Exploring Flavor Physics with Pions and Kaons

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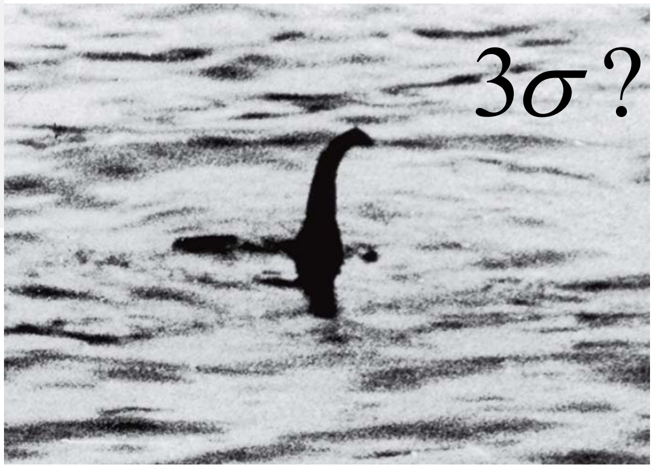
The Standard Model is great but doesn’t explain many observations: dark matter; dark energy; baryon asymmetry; flavor; hierarchy…

So far, revealing the origins of the BSM physics has resulted in no conclusive evidence…

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)



General principle: leave no lach unexplored.

Leptons, Flavor Universality & Violation

Electron *Thompson, Townsand, Wilson 1896*

Muon *Nedermeyer, Anderson 1937*

Tau *Perl et al. 1974*

↑ ±40 yrs ↓

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

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

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

Neutrino oscillations:

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

Lepton flavor is not conserved
Neutrinos have (small) mass and mix

Rare Pion and Kaon Decays

These special rare processes have strong connections to flavor physics, precise SM predictions, and are high sensitivity to BSM physics at high mass scales.

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

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

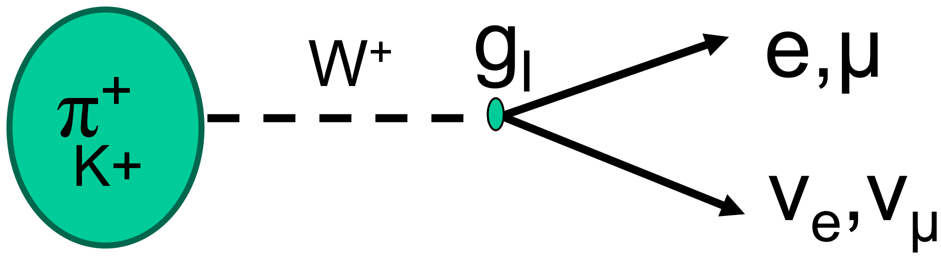
$$K^+ \to \pi^+\nu\bar{\nu} \sim 10^{-10}$$

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

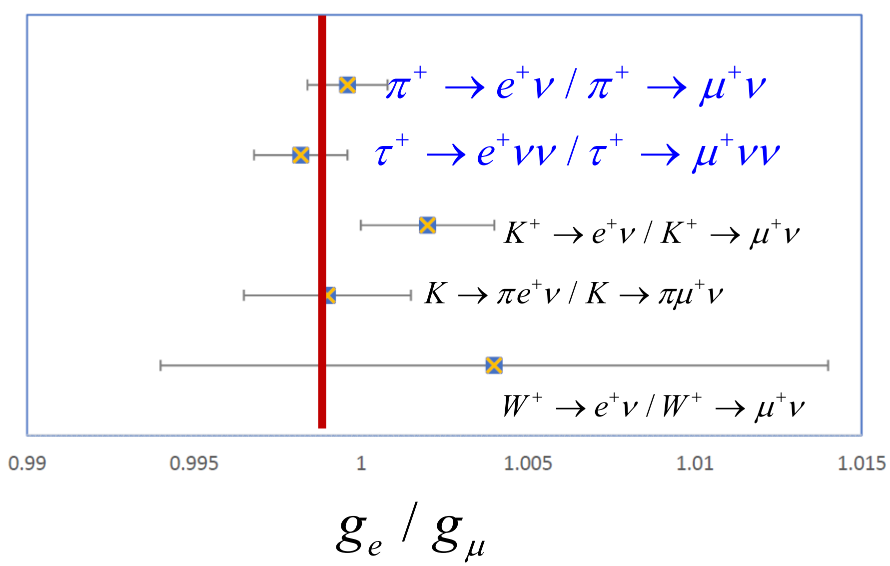
Deviations from SM predictions means new physics.

Charged Current e/μ Universality

Experiments compare expectations assuming $g_e = g_\mu$



π /τau Precision: $O(10^{-3})$



Charged Lepton Flavor Universality in π Decay

$$R_{e/\mu}^{theory} = \frac{\Gamma\left(\pi \to e\nu(\gamma)\right)}{\Gamma\left(\pi \to \mu\nu(\gamma)\right)} = \left(1.2352 \pm 0.0002\right) x10^{-4}$$ (±0.016%)

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%)

$$\frac{g_e}{g_\mu} = 0.9989 \pm 0.0009$$ (±0.09%)

PEN, PIENU goals ($R_{e/\mu}^{\exp} \leq \pm 0.1\%$)

Experiments are an order of magnitude less precise than theory.

τ Decay Universality Tests

<O(0.2%) effects

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

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

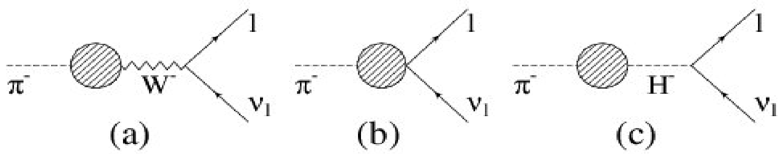
	$\Gamma_{\tau\to e}/\Gamma_{\mu\to e}$	$\Gamma_{\tau\to\pi}/\Gamma_{\pi\to\mu}$	$\Gamma_{\tau\to K}/\Gamma_{K\to\mu}$	$\Gamma_{W\to\tau}/\Gamma_{W\to\mu}$
$\lvert g_\tau/g_\mu \rvert$	1.0011 (15)	0.9962 (27)	0.9858 (70)	1.034 (13)

	$\Gamma_{\tau\to\mu}/\Gamma_{\mu\to e}$	$\Gamma_{W\to\tau}/\Gamma_{W\to e}$	$\Gamma_{\tau\to\pi}/\Gamma_{\pi\to e}$
$\lvert g_\tau/g_e \rvert$	1.0030 (15)	1.031 (13)	1.0044 (60)

Pich 2013, DB 1992

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

Pseudoscalar interactions



Charged Higgs (non-SM coupling)

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

Marciano…

0.1 % measurement→Λ~1000 TeV

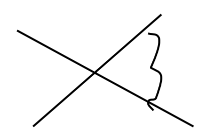
Many others:

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

Induced Scalar Currents

Campbell and Maybury (2005), Marciano

$R_{e/\mu}$: $\Lambda_S > 60\, TeV$ (!)



Lepton Flavor Universality Violation e.g. $\pi^+ \to l^+ \nu_{e4}$

Massive Sterile Neutrinos can be responsible for leptogenisis*

$$\nu_\ell = \sum_{i=1}^{3+n_s} U_{\ell i}\, \nu_i \ ,$$

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

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

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

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

- Ratio of kinematic factors

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

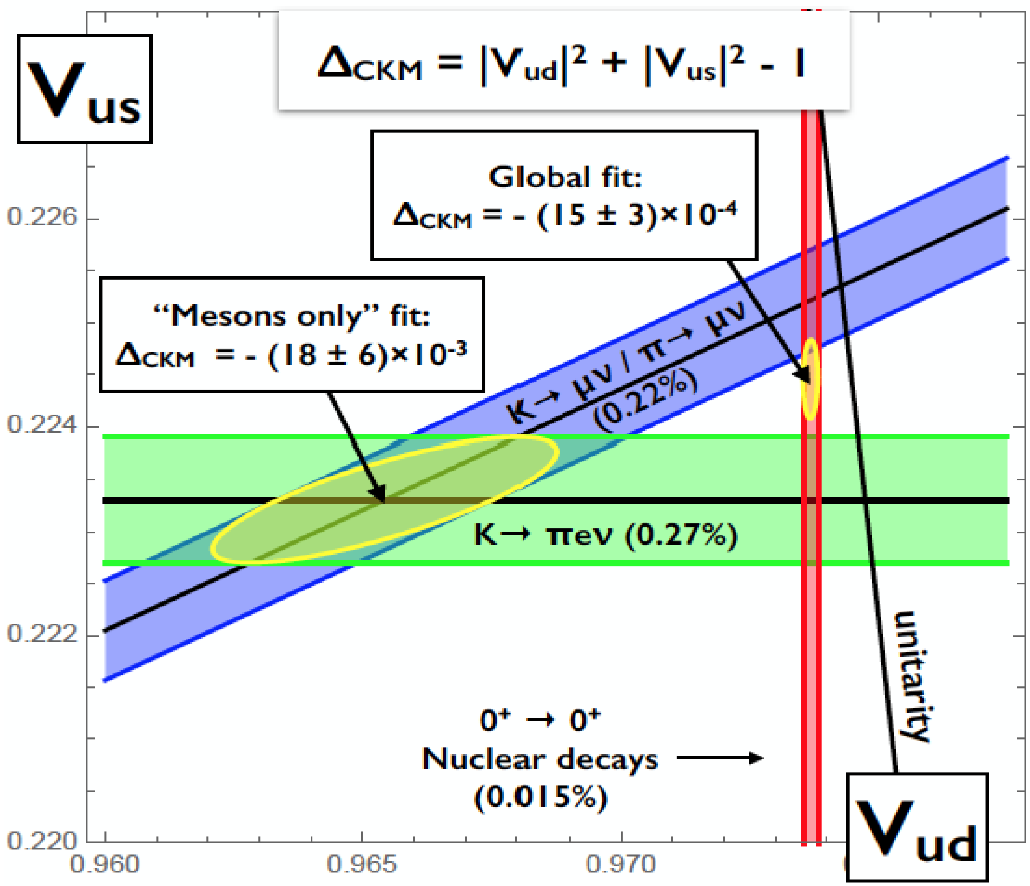
Decay	$(m_{\nu_4})_{\bar{\rho}_{max}}$	$\bar{\rho}_{max}$
$\pi^+ \to e^+ \nu_4$	80.6	1.105×10^4
$K^+ \to e^+ \nu_4$	285	1.38×10^5
$D^+ \to e^+ \nu_4$	1.08×10^3	1.98×10^6
$D_s^+ \to e^+ \nu_4$	1.14×10^3	2.20×10^6
$B^+ \to e^+ \nu_4$	3.05×10^3	1.58×10^7
$\pi^+ \to \mu^+ \nu_4$	3.46	1.00
$K^+ \to \mu^+ \nu_4$	263	4.13
$D^+ \to \mu^+ \nu_4$	1.07×10^3	47.3
$D_s^+ \to \mu^+ \nu_4$	1.13×10^3	52.4
$B^+ \to \mu^+ \nu_4$	3.05×10^3	371

Large kinematic enhancements possible at larger mass due to absence of helicity suppression

R. Shrock and D.B. 2019

*V. Domke et al., arXiv:2009.11678v1

Unitarity of CKM first row



V. Cirigliano

Tensions in V_{ud} and V_{us}

Possible connections between deviations of LFU and CKM unitarity. (See Martin Hoferichter's talk.)

Crivellin and Hoferichter 2020

CKM Unitarity: Vud, Vus/Vud

Tested in super-allowed β (V_{ud}) and K decays (V_{us}/V_{ud}) at precision $O(10^{-4})$

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

Present result: PIBETA Experiment (2004) $(\pm 0.64\%)$

$$V_{ud} = 0.9739(28)_{exp}(1)_{th}$$

$$\mathrm{B}(\pi^+ \to \pi^0 e^+ \nu) = (1.036 \pm 0.004_{\mathrm{stat}} \pm 0.004_{\mathrm{syst}} \pm 0.003_{\pi e2})\ \mathrm{x}10^{-8}\ (\pm 0.6\%)$$

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

Czarnecki, Marciano , Sirlin (2020)

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

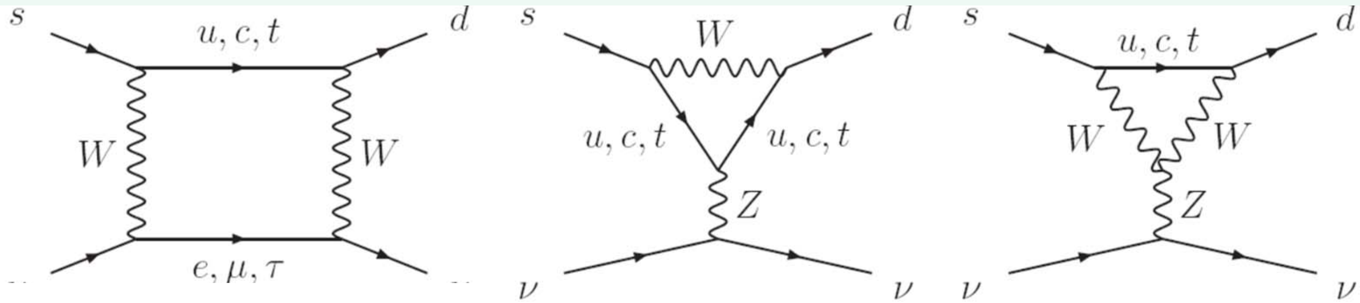
Improve $\mathrm{B}(\pi^+ \to \pi^0 e^+ \nu)$ precision by >3x $\to \dfrac{V_{us}}{V_{ud}} < \pm 0.2\%$

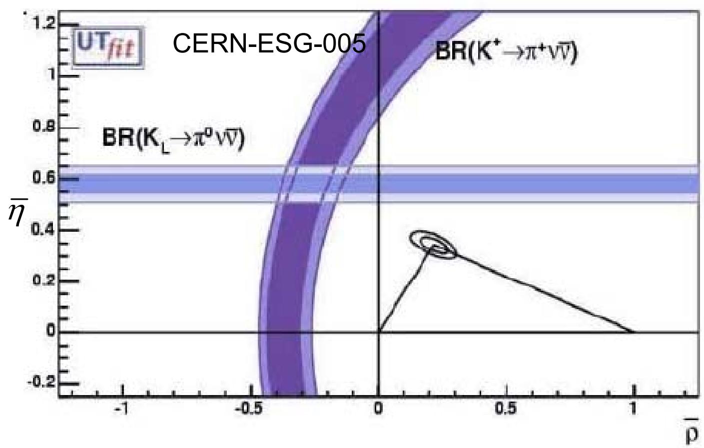
Offers a new complemetary constraint in the $V_{us} - V_{ud}$ plane.

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

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

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

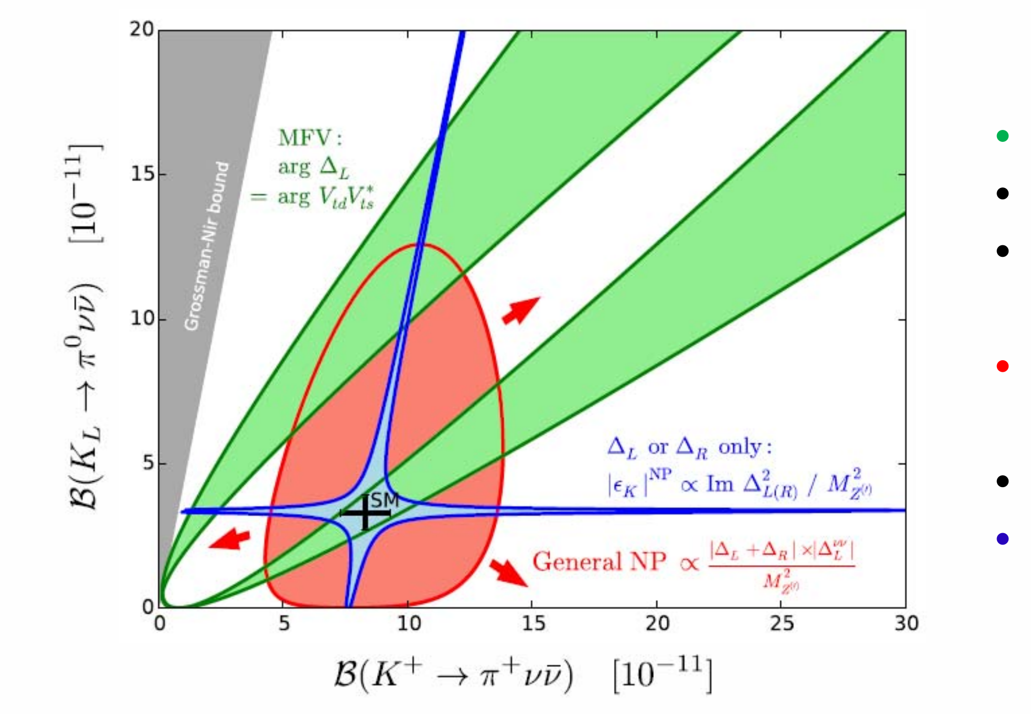
A. J. Buras, D. Buttazzo, R. Knegjens, ArXiv:1507.08672v2

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 $B(K^+ \to \pi^+ \nu\bar{\nu})$



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

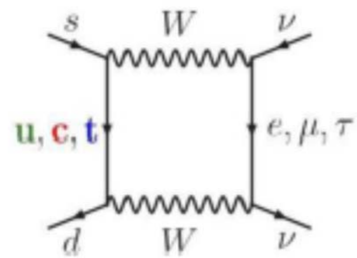
- Minimum flavor violation models
- Supersymmetric models
- Littlest Higgs (LH) model without/with T-parity
- Randall-Sundrum models
  -general LH, RH couplings
- Partial compositeness
- Models in which ε_k constraint applies

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



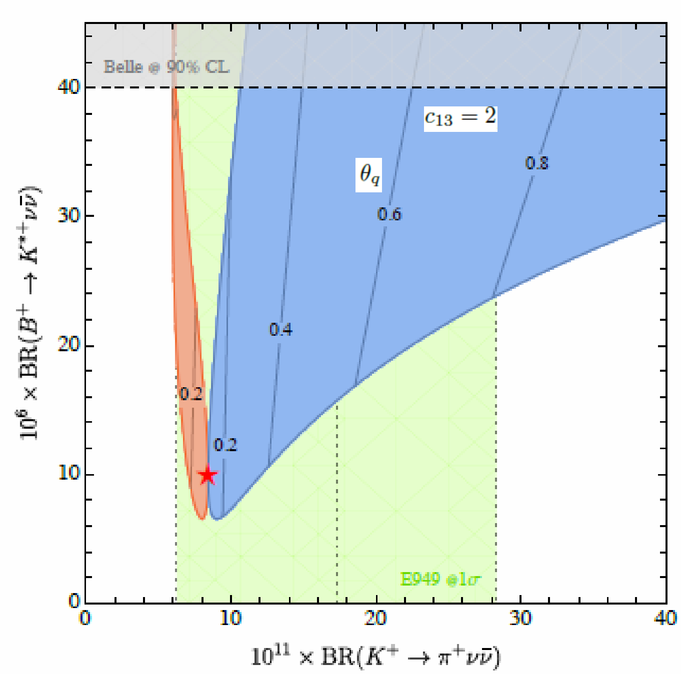
Involves third generation quarks (top) and leptons (τ, ν_τ)

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%]

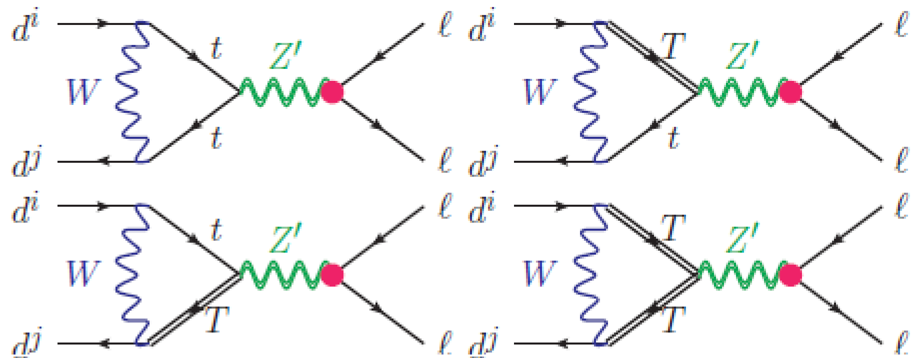


Kamenik, Soreq, Zupan arXiv:1704.06005v (2017)

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



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

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

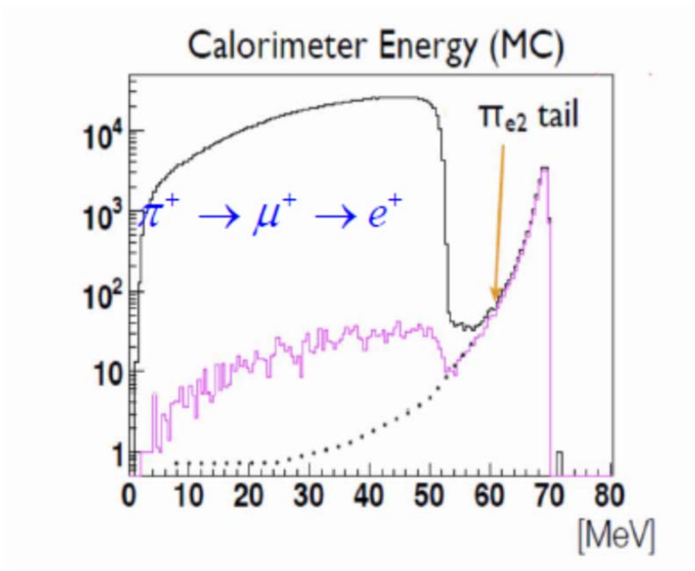
$$R_K \to C_9^{\mu,\rm NP} = -C_{10}^{\mu,\rm NP} \simeq 0.60(15)$$

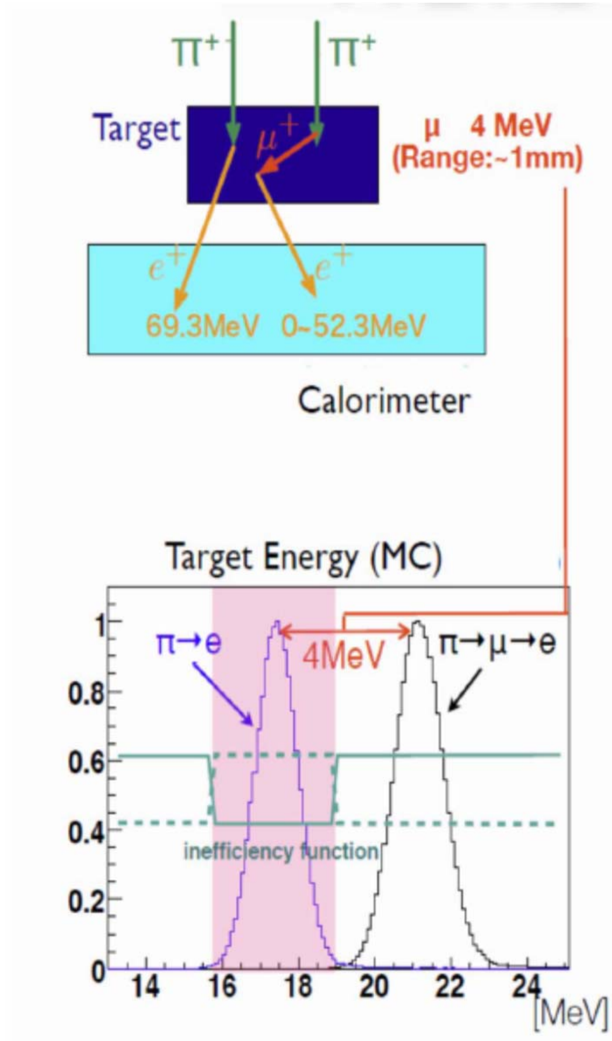
$$\frac{B(K^+ \to \pi^+ \nu\bar{\nu})}{B(K^+ \to \pi^+ \nu\bar{\nu})_{SM}} \sim 1.09 - 1.28 \text{ (Possibly within reach of NA62)}$$

Current and Future Pion and Kaon Decay Experiments with Implications on Lepton Flavor Physics

$\pi \to e\nu$: 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".



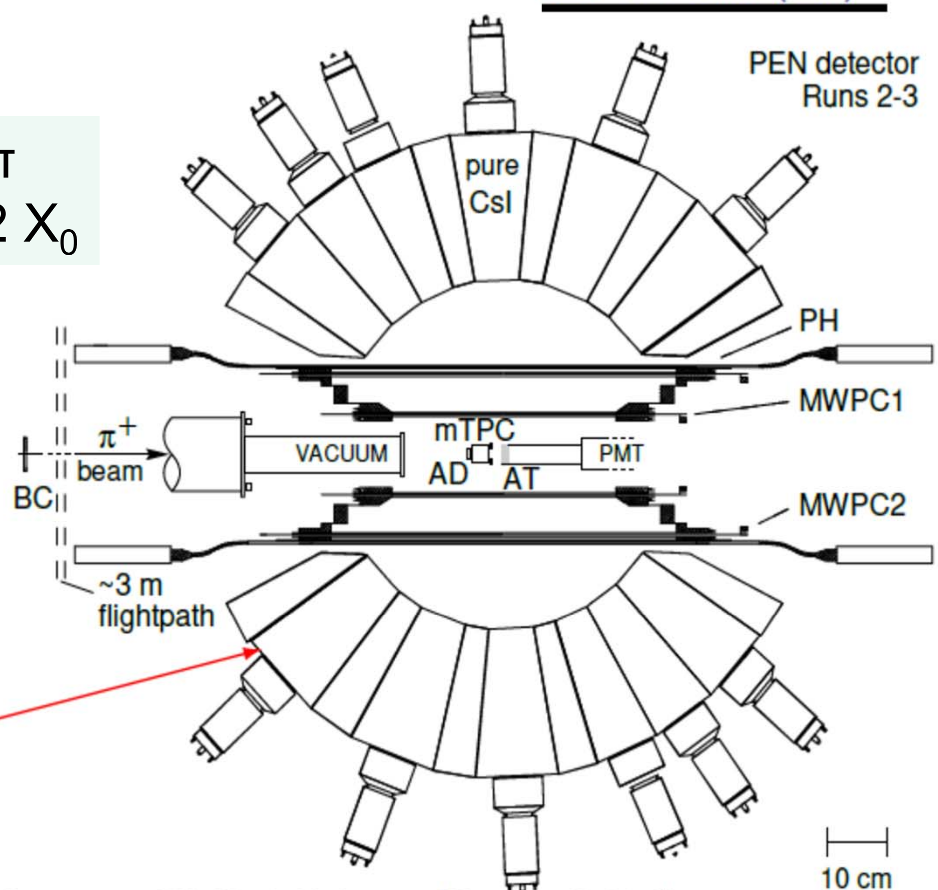


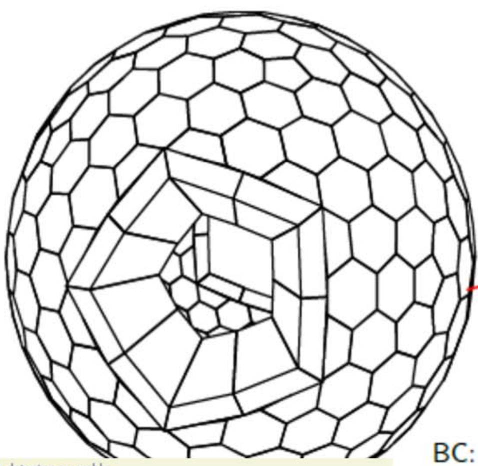
The PEN/PIBETA apparatus   Pion Beta Decay and $\pi \to e\nu\gamma_{SD}$

D. Počanić (UVa)

- 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

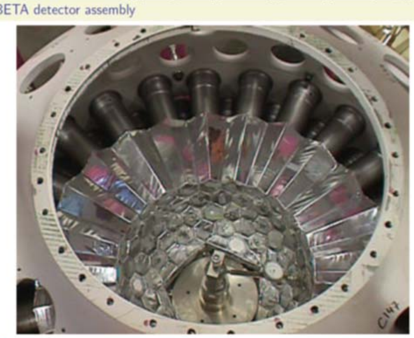




BC: Beam Counter
AD: Active Degrader
AT: Active Target

PH: Plastic Hodoscope (20 stave cylindrical)
MWPC: Multi-Wire Proportional Chamber (cylindrical)
mTPC: mini-Time Projection Chamber

PIBETA detector assembly

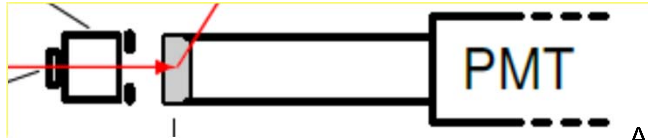


See parallel session talk by Dinko Pocanic.

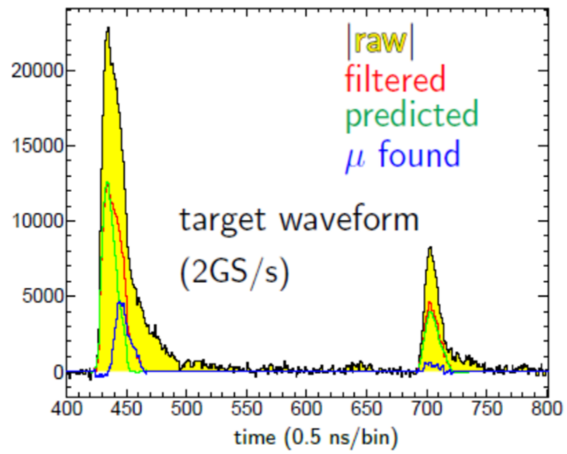
PEN

MTPC AT

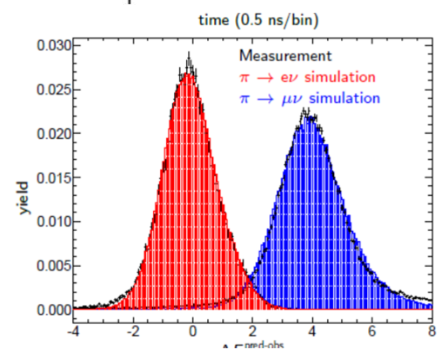
D. Počanić (UVa)



2GHz Digitizing in AT



AT energy



Tail Trigger

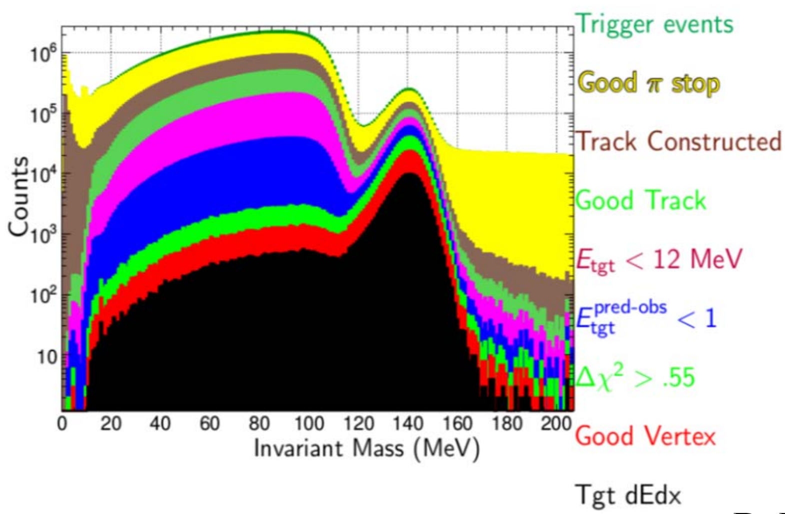


Table of uncertainties

$$R^{\pi}_{e/\mu} = \frac{N^{peak}_{\pi\to e\nu}}{N_{\pi\to\mu\nu}}(1+\epsilon_{tail})\frac{A_{\pi\text{-}\mu\text{-}e}}{A_{\pi\text{-}\mu\text{-}e}}\frac{\epsilon(E_{\mu\to e\nu\bar{\nu}})_{MWPC}}{\epsilon(E_{\pi\to e\nu})_{MWPC}}\frac{f_{\pi\text{-}\mu\text{-}e}(T_e)}{f_{\pi\text{-}\mu\text{-}e}(T_e)}$$

r_A r_ϵ r_f

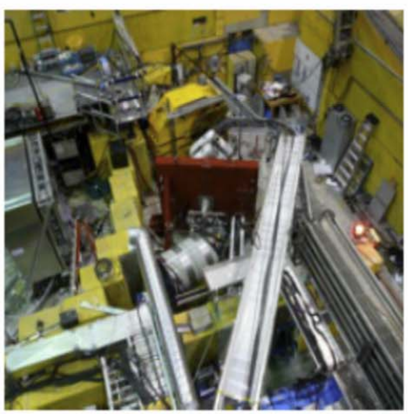
Systematics	Value	$\Delta R^{\pi}_{e/\mu}/R^{\pi}_{e/\mu}$
ϵ_{tail}	0.032	3.5×10^{-4}
r_f	0.04292034	5×10^{-6}
$^{*}r_A r_\epsilon$	$\simeq 0.98$	$\sim 3\times10^{-4}$
Statistical:		
$\Delta N_{\pi\to e\nu}/N_{\pi\to e\nu}$		5.15×10^{-4} (Runs $2^{\dagger}$&3)
Goal		5×10^{-4}

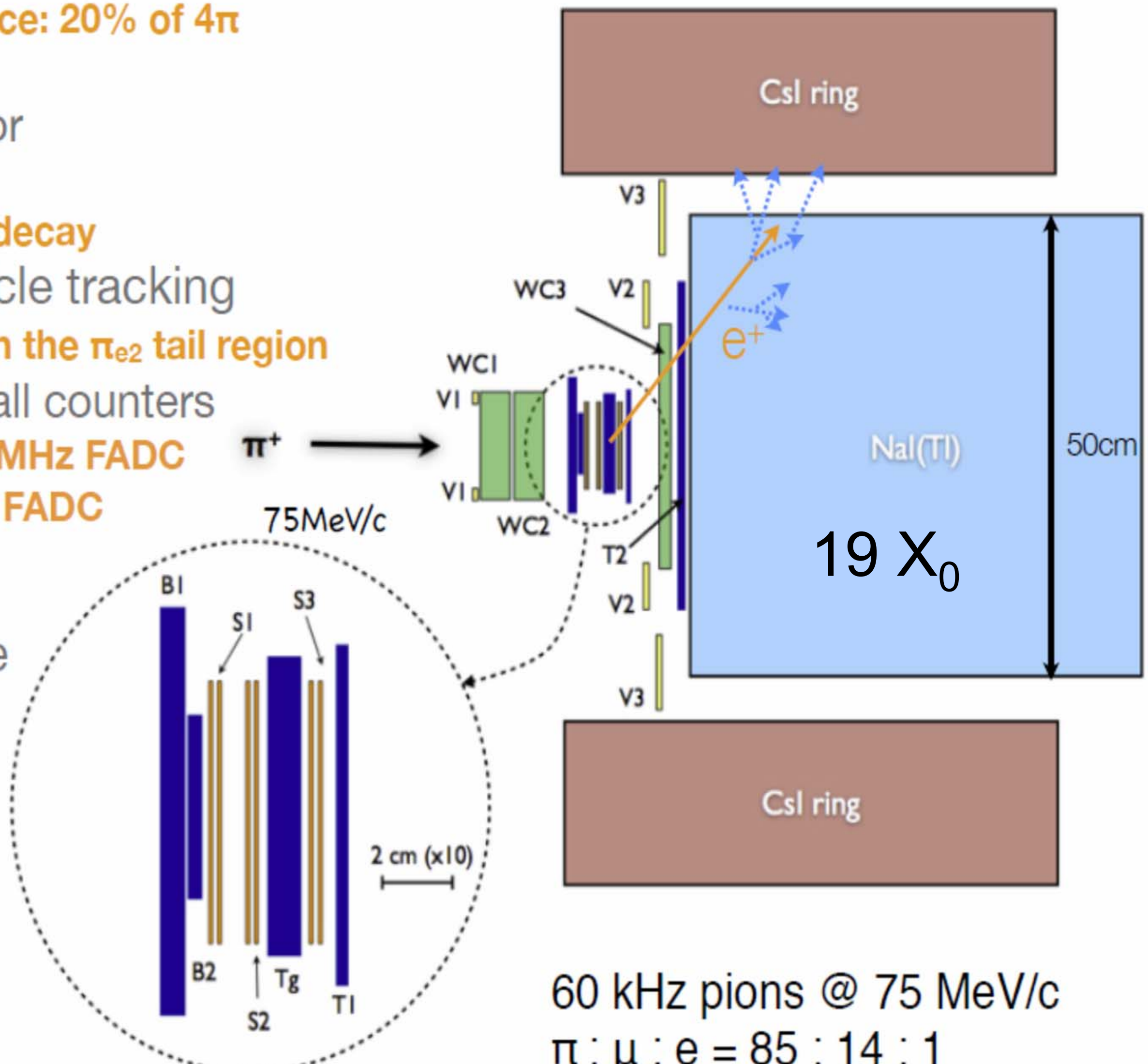
* Blinded † incomplete

PIENU Detector

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

- TRIUMF M13 beamline



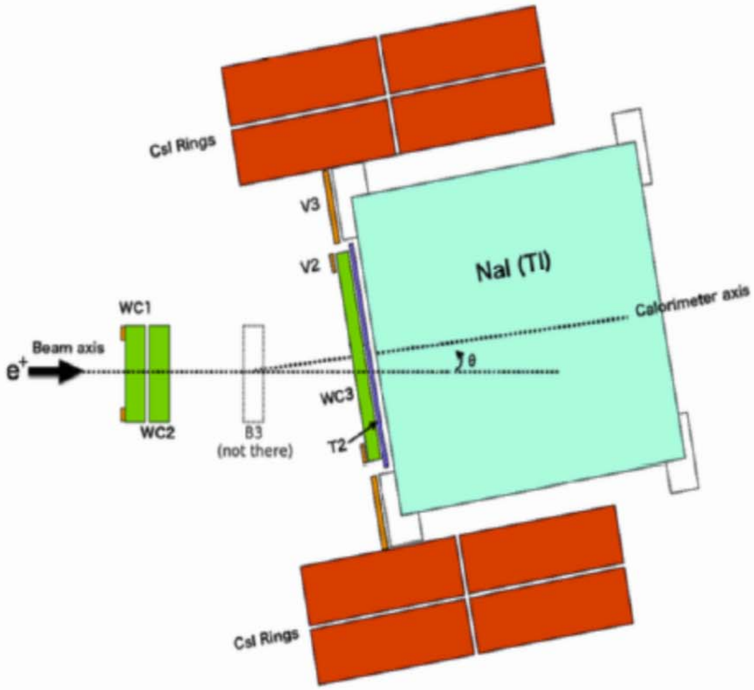


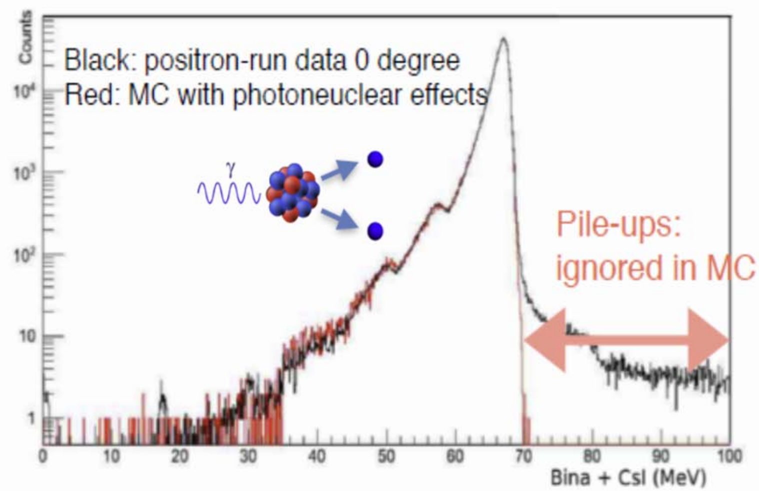
60 kHz pions @ 75 MeV/c

π : μ : e = 85 : 14 : 1

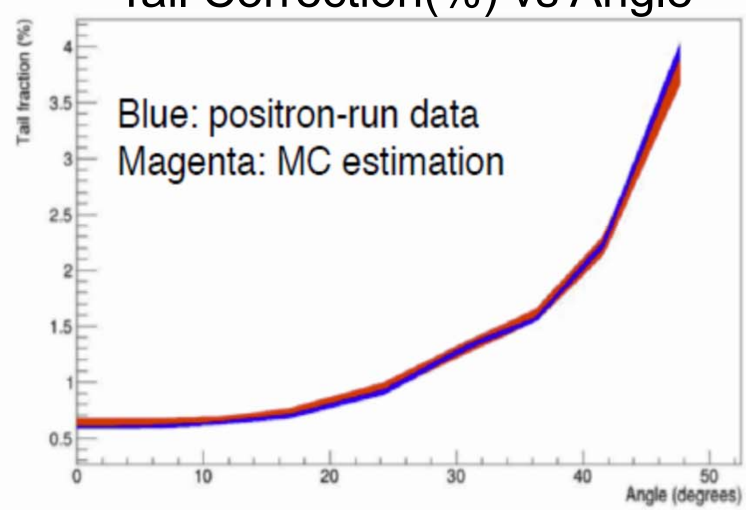
Tail Correction

Important photo-nuclear effects observed.





Tail Correction(%) vs Angle



- Special positron runs to understand the behavior of low-energy tail.

- Typical Tail-Correction factor is: $1.0261 \pm 0.0002(stat) \pm 0.0005(syst)$

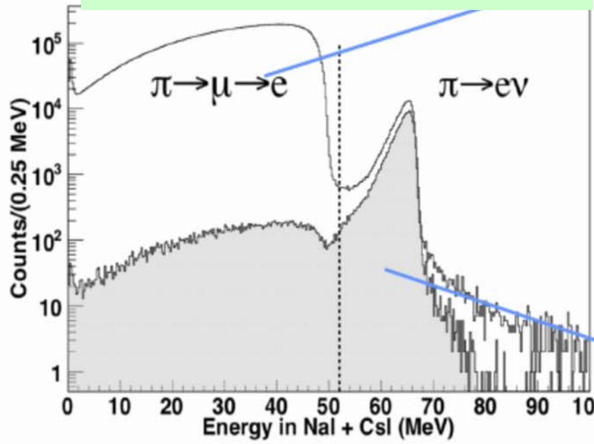
PI E NU

Energy and time selections

2015 publication

2010-data: 0.4 M $\pi^+ \rightarrow e^+ \nu$

Counts vs. Energy

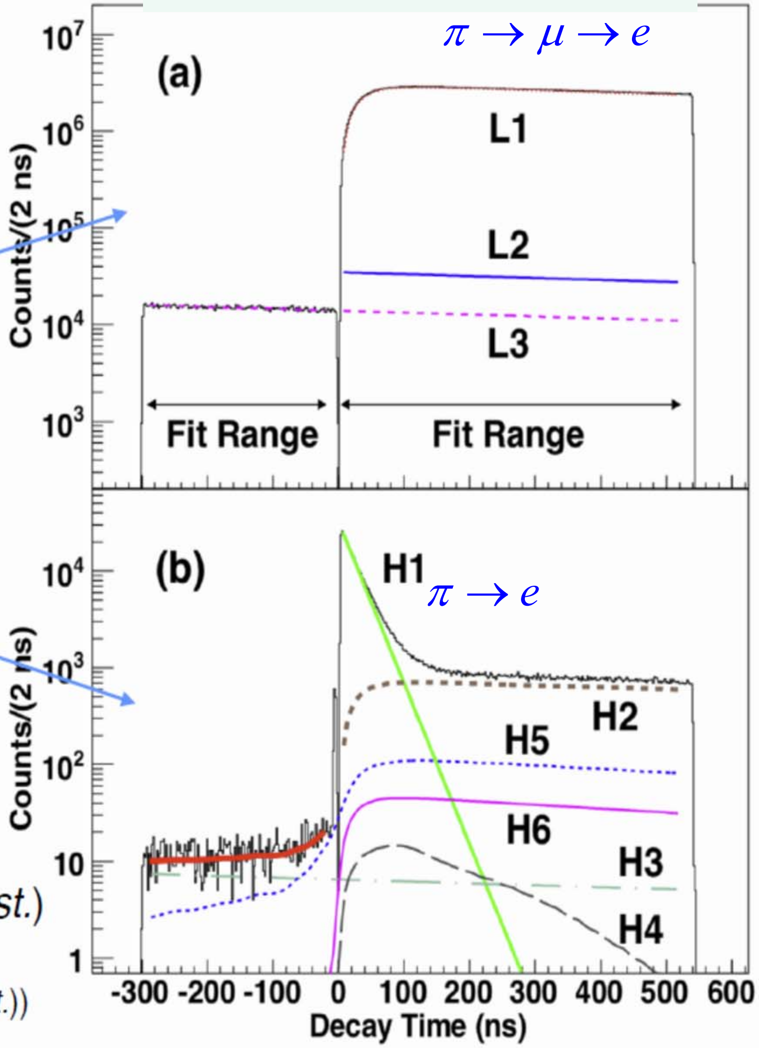


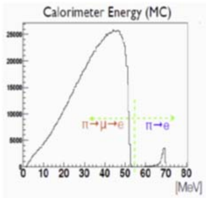
Every spectra of positrons in the time region 5—35 ns.

$R = 1.2344 \pm 0.0023(stat.) \pm 0.0019(syst.)$

($R_{@1992} = 1.2265 \pm 0.0034(stat.) \pm 0.0045(syst.)$)

Counts vs. Time

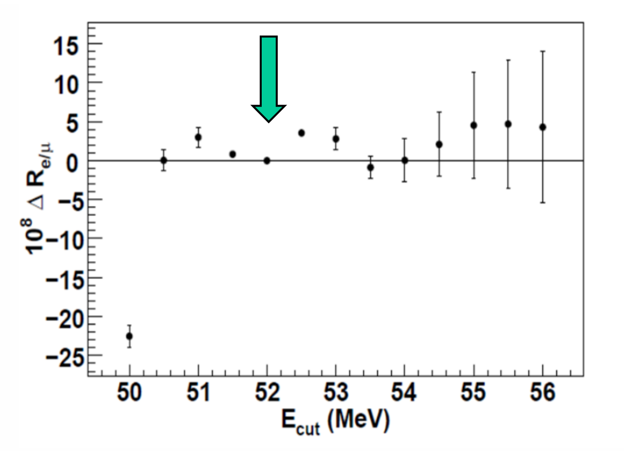




PI E NU

See Tristan Sullivan's talk in parallel sessions.

$R^{exp\pi}_{e/\mu}$ dependance on E_{cut}



PIENU Uncertainties

Error	PIENU 2010	PIENU goal
Statistical	0.19%	0.07%
Time Spectrum	0.04%	0.04%
Tail Correction	0.12%	0.06%
Others	0.07%	0.04%
Total	0.24%	< 0.1%

Current Result PIENU: $R^{exp\pi}_{e/\mu} = 1.2344 \pm 0.0030 x 10^{-4}$

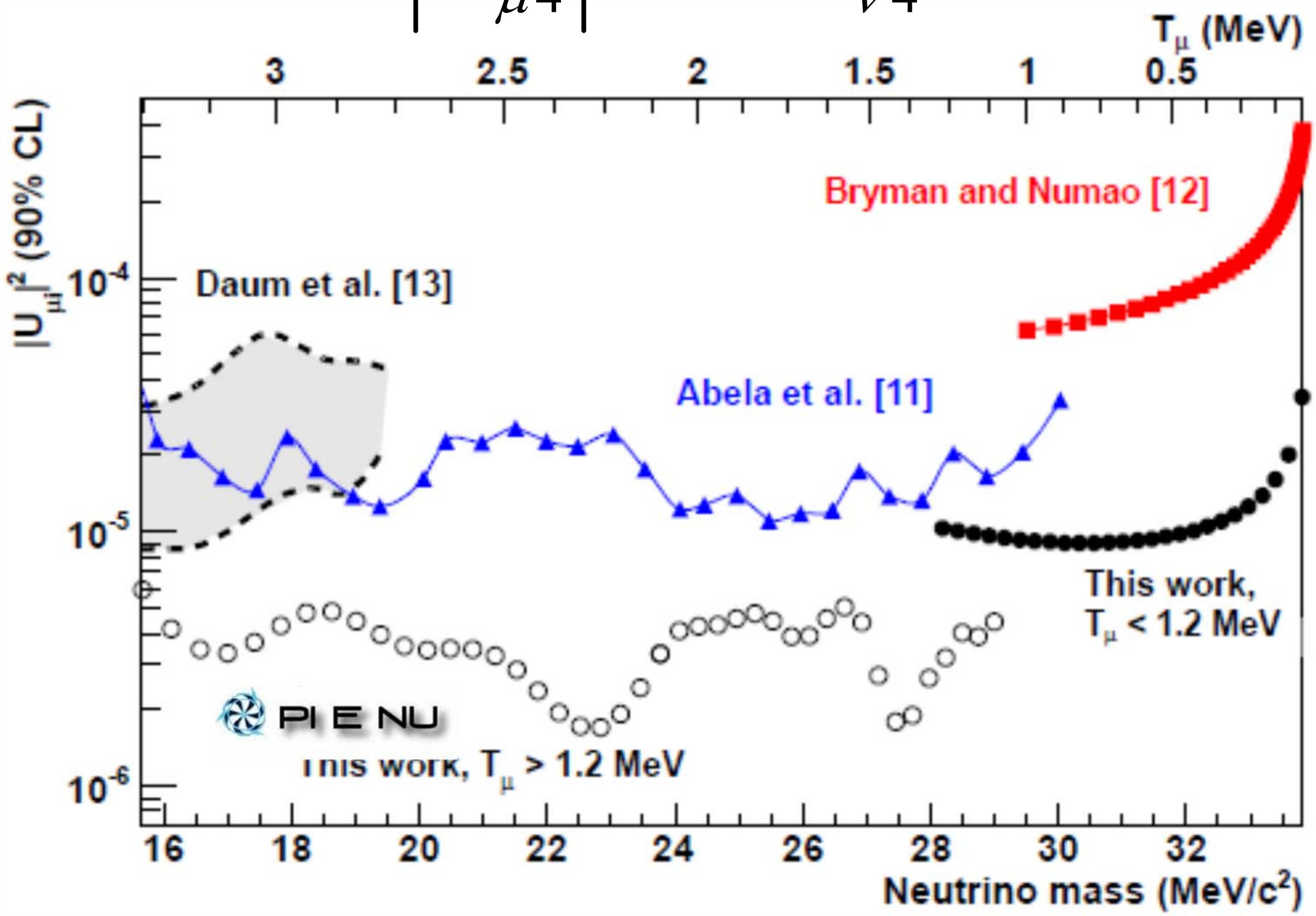
Full Data Sample: $10^7\ \pi^+ \rightarrow e^+\nu$ Events

Precision Goal: $\pm 0.1\%$

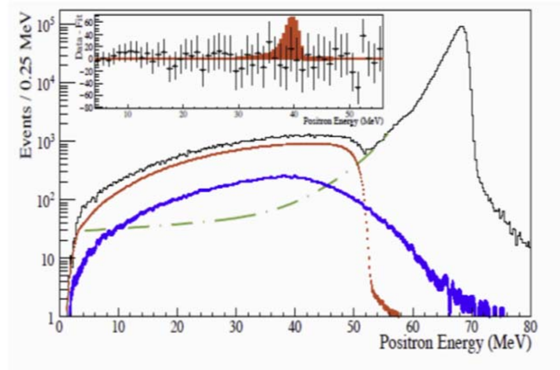
Search for Heavy Neutrinos in $\pi^+ \rightarrow \mu^+ \nu_H$ Decay

Order of magnitude improvement: 15-34 MeV

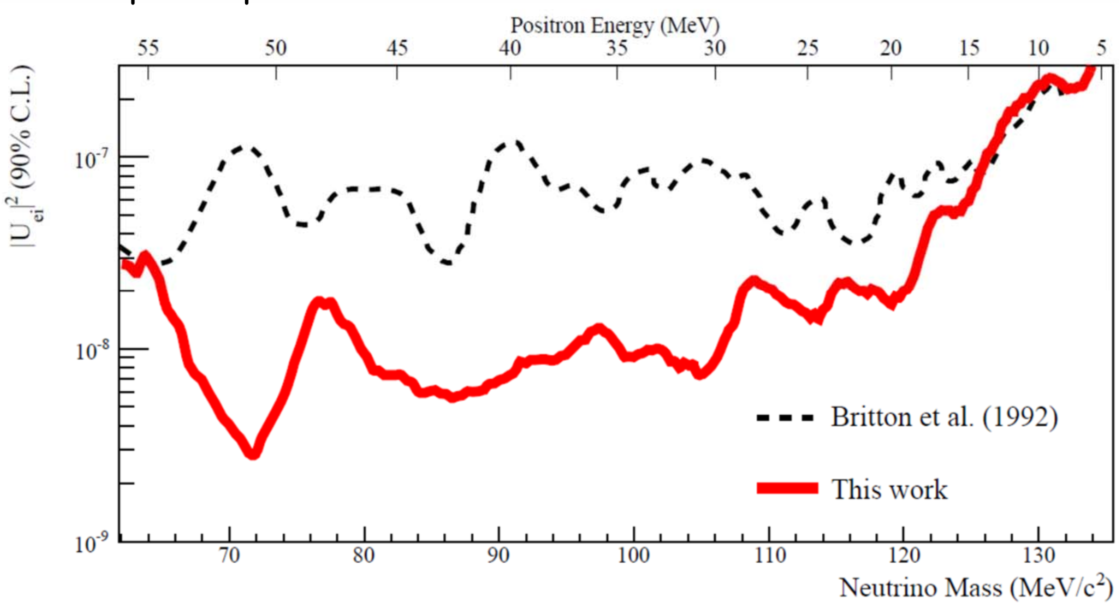
$$\left|U_{\mu 4}\right|^2 \text{ vs } \mathrm{m}_{\nu 4}$$



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



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

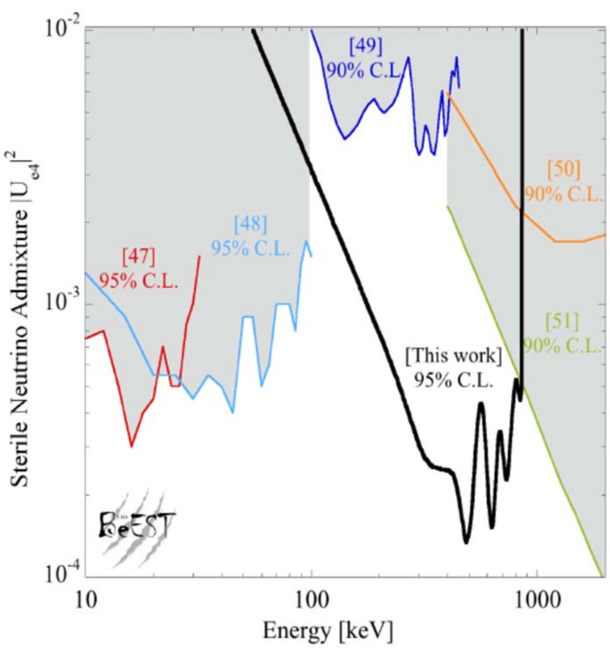


Substantial improvement: 60-120 MeV → 10^{-8} level

Massive Sterile Neutrinos

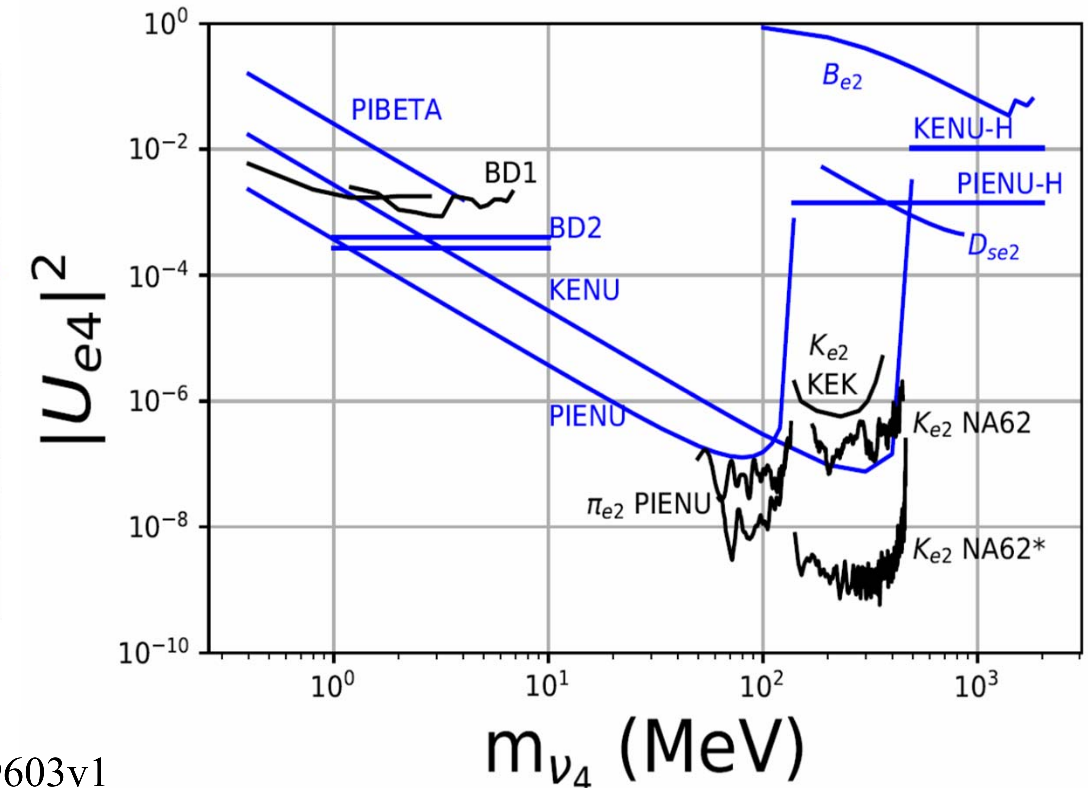
Could range in mass from eV to GUT scale; constraints from oscillations, cosmology, HEP….
Possible correlations with LFV, LNV…

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



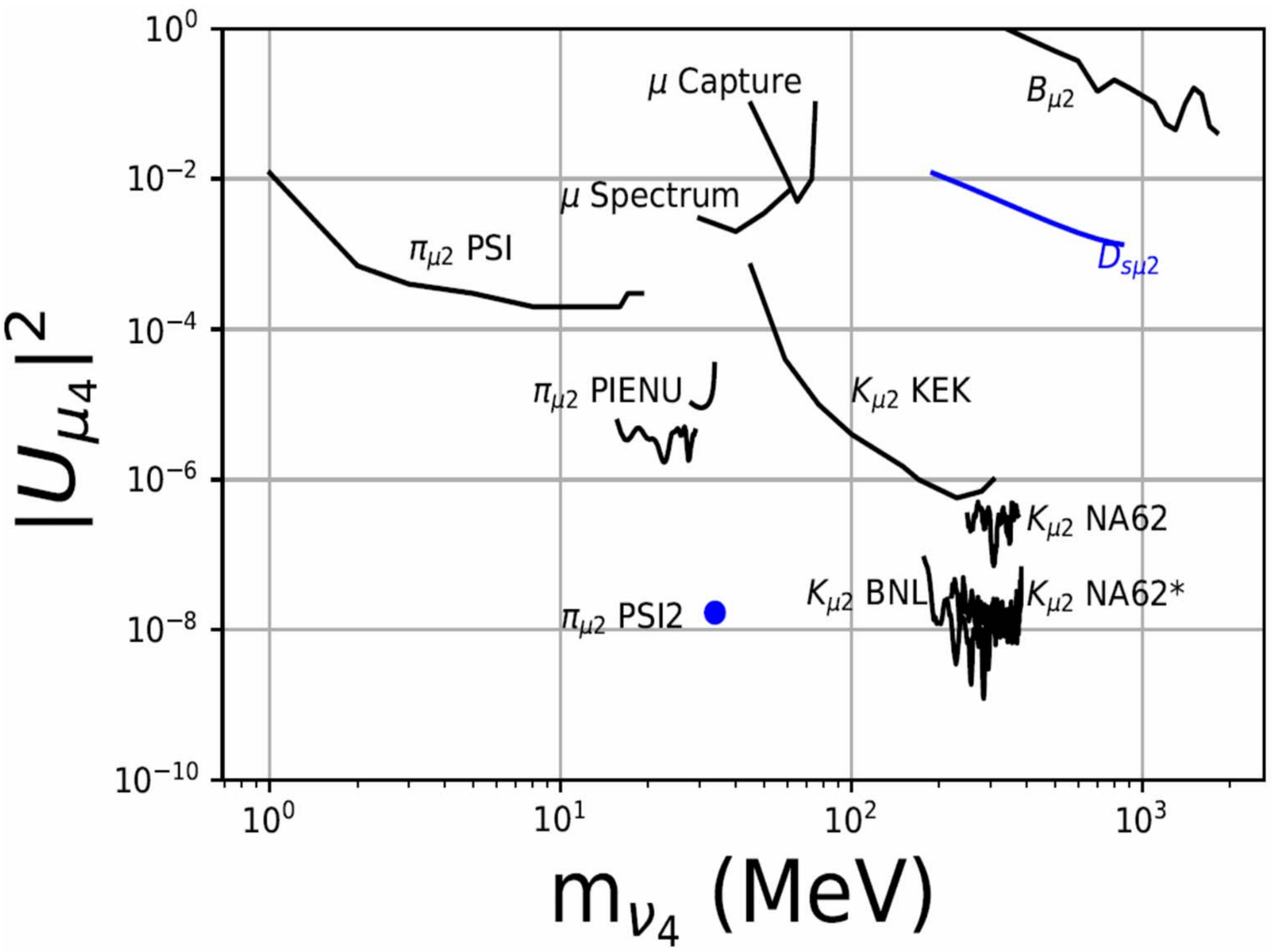
S. Friedrick et al., arXiv:2010.09603v1

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



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

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



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

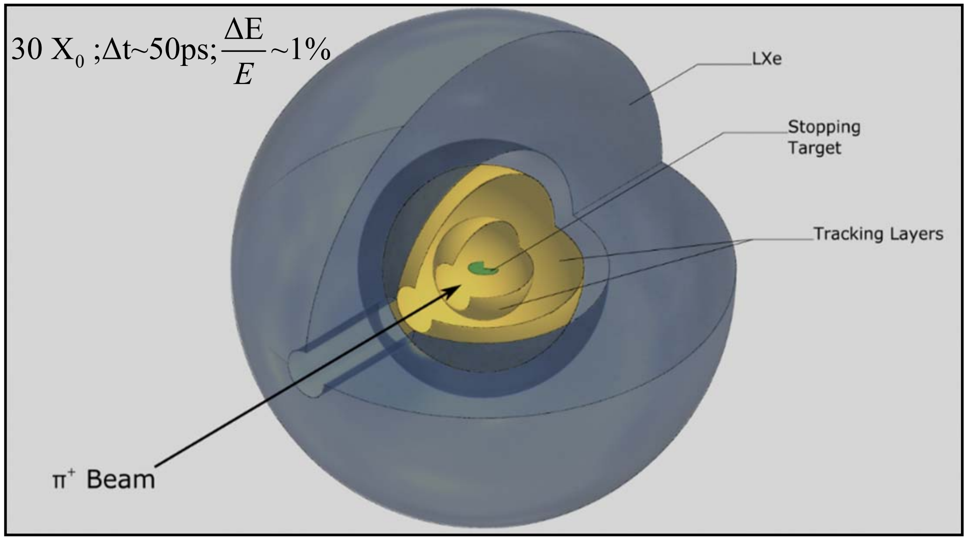
Snowmass RF2 LOI

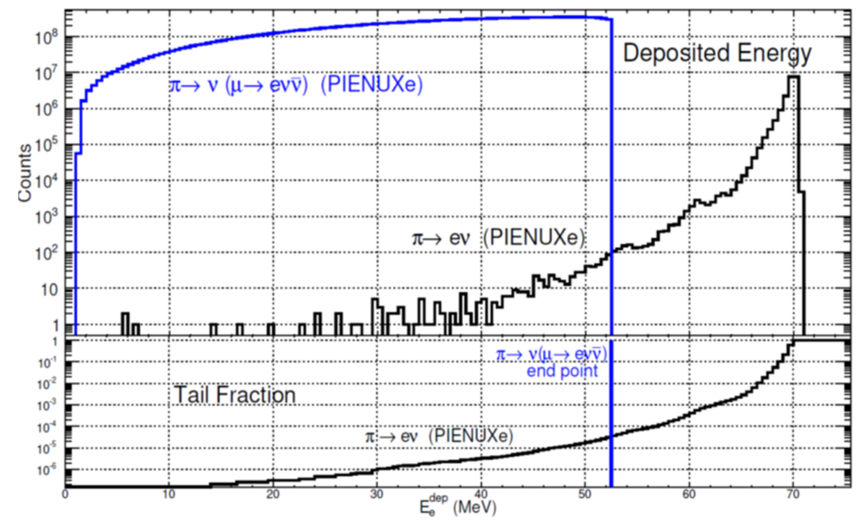
PIENUXE: Testing Lepton Flavor Universality and CKM Unitarity with Rare Pion Decays

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], T. Iwamoto[17], P. Kammel[12], J. Kaspar[12], K. Labe[13], J. Labounty[12], S. Ito[18], W. Marciano[19], S. Mihara[20], R. Mischke[3], T. Mori[17], T. Numao[3], W. Ootani[17], C. Ortega Hernandez[1], D. Pocanic[14], D. Salvat[21], T. Sullivan[22]

[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]University of Tokyo, [18]Okayama University,[19]Brookhaven National Laboratory, [20]KEK, [21]Indiana University, [22]University of Victoria

PIENUXE: New Rare π Decay Experiment with LXe





Faster calorimeter response time x10-100.

Low energy tail reduced x 10

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

- π^+Beam: 75 MeV/c ; 2x10^5 Hz
- Tracking –SciFi-SiPM, Si pixels
- LXe calorimeter
- Sensitivity, Precision: 10^8 events ±0.015% in 1 yr

$$\frac{g_e}{g_\mu} \sim (\pm 0.0075\%)$$

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

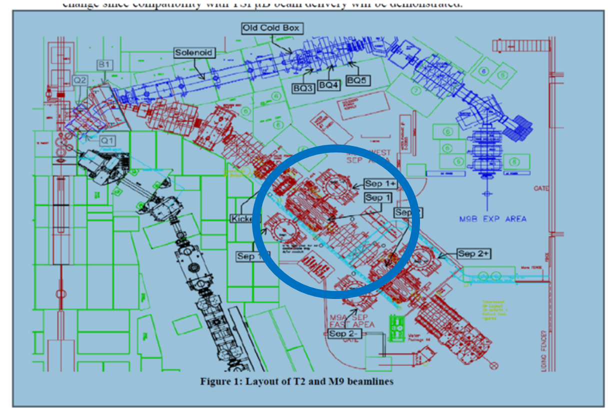
- π^+Beam: 75 MeV/c ; 3x10^7 Hz
- Sensitivity, Precision: 10^6 events ±0.1% in 1 yr

$$V_{ud} \sim (\pm 0.03\%) \qquad \frac{V_{us}}{V_{ud}} \sim (\pm 0.1\%)$$

Possible Sites for PIENUXE

TRIUMF

- M9A – only existing possibility
- New channel at T2 M8 port
- New target station/beamline elsewhere?

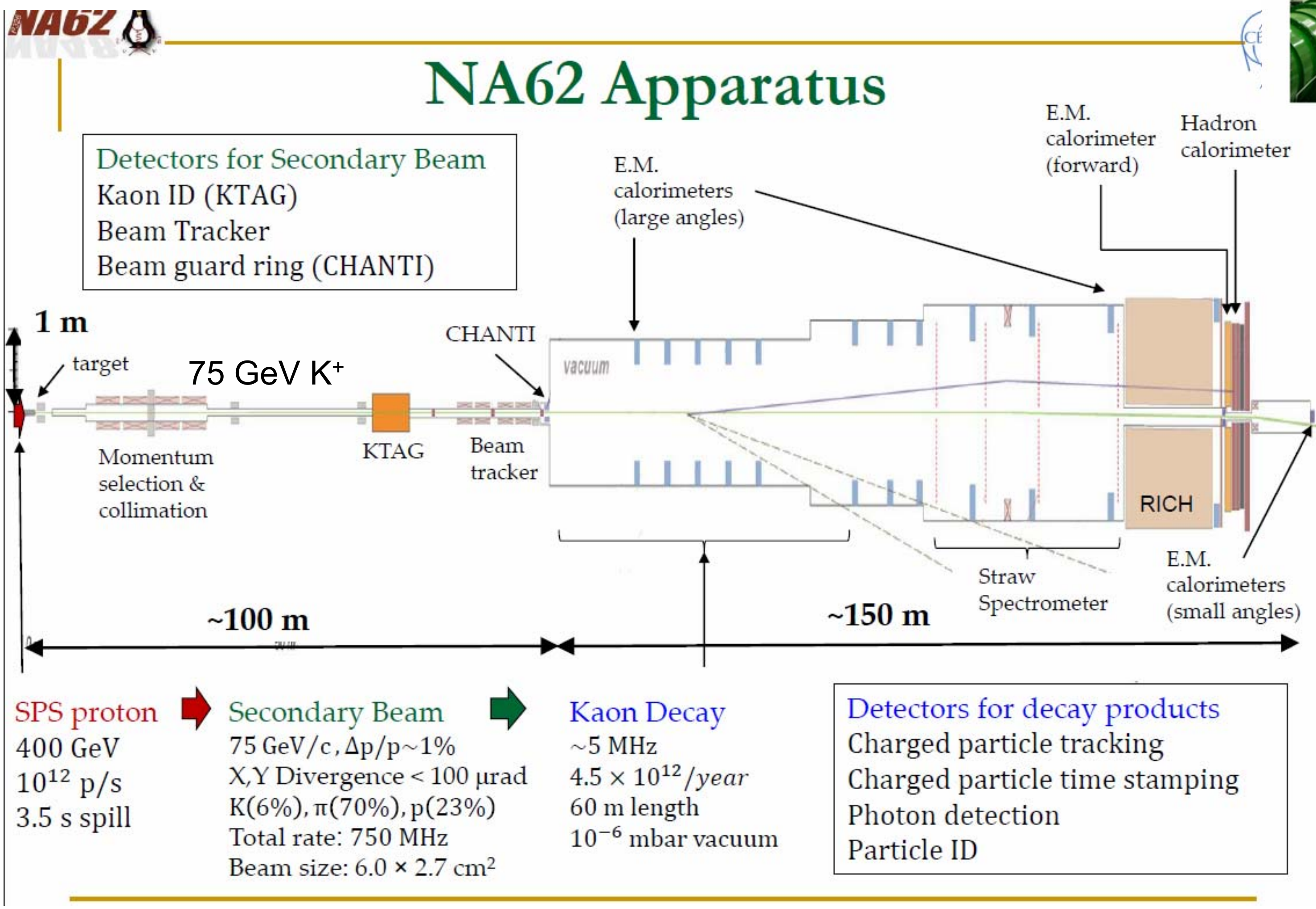


PSI: πE5 –short low energy beamline; πE1?

See talk by Andreas Knecht in parallel sessions

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

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



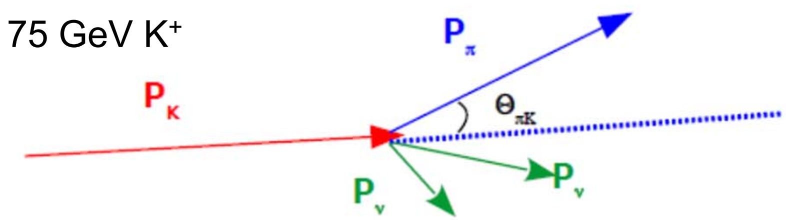
Most efficient detector ever built.

CERN's longest experiment?

In operation 2015-2018 (2021-2023 planned+ beam dump mode)

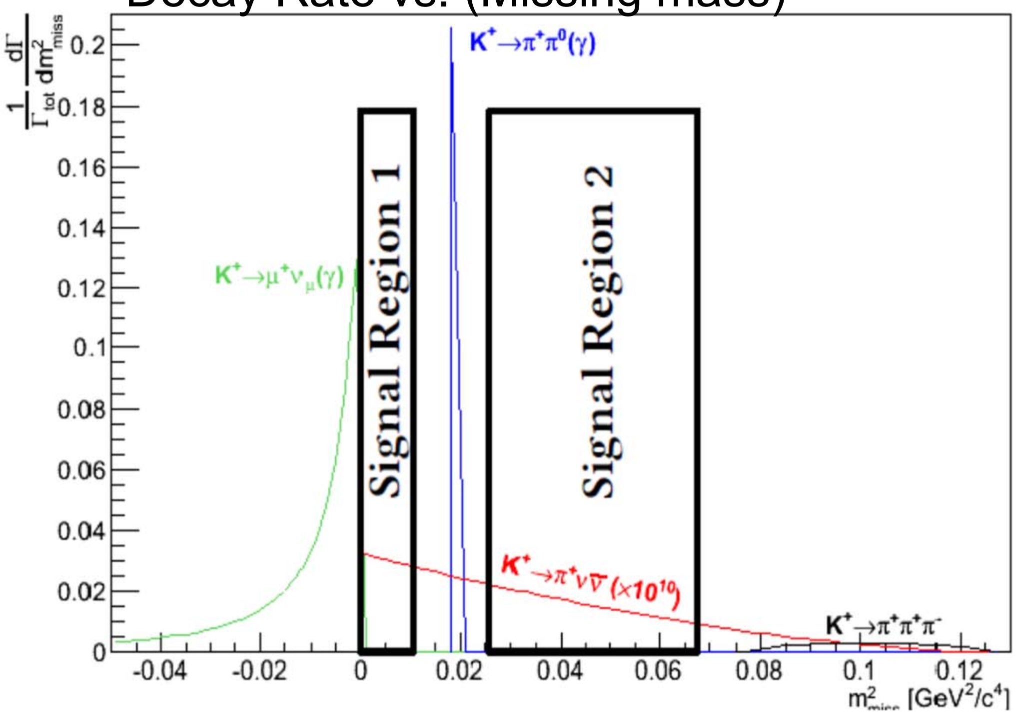
Analysis strategy

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

Decay Rate vs. (Missing mass)^2



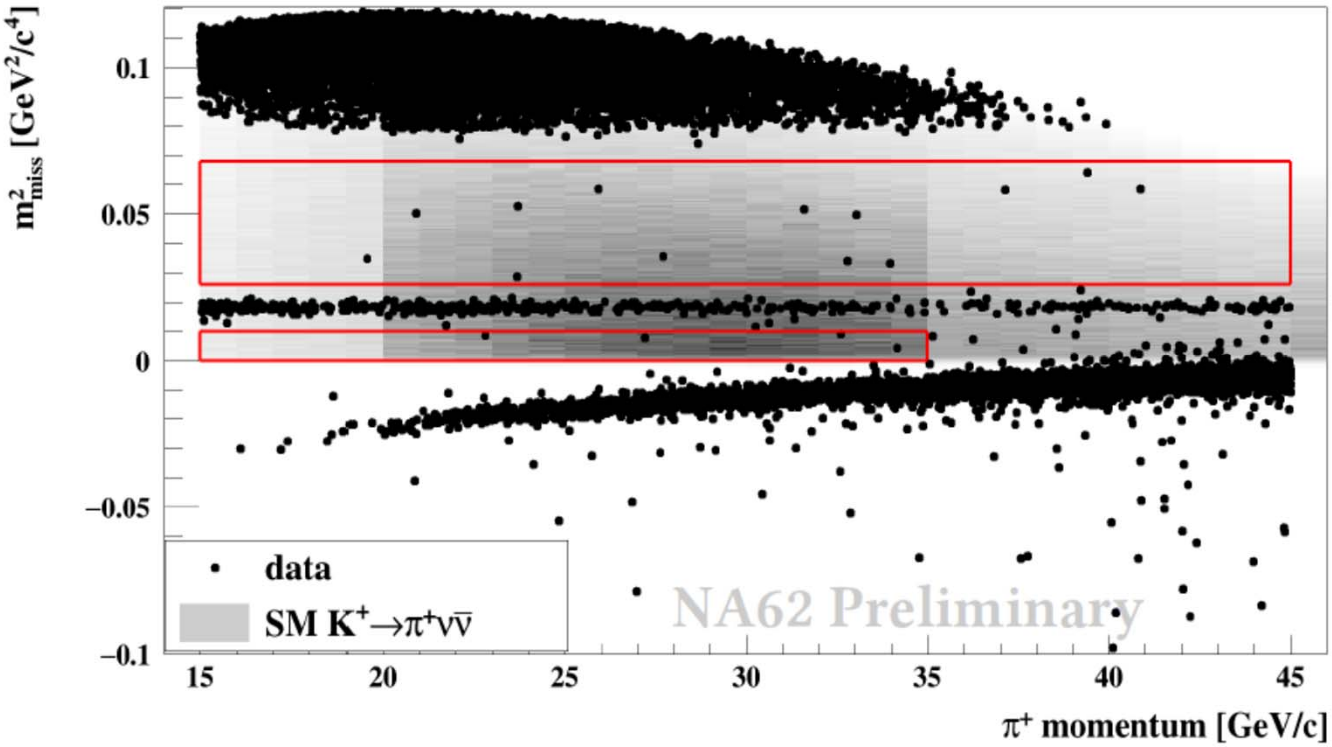
Process	Branching ratio
$K^+ \to \pi^+\pi^0$	0.2066
$K^+ \to \mu^+\nu_\mu$	0.6356
$K^+ \to \pi^+\pi^+\pi^-$	0.0558
$K^+ \to \pi^+\pi^- e\, \nu_e$	4.3×10^{-5}
$K^+ \to \pi^+\nu\nu$ (SM)	**8.4×10^{-11}**

NA62 2018 Data $K^+ \to \pi^+ \nu\bar{\nu}$

17 events observed

$5.28^{+0.99}_{-0.74}$ Background

$(\text{Missing Mass})^2$ *vs* P_π



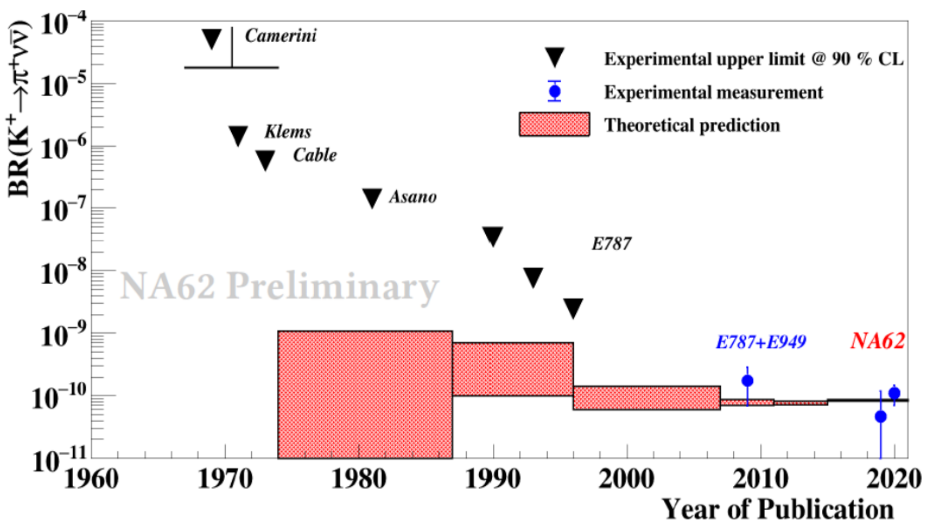
Background dominated by upstream random coincidences

Blinded control regions validated prior to opening box.

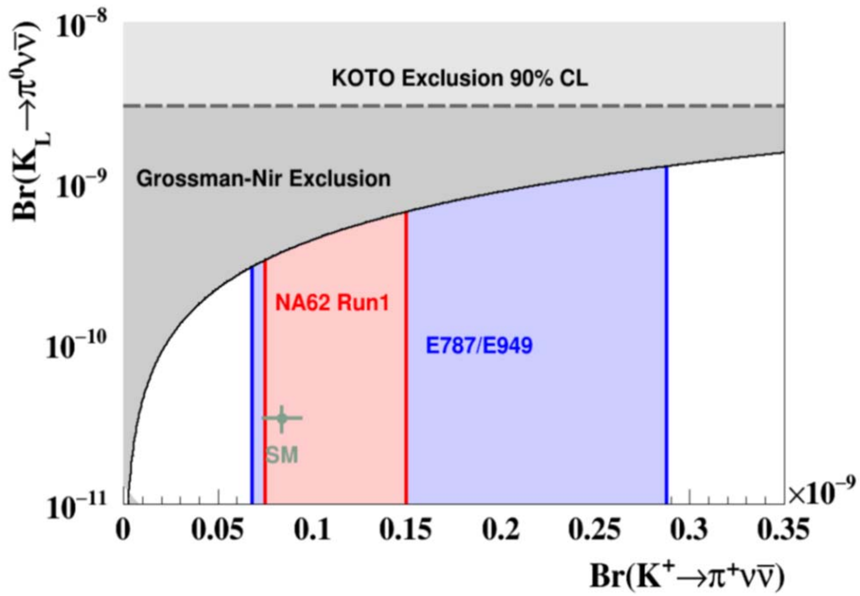
NA62 Results (2016-2018 data):

$B(K^+ \to \pi^+ \nu\bar{\nu}) = \left(11^{+4.0}_{-3.5}\right) x10^{-11}$ (3.5σ significance)

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



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



Next: Measure $B(K^+ \rightarrow \pi^+ \nu \bar{\nu})$ $\pm 20\%$

NA62 Run 2 Plans 2021-2024

Increase beam rate x 1.3

Mods to reduce upstream backgrounds

- Beamline rearrangement near GTK
- 4^{th} GTK beam tracker station
- New upstream vetos; other veto counters

Possible Future: Measure $B(K^+ \rightarrow \pi^+ \nu \bar{\nu})$ $\pm 5\%$

Increase beam rate x4

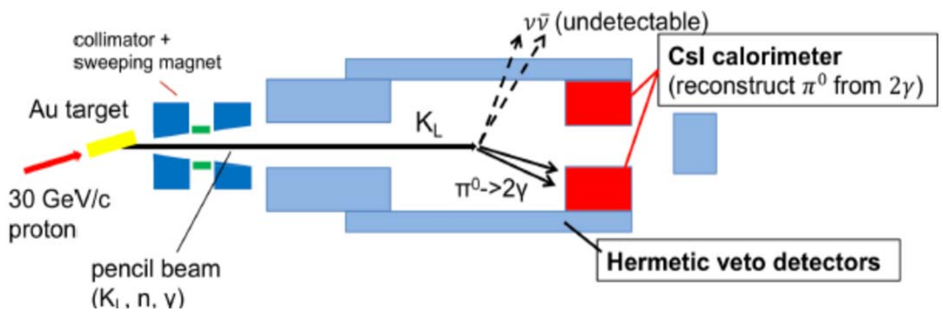
Improve time resolution to reduce randoms

e.g. Beam Cerenkov detectors 100 → 20 ps
GTK tracker 125 → 50 ps

KOTO at JPARC $K_L^0 \to \pi^0 \nu \bar{\nu}$

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

$K_L \to \pi^0 \nu \bar{\nu}$: $(\pi^0 \to)$ 2γ + nothing

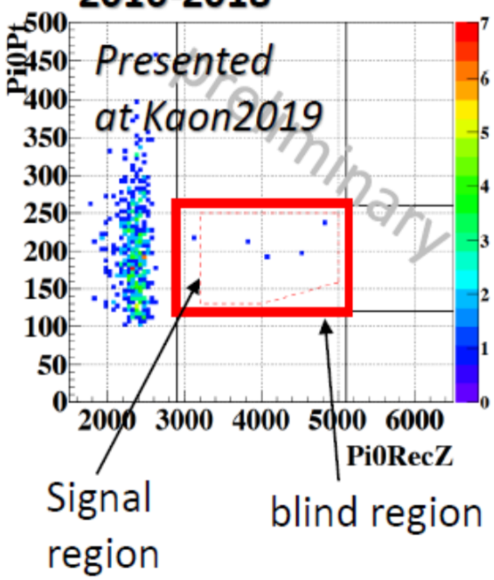


$B(K_L^0 \to \pi^0 \nu \bar{\nu}) < 3x10^{-9}$ (90% c.l.)

(2019) based on 2015 data

Data taken during 2016-2018

SM expectation 0.04 events



ICHEP2020 (Kaon2019)

Observed : 3(4) events

Background: 1.05 ± 0.28 (0.05 ± 0.2)

New background source found after analysis: K^+ decays

2019 run: analysis in progress

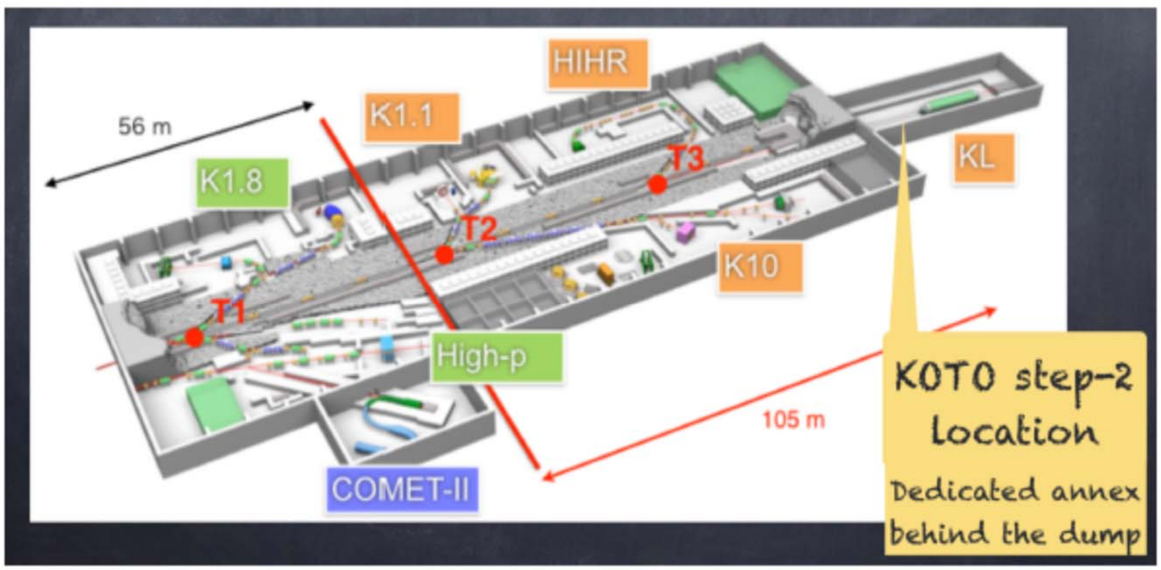
KOTO: Future Plans

2020 beam tests $\rightarrow$ adding upstream charged particle vetos

(> 2025): Goal: 100 $K_L^0 \rightarrow \pi^o \nu \bar{\nu}$ events (S/N~1)

Higher flux (thicker target x1.4, smaller production angle $16^o \rightarrow 5^o$)

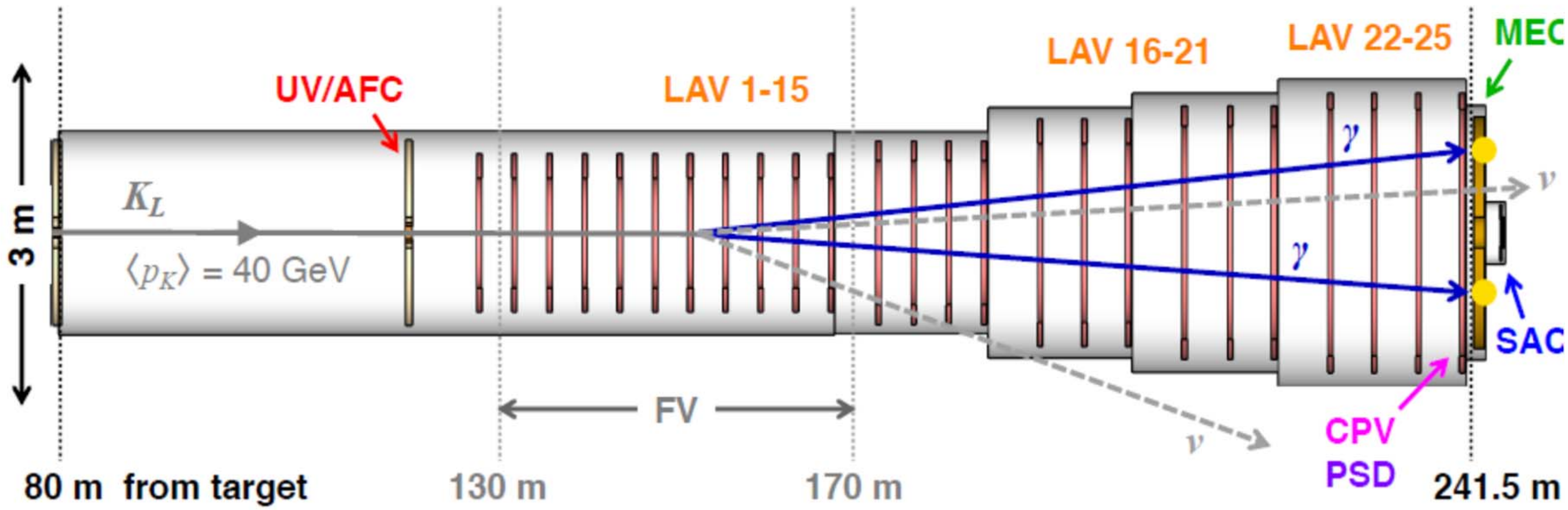
Increased detector acceptances: Calorimeter $2 \rightarrow 3$m dia., decay path $2 \rightarrow 15$m



M. Moulson Snowmass 2020

A $K_L \to \pi^0 \nu\bar{\nu}$ experiment at the SPS? KLEVER

400-GeV SPS proton beam on Be target at z = 0 m



KLEVER target sensitivity:
5 years starting Run 4

~60 SM $K_L \to \pi^0 \nu\nu$
S/B ~ 1

δBR/BR($\pi^0\nu\nu$) ~ 20%

- High-energy experiment: Complementary to KOTO
- Photons from K_L decays boosted forward
  - Makes photon vetoing easier - veto coverage only out to 100 mrad
- Roughly same vacuum tank layout and fiducial volume as NA62

Conclusions: *Flavor Physics 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, CKM Unitarity, and Lepton Flavor Violation* --- especially sensitivity to very high mass scales.

- New π/K/B results expected in the next few years from PIENU, PEN, NA62, and LHCb BESSIII, BELLE-II.

- New or extended projects under consideration for $\pi^+ \rightarrow e^+ \upsilon$, $\pi^+ \rightarrow \pi^0 e^+ \upsilon$, $K^+ \rightarrow \pi^+ \upsilon\bar{\upsilon}$, and $K_L{}^0 \rightarrow \pi^0 \upsilon\bar{\upsilon}$.

- Important connections with searches for sterile neutrinos, high mass scale physics and L(F/N)V tests ($0\nu\beta\beta$, $K \rightarrow \pi\, \mu^+\mu^+$, $K \rightarrow \pi\, e^+ e^+$, $\mu \rightarrow e\gamma$, $\mu^- Z \rightarrow e^- Z$, $\mu^- Z \rightarrow e^+ (Z-2)$, $\mu \rightarrow 3e$, muonium-antimuonium…).