SHiP@PS: sensitivity estimates

Kyrylo Bondarenko, Alexey Boyarsky, Alex Mikulenko, Maksym Ovchynnikov

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SHiP@PS experiment

We consider the following experimental setup:

1. PS beam with $N_{\text{p.o.t.}} = 10^{19}$ and two different energies: $E_p = 15, 25$ GeV
2. Tungsten target, with the target's length 1 m
3. The distance to the decay volume from the beginning of the target $l_{\text{min}} = 4$ m
4. The length of the decay volume $l_{\text{fid}} = 5$ m
5. Large angular coverage

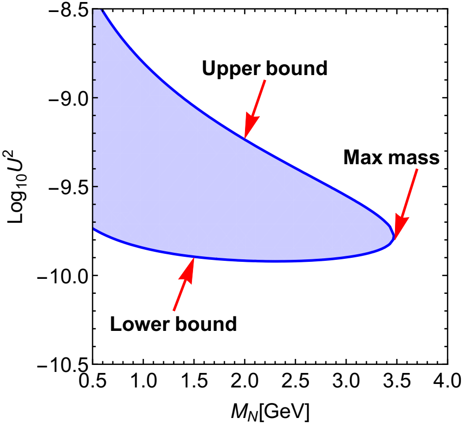
- We then estimate the sensitivity of this experiment to the scalar, pseudoscalar, fermion and vector portals, that introduce a Higgs-like scalar S, and ALP a, an HNL N and a dark photon V correspondingly, with effective interactions

$$\mathcal{L}_{\text{int, S}} = \theta m_h^2 S h, \quad \mathcal{L}_{\text{int, a}} = g_{a\gamma\gamma} a F_{\mu\nu}\tilde{F}^{\mu\nu}, \tag{1}$$

$$\mathcal{L}_{int,N} = U m_N \bar{N}^c \nu + \text{h.c.}, \quad \mathcal{L}_{\text{int,V}} = -\epsilon e V_\mu J^\mu_{\text{EM}} \tag{2}$$

- We use constraints from old experiments and sensitivities of future experiments from PBC report

Main sensitivity features



Sensitivity region $N_{\mathrm{events}} > 3$ for a toy model with one production and one decay channel

The number of detected particles N:

$$N_{\mathrm{events}} \approx N_{\mathrm{prod}} \times \epsilon_{\mathrm{tot}} \times P_{\mathrm{decay}},$$

where

- $N_{\mathrm{prod}} \approx N_{\mathrm{p.o.t.}} \cdot \mathrm{Br}_{X\ \mathrm{prod}} \propto U^2$
- $\epsilon_{\mathrm{tot}} = \epsilon_{\mathrm{geom}} \times \epsilon_{\mathrm{det}} \times \mathrm{Br}_{\mathrm{vis}}$
- $P_{\mathrm{decay}} \approx$
  $$\begin{cases} l_{\mathrm{fid}}\Gamma_N/\gamma, & \ell_{\mathrm{decay}} \gg \ell_{\mathrm{max}} \\ \exp(-\ell_{\mathrm{min}}\Gamma_N/\gamma), & \ell_{\mathrm{decay}} < \ell_{\mathrm{min}} \end{cases},$$
  $\Gamma_N \propto U^2$

Production from mesons

- Light portal particles with masses $< m_K$ may be produced in decays of π, K mesons
- We use the production cross sections of π, K from experimental data and theoretical fits [Blobel et al.], [9507031]
- We assume $\gamma_\pi = \gamma_K \approx 3.5$ (γ factor between CM and lab frames of the colliding protons)
- Produced kaons and charged pions experience numerous scatterings inside the target. The probability to decay before scattering may be estimated as

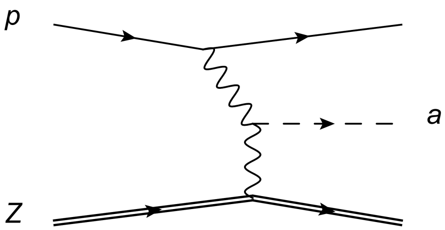
$$P^{\text{meson}}_{\text{decay}} \approx \frac{l_{\text{scat}}}{l^K_{\text{decay}}}, \quad (3)$$

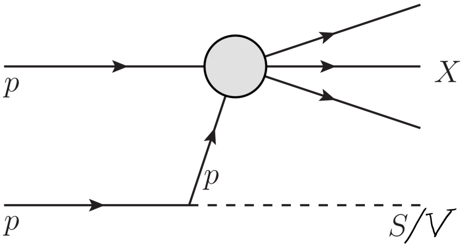
where the scattering length is $l_{\text{scat}} = (\sigma_{\text{scat}} \cdot n_N)^{-1} \approx 0.03$ m (assuming tungsten material and using $\sigma^{\pi N/KN}_{\text{scat}} \simeq 30$ mb from [pdg]), whereas the decay length is given by $l_{\text{decay}} = c\tau\gamma$, where τ is the meson lifetime

Meson	π^0	$\pi^\pm$	$K^\pm$	K^0_L	K^0_S
N_{Meson}	$1.4 \cdot 10^{19}$	$2.3 \cdot 10^{19}$	$1.1 \cdot 10^{18}$	$3.1 \cdot 10^{17}$	$3.1 \cdot 10^{17}$
$P^{\text{meson}}_{\text{decay}}$	1	$4.2 \cdot 10^{-3}$	$1.3 \cdot 10^{-2}$	$3.2 \cdot 10^{-3}$	$\simeq 1$

- We do not know the fraction of c-quarks at PS energies. Just as an example, we made an estimate for HNLs production from D-mesons assuming optimistic value $\chi_{c\bar{c}} = 10^{-5}$

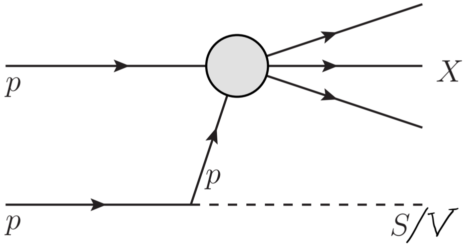
Production through bremsstrahlung





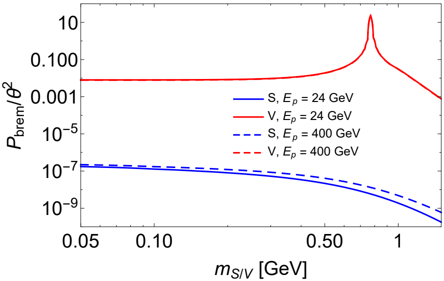
- HNLs $m > m_K$ can not be efficiently produced at PS, as B mesons are not produced and the number of D mesons is strongly suppressed
- However, such heavy **ALPs** [1512.03069], **dark scalars** [1904.10447] and **dark photons** [1311.3870] is possible to be produced in proton-proton and proton-nucleus collisions – **bremsstrahlung** and **photon fusion**

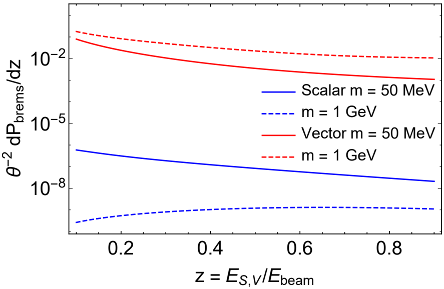
Production through bremsstrahlung: Scalar and Dark photon I



- In bremsstrahlung, particles are emitted directly by a proton, so proton-scalar/dark photon form factor is important: $\sigma_{\text{brem}} \propto |F_{ppS/V}(m_{S/V})|^2$.
- The ppV form-factor can be extracted from the experimental data [0910.5589]
- This is not possible for the ppS form-factor, as there are no light scalars in SM (could use ϕ meson, effective light scalar? [2008.08108])
- We consider two choices of the ppS form-factor: a dipole form-factor ("conservative") and a form-factor from [2008.08108], that incorporates the mixing with scalar ϕ resonances ("optimistic")
- We adopted a simple phenomenological model, details can change

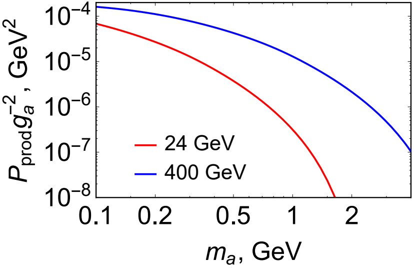
Production through bremsstrahlung: Scalar and Dark photon II

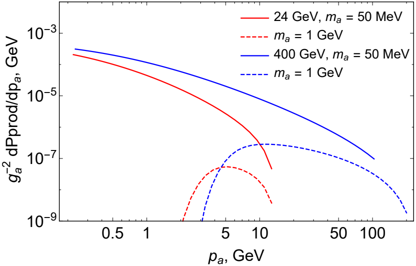




- σ_{brem} depends only weakly on the beam energy (no elastic vertex suppression). In particular, it is approximately the same at SHiP and at PS
- The production probability of scalars is suppressed by $\sim g_{SNN}^2/\alpha_{\text{EM}} = 2 \cdot 10^{-4}$ compared to the dark photon case, where g_{SNN} is phenomenological scalar coupling to nucleons.
- Energy distributions depend on on the energy fraction carried by particle $z = E_{S/V}/E_{\text{beam}}$

Direct production: ALPs





- Production from $\gamma\gamma$ fusion, only EM interactions involved
- Unlike the bremsstrahlung for scalars and dark photons, the ALP production probability strongly depends on beam energy and mass
  at high q^2 the production is suppressed as the nucleus cannot be treated as point-like
- Produced ALPs have small transverse momenta – large geometrical acceptance for an on-axis experiment!

Comparison with other experiments

Experiments for the comparison: CHARM, NA62, PS191, NuCal, SLAC-137

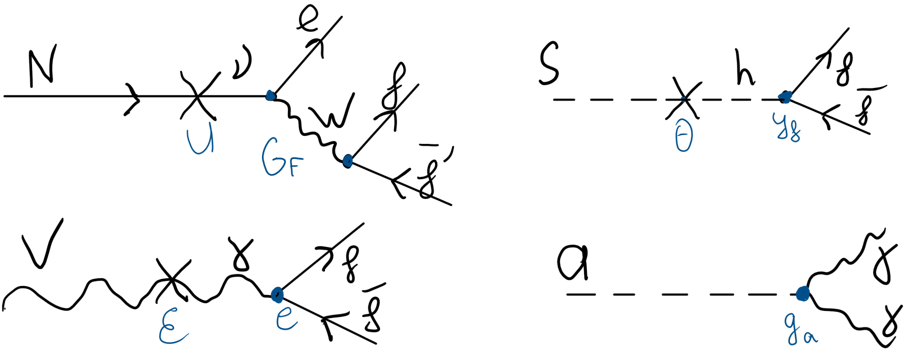
- $N_{\text{p.o.t.}}$ and the decay volume length l_{fid} are important for the lower bound
- Small angular size and displacement from the beam axis lower the geometric acceptance of a detector.
- $E_{\text{beam}}/l_{\text{min}}$ is important for the upper bound, $N_{\text{events}} \sim \exp(-\# l_{\text{min}}/E_{\text{beam}})$. For accurate estimate, one needs to take into account energy distribution of produced particles

	PS	SHiP	NA62	CHARM	PS191	NuCal	SLAC
$E_{\text{beam}}/l_{\text{min}}$ GeV/m	6	8	4	0.8	0.15	1.1	0.05
$N_{\text{p.o.t.}}, 10^{19}$	1	20	0.2	0.24	0.86	0.17	50, el.
ϵ_{geom} for K	1	0.4	0.15	0.1	0.01	-	-
ϵ_{geom}, brems.	1	1	1	0	0	1	1
l_{fid}, m	5	50	10	35	10	~ 20	0.2

Is there any large coupling region that is not yet excluded?

The answer depends on the model.

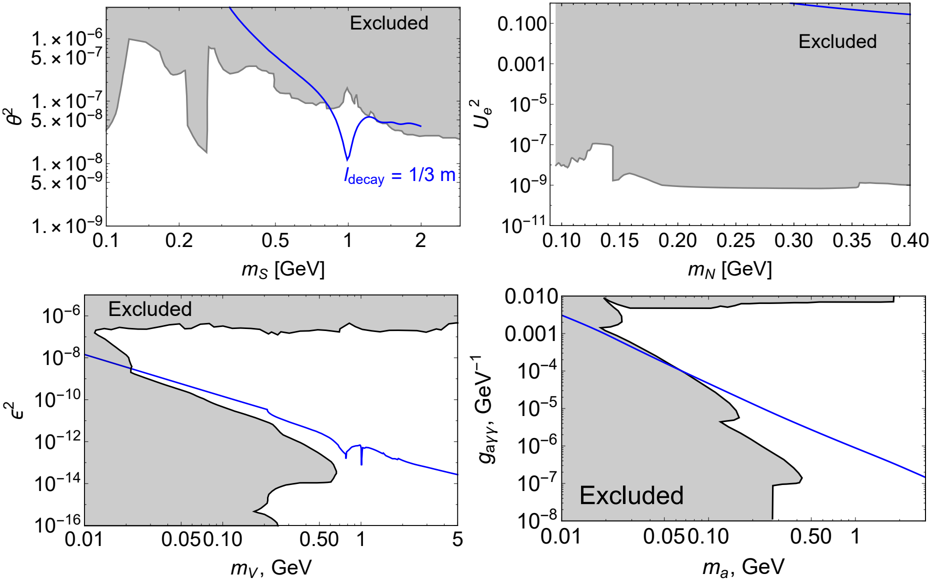
Decay width/length for different portals: different mass dependence



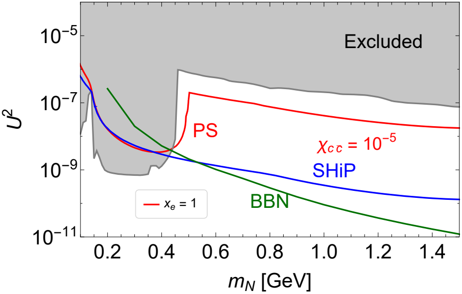
$$\Gamma_N \sim U^2 G_F^2 m_N^5, \qquad \Gamma_S \sim \theta^2 \frac{m_S^3}{v^2}, \tag{4}$$

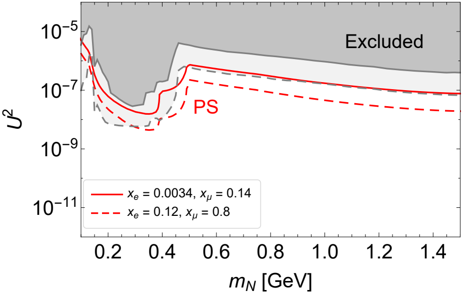
$$\Gamma_V \sim \epsilon^2 \alpha_{\text{EM}} m_V, \qquad \Gamma_a \sim (g_{a\gamma\gamma} m_a)^2 m_a \tag{5}$$

Decay width/length for different portals

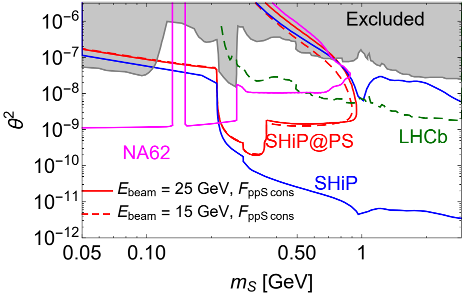


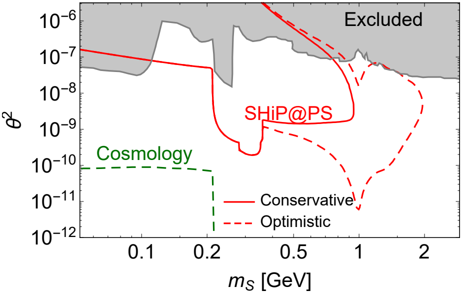
Results: HNLs

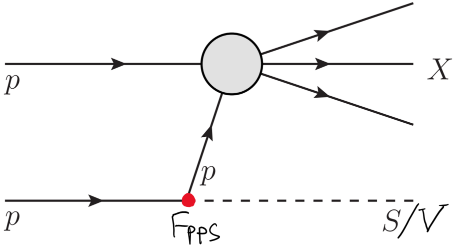




- Assuming νMSM and realistic mixing patterns, we come up with conclusion that SHiP@PS can have some potential for $m_N < m_K$, because the coupling to muons is less constrained.
- For the production from kaons, the K absorption in material should be carefully studied. If we underestimated the number of kaons, SHiP@PS is even more sensitive.

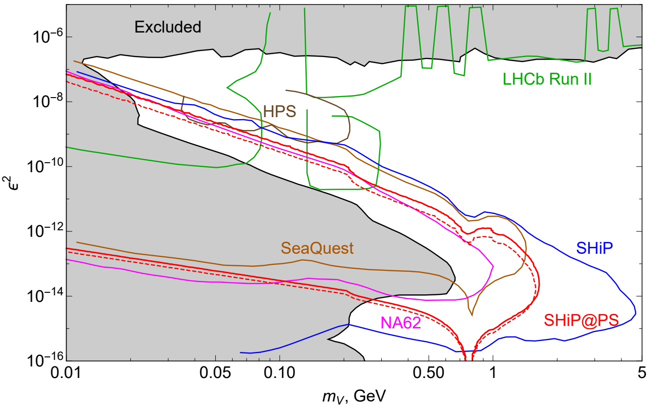






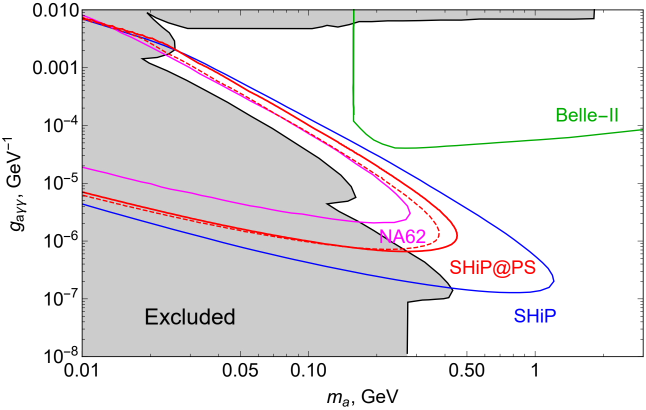
- Knowing the form-factor is very important (solid line on the right plot - dipole form-factor $F_{ppS\text{cons}}$, dashed - form-factor $F_{ppS\ \text{opt}}$ from [2008.08108])!

Results: dark photon



SHiP@PS wins at the upper bound, thanks to the larger value of the ratio between beam energy and l_{min} and large geometric acceptance for bremsstrahlung. No known caveats :)

Results: ALP



Similar to Dark Photon!

Summary

- SHiP@PS setup has a large intensity of the PS beam and a small distance to the decay volume, having high value of $E_{\text{beam}}/l_{\text{min}}$ ratio. This enhances the sensitivity to the portal particles with large couplings
- Another important ingredient is a bremsstrahlung production mechanism, that works effectively for low-energy PS beam
- As a result, SHiP@PS has a sensitivity to the unexplored parameter space of dark photons, ALPs and scalars. For HNLs, the potential strongly depends on the $c\bar{c}$ production fraction and on kaon scatterings

Prospects for future work

- Kaons – simulate their distribution taking into account scatterings
- D mesons – although the amount of D mesons in low energy collisions is suppressed, they may contribute to the sensitivity of PS to HNLs at masses $m_N \gtrsim 0.5$ GeV
- Bremsstrahlung for ALPs – *app* vertex

Backup slides

Adopted phenomenology I

- We use the phenomenology of **dark photons** from [1609.01770] for the production channels. For the decay channels, we used report
- We consider two production channels of dark photon: from π^0 and from proton bremsstrahlung
- We use the phenomenology of **HNLs** from [1805.08567]. For the production channel, we consider the decays $K \to N + l$

Adopted phenomenology II

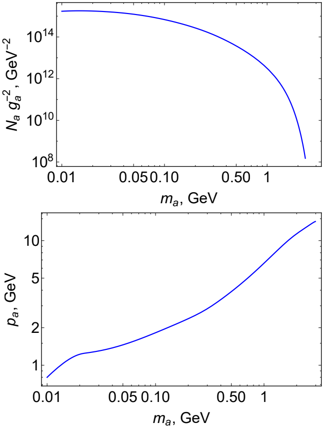
- For **dark scalars**, we use the phenomenology from [1904.10447]
- The main production channels of scalars at these energies are decays of kaons and bremsstrahlung [1904.10447]
- Bremsstrahlung suffers from theorerical uncertainties: *ppS* form-factor, that enters $\text{Br}_{\textbf{brem}} \propto |F_{ppS}|^2$, is unknown. It may enhance $\text{Br}_{\textbf{brem}}$ at $m_S \simeq 1$ GeV due to scalar ϕ resonances, and suppresses it at $m_V \gg 1$ GeV since the process probes the internal structure of the proton
- Further we use the dipole approximation

$$F_{ppS}(m_S) = \frac{1}{\left(1 + \left[\frac{m_S}{1\ \text{GeV}}\right]^2\right)^2} \tag{6}$$

See, however, [2008.08108], where a model that incorporates the mixing with ϕ mesons is considered

Adopted phenomenology III

- We use the phenomenology of **ALPs** from [1512.03069]. The production channel is the Primacoff proccess, $\gamma + \gamma \to a$ conversion in the field of charged particles
- Production is enhanced by the factor $Z^2/A^{0.77}$ for heavy ions in $p + N$ scattering; we assume that the target is made of tungsten.



The number and average momentum of produced axions for the PS-beam

Comparison with PS191 I

- PS191 has $N_{\text{p.o.t.}}^{\text{PS191}} \approx 0.5 \cdot 10^{19}$, $E_p = 19.2$ GeV. The target is Be, its thickness is 80 cm
- The decay volume is located $l_{\text{min}} = 128$ m away from the target and has the length $l_{\text{fid}} = 10$ m [report]. The angular coverage of the detector is $\theta \in (17, 63)$ mrad
- Using the kaon scattering cross section in beryllium, $\sigma_{Kp}^{\text{Be}} = 20 A_{\text{Be}}^{2/3}$ mb, and the beryllium number density $n_{\text{Be}} = 1.4 \cdot 10^{29}$ m^{-3}, for the scattering length of kaons we get $l_{\text{scat}} = 1/\sigma_{Kp}^{\text{Be}} n_{\text{Be}} = 0.9$ m. This means that

$$P_{\text{decay}}^{K,\text{PS191}} = e^{-l_{\text{target}}/l_{\text{scat}}} \approx 0.4 \tag{7}$$

  of kaons may decay before scattering
- The number of events may be roughly estimated as

$$N_{\text{events}}^{\text{PS191}} = N_{\text{p.o.t.}}^{\text{PS191}} \cdot \frac{\sigma_{pp \to K^{\pm} X}}{\sigma_{pp,\text{tot}}} \cdot P_{\text{decay}}^{K,\text{PS191}} \cdot \epsilon_{\text{geom}} \cdot \text{Br}(K \to N) \cdot P_{\text{decay}} \cdot \text{Br}_{N \to Y}, \tag{8}$$

  where ϵ_{geom} is the geometric acceptance for kaons flying to the PS191's decay volume, and $P_{\text{decay}} = (e^{-l_{\text{min}}/l_{\text{decay}}} - e^{-l_{\text{max}}/l_{\text{decay}}})$

Comparison with PS191 II

- Using this estimate and assuming $\langle p_K \rangle = 5$ GeV, we recover the sensitivity of PS191 to the decays $K \to N + e$, $N \to \pi + e$ of Dirac HNLs if $\frac{\sigma_{pp\to K^\pm X}}{\sigma_{pp,\mathbf{tot}}} \cdot \epsilon_{\text{geom}} \cdot P^{K,\text{PS191}}_{\text{decay}} \simeq 10^{-2}$
- The authors of PS191 search used the spectrum of kaons from the experimental work [report]
- In this work, the scattering of protons with a **thin** target was studied, so the spectrum is not affected by the kaons scattering, and the factor $P^{K,\text{PS191}}_{\text{decay}}$ was missing
- Using this work, we recover $\frac{\sigma_{pp\to K^\pm X}}{\sigma_{pp,\mathbf{tot}}} \cdot \epsilon^{K}_{\text{geom}} \simeq 10^{-3}$, which means that the factor $\frac{\sigma_{pp\to K^\pm X}}{\sigma_{pp,\mathbf{tot}}} \cdot \epsilon_{\text{geom}} \cdot P^{K,\text{PS191}}_{\text{decay}}$ is 25 times smaller

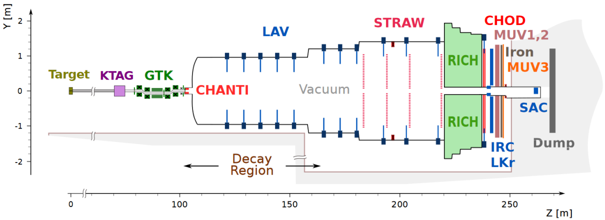


Figure 1: Scheme of NA62 experiment in kaon mode. Given from [1712.00297]

- SPS proton beam with $E_p = 400$ GeV and **decreased nominal intensity**
- Two regimes of experiment:
  1. Kaon mode — proton beam of 1% of nominal intensity collides with beryllium target, producing kaons; the latter can reach 120 m long decay volume located at 100 m away from the target; the decay channel $K \to Y_{\mathbf{SM}} + X$ is searched; detection by the charged track of $Y_{\mathbf{SM}}$ and squared missing mass $m^2_{\mathbf{miss}} = (p_K - p_{Y_{\mathbf{SM}}})^2$ computed by precise measurement of K and $Y_{\mathbf{SM}}$ 4-momenta
  2. Beam dump mode (planned to collect the data in 2021-2023) — the Be target is pulled up, the beam collides with the Cu-Fe hadron stoppers located 20 m long downstream the target, and HNLs produced in collisions can then decay in the detector (see, e.g., [1806.00100])

NA62 in kaon mode and scalars

- In kaon mode, NA62 searches for new physics particles X in decays $K \to X + \text{SM}$, where SM is a visible SM particle. If having $\tau_X > 50$ ns, the X particle escapes the detector and manifests itself as a missing mass/energy. Its mass may be then reconsructed using peak searches (see, e.g., [2005.09575])
- Scalars are produced in decays $K \to S + \pi$. Assuming that π may be reconstructed directly, the only **direct** background process for this channel is $K \to \pi\nu\bar{\nu}$, with $\text{Br}_{K\to\pi\nu\bar{\nu}} \approx 2 \cdot 10^{-10}$. Unlike the case of HNLs ($K \to N + e$, and thus the competing background process is $K \to \mu\nu \to e\nu\nu\nu$ with $\text{Br}_{K\to\mu\nu} \approx 0.6$), the background is expected to be negligible
- We estimate the sensitivity of this scheme following [1909.08632]:

$$N_K \cdot \text{Br}_{K\to\pi+S} \cdot \epsilon > 3, \tag{9}$$

  where $N_K \simeq 10^{13}$ is the number of K decays collected from the sample that will be collected for searching $K^+ \to \pi^+\nu\nu$ during the LHC-run3
- This gives a constraint at the level $\theta^2_{\text{NA62-K}} > \text{few} \times 10^{-10}$, which agrees with slides

NA62 in beam dump mode and scalars I

- We use parameters of NA62 in beam dump mode from [1806.00100]: $l_{\text{min}} = 100$ m, $l_{\text{fid}} = 120$ m, $N_{\text{p.o.t.}} = 2 \cdot 10^{18}$ (will be collected during Run III (2021-2023)), $E_p = 400$ GeV, $\theta \in (0, 0.01)$ rad
- We consider three production channels: proton bremsstrahlung, $B \to X_s S$, $K \to S + \pi$
- To estimate the spectrum of scalars from B mesons flying to NA62, we use the spectrum of B mesons provided by simulations for SPS beam and Appendix B from [1908.04635]. The geometric acceptance and average momentum for scalars that we have found are

$$\epsilon_{\text{geom}}^{\text{from B}} \approx 0.03, \quad \langle p_S \rangle \approx 100 \text{ GeV} \quad \text{for } m_S \lesssim 1 \text{ GeV} \tag{10}$$

- We assume the geometric acceptance for scalars from K the same as from B. We use the average γ factor of K meson $\gamma_K = \sqrt{s_{pp}^{\text{SPS}}}/2$, which is equal to the γ factor between the center of mass and laboratory frame of colliding protons, and $\sigma_{pp \to s\bar{s}}/\sigma_{pp} \approx 1/7$ [0705.1729]
- We assume that all decay channels except for $S \to 2\pi^0$ may be detected. We assume that all detectable scalar decays are reconstructed with an efficiency $\epsilon_{\text{red}} = 1/3$ (that roughly corresponds to the SHiP reconstruction efficiency)
- Unlike the production from B, the production from bremsstrahlung is the same as at SHiP, as produced scalars are highly collimated
- We assume background free setup and require $N_{\text{events}} > 3$