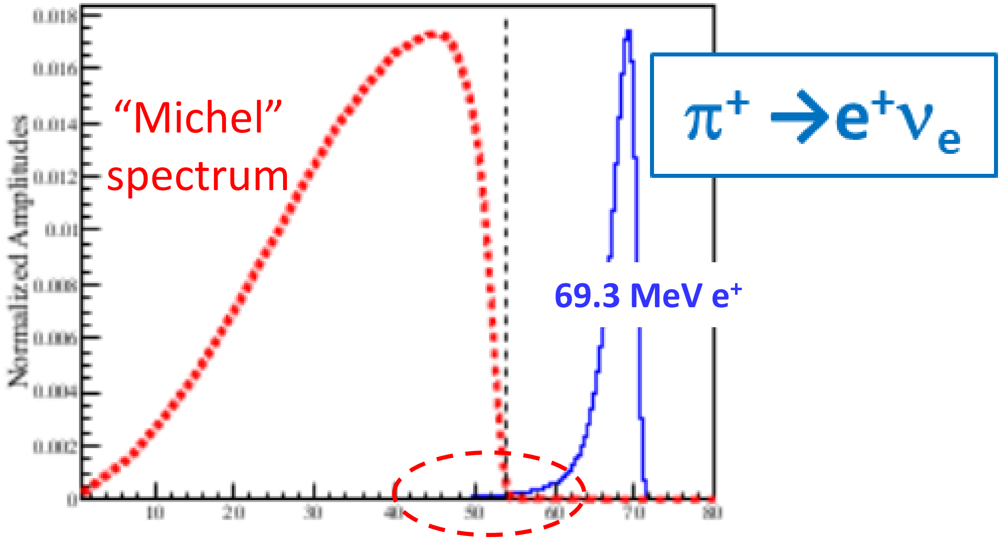
Muon lifetime: 2197 ns

Pion mass: 139.6 MeV

Muon mass: 105.7 MeV



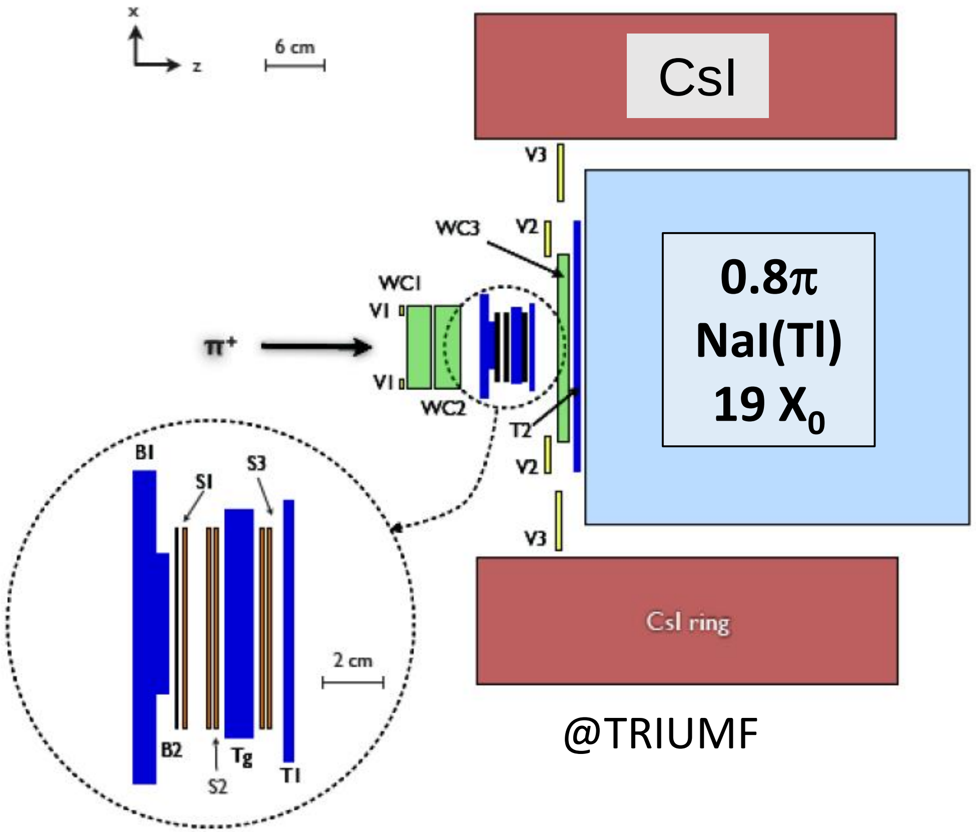
Timing



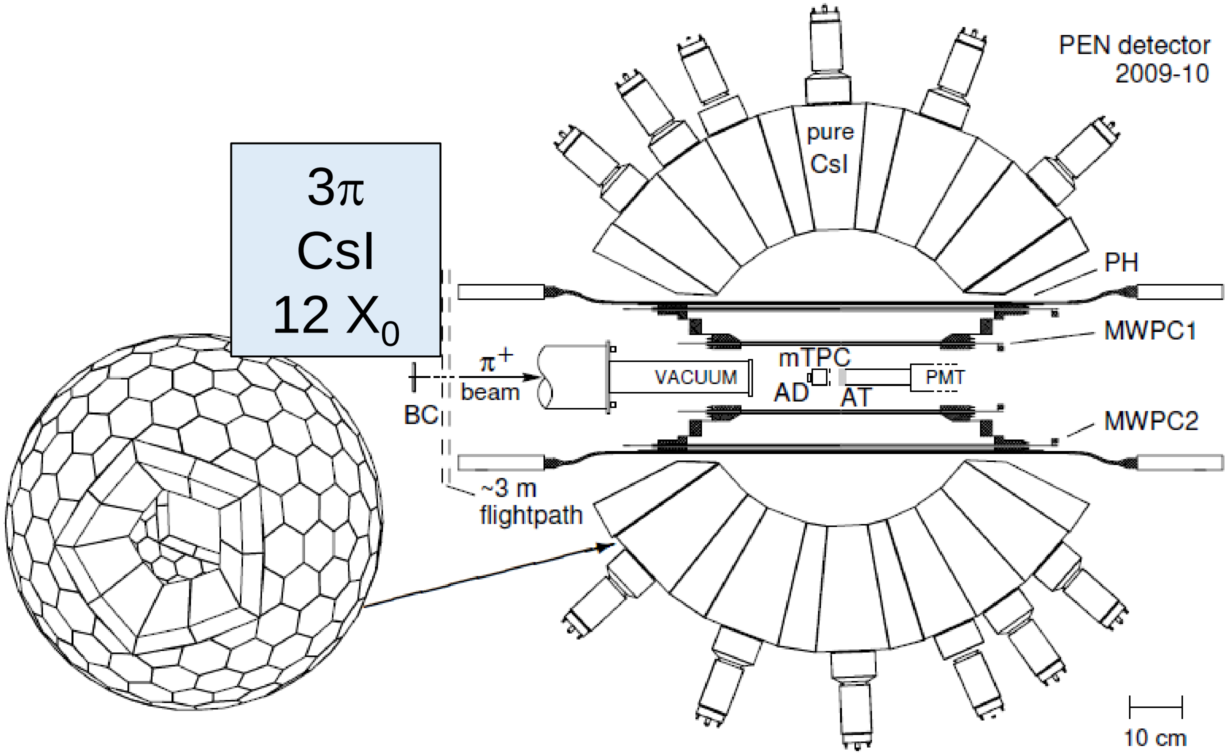
e^+ Energy

Two (rather different) Pion Decay Experiments: PIENU and PEN/PIBETA

Both took data a while ago but have (known) challenges to overcome before final results



@TRIUMF



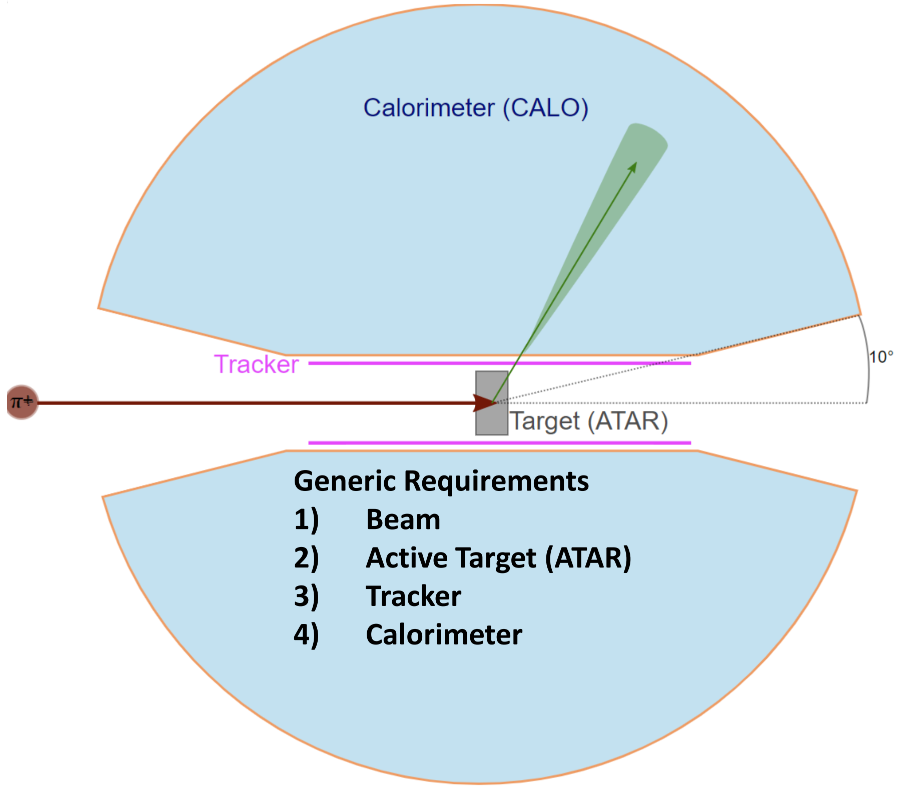
@PSI

- NaI slow, but excellent resolution
- Single large crystal but shower leakage depends on angle changing resolution and tail fraction
- Small solid angle

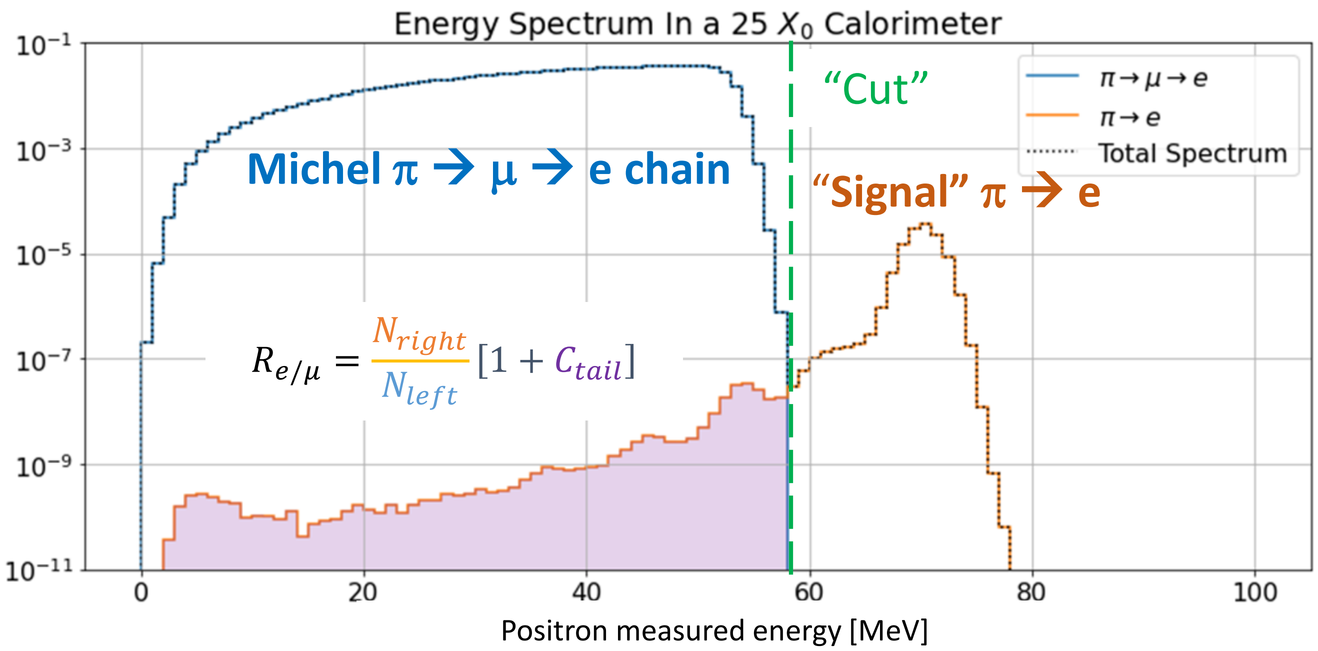
- Good geometry but calorimeter depth of $12X_0$ too small to resolve tail under muon spectrum.

Generic experiment: count e⁺ from stopped π⁺ and sort:

$$\frac{N(\pi \to e\nu)}{N(\pi \to \mu\nu)} \to \frac{N(\pi \to e\nu)}{N(\pi \to \mu \to e\nu\nu)}$$



Generic Requirements
1) **Beam**
2) **Active Target (ATAR)**
3) **Tracker**
4) **Calorimeter**

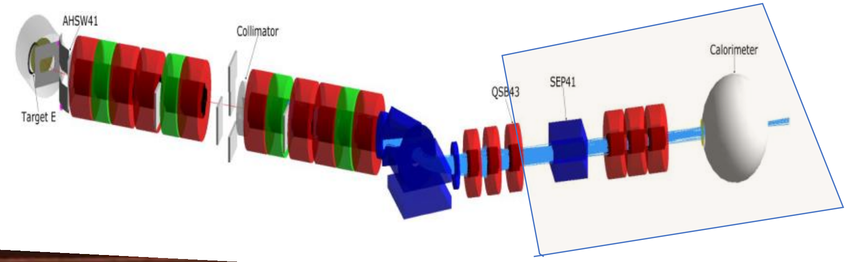


The mono-energetic 69 MeV "signal" spectrum is determined from
- Calo Resolution – better sharpens the "right/left" cut boundary
- Calo Depth – deeper minimizes the tail

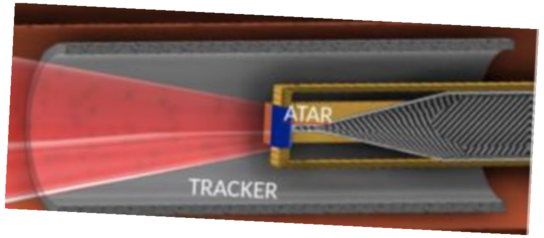
The key to success: minimize and measure the tail

Q: How can you possibly measure that tail under the Michel spectrum?

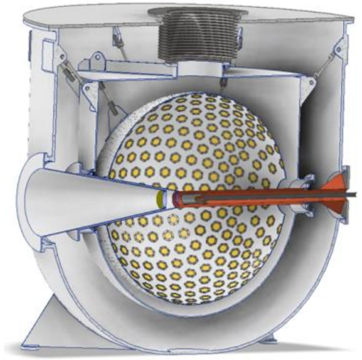
Technologies being explored



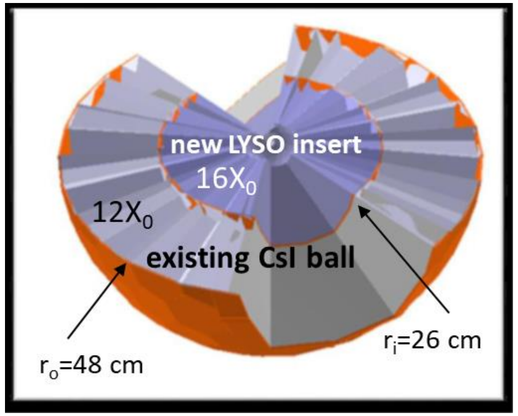
- World's most intense low-energy pion beamline at PSI



- Active, segmented target (ATAR) using AC LGADs



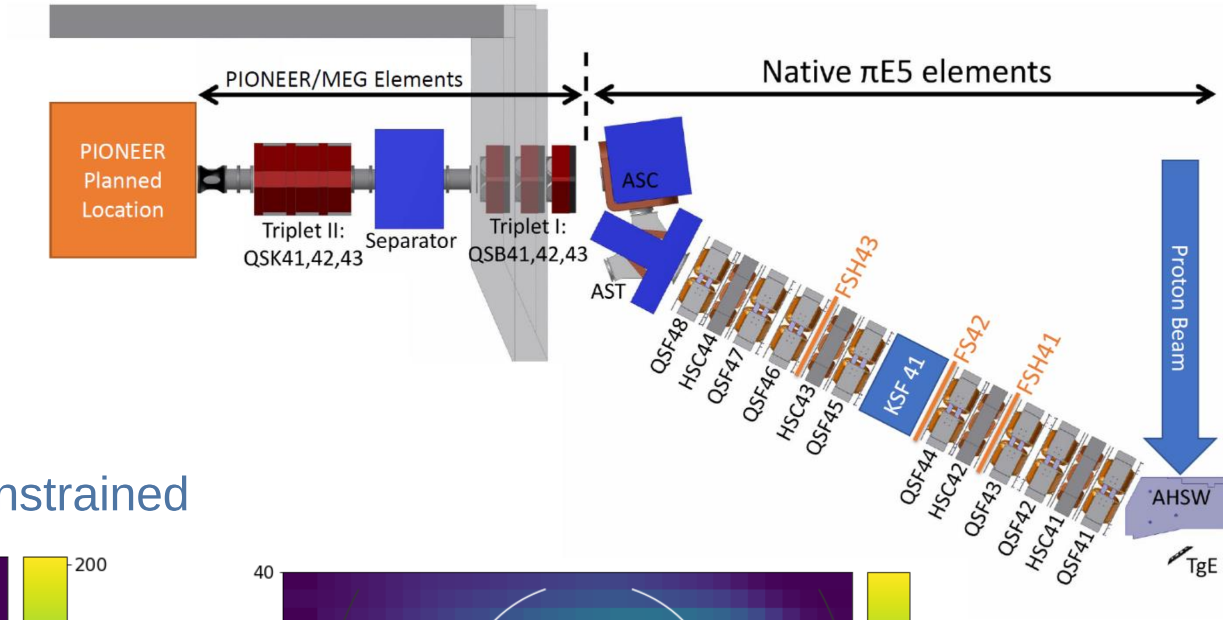
- Fast, deep, high-resolution calorimeter options
  - LXe following the example of the MEG II collaboration
  - Hybrid LYSO + CsI (existing) crystal combination



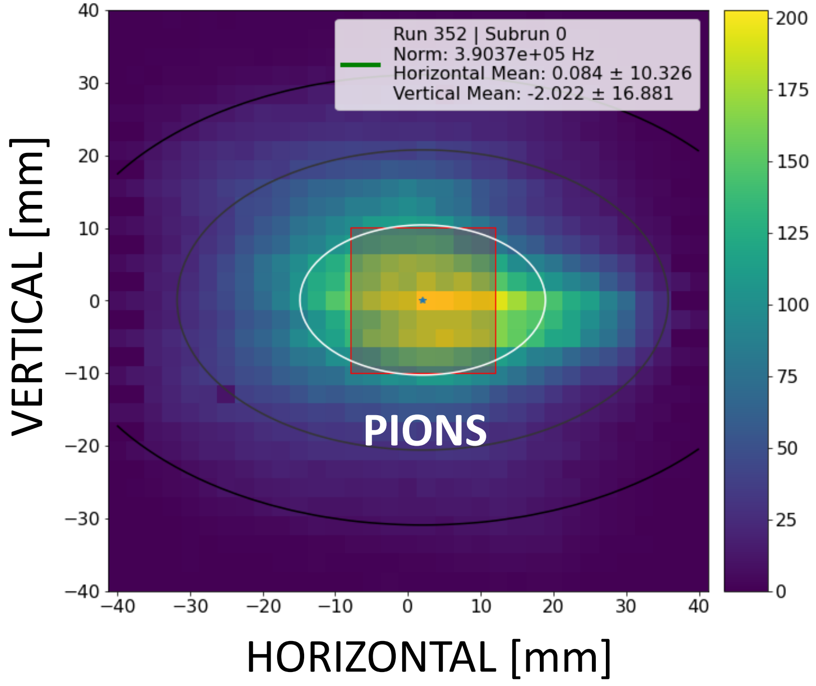
- And of course, very fast triggering, DAQ, high res digitization, etc.

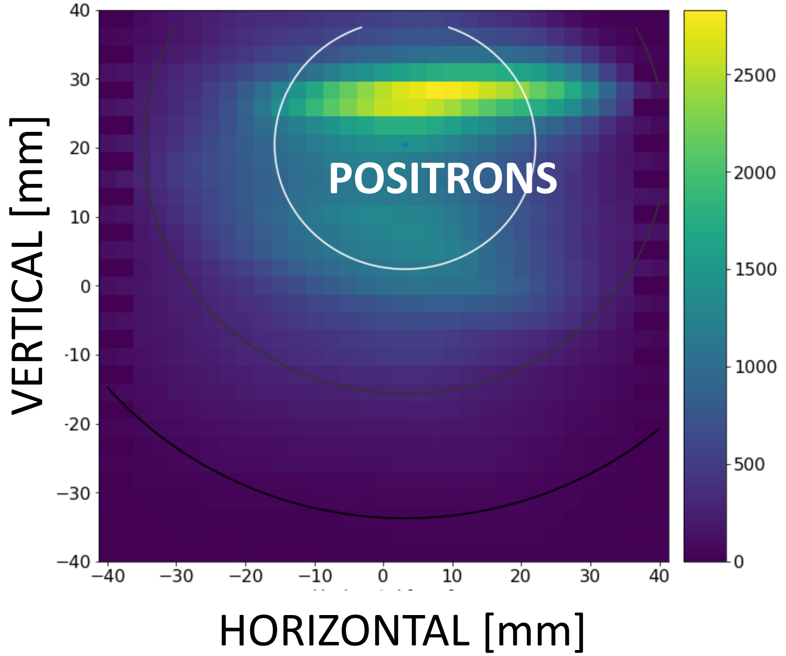
Use World's Brightest Stopped Pion Beam @ PSI: piE5

- Specifications (for Phase I) and first measurements
  - ✅ p = 55-70 MeV/c
  - ✅ σ_x, σ_y, < 10 mm and small divergence
  - 🚧 dp/p < 2% for π stop in 3±0.5 mm silicon
  - ✅ > 300 kHz stopping rate in target
  - 🚧 Separation of π / μ / e in beamline

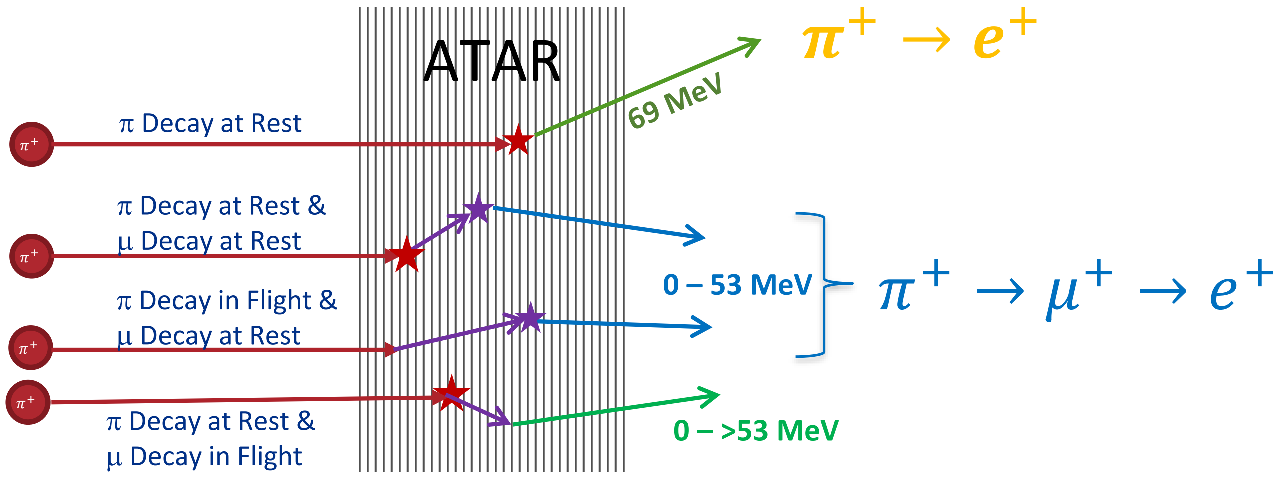


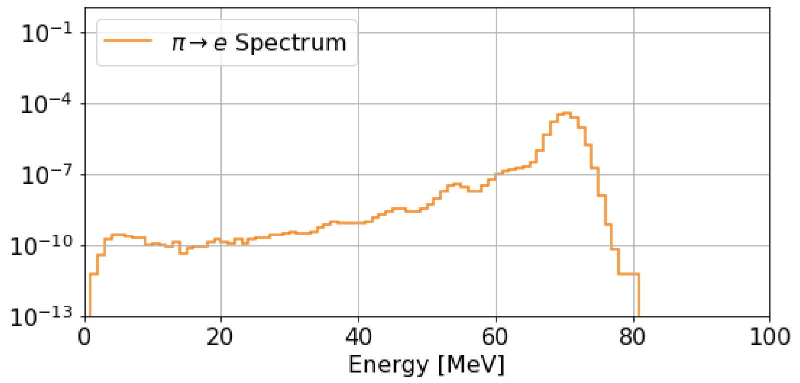
- Going forward
  - Much to do to model and minimize spot size
  - Must add an intermediate focus, but space is constrained

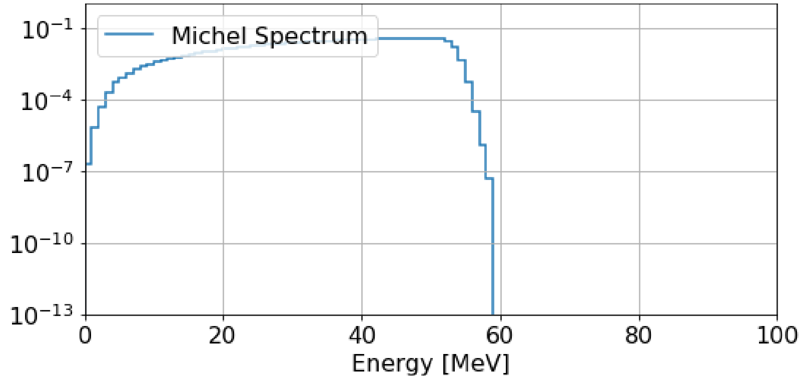


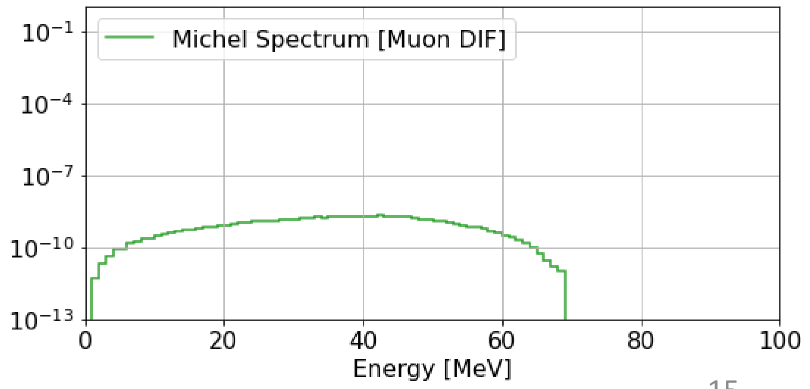


What forms the spectrum and the background

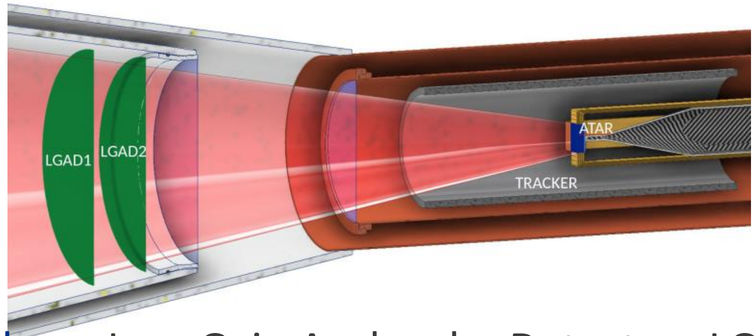




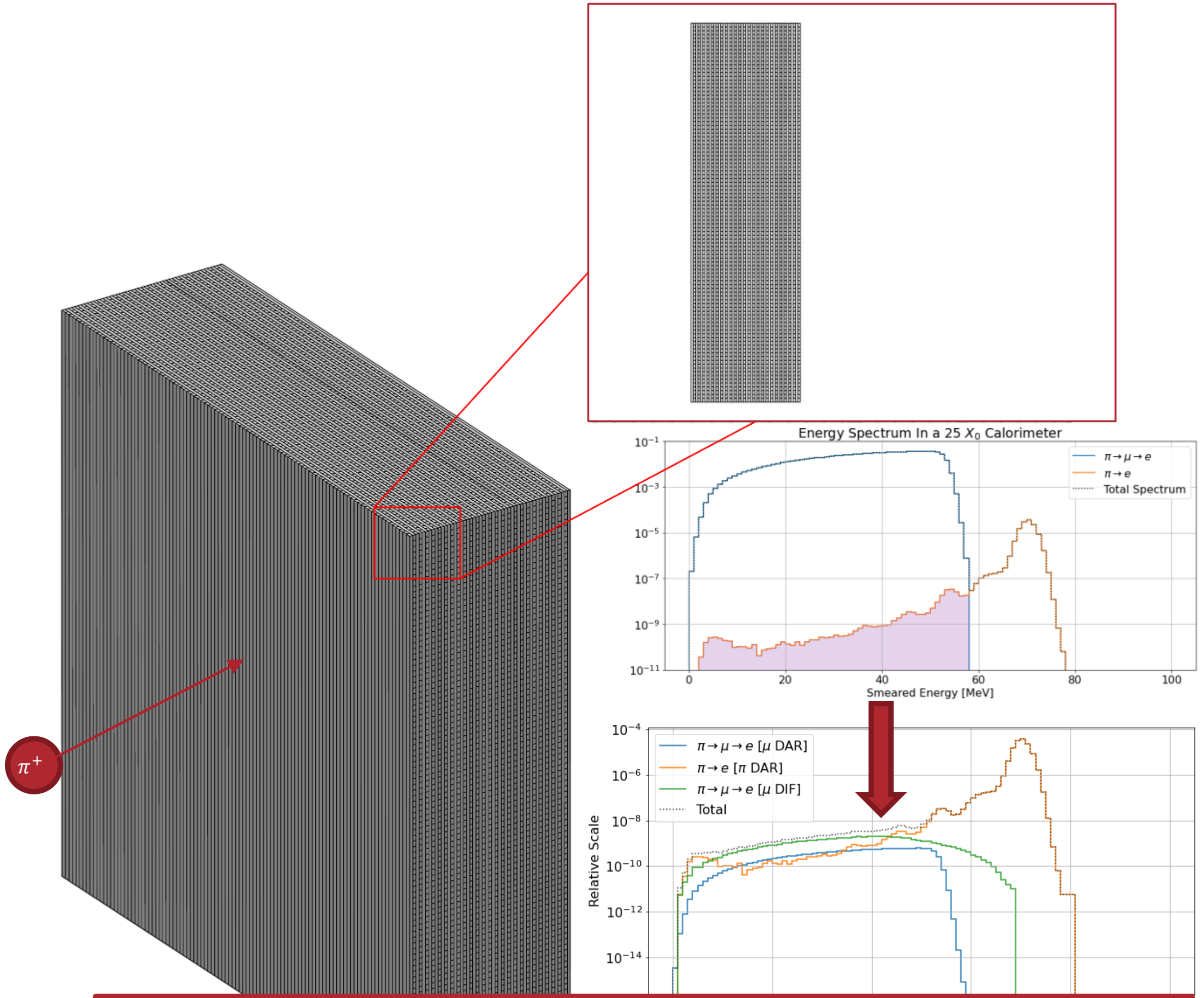


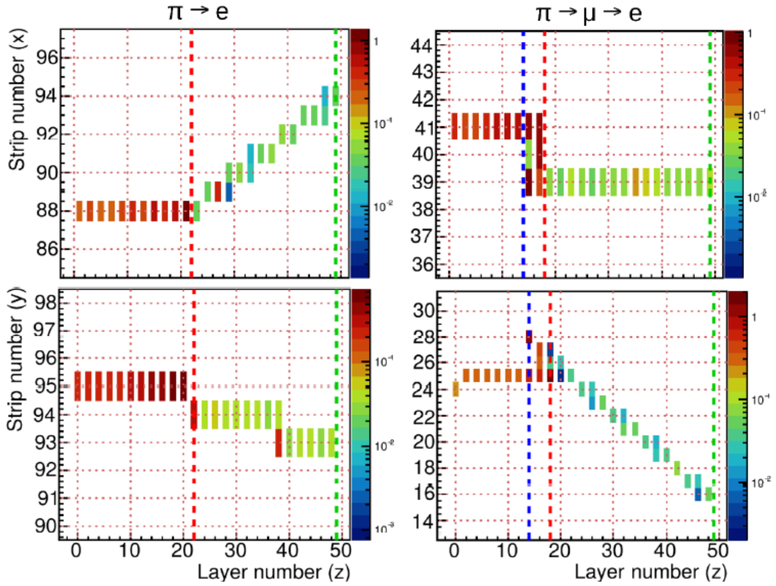


To measure the Tail



- **Technology:** Low Gain Avalanche Detectors LGADS
  - Silicon detector
    - Thin, 120 um layers
    - Modest gain (10-50), time res < 100 ps with full charge collection ~ 2 ns
    - Intense R&D at UCSC (talk ongoing in parallel now)



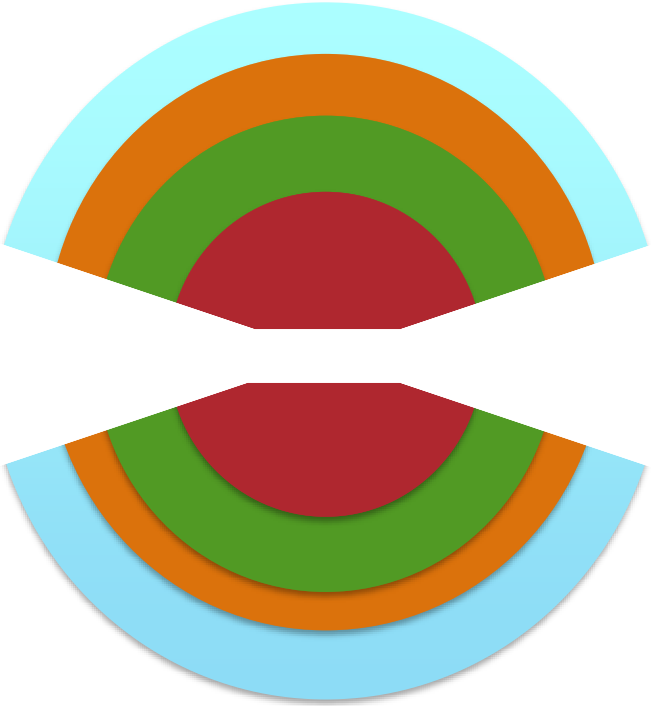


A trigger to suppress $\pi \to \mu$ (and other backgrounds) to measure tail

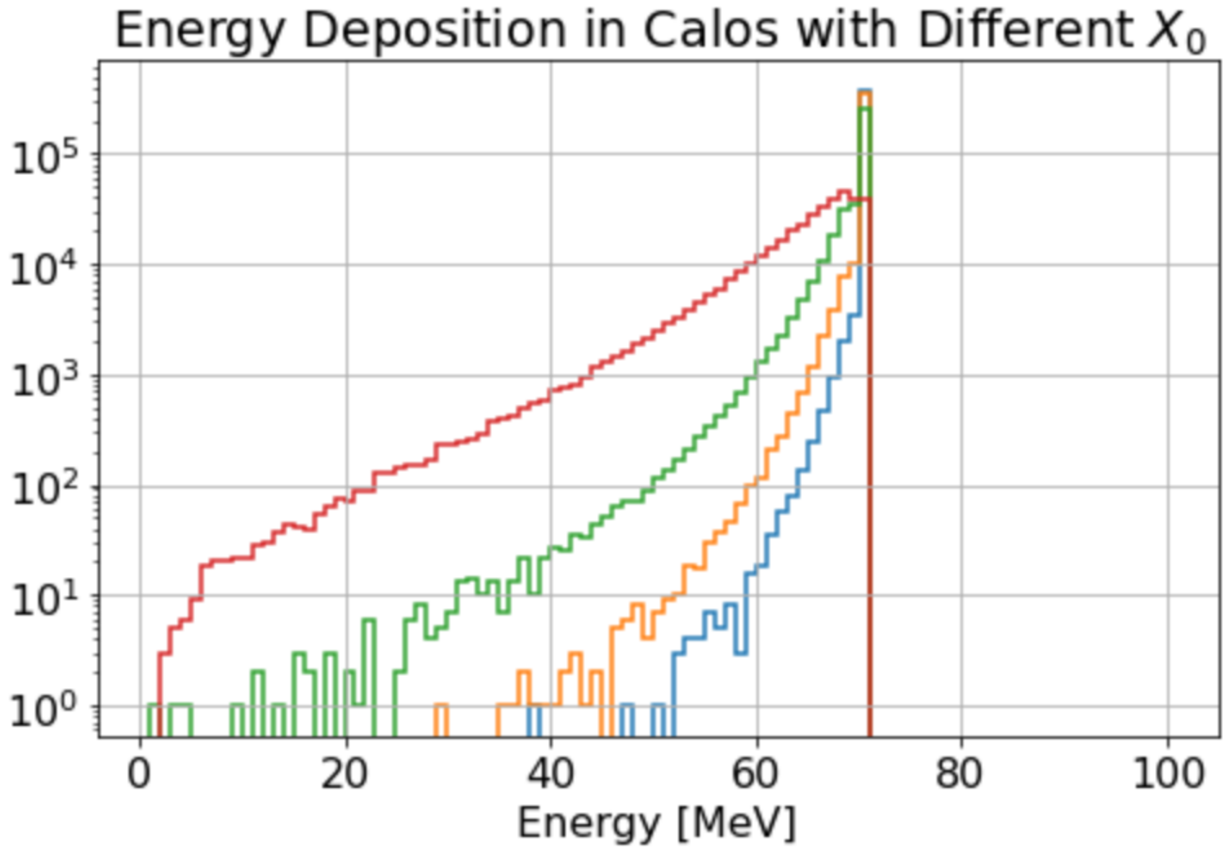
See Snowmass cont.: https://arxiv.org/pdf/2203.13900.pdf

To suppress the Tail

- Calorimeter generic specifications
  i. 3π coverage, high uniformity
  ii. Resolution <2% peak resolution
  iii. Depth: ~25 radiation length to suppress tail



Calorimeter of different “depths” by indicated by concentric sphere colors



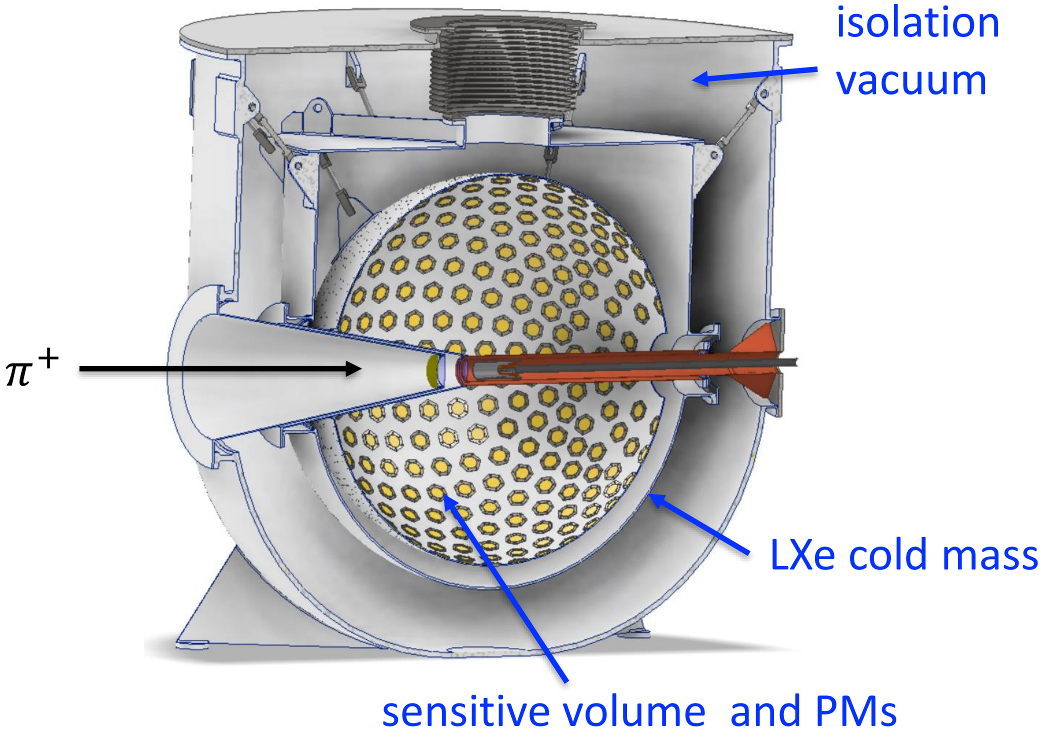
Increase X_0 in highly uniform CALO to suppress tail

LXe Calorimeter is Baseline Design

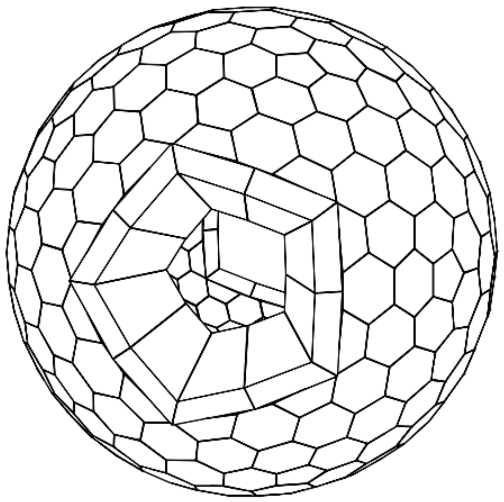
- Based on MEG II Experience
  i. Fast: sub-ns timing, ~40 ns decay
  ii. Resolution <2% peak resolution

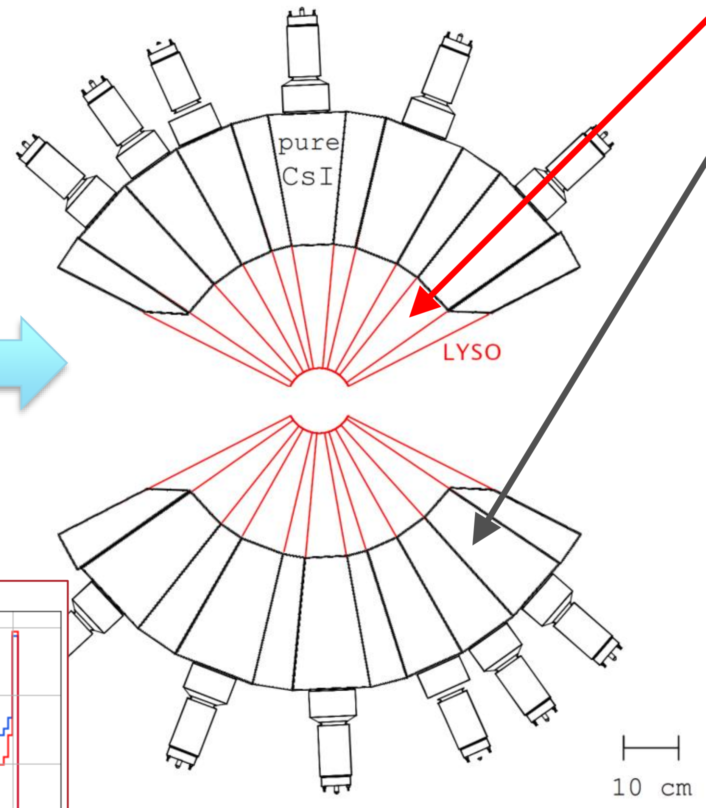
- LXe scintillating challenges
  – Optical segmentation
  – VUV Photosensors

- Conceptual design
  – 9 t LXe sphere in vacuum isolated dewar
  – ~1000 VUV sensitive PMT readout
  – Possibly introduce segmentation

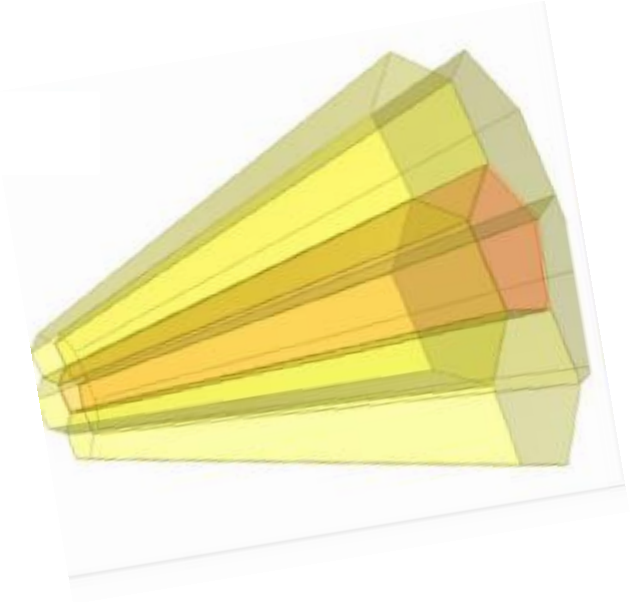


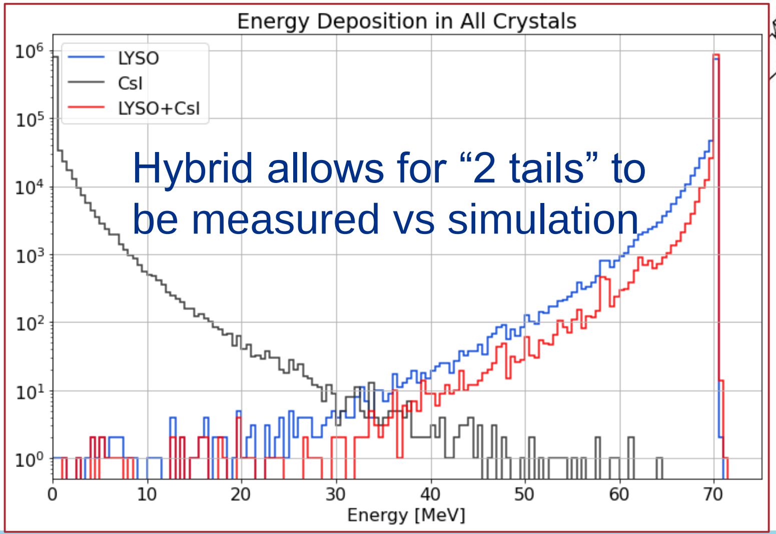
Crystal CALO alternative: New LYSO inner layer, matched to existing CsI (PEN) outer





New LYSO ($16\ X_0$)
+ PEN CsI xtals ($12\ X_0$)





- Fast, segmented, compact, "cheaper"
- Is resolution good enough?
- LYSO for HEP not yet demonstrated, given its promise and extensive use in PET

Summary / Conclusions

- Lots of exciting physics to be explored with a Next-Gen Pion Decay Experiment
  - Lepton Flavor Universality Violation – possible connected to the “many” existing flavor anomalies
    - B decays; CKM, issues, Muon g-2, …
  - Measurement of Pion Beta Decay; ratio with kaon decays gives important slope in V_{ud} vs V_{us} plane
  - Exotic physics searches will come out automatically from these precision measurements
    - Sterile neutrinos, ALPs, etc.

  - PIONEER is APPROVED and is a growing international collaboration of physicists from broad communities in HEP, NP, instrumentation, theory
  - To be successful it will require:
    - State of the art active target with 4D tracking
    - A very high resolution, fast, and deep EM calorimeter
    - An intense stopping pion beamline
    - State of the art triggering, digitization, DAQ, and offline
    - Simulations, simulations, etc.

LINKS!

  - This is an exciting time with a new collaboration forming and a “semi-blank slate” to design a new experiment together

Strategy for 10^{-4} precision experiment

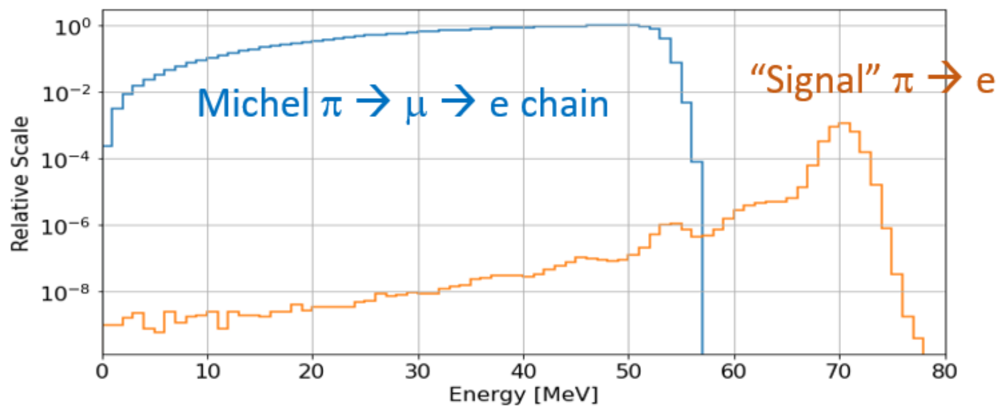
$$\sigma_{stat} = \sigma_{sys} = 0.7 \times 10^{-4}$$

- Analysis

$$R_{e/\mu} = \frac{\pi \to e\nu(\gamma)}{\pi \to \mu\nu(\gamma)}$$

  - fit high/low energy e^+ time distributions
    - $\pi - e$
    - $\pi - \mu - e$
    - background, pileup, etc

normalization & background



- Statistics
  - 2x10⁸ $\pi \to e\nu$ events in 2 years with 3×10^5 π/s beam

- Systematic improvements
  - intense, high quality π^+ beam
  - active target with key new ideas and technology
  - calorimeter: 3π, $25X_0$, high res., fast

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**	**$\lesssim$ 0.01**

CALO response with photonuclear physics included

1.5% Energy Resolution