# Composite Higgs models

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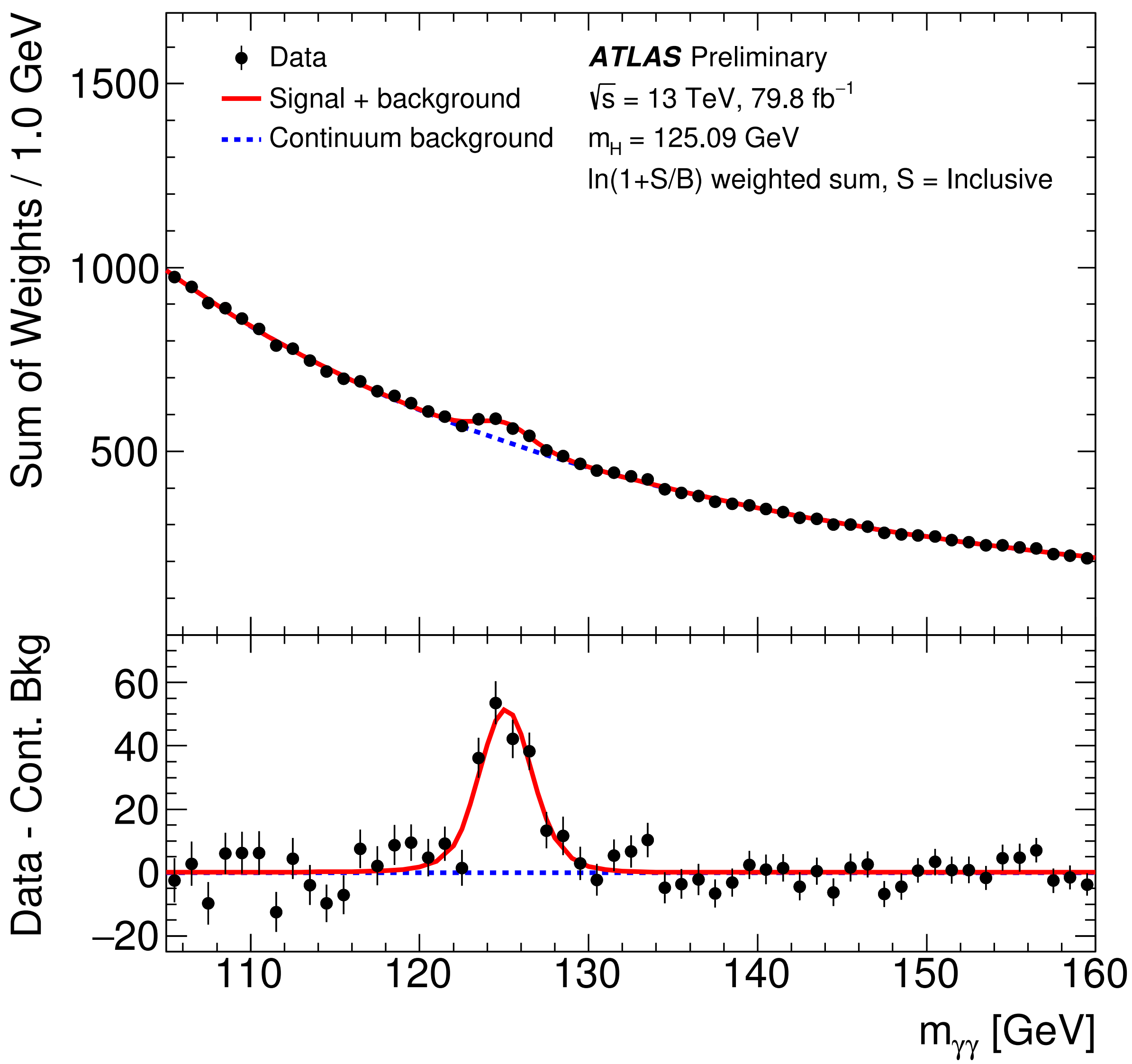
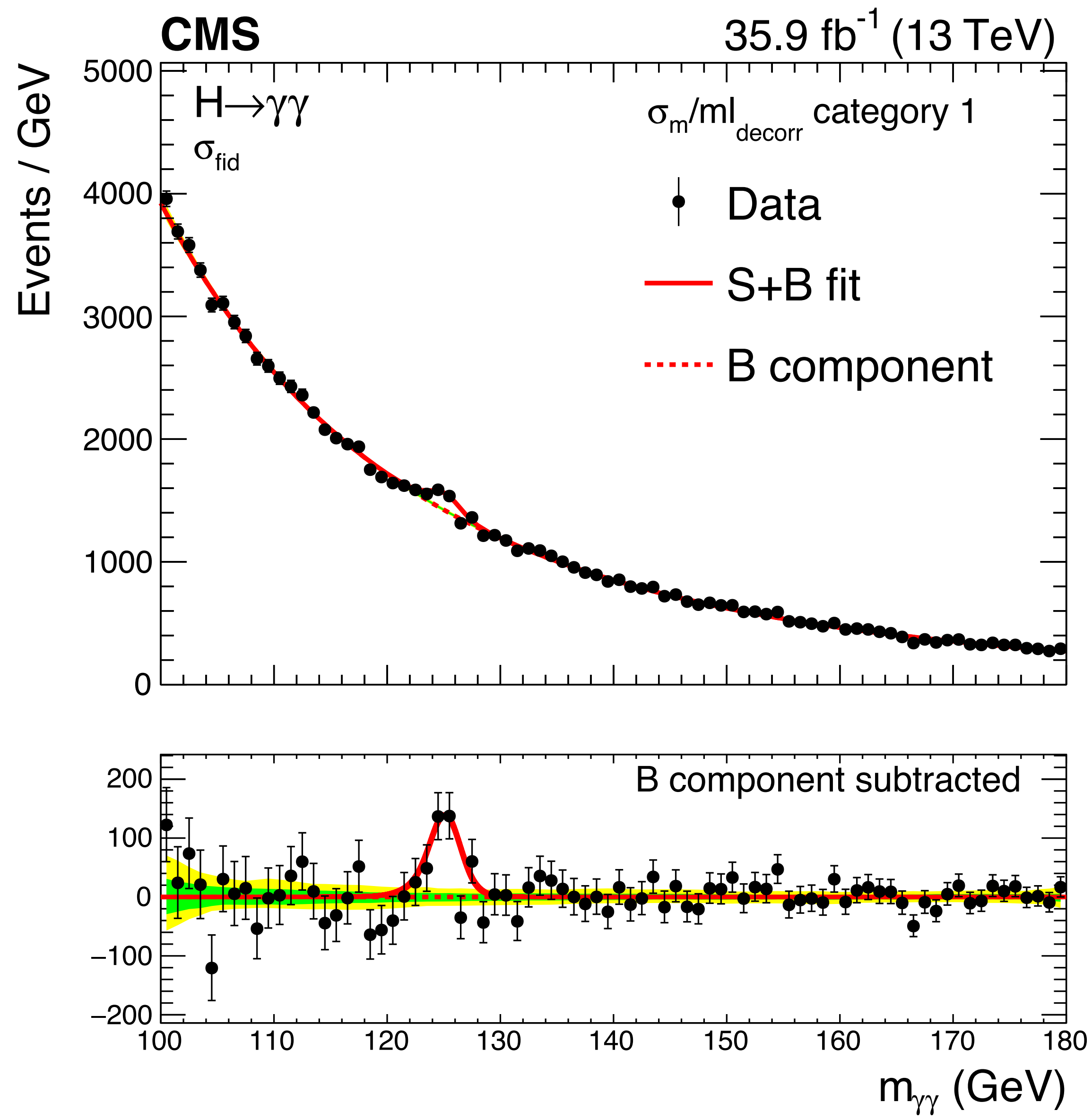
# Outline

- Naturalness as guideline
- Direct searches
- Indirect signatures
- Conclusion




**A first step towards the dynamics of EWSB!**

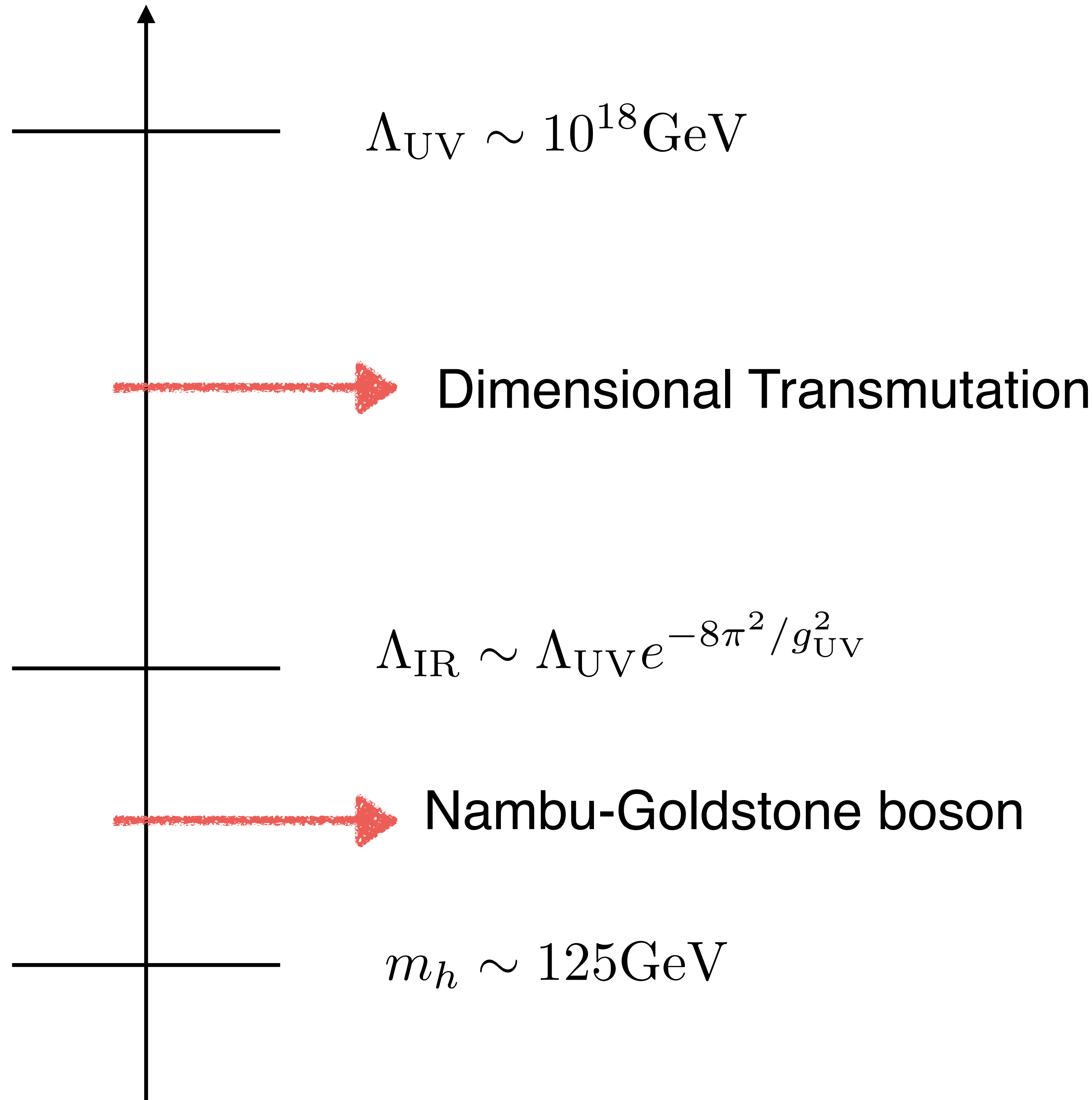
# t' Hooft Naturalness

A small parameter is natural
if setting it to zero leads to an enhanced symmetry

↓

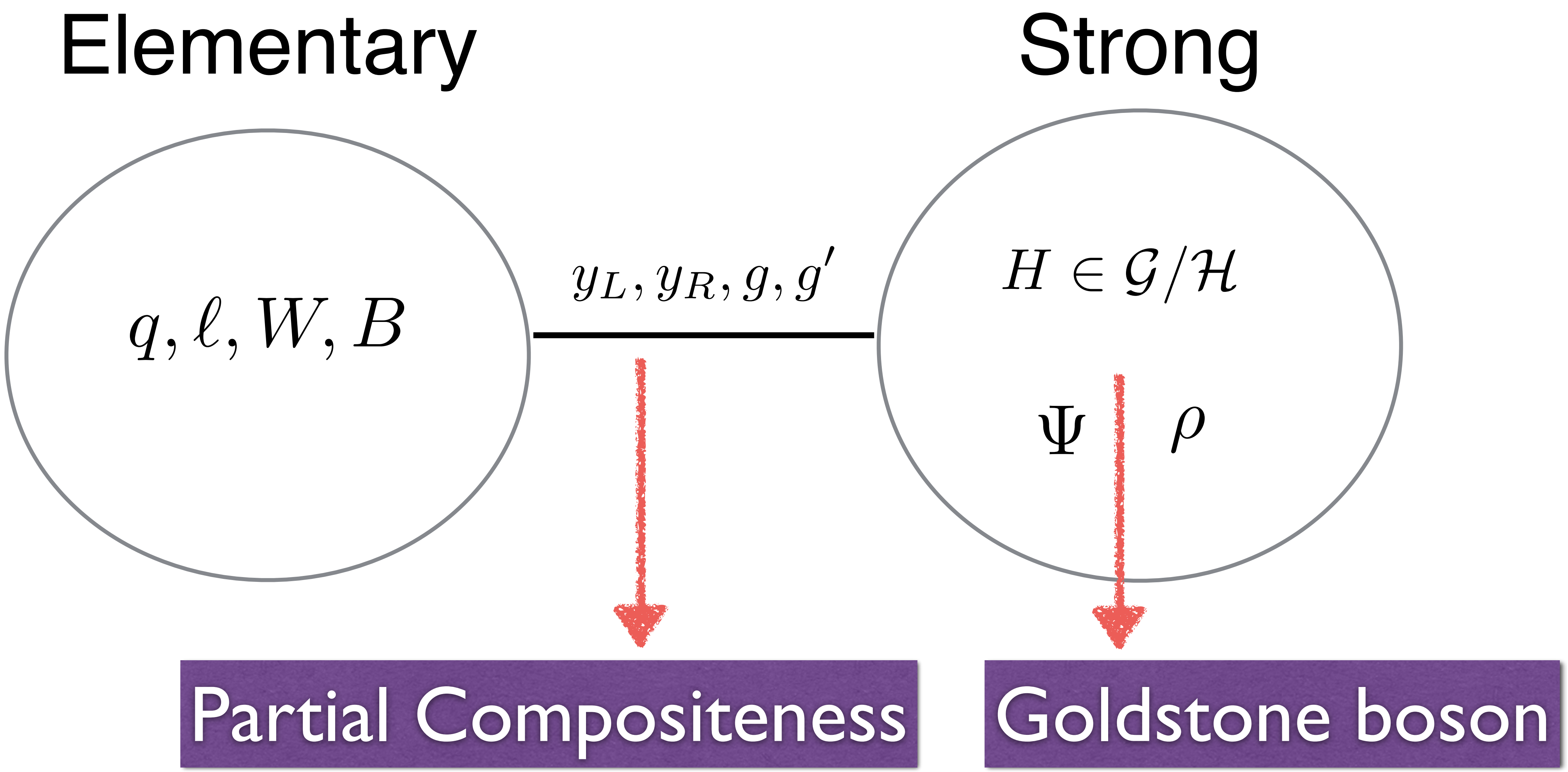
Guideline for model building

# Compositeness



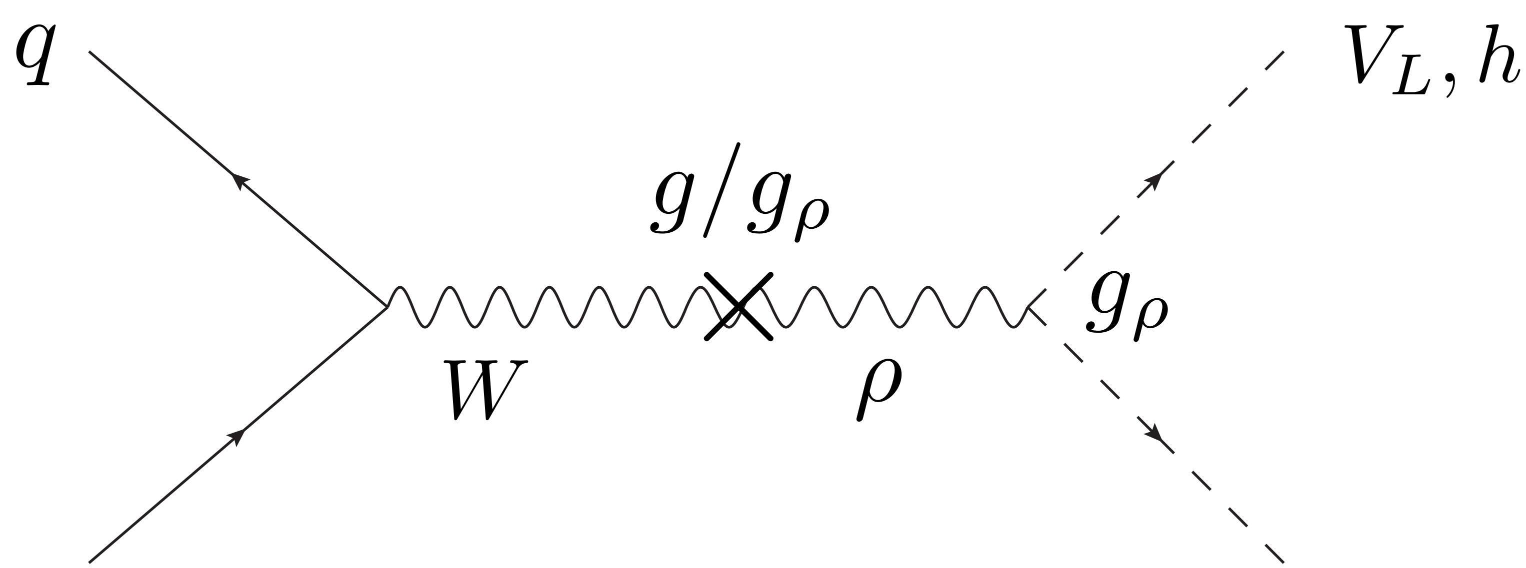

**Enhanced shift symmetry!**

# Composite Higgs models Sketch




Kaplan, Georgi ‘84
Contino, Nomura and Pomarol ’03
Agashe, Contino and Pomarol ‘04

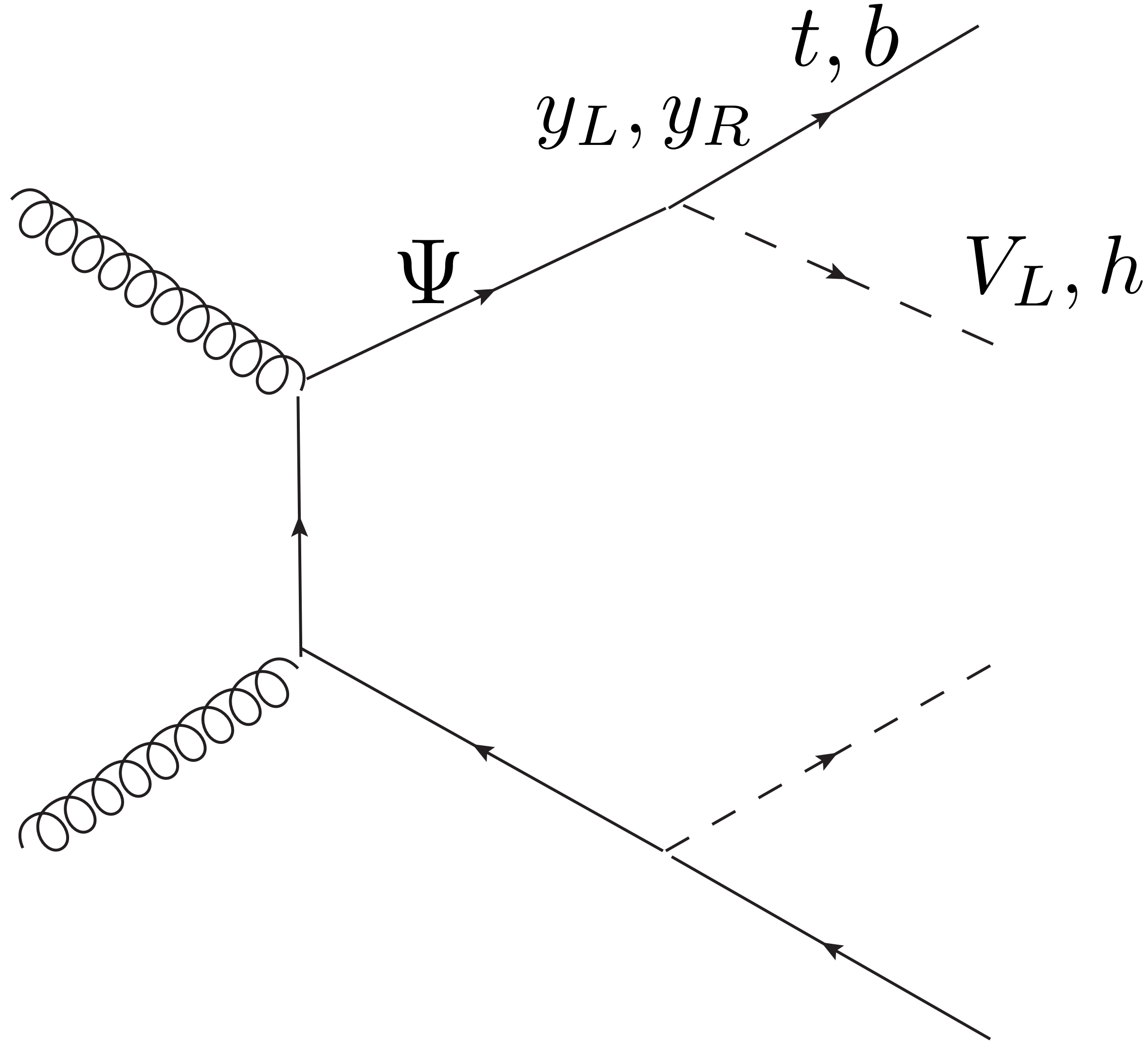
# Direct searches: Spin-1




Dibosons provide the smoking gun!

Pappadopulo, Thamm, Torre and Wulzer ‘14

# Direct searches: spin-1/2

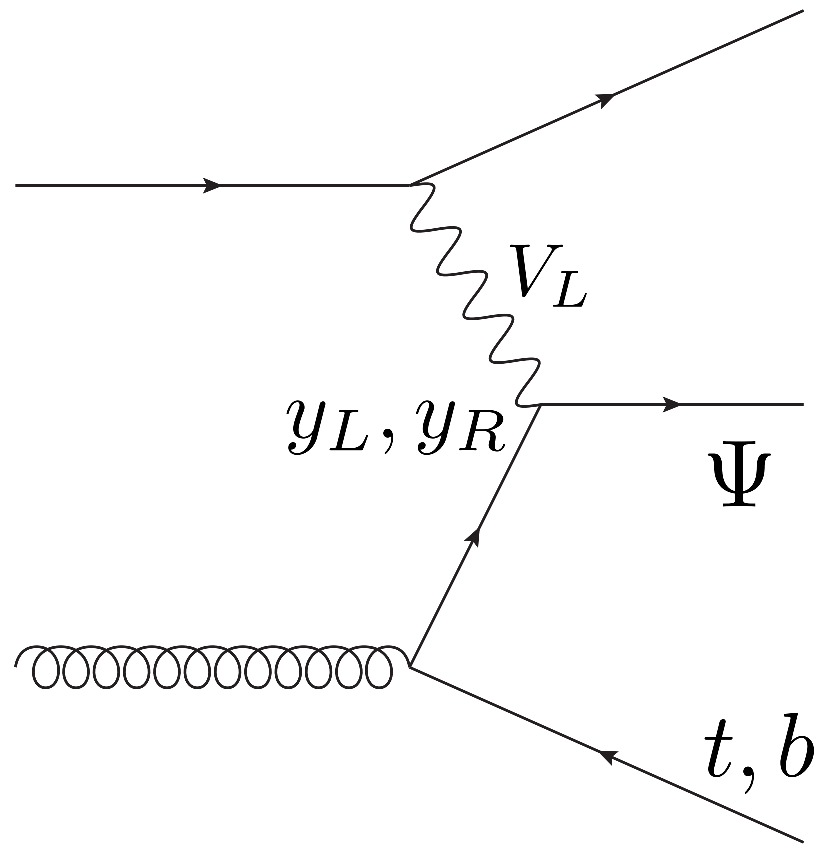



Top partners

$$\Psi \equiv X_{5/3}, T, B$$

Simone, Matsedonskyi, Rattazzi and Wulzer '12

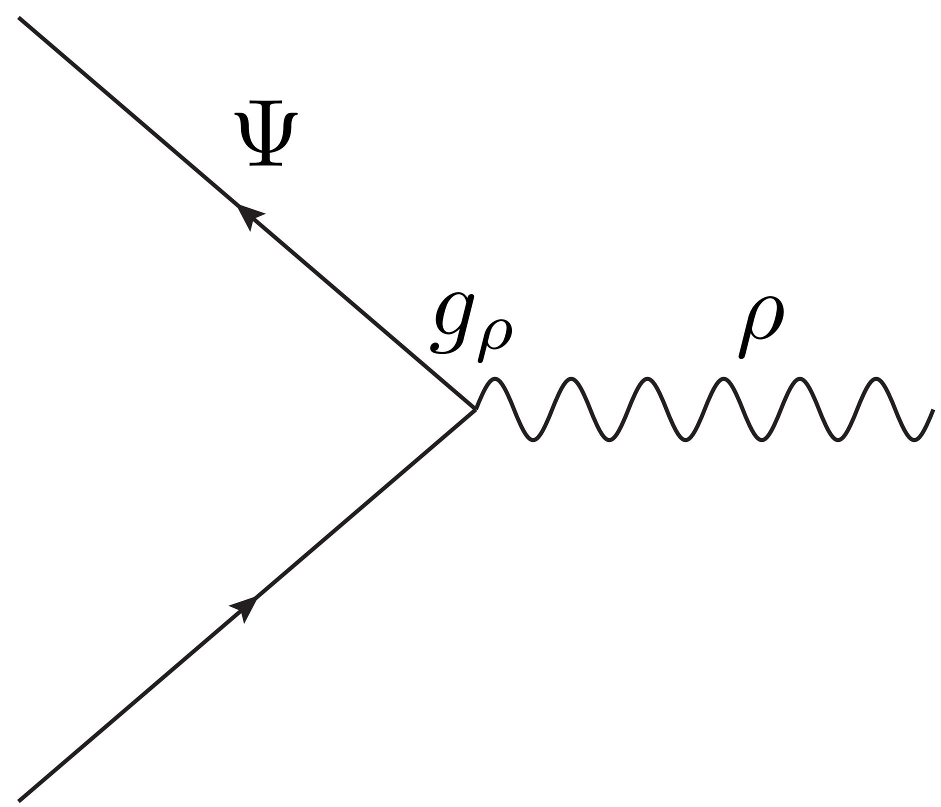
# Direct searches: Single production




Lower mass threshold!

Simone, Matsedonskyi, Rattazzi and Wulzer '12

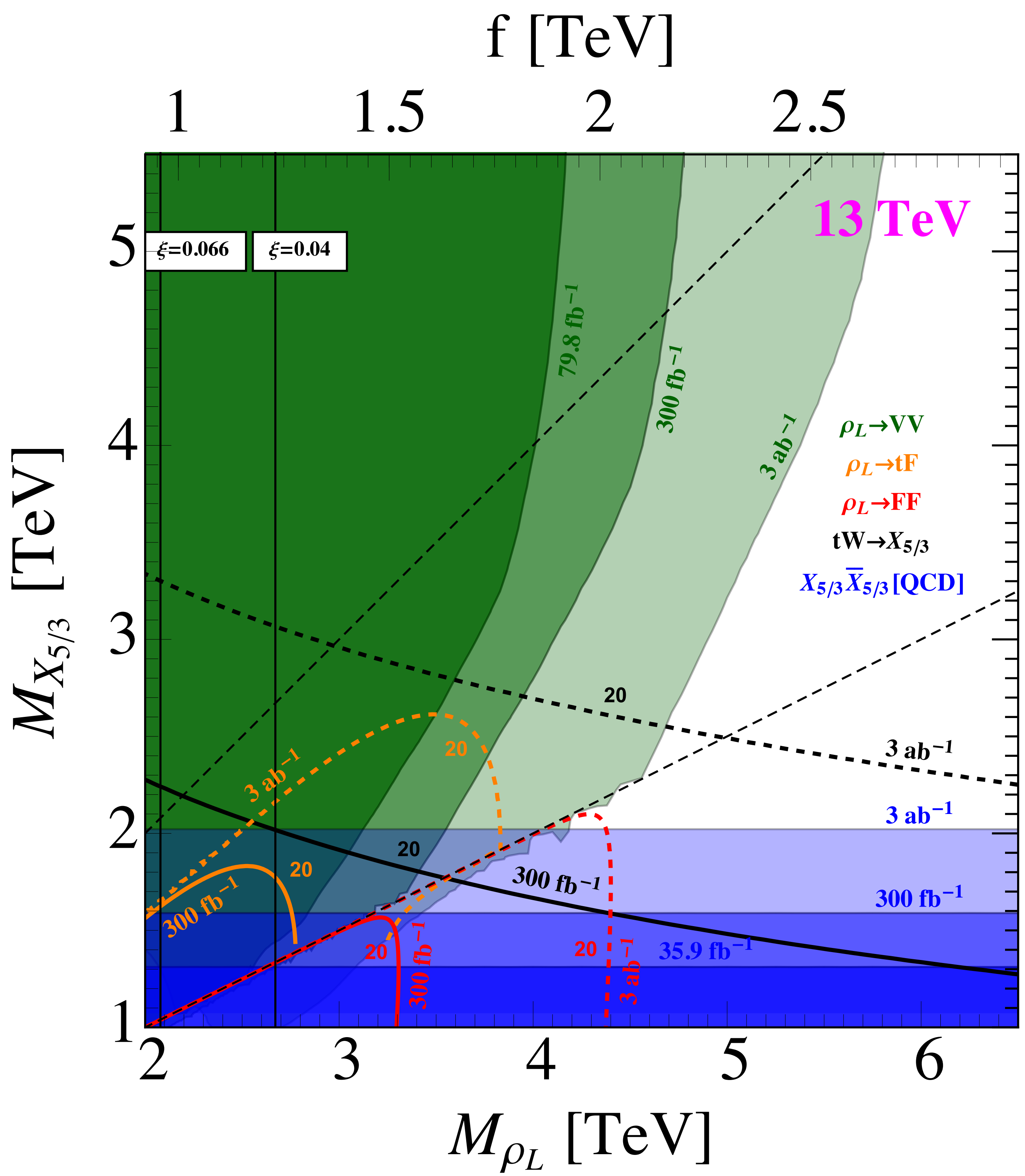
# Cascade decays




Have kinematical advantage!

D. Greco and DL '14

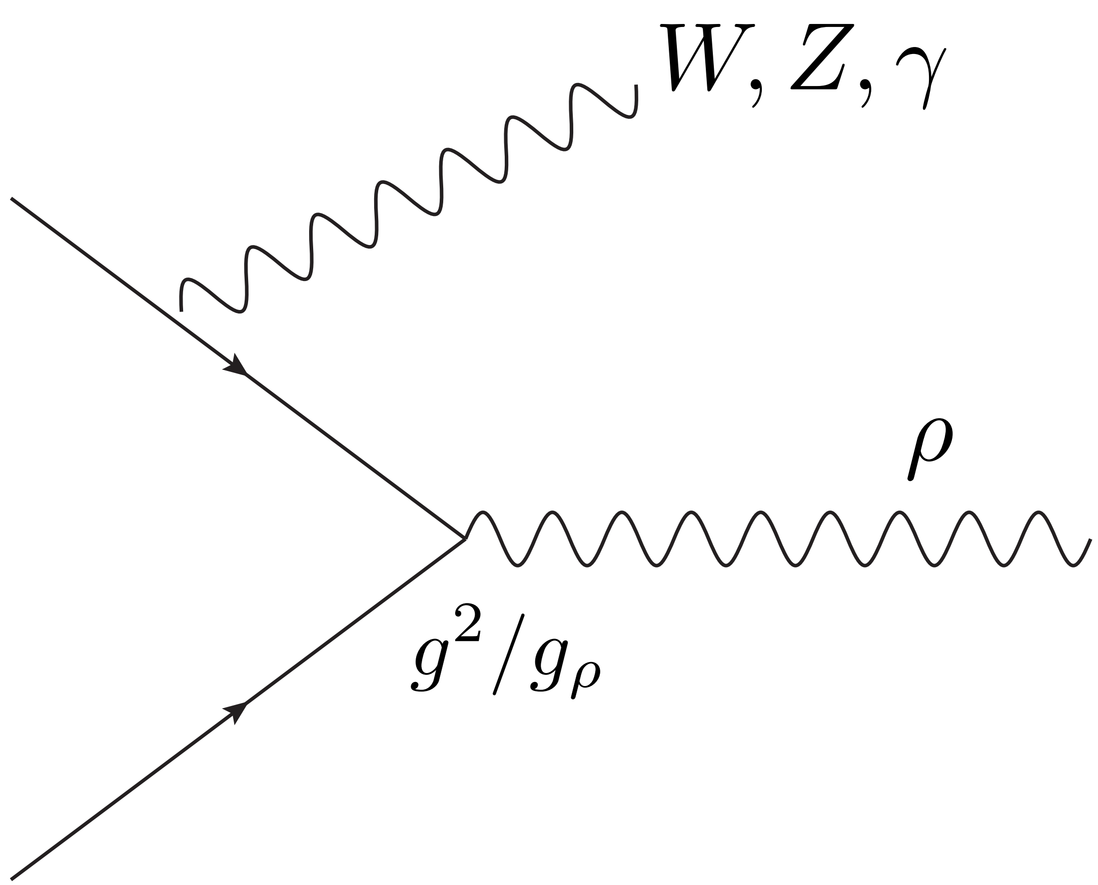
# Bounds and Projections




$g_\rho = 3$

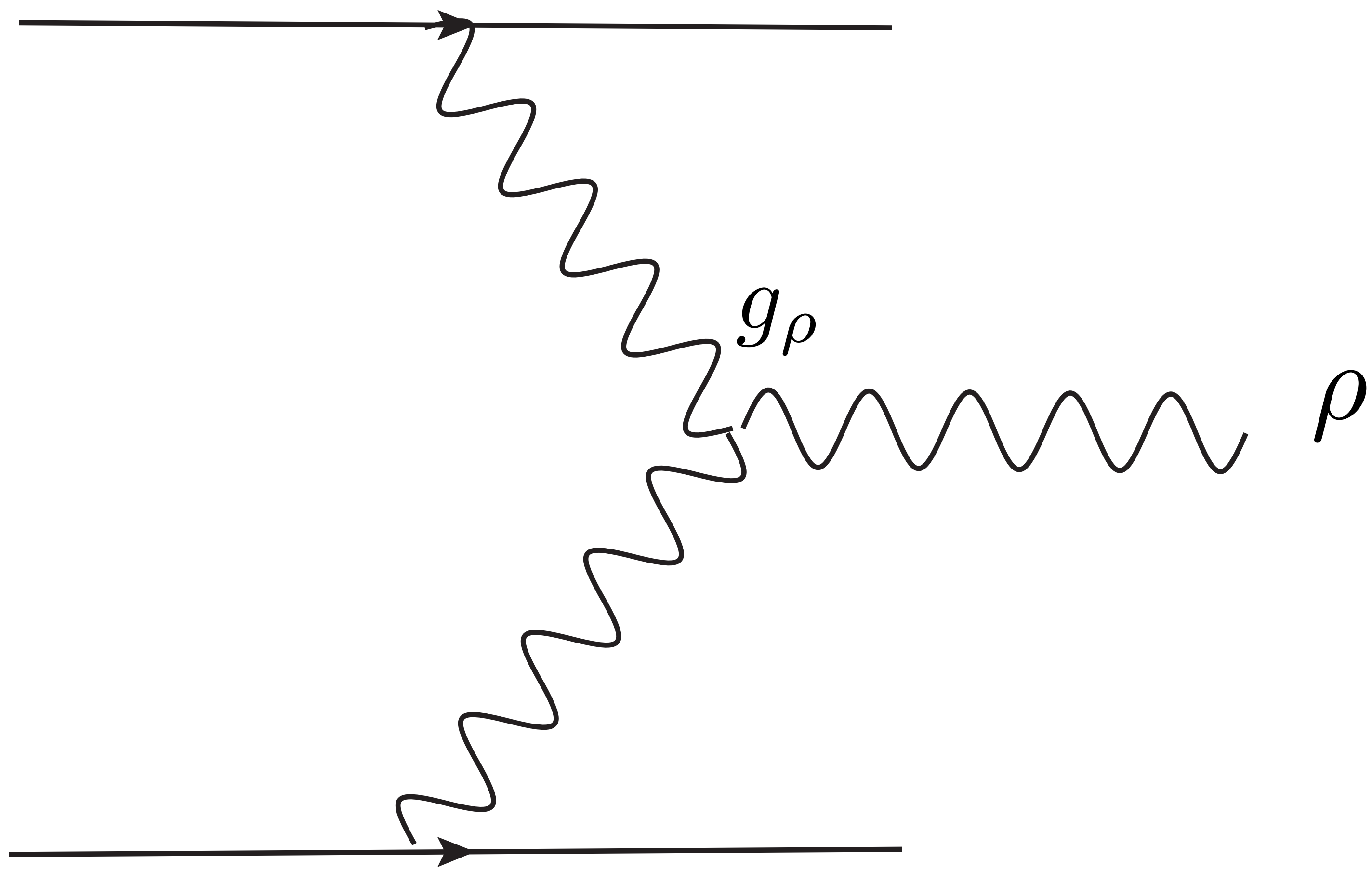
DL, L.T. Wang and K. P. Xie '18

# Muon Collider



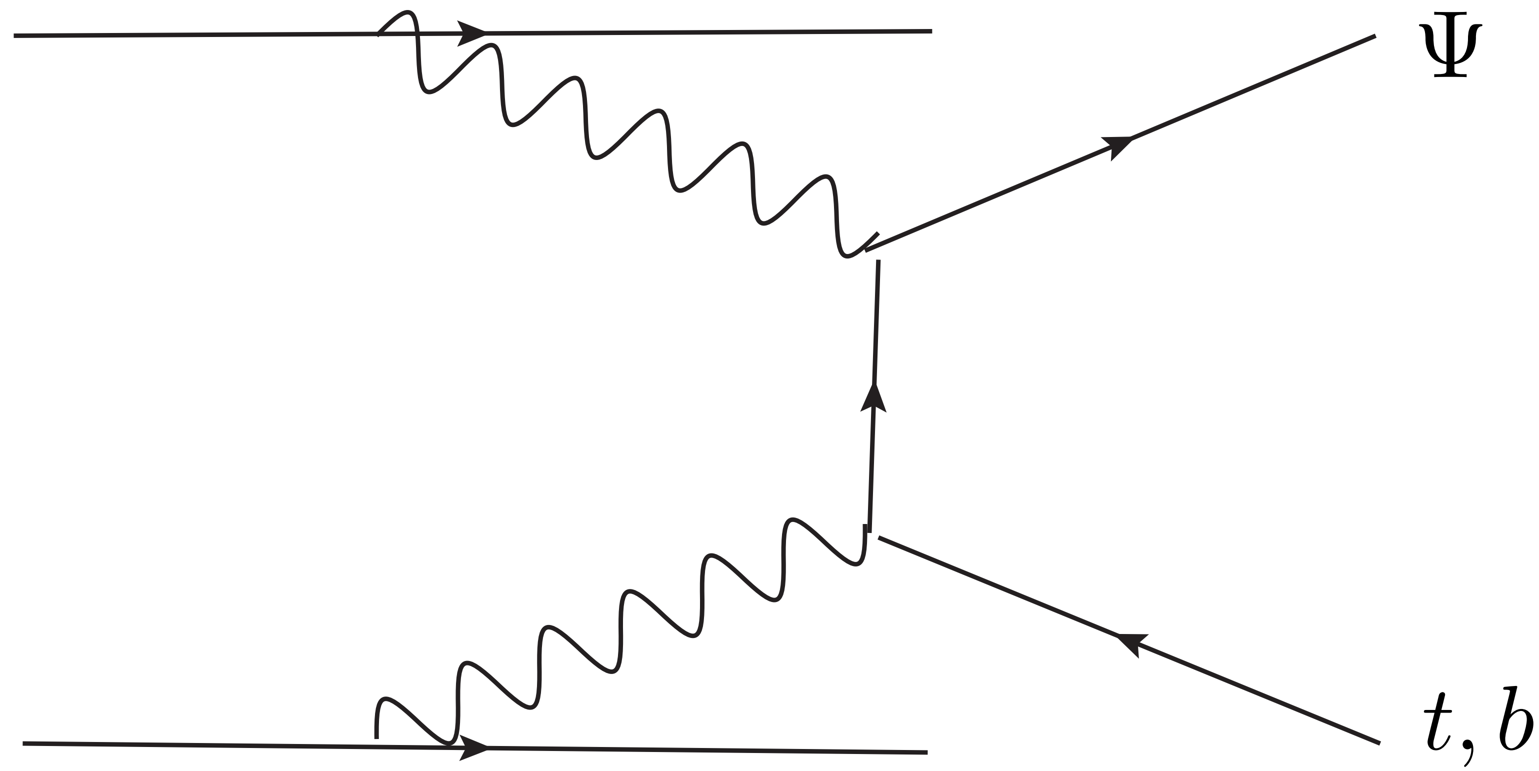

DL, L.T. Wang and K. P. Xie
Working in progress

# Muon Collider



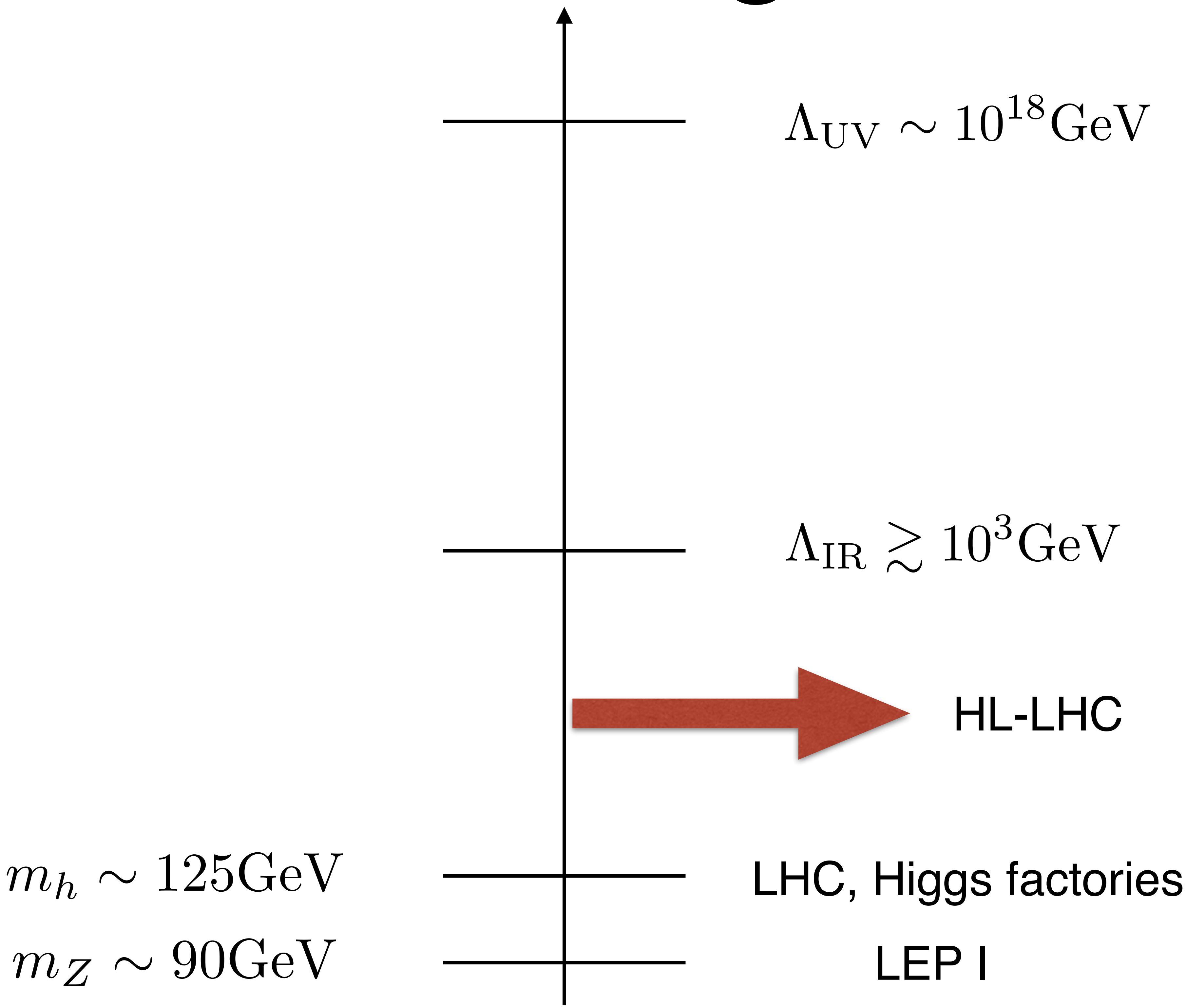

DL, L.T. Wang and K. P. Xie
Working in progress

# Muon Collider




DL, L.T. Wang and K. P. Xie
Working in progress

# Indirect Signatures



# Indirect Signature

- Two expansions

$$\frac{H}{f} \qquad \frac{\partial}{m_*} \qquad\qquad m_* \sim g_* f$$

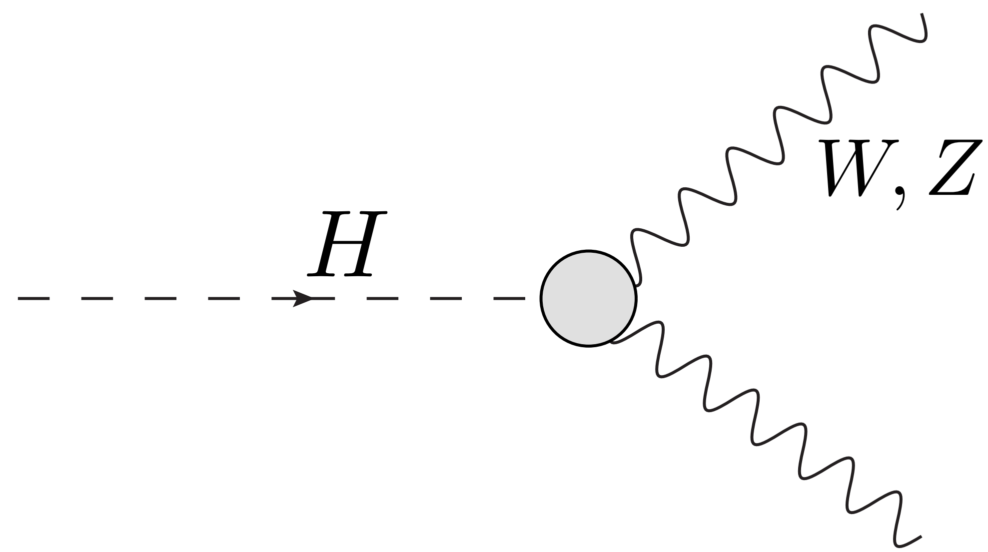
- A set of selection rules

  - Preserve the non-linearity: $g_*$
  - Explicit breaking

    $y_f, g, g'$

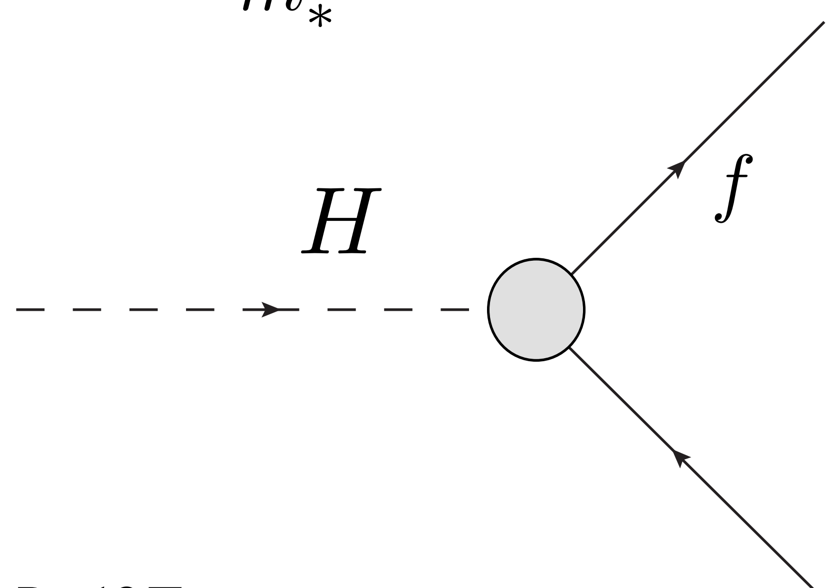
# Higgs Coupling Modification

$$\mathcal{O}_H = \frac{\partial_\mu (H^\dagger H) \partial^\mu (H^\dagger H)}{2m_*^2} \Rightarrow c_H \sim g_*^2$$




$$\sim -g_*^2 \, \frac{v^2}{2m_*^2}$$

$$\mathcal{O}_y = y_f \frac{H^\dagger H}{m_*^2} \bar{f}_L H f_R \Rightarrow c_y \sim g_*^2$$

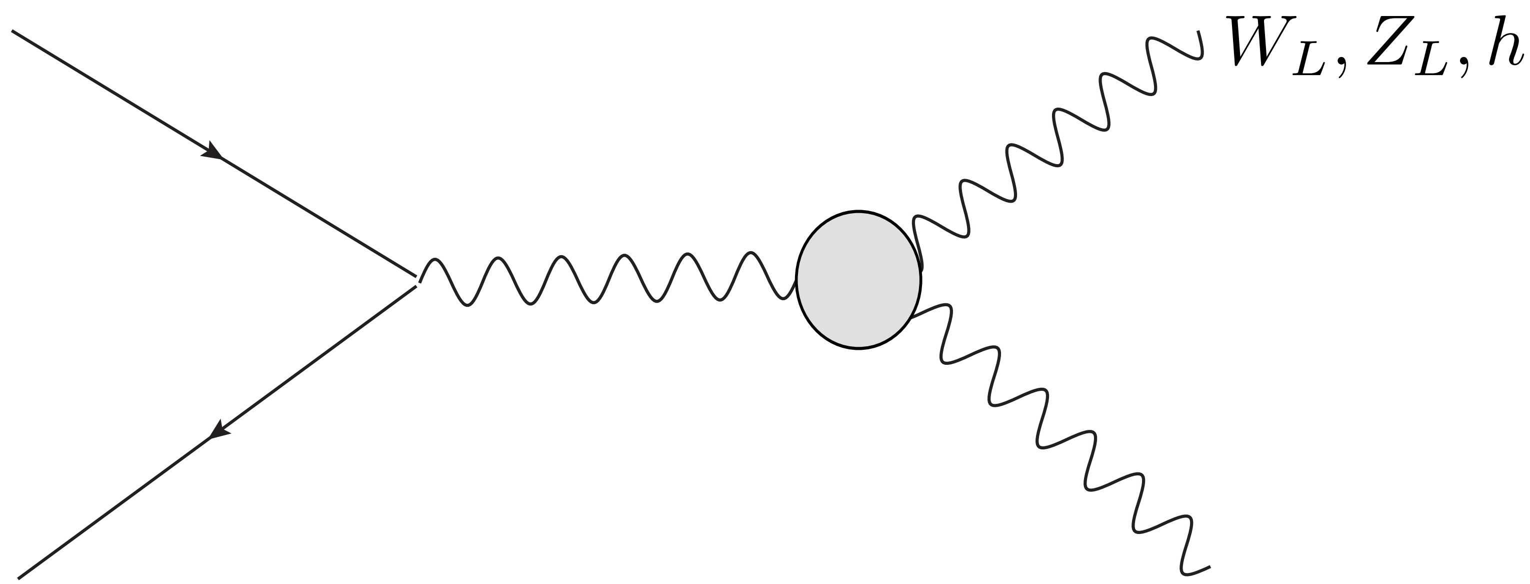



$$\sim -g_*^2 \, \frac{v^2}{2m_*^2}$$

G.F. G, C. G, A.P & R.R '07

# Energy Growing Behavior

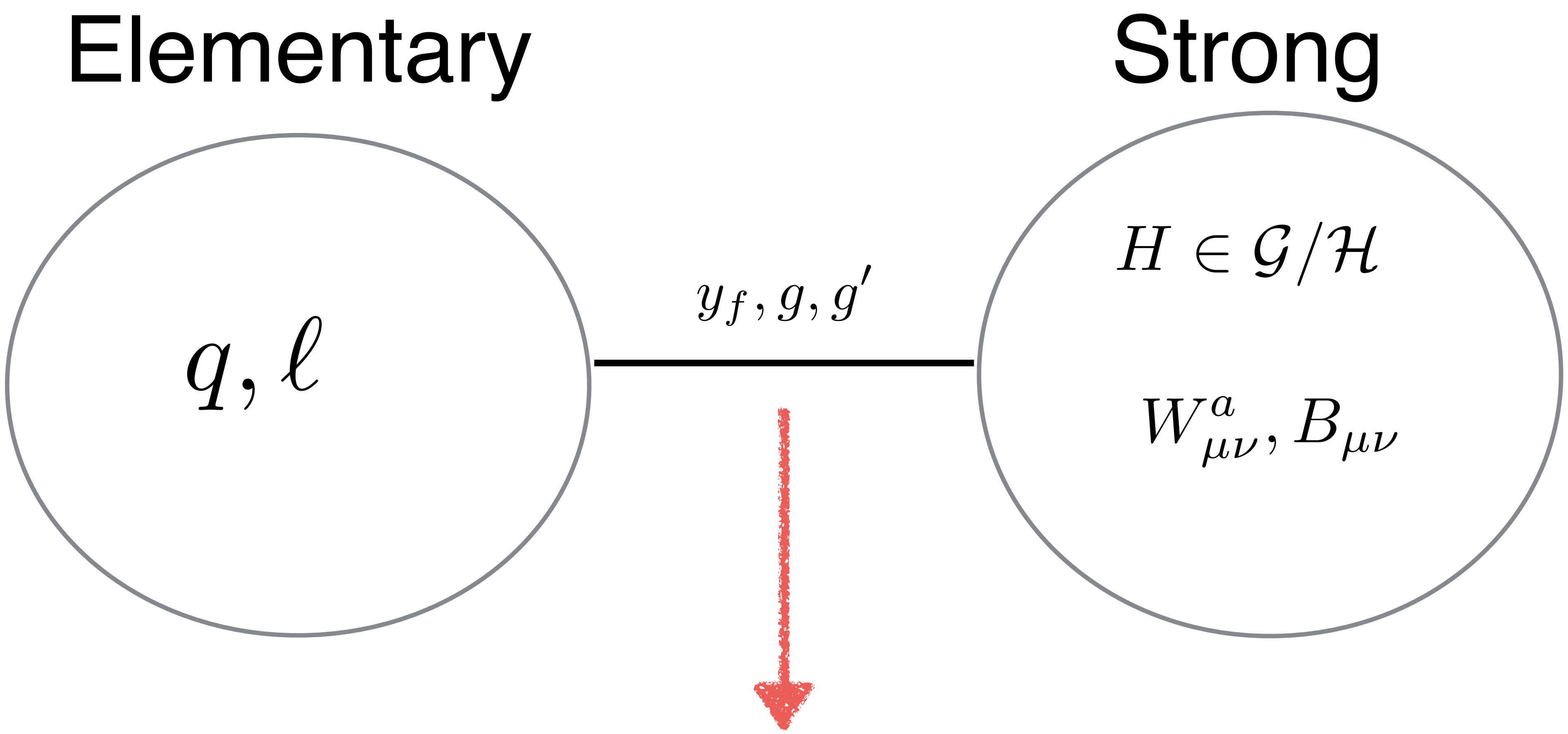
$$\mathcal{O}_W = \frac{ig}{2m_*^2}(H^\dagger \sigma^a \overleftrightarrow{D^\mu} H) D^\nu W^a_{\mu\nu} \Rightarrow c_W \sim 1$$




$$\sim \frac{E^2}{m_*^2}$$

HL-LHC can play a role!

# Strong multipole interactions



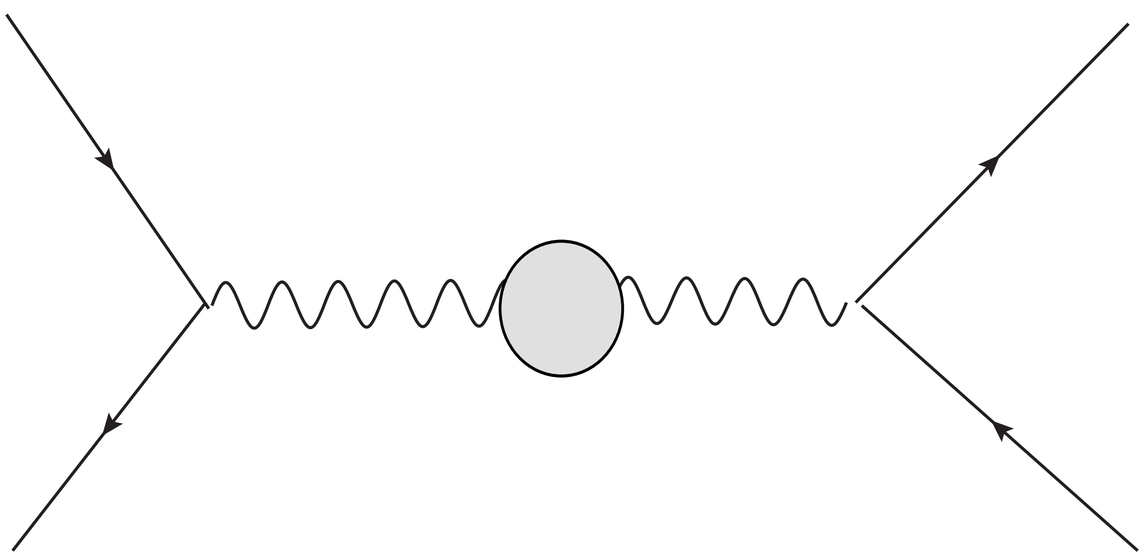

– New power-counting rules

$$W^a_{\mu\nu}, B_{\mu\nu} \, : \, g_*$$

DL, A. Pomarol, R. Rattazzi & F. Riva '16

# Strong multipole interactions

$$\mathcal{O}_{2W} = -\frac{1}{2m_*^2} D^\mu W^a_{\mu\nu} D_\rho W^{a\rho\nu} \Rightarrow c_{2W} \sim \frac{g^2}{g_*^2} \qquad c_{2W} \sim 1$$

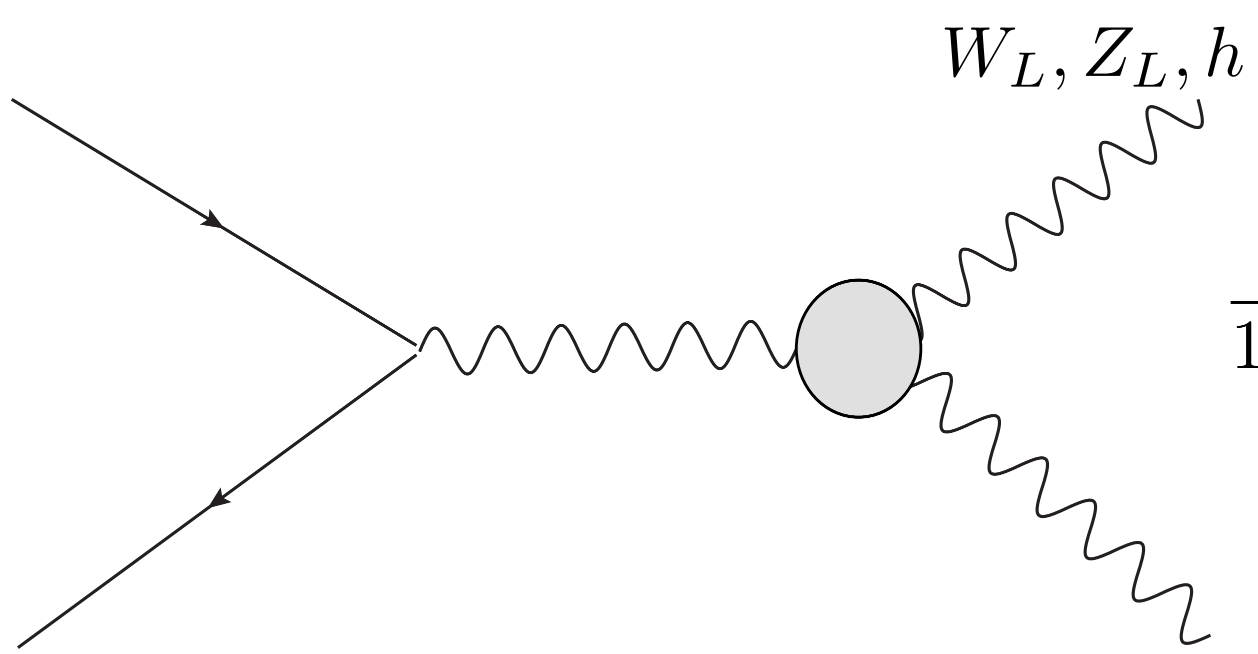


$$\sim \frac{g^2}{g_*^2} \frac{E^2}{m_*^2} \qquad \frac{E^2}{m_*^2}$$

DL, A. Pomarol, R. Rattazzi & F. Riva '16

# Strong multipole interactions

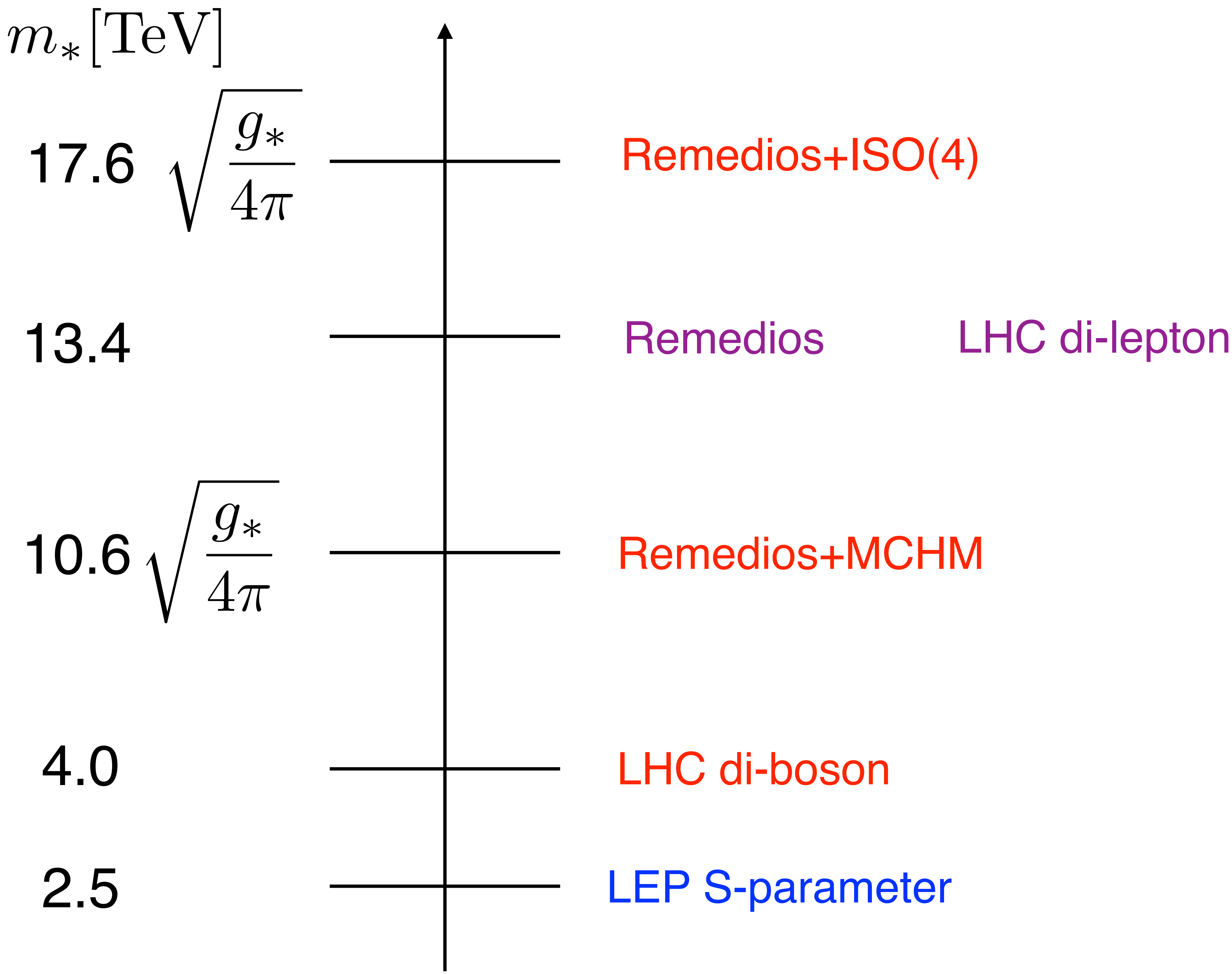
$$\mathcal{O}_{HW} = \frac{ig}{m_*^2}(D^\mu H)^\dagger \sigma^a (D^\nu H) W^a_{\mu\nu} \Rightarrow c_{HW} \sim \frac{g_*^2}{16\pi^2}, \quad 1 \qquad \frac{g_*}{g}$$




$$\frac{g_*^2}{16\pi^2}\frac{E^2}{m_*^2} \qquad \frac{E^2}{m_*^2} \qquad \frac{g_*}{g}\frac{E^2}{m_*^2}$$

DL, A. Pomarol, R. Rattazzi & F. Riva '16

# HL-LHC Reach




DL and L.T.Wang '18    see also R. Franceschini et al '17    dilepton: M. Farina et al '16

# Conclusion

- Compositeness is an elegant way to address the hierarchy problem.

- Resonance searches and precision measurement are both important.

# Back-up Slides

# Effective Operators

We are focusing on the following dimension-six operators:

$$\mathcal{O}_W = \frac{ig}{2}\left(H^\dagger \sigma^a \overleftrightarrow{D}^\mu H\right) D^\nu W^a_{\mu\nu}, \qquad \mathcal{O}_B = \frac{ig'}{2}\left(H^\dagger \overleftrightarrow{D}^\mu H\right) \partial^\nu B_{\mu\nu}$$

$$\mathcal{O}_{2W} = -\frac{1}{2} D^\mu W^a_{\mu\nu} D_\rho W^{a\rho\nu}, \qquad \mathcal{O}_{2B} = -\frac{1}{2}\partial^\mu B_{\mu\nu}\partial_\rho B^{\rho\nu}$$

$$\mathcal{O}_{HW} = ig(D^\mu H)^\dagger \sigma^a (D^\nu H) W^a_{\mu\nu}, \qquad \mathcal{O}_{HB} = ig'(D^\mu H)^\dagger (D^\nu H) B_{\mu\nu}$$

$$\mathcal{O}_{3W} = \frac{1}{3!} g \epsilon_{abc} W^{a\nu}_{\mu} W^b_{\nu\rho} W^{c\rho\mu}, \qquad \mathcal{O}_T = \frac{g^2}{2}(H^\dagger \overleftrightarrow{D}^\mu H)(H^\dagger \overleftrightarrow{D}_\mu) H$$

$$\mathcal{O}_R^u = ig'^2 \left(H^\dagger \overleftrightarrow{D}_\mu H\right) \bar{u}_R \gamma^\mu u_R, \qquad \mathcal{O}_R^d = ig'^2 \left(H^\dagger \overleftrightarrow{D}_\mu H\right) \bar{d}_R \gamma^\mu d_R$$

$$\mathcal{O}_L^q = ig'^2 \left(H^\dagger \overleftrightarrow{D}_\mu H\right) \bar{Q}_L \gamma^\mu Q_L, \qquad \mathcal{O}_L^{(3)q} = ig^2 \left(H^\dagger \sigma^a \overleftrightarrow{D}_\mu H\right) \bar{Q}_L \sigma^a \gamma^\mu Q_L$$

$$\mathscr{L} = \mathscr{L}_{\text{SM}} + \sum_i \frac{c_i}{\Lambda^2}\mathcal{O}_i + \cdots$$

# Helicity structure for WW

$$q_L\bar{q}_R \to W^+W^-$$

| $(h_{W^+}, h_{W^-})$ | SM | $\mathcal{O}_W$ | $\mathcal{O}_{HW}$ | $\mathcal{O}_B$ | $\mathcal{O}_{HB}$ | $\mathcal{O}_{3W}$ |
|---|---|---|---|---|---|---|
| $(\pm, \mp)$ | 1 | 0 | 0 | 0 | 0 | 0 |
| $(0, 0)$ | 1 | $\frac{E^2}{\Lambda^2}$ | $\frac{E^2}{\Lambda^2}$ | $\frac{E^2}{\Lambda^2}$ | $\frac{E^2}{\Lambda^2}$ | 0 |
| $(0, \pm), (\pm, 0)$ | $\frac{m_W}{E}$ | $\frac{Em_W}{\Lambda^2}$ | $\frac{Em_W}{\Lambda^2}$ | $\frac{Em_W}{\Lambda^2}$ | $\frac{Em_W}{\Lambda^2}$ | $\frac{Em_W}{\Lambda^2}$ |
| $(\pm, \pm)$ | $\frac{m_W^2}{E^2}$ | $\frac{m_W^2}{\Lambda^2}$ | $\frac{m_W^2}{\Lambda^2}$ | $\frac{m_W^2}{\Lambda^2}$ | 0 | $\frac{E^2}{\Lambda^2}$ |

$$q_R\bar{q}_L \to W^+W^-$$

| $(h_{W^+}, h_{W^-})$ | SM | $\mathcal{O}_W$ | $\mathcal{O}_{HW}$ | $\mathcal{O}_B$ | $\mathcal{O}_{HB}$ | $\mathcal{O}_{3W}$ |
|---|---|---|---|---|---|---|
| $(\pm, \mp)$ | 0 | 0 | 0 | 0 | 0 | 0 |
| $(0, 0)$ | 1 | $\frac{m_W^2}{\Lambda^2}$ | $\frac{m_W^2}{\Lambda^2}$ | $\frac{E^2}{\Lambda^2}$ | $\frac{E^2}{\Lambda^2}$ | 0 |
| $(0, \pm), (\pm, 0)$ | $\frac{m_W}{E}$ | $\frac{m_W^2 m_Z^2}{\Lambda^2 E^2}$ | $\frac{Em_W}{\Lambda^2}$ | $\frac{Em_W}{\Lambda^2}$ | $\frac{Em_W}{\Lambda^2}$ | $\frac{m_W^2 m_Z^2}{\Lambda^2 E^2}$ |
| $(\pm, \pm)$ | $\frac{m_W^2}{E^2}$ | $\frac{m_W^2}{\Lambda^2}$ | $\frac{m_W^2}{\Lambda^2}$ | $\frac{m_W^2}{\Lambda^2}$ | 0 | $\frac{m_W^2}{\Lambda^2}$ |