(Lepton Flavor) Portal Matter

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Based in part on work in collaboration with George Wojcik, Shu Tian Eu, and Ricardo Ximenes
2211.09918 [PLB 841 (2023) 137931], 2303.12983

THE UNIVERSITY of WISCONSIN MADISON

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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+

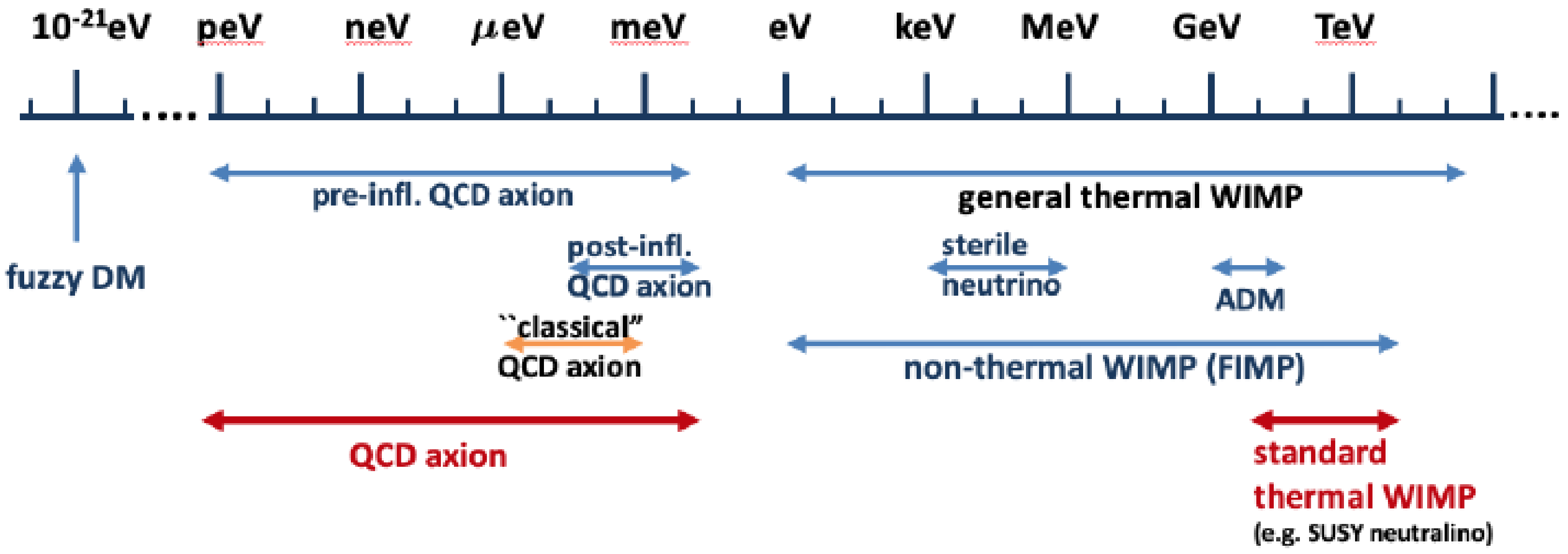
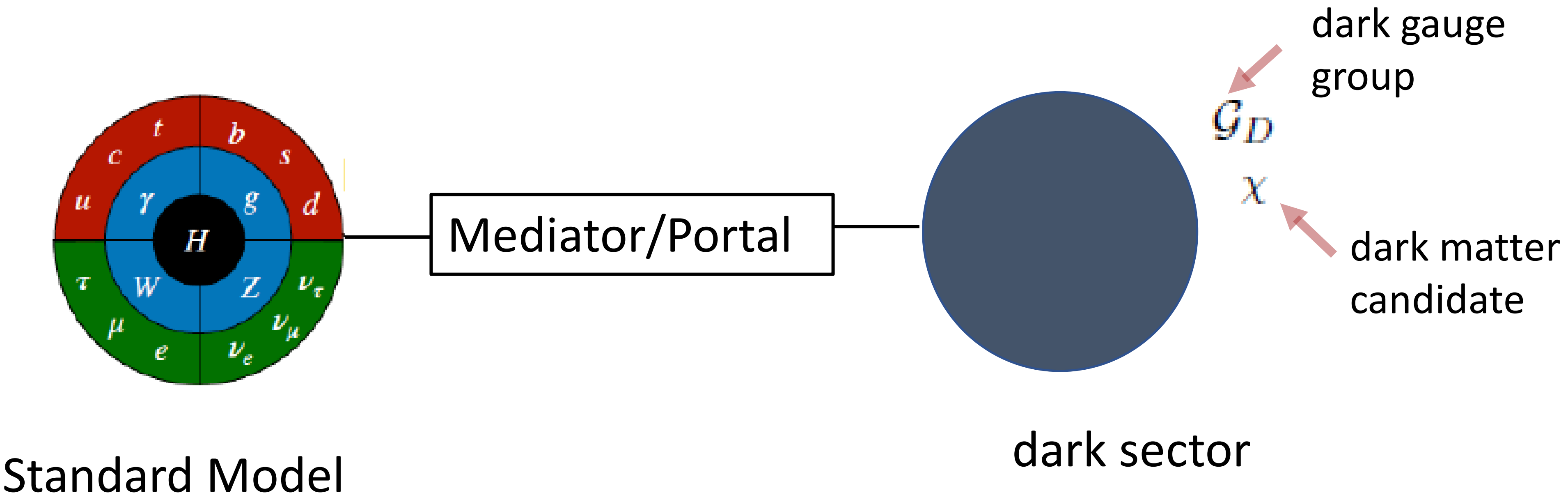


Image credit:
APPEC Rept. (2020)

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

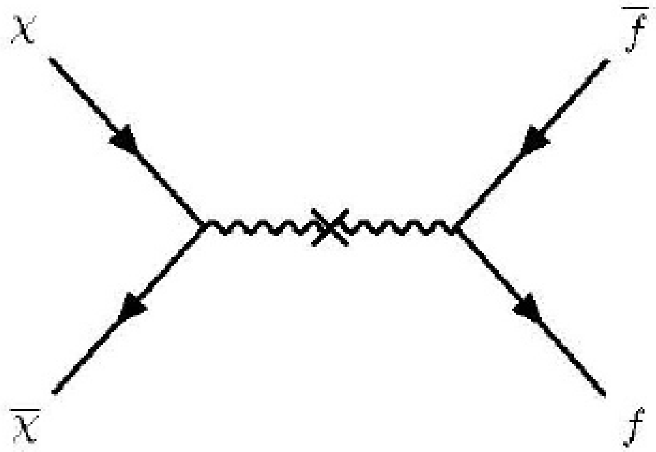


Many possible “portals” for interaction with SM (Higgs, gauge, neutrino,…)

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

Dark matter field χ charged under $U(1)_D$
(SM uncharged)

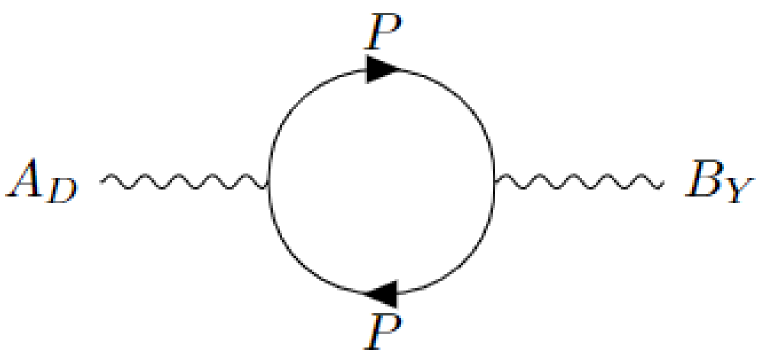
Kinetic mixing portal: $\frac{\epsilon}{2c_w} B_{\mu\nu} A_D^{\mu\nu}$

→ dark photon coupling to SM proportional to $\epsilon J^\mu_{\mathrm{EM}}$

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"

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

Consider fermionic PM that in principle is reachable in current/near-future expts

PM **vectorlike** wrt SM and $U(1)_D$

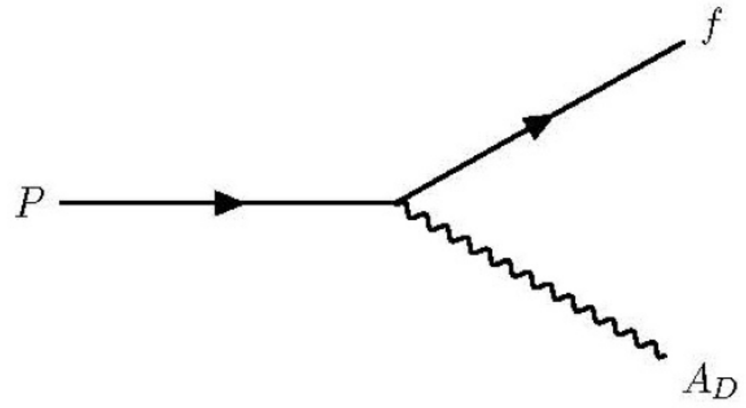
(anomaly constraints, direct searches, precision EW, Higgs constraints,…)

PM mixes with SM – same SM quantum numbers as some SM field

Distinctive collider signatures!

decays to (highly boosted) SM fermion/jet
+dark photon or dark Higgs

compare usual vectorlike fermion case –
preferential decays to SM EW gauge, Higgs bosons



Portal Matter Models (I)

Rizzo 1810.07531
Kim et al. 1904.05893
Carvunis et al. 2209.14305,…
Rizzo 2202.02222 (Snowmass report)

Minimal scenarios:

dark gauge group $\mathcal{G}_D = U(1)_D$

one dark Higgs h_D , single PM vectorlike pair

"VLL" $E^{\pm}, L^{\pm}$

"VLQ" $T^{\pm}, B^{\pm}, Q^{\pm}$

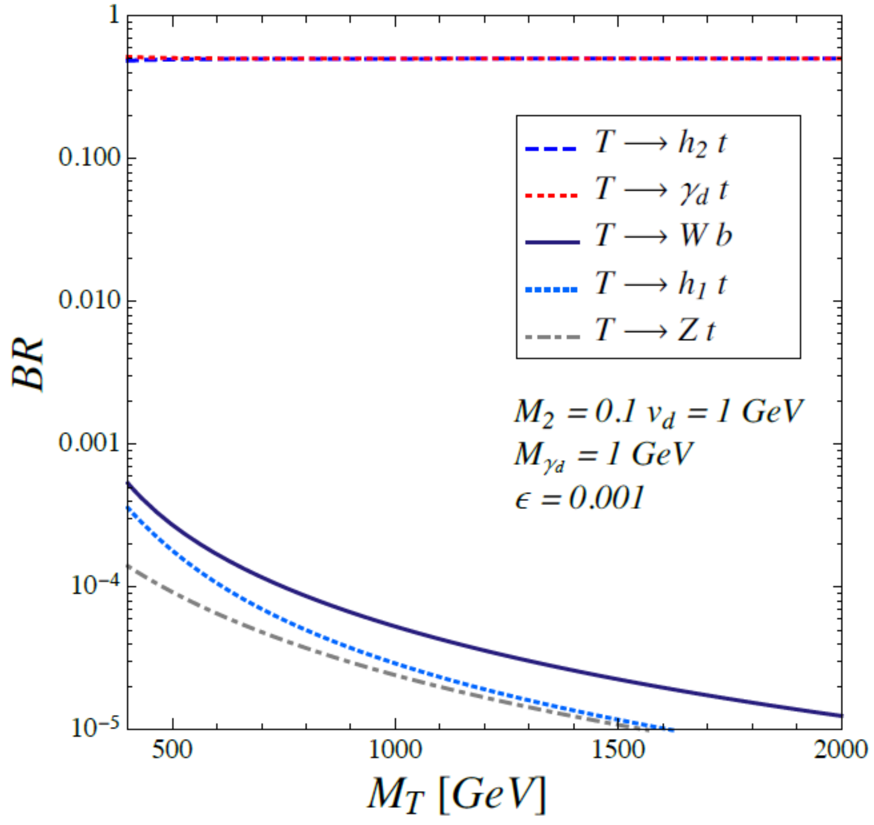
Example: "maverick top partners"

$$\frac{\Gamma(T \to t + h_2/\gamma_d)}{\Gamma(T \to t/b + W/Z/h_1)} \sim \left(\frac{M_T}{M_t}\right)^2 \left(\frac{v_{EW}}{v_d}\right)^2 \frac{1}{(1 + (M_T/M_t)^2 \sin^2\theta_L^t)^2}$$

production QCD strength, may be accessible at LHC

dark photon decay length depends on KM ϵ

Kim et al. 1904.05893



Portal Matter Models (II)

Non-minimal scenarios: →

Extended dark gauge groups: $\mathcal{G}_D \longrightarrow U(1)_D$

Extended fermion PM and scalar content:

nontrivial fermion sets for anomaly cancellation

multiple vacuum expectation value scales

Many BSM options →

Grand unification (-inspired)

Extra dimensions/Kaluza-Klein PM

…

Rizzo, Reuter 1909.09160

Rizzo, Wojcik 2012.05406

Rizzo 2209.00688,…

Wojcik 2205.11545

More generally: KM/PM as model-building framework for BSM physics

Example: E_6 inspired dark sector

Rizzo, Reuter 1909.09160

$$E_6 \longrightarrow SU(6) \times SU(2)_I \to SU(5) \times SU(2)_I \times U(1)_6$$

$$27 \to (\bar{5}, 2) + (5, 1) + (1, 2) + (10, 1) \quad (SU(5), SU(2)_I)$$

→ SM fermion content + vectorlike pair $(\mathbf{5}, \bar{\mathbf{5}})$ + singlets

important point: SM neutral wrt $U(1)_D$ can't arise from E_6 subgroup!

→ E_6 inspired dark group $\mathcal{G}_D = SU(2)_I \times U(1)_{I_Y} \longrightarrow U(1)_D$

Example: "flavorful" PM in Pati-Salam

Rizzo, Wojcik 2012.05406

SM embedded in PS: $SU(4)_c \times SU(2)_L \times SU(2)_R.$

dark gauge group: $SU(4)_F \times U(1)_F$

PM as vectorlike 4th generation, singlets with respect to $SU(3)_F$

Example: Kaluza-Klein PM

Wojcik 2205.11545

SM and PM fermions propagate in bulk, together in 5D gauge multiplets

concrete 5D orbifold model with dark gauge group $SU(2)$

→ Rich phenomenology, differs from “standard” case with VLL, VLQ

minimal cases – dark gauge charges lead to distinctive collider signatures

non-minimal – also have nontrivial new gauge bosons, scalars, KK towers, etc…

Focus here on lepton sector →

lepton **flavor** portal matter

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

(effect insensitive to DM details)

See talk here by George Wojcik

non-minimal extension with $\mathcal{G}_D = SU(2)_A \times SU(2)_B$

rich phenomenology, interesting framework for lepton flavor model-building

Dark photon models and muon *g-2*

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

Abi et al. (Muon g-2), PRL 126, 141801 (2021)
Aoyama et al., Phys. Rept. 887, 1 (2020),…

IF discrepancy is due to new physics $\Rightarrow$

can KM/PM framework provide a possible resolution?

(i) dark photon, no PM mixed with muon – too small

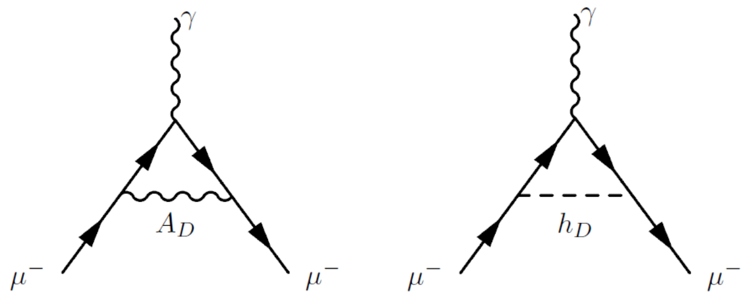
(vector coupling, small KM) $\sim \epsilon^2$

Davoudiasl et al. 1402.3620,…

(ii) mix muon with single lepton PM pair – still too small!

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
$S = v_S + h_D/\sqrt{2}$	$(\mathbf{1}, 0)$	$+1$



A minimal workable framework

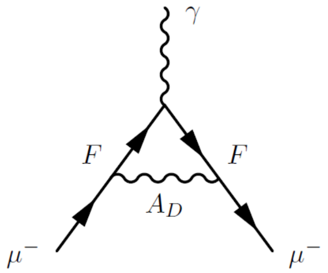
See talk here by George Wojcik

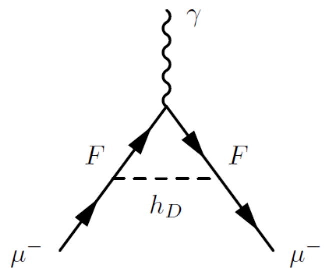
Wojcik, LE, Eu, Ximenes 2211.09918

Must couple new physics to **both** chiralities of the muon:

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

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

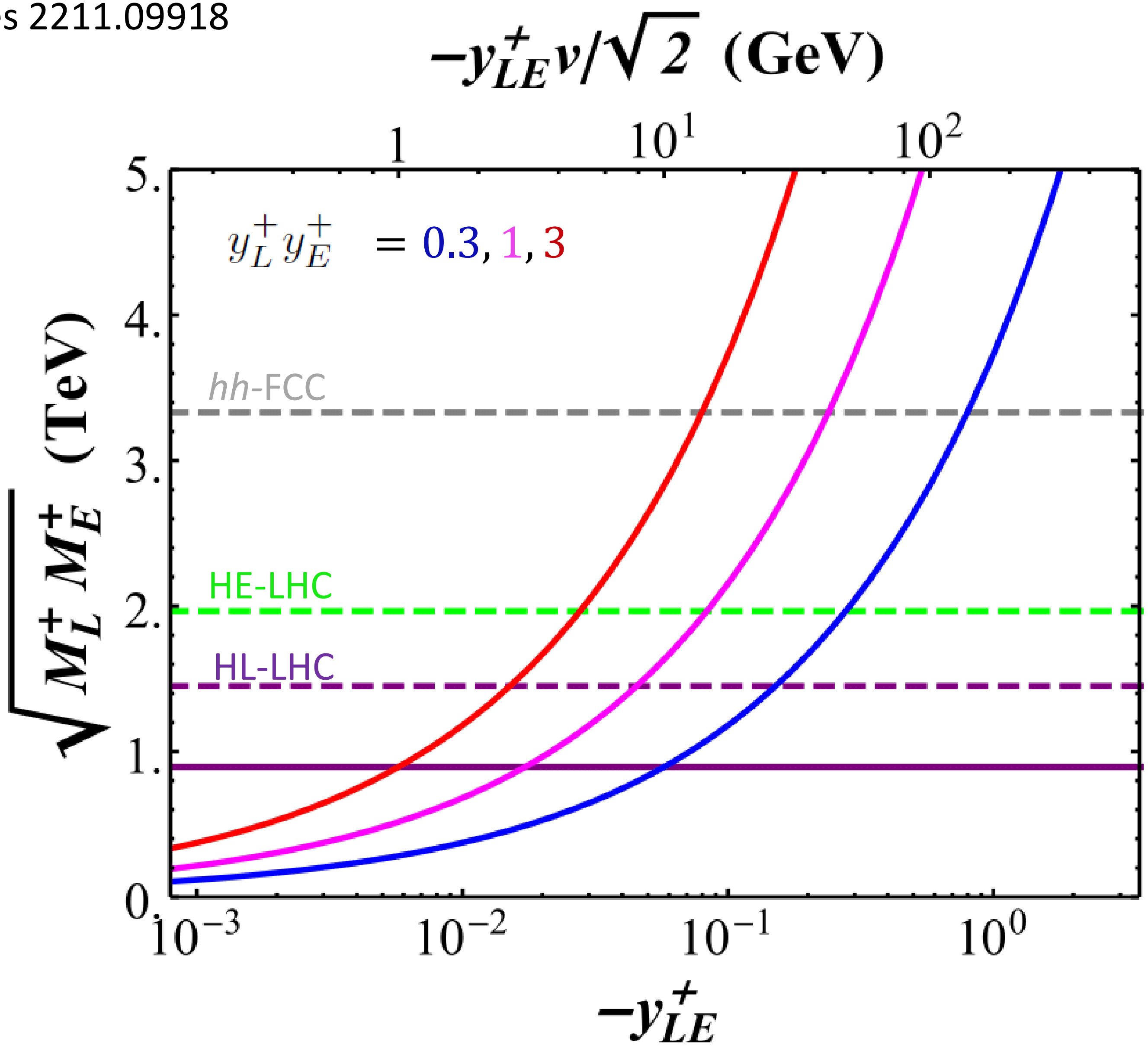




Chirally-enhanced (dominant) contribution:

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

Wojcik, LE, Eu, Ximenes 2211.09918



Similar mechanism as Carcamo Hernandez et al. 1910.10734, but very different constraints

Lepton Flavor Portal Matter

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

$|y^{\pm}_{LE}|v \sim O(\text{few GeV})$ $\Rightarrow$ perhaps suggestive of $y^{\pm}_{LE} \sim y_\tau$

distinguish lepton generations via their couplings to PM/dark sector fields

Lepton Flavor Portal Matter – extended model

Dark gauge group:

Wojcik, LE, Eu, Ximenes 2303.12983

$$\mathcal{G}_D = SU(2)_A \times SU(2)_B$$

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

(global)

$\langle \Phi \rangle \sim \mathrm{TeV}$ $\langle \Delta_A, \Delta_B \rangle \sim \mathrm{GeV}$

Scalar Fields	$SU(2)_L \times U(1)_Y$	$SU(2)_A$	$SU(2)_B$	Z_2
Φ	$(\mathbf{1}, 0)$	$\mathbf{2}$	$\mathbf{2}$	$+1$
Δ_A	$(\mathbf{1}, 0)$	$\mathbf{3}$	$\mathbf{1}$	-1
Δ_B	$(\mathbf{1}, 0)$	$\mathbf{1}$	$\mathbf{3}$	-1
H	$(\mathbf{2}, 1/2)$	$\mathbf{1}$	$\mathbf{1}$	$+1$

Fermion field content

Fermion Fields	$SU(2)_L \times U(1)_Y$	$SU(2)_A$	$SU(2)_B$	Z_2
L_L, e_R	$(\mathbf{2}, -1/2), (\mathbf{1}, -1)$	$\mathbf{1}$	$\mathbf{1}$	$+1$
Ψ_L, Ψ_R	$(\mathbf{2}, -1/2), (\mathbf{1}, -1)$	$\mathbf{2}$	$\mathbf{2}$	$+1$
V_L, V_R	$(\mathbf{1}, -1), (\mathbf{2}, -1/2)$	$\mathbf{1}$	$\mathbf{3}$	$+1$
S_L, S_R	$(\mathbf{2}, -1/2), (\mathbf{1}, -1)$	$\mathbf{1}$	$\mathbf{1}$	-1

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

→ 1 SM lepton family
(identified with electron)

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

→ 2 SM lepton families
(identified with muon, tau)

→ portal matter, VLL
($U(1)_D$ charged) ($U(1)_D$ neutral)

Gauge Symmetry Breaking and Scalar Sector

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

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

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

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

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

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

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

$$U(1)_D \longrightarrow D_A(\hat{z},\phi)\times D_B(\hat{z},\phi)$$

$$Z_2' \longrightarrow D_A(\hat{z},\pi)\times D_B(\hat{z},\pi)\times Z_2$$

**ignoring Higgs portal interactions – must be highly suppressed (generic in these constructions)

Boson masses:

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

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

$$M_{Z_D} \sim e_D v_\Phi \sim \mathrm{TeV} \qquad m_{A_D} \sim r_\Delta M_{Z_D}$$

$$r_\Delta \ll 1$$

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

dark photon → A_D

$$m_{h_3} = r_\Delta r_3 M_{h^\pm}$$

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

Fermion sector (second and third SM generations + heavy states)

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

$$y_P = y_L \cos\theta_L \qquad \tilde{y}_P = y_L \sin\theta_L$$

$$y'_P = y_E \cos\theta_E \qquad \tilde{y}'_P = y_E \sin\theta_E$$

$$M_L^+ = v_\Phi y_L \cos(\theta_L - \theta_\Phi)$$

$$M_E^+ = v_\Phi y_E \cos(\theta_E - \theta_\Phi)$$

$$M_L^- = v_\Phi y_L \sin(\theta_L + \theta_\Phi)$$

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

basis choice: (all couplings assumed to be real)

$$y_{L,E,SL,SE,HS} > 0$$

$$c_{\theta_L - \theta_\Phi},\, c_{\theta_E - \theta_\Phi},\, s_{\theta_L + \theta_\Phi} > 0$$

$y_H, y_{HV}, s_{\theta_E + \theta_\Phi}$ may be positive or negative

Fermion masses:

(second and third SM generations + heavy states)

$r_\Delta \ll 1$

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

$Z_2' = +1 \longrightarrow$

$\left(\Psi_{(L,R)_{11}}, \Psi_{(L,R)_{22}}, V^0_{(L,R)}\right)$

$Z_2' = -1 \longrightarrow$

$\left(S_{(L,R)}, \Psi^+_{(L,R)}, V^+_{(L,R)}, \Psi^-_{(L,R)}, V^-_{(L,R)}\right)$

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

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

$v \sim 100$ GeV $\qquad M^\pm_{L,E} \sim v_\Phi \sim$ TeV

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

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

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

Two embeddings: whether muon has

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

(resembles minimal PM scenario)

(stronger couplings of muon to dark sector gauge bosons, VLL)

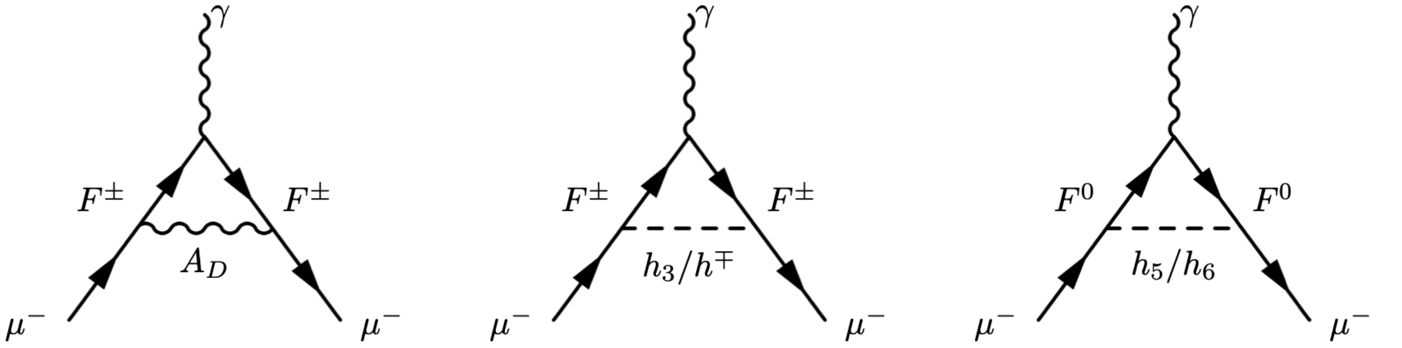
Muon *g-2*

Three relevant chirality-flipping mass terms: $m_a \approx \frac{y_{HS} v}{\sqrt{2}}$ $\quad m_b \approx O(1)\left(\frac{y_H v}{\sqrt{2}}\right)$ $\quad m_{HV} = \frac{y_{HV} v}{\sqrt{2}}$

Scenario A

$e_b \to \tau$

$e_a \to \mu$



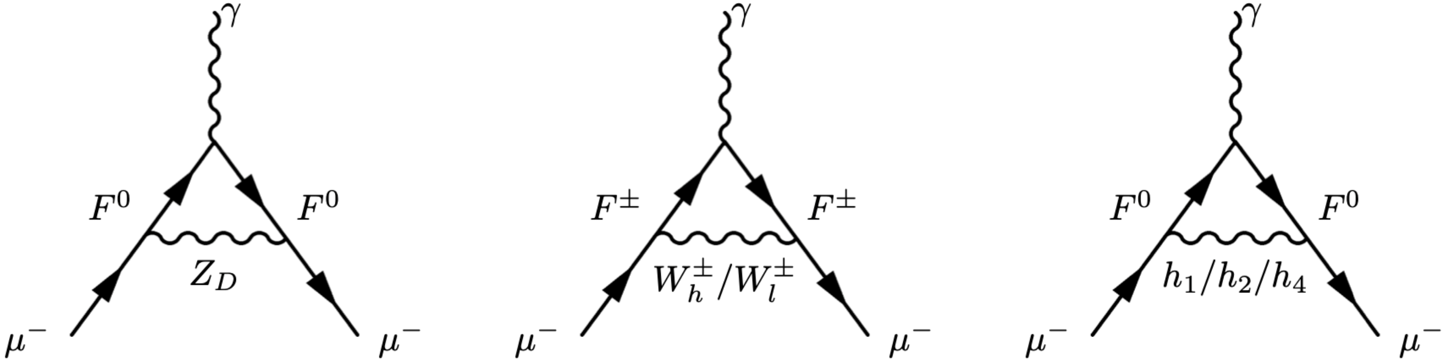
$$\Delta a_\mu = \frac{y_{SL} y_{SE}}{16\pi^2} m_\mu (m_\tau a^\tau + m_{HV} a^{HV})$$

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

Scenario B

$e_b \to \mu$

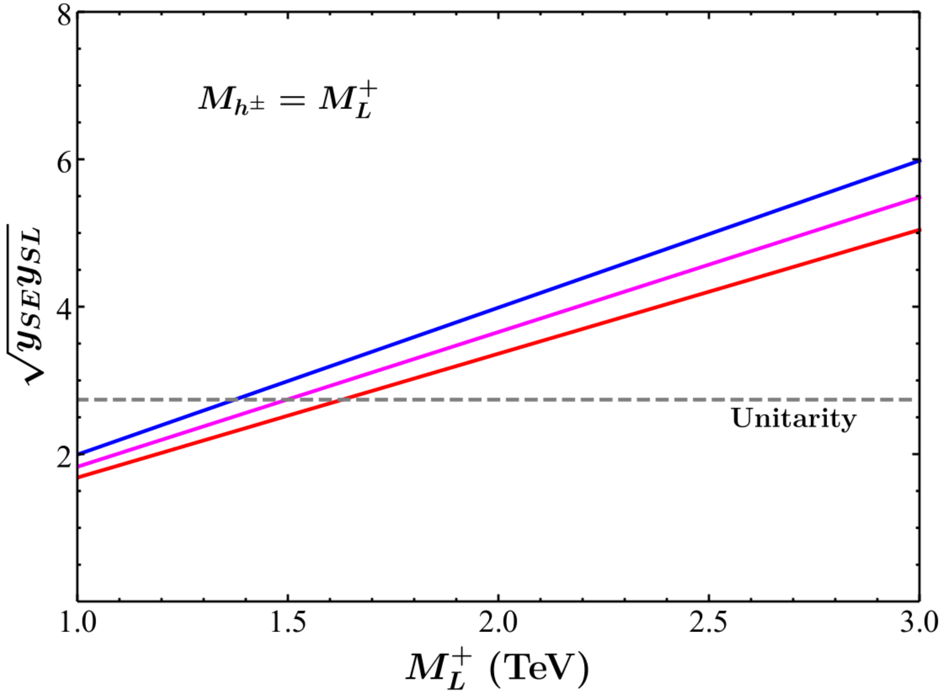
$e_a \to \tau$



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

Scenario A

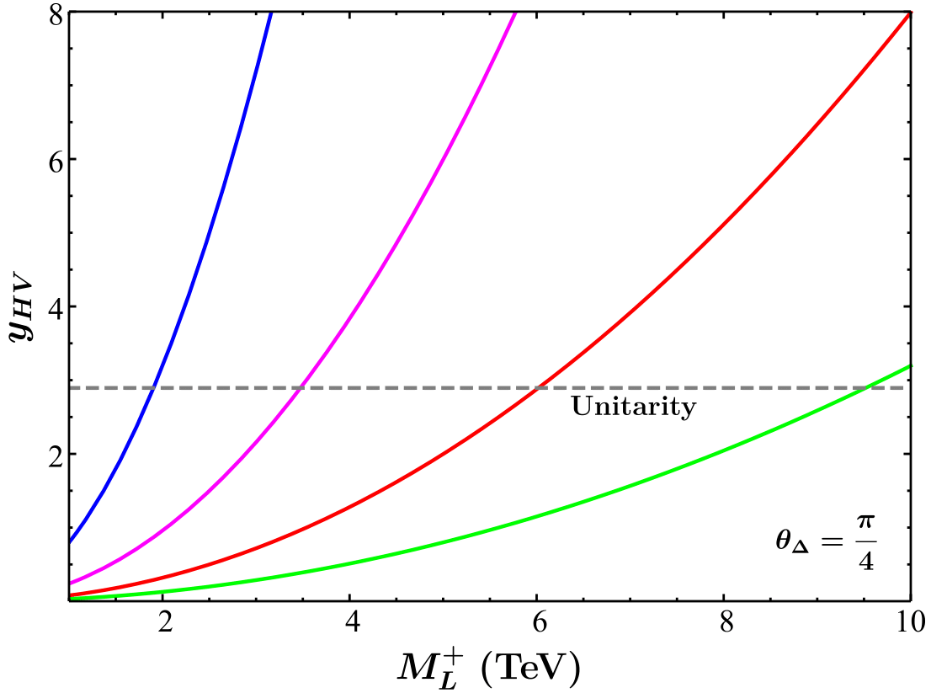
$m_{HV} \ll m_\tau$



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

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

$m_{HV} \gg m_\tau$



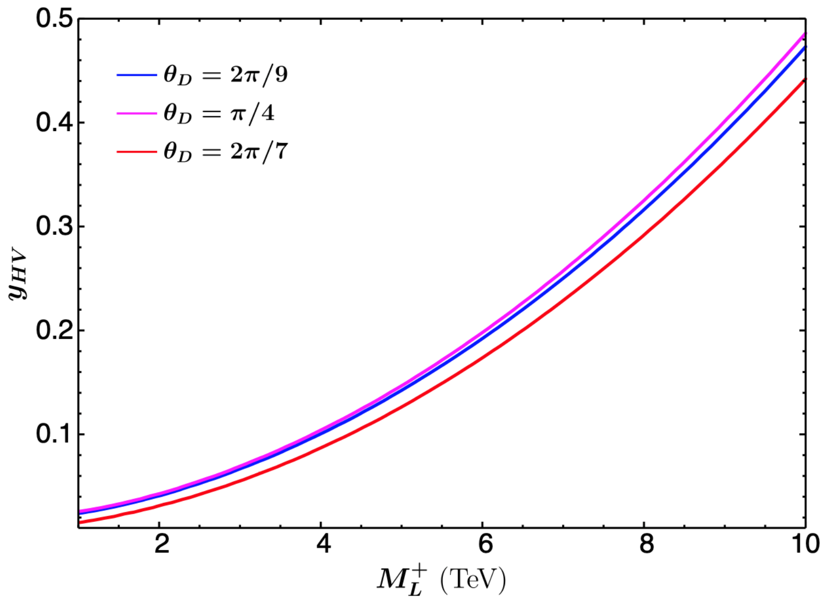
$$(M_L^-, M_E^+, M_E^-) = (1.3, 1.5, 1.3)M_L^+$$

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

Scenario B

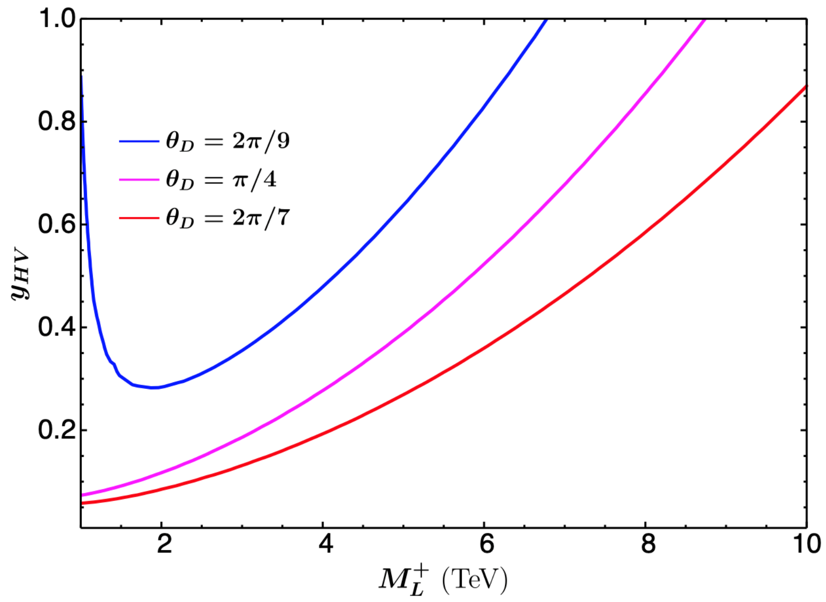
$$\sin(\theta_E + \theta_\Phi) > 0$$

(constructive interference)



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

(destructive interference)



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

Collider Phenomenology

Portal matter direct production ⟶ similar rates for scenarios A and B

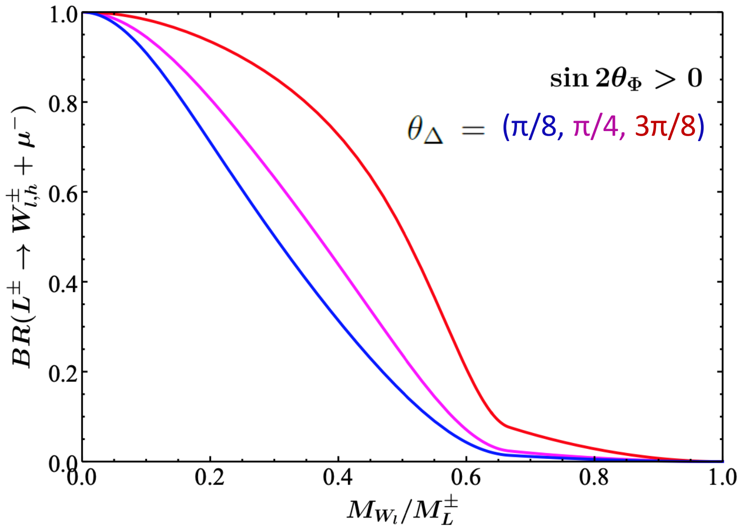
lightest heavy fermion state predicted to be PM $M^{\pm}_{L,E} \leq M^{0}_{L,E} \leq M^{\mp}_{L,E}$

Scenario A

$$L^{\pm}, E^{\pm} \to \mu + A_D, h_D \longrightarrow M_E^{\pm} \geq 895 \text{ GeV},\ M_L^{\pm} \geq 1050 \text{ GeV}$$

unless new decays via heavy scalars, gauge bosons

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



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

Scenario B

PM decays to taus – weaker limits

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)

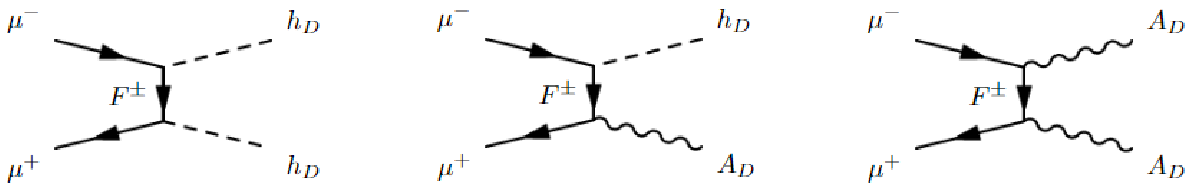
Scenario A

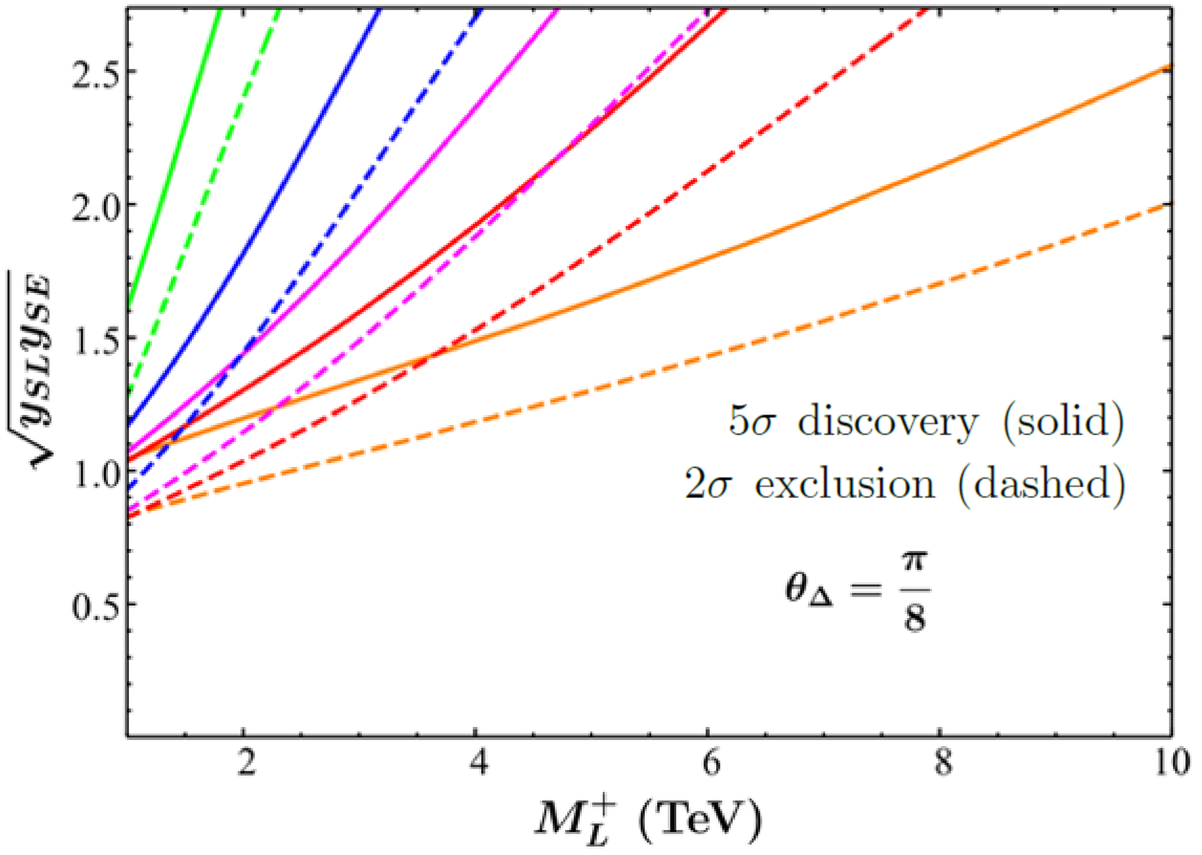
Pair production of dark photon, dark Higgs

upper limit on Yukawas:
perturbative unitarity

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

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





Diboson production

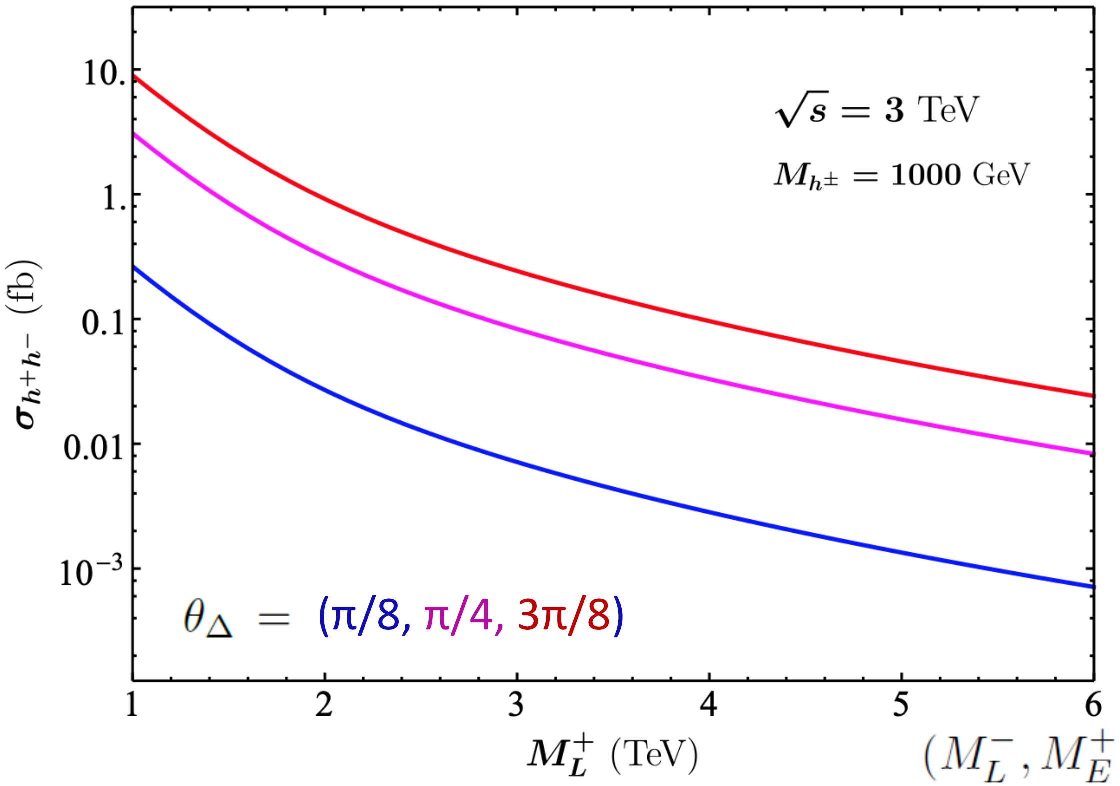
Scenario A

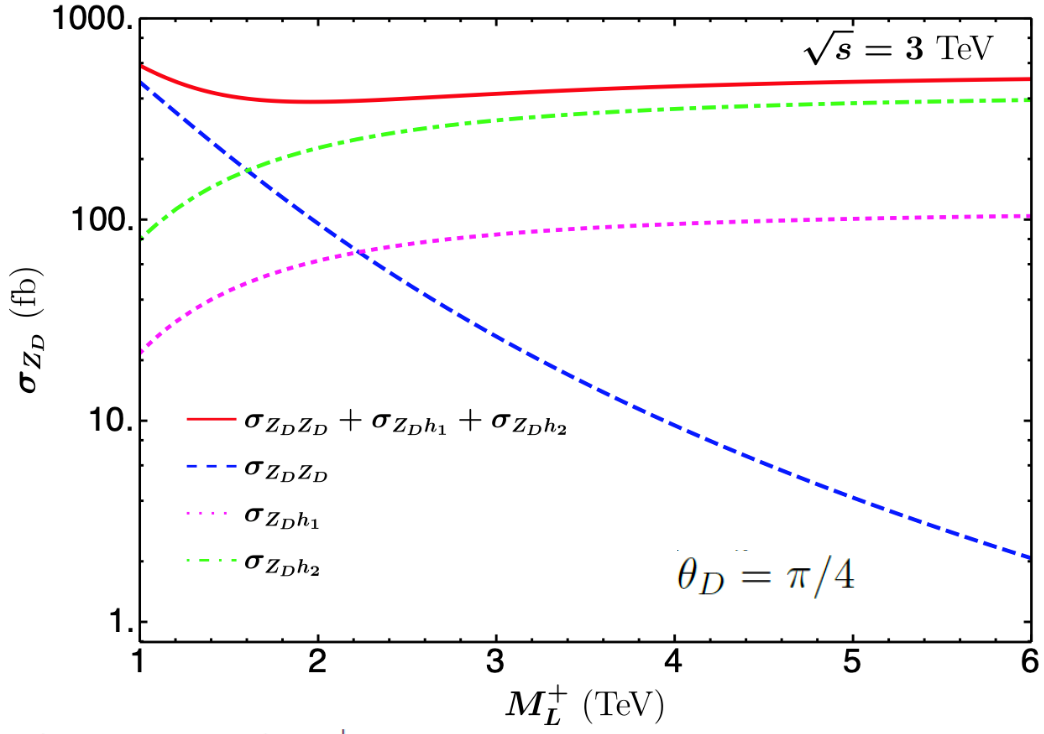
Scenario B

At muon collider, pair production of

$h_5h_5, h_6h_6, h_5h_6 \quad h^+h^-, h^\pm A_D, h^\pm h_D$

$h_{1,2}h_{1,2} \quad h_4h_4 \quad Z_DZ_D \quad Z_Dh_{1,2} \, W^\pm_{h,l}W^\mp_{h,l}$





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

Precision constraints

vectorlike new fermions $\longrightarrow$ mild precision constraints

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

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

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

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

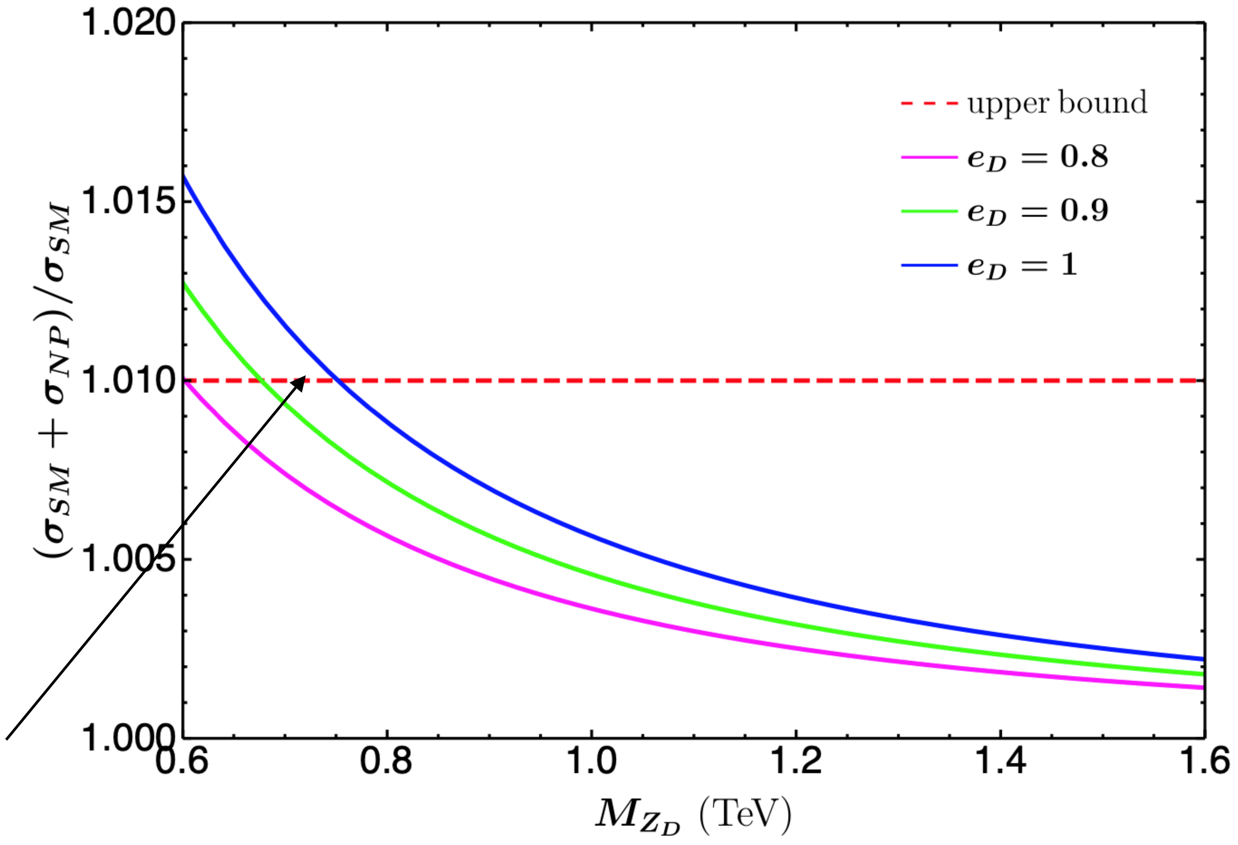
$$\nu_\mu N \to \nu_\mu \mu^+ \mu^- N$$

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

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

lower bound on mass of Z_D

(CHARM-II, CCFR, NuTeV)



Lepton flavor

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

SM charged lepton generations distinguished by dark gauge group couplings

preserved Z_2' isolates muon and tau lepton flavors

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

charged LFV constraints easily satisfied

Extend to include neutrino masses, lepton mixing –

requires 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

rich phenomenology even in minimal implementations

Lepton flavor portal matter

can accommodate muon *g-2* (portal matter effect – largely agnostic to DM sector)

especially well-suited for muon collider probes

extended models provide intriguing setting for lepton flavor model-building

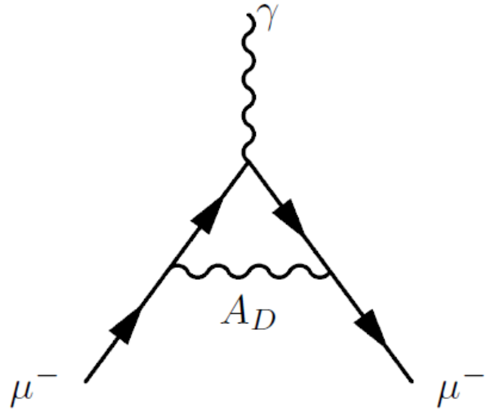
Backup

Muon g-2 for minimal PM scenarios

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

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

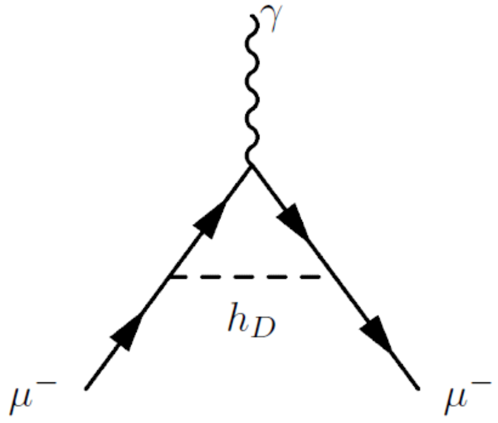
$$\Delta a_\mu^{(A_D^{(1)})} \sim 10^{-11}\left(\frac{\epsilon}{10^{-4}}\right)^2 R(y, m_{A_D}) \qquad |y| \sim 0.01 - 0.5$$



+ 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

Constraining the minimal model:

At LHC: PM decays – repurpose slepton searches

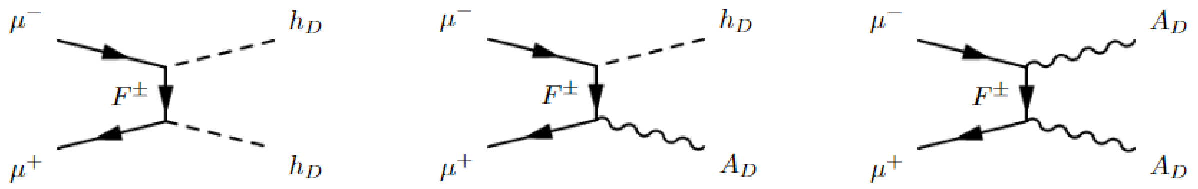
$$M_E^{\pm} \geq 895 \text{ GeV}, \; M_L^{\pm} \geq 1050 \text{ GeV}$$

$y_E^{\pm}, y_L^{\pm}, y_{LE}^{\pm}$: perturbative unitarity

can do better at a (multi-TeV) muon collider: probe PM masses up to $\sqrt{s}/2$

$y_E^{\pm}, y_L^{\pm}$ constrained by monophoton searches

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



$SU(2)_A \times SU(2)_B \times Z_2$ model

Wojcik, LE, Eu Ximenes 2303.12983

Minimizing the potential:

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

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

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

$$\langle \Delta^x_A \rangle = r_\Delta v_\Phi s_{\theta_\Delta} c_{\phi_A} s_{\theta_A} \quad \langle \Delta^y_A \rangle = r_\Delta v_\Phi s_{\theta_\Delta} s_{\phi_A} s_{\theta_A} \quad \langle \Delta^z_A \rangle = r_\Delta v_\Phi s_{\theta_\Delta} c_{\theta_A} \qquad 0 \le \theta_\Delta \le \pi/2$$

$$\langle \Delta^x_B \rangle = r_\Delta v_\Phi c_{\theta_\Delta} c_{\phi_B} s_{\theta_B} \quad \langle \Delta^y_B \rangle = r_\Delta v_\Phi c_{\theta_\Delta} s_{\phi_B} s_{\theta_B} \quad \langle \Delta^z_B \rangle = r_\Delta v_\Phi c_{\theta_\Delta} c_{\theta_B} \qquad 0 \le \theta_{A,B} \le \pi \qquad 0 \le \phi_{A,B} \le 2\pi$$

3 inequivalent classes of vacua, all CP-preserving:

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

Scalar masses:

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

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

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

$$r_\Delta \ll 1$$

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

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

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

$$W_{l,h} \equiv h_3 \approx \cos\theta_\Delta(\Delta_B^x - r_\Delta v_\Phi \cos\theta_\Delta) + \sin\theta_\Delta(\Delta_A^x - r_\Delta v_\Phi \sin\theta_\Delta)$$

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 $W_{A,B}^\pm$ $\qquad M_{W_l} = \sin\theta_{lh} M_{Z_D} \qquad M_{W_h} = \cos\theta_{lh} M_{Z_D}$

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

Parameters of the extended 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