Search for an invisible vector boson from π^0 decays at NA62

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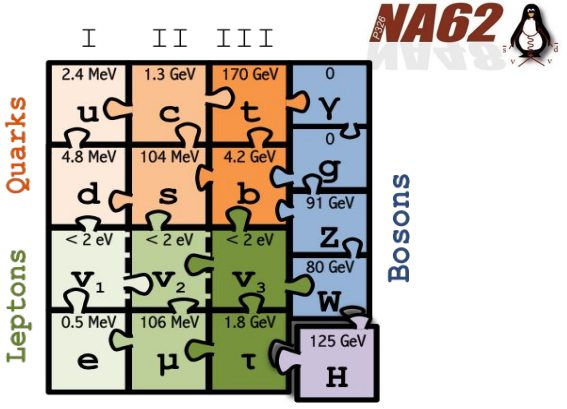
NA62

Outline

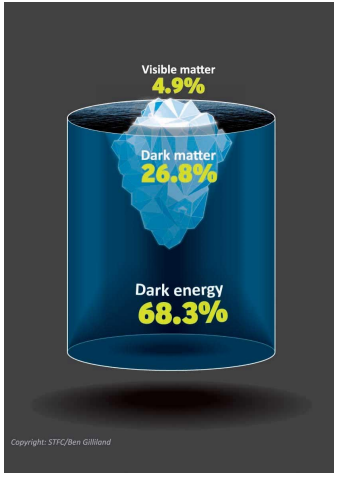
- Search for New Physics: Hidden Sectors
  - Vector portal
- The NA62 experiment at CERN SPS
- Search for a dark photon from π^0 decays at NA62
- Further opportunities for hidden sector searches at NA62
- Summary

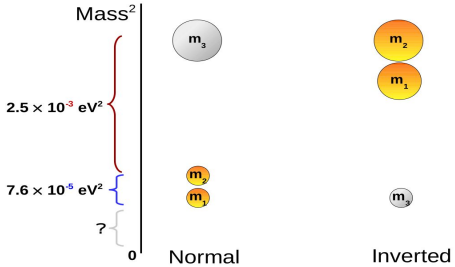
Search for New Physics: Hidden Sectors Motivations



The discovery of the Higgs boson at LHC had completed the Standard Model pattern, giving an additional confirmation of the most successful model of particle physics.

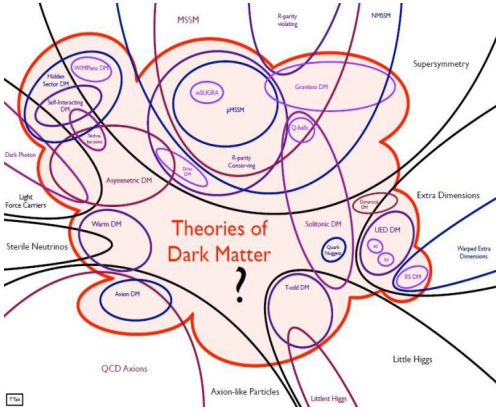
Nevertheless there are both theoretical and experimental issues, which do not find an explanation within the SM.
From cosmological and astrophysical observations





Hidden sectors consisting of new light, weakly-coupled particles that do not interact with the known forces are a particularly compelling possibility for new physics and can be accessible to intensity frontier experiment

Search for New Physics: Hidden Sectors Motivations



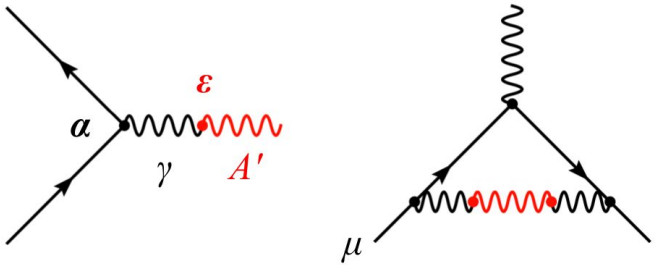
There are numerous hidden sectors,

- Vector portal → Dark Photons
- Scalar portal → Dark Scalars
- Neutrino portal → Heavy Neutral Leptons
- Axion portal → Axion-like particles

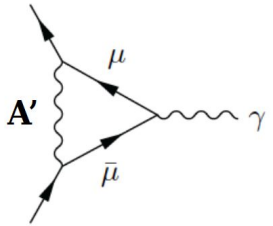
each with their own structure, particle, forces, providing excellent dark matter candidates and solving puzzles in particle and astroparticle physics

The simplest hidden sector model introduces an extra U(1) gauge symmetry with a corresponding new vector mediator field $\mathcal{A}'$ with a mass $M_{\mathcal{A}'}$, called dark photon [B. Holdom Phys.Lett. B166 (1986) 196]

$$\mathcal{L}_{mix} = \epsilon A'_{\mu\nu} F^{\mu\nu}$$



Interaction of a dark photon, in the MeV-GeV mass range, with SM particles can provide possible explanation for the 3.5 σ discrepancy in the muon (g-2) measurement

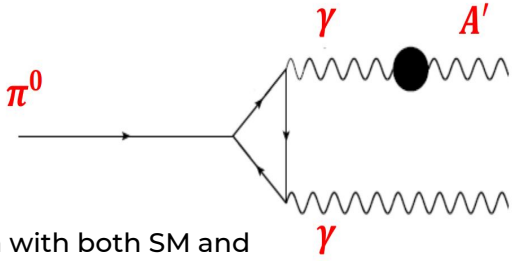


Dark Photon in π^0 decays

The dominant production mechanisms for the $\mathcal{A}'$ vector boson depends on the mass scale of the hidden sector portal.

If $M_{\mathcal{A}'} < M_{\pi}$ the dominant production mechanism is:

$$\pi^0 \to \gamma A' \qquad A' \to invisible$$



(if further interaction with both SM and secluded HS fields are lighter than the $\mathcal{A}'$)

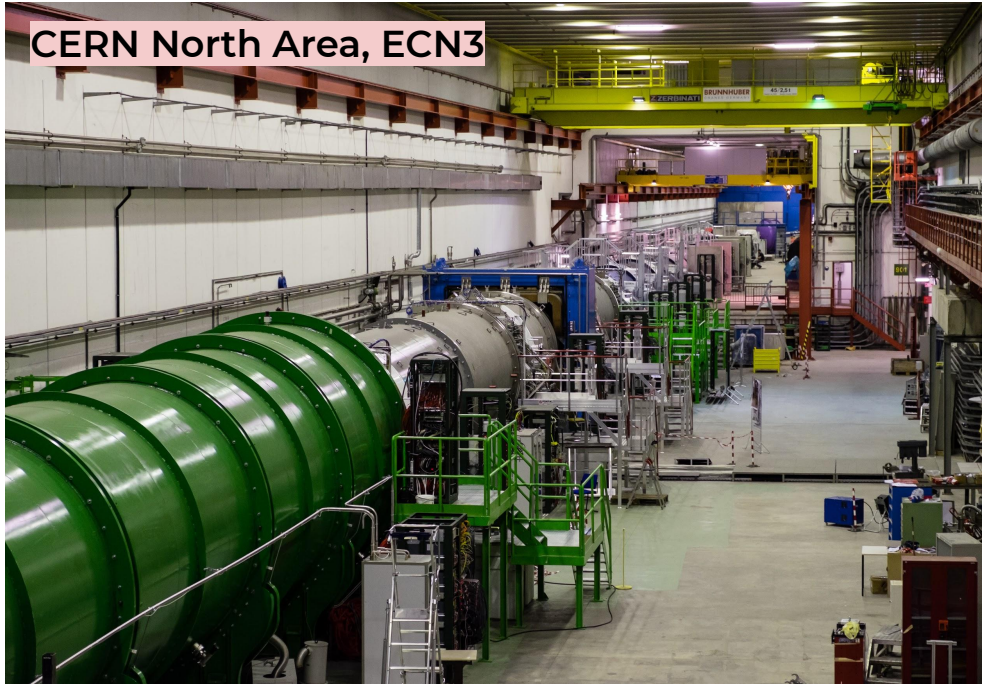
$$Br(\pi^0 \to \gamma A') = 2\epsilon^2 \left(1 - \frac{M^2_{A'}}{M^2_{\pi^0}}\right)^3 \times Br(\pi^0 \to \gamma\gamma)$$

Large production of π^0:

- @ colliders : $e^+e^- \to \rho,\eta,\Phi$
- @ fixed target experiment: production at target
- @ fixed target experiment: using a cascade process, where the π^0 is one of the products

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

The NA62 experiment at CERN SPS



~ 200 participants , 29 institutions from 13 countries

Data-taking: 2016-2018
Prepare for data-taking after LS2 (2021-2023)

Kaon physics at CERN

- Fixed target experiment
  (400 GeV/c proton from SPS onto a Beryllium target)
- Kaon decay-in-flight technique
  ~5 MHz K^+decay rate within the fiducial volume

Main goal:

Measure $Br(K^+ \to \pi^+ \nu\bar{\nu})$

with O(10%) precision

N.Lurkin's talk @ Flavor Physics and CP Violation parallel session

SM prediction :

$$Br(K^+ \to \pi^+ \nu\bar{\nu}) = (8.4 \pm 1.0) \times 10^{-11}$$

[Buras et al. JHEP 1511(2015)33]

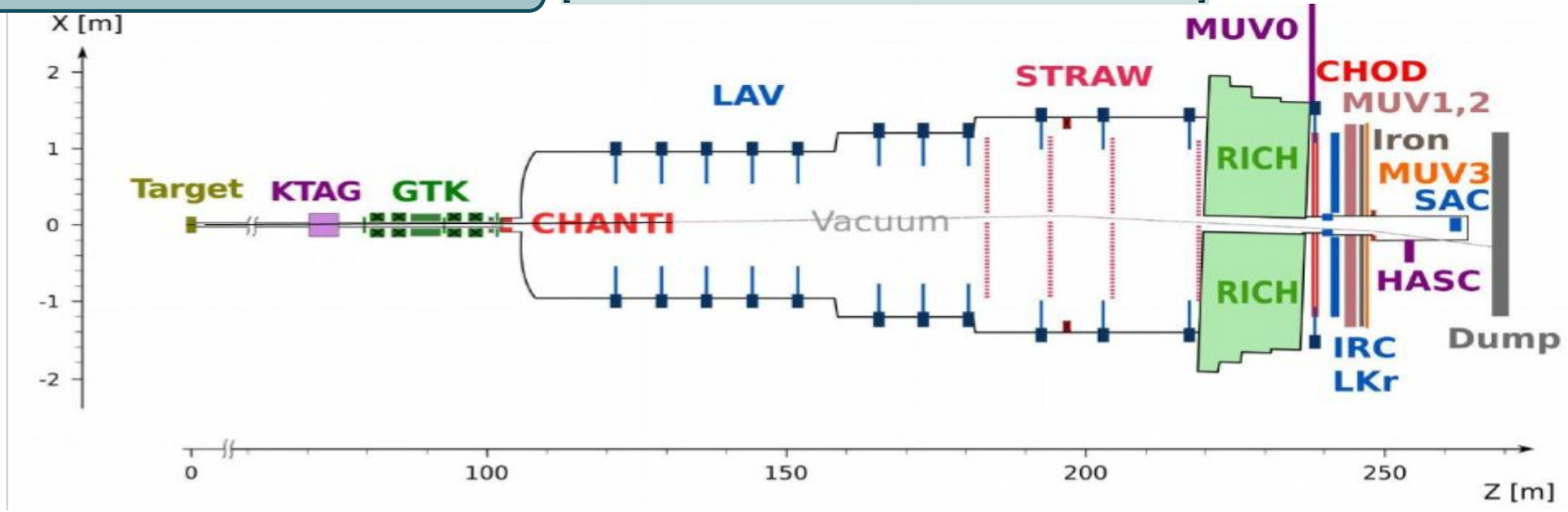
A large number of additional studies possible:

- Exotics searches — **This Talk**
- Rare and forbidden decays

A.Romano's talk @ Flavor Physics and CP Violation parallel session

The NA62 experiment

[NA62 Collaboration 2017 JINST 12 P05025]



Beam

Primary beam
400 GeV/c SPS proton on a Beryllium target
~10^{12} proton/s on spill (4.8 s spill)

Secondary beam:
75 GeV/c 1% bite
p:π:K= 23%:70%:6%
750 MHz

Kaon decay region

60 m long
vacuum O(10^{-6})mbar
~5 MHz K^+decay rate

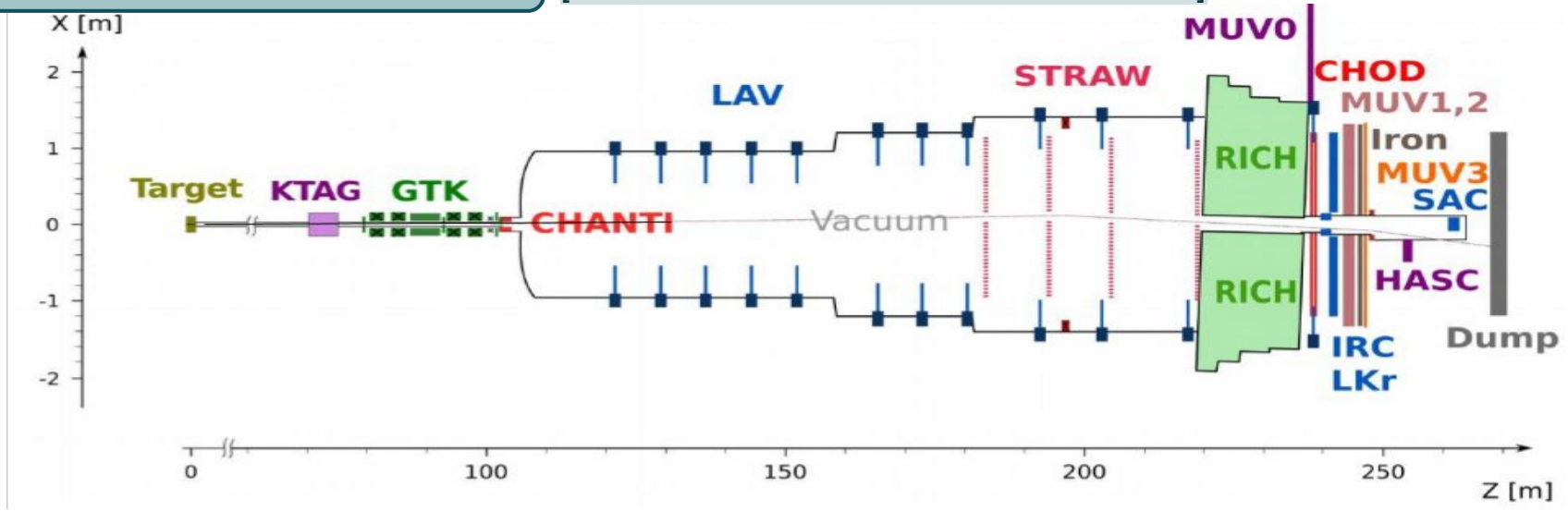
Tracking & ID

Beam Particles
CEDAR/KTAG: tag beam kaons
time resolution ~70 ps
GigaTraKer: beam particle tracking
time resolution ~ 100 ps
momentum resolution ~0.2 GeV/c

Decay Particles
STRAW: track decay charged particle,
RICH: ID of decay charged particles
time resolution ~100 ps

The NA62 experiment

[NA62 Collaboration 2017 JINST 12 P05025]



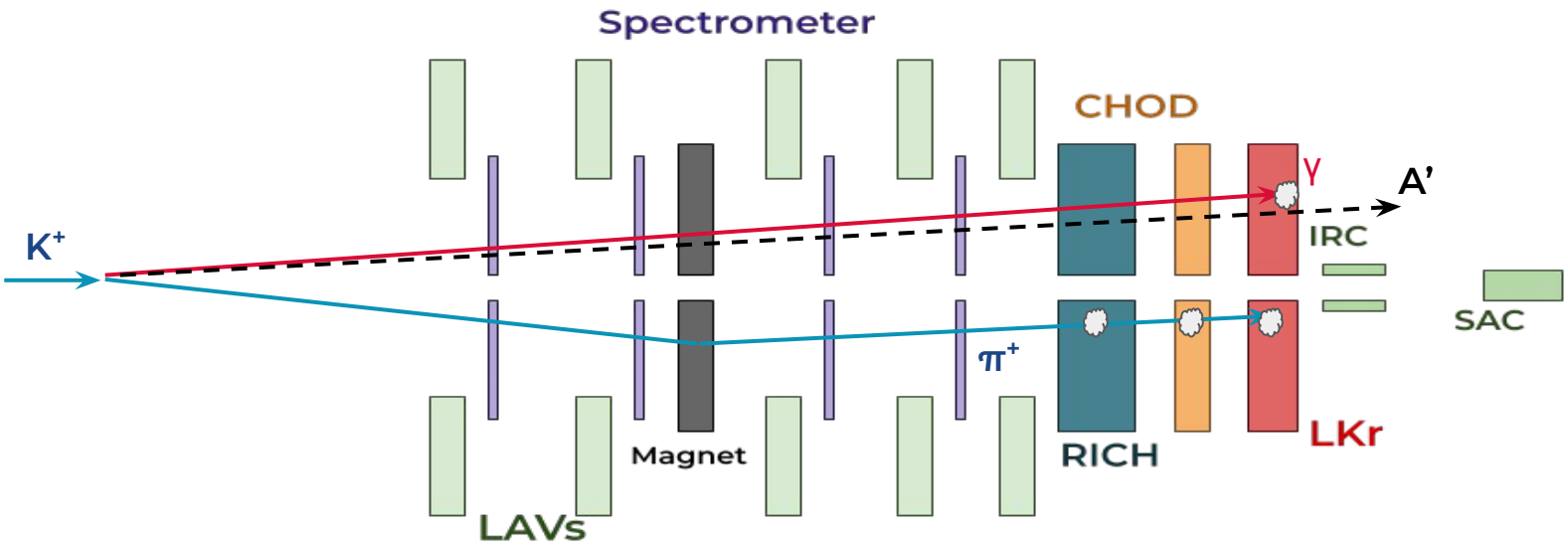
Performances:

- **Excellent time resolution O(100 ps)** to match beam and daughter particles (KTAG-GTK-RICH)
- **Kinematic background rejection O(10^4)** via kinematics reconstruction
- **High PID capability: O(10^7) π-μ separation** in 15-35 GeV/c momentum range
- **High photon-veto efficiency: O(10^8) π^0 rejection** for E(π^0) > 40 GeV

The high intensity, full particle identification, hermetic coverage, low material budget and high rate tracking of the NA62 detector perfectly adapt to perform several studies

Search for Dark Photon: Analysis Strategy

Search performed under the hypothesis of an invisible decay of a massive A' or long lived massive A'



Search for a peak in the missing mass distribution

$$M^2_{miss} = (P_K - P_\pi - P_\gamma)^2$$

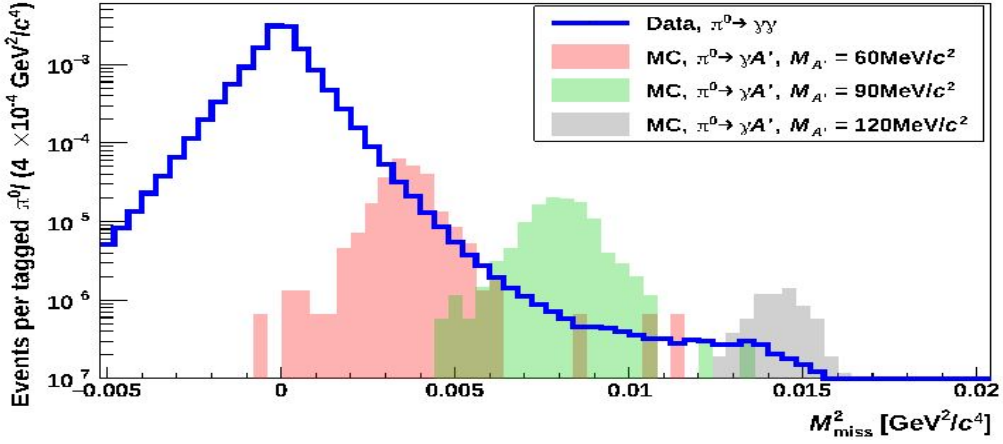
The results reported are from a subsample of 2016 data, corresponding to 1% of the full statistics collected by NA62 in 2016-2018

Search for Dark Photon: Analysis Strategy

$$M^2_{miss} = (P_K - P_\pi - P_\gamma)^2$$

M_{miss} Is expected to peak at $M_{A'}$ for the signal and at zero for the most abundant background $\pi^0 \to \gamma\gamma$

Data and MC A' signals with masses of 60,90, and 120 MeV/c^2 and ε^2=2.5 × 10^{-4}



Two trigger lines used:

- **Minimum-bias trigger:** to define the statistics of tagged π^0 mesons for normalization ($n_{\pi 0}$)
  K^+, π^+ - ID, $M_{miss}=(P_K-P_\pi)$ around the π^0 mass peak.
  $n_{\pi 0}$= 4.12 × 10^8 (accounting for the trigger downscaling factor)

- **Signal-trigger**: more strict conditions on π^+ to enforce the presence of a single charged track and only one photon on the LKr: photon veto, missing momentum pointing to LKr, veto on CHOD extra activity.

Search for Dark Photon: Analysis Strategy

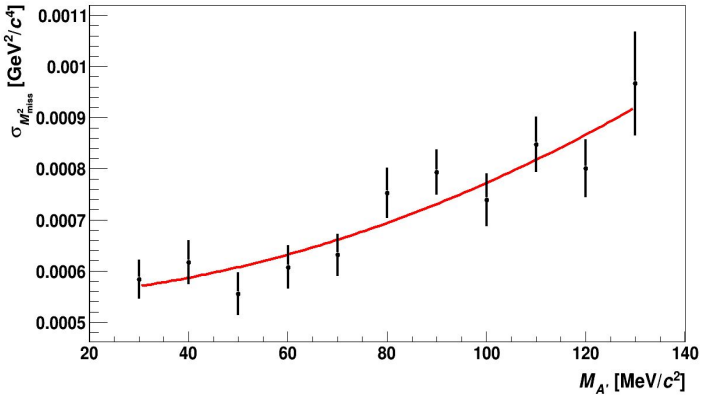
Peak search in the positive tails of M^2_{miss} distribution is performed.
n_{sig} counted in a sliding M^2_{miss} window of ($\pm 1\sigma_{M2miss}$) for each $\mathcal{A}'$ mass hypothesis

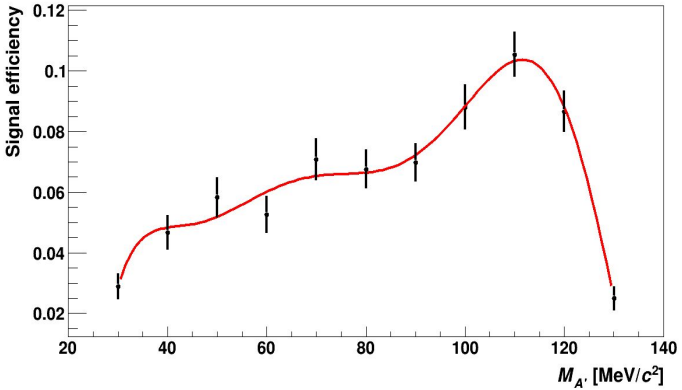
From n_{sig} to ε^2 coupling constant

$$Br(\pi^0 \to \gamma A') = Br(\pi^0 \to \gamma\gamma)\frac{n_{sig}}{n_{\pi^0}}\frac{1}{\epsilon_{sel}\epsilon_{trig}\epsilon_{mass}}$$

- ε_{sel} and ε_{trig} depend on the $M_{\mathcal{A}'}$
- ε_{mass} acceptance of the sliding M^2_{miss} window
- A_{geo} and π^0-tagging efficiency identical for signal and normalization

M^2_{miss} resolution in (30-130) MeV/c^2 mass range from MC simulation





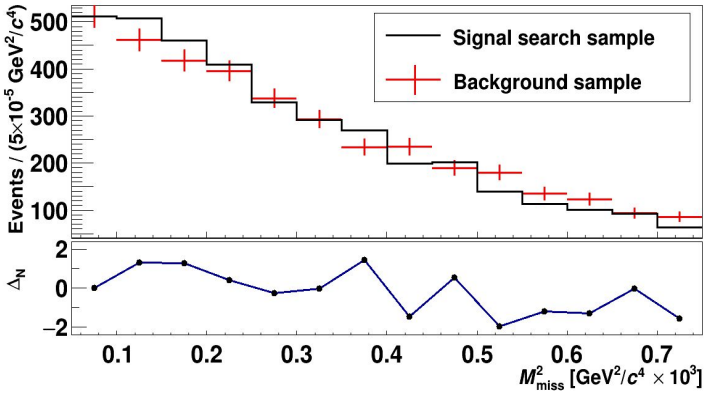
Total signal efficiency in (30-130) MeV/c^2 mass range from MC simulation

Search for Dark Photon: Background

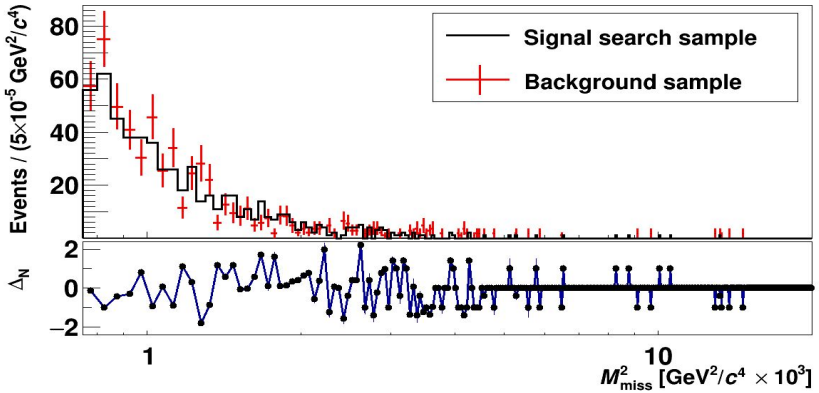
Most abundant background is $K^+ \to \pi^+\pi^0$,$\pi^0 \to \gamma\gamma$ with one photon lost due to photo-nuclear interaction or conversions downstream of NA48-CHOD.

Data-driven approach to evaluated the expected background:

- the same selection for the signal are applied but the cut on the NA48-CHOD extra activity → the sample is populated of $\pi^0 \to \gamma\gamma$ events with one photon lost due to photon conversion upstream the NA48-CHOD

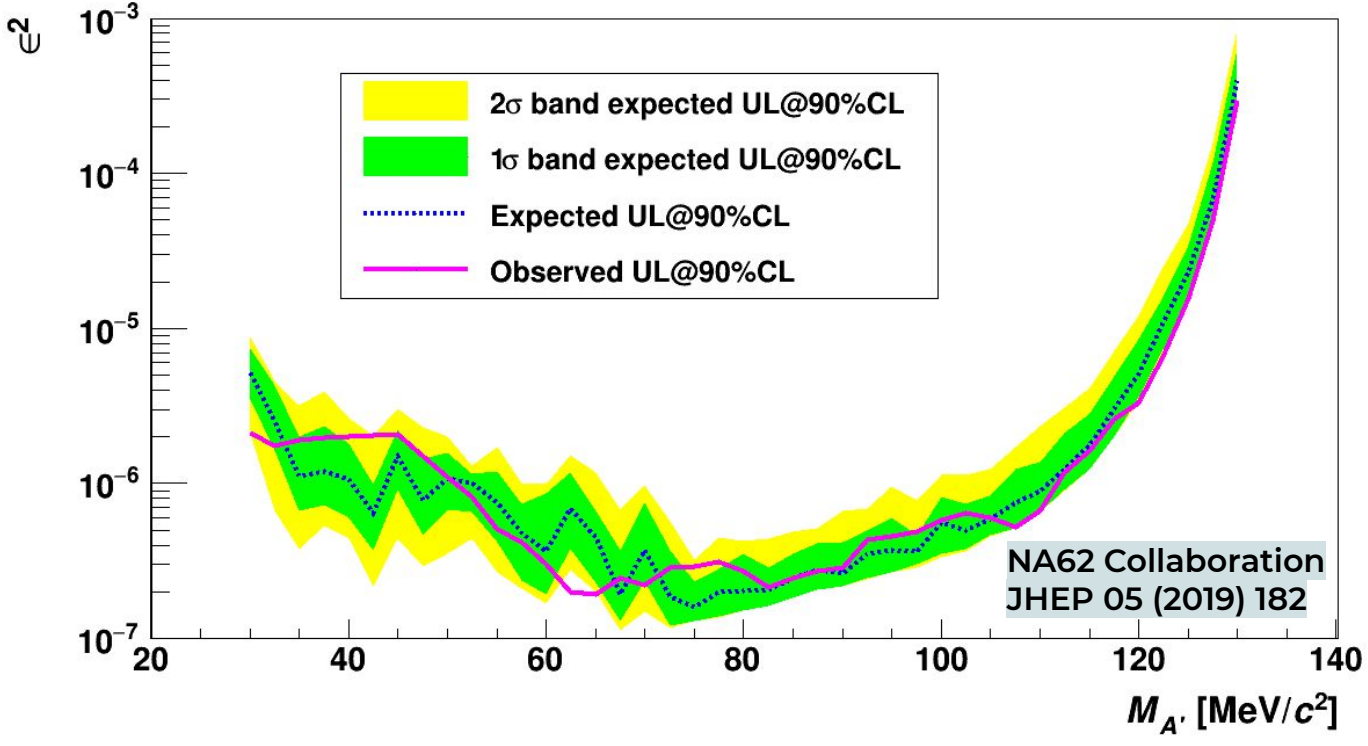


The background sample is scaled to the signal sample in a side-band region adjacent to but not overlapping with the *A'* search region:
$0.00005 < M^2_{miss} < 0.00075$ GeV^2/c^4



The *A'* search region is $0.00075 < M^2_{miss} < 0.01765$ GeV^2/c^4 for all the mass hypotheses (30-130 MeV/c^2).
O(1) background events in the tail with $n_{\pi^0} \approx 4\times10^8$ selected

Search for Dark Photon: Results

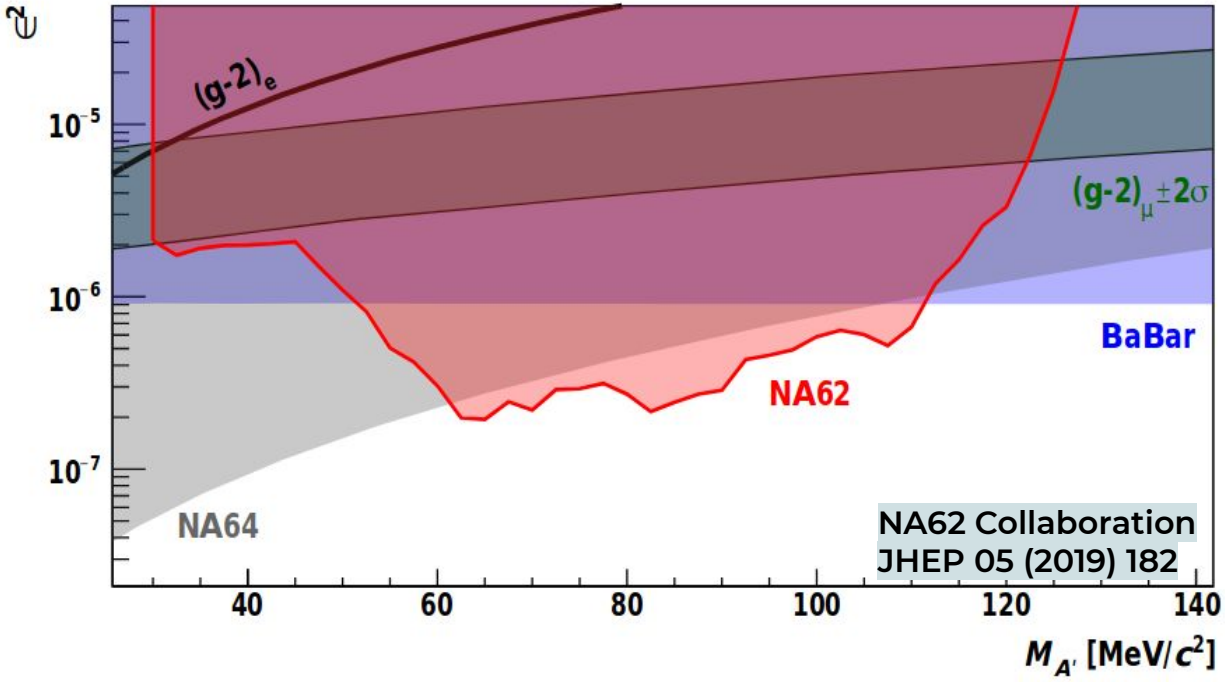


No statistically significant excess is detected: observed upper limits @ 90% CL compatible with fluctuations from the background-only hypothesis

Search for Dark photon: Results

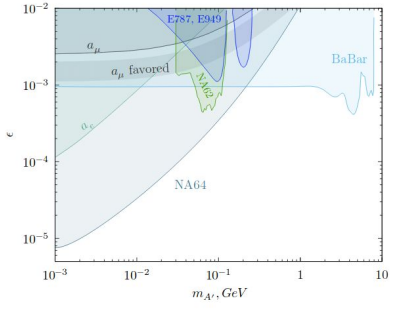
Upper Limit @ 90% CL from NA62 in the ε^2 vs $M_{A'}$ with A' decaying into invisible final state

NA62 experimental technique differs from that of previous results: models involving suppressed dark photon lepton coupling might produce a signal at NA62 despite the NA64 and BaBar experimental results.



New limits from NA64

[NA64 Collaboration CERN-EP-2019-116]

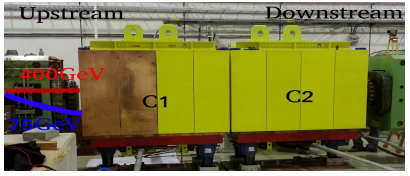


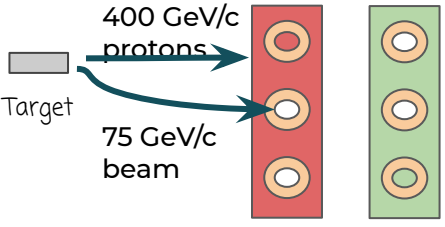
Slight changes in the analysis to conduct $\pi^0 \to \gamma\nu\nu$ search, $Br_{exp} \sim 10^{-18}$

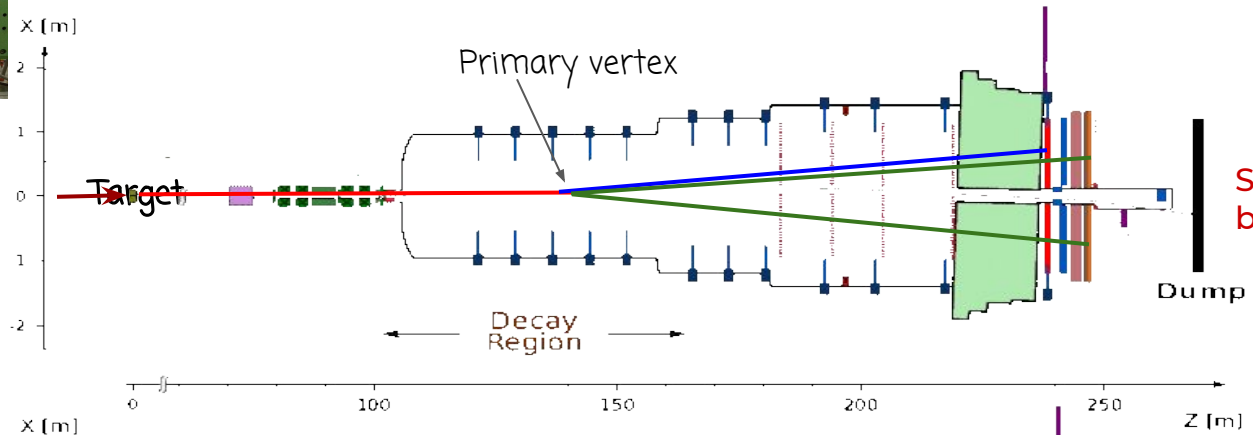
Present experimental limit:
$Br(\pi^0 \to \gamma\nu\nu) < 6 \times 10^{-4}$ at 90% CL

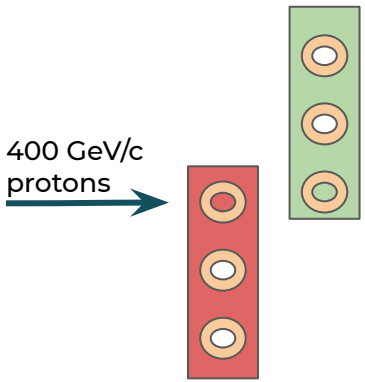
Upper limit obtained by NA62:
$Br(\pi^0 \to \gamma\nu\nu) < 1.9 \times 10^{-7}$ at 90% CL

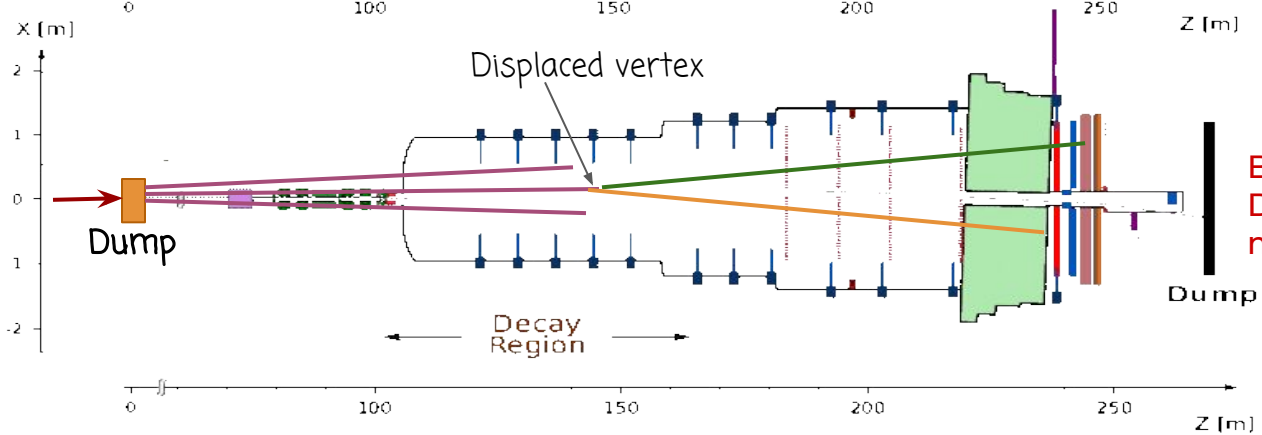
Other opportunities for hidden sector searches at NA62





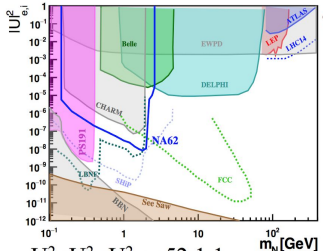




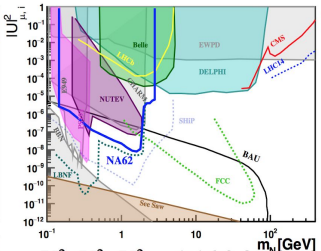


Other opportunities for hidden sector searches at NA62

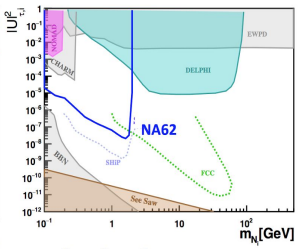
Model: Gorbunov, Shaposhnikov JHEP10(2007)015



$U^2_e : U^2_\mu : U^2_\tau = 52:1:1$
Normal hierarchy of active ν masses



$U^2_e : U^2_\mu : U^2_\tau = 1:16:3.8$
Normal hierarchy of active ν masses



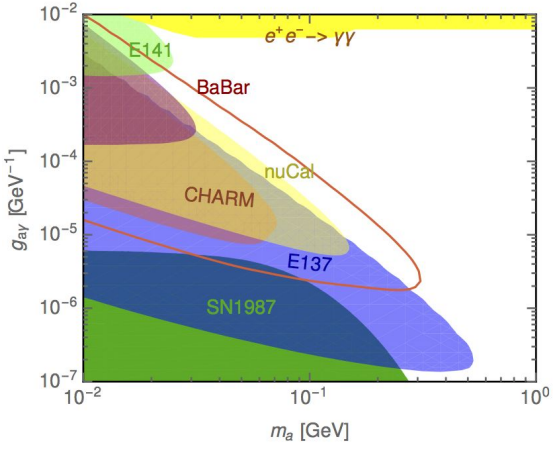
$U^2_e : U^2_\mu : U^2_\tau = 0.061:1:4.3$
Normal hierarchy of active ν masses

- **Search for long lived HNLs** produced in the TAXes decaying in $\nu_h \to \pi\mu$, $\nu_h \to \pi e$
  NA62 estimated sensitivity for 10^{18} POT
  assuming complete background rejection

- **ALPs produced in dump mode** directly in TAX
  via protons-nucleus elastic scattering
  ALPs decay in $a \to \gamma\gamma$ in fiducial volume
  NA62 sensitivity with 10^{18} POT, assuming zero background
  accounting for geometrical acceptance

  Expected improvements already with 1.3×10^{16} POT (1 day run)

  Analysis of 2017 beam-dump data is ongoing [~5×10^{15} POT]



- **Visible decays of long-lived $\mathcal{A}'$** produced from interaction into target/dump. Search for displaced dilepton vertex: $\mathcal{A}' \to \mu\mu$, $\mathcal{A}' \to ee$ in the fiducial volume.
  Expected improvements particularly relevant in the mass region of several hundreds of MeV.

Summary

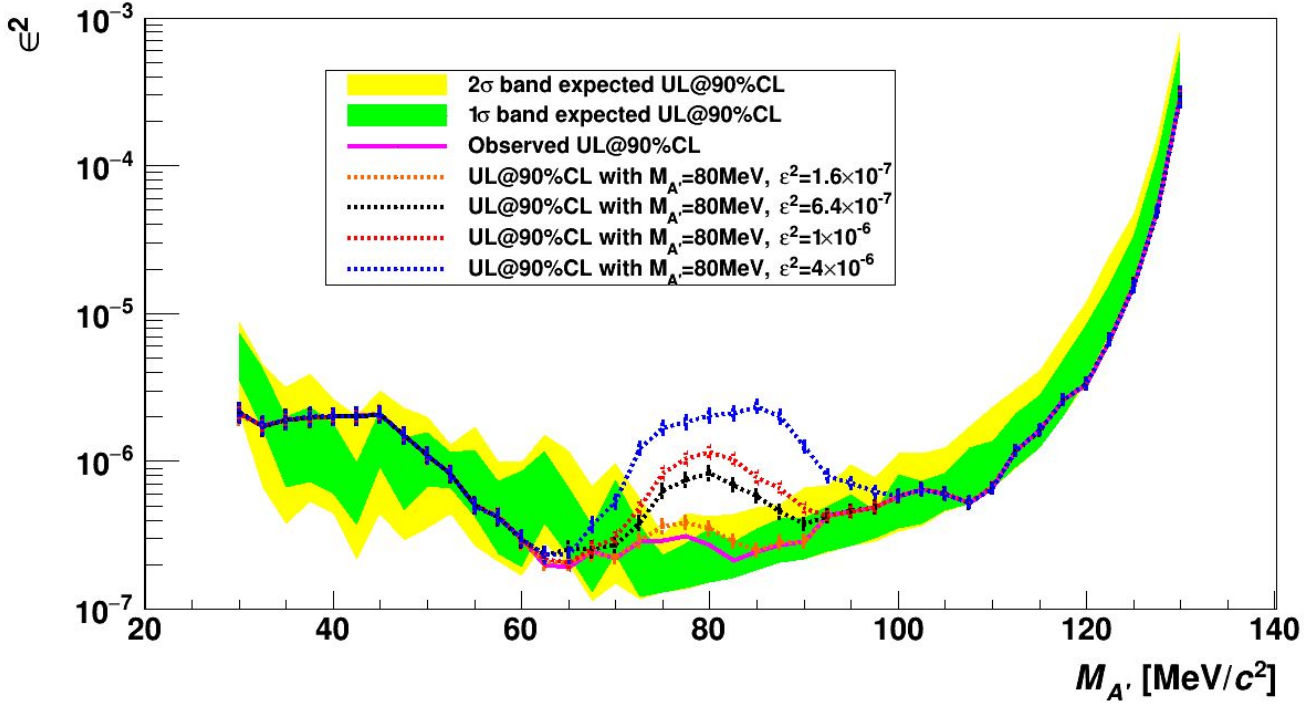
- The NA62 experiment took data with the complete setup in 2016-2018
- **A search for an invisible dark photon A' has been performed**, analysing a subsample from the 2016 data, corresponding to 1% of the full statistics, exploiting the efficient photon-veto capability and the high resolution tracking of NA62. **No A' signal is observed.**
- New limits set by the NA64 collaboration. Nevertheless the analysis of more data by the NA62 collaboration can set new improvements in the coupling - A' mass plane.
- Slight changes in the analysis in order to perform a **search for $\pi^0 \to \gamma\nu\bar{\nu}$** (Br $\approx 10^{-18}$ within the SM).
  An upper limits is set, **Br<1.9 × 10^{-7} at 90% CL**, improving the current upper limit by more than three order of magnitude
- The NA62 experiment is suited to perform a large variety of searches and it is already equipped to run in dump mode:
  Sensitivities with 10^{18} POT for HNLs, ALPs, visible decays of long-lived A' searches have been presented showing possible improvements

Thanks for your attentions

Backup slides

Search for Dark Photon

- A ' signal at 80 MeV/c^2 added to data collected with different values of ε^2 taking into account the full selection and trigger efficiency with its uncertainty.
- Statistical treatment applied to the signal-injected samples to prove the discovery sensitivity of the analysis



Systematic

- Data and MC missing mass distribution agree within 10%
  (estimated with a full reconstructed $K^+ \to \pi^+\pi^0$, $\pi^0 \to \gamma e^+ e^-$)
- The lower edge of the window used to evaluate the scale factors to compare background and signal-search samples has been varied: -0.00015, 0.00015, 0.00025 GeV^2/c^4
- The signal window has been varied: ±0.9,±1.1 and ±2 σ_{M2miss}
- The uncertainties on the signal efficiency, including statistical and systematic errors have been considered