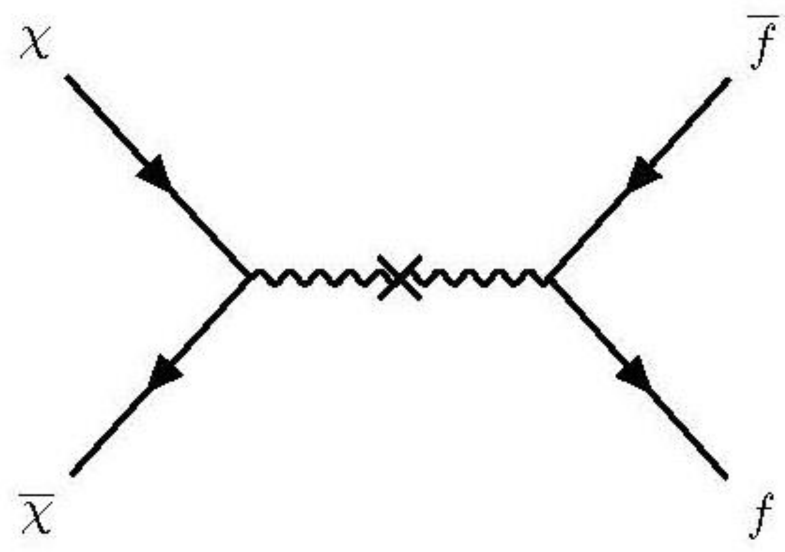
Kaluza Klein Portal Matter

GEORGE WOJCIK

BASED ON ARXIV:2205.11545 BY G. N. WOJCIK

Vector Portal/Kinetic Mixing DM

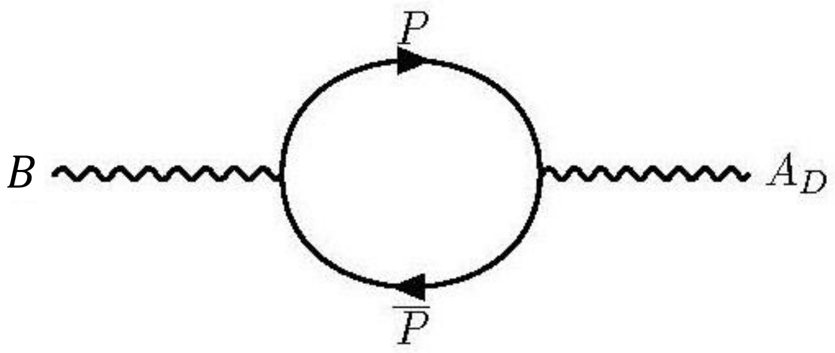
- WIMP miracle: $\langle \sigma v \rangle \sim g_D^4 / m_{DM}^2 \sim 10^{-26}\ \mathrm{cm^3 s^{-1}}$
- If $g_D \sim g_{EW}, m_{DM} \sim \mathrm{TeV}$
- Expand this parameter space: DM is a particle χ that interacts only with a new “dark force” given by the gauge group $U(1)_D$. The portal is the dark $U(1)_D$ gauge boson A_D.
- The Standard Model (SM) is entirely uncharged under $U(1)_D$.
- So, SM now couples with strength $\sim \epsilon e Q$ to A_D.
- $m_{DM}, m_{A_D} \sim 0.1 - 1$ GeV, $\epsilon \sim 10^{-(3-4)}$ reproduces the correct relic abundance without running afoul of other experimental constraints.



$$\sim \frac{\epsilon}{2\, c_W} B_{\mu\nu} A_D^{\mu\nu}$$

Portal Matter: Origins of ϵ

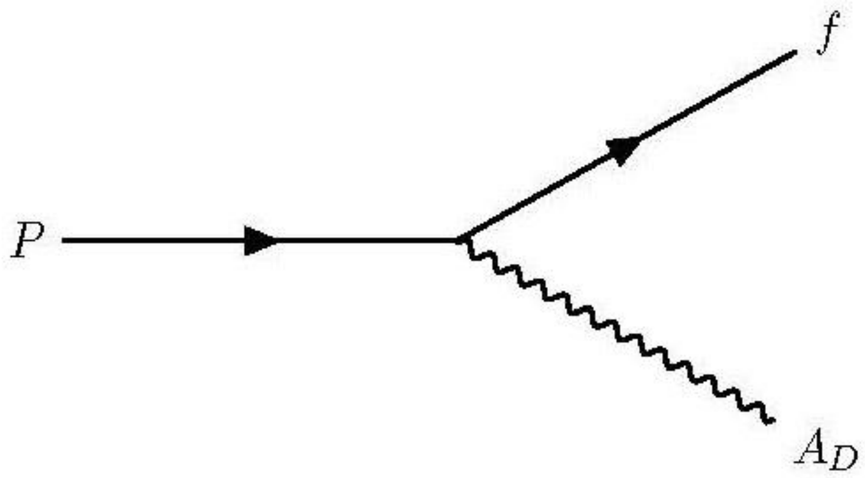
- The minimal setup: DM and a dark photon A_D. The small parameter ϵ is added by hand.
- By asking where ϵ comes from, can we get a window into higher-energy physics?
- A natural source for $\epsilon \sim 10^{-(3-4)}$ would be *portal matter*: Heavy particles charged under both $U(1)_D$ *and* SM hypercharge. 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 Phenomenology 101

- What can we say about portal matter? To keep it simple, we'll assume it's fermionic.
- Precision electroweak constraints, $H \to gg$ branching ratio → P is **vector-like**.
- Portal matter has SM charge, so it has to decay quickly (cosmological measurements).
- If portal matter P is a copy of an SM particle f, it can mix with that particle and decay via $P \to f\ A_D$. Depending on parameter space, A_D decays to either dark matter or charged SM fermions.
- Simple portal matter can give atypical signatures (e.g., displaced lepton-jets).[1,2] **Highly suppressed** decay via regular vector-like fermion decay channels, e.g. $P \to f\ Z$



[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]]

Non-Minimal Portal Matter

- Minimal portal matter:
  - No structure for requiring ϵ finite
  - Only additional gauge group is $U(1)_D$
- Why does the SM have vector-like copies??
  - Extend the dark group to a larger gauge group $\mathcal{G}_D \supset U(1)_D$ and assume portal matter and an SM field are part of **the same multiplet** of $\mathcal{G}_D$.
- Group structure of $\mathcal{G}_D$ might guarantee finite mixing
- But then… Why are the $U(1)_D$-neutral ones chiral & light? Why are the others vector-like?
- How do we ensure light chiral states for one set of charge states, and heavy vector-like states for others?
- How do we break $\mathcal{G}_D \to U(1)_D$?

$$\mathcal{G}_{SM} \times SU(2)_I \times U(1)_I \to \mathcal{G}_{SM} \times U(1)_D$$

$$(\mathbf{R}, 2)_{-\frac{1}{2}} \to \mathbf{R}_0 + \mathbf{R}_{-1}$$

$$(\overline{\mathbf{R}}, 1)_{+1} \to \overline{\mathbf{R}}_{+1}$$

$\boldsymbol{R}$: Some representation of $\mathcal{G}_{SM}$

Black: SM fermion

Blue: Portal matter fermion

[3] T. D. Reuter and T. G. Rizzo, Phys. Rev. D 101, No.1, 015014 (2020) [arXiv:1909.09160 [hep-ph]]

Portal Matter in an Extra Dimensions

- In theories of extra dimensions, we already see light fermion modes + heavy vector-like particles.
- Imagine a 5 D theory compactified on an $S_1/(Z_2 \times Z_2')$ orbifold
- Fields can have Neumann (+) or Dirichlet (-) boundary conditions at boundaries $\phi = 0, \pi$. In 5D to have a light mode, you need Neumann condition at both boundaries.
- On the right: Chiral SM fermion plus vector-like copies!

$$\mathcal{G}_{SM} \times SU(2)_D \to \mathcal{G}_{SM} \times U(1)_D$$

$$(\mathbf{F}, \mathbf{3}) \to \mathbf{F}^0 + \mathbf{F}^{+1} + \mathbf{F}^{-1}$$

Fermion	$\phi = 0$	$\phi = \pi$
F_L^0	+	+
F_R^0	-	-
$F_L^{\pm 1}$	+	-
$F_R^{\pm 1}$	-	+

Portal Matter in an Extra Dimension II

WHAT HAVE WE GAINED

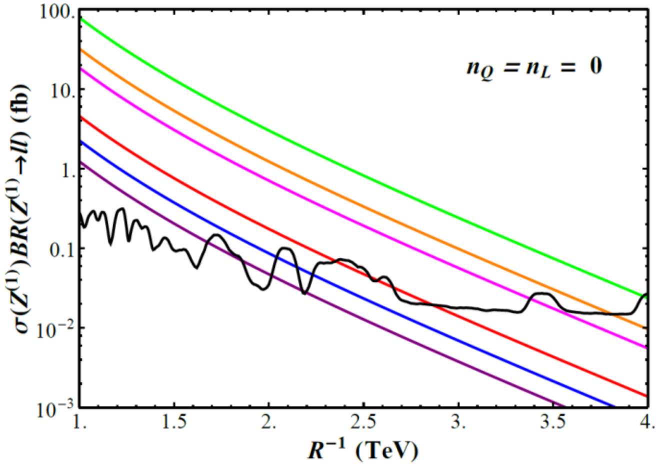
- Consistent boundary conditions also break $SU(2)_D \rightarrow U(1)_D$ at $\phi = \pi$– there's our high-scale symmetry breaking!
- $U(1)_D$ broken on $\phi = \pi$ brane by scalar: Simpler Higgs sector!
- No-muss, anomaly-free, *simple* non-minimal portal matter– vector-like and chiral fields come out of the same multiplet
- Condition for finite calculable KM is **still** $\sum Q_{Y_i} Q_{D_i} = 0$ (must apply to all sets of fields w/ the same $Z_2 \times Z_2$ parity individually), automatically satisfied.
- Scale motivation?

WHAT HAVE WE ADDED

- Kaluza Klein states for SM fields– can be produced directly or affect precision measurements
- Three new gauge bosons: A_D, I^+, I^-. Only A_D has a zero mode.
- **Lighter** Kaluza Klein states for portal matter, $I^{\pm}$.
- Need brane-localized kinetic terms for appropriate magnitude KM– we assume BLKT's for all fermions and $SU(2)_D$ gauge bosons. Call these various param's τ's and ω's

Phenomenology: SM-Only Constraints

Direct: (No PM)



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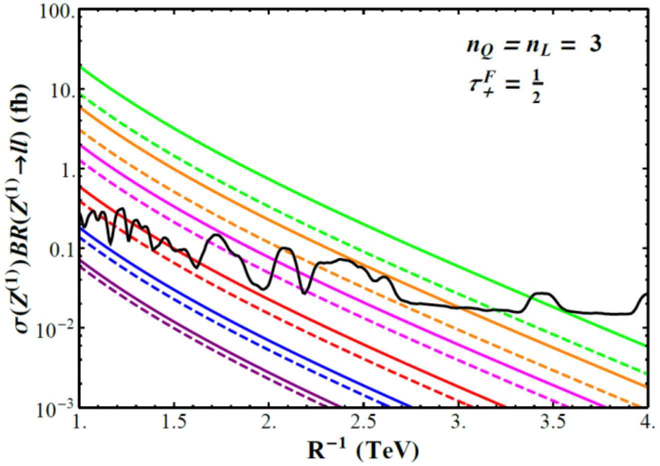
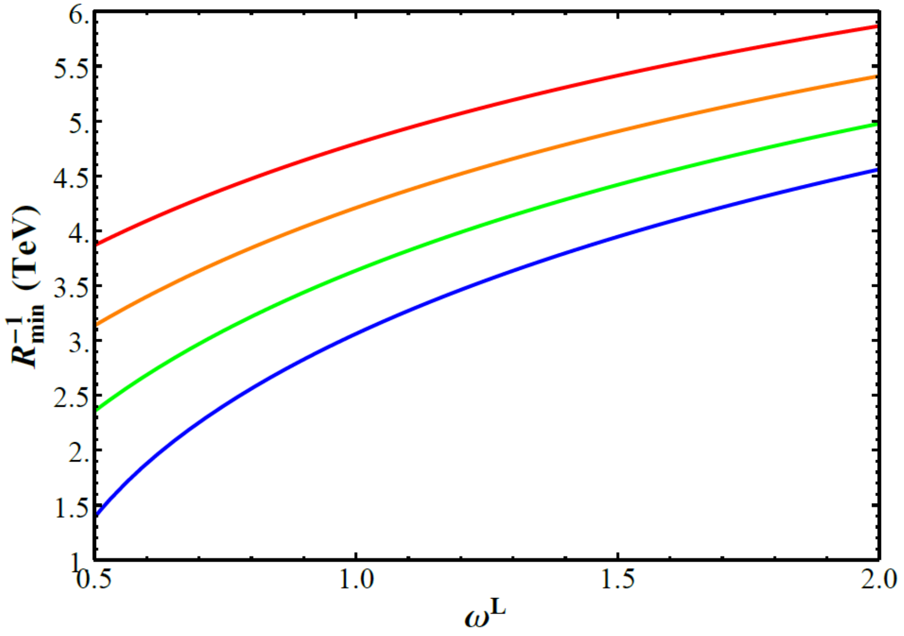
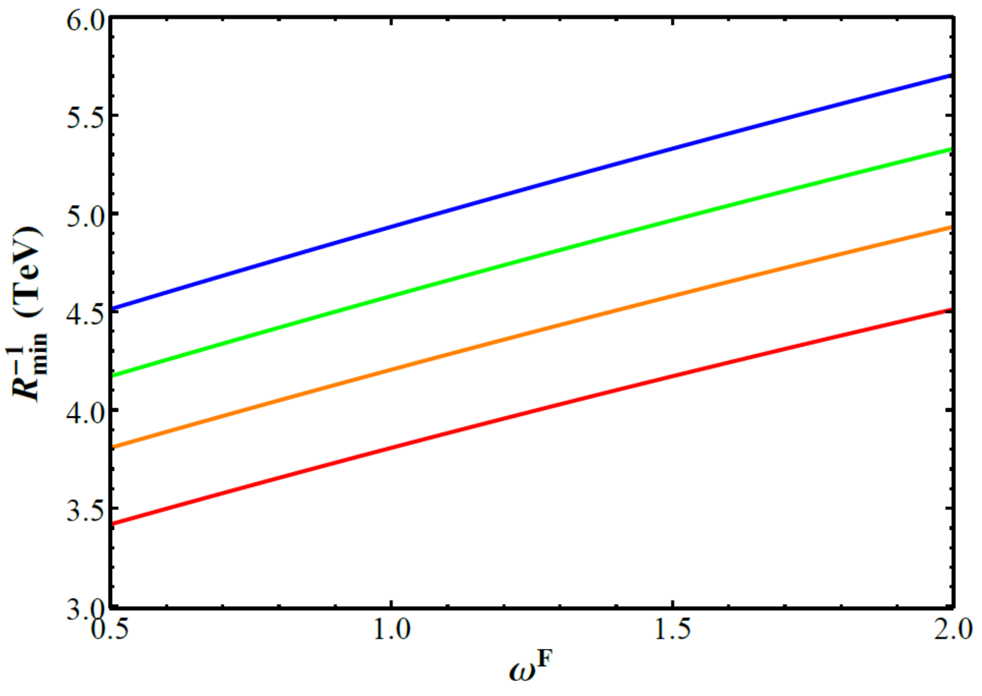


Precision (ρ_0):

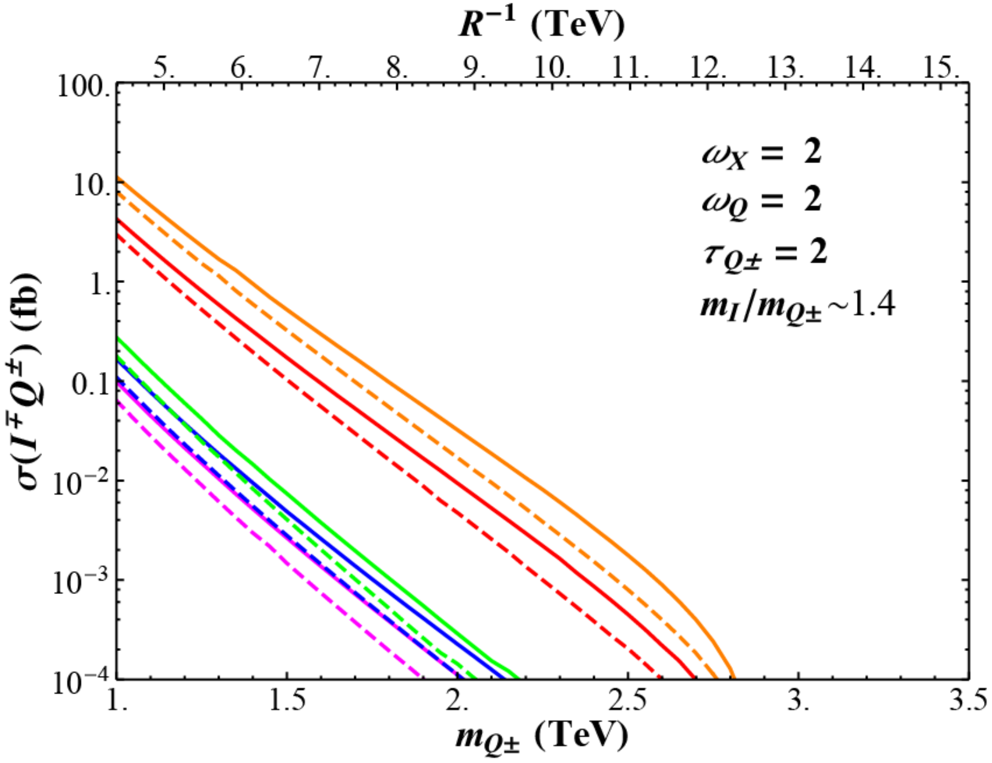


Phenomenology: Portal Matter

HADRONIC PM PAIR PRODUCTION



CROSS SECTION FOR PORTAL MATTER+I



Conclusions

- The scenario where vector-like copies of SM fermions act as portal matter is straightforwardly realized in the context of an extra dimension
- Leads to simpler Higgs sectors and fewer ad hoc particle introductions than equivalent in 4D
- Even in 5D, the naïve 4D condition for finite and calculable KM still works!
- Kaluza Klein portal matter will likely be the **lightest** new KK modes appearing in the theory and their existence weakens other direct KK mode searches– could be the first direct evidence we'd find of a TeV-scale extra dimension!

Thank You!

Backup Slides

QCD Pair Production