cLFV ALP search with the MEGII experiment

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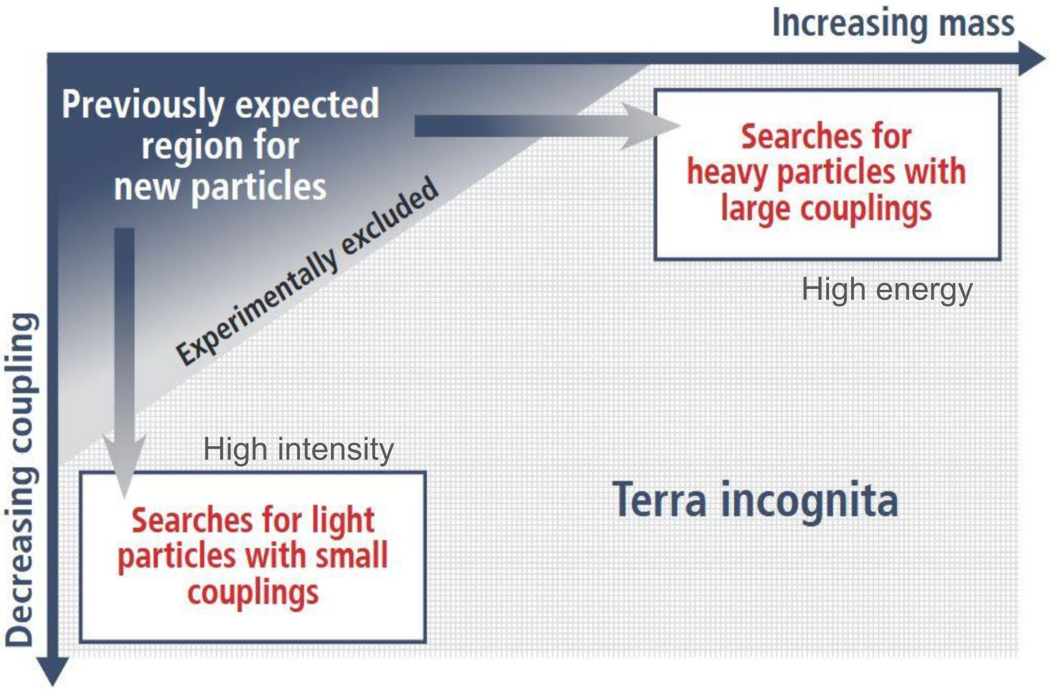
Search for New Physics

From SM we still have

1. many open questions
2. experimental deviation from the theoretical predictions

To answer this questions it is possible to extend the SM introducing

- new particles
- new interactions



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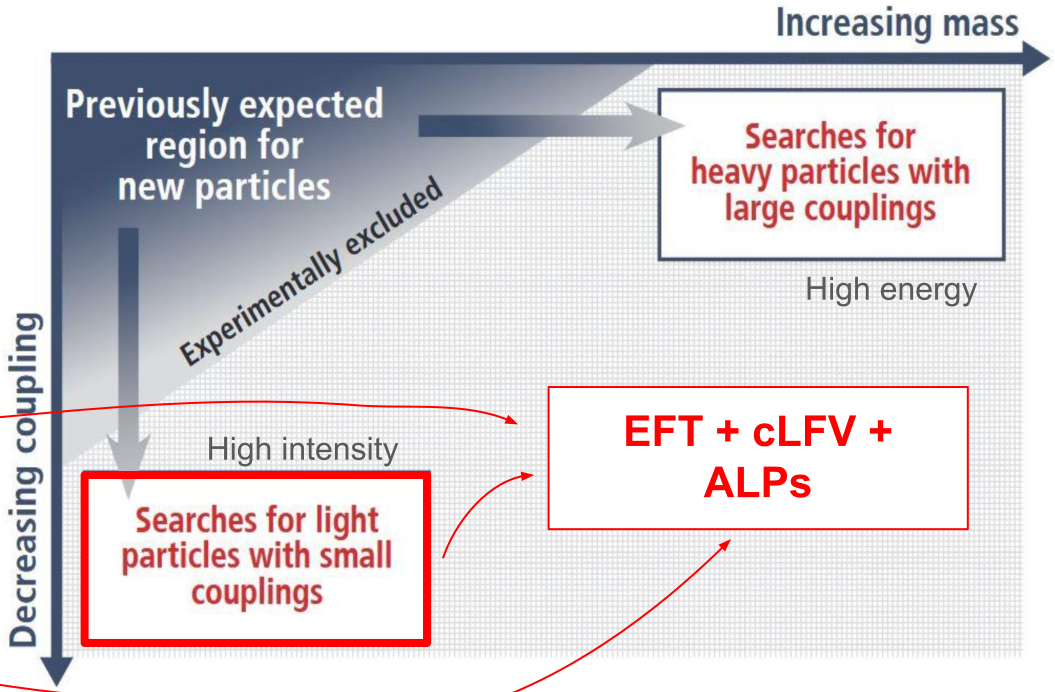
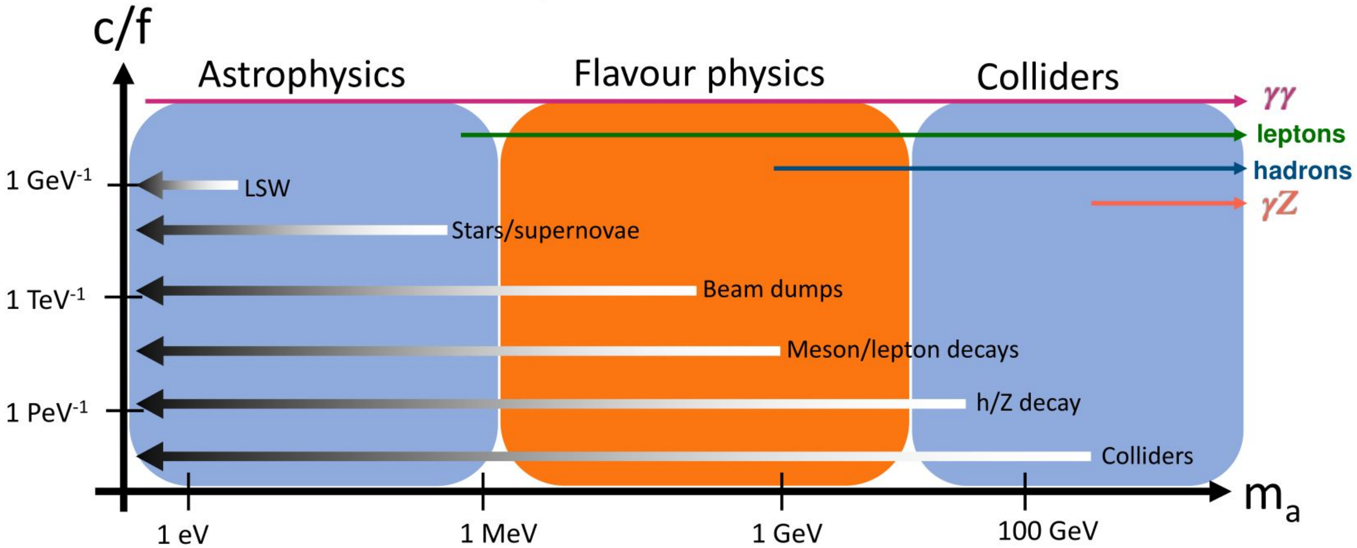


Why we look for ALPs

Axion Like Particles are pseudo-scalar particles that arise from many theories

- Strong CP problem ([hep-ph/0607268] The Strong CP Problem and Axions)
- DM candidate (Axion dark matter in the post-inflationary Peccei-Quinn symmetry breaking scenario)
- … (Looking forward to Lepton-flavor-violating ALPs)



Current status of the ALPs search in muon decays

Bounds on the Branching Ratio and the ALP coupling (F) to LFV processes to date from flavour experiments

Decay	$\mathcal{BR}$	Cte. dec.	Limit [GeV]	Experiment
$\mu \to ea$	2.6×10^{-6}	$F_{\mu e}$ (V o A)	4.8×10^{9}	Jodido at al.
$\mu \to ea$	2.5×10^{-6}	$F_{\mu e}$ (V + A)	4.9×10^{9}	Jodido at al.
$\mu \to ea$	5.8×10^{-5}	$F_{\mu e}$ (V - A)	1.0×10^{9}	TWIST
$\mu \to ea\gamma$	1.1×10^{-9}	$F_{\mu e}$	5.1×10^{8}	Crystal Box

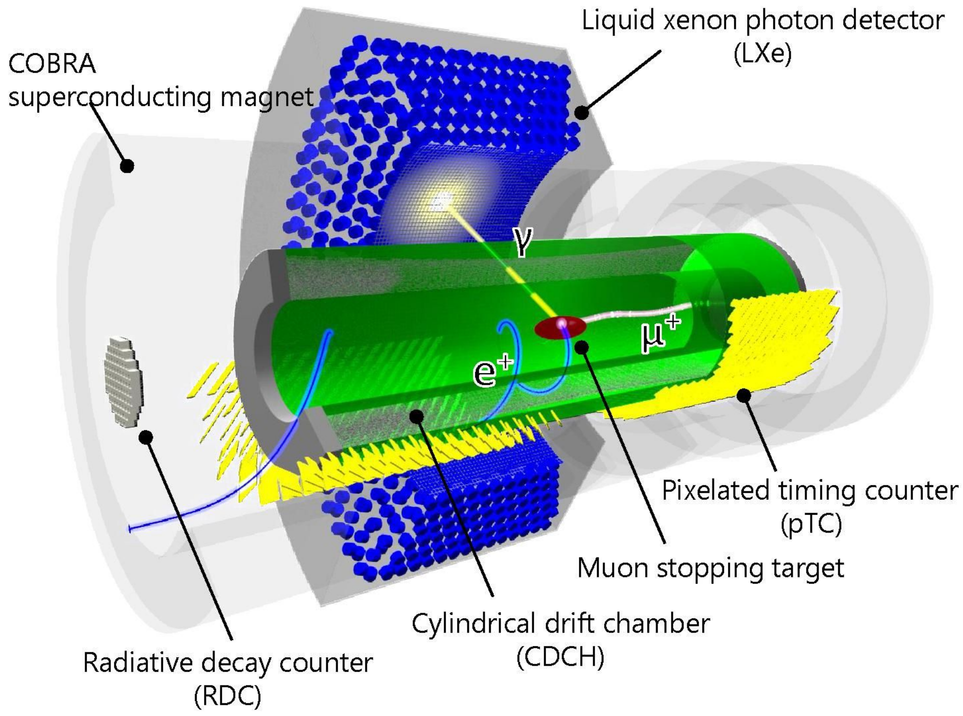
Search for Right-Handed Currents in Muon Decay (Jodido at al.)

Search for rare muon decays with the Crystal Box detector (Crystal Box)

A search for two body muon decay signals (TWIST)

The MEGII apparatus

More infos in Antoine's talk tomorrow



Main features:

- non solenoidal magnetic field (COBRA)
- polarized muons
- high intensity muon beam → nominal: R_{μ} ~ 4 x 10^7 μ/s

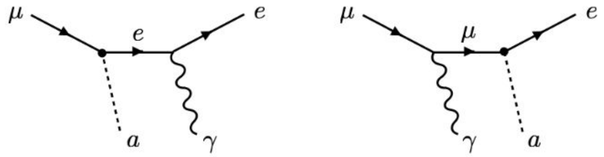
Trigger for $\mu^+ \to e^+\gamma$ (MEGII) decay:

- back to back topology
- $e^+\gamma$ of ~ 52 MeV energy
  - hardware for positrons
  - software for photons

The decay of interest

We look for the $\mu^+ \rightarrow e^+ a \gamma$ decay in the V-A chiral configuration → lagrangian EFT + QED

$$\mathcal{L}_{\mu e} = \mathcal{L}^{ALP} + \mathcal{L}^{QED} = \frac{\partial_\mu a}{2 f^a_{\mu e}} \overline{\psi}_\mu \gamma^\mu (C^V_{\mu e} - C^A_{\mu e} \gamma^5) \psi_e + Q|e| \overline{\psi}_f \gamma^\mu \psi_f A_\mu$$



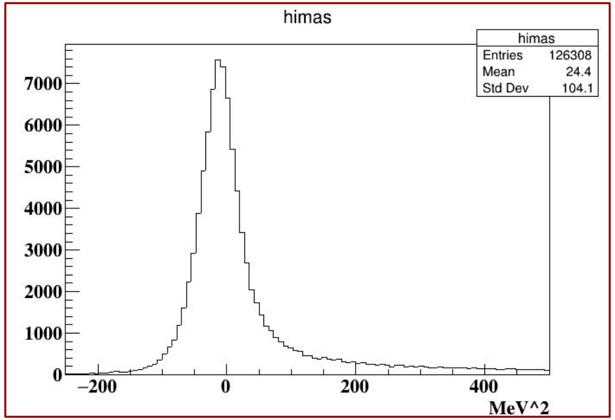
How can we enhance this search with MEGII?

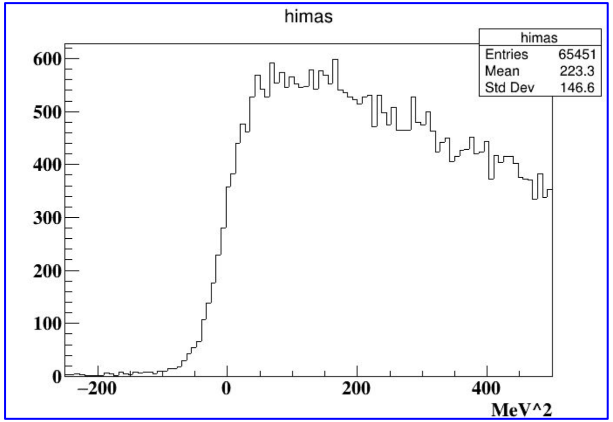
- it features different topology from MEG decay → 3 body instead of 2 in the final state
- different trigger selections to maximize signal acceptance
  - low photon energy cut → Eg > 10 MeV
  - no back to back topology
- need for lower beam rate to keep the trigger under 40 Hz → $R_\mu \sim 1 \times 10^6\ \mu/s$

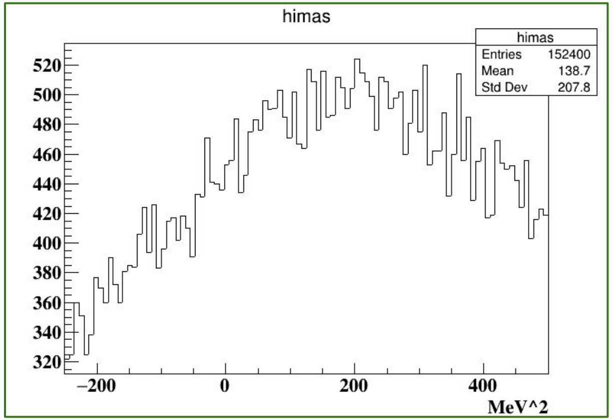
Discriminant distributions

The main discriminant distributions come from the missing mass squared

- signal
- background
  - RMD (main one)
  - accidental







Cuts for reconstructed distributions

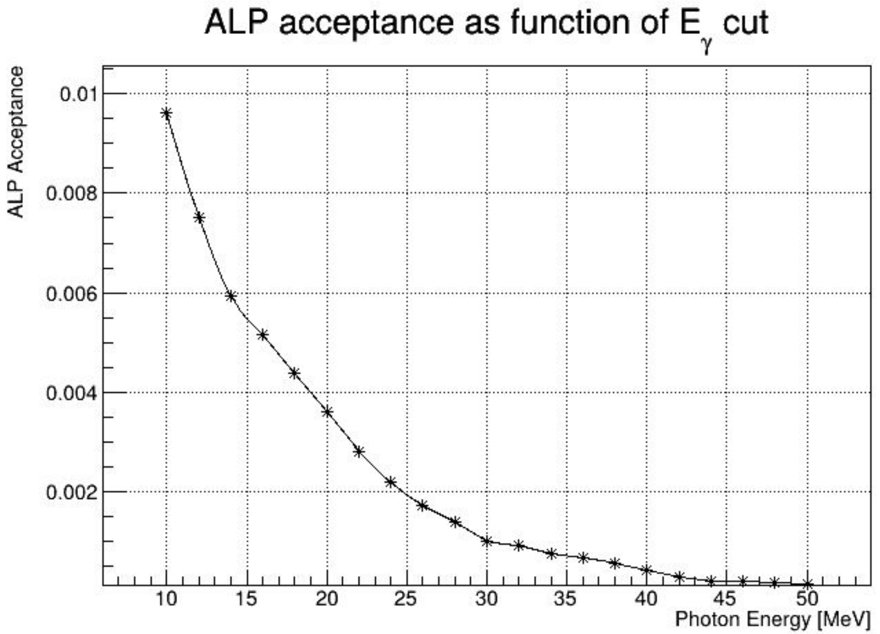
- time coincidence < 0.5 ns
- $e^+\gamma$ combination

Signal acceptance and efficiencies (1)

The **acceptance** and **efficiencies** are estimated using **MC simulations**

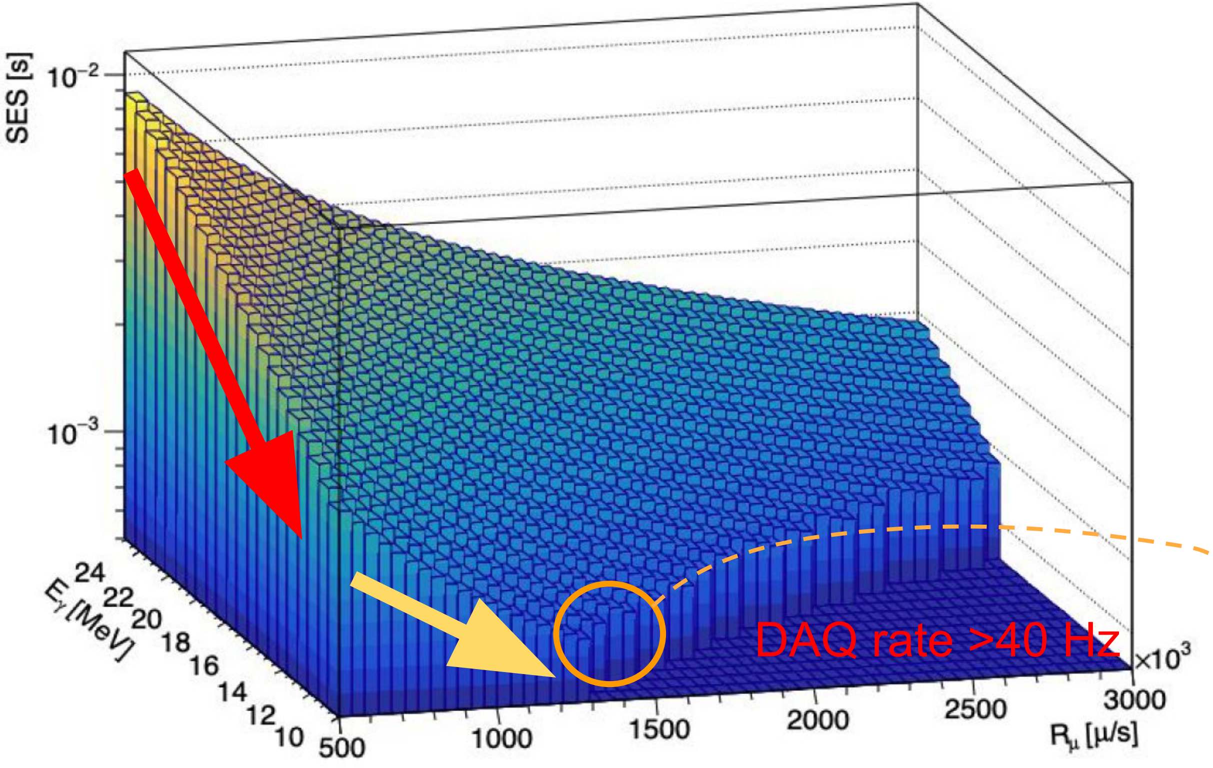
Acceptance evaluated from 4π distribution asking

- (> 0 TC hit) and (> 17 CDCH hits)
- different photon energy cuts
- Geometrical acceptance



These values (+ the efficiency ones) are used in the normalization estimate

Signal acceptance and efficiencies (2)



SES phase with the requirement of DAQ < 40Hz

It improves by lowering the trigger cut on photon energy and increasing the beam intensity

Optimised for:

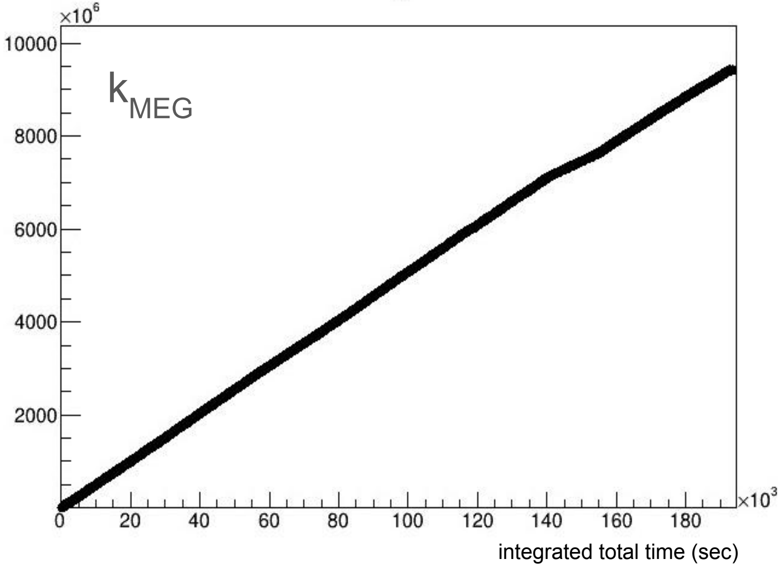
- E_γ > 10 MeV
- R_μ ~ 1.25 x 10^6 μ/s

ALP decay normalization and SES

Low intensity data are taken every year for calibration purposes

MEG normalization estimated with Michel decay from 2022 low beam intensity data intake, other year are normalised to 2022

ALP normalization from MEG's one through an overall acceptance & efficiency factor



Year	R_μ [μ/s]	Time (sec.)	E_γ [MeV]	k_{ALP}
2021	1.0×10^6	322080 ($\sim 3.7\,d.$)	20.0	4.9×10^7
2022	8.7×10^5	193421 ($\sim 2.2\,d.$)	20.0	2.5×10^7
2023	2.0×10^6	234790 ($\sim 2.7\,d.$)	18.0	8.5×10^7

$$k_{ALP}^{TOT} = 1.59 \times 10^8$$

$$SES_{ALP}^{TOT} = \frac{1}{k_{ALP}^{TOT}} = 6.29 \times 10^{-9}$$

Limit estimate

$$\begin{cases} \mathcal{BR} = SES(N_g) \cdot N_{ev} \\ \mathcal{BR} = \frac{C}{f_a^2} \mathcal{I} \end{cases} \rightarrow f_a = \sqrt{\frac{C \cdot \mathcal{I}}{SES(N_g) \cdot N_{ev}}} \implies F_{\mu e}^{V-A} = \sqrt{\frac{2 \cdot C \cdot \mathcal{I}}{SES(N_g) \cdot N_{ev}}}$$

Here are all the terms needed to estimate the sensitivity on the ALP coupling

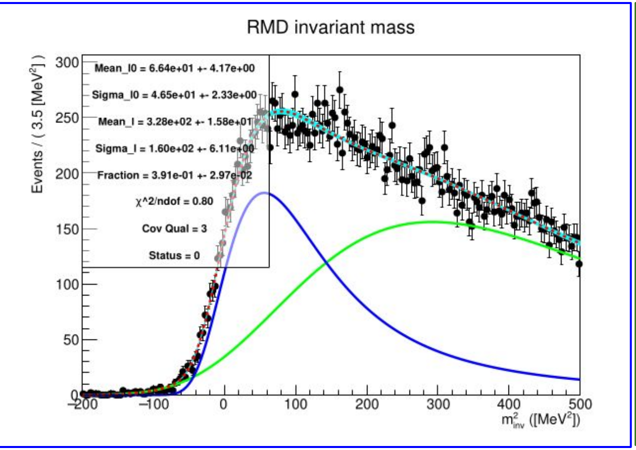
- C : is a set of constants from the Branching Ratio
- I : is the integral of the Branching ratio performed in the full phase space

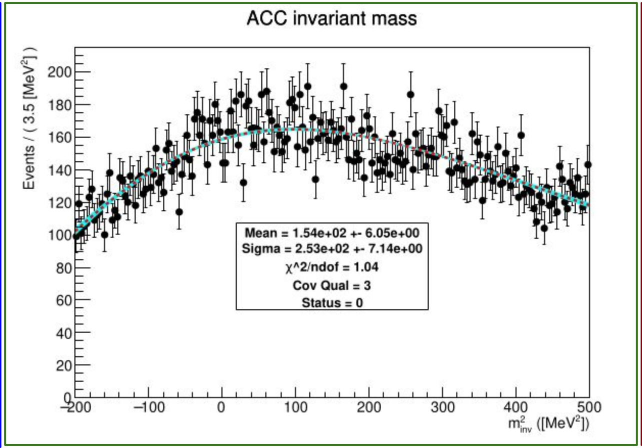
$$\mathcal{I} = 30.61 \qquad C = 4.55 \times 10^{10}$$

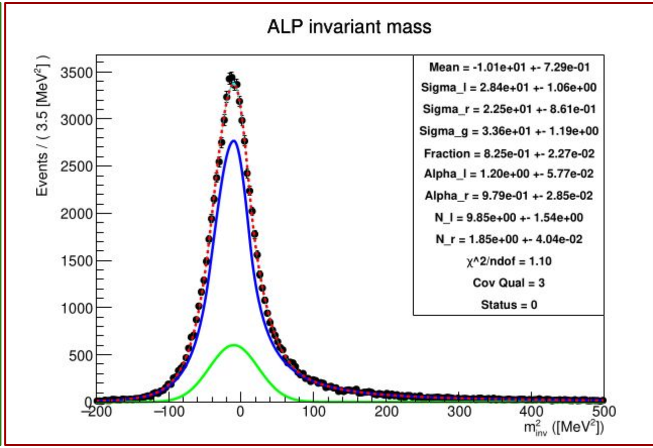
- $SES(N_g)$: is the SES estimated before for N_g days (previous slide)
- N_{ev} : is the number of signal event estimated from a likelihood fit to toys MC in the only background hypothesis

Missing mass squared PDFs

- Signal: Double sided CrystallBall + Gaussian (same mean)
- BKG:
  - RMD: double landau
  - accidentals: single landau

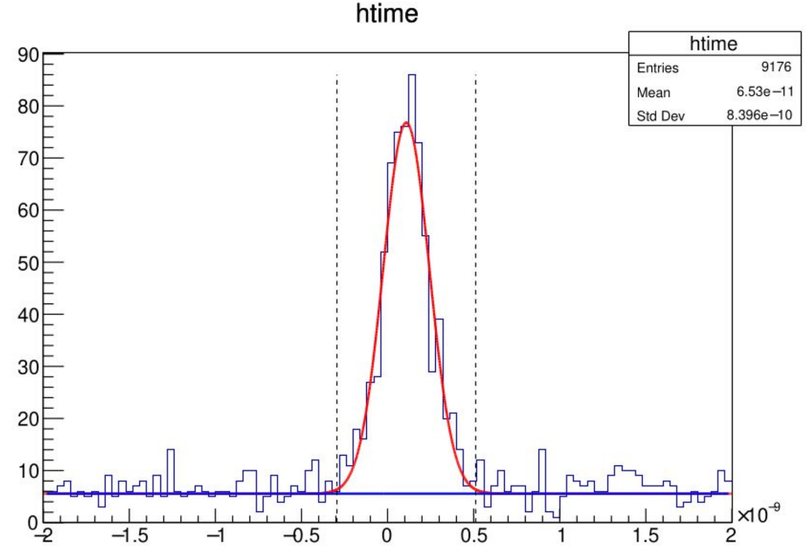




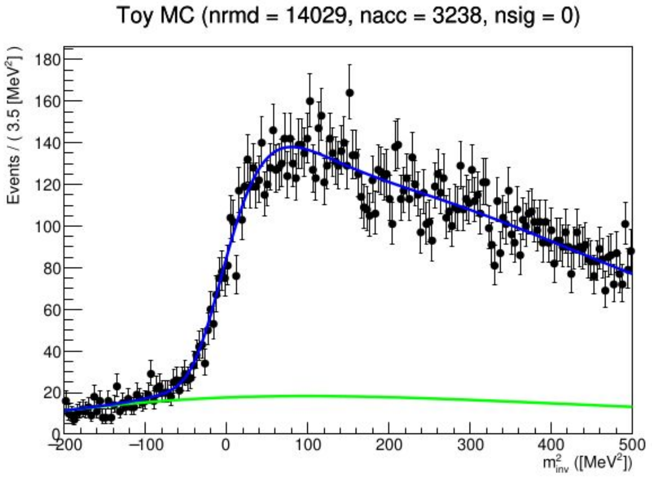


Toys

Estimate of the number of BKG events from 9h of the 2022 data intake → events inside 3 sigma of the time coincidence gaussian



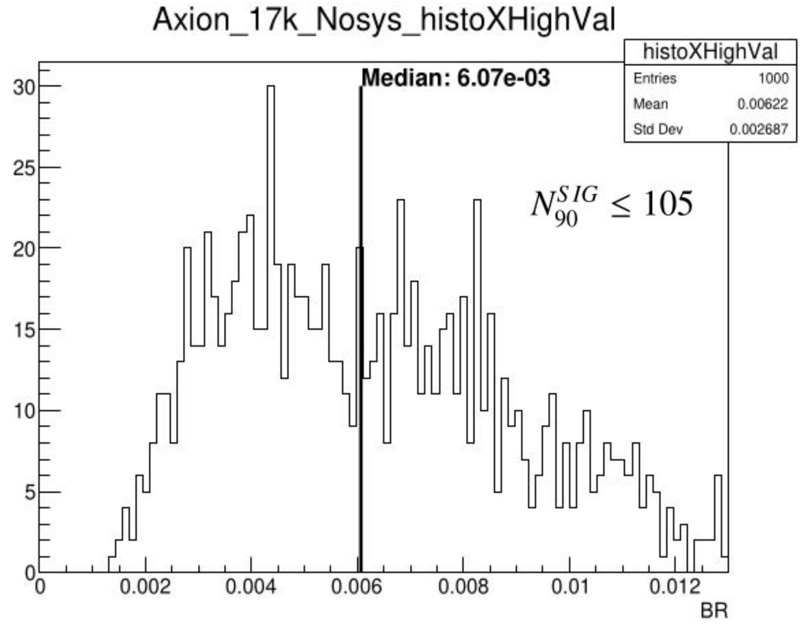
Year	RMD	Accidentals	Total
2021	4707	870	5574
2022	2459	423	2882
2023	6862	1946	8808
sum	14029	3238	17267

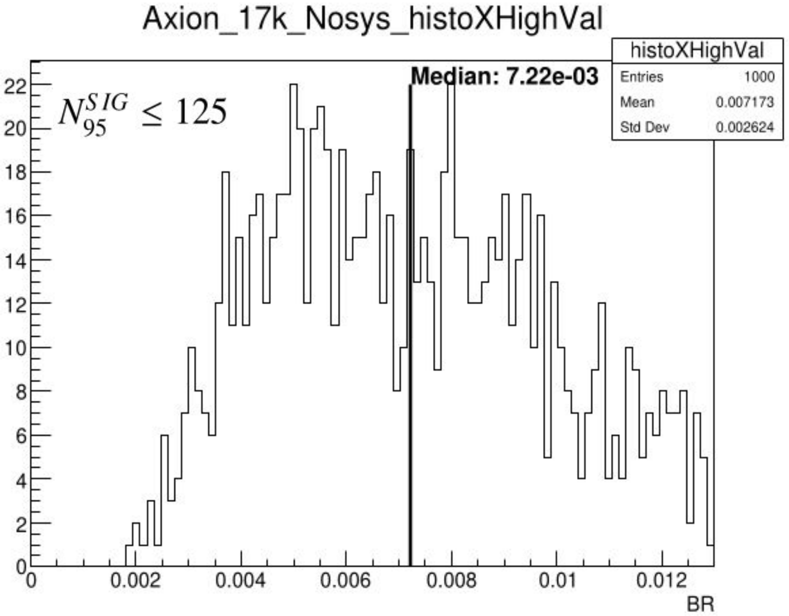


Only BKG toy

Analysis

Construct a sensitivity as the median of the histogram of the Upper Limits of 1000 Maximum Profile Likelihood ratios derived from the fits with the nominal PDFs to the Toys with only background hypothesis [90 (95) % CL left (right) image]





Current results on sensitivity studies

With the strategy described we assess a lower limit to the ALP decay constant of

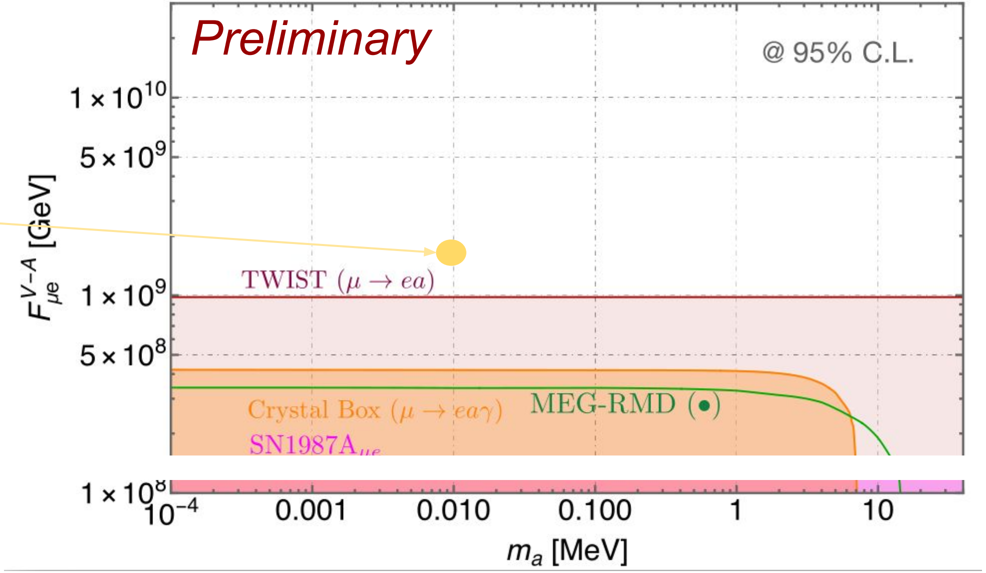
$$F_{V-A} \geq 1.66 \times 10^9 \text{ GeV @ 90 \% C.L.}$$

$$F_{V-A} \geq 1.52 \times 10^9 \text{ GeV @ 95 \% C.L.}$$

in only ~ 8.7 days of data intake (already acquired by the MEG II collaboration).

This can improve the current best limit set by TWIST collaboration Table slide 6.

Lepton-flavor violating axions at MEG II



Conclusion and prospects

- We showed the MEGII competitivity in the search of this rare cLFV ALP decay estimating a sensitivity that exceeds the current best limit in just ~ 9 days of data intake reaching $F_{V-A} \geq 1.52 \times 10^9$ GeV @ 95 % C.L.

➔ The prospects for one year from now are to conclude the full analysis on data with at least the 2021-2022 dataset and assess first results

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Thanks for your attention!

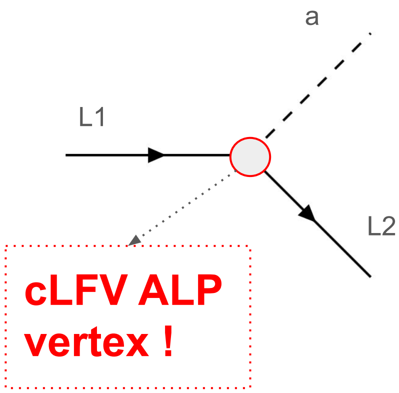
Backup slides

The Axion Like Particles

- ALPs are Pseudo Nambu Goldstone Bosons deriving from a spontaneous symmetry breaking of a BSM U(1) flavour symmetry.

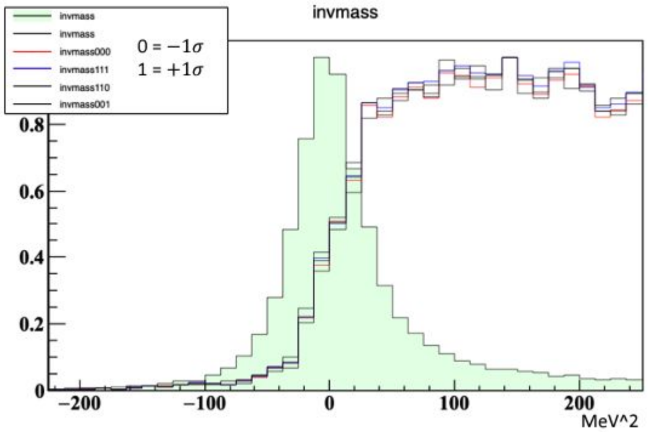
- We can introduce them using the EFT approach using a D = 5 operator that creates a vertex between an ALP and two fermions suppressed by the BSM energy scale f_a.

$$\mathcal{L}_{ALP} \supset \sum_{i \neq j} \frac{\partial_\mu a}{2 f_a} \overline{\psi}_i \gamma^\mu (C^V_{\ell_i \ell_j} + C^A_{\ell_i \ell_j} \gamma^5) \psi_j$$



Systematics effects

The systematics come from misknowledge of the energies and the relative angles of the decay products → this causes a rigid shift of the distributions.

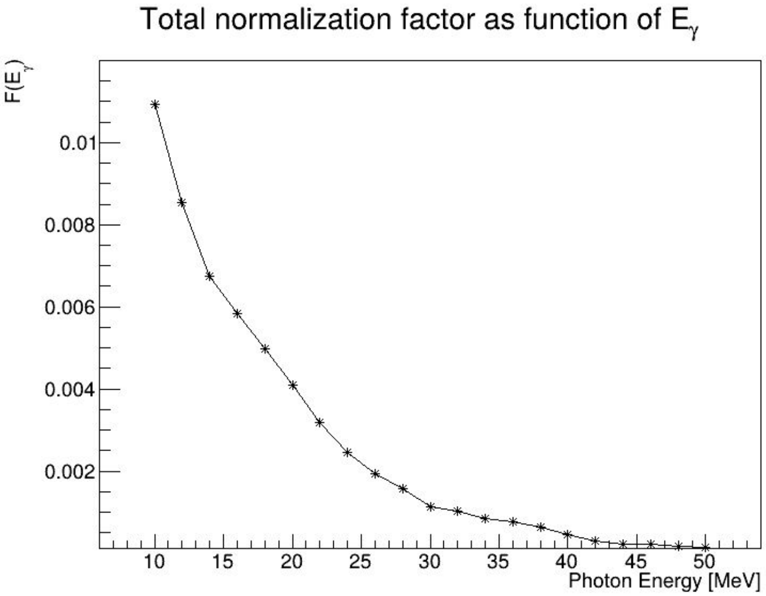


variable	systematic shift	effect
E_γ	$0.3\%\ E_\gamma$	$\sim 1\%$
E_p	6 keV	$\sim 1\%$
$\Theta_{p\gamma}$	1 mrad	$\sim 1\%$

Negligible effect of the analysis evaluated by doing the same procedure as before but with one nuisance parameter (gaussian constrained) that takes into account the systematic effect.

ALP normalization factor

Signal	positron acc.	photon acc	positron eff.	photon eff.	product
MEG	1	9.9e-1	1.2	6.3e-1	7.5e-1
ALP	2.9e-1	< 3.3e-2	9.7e-1	8.8e-1	< 8.2e-3



Factor (**$F(E_\gamma)$**) that we have to multiply (as function of the cut on photon energy) to the MEG normalization to obtain the ALP one.

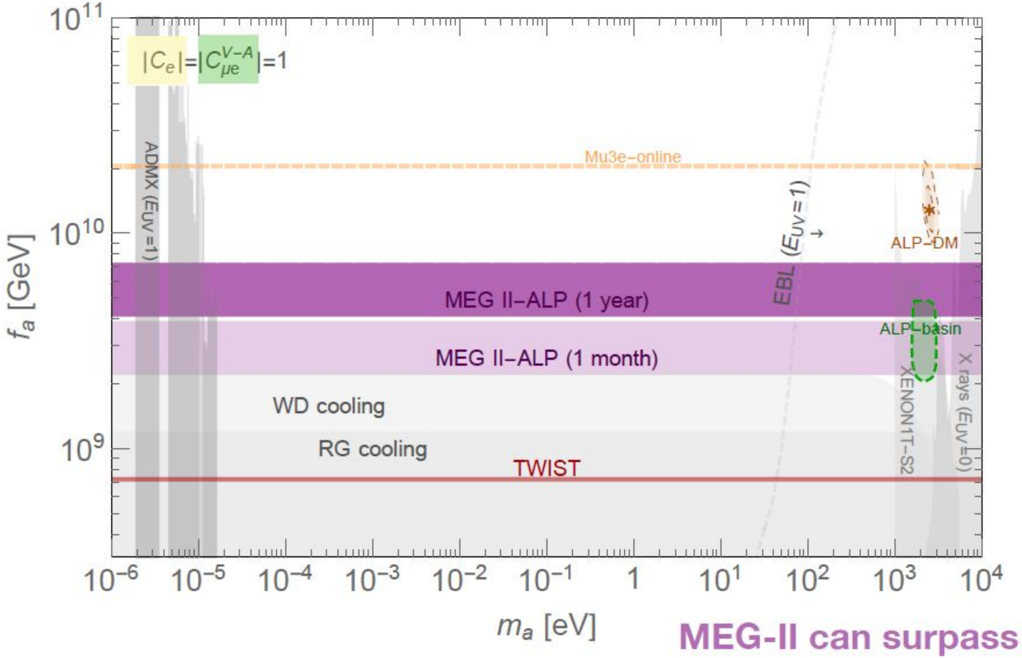
$$k_{ALP} = k_{MEG} \times F(E_\gamma)$$

Theoretical constraints

axions coupled to leptons anarchically: *flavor diagonal* = *flavor off-diagonal*

$$\frac{\partial_\mu a}{f_a}\bar{e}\gamma^\mu\gamma_5 e \quad = \quad \frac{\partial_\mu a}{2f_a}\bar{\mu}\gamma^\mu(C^V_{\mu e} + C^A_{\mu e}\gamma_5)e$$

Lepton-flavor violating axions at MEG II



Xenon 1T anomaly

See. *XENON 2006.09721*

as Dark Matter relic

See. *I. Bloch, A. Caputo, R. Essig, D.R, M. Sholapurkar, T. Volansky 2006.14521*

basin around the Sun

See. *K. Van Tilburg 2006.12431*

MEG-II can surpass bounds from star cooling!