Portal Matter & Kinetic Mixing Phenomenology

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5/7/19

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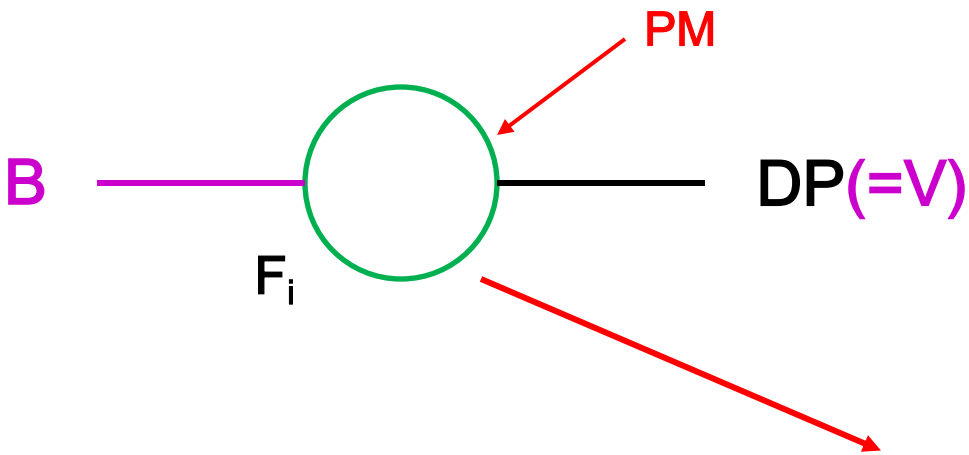
A popular mediator particle for SM - Dark Sector interactions is the Dark Photon which kinetically mixes with the SM hypercharge B:



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

ε = strength of the KM – expected to be finite in a UV theory

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

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

Complex SM singlet Dark Higgs, S, gives mass to the DP (vev = v_s) & CP-odd part becomes the DP Goldstone boson

→ $\epsilon = c_W \frac{g_D g_Y}{12\pi^2} \sum_i Q_{Y_i} Q_{D_i} \; ln \frac{m_i^2}{\mu^2}$ is finite if $\boxed{\sum_i Q_{Y_i} Q_{D_i} = 0}$

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:

$$\mathcal{L}_{Portal} = \lambda_{1a} \bar{F}_{1L} f_R^a S + \lambda_{2a} \bar{F}_{2L} f_R^a S^\dagger + h.c.$$

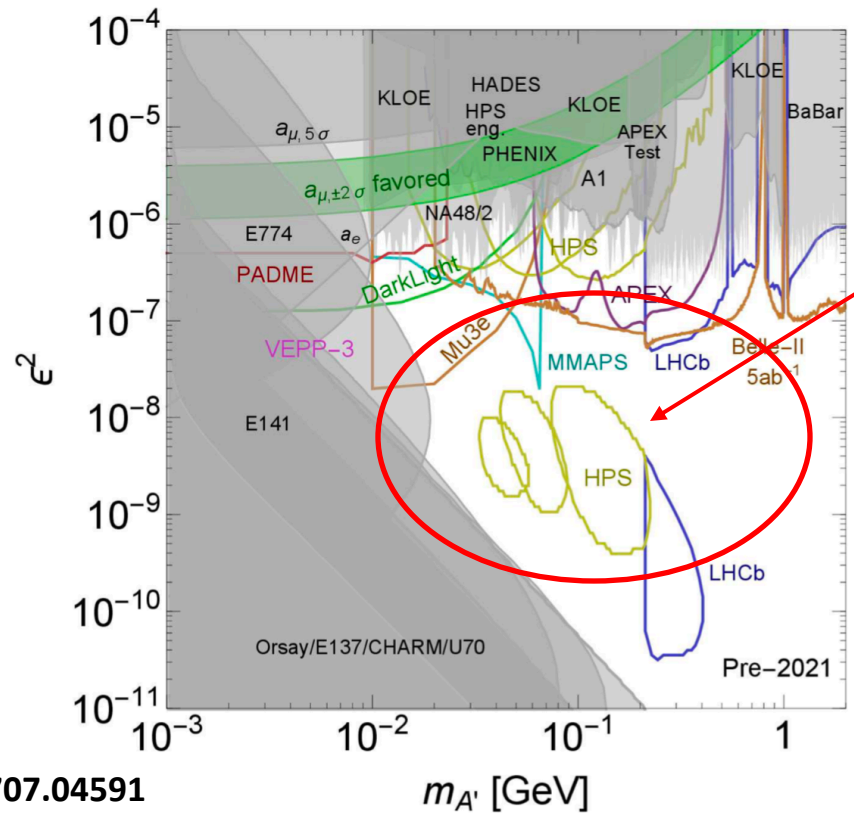
w/ λ_i being O(1)

→ 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:

$$(T, B)^T, \; (N, E)^T, \; T, \; B, \; E$$

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



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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 < ~1 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, ~ E or ~ B

- DP have multiple interactions: $g_D Q_D$ with DM, $\varepsilon e Q_{em}$ w/ SM via KM + new ones induced by mixing between SM & PM which are both 'diagonal' & 'off-diagonal'.

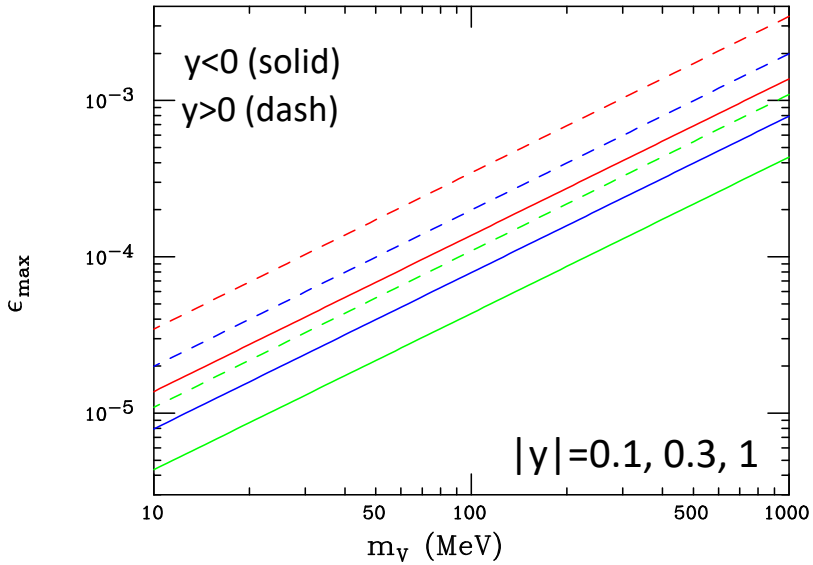
- Three general effects follow from this mixing:

(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(ε) & compete with the usual interactions. If f=e, can lead to effects in, e.g., APV & polarized Moller scattering:

$$\left[-e\epsilon\ \bar{e}\gamma_\mu e + \underline{g_D (C_R)_{11}\ \bar{e}\gamma_\mu P_R e}\right] V^\mu \equiv -e\epsilon\ \bar{e}\gamma_\mu (v_e - a_e\gamma_5) e V^\mu \qquad (C_R)_{11} \simeq 10^{-4}$$

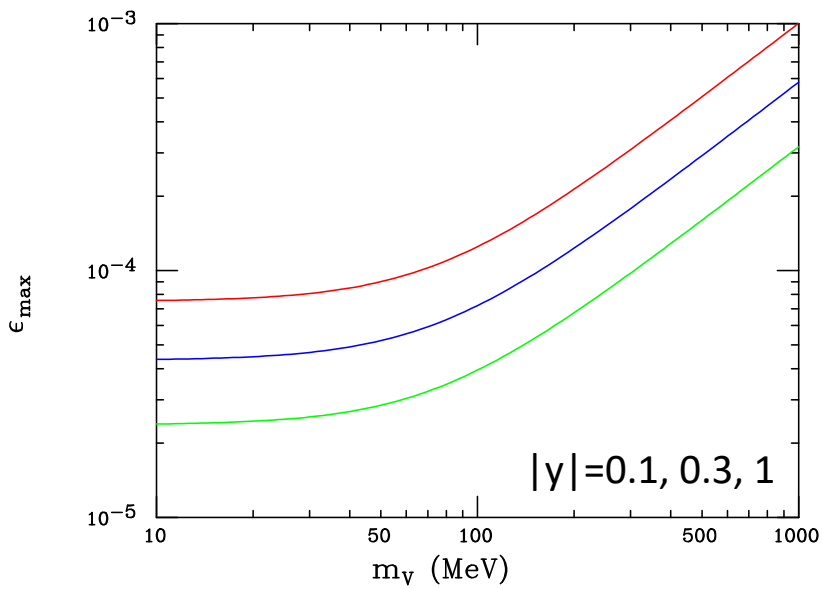
$$v_e = 1 - y \qquad a_e = -y \qquad y = g_D (C_R)_{11}/2e\epsilon \quad \sim <O(1)$$

$$\rightarrow\rightarrow \quad \Delta Q_W^V(Cs) \simeq -1.22\ y \left(\frac{100\text{MeV}}{m_V}\right)^2 \left(\frac{\epsilon}{10^{-4}}\right)^2 ,$$



← Current constraints from APV in Cs

For any given value of y≠ 0 we obtain an upper bound on ε as a function of the dark photon mass

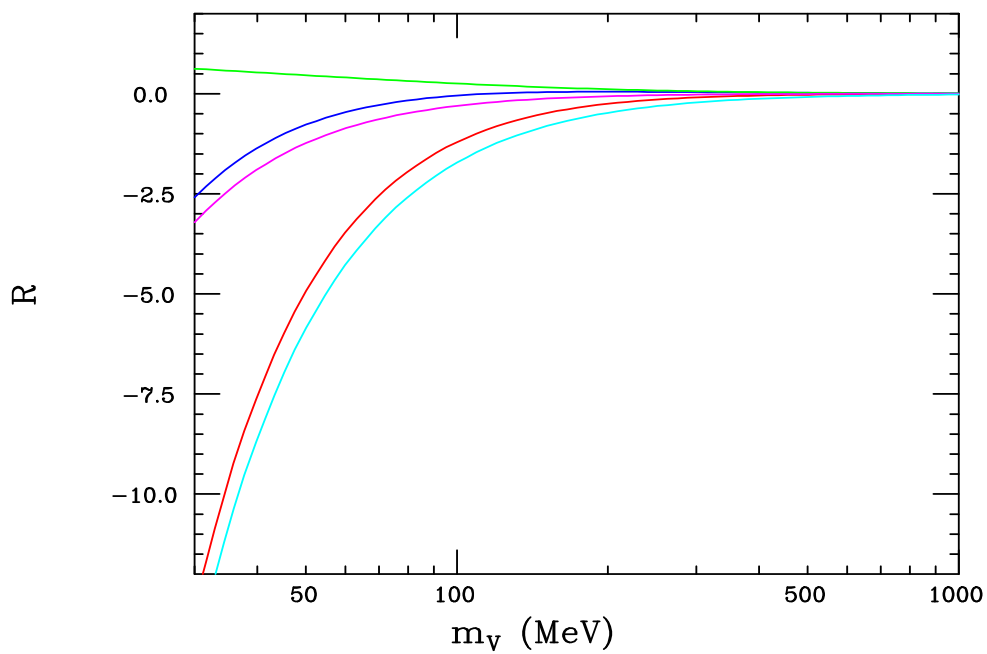


$$\Delta x_W \simeq 5.56 \cdot 10^{-3}\, y \left(\frac{100\text{MeV}}{m_V}\right)^2 \left(\frac{\epsilon}{10^{-4}}\right)^2 \frac{m_V^2}{< Q^2 > + m_V^2}$$

← Future constraints from polarized Moller scattering if the SM result realized

(ii) Due to new FfV & FfS couplings (besides the P.V. ffV ones) when f=μ new contributions to g-2 appear & can be significant. E.g., in addition to V+μ (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+μ 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 fV_L / fS and not to the usual fZ / fH 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

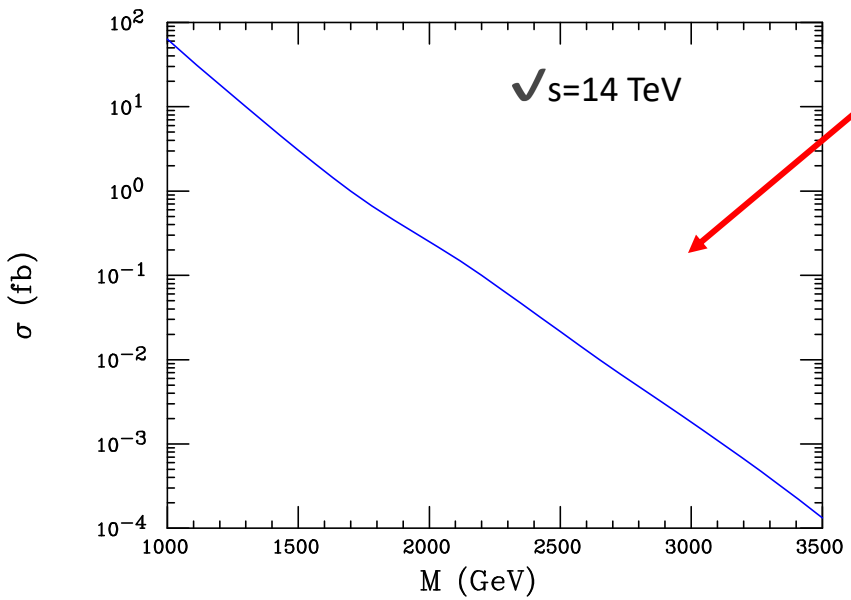
$\Gamma(F \to fV) \sim g_D^2\,(\text{mixing})^2\,(m_F/m_V)^2 \sim \lambda^2 \sim \Gamma(F \to fS)\ [\sim O(1)]$ (Goldstone Thm)

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

→ What are the V & S lifetimes & what are their decay products? Here $m_V < \sim 1$ 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 ~ B … it is produced via QCD at LHC w/ m_B ~ TeV



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

B → 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

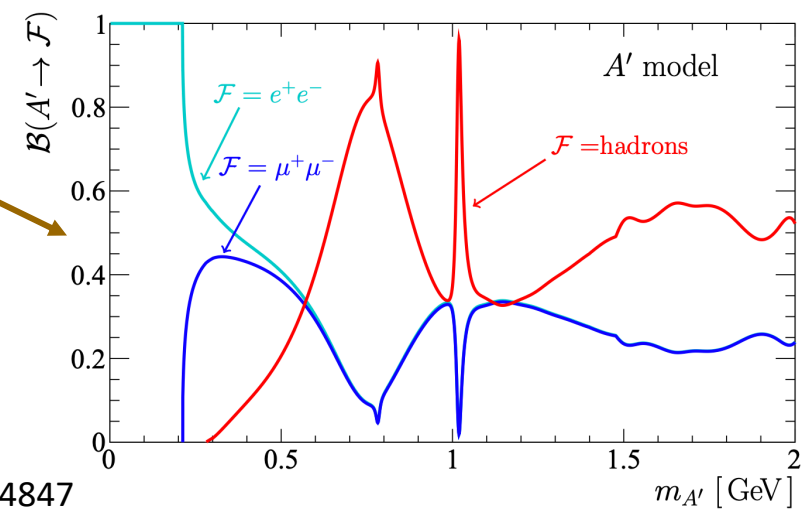
→ B's not very boosted → b-V(S) opening angles large

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

→ 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 γ ~ m_B /m_V is ~ $10^{3\text{-}4}$!



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→ What are the (highly) boosted decay lengths of V & S ?

S ?

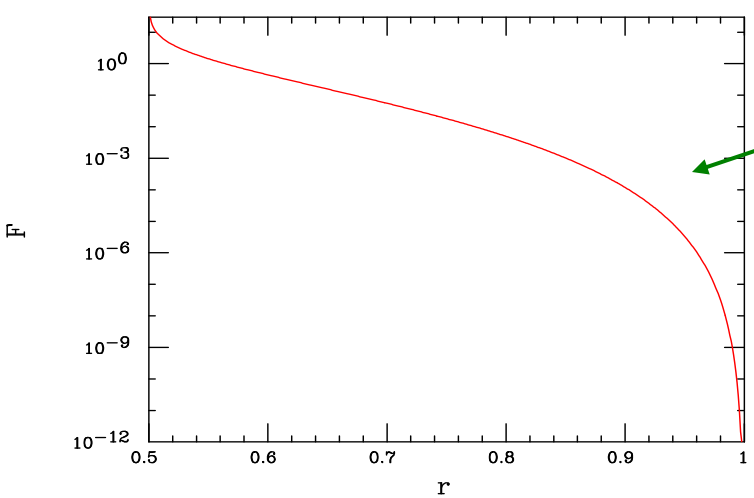
Strong sensitivity to m_S/m_V !

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

$$x_V = m_V^2/m_S^2$$

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

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



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

Leads to a very long decay length for S

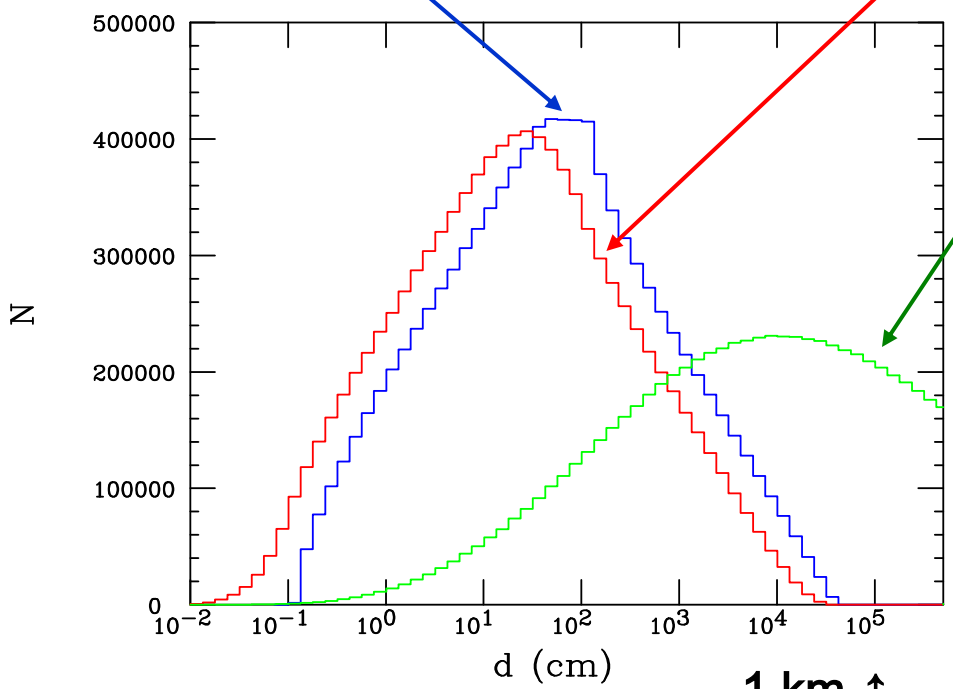
$$c\tau \simeq 170.8 \left(\frac{0.1}{g_D}\right)^2 \left(\frac{10^{-4}}{\epsilon}\right)^2 \left(\frac{150\ \text{MeV}}{m_S}\right)\frac{1}{F(r)}\ \text{cm}$$

For V/S, to get an idea of the range of boosted decay lengths, d, scan the allowed $m_V - \varepsilon$ parameter space. We assume m_B = 1 TeV w/ $m_V = 10^{1.5-3}$ MeV & $\varepsilon = 10^{-(3.5-5)}$ w/ log priors.

V from primary decay: B→bV

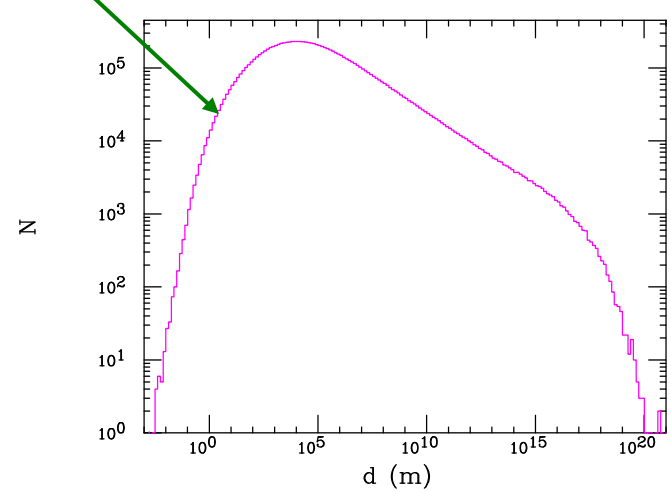
V from secondary decay: B→bS, S→VV
($2 < m_V / m_S < 5$ flat scan; S prompt)

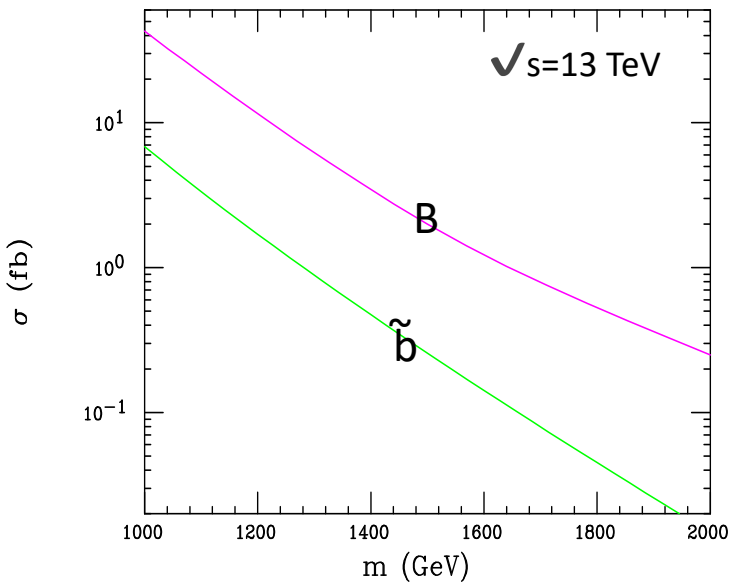
S boosted decay length B→bS
($1 < m_V / m_S < 2$ flat scan)
extends to very large values !



1 km ↑

1 meter ↑





'Trivial' Case

If V/S both have large d the final state is 2 b-jets + MET as in bsquark production with a larger σ but differing kinematics

σ → m_B > ~1.5 TeV

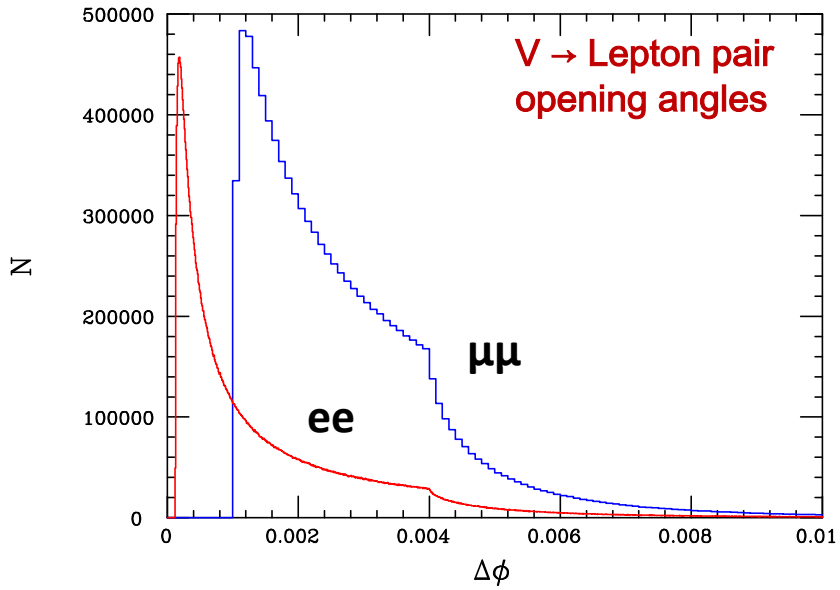
→ FASER or MATHUSLA ??

'More Interesting' Case

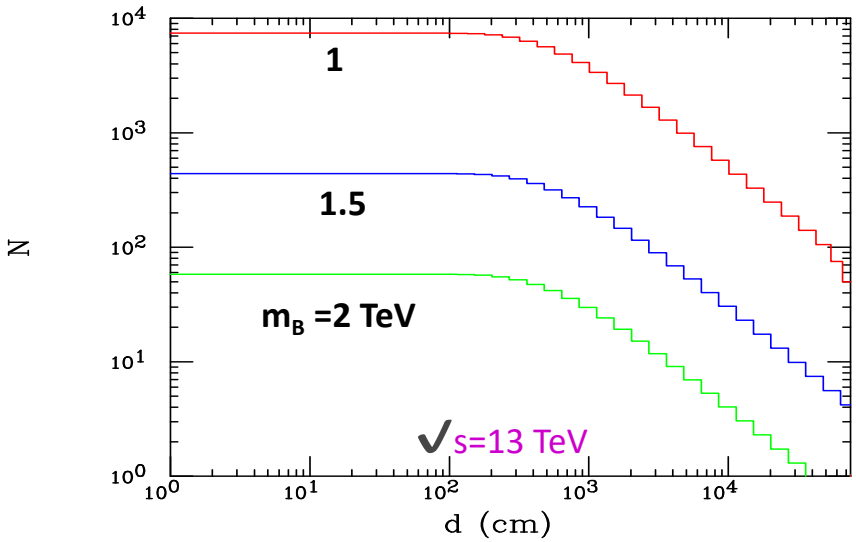
If d is not large V decays inside the detector → a very boosted lepton-jet

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

- Challenging for detectors due to tiny opening angles ~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 < ~ 10^2 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