Perspectives from the NA62 experiment

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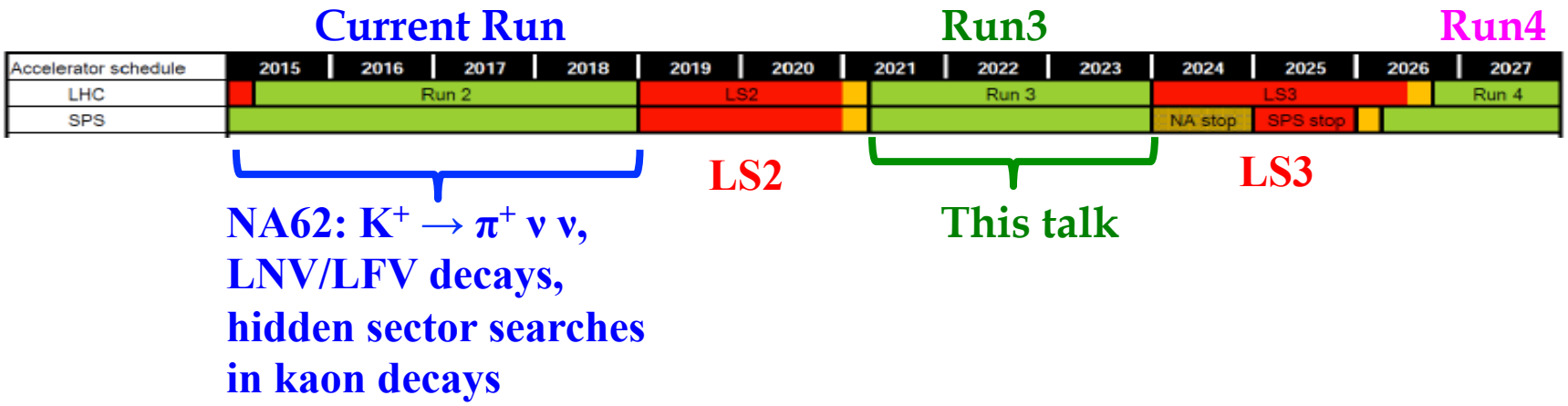
Introduction

NA62 experiment approved to run until LS2

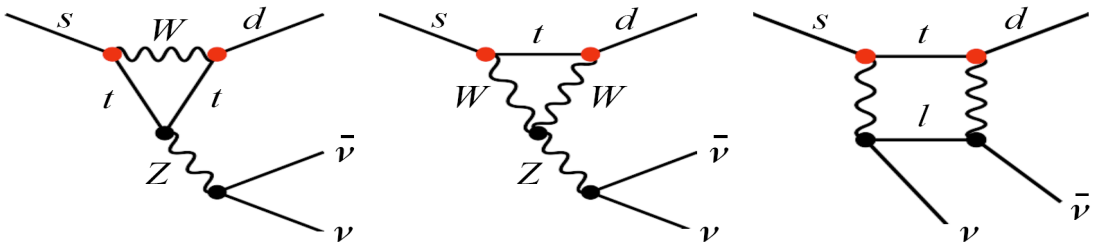
- **main goal**: measuring the BR($K^+ \rightarrow \pi^+ \nu$ anti-ν) with 10% accuracy;
- a broad physics program: searches for LFV/LNV modes, hidden sector particles

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



NA62 experiment: the goal

K → $\pi\nu\bar{\nu}$ decays: FCNC *s*--*d* loops, theoretically clean, sensitive to various NP models



SM prediction [Buras et al. arXiv:1503.02693, Brod, Gorbahn, Stamou, Phys.Rev.D 83, 034030 (2011)]:

$$\mathrm{BR}(K^+ \to \pi^+\nu\bar{\nu}) = (8.39 \pm 0.30)\cdot 10^{-11}\left(\frac{|V_{cb}|}{0.0407}\right)^{2.8}\left(\frac{\gamma}{73.2^\circ}\right)^{0.74} = (8.4 \pm 1.0)\cdot 10^{-11}$$

$$\mathrm{BR}(K_L \to \pi^0\nu\bar{\nu}) = (3.36 \pm 0.05)\cdot 10^{-11}\left(\frac{|V_{ub}|}{0.00388}\right)^{2}\left(\frac{|V_{cb}|}{0.0407}\right)^{2}\left(\frac{\sin\gamma}{\sin 73.2}\right)^{2} = (3.4 \pm 0.6)\cdot 10^{-11}$$

Experimental status:

$\mathrm{BR}(K^+ \to \pi^+\nu\bar{\nu}) = \left(17.3^{+11.5}_{-10.5}\right)\times 10^{-11}$ Phys. Rev. D 77, 052003 (2008), Phys. Rev. D 79, 092004 (2009)

$\mathrm{BR}(K_L \to \pi^0\nu\bar{\nu}) < 2.6\times 10^{-8}$ (90% C. L.) Phys. Rev. D 81, 072004 (2010)

NA62 goal: measure BR($K^+ \to \pi^+\nu\bar{\nu}$) with O(10%) total uncertainty

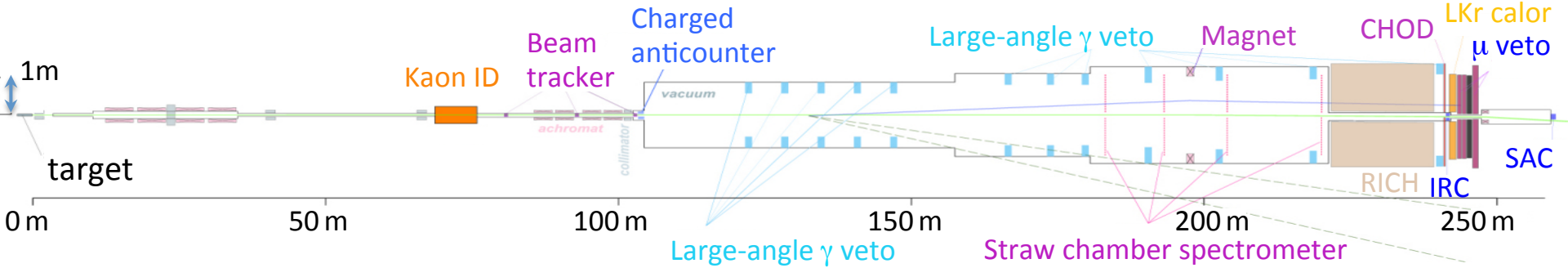
NA62: a high-intensity setup

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**

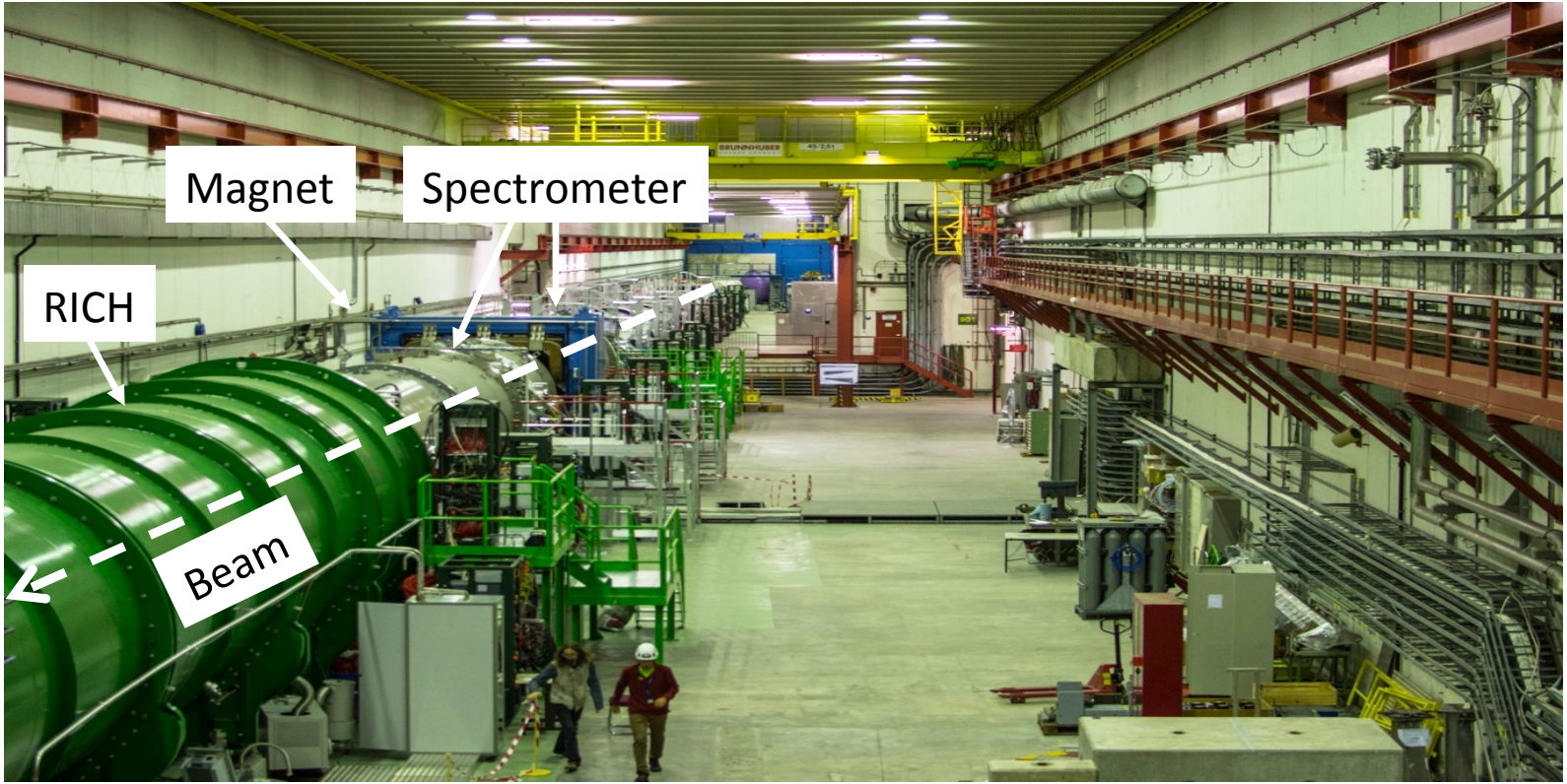
Excellent time resolution to match beam and daughter particle information

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



Status/timescale for $K \rightarrow \pi\nu\nu$

Run in 2015:

Commissioning of L0 trigger

Run up to nominal intensity, 3.3 10^{12} POT/spill, 3.5-s effective-length spill

Running in 2016:

Stable running at 20% of the nominal beam intensity

Data already collected: sensitivity to BR($K \rightarrow \pi\nu\nu$) up to 10^{-9}

End of 2016: reach SM-expectation sensitivity, **O(10^{-10})**

End of 2017 run: improve (by much) on present state of the art (BNL measurement)

End of 2018 run: measurement of BR at 10%

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

Such high-intensity, high-performance setup might be suited for other NP searches

- LFV/LNV studies with 10^{13} K^+ → SES 10^{-12}, improve by ~x100 on past results
- ultra-rare/forbidden π^0 decays, 10^{11} tagged π^0's → SES 10^{-10}, improve by ~x100
- chiral perturbation theory studies from other 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 (max 1 MHz)

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

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

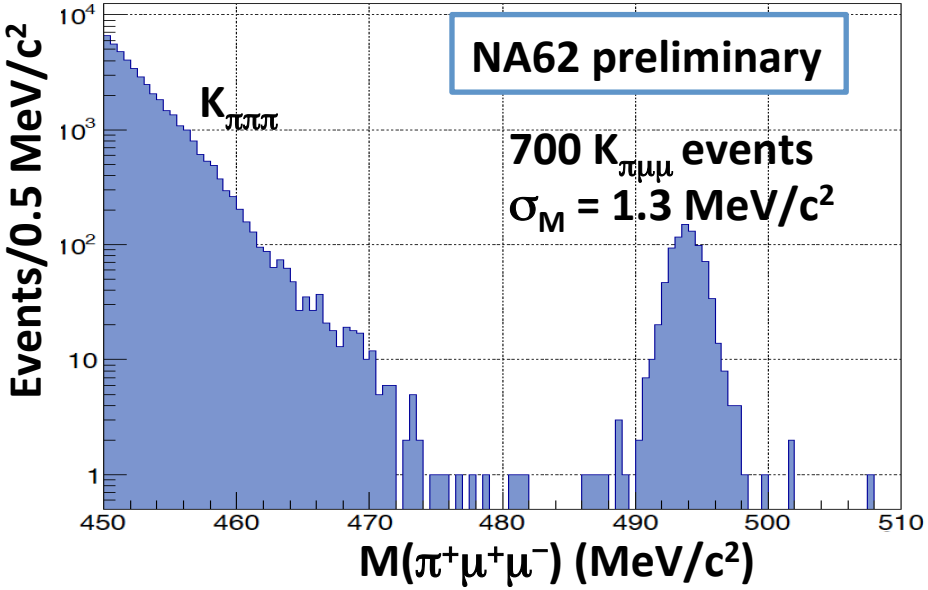
… others because can be made in parasitic mode with the main trigger:

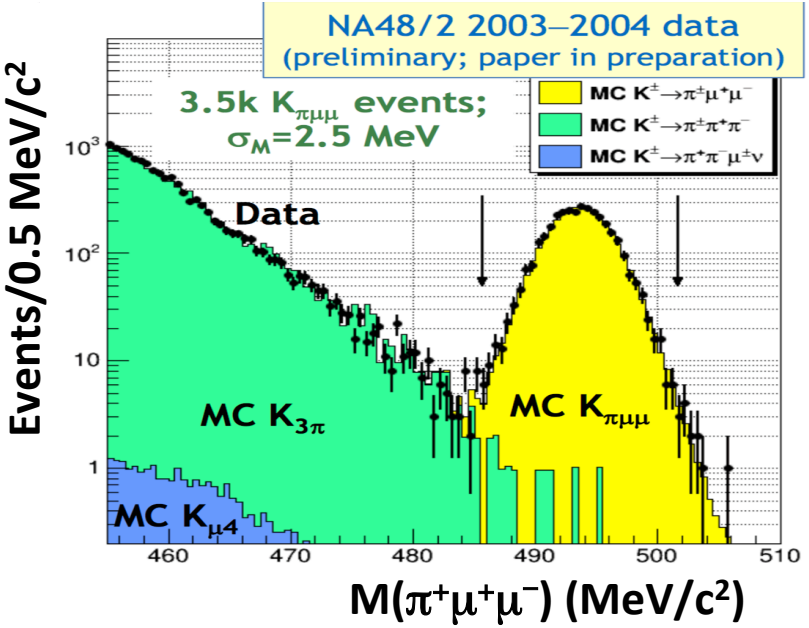
- search for heavy neutral leptons in $K^+ \rightarrow \mu^+ \nu_h$, $K^+ \rightarrow e^+ \nu_h$
- search for $\pi^0 \rightarrow \nu_1 \nu_2$, NA62 sensitive to BR($\pi^0$ → invisible) at 10^{-8} or better

An example from a dedicated trigger: $K \rightarrow \pi^+\mu^+\mu^-$

Sample from 2016 data: ~60k bursts (~2 week-equivalent) at ~18% intensity

- **Improvements on NA48/2: mass resolution better by ~ a factor of 2**
- **BR is $O(10^{-7})$, expects improved sensitivity on hidden sector search, $K \rightarrow \pi^+ \chi$, $\chi \rightarrow \mu^+\mu^-$**
- **Basis for the search for LNV decay $K \rightarrow \pi^-\mu^+\mu^+$**





Physics at NA62 in Run 3

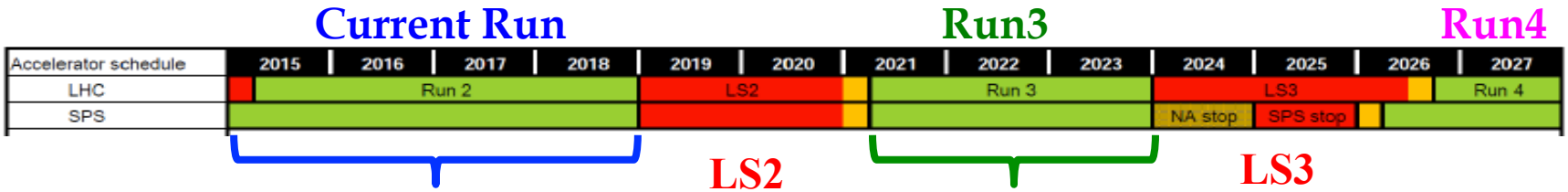
A rich field to be explored with minimal/no upgrades to the present setup

1. Present setup for K^+ beam + dedicated triggers: complete LFV/LNV high-sensitivity studies based on K^+/π^0:

$K^+ \to \pi^+\mu^\pm e^\mp$, $K^+ \to \pi^-\mu^+e^+$, $K^+ \to \pi^-e^+e^+$, $K^+ \to \pi^-\mu^+\mu^+$ (+ radiative modes)

$\pi^0 \to \mu e$, 3γ, 4γ, ee, $eeee$

2. 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: $K^+ \to \pi^+ \nu \nu$, 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:

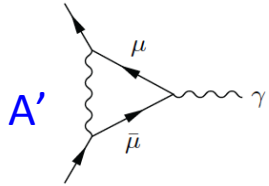
search for non-gravitational interactions DM-SM

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..

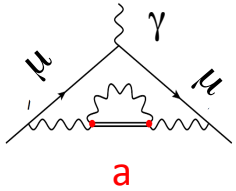
Various experimental hints for hidden sector at MeV-GeV, e.g., a_μ 3.5-σ discrepancy**:**

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}

NA62 perfectly suited for hidden sector searches

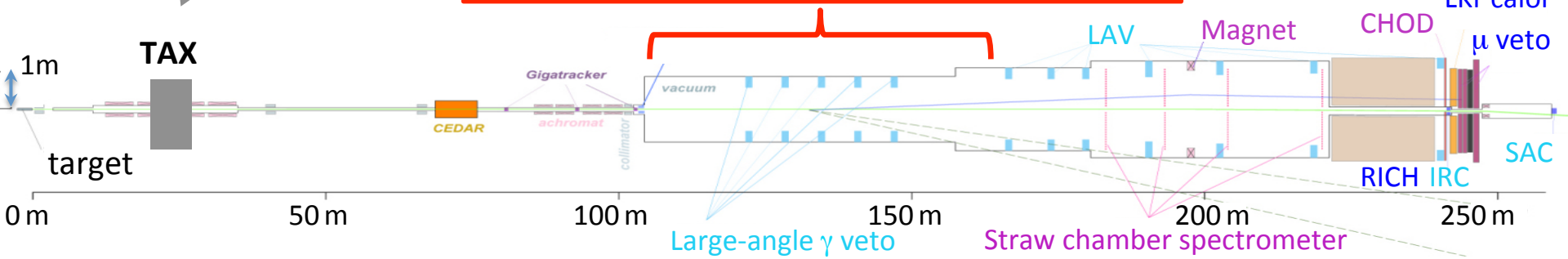
High-intensity 400-GeV proton beam → boost charm/beauty, other meson production

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: ~11 λ_I Cu-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

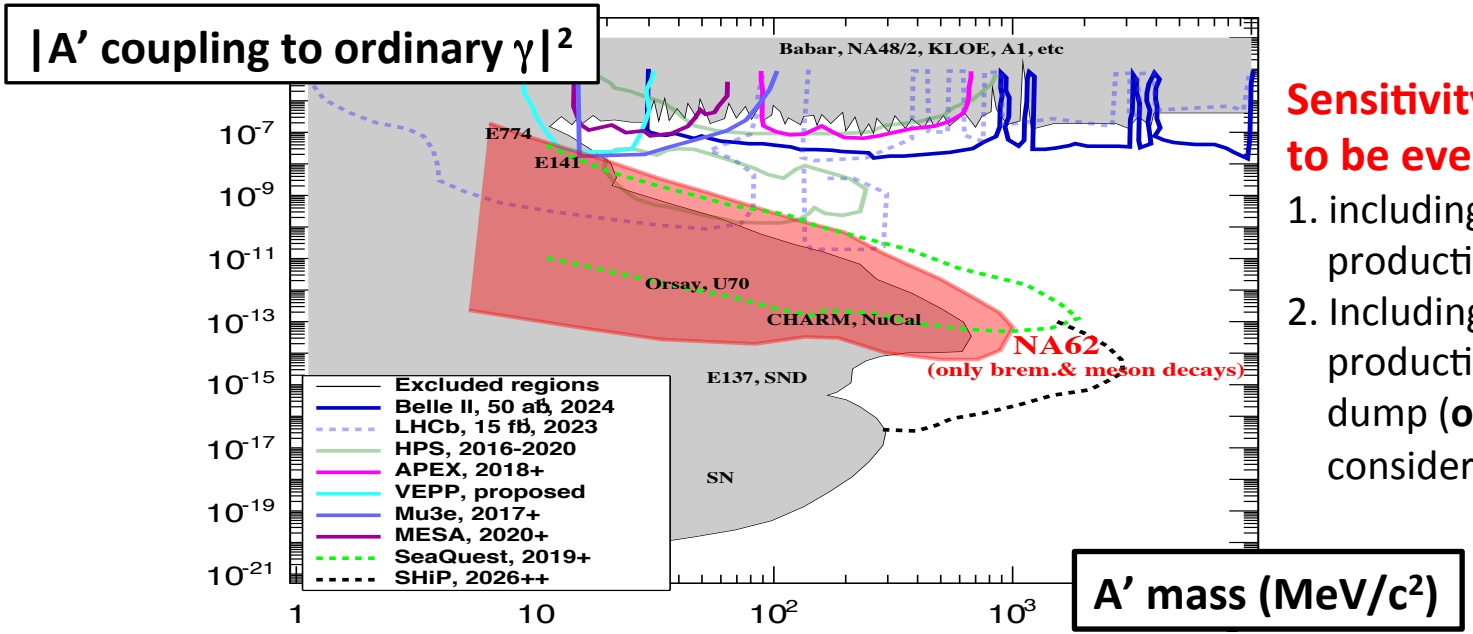
Search for visible decays of long-lived A'

Assume 2x10^{18} 400-GeV POT:

search for displaced, dilepton decays of dark photons, A' → ee, μμ

include trigger/acceptance/selection efficiency

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



Sensitivity expected to be even higher:

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

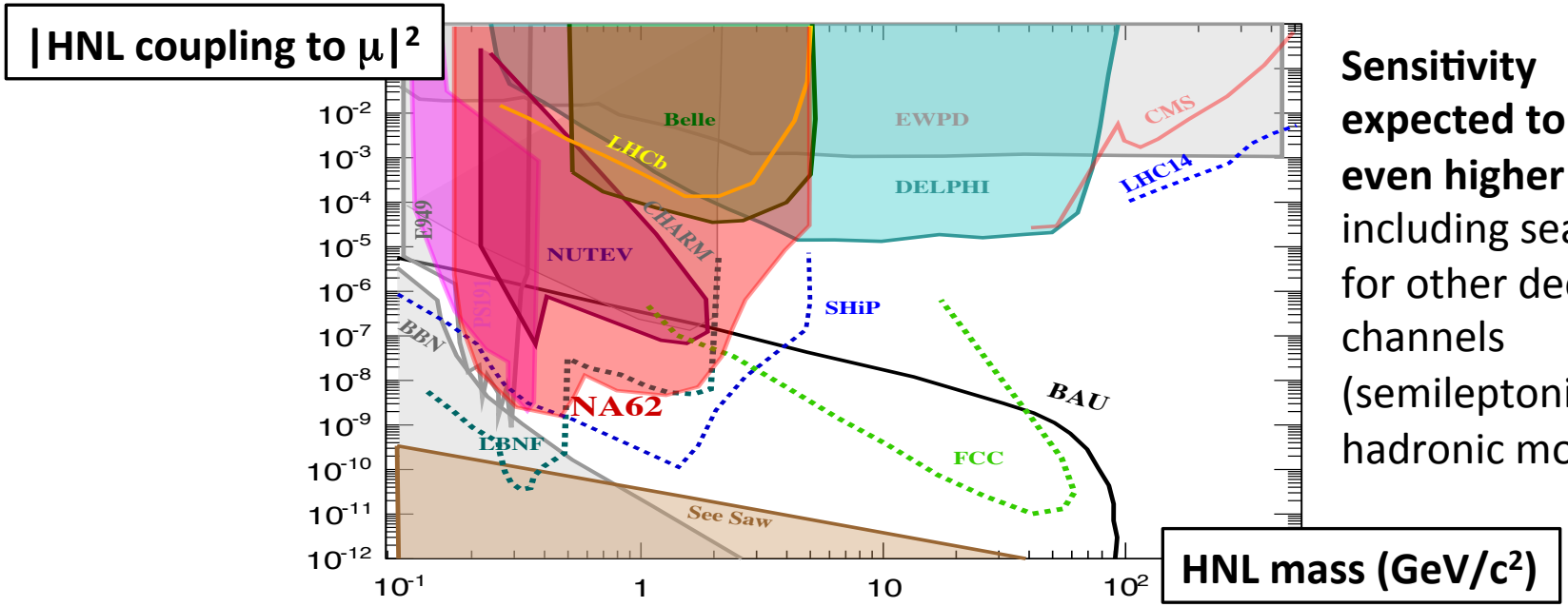
Search for visible decays of heavy neutral leptons

Assume 2 10^{18} 400-GeV POT:

search for displaced, leptonic decays HNL → πe, $\pi\mu$

include trigger/acceptance/selection efficiency

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



Sensitivity expected to be even higher after including search for other decay channels (semileptonic, hadronic modes)

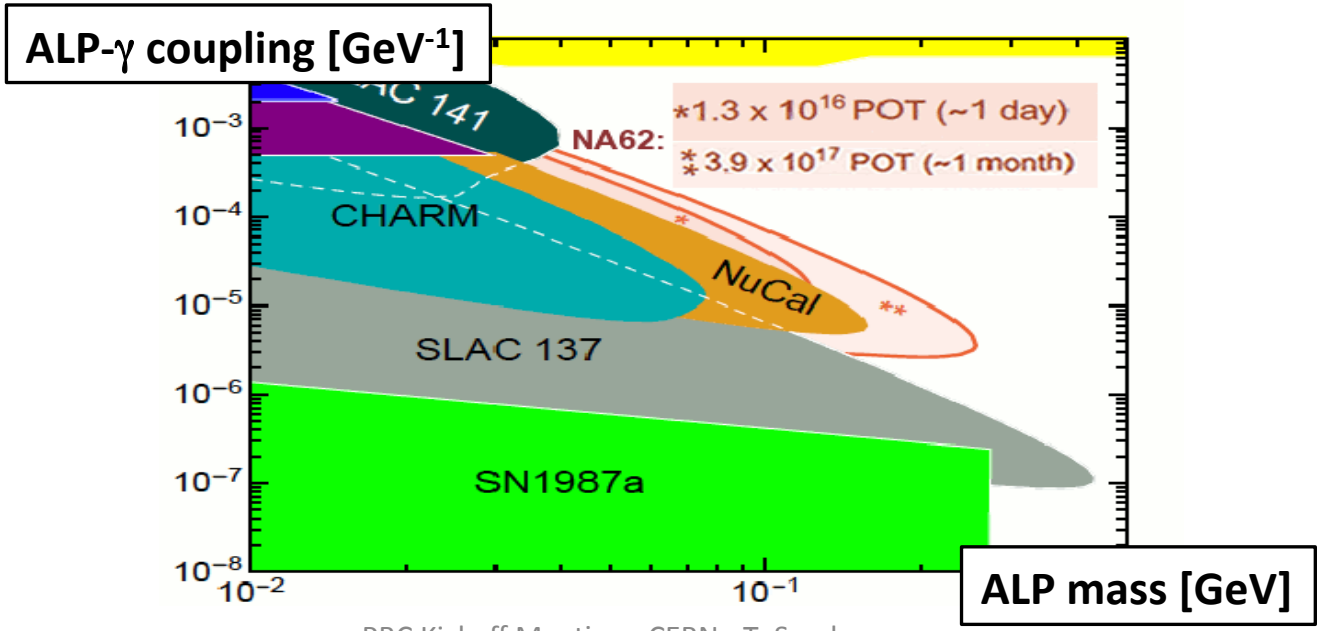
Search for visible decays of ALP's

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 γγ in NA62 fiducial volume, account for geometrical acceptance

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



On the zero-background assumption

Present sensitivity projections in the zero-background assumption

Study one of the most relevant sources of background using data:

muons from the beam "halo" (very upstream π, K decays)

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 sensitivity projections previously shown

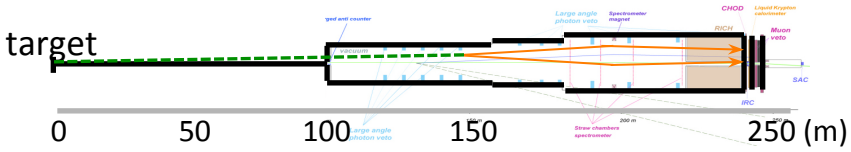
Search for A' → μμ: test on 2016 data

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

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

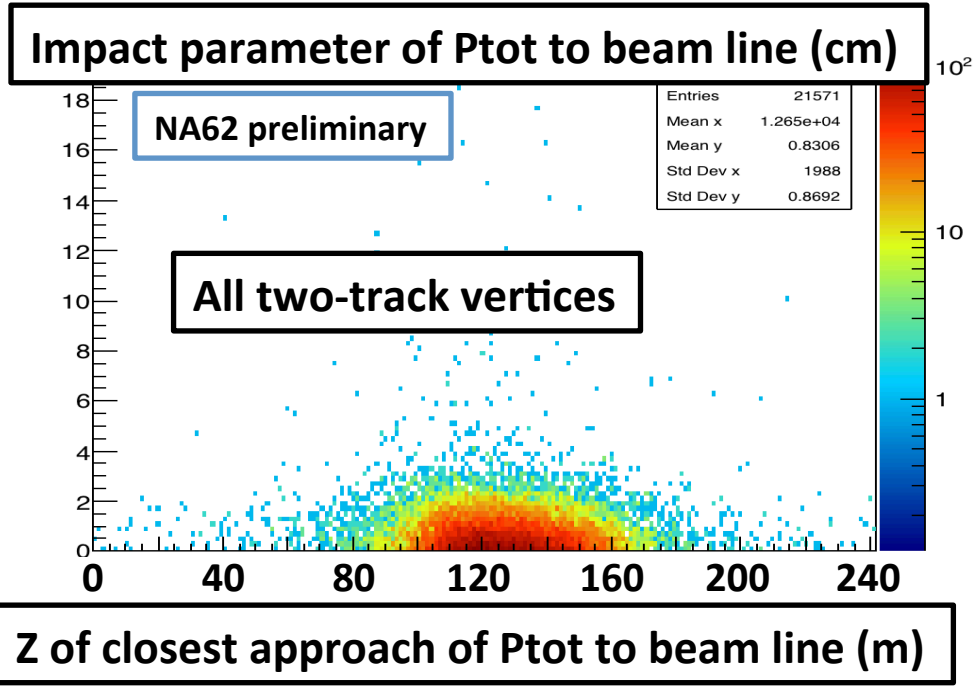
Vertex quality: two-track distance < 1 cm

Vertex position: 105 < Z < 165 m



Test if total momentum stems from target

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



Search for A' → μμ: test on 2016 data

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

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 stems from target

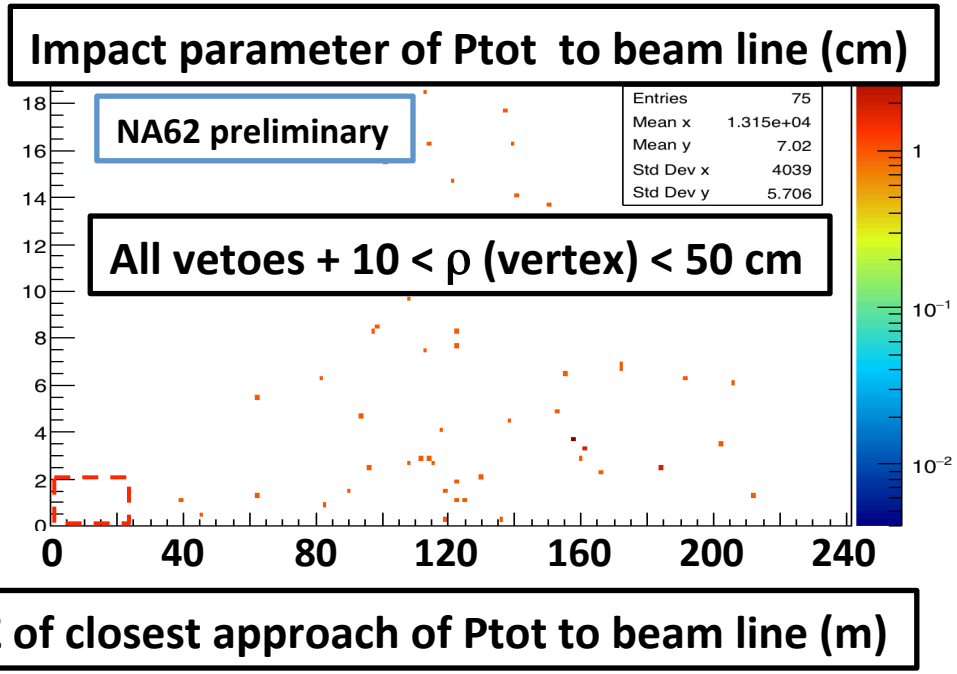
Further event-level veto conditions:

Additional energy in the LKr < 2 GeV

Veto on forward / large angle calorimeters

Veto on charged anti counter

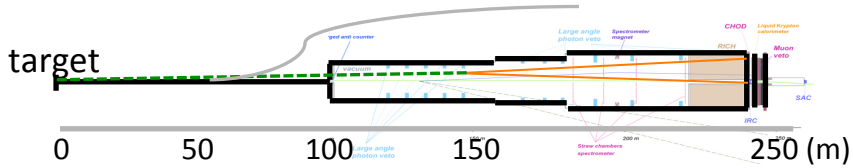
No events selected in the signal region (even with standard K^+ beam)

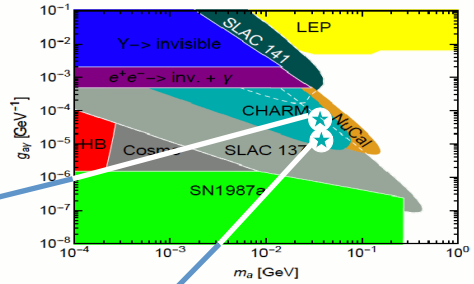


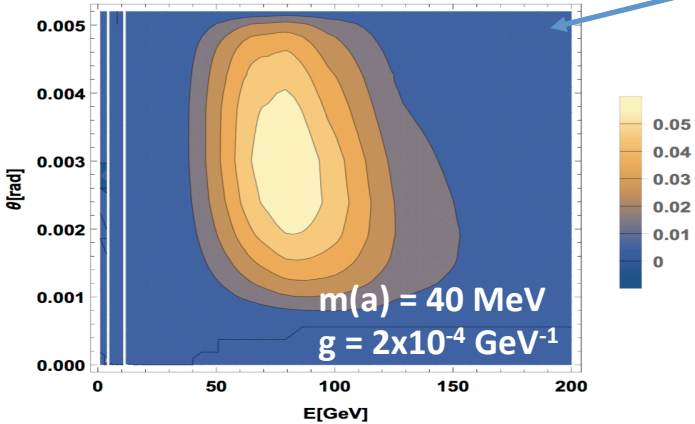
MeV-GeV ALP at NA62: test with 2015 data

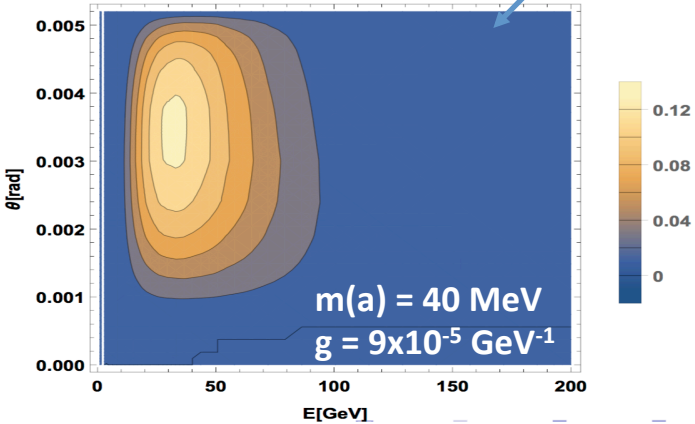
Data from a few-hour run with closed tax at full intensity: ~10^{14} POT's

Use correlation of ALP energy and θ angle for background rejection









Result: can achieve the zero-background limit

Conclusions: physics at NA62 after LS2

Assuming fulfillment of main goal, BR(K-> $\pi\nu\nu$), a broad physics program at NA62 after LS2

1. Present K^+ beam and dedicated triggers for one-year-long data taking :

- **LFV and LNV to SES ~ 10^{-12} from K and π^0 decays**
- **Ultra-rare/forbidden π^0 decays**

2. Year-long data-taking (10^{18} POT) in beam dump mode provides sensitivity to NP models:

- **Dark photons, Heavy Neutral Leptons, Axion-like particles, etc.**

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

Data demonstrate background rejection power for the searches proposed, up to 10^{15} POT's

The current NA62 run will be exploited to:

- **evaluate background rejection capability up to ~10^{17} – 10^{18} POT's**
- **understand how to optimize design for future beam-dump mode including, if needed, minor modifications to the existing apparatus**

Spare slides

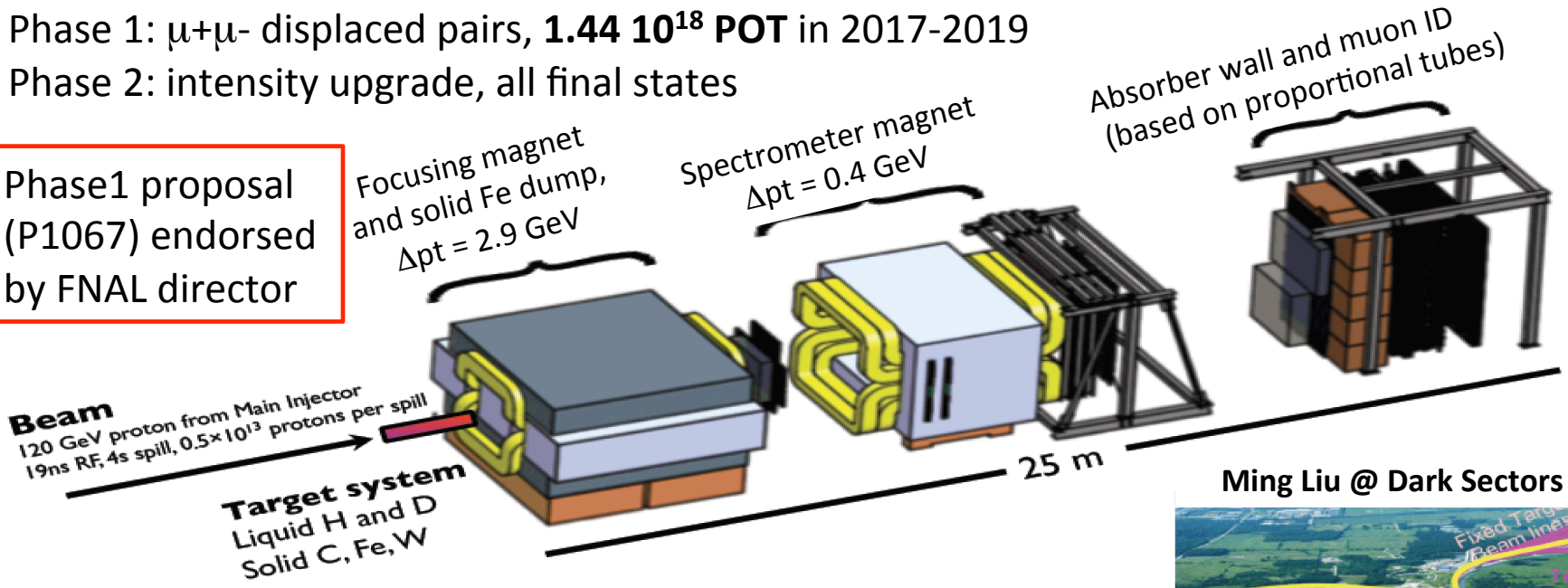
Future visible A' search: SeaQuest @FNAL

SeaQuest: 120-GeV p beam from FNAL main injector

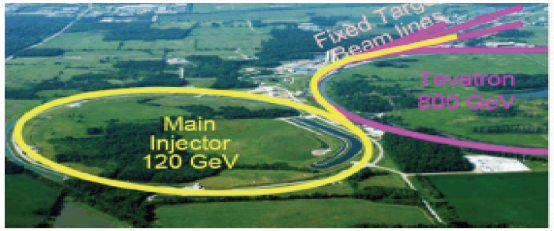
Phase 1: μ+μ- displaced pairs, **1.44 10^{18} POT** in 2017-2019

Phase 2: intensity upgrade, all final states

Phase1 proposal (P1067) endorsed by FNAL director



Ming Liu @ Dark Sectors 2016



Present/future of MeV-GeV A’

Vector portal: visible search

Name	Where	Source	Intensity	Production mode	Detection mode	Status
Belle-II	Super KEK-B	$e^+e^- \to \Upsilon(3S)$	> 100 fb^{-1} @ $\Upsilon(3S)$	$\Upsilon(3S) \to \gamma A'$	$A' \to e^+e^-, \mu^+\mu^-$	Commis. 2018
Apex	JLAB	e^-, 2 GeV	10^9 EOT (W)	A'-strahlung	$A' \to e^+e^-$	Commis. 2018
HPS	CEBAF12 @ JLAB	e^-,1-2 GeV	10^{14} EOT (W)	A'-strahlung	$A' \to e^+e^-$	Running 2016-20
MAGIX	MESA @ Mainz	e^-, 155 MeV	10^{16} EOT (Xe gas)	A'-strahlung	$A' \to e^+e^-$	Commis. 2020
Mu3e	πE5 line @ PSI	μ^-, 28 MeV	10^{15-16} μ^-	$\mu \to \nu\nu A'$	$A' \to e^+e^-$	Commis. 2017
ATLAS/CMS	LHC @CERN	pp 8, 13 TeV	few fb^{-1}	$H \to 4l$ + MET	$A' \to \mu^+\mu^-$	Running
LHCb	LHC @CERN	pp,13 TeV	15 fb^{-1}	$D^* \to DA'$	$A' \to e^+e^-, \mu^+\mu^-$	Running
NA62	SPS @CERN	p, 400 GeV	2 10^{18} POT	Meson, A'-strahlung	$A' \to e^+e^-, \mu^+\mu^-$	Running –2018
SeaQuest	Main Inj. @ FNAL	p, 120 TeV	1.5 10^{18}	Meson, A'-strahlung	$A' \to \mu^+\mu^-$	Proposed 2017–19
SHiP	SPS @CERN	p, 400 GeV	2 10^{20} POT	Meson, A'-strahlung	$A' \to e^+e^-, \mu^+\mu^-$	Proposed 2026

Vector portal: invisible search

Babar	PEP-II @ SLAC	$e^+e^- \to \Upsilon(3S)$	57 fb^{-1}	$\Upsilon(3S) \to \gamma A'$	Single-γ trigger	ICHEP 2016
VEPP-3	VEPP-3 @ Budker Inst.	e^+, 500 MeV	1.5 MHz $\gamma\gamma$	$e^+e^- \to A'\gamma$	detect $\gamma + M_{\rm miss}$	Proposed
PADME	BTF @ Frascati INFN	e^+, 550 MeV	15 Hz $\gamma\gamma$	$e^+e^- \to A'\gamma$	detect $\gamma + M_{\rm miss}$	Approved, 2017-19
MMAPS	CESR @ Cornell	e^+, 5.3 GeV	2.2 MHz $\gamma\gamma$	$e^+e^- \to A'\gamma$	detect $\gamma + M_{\rm miss}$	Not funded
NA64	SPS @ CERN	e^-, 100 GeV	$e^-N \to e^-NA'$	10^9–10^{12} EOT	detect $e^- + E_{\rm miss}$	Running, 2016-17
LDMX	LCLS-II @ SLAC	e^-, 4 GeV	$e^-N \to e^-NA'$	10^{15}–10^{16} EOT	detect $e^- + E_{\rm miss}$	Proposed, 2020

Vector portal: DM search

SBND	FNAL	p, 9 GeV	2 10^{20} POT	Meson, A'-strahlung $A' \to \varphi\varphi$	detect ϕ @ 110 m	Under study
T2K	Tokai-Kamioka	p, 30 GeV	10^{21} POT	Meson, A'-strahlung $A' \to \varphi\varphi$	detect ϕ @ 280 m	Running
COHERENT	SNS @ Oak Ridge	p, 1 GeV	10^{23} POT	Meson, A'-strahlung $A' \to \varphi\varphi$	detect ϕ @ 20 m 2°-OA	Proposed
SHiP	SPS @CERN	p, 400 GeV	2 10^{20} POT	Meson, A'-strahlung $A' \to \varphi\varphi$	detect ϕ @ 100 m	Proposed 2026
LBNF	DUNE @FNAL	p, 120 GeV	3 10^{21} POT	Meson, A'-strahlung $A' \to \varphi\varphi$	detect ϕ @ 500 m	Under study 2020

Some of the above will address neutrino portal, too: neutrino experiments, NA62, SHiP

Some of the above will address ALP portal, too: NA62, SHiP

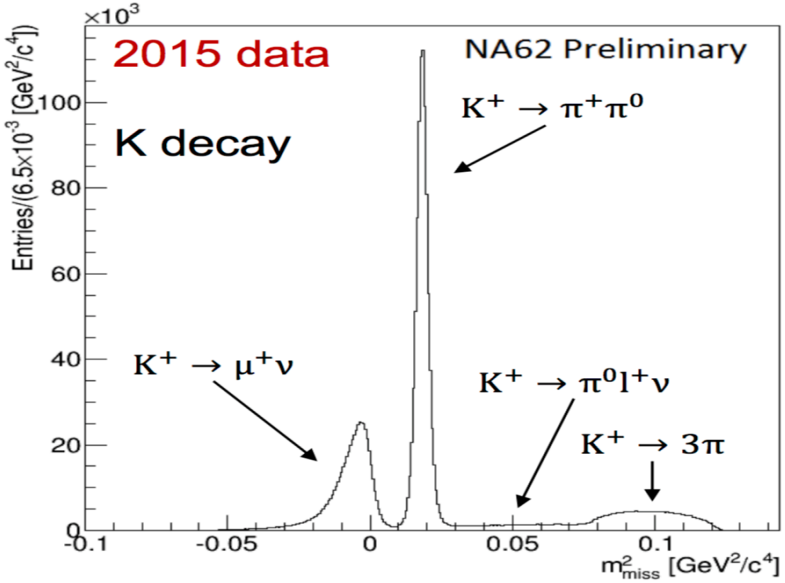
How to identify open-signature $K \rightarrow \pi\nu\nu$

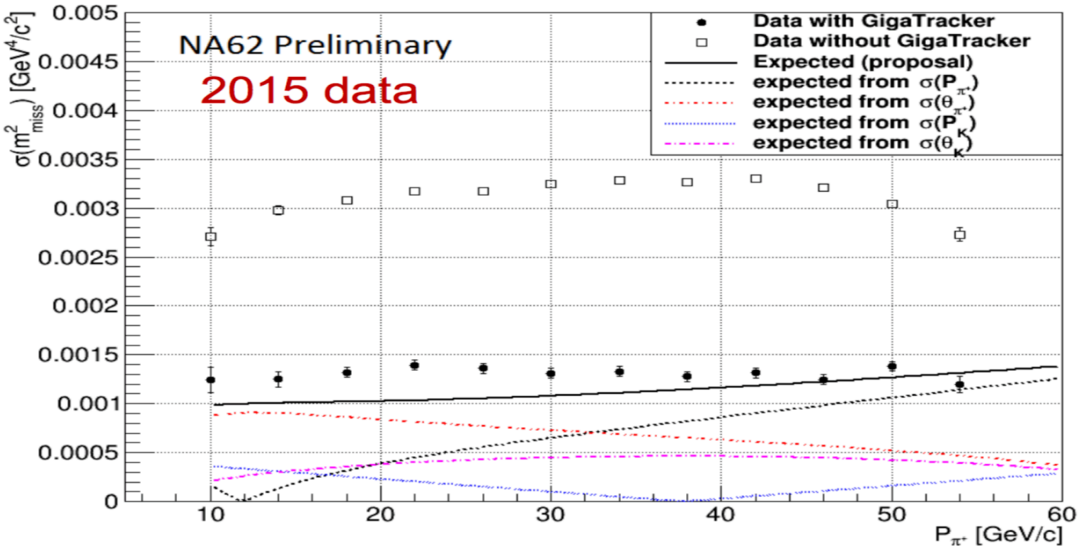
1. Kinematics, rejection of main K modes 10^4—10^5 via kinematic reconstruction:

75 GeV K decay to low-momentum $15 < p < 35$ GeV daughter pion, **both** tracked

Si-based stations upstream (GTK): $\sigma(p_K)/p_K \sim 0.2\%$, $\sigma(\theta_K,\phi_K) \sim 16\ \mu$rad

Straw-tubes in-vacuum downstream: $\sigma(p_\pi)/p_\pi < 1\%$, $\sigma(\theta_\pi,\phi_\pi) \sim 60\ \mu$rad





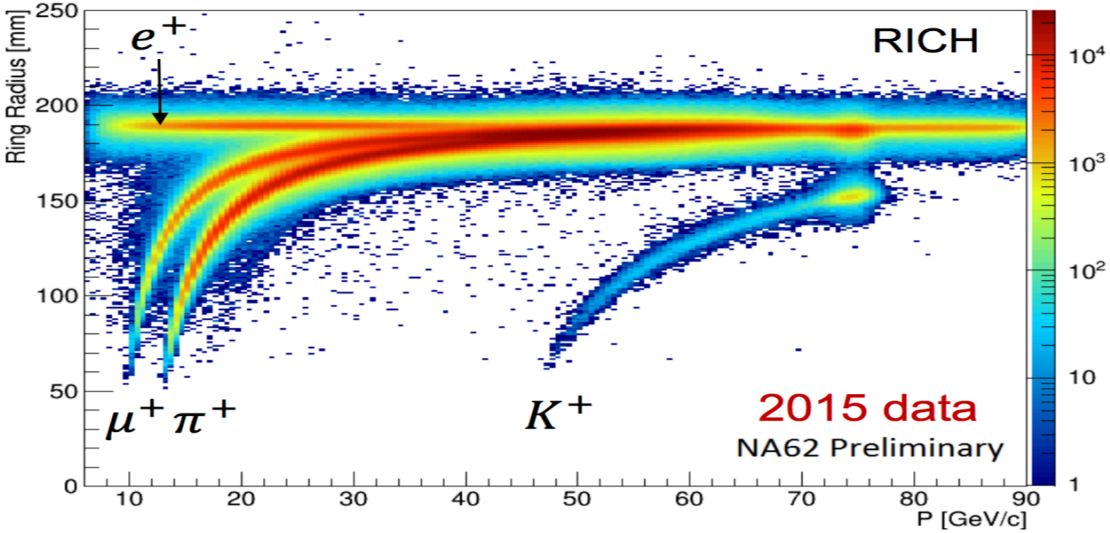
How to identify open-signature K→πνν

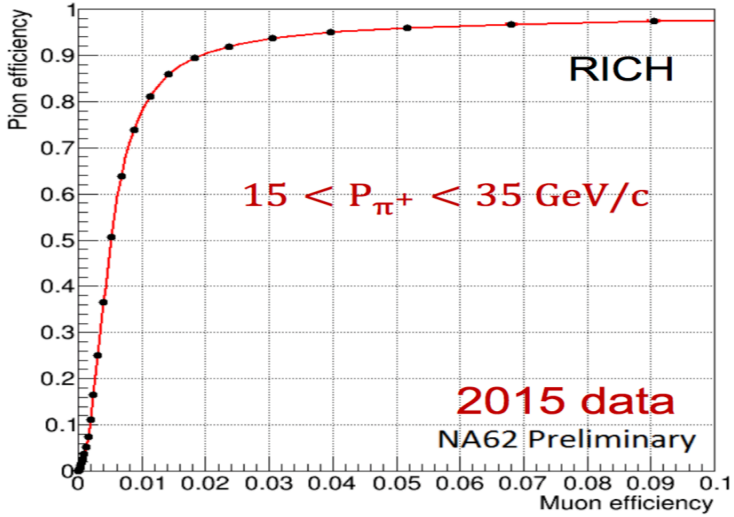
2. PID capability, μ vs π rejection of O(10^7):

better rejection in the low-momentum range, 15 < p < 35 GeV

10^2 from RICH with efficiency of 80%

10^4—10^6 from calorimeters with efficiency 90%—40%





How to identify open-signature $K \rightarrow \pi\nu\nu$

3. Hermetic, high-energy veto of additional photons:

10^8 rejection of π^0's: p <35 GeV → E(π^0) > 40 GeV

Three systems covering angle range θ < 50 mrad: LAV, LKr, IRC/SAC