DISCRETE 2024 in Ljubljana

2–6 Dec 2024

Searches for Hidden Sectors and Lepton Flavor Violation in Kaon Decays

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on behalf of NA62 Collaboration

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Outline:

The NA62 Experiment

Kaon Decay mode *vs* **Beam-Dump mode**

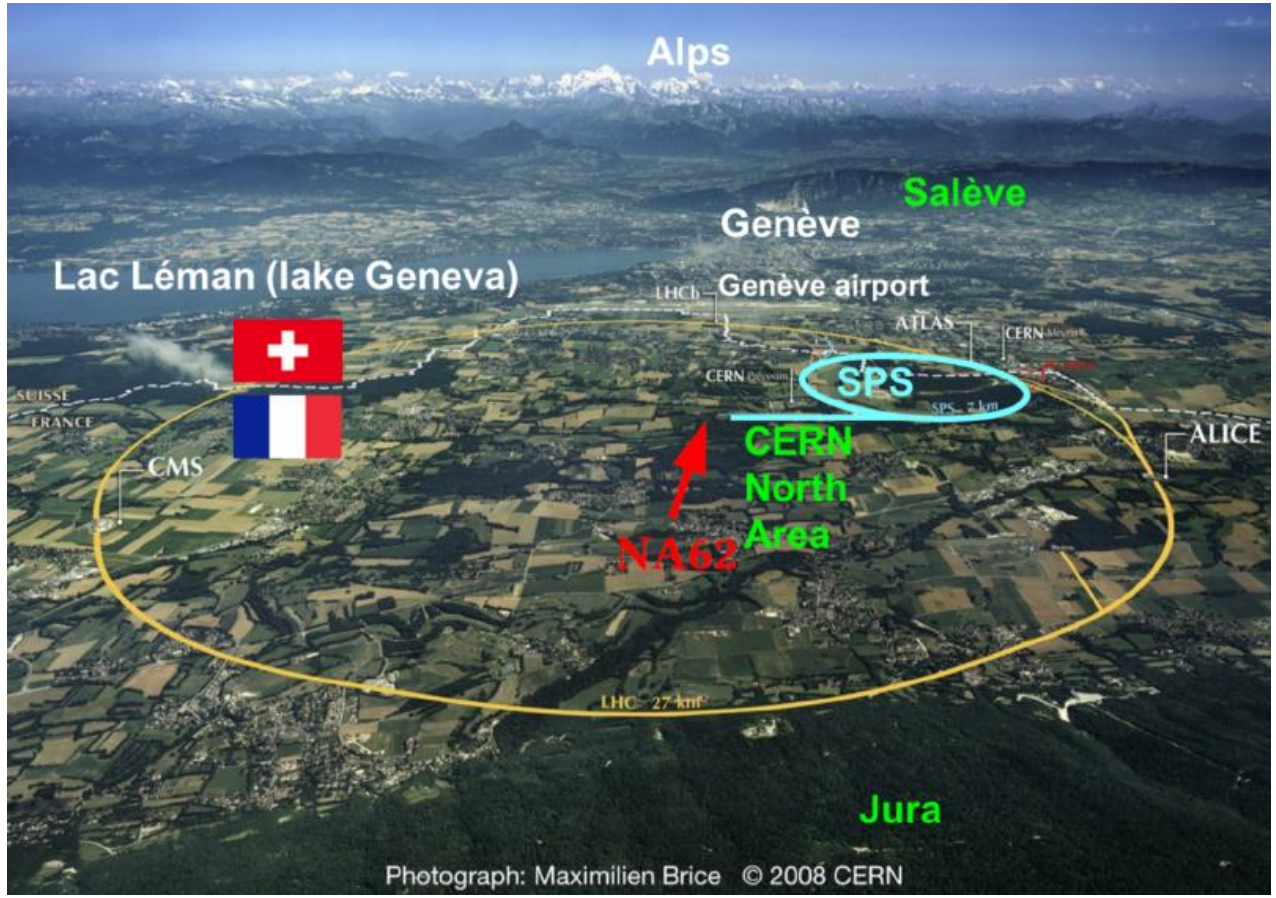
Exotic Messanger Signals and Benchmark Cases
in very clean detector setup

NA62 Results for Searches with $\ell\ell$ final states
and with hh final states

Recent NA62 Results for Lepton Flavor Violation Searches
in kaon decays

More on NA62 Results in Kaon decay mode please see talk by R.Marchevski at this conference

The NA62 Experiment at CERN



~ 30 institutes, ~ 300 collaborators

K^+ decays in flight

Data taking

2016 Comissioning + Physics run (45 days)

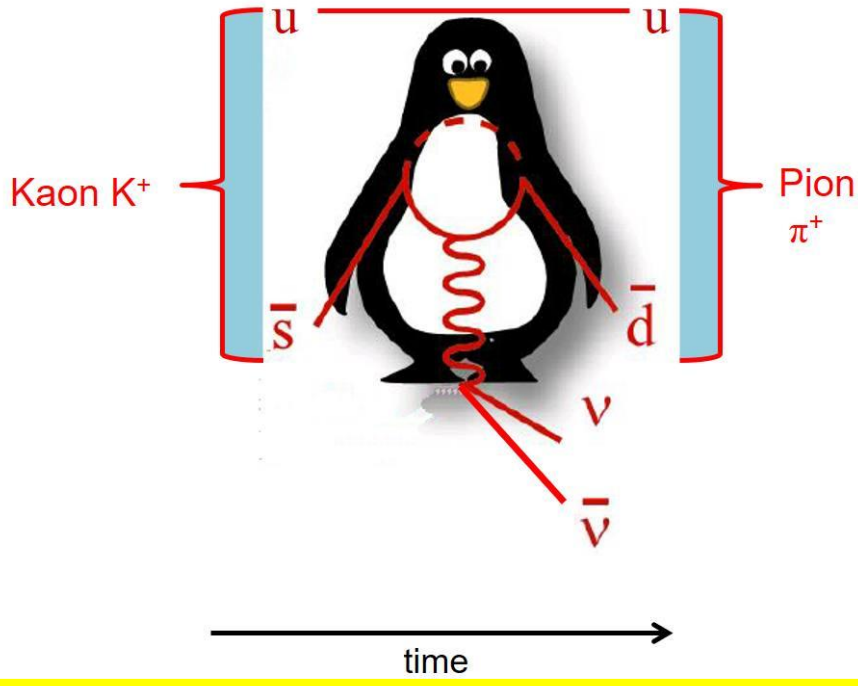
2017, 2018 Run 1 data taking

2021 Physics run (85 days, 10 days in BD mode)

2022, 2023, 2024 Run 2 data taking

Continues long history of Kaon Physics at CERN

Primary goal: measure $\mathcal{B}(K^+ \to \pi^+ \nu\bar{\nu})$



Theory: extra clean, ~ 10% uncertainty

Experiment: very rare, in SM below 10^{-10}

NA62: 20 signal evnts in 2016-8 data

JHEP 06 (2021) 93

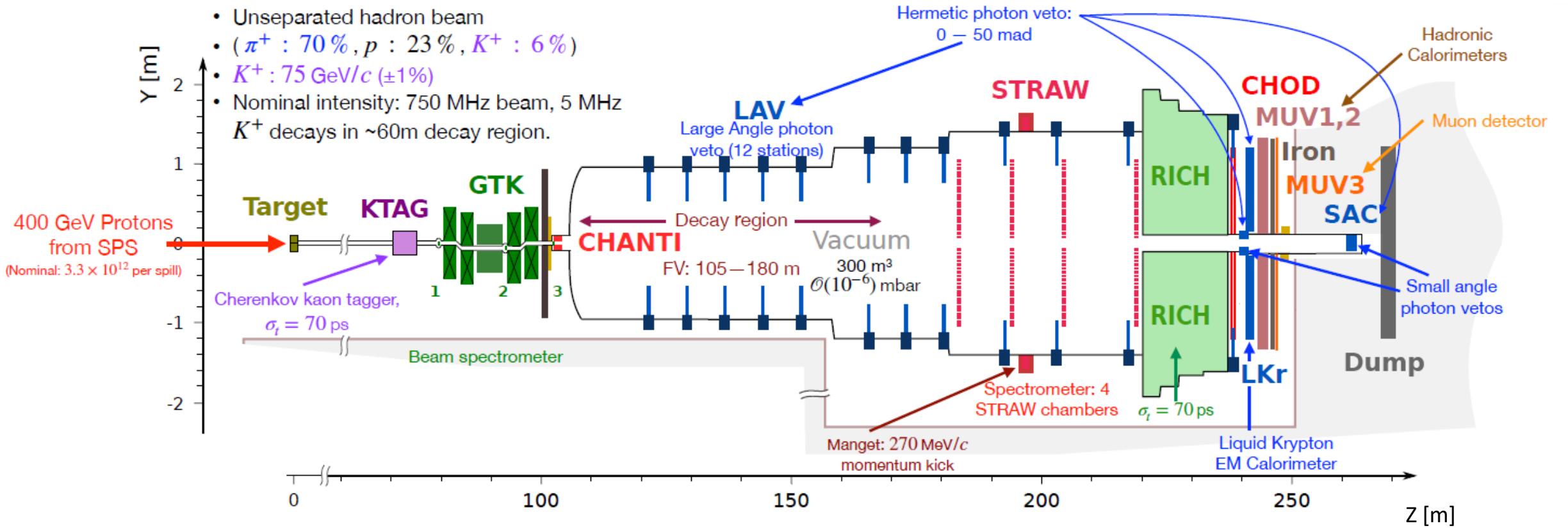
MORE events in 2021-22 data

Latest results: Marchevski talk 5/12

NA62 Beamline & Detector

400 GeV/c primary p^+ beam impinges Be target, 10^{12} protons/s on spill
75 GeV/c secondaries ($\sim 6\%$ K^+) selected using magnetic achromat, **TAX** collimators
5 MHz K^+ decay-in-flight in 60 m long fiducial volume

NA62 setup in K mode: studies of rare K^+ decays



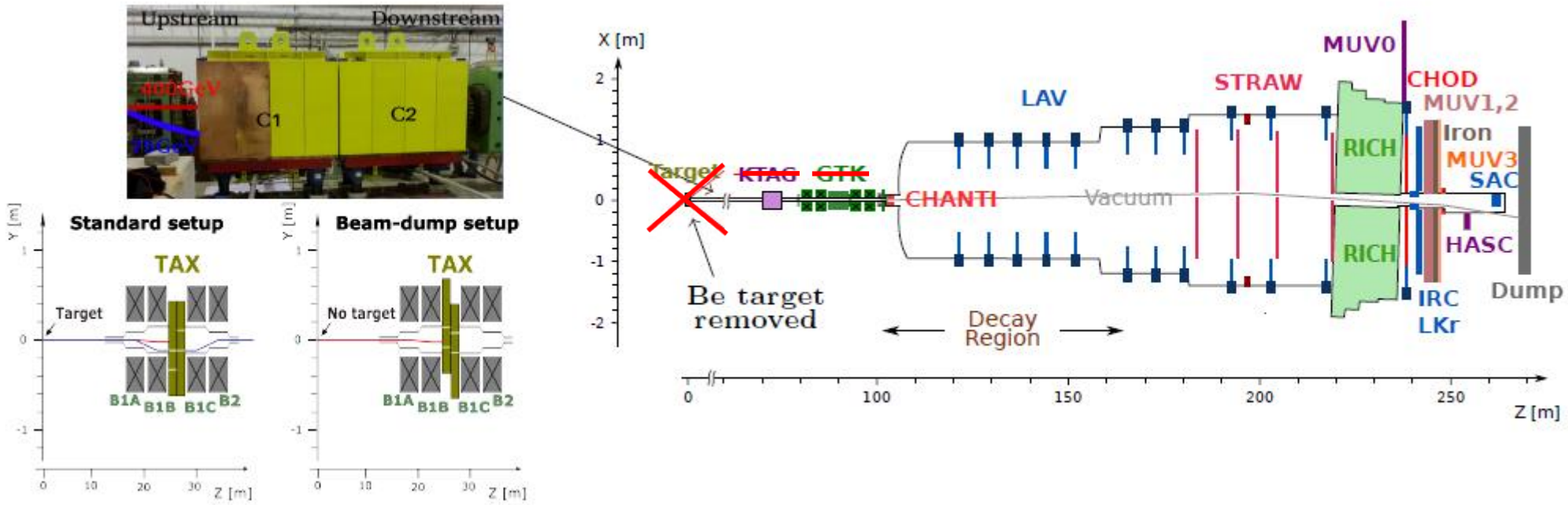
JINST 12 (2017) P05025

Particle Tracking: upstream: **GTK = silicon pixel tracker**, decay region: **STRAW = tracking momentum spectrometer**
P. Identification : upstream: **KTAG**, downstream: **RICH= π/μ/e ID Cherenkov**, **LKr, MUV1,2 calorimetry**
Veto: **CHANTI = inelastic collision Anticounter**, **LAV, IRC, SAC = Large & Small Angle photon vetos**

Overall experimental time resolution reaches $\mathcal{O}(100)$ps

NA62 setup in Beam-Dump (BD) mode: searches for dark messenger signals

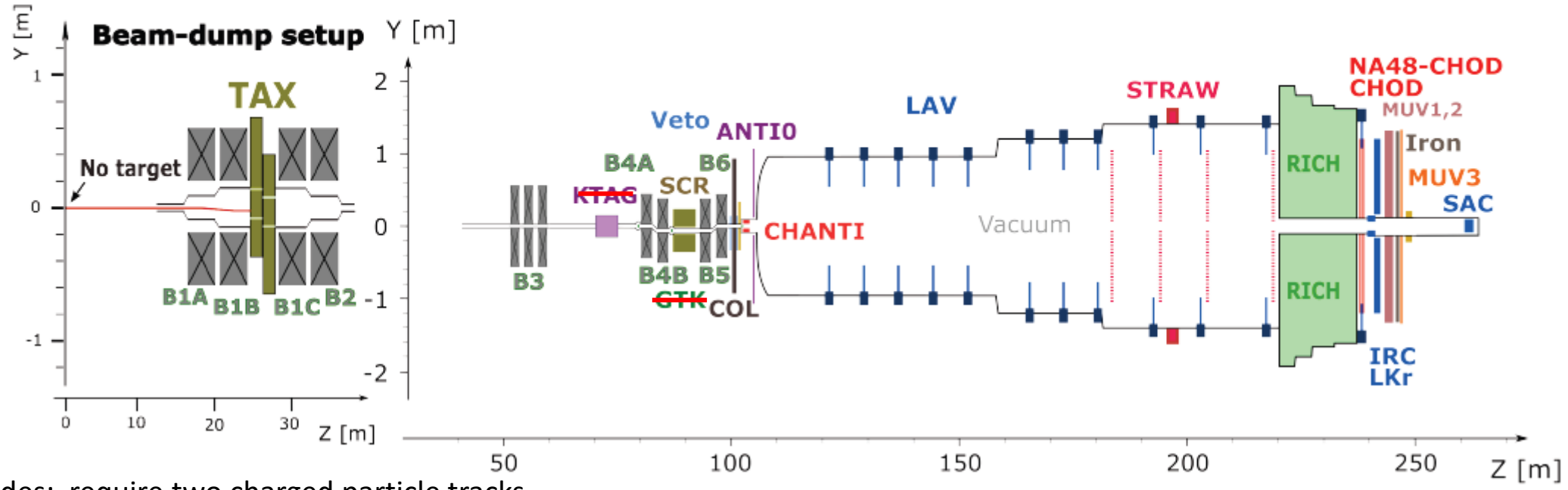
Target removed and TAX closed
KTAG and GTK not used



NA62 setup in Beam-Dump (BD) mode: searches for dark messenger signals

improved sweeping from magnets downstream of TAX, reduce background from penetrating particles

Proton beam intensity ×1.5 of nominal;



Trigger includes: require two charged particle tracks

Data Sample: 2021 (1.4 ± 0.28) x 10^{17} protons on target. Plan for complete Run 2: $N_{POT} \sim 10^{18}$

Published: NP searches with *μμ* and *ee in final state* in NA62 2021 BD sample: NA62 Collaboration *JHEP* 09 (2023) 035 [2303.08666]; [2312.12055]

hadronic final states: summer 2024 conferences

Searches for Dark Messenger signals / portals in visible decay channels

Motivation:

Searches for New Physics (NP) at fixed target experiments are complementary to the energy frontier searches (LHC) and indirect searches

Lower masses (MeV - GeV) and smaller couplings are accessible

Several / many models are constrained by experimental search

Searches for Dark Messenger signals / portals

EUROPEAN ORGANIZATION FOR NUCLEAR RESEARCH (CERN)

CERN-PBC-REPORT-2018-007

Physics Beyond Colliders at CERN
Beyond the Standard Model Working Group Report

J. Beacham[1], C. Burrage[2,*], D. Curtin[3], A. De Roeck[4], J. Evans[5], J. L. Feng[6], C. Gatto[7], S. Gninenko[8], A. Hartin[9], I. Irastorza[10], J. Jaeckel[11], K. Jungmann[12,*], K. Kirch[13,*], F. Kling[6], S. Knapen[14], M. Lamont[4], G. Lanfranchi[4,15,*,**], C. Lazzeroni[16], A. Lindner[17], F. Martinez-Vidal[18], M. Moulson[15], N. Neri[19], M. Papucci[4,20], I. Pedraza[21], K. Petridis[22], M. Pospelov[23,*], A. Rozanov[24,*], G. Ruoso[25,*], P. Schuster[26], Y. Semertzidis[27], T. Spadaro[15], C. Vallée[24], and G. Wilkinson[28].

Abstract: The Physics Beyond Colliders initiative is an exploratory study aimed at exploiting the full scientific potential of the CERN's accelerator complex and scientific infrastructures through projects complementary to the LHC and other possible future colliders. These projects will target fundamental physics questions in modern particle physics. This document presents the status of the proposals presented in the framework of the Beyond Standard Model physics working group, and explore their physics reach and the impact that CERN could have in the next 10-20 years on the international landscape.

* PBC-BSM Coordinators and Editors of this Report

** Corresponding Author: Gaia.Lanfranchi@lnf.infn.it

~12 Benchmark Cases (BC) proposed for searches

Searches for Dark Messenger signals / portals

CERN PBC working group Benchmark Cases

NP particle	Type	SM portal	PBC	Decay channels
dark photon (A'_μ)	vector	$-(\epsilon/2\cos\theta_W)F'_{\mu\nu}B^{\mu\nu}$	BC1-2	$\ell\ell$, 2π, 3π, 4π, 2K, 2Kπ
Dark Higgs (S)	scalar	$(\mu S + \lambda S^2)H^\dagger H$	BC4-5	$\ell\ell$, 2π, 4π, 2K
axion/ALP (a)	pseudoscalar	$(C_{VV}/\Lambda)aV_{\mu\nu}\tilde{V}^{\mu\nu}$ $(C_{ff}/\Lambda)\partial_\mu a\, f\, \gamma^\mu\gamma^5 f$	BC9,11 BC10	γγ, $\ell\ell$, 2πγ, 3π, 4π, 2πη, 2Kπ

NA62 in Beam-Dump mode: $\ell\ell$ and hadronic (2 charged tracks) final states

NA62 Dark Messenger searches – Monte Carlo simulations

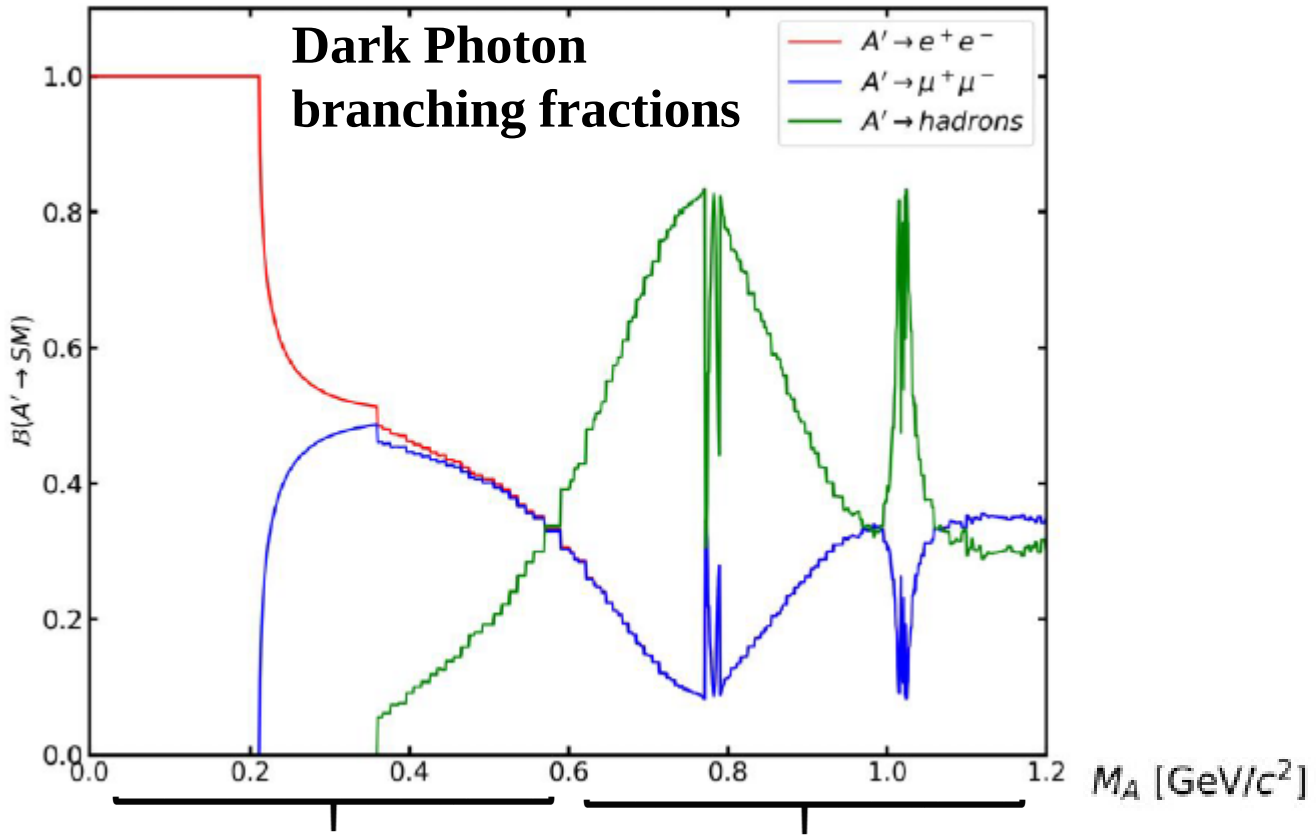
Numerous decay channels and production mechanism have been simulated:

DP Bremsstrahlung $\ell\ell$

Meson mediated

model	production channels	decay channels
DP	Bremsstrahlung	$\pi^+\pi^-$
		$\pi^+\pi^-\pi^0$
		$\pi^+\pi^-\pi^0\pi^0$
		K^+K^-
		$K^+K^-\pi^0$
	light meson decay	$\pi^+\pi^-$
		$\pi^+\pi^-\pi^0$
		$\pi^+\pi^-\pi^0\pi^0$
DS	B meson decay	$\pi^+\pi^-$
		$\pi^+\pi^-\pi^0\pi^0$
		K^+K^-
ALP	Primakoff mixing ($\pi^0/\eta/\eta'$) B meson decay	$\pi^+\pi^-\gamma$
		$\pi^+\pi^-\pi^0$
		$\pi^+\pi^-\pi^0\pi^0$
		$\pi^+\pi^-\eta$
		$K^+K^-\pi^0$

36 combinations of production and decay channels studied for hadronic analysis only



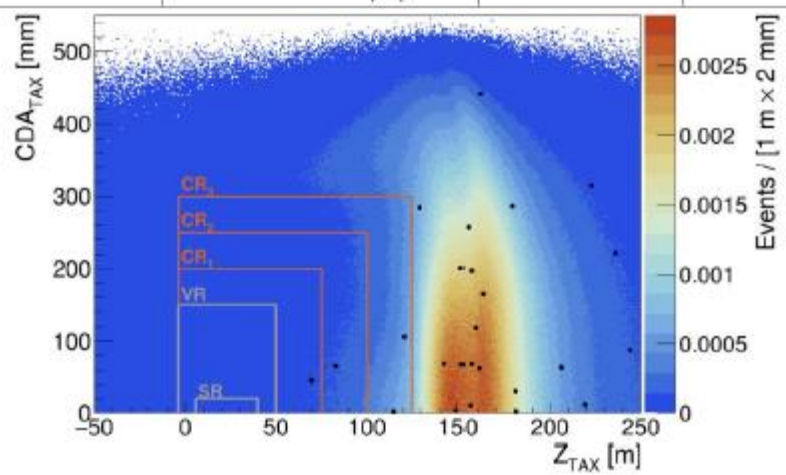
NA62 Dark Messenger searches – Background Determination

- **Combinatorial and neutrino-induced backgrounds**: negligible contributions in h^+h^- or e^+e^- , dominant for $\mu^+\mu^-$ (halo muons)
- **Prompt background**: inelastic interaction of halo muons can produce hadrons or e^+e^-
- **Upstream background**: formed by particles that are collected by the GTK achromat

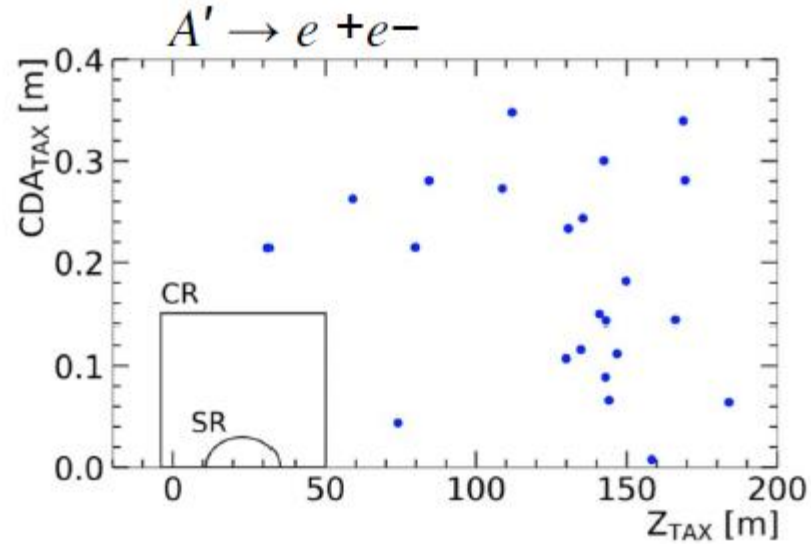
Background determination for A'→ℓℓ

- **Combinatorial and neutrino-induced backgrounds**
- **Prompt background**
- **Upstream background**

	Combinatorial	Prompt @ 90% CL	Upstream prompt@ 90% CL
N bkg SR	**0.016 ± 0.002**	<0.0004	< 0.007



$Nbkg \quad SR = 0.0094 - 0.009 + 0.049 \text{ @ } 90\% \; CL$

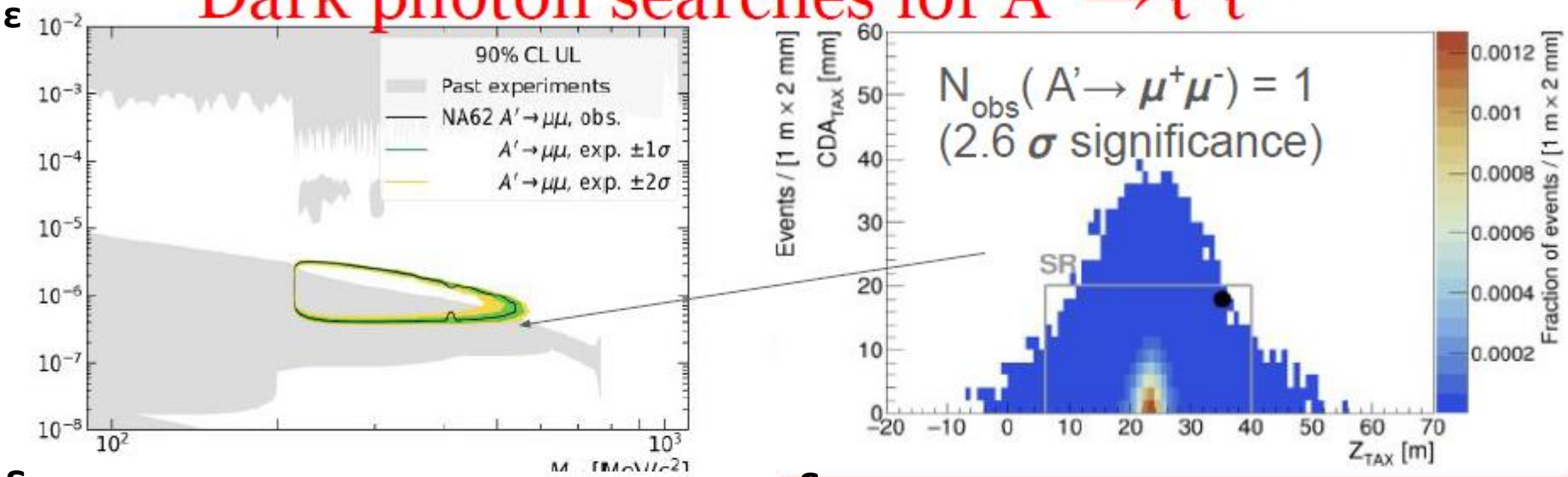


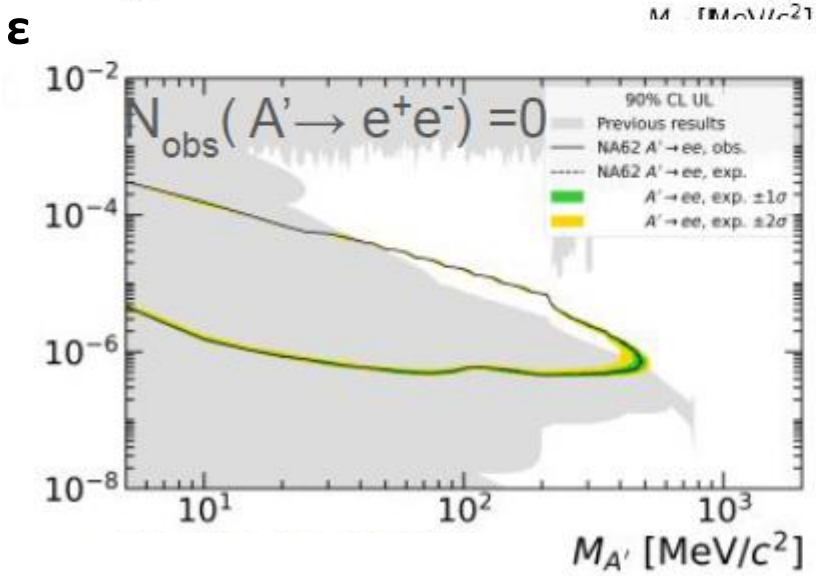
NA62 Dark Messenger searches
Results for leptonic final states

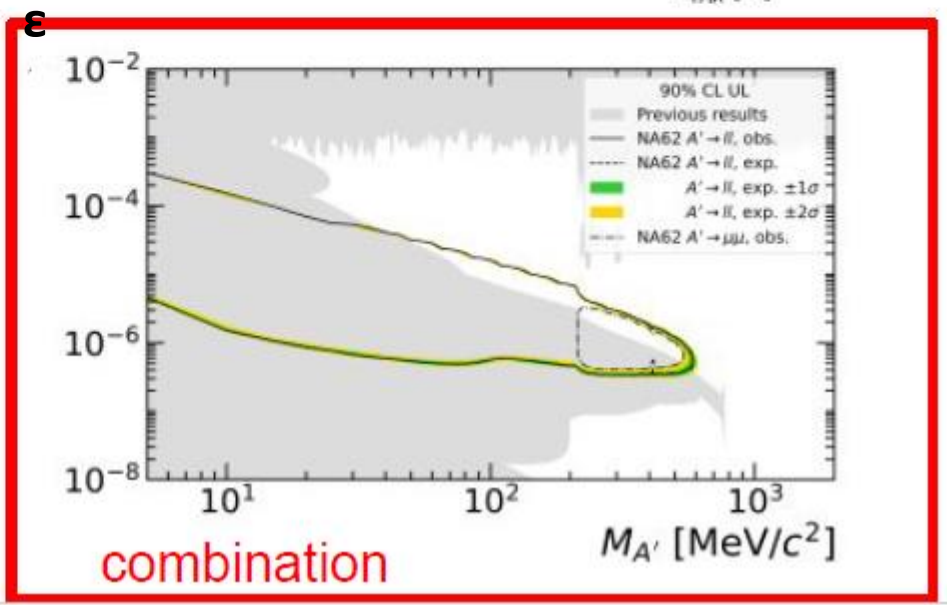
NA62 Collaboration collaboration, *Search for leptonic decays of dark photons at na62*, *Phys. Rev. Lett.* **133** (2024) 111802.

E. Cortina Gil et al., *Search for dark photon decays to $\mu^+\mu$ at NA62*, *JHEP* **09** (2023) 035 [2303.08666].

Dark photon searches for A' → $\ell^+\ell^-$







Combined
$\mu^+\mu^-$ and e^+e^-
Results

NA62 Dark Messenger searches – hh final state studies

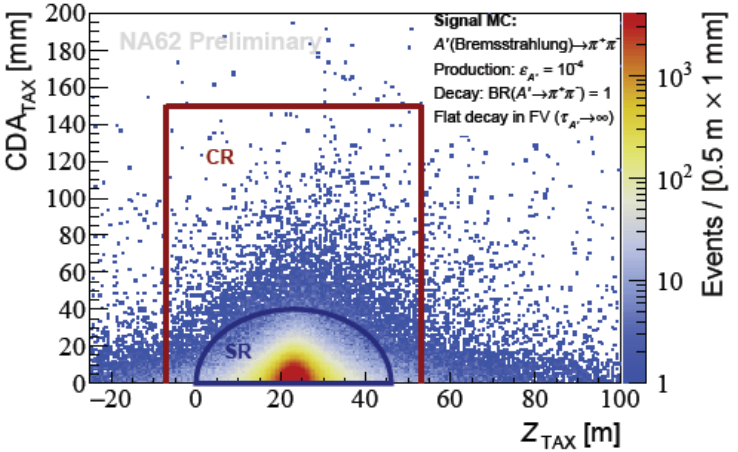


Figure: $A' \to \pi^+\pi^-$ MC: control (CR) and signal (SR) region

- In a model-independent approach $\mathrm{BR}_{X\to\pi^+\pi^-} = 1$,
  $N_{\mathrm{exp}}(M_X, \Gamma_X) =$
  $N_{\mathrm{POT}}\, \chi_{pp\to X}(C_{\mathrm{ref}})\, P_{\mathrm{rd}}\, A_{\mathrm{acc}}\, A_{\mathrm{trig}}$
- $\chi_{pp\to X}(C_{\mathrm{ref}})$: messenger prod. probability for ref. coupling
- P_{rd}: probability to reach NA62 FV and decay therein
- $A_{\mathrm{acc}}\, A_{\mathrm{trig}}$: signal selection and trigger efficiencies

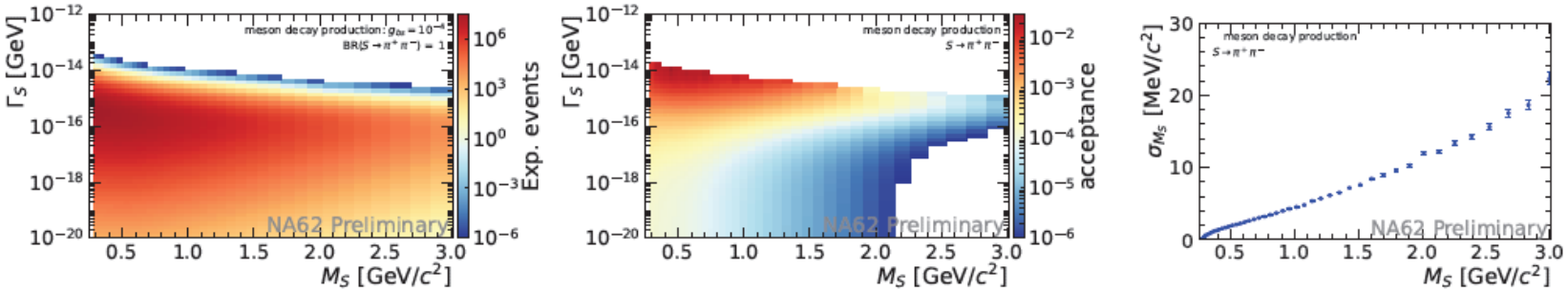


Figure: Left: expected number of $S \to \pi^+\pi^-$ selected events, for $g_{bs} = 10^{-4}$, BR = 1. Center: selection acceptance given a messenger decay in the FV. Right: Mass resolution of the reconstructed messenger.

if observed,
M_S could be resolved
at a per cent level

- Distributions evaluated for 36 combinations of production and decay channels

Background determination for hh analysis

- **Combinatorial and neutrino-induced backgrounds**
- **Prompt background**:
- **Upstream background**

- For the h^+h^- analysis channels at 68% CL:

Channel	$N_{\mathrm{exp,CR}} \pm \delta N_{\mathrm{exp,CR}}$	$N_{\mathrm{exp,SR}} \pm \delta N_{\mathrm{exp,SR}}$
$\pi^+\pi^-$	0.013 ± 0.007	0.007 ± 0.005
$\pi^+\pi^-\gamma$	0.031 ± 0.016	0.007 ± 0.004
$\pi^+\pi^-\pi^0$	$(1.3^{+4.4}_{-1.0}) \times 10^{-7}$	$(1.2^{+4.3}_{-1.0}) \times 10^{-7}$
$\pi^+\pi^-\pi^0\pi^0$	$(1.6^{+7.6}_{-1.4}) \times 10^{-8}$	$(1.6^{+7.4}_{-1.4}) \times 10^{-8}$
$\pi^+\pi^-\eta$	$(7.3^{+27.0}_{-6.1}) \times 10^{-8}$	$(7.0^{+26.2}_{-5.8}) \times 10^{-8}$
K^+K^-	$(4.7^{+15.7}_{-3.9}) \times 10^{-7}$	$(4.6^{+15.2}_{-3.8}) \times 10^{-7}$
$K^+K^-\pi^0$	$(1.6^{+3.2}_{-1.2}) \times 10^{-9}$	$(1.5^{+3.1}_{-1.2}) \times 10^{-9}$

background-free hypothesis not only at $N_{POTs} = 1.4 \times 10^{17}$ but also in the future full **Run 2 dataset** of $N_{POTs} = 10^{18}$

NA62 Dark Messenger searches – hh final state studies

Table: Expected number of background events (68% CL) in CR and SR. Minimum number of observed events N_{obs} for a background-only p-value above 5σ in SR and SR+CR (global significance, flat background in m_{inv} assumed).

Channel	$N_{exp,CR} \pm \delta N_{exp,CR}$	$N_{exp,SR} \pm \delta N_{exp,SR}$	$N_{obs,SR}^{p>5\sigma}$	$N_{obs,SR+CR}^{p>5\sigma}$
$\pi^+\pi^-$	0.013 ± 0.007	0.007 ± 0.005	3	4
$\pi^+\pi^-\gamma$	0.031 ± 0.016	0.007 ± 0.004	3	5
$\pi^+\pi^-\pi^0$	$(1.3^{+4.4}_{-1.0}) \times 10^{-7}$	$(1.2^{+4.3}_{-1.0}) \times 10^{-7}$	1	1
$\pi^+\pi^-\pi^0\pi^0$	$(1.6^{+7.6}_{-1.4}) \times 10^{-8}$	$(1.6^{+7.4}_{-1.4}) \times 10^{-8}$	1	1
$\pi^+\pi^-\eta$	$(7.3^{+27.0}_{-6.1}) \times 10^{-8}$	$(7.0^{+26.2}_{-5.8}) \times 10^{-8}$	1	1
K^+K^-	$(4.7^{+15.7}_{-3.9}) \times 10^{-7}$	$(4.6^{+15.2}_{-3.8}) \times 10^{-7}$	1	2
$K^+K^-\pi^0$	$(1.6^{+3.2}_{-1.2}) \times 10^{-9}$	$(1.5^{+3.1}_{-1.2}) \times 10^{-9}$	1	1

NA62 Dark Messenger hh final state ...

essentially background free not only for $N_{POT} = 1.4 \times 10^{17}$,

but also for the complete Run 2 in the future for $N_{POT} = 10^{18}$.

NA62 Dark Messenger searches – Results for hadronic final state

0 events observed in all control and signal regions

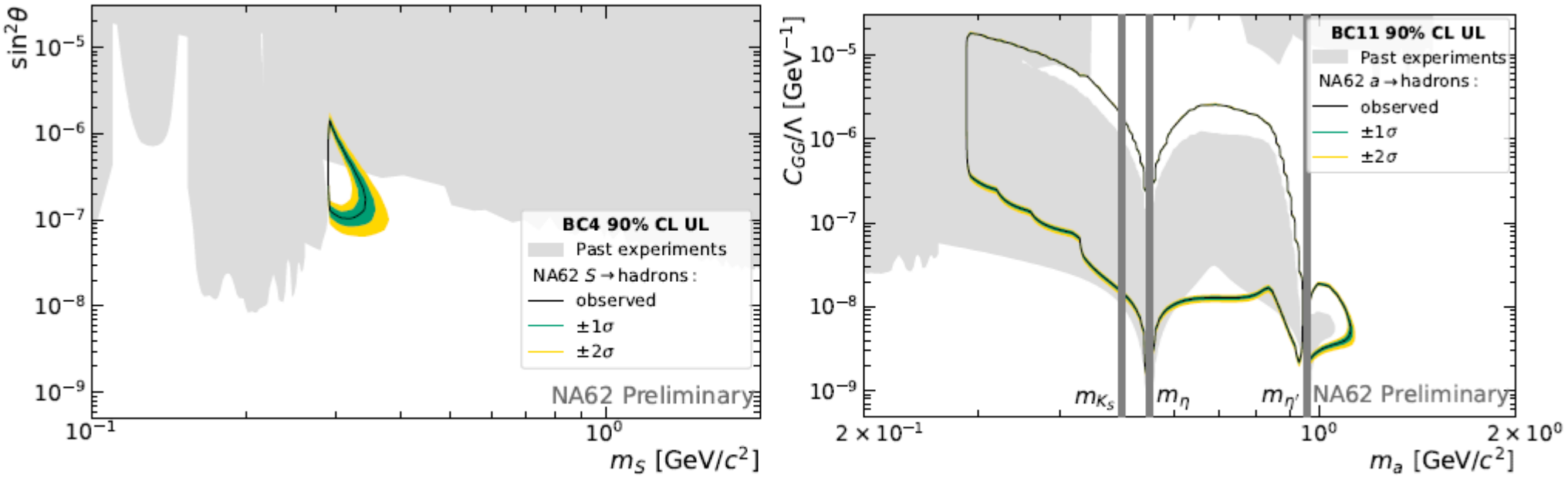


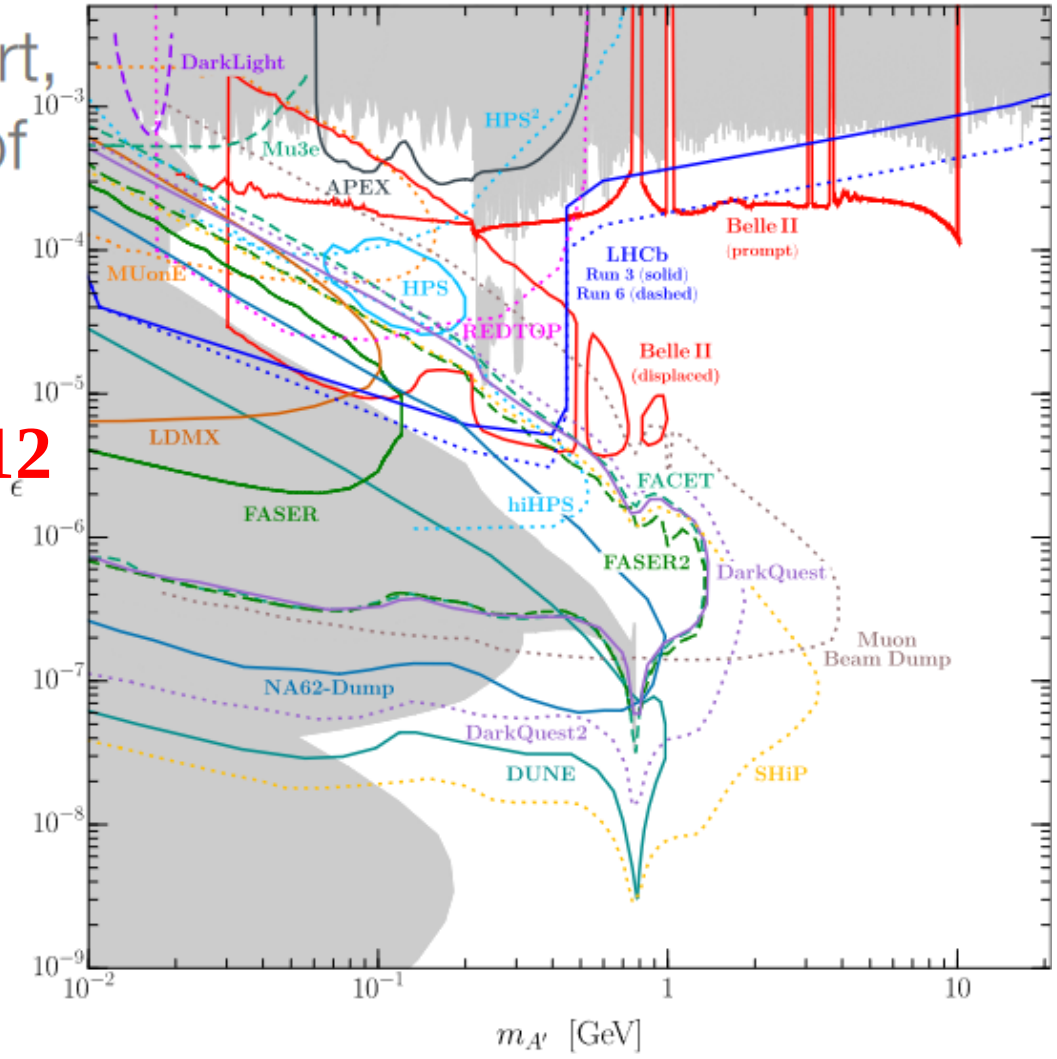
Figure: The observed 90% CL exclusion contours in BC4 (left) and BC11 (right) benchmarks together with the expected $\pm1\sigma$ and $\pm2\sigma$ bands (theory uncertainty not included). Public tool ALPINIST[5] used for the combination of the results from the individual production and decay channels. No standalone 90% CL exclusion for BC1 (dark photon).

ALPINIST JHEP 07 (2022) 094

Searching for the dark sector in the laboratory

- Extensive, world-wide effort, including a large number of dedicated projects.

Chris Hearty DISCRETE talk on 2/12



Batell, Blinov, Hearty, McGehee,
arXiv 2207.06905 (2022)

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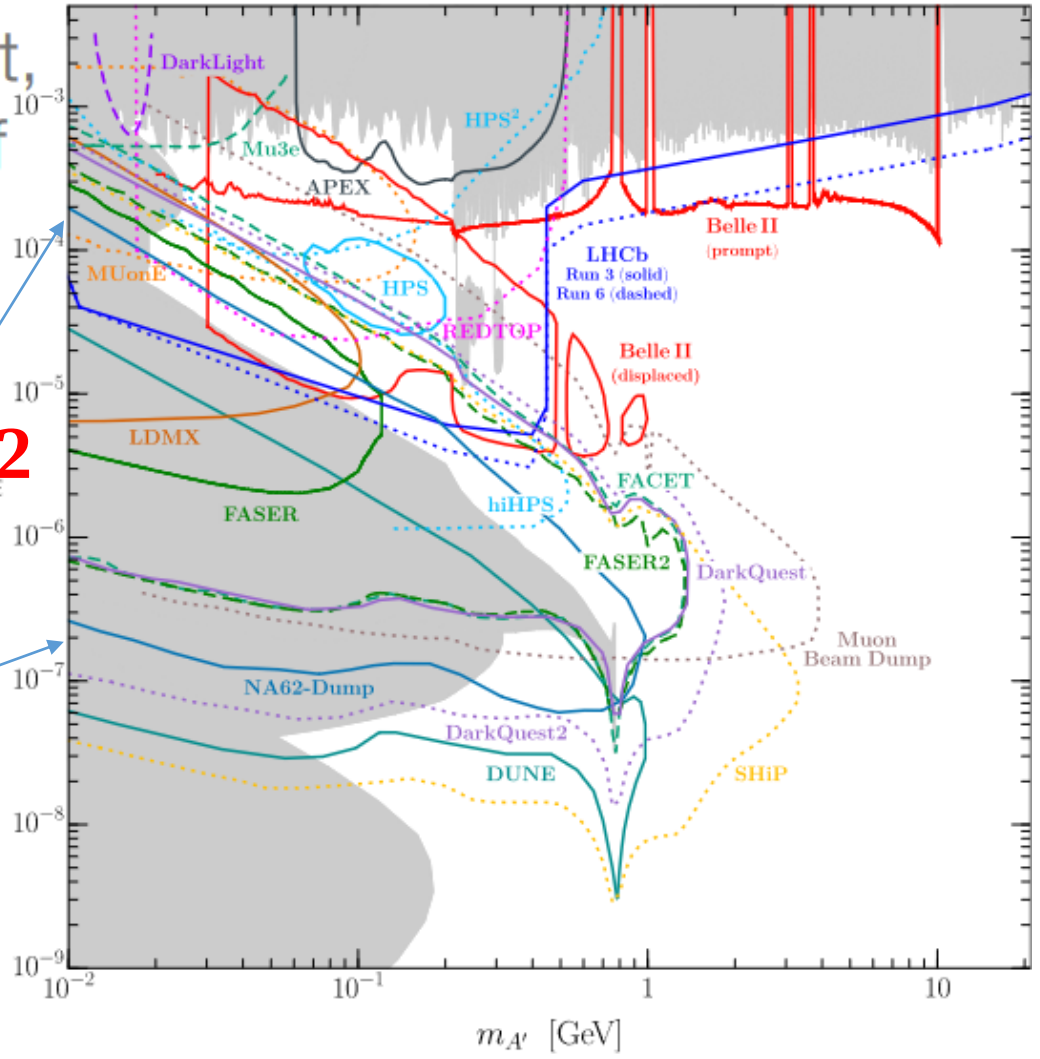
Chris Hearty DISCRETE talk on 2/12

NA62 in Dump Mode



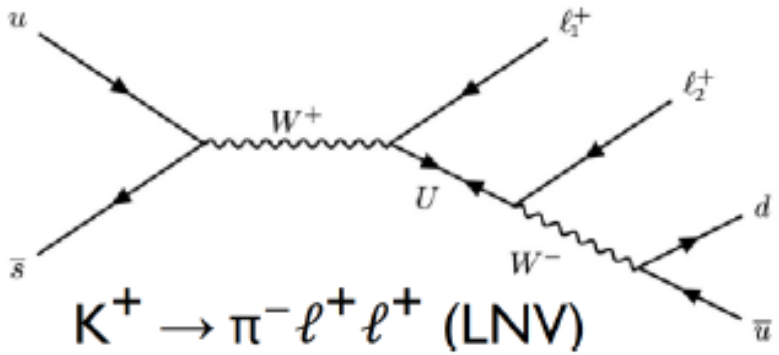
Batell, Blinov, Hearty, McGehee,
arXiv 2207.06905 (2022)

Searches for Lepton Flavor Violation in Kaon Decays

LF / LN are global symmetries in SM with m_ν=0. LFV observed in ν oscillations.

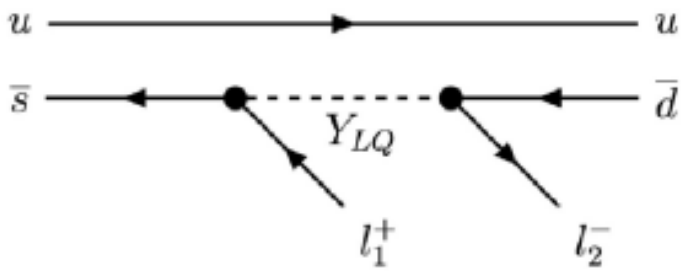
If observed in K+ decays, LFV/LNV would be clear sign of Beyond SM Physics

Example: $K^+ \to \pi^- \ell^+ \ell^+$ (LNV) Here, heavy Majorana neutrino might act similarly to the 0νββ decay



$K^+ \to \pi^- \ell^+ \ell^+$ (LNV)

Example: $K^+ \to \pi^\pm \mu^\mp e^+$ (LFV) Here, a heavy LeptoQuark might act to mediate such a decay



$K^+ \to \pi^\pm \mu^\mp e^+$ (LFV)

PLB 491 (2000) 285,
JHEP 05 (2009) 030

Searches for Lepton Flavor Violation in Kaon Decays

NA62 Searches:

All Limits are at 90% C.L.

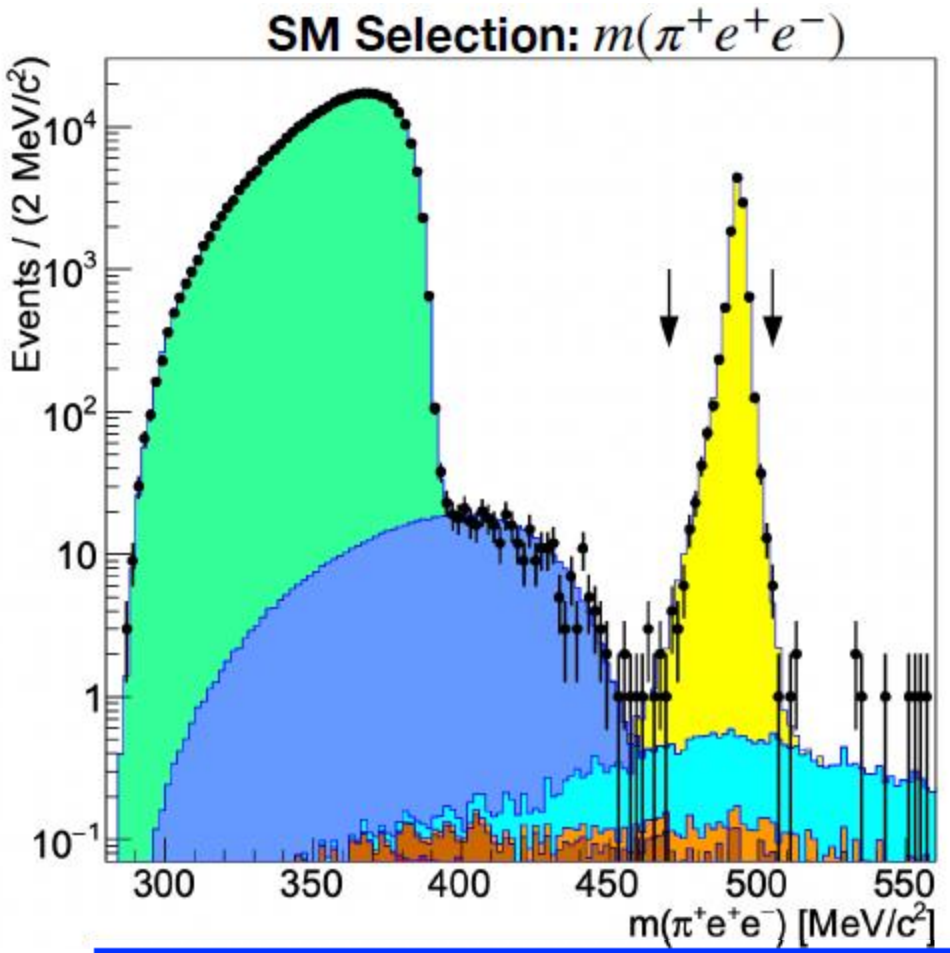
$K^+ \to \mu^- \nu e^+ e^+$	BF < 8.1×10^{-11}	PLB 838 (2023) 137679
$K^+ \to \pi^- e^+ e^+$	BF < 5.3×10^{-11}	PLB 830 (2022) 137172
$K^+ \to \pi^- \pi^0 e^+ e^+$	BF < 8.5×10^{-10}	
$K^+ \to \pi^- \mu^+ \mu^+$	BF < 4.2×10^{-11}	PLB 797(2019) 134794
$K^+ \to \pi^- \mu^+ e^+$	BF < 4.2×10^{-11}	
$K^+ \to \pi^+ \mu^- e^+$	BF < 6.6×10^{-11}	PRL 127(2021) 13, 131802
$\pi^0 \to \mu^- e^+$	BF < 3.2×10^{-10}	
$K^+ \to \pi^0 \pi \mu e$	BF < 3-5 $\times 10^{-10}$	

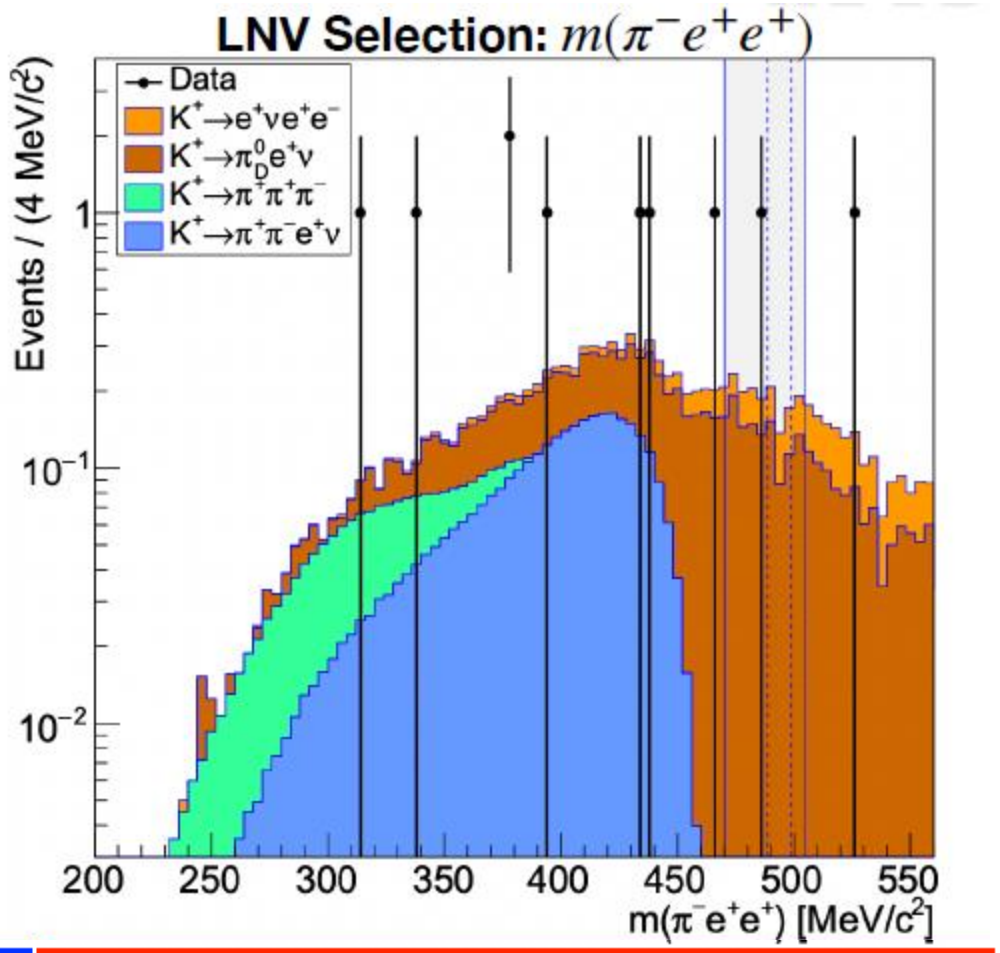
Mode	Expected Background	Observed candidates	Upper limit of BR at 90% CL
$K^+ \to \pi^0 \pi^- \mu^+ e^+$	0.33±0.07	0	2.9×10^{-10}
$K^+ \to \pi^0 \pi^+ \mu^- e^+$	0.004±0.003	0	3.1×10^{-10}
$K^+ \to \pi^0 \pi^+ \mu^+ e^-$	0.29±0.07	0	5.0×10^{-10}

To be publishe

Searches for Lepton Flavor Violation in Kaon Decays

Search for $K^+ \to \pi^- e^+ e^+$ as an example PLB 830 (2022) 137172





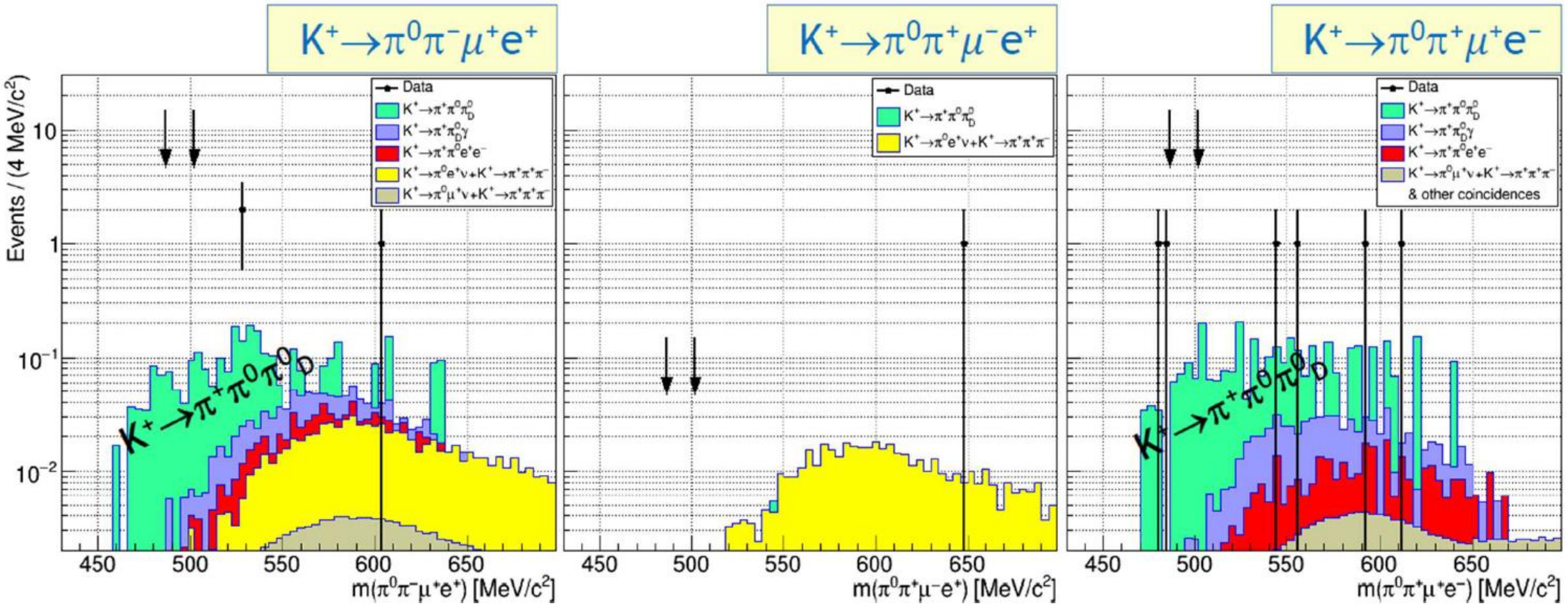
- 11041 candidates
- $\mathcal{B}(K^+ \to \pi^+e^+e^-) = (3.00 \pm 0.09) \times 10^{-7}$
- Effective # of K^+ decays in FV = $(1.015 \pm 0.031) \times 10^{12}$

- Expected background = 0.43 ± 0.09
- Candidates observed: 0
- $\mathcal{B}(K^+ \to \pi^-e^+e^+) < 5.3 \times 10^{-11}$ at 90 % CL

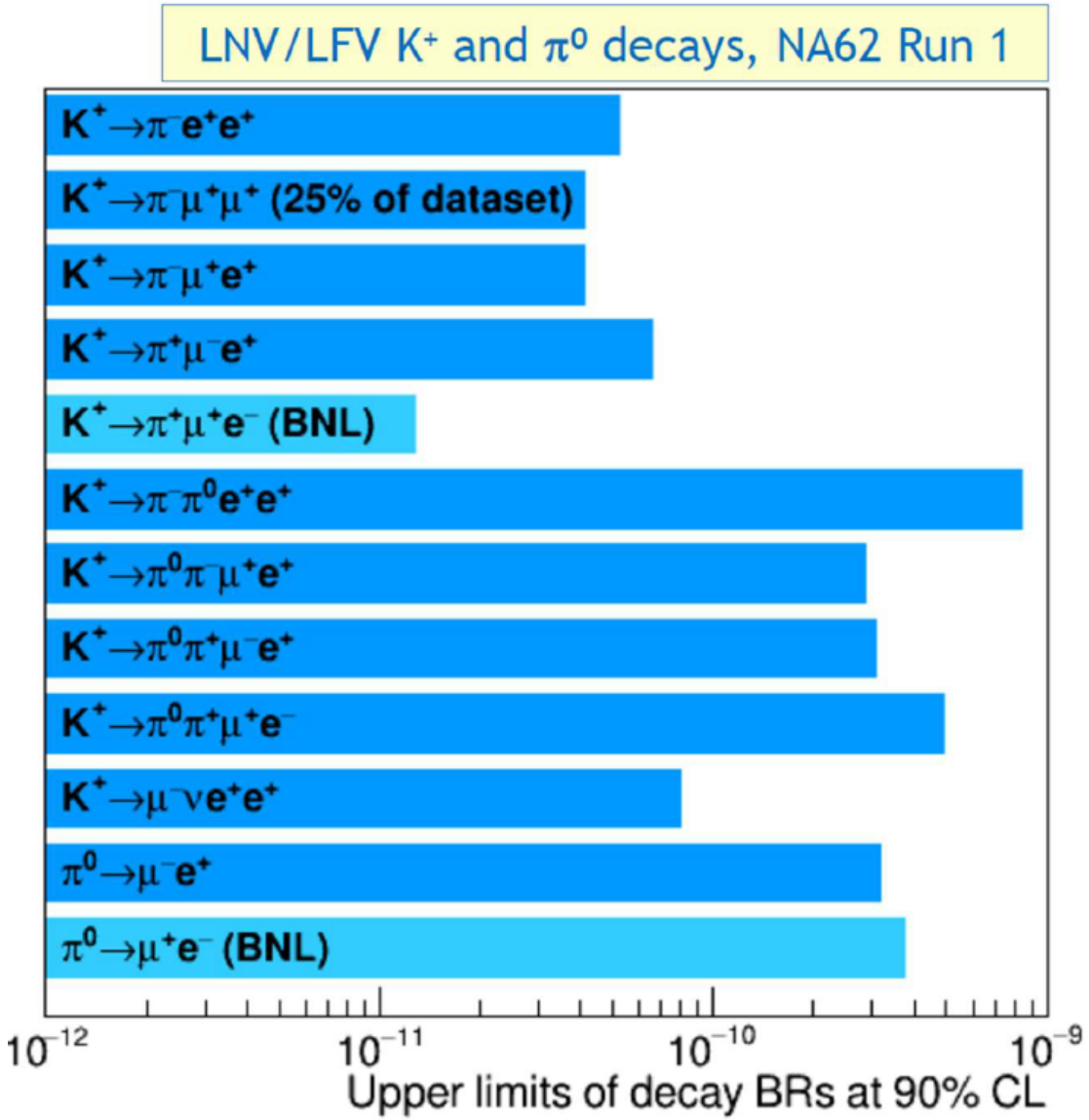
Searches for Lepton Flavor Violation in Kaon Decays

$K^+ \to \pi^0 \pi \mu e$ as a recent example

BF < 3-5 x 10^{-10} to be published



Searches for Lepton Flavor Violation in Kaon Decays



Summary

Besides the NA62 main goal many new physics searches have been performed

Blind searches for a **dark messenger particle decaying into ee, μμ and hadrons** have been performed on the 2021 data sample exploring new regions in the parameter space accessible to the **NA62 Experiment in the Beam-Dump mode**

With the (1.43± 0.28) x 10^{17} POTs 90% CL upper limits have been derived, **excluding new regions** in the parameter space shown here in respective plots

Searches for other (semi-leptonic, digamma, etc) final states are ongoing.
There is now **2023 NA62 data in Beam-Dump to be analyzed** and a total of 10^{18} POTs is expected by the LHC Long Shutdown 3

NA62 searches for **Lepton Flavor Violation** in Kaon decays have been ongoing, reaching down to the 10^{-17} BR level

NA62 Run 3 collection will last by the Long Shutdown 3 in 2026