Study of exotic processes @ NA62

Dario Soldi on Behalf of the NA62 Collaboration

08 – October 2018

NA62 – general purpose experiment

Flavor

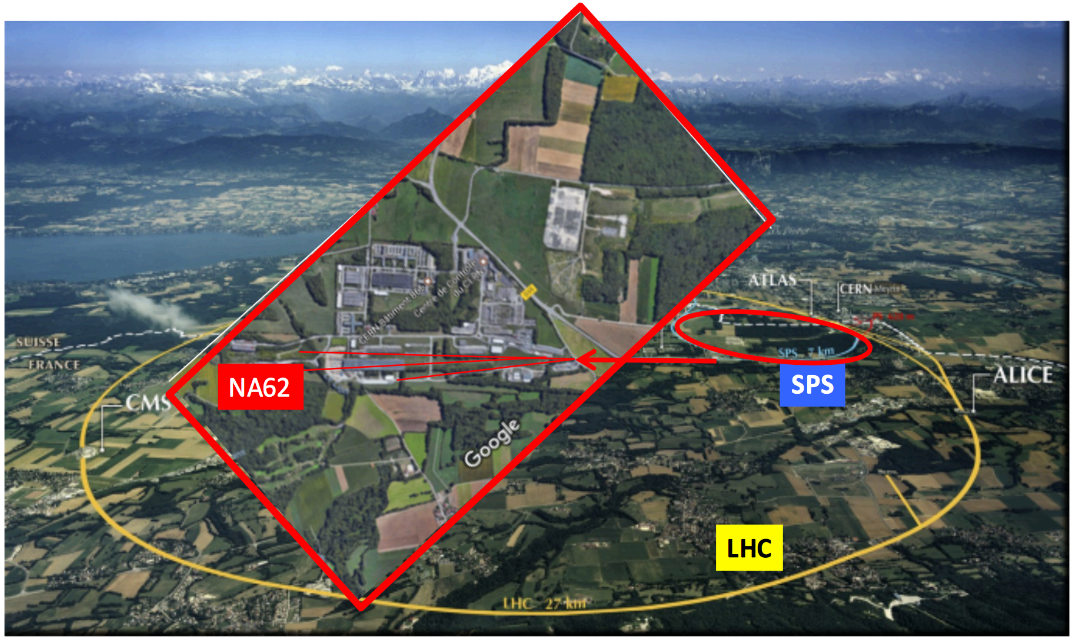
Search for new Physics at the EW scale with sizeable coupling to SM particles via indirect effects in loops: Golden mode: **$K^+ \rightarrow \pi^+ \nu\nu$**

Hidden Sector Physics

Search for New Physics below the EW scale (MeV-GeV range) feebly-coupled to SM particles via direct detection of long-lived particles: **HNL, Dark Photons, ALPs**

Fast recap of NA62

Birmingham, Bratislava, Bristol, Bucharest, CERN, Dubna (JINR), Fairfax (GMU), Ferrara, Florence, Frascati, Glasgow, Lancaster, Liverpool, Louvain-la-Neuve, Mainz, Moscow (INR), Naples, Perugia, Pisa, Prague, Protvino (IHEP) , Rome I, Rome II, San Luis Potosi, Sofia, TRIUMF, Turin, Vancouver (UBC)



Highest energy proton beam delivered for fixed target experiments in the world

2005 Proposal

2007 Design and construction

2014 Pilot run

2015 Commissioning run

2016 Full detector installation and commissioning completed. Start of physics data taking

2016–2018 Physics runs (continue also after LS2)

In this talk I will show you some results and perspectives from data samples collected during the lasts data takings performed in 2015 and 2016.
New data are collecting now, increasing the statistics of both for the $K^+ \rightarrow \pi^+\nu\nu$ branching ratio measurement and exotics research.

NA62: an exotic particle factory

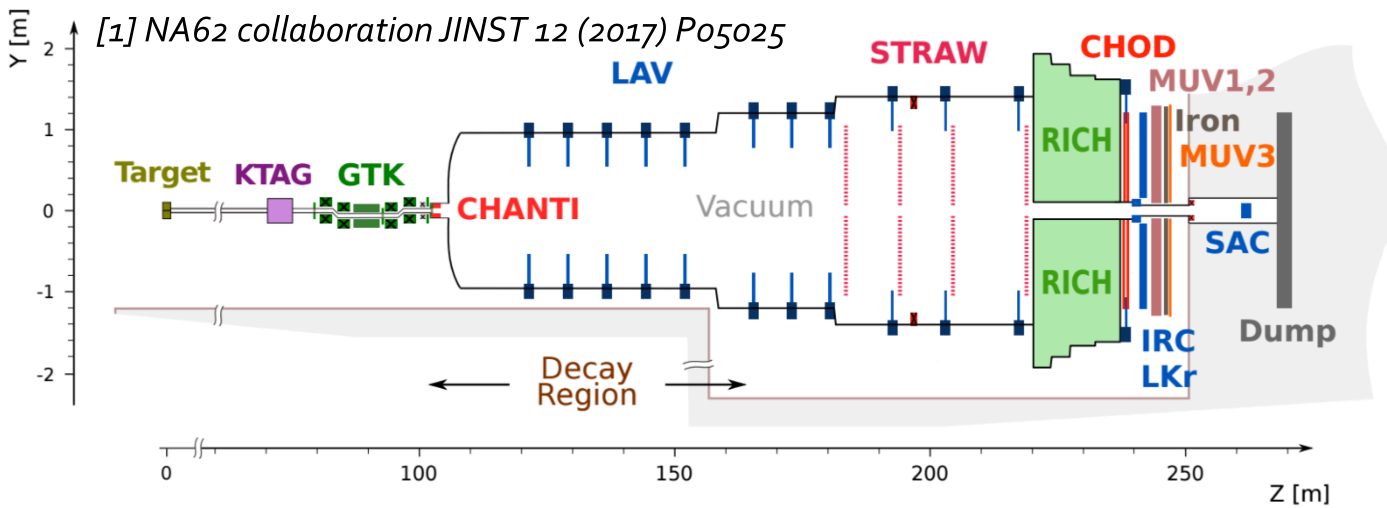
The high-intensity setup, trigger system flexibility, and detector performance as

- high - frequency tracking of beam particles (~1 GHz of beam particles → ~15 MHz trigger rate);
  - redundant PID;
    - ultra-high-efficiency photon vetoes;

make NA62 particularly suitable for searching for new-physics effect from different scenarios:

- *Heavy Neutrios* (2015 data sample);
  - *Majorana Neutrinos ($K+ \rightarrow \pi^- l^+ l^+$)*
    - *Dark Photons* (2016 data sample);
      - *ALP – Axion* (2016 data sample);

NA62: detector and strategy



Beam momentum: 75 GeV/c (±1%): 6% K^+

Subdetectors:

- *Beam Tracker*: kaon (GTK)
- *Downstream tracker*: π/μ/e (Straw)
- *Hermetic veto detectors*:
  - Photons (LAV, LKr, SAC, IRC)
  - Muons (MUV)
- *Particle identification:*
  - Kaon in the beam (KTAG)
  - π/μ/e (RICH, LKr, MUV)

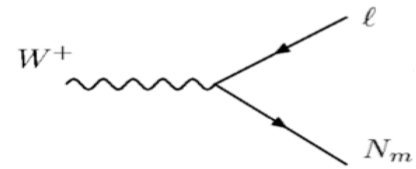
Data taking conditions in 2015:

- Minimum bias at 1% of design beam intensity;
- Beam tracker not available;
- kaon momentum estimated as beam average.

Data taking condition in 2016 - 2018:

- *Setup complete*, working at ~40 - 70% of the nominal beam intensity.

Heavy Neutrinos



Observation of neutrino oscillations -> massive neutrinos need to be accommodated in SM

The Neutrino Minimal SM (νMSM) [2] could give us a dark matter candidate explaining at the same time the neutrino masses greater than 0:

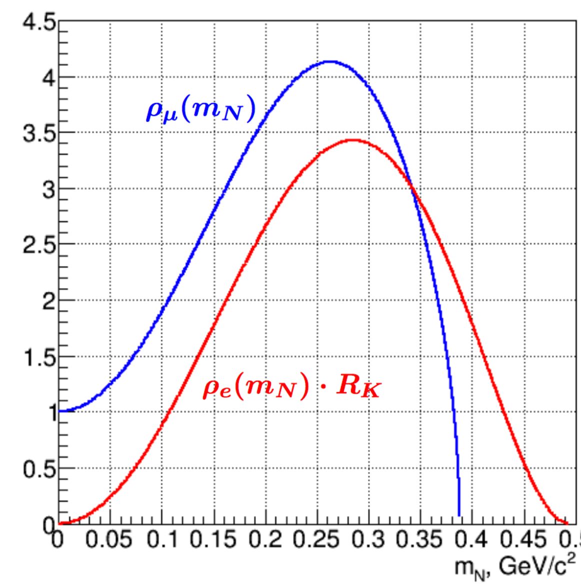
- 3 right-handed neutrinos added to SM, masses: m_1 ~ 10keV, $m_{2,3}$ ~ 1 GeV;
- N_1 can be the dark matter candidate;
- $N_{2,3}$ extra CPV-phases to account for Baryon Asymmetry, produce SM masses via see-saw mechanism.
- 18 new parameters in the Lagrangian…

in NA62: if $m_N < m_K$, heavy neutrinos become observable directly via production [3]:

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

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

Strategy: search for peaks in $m_{miss}(K_{l2}) = \sqrt{(P_K - P_l)^2}$



Data Samples:

2007: *muon sample*

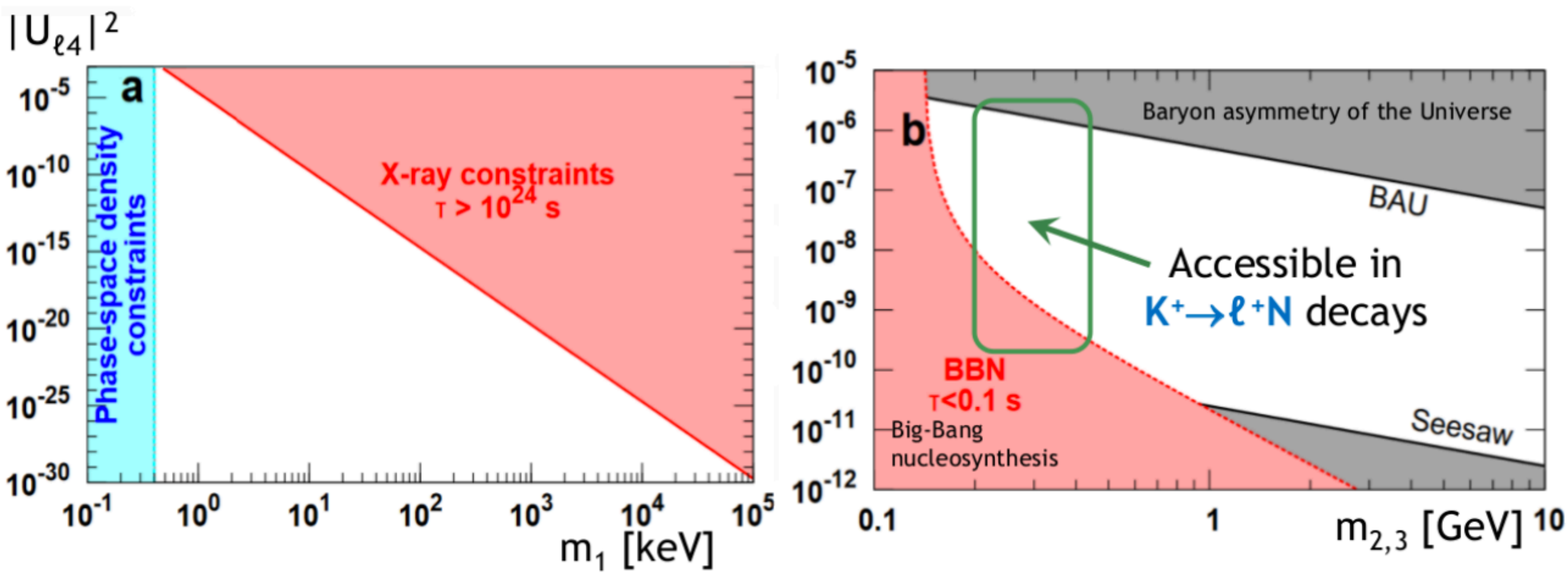
2015: *electron sample*

[2] Asaka et al., PLB 620 (2005) 17

[3] R. Shrock, Phys. Rev. D24 (1981) 1232.

Heavy Neutrinos - Production

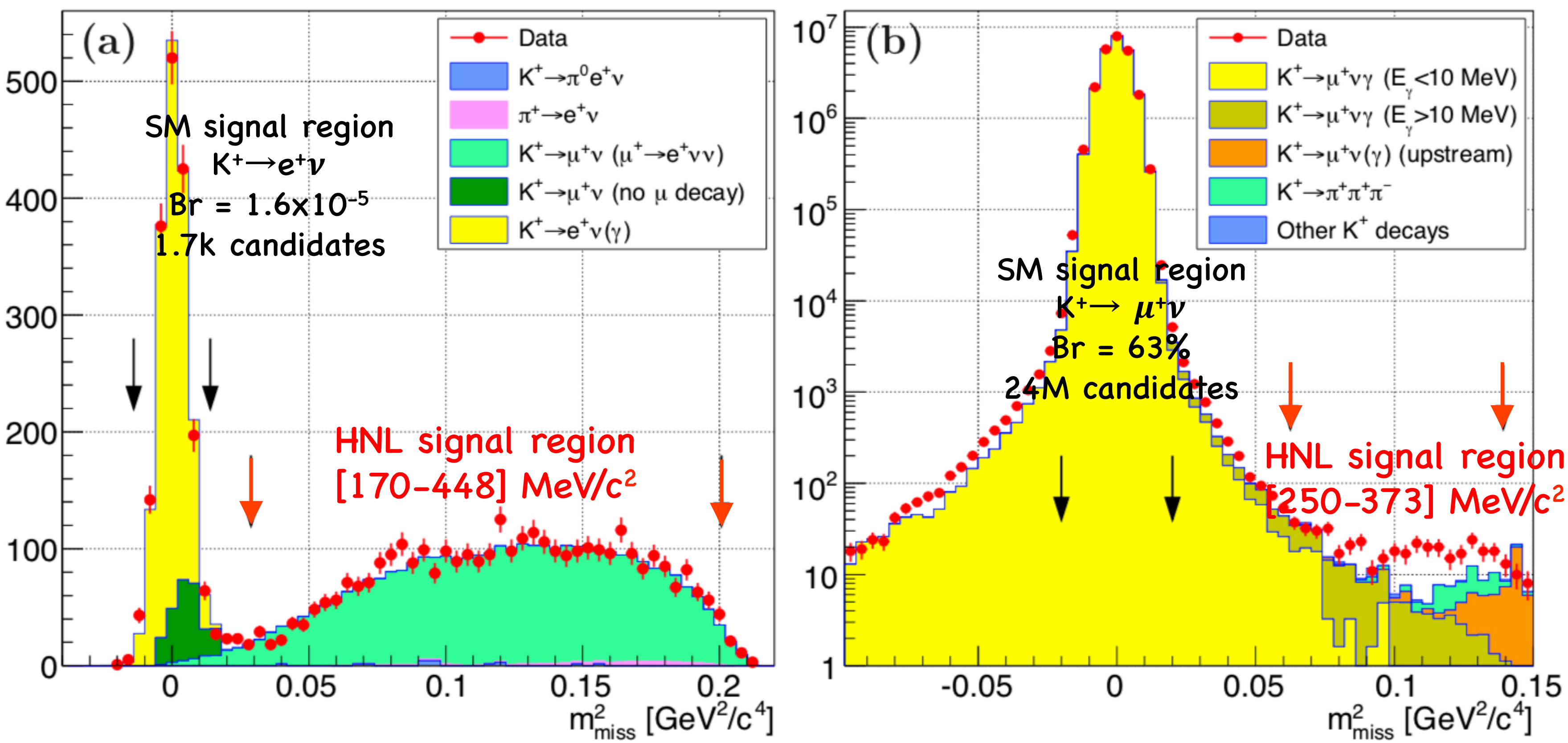
- PRODUCTION: in the decays of B, D, K and by photons originated in the interaction of protons with a target
- HNL couplings to SM particles are very suppressed - expected production rates ~ 10^{-10} or less => HNLs are long-lived
- HNL with m=1 GeV/c^2 has τ ~ 10^{-5} s and an average flight distance of > 10 km



[Boyarsky et al., Ann.Rev.Nucl.Part.Sci.59 (2009) 191]

Heavy Neutrinos – 2015 analysis

- 1 positively charged track;
- 1 single electron-cluster in the LKr;
- No photons in veto-detectors;
- Heavy neutrino mass step: 1 MeV/c²;
- Masses considered: 170 MeV/*c* < m_N < 448 MeV/*c*²;
- Rolke-Lopez method [5] used to find upper limits on number of signal events;



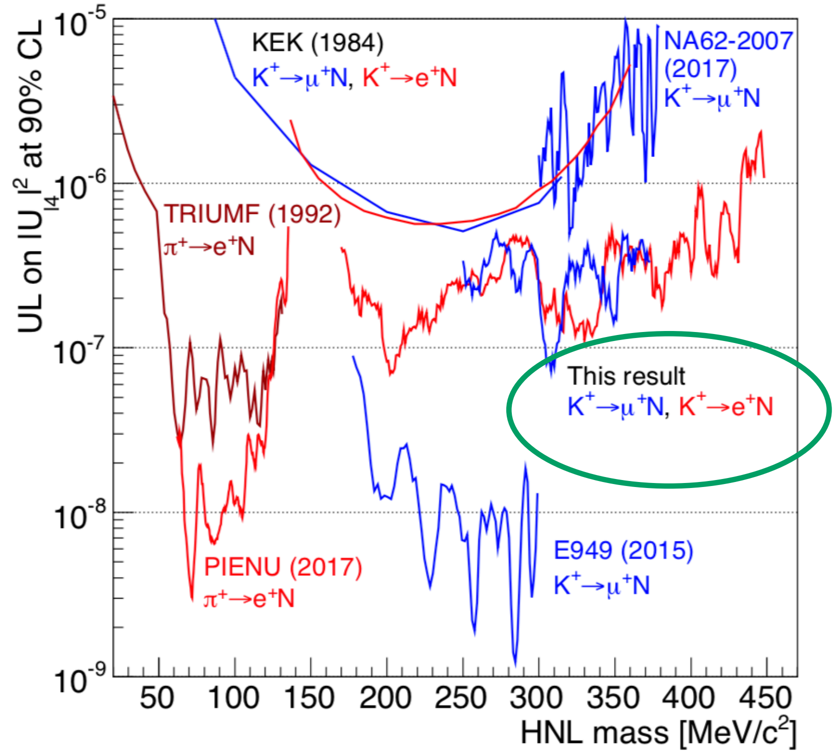
[5] ArXiv:physics/0403059

Heavy Neutrinos – 2015 results

Published results:

- **NA62 Coll. PL B778 137 (2018)**
- $N_K \sim 3.11 \times 10^8$ kaon decays in the fiducial volume
- 10^{-6}-10^{-7} limits for $|U_{\ell 4}|^2$
- mass range 170-448 MeV/c²

No excess above 3σ observed



- Analysis with 2016-2018 collected data on-going 2 order of magnitude improvement expected on $U_{\ell 4}$
- more statistics
- beam spectrometer (GTK) fully working: a factor ~2 improved HNL mass resolution
- lower background: ($K^+\to\mu^+\nu$, $\mu^+\to e^+\nu\nu$: muon decays in flight rejected geometrically);

Expected sensitivities to |Ul4|2 with 2016-18 data:
better than 10-8 for both |Ue4|2 and|Uμ4|2

Lepton flavour and lepton number violation

NA62 can improve over most existing limits:

- Search for the LNV decay **$K^+ \to \pi^- \mu^+ \mu^+$** [BR < 8.6×10^{-11} by NA48/2]
- Search for the LNV decay **$K^+ \to \pi^- e^+ e^+$** [BR < 6.4×10^{-10}]
- Searches for LNV / LFV decays **$K^+ \to \pi\mu e$**, including **$\pi^0 \to \mu e$**.

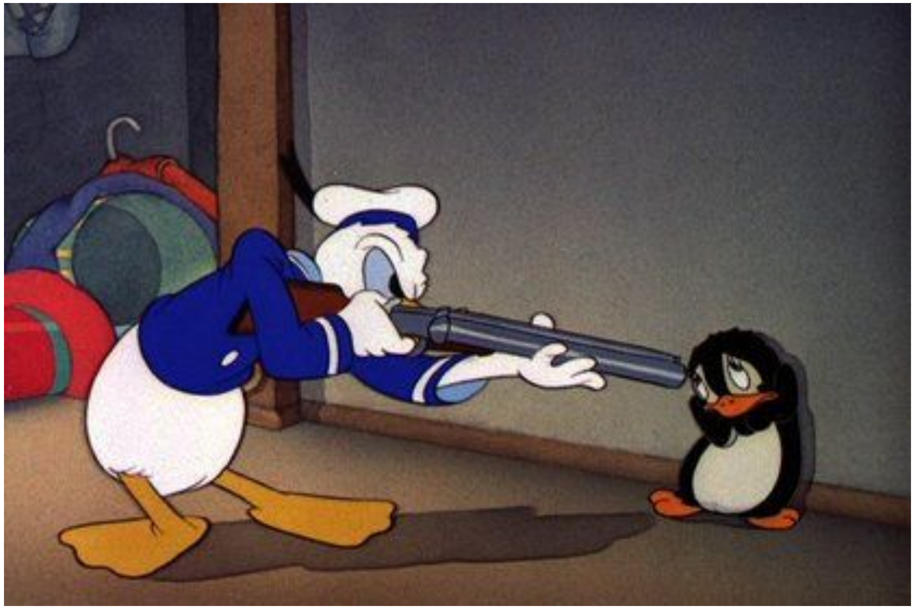
[BR($\pi^-\mu^+e^+$) < 5.0×10^{-10}; BR($\pi^-\mu^+e^+$) < 5.2×10^{-10}; BR($\pi^+\mu^+e^-$) < 1.3×10^{-11}]
[BR($\pi0 \to \mu^\pm e^\mp$) < 3.6×10^{-10}, kTeV@FNAL]

- Searches for $K^+ \to \mu^- \nu e^+ e^+$ and $K^+ \to e^- \nu \mu^+ \mu^+$ decays [BR($\mu^- \nu e^+ e^+$)<1.9×10^{-8} Geneva-Saclay, 1976]
- Searches for $\Delta S=\Delta Q$ violating decays $K^+ \to \pi^+\pi^+ e^- \nu$ and $K^+ \to \pi^+\pi^+\mu^-\nu$. [BR($\pi^+\pi^+e^-\nu$)<1.3×10-8; BR($\pi^+\pi^+\mu^-\nu$)<$3.0\times10^{-6}$: ~50 years old]

Statistics & Triggers

Approximate statistical reach with the 2016-17 data sample:

- Di-muon trigger stream: ~2×10^{12} K+ decays: SES~10^{-11}
- Decays to μe and ee pairs: ~5×10^{11} K+ decays: SES~10^{-10}
- Other 3-track decays: ~5×10^{10} K+ decays: SES~10^{-9}.

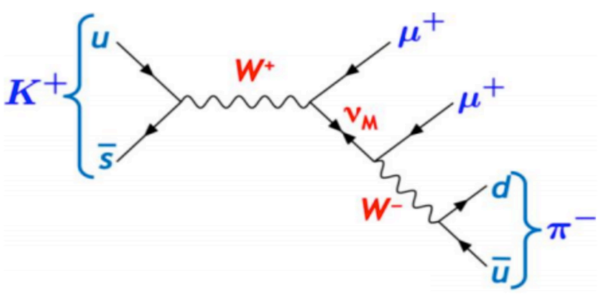


Majorana neutrinos @ NA62

- Search for Majorana neutrinos in **LNV $K^+ \to \pi^- l^+ l^+$ decays**
- DM + Baryon Asymmetry + low mass of SM ν can be explained by adding **three sterile Majorana neutrinos** to the SM
- Current limits:

$$\mathrm{BR}(K^\pm \to \pi^\mp \mu^\pm \mu^\pm) < 8.6 \times 10^{-11} \quad @\ 90\%\ \mathrm{CL}$$

$$\mathrm{BR}(K^+ \to \pi^- e^+ e^+) < 6.4 \times 10^{-10}$$

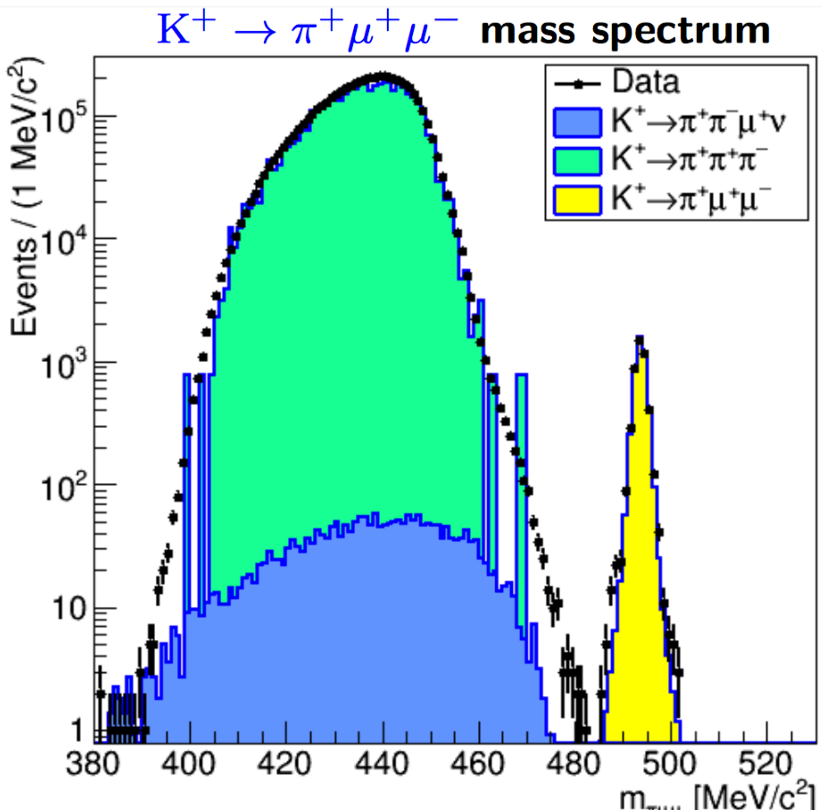


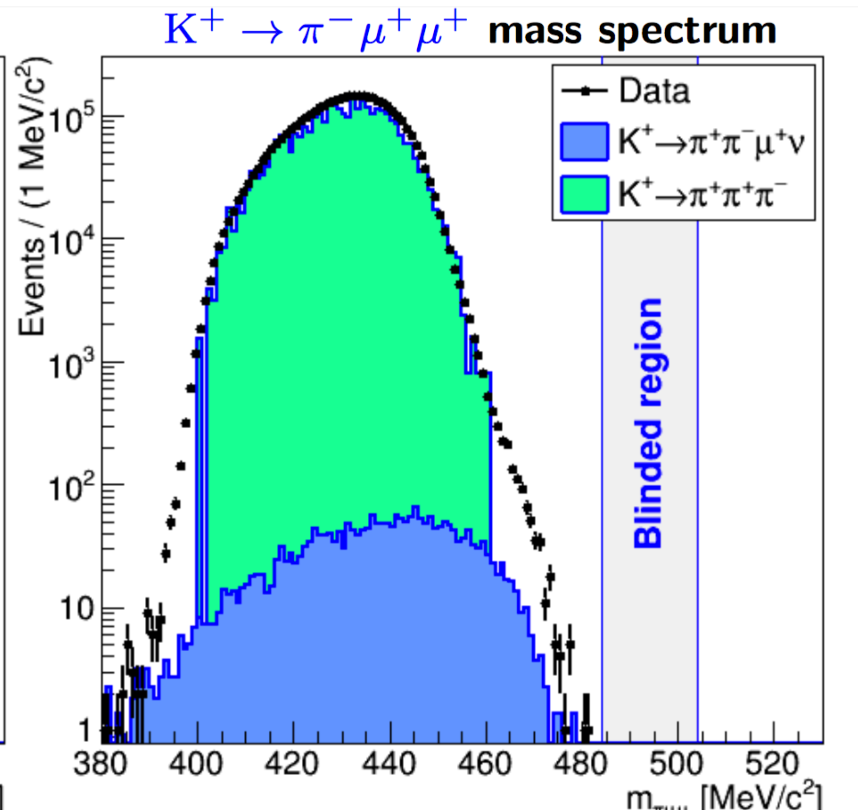
Asaka-Shaposhnikov model (νMSM) [PLB 620 (2005) 17]
[PLB 769 (2017) 67-76] for μμ set by NA48/2

$K^+ \to \pi\mu\mu$ analysis at NA62

World's largest $K^+ \to \pi^+\mu^+\mu^-$ sample: 4.6k candidates in this partial data set; expect ~20k candidates in total.

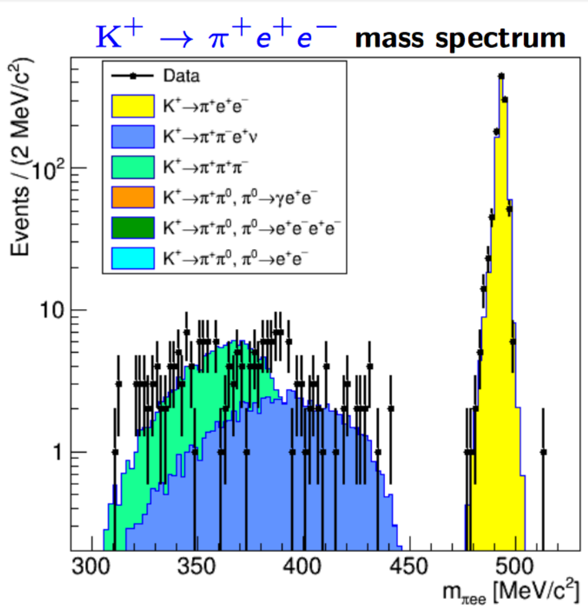
- Expect to make a competitive $K^+ \to \pi^+\mu^+\mu^-$ measurement.
- Search for new scalar: $K+ \to \pi^+ S$, $S \to \mu^+\mu^-$: SES~10^{-10}, lifetimes up to O(1 ns).
- Search for $K+ \to \pi^-\mu^+\mu^+$: background-free, reached SES~10-11.

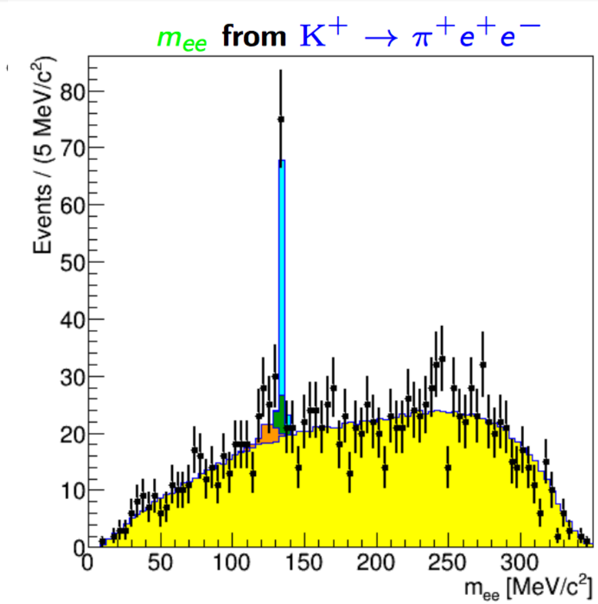


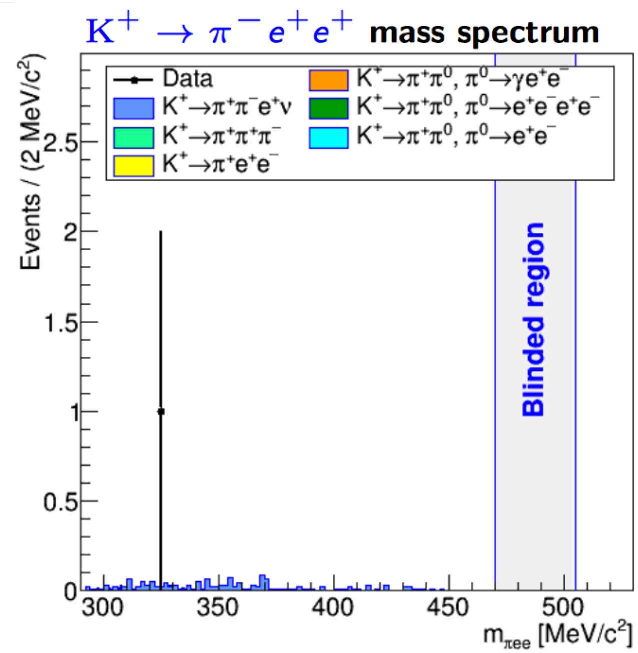


$K^+ \to \pi ee$ analysis at NA62

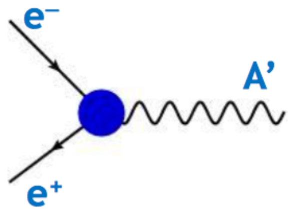
- A partial data set: **background-free** but not world's largest $K^+ \to \pi^+ e^+ e^-$ sample (1.1k events).
- **First observation** of $K^+ \to \pi^+ e^+ e^-$ decay in the mass range $m_{ee} < 140$ MeV/c^2.
- Observation of $\pi^0 \to e^+ e^-$ decay with an excellent m_{ee} resolution.
- Search for $K^+ \to \pi^+ X$, $X \to e^+ e^-$, $10 < mX < 100$ MeV/c^2: SES~10^{-9} for lifetime ≪1 ns.
- Search for $K^+ \to \pi^- e^+ e^+$: background-free, SES~10^{-10}.







Dark Photons



- DM as a thermal relic from the hot early universe
- A "new" dark sector with particles feebly coupled with SM particles (dark scalar, dark photon, HNL, axion)
- E.g. introduction of extra U(1) gauge symmetry and vector boson**: Dark Photon A'**
- DP decaying into SM fermions ruled out as explanation for **the muon g-2** anomaly.

In a simple realization of such a scenario [6, 7], A' would interact with the SM photon through a "kinetic mixing" lagrangian:

$$\mathcal{L} = \epsilon A'^{\mu\nu} F_{\mu\nu}$$

The lagrangian might be accompanied by further interactions, both with SM matter and with a secluded, hidden sector of possible dark-matter candidates.

Missing-energy signature might reveal its presence.

[6] L. Okun, Sov.Phys.JETP 56 (1982) 502;
[7] B. Holdom, Phys.Lett. B166 (1986) 196.

NA62: a π^0 generator

NA62 is looking for

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

$$A' \to \ invisible$$

where:

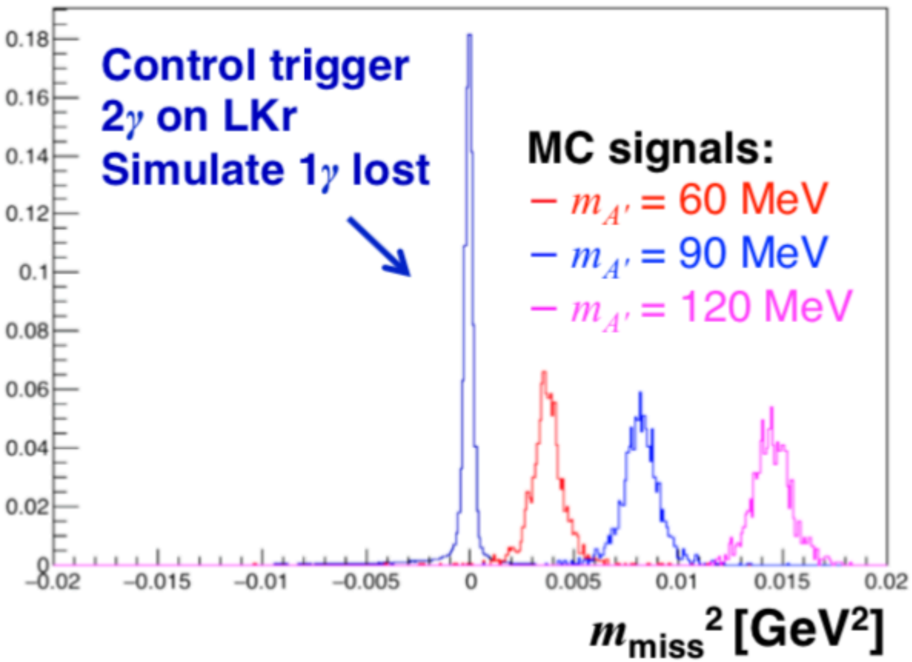
$$BR(\pi^0 \to A'\gamma) = 2\epsilon^2(1 - \frac{m_A^2}{m_{\pi 0}^2})^3 \times BR(\pi^0 \to \gamma\gamma)$$

Exploiting extreme photon-veto capability and high resolution tracking while sustaining a high-rate environment makes the dark photon analysis **synergic** with and **parasitic to the $K^+ \longrightarrow \pi^+\nu\nu$ measurement.**

Dark photon: Signal Vs Background

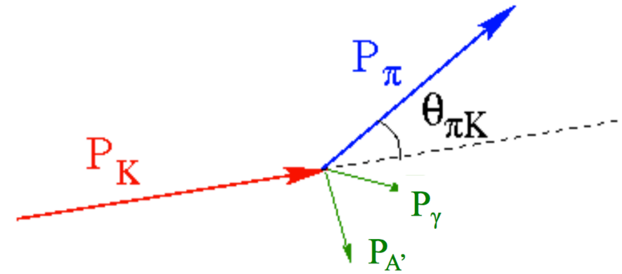
Analysis based on 1.5×10^{10} K^+ from 2016 data sample.
Squared missing mass is expected to peak around A' mass and around 0 for the Standard Model photon.

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



Results from MC simulations using various A' masses are superimposed to the expected contribution from $\pi^0 \to \gamma\gamma$ data in wich ne photon cluster in the electromagnetic calorimeter has been fictitiously excluded.

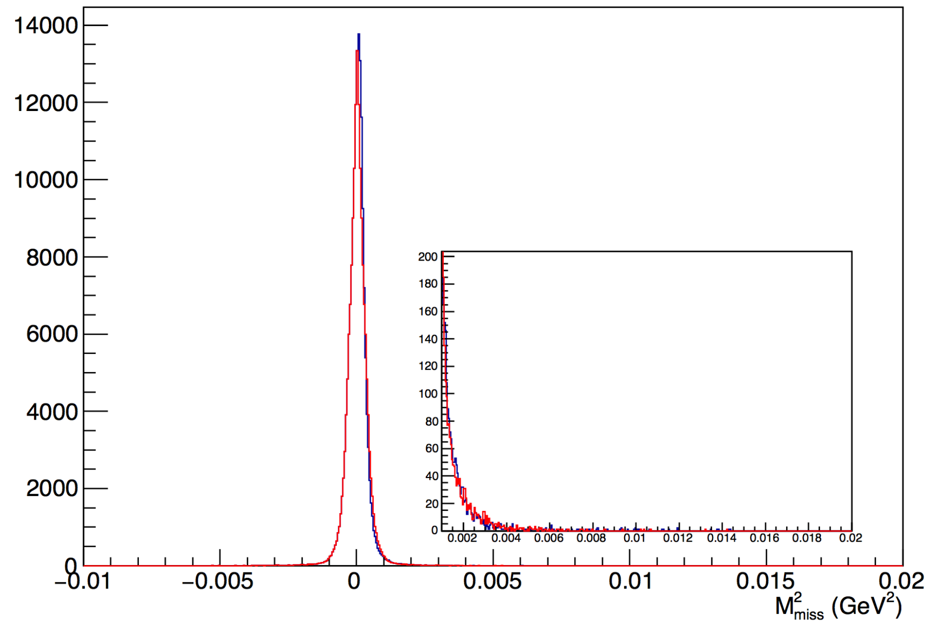
Dark Photon Strategy



The width of the background peak is due to experimental resolution effects.

They are mainly left-right symmetric.

data-driven background estimation, based on the tail with negative missing mass



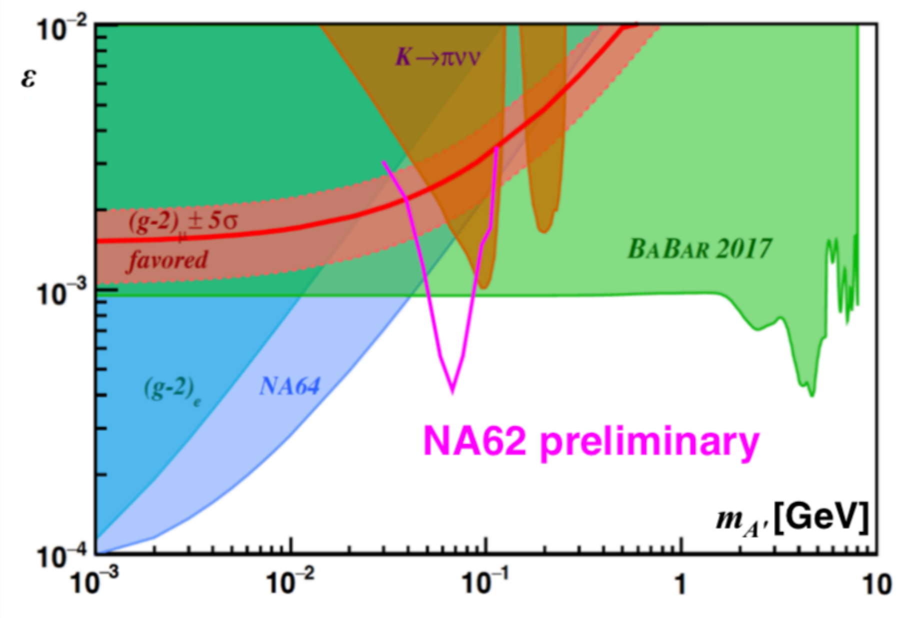
The total number of events can be calculated as:

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

Dark Photon Results

No statistically significant excess observed in ~1.5 x 10^{10} K^+ decays (5% of 2016 data sample).

New upper limits at the 90% CL in the plane of the coupling (ε) versus the A′ mass are obtained.

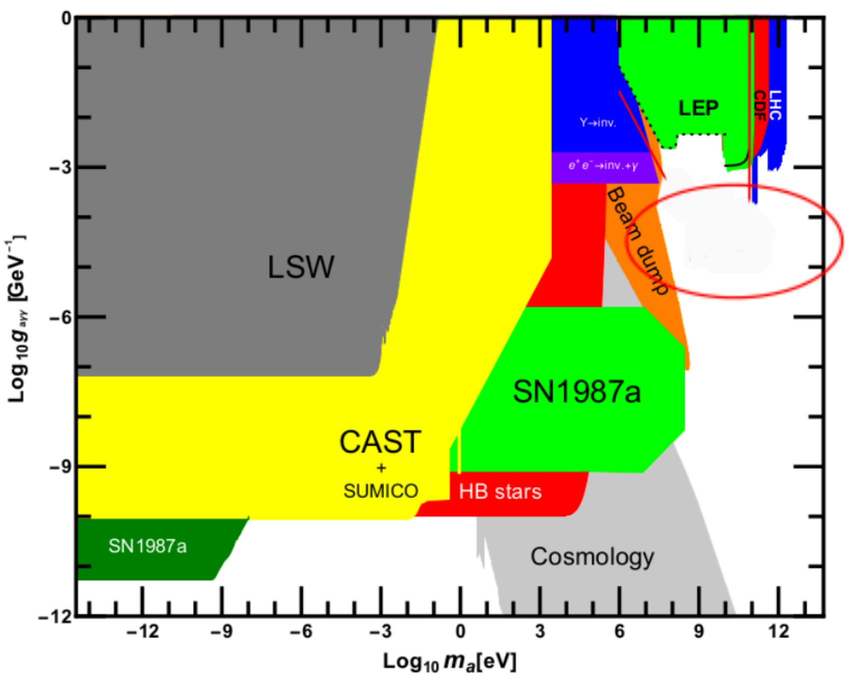


Limit improves linearly with N(K^+)

Results indicate that the statistical capability of NA62 allows an improvement on previous recent results. A more refined background evaluation is needed.

Axion-Like Particles

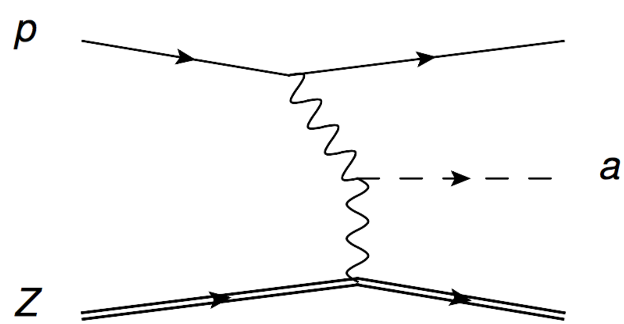
- **Not only Kaon decays;**
- NA62 offers a very good discovery potential for *Axion-Like Particles* (ALPs) in the MeV to GeV range[8]:
  - weak coupling: high reaction rate, longer lifetimes, sufficient energy.

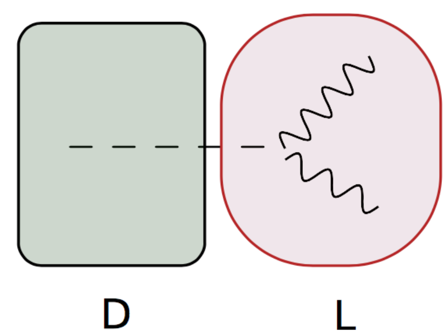


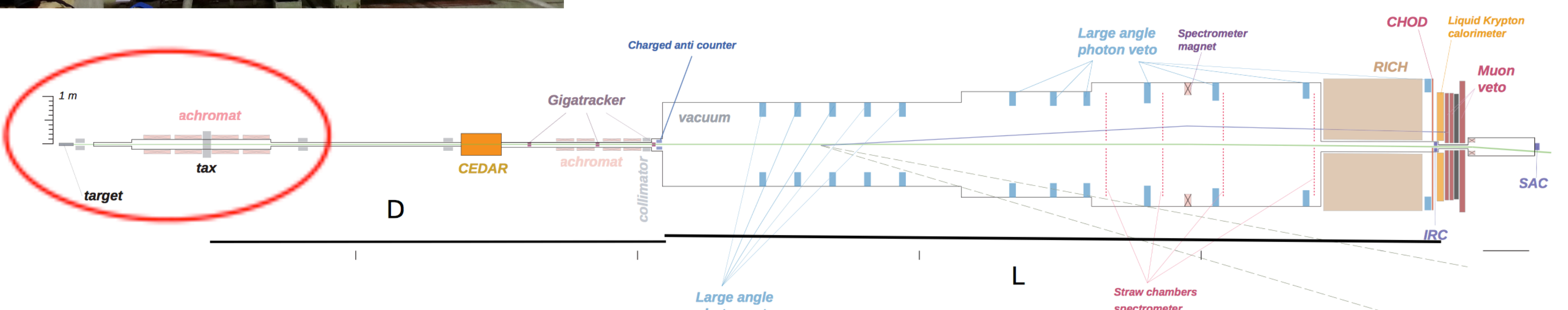
[8] *JHEP 1602 (2016) 018*

Axion-Like Particles

- Pseudo-scalar **ALP** created **by photon fusion (Primakov effect)**;
- Long-lived, weakly-interacting particles produced along with nominal beam directly/ decay;
- NA62 has the possibility to **dump the entire beam** by closing TAX (~10^{12} p/s) and removing target;
  - Copper TAX → coherent Z^2 enhancement with charge;
- collected ~ 2.5×10^{15} POT in dump in end of 2016.



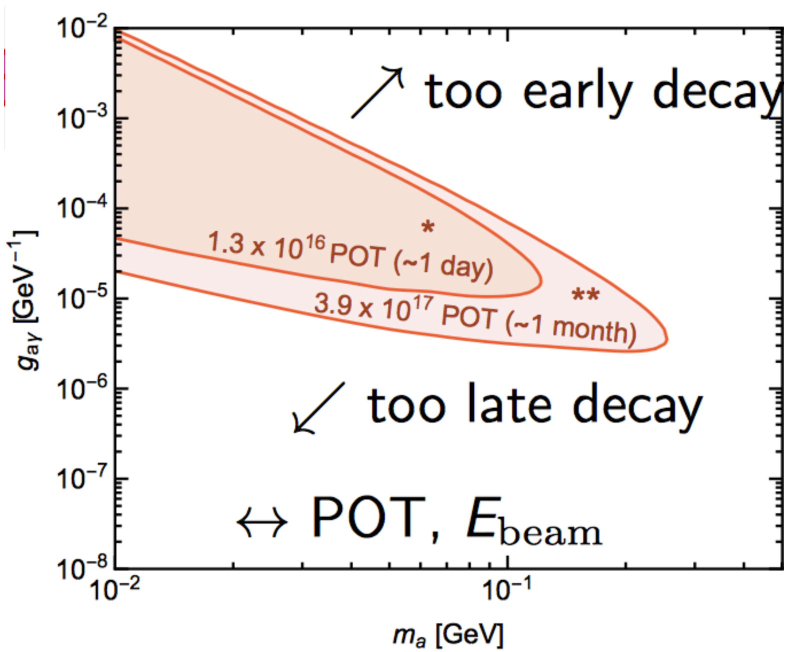


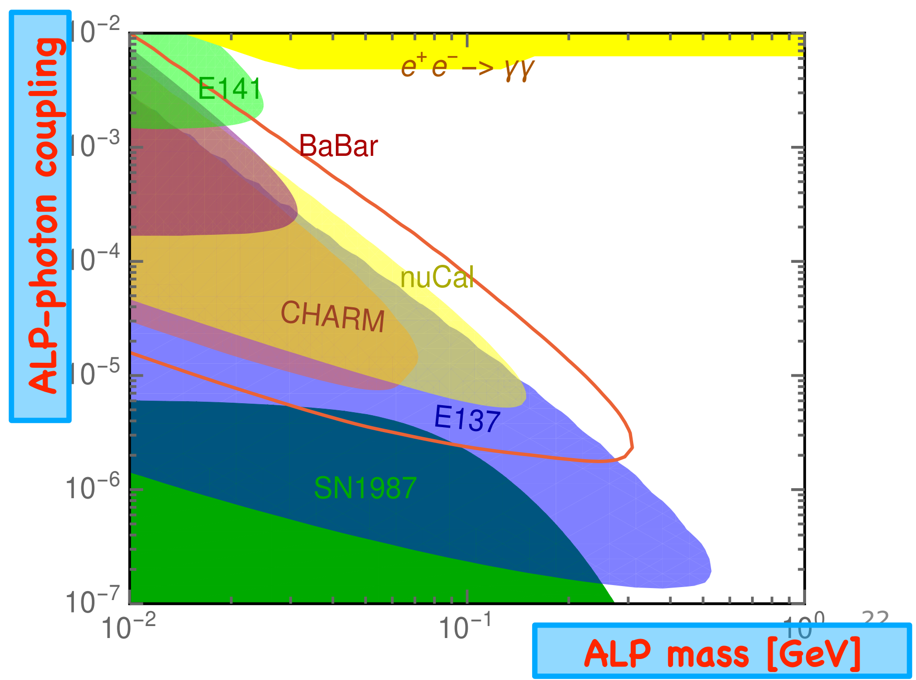


ALPs in NA62

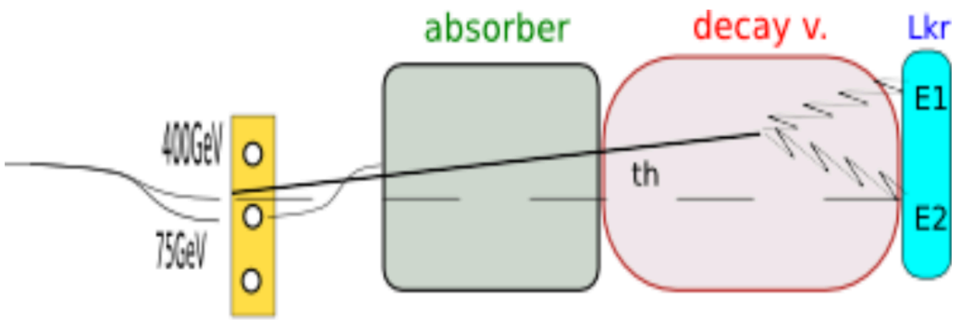
- decay length d = $\gamma\beta\tau$, ALP lifetime $\tau \sim 1/(g^2 m^3)$;
- the projected limits fold as input:
  - 1. the differential cross-section for production,
  - 2. coincidence and acceptance in EM calorimeter,
  - 3. probability to decay within the decay volume

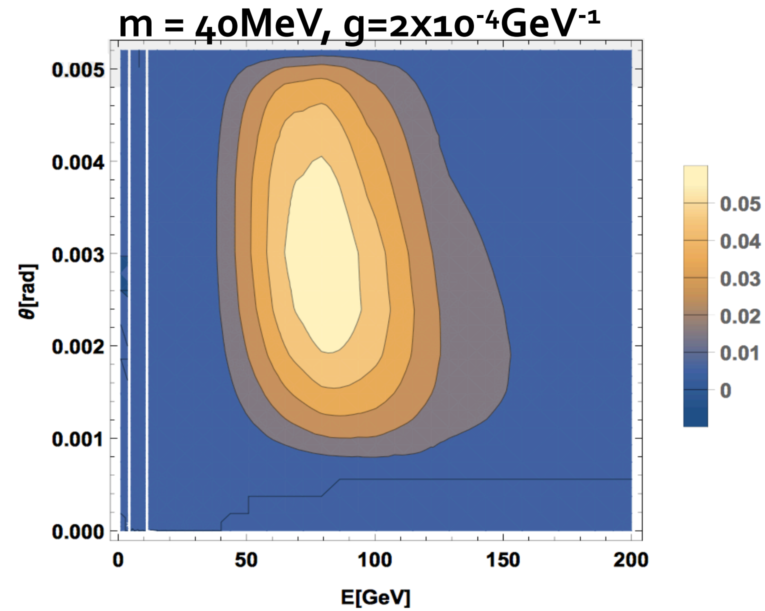
NA62 → small d, large E: one day runtime as 'dump' is sensitive to new physics (90% confidence at 0 background)





ALPs Analysis ongoing



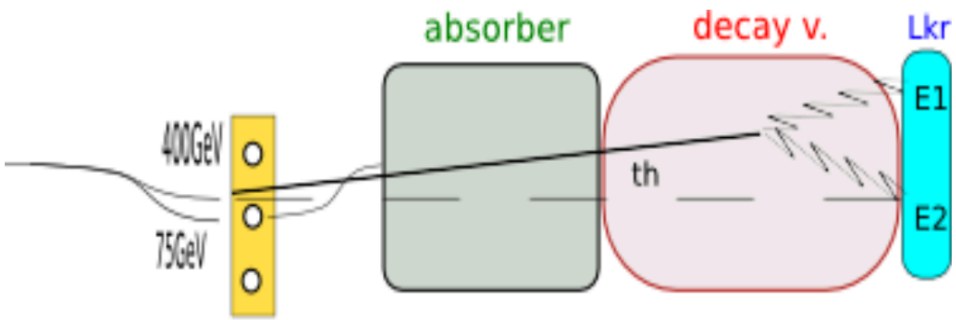


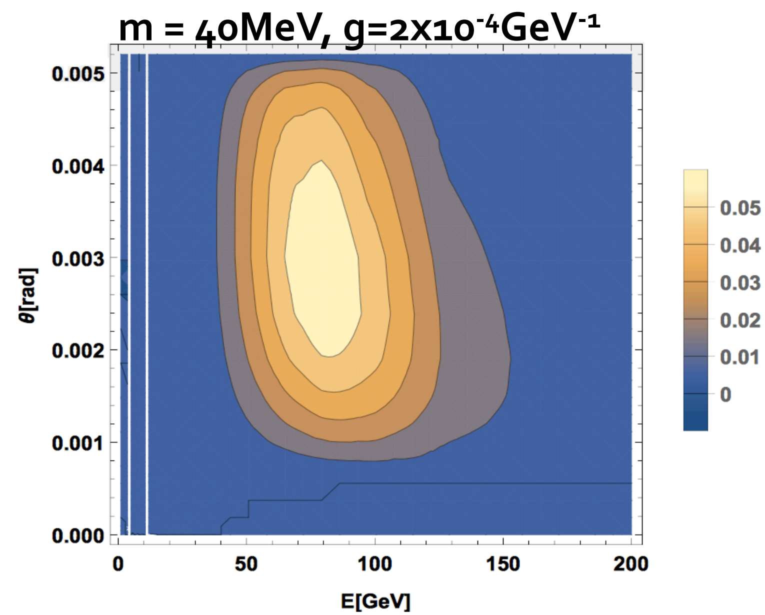
- **Challenging:** photon is not tracked: know only **E1, E2, d in Ecal**, need to impose mass or decay point to discriminate;
- **mitigation:** only extend beyond existing limits at small ld : decay in absorber:

$$\sim \exp(-l_{\rm abs}/l_d),\ l_d = \gamma\beta\tau \sim \frac{E_a}{m}\frac{64\pi}{m^3 g^2}$$

- yields the **ALPs** in reach **highly boosted** $E_a = E_{\gamma 1} + E_{\gamma 2}$
- their barycenter enclose a (computable) non-zero angle θ
- compare charged sample in side-band, **deduce expected background** in signal region → optimization of signal efficiency for (g,m) in full MC on the way

ALPs Analysis ongoing





Progress on data:

- 5×10^{15} POT already acquired in beam dump in 2017 & analysis on-going
- improvements expected already with only 1 day of run (1.3×10^{16} POT)

Conclusions

- **NA62** is a general purpose experiment, and its physics program **is complementary to the collider one**.

- NA62 searches for heavy neutrino production in charged kaon decays were presented:
  - ➢ **New limits on the heavy neutrinos production have been found.**

- A preliminary analysis on the dark photon search has been shown:
  - ➢ **A new limit on the dark photon production has been presented** already with only 5% of the entire 2016 data sample;
    - Huge improvements both on the statistics and on the analysis are on-going;

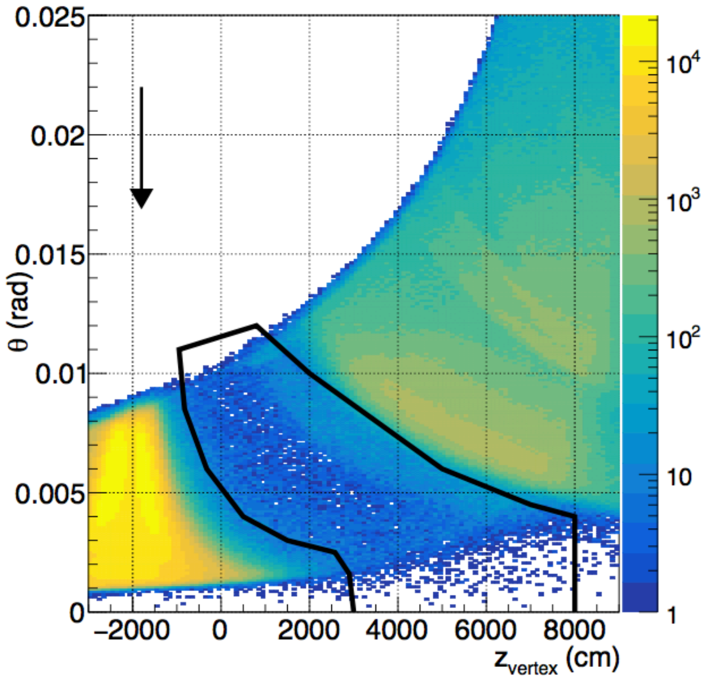
- Furthermore, NA62 has possibility to run as a dump experiment, looking for new physics produced in its TAX:
  - ➢ **Analysis for Axion like particles is on-going.**
  - ➢ Analysis of the backgrounds is fundamental for any other dump experiment project.

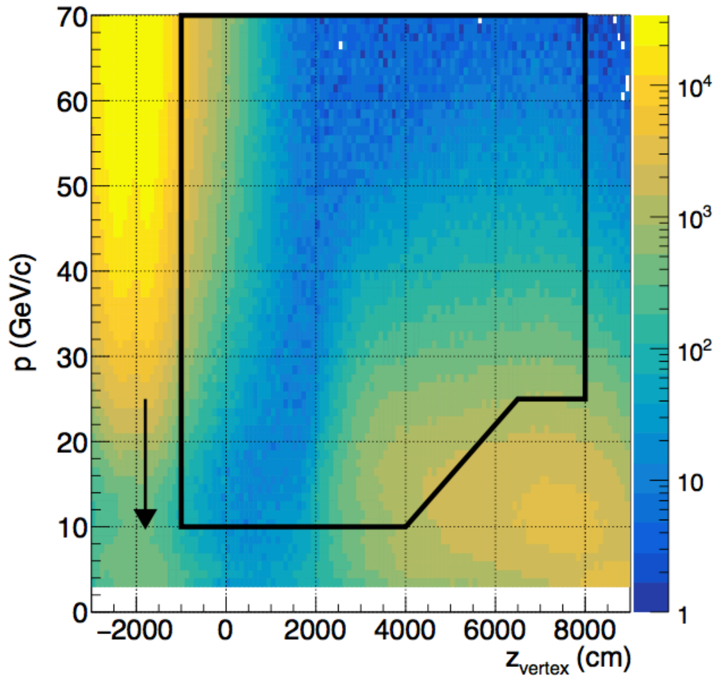
Thank you

SPARES

2007 - Heavy neutrinos halo reduction

In order to reduce the main background of muon halo, a 5-dimensional cut has been applied on Zvtx , θ, p, CDA, ϕ:

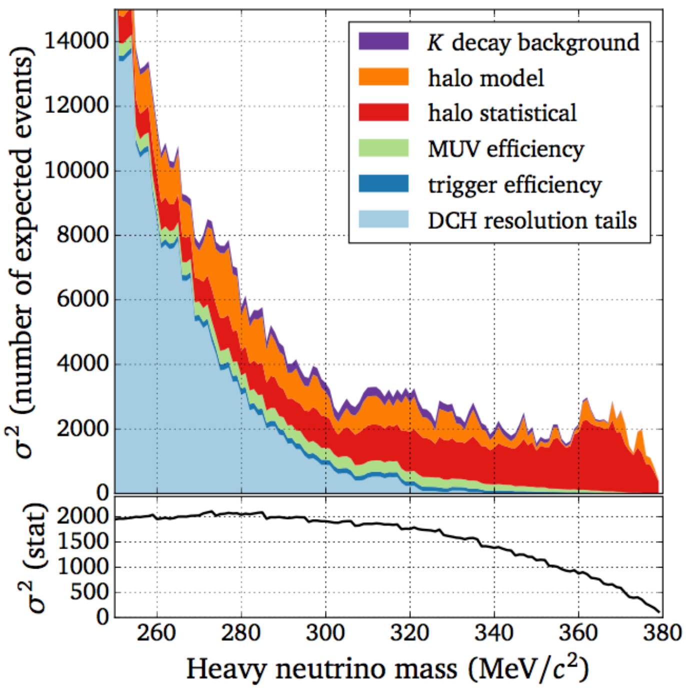




The events outside the contours are rejected. The arrow indicates the start of the fiducial volume.

2007 – background sources

- The estimate of systematic uncertainty associated with N_K is obtained by varying the cut on m^2_{miss} by $\pm\sigma_m^2$ resulting in a variation of 0.2%. The contribution from $B(K+ \rightarrow \mu^+\nu_\mu)$ results in a variation of 0.15%. The overall systematic uncertainty on kaon decay background varies from 0.6% to 1.0% of the total expected background as a function of m^2_{miss}
- To estimate the uncertainty on the $K+ \rightarrow \mu^+\nu_\mu$ background due to non-Gaussian tails in the DCH resolution: sample of $K^+ \rightarrow \pi+\pi^0$ decays, selected with only LKr calorimeter is used. From this comparison it is inferred that the uncertainty on the background estimate in the $K+ \rightarrow \mu^+\nu_h$ signal region does not exceed 6% of the total expected background;



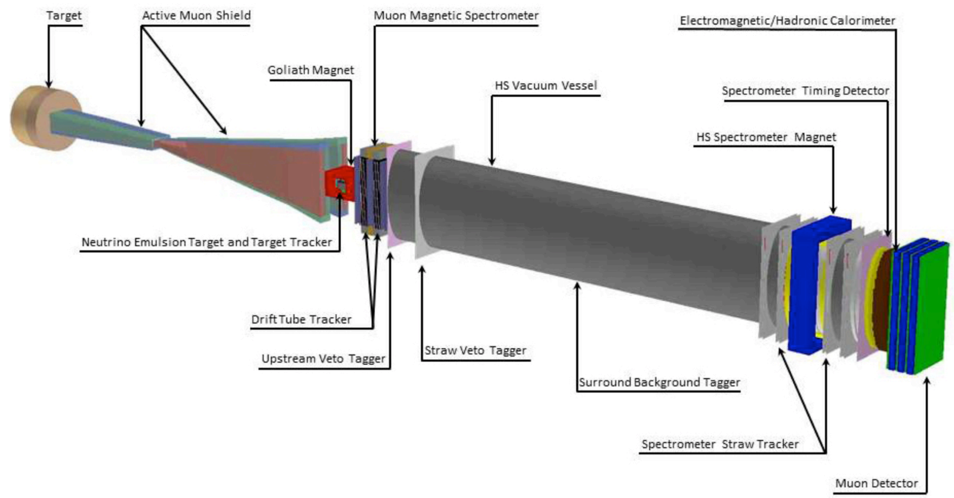
See-Saw mechanism

- The 3 light neutrinos are decoupled from heavy ones. Sterling active oscillations are negligible.
- It forecast:
  - Small masses for neutrinos (<< masses loaded fermions);
  - Neutrinos are Majorana particles;
  - Sterile neutrinos have masses >> of SM neutrinos.

  - SEE:

[21] T. Yanagida, in: O. Sawada, S. Sugamoto, (Eds.), Proc. of the Workshop on the Unified Theory and the Baryon Number in the Universe, Tsukuba, Japan, 13–14 February 1979, KEK Re- port KEK-79-18, Tsukuba, 1979, p. 95;

SHIP Experiment



- Expected 2 x 10^{20} proton on target in 5 years.

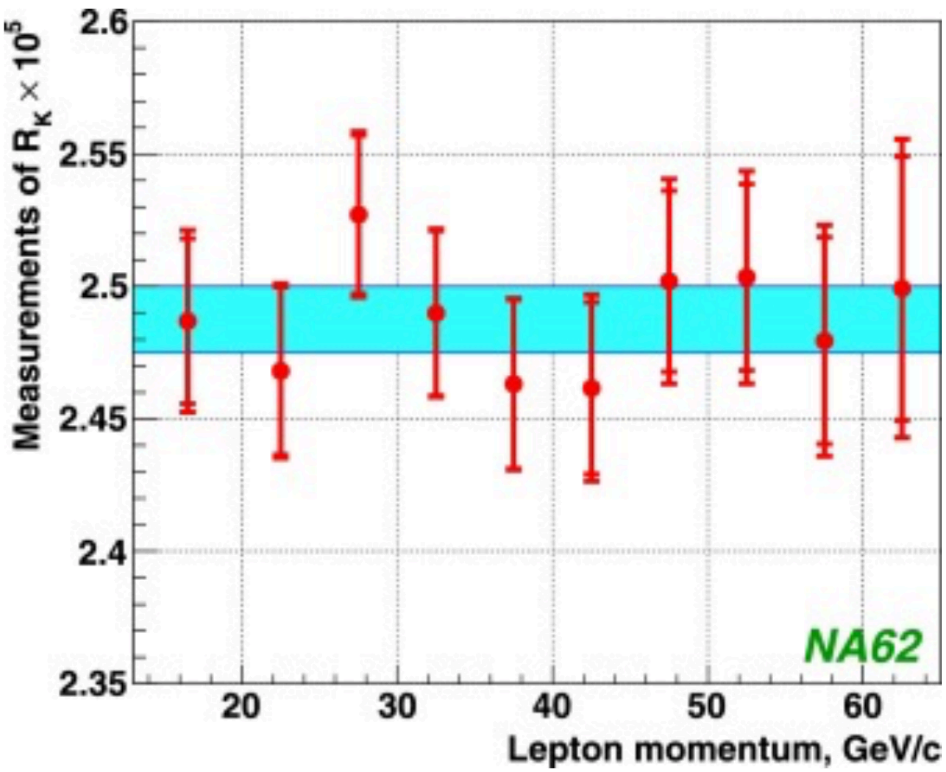
- Target closer to detector:
  - ➢ Angular acceptance up to 20 mrad (NA62 LKr angular acceptance between 1 and 8.5 mrad)

- Molybdenum target (Z = 42)
  - ➢ NA62 is using copper (Z = 29)

Rk 2007

$$R_K = (2.487 \pm 0.011_{\text{stat.}} \pm 0.007_{\text{syst.}}) \times 10^{-5} = (2.487 \pm 0.013) \times 10^{-5}$$

$$R_K^{\text{SM}} = \left(\frac{M_e}{M_\mu}\right)^2 \left(\frac{M_K^2 - M_e^2}{M_K^2 - M_\mu^2}\right)^2 (1 + \delta R_{\text{QED}}) = (2.477 \pm 0.001) \times 10^{-5}$$



Based on 59813 reconstructed electron decay, with 8% of contamitantion