Lepton Flavor Universality

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Reference: D.B., A. Crivillen, V. Cirigliano, and G. Inguglia, 2111.05338 [hep-ph], Ann. Rev. Nucl. Part. Sci. (to be pub.)

The University of British Columbia, Point Grey campus, and TRIUMF are located on the traditional, ancestral and unceded territory of the xwməθkwəy̓əm (Musqueam) people.

The Flavor Puzzle

Quarks

u	c	t
d	s	b

Leptons

e	μ	τ
ν_e	ν_μ	ν_τ

Experiment/observations (way) ahead of theory.

Unexplained observations (no theory of flavor)

- Three ("identical") generations; universal interactions (why = 3? <? >?)
- Huge mass differences between and within the generations
  Exceptionally small neutrino mass
- CP violation (at least in the quark sector)
- Remarkable symmetry between leptons and quarks (GUT, scale?)

How to Delve into the Flavor Puzzle?

Experiments

- Particle properties: dipole moments
- Lepton Flavor Universality (LFU) tests: compare ratios of rates "$X \to \ell_i / X \to \ell_j$"
- Non-SM flavor violation searches: $\ell_i \to \ell_j \gamma$

Theories – some may distinguish among flavors

- Short Distance effects
  - Distinct W-ℓ-ν couplings
  - Lepto-quarks
  - …
- Compositeness
- Heavy neutral leptons (confuse experimental tests)

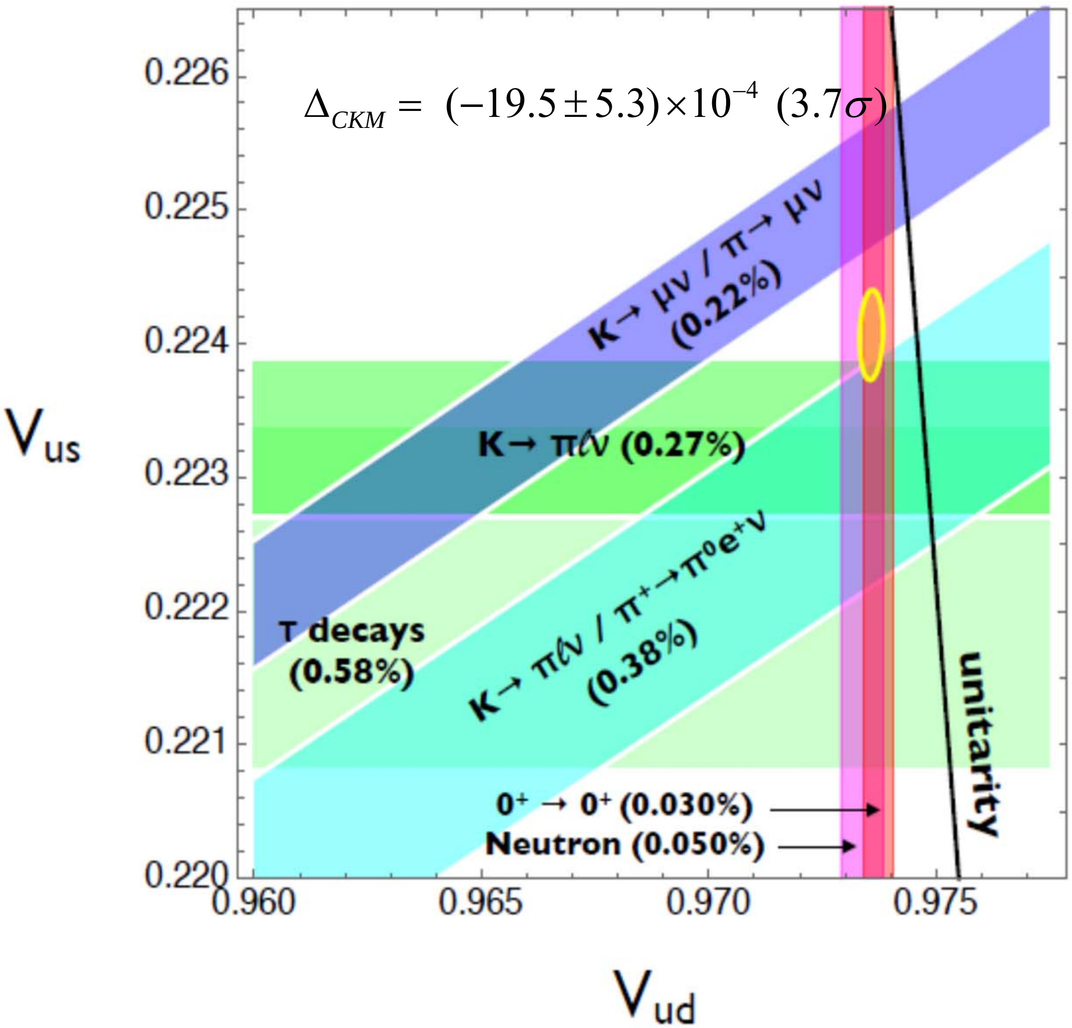
Current Flavor Tensions in the SM

Several high precision measurements of accurately predicted SM processes show possible indications of violating Lepton Flavor Universality and CKM unitarity.

- Muon g-2 (4.2 σ)
  Deviation from theory -- new physics?
- B Decay ratios: $B \rightarrow D^*\tau\nu / B \rightarrow D^*\mu\nu$; $B \rightarrow K^*\mu\mu / B \rightarrow K^*ee$
  $R(D^{(*)})$, $R(K^*)$, $R(K)$: (2-4 σ);
  O(10%) deviations from universality.
  Both heavy quarks and leptons involved!
- CKM unitarity tests (3.7 $\boldsymbol{\sigma}$): β and K decays
  May be related to LFUV.
- Lepton Flavor Universality in agreement with the SM at O(**10^{-3}**) level in π, τ and K decays.

CKM Unitarity

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



Connection to LFU

V_{ud} from β-decay & n-decay

G_F^μ Fermi const. from μ decay used to extract V_{ud}

V_{us} from K_{l3} and τ decay

$\frac{V_{us}}{V_{ud}}$ from $\frac{K_{\mu 2}}{\pi_{\mu 2}}$; also $\frac{K_{l3}}{\pi_{l3}}$

Agreement is poor; uncertainties from experiment and theory.

Deviations could be explained by small corrections ε_{ij} to W-l-ν couplings*

D.B., A. Crivellin, V. Cirigliano, and G. Inguglia, 2111.05338

*Crivellin, Hoferichter, PRL 125, 111801 (2020)

Hoferichter and Crivellin (2020)

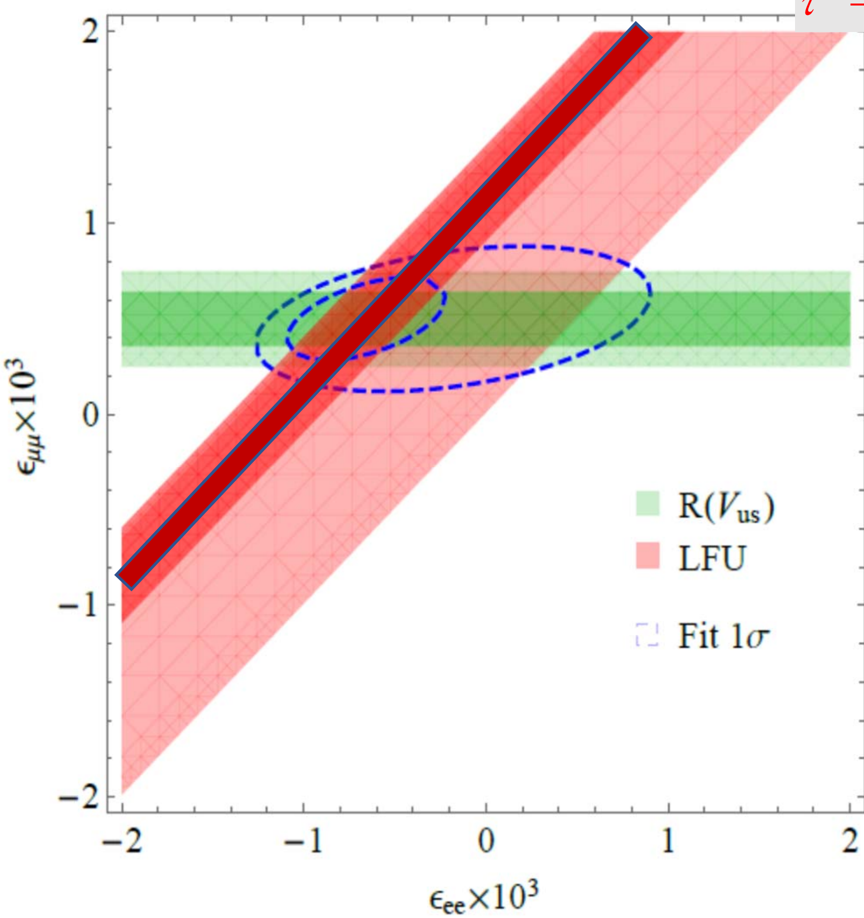
Connecting CKM Unitarity and Lepton Flavor Universality

Modified $W-l-\nu$ Couplings from μ decay; $G_F = G_F^{\mathcal{L}}(1+\varepsilon_{ee}+\varepsilon_{\mu\mu})$

input to V_{ud} from Super-allowed β decay: $V_{ud}^{\beta} = V_{ud}^{\mathcal{L}}(1-\varepsilon_{\mu\mu})$

LFU $\pi^+ \to e^+\nu / \pi^+ \to \mu^+\nu$

$\tau^+ \to e^+\nu\nu / \tau^+ \to \mu^+\nu\nu$



CKM

Charged Lepton Flavor Universality in π Decay

$$R_{e/\mu}^{theory} = \frac{\Gamma\left(\pi \to e\nu(\gamma)\right)}{\Gamma\left(\pi \to \mu\nu(\gamma)\right)} = \left(1.23524 \pm 0.00015\right) x10^{-4}$$ (±0.012%)

Marciano/Sirlin → Cirigliano

Possibly the most accurately calculated decay process involving hadrons.

Current Result (PDG): $R_{e/\mu}^{\exp} = 1.2327 \pm 0.0023 x10^{-4}$ (±0.19%)

PI E NU

$$\frac{A_\mu}{A_e} = 1.0010 \pm 0.0009$$ (±0.09%)

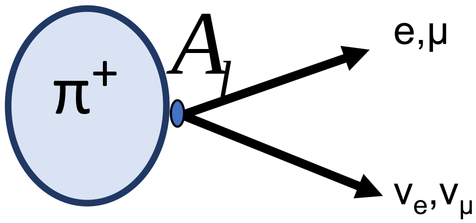
GOALS: PEN, PIENU ($R_{e/\mu}^{\exp} \leq \pm 0.1\%$); PIONEER ($\pm 0.01\%$)

Experiments are an order of magnitude less precise than theory.

μ-e Flavor Universality tested at O(10^{-3})

Light meson and Tau experiments compare SM expectations ($A_e=A_\mu=A_\tau$)

$$A_l = -2\sqrt{2}G_F V_{ud}$$

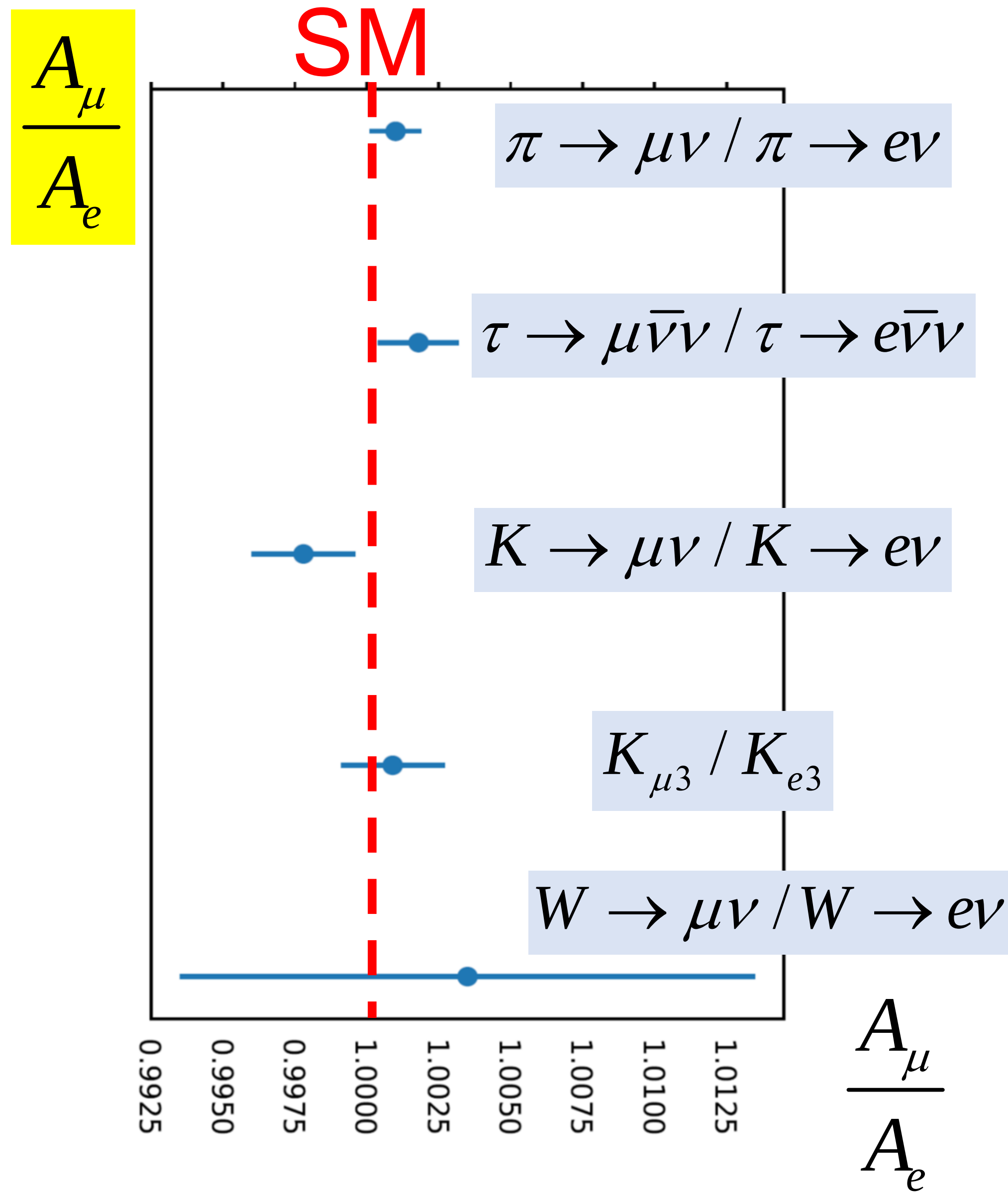


$$\left(\frac{A_\mu}{A_e}\right)_\pi = 1.0010 \pm 0.0009$$

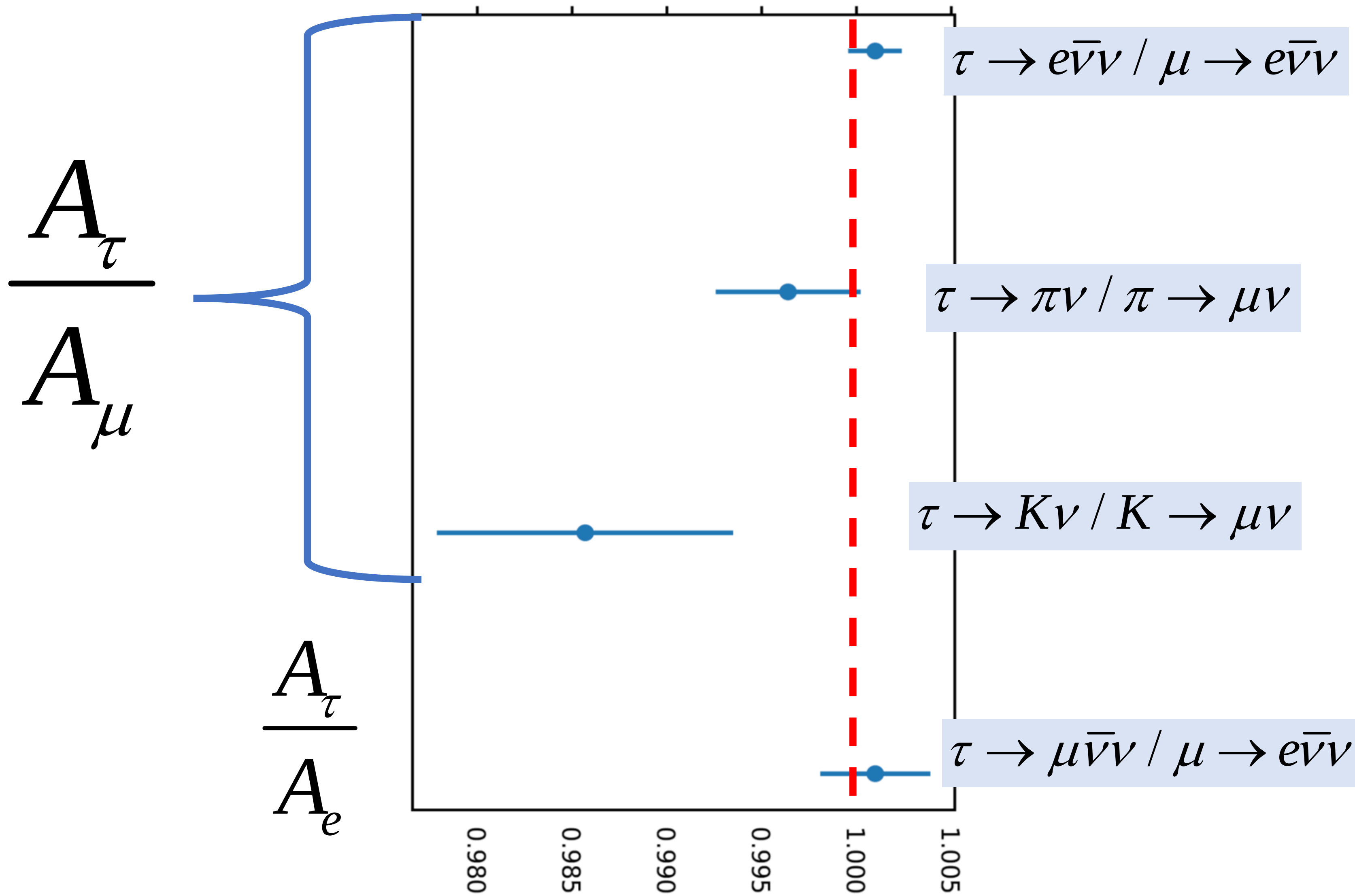
$$\left(\frac{A_\mu}{A_e}\right)_\tau = 0.9918 \pm 0.0014$$

$$\left(\frac{A_\mu}{A_e}\right)_{Kl2} = 0.9978 \pm 0.0018$$

$$\left(\frac{A_\mu}{A_e}\right)_{Kl3} = 1.0009 \pm 0.0018$$

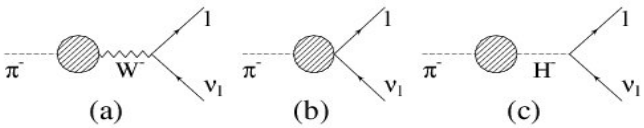


τ-μ/e Flavor Universality tested at O(10^{-3})



$\pi^+ \to e^+\nu$ *LFU* Tests: Sensitivity to High Mass Scales

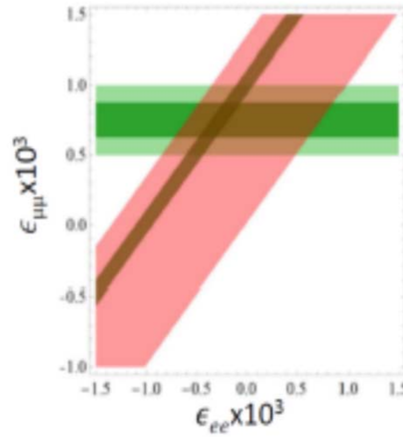
Pseudoscalar interactions



Charged Higgs (non-SM coupling)

$$1 - \frac{R_{e/\mu}^{New}}{R_{e/\mu}^{SM}} \sim \mp \frac{\sqrt{2}\pi}{G_\mu} \frac{1}{\Lambda_{eP}^2} \frac{m_\pi^2}{m_e(m_d + m_u)} \sim \left(\frac{1TeV}{\Lambda_{eP}}\right)^2 \times 10^3$$

Marciano…



Phase I PIONEER Goal: 0.01 % measurement→Λ~3000 TeV

Many others:

- **Leptoquarks**
- **Excited gauge bosons**
- **Compositeness**
- **SU(2)xSU(2)xSU(2)xU(1)**
- **Hidden sector ….**

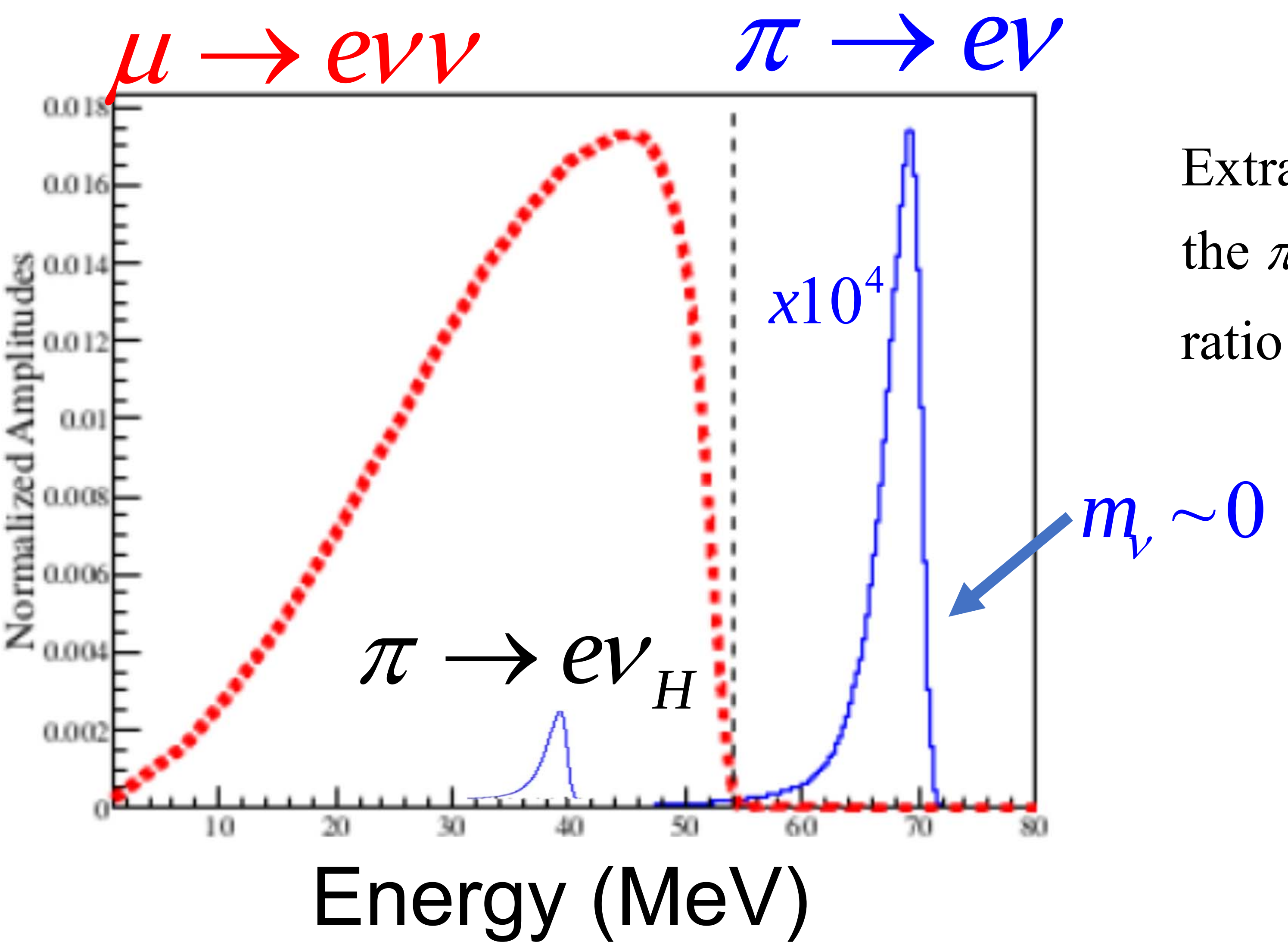
Induced Scalar Currents

Campbell and Maybury (2005), Marciano

$R_{e/\mu}(0.01\%):\quad \Lambda_S > 180\,TeV\,(!)$

Apparent LFUV could also appear via massive sterile neutrinos (e.g. in $\pi^+ \to l^+\nu_H$ with implications for leptogenesis (Elahi et al. 2109.09751).

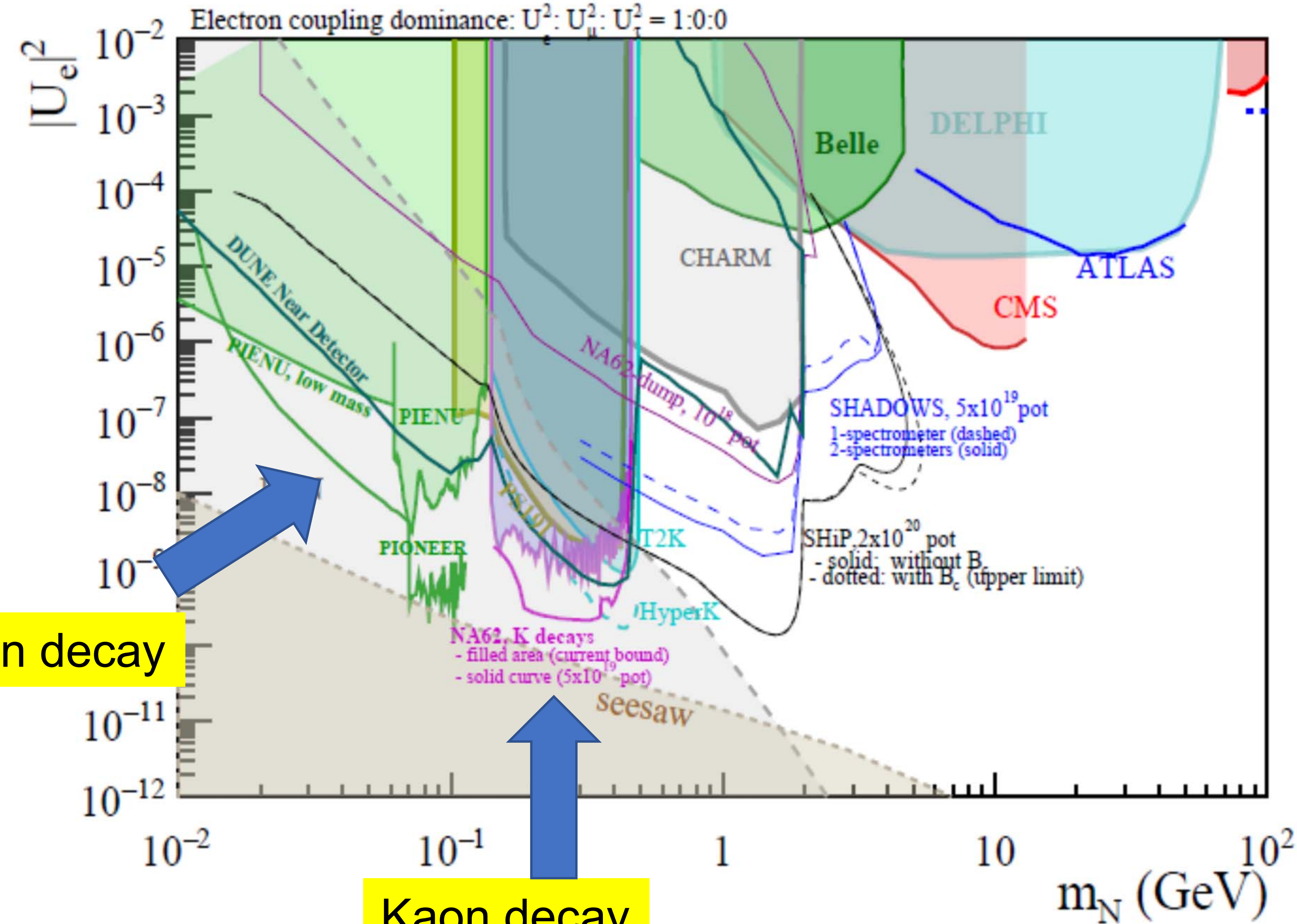
"LFU Violation" Example: Massive Sterile Neutrinos e.g. $\pi^+ \rightarrow e^+ \nu_H$



Extra channel changes the $\pi \rightarrow e\nu$ branching ratio $R^{exp}_{e/\mu}$

Heavy Neutral Leptons Coupling to 1st Generation

2203.08039 [hep-ph]



Pion decay

Kaon decay

CKM Unitarity: Vud, Vus/Vud

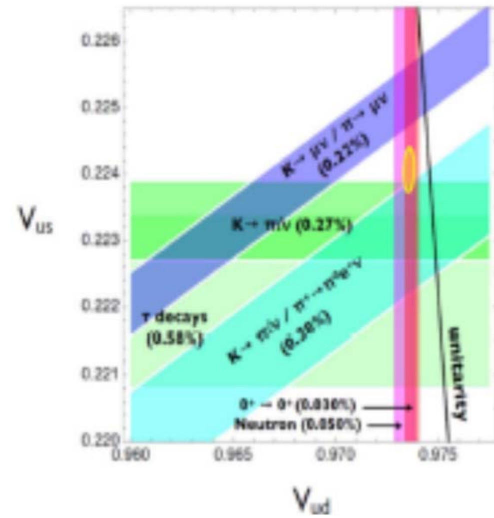
Tested in super-allowed β (V_{ud}) and K decays (V_{us}/V_{ud})

Czarnecki, Marciano , Sirlin (2020)

$$\frac{B(K\rightarrow \pi l \nu)}{B(\pi^+ \rightarrow \pi^0 e^+ \nu)}: \text{ Theoretically clean method to obtain } \frac{V_{us}}{V_{ud}}.$$

Improve $B(\pi^+ \rightarrow \pi^0 e^+ \nu)$ precision by >3x $\rightarrow \frac{V_{us}}{V_{ud}} < \pm 0.2\%$.

Offers a new complementary constraint in the $V_{us} - V_{ud}$ plane.



$\pi^+ \rightarrow \pi^0 e^+ \nu$: Theoretically cleanest method to obtain V_{ud}

PIBETA Experiment $(\pm 0.6\%)$

$$B(\pi^+ \rightarrow \pi^0 e^+ \nu) = (1.038 \pm 0.004_{stat} \pm 0.004_{syst} \pm 0.002_{\pi e2}) \times 10^{-8}$$

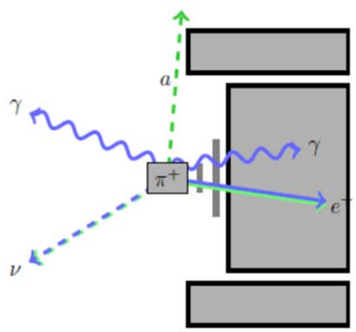
$$V_{ud} = 0.9738(28)_{exp}(1)_{th}$$

Not presently competitive precision for V_{ud}. (Needs 10x precision.)

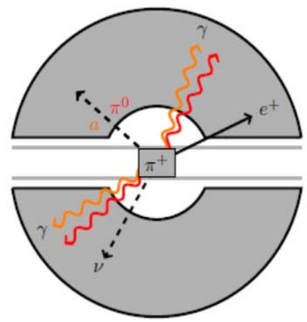
Altmannshofer, Gori, Robinson, *Phys.Rev.D* 101 (2020) 7, 075002

Pion “β” Decay with Axion-like particles (ALP):

$$\pi \rightarrow e\nu a \;\&\; \pi \rightarrow e\nu a;\, a \rightarrow \gamma\gamma$$

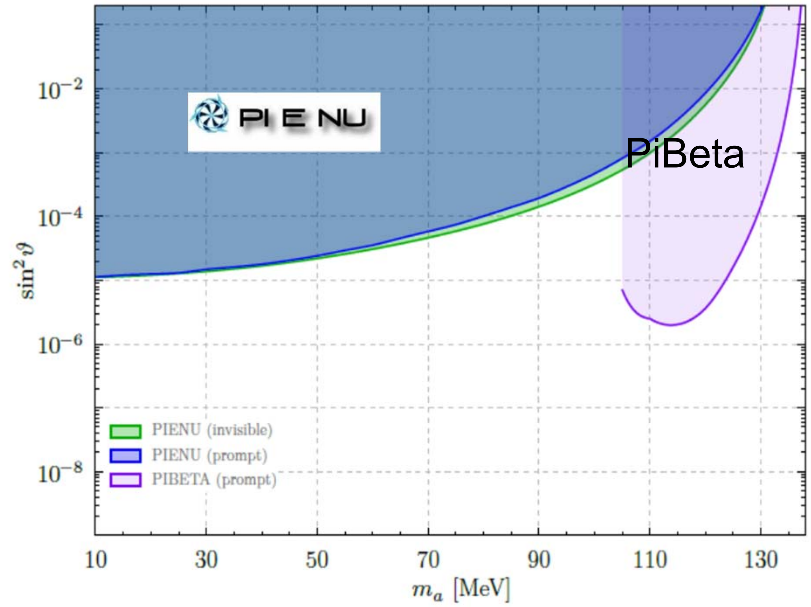


PI E NU

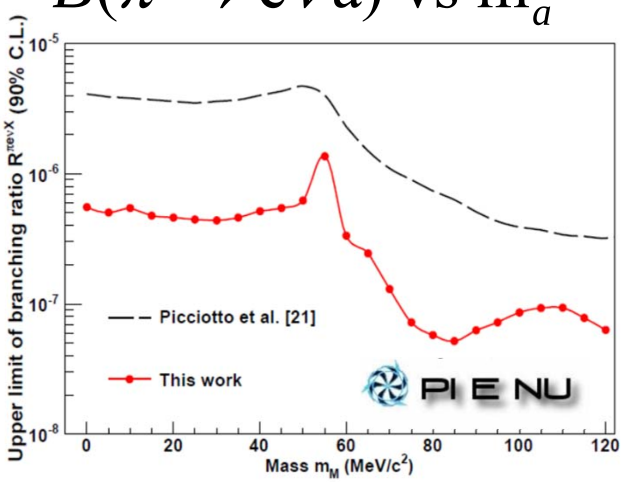


PiBeta

$alp-\pi$ Mixing vs. m_a



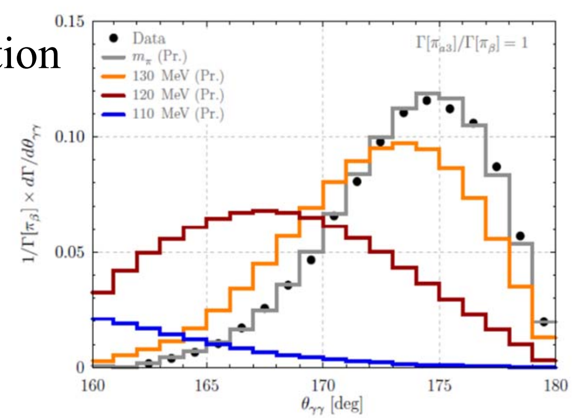
$B(\pi \rightarrow e\nu a)$ vs m_a



$a \rightarrow \gamma\gamma$ Angular distribution

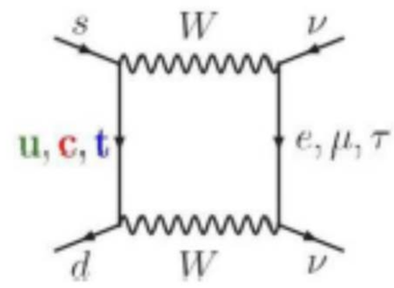
$\pi \rightarrow e\nu a;\, a \rightarrow \gamma\gamma$

for different m_a



Bordone, Buttazzo, Isidori, Monnard ArXiv:1705.10729

Testing LFU with $K^+ \to \pi^+ \nu\bar{\nu}$



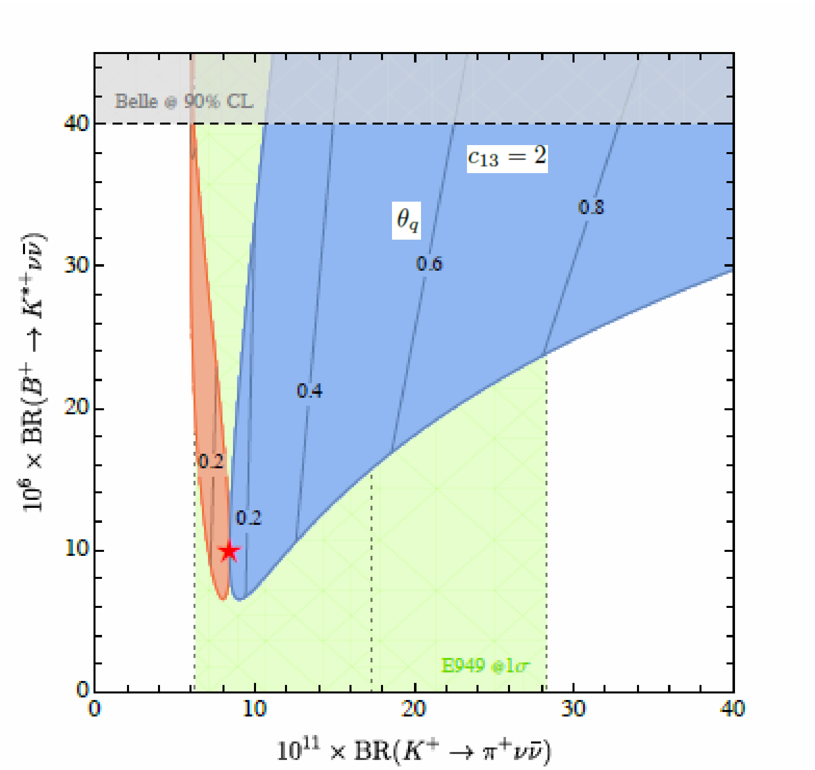
Involves third generation quarks (top) and leptons (τ, ν_τ)

EFT approach to LFU violations new interactions with $U(2)_q$ x $U(2)_l$ symmetry. NP coupled to left-handed lepton and quark singlets. Tuned to R(D*)=1.25*SM.

$$\mathcal{L}^{\rm NP}_{s\to d\nu\bar\nu} = \frac{1-c_{13}}{\Lambda^2}\theta_q^2\, V_{ts}^* V_{td}(\bar s_L\gamma_\mu d_L)(\bar\nu_\tau\gamma_\mu\nu_\tau).$$

Correlation of $K^+ \to \pi^+ \nu\bar{\nu}$ with $B^+ \to K^{*+} \nu\bar{\nu}$

$B(K^+ \to \pi^+ \nu\bar{\nu})$ [−30%,+100%]



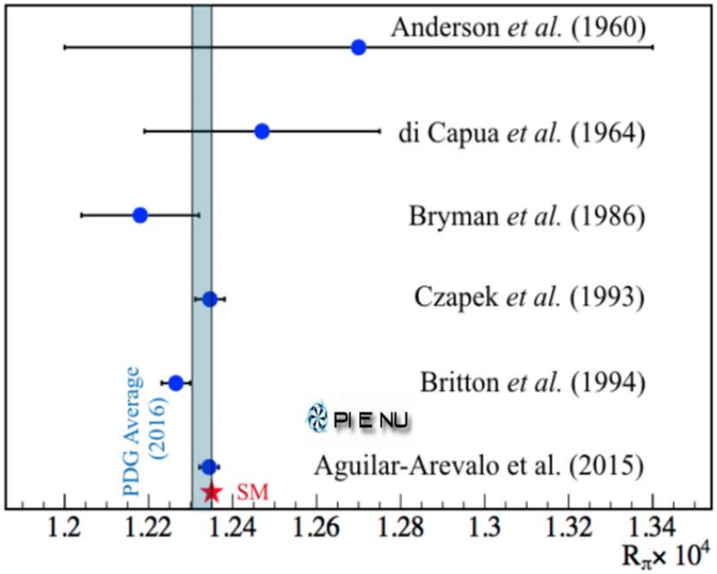
How to improve experimental precision by another order of magnitude to match theory?

$$R^{th}_{e/\mu} = (1.23524 \pm 0.00015)\, x10^{-4}$$ ±0.012%

15 x more precise than experiments!

$\pi^+ \rightarrow e^+\nu$ Experiments -- stopped pions

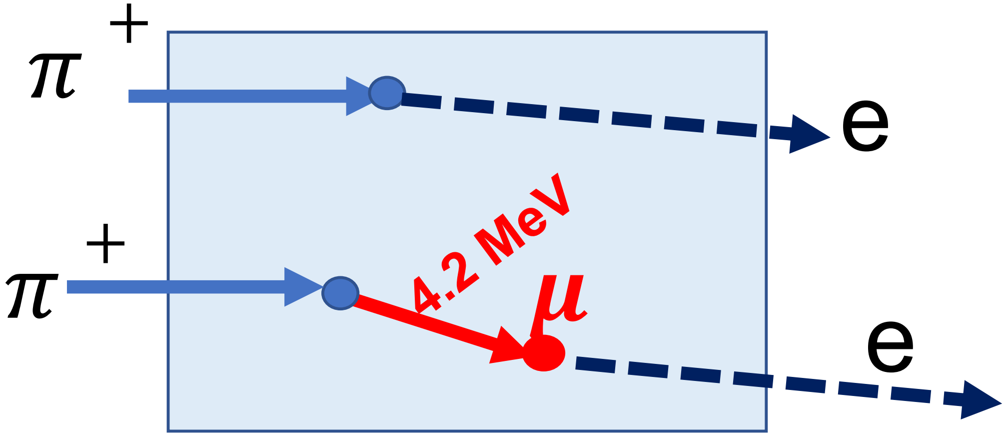
- CERN (1958) 6 events
- Chicago (1960) – ***magnetic spectrometer***
  - 1st precise measurement ±6%
- Columbia (1964) *NaI(Tl) crystal*; ± 2%
- TRIUMF (1986, 1992, 2015 → **PIENU**)
  NaI(Tl)/CsI crystals
  ± 0.24% →0.1%? 10^7 events
- PSI (1994 → **PEN**)
  BGO → CsI crystals >10^7 events
  ± 0.4% → <0.1%?
- ***PIONEER:*** → <0.01%?



L. Doria

$\frac{\Gamma(\pi \to e\nu)}{\Gamma(\pi \to \mu\nu)}$: Experimental Method

Simple experiment: count e^+ from π^+ decay

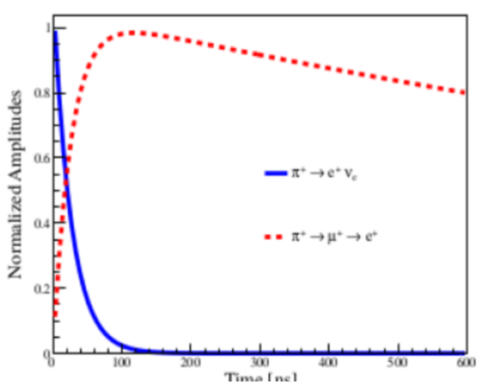


$$\frac{N(\pi \to e\nu)}{N(\pi \to \mu\nu)} \to \frac{N(\pi \to e\nu)}{N(\pi \to \mu \to e\nu\nu)}$$

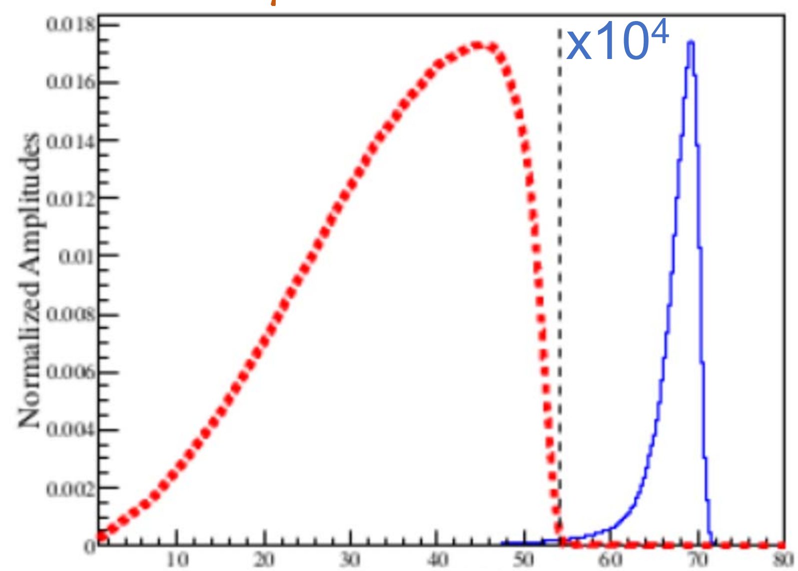
Lifetimes

$\tau_\pi = 26ns$

$\tau_\mu = 2.2\mu s$



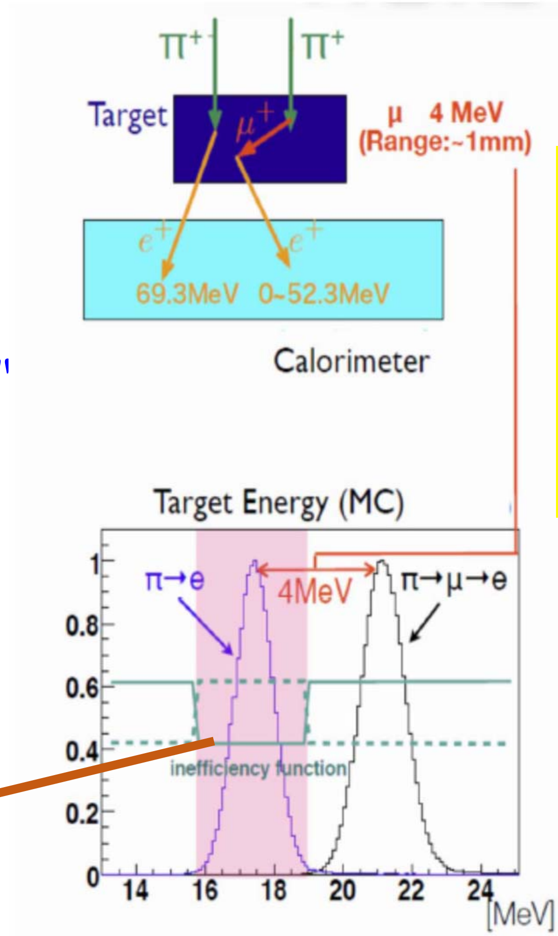
Time (ns)



Energy (MeV)

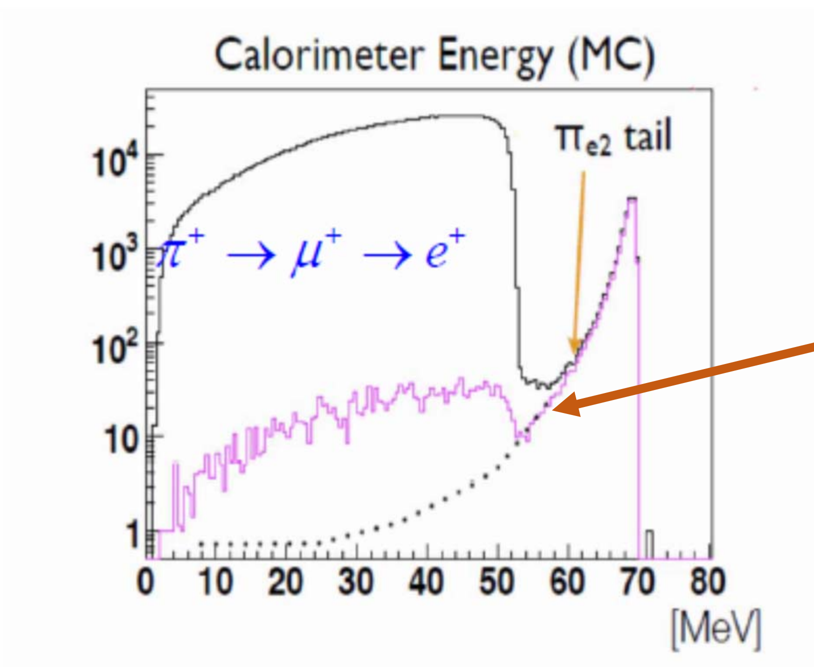
$\pi \to e\nu$: Experimental Method

- Pions stopped in an active target
- Positrons tracked and energy measured in a calorimeter
- Decays tagged in target and by energy and timing
- Principal sytematic uncertainty: Low energy "tail" of $\pi \to e\nu$ events under $\mu \to e\nu\nu$ "background".



Many systematic effects cancel in measuring the ratio

$$\frac{\pi \to e}{\pi \to \mu \to e}.$$



$\pi \to \mu\nu$

$T_\mu = 4.2 MeV$

PIONEER

Next Generation Rare Pion Decay Experiment
Paul Scherrer Institut

W. Altmannshofer[23], H. Binney[12], E. Blucher[28], D. Bryman[2,3], S. Chen[4], V. Cirigliano[5], A. Crivellin[6,7,8], S. Cuen-Rochin[9], A. Czarnecki[10], A. DiCanto[19], L. Doria[11], A. Fienbert[29], A. Gaponenko[24], A. Garcia[12], L. Gibbons[13], C. Glaser[14], M. Gorchtein[11], T. Gorringe[15], S. Gori[23], A. Grillo[23], D. Hertzog[12], Z. Hodge[12], M. Hoferichter[16], S. Ito[18], T. Iwamoto[17], D. Jaffe[19], P. Kammel[12], J. Kaspar [12], S. Kettel[19], B. Kiburg[24], A. Knecht[6], T. Koffas[26], K. Labe[13], J. LaBounty[12], U. Langenegger[6], C. Malbrunot[8], W. Marciano[19], S. M. Mazza[23], S. Mihara[20], R. Mischke[3], T. Mori[17], J. Mott[19], E. Muldoon[12], T. Numao [3], W. Ootani[17], C. Ortega Hernandez[1], K. Pachel[3], D. Počanić[14], C. Polly[24], D. Ries[11], R. Roehnelt[12], D. Salvat[21], B. Schumm[23], A. Seiden[23], A. Soter[25], R. Shrock[27], T. Sullivan[22], D. Sweigart[12], V. Tischenko[19], A. Tricoli[19], B. Velghe[3], T. Wataru[17], C. Welch[12], V. Wong[3], and E. Worster[19]

[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] Johannes Gutenberg University of Mainz
[12] University of Washington
[13] Cornell University
[14] University of Virginia
[15] University of Kentucky
[16] University of Bern
[17] University of Tokyo
[18] Okayama University
[19] Brookhaven National Laboratory
[20] KEK
[21] Indiana University
[22] University of Victoria
[23] University of California Santa Cruz
[24] Fermilab
[25] ETH Zurich
[26] Carleton University
[27] Stoney Brook University
[28] University of Chicago
[29] Pennsylvania State University

PIONEER
Next Generation Rare Pion Decay Experiment

PIONEER Goals:

- Phase I:

  * Measure $R_{e/\mu} = \frac{\Gamma(\pi \to e\nu + \pi \to e\nu\gamma)}{\Gamma(\pi \to \mu\nu + \pi \to \mu\nu\gamma)}$: $O(\pm 0.01\%)$

  * Improve exotic decay search sensitivities by an order of magnitude

  e.g. $\pi \to e\nu_H ; \pi \to \mu\nu_H ; \pi \to e/\mu\nu\nu\bar{\nu} ; \pi \to e/\mu\nu X$

- Phase II $\to$ III:

  * Measure $R_{\pi\beta} = \frac{\Gamma(\pi^+ \to \pi^0 e^+ \nu)}{\Gamma(\pi^+ \to all)}$: $O(\pm 0.2\% \to \pm 0.05\%)$

PIONEER Method : $\pi^+ \rightarrow e^+\nu$

(→ Improvements Compared to PIENU)

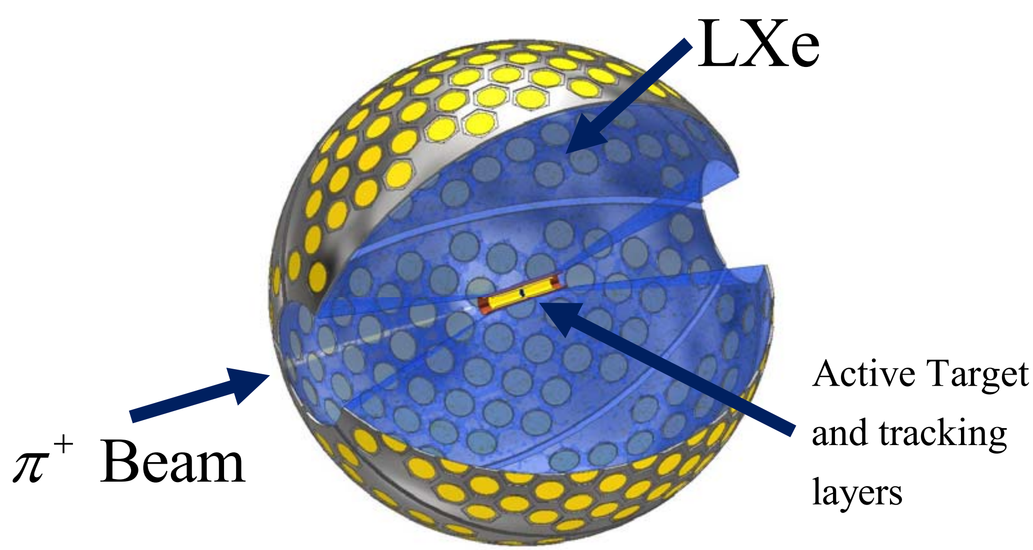
25 X_0, 3π sr calorimeter $\rightarrow$ Reduce Tail correction (5 x); $\rightarrow$ Improve uniformity (5 x)

Fast scintillation response (LXe)

Active Tracking Target $\rightarrow$ Reduce Tail correction uncertainty (10 x)

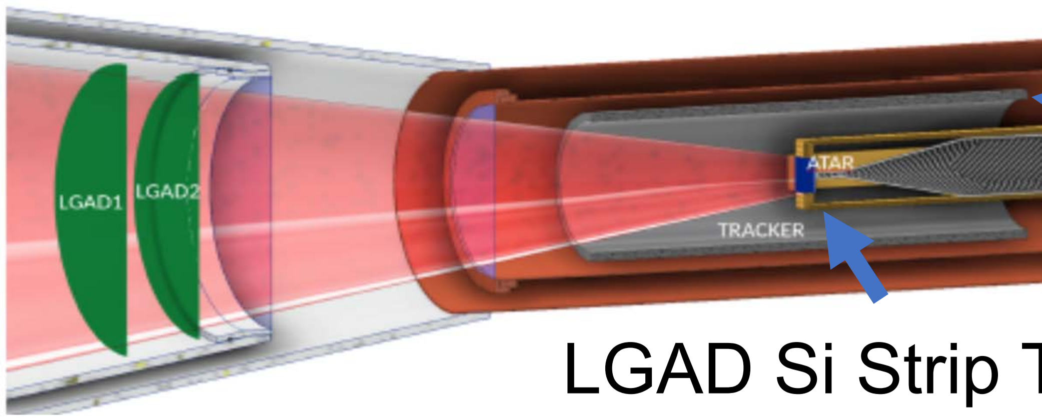
Fast pulse shape $\rightarrow$ allow $\pi \rightarrow \mu \rightarrow$ e decay chain observation

Fast electronics and pipeline DAQ $\rightarrow$ Improve efficiency



PIONEER Central Region

π^+



Si strip positron tracker

LGAD Si Strip Target **(ATAR)**

Active Target (ATAR)

Low Gain Avalanche Detector

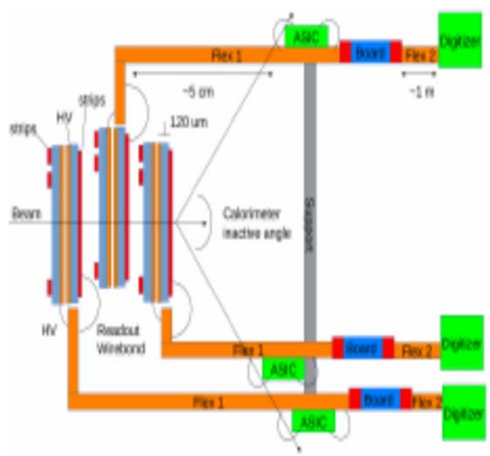
$\pi \rightarrow \mu \rightarrow$ e tracking

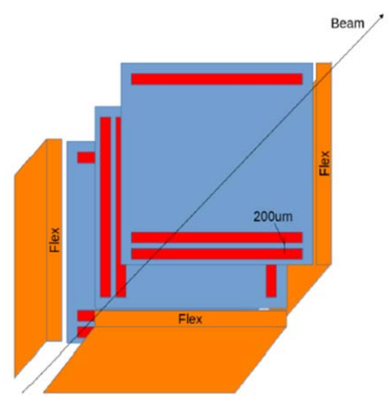
48 layers X/Y strips

Strips: 120 μm thick, 200 μm wide

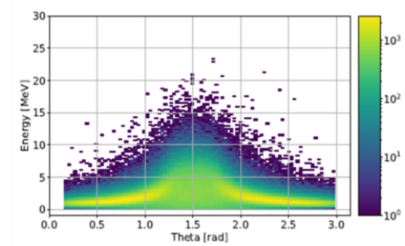
Fast pulses, timing <100 ps

Fully active for energy measurements



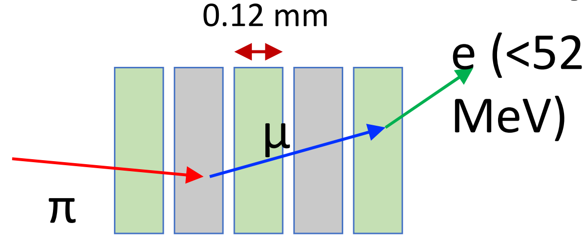


ATAR: ΔE_{e^+} vs θ



LGAD Si Strip Target

- **Design: 48 layer Si strip target; stop pions**
  - Compact 2x2x1 cm block full of silicon strips
  - See all π→μ decays;
  - Track π→e and π→ μ →e



- **Requirements**
  - **Longitudinal segmentation**:
    Track, stop, localize pions; *detect decays in flight*
  - **Compact, efficient**: no dead material
  - **Fast collection time**: separate pulses that are close in time from π→μ →e and π→e decays
  - **Large Dynamic range (1000)**: detect energy deposition from positrons and slow pions/muons

R&D in progress

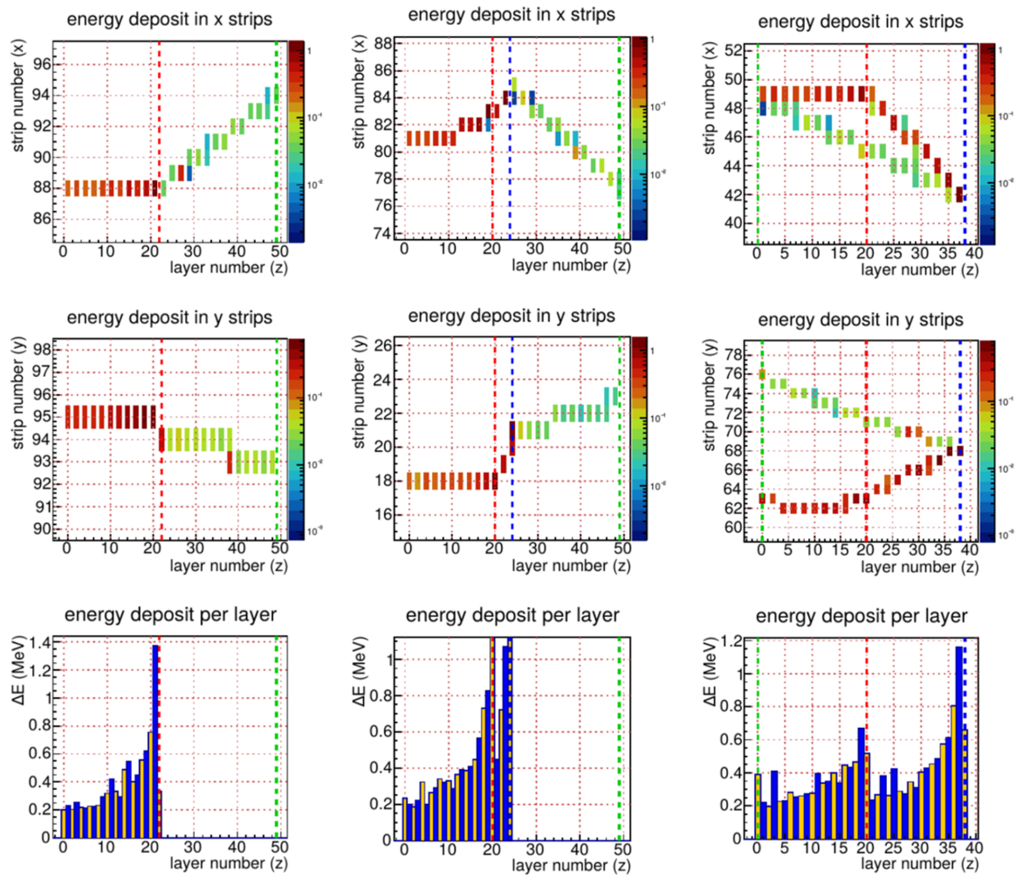
Simulated ATAR Event Displays

$\pi \rightarrow e$ | $\pi \rightarrow \mu \rightarrow e$ | $\pi DIF \rightarrow \mu \rightarrow e$

X vs. Z

Y vs. Z

$dE_{\pi,\mu}$ vs. Z



PIONEER: LXe Scintillation Calorimeter

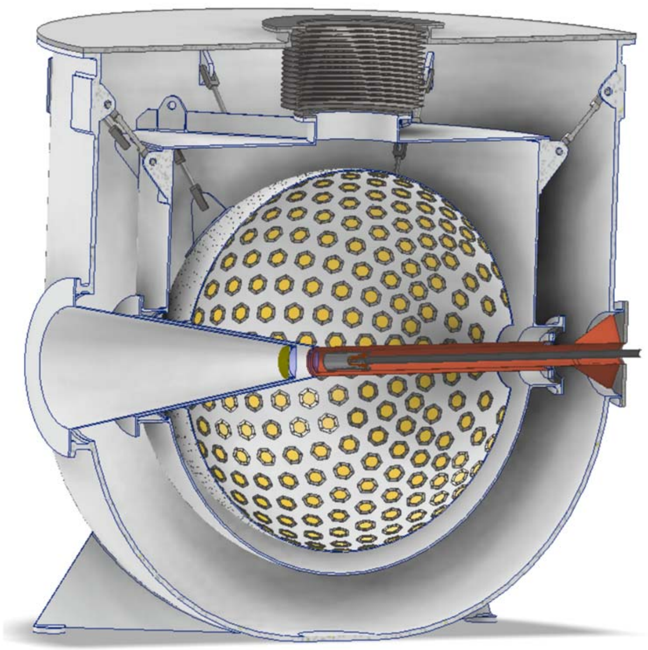
Performance expectations based on MEG LXe calorimeter
Active volume 2000 l

$$25\ X_0$$

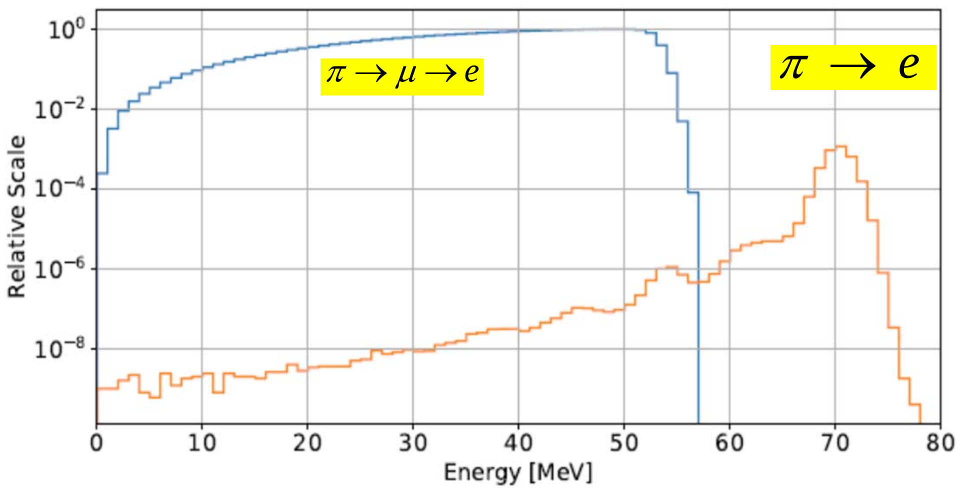
$$\Delta t \sim 100\ \mathrm{ps}$$

$$\frac{\sigma_E}{E} \sim 1.5\%$$

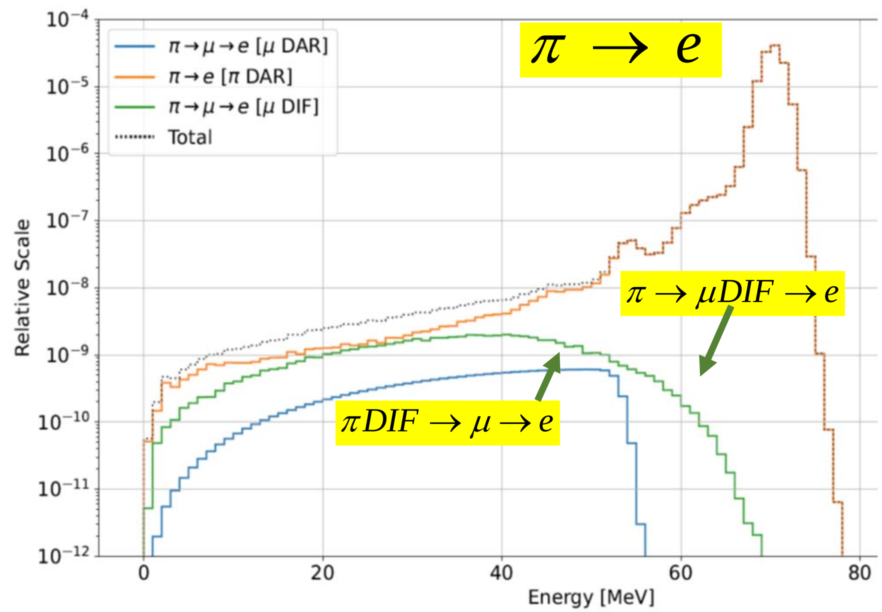
LXe



PIONEER Simulated Energy Spectra



Background Suppression



Low energy tail measured *in situ using ATAR suppression of μ decay backgrounds.*

$\pi \rightarrow e\nu$: Estimated Uncertainties

To be verified by simulations and prototype measurements.

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

* Pion lifetime uncertainty not included

$\pi^+ \rightarrow \pi^0 e^+ \nu$: Estimated Uncertainties

	PiBeta	**PIONEER (Phase II)**	
Statistics	0.4%	0.1%	
Systematics	0.4%	<0.1%	(ATAR (β), MC, Photonuclear, π→eν)
Total	0.64%	**0.2%**	

Exotic Searches in PIONEER Phase I

Searches for Sterile Neutrinos

$\pi \rightarrow e\nu_H$

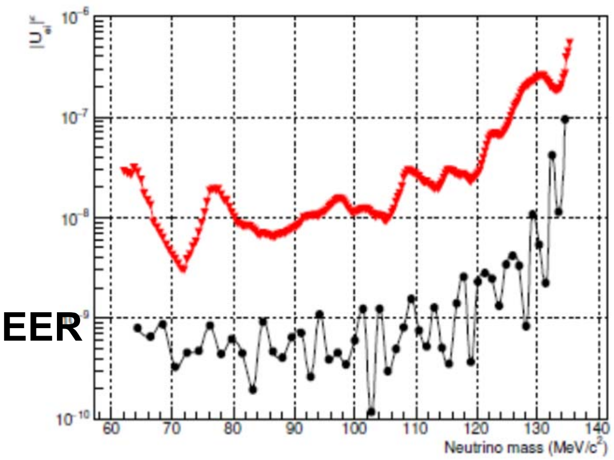
$\left|U_{e4}^{2}\right| vs\, m_H$

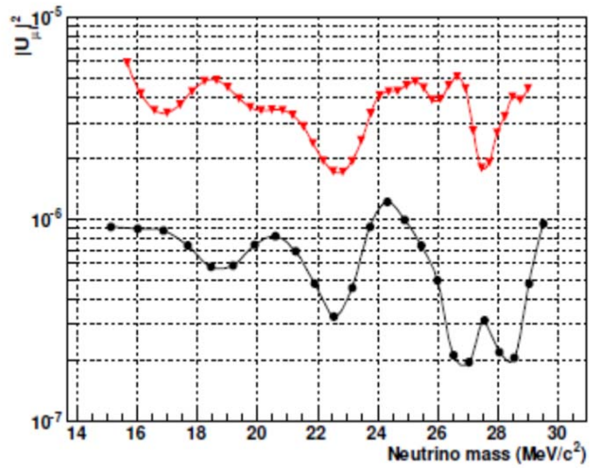
$\pi \rightarrow \mu\nu_H$

$\left|U_{\mu 4}^{2}\right| vs\, m_H$

PIENU

PIONEER





Also to be improved by an order of magnitude:

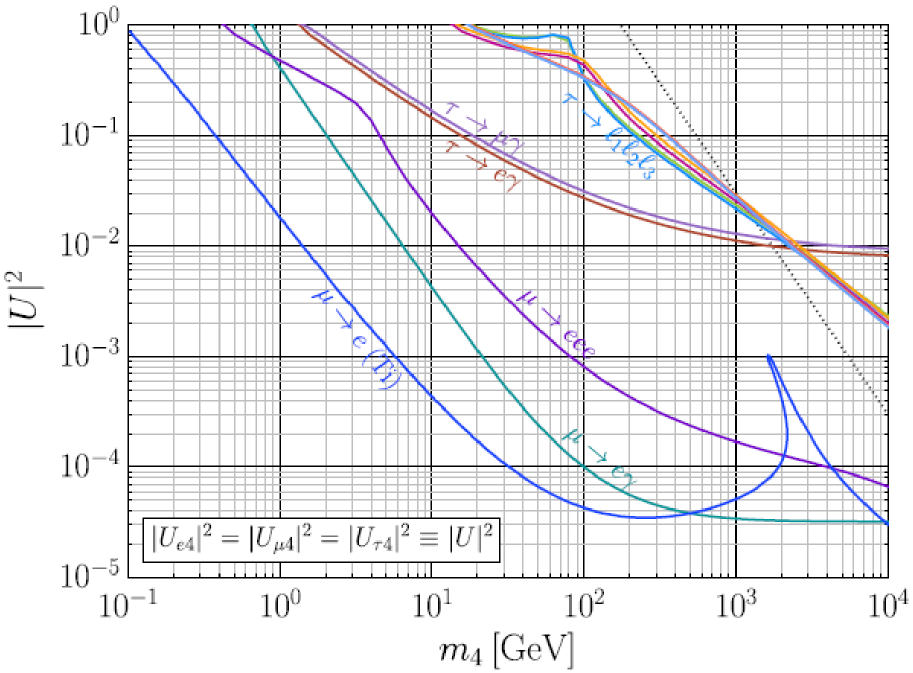
$$\pi \rightarrow e/\mu\nu X;\ \pi \rightarrow e/\mu\nu\nu\bar{\nu}$$

deGouvea, Kobach, PRD D 93, 033005 (2016)

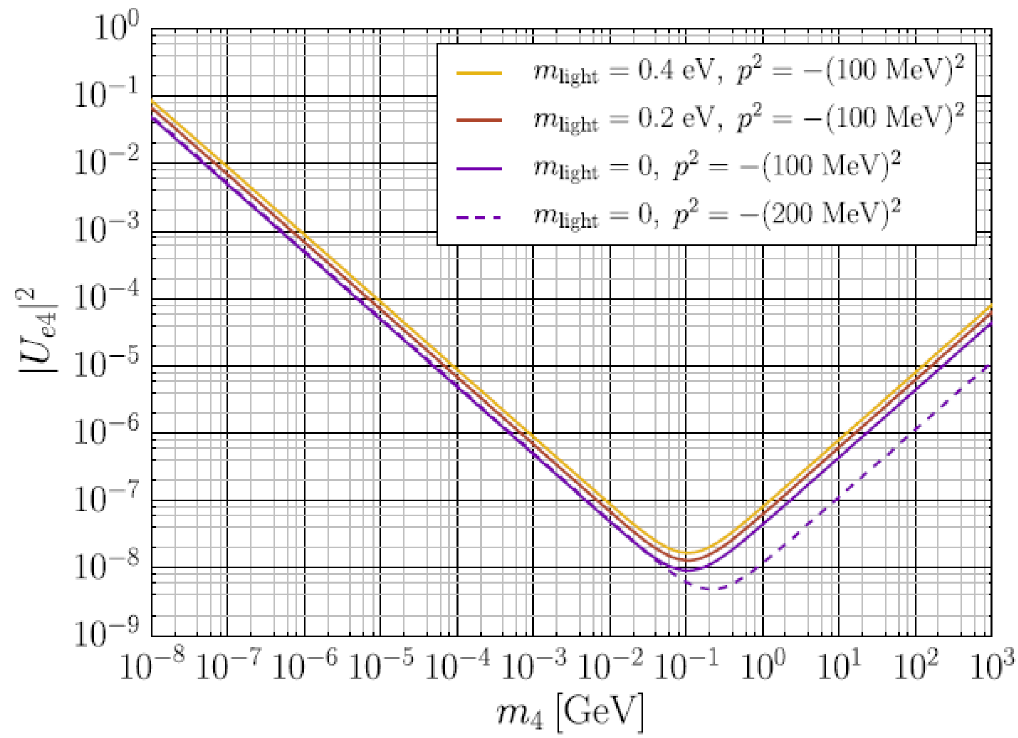
Connections: LFU, LFV, LNV and Sterile Neutrinos

Constraints on $|U_{ei}|^2$

$\mu / \tau \to e\gamma, \mu / \tau \to 3e, \mu eC$



$0\nu\ \beta\beta$ Decay -- Majorana ν



Other connections with LNV : $\mu^- Z \to e^+(Z-2)$, $K \to \pi\mu\mu$....

Charged Lepton Flavor Violation
Another probe of the flavor puzzle

Many ongoing CLFV Experiments:

$\mu - e$ Conversion ($\mu^- Z \to e^- Z$) : Mu2e (Fermilab); COMET (JPARC)

$O(10^{-12}) \to O(10^{-17})$

$\mu \to e\,\gamma,\ \mu \to 3e$: MEG (PSI); Mu3e (PSI)

$O(10^{-13}) \to O(10^{-14}),\ O(10^{-12}) \to O(10^{-16})$

$\tau \to e/\mu\gamma,\ \tau \to 3e...$: Belle II (KEK), BESIII

$O(10^{-8}) \to O(10^{-9})$

$K^+ \to \pi^+ \mu e, ...$: NA62 (CERN)

$O(10^{-10}) \to O(10^{-11})$

$B \to \mu e, \pi\mu e....$: *LHCB* (CERN)

$O(10^{-9}) \to O(10^{?})$

$Z \to \mu e,\ \tau\mu, \tau e...$: *LHC ATLAS, CMS (CERN)*

$O(10^{-7}) \to O(10^{?})$

Could a future upgrade of ARIEL or PERLE@Orsay Contribute?

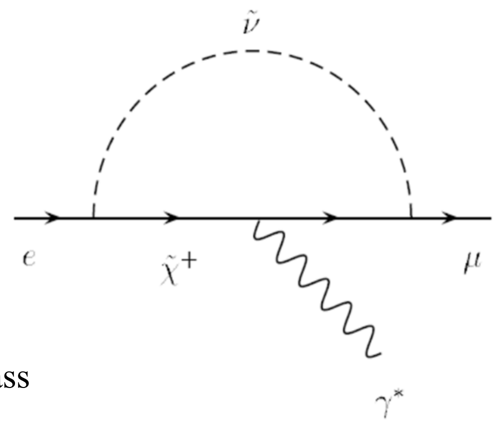
CLFV at "ARIEL200" or PERLE

Blazek and King (arXiv:hep-ph/0408157v1) estimated the cross section

for $e+N \rightarrow \mu+N$ at E_e=200 MeV in the Minimal Supersymmetric Standard Model $(MSSM)$:

$$\sigma(e+N \rightarrow \mu+N) \sim 10^{-1} \left(\frac{M_W}{M_2}\right)^4 \left(\frac{(M_L^2)_{12}}{M_2^2}\right)^2 \; fb; \text{ and}$$

$$BR(\mu \rightarrow e\gamma) \sim 10^{-4} \left(\frac{M_W}{M_2}\right)^4 \left(\frac{(M_L^2)_{12}}{M_2^2}\right)^2$$



M_2 Gaugino mass

$(M_L)_{21} \sim$ *Slepton* mass

$$\sigma(e+N \rightarrow \mu+N) = 10^3 \, x BR(\mu \rightarrow e\gamma) \; fb$$

Using the current MEG limit $BR(\mu \rightarrow e\gamma) < 4.2x10^{-13}$

results in $\sigma(e+N \rightarrow \mu+N) < 4.2x10^{-10}$ *fb*.

Is this measurable?

ARIEL200 Fantasy Experiment

Say, MEG II discovers $\mu \to e\gamma$ at BR = $4.2\text{x}10^{-13}$

$\sigma_{200\,MeV}(\text{e+Ta} \to \mu\text{+Ta}) = 4.2x10^{-10}\ fb$

10 mA; 10 mm thick Ta target

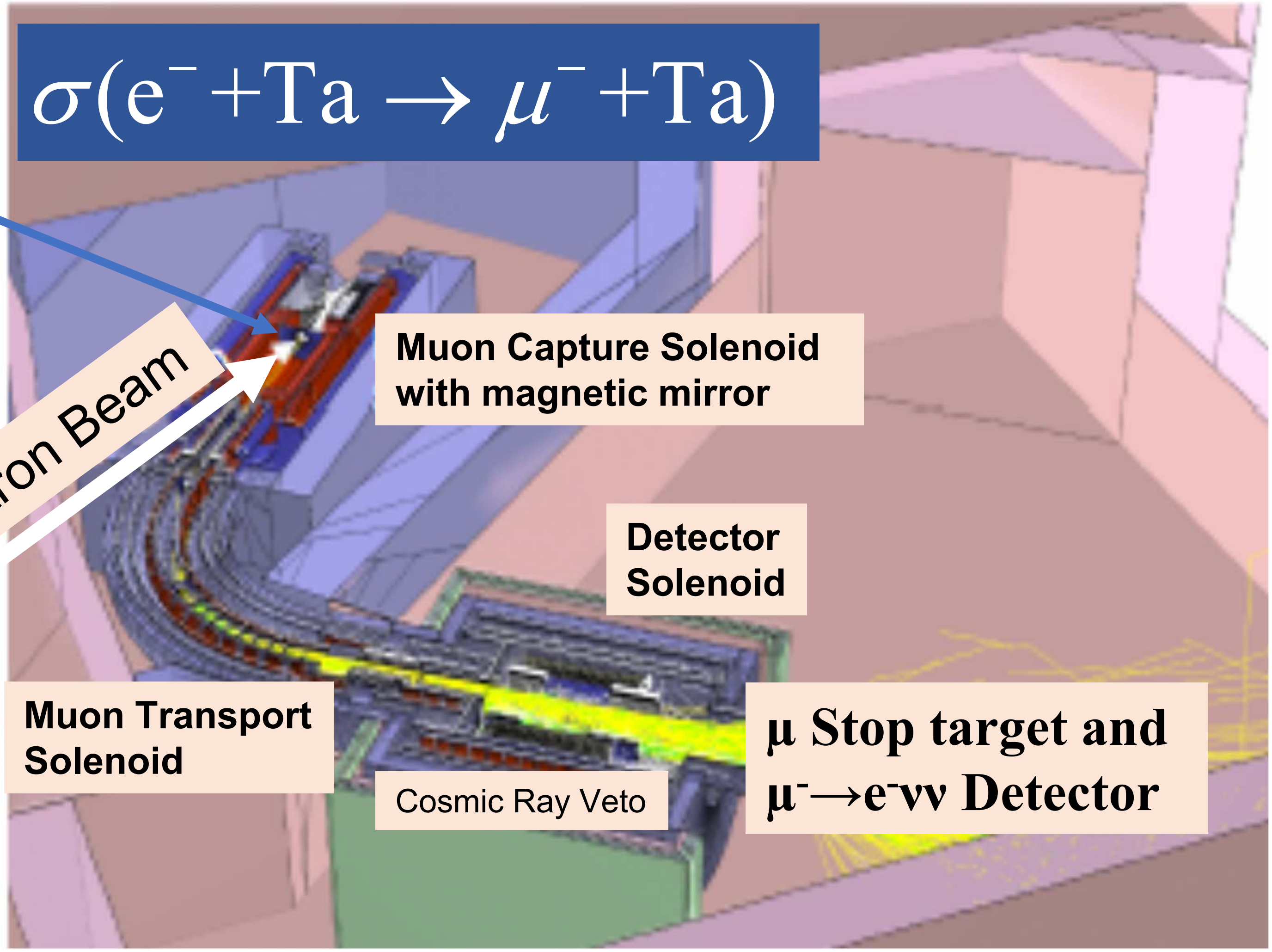
Number of μ^- events in 5 years: 230

Or, if 0 events observed $\to$ $\sigma(\text{e+Ta} \to \mu\text{+Ta}) < 4x10^{-12}\ fb$

$\to \text{BR}_{MSSM}(\mu \to e\gamma) < 4\,\text{x}10^{-15}$

(O(10) x lower than current MEGII goal)

ARIEL200 Fantasy Experiment (à la COMET Phase 1)



Conclusions: Lepton Flavor Universality

• ***Lepton Flavor Universality and Lepton Flavor Violation reactions are*** **especially sensitivity to new physics effects hinted at by several anomalies.**

• **$\mu/\pi/K/\tau/B/Z$ results anticipated from Muon g-2, MEGII, Mu2e, Mu3e, COMET, PIENU, PEN, NA62, BESSIII, BELLE-II, LHCB, LHC ATLAS/CMS. Important connections with searches for sterile neutrinos/dark sector particles , high mass scale physics, LNV, and $0\nu\beta\beta$ searches.**

• **A next generation pion decay experiment PIONEER aims at order of magnitude improvements in high precision for measurements of $\pi \rightarrow e\nu$ and pion beta decay to provide uniquely sensitive new information on Lepton Flavor Universality and CKM unitarity.**

• **Could a future ARIEL upgrade or PERLE@Orsay play a role in this field?**