Dark higher-form portals

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GDR Intensity Frontier, Marseille and Carry-le-Rouet, 2025

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<u>This presentation is based on the results of the article:</u>

- *Dark Higher-form portals and dualities*
- Cypris Plantier and Christopher Smith
- arXiv:2506.04795 [hep-ph]
- Published in *PR.D 112, 075043* (2025)

Differential forms as dark matter candidates

One can define fields with more than one Lorentz indices. They are antisymmetric and fundamentally tensorial.

Number of indices

$p = 0$	$p = 1$	$p = 2$	$p = 3$
Scalar field ϕ	Vector field A^{μ}	Kalb-Ramond field $B^{\mu\nu}$	Three-form $C^{\mu\nu\rho}$

Formally, these fields are differential forms → Often encountered in string theory

Here we adopt a phenomenological vision: Can these forms be suitable DM candidates?

[1] M. Kalb, P. Ramond, *Classical direct interstring action*, Phys.Rev.D (1974)

[2] T. Curtright, P. Freund, *Massive dual fields*, Nucl.Phys.B (1980)

Higher-forms and symmetries

Theories involving differential forms can exacerbate redundancies, known as *generalized symmetries*.

Like for the vector case, the transformations of the forms depend on gauge parameters.

$$A^\mu \to A^\mu + \partial^\mu \underbrace{\Lambda}_{\text{Zero-form gauge parameter}}$$

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$$B^{\mu\nu} \to B^{\mu\nu} + \partial^\mu \Lambda^\nu - \partial^\nu \Lambda^\mu$$

$$C^{\mu\nu\rho} \to C^{\mu\nu\rho} + \partial^\mu \Lambda^{\nu\rho} + \partial^\nu \Lambda^{\rho\mu} + \partial^\rho \underbrace{\Lambda^{\mu\nu}}_{\text{Two-form gauge parameter}}$$

Therefore, the strength tensor of a form is gauge-invariant

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$$\phi \rightarrow \phi + \underline{\lambda}$$

Shift-Symmetry parameter

$$A^{\mu} \rightarrow A^{\mu} + \partial^{\mu} \Lambda$$

$$B^{\mu\nu} \rightarrow B^{\mu\nu} + \partial^{\mu} \Lambda^{\nu} - \partial^{\nu} \Lambda^{\mu}$$

$$C^{\mu\nu\rho} \rightarrow C^{\mu\nu\rho} + \partial^{\mu} \Lambda^{\nu\rho} + \partial^{\nu} \Lambda^{\rho\mu} + \partial^{\rho} \Lambda^{\mu\nu}$$

Therefore, the strength tensor of a form is gauge-invariant

What do these forms propagate?

First step is to look at the number of degrees of freedom (*DOFs*) propagated by each form, taking into account for each free-theory:

The equations of motion

The gauge-symmetries

	Scalar field ϕ	Vector field A^{μ}	KR field $B^{\mu\nu}$	Three-form $C^{\mu\nu\rho}$
massless	1	2	1	0
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Two representations of a massive spin-one particle

[3] A.Hell, *On the duality of massive Kalb-Ramond and Proca fields*, JCAP 01, 2022

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Two representations of a massless spin-zero particle (axion)

[4] F.Quevedo, *Duality Beyond Global Symmetries: the Fate of the $B^{\mu\nu}$ Field* , arXiv: hep-th/9506081 (1995)

Unpacking the nature of the DOFs

A massive vector has two transverses and one longitudinal polarizations. It can be seen explicitly through Stueckelberg decomposition:

$$A^\mu_{\text{massive}} = A^\mu_{\text{massless}} + \frac{\partial^\mu \phi}{m}$$

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1 longitudinal DOF (scalar like)

2 transverse DOFs (photon like)

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$$A^\mu_{\text{massive}} = \underbrace{A^\mu_{\text{massless}}}_{\text{2 transverse DOFs (photon like)}} + \underbrace{\frac{\partial^\mu \phi}{m}}_{\text{1 longitudinal DOF (scalar like)}}$$

In the context of the Higgs mechanism:

$$W^\mu_{\text{massive}} = W^\mu_{\text{massless}} + \underbrace{\frac{\partial^\mu \phi}{v}}_{\text{Scalar EW Goldstone boson}}$$

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Scalar EW Goldstone boson

A massive vector can be seen as a massless vector + a scalar « would-be » Goldstone that brings the missing DOF

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For the Three-form:

$$C^{\mu\nu\rho}_{\text{massive}} = \underbrace{C^{\mu\nu\rho}_{\text{massless}}}_{\text{Nothing!}} + \overbrace{\frac{F^{\mu\nu\rho}_{B}}{m}}^{\text{1 longitudinal DOF}}$$

---

[6] G. Dvali, *Three-Form Gauging of Axion Symmetries and Gravity*, hep-th/0507215 (2005)

Parity-even Kalb-Ramond propagator

The massive Kalb-Ramond Lagrangian contains a kinetic term and a mass term:

$$L_B = \frac{1}{12} F^B_{\mu\nu\rho} F_B^{\mu\nu\rho} + \frac{m^2}{4} B_{\mu\nu} B^{\mu\nu} \, .$$

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Its propagator can be seen as a four indices, antisymmetric version of a massive vector propagator

Vector propagator

$$P_A^{\mu\alpha} = \frac{-i}{k^2 - m^2}\left[g^{\mu\alpha} - \frac{k^\mu k^\alpha}{m^2}\right]$$

KR propagator

$$P_B^{\mu\nu,\alpha\beta} = \frac{i}{k^2 - m^2}\left[\left(g^{\mu\alpha} g^{\nu\beta} - g^{\mu\beta} g^{\nu\alpha}\right) - \frac{1}{m^2}\left(g^{\nu\beta} k^\mu k^\alpha - g^{\mu\beta} k^\nu k^\alpha - g^{\mu\alpha} k^\nu k^\beta - g^{\nu\alpha} k^\mu k^\beta + g^{\mu\alpha} k^\nu k^\beta\right)\right]$$

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$\propto$ metric tensors

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$\propto$ impulsions/m^2

<u>KR propagator</u>

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The pseudo-scalar mass term

In 4 dimensions, the peculiar case $p = 2$ of the Kalb-Ramond field allows for an additional, parity-odd mass term:

$$L_B = \frac{1}{12} F^B_{\mu\nu\rho} F_B^{\mu\nu\rho} + \frac{m^2}{4} B_{\mu\nu} B^{\mu\nu} + \frac{\tilde{m}^2}{4} B_{\mu\nu} \tilde{B}^{\mu\nu}$$

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It translates in an additionnal term for the propagator:

$$P_B^{\mu\nu,\alpha\beta} = \frac{i}{k^2 - \frac{m^4 + \tilde{m}^4}{m^2}} \left[\left(g^{\mu\alpha} g^{\nu\beta} - g^{\mu\beta} g^{\nu\alpha} \right) - \frac{1}{m^2} \left(g^{\nu\beta} k^\mu k^\alpha - g^{\mu\beta} k^\nu k^\alpha - g^{\mu\alpha} k^\nu k^\beta - g^{\nu\alpha} k^\mu k^\beta + g^{\mu\alpha} k^\nu k^\beta \right) + \frac{\tilde{m}^2}{m^2} \varepsilon^{\mu\nu\alpha\beta} \right]$$

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antisymmetric tensor in the propagator

Corrected mass term

$$\boxed{\tilde{B}^{\mu\nu} = \frac{1}{2} \varepsilon^{\mu\nu\rho\sigma} B_{\rho\sigma}}$$

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A constraint on exotic fields: Duality

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Same thing for the massive vector field A^{μ} and Kalb-Ramond field $B^{\mu\nu}$ that both describe a massive spin-one particle (3 DOFs) or for a massless scalar field ϕ and Kalb-Ramond field $B^{\mu\nu}$ that both describe a massless spin-zero particle (axion).

The range of validity of duality

1) Duality is strict as long as the theories are free

The presence of interactions induces corrections to the duality relations (in the form of contact terms) that jeopardize the naive interpretation:

[6] D. Dalmazi, R. C. Santos, *Spin-1 duality in D-dimensions*, Phys. Rev. D 84 (2011)

[7] C.P. Burgess, F. Quevedo, *Dual is Different*, arXiv:2509.11340 (2025)

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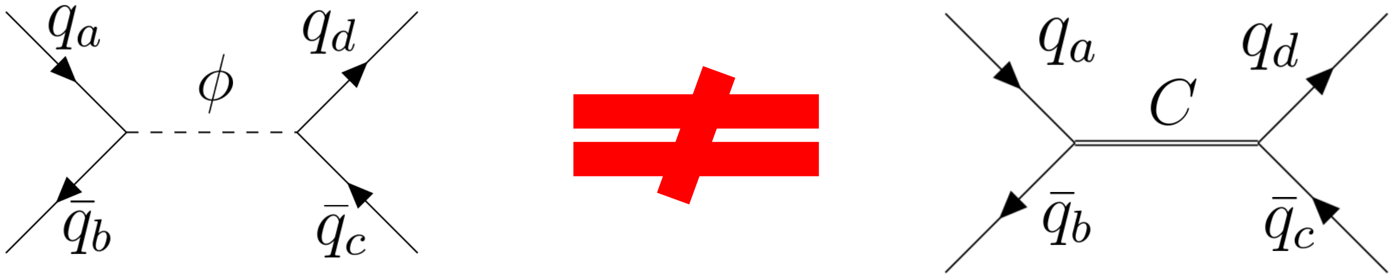
2) When differential forms are *OFF-SHELL* (meaning that they play the role of a propagator), duality is no longer valid



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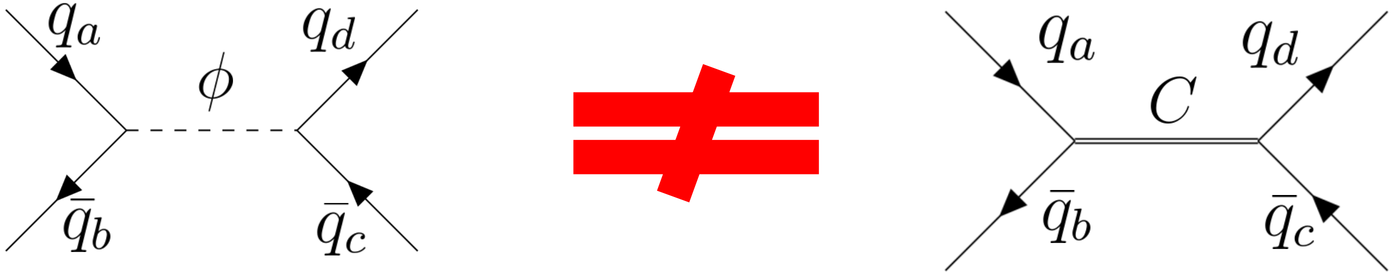

3) When differential forms are *ON-SHELL* (meaning that they are real), duality still holds but it shuffles the orders of mass of the effective interactions between the forms and the external fields.

[6] D. Dalmazi, R. C. Santos, *Spin-1 duality in D-dimensions*, Phys. Rev. D 84 (2011)
[7] C.P. Burgess, F. Quevedo, *Dual is Different*, arXiv:2509.11340 (2025)

Duality shuffles the orders of mass

Duality gives an algebraic prescription to go from a basis of effective interaction to another, but this mapping involves mass scales

$$\bar{\psi}_L \gamma^\sigma \psi_L \varepsilon_{\mu\nu\rho\sigma} C^{\mu\nu\rho}$$

Dominant three-form - fermions coupling

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$$\frac{1}{M} \bar{\psi}_L \gamma^\sigma \psi_L (\partial_\sigma \phi)$$

Suppressed scalar - fermions coupling

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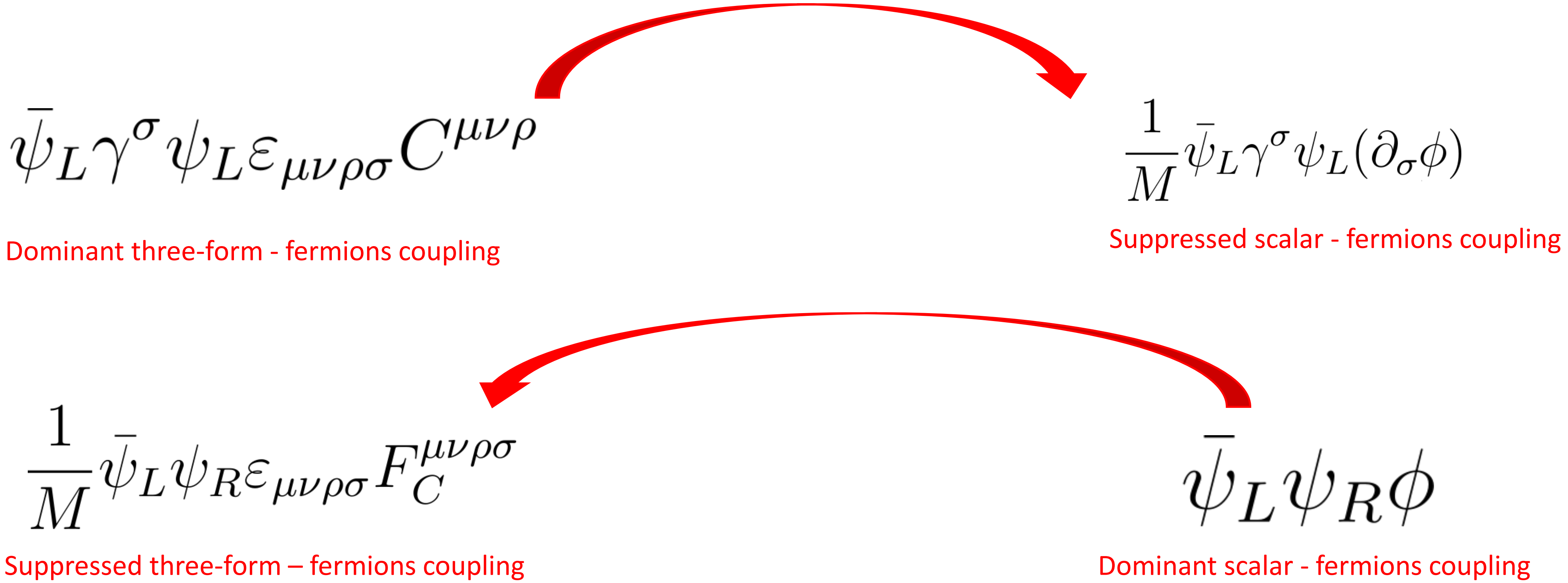

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Suppressed three-form – fermions coupling

$$\bar{\psi}_L \psi_R \phi$$

Dominant scalar - fermions coupling

Despite the duality, we see that the dominant effective couplings (for examples to fermions) will not be the same

Different three-body decays

For every form, the leading operator coupling two dark fields with fermions involves the same structure

$$\boxed{\bar{\psi}_L\psi_R\phi^2}$$

$$\boxed{\bar{\psi}_L\psi_R A_\mu A^\mu}$$

$$\boxed{\bar{\psi}_L\psi_R B_{\mu\nu}B^{\mu\nu}}$$

$$\boxed{\bar{\psi}_L\psi_R C_{\mu\nu\rho}C^{\mu\nu\rho}}$$

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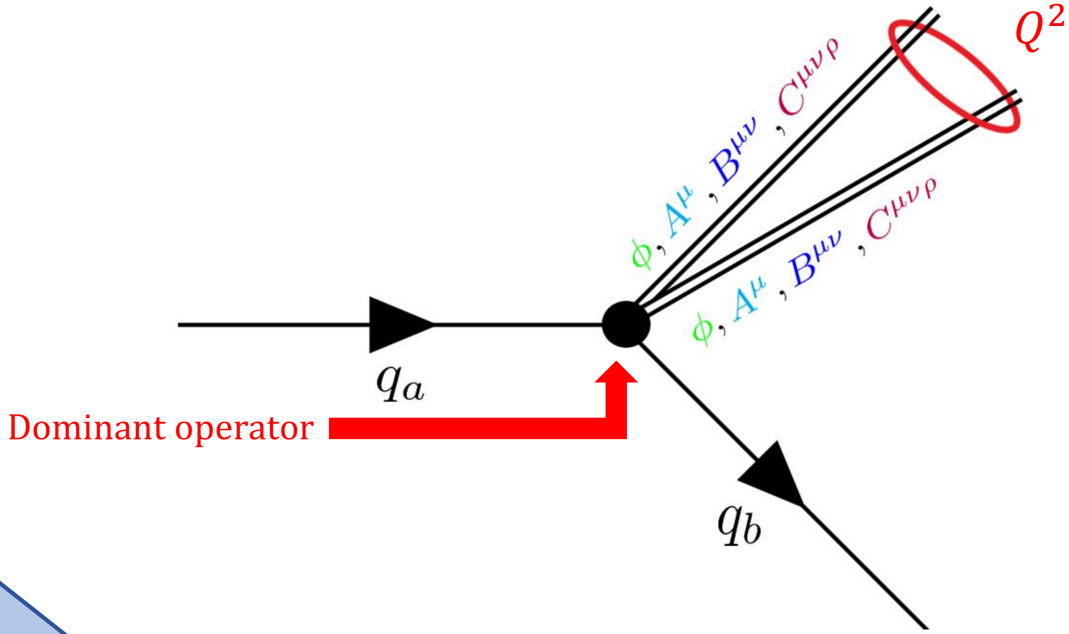

$q_a \to q_b XX$ with $X = \phi, A^\mu, B^{\mu\nu}, C^{\mu\nu\rho}$

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$\bar{\psi}_L \psi_R \phi^2$

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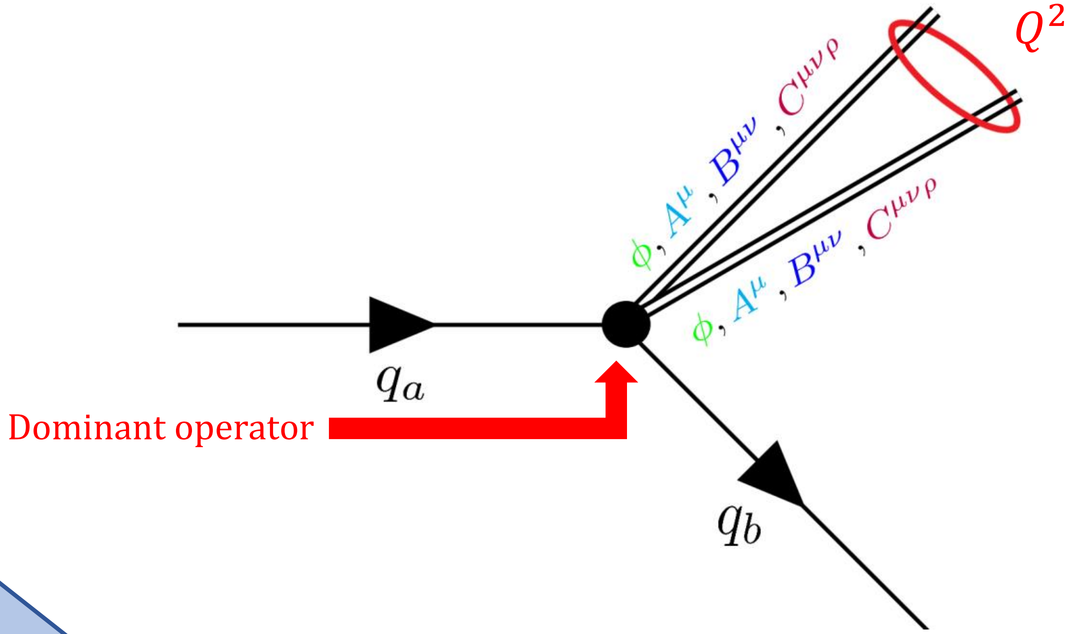
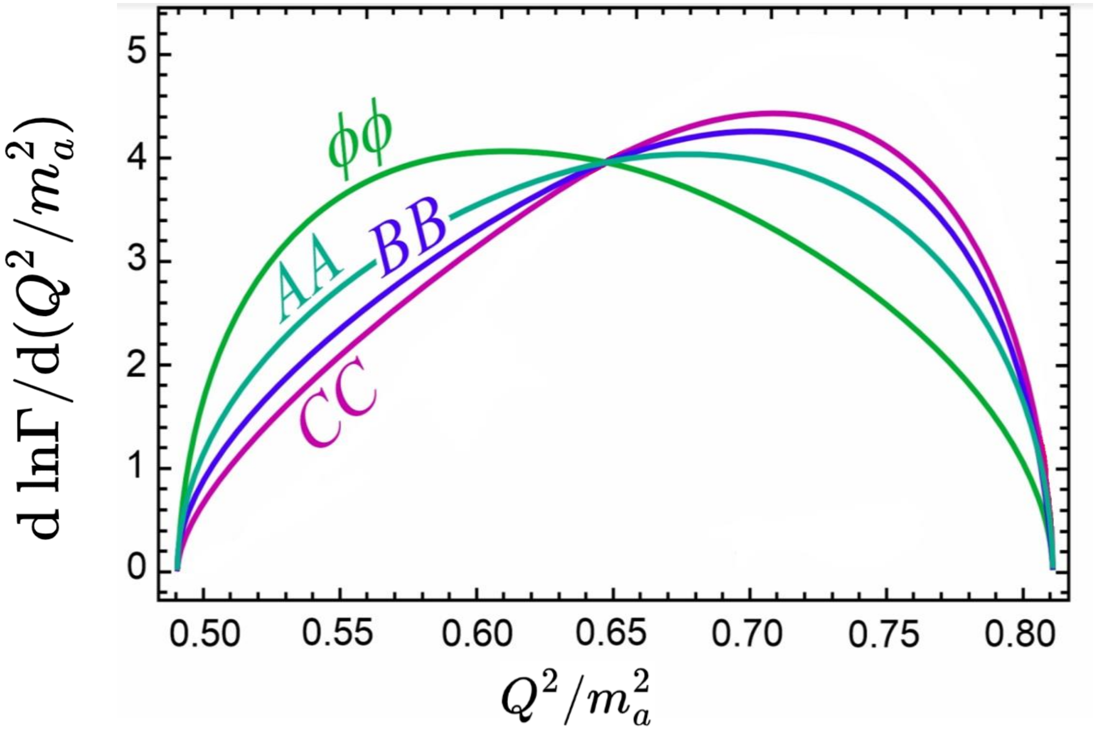


$q_a \to q_b XX$ with $X = \phi, A^\mu, B^{\mu\nu}, C^{\mu\nu\rho}$



Normalized differential decay rates for $q_a \to q_b XX$, in function of the squared impulsion Q^2 normalized by m_a^2. Here, $\frac{m_b}{m_a} = 0{,}1$, $\frac{m_X}{m_a} = 0{,}35$.

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Imposing symmetries to create unique models

Duality maps gauge-invariant operators of a basis with gauge-breaking operators of the other (and reciprocally).

Despite duality, if one imposes gauge invariance, the models are therefore very different!

Examples:

- Gauge invariant dark photon
- Gauge/Shift invariant dark spin-zero particle

Gauge /Shift invariant dark spin-zero particle

Embody a dark photon in a vector or a Kalb-Ramond field, you obtain completely different realizations:

Gauge /Shift invariant dark spin-zero particle

Embody a dark photon in a vector or a Kalb-Ramond field, you obtain completely different realizations:

Dark vector A^μ

Kinetic Mixing with SM fermions

$$\boxed{\epsilon' F^A_{\mu\nu} \tilde{F}^{\mu\nu}_\gamma} \quad \boxed{\epsilon F^A_{\mu\nu} F^{\mu\nu}_\gamma}$$

Vector/axial interaction forbidden

$$\boxed{\bar{\psi}\gamma^\mu\psi A_\mu} \quad \boxed{\bar{\psi}\gamma^\mu\gamma^5\psi A_\mu}$$

$$\boxed{F^A_{\mu\nu}\bar{\psi}\sigma^{\mu\nu}\psi} \quad \boxed{F^A_{\mu\nu}\bar{\psi}\sigma^{\mu\nu}\gamma^5\psi}$$

EDM/MDM operators are the dominant couplings

Gauge /Shift invariant dark spin-zero particle

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EDM/MDM operators are the dominant couplings

Kalb-Ramond $B^{\mu\nu}$

No kinetic Mixing with SM fermions

$\epsilon B_{\mu\nu} F^{\mu\nu}_{\gamma}$ $\quad$ $\epsilon' B_{\mu\nu} \tilde{F}^{\mu\nu}_{\gamma}$

Vector/axial operators are the dominant couplings

$F^{B}_{\mu\nu\rho}\varepsilon^{\mu\nu\rho\sigma}\bar{\psi}\gamma_{\sigma}\psi$ $\quad$ $F^{B}_{\mu\nu\rho}\varepsilon^{\mu\nu\rho\sigma}\bar{\psi}\gamma_{\sigma}\gamma_{5}\psi$

$B_{\mu\nu}\bar{\psi}\sigma^{\mu\nu}\psi$ $\quad$ $B_{\mu\nu}\bar{\psi}\sigma^{\mu\nu}\gamma^{5}\psi$

EDM/MDM operators are forbidden

Gauge /Shift invariant dark spin-zero particle

Like for the dark-photon, and despite duality, the dark scalar and the dark three-form have orthogonal coupling properties:

Gauge/Shift invariant dark spin-zero particle

Like for the dark-photon, and despite duality, the dark scalar and the dark three-form have orthogonal coupling properties:

Scalar field ϕ

Yukawa interaction forbidden by the shift-symmetry

$$\boxed{\phi\bar{\psi}\psi}$$

The dominant fermion coupling is *axion-like*

$$\boxed{(\partial_\mu\phi)\bar{\psi}\gamma^\mu\psi}$$

$$\boxed{(\partial_\mu\phi)\bar{\psi}\gamma^\mu\gamma^5\psi}$$

Gauge /Shift invariant dark spin-zero particle

Like for the dark-photon, and despite duality, the dark scalar and the dark three-form have orthogonal coupling properties:

Scalar field ϕ

Yukawa interaction forbidden by the shift-symmetry

$$\boxed{\phi\bar{\psi}\psi}$$

$$\boxed{(\partial_\mu\phi)\bar{\psi}\gamma^\mu\psi}$$

The dominant fermion coupling is *axion-like*

$$\boxed{(\partial_\mu\phi)\bar{\psi}\gamma^\mu\gamma^5\psi}$$

Three-form $C^{\mu\nu\rho}$

$$\boxed{F^C_{\mu\nu\rho\sigma}\varepsilon^{\mu\nu\rho\sigma}\bar{\psi}\psi}$$

The dominant fermion coupling is a Yukawa interaction

$$\boxed{C_{\mu\nu\rho}\varepsilon^{\mu\nu\rho\sigma}\bar{\psi}\gamma_\sigma\psi}$$

No *axion-like* interaction

$$\boxed{C_{\mu\nu\rho}\varepsilon^{\mu\nu\rho\sigma}\bar{\psi}\gamma_\sigma\gamma_5\psi}$$

Conclusion

Despite the constraints imposed by duality, higher-forms make natural candidates for dark matter:

- The dominant operators are not the same for two dual forms, giving distinct experimental signatures.
- Duality is broken *off-shell*, leading to distinct scattering amplitudes even for dual operators.
- Duality involves mass scales as free parameters, that enables us to suppress or boost certain operators naturally.
- Despite the growing number of indices, the number of effective operators is considerably small thanks to duality
- Imposing gauge symmetries breaks duality as well, allowing or preventing couplings depending on the regarded form.
  - ↳ Could lead to kinetic-mixing and EDM/MDM free dark photons, or to Yukawa coupling ALPs

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Thank you for your attention and feel free to ask questions!