Models for Ultralight Dark Matter

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Based upon: 2107.09493 [hep-ph]

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COST EUROPEAN COOPERATION IN SCIENCE AND TECHNOLOGY
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CENTRO 2020
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CIDMA CENTRO DE I&D EM MATEMÁTICA E APLICAÇÕES CENTER FOR R&D IN MATHEMATICS AND APPLICATIONS

LIGO-Virgo event GW190521

PRL 126, 081101 (2021), Bustillo, Sanchis-Gual, Torres-Forné, Font, Vajpeyi, Smith, Herdeiro, Radu, Leong

$$\boxed{\text{Proca stars merger} \quad \mu = 8.70^{+0.75}_{-0.69} \times 10^{-13}\,\text{eV}}$$

Can provide the first evidence for a vector dark matter particle

see C. Herdeiro lecture

Ultralight bosons are often seen as a natural consequence of the string landscape ⟶ $\boxed{\text{Fuzzy DM}}$

$\boxed{\text{However, a concrete proposal from simple extensions of the SM is lacking}}$

In this lecture I will discuss simple extensions of the SM where complex and real scalar and vector ultralight bosons can emerge.

Strong Gravity

Minimal coupling to spin-s field in 4d:

$$S = \int d^4x \sqrt{-g} \left[\frac{R}{16\pi G} + \mathcal{L}_{(s)} \right]$$

$$\mathcal{L}_{(0)} = - g^{\alpha\beta} \phi^{+}_{,\alpha} \phi_{,\beta} - \mu^2 \phi^{+}\phi - V^{int}_{(0)}(\phi^{+}\phi) \qquad \text{SCALAR}$$

$$\mathcal{L}_{(1)} = -\frac{1}{4} \bar{F}_{\alpha\beta} F^{\alpha\beta} - \frac{\mu^2}{2} A^{+}_{\alpha} A^{\alpha} - V^{int}_{(1)}(A^{+}_{\alpha} A^{\alpha}) \qquad \text{VECTOR}$$

$\mu^2 > 0$, ϕ and A_α are complex, $F_{\alpha\beta} = \partial_\alpha A_\beta - \partial_\beta A_\alpha$

If $\mu \in [10^{-20}, 10^{-10}]\,\mathrm{eV} \Longrightarrow \underset{\text{star}}{M_{\text{Bosonic}}} \in \underbrace{[1, 10^{20}]\, M_\odot}_{\text{Range of known astrophysical BHs}}$

Our goal!

Build simple SM extensions that can consistently explain ultralight bosons

$$\mathcal{L} = \mathcal{L}_{SM} + \mathcal{L}_{BSM}$$

General Principles for ultralight bosons

1. Fine-tuning: Tiny mass results from an accidental cancelation of parameters

2. Feebly coupled theory: Tiny mass proportional to tiny (but not zero) parameters

3. Symmetry protection
   - $\longrightarrow$ global $\longrightarrow$ scalar $s=0$
   - $\longrightarrow$ local $\longrightarrow$ vector $s=1$

- The SM Higgs potential: $SU(2)_w \times U(1)_Y$ → electroweak theory

$$V_0(H^\dagger H) = \mu_H^2 H^\dagger H + \frac{1}{2}\lambda_H (H^\dagger H)^2$$

- Extending the SM with a complex scalar Φ

$$V(H,\Phi) = V_0(H^\dagger H) + \mu_\Phi^2 \Phi^* \Phi + \frac{1}{2}\lambda_\Phi |\Phi^*\Phi|^2 + \underbrace{\lambda_{H\Phi} H^\dagger H \Phi^* \Phi}_{\text{PORTAL INTERACTION}}$$

Theory invariant under a $U(1)_{global}$ phase transformation $\Phi \rightarrow e^{i\alpha}\Phi$

The SM electroweak breaking vacuum $\langle H \rangle = \frac{1}{\sqrt{2}} \begin{pmatrix} 0 \\ v_h \end{pmatrix}$ implies the mass spectrum:

$\boxed{v_h = 246 \text{ GeV}}$

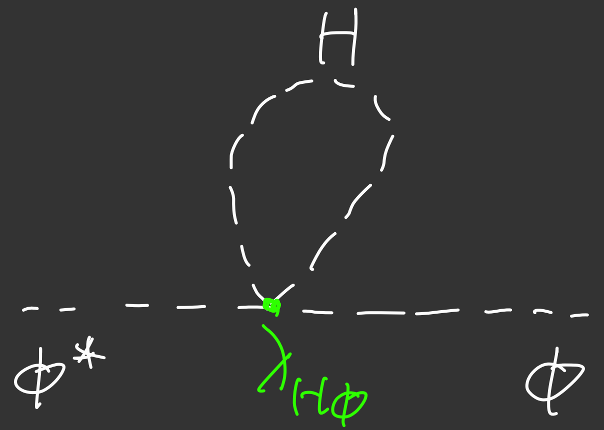
$$\underbrace{m_h^2 = 2 \lambda_H v_h^2}_{\text{Higgs Boson } 125 \text{ GeV}} \qquad \underbrace{m_\Phi^2 = \mu_\Phi^2 + \frac{1}{2} \lambda_{H\Phi} v_h^2}_{\text{ultralight candidate}}$$

if:

Fine-tuned case $\longleftarrow$ a) $\mu_\Phi^2 \simeq -\frac{1}{2} \lambda_{H\Phi} v_h^2$

Feebly-interacting case $\longleftarrow$ b) μ_Φ^2 and $\lambda_{H\Phi}$ are tiny

QUANTUM CORRECTIONS

$\Delta_\phi =$ 

$+$ higher orders

$$M_\phi^2 = m_\phi^2 + \Delta_\phi \quad , \quad \Delta_\phi \sim \frac{1}{16\pi^2}\,\lambda_{H\phi}\, v_h^2$$

- Quantum corrections push the mass to the Electroweak scale v_h unless $\lambda_{H\phi} \ll 1$ (Feebly int.)

- $\Delta\phi$ destroys fine-tuned case and requires a remarkable cancelation to all orders in perturbation theory $\longrightarrow$ often said to be unnatural

How to consistently build an extension to the SM with ultralight bosons?

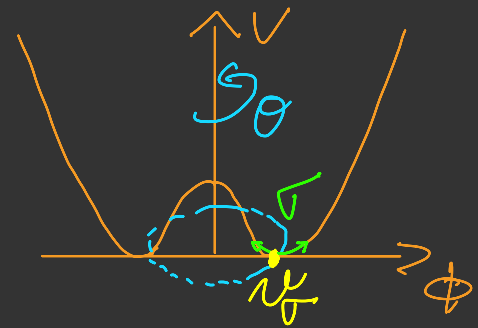
SYMMETRY PROTECTION

Case 1 : Continuous global symmetry

$U(1)_G$ example $\mathcal{L}(\phi) = \mathcal{L}(e^{i\alpha}\phi)$

$$V(H,\phi) = V_0(H^\dagger H) + \mu_\phi^2 \phi^* \phi + \frac{1}{2}\lambda_\phi |\phi^* \phi|^2 + \lambda_{H\phi} H^\dagger H \phi^* \phi$$

Radial and angular quantum fluctuations about the vacuum v_σ $\Big\}$ $\phi = \frac{1}{\sqrt{2}}(\sigma + v_\sigma)\, e^{i\theta/v_\sigma}$



SPONTANEOUSLY BREAKS $U(1)_G$ SYMMETRY

Goldstone's Theorem $\Longrightarrow$ 1 massless scalar per broken generator

$$m_\sigma^2 \neq 0 \qquad\qquad \boxed{m_\theta^2 = 0}$$

It is typically conjectured that continuous global symmetries are marginally violated by quantum gravitational effects Hui, Ostriker, Tremaine, Witten PRD 95, 043541 (2017)

Add an explicitly $U(1)_\sigma$ breaking term:

$$V(H,\phi) \longrightarrow V(H,\phi) + V_{soft}\,, \qquad V_{soft} = \frac{1}{2}\mu_s^2\left(\phi^2 + \phi^{*2}\right)$$

$$V_{soft}'(\phi e^{i\alpha}) = \frac{1}{2}\mu_s^2\left(\phi^2 e^{2i\alpha} + \phi^{*2} e^{-2i\alpha}\right) \neq V_{soft}(\phi) \implies \text{Broken } U(1)_\sigma$$

$$V_{soft} = \frac{1}{2}\mu_s^2\,(\sigma + v_\sigma)^2\cos\left(\frac{2\theta}{v_\sigma}\right)$$

<u>Minimization</u>

$$\mu_\phi^2 = -\frac{1}{2}\left[v_\sigma^2\lambda_\phi + v_h^2\lambda_{H\phi} + 2\mu_s^2\cos\left(\frac{2\theta}{v_\sigma}\right)\right], \quad \theta = n\pi v_\sigma\,,\ n\in\mathbb{Z}$$

$$\left.\frac{\partial V}{\partial\theta}\right|_{\sigma=0} = \mu_s^2 v_\sigma \sin\left(\frac{2\theta}{v_\sigma}\right) = 0$$

$$M^2 \simeq \begin{pmatrix} v_h^2 \lambda_H & v_h v_\sigma \lambda_{H\phi} & 0 \\ v_h v_\sigma \lambda_{H\phi} & v_\sigma^2 \lambda_\phi & 0 \\ 0 & 0 & -2\mu_s^2 \end{pmatrix} \longrightarrow m^2 = \mathcal{O}^T M^2 \mathcal{O} = \mathrm{diag}\Big(\underbrace{m_{h_1}^2}_{\text{Higgs boson}}, \underbrace{m_{h_2}^2}_{\text{BSM}}, \underbrace{m_\theta^2}_{\text{ultralight}}\Big)$$

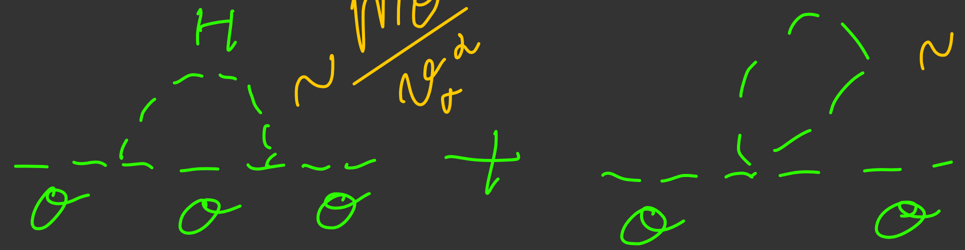
$$\mathcal{O} = \begin{pmatrix} c_\alpha & s_\alpha & 0 \\ -s_\alpha & c_\alpha & 0 \\ 0 & 0 & 1 \end{pmatrix}, \quad \begin{cases} c_\alpha = \cos\alpha \\ s_\alpha = \sin\alpha \end{cases}, \quad \alpha \longrightarrow \text{scalar mixing angle}$$

$$m_{h_{1,2}}^2 = \frac{1}{2}\left[v_h^2 \lambda_H + v_\sigma^2 \lambda_\phi \mp \sqrt{v_h^4 \lambda_H^2 + v_\sigma^2 \lambda_\phi^2 + 2 v_h^2 v_\sigma^2 \left(2\lambda_{H\phi}^2 - \lambda_H \lambda_\phi\right)}\right]$$

$$m_\theta^2 = -2\mu_s^2 \longrightarrow \text{Pseudo-Goldstone ultralight DM candidate}$$

$$h_1, h_2 \longrightarrow \text{Higgs} + \text{new visible scalar}$$

Quantum corrections to the DM mass



$$\sim \frac{m_\theta^4}{v_\sigma^2} \quad + \quad \sim \frac{p^4}{v_\sigma^2}$$

corrections calculated at $p = m_\theta$

scale as $\Delta_\theta \sim \dfrac{m_\theta^4}{v_\sigma^2}$ PROTECTED

For ultralight Θ the marginally violated global symmetry protects m_Θ^2 against large quantum corrections.

self interaction: $\lambda_{\Theta\Theta\Theta\Theta} = -\dfrac{m_\Theta^2}{6 v_\sigma^2}$

≈ 0 for $m_\Theta \ll v_\sigma$

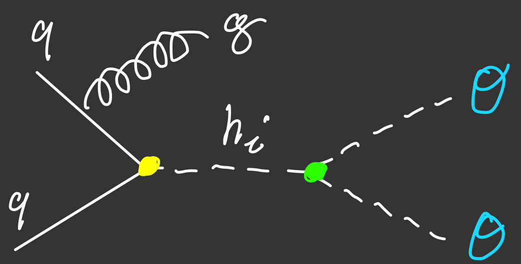
Θ is real $\longrightarrow$ Relevant for oscillatons

Seidel, Suen PRL 72, 2516-2519 (1994)

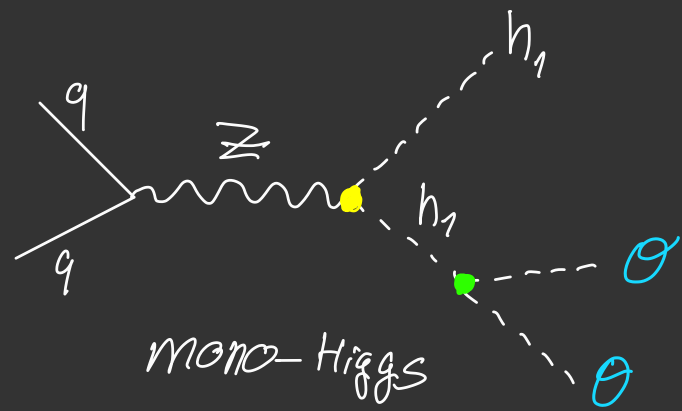
- $\lambda_{\theta\theta h_i} = \frac{m_{h_i}^2}{v_T} O_{2i}$,
- $\lambda_{h_i SM SM} = O_{1i}\, g_{SM}$

$$O = \begin{pmatrix} c_\alpha & s_\alpha & 0 \\ -s_\alpha & c_\alpha & 0 \\ 0 & 0 & 1 \end{pmatrix}$$

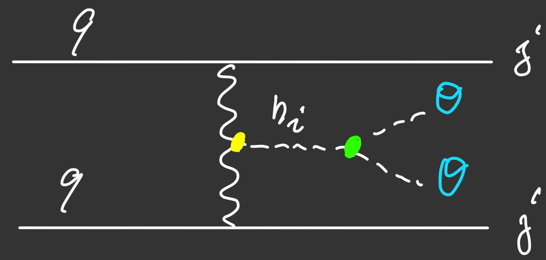
θ can be produced at collider experiments



mono-j/V

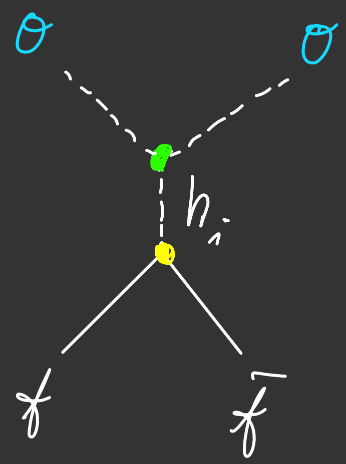


mono- Higgs



2j + MET

On being directly detected

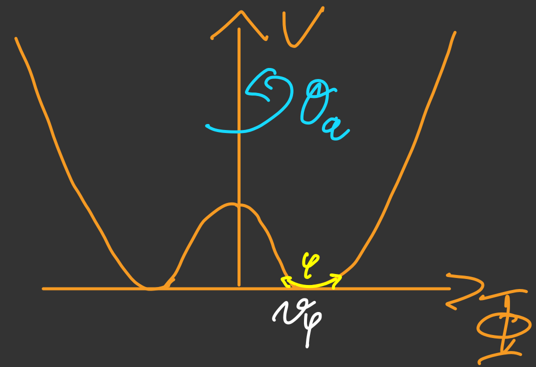


What about a complex scalar?

• Increase the global symmetry

$$SU(2)_G \times U(1)_G$$

$$\Phi = \frac{1}{\sqrt{2}} \begin{pmatrix} 0 \\ v_\varphi + \varphi \end{pmatrix} e^{\frac{i}{2} \frac{\tau^a \theta_a}{v_\varphi}}$$



$\tau^a \longrightarrow$ Pauli matrices $a = 1, 2, 3$

$\theta_a \longrightarrow$ 3 Goldstone bosons (angular directions)

$\varphi \longrightarrow$ Radial direction fluctuations

The vacuum v_φ must preserve a Noether charge : $SU(2)_G \times U(1)_G \longrightarrow U(1)_{G'}$

Define : $\eta_\pm = \frac{1}{\sqrt{2}}(\pm i\theta_1 + \theta_2)$

$\eta_0 \equiv \theta_3$

Expand $e^{\frac{i}{2}\frac{\tau^a\theta_a}{v_\varphi}}$ to obtain $\Phi \equiv \begin{pmatrix} \phi_+ \\ \phi_0 \end{pmatrix}$

$$\Phi_+ \equiv \eta_+ (v_\varphi + \varphi) \frac{\sin\left(\frac{\sqrt{\eta_0^2 + 2\eta^+\eta^-}}{v_\varphi}\right)}{\sqrt{\eta_0^2 + 2\eta^+\eta^-}}$$

changed

Neutral

$$\Phi_0 \equiv \frac{1}{\sqrt{2}} (v_\varphi + \varphi) \frac{\sqrt{\eta_0^2 + 2\eta^+\eta^-} \cos\left(\frac{\sqrt{\eta_0^2 + 2\eta^+\eta^-}}{v_\varphi}\right) - i \sin\left(\frac{\sqrt{\eta_0^2 + 2\eta^+\eta^-}}{v_\varphi}\right)}{\sqrt{\eta_0^2 + 2\eta^+\eta^-}}$$

$$V_{soft} = \underbrace{\mu_1^2 \, \phi_- \phi_+}_{\text{Preserves Noether change } U(1)_G,} + \frac{1}{2}\mu_2^2 \left(\phi_0^2 + \phi_0^{*2} \right)$$

$SU(2)_G \times U(1)_G \longrightarrow U(1)_G$,

Expansion for small fields:

$$V_{soft} \simeq -\mu_2^2 \, r_0^2 + (\mu_1^2 - \mu_2^2) \, r_+ r_-$$

$$+ \frac{2}{3} \frac{\mu_2^2 - \mu_1^2}{v_\varphi^2} |r_+ r_-|^2 + \frac{1}{3} \frac{\mu_2^2}{v_\varphi^2} r_0^4 + \frac{3\mu_2^2 - \mu_1^2}{3 v_\varphi^2} r_+ r_- \, r_0^2$$

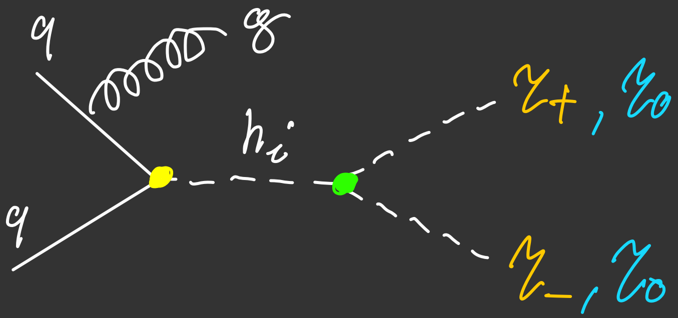
- Model contains a real, η_0, and a complex, $\eta_\pm$, scalar

$$m^2_{\eta_0} = -2\mu_2^2 \qquad m^2_{\eta_\pm} = \mu_1^2 - \mu_2^2$$

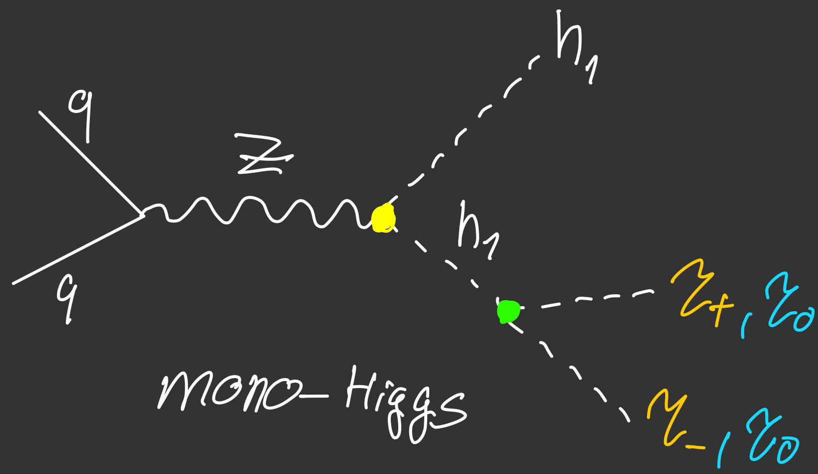
- One can choose μ_1^2 and μ_2^2 such that only $\eta_\pm$ is of astrophysical relevance

- For $v_\phi \gg \mu_{1,2}$ theory becomes free

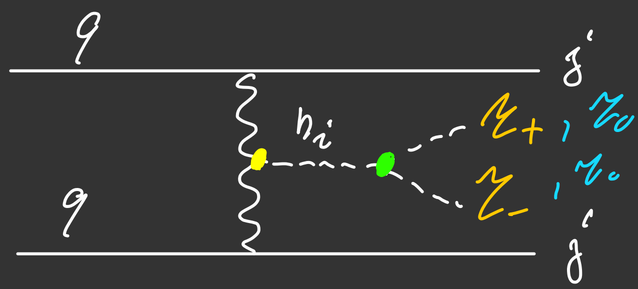
Production @ colliders



mono-j/V



mono-Higgs



2j + MET

- $\lambda_{h_i SM SM} = O_{1i}\, g_{SM}$
- $\lambda_{\eta_0 \eta_0 h_1} = \lambda_{\eta_+ \eta_- h_1} = \dfrac{m_{h_1}^2}{v_\varphi} \sin\alpha$
- $\lambda_{\eta_0 \eta_0 h_2} = \lambda_{\eta_+ \eta_- h_2} = \dfrac{m_{h_2}^2}{v_\varphi} \cos\alpha$

Case 2 : Continuous local abelian Symmetry

↳ Gauge Symmetry

$$U(1)_{H} \rtimes \mathbb{Z}_2 \longrightarrow \text{No } U(1)_Y \times U(1)_H \text{ kinetic mixing}$$

Hidden

$$\mathcal{L}_{kin} \supset \frac{1}{4} B'_{\mu\nu} B'^{\mu\nu} + (D_\mu \phi)^* D^\mu \phi$$

$$D_\mu = \partial_\mu + i g'_1 B'_\mu \quad , \quad B_{\mu\nu} = \partial_\mu B'_\nu - \partial_\nu B'_\mu$$

$$\mathbb{Z}_2 : \; B'_\mu \longrightarrow - B'_\mu \quad , \quad \phi \longrightarrow \phi^* \Longrightarrow \cancel{\frac{1}{2} \chi B_{\mu\nu} B'^{\mu\nu}}$$

$$(\partial_\mu - i g'_1 B'_\mu)\phi^* (\partial_\nu + i g'_1 B'_\nu)\phi \, g^{\mu\nu} \xrightarrow{\mathbb{Z}_2}$$

$$(\partial_\mu + i g'_1 B'_\mu)\phi (\partial_\nu - i g'_1 B'_\nu)\phi^* g^{\mu\nu} = D^\nu \phi (D_\nu \phi)^* \quad \boxtimes$$

$$\langle (D_\mu \Phi)^* D^\mu \Phi \rangle \longrightarrow \quad m_B = \frac{1}{2} g_1' v_\sigma$$

Astrophysical relevant, e.g. oscillatons,

if $\quad 10^{-20} \lesssim m_B^2/eV \lesssim 10^{-10} \Longrightarrow$

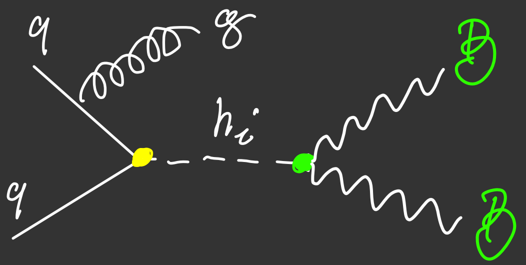
$$10^{-20} \lesssim \frac{g_1' v_\sigma}{2\,eV} \lesssim 10^{-10}$$

Either tiny scale v_σ, or feebly coupled theory, or a combination of both

$$g_{BBh_ih_j} = 2 g_1'^2 O_{2i} O_{2j} \quad , \quad \bullet \; g_{BBh_i} = 2 m_B g_1' O_{2i}$$

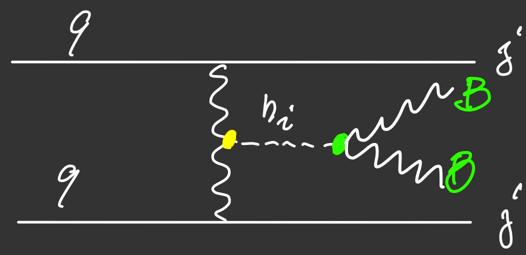
If tiny scale v_σ and sizeable g_1', $h^2\Omega_B$ depends on the annihilation $h_2 h_2 \to BB$

suppressed by m_B



mono-j/V

mono-Higgs



2j + MET

Case 3 : Continuous local non-abelian symmetry

↳ Gauge symmetry

$\mathbb{Z}_2 : B'_\mu \longrightarrow -B'_\mu \, , \, \Phi \longrightarrow \Phi^*$

$SU(2)_H \times U(1)_H \rtimes \mathbb{Z}_2$

$H \longrightarrow$ Hidden symmetry

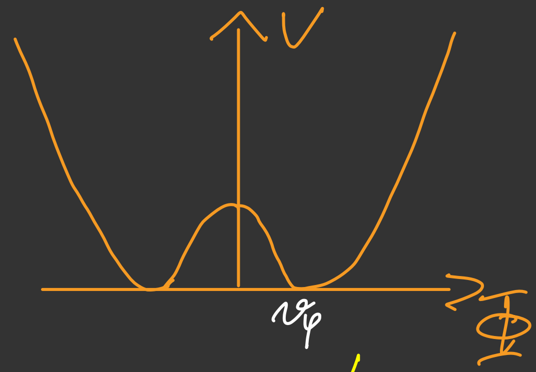
$$\mathcal{L}_{kin} = \frac{1}{4} B'_{\mu\nu} B'^{\mu\nu} + \frac{1}{4} F'^{a}_{\mu\nu} F'^{\mu\nu}_{a} + \mathcal{D}_\mu \Phi^* \mathcal{D}^\mu \Phi$$

$$\mathcal{D}_\mu = \partial_\mu \mathbb{1} + i g'_1 B'_\mu \mathbb{1} + i g'_2 \frac{\tau_a}{2} A'^a_\mu$$

$$B'_{\mu\nu} = \partial_\mu B'_\nu - \partial_\nu B'_\mu$$

$$F'^a_{\mu\nu} = \partial_\mu A'^a_\nu - \partial_\nu A'^a_\mu - g_2 \, \varepsilon^a{}_{bc} A'^b_\mu A'^c_\nu$$

Ground state of the theory $\langle \Phi \rangle = \frac{1}{\sqrt{2}} \begin{pmatrix} 0 \\ v_\varphi \end{pmatrix}$



$m_{\gamma'} = 0$ ⟶ Hidden photon

$m^2_{B^0} = \frac{1}{2} v_\varphi^2 e'^2 \csc(2\theta'_w)$ ⟶ Real Proca field

$m^2_{A^\pm} = \frac{1}{4} v_\varphi^2 e'^2 \csc\theta'_w$ ⟶ Complex Proca field

$$g'_1 = \underbrace{\frac{e'}{\cos\theta'_w}}_{e' \,\to\, \text{Hidden charge}}, \quad g'_2 = \frac{e'}{\sin\theta'_w}, \quad \begin{pmatrix} \gamma'_\mu \\ B^0_\mu \end{pmatrix} = \begin{pmatrix} \sin\theta'_w & \cos\theta'_w \\ -\cos\theta'_w & \sin\theta'_w \end{pmatrix} \begin{pmatrix} A'^3_\mu \\ B'_\mu \end{pmatrix}$$

similar to the SM $\gamma' \longrightarrow \gamma$, $B^0 \longrightarrow Z^0$, $A^\pm \longrightarrow W^\pm$

$$\left.\begin{aligned} m^2_{B^0} &= \frac{1}{2} v_\varphi^2\, e'^2 \csc^2(2\theta'_w) \\ m^2_{A^\pm} &= \frac{1}{4} v_\varphi^2\, e'^2 \csc^2\theta'_w \end{aligned}\right\}$$

ultralight for either
a) tiny v_φ scale
b) extremely small charge e'

when $\theta'_w \longrightarrow \frac{\pi}{2} \Longrightarrow m^2_{B^0} \gg m^2_{A^\pm}$

$\longrightarrow$ Only $A^\pm$ becomes of astrophysical relevance

GW 190521 $\longrightarrow$ PRL 126, 081101 (2021), C. Herdeiro et al.

GW 200114 $\longrightarrow$ work ongoing

$$\boxed{g_{AAAA} = \frac{m_{A^\pm}^2}{v_\varphi^2}} \Longrightarrow$$

Can become relevant for Proca stars for $m_{A^\pm} \sim v_\varphi$

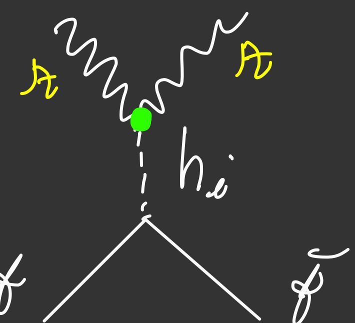
$$g_{AABB} = \frac{m_{A^\pm}^2}{v_\varphi^2}\cos^2\theta_w$$

$$g_{AAh_ih_j} = \frac{m_{A^\pm}^2}{v_\varphi^2} O_{2i} O_{2j}$$

If $m_{A^\pm}^2 \sim v_\varphi^2$, $h^2\Omega_{A^\pm}$ depends on the annihilation channels $h_2 h_2 \longrightarrow A^+ A^-$ and $BB \longrightarrow A^+ A^-$

$$g_{AAh_i} = 2 m_{A^\pm} O_{2i}$$

$m_{A^\pm}$ suppresses collider and direct detection events



Note that:

① For ultralight scalars $\lambda_{\eta\eta h_i} = \frac{m_{h_i}^2}{v_\varphi} O_{2i}$

can be sizeable $\Longrightarrow$ collider and direct detection falsifiable

② For ultralight vectors $g_{AAh_i} = 2 m_A O_{2i}$

Invisible at colliders and direct detection exp.

Conclusions

- Simple extensions of the SM can provide ultralight bosons
- Construction upon symmetry arguments is well formulated and stable against quantum effects
- Possible to constrain/test in multiple channels

- First list of HEP models proposed in 2107.09493 [hep-ph]

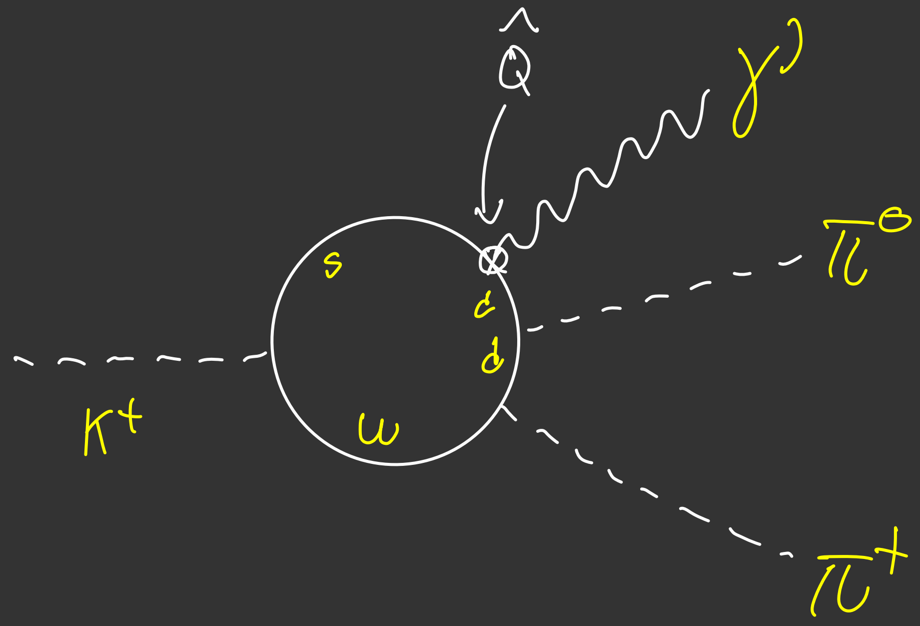
Model	Symmetry	Complex Vectors	Real Vectors	Complex Scalars	Real Scalars	Masses	Self Interactions
1	Global $\mathrm{U}(1)_{\mathrm{G}}$	✗	✗	✗	$\theta,\ h_2$	(30)	(35) (36) (37)
2	Global $\mathrm{U}(1)_{\mathrm{G}} \times \mathrm{U}(1)_{\mathrm{G'}}$	✗	✗	η	$h_2,\ h_3$	(51) (54)	(57) (A1) (A2)
3	Global $\mathrm{SU}(2)_{\mathrm{G}} \times \mathrm{U}(1)_{\mathrm{G}}$	✗	✗	$\eta^{\pm}$	$\theta_3,\ h_2$	(68) (69) (70)	(67) (73) (74)
4	Local $\mathrm{U}(1)_{\mathrm{H}}$	✗	$\mathcal{B}$	✗	h_2	(76)	(77)
5	Local $\mathrm{SU}(2)_{\mathrm{H}} \times \mathrm{U}(1)_{\mathrm{H}}$	$\mathcal{A}^{\pm}$	$\mathcal{B}, \gamma'$	✗	h_2	(87)	(88) (89) (90)

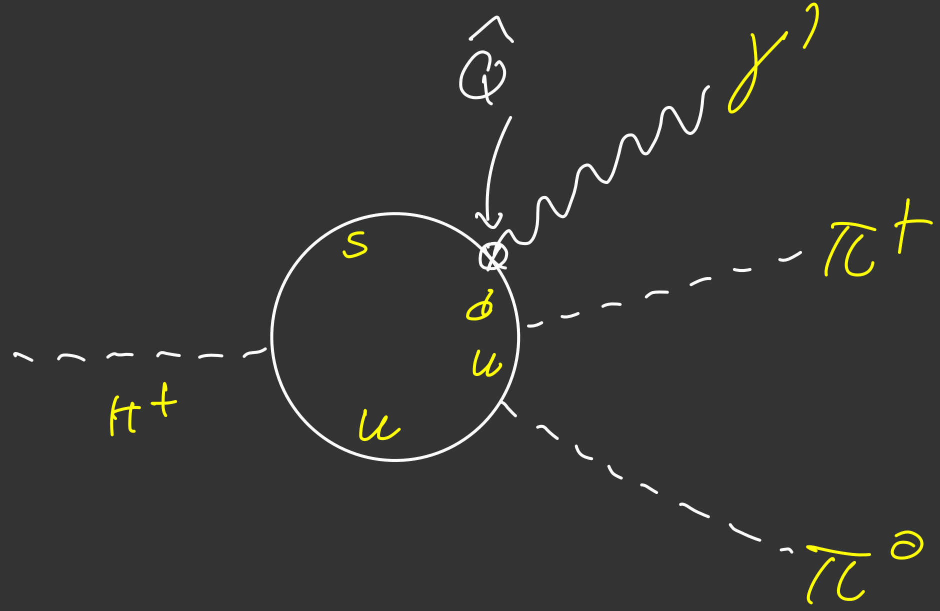
Thank you

Hidden Photon Searches

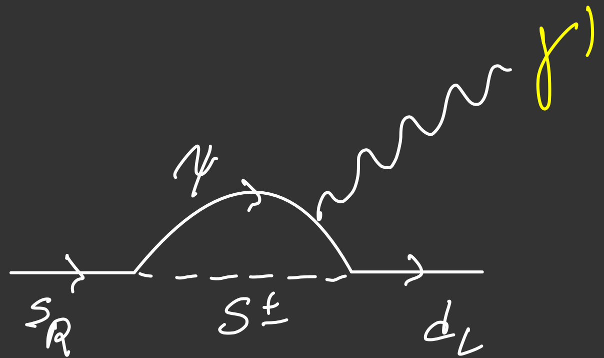
in Kaon Physics

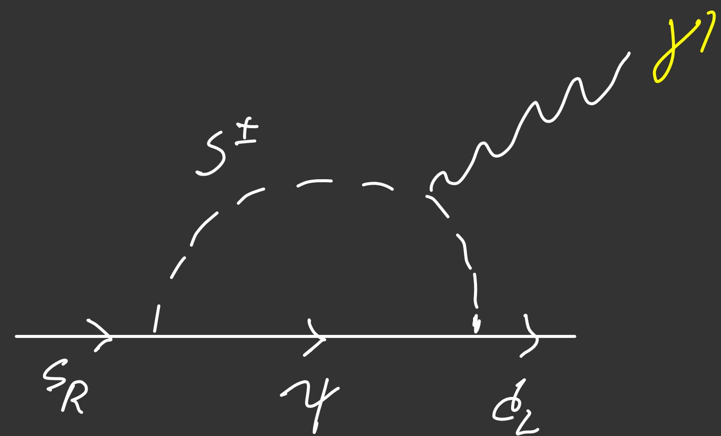
@ NA62 – CERN





$\hat{Q} \longrightarrow$ dipole operator





Phys. Rev. Lett. 119, 031801 (2017)