Rare Decay Experiments: PIENU & NA62

Doug Bryman

University of British Columbia &TRIUMF

Flavor in the News!

3 unconfirmed anomalies that involve Muons

Possible connection to Lepton Flavor Universality

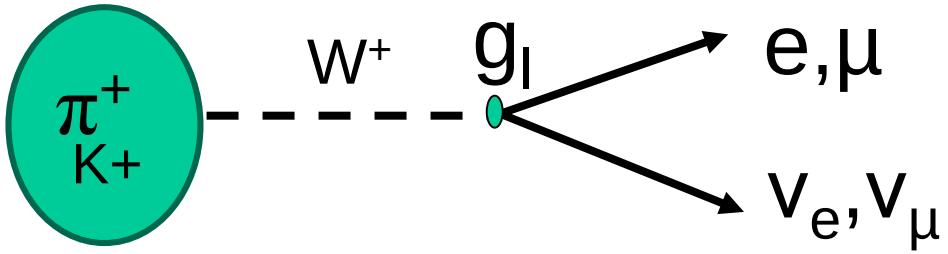
- **Proton radius puzzle** (6 σ)
  μ-H atom result differs from e-H and e-scattering
- **Muon g-2** (~3+ σ); Deviation from theory -- new physics?
- **Lepton Flavor Universality; possible deviation** O(10%) :
  $B \rightarrow D^{*}\tau\,\nu / B \rightarrow D^{*}\mu\nu$, $B \rightarrow K^{*}\mu\,\mu / B \rightarrow K^{*}ee$
  R(D*), R (K*): (3.7, 2.5 σ)
  Quarks and leptons must both involved!

PIENU & NA62

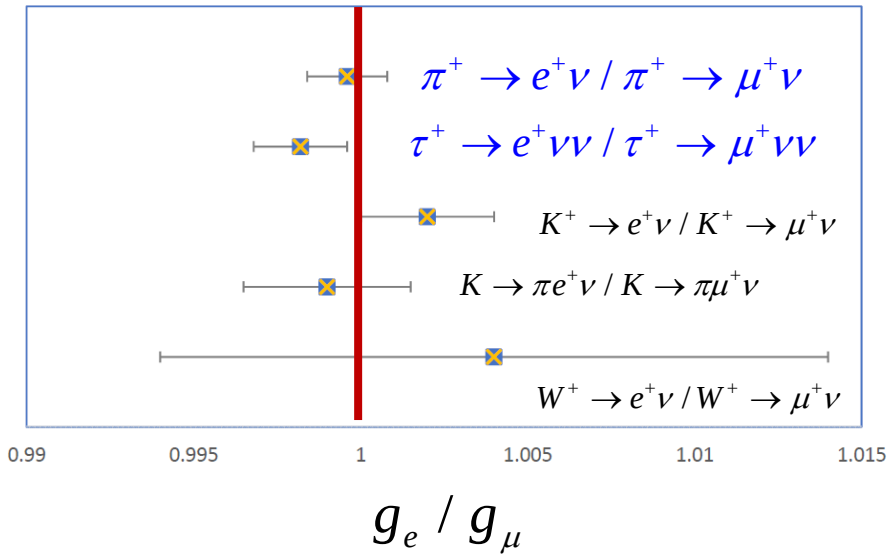
address related flavor issues.

Charged Lepton Flavor Universality

Experiments compare expectations assuming $g_e = g_\mu = g_\tau$

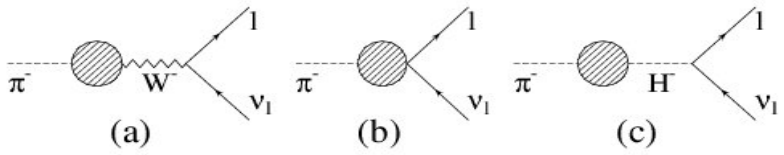


Precision: O(10^{-3})



LFU Tests: Sensitivity to High Mass Scales

New Pseudoscalar interaction



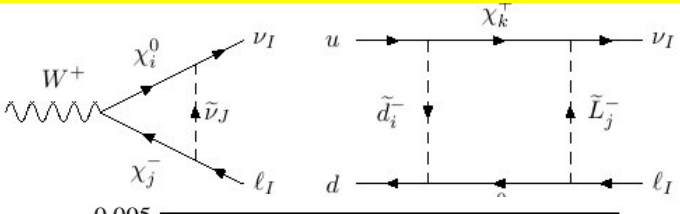
$$1 - \frac{R_{e/\mu}^{New}}{R_{e/\mu}^{SM}} \sim \mp \frac{\sqrt{2}\pi}{G_\mu} \frac{1}{\Lambda_{eP}^2} \frac{m_\pi^2}{m_e(m_d + m_u)}$$

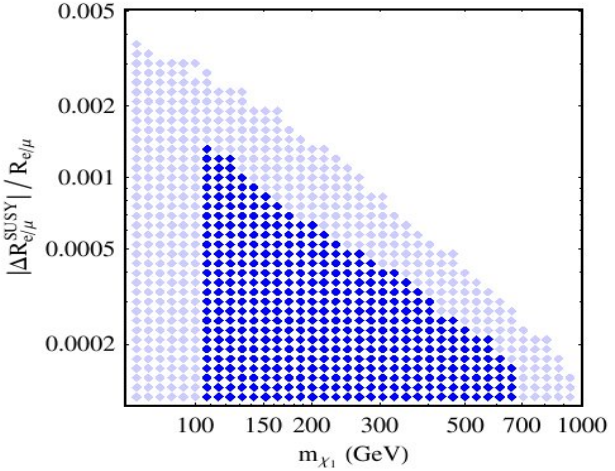
$$\sim (\frac{1TeV}{\Lambda_{eP}})^2 \times 10^3$$

0.1 % measurement→Λ~1000 TeV

Assuming non-SM Higgs' couplings. Marciano…

R-parity violating SUSY





Lowest chargino mass

Ramsey-Musolf…

Others:

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

$$\frac{\pi^+ \to e^+ \nu(\gamma)}{\pi^+ \to \mu^+ \nu(\gamma)}$$

W. Marciano → V. Cirigliano

$$R^{th}_{e/\mu} = (1.2353 \pm 0.0002)\, x10^{-4}$$

Possibly the most accurately calculated decay process involving hadrons. Structure-dependent radiation included (v. small).

PIENU

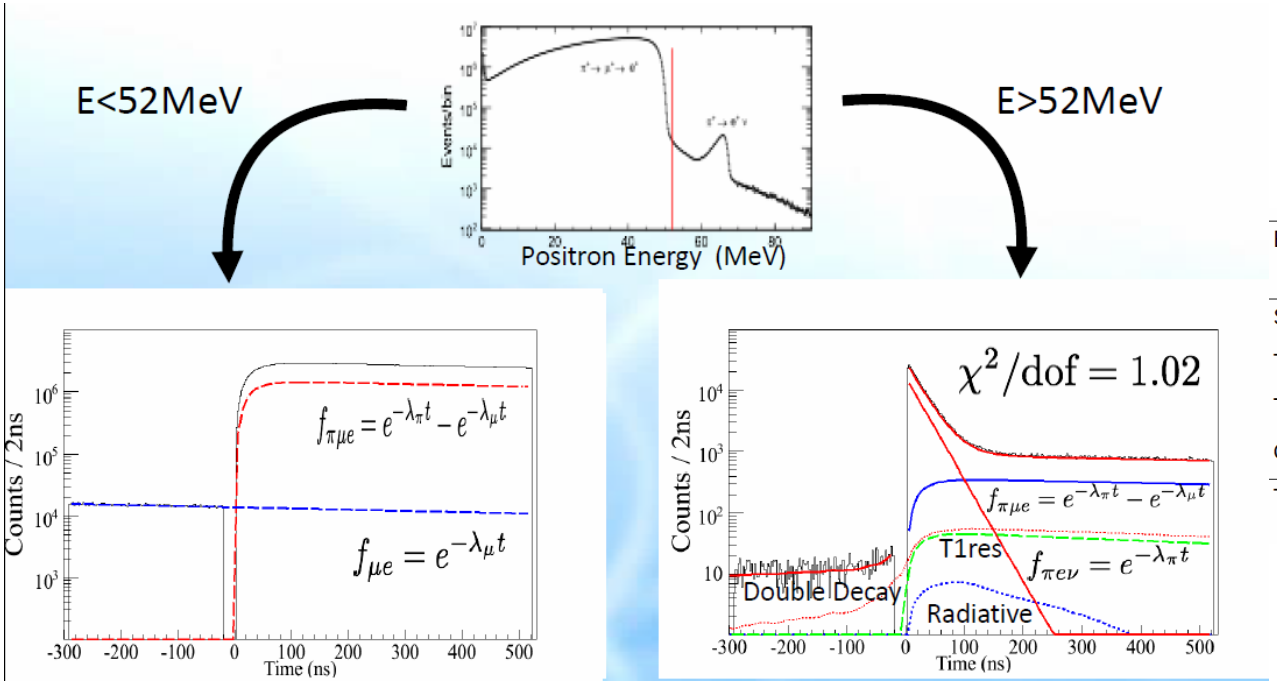
Initial result (4 x 10^5 events):

$$R^{\exp\pi}_{e/\mu} = 1.2344 \pm 0.0030 x10^{-4} \quad : \quad \frac{g_e}{g_\mu} = 0.9996 \pm 0.0012$$

PDG: $R^{\exp\pi}_{e/\mu} = 1.2327 \pm 0.0023 x10^{-4}$ (±0.19%)

Future: PIENU, PEN $\leq 0.1\%$

Full analysis nearly completed:



PIENU Uncertainties

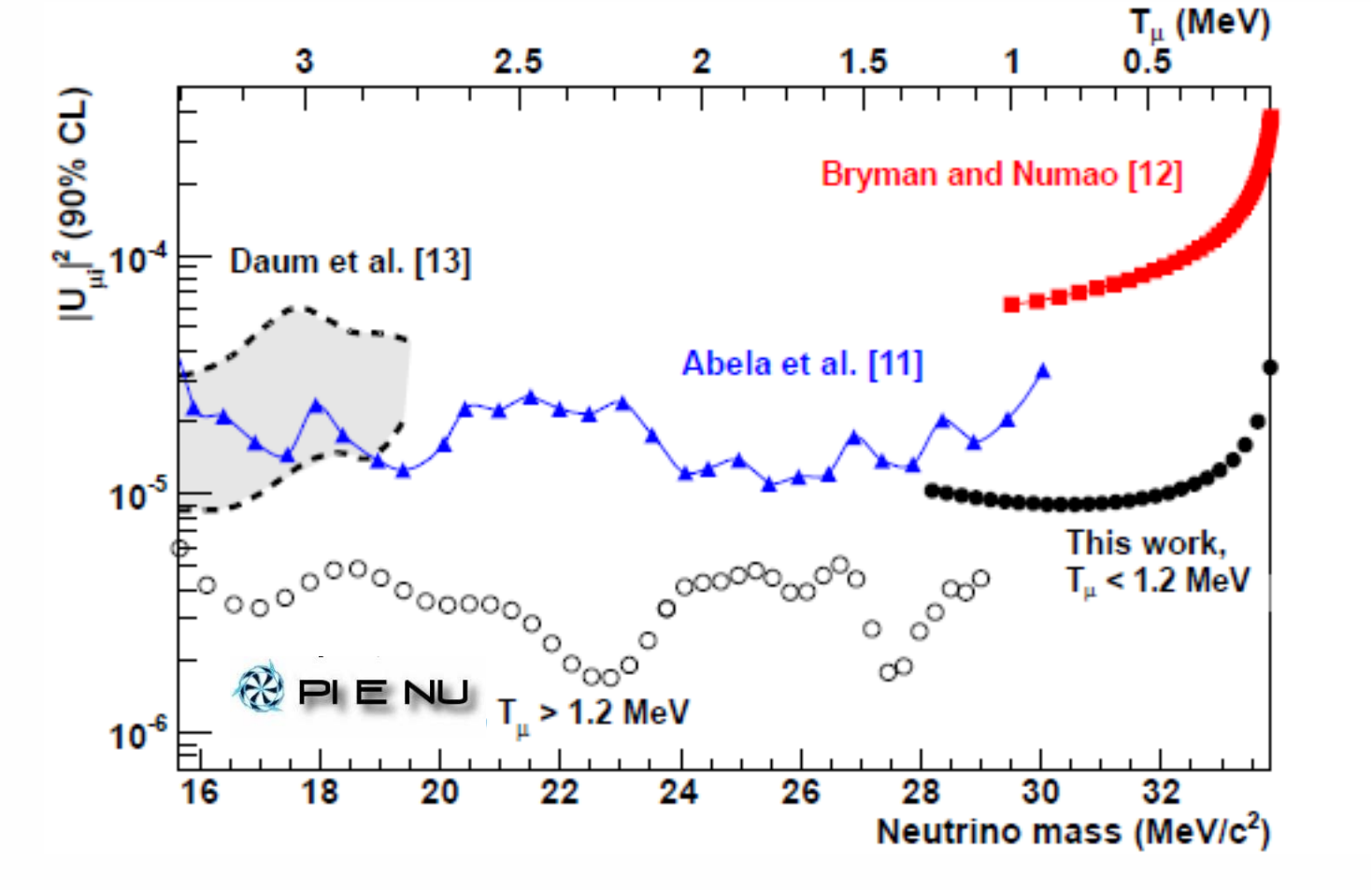
Error	PIENU 2010	PIENU goal
Statistical	0.19%	0.07%
Time Spectrum	0.04%	0.04%
Tail Correction	0.12%	0.06%
Others	0.07%	0.04%
Total	0.24%	< 0.1%

Full Data Sample: $3x10^6$ $\pi^+ \rightarrow e^+\nu$ Events

Precision Goal: $\pm 0.1\%$ (Coming Soon!)

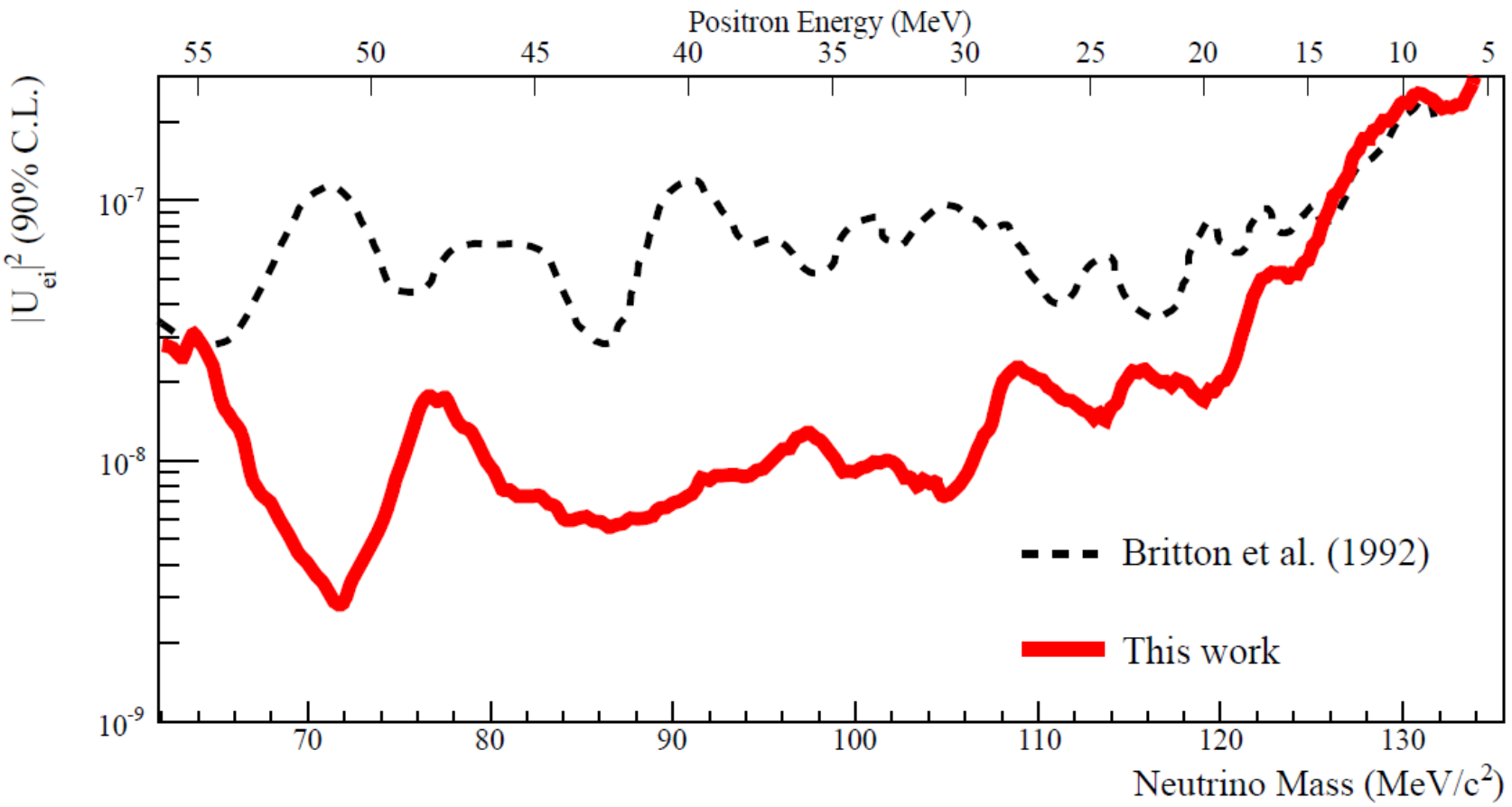
2019 *Search for Heavy Neutrinos in $\pi^+ \to \mu^+ \nu_H$ Decay*

Order of magnitude improvement: 15-34 MeV



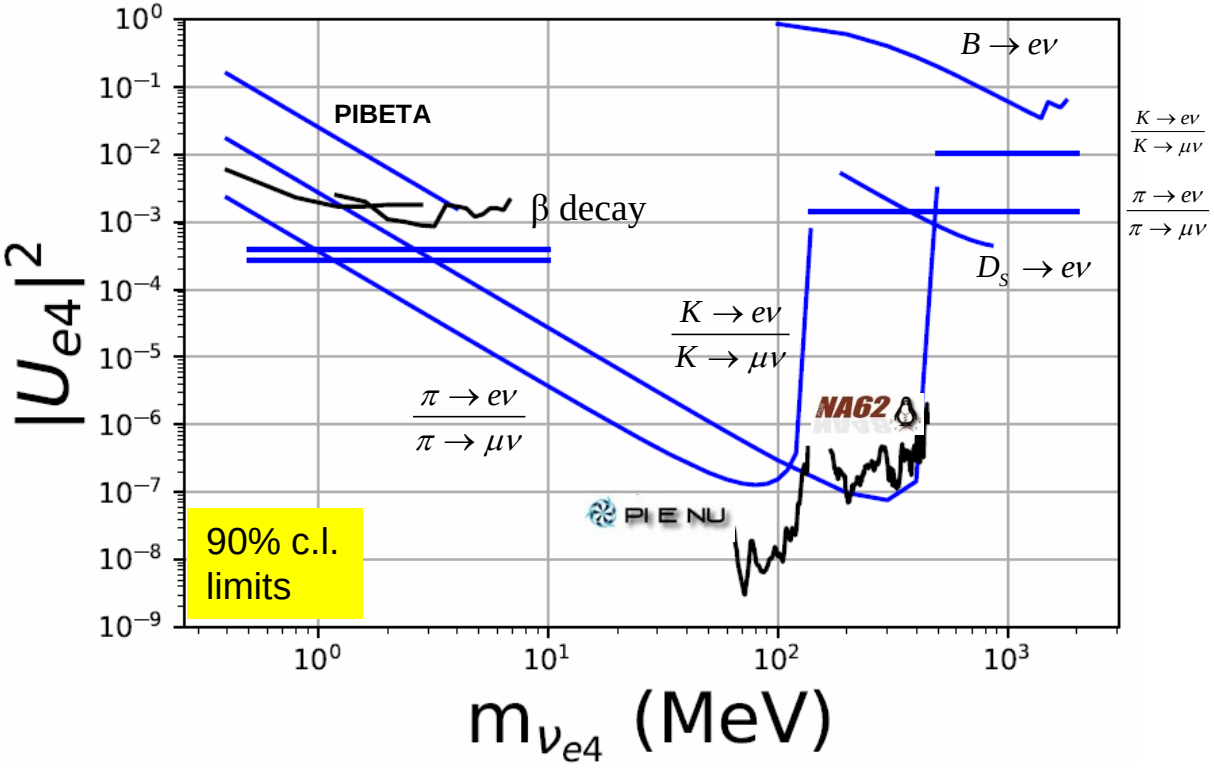
PIENU 2018: *Search for Heavy Neutrinos in* $\pi^+ \to e^+ \nu_H$ *Decay*

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



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

2019: Improved limits MeV-GeV **R. Shrock and D.B**



Sterile neutrinos could range in mass from eV to GUT scale; constraints from oscillations, cosmology, HEP…. Possible correlation with LFV, LNV….

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

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

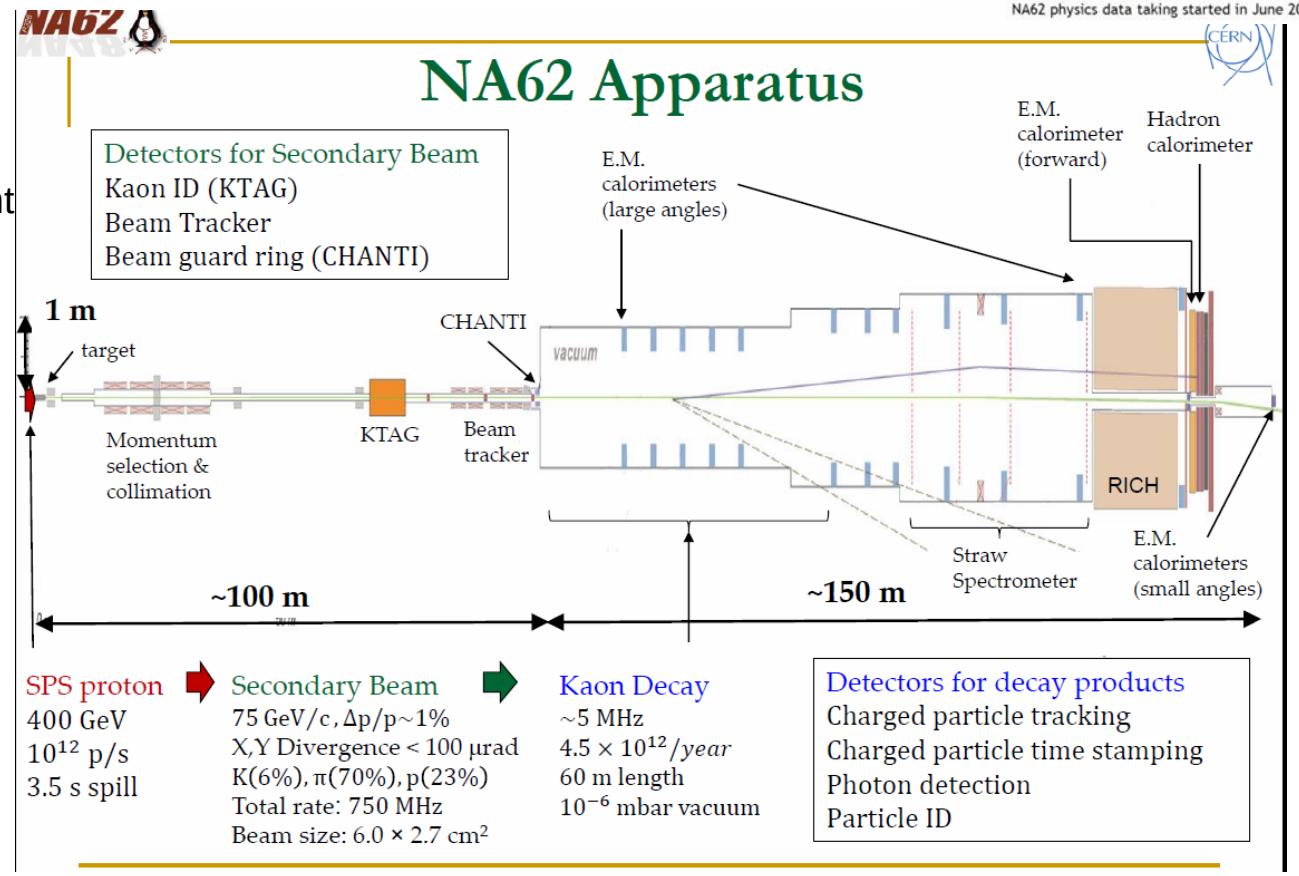
$BR(K^+ \to \pi^+ \nu\bar{\nu}) = (1.73\,^{+1.15}_{-1.05}) \times 10^{-10}$

BNL E787/E949: PRL101 (2008) 191802

BR(SM)=9.11 ± 0.72 x 10^{-11}

NA62 physics data taking started in June 2015

75 GeV K^+ decay in flight

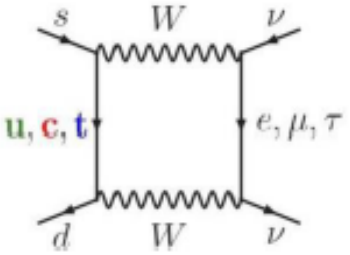


Most efficient detector ever built.

In operation 2015-2018 (2020-2022, to be proposed + beam dump mode)

Bordone, Buttazzo, Isidori, Monnard ArXiv:1705.10729

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



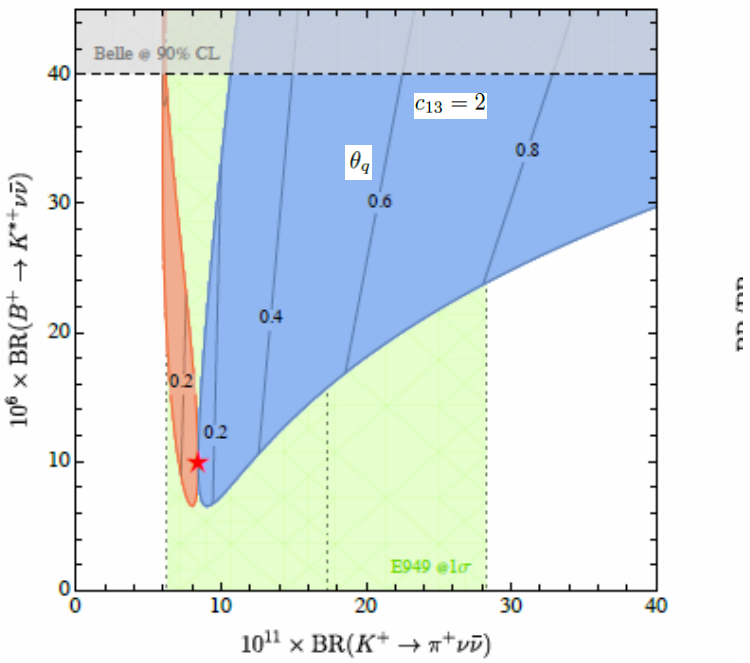
Involves third generation quarks (top) and leptons (τ, ν_τ)

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%]



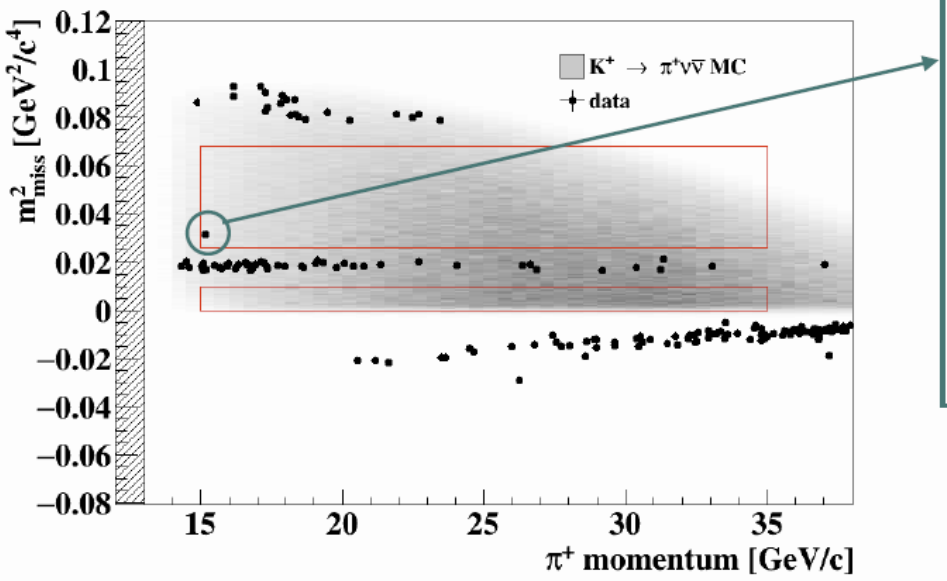
First NA62 Results on $K^+ \to \pi^+ \nu\nu$

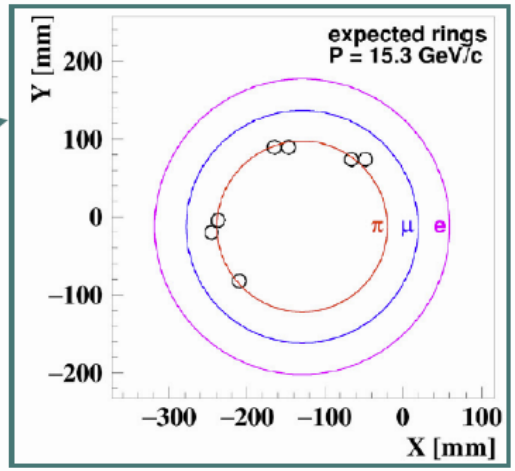
2019 Phys. Lett. B 791 (2019) 156-166, arXiv.1811.08508

$$N(Bkg) = 0.152^{+0.092}_{-0.033}|_{stat} \pm 0.013_{syst}$$

$$N^{exp}_{\pi\nu\nu}(\mathrm{SM}) = 0.267 \pm 0.001_{stat} \pm 0.020_{syst} \pm 0.032_{ext}$$

N(K) = 1.21(2) x 10^{11}





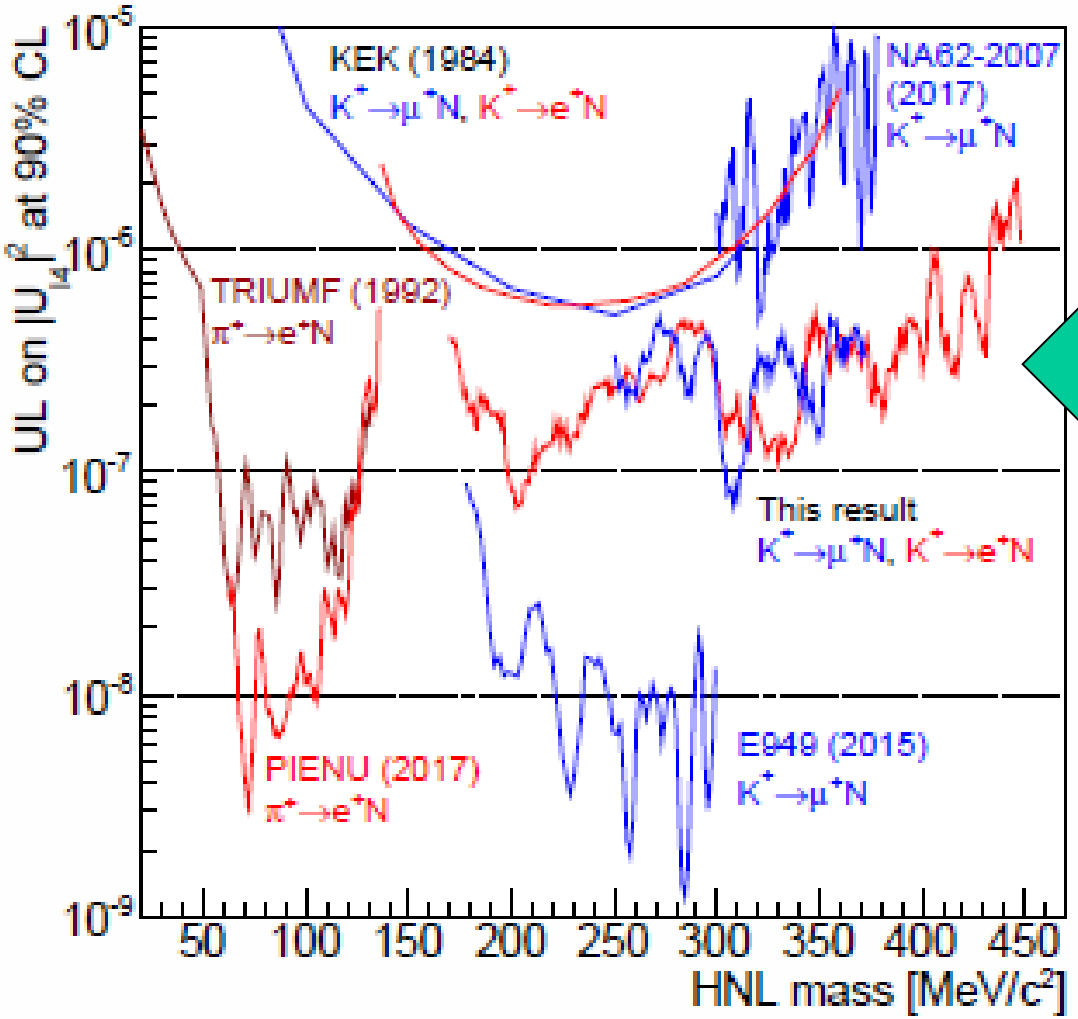
2016 data:
only 5% of the
2016-2018 dataset !

New decay in flight
technique works

$$Br(K^+ \to \pi^+ \nu\bar{\nu}) < 14x10^{-10}(95\%\ c.l.)$$

>20 x more data under analysis

Search for Heavy Neutrinos in $K^+ \to e^+ / \mu^+ \nu_H$ Decays

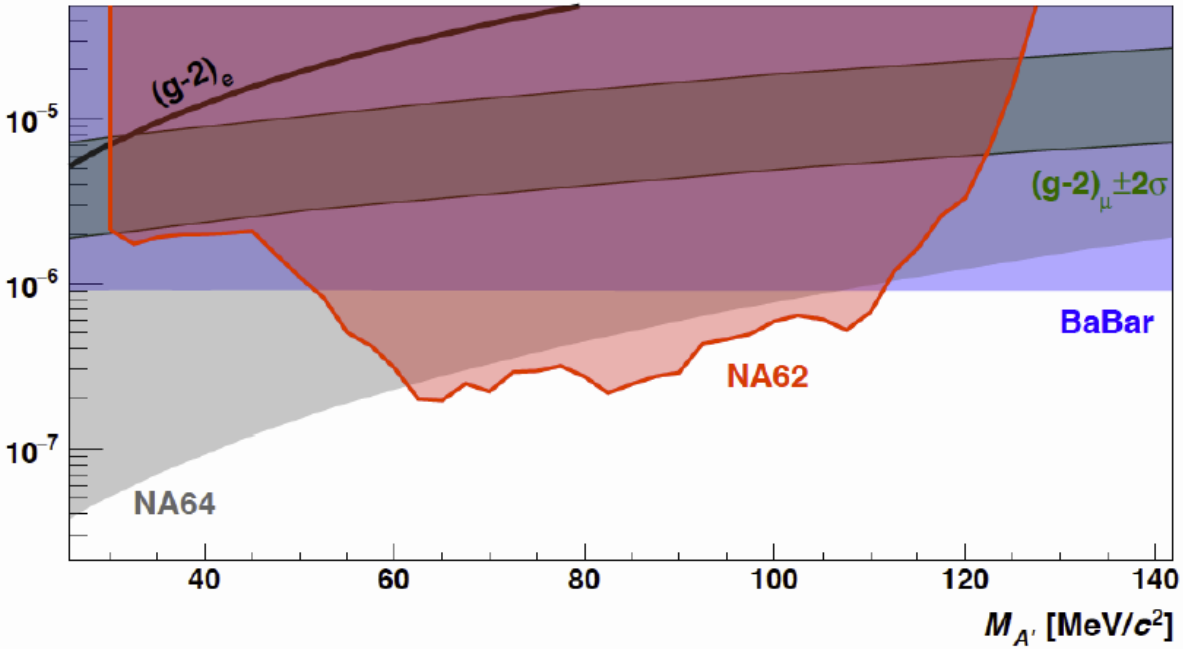


2018 PLB

Dark photon 2019

arXiv.1903.08767, accepted by JHEP

- Used a subsample of 2016 data: ~ 1% of the 2016-2018 period
- Data driven background estimation
- Scan on mass hypothesis and counting in mass window
- No excess observed
- Upper limit set with CL_S at 90% C.L. on number of signal and translated to ε^2



Improved upper limit in the range 60-110 MeV

Moreover:

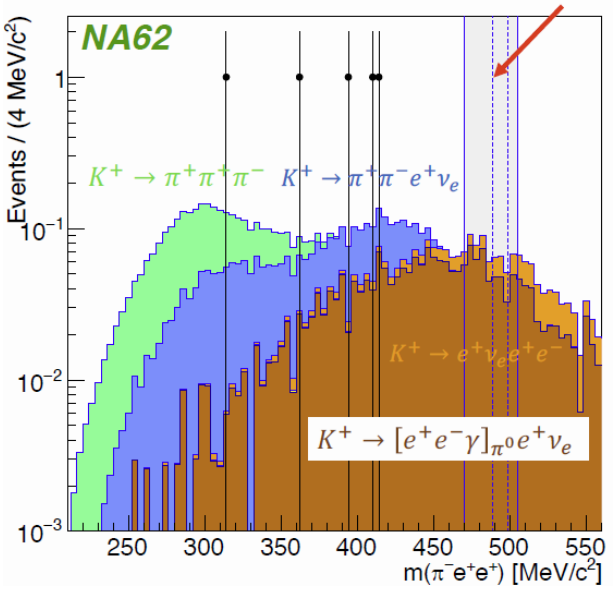
Limit improved by more than three orders of magnitude: **BR($\pi^0 \rightarrow \gamma\nu\nu$) < 1.9×10^{-7} at 90% CL**

(Improvement on BR($\pi^0 \rightarrow$invisible) over current limit of 2.7×10^{-7} is also possible)

Lepton *Number* Violation (2019)

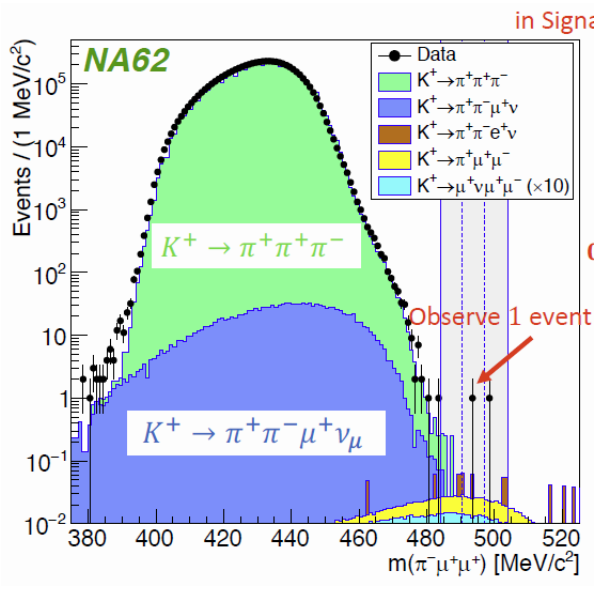
$K^+ \to \pi^+ ee$:

(0 (0.16) events observed)



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

(1 (0.9) events observed)



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}

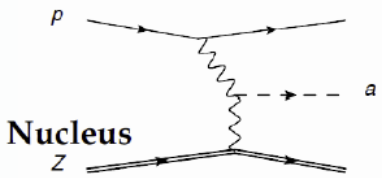
From J. Swallow at Moriond 2019

NA62: Beam Dump Mode

Axion-Like Particles

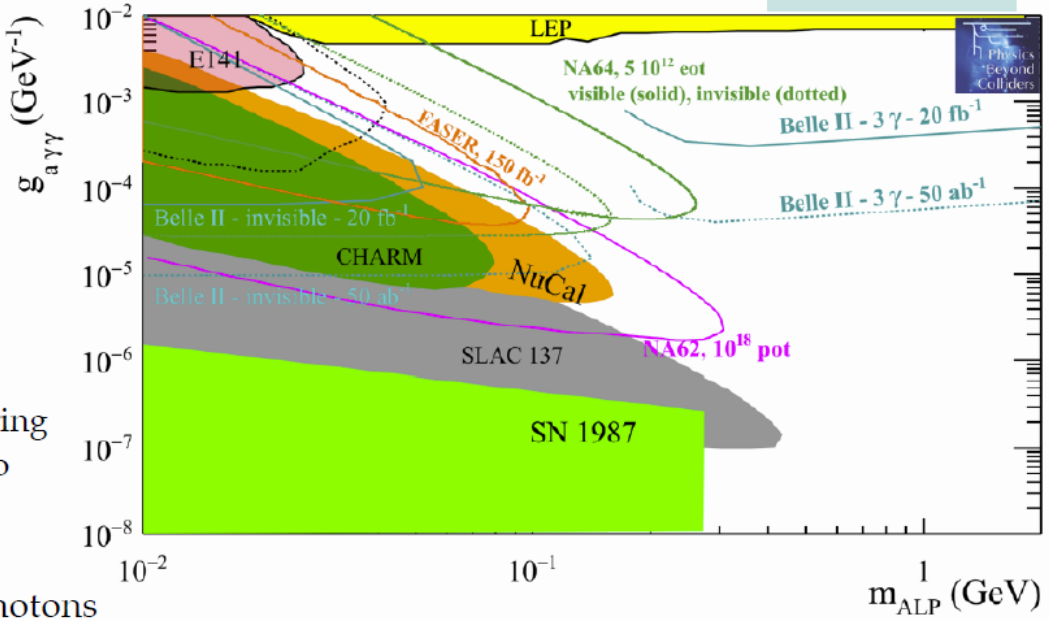
arXiv:1901.09966

Primakov production



JHEP 1602 (2016) 018

a produced via elastic scattering of beam proton dumped onto collimator material



predominant coupling to photons

Search for the decay: a->γγ

2 clusters in the LKr calorimeter

expected 90% C.L. exclusion contours

- account for geometrical acceptance
- zero-background assumption

Analysis of 2x10^{16} POT collected in dump mode in 2017-2018 in progress

Rare Decay Group

TRIUMF/UBC: Bryman, Numao, Sher, (Mischke*)
R.A.: Velghe, Nagao**
Students: Cuen (Ph.D. 5/2019), Feiler (B.Sc/M.Sc. 4/2019)

Support: NSERC, TRIUMF, Compute Canada, CERN
PIENU: CC: 50 c.y., 600 TB storage ($30k p.a.)
NA62: computing done at CERN

* Visitor, ** as of 9/2019

&

Papers 2018-2019

- Improved search for heavy neutrinos in the decay $\pi \rightarrow e\nu$, PIENU Collaboration (A. Aguilar-Arevalo et al.), Phys. Rev. D97 (2018) 072012.
- Search for heavy neutral lepton production in K^+ decays, NA62 Collaboration (Eduardo Cortina Gil (Louvain U.) *et al.*) Phys. Lett. B778 137 (2018).
- First search for $K^+ \rightarrow \pi^+ \nu\bar{\nu}$ using the decay-in-flight technique, NA62 Collaboration (Eduardo Cortina Gil et al.) Phys.Lett. B791 (2019) 156.
- Search for heavy neutrinos in the decay $\pi \rightarrow \mu\nu$, PIENU Collaboration (A. Aguilar-Arevalo *et al.*), arXiv:1904.03269 (2019,to be published).
- Improved constraints on sterile neutrinos in the MeV to GeV mass range, R. Shrock and D. A. Bryman, arXiv:1904.06787 (2019, to be published).
- Search for production of an invisible dark photon in π^0 decays, the NA62 collaboration, E. Cortina Gil et al. J. High Energ. Phys. (2019) 2019: 182. https://doi.org/10.1007/JHEP05(2019)182.

TRIUMF Project Support :

NA62 LKr Calorimeter purity monitor

Summary: Rare π & K Decays

- **Rare π and K decays: searching for new physics in $K \rightarrow \pi^+ \nu\nu$ decay, *lepton flavor Universality, lepton flavor/number violation, dark sector, sterile neutrinos* --- especially sensitivity to high mass scales.**

- **PIENU: Recent results on sterile neutrinos**
- **NA62: Recent results on $K \rightarrow \pi^+ \nu\nu$,sterile neutrinos, dark photons, LNV**

- **Improved results expected soon:**
  - **PIENU**
    - **Branching ratio: 0.1% precision**
    - **Searches: exotic pion decays, π+ -> e+3ν**
    - **Direct atomic muon capture**
  - **NA62:**
    - **$K \rightarrow \pi^+ \nu\nu$ branching ratio: several events at SM level 10^{-10}**
    - **NA62 Searches: $K^+ \rightarrow \pi^+ a$, dark scalars, dark photons, sterile neutrinos, π^0 -> νν, LFV e.g. $K \rightarrow \pi$ μe, LNV, ….**

- **Future operation of NA62 & beam dump mode expected 2020-2022+**