Portal Matter & Kinetic Mixing Phenomenology
A popular mediator particle for SM - Dark Sector interactions is the Dark Photon which kinetically mixes with the SM hypercharge B:

\[ \mathcal{L}_1 = -\frac{1}{4} \hat{V}_{\mu\nu} \hat{V}^{\mu\nu} - \frac{1}{4} \hat{B}_{\mu\nu} \hat{B}^{\mu\nu} + \frac{\epsilon}{2c_w} \hat{V}_{\mu\nu} \hat{B}^{\mu\nu} + \mathcal{L}_{SM} \]

\[ \mathcal{L}_2 = i \bar{\chi} \gamma^\mu D_\mu \chi - m_D \bar{\chi} \chi + (D_\mu S)^\dagger (D^\mu S) + \mu_S^2 S^\dagger S - \lambda_S (S^\dagger S)^2 \]

Complex SM singlet Dark Higgs, S, gives mass to the DP (vev = v_\text{s}) & CP-odd part becomes the DP Goldstone boson.

KM is loop generated by Portal Matter (here fermions, F_i) w/ both SM & dark charges

\( \epsilon = \) strength of the KM – expected to be finite in a UV theory
\[ \epsilon = c_W \frac{g_D g_Y}{12\pi^2} \sum_i Q_{Y_i} Q_{D_i} \ln \frac{m_i^2}{\mu^2} \quad \text{is finite if} \quad \sum_i Q_{Y_i} Q_{D_i} = 0 \]

But What is Portal Matter & What Does it Do??

- To avoid gauge/gravity anomalies & not conflict with precision data PM must be vector-like wrt the SM x U(1)\(_D\).
- To insure that PM can decay rapidly enough to avoid cosmological constraints there must be SM – PM (e.g., S-induced) mixing:

\[ \mathcal{L}_{Portal} = \lambda_1 f_1 L f_R^a S + \lambda_2 f_2 L f_R^a S^\dagger + h.c. \quad \text{w/ } \lambda_i \text{ being } O(1) \]

→ Since S is a SM singlet, PM must transform as (some number of) VL copies of at least one of the usual SM fermion representations:

\[ (T, B)^T, \quad (N, E)^T, \quad T, \quad B, \quad E \]
While restrictive, these constraints can lead to many phenomenologically distinct & interesting scenarios...

- **Simplest case**: PM = 2 copies of the same field w/ opposite dark charges

Then:

\[
\epsilon \simeq 1.0 \left( \frac{g_D}{0.1} \right) N_c Q_Y \frac{\ln(m_2/m_1)}{\ln 1.5} \cdot 10^{-4}
\]

which works well in our mass range of interest, i.e., \( m_V < \sim 1 \text{ GeV} \)

**A much more interesting case:** Cancellations occur between fields in different SM representations, e.g., those in a 5+5-bar of SU(5)

→ Will only consider the simplest case (time constraints!)

(simplest)² case → PM = EWK isosinglet, e.g., \( \sim E \) or \( \sim B \)
• DP have multiple interactions: $g_D Q_D$ with DM, $\epsilon e Q_{em}$ w/ SM via KM + new ones induced by mixing between SM & PM which are both ‘diagonal’ & ‘off-diagonal’.

• Three general effects follow from this mixing:

(i) The SM $f$ whose PM ‘partner’ is $F$ with the same SM QN’s has a parity-violating interaction with the DP -- can be $O(\epsilon)$ & compete with the usual interactions. If $f=e$, can lead to effects in, e.g., APV & polarized Moller scattering:

$$\left[ -ee \bar{e} \gamma_\mu e + g_D (C_R)_{11} \bar{e} \gamma_\mu P R e \right] V^\mu \equiv -ee \bar{e} \gamma_\mu (v_e - a_e \gamma_5)e V^\mu$$

$$v_e = 1 - y \quad a_e = -y \quad y = g_D (C_R)_{11}/2ee \sim <O(1)$$

$$\rightarrow \Delta Q_W^V (C's) \simeq -1.22 y \left( \frac{100\text{MeV}}{m_V} \right)^2 \left( \frac{\epsilon}{10^{-4}} \right)^2$$
For any given value of $y \neq 0$ we obtain an upper bound on $\varepsilon$ as a function of the dark photon mass.

$$\Delta x_W \simeq 5.56 \cdot 10^{-3} \; y \left( \frac{100\text{MeV}}{m_V} \right)^2 \left( \frac{\varepsilon}{10^{-4}} \right)^2 \frac{m_V^2}{<Q^2> + m_V^2}.$$
(ii) Due to new FfV & FfS couplings (besides the P.V. ffV ones) when $f=\mu$ new contributions to $g$-2 appear & can be significant. E.g., in addition to $V+\mu$ (now w/ P.V. couplings!), $V+F$ and $S+F$ loops appear.

For much of our parameter range the contributions are either too small to be relevant and/or of the wrong sign: e.g., the P.V. $V+\mu$ contribution is given by

$$\Delta g_{\mu}^{V_1} = 10^{-11} \left( \frac{\epsilon}{10^{-4}} \right)^2 R(y, m_V)$$

which is generally $<0$ & small

$y = -0.5$ (red), -0.25 (bl), 0 (gr), 0.25 (mag), 0.5 (cy)
(iii) The dominant decay of VL F is to $f_{V_L}/f_S$ and not to the usual $f_Z/f_H$ or $f'W$ final states which are the modes searched for at LHC…

Why?

e.g., $\Gamma(F\to fZ) \sim g_w^2 \text{(mixing)}^2$ BUT

\[ \Gamma(F\to fV) \sim g_D^2 \text{(mixing)}^2 \left( \frac{m_F}{m_V} \right)^2 \sim \lambda^2 \sim \Gamma(F\to fS) \sim O(1) \text{ (Goldstone Thm)} \]

→ VLF signatures at the LHC will depend on what V & S do…

→ What are the V & S lifetimes & what are their decay products? Here $m_V < \sim 1 \text{ GeV}$ & similarly for $m_S$ up to $O(1)$ terms but likely $m_V / m_S = g_D / (2\lambda_S)^{1/2} < 1$

→→ Here we assume that V decays visibly, i.e., $m_V < 2m_{DM}$
Consider $F \sim B$ ... it is produced via QCD at LHC w/ $m_B \sim$ TeV

$gg, q\bar{q} \to B\bar{B}$ is large @ 14 TeV

$B \to bV, bS$ with equal rates (GThm)
(b, V, S massless relative to B)

→ 2 high-$p_T$ (b-)jets [+ VV, VS, SS] act as a trigger. Jets not back to back
→ B’s not very boosted → b-V(S) opening angles large

$\Gamma(V \to all) = \frac{\alpha e^2 m_V}{3 B_e} = 2.432 \cdot 10^{-9} \left(\frac{\epsilon}{10^{-4}}\right)^2 \left(\frac{m_V}{100 \text{MeV}}\right) \frac{1}{B_e} \text{MeV}$

→ un-boosted decay length of

$c\tau \simeq 81.44 \left(\frac{10^{-4}}{\epsilon}\right)^2 \left(\frac{100 \text{ MeV}}{m_V}\right) B_e \mu m$

but $\gamma \sim m_B / m_V$ is $\sim 10^{3-4}$!
What are the (highly) boosted decay lengths of V & S?

Strong sensitivity to $m_S/m_V$!

$$\Gamma(S \rightarrow VV) = \frac{g_D^2 m_S}{128\pi} \frac{1}{x_V} (1 - 4x_V)^{1/2} (1 - 4x_V + 12x_V^2)$$

$$x_V = \frac{m_V^2}{m_S^2}$$

for $m_S > 2 m_V$ leads to a prompt decay for S. …but…

$$\Gamma(S \rightarrow Ve^+e^-) = \frac{g_D^2 \alpha \epsilon^2 m_S}{96\pi^2} F(r) = 7.7 \cdot 10^{-16} m_S \left( \frac{g_D}{0.1} \right)^2 \left( \frac{\epsilon}{10^{-4}} \right)^2 F(r)$$

$$1/2 < r = m_V/m_S = \sqrt{x_V} < 1$$

Leads to a very long decay length for S

$$c\tau \simeq 170.8 \left( \frac{0.1}{g_D} \right)^2 \left( \frac{10^{-4}}{\epsilon} \right)^2 \left( \frac{150 \text{ MeV}}{m_S} \right) \frac{1}{F(r)} \text{ cm}$$
For V/S, to get an idea of the range of boosted decay lengths, d, scan the allowed $m_V - \epsilon$ parameter space. We assume $m_B = 1$ TeV w/ $m_V = 10^{1.5-3}$ MeV & $\epsilon = 10^{-(3.5-5)}$ w/ log priors.

V from primary decay: $B \rightarrow bV$

V from secondary decay: $B \rightarrow bS$, $S \rightarrow VV$

(2 < $m_V / m_S$ < 5 flat scan; S prompt)

S boosted decay length $B \rightarrow bS$

(1 < $m_V / m_S$ < 2 flat scan)

extends to very large values!
‘Trivial’ Case

If V/S both have large d the final state is 2 b-jets + MET as in bsquark production with a larger $\sigma$ but differing kinematics $\sigma \rightarrow m_B > \sim 1.5$ TeV

→ FASER or MATHUSLA ??

‘More Interesting’ Case

If d is not large V decays inside the detector → a very boosted lepton-jet

E.g., ATLAS l-j search from Higgs decay involve $\gamma < \sim 100$ .. here $\sim 10^{3-4}$ !

• Challenging for detectors due to tiny opening angles $\sim 1/10$ as large..

• BUT here we have 2 b-jets to act as a trigger unlike in the Higgs case
These opening angles are much smaller than in conventional l-j analyses - but here we have 2 b-jets as trigger.

← Number of l-j in a perfect ATLAS detector vs the V boosted decay length for L = 100 fb⁻¹

Should be visible if d < ~ 10² m given sufficient lumi.
Summary & Conclusions

• Toy models of Portal Matter consistent w/ all constraints have been constructed w/ unique implications for both low & high energy experiments

• The production of VL Portal Matter at the LHC leads to signals distinct from those currently sought for VL fermions OR lepton-jets

• The construction of more realistic, at least partially UV-complete models is underway & leads to all the signatures discussed here (+ new ones) & a unique identification of the DM state
Backup
Single B + V/S associated production can also be sizeable

\[ m_B = 2 \text{ TeV} \]