Hidden sector searches at NA62

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on behalf of NA62 collaboration

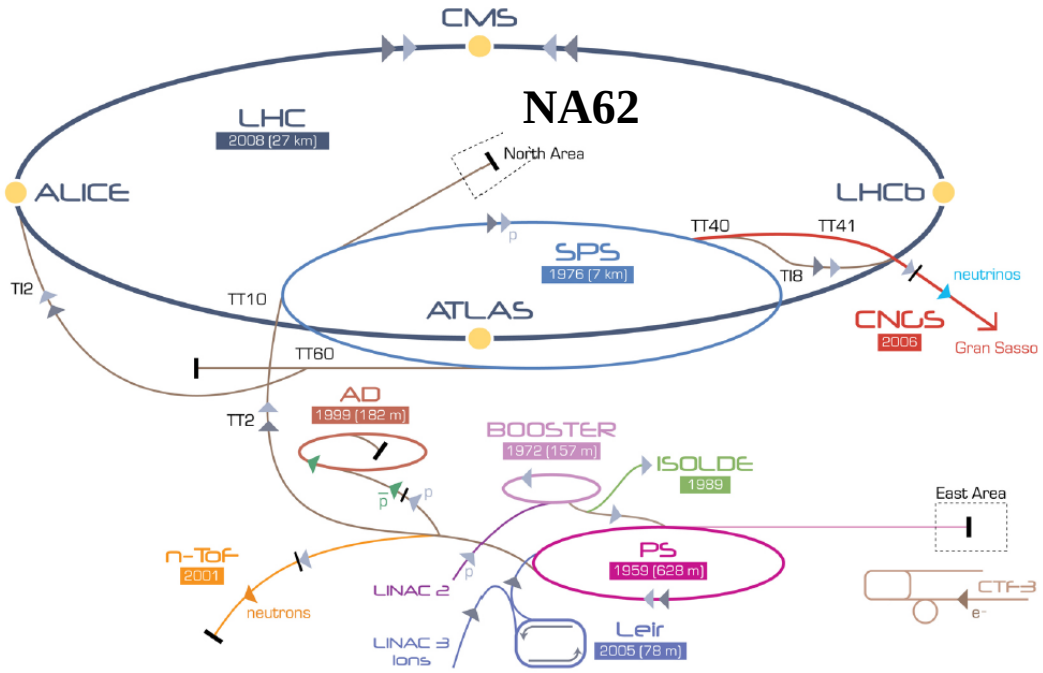
Light dark matter @ accelerators 2017

25 May 2017, La Biodola - Isola d'Elba, Italia

Outline

- **NA62 experiment**
- **Hidden sector searches in NA62**
- **Expected sensitivities for the hidden sector**
- **Preliminary studies on 2016 data in beam mode**
- **Conclusions**

NA62 experiment



Kaon physics at CERN:

- ✓ **Fixed target experiments at CERN SPS**
- ✓ **Kaon decay-in-flight**

Currently in NA62:

~200 participants

29 institutions from 13 countries

Main goal: $\mathbf{BR(K^+ \to \pi^+ \nu\bar{\nu})}$ **measurement with** $\mathcal{O}(10\%)$ **precision**

SM prediction: $\mathbf{BR(K^+ \to \pi^+ \nu\bar{\nu}) = (8.4 \pm 1.0) \times 10^{-11}}$

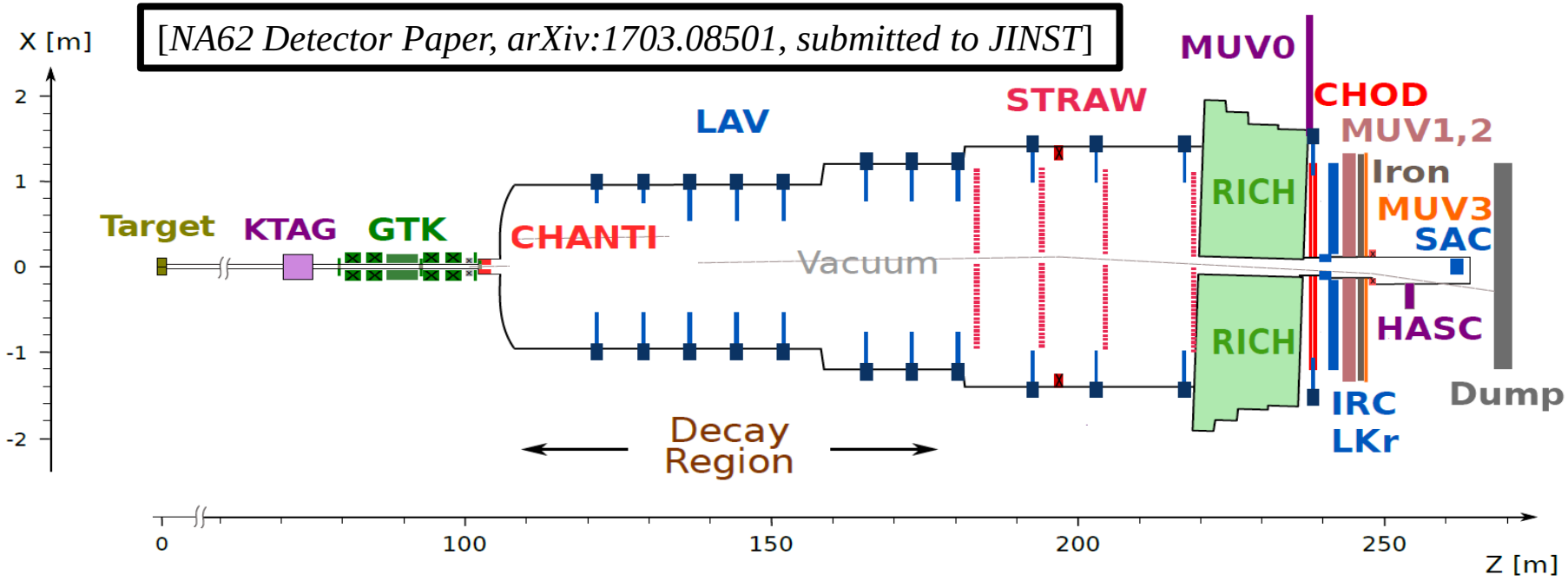
[*Buras et al. JHEP 1511(2015)33*]

Experimental status (E787, E949): $\mathbf{BR(K^+ \to \pi^+ \nu\bar{\nu}) = \left(17.3^{+11.5}_{-10.5}\right) \times 10^{-11}}$

[*Phys. Rev. D 77, 052003 (2008), Phys. Rev. D 79, 092004 (2009)*]

NA62 layout

[*NA62 Detector Paper, arXiv:1703.08501, submitted to JINST*]



Background Process	Branching ratio
$K^+ \to \pi^+\pi^0$	0.2066
$K^+ \to \mu^+\nu_\mu$	0.6356
$K^+ \to \pi^+\pi^+\pi^-$	0.0558

NA62 layout

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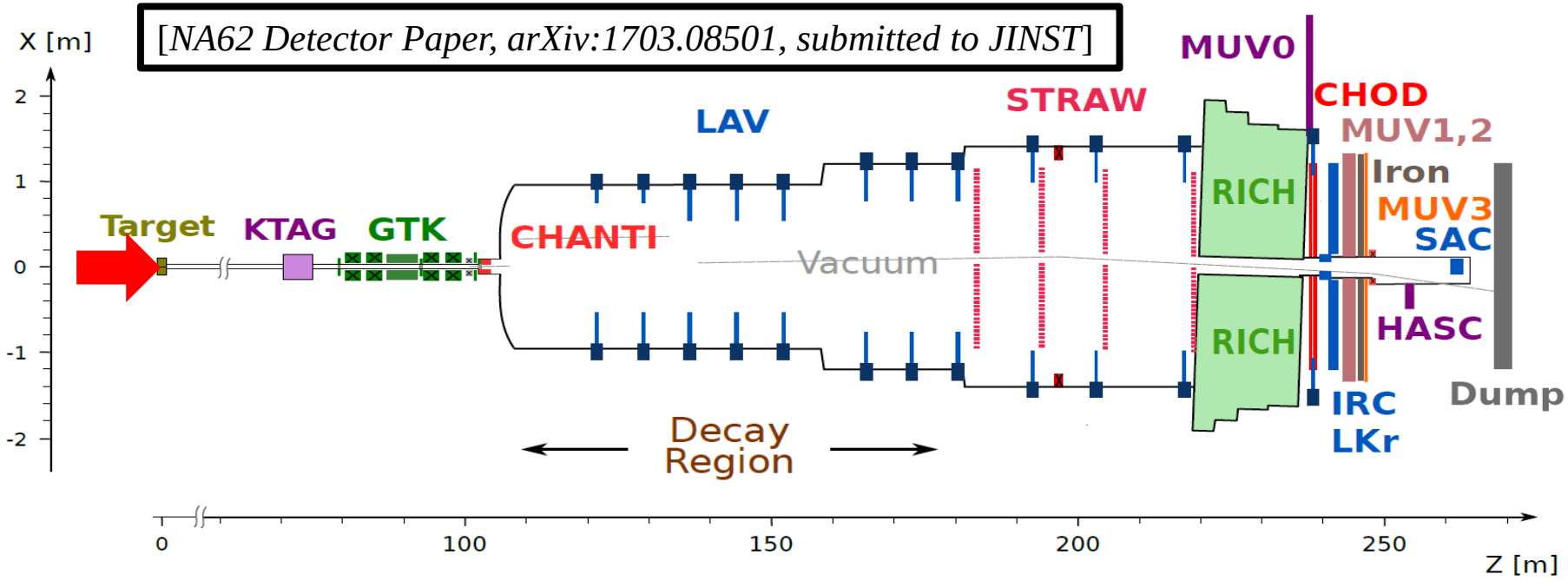

SPS protons:

400 GeV/c

10^{12} Proton on target(PoT)/sec on spill

3.5 sec spill

NA62 layout

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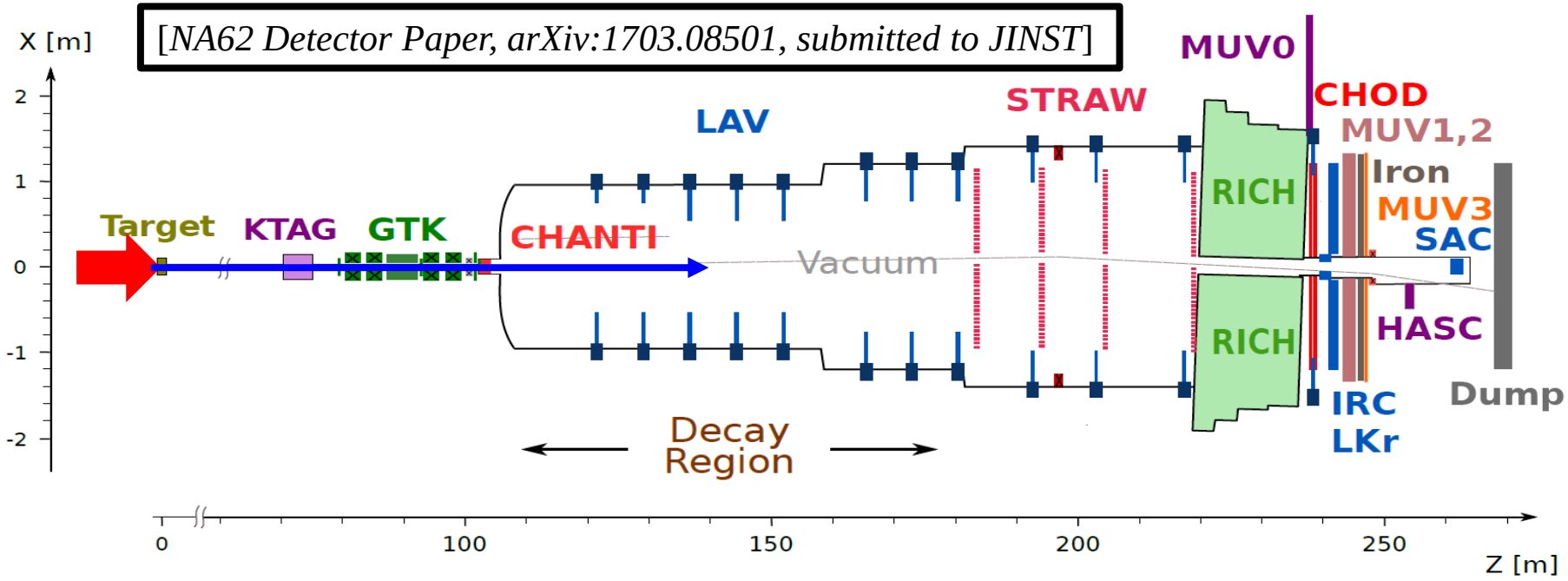

SPS protons:
400 GeV/c
10^{12} PoT/sec on spill
3.5 sec spill

Secondary beam:
75 GeV/c, 1% bite
100 μrad
60 × 30 mm^2
K^+(6%)/π^+(70%)/p(24%)
750 MHz at GTK3

NA62 layout

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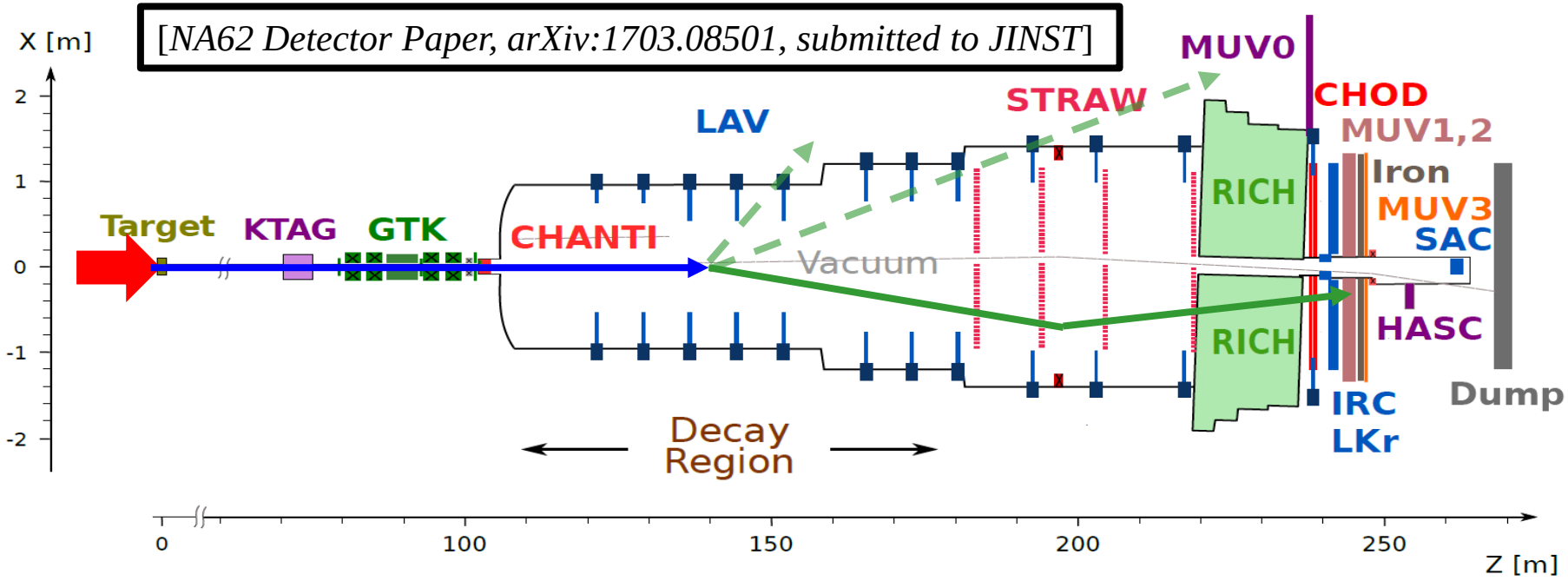

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Kaon decay region:
60 m
~5 MHz
$\mathcal{O}(10^{-6})$ mbar

NA62 layout

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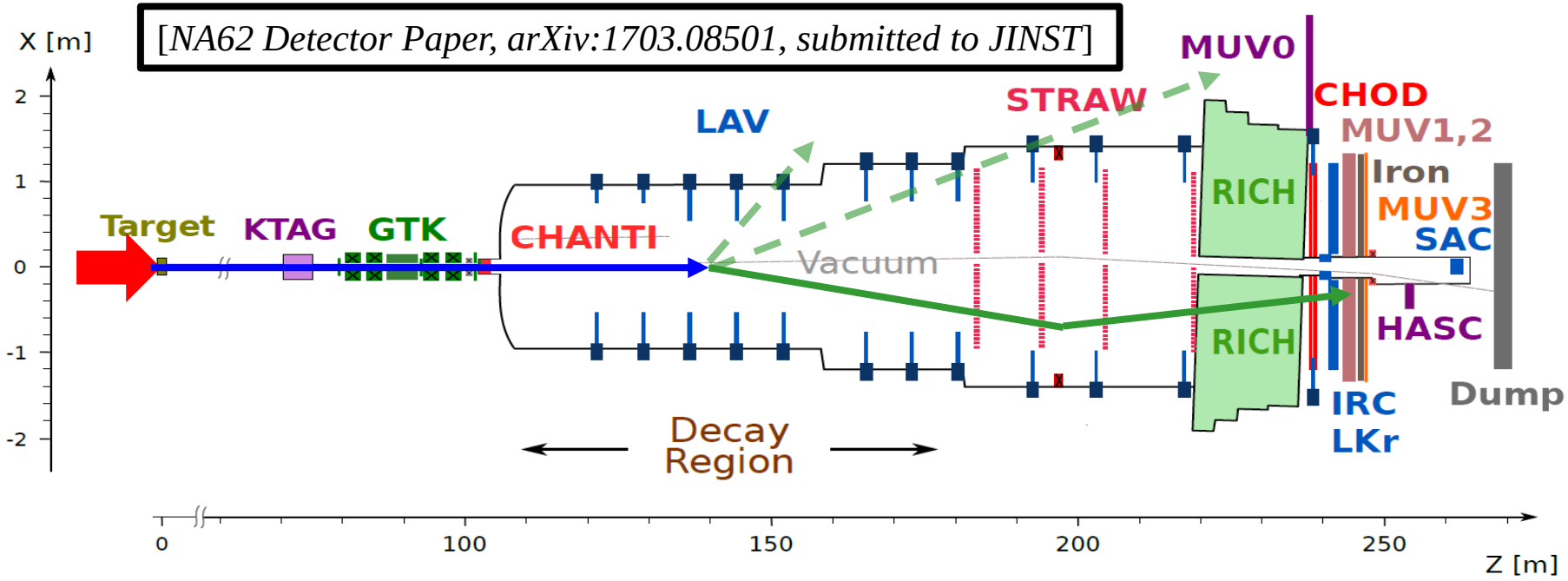


Performances

- ✓ **Excellent time resolution $\mathcal{O}$(100 ps) to match beam and daughter particle information**
- ✓ **Kinematics: rejection of main K modes 10^4 via kinematics reconstruction**
- ✓ **PID capability: μ vs π rejection of O(10^7) for 15 < p(π^+) < 35 GeV**
- ✓ **High-efficiency veto: 10^8 rejection of π^0 for E(π^0) > 40 GeV**

NA62 timescale for $K^+ \to \pi^+ \nu\bar{\nu}$ (2016-2018)

Run in 2014: pilot run

Run in 2015: commissioning run

- commissioning of L0 trigger
- run up to nominal intensity,
- 33×10^{11} PoT/spill, 3.5 s effective-length spill

Run in 2016: detector commissioning + physics run

- L1 trigger/detecotor final commissioning
- stable run at 40% of the nominal beam intensity
- the goal is to reach SM-expectation sensitivity $\mathcal{O}(10^{-10})$

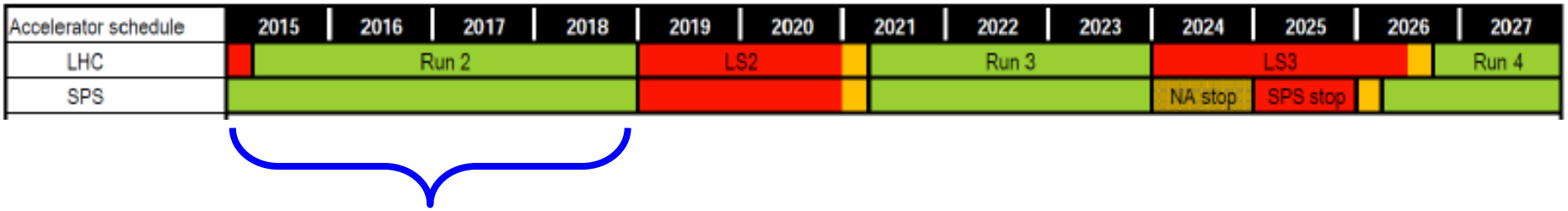
Run in 2017: physics run

- improve on present state of the art (BNL measurement) collecting 14-15 $K^+ \to \pi^+ \nu\bar{\nu}$ events

Run in 2018: physics run

- measurement of BR($K^+ \to \pi^+ \nu\bar{\nu}$) at 10%

Current run



$K^+ \to \pi^+ \nu\bar{\nu}$ physics program

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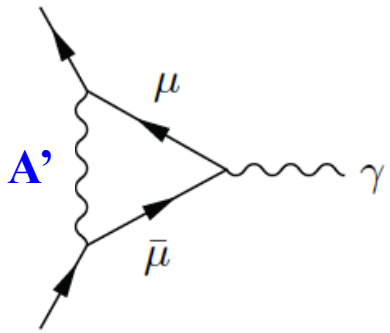
Hidden sector motivations

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' dark photon), neutrino (HNL), axial (ALP a), scalar..

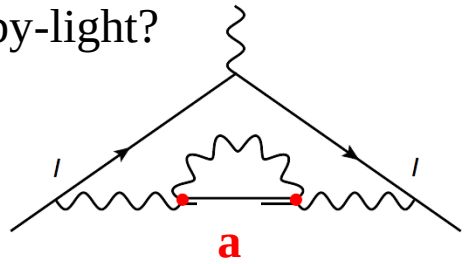
Various experimental hints for hidden sector at MeV-GeV, e.g., a_μ 3.5-σ discrepancy**:**

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



[*Okun, Holdom*]

…or to an ALP **a** enhancing light-by-light?



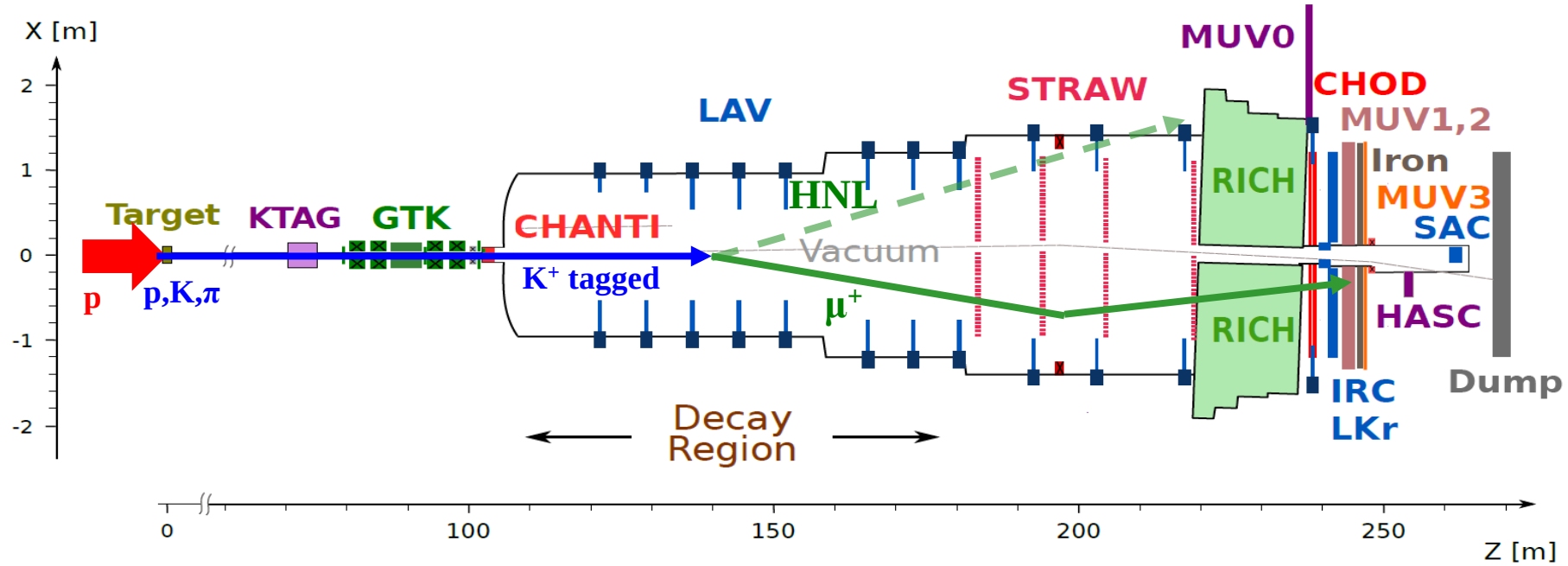
[*Marciano et al. arXiv:1607.01022*]

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}

Hidden sector particle at NA62 from kaons

Such high-intensity, high-performance setup as NA62 might be suited for these NP searches:



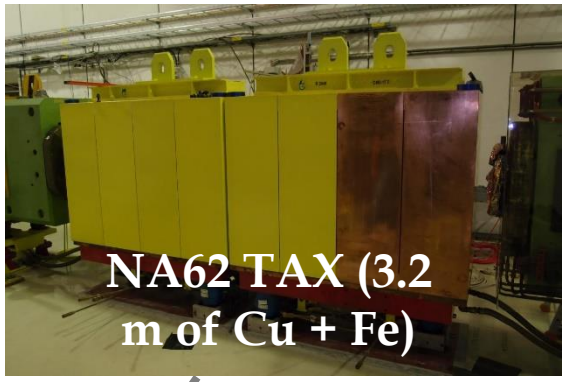
Trigger bandwidth for final states other than "π^+ + E_{miss}" (used for the $K^+ \to \pi^+ \nu\bar{\nu}$) limited. Some LFV/LNV studies can be performed because involve low-bandwidth trigger

- 3 daughter tracks at SES ~ 10^{-11}: $K^+ \to \pi^+ \mu^\pm e^\mp$, $K^+ \to \pi^- \mu^+ e^+$, $K^+ \to \pi^- e^+ e^+$, $K^+ \to \pi^\pm \mu^\mp \mu^+$

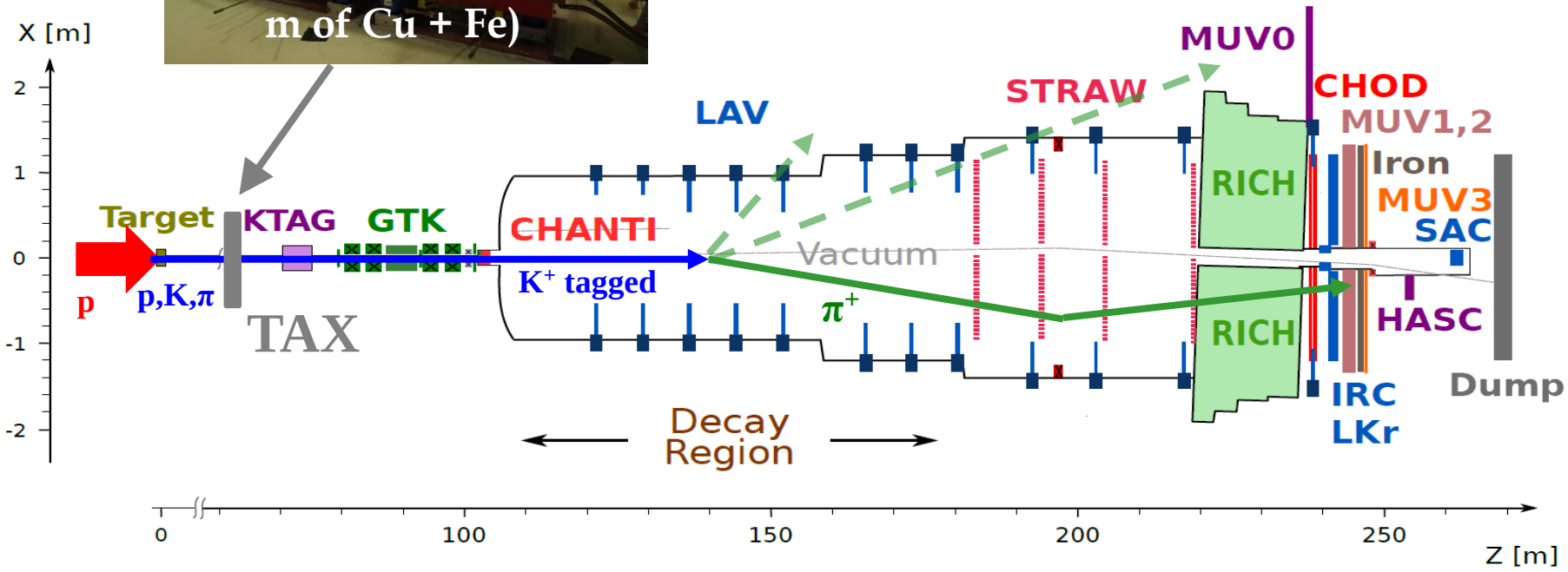
others because can be made in parasitic mode with the main trigger:

- search for heavy neutral leptons in $K^+ \to \mu^+ \nu_h$, $K^+ \to e^+ \nu_h$
- search for $\pi^0 \to invisible$, NA62 sensitive at 10^{-8} or better

Hidden sector particle at NA62: dump mode

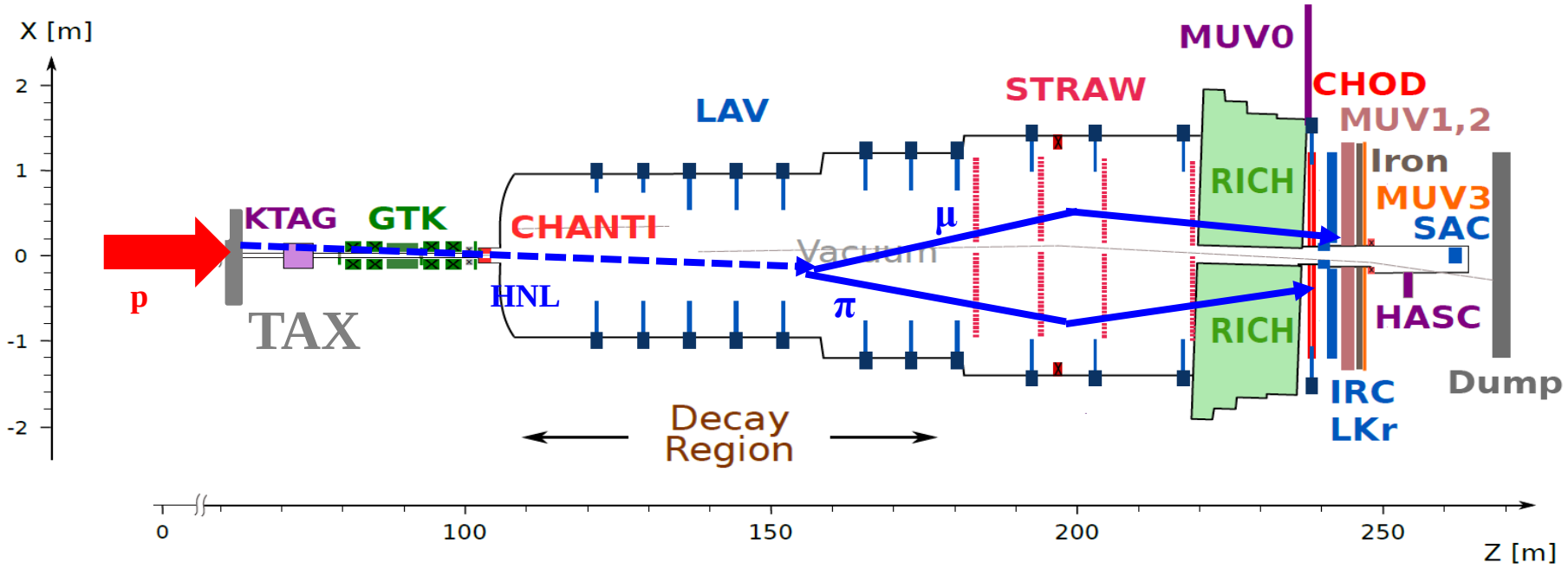


Compact beam dump: ~ 11×2 λ_I Cu-based beam-defining collimator (TAX)



The NA62 Be-target is followed 20-m downstream by two 1.6-m long, water-cooled, copper collimators, `Target Attenuator eXperimental areas' (TAXes) offering a choice of bores of different apertures for momentum selection.

Hidden sector particle at NA62: dump mode



In dump mode the target can be moved away from the beam and the beam let impinging on the copper. **The TAXes can act as a dump.**

Heavy Neutral Leptons, Dark Photons, Dark scalars, and ALPS can be originated by charm, beauty and photons produced in the interaction of protons with the dump.

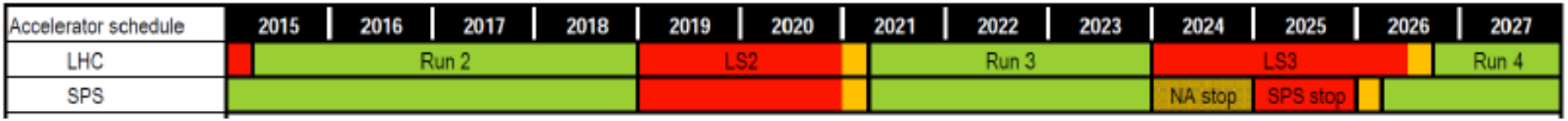
PS: **already in beam mode ~40% of protons do not interact with the target and are dumped onto the TAXes.**

NA62 timescale for exotic searches

Run 2 (2016-2018): present setup for K^+ beam + dedicated triggers. LFV/LNV sensitivity studies based.

- $K^+ \to \pi^+\mu^\pm e^\mp$, $K^+ \to \pi^-\mu^+e^+$, $K^+ \to \pi^-e^+e^+$, $K^+ \to \pi^-\mu^+\mu^+$ (+ radiative modes)
- $\pi^0 \to \mu e$, 3γ, 4γ, ee, $eeee$, $invisible$

Run 2: Current run **LS2** **LS2**



NA62: $K^+ \to \pi^+\nu\bar{\nu}$, LNV/LFV decays, hidden sector searches in K decays

SHiP LBNF

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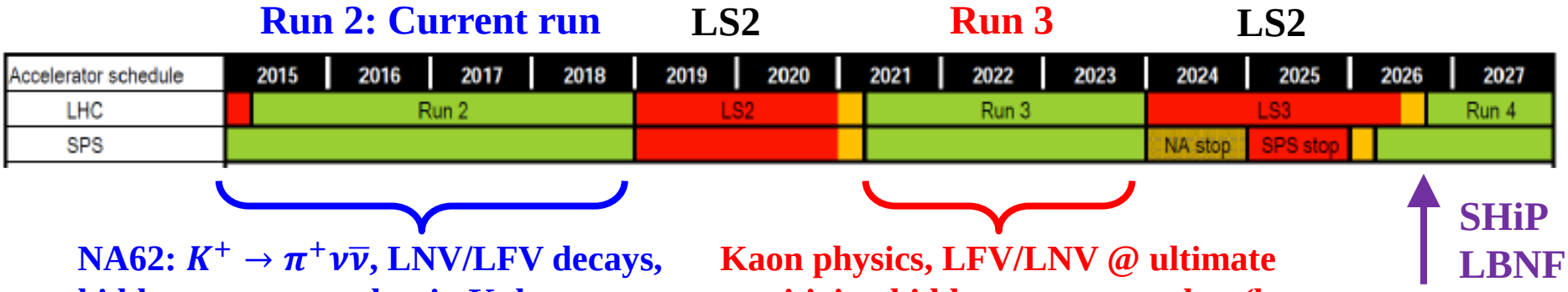
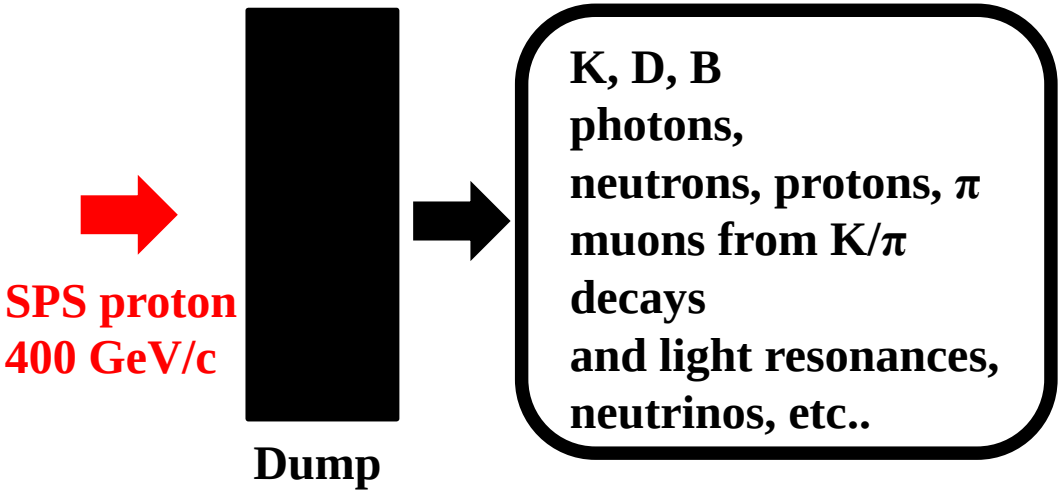
- $\pi^0 \to \mu e$, 3γ, 4γ, ee, $eeee$, $invisible$

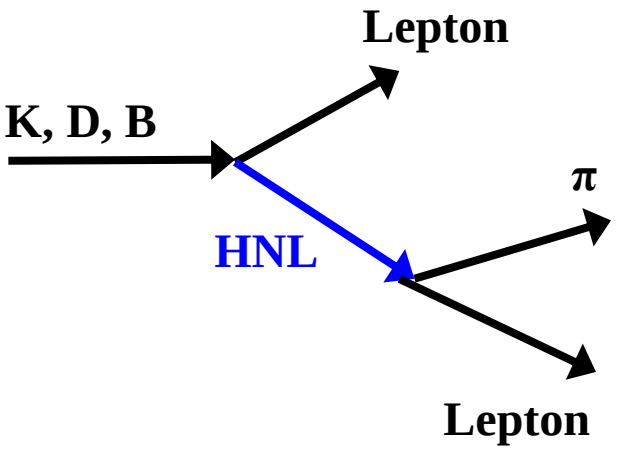
Run 3 (2021-2023): new program of NP searches for MeV-GeV mass hidden-sector candidates: dark photons, heavy neutral leptons, Axions/ALP's, etc.
Goal: integrate (1-2) x10^{18} pot in dump mode in Run 3: this corresponds overall to 100-200 integrated days of data taking at 100% proton intensity.
The beam time dedicated to the dump mode will be spread along the years to not disrupt the kaon programme



Hidden sector particle at NA62: dump mode

K, B, Bs, D, Ds → lepton HNL
K, B, Bs, D, Ds → semi-leptonic modes



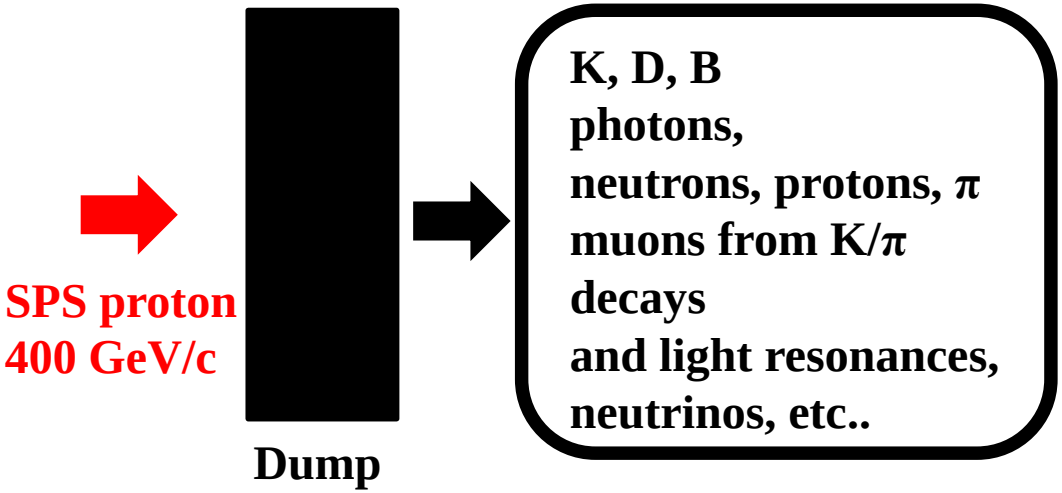


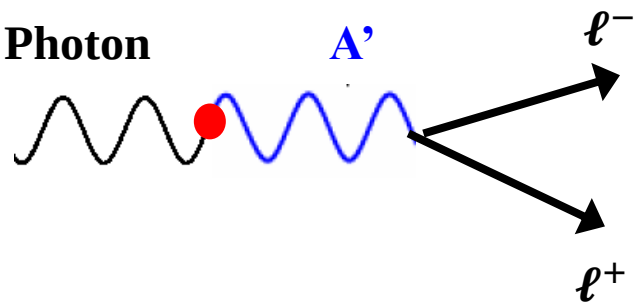
At SPS energies:
σ (pp → s sbar X) ~ 0.15
σ (pp → c cbar X) ~ 2 10^{-3}
σ (pp → b bbar X) ~ 1.6 10^{-7}

Heavy neutrino couplings enter both in production and in decay (~ U^2 process)

Hidden sector particle at NA62: dump mode

Dark photons





At SPS energies:

σ (pp → s sbar X) ~ 0.15

σ (pp → c cbar X) ~ 2 10^{-3}

σ (pp → b bbar X) ~ 1.6 10^{-7}

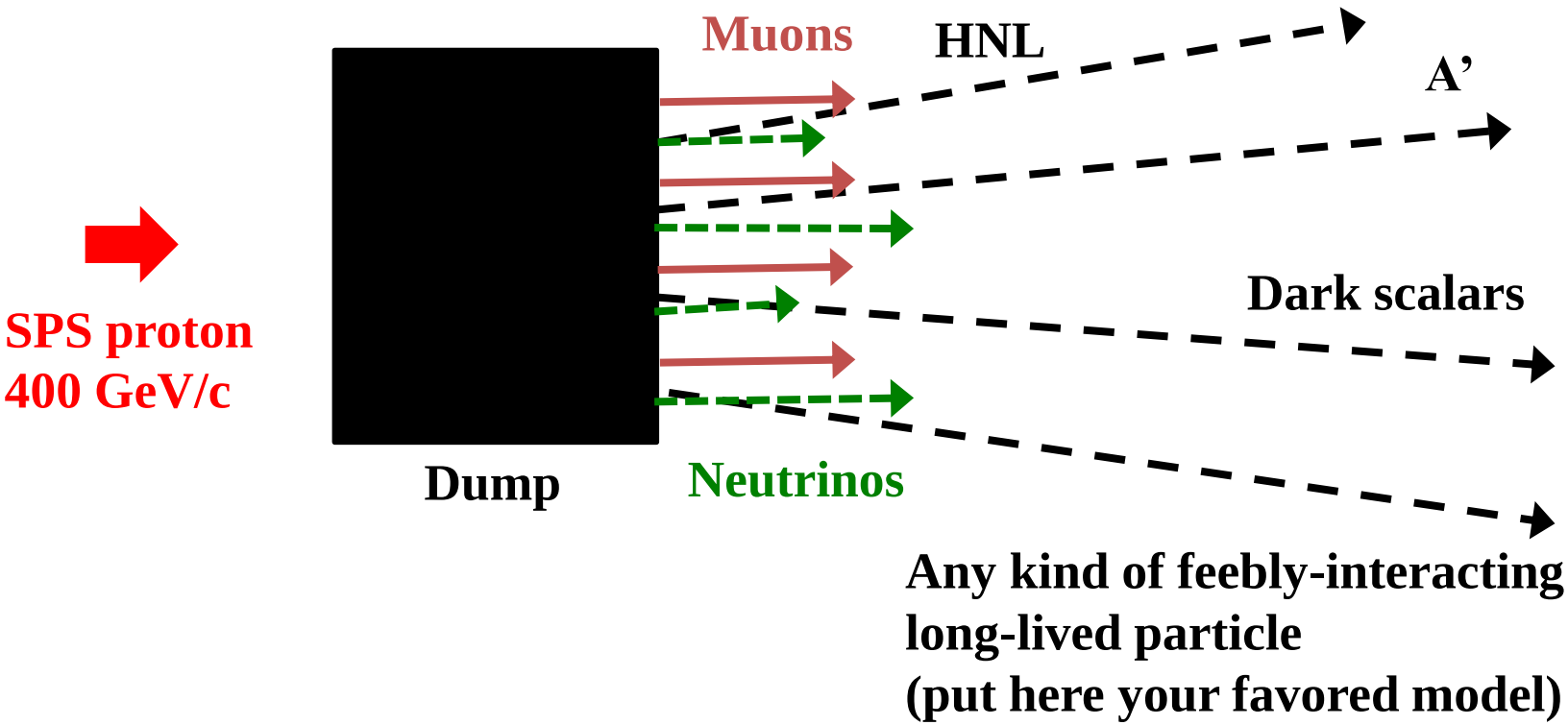
Photon produced in light meson resonances, bremsstrahlung, and QCD processes.

Search for massive particle mixing with the photon and decaying to visible final states ($e^+ e^-$, $\mu^+\mu^-$, etc.)

Hidden sector particle at NA62: dump mode

Dump mode

A dump with suitable length stops all beam-induced backgrounds but neutrinos and muons:



An experiment with a long decay volume will allow you to probe low values of couplings (as the lifetime of dark objects ~ 1/coupling^2)

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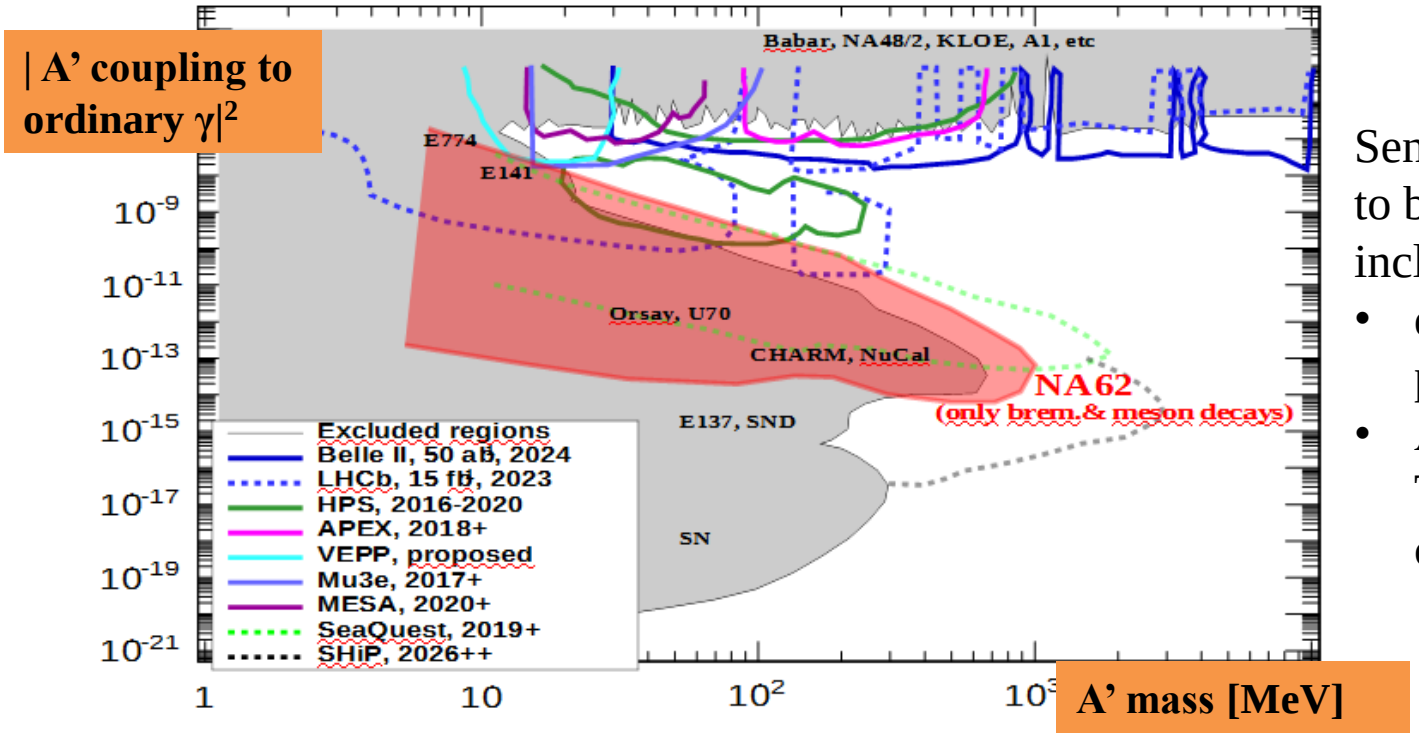
Search for visible decays of long-lived A’

Assume 2×10^{18} 400-GeV PoT:

- search for displaced, dilepton decays of dark photons, $A' \to \mu\mu, ee$
- include trigger/acceptance/selection efficiency
- assume zero-background, evaluate expected 90%-CL exclusion plot



Sensitivity expected to be even higher including :

- direct QCD production of A’
- A’ production in the TAX (only target considered here)

Search for visible decays of HNL

Assume 2×10^{18} 400-GeV PoT:

- search for displaced, leptonic decays HNL → πe, πμ
- include trigger/acceptance/selection efficiency
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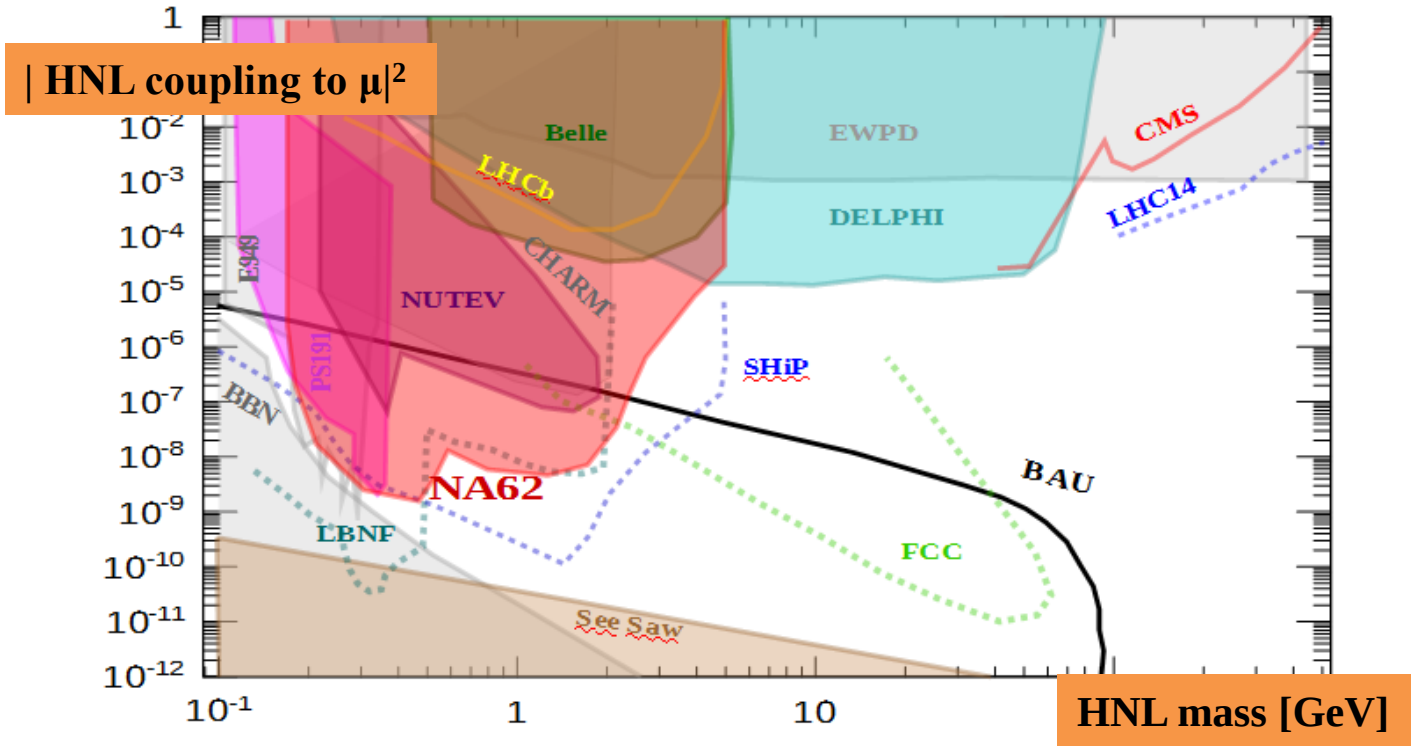
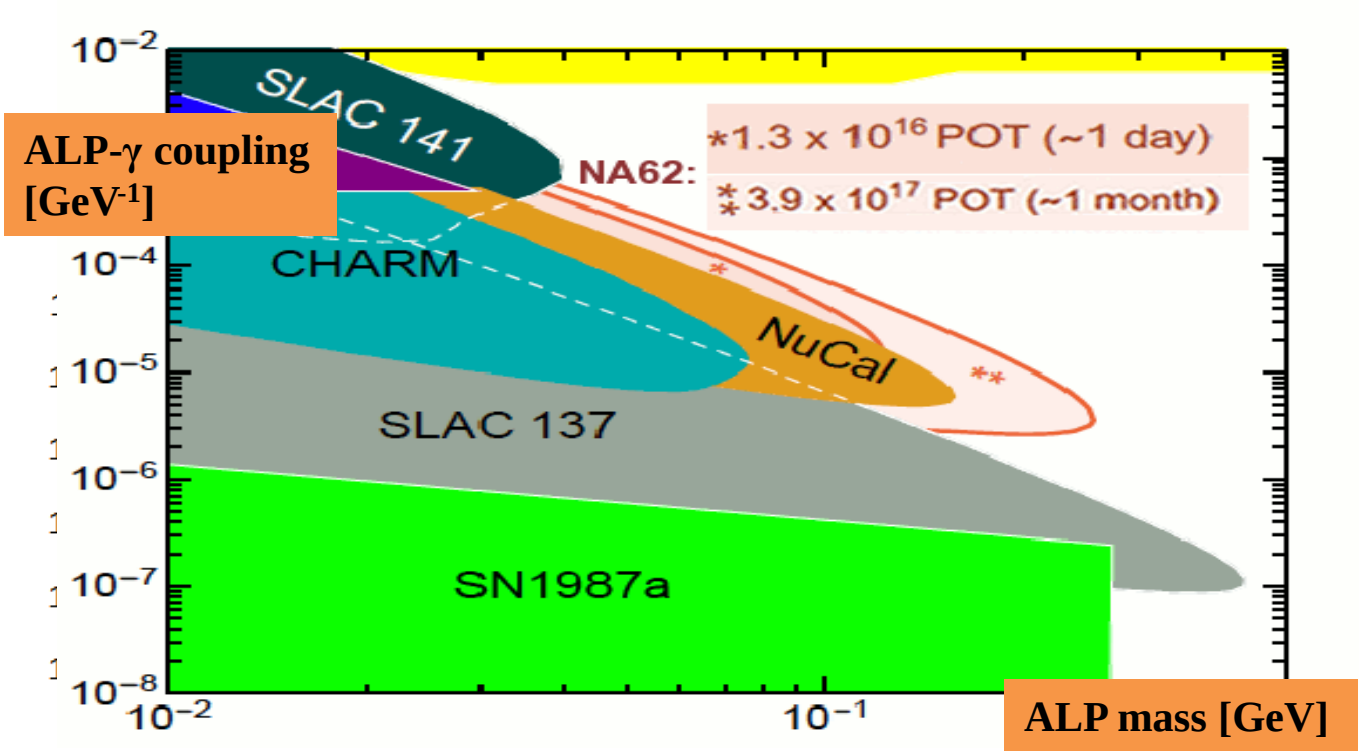


Search for visible decays of ALP

Assume 1.3×10^{16} (3.9×10^{17}) PoT corresponding to 1 day (1 month) runs:

- study ALP Primakoff production [*JHEP 1602 (2016) 018*] at target
- search for ALP-decay to $\gamma\gamma$ in NA62 fiducial volume, account for geometrical acceptance
- assume zero-background, evaluate expected 90%-CL exclusion plot



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Search for $A' \to \mu\mu$: test on 2016 data

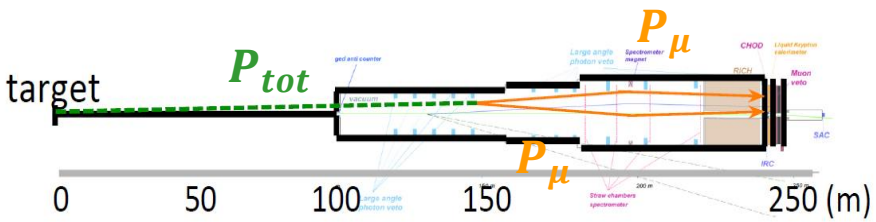
Statistics corresponds to ~10^{15} PoT

Track quality + acceptance cuts: forward detectors, CHOD, LKr, MUV3 associated to CHOD, LKr hits in time

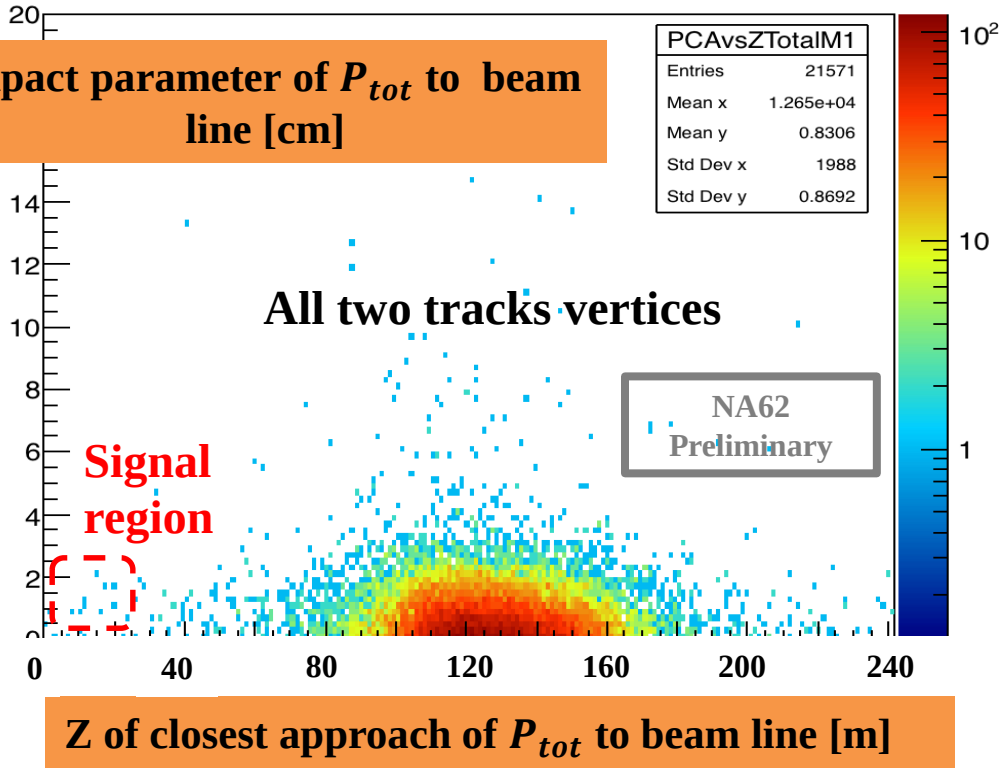
Vertex quality: two-track distance < 1 cm

Vertex position: 105 < Z < 165 m

Test if total momentum $P_{tot} = P_\mu + P_\mu$ stems from target



Background from K, π decays concentrated around beam after final collimator



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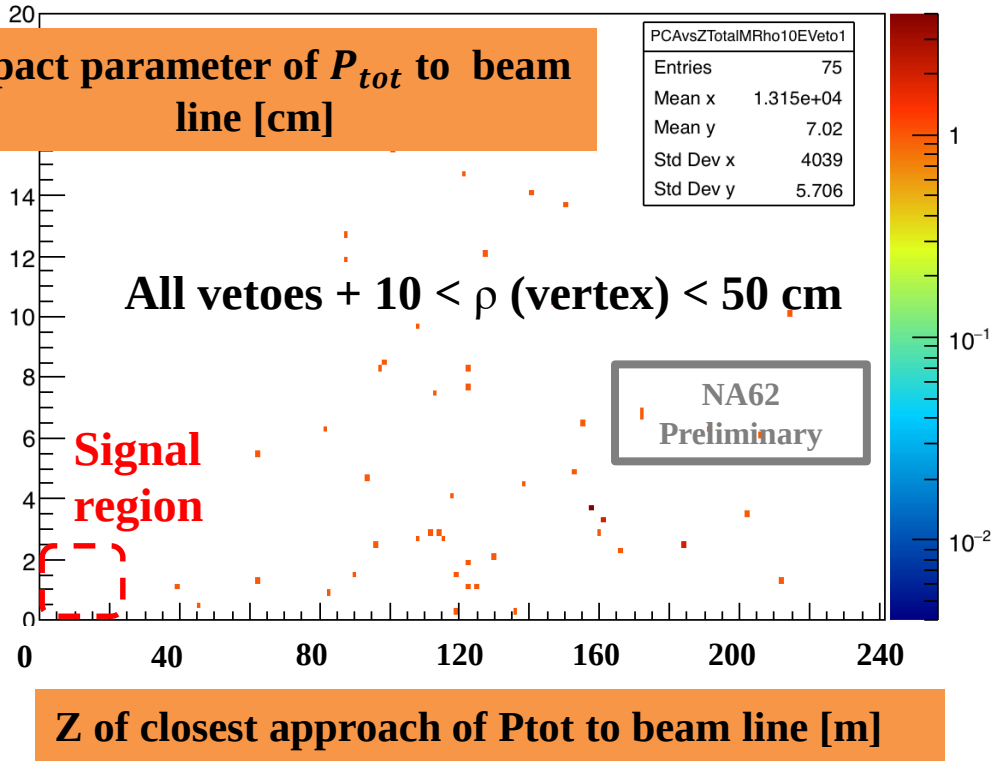
Vertex position: 105 < Z < 165 m

Test if total momentum stems from target

Further event-level veto conditions:
Additional energy in the LKr < 2 GeV
Veto on forward / large angle calorimeters
Veto on charged anti counter

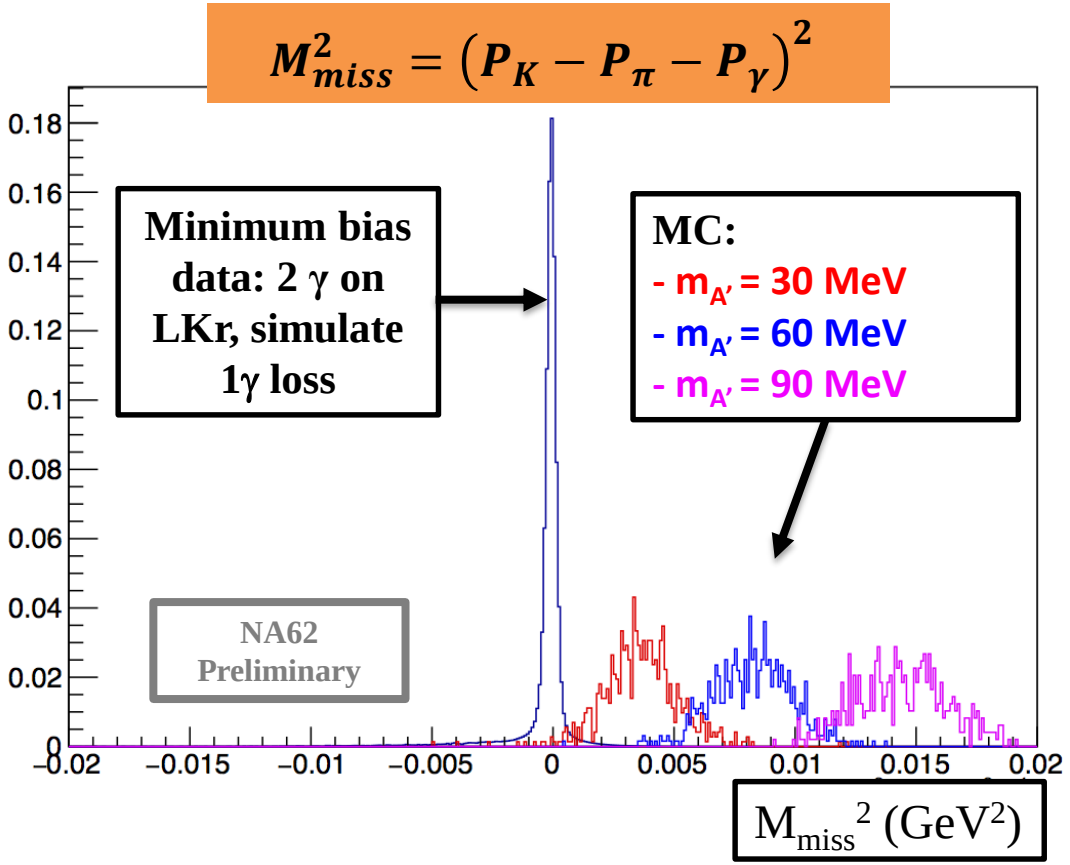
No events selected in the signal region (even with standard K^+ beam)



NA62 2016 data: dark photon from π^0 decay

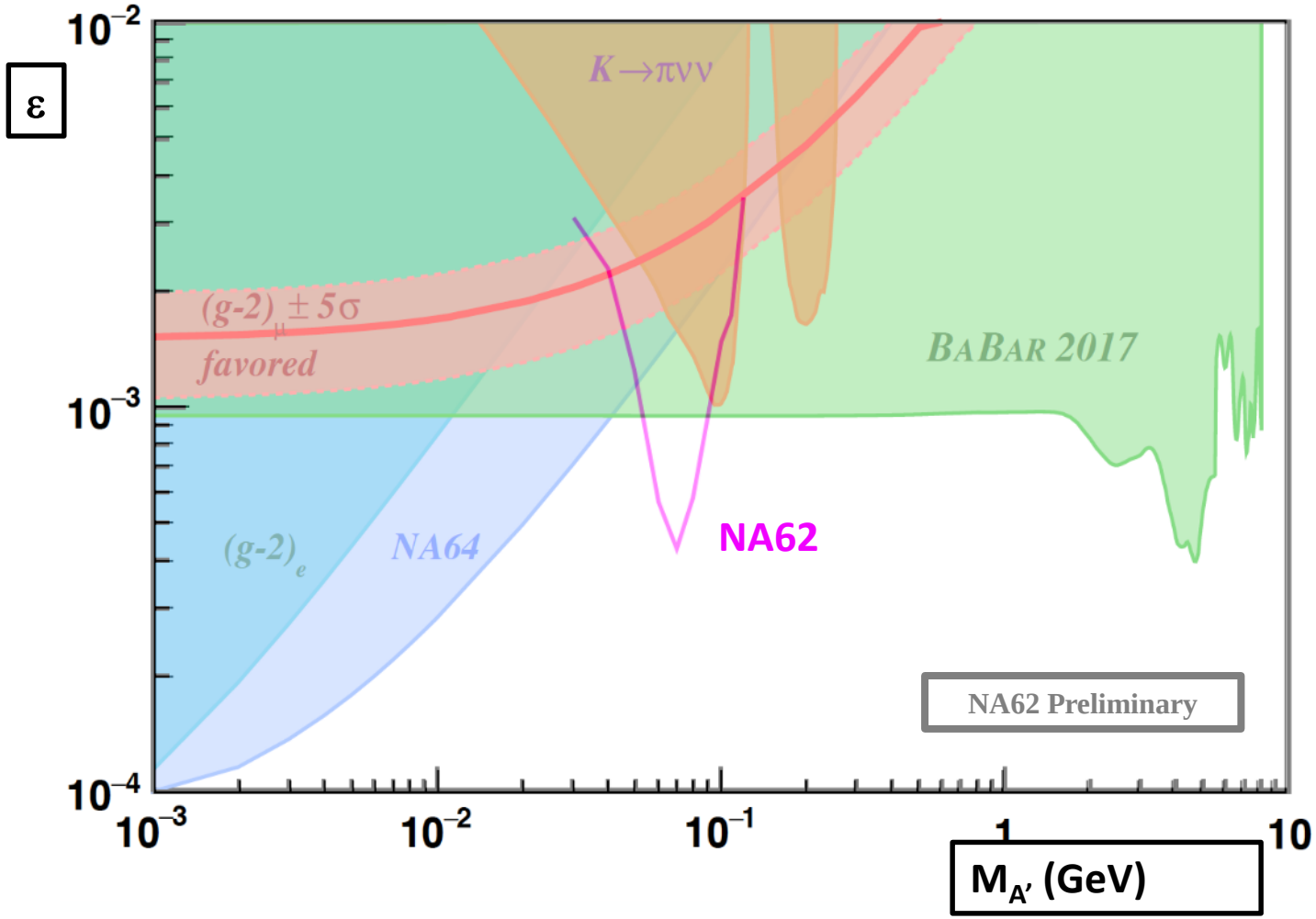
Decay chain: $K^+ \to \pi^+\pi^0, \pi^0 \to A'\gamma, A' \to invisible$

- **Signature:**
  - 1 photon + missing energy
- **Selection:**
  - π^+ as in $K^+ \to \pi^+\nu\bar{\nu}$
  - $15<p_{\pi^+}<35$ GeV/c
  - 1 γ in LKr
  - Missing momentum in LKr
  - Extra γ veto
- **Background:**
  - Negative tail of M^2_{miss}
- **Normalization:**
  - $K^+ \to \pi^+\pi^0$ from minimum bias



NA62 2016 data: dark photon from π^0 decay

NA62 limits in an interesting region; #K decays ~ 1.5×10^{10} (4% 2016 statistics) used



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- ✓ **NA62 is officially approved to run until LS2 with the main goal of measuring the BR($K^+ \to \pi^+ \nu\bar{\nu}$) with 10% accuracy;**
- ✓ **Before LS2 (2018) many searches in the hidden sector will be performed using the kaon beam (new limits on dark photon already investigated).**

- ✓ **After LS2 (2020++) there is a window of opportunity to run NA62 in beam-dump mode to search for hidden particles from charm and beauty decays and pave the way for the next generation experiments (SHiP).**
- ✓ **Preliminary studies with data taken in beam and beam-dump modes show that the background can be kept under control, further improvements in the setup are currently under study.**