Search for exotic decays with NA62

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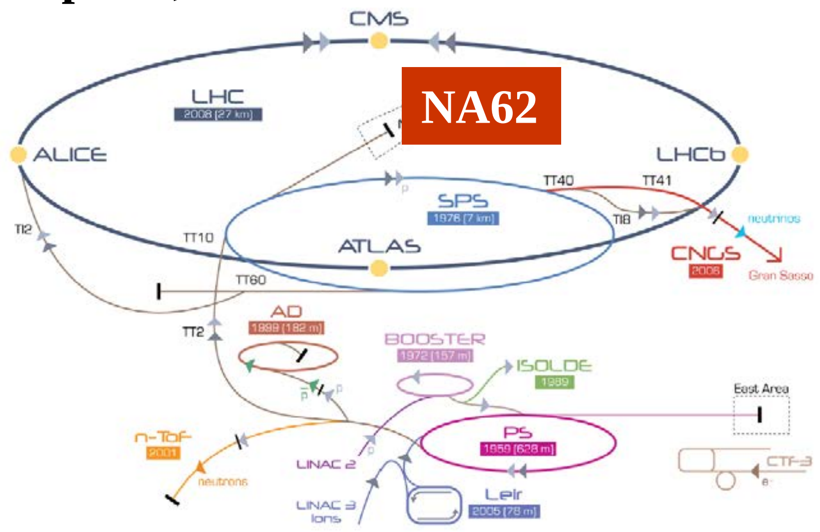
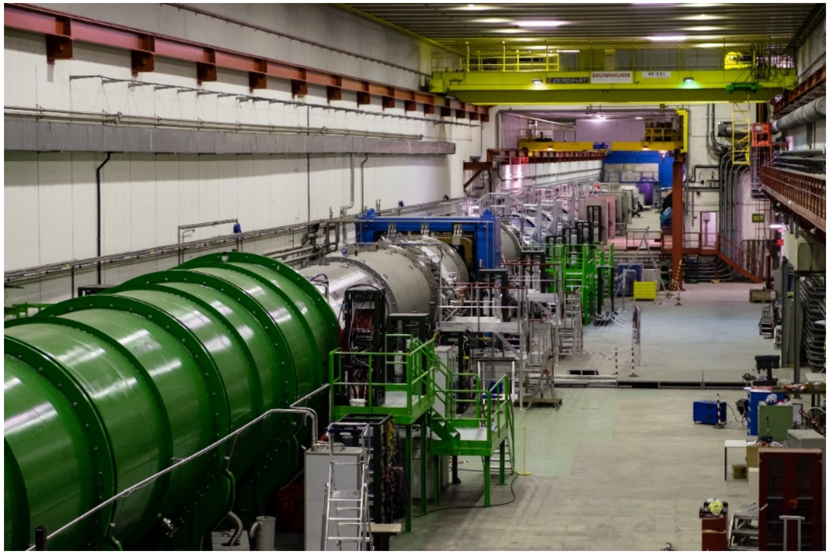
on behalf of NA62 collaboration

8th International Conference on New Frontiers in Physics
26 August 2019, Creta

The NA62 experiment at CERN

Kaon physics with fixed target experiments at CERN SPS. Currently in NA62: ~200 participants, 29 institutions from 13 countries





NA62 Main Goal: 10% precision BR($K^+ \to \pi^+ \nu\bar{\nu}$) measurement
LNV-LFV in K^+ decays

S. Ghinescu talk

Hidden sector particles from kaon decays and with a change in the beam-line setup (beam-dump mode)

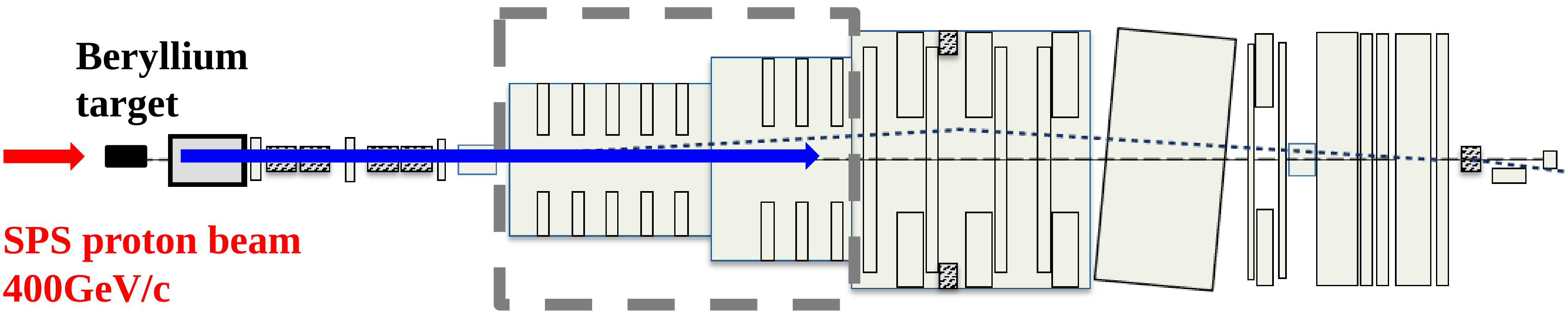
This talk

2014	2015	2016	2017	2018	2019-2020
Pilot Run	Commissioning	Commissioning + Physics Run	Physics Run	Physics Run	LS2 Long shutdown 2

NA62 layout

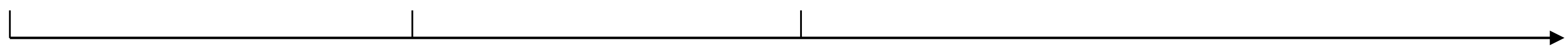
Fiducial volume: 60 m $\mathcal{O}(10^{-6})$ mbar
~5 MHz of K^+ decays

Beryllium target

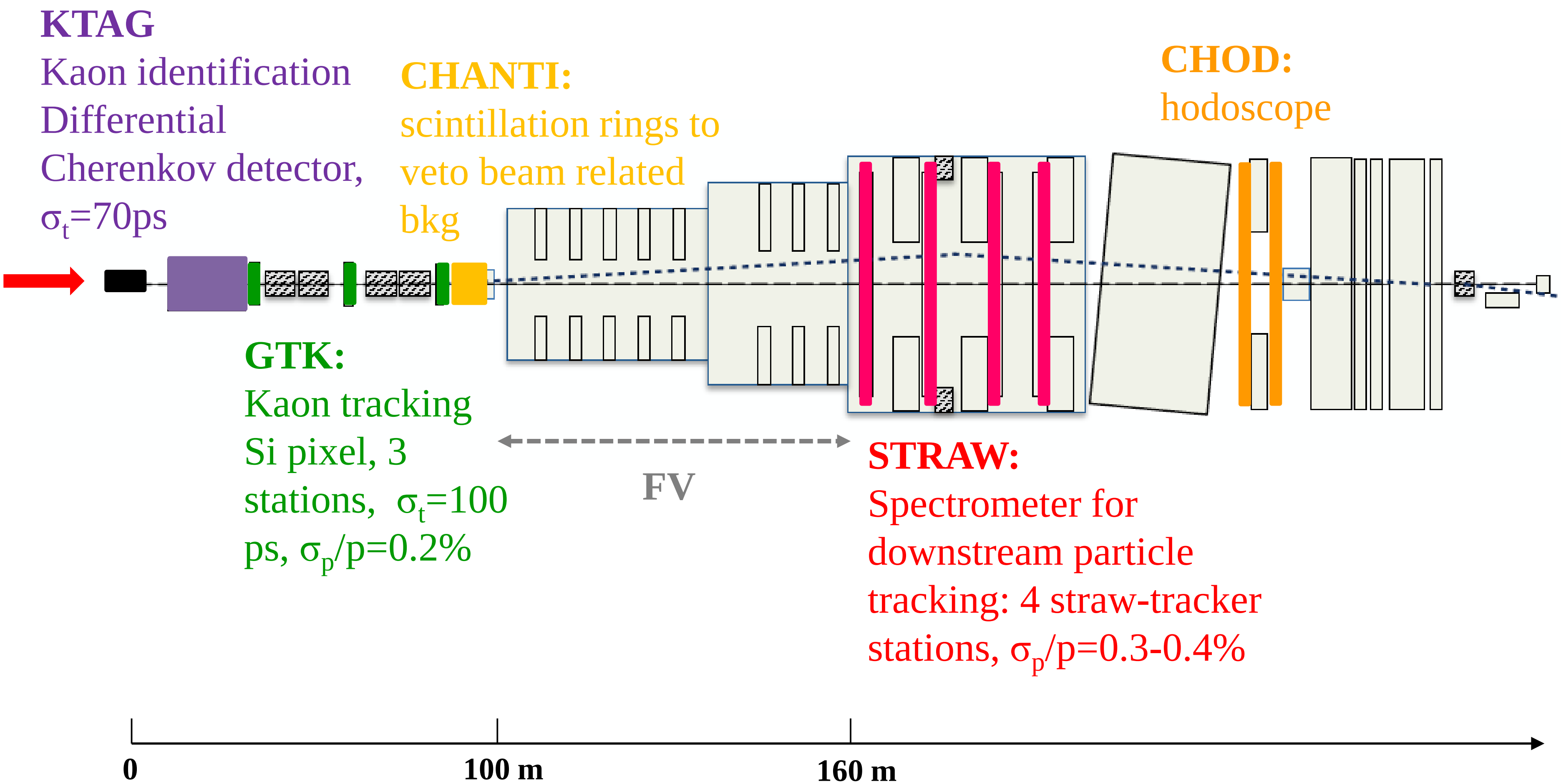


SPS proton beam
400GeV/c
10^{12} PoT/sec on spill
4.8 sec spill

Secondary beam
75 GeV/c, 1% bite
60×30 mm^2
K^+(6%)/π^+(70%)/p(24%)
750 MHz at GTK3



NA62 layout

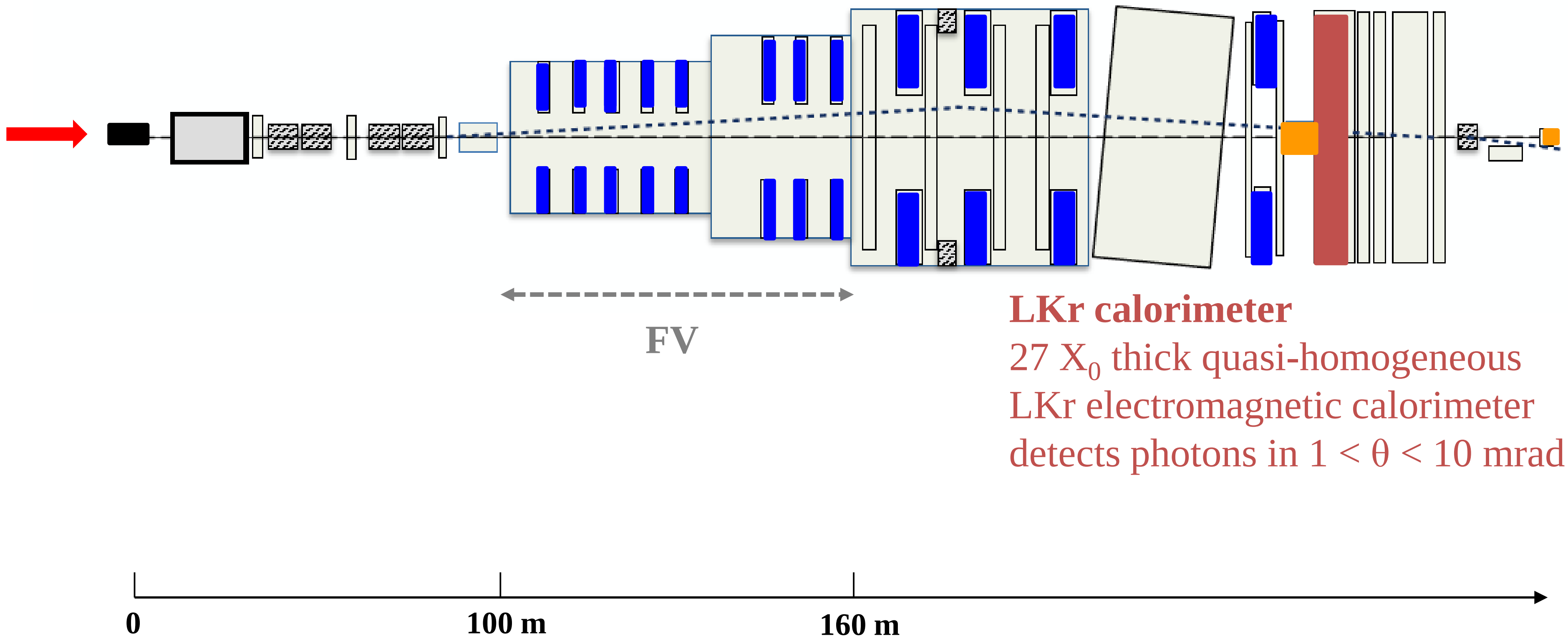


- **Kinematic reconstruction: $M^2_{miss}=(P_K - P_\pi)^2$, $\sigma_{M^2_{miss}}=10^{-3}$GeV²/c⁴ at $K^+ \to \pi^+\pi^0$**
- **Time resolution to match beam and daughter particle information: ~100ps**

NA62 layout

Large Angle Veto (LAV)
12 stations with lead glass blocks
Covering angles $10 < \theta < 50$ mrad

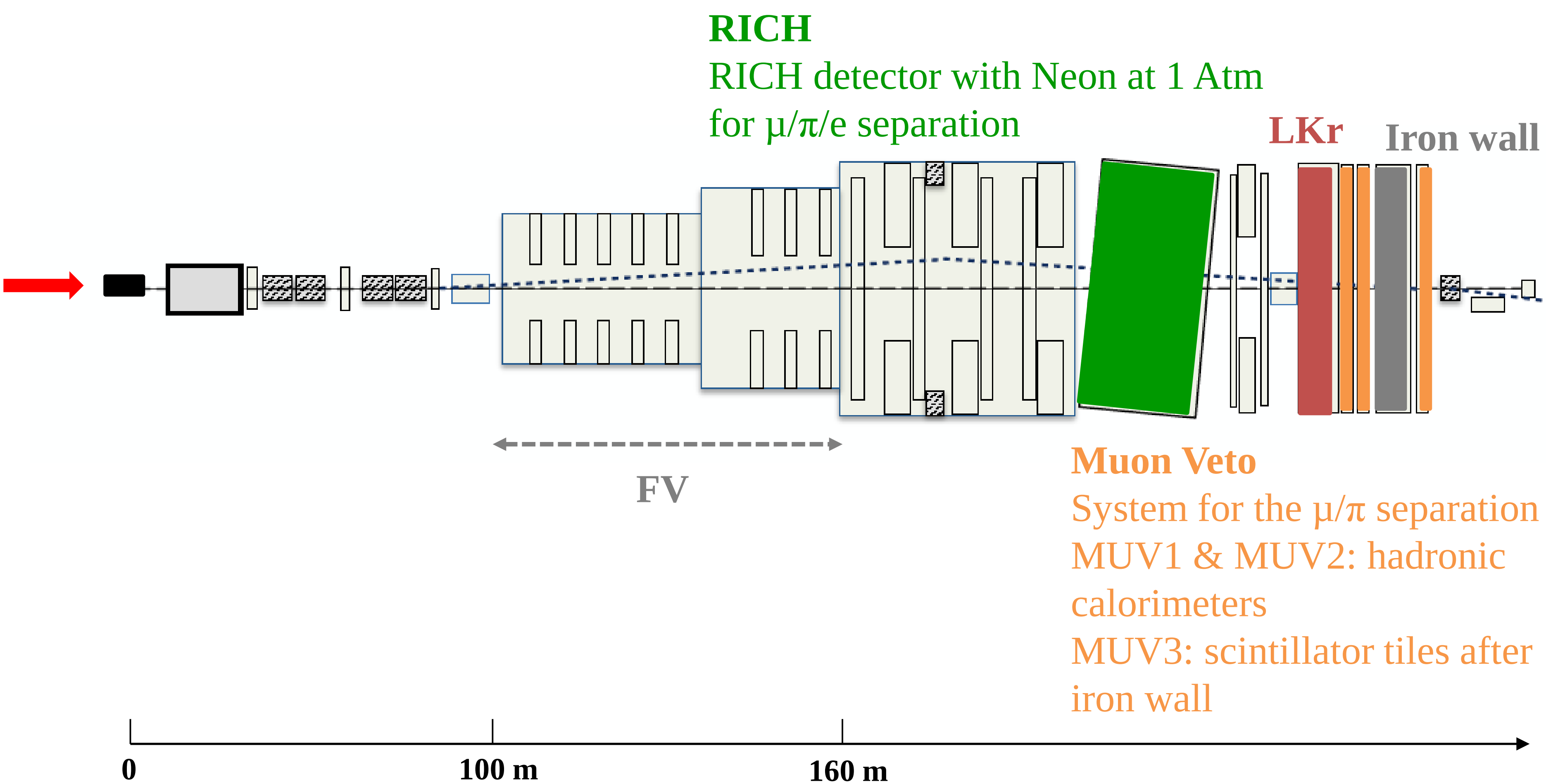
Small angle veto (SAV)
Two shashlik calorimeters, IRC and SAC, to cover $\theta < 1$ mrad



LKr calorimeter
27 X_0 thick quasi-homogeneous LKr electromagnetic calorimeter detects photons in $1 < \theta < 10$ mrad

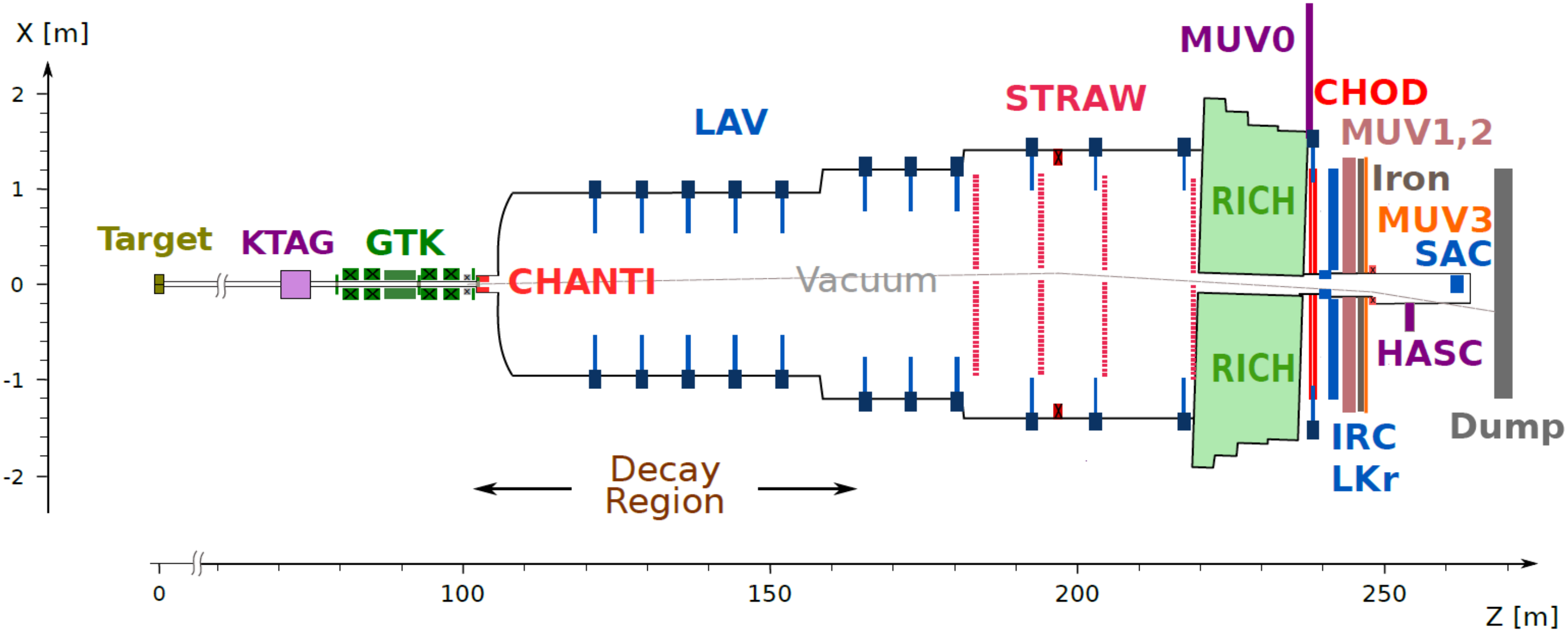
- **Photon vetoes to suppress bkg with π^0 in the final state for the main analysis: 10^8 rejection of π^0 for $E(\pi^0) > 40$ GeV**

NA62 layout



➢ **PID detectors to suppress bkg with μ^+or e^+ in the final state for the main analysis: μ vs π rejection of O(10^7) for 15 < p(π^+) < 35 GeV**

NA62 layout



Performances

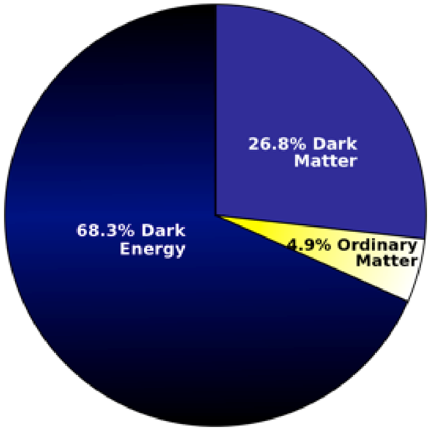
- ✓ **Excellent time resolution $\mathcal{O}$(100 ps)** to match beam and daughter particle information
- ✓ **Kinematics:** rejection of main K modes 10^4 via kinematics reconstruction
- ✓ **PID capability:** μ vs π rejection of $O(10^7)$ for $15 < p(\pi^+) < 35$ GeV
- ✓ **High-efficiency veto:** 10^8 rejection of π^0 for $E(\pi^0) > 40$ GeV

The beam and detector of the NA62 experiment at CERN, 2017 JINST 12 P0502

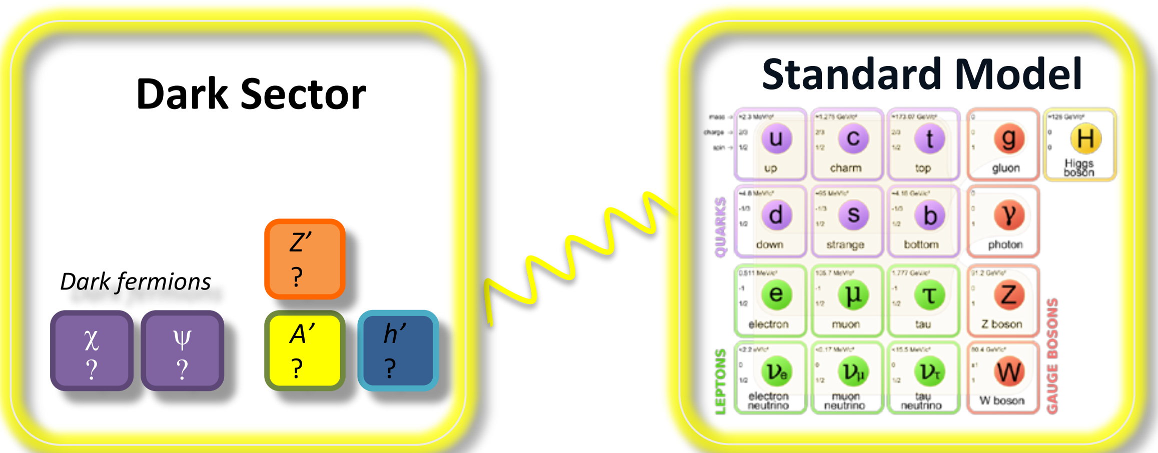
Hidden sector motivations

- With LHC a large new territory has been explored and no unambiguous signal of New Physics has been found at TeV scale.

- From Cosmological and Astrophysical observations something else than ordinary Baryonic matter should exist. The abundance of this new entity is 5 times larger than SM particles.



- An attractive possibility: the unresolved problems could be explained by NP, below the EW scale, feebly interacting with SM → intensity frontier experiment



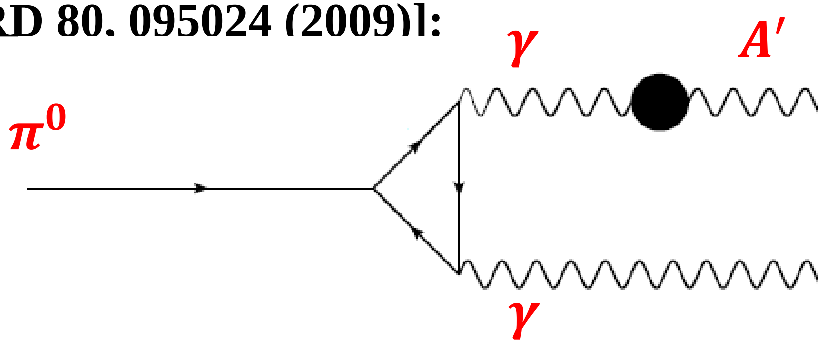
Interaction between DM and SM mediated by new Gauge-invariant operators. Many possible dynamics: neutrino (HNL), vector (Dark Photon), axial (ALP), scalar (S), ...

Dark photon

- Hidden sector model with one extra U(1) gauge symmetry and a corresponding gauge boson: the "dark photon" or A' boson [B. Holdom Phys.Lett. B166 (1986) 196]: kinetic mixing between the QED and the new U(1) gauge bosons

$$\mathcal{L}_{mix} = -\frac{\varepsilon}{2} F^{QED}_{\mu\nu} F^{\mu\nu}_{dark}$$

- A consequence of this interaction is the transition $\pi^0 \to \gamma A'$ [Batell, Pospelov and Ritz, PRD 80, 095024 (2009)]:

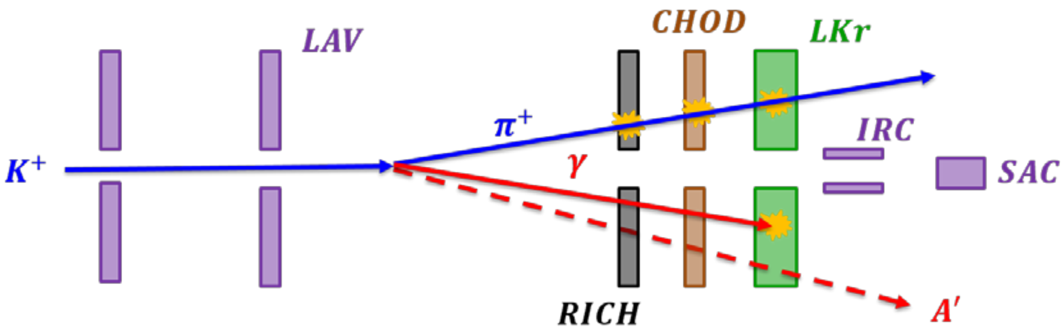


$$\frac{BR(\pi^0 \to \gamma A')}{BR(\pi^0 \to \gamma\gamma)} = 2\varepsilon^2 \left(1 - \frac{M^2_{A'}}{M^2_{\pi^0}}\right)^3$$

- Search for invisible decay of massive A' or long lived massive A'

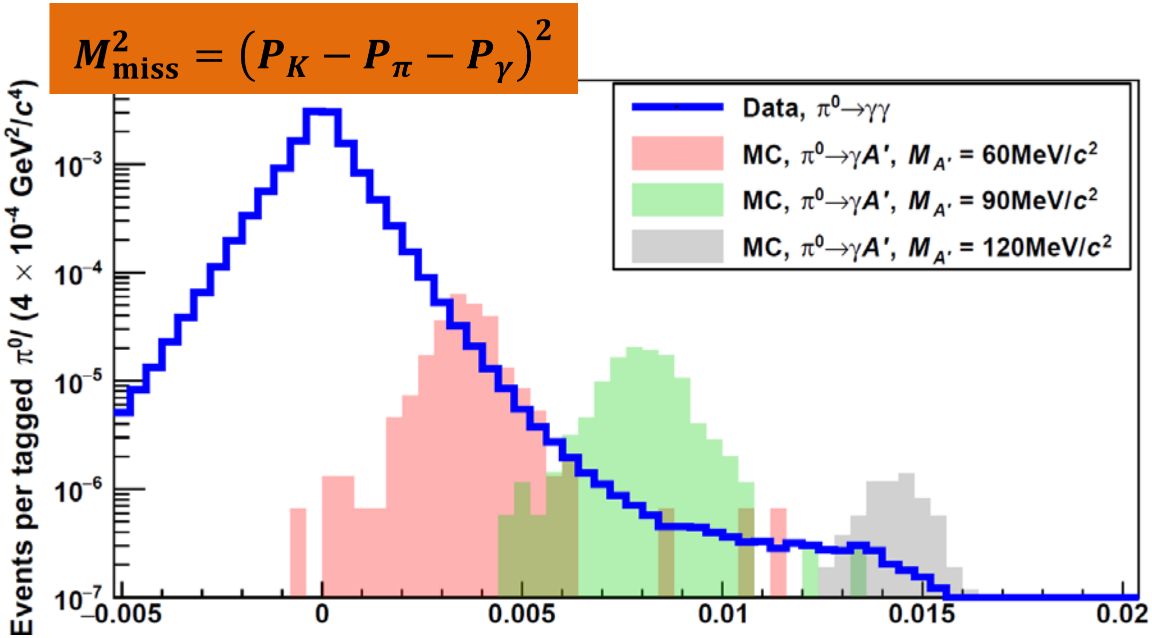
$$K^+ \to \pi^+\pi^0, \pi^0 \to \gamma A'$$

Measure K^+, π^+ momentum and detect one γ in LKr, veto other particles →missing energy signature

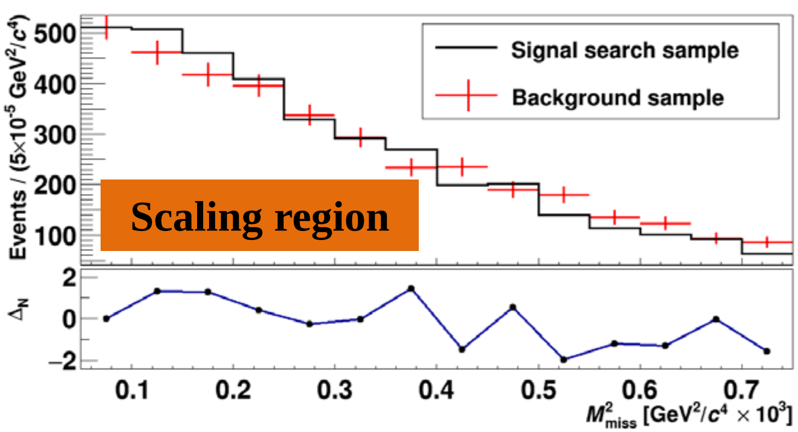


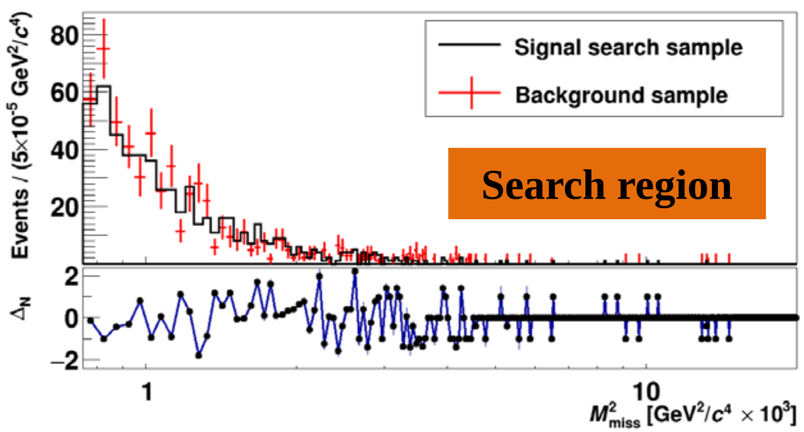
Dark photon search strategy

- A peak search in M^2_{miss} distribution performed. A sliding $M^2_{\rm miss}$ window ($\pm 1\sigma_{M^2_{\rm miss}}$) is used to count signals for different A' mass hypothesis.
- Background due to $\pi^0 \to \gamma\gamma$ with one γ not detected.

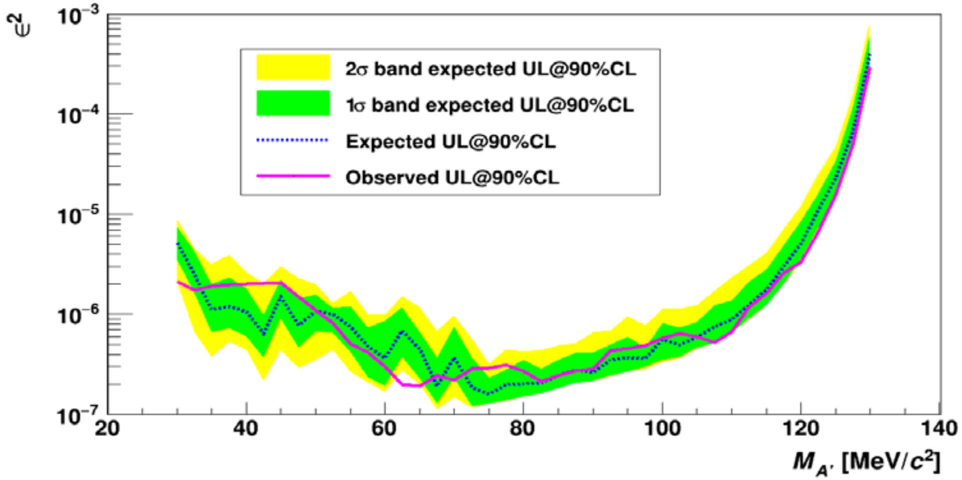


- Data-driven approach to evaluate background: same selection of the signal-sample but one cut inverted to ensures $\pi^0 \to \gamma\gamma$ events with one γ lost because of conversion.

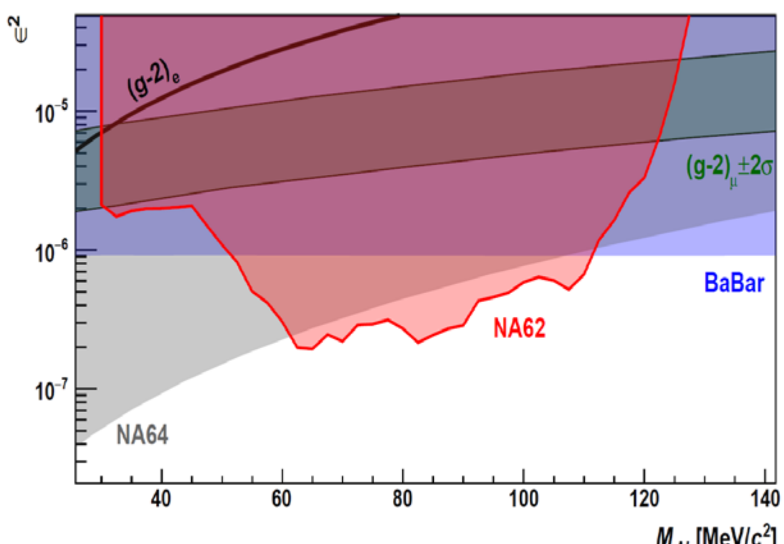




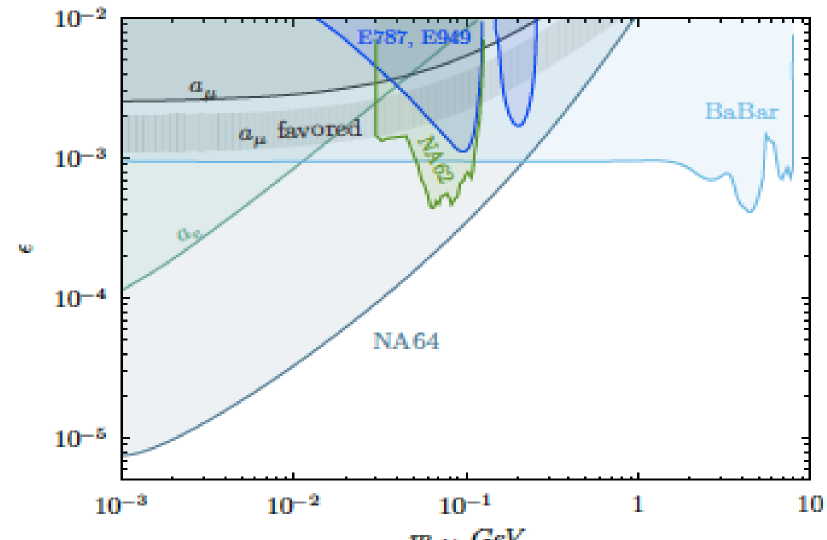
NA62 result for dark photon search



- CLs technique using 1% of the statistics collected by NA62 in 2016–2018.
- No statistically significant excess is detected: observed upper limits @ 90% CL compatible with fluctuations from the background-only hypothesis.
- Also set world's best upper limit on $\mathrm{BR}(\pi^0 \to \gamma\nu\bar{\nu}) < 1.9 \times 10^{-7}$ at 90% CL



NA62: JHEP 05 (2019) 182, 2016 data



NA64: arXiv:1906.00176, 2016-2018 data

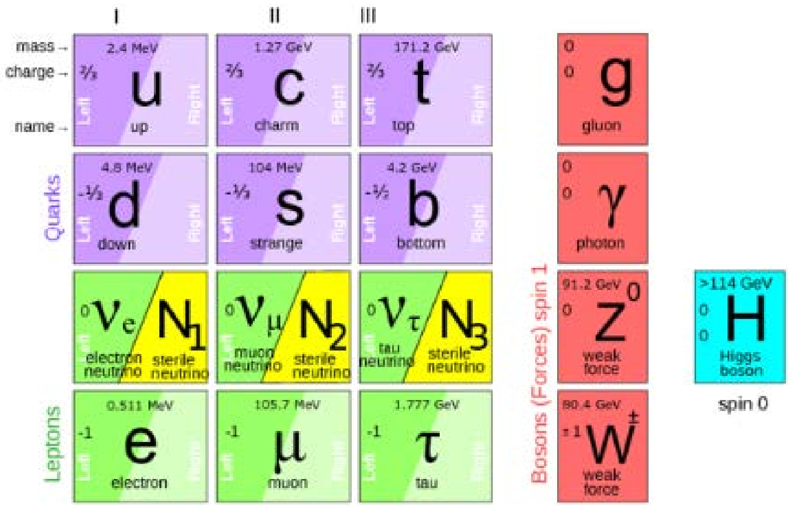
Heavy neutral lepton

- Dark Matter + Baryon Asymmetry of the Universe (BAU) + ν-oscillations can be explained by the addition of 3 massive sterile neutrinos N_i to the SM: Asaka-Shaposhnikov model (νMSM) [PLB 620 (2005) 17]

- Lightest of N_i mass O(10 keV/c^2) is candidate for DM; the others, of mass ~ 100 MeV/c^2 to few GeV/c^2, introduce extra CPV-phases to account for Baryon Asymmetry

- Standard neutrino masses produced through see-saw mechanism

- Production and decay modes same as SM ones, scaled by coupling factor $|U_{l4}|^2$ and kinematic factor $\rho_l(m_N)$



$$BR(K^+ \to l^+ N) = BR(K^+ \to l^+ \nu_l)\rho_l(m_N)|U_{l4}|^2$$

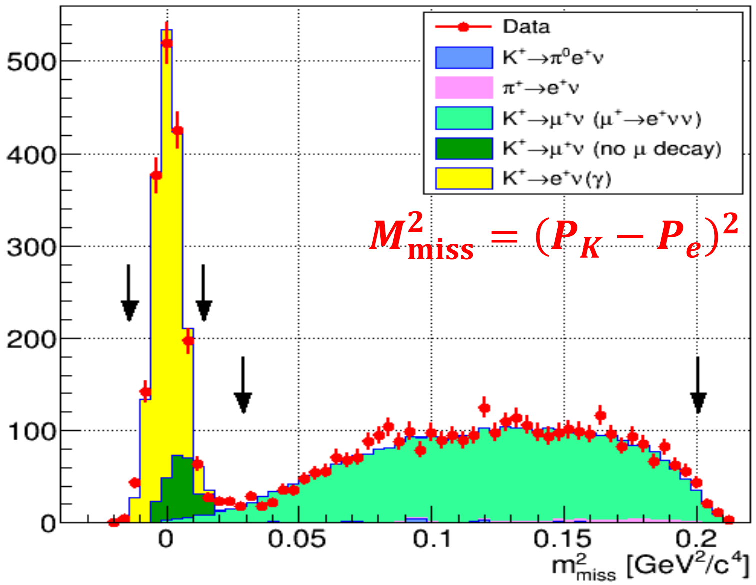
Heavy neutral lepton search at NA62

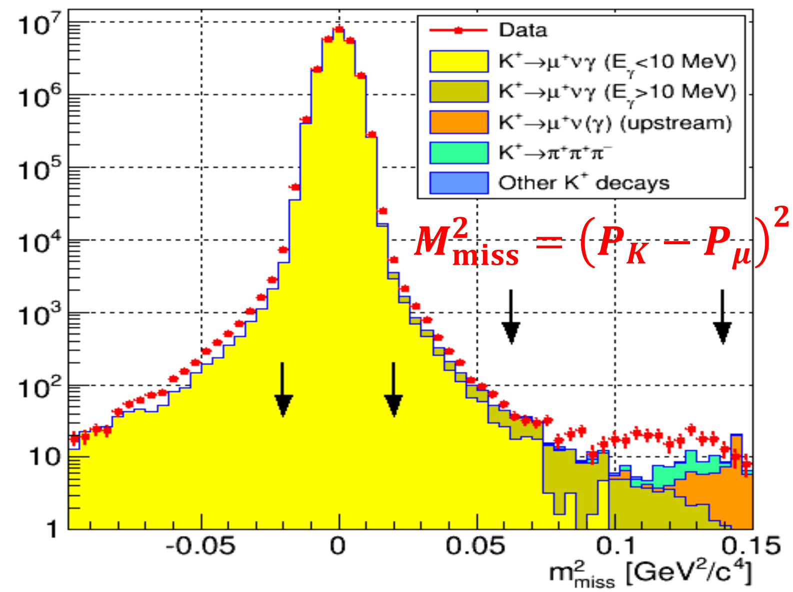
- Long lived N_i escapes the detector: single positively-charged downstream track topology

- Search for excess in the missing mass spectrum $M^2_{\text{miss}} = (P_K - P_l)^2$ expected to peak at M_N^2 for signal events. A sliding mass window is used with bkg evaluated from sidebands.

- Data sample 5 days @ 1% nominal intensity with minimum-bias trigger:
  - $N_K = 3 \times 10^8$ for $K^+ \to e^+ N$
  - $N_K = 1 \times 10^8$ for $K^+ \to \mu^+ N$

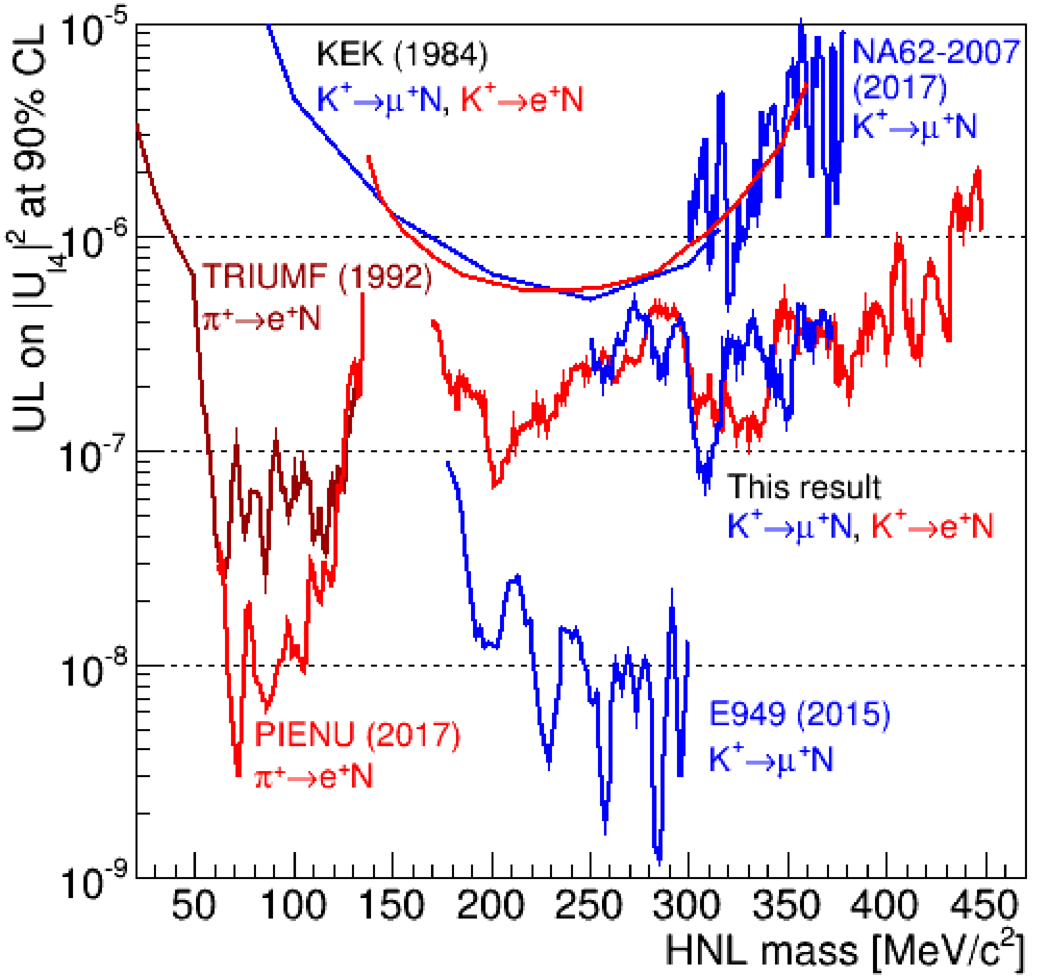
e/μ ID through E/p, Muon Veto and RICH (for p<40 GeV/c)





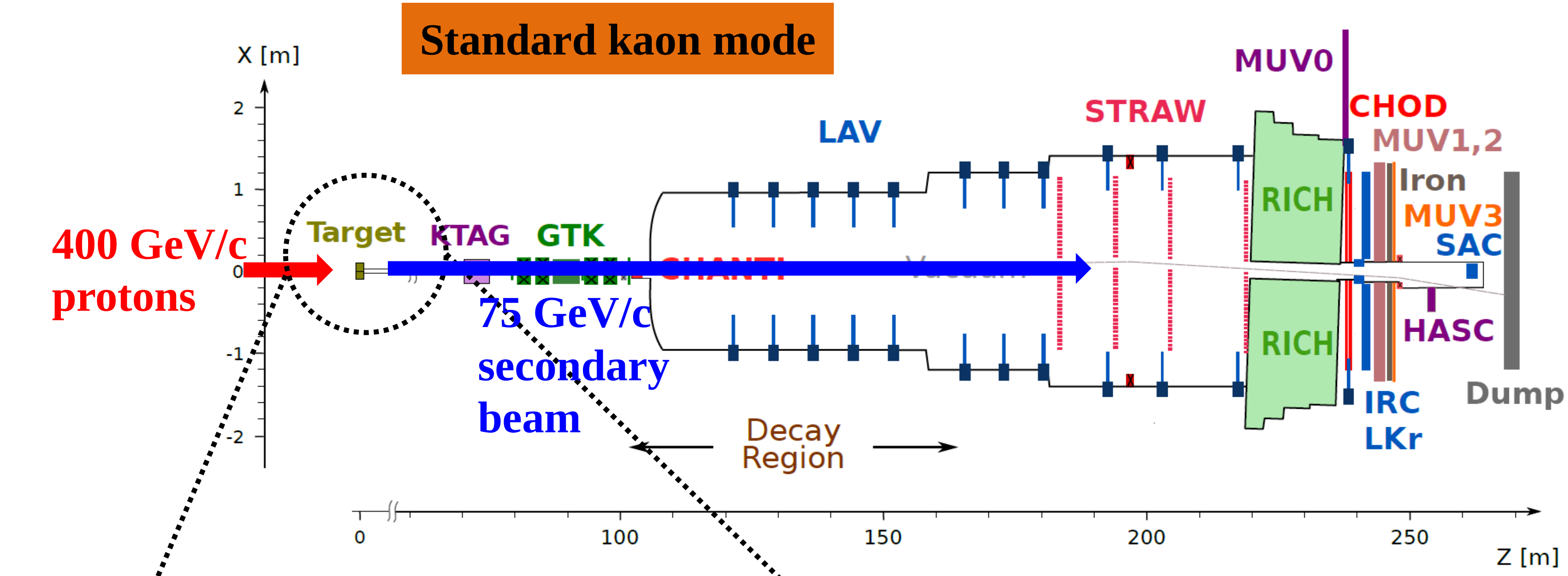
NA62 result for heavy neutral lepton search

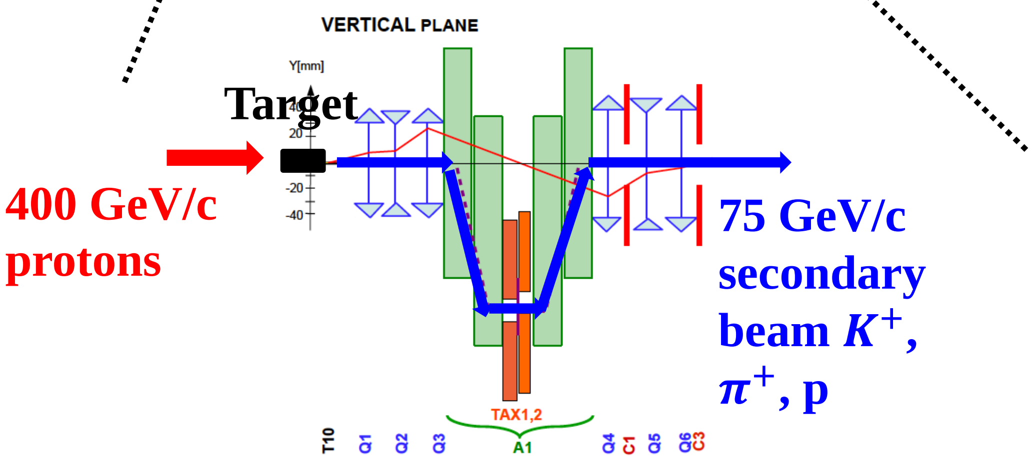
- No statistically significant excess observed
- Rolke-Lopez method to set 90% CL limits on the observed signals and $|U_{l4}|^2$
- Improved limits on $|U_{e4}|^2$ in 170 - 448 MeV/c²·. Improved limits on $\left|U_{\mu4}\right|^2$ above 300 MeV/c²
- O(10) improvement foreseen with full set of NA62 data (2016-2018)



Phys. Lett. B778 (2018) 137, NA62 2015 data

NA62 data taking configuration



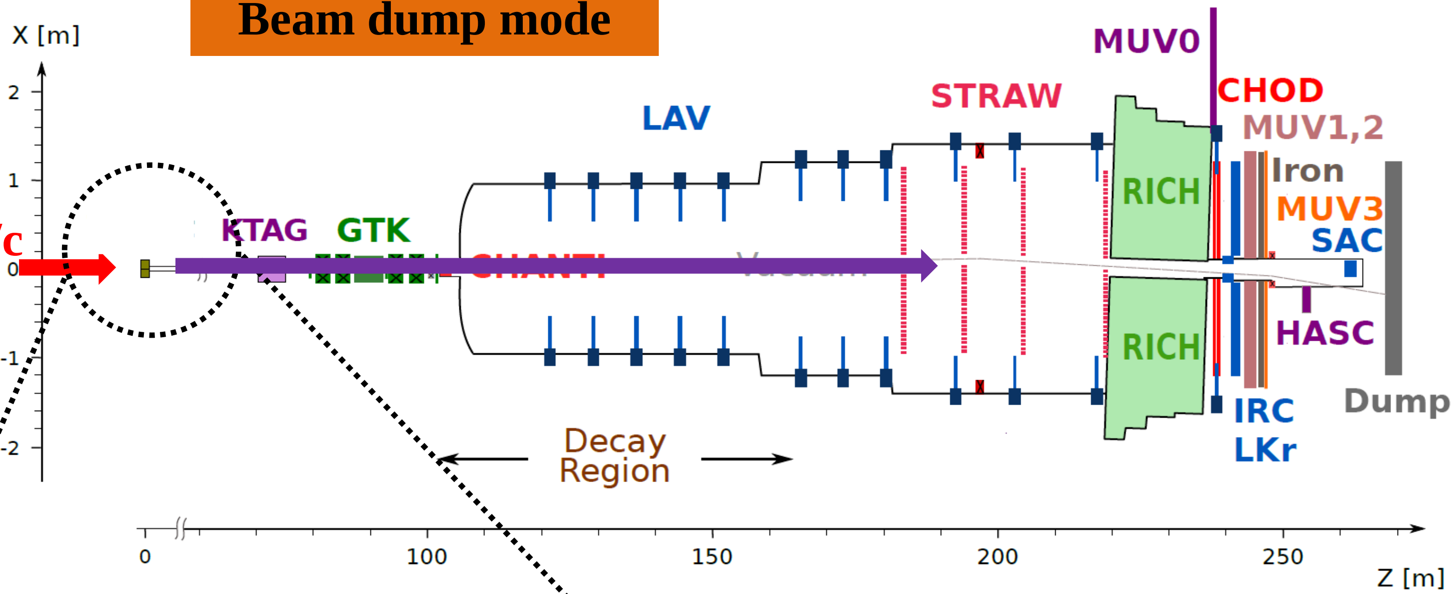


- In standard kaon mode the target for beam is a 400 mm long, 2 mm diameter beryllium block
- A rich exotic field can be explored also with minimal upgrades to the present setup

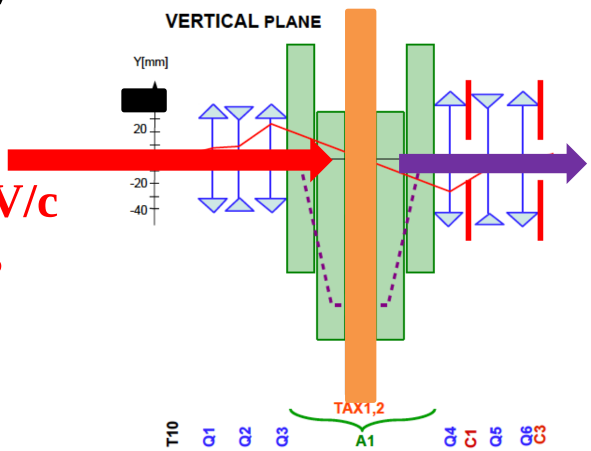
NA62 data taking configuration

Beam dump mode

400 GeV/c protons



400 GeV/c protons



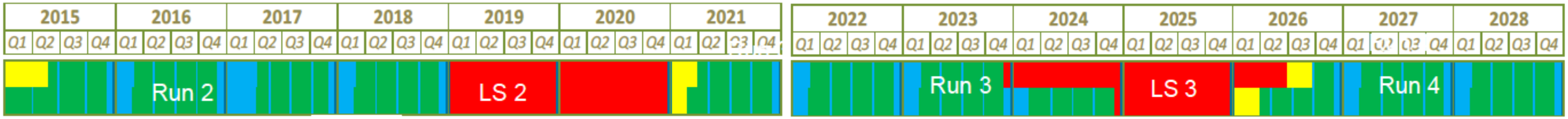
Muons
Neutrinos
Mesons
HNL
Dark scalars
Dark photon
ALP

- **400 GeV proton beam dump on a ~ 11 λ_I Cu-based beam-defining collimator**
- **Switching from standard beam to the beam-dump is quick (15 minutes) and fully reversible.**
- **New particles can then decay in the FV in visible modes**

NA62++ in Run3

- Already O(10^{16}) POT in dump mode were collected by NA62 in 2016-2018 and analysed for background studies

- NA62++ proposes to operate the detector in beam dump mode for few months during Run 3 in 2021-2023:
  - O(10^{18}) POT can be collected in about 3 months of data taking
  - the muon halo emerging from the dump is partially swept away by the existing muon clearing system, but an upstream veto is under study for further reduction



- The physics potential of NA62++ has been studied as part of the Physics Beyond Colliders – Beyond the Standard Model working group

- Following slides show NA62++ expected sensitivity assuming O(10^{18}) POT

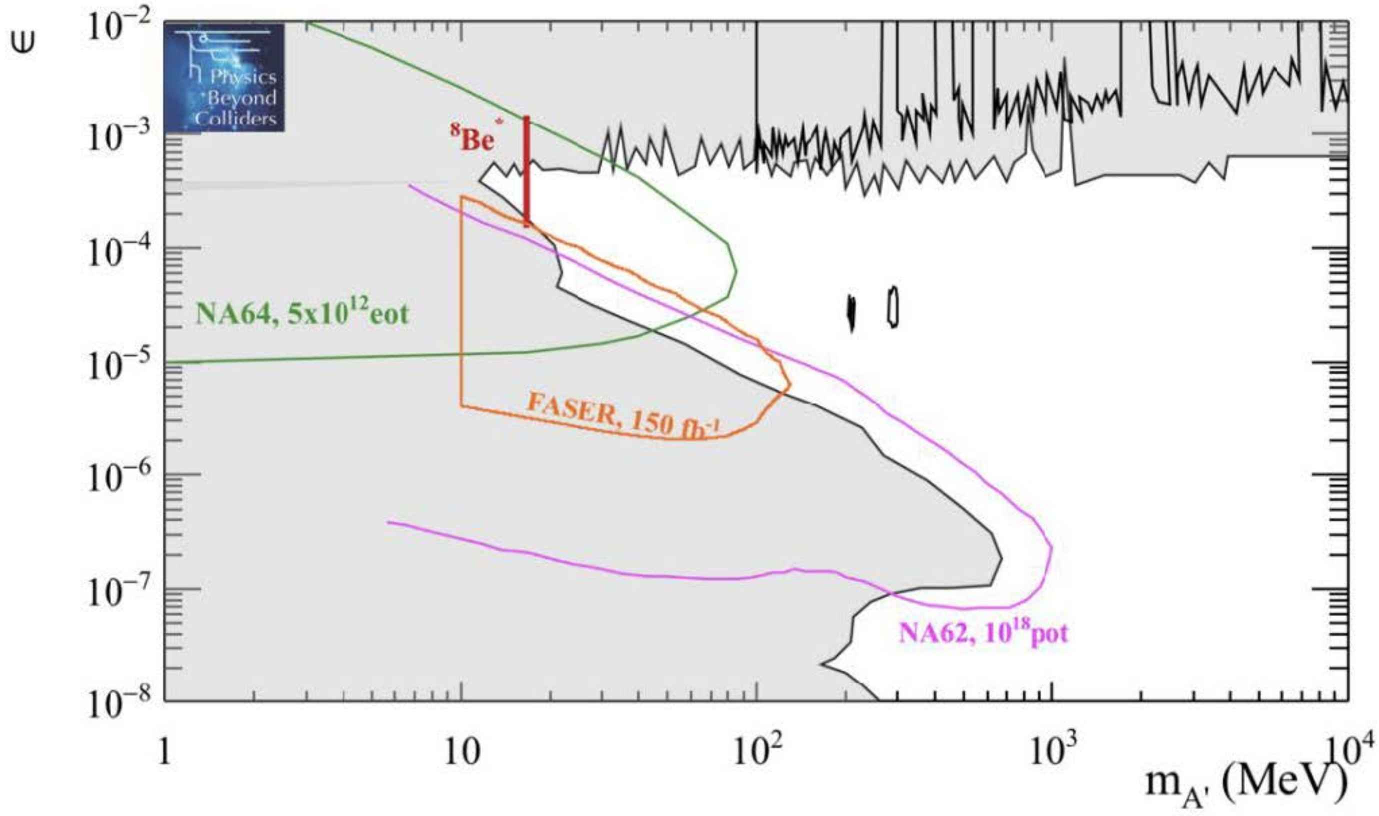
- The limits are set at 90% CL and are compared to other results expected on a 5-year scale

arXiv:1901.09966

NA62 sensitivity to dark photon

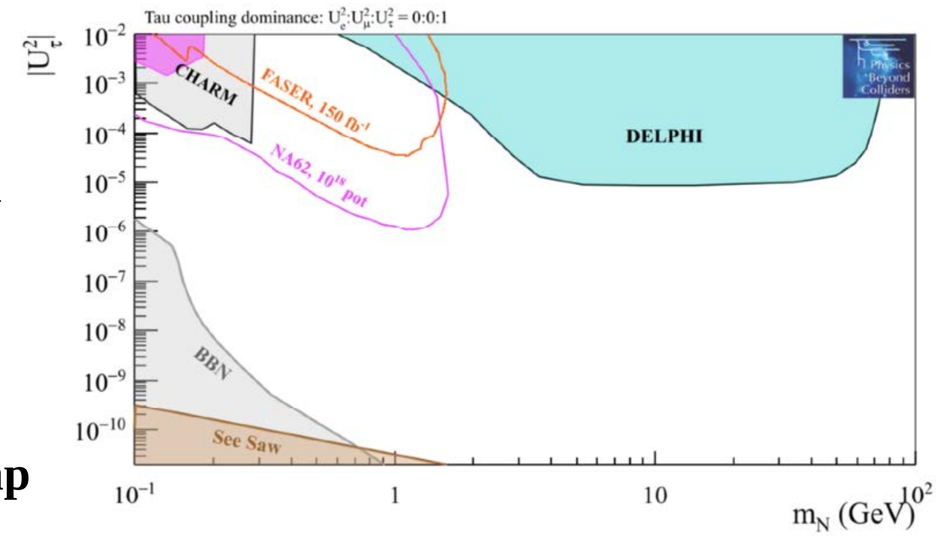
- **A' produced (meson decays, bremsstrahlung) from interaction into target**
- **Search for displaced, dilepton decays of dark photons, $A' \rightarrow \mu\mu, ee$**
- **Include trigger/acceptance/selection efficiency**
- **Assume zero-background, evaluate expected 90%-CL exclusion plot**

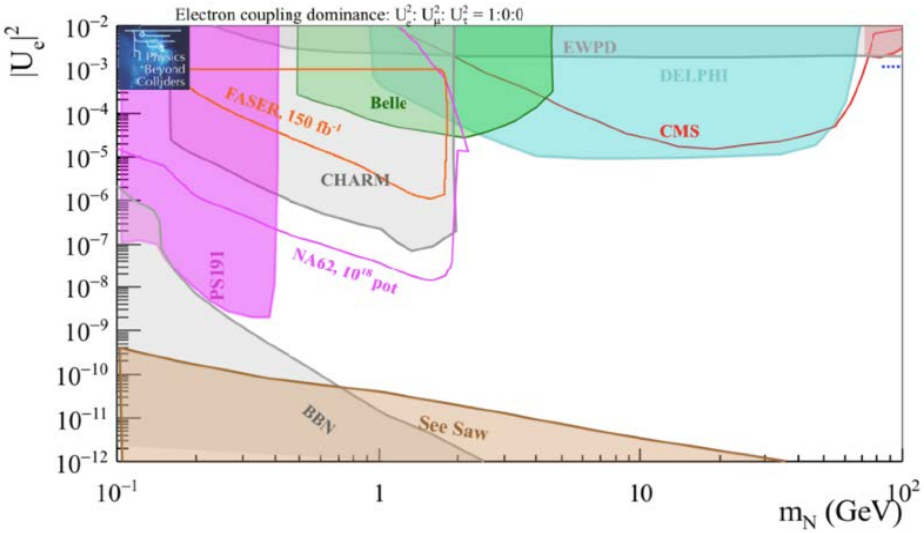
Sensitivity expected to be even higher including direct QCD production of A' and production in the Cu-based dump (only Be-target considered here)

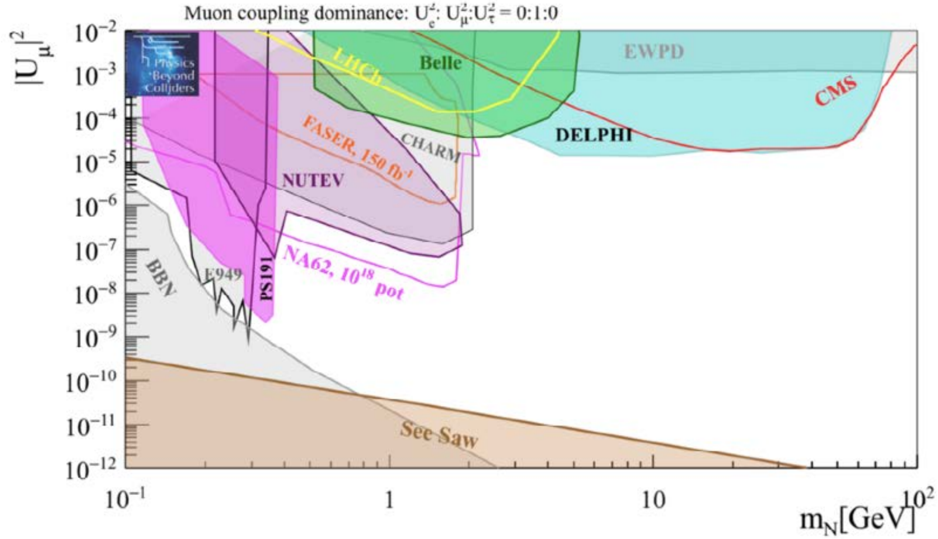


NA62 sensitivity to HNL

- **HNL produced in the decay chain:**
  $$D(Ds) \longrightarrow l^+ N, \qquad N \rightarrow \pi l$$
- **Account for trigger/acceptance/selection efficiency**
- **Assume zero-background**
- **Analysis of 3×10^16 POT collected in dump mode in 2016-2018 in progress**



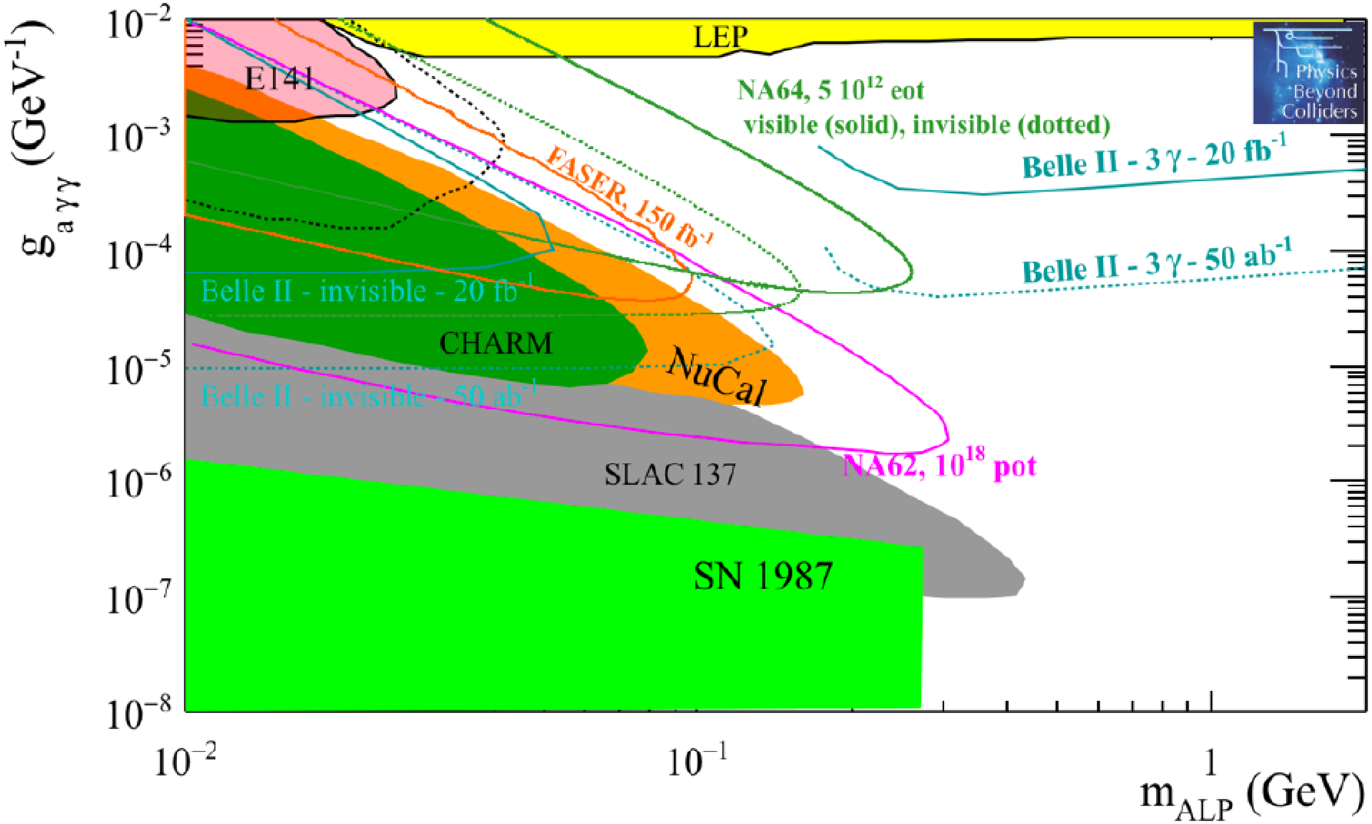




NA62 sensitivity to ALP

- **Good candidate for cold dark matter, produced via elastic scattering of beam proton dumped onto NA62 Cu collimators (Primakoff effect)**
- **Decay searches can be performed for ALP→γγ in MeV/c^2-GeV/c^2 mass range**
- **Ongoing analysis of 2017-2018 data taken in beam-dump mode (closed beam collimators) with 2×10^{16} POT.**

Expected sensitivity in zero-background hypothesis, account for geometrical acceptance. Improvements expected already with 1 day of run (1.3×10^{16} POT)



NA62 sensitivity to scalar

- Dark Scalar S : light scalar mixing with Higgs with angle θ, mediator between DM and SM particles. In the simplest scenario only one parameter controls production and decay processes.

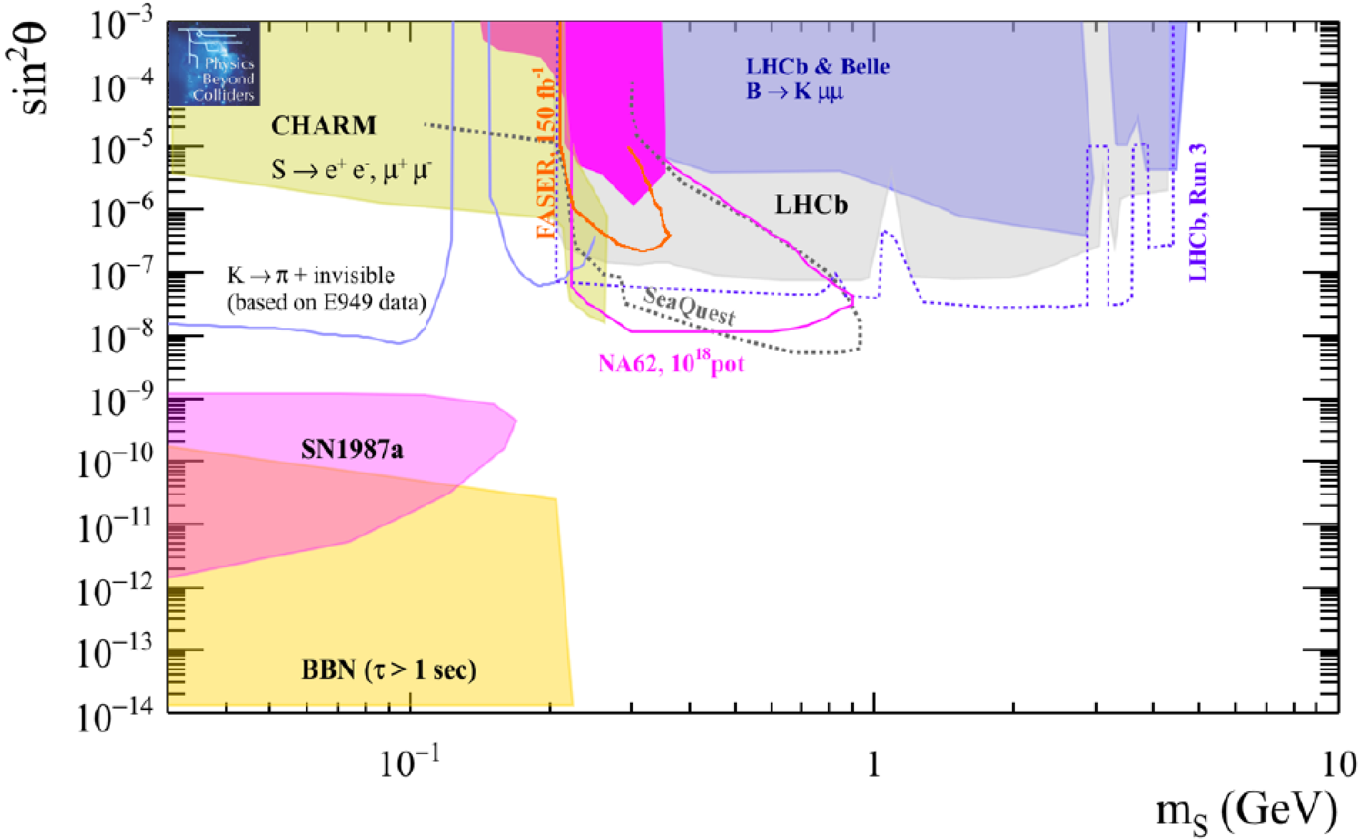
Dump mode:

$S \rightarrow \mu^+\mu^-$

but also accessible in NA62 kaon mode:

$K^+ \rightarrow \pi^+ S,\ S \rightarrow \text{inv}$

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



Conclusions

- ✓ **NA62 took data with the complete detector in 2016-2018. Owing to the high beam energy and high beam intensity, the long decay volume and the hermetic detector coverage, NA62 has the opportunity to directly search for a plethora of exotic decays**

- ✓ **Recently published results have been presented on HNL and Dark Photon searches with partial data sample**
  - **best limits set on $K^+ \to l^+ N$**
  - **limits on $\pi^0 \to \gamma A'$**

- ✓ **In Run3, $\pi\nu\nu$ program completion, then partially running in beam-dump mode: limit improvements for HNL, Dark Photon, Dark Scalar and ALPs have been shown**

- ✓ **Exploiting the available NA62 data:**
  - **preliminary studies indicate sufficient background rejection power**