Generalized Chern-Simons term and its Phenomenology in a Hypercharge Portal Model[1]

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In collaboration with O. Lebedev, Y. Mambrini, J. Quevillon and A. Ringwald
(DESY / LPT Orsay)

DESY Theory Seminar

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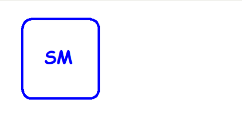
[1] [F. Domingo, O. Lebedev, Y. Mambrini, J. Quevillon and A. Ringwald, "More on the Hypercharge Portal into the Dark Sector," JHEP **1309** (2013) 020 arXiv:1305.6815 [hep-ph]].

Outline

The Hypercharge Portal Model – Basics

‘Portal’ Models: Description

- Hidden Sector (consisting of SM singlets) is postulated.
- ‘Portal’: operator relating the Hidden to the SM sector.
- Can be embedded in String constructions.
- Motivated by Inflation / Dark Matter.



Hypercharge Portal with one non-SM vector field

- Extra abelian vector field C^μ: $\mathcal{L}_{\text{Hidden}} \ni -\frac{1}{4}C_{\mu\nu}C^{\mu\nu} + \frac{1}{2}M_C^2 C_\mu C^\mu$
- Possible interactions with the SM (dimension 4 terms only):
  $O_{\text{KM}} = B_{\mu\nu}C^{\mu\nu}$ Kinetic Mixing with the hypercharge
  $\Downarrow$ (after kinetic diagonalization)
  $O_{\text{matter}} = \overline{\Psi}_f\gamma_\mu(1 + a_f\gamma_5)\Psi_f C^\mu + \text{h.c.}$ Direct coupling to SM matter
  $O_{\text{Higgs}} = H^\dagger H\, C_\mu C^\mu \; +\beta\, H^\dagger iD_\mu H\, C^\mu + \text{h.c.}$ Higgs Couplings
- Appears phenomenologically as an extra ‘Z-like’ boson. Small couplings to SM fields (constrained by EWPO's, Coulomb's law, etc.).
- Z_2-symmetry in the Hidden sector $C^\mu \leftrightarrow -C^\mu$: DM candidate $\Longrightarrow$ Vector Higgs Portal [arXiv:1111.4482].

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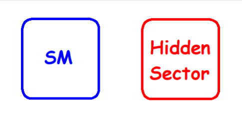

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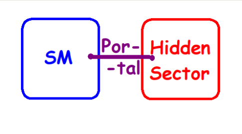

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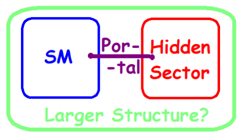

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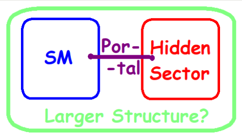

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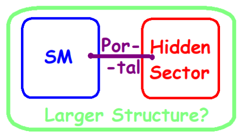

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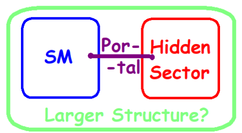

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Beyond one supplementary vector field…

…Two vector fields C, D!

Doubling of the 'old' structures…

$$\mathcal{L}_{\text{Hidden}} \ni \sum_{V=C,D} \left\{ -\frac{1}{4} V_{\mu\nu} V^{\mu\nu} + \frac{1}{2} M_V^2 V_\mu V^\mu \right\} - \frac{\delta_3}{2} C_{\mu\nu} D^{\mu\nu} + \delta M^2 C_\mu D^\mu$$

$$\mathcal{L}_{\text{Hyp.Port.}} \ni -\frac{\delta_1}{2} B_{\mu\nu} C^{\mu\nu} - \frac{\delta_2}{2} B_{\mu\nu} D^{\mu\nu} \qquad + (\ldots)$$

- Field redefinition (at first order in the parameters):

$$B_\mu \to B_\mu + \delta_1 C_\mu + \delta_2 D_\mu \; ; \; C_\mu \to C_\mu + \frac{\delta_3 M_D^2 - \delta M^2}{M_D^2 - M_C^2} D_\mu \; ; \; D_\mu \to D_\mu - \frac{\delta_3 M_C^2 - \delta M^2}{M_D^2 - M_C^2} C_\mu$$

But $C - D$ couplings to SM matter induced!

- Alternatively: $\mathbb{Z}_2$-symmetry $(C, D) \to (-C, -D)$ forbids kinetic coupling

$\Rightarrow$ The lighter state is stable (DM candidate)!

…and Additional structures!

$$\mathcal{L}_{\text{Hyp.Port.}} \ni \zeta B_{\mu\nu} C^\mu D^\nu + \kappa \, \epsilon_{\mu\nu\rho\sigma} B^{\mu\nu} C^\rho D^\sigma \quad \to \text{CP-conserving}$$

$\searrow$ CP-violating [arXiv:1211.4685]

$\to$ Phenomenological impact of this Chern-Simons-type term

$$\Delta\mathcal{L} = \kappa \cos\theta_W \, \epsilon_{\mu\nu\rho\sigma} F^{\mu\nu} C^\rho D^\sigma - \kappa \sin\theta_W \, \epsilon_{\mu\nu\rho\sigma} Z^{\mu\nu} C^\rho D^\sigma$$

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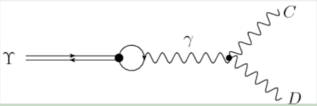
Unitarity

- Longitudinal components in $\epsilon_{\mu\nu\rho\sigma} B^{\mu\nu} C^{\rho} D^{\sigma}$
  $\Rightarrow$ Amplitudes growing with energy: $\mathcal{A}[C\,C \to D\,D] \sim \kappa^2 \,\frac{E^2}{M^2_{C,D}}$
- Regulate with a cutoff Λ: $|\mathcal{A}| \lesssim 8\pi \quad \Rightarrow \quad \frac{\kappa}{M} < \frac{\sqrt{8\pi}}{\Lambda} \sim 5 \cdot 10^{-3}\ \mathrm{GeV}^{-1}$

$$(M = \min\{M_C, M_D\}\ ;\ \Lambda \sim \mathrm{TeV})$$

Upsilon decays



C/D decay outside the detector: Invisible decay

- $\Gamma(\Upsilon \to CD) \propto \frac{\kappa^2}{M^2}$
- BaBar limit $BR(\Upsilon(1S) \to \text{inv}) < 3 \times 10^{-4}$ (90% CL, [arXiv:0908.2840]) ; SM negligible

$$\frac{\kappa}{M} < 4 \times 10^{-3}\ \text{GeV}^{-1} \quad ; \quad (\text{as long as } M \lesssim M_\Upsilon/2)$$

$D \to C + \gamma$ decay inside the detector: Radiative invisible decay

- BaBar: $BR(\Upsilon(1S) \to \gamma + \text{inv}) < 6 \times 10^{-6}$ (90% CL, [arXiv:1007.4646]) ; SM negligible

$$\frac{\kappa}{M} < 6 \times 10^{-4}\ \text{GeV}^{-1} \quad ; \quad (\text{as long as } M \lesssim 3\ \text{GeV})$$

N.B.: With kinetic mixing: C and D both decay within the detector
$\to$ complicated final states (no constraint).

Limits from LEP

Invisible Z decay

$$\Gamma(Z \to CD) \simeq \frac{\kappa^2 \sin^2\theta_W}{12\pi} \frac{m_Z^3}{M^2}$$

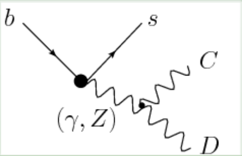
$\Delta\Gamma_{\rm inv}^Z \lesssim 3$ MeV [hep-ex/0509008] $\Rightarrow$ $\frac{\kappa}{M} < 8 \times 10^{-4}$ GeV^{-1} ; (as long as $M \lesssim M_Z/2$)

Monophoton searches: $e^+e^- \to \gamma + \text{inv}$

- $e^+e^- \to (\gamma, Z)^* \to C + (D \to C + \gamma)$
- [hep-ex/0402002], for $\sqrt{s} \sim 200$ GeV.

Weak limit $\frac{\kappa}{M} \lesssim 10^{-2}$ GeV^{-1}.

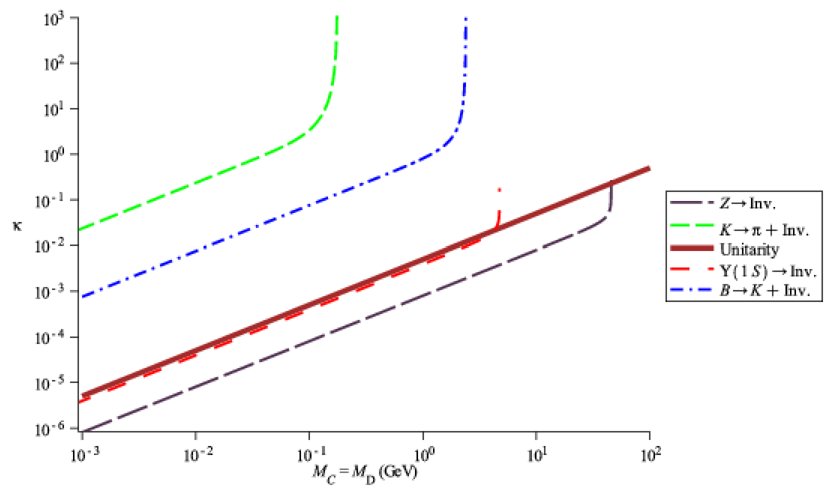
Flavour Transitions



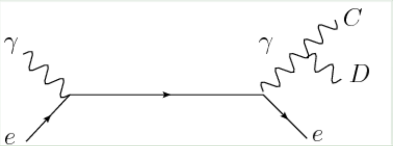
- $\Gamma(B \to K\ CD) \propto \frac{M_B^7}{M^2 M_Z^4}$
- BaBar [arXiv:1009.1529]: $\text{BR}(B^+ \to K^+ \nu\bar{\nu}) < 1.3 \times 10^{-5}$ (90% CL)

Weak limit: $\frac{\kappa}{M} < 1\ \text{GeV}^{-1}$

Summary of Collider constraints



Remark on Astrophysical Bounds



- Lifetime of Horizontal-Branch stars: $\kappa/M < 10^{-7}$ GeV^{-1} for $M \ll$ keV (by analogy with axion models).
- Bremsstrahlung processes in supernovae may extend the bound to $M \lesssim O(\text{MeV})$.

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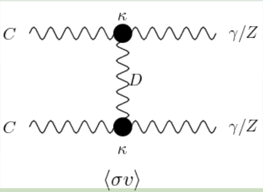
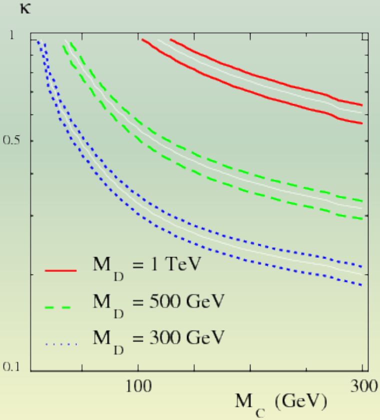
Relic Density

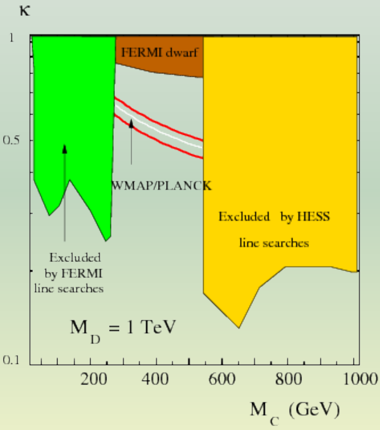




- $\langle \sigma v \rangle \sim \kappa^4 \, \frac{M_C^2}{M_D^4}$ (for $M_C \ll M_D$)
- WMAP/PLANCK relic density measurement [arXiv:1001.4744], [arXiv:1303.5062]

Indirect detection

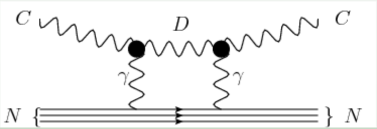
- Dark Matter annihilation in dense regions
  ⇒ monochromatic γ-ray lines.
- FERMI: constraints in the low-mass range [arXiv:1205.2739,1305.5597]
- HESS: constraints in the high-mass range [arXiv:1301.1173]
- mass-range 300 – 500 GeV:
  → limits from the continuum
  most relevant bounds from observation of dwarf galaxies [arXiv:1210.5558]



⇒ Thermal relic density cannot be achieved in the low- and high-mass regions

N.B.: The tentative γ-ray line [arXiv:1204.2797] at $\sim$ 135 GeV could be accounted for.

Direct detection



- Two effective nucleon-DM operators:

$$O_{SI} \sim \frac{\alpha\kappa^2}{4\pi}\frac{m_N}{M^2}\,\overline{\Psi}\Psi\, C^\mu C_\mu \quad ; \quad O_{SD} \sim \frac{\alpha\kappa^2}{4\pi}\frac{1}{M^2}\,\epsilon_{\mu\nu\rho\sigma}\overline{\Psi}\gamma^\mu\gamma^5\Psi\, C^\nu i\partial^\rho C^\sigma$$

- Spin-independent cross-section: Loop + Nucleon mass suppressions

$$\Rightarrow \quad \sigma_{SI} \sim \kappa^4 \left(\frac{100\text{ GeV}}{M}\right)^6 \cdot 10^{-46}\text{cm}^2$$

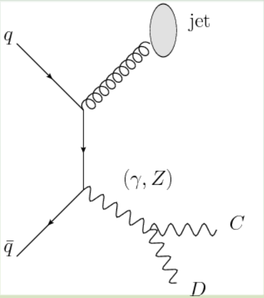
  XENON100 [arXiv:1207.5988] : $\sigma_{SI} \lesssim \mathcal{O}(10^{-45})\text{cm}^2$

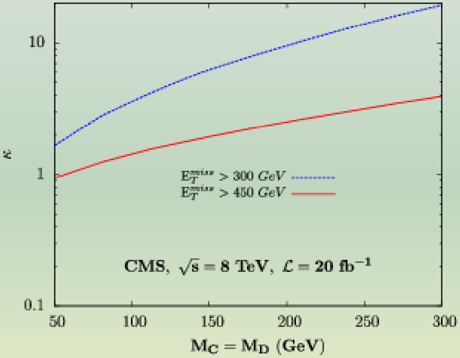
- Spin-dependent cross-section: Loop suppression $\Rightarrow \quad \sigma_{SD} \sim \kappa^4 \left(\frac{100\text{ GeV}}{M}\right)^4 \cdot 10^{-42}\text{cm}^2$

  XENON100 [arXiv:1301.6620] : $\sigma_{SD} \lesssim \mathcal{O}(10^{-40})\text{cm}^2$

$\Rightarrow$ Direct Detection limits negligible in this scenario!

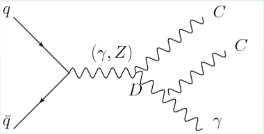
Production limits at LHC

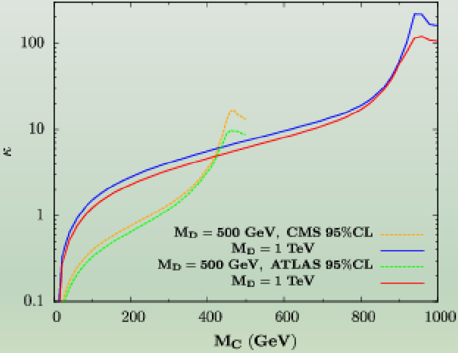




Monojet searches

- Photon originating from D decay undetected (cut $p_T > 150$ GeV).
- CMS searches [CMS-PAS-EXO-12-048] 19.5 fb^{-1} at 8 TeV.
- Sensitivity estimated through `Madgraph 5`, `Pythia 6`, `Delphes 1.9`





Monophoton searches

- Photon originating from D decay detected: $p_T \gtrsim 150$ GeV.
- CMS searches [arXiv:1204.0821] 5 fb^{-1} at 7 TeV.
- ATLAS searches [arXiv:1209.4625] 4.6 fb^{-1} at 7 TeV.
- Sensitivity estimated through `Madgraph 5`, `Pythia 6`, `Delphes 1.9`

Monophoton limits do not endanger the interpretation of the 135 GeV γ-line (yet).

Outline

1. The Hypercharge Portal Model with several extra $U(1)$ gauge fields
2. Phenomenological constraints up to the ~ 100 GeV scale
3. Dark Matter searches
4. **Conclusion**

Conclusion

- Considered the phenomenology associated to a Chern-Simons-like Hypercharge Portal.
- Strong collider constraints (Invisible Z-width) / Unitarity bound at low masses.
- $\mathbb{Z}_2$-symmetry ensures DM candidate: Signature with monochromatic γ-ray lines.
- Upper mass-range constrained by Indirect DM detection limits (FERMI/HESS).
- Indirect DM detection + LHC monophoton limits should be able to close the thermal-DM relic favored region / 135 GeV γ-line interpretation.