Axions and Axion-like particles
— selected recent results —

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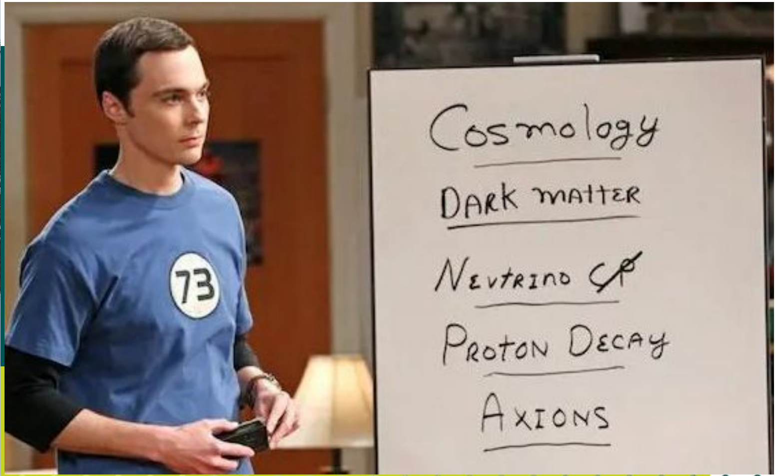
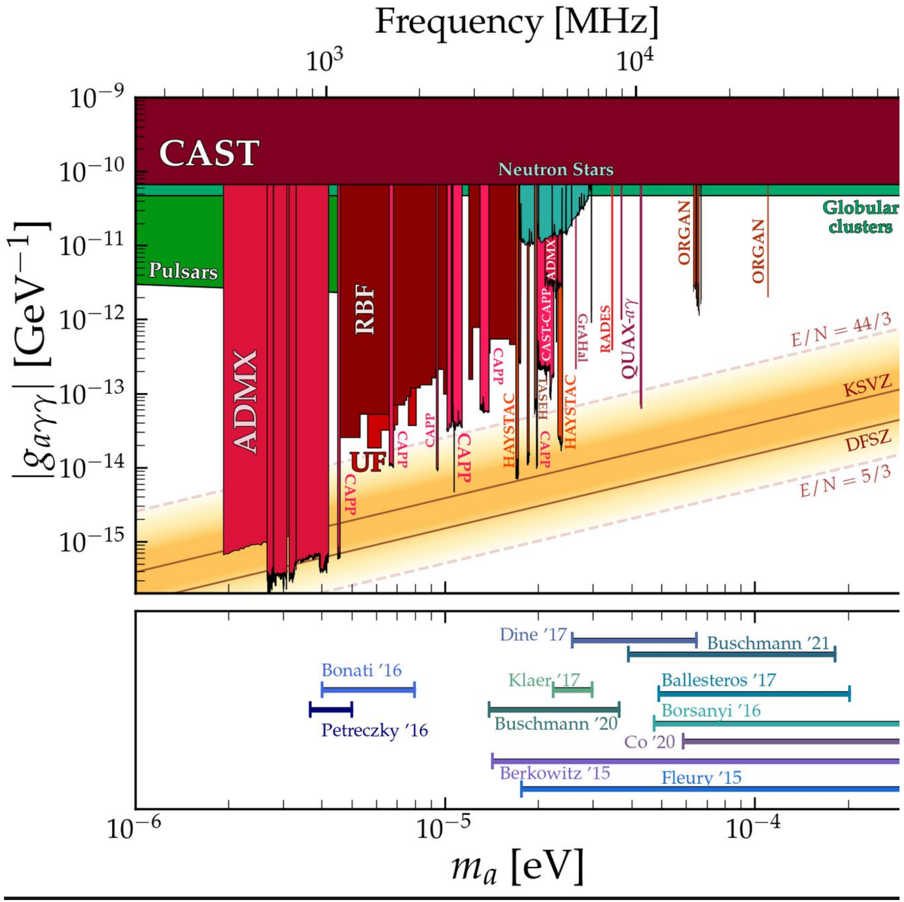


Found the axion on the way up here (few km down the road): in Livagno! At an ice kart racing place

Before we start, let's start with a small glossary:

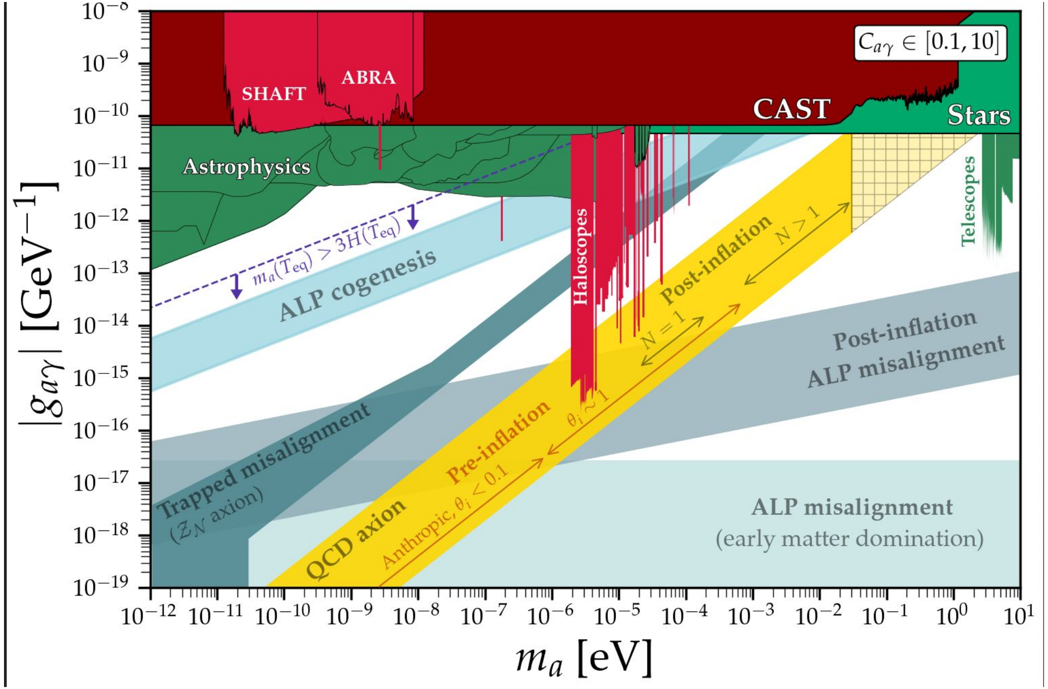
1. The axion

- Could solve the **strong CP problem**
- Ideally, **could constitute all of the Dark Matter** (non-thermally produced!)
- Vanilla `QCD axion Dark Matter': KSVZ and DFSZ models, with fixed mass-to-coupling ratio (here shown only for 2-photon-coupling)
- typically scanned in narrow mass-points with electromagnetic resonators in strong magnetic fields, see red areas on right-hand side [status nicely maintained at O'Hare GitHub]



Before we start, let's start with a small glossary:
2. The axion-like particle (ALP)

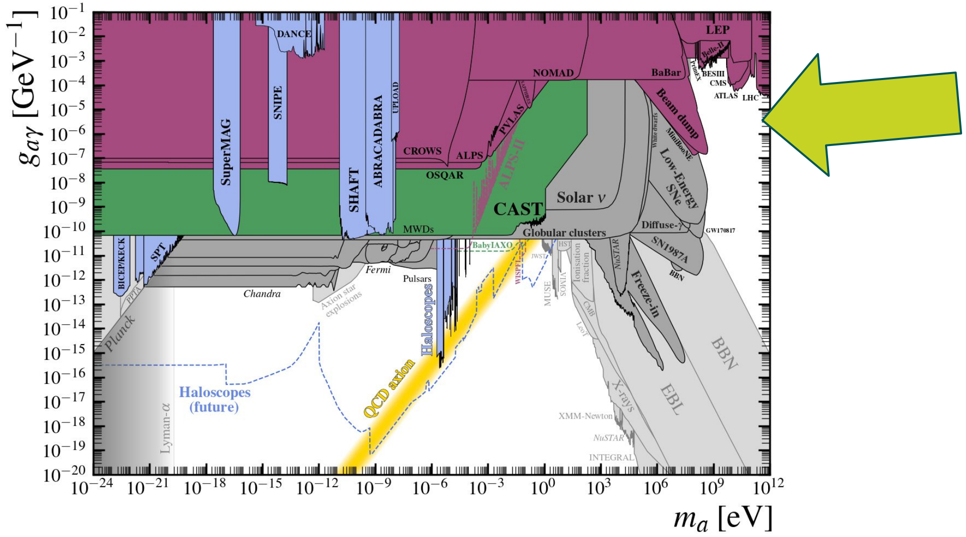
- Note the larger mass and coupling range with respect to the previous plot
- Theoretically interesting: relaxed/modified mass-to-coupling ratio: non-vanilla models
- Experimentally interesting: Novel approaches typically first sensitive to ALPs, before becoming sensitive enough to “proper axions”
- Preferred parameter range dependant on model behavior in early universe early universe
- References also maintained at [O'Hare GitHub]

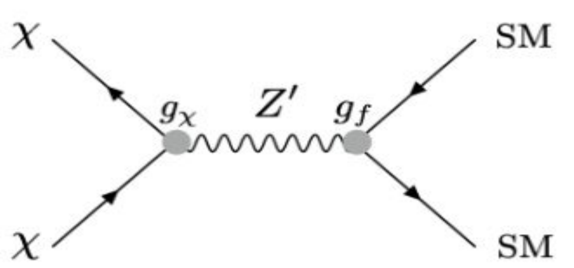


Before we start, let's start with a small glossary:

3. The axion-like particle as a DM `portal'

- Much larger couplings are still viable at high mass
- WIMPless miracle [see for example: Feng, Kumar] : thermally produced DM can be significantly lighter than GeV without overproducing it:
- Mediators that are BSM states -> "Portal"
- ALPs can constitute such a portal, in this case **they make sense also at MeV-GeV scale**



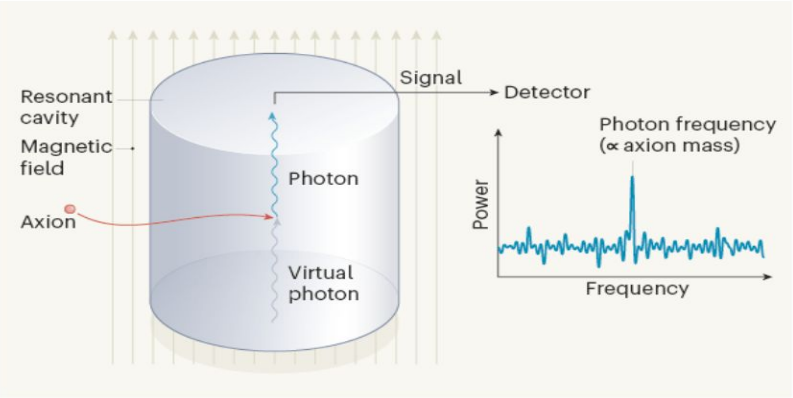


Also other portals are possible, Z' as the probably most well-known

Almost ready, just one more thing

- In the literature, axion and ALP (non-portal and portal) are used interchangeably
- Given the breadth of the before-mentioned physics, only some examples can be presented (which necessarily vary with personal taste)
- Personally I find most exciting the results/ developments in
  a. **QCD axion searches, particularly aimed at directly detecting Dark Matter**
  b. Techniques that tackle couplings other than the photon coupling. Particularly for **ultra-light axions**, opens field to methods from a variety of communities: NMR, storage rings, magnetometers… see this collection for an overview
  c. **Flavor-non-diagonal axions**: Relate the axion to SM flavor parameters and motivate smallness and hierarchy of such parameters, see e.g. [2006.04795], (e.g. interesting possibilities at MEG-II
  d. **Ultra-heavy axions (portal axions)**

a.) The classic (Sikivie) haloscope

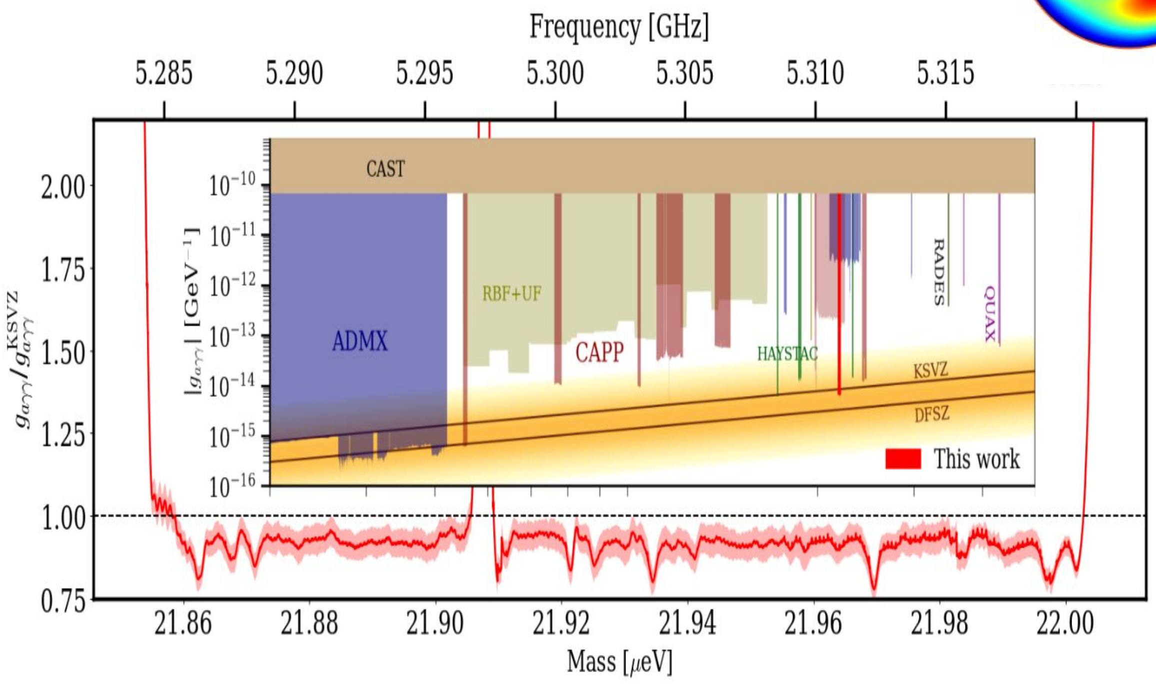


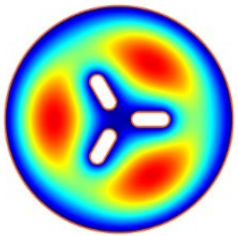
*Principle scheme of a cavity haloscope (from I. G. Irastorza, Nature **590**, 226-227 (2021))*

$$F \sim g^4 m^2 B^4 V^2 T_{\rm sys}^{-2} \mathcal{G}^4 Q$$

- **Resonantly convert the Axion Dark matter into RF signal by placing electromagnetic resonator (appropriate mode overlap parameterized in G, volume V) in a strong external magnetic field B**
- **m ~ f_resonance**
- **Advantage: profits from with amplification Q**
- **Disadvantage: scanning needed: Volume and Quality factor decrease at larger Axion masses (cavities become smaller, naively)**

(vanilla) Benchmark sensitivity: ADMX & CAPP

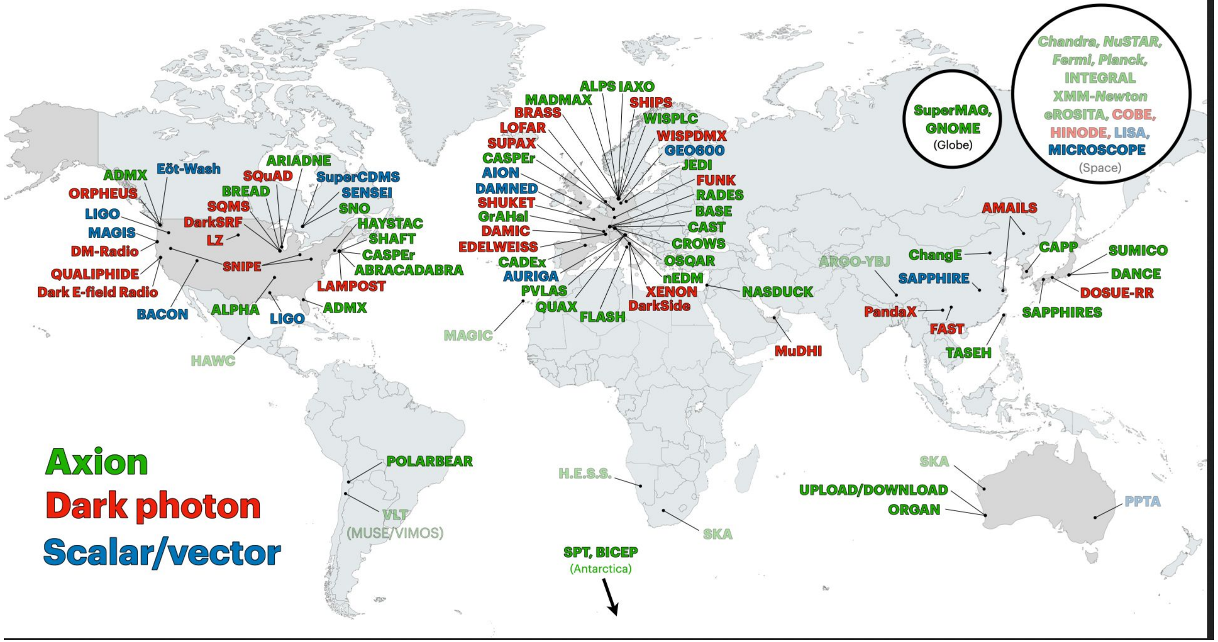




ADMX (US): key player since ~2010 with proven sensitivity to benchmark models using the classic Sikivie Haloscope

- Impressive pace of CAPP/Korea (started from scratch in 2013 (!)) exemplified by result on lhs from December 2023
- Peculiar cavity structure to reach larger masses ("Pizza-structure", pls keep in mind)
- Still rather narrow mass range (35Mhz)

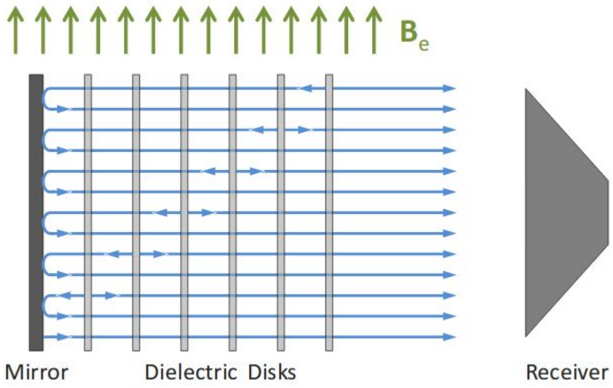
Plenty of room for R&D, newcomers and small groups

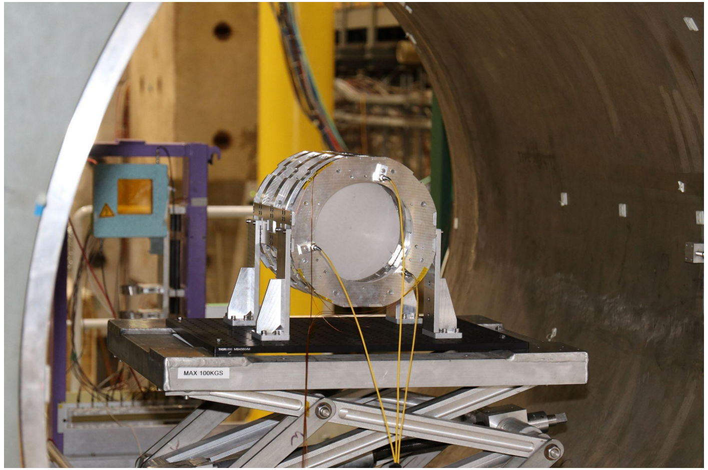


- R&D often immediately sensitive to novel axion-LIKE particles
- Map [O'Hare] contains dedicated efforts as well as parasitic sensitivity
- Not displayed are ad-hoc collaborative efforts which are common
- Excellent platform to train students in analysis, hardware and phenomenology

Another scheme for larger masses: dielectric Haloscope, e.g. MADMAX

- Elegant solution to fix the m ~ f_resonance problem
- Simply spoken: add index of refraction (adding coherently) to go to large resonance frequencies and broadband (by moving the disks) at the same time!
- Plan: ~9T magnet at 1.3m diam-> scan significant portion of “large DM axion mass” parameter space
- Prototype campaign in CERN’s morpurgo magnet in 2023/2024 at 1.6 T (results expected soon):





What can we do ultimately ?

- **Lever arms exploited: magnetic field, volume, temperature**
- **single-photon detectors become competitive and ultimately favored, when compared to quantum-limited linear amplifiers above ~ 10GHz [Lamoreaux et al (2013)]**
- **Example in the following**

$$\left[\frac{P_\ell}{P_{sp}}\right] \approx \sqrt{\frac{Q_c}{2\pi Q_a} e^{h\nu/k_B T}} \qquad (18)$$

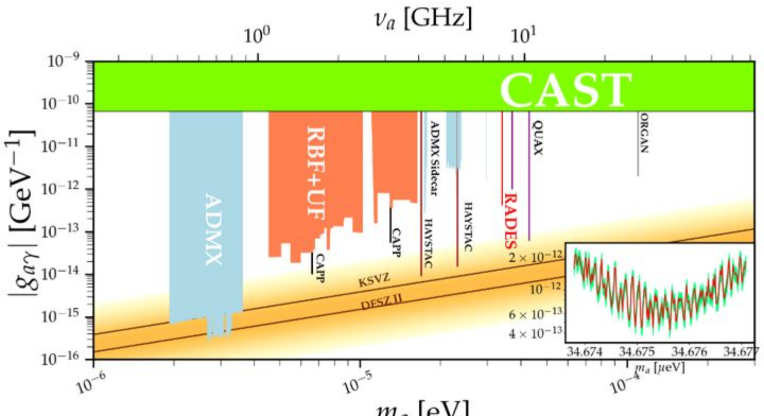
and when this number is large, cavity photon counting can have a lower noise than linear detection. At conservative values of $T = 100$ mK and $Q_a/Q_c = 20$, the crossover point occurs at a surprisingly low frequency (~10 GHz), not far above where the current round of experiments will be running. The device technology to support such a strategy may already be at hand.

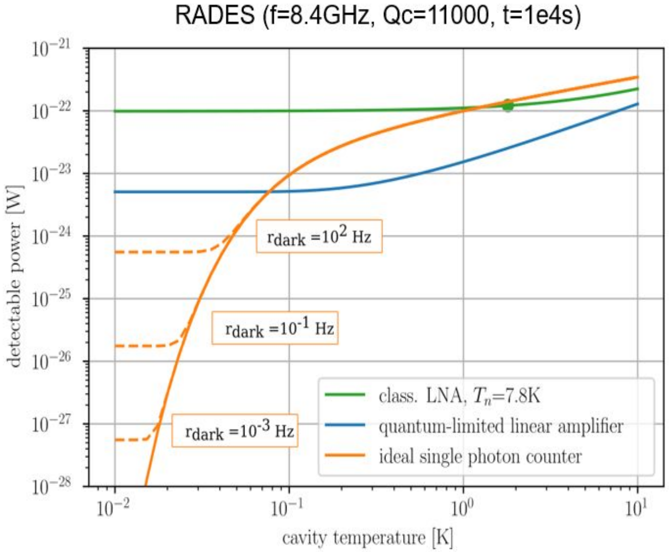
A wish-list: Single photon detection, an example

cavity from [Golm et al. 2023]

Figure 4.5: Photographs of the cavity halves installed in tuning holding structure with gears. Top view (left) and bottom view (right).

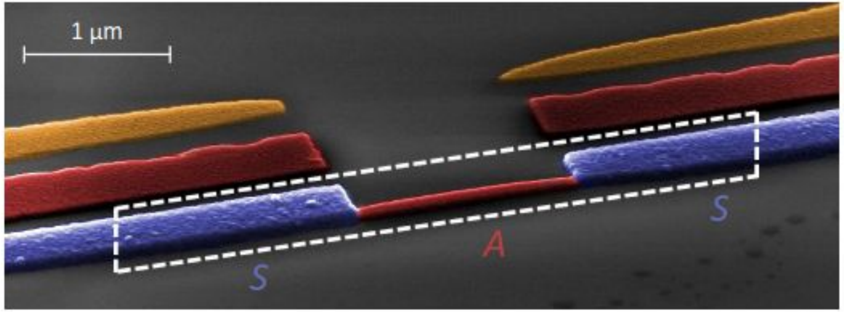
Result: 2018 data analysis published:
J. High Energy Physics 2021, 75 (2021)

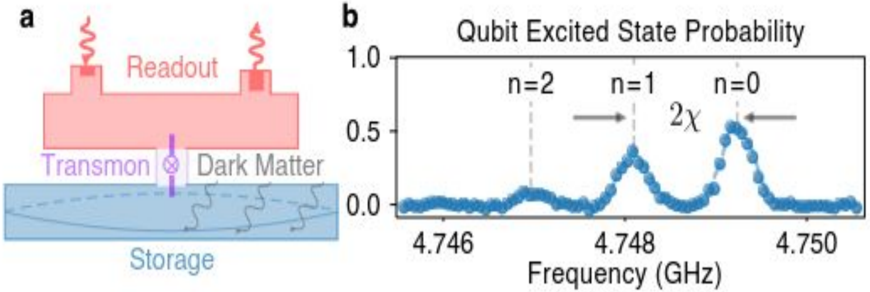




→ combined with low temperatures (~20mK), a single photon counter will boost RADES sensitivy to the QCD axion scale

Possible realizations & R&D: Single photon detection





nano-TES e.g. [2007.08320] or

QBITs e.g. [2008.12231] or…

Challenges:

- Achieving good coupling between photon and sensor
- Going broadband while maintaining resolution
- Functionality in/near strong magnetic fields
- ….

Bright future! Examples of european projects starting in 2024

- ERC-SYG “DarkQuantum”, lead-PI Irastorza, Zaragoza (~12Mio) -> magnetic field resilient QBITs
- QUANTERA “QRADES”, lead-PI Kontos, Paris (~1.8 Mio) -> low dark-count rate operation of the SPD in setup placedin a low radiation environment underground.
- …

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QUANTERA

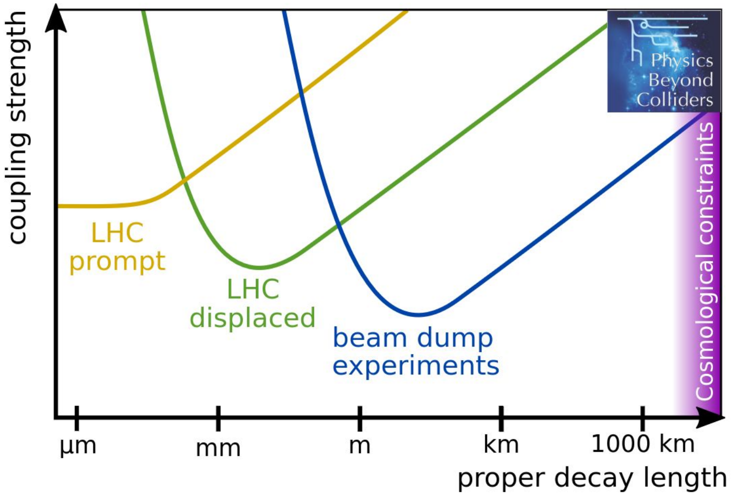
The programme

QuantERA ERA-NET Cofund in Quantum Technologies

d.) Ultra-heavy axions (MeV-GeV)

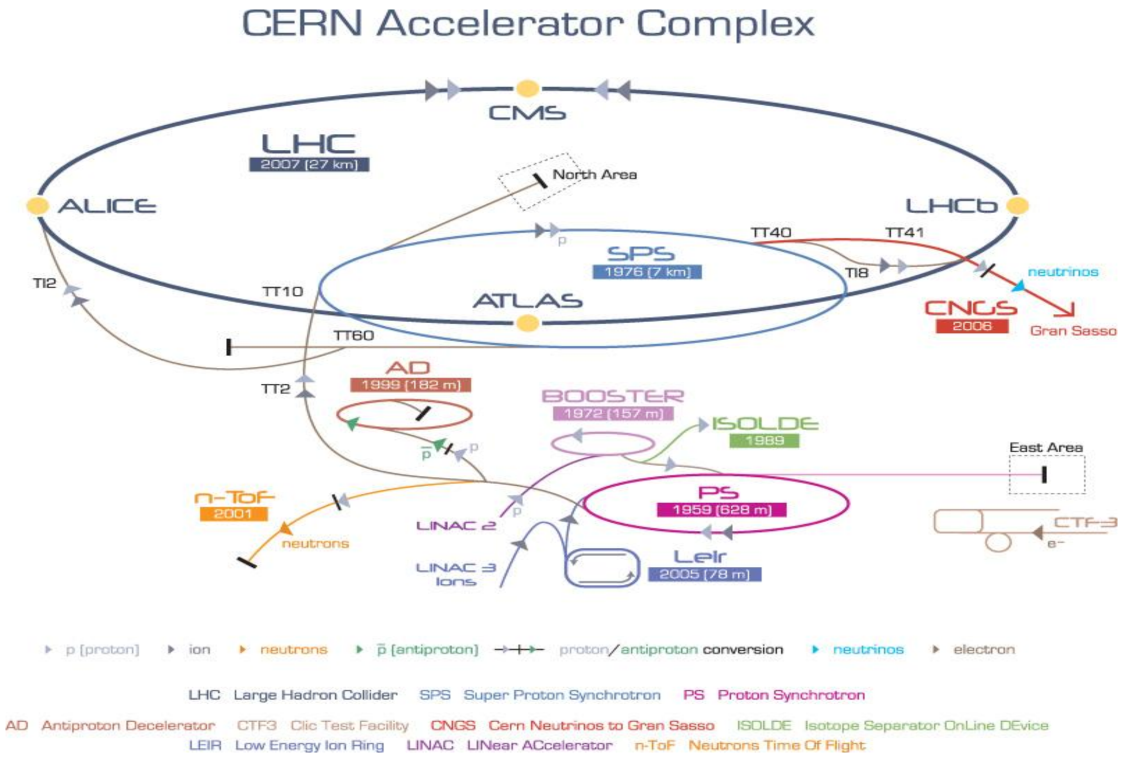
- Typically interesting in the `portal-type' models as mentioned in the Introduction (ALPs themselves not stable and thus not the Dark Matter)
- Sensitivity at detectors removed from interaction point very much complementary to collider-searches
- Lead to renewed interest in recent years (last beam-dump limits on Axions in the 80/90s!)

- Proposed experiments dedicated to Feebly Interacting Particles (FIPs): SHiP, Mathusla, Forward physics facility… see FIPs 2022 report
- Here will present a recent result of existing set-ups: NA62 in beam-dump



from [2310.17726]

NA62 @ CERN/Prevessin



- Fixed target experiment at CERN's north area (NA)
- Around 200 participants
- **Main goal:** measure branching ratio

$$K^+ \to \pi^+ \nu \bar{\nu}$$

- Precision measurements
- Rare and forbidden decays
- **Beam dump/Exotics**

Rigorous
Talk by R. Piandani…

Here schematics :-)

NA62 experiment: timeline and impressions

2008 NA62 approval → 2009-2014 detector R&D, installation → 2016-2018 Physis Run → 2019-2021 LS2 upgrades → 2021-2025 Physics Run

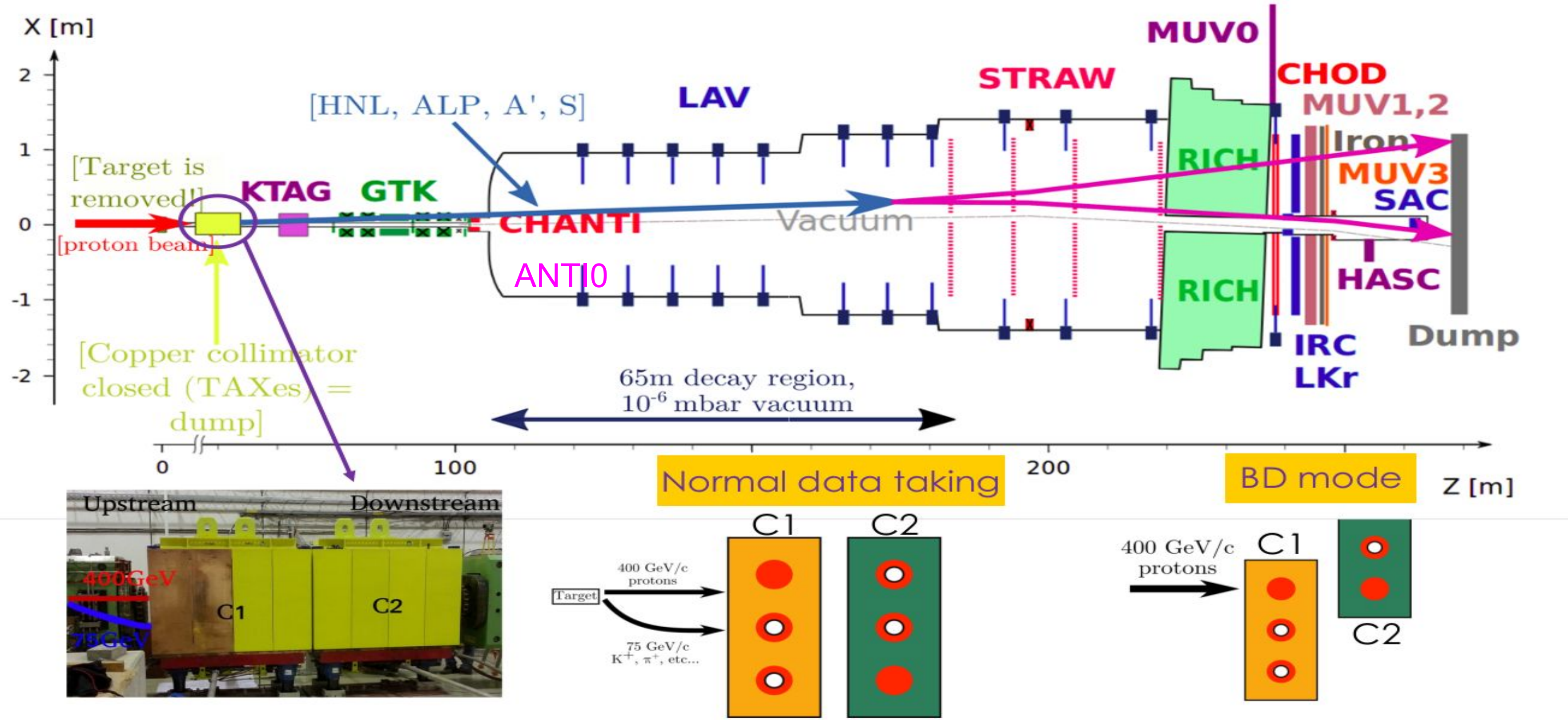
"Run 1" (2016-2018) "Run 2" (2021-2025)

<- View of the ECN3 hall

The target region

- Target (hit by p+) -> Kaons of 75GeV
- Collimators after target movable & go into “closed position” within few minutes. Target itself can also be removed within few minutes
- Then, 400 GeV protons from the SPS impinge **directly** on several meters of copper/iron *(dubbed TAXes)* **-> beam dump**
- The above settings can be reverted within few minutes.
- WHY? **Produce (weakly interacting) axion like particles in p+ interaction that could decay in the experimental volume of NA62 (e.g. B-> K a)!**

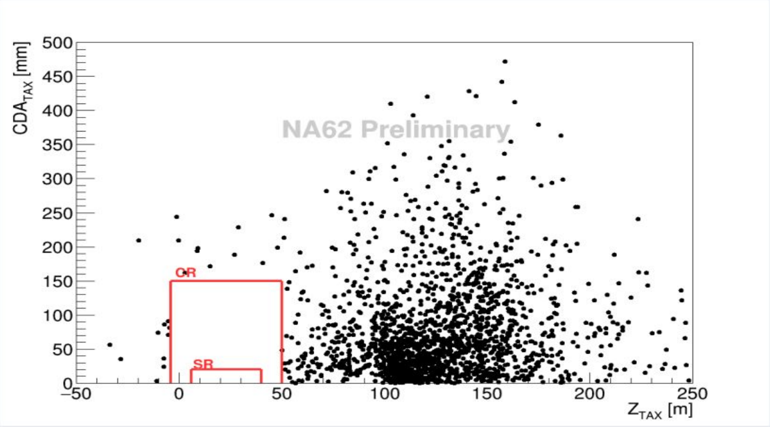
The NA62 experiment in Beam-Dump mode



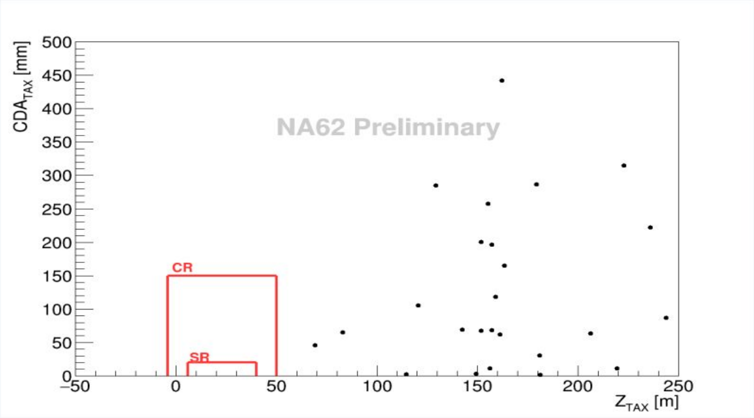
Challenge: reducing the background

- **Normally, 75GeV component retains focus, see bottom left**
- **upstream magnet tuned** to increase muon sweeping (studied with help from PBC)
- In 2021, compared to 2018, background rejection was increased by **O(200)** on most 2-track channels despite higher intensity (example below: $\mu^+\mu^-$)

2018 data: 2.6×10^{16} POT

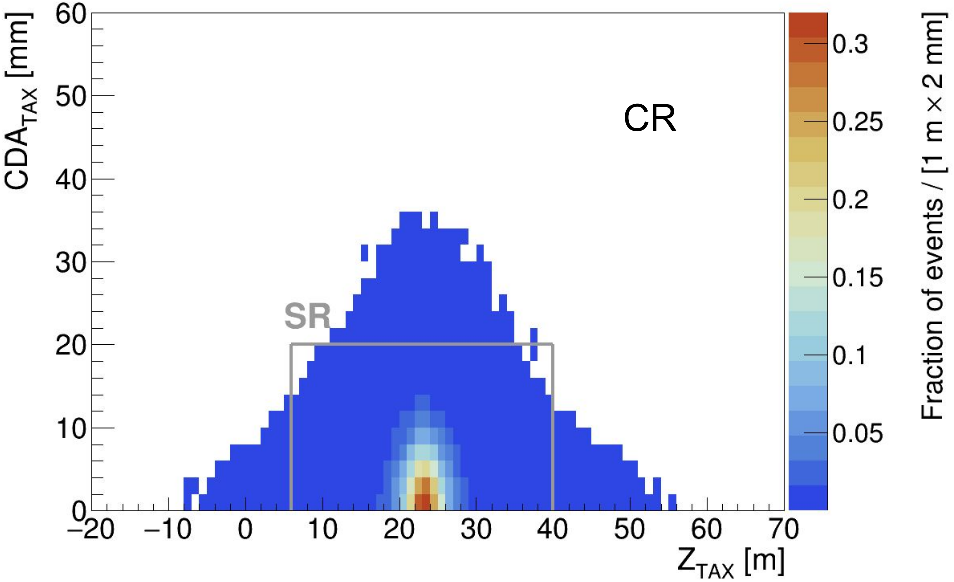


2021 data: 1.4×10^{17} POT



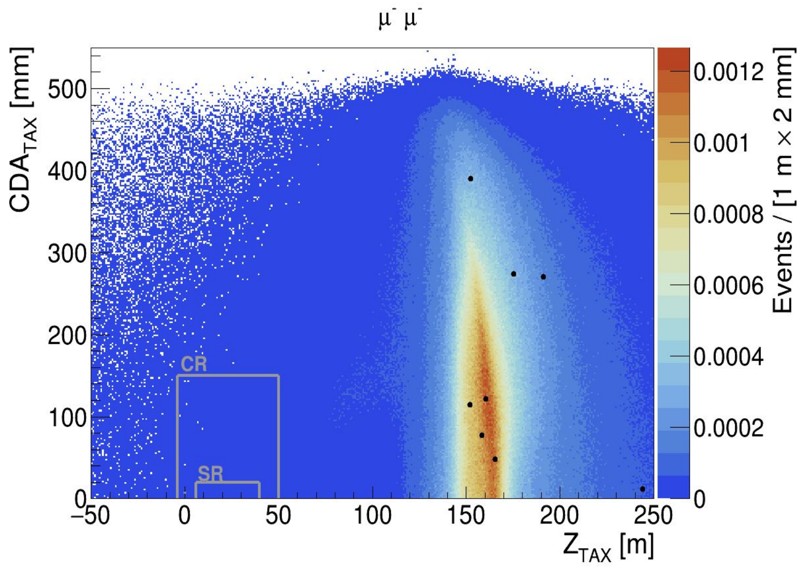
Analysis strategy for A' -> $\mu^+\mu^-$ with 2021 data

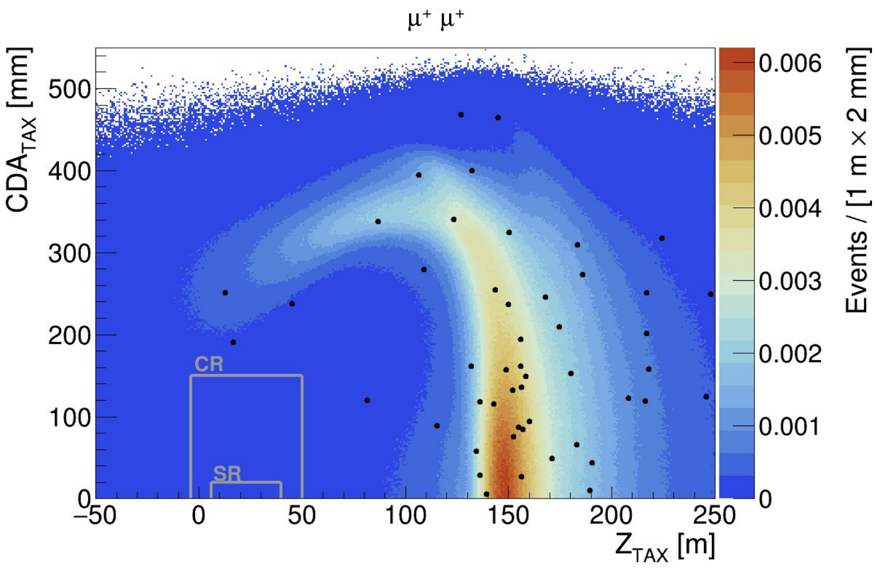
- **Pointing:** Exploit expectation of CDA between beam direction at the TAX entrance
- Event selection: track quality, timing coincidence, PID with calorimeter and muon detector, … and much more
- CR and SR kept blind up to analysis approval
- Dominant background combinatorial (well below 1 evt. In SR as well as CR)
- Build bkg artificially from single tracks (orthogonal to analysis sample - different trigger line)



Distribution of Monte Carlo signal events

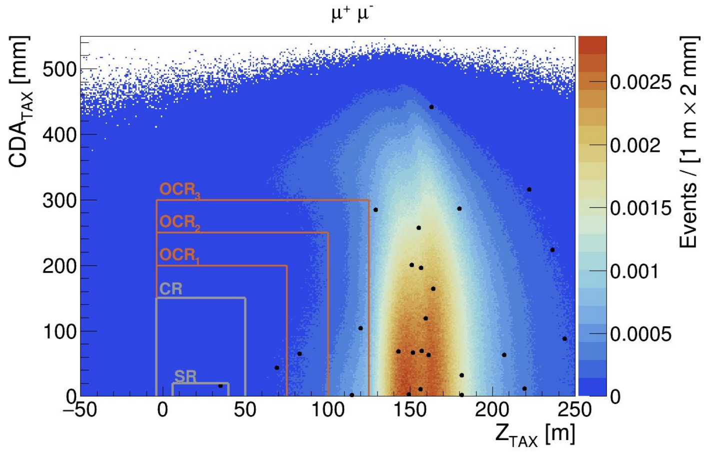
Data-MC comparison: Control sample for combinatorial sample



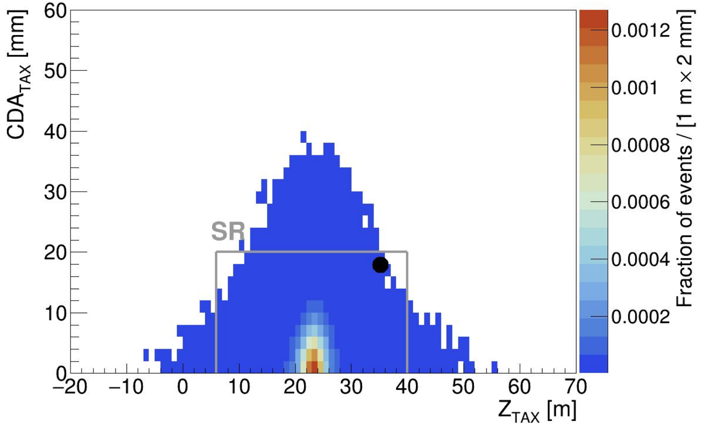


Peculiar shape in same-sign events due to beamline element focussing effects

Data-MC comparison: SR open



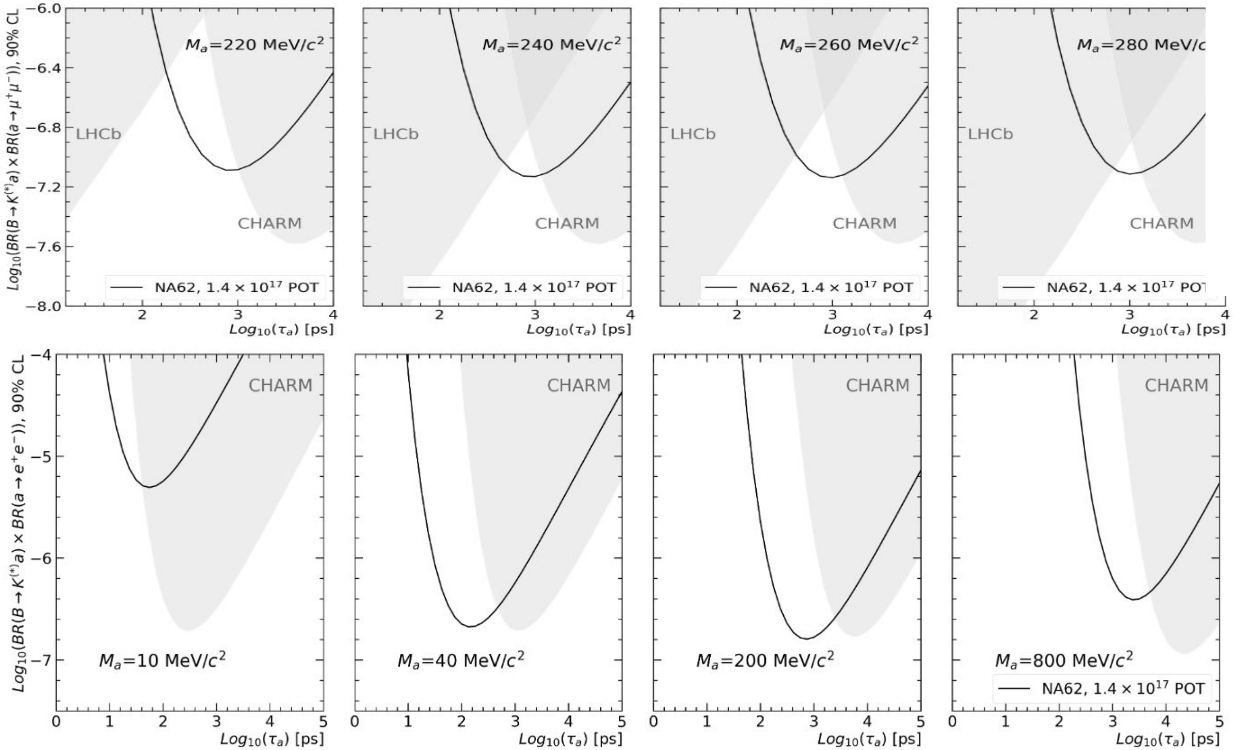
- Color scale: Expected background
- 1 event observed in SR

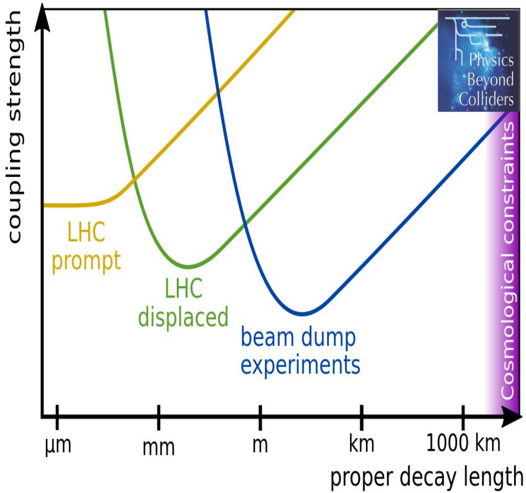


- Probability to observe 1 event in SR: 1.6 %:
- Invariant mass of event: 411 MeV
- Time difference ~2 sigma away from mean for signal events
- Event in far-tail of SR
- No events when opening SR e^+e^-

… result for axion-like particles

[fresh fom the arxiv [2312.12055]](https://arxiv.org/abs/2312.12055)





Top: $\mu^+\mu^-$,
bottom: e^+e^-

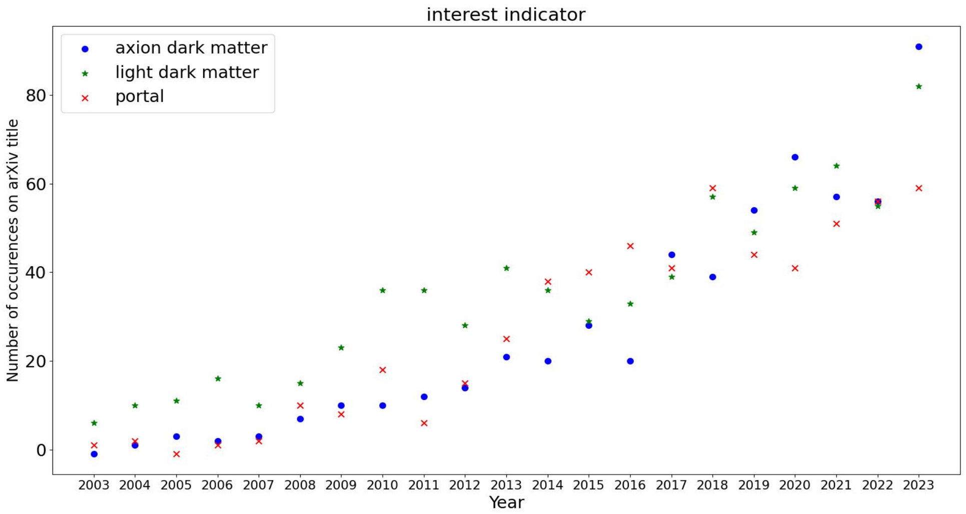
Assuming mass, lifetime and coupling to be independent parameters

see PLB 790 (2019) 537

Conclusions

- **Axions have gone from "niche" to "main-stream", see rhs**
- **in principle there is a vast parameter range which is motivated**
- **Direct Dark Matter detection (sub-eV) will be boosted by novel technological development (SPD at ~>10GHz)**
- **Heavy axions can be connected to rich phenomenology**
- **Hopefully, the increased attention can be rewarded with a proper discovery**
- **THANK YOU for your attention**

Interest indicator (python script whose outcome won't survive scientific scrutiny but carries a grain of truth):



Credit to: NA62, especially their Exotics WG, and my colleagues in RADES

Backup

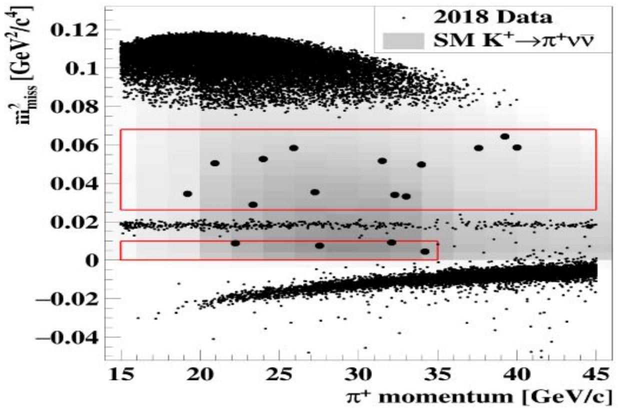
- **Here starts the backup**

Recent SPSC status report (G. Ruggiero, May 11th 2023)

$K^+ \to \pi^+ \nu\bar{\nu}$ from RUN1

$\mathbf{m^2_{miss} = (P_{K^+} - P_{\pi^+})^2}$

$\mathcal{O}(100\ \mathrm{ps})$	Timing
$\sim 10^3$	Kinematic background suppression
$\sim 10^8$	Muon suppression
$\sim 10^8$	π^0 suppression



$N^{exp}_{\pi\nu\bar{\nu}} = 10.01 \pm 0.42_{syst} \pm 1.19_{ext}$,

$N^{exp}_{background} = 7.03^{+1.05}_{-0.82}$.

$N_{obs} = 20$

3.4σ evidence $K^+ \to \pi^+\nu\bar{\nu}$

$BR = (10.6^{+4.0}_{-3.4} \pm 0.9) \times 10^{-11}$

JHEP06(2021)093

“Random Veto”

Probability of signal loss when rejecting photons

Loss due to random veto induced by accidental activity

“Upstream” background

K^+ decays upstream

Problem: lack of vetoes along the beam line

SEARCHES FOR NEW PHYSICS | NEWS

Searching for dark photons in beam-dump mode

24 April 2023

Intense Part of the NA62 detector in the ECN3 experimental hall in Prevessin, where beam travels from right to left. On the right-hand side is the STRAW spectrometer, with the analysing magnet in blue. Four large-angle vetoes serving to clean the samples from non-forward events are visible in white, while the green region houses the RICH detector. Credit: CERN-PHOTO-202104-059-6

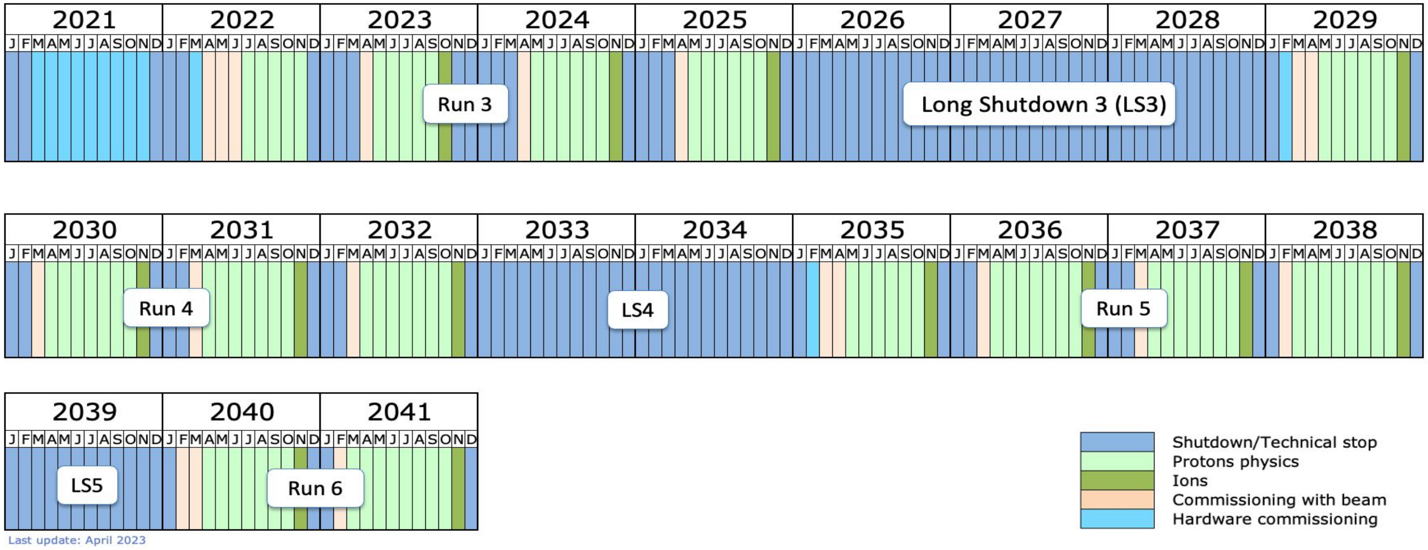
Faced with the no-show of phenomena beyond the Standard Model at the high mass and energy scales explored so far by the LHC, it has recently become a much considered possibility that new physics hides "in plain sight", namely at mass scales that can be very easily accessed but at very small coupling strengths. If this were the case, then high-intensity experiments have an advantage: thanks to the large number of events that can be generated, even the most feeble couplings corresponding to the rarest processes can be accessible.

Such a high-intensity experiment is NA62 at CERN's North Area. Designed to measure the ultra-rare kaon decay $K \to \pi\nu\bar{\nu}$, it has also released several results probing the existence of weakly coupled processes that could become visible in its apparatus, a prominent example being the decay of a kaon into a pion and an axion. But there is also an unusual way in which NA62 can probe this kind of physics using a configuration that was not foreseen when the experiment was planned, for which the first result was recently reported.

Article in CERN courier from April 24th 2023: link

Longer term LHC schedule

In January 2022, the schedule was updated with long shutdown 3 (LS3) to start in 2026 and to last for 3 years. HL-LHC operations now foreseen out to end 2041.



Defining plans for >2028. Currently HL-LHC operations foreseen out to end 2041 (but can still evolve very much obviously!).

ECN3 @Prevessin

- Discussion ongoing about ECN3 Future after 2029: [CERN courier article, January 2023]
- First step: experiment agnostic high-intensity facility: SPSC expressed “strong support” to the facility (February 2023)
- decision of experimental program foreseen in December 2023 postponed!
- Current proposals: SHiP, HIKE, SHADOWs, see article above for details

Possible extension of NA62: HIKE

- Idea: 4-fold increase on primary intensity. Requires major upgrades of the primary and secondary beamlines
- HIKE Program of multiple phases, first with charged and then neutral kaon beams, **periods in beam dump mode**
- Proposal released in October

  CDS proposal

HIKE, High Intensity Kaon Experiments at the CERN SPS

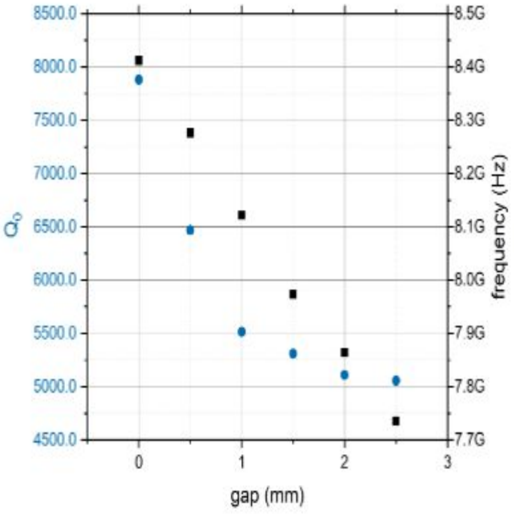
Letter of Intent

The HIKE Collaboration*

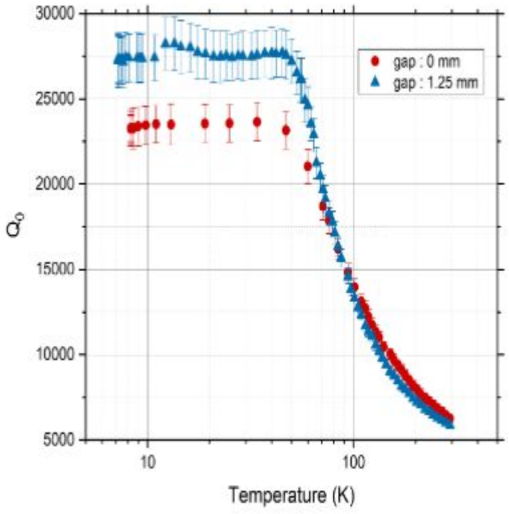
HIKE
High Intensity Kaon Experiments

Link to LOI with sensitivity projections

Ctd.: “Pizza structure” (larger masses with classical scheme), (different experiment, RADES)

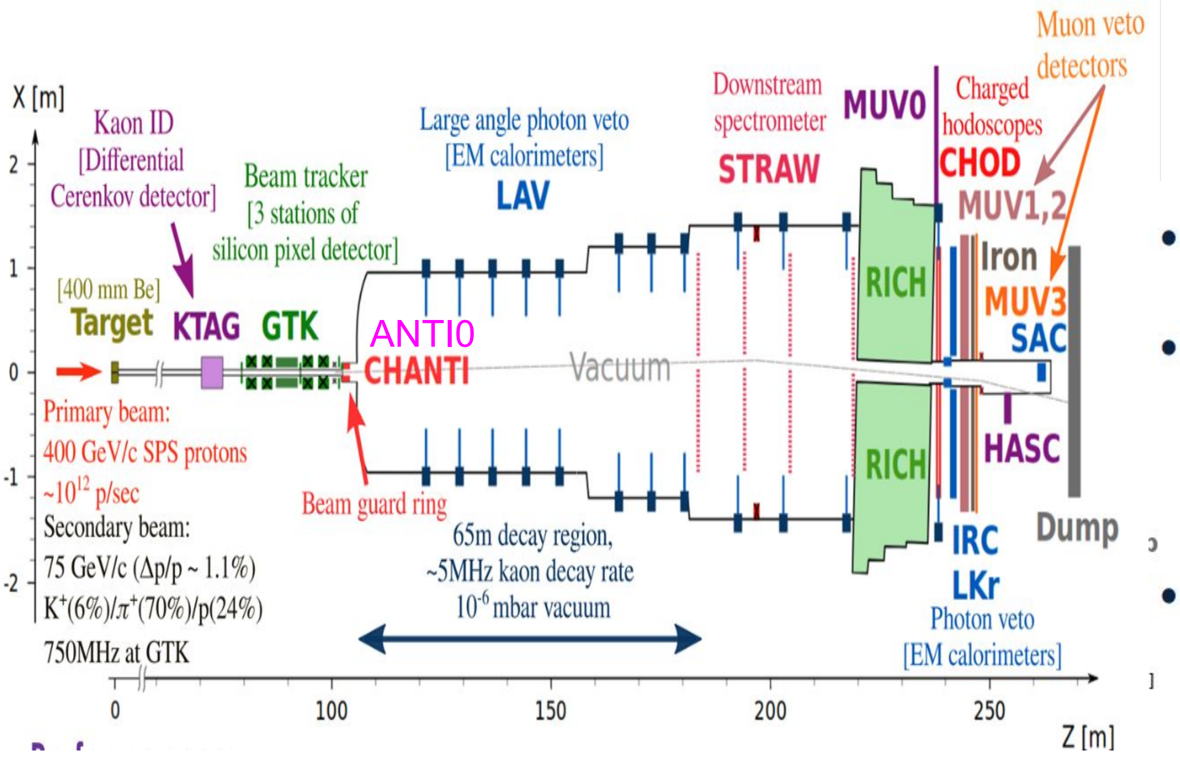


Golm et al. [2312.13109]



Tunable over 700Mhz in principle!

The NA62 experiment: beam and detectors



Beam from SPS: 400GeV protons on target

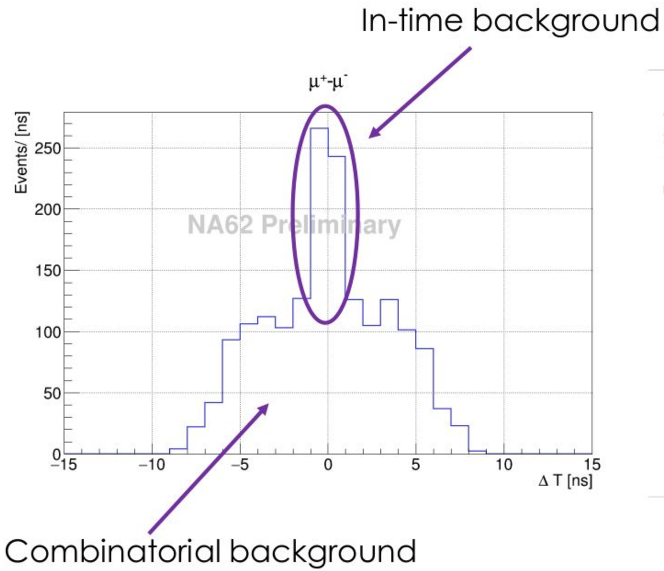
Suppressing main Kaon decays:

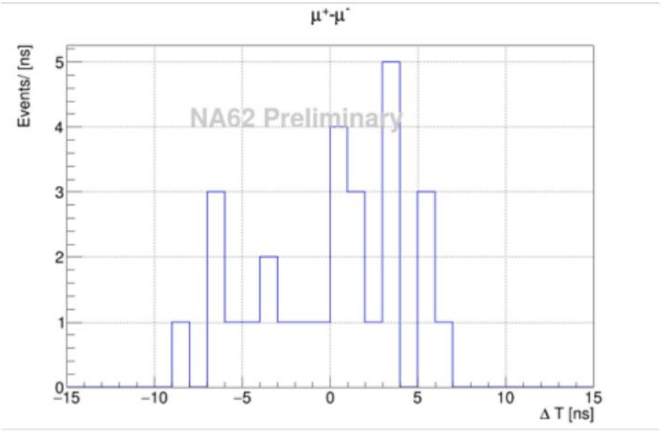
- K^+ tagged by **KTAG** and 3-mom. determined by **GTK**;
- Decay products' 3-mom. measured by **STRAW**, time measured by **CHOD** PID given by **LKr**, **MUV1**, **MUV2** and **RICH**; μ ID provided by **MUV3**;
- Photons can be vetoed by **LKr** and at large angles by 12 **LAV** stations or by **SAC**/**IRC** at small angles;

ANTI0 against upstream bkg

Observed track time difference

Suggests two main background mechanisms





Before LAV veto (CR & SR blind)

Final events selected (CR & SR blind)

Background studies

Combinatorial

- Build artificially from single tracks (orthogonal to analysis sample - different trigger line)
- Statistical accuracy from combinatorial enhancement
- Weight to account for analysis time window

Prompt

- Secondaries of a muon interaction in traversed material (usual π with consecutive decay to μ)
- Kinematics extracted from single tracks (backward MC - PUMAS)
- Relative uncertainty of MC expectation ~50%

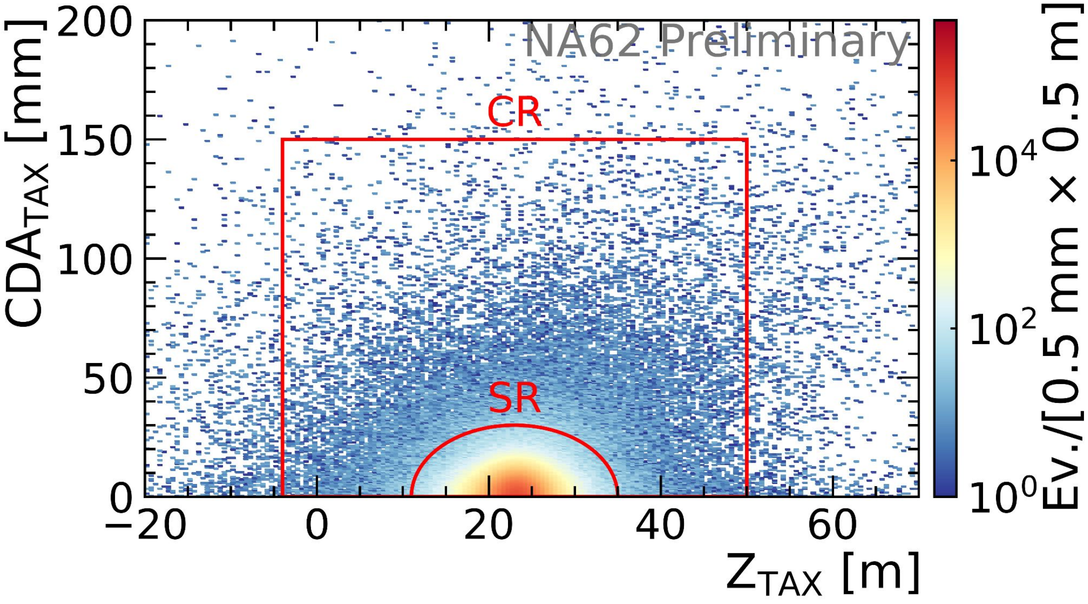
Table 4: Summary of expected numbers of background events for the search of $A' \to \mu^+\mu^-$ with the related uncertainty. The limits reported are defined with a 90% CL.

Region	Combinatorial	Prompt	Upstream-prompt
CR	0.17 ± 0.02	< 0.004	< 0.069
SR	0.016 ± 0.002	< 0.0004	< 0.007

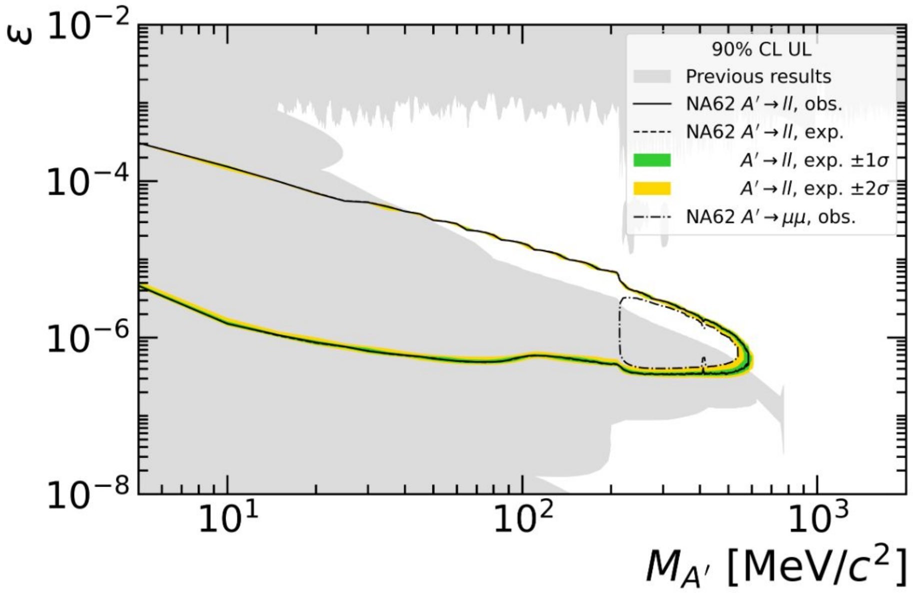
… the e^+e^- channel [very fresh from the arxiv: 2312.12055]

Differences with respect to $\mu^+\mu^-$

- Decay region optimization (cone-shape)
- PID optimization
- Inclusion of **ANTI0** detector
- New signal region definition (shown from bremsstrahlung on rhs)
- Background studies in backup slides



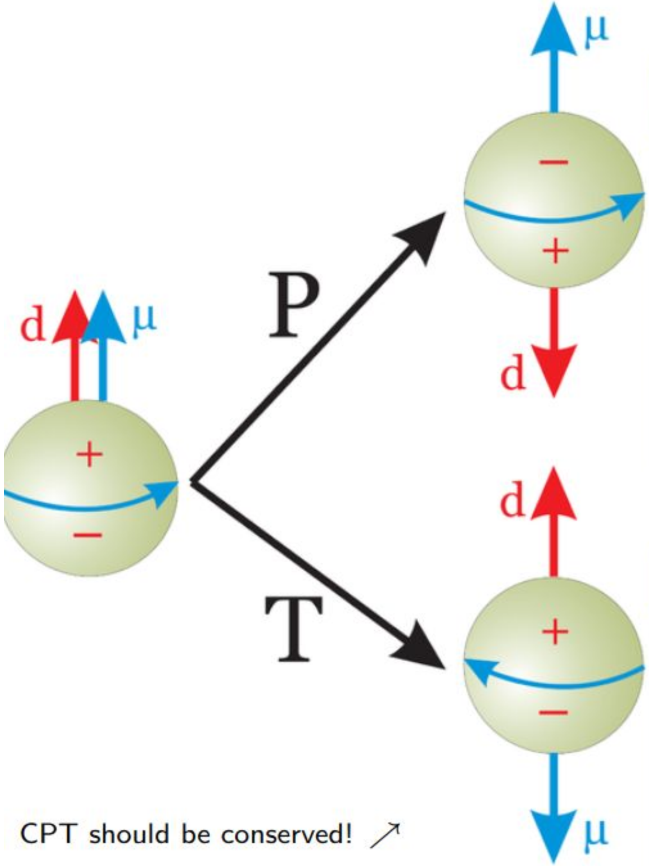
Completeness: Leptonic decay of Dark Photons



Together with FASER@LHC, first new limits in this region since the 80s!

in JHEP for muons
https://link.springer.com/article/10.1007/JHEP09%282023%29035

And on the arxiv for electrons
[2312.12055]



CPT should be conserved! ↗

Theory

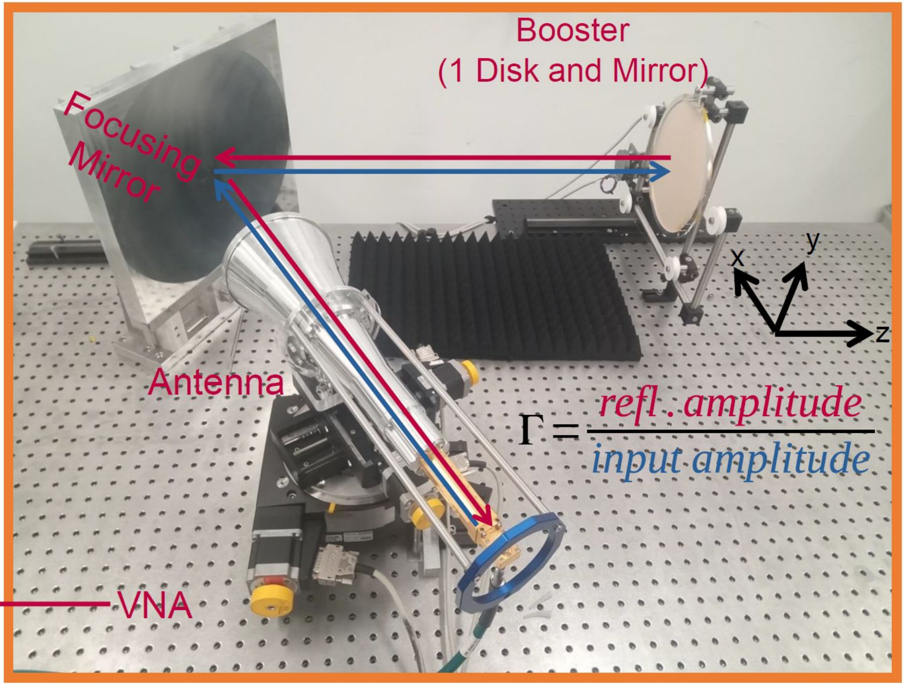
- QCD vacuum CP- violating term: $\mathcal{L}_\Theta \sim \alpha_s \bar{\Theta} G^a_{\mu\nu} \tilde{G}^{a\ \mu\nu}$
- QCD topological + EW contribution $\bar{\Theta} = \Theta + \mathrm{Arg}\det M$, M quark mass matrix

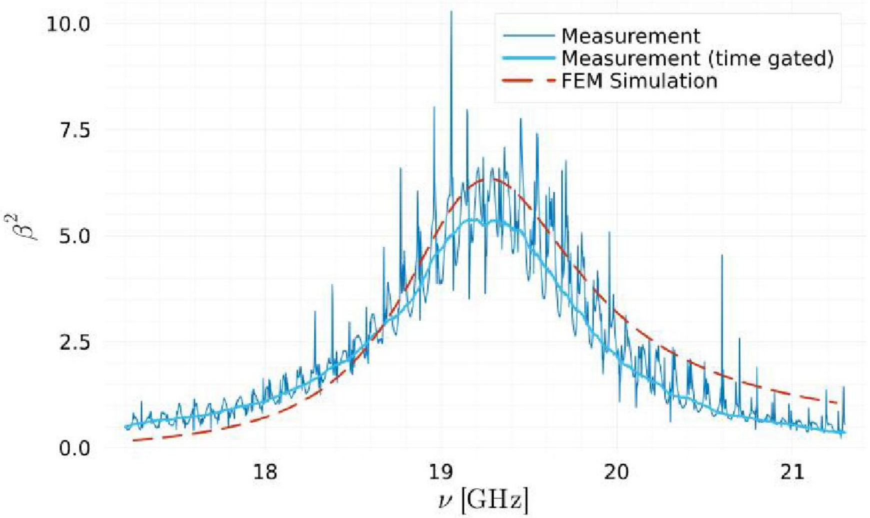
Experiment

- physical observable: e.g. Neutron EDM ($\vec{E}^a \vec{B}^a$ is CP violating)
- measured: $|d_\mathrm{n}(\bar{\Theta})| \lesssim 10^{-26}$ecm, naively: $e/2m_N \sim 10^{-14}$ecm

angle $\bar{\Theta} \lesssim 10^{-10}$ → **naturalness/finetuning problem!**

Setup to determine boost factor by direct measurement of the field using "bead pull method"





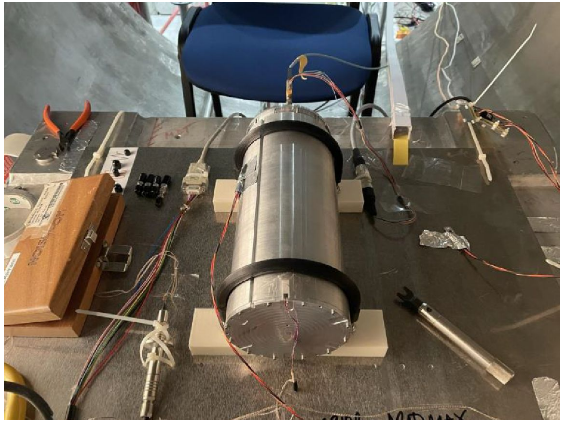
J. Egge, JCAP04(2023)064, arXiv:2211.11503
J. Egge et al. arXiv:2311.13359 [hep-ex]

CERN activities in 2022 and 2023

CB100 in 1.6T dipole field at room temperature

Results:

- Collected 10 hours integration time at 1.6T
- Influence of external RF signals not significantly effecting sensitivity
- Presence of B-field does not deteriorte performance
- No effect of 1.6 T dipoloe magnet fringe field seen
- Monitoring system: measuring most imporant parameters - temperatures, B-field at booster, life time / Allan variance
- Full data analysis chain developed:
  Determination of boost factor + application to data
   limit setting

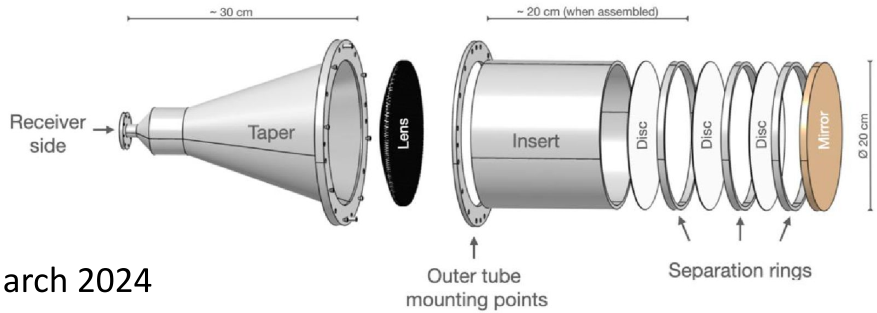


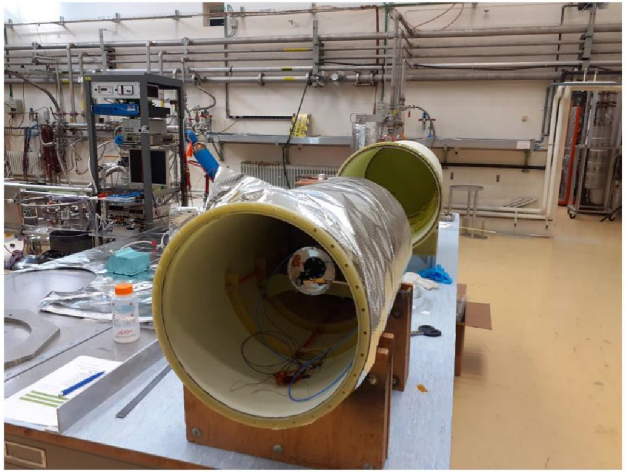
Next steps:

Prototype measurements at CERN in 1.6T field – Feb-March 2024

- CB200 increased area:
  - increased sensitivity by factor ~ 2 $g_{a\gamma}$ GeV^{-1}
  - Different booster configuration
  - scan mass in limited range range
- CB100 in cryostat at 5K
  - increased senstivity by factor ~ 5 $g_{a\gamma}$ GeV^{-1}

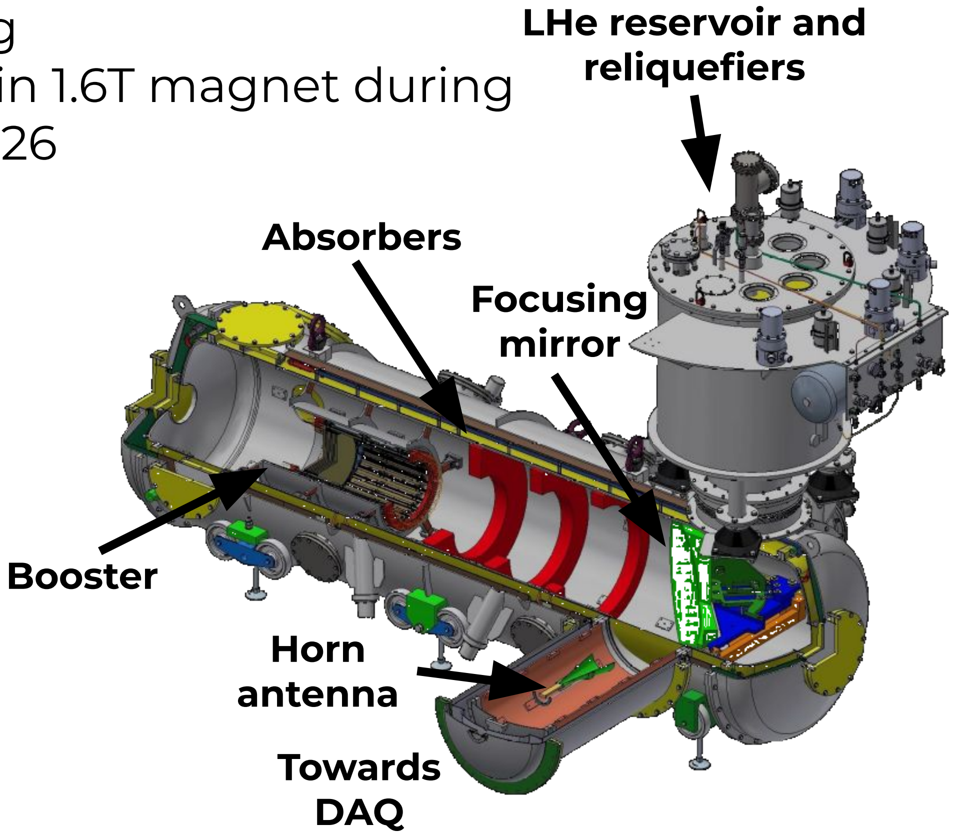
Exceed CAST ALPs limit in mutiple mass regions

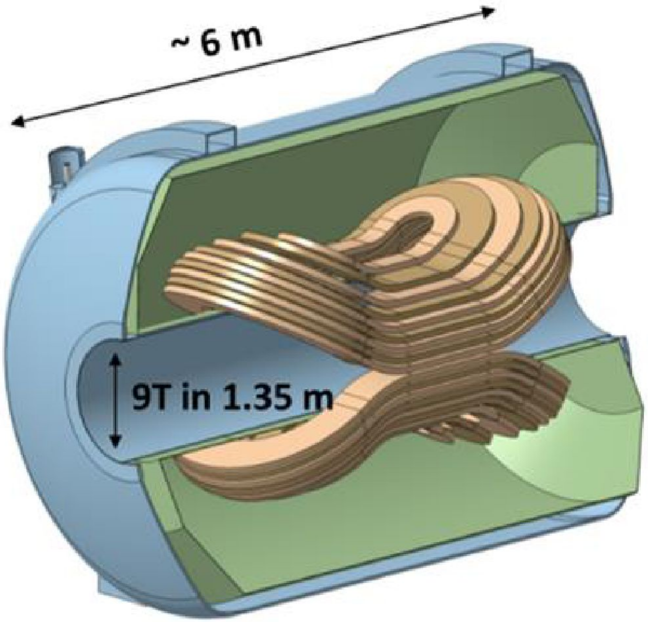




MADMAX prototype cryostat for booster system
Delivery expected April 2024

- Commissioning site: Hamburg
- Planned ALP search at CERN in 1.6T magnet during CERN long shutdown 2025 - 2026





MADMAX magnet:

- Design available
- Feasibilty of conductor design:
  Quench velocity fast enough can safely be detected
  CICC Conductor can be produced by industry, mechnically feasible

Next step – budget available:

- Production of demonstrator coils for verification of performance

MADMAX special issue:
IEEE Transactions on Applied Superconductivity vol. 33 Issue 7 (2023)