NON-LINEAR HIGGS PORTAL TO DARK MATTER

hep-ph/1511.01099

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The discovered Higgs boson may be the end
…. or the start

- ✔ It's a scalar, CP even
- ✔ Couplings agree with the SM

- ? hierarchy, triviality, vacuum stablility
- ? origin of EWSB
- ? Dark Matter
- ? m_ν, gravity, baryogenesis…

Disclaimer: some beautiful insertions and drawings taken from Brivio, Saa

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a good place to study their interplay:

Higgs portal to scalar DM

$S^2(\Phi^\dagger\Phi)$

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- ? origin of EWSB
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Method: Effective field theory
→ connection between EW symmetry breaking and EFT

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? hierarchy, triviality, vacuum stablility

? origin of EWSB

? Dark Matter II

? m_ν, gravity, baryogenesis…

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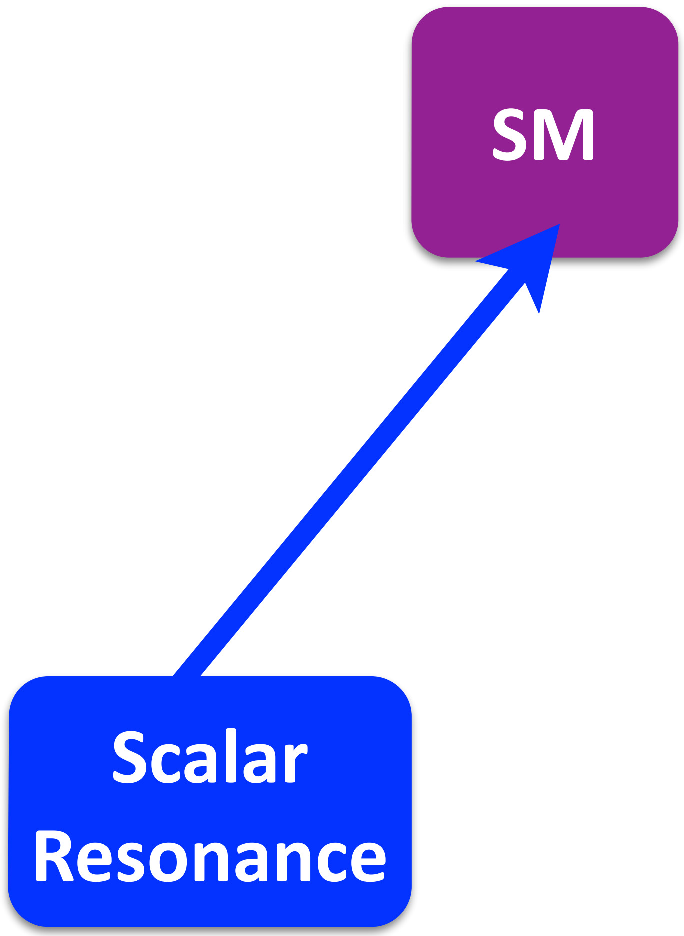
the Higgs portal for scalar Dark Matter in detail.
→ the Higgs nature can have a relevant impact on the DM phenomenology!

Higgs sector: the chiral EFT

Which Higgs?

Scalar Resonance

Which Higgs?



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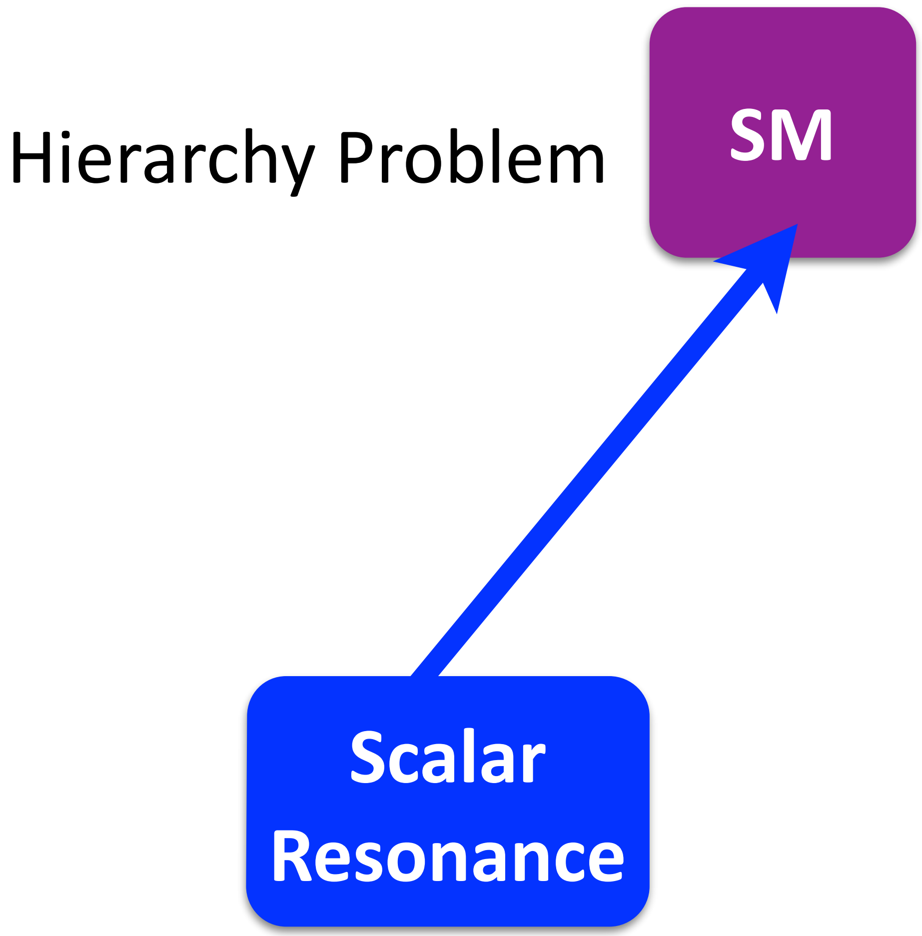

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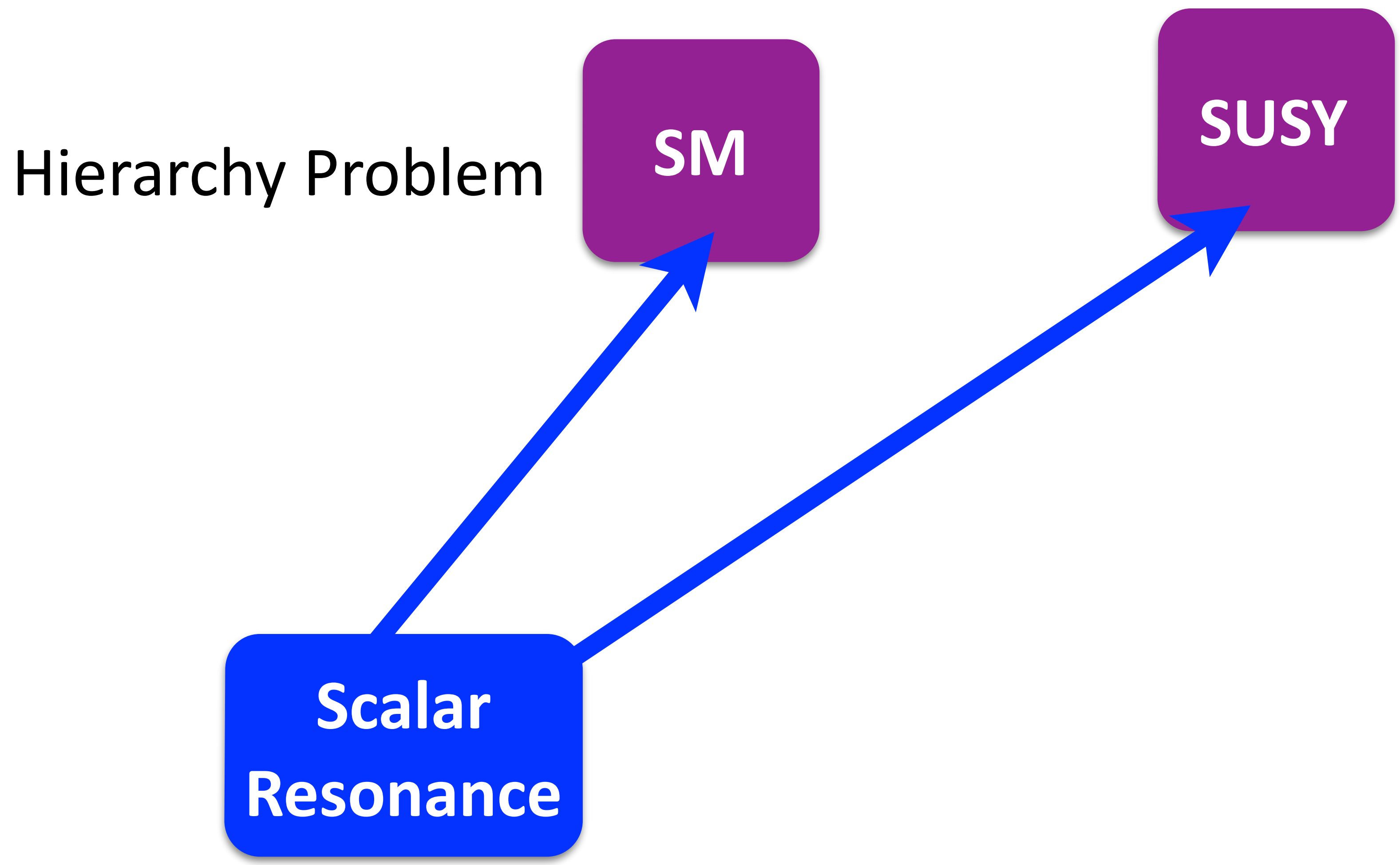

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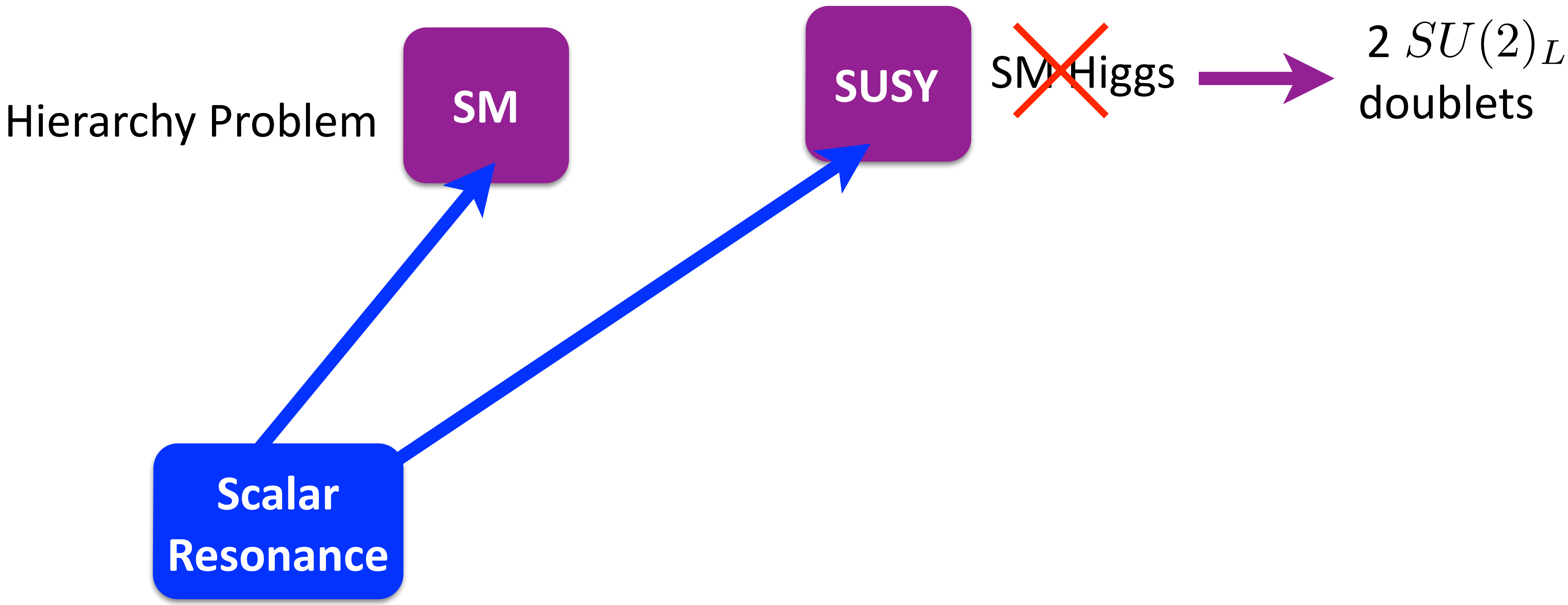
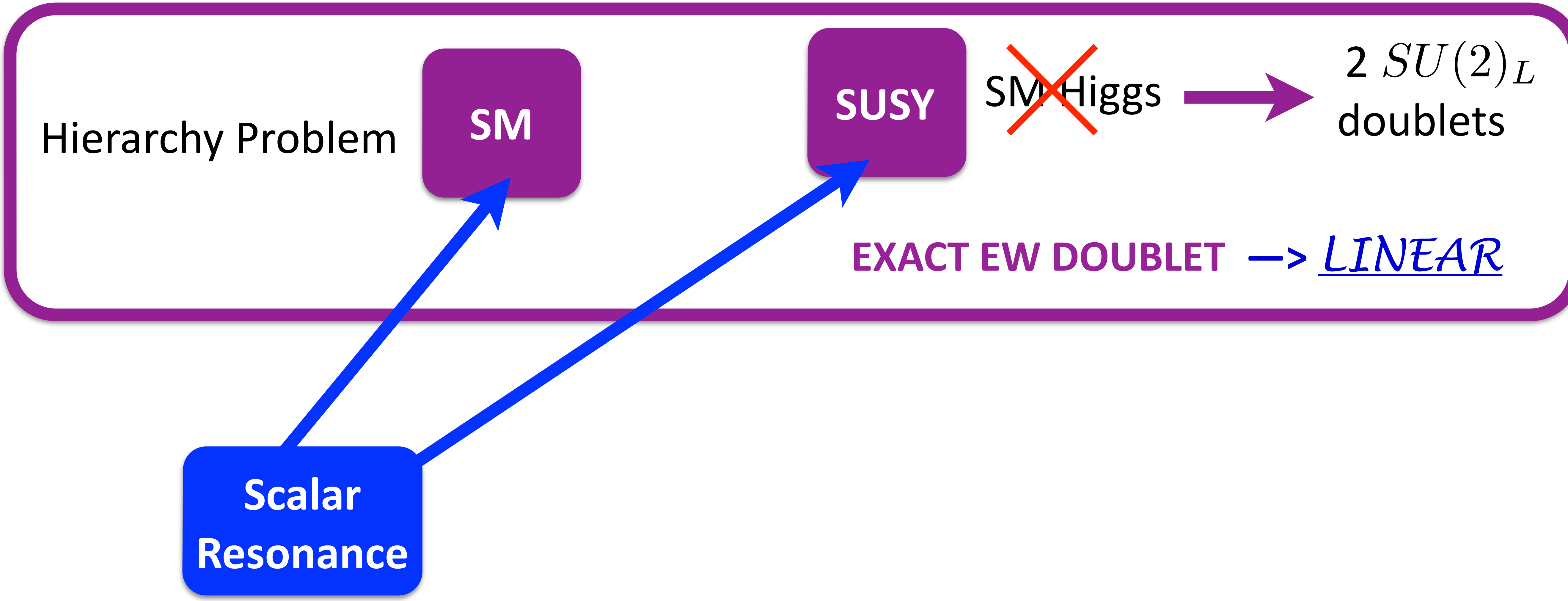


Hierarchy Problem
SM
SUSY
SM Higgs
2 $SU(2)_L$ doublets
Scalar Resonance

Which Higgs?



Hierarchy Problem
SM
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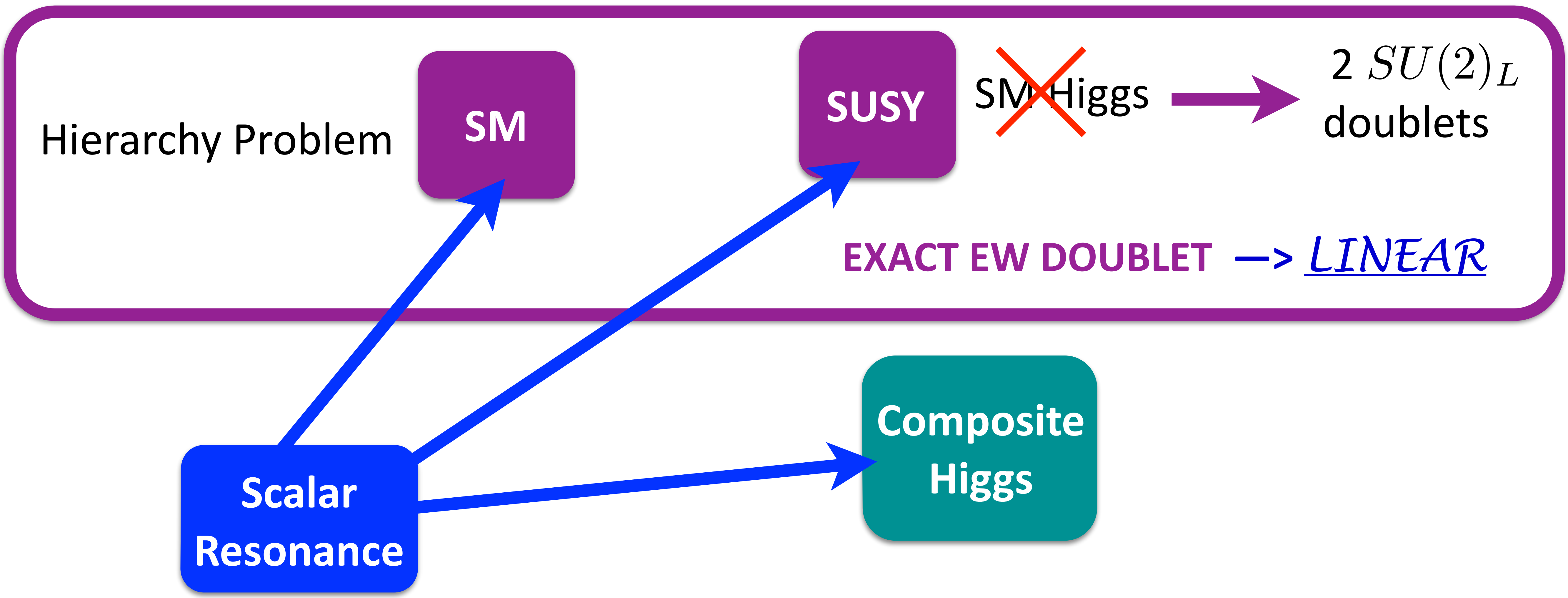
2 $SU(2)_L$ doublets
EXACT EW DOUBLET —> LINEAR
Scalar Resonance

Which Higgs?


Hierarchy Problem
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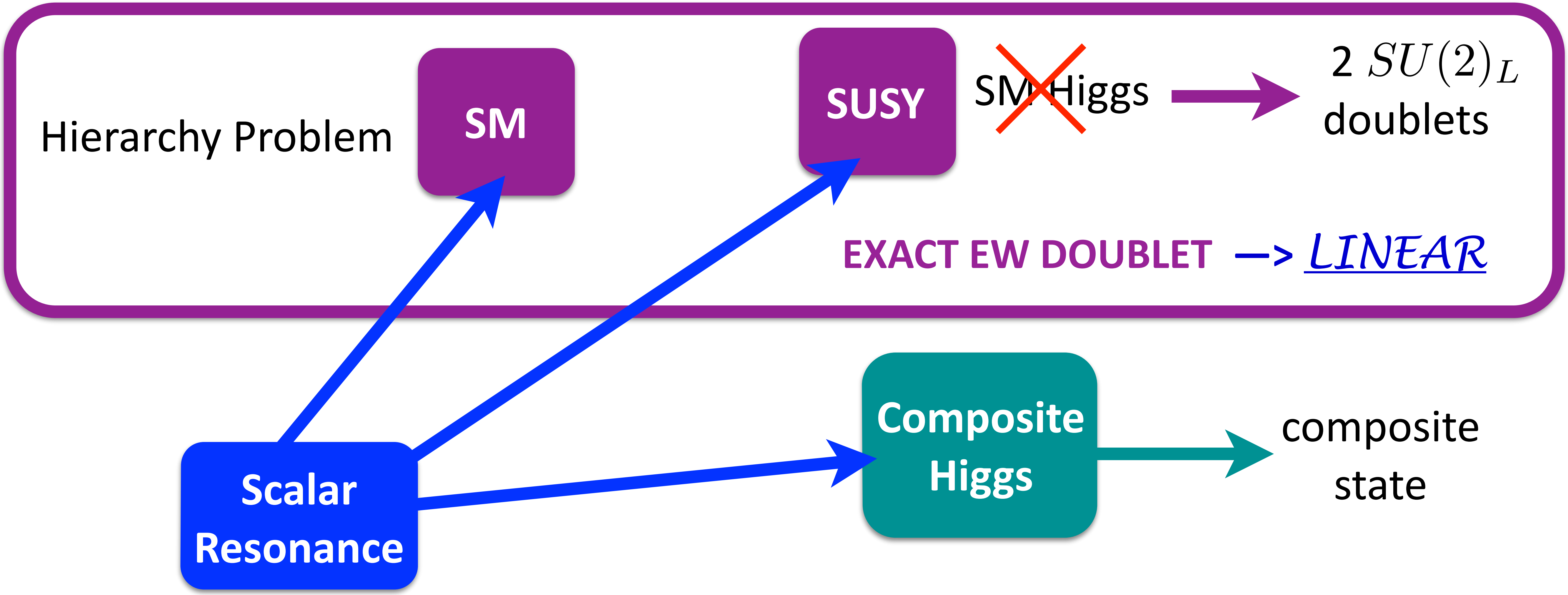
Composite Higgs
Scalar Resonance

Which Higgs?


Hierarchy Problem
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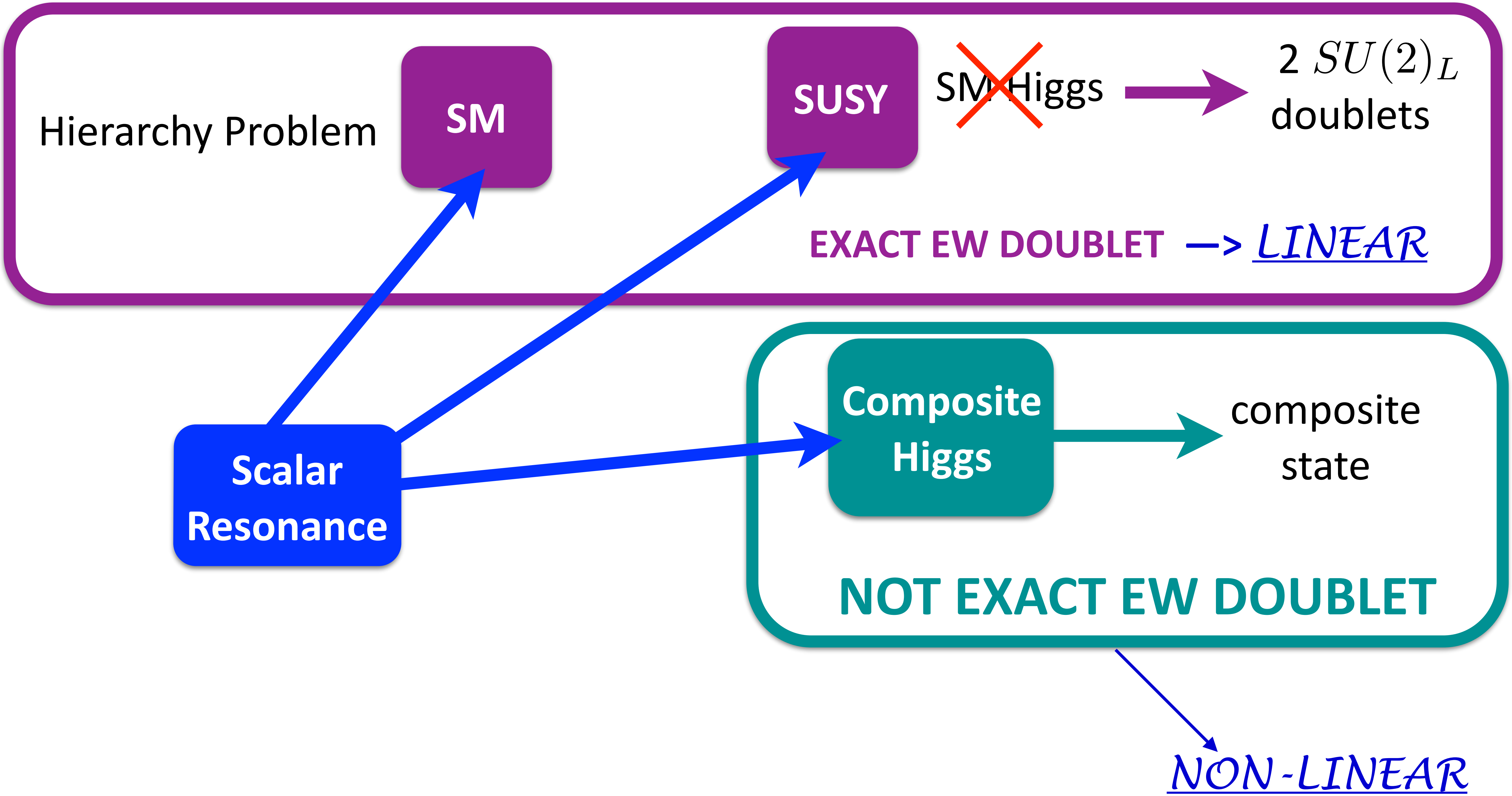
state

Which Higgs?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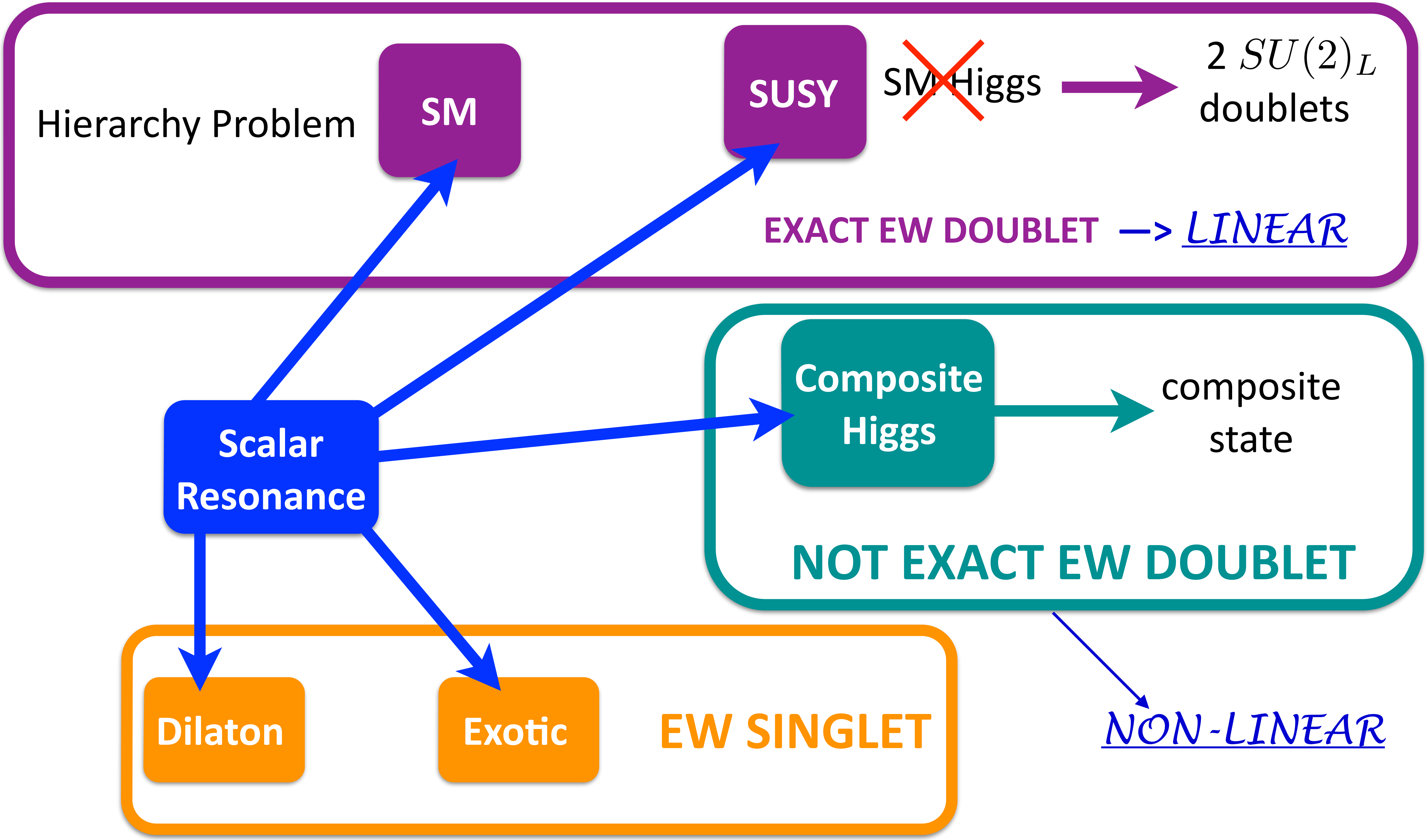
NOT EXACT EW DOUBLET
NON-LINEAR

Which Higgs?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NOT EXACT EW DOUBLET
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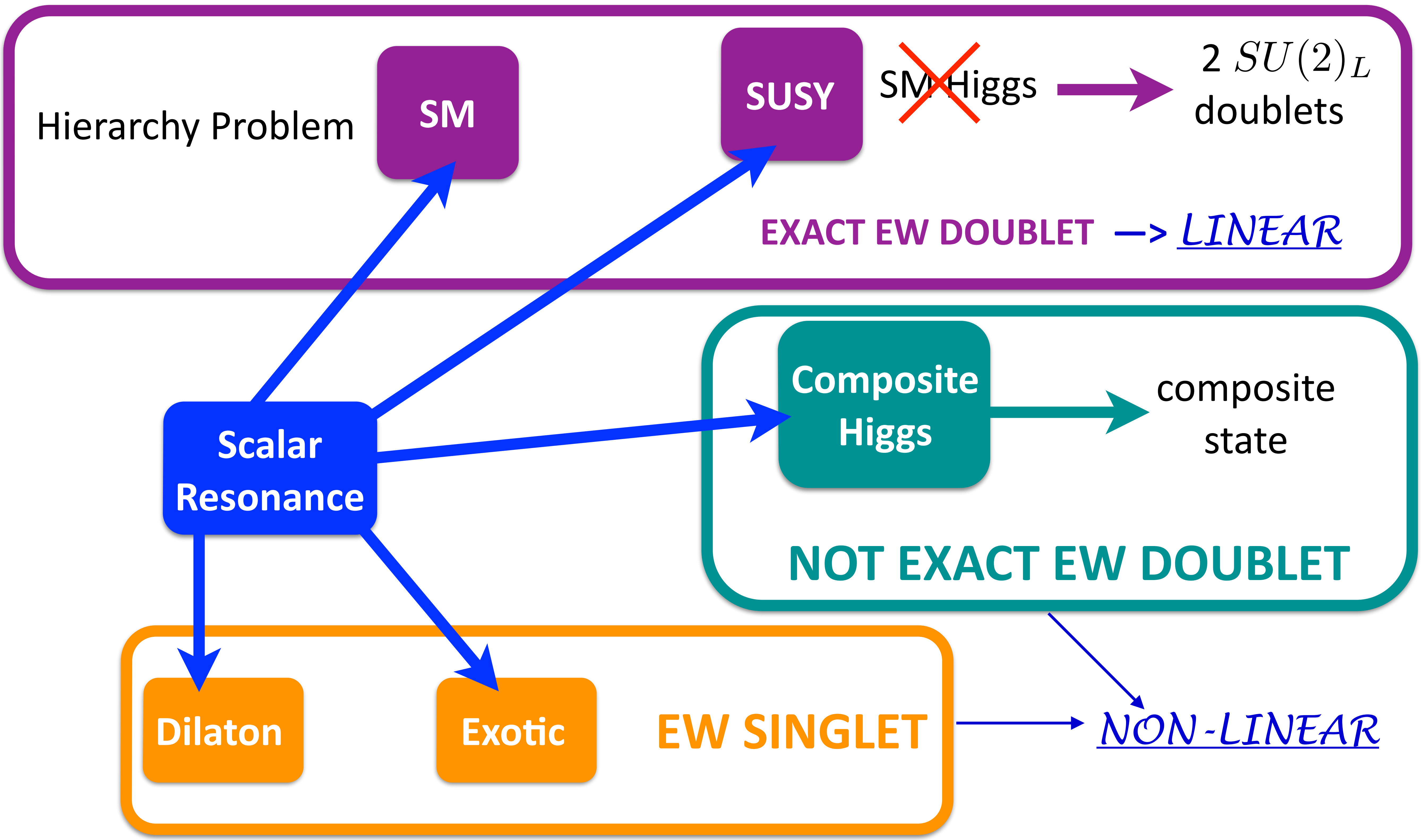
Dilaton
Exotic
EW SINGLET

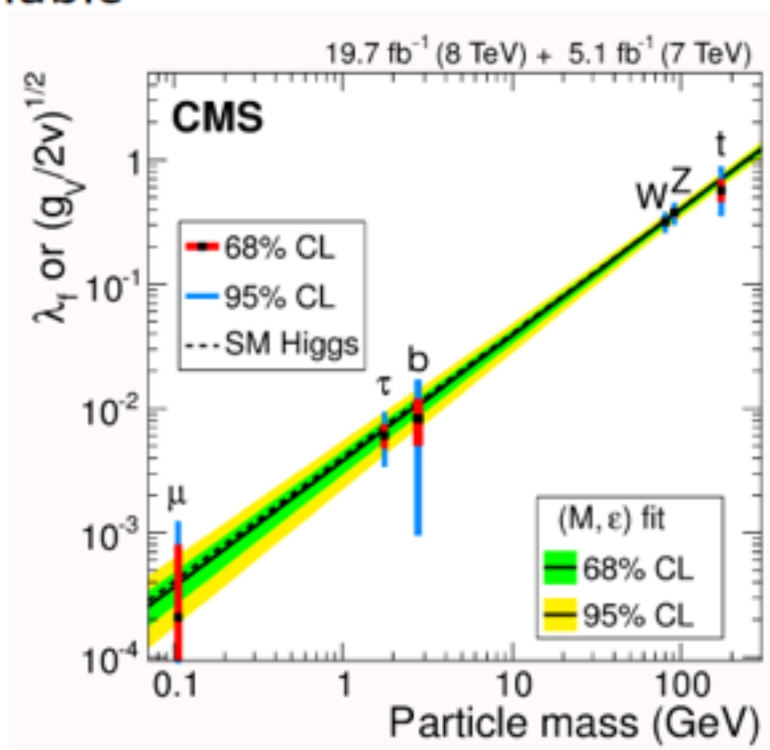
Which Higgs?

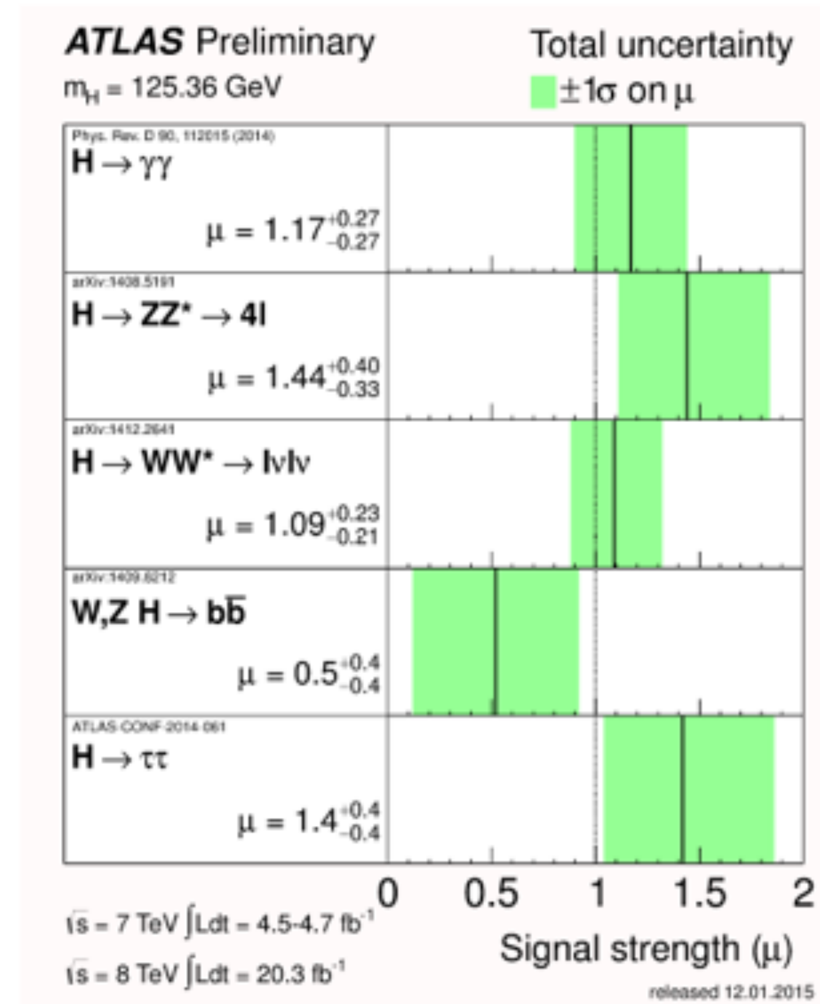


Does the Higgs boson behaves as an exact doublet or not?

Experimentally

Measurements compatible with the Standard Model.
Higgs compatible with an exact doublet at 20-30%
Still quite large uncertainties: all the possibilities above are still viable





Brivio slide

Higgs EFTs

Linear or **Chiral** (= non-linear)

Higgs EFTs

Linear or **Chiral**

Physical **h** and Goldstone bosons π^a together in the ϕ doublet

$$\phi = \begin{pmatrix} \pi^1 + i\pi^2 \\ v + \mathbf{h} + \pi^3 \end{pmatrix} \approx (v + \mathbf{h})\, e^{i\pi^a\sigma^a/v} \begin{pmatrix} 0 \\ 1 \end{pmatrix} = (v + \mathbf{h})\, \mathbf{U} \begin{pmatrix} 0 \\ 1 \end{pmatrix}$$

$\phi \longrightarrow \mathbf{L}\,\phi$ under $SU(2)_L$ transformations **L**

Higgs EFTs

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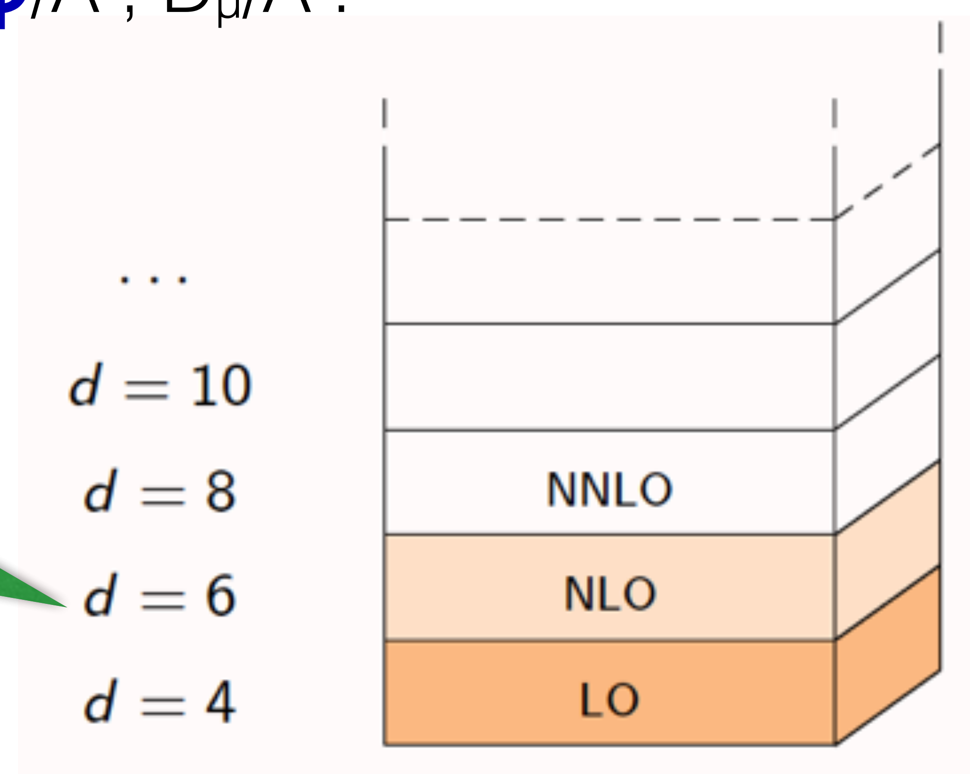
Expansion in canonical dimensions: ϕ/Λ , D_μ/Λ :

e.g. $\delta \mathscr{L} \sim = \frac{1}{\Lambda^2} \mathcal{O}_B = \sim \frac{1}{\Lambda^2} (D_\mu \phi)^\dagger B^{\mu\nu} (D_\nu \phi)$



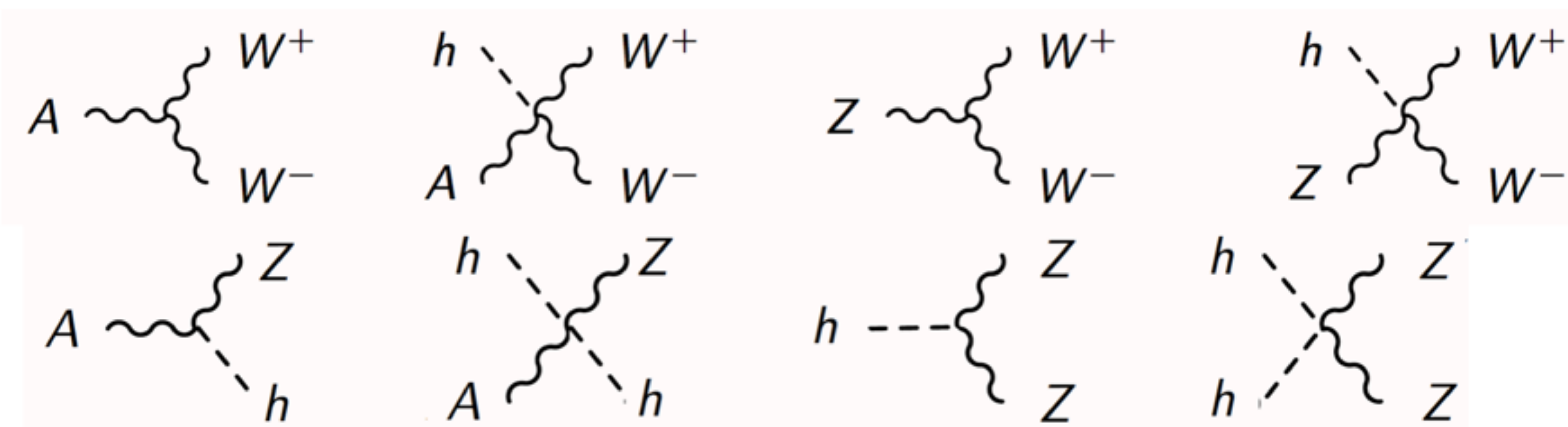
[Buchmuller&Wyler 1984]
[Gradkoski,Iskrzynski,Misiak&Rosiek 2010]

Example of LINEAR Correlation

$$\mathcal{O}_B = (D_\mu \Phi)^\dagger B^{\mu\nu} (D_\nu \Phi)$$

In unitary gauge can be rewritten as:

$$\mathcal{O}_B = \frac{ieg^2}{8} A_{\mu\nu} W^{-\mu} W^{+\nu} (v+h)^2 - \frac{ie^2 g}{8\cos\theta_W} Z_{\mu\nu} W^{-\mu} W^{+\nu} (v+h)^2$$
$$- \frac{eg}{4\cos\theta_W} A_{\mu\nu} Z^\mu \partial^\nu h (v+h) + \frac{e^2}{4\cos^2\theta_W} Z_{\mu\nu} Z^\mu \partial^\nu h (v+h)$$



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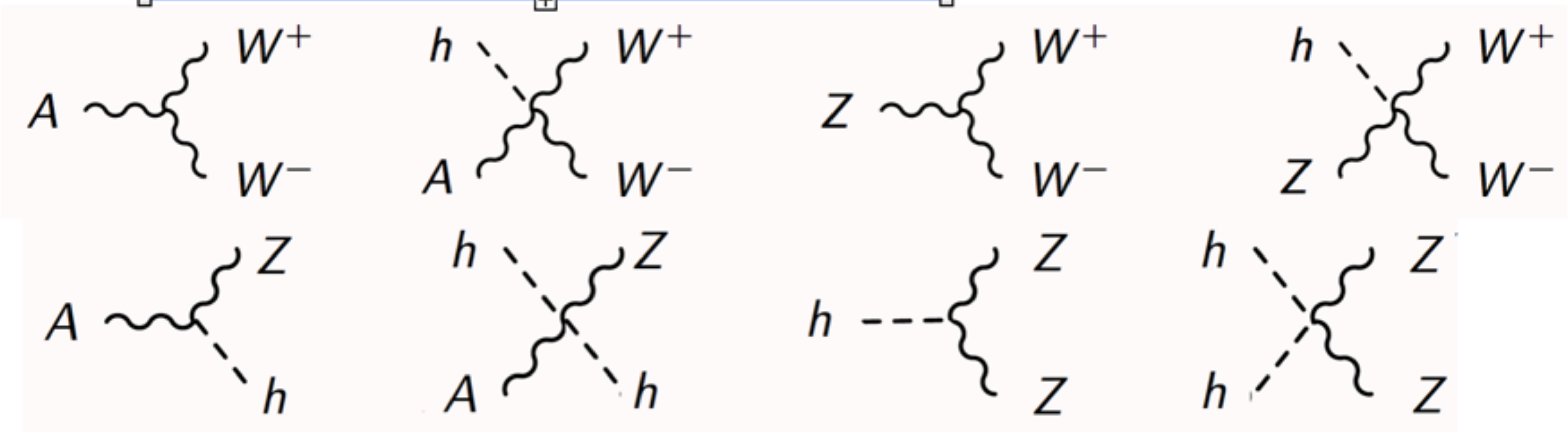


Higgs EFTs

Linear or **Chiral**

in linear: $\phi = (v + h)\ U \begin{pmatrix} 0 \\ 1 \end{pmatrix}$

physical Higgs

Godstone bosons = $e^{i\pi^a\sigma^a/v}$

Higgs EFTs

Linear or **Chiral**

in chiral: $\Phi \Rightarrow (v + h)\, U \begin{pmatrix} 0 \\ 1 \end{pmatrix}$

it becomes a generic function

$$\mathcal{F}(h) = 1 + 2a\frac{h}{v} + b\frac{h^2}{v^2} + \cdots \neq \left(1 + \frac{h}{v}\right)^n$$

with arbitrary coefficients a, b…

h is included as a generic singlet

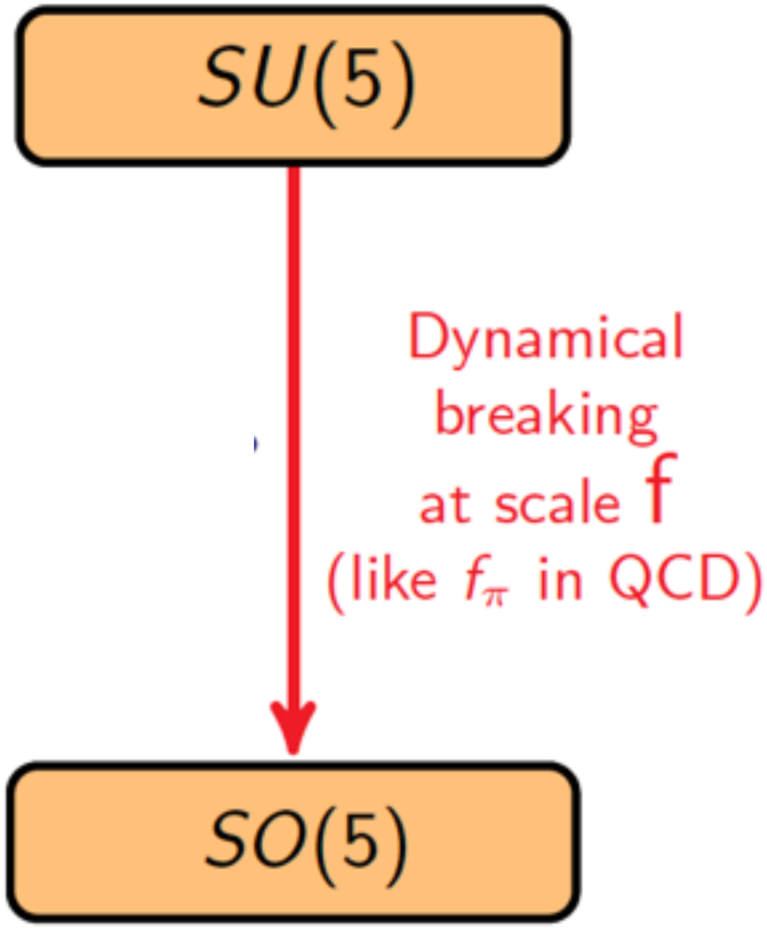
SM Higgs doublet recovered for a=b=1

Grinstein, Trott PRD76 073002
Contino et al. JHEP 1005 089

Generic F(h) is typical of composite Higgs models

h as a pseudo-goldstone boson

Georgi, Kaplan (1984)



Generic F(h) is typical of composite Higgs models

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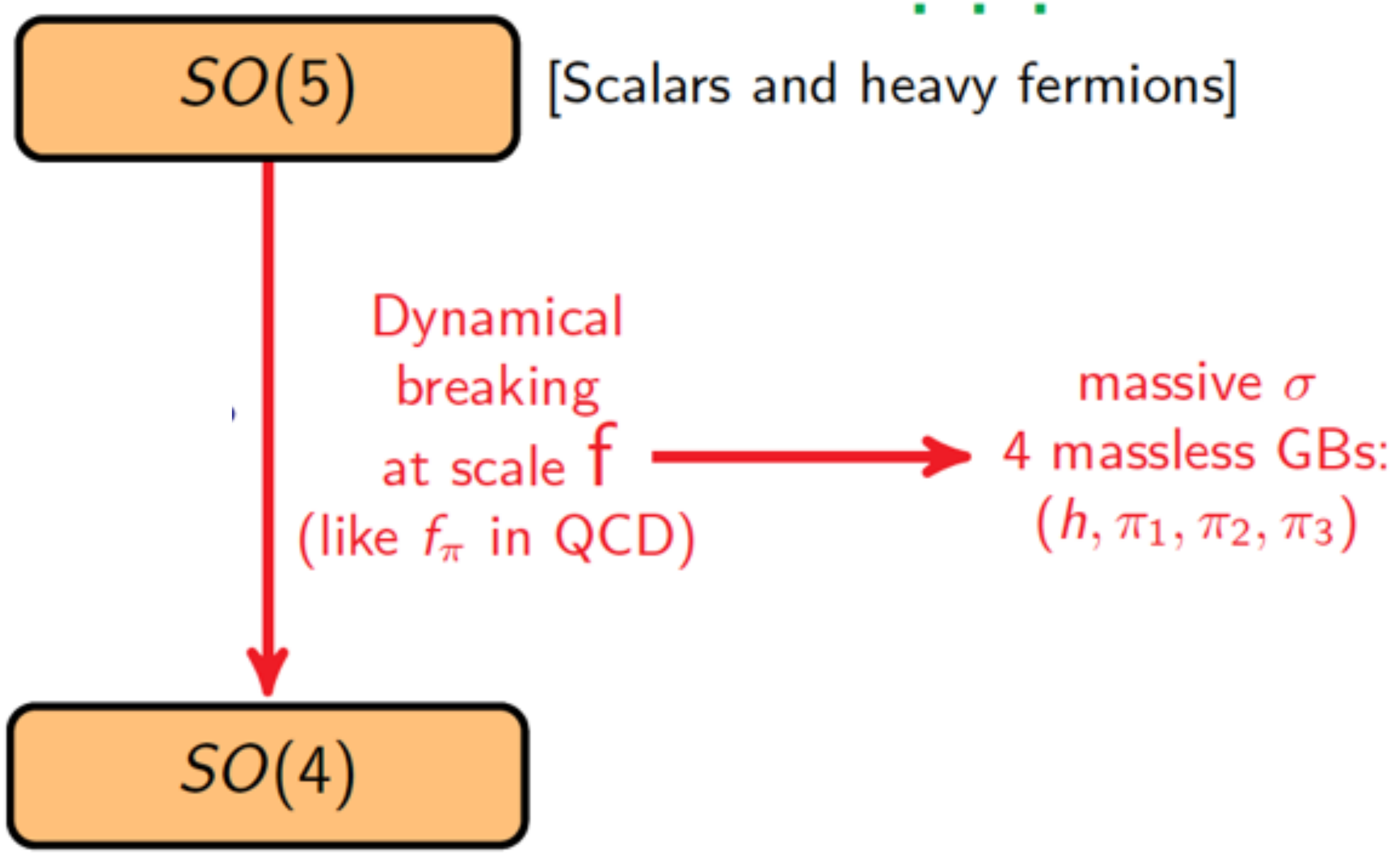
Agashe, Contino, Pomarol (2005)

. . .



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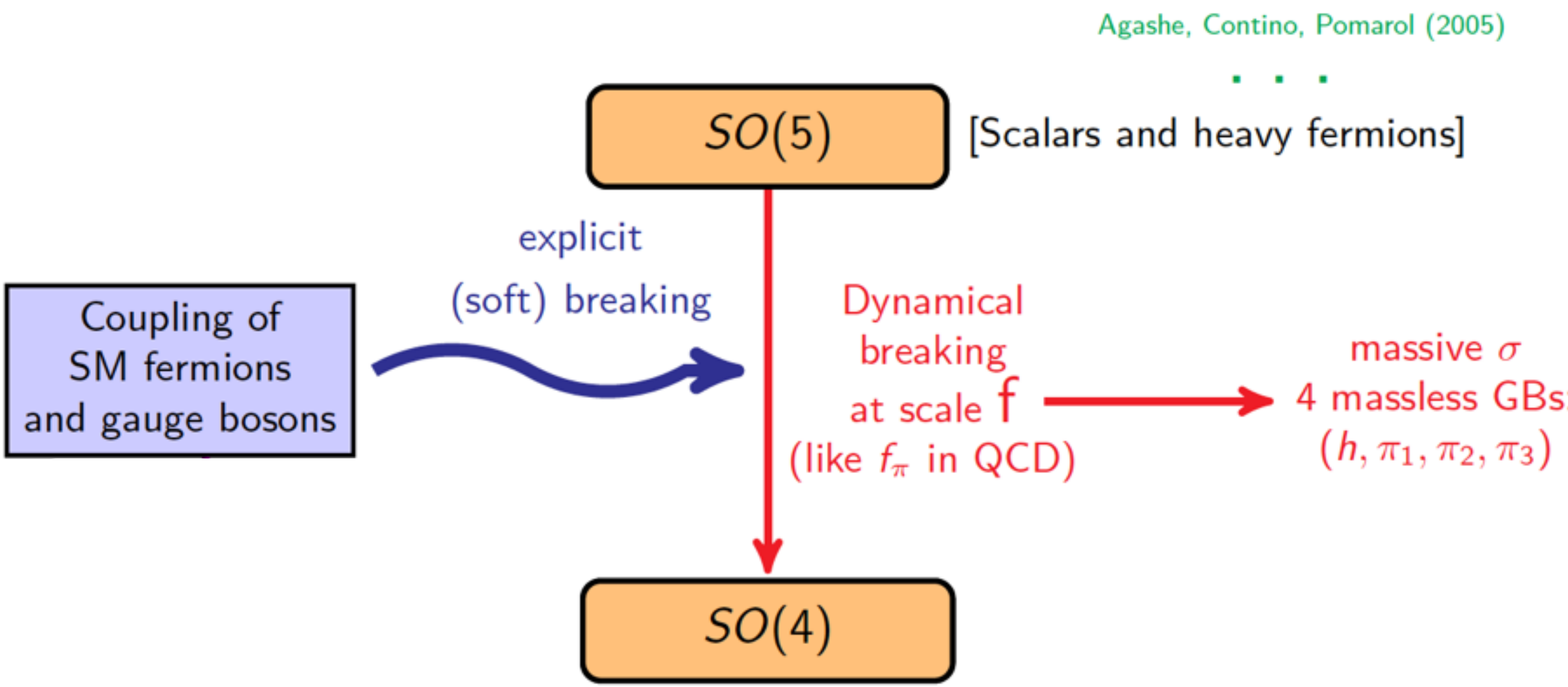

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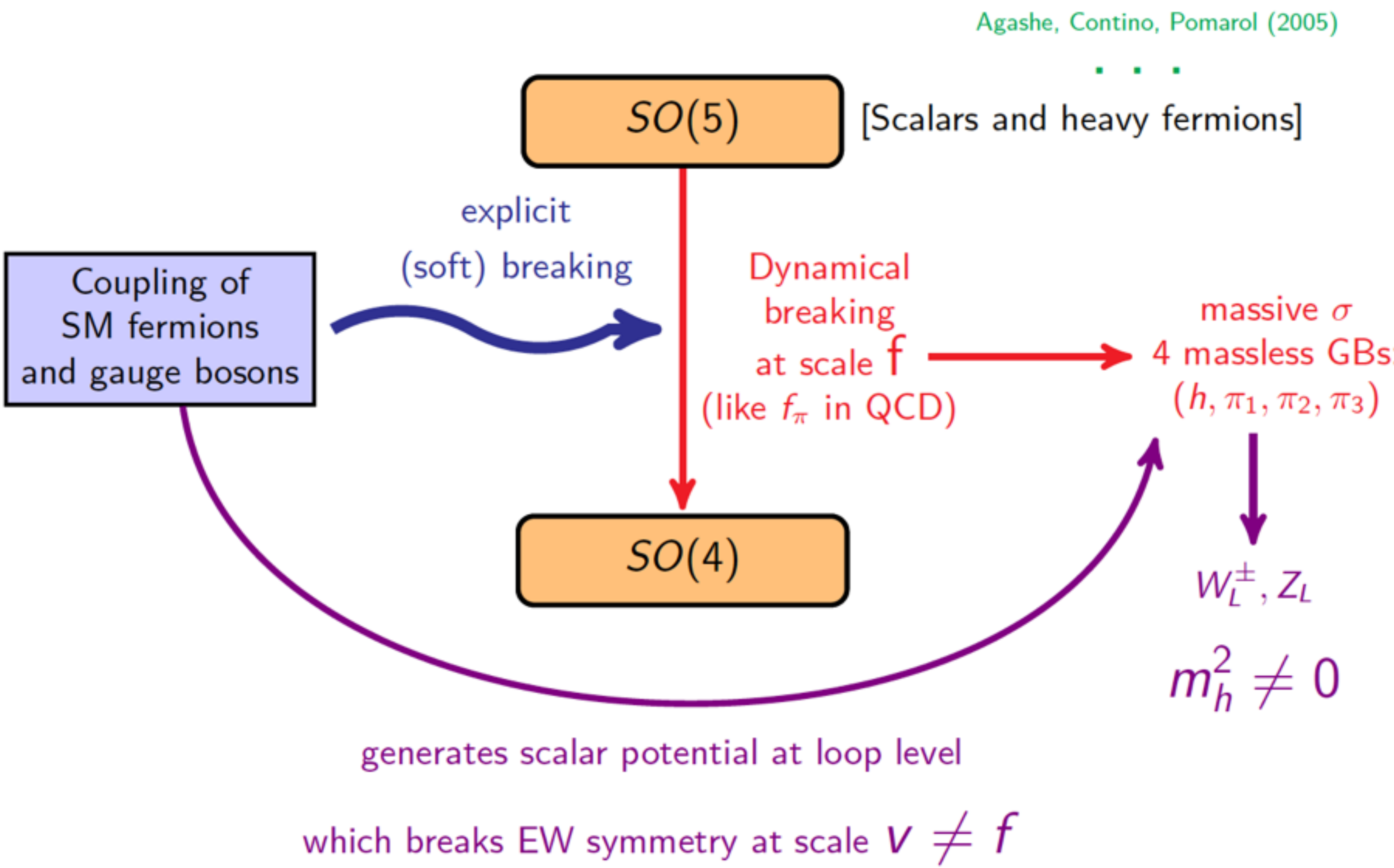

Generic F(h) is typical of composite Higgs models

h as a pseudo-goldstone boson

For instance:

instead of the SM coupling $(D_\mu\Phi^\dagger D^\mu \Phi) \supset 1/4\,(v+h)^2\,(D_\mu U^+ D^\mu U)$

SO(5)—> SO(4) leads to $\longrightarrow \dfrac{f^2}{4}\sin^2\left[\dfrac{\varphi}{2f}\right]\,(D_\mu U^+ D^\mu U)$

Agashe et al Nucl.Phys.B719 165

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SO(5)—> SO(4) leads to ⟶ $\frac{f^2}{4}\sin^2\left[\frac{\varphi}{2f}\right](D_\mu U^+ D^\mu U)$

F(h)

which implies $v \neq f$: $\xi \equiv \frac{v^2}{f^2} = 4\sin^2\frac{\langle\varphi\rangle}{2f}$

where: $\sin\left(\frac{\varphi}{2f}\right) = \frac{v}{2f}\cos\left(\frac{h}{2f}\right) + \sqrt{1-\frac{v^2}{4f^2}}\,\sin\left(\frac{h}{2f}\right)$

$$f^2\sin^2\left[\frac{\varphi}{2f}\right] \xrightarrow{\langle\varphi\rangle+h} v^2 + 2hv\sqrt{1+\frac{\xi}{4}} + h^2\left(1-\frac{\xi}{2}\right) + \cdots \neq (v+h)^2$$

Agashe et al Nucl.Phys.B719 165
Alonso et al JHEP 1412 034

Alonso, Brivio, Merlo, Rigolin, B.G.
hep-ph/1409.1589

$c_i\mathcal{F}_i(h)$	$SU(5)/SO(5)$ $SO(5)/SO(4)$	$SU(3)/SU(2)\times U(1)$	linear $d\leq 6$
$\mathcal{F}_C(h)$	$\frac{4}{\xi}\sin^2\frac{\varphi}{2f}$	$\frac{4}{\xi}\sin^2\frac{\varphi}{2f}$	$1+\frac{(v+h)^2}{2\Lambda^2}c_{\Phi 4}$
$\mathcal{F}_H(h)$	1	1	$1+\frac{(v+h)^2}{2\Lambda^2}(c_{\Phi 1}+2c_{\Phi 2}+c_{\Phi 4})$
$\mathcal{F}_B(h)$	$1-4g'^2\tilde{c}_{B\Sigma}\cos^2\frac{\varphi}{2f}$	$1-g'^2\frac{\tilde{c}_{B\Sigma}}{6}\left(1+3\cos\frac{2\varphi}{f}\right)$	$1+\frac{(v+h)^2}{2\Lambda^2}g'^2c_{BB}$
$\mathcal{F}_W(h)$	$1-4g^2\tilde{c}_{W\Sigma}\cos^2\frac{\varphi}{2f}$	$1-2g^2\tilde{c}_{W\Sigma}\cos\frac{\varphi}{f}$	$1+\frac{(v+h)^2}{2\Lambda^2}g^2c_{WW}$
$c_{\Box H}\mathcal{F}_{\Box H}(h)$	$-2\tilde{c}_6\xi$	$-2\tilde{c}_6\xi$	$\frac{v^2}{2\Lambda^2}c_{\Box\Phi}$
$c_{\Delta H}\mathcal{F}_{\Delta H}(h)$	–	–	–
$c_{DH}\mathcal{F}_{DH}(h)$	$4(\tilde{c}_4+\tilde{c}_5)\xi^2$	$2(2\tilde{c}_4+2\tilde{c}_5+\tilde{c}_7)\xi^2$	–
$c_1\mathcal{F}_1(h)$	$\tilde{c}_1\sin^2\frac{\varphi}{2f}$	$\frac{\tilde{c}_1}{4}\sin^2\frac{\varphi}{f}$	$\frac{(v+h)^2}{4\Lambda^2}c_{BW}$
$c_2\mathcal{F}_2(h)$	$\tilde{c}_2\sin^2\frac{\varphi}{2f}$	$\frac{\tilde{c}_2}{4}\sin^2\frac{\varphi}{f}$	$\frac{(v+h)^2}{8\Lambda^2}c_B$
$c_3\mathcal{F}_3(h)$	$2\tilde{c}_3\sin^2\frac{\varphi}{2f}$	$\frac{\tilde{c}_3}{2}\sin^2\frac{\varphi}{f}$	$\frac{(v+h)^2}{8\Lambda^2}c_W$
$c_4\mathcal{F}_4(h)$	$\tilde{c}_2\sqrt{\xi}\sin\frac{\varphi}{f}$	$\frac{\tilde{c}_2}{2}\sqrt{\xi}\sin\frac{2\varphi}{f}$	$\frac{v(v+h)}{2\Lambda^2}c_B$
$c_5\mathcal{F}_5(h)$	$-2\tilde{c}_3\sqrt{\xi}\sin\frac{\varphi}{f}$	$-2\tilde{c}_3\sqrt{\xi}\sin\frac{\varphi}{f}$	$-\frac{v(v+h)}{2\Lambda^2}c_W$
$c_6\mathcal{F}_6(h)$	$16\tilde{c}_4\sin^4\frac{\varphi}{2f}-\frac{1}{2}\tilde{c}_6\sin^2\frac{\varphi}{f}$	$8(2\tilde{c}_4+\tilde{c}_7)\sin^4\frac{\varphi}{2f}-\frac{1}{2}\tilde{c}_6\sin^2\frac{\varphi}{f}$	$\frac{(v+h)^2}{8\Lambda^2}c_{\Box\Phi}$
$c_7\mathcal{F}_7(h)$	$-2\tilde{c}_6\sqrt{\xi}\sin\frac{\varphi}{f}$	$-2\tilde{c}_6\sqrt{\xi}\sin\frac{\varphi}{f}$	$\frac{v(v+h)}{2\Lambda^2}c_{\Box\Phi}$
$c_8\mathcal{F}_8(h)$	$-16\tilde{c}_5\xi\sin^2\frac{\varphi}{2f}+4\tilde{c}_6\xi\cos^2\frac{\varphi}{2f}$	$-4(4\tilde{c}_5+\tilde{c}_7)\xi\sin^2\frac{\varphi}{2f}+4\tilde{c}_6\xi\cos^2\frac{\varphi}{2f}$	$-\frac{v^2}{\Lambda^2}c_{\Box\Phi}$
$c_9\mathcal{F}_9(h)$	$4\tilde{c}_6\sin^2\frac{\varphi}{2f}$	$4\tilde{c}_6\sin^2\frac{\varphi}{2f}$	$-\frac{(v+h)^2}{4\Lambda^2}c_{\Box\Phi}$
$c_{10}\mathcal{F}_{10}(h)$	$4\tilde{c}_6\sqrt{\xi}\sin\frac{\varphi}{f}$	$4\tilde{c}_6\sqrt{\xi}\sin\frac{\varphi}{f}$	$-\frac{v(v+h)}{\Lambda^2}c_{\Box\Phi}$
$c_{11}\mathcal{F}_{11}(h)$	$16\tilde{c}_5\sin^4\frac{\varphi}{2f}$	$16\tilde{c}_5\sin^4\frac{\varphi}{2f}$	–
$c_{20}\mathcal{F}_{20}(h)$	$-16\tilde{c}_4\xi\sin^2\frac{\varphi}{2f}$	$-4(4\tilde{c}_4+\tilde{c}_7)\xi\sin^2\frac{\varphi}{2f}$	–

Geometric interpretation of F(h)

Alonso, Jenkins, Manohar 1511.00724

Linear= flat GB metric ⟷ Chiral= curved GB metric

$$\mathscr{L} = \frac{1}{2} g_{\mathrm{ij}}(\phi)\, D_\mu \phi^{\mathrm{i}} D^\mu \phi^{\mathrm{j}}$$

h ↓ "Πs" ↓

$$g_{ij}(\phi) \equiv \begin{bmatrix} (1+h/v)^2 g_{ab}(\varphi) & 0 \\ 0 & 1 \end{bmatrix} \longleftrightarrow g_{\mathrm{ij}}(\phi) = \begin{bmatrix} F(h)^2 g_{ab}(\varphi) & 0 \\ 0 & 1 \end{bmatrix}$$

Riemann curvature tensor, Ricci tensor and Ricci scalar….

curvature param.—> $\mathfrak{r}_{0,2,4} \sim \frac{v^2}{f^2} \equiv \xi$

Higgs EFTs

Linear or **Chiral**

in chiral: $\phi \Rightarrow (v + h)\, U \begin{pmatrix} 0 \\ 1 \end{pmatrix}$

it becomes a generic function

$$\mathcal{F}(h) = 1 + 2a\frac{h}{v} + b\frac{h^2}{v^2} + \cdots \neq \left(1 + \frac{h}{v}\right)^n$$

with arbitrary coefficients a, b…

h is included as a generic singlet

SM Higgs doublet recovered for a=b=1

Grinstein, Trott PRD76 073002
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it becomes a generic function

independent !

some couplings decorrelate:
more operators

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Higgs EFTs

Linear or **Chiral**

$\Phi \Rightarrow (v + h)\, \mathbf{U} \begin{pmatrix} 0 \\ 1 \end{pmatrix}$

independent !

some couplings decorrelate:
more operators

in linear, correlations:

$$D_\mu \Phi \sim (v+h) D_\mu \mathbf{U} + \partial_\mu h \mathbf{U}$$

in chiral, decorrelations:

$D_\mu \mathbf{U}$ and $\partial_\mu h$ independent

Higgs EFTs

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in chiral: $\phi \Rightarrow (v + h)\, U \begin{pmatrix} 0 \\ 1 \end{pmatrix}$

it becomes a generic function

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some couplings decorrelate: more operators

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with arbitrary coefficients a, b…

h is included as a generic **singlet**

SM Higgs doublet recovered for a=b=1

no bias about the connection between the physical h and the field that triggers EWSB

Example of LINEAR Correlation

$$\mathcal{O}_B = (D_\mu \Phi)^\dagger B^{\mu\nu} (D_\nu \Phi)$$

In unitary gauge can be rewritten as:

$$\mathcal{O}_B = \frac{ieg^2}{8} A_{\mu\nu} W^{-\mu} W^{+\nu} (v+h)^2 - \frac{ie^2 g}{8 \cos\theta_W} Z_{\mu\nu} W^{-\mu} W^{+\nu} (v+h)^2$$
$$- \frac{eg}{4\cos\theta_W} A_{\mu\nu} Z^\mu \partial^\nu h (v+h) + \frac{e^2}{4\cos^2\theta_W} Z_{\mu\nu} Z^\mu \partial^\nu h (v+h)$$

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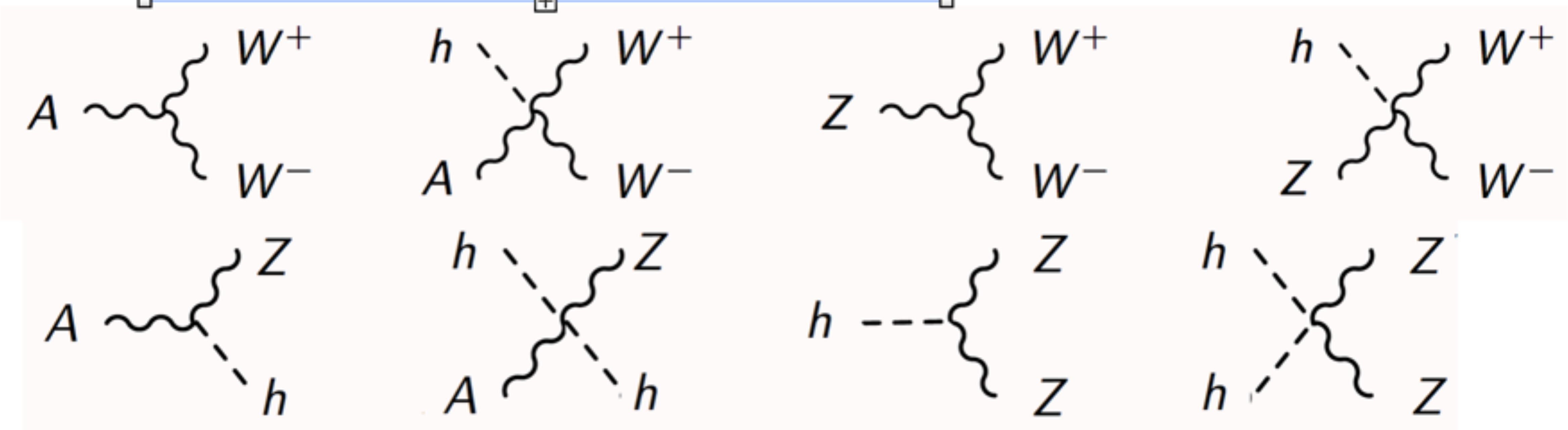


Example of CHIRAL Decorrelation

$$\mathcal{O}_B = (D_\mu \Phi)^\dagger \hat{B}^{\mu\nu} (D_\nu \Phi)$$

Chiral basis

$D^\nu \mathbf{U}$ $\qquad$ $\partial^\nu h$

$\mathcal{P}_2 = ig' B_{\mu\nu} \, \mathrm{Tr}(\mathbf{T}[\mathbf{V}^\mu, \mathbf{V}^\nu]) \mathcal{F}_2(h)$

$\mathcal{P}_4 = ig' B_{\mu\nu} \, \mathrm{Tr}(\mathbf{T}\mathbf{V}^\mu) \partial^\nu \mathcal{F}_4(h)$

$\mathbf{V}_\mu = (D_\mu \mathbf{U}) \mathbf{U}^\dagger$

$\mathbf{T} = \mathbf{U} \sigma^3 \mathbf{U}^\dagger$

Example of CHIRAL Decorrelation

$$\mathcal{O}_B = (D_\mu \Phi)^\dagger \hat{B}^{\mu\nu} (D_\nu \Phi)$$

Chiral basis

$D^\nu \mathbf{U}$ → $\mathcal{P}_2 = i g' B_{\mu\nu} \, \mathrm{Tr}(\mathbf{T}[\mathbf{V}^\mu, \mathbf{V}^\nu]) \mathcal{F}_2(h)$

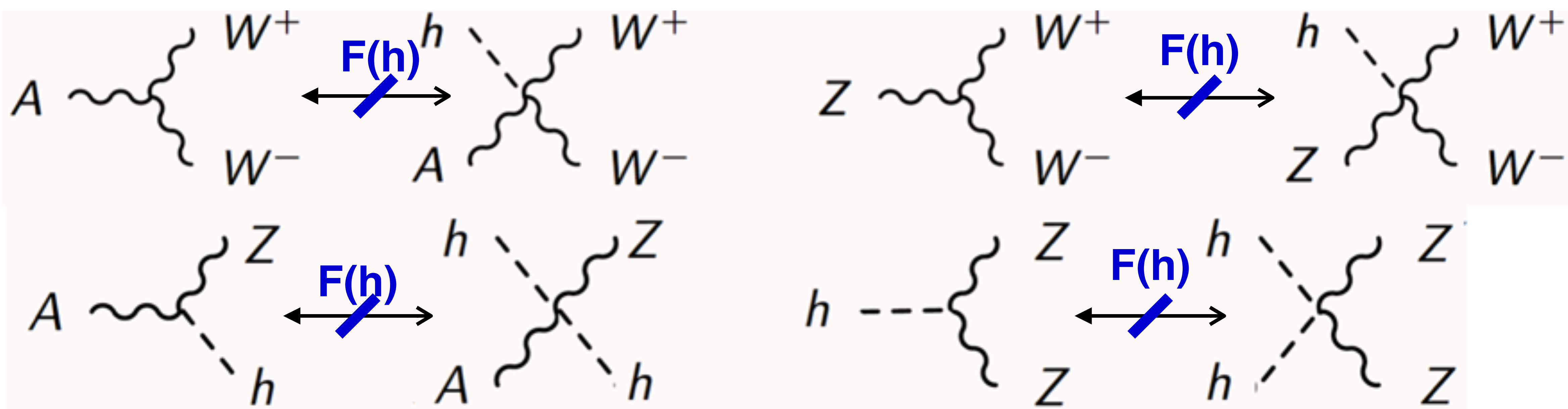
$\partial^\nu h$ → $\mathcal{P}_4 = i g' B_{\mu\nu} \, \mathrm{Tr}(\mathbf{T}\mathbf{V}^\mu) \partial^\nu \mathcal{F}_4(h)$

$\mathbf{V}_\mu = (D_\mu \mathbf{U}) \mathbf{U}^\dagger$

$\mathbf{T} = \mathbf{U} \sigma^3 \mathbf{U}^\dagger$

Decorrelations appear

1) because of the F(h) :



Isidori, Trott, 1307.4501

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Chiral basis

$D^\nu \mathbf{U}$ $\qquad$ $\partial^\nu h$

$$\mathcal{P}_2 = i g' B_{\mu\nu} \,\mathrm{Tr}(\mathbf{T}[\mathbf{V}^\mu, \mathbf{V}^\nu]) \mathcal{F}_2(h)$$

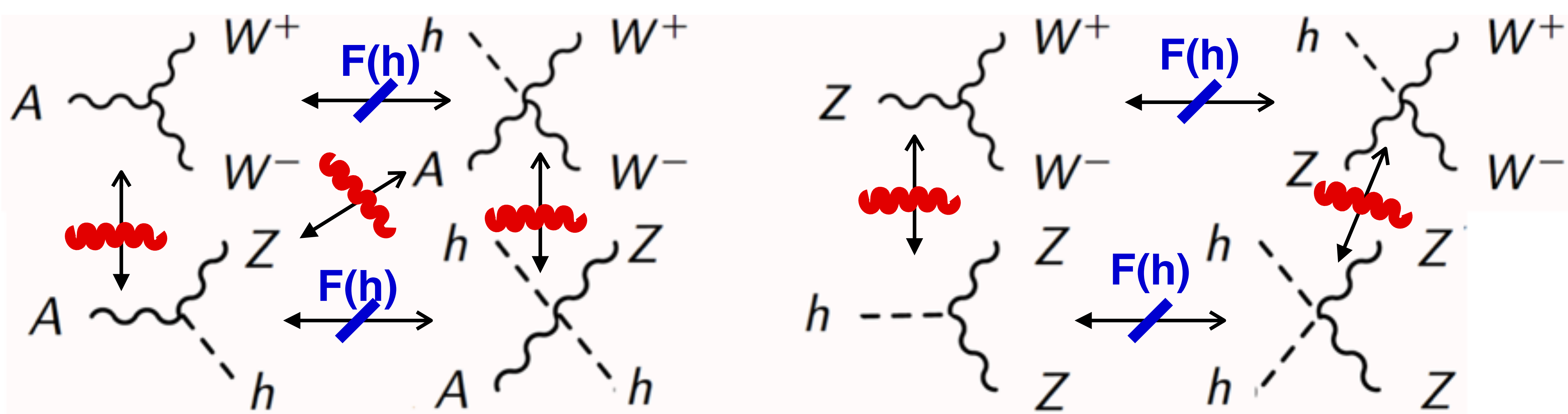
$$\mathcal{P}_4 = i g' B_{\mu\nu} \,\mathrm{Tr}(\mathbf{T}\mathbf{V}^\mu) \partial^\nu \mathcal{F}_4(h)$$

$$\mathbf{V}_\mu = (D_\mu \mathbf{U})\mathbf{U}^\dagger$$

$$\mathbf{T} = \mathbf{U}\sigma^3 \mathbf{U}^\dagger$$

Decorrelations appear

2) because of the :



in fact, all decor related related vertically

Higgs EFTs

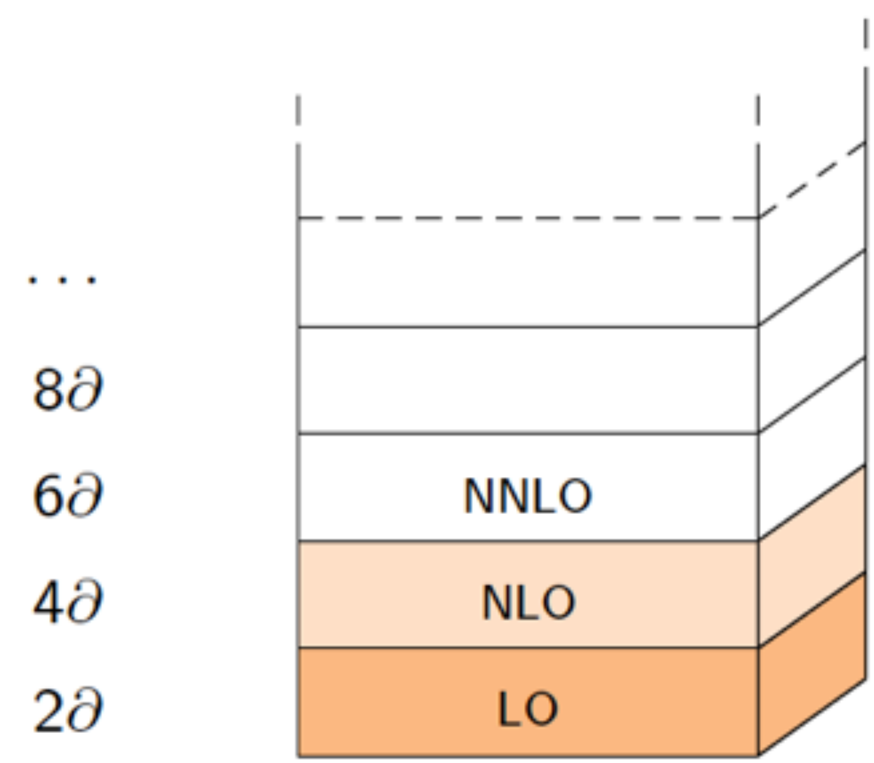
Linear or **Chiral**

in chiral: $\phi \rightarrow F(h)\, U \begin{pmatrix} 0 \\ 1 \end{pmatrix}$

Godstone bosons = $e^{i\pi^a\sigma^a/v}$

U adimensional

Expansion in derivatives: D_μ/Λ :



In EFT, the weight of h is arbitrary
we use h/v, but the conclusions
would be the same with h/f

Some recent bibliography

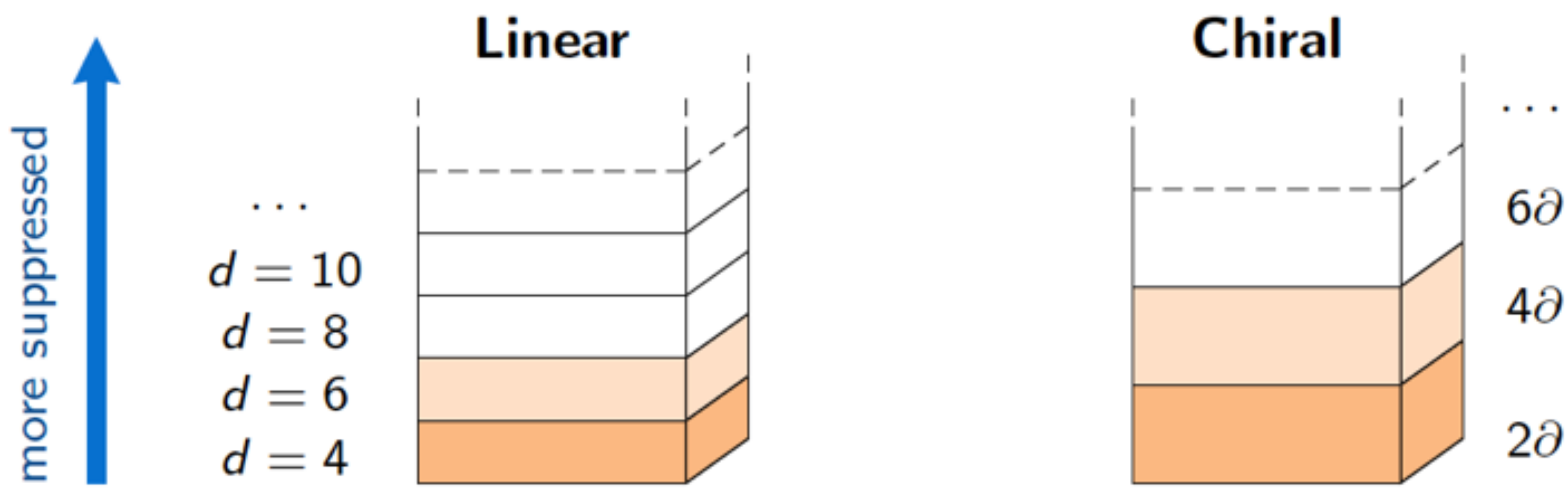
bosonic sector only	NLO (4∂) basis	Alonso et al. Phys.Lett.B722 330
	phenomenology	Brivio et al. JHEP 1403 024 Brivio et al. JHEP 1412 004 Gavela et al. JHEP 1410 44
	connection to composite Higgs models	Alonso et al. JHEP 1412 034 Hierro et al. 1510.07899
	one-loop renormalization	Gavela et al. JHEP 1503 043
with fermionic sector	complete NLO basis	Buchalla et al. Nucl.Phys.B880 552

Higgs EFTs

Linear versus **Chiral**

Equivalent when considering the whole tower: all couplings contained.

The expansions are physically inequivalent.



Higgs EFTs

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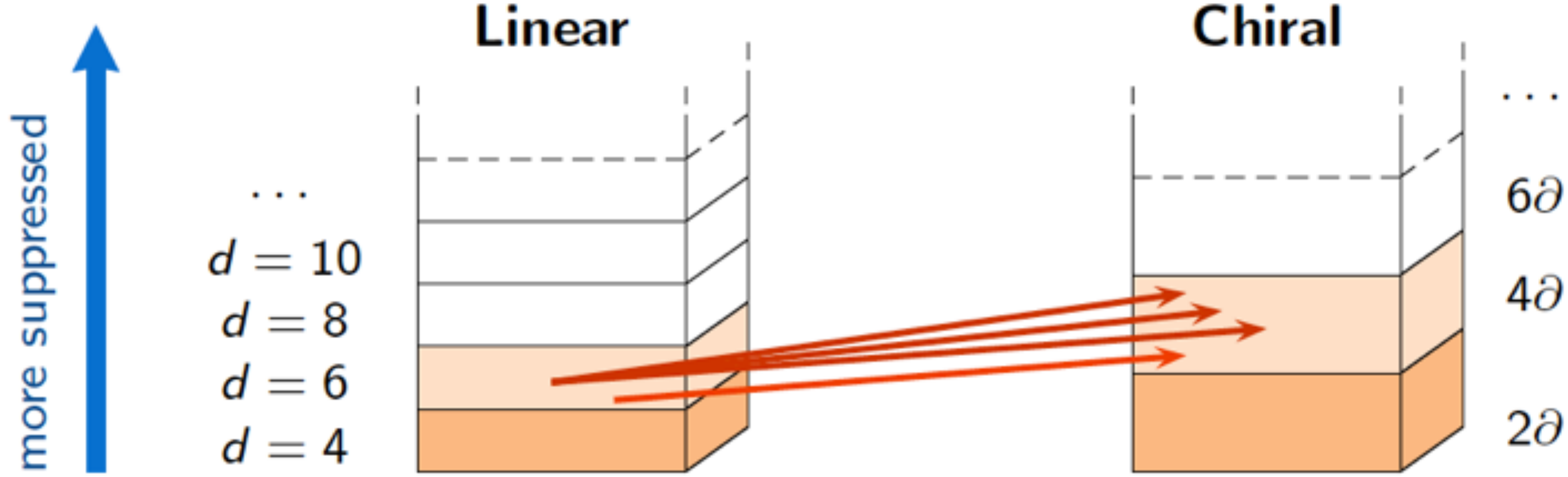


correlations:
$D_\mu \Phi \sim (v + h) D_\mu \mathbf{U} + \partial_\mu h \mathbf{U}$

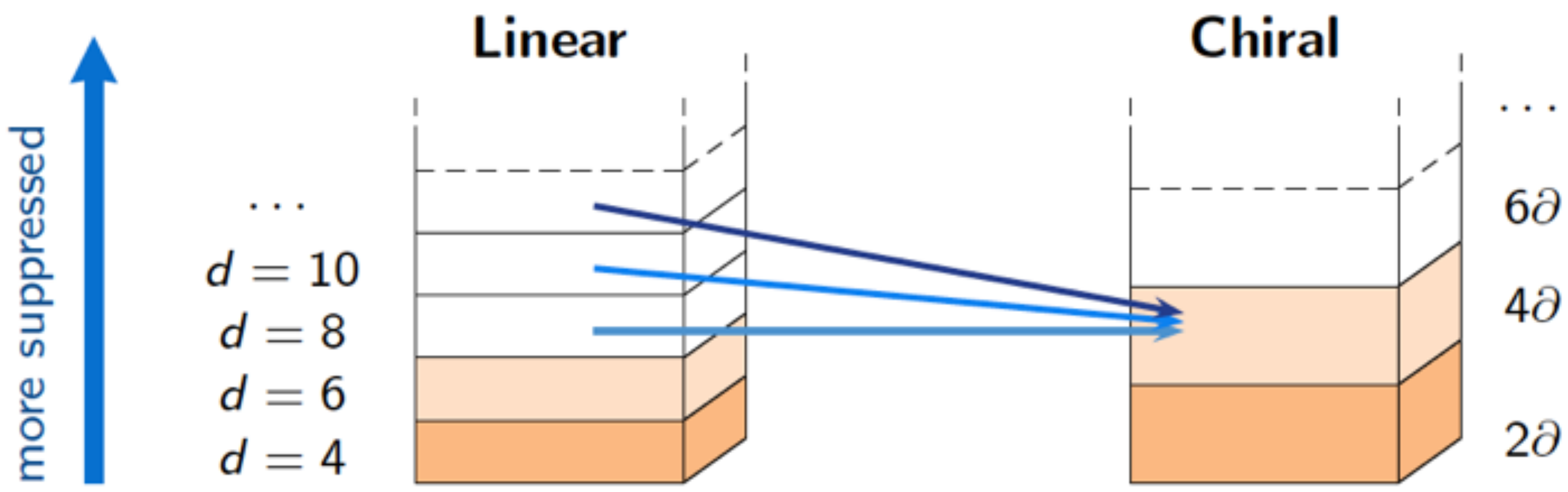
decorrelations:
$D_\mu \mathbf{U}$ and $\partial_\mu h$ independent

Higgs EFTs

Linear versus **Chiral**

Equivalent when considering the whole tower: all couplings contained.

The expansions are physically inequivalent.



Disentangling LINEAR signals from CHIRAL signals

Isidori, Trott; hep-ph/1307.4051

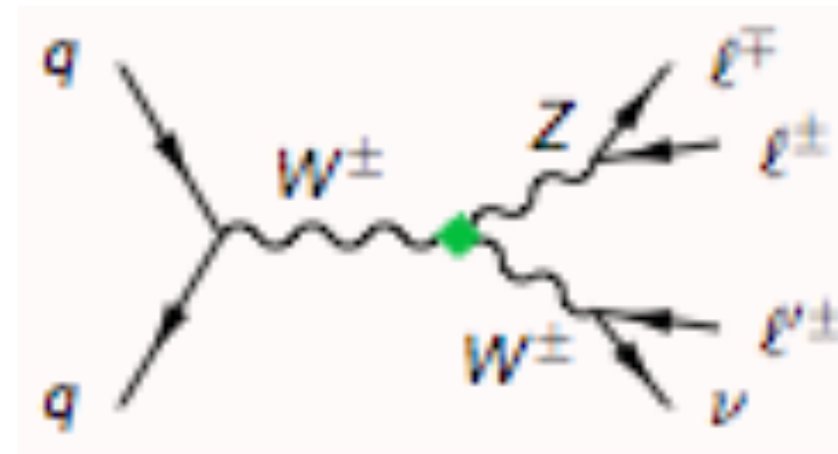
Brivio, Corbett, Evoli, Gonzalez-Garcia, Gonzalez-Fraile, Merlo, Rigolin, BG; JHEP 1403 (2014) 024

Brivio, Corbett, Evoli, Gonzalez-Garcia, Gonzalez-Fraile, Merlo, Rigolin, BG; JHEP 1412 (2014) 004

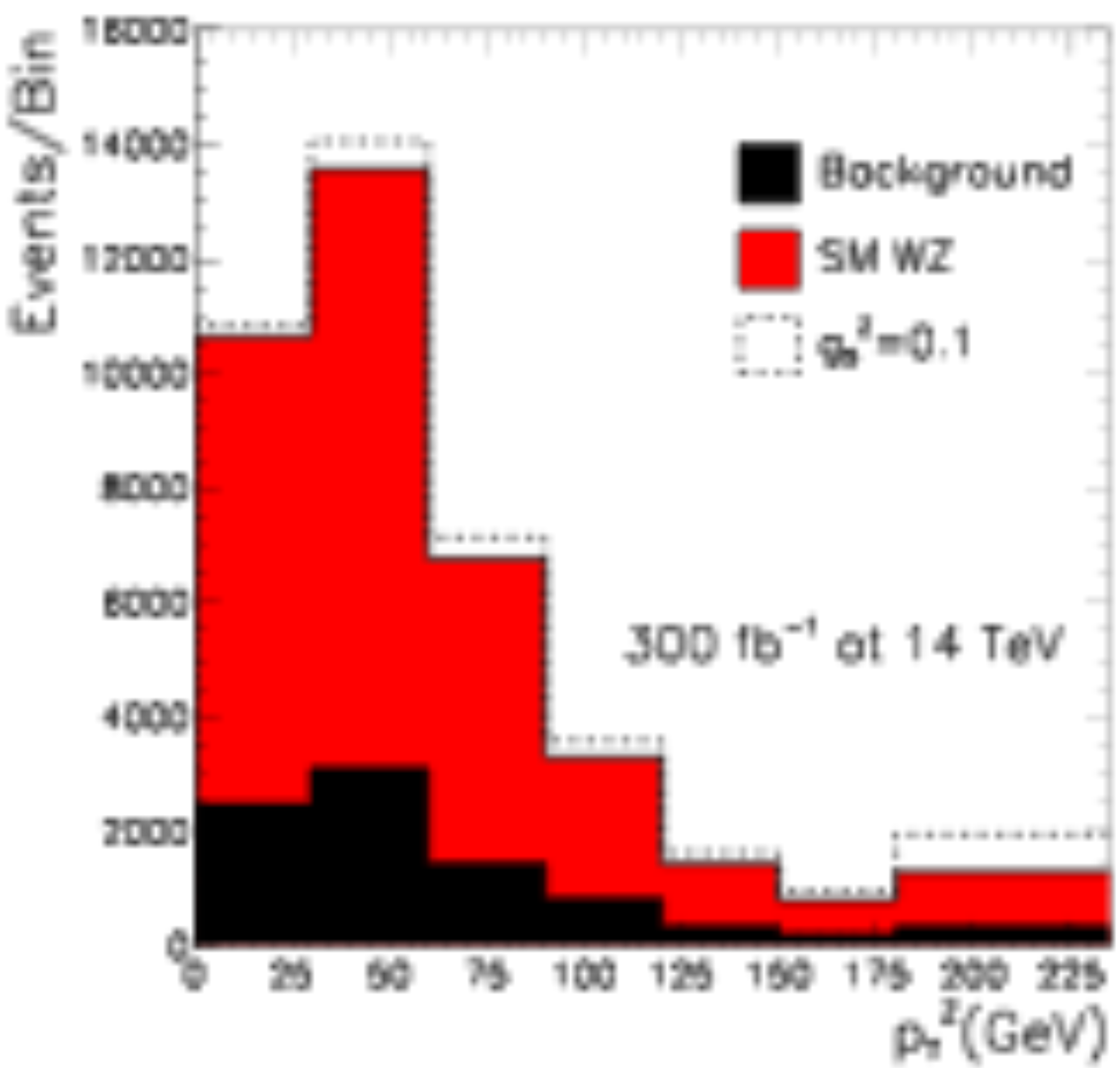
New Signals

<u>A coupling that appears at NLO in the chiral and NNLO (d=8) in linear</u>

$$\varepsilon^{\mu\nu\rho\lambda}\partial_\mu W^+_\nu W^-_\rho Z_\lambda \mathcal{F}_{14}(h)$$



number of expected events (WZ production) with respect to the Z p_T



@95% CL:

present $g_5^Z \in [-0.08, 0.04]$

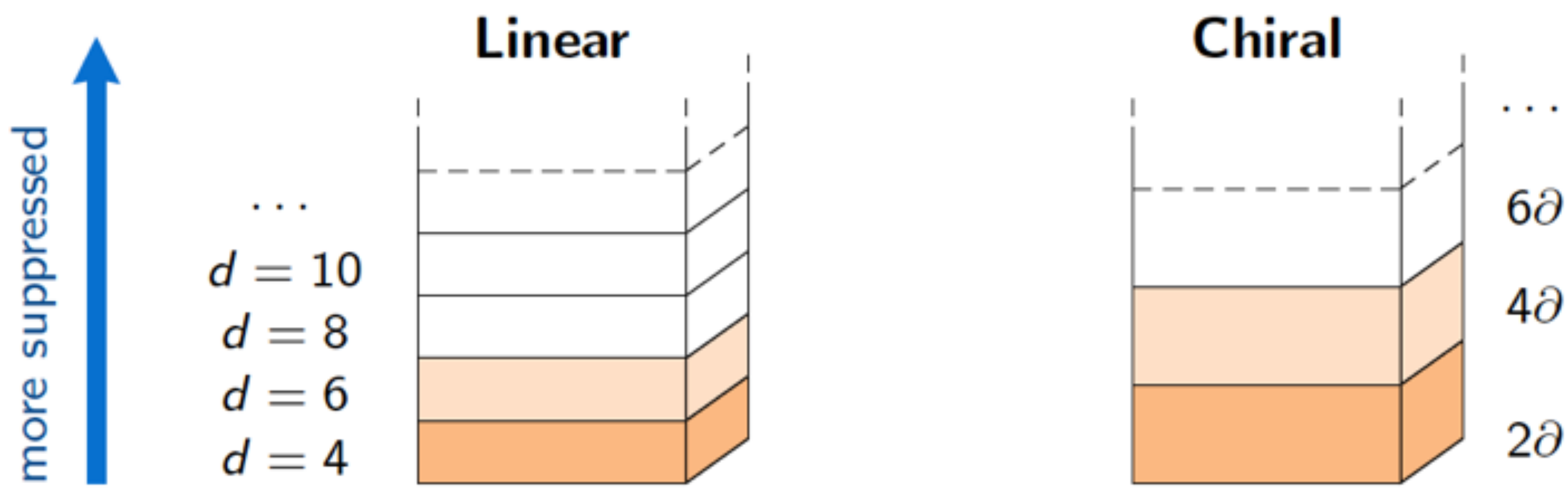
LHC(7+8+14) $g_5^Z \in [-0.033, 0.028]$

Higgs EFTs

Linear versus **Chiral**

Equivalent when considering the whole tower: all couplings contained.

The expansions are physically inequivalent.



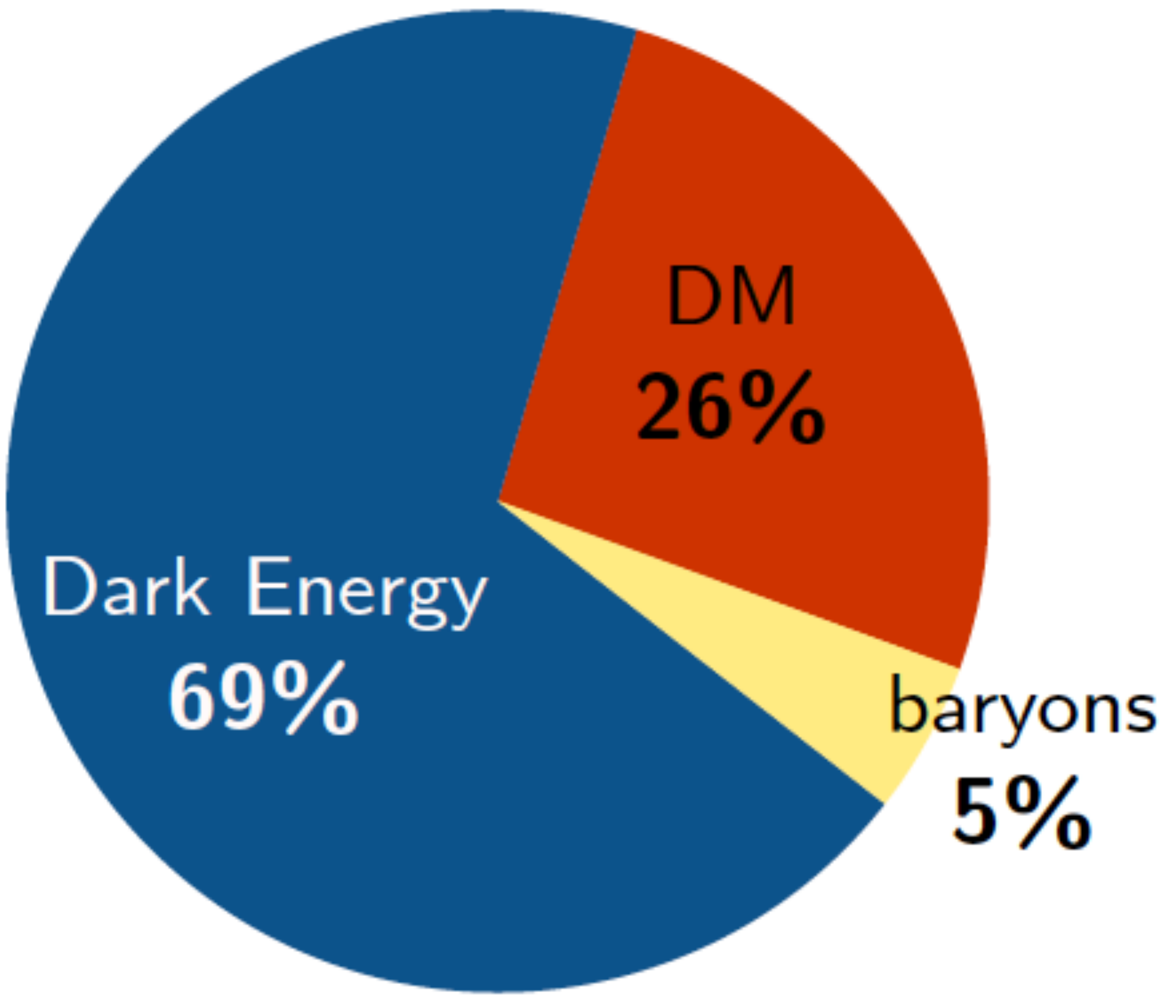
The chiral expansion is more general than the linear one

* **It contains the linear EFT in a specific limit**
* **It allows to ask the question of whether the Higgs field is an exact doublet or not**

Higgs portals to Dark Matter

hep-ph/1511.01099

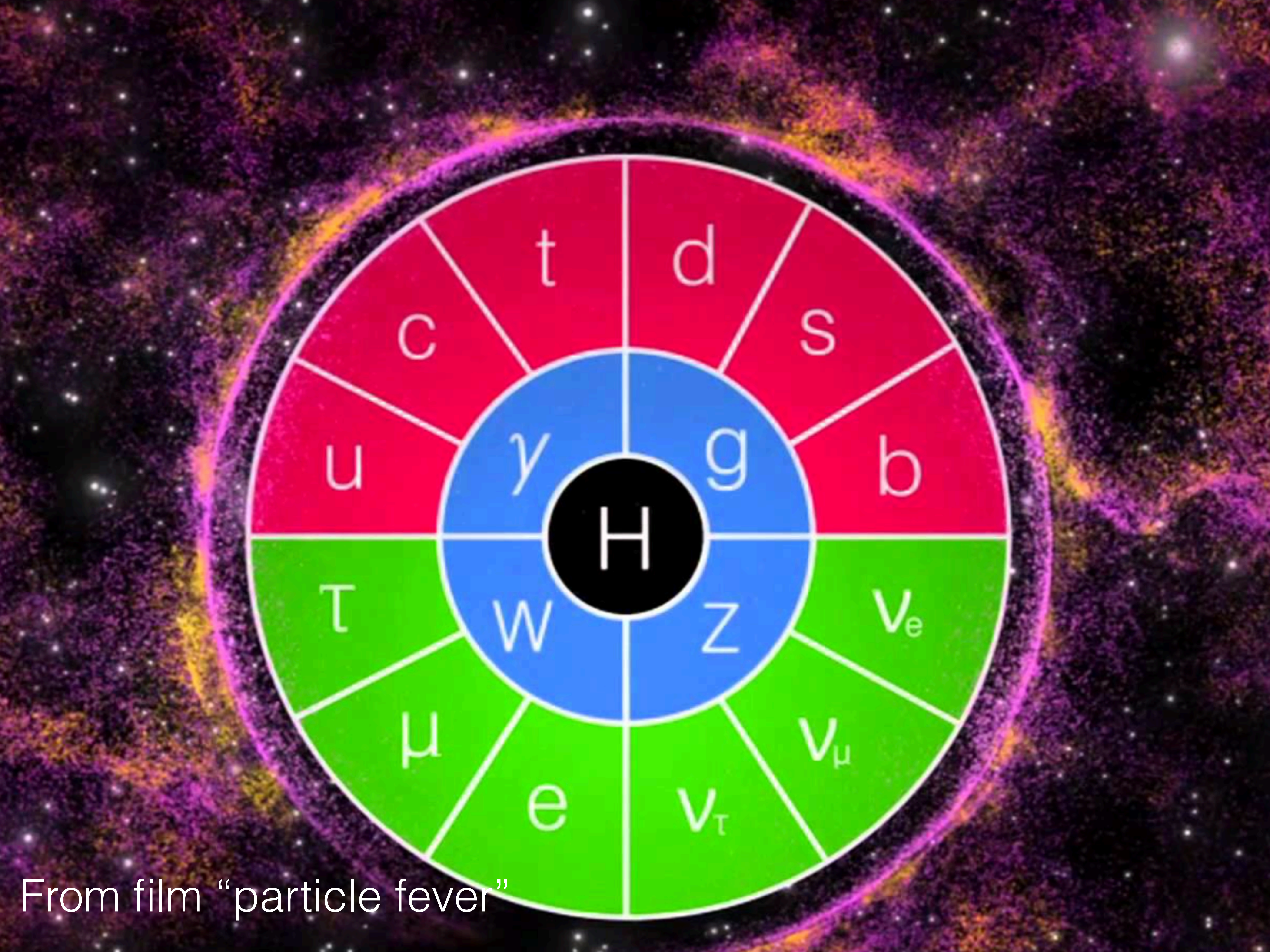
I. Brivio, L. Merlo, K. Mimasu, J.M. No,
R. del Rey, V. Sanz, BG



*** The presence of DM is only inferred through gravitational effects**

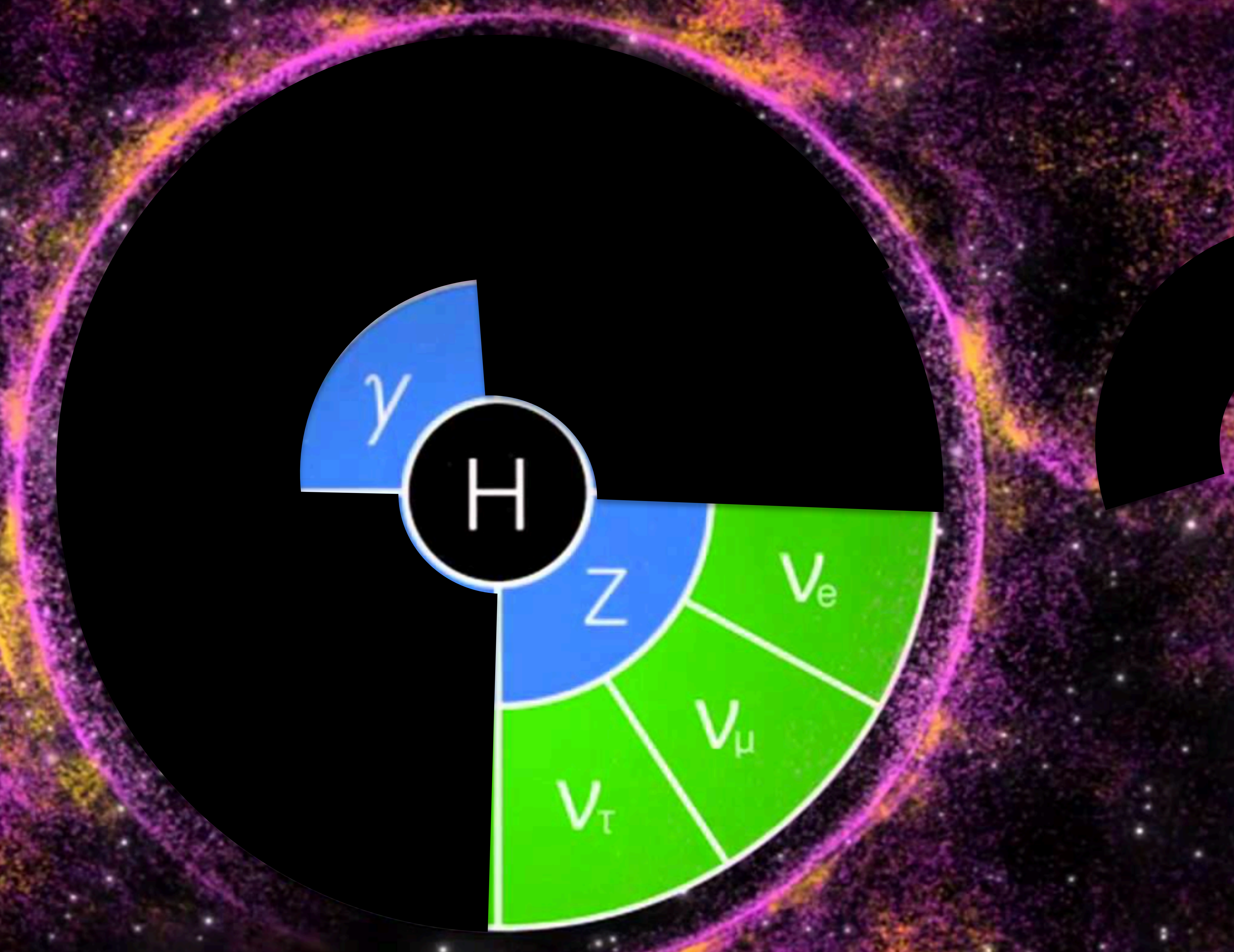
*** It is** (mainly?) **a singlet under the SM**

–> Does DM interact sizeably with visible matter?
We don't know, but worth exploring



From film “particle fever”

SM “PORTALS” TO THE DARK SECTORS



SM portals to the dark sectors

Only three singlet combinations in SM with d < 4:

SM Higgs doublet → $\Phi^{+}\Phi$ **Scalar**

$B_{\mu\nu}$ **Vector**

$\bar{L}\,H$ **Fermionic**

Any hidden sector, singlet under SM, can couple to the dark portals

SM portals to the dark sectors

Only three singlet combinations in SM with d < 4:

$\Phi^{+}\Phi\, S$ **Scalar**

$B_{\mu\nu}\, V^{\mu\nu}$ **Vector**

$\bar{L}\, H\, \Psi$ **Fermionic**

Any hidden sector, singlet under SM, can couple to the dark portals

SM portals to the dark sectors

Only three singlet combinations in SM with d < 4:

$\Phi^{+}\Phi\, S^{2}$	**Scalar**	(stable DM)
$B_{\mu\nu}\; V^{\mu\nu}$	**Vector**	
$\bar{L}\; H\; \Psi$	**Fermionic**	

Any hidden sector, singlet under SM, can couple to the dark portals

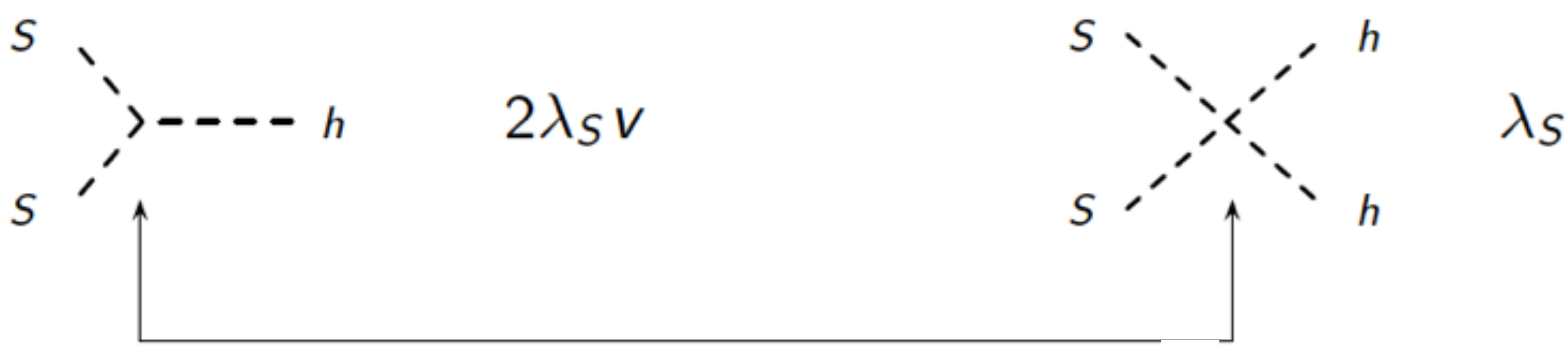
SM standard Higgs portal to DM

Silveira + Zee ;
Veltman+ Yndurain;
Patt + Wilczek

Consider a singlet scalar DM particle **S**

$$\lambda_S \, \Phi^+ \Phi \, S^2$$

$$(v + h)^2 = v^2 + 2vh + h^2$$



correlated: fixed relative strength v

which impacts directly on the DM relic abundance

SM standard Higgs portal to DM

Silveira + Zee ;
Veltman+ Yndurain;
Patt + Wilczek

Consider a singlet scalar DM particle **S**

portal

$$\mathscr{L} = \mathscr{L}_{SM} + \mathscr{L}_S$$

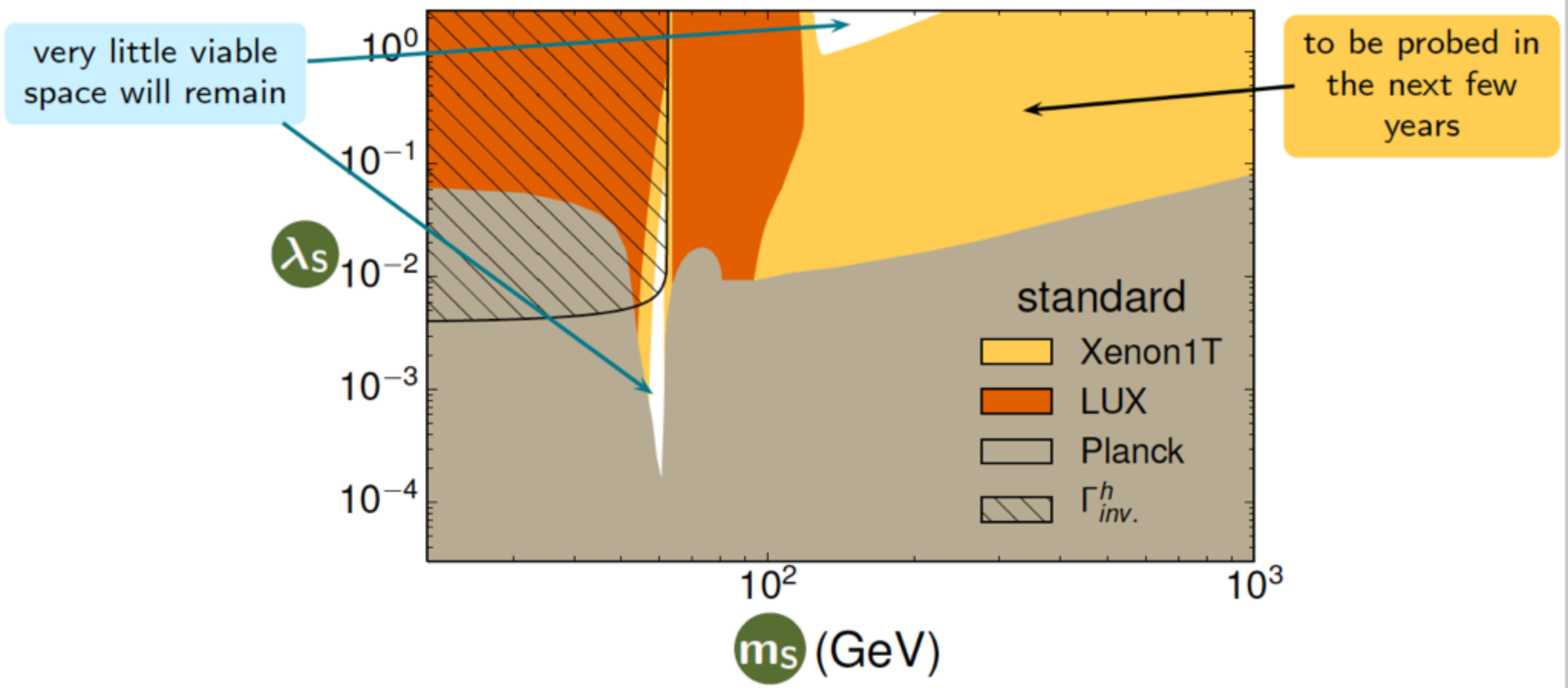
$$\mathscr{L}_S = \frac{1}{2}\partial_\mu S \partial^\mu S - \frac{\mu_S}{2} S^2 + \lambda_S (\Phi^\dagger \Phi) S^2 + \kappa S^4$$

$$\mathscr{L}_S = \frac{1}{2}\partial_\mu S \partial^\mu S - \frac{m_S}{2} S^2 + \frac{\lambda_S}{2} S^2 \left(2vh + h^2\right) + \dots$$

correlated: fixed relative strength

SM Higgs portal

$$\mathscr{L}_S = \frac{1}{2}\partial_\mu S \partial^\mu S - \frac{m_S}{2} S^2 - \lambda_S S^2 \left(2vh + h^2\right) + \ldots$$



Exclusion regions inferred from different eperimental measurements.
Yellow : within the 95% CL projected sensitivity of Xenon1T

recent analyses:
Cline et al. PRD88 055025
Feng et al. JHEP 1503 045

I. Brivio

New

Brivio et al. 1511.01099

Linear versus **Chiral**

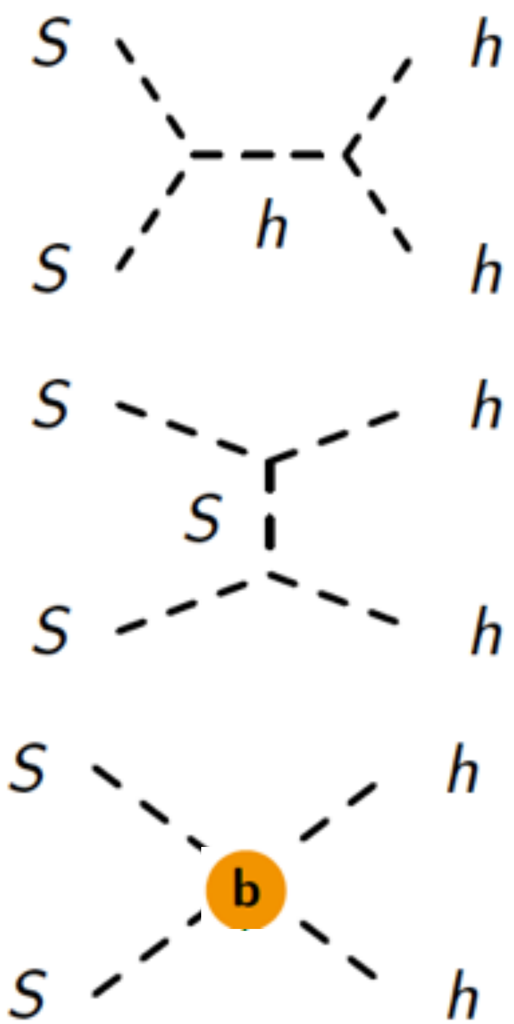
$\lambda_S \, \Phi^+ \Phi \, S^2 \longrightarrow \lambda_S \, F(h) \, S^2$

$(2vh + h^2)\, S^2 \longrightarrow (2vh + b\, h^2)\, S^2$

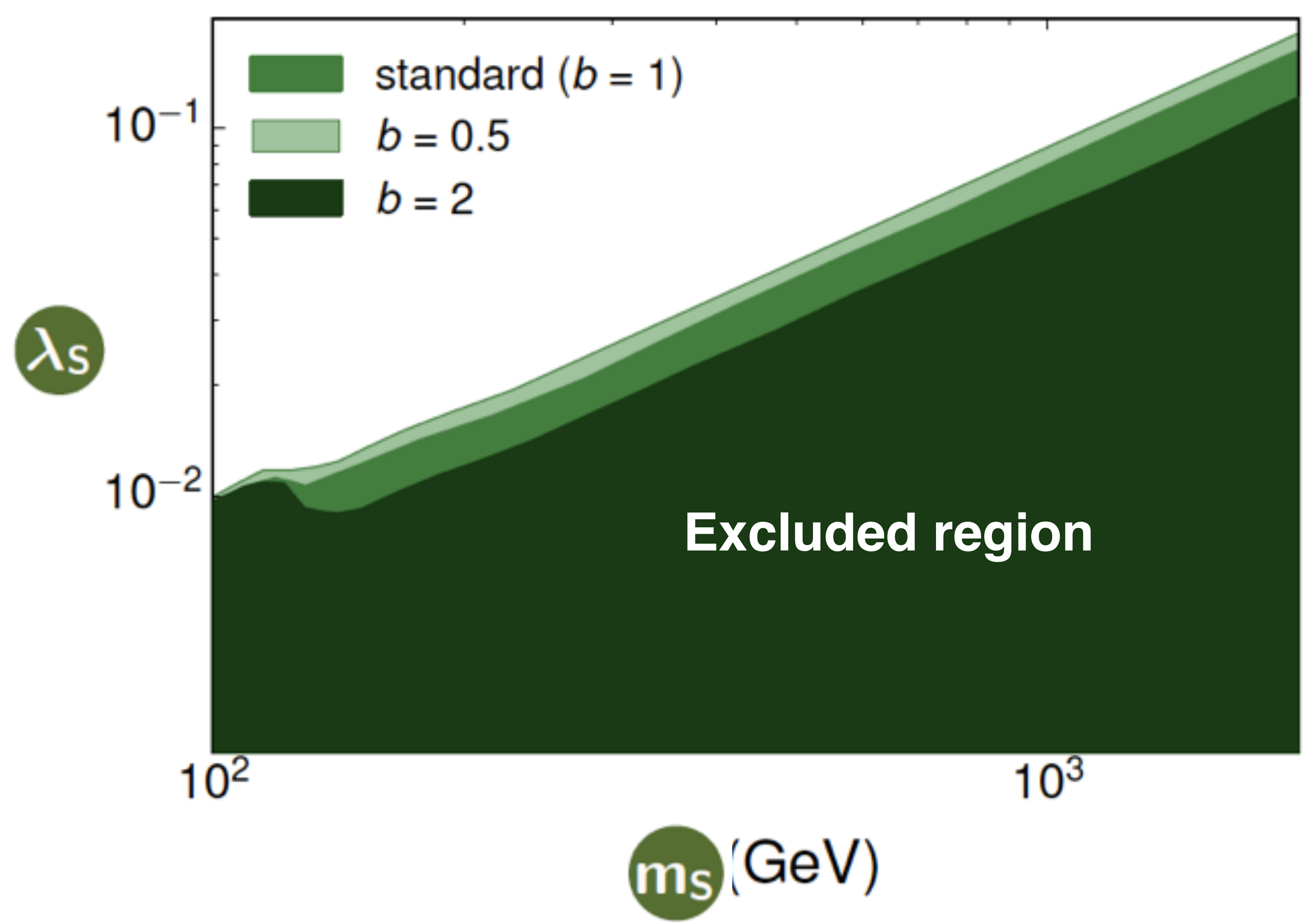
arbitrary coefficient

Relic abundance

Dominant contributions
for $m_S > m_h$



imposing $\Omega_S \leqslant \Omega_{DM}$



Linear versus **Chiral**

New

Brivio et al. 1511.01099

$$\lambda_S\, \Phi^+ \Phi\, S^2 \longrightarrow \lambda_S\, F(h)\, S^2$$

$$(2vh + h^2)\, S^2 \longrightarrow (2vh + \mathbf{b}\, h^2)\, S^2$$

arbitrary coefficient

and also new couplings appear —>

At the leading chiral order (2 derivatives), other couplings appear:

$$\mathscr{L}_S = \frac{1}{2}\partial_\mu S \partial^\mu S - \frac{m_S}{2} S^2 - \lambda_S S^2 \left(2vh + b\, h^2\right) + \sum_{i=1}^{5} c_i \mathcal{A}_i + \dots$$

$$\mathcal{A}_1 = \mathrm{Tr}(D_\mu \mathbf{U} D^\mu \mathbf{U}^\dagger) S^2 \mathcal{F}_1(h)$$

$$\mathcal{A}_2 = S^2 \Box \mathcal{F}_2(h)$$

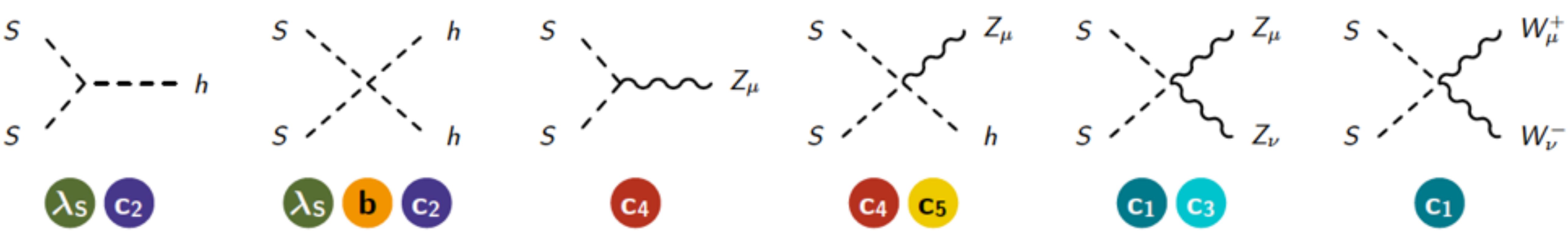
$$\mathcal{A}_3 = \mathrm{Tr}(D_\mu \mathbf{U} \sigma^3 \mathbf{U}^\dagger)^2 S^2 \mathcal{F}_3(h)$$

$$\mathcal{A}_4 = i\, \mathrm{Tr}(D_\mu \mathbf{U} \sigma^3 \mathbf{U}^\dagger)(\partial^\mu S^2) \mathcal{F}_4(h)$$

$$\mathcal{A}_5 = i\, \mathrm{Tr}(D_\mu \mathbf{U} \sigma^3 \mathbf{U}^\dagger) S^2 \partial^\mu \mathcal{F}_5(h)$$

where: $\mathcal{F}_i(h) = 1 + 2a_i \frac{h}{v} + b_i \frac{h^2}{v^2} + \dots$

several different couplings:



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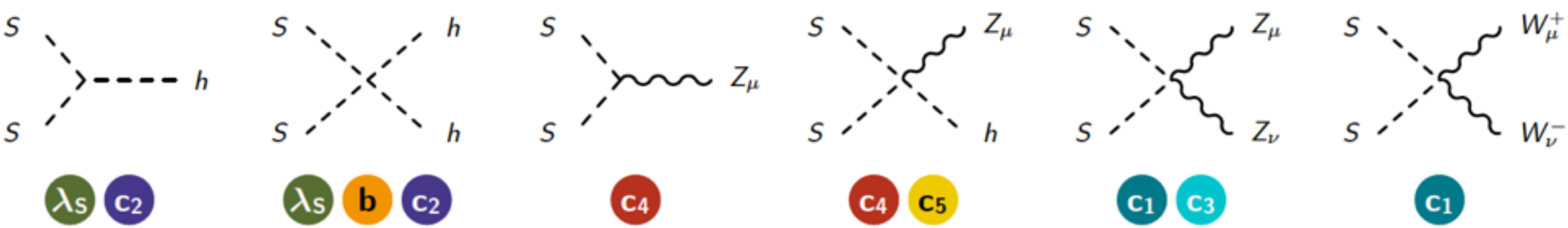
only $\mathcal{A}_3$ contributes to the ρ parameter (at one-loop) $\downarrow$ $c_3 \lesssim 0.1$

where: $\mathcal{F}_i(h) = 1 + 2a_i \frac{h}{v} + b_i \frac{h^2}{v^2} + \dots$

several different couplings:



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custodial breaking

$$\mathcal{A}_1 = \mathrm{Tr}(D_\mu \mathbf{U} D^\mu \mathbf{U}^\dagger) S^2 \mathcal{F}_1(h)$$

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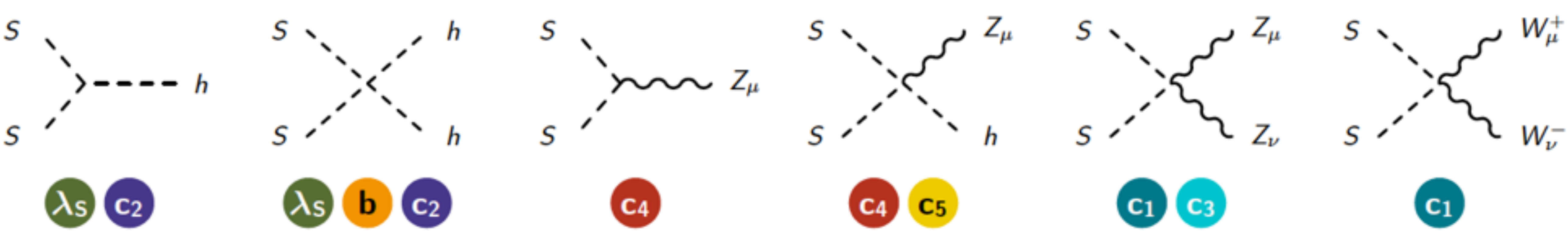

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custodial breaking

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CP-odd

$$\mathcal{A}_4 = i\, \mathrm{Tr}(D_\mu \mathbf{U} \sigma^3 \mathbf{U}^\dagger)(\partial^\mu S^2) \mathcal{F}_4(h)$$

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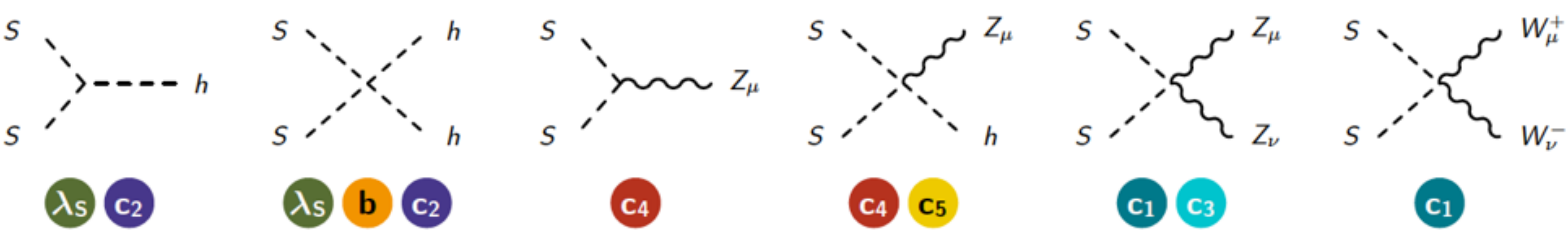
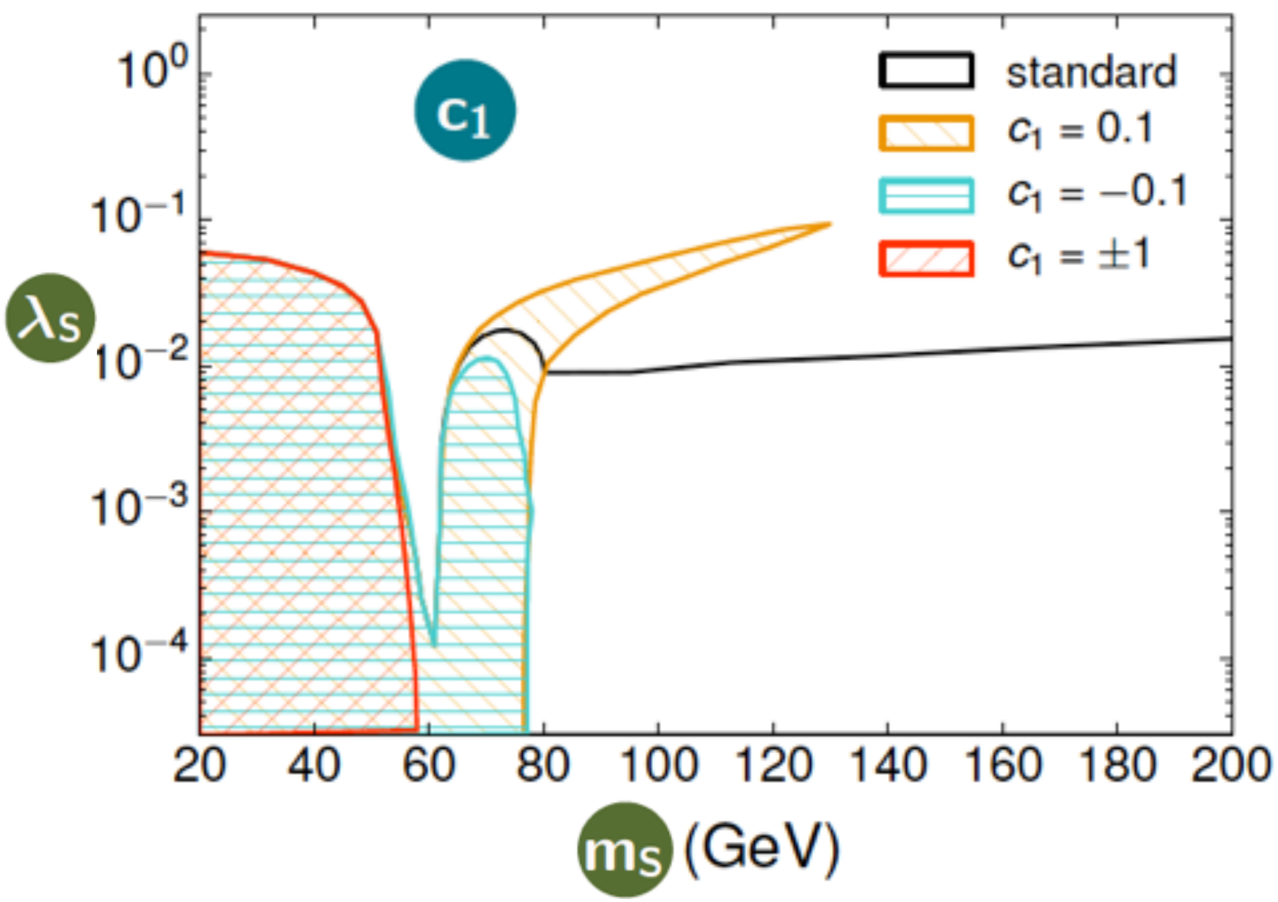
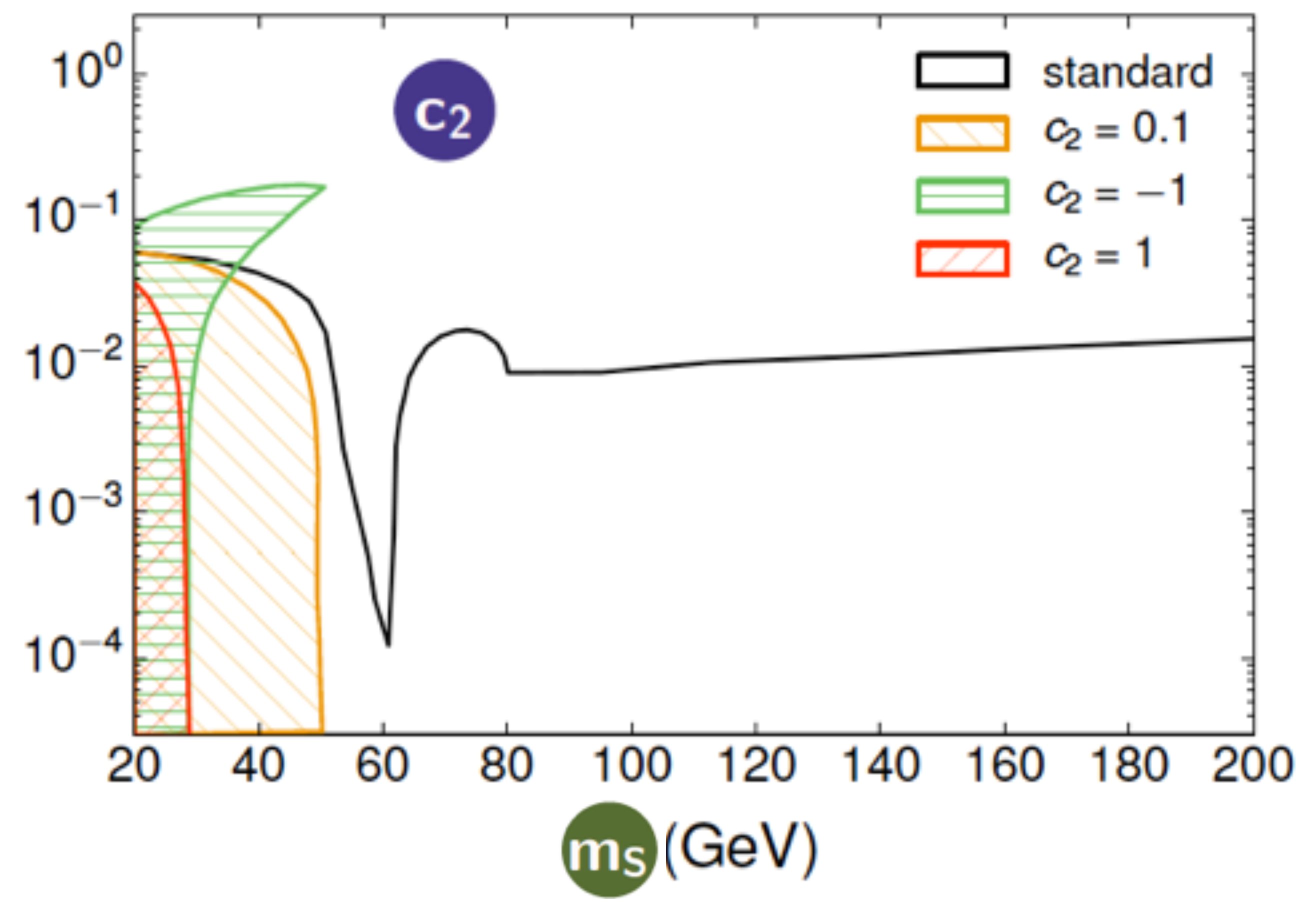


Relic abundance

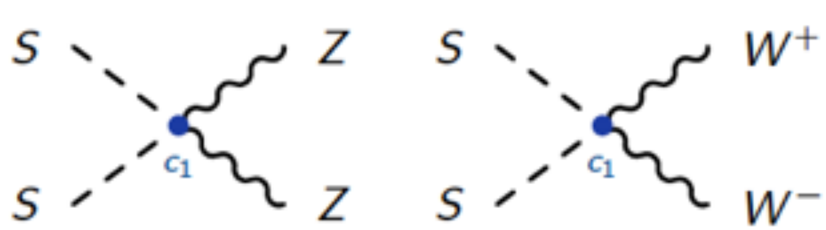
The insertion of the two custodial preserving operators $\mathcal{A}_1$ and $\mathcal{A}_2$ alters dramatically the exclusion regions!

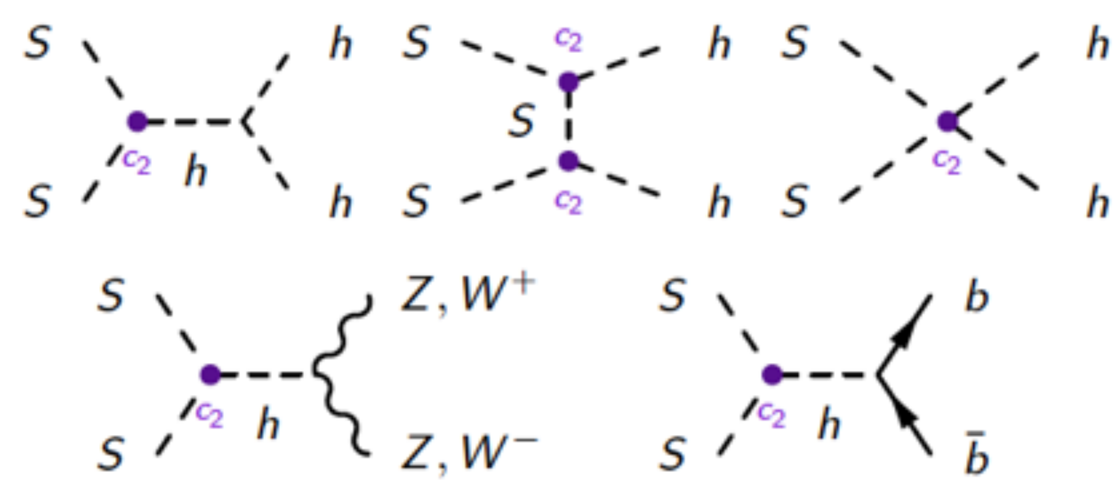
Excluded regions are under the curves imposing $\Omega_S \leqslant \Omega_{DM}$





because more channels open:





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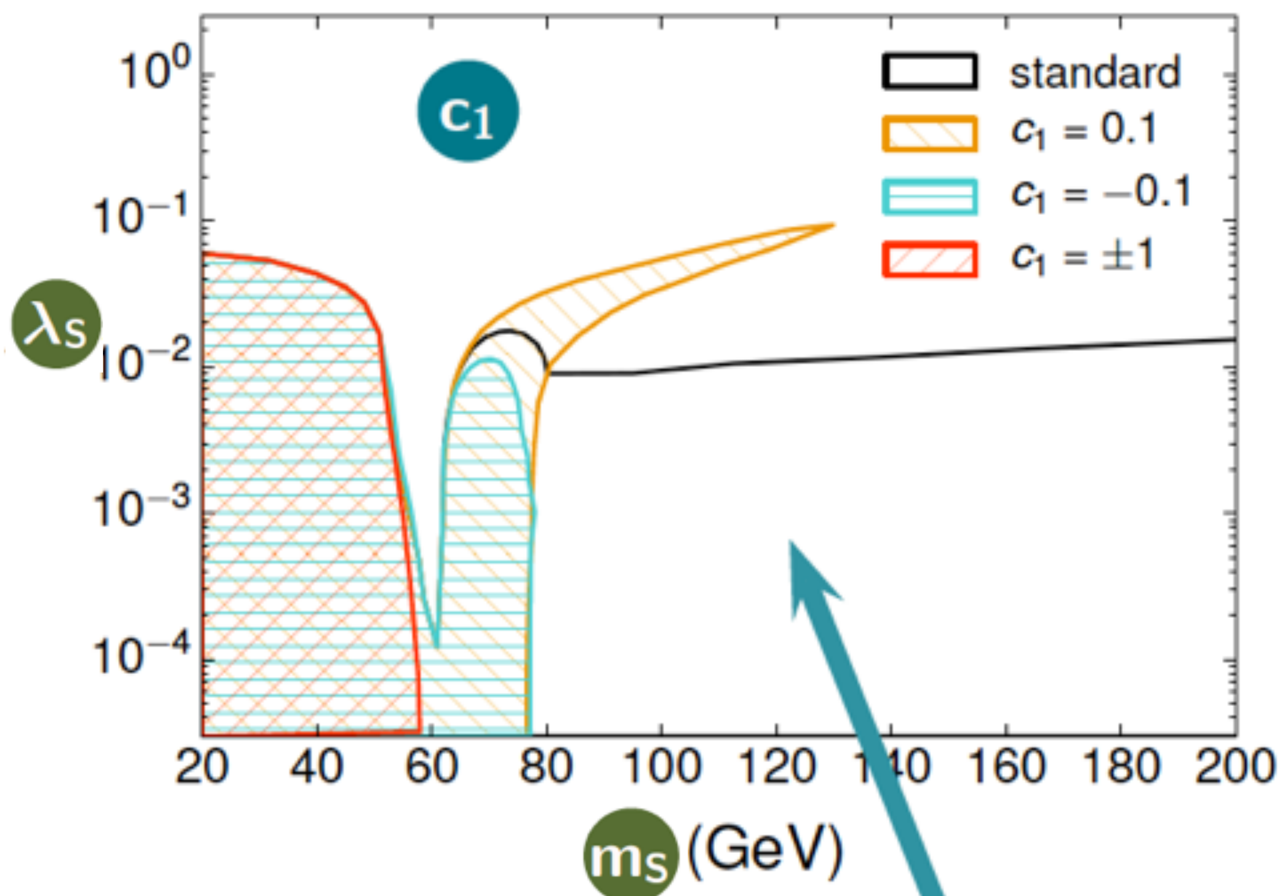
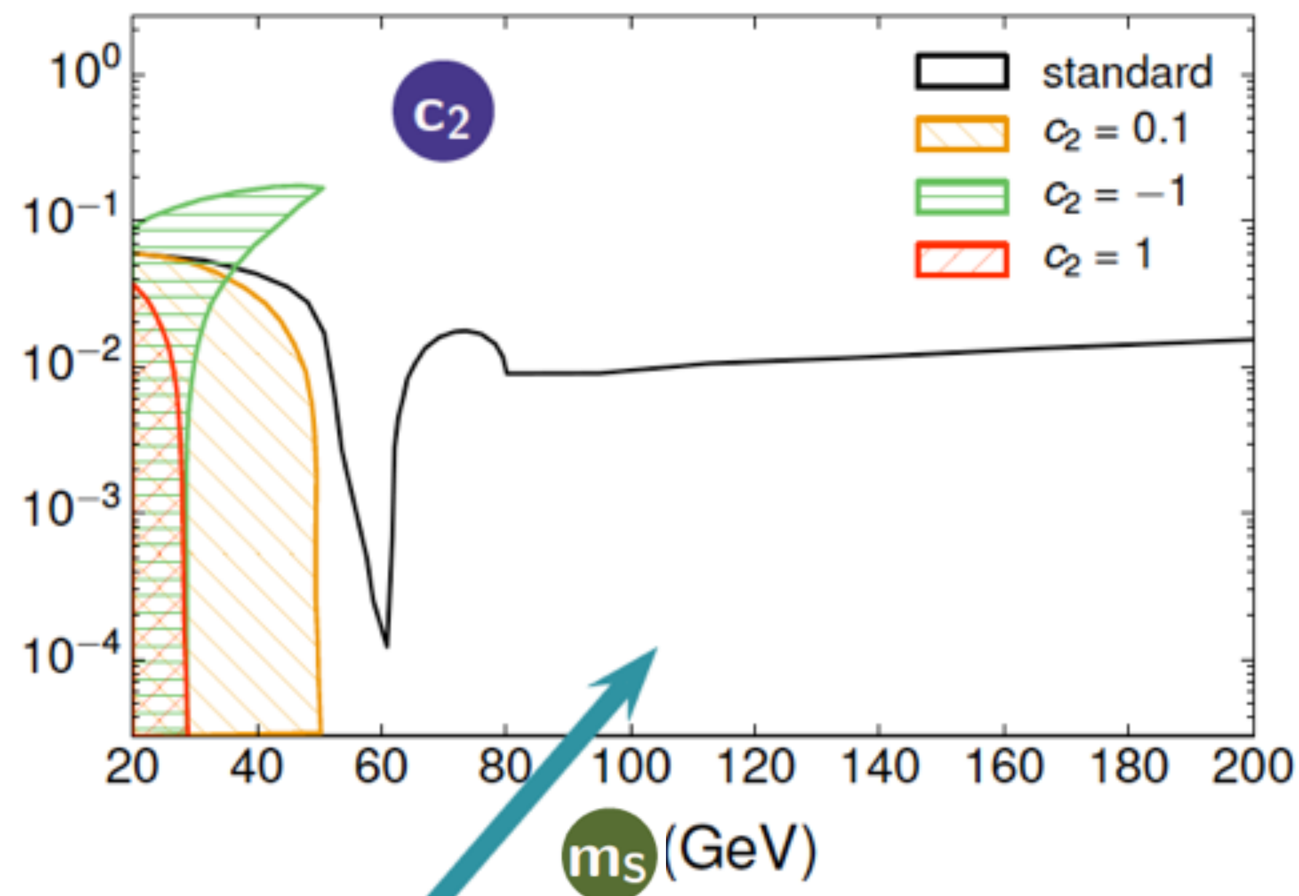


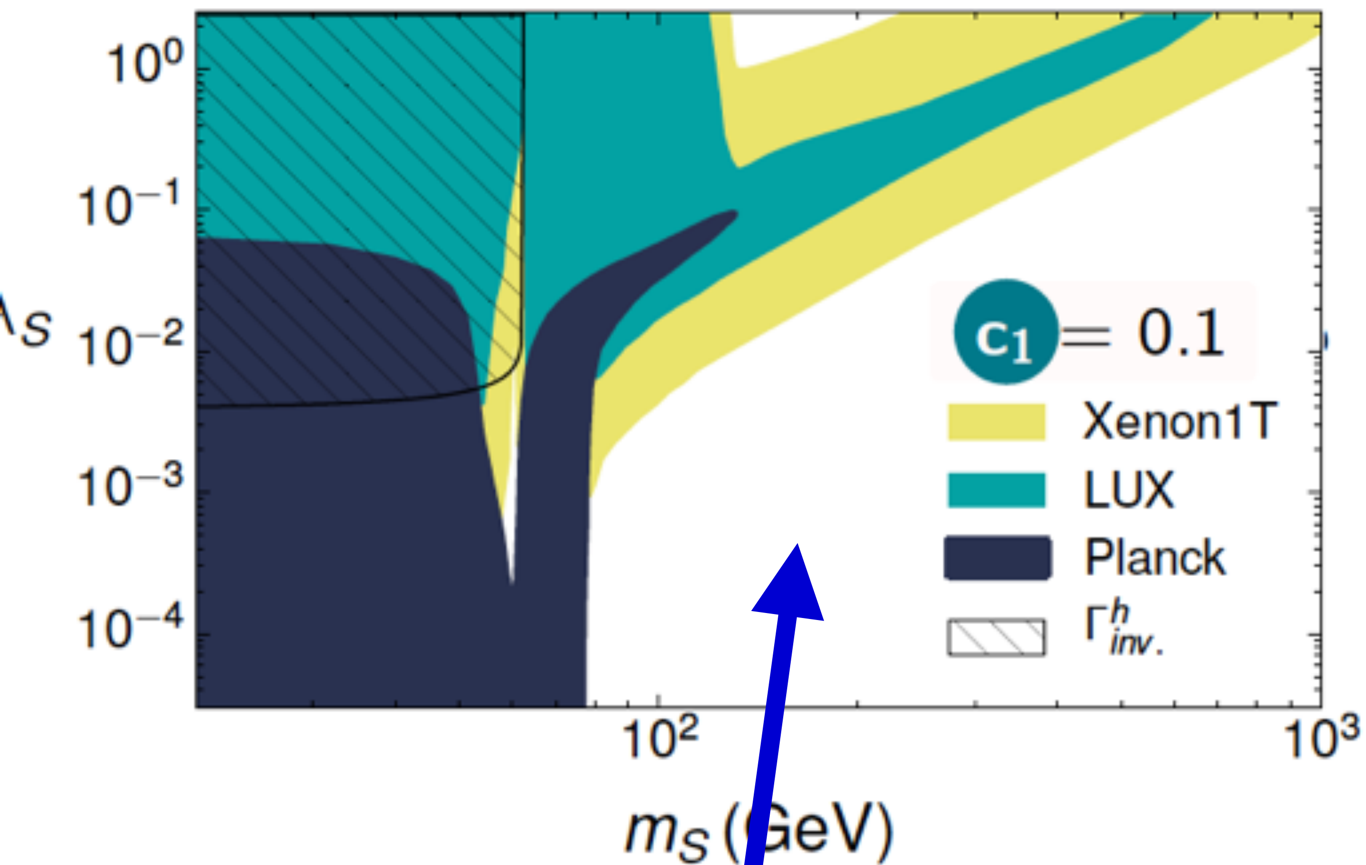


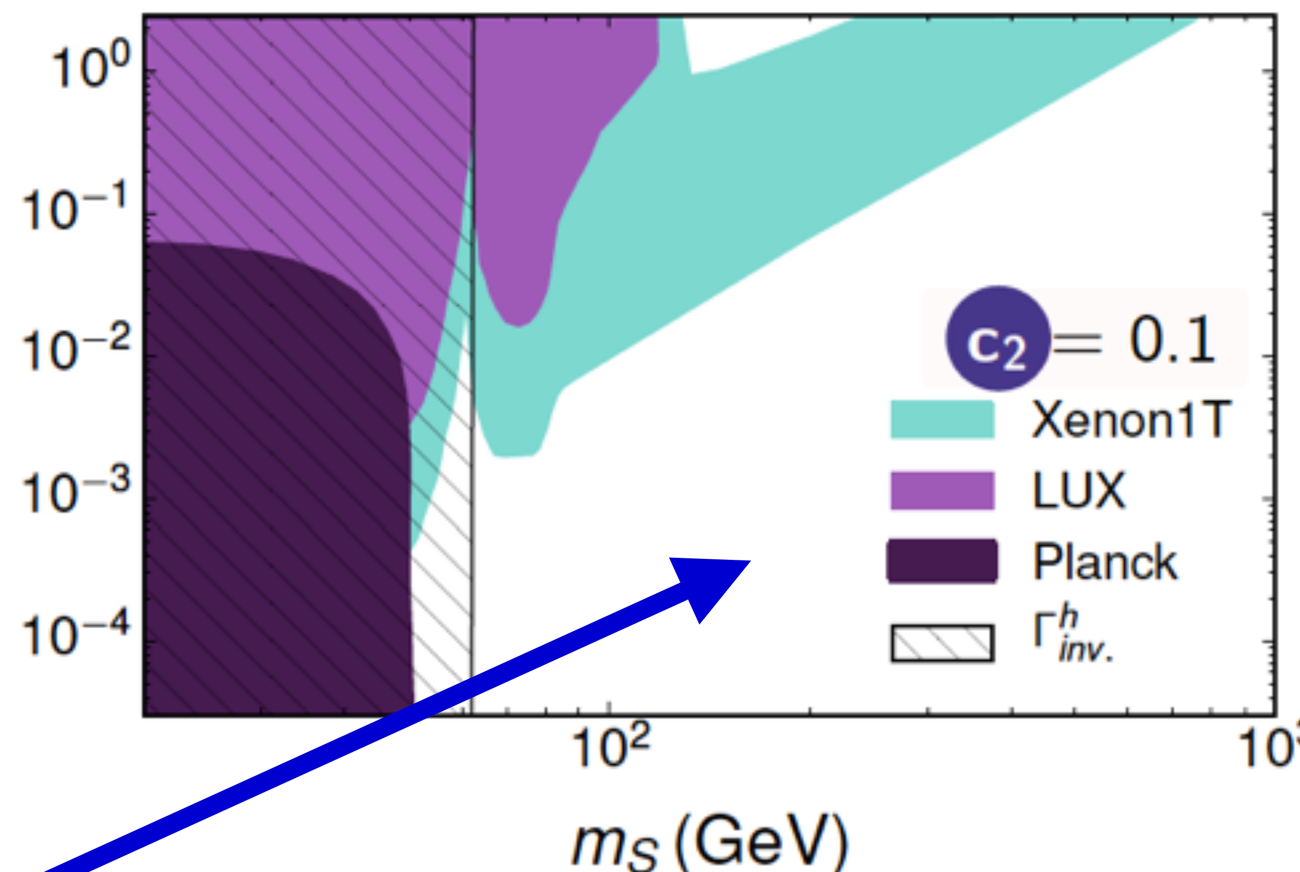
because more channels open:

enhancement of the annihilation
↓
lower Ω_S
↓
larger allowed space

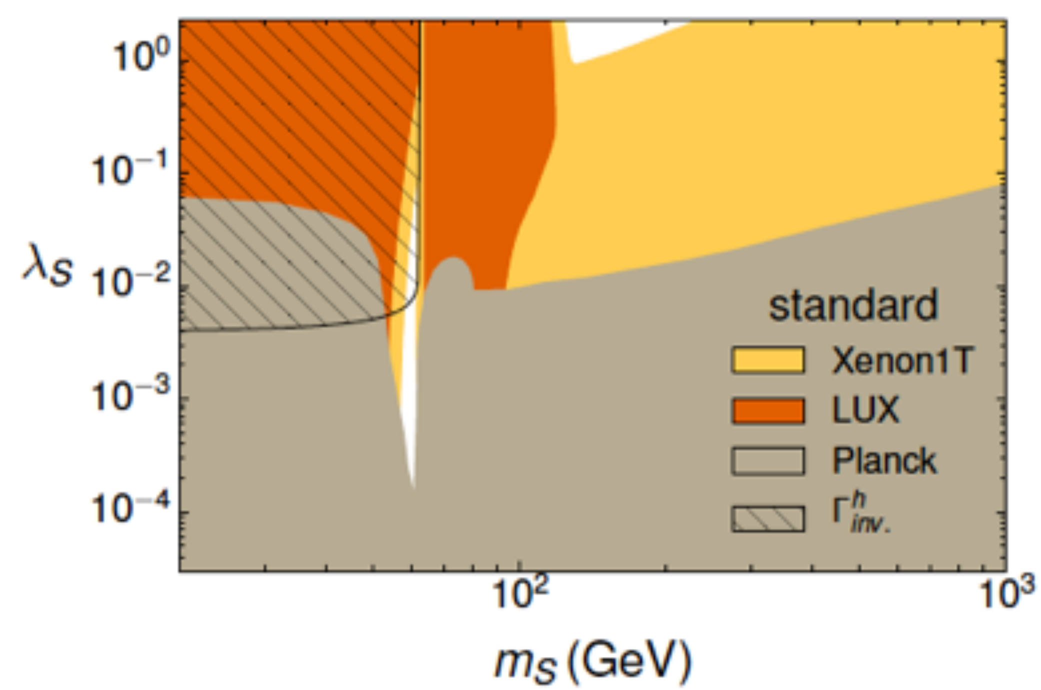
Most of the region excluded by the standard Higgs portal is now allowed !

Relic abundance + Direct detection + Invisible h width





to be compared with the standard portal plot:



Most of the region excluded by the standard Higgs portal is now allowed !

Phenomenological analysis

$0 < \lambda_S \lesssim 1$ $\qquad c_i \in [-1, 1]$

$20\,\mathrm{GeV} < m_S \lesssim 1\,\mathrm{TeV}$ $\qquad b \sim \mathcal{O}(1)$

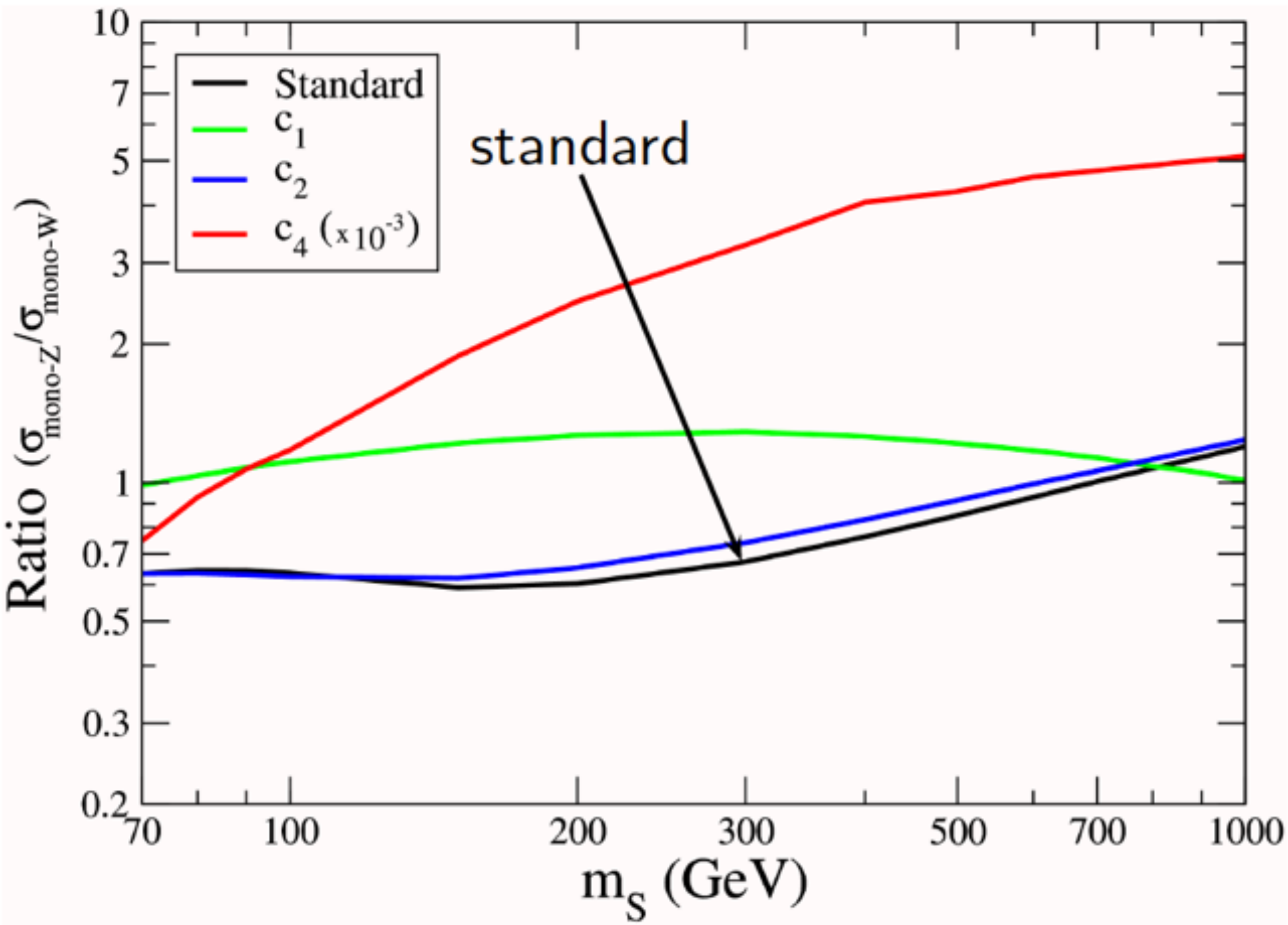
	Observable	Parameters contributing					
		b	c_1	c_2	c_3	c_4	c_5
Relic abundance	$\Omega_S h^2$	✓	✓	✓	✓	✓	✓
Direct detection	$\sigma_{\mathrm{SI}}(SN \to SN)$	-	-	✓	-	✓	-
Invisible h width	$\Gamma(h \to \mathrm{inv.})$	-	-	✓	-	-	-
Mono X signatures	$\sigma(pp \to hSS)$	✓	-	✓	-	✓	✓
	$\sigma(pp \to ZSS)$	-	✓	✓	✓	✓	✓
	$\sigma(pp \to W^+SS)$	-	✓	✓	-	✓	-

—>Talk (Sunday) by J.M. No

σ (mono-Z) / σ (mono-W)

a smoking gun

$$\text{Ratio } R_{ZW} = \frac{\sigma(pp \to ZSS)}{\sigma(pp \to W^+SS)} \text{ at } \sqrt{s} = 13\,\text{TeV}$$

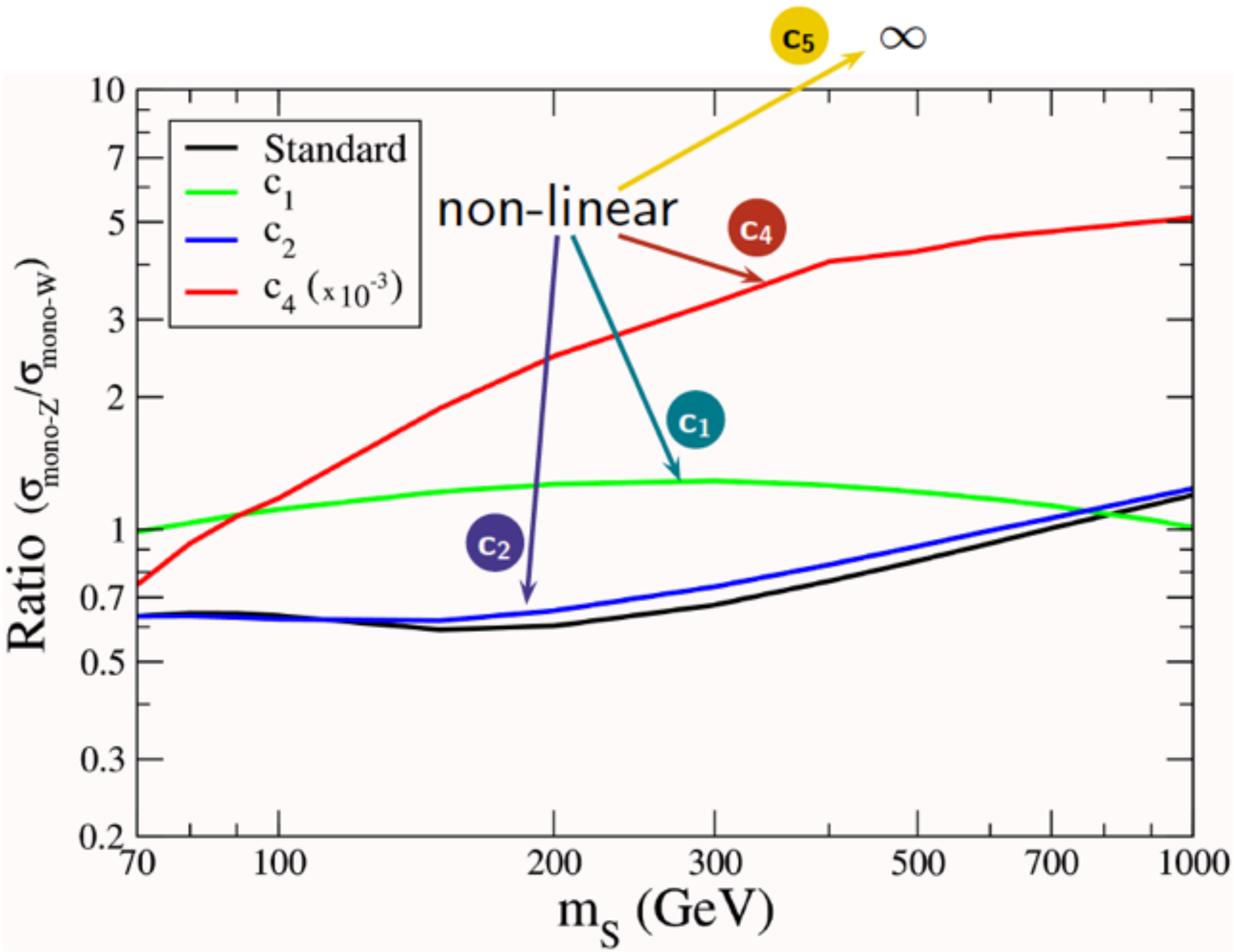


The standard Higgs portal predicts **a unique curve**, independently of λ_S

σ (mono-Z) / σ (mono-W)

a smoking gun

$$\text{Ratio } R_{ZW} = \frac{\sigma(pp \to ZSS)}{\sigma(pp \to W^+SS)} \text{ at } \sqrt{s} = 13\,\text{TeV}$$



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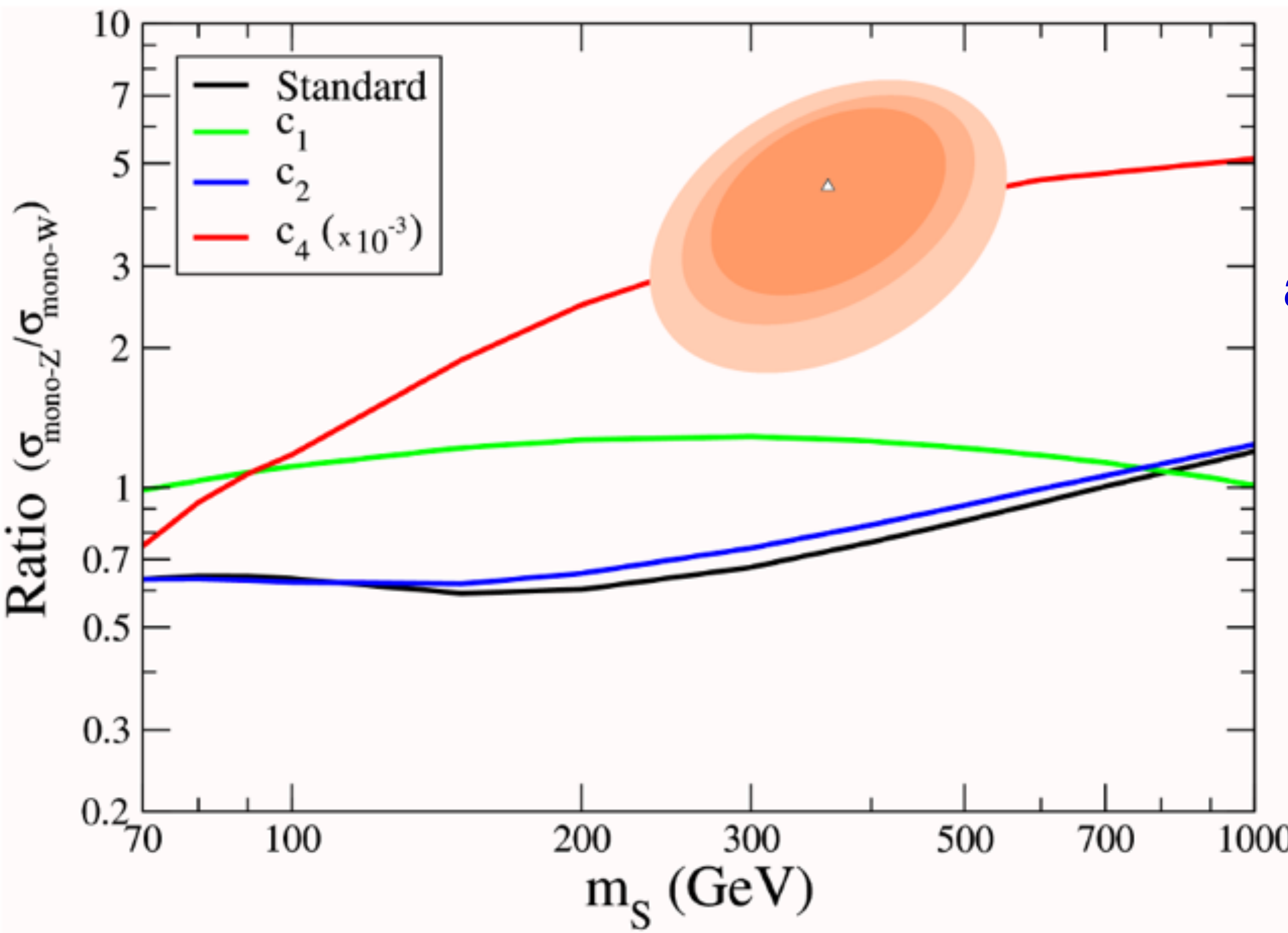

Such a signal would indicate a non-linear Higgs portal !

Or…. can a linear expansion mimic the same with higher dim. operators and fine-tuning of coeffs.?

Linear

$$\mathscr{L}_S = \mathscr{L}_{SM} + \mathscr{L}_S^{d=4} + \frac{1}{\Lambda^2}\mathscr{L}_S^{d=6}$$

$$\mathscr{L}_S^{d=4} = \frac{1}{2}\partial_\mu S \partial^\mu S + \frac{m_S^2}{2}S^2 + \lambda_S S^2(\Phi^\dagger \Phi) + \kappa S^4$$

$$\mathscr{L}_S^{d=6} = \sum_i c_i^L \mathcal{O}_i$$

the basis $\{O_i\}$ contains 9 operators with 4∂ (e.g. $g^2 S^2 W_{\mu\nu} W^{\mu\nu}$) plus

d=6

$$\mathcal{O}_b = (\Phi^\dagger \Phi)^2 S^2 \quad \rightarrow b$$

$$\mathcal{O}_1 = D_\mu \Phi^\dagger D^\mu \Phi S^2 \quad \rightarrow \mathcal{A}_1$$

$$\mathcal{O}_2 = \Box(\Phi^\dagger \Phi) S^2 \quad \rightarrow \mathcal{A}_2$$

$$\mathcal{O}_4 = (\Phi^\dagger \overleftrightarrow{D}_\mu \Phi) D^\mu S^2 \rightarrow \mathcal{A}_4$$

while the couplings in $\mathcal{A}_3$ and $\mathcal{A}_5$ only appear in ops. with d=8

The (de)correlation effect between couplings with different and with equal and different numbers of h legs remains a disentangling tool

Conclusions

* The chiral Effective Field Theory:

—> Accounts for many different scenarios of EWSB

—> Good to explore whether the physical Higgs is an $SU(2)_L$ doublet, essential question!

—> It contains the linear expansion in a specific limit

—> Possible to disentangle from data linear from chiral EWSB realisations: decorrelations and different dominant couplings

* We have defined the non-linear DM portal, and explored it

—> It has a dramatic phenomenological impact

—> Relic density, direct detection, collider signals … smoking guns

—> Talk Sunday by J.M. No

The Higgs chiral Lagrangian: LO

It's useful to define two objects that transform nicely under $SU(2)_L$:

$$\mathbf{V}_\mu = (D_\mu \mathbf{U})\mathbf{U}^\dagger \qquad = \tfrac{ig}{2} W_\mu^a \sigma^a - \tfrac{ig'}{2} B_\mu \sigma^3$$
$$\mathbf{T} = \mathbf{U}\sigma^3\mathbf{U}^\dagger \qquad = \sigma^3$$

in unitary gauge

LO lagrangian: up to two derivatives.

$$\mathscr{L}_{EW} = [\text{kinetic terms for } W,\, Z,\, \mathcal{G}] + \frac{1}{2}\partial_\mu h \partial^\mu h - V(h) +$$

$$- \frac{v^2}{4} \operatorname{Tr}(\mathbf{V}_\mu \mathbf{V}^\mu) \mathcal{F}_{\mathrm{C}}(\mathbf{h}) + \mathbf{c_T} \frac{\mathbf{v}^2}{\mathbf{4}} \operatorname{Tr}(\mathbf{T}\mathbf{V}_\mu) \operatorname{Tr}(\mathbf{T}\mathbf{V}^\mu) \mathcal{F}_{\mathrm{T}}(\mathbf{h})$$

SM Lagrangian, up to the presence of arbitrary $\mathcal{F}_{\mathrm{i}}(\mathbf{h})$ and of $\mathbf{c_T}$

in particular: $$D_\mu \Phi^\dagger D^\mu \Phi \;\to\; \frac{1}{2}\partial_\mu h \partial^\mu h - \frac{(v+h)^2}{4} \operatorname{Tr}(\mathbf{V}_\mu \mathbf{V}^\mu)$$

Brivio

The Higgs chiral Lagrangian: LO

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$$-\frac{g^2v^2}{4}\left(\frac{1}{2c_\theta^2} Z_\mu Z^\mu + W^+_\mu W^{-\mu}\right)\mathcal{F}_C(h)$$

gauge bosons' masses

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$$-\frac{g^2 v^2}{4c_\theta^2} Z_\mu Z^\mu \mathcal{F}_T(h)$$

breaks the custodial symmetry and contributes to the ρ parameter

↓

$c_T \lesssim 10^{-3}$

SM Lagrangian, up to the presence of arbitrary $\mathcal{F}_i(\mathbf{h})$ and of $\mathbf{c_T}$

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Brivio

Example of CHIRAL Decorrelation

The linear coupling $\mathcal{O}_B = (D_\mu \Phi)^\dagger \hat{B}^{\mu\nu} (D_\nu \Phi)$

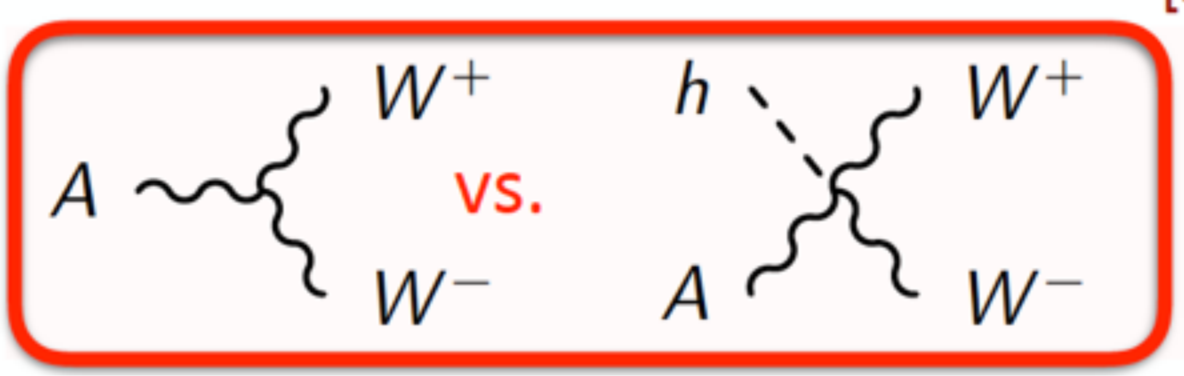
splits into two chiral ones:

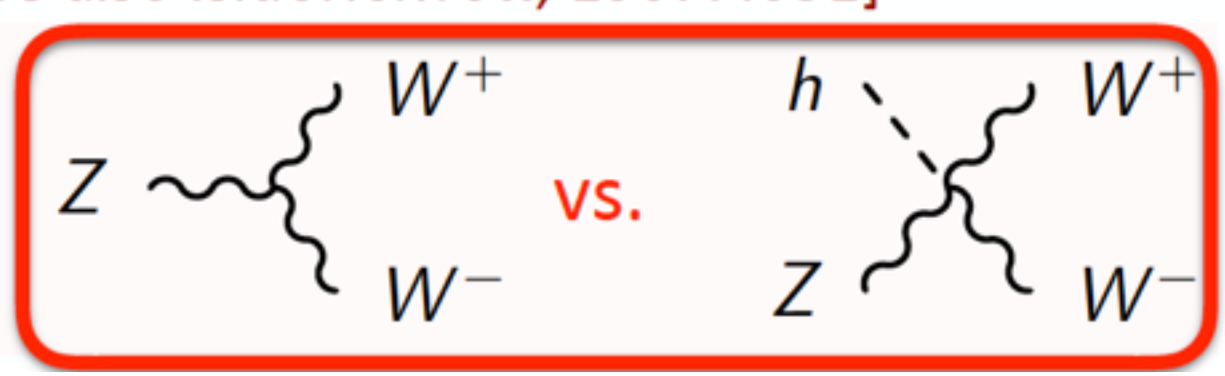
$$\mathcal{P}_2(h) = 2ieg^2 A_{\mu\nu} W^{-\mu} W^{+\nu} \mathcal{F}_2(h) - 2\frac{ie^2 g}{\cos\theta_W} Z_{\mu\nu} W^{-\mu} W^{+\nu} \mathcal{F}_2(h)$$

$$\mathcal{P}_4(h) = -\frac{eg}{\cos\theta_W} A_{\mu\nu} Z^\mu \partial^\nu \mathcal{F}_4(h) + \frac{e^2}{\cos^2\theta_W} Z_{\mu\nu} Z^\mu \partial^\nu \mathcal{F}_4(h)$$

due to the decorrelation in the $\mathcal{F}_i(h)$ functions: i.e.

[see also Isidori&Trott, 1307.4051]





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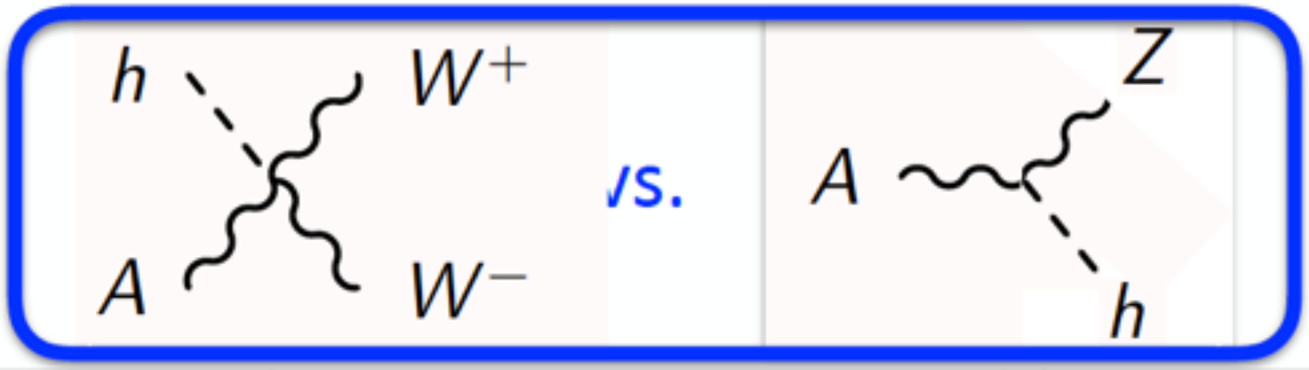
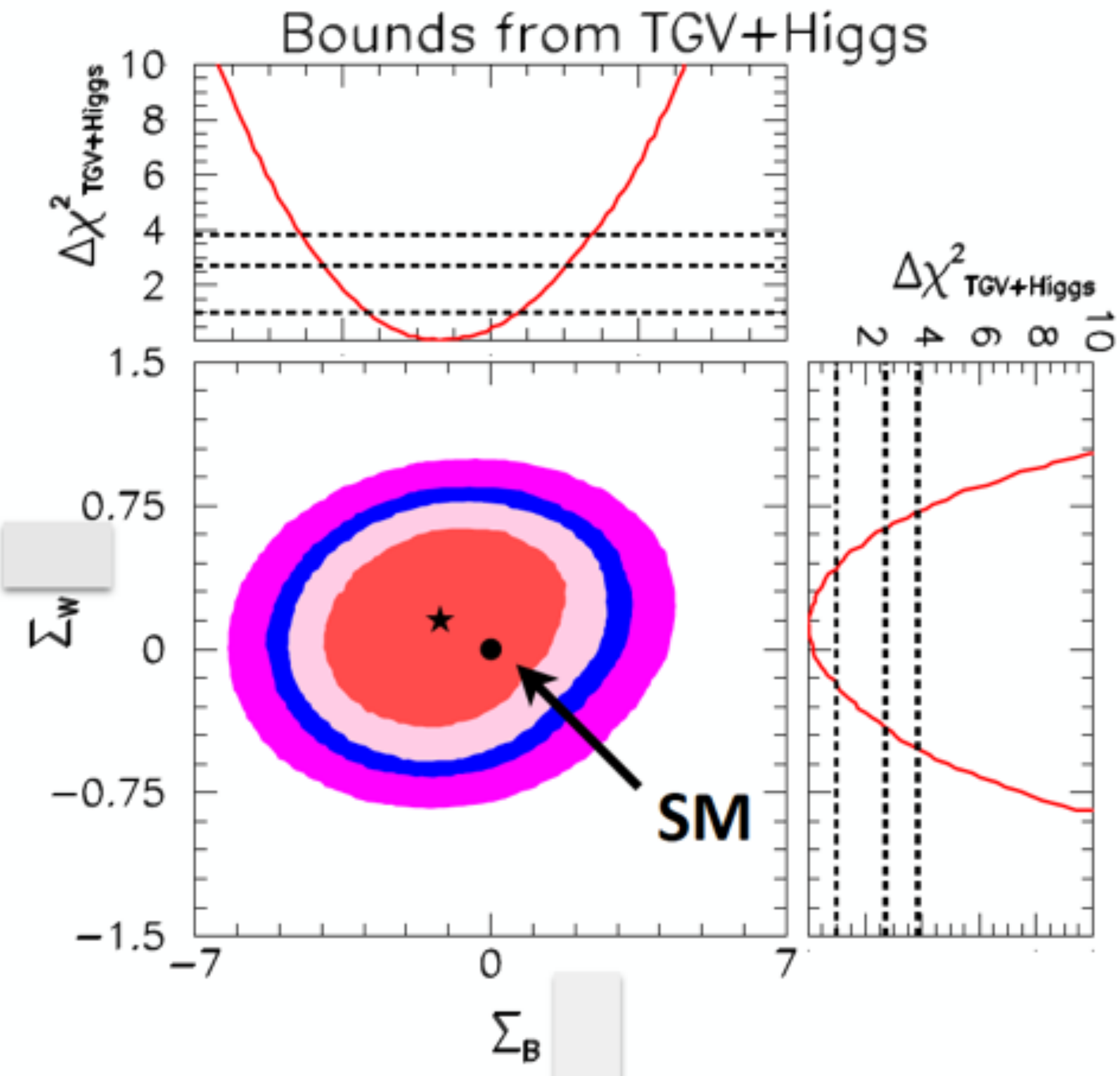
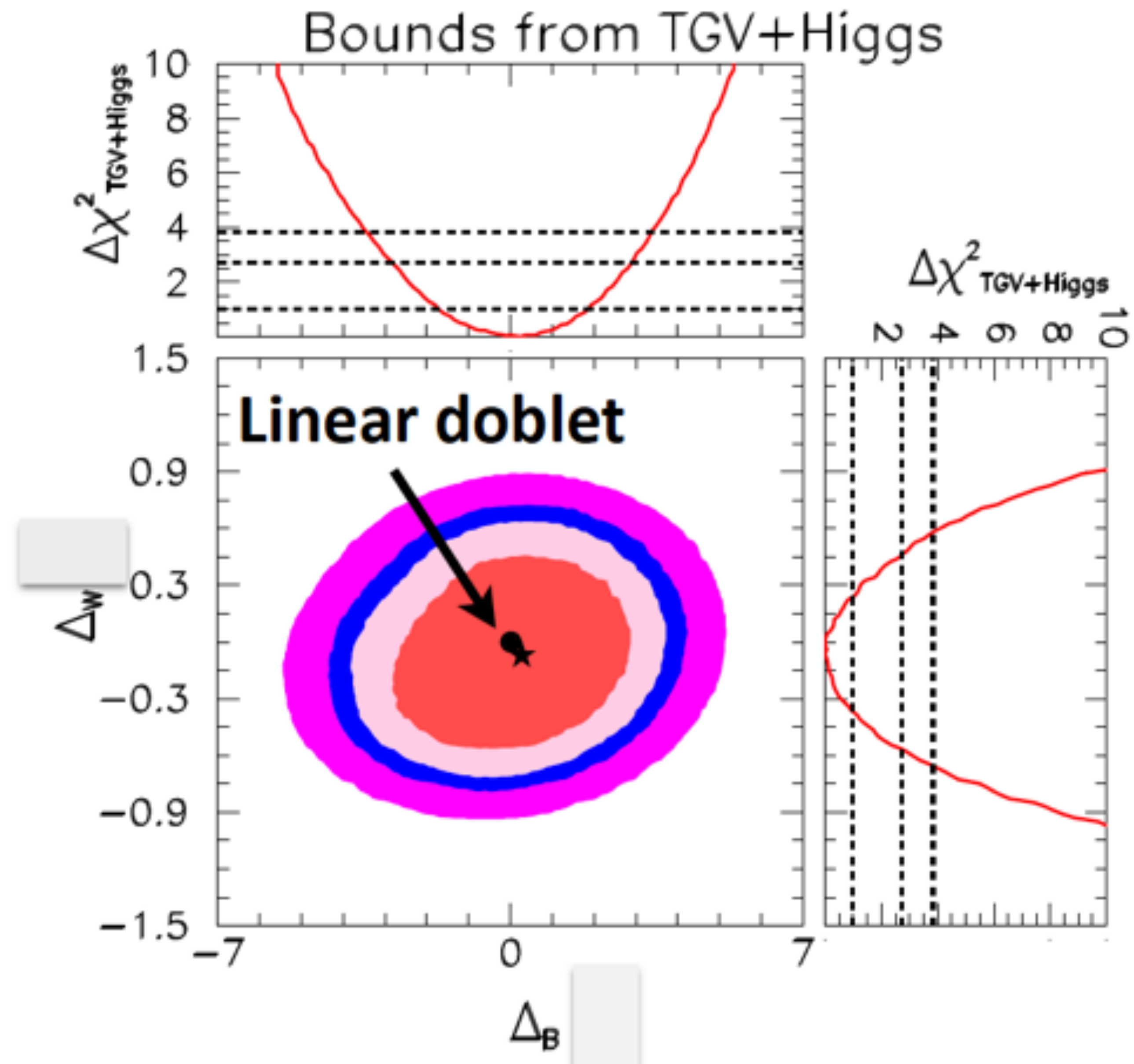
due to the nature of the chiral operators (different c_i coefficients): i.e.



Decorrelations





$$\Sigma_B = 4(2c_2 + a_4) \to f_B \xi \qquad \Delta_B = 4(2c_2 - a_4) \to 0$$

$$\Sigma_W = 2(2c_3 - a_5) \to f_W \xi \qquad \Delta_W = 2(2c_3 + a_5) \to 0$$

Data: Tevatron D0 and CDF Collaborations and LHC, CMS, and ATLAS Collaborations at 7 TeV and 8 TeV for final states $\gamma\gamma$, W^+W^-, ZZ, $Z\gamma$, $b\bar{b}$, and $\tau\bar{\tau}$