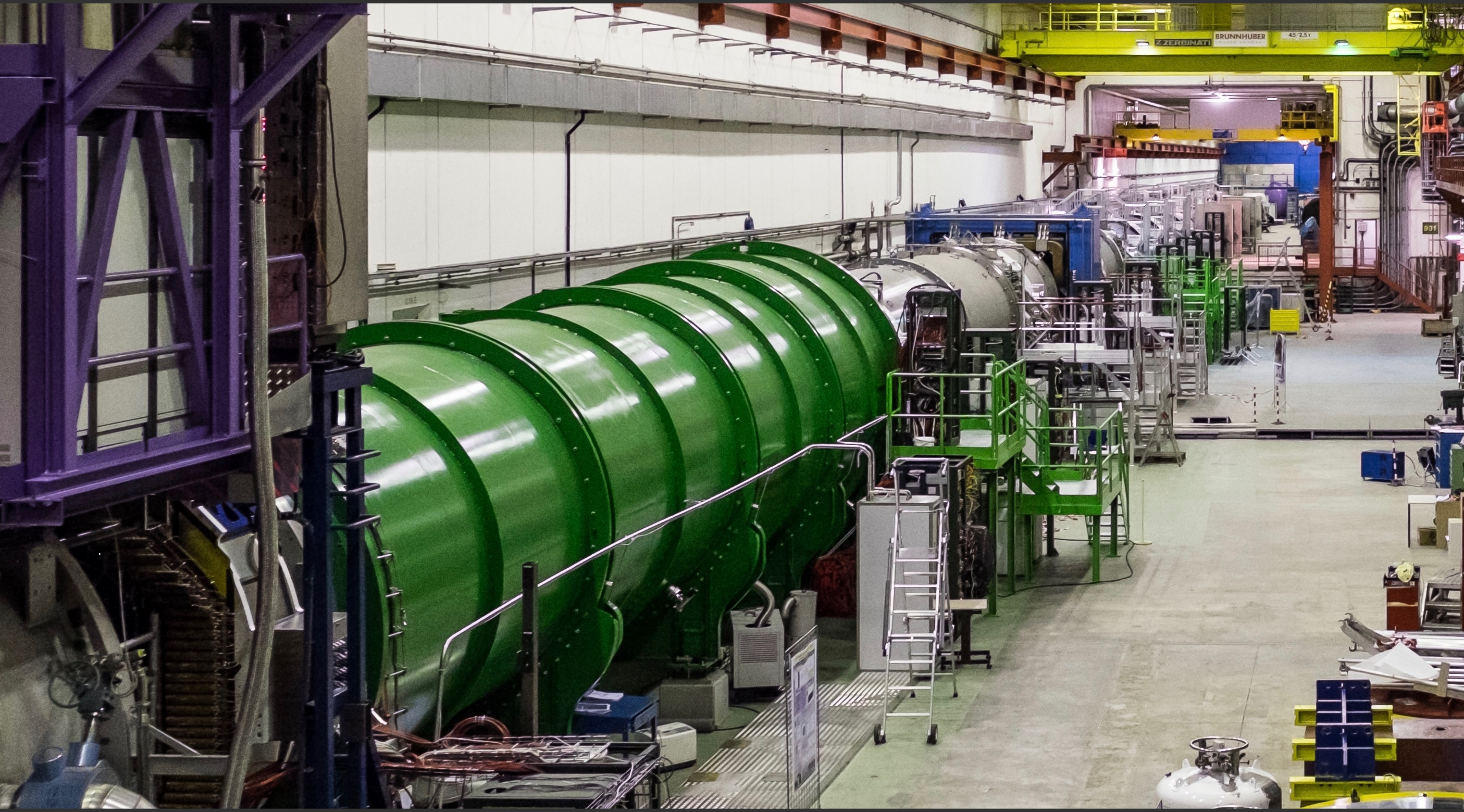
Searches for exotic particles at NA62



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Why search for exotic particles?

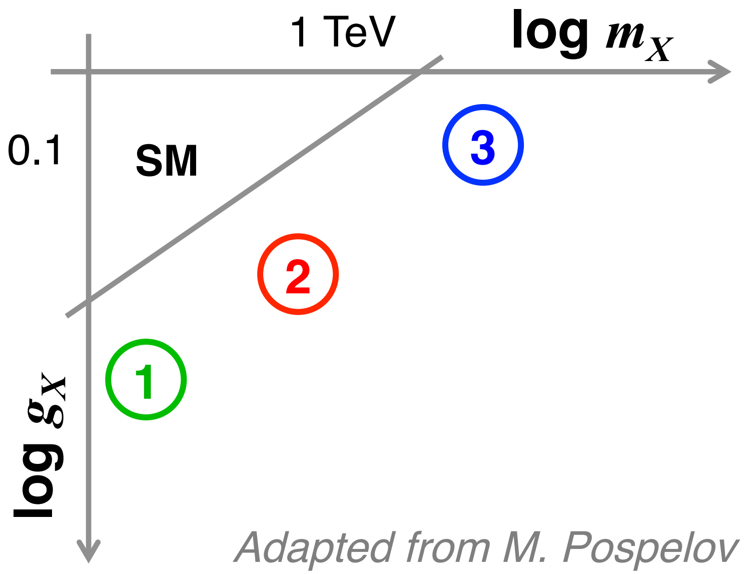
No hints of new physics at high energy so far?

- Strong constraints on SUSY, extra dimensions, technicolor, etc.
- Constraints on new Z' bosons push new gauge groups into multi-TeV territory

Yet, SM is obviously incomplete:

- **Neutrino masses and oscillations**
  - See-saw mechanism with RH neutrinos with masses from 10^{-9} to 10^{15} GeV, with Yukawa couplings to the Higgs and SM leptons?
- **Matter-antimatter asymmetry**
  - Requires violation of baryon number, C, and CP in the early universe. Not enough non-equilibrium CP violation in the SM to explain it.
- **Dark Matter**
  - SM particles alone cannot account for the observed matter in the universe
  - Masses for viable DM candidates: 10^{-31} GeV (ultralight scalars) to 10^{20} GeV (black holes) (10 keV to 100 TeV if from thermal origin)
- **Strong CP problem**
  - Apparent conservation of CP in QCD requires fine tuning
  - Axion (pseudo-Goldstone boson of spontaneously broken Peccei-Quinn symmetry) may resolve strong CP problem while providing DM candidate

Searches for exotic particles



Adapted from M. Pospelov

Distinguish searches by mass scale:

1. **Sub-eV:** Search for axions or axion-like particles (ALPs) via EDMs or in direct laboratory searches
2. **MeV-GeV:** Search for heavy neutrinos, ALPs, light DM particles and mediators (dark photons, dark scalars) in fixed-target or collider experiments
3. **10-1000 TeV:** Search for NP in clean and very rare flavor processes or in EDMs

Much attention has been dedicated to TeV-scale models and ideas

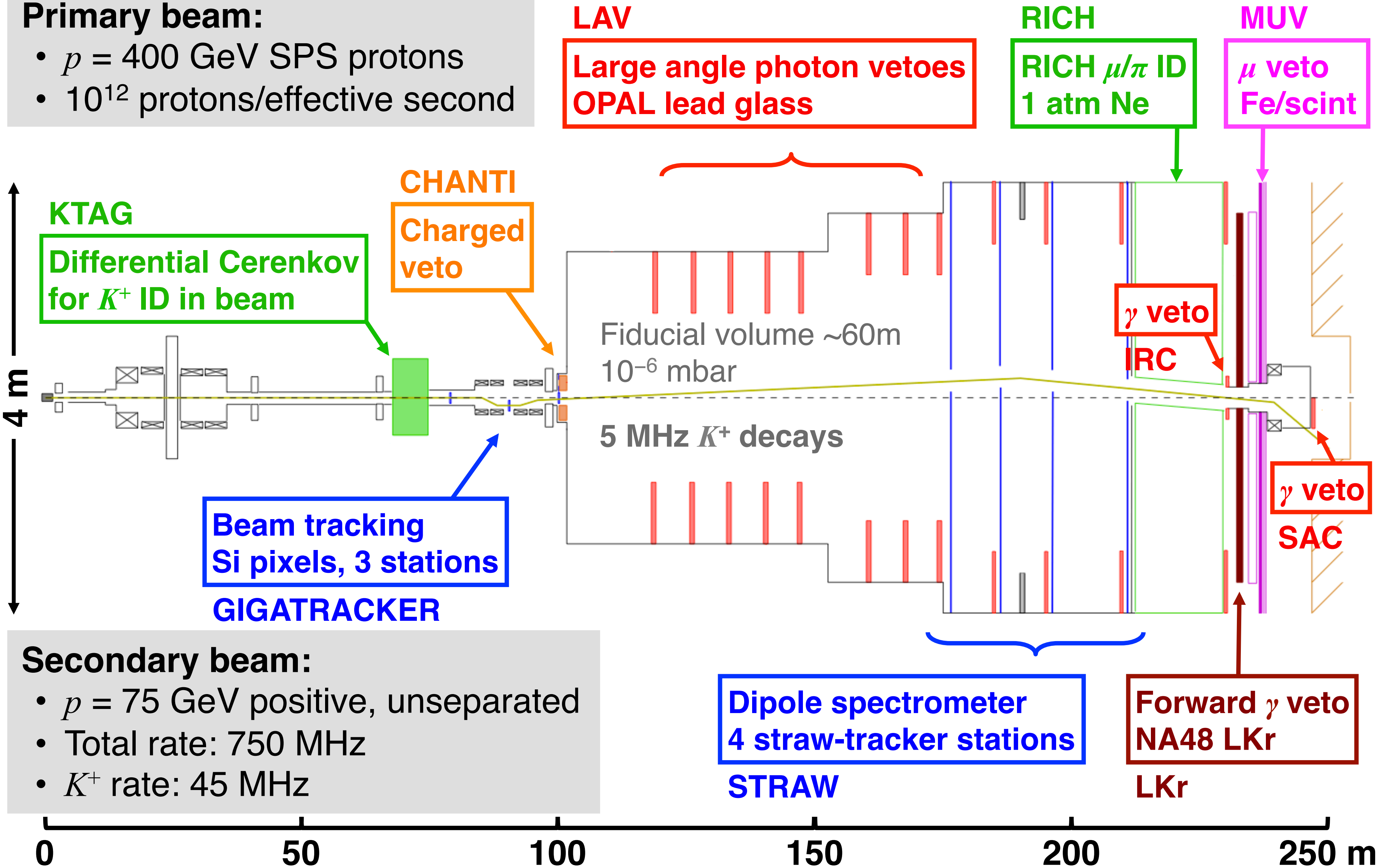
Need a systematic approach for NP at the intensity frontier

Portal	Coupling
Dark photon	$-\frac{\varepsilon}{2\cos\theta_W} F'_{\mu\nu} B^{\mu\nu}$
Scalar	$(\mu S + \lambda S^2) H^\dagger H$
Axion	$\frac{a}{f_a} F_{\mu\nu}\tilde{F}^{\mu\nu}, \frac{a}{f_a} G_{i,\mu\nu}\tilde{G}_i^{\mu\nu}, \frac{\partial_\mu a}{f_a} \bar{\psi}\gamma^\mu\gamma^5\psi$
Neutrino/HNL	$y_N LHN$

NA62 designed to be sensitive to K^+ BRs of order 10^{-12}
Well suited to explore new physics portals in the MeV-GeV scale

The NA62 experiment at the SPS

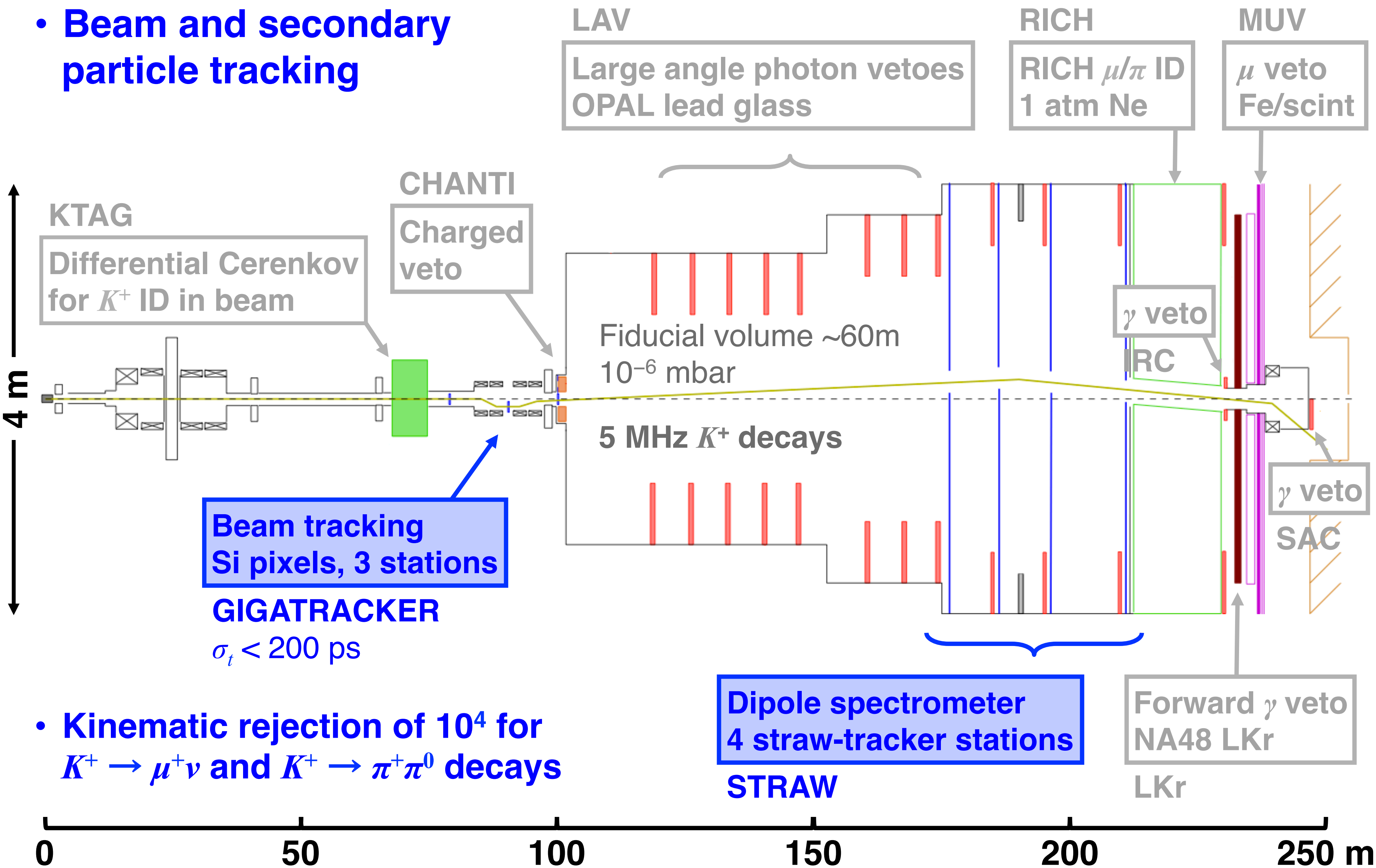
Primary beam:
- p = 400 GeV SPS protons
- 10^{12} protons/effective second



Secondary beam:
- p = 75 GeV positive, unseparated
- Total rate: 750 MHz
- K^+ rate: 45 MHz

The NA62 experiment at the SPS

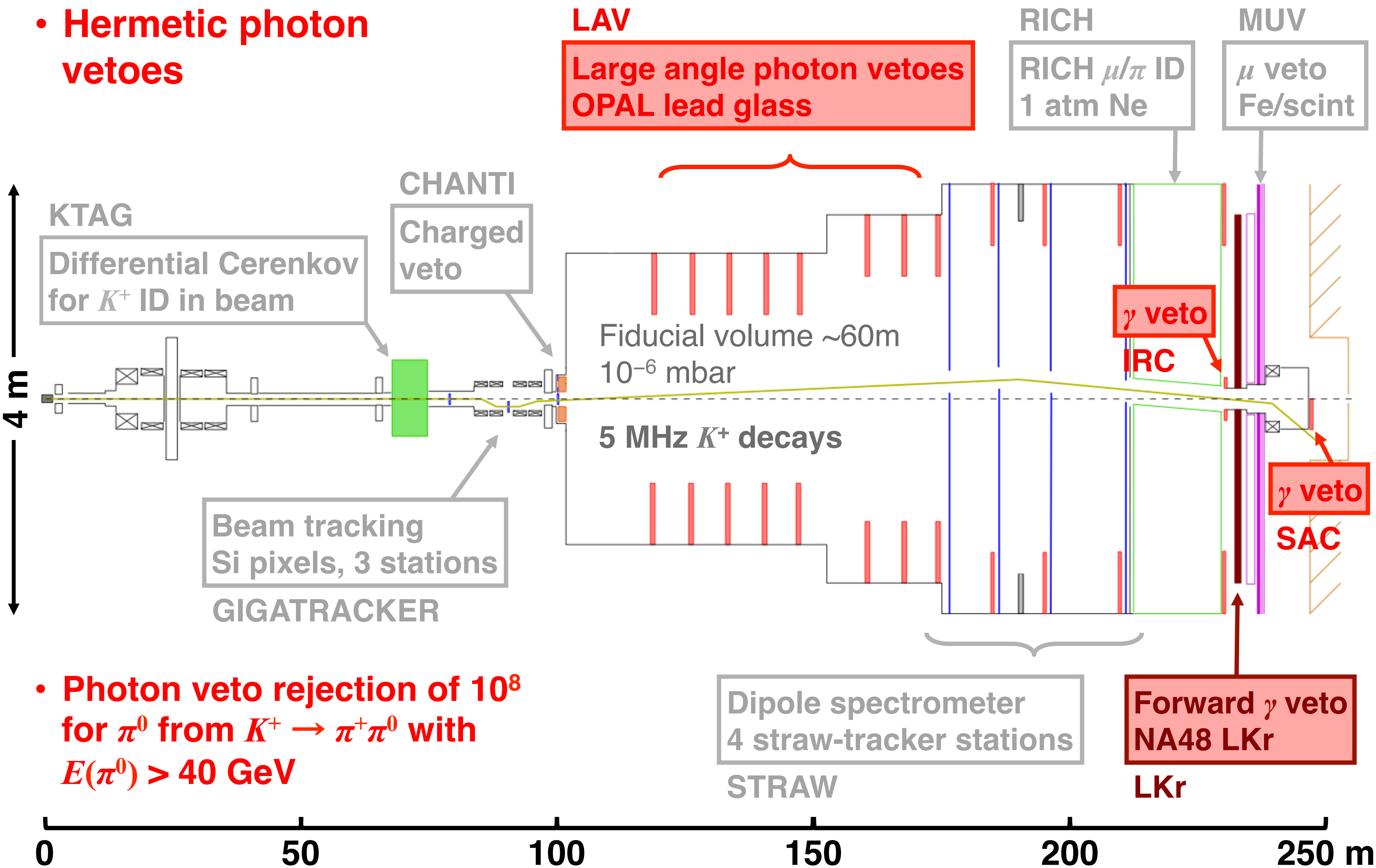
- **Beam and secondary particle tracking**



- **Kinematic rejection of 10^4 for $K^+ \rightarrow \mu^+\nu$ and $K^+ \rightarrow \pi^+\pi^0$ decays**

The NA62 experiment at the SPS

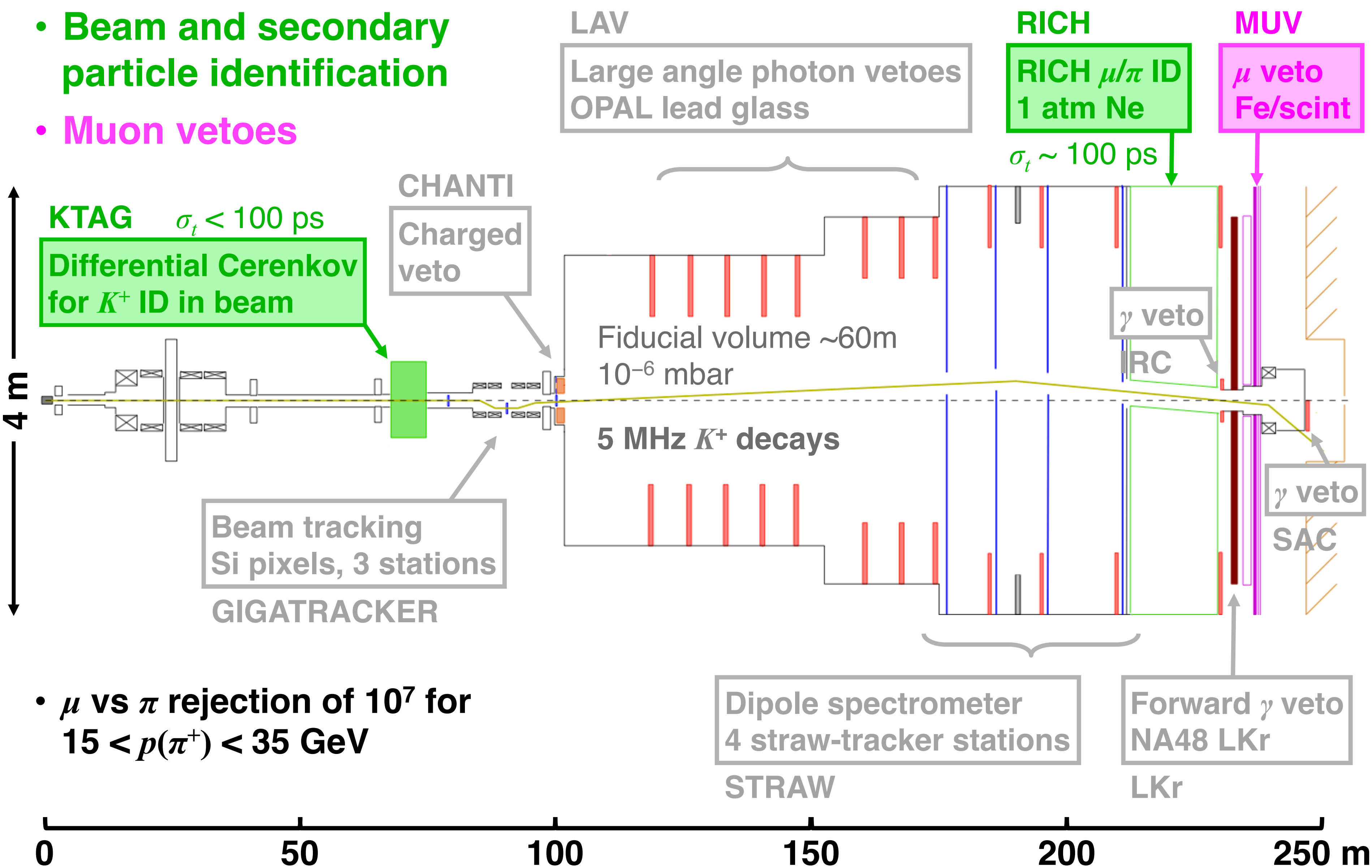
- **Hermetic photon vetoes**



- **Photon veto rejection of 10^8 for π^0 from $K^+ \to \pi^+\pi^0$ with $E(\pi^0) > 40$ GeV**

The NA62 experiment at the SPS

- **Beam and secondary particle identification**
- **Muon vetoes**



- **μ vs π rejection of 10^7 for $15 < p(\pi^+) < 35$ GeV**

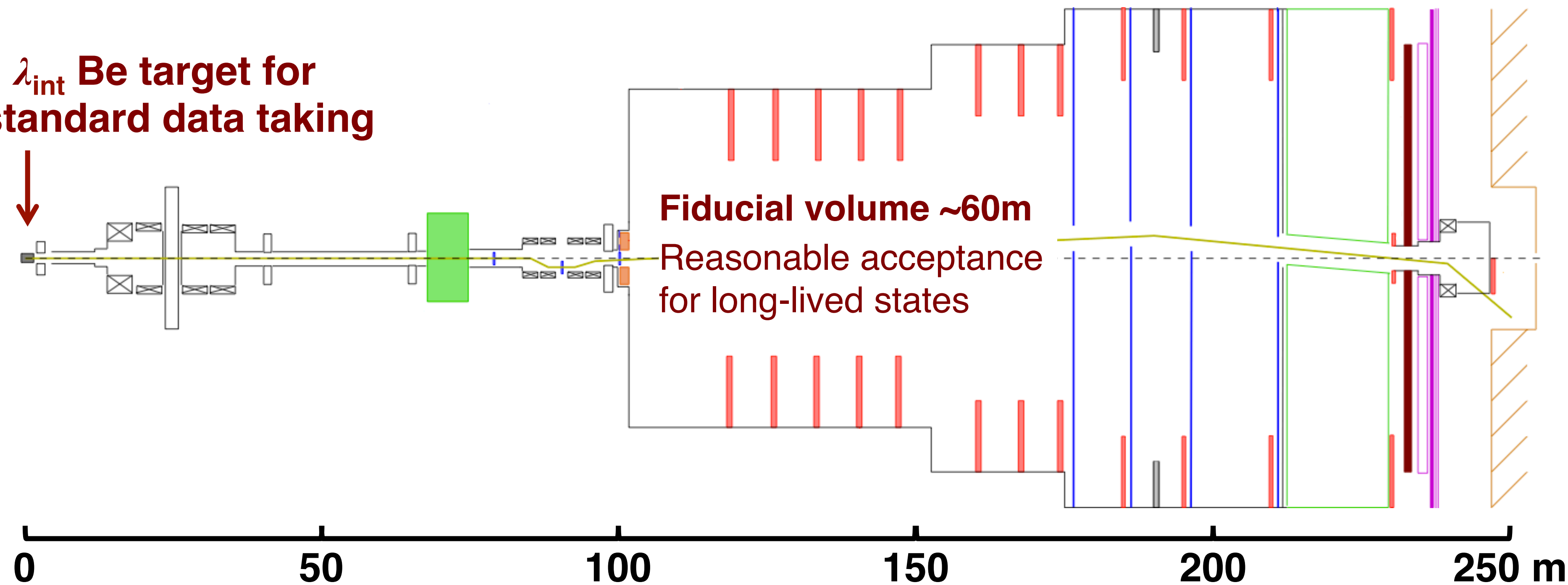
Exotic particle searches at NA62

Standard data taking during $K^+ \to \pi^+ \nu\nu$

- Possible approaches:
  1. Invisible exotic particles seen as missing mass from K decays

     E.g. $K^+ \to \pi^+ X$, with X = dark photon, HNL, etc.
  2. Exotic particles produced in target and reconstructed in FV
     - Dedicated triggers ($\mu\mu$, ee, $\pi\mu$, πe) using small fraction of $K^+ \to \pi^+ \nu\nu$ bandwidth
     - Currently existing samples on order of **10^{17} pot**

1 λ_{int} Be target for standard data taking



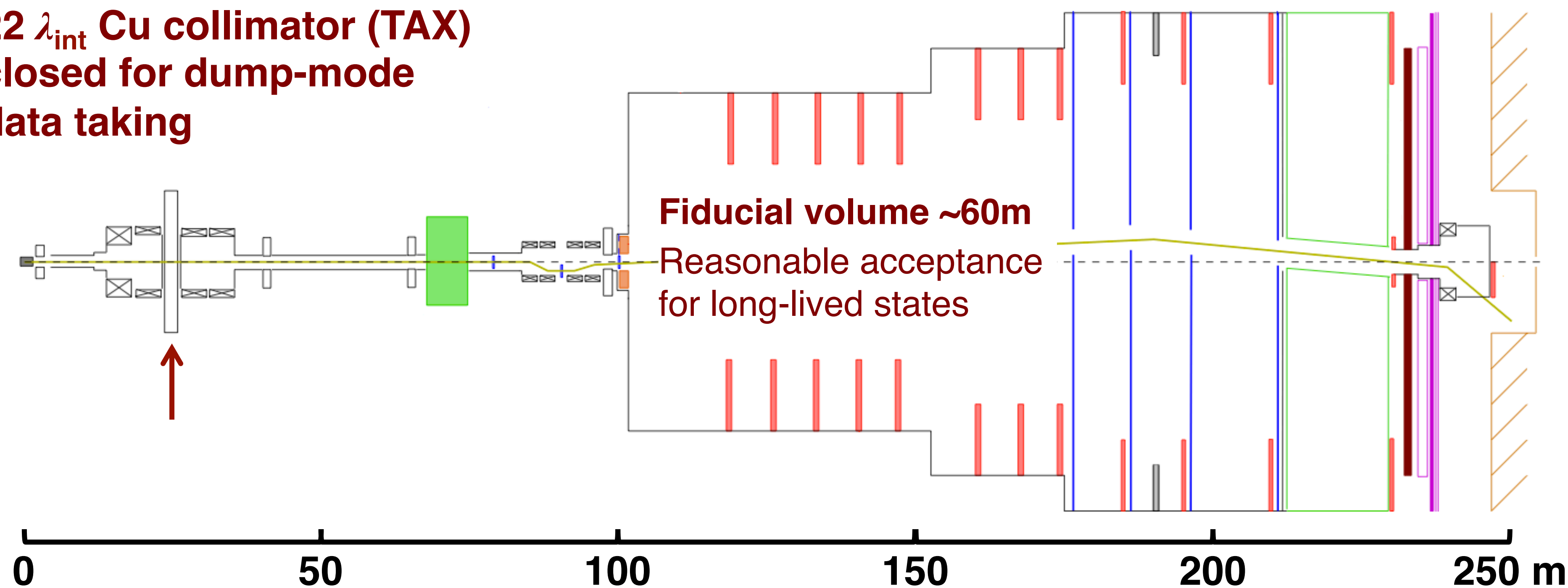
Exotic particle searches at NA62

Data taking with dumped beam

- Exotic particles produced from interactions of 400 GeV protons in closed collimator
- Dedicated data taking for short periods during $K^+ \rightarrow \pi^+ \nu \nu$ running

    Target lifted and collimator closed in 15-minute, reversible operation
- Background reduced enough to reconstruct exotic final states with open kinematics (proven for 4×10^{15} pot)
- Contemplate longer periods of dedicated data-taking in dump mode → **10^{18} pot**

22 λ_{int} Cu collimator (TAX) closed for dump-mode data taking



Dark photons

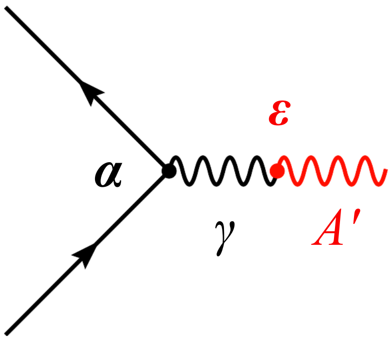
Simplest hidden sector model introduces a new U(1) gauge symmetry with one extra gauge boson: the dark photon A'

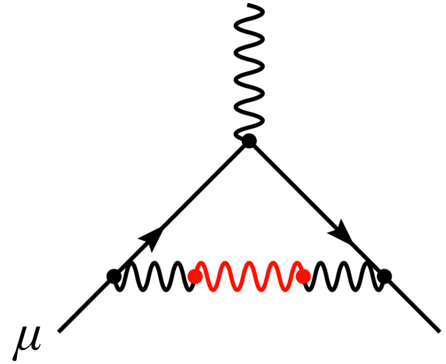
$$\mathcal{L}_{\text{vector}} = \mathcal{L}_{\text{SM}} + \mathcal{L}_{\text{DS}} - \frac{\epsilon}{2\cos\theta_W} F'_{\mu\nu} B_{\mu\nu}$$

$$\mathcal{L}_{\text{DS}} = -\frac{1}{4}(F'_{\mu\nu})^2 + \frac{1}{2} m^2_{A'} (A'_\mu)^2 + |(\partial_\mu + i g_D A'_\mu)\chi|^2 + \ldots$$

Interaction of A' with visible sector through kinetic mixing with SM hypercharge

- QED-like interactions with SM fermions
- Free parameters: ε and $m_{A'}$





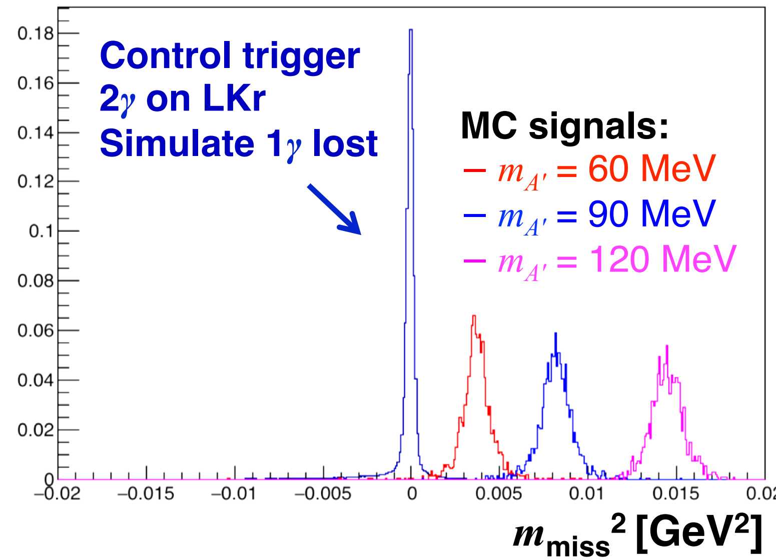
NA62 can search for dark photons:

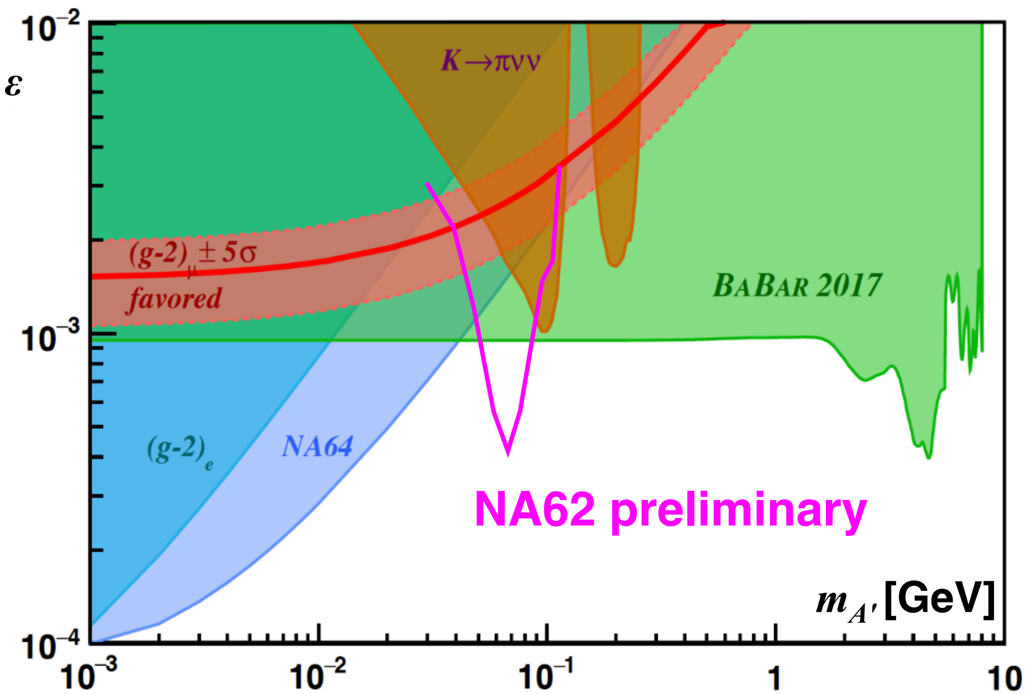
- With no decays to SM particles, in $K^+ \to \pi^+ X$ or $K^+ \to \pi^+\pi^0$ with $\pi^0 \to \gamma X$
- With dedicated trigger for decays such as $A' \to e^+e^-$ or $A' \to \mu^+\mu^-$

Dark photons with invisible decays

Search for $K^+ \to \pi^+\pi^0$ with $\pi^0 \to \gamma A'$ and A' invisible

- Sensitivity for $m_{A'} < m_{\pi 0}$
- Signal: 1 track + 1 γ + missing energy
- Search for missing mass peak corresponding to A'
- Main background: $\pi^0 \to \gamma\gamma$ with 1 γ lost





Preliminary result with 5% of 2016 data sample

- **1.5×10^{10} K^+ decays**
- Background from negative m_{miss} resolution tail from control data
- No significant excess observed
  90% CL UL within expected statistical uncertainty band
- Analysis with full 2016 data set in progress

Dark photons with visible decays

Search for A' produced in target or dump with decay to e^+e^- or $\mu^+\mu^-$ in FV

- Meson decays: From primary beam secondaries, e.g., $pN \to X\pi^0$, $\pi^0 \to \gamma A'$
- Bremsstrahlung from primary beam: $pN \to XA'$

Sensitivity estimate assumes:

- **10^{18} pot on Be target**
- Production in meson decays and bremsstrahlung
- Reconstruction of both e^+e^- and $\mu^+\mu^-$ channels
- 90% CL exclusion in zero-background assumption

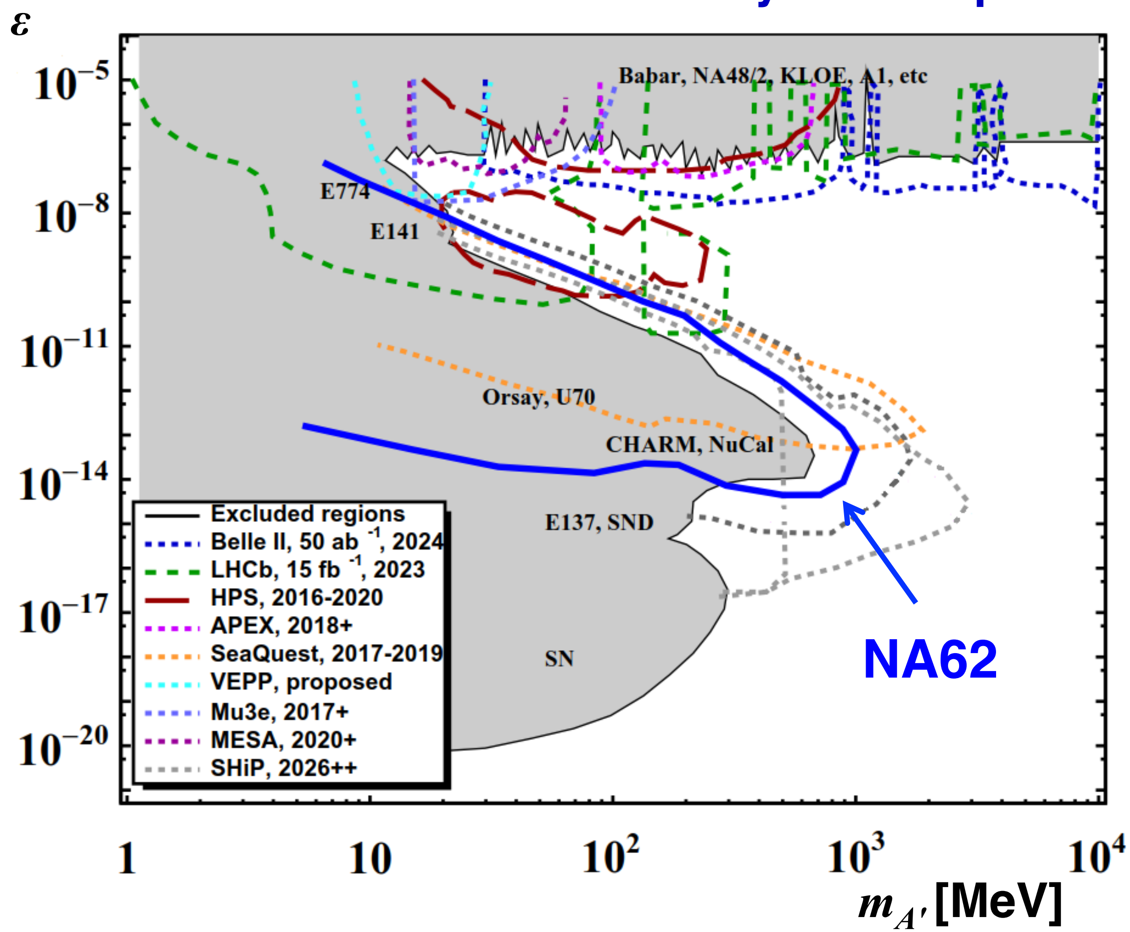
Sensitivity estimate does not include contributions from:

- A' from QCD processes
- A' produced in TAX

Data from 2016-2017 runs

- 3×10^{17} pot with $\mu\mu$ trigger
- 5×10^{16} pot with ee trigger

NA62 estimated sensitivity for 10^{18} pot



Dark scalar particles

Dark sector coupled to Higgs by new singlet scalar field S

Expansion of the field H around VEV v gives mixing of physical h and S with parameter θ

$$\mathcal{L}_{\text{scalar}} = \mathcal{L}_{\text{SM}} + \mathcal{L}_{\text{DS}} - (\mu S + \lambda S^2) H^\dagger H$$

$$\mathcal{L}_{\text{DS}} = S\bar{\chi}\chi + \dots \qquad \theta = \frac{\mu v}{m_h^2 - m_S^2}$$

Sensitivity estimate assumes:

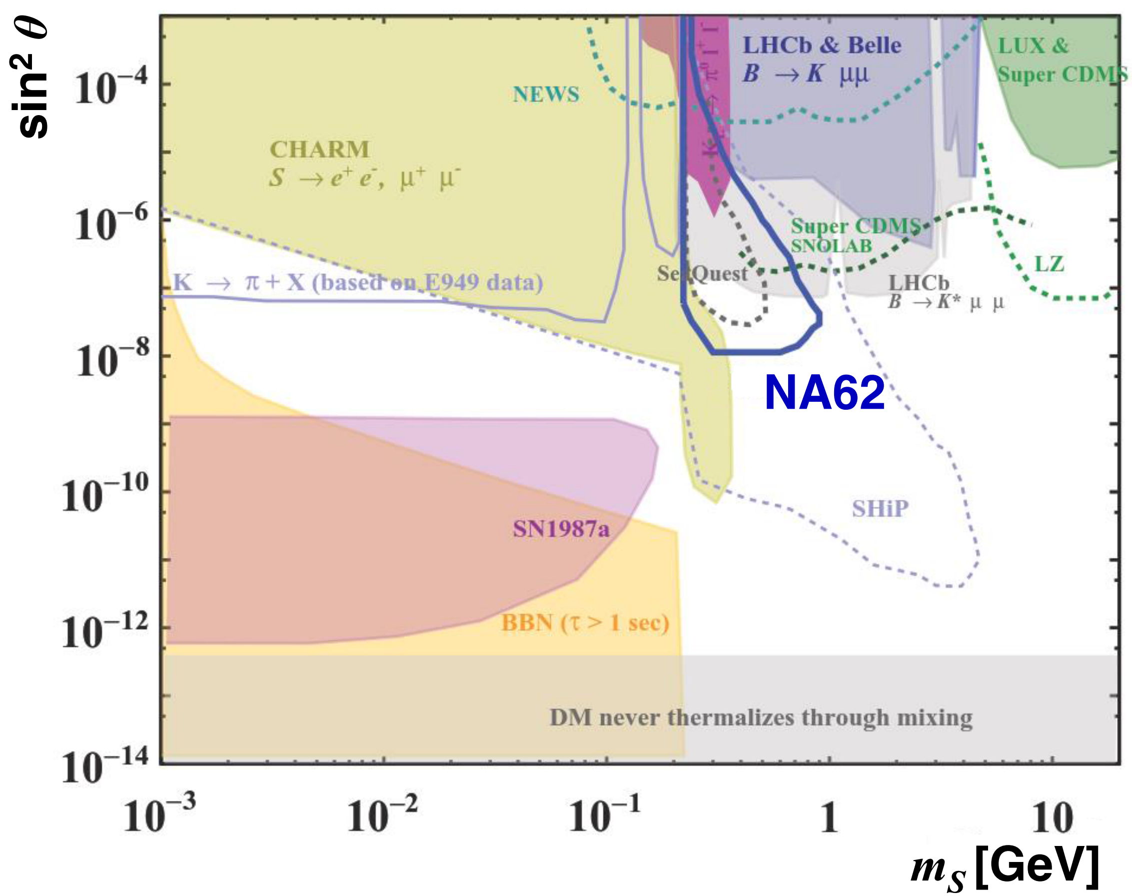
- **10^{18} pot on Be target**
- Reconstruction of 2-track final states (ee, $\mu\mu$, $\pi\pi$, KK) with vertex pointing back to TAX:

  S produced most efficiently by decays of B-mesons from interactions in TAX
- 90% CL exclusion in zero-background assumption

Data from 2016-2017 runs

- 3×10^{17} pot with $\mu\mu$ trigger
- 5×10^{16} pot with ee trigger

NA62 estimated sensitivity for 10^{18} pot



Axion-like particles

Light pseudoscalar ALP may act as a mediator between SM and dark matter

$$\mathcal{L}_{\text{axion}} = \mathcal{L}_{\text{SM}} + \mathcal{L}_{\text{DS}} + \frac{a}{4f_\gamma}F_{\mu\nu}\tilde{F}_{\mu\nu} + \frac{a}{4f_G}\text{Tr}G_{\mu\nu}\tilde{G}_{\mu\nu} + \frac{\partial_\mu a}{f_l}\sum_\alpha \bar{l}_\alpha\gamma_\mu\gamma_5 l_\alpha + \frac{\partial_\mu a}{f_q}\sum_\beta \bar{q}_\beta\gamma_\mu\gamma_5 q_\beta$$

NA62 can explore ALP masses in the MeV-GeV range

Focus on pseudoscalar ALPs whose dominant interaction is with photons:

- Dedicated running in beam dump mode (TAX closed)
- Primakoff ($\gamma\gamma$ fusion) production from interaction in TAX with $a \to \gamma\gamma$ decay
- ALP produced at low $p_\perp$ → good acceptance even if detector far from production point

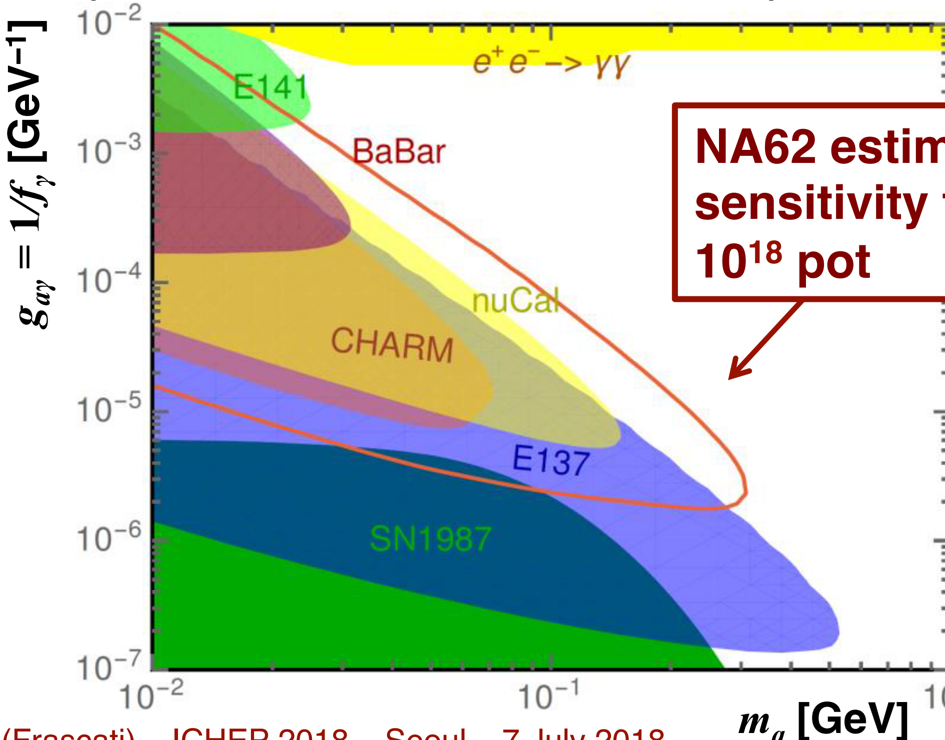
Sensitivity estimate assumes:

- **10^{18} pot on closed TAX**
- 90% CL exclusion in zero-background assumption

Significant results obtainable with only 1 day of data taking (1.3×10^{16} pot)

- Analysis of 2017 data in progress:

  5×10^{15} pot in dump mode



NA62 estimated sensitivity for 10^{18} pot

HNLs with visible decays

$\mathcal{L}_{\mathrm{DS}}$ may include mass terms for one or more HNLs N (Dirac or Majorana)

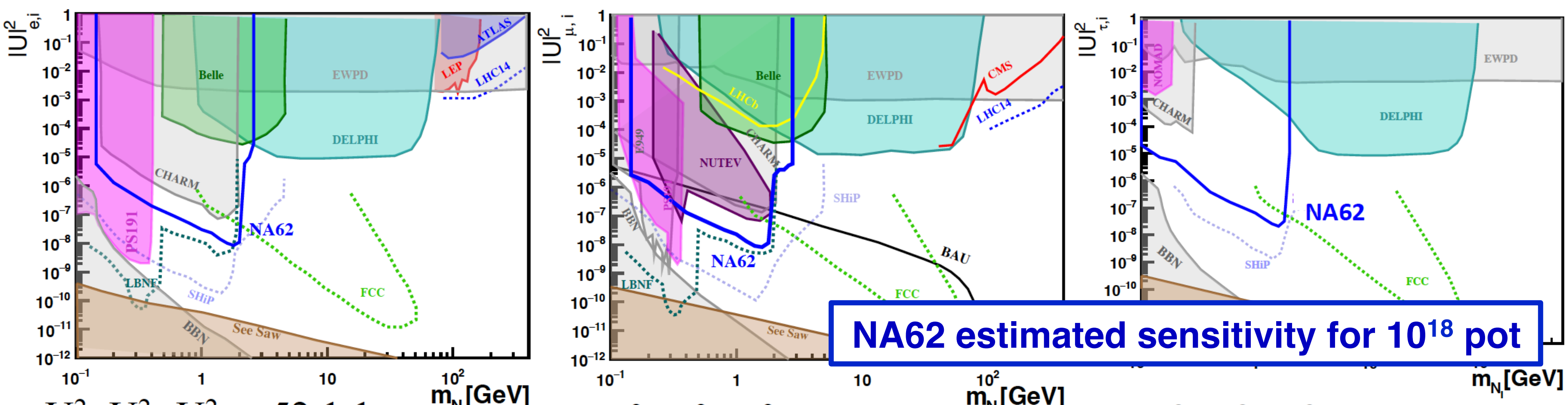
Ns mix with $\nu_{1,2,3}$ to give $\nu_{e,\mu,\tau}$ + RH "sterile" neutrinos

$$\mathcal{L} = \mathcal{L}_{\mathrm{SM}} + \mathcal{L}_{\mathrm{DS}} + \sum F_{\alpha I}(\bar{L}_\alpha H) N_I$$

$$\nu_\alpha \rightarrow \sum_I U_{\alpha I} N_I$$

Search for N produced in TAX with decays to two-track final states:

- Assume 10^{18} pot on closed TAX
- Reconstruct two-track final states, including open channels
- 90% CL exclusion in zero-background assumption
- Derive sensitivity for coupling scenarios in Shaposhnikov & Gorbunov 0705.1729v2



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

Data from 2016-2017 runs: 10^{17} pot with $\pi\mu$ trigger; few 10^{16} pot with πe trigger

Summary and outlook

Main goal of NA62 is to measure BR($K^+ \to \pi^+\nu\nu$) with 10% accuracy

- Physics runs in 2016, 2017, and 2018 – data taking in progress!

Hidden-sector physics program before LS2:

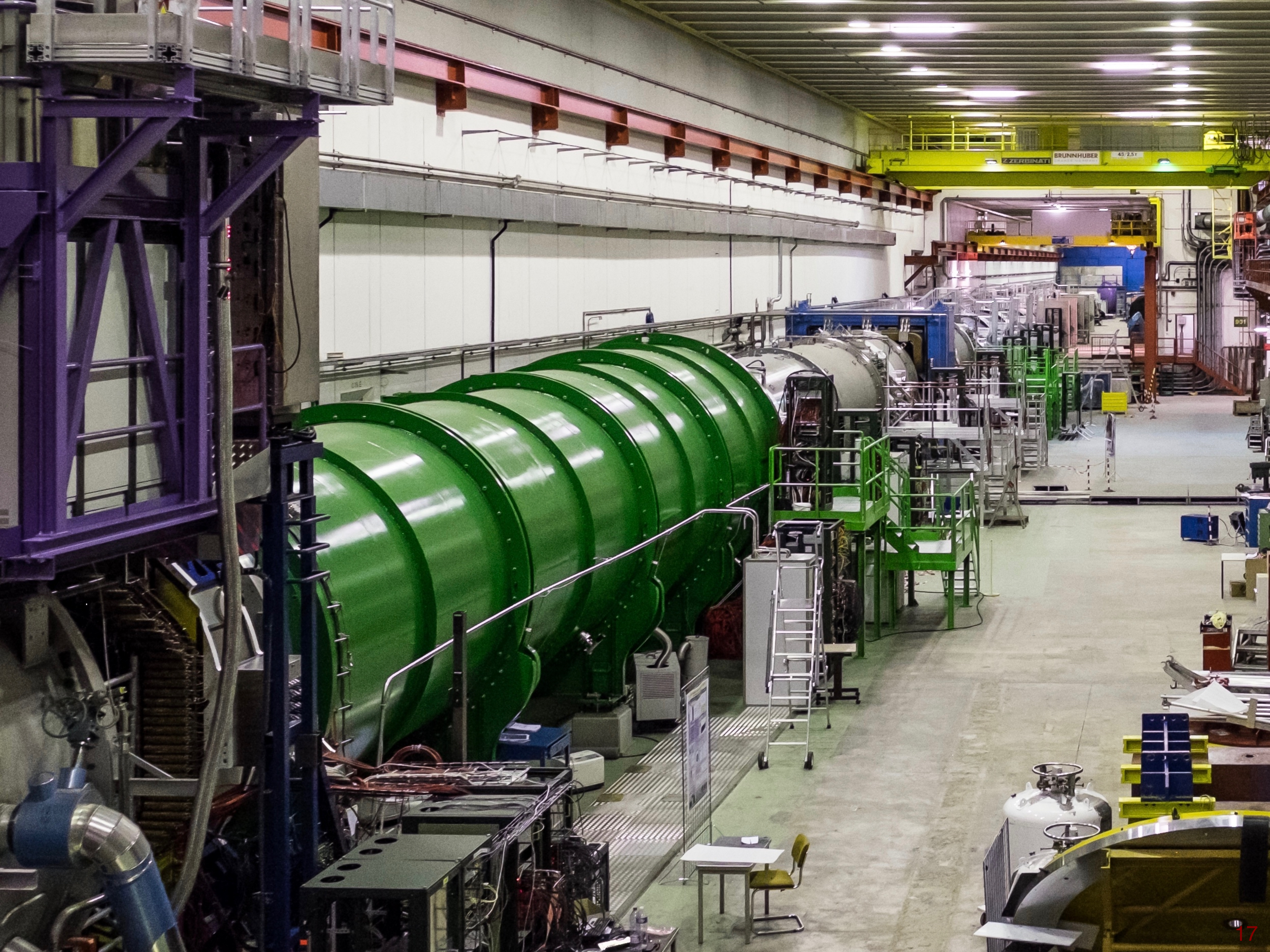
- Dedicated triggers compatible with $\pi\nu\nu$ program to search for dark photons, dark scalars, and HNLs
- Short, dedicated beam-dump runs to search for ALP decays to $\gamma\gamma$

After LS2, collection of 10^{18} pot in beam-dump mode will provide sensivity to various hidden-sector models

- Expected sensitivity beyond that of other initiatives with same time scale

Results from the current NA62 run will be exploited to:

- Evaluate background rejection capability up to $10^{17} \to 10^{18}$ pot
- Define setup optimizations for future beam-dump mode running, including, if needed, minor modifications to the existing apparatus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The zero-background assumption

Sensitivity estimates for channels with visible decays (dark photons, scalars, ALPs, HNLs) are based on zero-background assumption for 10^{18} pot

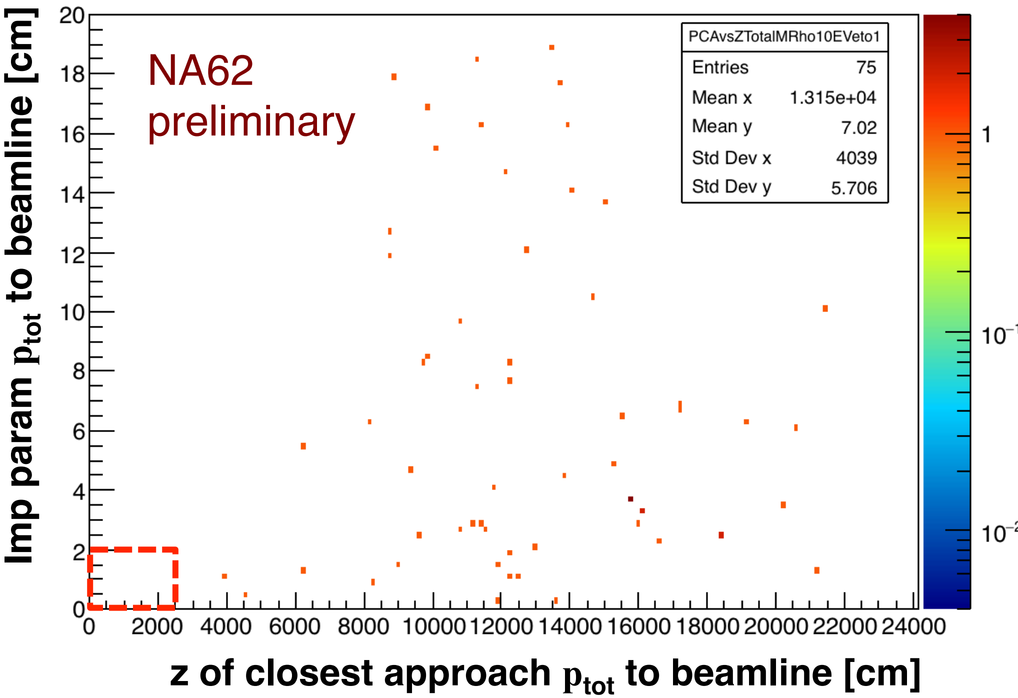
- Baseline selection: 2 tracks, opposite sign, vertex far from beamline

Test zero-background assumption using combinatorial background to $A' \to \mu\mu$ from halo muons

Halo rates from upstream decays/ interactions: 3 MHz μ^+ and 150 kHZ μ^-

Cuts:

- Track quality & acceptance
- Vertex quality
- Total momentum from target
- Veto extra LKr energy
- Photon veto: SAC/IRC/LAV
- Upstream charged particle veto (CHANTI)



No events selected in signal region for 10^{15} pot, even with standard K^+ beam
Assumption valid for 10^{15} pot in standard running (4×10^{15} pot in dump mode)