Lepton Flavor Portal Matter

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Based on 2211.09918 (PLB) and 2303.12983 with Lisa Everett, Shu Tian Eu, and George Wojcik

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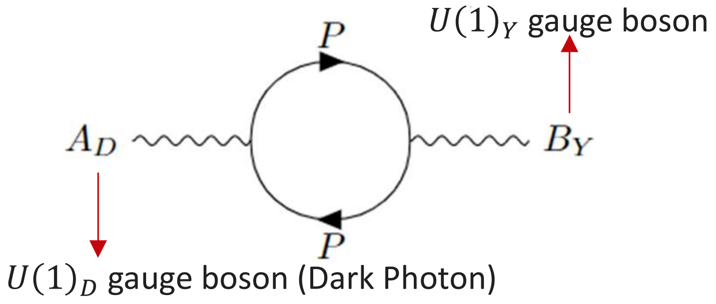
Vector Portal/Kinetic Mixing DM

- Vector portal matter (PM)[1,2] /kinetic mixing (KM) DM setup:

	G_{SM}	$U(1)_D$
SM	R_{SM}	0
DM (χ)	1_0	$\neq 0$
PM (P)	R_{PM}	$\neq 0$

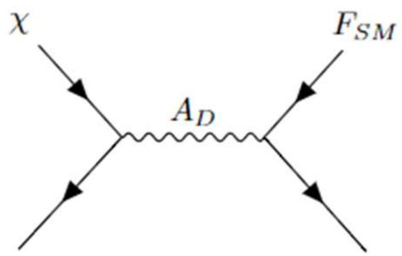


$U(1)_Y$ gauge boson

$U(1)_D$ gauge boson (Dark Photon)

- KM $\sim \frac{\epsilon}{2c_w} B_{\mu\nu} A_D^{\mu\nu}$ and $\epsilon \ll 1 \Rightarrow Q_D^{SM} \sim \epsilon Q_{em}$
- For $\mathrm{m_{DM,A_D}} \sim 0.1 - 1$ GeV and $\epsilon \sim 10^{-(3-5)}$

We can recreate the correct relic abundance!



- Nature of PM?
  - Precision electroweak constraints and $H \to gg, \gamma\gamma \Rightarrow$ Must be **Vector-like (VL)**!
  - VL PM must be unstable. Without adding more particles, the only possibility is $F_{PM} \to F_{SM} h_D \Rightarrow$ PM is either a VL Quark (VLQ) or **VL Lepton (VLL).** In this work we focus on VLL.

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[1] B. Holdom, Phys. Lett. B **166**, 196 (1986)

[2] B. Holdom, Phys. Lett. B **178**, 65 (1986)

PM/KM DM and coming up!

- Collider searches for VLL PM sugges $M_{PM} \geq 1$ TeV.
- For a set of VL PM, kinetic mixing coefficient $\epsilon \propto \sum_i Q_{Y_i} Q_{D_i} \log \frac{m_i^2}{\mu^2}$.
- Finite and calculable ϵ? $\sum_i Q_{Y_i} Q_{D_i} = 0$.
- $\epsilon \sim 10^{-(3-5)}$ can be achieved with PM fields coming in pairs with $Q_D = \pm 1$, same Q_Y and $O(1)$ mas splitting.
- The discrepancy between the measured value of a_μ and the theoretical expectation of the SM at (significance of 4.2σ) is currently placed at[1,2,3]

$$\Delta a_\mu = a_\mu^{exp} - a_\mu^{SM} = (251 \pm 59) \times 10^{-1}$$

- Assuming the discrepancy is due to new physics, we show that Δa_μ can be addressed in a minimal PM/KM model agnostic to the DM details.
- We present an embedding of $U(1)_D$ into a larger dark group of $SU(2)_A \otimes SU(2)_B \otimes Z_2$and explore its rich scalar and fermion sectors.

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[1] b. Abi *et al.* (Muon g-2), Phys. Rev. Lett. **126**, 141801 (2021), arXiv:2104.03281 [hep-ex]

[2] g. W. Bennett *et al.* (Muon g-2), Phys. Rev. D **73**, 072003 (2006), arxiv:hep-ex/0602035

[3] t. Aoyama *et al.*, Phys Rept. **887**, 1 (2020), arXiv:2006.04822 [hep-ph]

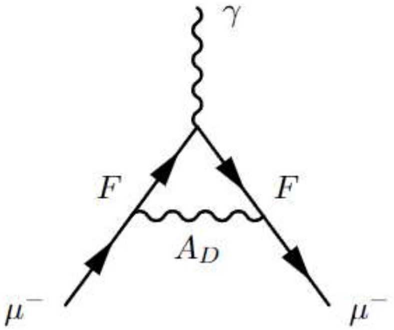
Minimal Construction

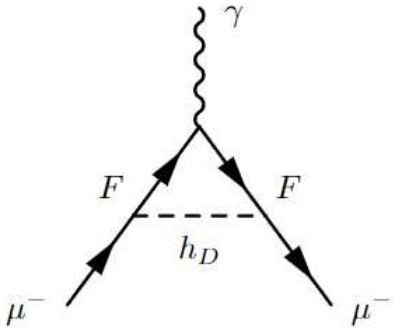
Field	$\boldsymbol{SU(2)_L \times U(1)_Y}$	$\boldsymbol{Q_D}$
$\boldsymbol{l_L} = (\nu_L^\mu, \mu_L)^T$	$\left(\mathbf{2}, -\frac{1}{2}\right)$	0
μ_R	$(\mathbf{1}, -1)$	0
$\boldsymbol{L_{L,R}^\pm} = (N_{L,R}^\pm, L_{L,R}^\pm)^T$	$\left(\mathbf{2}, -\frac{1}{2}\right)$	± 1
$E_{L,R}^\pm$	$(\mathbf{1},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

$$\begin{pmatrix} \bar{\mu}_L & \bar{L}_L^+ & \bar{E}_L^+ & \dots \end{pmatrix} \begin{pmatrix} m_\mu & y_{SL}^+ v_S & 0 & \\ 0 & M_L^+ & e^{i\phi_{LE}^+} \frac{y_{LE}^+}{y_\mu} m_\mu & \vdots \\ y_{SE}^+ v_S & e^{i\phi_{EL}^+} \frac{y_{EL}^+}{y_\mu} m_\mu & M_E^+ & \\ & \dots & & \ddots \end{pmatrix} \begin{pmatrix} \mu_R \\ L_R^+ \\ E_R^+ \\ \vdots \end{pmatrix}$$

- Five chirality-flipping masses:

$$m_\mu,\ e^{i\phi_{LE}^\pm} \frac{y_{LE}^\pm}{y_\mu} m_\mu,\ e^{i\phi_{EL}^\pm} \frac{y_{EL}^\pm}{y_\mu} m_\mu$$





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

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

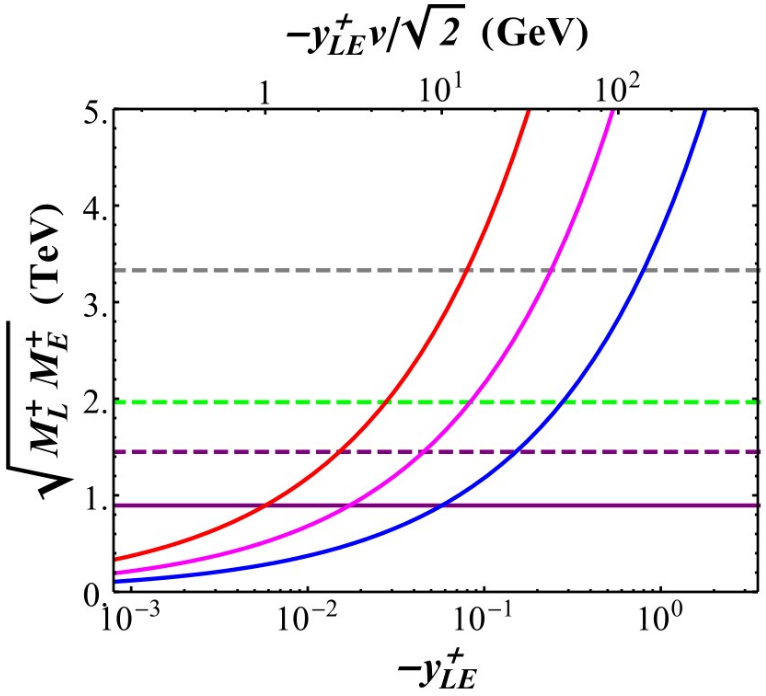
- Independent of parameters which govern the phenomenology of the dark sector!

PM Collider Production

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

- Plot of $\sqrt{M_L^+ M_E^+}$ as a function of y_{LE}^+ to reproduce Δa_μ :

- Continuous lines indicates the plots for $y_L^+ y_E^+ = 0.3, 1, 3$.
- Vertical lines indicate LHC, HL-LHC, HE-LHC, *hh*-FCC constraints on M_E^+.
- Observed anomaly can be accounted for with $\frac{y_{LE}^\pm}{y_\mu} \sim O(10)$, $M_{L,E}^\pm \sim O(\text{TeV})$.



$\boldsymbol{SU(2)_A \otimes SU(2)_B \otimes Z_2}$ Model

- Why embed $U(1)_D$ into a larger group?
  - Justify a priory arbitrary $U(1)_D$ charge assignments.
  - Natural reason for the flavor symmetry.
- Anomaly-free embedding with finite KM for $\boldsymbol{SU(2)_A \otimes SU(2)_B \otimes Z_2}$

$$SU(2)_A \times SU(2)_B \times Z_2 \xrightarrow{\langle\Phi\rangle\sim\mathrm{TeV}} U(1)_D \times Z_2 \xrightarrow{\langle\Delta_{A,B}\rangle\sim\mathrm{GeV}} Z_2'$$

Fields	$\boldsymbol{SU(2)_L \times U(1)_Y}$	$\boldsymbol{SU(2)_A}$	$\boldsymbol{SU(2)_B}$	$\boldsymbol{Z_2}$
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

Scalar Sector

$$SU(2)_A \times SU(2)_B \times Z_2 \xrightarrow{\langle\Phi\rangle\sim\text{TeV}} U(1)_D \times Z_2 \xrightarrow{\langle\Delta_{A,B}\rangle\sim\text{GeV}} Z_2'$$

- Scalar potential for this model is quite complicated ($8+3+3=14$ variables).
- There are 6 Goldstone modes (broken generators of $SU(2)_A \otimes SU(2)_B$) and $14-6=8$ massive states.

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

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	$m_{A_D} \sim \text{GeV}$	$+1$	$*$

Fermion Sector

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

- The Z_2' symmetry provides charged Lepton flavor protection.
- $Z_2' -$ positive block: One SM Lepton and Two heavy VLL.
- $Z_2' -$ Negative block: One SM Lepton and Two heavy VLL PM.
- Two scenarios of interest:

SM Field	Scenario A	Scenario B
Muon	e_a	e_b
Tau	e_b	e_a

Coming Up!

- Shu Tian's Flavor Portal Matter-II talk will discuss in scenarios A and B:
    - Muon $g-2$ anomaly: Contribution from new diagrams and bigger parameter space.
    - Rich phenomenology: Diboson, VLL and VLL PM collider production.

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