Preliminary thoughts on *Finding NP in "SM-like" muon decays?*
$(\mu^+ \to \mathcal{I} + \{\bar{e}, \bar{e}\gamma, \bar{e}e\bar{e}\}$ ($\mathcal{I} \equiv$*invisible*$\supset \bar{\nu}\nu$,*light NP* X,...)

about X:
talks@FIP2020
PhysBeyondColl 1901.09966
...

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1. measure $\tau_\mu \Leftrightarrow G_F$?

2. (generalised) Michel parameters ?

3. ($\mu \to e\gamma\gamma$?)

4. lots still on the todo list, please help with suggestions + questions :)

on website: a pdf of random thoughts and incomplete refs

Is it interesting to better measure $\tau_\mu \leftrightarrow G_\mu$?

1. measured by MuLAN (PSI) @ ppm with $\sim 1.6 \times 10^{12} \mu^+$. 1211.0960
2. PDB review (EW model and constraints on NP; Erler and Freitas) says all EW parameters enter the fits, but G_F is so precisely determined by MuLan, that other observables have little effect on its value.

$\Rightarrow$ maybe only interesting when second-best-determination of G_F becomes competitive? (from EWfit or β decay, current uncertainties $\sim$ few 10^{-4})

Maybe not?
(paper of ACrivellin 2102.02825
see backup+ask AC...)

A curiosity about PDB:

$e\bar{\nu}_e\nu_\mu$ $e\bar{\nu}_e\nu_\mu\gamma$ $e\bar{\nu}_e\nu_\mu e^+e^-$	$\dots$ $6\cdot 10^{-8} MEG$ $3\cdot 10^{-5} SINDRUM$
$e\nu_e\bar{\nu}_\mu$ $e\gamma$ $e\bar{e}e$ $e\gamma\gamma$	$< 1.2\times 10^{-2}$ $< 4.2\times 10^{-13}$ $< 10^{-12}$ $< 7.2\times 10^{-11}$

light particles are SM, invisible are νs
$\not{E}_T$ assigned to ν to conserve flavour (no light NP?)

- neutrino oscillations confirm most μ decays are SM :)

? Are constraints on BSM μ decays from ν oscillations interesting?

ex: In PDB, BR$(\mu\to e\nu_e\bar{\nu}_\mu) < 0.012$ ...? better sensitivity from modern ν osc expts? Info in ν angular distributions?

Can one find NP in angular distributions of visible final states?

?construct and measure generalised Michel parameters?

1. $\boldsymbol{\mu\to e\nu\bar{\nu}, \mu\to eXX}$ (X = boson):
   = Michel parameters for $\mathcal{I} = \bar{\nu}\nu$ (generalisation for 2 bosons?)
   Currently determined "poorly": 4 coeffs $\lesssim .01$, 5 coeffs $\lesssim .1$, 5 coeffs $\lesssim .5$!

   Andreas says any improvement is interesting :) (backupslide)

2102.02825

JodidioEtal:PRD34 (1988),1967
TWIST:1409.0638

2. $\boldsymbol{\mu \to eX}$, (X = boson) : with polarised μ^+, TRIUMF obtained
BR $\lesssim 2.6$(massless, isotropic) $\to$ 10 ($m >$ 10 MeV, anisotropic)$\to 58\times 10^{-6}$ (massless, SM-distributed)

pheno recast for ALPs 2006.04795 (=CRZZ; plot in backup).
MEGforward in snowmass LoI estimates reach BR$\sim 10^{-7} \to 10^{-8}$,
aim "to explore the broad context of light NP (s, a, γ') that could appear in μ decay"

Also $\mu^- \to^- e + X$ at $\mu A \to eA$ expts?

arXiv:1110.2874, ...
arXiv:2005.07894

E_e not fixed by 4-momentum conservation; tail up to $\sim m_\mu$ ($\sim 10^{-10}$ of the electrons are above $\sim$ 95 MeV), slightly different endpt shape from decay in orbit.
Reach $\lesssim \sqrt{BR(\mu A \to eA)}$, selon snowmass LoI, (possibly sensitive for $m_X \to 0$ where MEGforward struggles?).

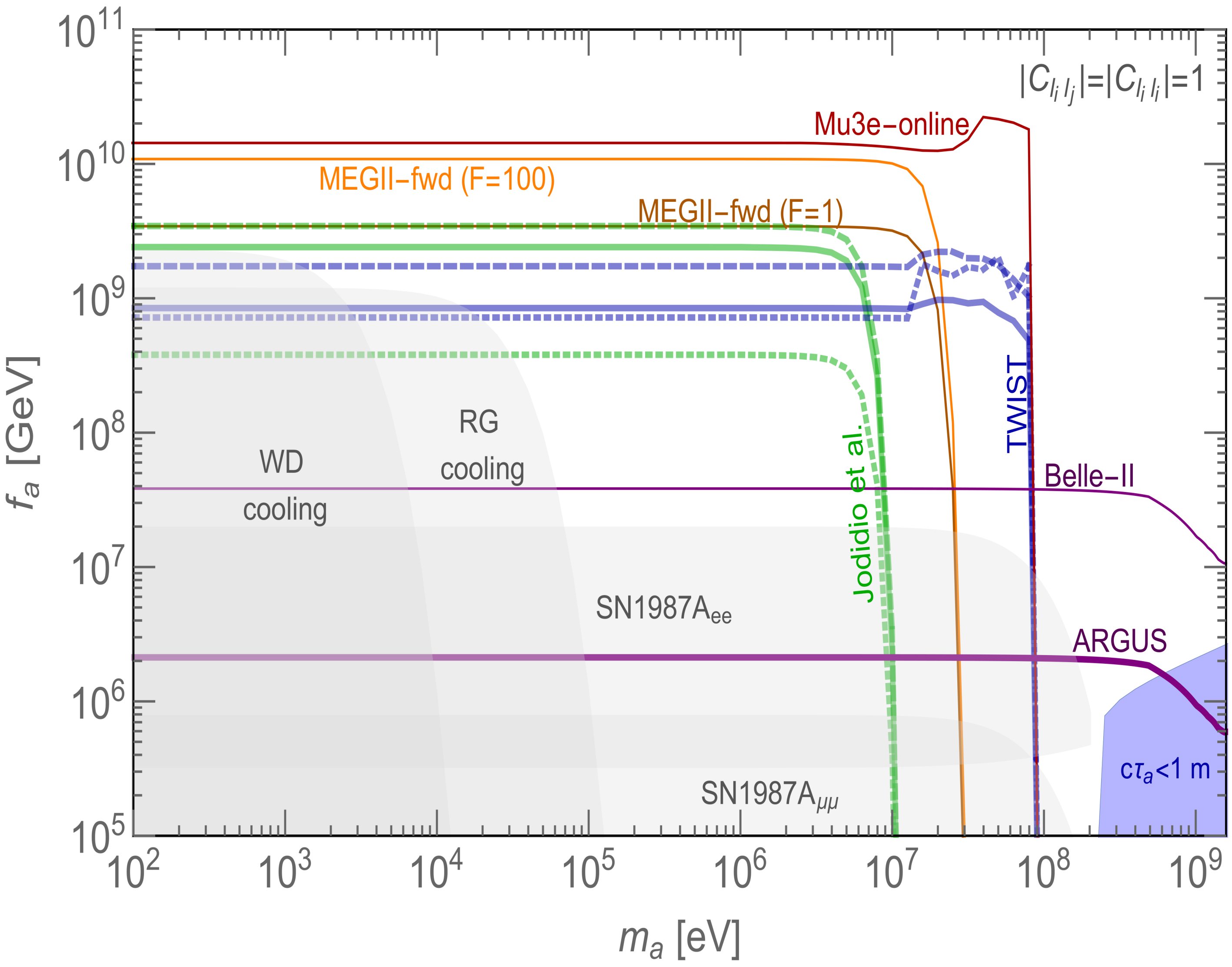
3. $\boldsymbol{\mu^+ \to e + \gamma + \mathcal{I}}$: Crystal Box ($\sim 10^{12}\mu$) obtained BR$(\mu \to e\gamma X) < 1.3\times 10^{-9}$,
for a $\approx$ massless X.

PRD36 (1987)1543

a doubt: ratio of $\mu^+ e^- \to \gamma X$, vs $\mu^+ \to e^+ \gamma X$? But wavefn overlaps are small: 1003.1578 (PRL)

There are various theoretical recasts of MEG results ... 0902.0525, 2008.01099 ...
? interesting to MEG? Included in MEGforward?

CRZZ pheno for scalars/ALP



4. **if X only interacts with neutrinos?** (interesting for cosmo:

interaction $\sim G_\nu(\overline{\nu}\Gamma\nu)(\overline{\nu}\Gamma\nu)$, $G_\nu \sim \frac{1}{(4.6MeV)^2} \to \frac{1}{(90MeV)^2}$ 1902.00534 2004.10868

could help address the H_0 tension$\Rightarrow m_{mediator} < m_\mu$)

For majoron J, $g_{\alpha\beta}\overline{\nu}_\alpha\gamma_5\nu_\beta J$, J bremstrahlung in pion/kaon decay removes chiral suppression, so more sensitive than Michel:

$$g_{e\alpha} \lesssim 3.3 \times 10^{-3} \quad g_{\mu\alpha} \lesssim 9.5 \times 10^{-3} \quad \text{(meson decays)}$$

$$g_{\mu\alpha} \lesssim 9 \times 10^{-2} \quad \text{(Michel param} = \rho)$$

hep-ph/0701068

$\alpha \in \{e, \mu, \tau\}$ (its a ν flavour)

$\Rightarrow$? need significant improvement in Michel to compete with meson decays?

(?loopholes?: true for scalars, pseudoscalars, vectors ? ...

5. **what about $\mu \to e + \bar{e}e + \mathcal{I}$?**

What about $\mu \to e\gamma\gamma$?

Crystal Box (1988) :
BR $< 7.2 \times 10^{-11}$

1. could be mediated by: dipole ($\mu \to e\gamma$) + radiation, or $\mu \to eX; X \to \gamma\gamma$, or contact interactions:

$$\delta\mathcal{L} = \frac{\sum_{X\in L,R}}{v^3}\left(C_{FF,X}\bar{e}P_X\mu F_{\alpha\beta}F^{\alpha\beta} + C_{F\tilde{F},X}\bar{e}P_X\mu F_{\alpha\beta}\widetilde{F}^{\alpha\beta}\right) + \mathrm{dim8}$$

2. $\mu A \to eA$ at SINDRUM has better sensitivity to $\bar{e}\Gamma\mu FF$ than Crystal Box
2007.09612
but can not probe $\bar{e}\Gamma\mu F\tilde{F} \sim \bar{e}\Gamma\mu\vec{E}\cdot\vec{B}$)

3. MEG looked for $\mu \to eX; X \to \gamma\gamma$, 20 MeV $< m_X <$40 MeV
2005.00339
(? for $\mu \to eX; X \to \gamma\gamma$, how do sensitivities of $X \to \gamma\gamma$ and $\mu \to eX$ compare to $\mu \to eX; X \to \gamma\gamma$?)

4. ? discussed for MEGII/MEGII-forward?

5. ...if one (or 2) of the γ's is off-shell (?), obtain $\mu \to e\bar{e}e + \gamma/\mu \to e(\bar{e}e)(\bar{e}e)$?

?
(how theoretically interesting is it?)

Summary: is it interesting to look for NP in angular distributions?

$BR(\mu \to e(+\bar{\nu}\nu) \sim 100\%$, $BR(\to e\gamma(+\bar{\nu}\nu)) \sim 6 \cdot 10^{-8}(MEG)$, $\to e\bar{e}e(+\bar{\nu}\nu) \sim 3 \cdot 10^{-5}(SINDRUM)$

See Adrian's discussion later: will want to measure SM decays, could do this at same time? (And Andreas says improvements to Michel welcome)

random thought: $\mu A \to eA$ will measure the endpt spectrum of their electron; how does their sensitivity to μ^- decays in orbit compare to μ^+ decays?

Backup

Q for theorists:

1. can one construct a generalisation of Michel parameters, (describe angular/polarisation distributions of visibles) for *generic* decays $\mu \to \{e, e\gamma, e\bar{e}e\}$ + SM/NP invisible?
   For instance, for $\mu \to e$+invisible; if write

   $$C_X^a (\overline{\mu}\Gamma_a P_X e)\mathcal{A}_a \quad , \Gamma_a \in \{I, \gamma_\alpha, \sigma_{\alpha\beta}\}, X \in \{L, R\}$$

   $\mathcal{A}_a$ describes invisibles ($\bar{\nu}\nu$,X, XX,X^μ...), then could map arbitrary invisible decay $\approx$ to Michel param $\Leftrightarrow$ constrain NP models
   (Recall Michel supposes 4-f contact interaction $\mu \to e\bar{\nu}\nu$)

   ...? something similar for $\mu \to e\gamma$+invis;, $\mu \to e\bar{e}e+$ invis.
   $\Rightarrow$? are such parametrisations constructable?
   are they useful, or do other processes/total rates have better sensitivity?

2. Matching out heavy sector of models with light NP coupled to (sterile) neutrinos — somewhere, there is a portal to the SM. At what loop level does it generate interactions of X with charged leptons?

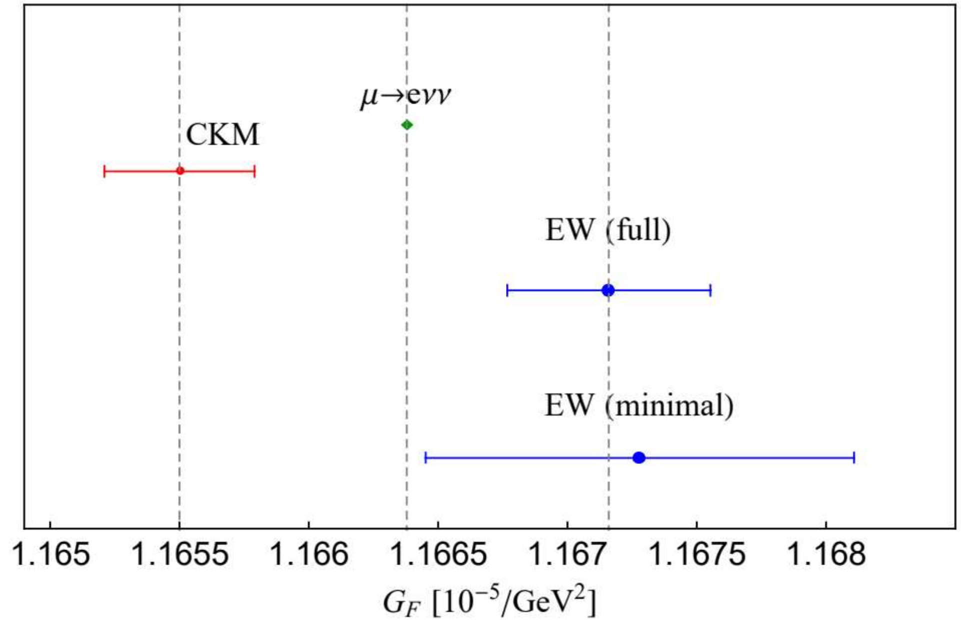
Michel Parameters

$\vert g^S_{RR}\vert < 0.035$	$\vert g^V_{RR}\vert < 0.017$	$\vert g^T_{RR}\vert \equiv 0$
$\vert g^S_{LR}\vert < 0.050$	$\vert g^V_{LR}\vert < 0.023$	$\vert g^T_{LR}\vert < 0.015$
$\vert g^S_{RL}\vert < 0.420$	$\vert g^V_{RL}\vert < 0.105$	$\vert g^T_{RL}\vert < 0.105$
$\vert g^S_{LL}\vert < 0.550$	$\vert g^V_{LL}\vert > 0.960$	$\vert g^T_{LL}\vert \equiv 0$
$\vert g^S_{LR} + 6\, g^T_{LR}\vert < 0.143$	$\vert g^S_{RL} + 6\, g^T_{RL}\vert < 0.418$	
$\vert g^S_{LR} + 2\, g^T_{LR}\vert < 0.108$	$\vert g^S_{RL} + 2\, g^T_{RL}\vert < 0.417$	
$\vert g^S_{LR} - 2\, g^T_{LR}\vert < 0.070$	$\vert g^S_{RL} - 2\, g^T_{RL}\vert < 0.418$	

New Physics in the Fermi Constant

- Fermi constant can be determined from
  - Muon decay
  - Electroweak fit (EW)
  - Kaon and
    beta decays (CKM)

A. Crivellin, M. Hoferichter, C. Manzari: 2102.02825



- Tension could be due to NP in μ→eνν
- Explanation via skalar operator leads to angular effects and is a the boarder of compatibility with current bounds

Improve Michel Parameters in Muon decay

What about bounds on flavour-diagonal couplings?

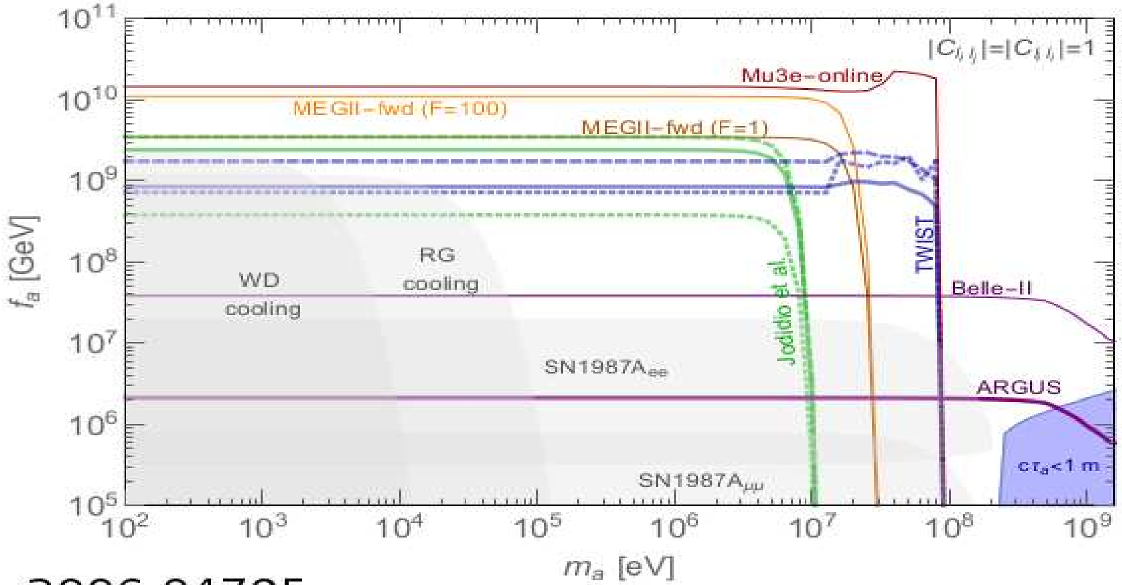
Suppose X interacts with leptons, has flavour-diagonal couplings $\gtrsim 10^{-10\pm few}$ with electrons; is is $m_X < m_\mu$ allowed by other constraints?

1. astrophysical/cosmo bounds exclude $m_X \lesssim$ MeV ($\sim T_U$ @ BBN,T_{core} for a Red Giant ~ 10 keV)

2. there is a SN constraint that can reach $m_X \lesssim 10$ MeV, for couplings somewhere around $\sim 10^{-6\pm few}$

3. in the PhysicsBeyondColliders paper [**?**] (see "Figure 18" and "Figure 39"), there is an un-excluded triangle for $m_{\gamma'} \gtrsim$ 10 MeV, $g_{\gamma' ee} \lesssim 10^{-4}$, $g_{\gamma' ee} \gtrsim 10^{-6}(100MeV/m_X)^2$. (I relate kinetic mixing parameter ϵ to coupling as $g_{\gamma' ee} \sim \epsilon e$). Above this triangle is the $g_X \to 1$ band that is excluded by the energy frontier for "not-to-small" masses, and below this triangle is the diagonal line excluded by beam dump expts, who aim to detect X at a detector behind a hill (so X has to get through the hill).

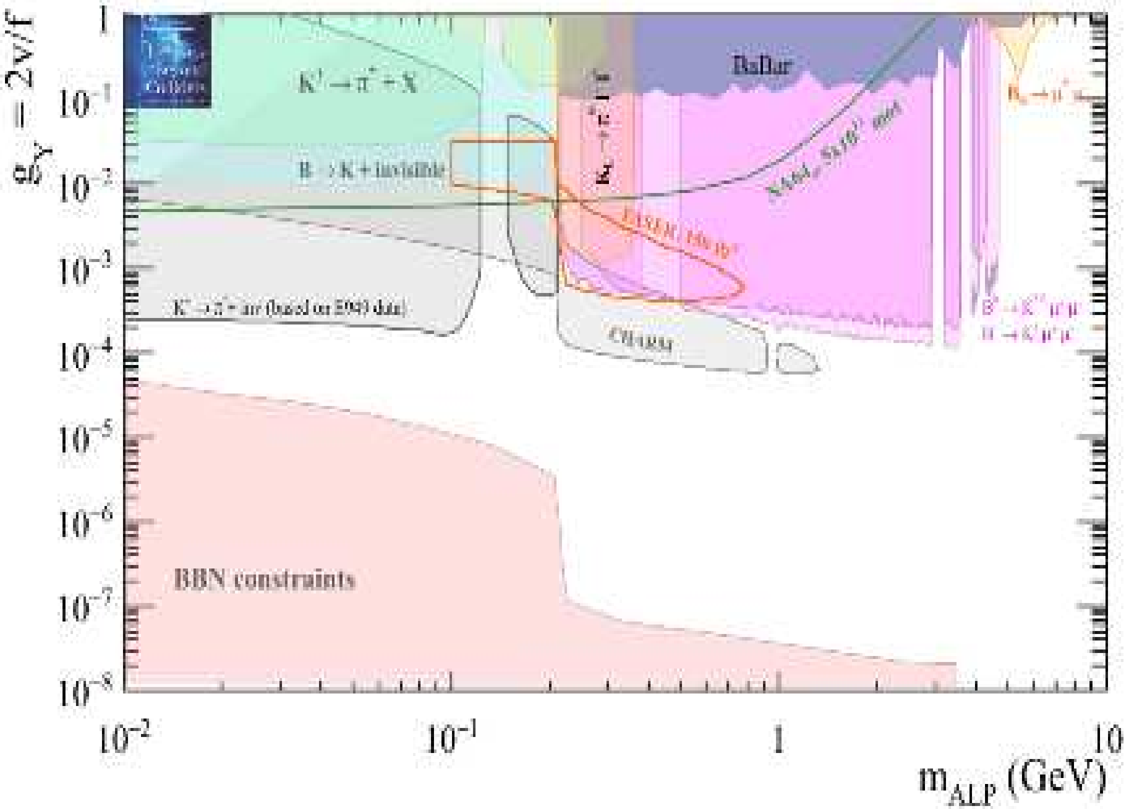
CRZZ pheno for scalars/ALP



2006.04795

Figure 1. Summary of the present bounds and future projections for an ALP with generic couplings to leptons, i.e., we set $C_{\ell\ell'} = 1$ for all the couplings in Eq. (2.1). For the isotropic case we set $C^V_{\mu e} = 0$ and $C^A_{\mu e} = 1$ (the opposite choice leads to the same results). In the V ± A case we set $C^V_{\mu e} = \pm C^A_{\mu e} = 1$. The **gray shaded** regions are excluded by the astrophysical bounds from star cooling due to C_{ee} and by SN1987A due to C_{ee} and and $C_{\mu\mu}$, see Sec. 6.1. We present these bounds for the isotropic case. The **blue shaded** region corresponds to a prompt/displaced ALP. The **green solid** line is the exclusion due to the bound on $\mu^+ \to e^+ a$ by Jodidio et al., assuming an isotropic ALP [9]. The **green dotted (dashed)** line is our recast of this bound for the $V - A$ $(V + A)$ case. The sensitivity in the $V - A$ case is worse since then the signal is suppressed in the forward direction as much as the background. The **blue solid (dotted, dashed)** lines are the bounds from the TWIST experiment on isotropic $(V - A,\ V + A)$ ALP [10]. The **dark orange thin solid** line is the MEGII-fwd projection for an isotropic ALP with no magnetic focusing while for the **orange thin solid** line we assumed that focusing increases the luminosity in the forward direction by a factor of 100, cf. Sec. 3.2 for details. The **dark red thin solid** line is the Mu3e projection from [42], for the isotropic ALP. The sensitivity for the other chiral structures is expected to be similar since there is no background suppression in this setup. The **purple solid** line is the bound from the $\tau \to ea$ search by the ARGUS collaboration [43], and does not dependent on the chirality of the ALP couplings. The **purple thin** line is the projected reach at Belle-II, see Sec. 5 for details. The bound on $\mu^+ \to e^+\gamma$ from Crystal Box is subdominant, see Sec. 4, and is not displayed for clarity.

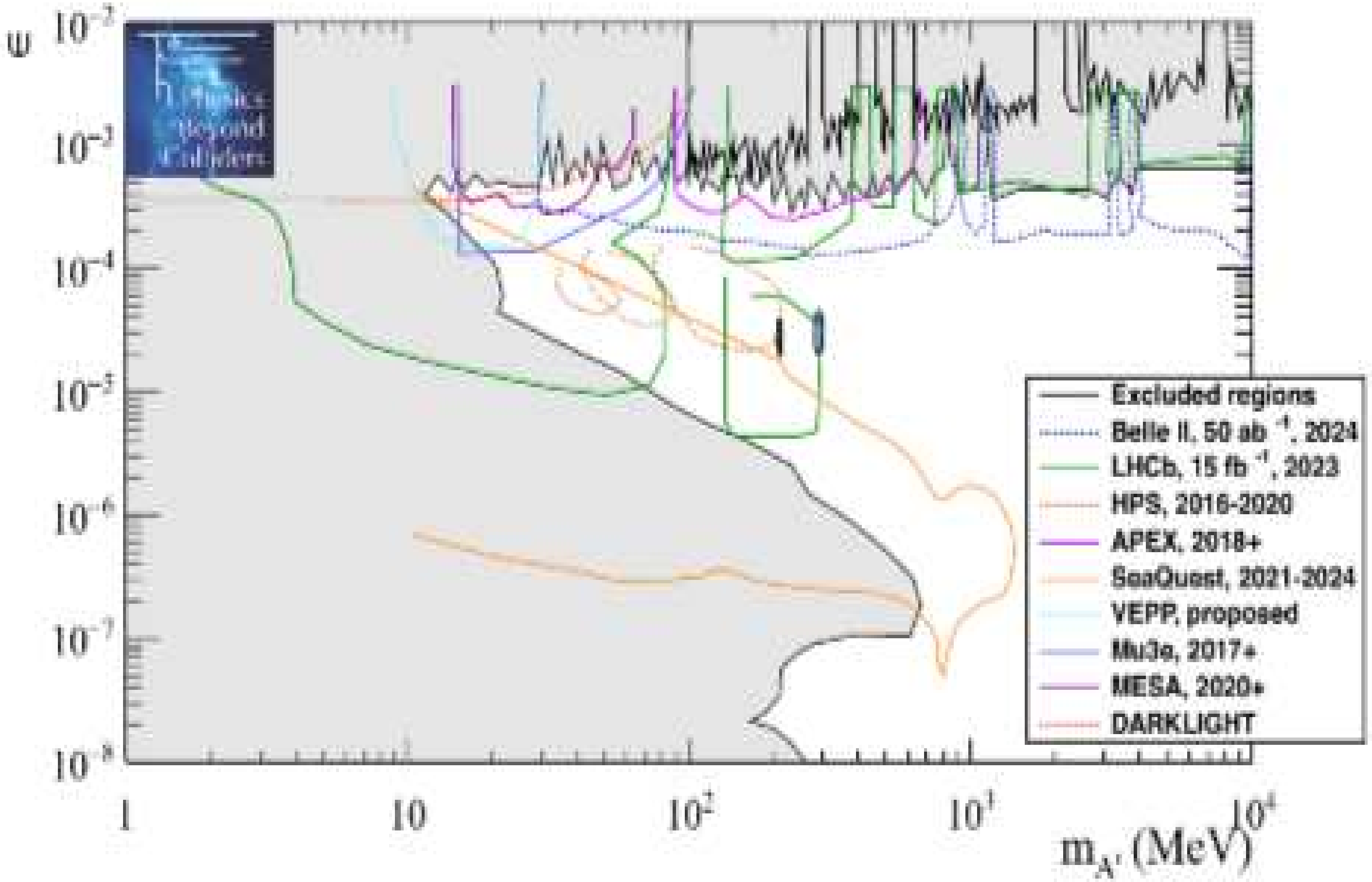
PBC summary plot for axions/ALPs



from 1901.0996

Figure 39: BC10: ALPs with fermion coupling. Current bounds (filled areas) and near ($\sim$ 5 years) prospects for PBC projects (solid lines). CHARM and LHCb filled areas have been adapted to PBC prescriptions by F. Kahlhoefer, following Ref. [319]. E949 area has been computed by the KLEVER collaboration and M. Papucci based on E949 data. All other exclusion regions have been properly re-computed by M. Papucci, following Ref. [318].

PBC figure for γ'



from 1901.09966

Figure 18: Future upper limits at 90 % CL for dark photond in visible decays in the plane mixing strength ϵ versus mass $m_{A'}$ from experiments and proposals not related to the PBC activity.