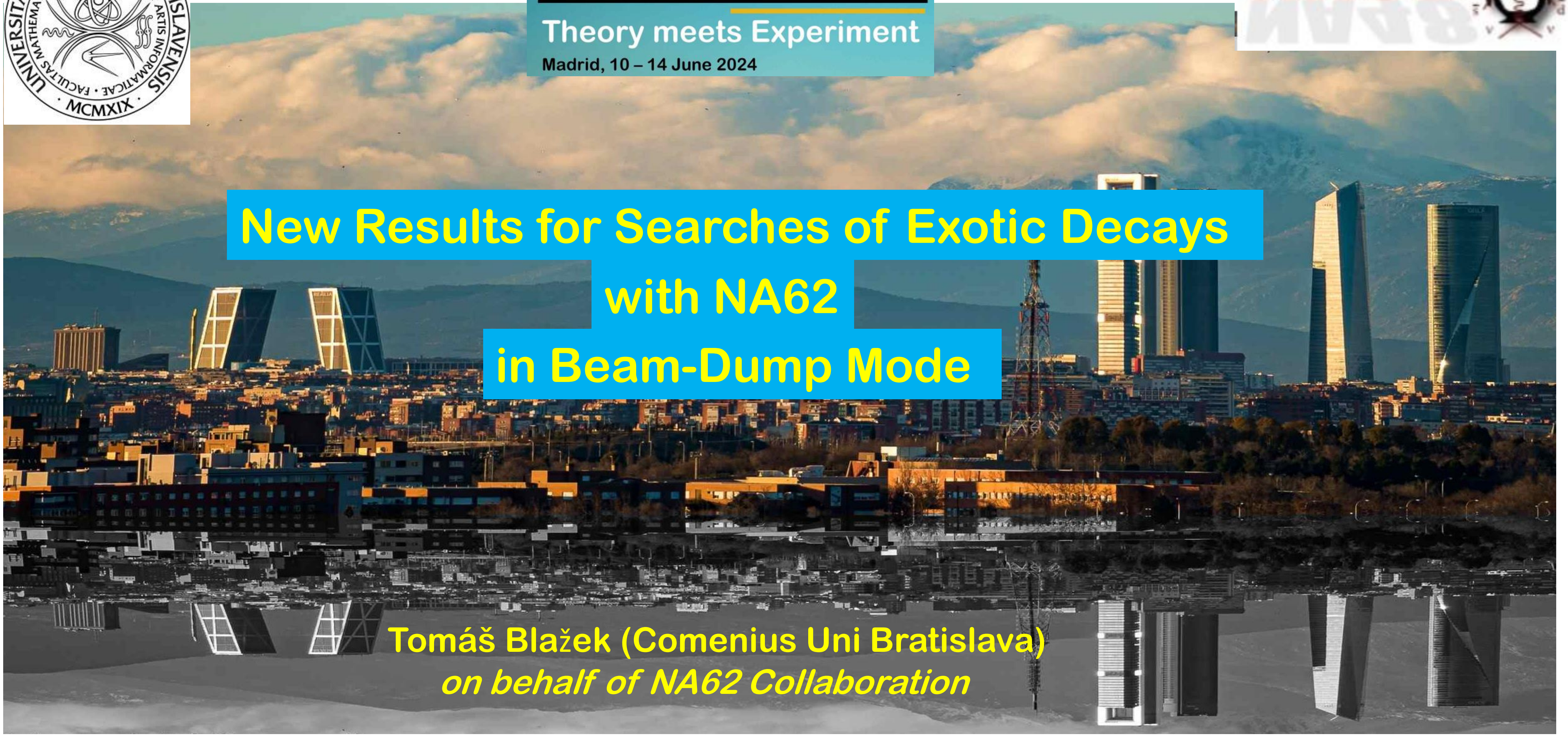


SUSY 2024

Theory meets Experiment

Madrid, 10 – 14 June 2024

New Results for Searches of Exotic Decays with NA62 in Beam-Dump Mode

Tomáš Blažek (Comenius Uni Bratislava)

on behalf of NA62 Collaboration

Tomas.Blazek@cern.ch

13/06/2024

Outline:

The NA62 Experiment

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

Exotic Messanger Signals and Benchmark Cases

NA62 in BD mode - Messanger Signal simulations:

$\mu^+\mu^-$, e^+e^-, hh final states

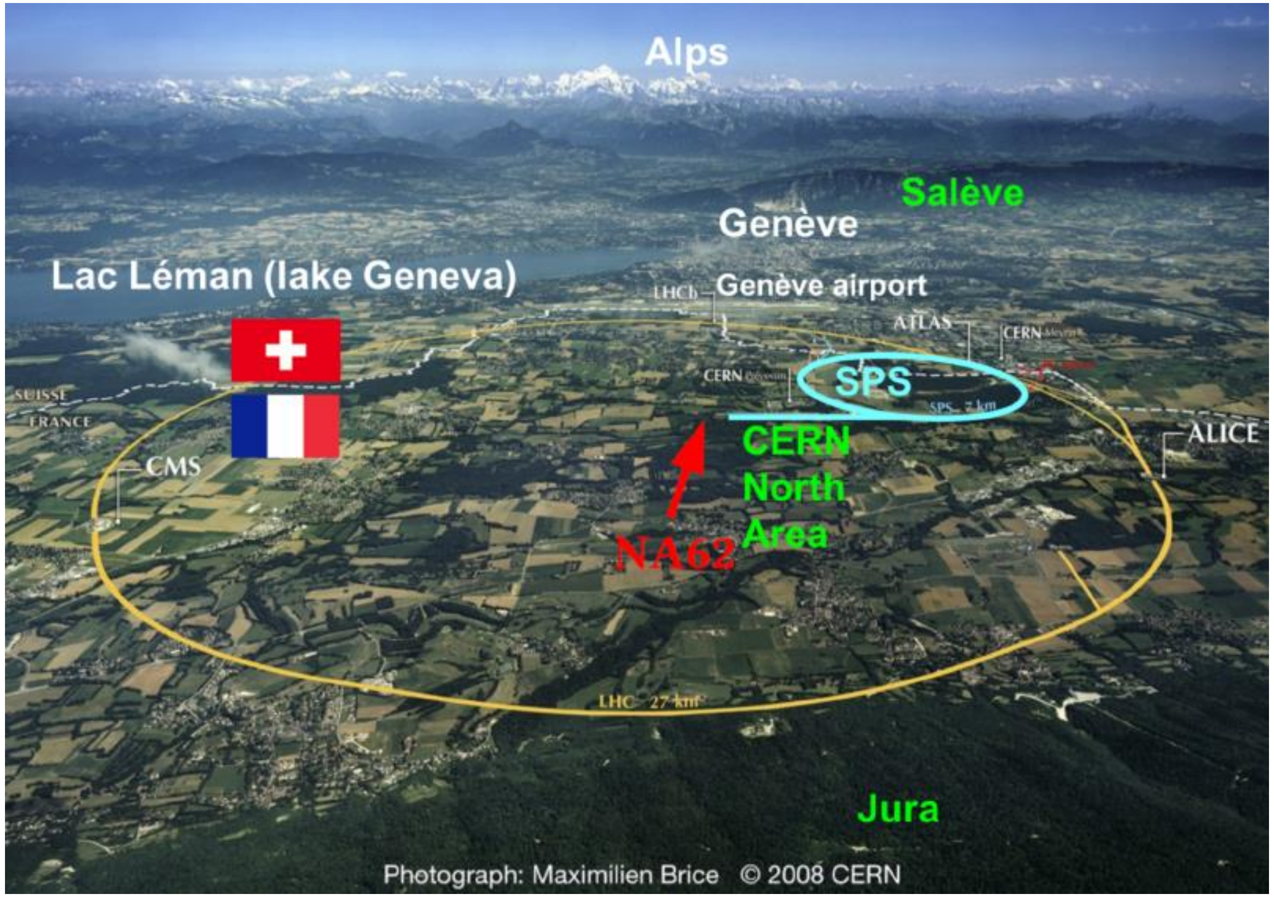
NA62 Analysis Strategy and Background Determination

NA62 Results for Searches with $\ell\ell$ final state (recently published)

and with hh final state (Summer 2024 conferences)

More on NA62 Results in Kaon mode please see Cristina Biino's Talk at this conference

The NA62 Experiment at CERN



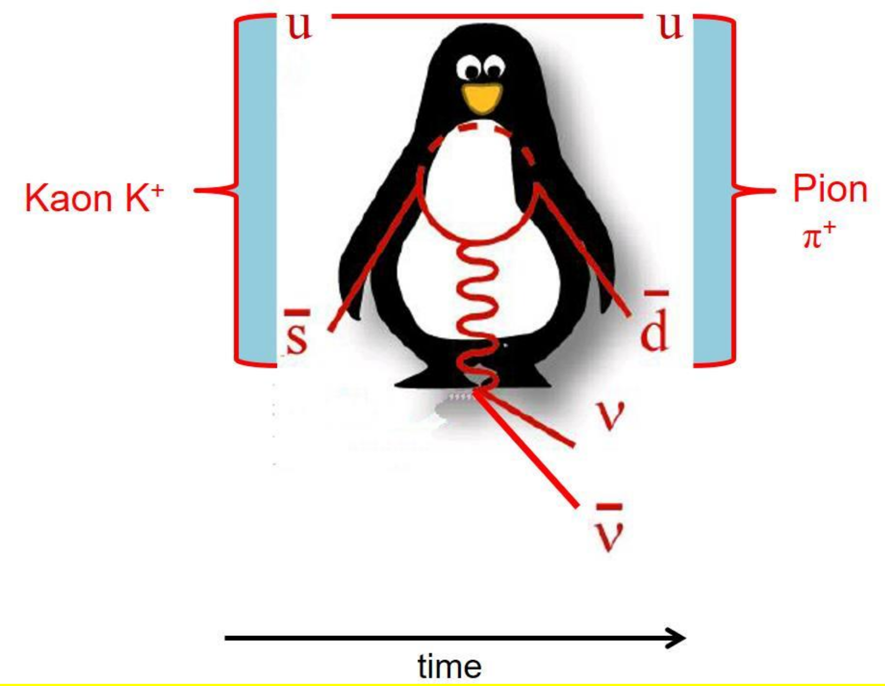
~ 30 institutes, ~ 300 collaborators
K^+ decays in flight

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
just about first evidence

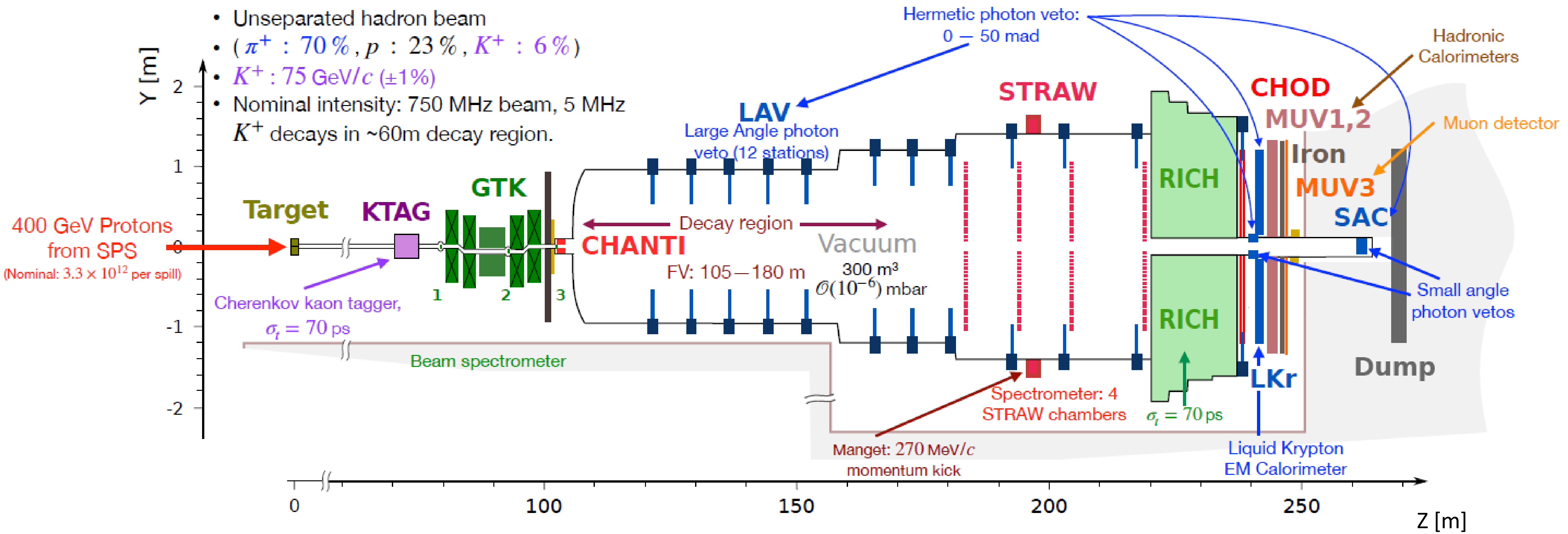
JHEP 06 (2021) 93

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

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



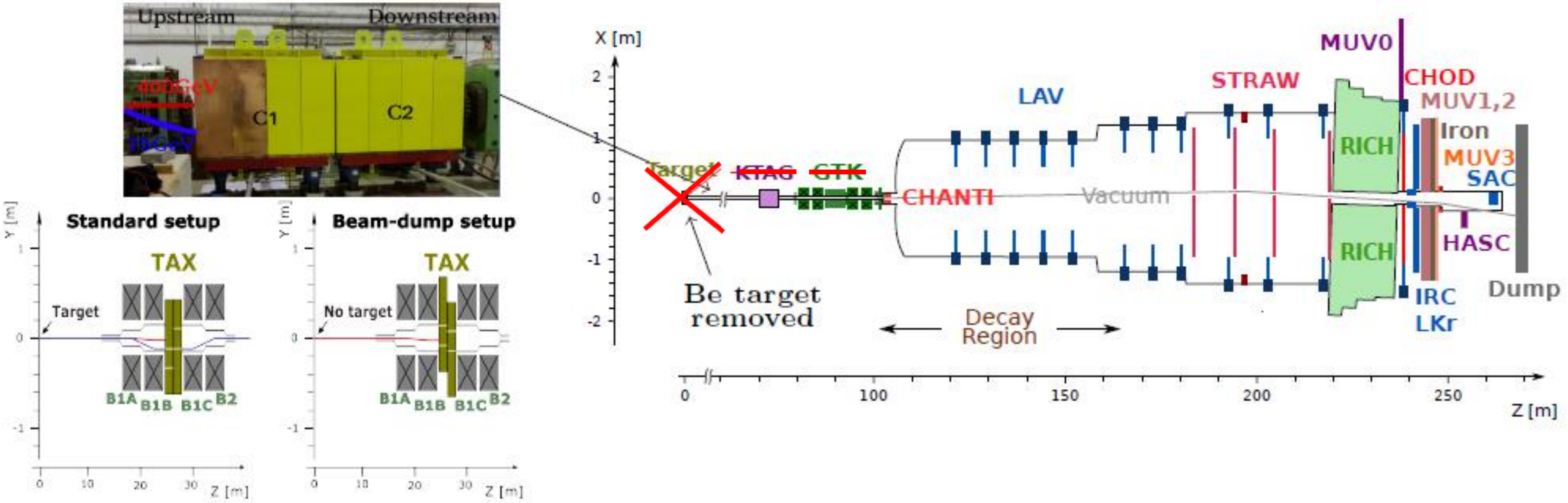
JINST 12 (2017) P05025

Particle Tracking: upstream: GTK = silicon pixel tracker, decay region: STRAW = tracking momentum spectrometer
P. Identification : upstream: KTAG, downstream: RICH= 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

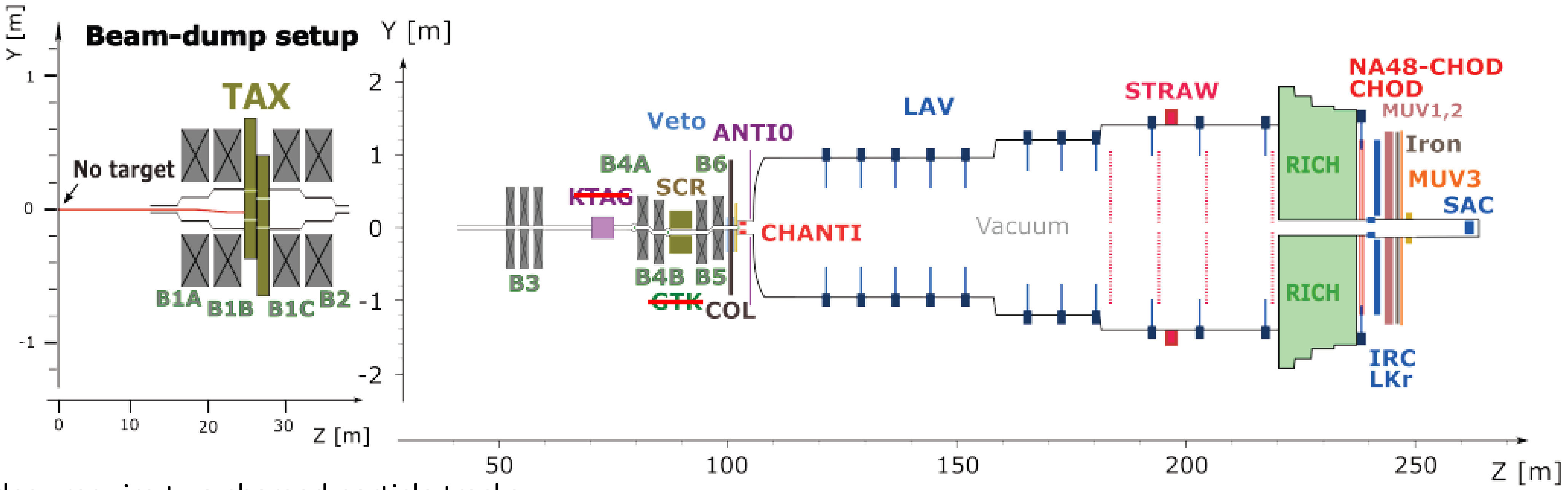
Target removed and TAX closed
KTAG and GTK not used



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 $\times 1.5$ of nominal;



<u>Trigger includes</u>: require two charged particle tracks

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

<u>Published:</u> NP searches with $\mu\mu$ 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

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

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

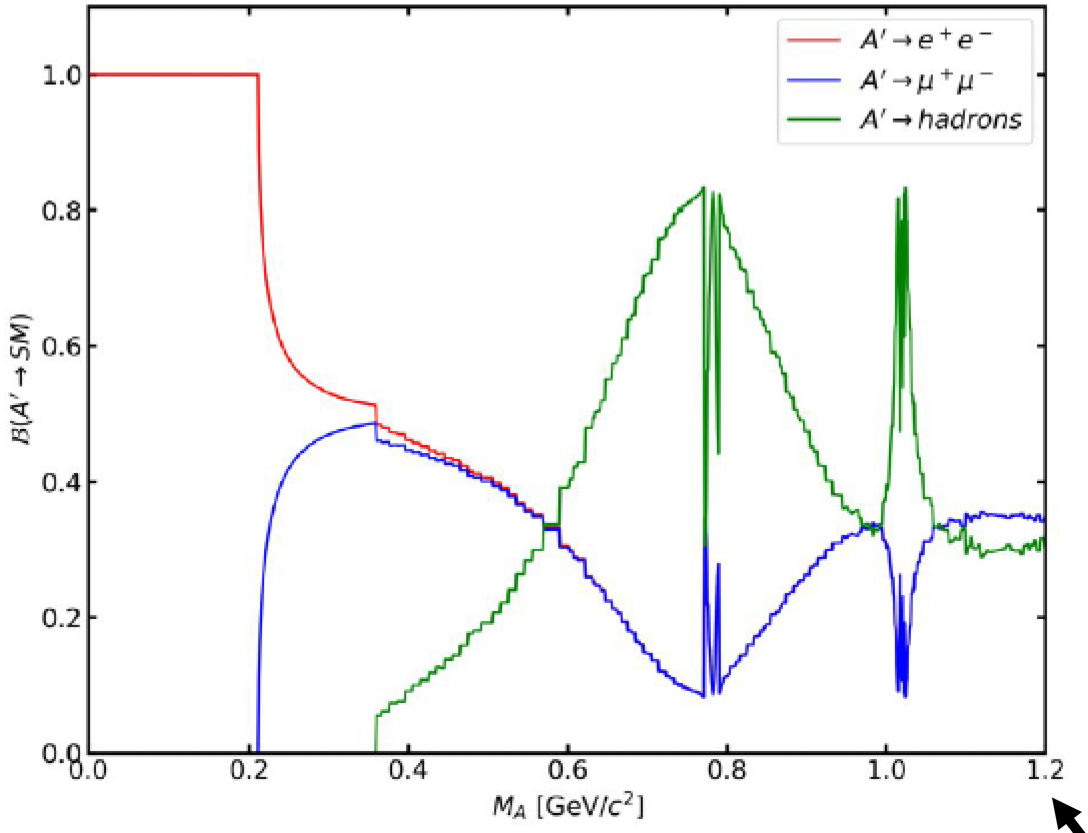
NA62 Dark Messenger searches – Monte Carlo simulations

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



Mass range < 600 MeV dominated by di-lepton decay

Dark Photon branching fractions

NA62 Dark Messenger searches – Analysis strategy
Fiducial Volume *vs* Upstream

Selection of two charged hadrons:

- 2 good quality STRAW tracks in coincidence with each other and the trigger
- Particle ID to select hadrons (LKr and MUV1-3), RICH for tagging K^+
- No in-time activity in LAV, SAV and ANTI0
- Decay vertex selected in a fiducial volume (FV), an upstream region defined as a control sample

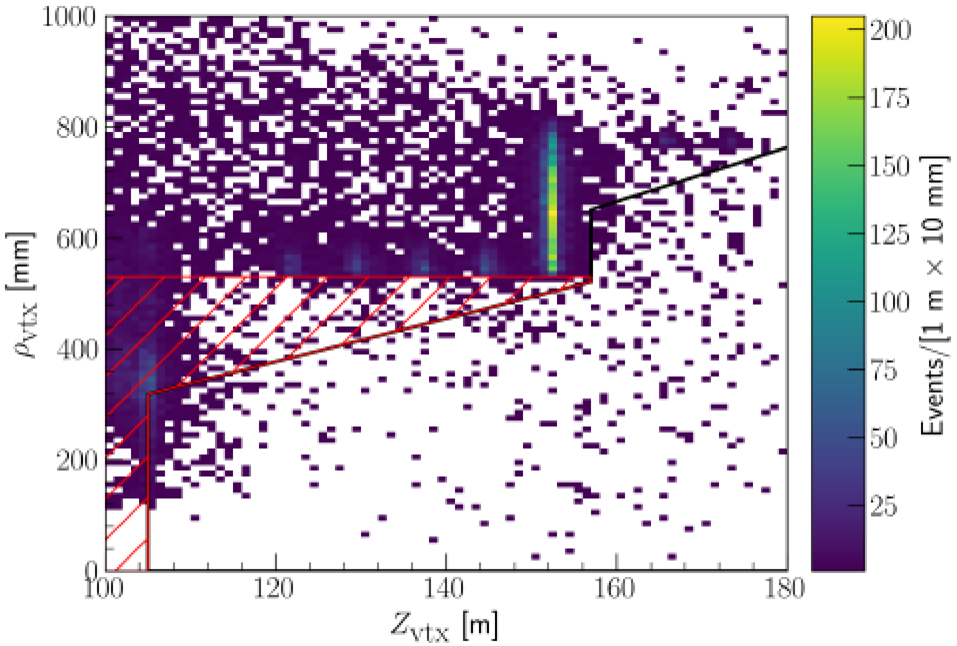


Figure: Two-track vertices (no PID) and definition of fiducial volume and upstream region (red hatched area).

NA62 Dark Messenger searches – Analysis strategy
Signal Region *vs* Control Region

Selection of two charged hadrons:

- 2 good quality STRAW tracks in coincidence with each other and the trigger
- Particle ID to select hadrons (LKr and MUV1-3), RICH for tagging K^+
- No in-time activity in LAV, SAV and ANTI0
- Decay vertex reconstructed in FV

Search strategy:

- select neutral LKr clusters, reconstruction of γ, π^0, η based on time and opening angle;
- dark messenger reconstructed from final states and extrapolation to TAX - definition of signal region (SR) in terms of primary vertex: $\mathrm{CDA_{TAX}}$ vs Z_{TAX}

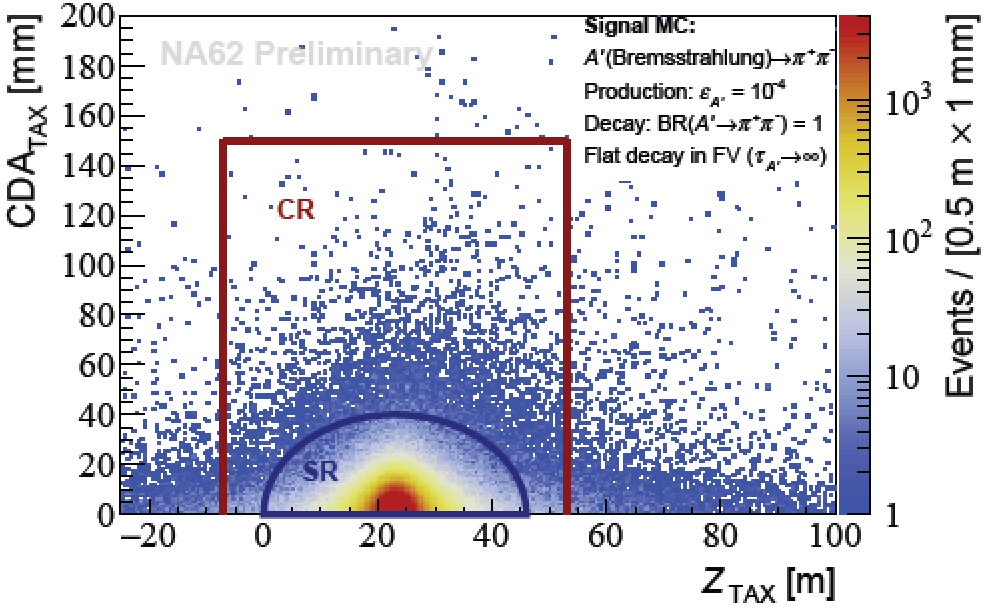


Figure: $A' \to \pi^+\pi^-$ MC: control (CR) and signal (SR) regions.

- SR: ellipse center $\{Z_{\mathrm{TAX}}, \mathrm{CDA_{TAX}}\} = \{23\,\mathrm{m}, 0\,\mathrm{mm}\}$, semi-axes of 23 m and 40 mm
- CR: $\mathrm{CDA_{TAX}} < 150\,\mathrm{mm}$ and $-7\,\mathrm{m} < Z_{\mathrm{TAX}} < 53\,\mathrm{m}$
- both SR and CR kept masked during the analysis

NA62 Dark Messenger searches – Background Determination

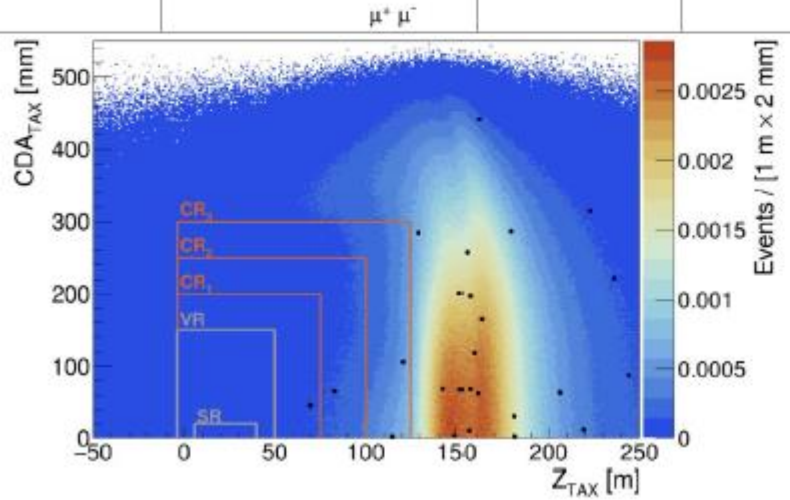
- **Combinatorial and neutrino-induced backgrounds**: negligible contributions in h^+h^- or e^+e^- , dominant for $\mu^+\mu^-$ (halo muons)
- **Prompt background**: inelastic interaction of halo muons can produce hadrons or e^+e^-
- **Upstream background**: formed by particles that are collected by the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

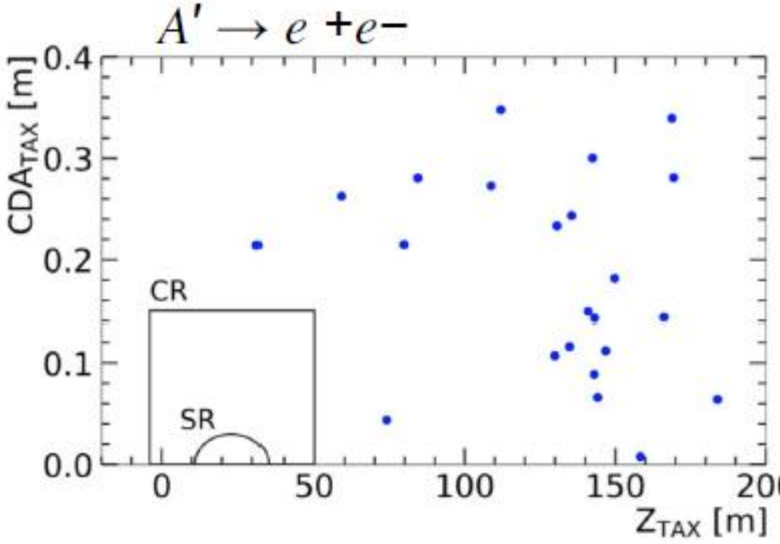
Background determination for A’→ℓℓ

- **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

$Nbkg \quad SR = 0.0094 - 0.009 + 0.049$ @ 90% CL





NA62 Dark Messenger searches – Background Determination for hh analysis

(i) Combinatorial and neutrino induced backgrounds, (ii)Prompt background, (iii)Upstream background

- 3 sub-components observed in an "ANTI0-blind" control sample in the $Z_{\mathrm{VTX}} - m_{\pi\pi}$ plane:
  - 19 upstream interactions
  - 2 $K_S \to \pi^+\pi^-$ candidates
  - 8 $K^+ \to \pi^+\pi^+\pi^-$, one π^+ lost (6 identified as $\pi^+\pi^-$, 2 $\pi^+\pi^-\gamma$)
- upstream interactions: vetoed by ANTI0 acceptance and vertex location
- K_S candidates: 3σ window ($\pm 5.7\,\mathrm{MeV}/c^2$) around m_{K_S} kept masked
- K^+-induced background: simulated using selected single K^+ tracks, forced to decay as $K \to \pi^+\pi^+\pi^-$ in the FV

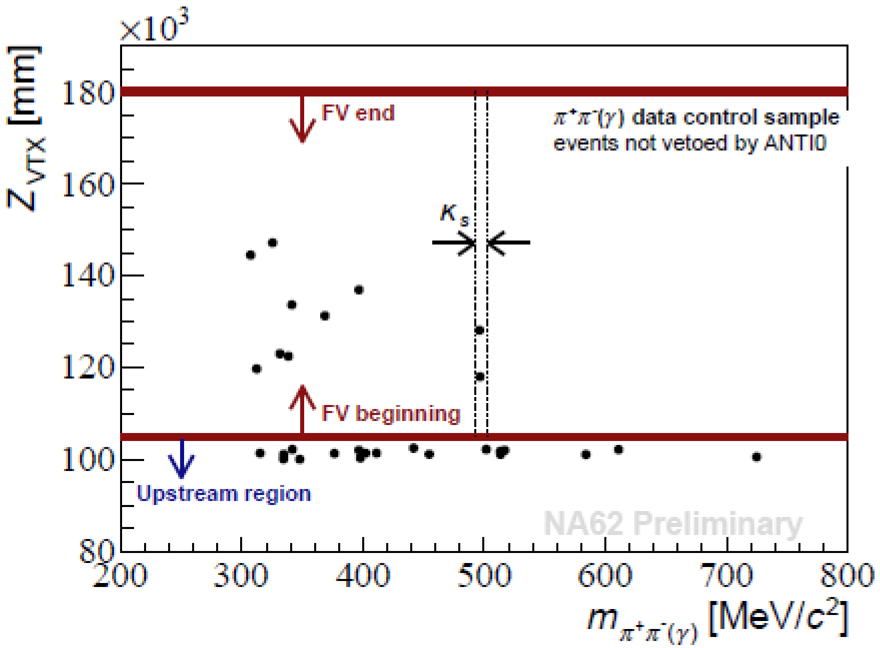


Figure: Events not in ANTI0 acceptance or not vetoed by ANTI0 in Z_{VTX} – invariant mass plane. Solid lines indicate the FV. Dashed lines indicate the K_S 3σ mass window.

Background determination for hh analysis

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

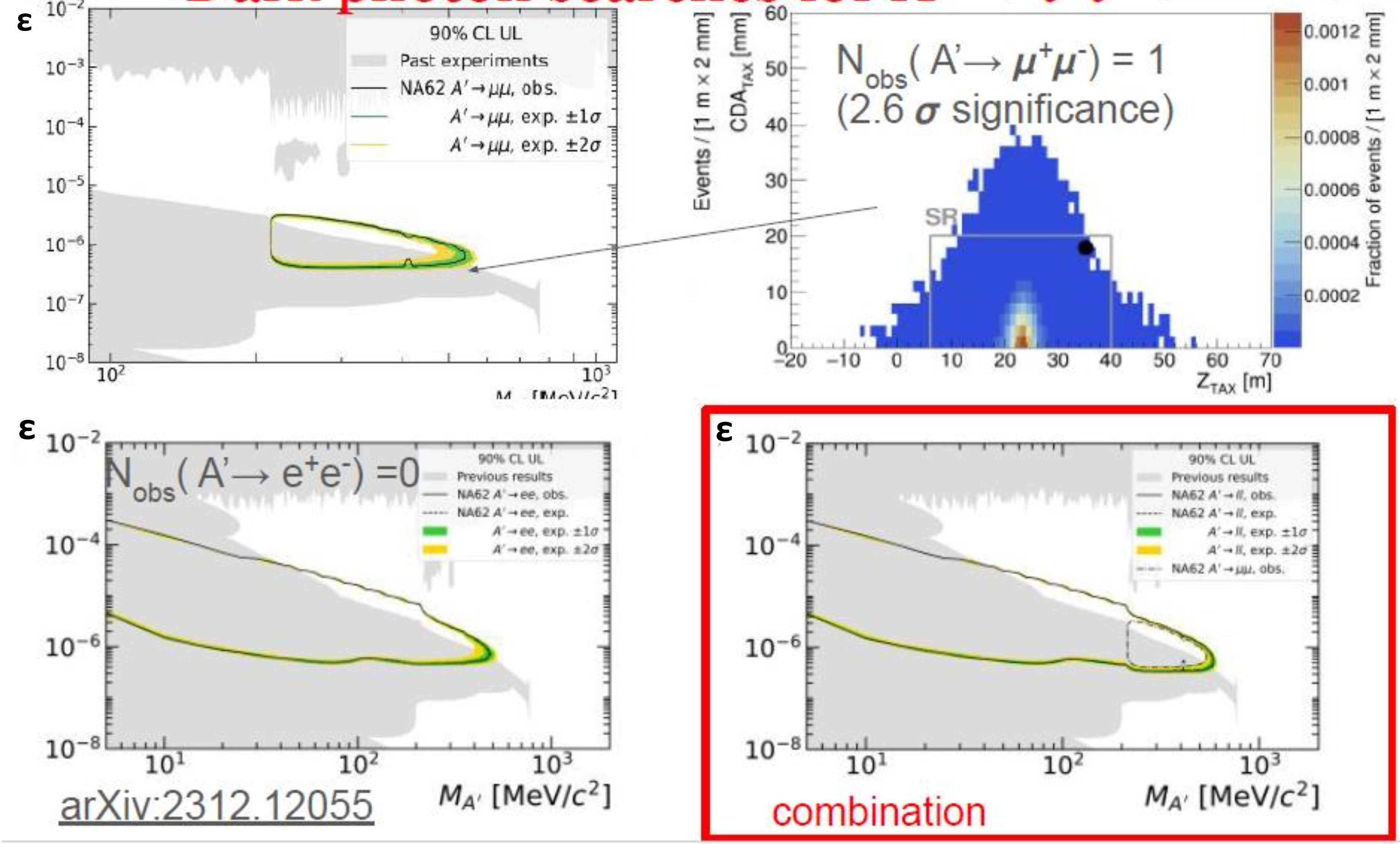
- For the h^+h^- analysis channels at 68% CL:

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 – Results for leptonic final states

Dark photon searches for $A' \to \ell^+\ell^-$ JHEP09 (2023) 035



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

NA62 Dark Messenger searches – hh final state studies

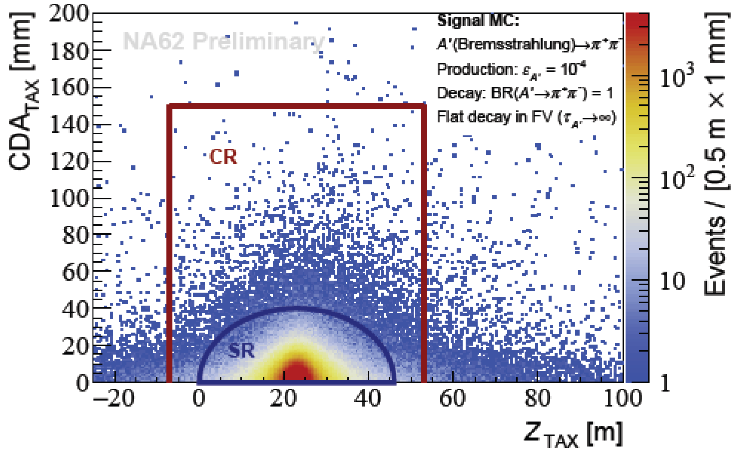


Figure: $A' \to \pi^+\pi^-$ MC: control (CR) and signal (SR) region

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

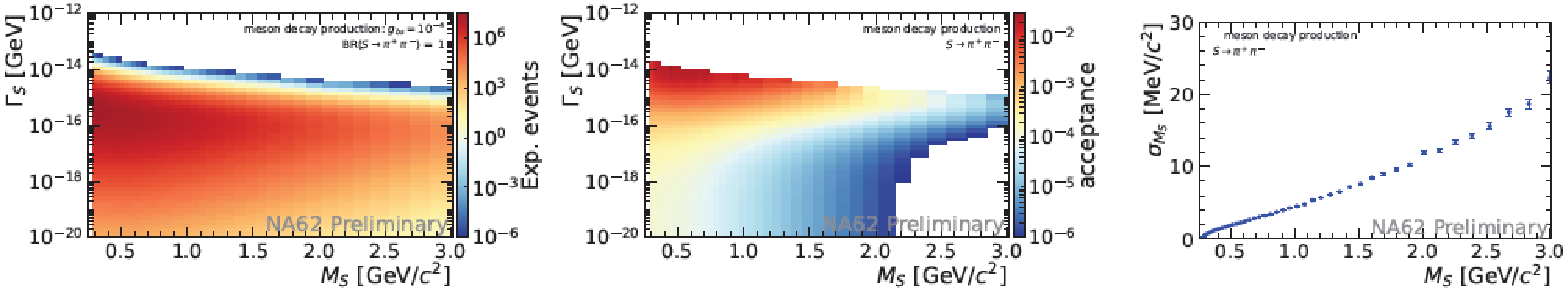


Figure: Left: expected number of $S \to \pi^+\pi^-$ selected events, for $g_{bs} = 10^{-4}$, BR = 1. Center: selection acceptance given a messenger decay in the FV. Right: Mass resolution of the reconstructed messenger.

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

- Distributions evaluated for 36 combinations of production and decay channels

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 $N_{POT} = 1.4 \times 10^{17}$,

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

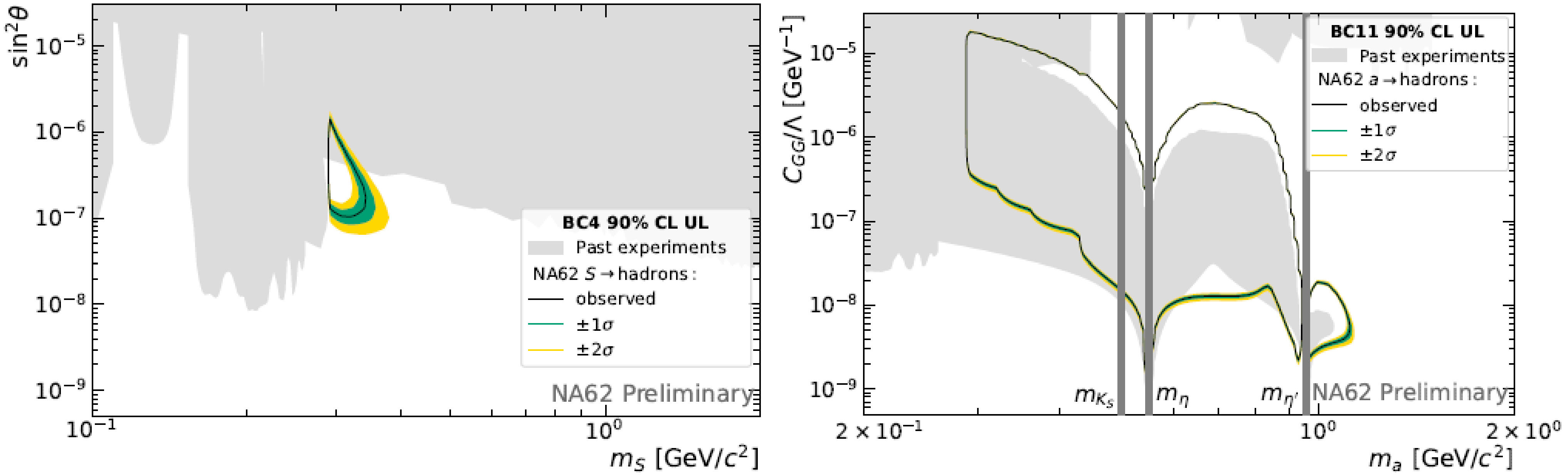


Figure: The observed 90% CL exclusion contours in BC4 (left) and BC11 (right) benchmarks together with the expected $\pm1\sigma$ and $\pm2\sigma$ bands (theory uncertainty not included). Public tool ALPINIST[5] used for the combination of the results from the individual production and decay channels.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

ALPINIST JHEP 07 (2022) 094

Summary

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 with other (semi-leptonic, digamma, etc) final states are ongoing based on the same 2021 data sample

There is **more NA62 data in Beam-Dump mode from 2023 to be analyzed** and a total of 10^{18} POTs is expected by the LHC Long Shutdown 3, with interesting perspectives on dark photons, ALPs, dark scalars, heavy neutral leptons and possibly other exotics.