AN EXCEPTIONAL COMPOSITE DARK MATTER CANDIDATE

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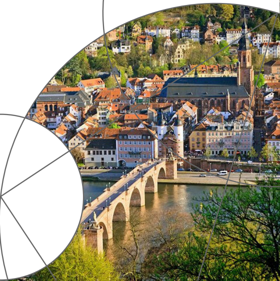
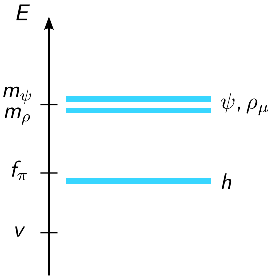
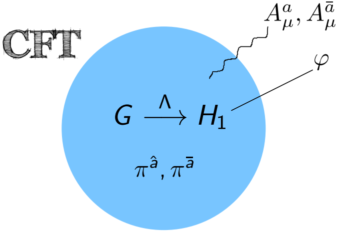


December 20, 2017

COMPOSITE HIGGS

- ✓ One interesting solution to the hierarchy problem is making the Higgs composite, the remnant of some new strong dynamics
  KAPLAN, GEORGI '84
- ✓ It is particularly compelling when the Higgs is the pNGB of some new strong interaction. Something like pions in QCD
  AGASHE, CONTINO, POMAROL '04





They can naturally lead to a light Higgs $m_\pi^2 = m_h^2 \sim g_{\text{el}}^2 \Lambda^2 / 16\pi^2$

COMPOSITE SCALAR DARK MATTER

We can have extra pNGBs η such that the symmetry protecting the Higgs mass GRIPAIOS, POMAROL, RIVA, SERRA '09; MRAZEK, POMAROL, RATTAZZI, REDI, SERRA, WULZER '11; FRIGERIO, POMAROL, RIVA, URBANO '12, BARNARD, GHERGHETTA, RAY, SPRAY 14; CHALA, NARDINI, SOBOLEV, 16,

- ✓ keeps them light
- ✓ renders the lightest one stable $\eta^0 \leftrightarrow -\eta^0$

One uses the fact that for a symmetric coset, $[X^a, X^b] = if_{abk}T^k$, and therefore, if $U = \exp\left(i\Pi^a X^a/f\right)$ and $-iU^{-1}\partial_\mu U = d_\mu^a X^a + E_\mu^i T^i$,

$$d_\mu = \frac{1}{f}\partial_\mu \Pi - \frac{i}{2f^2}\left[\Pi, \partial_\mu \Pi\right]_X - \frac{1}{6f^3}\left[\Pi, \left[\Pi, \partial_\mu \Pi\right]\right]_X + \frac{1}{24f^4}\left[\Pi, \left[\Pi, \left[\Pi, \partial_\mu \Pi\right]\right]\right]_X + \ldots,$$

$$\mathcal{L}_\sigma = \frac{1}{2} f^2 \mathrm{Tr}\left(d_\mu d^\mu\right) + \mathcal{O}(\partial^4) \sim 1 + \frac{1}{f^2} + \frac{1}{f^4} + \ldots + \mathcal{O}(\partial^4)$$

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THE QCD EXAMPLE

Pions are pNGB of $SU(2)_L \times SU(2)_R / SU(2)_{L+R}$

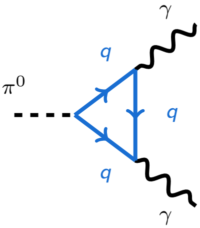
$$U = e^{i\pi^k \sigma^k / f} \qquad \mathcal{L}_{\text{eff}} = \frac{f^2}{4} \text{Tr}\left(\partial_\mu U^\dagger \partial^\mu U\right) + \ldots$$

In principle,

$$\pi \leftrightarrow -\pi \Leftrightarrow U \leftrightarrow U^\dagger$$

seems a good symmetry but it turns out to be anomalous

$$\mathcal{L}_{\text{WZW}} = \frac{e^3 N_c}{48\pi^2 f} 3\text{Tr}\left(Q^2 \sigma_3\right) \epsilon^{\mu\nu\alpha\beta} F_{\mu\nu} A_\alpha \partial_\beta \pi^0$$



THE CASE OF SO7/G2

FIRST CONSIDERED IN 1210.6208

- ✓ The group is non-anomalous but $SO(7)/G_2$ is not symmetric!
- ✓ It delivers a $\mathbf{7}$ of G_2, that decomposes under $SU(2) \times SU(2) \subset G_2$ as

$$\mathbf{7} = (\mathbf{2}, \mathbf{2}) \oplus (\mathbf{3}, \mathbf{1})$$

- ✓ Depending on which $SU(2)$ is weakly gauged, it means that

$$\mathbf{7} = \mathbf{2}_{\pm 1/2} + \mathbf{3}_0 \quad \text{or} \quad \mathbf{7} = \mathbf{2}_{\pm 1/2} + \mathbf{1}_{\pm 1} + \mathbf{1}_0$$

  under the EW group

- ✓ If the $\mathbb{Z}_2$ is succesfully enforced it will provide a natural version of Higgs portal DM or the Inert Triplet Model

THE CASE OF SO7/G2

Even though the coset is not symmetric, $f^2 \mathrm{Tr}(d_\mu d^\mu)$ only features even powers of $1/f$

$$
\begin{aligned}
d_\mu = &\frac{1}{f}\partial_\mu \Pi - \frac{i}{2f^2}\left[\Pi, \partial_\mu \Pi\right]_X - \frac{1}{6f^3}\left[\Pi, \left[\Pi, \partial_\mu \Pi\right]\right]_X \\
&+ \frac{1}{24 f^4}\left[\Pi, \left[\Pi, \left[\Pi, \partial_\mu \Pi\right]\right]\right]_X + \dots
\end{aligned}
$$

We make

$$
q_L \sim \mathbf{35} = \mathbf{1} \oplus \mathbf{7} \oplus \mathbf{27}, \quad t_R \sim \mathbf{1}
$$

leading to

$$
V(\Pi) \approx m_*^2 f^2 \frac{N_c}{16\pi^2} y_t^2 \left[c_1 V_1(\Pi) + c_2 V_2(\Pi)\right],
$$

with $c_{1,2} \lesssim 1$ numbers encoding the details of the UV dynamics

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A NATURAL INERT TRIPLET MODEL

✓ We consider first the case where the additional pNGBs span a triplet

✓ At the renormalizable level

$$V(H,\Phi) = \mu_H^2|H|^2 + \lambda_H|H|^4 + \frac{1}{2}\mu_\Phi^2|\Phi|^2 + \frac{1}{4}\lambda_\Phi|\Phi|^4 + \lambda_{H\Phi}|H|^2|\Phi|^2$$

with $H \sim \mathbf{2}_{1/2}$ and $\Phi \sim \mathbf{3}_0$ and

μ_H^2	μ_Φ^2	λ_Φ	$\lambda_{H\Phi}$
$-v^2\lambda_H$	$\frac{2}{3}f^2\lambda_H\left(1-\frac{8}{3}\frac{v^2}{f^2}\right)$	$-\frac{4}{9}\lambda_H\left(1-\frac{8}{3}\frac{v^2}{f^2}\right)$	$\frac{5}{18}\lambda_H\left(1+\frac{32}{15}\frac{v^2}{f^2}\right)$

✓ Extremely predictive, only one free parameter f !

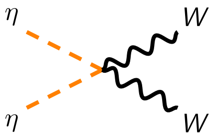
✓ $\mu_\Phi^2 > 0$ as well as $m_\Phi^2 = \mu_\Phi^2 + \lambda_{H\Phi}v^2 > 0$ so $\langle\Phi\rangle = 0$

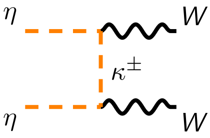
COANNIHILATIONS

✓ EW gauge bosons induce a radiative splitting between the neutral and the charged components

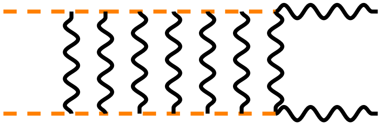
$$\Delta m_\Phi = g m_W \sin^2\theta_W/2 \sim 166\,\text{MeV}$$

✓ The coannihilation is dominated by gauge interactions



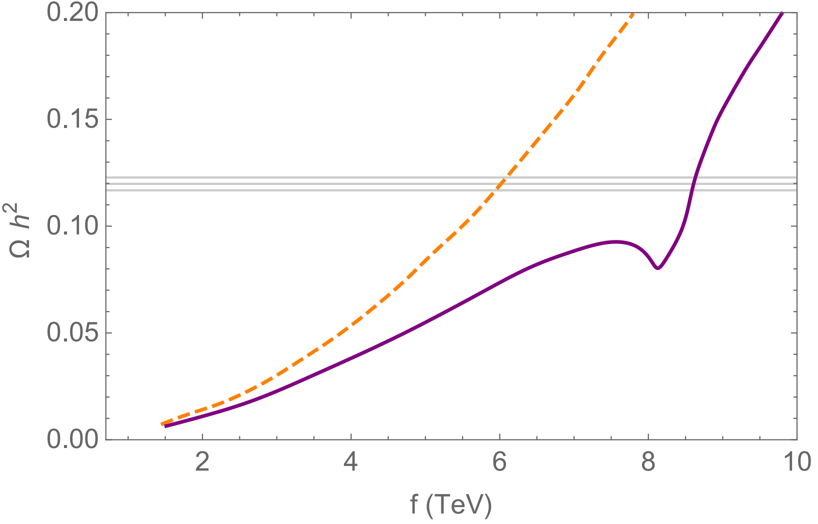


✓ Sommerfeld enhancement and bound state production are important! $g m_\Phi/m_W \gg 1$ CIRELLI, STRUMIA, TAMBURINI 07



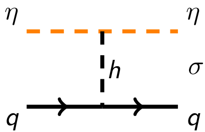
RELIC ABUNDANCE

RECAST OF CIRELLI, STRUMIA, TAMBURINI 07



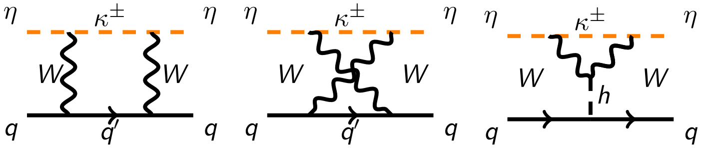
DIRECT DETECTION

✓ There is a m_Φ^2-suppressed tree-level contribution proportional to $\lambda_{H\Phi}$



$$\sigma = \lambda_{H\Phi}^2 m_N^4 f_N^2 / (\pi m_h^4 m_\Phi^2), \quad f_N = \sum_q \langle N|\bar{q}q|N\rangle \approx 0.3$$

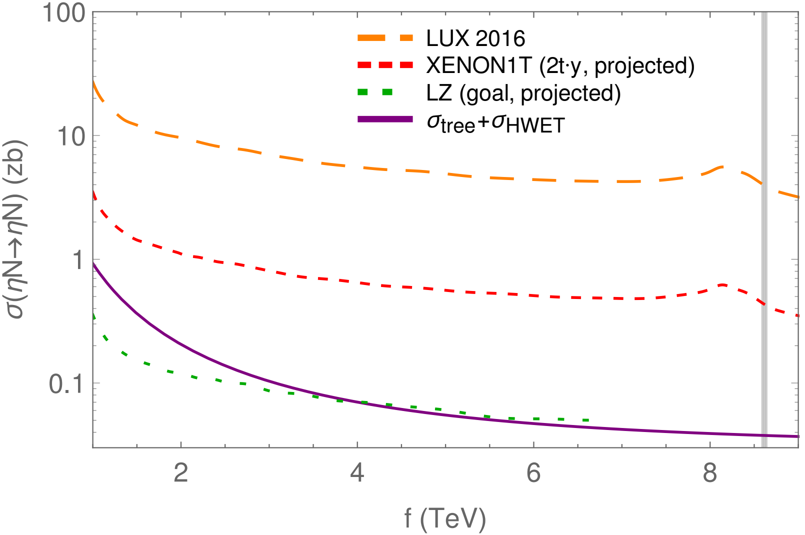
✓ But there are also m_Φ-independent loop induced contributions



They were computed in the heavy WIMP effective theory HILL, SOLLON, 13

$$\sigma(\eta N \to \eta N)_{\text{HWET}} = 1.3^{+0.4+0.4}_{-0.5-0.3} \times 10^{-2}\,\text{zb}$$

DIRECT DETECTION



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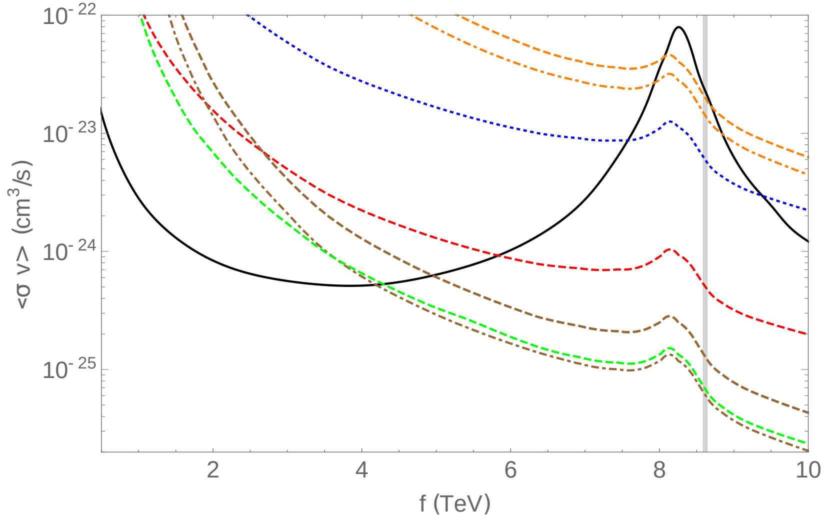

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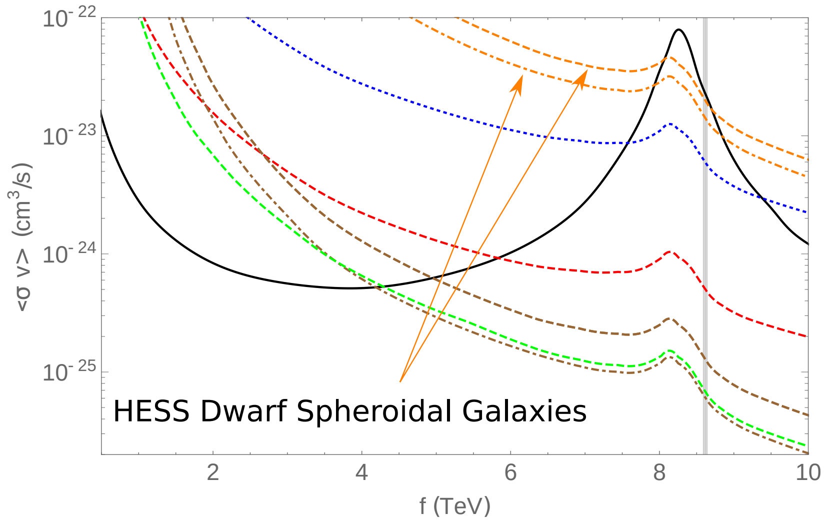

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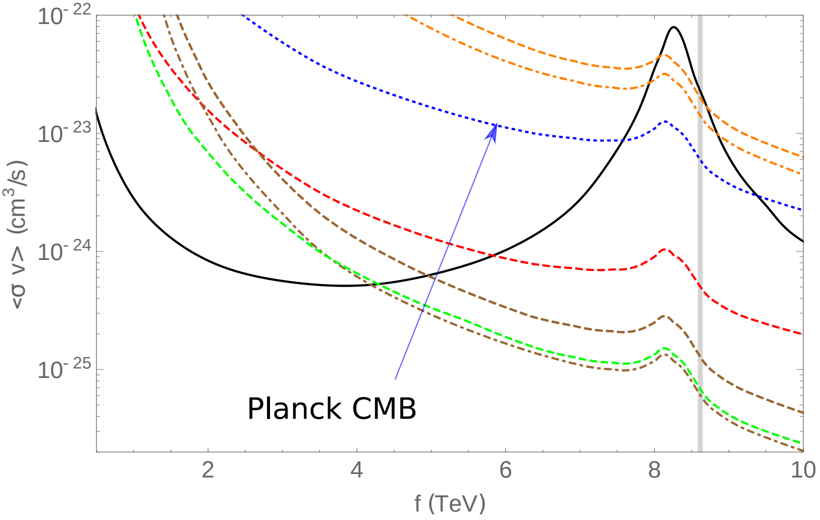

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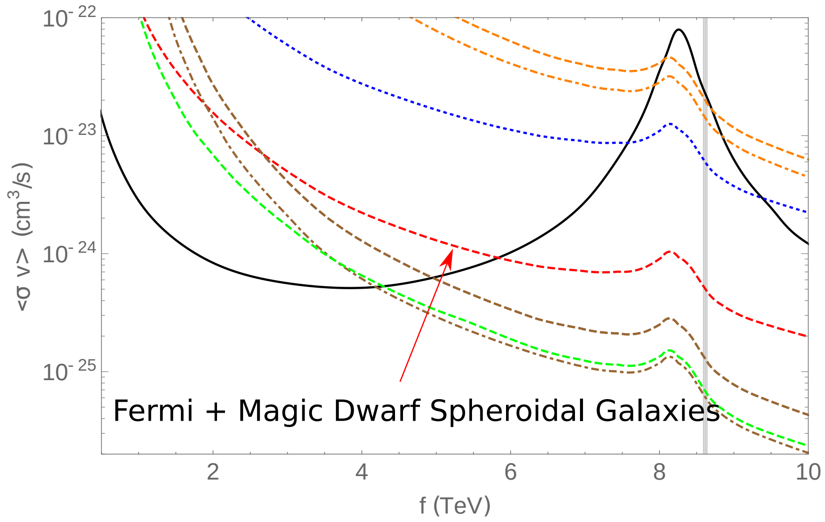

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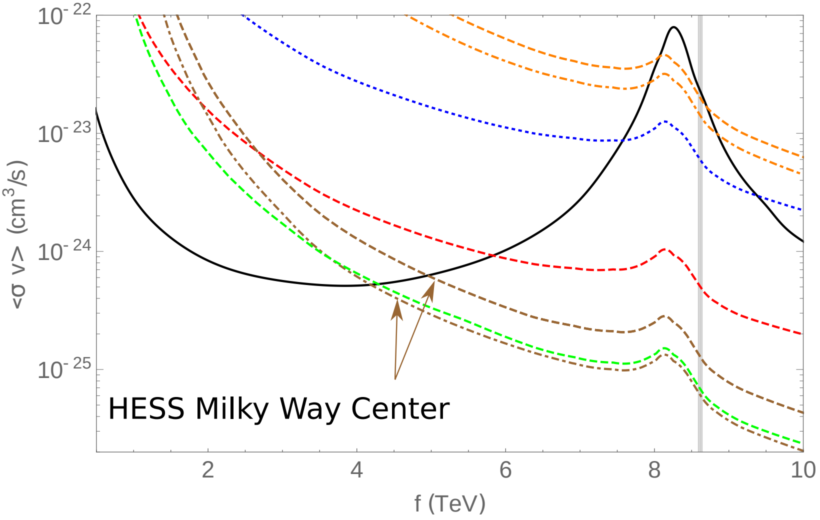

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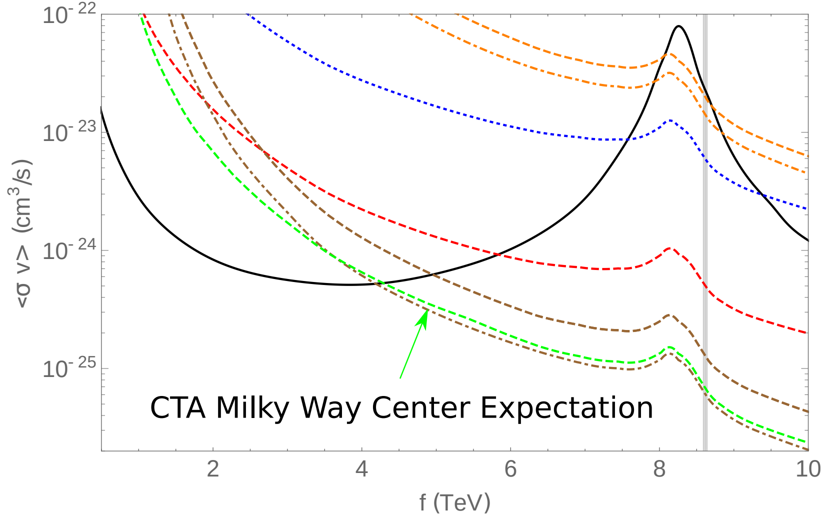


COLLIDER CONSTRAINTS

✓ EWPT: modification of hVV coupling $\Rightarrow f \gtrsim 900$ GeV 1511.08235

✓ Modification of Higgs production and decay

$$R_\gamma = \frac{\sigma(gg \to h) \times BR(h \to \gamma\gamma)}{\sigma_{SM}(gg \to h) \times BR_{SM}(h \to \gamma\gamma)} \sim 1 + \mathcal{O}\left(\frac{v^2}{f^2}\right) \Rightarrow f \gtrsim 800 \text{ GeV}$$

✓ Searches for dissapearing tracks: κ^+ has a decay length of a few cm

$f \gtrsim 650$ GeV RECAST OF AN ATLAS 8 TEV ANALYSIS 1310.3675

✓ Monojet searches are not competitive to the previous ones

CONCLUSIONS

- ✓ Scalar WIMPs can naturally arise in non-minimal composite Higgs models.
- ✓ Non symmetric cosets can also work
- ✓ In particular, the coset $SO(7)/G_2$ leads to natural versions of Higgs portal DM and the Inert Triplet Model
- ✓ The model is extremely predictive, having only one free parameter f

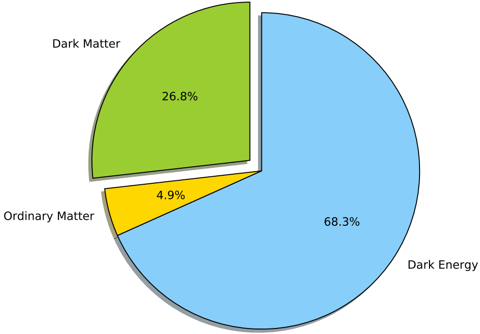
0.9 TeV $\lesssim f \lesssim 6$ TeV for the triplet case

THANKS!

BACK-UP SLIDES

DARK MATTER

✓ Explaining the observed DM relic abundance requires going beyond the SM



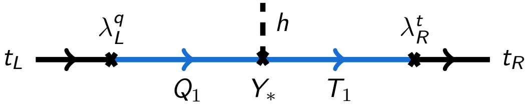
✓ The WIMP 'miracle' hinted the existence of some connection with the hierarchy problem and therefore with $\sim$ TeV NP

✓ SUSY and R-parity have been for a long time the paradigm for this, but what about other 'natural' frameworks?

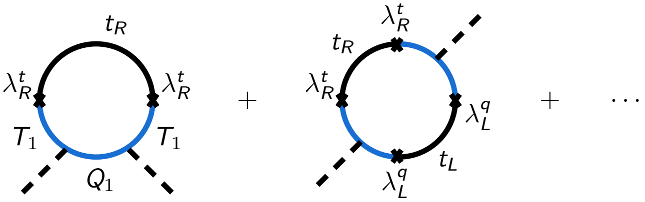
COMPOSITE HIGGS

✓ The gauge contribution is aligned in the direction that preserves the gauge symmetry WITTEN '83

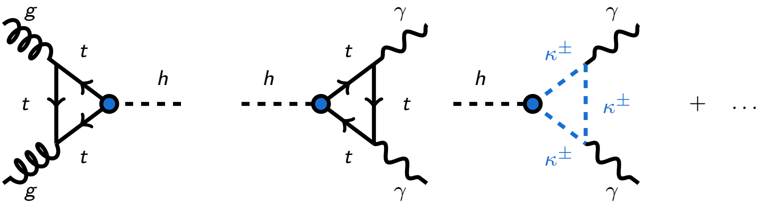
✓ However, the linear mixings $\mathcal{L}_{\text{mix}} = \lambda_L^q \bar{q}_L \mathcal{O}_L^q + \lambda_R^t \bar{t}_R \mathcal{O}_R^t + \text{h.c.}$ needed to generate the fermion masses



break the NGB symmetry and will be also responsible for EWSB



DIPHOTON DECAYS



$$\Gamma(h \to \gamma\gamma) = \frac{\alpha^2 v^2 m_h^3}{1024\pi^3}\left[\frac{g^2}{2m_W^2}\sqrt{1-\xi}A_1(\tau_W)+\frac{4y_t^2}{3m_t^2}\frac{1-2\xi}{\sqrt{1-\xi}}A_{1/2}(\tau_t)+\frac{\lambda_{H\Phi}}{m_\kappa^2}A_0(\tau_\kappa)\right]^2$$

where $\xi = v^2/f^2$ and

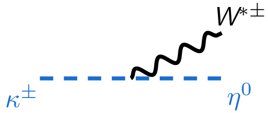
$$\sigma(gg \to h) = \frac{(1-2\xi)^2}{1-\xi}\sigma^{\text{SM}}(gg \to h)$$

7 and 8 TeV CMS+ATLAS data implies that

$$\sigma(gg \to h \to \gamma\gamma)/\sigma_{\text{SM}}(gg \to h \to \gamma\gamma) > 0.66 \ @95 \ \text{CL} \Rightarrow f \gtrsim 800 \ \text{GeV}$$

DISSAPEARING TRACKS

The small splitting between the neutral and the charged states makes $\kappa^\pm$ long-lived. It mainly decays through an off-shell W



$$\Gamma \sim \frac{1}{48\pi^3}\frac{\Delta m^5}{m_W^4} \sim \text{few cm}$$

ATLAS (and CMS) look for Wino (i.e. fermion triplet) pair production

$$pp \to \chi^+\chi^-, \chi^\pm\chi^0$$

where $\chi^\pm$ decay to a soft pion and missing energy. This implies that

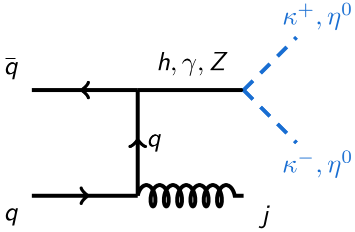
$$\sigma \lesssim 0.25\,\text{pb}$$

We have recasted this searched with `MadGraph` obtaining

$$f \gtrsim 650\,\text{GeV}$$

MONOJETS

A priori, monojets searches could be sensitive to processes like



However, the small cross sections makes such searches less constraining as we have explicitly checked

The Singlet Case

The scalar potential

The leading contribution to the scalar potential remains the same but there are subleading contributions

✓ Breaking the degeneracy of κ^+ and η (coming mostly from B_μ)

$$(m_{\kappa^\pm} - m_\eta)/m_\eta \sim g'^2/(N_c\, y_t^2) \sim 0.05$$

✓ Making $\kappa^\pm$ decay into $t_L b_R$ (coming from the b_R)

$$\frac{c_b}{2\sqrt{6}} \frac{\lambda_q^* \lambda_{b_R}}{g_*} \frac{f}{\hat{\Pi}} \sin\left(\frac{\hat{\Pi}}{f}\right) \bar{q}_L \left[H \cos\left(\frac{\hat{\Pi}}{f}\right) - i\tilde{H} \frac{3}{\sqrt{2}} \frac{\kappa^+}{\hat{\Pi}} \sin\left(\frac{\hat{\Pi}}{f}\right)\right] b_R + \text{h.c.}$$

$$= -y_b \bar{q}_L \left[H - i\tilde{H} \frac{3}{\sqrt{2}} \frac{\kappa^+}{f} \ldots \right] b_R + \text{h.c.}$$

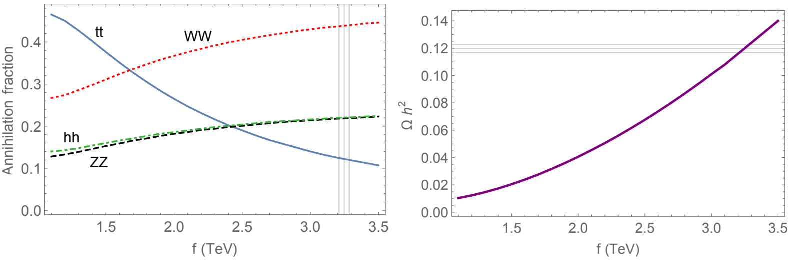
Disappearing tracks are no longer relevant !

THE SINGLET CASE

THE RELIC ABUNDANCE

- ✓ Sommerfeld effects and bound state production no longer relevant
- ✓ $|H|^2(\partial_\mu \eta)^2/f^2$ dominates over $\lambda_{H\Phi}|H|^2\eta^2$

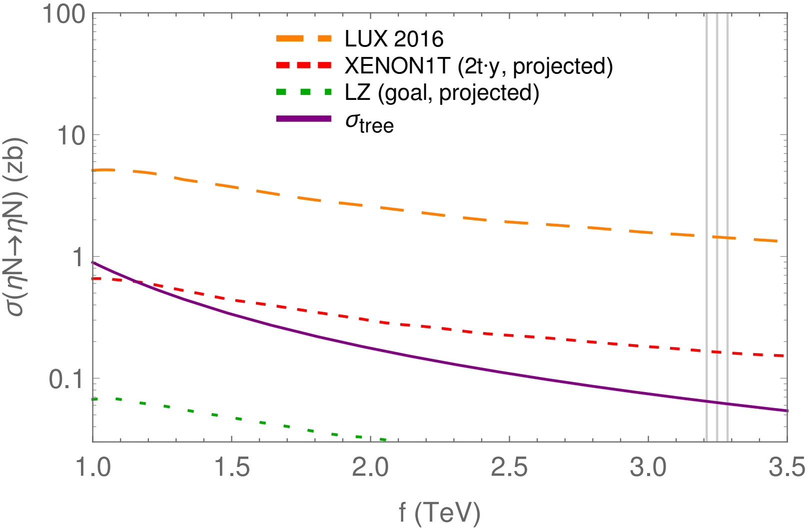
$$\frac{1}{2}\lambda_{H\Phi}\frac{f^2}{m_\eta^2} \sim \frac{1}{2}\frac{5}{18}\lambda_H\frac{3f^2}{2\lambda_H f^2} \sim 0.2$$



THE SINGLET CASE

DIRECT DETECTION

No m_Φ-independent contribution but the bounds rescale differently



Now it is possible to accommodate the whole DM abundance