



WIN 2025

9-13 June 2025
University of Sussex, Brighton, UK



Searches for Hidden Sectors and Lepton Flavor Violation in Kaon Decays at NA62



Tomáš Blažek (Comenius U. Bratislava)
on behalf of NA62 Collaboration

Outline

The NA62 Experiment

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

Exotic Messenger Signals and Benchmark Cases

NA62 in BD mode - Messenger Signal simulations:
 $\mu^+\mu^-$, e^+e^- , hh & $\gamma\gamma$ final states

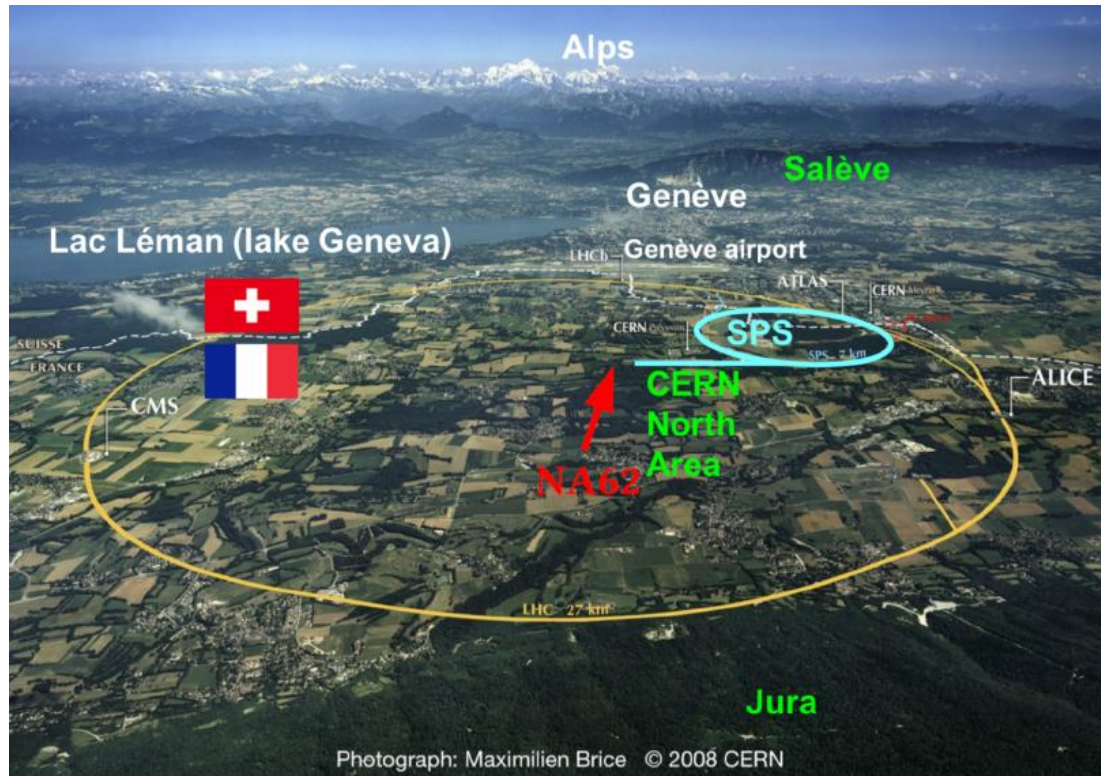
NA62 Analysis Strategy and Background Determination

NA62 Results for Searches with $\ell\ell$ final states (published in 2023 & 24)
and with hh and $\gamma\gamma$ final states (published in 2024 & 25)

NA62 Results for Searches of Lepton Flavor Violating Decays

[More on NA62 Results in Kaon mode please check Marchevski's Kaon Physics Talk at this conference](#)

The NA62 Experiment at CERN

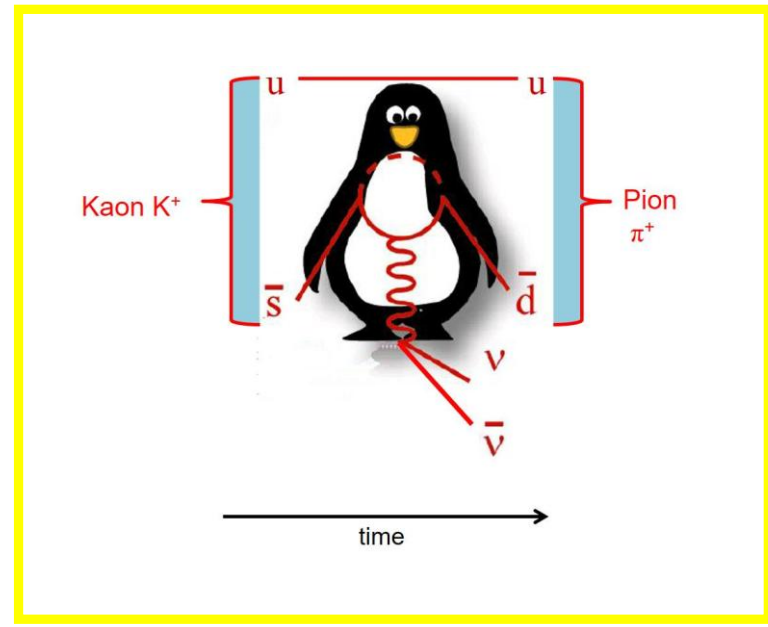


~ 30 institutes, ~ 300 collaborators
K⁺ decays in flight

- Data taking**
- Run 1 2017-18
 - Run 2 2021-26
 - 2016 Commissioning + Physics run (45 days)
 - 2017, 2018 Run 1 data taking (160+217 days)
 - 2021 Physics run (85 days, 10 days in BD mode)
 - 2022 Physics run (215 days)
 - 2023 Physics run (150 days, 10 days in BD mode)
 - 2024 Physics run (204 days, 12 days in BD mode)
 - 2025 Physics run (210 days foreseen, started 04/2025)

Continues long history of Kaon Physics at CERN

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



Theory: extra clean, ~ 10% uncertainty
very rare, SM value $8.60 \pm 0.42 \cdot 10^{-11}$

Experiment: NA62 new result JHEP 02 (2025) 191

$$\mathcal{B}_{2016-2022}(K^+ \rightarrow \pi^+ \nu \bar{\nu}) = (13.0^{+3.0}_{-2.7} |_{stat} \quad +1.3 |_{-1.3} |_{syst}) \times 10^{-11}$$

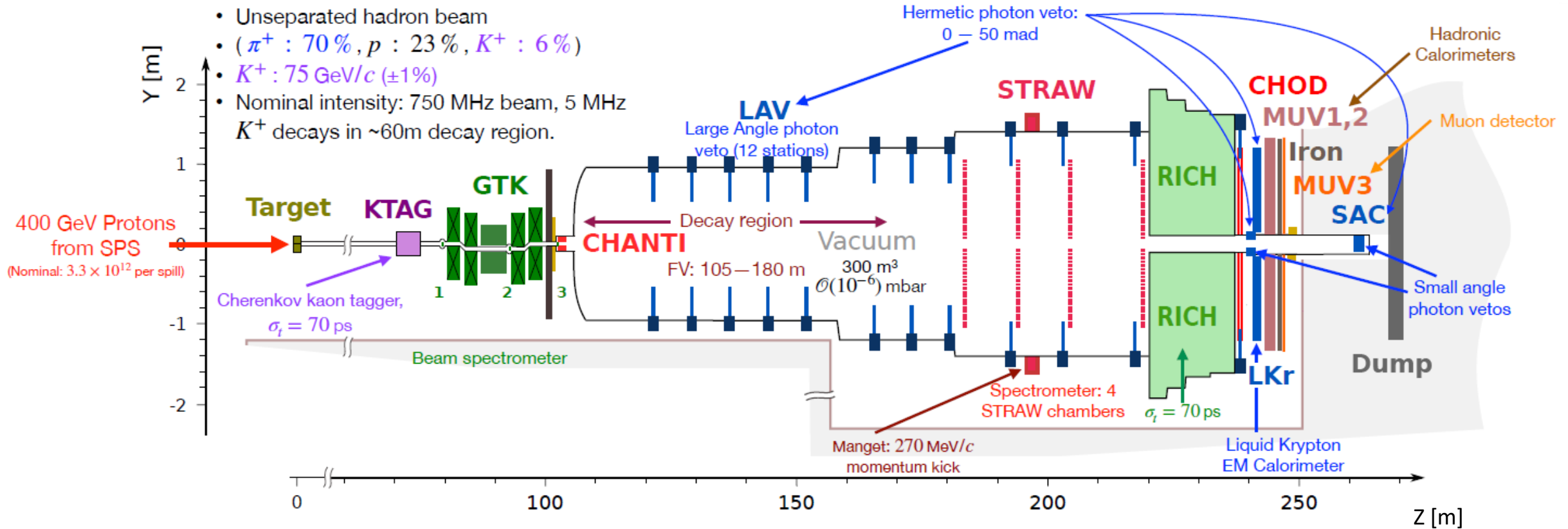
51 signal events observed

*More details:
Radoslav Marchevski's talk today*

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

- Unseparated hadron beam
- (π^+ : 70%, p : 23%, K^+ : 6%)
- K^+ : 75 GeV/c ($\pm 1\%$)
- Nominal intensity: 750 MHz beam, 5 MHz K^+ decays in ~ 60 m decay region.



JINST 12 (2017) P05025

Particle Tracking: upstream: **GTK** = silicon pixel tracker, decay region: **STRAW** = tracking momentum spectrometer

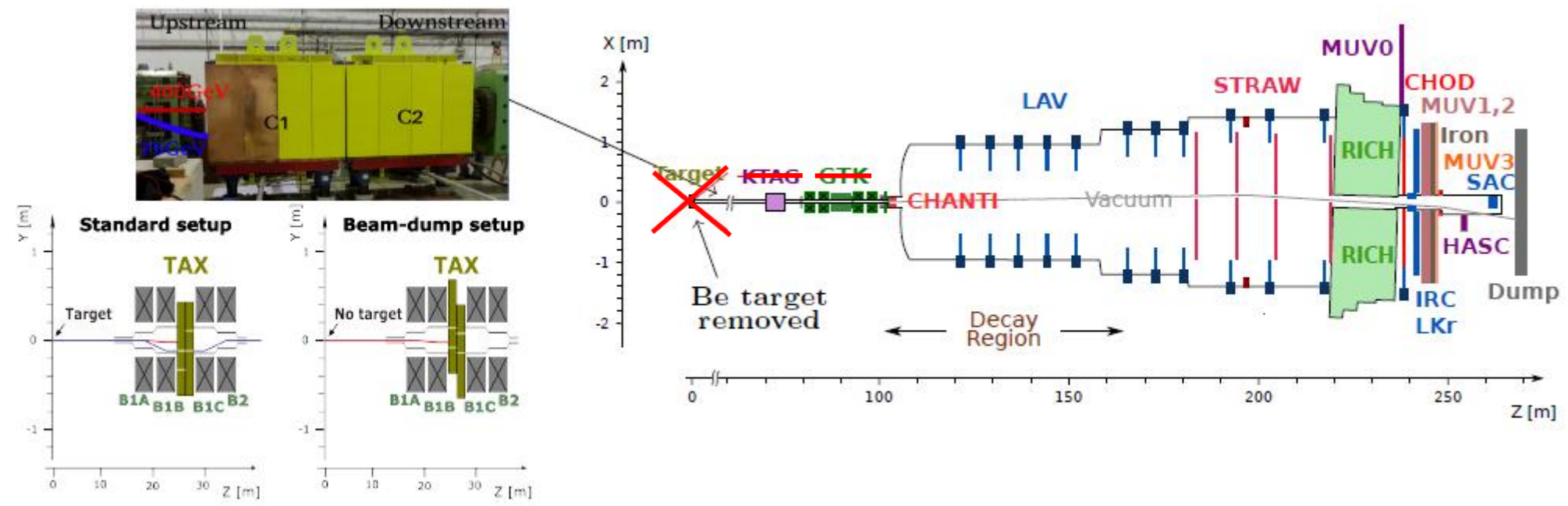
P. Identification: upstream: **KTAG**, downstream: **RICH**= $\pi/\mu/e$ ID Cherenkov, **LKr**, **MUV1,2** calorimetry

Veto: **CHANTI** = inelastic collision Anticounter, **LAV**, **IRC**, **SAC** = Large & Small Angle photon vetos

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

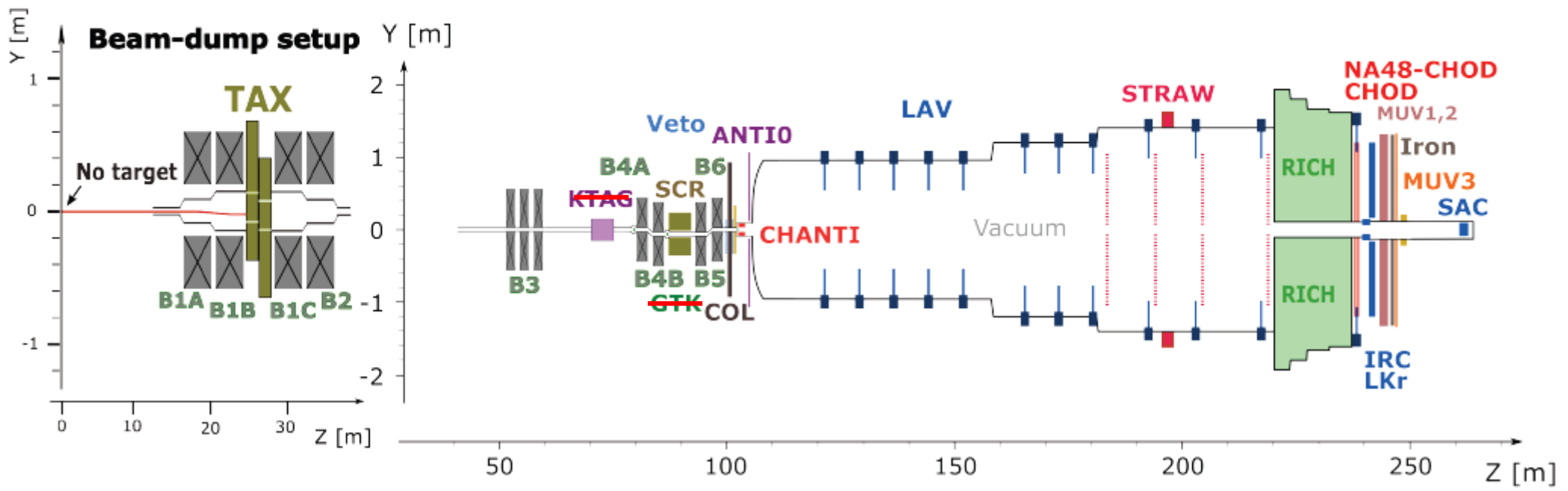
NA62 setup in Beam-Dump (BD) mode: searches for dark messenger signals

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 $\times 1.5$ of nominal;



Trigger includes: require two charged particle tracks

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

Published: NP searches with $\mu\mu$ and ee in final state in NA62 2021 BD sample: [NA62 Collaboration, JHEP 09 \(2023\) 035](#), [PRL 133 \(2024\) 111802](#).
 hadronic final states: [NA62 Collaboration, Eur. Phys. J C \(2025\) 85:571](#).

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 (due to large statistics)
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. Beacham¹, C. Burrage^{2,*}, D. Curtin², A. De Roeck⁴, J. Evans⁵, J. L. Feng⁶, C. Gatto⁷, S. Gninenko⁸, A. Hartin⁹, I. Irastorza¹⁰, J. Jaeckel¹¹, K. Jungmann^{12,*}, K. Kirch^{13,*}, F. Kling⁶, S. Knapen¹⁴, M. Lamont⁴, G. Lanfranchi^{4,15,***}, C. Lazzeroni¹⁶, A. Lindner¹⁷, F. Martinez-Vidal¹⁸, M. Moulson¹⁵, N. Neri¹⁹, M. Papucci^{4,20}, I. Pedraza²¹, K. Petridis²², M. Pospelov^{23,*}, A. Rozanov^{24,*}, G. Rucso^{25,*}, P. Schuster²⁶, Y. Semertzidis²⁷, T. Spadaro¹⁵, C. Vallée²⁴, and G. Wilkinson²⁸.

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

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arXiv:1901.09966v2 [hep-ex] 2 Mar 2019

2 Physics Motivations

2.1 Hidden Sector portals

2.1.1 Vector portal models

2.1.2 Scalar portal models

2.1.3 Neutrino portal models

2.1.4 Axion portal models

**~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	$\ell\ell, 2\pi, 3\pi, 4\pi, 2K, 2K\pi$
Dark Higgs (S)	scalar	$(\mu S + \lambda S^2) H^\dagger H$	BC4-5	$\ell\ell, 2\pi, 4\pi, 2K$
axion/ALP (a)	pseudoscalar	$(C_{VV}/\Lambda) a V_{\mu\nu} \tilde{V}^{\mu\nu}$ $(C_{ff}/\Lambda) \partial_\mu a f \gamma^\mu \gamma^5 f$	BC9,11 BC10	$\gamma\gamma, \ell\ell, 2\pi\gamma, 3\pi, 4\pi, 2\pi\eta, 2K\pi$

Two types of direct searches for NP particles at fixed-target experiments:

- (i) NP particle production in SM particle decays – reconstruction from both initial and final state particles
- (ii) NP particle decay to SM particles – reconstruction of original particle from the SM final states

NA62 Experiment can do both in two modes of operation: (i) kaon mode and (ii) beam-dump mode

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

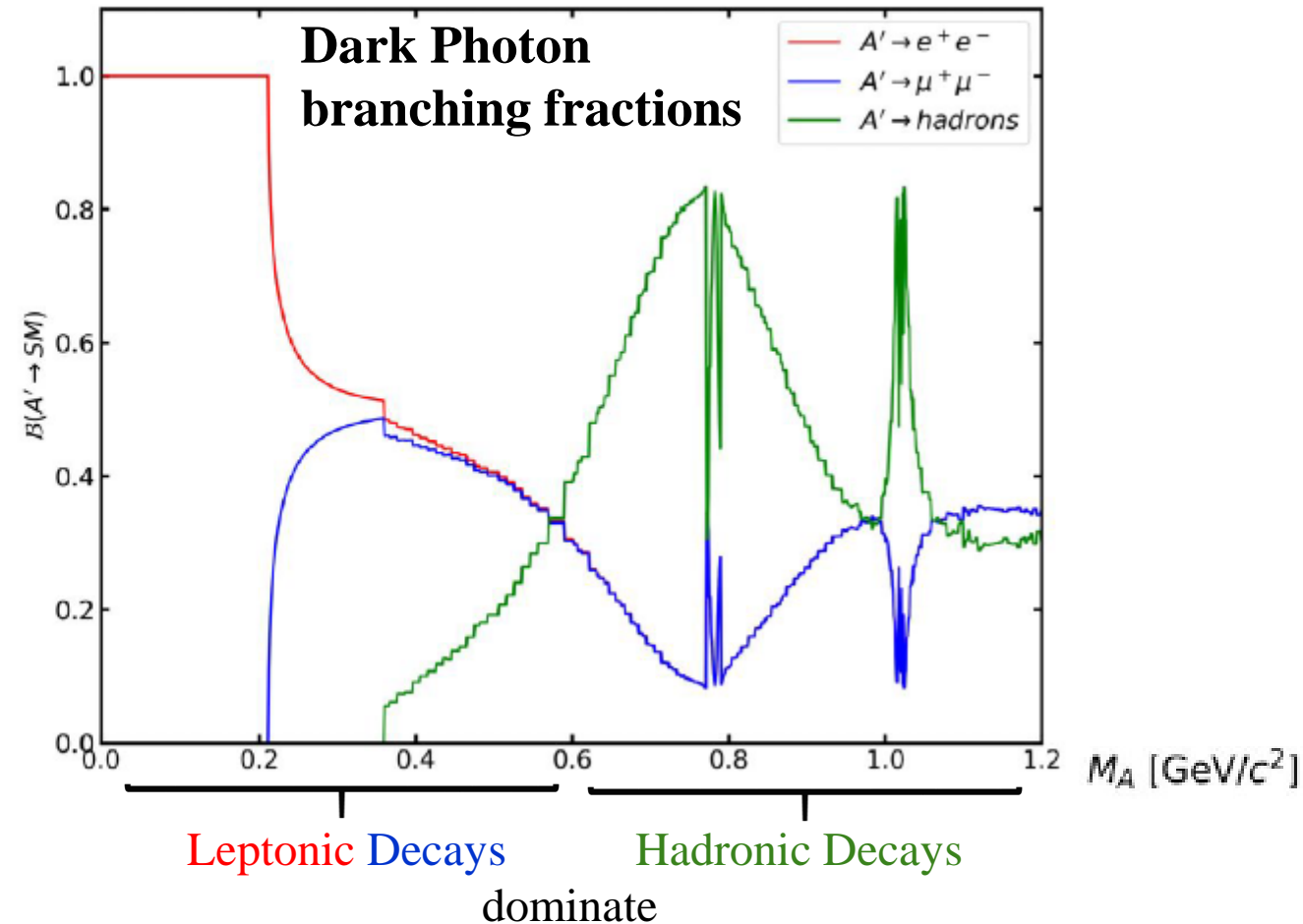
NA62 Dark Messenger searches – Monte Carlo simulations

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

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



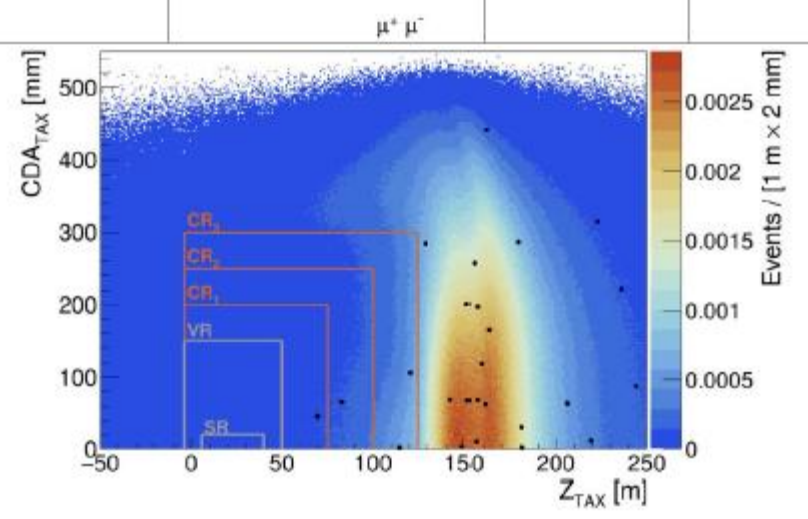
NA62 Dark Messenger searches – Background Determination

- **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

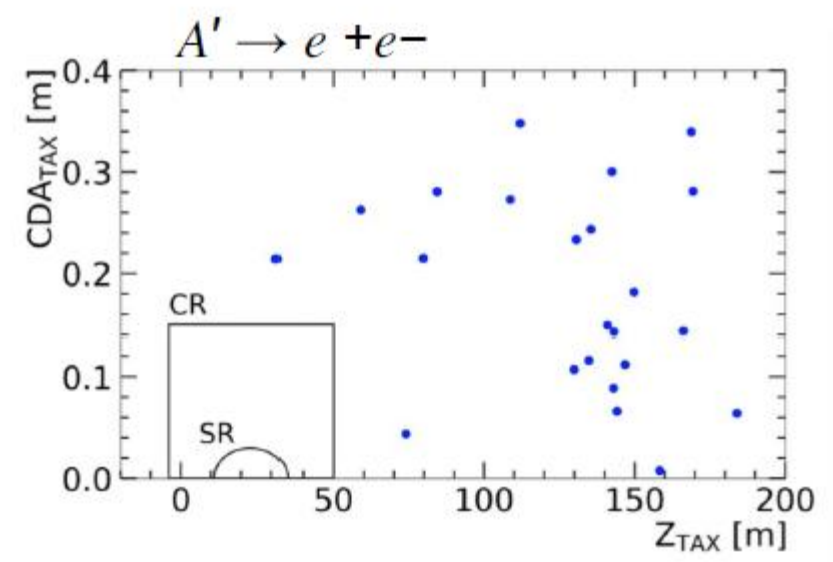
Background determination for $A' \rightarrow \ell\ell$

- 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



$$N_{bkg} \text{ SR} = 0.0094 - 0.009 + 0.049 \text{ @ 90\% CL}$$



NA62 Dark Messenger searches

Results for leptonic final states



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

NA62 Collaboration, *Search for dark photon decays to $\mu^+ \mu^-$ at NA62*, *JHEP* **09** (2023) 035.

NA62 Collaboration, *Search for hadronic decays of feebly-interacting particles at NA62*, *Eur. Phys. J C* (2025) 85:571.

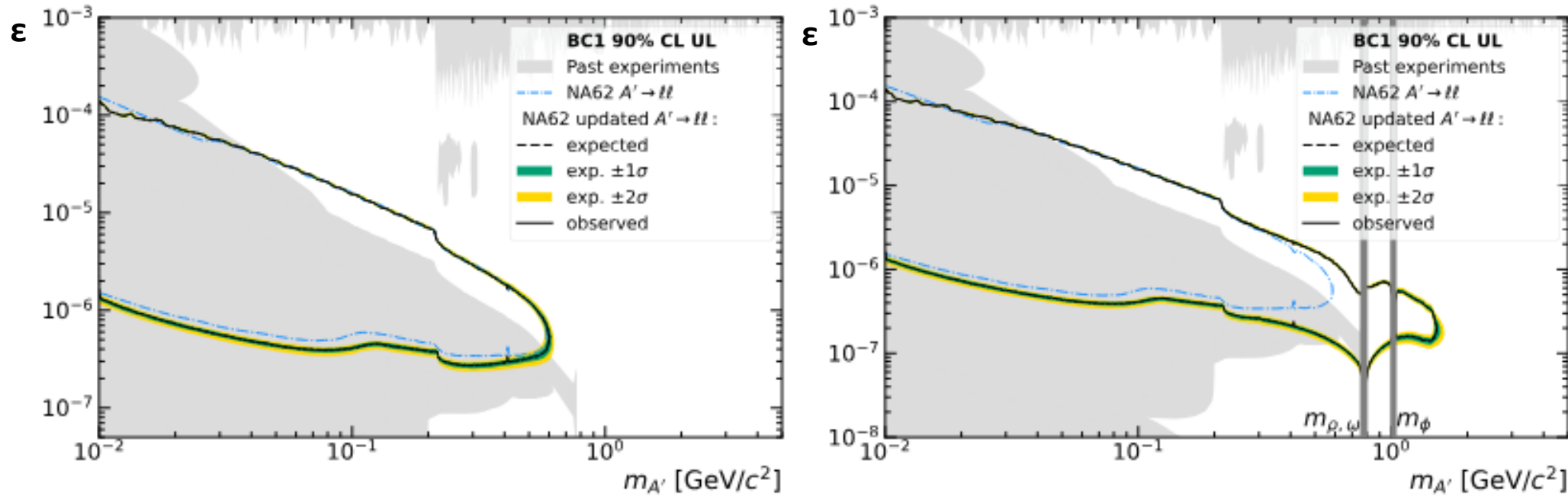


Fig. 10 The observed 90% CL exclusion contours in the plane $(m_{A'}, \epsilon)$ in *BC1* benchmark case for di-lepton final states together with the expected $\pm 1\sigma$ and $\pm 2\sigma$ bands (theory uncertainty not included) with

updated light meson spectra only (left) and with mixing production and time-like form factor for bremsstrahlung production (right). The exclusion contour obtained in [4] is displayed as a dash-dotted blue line

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

NA62 Dark Messenger searches – hh final state studies



- In a model-independent approach
 $BR_{X \rightarrow \pi^+ \pi^-} = 1$,
 $N_{\text{exp}}(M_X, \Gamma_X) =$
 $N_{\text{POT}} \chi_{pp \rightarrow X}(C_{\text{ref}}) P_{\text{rd}} A_{\text{acc}} A_{\text{trig}}$

- $\chi_{pp \rightarrow X}(C_{\text{ref}})$: messenger prod. probability for ref. coupling
- P_{rd} : probability to reach NA62 FV and decay therein
- $A_{\text{acc}} A_{\text{trig}}$: signal selection and trigger efficiencies

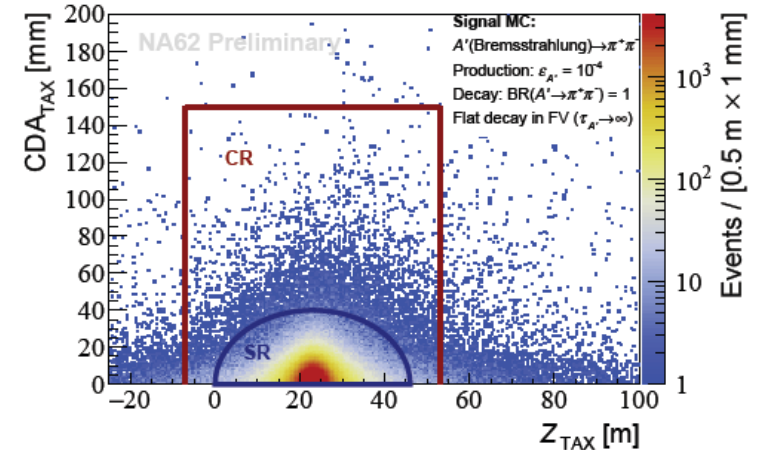


Figure: $A' \rightarrow \pi^+ \pi^-$ MC: control (CR) and signal (SR) region

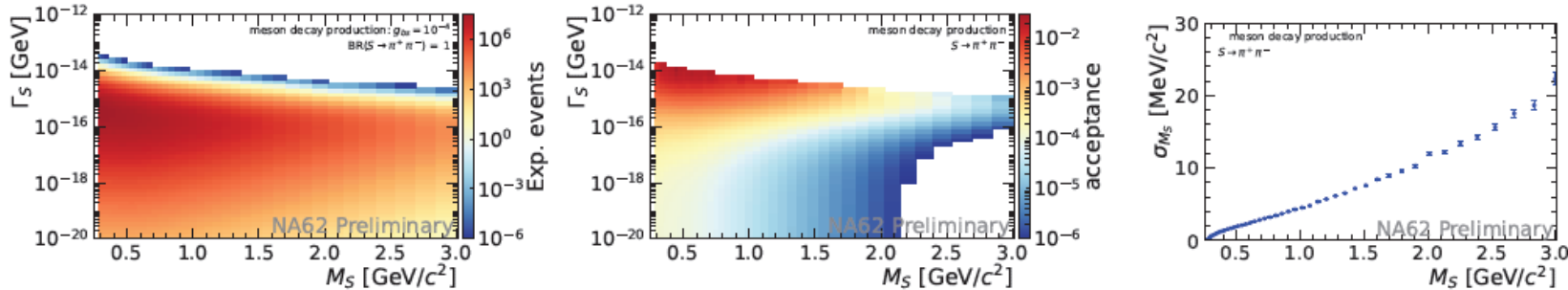


Figure: Left: expected number of $S \rightarrow \pi^+ \pi^-$ selected events, for $g_{b_s} = 10^{-4}$, $BR = 1$. Center: selection acceptance given a messenger decay in the FV. Right: Mass resolution of the reconstructed messenger.

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	$N_{\text{exp,CR}} \pm \delta N_{\text{exp,CR}}$	$N_{\text{exp,SR}} \pm \delta N_{\text{exp,SR}}$
$\pi^+\pi^-$	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 $N_{\text{POTs}} = 1.4 \times 10^{17}$ but also in the future full **Run 2 dataset** of $N_{\text{POTs}} = 10^{18}$

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	$N_{\text{exp,CR}} \pm \delta N_{\text{exp,CR}}$	$N_{\text{exp,SR}} \pm \delta N_{\text{exp,SR}}$	$N_{\text{obs,SR}}^{p>5\sigma}$	$N_{\text{obs,SR+CR}}^{p>5\sigma}$
$\pi^+\pi^-$	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 $N_{\text{POT}} = 1.4 \times 10^{17}$,
but also for the complete Run 2 in the future for $N_{\text{POT}} = 10^{18}$.

NA62 Dark Messenger searches – Results for both hadronic and leptonic final states

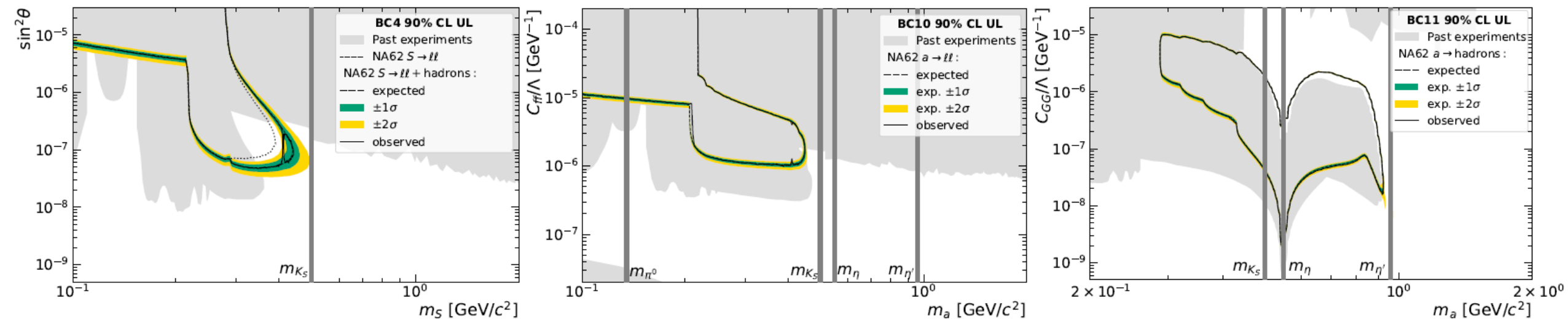
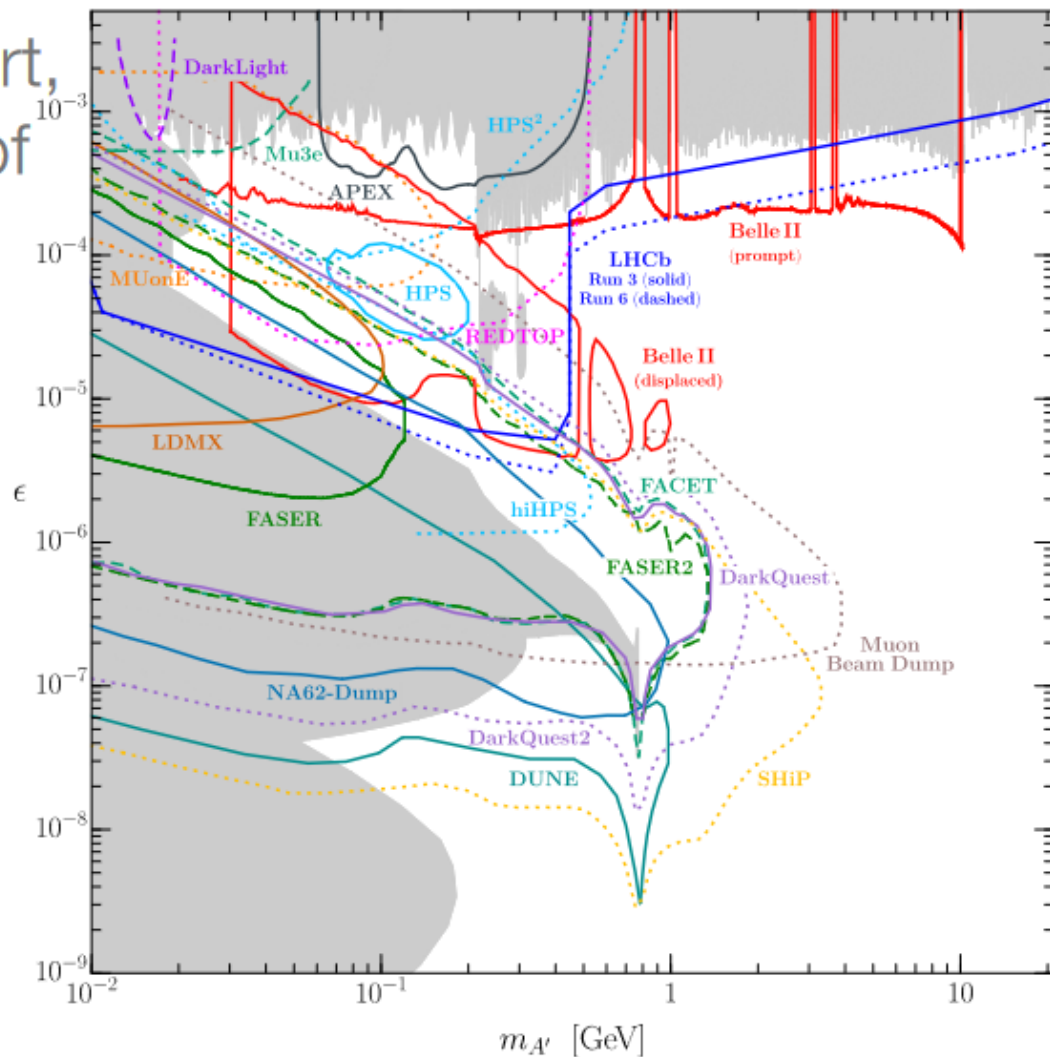


Figure: The observed 90% CL exclusion contours in BC4 (left), BC10 (center) and BC11 (right) benchmarks together with the expected $\pm 1\sigma$ and $\pm 2\sigma$ bands (theory uncertainty not included).

Searching for the dark sector in the laboratory

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

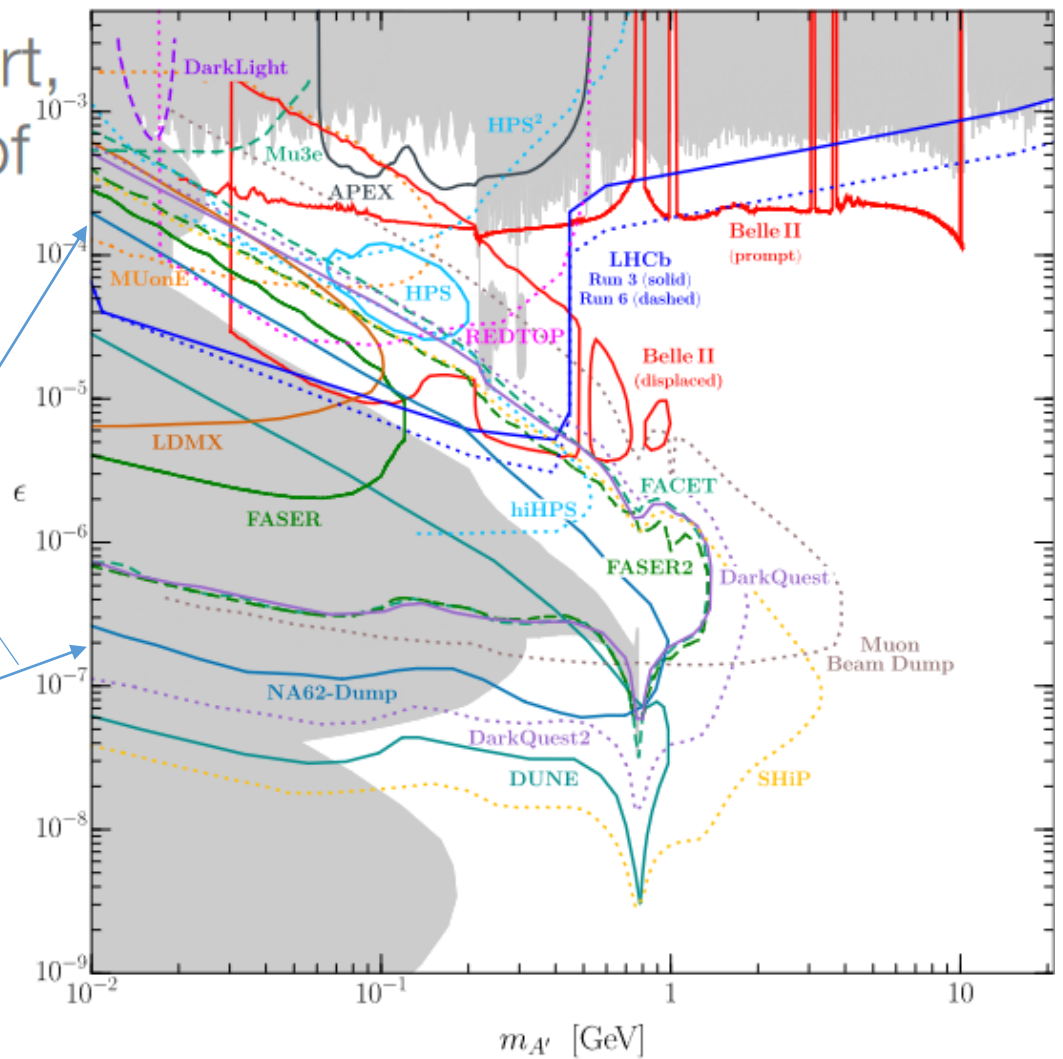


Batell, Blinov, Hearty, McGehee,
[arXiv 2207.06905](https://arxiv.org/abs/2207.06905) (2022)

Chris Hearty DISCRETE Dec'24

Searching for the dark sector in the laboratory

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



Chris Hearty DISCRETE Dec'24

NA62 in Dump Mode

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

NA62 Axion-like particle (ALP) search in $K^+ \rightarrow \pi^+ a$, $a \rightarrow \gamma\gamma$

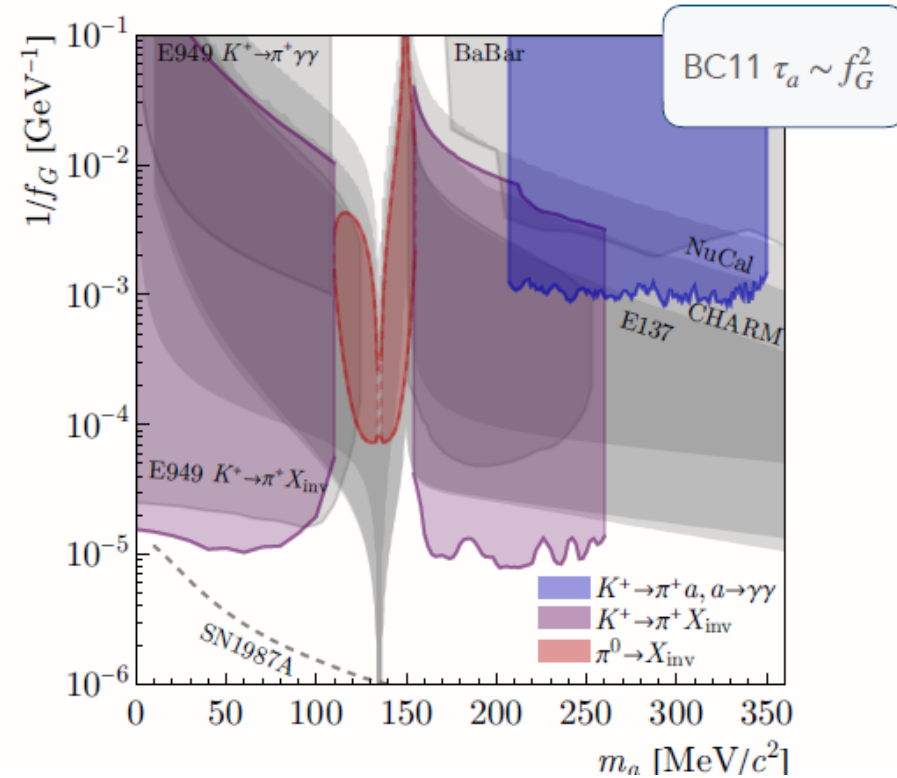
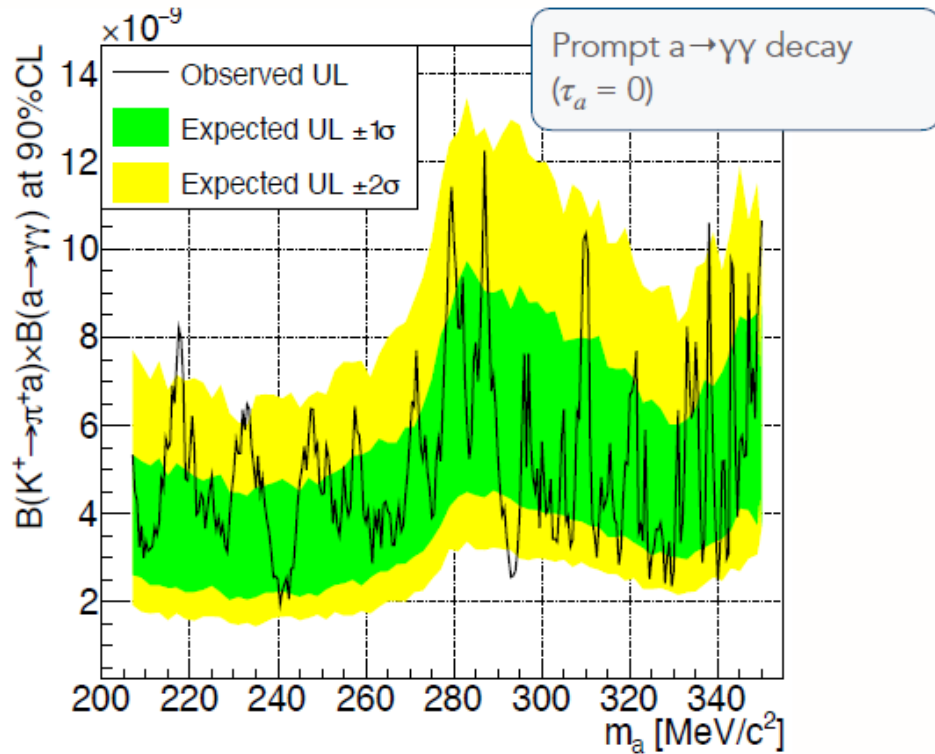
Results for photonic final states



NA62 Collaboration, *Phys.Lett B 850* (2024) 138513.

Peak search over $m_a = \sqrt{(P_K - P_\pi)^2}$ in the range 207-350 MeV/c² in steps of 0.5 MeV/c²

m_a resolution: from 2.0 MeV/c² to 0.2 MeV/c² across the search range

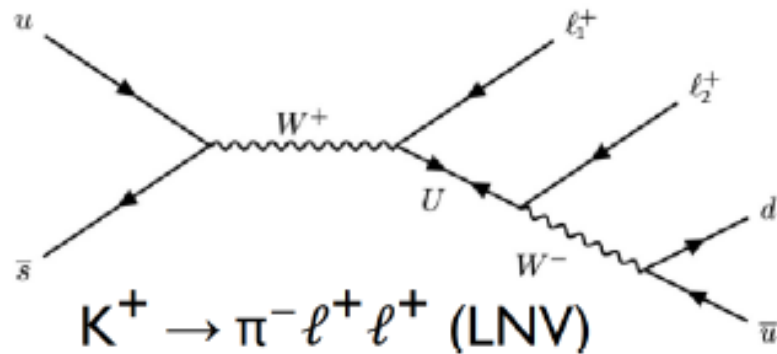


Searches for Lepton Flavor Violation in Kaon Decays

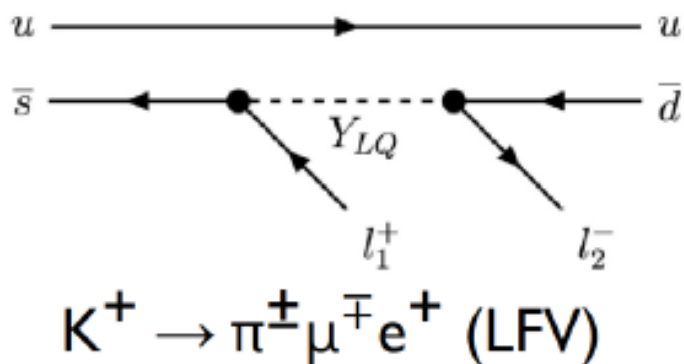
LF / LN are global symmetries in SM with $m_\nu=0$. LNV observed in ν oscillations.

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

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



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



Searches for Lepton Flavor Violation in Kaon Decays



NA62 Searches:

All Limits are at 90% C.L.

$$K^+ \rightarrow \mu^- \nu e^+ e^+$$

$$BF < 8.1 \times 10^{-11}$$

PLB 838 (2023) 137679

$$K^+ \rightarrow \pi^- e^+ e^+$$

$$BF < 5.3 \times 10^{-11}$$

PLB 830 (2022) 137172

$$K^+ \rightarrow \pi^- \pi^0 e^+ e^+$$

$$BF < 8.5 \times 10^{-10}$$

$$K^+ \rightarrow \pi^- \mu^+ \mu^+$$

$$BF < 4.2 \times 10^{-11}$$

PLB 797(2019) 134794

$$K^+ \rightarrow \pi^- \mu^+ e^+$$

$$BF < 4.2 \times 10^{-11}$$

$$K^+ \rightarrow \pi^+ \mu^- e^+$$

$$BF < 6.6 \times 10^{-11}$$

PRL 127(2021) 13, 131802

$$\pi^0 \rightarrow \mu^- e^+$$

$$BF < 3.2 \times 10^{-10}$$

$$K^+ \rightarrow \pi^0 \pi \mu e$$

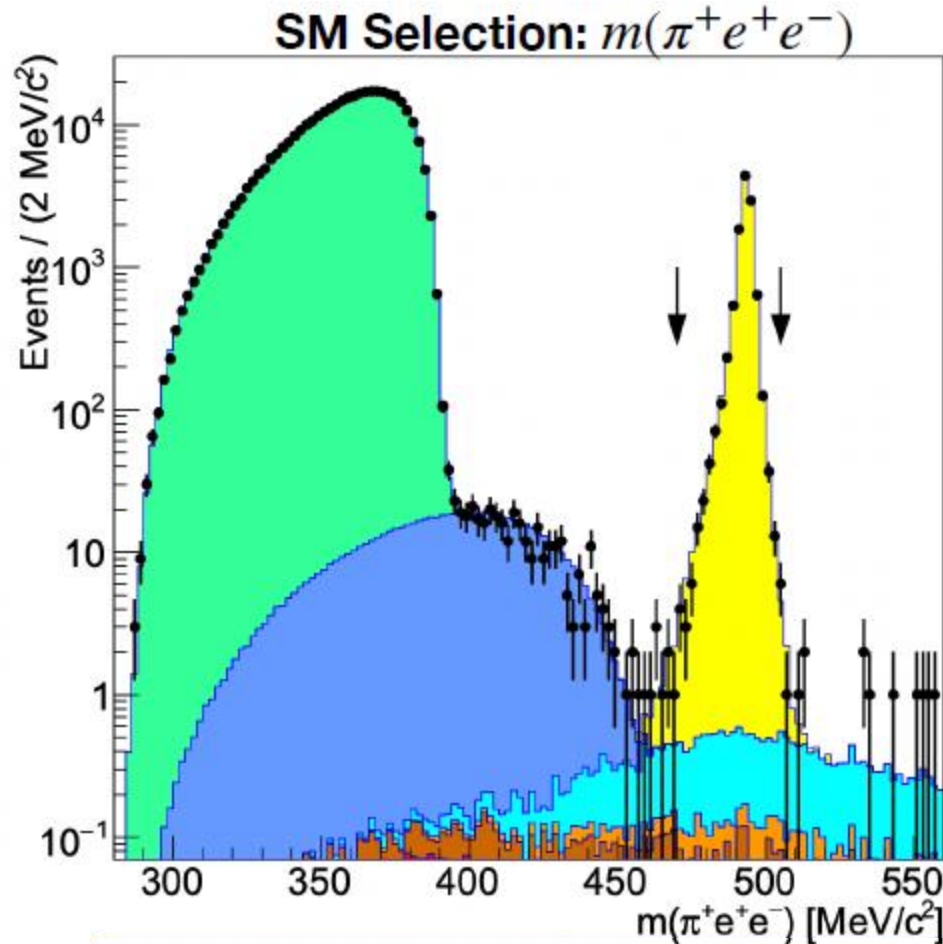
$$BF < 3-5 \times 10^{-10}$$

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

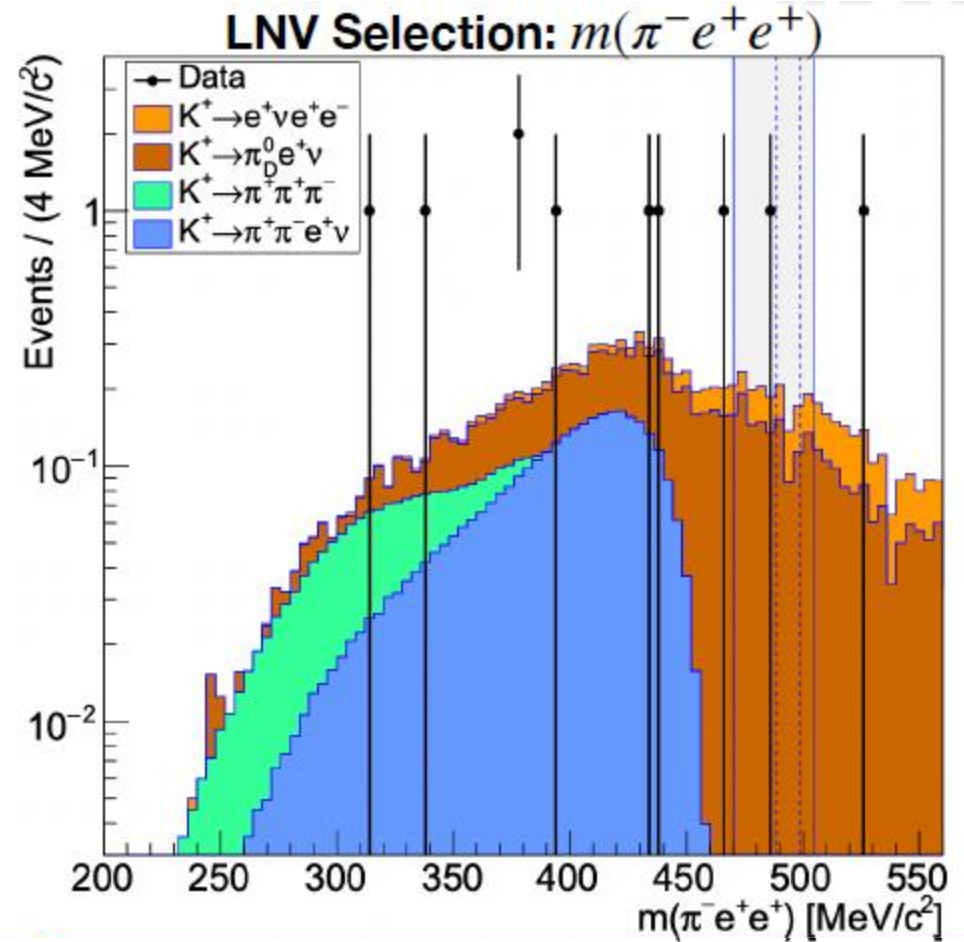
Searches for Lepton Flavor Violation in Kaon Decays

Search for $K^+ \rightarrow \pi^- e^+ e^+$ as an example

PLB 830 (2022) 137172



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

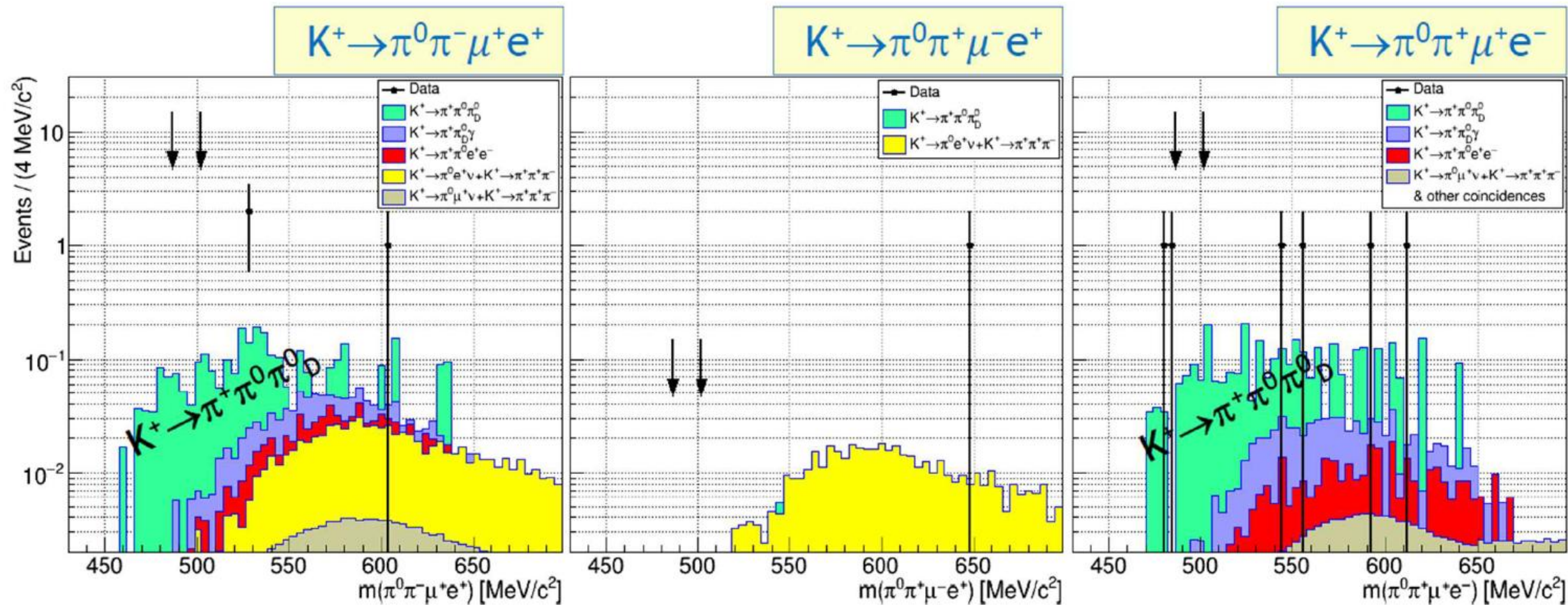


- Expected background = 0.43 ± 0.09
- Candidates observed: 0
- $\mathcal{B}(K^+ \rightarrow \pi^- e^+ e^+) < 5.3 \times 10^{-11}$ at 90 % CL

Searches for Lepton Flavor Violation in Kaon Decays

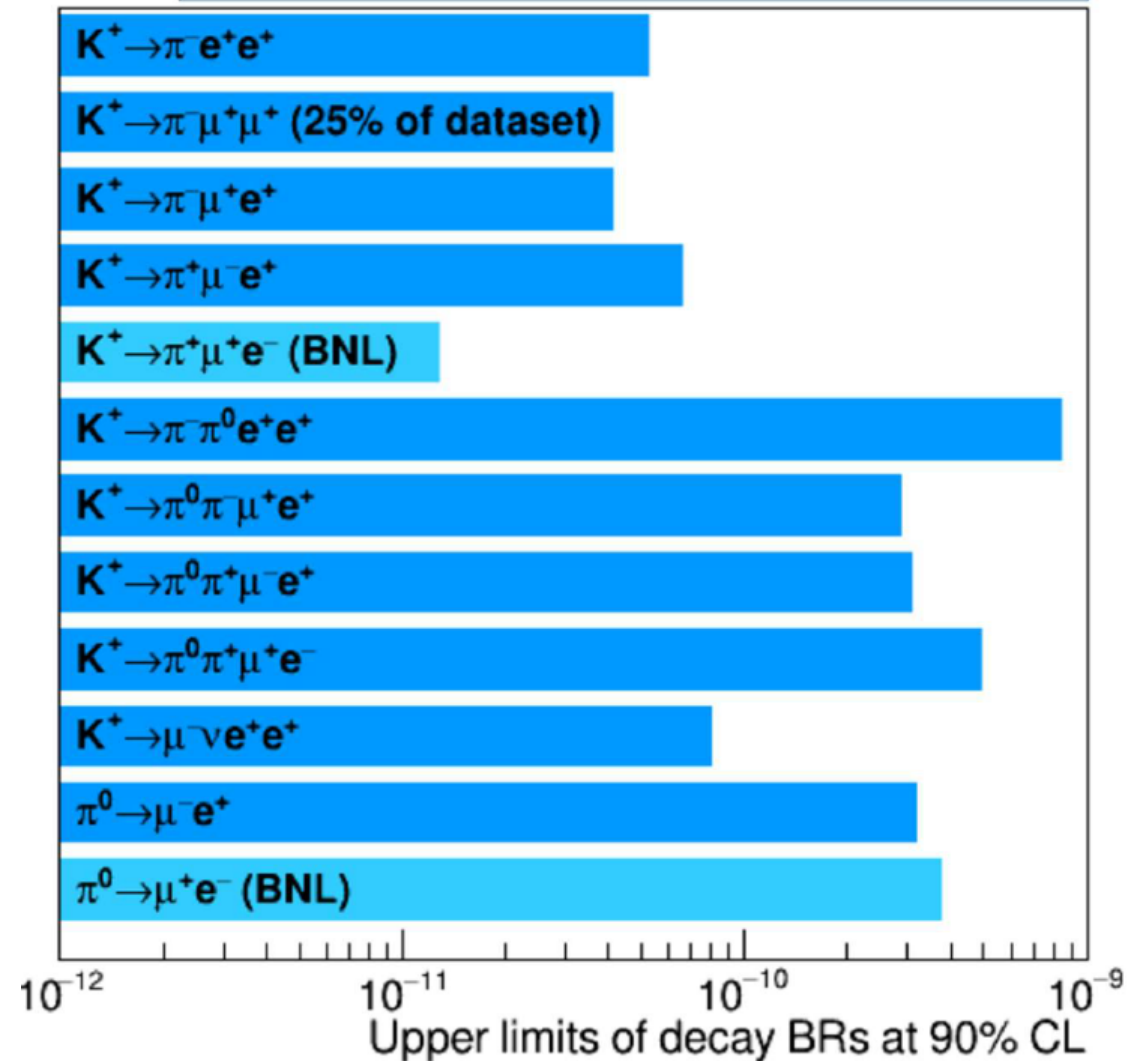
$K^+ \rightarrow \pi^0 \pi^- \mu^+ e^+$ as a recent example

BF $< 3-5 \times 10^{-10}$ to be published



Searches for Lepton Flavor Violation in Kaon Decays

LNV/LFV K^+ and π^0 decays, NA62 Run 1



Summary

The main goal of the NA62 Experiment remains the $\mathcal{B}(K^+ \rightarrow \pi^+ \nu \bar{\nu})$ measurement, however much broader new physics search has been performed

Blind searches for a **dark messenger particle decaying into $e\bar{e}$, $\mu\bar{\mu}$, hadrons and $\gamma\gamma$** 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 $(1.43 \pm 0.28) \times 10^{17}$ POTs 90% CL upper limits have been derived, **excluding new regions** in the parameter space shown here in respective plots

Searches for other (e.g., semi-leptonic, 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 end of next year

NA62 searches for **Lepton Flavor Violation** in Kaon decays have been ongoing, reaching down to the 10^{-17} BR level. The current NA62 Run will last by Fall 2026.