Search for Exotics @ NA62

Monica Pepe

INFN Perugia

On behalf of the NA62 Collaboration

XXV International Symposium

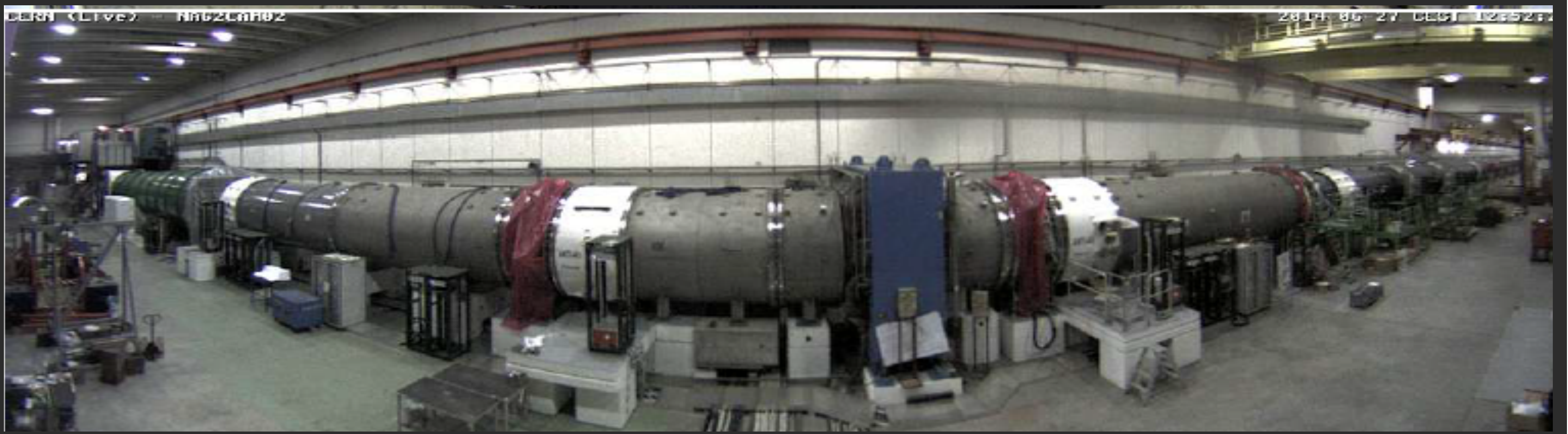
PASCOS 2019

Particle Physics, String Theory and Cosmology

1 – 5 July 2019, Manchester, UK

Outline

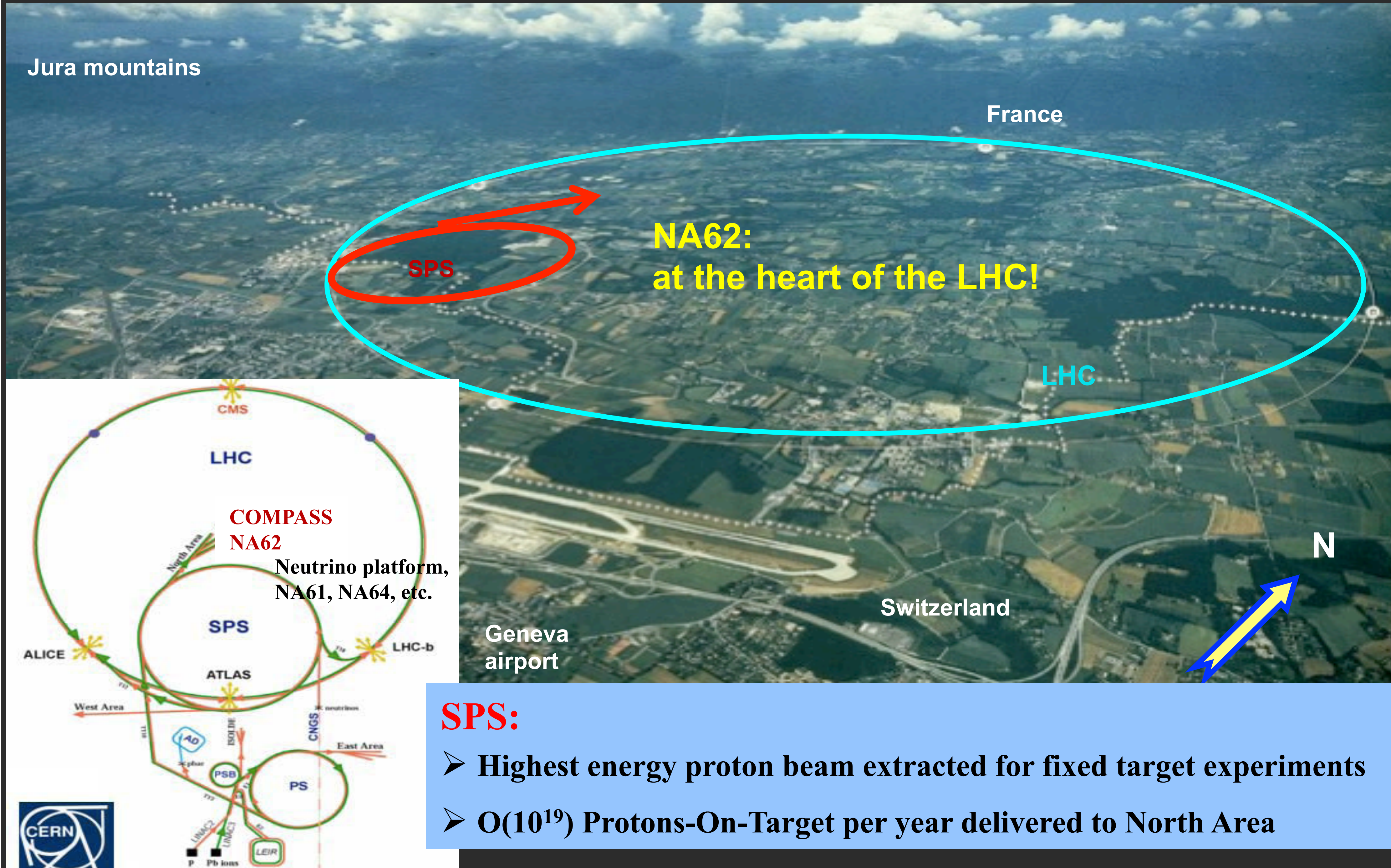
- The NA62 experiment
- Recent published results on Exotic searches:
  - Heavy Neutral Lepton (HNL)
  - Dark Photon (DP)
- Prospects for Exotics @ NA62++



<u>**The NA62 Collaboration**</u>

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

The CERN accelerator complex

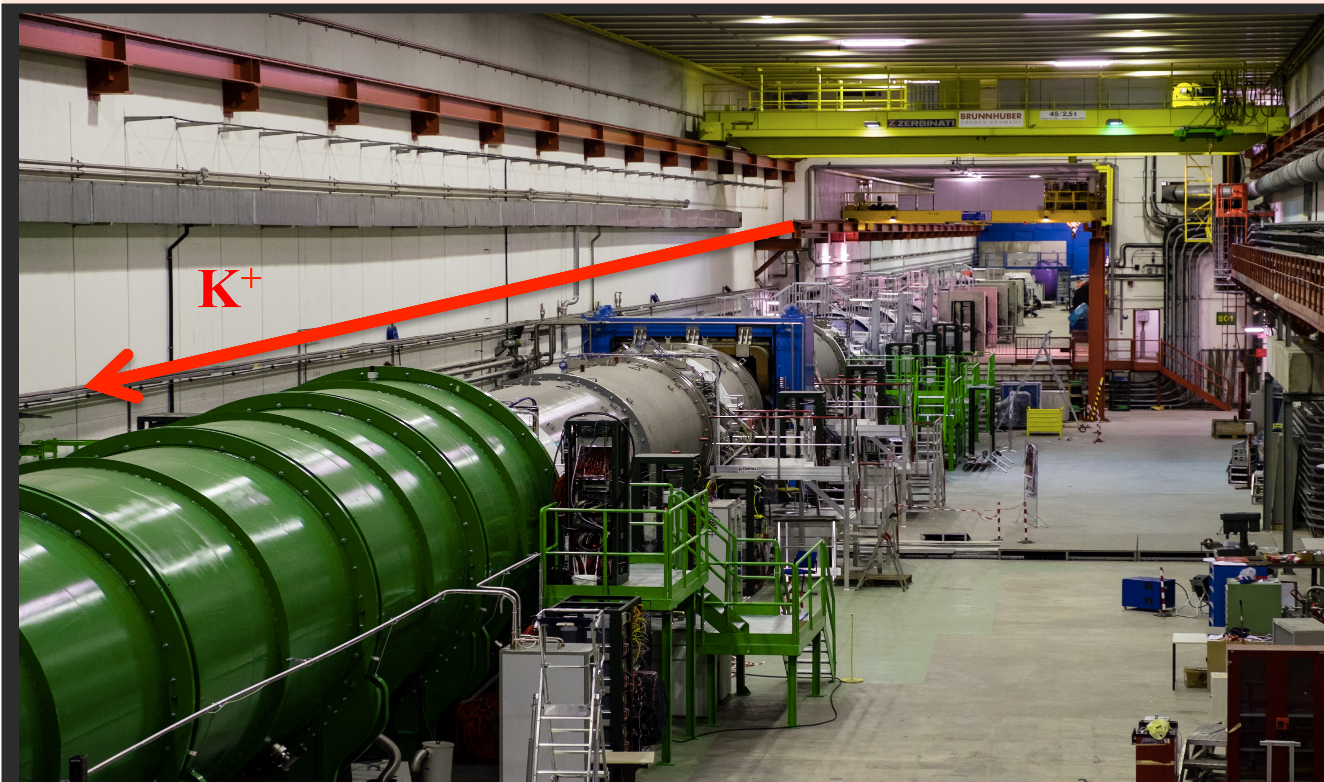


SPS:

- Highest energy proton beam extracted for fixed target experiments
- O(10^{19}) Protons-On-Target per year delivered to North Area

The NA62 Experiment @ CERN

MAIN GOAL: Measurement of BR($K^+ \to \pi^+ \nu \bar{\nu}$) @ 10% accuracy



Broad physics program

- Rare K^+ decays
- LNV-LFV in K^+ decays
- Hidden sector particles

J. Pinzino talk

Future plans: Run 3 (2021-2023)

- Complete $\pi^+\nu\nu$ measurement
- Address new physics cases:
  - LFV/LNV measurements, rare decays
  - Dump mode → MeV-GeV mass hidden-sector
    - ⇨ Dark Photons, Heavy Neutral Leptons, Axions/Axion-Like-Particles, etc

2012-2014	2014	2015	2016	2017	2018	2019-2020
Installation	Pilot run	Commissioning	Final Commissioning Physics run (30 days)	Physics run (160 days)	Physics run (217 days)	LS2

Parallel trigger masks with high efficiency have been developed:

→ negligible efficiency reduction for the main stream

→ rare decay studies, LNV/LFV, hidden sector investigation

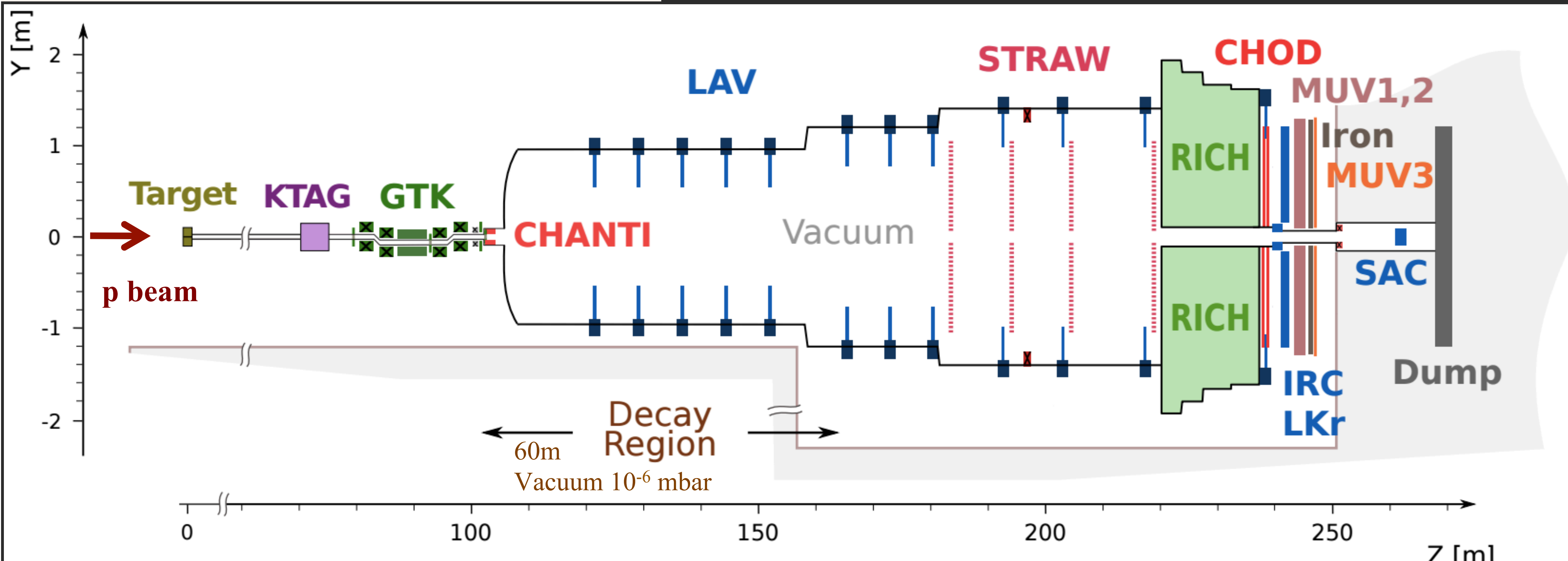
The NA62 Detector

Primary beam: CERN SPS protons
- 400 GeV/c
- 3.3×10^{12} ppp

See J. Pinzino talk

Secondary beam:
- unseparated positive beam π(70%)/K(6%)/p(23%)
- p_K = 75 GeV/c ($\Delta p/p \sim 1.1\%$)
- Nominal beam rate = 750 MHz@GTK
- K^+ rate ≈ 45 MHz
- ~5 MHz K^+ decays in the fiducial volume

Main Detectors
- **Tracking:** Si-pixel beam tracker **(GTK)** +
  Straw spectrometer in vacuum **(STRAW)**
- **PID:** Cherenkov for K^+ beam **(KTAG)** and for decay products **(RICH)**
- **Hermetic veto: Photon-veto/calorimeters** + muon veto system
- **CHANTI:** inelastic interactions of beam and collimator/GTK3
- **CHOD:** plastic scintillators for fast charged trigger

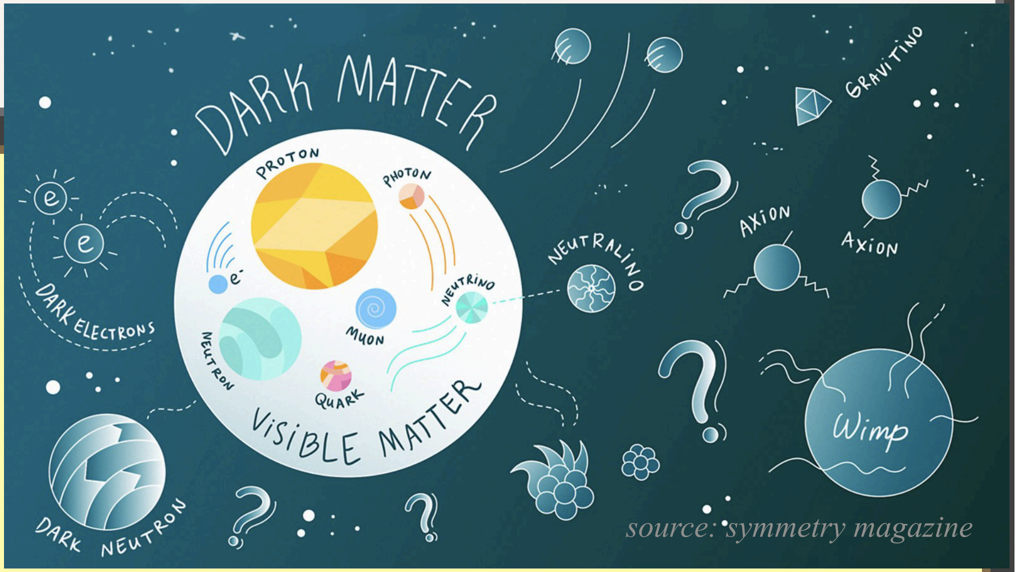


[NA62 Detector Paper: 2017 JINST 12 P05025]

Exotic searches: motivations

- Discovery of Higgs boson : experimental validation of SM completed
- Cosmic Dark Matter → suggest physics beyond SM
- Still no evidence for NP at LHC → **shift in interest towards the Intensity Frontier**

- **DM dominance** → **new mediators of a hidden sector might exist**, inducing feeble DM-SM coupling
- Many possible dynamics: neutrino (**HNL**), vector (**Dark Photon**), axial (**ALP**), scalar (**S**), ...
- New Physics below the EW scale (MeV – GeV range):
  light DM with light mediators feebly coupled to SM



- **NA62 is particularly suitable for NP searches:**
  - **High Intensity** set-up
  - **Trigger** system flexibility
  - **High rate tracking** of beam particle
  - Redundant **PID**
  - High efficiency **photon vetoes**

New Physics @ NA62

- **Heavy neutral leptons (HNL)**
- **Invisible vector bosons (Dark Photon A′)**
- **Dark Scalar (S)**
- **Axion-like particles (ALPs)**

Portal	Coupling
Dark Photon, A_μ	$-\frac{\epsilon}{2\cos\theta_W}F'_{\mu\nu}B^{\mu\nu}$
Dark Higgs, S	$(\mu S + \lambda S^2)H^\dagger H$
Axion, a	$\frac{a}{f_a}F_{\mu\nu}\tilde{F}^{\mu\nu}$, $\frac{a}{f_a}G_{i,\mu\nu}\tilde{G}_i^{\mu\nu}$, $\frac{\partial_\mu a}{f_a}\overline{\psi}\gamma^\mu\gamma^5\psi$
Sterile Neutrino, N	$y_N LHN$

Exotic particle production @ NA62

A large variety of exotic searches can be performed at NA62

Standard data taking

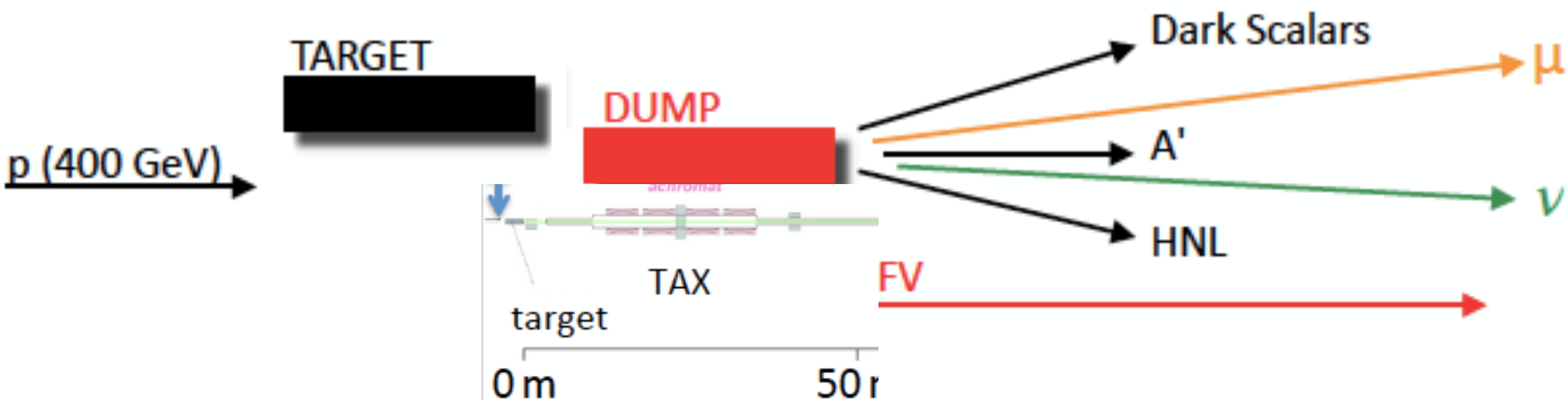
- Meson decays in the FV → Exotic particles created from K or π decays
- Proton-Target interactions → dedicated trigger chains (multi-track)

High-intensity 400-GeV proton beam → beauty/charm hadrons, mesons in a dump

Dedicated dump runs

- Best possible sensitivity for weakly-coupled particles produced upstream
- In this setting background is minimized
- Specific trigger chains

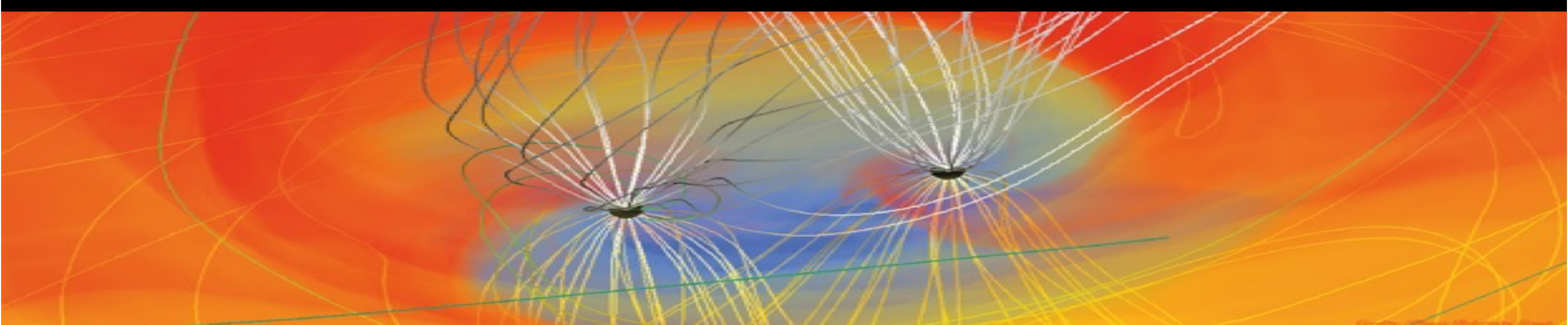
Act as a compact beam dump if 11 λ_I Cu-based beam defining collimator (TAX) closed



All beam-induced backgrounds are stopped except:
μ ν and any kind of feebly-interacting long-lived particle

Decay volume 60 m long (in vacuum) :
reasonable acceptance for long-lived states

HNL & Dark Photon production searches

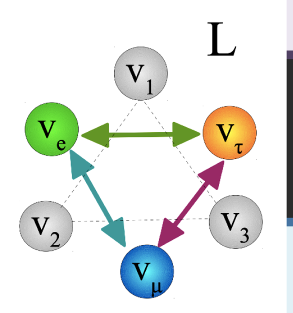


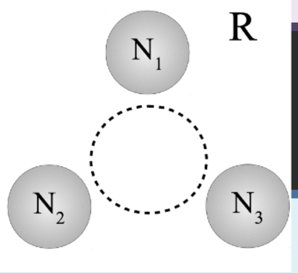
Heavy Neutral Lepton

- Observation of neutrino oscillations → Neutrino mass needs to be accomodated in the SM

➢ **Asaka-Shaposhnikov model (νMSM)** ***[PLB 620 (2005) 17]***

➢ 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





- N_1 is the lightest O(keV) → **Dark Matter candidate**
- N_2 N_3 (mass ~ 100 MeV to few GeV) introduce extra CPV-phases to account for Baryon Asymmetry
- N_2 N_3 produce standard neutrino masses through see-saw mechanism with a Yukawa coupling of ~10^{-8}
- **Sterile (HNL) – Active (SM) neutrino mixing → HNL production in meson decays**

Heavy Neutrino production in K^+ decays: $K^+ \rightarrow \ell^+ N$ ($\ell = e$, μ)

→ Sensitivity for masses below K^+ mass

→ Independent of HN decay modes

→ Sensitive to long-lived HN

→ Rate scales linearly with kaon flux

$$\mathcal{B}(K^+ \rightarrow \ell^+ N) = \mathcal{B}(K^+ \rightarrow \ell^+ \nu) \cdot \rho_\ell(m_N) \cdot |U_{\ell 4}|^2$$

kinematic factor — mixing parameter

HNL from K^+ decays : 2015 data

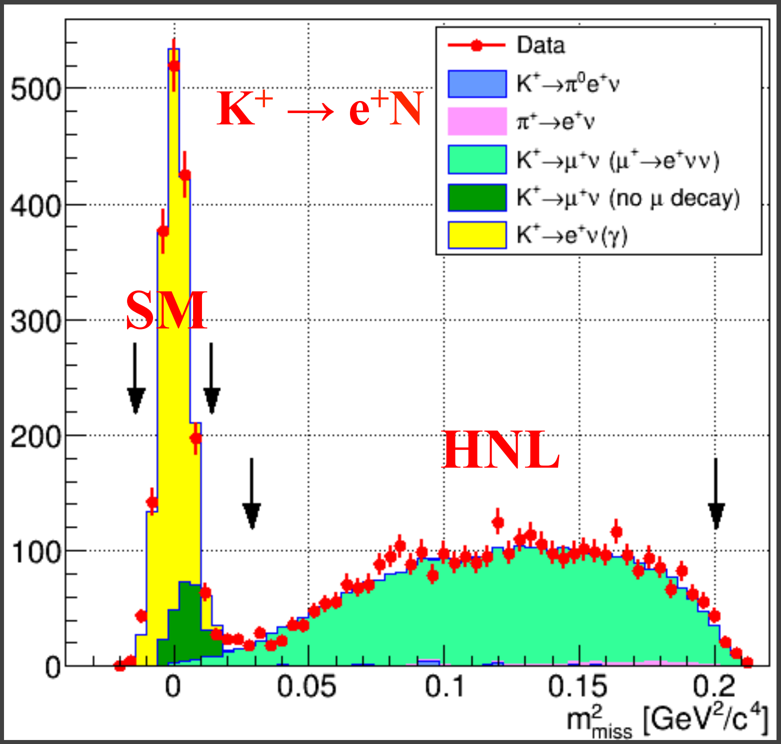
Analysis strategy:

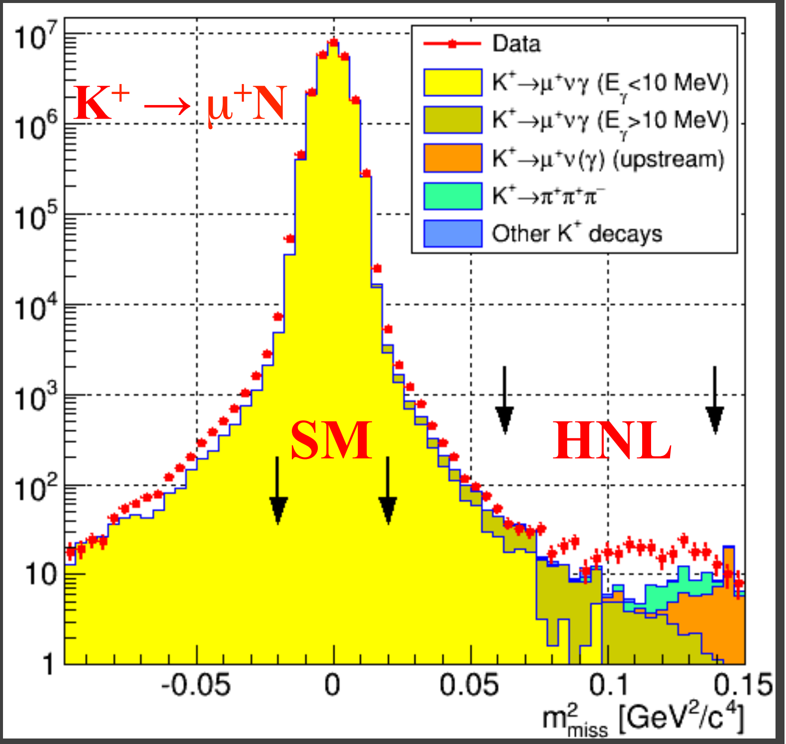
- HN (N) is long lived and escapes the detector
- search for excess in the missing mass spectrum $m^2_{miss} = (P_K - P_\ell)^2 = m^2_N$
- count N_{sig} in sliding mass window across m^2_{miss}
- convert N_{sig} to limits on $|U_{\ell 4}|^2$

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 $K^+ \to \mu^+N$

- Single positively-charged track topology
- kaon decay vertex close to beam axis
- e/μ ID through E/p





[Phys. Lett. B778 (2018) 137]

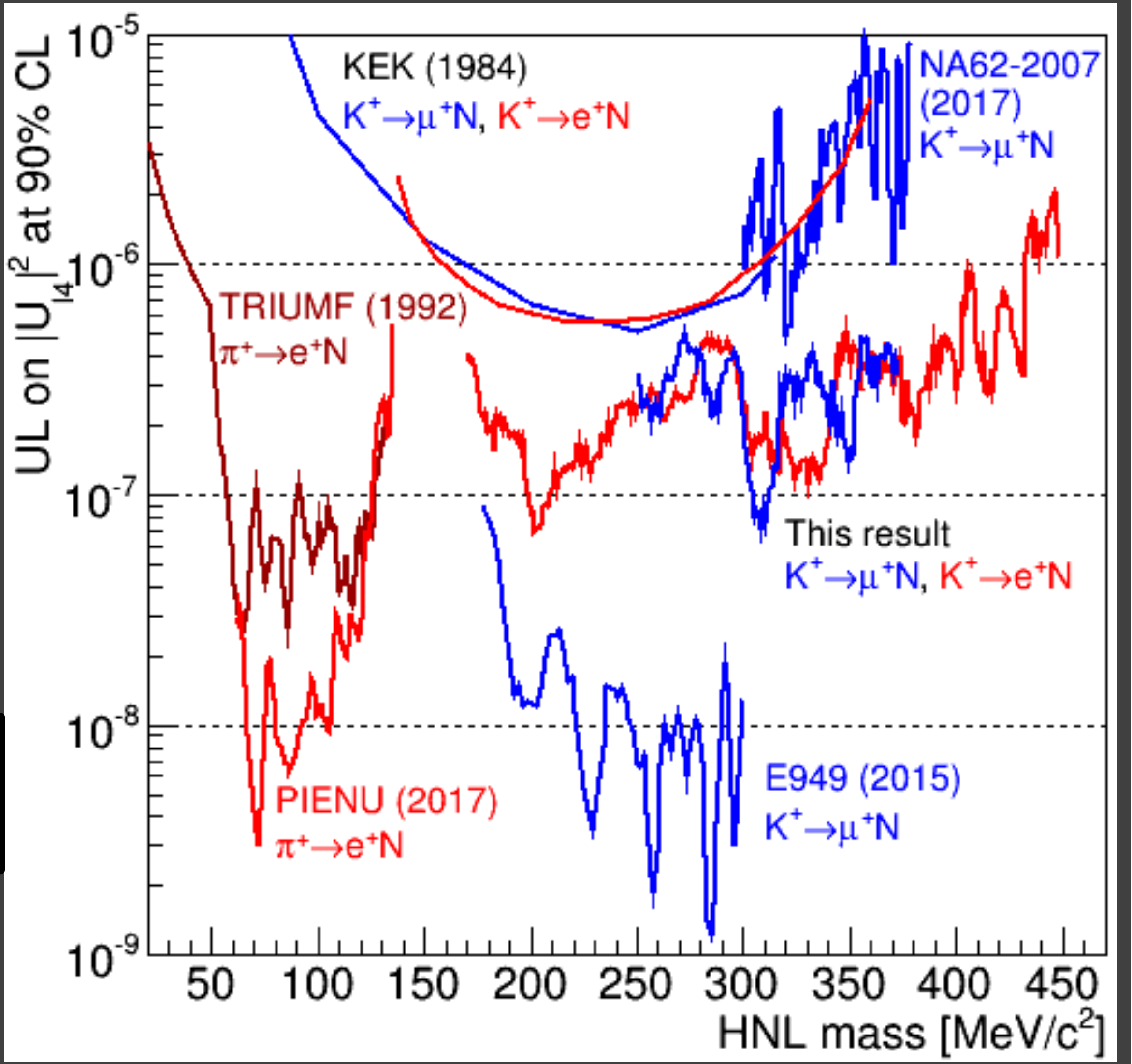
HNL production searches

- Scan with 1 MeV/c^2 steps
- Data driven background evaluation
- Rolke-Lopez method to set 90% CL limits on N_{sig}
- No statistically significant excess observed

Results:

- Limits on $|U_{\ell 4}|^2$ at 10^{-7} – 10^{-6} level
- Improved limits on $|U_{e4}|^2$ in 170 – 448 MeV/c^2
- Improved limits on $|U_{\mu 4}|^2$ above 300 MeV/c^2

O(10) improvement foreseen with full set of NA62 data (2016-2018)



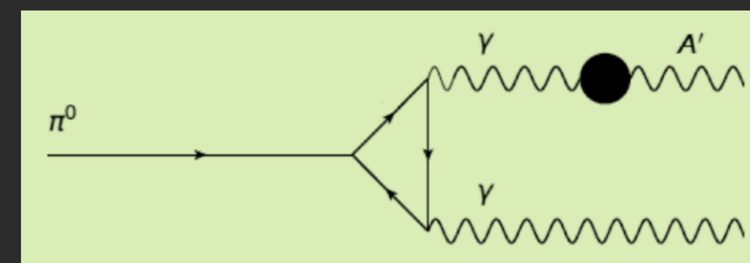
[Phys. Lett. B778 (2018) 137]

The Dark Photon A′

- The abundance of DM in the universe could be explained by a new U(1) gauge symmetry with a vector mediator field, the **Dark Photon A′**
- Interaction of **A′** with the SM photon proceeds through a kinetic-mixing Lagrangian with a coupling parameter ε

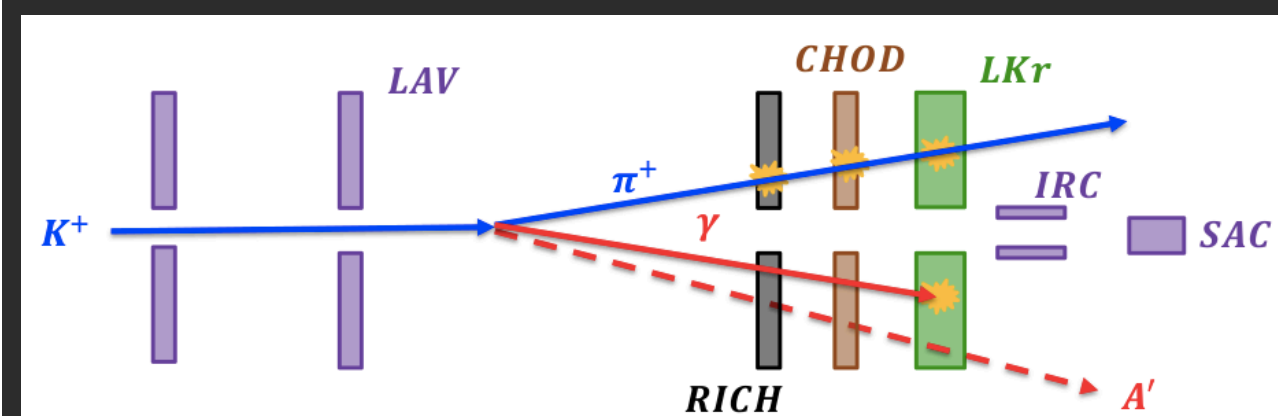
$$\mathcal{L} = -\frac{\epsilon}{2} F^{QED}_{\mu\nu} \; F^{\mu\nu}_{dark}$$

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



- Dark Photon produced in π^0 decay: $K^+ \rightarrow \pi^+\pi^0$, $\pi^0 \rightarrow \gamma A'$
- Same process as SM but scaled by coupling factor ε^2 and kinematic factor
- Rate driven by the mixing strength ε

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



If A′ is not the lightest DM candidate would decay mostly "invisibly"
→ missing energy signature

A′ from π^0 decays: 2016 data

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

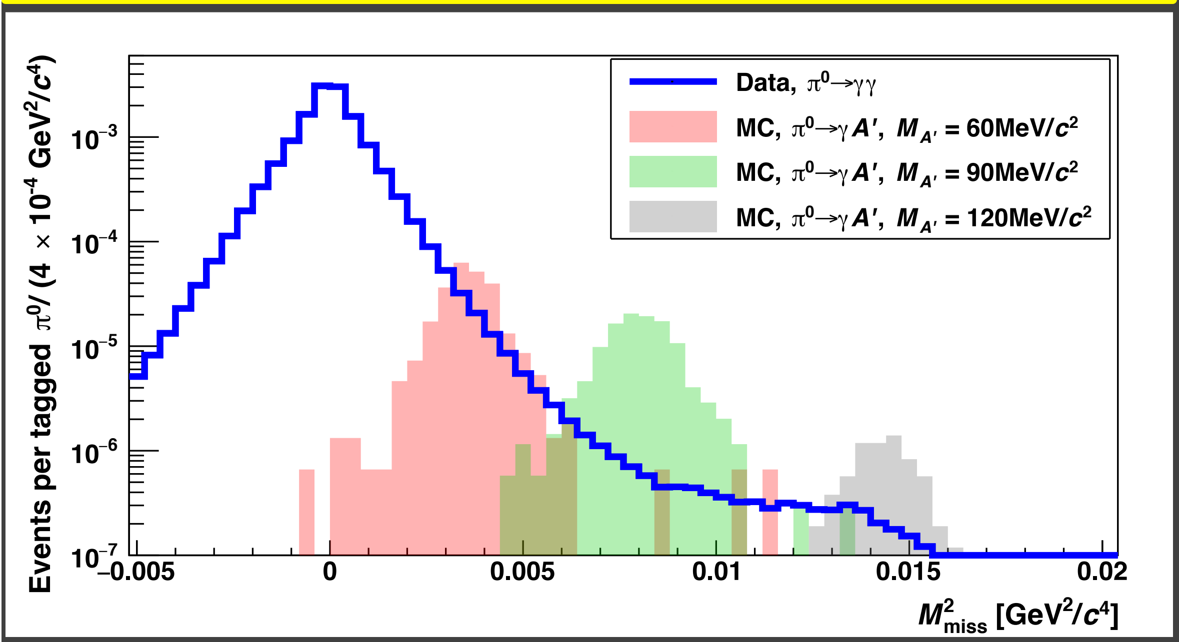
- Sensitivity below the π^0 mass
- Search parasitic to $\pi\nu\nu$-trigger (1 track + small forward energy)
- Signal: 1 track, 1 photon cluster in Lkr + missing energy
- Main bkg from $\pi^0 \to \gamma\gamma$ with 1 lost photon
- Expect a peak around the squared A′ mass

Analysis of a subsample of 2016 data

→ 1% of 2016-2018 full statistics

→ 4.12×10^8 tagged π^0

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

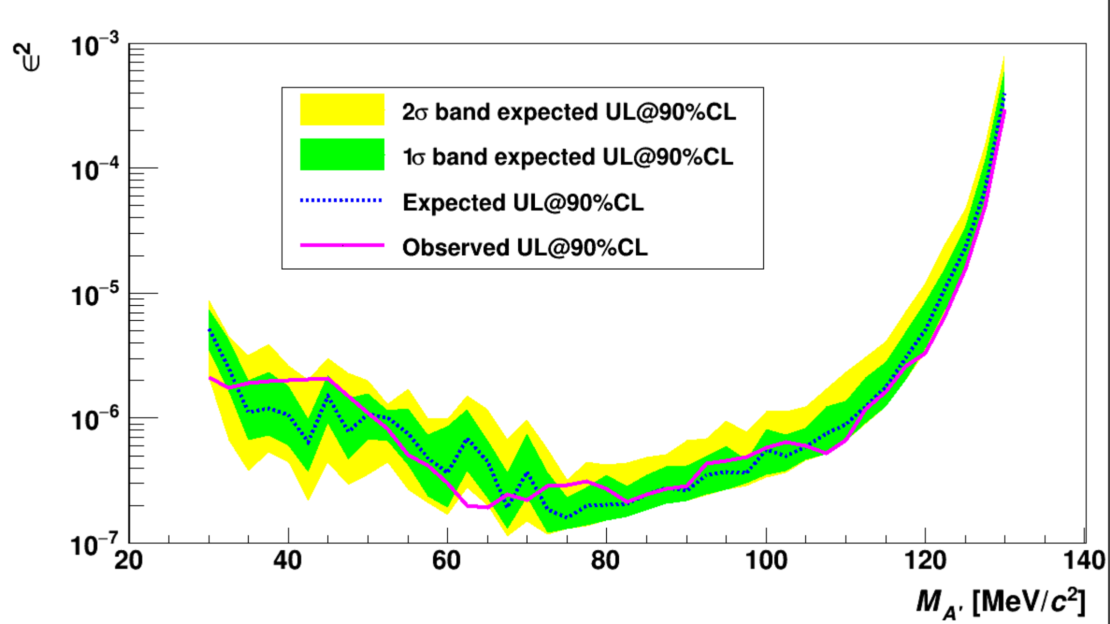


Analysis strategy:

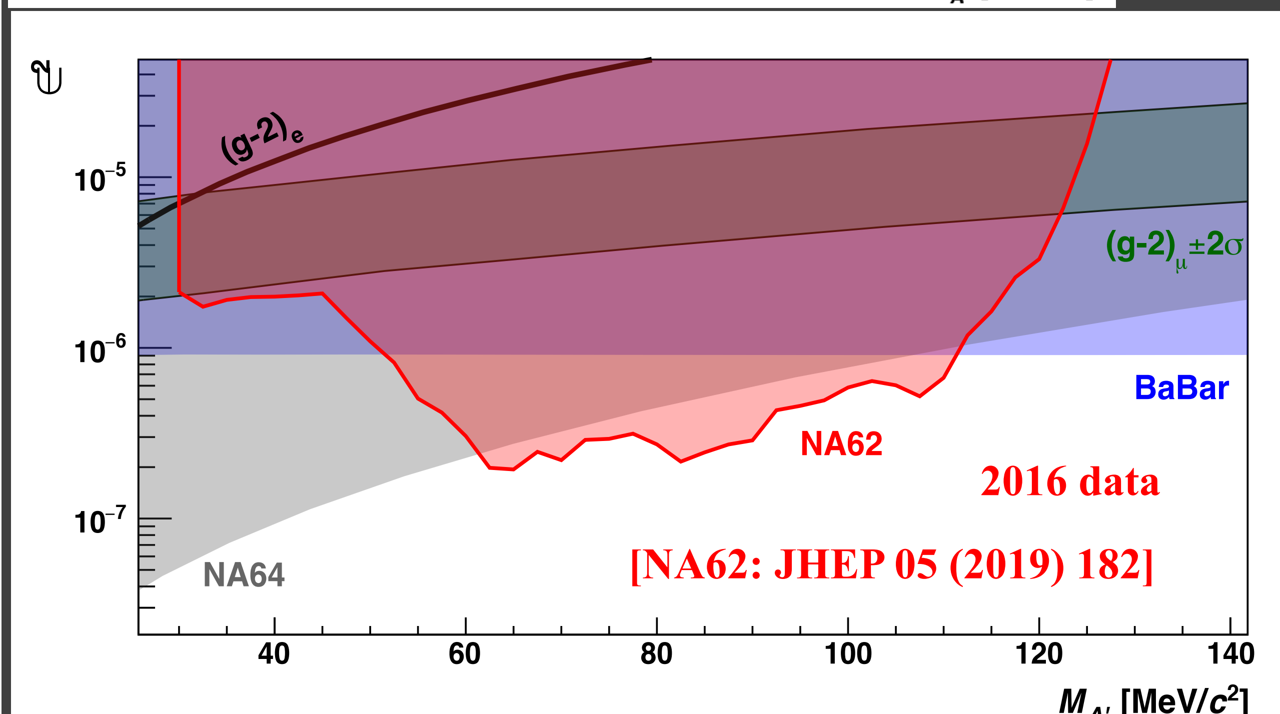
- Search for excess of events in the missing mass spectum
- Count N_{sig} in sliding mass window across M^2_{miss}
- Convert N_{sig} to limit on ε

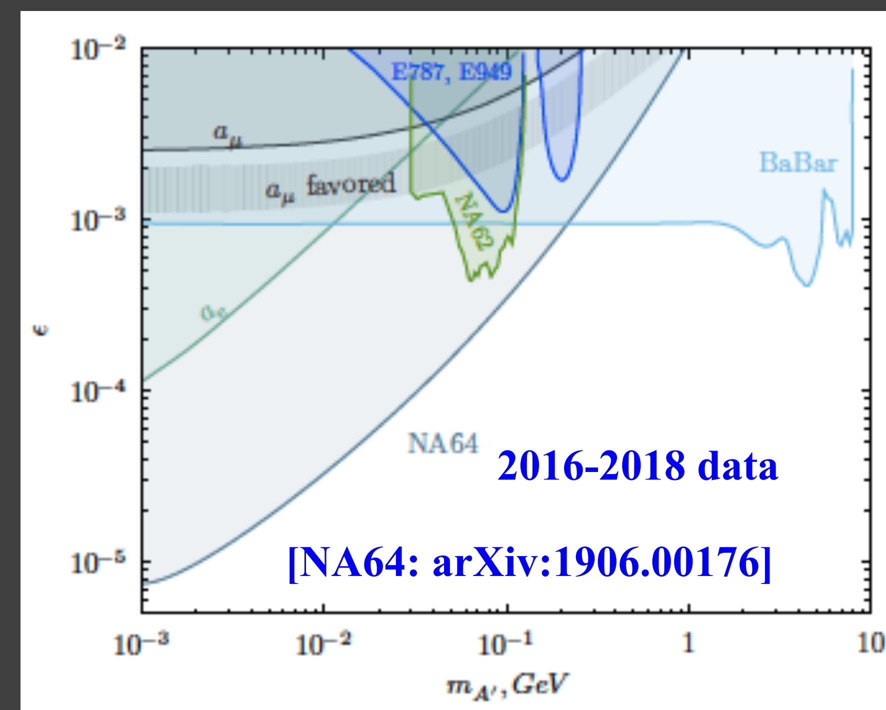
[JHEP 05 (2019) 182]

$A' \to$ invisible: results with 2016 data



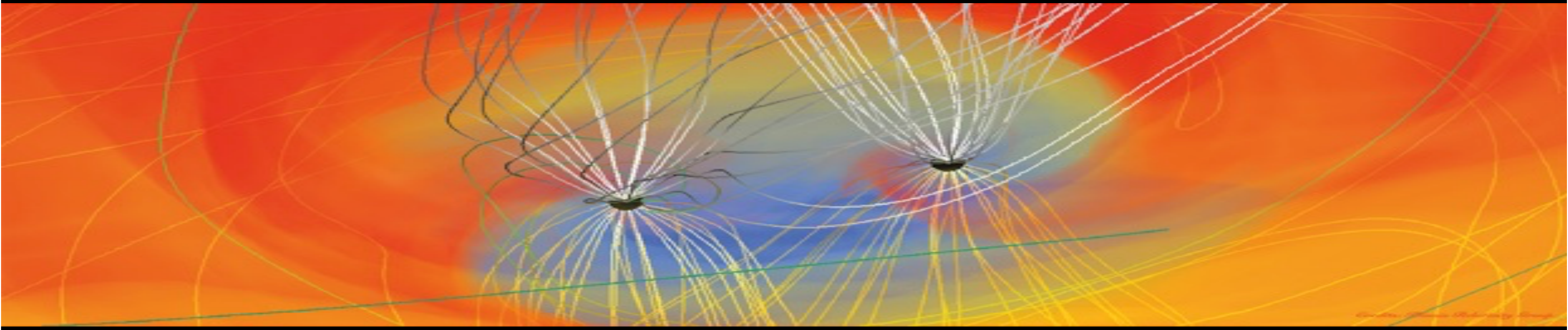
- Scan with 10 MeV/c^2 steps
- Data driven background evaluation
- CLs method used
- No statistically significant excess observed
- Set 90%CL limits on ε^2 in 30-130 MeV/c^2





Also set world's best upper limit on $B(\pi^0 \to \gamma\nu\nu) < 1.9 \times 10^{-7}$ at 90% CL

NA62++ prospects on Exotics



NA62++ in Run3

Same NA62 apparatus operating in "dump mode" :

- Switching from the standard beam mode to the beam-dump is easy, quick (15 minutes) and fully reversible.
- $O(10^{16})$ POT in dump mode were collected in 2016-2018 and analysed for background studies

Dump Statistics (POT)	Trigger
9×10^{15}	Two Tracks
5.5×10^{15}	> 3 GeV in Lkr

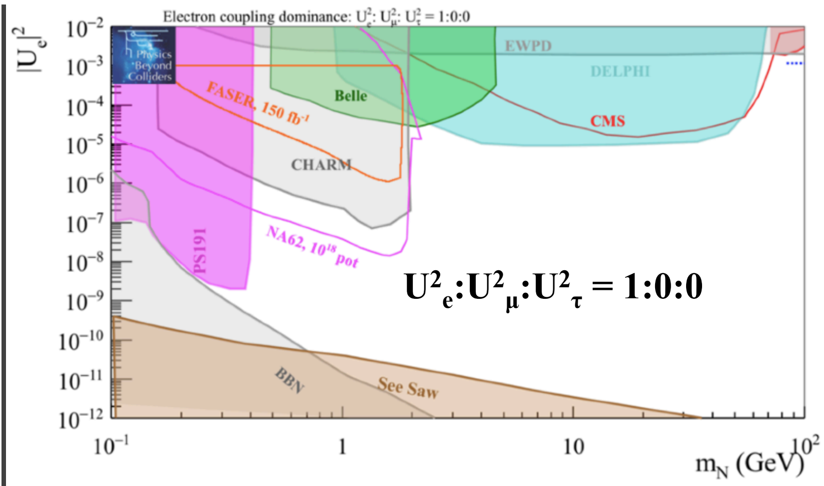
NA62++ proposes to operate the detector in beam dump mode for few months during Run 3 in 2021-2023:

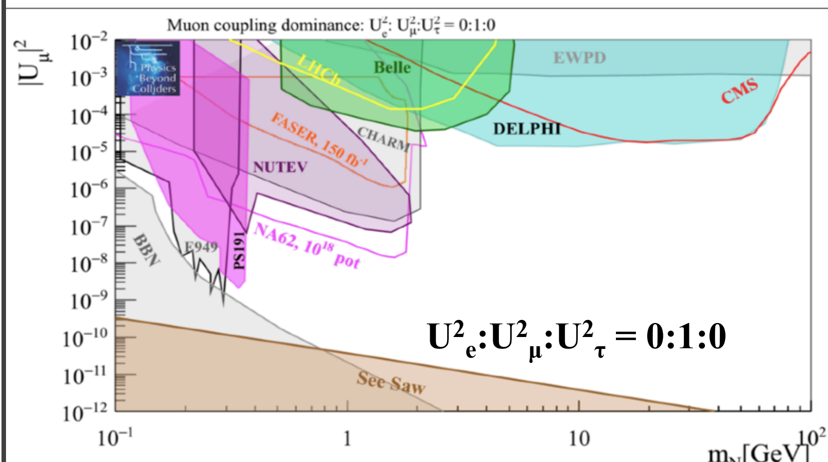
- $O(10^{18})$ POT can be collected in about 3 months of data taking
- the muon halo emerging from the dump is partially swept away by the existing muon clearing system, but an upstream veto is under study for further reduction

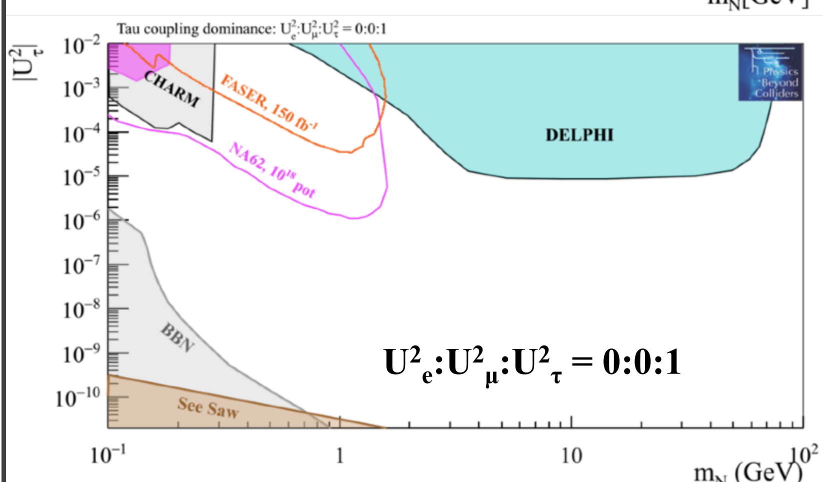
The physics potential of NA62++ has been studied as part of the 'Physics Beyond Colliders – Beyond the Standard Model' working group

- Following slides show NA62++ expected sensitivity assuming $O(10^{18})$ POT
- Plots taken from the PBC-BSM report [arxiv:1901.09966]
- The limits are set at 90% CL and are compared to other results expected on a 5-year scale
- Results of background studies are based on $O(10^{16})$ POT

NA62 potential for HNL







- **HN emitted by secondary mesons produced in the dump**
- **Leptonic decays of D (D_s) → ℓ^+N in FV** (mass up to ~1.7 GeV/c^2)

N→ final states with at least 2 charged tracks

Benchmark scenarios with HNL coupling to one SM generation at the time

- **Account for trigger/acceptance/selection efficiency**
- **Assume zero-background → 90% CL exclusion plot**

NA62 can improve limits on the HNL parameter space

Analysis of 3×10^{16} POT collected in dump mode in 2016-2018 in progress….

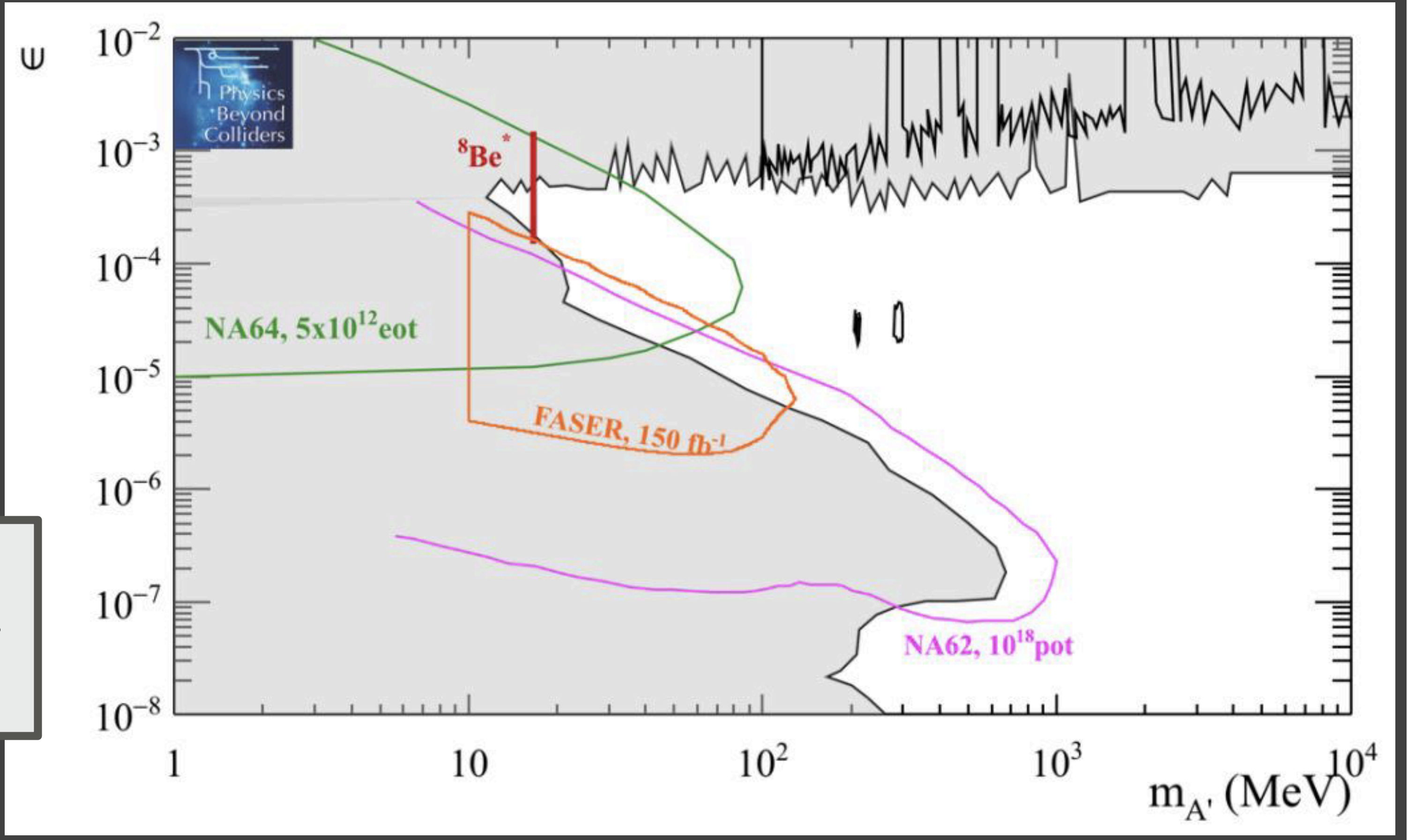
NA62 potential for A′ visible decays

- A′ produced only from interaction with Be-target (bremsstrahlung and meson decays)
- Search for dilepton decays of DP in FV : $A' \to \mu^+\mu^-$, e^+e^-
- Account for trigger/acceptance/selection efficiency
- Assume zero-background → 90% CL exclusion plot

Higher sensitivity expected:

- including A′ production in the dump (here only target)
- including direct QCD production of A′

NA62 can improve limits on the A′ parameter space



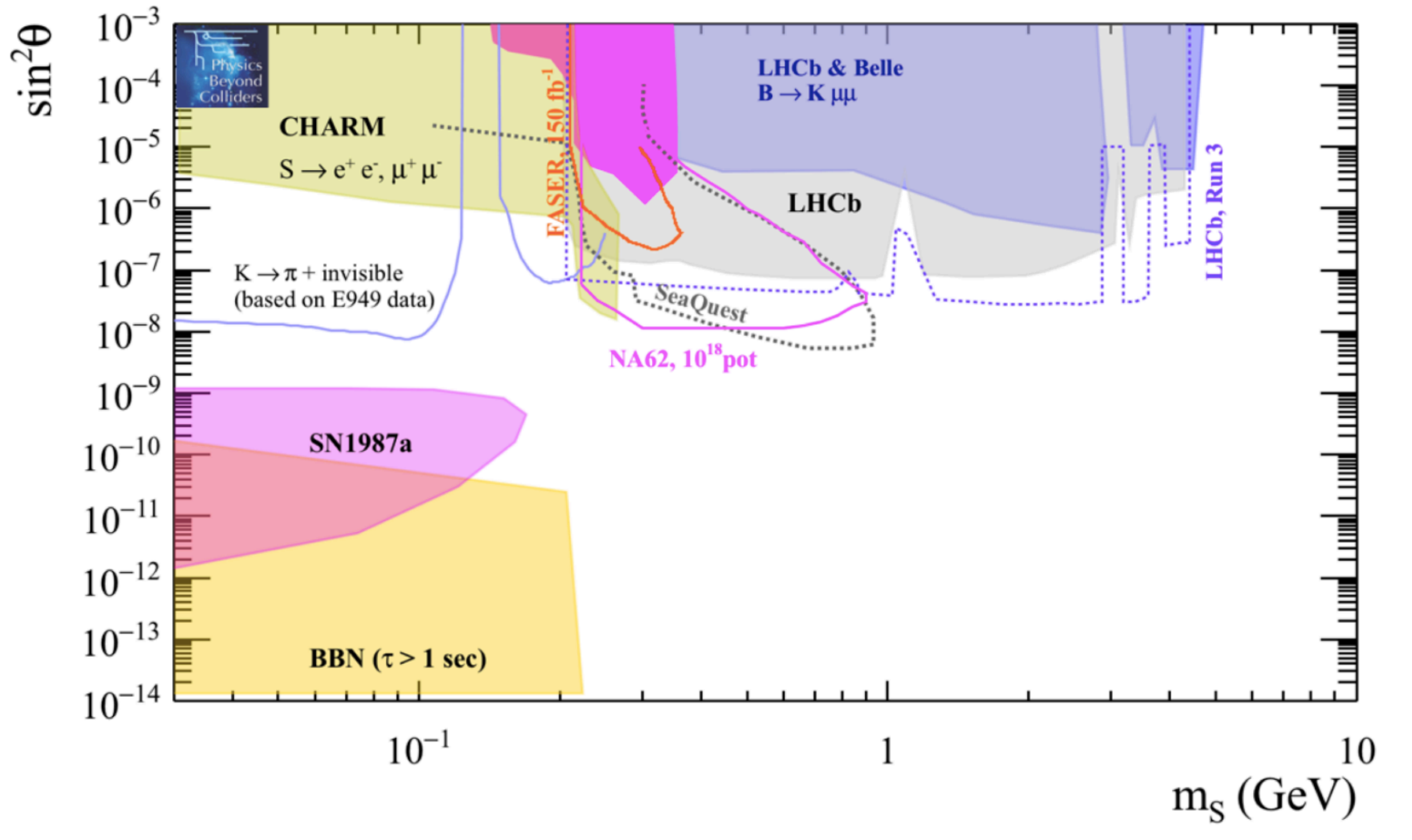
NA62 Runs 2016-2018 (parasitic)
- ~10^{18} POT with di-muon trigger
- 5×10^{16} POT with e^+e^- trigger

NA62 potential for Dark Scalar

Dark Scalar S : **light scalar mixing with Higgs with angle θ**
mediator between DM and SM particles

$$\mathcal{L}_{\text{scalar}} = \mathcal{L}_{\text{SM}} + \mathcal{L}_{\text{DS}} - (\mu S + \lambda S^2) H^\dagger H$$

Minimal scenario:
- $\lambda = 0$
- All production and decay processes are controlled by the same parameter $\mu = \sin\theta$



- **Dump mode:**
  $S \to \mu^+\mu^-$

but also accessible in NA62

- **Kaon mode:**
  $K^+ \to \pi^+ S,\ S \to$ invisible
  $K^+ \to \pi^+ S,\ S \to \mu^+\mu^-$

NA62 potential for ALPs

Axion-Like Particle (ALP)

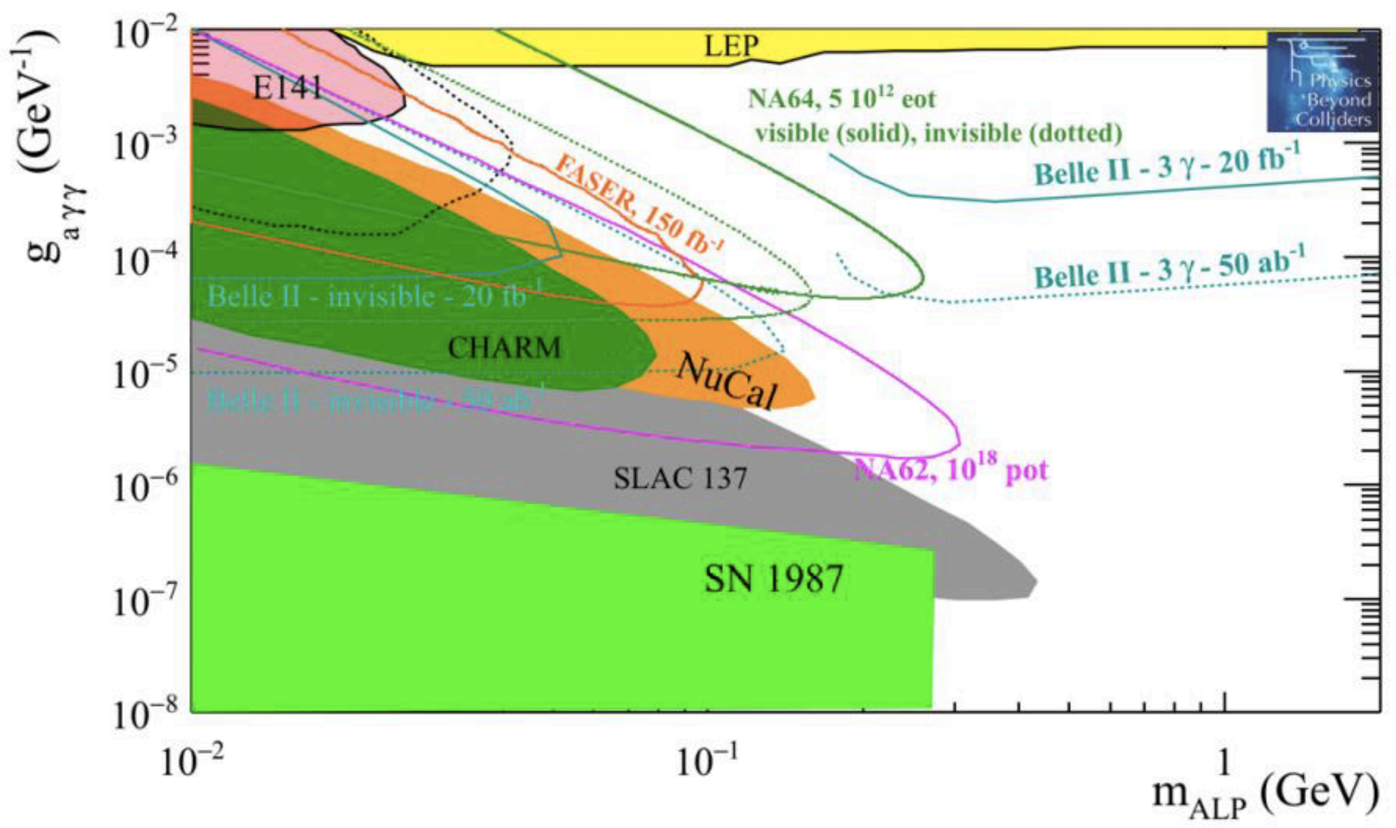
- **pseudoscalar with good properties as a Dark Matter mediator**

NA62 can explore ALP masses in the MeV - GeV range

- **assume predominant coupling to photons → beam dump mode only**
- **ALP Primakoff production from interaction onto TAX** *[JHEP 1602 (2016) 018]*

→ **from proton itself**

→ **from daughter-photons of secondary π^0 and η created in the proton shower** *[arXiv:1904.02091]*



- **ALP produced with low P_T**
  → **good acceptance for $ALP \to \gamma\gamma$ in NA62 FV**
- **account for acceptance**
- **assume zero-background**
  → **90% CL exclusion plot**

- **Significant results expected with only 1 day of data taking (~1.3 × 10^{16} POT)**
- **Analysis of 3 × 10^{16} POT from 2016-2018 data in dump mode in progress**

Conclusions

NA62 is a powerful laboratory to search for exotic decays

- **Recently published results have been presented on HNL and Dark Photon searches**
  - **best limits set on $K^+ \to \ell^+ N$**
  - **limits on** $\pi^0 \to \gamma A'$ with only 1% of available statistics
- **Improved results expected after the analysis of NA62 full 2016-2018 data set**

- **After LS2 : complete the $\pi\nu\nu$ program, afterwords partially running in beam-dump mode (10^{18} POT) would open a window of opportunity to search for hidden particles:**
  → **limit improvements for HNL, Dark Photon, Dark Scalar and ALPs have been shown**

- **Exploiting the available NA62 data:**
  → **Evaluate background rejection capability: preliminary studies indicate sufficient background rejection power**

- **Improvement for the NA62++ set-up**
  → **new upstream veto, beam-line modification, higher intensity**
  → **NOT discussed here but initial studies are promising**

SPARES

Bakcgound studies

Background in beam mode would greatly reduce sensitivity to hidden sector particles originated from TAX
→ **To reach an acceptable background level, the experiment must be operated in dump mode**

BUT

Sensitivity to hidden particles originated from dump can be greatly spoiled by the presence of background:
- dump length (22 λ_I) sufficient to absorb hadrons and electromagnetic radiation
- decays of π, K and short-lived resonances result in a ***large flux of muons and neutrinos***

ν and μ induced background: inelastic interactions with material upstream and surrounding decay volume
→fake signal appearing as an isolated vertex in FV

Combinatorial background: random combinations of tracks from the muon halo
→fake vertices randomly positioned along the FV not pointing backward to the dump

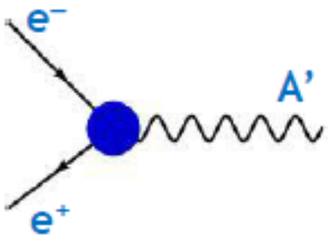
- **Analysis of 2016 data in dump mode (2×10^{15} POT) :**
  - **topologies and rates of background for long-lived particles decaying into 2-track final states**
  - **control sample from same sign 2-tracks , background from opposite charge 2-tracks**
- **Extrapolation to 10^{18} POT :**
  - **fully reconstructed final states: background under control with existing set-up**
  - **partially reconstructed final states: reduced to zero by adding an Upstream Veto in front of decay vessel**

Dark Photon visible decays @ NA48/2

The simplest hidden sector model introduces one extra U(1) gauge symmetry with one extra gauge boson: the **Dark Photon A′** *[B.Holdom, Phys. Lett. B166 (1986) 196]*

- QED-like interactions with SM fermions

not all the SM particles need to be charged under this new symmetry



$$\mathcal{L} \sim g' q_f \bar{\psi}_f \gamma^\mu \psi_f U'_\mu$$

- Interactions of **A′** with the visible sector proceed through kinetic mixing with the SM hypercharge

Limits assuming decays into visible SM particles include $K^\pm \to \pi^\pm\pi^0$, $\pi^0 \to \gamma A'$, $A' \to e^+e^-$ by NA48/2 *[PLB 746 (2015) 178]*

DP exclusion : visible decays