Scalar Dark matter: from minimal to composite scenarios

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in collaboration with N. Fonseca, R. Zukanovich Funchal & A. Lessa

Invisibles Workshop '15 - Madrid

Framework: both H & ξ PNGBs associated to $\mathcal{G} \to \mathcal{H}$

[Georgi '84+,Dungan'85,...,Kaplan'91,Agashe'04, ... Ryttov '08, Frigerio '12, Marzocca '14, Chala'13 see also talks]

In our analysis [Fonseca'15]:

- No a priori specification of the coset $\mathcal{G}/\mathcal{H}$ involved in $\mathcal{G} \to \mathcal{H}$ or of the fermion representations but effect parametrized.
- $SO(4) \supset \mathcal{H}$ & H is a $(\mathbf{2}, \mathbf{2})$ of $SO(4) \cong SU(2) \times SU(2)$
- Only states present in the low energy eff. theory: $H \& DM \equiv \xi$
- Minimal $\mathcal{L}$ considered:
  $\mathcal{L}_{SM} + \frac{a_{2H}}{F^2}\left(\partial_\mu |H|^2\right)^2 - \frac{\lambda_1 \lambda_{H6}}{F^2}|H|^6 - \frac{c_4}{F^2}|H|^2\left[\left(y_t \bar{Q}_L H^c t_R + y_b \bar{Q}_L H b_R\right) + \text{h.c.}\right]$

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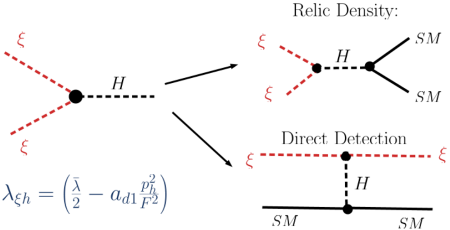
- Z_2 symmetry unbroken to guarantee DM stability
- ξ is $(\mathbf{1}, \mathbf{1}), (\mathbf{2}, \mathbf{2}), (\mathbf{n}, \mathbf{1}), \ldots$ of $SO(4) \cong SU(2) \times SU(2)$
- DM relic abundance through thermal freeze-out (WIMP-like DM)

Singlet DM case

Singlet DM: Generic case

$$\mathcal{L} \supset \frac{1}{2}\partial_\mu\xi\partial^\mu\xi - \frac{1}{2}\mu_\xi^2\xi^2 - \frac{\lambda_3}{2}\left(1+\frac{\lambda_3'}{F^2}|H|^2\right)\xi^2|H|^2$$
$$+\frac{a_{d1}}{F^2}\partial_\mu\xi^2\partial^\mu|H|^2$$
$$-\frac{1}{2}\left[\frac{d_4}{F^2}\xi^2\left(y_t\bar{Q}_L H^c t_R + y_b\bar{Q}_L H b_R\right)+\text{h.c.}\right]$$

effective DM-Higgs coupling



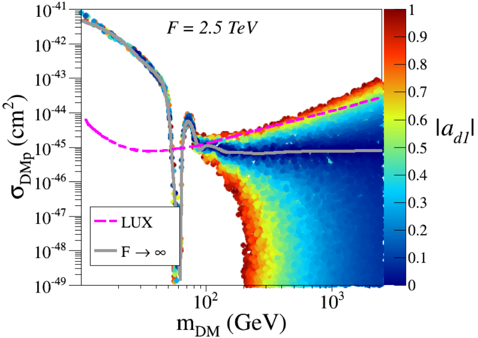
$\lambda_{\xi h} \simeq \left(\frac{\bar\lambda}{2} - 4a_{d1}\frac{m_{DM}^2}{F^2}\right)$

$\lambda_{\xi h} \simeq \frac{\bar\lambda}{2}$

$\lambda_{\xi h} = \left(\frac{\bar\lambda}{2} - a_{d1}\frac{p_h^2}{F^2}\right)$

with $\bar\lambda = \lambda_3(1+\lambda_3' v^2/F^2)$

Viable parameter space & constraints from DM searches



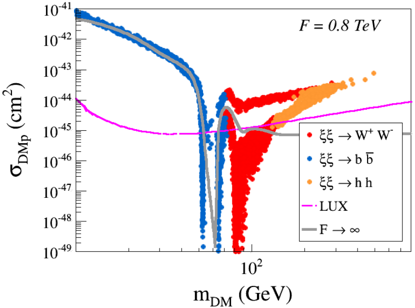
- Compared to minimal case with a_{d_1} σ_{DMp} can be enhanced (if a_{d_1} cancels $\bar{\lambda}$ for Ω_{DM}) or suppressed (if a_{d_1} & $\bar{\lambda}$ add up for Ω_{DM}). $\rightsquigarrow$ beyond the h-resonance the viability depends on a_{d1} which is fixed for a choice of $\mathcal{G}/\mathcal{H}$

- DM with $m_{DM} \gtrsim 100$ GeV could evade current and future data (depends on F) *while* the minimal singlet DM will be fully probed up to $m_{DM} = 7$ TeV by Xenon1T [Cline'12]

Viable parameter space & constraints from DM searches

Singlet DM see also [Frigerio '12, Marzocca '14]

$SO(6)/SO(5)$ with $a_{d_1} = 1/2$



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- DM with $m_{DM} \gtrsim 100$ GeV could evade current and future data (depends on F) *while* the minimal singlet DM will be fully probed up to $m_{DM} = 7$ TeV by Xenon1T [Cline'12]
- DM viable parameter space can be reduced for fixed choice of $\mathcal{G}/\mathcal{H}$ ($\equiv$ of a_{d1}) and F when derivative coupling is too large.

Higher dimensional representations

Models with DM charged under $SU(2)_L$ differs from singlet DM:

- they include (unsuppressed) DM-gauge boson couplings;
- they allow for co-annihilations between the DM multiplet components.

ξ doublet of SU(2)

is particular because same representation as the Higgs
$\rightsquigarrow$ largest number of couplings/operators to be considered

- $V(h,\xi) \supset$ 3 quartic coupl. :
  $-\lambda_3|\xi|^2|H|^2 - \lambda_4|\xi^\dagger H|^2 - \frac{\lambda_5}{2}\left[\left(\xi^\dagger H\right)^2 + \text{h.c.}\right]$
  + 3 correct. (λ_i') from dim 6 operators
  $\rightsquigarrow$ mass splittings between charged and neutrals components
  $\equiv$ minimal NC case = Inert Doublet Model
- 4 possible derivative interactions (a_{di})

together with Yukawa F^2-suppressed interactions

Consequences for Composite models:

- effective DM-H coupling: $\lambda_{\xi h} = \lambda_{\xi h}(\lambda_i, \lambda_i', a_{di})$
- modifications of the DM sector-W,Z direct coupling potentially modifying the picture for $m_{DM} > m_W$

Doublet: viable parameter space

Eventhough DM-W, Z are modified by new $\lambda_{\xi h}$ and a_{di}, still 2 separated viable regions: $m_{DM} < m_h$ and $m_{DM} > 500$ GeV.

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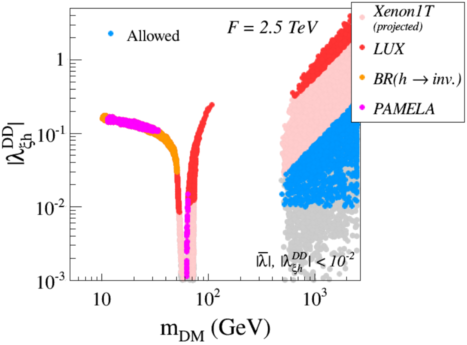

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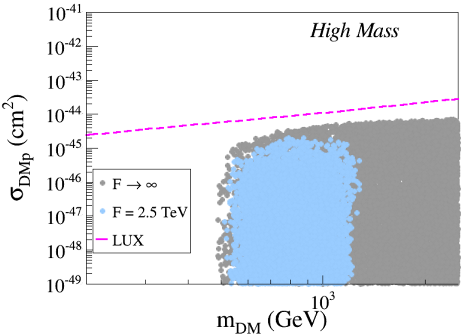
- For fixed $\mathcal{G}/\mathcal{H}$ (a_{di} fixed) $\rightsquigarrow$ reduced viable parameter space

large mass range

SO(6)/SO(4)× SO(2), $a_{d2} = 1$

$$\mathcal{L} \supset \frac{a_{d2}}{F^2} \left(H^\dagger D_\mu \xi + \text{h.c.}\right) \left(\xi^\dagger D^\mu H + \text{h.c.}\right)$$



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With higher dimensional representation we assume DM= real n-plet

- 2 new dim 6 Operators in $V(\xi, h)$
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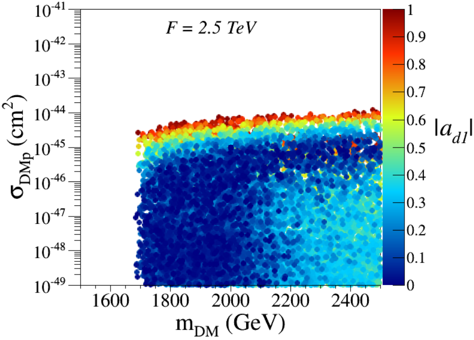
  BUT very constrained by data
- σ_{DMp} can again become larger/smaller than in NC cases
  $\rightsquigarrow$ possible to discriminate from NC case depending on a_{di} and $F > m_{DM}^{min}$

Triplet DM

$\mathcal{L} \supset \frac{a_{d1}}{2F^2} \partial_\mu |\xi|^2 \partial^\mu |H|^2$



Conclusion

- We have studied the composite DM & h phenomenology associated to PNGB from arising within global symmetry $\mathcal{G}$ spontaneously broken to $\mathcal{H}$ at scale F
- We work in $\mathcal{G}/\mathcal{H}$ model independent approach with generic $V(\xi, h)$ (dim 4 and 6 operators) and derivative interactions (dim 6 operators)
- Within this framework composite DM scenarios can typically:
  - evade constraints from present & future DM searches for masses lower than in the minimal (non-composite) scenarios due to cancellations between $V(\xi, h)$ couplings and derivative interactions.
  - get their viable parameter reduced to lower mass range when derivative interactions are too important.

Thank you for your attention !!!

Backup

What to expect compared to min. Higgs portal scenarios ?

Assumptions for DM $\equiv \xi$:

- Z_2 symmetry unbroken to guarantee DM stability
- ξ is $(\mathbf{1},\mathbf{1}), (\mathbf{2},\mathbf{2}), (\mathbf{n},\mathbf{1}), ...$ of $SO(4) \cong SU(2) \times SU(2)$
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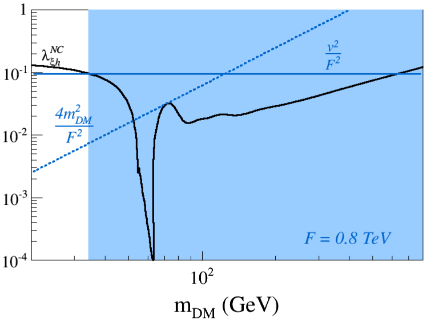
Singlet DM through H-portal



In the effective low energy theory from dimension 6 operators involving DM$\equiv \xi$ give:

- new derivative interactions: $1/F^2 \partial_\mu |\xi|^2 \partial_\mu |H|^2 \rightsquigarrow \frac{p^2}{F^2} \xi^2 \, vh$
- new "contact" interactions: $1/F^2 \xi^2 y_f \bar{F}_L H f_R \rightsquigarrow \frac{v^2}{F^2} \xi^2 \, \frac{y_f}{v} \bar{f} f$

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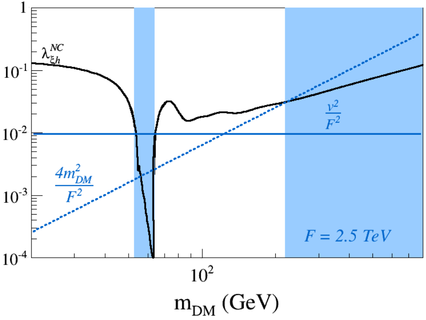

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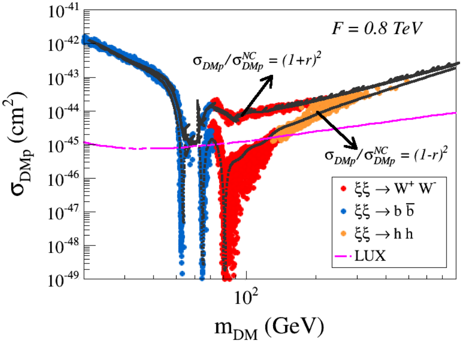
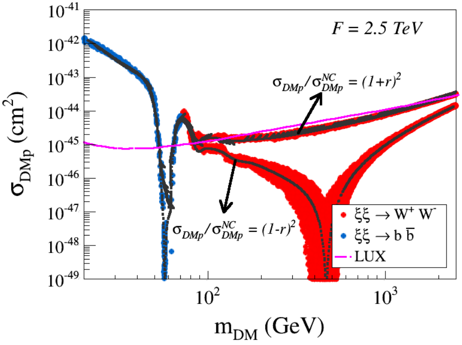
Example: singlet DM with $\mathcal{G}/\mathcal{H} = SO(6)/SO(5)$

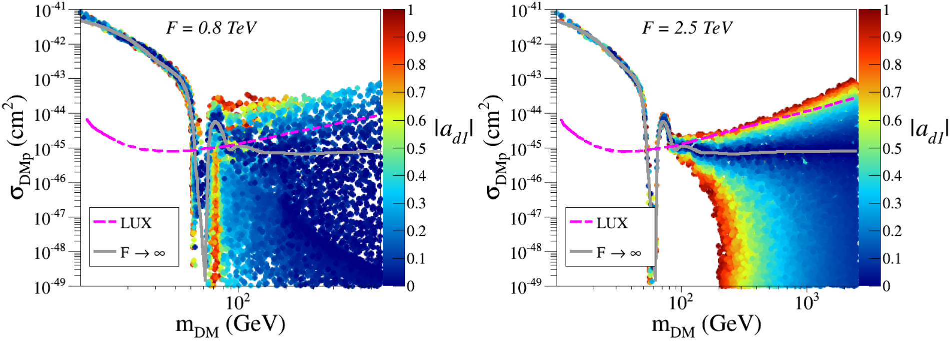




We recover $\mathcal{G}/\mathcal{H} = SO(6)/SO(5)$ i.e. $a_{d1} = 1/2$ [Frigerio '12, Marzocca '14]

- for small F we have no solutions for $m_{DM} > 500$ GeV due to derivative interactions
- the dependence $\sigma_{DMp}/\sigma^{NC}_{DMp} = (1 \pm r)^2$ is clearly visible

ξ Singlet DM



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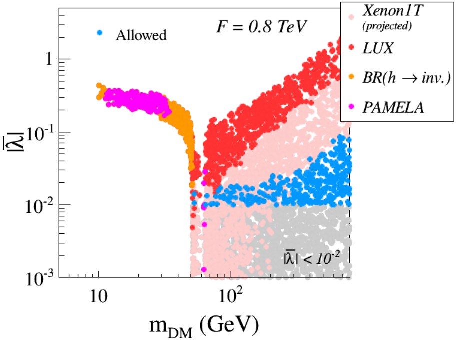
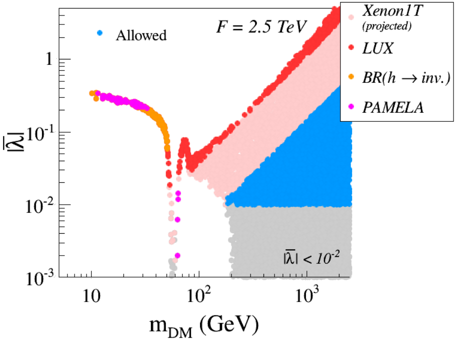


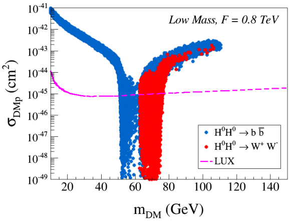


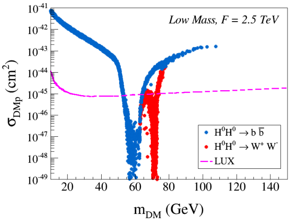
ξ doublet of SU(2)

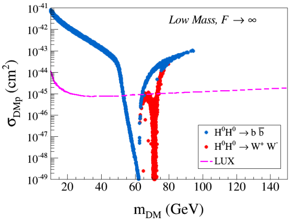
$$\mathcal{L} \supset (D_\mu \xi)^\dagger D^\mu \xi - \mu_\xi^2 |\xi|^2 - \lambda_3 \left(1 + \frac{\lambda_3'}{F^2}|H|^2\right) |\xi|^2 |H|^2 - \lambda_4 \left(1 + \frac{\lambda_4'}{F^2}|H|^2\right) |\xi^\dagger H|^2$$
$$- \frac{\lambda_5}{2} \left(1 + \frac{\lambda_5'}{F^2}|H|^2\right) \left[\left(\xi^\dagger H\right)^2 + \text{h.c.}\right]$$
$$+ \frac{a_{d1}}{2F^2} \partial_\mu |H|^2 \partial^\mu |\xi|^2 + \frac{a_{d2}}{F^2} \left(H^\dagger D_\mu \xi + \text{h.c.}\right) \left(\xi^\dagger D^\mu H + \text{h.c.}\right)$$
$$+ \frac{a_{d3}}{F^2} \left[\partial_\mu \left(\xi^\dagger H + \text{h.c.}\right)\right]^2$$
$$+ \frac{a_{d4}}{F^2} \left[\xi^\dagger \overleftrightarrow{D}_\mu \xi H^\dagger \overleftrightarrow{D}^\mu H + \xi^\dagger \overleftrightarrow{D}_\mu \xi^C H^{C\dagger} \overleftrightarrow{D}^\mu H - \xi^\dagger \vec{\sigma} \overleftrightarrow{D}_\mu \xi H^\dagger \vec{\sigma} \overleftrightarrow{D}^\mu H + \text{h.c.}\right]$$
$$- \left[\frac{d_4}{F^2} |\xi|^2 \left(y_t \bar{Q}_L H^c t_R + y_b \bar{Q}_L H b_R\right) + \text{h.c.}\right]$$
$$- \frac{d_6}{F^2} \left[\xi^\dagger \vec{\sigma} \xi \left(y_t \bar{Q}_L \vec{\sigma} H^c t_R - y_b \bar{Q}_L \vec{\sigma} H b_R\right) + y_b \xi^{c\dagger} \vec{\sigma} \xi \bar{Q}_L \vec{\sigma} H^c b_R + y_t \xi^\dagger \vec{\sigma} \xi^c \bar{Q}_L \vec{\sigma} H t_R + \text{h.c.}\right]$$

effective DM-H coupling: $\lambda_{\xi h} = \frac{\bar{\lambda}}{2} - (a_{d1} + 2a_{d2} + 4a_{d3}) \frac{p_h^2}{4F^2} + a_{d3} \frac{p_h^2 - 2m_{DM}^2}{F^2}$,

ξ doublet DM







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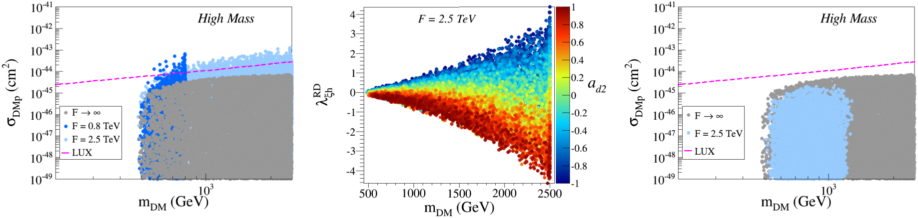

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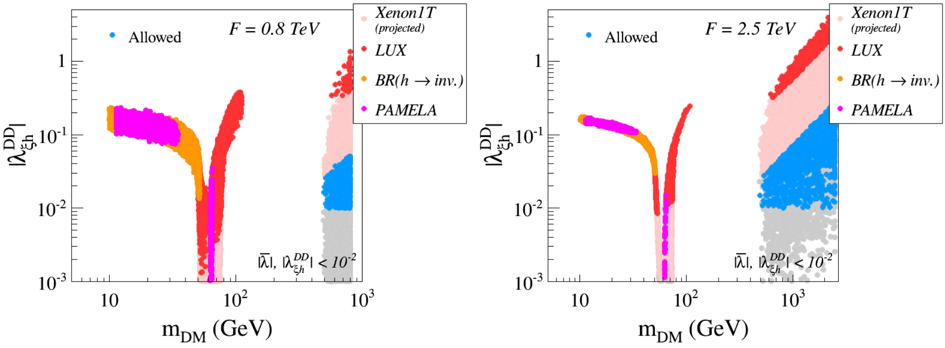

ξ triplet of SU(2)

$$
\begin{aligned}
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& - \frac{\lambda_4}{F^2} \xi^\dagger \left\{\Gamma^i, \Gamma^j\right\} \xi H^\dagger \sigma^i H H^\dagger \sigma^j H - \frac{\lambda_5}{F^2} \xi^\dagger \left\{\Gamma^i, \Gamma^j\right\} \xi H^{c\dagger} \sigma^i H H^\dagger \sigma^j H^c \\
& + \frac{a_{d1}}{2F^2} \partial_\mu |\xi|^2 \partial^\mu |H|^2 - \frac{a_{d4}}{F^2} \xi^\dagger \vec{\Gamma} \overleftrightarrow{D}^\mu \xi H^\dagger \vec{\sigma} \overleftrightarrow{D}_\mu H \\
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$$
m_{T\pm}^2 - m_{DM}^2 = \frac{v^4}{2F^2} \left(\lambda_4 - \lambda_5\right) .
$$

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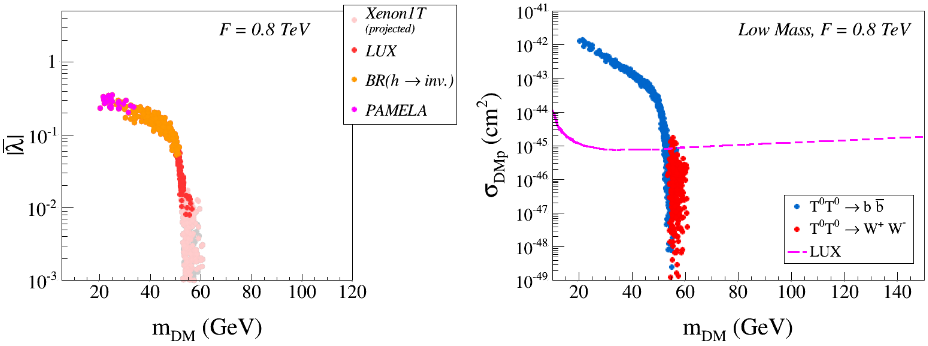

Doublet: viable parameter space

Eventhough DM-W, Z are modified by new $\lambda_{\xi h}$ and a_{di}, still 2 separated viable regions: $m_{DM} < m_h$ and $m_{DM} > 500$ GeV.

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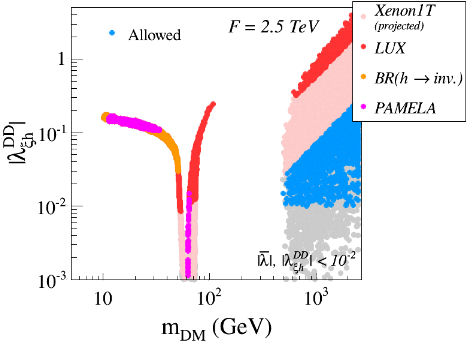

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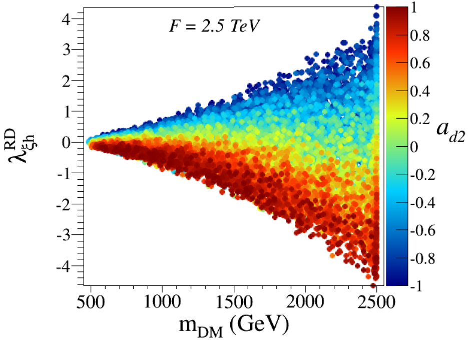

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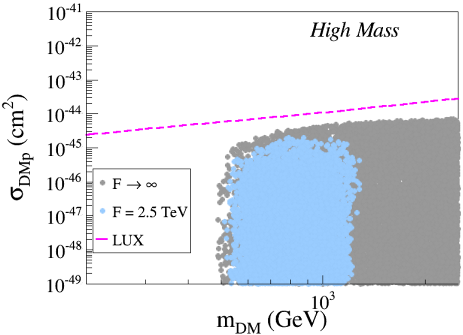
large mass range
SO(6)/SO(4)× SO(2), $a_{d2} = 1$



- Composite H scenarios: H are made of PNGB associated to $\mathcal{G} \to \mathcal{H}$ [Georgi '84+,Dungan'85,...,see also talks]
  $V(h)$ is generated at loop level due to explicit breaking by Yukawa and gauge interactions (within partial compositness [Kaplan'91,Agashe'04]).
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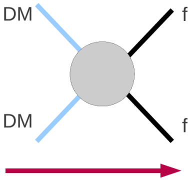
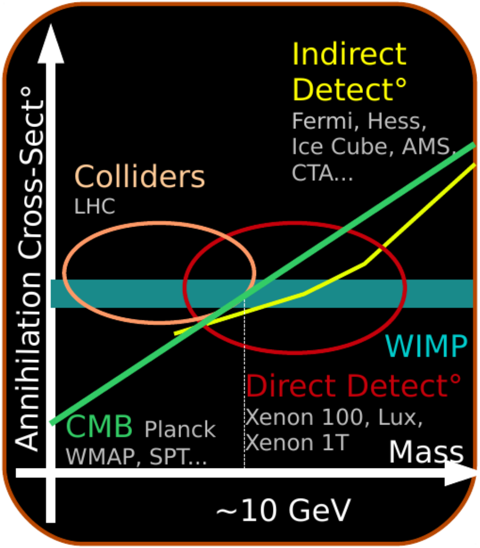
- Composite H scenarios: H are made of PNGB associated to $\mathcal{G} \to \mathcal{H}$ [Georgi '84+,Dungan'85,...,see also talks]
  $V(h)$ is generated at loop level due to explicit breaking by Yukawa and gauge interactions (within partial compositness [Kaplan'91,Agashe'04]).
- Could DM be composite made of PNGB associated to $\mathcal{G} \to \mathcal{H}$?
  $\rightsquigarrow$ Yes see also [Ryttov '08, Frigerio '12, Marzocca '14, Chala'13]

- No a priori specification of the coset $\mathcal{G}/\mathcal{H}$ involved in $\mathcal{G} \to \mathcal{H}$ or of the fermion representations but effect parametrized.
- $SO(4) \supset \mathcal{H}$ & H is a $(\mathbf{2}, \mathbf{2})$ of $SO(4) \cong SU(2) \times SU(2)$
- Only states present in the low energy eff. theory: $H\&DM \equiv \xi$
- Minimal $\mathcal{L}$ considered:
  $\mathcal{L}_{SM} + \frac{a_{2H}}{F^2}\left(\partial_\mu |H|^2\right)^2 - \frac{\lambda_1 \lambda_{H6}}{F^2}|H|^6 - \frac{c_4}{F^2}|H|^2\left[\left(y_t \bar{Q}_L H^c t_R + y_b \bar{Q}_L H b_R\right) + \text{h.c.}\right]$
- Z_2 symmetry unbroken to guarantee DM stability
- ξ is $(\mathbf{1}, \mathbf{1}), (\mathbf{2}, \mathbf{2}), (\mathbf{n}, \mathbf{1}), \ldots$ of $SO(4) \cong SU(2) \times SU(2)$
- DM relic abundance through thermal freeze-out (WIMP-like DM)

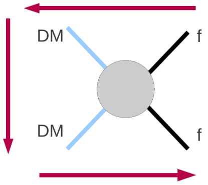
Focus on WIMP



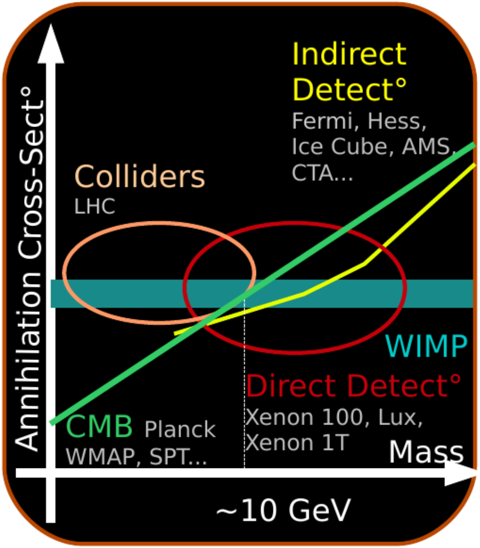
In the framework of Composite scenarios including both DM and Higgs made of PNGB



Focus on WIMP



In the framework of Composite scenarios including both DM and Higgs made of PNGB



title

This is really the end