CERN NA62: Rare Kaon Decays

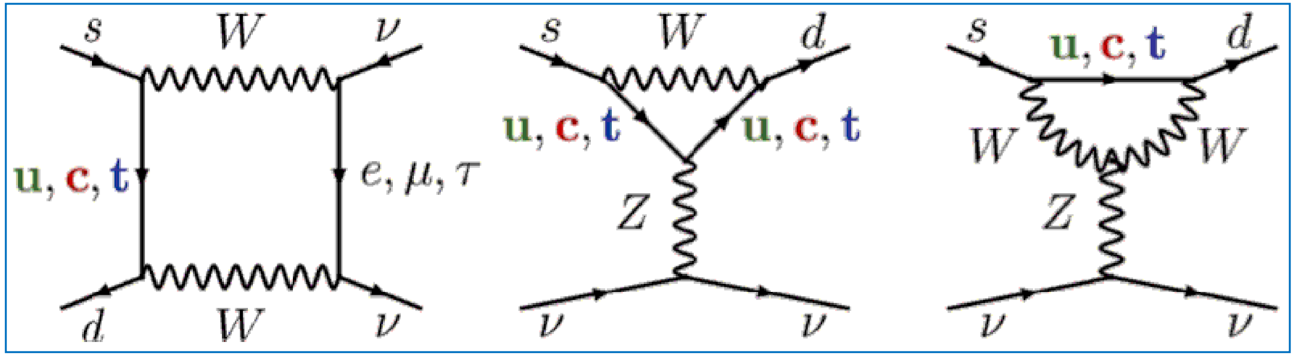
Doug Bryman

University of British Columbia and TRIUMF

Canada's national laboratory for particle and nuclear physics and accelerator-based science

Rare kaon decays: $K \to \pi \nu \bar{\nu}$

SM: box and penguin diagrams



Theoretically clean, highly, sensitive to new physics at high mass scales O(100 TeV).

Ultra-rare decays with the highest CKM suppression:

$$A \sim (m_t/m_W)^2 |V^*_{ts} V_{td}| \sim \lambda^5$$

SM branching ratios

Buras et al., JHEP 1511 (2015) 033

Mode	$BR_{SM} \times 10^{11}$
$K^+ \to \pi^+ \nu \bar{\nu}(\gamma)$	8.4±1.0
$K_L \to \pi^0 \nu \bar{\nu}$	3.4±0.6

- SM precision surpasses any other FCNC process involving quarks.
- Measurement of $|V_{td}|$ complementary to those from e.g. B–$\bar{B}$ mixing.
- Main focus of kaon physics: measurement of both $K^+ \to \pi^+ \nu \bar{\nu}$ and $K_L \to \pi^0 \nu \bar{\nu}$ decays.

BNL E787/E949 (2008)

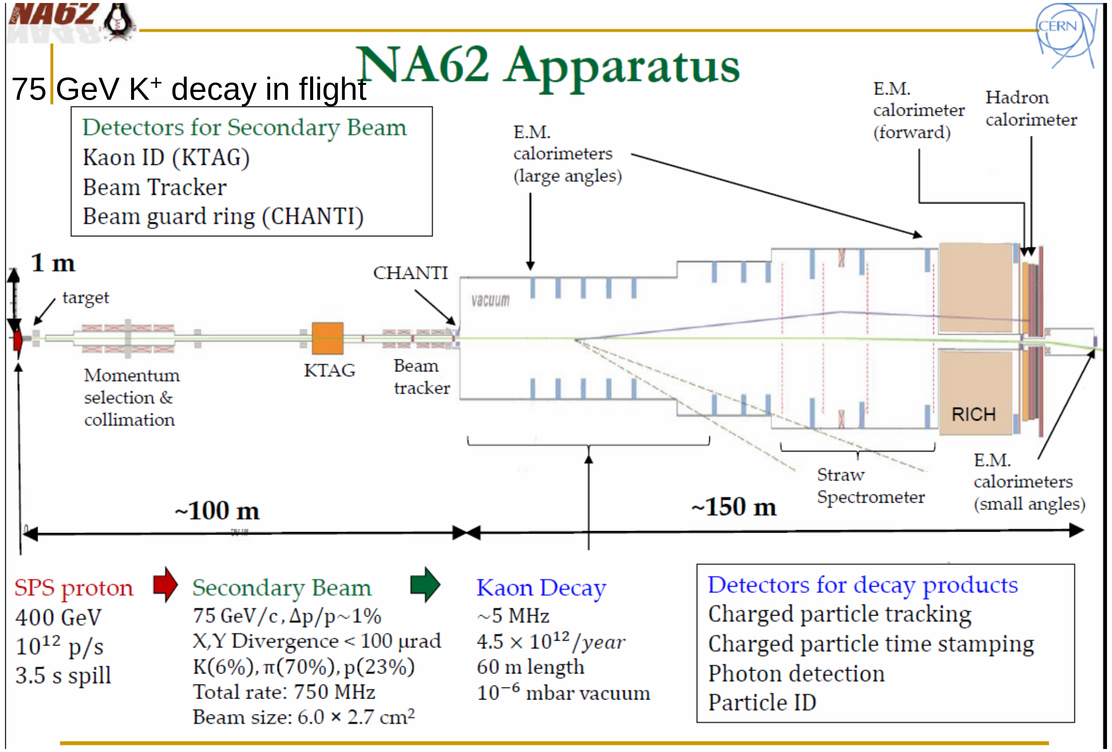
$$BR(K^+ \to \pi^+ \nu \bar{\nu}) = 1.73^{+1.15}_{-1.05} x 10^{-10}$$

7 events observed

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

Goal: 10% precision.

Operation 2015-2018; resumes in 2021



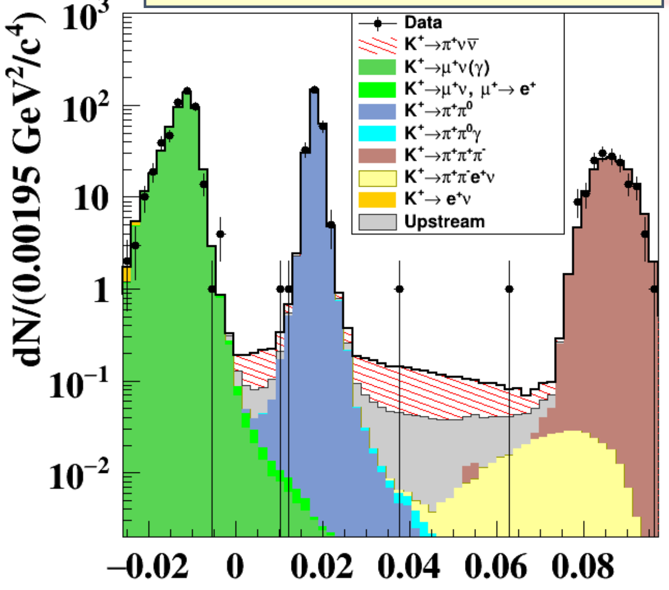
The NA62 detector

NA62 physics data taking started in June 2015

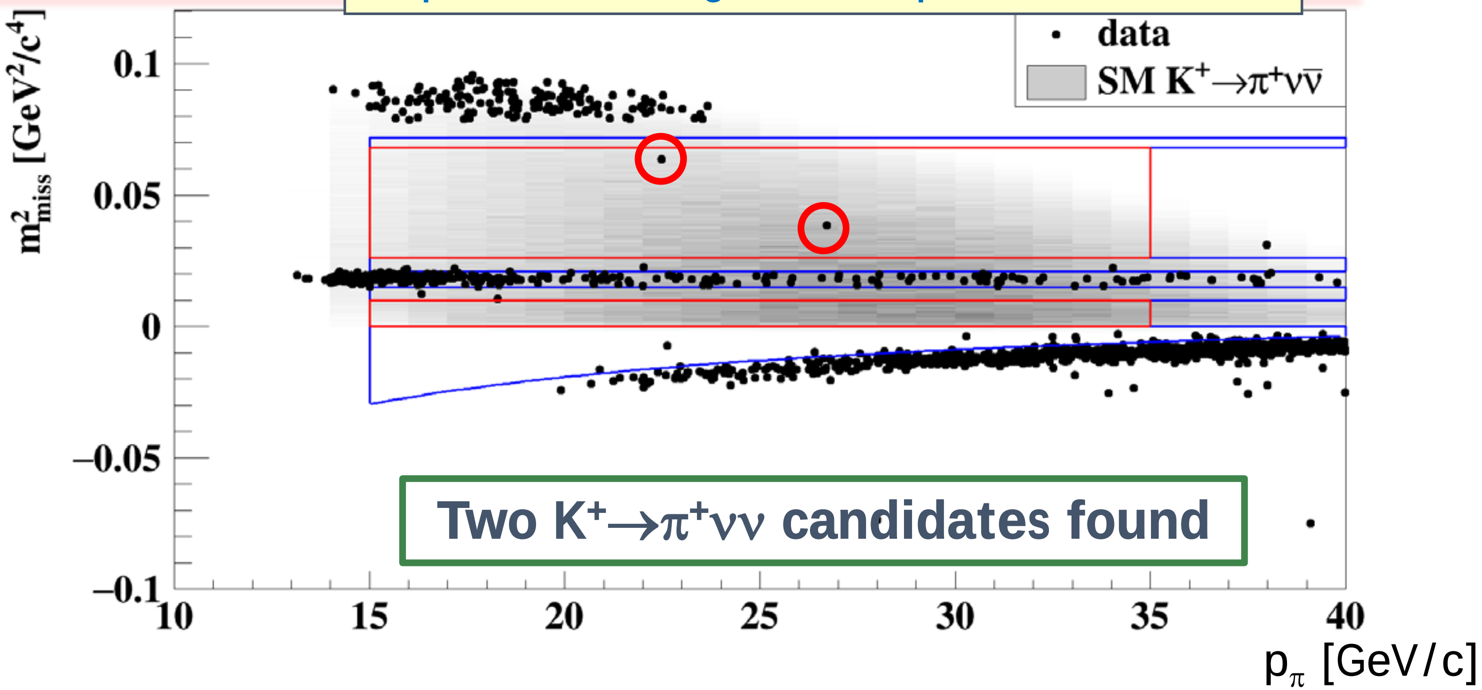
Other studies on lepton number violation, π^0 decay, sterile neutrinos, rare/exotic channels….

BR($K^+ \to \pi^+ \nu\nu$) Results (2017)

Squared missing mass



Squared missing mass vs pion momentum

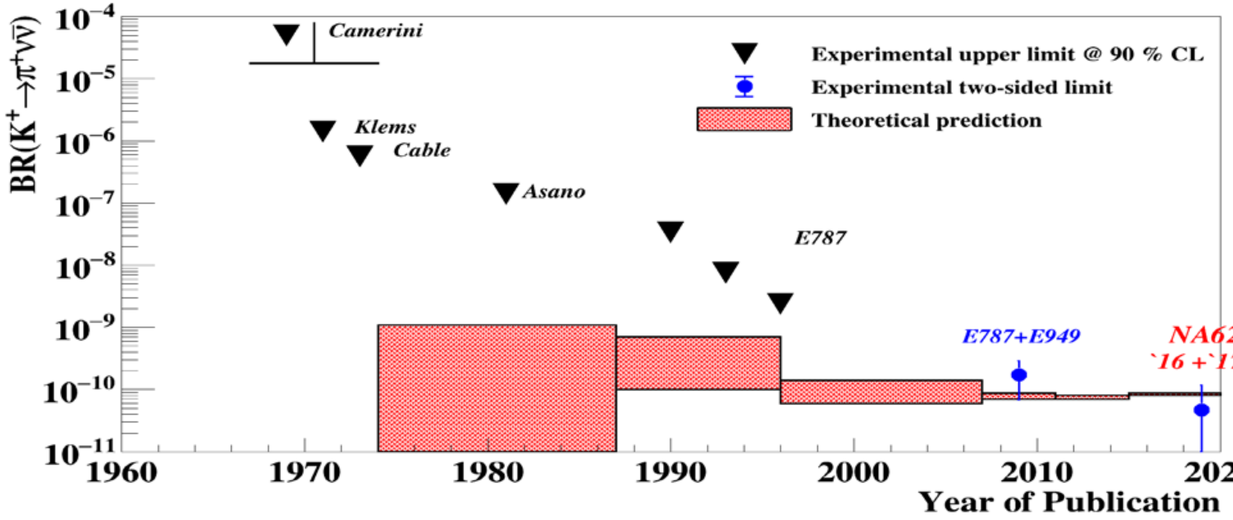


The 2016+2017 data set

Candidates observed: **3**
Expected background: **1.5±0.3**
Expected SM events: **2.2±0.4**

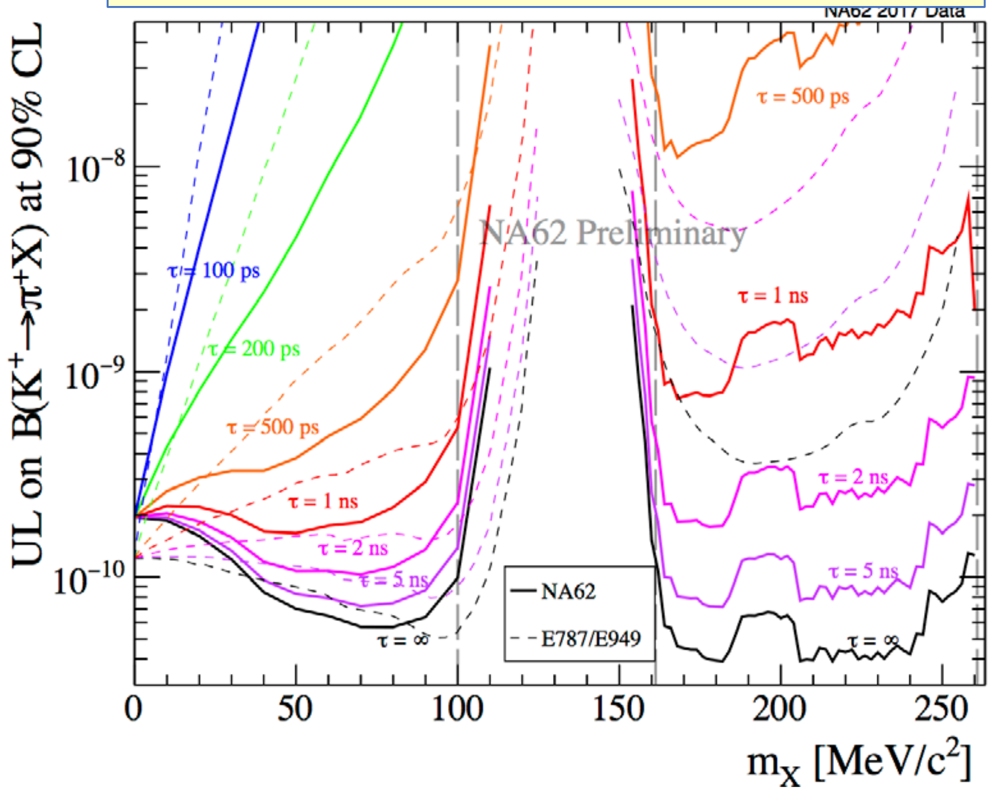
One-sided limit at **90%** CL:
BR($K^+ \to \pi^+ \nu\nu$) < 1.78×10^{-10}

One-sided confidence interval:
BR($K^+ \to \pi^+ \nu\nu$) = $(0.48^{+0.72}_{-0.48}) \times 10^{-10}$



Search for $K^+ \to \pi^+ X$

UL at 90% CL on $BR(K^+ \to \pi^+ X)$ vs m_X



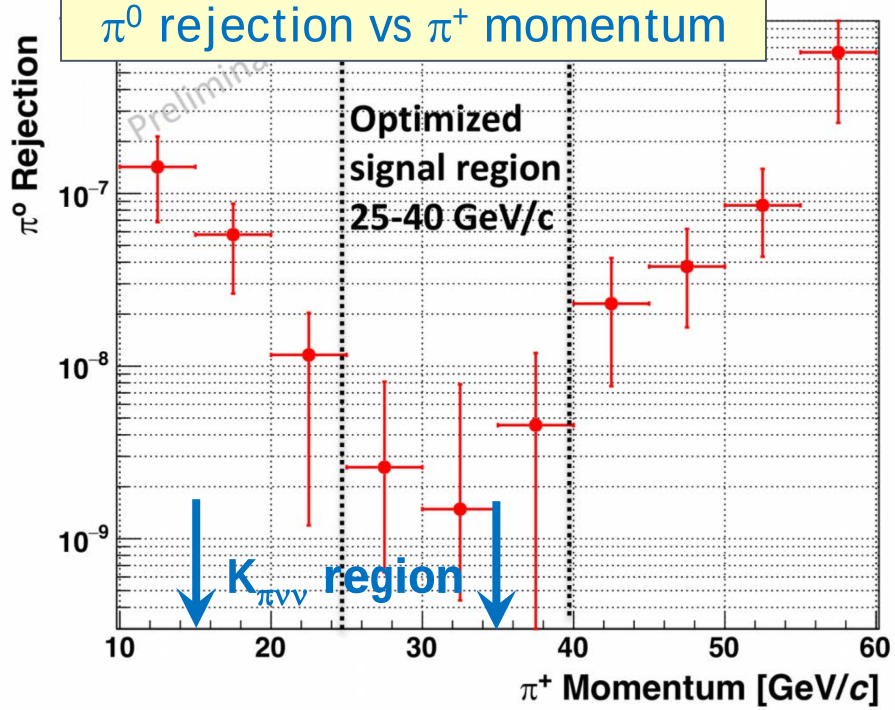
- Signature: a spike in m^2_{miss} spectrum of the $K^+ \to \pi^+ \nu\nu$ candidates.
- Two candidates observed consistent with background: no signal.
- Upper limits of **$BR(K^+ \to \pi^+ X)$** depending on **X** mass and lifetime.
- Region 2: **order of magnitude improvement on BNL E949 in high energy region.**

Search for $\pi^0 \to$invisible

- Single-photon detection efficiency vs momentum measured with $K^+ \to \pi^+\pi^0$ decays: minimum-bias data sample, tag & probe method.
- Rejection of ($K^+ \to \pi^+\pi^0(\gamma)$, $\pi^0 \to \gamma\gamma$) decays: MC simulation based on measured single-photon efficiency.
- Rejection for $K^+ \to \pi^+\nu\nu$ ($15<p_\pi<35$ GeV/c): $\varepsilon = (1.4\pm0.1)\times10^{-8}$.
- Rejection for $\pi^0 \to$invisible search ($25<p_\pi<40$ GeV/c): $\varepsilon = (2.8^{+5.0}_{-2.1})\times10^{-9}$
- Validation: sidebands with $\varepsilon>10^{-7}$ with $\pi^0 \to \gamma\gamma$ excluded

[BNL-E949, PRD72 (2005) 091102]

π^0 rejection vs π^+ momentum



Search for $\pi^0 \to$invisible:

- About **1/3** of the **2017** data set.
- $K_{\pi\nu\nu}$ trigger and selection used, but $0.015<m^2_{miss}<0.021$ GeV^2/c^4.
- Expected $\pi^0 \to \gamma\gamma$ events: 10^{+22}_{-8} .
- Events observed: **12**.

$BR(\pi^0 \to inv)<4.4\times10^{-9}$ at 90% CL

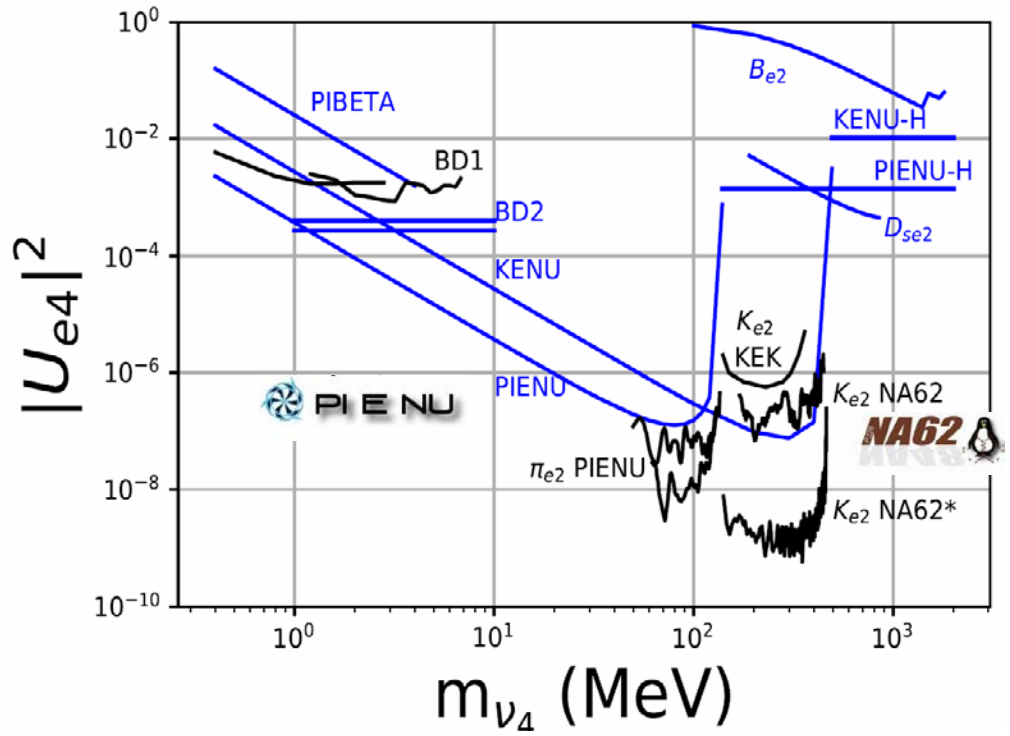
(factor 60 improvement on E949)

Limits on LFU Violation due to Massive Sterile Neutrinos: MeV to GeV

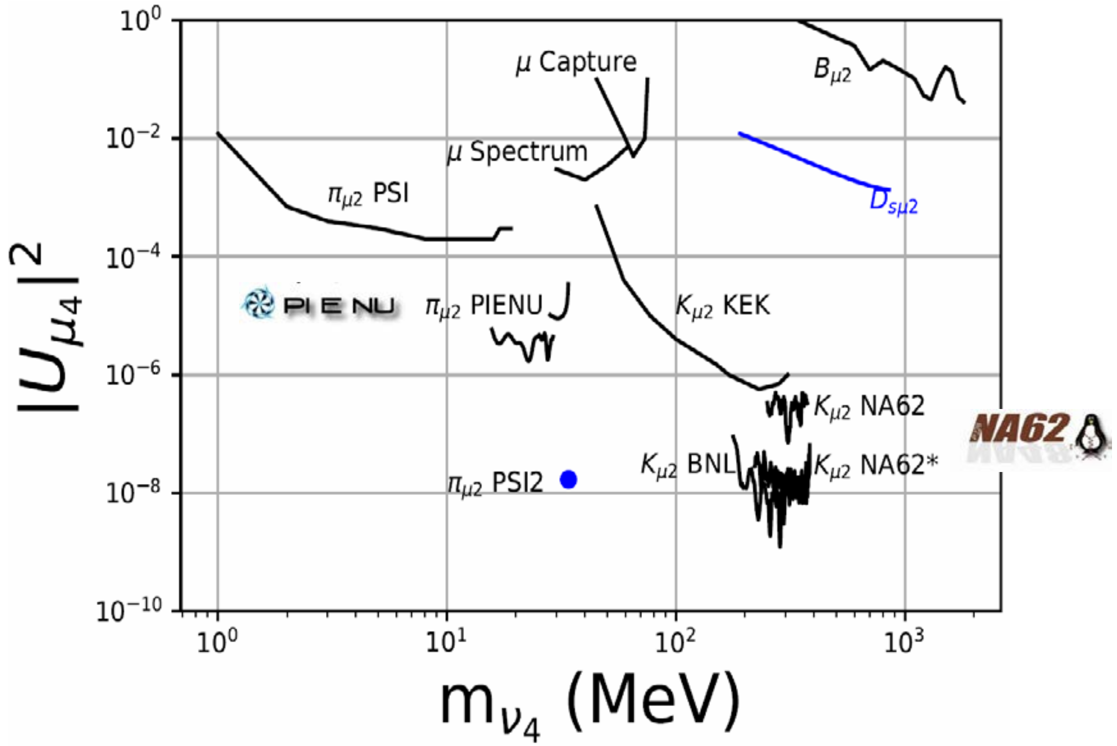
NA62 & PIENU have recently made orders of magnitude improvements in mixing limits.

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

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



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

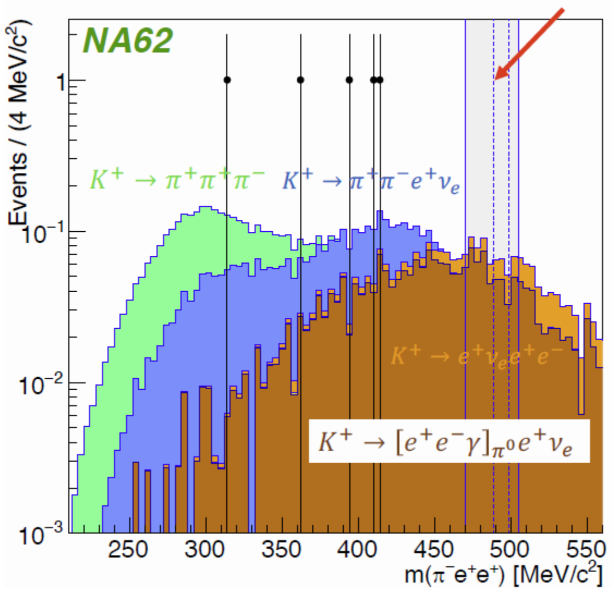


Bryman and Shrock, 2019

Lepton *Number* Violation

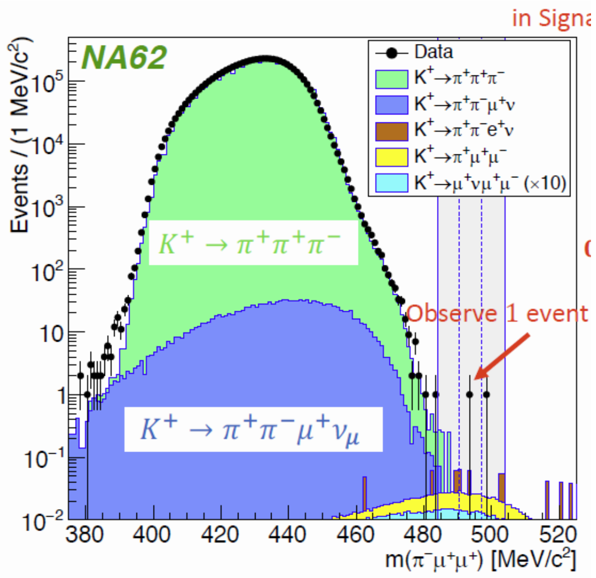
$K^+ \to \pi^+ ee$:

(0 (0.16) events observed)



$K^+ \to \pi^+ \mu\mu$:

(1 (0.9) events observed)



NA62 | BNL 865

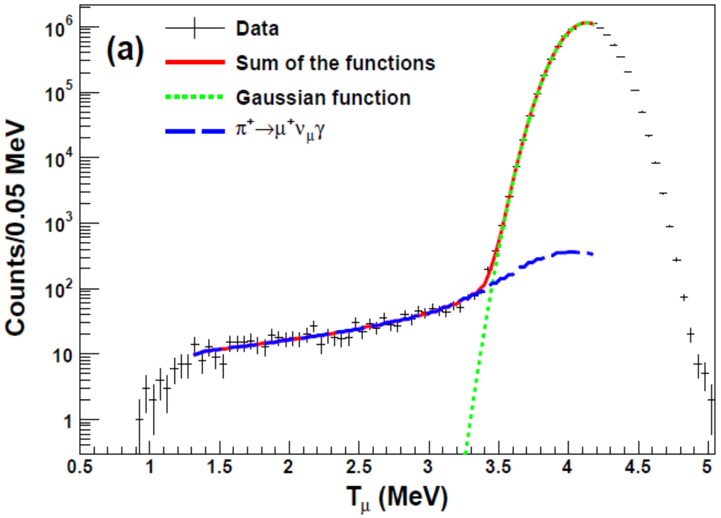
Decay	*BR* UL @ 90% CL	PDG UL @ 90% CL
$K^+ \to \pi^- e^+ e^+$	2.2×10^{-10}	6.4×10^{-10}
$K^+ \to \pi^- \mu^+ \mu^+$	4.2×10^{-11}	8.6×10^{-11}

From J. Swallow at Moriond 2019

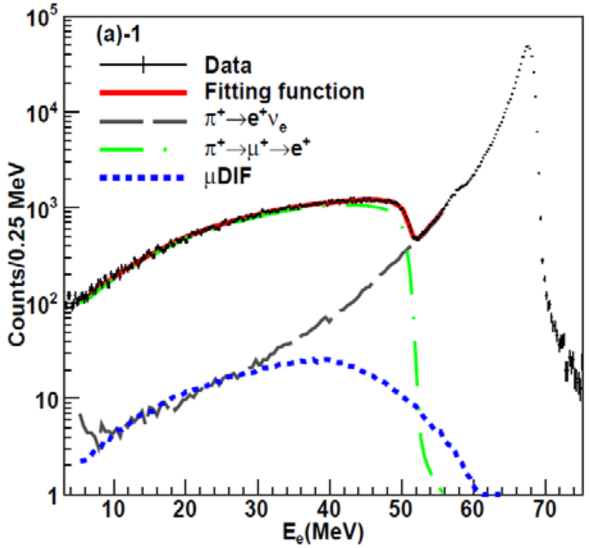
2019-20

New Measurements of $\pi\to\mu\nu\nu\nu$ and $\pi\to e\nu\nu\nu$

$Br(\pi\to\mu\nu\nu\nu)<8.6 \times 10^{-6}$ First result on this mode.

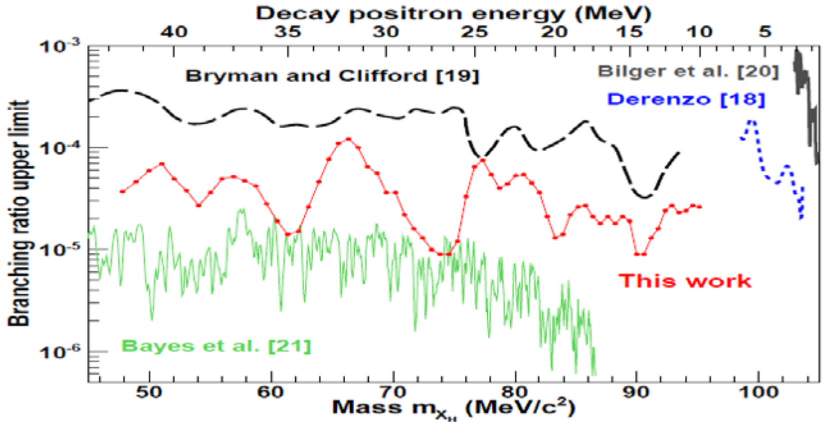


$Br(\pi\to e\nu\nu\nu)<1.6 \times 10^{-7}$ Order of magnitude improvement.



LFU Violation: Exotic muon decay: $\mu\to eX$

2020



Expanded the X mass range.

UBC/TRIUMF Rare Decay Group

Faculty: Doug Bryman (UBC/TRIUMF), Toshio Numao (TRIUMF)
Postdocs: Bob Velghe (2018 run coordinator, GTK expert)
Daiki Nagao (from 9/2020)
Students: MSc. and undergrad Eng. Phys. Capstone, honors theses
Previous students and postdocs have faculty-level positions at UBC, BNL, CERN, Glasgow, LASL, Osaka, TRIUMF, U. Sinaloa (Mex.) ….

NSERC support through 2023
Compute Canada Resources (CPU and storage on CEDAR)
TRIUMF detector science/engineering group support

EDI: 40% of past students/postdocs from under-represented groups

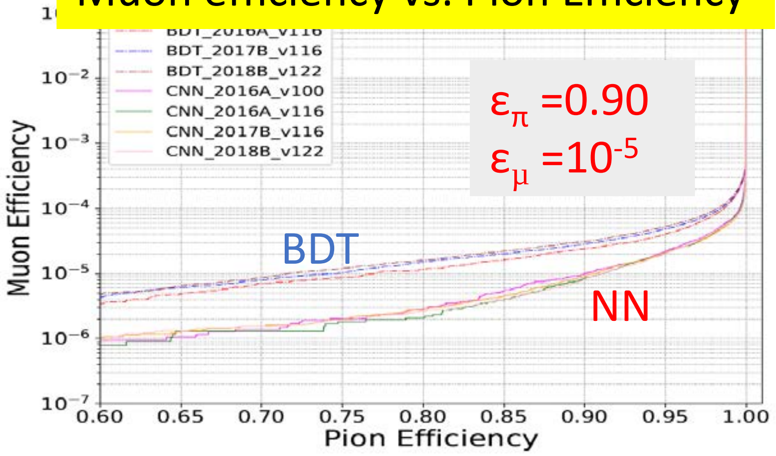
Examples of Canadian Group Projects

- **Particle ID: Machine learning**

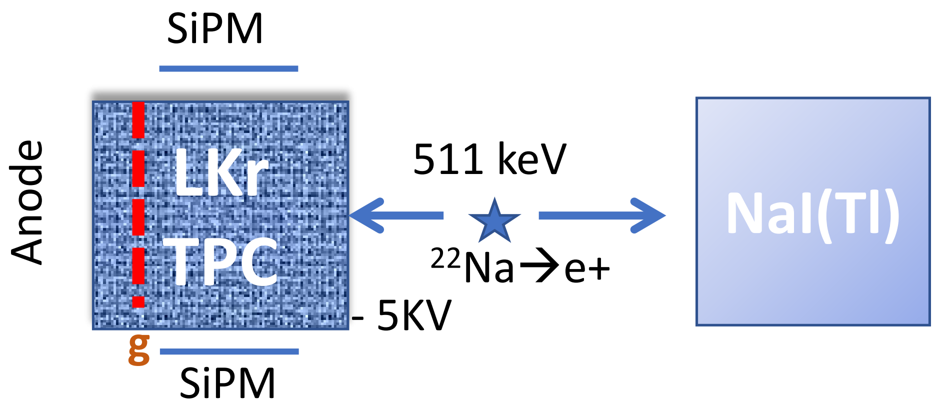
Collaboration with 4 MSc Computing Science students & W. Fedorko

Improved the π/μ identification/rejection by a factor 5;
Increase the acceptance for $K^{+} \rightarrow \pi^{+}\nu\nu$ by 25%.

Muon efficiency vs. Pion Efficiency

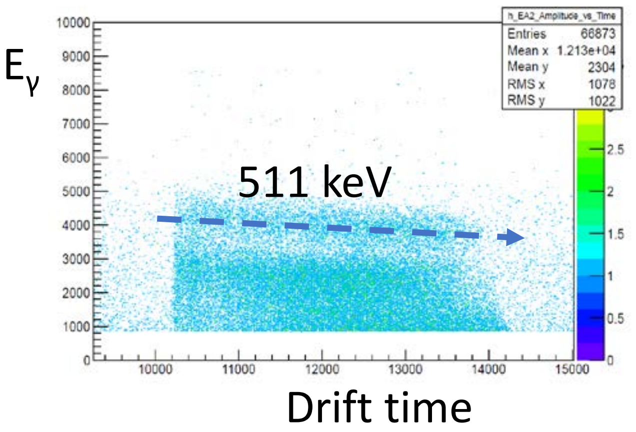


- **Liquid Krypton TPC Purity Monitor: Essential for operation of the primary NA62 Calorimeter**



LKr TPC built at TRIUMF with UV SiPMs & charge preamps in LKr; external postamps.

Charge attenuation in LKr



Measured attenuation of 511 keV photon signals in LKr → contamination <5ppb;
Allows refilling of the 10K l NA62 LKr calorimeter.

Future Prospects for NA62

- 2018 data has 5 x the sensitivity of reported data (see ICHEP 2020); expect ~10 SM events.
- Detector improvements in progress:
  - New beam line configuration to suppress upstream random backgrounds
  - New beamline veto counter to suppress upstream decay backgrounds
  - 4^{th} kaon Gigatracker station to allow for higher beam rates with reduced backgrounds
- 2021-24 operation planned: Expected SM sensitivity, 50 events with improved S/N.
- > 2024:
  - Possible operation in beam dump mode for ALP searches
  - Further operation for rare kaon decays depends on results.