New physics searches at the NA62 experiment

MAX-PLANCK-INSTITUT FÜR PHYSIK

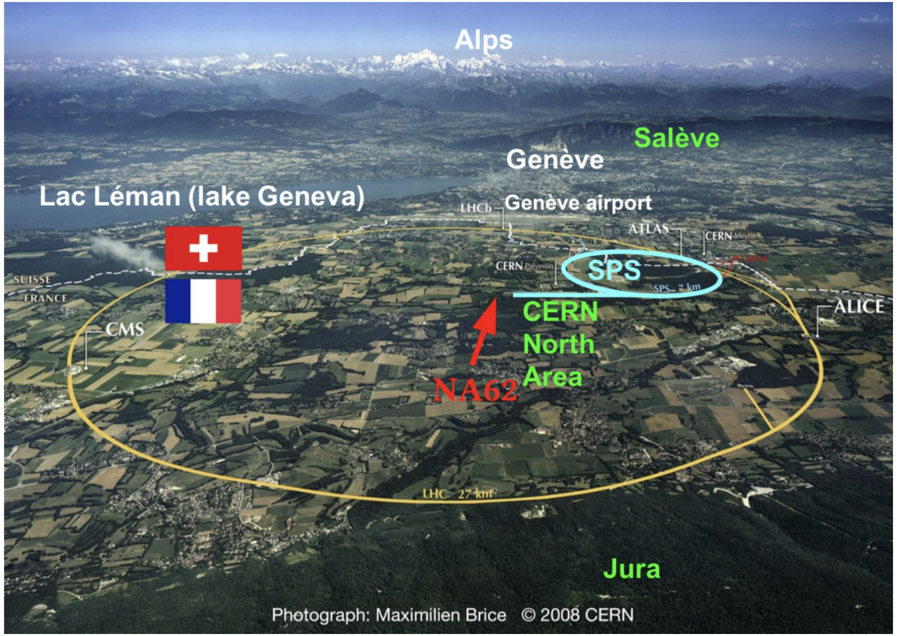
NA62

TeV Particle Astrophysics
TeVPA
Valencia 2025

European Research Council
Established by the European Commission

Babette Döbrich
(Max Planck Institute for Physics)
On behalf of the NA62 collaboration

NA62 @CERN/Prevessin



- Fixed target experiment at CERN's North Area (NA) with ~200 participants
- **Main goal:** measure branching ratio

$$K^+ \to \pi^+ \nu \bar{\nu}$$

- Highly suppressed & very precisely predicted in theory, Mainly parametric uncertainty (choice of CKM)

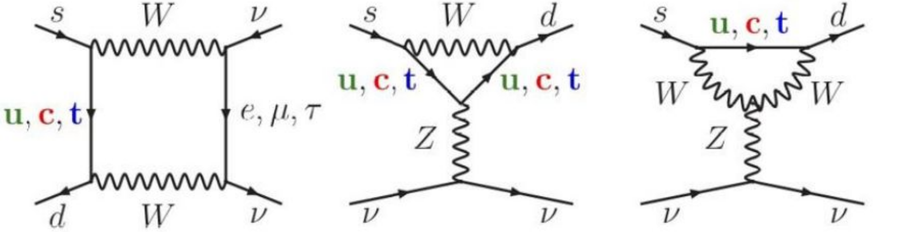
SM [D'Ambrosio et al. JHEP 09 (2022) 148

$$BR(K^+ \to \pi^+ \nu \nu)_{SM} = (8.60 \pm 0.42) \times 10^{-11}$$

and Buras et al. EPJC 82 (2022) 7, 615**]**

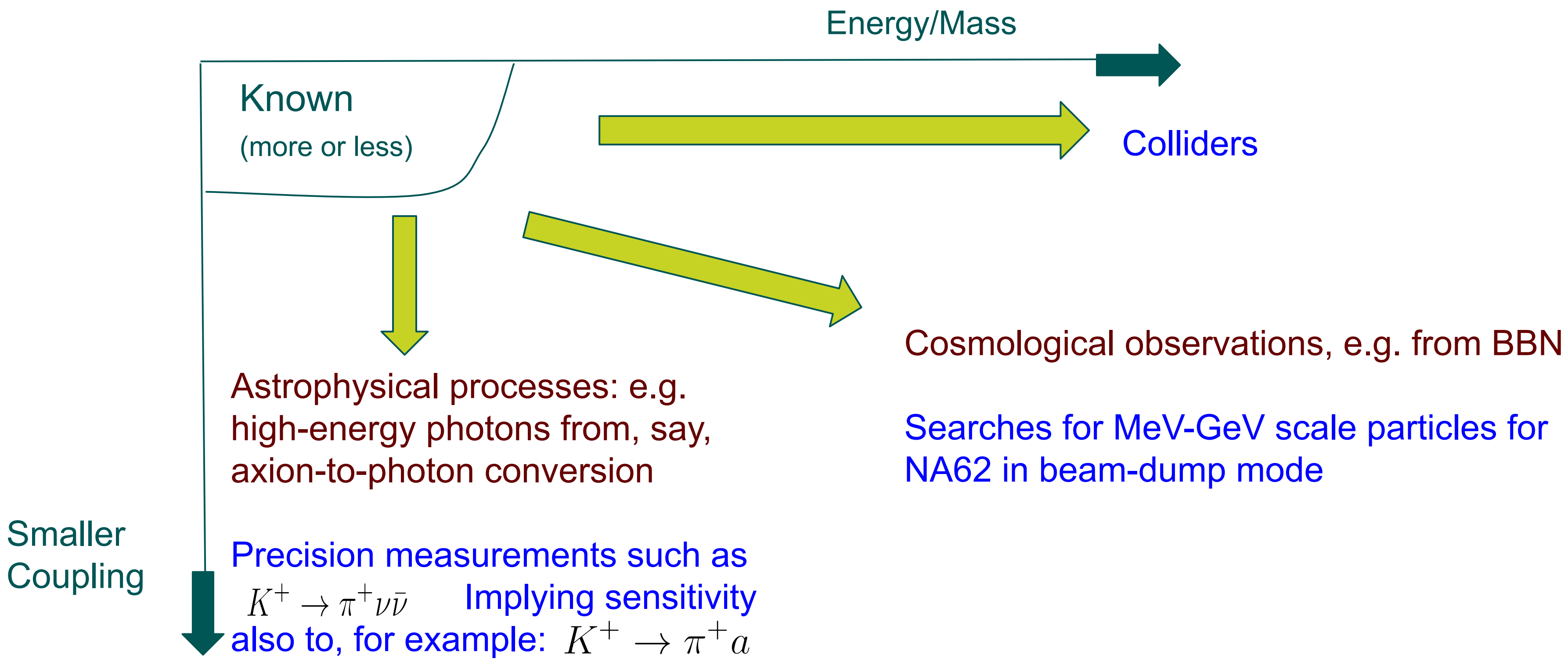
$$BR(K^+ \to \pi^+ \nu \nu)_{SM} = (7.86 \pm 0.61) \times 10^{-11}$$

SM: Z-penguin & box diagrams



TeVPA connections to particle physics (simplified picture):

where is new physics such as Dark Matter or other new particles?

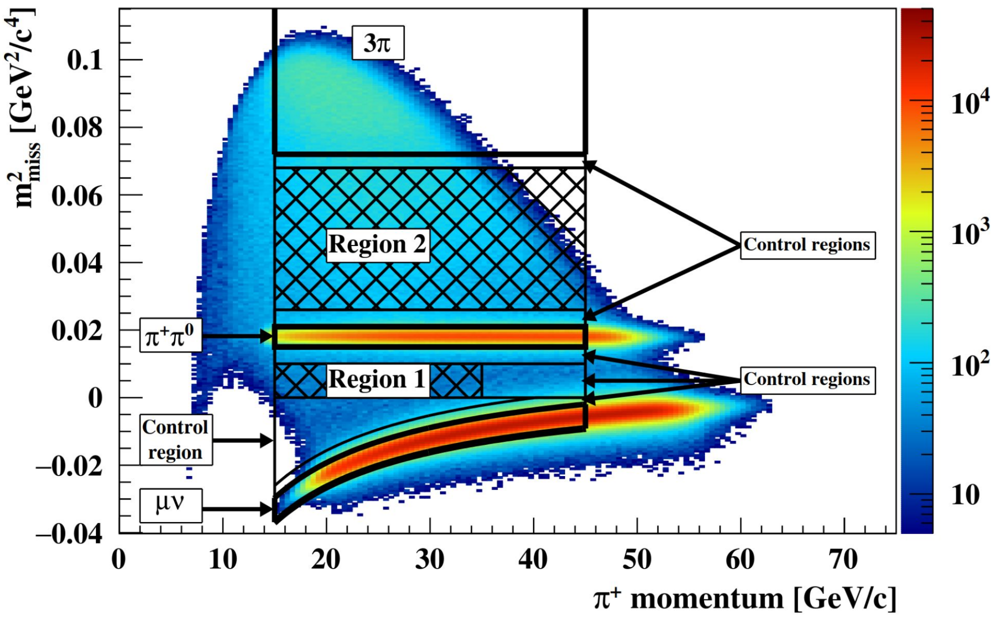


How to precisely measure

$$K^+ \rightarrow \pi^+ \nu \bar{\nu}$$

Overall strategy

- Tag Kaon and measure its momentum
- Identify Pion and measure momentum
- Match Kaon & Pion in time & space
- Determine $m^2_{miss} = (p_K - p_\pi)^2$
- Reject ANY additional activity!

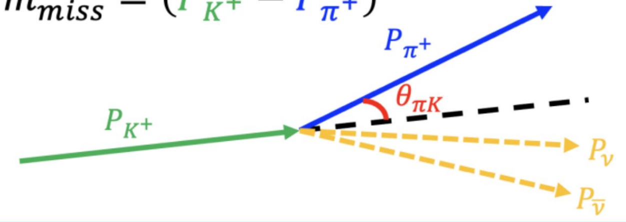


[JHEP06 (2021) 093]

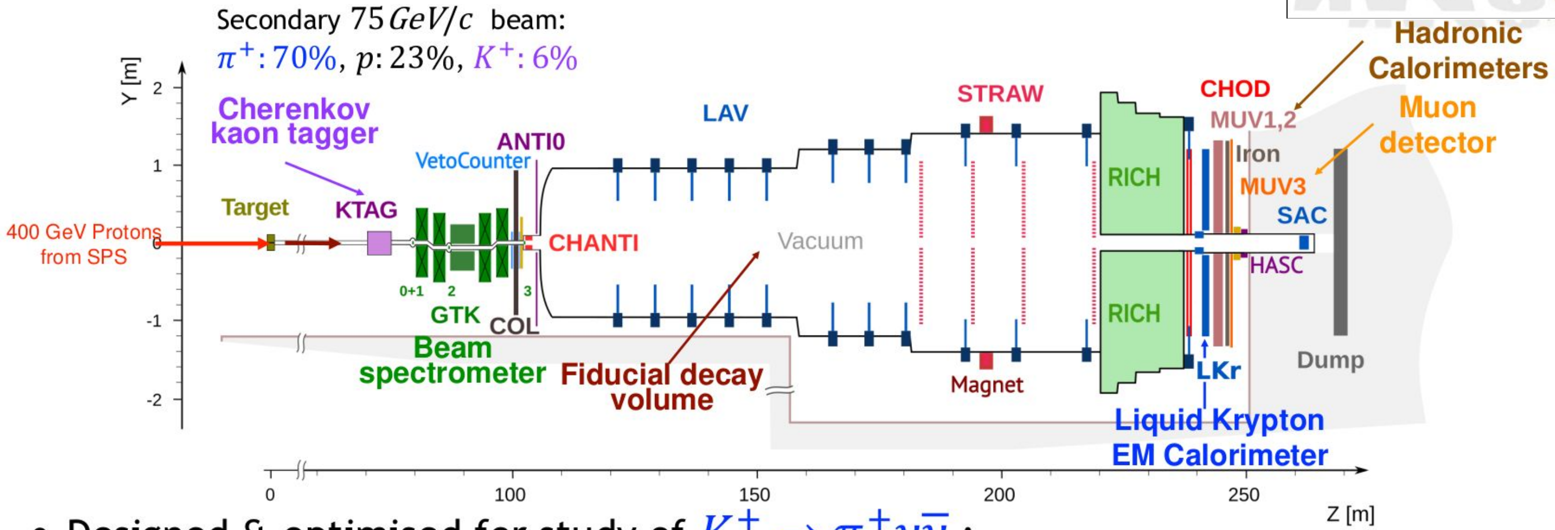
What it takes

- O(100)ps resolution timing between detectors!
- $> 10^7$ in photon and muon rejection
- $\mathcal{O}(10^4)$ background suppression from kinematics

$$m^2_{miss} = (P_{K^+} - P_{\pi^+})^2$$



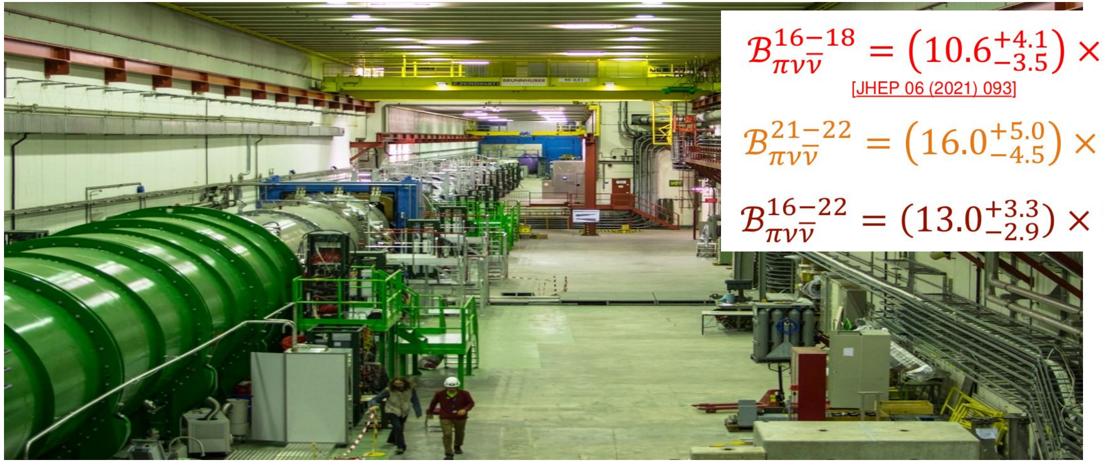
NA62 beamline & detector [JINST 12 (2017) 05, P05025]



- Designed & optimised for study of $K^+ \to \pi^+ \nu\bar{\nu}$:
  - **Particle tracking:** beam particle (GTK) & downstream tracks (STRAW)
  - **PID:** K^+ - KTAG, π^+ - RICH, Calorimeters (LKr, MUV1,2), MUV3 (μ detector)
  - **Comprehensive veto systems:** CHANTI (beam interactions), LAV,LKr,IRC,SAC (γ)

    + new additions since LS2: VetoCounter, ANTI0, HASC2

Timing: CHOD, RICH KTAG

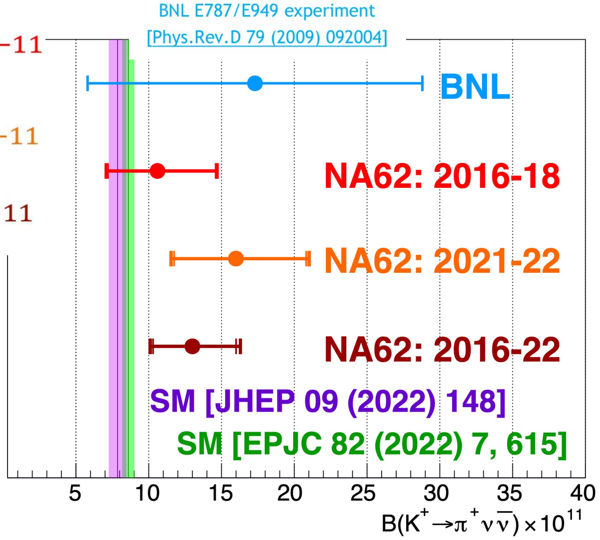


$$\mathcal{B}_{\pi\nu\bar{\nu}}^{16-18} = \left(10.6^{+4.1}_{-3.5}\right) \times 10^{-11}$$

[JHEP 06 (2021) 093]

$$\mathcal{B}_{\pi\nu\bar{\nu}}^{21-22} = \left(16.0^{+5.0}_{-4.5}\right) \times 10^{-11}$$

$$\mathcal{B}_{\pi\nu\bar{\nu}}^{16-22} = \left(13.0^{+3.3}_{-2.9}\right) \times 10^{-11}$$



2008 Approval
2009-2014 detector R&D & Installation

2008

2016

Run 1

Measurement of the very rare $K+ \to \pi+\nu\bar{\nu}$ decay

[JHEP 06 (2021) 093]

2018

LS2 Upgrades
E.g. additional vetos

2021

Run2

Data up to 2022: Observation
of the very rare $K+ \to \pi+\nu\bar{\nu}$ decay

[JHEP 02 (2025) 191]

2026

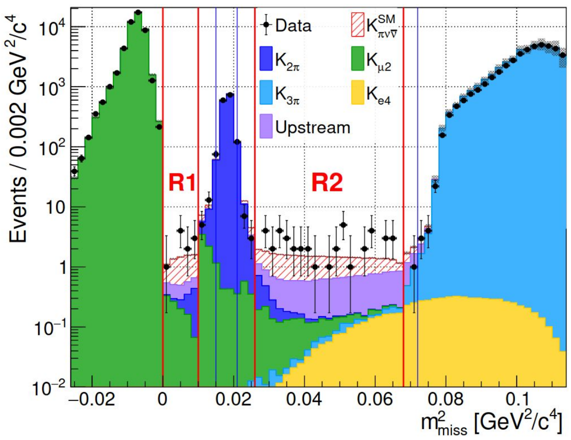
End of data-taking: Need full data-set to evaluate agreement or tension with Standard Model of current measurement

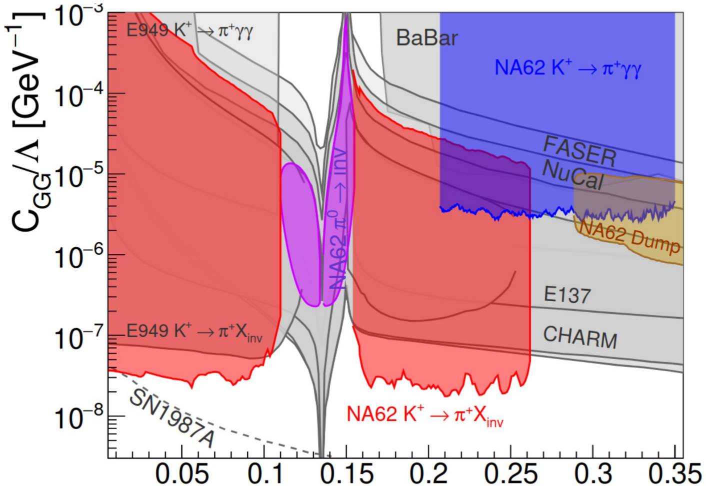
Sensitivity to new physics from Kaon decays (example)

- Measuring $K^+ \to \pi^+ \nu \bar{\nu}$ is also sensitive to the process $K^+ \to \pi^+ X_{inv}$
- In a concrete model (dubbed BC11 by CERN PBC),

  this could be an axion-like particle (pseudoscalar), coupled to gluons
- In this model, also several other NA62 measurements provide sensitivity, in this scenario through

  $$K^+ \to \pi^+ \gamma\gamma$$

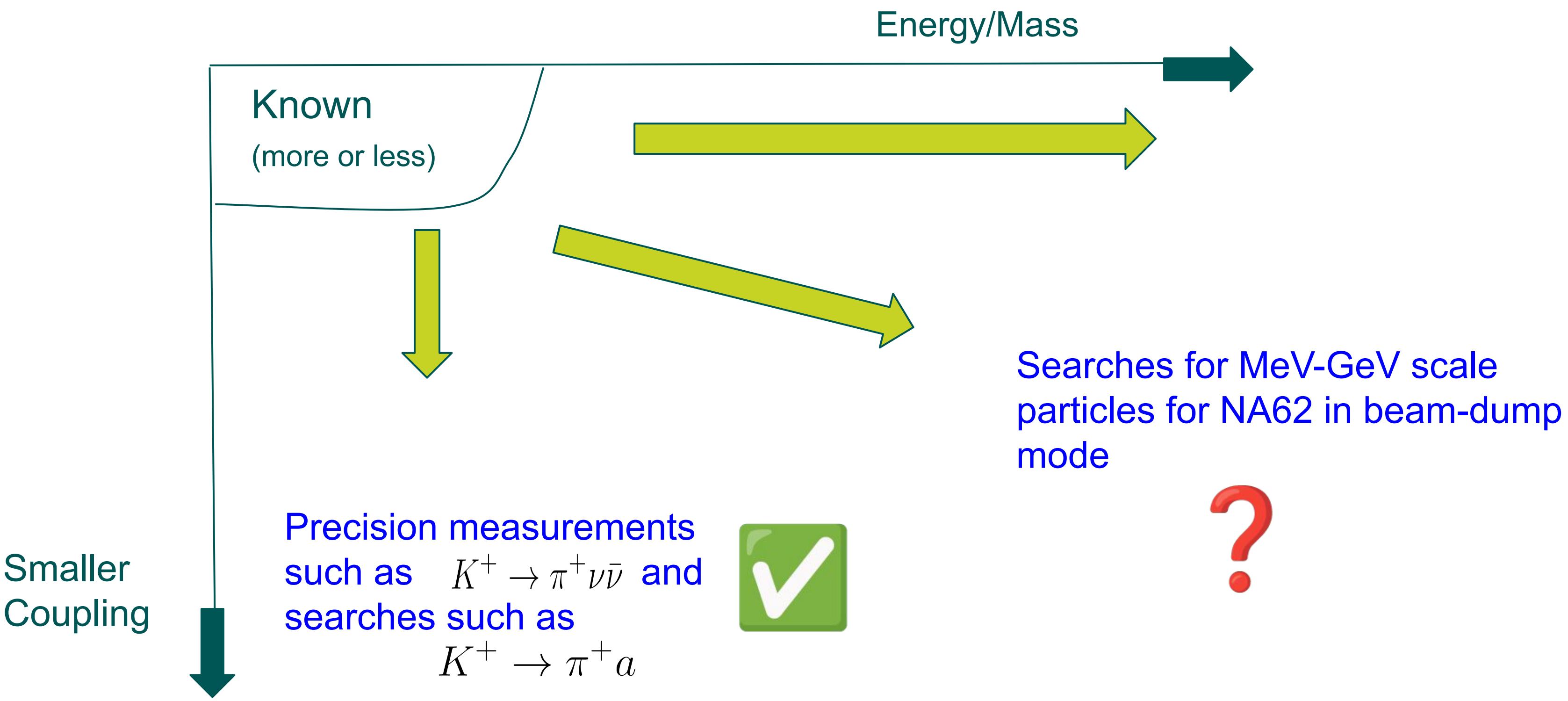




[2507.17286]

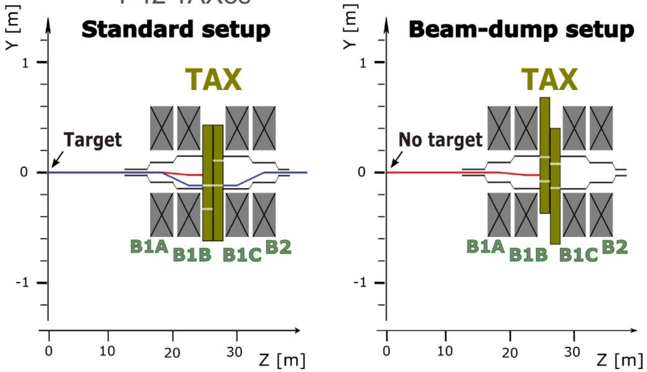
More generally, NA62 is sensitive to new physics in most Kaon and a number of pion decays!

Coming back to the below picture

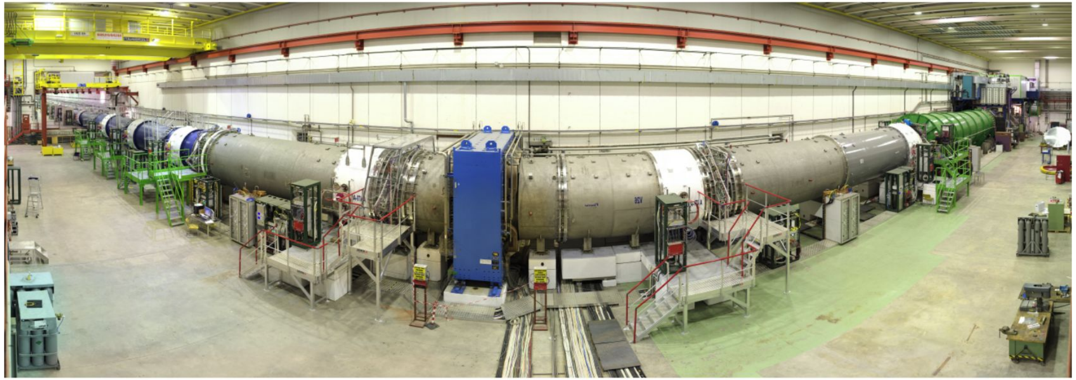


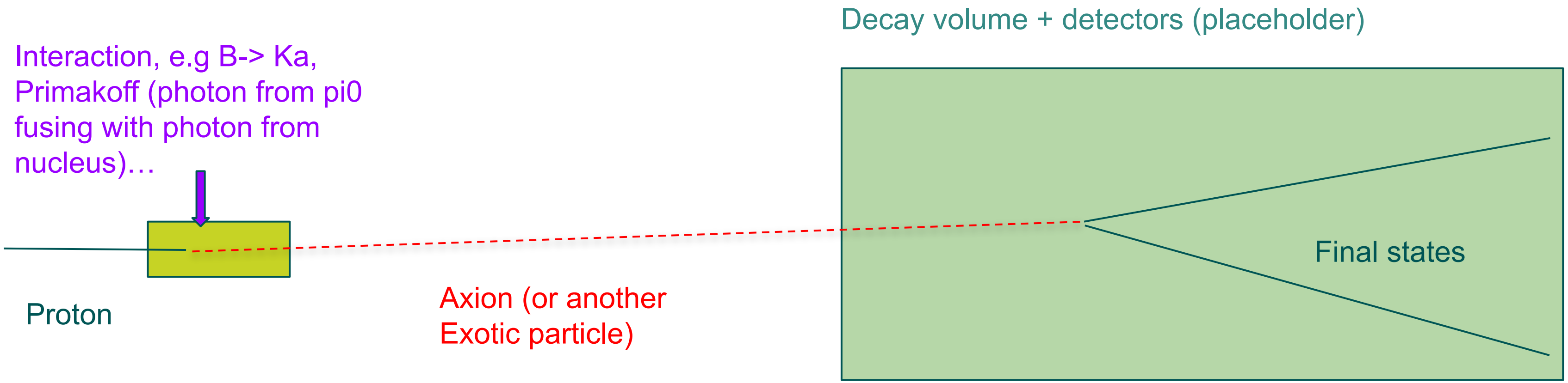
How to do that?

P42 TAXes

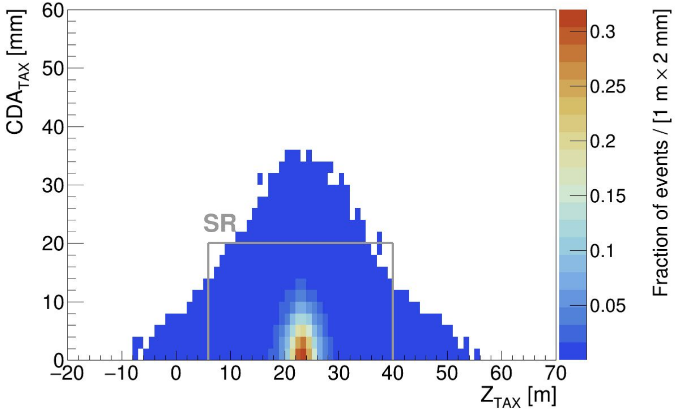


- Remove target in which Kaons are created
- Move collimators in `closed position’
- Magnet currents in `optimal sweeping’ configuration [Int.J.Mod.Phys.A 34 (2019) 36, 1942026]
- Dedicated trigger lines for beam-dump mode
- Sensitivity profits from large number of POT, high energy, short distance, large acceptance
- Including 2025, we have almost 10^{18} POT on tape, results shown in the following based on 1.4×10^{17} POT (2021 data only!)

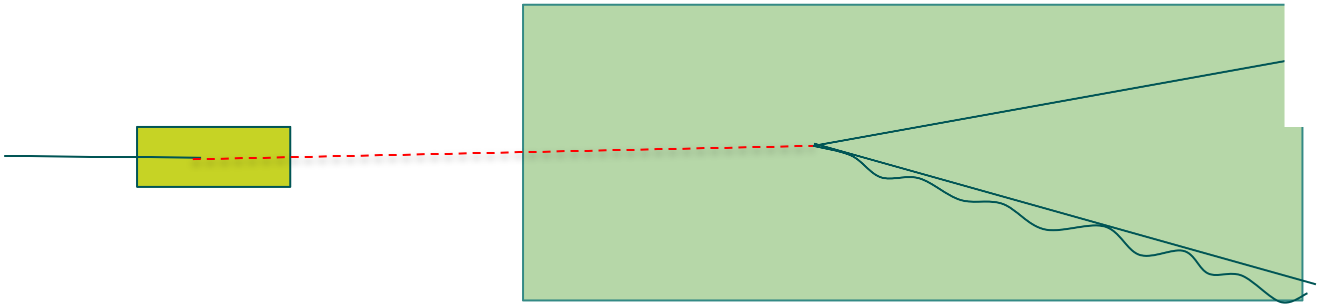


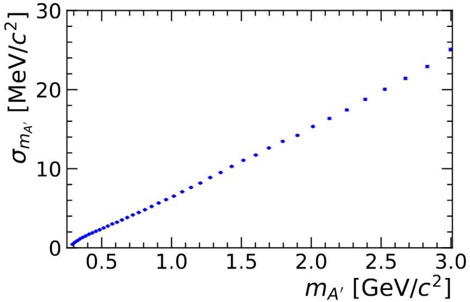


Example of Monte Carlo signal event distribution for exotic particle to di-muon final state



Completed searches in Beam-dump mode





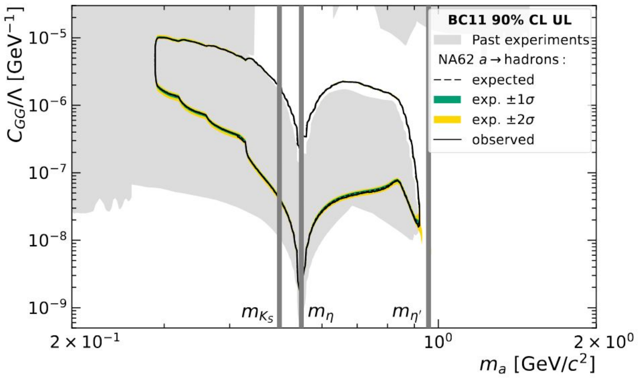
Mass resolution in reconstructed $\pi^+\pi^-$

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^-	$(4.7^{+15.7}_{-3.9}) \times 10^{-7}$	$(4.6^{+15.2}_{-3.8}) \times 10^{-7}$
$K^+K^-\pi^0$	$(1.6^{+3.2}_{-1.2}) \times 10^{-9}$	$(1.5^{+3.1}_{-1.2}) \times 10^{-9}$
$\mu^+\mu^-$	0.17 ± 0.02	0.016 ± 0.002
e^+e^-	$0.0097^{+0.049}_{-0.009}$	$0.0094^{+0.049}_{-0.009}$

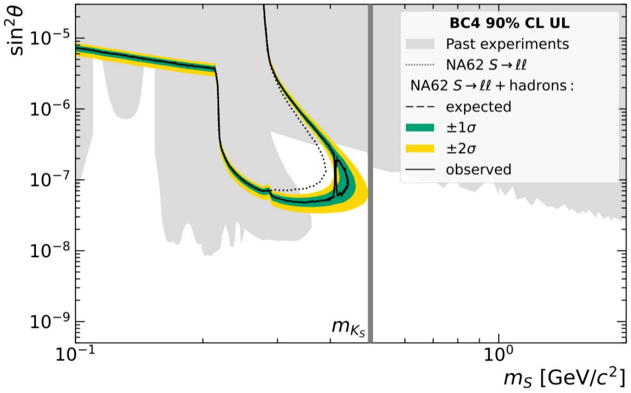
1. $\mu^+\mu^-$ JHEP 09 (2023) 035
2. e^+e^- Phys. Rev. Lett. 133 (2024) 111802
3. $\pi^+\pi^-, \pi^+\pi^-\gamma, \pi^+\pi^-\pi^0, \pi^+\pi^-\pi^0\pi^0, \pi^+\pi^-\eta, K^+K^-, K^+K^-\pi^0$
   Eur.Phys.J.C 85 (2025) 5, 571

No evidence of a New Physics signal is observed, excluding new regions of parameter spaces of multiple models.

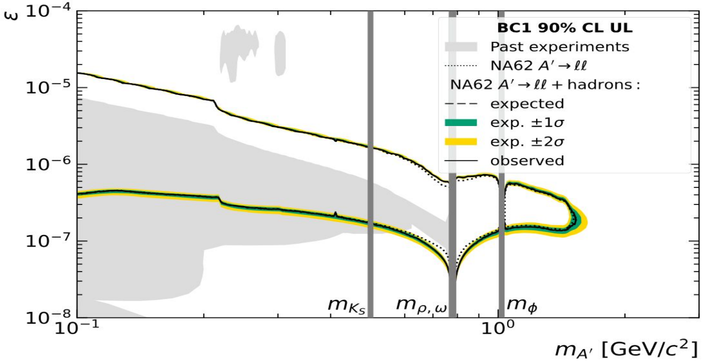
Summary of combined results in terms of PBC benchmark models:



BC11 (axion-like particle coupled to gluons)



BC4 (Higgs-like scalar)



BC1 (Dark Photon)

Significant improvement of state-of the art with only 10 days of data, no background limitation!

More data on-tape!

Summary

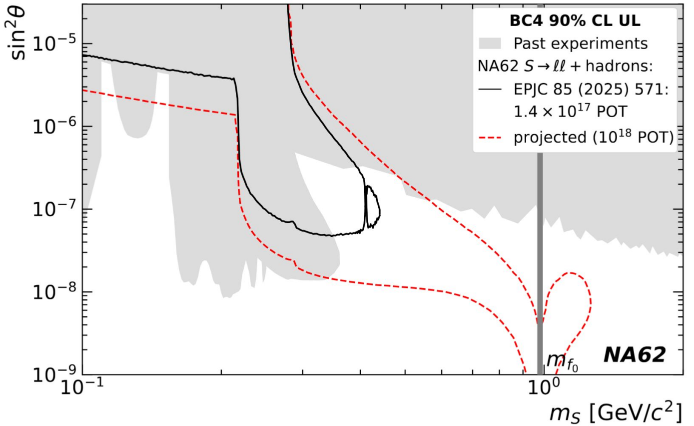
- The BR of $K^+ \to \pi^+ \nu\bar{\nu}$ becomes the smallest branching ratio measured with a signal significance above 5 σ.
- A plethora of measurements I could not talk about!
- The NA62 experiment provides a number of channels to search new-physics particles at the sub-eV to GeV scale, a number of results in exotics searches released

Data-taking ongoing until August 2026

Several measurements and search results not shown here or in the pipeline, would be happy to talk more about it throughout the conference

2024 NA62 collaboration week Birmingham

Vast parameter space still to be searched with data-on-tape

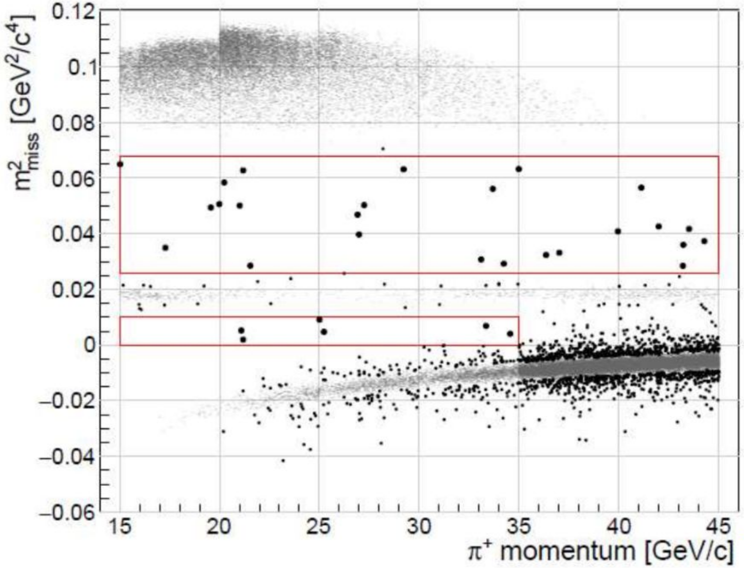


[NA62-PUB-2025-01]

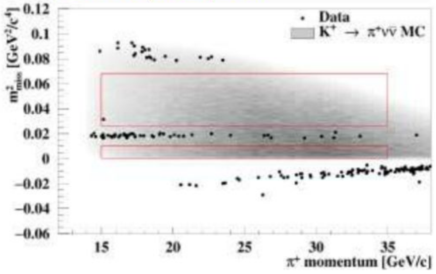
Start of backup

Results 21/22 and 2016-2018

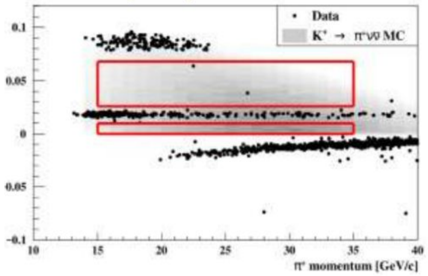
Single Event Sensitivity	$(0.84 \pm 0.03) \times 10^{-11}$
Expected background	$11.0^{+2.1}_{-1.9}$
Observed	**31**



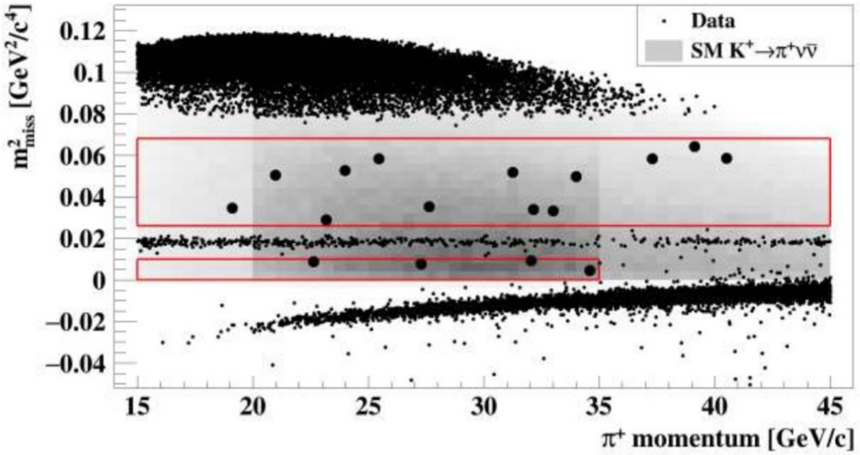
PLB 791 (2019) 156



JHEP 11 (2020) 042



JHEP 06 (2021) 093



The axion(-like-particle): prime example for a weakly interacting particle

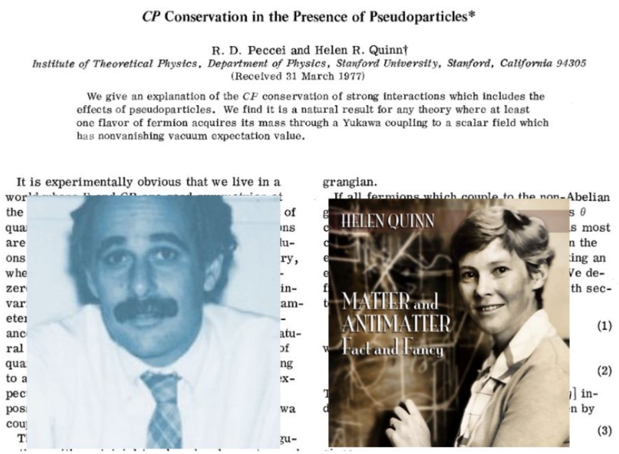
- "Vanilla axion": solve the strong CP problem + DM candidate
- QCD vacuum allows for a CP violating term to which one has topological + EW contribution
- Physical observable: Neutron EDM

Naively $e/2m_n \sim 10^{-14}$ e cm

Measured $|d_n| < 10^{-26}$ e cm

→ fine-tuning $\theta < 10^{-10}$

This can be considered a problem, unless θ is related to a dynamical field, the axion


CP Conservation in the Presence of Pseudoparticles*

R. D. Peccei and Helen R. Quinn†
Institute of Theoretical Physics, Department of Physics, Stanford University, Stanford, California 94305
(Received 31 March 1977)

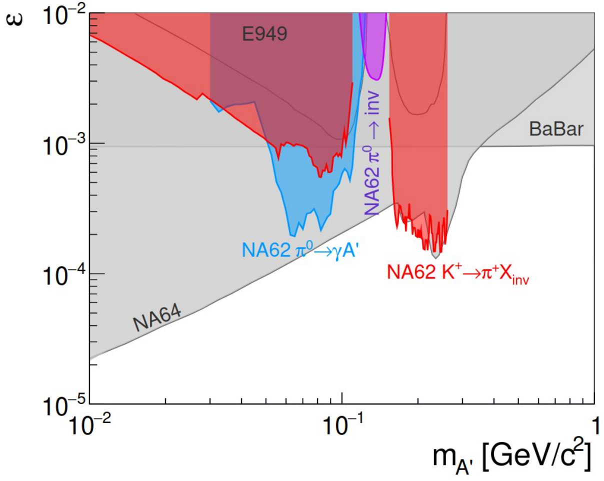
We give an explanation of the *CP* conservation of strong interactions which includes the effects of pseudoparticles. We find it is a natural result for any theory where at least one flavor of fermion acquires its mass through a Yukawa coupling to a scalar field which has nonvanishing vacuum expectation value.

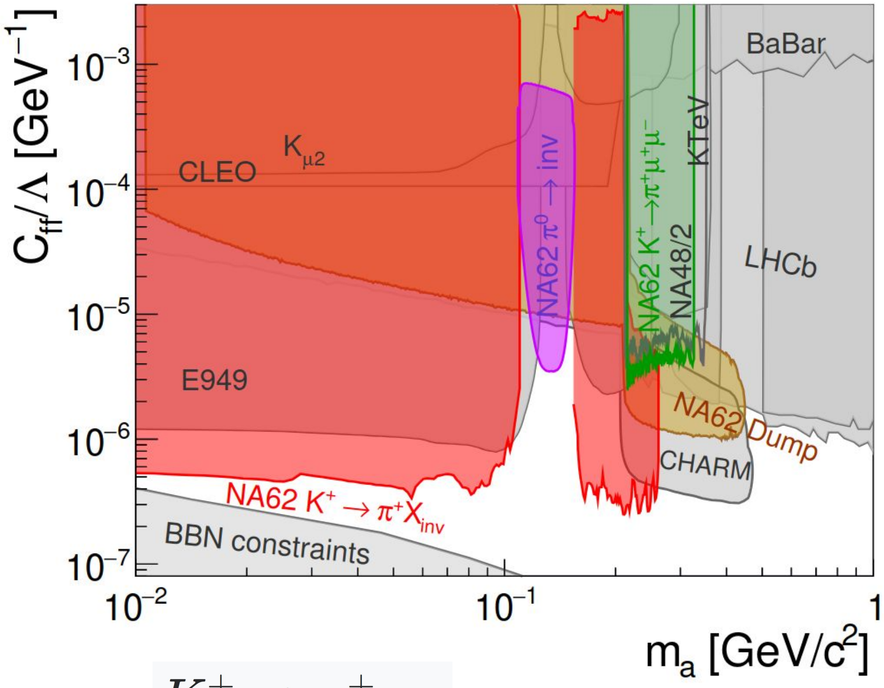
It is experimentally obvious that we live in a

grangian.

Sensitivity to new physics from Kaon decays (more plots)

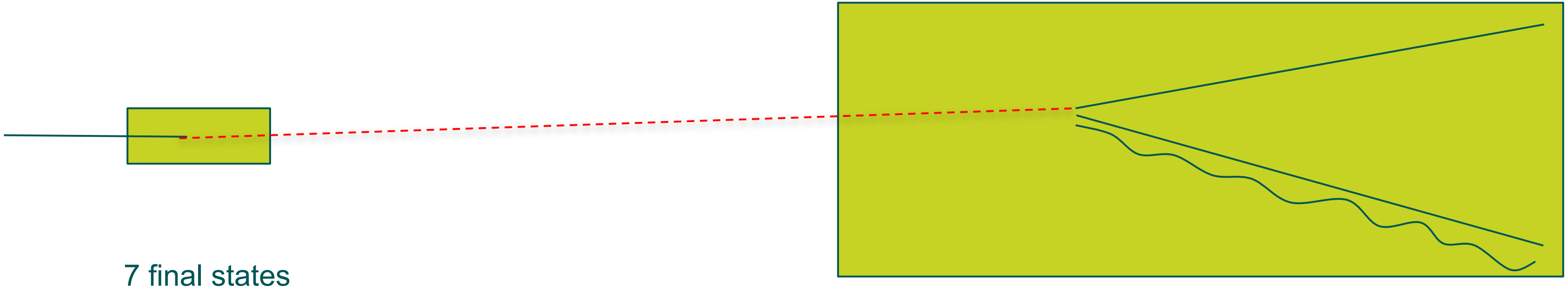
Benchmark	BSM particle (X)	Type	Coupling to SM	Search
BC1	dark photon (A')	vector	ε	$\mu^+\mu^-$
BC2	dark photon (A')	vector	ε	invisible
BC4	dark scalar (S)	scalar	θ	invisible, $\mu^+\mu^-$
BC4-inv	dark scalar (S)	scalar	θ	invisible
BC10	axion-like particle (a)	pseudoscalar	C_{ff} (to fermions)	invisible, $\mu^+\mu^-$
BC10-inv	axion-like particle (a)	pseudoscalar	C_{ff} (to fermions)	invisible
BC11	axion-like particle (a)	pseudoscalar	C_{GG} (to gluons)	invisible, $\gamma\gamma$





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

Completed searches in Beam-dump mode (2021 data) [2502.04241]



7 final states

$$\pi^+\pi^-, \pi^+\pi^-\gamma, \pi^+\pi^-\pi^0, \pi^+\pi^-\pi^0\pi^0, \pi^+\pi^-\eta, K^+K^-, K^+K^-\pi^0$$

- Upgraded PID (NN) + Refined box-opening strategy (from more complicated to simpler topologies)
- Low Background from "beam Kaons"
- **No data events observed in the control and signal regions -> again, set limits in different NP scenarios**

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	$\pi^+\pi^-\gamma$
		$\pi^+\pi^-\pi^0$
		$\pi^+\pi^-\pi^0\pi^0$
		$\pi^+\pi^-\eta$
		$K^+K^-\pi^0$