CERN NA62: Flavor and Dark Mater Factory

Bob Velghe*

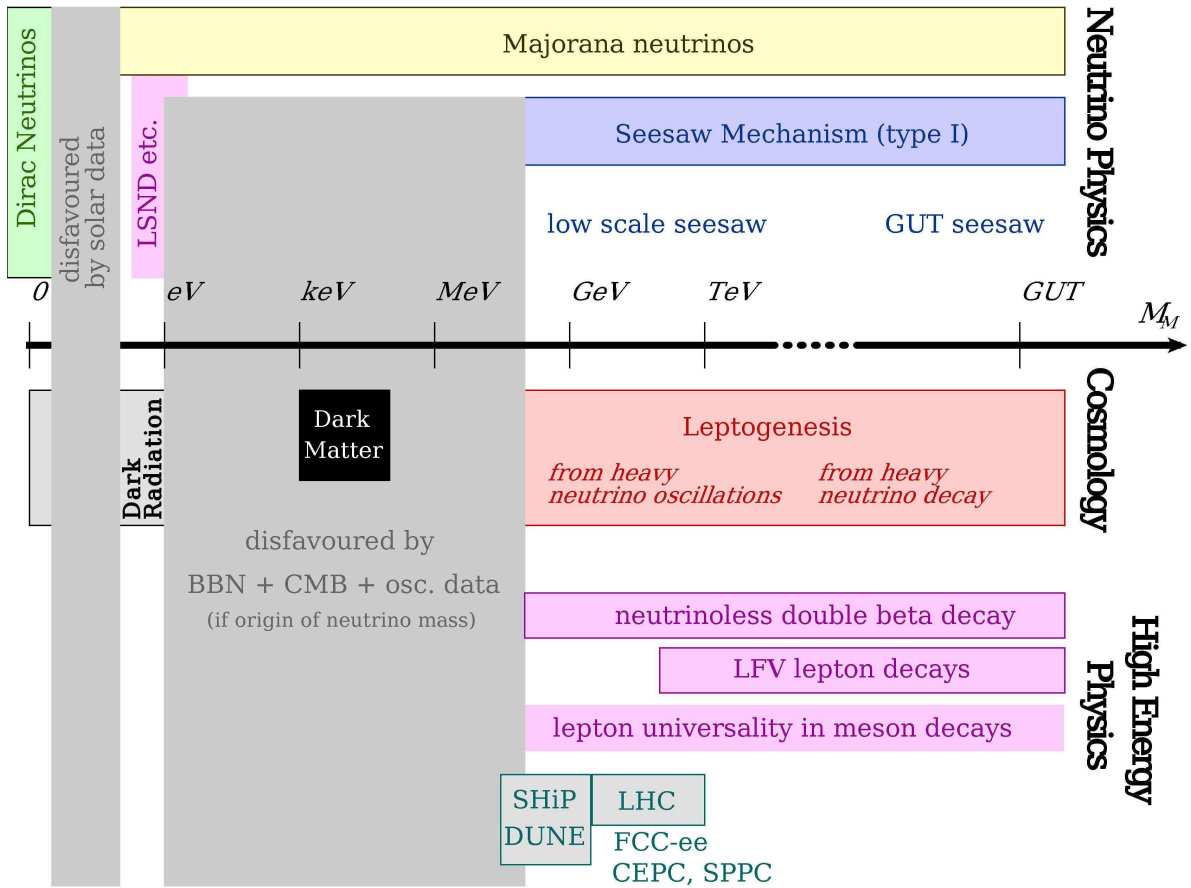
TRIUMF Science Week, July 13, 2017

Futures studies of rare π and K decays ($\mathrm{K}^+ \to \pi^+\nu\overline{\nu}$, $\pi^+/\mathrm{K}^+ \to e^+\nu$, $\pi^+/\mathrm{K}^+ \to \mu^+\nu$) and search for **dark particles** using extension of CERN NA62 could results in order of magnitudes advances.

* For TRIUMF and UBC NA62 Group

Motivations

In the SM, flavor is an ad hoc add-on; no fundamental theory. Flavor issues impact many aspects of BSM tests.
Illustration: Impact of heavy sterile neutrinos on various phenomena:



Drewes and Garbrecht. [arXiv:0808.2459].

There are hints of new flavor anomalies in B physics.

Lepton Flavor Universality – Current Situation

On the experimental front:

- Charged currents ($\mathrm{B}^0 \to \mathrm{D}^{(\star)-}\tau^+\nu_\tau, \mathrm{B}^0 \to \mathrm{D}^{(\star)-}\mu^+\nu_\tau$):
  Possible $\mathcal{O}\left(10-20\%\right)$ flavor universality violation in $\mathrm{b} \to \mathrm{c}\tau\nu$

  $2-3\sigma$ effect [(Belle, Babar, LHCb)].

  Not seen at $\mathcal{O}\left(0.2\%\right)$ in other charged current reactions involving e, μ, τ decays.
- Neutral currents ($\mathrm{B}^0 \to \mathrm{K}^{\star 0} l^+ l^-$):
  Possible e/μ universality violation in $\mathrm{b} \to \mathrm{s}\mu\mu$

  2σ effects [LHCb collaboration. arXiv:1705.05802].

On the theoretical front:

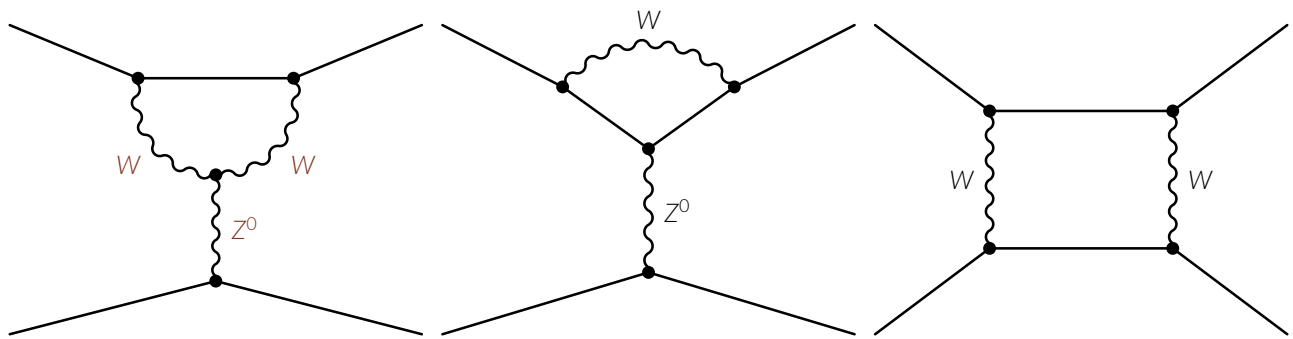
LFV confined to the 3rd generation. Effect related to the masses e.g. $m_\tau^2/m_\mu^2 \approx 283$

- New flavor changing coupling beyond the SM or MFV?
- Lepton flavor violating couplings?
- Scalar leptoquarks, new Z', etc.

Precise measurements of $\mathrm{K}^+ \to \pi^+\nu\bar{\nu}$, $\pi^+ \to e^+\nu$, $K^+ \to e^+\nu$ can be used to corroborate models and search for BSM effects at the 1000 TeV scale.

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

Flavour Changing Neutral Current (FCNC)



- Short distance contribution dominates (top, charm),
- Hadronic matrix elements $< K|Q_i(\mu)|\pi\nu\bar{\nu} >$ are related to $K^+ \to \pi^0 e^+ \nu_e$ decay[F. Mescia and C. Smith (Phys. Rev. D, 76, 034017)].,
- Long distance contribution suppressed (GIM mechanism).

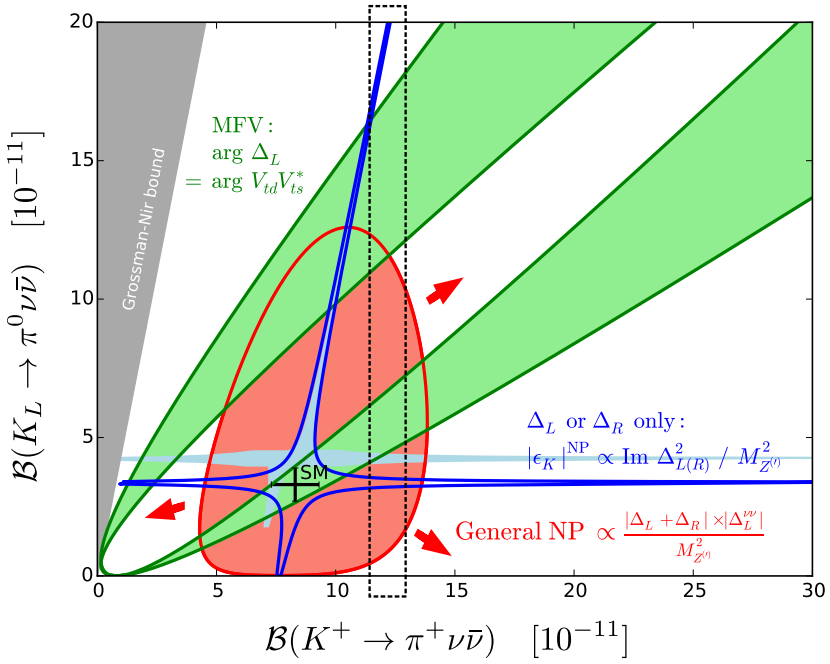
$$\mathcal{B}_{\text{Exp}}\left(K^+ \to \pi^+ \nu\bar{\nu}\right) = \left(17.3^{+11.5}_{-10.5}\right) \times 10^{-11}$$

E949, A.V. Artamonov et al. [arXiv:0808.2459].

$$\mathcal{B}_{\text{SM}}\left(K^+ \to \pi^+ \nu\bar{\nu}\right) = (9.11 \pm 0.72) \times 10^{-11}$$

J. Brod, M. Gorbahn and E.Stamou, [arXiv:1009.0947], updated by A.J. Buras et al. [arXiv:1503.02693].

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



- Minimal Flavor Violation models,
- Randall-Sundrum models, general LH/RH couplings,
- Models in which ϵ_K constraint applies,
- SUSY models, Littlest Higgs models, etc.

A. J. Buras, D. Buttazzo and R. Knegjens [arXiv:1507.08672].

Other potential correlations of $K^+ \to \pi^+ \nu\bar{\nu}$ with $K_L^0 \to \mu\mu, \epsilon'/\epsilon, B \to K\,(K^\star)\,\mu\mu$.

PI E NU

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

W. Marciano → V. Cirigliano

Possibly the most accurately calculated weak process involving hadrons – FLAVOR Universality

$$R^{th}_{e/\mu} = (1.2353 \pm 0.0001)\, x10^{-4}$$

Current Result PIENU: $R^{\exp\pi}_{e/\mu} = 1.2344 \pm 0.0030 x10^{-4}$ (±0.2%)

Future: PIENU, PEN <0.1%

New NA62 DIF experiment could reach SM precision 0.01%!

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

$$R^{th}_{K\to e/\mu} = (2.477 \pm 0.001)\, x10^{-5}$$

Finkemeier (1995)
Cirigliano, Rosell (2007)

Current Result NA62: $R^{\exp K}_{e/\mu} = 2.488 \pm 0.010 x10^{-5}$ (±0.4%)

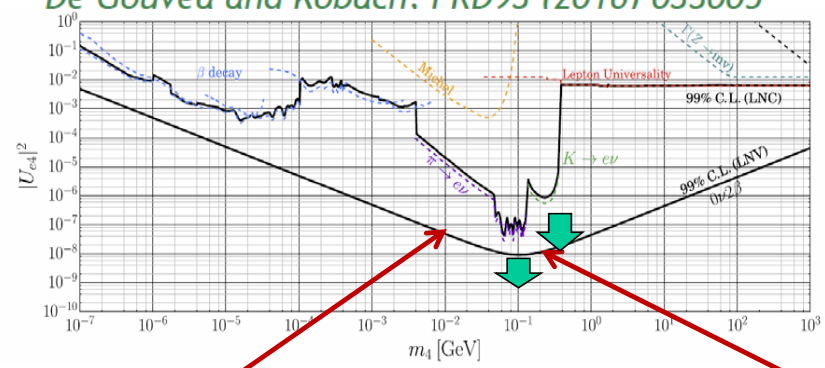
Future: NA62, TREK: 0.2%

New NA62 could reach SM precision 0.04%!

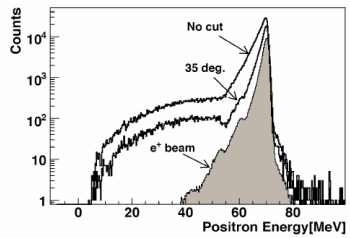
Heavy Neutrinos Coupled to e/μ $\pi \to l\nu_H$

$|U_{ei}|^2$ vs Mass

De Gouvêa and Kobach. PRD93 (2016) 033005



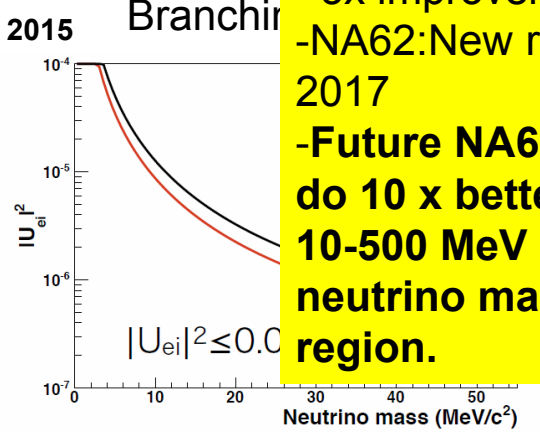
$$\frac{\Gamma(\pi \to e\nu_i)}{\Gamma(\pi \to e\nu_e)} = |U_{ei}|^2 \rho_e$$

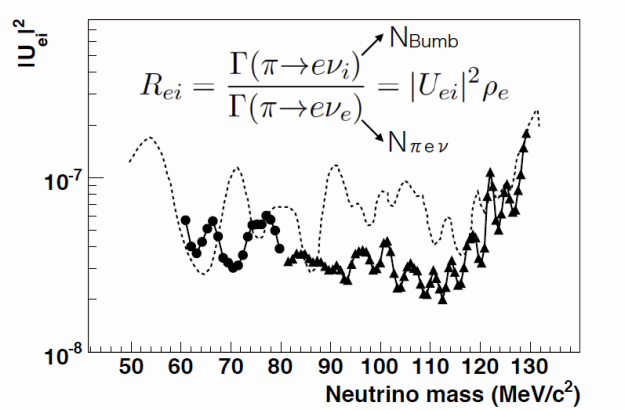


PIENU

-PIENU: Expect ~3x improvement
-NA62:New results in 2017
-Future NA62 could do 10 x better in 10-500 MeV sterile neutrino mass region.

PIENU Peak Search





M.Aoki et al, Phys.Rev.D 84 052002 (2011)

NA62 Experiment for $K^+ \to \pi^+ \nu\bar{\nu}$

$\mathcal{B}(K^+ \to \pi^+ \nu\bar{\nu})$ with a relative (statistical) uncertainty around 10 %.

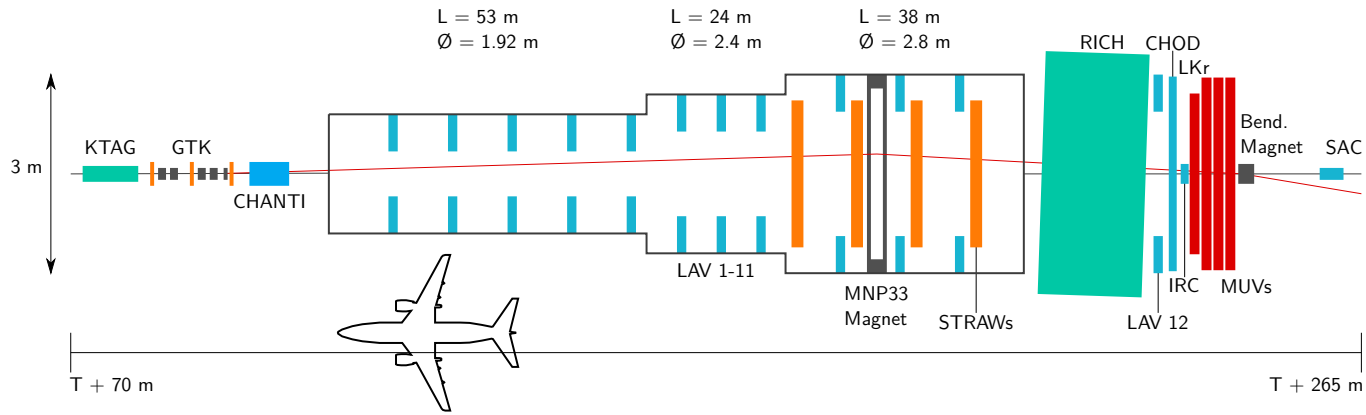
We need $\mathcal{O}(100)$ events with 10% precision background measurement.

Kaon decay in flight

- 10^{13} kaon decays,
- 10% signal acceptance,
- $> 10^{12}$ background rejection.

NA62 Setup

In operation 2015-2018; possible extension 2020-2014.



- Beam [75 GeV/c, $\mathbf{K}$, π and $\mathbf{p}$ (6:70:23)] tracking and PID at 750 MHz,
- Charged decay particle tracking,
- Charged decay particle time stamping $\mathcal{O}\left(100\,\mathbf{ps}\right)$,
- Hermetic photon coverage,
- Particle ID.

$$m^2_{\text{mass}} = \left(P_{\mathbf{K}} - P_{\pi^+}\right)^2$$

NA62 is a versatile tool!

NA62: Kaon Factory!

Up to 10^{13} kaon decays → 1-3 orders of magnitude improvement for rare decays.

K^+ decay mode	Physics	Present limit (90 % C.L.) / Result	NA62
$\pi^+\mu^+e^-$	LFV	1.3×10^{-11}	$10^{-12}/10^{-13}$
$\pi^+\mu^-e^+$	LFV	5.2×10^{-10}	$10^{-12}/10^{-13}$
$\pi^-\mu^+e^+$	LNV	5.0×10^{-10}	$10^{-12}/10^{-13}$
$\pi^-e^+e^+$	LNV	6.4×10^{-10}	10^{-12}
$\pi^-\mu^+\mu^+$	LNV	1.1×10^{-9}	$10^{-12}/10^{-13}$
$\mu^-\nu e^+e^+$	LNV / LFV	2.0×10^{-8}	10^{-12}
$e^-\nu\mu^+\mu^+$	LNV	–	10^{-12}
π^+X^0	New Particle	5.9×10^{-11} ($m_{X^0} = 0$)	10^{-12}
$\pi^+\chi\chi$	New Particle	N.A.	10^{-12}
$\pi^+\pi^+e^-\nu$	$\Delta S \neq \Delta Q$	1.2×10^{-8}	10^{-11}
$\pi^+\pi^+\mu^-\nu$	$\Delta S \neq \Delta Q$	3.0×10^{-6}	10^{-11}
$\pi^+\gamma$	Angular Mom.	2.3×10^{-9}	10^{-12}
$\mu^+\nu_h$, $\nu_h \rightarrow \nu\gamma$	Heavy neutrino	Limits up to $m_{\nu_h} = 350$ MeV	–
R_K	LU	$(2.488 \pm 0.010) \times 10^{-5}$	$> 2\times$ better
$\pi^+\gamma\gamma$	χPT	< 500 events	10^5 events
$\pi^0\pi^0e^+\nu$	χPT	66000 events	$\mathcal{O}(10^6)$ events
$\pi^0\pi^0\mu^+\nu$	χPT	–	$\mathcal{O}(10^5)$ events
$\pi^0 \rightarrow$ invisible, $\pi^0 \rightarrow U\gamma$ Dark sector			

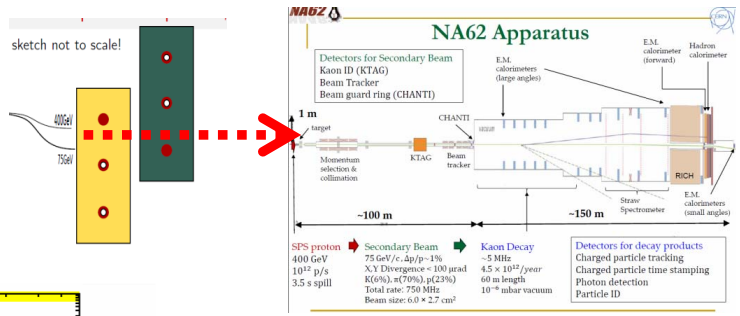
Babette Döbrich (CERN) arxiv:1512.03069

Search for Dark Stuff with NA62

400 GeV p into closed target dump

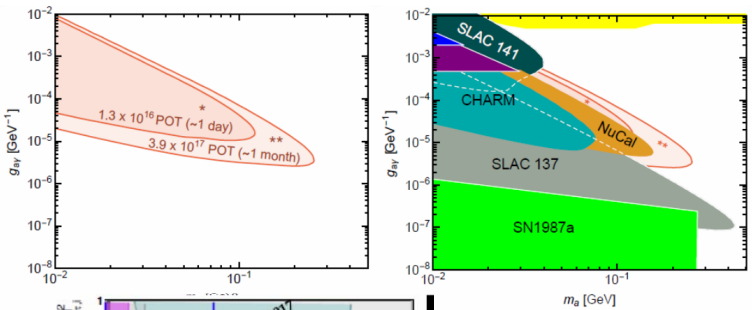
Look for a $\rightarrow \gamma\gamma$ in LAr Calorimeter

- decay length $\gamma\beta\tau$, ALP lifetime
  $\Gamma = \tau^{-1} = g_{a\gamma}^2 m_a^3/(64\pi)$

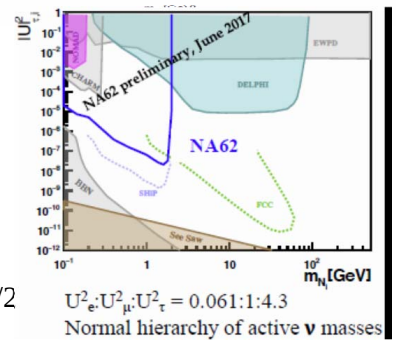


ALP

Axion-like particles

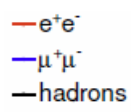


Heavy Neutral Leptons

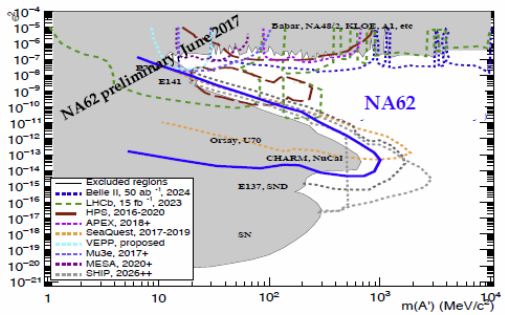


$U^2_e : U^2_\mu : U^2_\tau = 0.061 : 1 : 4.3$

Normal hierarchy of active ν masses



Dark Photons



There's a Lot to Come !

- Rare $\mu, \pi, \mathrm{K}, \mathrm{B}$ decays have unique and important roles to play in the search of new physics including exotic effects like Flavor Universality and Lepton Flavor Violations
  $\rightarrow$ **Sensitivity to very high mass scales.**
- Future NA62 could make orders of mag. advances. Complementary to experiments involving muons, pions, and *B* mesons.
  Rich experimental program: KOTO, MEG, DeeMee, COMET, Mu2E, Mu3E, Belle II, LHCb, ATLAS, CMS, etc.