CERN

(Opportunistic) search for axion Dark Matter with the Relic Axion Detector Exploratory Setup and NA62

Babette Döbrich

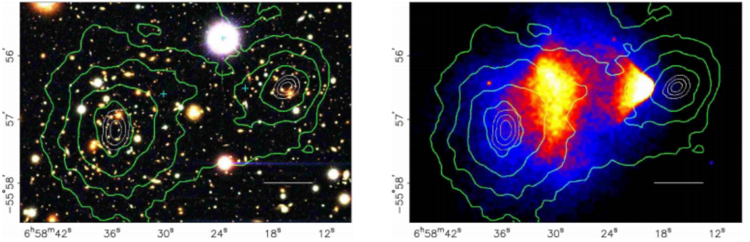
European Research Council
Established by the European Commission

Disclaimer

My talk will cover axions as general theme but vastly different experimental methods. Hopefully, this will not only be confusing but lead to the fact that everyone gets something that interests her/him. Feel free to interrupt any time.

We have yet to understand what 80% of matter is made of

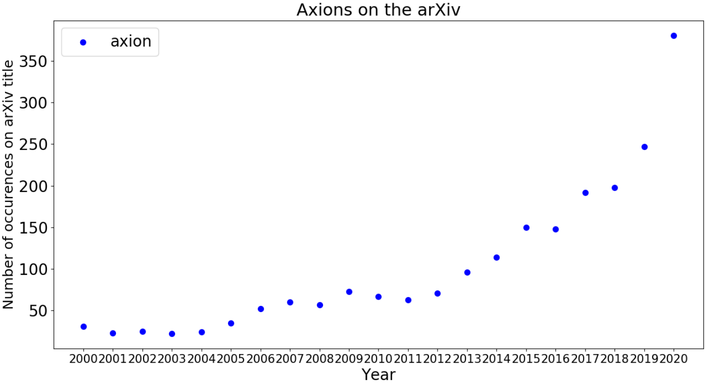
The bullet cluster might be the most famous evidence for the need for Dark Matter



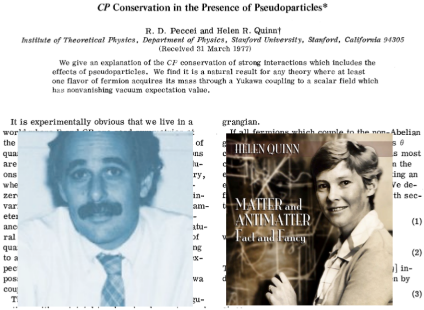
but most importantly: evidence exists on multiple scales: CMB, structure formation, galaxy rotation curves...

A prime goal of particle physics to find out what Dark Matter is

Community interest explodes in something called 'the axion'



The Axion was not invented to be the Dark Matter!



CP Conservation in the Presence of Pseudoparticles*

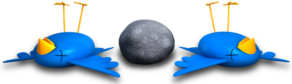
R. D. Peccei and Helen R. Quinn†
Institute of Theoretical Physics, Department of Physics, Stanford University, Stanford, California 94305
(Received 31 March 1977)

We give an explanation of the *CP* conservation of strong interactions which includes the effects of pseudoparticles. We find it is a natural result for any theory where at least one flavor of fermion acquires its mass through a Yukawa coupling to a scalar field which has nonvanishing vacuum expectation value.

It is experimentally obvious that we live in a

grangian.

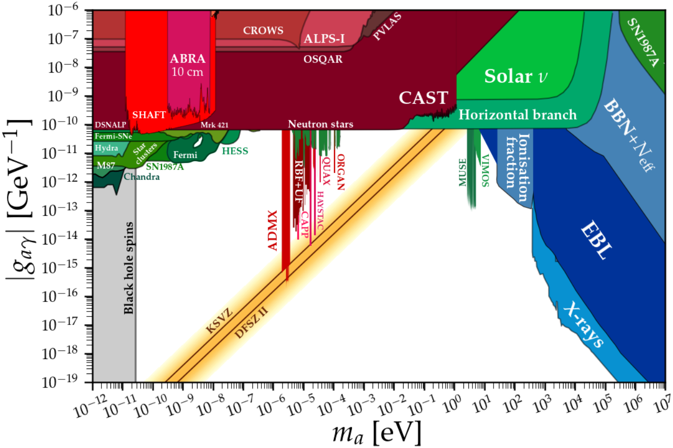
If all fermions which couple to the non-Abelian



but Axions (or more generally axion-like particles (ALPs)) which must be extremely weakly interacting can be the Dark Matter or a portal to it!

Present and future hide-outs of (low-mass) axions

limit compilation (and disclaimer) by C O'Hare `https://github.com/cajohare/AxionLimits`



QCD axion lives on yellow line
an ALP almost anywhere.

Present and future hide-outs of (low-mass) axions

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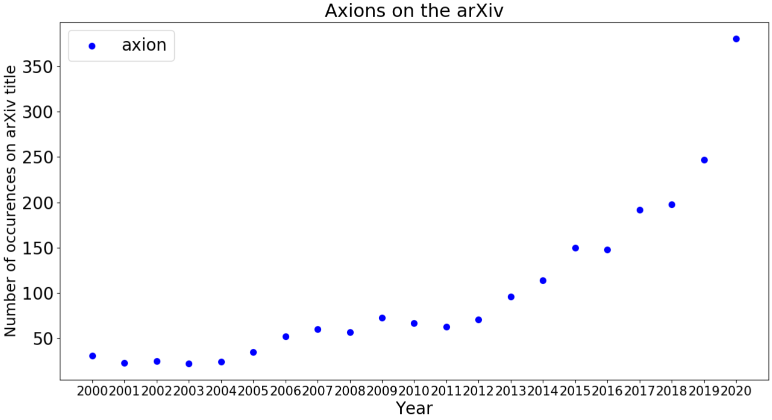

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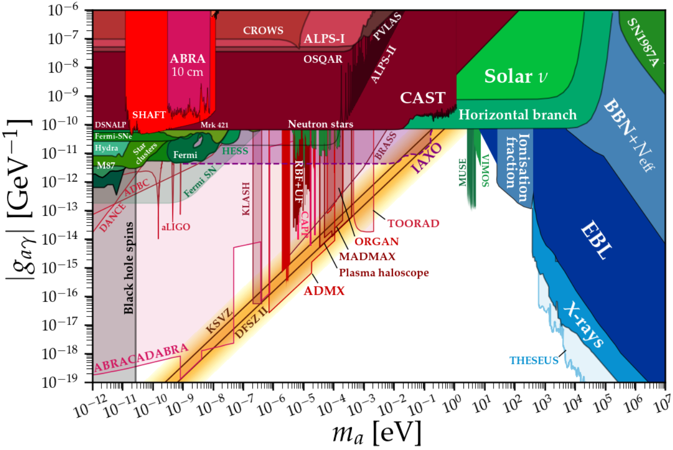

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Projections!!! with

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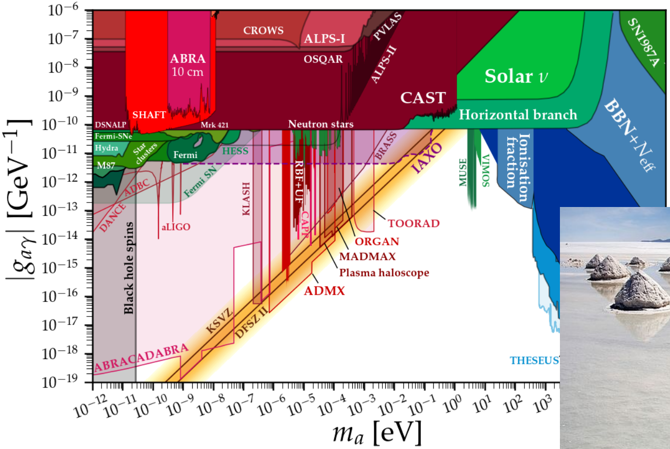

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an ALP almost anywhere.

Projections!!! with

more than a grain of salt

Luca Galuzzi via Wikimedia Commons

Main search types

1. **Produce** an axion, then detect it: light shining through walls also **beam dump, rare decays**, LHC (at higher masses)
2. look for axions from a **natural source**, most prominently solar axion searches: CAST, (baby-)IAXO
3. **assume that axions are THE Dark matter** (normally assume they are all of Dark Matter), infer their presence

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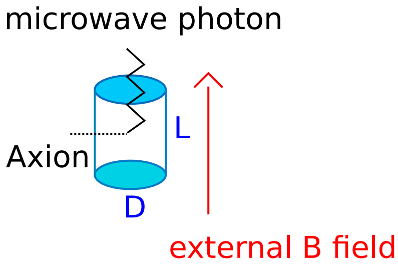
... I exploit my talk

to elaborate more first on point 3 (and in the end point 1) and what we do about that (opportunistically) at some experiments at CERN

A poor (wo-)man's axion haloscope



- figure of merit: $F \sim g^4 m^2 B^4 V^2 T_{\mathrm{sys}}^{-2} \mathcal{G}^4 Q$
- typically high-field solenoids, several Tesla
- typically few-/sub- Kelvin
- scanning: tune in steps $\sim$ size of axion width
- resonance quality Q worth to push up to $\sim 10^6$
- design requirement $\mathcal{G}$: cavity modes: right direction/ well spaced/ correctly coupled

The pioneers & 'old hands' - ADMX

Bartram et al: Axion Dark Matter eXperiment: Run 1B Analysis

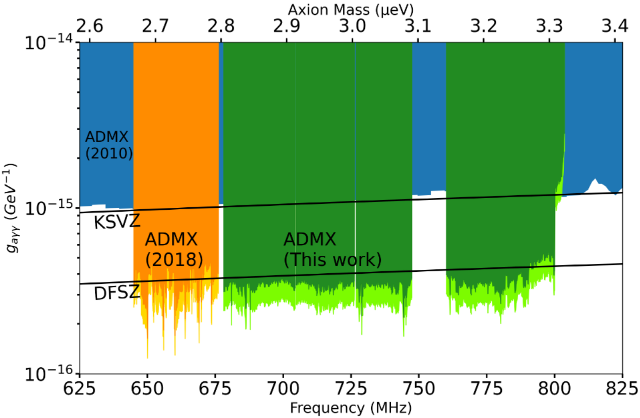
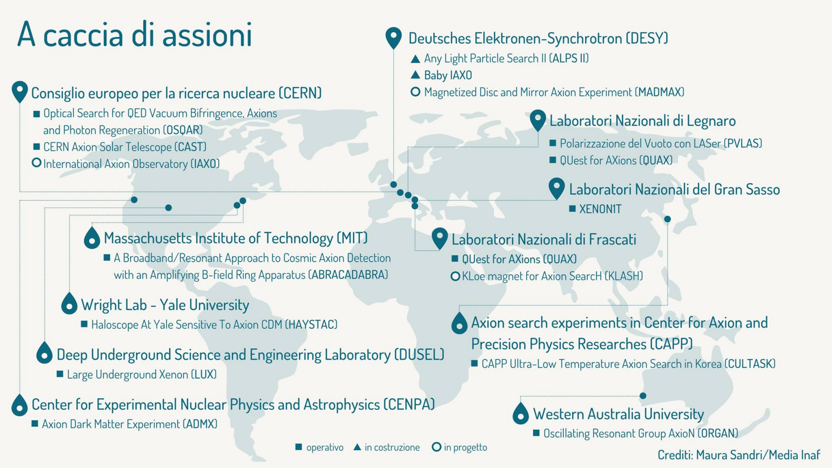
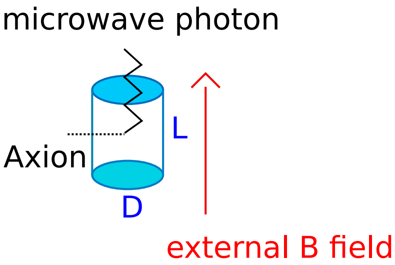


FIG. 17. Exclusion plot for Run 1B, shown in green. Dark green represents the region excluded using a standard Maxwell-Boltzmann filter, whereas light green represents the region excluded by an N-body filter [42].

That's not all... (incomplete, but nicely prepared)

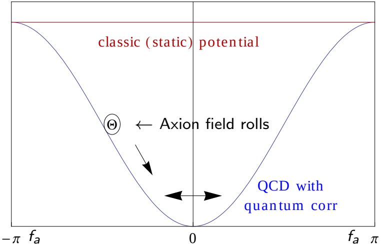


Interlude: Why large masses are harder to test

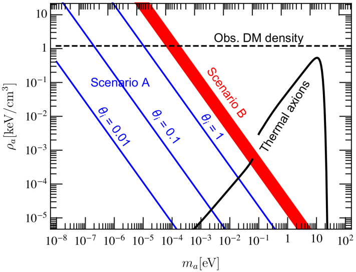


- figure of merit: $F \sim g^4 m^2 B^4 V^2 T_{\rm sys}^{-2} \mathcal{G}^4 Q$
- naively: large $m \rightarrow$ higher resonance $f \rightarrow$ lower dimension
- $Q \sim \frac{V}{\delta S}$ Volume to surface ratio: gets bad at low Volumes

Interlude: Why large masses are interesting to test



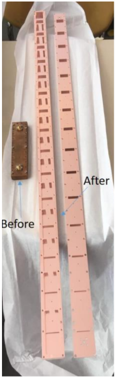
↓ time

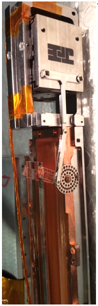


- axion mass depends on initial misalignment angle & inversely proportional to symmetry breaking scale
- large axion masses test the 'post-inflationary' axion, in which the axion mass can be more "easily" predicted

  (average of possible initial conditions, whereas otherwise one unknown initial condition stretched by inflation)
- scenario B: *m* prediction somewhat possible

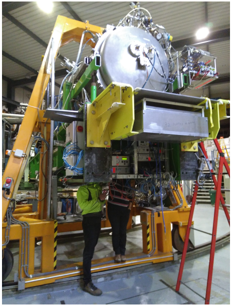
The opportunists - RADES & CAPP-CAST





2018-2021 ⟶

in CAST LHC dipole



⟵ true dedication:
hands-on and heads-in
(80% of us: this is 'hobby'!)

cavity R&D to search DM axions in **dipole magnets**

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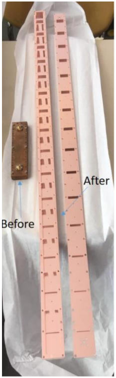
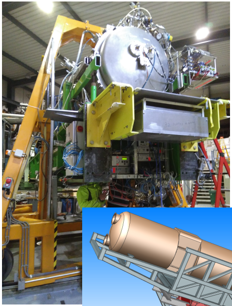
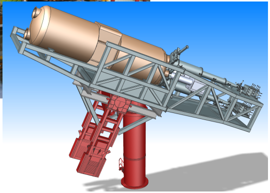


2018-2021 $\longrightarrow$ in CAST LHC dipole

RADES: long term $\longrightarrow$ babyIAXO (lower frequ)





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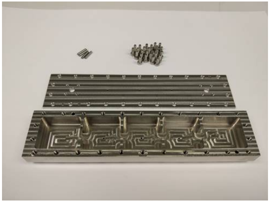
cavity R&D to search DM axions in **dipole magnets**

see e.g. Alvarez-Melcon et al, JHEP 07 (2020) 084

Basic idea of RADES: E pluribus unum JCAP 05 (2018) 040



- retain large volume at high resonance frequencies using a division into subcavities
- sub-cavity scale sets resonance scale

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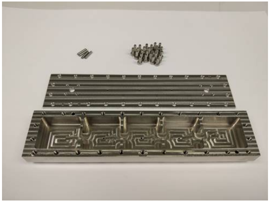

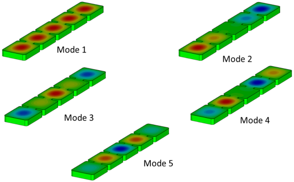

↑

ext. B-field

- retain large volume at high resonance frequencies using a division into subcavities
- sub-cavity scale sets resonance scale
- N of subcavities $= N$ of modes: not all cavity modes couple to the axion, but we can find one, here 'mode 1'!

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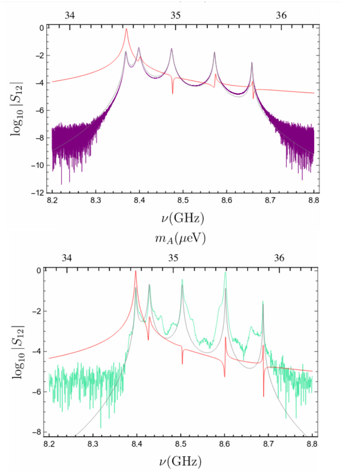

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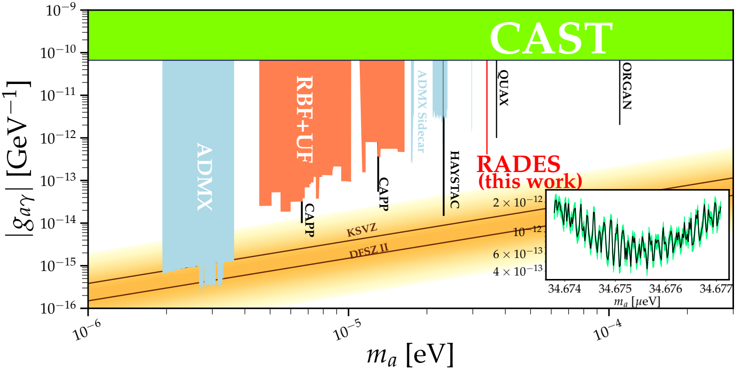
- sub-cavity scale sets resonance scale
- N of subcavities = N of modes: not all cavity modes couple to the axion, but we can find one, here 'mode 1'!
- (mode mixing at big N & tuning solved)

modest but brand-new: RADES' first analysis result

JHEP 2021, 75 (main analyst: S. Arguedas Cuendis)

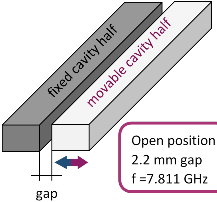
→ one of the strongest results to date above 25μeV



RADES tuning

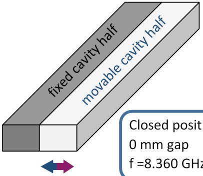
Jessica Golm (CERN & University of Jena)

Mechanical tuning by changing the distance of cavity halves

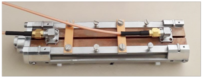


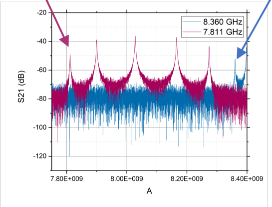
Open position
2.2 mm gap
f =7.811 GHz

Tuning range:
550 MHz



Closed position
0 mm gap
f =8.360 GHz





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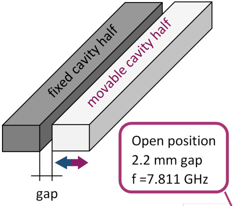

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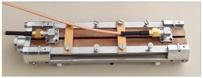
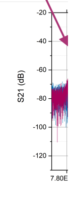
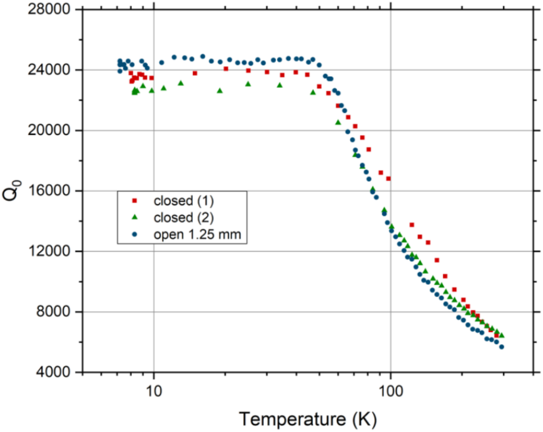
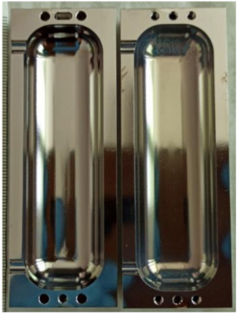






other activities - RADES HTS studies [J. Golm]

Nb_3Sn ≈ 2 µm layer



Coated at CERN by G. Rosaz and C. Pereira Carlos

HTS tape

Tape attached at ICMAB by G. Telles, N. Lamas, X. Granados, T. Puig, J. Gutierrez

HTS coating ≈ 2.3 µm layer

Coated by THEVA and Ceraco.

cavities redesigned w/o irises for easier coating

ongoing data-taking in SM18 (11 Tesla) https://arxiv.org/abs/2110.01296

RADES team in 2019 (last in-person meeting)

The current team

at CERN

Sergio Calatroni
Babette Döbrich
Jessica Golm
Chloe Malbrunot
Marc Siodlaczek
Walter Wuensch

at Zaragoza

Cristian Cogollos
Igor Irastorza
Javier Redondo

at Barcelona

Sergio Arguedas Cuendis
Jordi Miralda

at Cartagena

Alejandro ´Alvarez Melcon
Alejandro Dıaz-Morcillo
Jose Maria Garcıa Barcelo
Antonio Lozano-Guerrero
Jose Ramon Navarro
Pablo Navarro

at Valencia

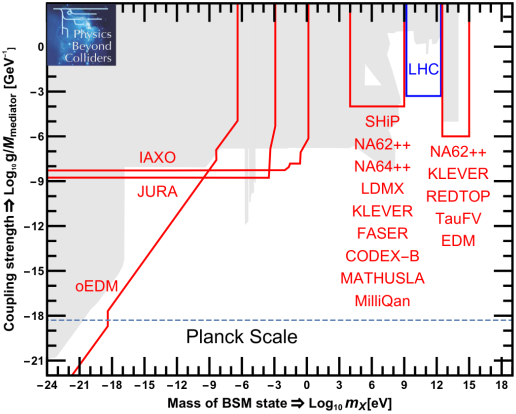
Benito Gimeno
Carlos Pena Garay

at Yebes

Juan Daniel Gallego

Complete change of gears

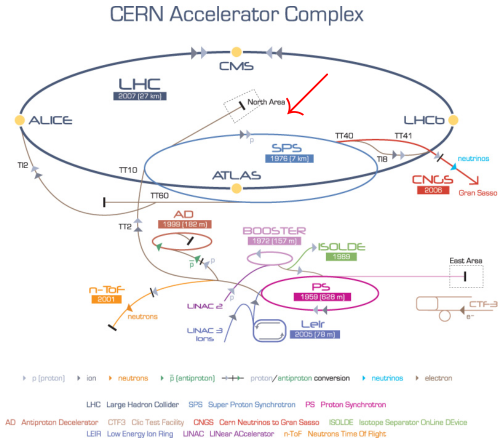
from Physics Beyond Collider summary report (1902.00260)



Disclaimer

- not an overview about the 'recent NA62 analysis exotics results'
- the reason is that 'recent NA62 analysis results' are discussed in many topical conferences this summer, here are some links to talks, for example at Pheno 2021: *lepton flavour and lepton number violation*, *ALPs*, *HNLs*
- instead I'd like to show-case some 'behind-the-scenes' work in phenomenology and simulation (with a focus on NA62 aspects) that are essential to make searches for axions and other exotics work

NA62 at CERN



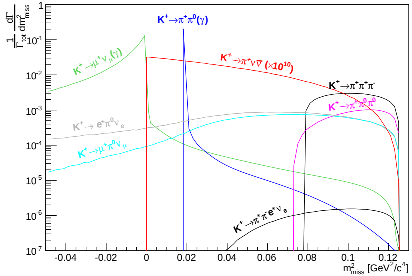
$$K^+ \to \pi^+ \bar{\nu}\nu$$

BR theory:

$$(8.4 \pm 1.0) \times 10^{-11}$$

Buras et al. JHEP 1511, 33

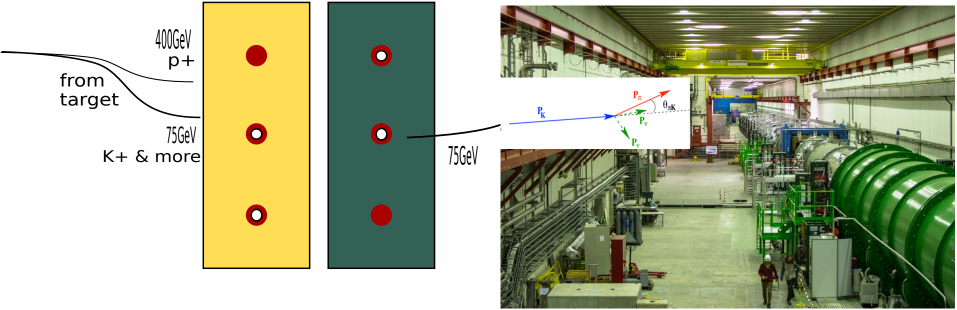
New Result! arXiv:2103.15389: data 2016-2018 analyzed

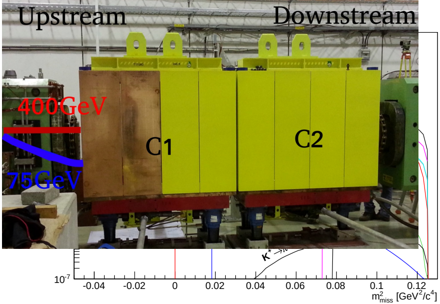


"straightforward": flavored axion

$$K^+ \to \pi^+ + a$$

(https://arxiv.org/abs/2011.11329)



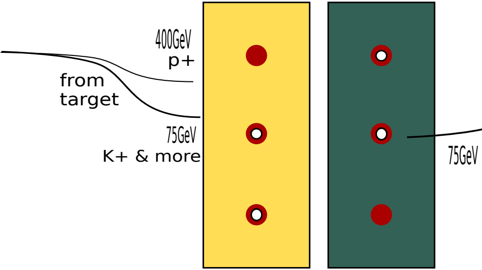


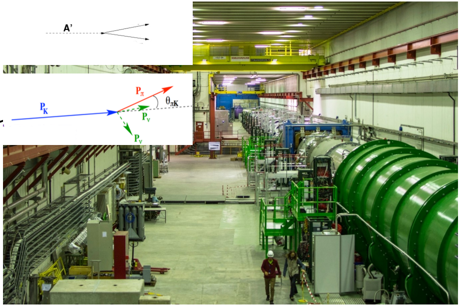
parasitic (charged) triggers not requiring an initial Kaon

$\Rightarrow$ **upstream production**

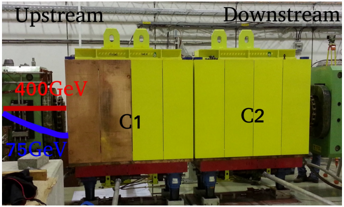
60 % target interaction & 40 % direct p

e.g. $\mu\mu$: $\mathcal{O}(10^{17})$ POT





Possibility to run NA62 as beam dump



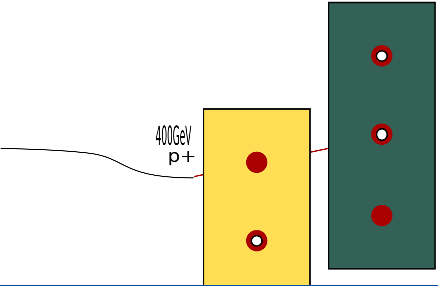
Primakoff production of MeV-GeV ALPs

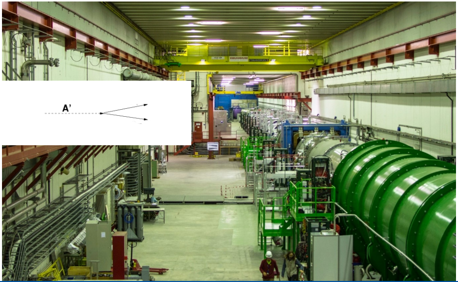
in upstream collimator: run as dump

critical for $\gamma\gamma$ final state

$\sim 3{\times}10^{16}$ POT collected in 2018

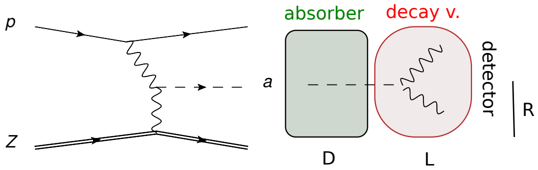
2021 run ongoing





Getting the signal yield right: example photon-coupled ALPs

predominant process proposed and computed in JHEP 1602 (2016) 018:



Theoretically rather clean: Well-tested equivalent photon approximation

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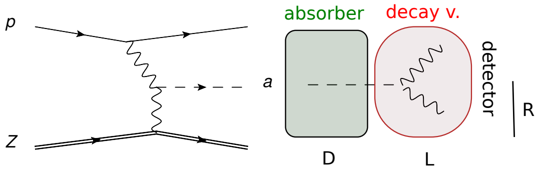

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.... some time passes.... working on analysis & data-taking ...

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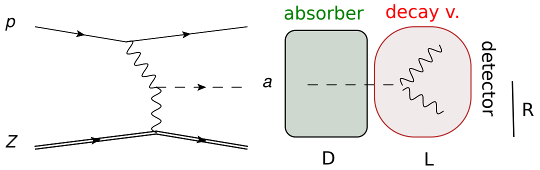

Theoretically rather clean: Well-tested equivalent photon approximation

.... some time passes.... working on analysis & data-taking ...

M. Pospelov: "If your initial photon comes from a π^0, you'll be more sensitive"'

Me: ...


D'oh!

The challenge

- can one reliably compute the π^0 yield and spectra in the NA62 beam-dump in a way that is sufficiently certain to base upon it a discovery or an exclusion limit?

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- whatever solution, it needs to be data-driven
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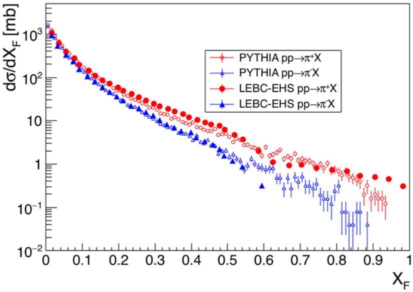
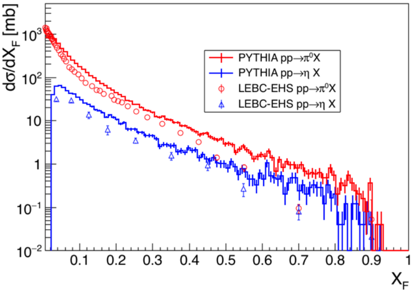
- no measurements of inclusive neutral meson production available at exactly desired energies & target materials employed in the experiments. But data available covering the energy range from 60 GeV to 450 GeV and different target materials, in particular hydrogen and beryllium, as well as different meson types
- validate simulation on data as much as possible, in the following $x_f = P_z/P_z(max)$

I: Tuning pythia to data, pions at 400GeV

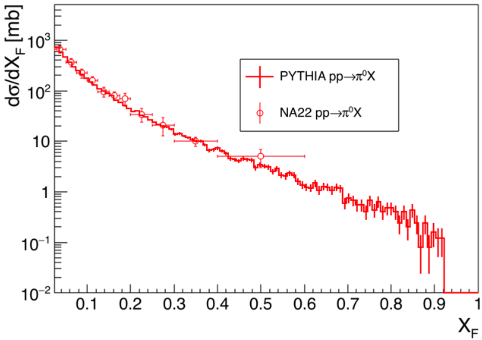




1) Modelled acceptance of LEBC-EHS (1991)

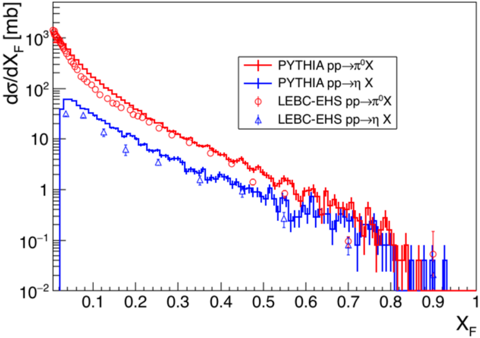
2) observed: MC tends to overshoot at high energies more for neutral than charged

II: Tuning pythia to data neutral pions at 250GeV



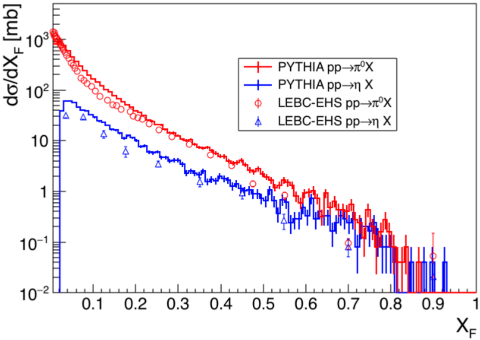
found better agreement in neutral mode for a different experiment ...

III: Tuning pythia to data, pions at 400GeV with trigger in MC



corrected for re-modelled trigger conditions

III: Tuning pythia to data, pions at 400GeV with trigger in MC

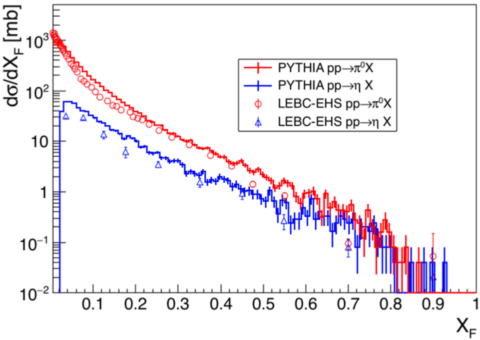


corrected for re-modelled trigger conditions

basically the trigger efficiency is very low and non-flat across x_f *...*

one has to understand the number of charged tracks co-emitted with the π^0

III: Tuning pythia to data, pions at 400GeV with trigger in MC



corrected for re-modelled trigger conditions

basically the trigger efficiency is very low and non-flat across x_f *...*

one has to understand the number of charged tracks co-emitted with the π^0

can use now MC-scaled to data with good conscience ...

(scaling to target material also done, not discussed here) ...

The resulting projections from JHEP05(2019)213 , missing the recent NA64 & Belle II results

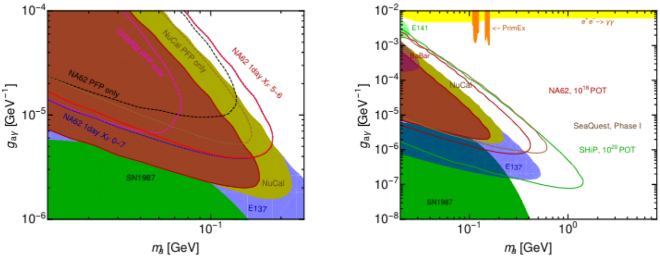


Figure 10. Both plots: filled areas: 90%-CL excluded regions from past experiments (cf. [7, 38]); contours: projected 90%-CL exclusion capability at present or future experiments. Left: Excerpt of the limit plot as in Fig 1 but with updated CHARM region (brown): including PFP and π^0 contributions from X_F bins 5–6, magenta dashed contour: PFP alone). In addition we show three projections for NA62 at 1.3×10^{16} POT (1 day): Black dashed: PFP alone, red solid and blue dotted: Yield from π^0 in using X_F bins 5–6 and 0–7, respectively. Right: projections for NA62 at 1×10^{18} POT, as well as SHiP and SeaQuest (Phase I) at 1×10^{20} POT and 1.44×10^{18} POT, respectively. We have checked that the MC statistical uncertainty is negligible compared to the uncertainties of the PYTHIA/data agreement (see Section 2).

backgrounds! general considerations

- in 'naive' beam-dump mode (no optimization of upstream magnets) sees around 60 kHz after 'downscaling'. These are mostly muons
- **muon's parent particles are mostly mesons produced by protons. Thus we need control over that as well (as discussed before)**
- most dangerous to searches are in-time components of multiple particles
- this can be muons 'accidentally' in time
- in addition: secondaries created at the beginning of the decay volume
- example: K_s, Λ, π^0....

Why this is important (and non-trivial)

- starting point are 10^{16} (or more) POT, end-point are a handful of events $\Rightarrow$ extrapolation over many orders of magnitude
- let's try understand the muon spectrum in the detector from first principles

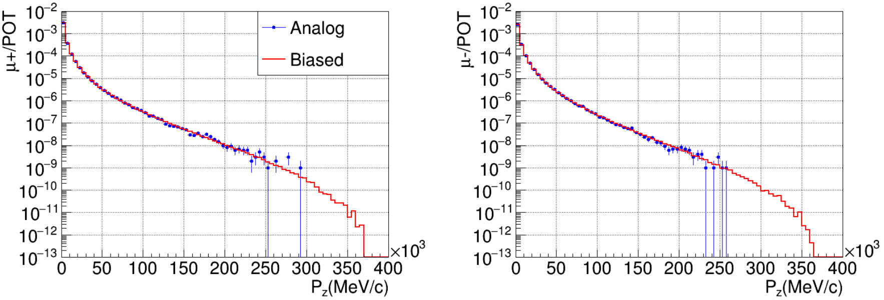
Why this is important (and non-trivial)

- starting point are 10^{16} (or more) POT, end-point are a handful of events $\Rightarrow$ extrapolation over many orders of magnitude
- let's try understand the muon spectrum in the detector from first principles
- muon yield per proton shot on thick target can be very low $\sim 10^{-4}$, while $\mathcal{O}(10^{10-12})$ POT can be sensibly simulated brute force
- possible approach: parameterization (pursued in the past (M. Rosenthal, PBC)): however the high-momentum part of the distribution will suffer from severe statistical fluctuations

Better: biasing technique: Eur.Phys.J.C 81 (2021) 8, 76 S. Ghinescu et al.

analog = brute force simulation

biasing = if meson of interest is produced, clone and mark that particle



Better: biasing technique: Eur.Phys.J.C 81 (2021) 8, 76 S. Ghinescu et al.

analog = brute force simulation

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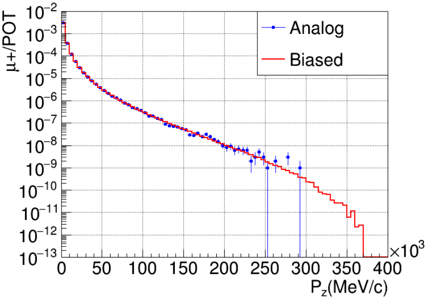
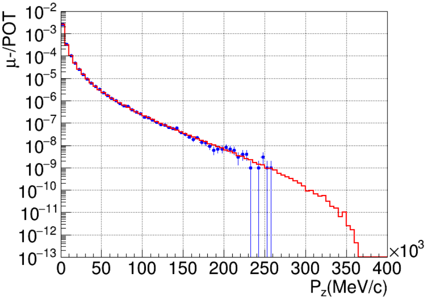
develop analog 'normally', biased forbidden to be killed w/o yielding μ

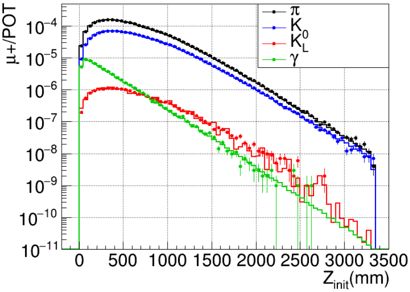
at the same time, keep 'original' interaction length





Better: biasing technique: arxiv:2106.01932 S. Ghinescu et al.

illustration of the main muon sources



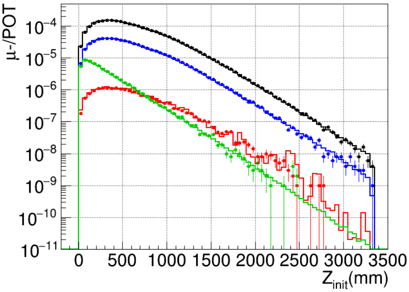


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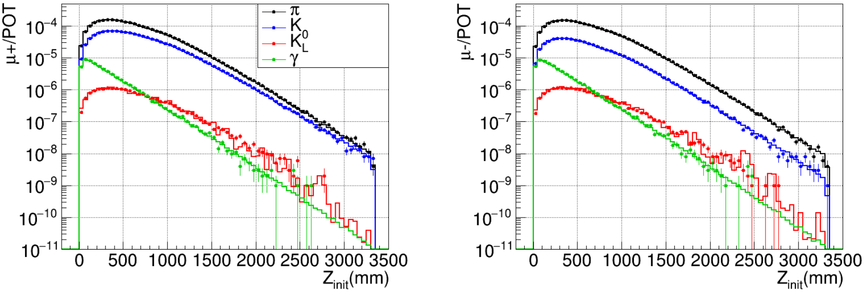
illustration of the main muon sources

gain in statistics: $\sim 2 \times 10^3$



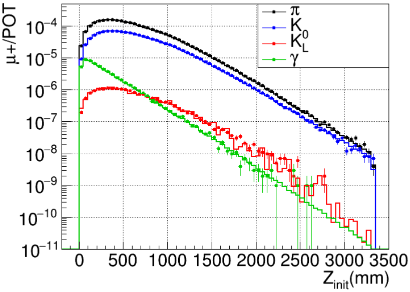
Better: biasing technique: arxiv:2106.01932 S. Ghinescu et al.

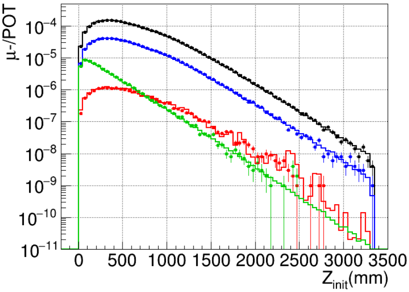
illustration of the main muon sources

gain in statistics: $\sim 2 \times 10^3$

second use of validated meson spectra!

enough to produce sufficient MC for analysis!





The presented work in this second part is an effort of many!

Credit for work presented here goes to

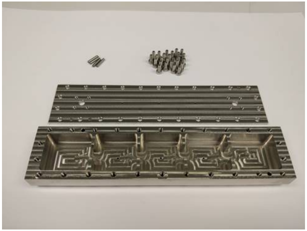
- Stefan Ghinescu
- Tommaso Spadaro
- Elisa Minucci
- Joerg Jaeckel
- special thanks also to Felix Kahlhöfer for an insightful cross-check of our results

Conclusions

- the axion warrants to build some **strategic** (Dark Matter) experiments that cover large chunks of parameter space (like MADMAX, babyIAXO, ...)
- there is also space for **opportunistic** searches that might just be 'lucky' to 'hit' the right axion mass (or target it in case of prediction). RADES is an example for that, long-term plans of these studies aimed at exploiting the babyIAXO magnet (that is then strategic)
- NA62 is a perfect place for opportunistic high-mass axion searches, **more data is being taken now**
- remain optimistic that within (few) decades, a final word on axions (as DM) is spoken
- happy to take questions now or later: babette@cern.ch

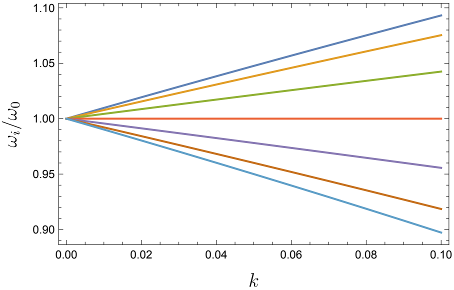
start of backup material

Solving the mode-mixing issue Alvarez-Melcon et al, JHEP 07 (2020) 084



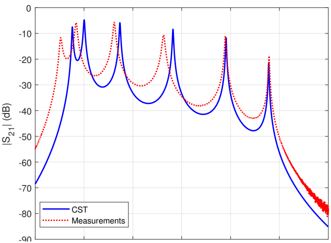
- reminder: sub-cavities coupled by irises, parameterized by k_i

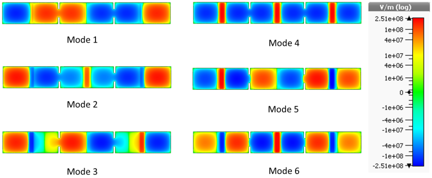
Solving the mode-mixing issue Alvarez-Melcon et al, JHEP 07 (2020) 084

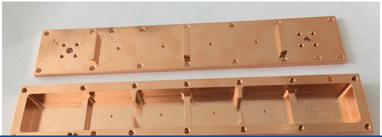


- reminder: sub-cavities coupled by irises, parameterized by k_i
- observation: central modes more seperated from their neighbours, especially at high N $\Rightarrow$ should couple that one to axions

e Alvarez-Melcon et al, JHEP 07 (2020) 084







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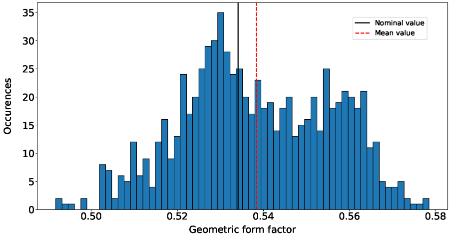
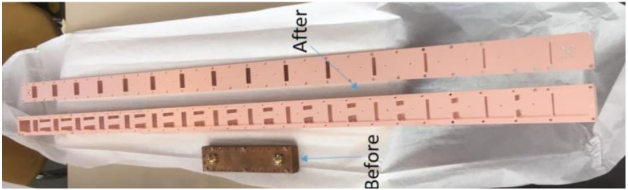
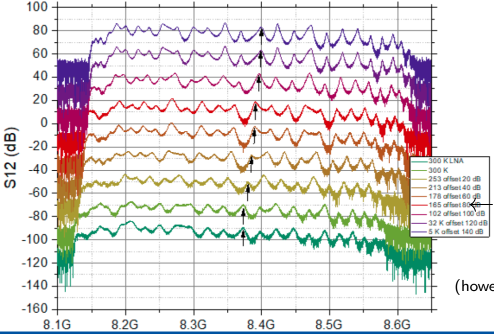


varying randomly all geometrical in the range of $\pm 30\,\mu$m.

- reminder: sub-cavities coupled by irises, parameterized by k_i
- observation: central modes more seperated from their neighbours, especially at high $N \Rightarrow$ should couple that one to axions
- solution: alternate between inductive and capacitive irises
- Better resistance to fabrication errors

30-cavities structure (1m) took data in 2020!

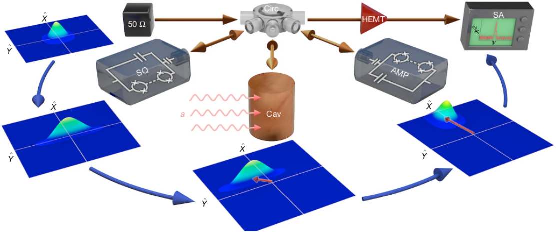


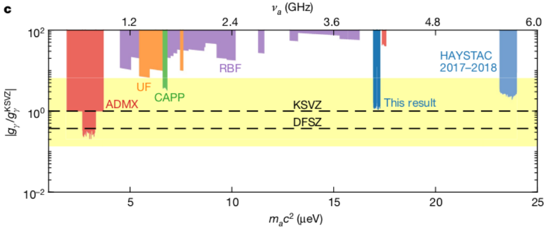


← peak structure during cool-down alternating is indeed scalable!

(however issue with Q factor due to manner of fabrication)

Notable progress at large m: going 'beyond' quantum uncertainty

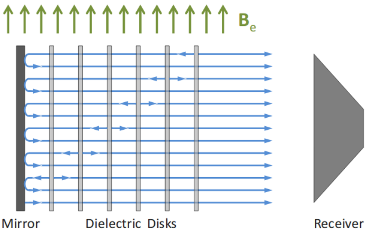


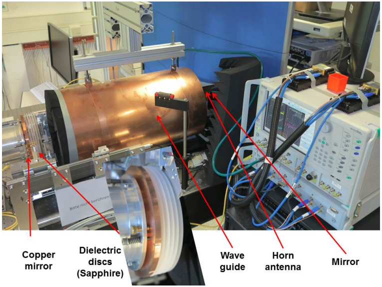


Bakes et al. Nature volume 590, pages 238–242(2021)

Backup: biggest european contender at large mass - MADMAX

- constructively combine axion emission at dielectric surface by choice of plate separation → allows to probe 'large' axion DM mass
- amongst challenges: 9T dipole with 1.35m bore





parameterization presented at icap (M. Rosenthal etc al, PBC)

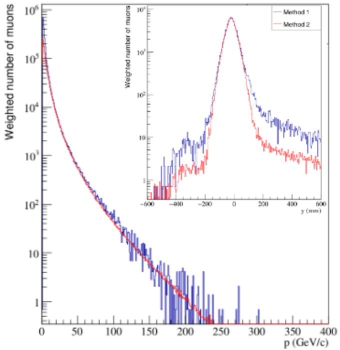
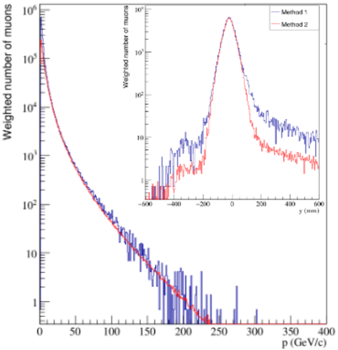


Figure 6: Simulated antimuon momentum spectrum and vertical distribution after the TAX for both methods. The distributions are normalized to 10^9 incident protons.

parameterization presented at ica BC)



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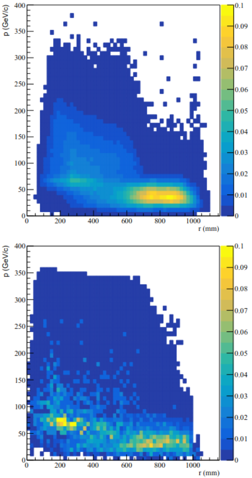

Figure 7: Comparison of measured (up) and simulated distributions (down) of positively charged muons in beam dump configuration reconstructed at 180 m, close to the first straw chamber of NA62. The color scale represents the number of tracks per 10^9 incident protons and bin. The measured data is downscaled by a factor five.

Example: Secondary K_s, see NA62 SPSC report

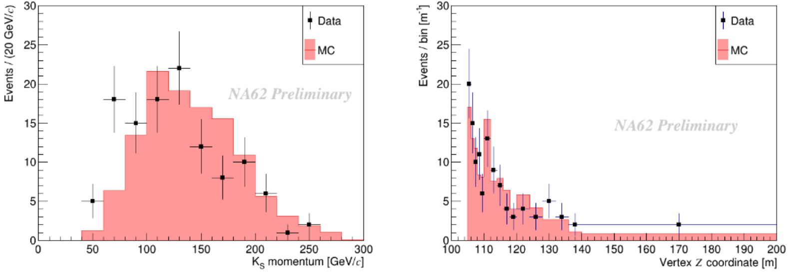

Figure 8: Distributions from reconstructed $K_S \to \pi^+\pi^-$ decays: momentum (left) and Z-coordinate of the decay vertex (right). Data corresponding to 1.6×10^{16} POT (117 events, black dots, error bars statistical only) are compared to simulation data obtained from a combination of the G4BeamLine and NA62MC Monte Carlo software (red, normalized to the data integral).

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