cLFV ALP search with the MEGII experiment

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Elia Giulio Grandoni
eliagiulio.grandoni@phd.unipi.it

MEG II

INFN PISA
Istituto Nazionale di Fisica Nucleare
Sezione di Pisa

IN SUPREMÆ DIGNITATIS
1343

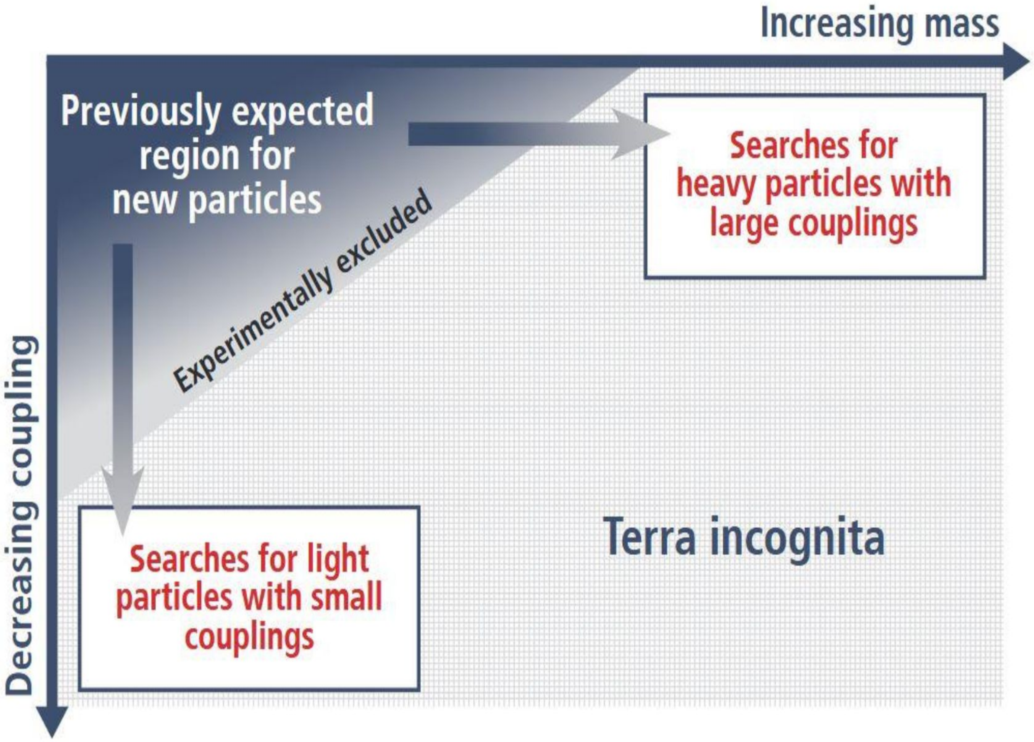
New physics searches

From SM we still have

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

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

- new particles
- new interactions



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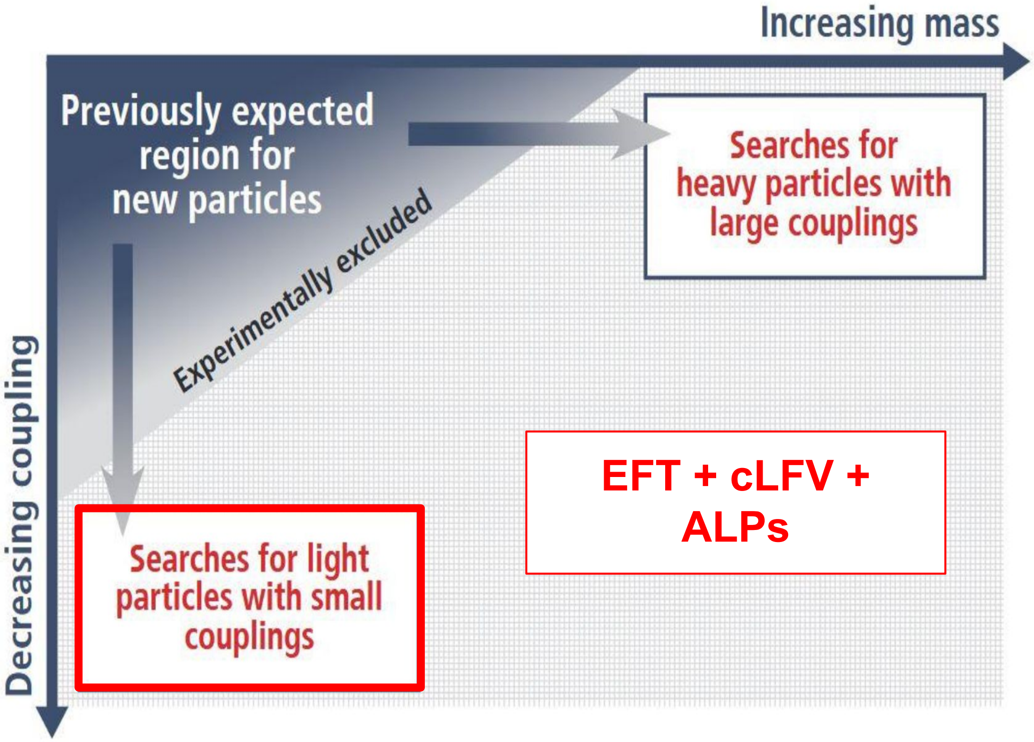
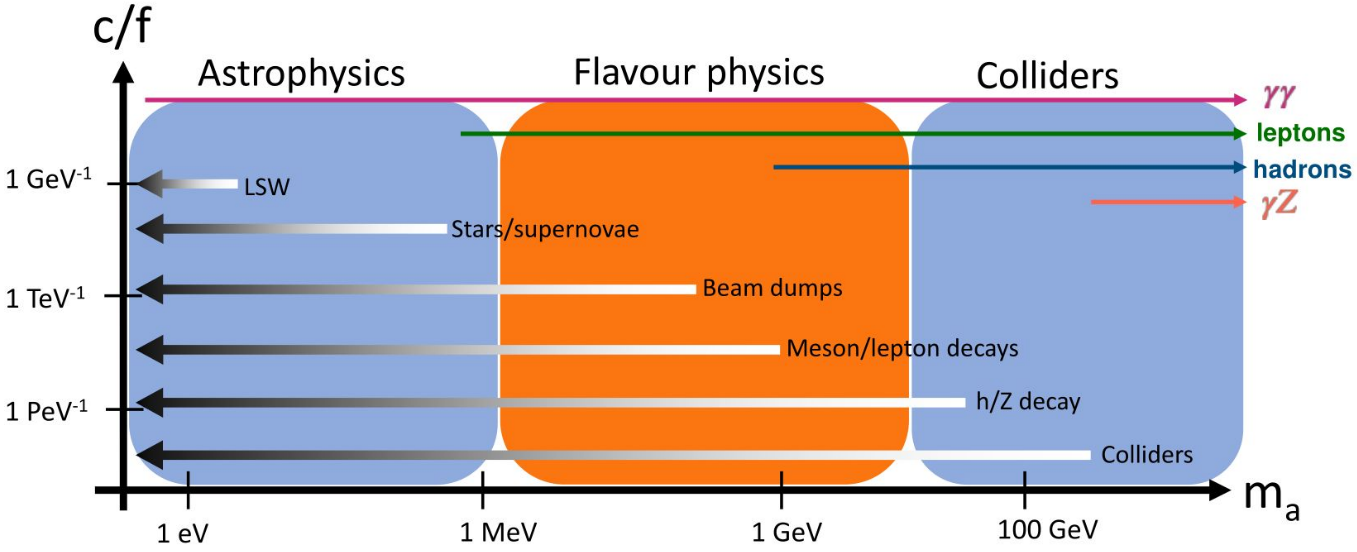


Why axion like particles?

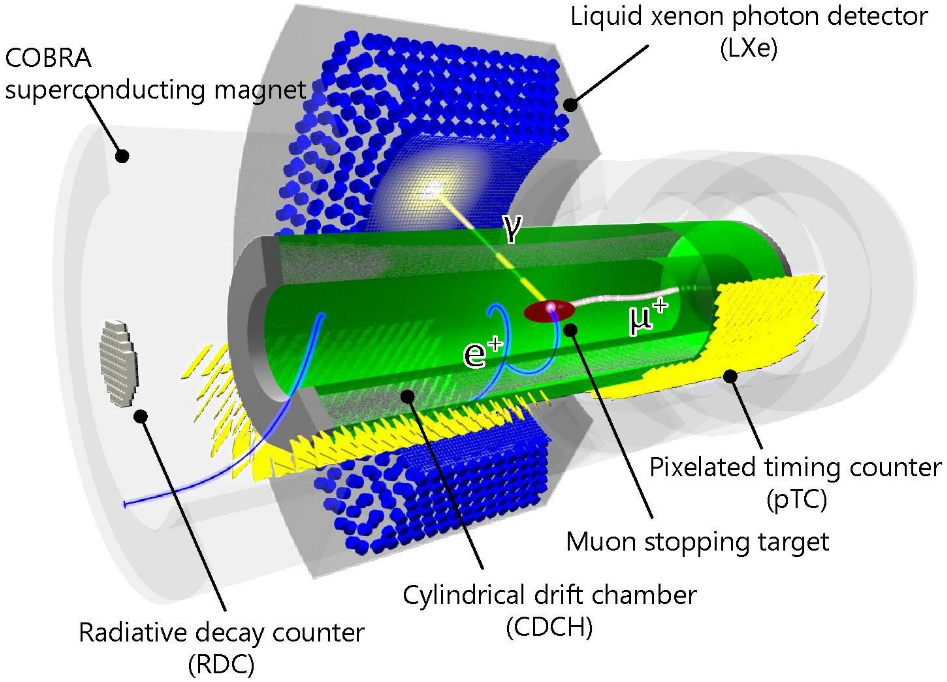
Axion Like Particles are pseudo-scalar particles that arise from many theories

- 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)



The MEG II experiment

New limit on the μ+ → e+γ decay with the MEG II experiment



Main features:

- non solenoidal magnetic field
- high intensity polarized muon beam → R_μ ~ 4 x 10^7 μ/s

Resolutions	
E_{e^+} (keV)	89
ϕ_{e^+}, θ_{e^+} (mrad)	5.2/6.2
y_{e^+}, z_{e^+} (mm)	0.61/1.76
$E_\gamma(\%)$ $(w_\gamma<2\,\text{cm})/(w_\gamma>2\,\text{cm})$	2.4(2.1)/1.9(1.8)
$u_\gamma, v_\gamma, w_\gamma$ (mm)	2.5/2.5/5.0
$t_{e^+\gamma}$ (ps)	78

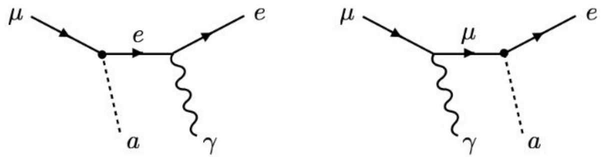
Trigger for **$\mu^+ \to e^+\gamma$ (MEGII) decay**:

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

The decay of interest

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

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



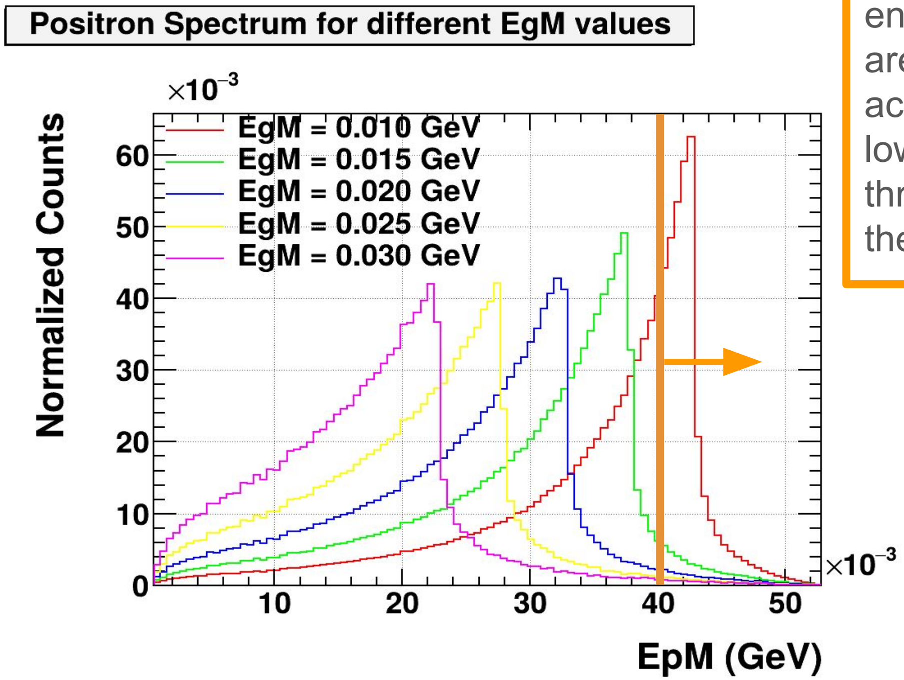
How can we enhance this search with MEGII?

- 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 50 Hz

Signal acceptances and efficiencies

Signal **acceptance** and **efficiency** are estimated using **MC simulations**:

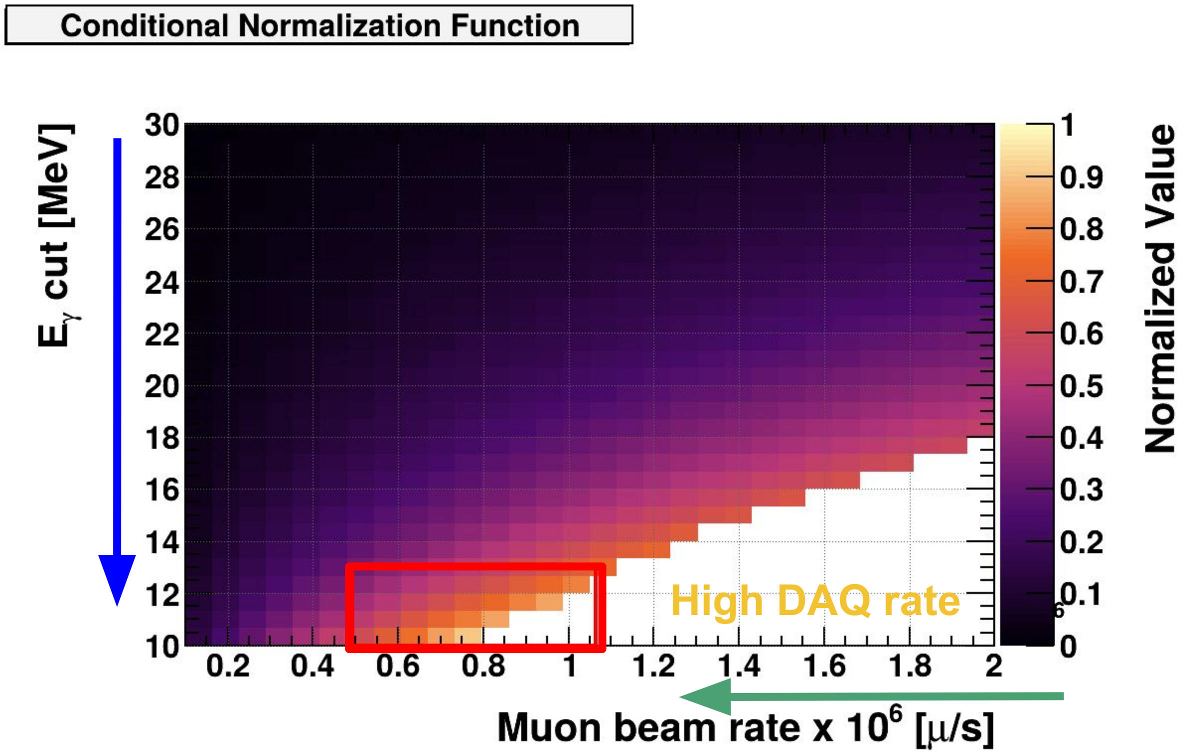
- **Acceptance:** fraction of isotropically generated events passing geometric and energy cuts
- **Efficiency:** fraction of accepted events with a reconstructed positron-photon pair in time coincidence



Only positrons with energy > 40 MeV are in energetic acceptance → a low photon energy threshold optimizes the data intake

Signal acceptances and efficiencies

The signal **acceptances** and **efficiencies** go into the normalization estimate



The goal is to tune the experimental settings to maximize the normalization

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

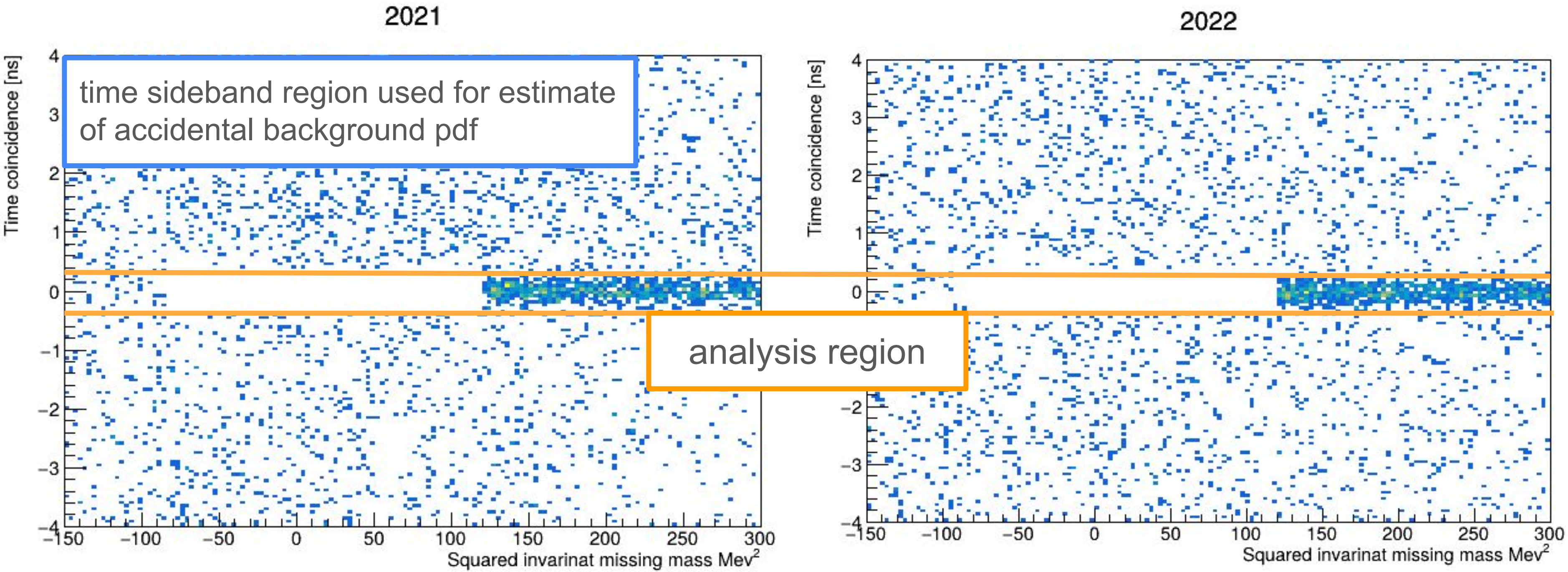
Optimised for:

- E_γ ~ 10 MeV
- R_μ ~ O(10^5 - 10^6) μ/s

2021 and 2022 datasets

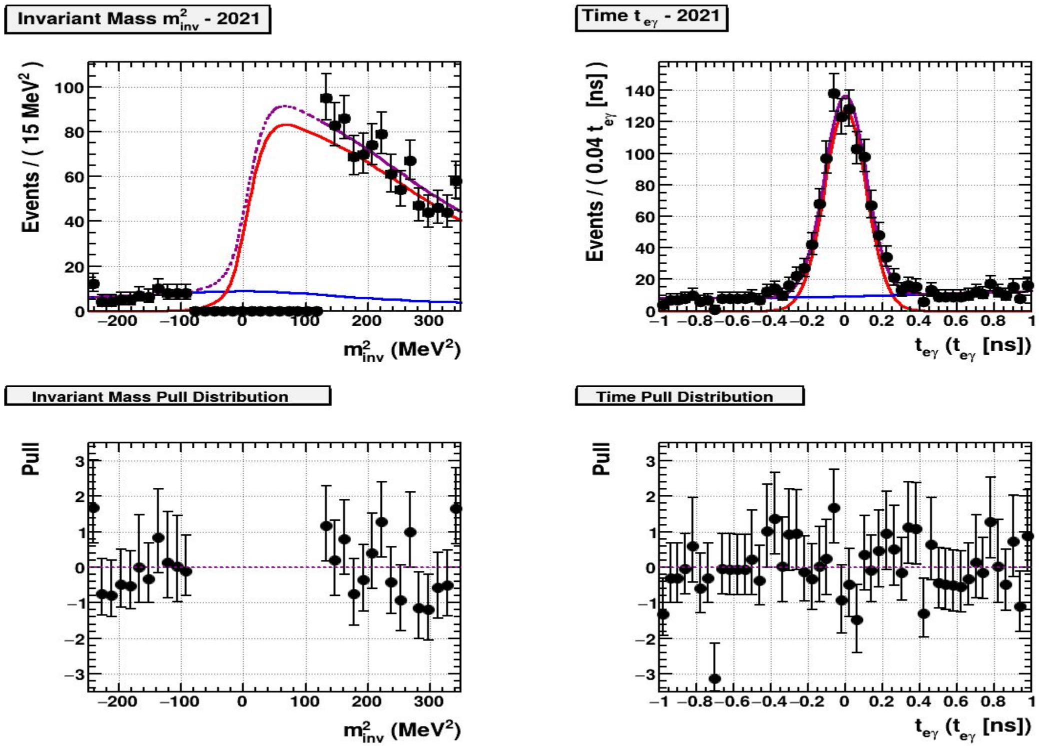
The MEG II collaboration collects low-intensity data annually for trigger calibration

We have begun analyzing the 2021 and 2022 datasets, focusing on low ALP masses (10 keV example), using a blinding box defined in time coincidence and invariant mass squared



Signal normalization and expected number of background events

Dedicated MC simulations are used to estimate normalization factors for the 2021 and 2022 datasets accounting for the signal decay acceptances and efficiencies.



The number of background events is estimated by a sideband region fit using the two blinding observables.

	2021	2022
E_γ^{cut}	22 MeV	26 MeV
k^{ALP}	1.64x10^7	1.06x10^7
Acc.	272+-14	242+-13
RMD	1563+-55	1764+-57

F_A limit estimate strategy

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

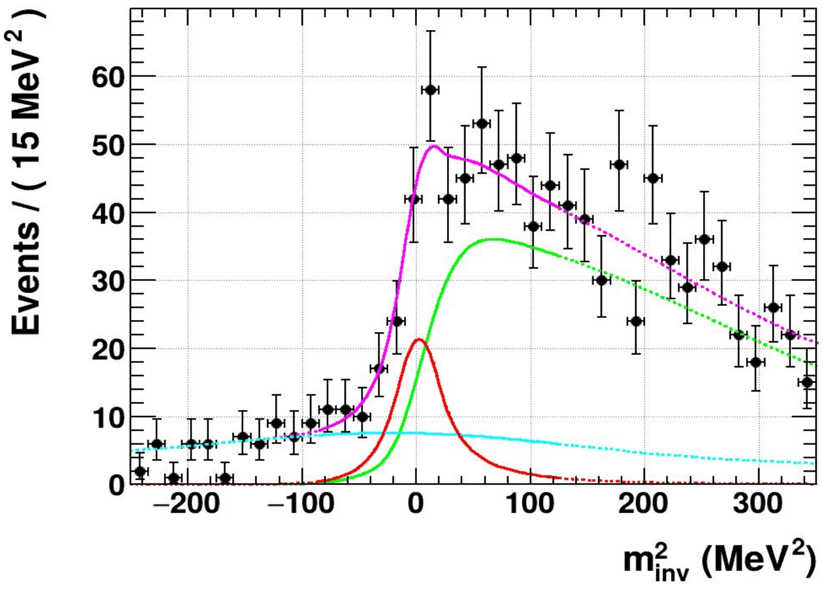
- ***C*** : is a set of constants from the Branching Ratio → ***C* = 4.55 x 10^{10} GeV^2**
- ***I*** : is the integral of the Branching ratio performed in the full phase space → ***I* = 30.6**
- ***SES(N_g)*** : is the SES (= 1/k) estimated before for N_g days → ***SES(N_g)* = 3.7 x 10^{-8}**
- ***N_{ev}*** : is the median of the upper limits (at designated CL) on the number of signal events is estimated from a full frequentist analysis using the Feldman Cousins approach → this employs likelihood fit in the blinding region to toy Monte Carlo datasets generated under the background-only hypothesis

Distributions and toys

We have three distributions: from MC templates: **signal**, **radiative muon decay**, from sidebands: **accidental background** added together to form the **full signal plus background pdf**

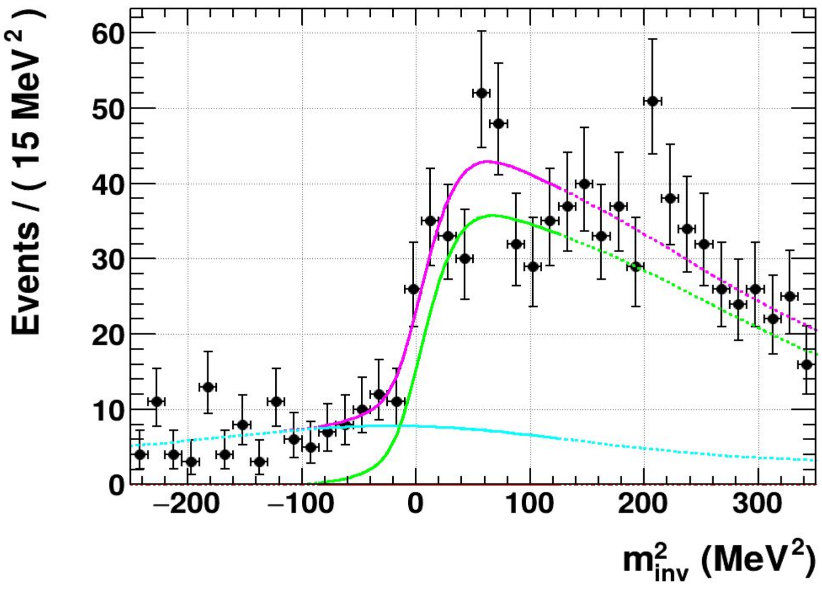
2021

toy with 100 **signal** events



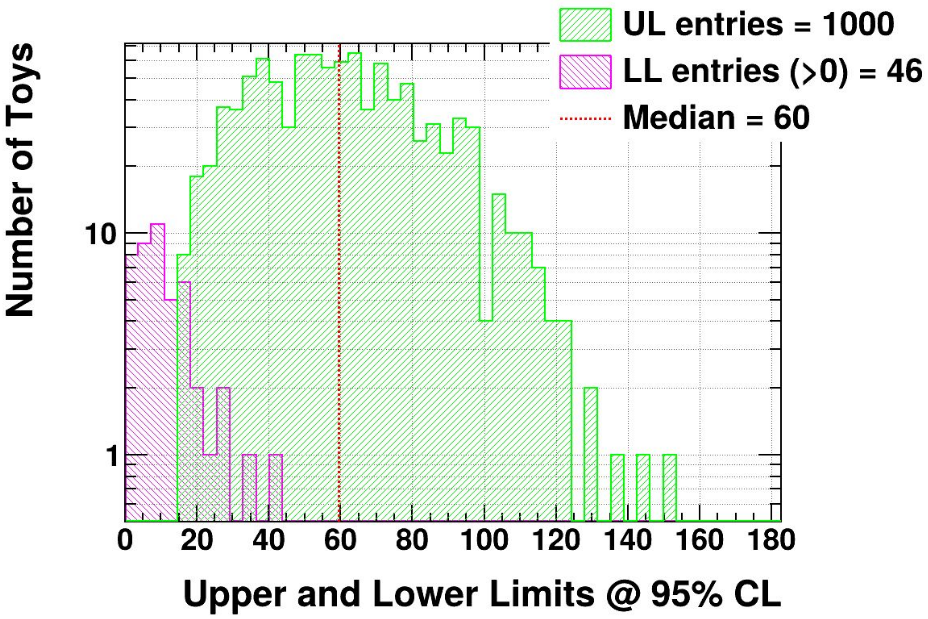
2021

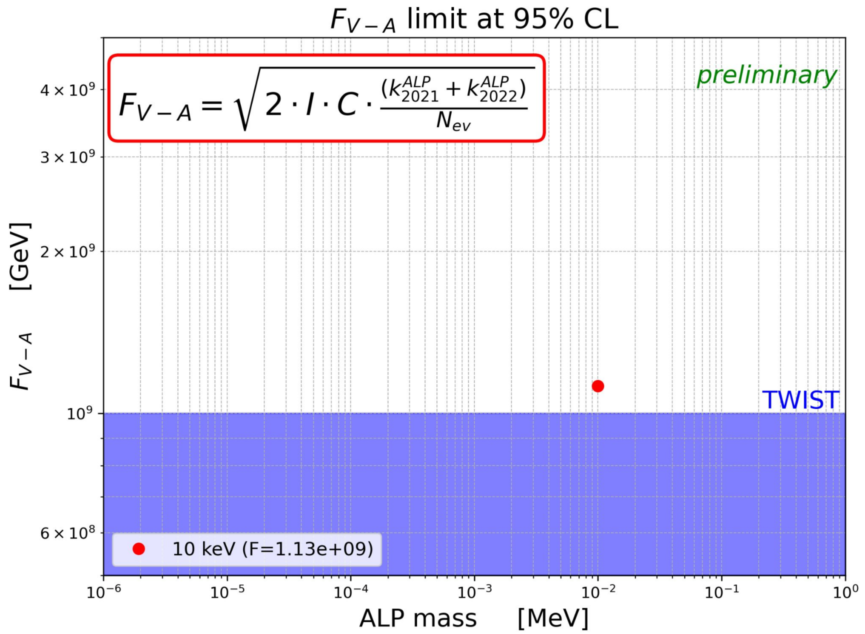
toy with no **signal** events



MC sensitivity limit results

We performed the analysis on 1000 toy MC with no signal and took the median of the upper limits as our sensitivity estimate → $\boldsymbol{N_{ev}}$ **= 60 @ 95% CL**





Search for two body muon decay signals

Conclusions and prospects

- We showed the MEG II competitivity in the search of this rare cLFV ALP decay estimating a MC sensitivity using only the 2021 and 2022 datasets statistics

$F_A > 1.13 \times 10^9$ GeV @ 95% CL

➢ The prospects for the end of 2025 are to conclude the full analysis on 2021 and 2022 data — including wider mass range for the ALP (eV → 10MeV) —

➢ We already have 2023-2024 data and we foresee also 2025-2026 ones, adding this contribution will further enhance the limit estimate

BACKUP

Acceptances and efficiencies factors

$$F(E_{\gamma,y}) = \left[\frac{A_e^{ALP}(\text{nSPX, nCDCH, geom})}{A_e^{MICH}(\text{nSPX, nCDCH, geom})} \cdot (A_\gamma^{ALP})|_e \cdot f(E_{\gamma,y}) \cdot \frac{\varepsilon_e^{ALP}}{\varepsilon_e^{MICH}} \cdot \varepsilon_\gamma^{ALP}|_{det} \cdot \varepsilon_{sel}^{ALP}\right] \cdot \left[(A_\gamma^{e\gamma})|_e \cdot \frac{\varepsilon_e^{e\gamma}}{\varepsilon_e^{Mich}} \cdot \varepsilon_\gamma^{e\gamma}|_{det} \cdot \varepsilon_{sel}^{e\gamma}\right]^{-1}$$

MEG to ALP normalization conversion factor

	$\frac{A_e^{ALP}}{A_e^{MICH}}$	$(A_\gamma^{ALP})\|_e$	$f(E_\gamma)$	$\frac{\varepsilon_e^{ALP}}{\varepsilon_e^{MICH}}$	$\varepsilon_\gamma^{ALP}\|_{det} \cdot \varepsilon_{sel}^{ALP}$
ALP 2021	$\frac{0.097 \pm 0.002\ \%}{2.14 \pm 0.03\ \%}$	$13.3 \pm 0.6\ \%$	$26.87 \pm 0.02\ \%$	1.005 ± 0.003	$70.3 \pm 0.2\ \%$
ALP 2022	$\frac{0.068 \pm 0.002\ \%}{2.68 \pm 0.03\ \%}$	$20.3 \pm 0.9\ \%$	$18.57 \pm 0.04\ \%$	1.003 ± 0.003	$69.3 \pm 0.3\%$

	$(A_\gamma^{e\gamma})\|_e$	$\frac{\varepsilon_e^{e\gamma}}{\varepsilon_e^{MICH}}$	$\varepsilon_\gamma^{e\gamma}\|_{det} \cdot \varepsilon_{sel}^{e\gamma}$
MEG II 2021	$97 \pm 1\%$	1.08 ± 0.01	$62 \pm 1\%$
MEG II 2022	$97 \pm 1\%$	1.04 ± 0.01	$62 \pm 1\%$

$\boldsymbol{C}$ and $\boldsymbol{I}$ factors

$$x \equiv \frac{2E_e}{m_\mu}, \qquad y \equiv \frac{2E_\gamma}{m_\mu}, \qquad r \equiv \frac{m_X}{m_\mu}, \qquad \eta = r^2$$

$$\begin{aligned}\mathcal{BR}(\mu^+ \to e^+ a \gamma) = {} & \frac{(2\pi)\,\alpha_{\rm em}}{f_a^2}\left(\frac{M_\mu}{2}\right)^2 \frac{1}{16 M_\mu (2\pi)^5} \times \int \Big[\left(|C^V_{\mu e}|^2 + |C^A_{\mu e}|^2\right) F_I(x,y) \\ & + 2\,\mathbb{R}e\left\{(C^V_{\mu e} C^{A*}_{\mu e})\,\mathcal{P}\, F_A(x,y,\theta_e,\theta_\gamma)\right\}\Big]\, dx\, dy\, d\cos\theta_e\, d\phi_e\, d\phi'_\gamma \\ = {} & \frac{1}{f_a^2}\cdot\frac{C}{2}\times 2\cdot I\end{aligned}$$

$$F_I(x,y) = y(1 - x^2 - \eta_a^2) - 2(1-\eta_a)(1 - x - \eta_a)$$

$$\begin{aligned}F_A(x,y,\theta_e,\theta_\gamma) = {} & \cos\theta_e(x(2\eta_a + x(2-y) + (\eta_a+1)y - 2)) \\ & + \cos\theta_\gamma(y(1-\eta_a)(\eta_a + x - 1))\end{aligned}$$

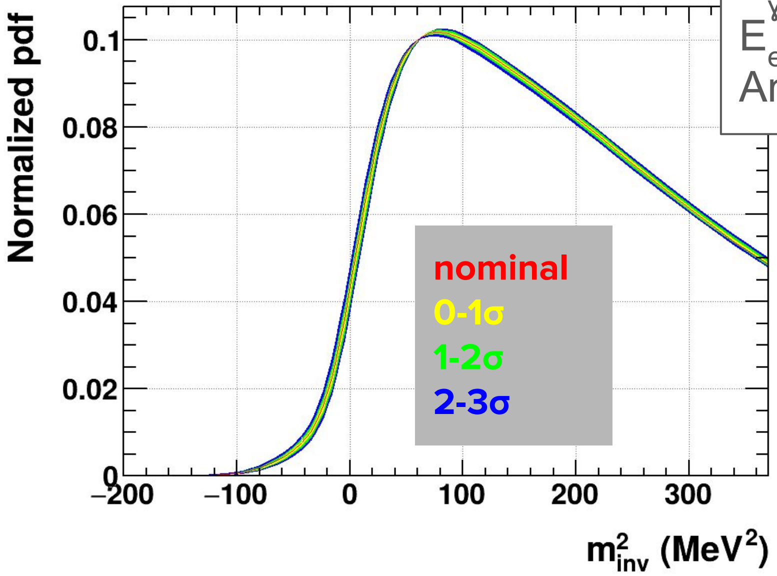
Muon polarization in the MEG experiment: predictions and measurements

Lepton-flavor violating axions at MEG II

Systematic effect on limit

Systematics (photon energy, positron energy and relative angle) can affect the shape of the invariant missing mass squared pdf for all background and signal

RMD PDF 2022



E_γ = 0.5% x E_γ
E_{e^+} = 0.6 keV
Angle = 1 mrad

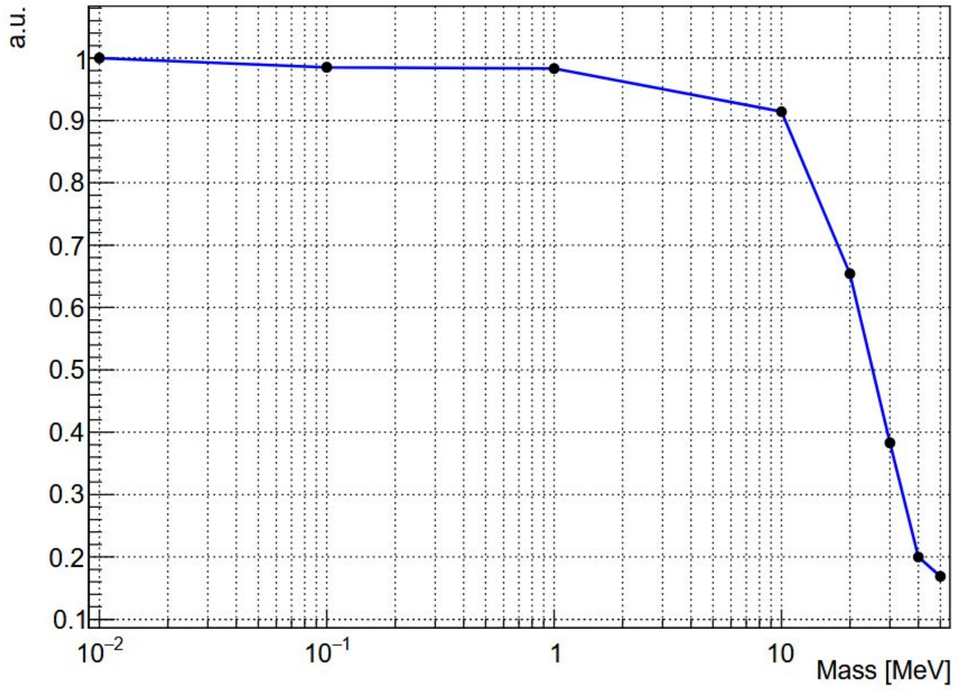
	systematic impact on sensitivity
E_γ	2.4%
E_e	-
$\Theta_{e\gamma}$	2.4%

Limitation for high ALP masses

The analysis can be performed across different ALP mass ranges

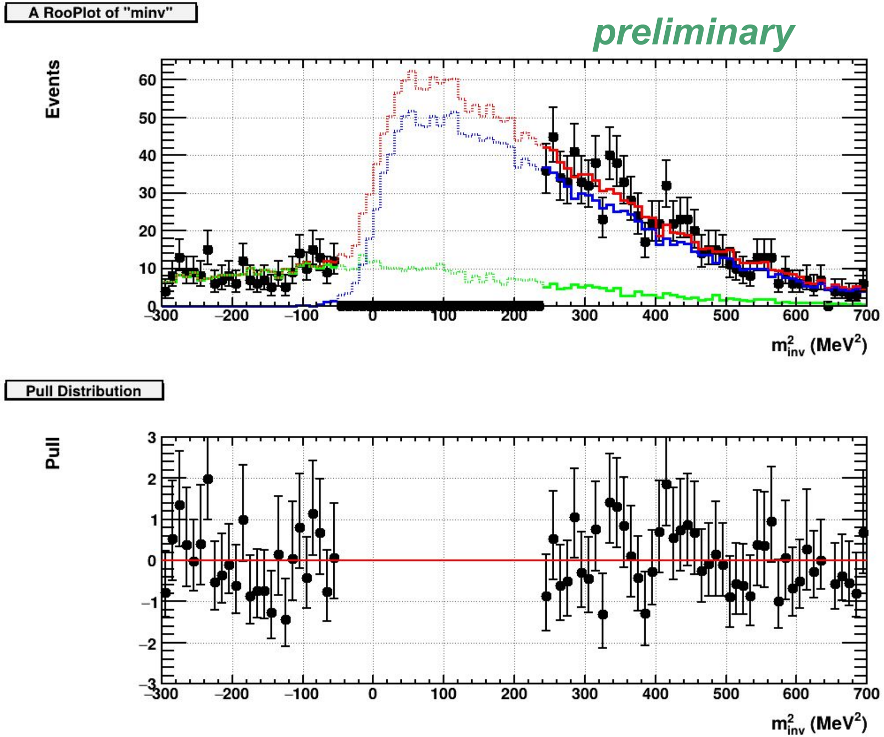
[eV to 10 MeV]

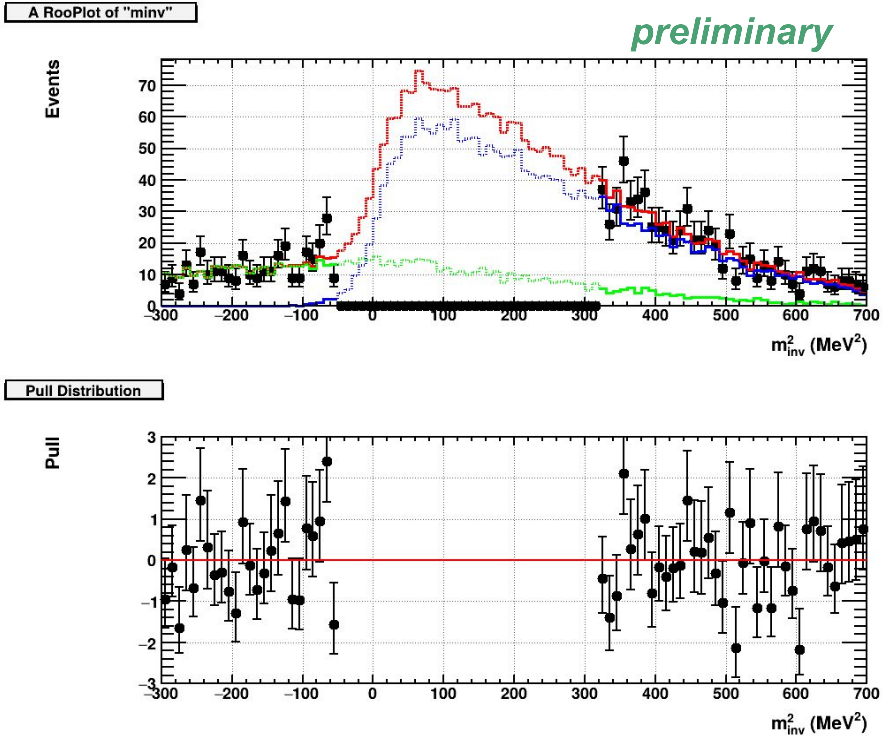
The high mass boundary is determined by the limitation from the detector's energy acceptance



Preliminary binned analysis for high masses

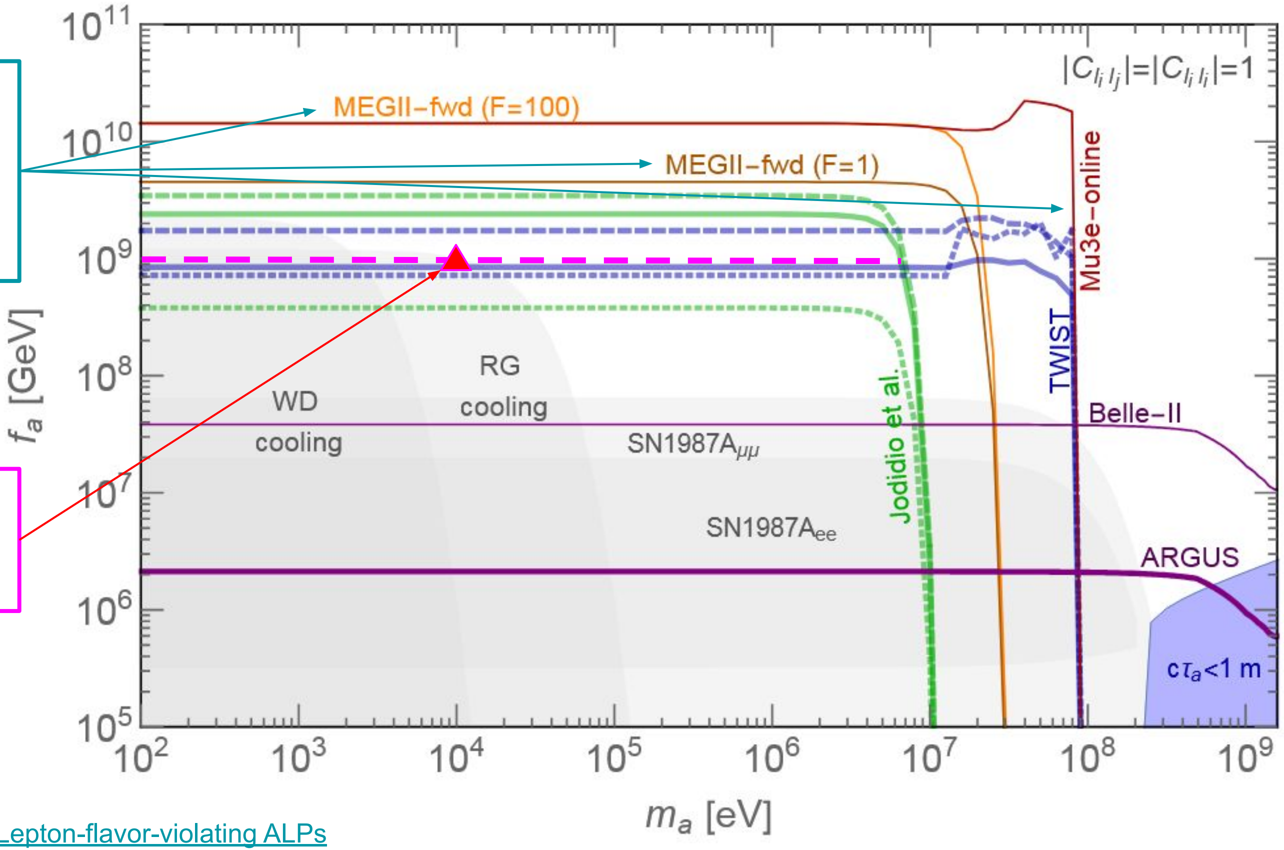
The data are blinded by defining a blinding region in two variables: the time coincidence and the region of the observable that encompasses 90% of the expected signal distribution





Current bounds on LFV ALPs

theoretical claims for future experiments



my search projection

[Looking forward to Lepton-flavor-violating ALPs]