

Dark Photons Protected by Dark Charge Conjugation with SM-Charged Portals

Can a single portal multiplet be enough?

Xiaoyong Chu¹, **Qiyuan Gao**¹, Teng Ma¹, and Lingfeng Li²

Work in progress

¹International Centre for Theoretical Physics Asia-Pacific (ICTP-AP), University of Chinese Academy of Sciences (UCAS), Beijing 100190, China

²Nanjing Normal University, Nanjing, China

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Weak Portals Can Hide an Interacting Dark Sector

$$\mathcal{L} = \mathcal{L}_{\text{SM}} + \mathcal{L}_D + \mathcal{L}_{\text{portal}}$$

Higgs portal: $\lambda_{HD}|H|^2|\Phi_D|^2$
small λ_{HD} or heavy h_D

Standard Model

known fields



Dark sector

new states and interactions

SM–dark bi-charged mediator
large mass and loop suppression

Weak connection $\implies$ dark sector; stable light state $\implies$ dark-matter candidate.

Exact $\mathcal{C}_D$ Protects Dark-Photon Stability

Kinetic mixing is itself a renormalizable portal

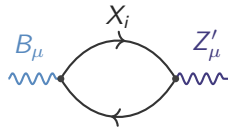
$$-\frac{\epsilon_Y}{2} B_{\mu\nu} Z'^{\mu\nu} \xrightarrow{\text{physical basis}} \epsilon e Z'_\mu J_{\text{EM}}^\mu + \dots$$

No explicit mediator appears in the low-energy theory.

Kinetic mixing: B. Holdom, Phys. Lett. B **166** (1986) 196.

$$m_{Z'} > 2m_e, \epsilon \neq 0 \implies Z' \rightarrow e^+ e^-$$

Bi-charged portal matter



Portal loops regenerate $\epsilon_Y(\mu) \neq 0$,
even if $\epsilon_Y^{\text{UV}} = 0$.

Z' is not stable.

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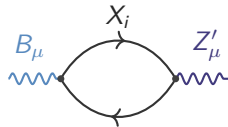
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Z' is not stable.

Exact dark charge conjugation forbids the SM-relevant decay channel (E. Ma, Phys. Lett. B **772** (2017) 442)

$$\mathcal{C}_D : Z'_\mu \rightarrow -Z'_\mu, \quad \text{all SM fields fixed,}$$

$$B_{\mu\nu} Z'^{\mu\nu} \rightarrow -B_{\mu\nu} Z'^{\mu\nu} \implies \boxed{\epsilon_Y = 0}.$$

If Z' is the lightest $\mathcal{C}_D$ -odd state, exact unbroken $\mathcal{C}_D$ makes the dark photon stable.

The Minimal Higgs Portal Preserves Exact $\mathcal{C}_D$

$$\mathcal{L}_{\min} = \mathcal{L}_{\text{SM}} - \frac{1}{4} Z'_{\mu\nu} Z'^{\mu\nu} + (D_\mu \Phi_D)^\dagger D^\mu \Phi_D + \mu_D^2 |\Phi_D|^2 - \lambda_D |\Phi_D|^4 - \lambda_{HD} (H^\dagger H) |\Phi_D|^2,$$

$$D_\mu \Phi_D = (\partial_\mu - ig_D q_\Phi Z'_\mu) \Phi_D.$$

Exact dark charge conjugation

$$\mathcal{C}_D : \quad Z'_\mu \rightarrow -Z'_\mu, \quad \Phi_D \rightarrow \Phi_D^*, \quad H \rightarrow H, \quad \text{SM} \rightarrow \text{SM}.$$

$$\langle \Phi_D \rangle = \frac{v_D}{\sqrt{2}} \in \mathbb{R} \quad \Longrightarrow \quad \mathcal{C}_D \text{ remains unbroken} \quad \Longrightarrow \quad \mathcal{C}_D(Z'_\mu, h_D, H, \text{SM}) = (-, +, +, +).$$

Higgs portal: Patt and Wilczek, hep-ph/0605188.

Exact $\mathcal{C}_D$ vector models: Lebedev, Lee and Mambrini, PLB **707** (2012) 570; Farzan and Rezaei Akbarieh, JCAP **10** (2012) 026.

Non-resonant thermal slice: $\Delta m \equiv m_{h_D} - m_{Z'} > 0$, with $2m_{Z'} \not\approx m_h, m_{h_D}$.

SM-Charged $\mathcal{C}_D$ -Symmetric Portals Usually Come in Pairs

$$\Psi_+ \sim (\mathcal{R}_3, \mathcal{R}_2)_{Y, +q_D}, \quad \Psi_- \sim (\mathcal{R}_3, \mathcal{R}_2)_{Y, -q_D}, \quad M_+ = M_- = M.$$

Same SM representation and mass; opposite $U(1)_D$ charges.

Original mechanism: Dienes, Kolda and March–Russell, Nucl. Phys. B **492** (1997) 104 [hep-ph/9610479].

$$\Psi_+ \xleftrightarrow{\mathcal{C}_D} \Psi_-$$

$$\mathcal{L}(\Psi_+, \Psi_-) \xrightarrow{\mathcal{C}_D} \mathcal{L}(\Psi_-, \Psi_+) = \mathcal{L}(\Psi_+, \Psi_-).$$

One-loop illustration: $\epsilon_{\text{loop}} \propto \sum_i Y_i q_{D,i} = Y(+q_D) + Y(-q_D) = 0.$

The cancellation is exact: $\mathcal{C}_D$ forbids kinetic mixing to all orders.

Do We Really Need Two Portal Multiplets?

From an exchanged pair to one SM-irreducible multiplet

$$\{\Psi_+, \Psi_-\} \implies X \sim (\mathcal{R}_3, \mathcal{R}_2)_{Y, q_X}, \quad q_X \neq 0.$$

Can one SM-irreducible portal multiplet realize exact $\mathcal{C}_D$?

Which Standard Model representations $(\mathcal{R}_3, \mathcal{R}_2)_Y$ allow it?

Work in progress with Xiaoyong Chu, Teng Ma, and Lingfeng Li.

Next: impose exact $\mathcal{C}_D$ on the gauge interactions.

Start from One SM-Irreducible Portal Multiplet

$$X \sim (\mathcal{R}_3, \mathcal{R}_2)_{Y, q_X}, \quad q_X \neq 0, \quad X = \underbrace{\Psi}_{\text{vectorlike Dirac}} \quad \text{or} \quad \underbrace{\Phi}_{\text{complex scalar}}.$$

$$\mathcal{L}_F = \bar{\Psi}(i\gamma^\mu D_\mu - M_F)\Psi,$$

$$\mathcal{L}_S = (D_\mu \Phi)^\dagger D^\mu \Phi - M_S^2 \Phi^\dagger \Phi,$$

$$D_\mu = \partial_\mu - ig_D q_X Z'_\mu - ig_s G_\mu^a T_{\mathcal{R}_3}^a - ig W_\mu^i T_{\mathcal{R}_2}^i - ig' Y B_\mu.$$

$T_{\mathcal{R}_3}^a$ and $T_{\mathcal{R}_2}^i$ are the generators of $SU(3)_c$ and $SU(2)_L$ in the representations $\mathcal{R}_3$ and $\mathcal{R}_2$, respectively.

Dark Charge Conjugation Maps the Portal to Its Conjugate

$$\mathcal{C}_D : \quad Z'_\mu \rightarrow -Z'_\mu, \quad \Psi \rightarrow S_{\mathcal{R}} \Psi^c, \quad \Phi \rightarrow S_{\mathcal{R}} \Phi^*.$$

$$\Psi^c \equiv C \bar{\Psi}^T, \quad C^{-1} \gamma^\mu C = -(\gamma^\mu)^T, \quad S_{\mathcal{R}}^\dagger S_{\mathcal{R}} = \mathbf{1}.$$

$S_{\mathcal{R}}$ is a candidate unitary matrix acting only on the $SU(3)_c \times SU(2)_L$ representation space.

$$G_\mu^a, \quad W_\mu^i, \quad B_\mu \quad \text{are held fixed under } \mathcal{C}_D.$$

Portal $\mathcal{C}_D$ extends the dark-sector symmetry; the Standard Model gauge fields remain fixed.

$\mathcal{C}_D$ Invariance Fixes the Portal Quantum Numbers

With the SM gauge fields held fixed, invariance of $\mathcal{L}_F$ or $\mathcal{L}_S$ gives

$$Y = -Y, \quad S_{\mathcal{R}}(T_{\mathcal{R}}^{A,a})^* S_{\mathcal{R}}^{-1} = -T_{\mathcal{R}}^{A,a}.$$

for every non-Abelian generator, with $A = 3, 2$.

$$U(1)_D : \quad q_X Z'_\mu \longrightarrow (-q_X)(-Z'_\mu) = q_X Z'_\mu \quad \textbf{automatic.}$$

$$Y = -Y \quad \implies \quad \boxed{Y = 0}$$

$$S_{\mathcal{R}}(T_{\mathcal{R}}^{A,a})^* S_{\mathcal{R}}^{-1} = -T_{\mathcal{R}}^{A,a} \quad \implies \quad \boxed{(\mathcal{R}_3, \mathcal{R}_2) \simeq (\overline{\mathcal{R}}_3, \overline{\mathcal{R}}_2)}.$$

Thus $(\mathcal{R}_3, \mathcal{R}_2)$ must be real or pseudoreal.

Only Self-Conjugate $Y = 0$ Representations Survive

$$SU(3)_c : \quad (p, q)^* = (q, p) \quad \implies \quad \boxed{p = q}. \quad SU(2)_L : \quad \begin{cases} j \in \mathbb{Z}_{\geq 0}, & \text{real,} \\ j \in \mathbb{Z}_{\geq 0} + \frac{1}{2}, & \text{pseudoreal.} \end{cases}$$

$\mathcal{R}_3$	$\mathcal{R}_2$	Y	Type	$\mathcal{C}_D$
(p, p)	$j \in \mathbb{Z}_{\geq 0}$	0	Real	Allowed
(p, p)	$j \in \mathbb{Z}_{\geq 0} + \frac{1}{2}$	0	Pseudoreal	Allowed
$(p, q), p \neq q$	Any j	0	Complex	Forbidden
Any	Any	$Y \neq 0$	—	Forbidden

Gauge-sector classification only; phenomenological viability and the precise realization of $\mathcal{C}_D^2$ in pseudoreal cases are model dependent.

Next: choose a concrete self-conjugate portal representation.

Heavy Colored Portals Generate a Dimension-Eight Gluonic EFT

$$X = \underbrace{\Psi}_{\text{vectorlike Dirac fermion}} \quad \text{or} \quad \underbrace{\Phi}_{\text{complex scalar}}, \quad X \sim (\mathcal{R}_3, \mathbf{1})_{0, q_X}, \quad \mathcal{R}_3 \neq \mathbf{1}, \quad q_X \neq 0.$$

Heavy $SU(3)_c \times U(1)_D$ matter, electroweak neutral and separate from $U(1)_D$ breaking; C, P conserved.

Two- Z' operators

$$\mathcal{O}_1 = \frac{X_1}{\Lambda^4} Z'_{\alpha\beta} Z'^{\alpha\beta} \text{Tr}(G_{\mu\nu} G^{\mu\nu}),$$

$$\mathcal{O}_2 = \frac{X_2}{\Lambda^4} Z'_{\mu\beta} Z'^{\alpha\nu} \text{Tr}(G_{\alpha\nu} G^{\mu\beta}),$$

$$\mathcal{O}_3 = \frac{X_3}{\Lambda^4} Z'_{\nu\beta} Z'^{\alpha\nu} \text{Tr}(G_{\alpha\mu} G^{\mu\beta}),$$

$$\mathcal{O}_4 = \frac{X_4}{\Lambda^4} Z'_{\mu\beta} Z'_{\nu\alpha} \text{Tr}(G^{\alpha\mu} G^{\beta\nu}).$$

Single- Z' operators

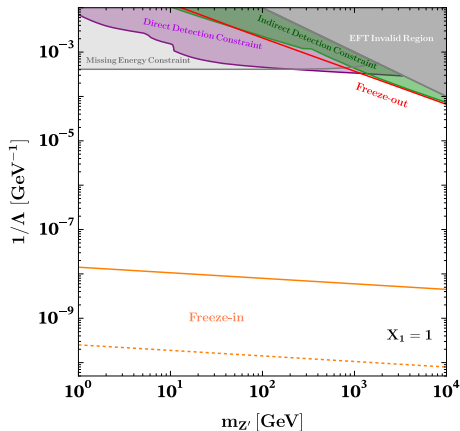
$$\mathcal{O}_5 = \frac{Y_1}{\Lambda^4} Z'_{\nu\alpha} \text{Tr}(G^{\alpha\beta} G_{\beta\mu} G^{\mu\nu}),$$

$$\mathcal{O}_6 = \frac{Y_2}{\Lambda^4} Z'_{\alpha\beta} \text{Tr}(G^{\alpha\beta} G_{\mu\nu} G^{\mu\nu}).$$

For a self-conjugate mediator, exact $\mathcal{C}_D$ forbids all single- Z' operators.

Operator basis: X. Chu et al., JHEP **06** (2026) 156 [arXiv:2512.03153], Eqs. (2.1)–(2.2).

Current Constraints on the Gluonic Portal



From X. Chu et al., JHEP 06 (2026) 156 [arXiv:2512.03153], Fig. 7 (right).

Constraints

- Direct detection
- Indirect detection
- Missing energy
- EFT invalid region

Relic targets

- Thermal freeze-out
- Freeze-in (solid/dashed)

For each experimental bound, the region above the curve is excluded; the gray wedge marks EFT breakdown.

A phenomenological study of the color-adjoint fermion UV completion is in preparation.

Exact $\mathcal{C}_D$ Gives a Systematic Recipe for Protected Portals

one SM-irreducible portal $X \xrightarrow{\mathcal{C}_D} \boxed{Y = 0, \quad \mathcal{R}_{\text{SM}} \simeq \overline{\mathcal{R}_{\text{SM}}},}$

$\implies Z'$ is stable if it is the lightest $\mathcal{C}_D$ -odd state.

**Exact $\mathcal{C}_D$ can be realized within
one SM-irreducible portal multiplet.**

Minimal colored realization: $\Psi \sim (\mathbf{8}, \mathbf{1})_{0, q_\Psi}.$

Thank You

With thanks to my collaborators

Xiaoyong Chu, Teng Ma, and Lingfeng Li

and to the organizers and participants of the
2nd New Horizons for Ψ Workshop

Questions?

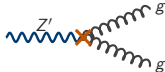
Why the Gluonic Portal Starts at Dimension Eight

Dimension four: $Z' G$



$Z'_{\mu\nu} G^{\mu\nu}$ carries an open adjoint index; equivalently, $\text{Tr } G_{\mu\nu} = 0$.

Dimension six: $Z' GG$



Exact $\mathcal{C}_D$ forbids all one- Z' structures. In the C, P -even field-strength basis,

$$K^{\mu\nu} \equiv \text{Tr}(G^{\mu\rho} G_{\rho}{}^{\nu}) = K^{\nu\mu},$$

$$Z'_{\mu\nu} K^{\mu\nu} = 0.$$

X_i, Y_j : Wilson coefficients. Operator basis: X. Chu et al., JHEP **06** (2026) 156 [arXiv:2512.03153], Eqs. (2.1)–(2.2).

Two- Z' operators

$$\mathcal{O}_1 = \frac{X_1}{\Lambda^4} Z'_{\alpha\beta} Z'^{\alpha\beta} \text{Tr}(G_{\mu\nu} G^{\mu\nu}),$$

$$\mathcal{O}_2 = \frac{X_2}{\Lambda^4} Z'_{\mu\beta} Z'^{\alpha\nu} \text{Tr}(G_{\alpha\nu} G^{\mu\beta}),$$

$$\mathcal{O}_3 = \frac{X_3}{\Lambda^4} Z'_{\nu\beta} Z'^{\alpha\nu} \text{Tr}(G_{\alpha\mu} G^{\mu\beta}),$$

$$\mathcal{O}_4 = \frac{X_4}{\Lambda^4} Z'_{\mu\beta} Z'_{\nu\alpha} \text{Tr}(G^{\alpha\mu} G^{\beta\nu}).$$

Preliminary work with Xiaoyong Chu, Teng Ma, and Lingfeng Li.

$d = 7$: $D(Z' GG)$ no Lorentz scalar,

$d = 8$: $Z' Z' GG$ and $Z' GGG$.

$$\mathcal{C}_D : \quad \underbrace{Z' Z' GG}_{\text{even, allowed}} \quad \underbrace{Z' GGG}_{\text{odd, forbidden}}.$$

Single- Z' operators $Z' \rightarrow ggg, \quad gZ' \rightarrow gg$

$$\mathcal{O}_5 = \frac{Y_1}{\Lambda^4} Z'_{\nu\alpha} \text{Tr}(G^{\alpha\beta} G_{\beta\mu} G^{\mu\nu}),$$

$$\mathcal{O}_6 = \frac{Y_2}{\Lambda^4} Z'_{\alpha\beta} \text{Tr}(G^{\alpha\beta} G_{\mu\nu} G^{\mu\nu}).$$

self-conjugate mediator + exact $\mathcal{C}_D$,

$$\Rightarrow \boxed{Y_1 = Y_2 = 0},$$

minimal example: $\Psi \sim (8, 1)_{0,q_X}$.