Portal Matter Model Building for g-2

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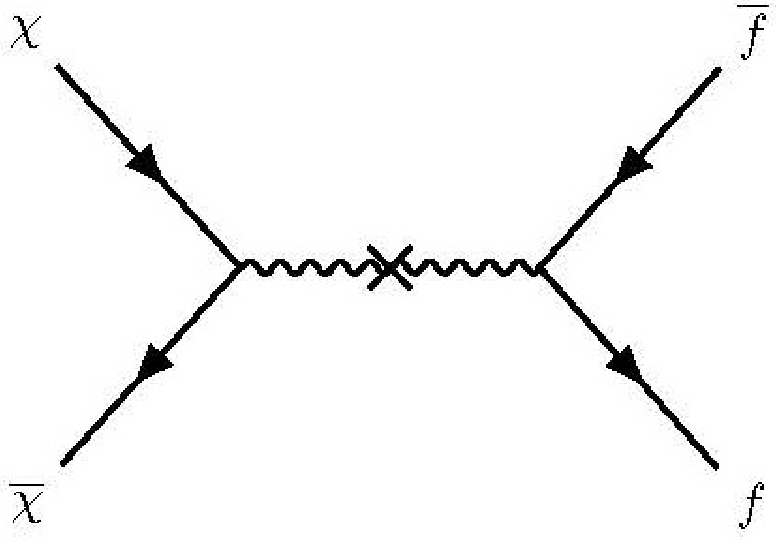
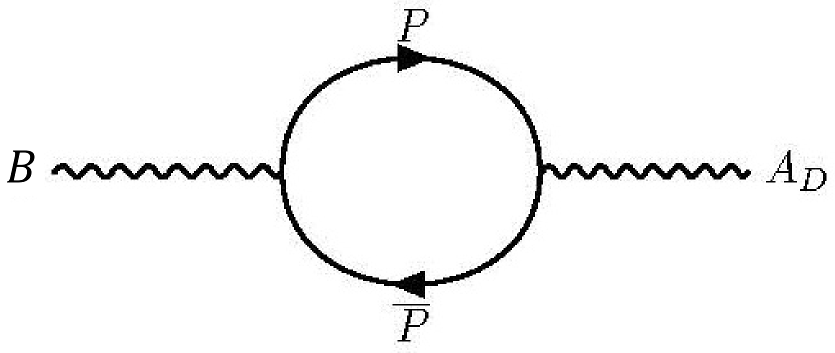
Vector Portal/Kinetic Mixing DM

- One popular idea: Dark Matter (DM) is a particle χ that interacts only with a new "dark force" given by the gauge group $U(1)_D$.
- The Standard Model (SM) is entirely uncharged under $U(1)_D$.
- Interaction between the SM and DM is achieved via kinetic mixing: $\sim \frac{\epsilon}{2\, c_W} B_{\mu\nu} A_D^{\mu\nu}$.
- So, SM now couples with strength $\sim \epsilon e Q$ to A_D.
- $m_{DM}, m_{A_D} \sim 0.1 - 1$ GeV, $\epsilon \sim 10^{-(3-5)}$ reproduces the correct relic abundance without running afoul of other experimental constraints.
- Portal Matter: How do we generate ϵ?



Portal Matter: Origins of ϵ

- The minimal setup: DM and a dark photon A_D. The small parameter ϵ is added by hand.
- By asking where ϵ comes from, can we get a window into higher-energy physics?
- A natural source for $\epsilon \sim 10^{-(3-5)}$ would be *portal matter*: Heavy particles charged under both $U(1)_D$ *and* SM hypercharge. [1,2] Call the particle P, for portal matter.
- To get *finite* and *calculable* ϵ, we need $\sum Q_{Y_i} Q_{D_i} = 0$ to eliminate dependence on the renormalization scale μ.



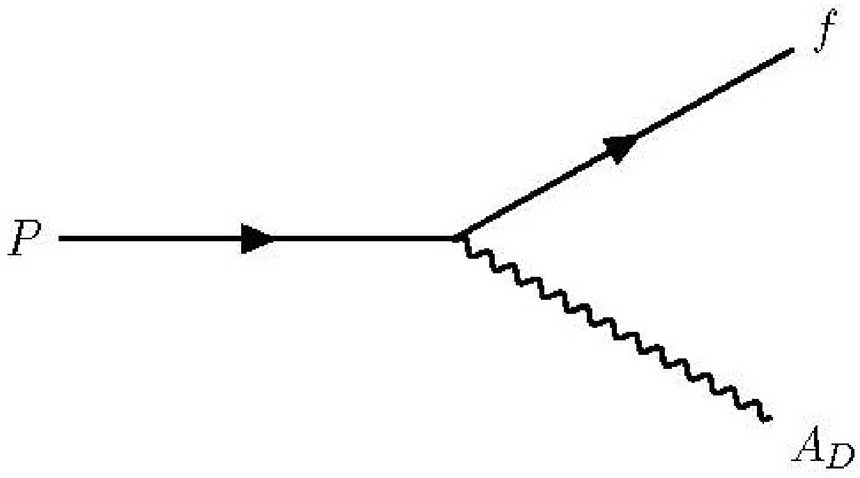
$$\epsilon \propto \sum_i Q_{Y_i} Q_{D_i} \log\left(\frac{m_i^2}{\mu^2}\right)$$

Portal Matter Theory 101

- What can we say about the portal matter? For this talk, we'll stick to fermionic portal matter.
  1) Precision electroweak constraints, $H \rightarrow gg, \gamma\gamma$ branching ratio → P is **vector-like**.
  2) If it's light enough to be thermally produced after reheating, it needs to decay before BBN
- How to get it to decay? Decay has to violate $U(1)_D$, and therefore should come from coupling to the scalar(s) that break that symmetry.
- Simplest path: Portal Matter has the same SM quantum numbers as some SM fermion and mixes with it (easy)

Portal Matter Phenomenology 101

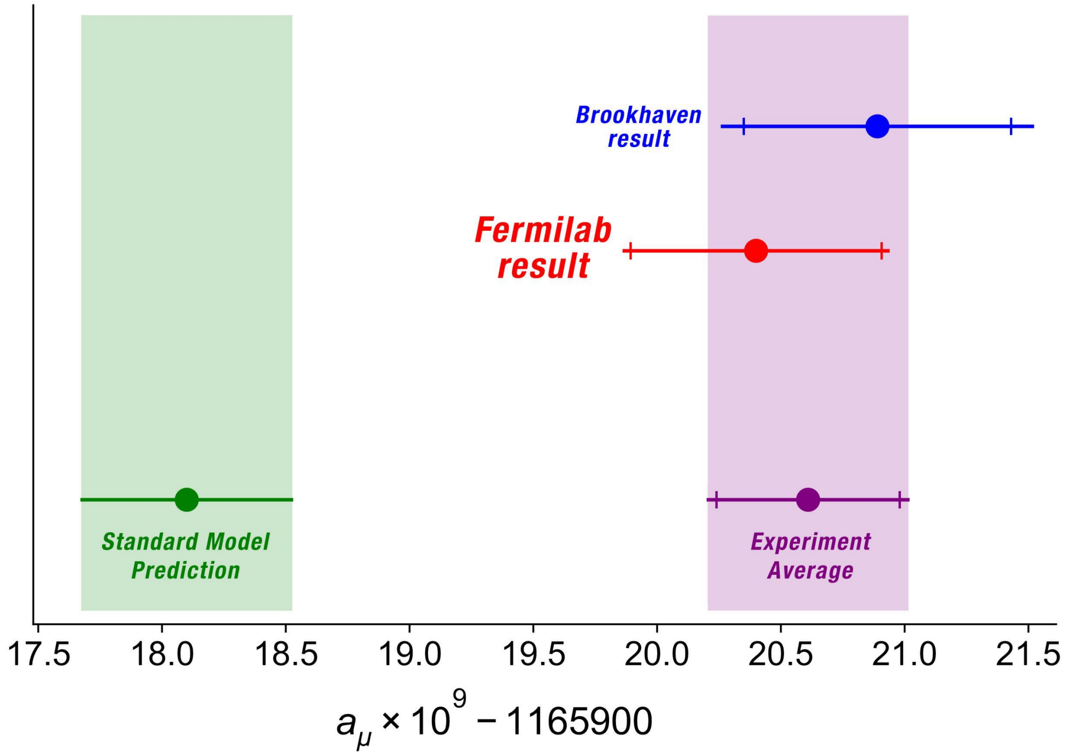
- So we're looking for a portal matter ensemble that satisfies:
  1) All P are vector-like copies of SM fermions, but with $U(1)_D$ charge.
  2) Ensemble satisfies $\sum Q_{Y_i} Q_{D_i} = 0$
- **Highly suppressed** decay via regular vector-like fermion decay channels, e.g. $P \to f\ Z$, instead dominantly decays via $P \to f\ A_D, h_D$.
- Collider signature is then a **highly boosted** SM fermion (or jet) plus A_D or h_D.
- A_D, h_D signatures are model-dependent: May decay invisibly (to dark matter) or visibly (to light SM fermions)
- Leads to atypical signatures (e.g., displaced lepton-jets, slepton-like signatures).[1,2]



[1]T. G. RIZZO, PHYS. REV D **99**, NO.11, 115024 (2019) [ARXIV:1810.07531 [HEP-PH]]
[2]T. D. REUTER AND T. G. RIZZO, PHYS. REV. D **101**, NO.1, 015014 (2020) [ARXIV:1909.09160 [HEP-PH]]

Muon $g - 2$

- An obvious question: Can portal matter address other mysteries in physics? Let's focus on one: **Muon anomalous magnetic moment**
- $4.2\ \sigma$ discrepancy between SM expectation and experiment [1,2,3]:
  $$\Delta a_\mu = a_\mu^{\text{exp}} - a_\mu^{\text{SM}} = (251 \pm 59) \times 10^{-11}$$
- Why? Could be hadronic vacuum polarization is wrong[4]
- Could be **new physics**



[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]
[4]S. BORSANYI *ET AL.*, NATURE **593**, 51 (2021), ARXIV:2002.12347 [HEP-LAT]

The BSM $g-2$ Cookbook

- Three habits of highly effective $g-2$ models:
    1) Couple something new to the muon, or you won't change its magnetic moment.
    2) New physics should have a scale $< O(10\ \mathrm{TeV})$, or your correction will be too small.
    3) New physics couples to *both* chiralities μ_L and μ_R.
- Muon-mixed portal matter can do (1) and (2).
- Doesn't do so well at (3)– Only chirality violation is from m_μ, and falls short by an order of magnitude

A Minimal Workable Framework

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
$\boldsymbol{L^\pm_{L,R}} = (N^\pm_{L,R}, L^\pm_{L,R})^T$	$\left(\mathbf{2}, -\frac{1}{2}\right)$	± 1
$E^\pm_{L,R}$	$(\mathbf{1}, -1)$	± 1
$S = v_S + (h_D + i\,\sigma_D)/\sqrt{2}$	$(\mathbf{1}, 0)$	$+1$

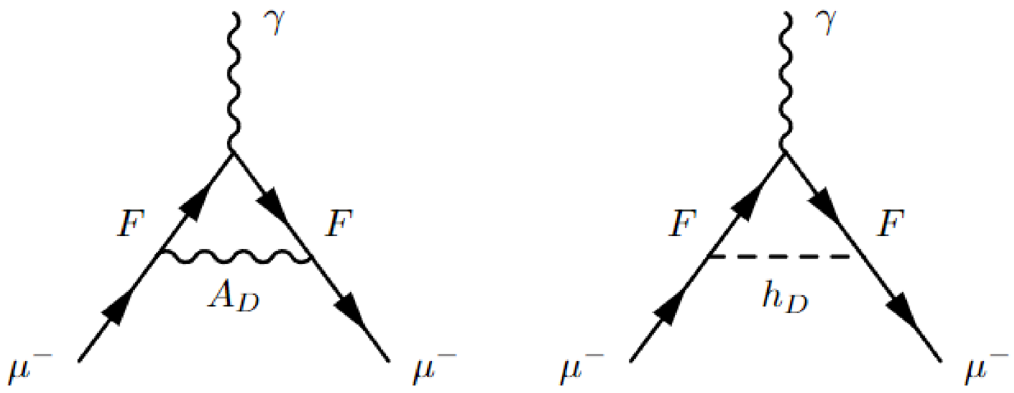
$$(\bar{\mu}_L \quad \bar{L}^+_L \quad \bar{E}^+_L \quad \ldots) \begin{pmatrix} m_\mu & y^+_{SL}\, v_S & 0 & \\ 0 & M^+_L & e^{i\phi^+_{LE}} \frac{y^+_{LE}}{y_\mu} m_\mu & \vdots \\ y^+_{SE}\, v_S & e^{i\phi^+_{EL}} \frac{y^+_{EL}}{y_\mu} m_\mu & M^+_E & \\ & \cdots & & \ddots \end{pmatrix} \begin{pmatrix} \mu_R \\ L^+_R \\ E^+_R \\ \vdots \end{pmatrix}$$

- There are 5 chirality-flipping masses: $m_\mu, e^{i\phi^\pm_{EL}} \frac{y^\pm_{EL}}{y_\mu} m_\mu, e^{i\phi^\pm_{LE}} \frac{y^\pm_{LE}}{y_\mu} m_\mu$.[1]
- Naively, $y^\pm_{EL,LE}$ can be $\gg y_\mu \sim 10^{-4}$
- In this basis, all Yukawas are positive, only complex phases are ϕ's

[1]A.E. CARCAMO HERNANDEZ, S. F. KING, H.LEE, AND S.J. ROWLEY, PHYS REV D **101** 115016 (2020), [ARXIV:1910.10734 [HEP-PH]]

$g-2$ in the Minimal Model

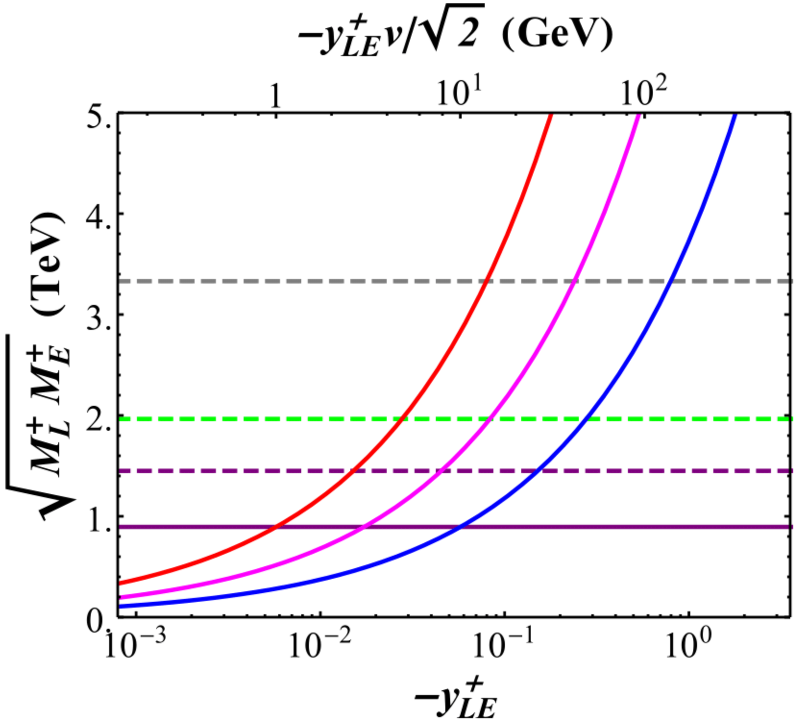
- Observed anomaly is entirely accounted for with $y_{LE}^{\pm}/y_{\mu} \sim O(10)$, $M_{L,E}^{\pm} \sim O(\text{TeV})$
- Light dark Higgs, dark photon means that there is *no* dependence on any parameters that directly enter the simplified dark matter model– this is entirely a portal matter effect.
- The physical phases $\phi_{LE}^{\pm}$ are critical to generating the correct sign correction here



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

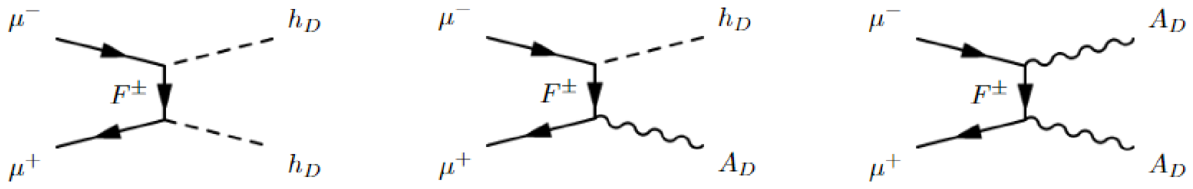
Portal Matter Collider Production

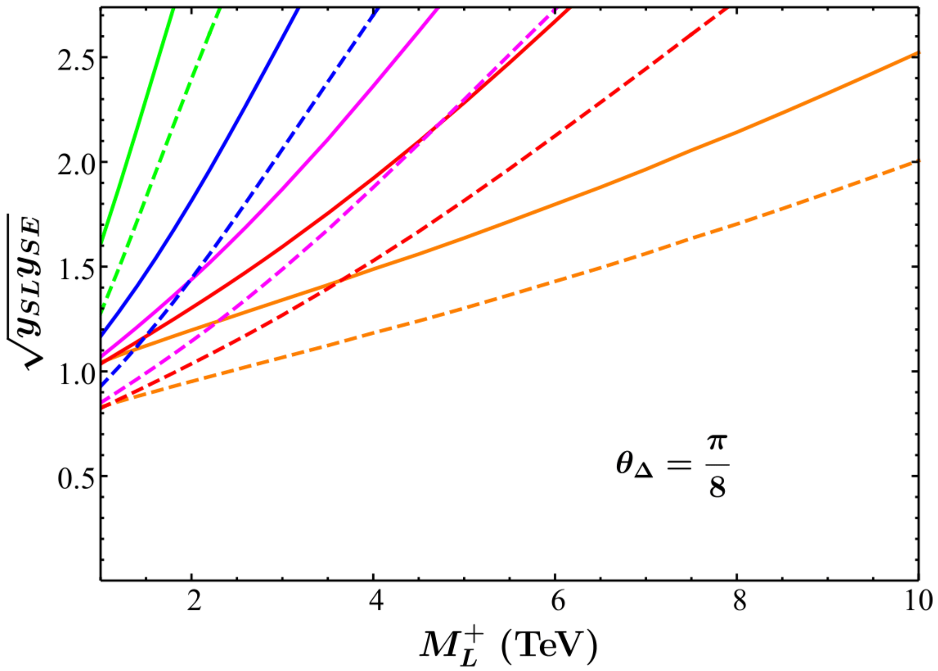
- First step in constraining the model: Limits on portal matter masses.
- On the right, we have the $\sqrt{M_L^+ M_E^+}$ needed to recreate Δa_μ, plus LHC constraints on M_E^+, as well as HL-LHC, HE-LHC, *hh*-FCC[1]
- $y_{LE}^{\pm}, y_{SL,SE}^{\pm}$ can only be constrained (at LHC) by perturbative unitarity.
- Multi-TeV muon collider can do better, probing portal matter masses up to $\lesssim \sqrt{s}/2$ *and* constraining $y_{SL,SE}^{\pm}$



Portal Matter Monophoton Signal

- With a muon collider, we could constrain $\Delta a_\mu \propto y^{\pm}_{SL} y^{\pm}_{SE}$ through monophoton events
- On the right, estimated discovery (solid) and exclusion (dashed) reach for c.o.m. energies of 3, 6, 10, 14, 30 TeV
- Feasible* to probe region $y^{\pm}_{SL,SE} \sim O(1)$, which is exactly what we need!





Conclusions

- Portal matter provides guidance to BSM model building, with ready constraints from searches for distinctive vector-like fermions
- Example: Muon $g-2$ model building led us to a new parameter space
- In the muon $g-2$ model, parameter space that explains the anomaly can be readily probed in a multi-TeV muon collider

Thank You!