Perspectives on feebly-interacting particles from NA62

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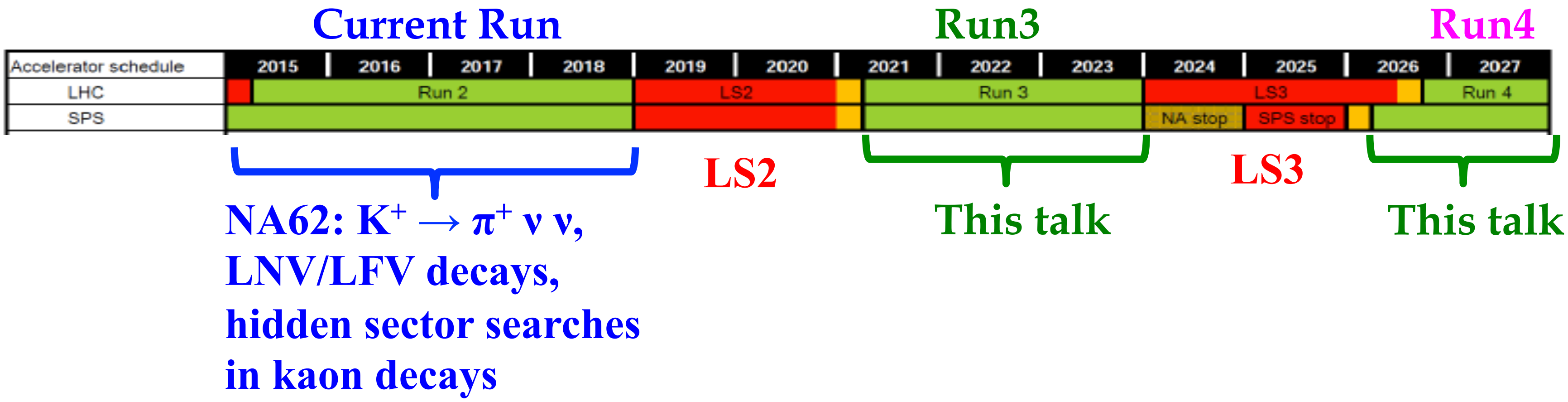
Introduction

NA62 experiment approved to run until LS3

- **main goal**: measuring the BR($K^+ \rightarrow \pi^+ \nu$ anti-ν) with 10% accuracy;
- a broad physics program: searches for LFV/LNV modes, hidden sector particles

Present talk covers possible plans for dedicated searches in **Run3** and beyond

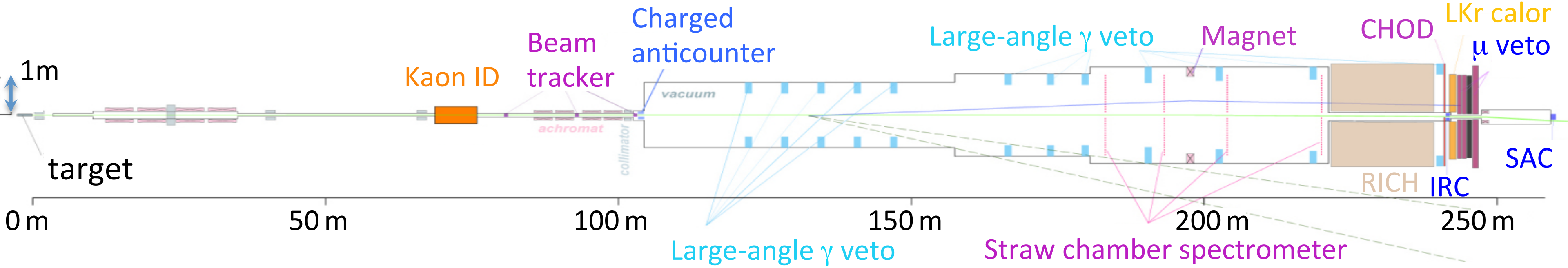


NA62: a high-intensity setup

Main goal: collect 100 $\pi\nu\bar{\nu}$ events in 2 years of data taking, 10% signal acceptance (10^{13} K^+)

High-intensity proton-produced charged hadron beam:

- **10^{12} 400-GeV p/s from ~3.5-s SPS spills onto a Be target**
- Secondary 75-GeV beam selected: 1% momentum bite, X,Y divergence < 100 μrad



Can **track 750 MHz beam** (6% K^+) and sustain ~5 MHz K^+ decay in a **60-m long volume in vacuum**

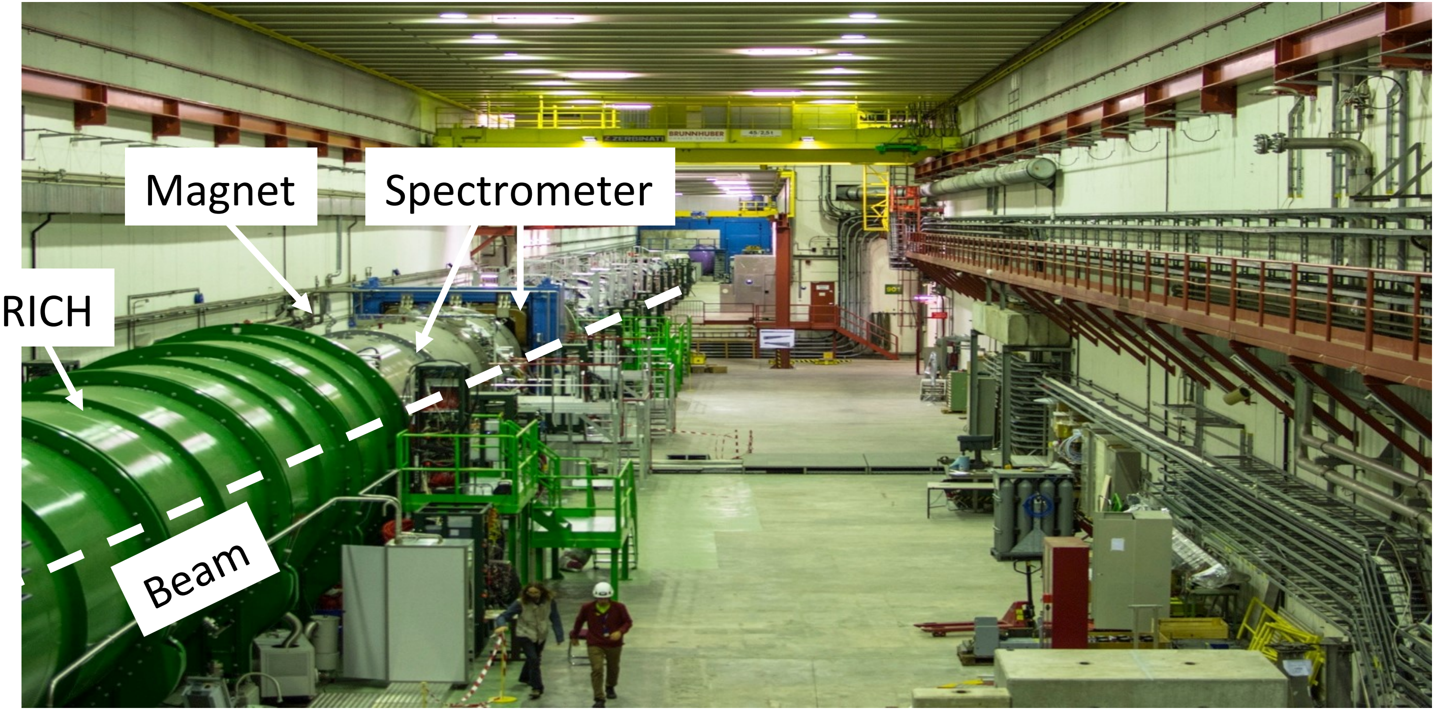
- **Excellent time resolution** to match beam and daughter particle information

Kinematics, rejection of main K modes 10^4—10^5 via kinematic reconstruction

PID capability, μ vs π rejection of $O(10^7)$ for $15 < p(\pi^+) < 35$ GeV

High-efficiency veto, 10^8 rejection of π^0's for $E(\pi^0) > 40$ GeV

NA62: a high-intensity setup



New $K^+ \rightarrow \pi\nu\nu$ result, full analysis of data taken in 2016-18: arXiv:2103.15389, accepted by JHEP

Physics at NA62 in Run 2 and Run 3

A rich field to be explored with minimal/no upgrades to the present setup

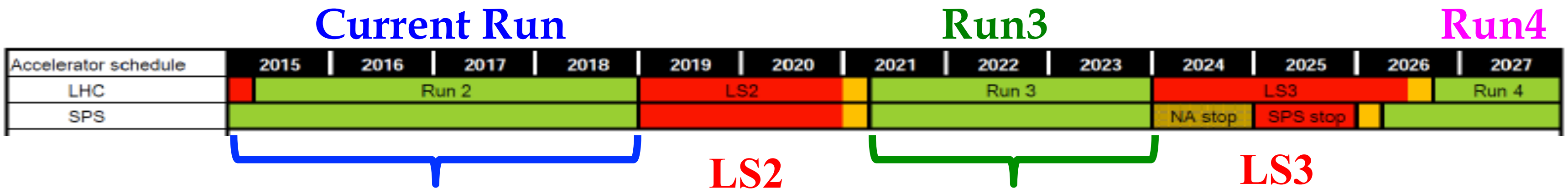
1. Present setup for K^+ beam + dedicated triggers: complete LFV/LNV high-sensitivity studies based on K^+/π^0, e.g. see recent talks at the Phenomenology 2021 symposium:

LFV/LNV, J. Swallaw https://indico.cern.ch/event/982783/contributions/4364566/

$K^+ \rightarrow \pi^+ X$, $\pi^0 \rightarrow$ inv., $K^+ \rightarrow \mu\nu X$, R. Volpe https://indico.cern.ch/event/982783/contributions/4362249/

$K^+ \rightarrow e^+ X$, $K^+ \rightarrow \mu^+ X$, M. Mirra https://indico.cern.ch/event/982783/contributions/4362325/

2. In Run3, year-long run in "beam-dump" mode, new program of NP searches for MeV-GeV mass hidden-sector candidates: Dark photons, Heavy neutral leptons, Axions/ALP's, etc.



NA62: $K^+ \rightarrow \pi^+ \nu \nu$, LNV/LFV decays, hidden sector searches in K decays

LFV/LNV @ ultimate sensitivity, hidden sector searches (beam dump)

Hidden sector at NA62: motivations

If DM is a thermal relic from hot early universe, can hunt for it in particle-physics:

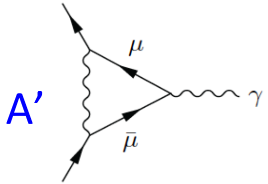
search for non-gravitational interactions DM-SM

A mediator of a hidden sector might exist, inducing DM-SM field **(feeble)** interactions

many possible dynamics: vector (A', aka dark photon), neutrino (HNL), axial (ALP a), scalar..

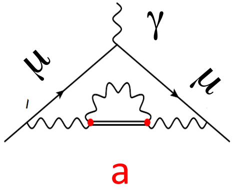
Various experimental hints for hidden sector at MeV-GeV, e.g., a_μ 3.5-σ discrepancy:

Might be due to a dark photon A' ...



[Okun, Holdom]

...or to an ALP a enhancing light-by-light?



[Marciano, et al. arXiv:1607.01022]

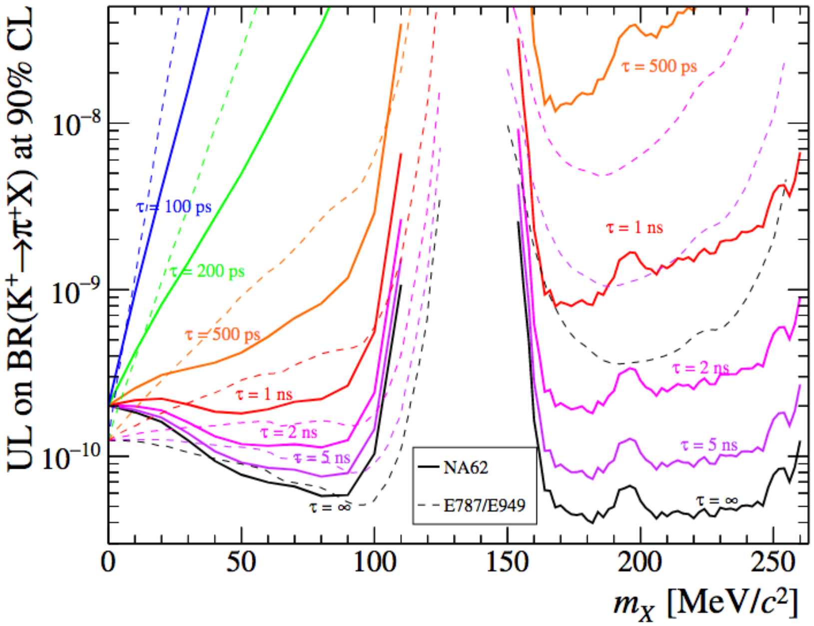
Model dependence: experimentally driven approach

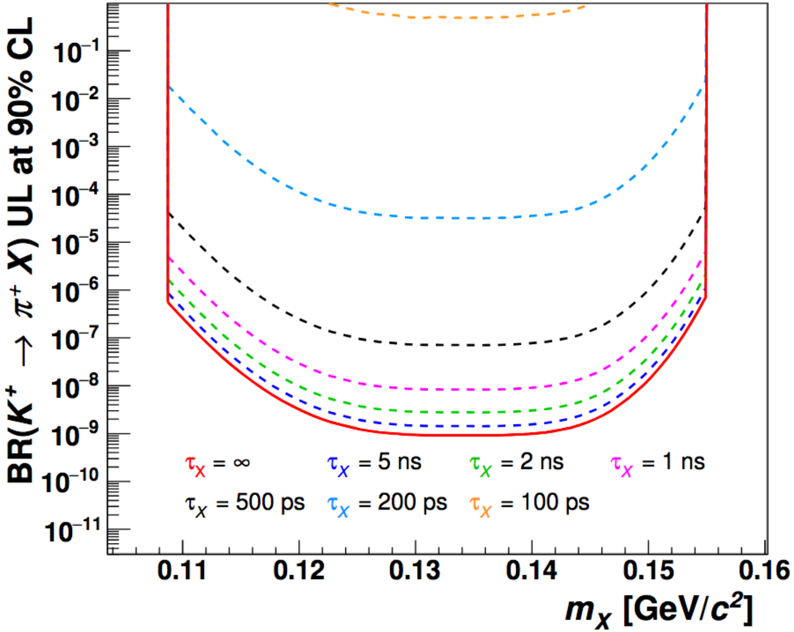
Feeble interaction: ultra-suppressed production rate, **very** long-lived states

E.g.: 1-GeV mass HNL, $\tau \sim 10^{-5}$--10^{-2} s, decay length ~ 10--10000 Km at SPS energies, suppression at production 10^{-7}--10^{-10}

$K^+ \rightarrow \pi^+\nu\nu$ as a search for $K^+ \rightarrow \pi^+X$

Can re-interpret the search: assume a SM background for $\pi\nu\nu$ and assume X to be either long-lived/dominantly invisible [JHEP03 (2021) 058, JHEP02 (2021) 201]





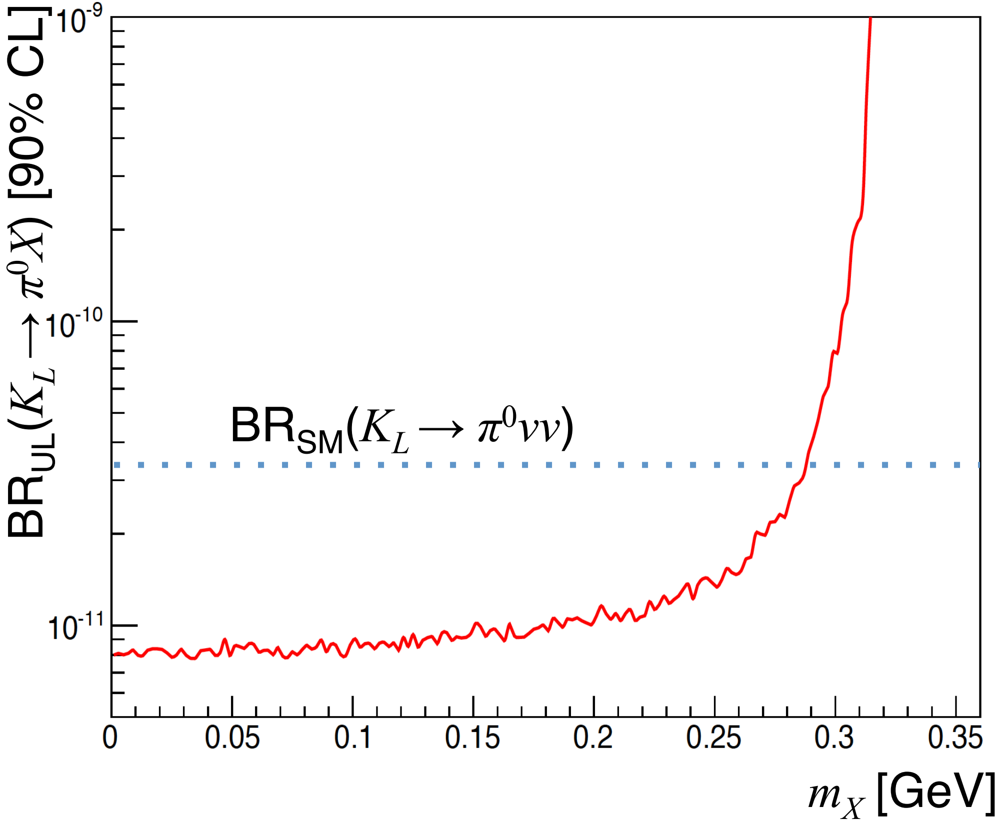
Interpretations possible, e.g. with X as a dark scalar or fermion-coupled ALP

$K_L \to \pi^0\nu\nu$ as a search for $K_L \to \pi^0 X$

Obviously, same holds at KLEVER

Assuming:

- $K_L \to \pi^0 \nu\nu$ according to SM
- **60 expected evts from $K_L \to \pi^0 \nu\nu$** (± 18%)
- **60 expected evts from $K_L \to \pi^0\pi^0$** (± 8 evts)
- **120 observed evts in 5 yrs (no excess)**
- For each value of m_X ascribe zero excess to $K_L \to \pi^0 X$
- 2-body acceptance for $K_L \to \pi^0 X$ (± stat ⊕ 5%)
- Derive 90% Rolke-Lopez UCL

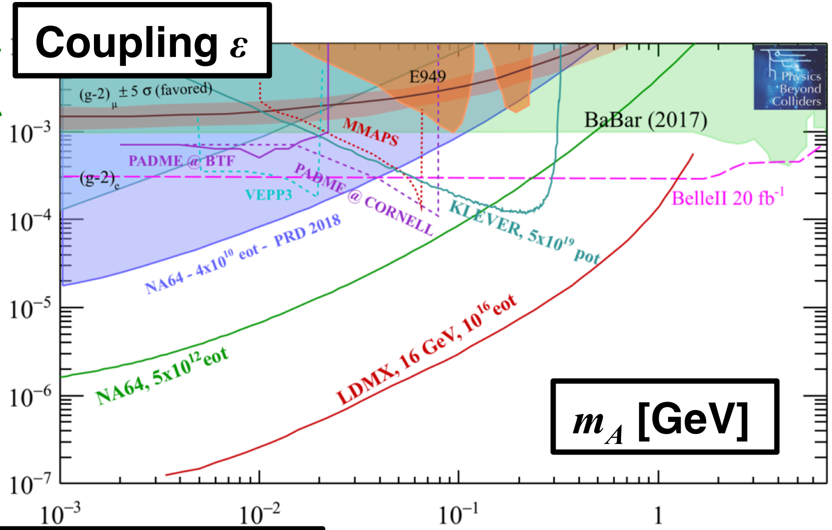


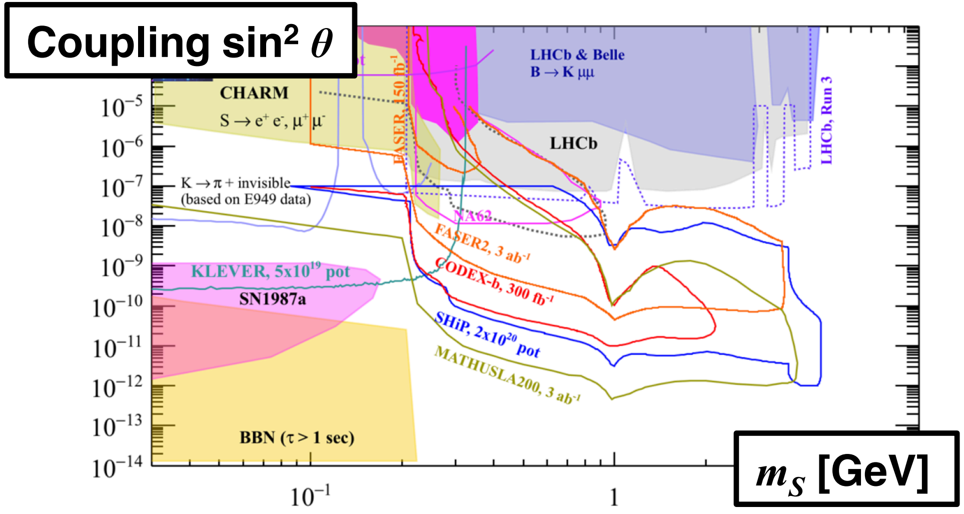
Exclusion from $K_L \to \pi^0 X$

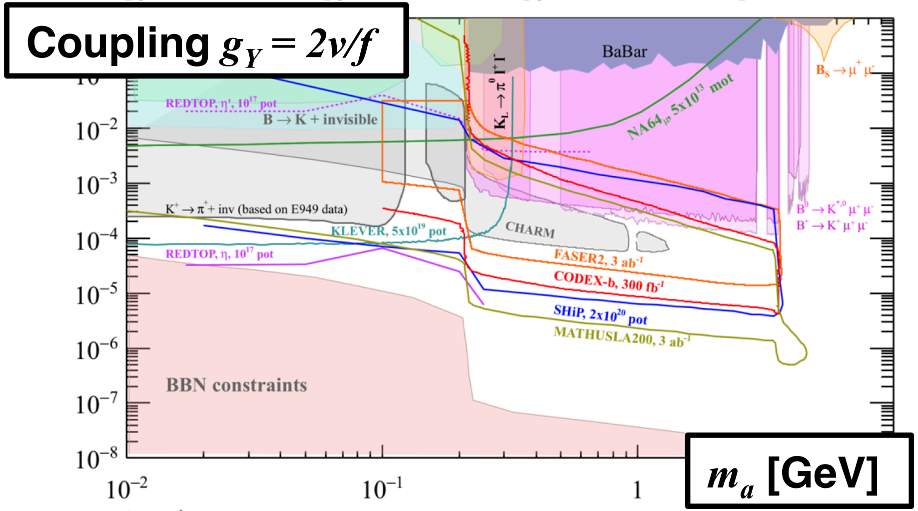
For $K_L \to \pi^0 X$, interpret X as:

- Invisible dark photon A'
- Higgs-mixed scalar S
- Axion-like particle a with fermion couplings

Limits in coupling vs. mass for each scenario*







NA62 perfectly suited for hidden sector searches

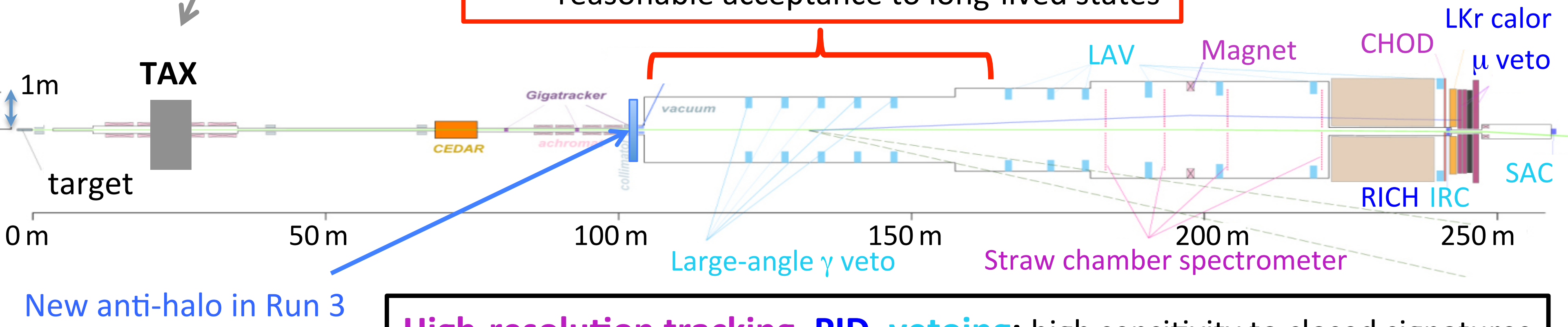
High-intensity 400-GeV proton beam → boost charm/beauty, other meson production

10^{18} POT / nominal year: 10^{12} POT/sec on spill, 3.5-s/16.8 s, 100 days/year, 60% run efficiency

10^{15} $D_{(S)}$, 10^{14} K, 10^{18} $\pi^0/\eta/\eta'/\Phi/\rho/\omega$ with ratios 6.4/0.68/0.07/0.03/0.94/0.95 (& B mesons, too)

Compact beam dump: ~20 λ_I Cu/Fe-based beam-defining collimator (TAX) radioprotection-compliant even if target removed

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



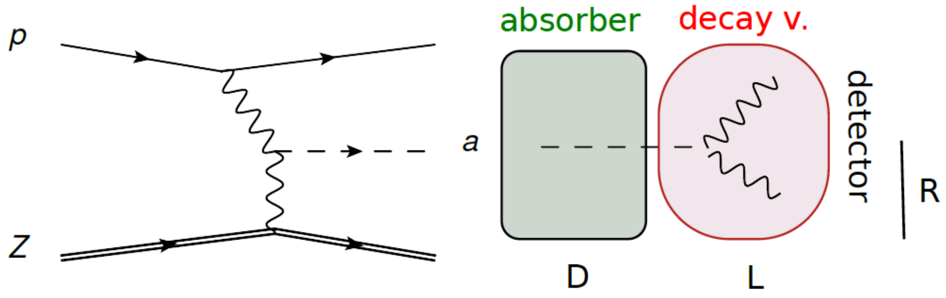
High-resolution tracking, PID, vetoing: high sensitivity to closed signatures

On the phenomenological effort for FIPs

While the searches should be kept mainly model-independent, a large effort still going on by the community devoted to evaluate production/decay of feebly interacting particles (FIP)

An example, photon-coupled ALP:

"Dominant" Primakoff production, proposed and computed in JHEP 1602 (2016) 018



Later, JHEP 05 (2019) 213: production from real photons from π^0 decay usually dominates

Effort results made systematic also thanks to first mandate of PBC WG at CERN

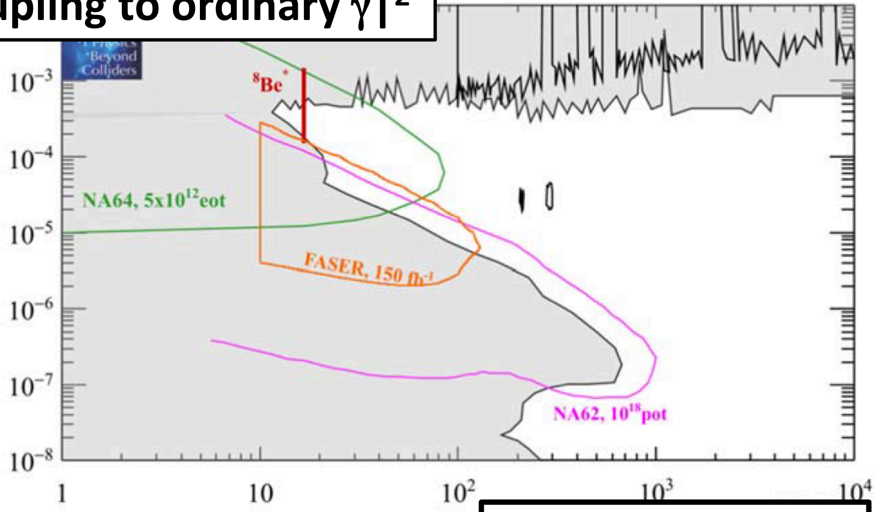
Search for visible decays of FIPs: A’ search in Run3

Assume 10^{18} 400-GeV POT (Run 3 statistics, several months at full nominal intensity)

search for displaced decays to two charged particles

assume zero-background, evaluate expected 90%-CL exclusion plot

|A’ coupling to ordinary γ|²



A’ mass (MeV/c²)

Physics Beyond Colliders BSM report: J. Phys. G 47 (2020) 1, 010501

Compare to some of the competitive projects in the same time range

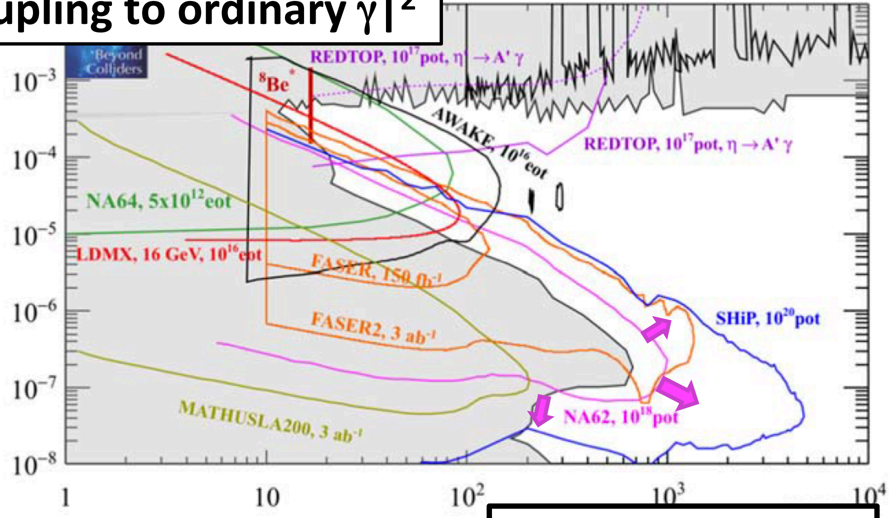
Search for visible decays of FIPs: A’ search in Run4

Assume 10^{19} 400-GeV POT (Run 4 nominal statistics, running at x4 intensity)

search for displaced decays to two charged particles, assume zero-background

90%-CL exclusion plot from NA62 (not shown) will be within that from SHiP

|A’ coupling to ordinary γ|²



A’ mass (MeV/c²)

Compare to some of the competitive projects in the same time range

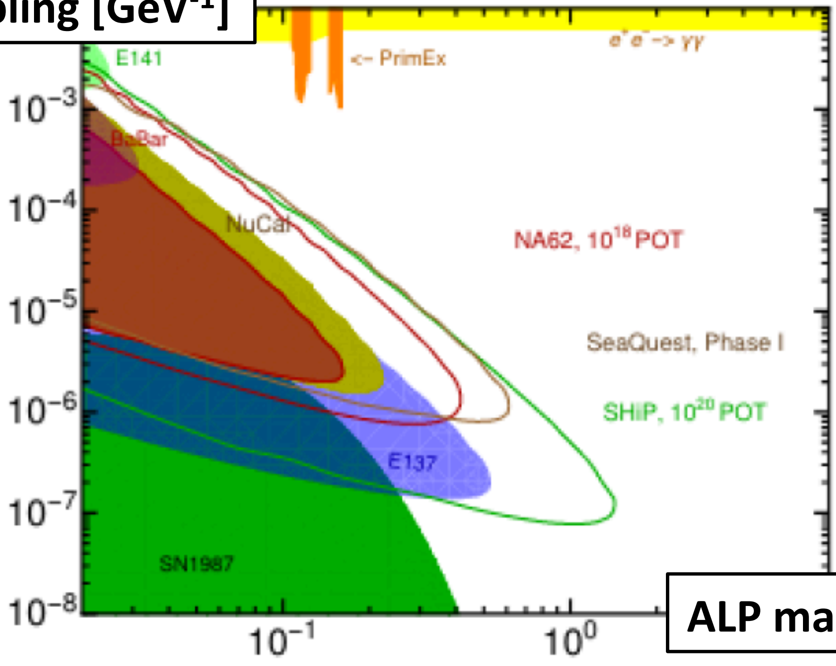
Physics Beyond Colliders BSM report: J. Phys. G 47 (2020) 1, 010501

Similar scenarios for dark scalar, HNL shown in the PBS BSM report

Search for visible decays of ALP's in Run 3

Production: ALP Primakoff [JHEP 1602 (2016) 018] + real-γ induced [JHEP 05 (2019) 013]
Decay: ALP → γγ, account for geometrical acceptance, assume zero-background

ALP-γ coupling [GeV^{-1}]



ALP mass [GeV]

Search for ALP→γγ less constrained than search for charged decay modes: no extrapolation to dump possible

Results from NA64, Belle-II missing

On the zero-background assumption

Ongoing background studies using Run 2 data**:**

$3\text{x}10^{16}$ POT taken in “beam dump” mode (no beam tuning, just TAX collimator closed)

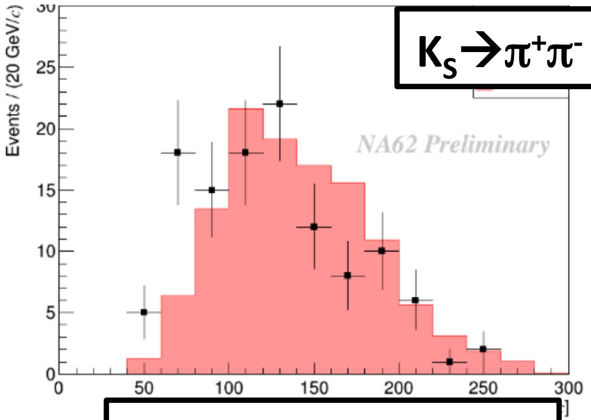
$2\text{x}10^{17}$ POT taken in “parasitic” mode during standard data taking with di-muon trigger

Ongoing effort using data and MC:

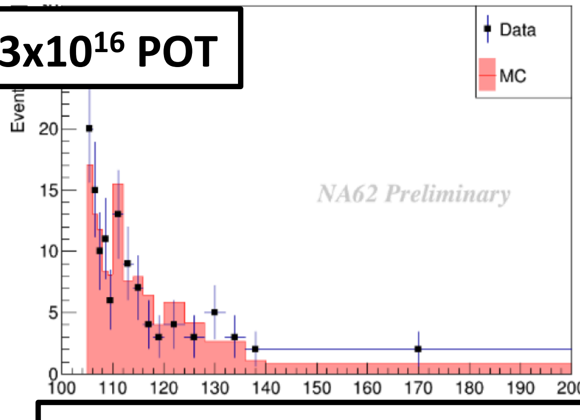
simulation of muons from the beam “halo” (π, K decays in dump, etc.)

background from K_S/Λ produced from survived K^+ mesons

$K_S \rightarrow \pi^+\pi^-$ in $3\text{x}10^{16}$ POT



K_S momentum (GeV)



K_S decay vertex position (m)

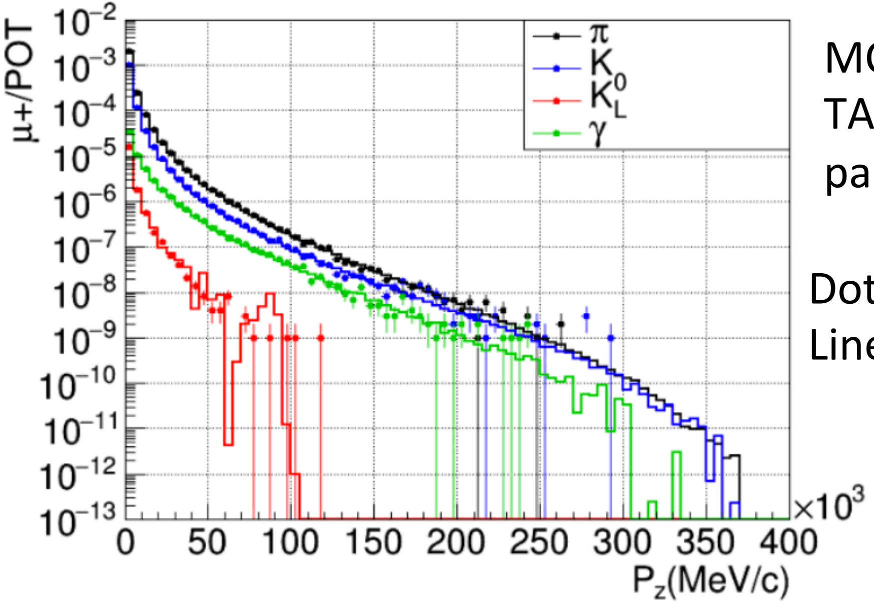
NA62 SPSC report https://cds.cern.ch/record/2759557/files/SPSC-SR-286.pdf

Can use MC for background estimates @ 10^{18} POT?

CPU power: low efficiency of simulation for muons from hadronic showers, ~10^{-4} μ/proton

- NA62 work within the PBC: score + parameterize [https://doi.org/10.18429/JACoW-ICAP2018-SUPAG05]
- SHiP coll.: MC gun using generative adversarial networks [JINST 14 (2019) P11028]
- Biasing MC technique to boost by 2×10^3 with no information loss [2106.01932 [hep-ex]]

2106.01932 [hep-ex]



MC: Muon yield from NA62 TAX mock-up by mother particle

Dots: brute-force MC (10^9 POT)
Lines: biased MC (10^8 POT)

Can use MC for background estimates @ 10^{18} POT?

Reliability of hadronic interaction simulation:

The SHiP collaboration gathered data for muon flux validation [2001.04784 [physics.ins-det]]
Data/MC agreement of ~20% for μ below 200 GeV (a factor x3 above), still remarkable

From the GEANT4 manual:

For the evaluation of systematic errors due to uncertainties in the Geant4 hadronic cross sections we recommend the following approach. Scaling up (e.g. **by 10%**, by using a scaling factor of 1.10) or down (e.g. using a scaling factor of 0.90) the cross sections, independently for elastic and inelastic interactions, and independently for different types of hadrons.

Even a relative uncertainty on interaction cross sections within FTFP-based models of ~10% can lead to ~x10 in flux of punch-through secondaries, e.g. K+

Known limitations from the treatment of multiple Coulomb scattering in Geant4 [Longhin, Paoloni *IEEE Trans.Nucl.Sci.* 62 (2015) 5]

Work ongoing within NA62 to track down various background sources

Conclusions: FIP searches at NA62

One year long data taking (10^{18} POT) in "beam dump mode" in Run 3:

- **Sensitivity to Dark photons, Heavy Neutral Leptons, Axion-like particles, etc.**
- **Rejection of upstream background improved with a new hodoscope (Anti-halo)**
- **Beam-line magnet tuning allows reduction of muon flux by x5**

Expected sensitivity competitive to that from other initiatives in the same time range

Data demonstrate background rejection power for the searches proposed, up to 10^{17} POT's

- **background to charged decay modes negligible at 10^{17} POT [tested for di-muon]**
- **background to $\gamma\gamma$ mode under control at 3×10^{16} POT**

If the sensitivity of the Run-3 NA62 data set will prove not background limited, a future data taking at 10^{19} POT @ Run 4 would extend the sensitivity for various NP scenarios

Particularly appealing: searches for long-lived A', photon-coupled ALP visible decays