RKF: 2nd Forum on Rare Kaon decays - May 29-31, 2019

Exotic searches at NA62 experiment

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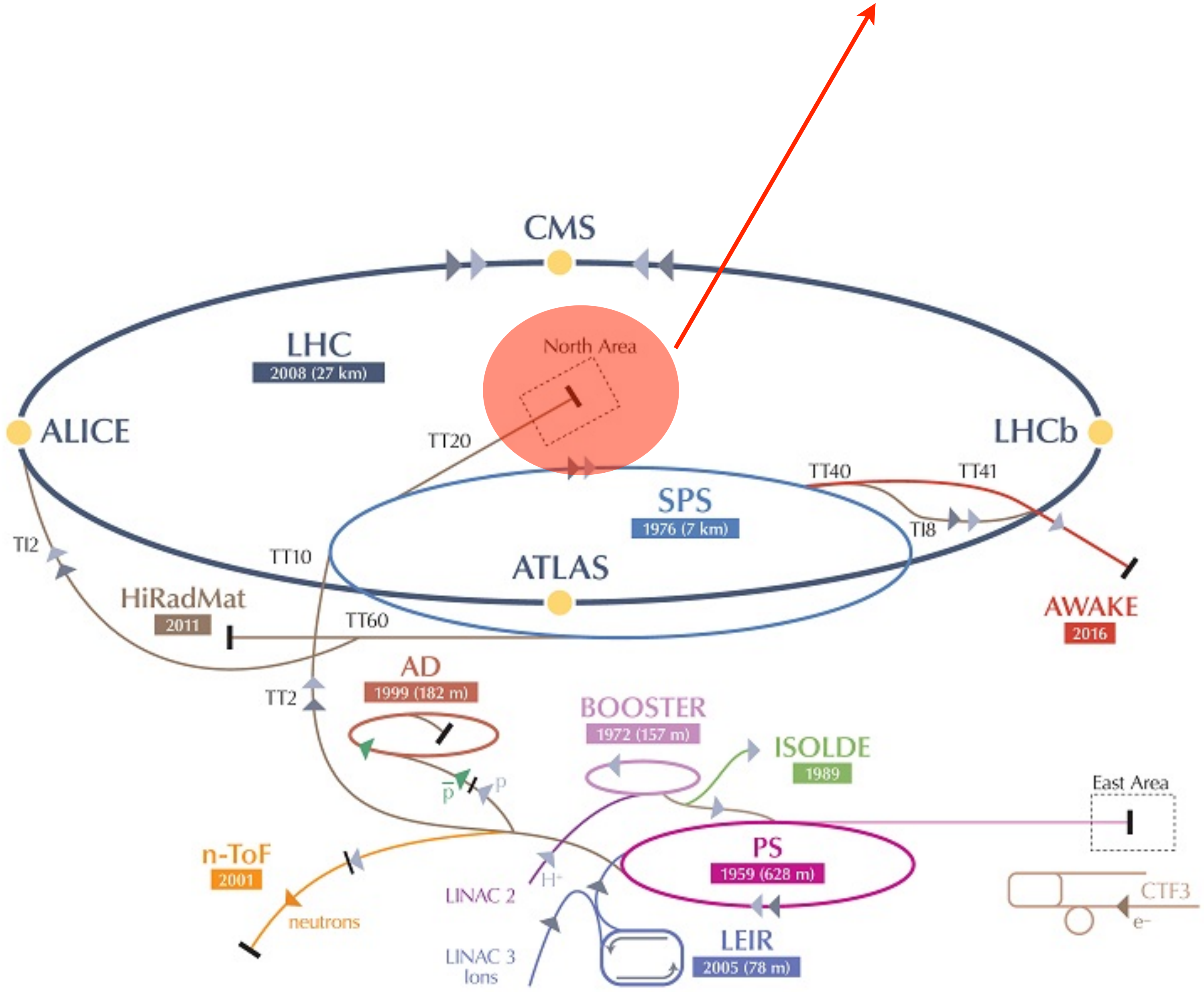
Outline

- Overview of the NA62 experiment
- NA62 broader physics program: exotic particle searches
  - Published results obtained so far
  - Future perspectives: NA62++ (2021-2023)

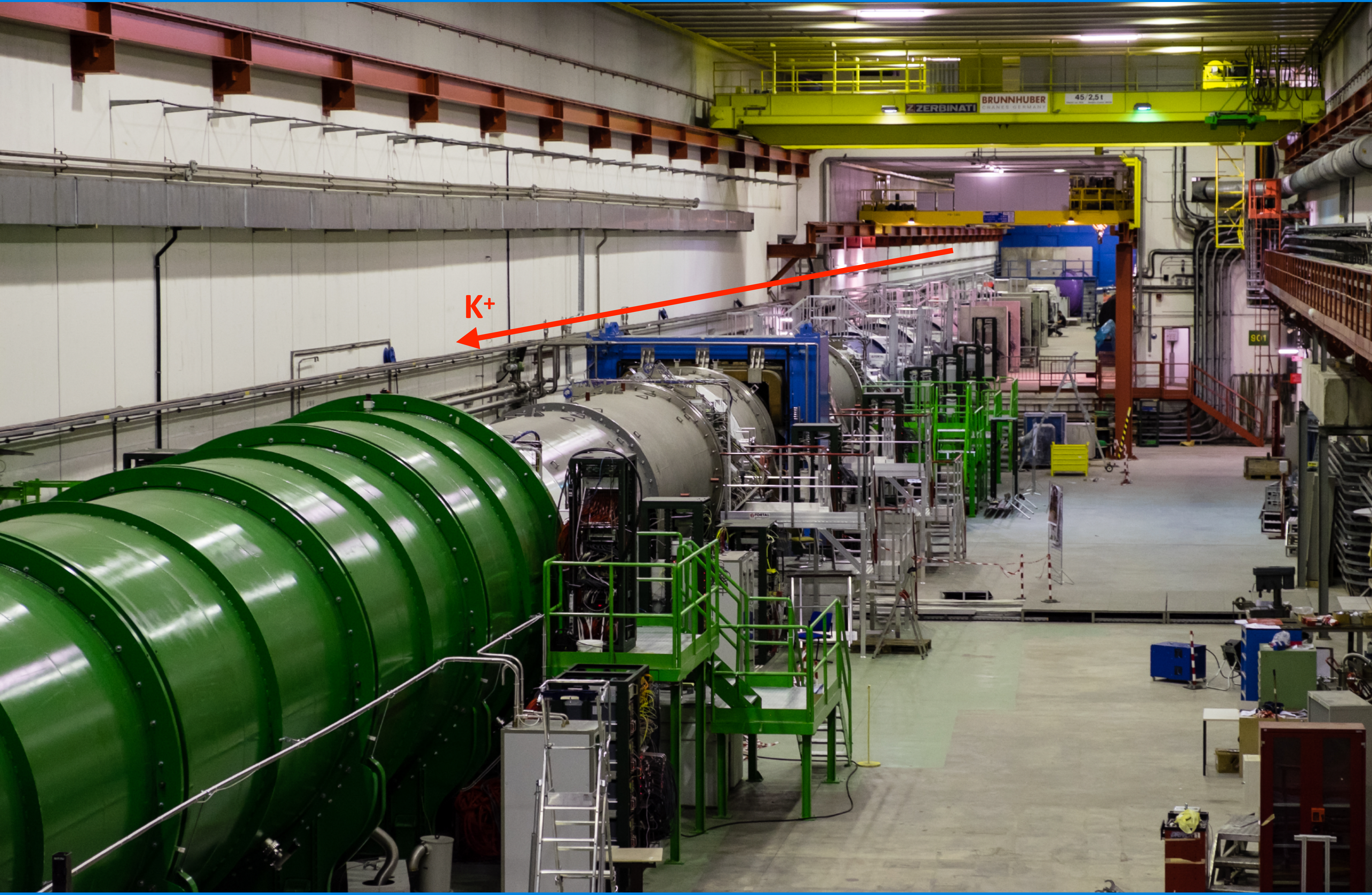
Kaon at CERN SPS

In the North Area the CERN-SPS extraction line is providing a secondary charged hadron beam



- 400 GeV/c primary proton beam
- 3 x 10^{12} protons/pulse
- 5 second spills every 15 sec.
- 40 cm beryllium target
- **75 GeV/c** unseparated hadrons beam: **π^+, K^+ (6%), protons** ($\Delta p/p \pm 1\%$)
- 4.8 x 10^{12} K^+ decays/year

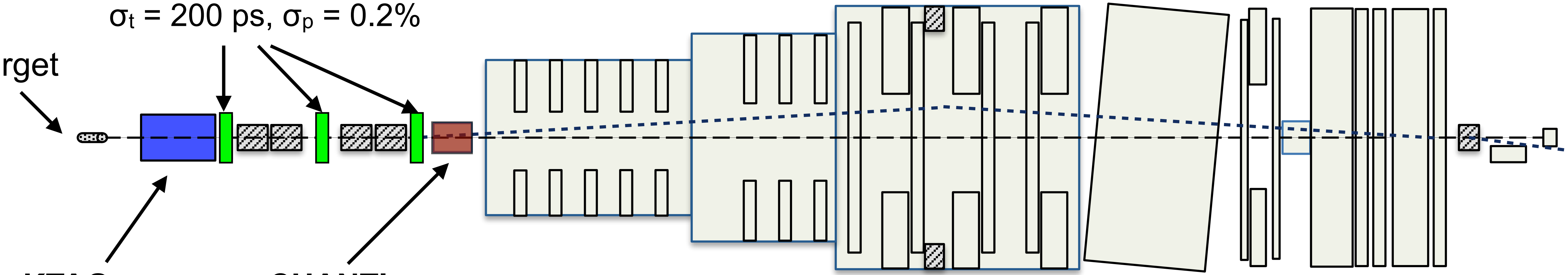
NA62 Experiment



NA62 Apparatus

270 m long region starting about 100 m downstream of the beryllium target. Detector diameters go from 20 to 400 cm. About 20% of K^+ decay inside the fiducial volume (5 MHz of K^+ decays)

Hadron Beam
750 MHz →



GTK (GigaTracker):
Spectrometer for
momentum measurement
σ_t = 200 ps, σ_p = 0.2%

Target

KTAG:
Differential
Cherenkov fot
Kaon
Identification
σ_t = 70 ps

CHANTI:
Charged
particle veto
to reduce
inelastic
background

Beam particles
identification and tracking

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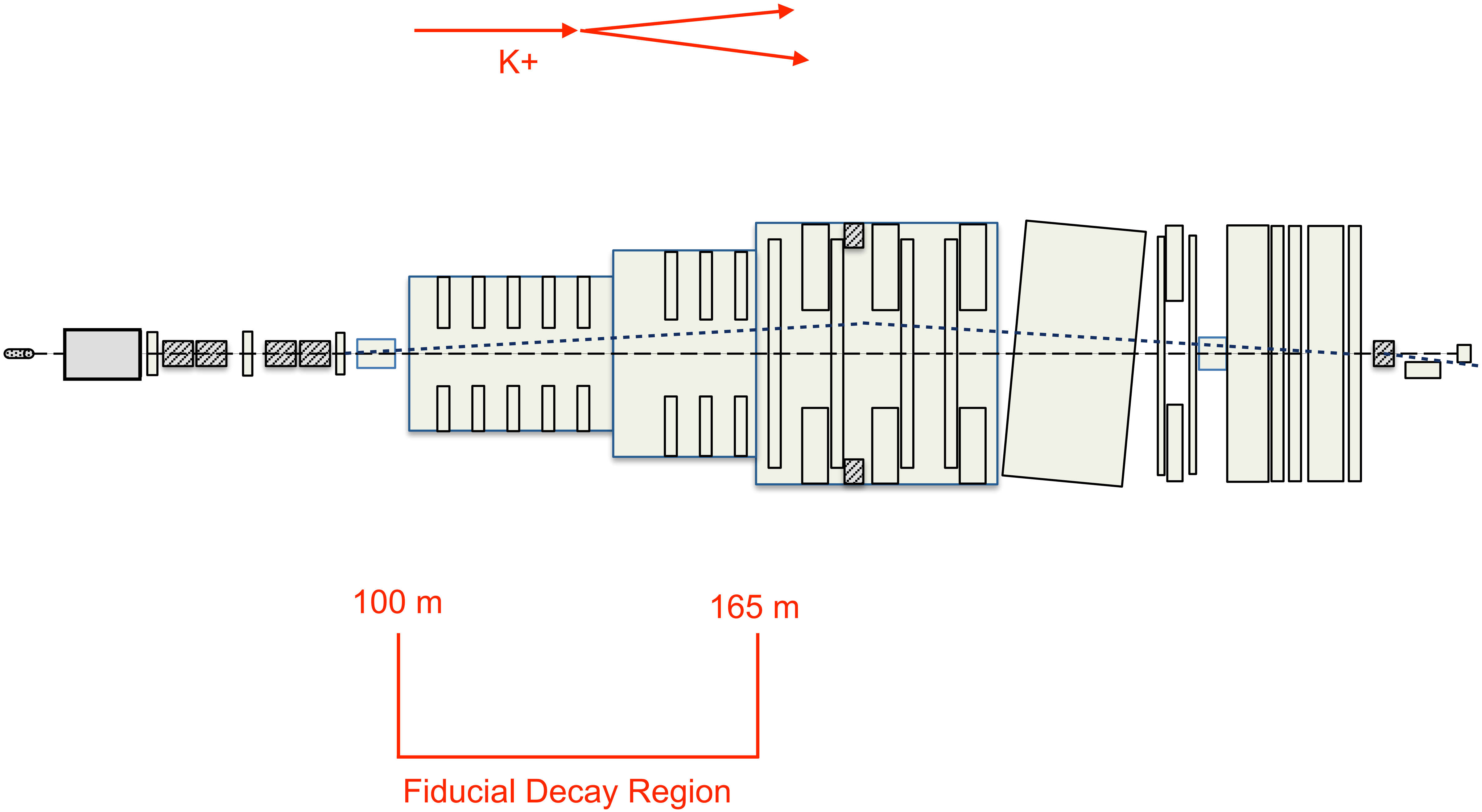

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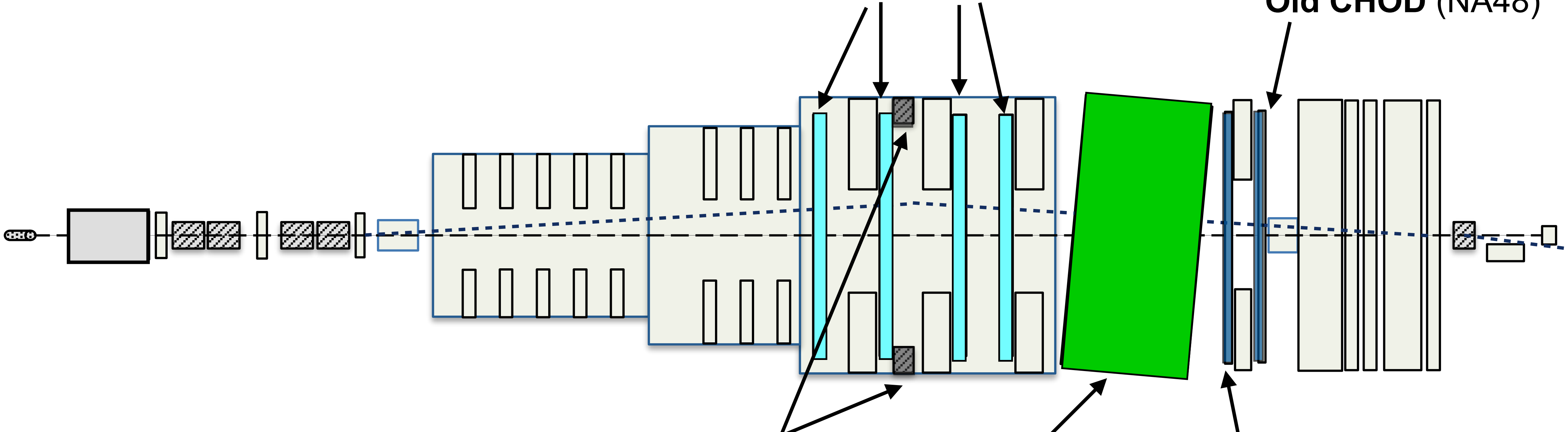

STRAW CHAMBERS: Spectrometer for momentum measurement $\sigma_p = 0.3\%$

Old CHOD (NA48)

MAGNET

RICH: Ring Imaging Cherenkov detector for particle ID (π/μ/e)

CHOD : Charged Hodoscope. Plastic scintillator for fast signal. $\sigma_t = 200$ ps

Secondary particles identification and tracking

NA62 Apparatus

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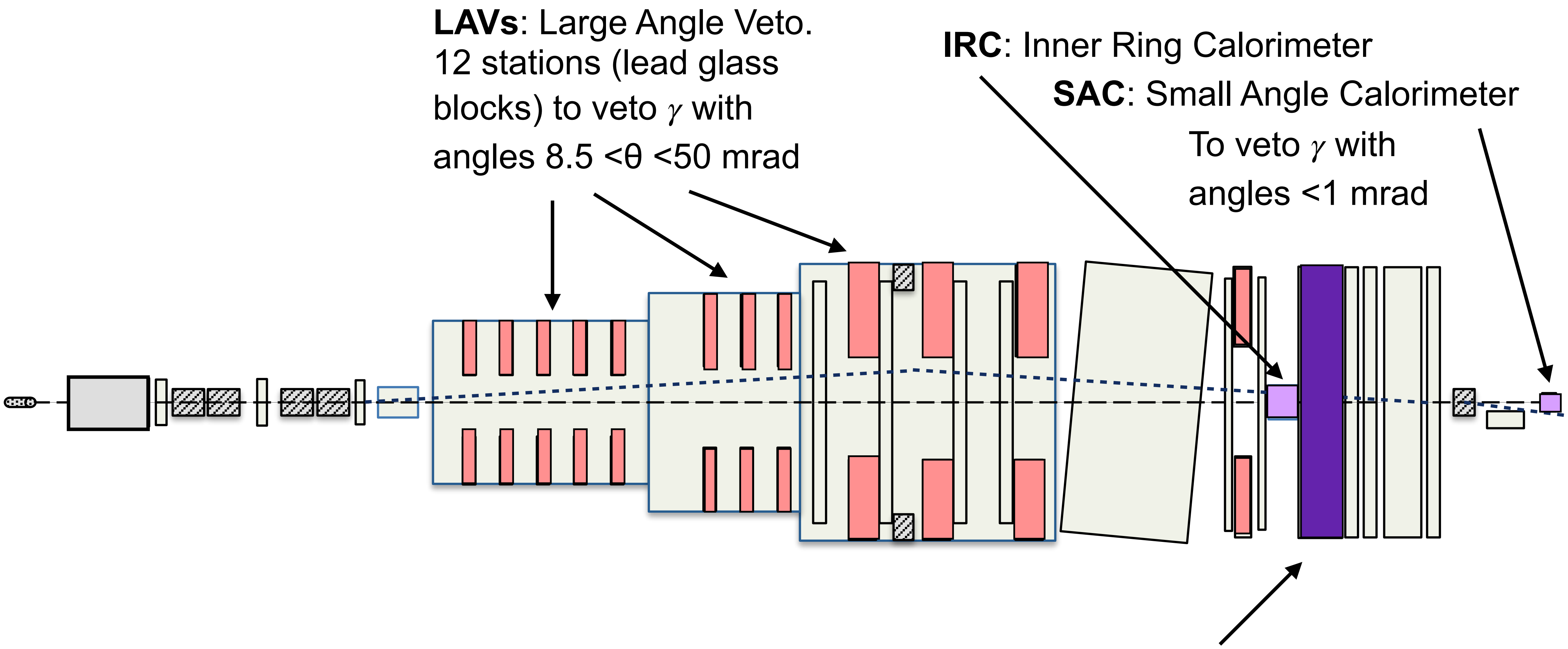

LAVs: Large Angle Veto. 12 stations (lead glass blocks) to veto γ with angles 8.5 <θ <50 mrad

IRC: Inner Ring Calorimeter

SAC: Small Angle Calorimeter

To veto γ with angles <1 mrad

NA48 **LKr** Calorimeter: to veto γ with angles 1<θ<8.5 mrad and for PID & energy reconstruction.

Hermetic Photon Veto System

NA62 Apparatus

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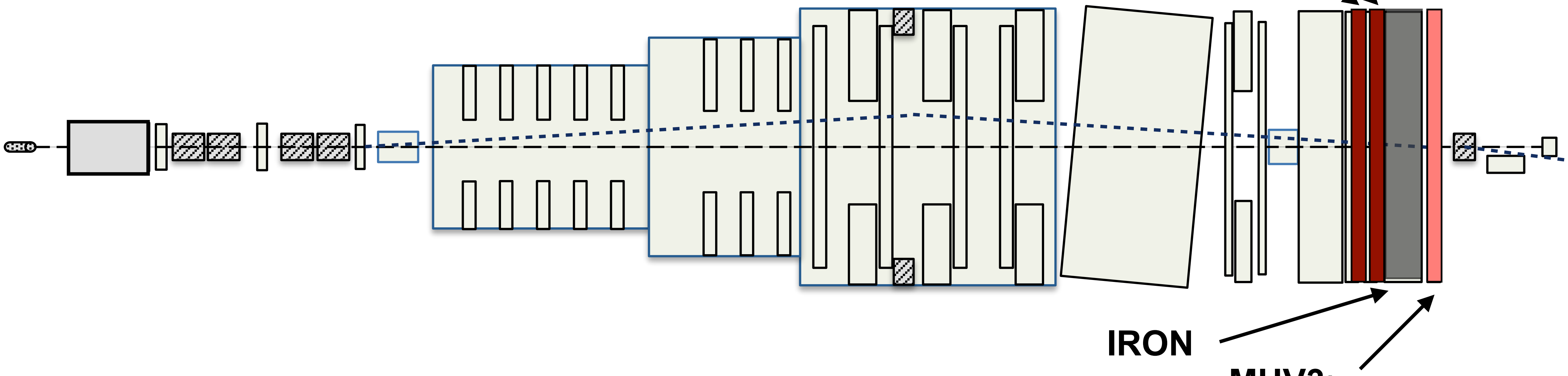


MUV1 & **MUV2**: Hadronic calorimeters for the μ/π separation

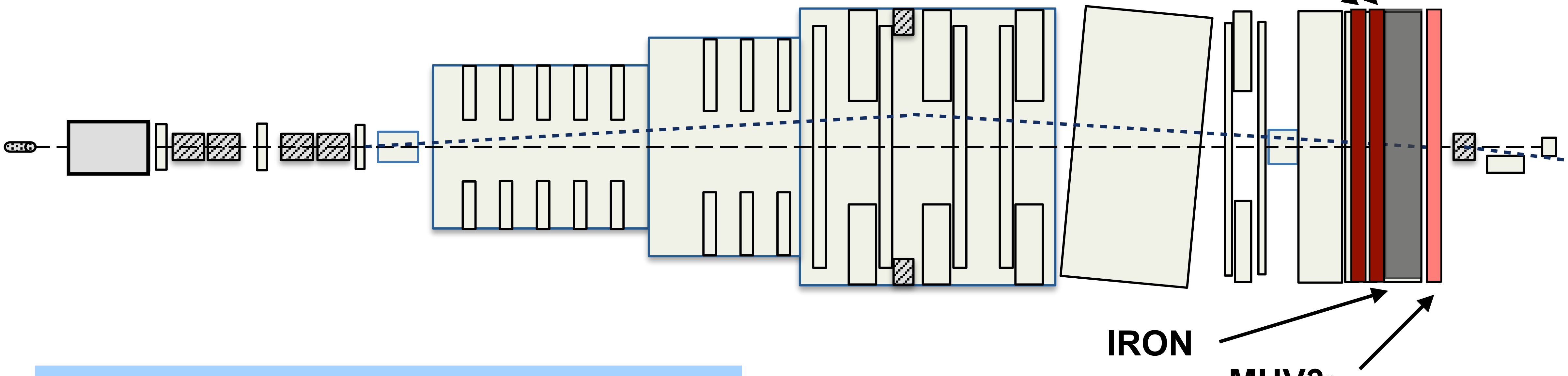
IRON

MUV3:
Efficient fast Muon Veto used in the hardware trigger level.

Muon Veto System

NA62 Apparatus

270 m long region starting about 100 m downstream of the beryllium target. Detector diameters go from 20 to 400 cm. About 20% of K^+ decay inside the fiducial volume (5 MHz of K^+ decays)



MUV1 & **MUV2**: Hadronic calorimeters for the μ/π separation

IRON

MUV3:
Efficient fast Muon Veto used in the hardware trigger level.

Muon Veto System

High-intensity setup, trigger system flexibility and detector performances (extremely high efficiency photon veto) make NA62 ideal for many other measurements besides BR($K^+ \rightarrow \pi^+ \nu \nu$)

A general purpose experiment

Flavour Physics

Search for New Physics at the EW scale with sizeable coupling to SM particles via indirect effects in loops:

Main goal:

BR($K^+ \rightarrow \pi^+ \nu\nu$)

Search for lepton flavour and number violation, rare and forbidden decays:

LFV, LNV

Hidden sector Physics

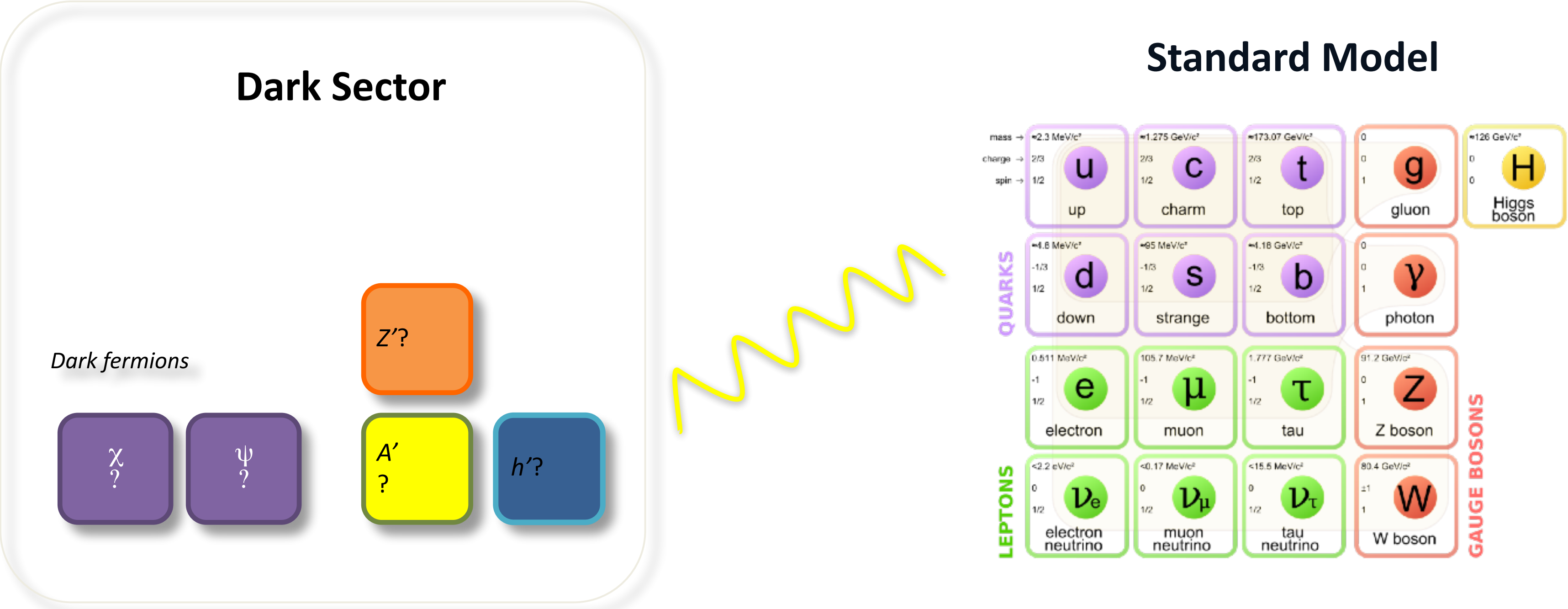
Search for New Physics below the EW scale (MeV-GeV) feebly-coupled to SM particles via direct detection of long-lived particles:

Heavy neutral Lepton(**HNL**)
Dark Photon(**DP**), Axion Like Particle (**ALPs**), Dark Scalar (**S**)

Exotic Particles

- No convincing signature of new physics discovered at the energy frontier (LHC)
- Shift in interest towards the intensity frontier
- Searches for light particles below the EW scale with feeble coupling to the SM (dark sector portals):

dark photon (A')
dark scalars (S)
axion-like particles (ALP)
heavy neutrino (N)



Portal	Coupling
Dark Photon, A_μ	$-\frac{\epsilon}{2\cos\theta_W} F'_{\mu\nu} B^{\mu\nu}$
Dark Higgs, S	$(\mu S + \lambda S^2) H^\dagger H$
Axion, a	$\frac{a}{f_a} F_{\mu\nu} \tilde{F}^{\mu\nu}$, $\frac{a}{f_a} G_{i,\mu\nu} \tilde{G}_i^{\mu\nu}$, $\frac{\partial_\mu a}{f_a} \overline{\psi} \gamma^\mu \gamma^5 \psi$
Sterile Neutrino, N	$y_N L H N$

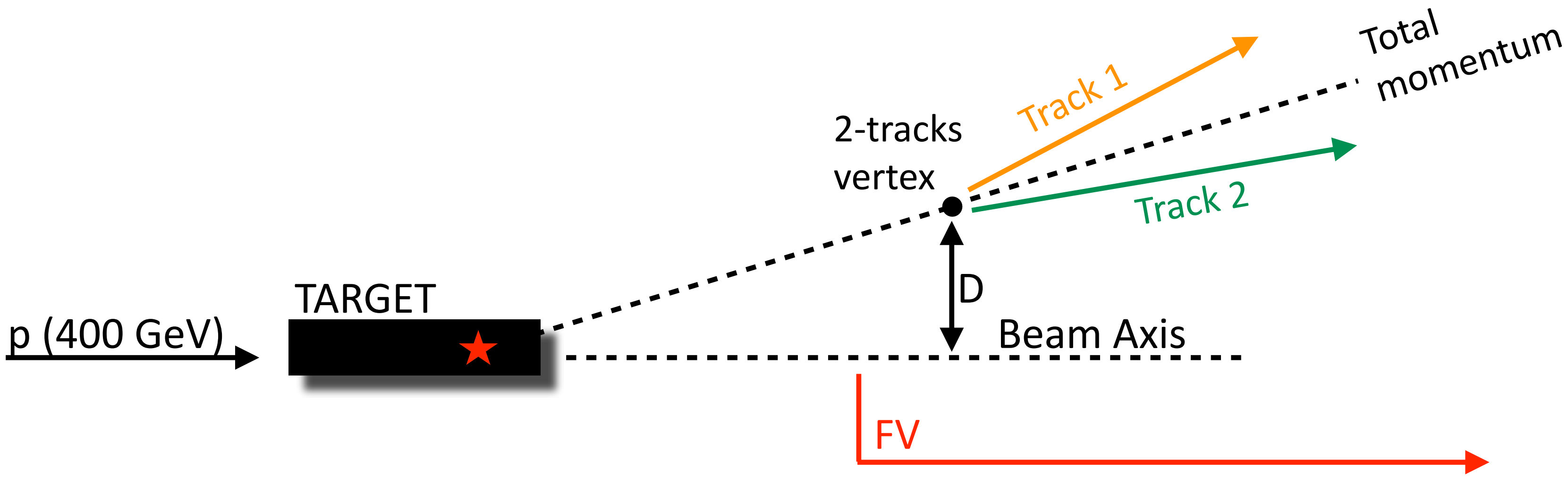
Interaction between DM and SM mediated by these new Gauge-invariant operators

All of these could be discovered in the NA62 experiment at CERN

Exotic particle production at NA62

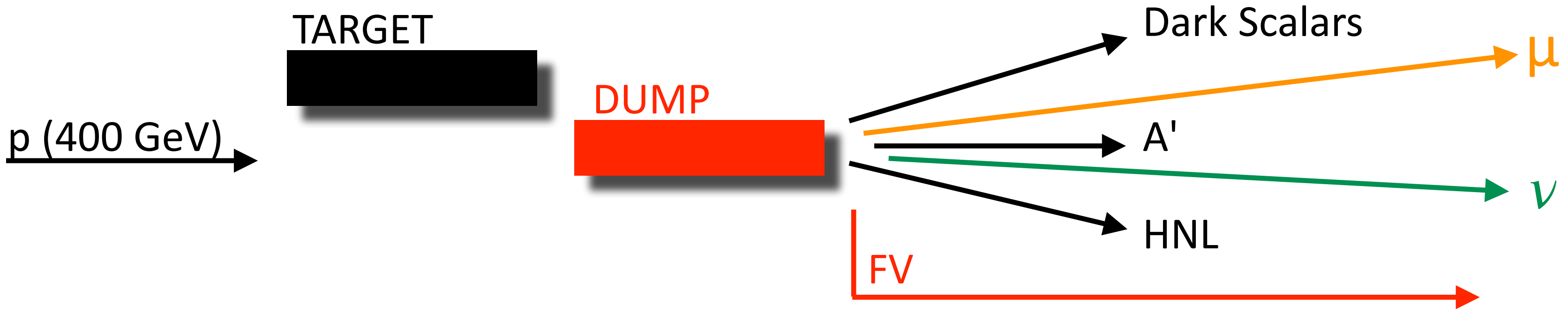
We can search for exotic particle created in K or π decays but also
Long-lived exotic particles from Hidden Sector may be created:

In the proton-target interaction and reach the NA62 decay volume



Recorded in parallel to the standard data-taking using dedicated low bandwidth triggers that select configuration topologies with pair of tracks in the final state.

In the proton-collimator interaction. NA62 can run in “**dump mode**"



The target may be lifted and the copper collimators closed, so that the whole beam interacts in a higher Z material (~11 λ_I) closer to the detector (20 m downstream the target), increasing the sensitivity.

All beam-induced backgrounds are stopped but muons and neutrinos and any kind of feebly-interacting long-lived particle

NA62 data taking

2014	2015	2016	2017	2018	2019-2020
Pilot Run	Commissioning	Commissioning + Physics Run	Physics Run	Physics Run	LS2 Long shutdown 2

TRIGGER STREAMS

πνν Trigger
- 1 track
- γ/μ veto

Data Sample

Control Trigger

$K^+ \rightarrow \pi^+\pi^0$, $K^+ \rightarrow \mu^+\nu$,
$K^+ \rightarrow \pi^+\pi^+\pi^-$ samples for background estimation

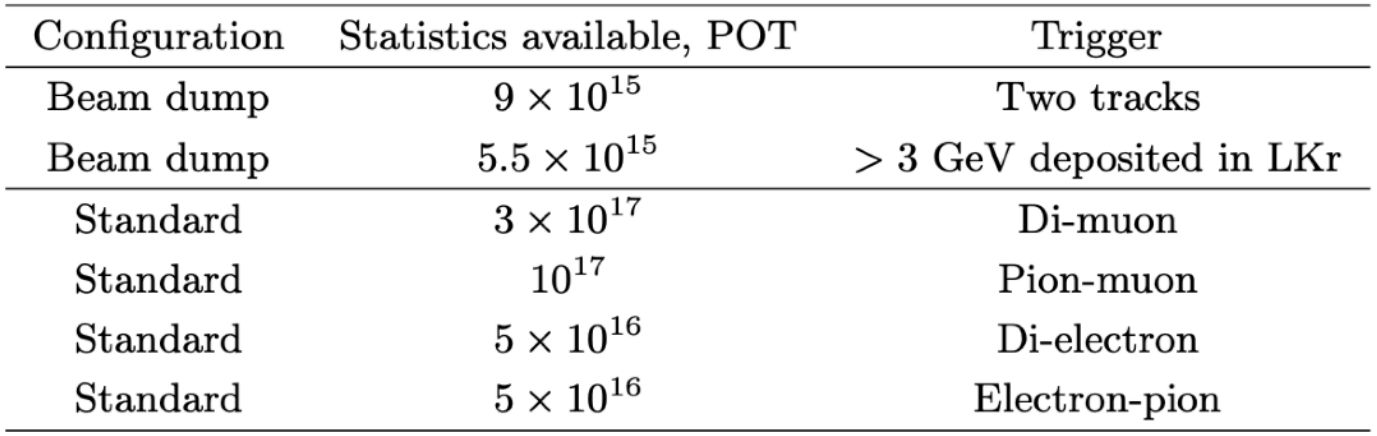
750 kHz, including calibration and control triggers, little free bandwidth!
Parallel trigger masks with high efficiency & negligible efficiency reduction for the main stream have been developed:

πμ
ee
μμ
multi-tracks

New Physics searches
(exotic particles decaying in visible SM particles)

+ Test Runs in dump mode

NA62++ during Run3



Configuration	Statistics available, POT	Trigger
Beam dump	9×10^{15}	Two tracks
Beam dump	5.5×10^{15}	> 3 GeV deposited in LKr
Standard	3×10^{17}	Di-muon
Standard	10^{17}	Pion-muon
Standard	5×10^{16}	Di-electron
Standard	5×10^{16}	Electron-pion

Summary of data recorded in 2016 and 2017 to be used for searches for long-lived new-physics exotic states. 2018 statistics still to be added!

Dump mode

- The switching from the standard beam mode to the beam-dump mode takes a few minutes and it is already done regularly. About 3×10^{16} POT (proton on target) in dump mode have already been collected considering the full 2016-2018 data taking and are being analysed for background studies

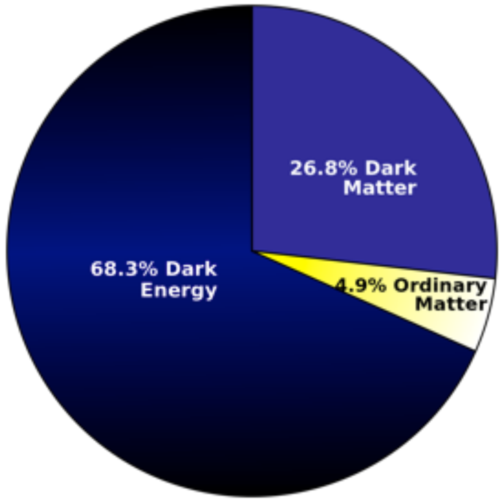
NA62++ proposes to integrate with O(10^{18}) POT operating the detector in dump mode for few months during Run 3 (2021- 2023, 3 years: πνν + dump).

- The muon halo emerging from the dump is partially swept away by the existing muon clearing system, an upstream veto is under study to reduce this background in Run3

The physics prospects of NA62++ have been studied as part of the *‘**Physics Beyond Colliders – Beyond the Standard Model**’* working group. Plots shown in the following about the expected sensitivities in ~5 years scale are from the PBC report **arXiv:1901.09966.**

Dark Photon

A new U(1) gauge-symmetry sector, with a vector mediator field A' named as "dark photon", could explain the abundance of dark matter in our universe. In this scenario [1][2] the A' field would (feebly) interact with the SM photon through a "kinetic mixing" Lagrangian with a coupling parameter ε



Kinetic mixing Lagrangian

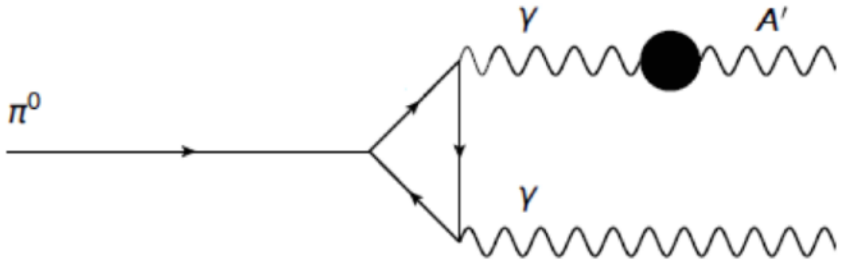
$$\mathcal{L}_{\text{mix}} = -\frac{\varepsilon}{2} F^{\text{QED}}_{\mu\nu} F^{\mu\nu}_{\text{dark}}$$

[1] L. Okun, Sov.Phys.JETP 56 (1982) 502.
[2] B. Holdom, Phys.Lett. B166 (1986) 196.

- ε is kinetic mixing strength. The smaller ε, the longer lifetime of A'
- If A′ is lightest "Dark Sector" particle: can only decay to SM particles
- If A′ is not lightest: decays "invisibly," so that a missing-energy signature might reveal its presence
- two-body final states should dominate for masses below 500 MeV

NA62 searched for Dark Photon produced in π^0 decay: **$K^+ \to \pi^+\pi^0$, $\pi^0 \to \gamma$ A', A' → invisible**

$$\frac{B(\pi^0 \to \gamma A')}{B(\pi^0 \to \gamma\gamma)} = 2\varepsilon^2 \left(1 - \frac{m^2_{A'}}{m^2_{\pi^0}}\right)^3$$

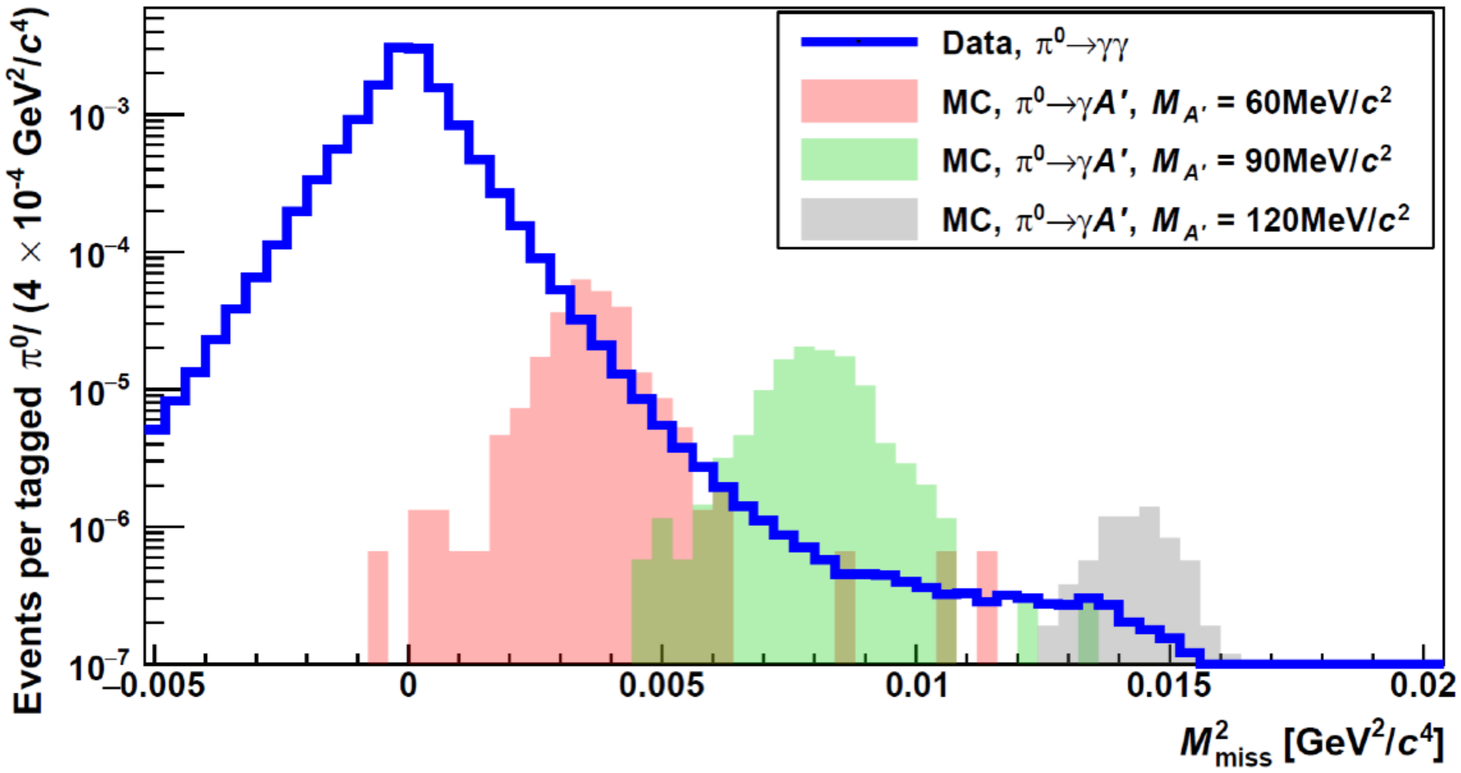


Sensitivity for masses **below the π⁰ mass**

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

From 2 years running at nominal intensity:

$O(10^{13})$ K^+ decays in fiducial volume ⇒ $O(10^{12})$ π^0 decays $BR(K^+ \rightarrow \pi^+\pi^0 \approx 20\%)$



Analysis Strategy

- Search for excess of events in missing mass spectrum:

$$M^2_{miss} = (P_K - P_\pi - P_\gamma)^2$$

- Count n_{sig} in sliding mass window across m^2_{miss}
- Convert n_{sig} to limit on ε

Expected to peak around the squared A' mass for the signal and around zero for the dominant background due to $\pi^0 \rightarrow \gamma\gamma$ decays

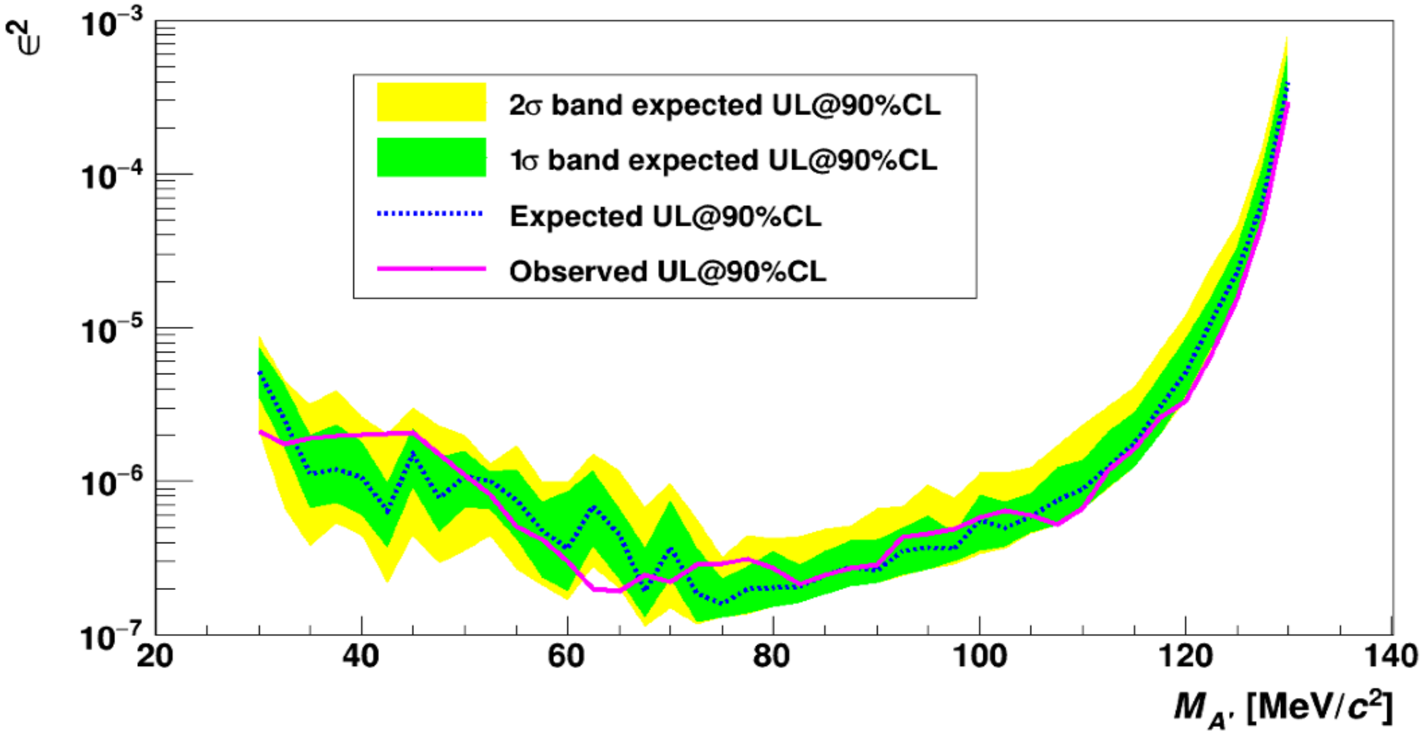
Signal selection

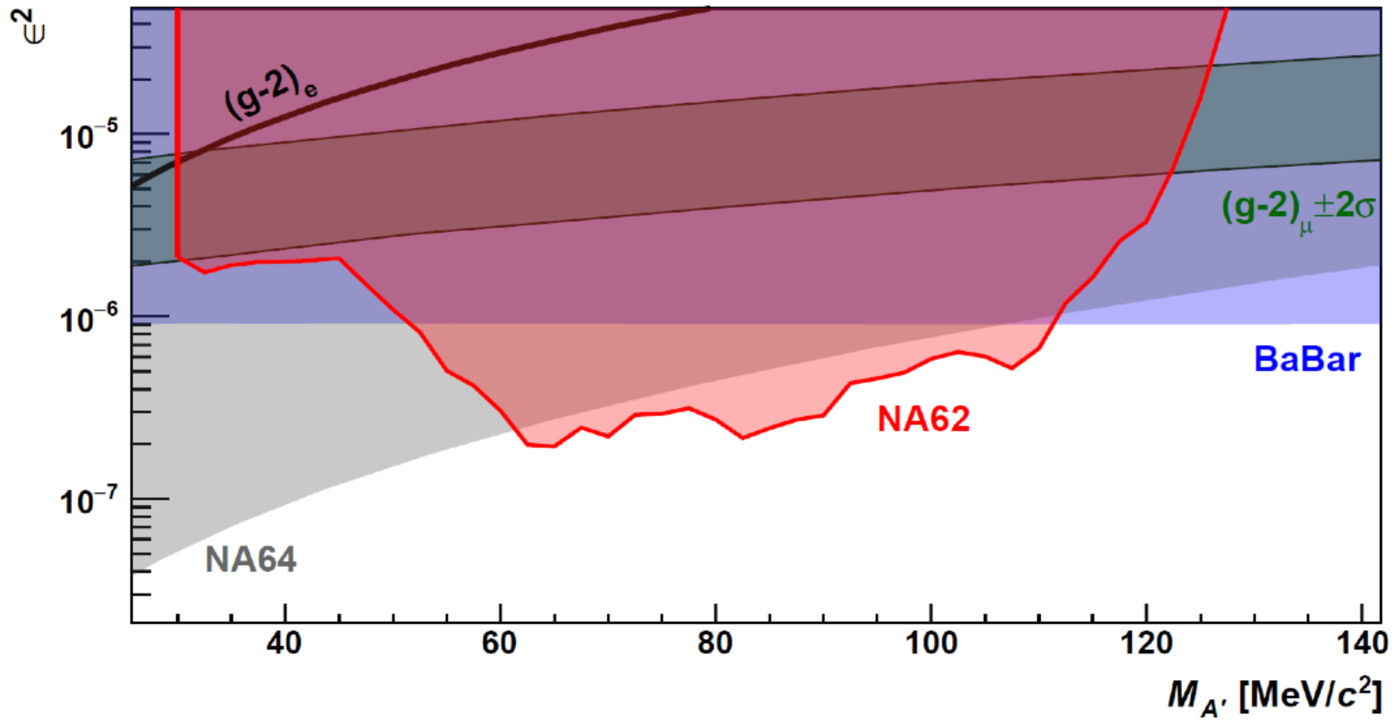
- Search parasitic to πνν-trigger ("1 track" + small forward energy)
- Signal signature: 1 track + 1 photon cluster in LKr + missing energy
- Data driven background estimation.

  Dominant background: $\pi^0 \rightarrow \gamma\gamma$ with 1 γ missing

The NA62 photon-veto rejection, precisely studied in the context of the analyses for $K^+ \rightarrow \pi^+\nu\nu$, is paramount for the A' search

A'→invisible results with 2016 data





arXiv:1903.08767 (JHEP)

The analysis has been performed with a fraction of 2016 data, equivalent to ≈ 1% of the total kaon flux collected by NA62 through 2018.

A peak search has been conducted, comparing signal-selected samples and data-driven background estimates.

No significant statistical excess has been identified and upper limits on the coupling strength ε^2 in the mass range 30–130 MeV/c^2 have been set, improving on the previous limits over the mass range **60–110 MeV/c^2**

- Limit improved by more than three orders of magnitude:

  BR($\pi^0 \to \gamma\nu\nu$) < 1.9 × 10^{-7} at 90% CL
- Improvement on BR(π^0→invisible) over current limit of 2.7×10^{-7} is also possible

NA62 potential for A' visible decays(PBC)

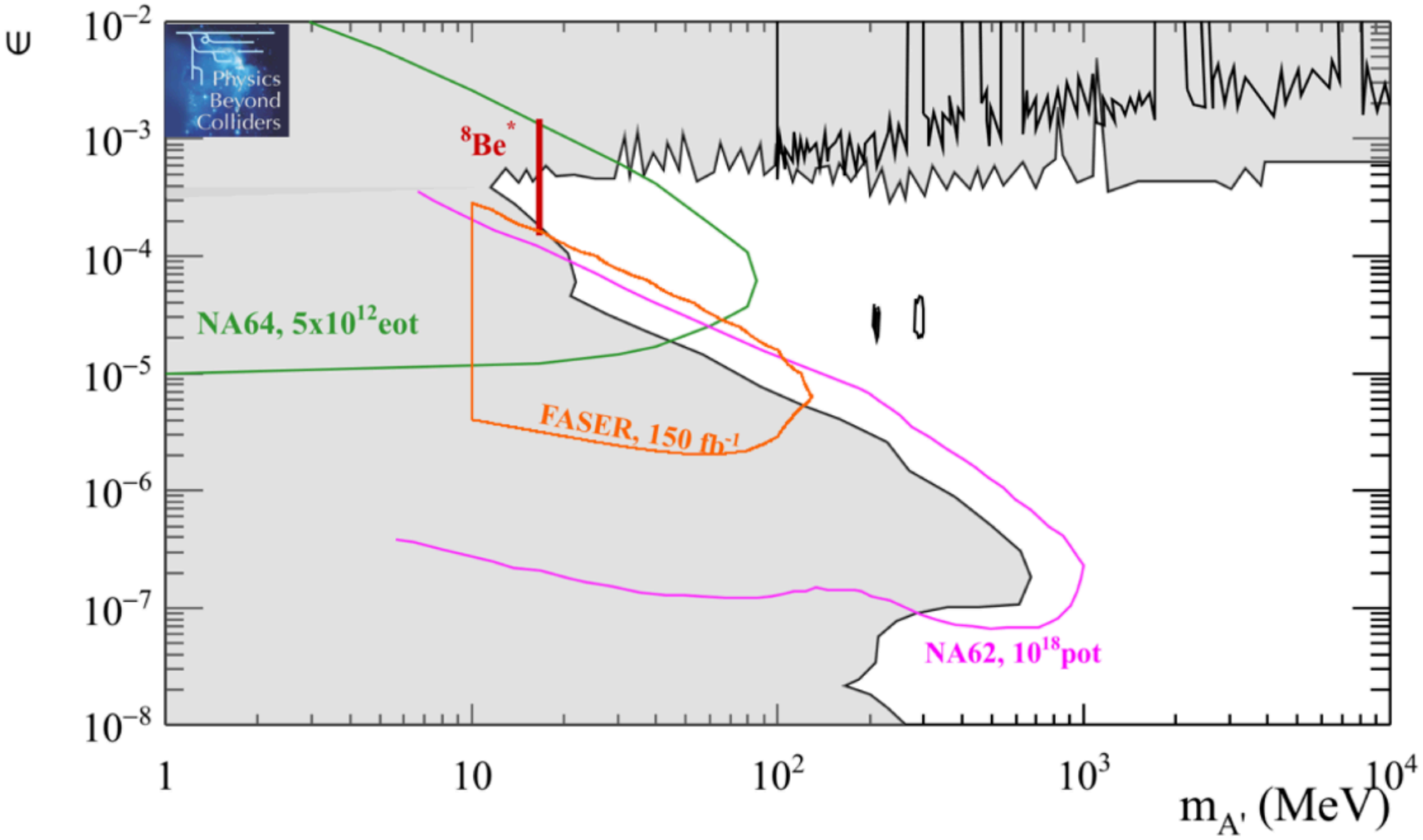
Expected sensitivity to dark photons di-lepton decays from the sole contribution of the Be-target: **$A'\to e^+e^-$, $A'\to\mu^+\mu^-$** in NA62 fiducial volume

Expectation plot:

- account for acceptance/trigger/ selection efficiency
- assumption of complete background rejection
- Evaluate 90% CL exclusion plot

Sensitivity expected to be higher than shown:

- including direct QCD production of A'
- Including A' production in the collimator (here, only target)

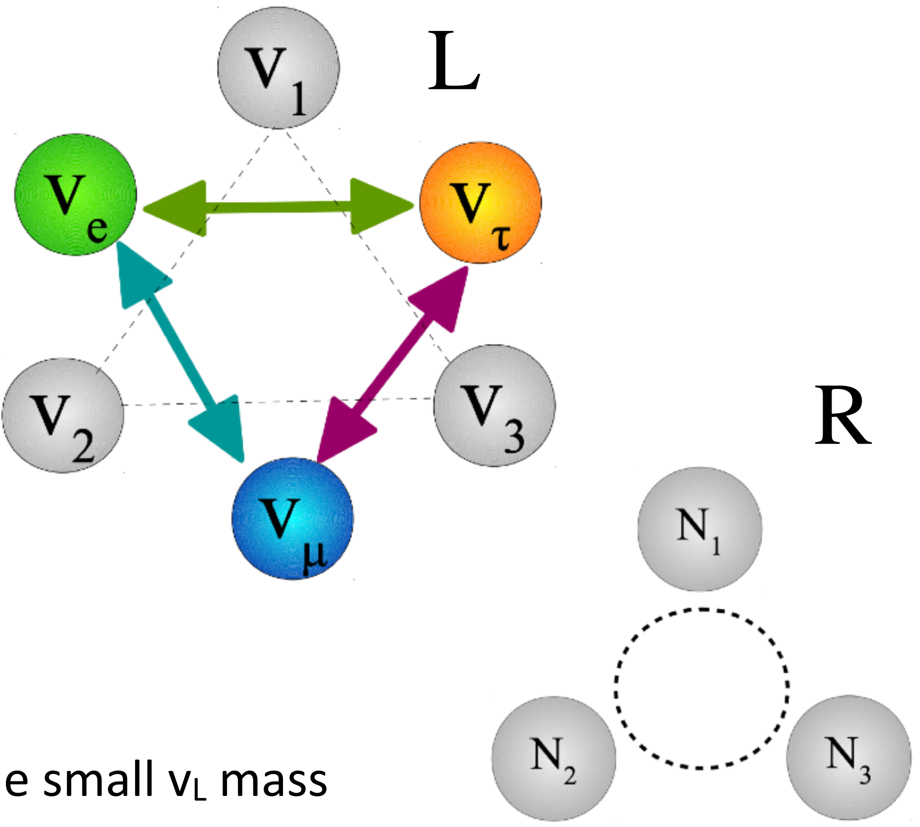


PBC projects on ~ 5 year timescale: upper limits at 90 % CL for Dark Photon in visible decays in the plane mixing strength with SM photon versus mass m_{A}.

Acquired in 2016-2018: ~ 10^{18} POT with μμ-parasitic trigger, ~5 10^{16} POT with *ee*-parasitic trigger

Background rejection has been proven with 4 × 10^{15} POT statistic for the $\mu^+\mu^-$ final state, polluted by background due to accidental pairing of two muons from the beam halo

Heavy Neutral Lepton



What is the origin of the neutrino masses?

- Dark Matter

- Baryon Asymmetry of the Universe (BAU)

- Low mass of SM ν

explained **adding three sterile Majorana neutrinos N_R to the SM**[1]

- Lightest O(keV) → Dark Matter candidate
- Others: O(100 MeV – GeV), Seesaw for ν_S

New heavy neutral leptons N_R would be a “natural” explanation for the small ν_L mass

- Different phenomenology depending on the mass parameters

NA62 searched for Heavy Neutrino produced in K^+ decay: **$K^+ \to \ell^+ N$ ($\ell = \mu, e$)** due to mixing with SM neutrinos

$$\mathcal{B}(K^+ \to \ell^+ N) = \mathcal{B}(K^+ \to \ell^+ \nu) \cdot \underbrace{\rho_\ell(m_N)}_{\text{phase-space factor}} \cdot \underbrace{|U_{\ell 4}|^2}_{\text{mixing strength}}$$

Sensitivity for masses **below the K^+ mass**

[1]Asaka and Shaposhnikov, PLB 620 (2005) 17

HNL from K decays with 2015 data

Analysis Strategy

- Search for excess of events in missing mass spectrum:

$$M^2_{miss} = (P_K - P_\ell)^2 = m^2_N$$

- Count n_{sig} in sliding mass window across m^2_{miss}
- Convert n_{sig} to limit on $|U_\ell|$

Data sample

- $N_K = 3 \times 10^8$ for $K^+ \rightarrow e^+N$
- $N_K = 1 \times 10^8$ for $K^+ \rightarrow \mu^+N$

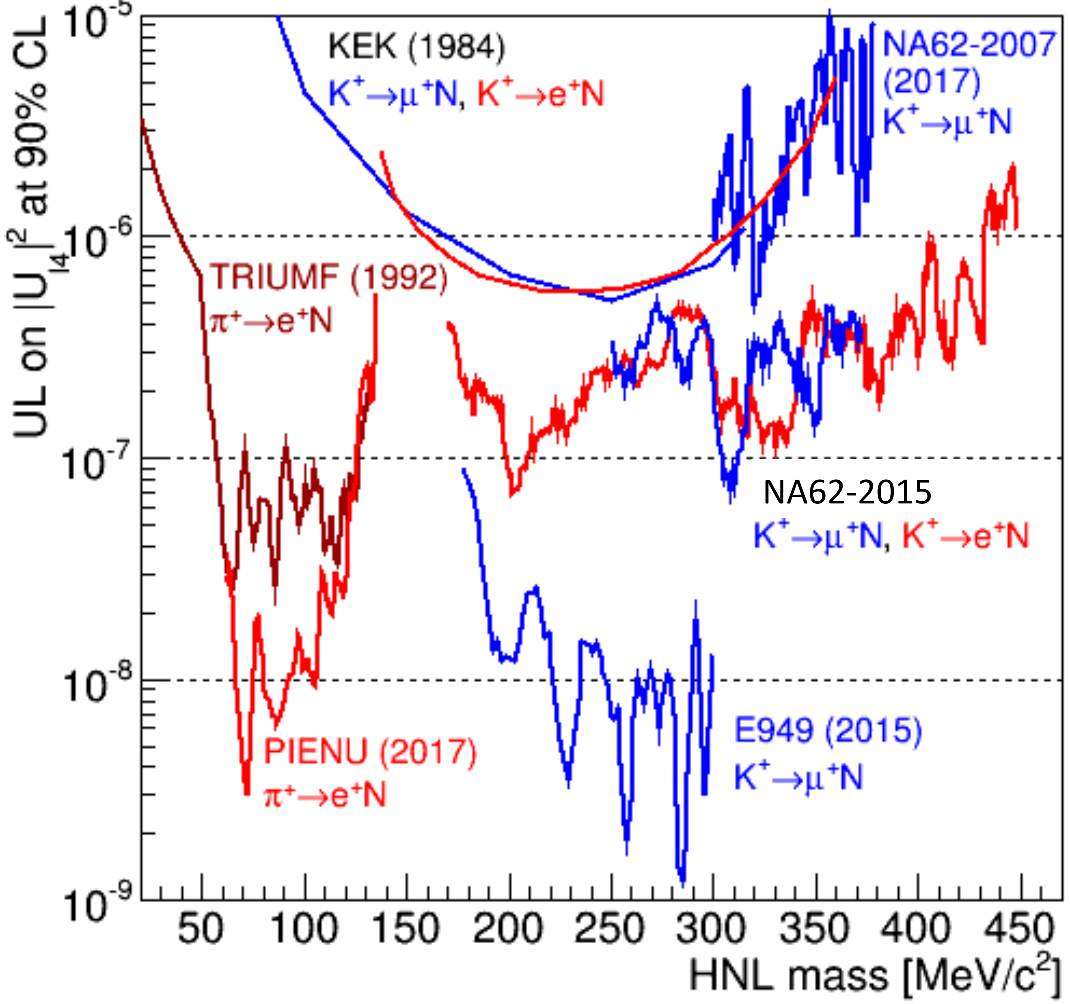
Reached **10^{-6}-10^{-7}** limits for **$|U_{l4}|^2$**

- Improved limits on **$|U_e|$** from 170 – 448 MeV/c^2
- Improved limits on **$|U_\mu|$** above 300 MeV/c^2

Full 2016-2018 data set analysis will explore $|U_{l4}|^2 \lesssim 10^{-8}$ range

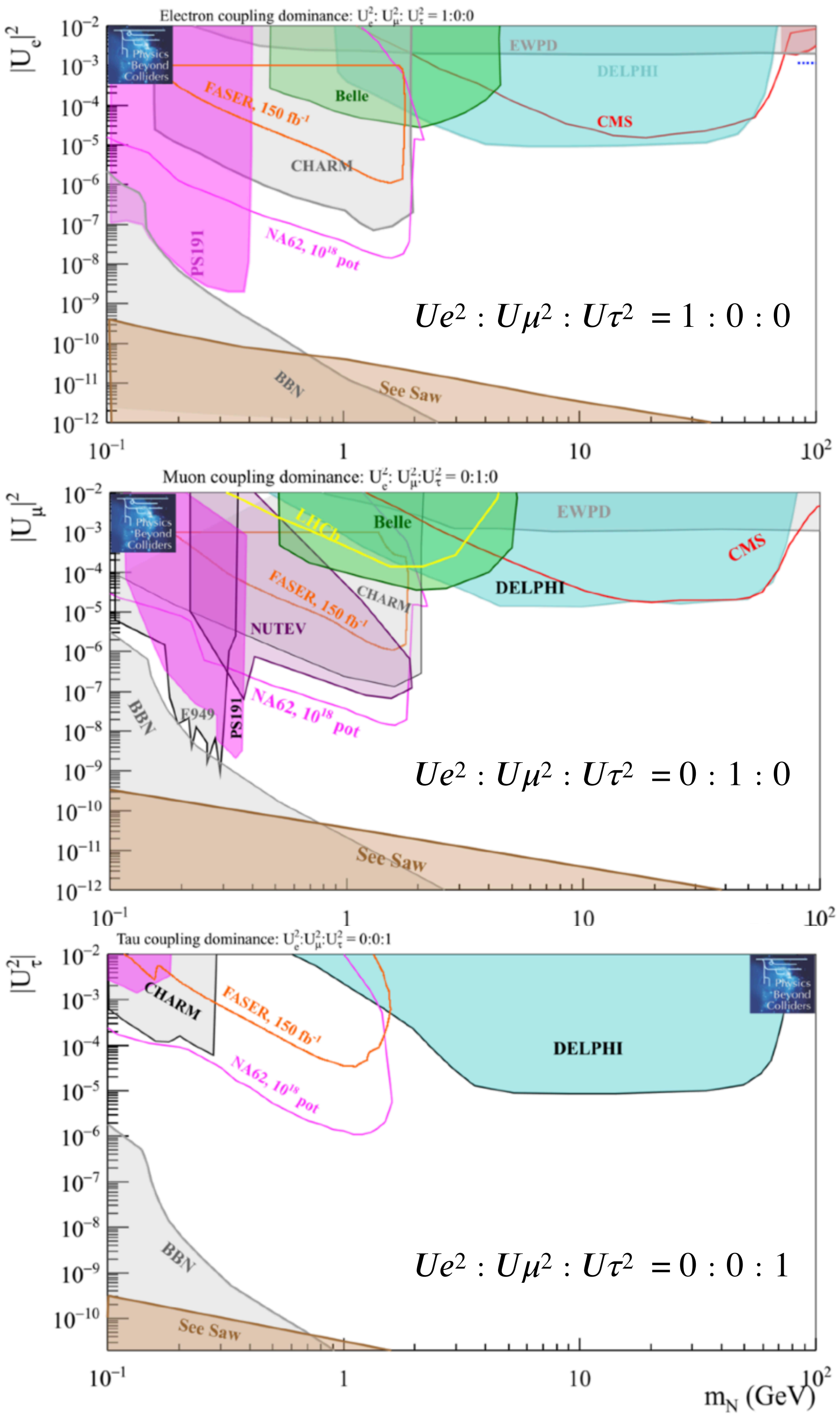
The analysis has been performed with 5 days of 2015 data with a minimum-bias trigger. NA62 running at ≈ 1% of the nominal intensity

Limits from heavy neutrino searches



[Phys. Lett. B778 (2018) 137]

Potential for HNL from beam dump (PBC)



From leptonic decays of **D(D$_s$)** → l^+**N** soon after production in the dump (mass up to ~ 1.7 GeV)

- **N → πe, N → πμ**:

2 oppositely-charged, in-time, tracks reconstructed as originating from the 60-m long fiducial volume, 1-lepton final states

Invariant mass should reconstruct HNL mass

- include trigger/acceptance/selection efficiency
- assume zero-background

Analysis of 3x10^{16} POT collected in dump mode in 2017-2018 in progress….

Sensitivity to Heavy Neutral Leptons with coupling to one lepton generation only (e, μ, τ, respectively). Current bounds (filled areas) and near (~ 5 years) future physics

NA62 potential for Axion Like Particles

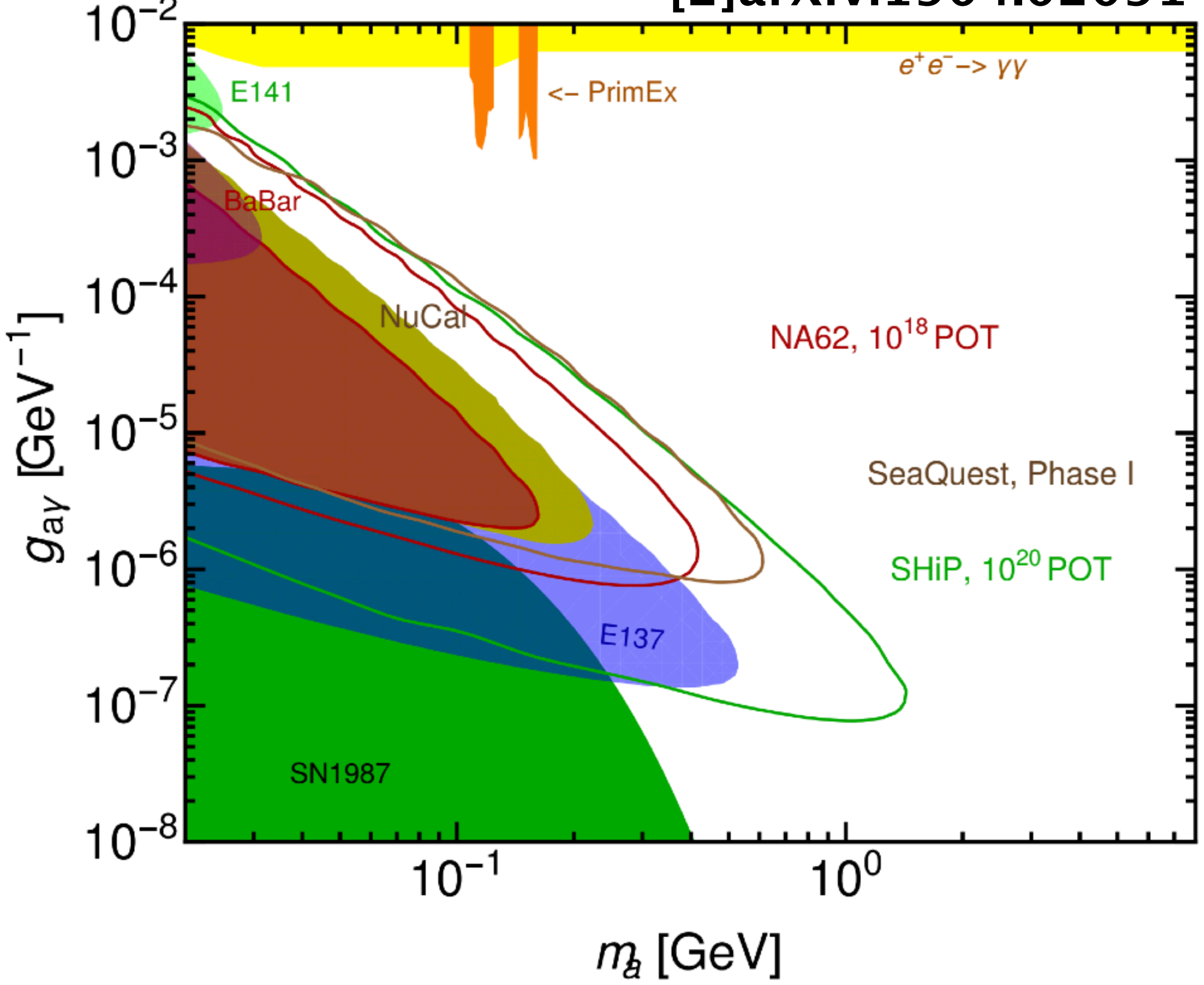
Axion Like Particle (ALP) production via Primakoff effect[1] from interaction onto collimator, assuming a single ALP state "a", and the predominant coupling to photons ⇒ search can be performed only in **beam-dump** mode

Production mechanism

- ALP created by the charged proton itself
- Protons interact with the target nucleus and produce neutral mesons. The mesons (mostly π^0) decay into $\gamma\gamma$ which subsequently can interact with another nucleus to produce an ALP. Recently found to be very relevant[2]:

The decay $a \to \gamma\gamma$ may occur in NA62 fiducial volume

[2]arXiv:1904.02091



ALPs with photon coupling. Current bounds -90% CL (filled areas) and prospects on 5 years timescale (solid lines) in the plane coupling $g_{a\gamma\gamma}$ versus mass m_{ALP}. Geometrical acceptance considered with zero background assumption

Analysis of 3x10^{16} POT collected in dump mode in 2016-2018 in progress (1 day of run in real beam-dump mode :~ 1.3 10^{16} POT's, enough statistic to put a new upper limit).

[1]JHEP 1602 (2016) 018

NA62 potential for Dark Scalar (PBC)

Dark Scalar: a light scalar particle mixing with the Higgs with the angle θ can be a mediator between DM and SM particles

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

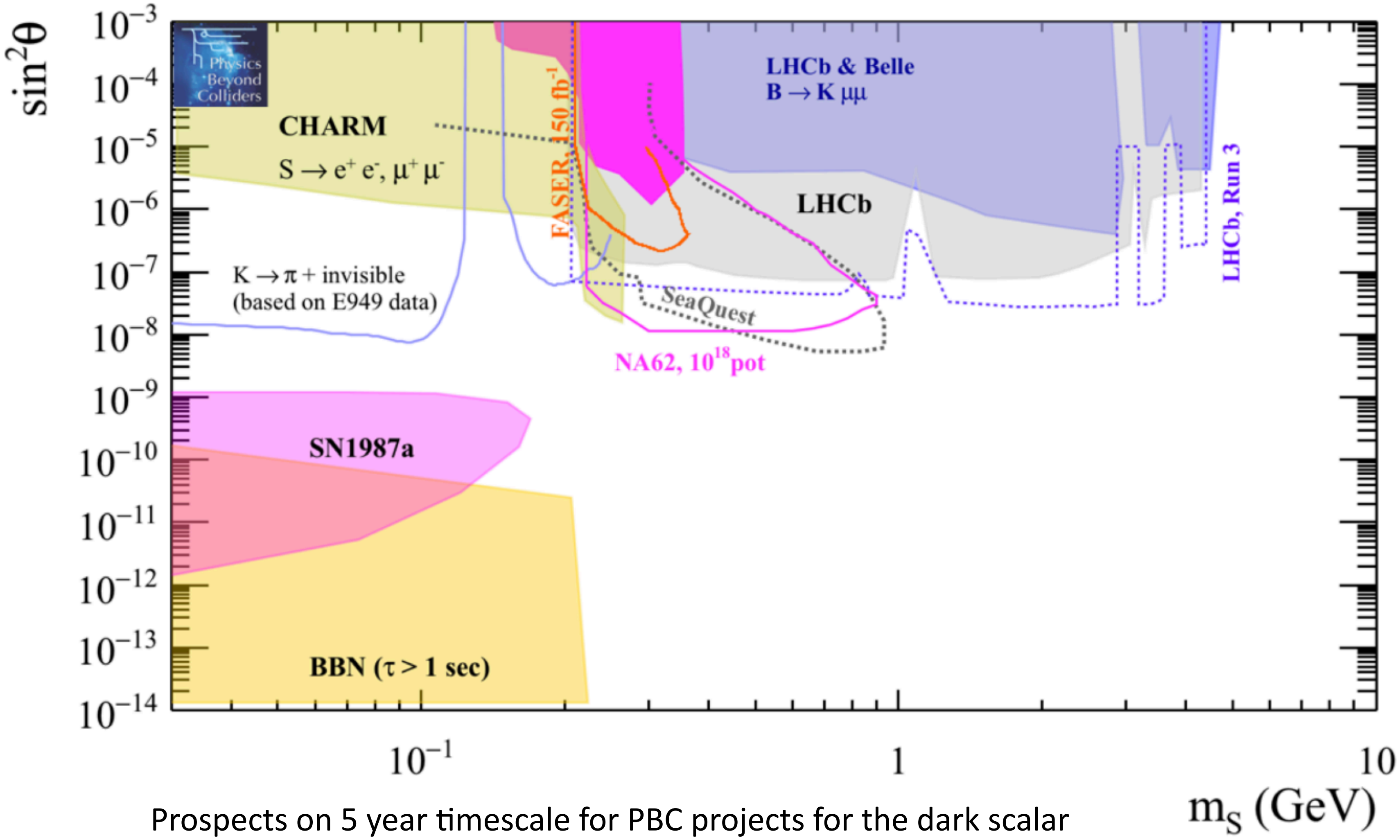
The minimal scenario assumes for simplicity that λ = 0 and all production and decay processes of the dark scalars are controlled by the same parameter μ = sin θ

Dump mode

- $S \rightarrow$ μ+μ-

Kaon mode

- K+ ⟶ π+ S, S ⟶ invisible
- K+ ⟶ π+ S, S ⟶ μ+μ-



Prospects on 5 year timescale for PBC projects for the dark scalar mixing with the Higgs in the plane strength of mixing with SM Higgs ($\sin^2\theta$) versus dark scalar mass m_S

Conclusions

- **The NA62 experiment is a powerful laboratory to make searches for exotic decays**
  - Results of recent searches for the exotic decays

  $\mathbf{K^+} \to \ell^+ \mathbf{N}$ and $\boldsymbol{\pi^0} \to \gamma\, \mathbf{A'}$ were presented. Worlds-best limits have been set.

- **Further results and useful studies will be obtained with the NA62 full data set analysis (2016-2018)**

- **Partially running in dump mode after LS2 (2021-2023) will allow to fully exploit the physics reach with the current NA62 setup**

  \- The limits improvement foreseen for dark photons (A’), dark scalars (S), axion-like particles (ALP) and heavy neutrinos (N) searches have been shown

- **Improvements to the NA62++ setup are not included here, but initial studies are promising**
  - New upstream veto,
  - Beamline modifications, higher intensity

Thank you for your attention!!
From the NA62 Collaboration