LPC - Clermont-Ferrand

April 2012

Could a light Higgs boson illuminate the dark sector?

Christopher Smith

Based on: Kamenik and C.S., arXiv:1111.6402 & arXiv:1201.4814.

I. Introduction

A. Are there only SM particles at low-energy?

Experimentally:

- Even very light states could be missed if very weakly interacting,
- There is dark matter in the Universe; it could be relatively light.

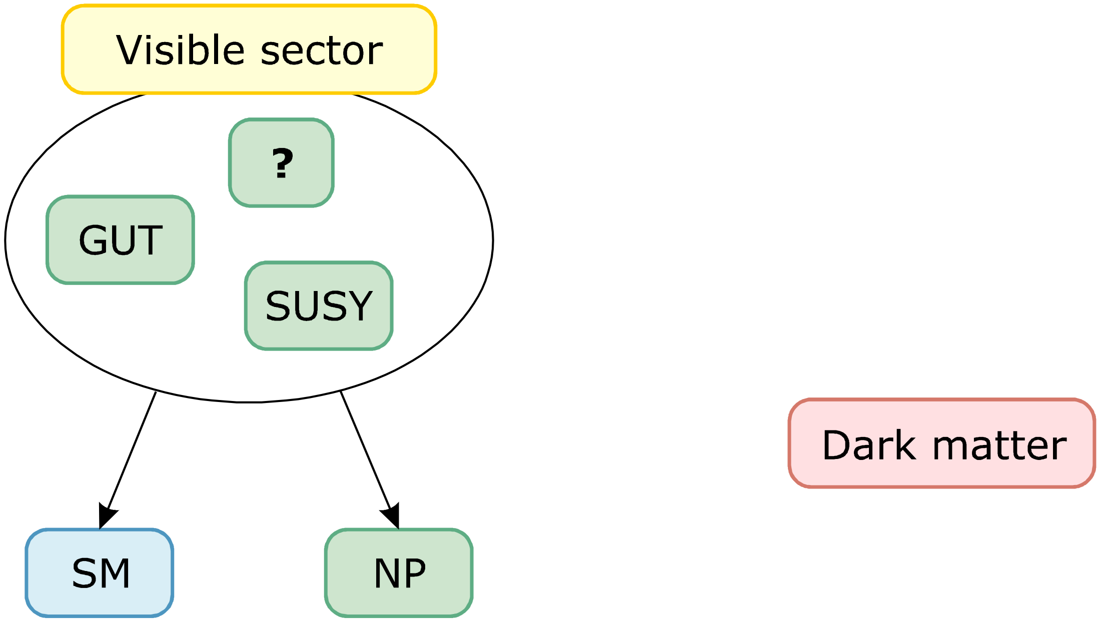
Theoretically: Plenty of models predict new light particles.

- Pseudo-Goldstone scalars (axion, familon,...),
- U(1) vectors (string, ED,...),
- Hidden sectors & messengers (SUSY, mirror worlds,...)
- Many others: millicharged fermions, dilaton, majoron,
  neutralino, sterile neutrino, gravitino,...

Phenomenologically:

New light states must be searched for systematically,
and as model-independently as possible.

B. How to systematically investigate the low-energy particle content?

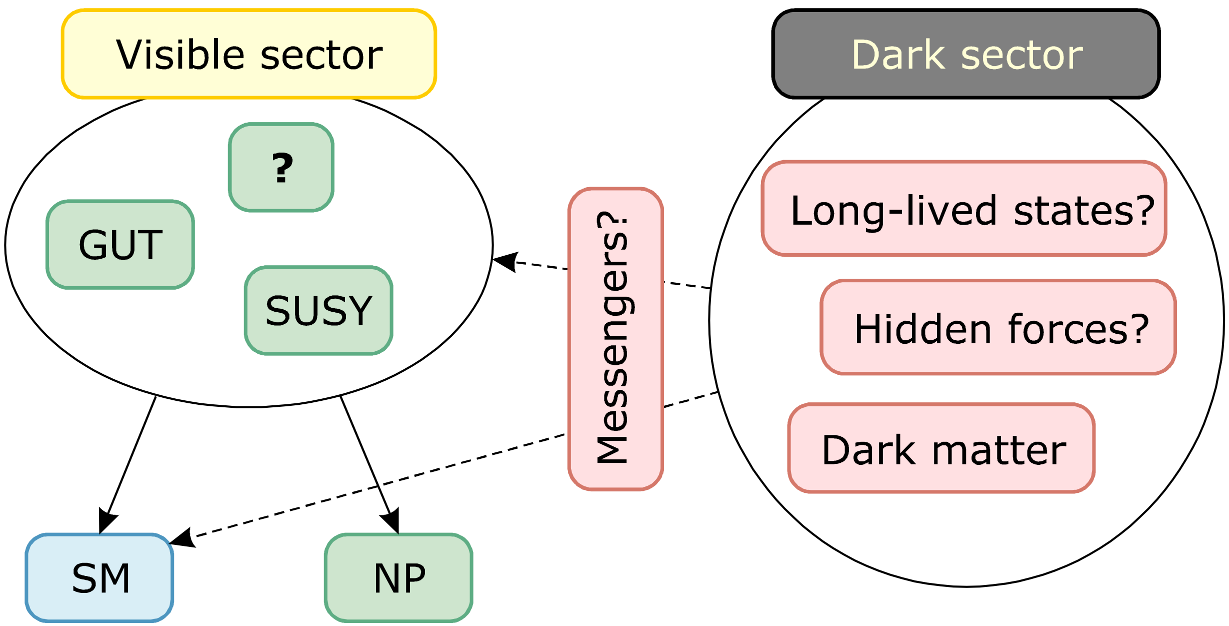


$$\mathcal{L}_{SM} + \frac{c_\nu}{\Lambda}(HL)^2 + \frac{c_i}{\Lambda^2} Q_i + \ldots$$

Heavy NP can be projected onto 65
effective gauge-invariant operators
built in terms of SM fields.

Buchmüller, Wyler ‘86

B. How to systematically investigate the low-energy particle content?



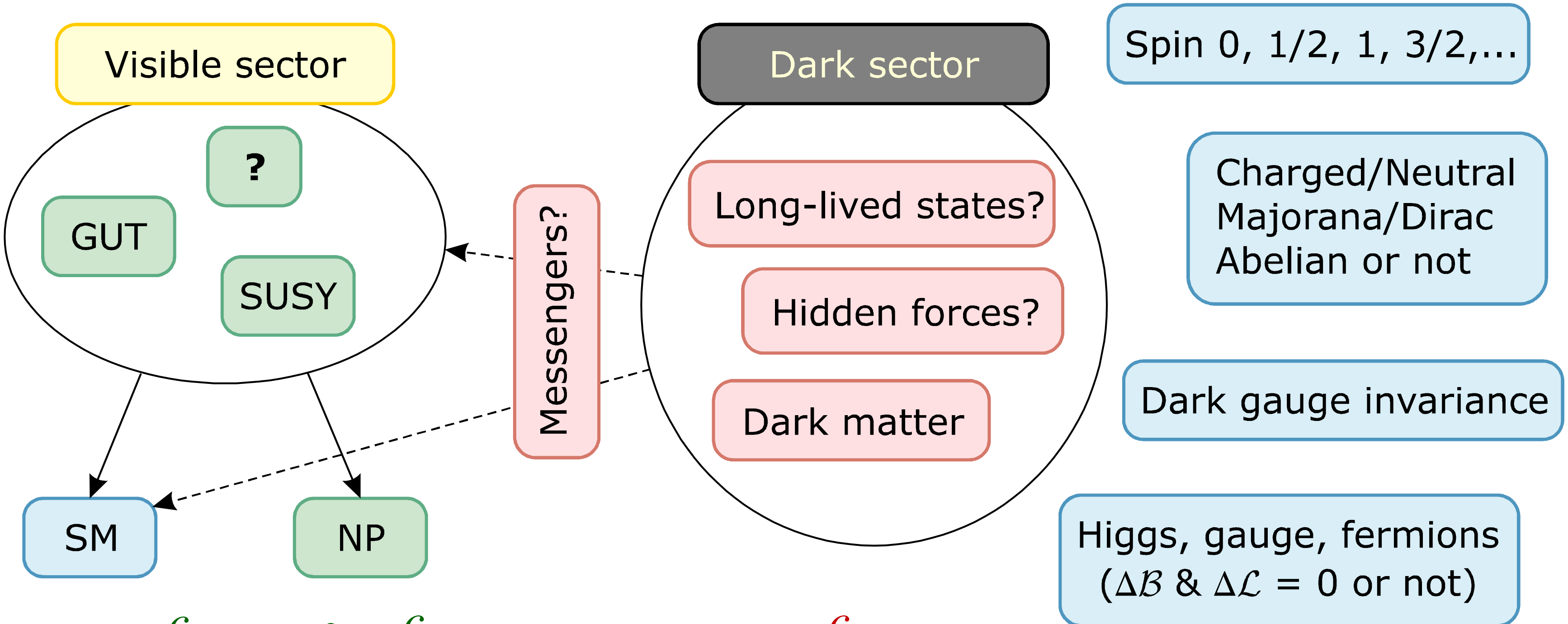
X = dark sector state connected to the SM, or a light messenger.

$$\mathcal{L}_{SM} + \frac{c_\nu}{\Lambda}(HL)^2 + \frac{c_i}{\Lambda^2}Q_i + \ldots \quad + \sum_{d\geq 3} \frac{c_i}{\tilde{\Lambda}^{d-4}} Q_i' + \ldots$$

Very weakly interacting → Take X as neutral, but include all possible interactions as gauge-invariant effective operators.

Kamenik, CS '11

B. How to systematically investigate the low-energy particle content?



$$\mathcal{L}_{SM} + \frac{c_\nu}{\Lambda}(HL)^2 + \frac{c_i}{\Lambda^2}Q_i + \ldots \qquad + \sum_{d\geq 3} \frac{c_i}{\tilde{\Lambda}^{d-4}} Q_i' + \ldots$$

The leading operators must be kept separately for each scenario.

The renormalizable operators called portals may not dominate.

Kamenik, CS ‘11

C. What a light Higgs could tell?

Assumptions about the dark state X :

- Not stable → No DM constraints!
- Long-lived → Escape as missing energy.
- Weakly coupled → Do not affect SM processes.

For DM, see e.g.:
Kanemura et al. '10
Lebedev et al. '11
Mambrini '11
Djouadi et al. '11

$\Rightarrow$ Main impact is then to open new decay channels.

To find these dark decays, better use SM suppressed observables:

~ scale (GeV)		
0.001	Orthopositronium	C, P + phase-space
0.1	Light mesons (π, η, η')	Loop or helicity
	Lepton (flavor changing)	Forbidden
1	K & B (rare FCNC decays)	CKM
10	Quarkonium (ϕ, J/ψ, Υ)	Zweig rule
100	Higgs boson (if light)	Loop or helicity

C. What a light Higgs could tell? Three points for the LHC:

Kamenik, CS '12

1- Could dark decays hide the Higgs?

$$\Gamma(h \to SM)^{SM} = \Gamma_h \times B(h \to SM)^{\exp}$$

$$\Gamma_h = \Gamma_h^{SM} + \Gamma(h \to \not{E}) \qquad \sigma(pp \to h)^{SM}$$

2- A light Higgs is very narrow in the SM: $\dfrac{\Gamma_h^{SM}}{M_h} \approx 3 \times 10^{-5}$ for $M_h \approx 125\ GeV$.

Comparable to 3×10^{-5} and 6×10^{-6} for the J/ψ and Υ(1S).

If current hint at 125 GeV true → Invisible rate must be small.

($\Gamma(h \to \not{E}) > 20\% \times \Gamma_h^{SM}$ to be seen at LHC)

3- Are there better channels?

Invisible: $h \to \not{E}$

Gauge: $h \to \not{E} + (\gamma, Z)$

Fermionic: $h \to \not{E} + (fermions)$

C. What a light Higgs could tell?

Three more reasons to look at the Higgs decays:

1. The Higgs boson is heavy → probes a large kinematical range.

2. The Higgs doublet has mass dimension 1:

   → Couplings with mesons or leptons require higher dimensional operators.

3. The Higgs doublet has no Lorentz vector/spinor index:

   → Occurs in most operators, including the simplest ones.

$$H^\dagger H \to \frac{1}{2}(v^2 + 2vh + h^2)$$

$$H^\dagger \overleftrightarrow{D}^\mu H \to \frac{ig}{2c_W}(v+h)^2 Z^\mu \qquad \text{when } H \to \frac{1}{\sqrt{2}}\begin{pmatrix} 0 \\ v+h \end{pmatrix}$$

$$HL \to \frac{1}{\sqrt{2}}(v+h)\nu_\ell$$

II. Spin 0 and 1/2

A. Simplest operators - The invisible decay channels

The simplest operators are constructed using $H^{\dagger}H$:

$$\mathcal{H}_{eff}^{0} = \lambda' H^{\dagger}H \times \phi^{\dagger}\phi$$

$$\mathcal{H}_{eff}^{1/2} = \frac{1}{\tilde{\Lambda}} H^{\dagger}H \times \overline{\psi}(1,\gamma_5)\psi$$

They induce both a mass correction and an invisible decay rate:

$$H^{\dagger}H \to \tfrac{1}{2}(v^2 + 2vh + h^2)$$

$$\delta m \qquad\qquad \Gamma(h \to \not{E})$$

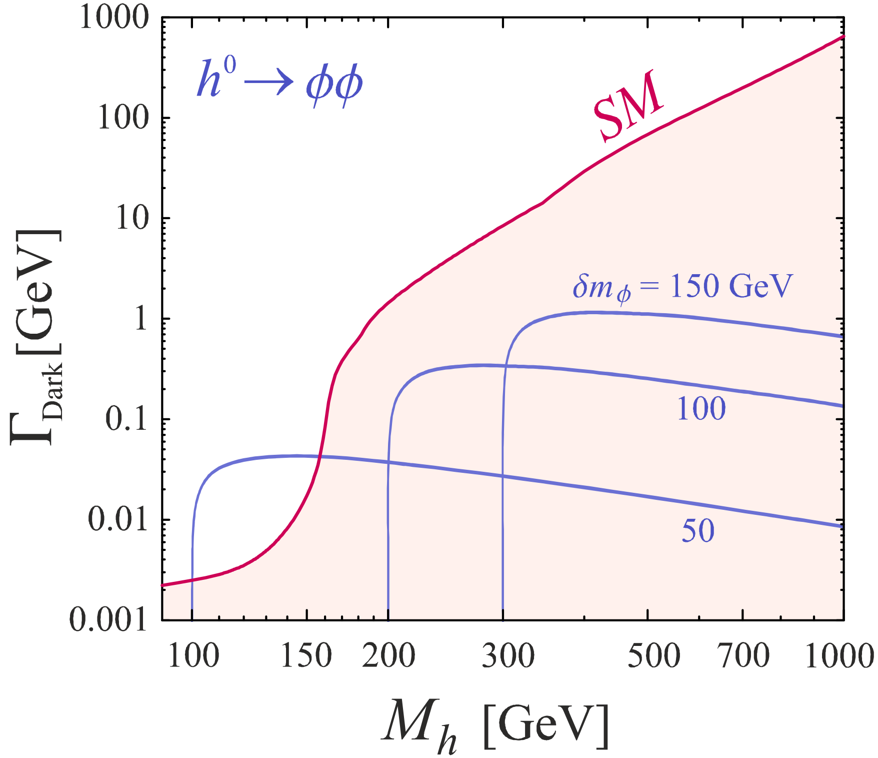
Without fine-tuning the dark and electroweak mass terms,

$$m_{\phi}^2 \approx \overline{m}_{\phi}^2 + \delta m_{\phi}^2 \gtrsim \left|\delta m_{\phi}^2\right|$$

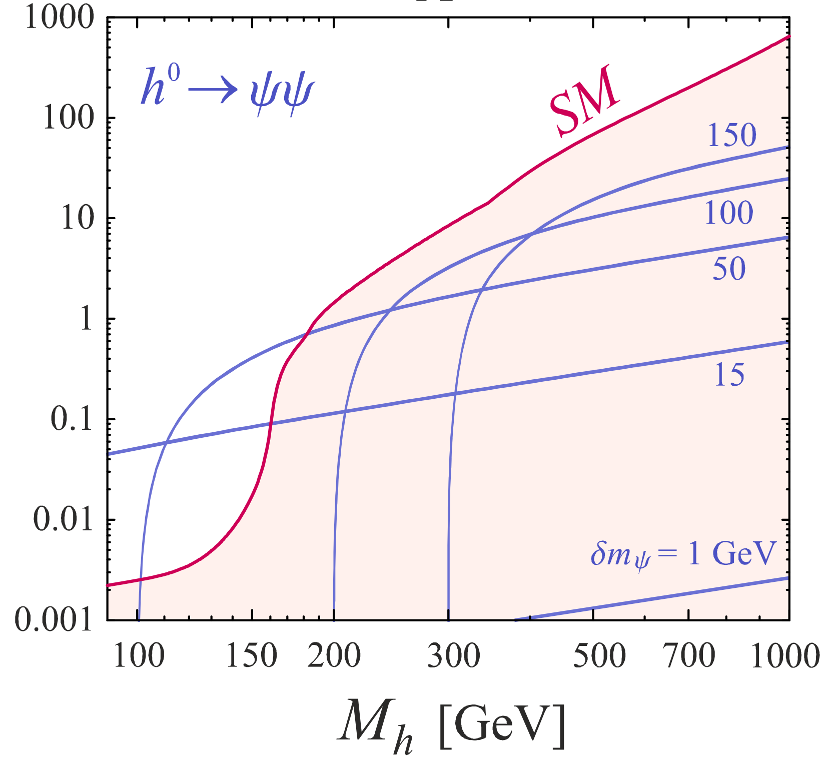
$$m_{\psi} \approx \overline{m}_{\psi} + \delta m_{\psi} \gtrsim \left|\delta m_{\psi}\right|$$

A. Simplest operators – No hiding for a heavy Higgs

$\lambda' H^\dagger H \times \phi^\dagger \phi$



$\frac{1}{\tilde{\Lambda}} H^\dagger H \times \bar{\psi}(1, \gamma_5)\psi$

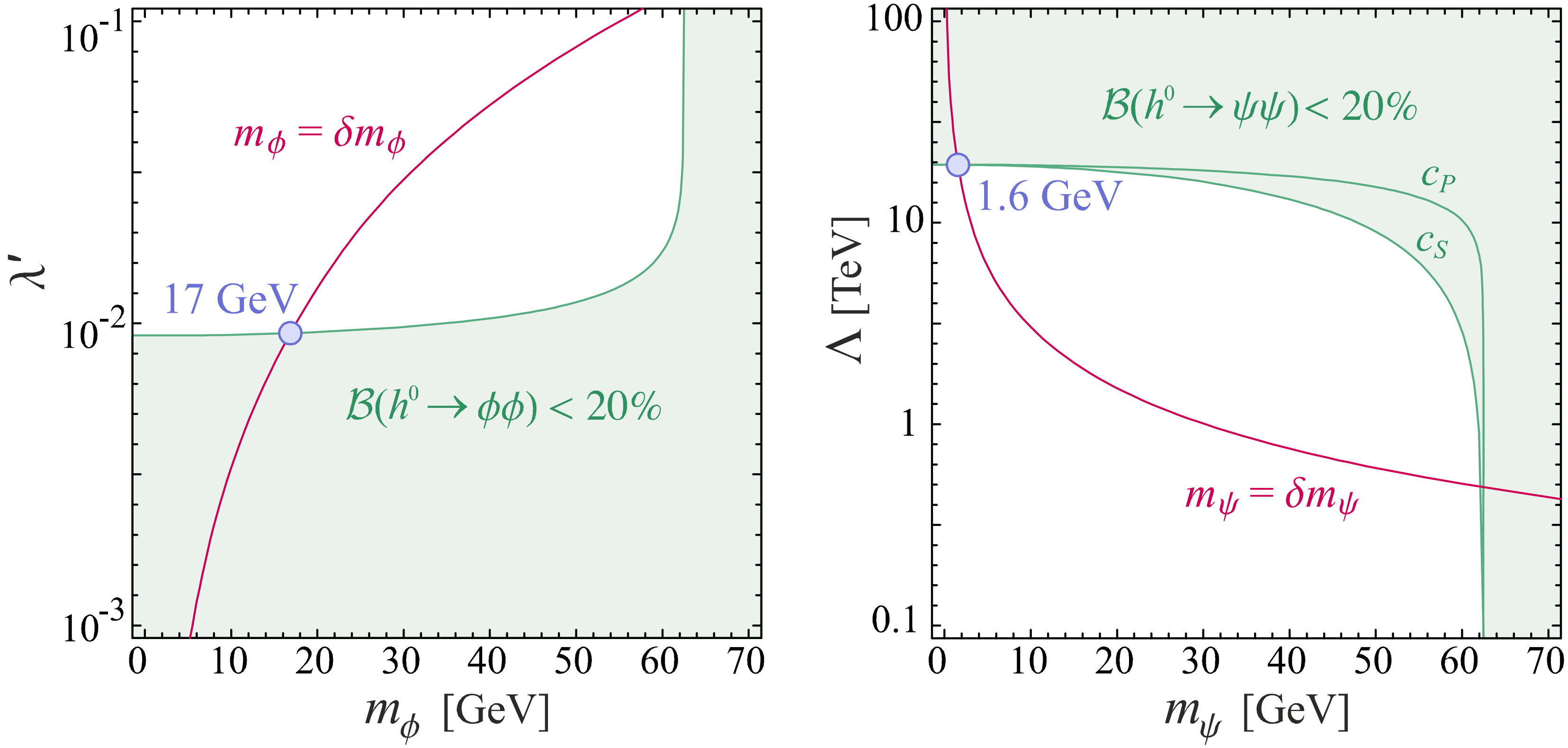


Those rates are upper bounds since $m_\phi^2 \gtrsim |\delta m_\phi^2|$ and $m_\psi \gtrsim |\delta m_\psi|$.

So, for $M_h \gtrsim 180\, GeV$, spin 0 and 1/2 cannot hide the Higgs.

A. Simplest operators – Mass bounds for a light Higgs

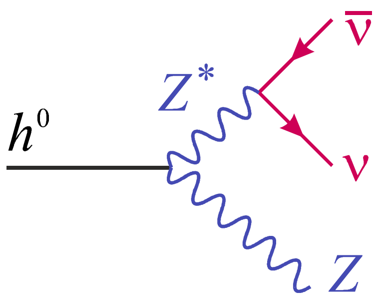
$\lambda' H^\dagger H \times \phi^\dagger \phi$ $\qquad\qquad$ $\frac{1}{\tilde{\Lambda}} H^\dagger H \times \bar{\psi}(1, \gamma_5)\psi$



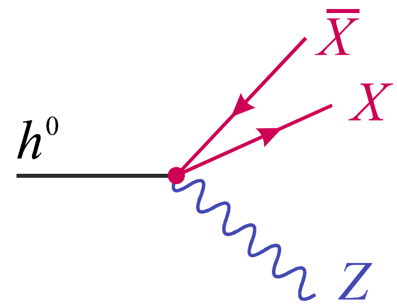
If initially massless (or very light), these dark states must remain light.

B. Other operators & decay channels?

Higgs vector current operators: $\frac{1}{\tilde{\Lambda}^2} H^\dagger \overleftrightarrow{\mathcal{D}}^\mu H \times (\phi^\dagger \overleftrightarrow{\partial}_\mu \phi \,,\, \bar{\psi}\gamma_\mu \psi)$



$$\sim \frac{1}{M_Z^2} > \frac{1}{\tilde{\Lambda}^2} \sim$$



Subleading compared to SM at tree-level (same for fermionic ops).

Neutrino portal operators (violating lepton number)

$H\bar{L}^C \times \psi$: Must be negligible since it induces a neutrino mass.

$\frac{1}{\tilde{\Lambda}^2} B_{\mu\nu} H\bar{L}^C \sigma^{\mu\nu} \times \psi$: No SM tree-level for γ → may be accessible.

$\mathcal{B}(h \to \gamma\nu\psi) \approx 2\,\%$ for $\tilde{\Lambda} \approx 0.5\,TeV$

$\frac{1}{\tilde{\Lambda}^3} H\bar{L}^C L H \times \phi^\dagger \phi$: Negligible since 7-dim and 4-body ($h \to \nu\nu\phi\phi$).

III. Spin 1 and 3/2

A. On the fate of a dark gauge invariance

The leading operators break a dark gauge invariance:

$$\mathcal{H}_{eff}^{1} = \varepsilon_H H^\dagger H \times V_\mu V^\mu + i\varepsilon'_H H^\dagger \overleftrightarrow{\mathcal{D}}^\mu H \times V_\mu$$

$$\mathcal{H}_{eff}^{3/2} = \frac{c_\Psi}{\tilde{\Lambda}} H^\dagger H \times \bar{\Psi}^\mu (1,\gamma_5)\Psi_\mu + \frac{c'_\Psi}{\tilde{\Lambda}} \mathcal{D}_\mu H \bar{L}^C \times \Psi^\mu$$

Consequently, decay rates are singular in the massless limit:

$$\sum_{pol} \varepsilon_k^\mu \varepsilon_k^\nu = -P_V^{\mu\nu}$$

$$\sum_{spin} u_k^\mu \bar{u}_k^\nu = -(\not{k} + m_\Psi)\left(P_\Psi^{\mu\nu} - \tfrac{1}{3} P_\Psi^{\mu\rho} P_\Psi^{\nu\sigma} \gamma_\rho \gamma_\sigma\right)$$

$$P_X^{\mu\nu} = g^{\mu\nu} - \frac{k^\mu k^\nu}{m_X^2}$$

Naively, the bounds diverge → How to make sense of them?

A. On the fate of a dark gauge invariance

Hard breaking: The dark gauge invariance is entirely broken, for example, dark SSB or Stückelberg.

Williams et al. '11
Lebedev et al. '11

For instance, remember that in the SM:

$$\Gamma(h \to WW) \sim g^4 v^2 P_W^{\mu\nu} P_{W,\mu\nu} \xrightarrow{M_W \to 0} \frac{g^4 v^2}{M_W^4} + \ldots \xrightarrow{M_W \sim gv} \frac{1}{v^2} + \ldots$$

So, we can deal with the singularity as $m_V \sim \varepsilon_H v_{dark}$ with $v_{dark} \geq v$.

Soft breaking in the dark sector:

Massive dark particle with gauge invariant couplings to the SM.

No breaking either in the visible or dark sector (massless dark particle).

B. Hard breaking

The $H^\dagger H$ operator automatically regulates its massless limit:

$$\varepsilon_H H^\dagger H \times V_\mu V^\mu$$

$$\sum_{pol} \varepsilon_k^\mu \varepsilon_k^\nu = -g^{\mu\nu} + \frac{k^\mu k^\nu}{m^2}$$

$$\delta m_V^2 = \varepsilon_H v^2 \qquad \Gamma(h \to VV) \sim \varepsilon_H^2 \frac{v^2 M_h^3}{m_V^4}$$

$$m_V^2 \approx \delta m_V^2 : \;\; \Gamma(h \to VV) \gtrsim 80 \times \Gamma_h^{SM}$$ (for $M_h \approx 125\ GeV$)

125 GeV hint : - Dark decay must be forbidden, $\delta m_V > M_h / 2$.

- A large dark mass must soften the singularity:

$$m_V^2 = \bar{m}_V^2 + \delta m_V^2 = \varepsilon_H (v_{dark}^2 + v^2)$$ with $v_{dark} > 1.1\ TeV$.

B. Hard breaking

The $H^\dagger \overleftrightarrow{\mathcal{D}}^\mu H$ operator fails at doing the same:

$$\varepsilon'_H H^\dagger \overleftrightarrow{\mathcal{D}}^\mu H \times V_\mu$$

$$\sum_{pol} \varepsilon_k^\mu \varepsilon_k^\nu = -g^{\mu\nu} + \frac{k^\mu k^\nu}{m^2}$$

$$\delta m_V^2 = -\varepsilon_H'^2 v^2 < 0!$$

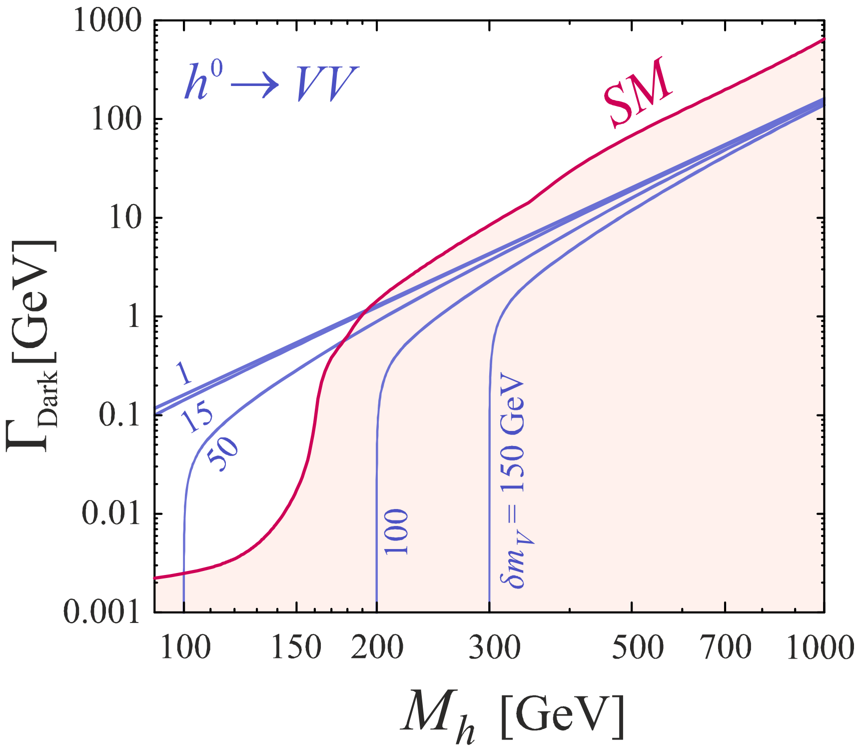
$$\Gamma(h \to ZV) \sim g^2 \varepsilon_H'^2 \frac{v^2 M_h^3}{M_Z^2 m_V^2}$$

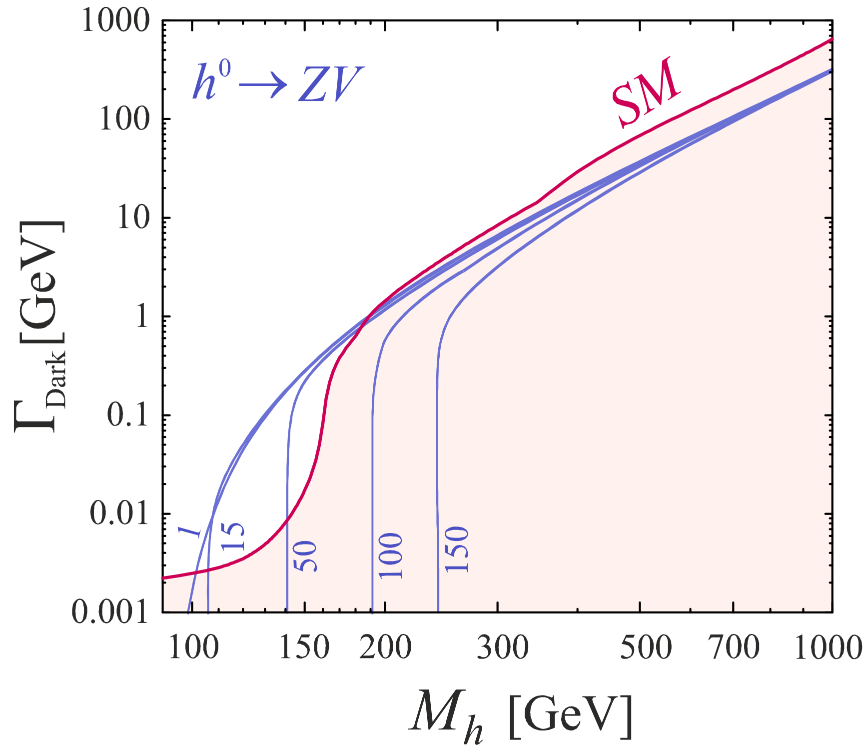
$$m_V^2 \approx -\delta m_V^2 : \quad \Gamma(h \to ZV) \gtrsim 15 \times \Gamma_h^{SM} \Rightarrow m_V > M_h - M_Z$$

(for $M_h \approx 125\ GeV$)

Mixes Z and V → Tight constraints, e.g. $\delta\rho \Rightarrow m_V < 2.4\ GeV$.

B. Hard breaking





The $h \to VV$ rate does not catch up with the SM rate.

The $h \to ZV$ rate catches up, but it is in principle visible.

C. No breaking

Starting from the kinematic mixing or with a dark charge for the Higgs:

$$\mathcal{L}_{kin} = \frac{\chi}{2} B_{\mu\nu} \times V^{\mu\nu}$$

B-V redefinition

$$\mathcal{L}_{kin} = \mathcal{D}_\mu H^\dagger \mathcal{D}^\mu H - i\frac{\lambda}{2} H^\dagger \overleftrightarrow{\mathcal{D}}^\mu H \times V_\mu + \frac{\lambda^2}{4} H^\dagger H \times V_\mu V^\mu$$

After diagonalizing the mass:

The dark vector is massless and entirely decoupled!

Holdom, 1986

Dominant effects then come from higher-dimensional operators:

$$\mathcal{H}^1_{eff} = \frac{\eta_1}{\tilde{\Lambda}^2} H^\dagger H B_{\mu\nu} \times V^{\mu\nu} + \frac{i\tilde{\eta}_1}{\tilde{\Lambda}^2} H^\dagger H B_{\mu\nu} \times \tilde{V}^{\mu\nu} + \frac{i\tilde{\eta}_E}{\tilde{\Lambda}^2} HQ\sigma^{\mu\nu} D \times V_{\mu\nu} + \ldots$$

$$+ \frac{\eta_2}{\tilde{\Lambda}^2} H^\dagger H \times V_{\mu\nu} V^{\mu\nu} + \frac{i\tilde{\eta}_2}{\tilde{\Lambda}^2} H^\dagger H \times V_{\mu\nu} \tilde{V}^{\mu\nu} + \ldots$$

Typically, $\Gamma(h \to VV, ZV, \gamma V, f\bar{f}V) < 20\% \times \Gamma_h^{SM}$ requires $\tilde{\Lambda} \gtrsim 1 TeV$.

D. Soft breaking

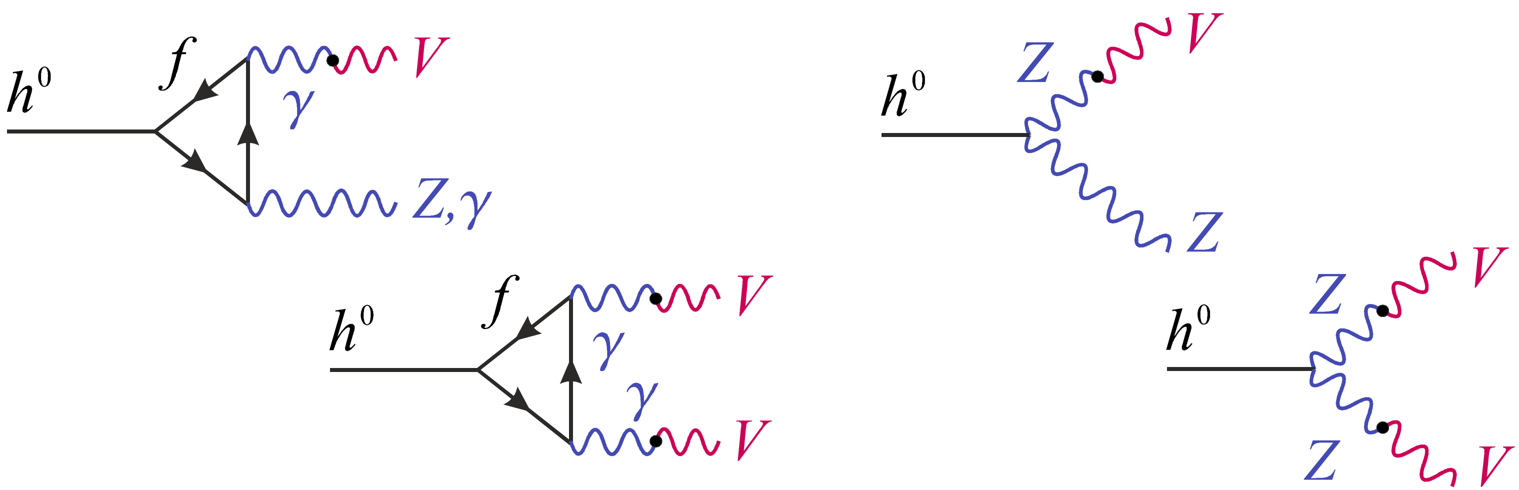
A vector mass changes the diagonalization, and upsets its elimination:

$$\mathcal{L}_{kin} = \frac{\chi}{2} B_{\mu\nu} \times V^{\mu\nu} + \frac{\bar{m}_V^2}{2} V_\mu V^\mu$$

Holdom, 1986

The dark field has some couplings to the fermions & to the Higgs

$$B_{\mu\nu} \times V^{\mu\nu} \to c_W J_\mu^{em} \times V^\mu - s_W m_V^2 Z_\mu \times V^\mu$$



All are very suppressed; only $\mathcal{B}(h \to ZV) \sim 10^{-3}$ may be accessible.

E. What about spin 3/2 dark states?

Hard breaking?

No simple way to regulate the divergences:

$$\mathcal{H}_{eff}^{3/2} = \frac{c_\Psi}{\tilde{\Lambda}} H^\dagger H \times \bar{\Psi}^\mu (1,\gamma_5)\Psi_\mu + \frac{c'_\Psi}{\tilde{\Lambda}} \mathcal{D}_\mu H \overline{L}^C \times \Psi^\mu$$

Setting $\tilde{\Lambda} \sim (v_{dark}^2 + v^2)/m_\Psi$ is not sufficient.

[cf $M_{Planck} \sim \Lambda_{SUSY}^2 / m_\Psi$]

Soft or no breaking:

All effects from gauge-invariant higher dimensional operators:

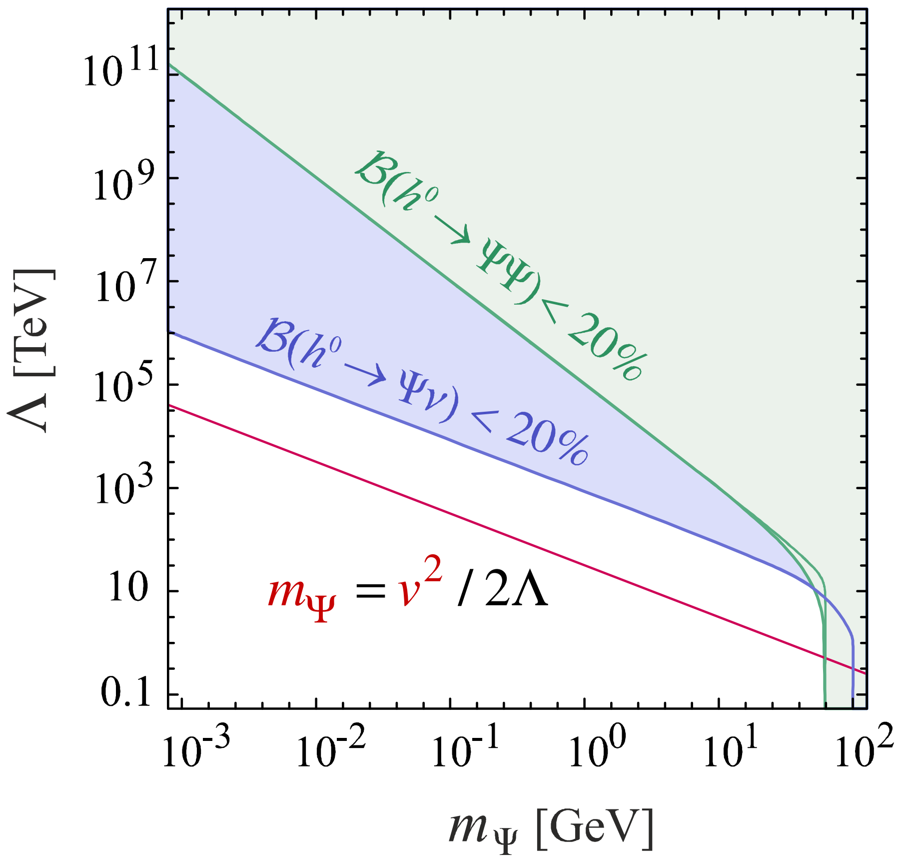
$$\mathcal{H}_{eff}^{3/2} = \frac{1}{\tilde{\Lambda}^3} H^\dagger H \times \bar{\Psi}^{\mu\nu}\Psi_{\mu\nu} + \frac{1}{\tilde{\Lambda}^2} \mathcal{D}_\mu H \overline{L}^C \gamma_\nu \times \Psi^{\mu\nu}$$

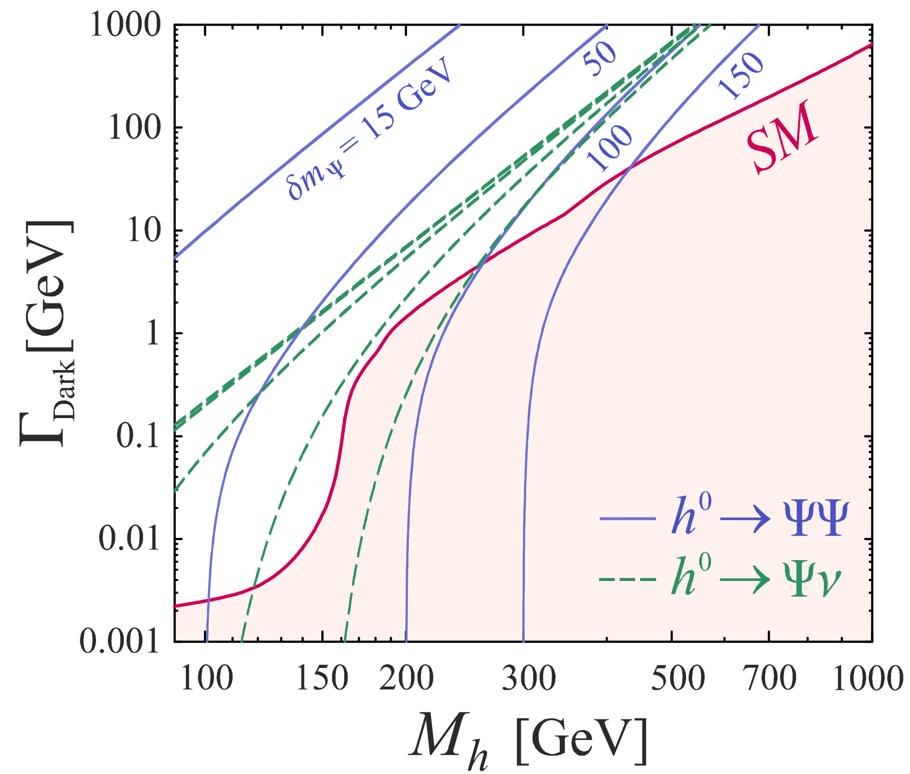
$$(\Psi_{\mu\nu} = \partial_\mu \Psi_\nu - \partial_\nu \Psi_\mu)$$

Requiring $\Gamma(h \to \Psi\Psi, \Psi\nu) < 20\% \times \Gamma_h^{SM}$ imposes $\Lambda \gtrsim 0.7\ TeV$.

The Higgs width is our best window for such kind of operators.

E. What happens for spin 3/2 dark states?





When the dark gauge invariance is broken, the rates are huge!

Conclusion

If a light and long-lived "dark" particle exists:

The small width of a light Higgs boson offers a unique window also well beyond the portals.

Worth to search also for deviations in missing energy modes, $h \to \not{E}$, $h \to \not{E} + (\gamma, Z)$, $h \to \not{E} + (fermions)$.

Difficult to hide a heavy higgs: the SM is simply too large.

Could this state be the dark matter constituent?

Couplings only through the portals disfavored for light DM.

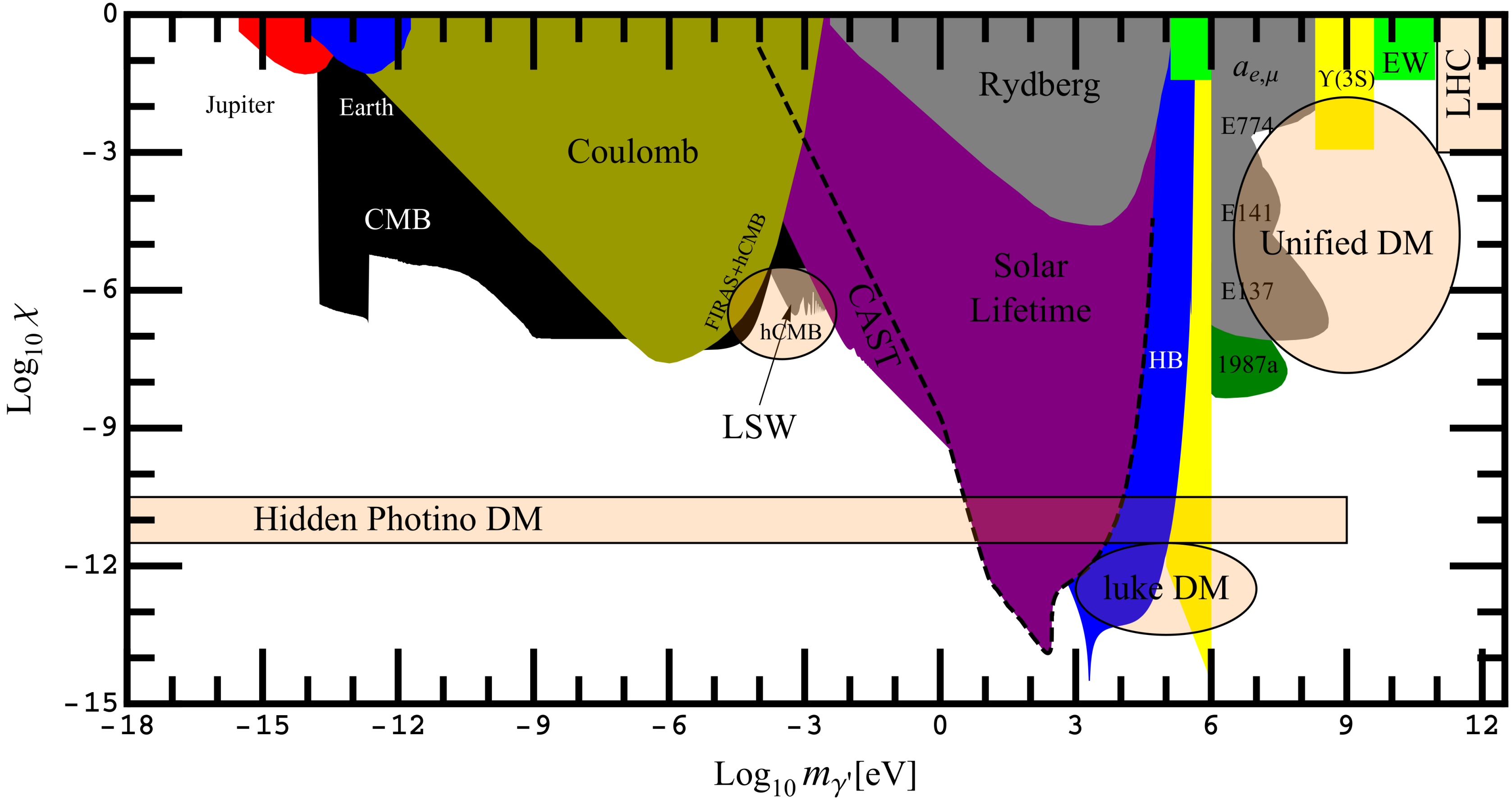
See e.g. Kanemura et al. '10, Lebedev et al. '11, Mambrini '11, Djouadi et al. `11

Questions: What happens beyond the portals?
If a dark gauge invariance is enforced?
If it is not stable, how could it couple to DM?

Backup

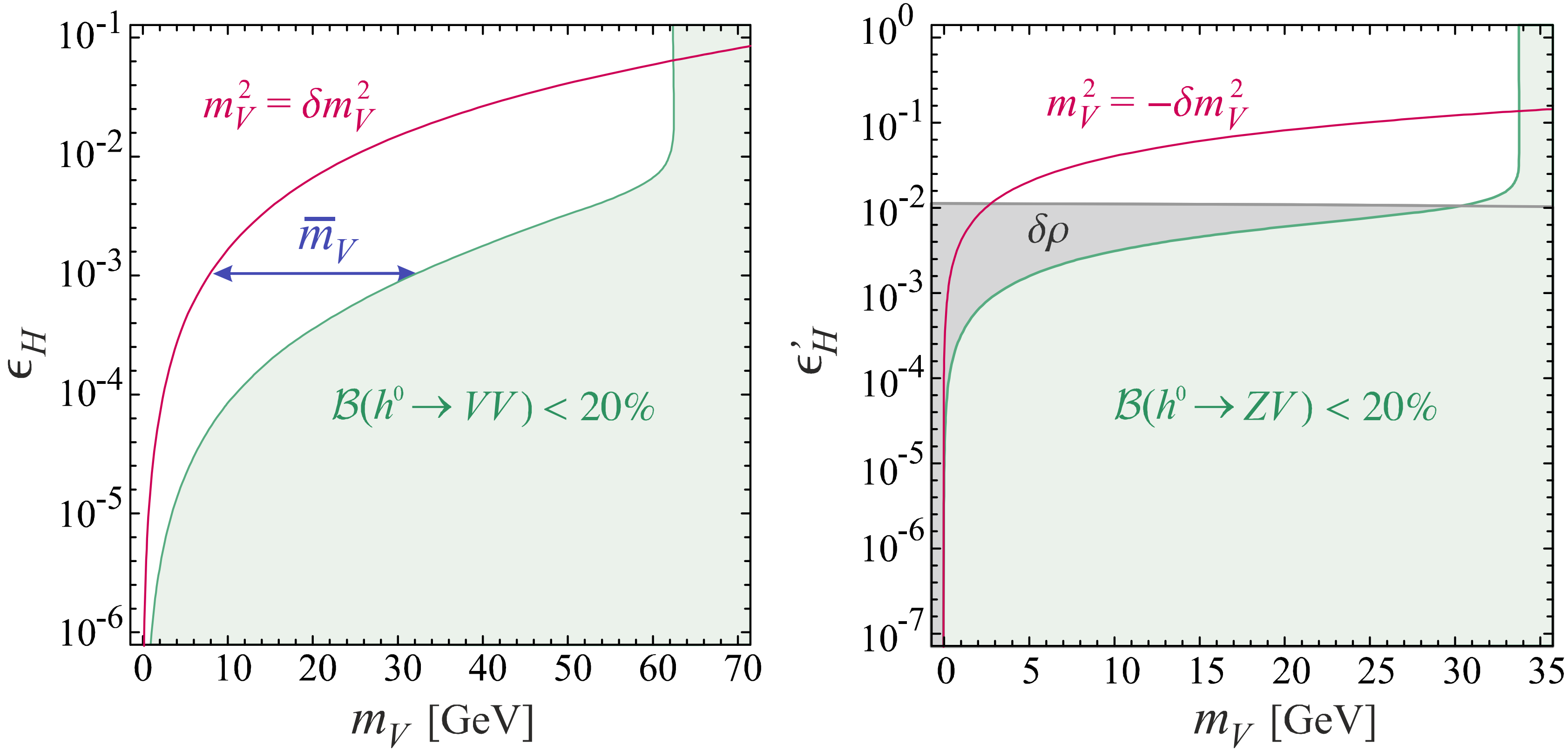
Backup A: Constraints in the coupling – mass planes

Overview of the constraints for the kinetic mixing $\mathcal{L}_{kin} = \frac{\chi}{2} B_{\mu\nu} \times V^{\mu\nu}$.



(from Jaeckel & Ringwald, arXiv:1002.0329)

Backup A: Constraints in the coupling – mass planes



In both cases, a large dark mass term is needed.

Backup B: Dark gauge invariance

1. If the Higgs doublet is charged under the dark U(1):

$$D^{\mu} H = \left(D^{\mu} - i \frac{\lambda}{2} V^{\mu} \right) H \quad \Rightarrow$$

$$\mathcal{L}_{kin} = D_{\mu} H^{\dagger} D^{\mu} H - i \frac{\lambda}{2} H^{\dagger} \overleftrightarrow{D}^{\mu} H \times V_{\mu} + \frac{\lambda^{2}}{4} H^{\dagger} H \times V_{\mu} V^{\mu}$$

Both the renormalizable operators appear.

Backup B: Dark gauge invariance

2. If the vector field couples to the SM through the kinetic mixing:

$$\delta\mathcal{L}_{kin} = \frac{\chi}{2} B_{\mu\nu} \times V^{\mu\nu}$$

B-V redefinition (non-unitary)

$$\mathcal{L}_{kin} = D_\mu H^\dagger D^\mu H - i\frac{\lambda}{2} H^\dagger \overleftrightarrow{D}^\mu H \times V_\mu + \frac{\lambda^2}{4} H^\dagger H \times V_\mu V^\mu$$

Backup B: Dark gauge invariance

3. Decoupling of massless vectors:

$$\delta\mathcal{L}_{kin} = \frac{\chi}{2} B_{\mu\nu} \times V^{\mu\nu}$$

B-V redefinition (non-unitary)

$$\mathcal{L}_{kin} = D_\mu H^\dagger D^\mu H - i\frac{\lambda}{2} H^\dagger \overleftrightarrow{D}^\mu H \times V_\mu + \frac{\lambda^2}{4} H^\dagger H \times V_\mu V^\mu$$

EW SSB

$$\mathcal{L}_{kin} = \frac{1}{2}\partial_\mu h \partial^\mu h + \frac{M_Z^2}{2}\left(1+\frac{h}{v}\right)^2 (Z_\mu + \lambda V_\mu)(Z^\mu + \lambda V^\mu)$$

Z-V diagonalization (unitary)

The dark vector remains massless, and decouples entirely!

Holdom, 1986

Backup B: Dark gauge invariance

4. If the dark gauge symmetry is softly broken by a vector mass:

$$\delta\mathcal{L}_{kin} = \frac{\chi}{2} B_{\mu\nu} \times V^{\mu\nu} + \frac{\overline{m}_V^2}{2} V_\mu V^\mu$$

B-V redefinition (non-unitary)

$$\mathcal{L}_{kin} = D_\mu H^\dagger D^\mu H - i\frac{\lambda}{2} H^\dagger \overleftrightarrow{D}^\mu H \times V_\mu + \frac{\lambda^2}{4} H^\dagger H \times V_\mu V^\mu + \frac{\overline{m}_V^2}{2} V_\mu V^\mu$$

EW SSB

$$\mathcal{L}_{kin} = \frac{1}{2}\partial_\mu h \partial^\mu h + \frac{M_Z^2}{2}\left(1+\frac{h}{v}\right)^2 (Z_\mu + \lambda V_\mu)(Z^\mu + \lambda V^\mu) + \frac{\overline{m}_V^2}{2} V_\mu V^\mu$$

Backup B: Dark gauge invariance

4. If the dark gauge symmetry is softly broken by a vector mass:

$$\delta\mathcal{L}_{kin} = \frac{\chi}{2} B_{\mu\nu} \times V^{\mu\nu} + \frac{\bar{m}_V^2}{2} V_\mu V^\mu$$

B-V redefinition (non-unitary)

$$\mathcal{L}_{kin} = D_\mu H^\dagger D^\mu H - i\frac{\lambda}{2} H^\dagger \overleftrightarrow{D}^\mu H \times V_\mu + \frac{\lambda^2}{4} H^\dagger H \times V_\mu V^\mu + \frac{\bar{m}_V^2}{2} V_\mu V^\mu$$

EW SSB

$$\mathcal{L}_{kin} = \frac{1}{2}\partial_\mu h \partial^\mu h + \frac{M_Z^2}{2}\left(1+\frac{h}{v}\right)^2 (Z_\mu + \lambda V_\mu)(Z^\mu + \lambda V^\mu) + \frac{\bar{m}_V^2}{2} V_\mu V^\mu$$

Z-V mass diagonalization (unitary)

$$\mathcal{L}_{kin} = \frac{1}{2}\partial_\mu h \partial^\mu h + \frac{M_Z^2}{2}\left(1+\frac{h}{v}\right)^2 Z_\mu Z^\mu + M_Z^2 \frac{h}{v}\left(2\varepsilon Z_\mu V^\mu + \varepsilon^2 V_\mu V^\mu\right) + \frac{m_V^2}{2} V_\mu V^\mu$$

with either $\varepsilon = \dfrac{v\lambda r_{VZ}^2}{2M_Z}$ (kinetic) or $\varepsilon = \dfrac{\chi s_W r_{VZ}^2}{1-r_{VZ}^2}$ (Higgs), with $r_{VZ} = \dfrac{m_V}{M_Z}$.

Backup B: Dark gauge invariance

5. So, what are the *phenomenological consequences*? (for $M_h \approx 125\ GeV$)

- *Suppressed direct couplings*

$$\Gamma(h \to VV) \leq (14\,MeV) \times \varepsilon^4 \quad \leq 10^{-6} \times \Gamma_h^{SM}$$

$$\Gamma(h \to ZV) \leq (6\,MeV) \times \varepsilon^2 \quad \leq 10^{-3} \times \Gamma_h^{SM}$$

$(\delta\rho \Rightarrow \varepsilon < 0.03)$

(vanish for $m_V = 0$, max for $57\ \&\ 29\,GeV$ resp.)

- Even more *suppressed fermionic and W loops*:

$$\Gamma(h \to VV) \sim \lambda^4 \times \Gamma(h \to \gamma\gamma)^{SM} \quad \leq 10^{-9} \times \Gamma_h^{SM}$$

$$\Gamma(h \to ZV) \sim \lambda^2 \times \Gamma(h \to \gamma\gamma)^{SM} \quad \leq 10^{-6} \times \Gamma_h^{SM}$$

$$\Gamma(h \to \gamma V) \sim \lambda^2 \times \Gamma(h \to \gamma\gamma)^{SM} \quad \leq 10^{-6} \times \Gamma_h^{SM}$$

$(\delta\rho \Rightarrow \lambda < 0.03)$

- In the absence of a hard breaking: *No large effect*!

Only $\Gamma(h \to ZV)$, of the order of $\Gamma(h \to \gamma\gamma)^{SM}$, may be accessible.

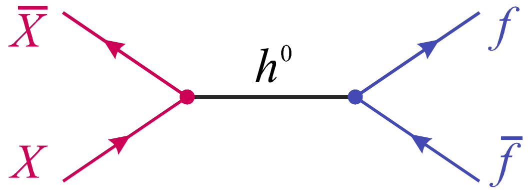
Backup C: Dark matter constraints

If the dark state is stable, it becomes a constituent of dark matter.

Through its coupling to the Higgs boson, it gets submitted to:

- Relic abundance:

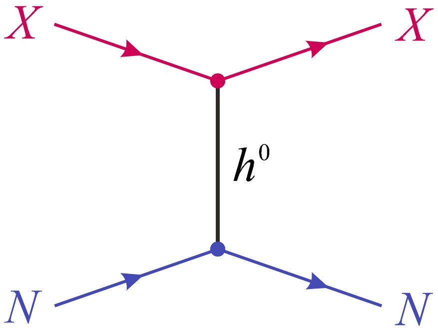
Strong constraints from WMAP.



$+ \ldots$

- Direct detection:

Constraints from various experiments (XENON).



Backup C: Dark matter constraints

Many recent analyses, among which:

Kanemura, Matsumoto, Nabeshima, Okada, arXiv:1005.5651.

Lebedev, Lee, Mambrini, arXiv:1111.4482.

Mambrini, arXiv:1112.0011.

Djouadi, Lebedev, Mambrini, Quevillon, arXiv:1112.3299.

Similar operators, but always with a non-zero dark mass:

$$\mathcal{L}_{eff}^{0} = \lambda' H^\dagger H \times \phi^\dagger \phi - \frac{1}{2}\bar{m}_\phi^2 \phi^2$$

$$\mathcal{L}_{eff}^{1/2} = \frac{c_{LR,RL}}{\Lambda} H^\dagger H \times \bar{\psi}_{L,R}\psi_{R,L} - \bar{m}_\psi (\bar{\psi}_L \psi_R + \bar{\psi}_R \psi_L)$$

$$\mathcal{L}_{eff}^{1} = \varepsilon_H H^\dagger H \times V_\mu V^\mu + \frac{1}{2}\bar{m}_V^2 V_\mu V^\mu$$

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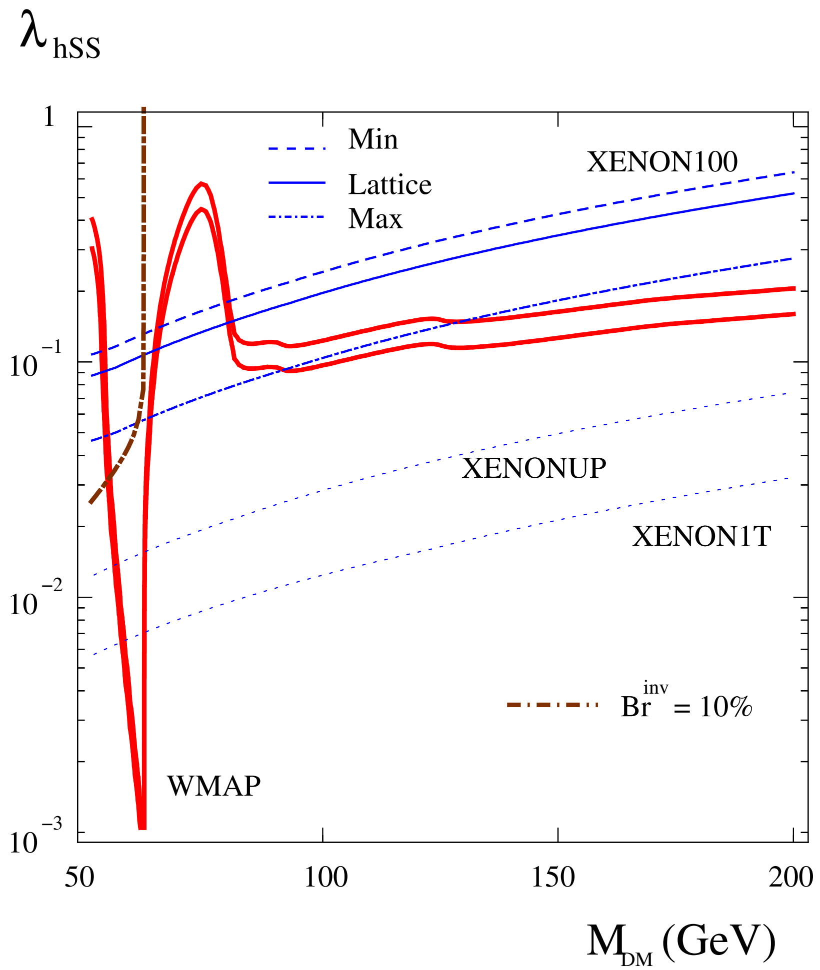
$$\mathcal{L}^0_{eff} = -\frac{\lambda_{hSS}}{4} H^\dagger H \times \phi^2 - \frac{1}{2} \bar{m}^2_\phi \phi^2$$

Djouadi *et al*., arXiv:1112.3299.

(similar for dark fermions
& dark vectors)



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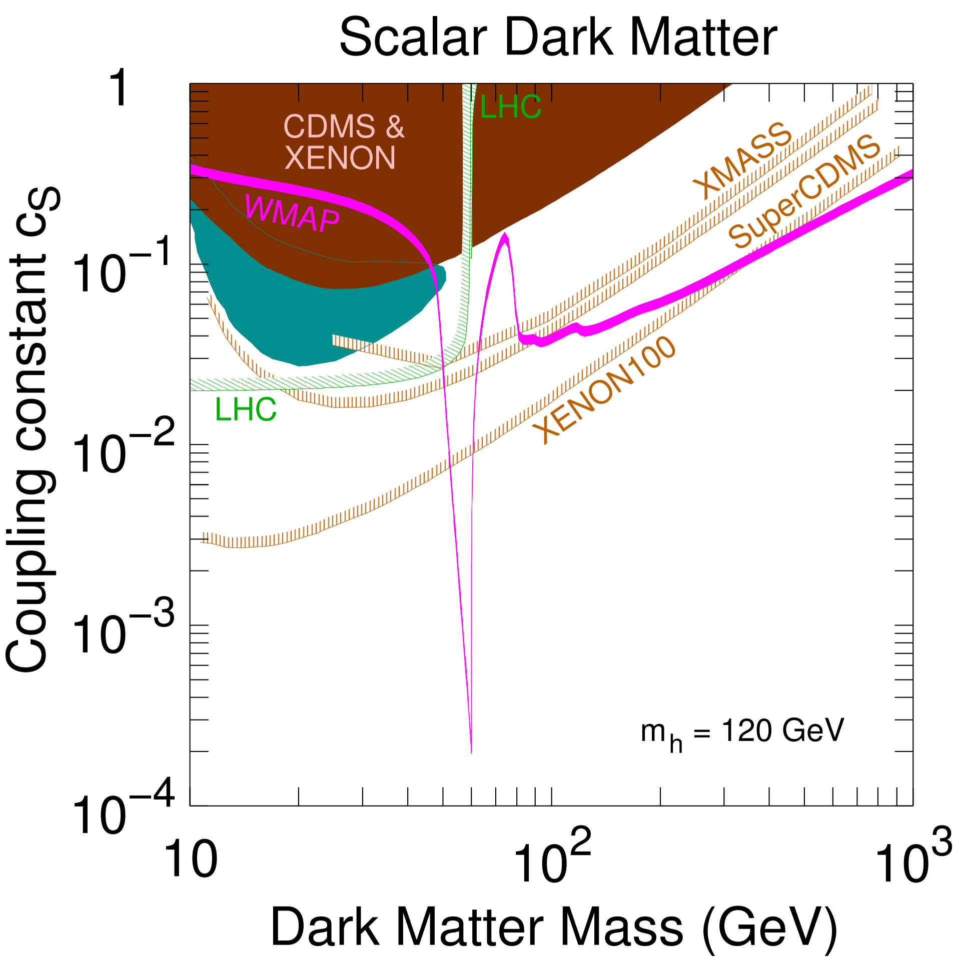
$$\mathcal{L}_{eff}^{0} = -\frac{c_S}{2} H^\dagger H \times \phi^2 - \frac{1}{2}\bar{m}_\phi^2 \phi^2$$

Kanemura *et al.*, arXiv:1005.5651.



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- Naturality eats away a big chunk of the plane.

- The invisible width plays a role only for medium values of the scalar mass.

- WMAP and naturality are in conflict for light states.