Composite Dark Sectors

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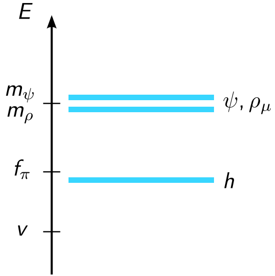
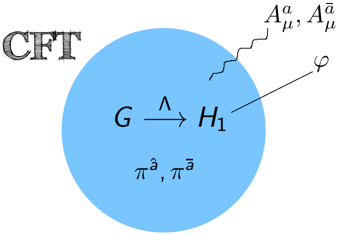
Composite Higgs

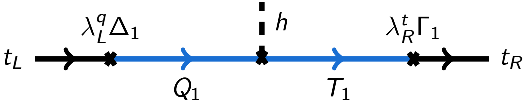
- One interesting solution to the hierarchy problem is making the Higgs composite, the remnant of some new strong dynamics
  [Kaplan, Georgi '84]
- It is particularly compelling when the Higgs is the pNGB of some new strong interaction. Something like pions in QCD
  [Agashe, Contino, Pomarol '04]



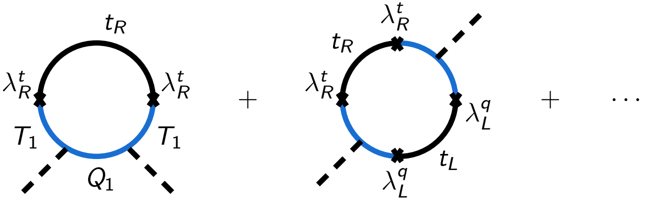


The Higgs Effective Potential

- The coupling to the elementary sector breaks the global symmetry, generating a Higgs potential at the loop level
- 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

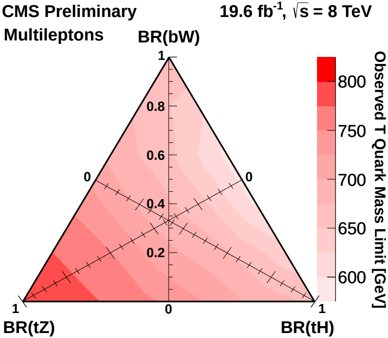


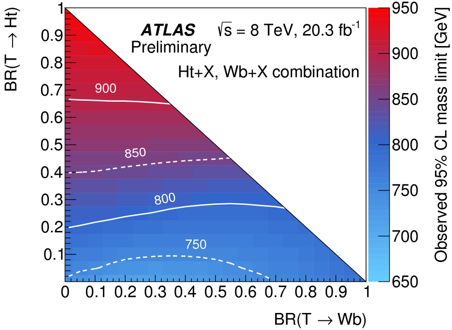
Light Top Partners at the LHC

In general

$m_H \sim 125$ GeV and $m_{top} \sim 170$ GeV $\Rightarrow$ light top partners $\lesssim 1$ TeV

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





A different look at the Composite Idea

Leaving aside naturalness?

- We consider SM extensions in which the SM matter content (including the Higgs) is fully elementary
  [Kilic, Okui, Sundrum '10] [Antipin, Redi, Strumia '14]

- If the coset $\mathcal{G}/\mathcal{H}$ is symmetric, i.e., $[X^i, X^j] = i f_{ijk} T^k$, with (T^k) X^i the (un)broken generators, only terms with an even number of pNGBs are present in the Lagrangian
- This means in particular that the Composite Sector has an accidental $\mathbb{Z}_2$ symmetry $\pi^i \leftrightarrow -\pi^i$ not even spontaneously broken

Composite Dark Sectors

If we consider $\mathcal{G}_{\mathrm{SM}} = \mathcal{H} \subset \mathcal{G}$ and elementary fermions, the lightest pNGB provides a DM candidate!

1. We have just two parameters f_D and g_D
2. f_D is not longer required to be $\lesssim 1$ TeV by naturalness
3. The Coleman-Weinberg potential is expected to preserve the EW symmetry

The two smallest viable groups are $\mathcal{G} = SU(2)^2 \times U(1)$ and $SU(3)$, which provide an additional scalar triplet and doublet, respectively.

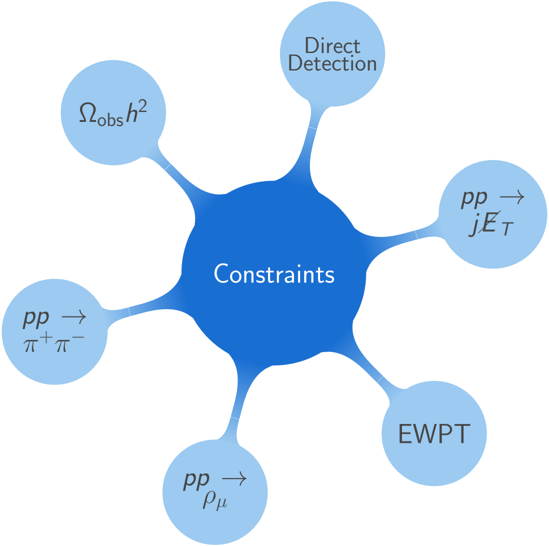
$$\Delta = \left(\frac{\pi^+ + \pi^-}{\sqrt{2}}, -i\frac{\pi^+ - \pi^-}{\sqrt{2}}, \pi^0 \right)^T \qquad \phi = \left(\pi^+, \frac{\pi^0 + iA^0}{\sqrt{2}} \right)^T$$

Inert Triplet Model — Inert Doublet Model

Some general comments

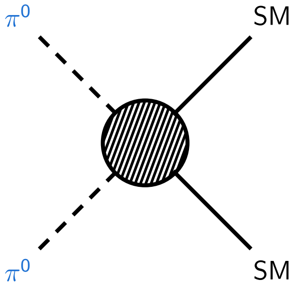
- g_D is expected to be $1 \lesssim g_D \lesssim 4\pi$
- Vector masses $\sim m_\rho \sim f_D g_D \gtrsim$ few TeV, from current constraints
- The pNGBs π are naturally expected to live around $\lesssim$ TeV
- Non-derivative scalar interactions are generated at the quantum level and thus expected to be 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 $\sim v$

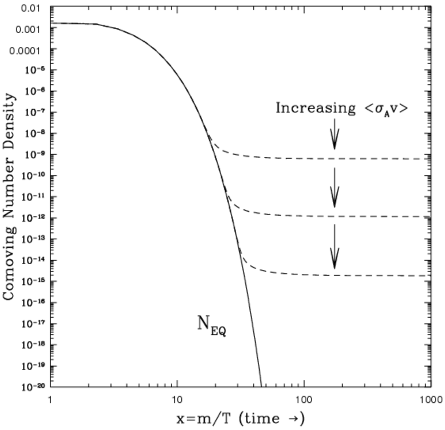
Constraints



Relic Abundance

Freeze-out mechanism





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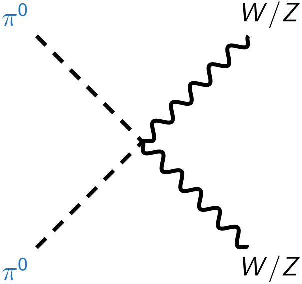
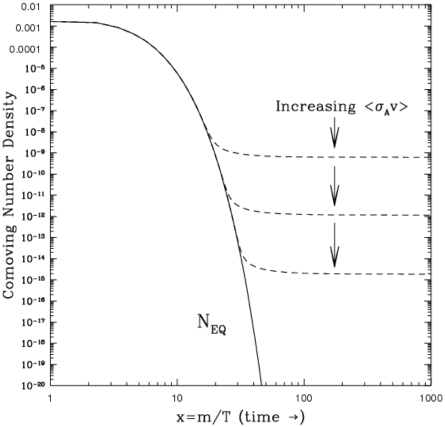
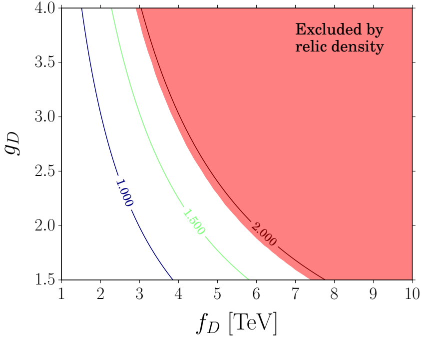


$$\sigma \sim \frac{g^4}{m_{\pi^0}^2}$$

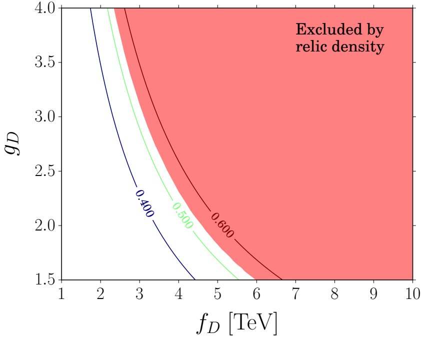


Relic Abundance

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

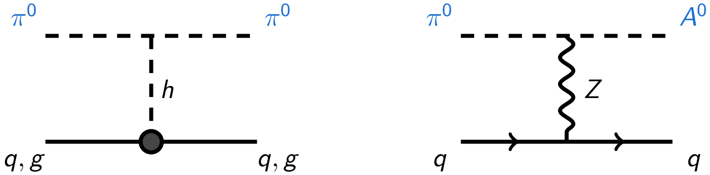


$[SU(2)^2 \times U(1)]/[SU(2) \times U(1)]$



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

Direct Detection



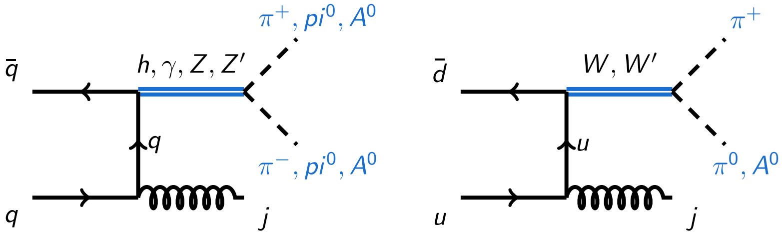
Most important channel

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

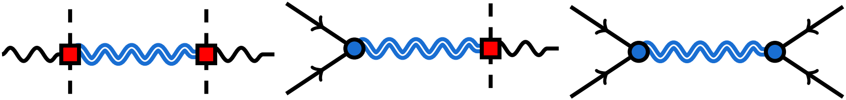
- `MadGraph v5` + `Pythia v6` + `MadAnalysis v5` + CMS analysis
- $\not{E}_T > 450$ GeV $\Rightarrow \sigma \times \epsilon \leq 7.8$ fb, upper bound stated by CMS [arXiv:1408.3583]

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



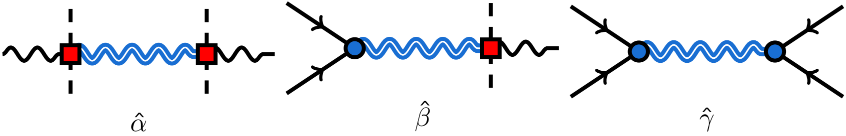
$\hat{\alpha}$ $\hat{\beta}$ $\hat{\gamma}$

and $\blacksquare \sim \sqrt{L}$, $\bullet \sim 1/\sqrt{L}$, $\sqrt{L} \sim g_D/g$. 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

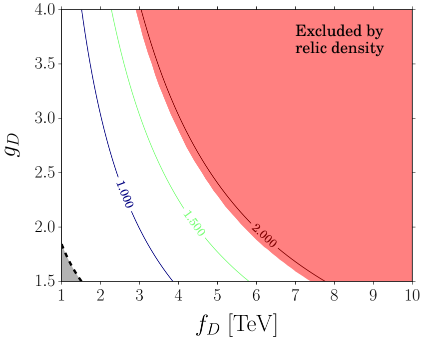
$$\hat{T} \sim [\hat{\alpha} - 2\hat{\beta} + \hat{\gamma}] = 0, \qquad \hat{S} \sim [-\hat{\beta} + \hat{\gamma}] = 0, \qquad W = Y \sim \hat{\gamma} \sim 1/L$$

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 $W = Y$



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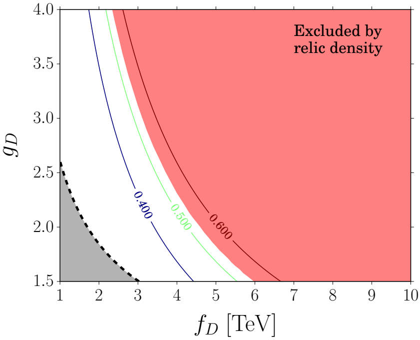
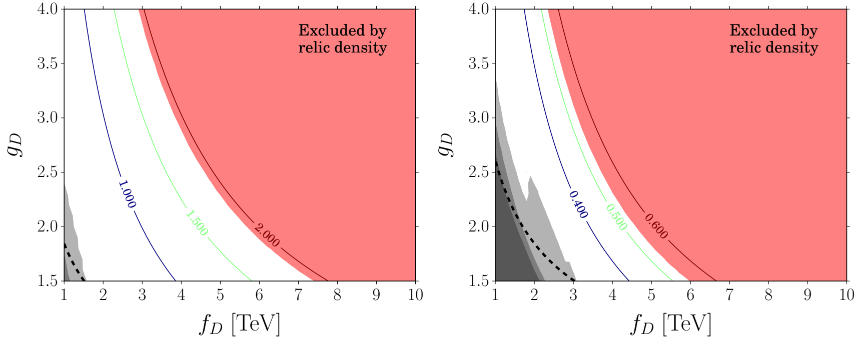


$SU(3)/[SU(2) \times U(1)]$

LHC constraints on new heavy resonances

The new vector resonances G', Z', γ' and W' can mediate decays into

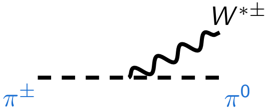
dijets [CMS, arXiv:1501.0419] $t\bar{t}$ [CMS, arXiv:1309.2030] $\ell^+\ell^-$ [CMS, arXiv:1405.4123]



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

LHC constraints on long-lived charged particles

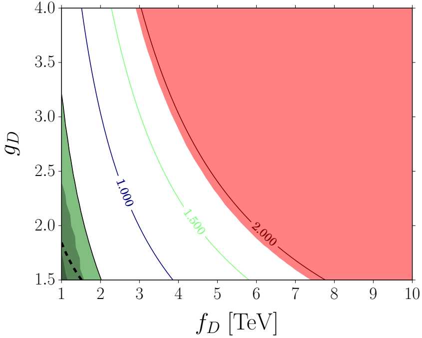
The small splitting between the neutral and the charged states in the triplet case makes $\pi^\pm$ long-lived. It mainly decays through an off-shell W



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

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

Everything Together



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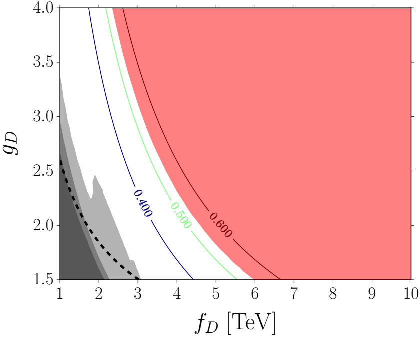

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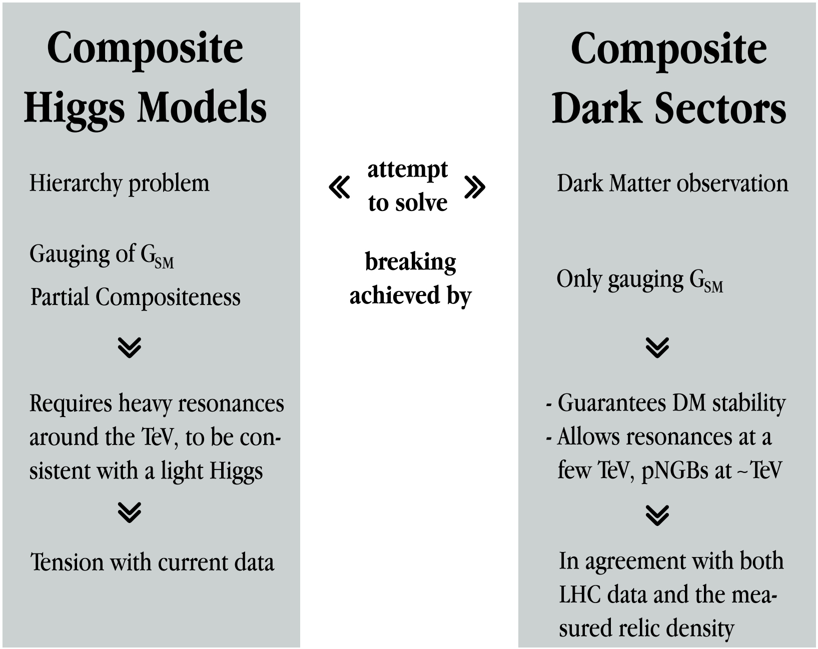
Composite Higgs Models
Hierarchy problem
Gauging of G_SM
Partial Compositeness
Requires heavy resonances around the TeV, to be consistent with a light Higgs
Tension with current data
« attempt to solve »
breaking achieved by
Composite Dark Sectors
Dark Matter observation
Only gauging G_SM
- Guarantees DM stability
- Allows resonances at a few TeV, pNGBs at ~TeV
In agreement with both LHC data and the measured relic density

Thanks!

Back-up Slides

The Light Top Partner Connection

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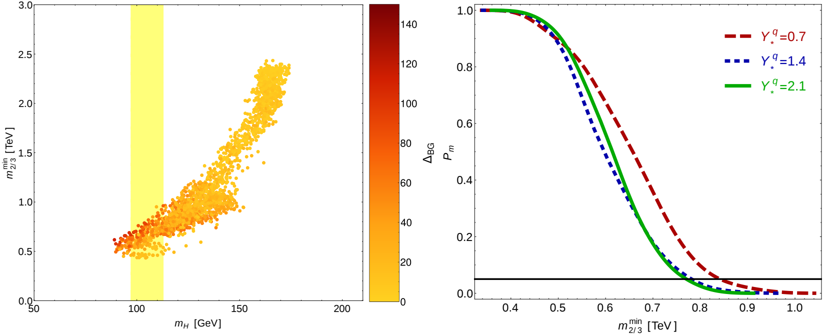
- We have light top partners at the reach of the LHC!

Light Top Partners at the LHC

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

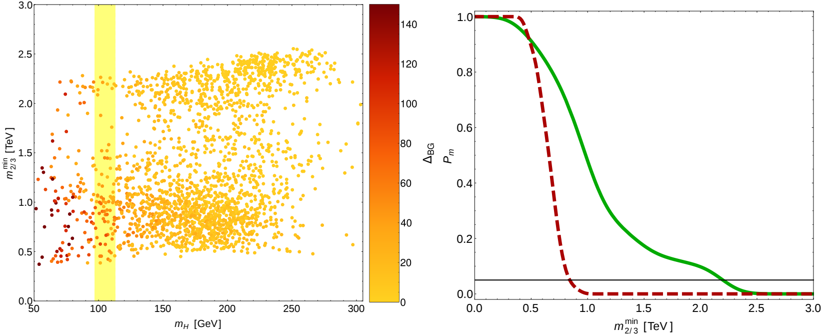


$f_\pi = 0.8$ TeV, $g_\psi \sim 4.4$. $Y_q^* = 0.7$ is the maximum allowed "Yukawa"

Still model dependent

There are cases where the top partners are heavier, e.g. the $\mathrm{mMCHM}_5^{\mathrm{III}}$

[AC, Goertz, arXiv:1410.8555]

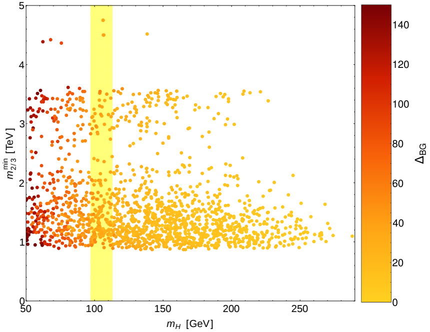


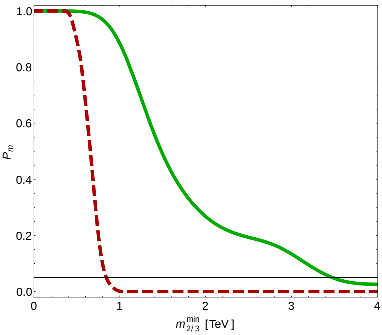
$$Y_*^l = 0.35, \quad Y_*^q = 0.7, \quad f_\pi = 0.8 \text{ TeV}, \quad g_\psi \sim 4.4$$

Still model dependent

Leptons can even be the main source of the Higgs mass, allowing for the most minimal quark model $q_L \sim \mathbf{5}_{-2/3}$, $t_R \sim \mathbf{1}_{-2/3}$, the mMCHM$^{\text{III}>}_{5-1}$

[AC, Goertz, arXiv:1410.8555]

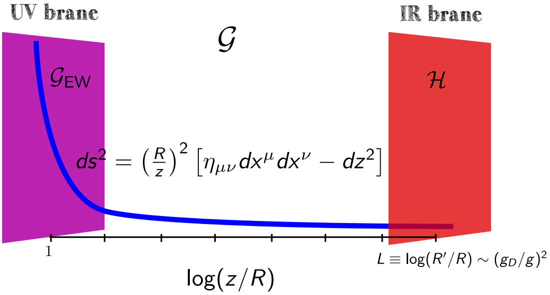




$$Y_*^l = 0.7, \quad Y_*^q = 0.7, \quad f_\pi = 0.8 \text{ TeV}, \quad g_\psi \sim 4.4$$

Holographic DM

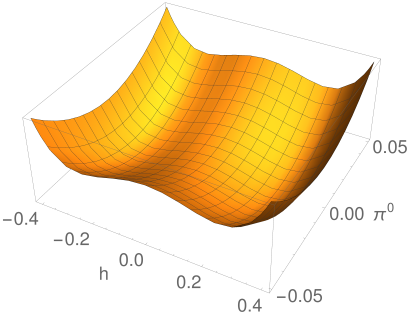
In order to estimate the strongly-coupled effects we work in a 5D holographic description

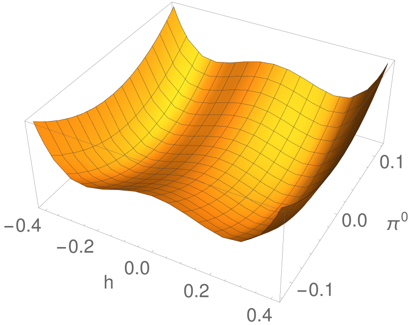


- All SM matter content (including the Higgs) is confined on the UV brane.
- Only gauge bosons will propagate into the bulk

Scalar Potential

We can explicitly confirm that the usual EWSB is not spoiled





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

Masses

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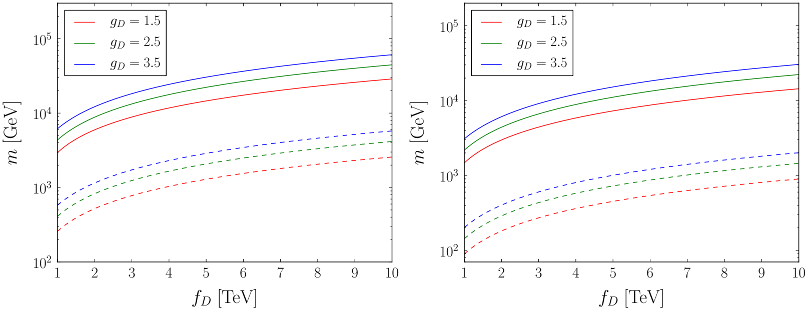

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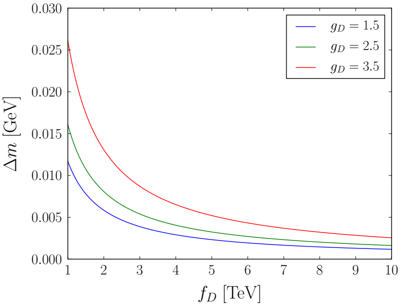

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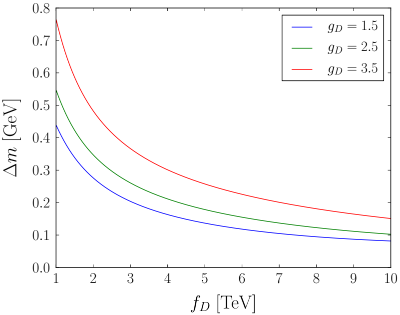

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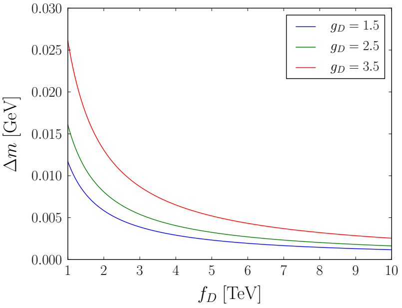

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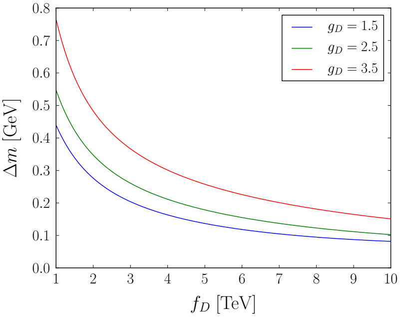

The splitting arises at order m_W^4/f_D^4 in the triplet case but at order m_W^2/f_D^2 for the doublet

Masses

- In principle, π^0 and A^0 are degenerated in mass in the doublet case 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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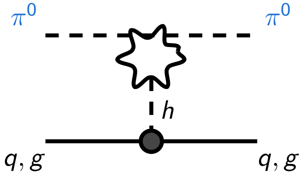
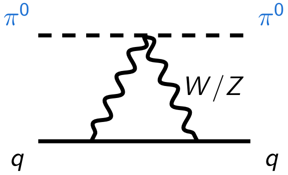
- However, it can always be assumed that this symmetry is broken at a higher scale

Provided the splitting is small (as expected if the $U(1)$ is broken at a high scale) we can neglect the dependence on it!

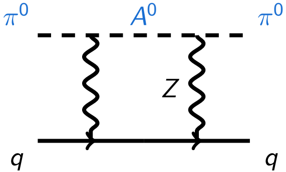
Direct Detection

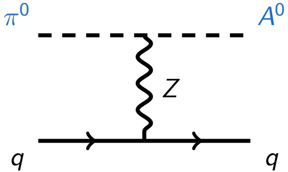




- We have always loop-induced processes
- They are beyond the current sensitivity of any of these experiments

Direct Detection





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