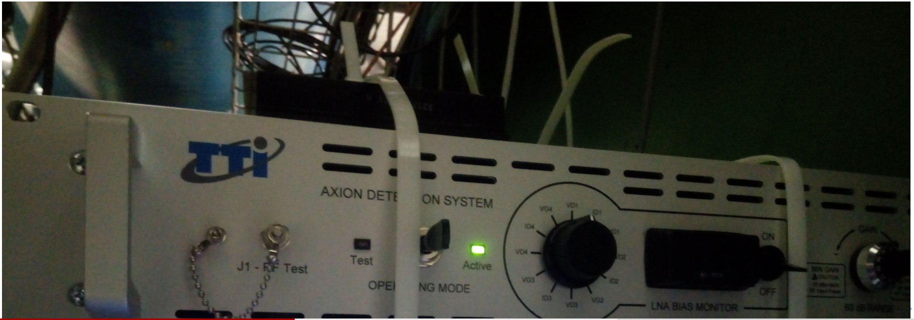
g

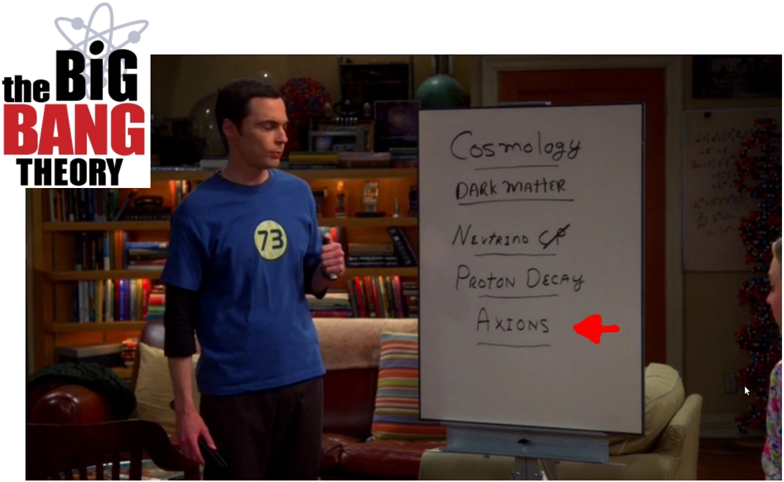
Axion and ALP searches with NA62 and RADES

Babette Döbrich (CERN) based on work within the NA62 collaboration and the RADES team

Marseille, 24/08/18

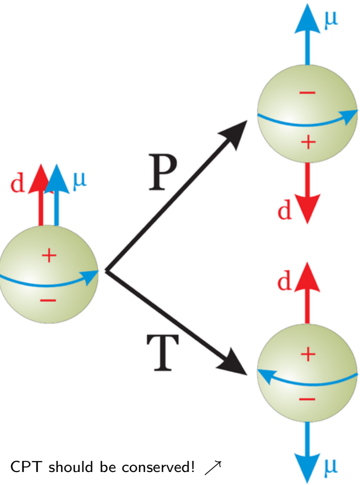


The axion in popular culture...



Sheldon looks for a new field of study... after BICEP 2 announcement
The Relationship Diremption, Aired April 10, 2014

Why Axions? The strong CP problem!



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

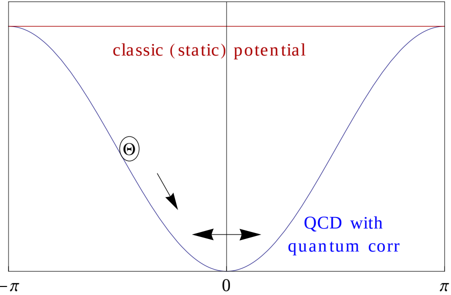
- physical observable: e.g. Neutron EDM ($\vec{E}^a \vec{B}^a$ is CP violating)
- measured: $|d_{\mathrm{n}}(\bar{\theta})| \lesssim 10^{-26}$ecm, naively: $e/2m_N \sim 10^{-14}$ecm

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

Axions in a (too small) nutshell see, e.g. 0807.3125

- make $\bar{\Theta} \equiv a(x)/f_a$ dynamical $\rightarrow$ zero through potential Peccei & Quinn, 77
- realized w global $U(1)_{\mathrm{PQ}}$ spontaneously broken at f_a, the axion is phase (Goldstone boson) of this symmetry

Weinberg, Wilczek, 78



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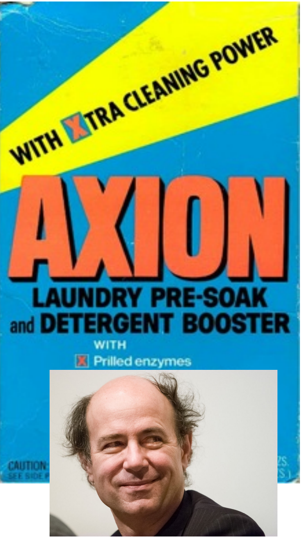

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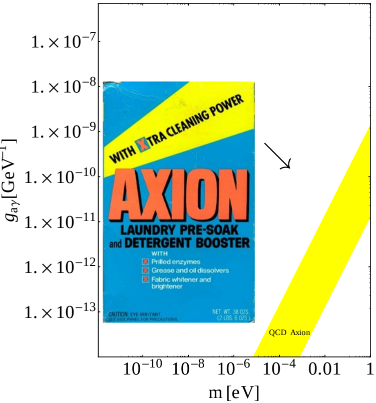
- originally $f_a \sim \Lambda_{\mathrm{EW}}$ (see arxiv:1710.03764 for revival)
- $f_a \gg \Lambda_{\mathrm{EW}}$ 'invisible axion models' 'KSVZ' & 'DFSZ' Kim, Shifman, Vainshtein, Zakharov

  & Dine, Fischler, Srednicki, Zhitnitsky

"I named them after a laundry detergent, since they clean up a problem with with an axial current." (Nobel lecture 2004)

Axions in a (too small) nutshell see, e.g. 0807.3125



[good reading: 9506229 Sikivie's Pooltable]

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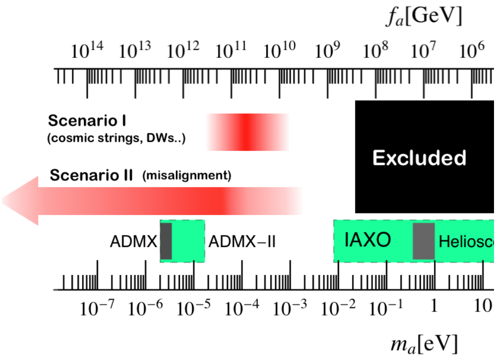
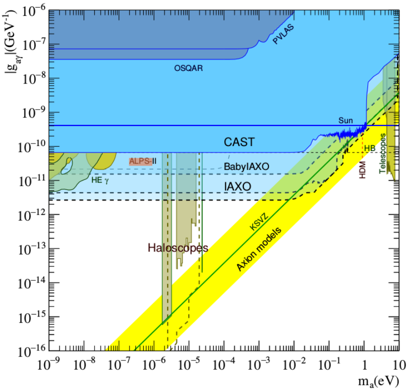
  & Dine, Fischler, Srednicki, Zhitnitsky
- $m \sim 0.6\mathrm{meV}/(f_a/10^{10}\mathrm{GeV}) \rightarrow$ pseudo-Goldstone boson
- couple to photons: Primakoff effect $\rightarrow$ basis of most experiments

Axions in a (too small) nutshell see, e.g. 0807.3125

[Figure taken from Redondo, BD, 1311.5341]

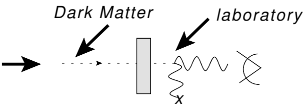


[plot taken from review: 1801.08127 by Irastorza/Redondo]

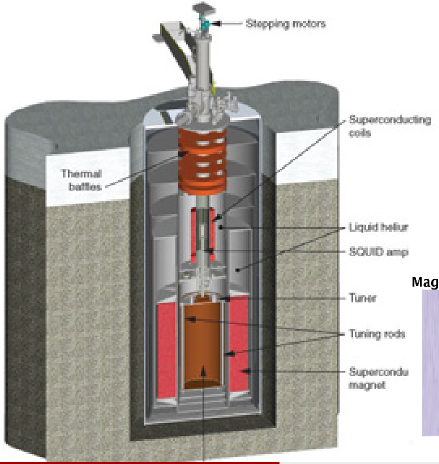


- Axion ColdDM via 'misalignment'

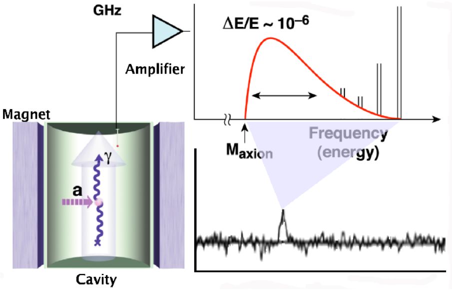
Dark Matter Axions (Haloscopes)



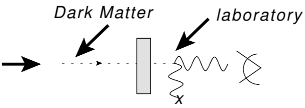
- Axions & ALPs $\to$ dark matter candidate $\to$ Haloscope [Sikivie '83]
  resonant technique
  $f_{\text{cavity}} \sim \omega_{\text{photon}} \sim m_{\text{axion}}$



ADMX status cf [1403.5332]



Dark Matter Axions (Haloscopes)



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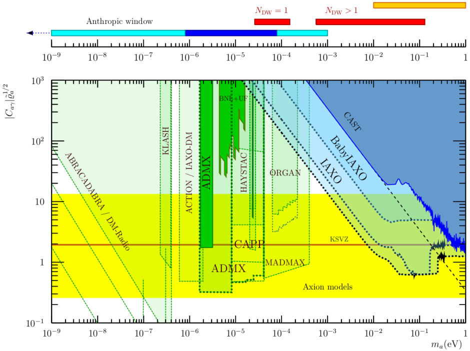
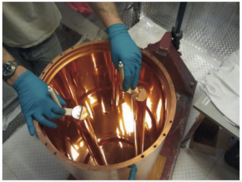
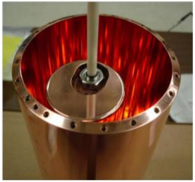
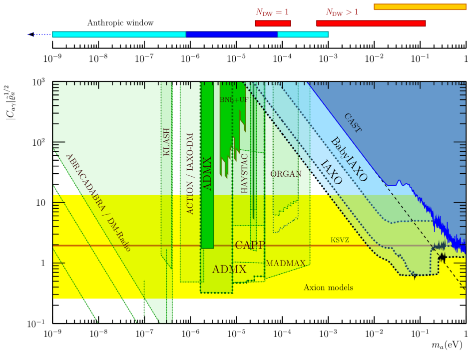


- Axions & ALPs → dark matter candidate → Haloscope [Sikivie '83] **resonant** technique
  $f_{\text{cavity}} \sim \omega_{\text{photon}} \sim m_{\text{axion}}$
- results obtained in Axion Band: ADMX and HAYSTACK
  - ☹ $\vec{E}\,.\,\vec{B}$ (only certain modes OK)
  - ☹ very narrow band (tuning)





Interlude: the problem with large axion masses



- Axion not overabundant above masses of $\sim 10^{-6}$eV
- naively: large $m \rightarrow$ lower resonance $f \rightarrow$ lower dimension
- Output power from cavity: $P \sim g^2 \frac{\rho}{m} B^2 \ V \ Q \ G$
- Quality factor $Q \sim 1/\Delta f \rightarrow$ long scan times
- $Q \sim \frac{V}{\delta S}$ Volume to surface ratio: gets bad at large Volumes
- proposed soln's: larger B (CAPP), superconducting cavity, very low $T_{\rm noise}$, dielectric layers (MADMAX)...

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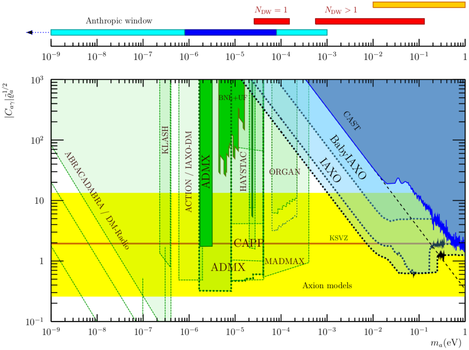

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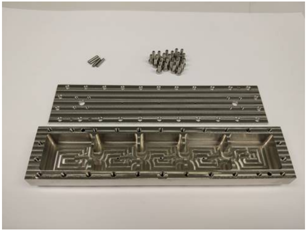
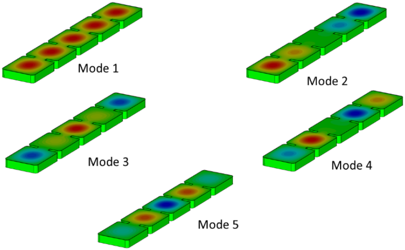
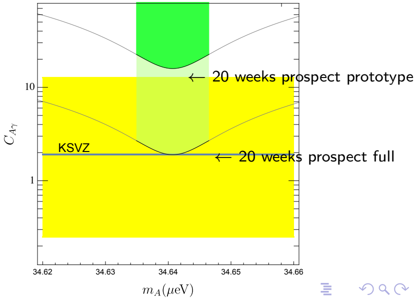


Melcon et al [1803.01243]



- RADES at CERN: retain large volume at high resonance frequencies large using subcavities $m \sim 34\mu$eV
- sub-cavity sets resonance scale
- only first resonant mode couples to the axion



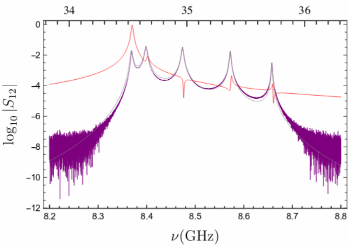
Interlude: RADES concept explored at CERN Melcon et al [1803.01243]

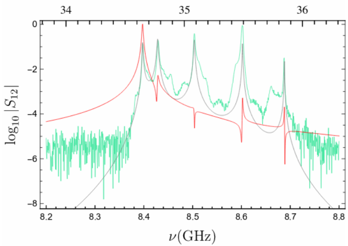
top: room, bottom 2.3K

red: coupling to axion

green/purple: data

grey: analytical fit





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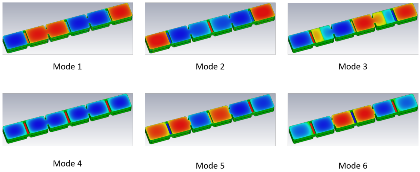
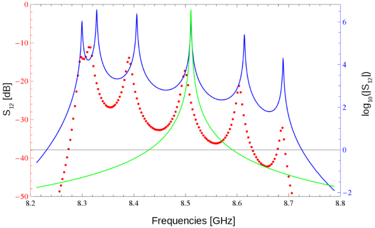
- currently conceiving larger number of sub-cavities and **tuning**

Interlude: RADES concept explored at CERN Melcon et al [1803.01243]



Analytical model vs Simulations (Preliminary results)



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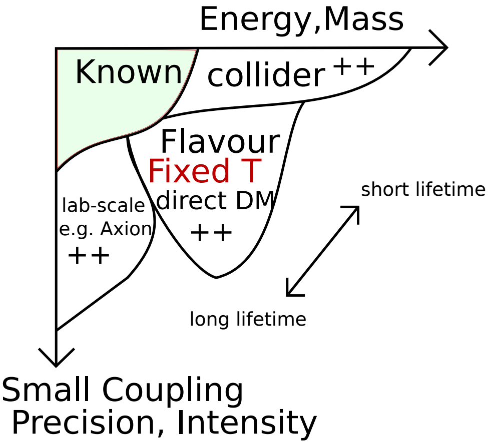
- only first resonant mode couples to the axion
- 5-cavities prototype tested this winter 2017/2018
- currently conceiving larger number of sub-cavities and **tuning**
- now 3 prototypes exploring these aspects

ALPs at higher masses

want to produce DM

or something 'mediating' it



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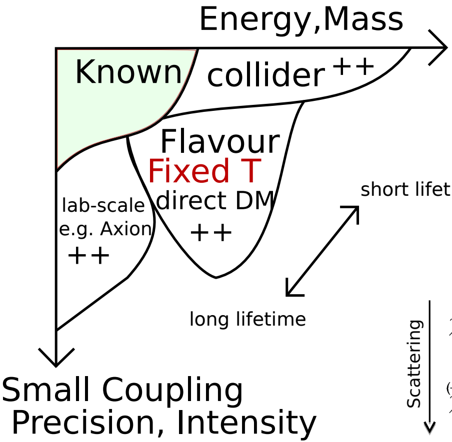
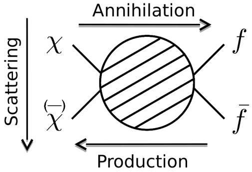
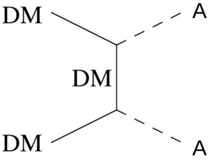
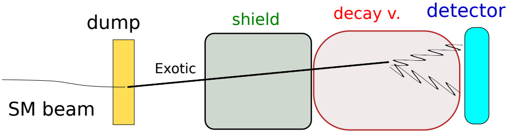


- Some models of Dark Matter propose MeV mass, very weakly-coupled particles e.g. [1502.06000]
- production needs sufficiently high energy & high intensity & long detection volumes
- fixed target facility is an obvious choice



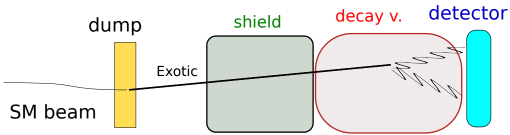


Important parameters in the fixed-target setup



- Beam energy & type (e, p, μ), number of beam particles shot on target, composition of target material
- 'shield length' and length & volume of the decay region
- background rejection by shield or detector capabilities
- detector types for decay products: charged/neutral Standard Model Particles or scattering of DM itself
- timeline of data-taking and cost

Important parameters in the fixed-target setup



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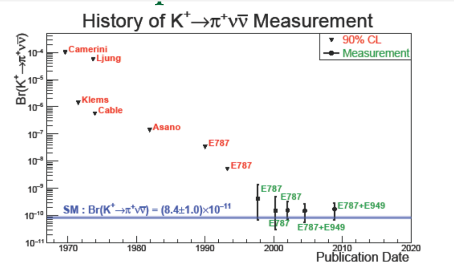
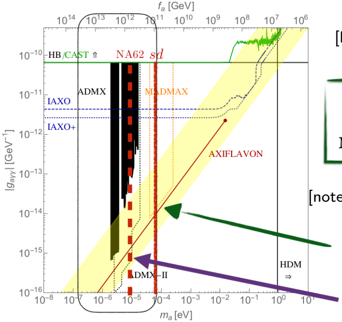
- detector types for decay products: charged/neutral Standard Model Particles or scattering of DM itself
- timeline of data-taking and cost
- **An experiment perfect for long-lived exotics searches is taking data as we speak: NA62**

NA62 and $K \to \pi\nu\bar{\nu}$: motivation and state of art



- ultra-rare FCNC decay, theory prediction:
  $(K \to \pi\nu\bar{\nu}) = (8.4 \pm 1.0) \times 10^{-11}$ Buras et al. JHEP 1511, 33
- experiment at BNL, E949 (2008), stopped Kaons:
  $\mathrm{BR}(K \to \pi\nu\bar{\nu}) = (17.3^{+11.5}_{-10.5}) \times 10^{-11}$ Phys. Rev. D 79, 092004

NA62 and $K \to \pi\nu$



[R. Ziegler at Annecy, May 3rd 2018]

Natural axion DM window testable at NA62 and ADMX-II!

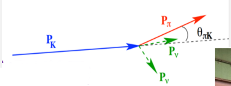
[note added: and RADES and many others :-)]

Present bound from E787+E949

Expected future bound from NA62

- ultra-rare FCNC decay, theory prediction:
  $(K \to \pi\nu\bar{\nu}) = (8.4 \pm 1.0) \times 10^{-11}$ Buras et al. JHEP 1511, 33
- experiment at BNL, E949 (2008), stopped Kaons:
  $\mathrm{BR}(K \to \pi\nu\bar{\nu}) = (17.3^{+11.5}_{-10.5}) \times 10^{-11}$ Phys. Rev. D 79, 092004
- NA62 primary goal: measurement of $\mathrm{BR}(K \to \pi\nu\bar{\nu})$ with 10% signal acceptance (decay in flight) $\Rightarrow 10^{13} K^+$ in fiducial volume
- BR correlated with flavor observables & sensitive to new physics, e.g. **flavored axion models** Phys. Rev. D 95, 095009 (2017)

NA62 rationale

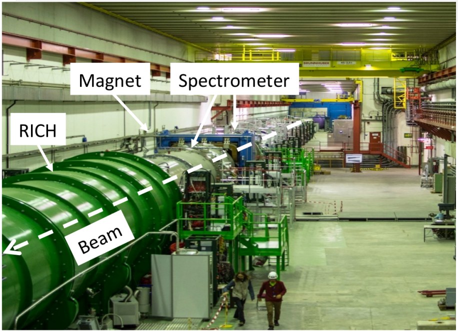


A Kaon's life:

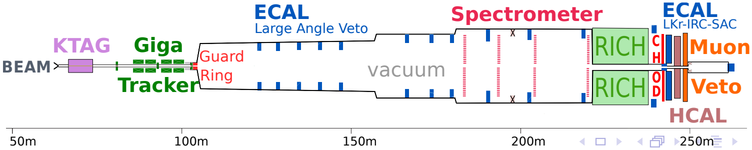
- $BR(K \to \pi^+\pi^0) \simeq 0.21$
- $BR(K \to \mu^+\nu) \simeq 0.64$
- $BR(K \to \pi^+\pi^-\pi^+) \simeq 0.06$

Detector system

- Kaon: KTAG, GTK, CHANTI
- Pion: STRAW, CHOD, RICH
- γ Vetoes: LAV, IRC, SAC, LKr
- MUV system: μ & Hadron

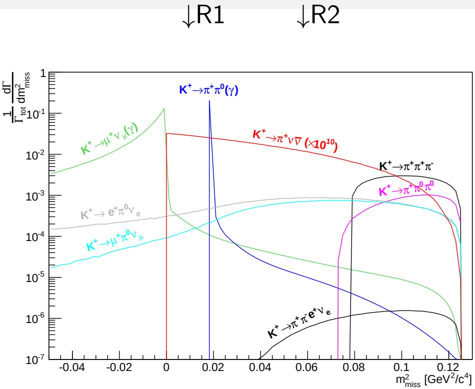


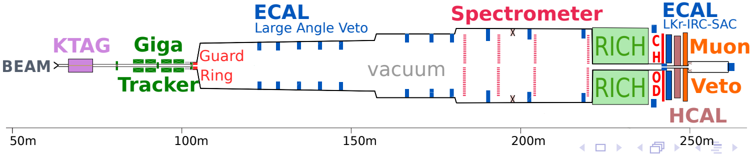
unseparated 750 MHz beam at GTK3 (6.6 % Kaons at 75 GeV, 1 % bite)



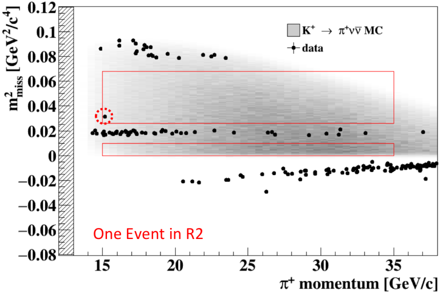
NA62 rationale II & requirements

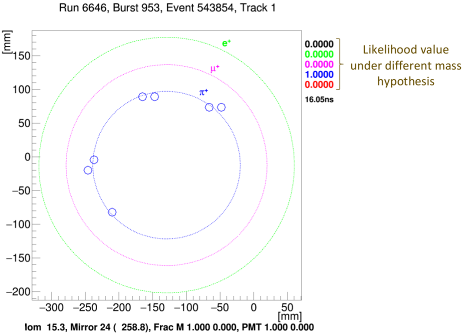
- $m^2_{\text{miss}} = (P_K - P_\pi)^2$
- 10^{12} background rejection!
- kinematic $\mathcal{O}(10^4)$
- high-efficiency veto: $\mathcal{O}(10^8)$ rejection of π^0 for $E(\pi^0) > 40\text{GeV}$
- particle ID μ vs π: rejection of $\mathcal{O}(10^7)$ for $15 < p_{\pi^+} < 35\text{GeV}$
- timing subdetectors $\mathcal{O}(100\text{ps})$





1 event in 2016 data (see R. Marchevski, June seminar)





Events Observed	1
SES	$(3.15 \pm 0.01_{stat} \pm 0.24_{syst}) \cdot 10^{-10}$
Expected Background	$0.15 \pm 0.09_{stat} \pm 0.01_{syst}$

$BR(K^+ \to \pi^+\nu\bar{\nu}) < 11 \times 10^{-10}$ @ 90% CL

$BR(K^+ \to \pi^+\nu\bar{\nu}) < 14 \times 10^{-10}$ @ 95% CL

Preliminary

Expected limit: $BR(K^+ \to \pi^+\nu\bar{\nu}) < 10 \times 10^{-10}$ @ 95% CL

For comparison $BR(K^+ \to \pi^+\nu\bar{\nu}) = 2.8^{+4.4}_{-2.3} \times 10^{-10}$ @ 68% CL

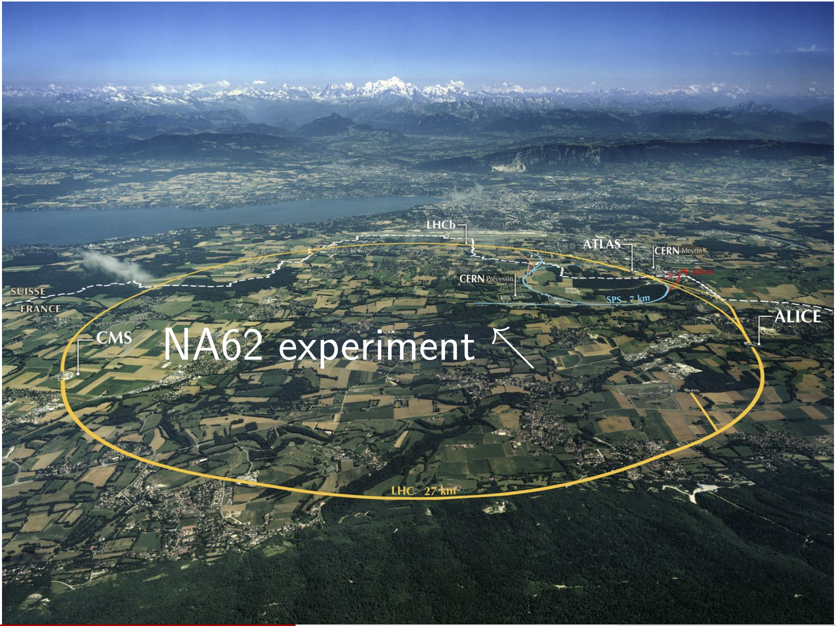
Preliminary

$BR(K^+ \to \pi^+\nu\bar{\nu})_{SM} = (0.84 \pm 0.10) \times 10^{-10}$ SM prediction

$BR(K^+ \to \pi^+\nu\bar{\nu}) = (1.73^{+1.15}_{-1.05}) \times 10^{-10}$ BNL E949/E787 Kaon Decay at Rest

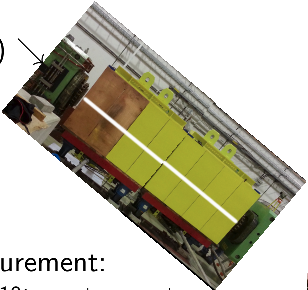
- Processing of 2017 data ongoing (20-fold present statistics)
- 2018: data taking ongoing → **This topic deserves its own talk! → stop here :-)**

widening the horizon



widening the horizon

protons on target (POT)



← beam collimator (TAX) ‘open’

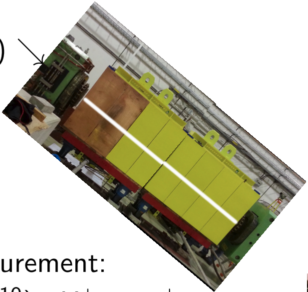
⇒ K^+ to detector ↓

main measurement:

BR $\mathcal{O}(10^{-10})$: $K^+ \to \pi^+ \nu \bar{\nu}$

widening the horizon

protons on
target (POT) $\searrow$



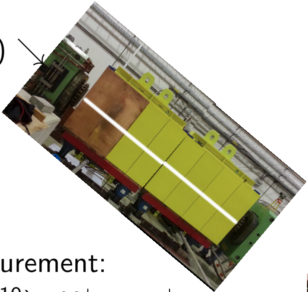
$\leftarrow$ beam collimator (TAX) 'open'

$\Rightarrow$ K^+ to detector $\downarrow$

main measurement:
BR $\mathcal{O}(10^{-10})$: $K^+ \to \pi^+ \nu\bar{\nu}$
1) Kaon decay
with exotic: $\to \pi a$

widening the horizon

protons on target (POT) can produce exotics



← beam collimator (TAX) 'open'

⇒ K^+ to detector ↓

+ exotic away from beamline

main measurement:

BR $\mathcal{O}(10^{-10})$: $K^+ \to \pi^+ \nu \bar{\nu}$

1) Kaon decay

with exotic: $\to \pi a$

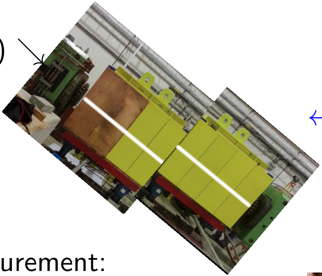
2) parasitically:

e.g. exotic $\to l^+ l^-$

n.b. $\sim$ half the protons don't interact in target

widening the horizon

protons on
target (POT) $\searrow$
can produce
exotics



main measurement:
BR $\mathcal{O}(10^{-10})$: $K^+ \to \pi^+ \nu \bar{\nu}$
1) Kaon decay
with exotic: $\to \pi a$
2) parasitically:
e.g. exotic $\to l^+ l^-$
3) dedicated data-taking
e.g. axion $\to \gamma\gamma$

will be used as example later on

$\leftarrow$ beam collimator closed $\to$ dump

$\Rightarrow$ exotics to detector $\downarrow$
with much reduced backgrounds

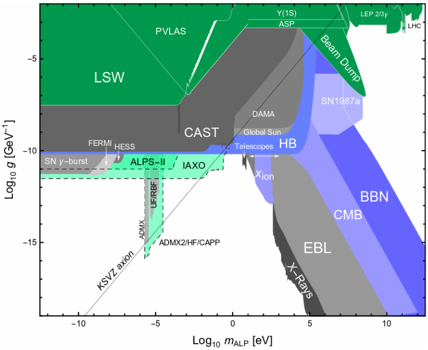
Heavy ALPs coupled to photons

$$\mathcal{L}_{\text{axion}} = \mathcal{L}_{\text{SM}} + \mathcal{L}_{\text{DS}} + \frac{a}{f_\gamma} F_{\mu\nu} \tilde{F}_{\mu\nu}$$

ALP= Axion-like particle

→ no $f - m$ relation as for QCD axion

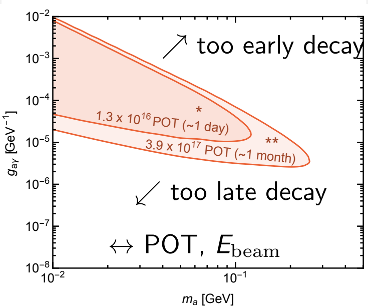
warning: plot not 100 % up to date

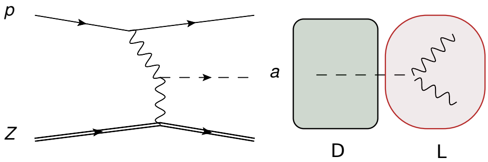


why? pseudoscalar portal DM [1502.06000]

- following projections based on Primakov production with in equivalent photon approximation (photon-from-proton) and 0 background assumption (see later...)

Detailed example: understanding ALP contours





[BD et al, JHEP 1602, 018, see also Dolan JHEP 1712, 127]

- production is not exactly forward (but not relevant for the moment)
- NA62: $d_{\rm tax} \sim 81$m, $L_{\rm tracker} \sim 65$m, $L_{\rm calo} \sim 135$m

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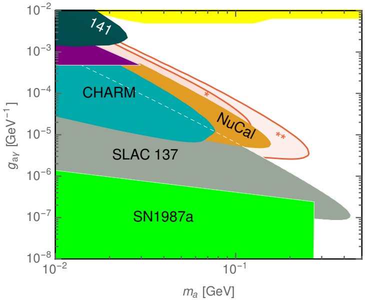

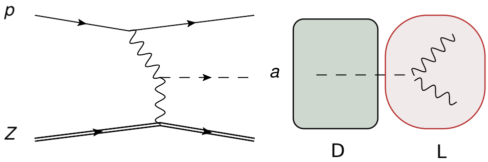

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- CHARM: $d_{\rm dump} \sim 480$m, $L_{\rm tracker} \sim 35$m **but** offset 5m from beam-axis $\rightarrow A_{\rm effective} = 0.09 \rightarrow N_{\rm POT,effective} \sim 2 \times 10^{17}$
- NuCal: $d_{\rm dump} \sim 64$m, $L_{\rm tr.} \sim 23$m, $N_{\rm POT} \sim 2 \times 10^{18}$ **but** $E = 70$GeV

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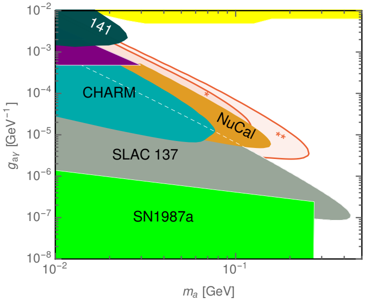

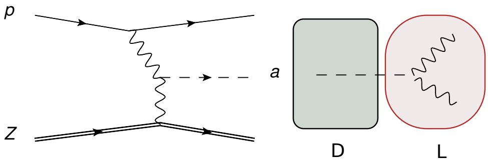

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- general picture persists for other use-cases $\rightarrow$ reason for parasitic triggers: complementary sensitivity also, e.g. for ALPs to l^+l^- + Dark Photons + Heavy Neutral Leptons...

Thanks for listening :-)

we are in the middle of 2018 NA62 data-taking

- NA62 first result for main analysis channel just released
- analysis of $\mathcal{O}(10^{16})$ POT in dump-mode ongoing for neutral & charged final states
- analysis of $\mathcal{O}(10^{17})$ POT in parastic mode on-going for charged final states

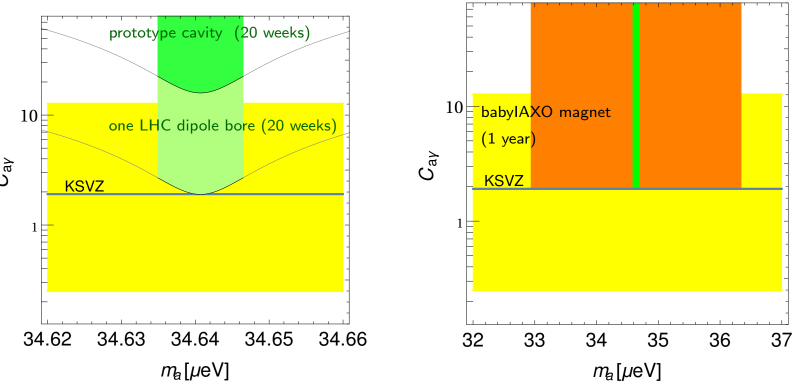
we are taking new data with the RADES cavity from mid-september

- our aim is to delevop a cavity concept sensitive to QCD axions $\gg 10\mu$eV
- test cavity performance validated, working on several improvements

Additional slides/backup

Supplement: Projections for DM Axions with RADES

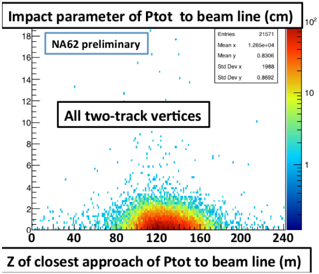
From JCAP 05, 040: Melcón,[...], BD et al.

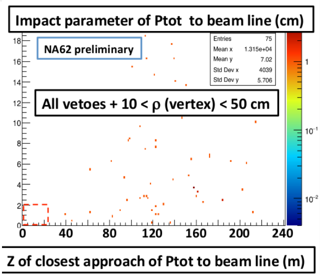


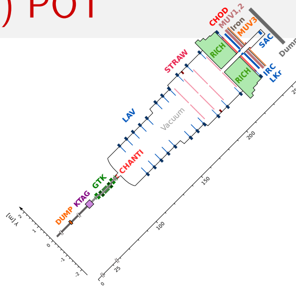
→ QCD Axion relation: $g_{a\gamma} \equiv 2 \times 10^{-16}\ C_{a\gamma}\ \frac{\mathrm{m_a}}{\mu eV}\ \mathrm{GeV}^{-1}$
KSVZ and yellow band: Axion models

→ note: prospect 'Axiflavon' reach for NA62: $m_a \gtrsim 10^{-5}$eV [PRD 95, 095009]

Charged bkg rejection: 2016 data $\mathcal{O}(10^{15})$ POT



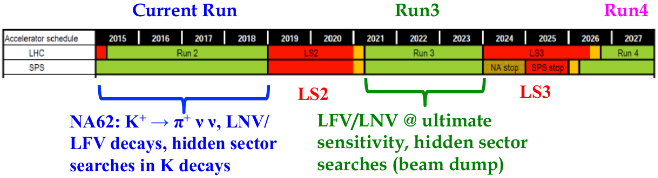




- Track quality (association with CHOD, LKr hits in time) + acceptance (CHOD, LKr, MUV3)
- Vertex quality: two-track-distance < 1cm, vertex-position 105< z <165 m
- further veto (rhs): $E_{\mathrm{LKr,additional}} < 2$ GeV; IRC, SAC, LAV no hits with $\pm$ 5ns, CHANTI no candidate within $\pm$ 5ns
- no events in signal region at TAX even with standard K^+ beam at $\mathcal{O}(10^{15})$ POT, background rejection OK for $\mathcal{O}(10^{15})$ POT in standard conditions and $\mathcal{O}(10^{16})$ in dump

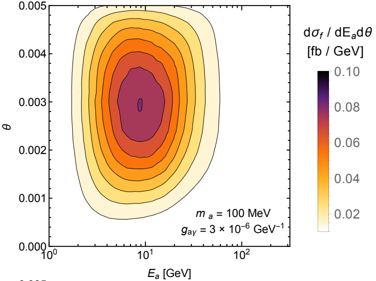
2+3) Exotic from dumped-beam: prospects

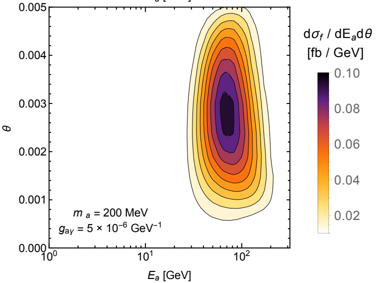
1. Parasitic to $\pi\nu\bar{\nu}$: flavored axion, invisible Dark Photons, heavy Neutrinos, Dark Scalars...
2. Trigger Parasitic to $\pi\nu\bar{\nu}$: $\mu\pi + \mu\mu$ away from beamline: 2017: $\mathcal{O}(10^{17})$ POT, sizable statistics $\mathcal{O}(10^{18})$ POT possible this year
3. dump-mode: sizable statistics $\mathcal{O}(10^{18})$ reserved for future, but some channels discovery potential with moderate statistics (e.g. ALP $\mathcal{O}(10^{16})$)



Under study / definition, interaction/synergy with the Physics Beyond Collider CERN initiative

Fiducial cross-section: importance of being boosted





fiducial cross-section

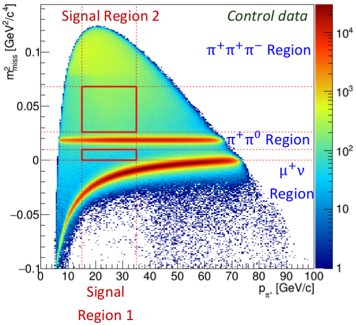
- requirement: reach the decay volume and detect two γ with certain geometrical constraints in Calorimeter
- two examplary parameter points of the fiducial cross-section

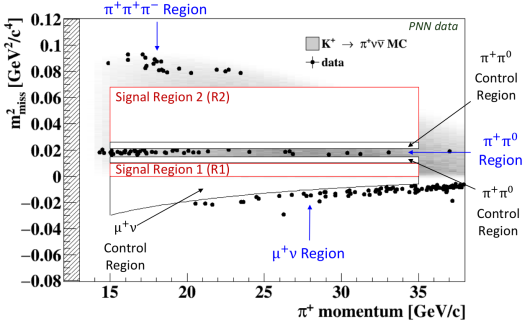
analysis impact

- probability to reach decay volume $\sim \exp(-l_{\rm absorber}/l_d)$, $l_d = \gamma\beta\tau \sim \frac{E_a}{m}\frac{64\pi}{m^3 g^2}$
- large (g, m) more boosted, possibility to choose appropriate signal box for such (g, m)

2016 data: $\sim 10^{11} K^+$ useful for analysis

Selected K^+ decays, before π^+ id and γ/multi rejection





- K^+ decay into single charged track, π^+ PID, γ & multi-track rejection
- Performances: GTK-KTAG-RICH timing: $\mathcal{O}(100\text{ps})$, γ/multi-track rejection: 3×10^{-8}, overall π^+ ID: 64%,

Single Event Sensitivity and background budget

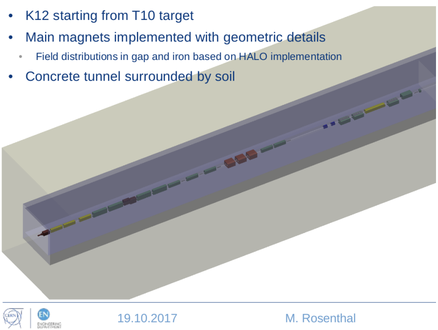
$$SES = \frac{1}{N_K \cdot (A_{\pi\nu\nu} \cdot \epsilon_{RV} \cdot \epsilon_{trig})} \qquad N_K = \frac{N_{\pi\pi} \cdot D}{A_{\pi\pi} \cdot BR_{\pi\pi}}$$

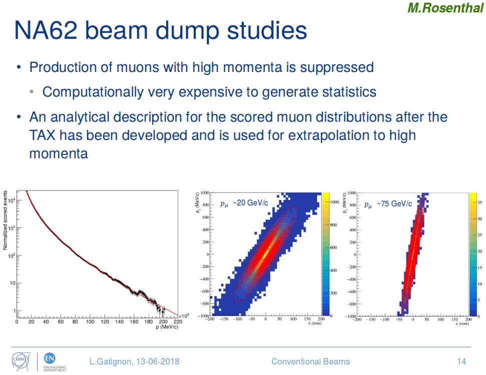
Number of K^+ Decays	$\mathbf{N_K = (1.21 \pm 0.02) \times 10^{11}}$
Acceptance $K^+ \to \pi^+\nu\bar{\nu}$	$A_{\pi\nu\nu} = 0.040 \pm 0.001$
PNN trigger efficiency	$\epsilon_{trig} = 0.87 \pm 0.02$
Random veto	$\epsilon_{RV} = 0.76 \pm 0.04$
SES	$\mathbf{(3.15 \pm 0.01_{stat} \pm 0.24_{syst}) \times 10^{-10}}$
Expected SM $K^+ \to \pi^+\nu\bar{\nu}$	$0.267 \pm 0.001_{stat} \pm 0.020_{syst} \pm 0.032_{ext}$

Process	**Expected events in R1+R2**
$K^+ \to \pi^+\nu\bar{\nu}$ (SM)	$0.267 \pm 0.001_{stat} \pm 0.020_{syst} \pm 0.032_{ext}$
Total Background	$\mathbf{0.15 \pm 0.09_{stat} \pm 0.01_{syst}}$
$K^+ \to \pi^+\pi^0(\gamma)$ IB	$0.064 \pm 0.007_{stat} \pm 0.006_{syst}$
$K^+ \to \mu^+\nu(\gamma)$ IB	$0.020 \pm 0.003_{stat} \pm 0.003_{syst}$
$K^+ \to \pi^+\pi^-e^+\nu$	$0.018^{+0.024}_{-0.017}\vert_{stat} \pm 0.009_{syst}$
$K^+ \to \pi^+\pi^+\pi^-$	$0.002 \pm 0.001_{stat} \pm 0.002_{syst}$
Upstream Background	$0.050^{+0.090}_{-0.030}\vert_{stat}$

- N_K computed from $K^+ \to \pi^+\pi^0$ on control trigger stream ($D = 400$), w/o γ and multiplicity rejection and modified $m^2_{\rm miss}$-cut
- Expected number of events from 2016 data: $\mathrm{BR}_{\rm SM\ theory}/$SES
- validation of background expectations in control regions, see e.g. `https://indico.cern.ch/event/714178/` for details

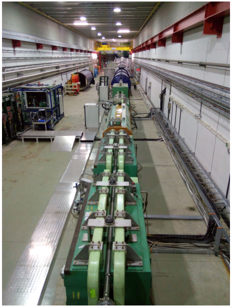
Background modelling by conventional beams group

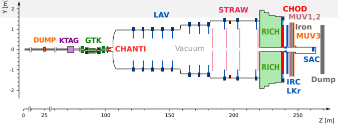




- Geant4 beamline model, aim: potential optimization of beamline for future longer exotics/dump runs
- can provide valuable input for data already on tape

Benchmarking the Muon Halo + secondaries

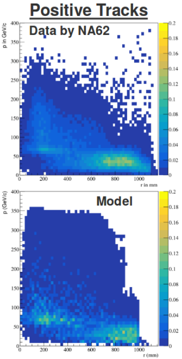




- impressive benchmark for single charged tracks; reduction factor: $> \mathcal{O}(10^5)$
- ongoing benchmarking for coincident charged tracks (e^+e^-), suspicion of double-bremsstrahlung with 'lost tracks' as di-γ background

Benchmarking continued

- Characteristic muon distribution reproduced
- Rates at higher momenta estimated from extrapolation
- Absolute scaling of data and MC differs by factor ~5
  → under investigation (comp. expensive)



L.Gatignon, 13-06-2018 Conventional