

Dark sector searches in NA62 and other non-LHC experiments



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Outline

- 1 Dark Photon
- 2 Heavy Neutrino
- 3 Stable Six-Quark State
- 4 Prospects

Non-LHC experiments mentioned here



Search for dark sectors in missing energy events



Possible Dark Sector Particles

- Vector Interaction: Dark Photon
- Axial: Axions, ALPs
- Scalar: “dark Higgs”
- Others: Heavy neutral leptons (neutrino)
- And other things. . .

Dark Photon – Introduction

- Introduce new Interaction with $U(1)$ gauge symmetry, with gauge boson: the “dark photon” A'
[P.Fayet, PLB95 (1980) 285; B.Holdom, PLB160 (1986) 196]

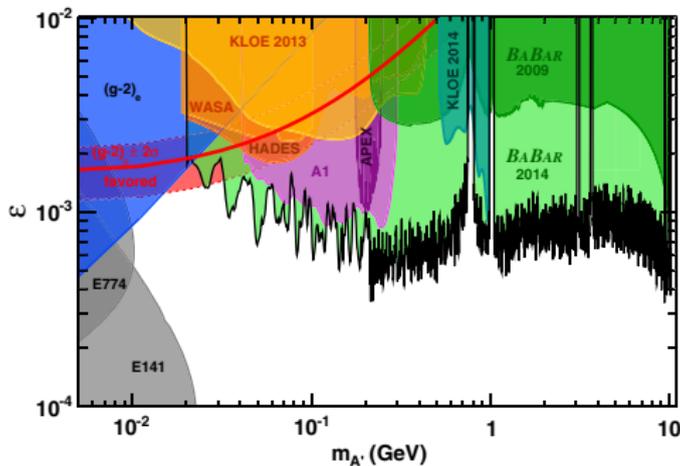
- Coupling constant and charges generated through kinetic mixing:

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

- 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 “dark”.
- Could explain also other things ($(g - 2)_{\mu}, \dots$)

BABAR: $e^+e^- \rightarrow \gamma A', A' \rightarrow e^+e^-, \mu^+\mu^-$

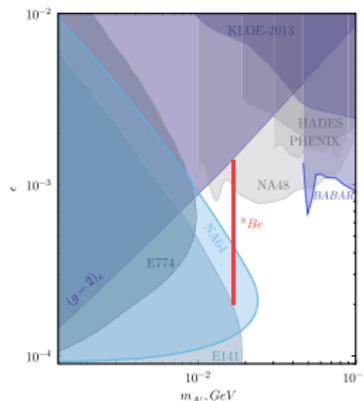
- $e^+e^- \rightarrow \gamma A', A' \rightarrow e^+e^-, \mu^+\mu^-$
- No signal observed: $\epsilon \lesssim 10^{-3}$ for $0.02 \text{ GeV}/c^2 \lesssim m_{A'} \lesssim 10.2 \text{ GeV}/c^2$



[Phys. Rev. Lett. 113, 201801 (2014), arXiv:1406.2980]

NA64: $e^- Z \rightarrow e^- Z A'$, $A' \rightarrow e^+ e^-$

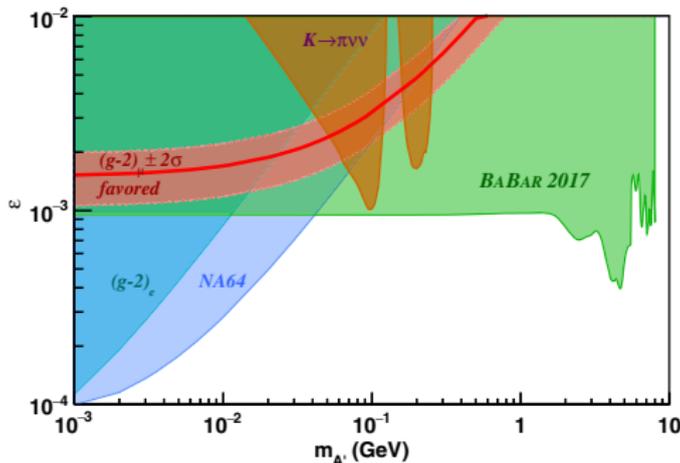
- Fixed target experiment, 100 GeV e^- beam,
- $e^- Z \rightarrow e^- Z A'$, $A' \rightarrow e^+ e^-$
- Special consideration for $A' = X$ with $m_X = 16.7 \text{ MeV}/c^2$
- No signal observed: No X , and
 $\epsilon \lesssim 4.2 \times 10^{-4} - 1.4 \times 10^{-3}$ for $m_{A'} < 23 \text{ MeV}/c^2$



[Phys. Rev. Lett. 120, 231802 (2018), arXiv:1803.07748]

BABAR: $e^+e^- \rightarrow \gamma A'$, $A' \rightarrow$ invisible

- $e^+e^- \rightarrow \gamma A'$, $A' \rightarrow$ invisible, single photon and large missing momentum and energy
- No signal observed: $\epsilon \lesssim 10^{-3}$ for $m_{A'} < 8 \text{ GeV}/c^2$

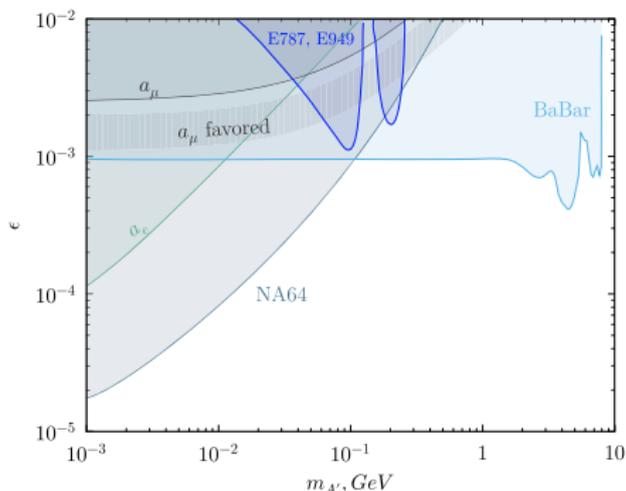


[Phys. Rev. Lett. 119, 131804 (2017), arXiv:1702.03327]

NA64: $e^- Z \rightarrow e^- Z A'$, $A' \rightarrow$ invisible

single electron and large missing energy

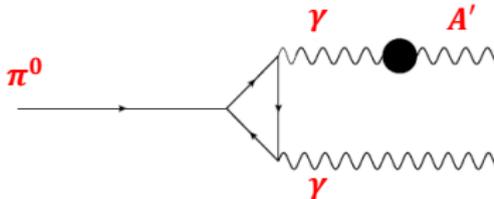
- $e^- Z \rightarrow e^- Z A'$, $A' \rightarrow$ invisible
- No signal observed: $10^{-5} \lesssim \epsilon \lesssim 10^{-3}$ for $m_{A'} < 1 \text{ GeV}/c^2$



[Phys. Rev. D 97, 072002 (2018), arXiv:1710.00971]

NA62: $K^+ \rightarrow \pi^+ \pi^0$, $\pi^0 \rightarrow \gamma A'$, $A' \rightarrow$ invisible

- Accepted in JHEP (2019), arXiv:1903.08767
- $\pi^0 \rightarrow \gamma A'$, $A' \rightarrow$ invisible, π^0 's from $K^+ \rightarrow \pi^+ \pi^0$ decays

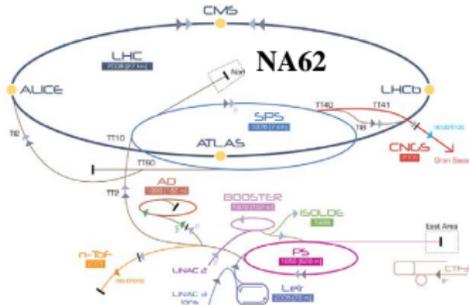


$$\frac{BR(\pi^0 \rightarrow \gamma A')}{BR(\pi^0 \rightarrow \gamma \gamma)} = 2\varepsilon^2 \left(1 - \frac{M_{A'}^2}{M_{\pi^0}^2}\right)^3$$

[Batell, Pospelov, Ritz, PRD80, 095024 (2009)]

- Profit from extremely high-efficiency photon vetoes for $K^+ \rightarrow \pi^+ \nu \bar{\nu}$.
- Using of subsample of 2016 data, corresponding to 1 % of the statistics collected by NA62 in 2016-2018

NA62: the CERN Kaon Factory



Kaon physics at CERN:

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

Currently in NA62:

~200 participants

29 institutions from 13 countries

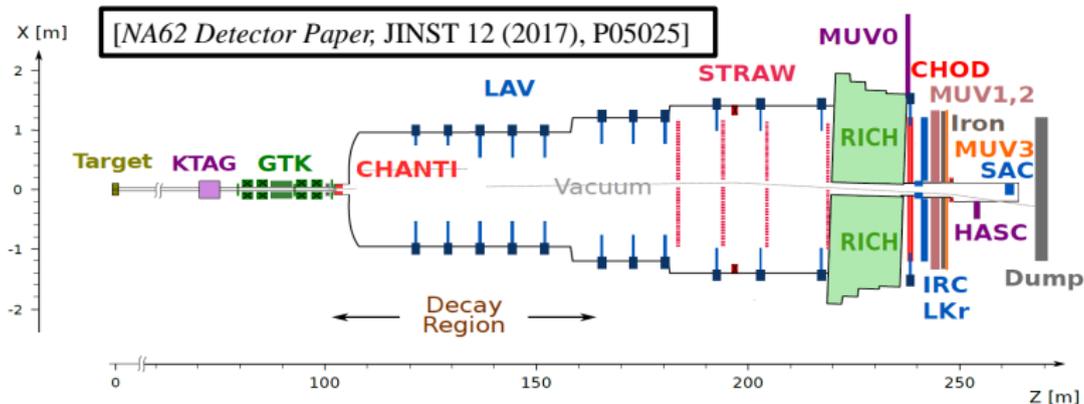


Main goal: $BR(K^+ \rightarrow \pi^+ \nu \bar{\nu})$
measurement with $\mathcal{O}(10\%)$
precision

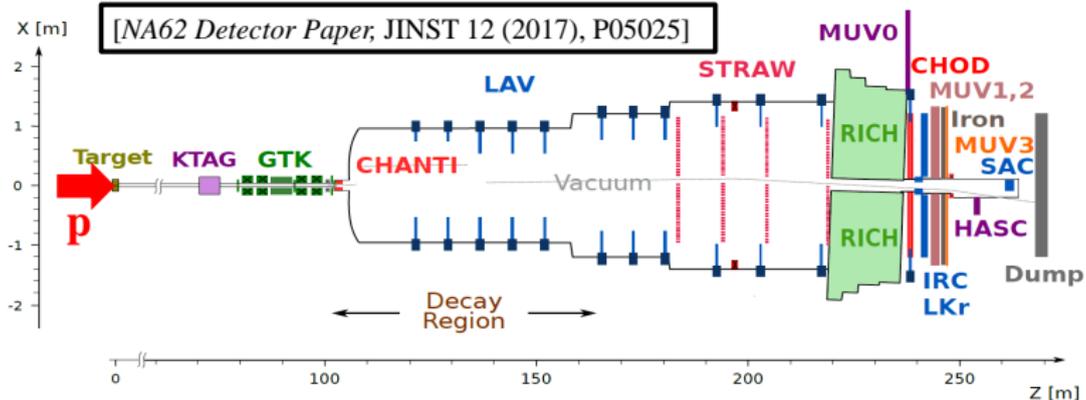
SM prediction: $BR(K^+ \rightarrow \pi^+ \nu \bar{\nu}) =$
 $(8.4 \pm 1.0) \times 10^{-11}$

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

NA62 Layout



NA62 Layout



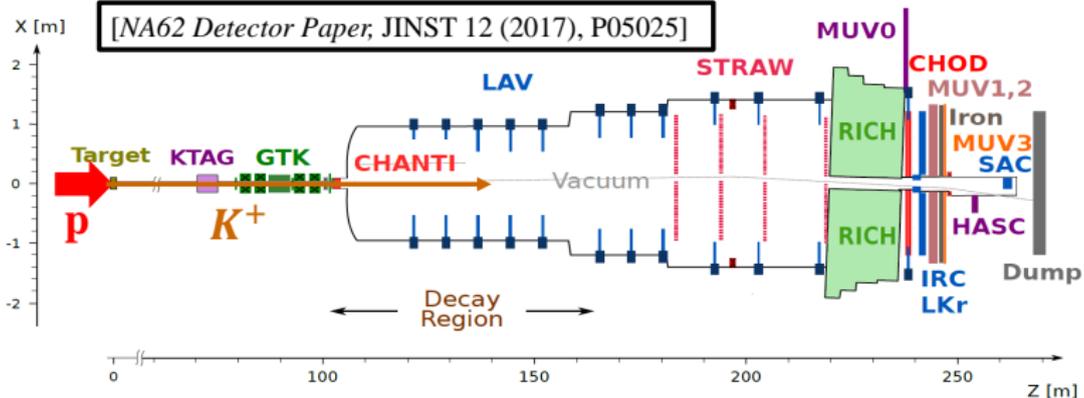
SPS protons:

400 GeV/c

10^{12} PoT/sec on spill

4.8 sec spill

NA62 Layout



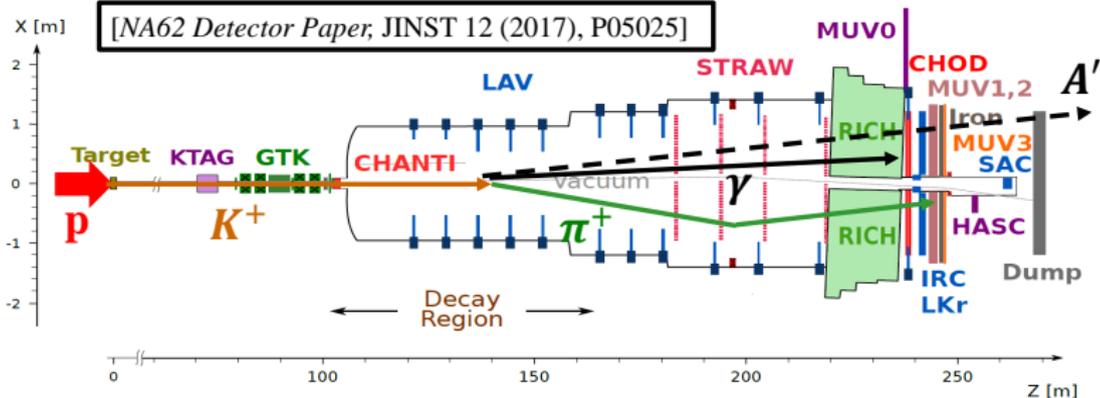
SPS protons:

400 GeV/c
 10^{12} PoT/sec on spill
 4.8 sec spill

Secondary beam:

75 GeV/c, 1% bite
 100 μ rad
 60×30 mm²
 K^+ (6%)/ π^+ (70%)/p (24%)
 750 MHz at GTK3

NA62 Layout



SPS protons:

400 GeV/c
 10^{12} PoT/sec on spill
 4.8 sec spill

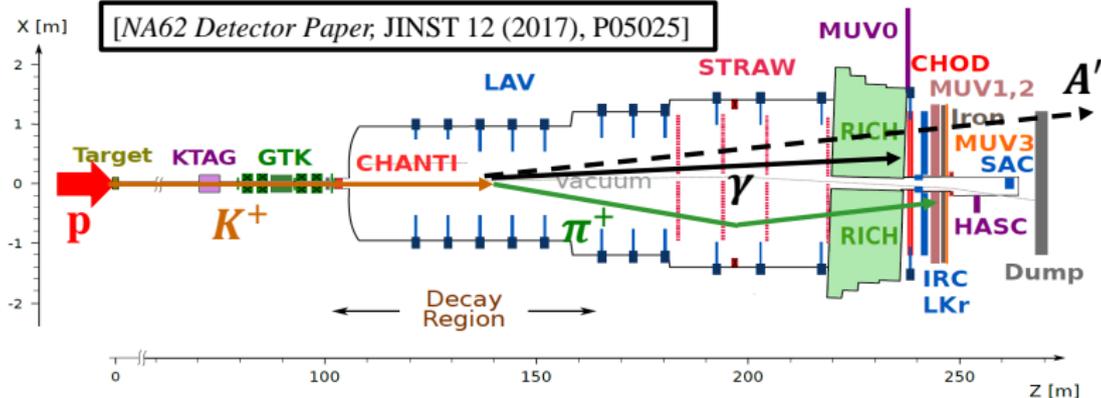
Secondary beam:

75 GeV/c, 1% bite
 100 μ rad
 60×30 mm²
 K^+ (6%)/ π^+ (70%)/p (24%)
 750 MHz at GTK3

Kaon decay region:

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

NA62 Layout



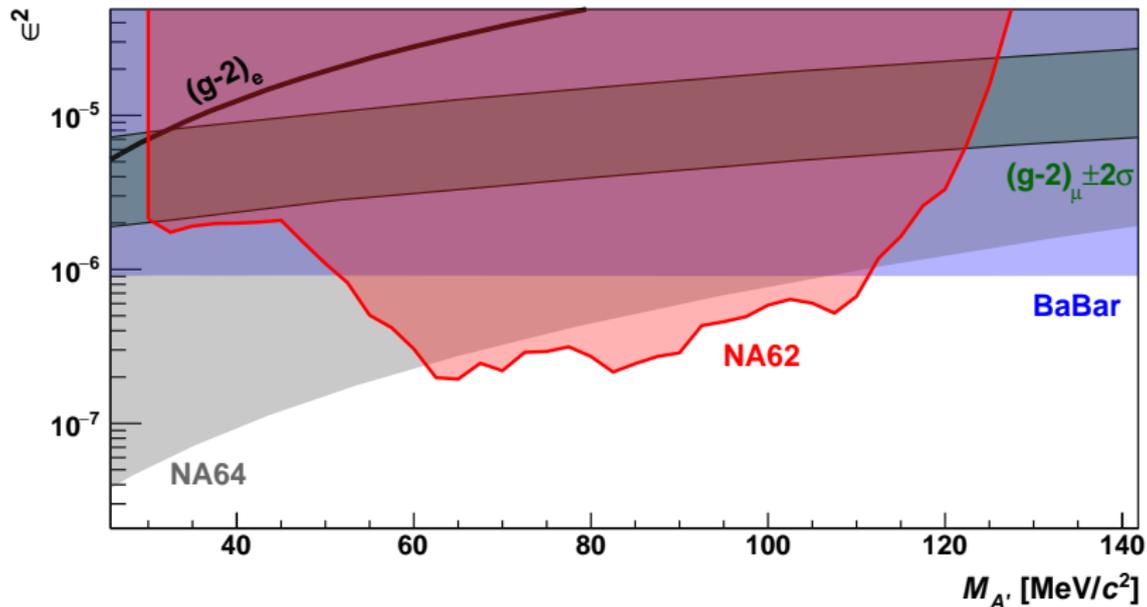
Performances

- ✓ Excellent time resolution $\mathcal{O}(100 \text{ ps})$ 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 $\mathcal{O}(10^7)$ for $15 < p(\pi^+) < 35 \text{ GeV}$
- ✓ High-efficiency veto: 10^8 rejection of π^0 for $E(\pi^0) > 40 \text{ GeV}$

Analysis Principle

- Invisible decay of massive A' or long lived massive A' hypothesis.
- Using 2 trigger streams: Signal, Minimum-bias for background evaluation and normalization
- Most abundant background due to $\pi^0 \rightarrow \gamma\gamma$ with one γ not detected (acceptance, inefficiency, photon conversions)
- Background evaluated with data from minimum bias stream, independent of signal stream
- In signal sample: Peak search in $M_{\text{miss}}^2 = (P_{K^+} - P_{\pi^+} - P_{\gamma})^2$ distribution.

NA62 Dark Photon Result

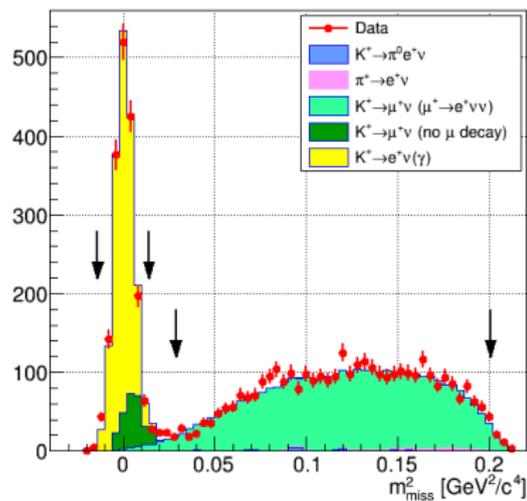


~ 1% of full 2016-2018 NA62 data set

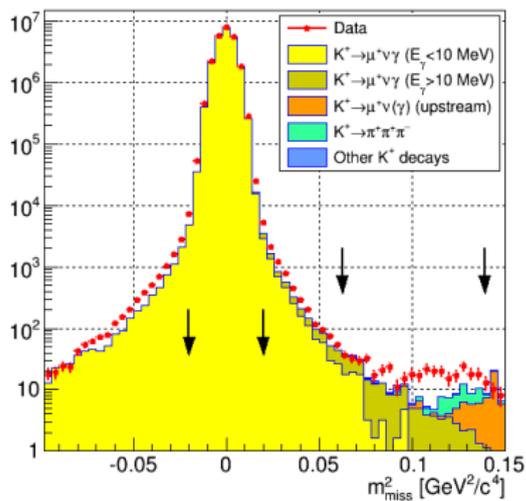
[arXiv:1903.08767]

NA62: Search for heavy Neutrinos in Kaon decays

Search for a peak in missing mass in
 $K^+ \rightarrow e^+ \nu$

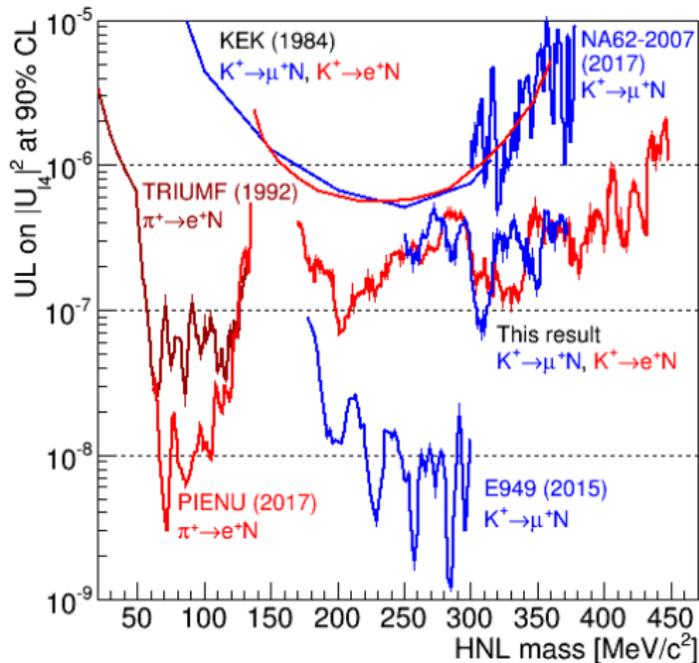


$K^+ \rightarrow \mu^+ \nu$



[PLB 778, (2018) 137-145, arXiv:1712.00297]

NA62: Search for heavy Neutrinos in Kaon decays



NA62 2016 data

[PLB 778, (2018) 137-145, arXiv:1712.00297]

More NA62 results from Kaon decays tomorrow
in Poster Session (N.Estrada-Tristan)

BABAR: Search for Stable Six-Quark State

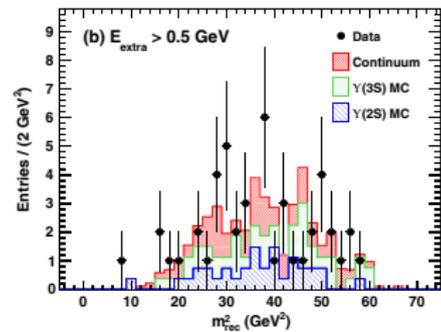
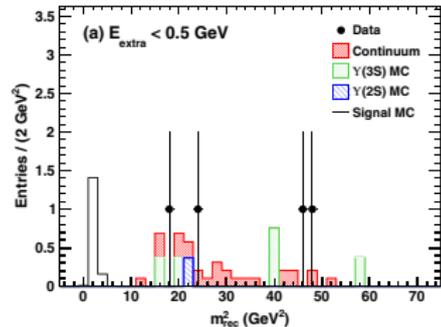
- Completely symmetric six-quark combination $uuddss$ could be deeply bound: S [Farrar, arXiv:1708.08951]
- Jaffe (1977): H Dibaryon with $m_H \approx 2150 \text{ GeV}/c^2$
- $m_H > m_P + m_e + m_\Lambda = 2055 \text{ MeV}/c^2$: typical weak lifetime
- If deeply bound ($m_S < 2055 \text{ MeV}/c^2$): Cosmological lifetime
- If $m_S < 1878 \text{ MeV}/c^2$: Stable
- Search in $\Upsilon \rightarrow S\bar{\Lambda}\bar{\Lambda}$, missing mass recoiling against the $\bar{\Lambda}\bar{\Lambda}$ system

BABAR: Search for Stable Six-Quark State

No signal observed

$$B(\Upsilon \rightarrow S\bar{A}\bar{A}) \lesssim (1.2 - 1.4) \times 10^{-7}$$

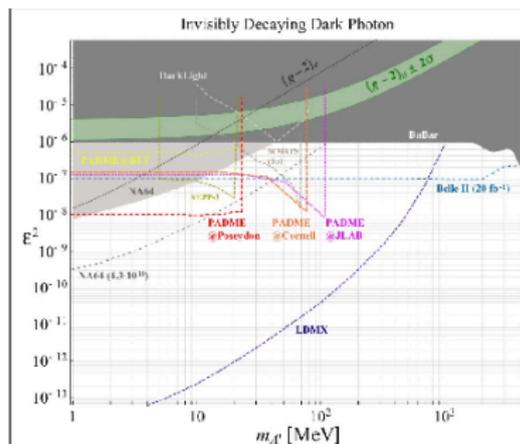
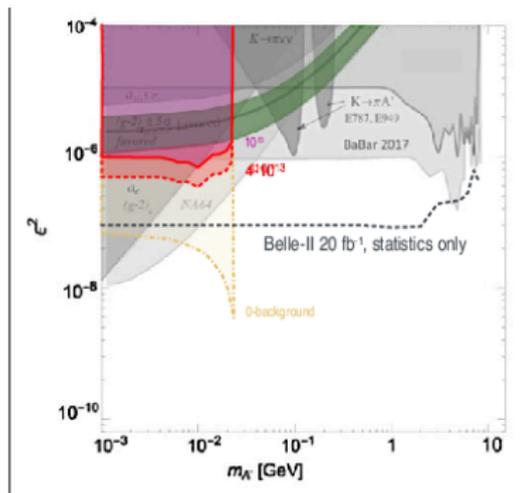
@90% C.L. for $m_S < 2.05 \text{ GeV}/c^2$



More results to come from existing and new experiments

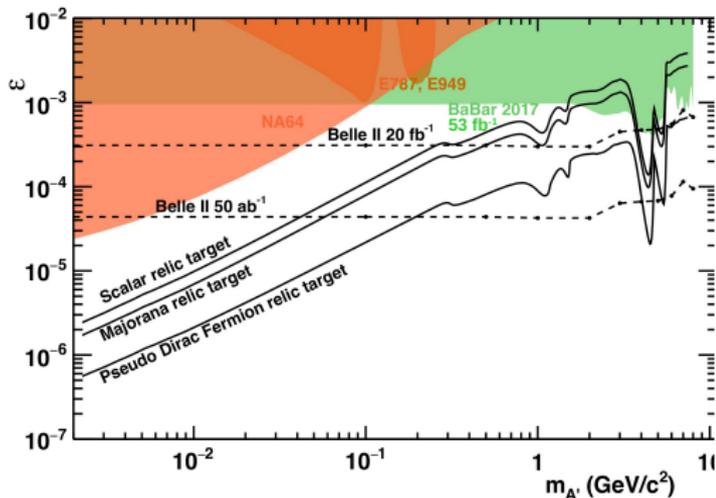
- PADME: New fixed target experiment at Frascati. Took first test data
- Belle II: Just starting to take data. But well prepared for analysis with experience from Belle and Babar.
- NA64: preparing for muon beam as well
- NA62
 - Analysing the statistics from 2016-2018 data taking
 - Beam Dump: has $\mathcal{O}(10^{16})$ POT to analyze
 - Beam Dump: $\mathcal{O}(10^{18})$ POT in 2021-2023 data taking

PADME Prospects: A' \rightarrow invisible



[P.Valente, La Thuile 2019]

BELLE II Prospects: $A' \rightarrow$ invisible

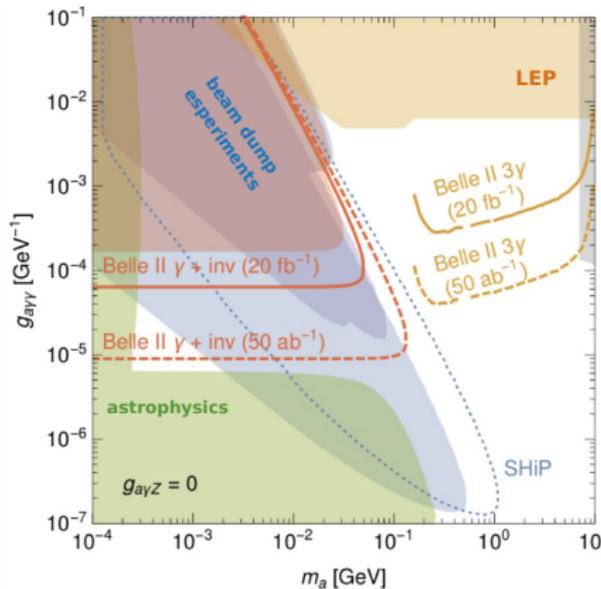
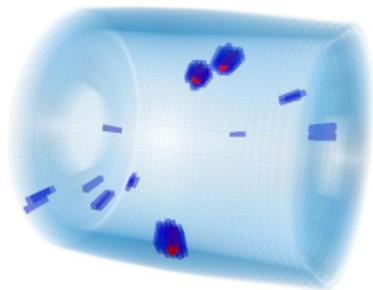
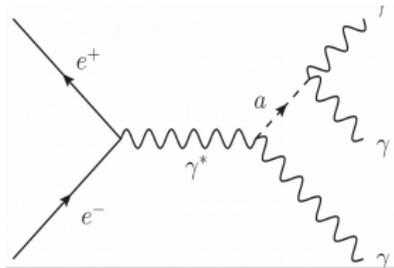


The Belle II Physics book
[arXiv:1808.10567](https://arxiv.org/abs/1808.10567)
BaBar's analysis
[PRL 119,131804](https://arxiv.org/abs/1109.13180)

Why does Belle II perform better than BaBar?
→ no ECL cracks pointing to the interaction regions

[G.Ingulia, La Thuile 2019]

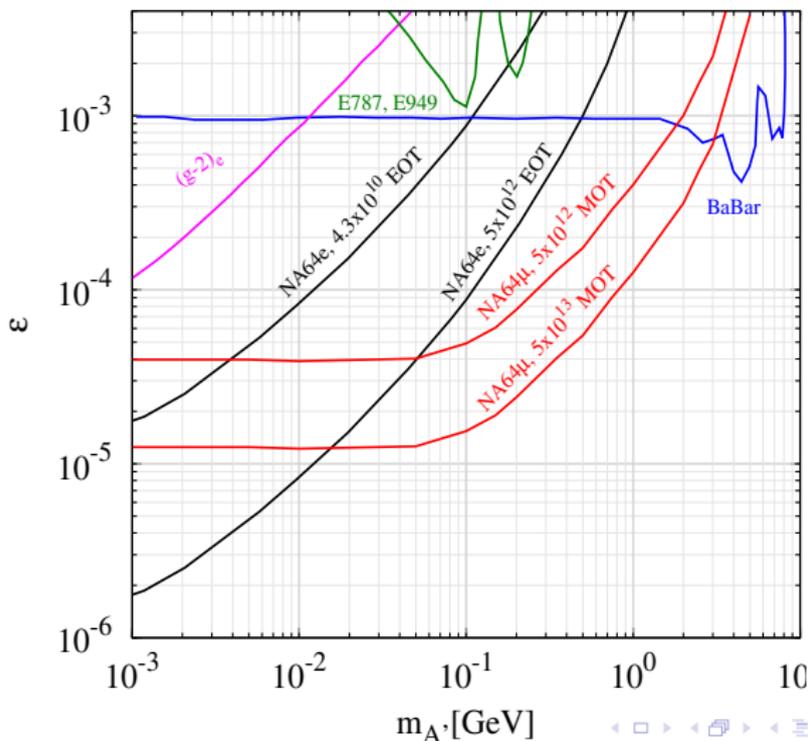
BELLE II Prospects: $ALP \rightarrow \gamma\gamma$



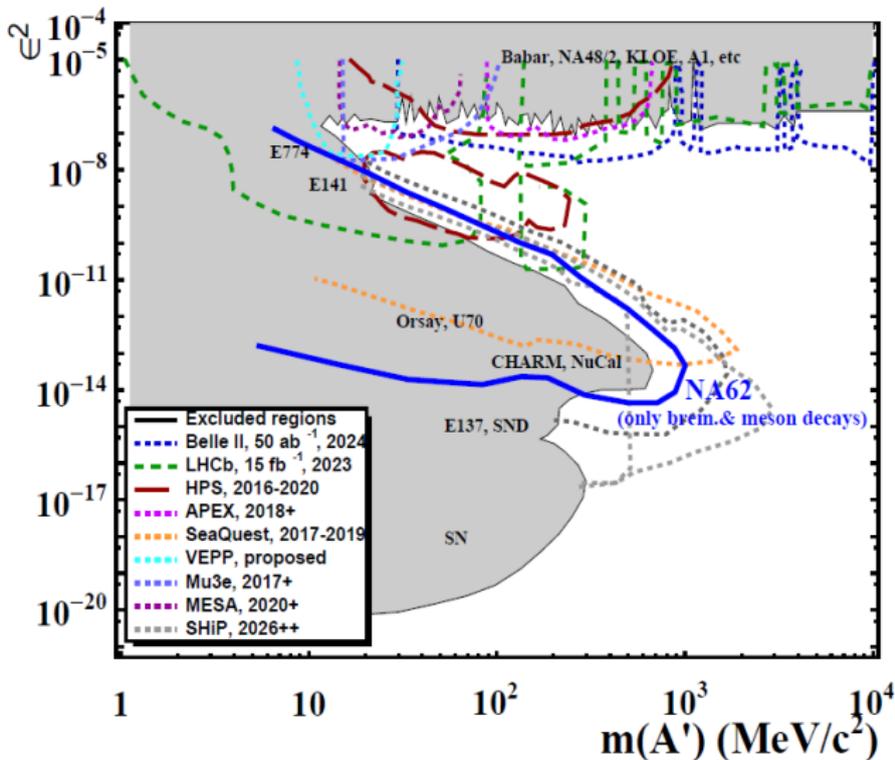
[JHEP 1712 \(2017\) 094](#)

[G.Inguglia, La Thuile 2019]

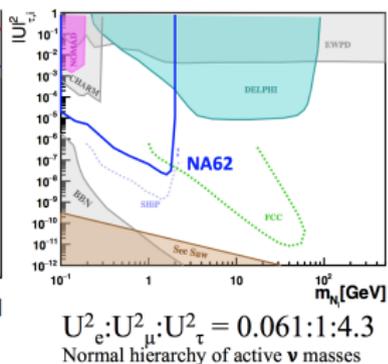
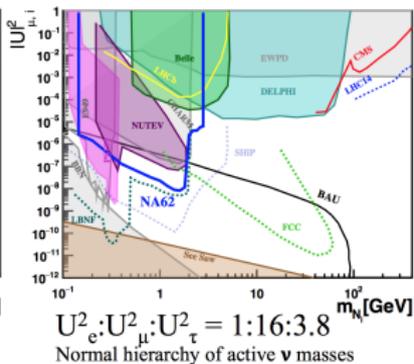
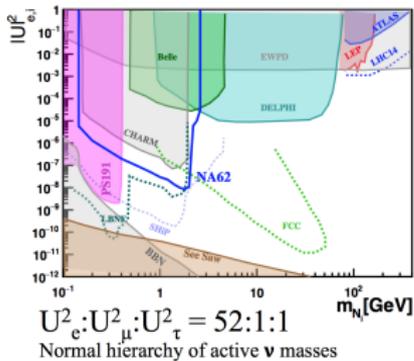
NA64 Prospects: $A' \rightarrow \text{invisible}$



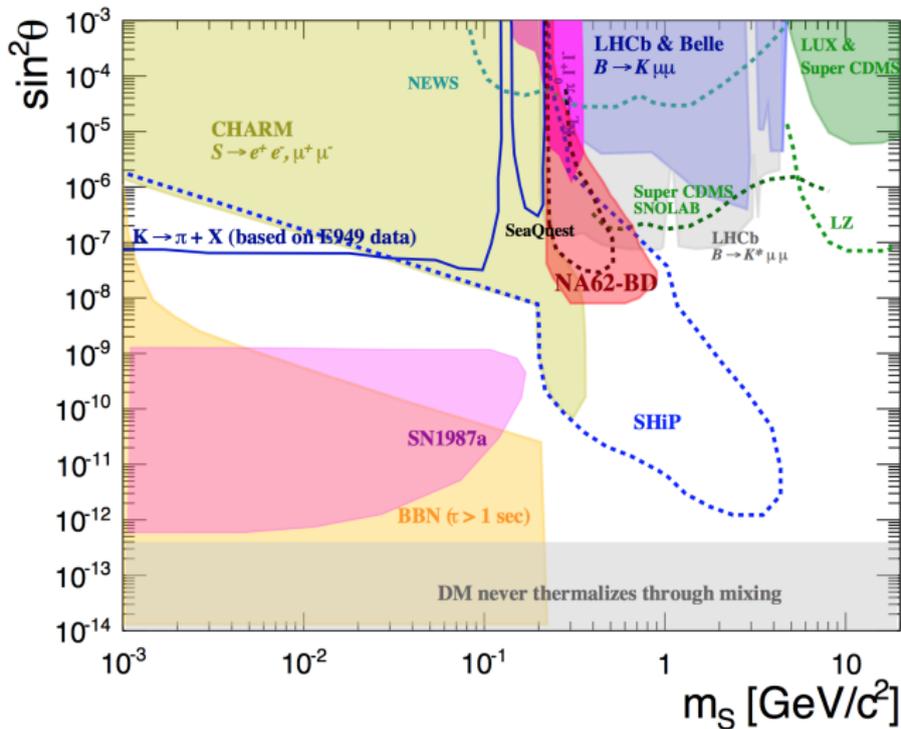
NA62 Prospects: Beam Dump $A' \rightarrow e^+e^-, \mu^+\mu^-$



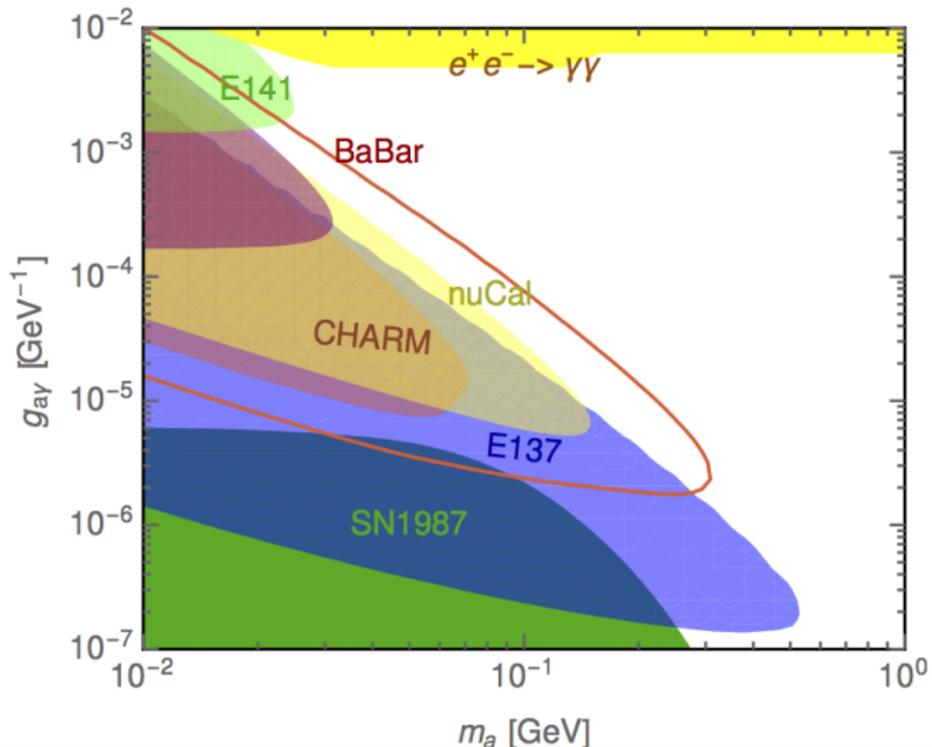
NA62 Prospects: Beam Dump HNL \rightarrow visible



NA62 Prospects: Beam Dump DarkScalar \rightarrow visible



NA62 Prospects: Beam Dump ALP $\rightarrow \gamma\gamma$



Summary

- Several experiments (in addition to LHC) active in the field
- Babar still publishing
- NA62, NA64 with first results
- New Experiments coming up: Belle II, PADME
- NA62, NA62 will continue with increased statistics