PHENOMENOLOGY OF A DYNAMICAL HIGGS

Luca Merlo

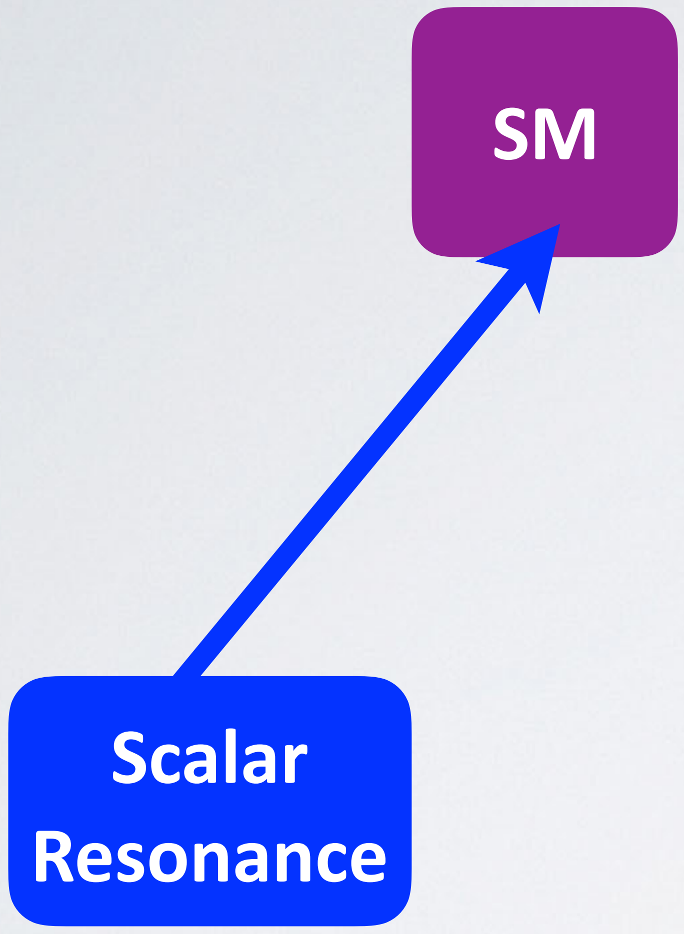
HEFT15

November 5, 2015, Chicago

Which Higgs?

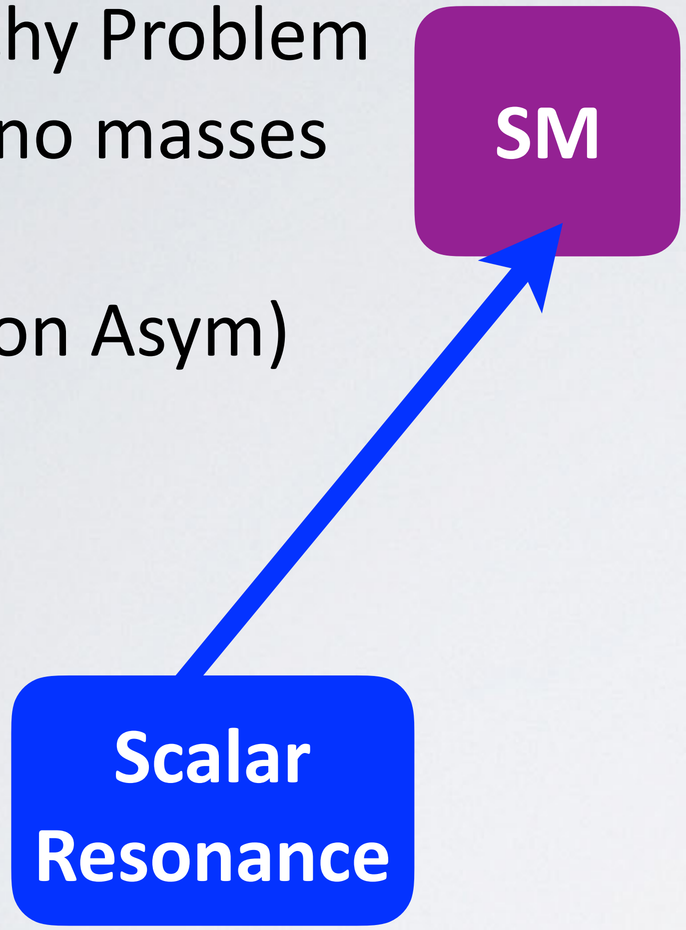
Scalar Resonance

Which Higgs?



Which Higgs?

Hierarchy Problem
(neutrino masses
& DM
& Baryon Asym)



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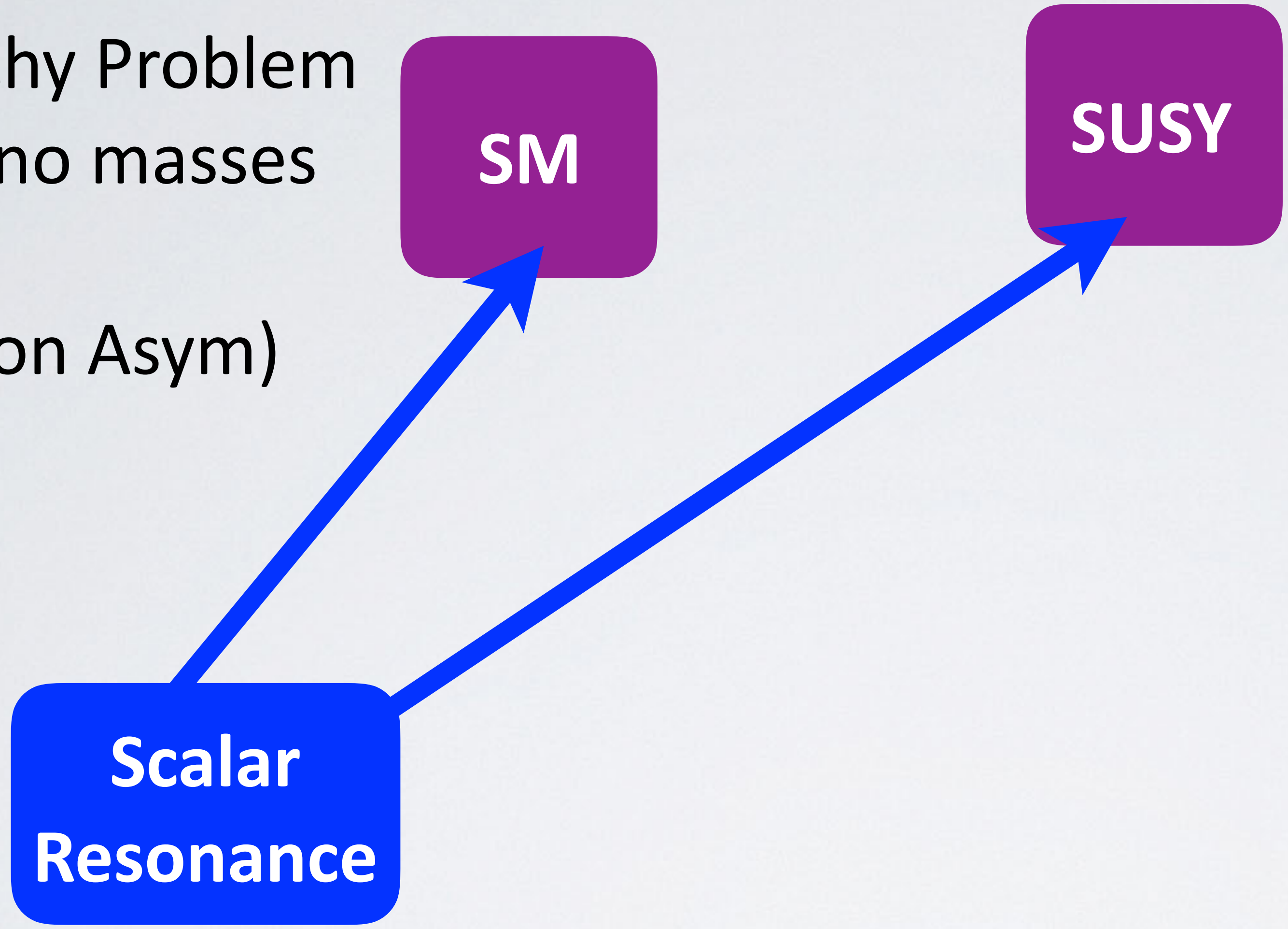

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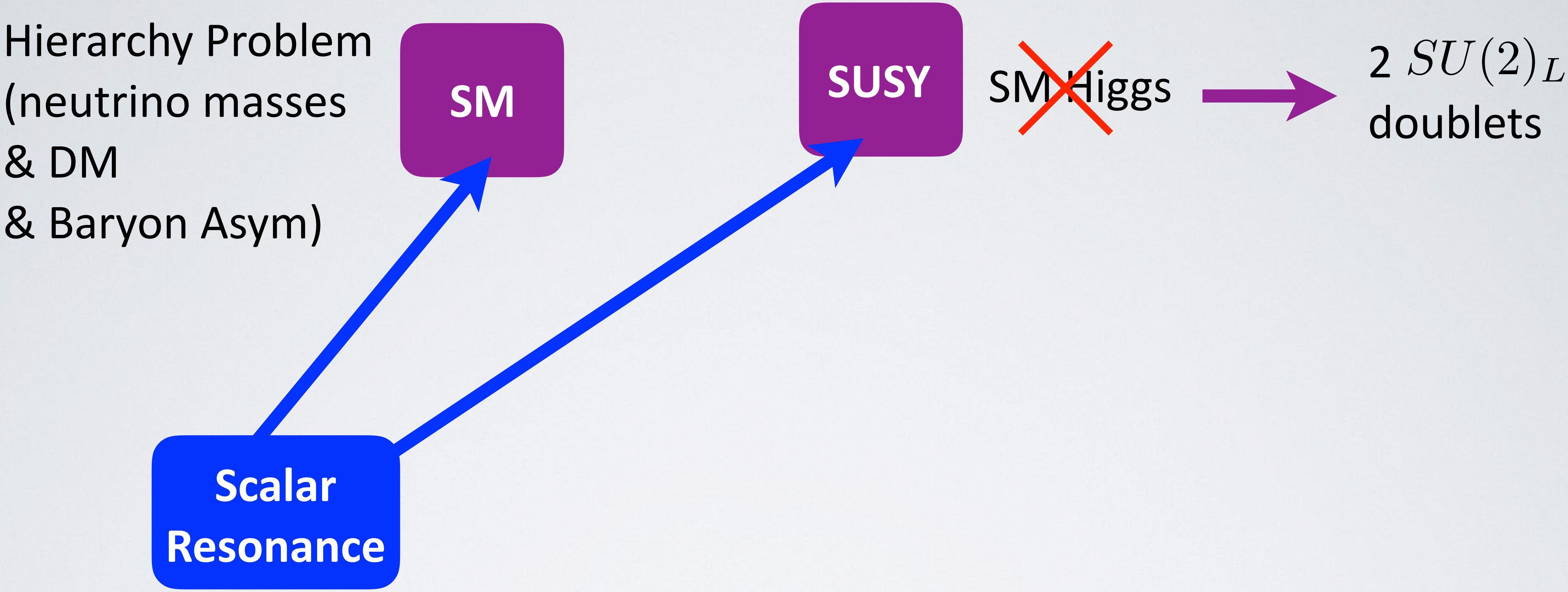
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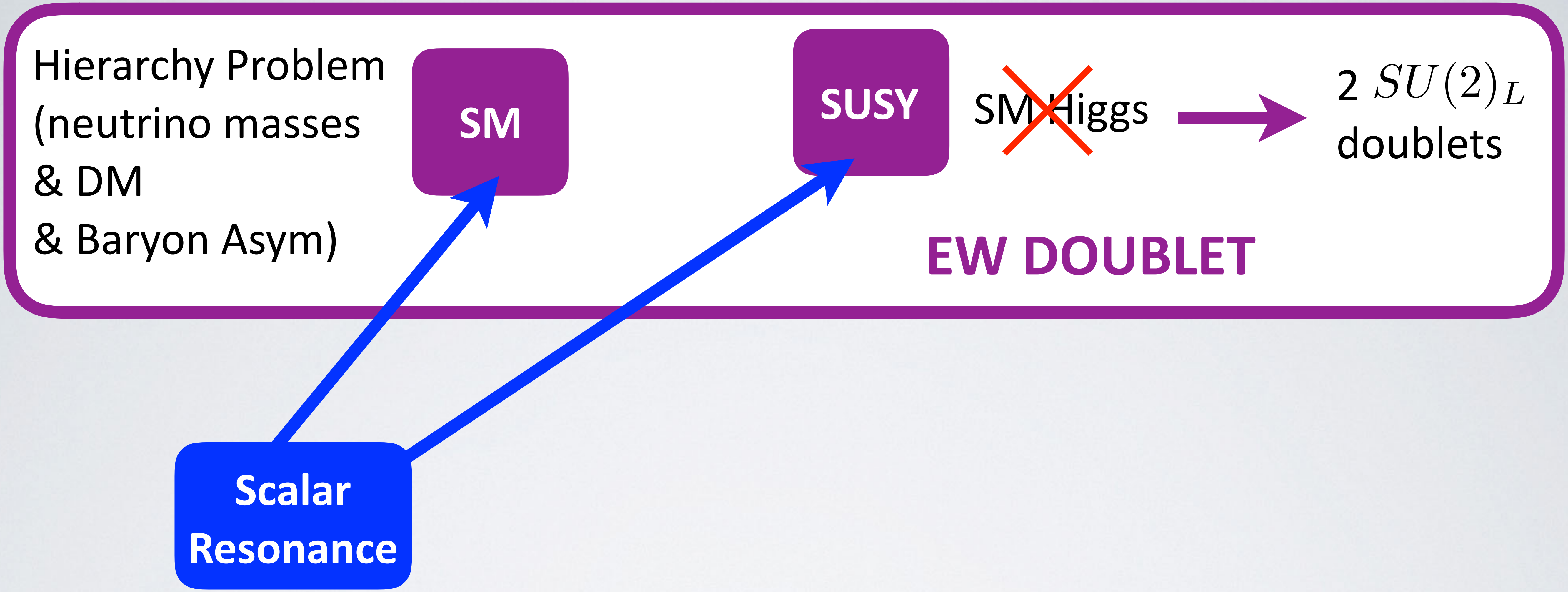

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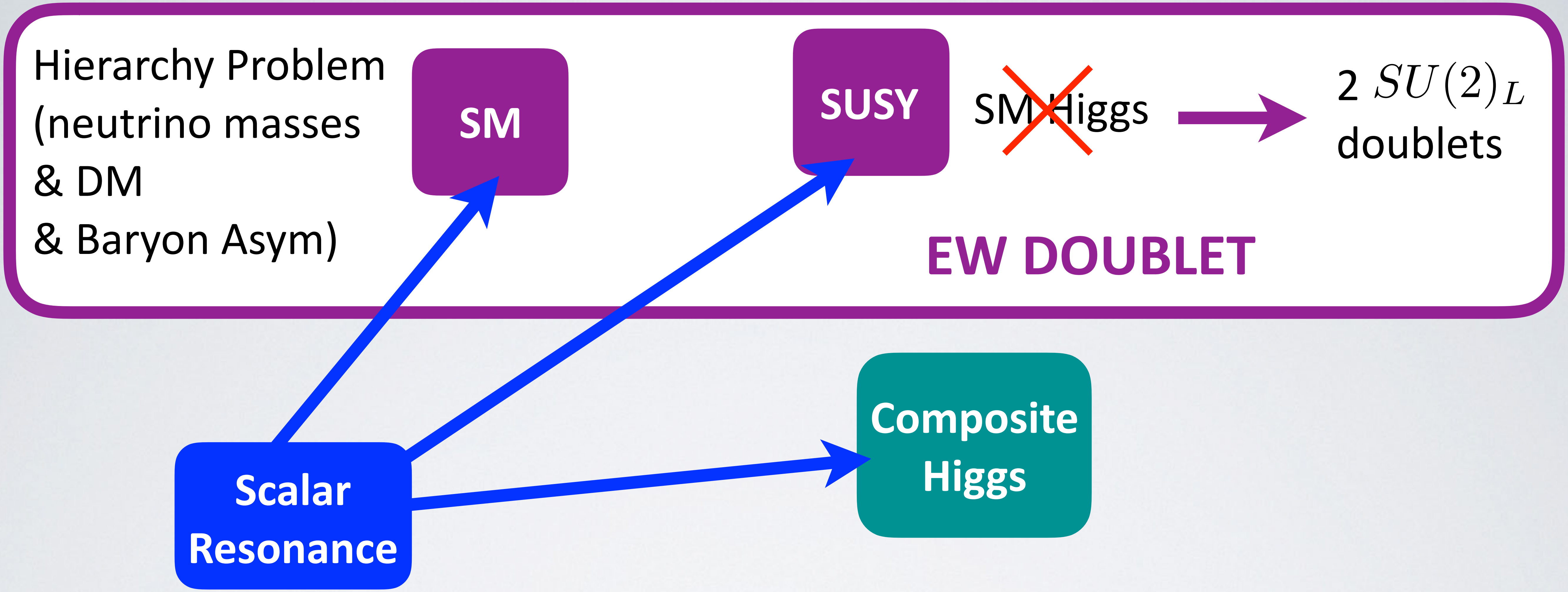
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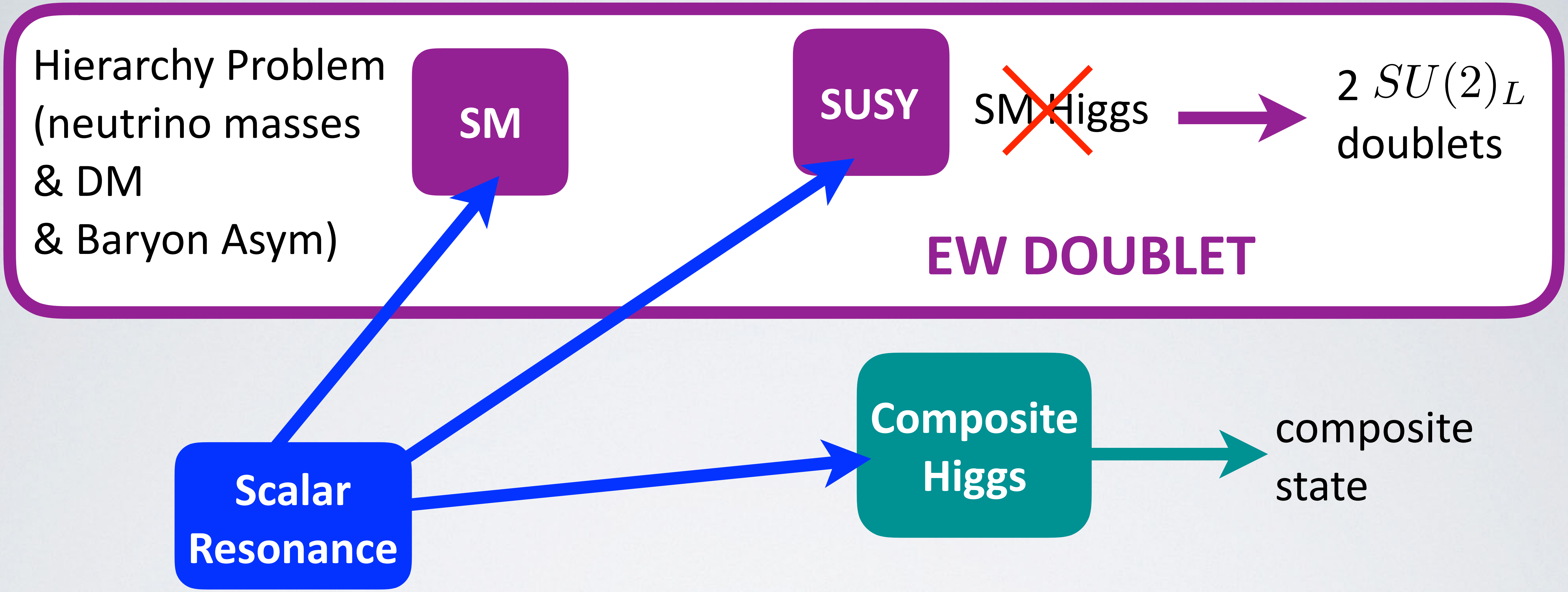
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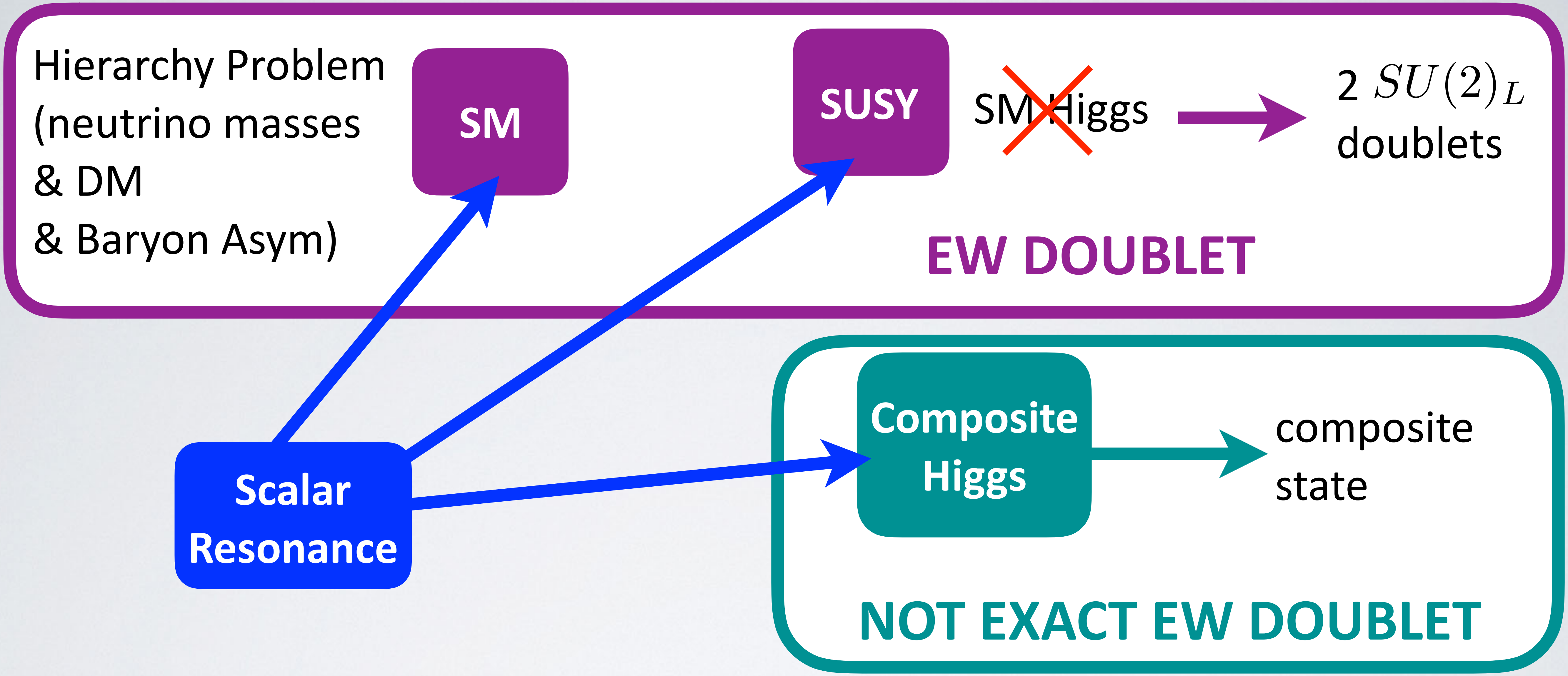
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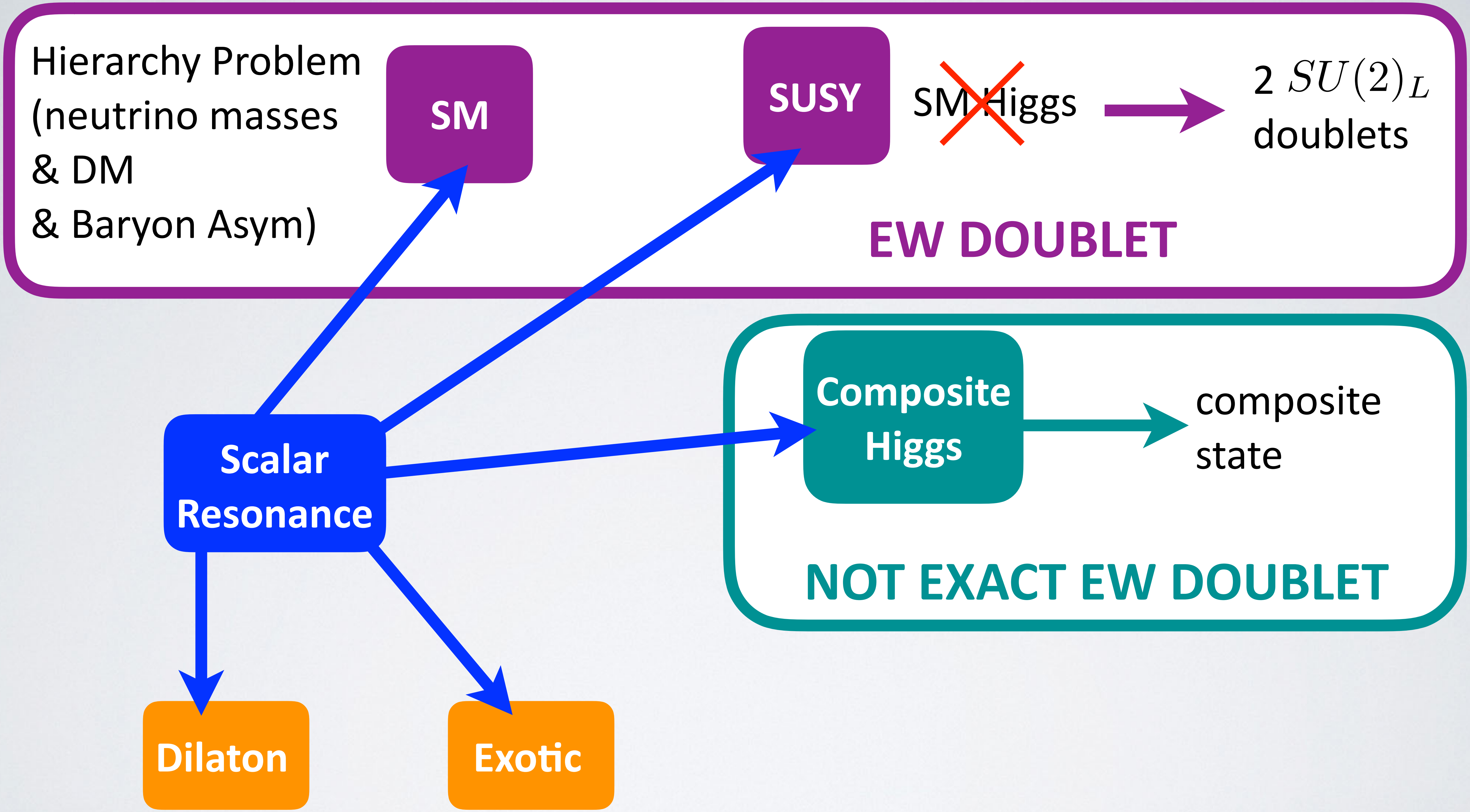
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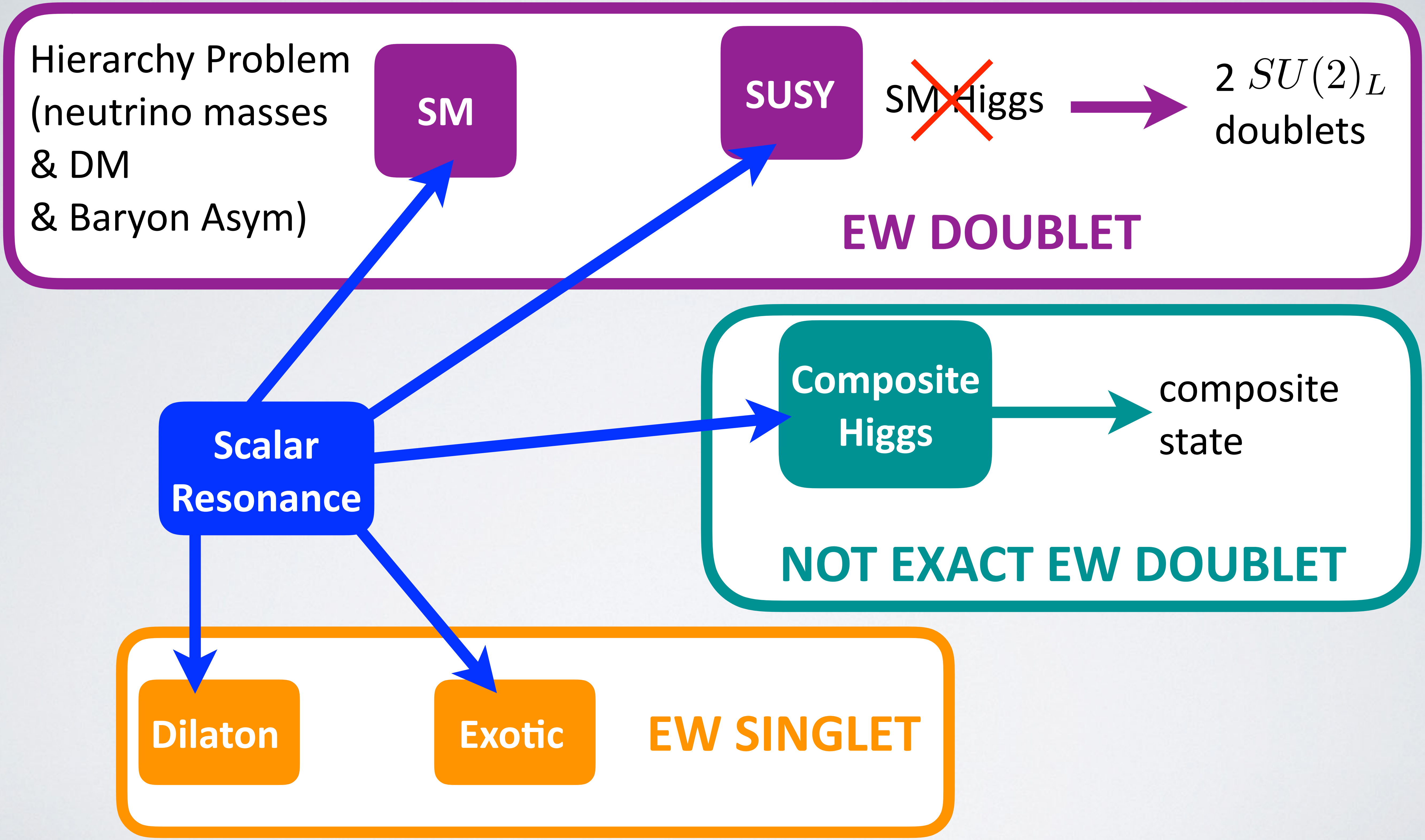
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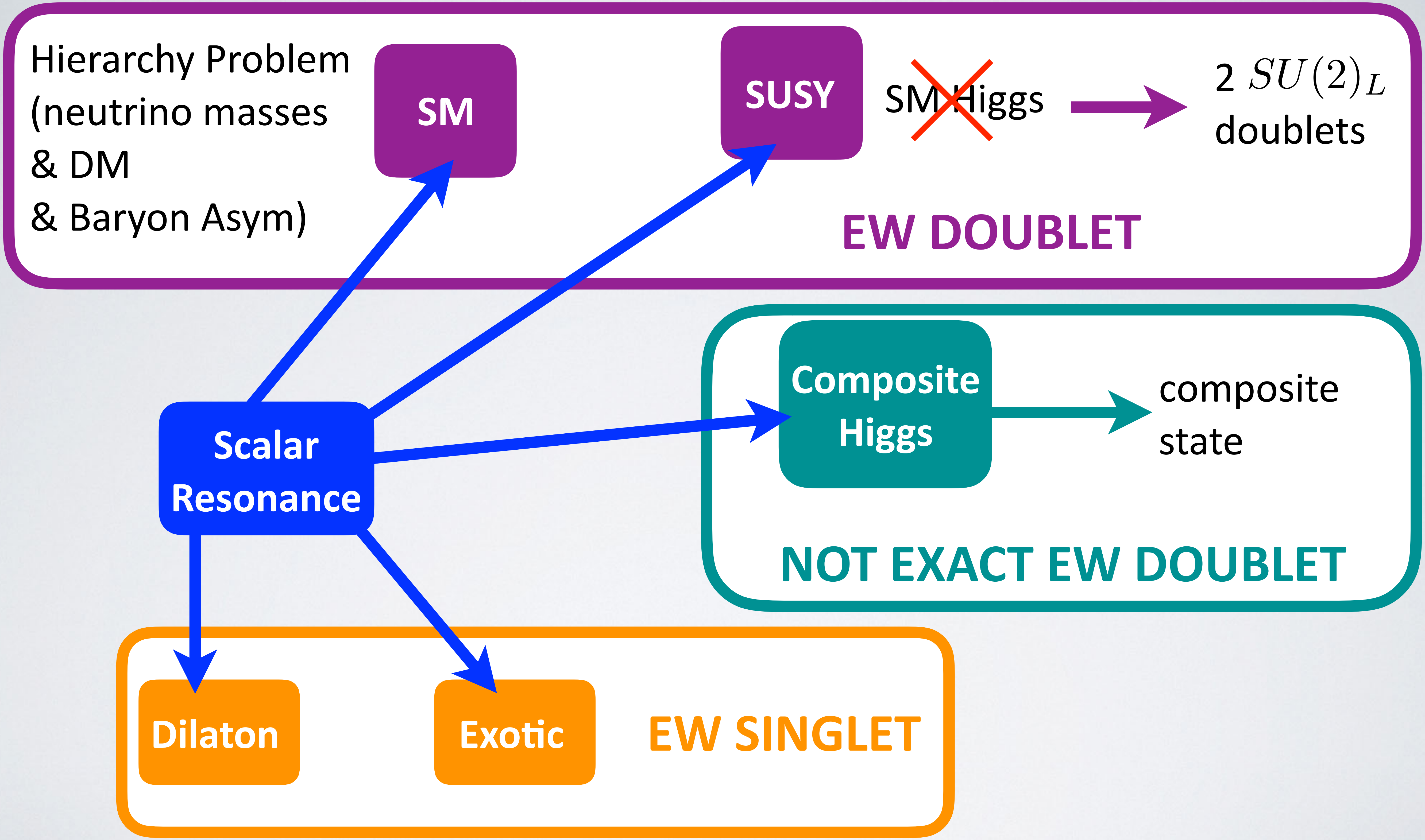

<u>Identify the observables that distinguish the Higgs Nature</u>

Method: HEFT

- Without any evidence of New Physics:

Chiral Higgs Effective Field Theory

is the most generic way to describe the couplings of a singlet Higgs!

- It encodes the low-energy couplings of several theories, including those with the Higgs being a (exact) doublet!

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Bosonic Lagrangian

(first part of the talk)

works with: Alonso, Brivio, Corbett, Eboli, Gavela, Gonzalez- Fraile, Gonzalez-Garcia, Hierro, Rigolin, Yepes

Dark Matter Lagrangian

(second part of the talk)

work with: Brivio, Gavela, Mimasu, No, Rey, Sanz

TODAY on arXiv

The linear effective Lagrangian

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

See talks by Perelstein, Sanz, Trott, Eboli…

The d=6 linear effective Lagrangian

- NP effects above the TEV scale can be parametrised by writing the **Linear** Effective Lagrangian including up to d=6 operators in terms of the **Higgs doublet**:

$$\mathcal{L}_{\rm linear} = \mathcal{L}_{SM} + \sum_i \frac{f_i}{\Lambda^2}\mathcal{O}_i + \text{higher orders}$$

with Λ (≥ few TeV) the NP scale.

$$\mathcal{L}_{SM} = -\frac{1}{4}W^a_{\mu\nu}W^{a\mu\nu} - \frac{1}{4}B_{\mu\nu}B^{\mu\nu} - \frac{1}{4}G^a_{\mu\nu}G^{a\mu\nu} - V(h)$$
$$+ (D_\mu\Phi)^\dagger(D^\mu\Phi) + i\bar{Q}\not{D}Q + i\bar{L}\not{D}L$$
$$- (\bar{Q}_L\Phi\mathcal{Y}_D D_R + \text{h.c.}) - \left(\bar{Q}_L\tilde{\Phi}\mathcal{Y}_U U_R + \text{h.c.}\right)$$
$$- (\bar{L}_L\Phi\mathcal{Y}_L L_R + \text{h.c.})$$

The d=6 linear Lagrangian: HISZ

[Hagiwara,Ishihara,Szalapski,Zeppenfeld 1993]

$$\mathcal{L}_{\text{linear}} = \mathcal{L}_{SM} + \sum_i \frac{f_i}{\Lambda^2}\mathcal{O}_i + \text{higher orders}$$

$$\mathcal{O}_{GG} = \Phi^\dagger\Phi\, G^a_{\mu\nu}G^{a\mu\nu}$$

$$\mathcal{O}_{WW} = \Phi^\dagger \hat{W}_{\mu\nu}\hat{W}^{\mu\nu}\Phi$$

$$\mathcal{O}_{BB} = \Phi^\dagger \hat{B}_{\mu\nu}\hat{B}^{\mu\nu}\Phi$$

$$\mathcal{O}_{BW} = \Phi^\dagger \hat{B}_{\mu\nu}\hat{W}^{\mu\nu}\Phi$$

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

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

$$\mathcal{O}_{\Phi,1} = (D_\mu\Phi)^\dagger\,\Phi\,\Phi^\dagger\,(D^\mu\Phi)$$

$$\mathcal{O}_{\Phi,2} = \frac{1}{2}\partial^\mu\left(\Phi^\dagger\Phi\right)\partial_\mu\left(\Phi^\dagger\Phi\right)$$

$$\mathcal{O}_{\Phi,3} = \frac{1}{3}\left(\Phi^\dagger\Phi\right)^3$$

$$\mathcal{O}_{\Phi,4} = (D_\mu\Phi)^\dagger\,(D^\mu\Phi)\left(\Phi^\dagger\Phi\right)$$

$$\mathcal{O}_{\Box\Phi} = (D_\mu D^\mu\Phi)^\dagger\,(D_\nu D^\nu\Phi)$$

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$$\mathcal{O}_{BB} = \Phi^\dagger \hat{B}_{\mu\nu} \hat{B} \ldots \qquad \ldots \Phi^\dagger \hat{B}_{\mu\nu} \hat{W}^{\mu\nu} \Phi$$

$$\mathcal{O}_{W} = (D_\mu \Phi)^\dagger \hat{W}^{\mu} \ldots \qquad \ldots \Phi)^\dagger \hat{B}^{\mu\nu} (D_\nu \Phi)$$

$$\mathcal{O}_{\Phi,1} = (D_\mu \Phi)^\dagger\, \Phi\, \Phi \ldots \qquad \ldots (\Phi^\dagger \Phi)\, \partial_\mu \left(\Phi^\dagger \Phi\right)$$

11 parameters

$$\mathcal{O}_{\Phi,3} = \frac{1}{3}\left(\Phi^\dagger \Phi\right)^3 \qquad \mathcal{O}_{\Phi,4} = (D_\mu \Phi)^\dagger \left(D^\mu \Phi\right)\left(\Phi^\dagger \Phi\right)$$

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These operators describe pure gauge, gauge-*h* and pure-*h* interactions and several **correlations** among observables are predicted: i.e. triple gauge couplings vs. HVV couplings. **SMOKING GUNS!!!**

Example of Correlation

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

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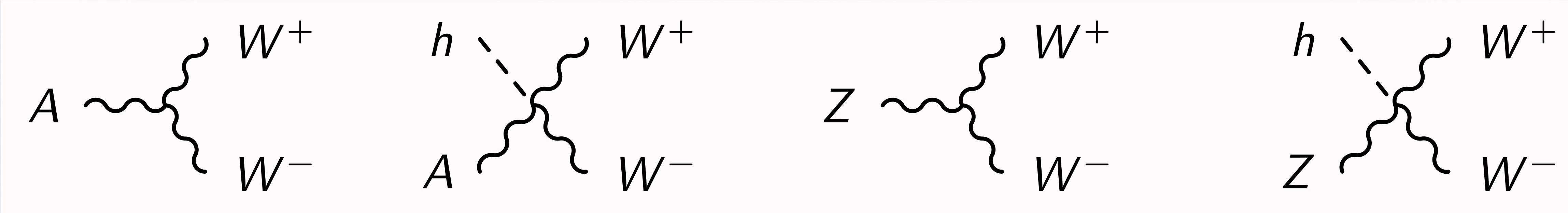
In unitary gauge can be rewritten as:

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



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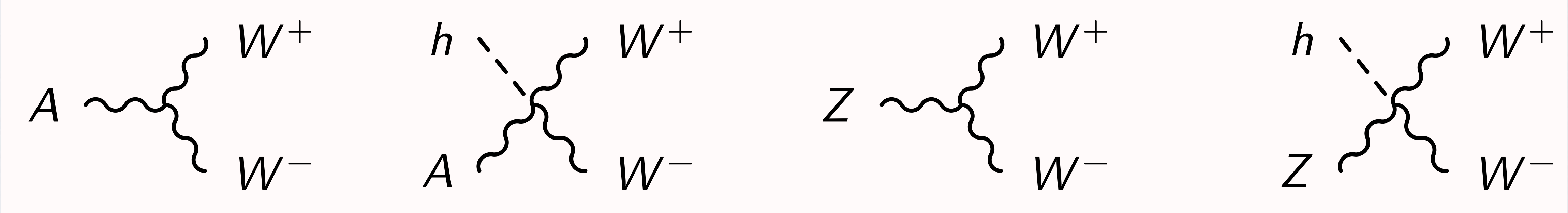

All these couplings are correlated!!

The chiral effective Lagrangian

[Alonso, Gavela, LM, Rigolin & Yepes, JHEP 1206 (2010) 07**6**
Alonso, Gavela, LM, Rigolin & Yepes, Phys.Lett. **B722** (2013) 330-335
Alonso, Gavela, LM, Rigolin & Yepes, Phys.Rev. **D87** (2013) 055019
Gavela, Gonzalez-Fraile, Gonzalez-Garcia, LM Rigolin & Yepes, Phys.Lett. JHEP **1410** (2014) 44]

Moving to the non-linear case

$$\Phi(x) = \frac{v+h}{\sqrt{2}} e^{i\sigma_a \pi^a(x)/v} \left(\begin{array}{c} 0 \\ 1 \end{array} \right)$$

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Higgs: h

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GBs: $\mathbf{U}(x) = e^{i\sigma_a \pi^a(x)/v}$

$\mathbf{U}(x) \to L\,\mathbf{U}(x) R^\dagger$

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- Being h a singlet: generic functions of h $\mathcal{F}_i(h) = 1 + 2\alpha_i \frac{h}{v} + \beta_i \frac{h^2}{v^2} + \dots$

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- Being h a singlet: generic functions of h $\mathcal{F}_i(h) = 1 + 2\alpha_i \frac{h}{v} + \beta_i \frac{h^2}{v^2} + \ldots$
- Being $\mathbf{U}(x)$ **vs.** h independent, many more operators can be constructed

The SM Lagrangian can be rewritten as

$$\mathcal{L}_0 = D_\mu \Phi^\dagger D^\mu \Phi - V(h) + \\ - \frac{1}{4} W^a_{\mu\nu} W^{a\mu\nu} - \frac{1}{4} B_{\mu\nu} B^{\mu\nu} - \frac{1}{4} G^a_{\mu\nu} G^{a\mu\nu} + \\ - \bar{Q}_L \Phi \mathcal{Y}_d D_R - \bar{Q}_L \tilde{\Phi} \mathcal{Y}_u U_R + h.c. + \ldots$$

$$\Phi(x) = \frac{v+h}{\sqrt{2}} \mathbf{U} \begin{pmatrix} 0 \\ 1 \end{pmatrix}$$

See talk by Alonso

$$\mathbf{V}_\mu \equiv (\mathbf{D}_\mu \mathbf{U})\, \mathbf{U}^\dagger$$

$$\mathbf{V} \to L\, \mathbf{V}\, L^\dagger$$

$$\mathcal{L}_0 = \frac{1}{2} \partial_\mu h \partial^\mu h + \frac{v^2}{4} \left(1 + \frac{h}{v}\right)^2 Tr[\mathbf{V}_\mu \mathbf{V}^\mu] - V(h) + \\ - \frac{1}{4} W^a_{\mu\nu} W^{a\mu\nu} - \frac{1}{4} B_{\mu\nu} B^{\mu\nu} - \frac{1}{4} G^a_{\mu\nu} G^{a\mu\nu} + \\ - \frac{v}{\sqrt{2}} \left(1 + \frac{h}{v}\right) \bar{Q}_L \mathbf{U} \mathcal{Y}_Q Q_R + h.c. + \ldots$$

SM Lag in chiral **notation**

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We now introduce the hypothesis of ***h*** **as a singlet**:

$$\mathcal{F}_i(h) = 1 + 2\alpha_i \frac{h}{v} + \beta_i \frac{h^2}{v^2} + \dots$$

$$\mathcal{L}_0 = \frac{1}{2}\partial_\mu h \partial^\mu h + \frac{v^2}{4}\mathcal{F}_C Tr[\mathbf{V}_\mu \mathbf{V}^\mu] - V(h) +$$
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$$- \frac{v}{\sqrt{2}}\mathcal{F}_Y \bar{Q}_L \mathbf{U}\mathcal{Y}_Q Q_R + h.c. + \dots$$

α_i, β_i are independent coefficients!!

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$$\begin{cases} \mathbf{U}(x) = e^{i\sigma_a \pi^a(x)/v} \\ \mathbf{T} \equiv \mathbf{U}\sigma_3\mathbf{U}^\dagger \qquad \mathbf{V}_\mu \equiv (\mathbf{D}_\mu \mathbf{U})\,\mathbf{U}^\dagger \end{cases}$$

Appelquist-Longhitano-Feruglio basis

[Appelquist&Bernard 1980; Longhitano 1980, 1981; Appelquist&Wu 1993; Feruglio 1993]

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$\mathbf{U}(x)$ is a 2x2 **adimensional** matrix. This leads to a fundamental difference between the linear and chiral Lagrangians:

SM	**σ-model**
▪ The GBs are in the Higgs doublet Φ ▪ Φ has dimension 1 in mass ▪ d=4+n operators are suppressed by Λ^n_{NP}	▪ The $\mathbf{U}(x)$ matrix is adimensional and any its extra insertions do not lead to any suppression

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→ **The dimension of the leading low-energy operators differs for a purely linear and a non-linear regime**

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→ **The dimension of the leading low-energy operators differs for a purely linear and a non-linear regime**

- Introducing a **light CP-even singlet scalar *h***, with an associated scale *f*

$$\begin{cases} h \\ \partial_\mu h \end{cases}$$

[Grinstein&Trott 2007; Contino *et al.* 2010; Azatov *et al.* 2012]

The complete CP-even pure-gauge & gauge-*h* basis

[Alonso, Gavela, LM, Rigolin & Yepes, Phys.Lett. **B722** (2013) 330-335]

[CP-Odd: Gavela, Gonzalez-Fraile, Gonzalez-Garcia, LM Rigolin & Yepes, Phys.Lett. JHEP **1410** (2014) 44]

[Compare with Buchalla,Cata&Krause 2013]

See talk by Krause

$$\mathcal{L}_{\rm chiral} = \mathcal{L}_0 + \Delta\mathcal{L}$$

$$\begin{aligned}\mathcal{L}_0 =& \frac{1}{2}\partial_\mu h \partial^\mu h + \frac{v^2}{4}\mathcal{F}_C Tr[\mathbf{V}_\mu \mathbf{V}^\mu] - V(h) + \\ & - \frac{1}{4}W^a_{\mu\nu}W^{a\mu\nu} - \frac{1}{4}B_{\mu\nu}B^{\mu\nu} - \frac{1}{4}G^a_{\mu\nu}G^{a\mu\nu} + \\ & - \frac{v}{\sqrt{2}}\mathcal{F}_Y \bar{Q}_L \mathbf{U}\mathcal{Y}_Q Q_R + h.c. + \dots\end{aligned}$$

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$$\mathcal{L}_{\text{chiral}} = \mathcal{L}_0 + \Delta\mathcal{L}$$

$$\Delta\mathcal{L} = \sum c_i \mathcal{P}_i \quad \Rightarrow \quad \mathcal{P}_B(h) = \frac{g'}{4} B_{\mu\nu} B^{\mu\nu} \mathcal{F}_B(h)$$

$$\vdots$$

$$\mathcal{P}_1(h) = g g' B_{\mu\nu} \text{Tr}(\mathbf{T} W^{\mu\nu}) \mathcal{F}_1(h)$$

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

$$\vdots$$

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

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33 parameters

To compare with 10 in the linear case

→ **New Effects!!**

Disentangling a dynamical Higgs from an elementary one: <u>Pure-gauge & Gauge-Higgs</u>

[Brivio,Corbett,Eboli,Gavela,Gonzalez-Fraile,Gonzalez-Garcia,LM&Rigolin, JHEP **1403** (2014) 024
Brivio,Eboli,Gavela,Gonzalez-Garcia,LM&Rigolin, JHEP **12** (2014) 004]

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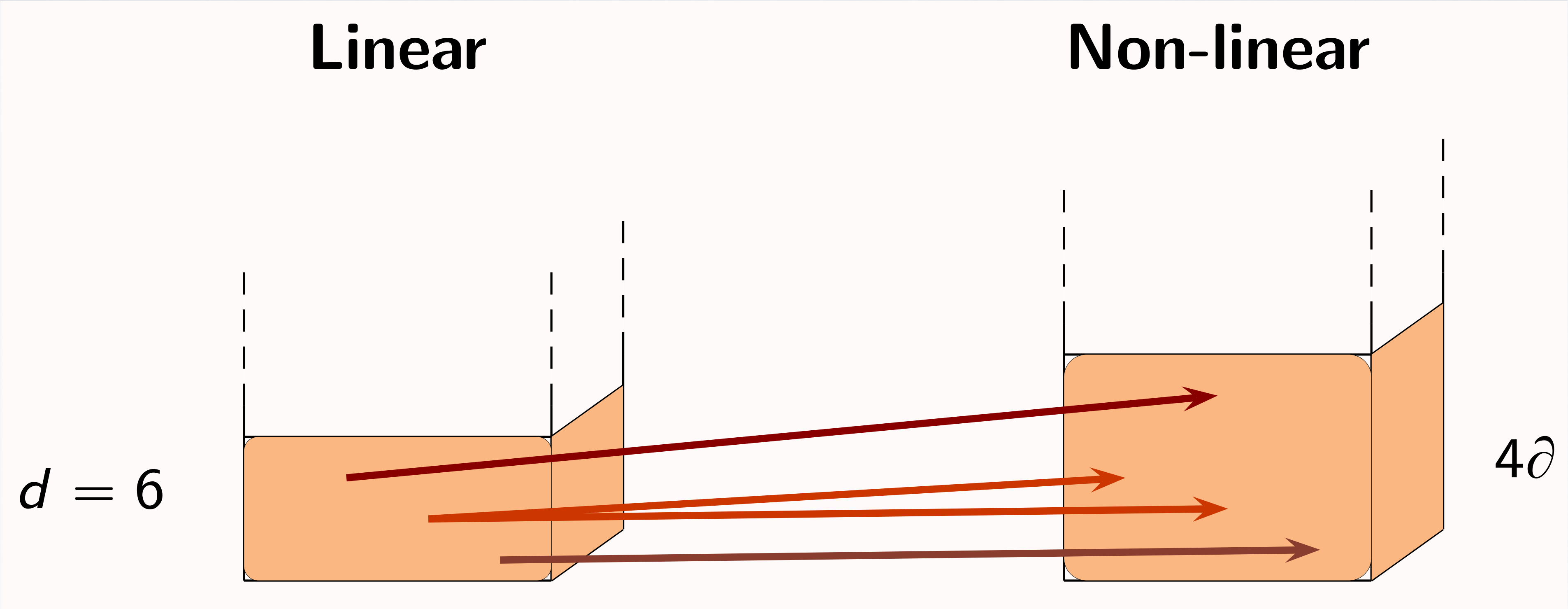
- Investigate on the signals of decorrelations: due to the nature of the chiral expansion vs. the linear one, and due to $\mathcal{F}_i(h) \neq \left(1+\frac{h}{v}\right)^2$



For a generic Composite Higgs model:

h is embedded in a doublet of $SU(2)_L$ (reducible rep of $\mathcal{G}$)

$\mathcal{F}_i(h) = 1 + 2\alpha_i \frac{h}{v} + \beta_i \frac{h^2}{v^2} + \ldots$ not generic but specific: $\sin\left[\frac{h}{2f}\right]$

At low-energy, there are correlations among operators

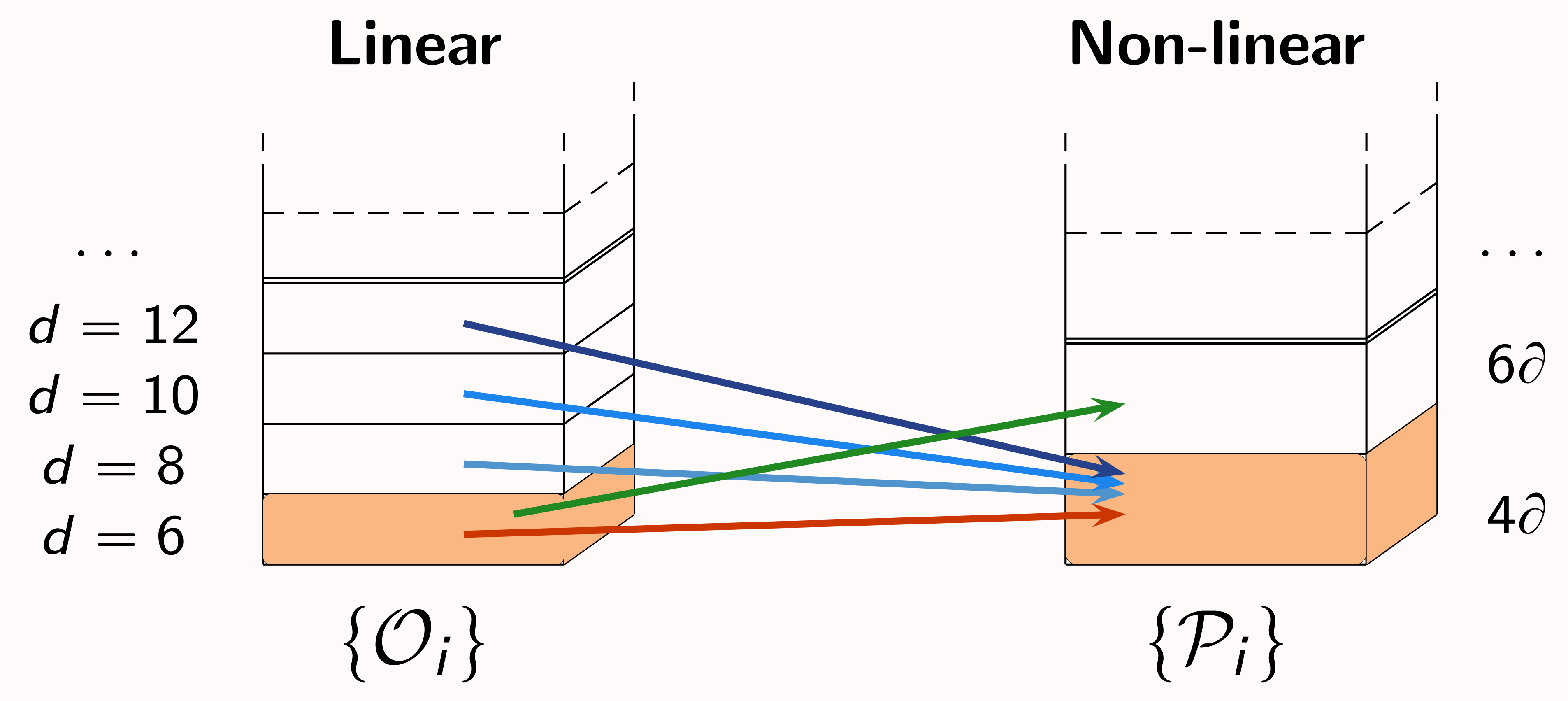
[Alonso,Brivio,Gavela,LM&Rigolin, JHEP **12** (2014) 034]

[Hierro,LM&Rigolin, arXiv:1510.07899 LAST WEEK]

See talk by Panico

Strategy

- Investigate on the signals of decorrelations: due to the nature of the chiral expansion vs. the linear one, and due to $\mathcal{F}_i(h) \neq \left(1+\frac{h}{v}\right)^2$
- Study the anomalous signal present in the chiral description, but absent in the linear one



Example of Decorrelation

Correlations present in the linear basis are absent in the chiral basis

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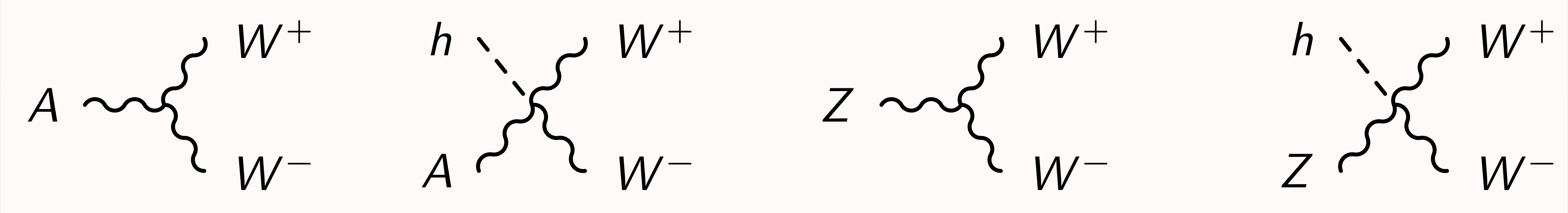

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$$\mathcal{O}_B = \frac{v^2}{16}\mathcal{P}_2(h) + \frac{v^2}{8}\mathcal{P}_4(h) \quad \text{with} \quad \mathcal{F}_i(h) = \left(1+\frac{h}{v}\right)^2$$

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

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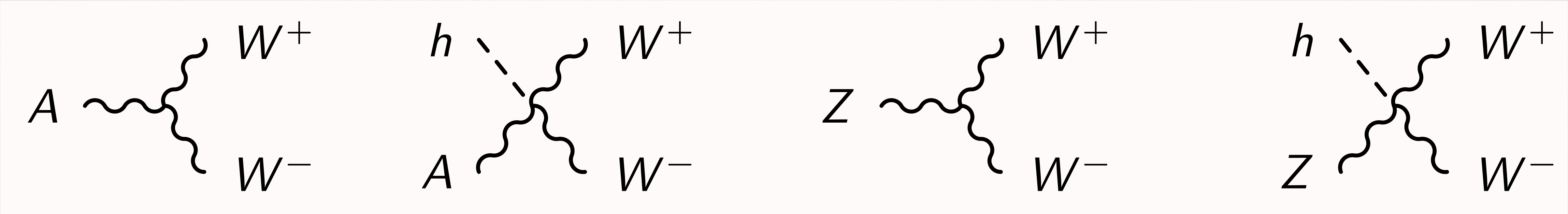

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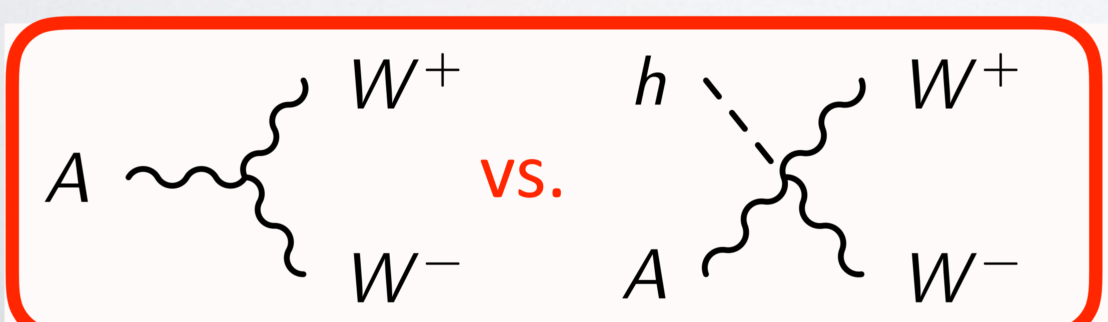
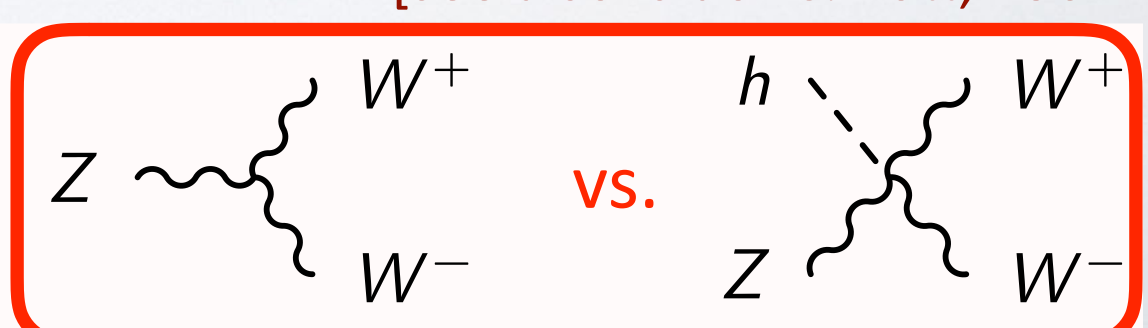
due to the decorrelation in the $\mathcal{F}_i(h)$ functions: i.e.

[see also Isidori&Trott, 1307.4051]





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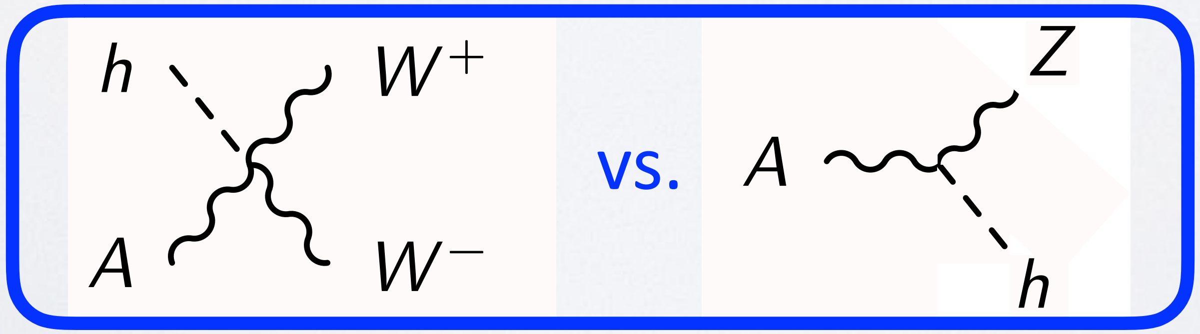
due to the nature of the chiral operators (different c_i coefficients): i.e.



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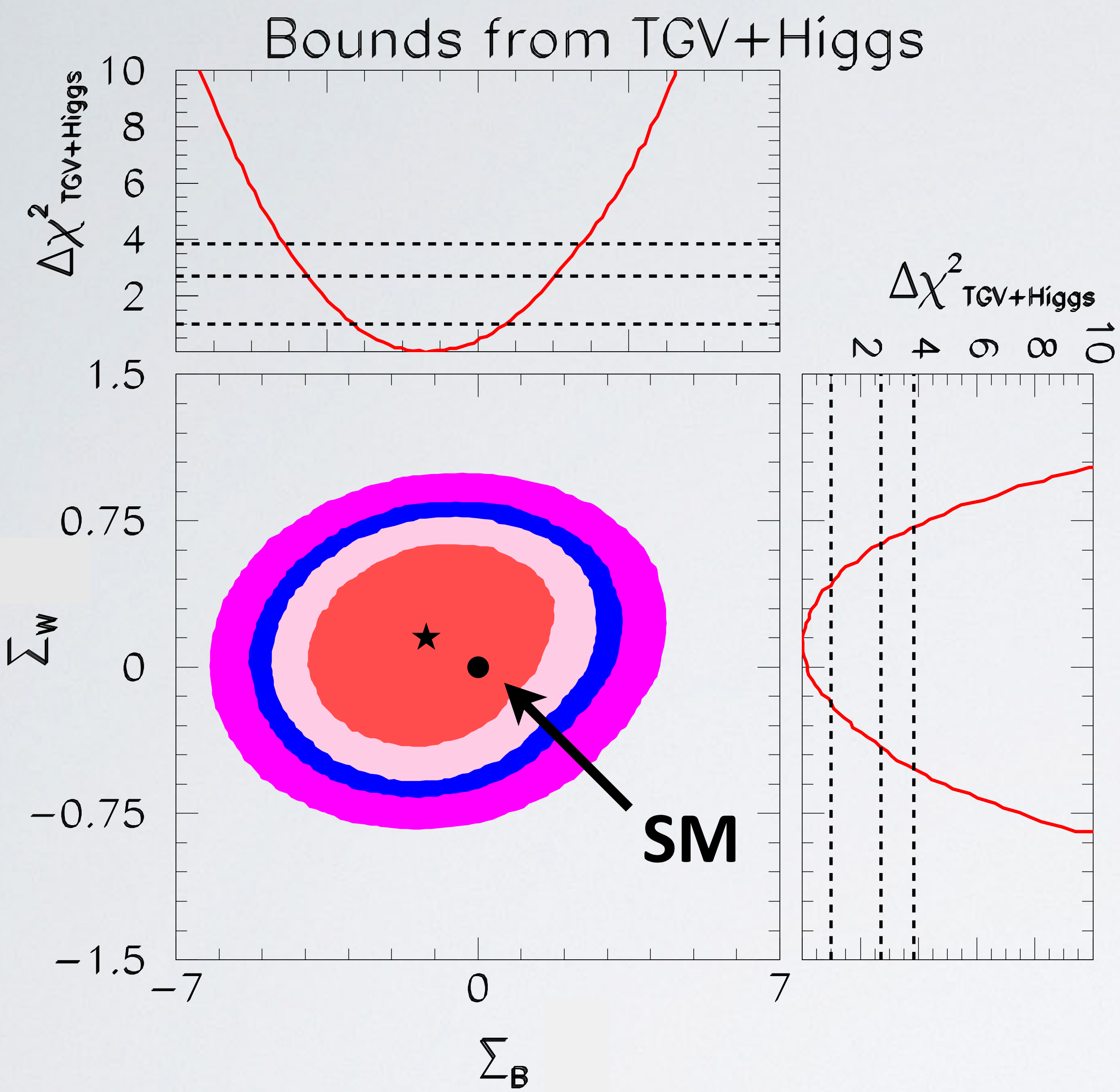
$$\mathcal{O}_W = \frac{v^2}{8}\mathcal{P}_3(h) - \frac{v^2}{4}\mathcal{P}_5(h) \quad \text{with} \quad \mathcal{F}_i(h) = \left(1+\frac{h}{v}\right)^2$$

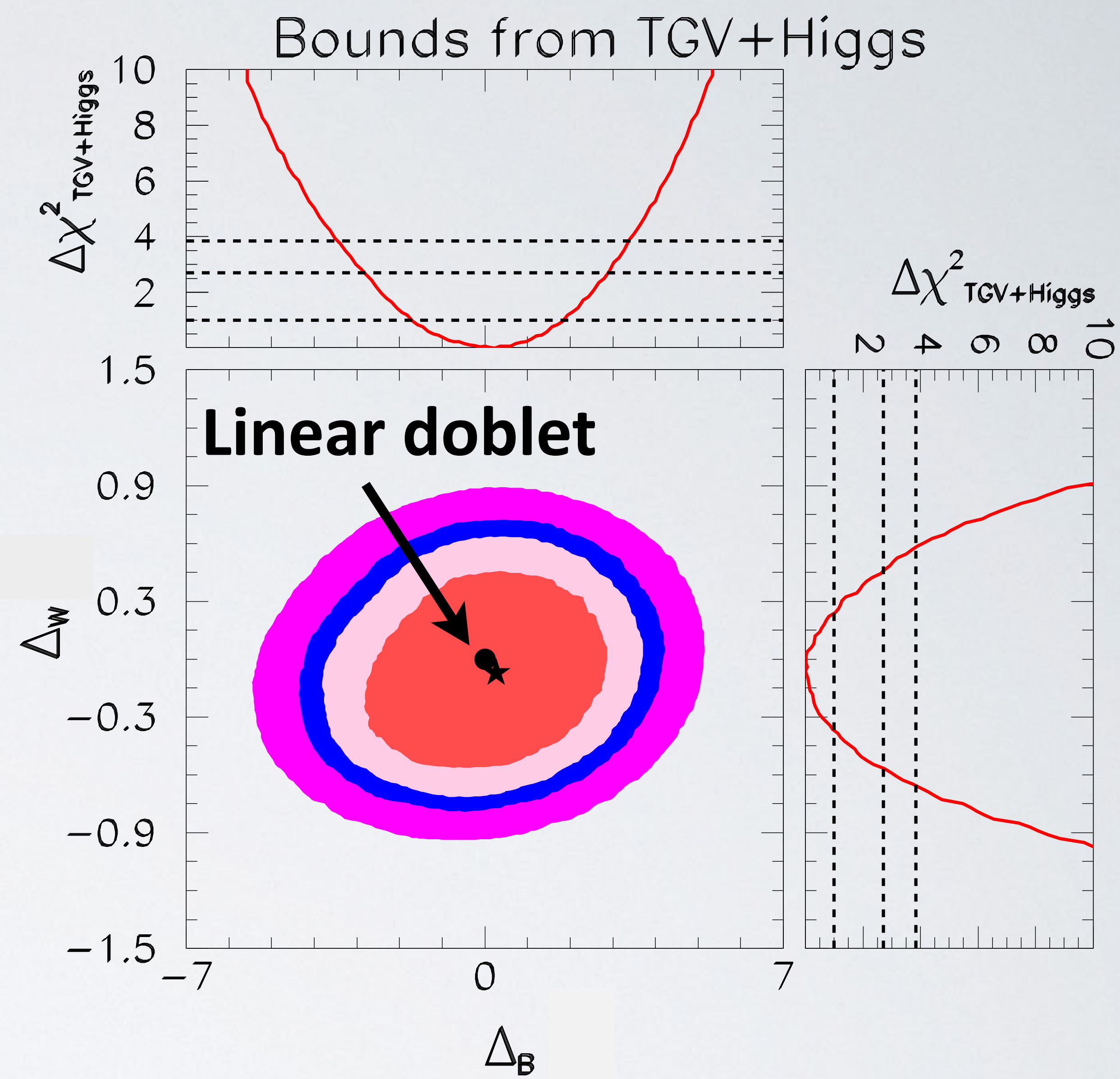
$$\mathcal{O}_W = (D_\mu\Phi)^\dagger \hat{W}^{\mu\nu}(D_\nu\Phi)$$

$$\mathcal{P}_3(h) = ig\mathrm{Tr}(W_{\mu\nu}[\mathbf{V}^\mu, \mathbf{V}^\nu])\mathcal{F}_3(h)$$

$$\mathcal{P}_5(h) = ig\mathrm{Tr}(W_{\mu\nu}\mathbf{V}^\mu)\partial^\nu\mathcal{F}_5(h)$$

Decorrelations



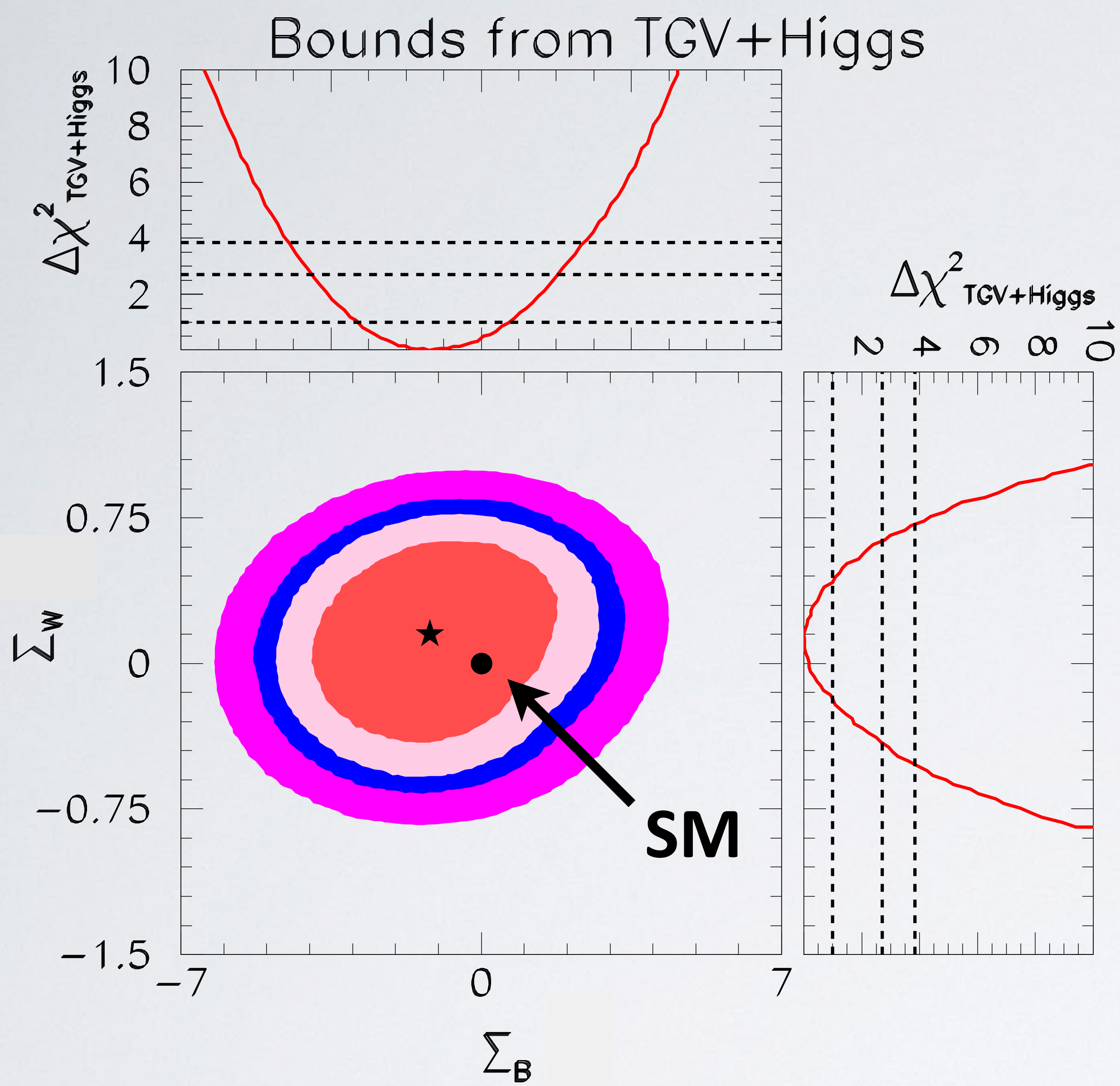


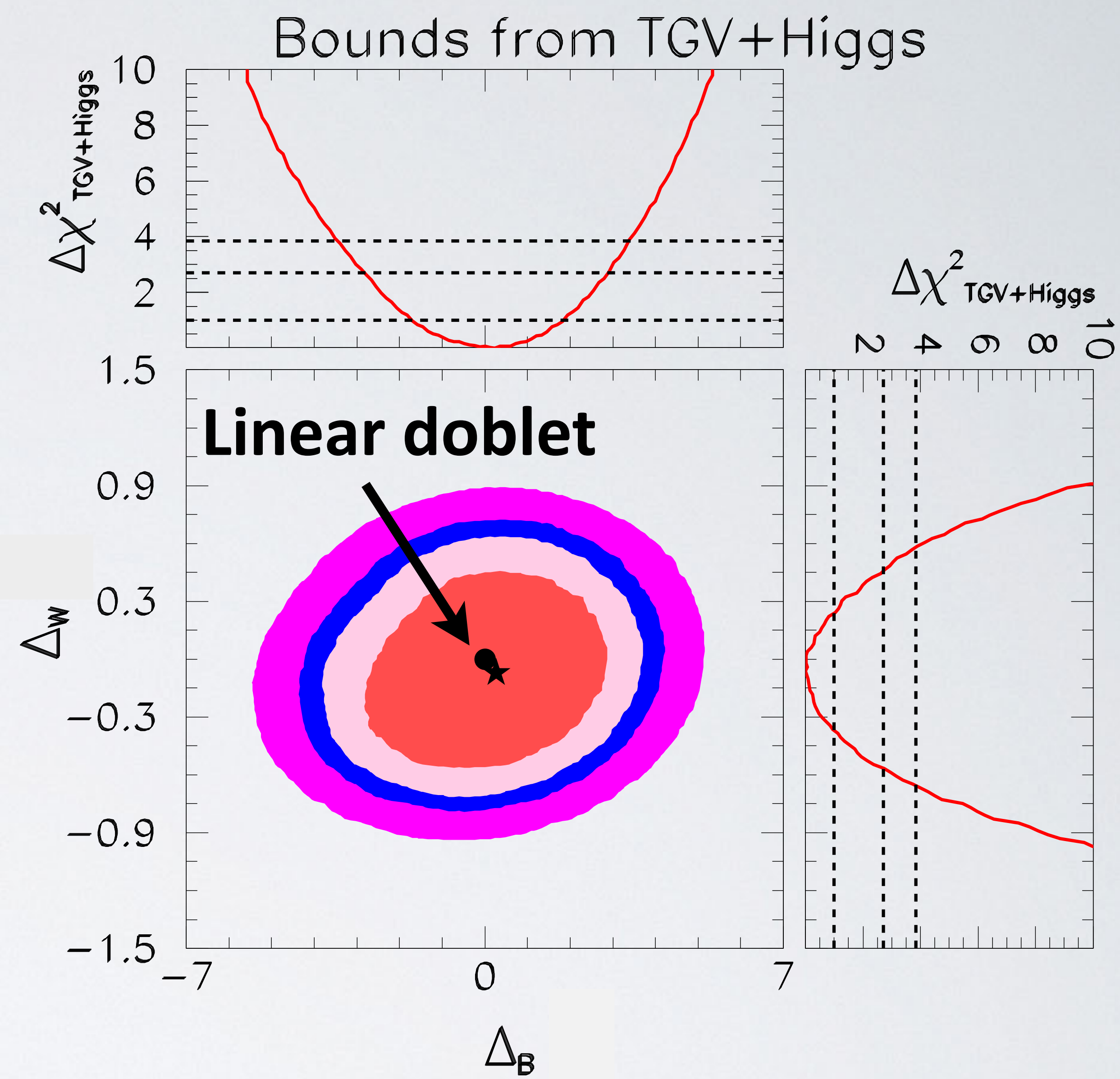
$$\Sigma_B = 4(2c_2 + a_4) \to f_B \xi \qquad \Delta_B = 4(2c_2 - a_4) \to 0$$

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

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 $\tau\bar{\tau}$

Decorrelations





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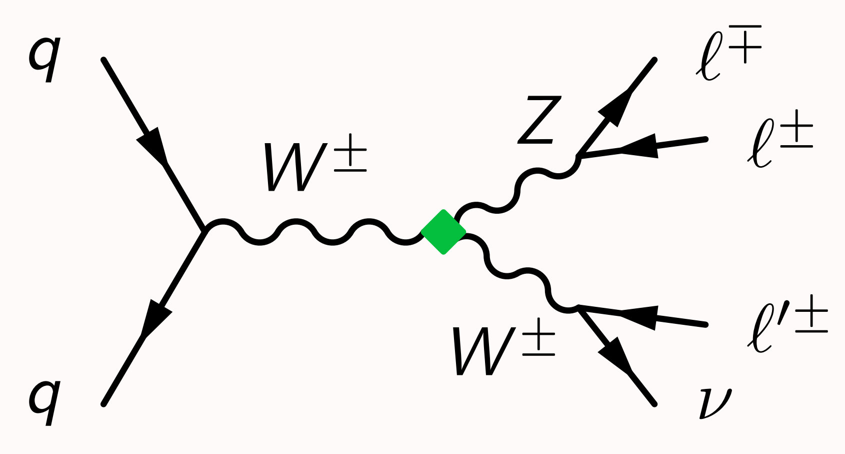
More precision for: - **discovering BSM physics with TGV and HVV**

- **disentangling dynamical from elementary**

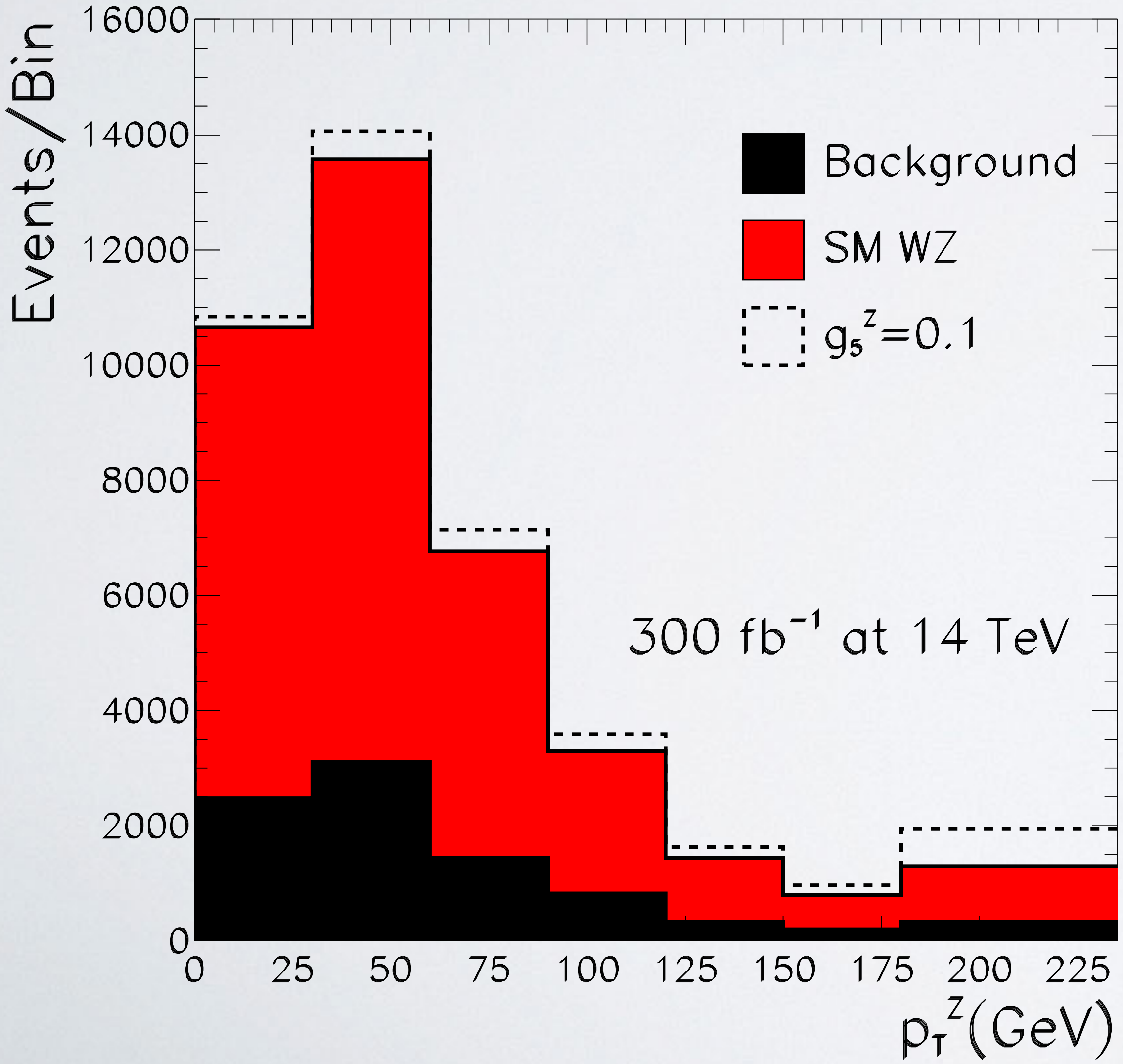
New Signals

<u>Signals expected in the chiral basis, but not in the linear one (d=8)</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) $g_5^Z \in [-0.033, 0.028]$

Much more pheno in:

Brivio,Gonzalez-Garcia,LM,

to appear in the next weeks

The Dark Matter Lagrangian

[Brivio,Gavela,LM,Mimasu,No,Rey,Sanz, TODAY on arXiv: 1511.01099]

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- Standard Higgs portal

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Deviations!!!

$$\mathcal{L} \supset \frac{m_S^2}{2} S^2 + \lambda_S S^2 (2vh + bh^2)$$

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No other portals

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$\mathbf{U}(x)$ **vs.** h

New Portals:

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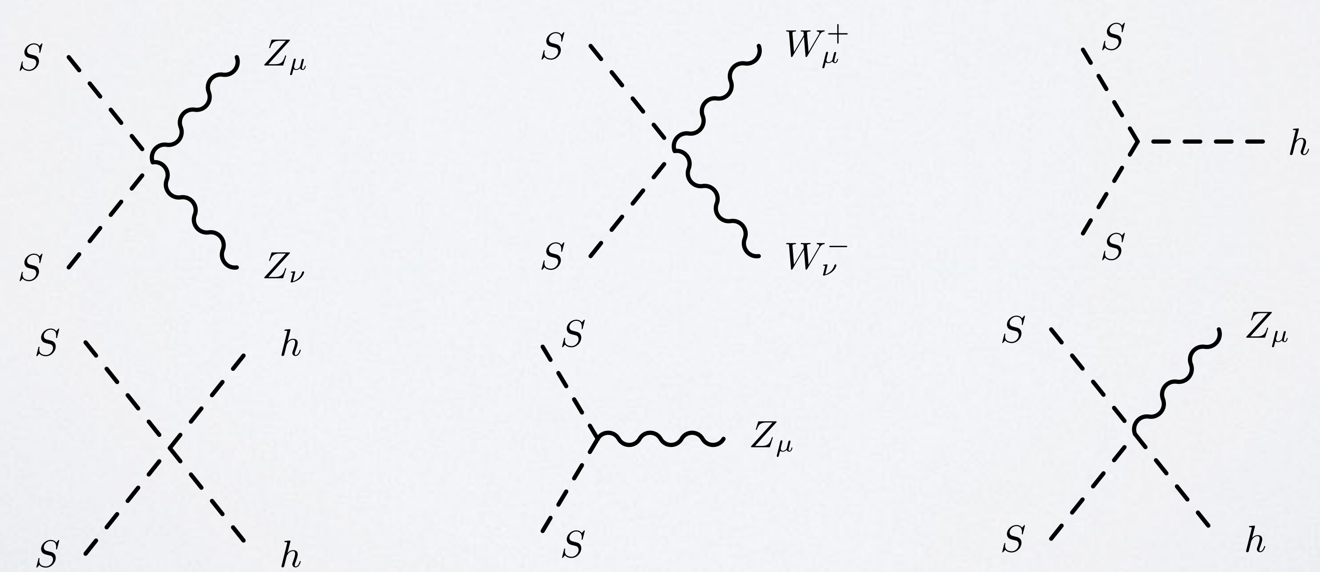

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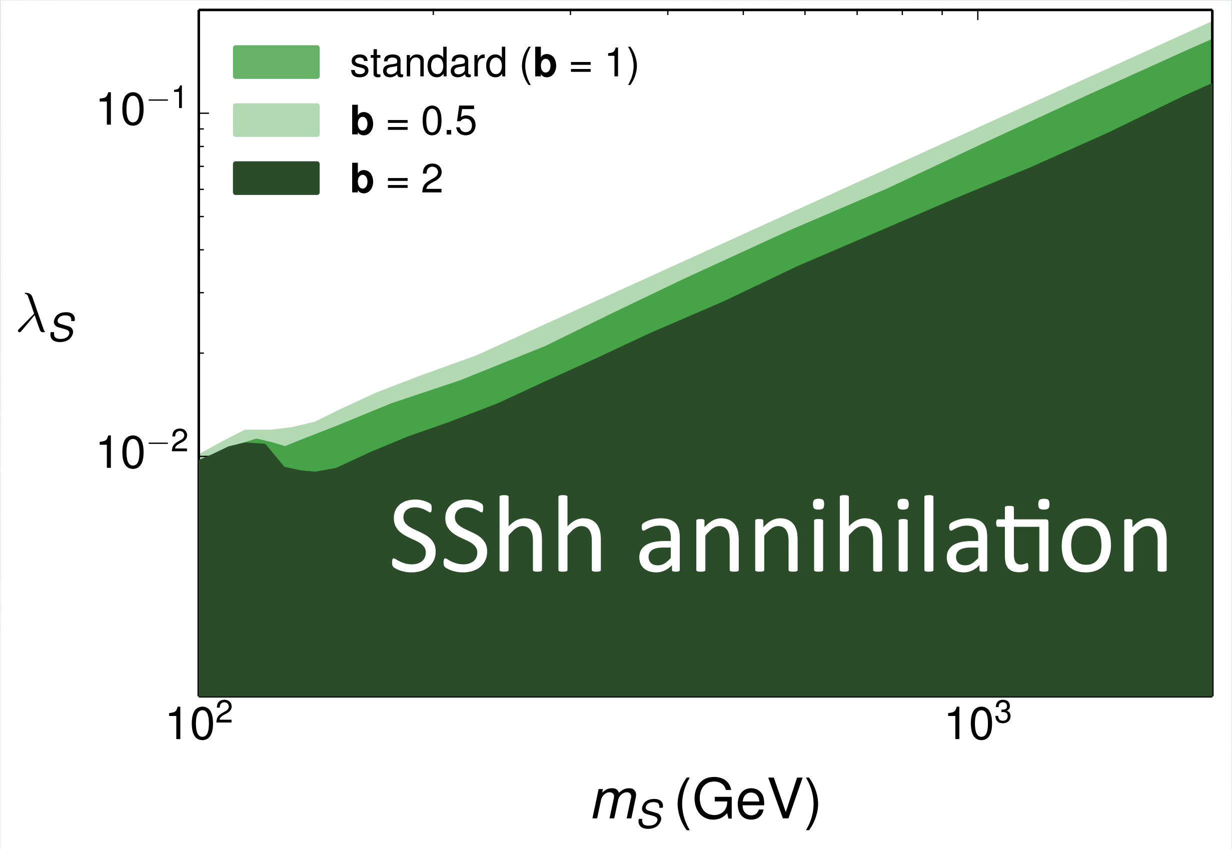
Observable		Parameters contributing					
		b	c_1	c_2	c_3	c_4	c_5
Thermal relic density	$\Omega_S h^2$	✓	✓	✓	✓	✓	✓
DM-nucleon scattering in direct detection	σ_{SI}	–	–	✓	–	✓	–
Invisible Higgs width	Γ_{inv}	–	–	✓	–	–	–
Mono-h production at LHC	$\sigma(pp \to hSS)$	✓	–	✓	–	✓	✓
Mono-Z production at LHC	$\sigma(pp \to ZSS)$	–	✓	✓	✓	✓	✓
Mono-W production at LHC	$\sigma(pp \to W^+SS)$	–	✓	✓	–	✓	–

DM Relic Density

$$\Omega_S h^2 \leq 0.12$$

Planck 2015



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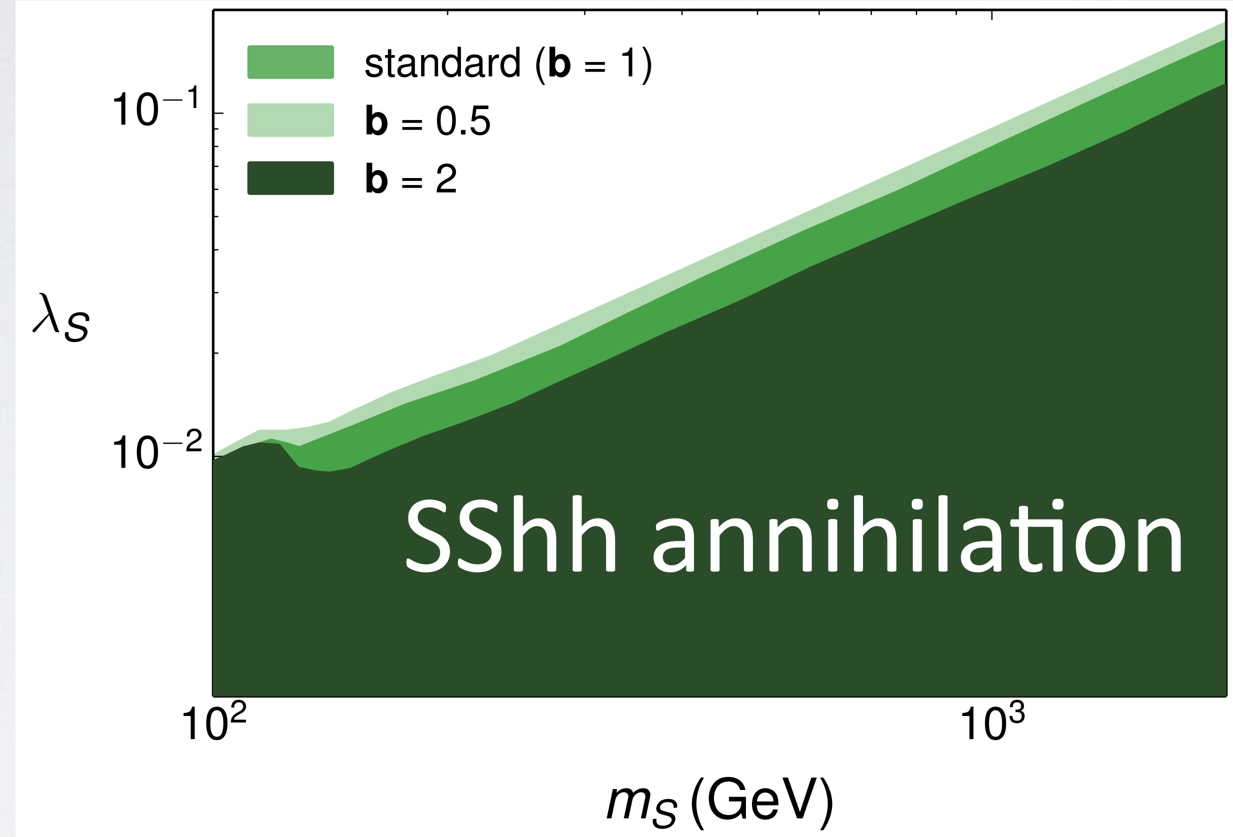
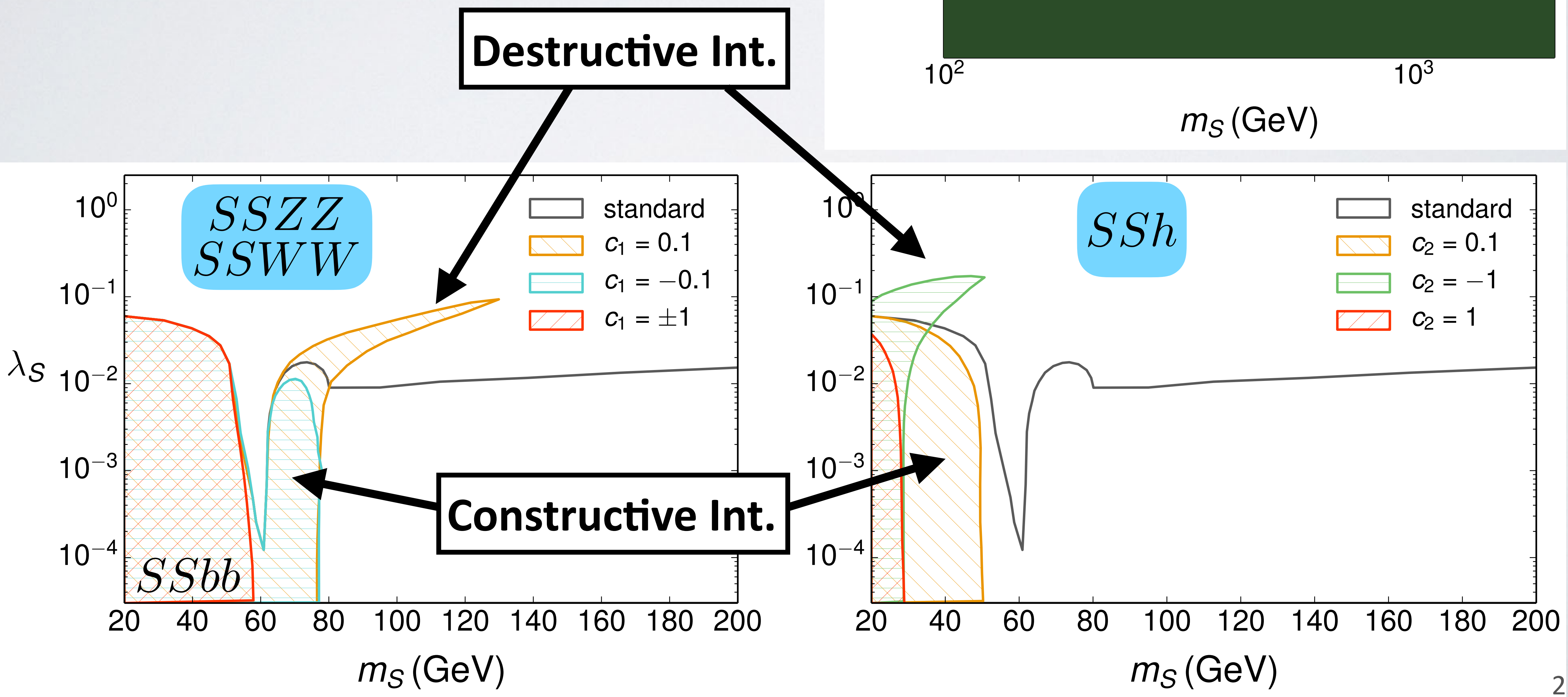
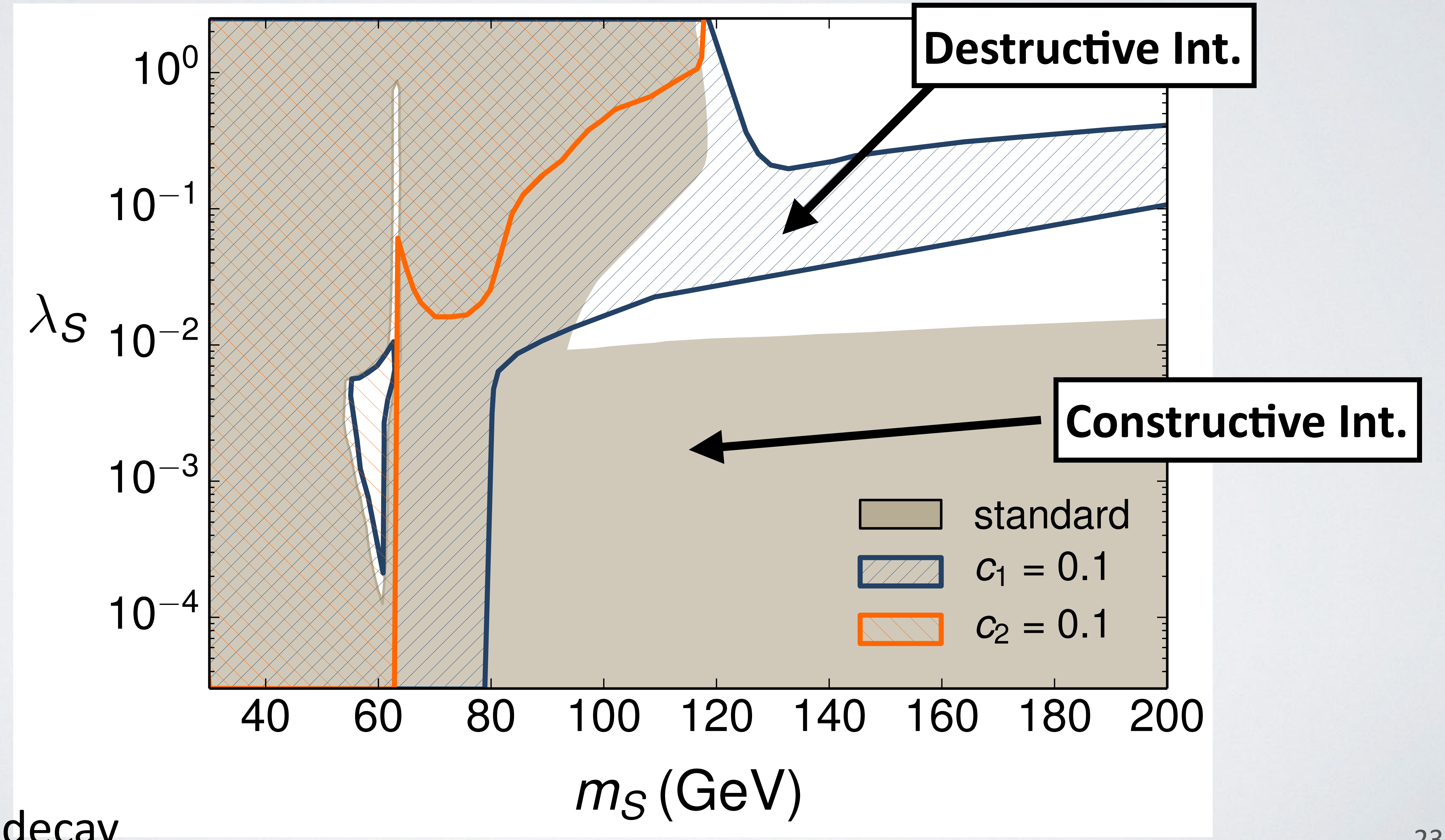




...+ Direct Detec. + Invisible h Decay

$\mathcal{A}_1$ and $\mathcal{A}_2$ do not contribute directly to the scattering, but through the relic density:

$$\sigma_{SI}(SN \to SN)\frac{\Omega_S}{\Omega_{DM}} \leq \sigma_{\rm exp}^{\rm lim}$$



Planck

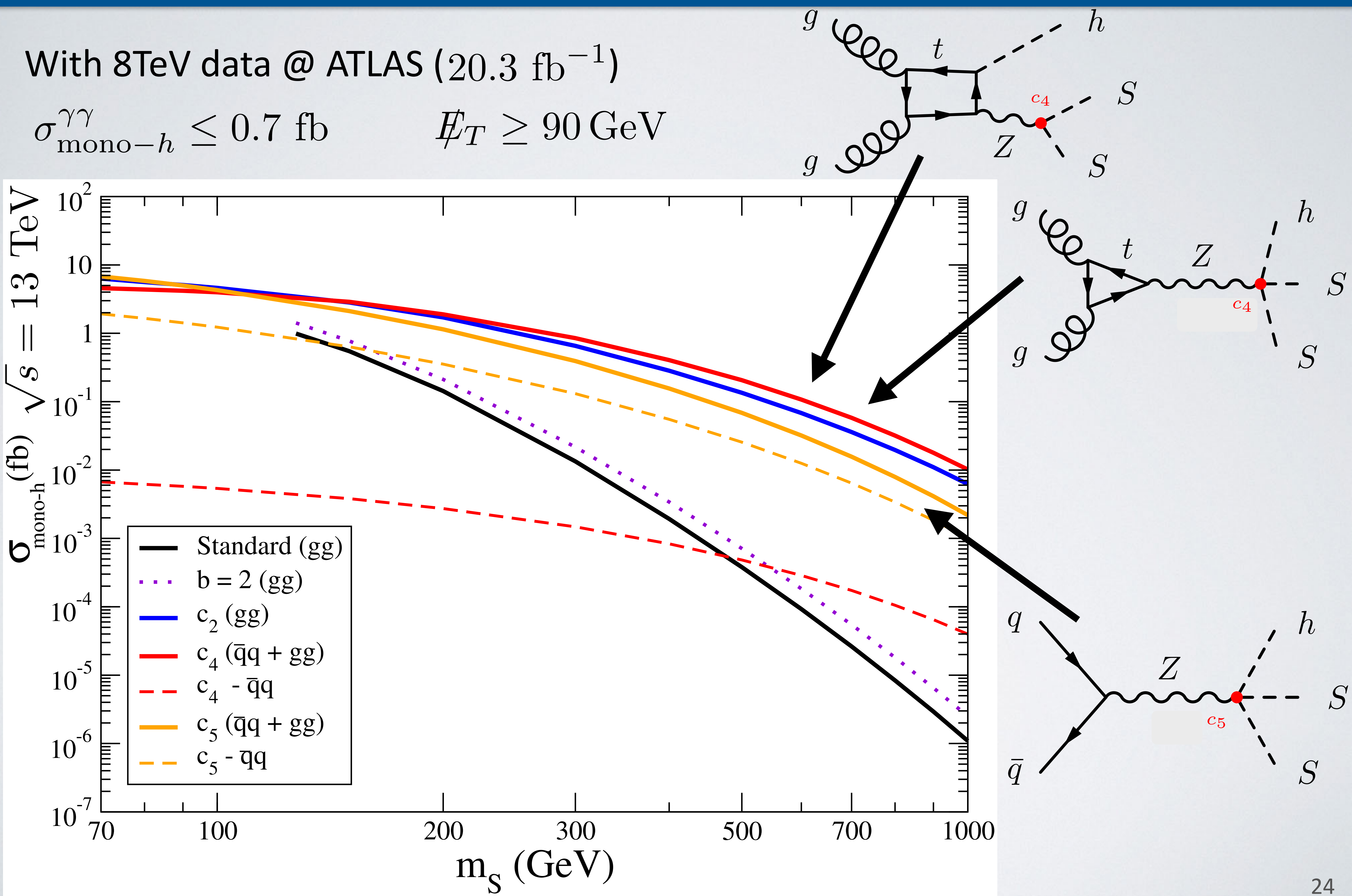
LUX

Invisible h decay

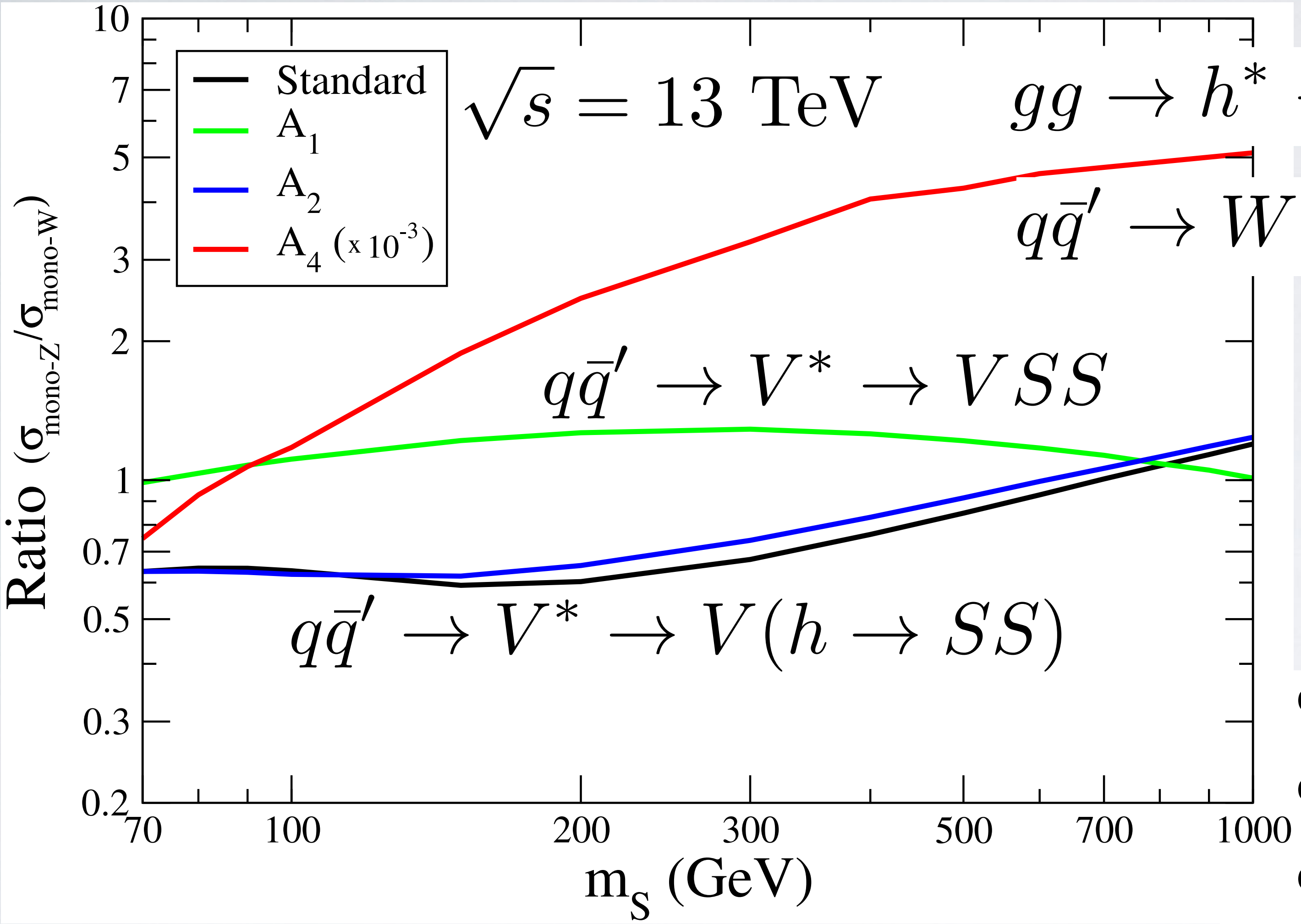
Mono-h Searches

With 8TeV data @ ATLAS ($20.3\ \text{fb}^{-1}$)

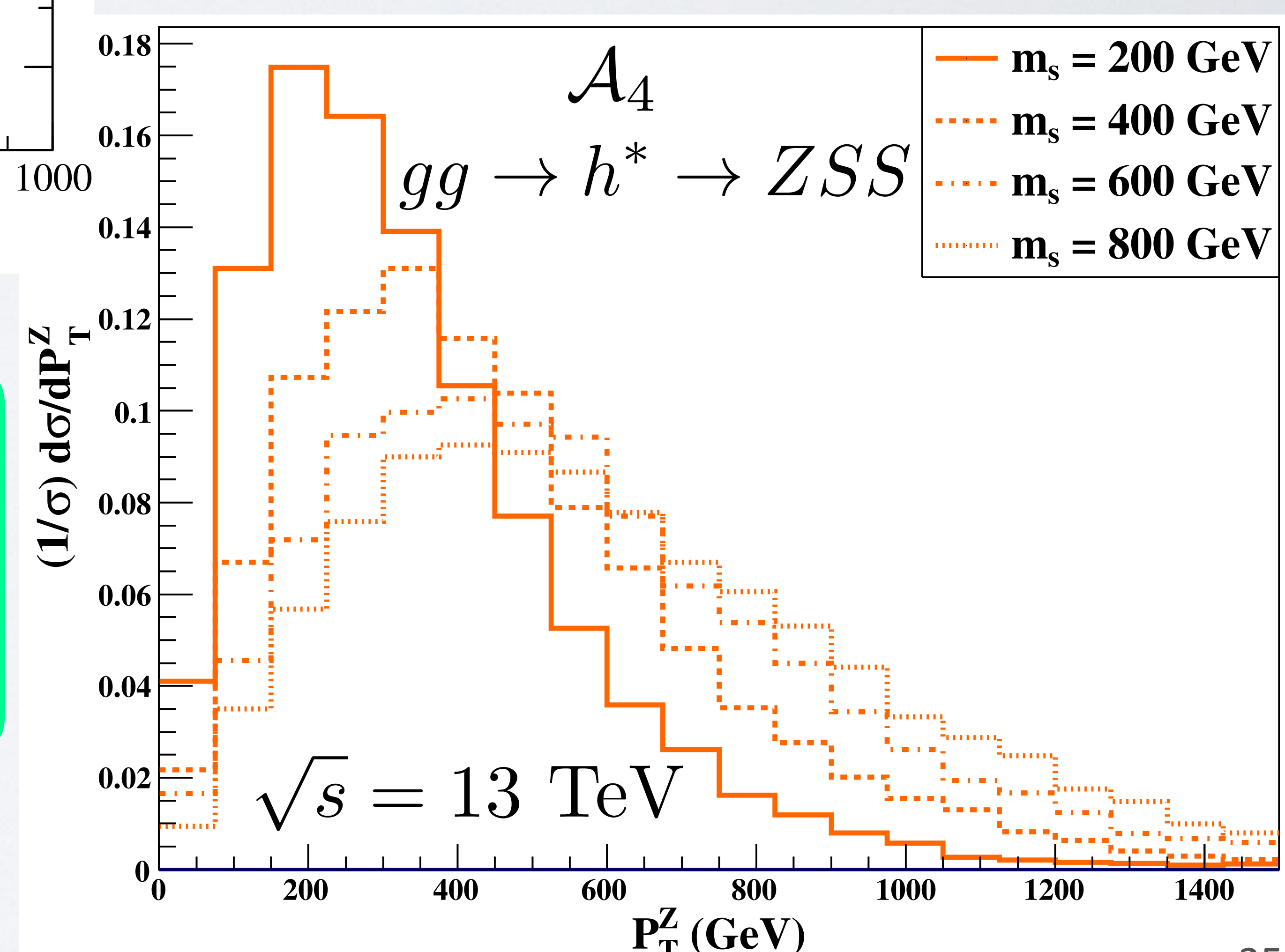
$\sigma^{\gamma\gamma}_{\text{mono}-h} \leq 0.7\ \text{fb}$ $\quad\quad$ $\not{E}_T \geq 90\,\text{GeV}$



Mono-Z & Mono-W Searches



<u>The Ratio is independent from the operator coefficients!!</u>



The combined measure of the Ratio and of the distribution of the signal, allows to fix a point in the parameter space!!

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➡ It is fundamental searching for it with dedicated studies, without biases

Pure Gauge, Gauge-Higgs, Pure-Higgs, DM…