Leptophilic Dark Matter

Gerrit Bickendorf

April 23, 2019

Outline

- Introduce need for leptophilic mediators
- Introduce a vector and scalar model
- Constrains from muon decay spectrum
- Constrains from lepton universality in π^+ decays
- Constrains from π^+ decay spectrum

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- Need dark matter to stay dark

  $\rightarrow$ Introduce secluded dark sector without SM interactions
- Only interaction: Through mediator
- Try to constrain mediator models

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- Why is there only indirect evidence for states beyond the standard model?
- No tree level coupling to quarks and SM-gauge bosons
- Only direct coupling to leptons
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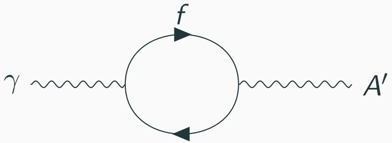
Vector Model

$$
\begin{aligned}
\mathcal{L} =& \mathcal{L}_{\mathsf{SM}} - \frac{1}{4} F'_{\mu\nu} F'^{\mu\nu} + \frac{m_{A'}^2}{2} A'_\mu A'^\mu + \frac{\epsilon}{2} F'_{\mu\nu} F^{\mu\nu} \\
& - \sum_{l=e,\mu,\tau} e'_l \left(\bar{l} \gamma^\mu A'_\mu l + \bar{\nu}_l \gamma^\mu A'_\mu \nu_l \right) \\
& + \bar{\chi}(i\not{\partial} - m_\chi)\chi - g_D \bar{\chi} \gamma^\mu A'_\mu \chi
\end{aligned}
$$

Vector Model



$$\epsilon = \sum_l \frac{ee'_l}{12\pi^2} \ln\left(\frac{m_\tau^2}{\mu^2}\right)$$

After diagonalisation:

$$\mathcal{L} \supset e\epsilon A'_\mu J^\mu_{em}$$

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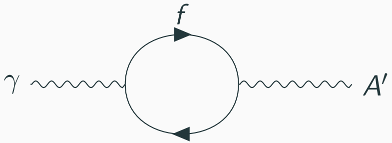

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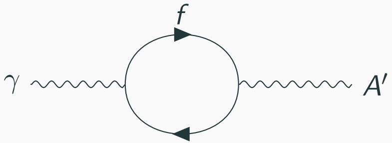

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Scalar Model

$$\mathcal{L} = \mathcal{L}_{\text{SM}} + \frac{1}{2}\partial_\mu\phi\partial^\mu\phi - \frac{m_\phi^2}{2}\phi - \sum_{l=e,\mu,\tau} e'_l \bar{l} l \phi$$
$$+ \bar{\chi}(i\not{\partial} - m_\chi)\chi - g_D\bar{\chi}\chi\phi$$

- From effective dim. 5 operator

$$\frac{c_l}{\Lambda}\phi\bar{L}_i\Phi e_{iR} + h.c.$$

- After SSB

$$e'_l = \frac{c_l v}{\Lambda\sqrt{2}}.$$

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Experimental constrains

Neutrino Trident Production

Contribution to [1]

$$\frac{\sigma_{CCFR}}{\sigma_{SM}} = 0.82 \pm 0.28$$

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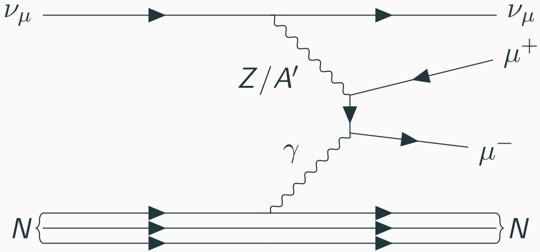

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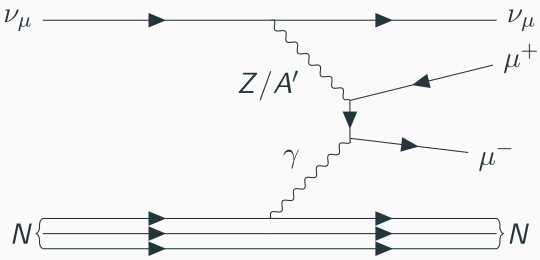

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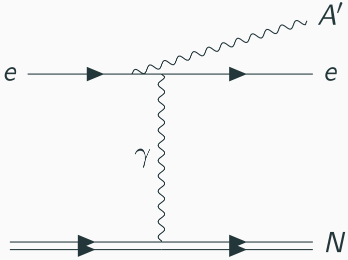
Experimental constrains

NA64 [2]:

- Missing energy search for invisible dark photo decay

$$e^- N \to e^- N A'(A' \to \bar{\chi}\chi)$$

- Only $m_{A'} > 1 MeV$



Experimental constrains

BABAR:

- e^+e^- collider process:

$$e^+e^- \to \gamma A'(A' \to \bar{\chi}\chi)$$

- Detect mono photon events with CM energy E^*_γ and search for peak in $M_X^2 = s - 2E^*_\gamma\sqrt{s}$
- $0 < m_{A'} < 8GeV$

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Atomic physics [3] :

- Additional scalars add potential:

$$V^{ij}(r) = -\frac{e'_i e'_j}{4\pi} \frac{e^{-m_\phi}}{r}$$

$\rightarrow$ Energy shift

- Positronium (e^+e^-) 1S-2S transition
  $\rightarrow$ bound on e'_e
- Muonium ($e^-\mu^+$) 1S-2S transition and Lamb shift
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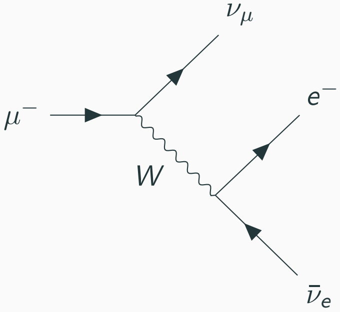
Standard Model Muon Decay



$$\mathcal{M} = \frac{g^2}{8m_W^2}\bar{u}(P_{\nu_\mu}, s_{\nu_\mu})\gamma_\mu(1-\gamma^5)u(P, s)\bar{u}(P_e, s_e)\gamma^\mu(1-\gamma^5)v(P_{\nu_e}, s_{\nu_e})$$

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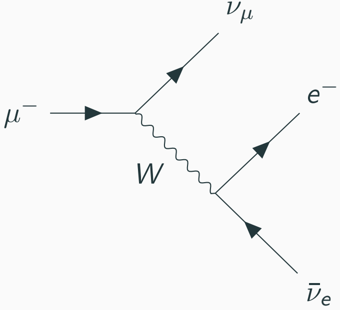

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Muon decay spectrum

$$\frac{d^2\Gamma}{dxd\cos\theta} = \frac{m_\mu}{4\pi^3} W_{e\mu}^4 G_f^2 \sqrt{x^2 - x_0^2}\,(F_{\mathrm{IS}}(x) - P_\mu \cos\theta F_{\mathrm{AS}}(x))$$

$$F_{\mathrm{IS}} = x(1-x) + \frac{2}{9}\rho(4x^2 - 3x - x_0^2) + \eta x_0(1-x)$$

$$F_{\mathrm{AS}} = \frac{1}{3}\xi\sqrt{x^2 - x_0^2}\left[1 - x + \frac{2}{3}\delta(4x - 4 + \sqrt{1 - x_0^2}\right]$$

SM Michel Parameters values:

$$\rho = 3/4$$

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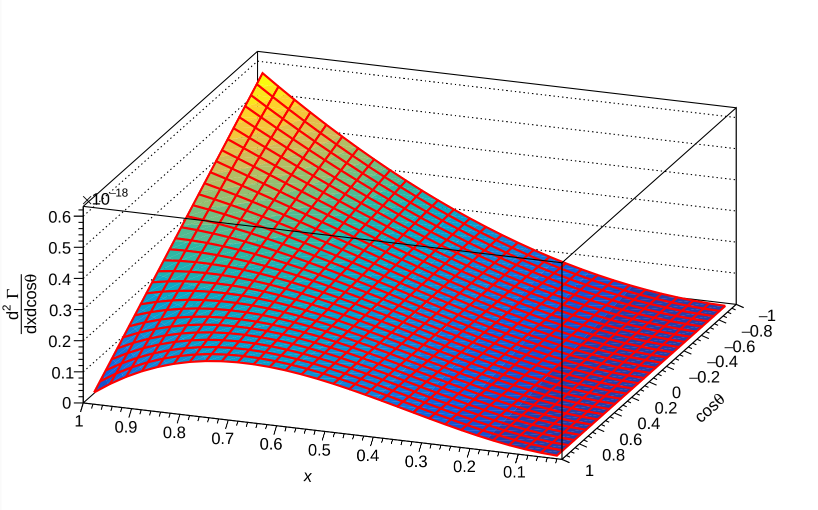

Michel Parameters

- Sensitive to interactions besides V-A
- Experimental results [4]:

$$\rho = 0.74979 \pm 0.00026$$
$$\eta = 0.057 \pm 0.034$$
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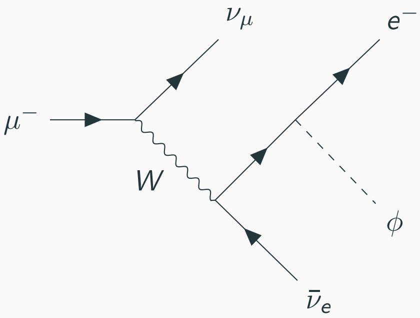

Same experimental signature as $\mu^- \to \nu_\mu \bar{\nu}_e e^-$

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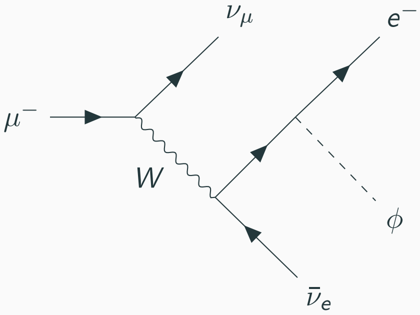

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Method

1. Generate Matrix elements and square
2. Numerically integrate phase space except E_e and $\cos\theta$
   Standard MC (e.g. MadGraph) slow for $N \sim 10^9$
   $\rightarrow$ Quadrature on GPU
3. Combine BSM and SM spectrum
4. Fit to extract Michel Parameters
5. Find coupling constants that violate experimental values

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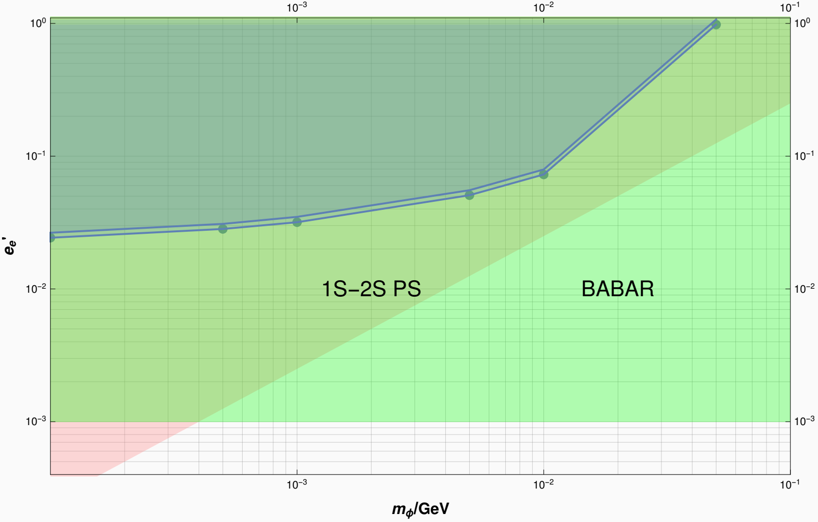
Scalar to Electron



Scalar to Muon

- Muon specific scalar mediator badly motivated
  $\rightarrow$ no existing bounds
- Better motivated: Mass-hierarchical couplings

$$\frac{e'_e}{e'_\mu} = \frac{m_e}{m_\mu}$$

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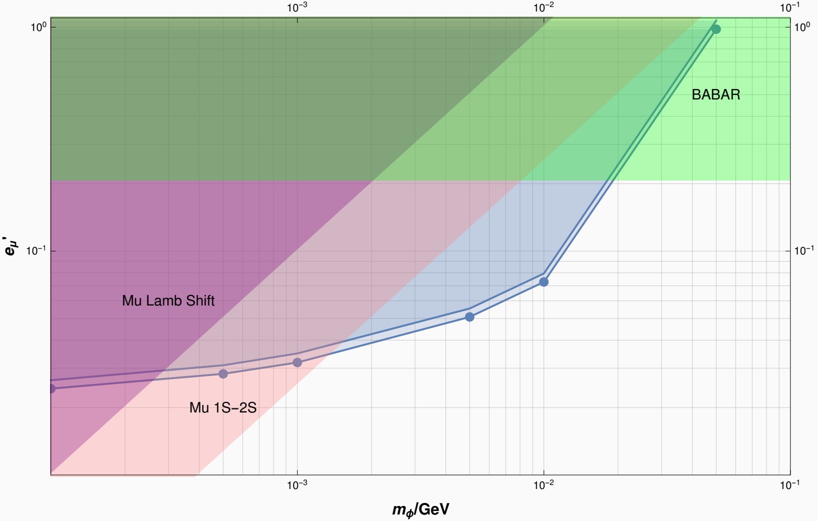

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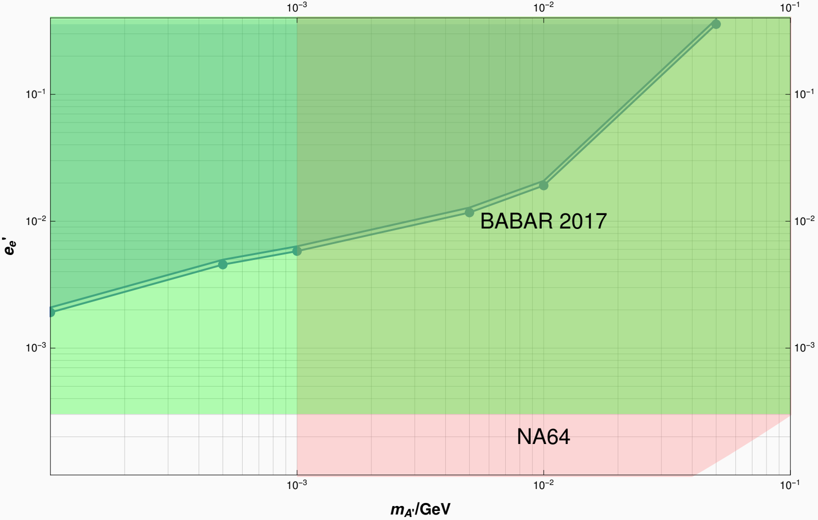

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- Muon-specific difficult to implement
  $\rightarrow$ scarce literature
- Use least constrained model:
  Gauged $L_{\mu-\tau}$
- Additionally constrained by 1 loop kinetic mixing

$$\epsilon = \frac{ee'_\mu}{12\pi^2} \ln \frac{m_\mu^2}{m_\tau^2}$$

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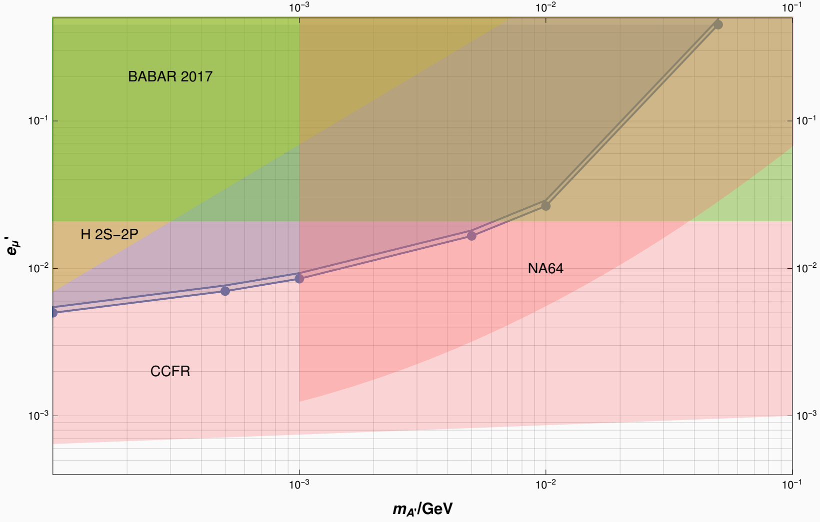

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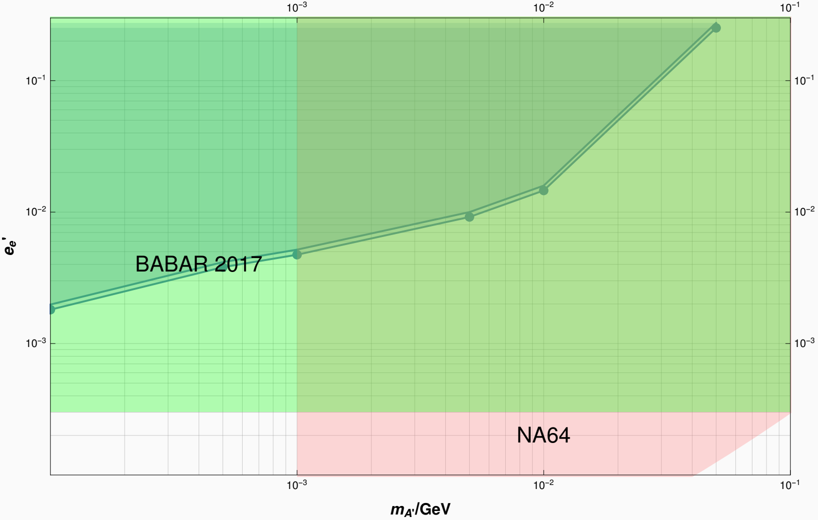
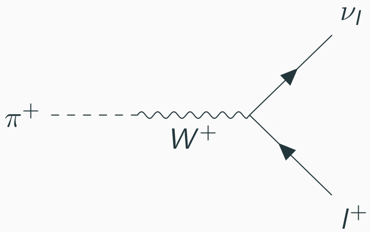


Standard Model Pion Decay



$$\mathcal{L} \supset -g\frac{F_0 V_{ud}}{2}\left[W_\nu^+ \partial^\nu \pi^- + W_\nu^- \partial^\nu \pi^+\right]$$

$$\Gamma = \frac{G_f^2 |V_{ud}|^2}{4\pi} F_0^2 m_\pi m_l^2 \left(1 - \frac{m_l^2}{m_\pi^2}\right)^2$$

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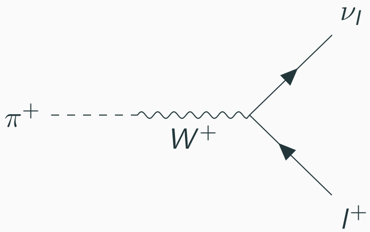

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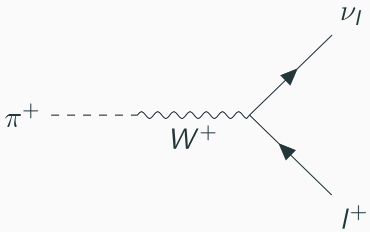

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Helicity Suppression

- $\pi^+ \to e^+\nu_e$ suppressed

$$\frac{\Gamma_e}{\Gamma_\mu} \sim \frac{m_e^2}{m_\mu^2}$$

- Full standard model prediction [5]:

$$R^\pi_{e/\mu} \equiv \frac{\Gamma(e^+\nu_e(\gamma))}{\Gamma(\mu^+\nu_\mu(\gamma))} = (1.2352 \pm 0.0001) \cdot 10^{-4}$$

- Sensitive to coupling between scalar and electron

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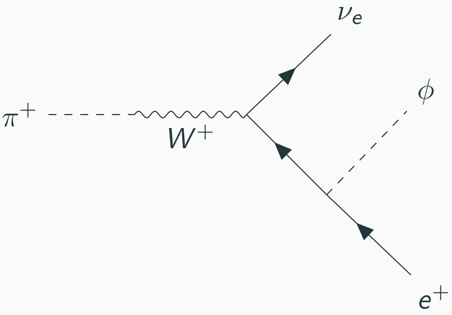

Method II

- Calculate width

$$\Gamma(e^+\nu_e\phi) = \frac{e_e'^2 G_f^2 F_0^2 V_{ud}^2 m_\pi^3}{384\pi^3} \times \left(1 - \left(\frac{m_\phi}{m_\pi}\right)^6 + \left(\frac{m_\phi}{m_\pi}\right)^2 \left(9 + 6\ln\left(\frac{m_\phi^2}{m_\pi^2}\right)\right) - \left(\frac{m_\phi}{m_\pi}\right)^4 \left(9 - 6\ln\left(\frac{m_\phi^2}{m_\pi^2}\right)\right)\right)$$

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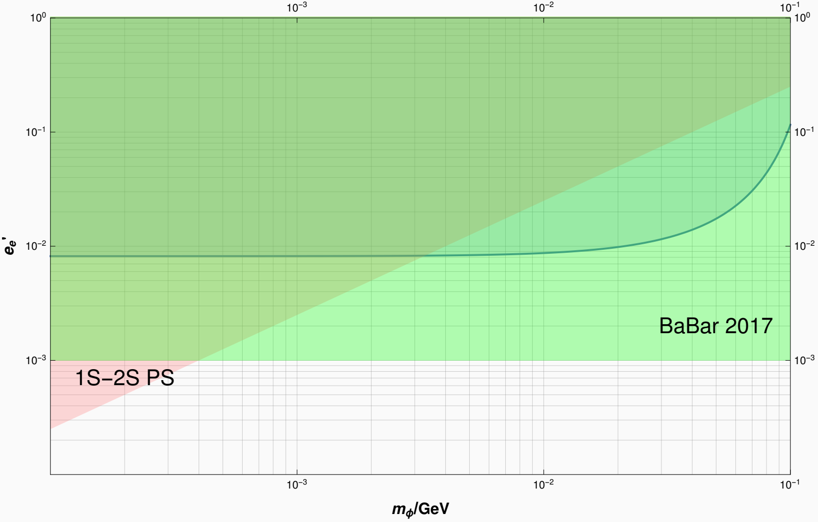
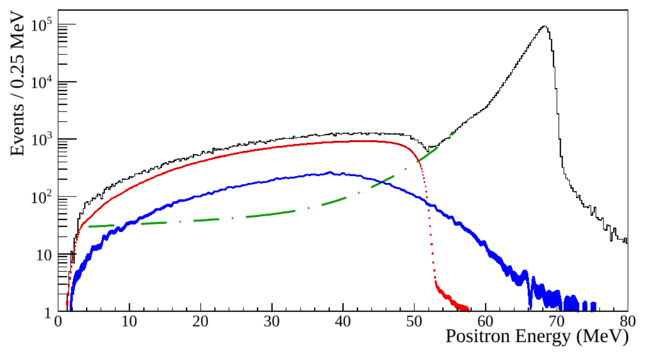


PIENU

PIENU: Search for heavy neutrino [7]



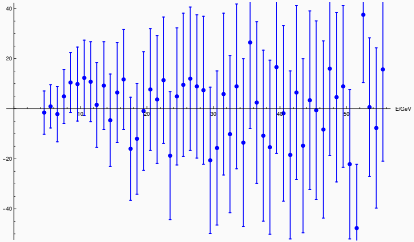
Decay in flight (blue)

$\pi^+ \to e^+\nu_e$ (green)

$\pi^+ \to \mu^+ + \nu_\mu \to e^+\nu_e + \nu_\mu$ (red)

PIENU

- Subtract background



- Additional peaks → heavy neutrinos
- Similar to additional couplings

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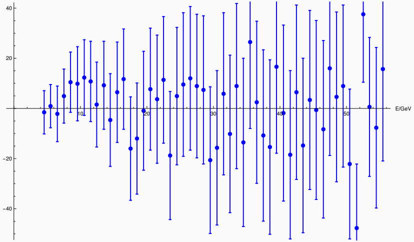

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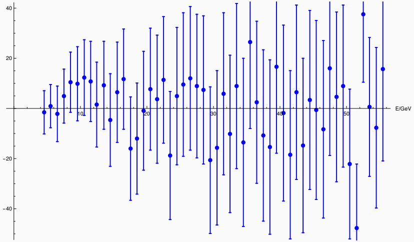

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Method III

1. Generate MC spectrum
2. Compare to PIENU data
3. Carry out χ^2-test
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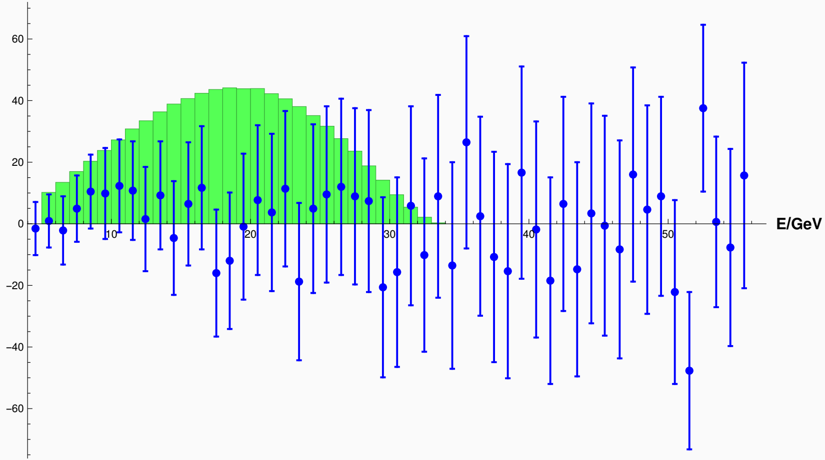
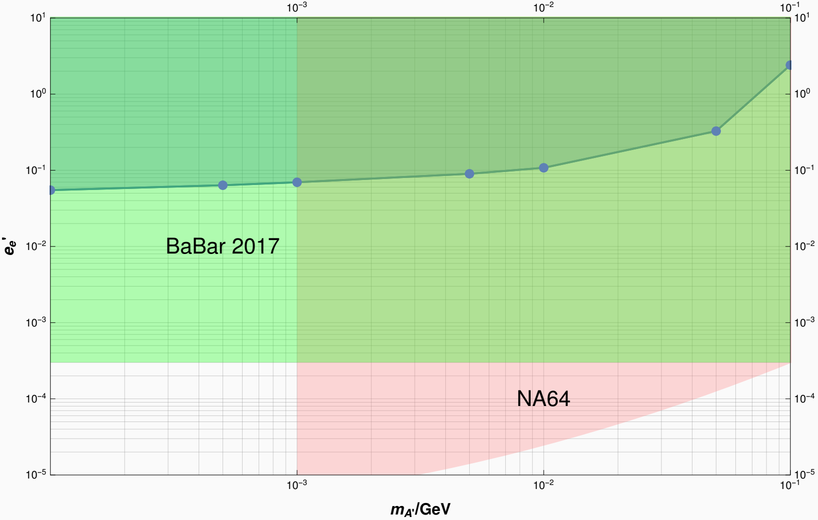
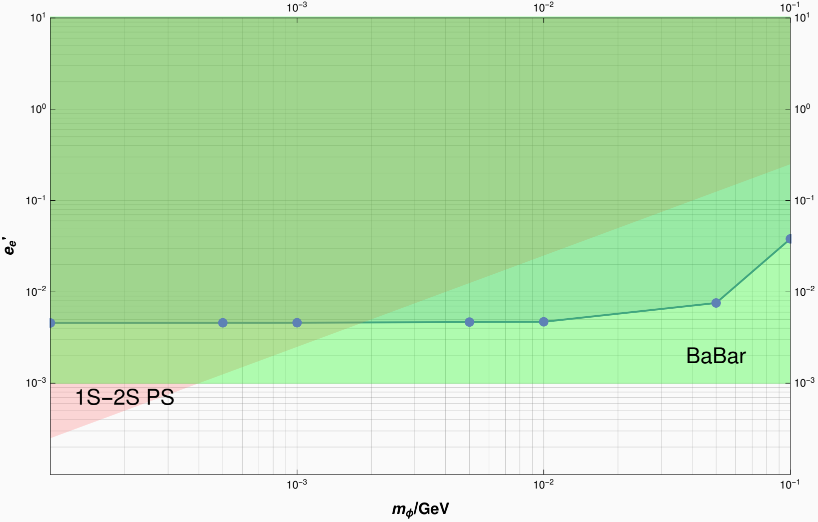
Example 90% C.L bound



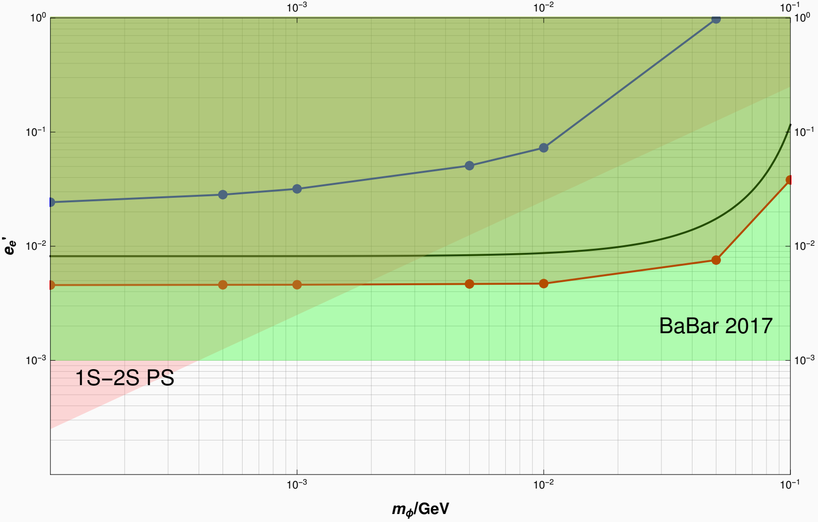
Vector to Electron



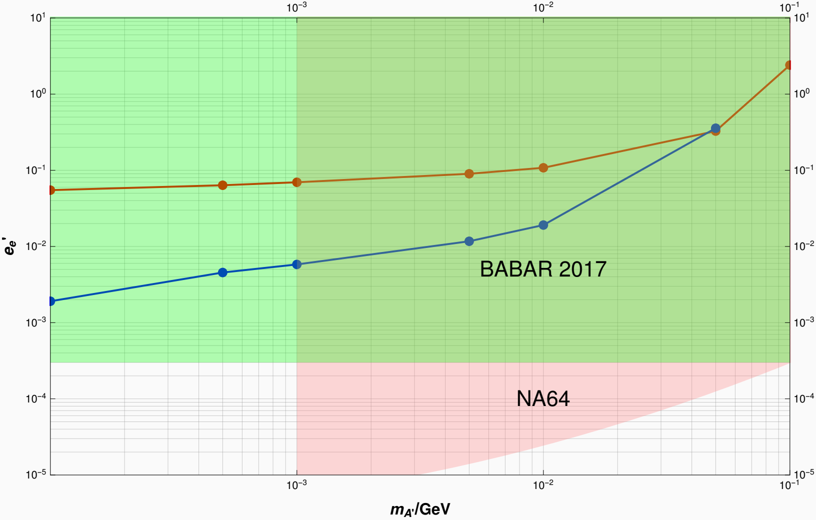
Scalar to Electron



Combined Scalar to Electron



Combined Vector to Electron



Conclusion

Muon decay

- Only scalar-muon coupling bound competitive for $m_\phi = 1 - 10\text{MeV}$
- Others more competitive if Michel parameters $\sim$two orders of magnitude more precise

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Literature

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