What to learn from μ decay, about neutrinos and other light physics?
Homework for PSI HIMB Workshop[1], april 6-9, 2021

PSI has a low-energy continuous beam of μ^+, which it considers to upgrade to $\sim 10^{10}\mu^+$/sec. Adrian asks whether its interesting to better measure Michel parameters. So question: *what can one learn about New Physics in muon decay?* "Pebbles" (=•) are questions/things to think about; stars(=$\star$) are things to do.

Reading the PDB

lifetime

The lifetime of the muon $\approx G_F$, was measured by MuLAN collaboration[3] (PSI) with $\sim 1.6 \times 10^{12}\mu^+$ to $\simeq$ 1ppm. In the PDB review (EW model and constraints on NP; Erler and Freitas), it 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 (next best determinations, from EWfit and mesons selon Crivellin et al [4] are to $\sim$ few parts in 10^4.)
• is there point to measure better? If yes, and if want G_F rather than τ_μ, then are loop effects specific to muon decay calculated to sufficient precision (need to subtract them to get G_F)?

final states

The final states listed in the PDB are

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

The observed modes are to right of central double line; the neutrino flavours maybe are assumed, not observed(?). But neutrino oscillation experiments might be better able to test "wrong" flavour neutrinos decays (See [19, 20]).

It seems that all $\mu \to e$ + invisible are effectively included in $\mu \to e\bar{\nu}_\mu\nu_e$?

Among the unobserved decays (not including $\mu \to e\gamma$ and $\to e\bar{e}e$):
$\boldsymbol{\mu \to e\bar{\nu}_e\nu_\mu}$: for ν-osc expts? (?better limit on BR by combining $\sin\theta_{13}$ of T2K ($\nu_\mu \to \nu_e$)+ reactors ($\bar{\nu}_e$ disappear)?)
$\boldsymbol{\mu \to e\gamma\gamma}$: $\mu A \to eA$ has better sensitivity to $\bar{e}\Gamma\mu FF$[14] than the current Crystal Box bd[15] (but $\mu A \to eA$ can not test $\bar{e}\Gamma\mu F\tilde{F} \sim \bar{e}\Gamma\mu\vec{E}\cdot\vec{B}$)
• Is this decay discussed for MEGII/MEGII-forward?

Michel parameters

Michel parameters describe the angular distribution and polarisation of the electron in muon decay. Lots of diverse notn in PDB.
$\star$ Make some new notation? 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 the invisible part of the amplitude, that would allow to map arbitrary invisible decay to Michel param? $\Rightarrow$ What A_a is for three possible Lorentz currents of leptons, and various BSM invisibles?

1. two-body is kinematically distinct from > 2 final state particles. In[13], from the Lagrangian ($X \in \{L, R\}$)

$$\mathcal{L} = g_X^0 X\overline{e}P_X\mu + g_X^1\frac{i\partial^\alpha X}{\Lambda}\overline{e}\gamma_\alpha P_X\mu + g_X^V\frac{X^{\alpha\beta}}{2\Lambda}\overline{e}\sigma_{\alpha\beta}P_X\mu \tag{1}$$

   the branching ratios are obtained:

$$BR(\mu \to eX) \quad = \quad \left\{ \begin{array}{ll} \frac{6\pi^2}{m_\mu^4 G_F^4}(|g_L^0|^2 + |g_R^0|^2) & g_X^0 \lesssim 2\times 10^{-11} \\ \frac{6\pi^2}{m_\mu^4 G_F^4}\frac{m_\mu^2}{\Lambda^2}(|g_L^1|^2 + |g_R^2|^2) & g_X^1\frac{GeV}{\Lambda} \lesssim 2\times 10^{-10} \\ \frac{12\pi^2}{m_\mu^4 G_F^4}\frac{m_\mu^2}{\Lambda^2}(|g_L^V|^2 + |g_R^2|^2) & g_X^V\frac{GeV}{\Lambda} \lesssim 10^{-10} \end{array} \right. \tag{2}$$

   where the numerical bounds arise from applying the TRIUMF "isotropic" bound BR$< 2.6 \times 10^{-6}$. (One sees equivalence of Yukawa and derivative couplings for X: $g_X^0 \leftrightarrow \frac{m_\mu}{\Lambda}g_X^1$, but YU notes that this will not follow from eqns of motion for a bound muon?)

   • Is it possible, a flavour-changing renormalisable vertex with a massive vector: $A'^{\alpha}\overline{e}\gamma_\alpha P_X\mu$?

   But ideally want differential decay rate for polarised muon decay; would allow to check that studies for a apply also to γ', and possible diffs between derivative and Yukawa couplings of scalars?

2. three or more final states (with muon polarisation?) includes Michel parameters in the case of 2 invisible fermions.
   Also 2-bosons, two neutrinos + a boson, 3 bosons, etc.
   exercise for calculators of $\mu \to e\bar{\nu}_e \nu_\mu \gamma$, $e\bar{\nu}_e \nu_\mu e^+ e^-$:)
   Allows to figure out constraints Michel parameters set on decays to two invisibles...

New Physics in $\mu \to e + \mathcal{I}$ (and $\mu \to e\gamma + \mathcal{I}$ (or $\mu \to e\bar{e}e + \mathcal{I}$?)), where $\mathcal{I} =$ invisible

Consider invisibles to be an even number of light neutral fermions ("neutrinos"), one or more light bosons, or two neutrinos and a boson. The boson is called X, and can be a (pseudo)scalar s or a vector γ', potentially massive.

Suppose $\mathcal{I}$ is just made of neutrinos?

That is, does one learn about New Physics by better measuring Michel parameters?

1. selon Crivellin etal[4], yes.

2. neutrino oscillation expts must know something about angular distribution and flavour of neutrinos from muon decay; how does this compare to Michel parameters?

3. ... $\mu \to e\bar{e}e + \bar{\nu}\nu$? Can one learn anything here that one does not learn in $\mu \to e + \bar{\nu}\nu$...rate is lower, is that useful??

Suppose a light invisible boson X in $\mathcal{I}$

There are interesting talks at FIP2020 [2], and Physics BeyondColliders writeup[6] is relevant.

Can wonder if $m_X < m_\mu$ is allowed by other constraints? ... depends on other interactions of X. Lets focus on X who interacts with leptons:

1. if X has flavour-diagonal couplings $\gtrsim 10^{-10 \pm few}$ with electrons/charged-first-generation-fermions

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

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

   (c) in the PhysicsBeyondColliders paper [6] (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).

2. if X has flavour-changing interactions with charged leptons (ie $\mu X \bar{e}$), then can have 2-body decay $\mu \to eX$.

   (a) TRIUMF looked for 2-body muon decays (Jodidio etal[7], TWIST[8]), in various scenarios. JodidioEtal obtain $BR(\mu \to ea) \leq 2.6 \times 10^{-6}$ for an $\approx$ massless scalar (assumed isotropic distribution of e wrt polarisation of μ, so searched at min of SM distribution), whereas TWIST can constrain up to $m_W \sim 80$ MeV ($BR(\mu \to ea) \leq 5.8 \times 10^{-5}$ for isotropic es), and considered anisotropically distributed e.

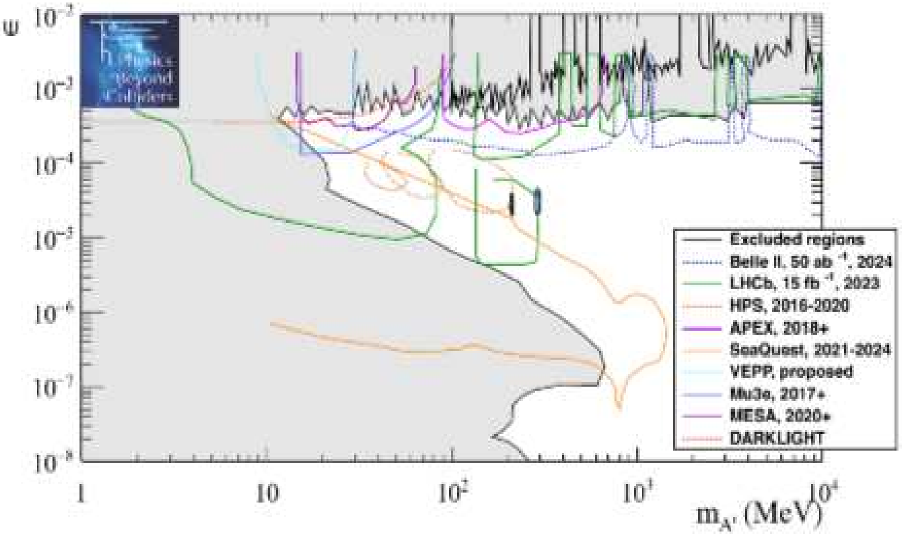
   (b) These studies are applied/recast to ALPs in the detailed pheno study [9], whose summary plot is below.

   $\star$ is it obvious that $\mu \to eX$ decay is the same for a free μ^+ and a $\mu^+ e^-$ bd state? (by analogy with muon decay when in bd state with nucleus, where electron spectrum is distorted)
   Ref [5] studied the change to SM muon lifetime from being in $\mu^+ e^-$ bd state, say has to be $\propto \alpha, m_e^2/m_\mu^2$, and found effect $\mathcal{O}(\alpha^2 m_e^2/m_\mu^2)$.
   I wonder about relative rates/experimental interest of $\mu^+ \to e^+ \gamma s$, and $(\mu^+ e^-) \to \gamma s$?

   (c) MEGforward envisages to search for such $\mu \to e$+invisibledecays, and a letter of Intent has been submitted to snowmass, with aim to explore the broad context of light NP (s, a, γ') that could appear in μ decay [10].

   (d) There is also a snowmass LoI about searching for $\mu^- \to e^- X$ at COMET [11], who estimate a sensitivity of order $BR(\mu \to ea)\sqrt{\text{single event sensitivity}} \sim 10^{-8}$, for SES to $\mu A \to eA$ of $\sim 10^{-17}$.

   $\mu \to e + X$ in orbit is different from the free decay, because the electron energy is not fixed by 4-momentum conservation; instead, the electron spectrum has a tail of energy up to $m_\mu - E_B - E_{rec}$ (where E_B was binding energy of muon and E_{rec} is recoil energy of nucleus): only $\sim 10^{-10}$ of the electrons are above ~ 95 MeV, ie at the end-pt where $\mu A \to eA$ expts look for electrons. The spectrum was calculated in [12], and discussed recently for various X in [13]. It has a slightly different shape at the endpt from the e spectrum

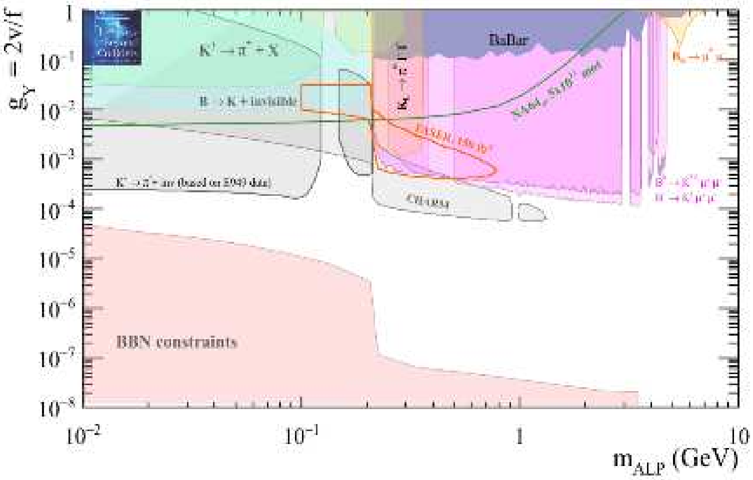


from 1901.09966

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.

from decay in orbit (?drops as $\sim (\Delta E)^3$ — more or less; see[13] discussion — whereas e from decay in orbit drop as $(\Delta E)^5$)?) Czarnecki etal constrain the $\mu \to e\{a, s\}$ decay by allowing all the events near the endpt to be from this process(?), and obtain BR$\lesssim 10^{-3}$ from Gold.

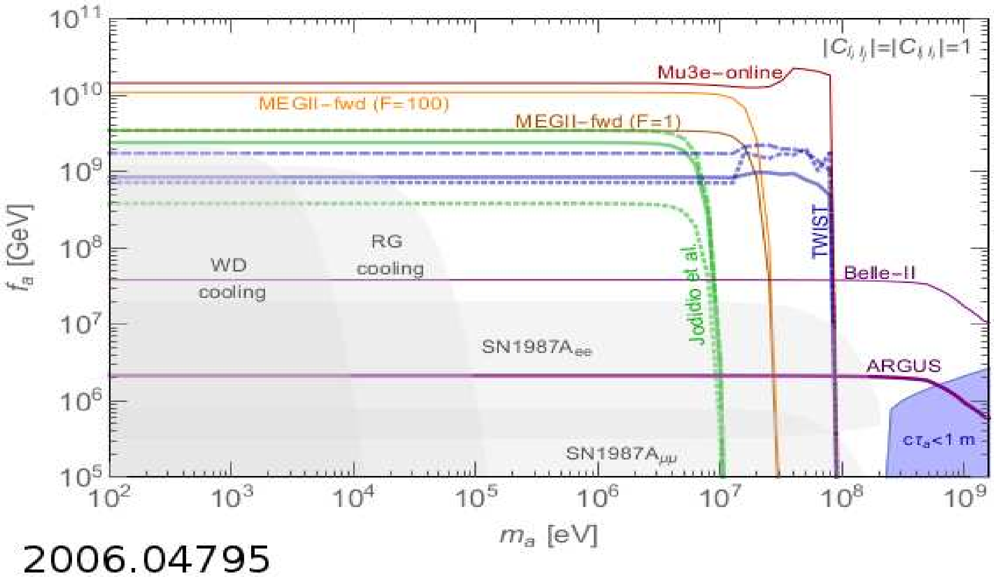
3. still for X with flavour-changing interactions with charged leptons (ie $\mu X \bar{e}$), can have decay $\mu \to e\gamma X$.
   (a) searched for by Crystal Box[15], with $\sim 10^{12}$ stopped muons, and obtained BR$(\mu \to e\gamma X) < 1.3 \times 10^{-9}$[16]. This bound applies for a massless X (?or sufficiently light; see comments after ref)
   (b) there are various theoretical recasts of MEG results:[31, 32]...
      - does MEG do this?



from 1901.0996

Figure 39: BC10: ALPs with fermion coupling. Current bounds (filled areas) and near (~ 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].

4. if X only interacts with neutrinos...
   (a) there should be a BBN bound (or not, if allow an extra 2 dof at BBN), and the lab expts that rely on production/detection via charged leptons would not constrain such particles at tree level (so "Figure 18" does not apply).
   (b) there is a SN bound[25, 26], for both flavour-diagonal and flavour-changing vertices. [25] have a massless majoron, but express their exclusions in curious way I did not try to understand. [27] give exclusion of
   $$3 \times 10^{-7} \lesssim g_{\alpha\beta} \lesssim 2 \times 10^{-5}$$
   (for $\alpha\beta \in \{e\mu\}$?). The SN bounds for $\alpha\beta \in \{e\mu\}$ of [26] (?computed only from inverse decays $\nu\nu \to \phi$) for $10MeV \simeq m$ (excusion is mass-dep) roughly exclude
   $$2 \to 20 \times 10^{-9} \lesssim g_{\alpha\beta} \lesssim .5 \to 1 \times 10^{-6}$$
   •? is there a stellar burning bound on scalars who only couple to neutrinos? (no bath of neutrinos)
   (c) "sticky" neutrinos could help address the H_0 tension; according to [33] they should ideally have a four-neutrino vertex strength $G_\nu \sim 1/(4.6MeV)^2 \to 1/(90MeV)^2$ or $G_\nu \sim 4 \times 10^9 G_F \to 10^7 G_F$. This suggests mediator should be kinematically accessible in muon decay (even with couplings to neutrinos of $\mathcal{O}(1)$).
   (d) There is a bound from $0\nu 2\beta$ on light scalars (with $L = 0$) coupled to ν_e : the renormalisable coupling should be $g_{ee} \lesssim 10^{-4}$.
   (e) for very light bosons s coupled to neutrinos, there is a bound from solar neutrino oscillations: if heavy neutrino mass eigenstates decayed into lighter ones, would disagree with observations, so in neutrino mass eigenstate basis $g_{21}\overline{\nu_2}\nu_1 J \lesssim 10^{-3}$ [28].
   $\star$: according to [29], which has ~ 200 citations, there is an Icecube bound; what is it? Might apply to any flavour?
   (f) Lessa and Peres consider a majoron J coupled as $g_{\alpha\beta}\overline{\nu}_\alpha \gamma_5 \nu_\beta J$, and use the observation of GelminiRoncadelli and Nussinov [30] that J bremstrahlung in pion decay gives an energy distribution to the charged lepton (GRN give formula) and dispenses with the chirality suppression factor. LP get the best bds from Kaon decays $K \to e\bar{\nu}$ and $K \to \mu\nu\bar{\nu}$ (where they say they $K \to \mu\bar{\nu}J$ would appear):
   $$g_{e\alpha} \lesssim 3.3 \times 10^{-3} \quad g_{\mu\alpha} \lesssim 9.5 \times 10^{-3} \quad \text{(meson decays)}$$
   where $\alpha \in \{e, \mu, \tau\}$ (its a ν flavour).



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.

They also consider bounds from muon decay. Using PDG results of 2006 (I did not check; where do they get G_F from? β-decay?), they obtain

$$g_{\mu\alpha} \lesssim 2 \times 10^{-2} \quad (\mu \text{ decay})$$

Then they consider Michel parameters: plot the spectrum for $\mu \to \nu\bar{\nu}J$ as a function of E_e, since it mostly affects large E_e, they treat Majoron as a modification of the ρ parameter (again I not check; what value of ρ did they take?) and obtain

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

So umm. Suggests that need to improve Michel parameters significantly, if want to compete with pseudoscalar meson constraints on neutrino properties?

$\star$ what are loopholes to that conclusion? Does it apply for scalars, pseudoscalars, vectors... ? (read scalar Peres paper in[27])

Initial question (?from Adrian?) was " what can one learn about light NP from Michel params"; since above estimates suggest that BRs are more restrictive, can one show that *in absence of a discovery*, its more interesting to constrain rates than angular shapes? (With and without 4π detector...)

$\star$ 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?

A Appendix:to build singlet majoron model [25]

Suppose a one-gen Lagrangian with two singlet fermions (so can do inverse seesaw?) and spontaneous breaking of L by a complex scalar σ who has L=2:

$$\mathcal{L} = \partial_\mu \sigma^\dagger \partial_\mu \sigma + i\overline{N} \not{\partial} N - \overline{N^c}\frac{M_N}{v_\sigma}\sigma N + i\overline{S}\not{\partial} S - \overline{S^c}\frac{M_S}{v_\sigma}\sigma S + \overline{\ell}\frac{M_D}{v} HN - \overline{S} M_M N - V(\sigma, H) + hc_{as\ req}. \quad (3)$$

Want SSB of both scalars, so put potential

$$V(\sigma, H) = \lambda_H (H^\dagger H - v^2)^2 + \lambda_\sigma (\sigma^\dagger \sigma - v_\sigma^2)^2 + \lambda_{\sigma H}(H^\dagger H - v^2)(\sigma^\dagger \sigma - v_\sigma^2)$$

(and suppose λs satisfy appropriate bdded from below bds). Write

$$\sigma = \frac{\rho}{\sqrt{2}} e^{i\phi/v_\sigma}$$

and then CS make a field redef $N \to N e^{i\phi/2v_\sigma}$, $S \to S e^{i\phi/2v_\sigma}$ and $\nu_L \to \nu_L e^{i\phi/2v_\sigma}$, in order to get the majoron ϕ out of the mass terms.
(CHECK: could I make field redefn on charged leptons too? Would have to transform e_R too, to keep mass invar? But selon[26] there are peculiar global syms such that majorons only couple to charged leptons at loop?) Then CS get:

$$\mathcal{L} = \partial_\mu \phi \partial_\mu \phi + i\overline{N}\not{\partial} N - \overline{N^c} M_N N + i\overline{S}\not{\partial} S - \overline{S^c} M_S S + \overline{\ell} M_D N - \overline{S} M_M N \pm \frac{\partial_\mu \phi}{2v_\sigma}(\overline{N}\gamma_\mu N + \overline{S}\gamma_\mu S + \overline{\ell}\gamma_\mu \ell) + hc_{as\ req} \quad (4)$$

where I neglected the dynamics of ρ (included by CS in an appendix).

So it seems the usual effective Lagrangian for majorons is at dim 5 (in not-χ-PT powercounting?) Then [33] include some dim6 operators that could arise.
$\star$ CHECK : does one need to count a la Weinberg for χPT?.

B Appendix: models of bosons who only couple to neutrinos

Lagrangian for the model of [34] must be something like:

$$\mathcal{L} = i\overline{\nu}_s \not{D} \nu_s + \overline{X}(i\not{D} - m_X)X + (D_\alpha h_x)^\dagger D_\alpha h_x + \overline{N}(i\not{\partial} - M_N)N + Y_{Ns}\overline{N} h_X \nu_s + Y_{N\ell}\overline{N} H^\dagger \ell - V(h_x)$$

where $D_\alpha = \partial_\alpha + igQP_\alpha$, and the DM X annihilates to PP pairs for $m_X > m_P$, to neutrinos if $m_X \ll m_P$. (?heavy N supposed to decay, and h_X to annihilate sufficiently?) Without the DM X, this must more-or-less be Yasaman Farzan's model?

Does this model make sticky neutrinos?

The idea is that the secluded sector is inhabited by a scalar h who gets a vev, a fermion X who is DM, and a sterile neutrino ν_s, who can all talk to each other by exchanging a massive shadow-photon P. They can only talk to our world via the N who is "heavy", so at dim5 get secluded-SM-neutrino mass mixing :

$$\frac{Y_{Ns} Y_{N\ell}}{M_N} h_X \nu_s H^\dagger \ell$$

If I try to build at dim6, seems to cost two factors of heavy neutrino mass scale (get an N with each ℓ), so get the gradient operator $YY^\dagger \overline{\ell}\not{\partial}\ell v^2/M^2$ at tree level, or possibly loops, but potentially all very suppressed?

However, I am not sure this is a good model for PSI, because the γ' coupling to active neutrinos vanishes for flavour eigenstate neutrinos; it can couple to the sterile component of mass eigenstate neutrinos, but then one needs the neutrino masses in the process?

References

[1] https://indico.psi.ch/event/10547/overview

[2] https://indico.cern.ch/event/864648/timetable/

[3] V. Tishchenko *et al.* [MuLan], "Detailed Report of the MuLan Measurement of the Positive Muon Lifetime and Determination of the Fermi Constant," Phys. Rev. D **87** (2013) no.5, 052003 doi:10.1103/PhysRevD.87.052003 [arXiv:1211.0960 [hep-ex]].

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$\mu \to eX$

[5] A. Czarnecki, G. P. Lepage and W. J. Marciano, "Muonium decay," Phys. Rev. D **61** (2000), 073001 doi:10.1103/PhysRevD.61.073001 [arXiv:hep-ph/9908439 [hep-ph]].

Effect on μ^+ lifetime due to being in a mu^+e^- bd state is $\mathcal{O}(\alpha^{\in}\Updownarrow_{\rceil}^{\in}/\Updownarrow_{\mu}^{\in})$.

[6] J. Beacham, C. Burrage, D. Curtin, A. De Roeck, J. Evans, J. L. Feng, C. Gatto, S. Gninenko, A. Hartin and I. Irastorza, *et al.* "Physics Beyond Colliders at CERN: Beyond the Standard Model Working Group Report," J. Phys. G **47** (2020) no.1, 010501 doi:10.1088/1361-6471/ab4cd2 [arXiv:1901.09966 [hep-ex]].

[7] A. Jodidio, B. Balke, J. Carr, G. Gidal, K. A. Shinsky, H. M. Steiner, D. P. Stoker, M. Strovink, R. D. Tripp and B. Gobbi, *et al.* "Search for Right-Handed Currents in Muon Decay," Phys. Rev. D **34** (1986), 1967 [erratum: Phys. Rev. D **37** (1988), 237] doi:10.1103/PhysRevD.34.1967

1.7×10^7 polarised μ^+s, looked for positrons in "backwards " direction.

[8] R. Bayes *et al.* [TWIST], "Search for two body muon decay signals," Phys. Rev. D **91** (2015) no.5, 052020 doi:10.1103/PhysRevD.91.052020 [arXiv:1409.0638 [hep-ex]].

5.8×10^8 muons; look for positron excess over wider angular distribution. Extend previous bound on $\mu \to e$ 2-body decay to higher masses (13-80 MeV; say their analysis inappropriate for light invisibles because distorts endpt) and allow for anisotropic decay (not allowed in Jodidio etal)

[9] L. Calibbi, D. Redigolo, R. Ziegler and J. Zupan, "Looking forward to Lepton-flavor-violating ALPs," [arXiv:2006.04795 [hep-ph]].

CRZZ consider $\mu \to ea$, and do a recast of Jodidio Etal for the case where the e distribution is asymmetric. An invisible scalar is probably isotropic; but for gradient-coupled goldstone

$$\frac{\partial_\alpha a}{2f_a}\overline{f}_i\gamma^\alpha(C_V^{ij} + C_A^{ij}\gamma_5)f_j$$

where i, j generation indices and CRZZ set $C_V^{ij} = 0$ ("by a field redefn that affects ALP cplings to EWbosons"), get

$$\frac{d\Gamma(\ell_i \to \ell_j a)}{d\cos\theta} \propto \frac{m_i^3}{32f_a^2}\left((|C_V^{ij}|^2 + |C_A^{ij*}|^2) + P_i\cos\theta Re C_V^{ij}C_A^{ij*}\right)$$

Also discuss prospects for MEGII (forward) and Mu3e.

[10] Snowmass LoI: go to
https://snowmass21.org/rare/clfv
then #11 should be: RF/SNOWMASS21-RF5$_R$F0-080.pdf

[11] Snowmass LoI: go to
https://snowmass21.org/rare/clfv
then #26 should be: RF/SNOWMASS21-RF5-RF0-C-Wu-120.pdf

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[13] Y. Uesaka, "Model identification in $\mu^- \to e^-$ conversion with invisible boson emission using muonic atoms," Phys. Rev. D **102** (2020) no.9, 095007 doi:10.1103/PhysRevD.102.095007 [arXiv:2005.07894 [hep-ph]].

Mentions that MEG proposal to search for $\mu^+ \to eX$ has difficulty with low m_X, where $\mu A \to eA$ can have sensitivity.

Consider three cases: a scalar X with Yukawa couplings $X\bar{e}g_X^0 P_X\mu$, a scalar with derivative coupling $\partial^\alpha X\bar{e}\gamma_\alpha g_X^1 P_X\mu/\Lambda$, and a dipole vertex with invisible X.

But I am confused by his conclusion; he plots the electron spectrum close to its endpt, where the three models differ by 10-20%, and says this can be used to discriminate among the interactions. ? I do not "get" it... is a result of the different Lorentz structure of the $\mu - e$ vertex?

[14] S. Davidson, Y. Kuno, Y. Uesaka and M. Yamanaka, "Probing $\mu e\gamma\gamma$ contact interactions with $\mu \to e$ conversion," Phys. Rev. D **102** (2020) no.11, 115043 doi:10.1103/PhysRevD.102.115043 [arXiv:2007.09612 [hep-ph]].

[15] R. D. Bolton, M. D. Cooper, J. S. Frank, A. L. Hallin, P. A. Heusi, C. M. Hoffman, G. E. Hogan, F. G. Mariam, H. S. Matis and R. E. Mischke, *et al.* "Search for Rare Muon Decays with the Crystal Box Detector," Phys. Rev. D **38** (1988), 2077 doi:10.1103/PhysRevD.38.2077

[16] J. T. Goldman, A. L. Hallin, C. M. Hoffman, L. E. Piilonen, D. Preston, R. D. Bolton, M. D. Cooper, J. S. Frank, P. A. Heusi and G. E. Hogan, *et al.* "Light Boson Emission in the Decay of the μ^+," Phys. Rev. D **36** (1987), 1543-1546 doi:10.1103/PhysRevD.36.1543

Obtain BR$(\mu \to e\gamma X) < 1.3 \times 10^{-9}$, with requirement that X is massless; the Crystal Box paper [15] says it applies for $m_X < 2m_e$ "because otherwise would have $X \to e\bar{e}$". (? But I could turn off flavour diagonal interactions? I guess this means the exptal cut on missing mass is $> m_e$; I did not find in either paper — they do maximum likelyhood sum of curves for $\mu \to e\gamma X$, $\mu \to e\gamma\nu\bar{\nu}$ and other backgrd, and conclude less that 165 events. But if they allowed a mass, how would that change??).

[17] M. Hirsch, A. Vicente, J. Meyer and W. Porod, "Majoron emission in muon and tau decays revisited," Phys. Rev. D **79** (2009), 055023 [erratum: Phys. Rev. D **79** (2009), 079901] doi:10.1103/PhysRevD.79.055023 [arXiv:0902.0525 [hep-ph]].

[18] B. Echenard, R. Essig and Y. M. Zhong, "Projections for Dark Photon Searches at Mu3e," JHEP **01** (2015), 113 doi:10.1007/JHEP01(2015)113 [arXiv:1411.1770 [hep-ph]].

wrong-flavoured neutrinos

[19] S. Bergmann and Y. Grossman, "Can lepton flavor violating interactions explain the LSND results?," Phys. Rev. D **59** (1999), 093005 doi:10.1103/PhysRevD.59.093005 [arXiv:hep-ph/9809524 [hep-ph]].

S. Bergmann, Y. Grossman and D. M. Pierce, "Can lepton flavor violating interactions explain the atmospheric neutrino problem?," Phys. Rev. D **61** (2000), 053005 doi:10.1103/PhysRevD.61.053005 [arXiv:hep-ph/9909390 [hep-ph]].

S. Bergmann, Y. Grossman and E. Nardi, "Neutrino propagation in matter with general interactions," Phys. Rev. D **60** (1999), 093008 doi:10.1103/PhysRevD.60.093008 [arXiv:hep-ph/9903517 [hep-ph]].

Neutrino flavour eigenstates are defined as the linear combination of neutrinos that enter Fermi interactions with a charged lepton; study some effects of flavour-changing BSM contact interactions, CC and NC, fot instance for LSND anomaly (LSND anomaly suggests short baseline $\nu_\mu \to \nu_e$ oscillations, and $\bar{\nu}_\mu \to \bar{\nu}_e$ corresponding to $\Delta m^2 \sim$ eV^2).

[20] K. S. Babu and S. Pakvasa, "Lepton number violating muon decay and the LSND neutrino anomaly," [arXiv:hep-ph/0204236 [hep-ph]].

Explore whether can explain LSND with BSM muon decays mediated by LNV operators

sticky cosmo neutrinos

There is a tension between the value of H_0 (expansion rate of U today) extracted from CMB data by the Planck satellite[21] in the ΛCDM model, $(67.4 \pm 0.5$km/sec/Mpc), and the value extracted from supernovae is more like 73 ± 2km/sec/Mpc[22]. One way to address this, is to change the behaviour of the thermal soup prior to/around the time of decoupling — for instance, by making neutrinos "sticky", such that they cannot free-stream over long distances until the U becomes matter-dominated. The paper I was reading abut this is [23].

[21] N. Aghanim *et al.* [Planck], "Planck 2018 results. VI. Cosmological parameters," Astron. Astrophys. **641** (2020), A6 doi:10.1051/0004-6361/201833910 [arXiv:1807.06209 [astro-ph.CO]].

[22] J. L. Bernal, L. Verde and A. G. Riess, "The trouble with H_0," JCAP **10** (2016), 019 doi:10.1088/1475-7516/2016/10/019 [arXiv:1607.05617 [astro-ph.CO]].

[23] C. D. Kreisch, F. Y. Cyr-Racine and O. Doré, "Neutrino puzzle: Anomalies, interactions, and cosmological tensions," Phys. Rev. D **101** (2020) no.12, 123505 doi:10.1103/PhysRevD.101.123505 [arXiv:1902.00534 [astro-ph.CO]].

majorons

[24] Y. Chikashige, R. N. Mohapatra and R. D. Peccei, "Are There Real Goldstone Bosons Associated with Broken Lepton Number?," Phys. Lett. B **98** (1981), 265-268 doi:10.1016/0370-2693(81)90011-3

The CMP singlet majoron

[25] K. Choi and A. Santamaria, “17-KeV neutrino in a singlet - triplet majoron model,” Phys. Lett. B **267** (1991), 504-508 doi:10.1016/0370-2693(91)90900-B

(cited by KCRD) About the 17 keV Simpsons neutrino, so prior to “discovery” of neutrino oscillations. Their singlet extension of the majoron model allows to avoid LEP constraints. They have a prior SN cooling paper:

K. Choi and A. Santamaria, “Majorons and Supernova Cooling,” Phys. Rev. D **42** (1990), 293-306 doi:10.1103/PhysRevD.42.293

Mostly interested in singlet Majoron models, (triplet Majoron constrained by Z decay width, and in SN the majorons are trapped in SN core by scattering on nuclei.) Say that Majoron can have weak couplings to matter while independent couplings to neutrinos that are related to neutrino masses. At the time, the upper bd on ν_τ mass was 35 MeV.

Then there is nice clear derivation of how to obtain low-E majoron interactions with neutrinos in singlet Majoron model (its in the APpendix above).

[26] L. Heurtier and Y. Zhang, “Supernova Constraints on Massive (Pseudo)Scalar Coupling to Neutrinos,” JCAP **02** (2017), 042 doi:10.1088/1475-7516/2017/02/042 [arXiv:1609.05882 [hep-ph]].

SN update.

[27] A. P. Lessa and O. L. G. Peres, “Revising limits on neutrino-Majoron couplings,” Phys. Rev. D **75** (2007), 094001 doi:10.1103/PhysRevD.75.094001 [arXiv:hep-ph/0701068 [hep-ph]].

Consider 4-bdy decay $\mu \to e\nu\bar{\nu} + J$, say that Michel parameters distorted.

P. S. Pasquini and O. L. G. Peres, “Bounds on Neutrino-Scalar Yukawa Coupling,” Phys. Rev. D **93** (2016) no.5, 053007 [erratum: Phys. Rev. D **93** (2016) no.7, 079902] doi:10.1103/PhysRevD.93.053007 [arXiv:1511.01811 [hep-ph]].

[28] J. F. Beacom and N. F. Bell, “Do Solar Neutrinos Decay?,” Phys. Rev. D **65** (2002), 113009 doi:10.1103/PhysRevD.65.113009 [arXiv:hep-ph/0204111 [hep-ph]].

[29] J. F. Beacom, N. F. Bell, D. Hooper, S. Pakvasa and T. J. Weiler, “Decay of High-Energy Astrophysical Neutrinos,” Phys. Rev. Lett. **90** (2003), 181301 doi:10.1103/PhysRevLett.90.181301 [arXiv:hep-ph/0211305 [hep-ph]].

[30] G. B. Gelmini, S. Nussinov and M. Roncadelli, “Bounds and Prospects for the Majoron Model of Left-handed Neutrino Masses,” Nucl. Phys. B **209** (1982), 157-173 doi:10.1016/0550-3213(82)90107-9

[31] P. Escribano and A. Vicente, “Ultralight scalars in leptonic observables,” JHEP **03** (2021), 240 doi:10.1007/JHEP03(2021)240 [arXiv:2008.01099 [hep-ph]].

[32] M. Hirsch, A. Vicente, J. Meyer and W. Porod, “Majoron emission in muon and tau decays revisited,” Phys. Rev. D **79** (2009), 055023 [erratum: Phys. Rev. D **79** (2009), 079901] doi:10.1103/PhysRevD.79.055023 [arXiv:0902.0525 [hep-ph]].

[33] K. F. Lyu, E. Stamou and L. T. Wang, “Self-interacting neutrinos: Solution to Hubble tension versus experimental constraints,” Phys. Rev. D **103** (2021) no.1, 015004 doi:10.1103/PhysRevD.103.015004 [arXiv:2004.10868 [hep-ph]].

sectII: We begin with the assumption that, with the exception of the Majoron ϕ, new physics is heavier than the electroweak scale. ...We restrict the discussion to flavour diagonal operators.

Then they consider seesaw and inverse seesaw models, augmented by a real scalar (identified as Majoron) with renorm couplings, and study SMEFT ops at dim6 generated in these models.

So they do not allow for light sterile neutrinos/secluded sector? (And is unclear whether the Majoron is a goldstone?)

I am a bit confused; other models could have othr effects, so why not just do EFT? And maybe needed to allow for dim8 operators, since that allows to avoid some of the charged lepton constraints.

Sec III considerd observables: Z decay, T-parameter, meson decays, and relate to neutrino self-interactions in cosmology to fit H0.

[34] J. F. Cherry, A. Friedland and I. M. Shoemaker, “Neutrino Portal Dark Matter: From Dwarf Galaxies to IceCube,” [arXiv:1411.1071 [hep-ph]].

“In this letter, we consider a simple, consistent model of neutrinophilic DM with these features where DM and a “secluded" SMsinglet neutrino species are charged under a new U(1) gauge symmetry. An important ingredient of this model is that the secluded sector couples to the Standard Model fields only through neutrino mixing. We observe that the secluded and active neutrinos recouple, leading to a large relic secluded neutrino population. ... potentially observable consequences for the IceCube high energy signal ...”

Paper focuses on relic neutrino abundance over cosmo time, and on oscillations of active neutrinos to sterile to change optical depth for Icecube. They say there will be another paper about constraints on the model, which I do not find.

a lire

[35] P. Bakhti and Y. Farzan, “Constraining secret gauge interactions of neutrinos by meson decays,” Phys. Rev. D **95** (2017) no.9, 095008 doi:10.1103/PhysRevD.95.095008 [arXiv:1702.04187 [hep-ph]].

[36] J Heeck, LFV with light vector bosons, 1602.03810

not read

[37] T. Brune and H. Päs, “Massive Majorons and constraints on the Majoron-neutrino coupling,” Phys. Rev. D **99** (2019) no.9, 096005 doi:10.1103/PhysRevD.99.096005 [arXiv:1808.08158 [hep-ph]].

We revisit a singlet Majoron model in which neutrino masses arise from the spontaneous violation of lepton number. If the Majoron obtains a mass of order MeV, it can play the role of dark matter. We discuss constraints on the couplings of the massive Majoron with masses of order MeV to neutrinos from supernova data. In the dense supernova core, Majoron-emitting neutrino annihilations are allowed and can change the signal of a supernova. Based on the observation of SN1987A, we exclude a large range of couplings from the luminosity and the deleptonization arguments, taking the effect of the background medium into account. If the Majoron mass does not exceed the Q-value of the experiment, the neutrino-Majoron couplings allow for neutrinoless double beta decay with Majoron emission. We derive constraints on the couplings for a Majoron mass of order MeV based on the phase space suppression and the diminishing signal-to-background ratio due to the Majoron mass. The combination of constraints from astrophysics and laboratory experiments excludes a large range of neutrino-Majoron couplings in the mass range of interest for Majoron dark matter, where they complement existing cosmological bounds from dark matter stability and the effects of a decaying Majoron on the cosmic microwave background anisotropy spectrum.

[38] V. Brdar, M. Lindner, S. Vogl and X. J. Xu, “Revisiting neutrino self-interaction constraints from Z and τ decays,” Phys. Rev. D **101** (2020) no.11, 115001 doi:10.1103/PhysRevD.101.115001 [arXiv:2003.05339 [hep-ph]].

In this work we focus on additional contributions to the invisible decay width of Z boson as well as the leptonic τ decay width in the presence of a neutrino coupling to a relatively light scalar. For invisible Z decays we derive a complete set of constraints by considering both three-body bremsstrahlung as well as the loop correction to two-body decays.