Exotic searches at NA62

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on behalf of the NA62 collaboration

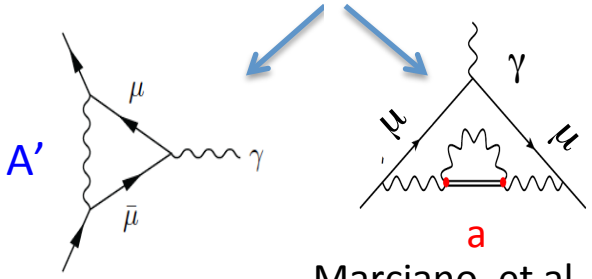
Hidden sector searches: motivations

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

Mediators 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), Higgs..

Various experimental hints for hidden sector at MeV-GeV: e.g., muon **g-2**

Model freedom → be experimentally-driven



Marciano, et al.
arXiv:1607.01022

Feeble interaction: suppressed production rate, 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}
fully profit of a high-intensity setup

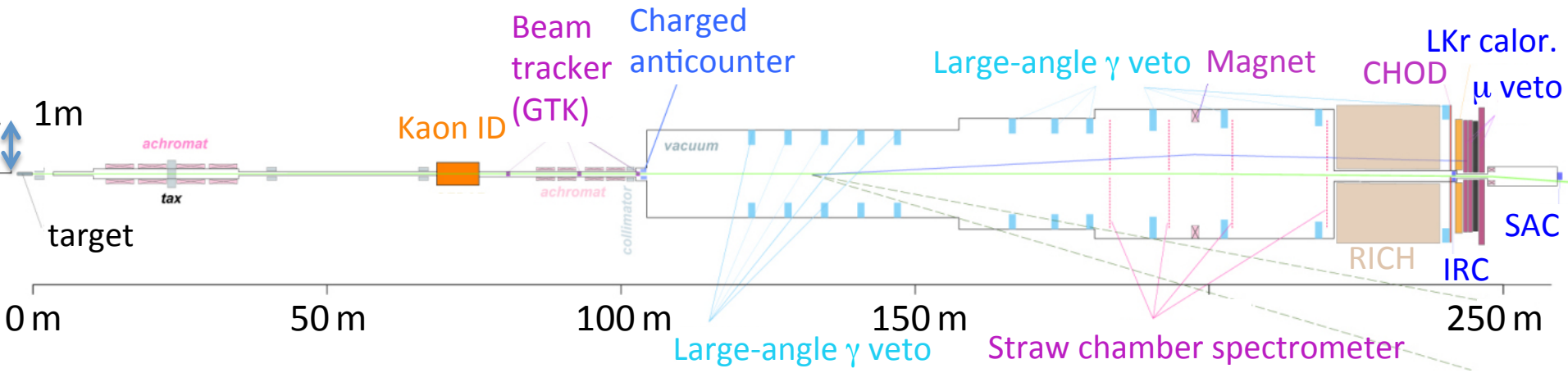
NA62: a high-intensity setup

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

High-intensity proton-produced charged hadron beam:

10^{12} 400-GeV protons/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

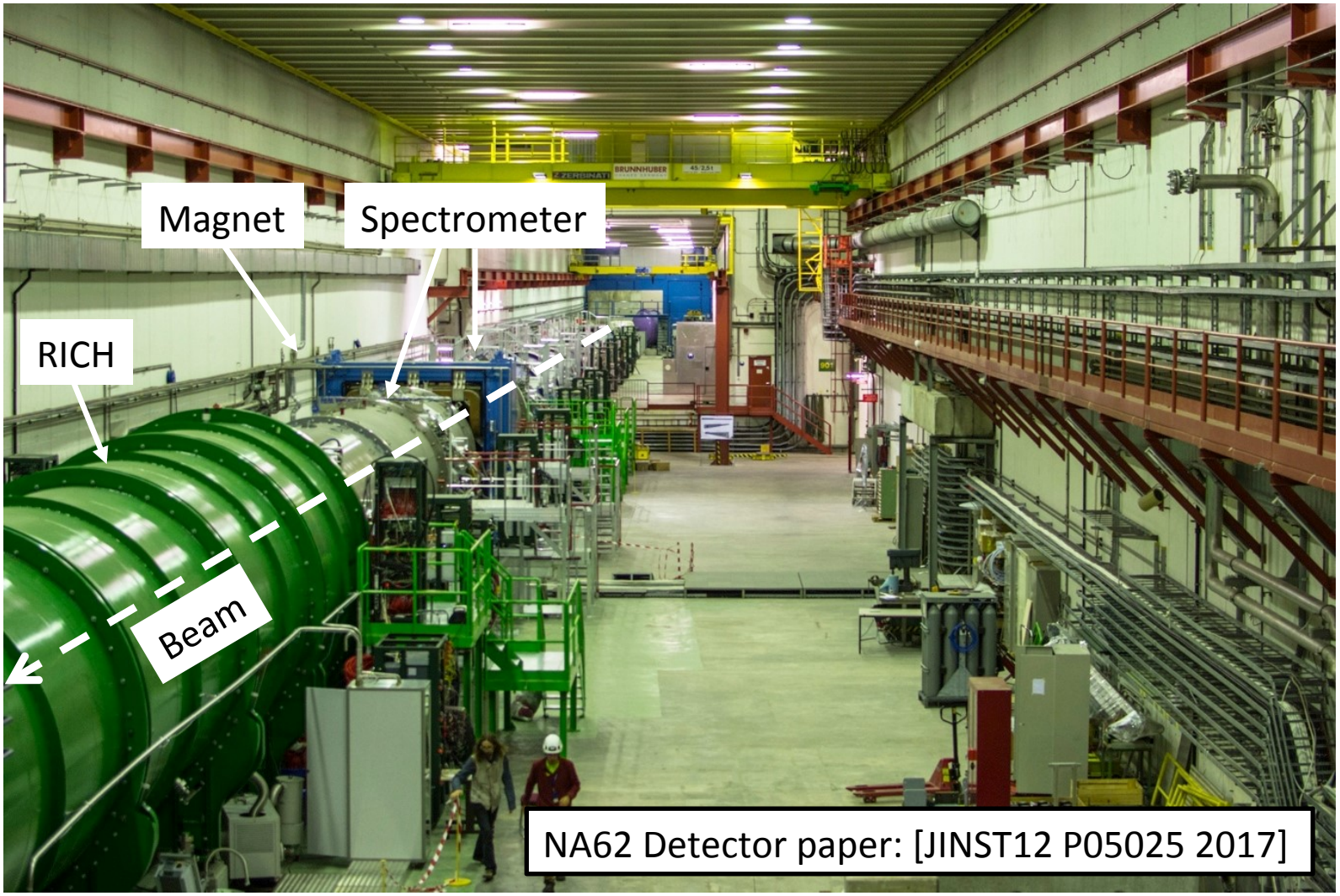
Fw-programmable **L0 trigger 1-MHz** max bandwidth, down by x100 in two sw-based levels

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(π^+) < 35 GeV

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

NA62: a high-intensity setup



Physics from NA62 up to 2018, besides $K \rightarrow \pi\nu\nu$

High-intensity, high-performance setup suited for other NP searches

- LFV/LNV studies
- ultra-rare/forbidden π^0 decays
- **searches for exotic states**
- chiral perturbation theory studies from kaon decays

Trigger bandwidth for final states other than "$\pi^+ + E_{miss}$" anyway limited

- 15 MHz single-tracks: ask 1 track, no muon, E_{miss} and reduce L0 to ~750 KHz
- Including calibration and control triggers, little free bandwidth

Some LFV/LNV studies can be performed because involve low-bandwidth triggers…

- three tracks in the final state: $K^+ \rightarrow \pi^+ \mu^\pm e^\mp$, $K^+ \rightarrow \pi^- \mu^+ e^+$, $K^+ \rightarrow \pi^- e^+ e^+$, $K^+ \rightarrow \pi^\pm \mu^\mp \mu^+$
  - achieving SES ~ 10^{-11}, improve by ~x10 on past results
  - allow di-muon resonance search in $K^+ \rightarrow \pi^+ \mu^- \mu^+$ (inflaton, sgoldstino)

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

- search for heavy neutrino in $K^+ \rightarrow \mu^+ \nu_h$, $K^+ \rightarrow e^+ \nu_h$
- sensitivity for BR($\pi^0 \rightarrow$ invisible) at 10^{-8}, search for $\pi^0 \rightarrow A' \gamma$

Hidden sector: opportunities at NA62

A number of production schemes / signals can be simultaneously explored @ NA62

Using dark photon (A') as benchmark:

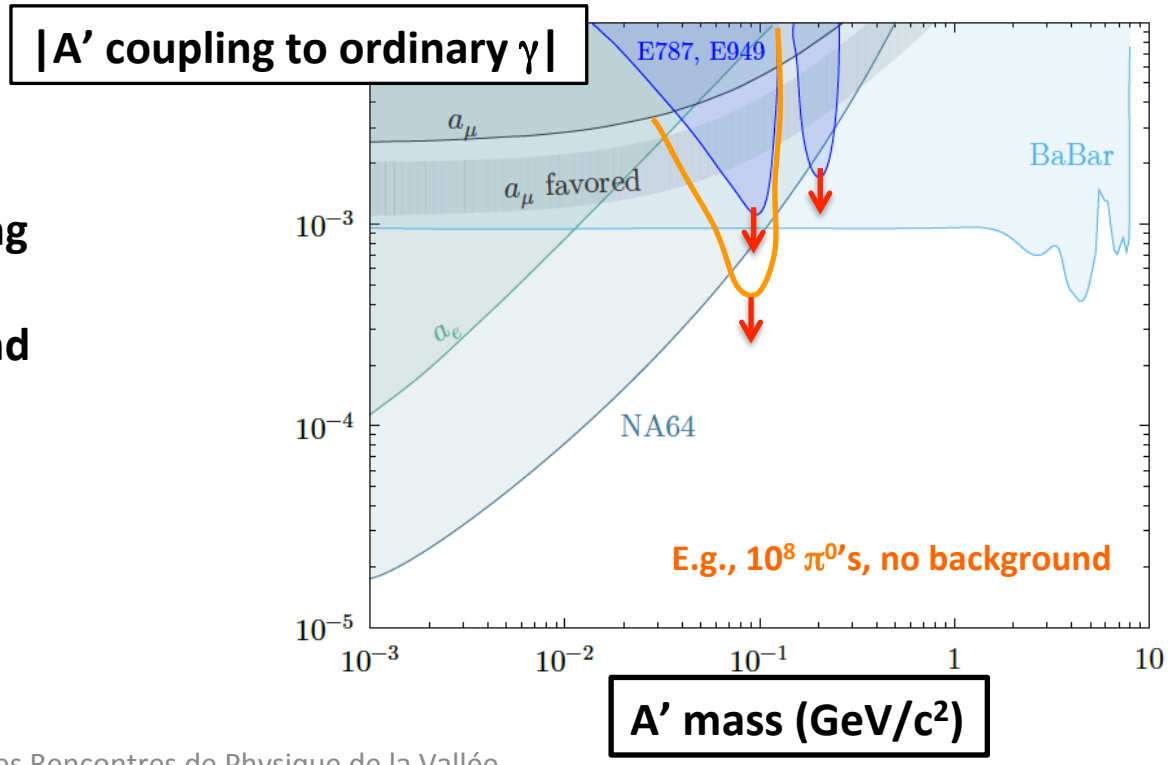
1. Search for <u>invisible decays</u> (production in fiducial volume, missing mass signals):

From K^+ beam: $K^+ \rightarrow \pi^+ A'$, by-product of $K^+ \rightarrow \pi\nu\nu$ [Marciano, et al. PRD 89 2014]

From K^+ decay daughters: $K^+ \rightarrow \pi^+\pi^0$, $\pi^0 \rightarrow \gamma A'$

Rate scales with square of coupling

Up with intensity, if no background limited, improve "from above"



Hidden sector: opportunities at NA62

A number of production schemes / signals can be simultaneously explored

Using dark photon (A') as benchmark:

2. Search for visible decays to SM particles (production at target/dump, exclusive ID in FV):

Production from primary beam secondaries, e.g. pN → X π^0 , π^0 → γA', A'→ e^+e^-, $\mu^+\mu^-$, …

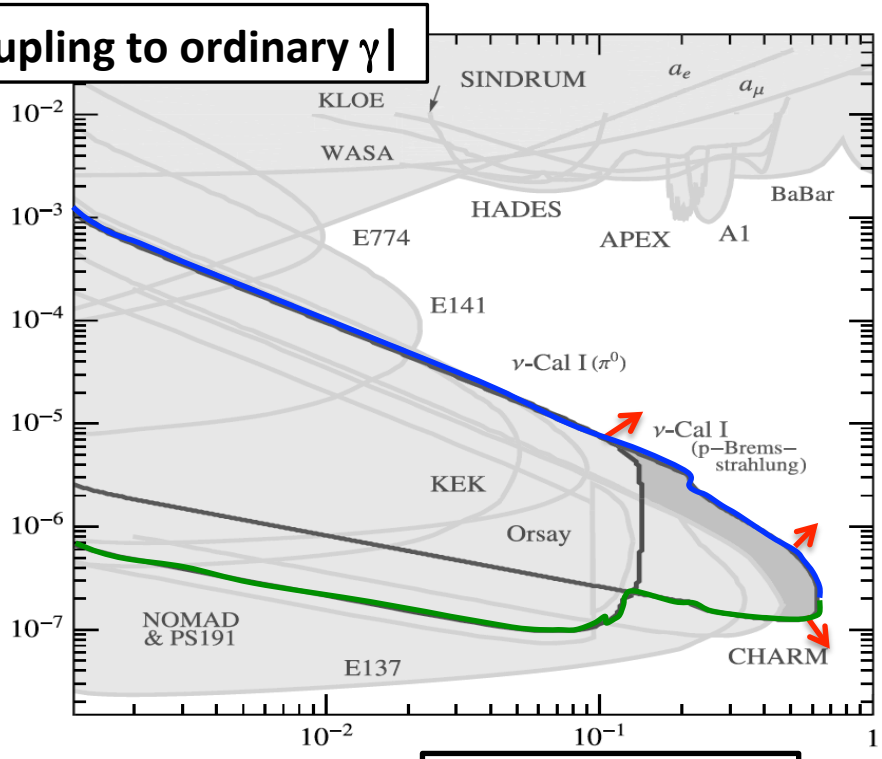
Direct production from primary beam, e.g. pN → X A', A'→ e^+e^-, $\mu^+\mu^-$, …

Rate scales with 4th power of coupling

Sensitivity region shape depends on:

- **minimum distance from production point to decay volume (upper curve)**
- **decay volume acceptance (lower curve)**

Up with intensity, if not background limited → improve "from below"



NA62 well suited to search for long-lived states

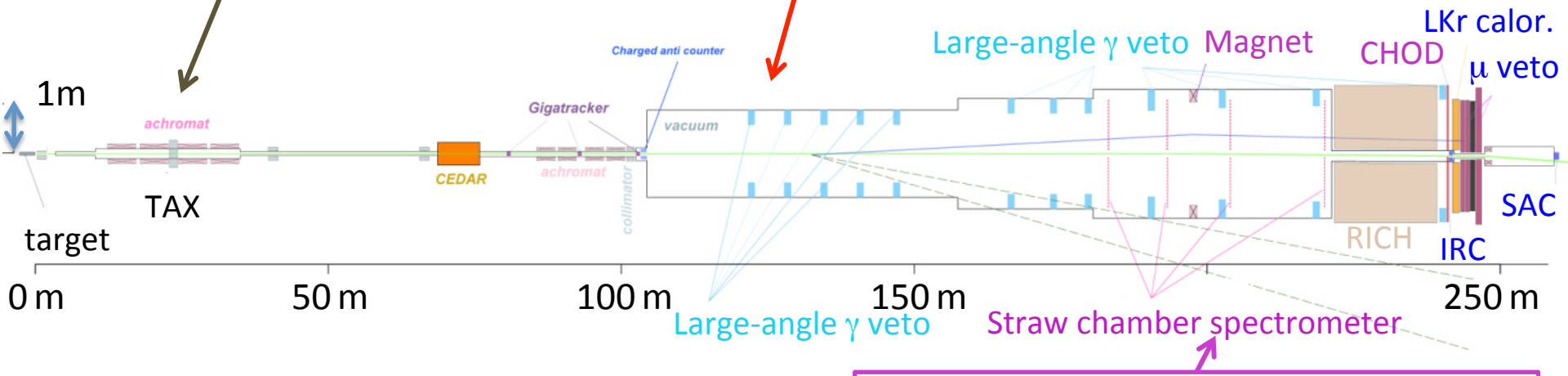
High-intensity 400-GeV proton beam → boost charm/beauty, other meson production

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

Produce 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

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

Search for $\pi^0 \rightarrow \gamma A'$, $A' \rightarrow$ invisible

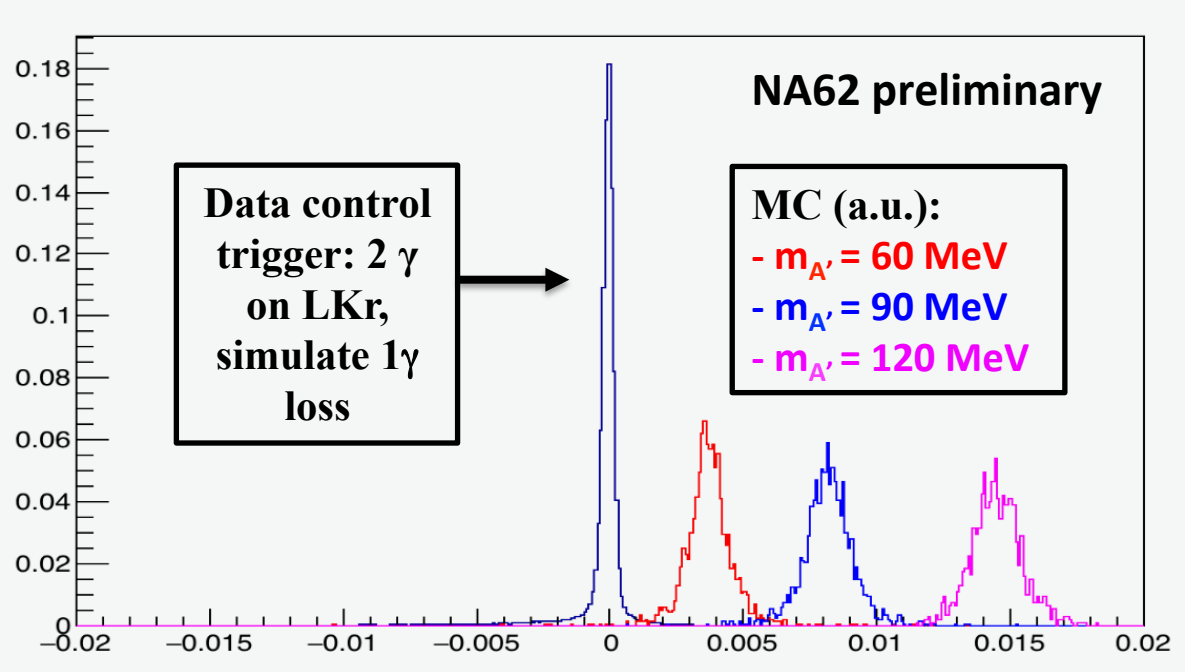
Sensitivity for masses below the π^0 mass: $\mathrm{BR}\left(\pi^0 \to A'\gamma\right) = 2\epsilon^2 \left(1 - \frac{m_A^2}{m_{\pi^0}^2}\right)^3 \times \mathrm{BR}\left(\pi^0 \to \gamma\gamma\right)$

Signal signature: 1 track, 1 photon + missing energy

Search parasitic to $\pi\nu\nu$, trigger based on "1 track" + small forward energy

Search for an invariant mass peak around A' mass

dominant background from $\pi^0 \rightarrow \gamma\gamma$, 1 photon missing

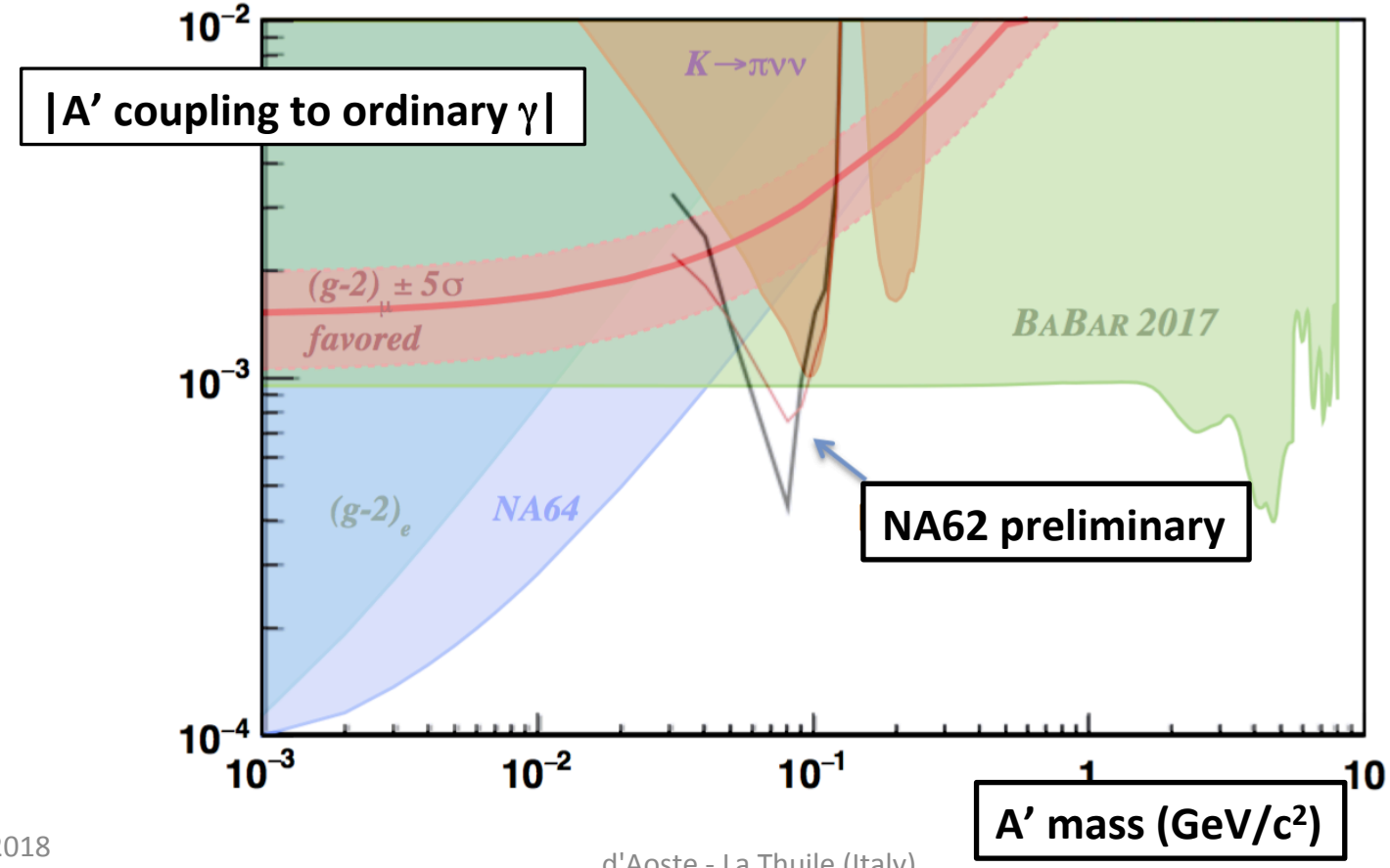


Search for $\pi^0 \rightarrow \gamma A'$, $A' \rightarrow$ invisible

Background from data, symmetrizing resolution tails

Data from 2016 run corresponding to ~1.5 10^{10} K^+, ~4% of 2016 statistics

No signal observed, 90% CL UL within expected statistical uncertainty band



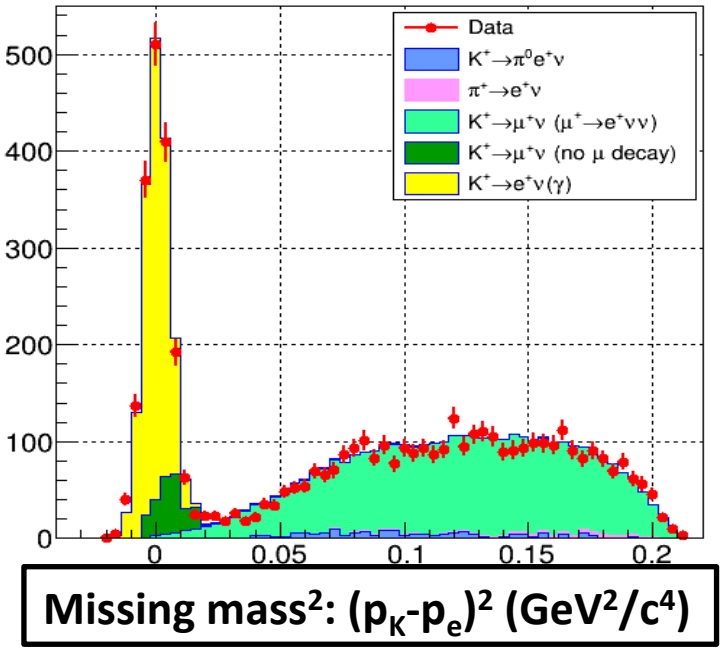
Search for $K^+ \rightarrow e/\mu$ HNL, HNL $\rightarrow$ invisible

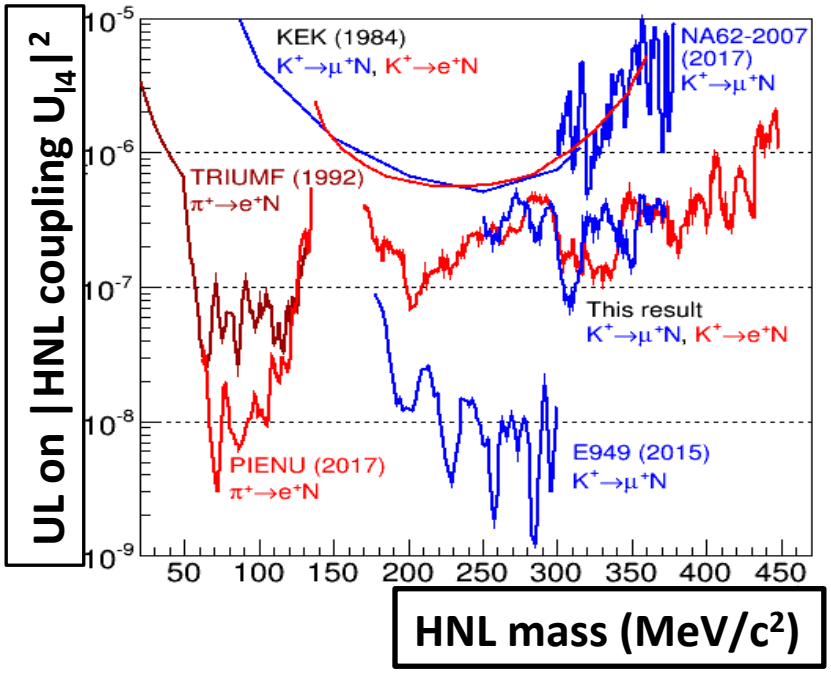
Again bump hunting, two results released in 2017:

Data from 2007 corresponding to ~ 10^7 $K^+ \rightarrow \mu\nu$ decays [NA62 coll., PL B772 712 (2017)]

Min. bias data from 2015 equivalent to ~3 10^8 K^+ decays [NA62 coll. PL B778 137 (2018)]

No signal observed, 90% CL UL extends sensitivity for high masses





Expect major improvement from high-intensity 2016 data

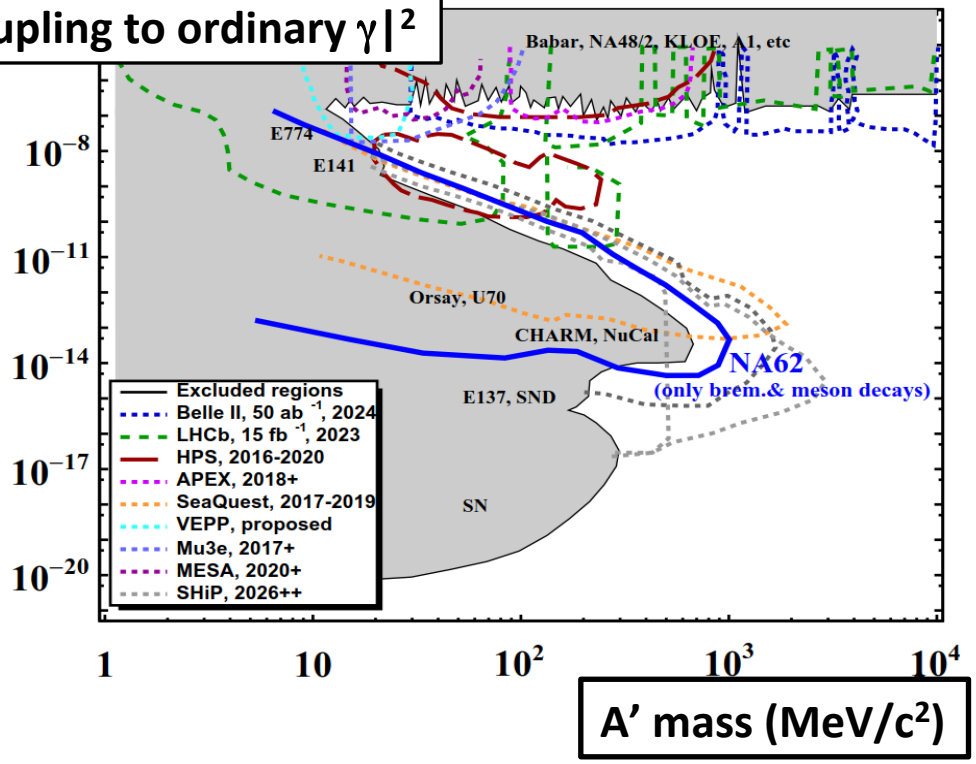
NA62 potential for A' visible decays

Assume 10^{18} 400-GeV POT :

Study DP production (meson decays, bremsstrahlung) from interaction onto **target**
search for DP-decay to ee, μμ in NA62 fiducial volume, account for geometrical acceptance
assume zero-background, evaluate expected 90%-CL exclusion plot

Sensitivity expected to be higher than shown:

1. including direct QCD production of A'
2. Including A' production in the dump (here, only target)



NA62 evaluation cross-checked with full MC

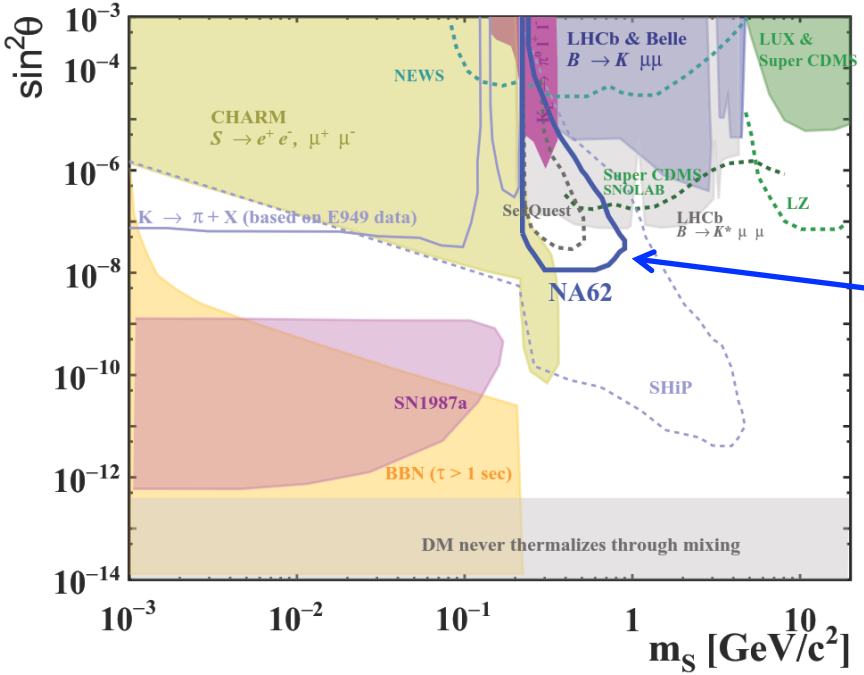
~3 10^{17} POT acquired in 2016/17 with di-muon parasitic trigger, 5 10^{16} POT with ee trigger

NA62 potential dark-scalar visible decays

Assume 10^{18} 400-GeV POT, sensitivity to hidden scalars charged decays

search for ee, μμ, ππ, KK two-track final states originating **at the TAX**

assume 0 background



NA62 projected sensitivity

dominated by beauty production

~3 10^{17} POT acquired in 2016/17 with di-muon parasitic trigger, 5 10^{16} POT with ee trigger

NA62 potential for HNL visible decays

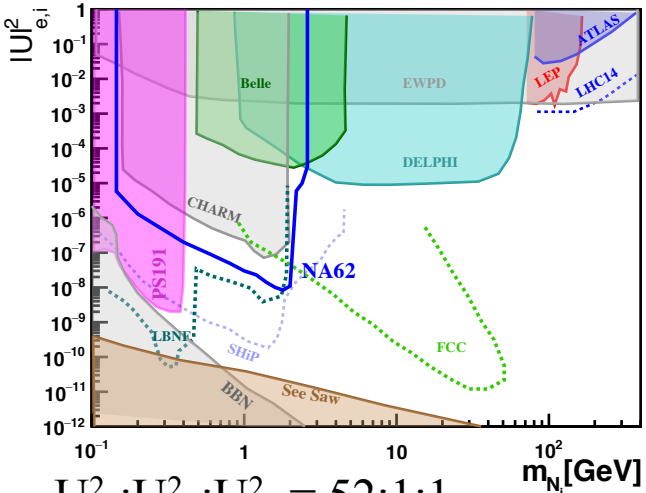
Assume 10^{18} 400-GeV POT:

search for two-track final states originating **at the TAX**

sensitivity includes open channels, assuming 0 background

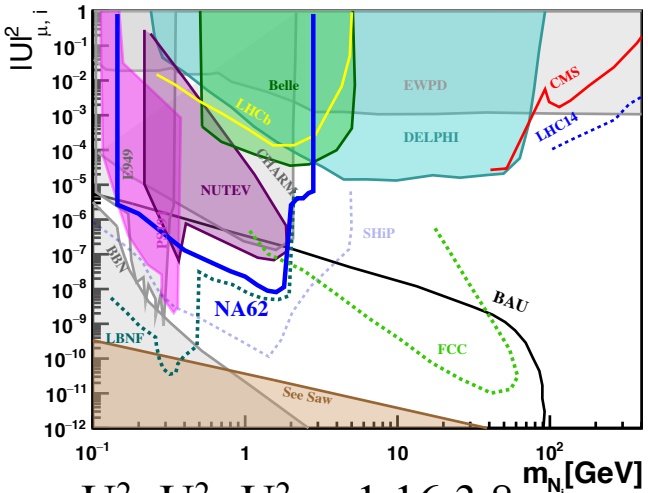
separately address 3 extreme coupling scenarios **[Shaposhnikov, Gorbunov arXiv:0705.1729v2]**

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



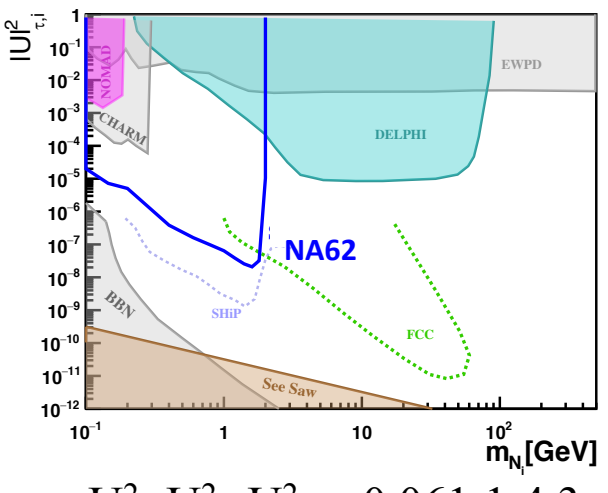
$U^2_e:U^2_\mu:U^2_\tau = 52:1:1$

Normal hierarchy of active **ν** masses



$U^2_e:U^2_\mu:U^2_\tau = 1:16:3.8$

Normal hierarchy of active **ν** masses



$U^2_e:U^2_\mu:U^2_\tau = 0.061:1:4.3$

Normal hierarchy of active **ν** masses

~10^{17} POT acquired in 2016/17 with μπ parasitic trigger, few 10^{16} POT with eπ trigger

On the zero-background assumption

Present sensitivity projections in the zero-background assumption

The standard beam setup corresponds to a flux of ~4.5 10^{-6} K^+ decays in FV per POT
previous signals: 2 opposite charged tracks from a vertex away from beam-line

Study one of the most relevant sources of background using data:
muons from the beam "halo" (very upstream π, K decays, μ from hadronic showers)
for the present K^+ beam, expects ~3 MHz μ^+ and ~150 KHz μ^- in the LKr acceptance

Test background rejection capability with present data searching for A' → $\mu\mu$
background from combinatorial pairing of halo muons

Trigger parasitic to $\pi\nu\nu$:
require 2 muons downstream (in time within 10 ns) & LKr Energy < 20 GeV
trigger efficiency included in DP sensitivity projection previously shown

Search for A' → μμ: test on 2016 data

Statistics shown here corresponds to ~**10^{15} POT**'s

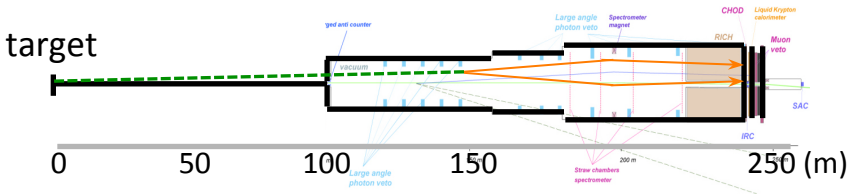
Track quality + acceptance cuts (forward detectors: CHOD, LKr, MUV3)

association with CHOD, LKr hits in time

Vertex quality:

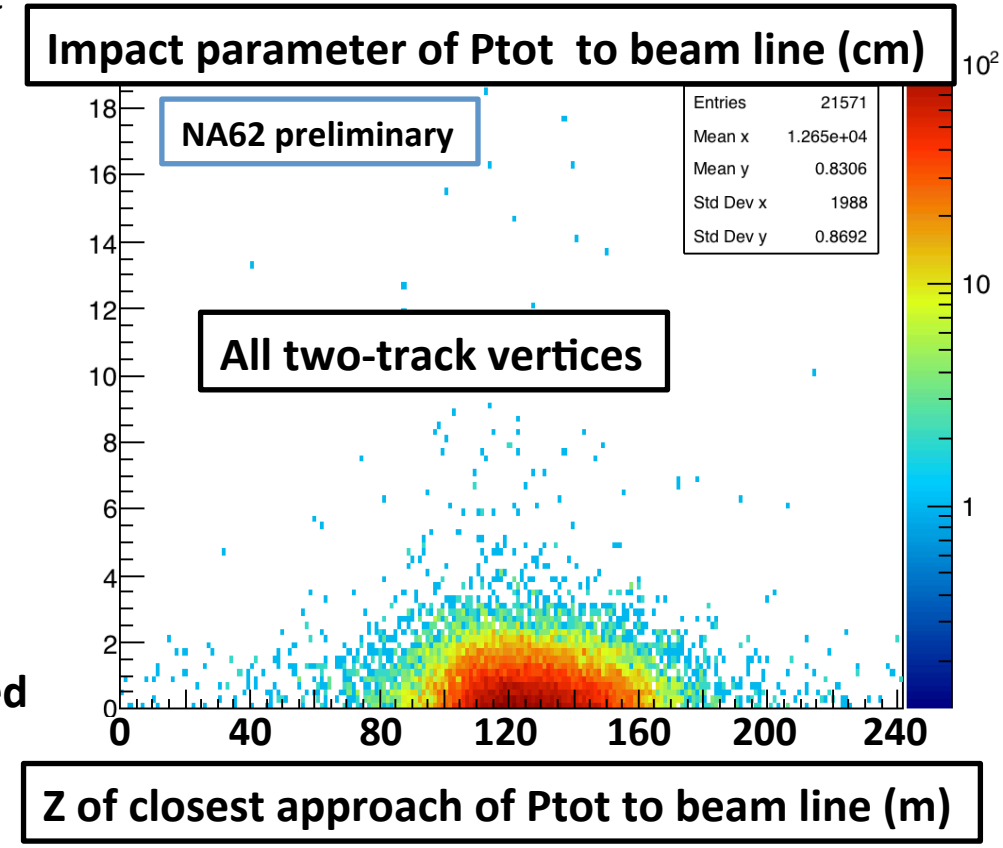
two-track distance < 1 cm

vertex position 105 < Z < 165 m



Test if total momentum stems from target

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



Search for A' → μμ: test on 2016 data

Track quality + acceptance cuts (forward detectors: CHOD, LKr, MUV3)

association with CHOD, LKr hits in time

Vertex quality:

two-track distance < 1 cm

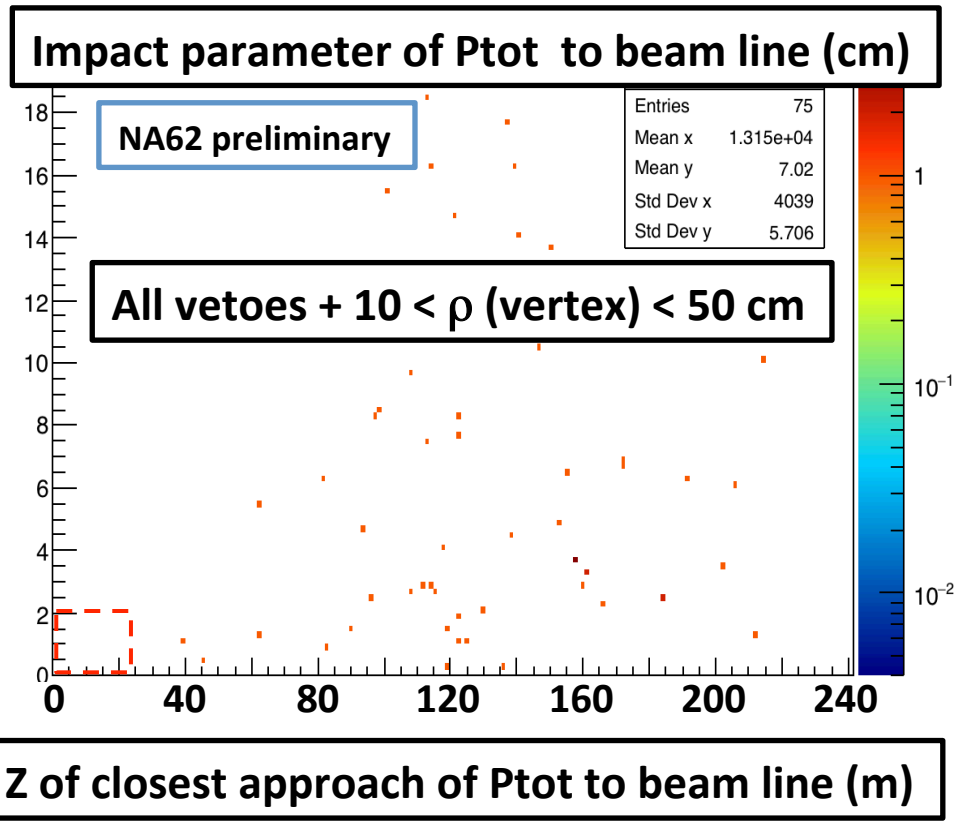
vertex position 105 < Z < 165 m

Test if total momentum stems from target

Further event-level veto conditions:

- Additional energy in the LKr < 2 GeV
- IRC SAC: no hits within +-5 ns
- LAV: no hits within +-5 ns
- CHANTI: no candidate within +-5 ns

No events selected in the signal region (even with standard K^+ beam) @ 10^{15} POT's



Background rejection proved **@10^{15} POT** in standard condition, **@4x10^{15} POT** in dump mode

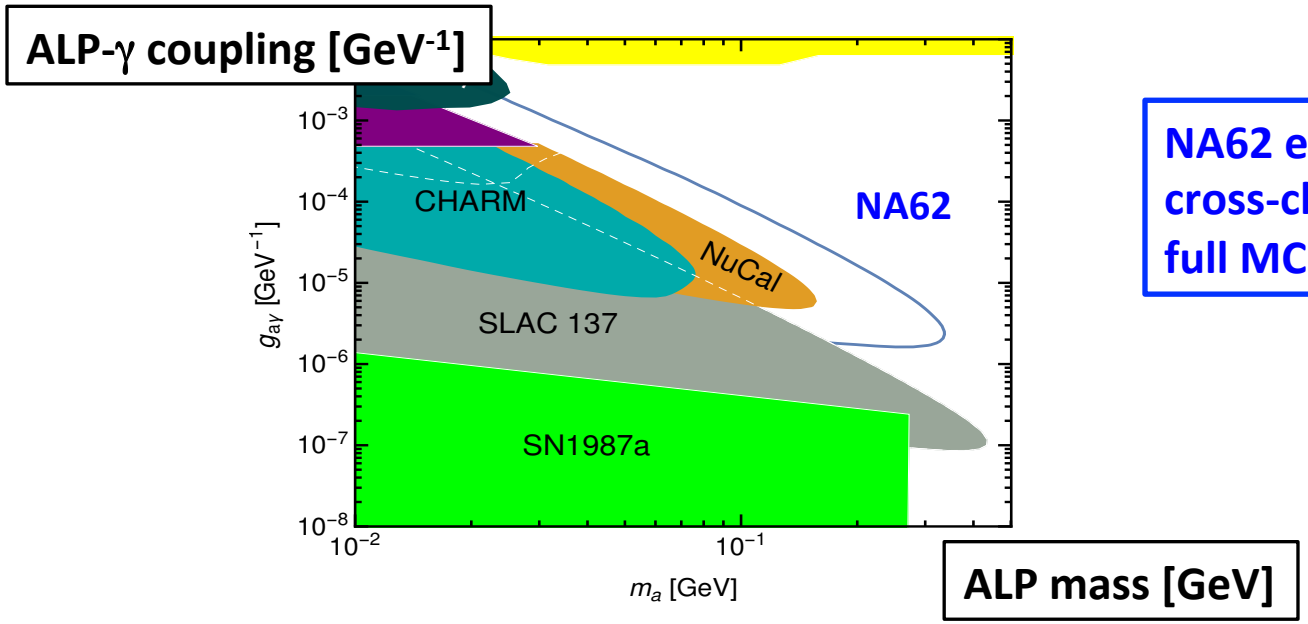
NA62 potential for ALP visible decays

Study ALP Primakoff production from interaction onto TAX + decay to γγ [JHEP 1602 (2016) 018]

γγ final state → search must be performed in real beam-dump mode: closed TAX

Assume 10^{18} 400-GeV POT :

search for ALP-decay to γγ in NA62 fiducial volume, account for geometrical acceptance
assume zero-background, evaluate expected 90%-CL exclusion plot



NA62 evaluation cross-checked with full MC

Improvements expected already with 1 day of run (1.3 10^{16} POT's)
Analysis of 2017 data for ~5x10^{15} POT's taken in "dump mode" in progress

Present NA62 exotic physics potential

Data from 2016-17 runs being analyzed, feasibility studies / first results:

1. Closed-TAX mode, present statistics ~6 x 10^{15} POT's:

- **ALP→$\gamma\gamma$ search**
- **Background estimate for a future beam-dump operation**

2. Low-bandwidth triggers parasitic to $\pi\nu\nu$:

- **Di-muons 3x10^{17} POT's, approaching allowed regions of parameter space (DP, scalar)**
- **Muon-Pion 10^{17} POT, useful for HNL search studies**
- **Di-electrons 5x10^{16} POT's, exploratory DP search**
- **Electron-Pion fewx10^{16} POT's, exploratory HNL search**

3. Searches parasitic to the $\pi\nu\nu$:

- **Dark photons from O(10^{12}) K^+ or O(10^{10}) π^0 decays**

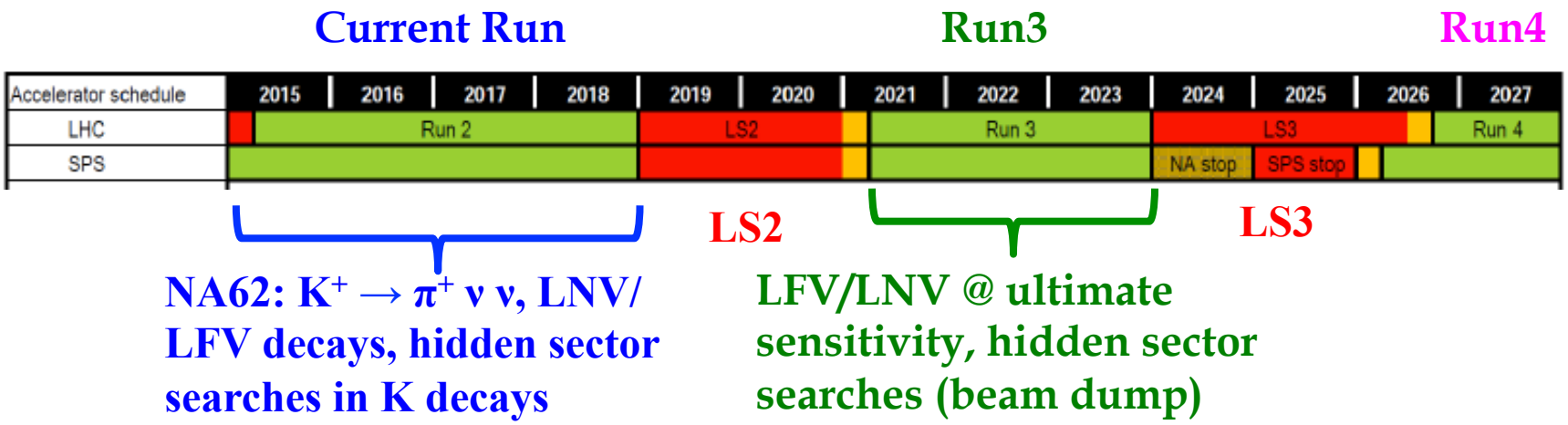
For 2018 run, new high-level trigger to improve sensitivity for long-lived states:

- **Possibility to reach O(10^{18}) POT in standard run conditions**

NA62 Run3 plan under discussion

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

0. **If needed, run for refining $\pi\nu\nu$ measurement, depending on measurement scenario**
1. **Present K^+ beam setup + dedicated runs: unprecedented LFV/LNV sensitivities from K^+/π^0**
2. **10^{18}-POT 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.**



Under study / definition, interaction/synergy with the Physics Beyond Collider CERN initiative

Conclusions

NA62 approved up to LS2 (2018) for measuring BR(K-> $\pi\nu\nu$) at 10%

Hidden-sector physics program before LS2:

- **$\pi\nu\nu$-parasitic triggers/searches → A', HNL production**
- **short dedicated beam-dump runs → search for ALP decay to $\gamma\gamma$**

After LS2, a year-long data-taking (10^{18} POT) in beam dump mode would provide sensitivity to various hidden-sector models:

- **Expected sensitivity beyond that of other initiatives in the same time range**
- **Preliminary studies suggest sufficient background rejection power**

The current NA62 run can be exploited to:

- **Evaluate background rejection capability up to ~10^{17} – 10^{18} POT's**
- **Define setup optimizations for future beam-dump mode including, if needed, minor modifications to the existing apparatus**