Scalar Heavy WIMPs from Composite Dynamics

Adrián Carmona

In collaboration with Mikael Chala, arXiv:1504.00332 **JHEP 1506 (2015) 105**

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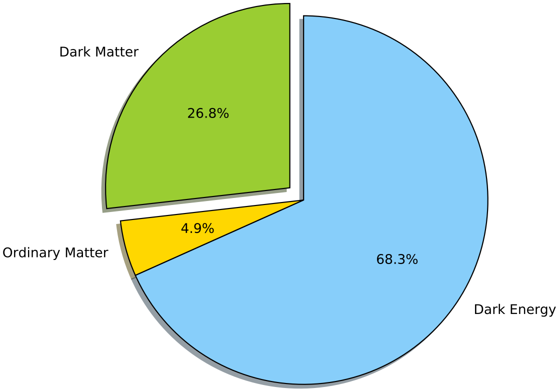
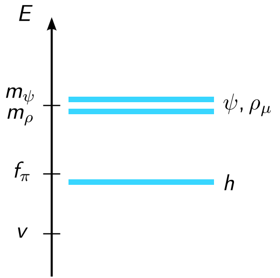
Where do we stand?

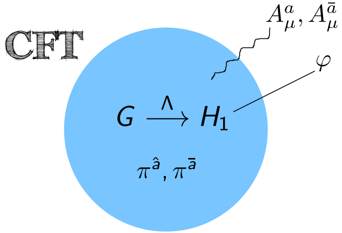
- We have now something that looks more & more like the SM
- It starts to be some rethinking on the question of naturalness (e.g. relaxation)
- However, we still need to deal with the observation of DM



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]





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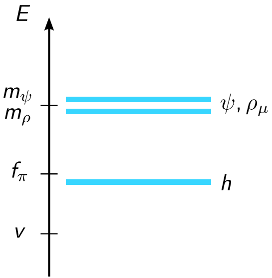

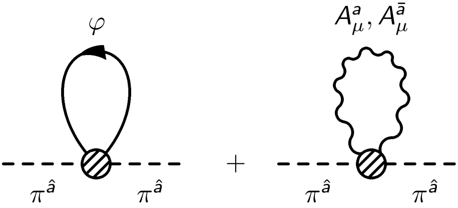

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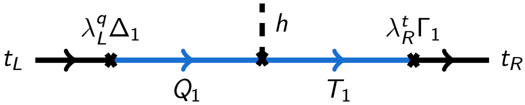
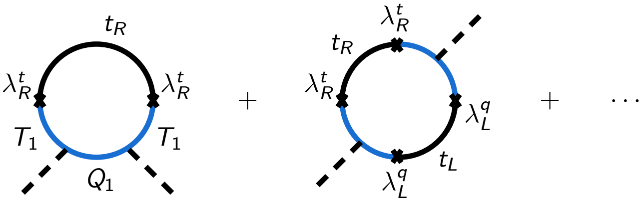
The CW Higgs Effective Potential

- The gauge contribution is aligned in the direction that preserves the gauge symmetry [Witten '83]

- However, the linear mixings needed to generate the fermion masses



will be also responsible for a viable EWSB



Light Top Partners

- Top quark is typically responsible for triggering the EWSB
  [Contino,da Rold,Pomarol, '06]

$$V(h) \cong \alpha \sin^2(h/f_\pi) - \beta \sin^2(h/f_\pi) \cos^2(h/f_\pi)$$

- The Higgs mass read

$$\begin{aligned} m_h^2 &= \frac{8}{f_\pi^2} \beta \cos^2(v/f_\pi) \sin^2(v/f_\pi) \sim \frac{N_c}{2\pi^2} |y|^4 v^2 \\ \Rightarrow & \quad m_h \sim \frac{v}{\sqrt{2}} \sqrt{\frac{N_c}{\pi^2}} |y|^2 \sim \sqrt{\frac{N_c}{\pi^2}} m_t \frac{m_q^*}{f_\pi} \end{aligned}$$

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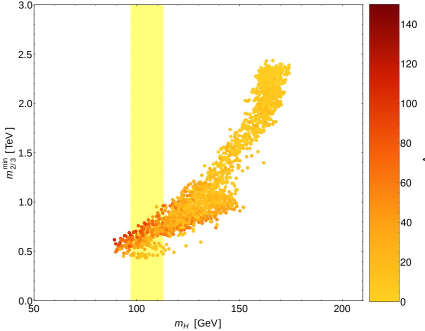
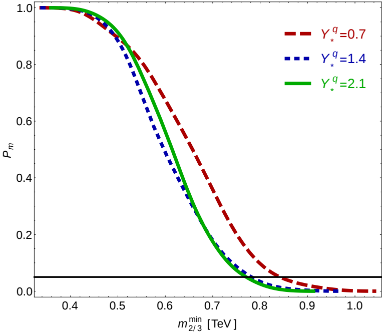
- We have light top partners at the reach of the LHC!

Light Top Partners at the LHC

We can see e.g. the MCHM_5, [AC, Goertz, arXiv:1410.8555]

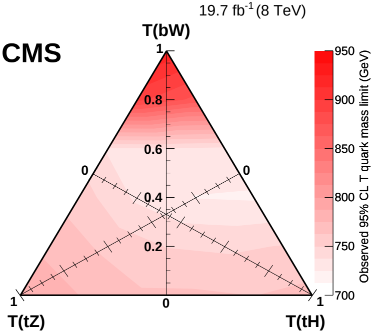


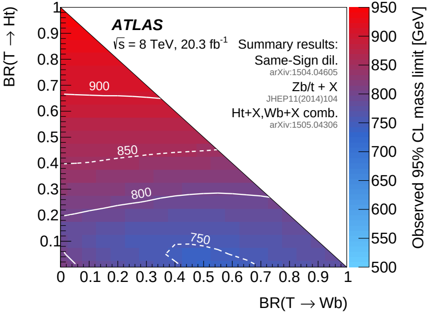


$f_\pi = 0.8$ TeV, $g_\psi \sim 4.4$. $Y_q^* = 0.7$ is the maximum allowed "Yukawa"

Light Top Partners at the LHC

This leads to some tension with current top partner searches performed by ATLAS and CMS



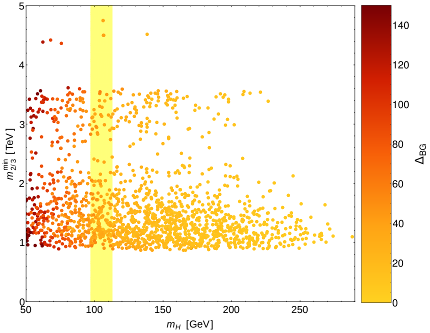


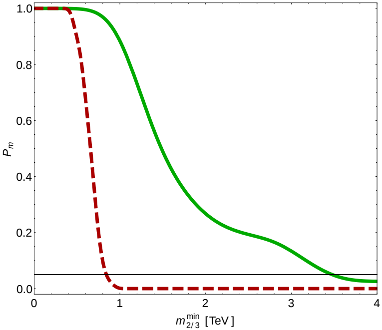
arXiv:1509.04177 arXiv:1505.04306

Still model dependent

Light partners with $f_\pi \sim 1$ TeV can be avoided

- Using larger quark representations **14**
  [Panico, Redi, Tesi, Wulzer, arXiv:1210.7114]
- Enlarging the global symmetries: Composite Twin Higgs
  [Geller, Telem, arXiv:1411.2974] [Barbieri, Greco, Rattazzi, Wulzer, arXiv:1501.07803]
  [Low, Tesi, Wang, arXiv:1501.07890]
- Considering minimal lepton realizations [AC, Goertz, arXiv:1410.8555]





Violation of LFU

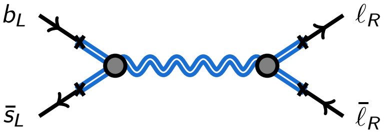
Since

$$\mathcal{L}_{\text{mix}} = \frac{\lambda_L^\ell}{\Lambda^{\gamma_L^\ell}} \bar{l}_{\ell L} \mathcal{O}_{\ell L} + \frac{\lambda_R^\ell}{\Lambda^{\gamma_R^\ell}} \bar{\Psi}_{\ell R} \mathcal{O}_{\ell R} + \text{h.c.}$$

with $\Psi_R \supset \ell_R, \Sigma_R$, asking for

- Non-hierarchical (and not too small) neutrino masses
- And hierarchical charged lepton masses

makes $\epsilon_{\tau R} \ll \epsilon_{\mu R} \ll \epsilon_{eR}$, violating LFU

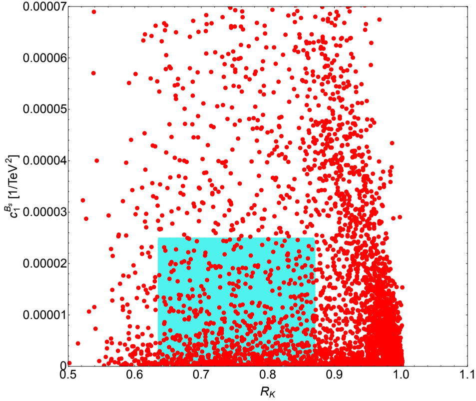


$\sim g_\rho^2/m_\rho^2 \ (\epsilon_{s_L} \epsilon_{b_L} \epsilon_{\ell_R}^2)$

Violation of LFU

Actually, we might have already proben this, since LHCb [arXiv:1406.6482] reported a 2.6σ deviation in

$$R_K = \frac{\mathcal{B}(B^+ \to K^+ \mu^+ \mu^-)}{\mathcal{B}(B^+ \to K^+ e^+ e^-)} = 0.745^{+0.097}_{-0.082}$$



[AC, Goertz, arXiv:1510.xxxxx]

What about DM?

Contrary to SUSY, there is no inmediate way of getting a DM candidate. However, larger cosets can provide them

[Frigerio, Pomarol, Riva, Urbano, arXiv:1204.2808] [Gripaios, Pomarol, Riva, Serra, arXiv:0902.1483] [Chala, arXiv:1210.6208] [Barnard, Gherghetta, Ray, Spray, arXiv:1409.7391]

Some of them use the fact that for a symmetric coset, i.e., where

$$[X^i, X^j] = i f_{ijk} T^k$$

there is a $\mathbb{Z}_2$ symmetry $\pi^{\hat{a}} \leftrightarrow -\pi^{\hat{a}}$ of

$$\mathcal{L}_\pi = \frac{f^2}{2}\mathrm{Tr}(d_\mu d^\mu), \qquad \text{with } \omega_\mu = -iU^\dagger D_\mu U = d_\mu^a X^a + E_\mu^a T^a,$$

not respected in general by partial compositeness.

A very simple idea

If we forget naturalness for the moment see also e.g. [Kilic, Okui, Sundrum '10] [Antipin, Redi, Strumia '14]

- The Higgs can be also made elementary
- We no longer need partial compositeness to generate the Yukawa couplings
- The pNGBs will not get a vev

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If we assumme the theory to be anomaly-free, the lightest pNGB will be stable and thus a DM candidate!

Composite Dark Sectors

If we assume G/H with $G_{\mathrm{EW}} \subset H$, the two (viable) smallest cosets are

$$[SU(2)^2 \times U(1)]/[SU(2) \times U(1)] \qquad SU(3)/[SU(2) \times U(1)]$$

which provide an additional scalar triplet and doublet, respectively,

$$\Delta = \left(\frac{\pi^+ + \pi^-}{\sqrt{2}}, -i\frac{\pi^+ - \pi^-}{\sqrt{2}}, \pi^0 \right)^T \qquad \phi = \left(\pi^+, \frac{\pi^0 + iA^0}{\sqrt{2}} \right)^T$$

We could also have e.g. $SO(5)/SO(4), \ldots$

Some general comments

- The phenomenology is dictated by the symmetries and only two free parameters, namely f_D and g_D, with $1 \lesssim g_D \lesssim 4\pi$
- We will have vector resonances with masses $m_\rho \sim f_D g_D \gtrsim$ few TeV, according to current constraints
- The pNGBs π are naturally expected to live around (or slightly below) the TeV
- Non-derivative scalar interactions are generated at the quantum level and thus expected to be subdominant with respect to gauge ones
- As neutral and charged pNGB come in complete irreps of the EW group, its mass splitting can only be $\sim v$

Minimal Case

Let's consider for concreteness the coset $[SU(2)^2 \times U(1)]/[SU(2) \times U(1)]$

$$
\begin{aligned}
\mathcal{L}_\pi = & \, g^2(\pi^0)^2 W^+_\mu W^{\mu\,-} + \left[igW^{\mu\,+}(\pi^0 \overleftrightarrow{\partial_\mu} \pi^-) - \frac{1}{2} g^2 W^+_\mu W^{+\,\mu} \pi^- \pi^- + \text{h.c.} \right] \\
& + g^2 W^+_\mu W^{\mu\,-} \pi^+ \pi^- + \frac{g^2}{c_W^2}(s_W^2 - 1)^2 Z_\mu Z^\mu \pi^+ \pi^- + \frac{ig(1-s_W^2)}{c_W} Z^\mu (\pi^+ \overleftrightarrow{\partial_\mu} \pi^-) \\
& + e^2 A_\mu A^\mu \pi^+ \pi^- + ieA^\mu (\pi^+ \overleftrightarrow{\partial_\mu} \pi^-) + \frac{2eg}{c_W}(s_W^2 - 1) A_\mu Z^\mu \pi^+ \pi^- \\
& + \left[egA_\mu \pi^0 W^{\mu\,+} \pi^- + \frac{g^2}{c_W}(s_W^2 - 1) W^+_\mu Z^\mu \pi^0 \pi^- + \text{h.c.} \right] \\
& + \ldots
\end{aligned}
$$

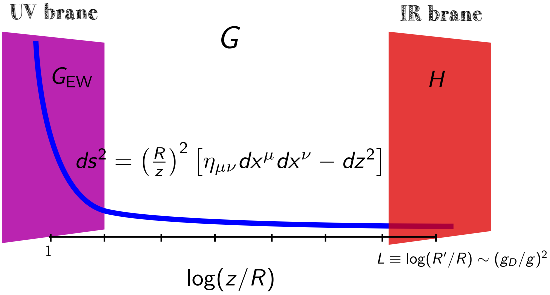
The potential

$$V = V(h, \pi^i) + V_{\text{SM}}(h)$$

and the relevant couplings of the resonances Z', γ', W', G' will be computed through AdS/CFT.

Holographic DM

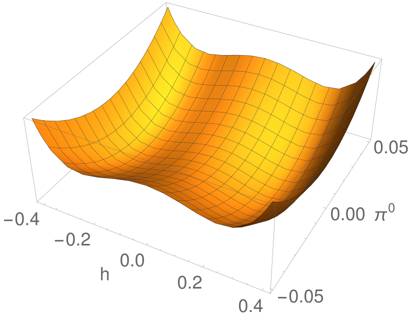
In order to estimate the strongly-coupled effects we work in a 5D holographic description



- All SM matter content (including the Higgs) is confined on the UV brane.
- Only gauge bosons will propagate into the bulk

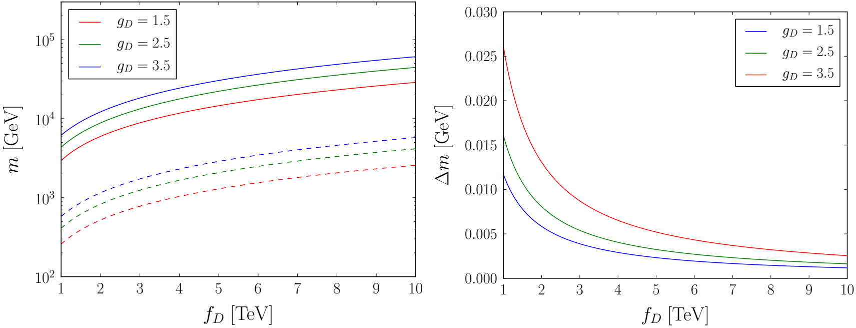
Scalar Potential

$$V(h,\pi^i) \approx \left[\lambda_0 + \lambda_2 \left(\frac{h}{f_D}\right)^2 + \lambda_4 \left\{1 + \frac{1}{2}\tan^2\hat{\theta}_W \frac{\pi^+\pi^-}{\Pi^2}\right\}\left(\frac{h}{f_D}\right)^4\right] \sin^2\left(\frac{\Pi}{f_D}\right)$$

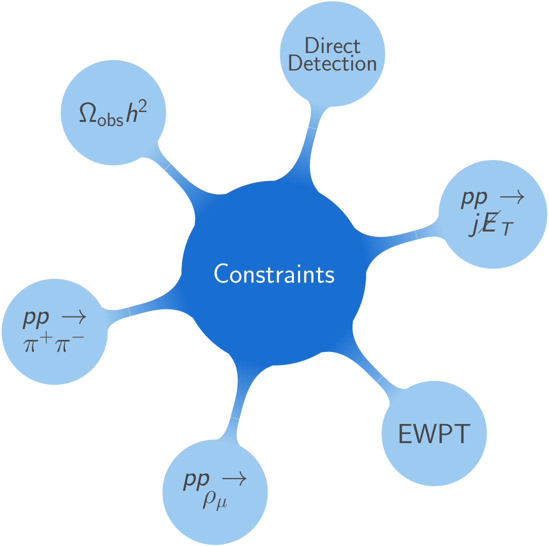


Masses

Scalar (dashed) and vector resonance (solid) masses and splittings

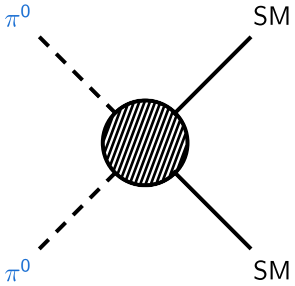


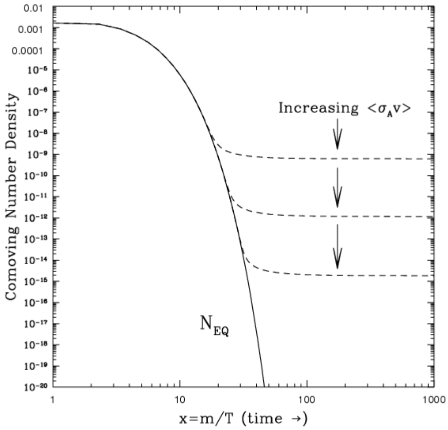
Constraints



Relic Abundance

Freeze-out mechanism





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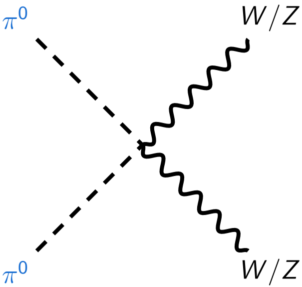
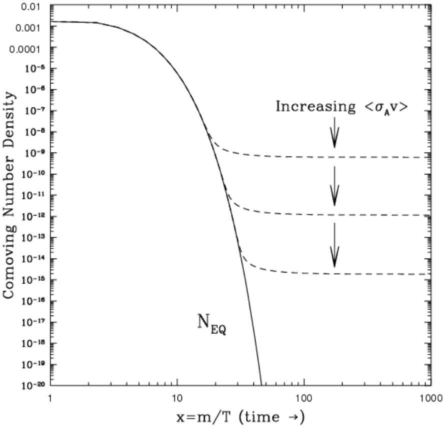
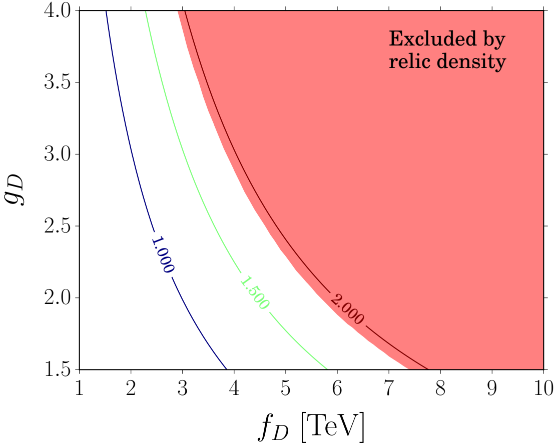


$$\sigma \sim \frac{g^4}{m_{\pi^0}^2}$$

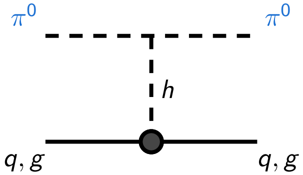


Relic Abundance

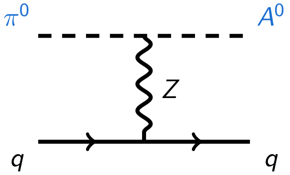
We consider a region in the $g_D - f_D$ plane, parametrized by $g_D \in [1.5, 4]$ and $f_D \in [1, 10]$ TeV



Direct Detection



Most important channel

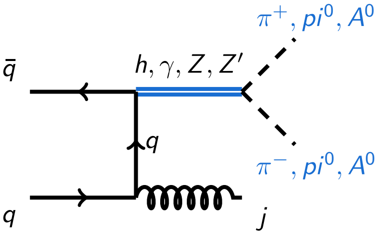


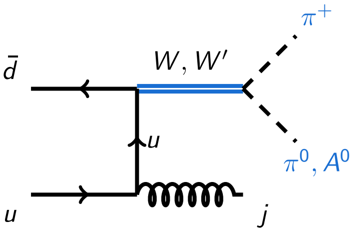
Negligible if $m_{A^0} - m_\pi^0 \gtrsim 0.1$ MeV

- Direct detection experiments are not sensitive to small values of the trilinear coupling $h\pi^0\pi^0$, specially for large DM masses
- Our small loop-induced couplings are out of the reach of any of these experiments

Monojets

A priori, monojets searches could be sensitive to processes like





We have explicitly checked that this is not the case

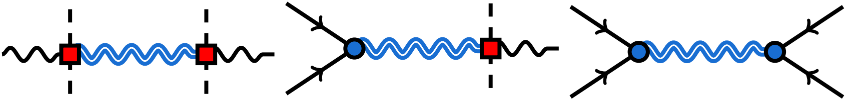
- `MadGraph v5` + `Pythia v6` + `MadAnalysis v5` + CMS analysis
- $\not{E}_T > 450$ GeV $\Rightarrow \sigma \times \epsilon \leq 7.8$ fb, upper bound stated by CMS [arXiv:1408.3583]

EWPT

Normally, for elementary fermions and a composite Higgs,

$$\hat{T} \sim [\hat{\alpha} - 2\hat{\beta} + \hat{\gamma}], \qquad \hat{S} \sim [-\hat{\beta} + \hat{\gamma}], \qquad W = Y \sim \hat{\gamma}$$

where



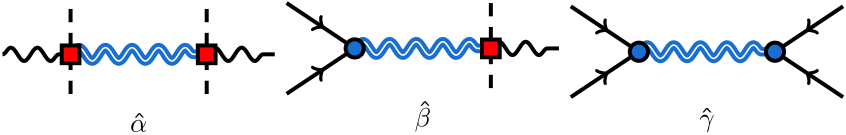
$\hat{\alpha}$ $\hat{\beta}$ $\hat{\gamma}$

and ■ $\sim \sqrt{L}$, ● $\sim 1/\sqrt{L}$, $\sqrt{L} \sim g_D/g$. Thus,

$$\hat{T} \sim L, \qquad \hat{S} \sim 1, \qquad W = Y \sim 1/L$$

EWPT

Now the situation is pretty different, as for an elementary Higgs,



all these coefficients become the same $\hat{\alpha} = \hat{\beta} = \hat{\gamma}$ and

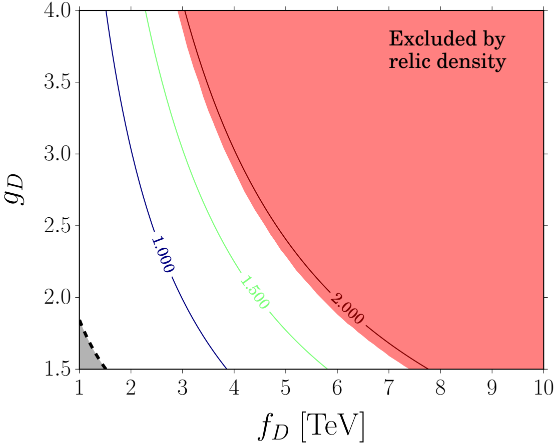
$$\hat{T} \sim [\hat{\alpha} - 2\hat{\beta} + \hat{\gamma}] = 0, \qquad \hat{S} \sim [-\hat{\beta} + \hat{\gamma}] = 0, \qquad W = Y \sim \hat{\gamma} \sim 1/L$$

Since $W = Y \sim (g/g_D)^4 (v/f_D)^2$,

$W = Y$ may become relevant for $g_D \sim 1$ and $f_D \gtrsim 1$ TeV

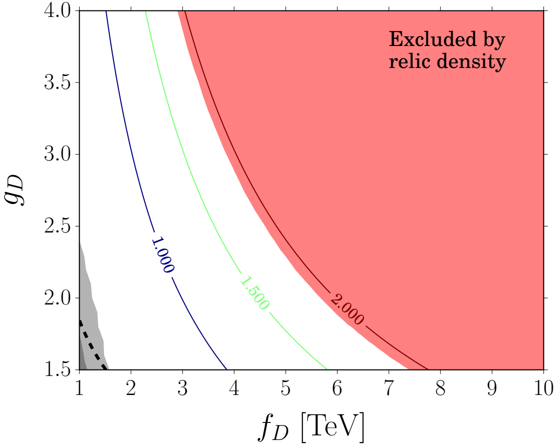
EWPT

We have performed an up-to-date EW precision fit to $W = Y$



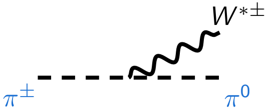
LHC constraints on new heavy resonances

The new vector resonances G', Z', γ' and W' can mediate decays into dijets [CMS, arXiv:1501.0419] $t\bar{t}$ [CMS, arXiv:1309.2030] $\ell^+\ell^-$ [CMS, arXiv:1405.4123]



LHC constraints on long-lived charged particles

The small splitting between the neutral and the charged states in the triplet case makes $\pi^{\pm}$ long-lived. It mainly decays through an off-shell W

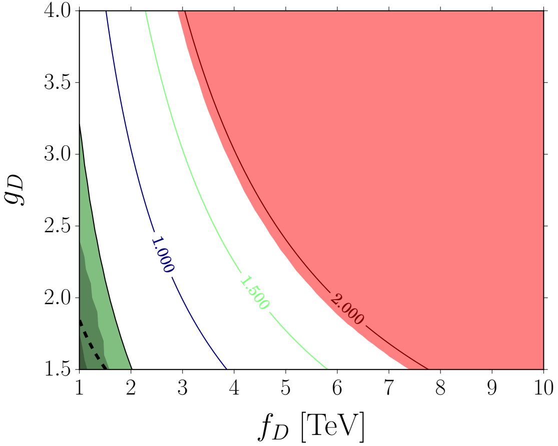


$$\Gamma \sim \frac{g^4\alpha}{48\pi^3}\frac{\Delta m^5}{m_W^4}$$

- This is OK for cosmological scales but large enough to scape LHC detectors
- The trace of $\pi^{\pm}$ can be still observed for they give rise to anomalous energy loss [CMS, arXiv:1305.0491]

Everything Together

Besides the relic abundance constraint, $\Omega h^2 \leq 0.12$, the strongest bounds come from searches on long-lived charged particles



The doublet model

The $SU(3)/[SU(2) \times U(1)]$ case is very similar, but ...

- In principle, π^0 and A^0 are degenerated in mass since the operator that could be responsible for the splitting,

$$\lambda \left[(H^\dagger \phi)^2 + \text{h.c.} \right]$$

  does not arises at the quantum level

- The reason is that the pNGB sector respects a $U(1)$ symmetry $\supset \mathbb{Z}_2$
- This would be lethal from the point of view of direct detection
- However, it can always be assumed that this symmetry is broken at a higher scale

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Provided the splitting is small (as expected if the $U(1)$ is broken at a high scale) we don't need to worry about it!

The doublet model

We can realize another interesting difference looking at the CW potential

$$
\begin{aligned}
V(h,\pi^{\hat{a}}) \quad \approx \quad & \left[\lambda_0 - \left(7 + 2\sec^2\hat{\theta}_W\right)\lambda_2\left(\frac{h}{f_D}\right)^2\right]\sin^2\left(\frac{\Pi}{f_D}\right) + \frac{1}{8}\left[\left(1 + 3\tan^2\hat{\theta}_W\right)\lambda_0\right. \\
& \left. + \left(38 - 20\sec^2\hat{\theta}_W + 12\sec^4\hat{\theta}_W\right)\lambda_2\left(\frac{h}{f_D}\right)^2\right]\sin^2\left(2\frac{\Pi}{f_D}\right) \\
& + 2\tan^2\hat{\theta}_W\lambda_2\left(\frac{h}{f_D}\right)^2 \frac{\left((\pi^0)^2 + (A^0)^2\right)^2 - (\pi^+\pi^-)^2}{\Pi^4}\sin^2\left(2\frac{\Pi}{f_D}\right),
\end{aligned}
$$

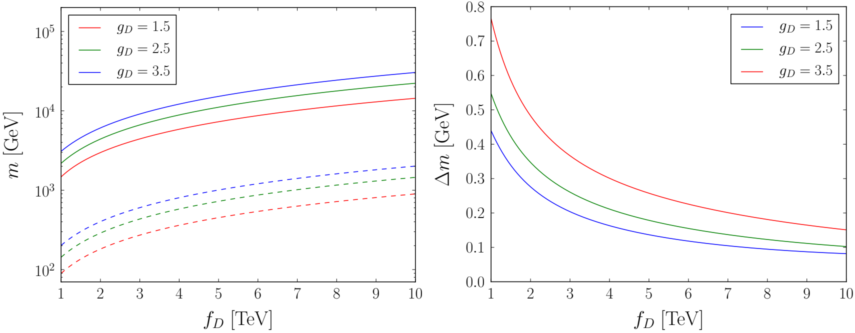
The doublet model

We can realize another interesting difference looking at the CW potential

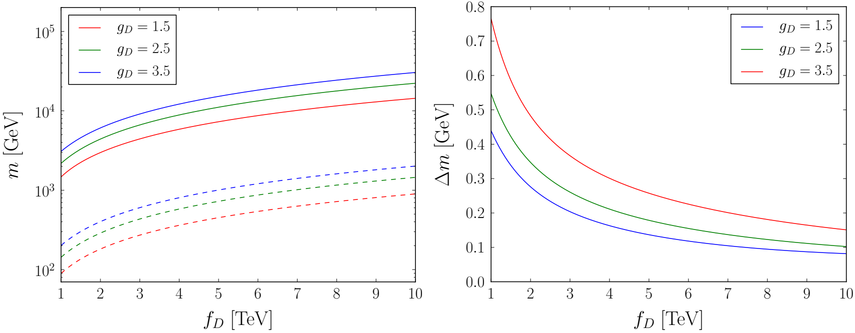
$$\begin{aligned} V(h,\pi^{\hat{a}}) \quad \approx \quad & \left[\lambda_0 - \left(7 + 2\sec^2\hat{\theta}_W\right)\lambda_2\left(\frac{h}{f_D}\right)^2\right]\sin^2\left(\frac{\Pi}{f_D}\right) + \frac{1}{8}\left[\left(1 + 3\tan^2\hat{\theta}_W\right)\lambda_0 \right. \\ & \left. + \left(38 - 20\sec^2\hat{\theta}_W + 12\sec^4\hat{\theta}_W\right)\lambda_2\left(\frac{h}{f_D}\right)^2\right]\sin^2\left(2\frac{\Pi}{f_D}\right) \\ & + 2\tan^2\hat{\theta}_W\lambda_2\left(\frac{h}{f_D}\right)^2\frac{\left((\pi^0)^2 + (A^0)^2\right)^2 - (\pi^+\pi^-)^2}{\Pi^4}\sin^2\left(2\frac{\Pi}{f_D}\right), \end{aligned}$$

The mass splitting between the charged and the neutral pNGBs arises at order v^2/f_D^2

The doublet model

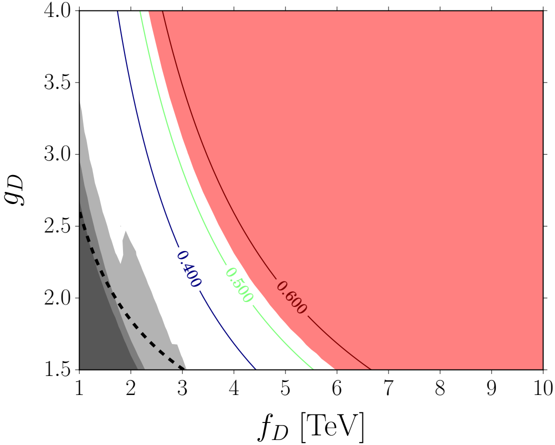


The doublet model



Now Δm is big enough to make the charged pNGBs decay within the detector

The doublet model



Conclusions

We have presented dynamical realizations of the ITM and the IDM

- Arising from composite dark sectors
- Very predictive (only two free parameters)
- With relevant constraints from relic abundance and collider searches

Thanks!