Overview of composite Higgs models

Mikael Chala
(University of Granada)

based mostly on *1806.02836, 1812.01901, 2203.14984*

and ongoing work with Renato Fonseca

Disclaimer

One of the most important implications of CHMs is the presence of heavy quarks, which I will not discuss

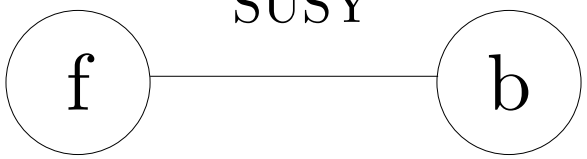
Very few studies about CHMs at e+e- colliders

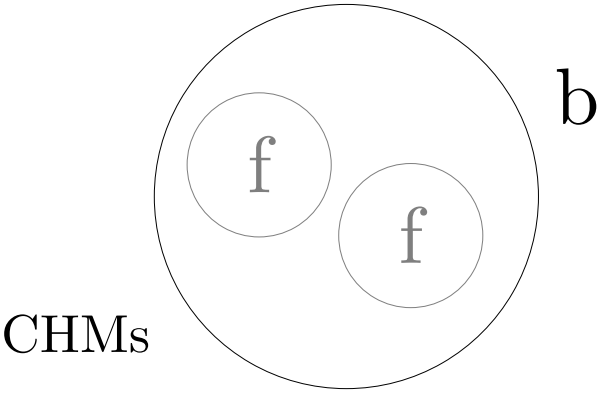
Though not only, I will discuss mostly my own work

Motivation for CHMs

If we accept that fine-tuning is a problem (not generally accepted [Manohar '18]), then it requires a solution

CHMs relate unprotected fields (scalars) to protected ones (fermions) through compositeness





Two-flavour QCD

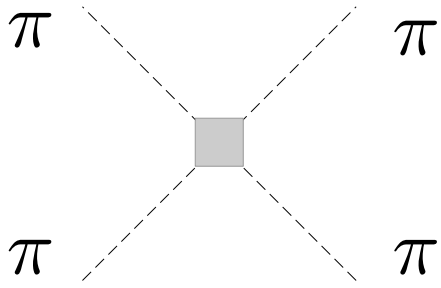
$$L_{\mathrm{QCD}} = \overline{q} i D q + \cdots \qquad SU(2)_L \times SU(2)_R$$

$$\downarrow$$

$$\langle \overline{q_L} q_R + \mathrm{h.c.} \rangle \neq 0 \qquad\qquad SU(2)_{L+R}$$

Three NGBs (pions), much lighter than the characteristic scale f of about GeV

$$L_{\mathrm{pions}} = \frac{1}{f^2} \partial\pi^2 \partial\pi^2 + \cdots$$



CHMs

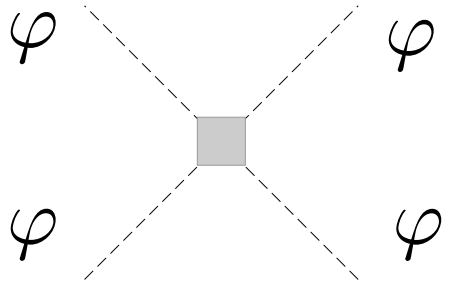
unknown Lagrangian $\quad G$

$\downarrow$

$\langle \text{vacuum} \rangle \neq 0 \quad H$

At least four NGBs (Higgs), much ligther than the characteristic scale f of TeV

$$L_{\text{NGBs}} = \frac{1}{f^2} \partial\varphi^2 \partial\varphi^2 + \cdots$$



Conditions over $G \to H$

1. Custotial symmetry SU(2)×SU(2) in H

2. Higgs is a (2, 2) of SU(2)×SU(2)

3. There are no fractional electric charges

minimal case:

$$SO(5) \to SO(4)$$

$$\mathbf{4} = (\mathbf{2}, \mathbf{2}) = \mathbf{2}_{\frac{1}{2}} + \mathbf{2}_{-\frac{1}{2}} = (\varphi^+, \varphi^0)$$

Agashe, Contino, Pomarol ‘05

Important results

1. Any scalar sector can ensue from a CHM (actually of the form SO(n+1) $\rightarrow$ SO(n))

2. The symmetry of the scalar sector can not be arbitrary

3. For a given number of NGBs, there is a finite number of CHMs (the "landscape")

MC, Fonseca 'ongoing

Landscape of CHMs with at most eight NGBs

$(\mathbf{2},\mathbf{2})$

{SO5}	{SU2, SU2}	{{**2**⊗**2**, 1}}
{SU4}	{SO5}	{{**1**⊗**1**, 1}, {**2**⊗**2**, 1}}
{SU4}	{SU2, SU2, U1}	{{**1**⊗**1**, 0}, {**2**⊗**2**, 2}}
{SO7}	{G2}	{{**2**⊗**2**, 1}, {**3**⊗**1**, 1}}
{SO7}	{SU4}	{{**1**⊗**1**, 2}, {**2**⊗**2**, 1}}
{SP6}	{SU2, SO5}	{{**2**⊗**2**, 2}}
{SP6}	{SU2, SO5}	{{**1**⊗**1**, 1}, {**2**⊗**2**, 1}, {**3**⊗**1**, 1}}
{SU2, SO5}	{SU2, SU2, U1}	{{**1**⊗**1**, 2}, {**2**⊗**2**, 1}}
{SU2, SO5}	{SU2, SU2}	{{**2**⊗**2**, 1}, {**3**⊗**1**, 1}}
{SU5}	{SU4, U1}	{{**1**⊗**1**, 0}, {**2**⊗**2**, 2}}
{SO8}	{SO7}	{{**2**⊗**2**, 1}, {**3**⊗**1**, 1}}
{SO8}	{SO7}	{{**1**⊗**1**, 3}, {**2**⊗**2**, 1}}
{SO9}	{SO8}	{{**2**⊗**2**, 2}}
{SO9}	{SO8}	{{**1**⊗**1**, 4}, {**2**⊗**2**, 1}}
{SO9}	{SO8}	{{**1**⊗**1**, 1}, {**2**⊗**2**, 1}, {**3**⊗**1**, 1}}
{SU2, SU4}	{SO5, U1}	{{**1**⊗**1**, 3}, {**2**⊗**2**, 1}}
{SU2, SO7}	{SU4, U1}	{{**1**⊗**1**, 4}, {**2**⊗**2**, 1}}
{SO5, SO5}	{SU2, SU2, SU2, SU2}	{{**1**⊗**1**, 4}, {**2**⊗**2**, 1}}
{SO5, SO5}	{SU2, SU2, SU2, SU2}	{{**1**⊗**1**, 1}, {**2**⊗**2**, 1}, {**3**⊗**1**, 1}}
{SU2, SU2, SO5}	{SU2, SU2, U1, U1}	{{**1**⊗**1**, 4}, {**2**⊗**2**, 1}}
{SU2, SU2, SO5}	{SU2, SU2, SU2}	{{**1**⊗**1**, 3}, {**2**⊗**2**, 1}}
{SU2, SU2, SO5}	{SU2, SU2, SU2}	{{**2**⊗**2**, 1}, {**3**⊗**1**, 1}}
{SU2, SU2, SU4}	{SU2, SO5}	{{**1**⊗**1**, 4}, {**2**⊗**2**, 1}}
{SU2, SU2, SU4}	{SU2, SO5}	{{**1**⊗**1**, 1}, {**2**⊗**2**, 1}, {**3**⊗**1**, 1}}

MC, Fonseca ‘ongoing

Landscape of CHMs with at most eight NGBs

$(\mathbf{2},\mathbf{2})+(1,1)$

{SO5}	{SU2, SU2}	{{**2**⊗**2**, 1}}
{SU4}	{SO5}	{{**1**⊗**1**, 1}, {**2**⊗**2**, 1}}
{SU4}	{SU2, SU2, U1}	{{**1**⊗**1**, 0}, {**2**⊗**2**, 2}}
{SO7}	{G2}	{{**2**⊗**2**, 1}, {**3**⊗**1**, 1}}
{SO7}	{SU4}	{{**1**⊗**1**, 2}, {**2**⊗**2**, 1}}
{SP6}	{SU2, SO5}	{{**2**⊗**2**, 2}}
{SP6}	{SU2, SO5}	{{**1**⊗**1**, 1}, {**2**⊗**2**, 1}, {**3**⊗**1**, 1}}
{SU2, SO5}	{SU2, SU2, U1}	{{**1**⊗**1**, 2}, {**2**⊗**2**, 1}}
{SU2, SO5}	{SU2, SU2}	{{**2**⊗**2**, 1}, {**3**⊗**1**, 1}}
{SU5}	{SU4, U1}	{{**1**⊗**1**, 0}, {**2**⊗**2**, 2}}
{SO8}	{SO7}	{{**2**⊗**2**, 1}, {**3**⊗**1**, 1}}
{SO8}	{SO7}	{{**1**⊗**1**, 3}, {**2**⊗**2**, 1}}
{SO9}	{SO8}	{{**2**⊗**2**, 2}}
{SO9}	{SO8}	{{**1**⊗**1**, 4}, {**2**⊗**2**, 1}}
{SO9}	{SO8}	{{**1**⊗**1**, 1}, {**2**⊗**2**, 1}, {**3**⊗**1**, 1}}
{SU2, SU4}	{SO5, U1}	{{**1**⊗**1**, 3}, {**2**⊗**2**, 1}}
{SU2, SO7}	{SU4, U1}	{{**1**⊗**1**, 4}, {**2**⊗**2**, 1}}
{SO5, SO5}	{SU2, SU2, SU2, SU2}	{{**1**⊗**1**, 4}, {**2**⊗**2**, 1}}
{SO5, SO5}	{SU2, SU2, SU2, SU2}	{{**1**⊗**1**, 1}, {**2**⊗**2**, 1}, {**3**⊗**1**, 1}}
{SU2, SU2, SO5}	{SU2, SU2, U1, U1}	{{**1**⊗**1**, 4}, {**2**⊗**2**, 1}}
{SU2, SU2, SO5}	{SU2, SU2, SU2}	{{**1**⊗**1**, 3}, {**2**⊗**2**, 1}}
{SU2, SU2, SO5}	{SU2, SU2, SU2}	{{**2**⊗**2**, 1}, {**3**⊗**1**, 1}}
{SU2, SU2, SU4}	{SU2, SO5}	{{**1**⊗**1**, 4}, {**2**⊗**2**, 1}}
{SU2, SU2, SU4}	{SU2, SO5}	{{**1**⊗**1**, 1}, {**2**⊗**2**, 1}, {**3**⊗**1**, 1}}

Landscape of CHMs with at most eight NGBs

$(\mathbf{2},\mathbf{2})+(1,\mathbf{3})$

{SO5}	{SU2, SU2}	{{**2**⊗**2**, 1}}
{SU4}	{SO5}	{{**1**⊗**1**, 1}, {**2**⊗**2**, 1}}
{SU4}	{SU2, SU2, U1}	{{**1**⊗**1**, 0}, {**2**⊗**2**, 2}}
{SO7}	{G2}	{{**2**⊗**2**, 1}, {**3**⊗**1**, 1}}
{SO7}	{SU4}	{{**1**⊗**1**, 2}, {**2**⊗**2**, 1}}
{SP6}	{SU2, SO5}	{{**2**⊗**2**, 2}}
{SP6}	{SU2, SO5}	{{**1**⊗**1**, 1}, {**2**⊗**2**, 1}, {**3**⊗**1**, 1}}
{SU2, SO5}	{SU2, SU2, U1}	{{**1**⊗**1**, 2}, {**2**⊗**2**, 1}}
{SU2, SO5}	{SU2, SU2}	{{**2**⊗**2**, 1}, {**3**⊗**1**, 1}}
{SU5}	{SU4, U1}	{{**1**⊗**1**, 0}, {**2**⊗**2**, 2}}
{SO8}	{SO7}	{{**2**⊗**2**, 1}, {**3**⊗**1**, 1}}
{SO8}	{SO7}	{{**1**⊗**1**, 3}, {**2**⊗**2**, 1}}
{SO9}	{SO8}	{{**2**⊗**2**, 2}}
{SO9}	{SO8}	{{**1**⊗**1**, 4}, {**2**⊗**2**, 1}}
{SO9}	{SO8}	{{**1**⊗**1**, 1}, {**2**⊗**2**, 1}, {**3**⊗**1**, 1}}
{SU2, SU4}	{SO5, U1}	{{**1**⊗**1**, 3}, {**2**⊗**2**, 1}}
{SU2, SO7}	{SU4, U1}	{{**1**⊗**1**, 4}, {**2**⊗**2**, 1}}
{SO5, SO5}	{SU2, SU2, SU2, SU2}	{{**1**⊗**1**, 4}, {**2**⊗**2**, 1}}
{SO5, SO5}	{SU2, SU2, SU2, SU2}	{{**1**⊗**1**, 1}, {**2**⊗**2**, 1}, {**3**⊗**1**, 1}}
{SU2, SU2, SO5}	{SU2, SU2, U1, U1}	{{**1**⊗**1**, 4}, {**2**⊗**2**, 1}}
{SU2, SU2, SO5}	{SU2, SU2, SU2}	{{**1**⊗**1**, 3}, {**2**⊗**2**, 1}}
{SU2, SU2, SO5}	{SU2, SU2, SU2}	{{**2**⊗**2**, 1}, {**3**⊗**1**, 1}}
{SU2, SU2, SU4}	{SU2, SO5}	{{**1**⊗**1**, 4}, {**2**⊗**2**, 1}}
{SU2, SU2, SU4}	{SU2, SO5}	{{**1**⊗**1**, 1}, {**2**⊗**2**, 1}, {**3**⊗**1**, 1}}

Landscape of CHMs with at most eight NGBs

$2 \times (\mathbf{2}, \mathbf{2})$

{SO5}	{SU2, SU2}	{{**2**⊗**2**, 1}}
{SU4}	{SO5}	{{**1**⊗**1**, 1}, {**2**⊗**2**, 1}}
{SU4}	{SU2, SU2, U1}	{{**1**⊗**1**, 0}, {**2**⊗**2**, 2}}
{SO7}	{G2}	{{**2**⊗**2**, 1}, {**3**⊗**1**, 1}}
{SO7}	{SU4}	{{**1**⊗**1**, 2}, {**2**⊗**2**, 1}}
{SP6}	{SU2, SO5}	{{**2**⊗**2**, 2}}
{SP6}	{SU2, SO5}	{{**1**⊗**1**, 1}, {**2**⊗**2**, 1}, {**3**⊗**1**, 1}}
{SU2, SO5}	{SU2, SU2, U1}	{{**1**⊗**1**, 2}, {**2**⊗**2**, 1}}
{SU2, SO5}	{SU2, SU2}	{{**2**⊗**2**, 1}, {**3**⊗**1**, 1}}
{SU5}	{SU4, U1}	{{**1**⊗**1**, 0}, {**2**⊗**2**, 2}}
{SO8}	{SO7}	{{**2**⊗**2**, 1}, {**3**⊗**1**, 1}}
{SO8}	{SO7}	{{**1**⊗**1**, 3}, {**2**⊗**2**, 1}}
{SO9}	{SO8}	{{**2**⊗**2**, 2}}
{SO9}	{SO8}	{{**1**⊗**1**, 4}, {**2**⊗**2**, 1}}
{SO9}	{SO8}	{{**1**⊗**1**, 1}, {**2**⊗**2**, 1}, {**3**⊗**1**, 1}}
{SU2, SU4}	{SO5, U1}	{{**1**⊗**1**, 3}, {**2**⊗**2**, 1}}
{SU2, SO7}	{SU4, U1}	{{**1**⊗**1**, 4}, {**2**⊗**2**, 1}}
{SO5, SO5}	{SU2, SU2, SU2, SU2}	{{**1**⊗**1**, 4}, {**2**⊗**2**, 1}}
{SO5, SO5}	{SU2, SU2, SU2, SU2}	{{**1**⊗**1**, 1}, {**2**⊗**2**, 1}, {**3**⊗**1**, 1}}
{SU2, SU2, SO5}	{SU2, SU2, U1, U1}	{{**1**⊗**1**, 4}, {**2**⊗**2**, 1}}
{SU2, SU2, SO5}	{SU2, SU2, SU2}	{{**1**⊗**1**, 3}, {**2**⊗**2**, 1}}
{SU2, SU2, SO5}	{SU2, SU2, SU2}	{{**2**⊗**2**, 1}, {**3**⊗**1**, 1}}
{SU2, SU2, SU4}	{SU2, SO5}	{{**1**⊗**1**, 4}, {**2**⊗**2**, 1}}
{SU2, SU2, SU4}	{SU2, SO5}	{{**1**⊗**1**, 1}, {**2**⊗**2**, 1}, {**3**⊗**1**, 1}}

Landscape of CHMs with at most eight NGBs

$(\mathbf{2},\mathbf{2}) + 2 \times (1,1)$

{SO5}	{SU2, SU2}	{{**2**⊗**2**, 1}}
{SU4}	{SO5}	{{**1**⊗**1**, 1}, {**2**⊗**2**, 1}}
{SU4}	{SU2, SU2, U1}	{{**1**⊗**1**, 0}, {**2**⊗**2**, 2}}
{SO7}	{G2}	{{**2**⊗**2**, 1}, {**3**⊗**1**, 1}}
{SO7}	{SU4}	{{**1**⊗**1**, 2}, {**2**⊗**2**, 1}}
{SP6}	{SU2, SO5}	{{**2**⊗**2**, 2}}
{SP6}	{SU2, SO5}	{{**1**⊗**1**, 1}, {**2**⊗**2**, 1}, {**3**⊗**1**, 1}}
{SU2, SO5}	{SU2, SU2, U1}	{{**1**⊗**1**, 2}, {**2**⊗**2**, 1}}
{SU2, SO5}	{SU2, SU2}	{{**2**⊗**2**, 1}, {**3**⊗**1**, 1}}
{SU5}	{SU4, U1}	{{**1**⊗**1**, 0}, {**2**⊗**2**, 2}}
{SO8}	{SO7}	{{**2**⊗**2**, 1}, {**3**⊗**1**, 1}}
{SO8}	{SO7}	{{**1**⊗**1**, 3}, {**2**⊗**2**, 1}}
{SO9}	{SO8}	{{**2**⊗**2**, 2}}
{SO9}	{SO8}	{{**1**⊗**1**, 4}, {**2**⊗**2**, 1}}
{SO9}	{SO8}	{{**1**⊗**1**, 1}, {**2**⊗**2**, 1}, {**3**⊗**1**, 1}}
{SU2, SU4}	{SO5, U1}	{{**1**⊗**1**, 3}, {**2**⊗**2**, 1}}
{SU2, SO7}	{SU4, U1}	{{**1**⊗**1**, 4}, {**2**⊗**2**, 1}}
{SO5, SO5}	{SU2, SU2, SU2, SU2}	{{**1**⊗**1**, 4}, {**2**⊗**2**, 1}}
{SO5, SO5}	{SU2, SU2, SU2, SU2}	{{**1**⊗**1**, 1}, {**2**⊗**2**, 1}, {**3**⊗**1**, 1}}
{SU2, SU2, SO5}	{SU2, SU2, U1, U1}	{{**1**⊗**1**, 4}, {**2**⊗**2**, 1}}
{SU2, SU2, SO5}	{SU2, SU2, SU2}	{{**1**⊗**1**, 3}, {**2**⊗**2**, 1}}
{SU2, SU2, SO5}	{SU2, SU2, SU2}	{{**2**⊗**2**, 1}, {**3**⊗**1**, 1}}
{SU2, SU2, SU4}	{SU2, SO5}	{{**1**⊗**1**, 4}, {**2**⊗**2**, 1}}
{SU2, SU2, SU4}	{SU2, SO5}	{{**1**⊗**1**, 1}, {**2**⊗**2**, 1}, {**3**⊗**1**, 1}}

Landscape of CHMs with at most eight NGBs

$$(\mathbf{2},\mathbf{2}) + (1,1) + (\mathbf{3},1)$$

{SO5}	{SU2, SU2}	{{**2**⊗**2**, 1}}
{SU4}	{SO5}	{{**1**⊗**1**, 1}, {**2**⊗**2**, 1}}
{SU4}	{SU2, SU2, U1}	{{**1**⊗**1**, 0}, {**2**⊗**2**, 2}}
{G2}	{G2}	{{**2**⊗**2**, 1}, {**3**⊗**1**, 1}}
{SU4}	{SU4}	{{**1**⊗**1**, 2}, {**2**⊗**2**, 1}}
{SP6}	{SU2, SO5}	{{**2**⊗**2**, 2}}
{SP6}	{SU2, SO5}	{{**1**⊗**1**, 1}, {**2**⊗**2**, 1}, {**3**⊗**1**, 1}}
{SU2, SO5}	{SU2, SU2, U1}	{{**1**⊗**1**, 2}, {**2**⊗**2**, 1}}
{SU2, SO5}	{SU2, SU2}	{{**2**⊗**2**, 1}, {**3**⊗**1**, 1}}
{SU5}	{SU4, U1}	{{**1**⊗**1**, 0}, {**2**⊗**2**, 2}}
{SO8}	{SO7}	{{**2**⊗**2**, 1}, {**3**⊗**1**, 1}}
{SO8}	{SO7}	{{**1**⊗**1**, 3}, {**2**⊗**2**, 1}}
{SO9}	{SO8}	{{**2**⊗**2**, 2}}
{SO9}	{SO8}	{{**1**⊗**1**, 4}, {**2**⊗**2**, 1}}
{SO9}	{SO8}	{{**1**⊗**1**, 1}, {**2**⊗**2**, 1}, {**3**⊗**1**, 1}}
{SU2, SU4}	{SO5, U1}	{{**1**⊗**1**, 3}, {**2**⊗**2**, 1}}
{SU2, SO7}	{SU4, U1}	{{**1**⊗**1**, 4}, {**2**⊗**2**, 1}}
{SO5, SO5}	{SU2, SU2, SU2, SU2}	{{**1**⊗**1**, 4}, {**2**⊗**2**, 1}}
{SO5, SO5}	{SU2, SU2, SU2, SU2}	{{**1**⊗**1**, 1}, {**2**⊗**2**, 1}, {**3**⊗**1**, 1}}
{SU2, SU2, SO5}	{SU2, SU2, U1, U1}	{{**1**⊗**1**, 4}, {**2**⊗**2**, 1}}
{SU2, SU2, SO5}	{SU2, SU2, SU2}	{{**1**⊗**1**, 3}, {**2**⊗**2**, 1}}
{SU2, SU2, SO5}	{SU2, SU2, SU2}	{{**2**⊗**2**, 1}, {**3**⊗**1**, 1}}
{SU2, SU2, SU4}	{SU2, SO5}	{{**1**⊗**1**, 4}, {**2**⊗**2**, 1}}
{SU2, SU2, SU4}	{SU2, SO5}	{{**1**⊗**1**, 1}, {**2**⊗**2**, 1}, {**3**⊗**1**, 1}}

Landscape of CHMs with at most eight NGBs

$(\mathbf{2},\mathbf{2}) + 3 \times (1,1)$

{SO5}	{SU2, SU2}	{{**2**⊗**2**, 1}}
{SU4}	{SO5}	{{**1**⊗**1**, 1}, {**2**⊗**2**, 1}}
{SU4}	{SU2, SU2, U1}	{{**1**⊗**1**, 0}, {**2**⊗**2**, 2}}
{SO7}	{G2}	{{**2**⊗**2**, 1}, {**3**⊗**1**, 1}}
{SO7}	{SU4}	{{**1**⊗**1**, 2}, {**2**⊗**2**, 1}}
{SP6}	{SU2, SO5}	{{**2**⊗**2**, 2}}
{SP6}	{SU2, SO5}	{{**1**⊗**1**, 1}, {**2**⊗**2**, 1}, {**3**⊗**1**, 1}}
{SU2, SO5}	{SU2, SU2, U1}	{{**1**⊗**1**, 2}, {**2**⊗**2**, 1}}
{SU2, SO5}	{SU2, SU2}	{{**2**⊗**2**, 1}, {**3**⊗**1**, 1}}
{SU5}	{SU4, U1}	{{**1**⊗**1**, 0}, {**2**⊗**2**, 2}}
{SO8}	{SO7}	{{**2**⊗**2**, 1}, {**3**⊗**1**, 1}}
{SO8}	{SO7}	{{**1**⊗**1**, 3}, {**2**⊗**2**, 1}}
{SO9}	{SO8}	{{**2**⊗**2**, 2}}
{SO9}	{SO8}	{{**1**⊗**1**, 4}, {**2**⊗**2**, 1}}
{SO9}	{SO8}	{{**1**⊗**1**, 1}, {**2**⊗**2**, 1}, {**3**⊗**1**, 1}}
{SU2, SU4}	{SO5, U1}	{{**1**⊗**1**, 3}, {**2**⊗**2**, 1}}
{SU2, SO7}	{SU4, U1}	{{**1**⊗**1**, 4}, {**2**⊗**2**, 1}}
{SO5, SO5}	{SU2, SU2, SU2, SU2}	{{**1**⊗**1**, 4}, {**2**⊗**2**, 1}}
{SO5, SO5}	{SU2, SU2, SU2, SU2}	{{**1**⊗**1**, 1}, {**2**⊗**2**, 1}, {**3**⊗**1**, 1}}
{SU2, SU2, SO5}	{SU2, SU2, U1, U1}	{{**1**⊗**1**, 4}, {**2**⊗**2**, 1}}
{SU2, SU2, SO5}	{SU2, SU2, SU2}	{{**1**⊗**1**, 3}, {**2**⊗**2**, 1}}
{SU2, SU2, SO5}	{SU2, SU2, SU2}	{{**2**⊗**2**, 1}, {**3**⊗**1**, 1}}
{SU2, SU2, SU4}	{SU2, SO5}	{{**1**⊗**1**, 4}, {**2**⊗**2**, 1}}
{SU2, SU2, SU4}	{SU2, SO5}	{{**1**⊗**1**, 1}, {**2**⊗**2**, 1}, {**3**⊗**1**, 1}}

Landscape of CHMs with at most eight NGBs

$(\mathbf{2},\mathbf{2}) + 4 \times (1,1)$

{SO5}	{SU2, SU2}	{{**2**⊗**2**, 1}}
{SU4}	{SO5}	{{**1**⊗**1**, 1}, {**2**⊗**2**, 1}}
{SU4}	{SU2, SU2, U1}	{{**1**⊗**1**, 0}, {**2**⊗**2**, 2}}
{SO7}	{G2}	{{**2**⊗**2**, 1}, {**3**⊗**1**, 1}}
{SO7}	{SU4}	{{**1**⊗**1**, 2}, {**2**⊗**2**, 1}}
{SP6}	{SU2, SO5}	{{**2**⊗**2**, 2}}
{SP6}	{SU2, SO5}	{{**1**⊗**1**, 1}, {**2**⊗**2**, 1}, {**3**⊗**1**, 1}}
{SU2, SO5}	{SU2, SU2, U1}	{{**1**⊗**1**, 2}, {**2**⊗**2**, 1}}
{SU2, SO5}	{SU2, SU2}	{{**2**⊗**2**, 1}, {**3**⊗**1**, 1}}
{SU5}	{SU4, U1}	{{**1**⊗**1**, 0}, {**2**⊗**2**, 2}}
{SO8}	{SO7}	{{**2**⊗**2**, 1}, {**3**⊗**1**, 1}}
{SO8}	{SO7}	{{**1**⊗**1**, 3}, {**2**⊗**2**, 1}}
{SO9}	{SO8}	{{**2**⊗**2**, 2}}
{SO9}	{SO8}	{{**1**⊗**1**, 4}, {**2**⊗**2**, 1}}
{SO9}	{SO8}	{{**1**⊗**1**, 1}, {**2**⊗**2**, 1}, {**3**⊗**1**, 1}}
{SU2, SU4}	{SO5, U1}	{{**1**⊗**1**, 3}, {**2**⊗**2**, 1}}
{SU2, SO7}	{SU4, U1}	{{**1**⊗**1**, 4}, {**2**⊗**2**, 1}}
{SO5, SO5}	{SU2, SU2, SU2, SU2}	{{**1**⊗**1**, 4}, {**2**⊗**2**, 1}}
{SO5, SO5}	{SU2, SU2, SU2, SU2}	{{**1**⊗**1**, 1}, {**2**⊗**2**, 1}, {**3**⊗**1**, 1}}
{SU2, SU2, SO5}	{SU2, SU2, U1, U1}	{{**1**⊗**1**, 4}, {**2**⊗**2**, 1}}
{SU2, SU2, SO5}	{SU2, SU2, SU2}	{{**1**⊗**1**, 3}, {**2**⊗**2**, 1}}
{SU2, SU2, SO5}	{SU2, SU2, SU2}	{{**2**⊗**2**, 1}, {**3**⊗**1**, 1}}
{SU2, SU2, SU4}	{SU2, SO5}	{{**1**⊗**1**, 4}, {**2**⊗**2**, 1}}
{SU2, SU2, SU4}	{SU2, SO5}	{{**1**⊗**1**, 1}, {**2**⊗**2**, 1}, {**3**⊗**1**, 1}}

The **8** of Sp(8) not a symmetry 2HDM

{SO5}	{SU2, SU2}	{{**2**⊗**2**, 1}}
{SU4}	{SO5}	{{**1**⊗**1**, 1}, {**2**⊗**2**, 1}}
{SU4}	{SU2, SU2, U1}	{{**1**⊗**1**, 0}, {**2**⊗**2**, 2}}
{SO7}	{G2}	{{**2**⊗**2**, 1}, {**3**⊗**1**, 1}}
{SO7}	{SU4}	{{**1**⊗**1**, 2}, {**2**⊗**2**, 1}}
{SP6}	{SU2, SO5}	{{**2**⊗**2**, 2}}
{SP6}	{SU2, SO5}	{{**1**⊗**1**, 1}, {**2**⊗**2**, 1}, {**3**⊗**1**, 1}}
{SU2, SO5}	{SU2, SU2, U1}	{{**1**⊗**1**, 2}, {**2**⊗**2**, 1}}
{SU2, SO5}	{SU2, SU2}	{{**2**⊗**2**, 1}, {**3**⊗**1**, 1}}
{SU5}	{SU4, U1}	{{**1**⊗**1**, 0}, {**2**⊗**2**, 2}}
{SO8}	{SO7}	{{**2**⊗**2**, 1}, {**3**⊗**1**, 1}}
{SO8}	{SO7}	{{**1**⊗**1**, 3}, {**2**⊗**2**, 1}}
{SO9}	{SO8}	{{**2**⊗**2**, 2}}
{SO9}	{SO8}	{{**1**⊗**1**, 4}, {**2**⊗**2**, 1}}
{SO9}	{SO8}	{{**1**⊗**1**, 1}, {**2**⊗**2**, 1}, {**3**⊗**1**, 1}}
{SU2, SU4}	{SO5, U1}	{{**1**⊗**1**, 3}, {**2**⊗**2**, 1}}
{SU2, SO7}	{SU4, U1}	{{**1**⊗**1**, 4}, {**2**⊗**2**, 1}}
{SO5, SO5}	{SU2, SU2, SU2, SU2}	{{**1**⊗**1**, 4}, {**2**⊗**2**, 1}}
{SO5, SO5}	{SU2, SU2, SU2, SU2}	{{**1**⊗**1**, 1}, {**2**⊗**2**, 1}, {**3**⊗**1**, 1}}
{SU2, SU2, SO5}	{SU2, SU2, U1, U1}	{{**1**⊗**1**, 4}, {**2**⊗**2**, 1}}
{SU2, SU2, SO5}	{SU2, SU2, SU2}	{{**1**⊗**1**, 3}, {**2**⊗**2**, 1}}
{SU2, SU2, SO5}	{SU2, SU2, SU2}	{{**2**⊗**2**, 1}, {**3**⊗**1**, 1}}
{SU2, SU2, SU4}	{SU2, SO5}	{{**1**⊗**1**, 4}, {**2**⊗**2**, 1}}
{SU2, SU2, SU4}	{SU2, SO5}	{{**1**⊗**1**, 1}, {**2**⊗**2**, 1}, {**3**⊗**1**, 1}}

(More or less) robust predictions of CHMs (about the scalar sector)

Liu, Low, Yin ‘18

1. Effective field theory with many restrictions, e.g. h → h+c. Reduced Higgs couplings

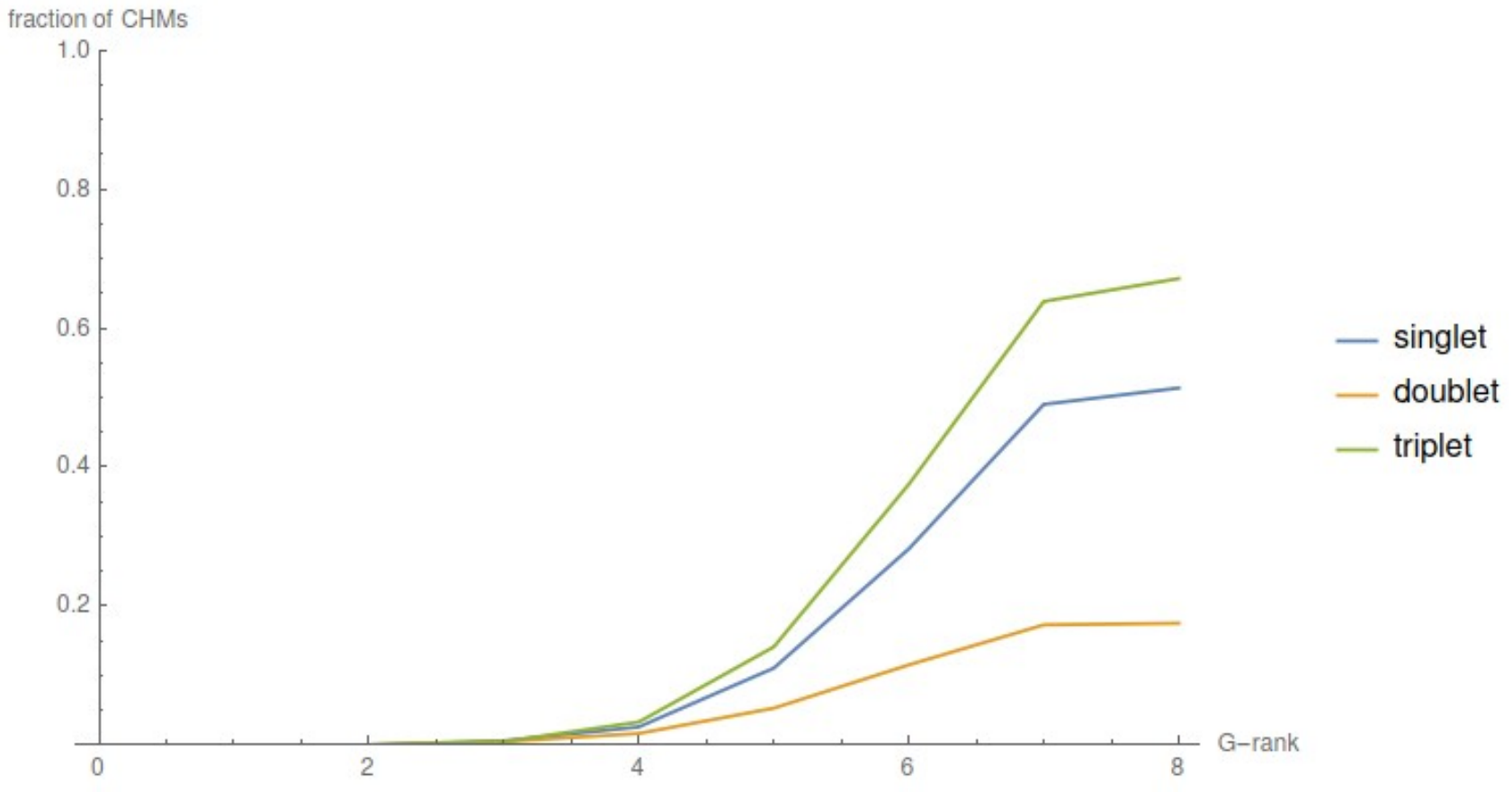
$$1 + 2\sqrt{1-\epsilon}\frac{h}{v} + (1-2\epsilon)\frac{h^2}{v^2} + \cdots, \quad \epsilon < 1$$

2. Extra scalars. Only one minimal model, SO(5)→SO(4), “not UV completable”

Ferreti, Karatev ‘13;
Cacciapaglia, Sannino ‘14

Not all extra scalars equally likely

851 CHMs with at most 13 NGBs



MC, Fonseca ‘ongoing

One extra singlet: SO(6)→ SO(5)

1. Rare Higgs decays (beyond h→SS). About O(10^6) Zh events at 240 GeV FCC-ee, ILC, ...

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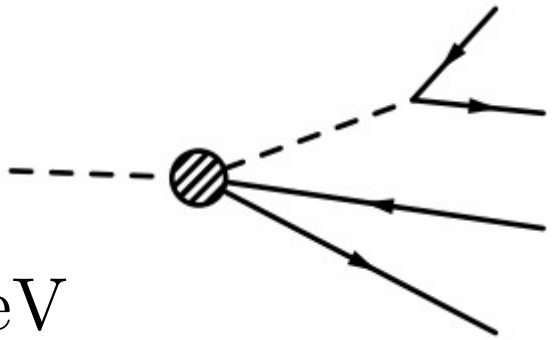
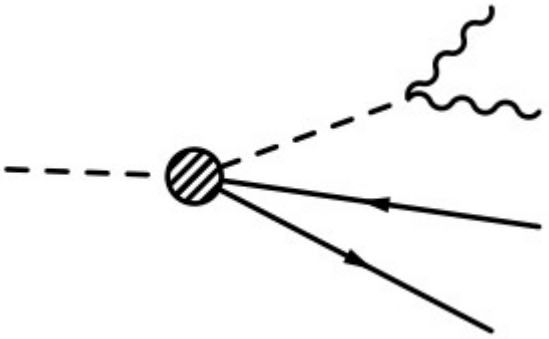
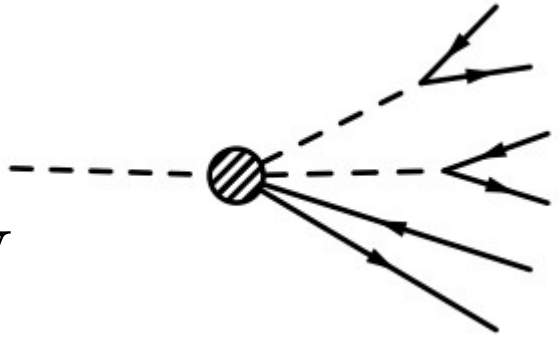
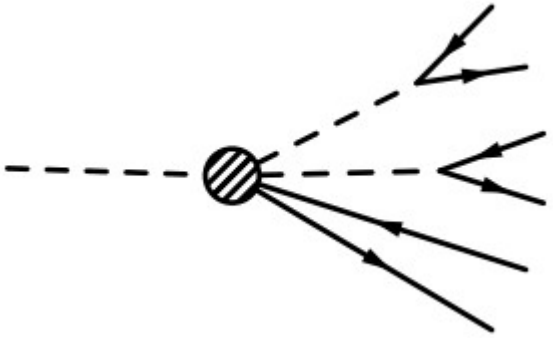




$f_{\max} \sim 10\,\mathrm{TeV}$

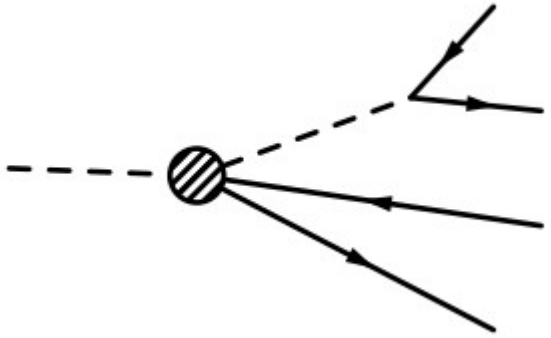




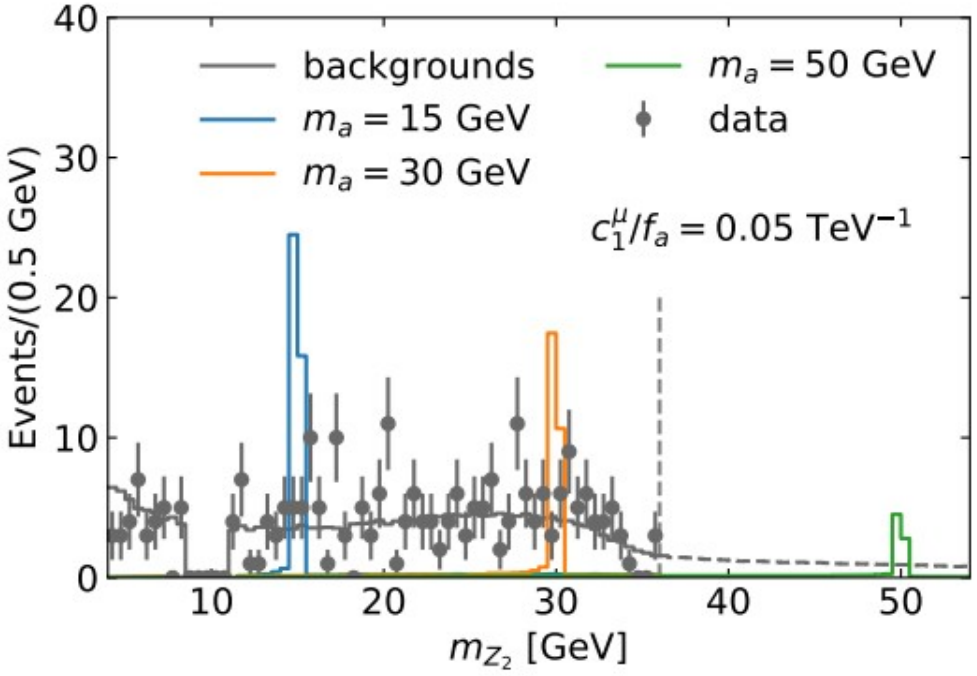
$f_{\max} \sim 1\,\mathrm{TeV}$

One extra singlet: SO(6)→ SO(5)

1. Rare Higgs decays (beyond h→SS). About O(10^6) Zh events at 240 GeV FCC-ee, ILC, ...



$f_{\max} \sim 10\,\text{TeV}$

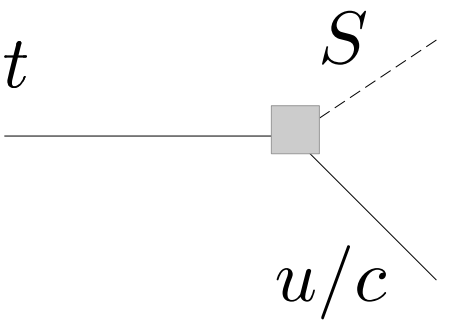


Biekotter, MC, Spannowsky ‘22

One extra singlet: SO(6)→ SO(5)

2. Rare top decays. About O(10^6) ttbar events at 350 GeV FCC-ee, ILC, ...

Supressed only by *1/f*



Higgs-mediated FCNC forbidden

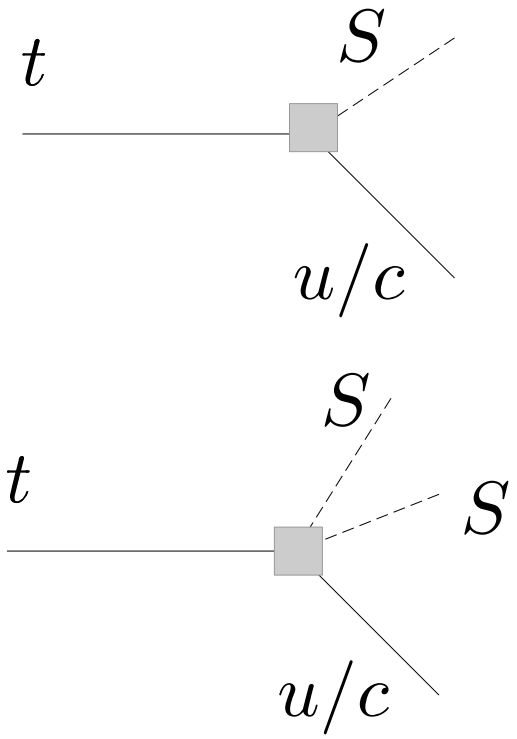
Agashe, Contino '09

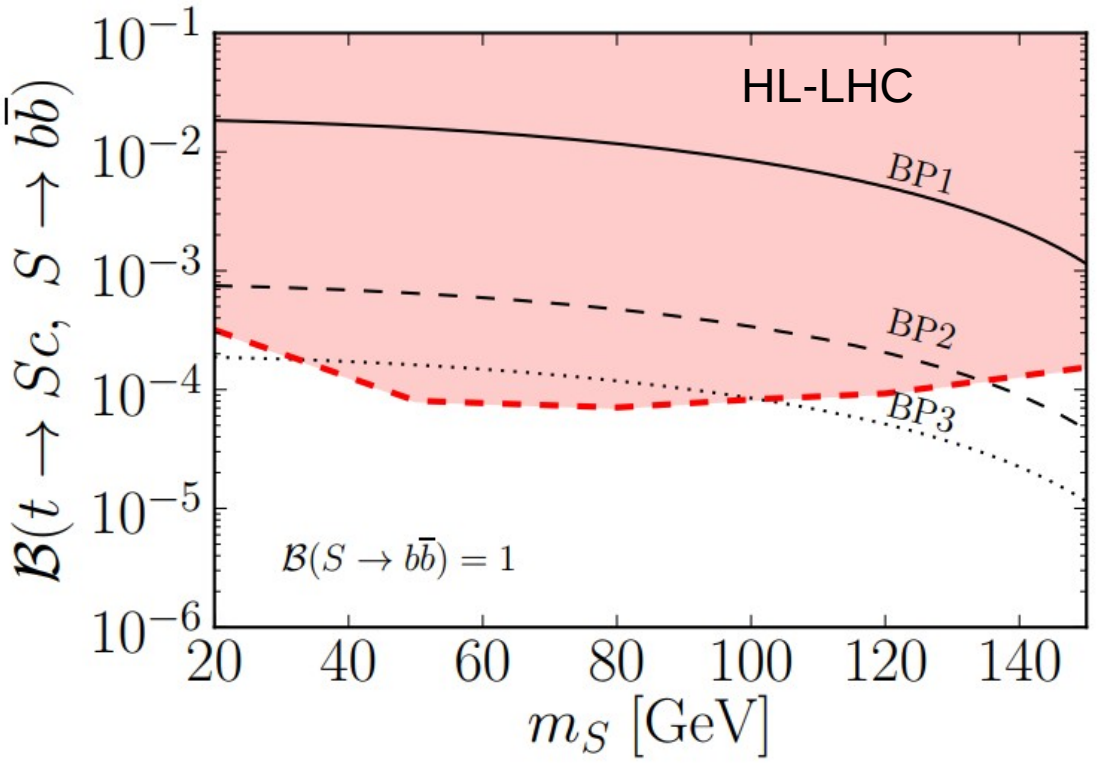
In principle, S can have large decays into clean final states (leptons, photons, ...)

D^0-$\overline{D}^0$ oscillations not fully constraining

One extra singlet: SO(6)→ SO(5)

2. Rare top decays. About O(10^6) ttbar events at 350 GeV FCC-ee, ILC, ...



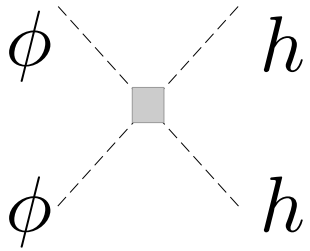


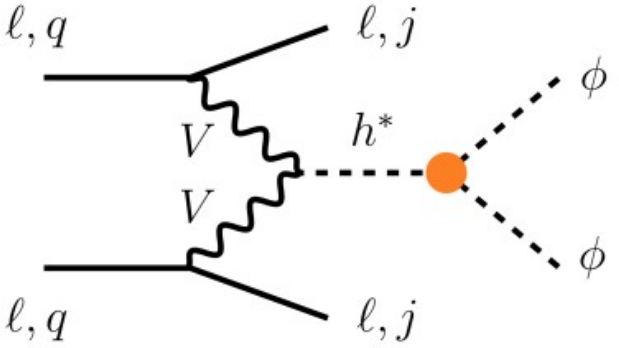
$f_{\max} \sim 100\,\text{TeV}$

Banerjee, MC, Spannowsky '18

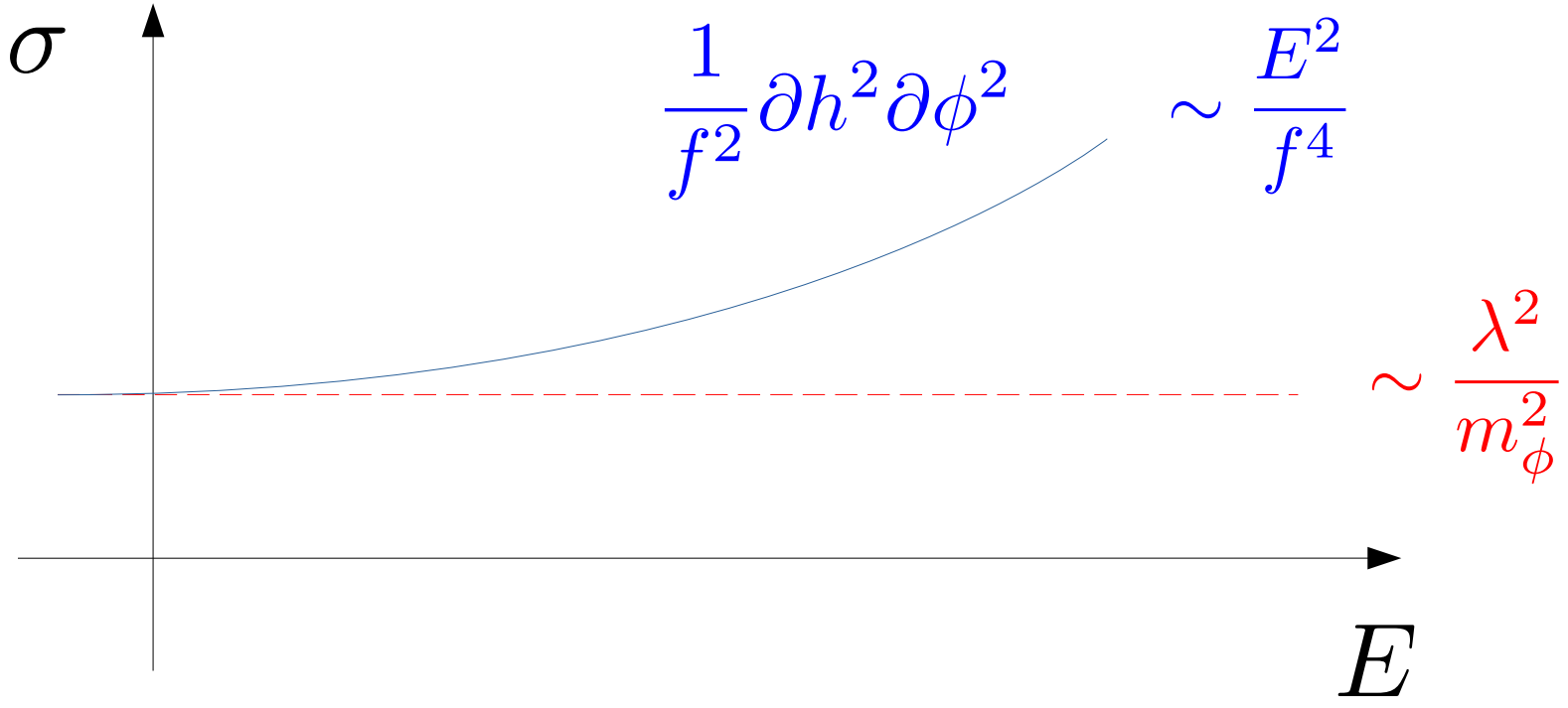
One extra singlet: SO(6)→ SO(5)

dark matter





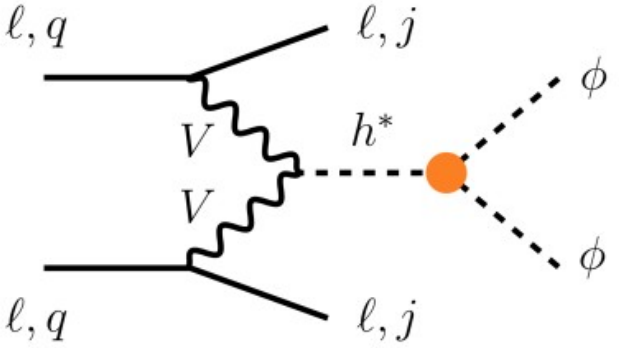
3. Off-shell Higgs portal

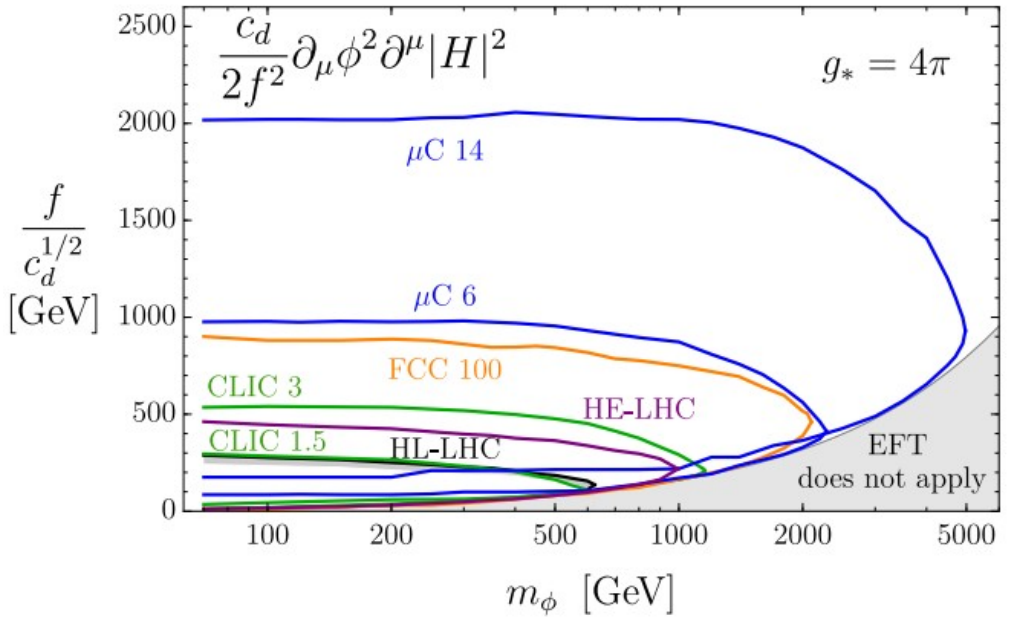


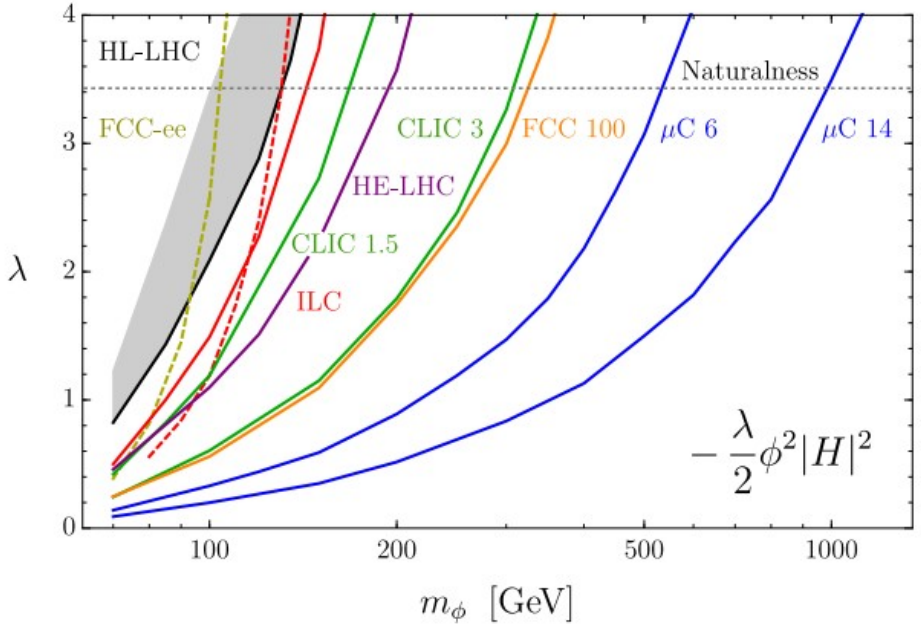
Ruhdorfer, Salvioni, Weiler ‘19

One extra singlet: SO(6)→ SO(5)

3. Off-shell Higgs portal





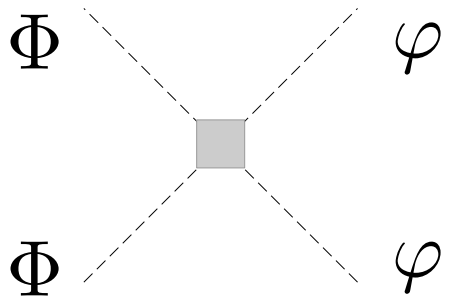


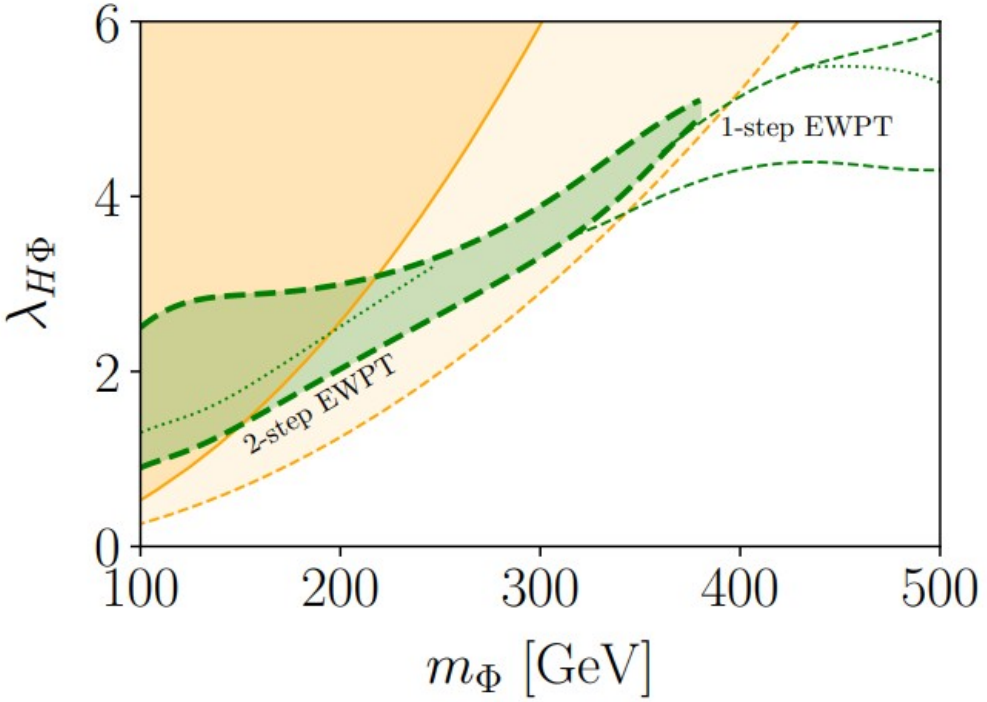
Ruhdorfer, Salvioni, Weiler ‘19

One extra triplet: SO(8)→ SO(7)

Baryogenesis occurs in the mass region 100-350 GeV

$$\Phi = \begin{pmatrix} \phi^+ \\ \phi^0 \\ \phi^- \end{pmatrix}$$

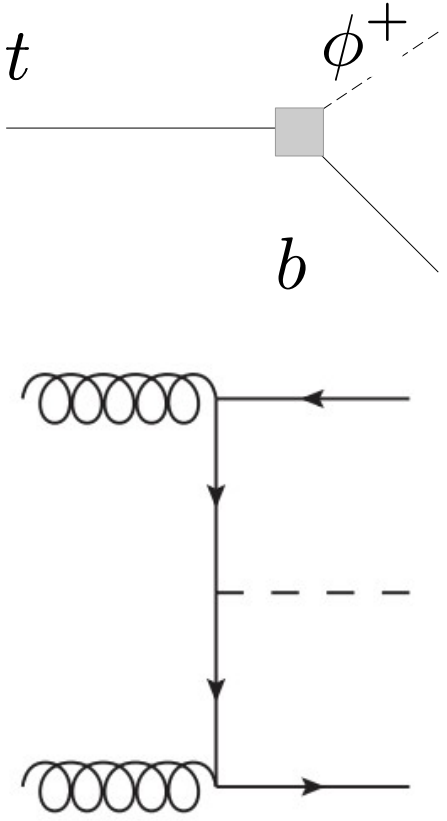


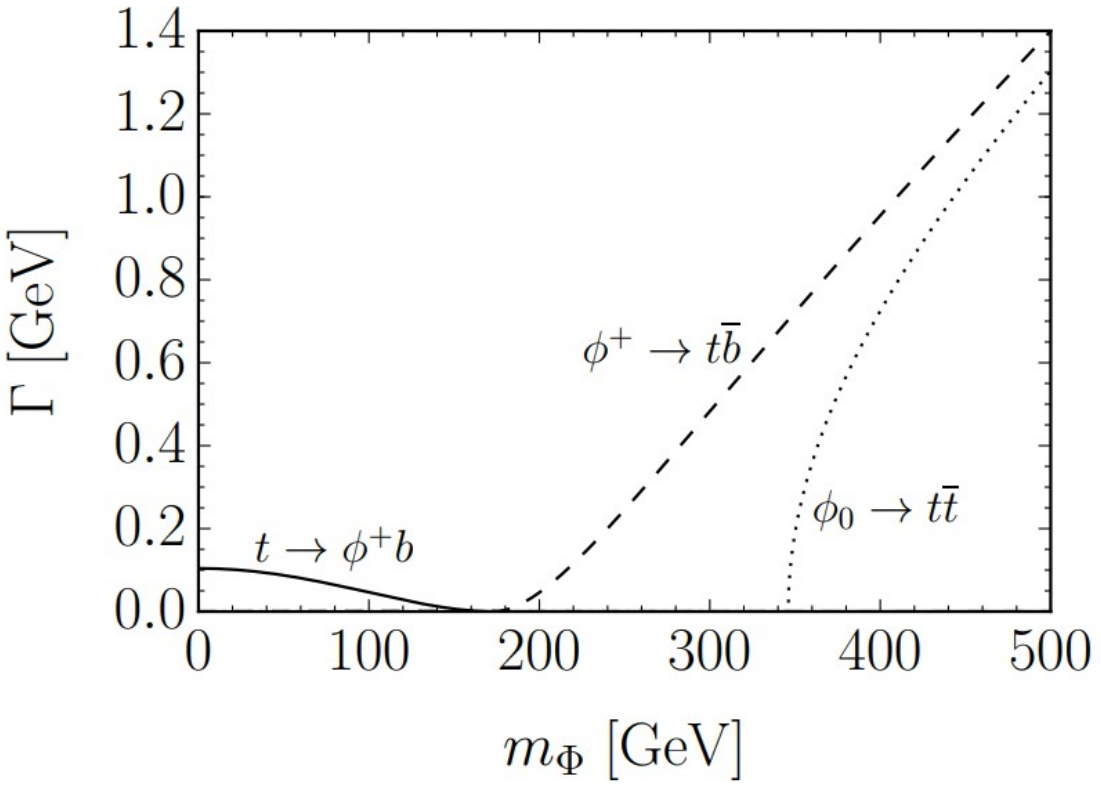


MC, Ramos, Spannowsky '18

One extra triplet: SO(8)→ SO(7)

Rare top decays. Still mediated by effective interactions. Conserve flavor





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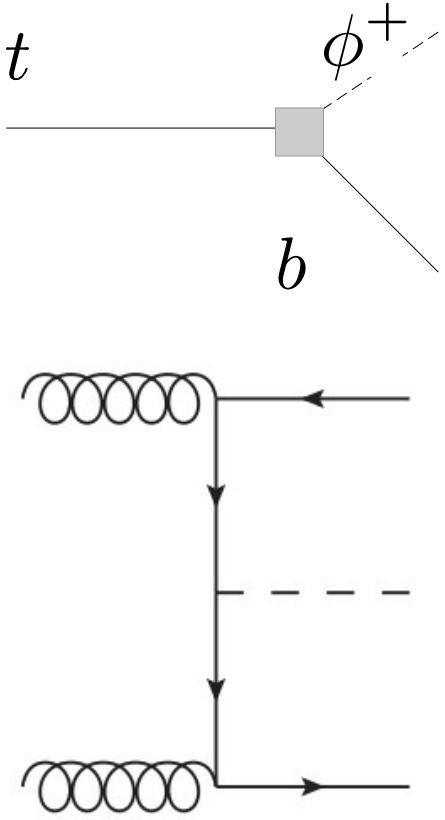
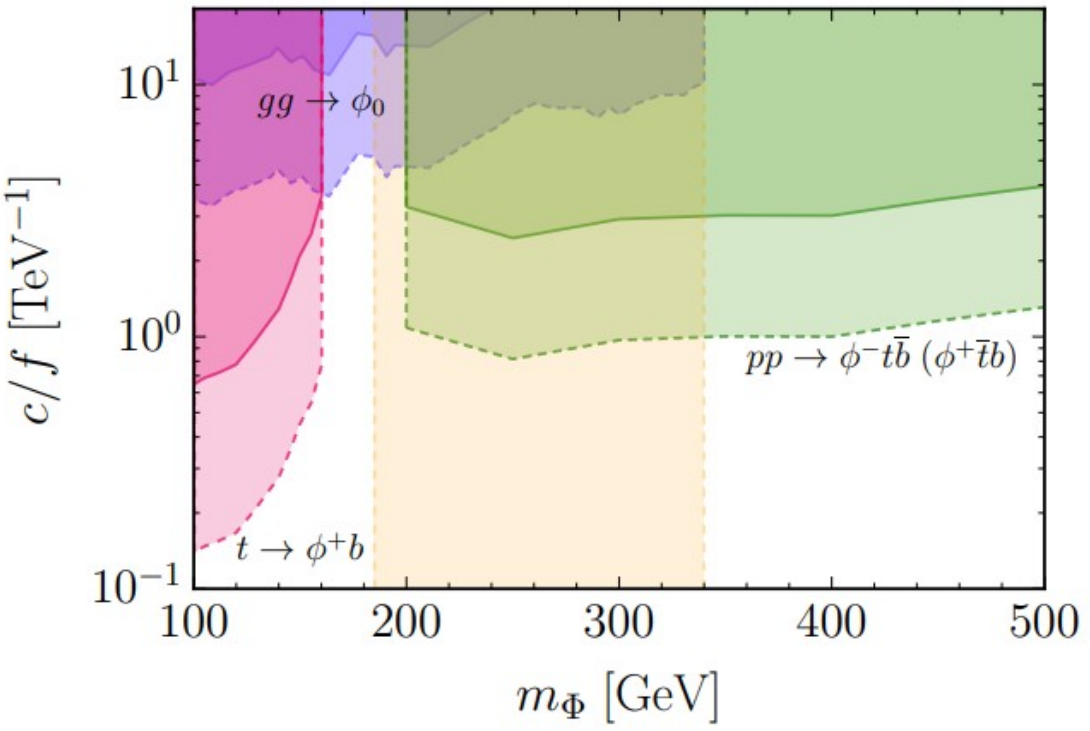
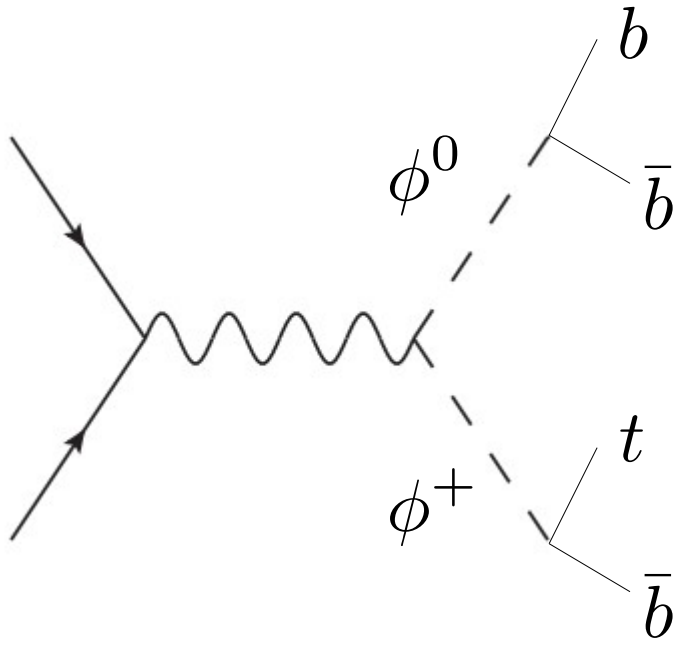




One extra triplet: SO(8)$\rightarrow$ SO(7)

Within this region, pair production of triplets in 3t+b final state (no Z exchange)

Not particularly clean at hadron colliders



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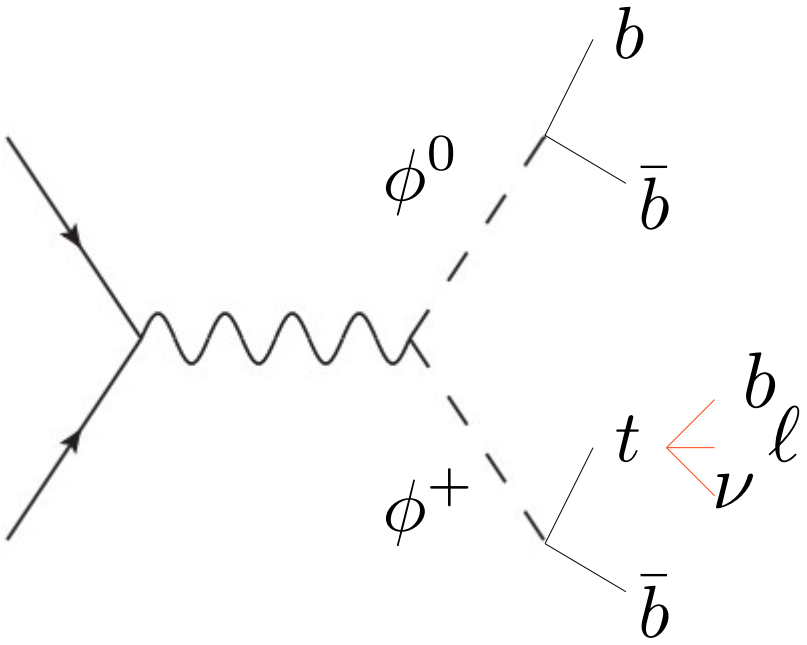

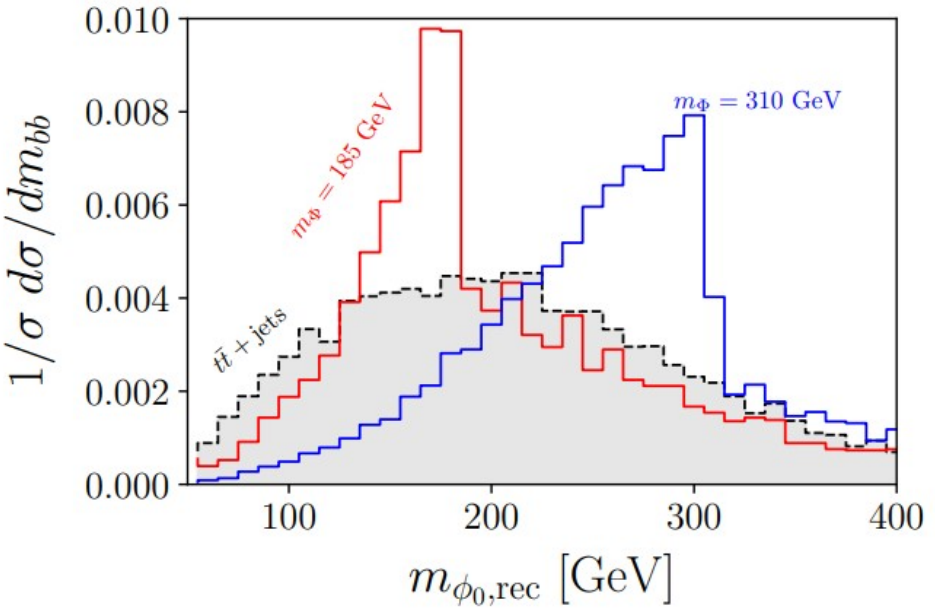

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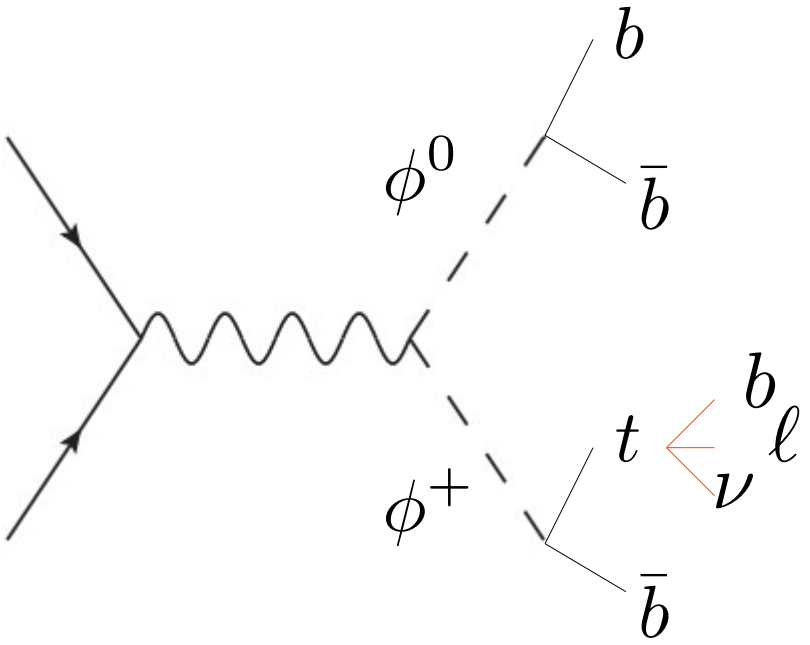


final rec	signal	background	$s/\sqrt{s+b}$
$\Phi(185)$	0.39	25.6	4.2
$\Phi(235)$	0.78	33.5	7.3
$\Phi(285)$	0.41	26.5	4.3
$\Phi(335)$	0.22	19.0	2.7

Other possibilities

Precise measurements of custodial symmetry violation

$$\rho = \frac{m_Z^2}{c_W^2 m_W^2} = 1$$

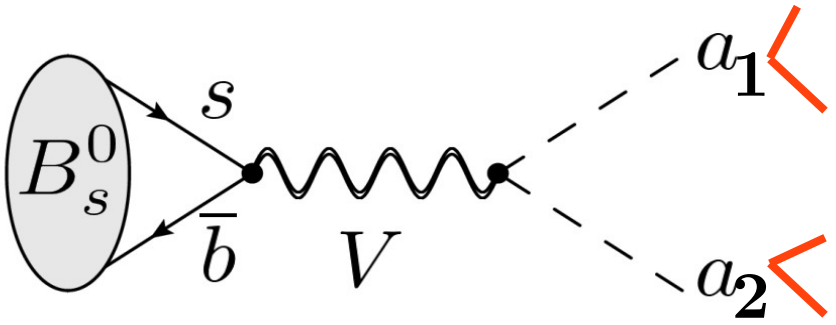
SU(2)×SU(2) symmetry guarantees this relation at tree level in renormalisable theories.

Generally, non-minimal CHMs (even 2HDMs) violate this

Mrazek, Pomarol, Rattazzi, Redi, Serra, Wulzer '11

Other possibilities

New B-meson decays, in CHMs with several extra singlets, e.g. SO(7)/SO(6)



$$\Gamma = \frac{f_B^2}{16\pi m_V^4} \left(g_{sb} g_{12}\right)^2 \frac{\left(m_1^2 - m_2^2\right)^2}{m_B} \mathcal{K}\left(\frac{m_1}{m_B}, \frac{m_2}{m_B}\right)$$

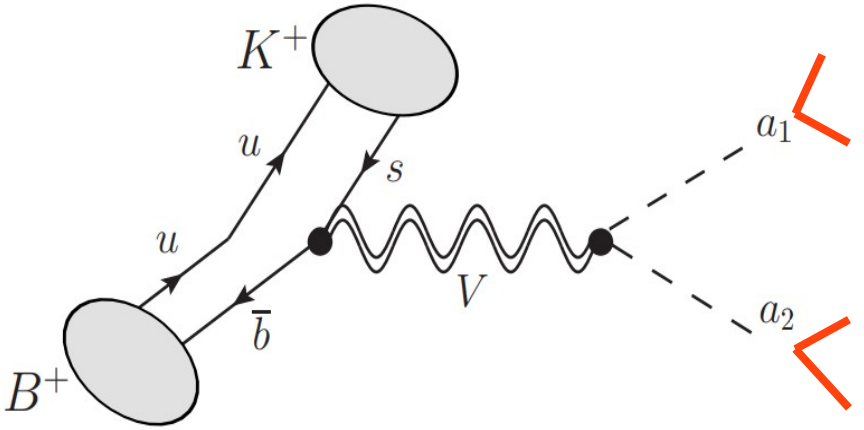
MC, Egede, Spannowsky, ‘19
Blance, MC, Ramos, Spannowsky ‘19

Other possibilities

New B-meson decays, in CHMs with several extra singlets, e.g. SO(7)/SO(6)

Not yet searched for. Smaller efficiency, compensated by larger cross section

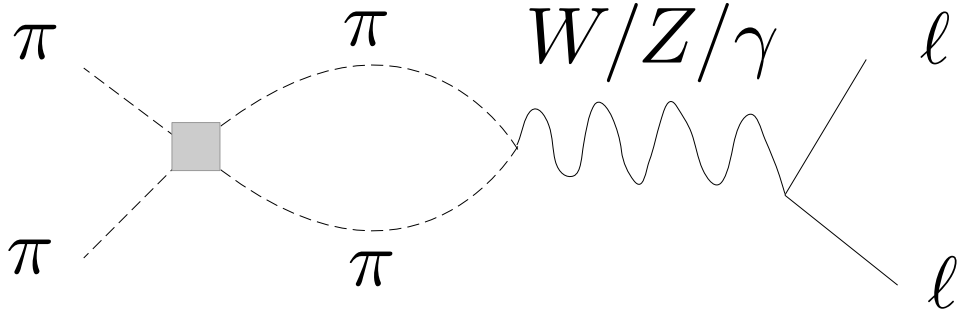
$\mathcal{B}_{\rm min} \sim 10^{-11}$ @ ILC-250



Other possibilities

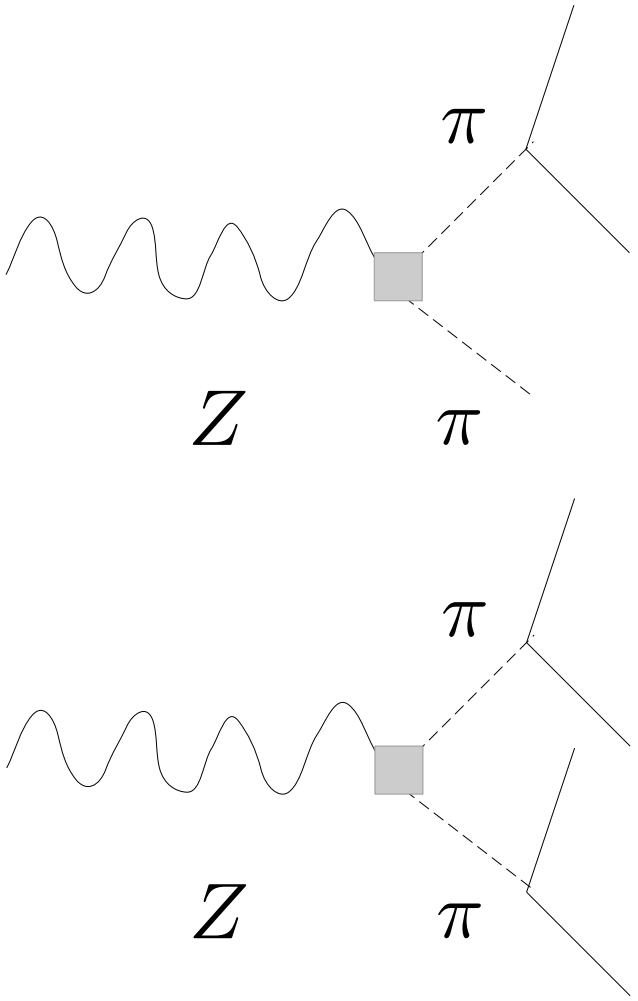
Radiative corrections to pair-production of new scalars

Fixed by coset structure. Sheds light on spontaneous-symmetry breaking

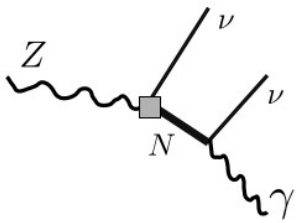


Other possibilities

Variety of (probably off-shell) Z decays



$\mathbf{Z \to \nu\nu\gamma}$



$$\Gamma \sim \frac{m_Z^3 v^2}{\pi \Lambda^4} \alpha_{NZ}^2$$

$$\mathcal{B}^{\text{the}} \sim 10^{-3}$$

$$\mathcal{B}^{\text{exp}} < 3.2 \times 10^{-6}$$

[PLB 412 (1997) 201-209]

Theoretical estimates hold for $\Lambda = 1$ TeV and O(1) couplings; I assume Z width is dominated by Standard Model

Naive estimate, based on 5×10^{12} Z bosons, requiring about 10 observed events and efficiency or order 0.2:
(0.85 exp. ref.)

$$\mathcal{B}^{\text{exp}} \sim 10^{-11} \ (\Lambda \sim 100\,\text{TeV})$$

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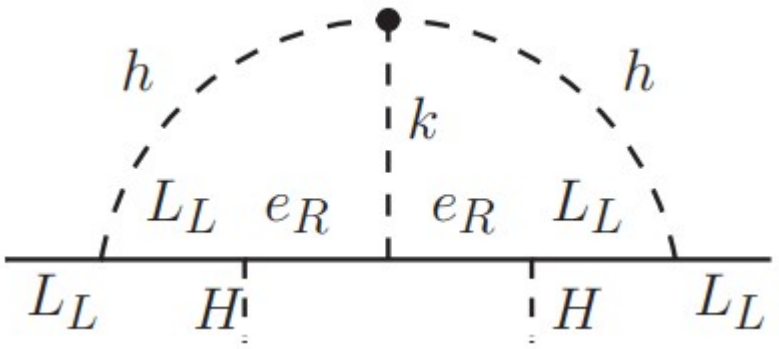
ECFA HTE meeting on Z pole physics; September 2022

Other possibilities

Scalars related to neutrino masses

SO(10)/SO(9), 9 NGBs: $H, k^{\pm\pm}, h^{\pm}, \sigma$

Smallness of neutrino masses explained from their radiative origin



$$k^{++} \to h^+ h^+ \to \ell^+ \nu \ell^+ \nu$$

Conclusions

The sharpest prediction of CHMs in the scalar sector is modified (reduced) Higgs-gauge-boson couplings

It seems very plausible that the scalar sector is extended (singlets and triplets specially)

Plenty of different signals: rare top and Higgs (and Z and B meson) decays, untested production of new scalars, ...

Competitive with LHC? Definitely in some channels (involving hadronic activity)

Thank you!