Lepton Flavor Portal Matter

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2211.09918 [PLB 841 (2023) 137931], 2303.12983

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THE UNIVERSITY of WISCONSIN MADISON

Introduction/Motivation

Dark matter: gravitationally confirmed by a range of astrophysical observations,

but wide range of possibilities for its properties (mass and couplings)

Landscape of DM candidates has exploded in the past decade+

(see e.g. K. Zurek's talk at Dark Matter 2023 for an excellent recent review)

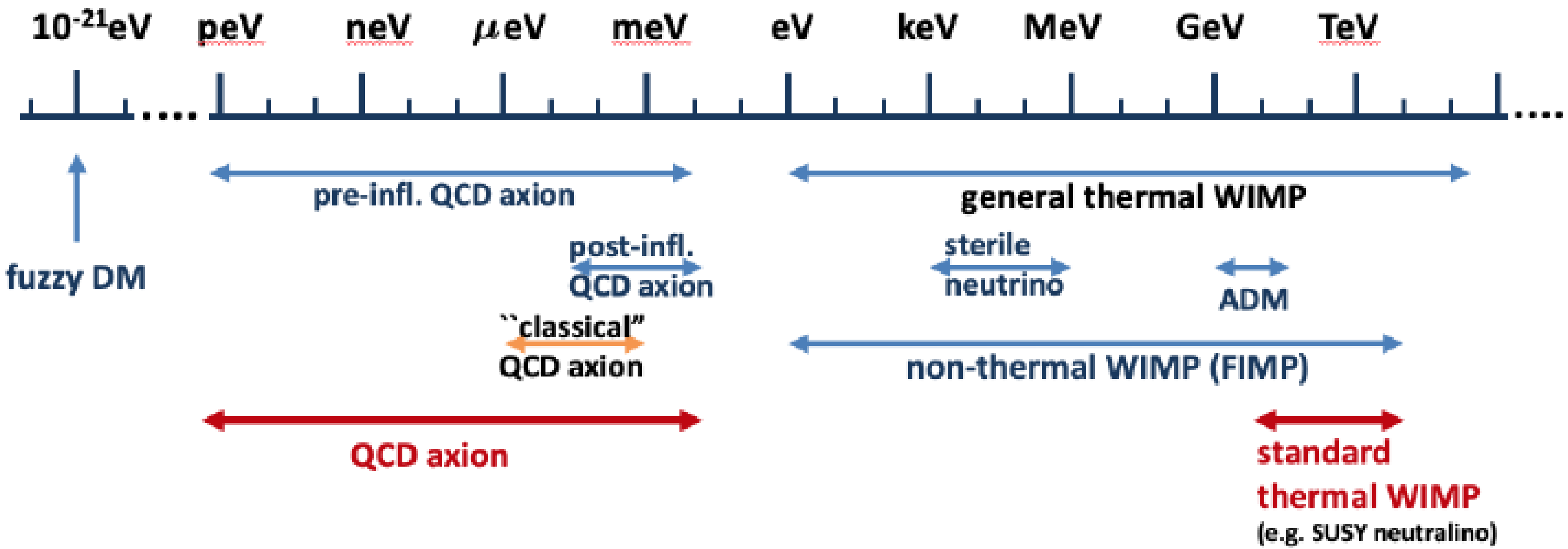
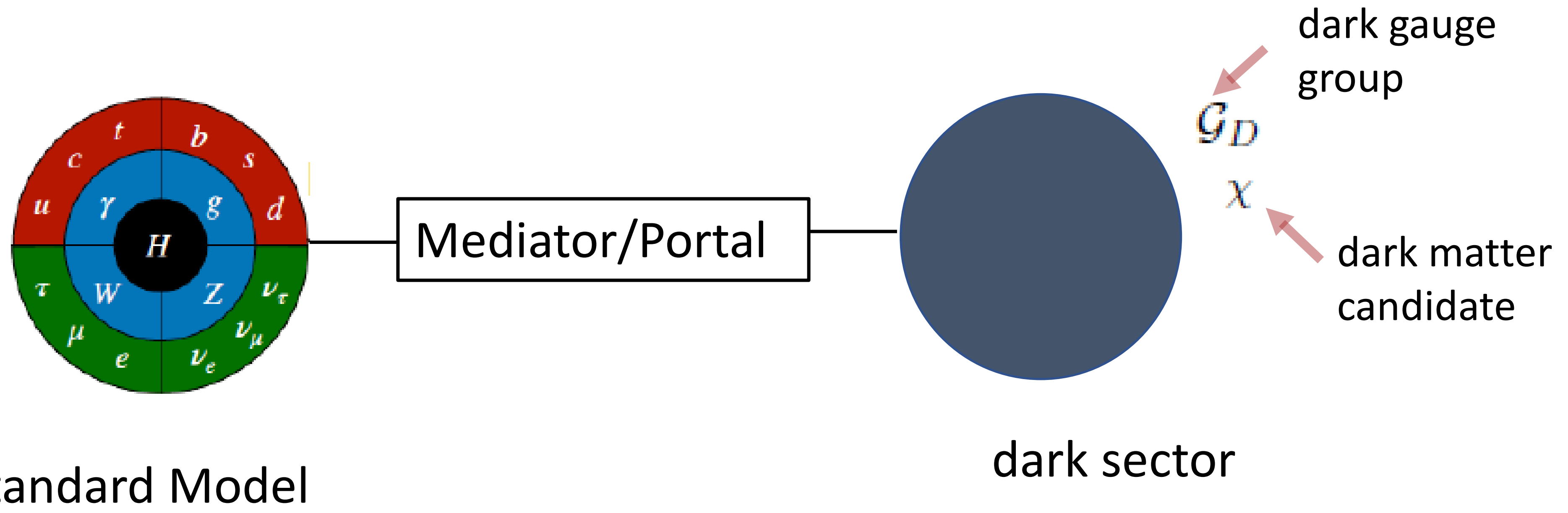


Image credit:
APPEC Rept. (2020)

many reviews: see e.g. Battaglieri et al. ’17, Gori et. al, Snowmass 2021 report

Here, interested in a particular category of theories:

“dark sector” paradigm with light DM, light mediator



Many possible “portals” for interaction with SM (Higgs, gauge, neutrino,…)

vast literature: see e.g. Pospelov et al. ’08, Davoudiasl et al. ’12, Curtin et al. ’14, …

Focus here on a certain sub-category:

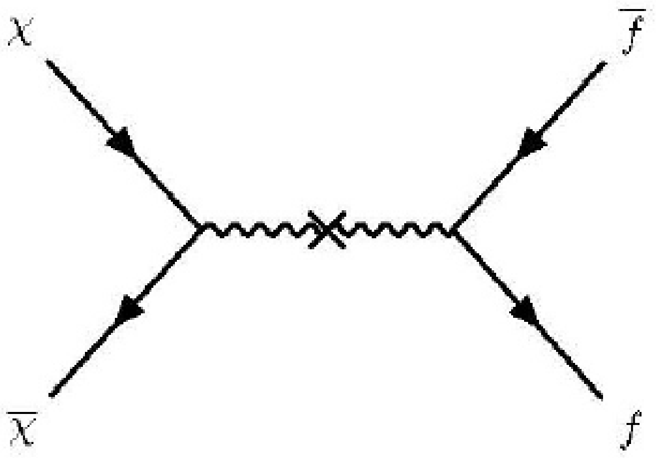
Vector portal/kinetic mixing models

Dark gauge group:

$$U(1)_D \leq \mathcal{G}_D$$

SM uncharged wrt $U(1)_D$

Kinetic mixing portal: $\frac{\epsilon}{2c_w} B_{\mu\nu} A_D^{\mu\nu}$

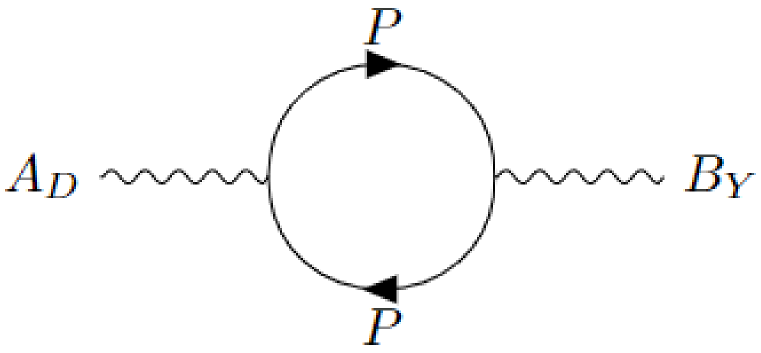


Via KM, SM develops couplings $\sim \epsilon e Q$ to dark photon

can obtain correct DM relic abundance for $m_\chi, m_{A_D} \sim 0.1 - 1$ GeV, $\epsilon \sim 10^{-(3-5)}$

Model-building framework: origin of KM parameter ϵ

Loop-generated due to new states:



"portal matter"

$\downarrow$

heavy particles charged under SM hypercharge and $U(1)_D$

$$\epsilon = c_W \frac{g_D g_Y}{12\pi^2} \sum_i Q_{Y_i} Q_{D_i} \log\left(\frac{m_i^2}{\mu^2}\right)$$

finite and calculable ϵ $\longrightarrow$ $\sum_i Q_{Y_i} Q_{D_i} = 0$

Holdom 1986,...

Portal Matter Theory/Phenomenology Basics

interested in fermionic PM light enough to be probed at current/near-future expts

direct searches, precision EW, Higgs constraints $h_{\mathrm{SM}} \to gg, \gamma\gamma$

$\Longrightarrow$ PM should be vectorlike under SM and $U(1)_D$

most straightforward option for decay:

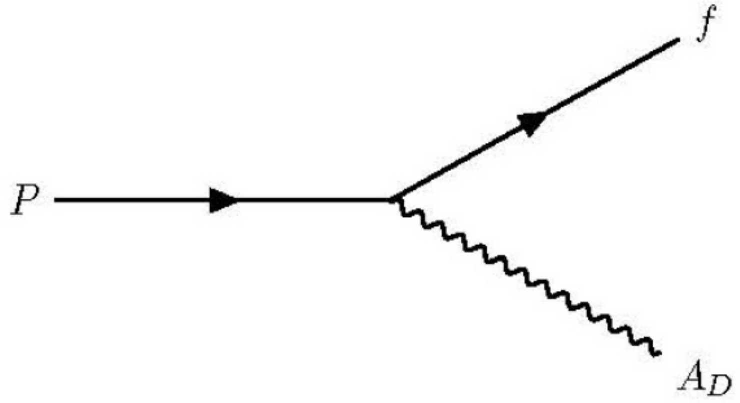
$\Longrightarrow$ PM should have identical SM quantum numbers as some SM matter field(s) and mix with them

Distinctive phenomenological signatures!

decays to (highly boosted) SM fermion/jet

+dark photon or dark Higgs

(compare usual vectorlike fermion case)



Portal Matter Model-Building Framework

minimal scenarios: $U(1)_D$

one dark Higgs h_D , single PM vectorlike pair

VLL: $E^{\pm}, L^{\pm}$ VLQ: $T^{\pm}, B^{\pm}, Q^{\pm}$

Rizzo 1810.07531
Kim et al. 1904.05893
Carvunis et al. 2209.14305

more involved models:

extended dark sector gauge group $\mathcal{G}_D \longrightarrow U(1)_D$

extended fermion PM and scalar content

Rizzo 2206.09814, 2209.00688, 2302.12698

many BSM options:

GUT paradigm, extra dimensions...

Rizzo, Reuter 1909.09160, 2011.03529;
Rizzo, Wojcik 2302.12698; Wojcik 2205.11545

This talk:

Lepton portal matter and muon *g-2*

construct minimal workable lepton PM scenario that can accommodate $\Delta a_\mu = (g_\mu - 2)/2$

→ effect dominated by PM, insensitive to DM details

Lepton **flavor** portal matter

extension with $\mathcal{G}_D = SU(2)_A \times SU(2)_B$ (w/partial $\mu - \tau$ flavor symmetry)

→ can accommodate muon *g-2*, rich collider phenomenology

Muon anomalous magnetic dipole moment

Current discrepancy: (4.2 sigma)

$$\Delta a_\mu = a_\mu^{\exp} - a_\mu^{\mathrm{SM}} = (251 \pm 59) \times 10^{-11}$$

Abi et al. (Muon g-2), PRL 126, 141801 (2021)

Bennett et al. (Muon g-2), PRD 73, 072003 (2006)

Aoyama et al., Phys. Rept. 887, 1 (2020)

Might be due to errors in calculation of hadronic contributions…

See e.g. Borsanyi et. al, Nature 593, 51 (2021)

Might be due to physics beyond the SM!

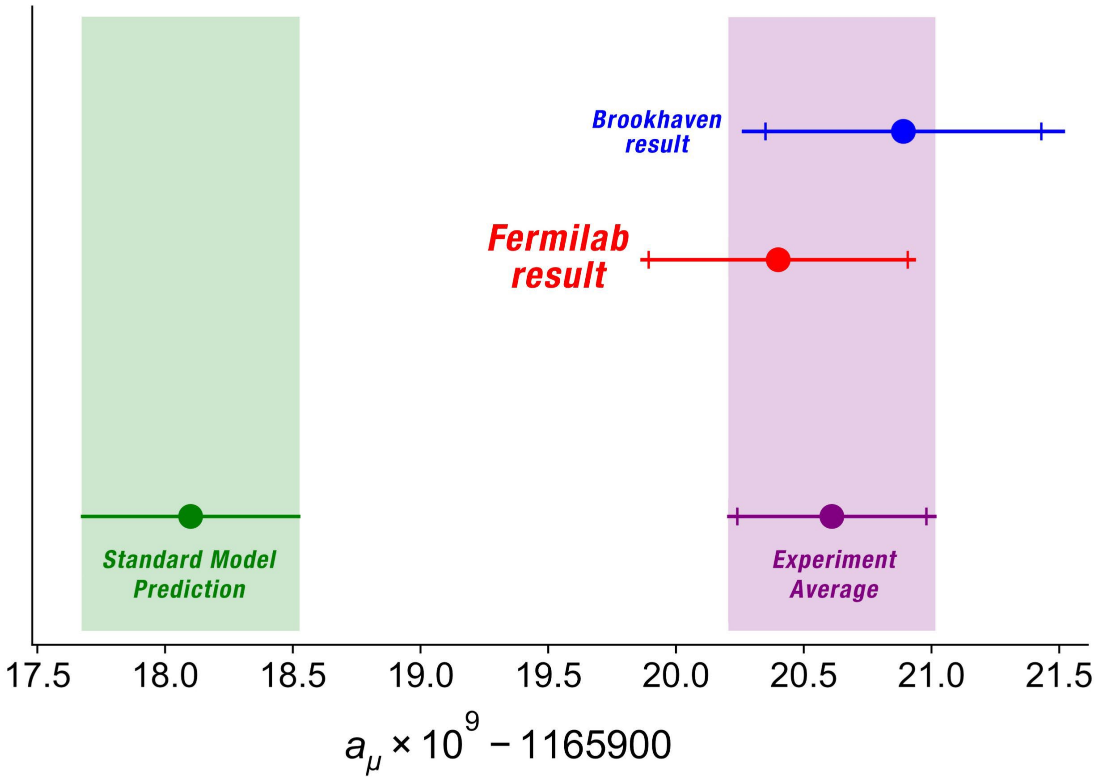


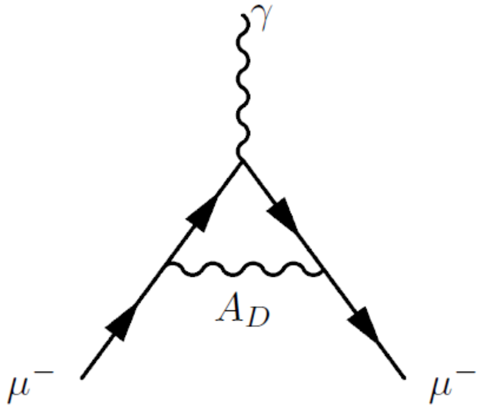
Image credit: R. Postel, Fermilab/Muon g-2 collaboration

Dark photon models and muon *g-2*

minimal scenarios: too small!

(i) dark photon, no PM mixed with muon

(vector coupling, small KM) $\sim \epsilon^2$



Davoudiasl et al. 1402.3620,...

(ii) mix muon with single lepton PM pair $E^{\pm}$

Rizzo 1810.07531,...

Field	$SU(2)_L \times U(1)_Y$	Q_D
$l_L = (\nu_L^{\mu}, \mu_L)^T$	$\left(\mathbf{2}, -\frac{1}{2}\right)$	0
μ_R	$(\mathbf{1}, -1)$	0
$E^{\pm}_{L,R}$	$(\mathbf{1}, -1)$	± 1
$S = v_S + h_D/\sqrt{2}$	$(\mathbf{1}, 0)$	$+1$

$$y_\mu \bar{l}_L H \mu_R + y_E^+ \bar{E}_L^+ S \mu_R + y_E^- \bar{E}_L^- S^\dagger \mu_R$$
$$+ M_E^+ \bar{E}_L^+ E_R^+ + M_E^- \bar{E}_L^- E_R^- + h.c.$$

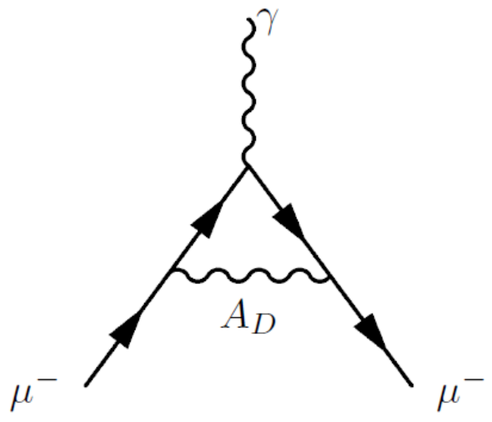
Now several new contributions...

Now both vector and axial vector couplings of muon to dark photon…

$$-e\epsilon\bar{\mu}\gamma_\mu(1-y-y\gamma_5)\mu A_D^\mu \qquad y \sim \left(\frac{g_D}{e\epsilon}\right)\left(\frac{(y_E^+)^2 v_s^2}{(M_E^+)^2} - \frac{(y_E^-)^2 v_s^2}{(M_E^-)^2}\right)$$

$$|y| \sim 0.01 - 0.5$$

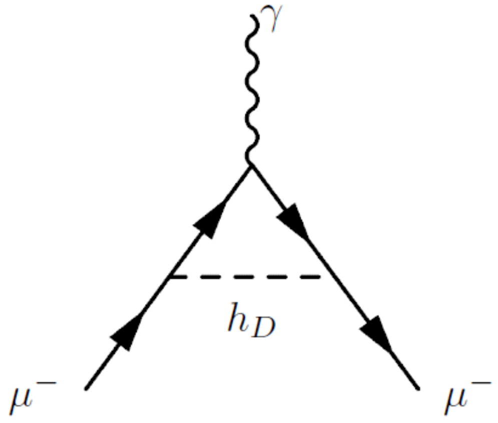
$$\Delta a_\mu^{(A_D^{(1)})} \sim 10^{-11}\left(\frac{\epsilon}{10^{-4}}\right)^2 R(y, m_{A_D})$$



+ scalar and gauge boson contributions with PM on internal line…

$$\Delta a_\mu^{(h_D)} \sim 10^{-10} \sum_{i=E^+,E^-} \left(\frac{200\ \text{GeV}}{m_i}\right)^2$$

$$\Delta a_\mu^{(A_D^{(2)})} \sim -(2\times 10^{-4})\left(\frac{g_D}{0.1}\right)^2\left(\frac{100\ MeV}{m_{A_D}}\right)^2 \sum_{i=E^+,E^-} \frac{y_i^2 v_s^2}{m_i^2}$$



still too small to accommodate the muon *g-2* anomaly

Rizzo 1810.07531

A minimal workable framework

Wojcik, LE, Eu, Ximenes 2211.09918

Issue – need to couple new physics to **both** chiralities of the muon!

Field	$SU(2)_L \times U(1)_Y$	Q_D
$\boldsymbol{l_L} = \left(\nu_L^\mu, \mu_L\right)^T$	$\left(\mathbf{2}, -\frac{1}{2}\right)$	0
μ_R	$(\mathbf{1}, -1)$	0
$\boldsymbol{L^\pm_{L,R}} = \left(N^\pm_{L,R}, L^\pm_{L,R}\right)^T$	$\left(\mathbf{2}, -\frac{1}{2}\right)$	± 1
$E^\pm_{L,R}$	$(\mathbf{1}, -1)$	± 1
$S = v_S + h_D/\sqrt{2}$	$(\mathbf{1}, 0)$	$+1$

$$
\begin{aligned}
\mathcal{L}_{\mathrm{Y}} \supset & -y_\mu \bar{l}_L H \mu_R - y_L^+ \bar{l}_L S^\dagger L_R^+ - y_L^- \bar{l}_L S L_R^- - y_E^+ \overline{E}_L^+ S \mu_R - y_E^- \overline{E}_L^- S^\dagger \mu_R \\
& - y_{LE}^+ \overline{L}_L^+ H E_R^+ - y_{EL}^+ \overline{E}_L^+ H^\dagger L_R^+ - y_{LE}^- \overline{L}_L^- H E_R^- - y_{EL}^- \overline{E}_L^- H^\dagger L_R^- \\
& - M_L^+ \overline{L}_L^+ L_R^+ - M_E^+ \overline{E}_L^+ E_R^+ - M_L^- \overline{L}_L^- L_R^- - M_E^- \overline{E}_L^- E_R^- + h.c.,
\end{aligned}
$$

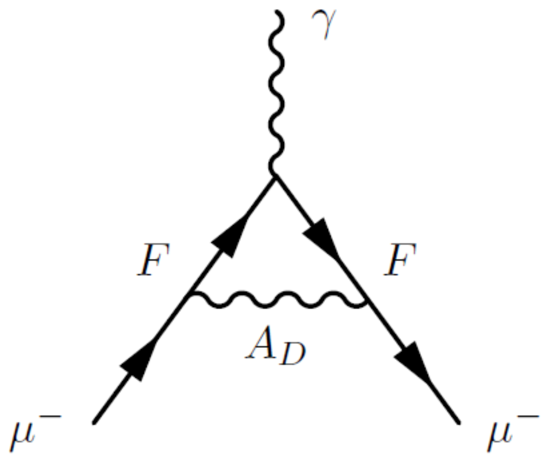
$$
\begin{pmatrix} \bar{\mu}_L & \bar{L}_L^+ & \bar{E}_L^+ & \cdots \end{pmatrix}
\begin{pmatrix}
m_\mu & y_L^+ \frac{v_s}{\sqrt{2}} & 0 & \\
0 & M_L^+ & e^{i\phi_{LE}^+} \frac{y_{LE}^+}{y_\mu} m_\mu & \vdots \\
y_E^+ \frac{v_s}{\sqrt{2}} & e^{i\phi_{EL}^+} \frac{y_{EL}^+}{y_\mu} m_\mu & M_E^+ & \\
 & \cdots & & \ddots
\end{pmatrix}
\begin{pmatrix} \mu_R \\ L_R^+ \\ E_R^+ \\ \vdots \end{pmatrix}
$$

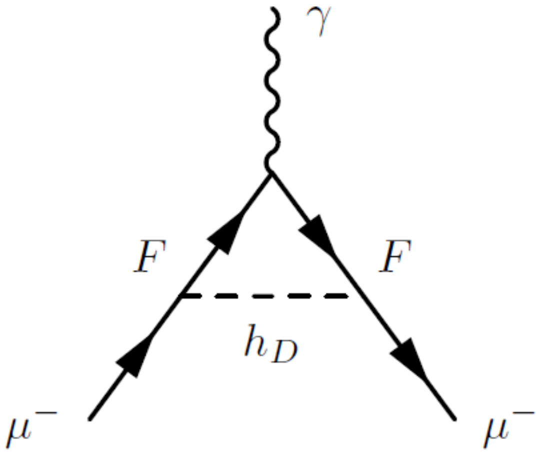
Now several chirality-flipping masses: $m_\mu \quad e^{i\phi_{LE}^\pm} \frac{y_{LE}^\pm}{y_\mu} m_\mu \quad e^{i\phi_{EL}^\pm} \frac{y_{EL}^\pm}{y_\mu} m_\mu$

Chirally-enhanced (dominant) contribution:

$$\Delta a_\mu \sim \left(\frac{c_L c_R}{24\pi^2}\frac{m_F}{m_\mu}\right)\left(\frac{m_\mu}{M_{\rm NP}}\right)^2$$

$$\Delta a_\mu \approx -\frac{m_\mu}{16\pi^2}\sum_{i=+,-}\frac{y_L^i y_E^i}{M_L^i M_E^i}\frac{y_{LE}^i}{y_\mu}\cos\phi_{LE}^i$$





Note:

$y_{EL}^{\pm}$, $y_{LE}^{\pm}$ can be significantly larger than $y_\mu \sim 10^{-4}$

phases (here just relative signs) crucially important for achieving the right sign of the effect

Light dark Higgs + dark photon: no dependence on DM model parameters

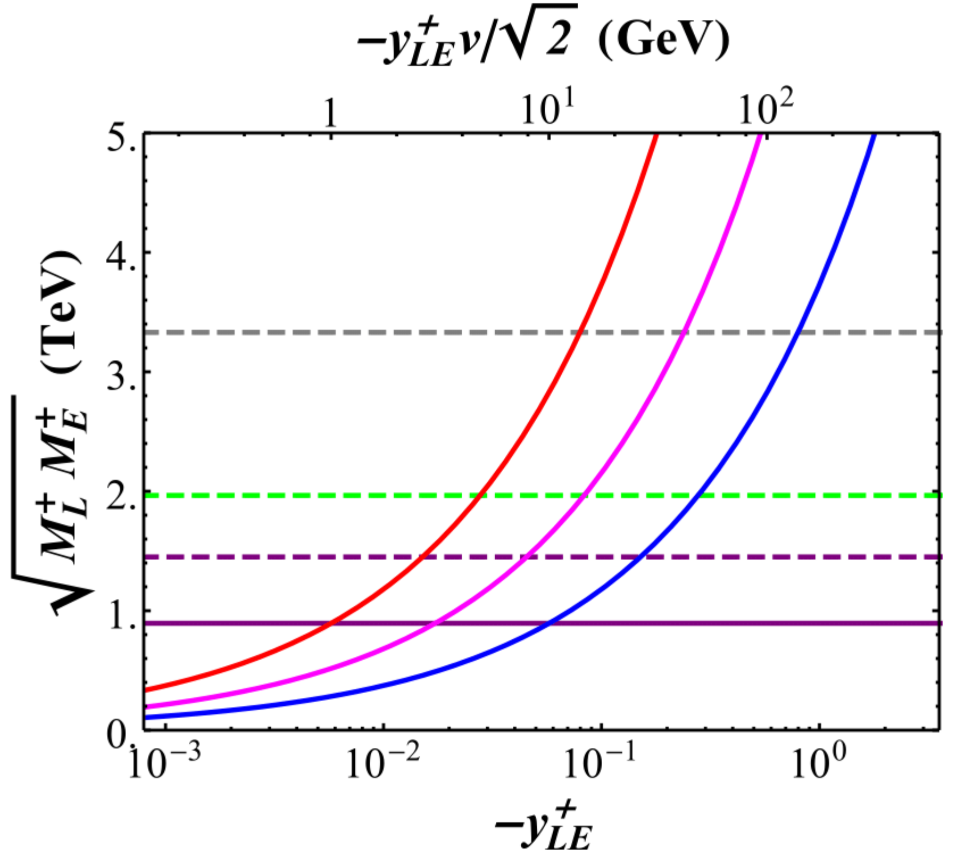
$\longrightarrow$ entirely a PM effect!

$$\Delta a_\mu \approx -\Delta a_\mu^{(\mathrm{obs})} \left(\frac{y_{LE}^{+}/y_\mu}{36}\right)\left(\frac{1\ \mathrm{TeV}}{M_L^{+}/y_L^{+}}\right)\left(\frac{1\ \mathrm{TeV}}{M_E^{+}/y_E^{+}}\right)$$

$\sqrt{M_L^+ M_E^+}$ required to obtain Δa_μ for

$y_L^+ y_E^+ = 0.3, 1, 3$, with LHC constraints

(HL-LHC, HE-LHC, *hh*-FCC) on M_E^+



Δa_μ can be accommodated for

$y_{LE}^{\pm}/y_\mu \sim O(10) \quad M_{L,E}^{\pm} \sim O(\mathrm{TeV})$

Note: same mechanism as Carcamo Hernandez et al. 1910.10734,

but very different parameter space constraints due to $M_{Z'} \sim \mathrm{TeV}$

Constraining the model:

At LHC: $M^{\pm}_{L,E}$: PM decays – repurpose LHC slepton searches

$$M^{\pm}_{E} \geq 895 \text{ GeV}, \; M^{\pm}_{L} \geq 1050 \text{ GeV}$$

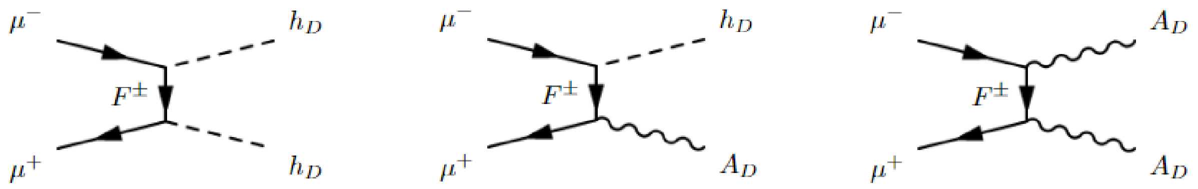
$y^{\pm}_{E}, y^{\pm}_{L}, y^{\pm}_{LE}$: perturbative unitarity

can do better at a (multi-TeV) muon collider:

probe PM masses up to $\sqrt{s}/2$

$y^{\pm}_{E}, y^{\pm}_{L}$ constrained by monophoton searches

$y^{\pm}_{LE}$ more challenging – only enters in PM decays to other PM



Summary and next steps

achieved a minimal workable lepton PM model that can accommodate Δa_μ

for $y_E^\pm, y_L^\pm \sim O(1)$ and TeV-scale PM masses, require $|y_{LE}^\pm| v \sim O(\text{few GeV})$

$\Rightarrow$ perhaps suggestive of $y_{LE}^\pm \sim y_\tau$

Extension to non-Abelian dark gauge group $\Rightarrow$

finite and calculable kinetic mixing parameter ϵ

origin of $U(1)_D$ charge quantization

origin of PM field content and mixing with muon

(partial) $\mu - \tau$ flavor symmetry (start of framework for lepton flavor mixing)

Lepton Flavor Portal Matter Model

Wojcik, LE, Eu, Ximenes 2303.12983

Choice of non-Abelian semi-simple $\mathcal{G}_D = SU(2)_A \times SU(2)_B$

Desired dark gauge symmetry breaking pattern:

$$SU(2)_A \times SU(2)_B \longrightarrow U(1)_D \longrightarrow \text{nothing}$$

achieved via dark Higgs fields Φ (bi-doublet) $\langle \Phi \rangle \sim \text{TeV}$

Δ_A, Δ_B (triplets) $\langle \Delta_A, \Delta_B \rangle \sim \text{GeV}$

will add here dark global symmetry Z_2 Φ (even) $\Delta_{A,B}$ (odd)

$$\Longrightarrow \quad SU(2)_A \times SU(2)_B \times Z_2 \longrightarrow U(1)_D \times Z_2 \longrightarrow Z_2'$$

Fermion and scalar field content

Fields	$SU(2)_L \times U(1)_Y$	$SU(2)_A$	$SU(2)_B$	Z_2
L_L, e_R	$\left(\mathbf{2}, -\frac{1}{2}\right), (\mathbf{1}, -1)$	$\mathbf{1}$	$\mathbf{1}$	$+1$
Ψ_L, Ψ_R	$\left(\mathbf{2}, -\frac{1}{2}\right), (\mathbf{1}, -1)$	$\mathbf{2}$	$\mathbf{2}$	$+1$
V_L, V_R	$(\mathbf{1}, -1), \left(\mathbf{2}, -\frac{1}{2}\right)$	$\mathbf{1}$	$\mathbf{3}$	$+1$
S_L, S_R	$\left(\mathbf{2}, -\frac{1}{2}\right), (\mathbf{1}, -1)$	$\mathbf{1}$	$\mathbf{1}$	-1
$\Phi \sim \mathrm{TeV}$	$(\mathbf{1}, 0)$	$\mathbf{2}$	$\mathbf{2}$	$+1$
$\Delta_A \sim \mathrm{GeV}$	$(\mathbf{1}, 0)$	$\mathbf{3}$	$\mathbf{1}$	-1
$\Delta_B \sim \mathrm{GeV}$	$(\mathbf{1}, 0)$	$\mathbf{1}$	$\mathbf{3}$	-1
$H \sim 100\ \mathrm{GeV}$	$\left(\mathbf{2}, \frac{1}{2}\right)$	$\mathbf{1}$	$\mathbf{1}$	$+1$

anomaly-free

finite, calculable ϵ

$SU(2)_A \times SU(2)_B \times Z_2$ singlets:

- 1 SM lepton family
  (identified with electron)
- SM Higgs H

$SU(2)_A \times SU(2)_B \times Z_2$ charged:

- 2 SM lepton families
- dark photon, dark Higgs
- PM, new gauge + scalar bosons

Gauge Symmetry Breaking and Scalar Sector

Scalar potential** $\longrightarrow$ $V = V_{\rm SM}(H) + V(\Phi, \Delta_{A,B})$

$$
\begin{aligned}
V(\Phi, \Delta_{A,B}) = & -\mu_1^2 \,\mathrm{Tr}(\Phi^\dagger \Phi) - \frac{\mu_2^2}{2}\left[\mathrm{Tr}\left(\widetilde{\Phi}^\dagger \Phi\right) + \mathrm{h.c.}\right] - \mu_3^2 \,\mathrm{Tr}(\Delta_A^2) - \mu_4^2 \,\mathrm{Tr}(\Delta_B^2) \\
& + \lambda_1 \,\mathrm{Tr}(\Phi^\dagger \Phi)^2 + \frac{\lambda_2}{2}\left[\mathrm{Tr}\left(\widetilde{\Phi}^\dagger \Phi\right)^2 + \mathrm{h.c.}\right] + \frac{\lambda_3}{2}\left[\mathrm{Tr}(\Phi^\dagger \Phi)\,\mathrm{Tr}\left(\widetilde{\Phi}^\dagger \Phi\right) + \mathrm{h.c.}\right] + \lambda_4 \,\mathrm{Tr}(\Delta_B^4) \qquad (4) \\
& + \lambda_5 \,\mathrm{Tr}(\Phi^\dagger \Phi)\,\mathrm{Tr}(\Delta_B^2) + \frac{\lambda_6}{2}\left[\mathrm{Tr}\left(\widetilde{\Phi}^\dagger \Phi\right)\mathrm{Tr}(\Delta_B^2) + \mathrm{h.c.}\right] + \lambda_7 \left|\mathrm{Tr}\left(\widetilde{\Phi}^\dagger \Phi\right)\right|^2 + \lambda_8 \,\mathrm{Tr}(\Phi^\dagger \Delta_A \Phi \Delta_B) \\
& + \frac{\lambda_9}{2}\left[\mathrm{Tr}\left(\widetilde{\Phi}^\dagger \Delta_A \Phi \Delta_B\right) + \mathrm{h.c.}\right] + \lambda_{10} \,\mathrm{Tr}(\Delta_A^4) + \lambda_{11} \,\mathrm{Tr}(\Phi^\dagger \Phi)\,\mathrm{Tr}(\Delta_A^2) \\
& + \frac{\lambda_{12}}{2}\left[\mathrm{Tr}\left(\widetilde{\Phi}^\dagger \Phi\right)\mathrm{Tr}(\Delta_A^2) + \mathrm{h.c.}\right] + \lambda_{13} \,\mathrm{Tr}(\Delta_A^2)\,\mathrm{Tr}(\Delta_B^2),
\end{aligned}
$$

$$\widetilde{\Phi}_{i\alpha} = -\epsilon_{ij} \Phi^{*j\beta} \epsilon_{\beta\alpha}$$

8+3+3=14 real degrees of freedom $\longrightarrow$ 6 Goldstone modes, 8 massive scalars

**ignoring Higgs portal interactions, which must be strongly suppressed due to *H* invisible width constraints (a standard issue in this class of constructions)

Wojcik, LE, Eu, Ximenes 2303.12983

Minimizing the potential:

$$\Phi = \frac{1}{2}\left(\mathrm{Re}\,\Phi_0 + i\,\mathrm{Im}\,\Phi_0\right) + \sum_{a=x,y,z} \tau_a \left(\mathrm{Re}\,\Phi_a + i\,\mathrm{Im}\,\Phi_a\right) \qquad \Delta_{A,B} = \sum_{a=x,y,z} \tau_a \Delta^a_{A,B} \qquad \tau_a \equiv \sigma_a/2$$

$SU(2)_A \times SU(2)_B$ rotations: set Φ vev diagonal and real

$$\langle \mathrm{Re}\,\Phi_0 \rangle = v_\Phi(\cos\theta_\Phi + \sin\theta_\Phi) \qquad \langle \mathrm{Re}\,\Phi_z \rangle = v_\Phi(\cos\theta_\Phi - \sin\theta_\Phi) \qquad 0 \le \theta_\Phi \le \pi$$

$$\langle \Delta^x_A \rangle = r_\Delta v_\Phi s_{\theta_\Delta} c_{\phi_A} s_{\theta_A} \quad \langle \Delta^y_A \rangle = r_\Delta v_\Phi s_{\theta_\Delta} s_{\phi_A} s_{\theta_A} \quad \langle \Delta^z_A \rangle = r_\Delta v_\Phi s_{\theta_\Delta} c_{\theta_A}$$

$$\langle \Delta^x_B \rangle = r_\Delta v_\Phi c_{\theta_\Delta} c_{\phi_B} s_{\theta_B} \quad \langle \Delta^y_B \rangle = r_\Delta v_\Phi c_{\theta_\Delta} s_{\phi_B} s_{\theta_B} \quad \langle \Delta^z_B \rangle = r_\Delta v_\Phi c_{\theta_\Delta} c_{\theta_B}$$

$0 \le \theta_\Delta \le \pi/2$

$0 \le \theta_{A,B} \le \pi$

$0 \le \phi_{A,B} \le 2\pi$

3 inequivalent classes of vacua, all CP-preserving:

		preserved subgroup
(i)	$r_\Delta = 0$	$U(1)_D \times Z_2$
(ii)	$r_\Delta \neq 0,\ 0 < \theta_\Delta < \pi/2,\ \theta_{A,B} = 0$	$U(1)_D \rightarrow D_A(\hat{z},\phi) \times D_B(\hat{z},\phi)$
→ (iii)	$r_\Delta \neq 0,\ 0 < \theta_\Delta < \pi/2,\ \theta_{A,B} = \pi/2$	$Z_2' \rightarrow D_A(\hat{z},\pi) \times D_B(\hat{z},\pi) \times Z_2$

$\phi_A = \phi_B = 0.$ (simplicity)

need both triplets!!

$$\langle \Phi \rangle = v_\Phi \begin{pmatrix} \cos\theta_\Phi & 0 \\ 0 & \sin\theta_\Phi \end{pmatrix} \quad \langle \Delta_{A,B} \rangle = \begin{pmatrix} 0 & v_{\Delta_{A,B}} \\ v_{\Delta_{A,B}} & 0 \end{pmatrix}$$

$$v_\Delta = \sqrt{v_{\Delta_A}^2 + v_{\Delta_B}^2}$$

$$\tan\theta_\Delta = v_{\Delta_A}/v_{\Delta_B}$$

$$r_\Delta = v_\Delta / v_\Phi$$

$$r_\Delta \ll 1$$

Gauge boson masses:

$$e_D = g_A \cos\theta_D = g_B \sin\theta_D$$

$$Z_D = \cos\theta_D W_A^z + \sin\theta_D W_B^z \qquad M_{Z_D} = \sqrt{2} v_\Phi e_D \csc(2\theta_D)$$

$$A_D = -\sin\theta_D W_A^z + \cos\theta_D W_B^z \qquad m_{A_D} = \frac{1}{\sqrt{2}} r_\Delta \sin 2\theta_D M_{Z_D}$$

$W_{l,h}$ admixtures of $W_{A,B}^\pm$ $\quad M_{W_l} = \sin\theta_{lh} M_{Z_D} \quad M_{W_h} = \cos\theta_{lh} M_{Z_D}$

$$\cos 2\theta_{lh} = \cos 2\theta_D \sqrt{1 + \sin^2\theta_\Phi \tan^2\theta_D}$$

Gauge Bosons	Mass	Z_2'	Q_D
Z_D	$M_{Z_D} \sim \text{TeV}$	$+1$	0
$W_l^\pm$	$M_{W_l} \sim \text{TeV}$	-1	± 1
$W_h^\pm$	$M_{W_h} \sim \text{TeV}$	-1	± 1
A_D	$m_{A_D} \sim \text{GeV}$	$+1$	$*$

dark photon

Scalar masses:

8 degrees of freedom: 6 real scalars h_{1-6} 1 complex scalar $h^{\pm}$

Scalars	Mass	Z_2'	Q_D
h_1, h_2, h_4	$M_{h1,h2,h4} \sim \mathrm{TeV}$	$+1$	0
$h^{\pm}$	$M_h^{\pm} \sim \mathrm{TeV}$	$+1$	± 1
h_5, h_6	$M_{h5,h6} \sim \mathrm{TeV}$	-1	0
h_3	$m_{h3} \sim \mathrm{GeV}$	$+1$	$*$

dark Higgs → h_3

$M_{h^\pm}$ input parameter $M_{h_{1,2,4}} = r_{1,2,4} M_{h^\pm}$ $M_{h_5} = \cos\theta_M M_{h^\pm}$ $M_{h_6} = \sin\theta_M M_{h^\pm}$

$m_{h_3} = r_\Delta r_3 M_{h^\pm}$ $|c_{2\theta_M}| > |c_{2\theta_\Delta}|$ $r_i \sim O(1)$

$$h_D \equiv h_3 \approx \cos\theta_\Delta(\Delta_B^x - r_\Delta v_\Phi \cos\theta_\Delta) + \sin\theta_\Delta(\Delta_A^x - r_\Delta v_\Phi \sin\theta_\Delta)$$

positivity of scalar mass-squares ensures (iii) is a relative minimum

Fermion masses: (second and third SM generations + heavy states)

$$\begin{aligned}\mathcal{L}_Y = & y_H\left[\mathrm{Tr}\left(\overline{\Psi_L} H \Psi_R\right)+\mathrm{h.c.}\right]+y_{HV}\left[\mathrm{Tr}\left(\overline{V_L} H V_R\right)+\mathrm{h.c.}\right]+y_{HS}\left[\mathrm{Tr}\left(\overline{S_L} H S_R\right)+\mathrm{h.c.}\right] \\ & +y_P\left[\mathrm{Tr}\left(\overline{\Psi_L}\Phi V_R\right)+\mathrm{h.c.}\right]+\tilde{y}_P\left[\mathrm{Tr}\left(\overline{\Psi_L}\widetilde{\Phi} V_R\right)+\mathrm{h.c.}\right]+y_{P'}\left[\mathrm{Tr}\left(\overline{V_L}\Phi^\dagger \Psi_R\right)+\mathrm{h.c.}\right] \\ & +\tilde{y}'_P\left[\mathrm{Tr}\left(\overline{V_L}\widetilde{\Phi}^\dagger \Psi_R\right)+\mathrm{h.c.}\right]+y_{SE}\left[\mathrm{Tr}\left(\overline{V_L} S_R \Delta_B\right)+\mathrm{h.c.}\right]+y_{SL}\left[\mathrm{Tr}\left(\overline{S_L} V_R \Delta_B\right)+\mathrm{h.c.}\right]\end{aligned}$$

Fields	$SU(2)_L \times U(1)_Y$	$SU(2)_A$	$SU(2)_B$	Z_2
Ψ_L, Ψ_R	$\left(\mathbf{2}, -\frac{1}{2}\right), (\mathbf{1}, -1)$	**2**	**2**	+1
V_L, V_R	$(\mathbf{1}, -1), \left(\mathbf{2}, -\frac{1}{2}\right)$	**1**	**3**	+1
S_L, S_R	$\left(\mathbf{2}, -\frac{1}{2}\right), (\mathbf{1}, -1)$	**1**	**1**	−1

$$y_P = y_L \cos\theta_L \quad \tilde{y}_P = y_L \sin\theta_L$$
$$y'_P = y_E \cos\theta_E \quad \tilde{y}'_P = y_E \sin\theta_E$$

$$M_L^+ = v_\Phi y_L \cos(\theta_L - \theta_\Phi)$$
$$M_E^+ = v_\Phi y_E \cos(\theta_E - \theta_\Phi)$$
$$M_L^- = v_\Phi y_L \sin(\theta_L + \theta_\Phi)$$
$$M_E^- = v_\Phi y_E |\sin(\theta_E + \theta_\Phi)|$$

basis choice: $y_{L,E,SL,SE,HS} > 0 \quad c_{\theta_L-\theta_\Phi}, c_{\theta_E-\theta_\Phi}, s_{\theta_L+\theta_\Phi} > 0$

$y_H, y_{HV}, s_{\theta_E+\theta_\Phi}$ may be positive or negative (all couplings assumed to be real)

Fermion masses (continued): block diagonal form

$$Z_2' = +1 \longrightarrow \left(\Psi_{(L,R)_{11}}, \Psi_{(L,R)_{22}}, V^0_{(L,R)}\right)$$

$$M_F^{(1)} = \begin{pmatrix} \frac{y_H v}{\sqrt{2}} & 0 & M_L^+ \\ 0 & \frac{y_H v}{\sqrt{2}} & -M_L^- \\ M_E^+ & \mp M_E^- & \frac{y_{HV} v}{\sqrt{2}} \end{pmatrix}$$

$$Z_2' = -1 \longrightarrow \left(S_{(L,R)}, \Psi^+_{(L,R)}, V^+_{(L,R)}, \Psi^-_{(L,R)}, V^-_{(L,R)}\right)$$

$$M_F^{(2)} = \begin{pmatrix} \frac{y_{HS} v}{\sqrt{2}} & 0 & y_{SL}^{\Delta} r_\Delta v_\Phi & 0 & y_{SL}^{\Delta} r_\Delta v_\Phi \\ 0 & \frac{y_H v}{\sqrt{2}} & M_L^+ & 0 & 0 \\ y_{SL}^{\Delta} r_\Delta v_\Phi & M_E^+ & \frac{y_{HV} v}{\sqrt{2}} & 0 & 0 \\ 0 & 0 & 0 & \frac{y_H v}{\sqrt{2}} & M_L^- \\ y_{SL}^{\Delta} r_\Delta v_\Phi & 0 & 0 & \pm M_E^- & \frac{y_{HV} v}{\sqrt{2}} \end{pmatrix}$$

For EW vev $v \to 0$ $\longrightarrow$ one 0 eigenvalue in each block

$\downarrow$

identified with SM μ and τ

Fermion masses (continued): mass eigenstates

Fermions	Mass	Z_2'	Q_D
e_b	m_b	$+1$	0
L^0, E^0	$M_L^0, M_E^0 \sim \mathrm{TeV}$	$+1$	0
e_a	m_a	-1	0
$L^\pm, E^\pm$	$M_L^\pm, M_E^\pm \sim \mathrm{TeV}$	-1	± 1

"standard" VLL

portal matter

Scenario A

$e_b \to \tau$
$e_a \to \mu$

Scenario B

$e_b \to \mu$
$e_a \to \tau$

$$(e_a)_{L,R} \approx S_{L,R} \qquad (e_b)_{L,R} \approx \frac{1}{\sqrt{2}} \left(\frac{M^-_{L,E}}{M^0_{L,E}} (\Psi_{L,R})_{11} + \frac{M^+_{L,E}}{M^0_{L,E}} (\Psi_{L,R})_{22} \right)$$

$$M^0_{L,E} = \sqrt{((M^-_{L,E})^2 + (M^+_{L,E})^2)/2}$$

Two embeddings: whether muon has $Z_2' = -1$ (Scenario A)

or $Z_2' = +1$ (Scenario B)

Muon *g-2* in our lepton flavor PM model

Now the chirality-flipping mass terms are

$$m_a \approx \frac{y_{HS} v}{\sqrt{2}} \qquad m_b \approx O(1)\left(\frac{y_H v}{\sqrt{2}}\right) \qquad m_{HV} = \frac{y_{HV} v}{\sqrt{2}}$$

details depend on assignment of μ, τ ➡

Scenario A

$e_b \rightarrow \tau$
$e_a \rightarrow \mu$

resembles minimal workable PM model, with additional contributions (additional heavy scalars)

Scenario B

$e_b \rightarrow \mu$
$e_a \rightarrow \tau$

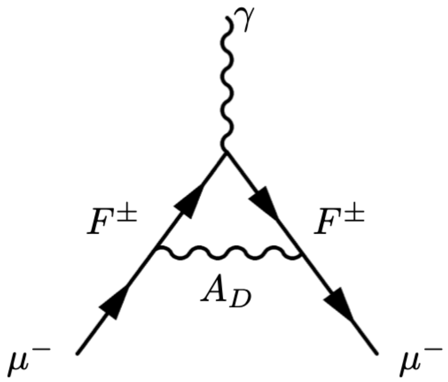
includes terms with heavy gauge bosons and heavy scalars (and thus some sensitivity to the DM model parameters)

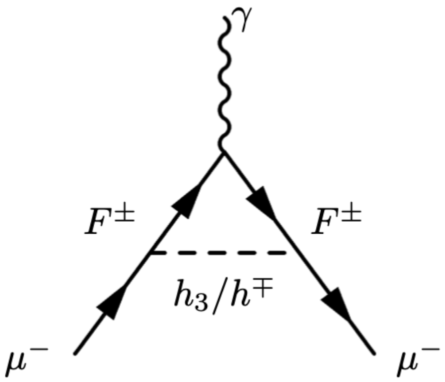
Dominant (chirally-enhanced) contributions:

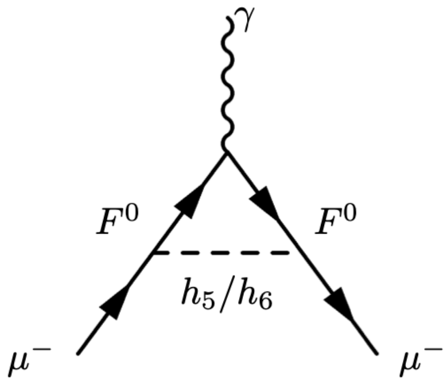
Scenario A

$e_b \to \tau$

$e_a \to \mu$







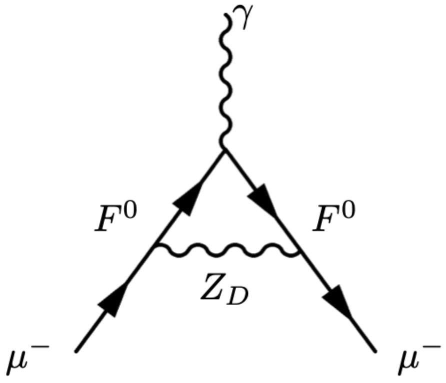
$$\Delta a_\mu = \frac{y_{SL} y_{SE}}{16\pi^2} m_\mu (m_\tau a^\tau + m_{HV} a^{HV})$$

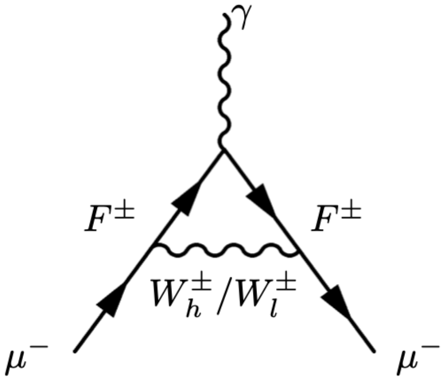
$$a^{\tau, HV} \sim O((M^\pm_{L,E})^{-2})$$

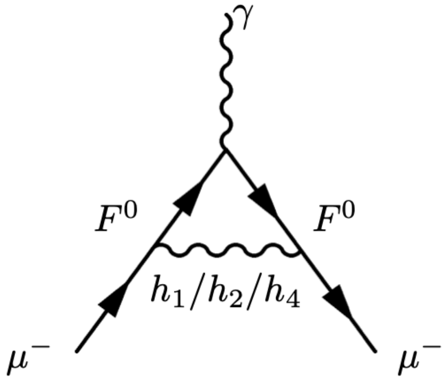
Scenario B

$e_b \to \mu$

$e_a \to \tau$





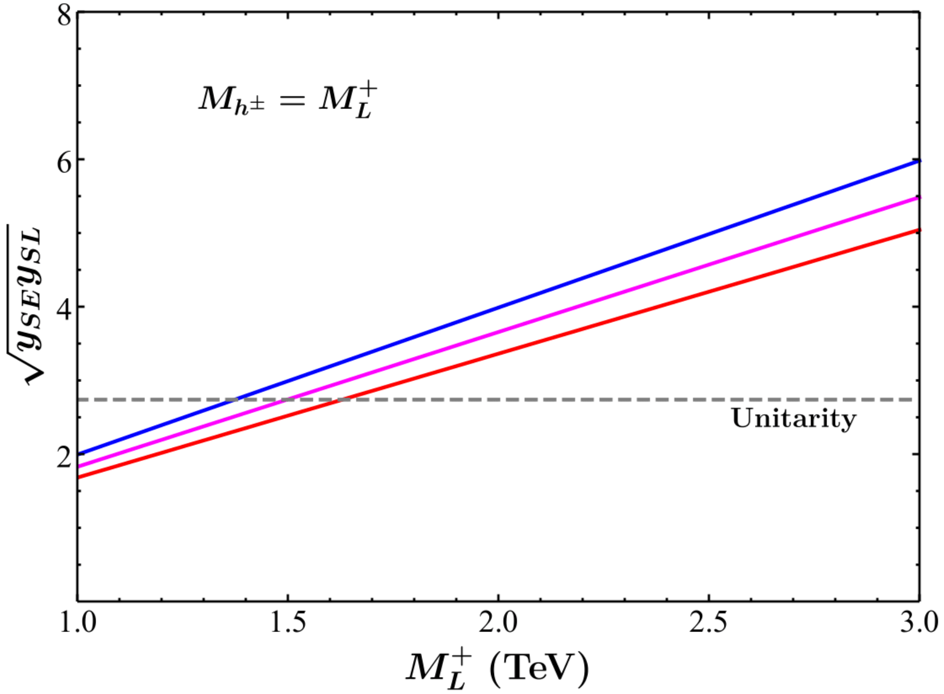


$$\Delta a_\mu = \frac{e_D^2}{16\pi^2} m_\mu m_{HV} a^{HV}$$

Scenario A

$$M_{h^\pm}, m_{HV}, M^\pm_{L,E}, y_{SL,SE}, \theta_\Delta, \theta_M$$

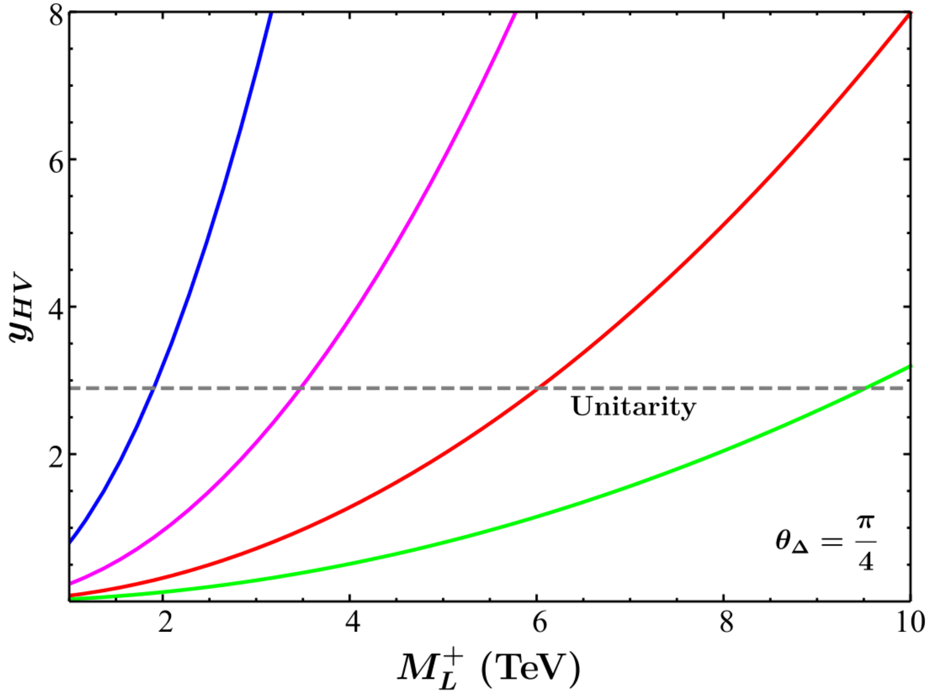
$m_{HV} \ll m_b = m_\tau$



$$(M_L^-, M_E^+, M_E^-) = (1.3, 1.5, 1.8) M_L^+$$

$(\theta_\Delta, \theta_M) =$ (π/8,3π/8) (π/4,π/4) (π/8,π/8)

$m_{HV} \gg m_b = m_\tau$



$$(M_L^-, M_E^+, M_E^-) = (1.3, 1.5, 1.3) M_L^+$$

$y_{SL} y_{SE} =$ 0.3, 1, 3, 7.5

can easily accommodate Δa_μ

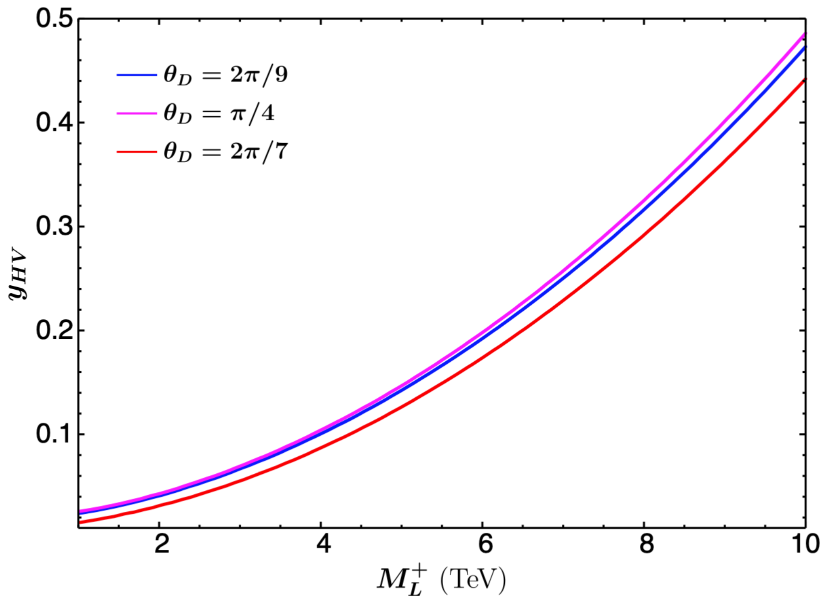
Scenario B

$$M_{h^\pm}, m_{HV}, M_{Z_D}, M^{\pm}_{L,E}, M_{h_{1,2,4}}, \lambda_1, e_D, \theta_D, \theta_{lh}$$

$$M_{h_2} < \sqrt{2\lambda_1} e_D^{-1} \sin 2\theta_{lh} M_{Z_D} < M_{h_1}$$

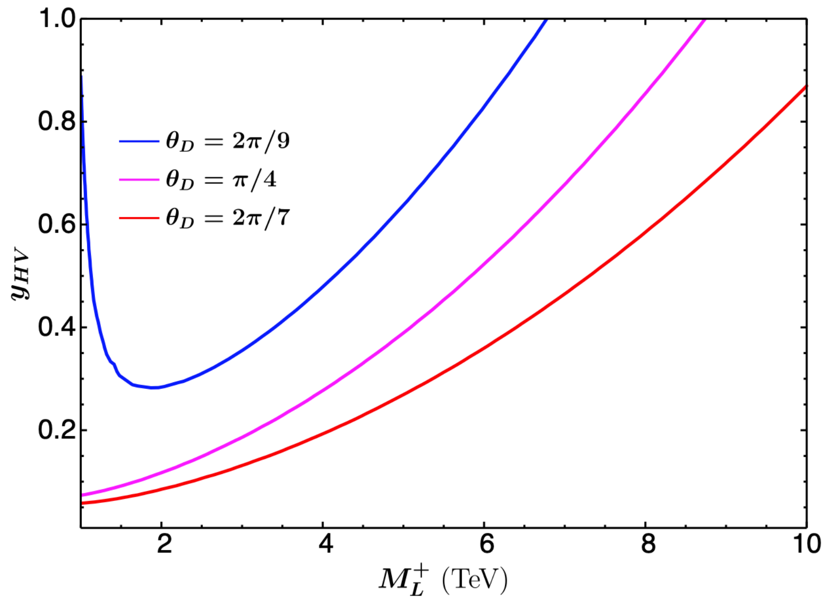
$\sin(\theta_E + \theta_\Phi) > 0$

(constructive interference)



$\sin(\theta_E + \theta_\Phi) < 0$

(destructive interference)



$(M_L^-, M_E^+, M_E^-) = (1.3, 1.5, 1.8) M_L^+$ $(M_{h_1}, M_{h_2}, M_{h_4}) = (1.2, 1.4, 1)$ TeV $M_{Z_D} = 0.7$ TeV

Again, Δa_μ can easily be accommodated

Collider Phenomenology

Portal matter direct production $\longrightarrow$

similar rates for both scenarios A and B

lightest heavy fermion state predicted to be PM $(U(1)_D$ charged)

$$M^{\pm}_{L,E} \leq M^{0}_{L,E} \leq M^{\mp}_{L,E}$$

Scenario A

$L^{\pm}, E^{\pm} \to \mu + A_D \quad L^{\pm}, E^{\pm} \to \mu + h_D$ $\longrightarrow$

expect usual bounds: $M_E^{\pm} \geq 895 \text{ GeV}, \; M_L^{\pm} \geq 1050 \text{ GeV}$

unless new decay channels via heavy scalars and gauge bosons

again, can do better at a (multi-TeV) muon collider:

probe PM masses up to $\sqrt{s}/2$

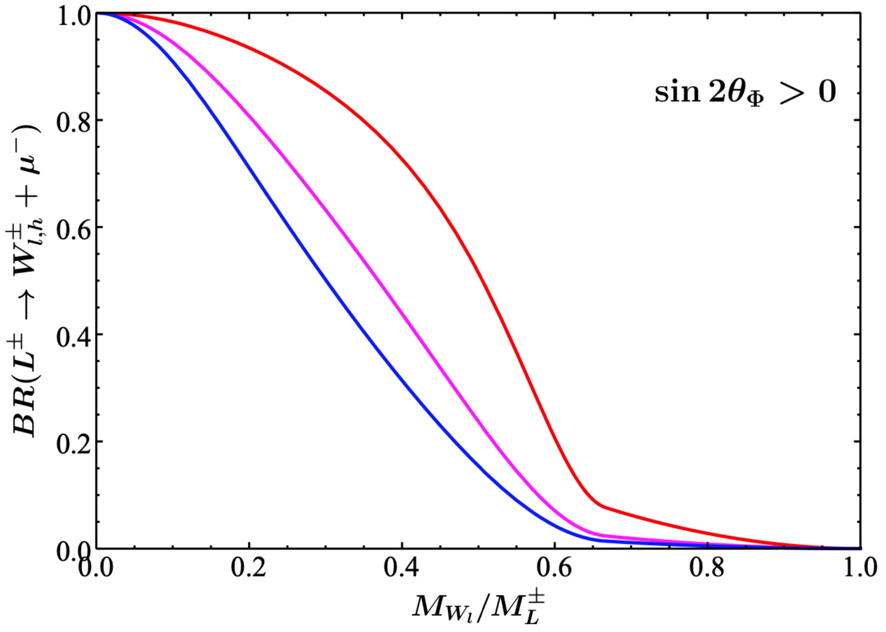
Scenario A (continued)

Example: PM decays to heavy gauge bosons

$$L^{\pm} \rightarrow \mu + W^{\pm}_{l,h}$$

$$M_{W_h} = 1.5 M_{W_l} \quad M_L^- = 1.3 M_L^+$$

$$y_{SL} = 1 \quad \theta_{\Delta} = (\pi/8, \pi/4, 3\pi/8)$$



Scenario B

PM decays to tau leptons rather than muons → correspondingly weaker limits on PM masses

VLL direct production ($U(1)_D$ neutral heavy fermions)

Scenario A

Scenario B

$$\Gamma(E^0 \to \tau, \mu + h, Z, W) \sim M_E^0 \times O\left(\frac{m_{\tau,\mu}^2}{v^2}\right)$$

$$\Gamma(E^0 \to L^0 + h, Z, W) \sim M_E^0 \times O\left(\frac{m_{\tau,\mu}^2}{v^2}, \frac{m_{HV}^2}{v^2}\right)$$

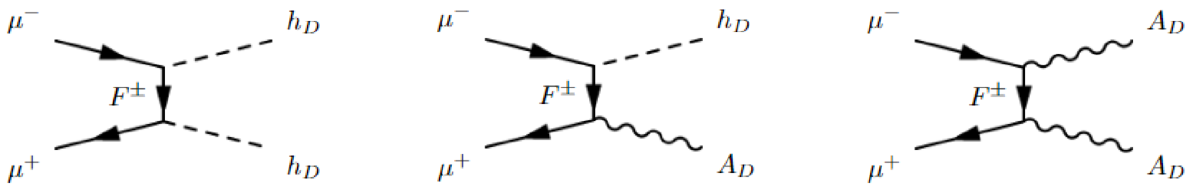
➡ standard VLL bounds may be weakened if heavy gauge bosons and scalars are kinematically accessible for 2-body decays

if so, distinctive signature: **2** EW gauge bosons emitted instead of 1

➡ can constrain m_{HV} via decays of heavy VLL to lighter VLL

Monophoton search (muon collider)

Scenario A



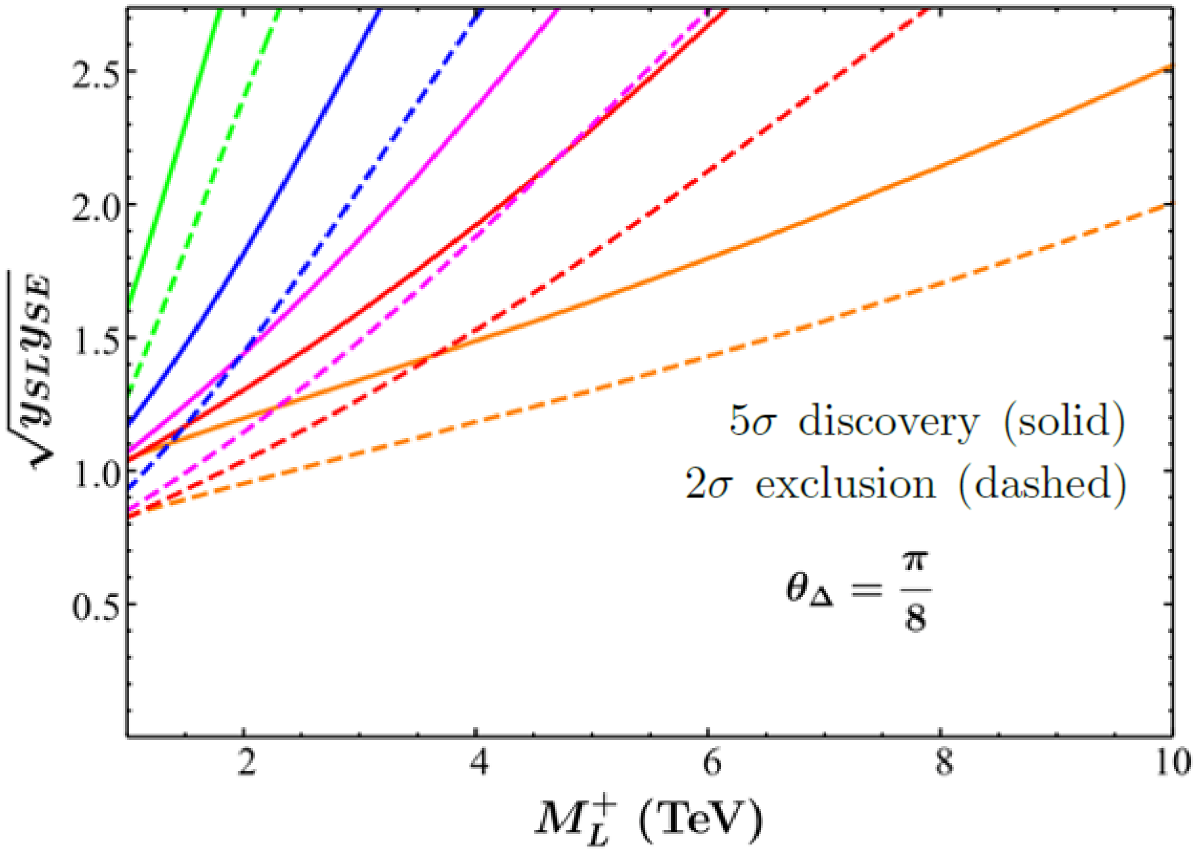
Pair production of dark photons, dark Higgs:

constraints on $\sqrt{y_{SL}y_{SE}}$

$\sqrt{s} =$ 3, 6, 10, 14, 30 TeV

upper limit on Yukawas:
perturbative unitarity

$(M_L^-, M_E^+, M_E^-) = (1.3, 1.5, 1.8)M_L^+$



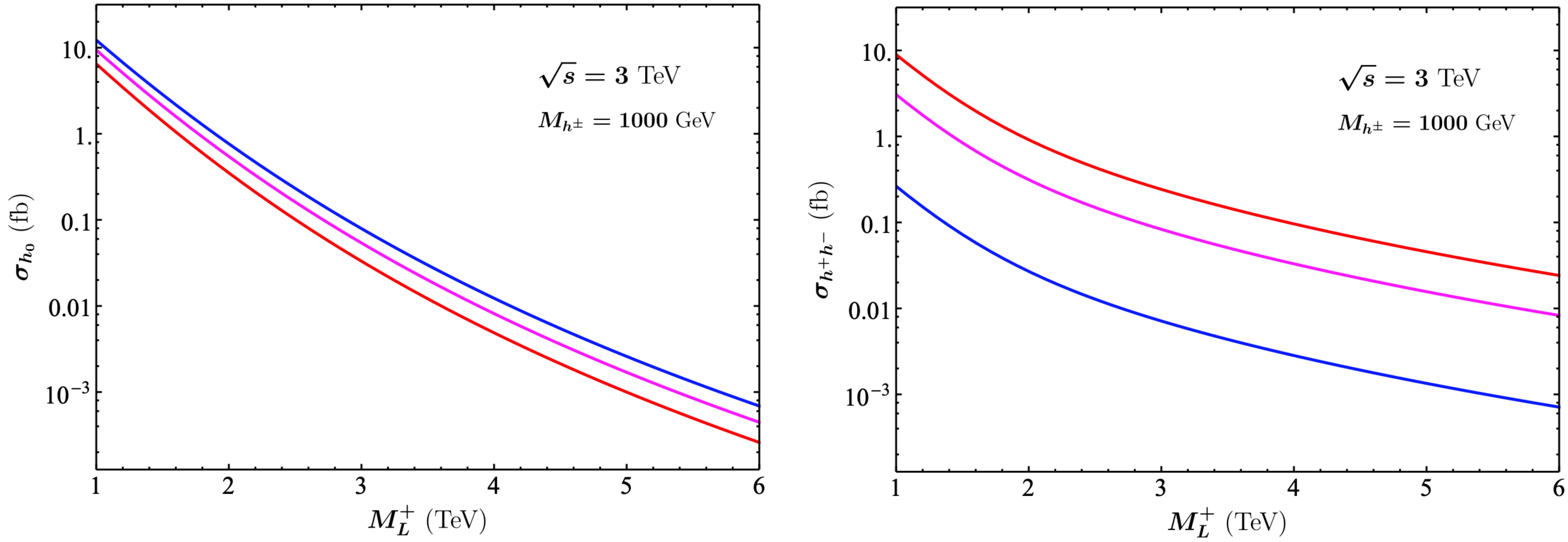
Other diboson production

Scenario A

$M_{h^\pm}, M^\pm_{L,E}, y_{SL}, y_{SE}, \theta_\Delta$

In addition to monophoton searches at a muon collider, can have pair production of

$Z_2' = -1$ heavy scalars $h_5 h_5, h_6 h_6, h_5 h_6$ $\quad Z_2' = +1$ states $h^+ h^-, h^\pm A_D, h^\pm h_D$



$(M_L^-, M_E^+, M_E^-) = (1.3, 1.5, 1.8) M_L^+$ $\quad \theta_\Delta =$ (π/8, π/4, 3π/8)

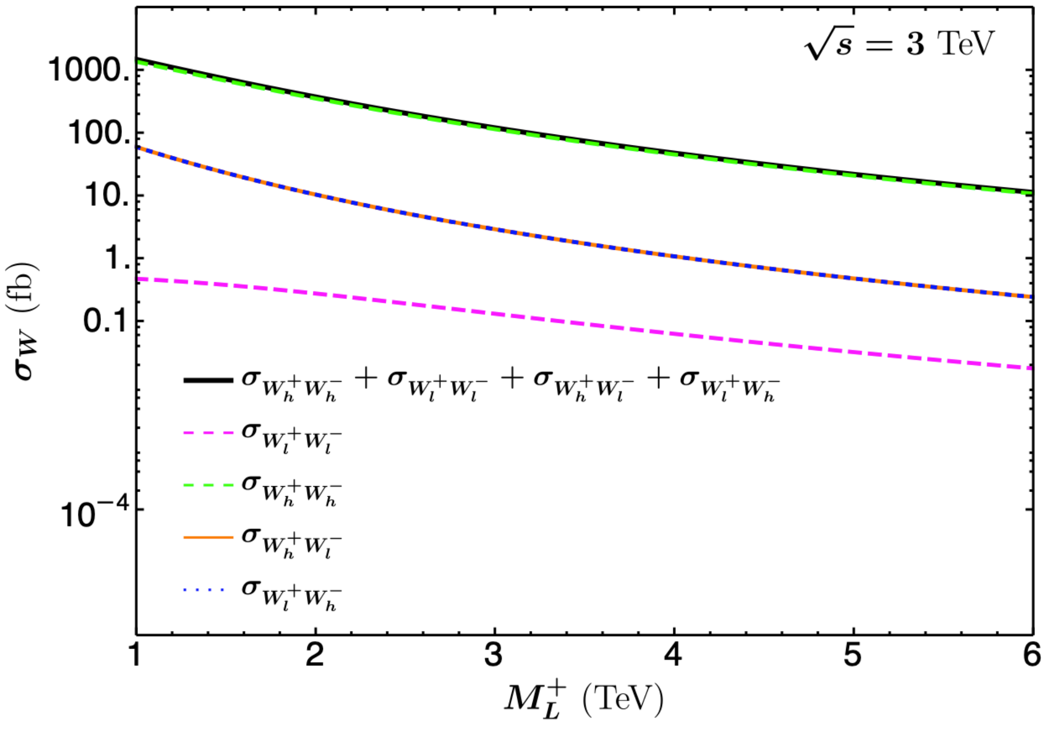
Diboson production

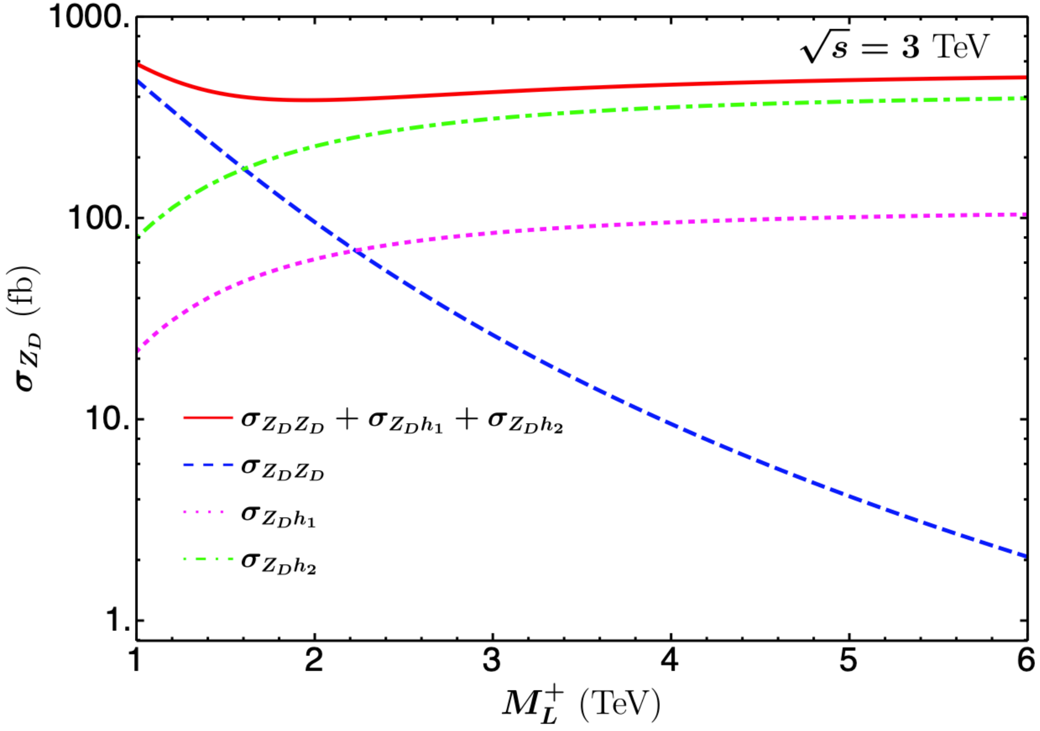
Scenario B

$M_{h^\pm}, M_{Z_D}, M^{\pm}_{L,E}, M_{h_{1,2,4}}, e_D, \theta_D, \theta_{lh}$

pair production of heavy gauge bosons and scalars at a muon collider

$h_{1,2}h_{1,2} \quad h_4 h_4 \quad Z_D Z_D \quad Z_D h_{1,2} \quad W^{\pm}_{h,l} W^{\mp}_{h,l}$





$(M_L^-, M_E^+, M_E^-) = (1.3, 1.5, 1.8) M_L^+ \qquad s_{lh} M_{Z_D} = 0.75\,\text{TeV} \qquad \theta_D = \pi/4$

Precision constraints

vectorlike new fermions $\longrightarrow$ mild precision constraints

kinetic mixing of SM Z with Z_D, A_D

$$\epsilon_{Z-A_D} = \frac{e_D e}{6\pi^2}\frac{s_w}{c_w}\log\left(\frac{M_L^+ M_E^+}{M_L^- M_E^-}\right)$$

(leading order)

$$\epsilon_{Z-Z_D} = \frac{e_D e}{12\pi^2\sin(2\theta_D)}\frac{s_w}{c_w}\left[\frac{{M_L^+}^2 - {M_L^-}^2}{{M_L^+}^2 + {M_L^-}^2}\left(\frac{5}{6} + \log\frac{M_L^0}{m_Z}\right) + (1-2\cos(2\theta_D))\log\frac{M_L^+}{M_L^-} + (L\to E)\right]$$

$\longrightarrow$ $M_{Z_D} - m_Z \gtrsim 10\ \mathrm{GeV}$

Z_D couples at leading order to taus or muons

Scenario A

Scenario B

expect stronger constraints in Scenario B

Neutrino trident production

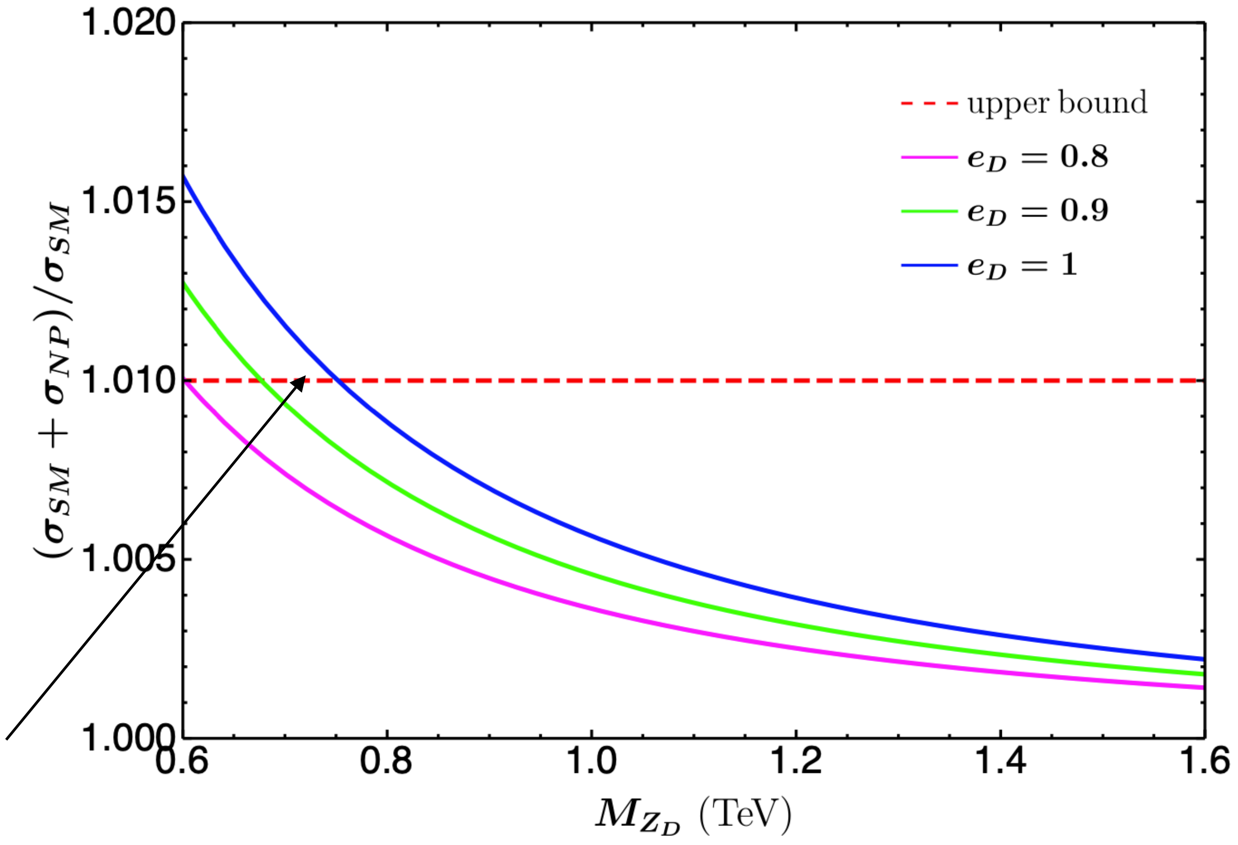
Scenario B

$$\nu_\mu N \to \nu_\mu \mu^+ \mu^- N$$

$$\frac{\sigma_{SM+NP}}{\sigma_{SM}} = 1 + 8\frac{(1+4s_W^2)\frac{g^L_{\mu\mu}(g^L_{\mu\mu}+g^R_{\mu\mu})}{g_2^2}\frac{m_W^2}{M^2_{Z_D}} - \frac{g^L_{\mu\mu}(g^L_{\mu\mu}-g^R_{\mu\mu})}{g_2^2}\frac{m_W^2}{M^2_{Z_D}}}{1+(1+4s_W^2)^2}$$

$$g^{L,R}_{\mu\mu} = \frac{e_D((M^-_{L,E})^2 - (M^+_{L,E})^2)}{\sin 2\theta_D((M^-_{L,E})^2 + (M^+_{L,E})^2)}$$

lower bound on mass of Z_D



(CHARM-II, CCFR, NuTeV)

Lepton flavor violation

(partial) lepton flavor symmetry (no theory yet of small Yukawa couplings)

Z_2' isolates muon and tau lepton flavors

(electron is taken to be $\mathcal{G}_D$ singlet)

⟶ FCNC mediation via $W_{h,l}$ $h_{5,6}$ (suppressed)

charged LFV constraints easily satisfied

Extend to include neutrino masses –

will require violation of the preserved Z_2'

⟶ work in progress

Summary and conclusions

Within general paradigm of light/secluded DM models →

Portal matter – useful model-building framework for physics beyond the SM

Minimal workable portal matter model that can accommodate muon *g-2*

Extended theory based on non-Abelian dark group $SU(2)_A \times SU(2)_B \times Z_2$

can also accommodate muon *g-2*

rich phenomenology, well-suited for muon collider probes

intriguing setting for exploration of lepton family symmetries

Parameters of the model

$$(e_D, \lambda_1, M_{Z_D}, M_{h_{1,2,4}}, M_{h^\pm}, \theta_M, \theta_D, \theta_\Delta, \theta_{lh})$$

$$(M_L^\pm, M_E^\pm, |y_{HV}|, |y_H|, |y_{SL}|, |y_{SE}|)$$

$$\mathrm{sign}(y_{HV}, y_H, \sin(\theta_E + \theta_\Phi), \sin(2\theta_\Phi))$$

Dark photon and dark Higgs masses (sub-GeV)

Other scalar quartics either expressible in terms of other parameters or only enter four-scalar interactions not of interest here

Diboson (monophoton and other) details

Scenario A

$$N_{SD} = \frac{\sqrt{\mathcal{L}}\cos^4\theta_\Delta}{\sqrt{\sigma_{SM}}}(y_{SL}^4\sigma^L + y_{SE}^4\sigma^E) \qquad \sigma^{L,E} \equiv \sum_{XY}\sigma_{XY}^{L,E} \qquad XY = h_D h_D, A_D h_D, A_D A_D$$

$$N_{SD} > 2y_{SL}^2 y_{SE}^2 \cos^4\theta_\Delta \sqrt{\mathcal{L}}\sqrt{\frac{\sigma^L\sigma^E}{\sigma_{SM}}}$$

$\sqrt{s}$ (TeV)	$\mathcal{L}$ (ab^{-1})
3	1
6	4
10	10
14	20
30	90

Hypothetical muon collider parameters

Cuts: $E_\gamma > 50$ GeV $\quad m_{\text{miss}}^2 \equiv (p_{\mu^+} + p_{\mu^-} - p_\gamma)^2 > (200 \text{ GeV})^2 \quad |\eta_\gamma| < 2.5$

Scenario B