Study of exotic processes @ NA62

Dario Soldi on Behalf of the NA62 Collaboration

17 – August 2017

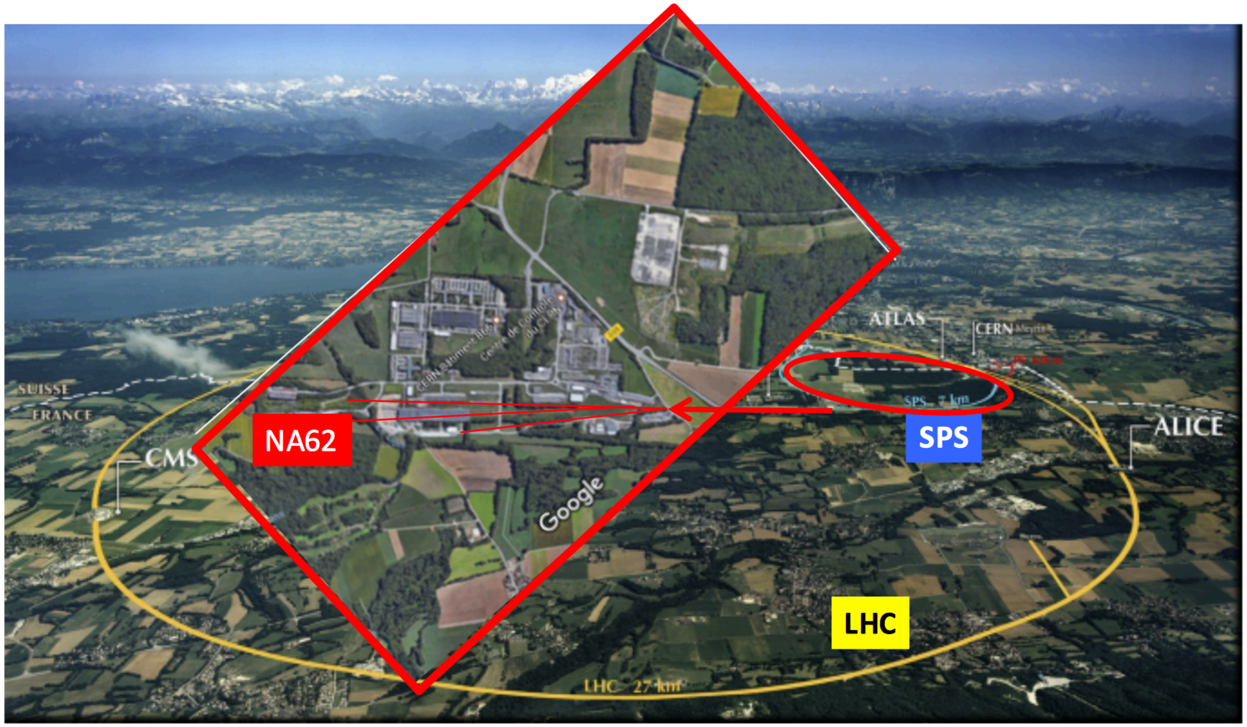
NA62 – general purpose experiment

See C.Lazzeroni's talk!

Flavor Physics → 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



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

NA48 discovery of direct CPV	1997: ε'/ε: K_L+K_S	
	1998: K_L+K_S	
	1999: K_L+K_S	K_S HI
	2000: K_L only	K_S HI
	2001: K_L+K_S	K_S HI
NA48/1	2002: K_S/hyperons	
NA48/2	2003: K^+/K^-	
	2004: K^+/K^-	
NA62 R_K phase	2007: $K^\pm_{e2}/K^\pm_{\mu2}$	tests
	2008: $K^\pm_{e2}/K^\pm_{\mu2}$	tests
NA62	2014: pilot run	
	2015: commissioning run	
	2016 – : $K^+\to\pi^+\nu\nu$ run	

In this talk I will show you some results and perspectives from data samples collected in 2007 and during the lasts data takings performed in 2015 and 2016.

New data are collecting now, increasing the statistics of both for the $\pi^+\nu\nu$ branching ratio measurement and exotics research.

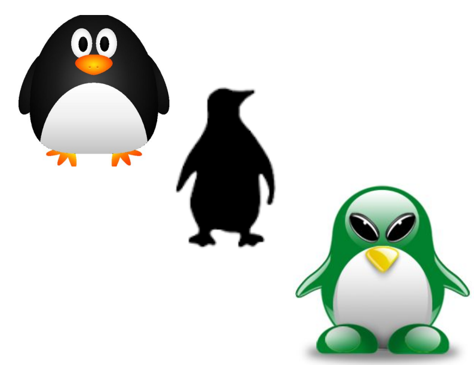
NA62: an exotic particle factory

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

- high - frequency tracking of beam particles;
- redundant PID;
- ultra-high-efficiency photon vetoes;

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

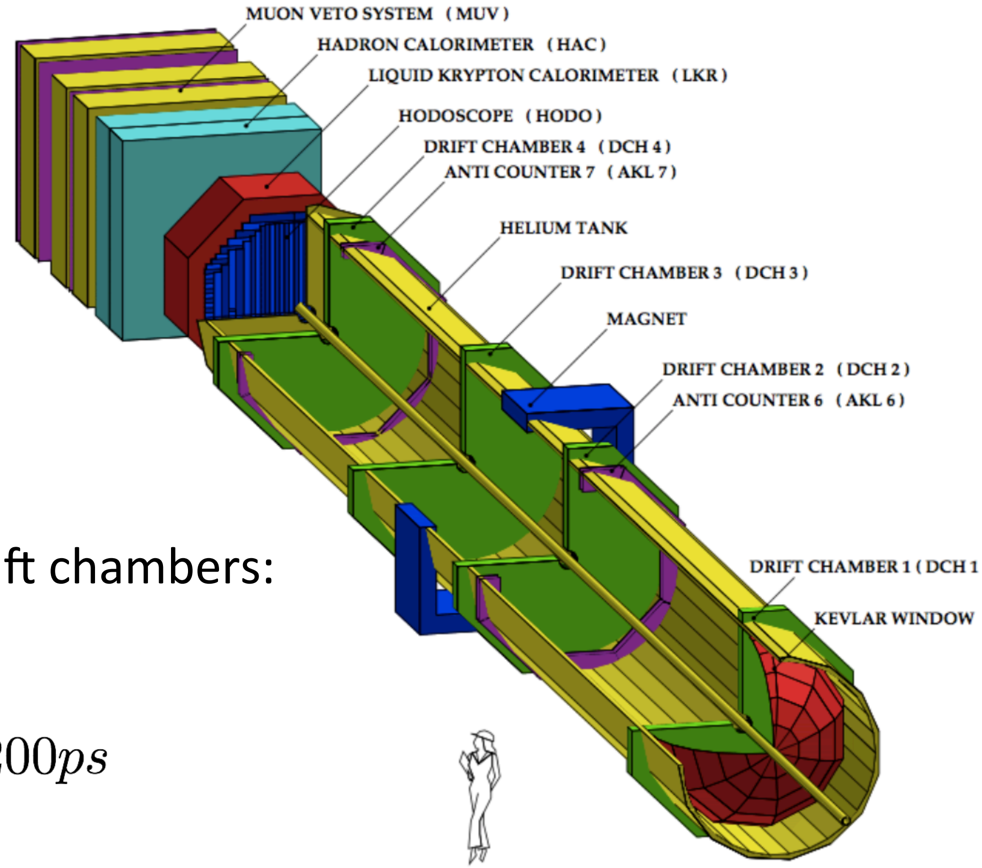
- *Hevy Neutrios* (2007 & 2015 data sample);
- *Dark Photons* (2016 data sample)*;*
- *ALP – Axion* (2016 data sample)*;*



NA62: the 2007 setup

Main measurement [1]:

$R_K = \Gamma(K_{e2}/K_{\mu2})$ **(SM compatible)**



Beam momentum: (74 ± 2) GeV
Alternate K^+/K^- beam
Trigger used: 1 track $e^{\pm}$, 1 track $\mu^{\pm}$

Principal Detectors:

Spectrometer for decay products: Drift chambers:

$$\sigma_p/p = 0.48\% \oplus 0.009\% \cdot p[GeV/c]$$

Scintillator hodoscope (HOD): $\sigma_t \sim 200ps$

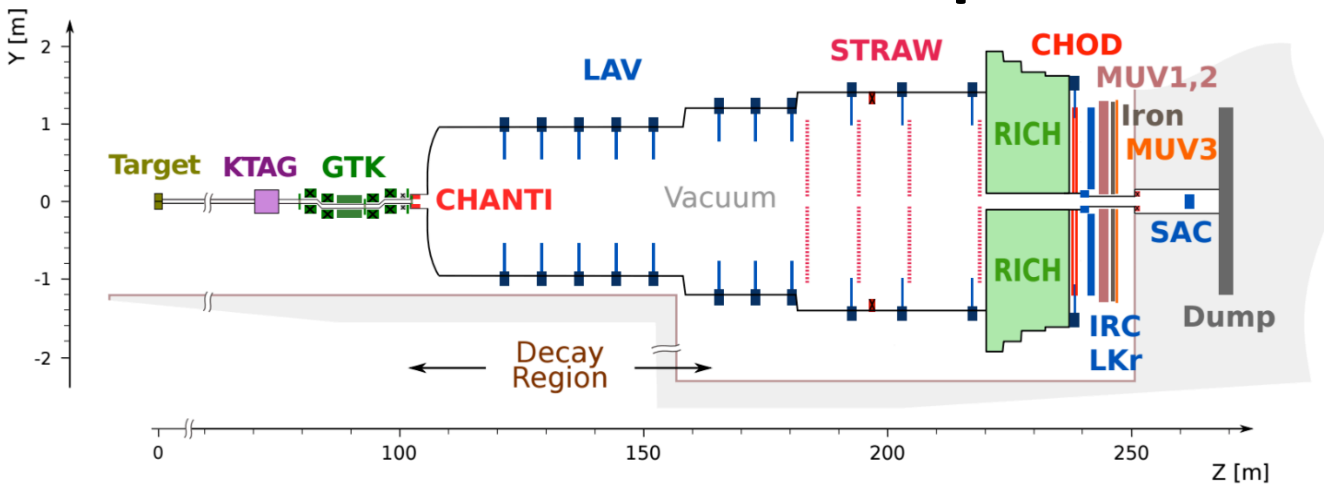
Liquid Krypton EM calorimeter (LKr):

$$\sigma_E/E = 3.2\%/\sqrt{E(GeV)} \oplus 9\%E(GeV) \oplus 0.42\%(1.4\% \text{ @ } 10\ GeV)$$

Muon veto system (MUV)

[1] Phys. Lett. B 719 (2013) 326

NA62: the actual setup



Main goal[2]: BR($K^+ \to \pi^+ \nu\nu$) at 10% precision
Beam momentum: 75 GeV/c (±1%)
Subdetectors:

- Beam Tracker: kaon (GTK), 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)

[2] NA62 collaboration, JINST 12 (2017) P05025

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:

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

Heavy Neutrinos 

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

The Neutrino Minimal SM (νMSM) [3] 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.

in NA62: if $m_N < m_K$, heavy neutrinos become observable directly via production [4]:

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

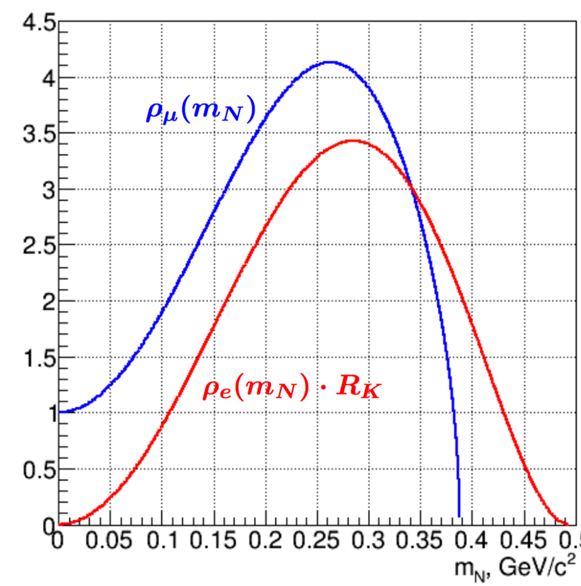
$$|U_{l4}|^2 = \frac{\mathcal{B}(K^+ \to l^+ N)}{\mathcal{B}(K^+ \to l^+ \nu_l)\ \rho_l(m_N)}$$

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

Data Samples:

2007: *muon sample*

2015: *electron sample*



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

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

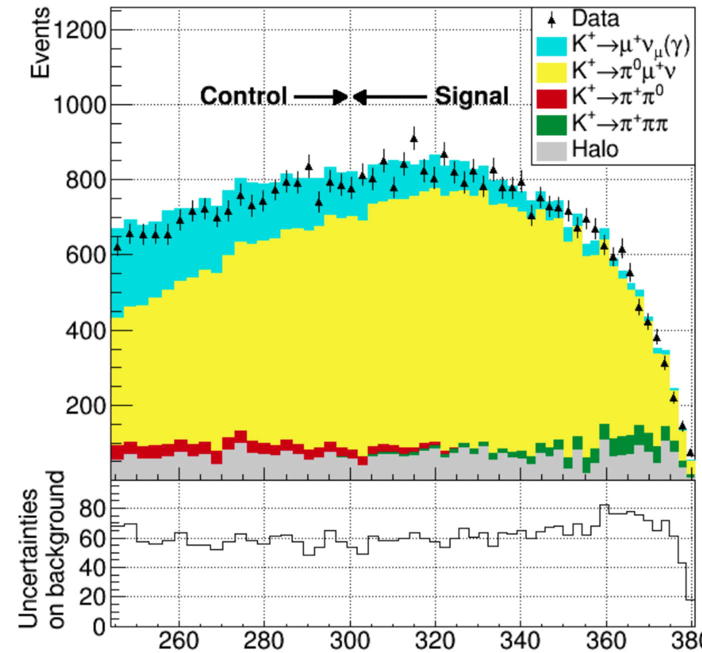
Heavy Neutrinos – 2007 results

- Dedicated ν_h MC simulation for acceptance and resolution as a function of the $\boldsymbol{m_h}$ at 1 MeV/c^2 intervals;
- 1 positively charged muon track;
- No cluster of energy deposition with E > 2 GeV associated to the track;
- Cuts on (Zvtx , θ, p, CDA, ϕ) to suppress muon halo background;
- Masses considered: 300 MeV/c^2 < m_N < 375 MeV/c^2
- Rolke-Lopez method [5] used to find upper limits on number of signal events;

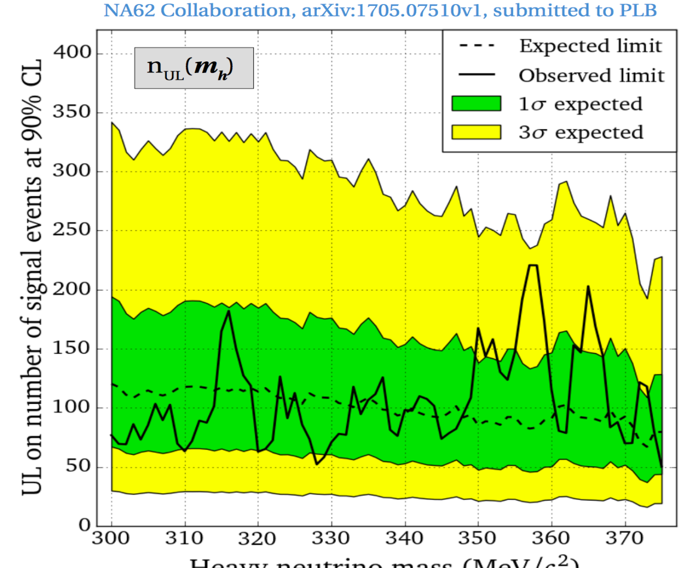
N_K ~ 6 x 10^7 kaon decays in the fiducial volume

No excess above 3σ observed

[5] ArXiv:physics/0403059



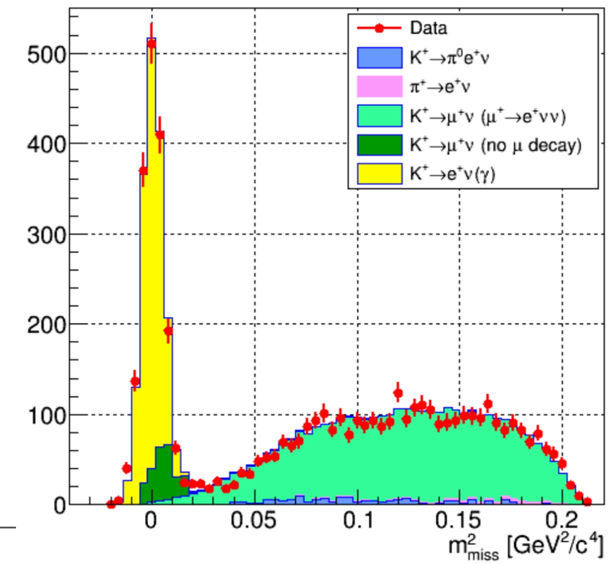
NA62 Collaboration, arXiv:1705.07510v1, submitted to PLB

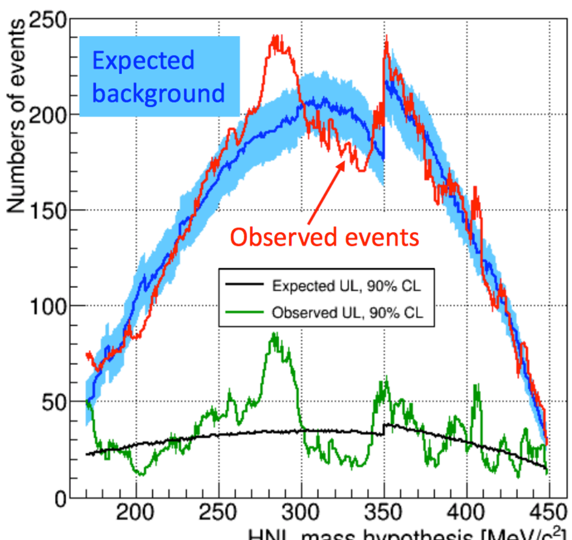


Heavy Neutrinos – 2015 results

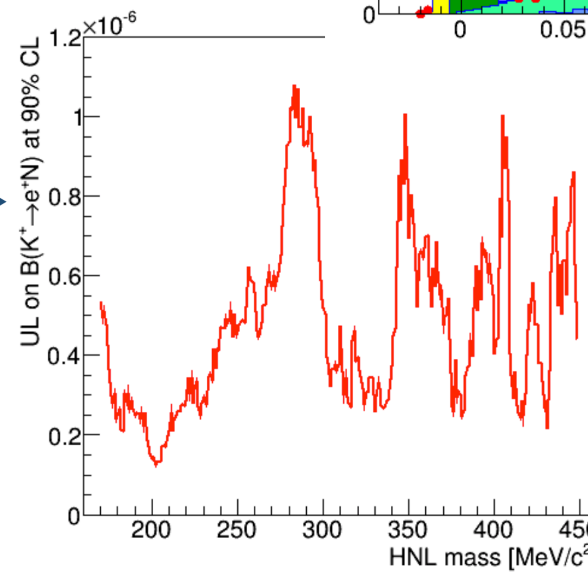
- 1 positively charged track;
- 1 single electron-cluster in the LKr;
- No photons in veto-detectors;
- As before, heavy neutrino mass step: 1 MeV/c^2;
- Masses considered: 170 MeV/c < m_N < 448 MeV/c^2;
- Rolke-Lopez method [5] used to find upper limits on number of signal events;

Squared missing mass: $m^2_{miss} = (P_K - P_e)^2$





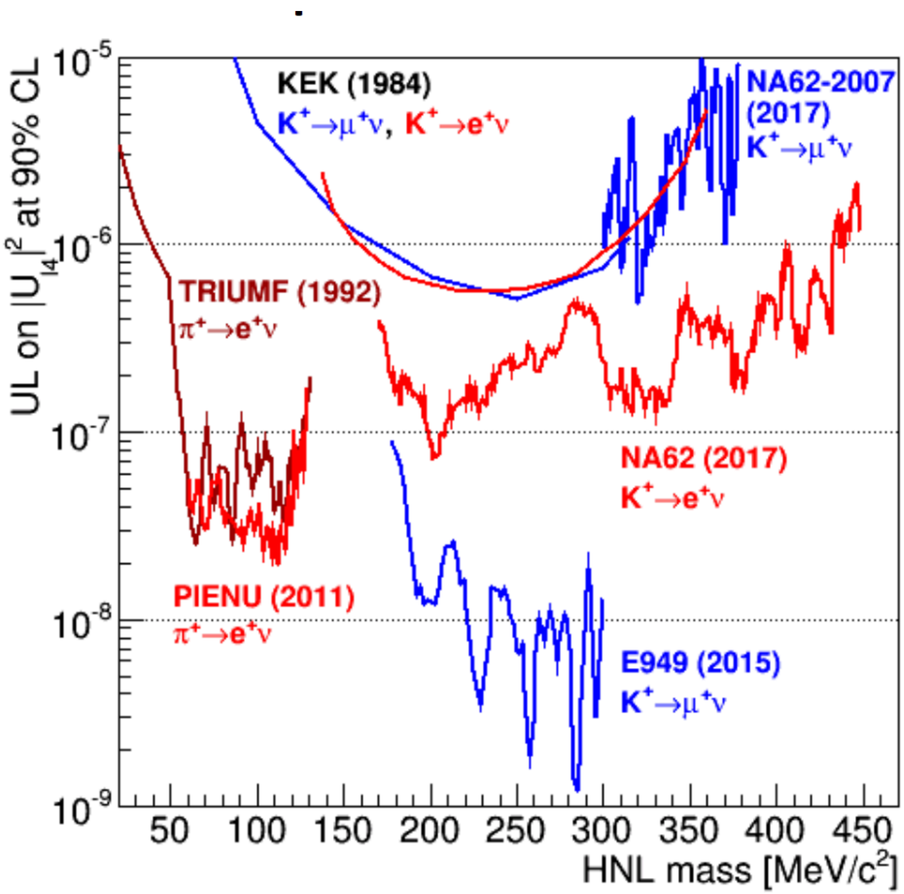
$$\frac{1}{N_K \cdot A(m_N)} \longrightarrow$$



N_K ~ 3.11 x 10^8 kaon decays in the fiducial volume

No excess above 3σ observed

Heavy Neutrinos summary 



- No heavy neutrino signal observed;
- Improves limits on for $|U4_{\mu 4}|^2$
- Improves limits on for $|U4_{e4}|^2$

Major analysis improvements with NA62 2016 high intensity data set, e.g. fully working beam tracker

Dark Photons

New *U(1)* gauge-symmetry sector, with a vector mediator field A';

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

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

$$A' \rightarrow \ invisible$$

where:

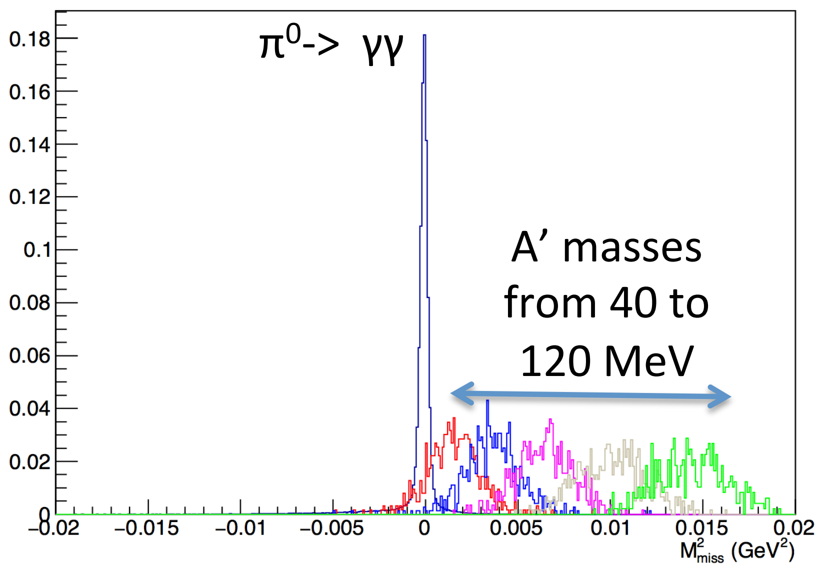
$$BR(\pi^0 \rightarrow A'\gamma) = 2\epsilon^2(1 - \frac{m_A^2}{m_{\pi 0}^2})^3 \times BR(\pi^0 \rightarrow \gamma\gamma)$$

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 $K^+ \rightarrow \pi^+\nu\nu$ measurement.

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.

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



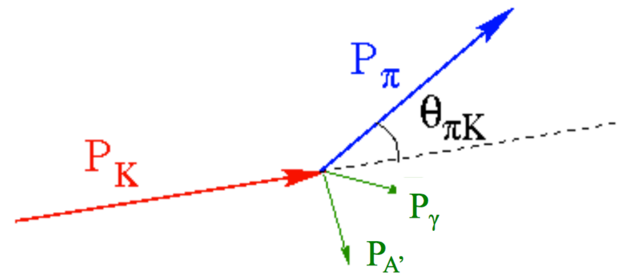
Results from MC simulations using various A' masses are superimposed to the expected contribution from $\pi^0 \to \gamma\gamma$ data in wich ne photon cluster in the electromagnetic calorimeter has been fictitiously excluded.

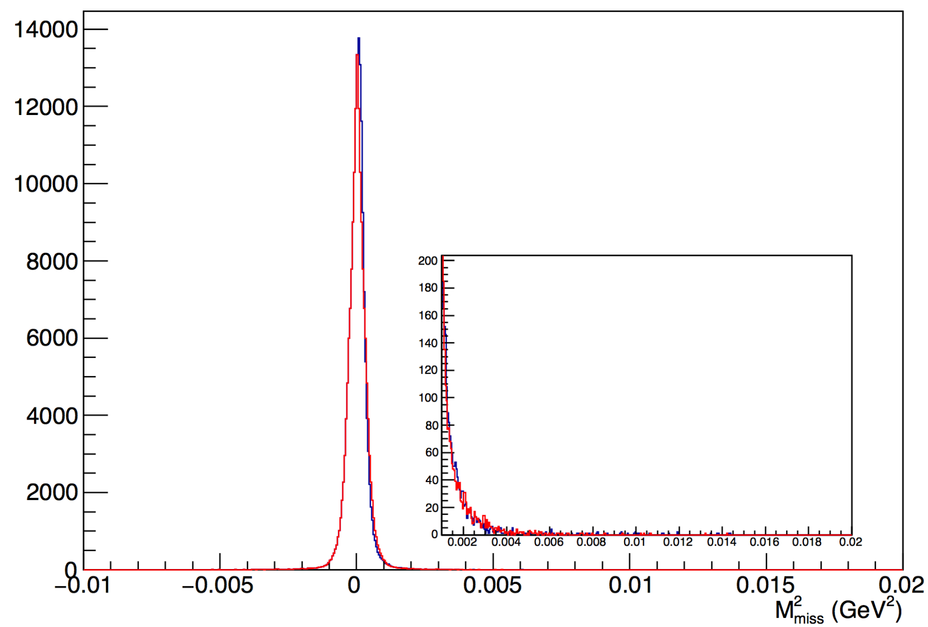
Strategy

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 values.



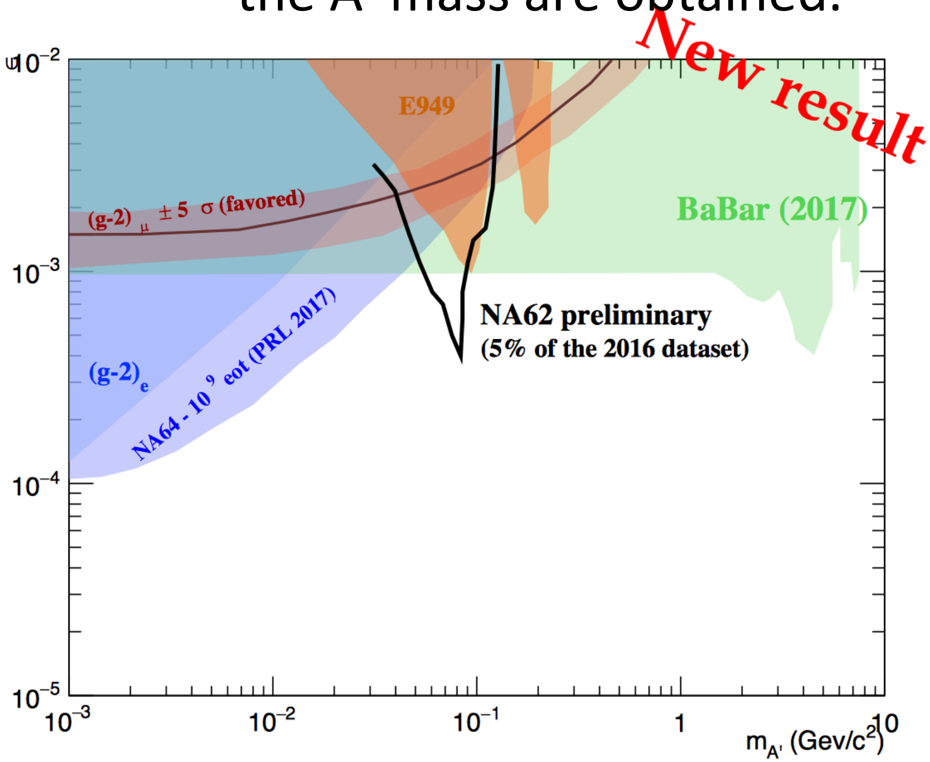


The total number of events can be calculated as:

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

Results

No statistically significant excess observed in ~1.5 x 10^{10} K^+ decays. New upper limits at the 90% CL in the plane of the coupling (ε) versus the A′ mass are obtained.

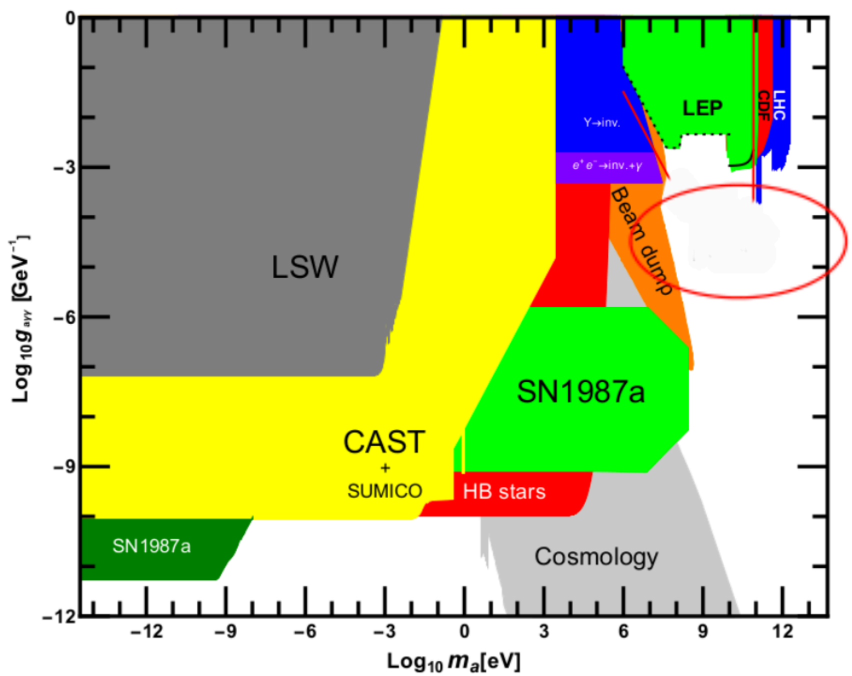


Limit improves linearly with N(K^+)

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

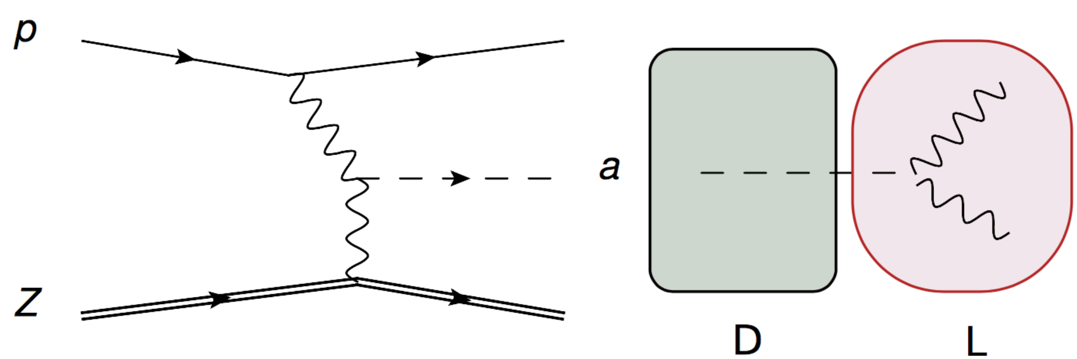
- **Not only Kaon decays;**
- NA62 offers a very good discovery potential for *Axion-Like Particles* (ALPs) in the MeV to GeV range[8]:
  - weak coupling: high reaction rate, longer lifetimes, sufficient energy.

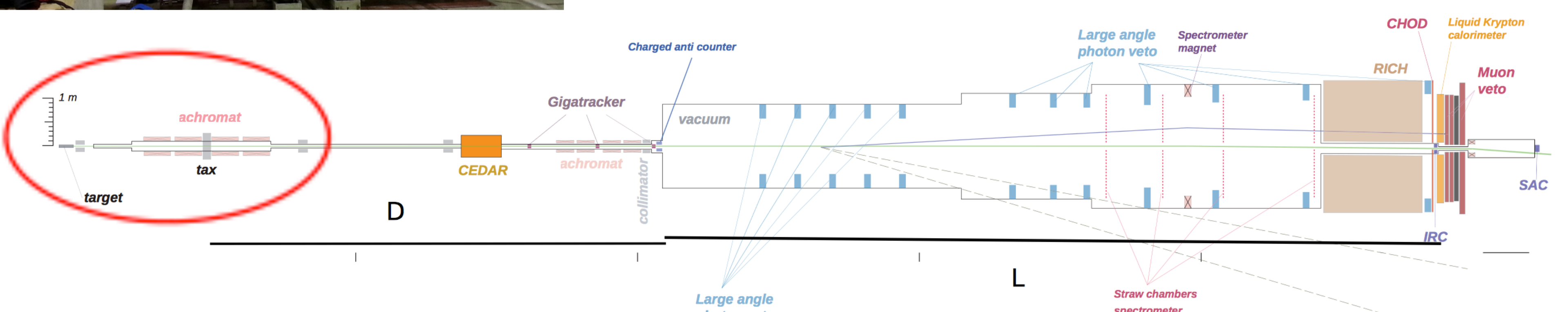


[8] arXiv:1512.03069

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.

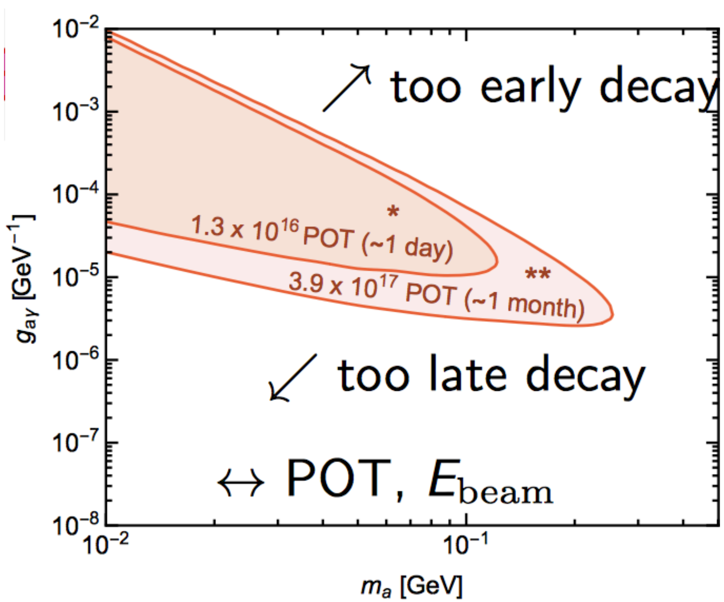


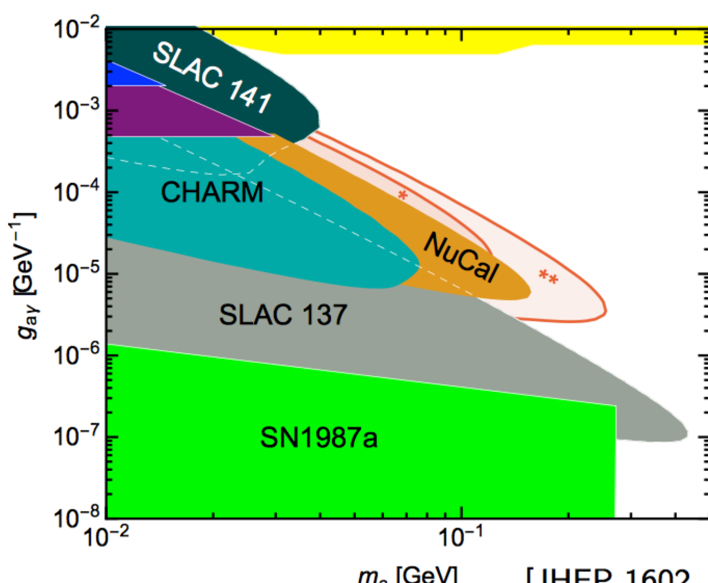


ALPs in NA62

- decay length γβτ, 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

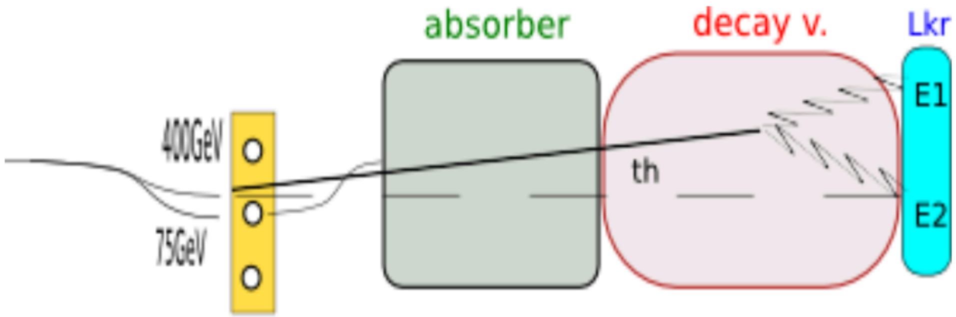
NA62 → small d, large E: one day runtime as 'dump' is sensitive to new physics (90% confidence at 0 background)

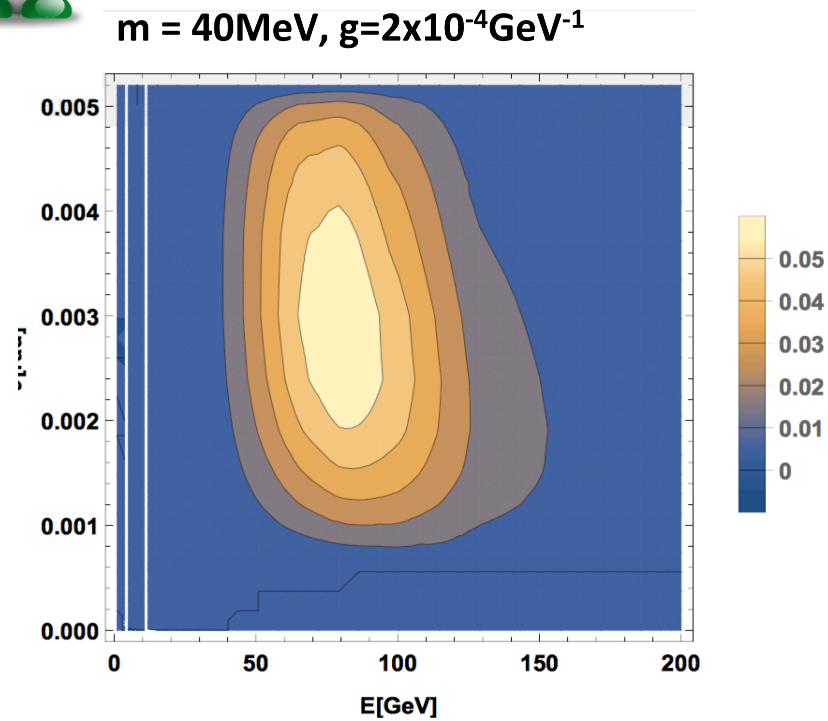




[JHEP 1602, 018]

Analysis ongoing



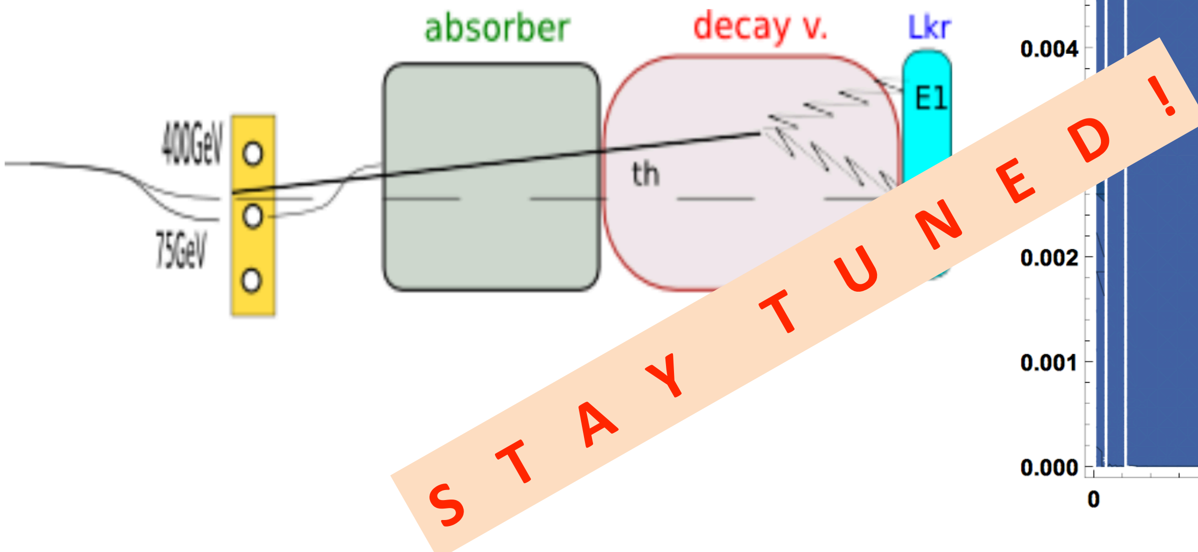


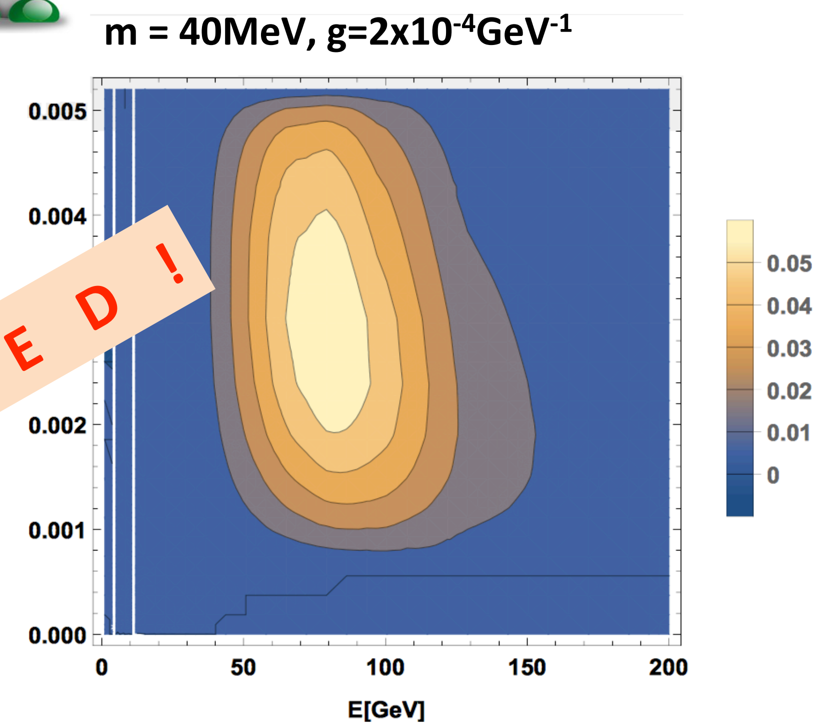
- **Challenging:** photon is not tracked: know only **E1, E2, d in Ecal**, need to impose mass or decay point to discriminate;
- **mitigation:** only extend beyond existing limits at small ld : decay in absorber:

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

- 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

Analysis ongoing





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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.**

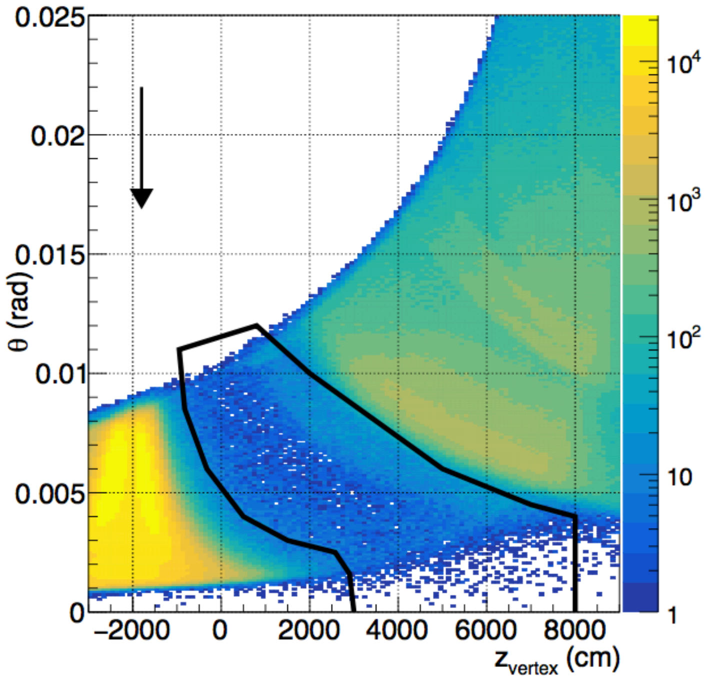
- A preliminary analysis on the dark photon search has been shown:
  - **A new limit on the dark photon production has been presented** already with only 5% of the entire 2016 data sample;
    - Huge improvements both on the statistics and on the analysis are on-going;

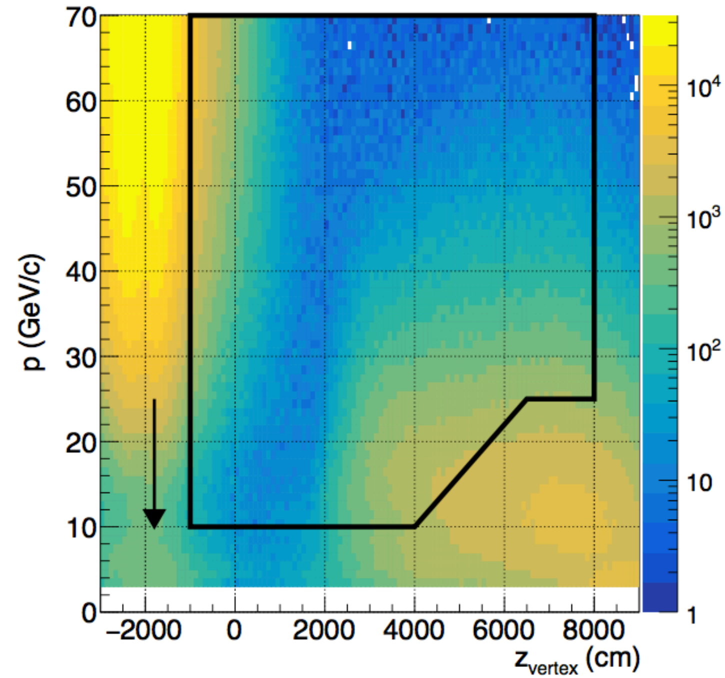
- Furthermore, NA62 has possibility to run as a dump experiment, looking for new physics produced in its TAX:
  - **Analysis for Axion like particles is on-going.**
  - Analysis of the backgrounds is fundamental for any other dump experiment project.

HELPFUL SLIDES

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:

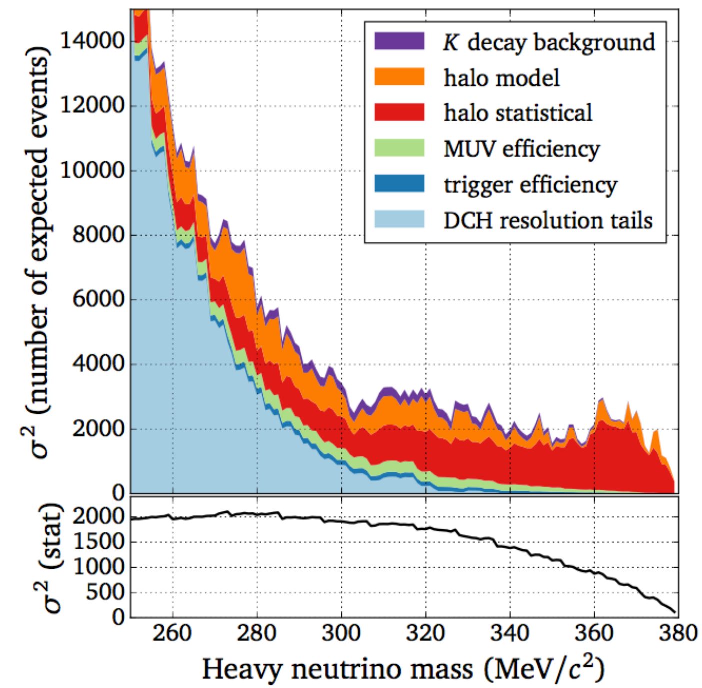




The events outside the contours are rejected. The arrow indicates the start of the fiducial volume.

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;



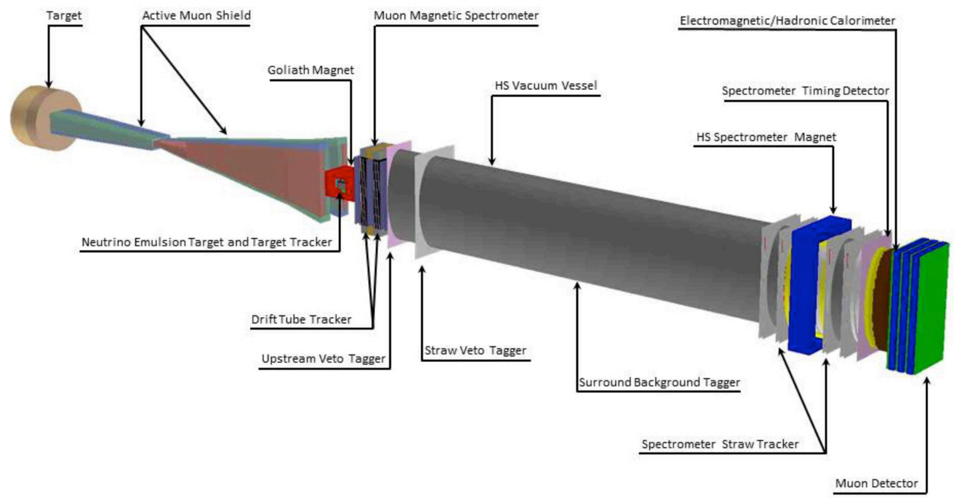
See-Saw mechanism

- 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

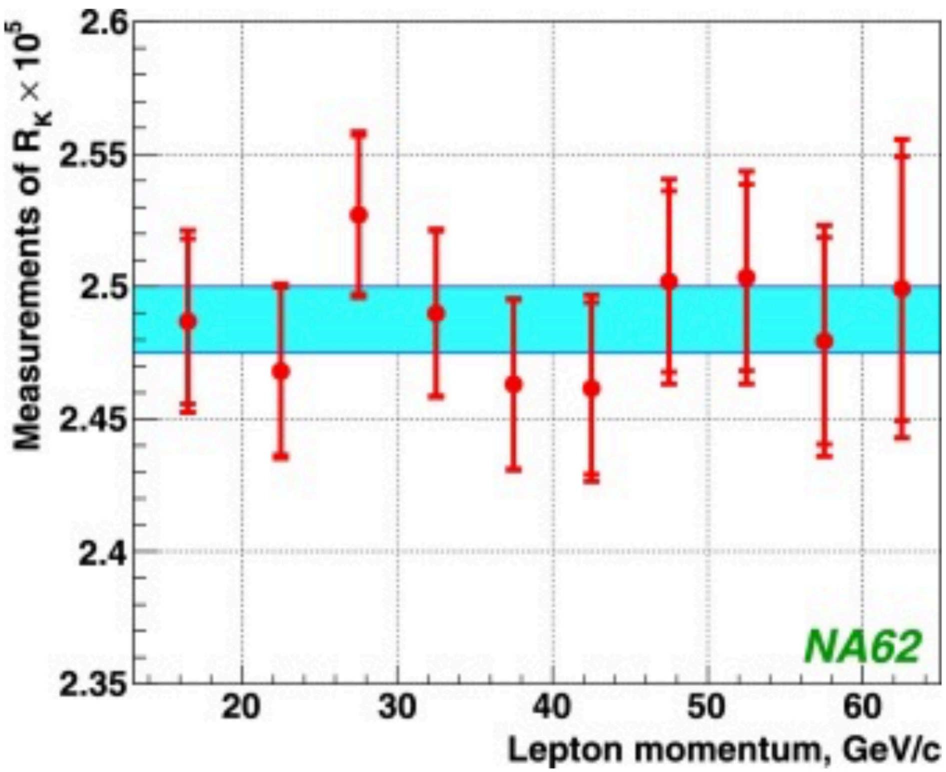


- Expected 2 x 10^{20} proton on target in 5 years.
- Target closer to detector:
  - Angular acceptance up to 20 mrad (NA62 LKr angular acceptance between 1 and 8.5 mrad)
- Molybdenum target (Z = 42)
  - NA62 is using copper (Z = 29)

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