Recent Research and Interests

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November 4, 2015

About me

Since October, Marie Curie Fellow at CERN

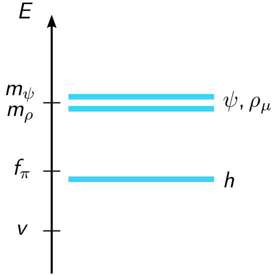
Jerez (1983) → Sevilla → Granada (PhD) → ETH Zurich → CERN

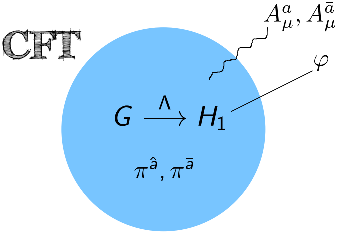
Research Interests:

- BSM (CHMs, WEDs, . . .)
- Flavor
- Neutrino Physics
- Dark Matter
- . . .

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 $m_\pi^2 = m_h^2 \sim g_{\rm el}^2 \Lambda^2/16\pi^2$

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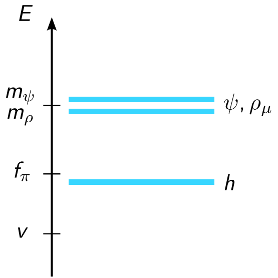

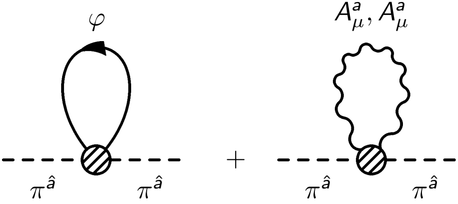

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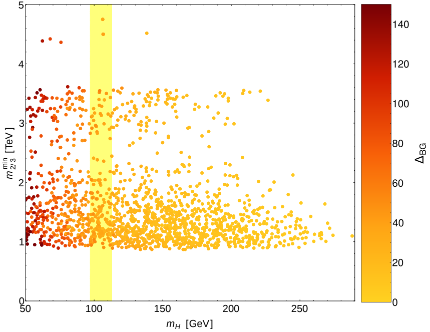
Leptons can play a role

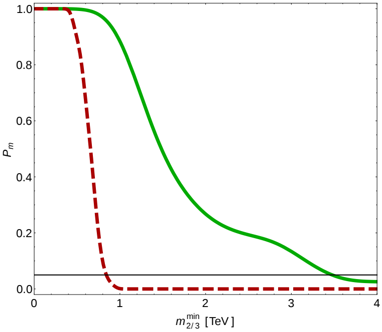
[AC, Goertz, **JHEP 1505 (2015) 002]**

A lepton sector featuring a type-III seesaw can be embedded with only two conformal operators (per generation)

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

with $\Psi_R \supset \ell_R, \Sigma_R$, if $\mathcal{O}_{\ell L} \sim \mathbf{5}$ and $\mathcal{O}_{\ell R} \sim \mathbf{14} = (\mathbf{1},\mathbf{1}) \oplus (\mathbf{2},\mathbf{2}) \oplus (\mathbf{3},\mathbf{3})$





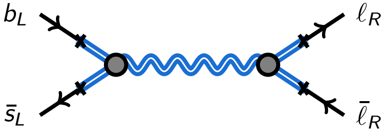
Violation of LFU

[AC, Goertz, **arXiv:1510.07658**]

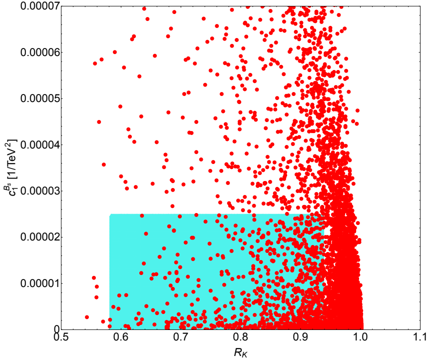
Asking for

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

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



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



Composite Dark Sectors

[AC, Chala, **JHEP 1506 (2015) 186**]

For a symmetric coset, i.e., where

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

there is a $\mathbb{Z}_2$ symmetry $\pi^{\hat{a}} \leftrightarrow -\pi^{\hat{a}}$ of the chiral Lagrangian not respected in general by partial compositeness. If we forget naturalness for the moment

- 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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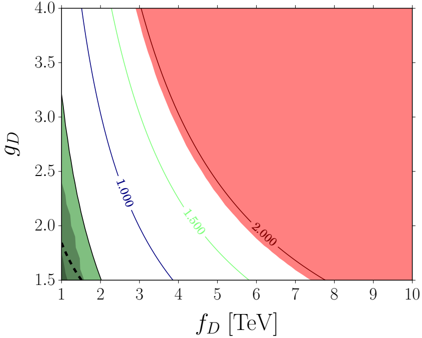
- The pNGBs will not get a vev

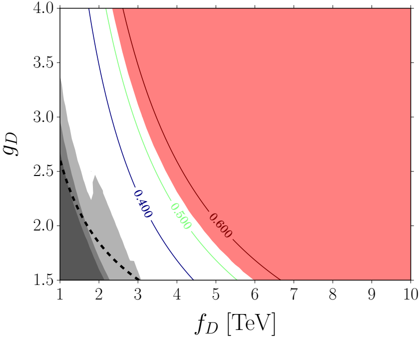
If we assumme the theory to be anomaly-free, the lightest pNGB will be stable and thus a DM candidate!

Composite Dark Sectors

[AC, Chala, **JHEP 1506 (2015) 186**]



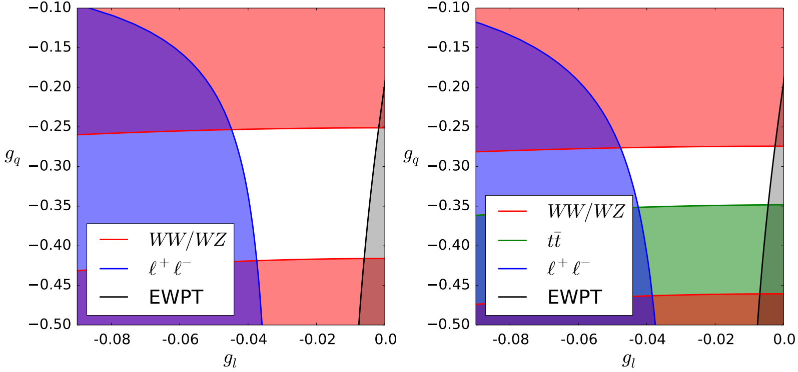
$[SU(2)^2 \times U(1)]/[SU(2) \times U(1)]$



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

Diboson resonant production

[AC, Delgado, Quirós, Santiago, **JHEP 1509 (2015) 186**]



$M = 1.9$ TeV, $g_V = 0.80$, $g_{q_3} = 0.3$, $g_{t_R} = 0.3, 0.5$

Future

I am thinking to see if I can say something interesting about

- Dark Matter and strong interactions
- Neutral Naturalness
- Relaxation
- Flavor ($h \to \mu\tau$, . . .)
- . . .

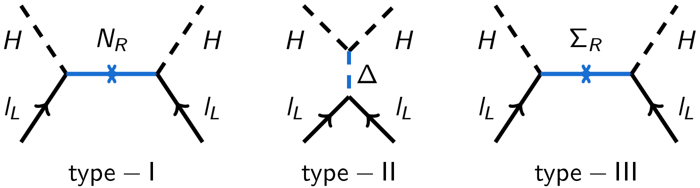
Thanks!

Back-up

Leptons can play a role

[AC, Goertz, **JHEP 1505 (2015) 002**]

The seesaw mechanism is a very economical way of producing very small neutrino masses. It also provide a rationale for leptogenesis

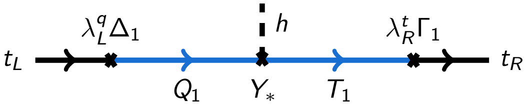


- They can also be implemented in CHM/GHU, with UV localized Majorana masses and IR localized Dirac ones
- The multiplet hosting N_R or Σ_R need to be out of the UV brane as otherwise $m_\nu \sim m_D^2/m_M$ would be far too small

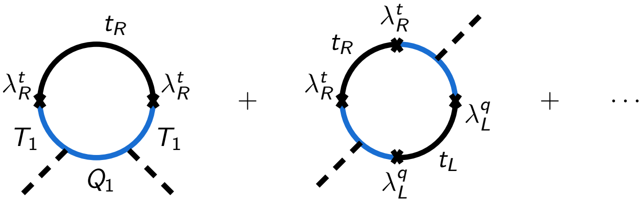
A radiative Higgs potential

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

- The linear mixings needed to generate the fermion masses



are also required to get a viable EWSB



Composite Dark Sectors

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

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

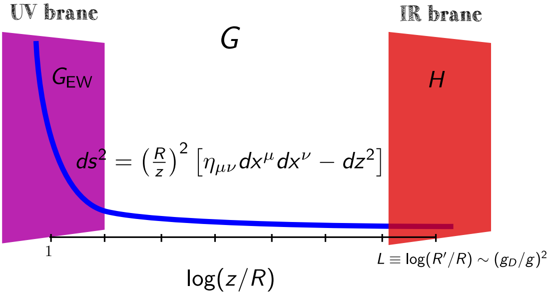
The potential

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

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

Holographic DM

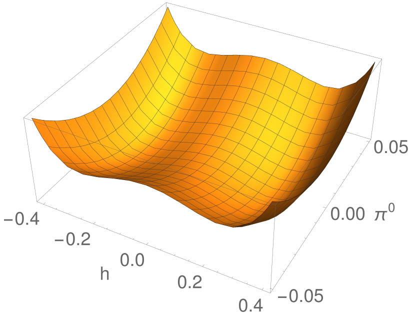
In order to estimate the strongly-coupled effects we work in a 5D holographic description



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

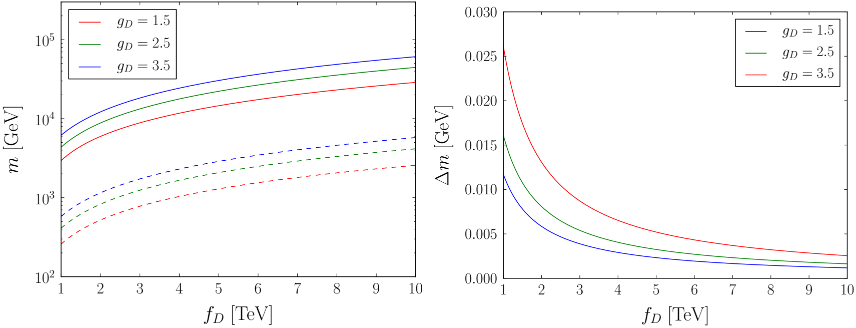
Scalar Potential

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

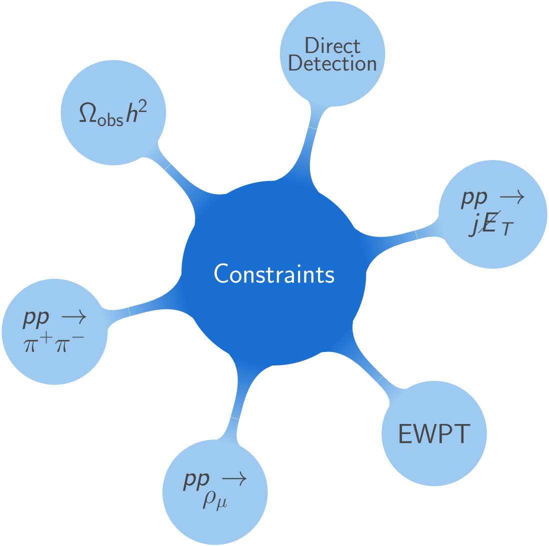


Masses

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

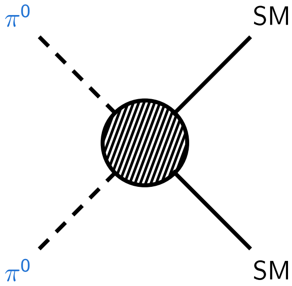


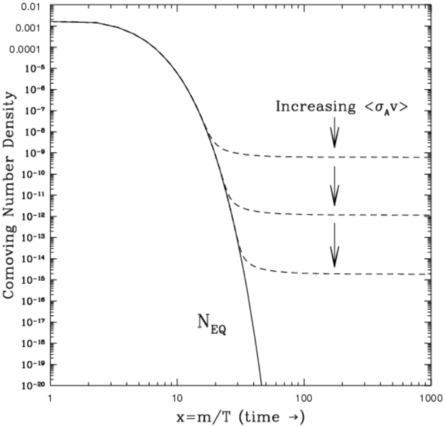
Constraints



Relic Abundance

Freeze-out mechanism





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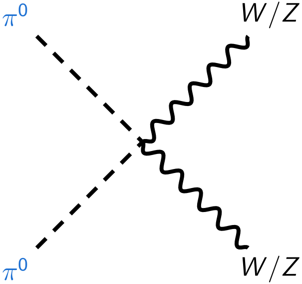
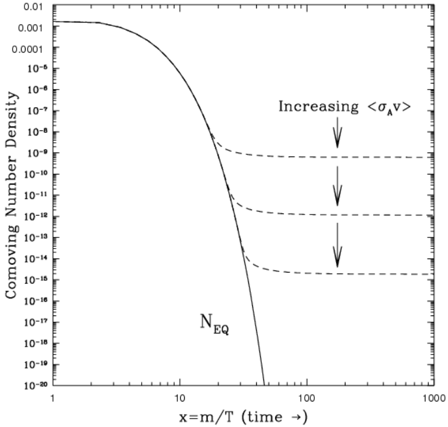
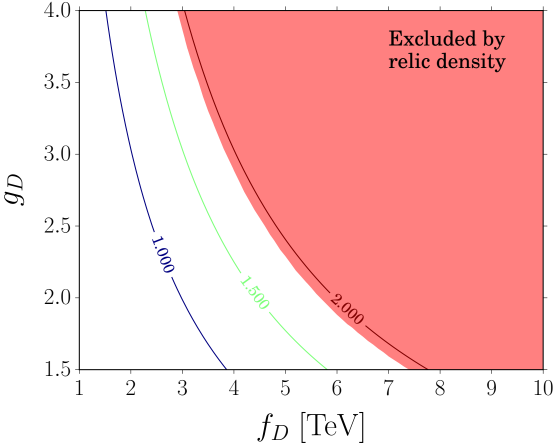


$$\sigma \sim \frac{g^4}{m_{\pi^0}^2}$$

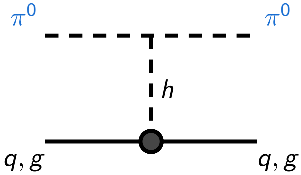


Relic Abundance

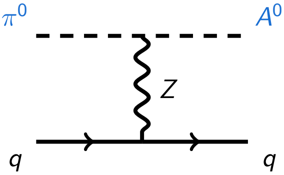
We consider a region in the $g_D - f_D$ plane, parametrized by $g_D \in [1.5, 4]$ and $f_D \in [1, 10]$ TeV



Direct Detection



Most important channel

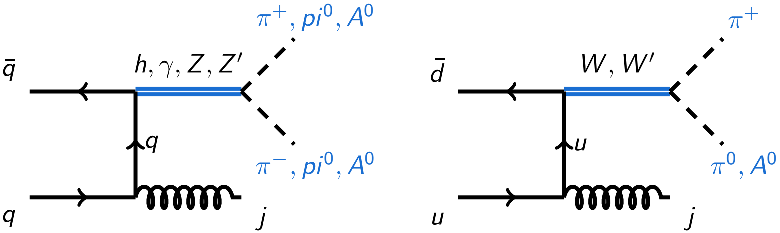


Negligible if $m_{A^0} - m_\pi^0 \gtrsim 0.1$ MeV

- 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

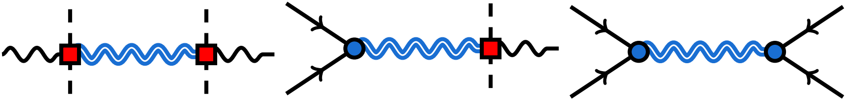
- `MadGraph v5` + `Pythia v6` + `MadAnalysis v5` + CMS analysis
- $\not{E}_T > 450$ GeV $\Rightarrow \sigma \times \epsilon \leq 7.8$ fb, upper bound stated by CMS [arXiv:1408.3583]

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,

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

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

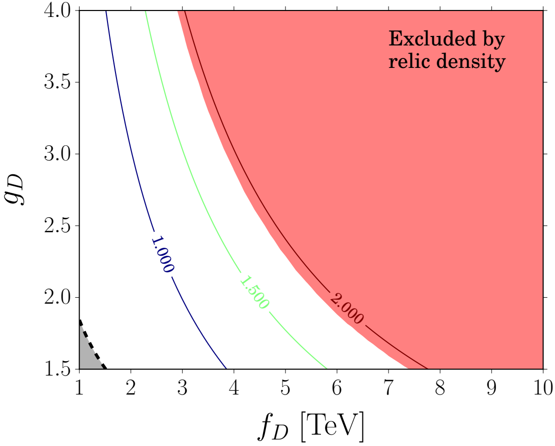
$$\hat{T} \sim [\hat{\alpha} - 2\hat{\beta} + \hat{\gamma}] = 0, \qquad \hat{S} \sim [-\hat{\beta} + \hat{\gamma}] = 0, \qquad W = Y \sim \hat{\gamma} \sim 1/L$$

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

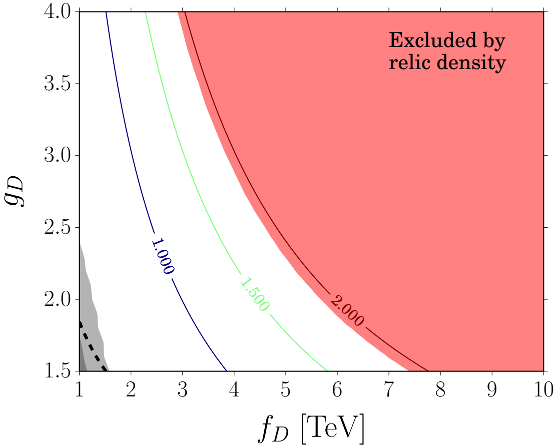
We have performed an up-to-date EW precision fit to $W = Y$



LHC constraints on new heavy resonances

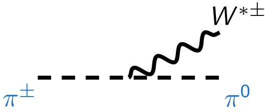
The new vector resonances G', Z', γ' and W' can mediate decays into

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

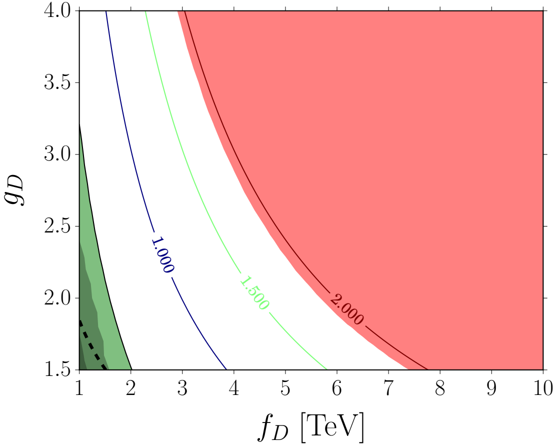


$$\Gamma \sim \frac{g^4 \alpha}{48\pi^3} \frac{\Delta m^5}{m_W^4}$$

- 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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- 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

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

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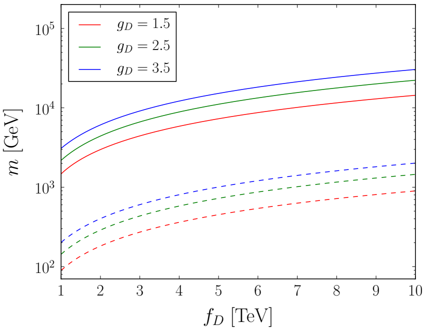
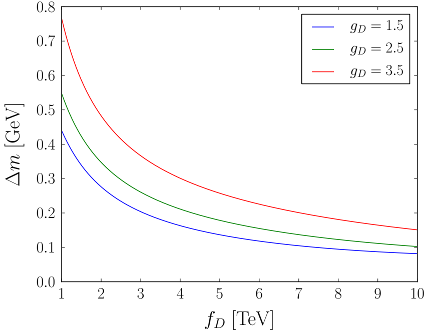
\end{aligned}
$$

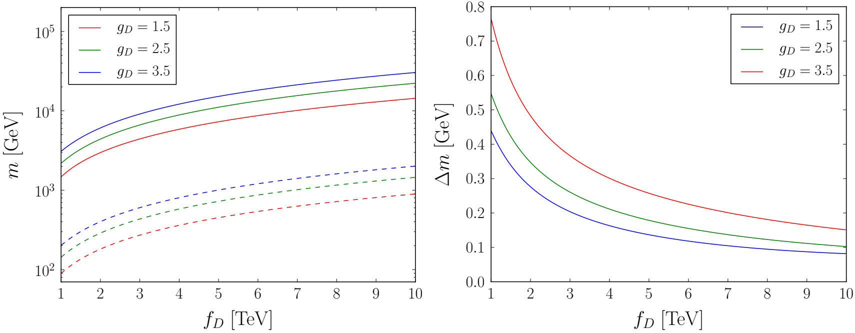
The mass splitting between the charged and the neutral pNGBs arises at order v^2/f_D^2

The doublet model



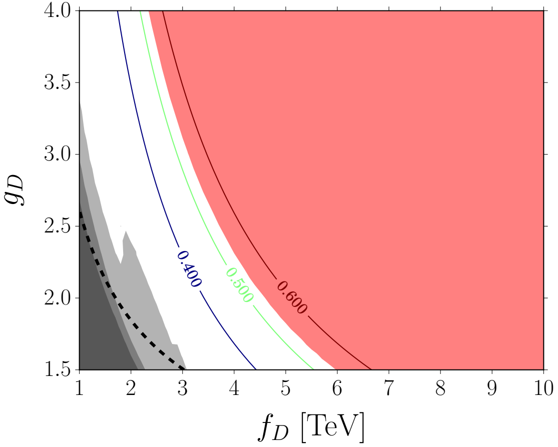


The doublet model



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

The doublet model



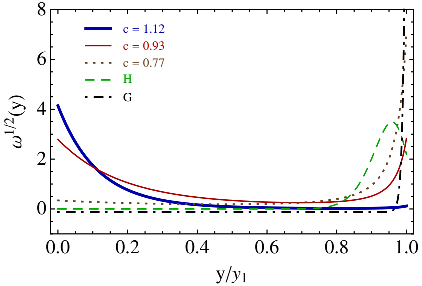
Diboson

Non-Custodial Warped Models

An interesting possibility is to modify the AdS_5 metric in the vicinity of the IR brane [Cabrer, Gersdorff, Quirós, '11]

$$ds^2 = e^{-2A(y)}\eta_{\mu\nu}dx^\mu dx^\nu - dy^2, \qquad A(y) = ky - \frac{1}{\nu}\log\left(1 - \frac{y}{y_s}\right),$$

modifying the profiles for the bulk Higgs and the different KK gauge bosons and fermions, leading to a reduction of ■ and ●



We obtain

- A large suppresion of $\hat{T} \propto$ (■)^2
- A milder reduction of $\hat{S} \propto$ ■ $\times$ ●

Simplified model

Instead of working with the full 5D model we consider a simplified model with $W_\mu^{(1)}$ and $B_\mu^{(1)}$ resonances, and relevant Lagrangian

$$\mathcal{L} = \mathcal{L}_{\text{SM}}^{(0)} + \mathcal{L}_{\text{Gauge}}^{(1)} + \mathcal{L}_{\text{Fermion}}^{(1)} + \mathcal{L}_{\text{Higgs}}^{(1)}$$

with

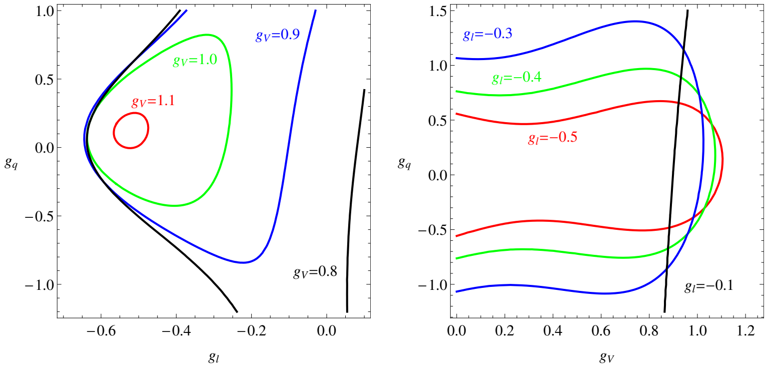
$$\begin{aligned}
\mathcal{L}_{\text{Gauge}}^{(1)} &= -\frac{1}{4} W_{\mu\nu}^{(1)i} W^{(1)i\mu\nu} - \frac{1}{4} B_{\mu\nu}^{(1)} B^{(1)\mu\nu} + \frac{1}{2} M^2 (W_\mu^{(1)i})^2 + \frac{1}{2} M^2 (B_\mu^{(1)})^2 \\
&\quad -g\varepsilon^{ijk} \partial_{[\mu} W_{\nu]}^{(1)i} W_\mu^{(1)j} W_\nu^{(0)k} - \frac{1}{2} g\varepsilon^{ijk} \partial_{[\mu} W_{\nu]}^{(0)i} W_\mu^{(1)j} W_\nu^{(1)k} \\
\mathcal{L}_{\text{Higgs}}^{(1)} &= \frac{g g_V}{2} W_\mu^{(1)i} \phi^\dagger \mathrm{i} \overset{\leftrightarrow}{D}^{i\,\mu} \phi + \frac{g' g_V}{2} B_\mu^{(1)} \phi^\dagger \mathrm{i} \overset{\leftrightarrow}{D}^{\mu} \phi \\
\mathcal{L}_{\text{Fermion}}^{(1)} &= \sum_{\psi_L} g g_{\psi_L} W_\mu^{(1)i} \bar{\psi}_L \gamma^\mu \frac{\sigma^i}{2} \psi_L + \sum_{\psi} g' g_\psi Y_\psi B_\mu^{(1)} \bar{\psi} \gamma^\mu \psi,
\end{aligned}$$

Simplified model

We take

$$g_\ell\,,\ g_q\,,\ g_{q_3}\,,\ g_{t_R}\,,$$

which leads to a 5-dimensional parameter space together with g_V.
For $M = 2$ TeV and $g_{q_3} = 0.5$

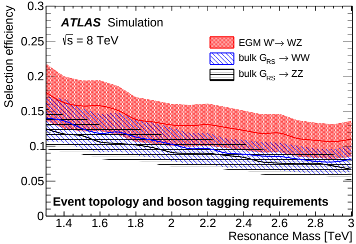


Not such a big cross section

To have a first estimate of the required xsec we compute

$$N_{\rm ev} = \mathcal{L}\times\varepsilon\times\sigma(pp\to V')\times BR(V'\to V_1V_2)\times BR(V_1\to jj)\times BR(V_2\to jj),$$

where $\mathcal{L} = 20.3$ fb^{-1} and $V_{1,2} = W/Z$. From [arXiv:1506.00962]



we conservatively estimate

$$\varepsilon \approx 0.14\times 0.7 \approx 0.1$$

where 0.7 is the fraction of events in the region around the V' mass

We obtain thus

$$\sigma(pp\to V')\times BR(V'\to V_1V_2)\approx N_{\rm ev}\ \text{fb}\approx 6-8\ \text{fb}$$