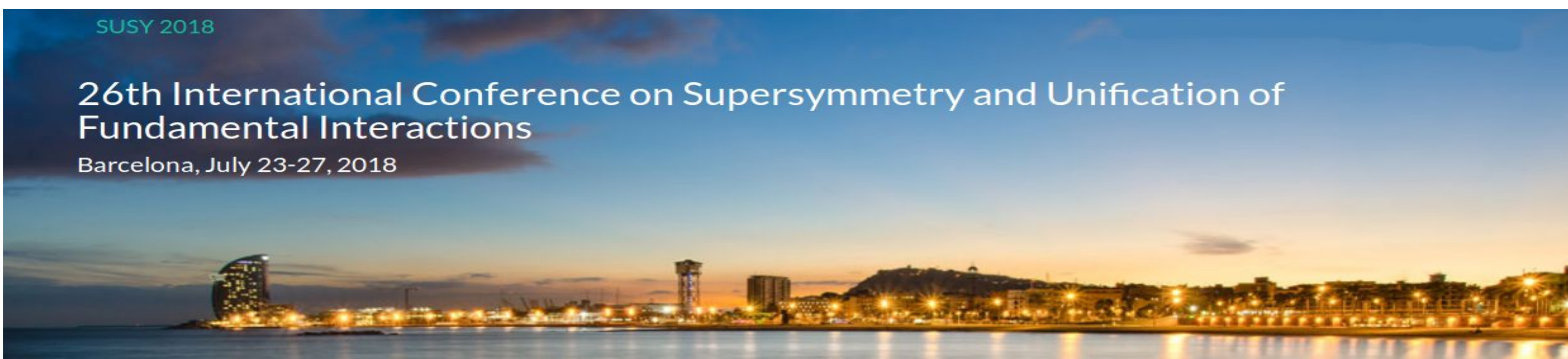
# Search for exotic particles at NA62

Elisa Minucci
(Universite' catholique de Louvain)
on behalf of the NA62 Collaboration



# Why search for exotic particles?

With the discovery at LHC of the Higgs boson the last piece of the SM puzzle has been settled

So far no evidence of New Physics at high energy has been found...

...but open theoretical issues and unresolved experimental evidences remain:

- Neutrino oscillation → Neutrino non-zero mass

  See-saw mechanism with RH neutrinos → Heavy Neutral Leptons (HNL)

- Ordinary matter does not account for all matter in the Universe → Dark Matter

  If DM is a thermal relic from hot early universe, can look for DM-SM interaction.
  Possible dynamics: vector (Dark photon), neutrino (HNL), axial (Axion-like particle)

- Matter-Antimatter asymmetry

  Starting from an initial equilibrium baryon number (B) violation, C-symmetry and CP-symmetry violation are needed.
  The amount of CP-violation in the SM is not enough and there are no experimental evidence of B-violation and L-violation.

- ...

# Search for exotic particles at NA62

NA62 is designed to measure the $K^+ \to \pi \nu\nu$ branching ratio with 10% precision using a decay in flight technique

Theory: $\mathcal{B}(K^+ \to \pi\nu\nu) = (8.4 \pm 0.1) 10^{-11}$ [Buras JHEP11 (2015)033]

Experimental: $\mathcal{B}(K^+ \to \pi\nu\nu) = (17.3^{+11.5}_{-10.5}) 10^{-11}$ [Phys. Rev D 79, 092004 (2009)]

See M.Piccini's talk for more details

The high intensity set-up, trigger system flexibility and detector performance:

-high-frequency tracking of beam particles;

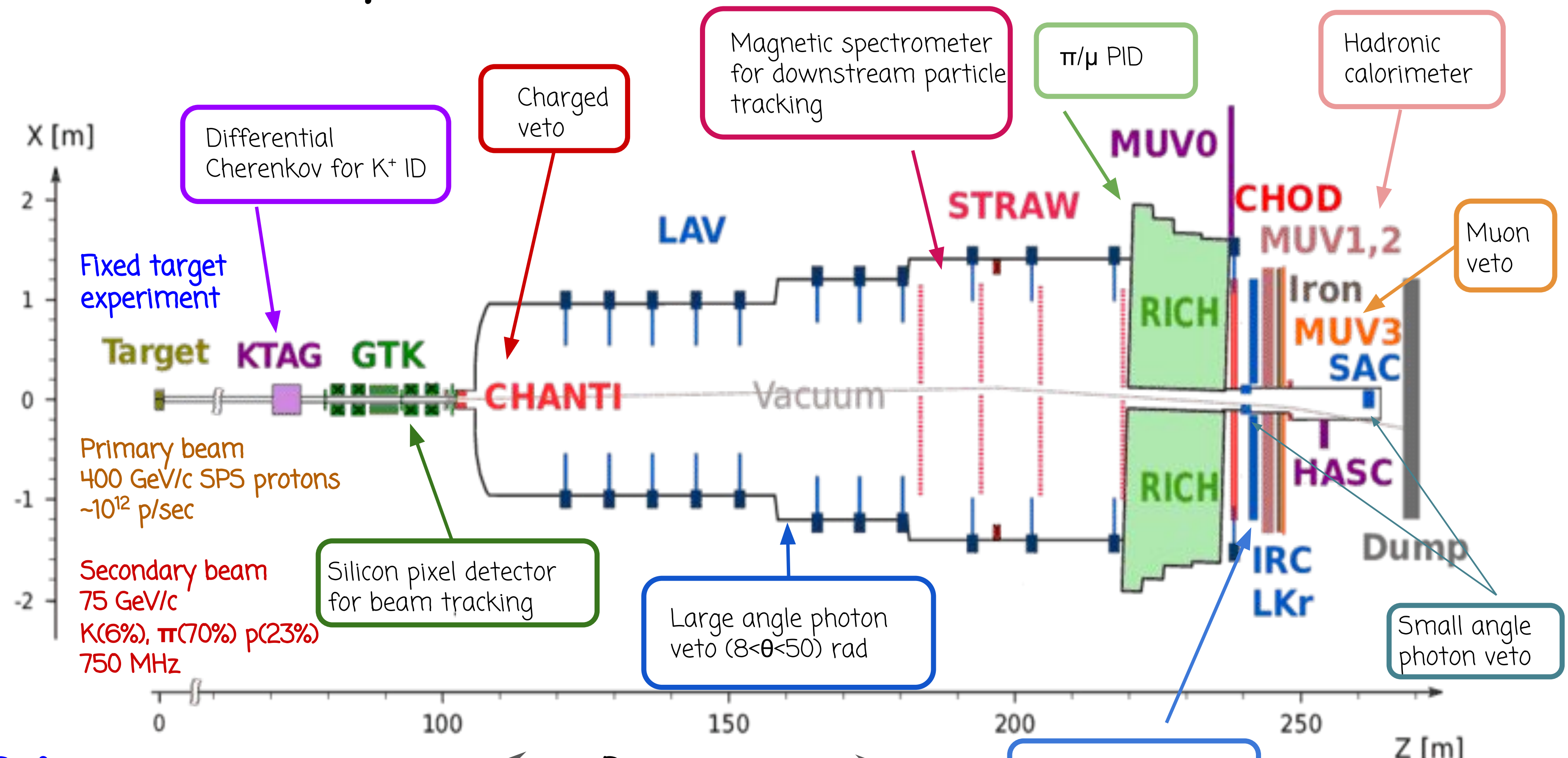
-redundant PID,

-ultra-high-efficiency photon vetoes

make NA62 particularly sensitive to $K^+$ branching ratio of order $10^{-12}$ and then suitable for searching new-physics manifestation from different scenarios in the MeV-GeV mass scale: heavy neutrinos, ALPs, light DM particles and mediators (dark photons, dark scalars)

This Talk

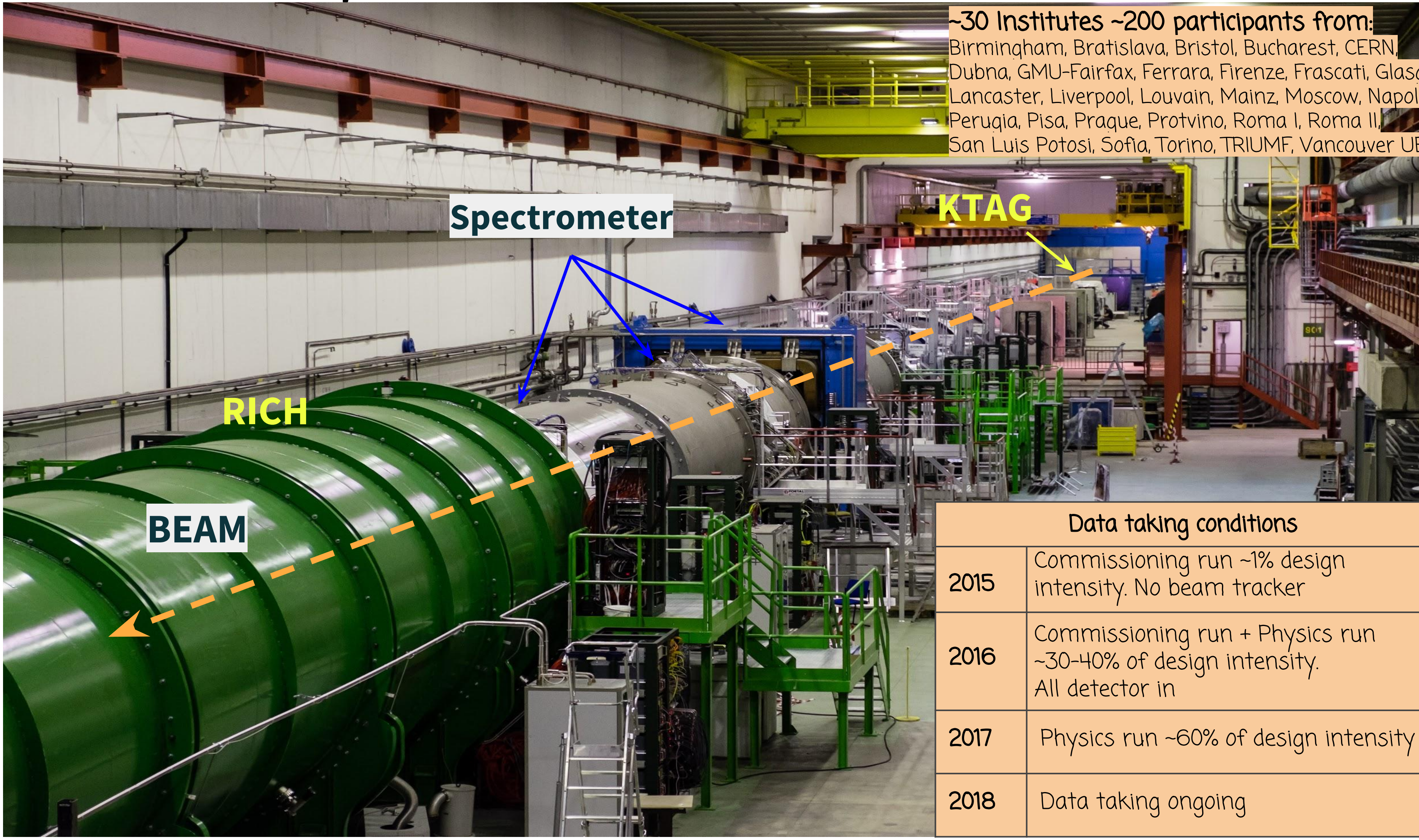
# The NA62 experiment at CERN SPS




**Performances:**
GTK-KTAG-RICH time resolution O(100)ps
$O(10^4)$ kinematic background rejection
$O(10^7)$ muon rejection for $15<P(\pi^+)<35$ GeV
$O(10^8)$ $\pi^0$ rejection for $E(\pi^0)>40$ GeV

Decay region
~ 5MHz kaon decay rate

# The NA62 experiment at CERN SPS




**~30 Institutes ~200 participants from:**
Birmingham, Bratislava, Bristol, Bucharest, CERN, Dubna, GMU-Fairfax, Ferrara, Firenze, Frascati, Glasgow, Lancaster, Liverpool, Louvain, Mainz, Moscow, Napoli, Perugia, Pisa, Prague, Protvino, Roma I, Roma II, San Luis Potosi, Sofia, Torino, TRIUMF, Vancouver UBC

| Data taking conditions | |
|---|---|
| 2015 | Commissioning run ~1% design intensity. No beam tracker |
| 2016 | Commissioning run + Physics run ~30-40% of design intensity. All detector in |
| 2017 | Physics run ~60% of design intensity |
| 2018 | Data taking ongoing |

# New-Physics searches at NA62

- Heavy Neutral Leptons (HNLs)
- Dark Photons
- Lepton Number (LN) and Lepton Flavor (LF) violation in kaon decays
- Axion-like particles (ALPs)

| Triggers | |
|---|---|
| Name | Downscaling |
| PiNuNu | 1 |
| Multi track | 50 |
| Muon Multi track | 5 |
| Electron Multi track | 2 |
| Di-Muon | 1 |
| Muon exotic | 10 |
| Non-muon | 200 |
| Control | 400 |

Triggers for searches of exotic particles

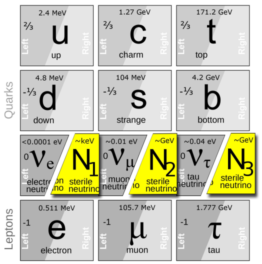
# Heavy neutral leptons

A simple extension of SM to generate neutrinos mass is the Neutrino Minimal Standard Model ($\nu$MSM)
[Asaka-Shaposhnikov, PLB 620(2005)17]

Add 3 RH neutrinos, $N_I$, with masses of the order or below the EW scale ($10^2$ GeV).

$N_1$: $m_1 \sim 10$ KeV $\rightarrow$ possible dark matter candidate

$N_{2,3}$: $m_{2,3} \sim 1$ GeV $\rightarrow$ additional CPV-phases to account for Baryon Asymmetry




How detect HNLs:

**Production: $K^+ \rightarrow l + \nu_h$**

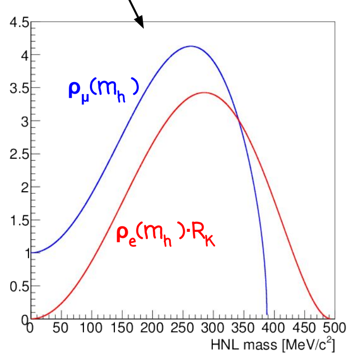
Search for a peak in $m_h^2 = m_{miss}^2 = (P_K - P_l)^2$

$\Gamma(K^+ \rightarrow l^+ \nu_h) = \Gamma(K^+ \rightarrow l^+ \nu) \cdot \rho_l(m_h) \cdot |U_{l4}|^2$

Mixing matrix element

Width of the K + leptonic decay involving SM neutrino

Kinematic factor phase space and helicity suppression




**Decay: $\nu_h$ decay only in SM particles**

$\Gamma(\nu_h \rightarrow \text{SM particles}) \sim |U_{l4}|^2 \cdot m_h^3$

For HN mass below 500 MeV/c 2 the dominant decays are :

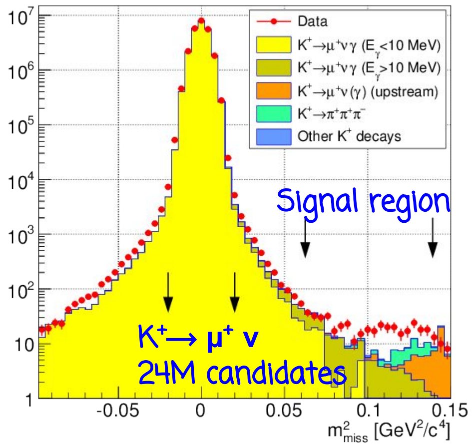
$\nu_h \rightarrow \pi^0 \nu$ , $\nu_h \rightarrow \pi^\pm \mu^\pm$ , $\nu_h \rightarrow \pi^\pm e^\pm$, $\nu_h \rightarrow \nu\nu\nu$

In NA62 the mean free path for $K^+ \rightarrow l^+ \nu_h$ , assuming $|U_{l4}|^2 < 10^{-4}$ is greater than 10 Km $\rightarrow$ heavy neutrinos decays are negligible.

# Heavy neutral leptons

Peak search in the mass spectrum $m_{miss}^2 = (P_K - P_l)^2$

2015 data sample @ 1% of design beam intensity (Minimum bias trigger, no beam tracker in)




$K^+ \rightarrow \mu^+ \nu_h$

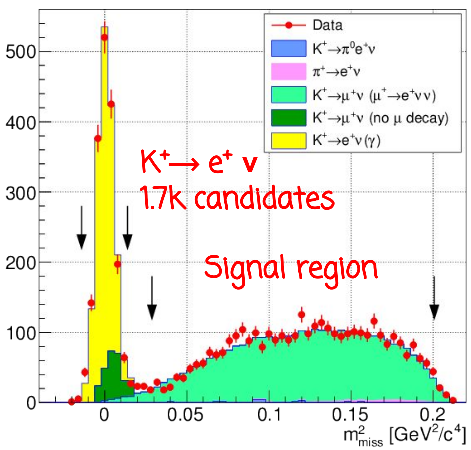
Signal region:

$250 < m_{miss} < 373$ MeV/c$^2$

$N_K \sim 1.7 \times 10^8$

HNL MC simulation for different mass hypothesis
HNL mass scan:

- Signal acceptance $A(m_h)$
- Missing mass resolution $\sigma(m_h)$

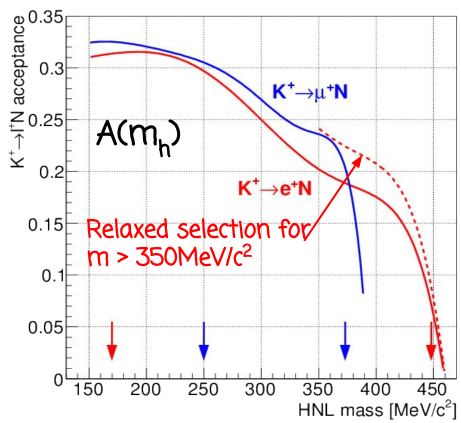


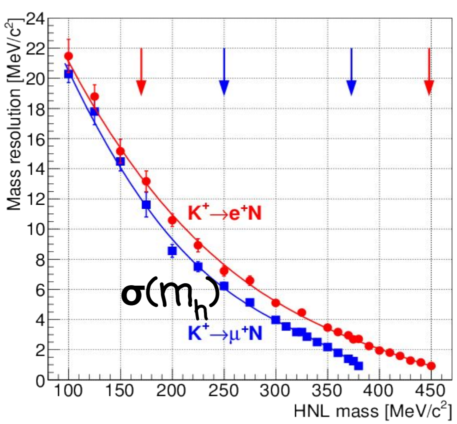

$K^+ \rightarrow e^+ \nu_h$

Signal region:

$170 < m_{miss} < 478$ MeV/c$^2$

$N_K \sim 3 \times 10^8$



# Heavy neutral leptons

No heavy neutrino signal observed

$K^+ \to \mu^+ \nu_h$

Improvement on UL in $|U_{\mu 4}|$

in HNL mass 250-373 MeV/c$^2$

$K^+ \to e^+ \nu_h$

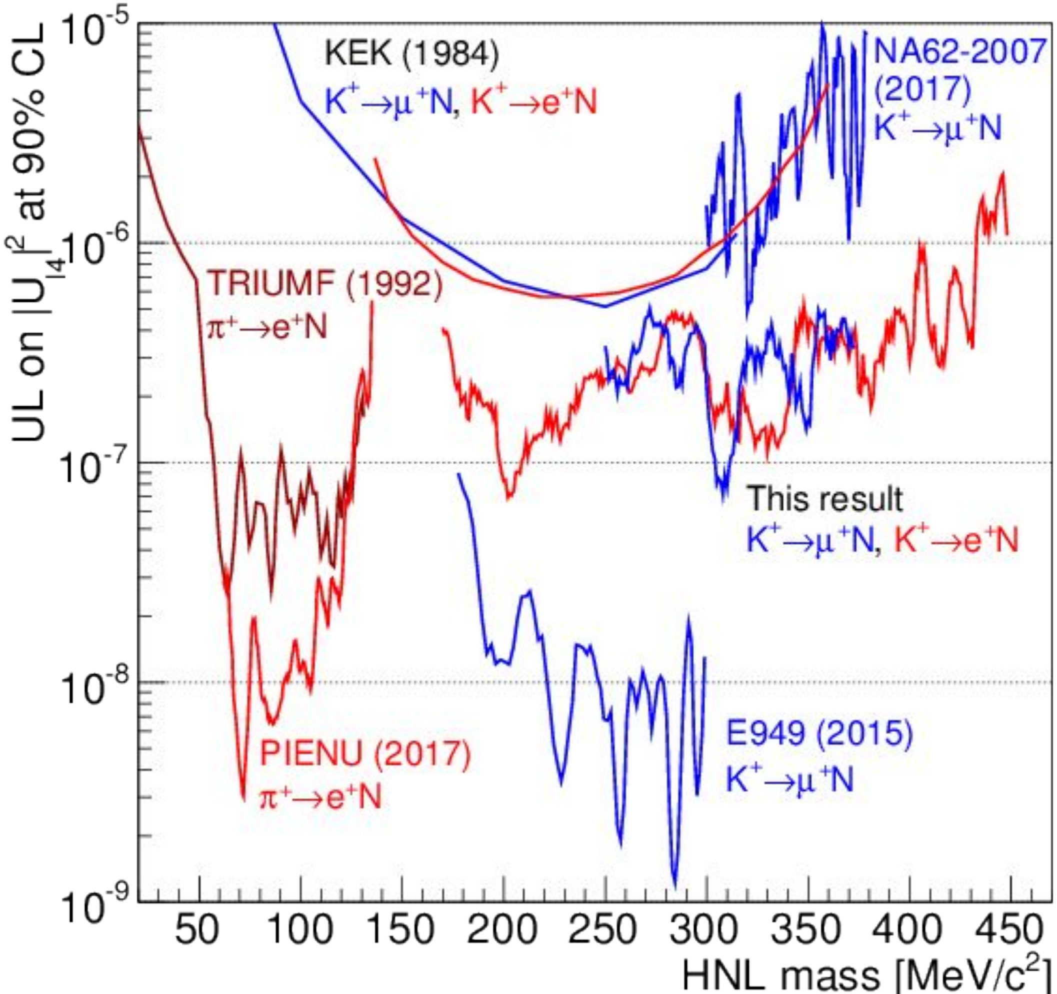
Improvement on UL in $|U_{e4}|$

in HNL mass 170-478 MeV/c$^2$

Analysis of 2016-2017 data ongoing

Expected improvements mainly thanks to the presence of the beam tracker

Expected sensitivity $\mathcal{O}(10^{-8})$ for both channels




[NA62 collaboration, Phys.Lett.B778 (2018) 137]

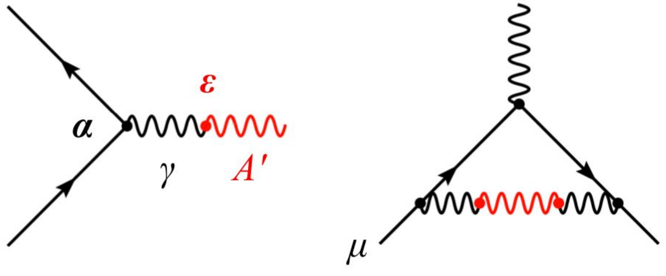
# Dark Photons

SM + extra U(1) gauge symmetry with one extra gauge boson:

the dark photon A' which can mix with SM particles.

Free parameters: **ε** and $m_{A'}$

[B. Holdom, Phys. Lett. B 166 (1986) 196]




Several signals of A' at NA62:

- Search for invisible decays from $K^+$, peak search in the missing mass spectrum (standard beam setup)

  $K^+ \to \pi^+ A'$ , $A' \to \nu\nu$ by product of $K^+ \to \pi^+ \nu\nu$ [Marciano et al. PRD 892014]

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

- Search for visible decays in SM particles (production at target/dump)

  Meson decay from primary beam secondaries: $pN \to X\pi^0$, $\pi^0 \to A'\gamma$, $A' \to l^+l^-$

  Bremsstrahlung from primary beam: $pN \to XA'$, $A' \to l^+l^-$

# Dark Photons: Invisible decays

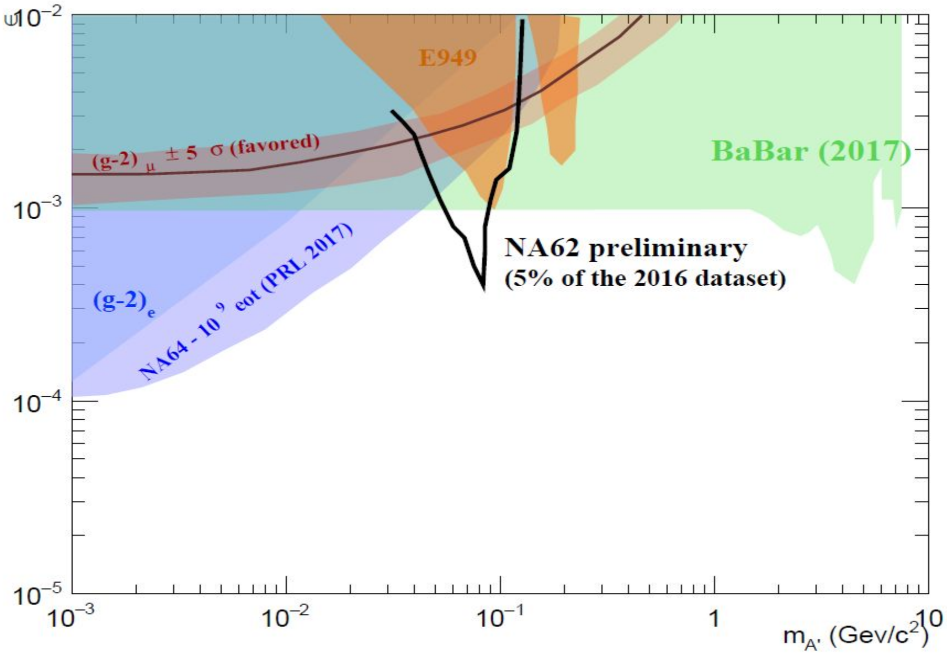
$K^+ \to \pi^+\pi^0$ , $\pi^0 \to A'\gamma$ with $A' \to$ invisible

Search for missing mass peak

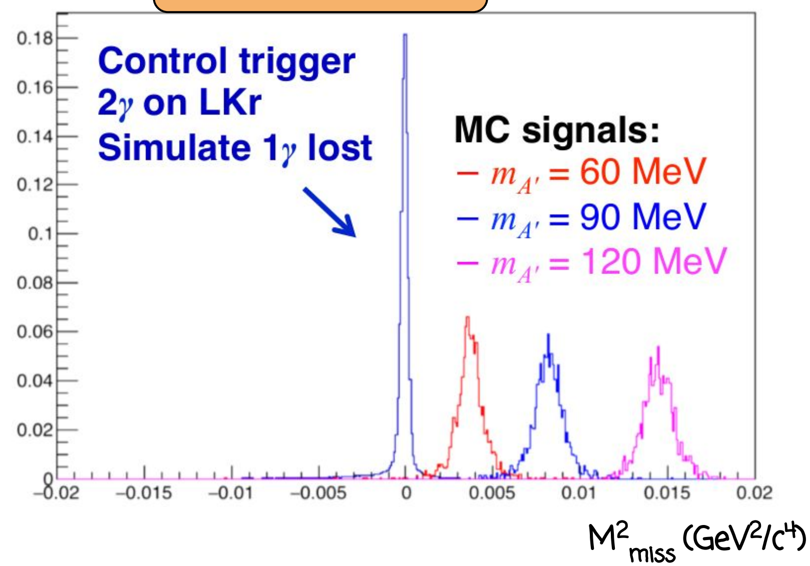
Signal: 1 track with $15 < P_{\pi+} < 35$ GeV/c

1 photon in LKr+Missing energy

Main background: $K^+ \to \pi^+\pi^0$ , $\pi^0 \to \gamma\gamma$




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




Results from 5% of the 2016 dataset
$N_K \sim 1.5 \times 10^{10}$

No significant excess observed at 90% CL

New Limit in the ($\varepsilon/m_{A'}$) plane

Analysis with full 2016 data ongoing

# Rare decays and LN/LF violation: $K \to \pi\mu\mu$

$K^+ \to \pi^+\mu^+\mu^-$ world's largest sample

Present measurement: $\mathcal{B}(K^+ \to \pi^+\mu^+\mu^-)=(9.4\pm0.6)\times10^{-8}$

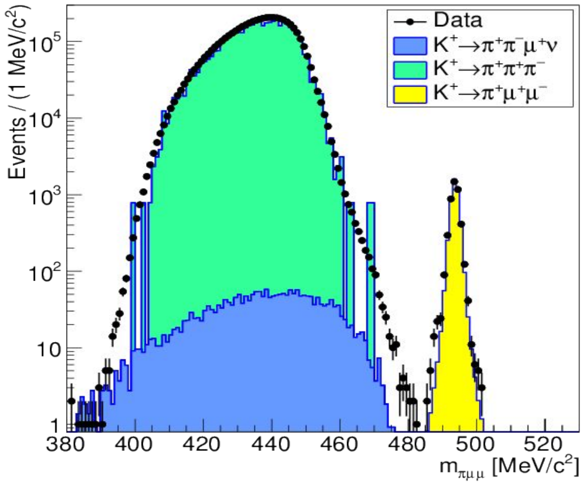
is limited by the data size (3.1k candidates) [PLB697 (2011) 107]

$N_K \sim 6.3 \times 10^{11}$ (partial dataset)

4.6k candidates with

$\sigma(m_{\pi\mu\mu})=1.2$ MeV/$c^2$ and no background

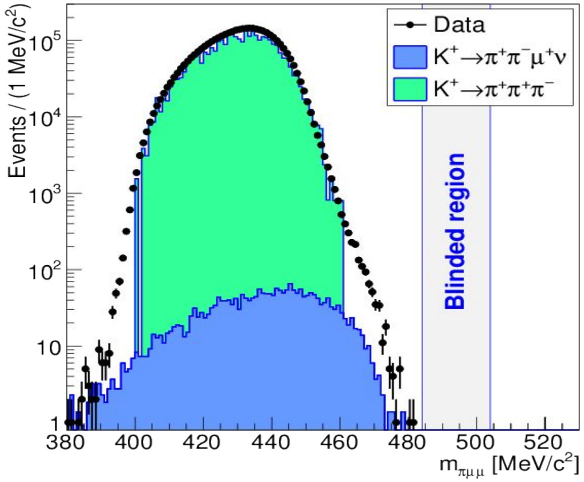
With full dataset expected ~20k candidates




$K^+ \to \pi^-\mu^+\mu^+$ not limited by the background

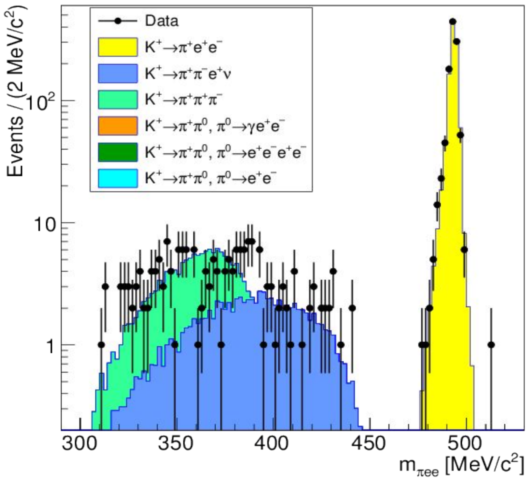
SES $2 \times 10^{-11}$ improved over the current limit UL=$8.6 \times 10^{-11}$

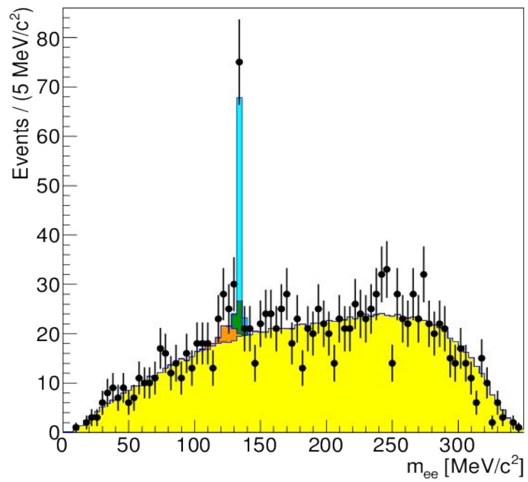
[PLB769 (2017) 67]

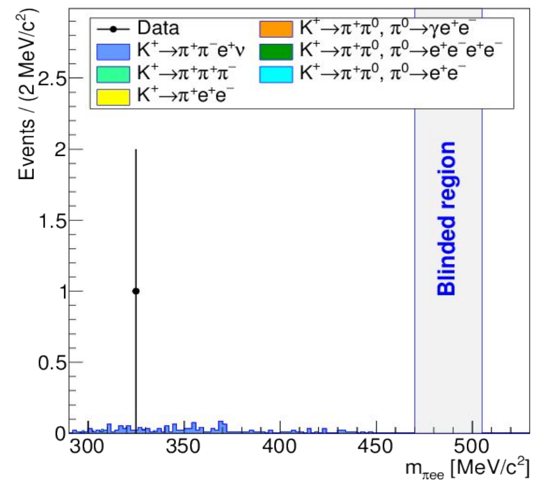



$K^+ \to \pi^+ S$, $S \to \mu^+\mu^-$ sensitivity $\mathcal{O}(10^{-10})$ for lifetime up to 1ns

# Rare decays and LN/LF violation: $K \rightarrow \pi ee$




## $K^+ \rightarrow \pi^+ e^+ e^-$

$N_K$~1.3 x $10^{11}$ (partial dataset)

1.1k candidates in the $m_{ee}$ mass region > 140 MeV/$c^2$

$\sigma(m_{\pi ee})$=1.7MeV/$c^2$ and $\delta(m_{ee})/m_{ee}$=0.004

First observation in the kinematic region $m_{ee}$< 140 MeV/$c^2$

thanks to the suppression of the decay chain

$K^+ \rightarrow \pi^+ \pi^0_D$ , $\pi^0_D \rightarrow e^+ e^- \gamma$ by the photon veto system

## $K^+ \rightarrow \pi^- e^+ e^+$

is not limited by the background

SES of 2 x $10^{-10}$ is achieved improving on the present limit UL=6.4x $10^{-10}$

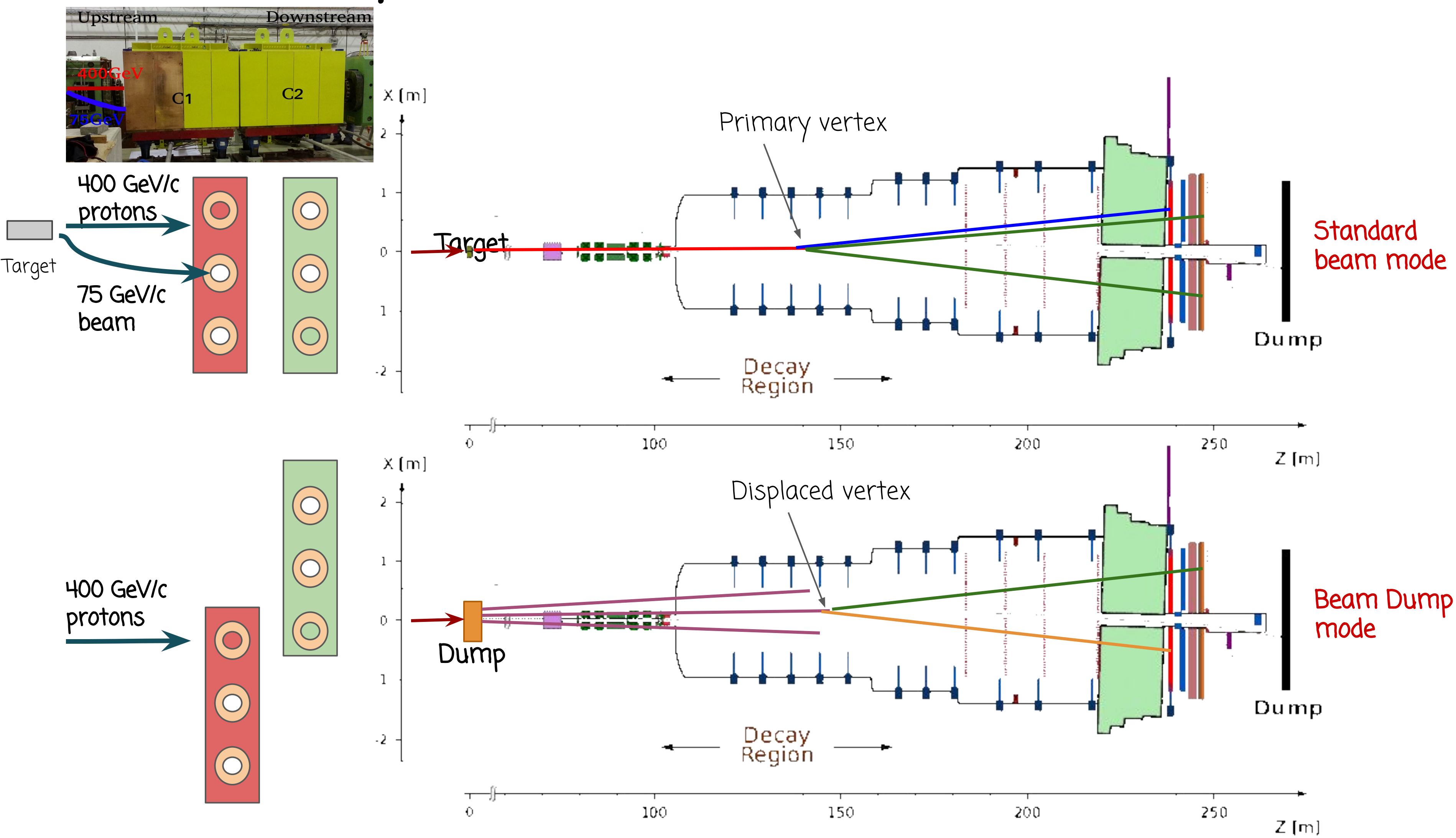
[PRL85 (2000) 2877.]

## $K^+ \rightarrow \pi \mu e$ ongoing analysis

$N_K$~2.3 x $10^{11}$ (partial dataset)

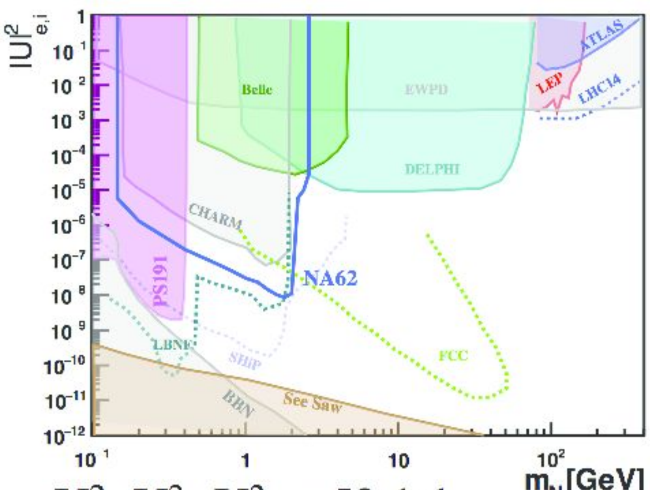
SES close to $10^{-10}$ for all channels

# NA62 in dump mode

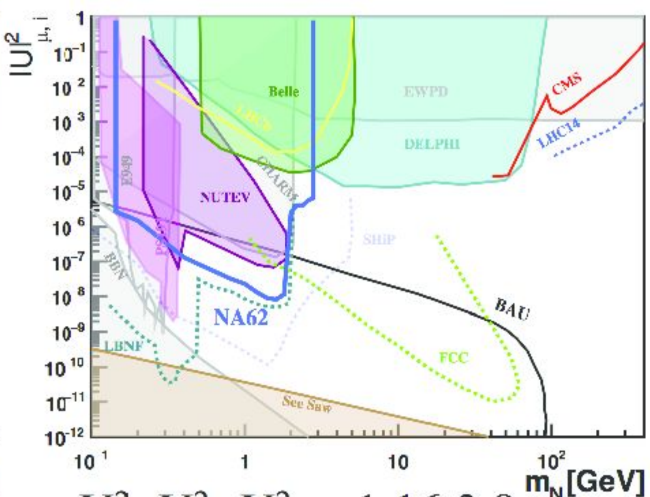


# Prospects for Heavy neutral leptons

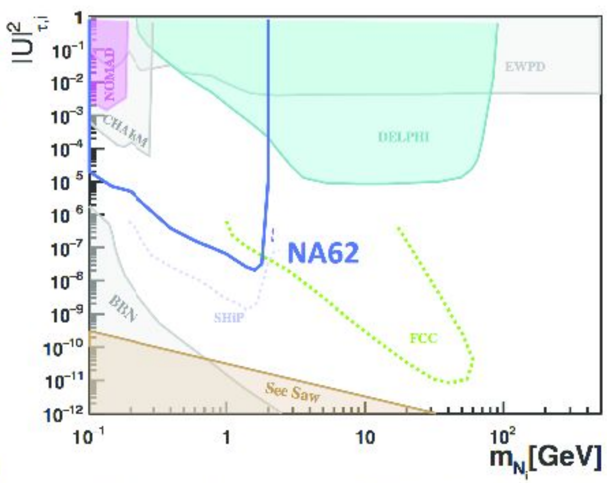
Search for long lived HNLs produced in the TAXes decaying in $\nu_h \to \pi\mu$, $\nu_h \to \pi e$




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




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




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

NA62 estimated sensitivity for $10^{18}$ POT assuming complete background rejection

for three scenario in which the HNL has the strongest Yukawa coupling for a certain flavor than the other two [Shaposhnikov, Gorbunov arXiv:0705.1729v2]

# Prospects for Dark Photons

Visible decays of long-lived A' produced from interaction into target/dump

Search for displaced, dilepton vertex: A'→μμ, A'→ee

in the fiducial volume

Sensitivity assumes:

$10^{18}$ proton on target (POT) (equivalent of 1 year of running)

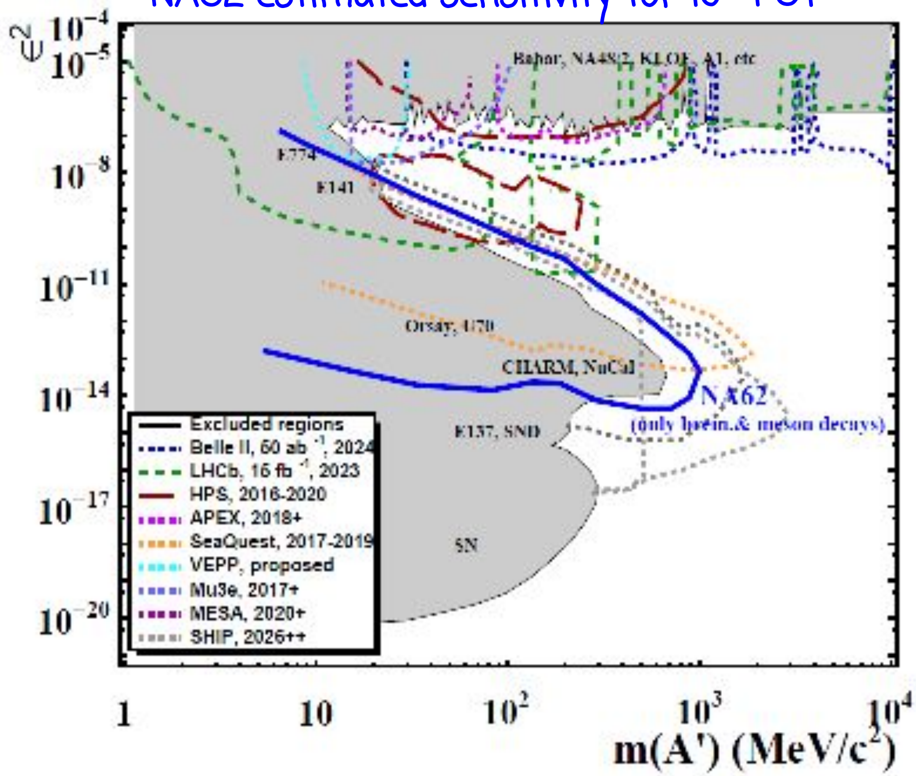
geometrical acceptance

zero background assumption

(Preliminary studies at ~ $5 \times 10^{15}$ POT show no residual background)

The expected improvement is particularly relevant in the mass region of several hundreds of MeV.

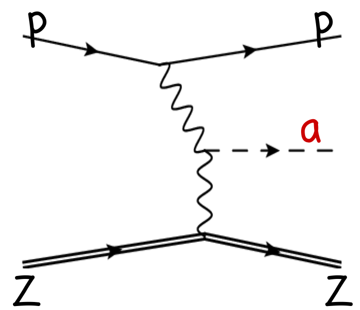
NA62 estimated sensitivity for $10^{18}$ POT



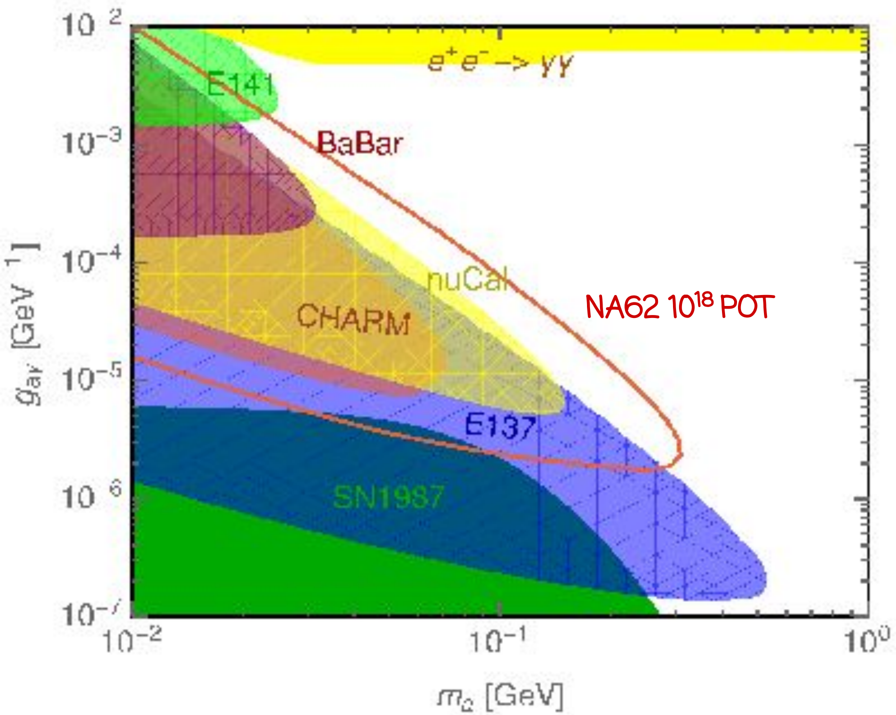
# Prospects for ALPs

ALPs possible candidate for cold Dark Matter

ALPs produced in dump mode directly in TAX via protons-nucleus elastic scattering




Primarykoff production (photon fusion)




ALPs decay in $a \to 2\gamma$ in fiducial volume

NA62 sensitivity with

- $10^{18}$ POT
- assuming zero background
- accounting for geometrical acceptance

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

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

# Summary

NA62 can contribute in searching for exotic particles and in probing the SM with a large variety of processes.

A broad physics program has been set-up for 2016-2018 data taking and good results are already obtained :

- HNLs: new limits with 2015 data in both $K^+ \rightarrow \mu^+ \nu_h$ and $K^+ \rightarrow e^+ \nu_h$ (analysis of 2016-2018 data ongoing)
- Rare decays: analysis of 2016-2018 data ongoing. Largest sample of $K^+ \rightarrow \pi^+\mu^+\mu^-$.
- LNV/LFV decays: analysis ongoing. With full statistics expecting to reach sensitivities up to $10^{-11}$
- Dark Photons: preliminary results. New limits with ~ 5% of 2016 data sample

A physics program for a possible future running after LS2 is under discussion, including:

- standard beam mode: to achieve ultimate sensitivity on $K^+ \rightarrow \pi\nu\nu$ and increase sensitivity on LNV/LFV searches
- beam-dump mode for hidden sector searches ($10^{18}$ POT)


BRUNNHUBER
ZERBINATI

# HNL

Mass scan step of 1 MeV/$c^2$

Number of observed events

in each HNL mass hypothesis

evaluated within $\pm 1.5\sigma_m$ window

Background estimation comes from

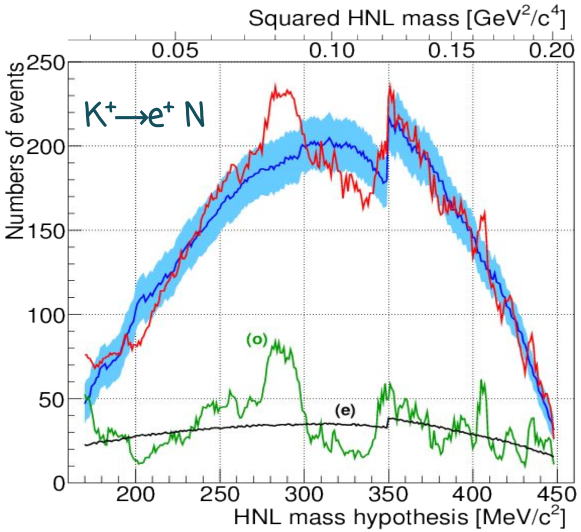
polynomial fit of data missing

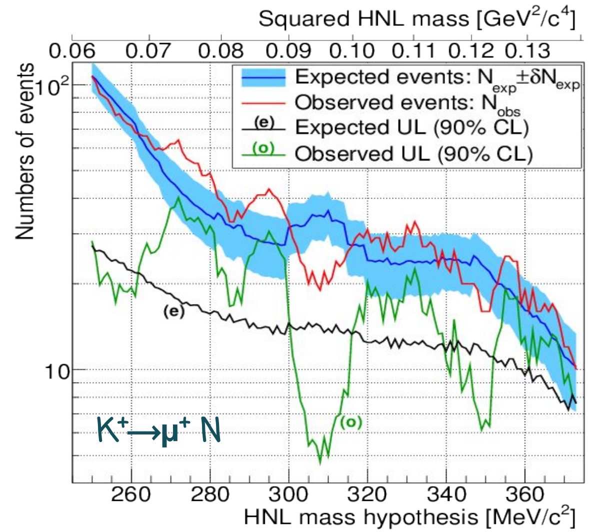
mass spectrum

Uncertainty ~10 % due to:

limited size of data

systematic (assessed with toy MC)




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

$$N^l_{sig}=N^l_K\,\mathcal{B}(K^+\to l^+ N)A^N_l$$

$$N^e_K=N_e/(A^e_e\,\mathcal{B}(K^+\to e^+\nu)+A^\mu_e\,\mathcal{B}(K^+\to\mu^+\nu)) \qquad N^\mu_K=N_\mu/(A^\mu_\mu\,\mathcal{B}(K^+\to\mu^+\nu))$$

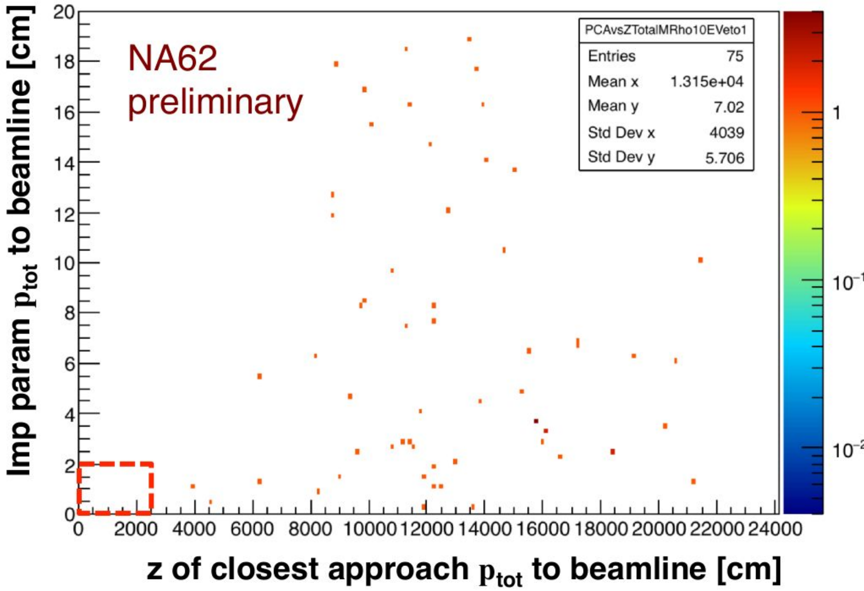
# Zero background assumption

Sensitivity for channels with visible decays for HNLs, Dark Photons and ALPs searches, are based on the assumption of zero background for $10^{18}$ POT

Preliminary study with data ($10^{15}$ POT) using combinatorial background to $A' \to \mu\mu$ from muon halo

Selection:

- 2 tracks with opposite sign (quality and acceptance cuts)
- vertex far from the beamline (quality cut)
- Photon veto (IRC/SAC/LAV)
- Upstream charged particle veto (CHANTI)
- Total momentum from target




Zero events selected in the signal region for $10^{15}$ POT

Assumption valid for $10^{15}$ POT in standard running ($4 \times 10^{15}$ POT in dump mode)