Testing Lepton Flavor Universality with Pions and Kaons

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University of British Columbia &TRIUMF

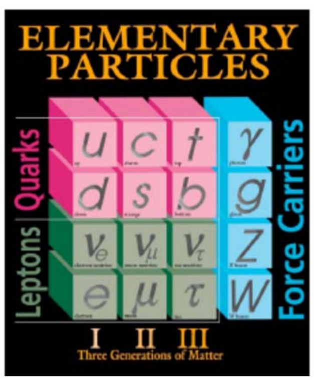
The University of British Columbia, Point Grey campus, and TRIUMF are located on the traditional, ancestral and unceded territory of the xwməθkwəy̓əm (Musqueam) people. September 30 is a Canadian National Day for Truth and Reconciliation.

"It was the best of times, it was the worst of times, it was the age of wisdom, it was the age of foolishness, it was the epoch of belief, it was the epoch of incredulity, it was the season of light, it was the season of darkness, it was the spring of hope, it was the winter of despair."

— Charles Dickens, A Tale of Two Cities

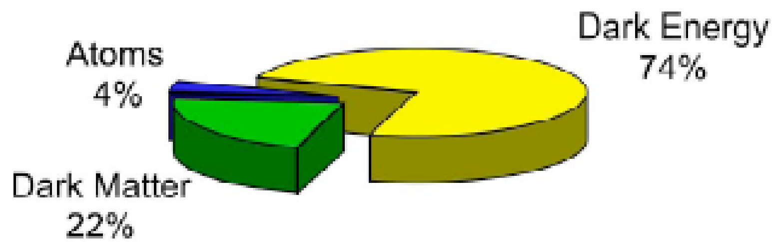
BEST of Times

Experiments &
Standard Model



+ Higgs (√)

WORST of Times



Matter in the Universe; **Flavor**;
Strong CP; Hierarchy…. (Gravity)

Lepton Flavor

Electron *Thompson, Townsand, Wilson 1896*

Muon *Nedermeyer, Anderson 1937*

Tau *Perl et al. 1974*

±40 yrs

Lepton Flavor Universality ***Pontecorvo*** *1946*

Conserved Lepton Number ***Konopinski, Mahmoud*** *1953*

Separate lepton "numbers (flavors)" ***Pontecorvo*** *1959*

Neutrino oscillations:

Pontecorvo *1957 → Davis, Kamioka, SNO, OPERA, MINOS… 1960-2001*

Lepton flavor is not conserved

Neutrinos have (small) mass and mix

The Flavor Puzzle

Quarks

u	c	t
d	s	b

Leptons

e	μ	τ
ν_e	ν_μ	ν_τ

Weak states $\not\Leftrightarrow$ mass states: mixing matrix; flavor not conserved.

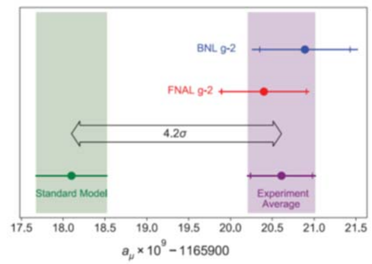
Unexplained observations (no theory of flavor):

- Three (“identical”) generations; universal interactions
- Huge mass differences between and within the generations
  Exceptionally small neutrino mass
- CP violation
- Symmetry between lepton and quark sectors (GUT, scale?)

Flavor Tensions

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

- Muon g-2 (4.2 σ)
- B Decays (2-4 σ)



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

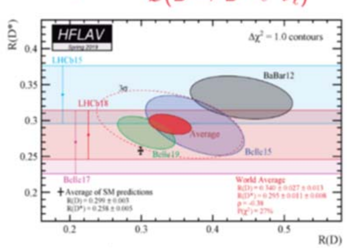
$B \to K^{(*)}\mu^+\mu^- / B \to K^{(*)}e^+e^-$; neutral currents

O(10%) deviations from universality.

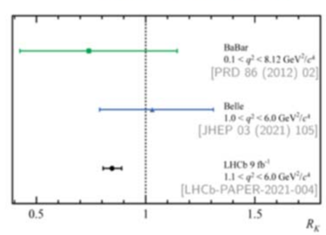
Both heavy quarks and leptons involved!

S. Benson, A. Rostomyan, TAU 18

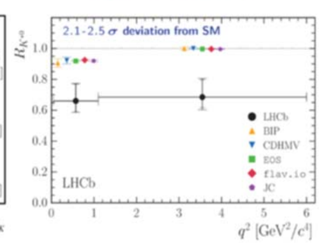
$$\mathcal{R}_{D^{(*)}} \equiv \frac{\mathcal{B}(\bar{B} \to D^{(*)}\tau^-\bar{\nu}_\tau)}{\mathcal{B}(\bar{B} \to D^{(*)}\ell^-\bar{\nu}_\ell)} \qquad R_K \equiv \frac{\Gamma(B^+ \to K^+\mu^+\mu^-)}{\Gamma(B^+ \to K^+e^+e^-)} \qquad \frac{\Gamma(B \to K^*\mu^+\mu^-)}{\Gamma(B \to K^*e^+e^-)}$$



A. Pich



30th TAU Anniversary



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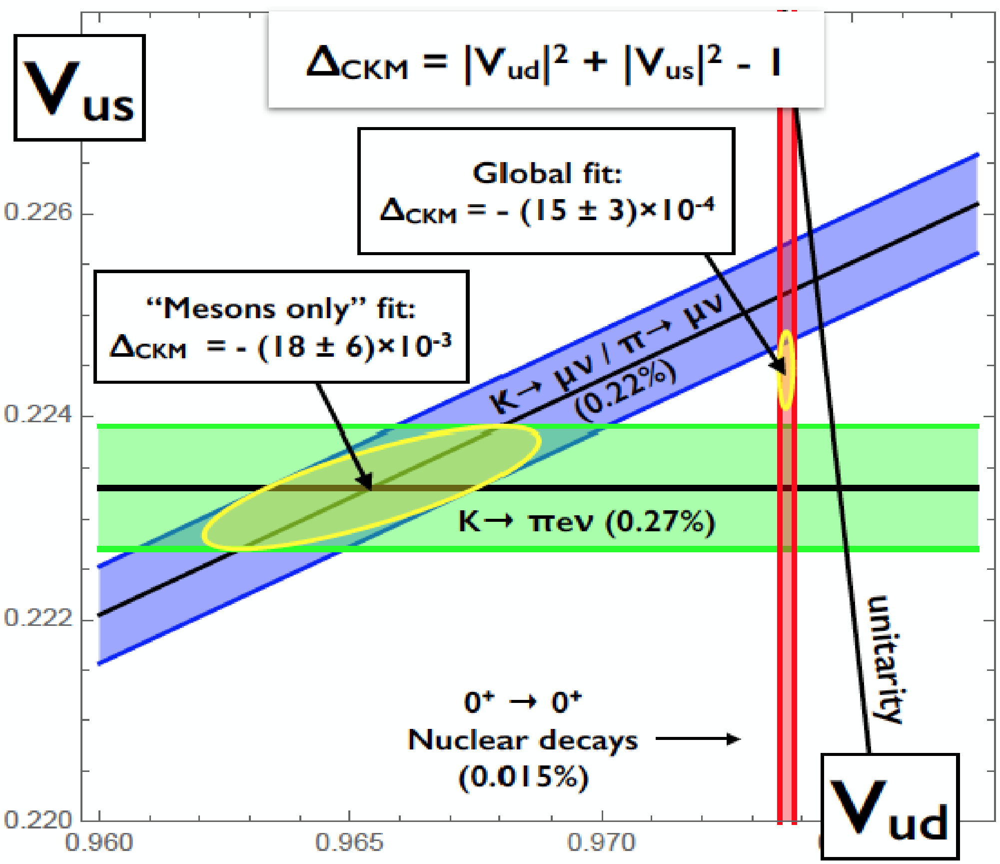
Flavor Tensions

$$\begin{bmatrix} d' \\ s' \\ b' \end{bmatrix} = \begin{bmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{bmatrix} \begin{bmatrix} d \\ s \\ b \end{bmatrix}.$$

- Unitarity of Quark mixing matrix (CKM): $V_{ud}^2 + V_{us}^2 + V_{ub}^2 = 1$

3-5 **σ** Discrepancy*



V. Cirigliano

- V_{ud}(β decay)
- V_{us} (K decay)

May be related to LFU violation

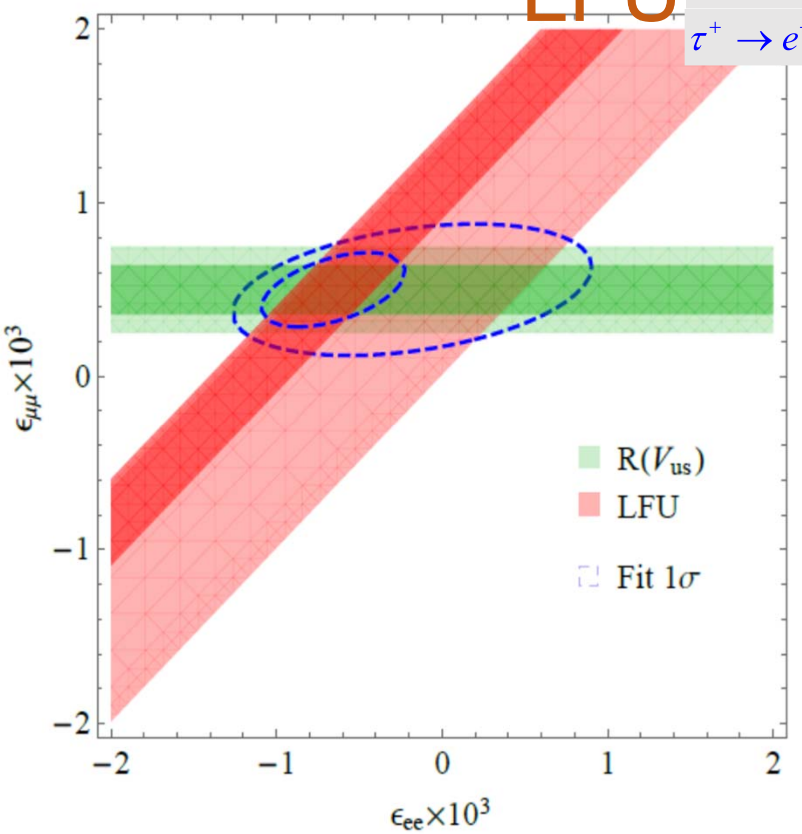
*Seng et al. arXiv:2107.14708 [hep-ph]

Hoferichter and Crivellin (2020)

Connecting CKM Unitarity and Lepton Flavor Universality

Modified $Wl\nu$ 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

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



CKM

Rare Pion and Kaon Decays

A few special rare processes have strong connections to flavor physics, precise Standard Model predictions, and have high sensitivity to non-SM physics.

$$\pi^+ \to e^+\nu(\gamma) \sim 10^{-4}$$

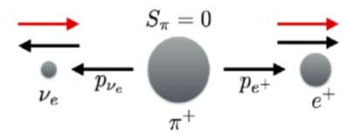
$$\pi^+ \to \pi^0 e^+\nu(\gamma) \sim 10^{-8}$$

$$K^+ \to \pi^+\nu\bar{\nu} \sim 10^{-10}$$

$$K_L{}^0 \to \pi^0\nu\bar{\nu} \sim 10^{-11}$$

Deviations from SM predictions means new physics.

Charged Lepton Flavor Universality in π Decay



$$R_{e/\mu}^{SM} = \frac{\Gamma\left(\pi^+ \to e^+ \nu(\gamma)\right)}{\Gamma\left(\pi^+ \to \mu^+ \nu(\gamma)\right)} = \left(1.2352 \pm 0.0001\right) x10^{-4}$$

(±0.008%)

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%)

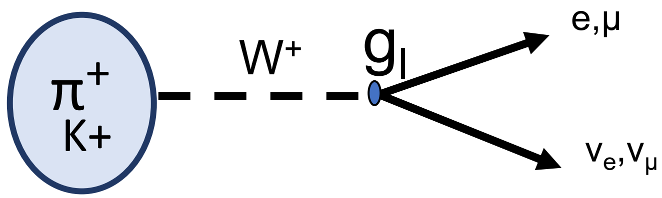
PI E NU

→ Relative weak interaction strength: $\frac{g_e}{g_\mu} = 0.9990 \pm 0.0009$ (±0.09%)

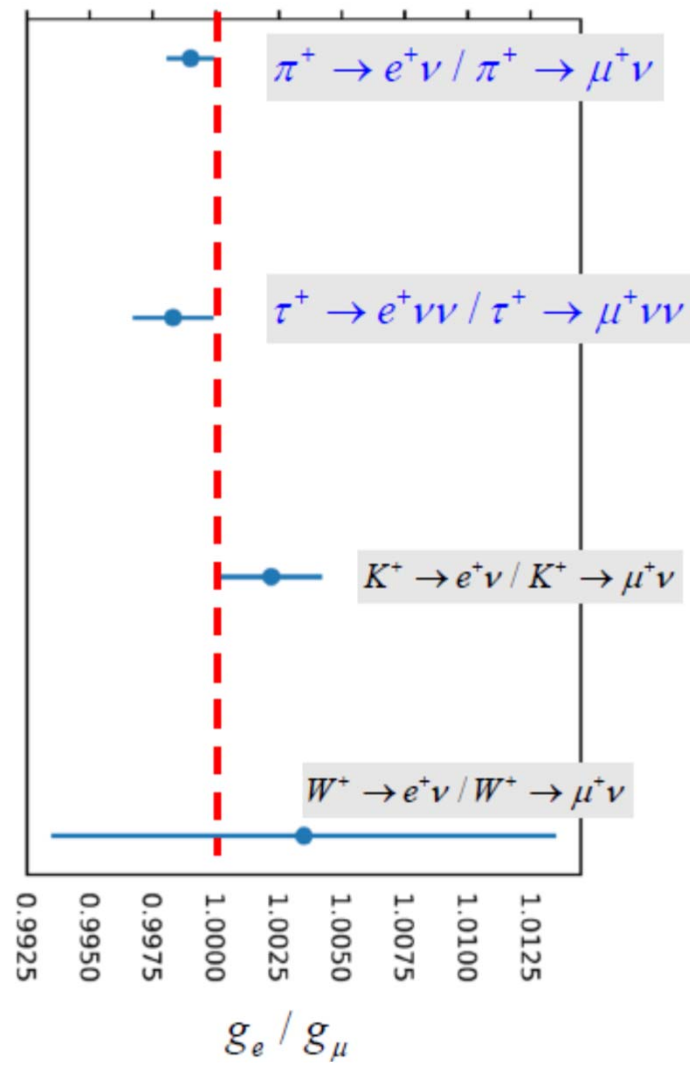
Experiments are an order of magnitude less precise than theory.

Charged Lepton Flavor Universality tested at O(10^{-3})

Light meson and Tau experiments compare SM expectations assuming $g_e = g_\mu = g_\tau$



$$\frac{g_e}{g_\mu} = 0.9990 \pm 0.0009$$



Universality Tests with τ Decays

<O(0.2%) effects

$$\frac{\tau \to e\nu\nu}{\mu \to e\nu\nu}$$ for τ-μ Universality and $$\frac{\tau \to \mu\nu\nu}{\mu \to e\nu\nu}$$ for τ-e Universality

$$\frac{\tau \to \pi\nu}{\pi \to \mu\nu}$$ for τ-μ Universality and $$\frac{\tau \to \pi\nu}{\pi \to e\nu}$$ for τ-e Universality

Table 1. Experimental determinations of the ratios $g_\ell/g_{\ell'}$ [1,8,9].

	$\Gamma_{\tau\to\mu}/\Gamma_{\tau\to e}$	$\Gamma_{\pi\to\mu}/\Gamma_{\pi\to e}$	$\Gamma_{K\to\mu}/\Gamma_{K\to e}$	$\Gamma_{K\to\pi\mu}/\Gamma_{K\to\pi e}$	$\Gamma_{W\to\mu}/\Gamma_{W\to e}$
$\lvert g_\mu/g_e\rvert$	1.0017 (16)	1.0010 (9)	0.9978 (18)	1.0010 (25)	0.998 (4)
	$\Gamma_{\tau\to e}/\Gamma_{\mu\to e}$	$\Gamma_{\tau\to\pi}/\Gamma_{\pi\to\mu}$	$\Gamma_{\tau\to K}/\Gamma_{K\to\mu}$	$\Gamma_{W\to\tau}/\Gamma_{W\to\mu}$	
$\lvert g_\tau/g_\mu\rvert$	1.0011 (14)	1.0021 (25)	0.986 (7)	1.004 (16)	
	$\Gamma_{\tau\to\mu}/\Gamma_{\mu\to e}$	$\Gamma_{W\to\tau}/\Gamma_{W\to e}$	$\Gamma_{\tau\to\pi}/\Gamma_{\pi\to e}$		
$\lvert g_\tau/g_e\rvert$	1.0028 (15)	1.022 (12)	1.0031 (26)		

Pich 2012.07099 [hep-ph];
DB 1992 (updated)

How to interpret non-universality observations?

Speculations :

- New non-SM couplings?

  1000 TeV scale with couplings O(1)

  Charged Higgs H^+

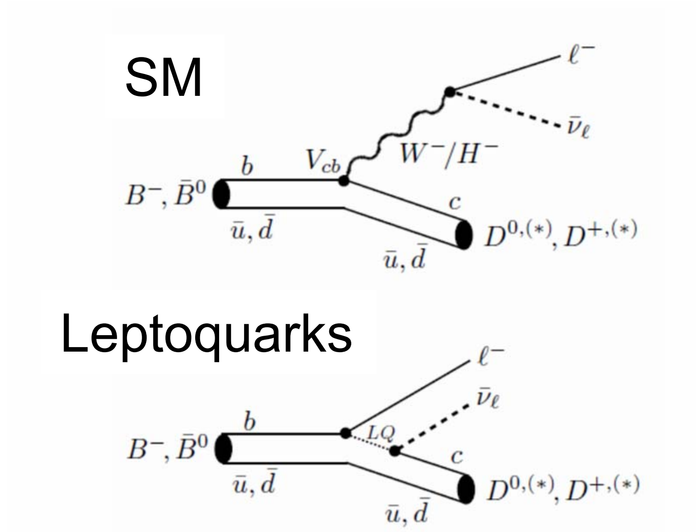
  Leptoquarks

  New Z'

  Hidden sector ...

- Sterile neutrinos or dark sector particles*

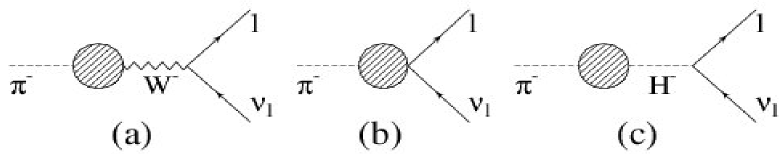
  * Mesogenesis (Elahi et al. 2109.09751[*hep* – *ph*])



Could precise measurements of 1st, 2nd generation decays be used to distinguish between models explaining 3rd generation LFUV effects?

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

Pseudoscalar interactions



Charged Higgs (non-SM coupling)

$$1 - \frac{R^{New}_{e/\mu}}{R^{SM}_{e/\mu}} \sim \mp \frac{\sqrt{2}\pi}{G_\mu}\frac{1}{\Lambda^2_{eP}}\frac{m^2_\pi}{m_e(m_d+m_u)} \sim (\frac{1TeV}{\Lambda_{eP}})^2 \times 10^3$$

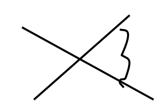
Marciano…

0.01 % measurement→Λ~3000 TeV

Many hypotheses:

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

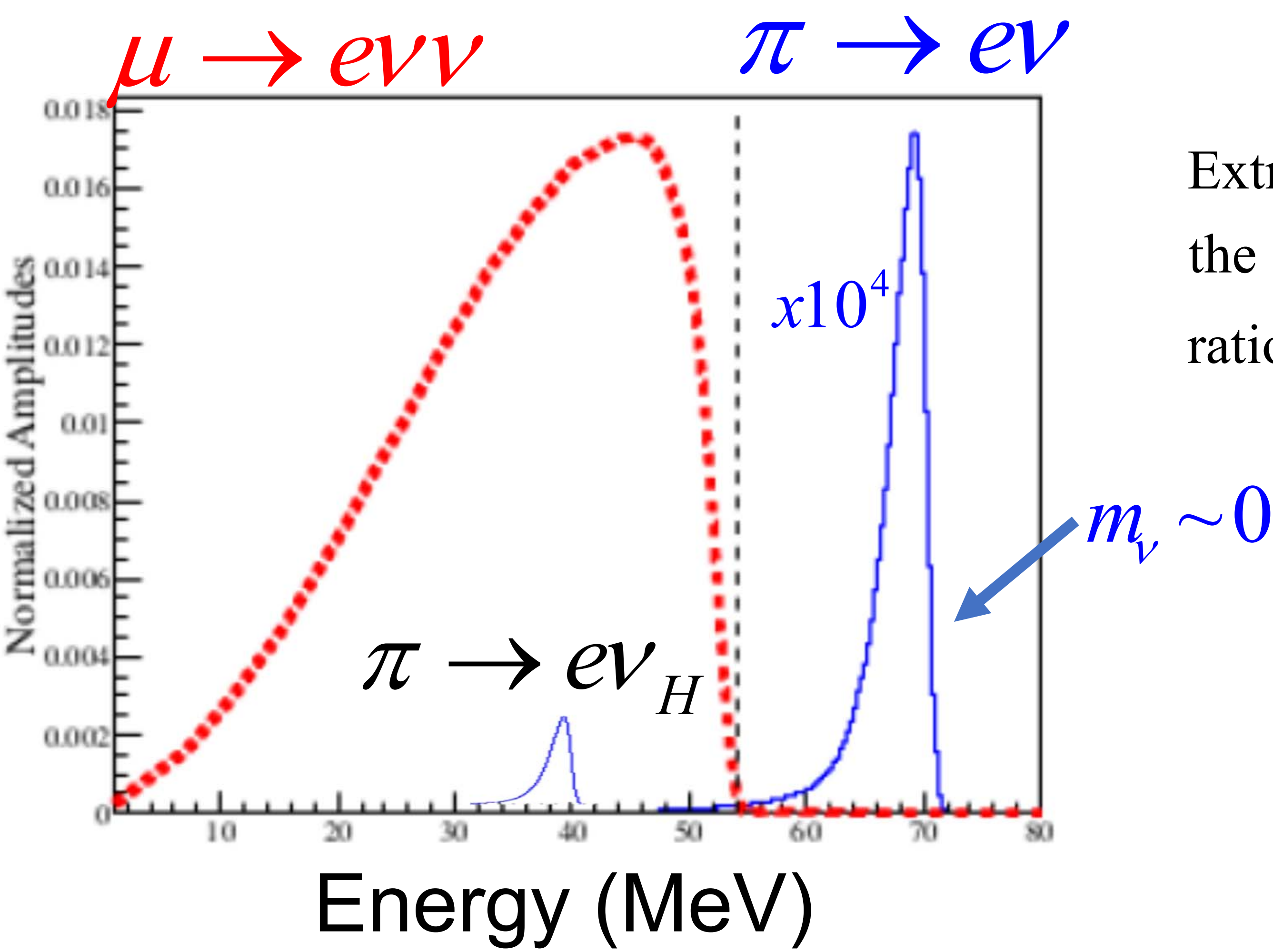
Induced Scalar Currents



Campbell and Maybury (2005), Marciano

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

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



Extra channel changes the $\pi \to e\nu$ branching ratio $R_{e/\mu}^{\exp}$

"LFU Violation" Example: Massive Sterile Neutrinos e.g. $\pi^+ \to l^+ \nu_{e4}$

$$\nu_l = \sum_{i=1}^{3+n_s} U_{li} \nu_i$$

- Extra peak in 2-body spectrum
- Effect on branching ratio

  $R^{\pi}_{e/\mu} = \Gamma(\pi^+ \to e^+ \nu_e) / \Gamma(\pi^+ \to \mu^+ \nu_e)$

$|U_{e4}|^2$: mixing coefficient for e and ν_{e4}

$$\bar{R}^{\pi}_{e/\mu} = \frac{R^{\pi\,\exp}_{e/\mu}}{R^{SM}_{e/\mu}} = \frac{(1-|U_{e4}|^2) + |U_{e4}|^2\, \bar{\rho}(m_e, m_{\nu 4})}{(1-|U_{\mu 4}|^2) + |U_{\mu 4}|^2\, \bar{\rho}(m_\mu, m_{\nu 4})} \sim (1-|U_{e4}|^2) + |U_{e4}|^2\, \bar{\rho}(m_e, m_{\nu 4})$$

$$|U_{\ell 4}|^2 < \frac{\bar{R}^{(M)}_{\ell/\ell'} - 1}{\bar{\rho}(\delta^{(M)}_{\ell}, \delta^{(M)}_{\nu_4}) - 1}$$

- Ratio of kinematic factors

$$\bar{\rho}(x,y) = \frac{\rho(x,y)}{\rho(x,0)} = \frac{\rho(x,y)}{x(1-x)^2}$$

Kinematic enhancements at large ν_{e4} mass

Decay	$(m_{\nu_4})_{\bar{\rho}_{\max}}$	$\bar{\rho}_{\max}$
$\pi^+ \to e^+ \nu_4$	80.6	1.105×10^4
$K^+ \to e^+ \nu_4$	285	1.38×10^5
$D^+ \to e^+ \nu_4$	1.08×10^3	1.98×10^6
$D_s^+ \to e^+ \nu_4$	1.14×10^3	2.20×10^6
$B^+ \to e^+ \nu_4$	3.05×10^3	1.58×10^7

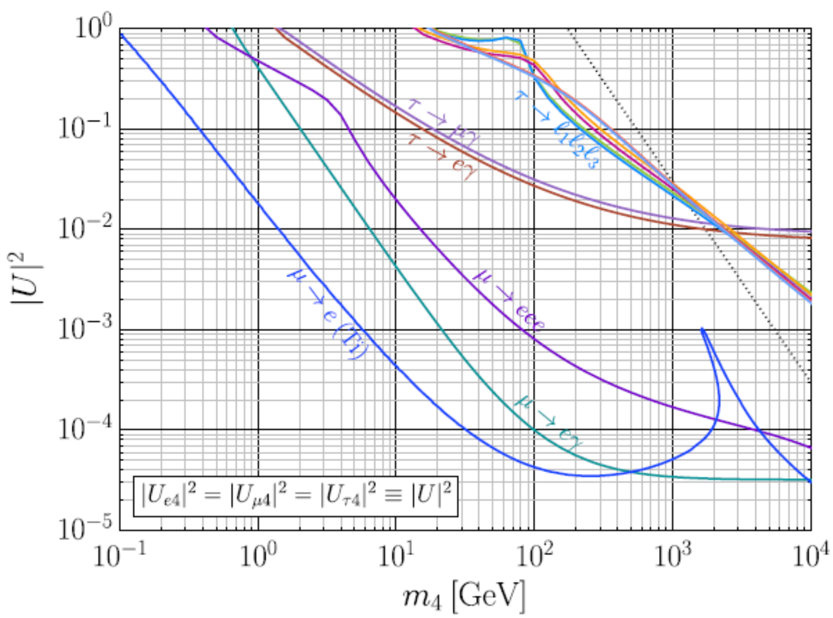
R. Shrock and D.B. 2019

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

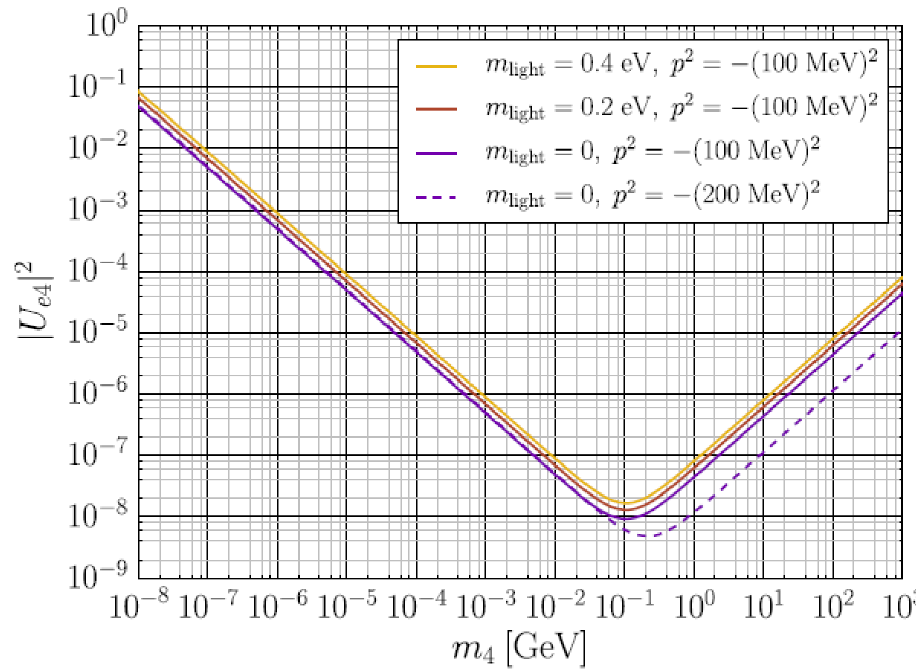
Connections: LFU, LFV, LNV with Sterile Neutrinos

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

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



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



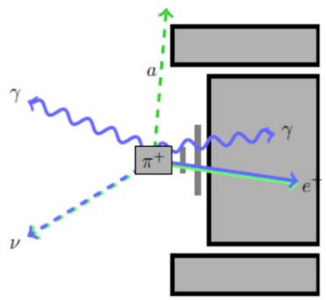
Other connections with LNV : $\mu^- Z \to e^+(Z-2),\ K \to \pi\mu\mu....$

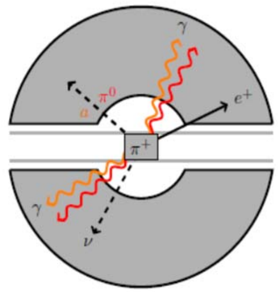
Altmannshofer, Gori, Robinson, *Phys.Rev.D* 101 (2020) 7, 075002

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

$$\pi \to e\nu a \;\&\; \pi \to e\nu a;\ a \to \gamma\gamma$$

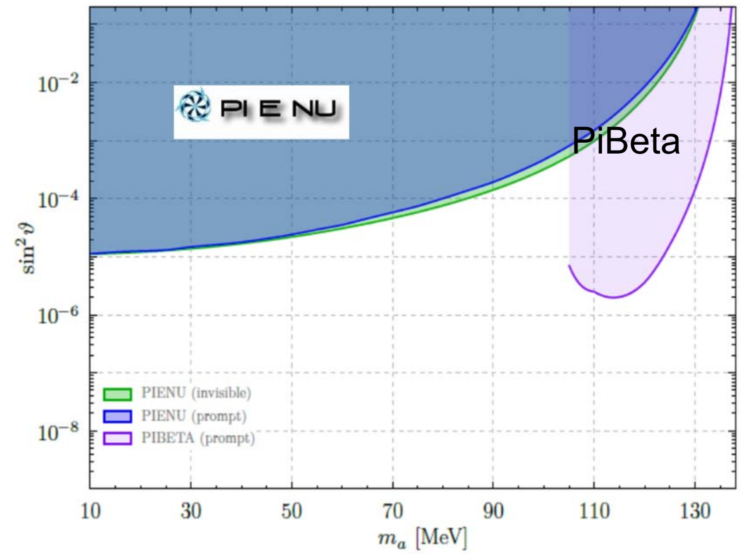
$alp - \pi$ Mixing vs. m_a



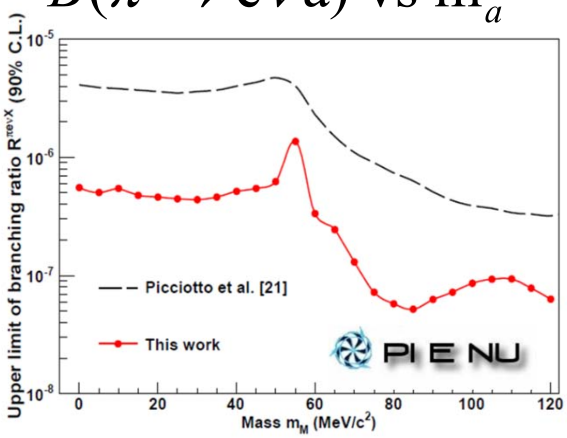


PI E NU

PiBeta



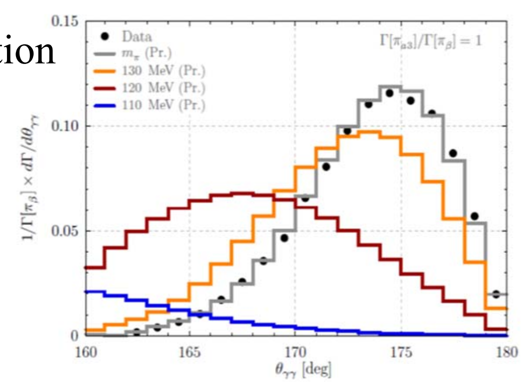
$B(\pi \to e\nu a)$ vs m_a



$a \to \gamma\gamma$ Angular distribution

$\pi \to e\nu a;\ a \to \gamma\gamma$

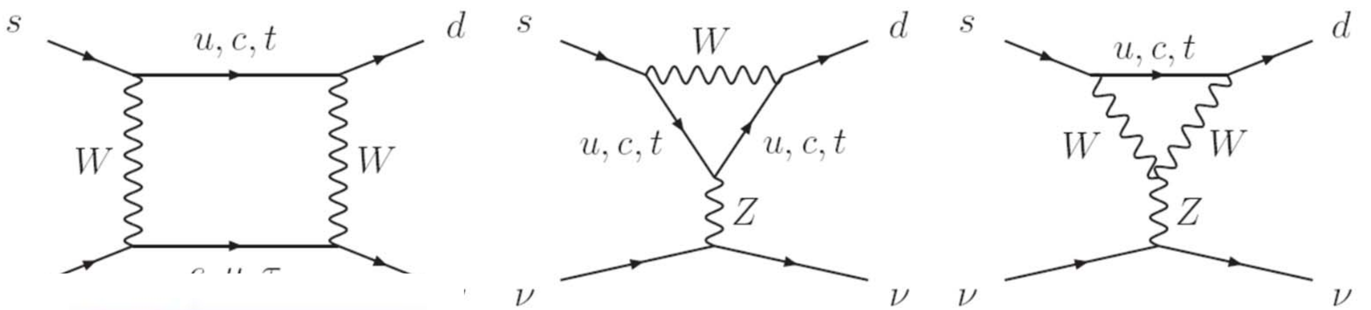
for different m_a

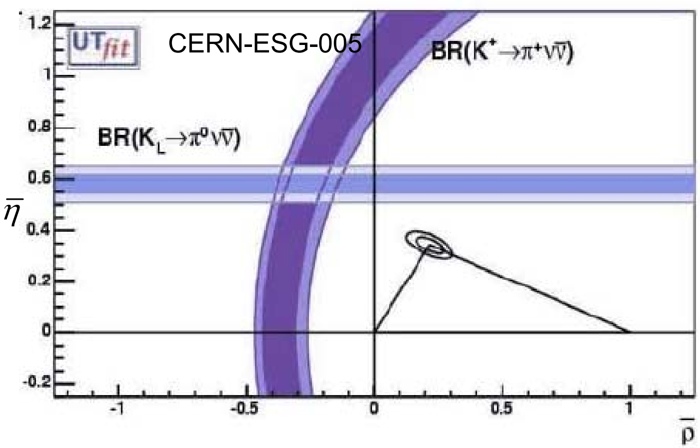


$K^+ \to \pi^+ \nu \bar{\nu}$ in the Standard Model

The $K \to \pi \nu \bar{\nu}$ decays are the most precisely predicted FCNC decays.

SM diagrams involve all 3 generations of quarks and leptons.





A single effective operator $(\bar{s}_L \gamma^\mu d_L)(\bar{\nu}_L \gamma_\mu \nu_L)$

Dominated by top quark

(charm significant, but controlled)

Hadronic matrix element shared with Ke3

Remains clean in most New Physics models

$$B_{SM}(K^+ \to \pi^+ \nu \bar{\nu}) = (8.4 \pm 1.0) \times 10^{-11}$$

$$B_{SM}(K_L^0 \to \pi^0 \nu \bar{\nu}) = (3.4 \pm 0.6) \times 10^{-11}$$

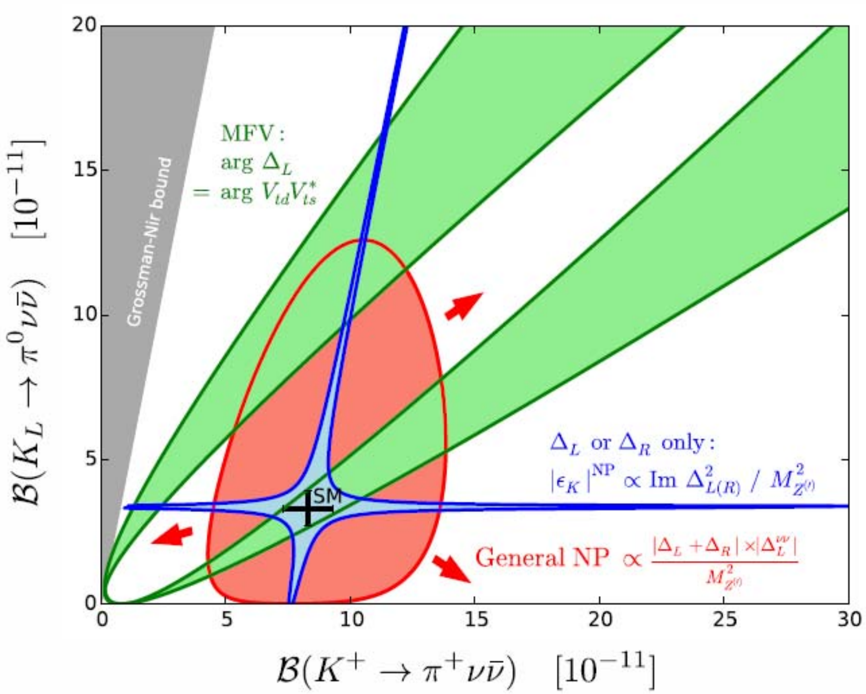
A. J. Buras, D. Buttazzo, R. Knegjens, ArXiv:1507.08672v2

Expect total SM theory error ≤6%.

30% deviation from the SM would be a 5σ signal of NP

New Physics Sensitivity of $K^+ \to \pi^+ \nu\bar{\nu}$

$B(K_L^0 \to \pi^0 \nu\bar{\nu})$ *vs* $B(K^+ \to \pi^+ \nu\bar{\nu})$



- Minimum flavor violation models
- Supersymmetric models
- Littlest Higgs (LH) model without/with T-parity
- Randall-Sundrum models
  -general LH, RH couplings
- Partial compositeness
- Models in which ε_k constraint applies

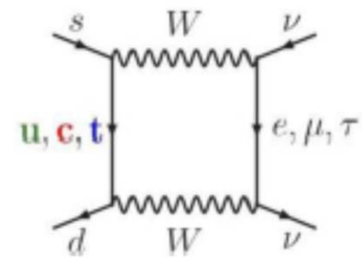
Andrzej J. Buras, Dario Buttazzo and Robert Knegjens arXiv:1507.08672 (2015)

Other potential correlations of $K^+ \to \pi^+ \nu\bar{\nu}$ with

$$K_L^0 \to \mu\mu,\ \varepsilon'/\varepsilon,\ B \to K(K^*)\mu\mu$$

Bordone, Buttazzo, Isidori, Monnard ArXiv:1705.10729

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



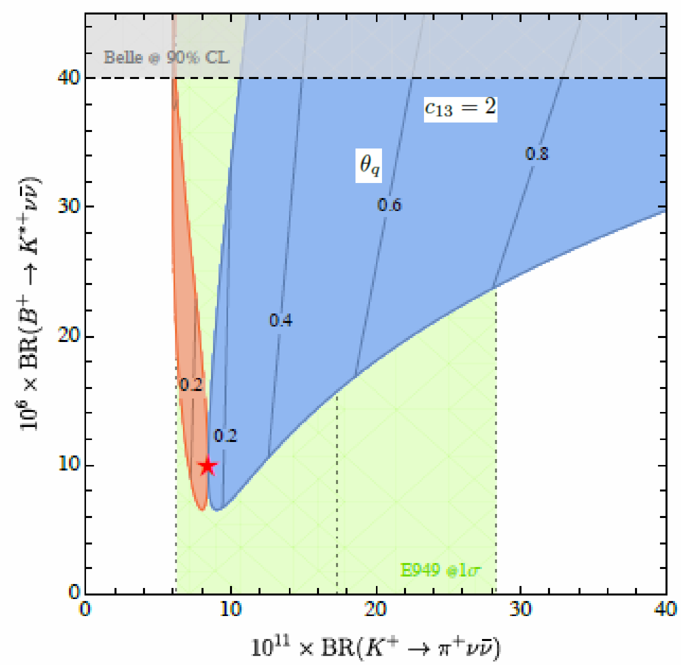
Involves third generation quarks (top) and leptons (τ, ν_τ)

EFT approach to LFU violations new interactions with $U(2)_q \times U(2)_l$ 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%]

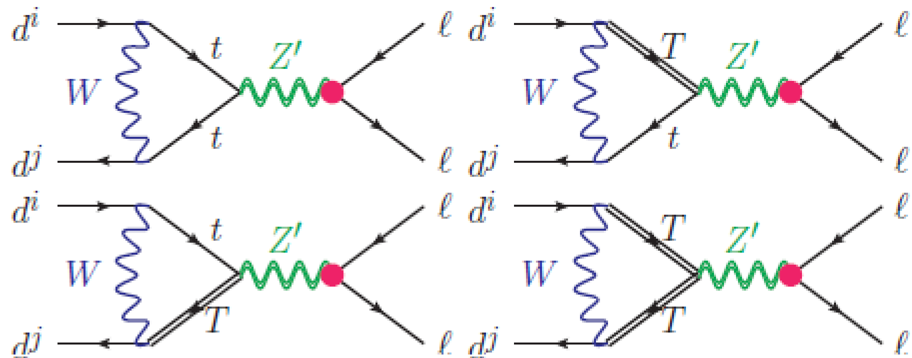


Kamenik, Soreq, Zupan arXiv:1704.06005v (2017)

Example: Effects of LFU violation on $K^+ \to \pi^+ \nu\bar{\nu}$

Light Z' in b $\to s\mu\mu$ decays to explain R(K)

Couples to rt. handed top and muons



$$\mathcal{H}_{\rm eff} = -\frac{4G_F}{\sqrt{2}} V_{tb} V_{ts}^* \frac{e^2}{16\pi^2} \sum_i \left(C_i^\ell O_i^\ell + C_i'^\ell O_i'^\ell \right) + \text{h.c.}$$

$$\mathcal{B}(K^+ \to \pi^+ \nu\bar{\nu}(\gamma)) = (8.4 \pm 1.0) \times 10^{-11} \times \frac{1}{3} \sum_\ell \left| 1 + \frac{s_W^2 (C_9^{\ell,\rm NP} - C_{10}^{\ell,\rm NP})}{X_{\rm SM}} \right|^2,$$

$$R_K \to C_9^{\mu,\rm NP} = -C_{10}^{\mu,\rm NP} \simeq 0.60(15)$$

$$\frac{B(K^+ \to \pi^+ \nu\bar{\nu})}{B(K^+ \to \pi^+ \nu\bar{\nu})_{SM}} \sim 1.09 - 1.28 \ \text{(Possibly within reach of NA62)}$$

Experiments Status and Prospects

$$K^+ \to \pi^+ \nu \overline{\nu}$$

$$\pi^+ \to e^+ \nu(\gamma)$$

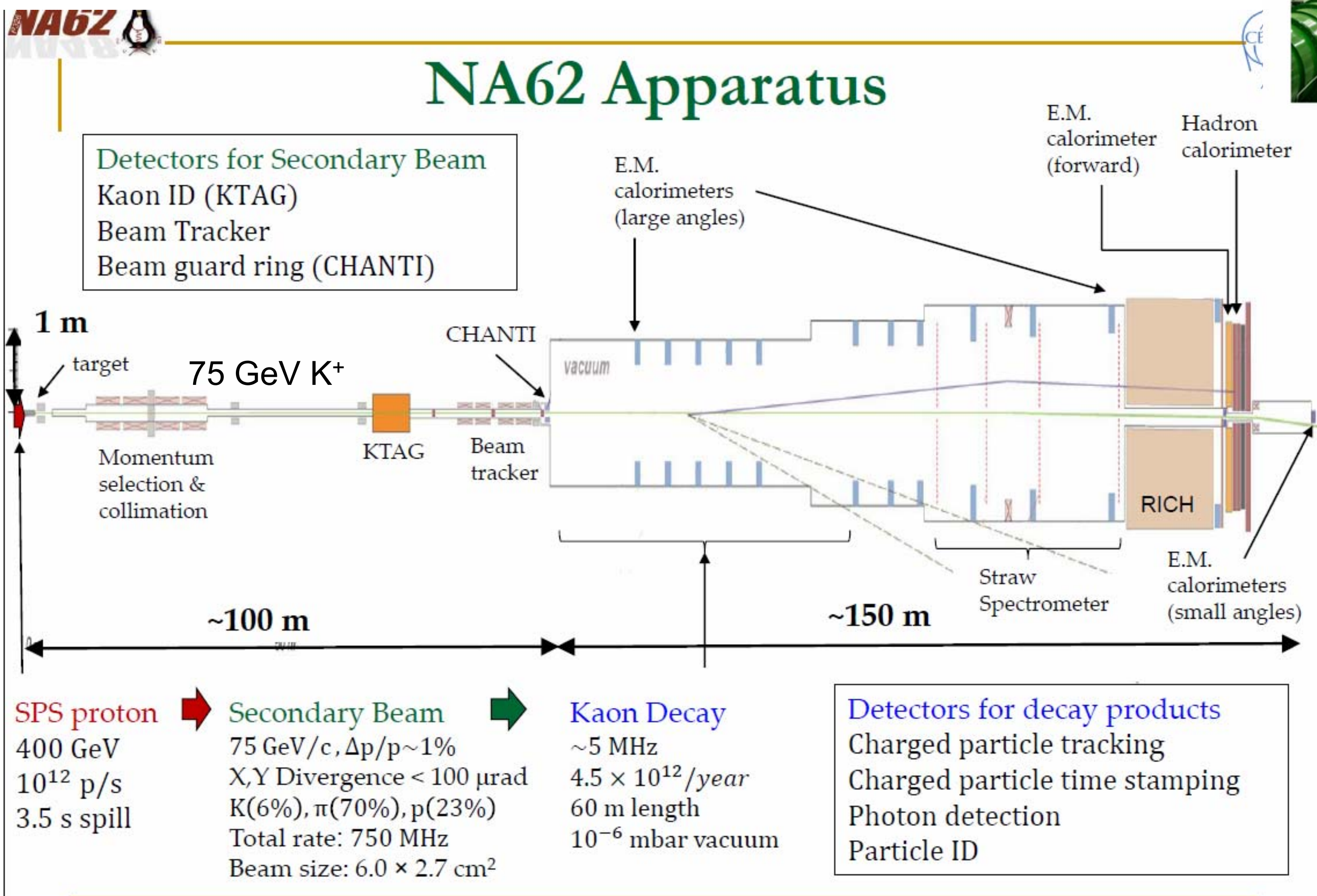
$$\pi^+ \to \pi^0 e^+ \nu(\gamma)$$

Measurement of $K^+ \rightarrow \pi^+ \nu\bar{\nu}$ and other rare decays

Aiming for 10-20% precision for SM $K^+ \rightarrow \pi^+ \nu\bar{\nu}$

The NA62 detector

NA62 physics data taking started in June 2015



Most "efficient" detector ever built.

CERN's longest experiment?

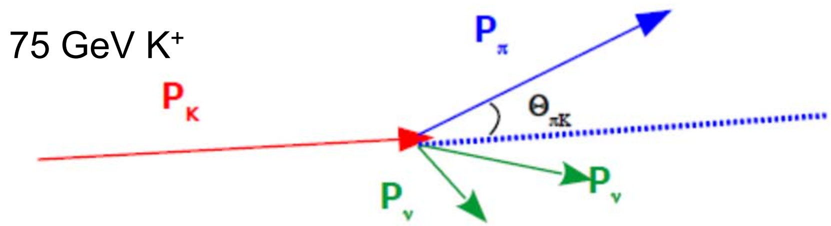
Operation 2015-2018, 2021-2023 + beam dump mode)

Analysis strategy $K^+ \to \pi^+ \nu \bar{\nu}$

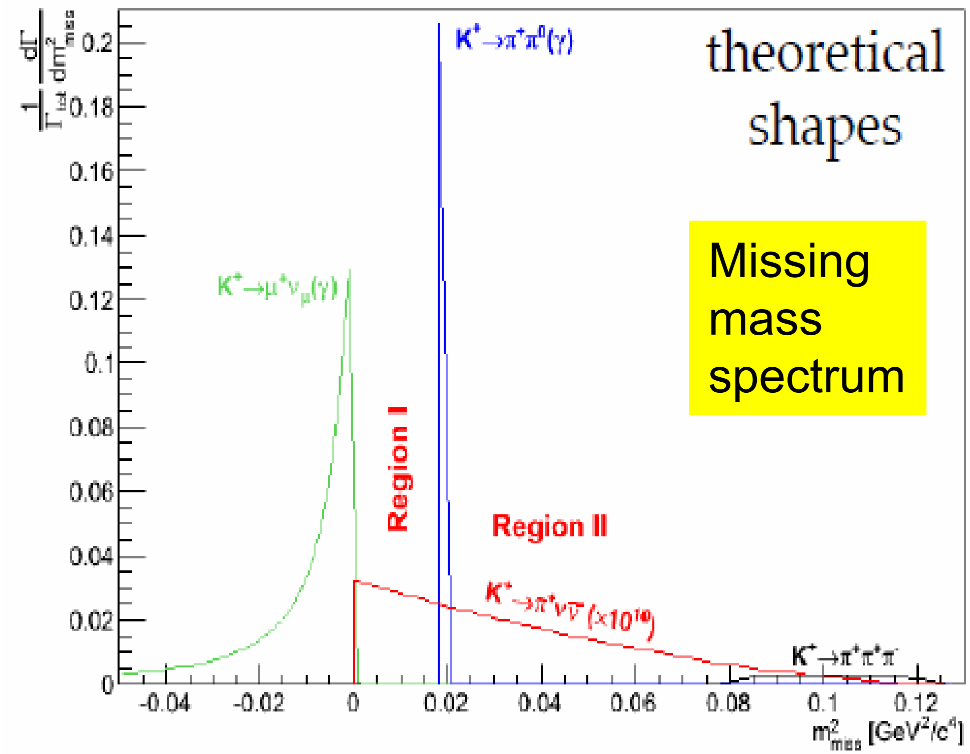
Decay-in-flight technique

$$m^2_{miss} = (P_K - P_{\pi^+})^2$$

π^+ mass assumed for the track



- **Muon suppression:** > 10^7
- **π^0 suppression (from $K^+ \to \pi^+\pi^0$):** > 10^8
- **Excellent time resolution:** O(100ps)
- **Kinematic suppression:** ~ O(10^4)



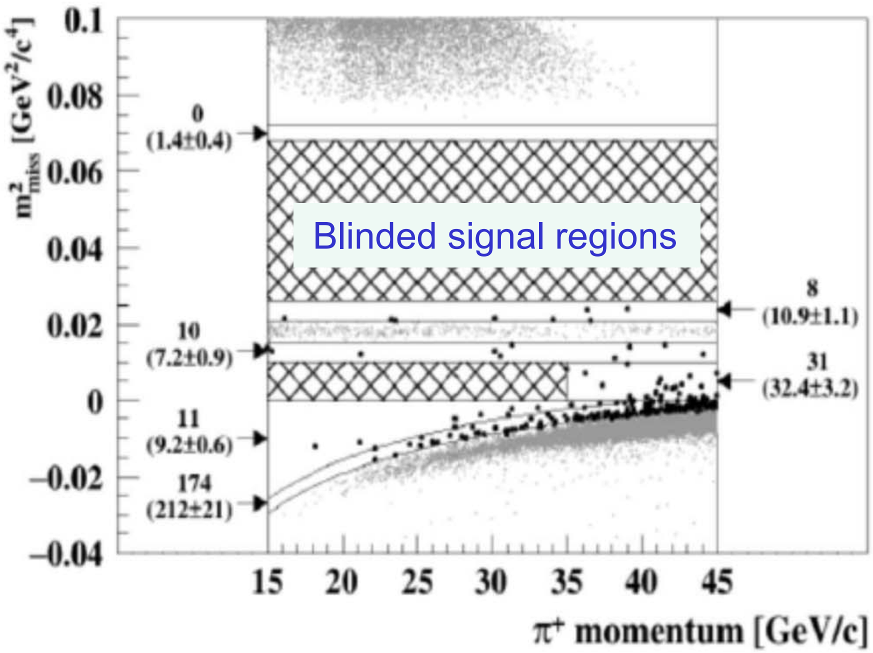
Process		Branching ratio
$K^+ \to \pi^+\pi^0$	$(K_{\pi 2})$	0.2066
$K^+ \to \mu^+\nu_\mu$	$(K_{\mu 2})$	0.6356
$K^+ \to \pi^+\pi^+\pi^-$		0.0558
$K^+ \to \pi^+\pi^- e\, \nu_e$		4.3×10^{-5}
$K^+ \to \pi^+\nu\nu$ (SM)		**8.4×10^{-11}**

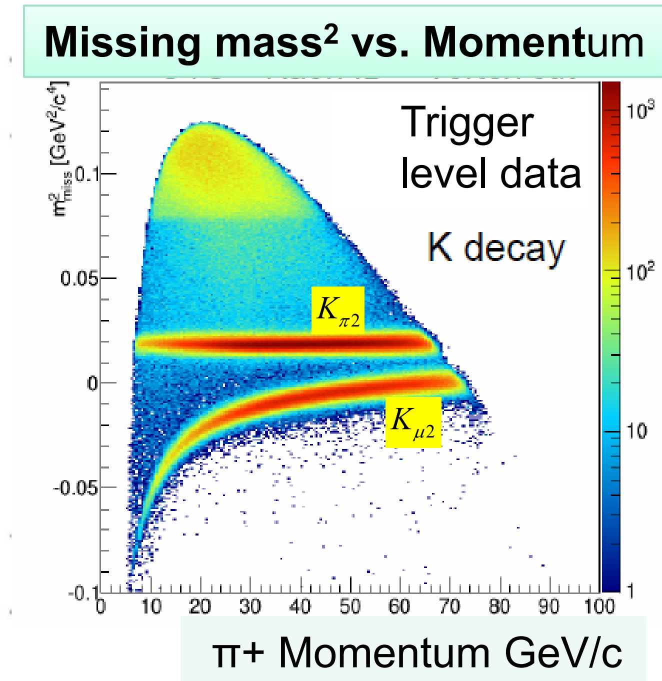
NA62 Data Taking 2016-18

Blind analysis: control regions validated prior to opening box.

Backgrounds dominated by accidental upstream decays.

NA62 $(\text{Missing Mass})^2 \; vs \; P_\pi$ (2018 data)





Measurement of $K^+ \rightarrow \pi^+ \nu \bar{\nu}$

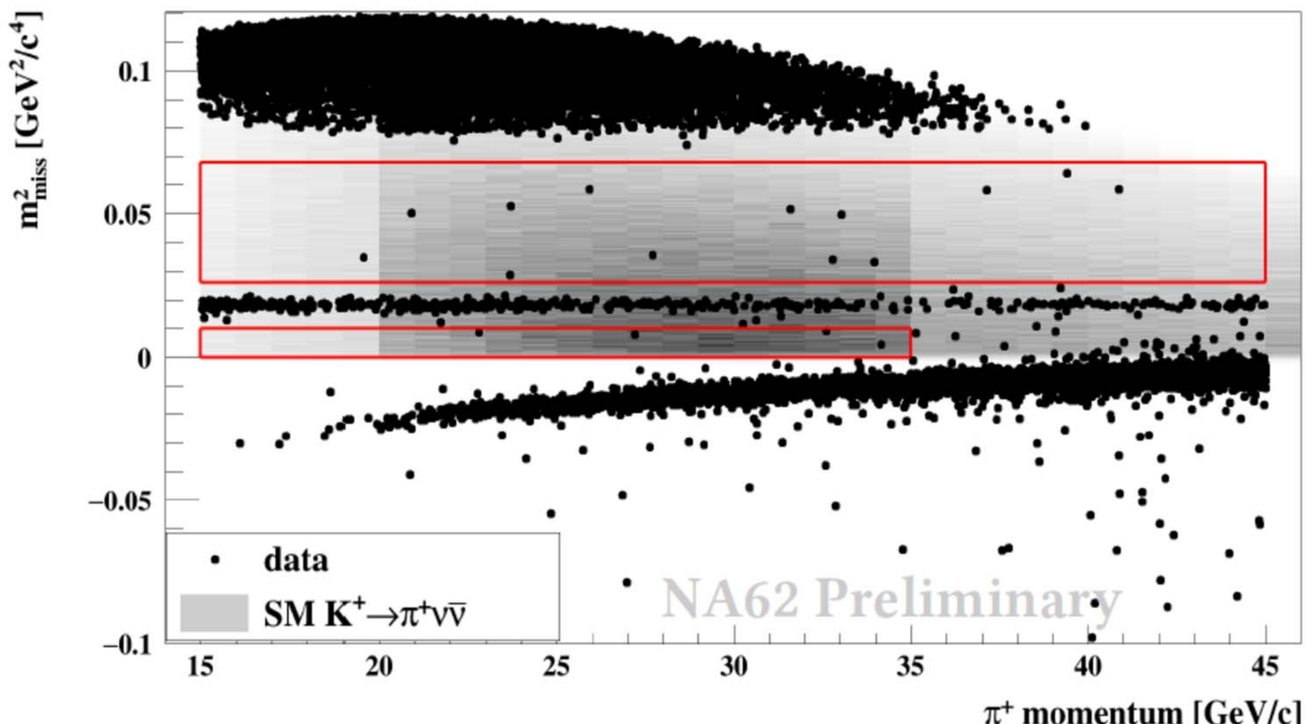
NA62 (2020) Results (2016-2018 data):

$B(K^+ \rightarrow \pi^+ \nu \bar{\nu}) = \left(10.6^{+4.0}_{-3.6}\,_{Stat} \pm 0.9_{Syst}\right) x10^{-11}$ (3.4σ significance)

SM expectation: 10
Expected bkg.: 7
Observed: 20

In agreement with Standard Model: $B_{SM}(K^+ \rightarrow \pi^+ \nu \bar{\nu}) = (8.4 \pm 1.0) \text{ x } 10^{-11}$

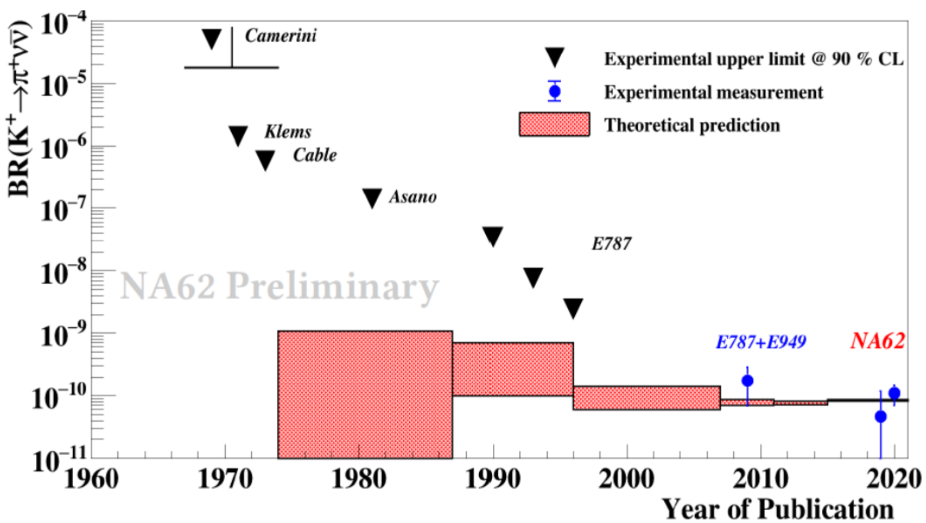
$(\text{Missing Mass})^2$ *vs* P_π (2018 data)



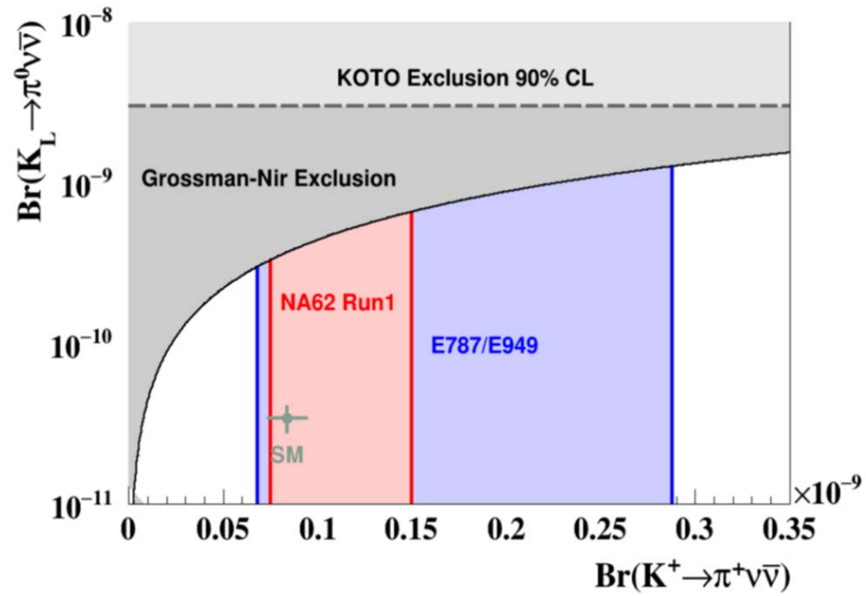
Blinded control regions validated prior to opening box.

Backgrounds dominated by accidental upstream decays.

$B(K^{+} \to \pi^{+}\nu\overline{\nu})$ vs. Year



$B(K_L^0 \to \pi^0\nu\overline{\nu})$ vs. $B(K^{+} \to \pi^{+}\nu\overline{\nu})$



Two Pion Decay Experiments: PIENU and PEN

TRIUMF

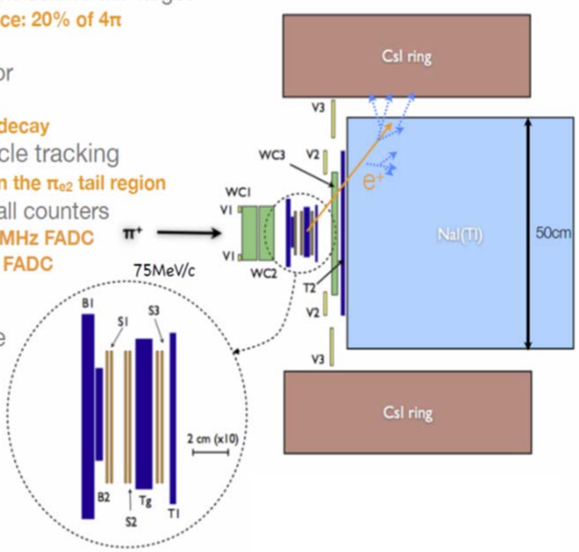
PSI

PI E NU

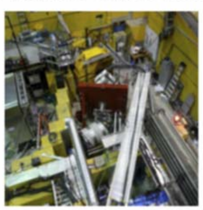
$$\frac{\pi^+ \to e^+ \nu}{\pi^+ \to \mu^+ \nu} \;\&\; \pi^+ \to e/\mu^+ \nu_H$$

& exotics

- 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



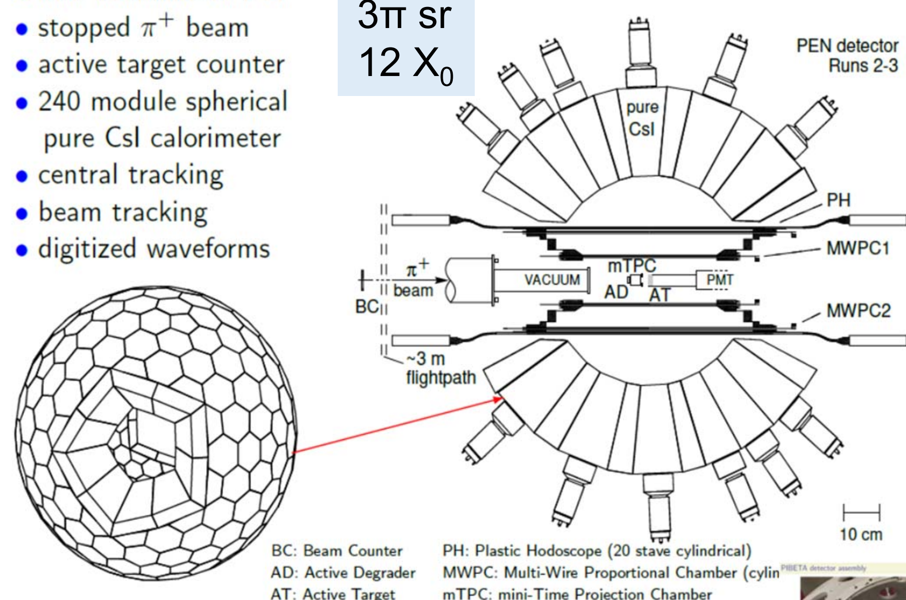
- TRIUMF M13 beamline

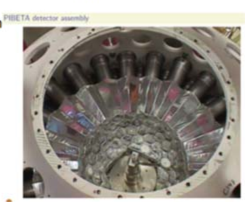


The PEN/PIBETA apparatus $\pi^+ \to \pi^0 e^+ \nu \;\&\; \pi^+ \to e^+ \nu(\gamma)$

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

3π sr
12 X_0





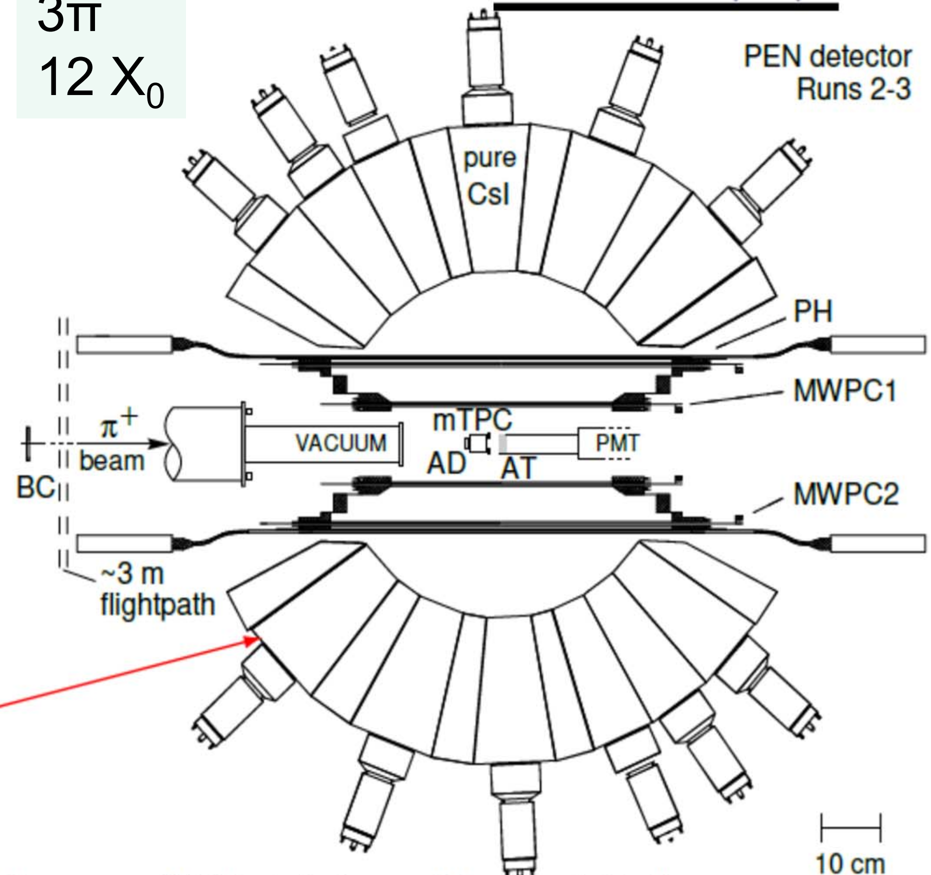
PIBETA signal: $\pi^0 \to \gamma\gamma$

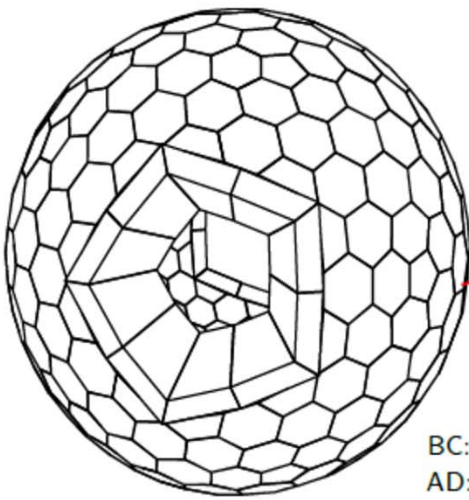
The PEN/PIBETA apparatus Pion Beta Decay and $\pi \to e\nu\gamma_{SD}$

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

3π
12 X_0

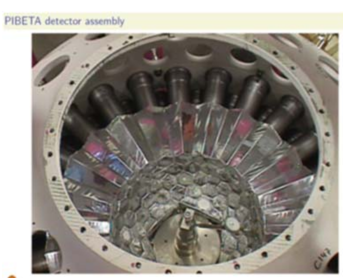
D. Počanić (UVa)





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



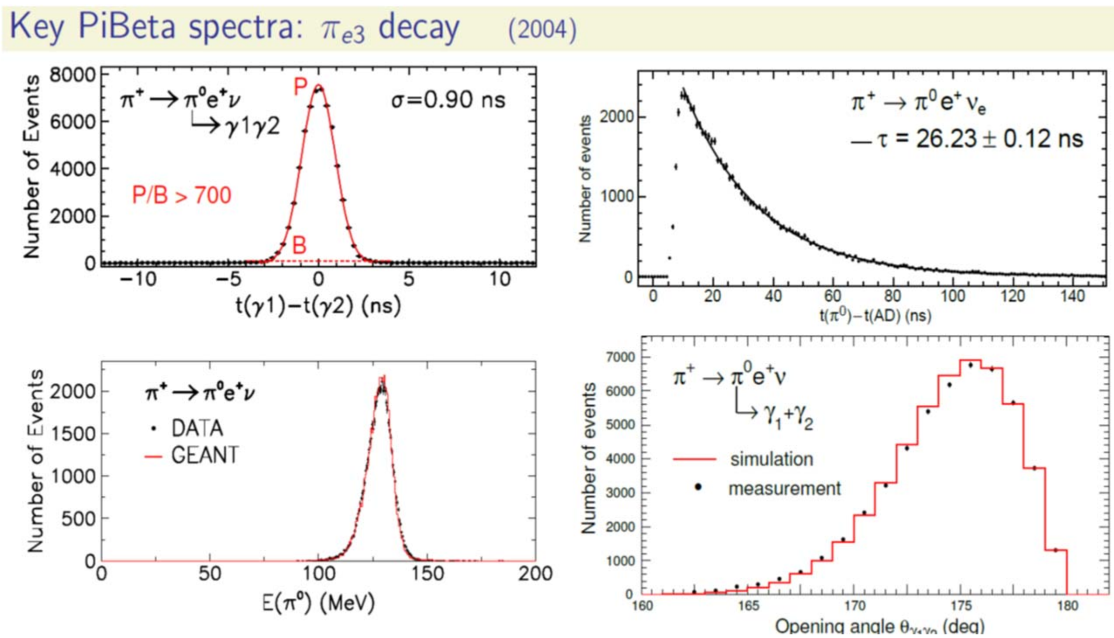
$R^{\pi}_{\mu/e}$ Precision Goal: <0.1%

PiBeta result for $\pi^+ \to \pi^0 e^+ \nu$ (π_β) decay [PRL **93**, 181803 (2004)]

Pion beta decay yield normalized to measured $\pi \to e\nu$ events:

$$B(\pi^+ \to \pi^0 e^+ \nu) = (1.038 \pm 0.004_{stat} \pm 0.004_{syst} \pm 0.002_{\pi e2})\ \mathrm{x}10^{-8} \quad (\pm 0.66\%)$$

$$PiBeta:\ V_{ud} = 0.9738(28)_{exp}(1)_{th}\ ;\ PDG: V_{ud} = 0.97370(14)$$



64000

$\pi^+ \to \pi^0 e^+ \nu$

events

KEY Systematics
Acceptance: 0.19%
Normalization: 0.26%

CKM Unitarity: Vud, Vus/Vud

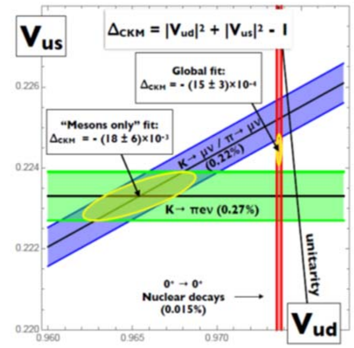
Tested in super-allowed β (V_{ud}) and K decays (V_{us}/V_{ud})

Czarnecki, Marciano , Sirlin (2020)

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

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

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



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

PIBETA Experiment $(\pm 0.6\%)$

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

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

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

PIENU Detector

BNL Crystals

- 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
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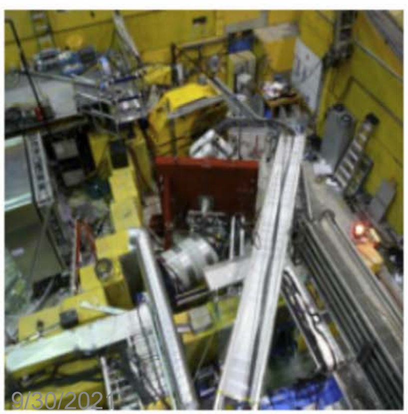
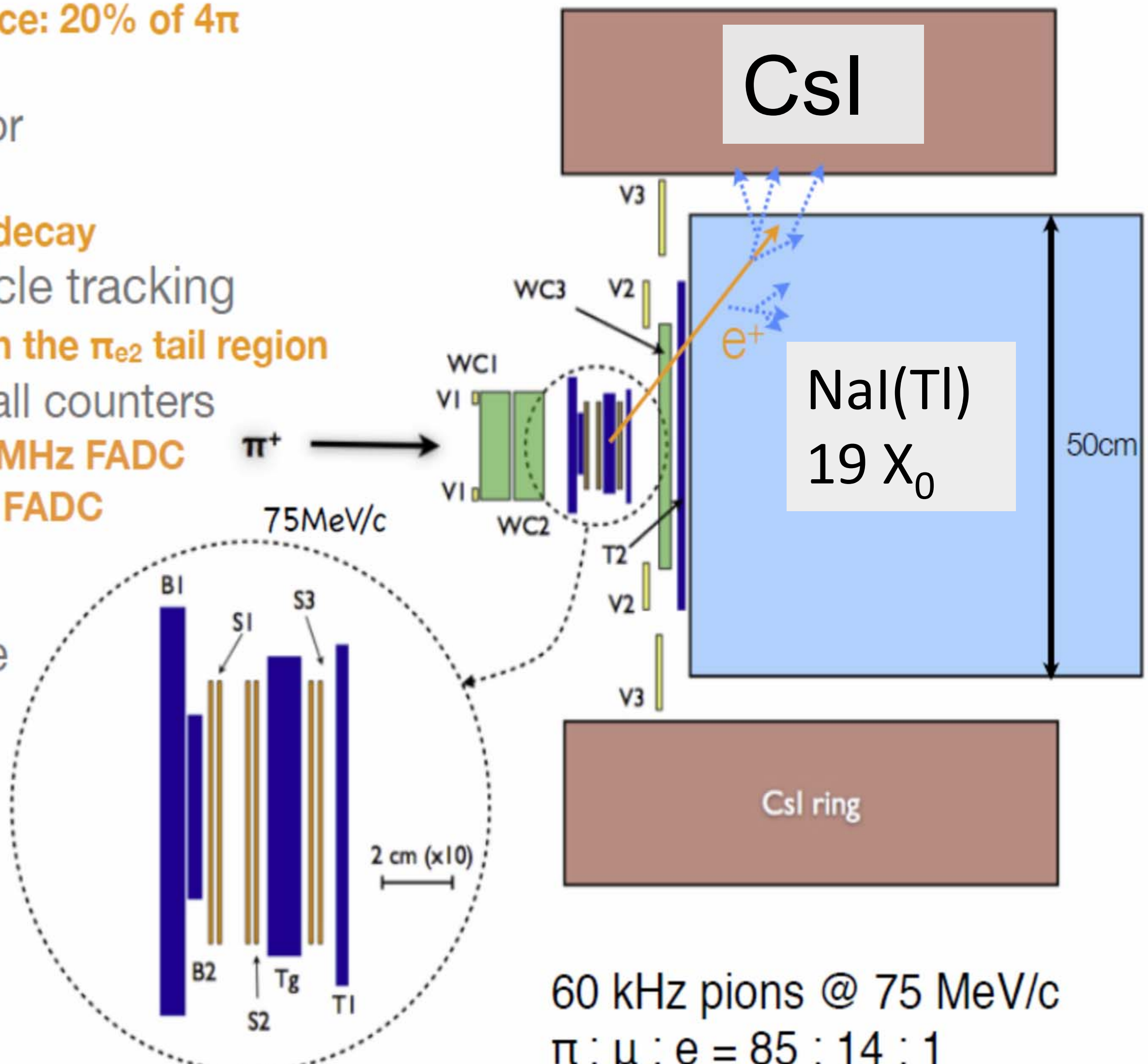
  - Pile-up tagging

- TRIUMF M13 beamline

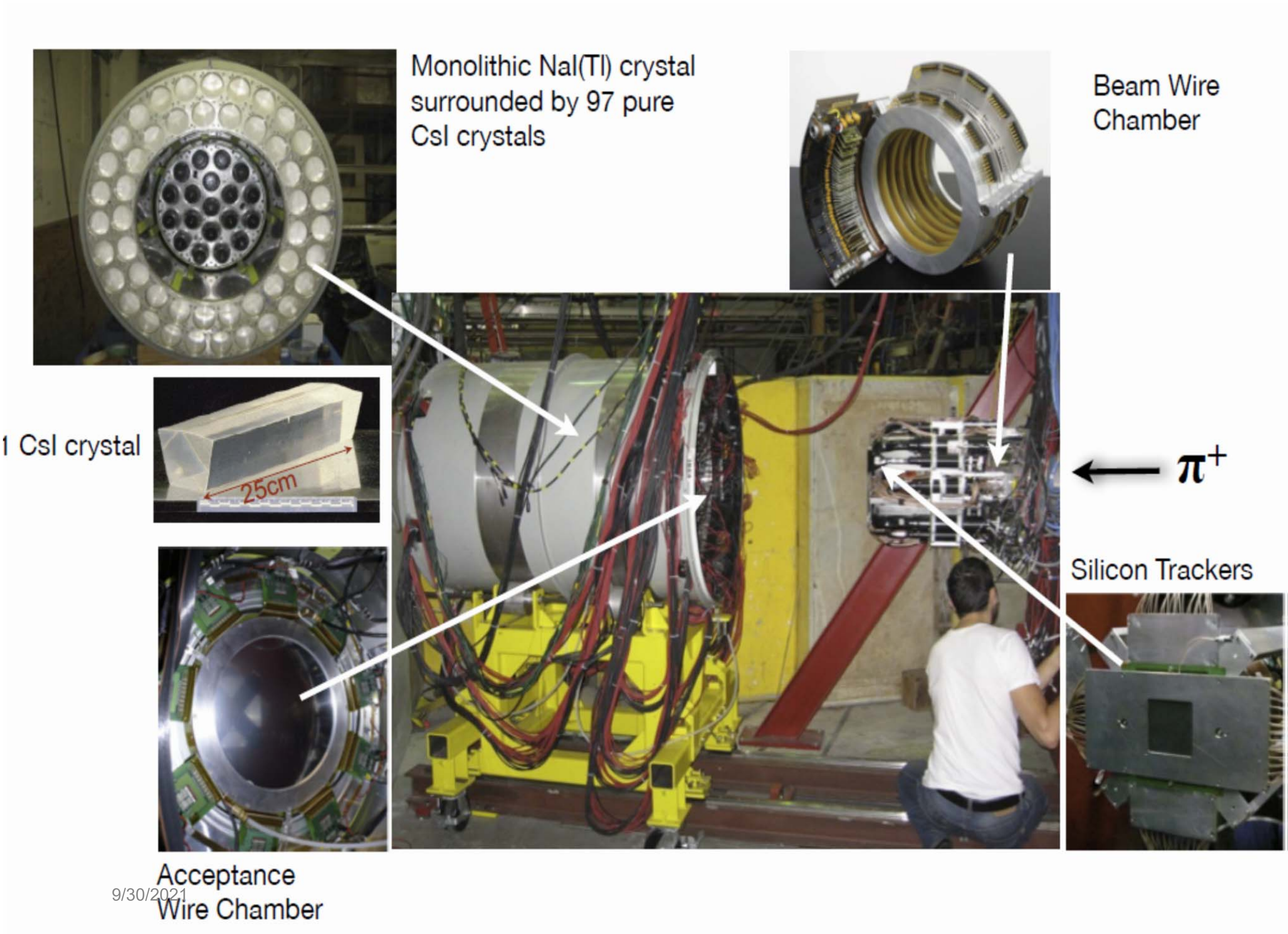




60 kHz pions @ 75 MeV/c

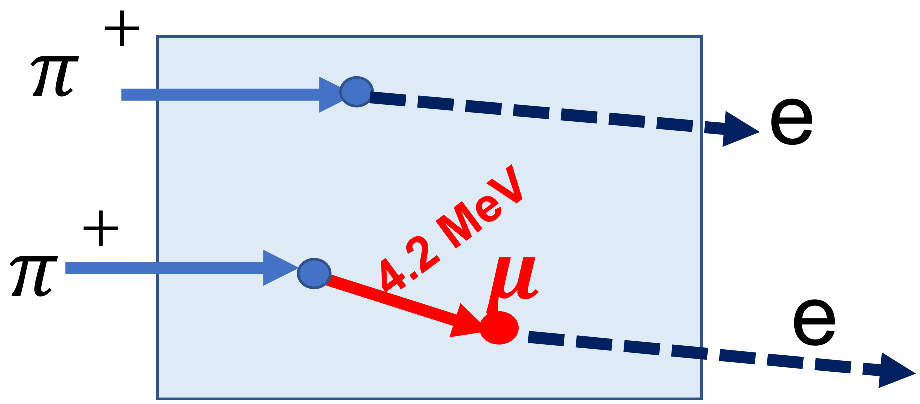
π : μ : e = 85 : 14 : 1

Table Top Experiment



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

Simple experiment: count e^+ from π decay

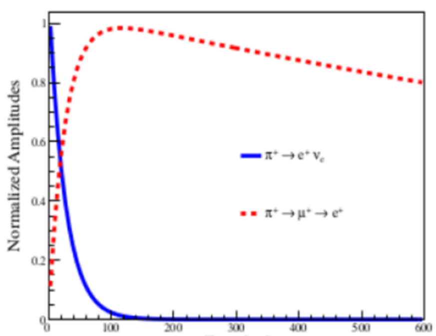


$$\frac{N(\pi \to e\nu)}{N(\pi \to \mu\nu)} \to \frac{N(\pi \to e\nu)}{N(\pi \to \mu \to e\nu\nu)}$$

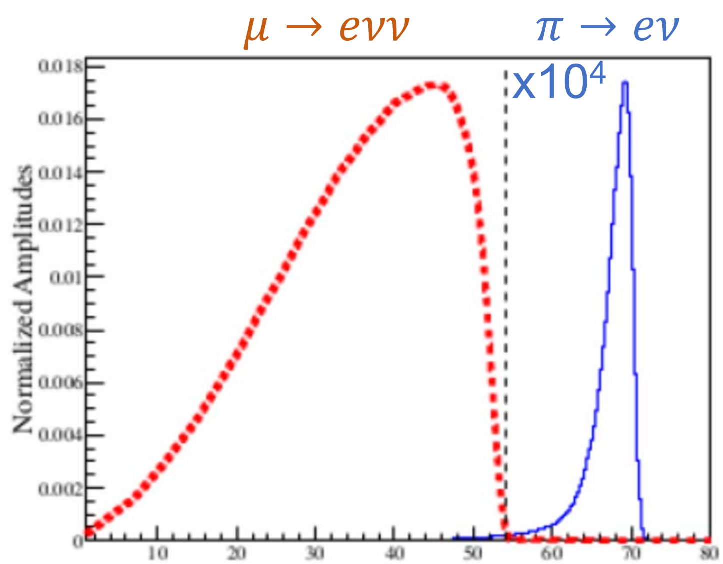
Lifetimes

$\tau_\pi = 26ns$

$\tau_\mu = 2.2\mu s$



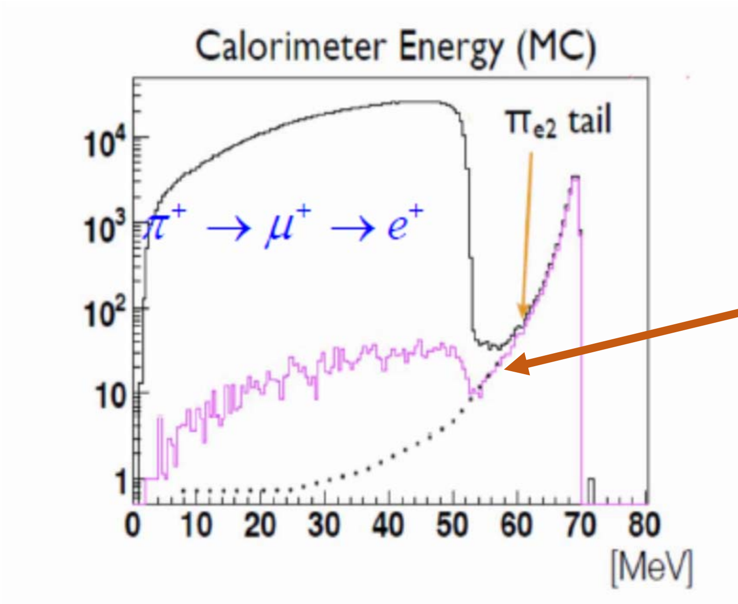
Time (ns)

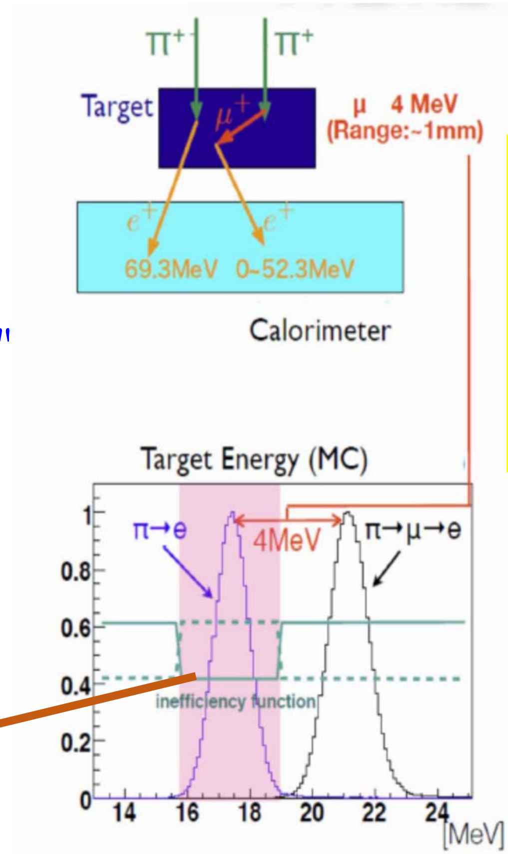


Energy (MeV)

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

$\pi \to \mu\nu$

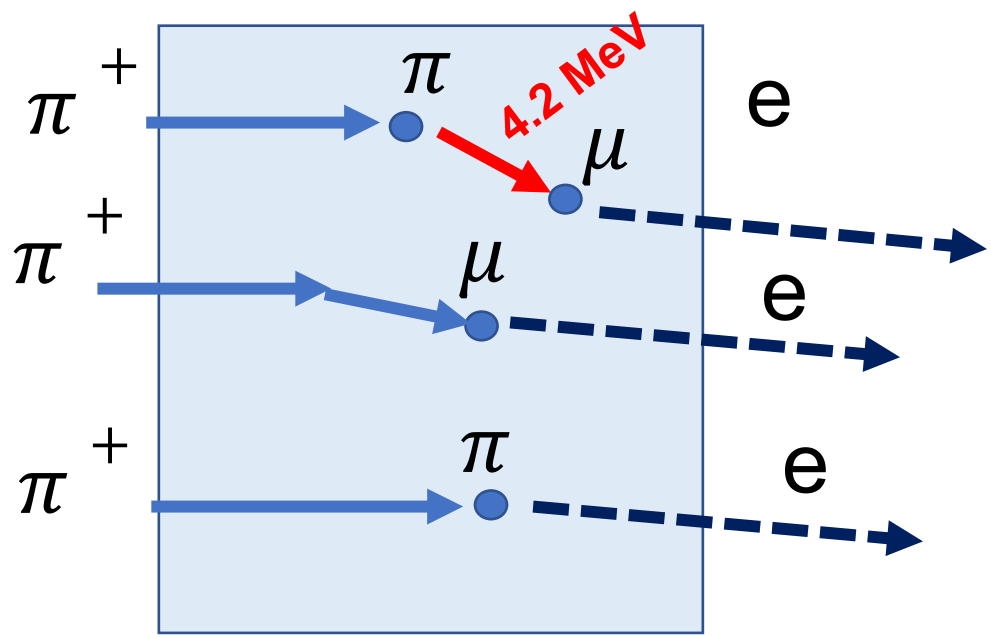
$T_\mu = 4.2MeV$

Background: $\pi \rightarrow \mu$ Decay-in-Flight (DIF) in target

Normal $\pi \rightarrow \mu \rightarrow e$

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

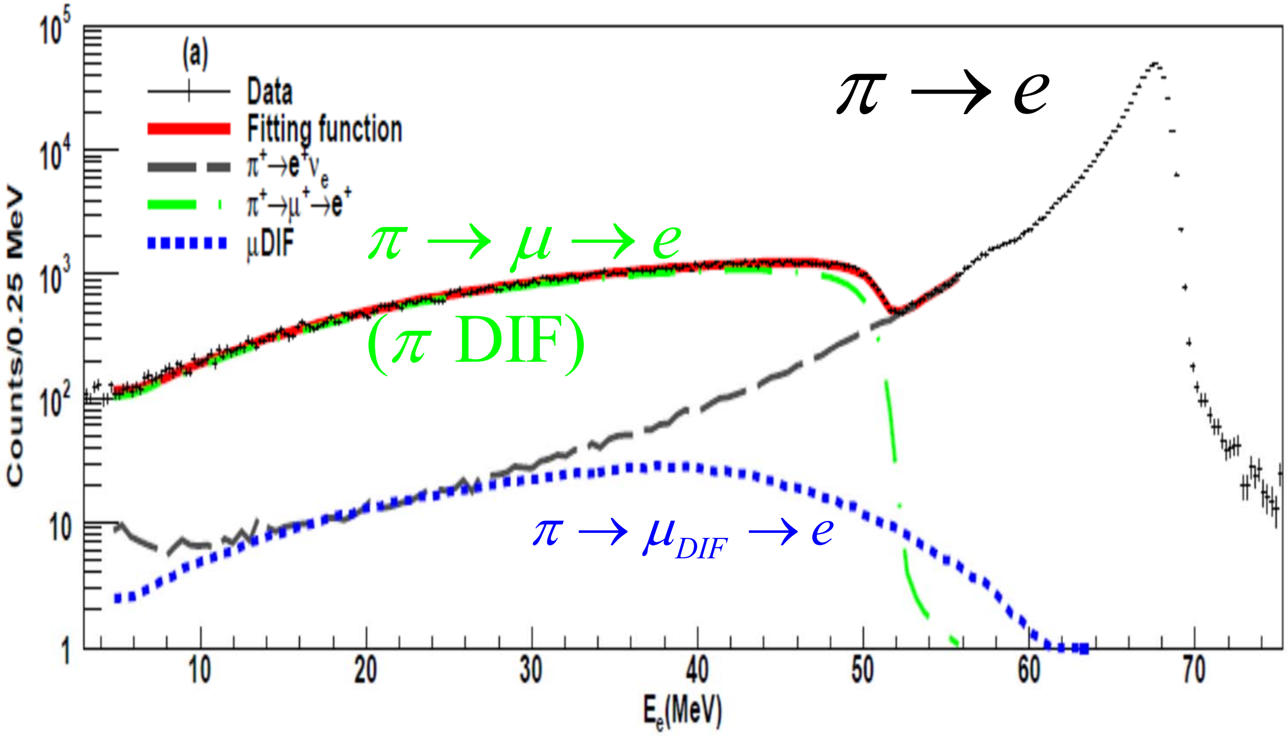
Normal $\pi \rightarrow e$



Background Suppressed $\pi \to e$

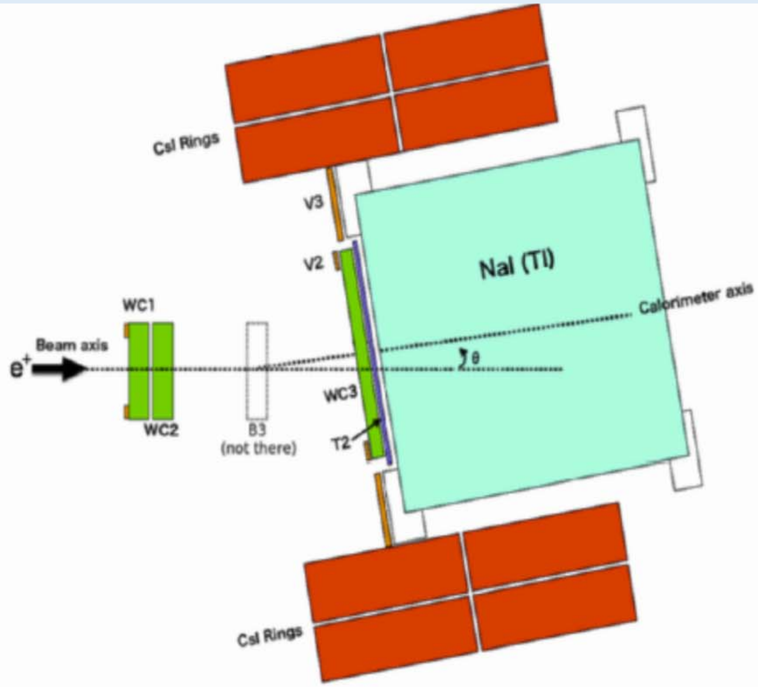
Suppress $\pi \to \mu \to e \sim 10^5$;

Residual bkg.: π – DIF in target.

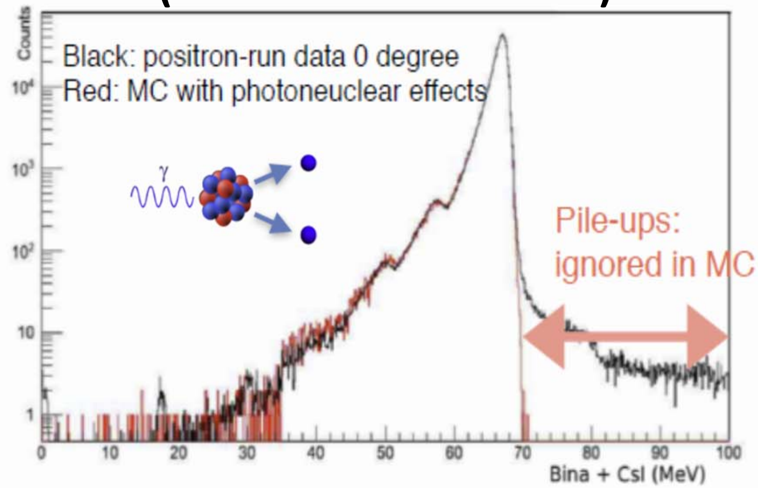


Tail Correction

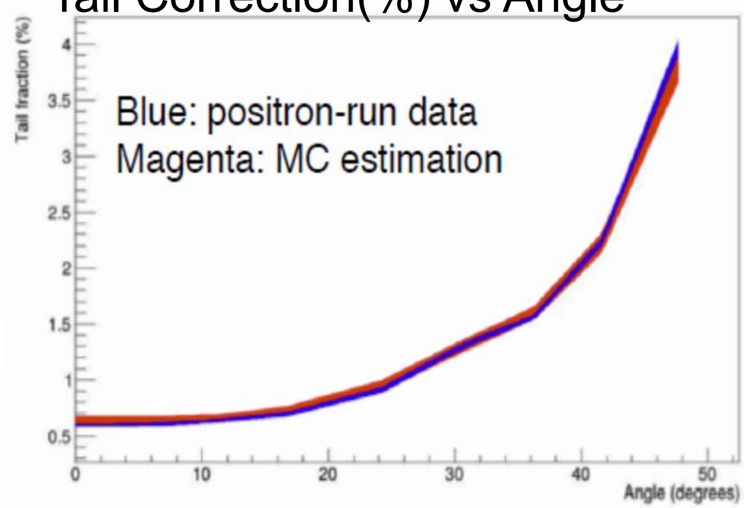
Important photo-nuclear effects observed.



Crystal Spectrometer Response (Photo-nuclear effects)



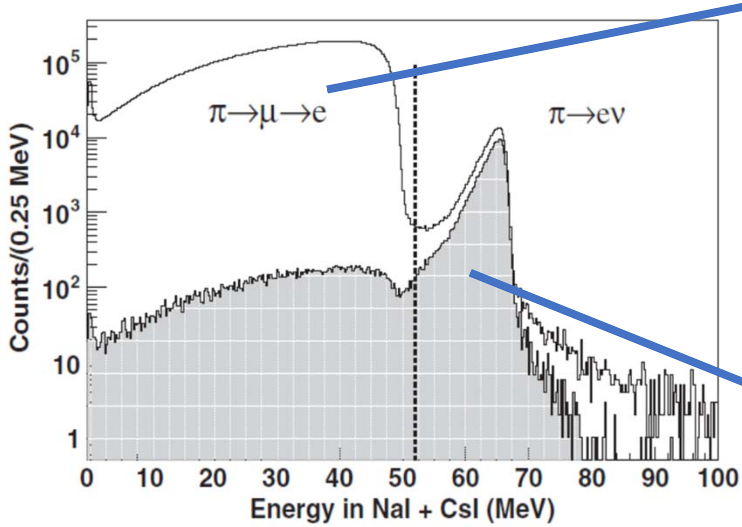
Tail Correction(%) vs Angle

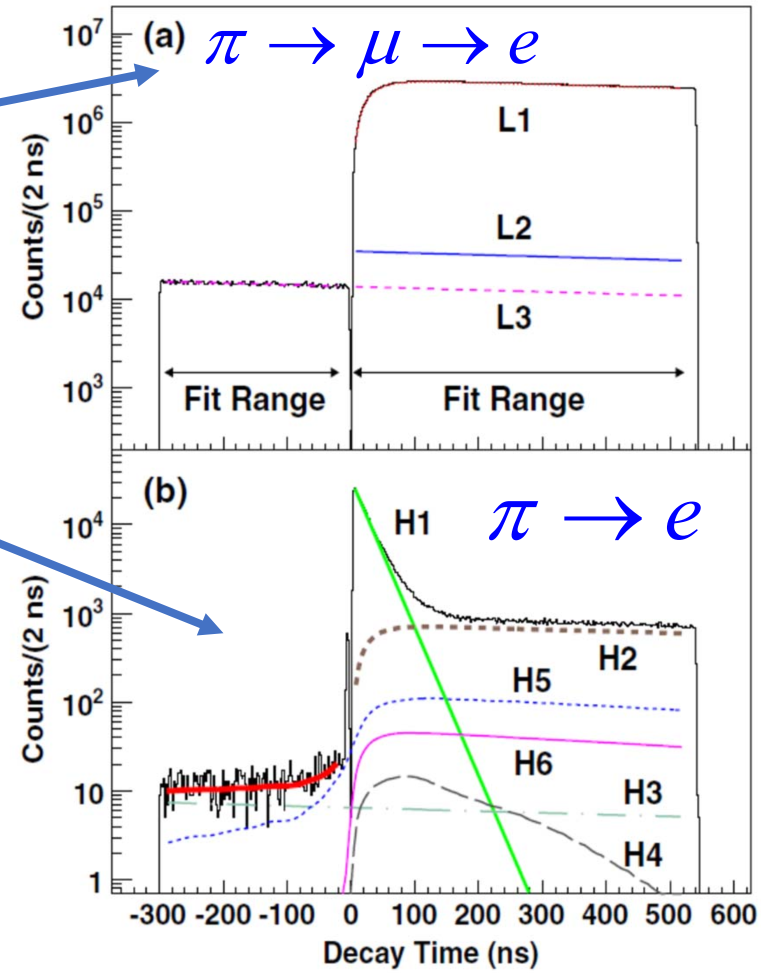


- Special positron runs to understand the behavior of low-energy tail.
- Typical Tail-Correction factor is: $1.0261 \pm 0.0002(stat) \pm 0.0005(syst)$

Counts vs. Time

Energy and time selections





Current PIENU Result :

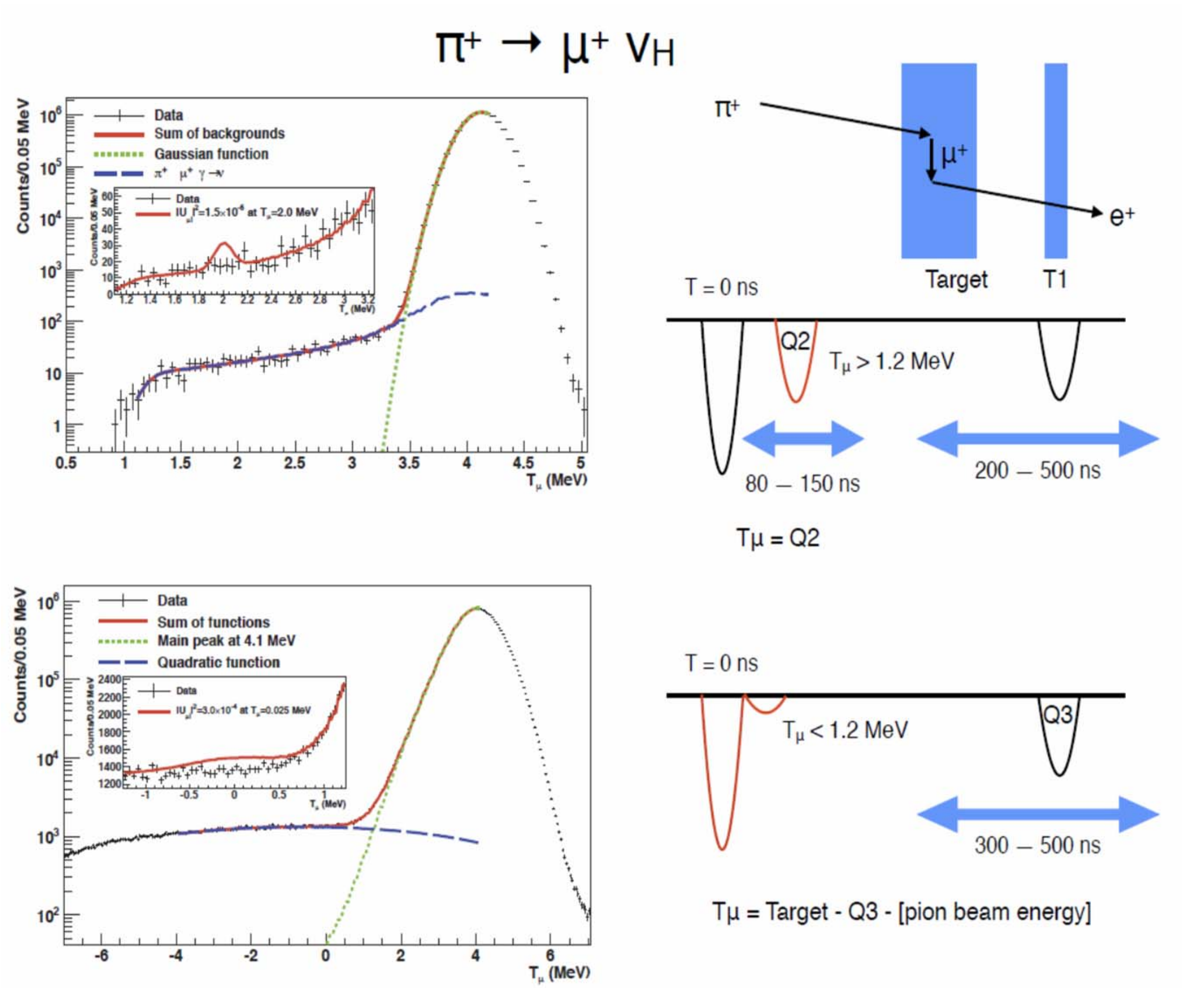
$$R_{e/\mu}^{\exp\pi} = (1.2344 \pm 0.0023_{stat} \pm 0.0019_{sys}) x10^{-4}$$

Consistent with SM and lepton flavor universality.

Statistics	0.19%
Tail correction	0.12%
t_0 correction	0.05%
μ decay-in-flight correction	0.05%
Fitting parameters	0.05%
Selection cuts	0.04%
Acceptance correction	0.03%
Total	**0.24%**

Full Data Sample: 10^7 $\pi^+ \to e^+\nu$ Events; Precision Goal: $\pm 0.1\%$

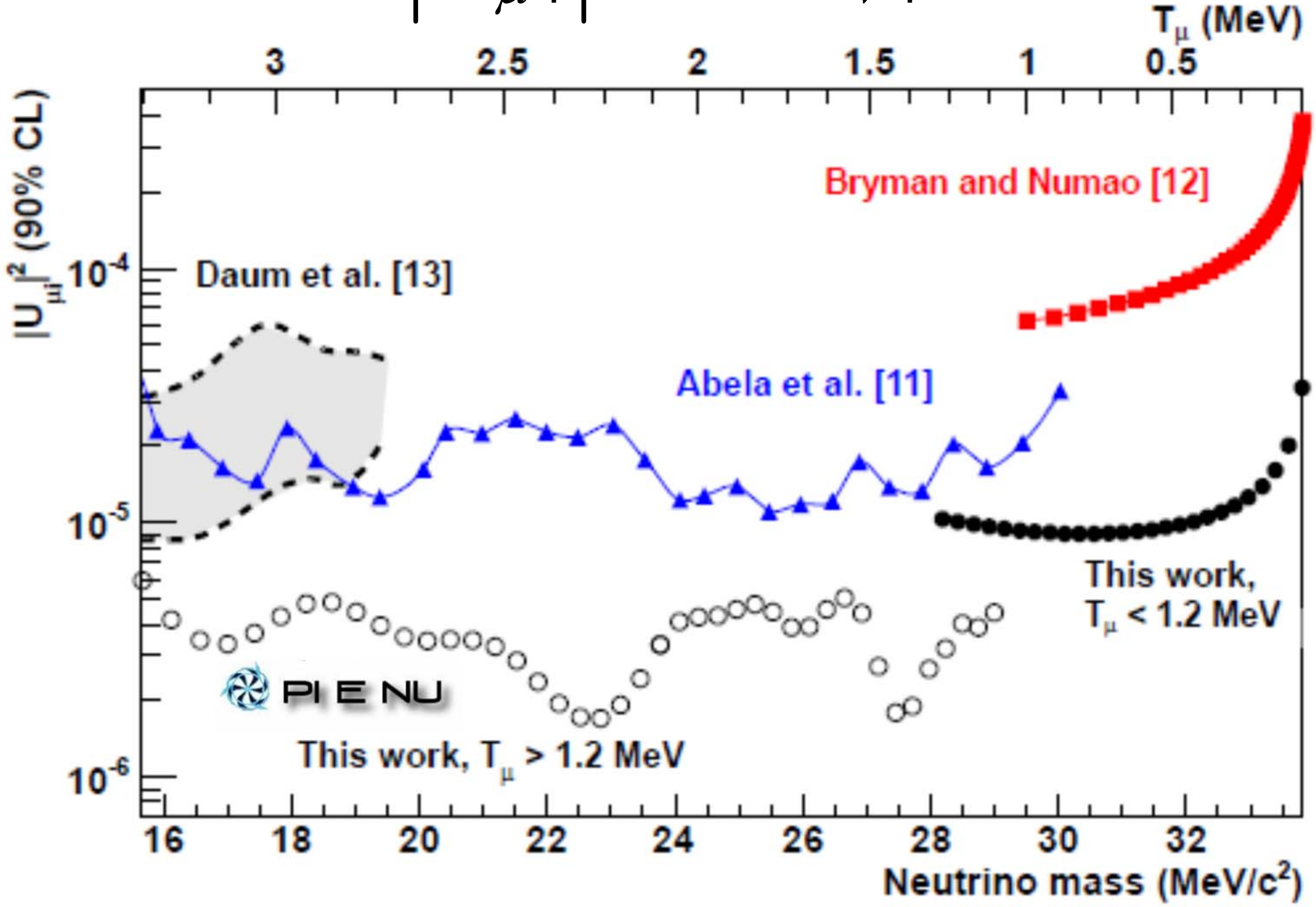
Search of Massive Neutrinos e.g. $\pi^+ \rightarrow \mu^+ \nu_H$



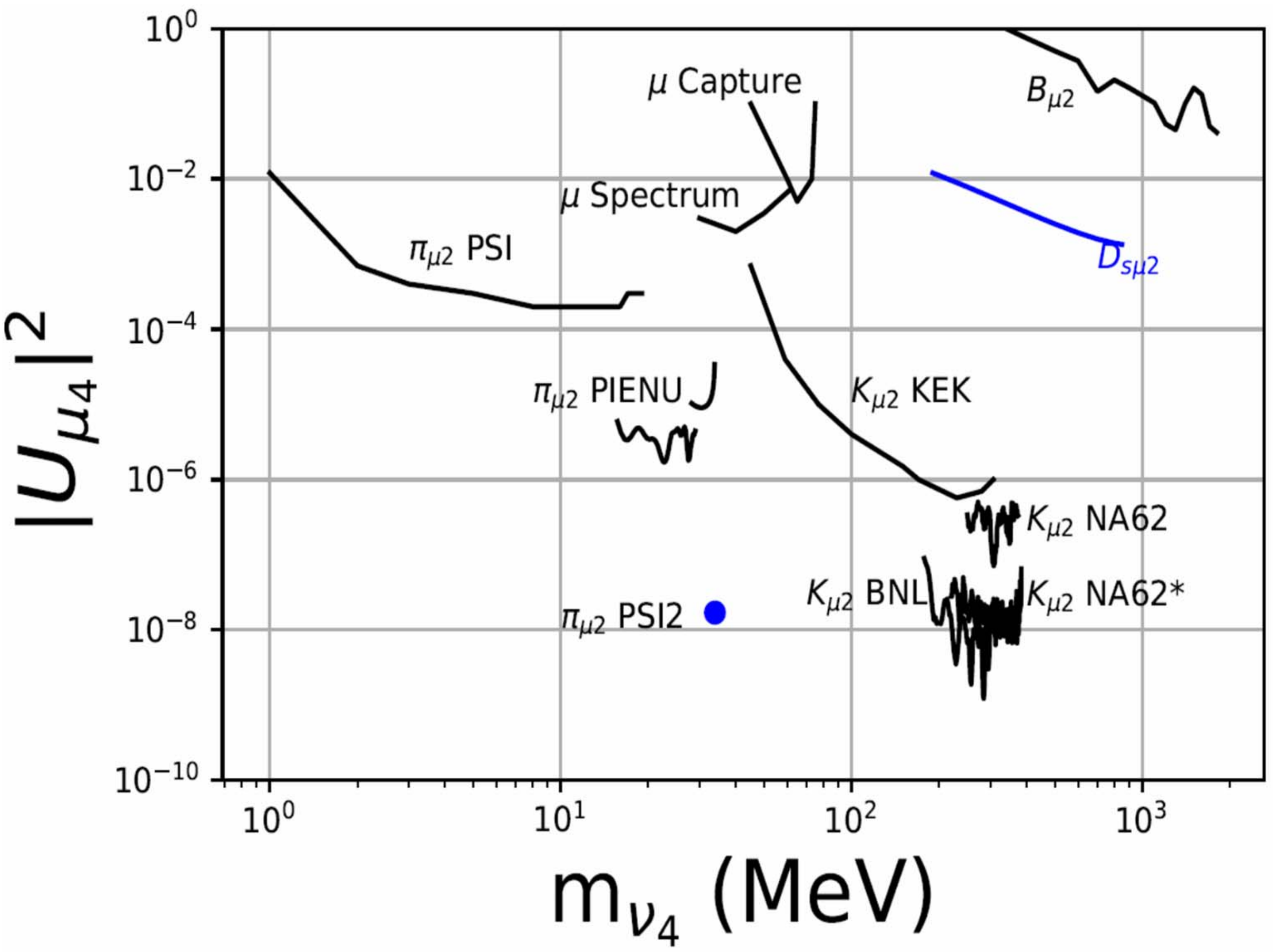
PI E NU

Search for Heavy Neutrinos in $\pi^+ \to \mu^+ \nu_H$ Decay

$$|U_{\mu 4}|^2 \text{ vs } m_{\nu 4}$$

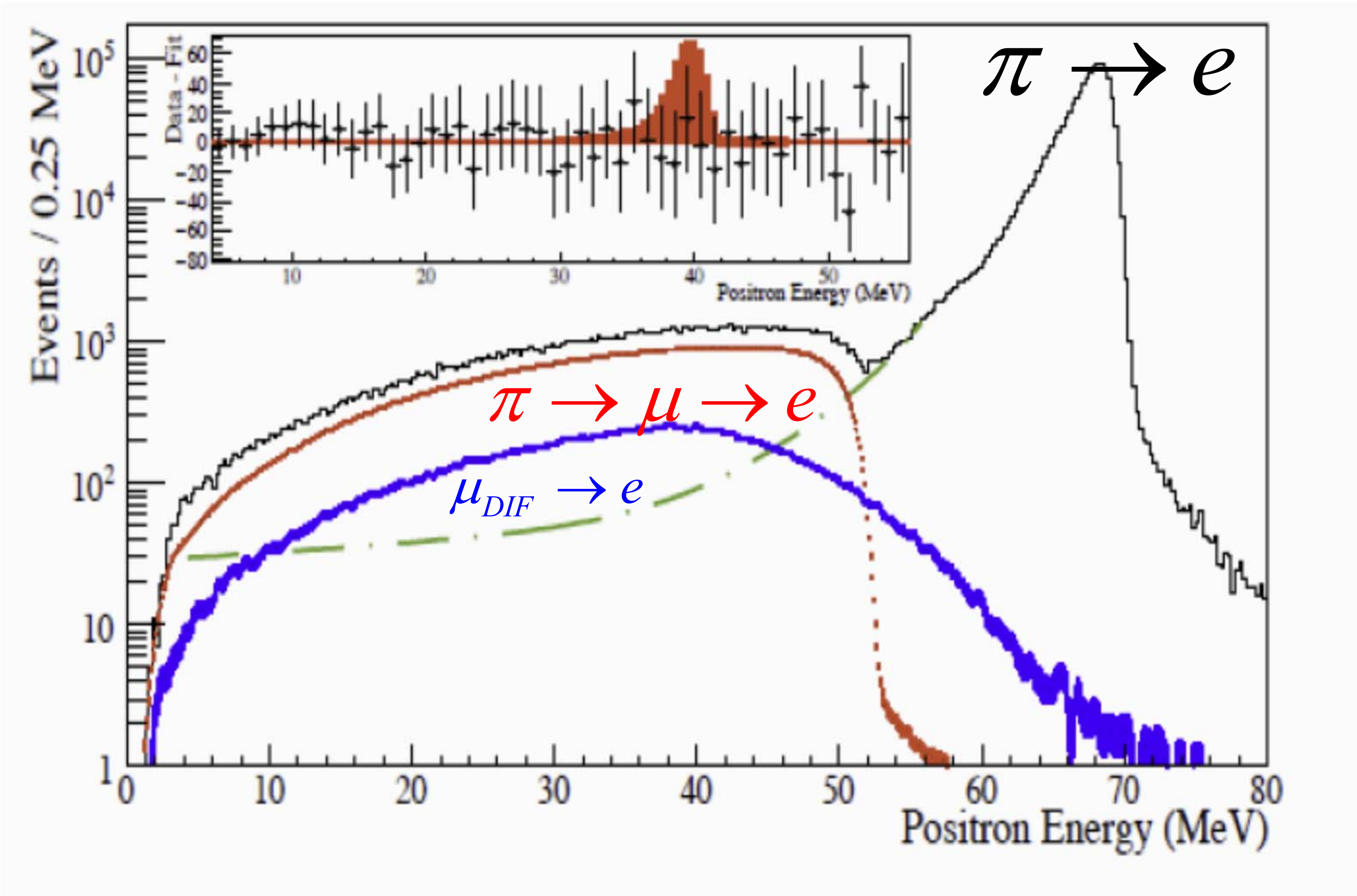


$\left|U_{\mu 4}\right|^2$ vs $m_{\nu 4}$ (MeV - GeV)



R. Shrock and D.B. 2019

$\pi^+ \rightarrow e^+ \nu_{e4}$

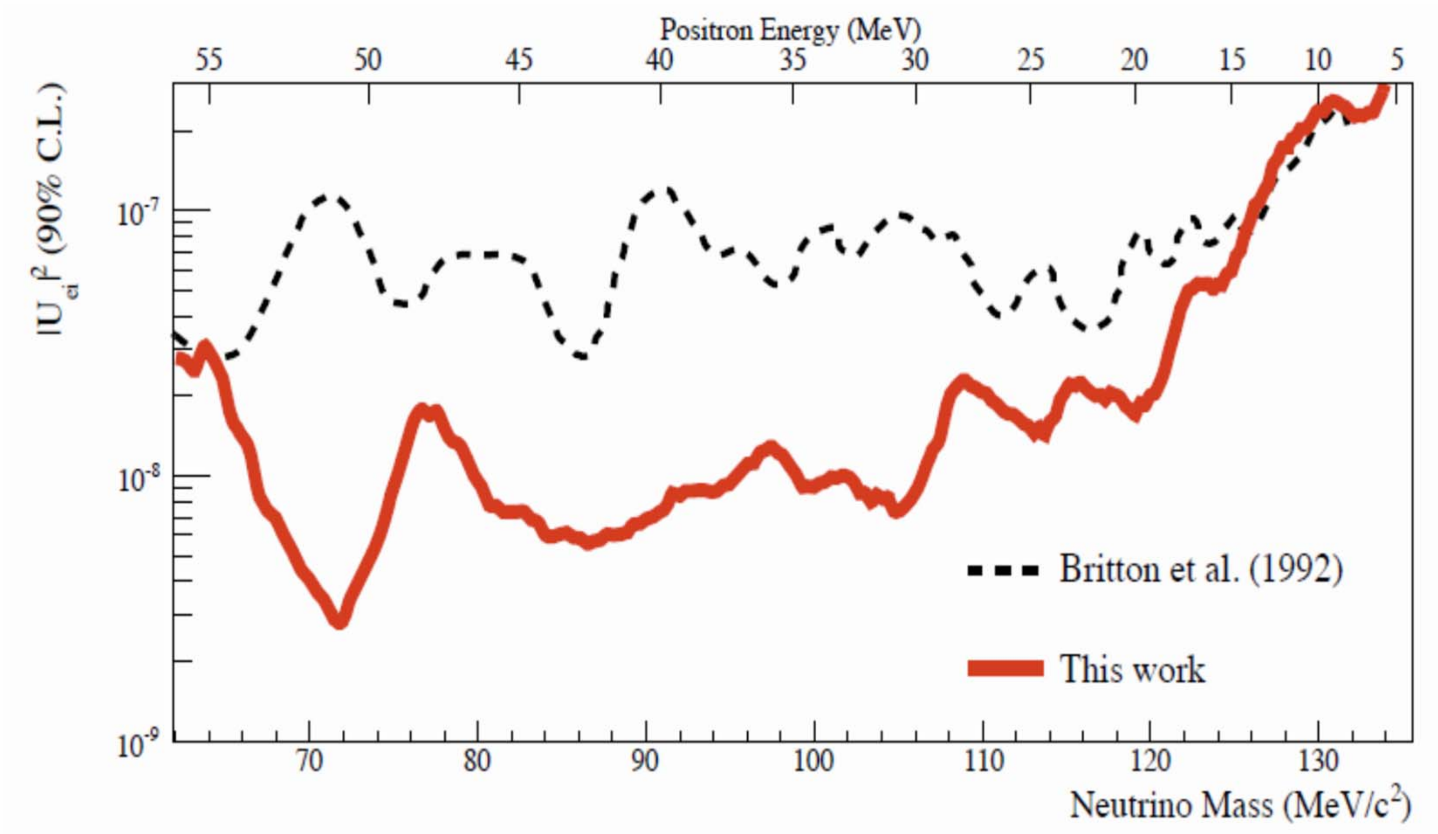


A. Aguilar-Arevalo *et al.*
Phys. Rev. D **97**, 072012 (2018)

PI E NU

$\left|U_{e4}\right|^2$ vs $m_{\nu 4}$

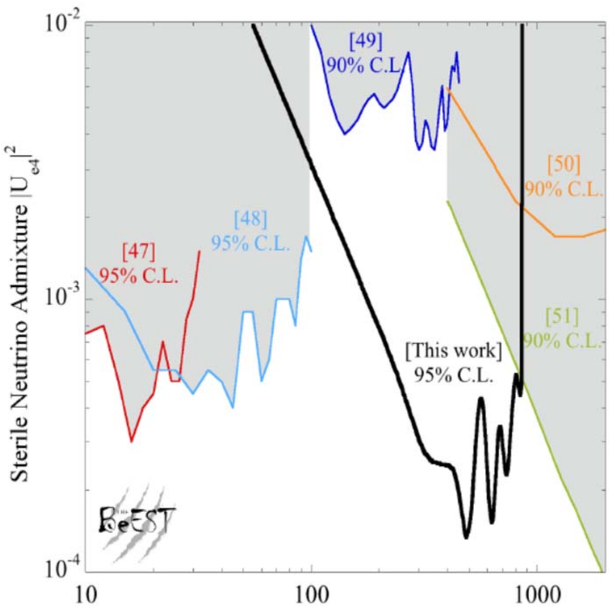
$\pi^+ \rightarrow e^+ \nu_{e4}$



Massive Sterile Neutrinos

Could range in mass from eV to GUT scale; constraints from oscillations, cosmology, HEP….
Possible correlations with LFV, LNV…

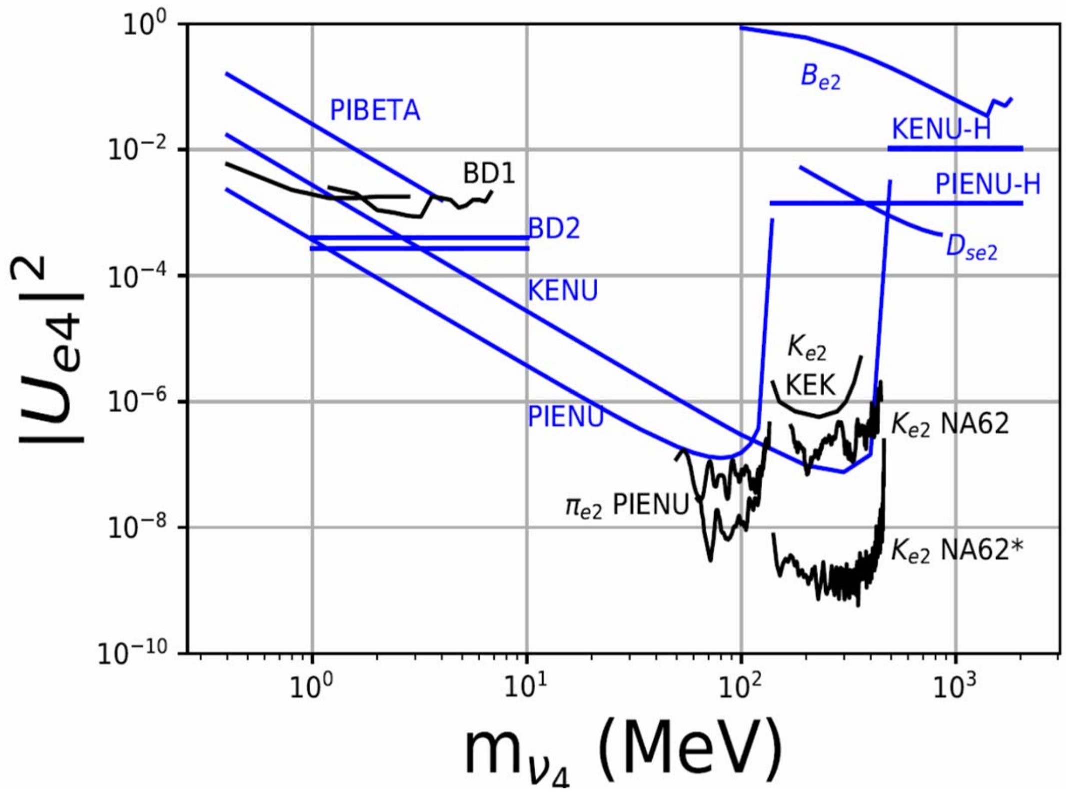
$|U_{e4}|^2$ vs $m_{\nu 4}$ (<1 MeV)



$m_{\nu 4}(keV)$

S. Friedrick et al., arXiv:2010.09603v1

$|U_{e4}|^2$ vs $m_{\nu 4}$ (MeV - GeV)



R. Shrock and D.B. Phys. Rev. D 100 (2019) 073011

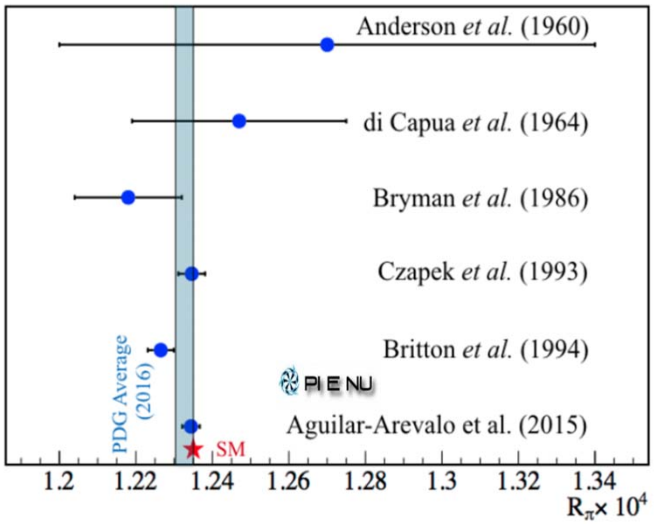
How to improve experimental precision by another order of magnitude to match theory?

$$R^{th}_{e/\mu} = \left(1.2353 \pm 0.0001\right) x10^{-4}$$ ±0.008%

10 x more precise than experiments!

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

- CERN (1958) 6 events
- Chicago (1960) – ***magnetic spectrometer***
  - 1^{st} 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

PIONEER

Next Generation Rare Pion Decay Experiment

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

Goals:

- Measure $R_{e/\mu} = \frac{\Gamma(\pi \to e\nu + \pi \to e\nu\gamma)}{\Gamma(\pi \to \mu\nu + \pi \to \mu\nu\gamma)}$: $O(\pm 0.01\%)$
- Measure $R_{\pi\beta} = \frac{\Gamma(\pi^+ \to \pi^0 e^+ \nu)}{\Gamma(\pi^+ \to all)}$: $O(\pm 0.05\%)$
- Improve search sensitivities by more than an order of magnitude

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

$\pi^+ \rightarrow e^+ \nu$

PIONEER Method

(→ Improvements Compared to PIENU)

Calorimeter : 30 X_0; 3π sr; LXe or L(Y)SO

→ Reduce Tail correction (10 x);

→ Improve uniformity (5 x)

→ Reduce pile-up uncertainties (5 x)

Active Target

→ Reduce Tail correction uncertainty (10 x), pile-up effects (5 x)

→ allow $\pi \rightarrow \mu \rightarrow$ e decay chain observation

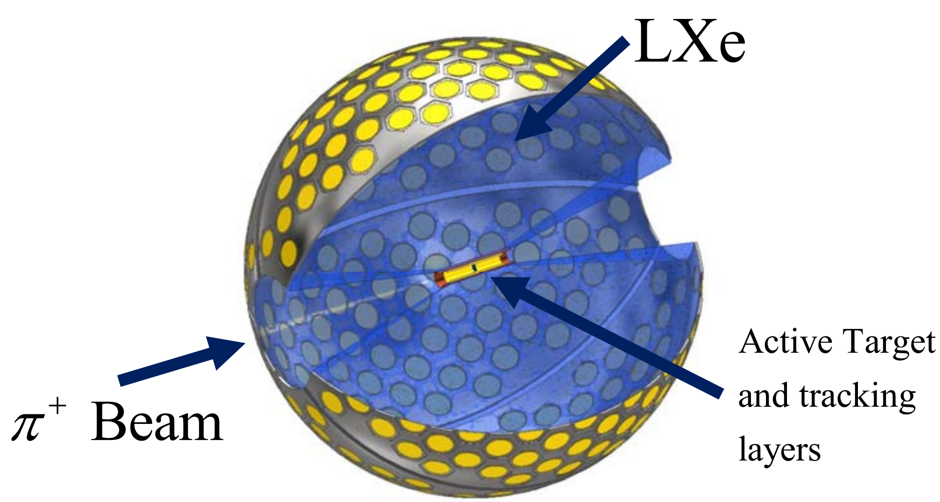
Fast electronics and pipeline DAQ

→ Improve efficiency

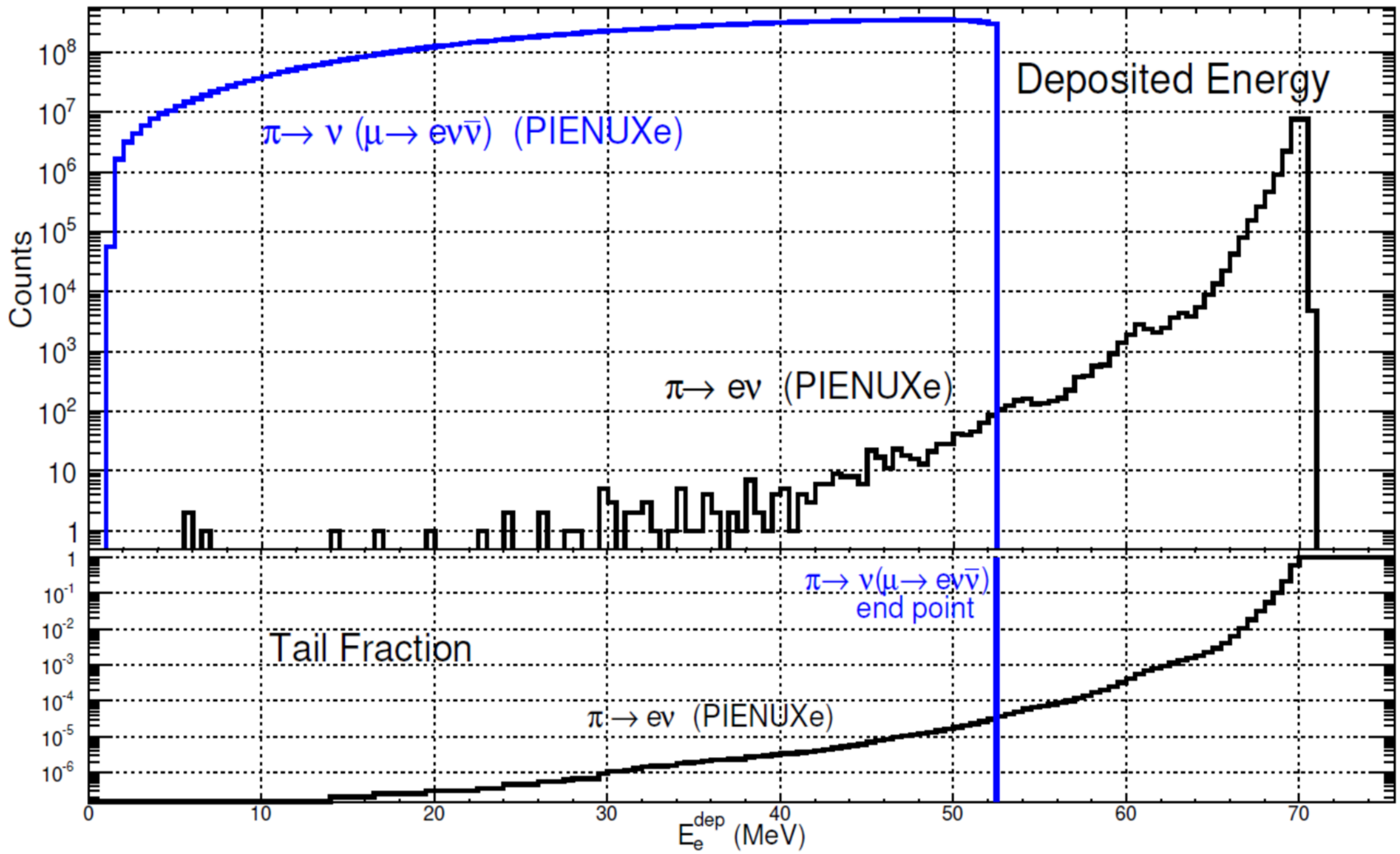
30 X_0 ;

$\Delta t \sim 50 ps$;

$\frac{\Delta E}{E} \sim 1\%$

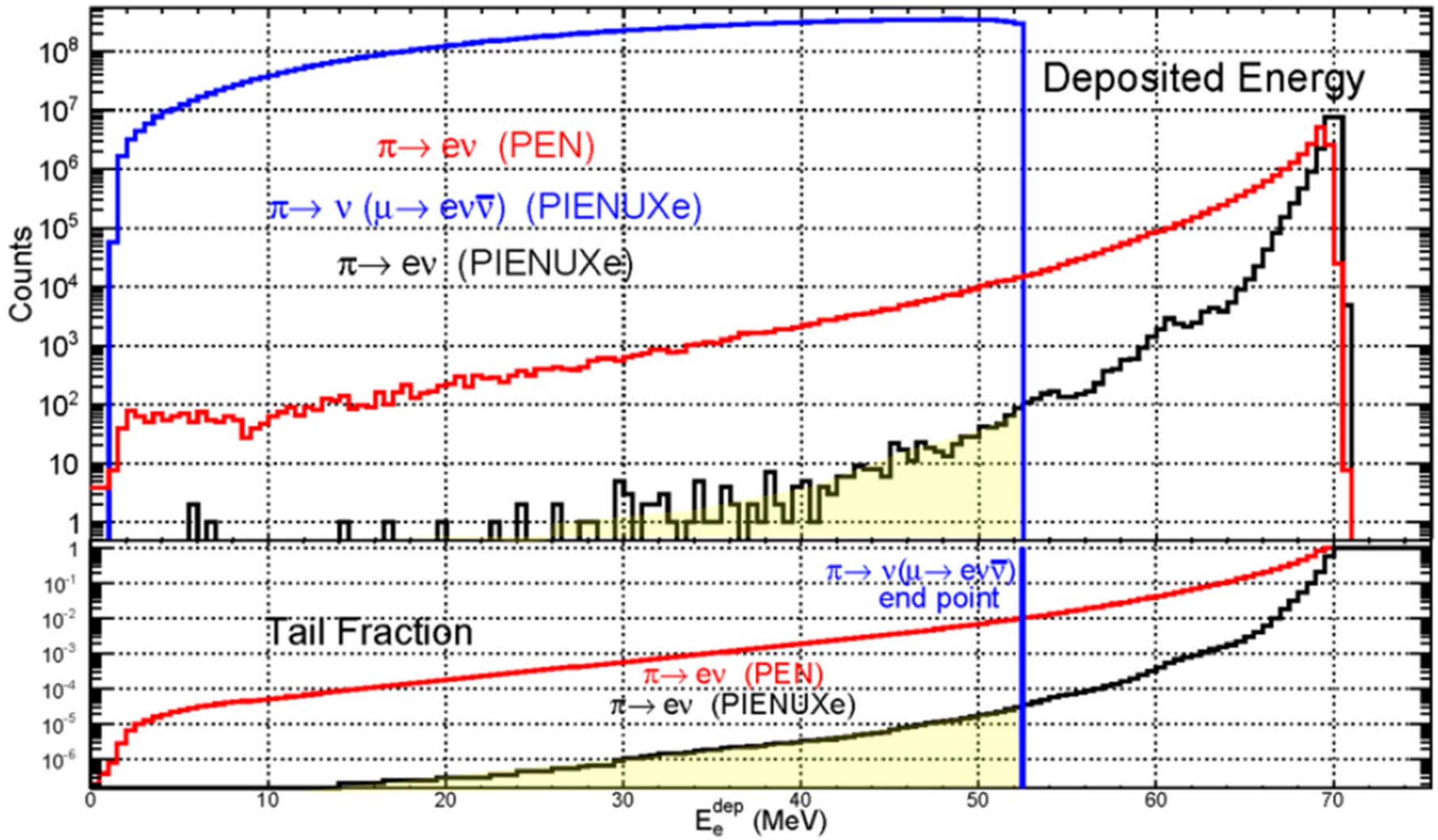


Simulated line shapes with 30 X_0 LXe



Low energy tail reduced x 10 (PIENU) → uncertainty on $R_{e/\mu}$: ± 0.01%

Simulated line shapes with 30 X_0 LXe

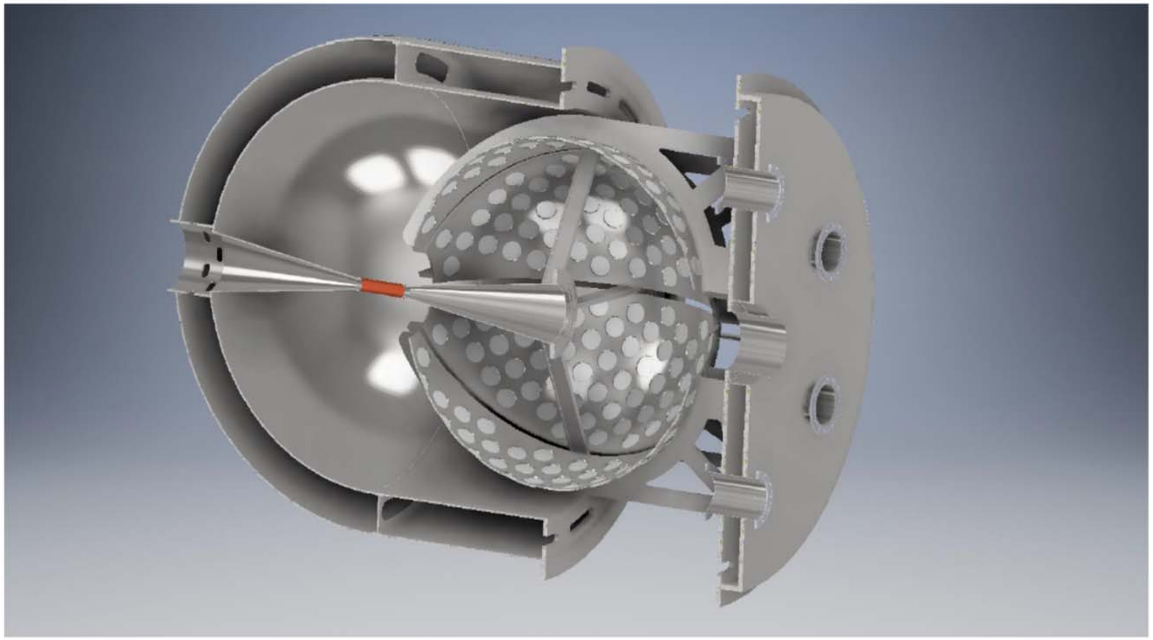


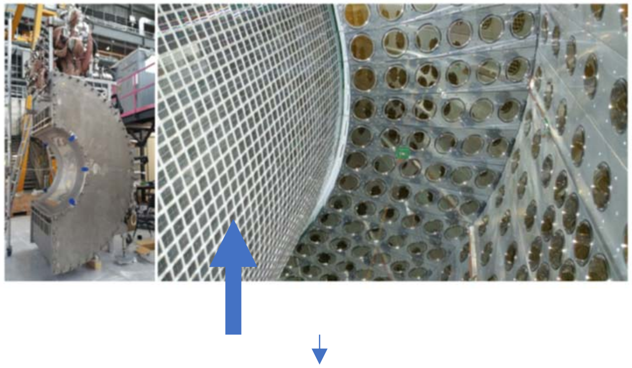
Low energy tail reduced x 10 (PIENU) → uncertainty on $R_{e/\mu}$: ± 0.01%

PIONEER : Calorimeter Concepts

Candidate materials (30 X_0): **LXe** (like MEG II) and **LSO/LYSO**("like" PiBETA/PEN);
Desire high energy resolution σ~1% (like PIENU) with 5x faster timing.

LXe mechanical concept showing LXe calorimeter being extracted.

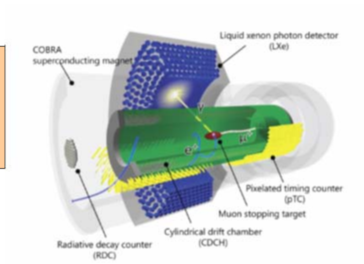




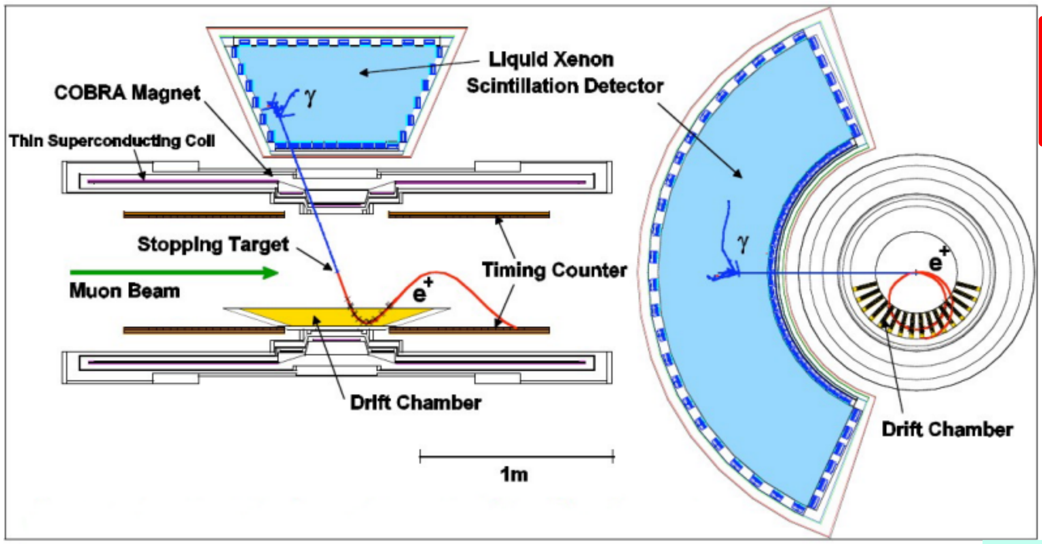
MEG II
SiPM
array

MEG & MEGII Experiments at PSI

$\mu \rightarrow e\ \gamma$



High rate LXe Calorimeter



Variable	Foreseen	Obtained	Upgrade Scenario
ΔE_γ (%)	1.2	1.7	1.0
Δt_γ (ps)	43	67	≤ 67
γ position (mm)	4-6	4-6	~ 2
γ efficiency (%)	> 40	63	70
ΔP_e (keV)	200	306	≤ 130
e^+ angle (mrad)	$5(\varphi), 5(\theta)$	$8.7(\varphi), 9.4(\theta)$	$\leq 4(\varphi), \leq 5(\theta)$
Δt_{e^+} (ps)	50	107	30
e^+ efficiency (%)	90	40	≥ 85
$\Delta t_{e\gamma}$ (ps)	65	122	80

MEG II

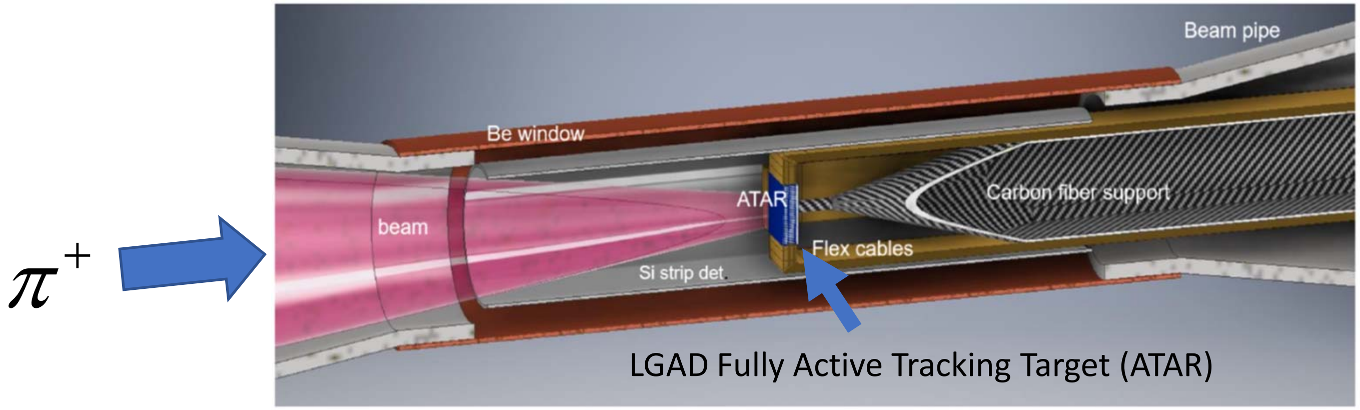
- Proposal (1999): goal $<2 \times 10^{-14}$
- 2016 Result*: $<4.2 \times 10^{-13}$
- New goal (~202X): $<6 \times 10^{-14}$

- 7×10^7 μ/sec; 100% duty factor
- LXe for efficient γ detection -SiPMs
- Solenoidal magnetic spectrometer

*Baldini A. et al, et al., Eur. Phys. J. C (2016) 76.

S. Ritt

PIONEER : LGAD Si Strip Target Concept



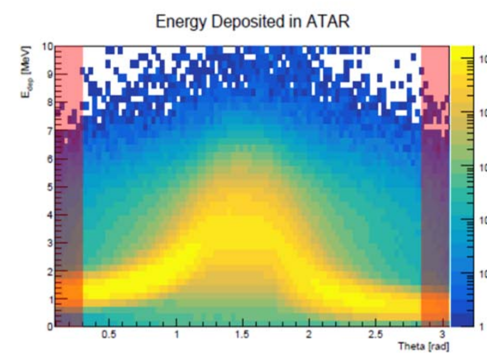
Additional LGAD Si strip beam and positron tracking (not shown).

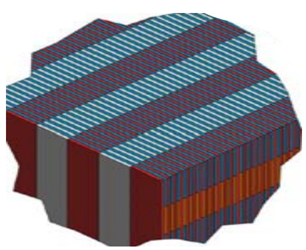
Low Gain Avalanche Detector (LGAD "4D")

Active Target (ATAR) concept for $\pi \rightarrow \mu \rightarrow$ e tracking;

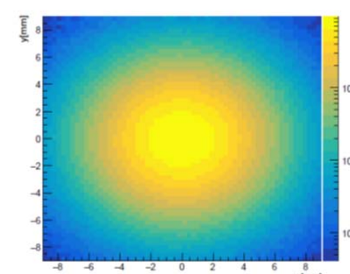
Fully active for energy measurements and tracking;

Challenge: wide dynamic range in Si strips (~1000).





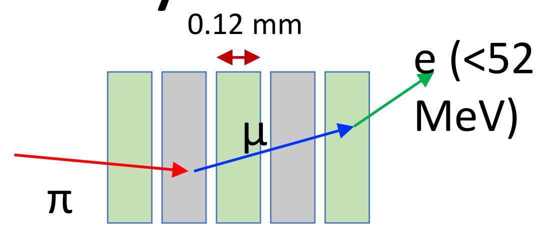
X-Y π stop position



PSI seminar Sept. 2021 S. Mozza

LGAD Si Strip Target

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

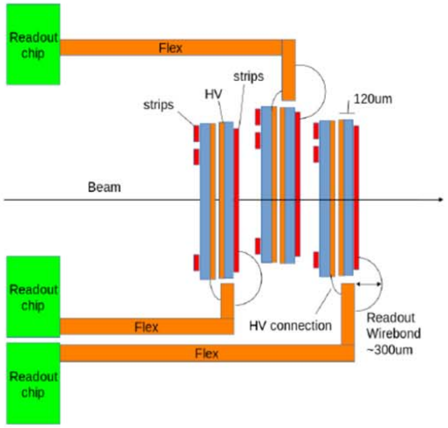


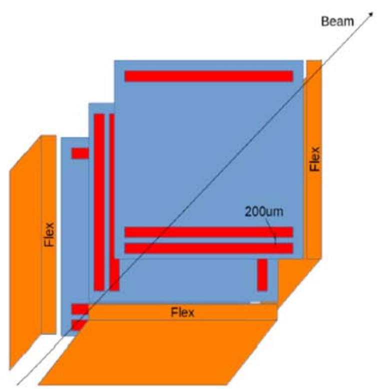
- **Requirements**
  - **Longitudinal segmentation**:
    Track, stop, localize pions; *detect decays in flight*
  - **Compact, efficient**: no dead material
  - **Fast collection time**: separate pulses that are close in time from π→μ →e and π→e decays
  - **Large Dynamic range (1000)**: detect energy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

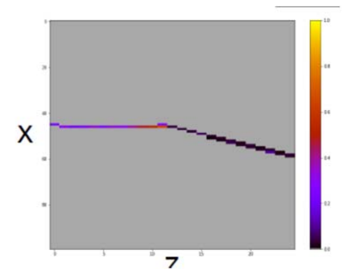
AC-LGAD Target Concept

48 layers of 2 cm x 200 μm (wide) x 120 μm (thick) strips

Fast signals







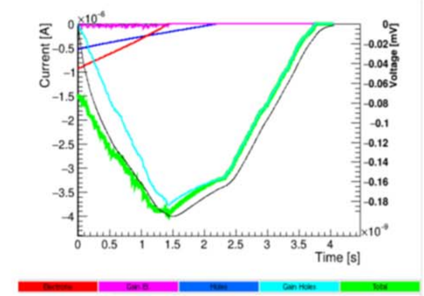


Figure 9: Simulated 120um thick LGAD pulse shape for a MiP (weightfield2 [22]). The black line is the response of a 2GHz bandwidth electronic readout.

BNL AC-LGAD strip prototypes

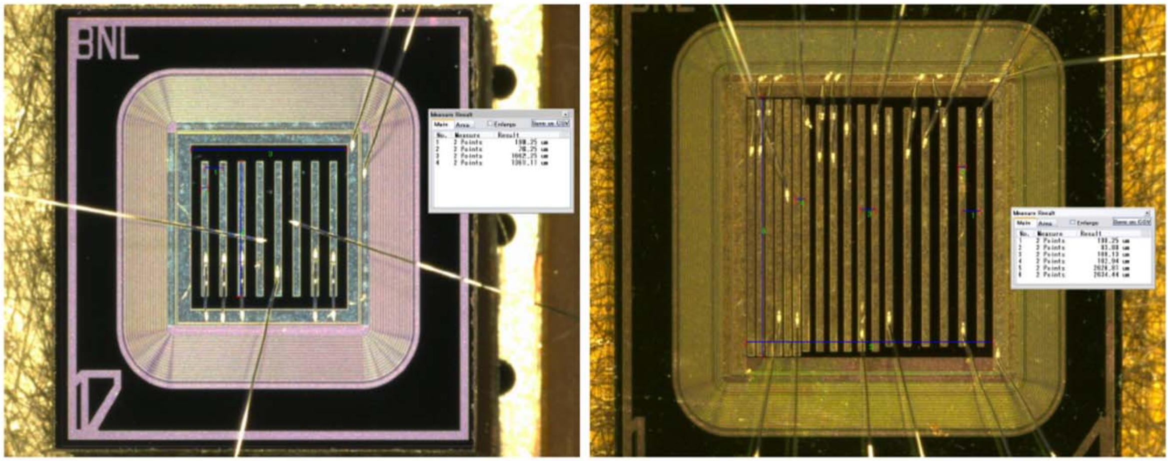


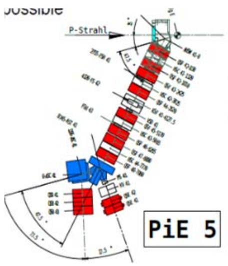
Figure 8: Prototype strip AC-LGADs produced at BNL, sensors dimensions are 1.6x1.6 mm with 200 um pitch (left) and 2.6x2.6 mm with 200 um, 150 um and 100 um pitch (right)

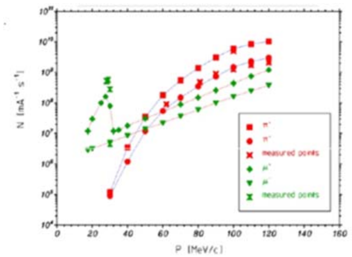
PIONEER Beam Requirements:

Matched well to PSI beam: PIE5*

$\pi \rightarrow e\nu$:

- π^{+}Beam: 75 MeV/c ; $\frac{\Delta p}{p}$~1-2%; $3\text{x}10^{5}$ Hz
- 3 $\text{x}10^{8}$ events; $R_{e/\mu}$ ±0.01% in 2 yrs





$\pi^{+} \rightarrow \pi^{0} e\nu$:

- π^{+}Beam: 100 MeV/c ; $\frac{\Delta p}{p}$~3%; 10^{7} Hz
- 7 $\text{x}10^{6}$ events; $R_{\pi\beta}$ ±0.04% in 4 yrs

*(And possibly PIE1)

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

To be verified by simulations
and prototype measurements.

PIENU (Current)		PIONEER
Statistics	0.19%	0.006%
Tail correction	0.12%	< 0.01% (Calorimeter/ATAR)
t_0 correction	0.05%	-- *(ATAR timing)*
μ decay-in-flight correction	0.05%	*< 0.01% (ATAR)*
Fitting parameters	0.05%	*< 0.01%* (Calorimeter/ATAR) *
Selection cuts	0.04%	*< 0.01%* (Calorimeter/ATAR) *
Acceptance correction	0.03%	*0.005%* (Calorimeter)
Total	0.24%	< 0.02%

* Reductions in uncertainties due to reduced pile-up effects.

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

	PiBeta	**PIONEER**	
Statistics	0.4%	0.04%	
Systematics	0.4%	<0.04%	(ATAR (β), MC, Photonuclear, π→e ν)
Total	0.64%	**0.06%**	

Conclusions: Testing of Lepton Flavor Universality with Pions and Kaons

- **Rare μ, π and K decays have unique and important roles to play in the search for new physics involving exotic effects like *Flavor Universality and Lepton Flavor Violation* --- especially sensitivity to very high mass scales.**

- **π/K/B results expected soon from PIENU, PEN, NA62, and LHCb BESSIII, BELLE-II. Important connections with searches for sterile neutrinos/dark sector particles , high mass scale physics, and L(F/N)V tests.**

- **Next generation pion decay experiment PIONEER aims at order of magnitude improvements in high precision for measurements of π →eν and pion beta decay to provide unique new information on Lepton Flavor Universality and CKM unitarity.**