

# ONE LOOP ELECTROWEAK CONSTRAINTS IN COMPOSITE HIGGS MODELS

R. Contino, M. Salvarezza, arXiv:1504.02750 [hep-ph]

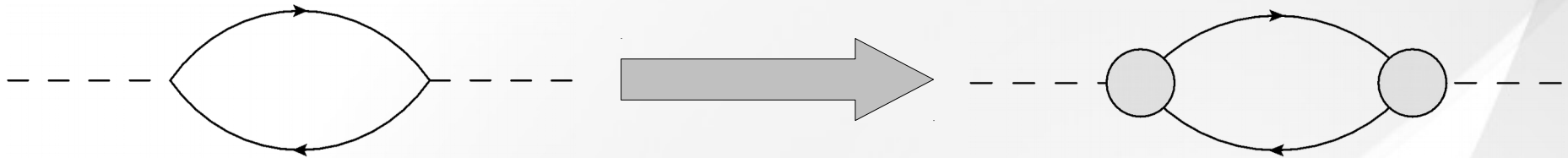
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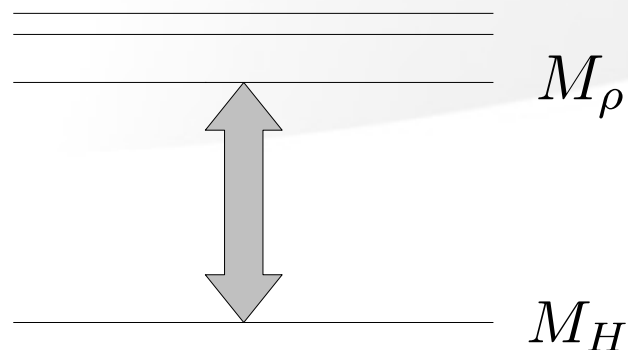
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# STRONG EWSB: COMPOSITE HIGGS MODELS

- A heavy ( $\sim \text{TeV}$ ) strong sector triggers the EWSB: the Higgs Boson is **composite**



- **Problem**: big mass gap between the Higgs and the other resonances!



$$M_H = 126 \text{ GeV}$$

$$M_\rho \gtrsim \text{TeV}$$

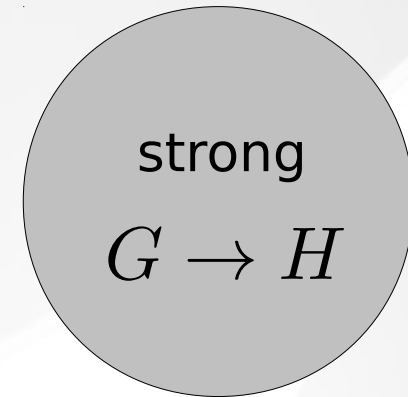
# STRONG EWSB: COMPOSITE HIGGS MODELS

- Learn from QCD: the Higgs as a **pseudo Nambu-Goldstone Boson** accounts naturally for such a picture

[Georgi, Kaplan, 1984]

- General recipe:

- EFT for NGB Higgs: spontaneous symmetry breaking  $G \rightarrow H$  at a scale  $f > v$



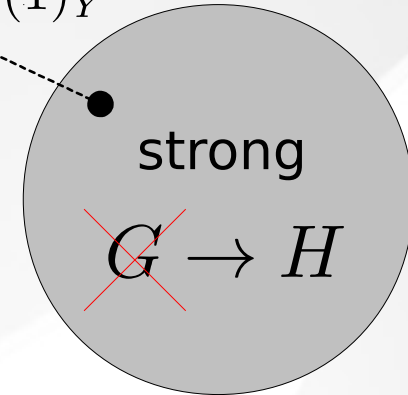
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$$SU(2)_L \otimes U(1)_Y$$



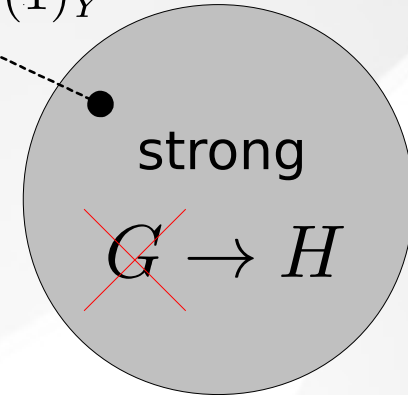
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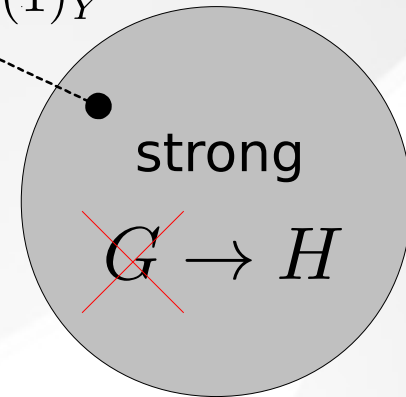
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➤ Separation of scales:

$$\xi = (v/f)^2$$

Decoupling:  $\xi \rightarrow 0$

# COMPOSITE HIGGS MODELS AND EWPT

- Oblique EWPO relevant for our purpose:

$$\epsilon_1 = \frac{1}{M_W^2} (A_{33}(0) - A_{W+W-}(0)) - M_Z^2 F'(M_Z^2)$$

$$\epsilon_3 = \frac{c}{s} F'_{3B}(M_Z^2) + c^2 (F_{\gamma\gamma}(0) - F_{\gamma\gamma}(M_Z^2)) - c^2 M_Z^2 F'_{ZZ}(M_Z^2)$$

$$\Pi_{ij}(q^2) = A_{ij}(0) + q^2 F_{ij}(q^2)$$

[Altarelli, Barbieri, Caravaglios, 1993]

- Two sources of deviations  $\Delta\epsilon_i = \epsilon_i - \epsilon_i^{SM}$

- IR effect from modified Higgs dynamics
- UV effect from composite resonances

# COMPOSITE HIGGS MODELS AND EWPT

➤ IR effect on EWPO:

$$\epsilon_3 \supset \text{wavy line} \text{---} \text{circle} \text{---} \text{wavy line} + \text{wavy line} \text{---} \text{circle} \text{---} \text{wavy line} \propto \xi \log \left( \frac{\Lambda}{M_H} \right)$$

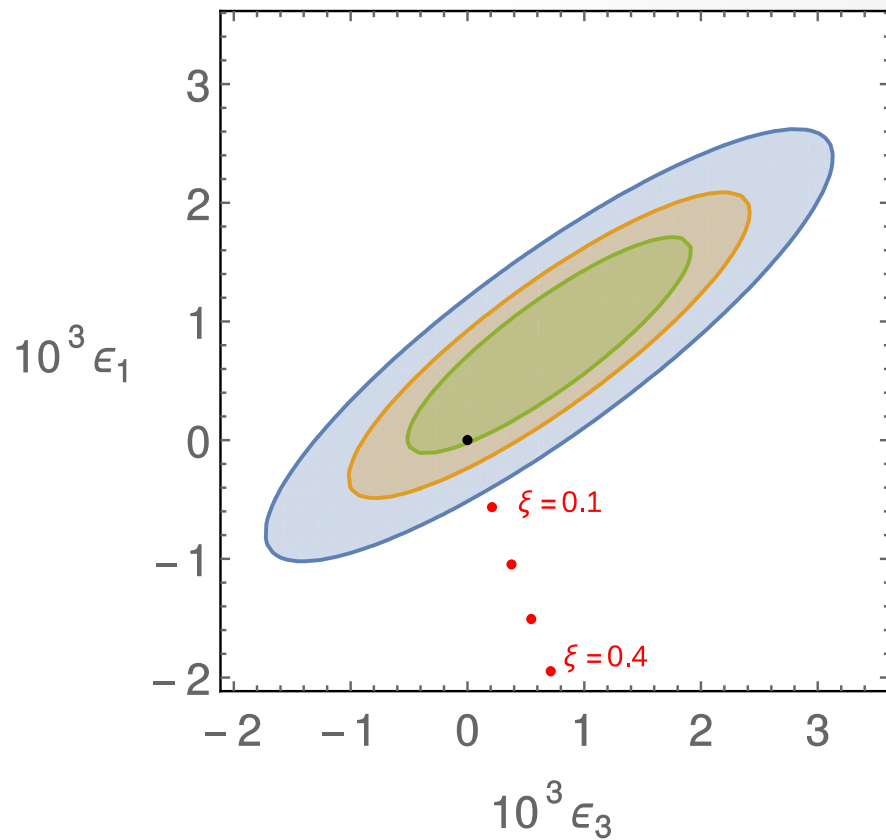
The diagram shows two Feynman diagrams for the photon vacuum polarization. The first diagram is a solid circle loop. The second diagram is a circle loop with a dashed lower arc and two vertices marked with black dots. An arrow labeled  $\sqrt{1-\xi}$  points to the upper arc of the second diagram.



# COMPOSITE HIGGS MODELS AND EWPT

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$$\epsilon_3 \supset \text{wavy line} \text{---} \text{circle} \text{---} \text{wavy line} + \text{wavy line} \text{---} \text{circle} \text{---} \text{wavy line} \propto \xi \log \left( \frac{\Lambda}{M_H} \right)$$



- Same effect for  $\epsilon_1$
- $\sim 5\text{-}10\%$  fine tuning on  $\xi$  required!
- Investigate if this picture can be improved (or not) with contributions from resonances

# VECTOR RESONANCES LAGRANGIAN

- Introduce a single spin-1 resonance lighter than the others

\_\_\_\_\_  $\Lambda$

\_\_\_\_\_  $M_\rho$

\_\_\_\_\_  $M_H$

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Calculate the 1-loop contributions of such resonance to EWPO.

# VECTOR RESONANCES

## LAGRANGIAN

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- Goal:

Calculate the 1-loop contributions of such resonance to EWPO.

- Estimates:  $\Delta\epsilon_i^{(\rho)} \sim \frac{1}{16\pi^2} \xi \log\left(\frac{\Lambda}{M_\rho}\right)$        $\Delta\epsilon_i^{(\Lambda)} \sim \frac{1}{16\pi^2} \xi$

- Not really a sizeable enhancement
- Not an actual precise calculation
- Rather a refined qualitative estimate

# VECTOR RESONANCES LAGRANGIAN

- Coset G/H: focus on the minimal SO(5)/SO(4) Composite Higgs model
- Spin-1 resonance **in a  $(\mathbf{1},\mathbf{3})\oplus(\mathbf{3},\mathbf{1})$  of  $SU(2)_L\otimes SU(2)_R\sim SO(4)$**
- Two-derivatives lagrangian:

$$\mathcal{L}_\rho = \sum_{r=L,R} -\frac{1}{4g_{\rho r}^2} \text{Tr} [\rho_{\mu\nu}^r \rho^{r\mu\nu}] + \frac{1}{2} \frac{M_{\rho r}^2}{g_{\rho r}^2} \text{Tr} \left[ (\rho_\mu^r - E_\mu)^2 \right]$$

$$E^\mu = \pi D^\mu \pi + \dots$$

Mass + interactions:



- Interactions regulated by  $a_\rho \equiv \frac{M_\rho}{g_\rho f} \sim 1$

# VECTOR RESONANCES

## LAGRANGIAN

- Vector resonances **mix linearly** with EW gauge boson (**partial compositeness**)

$$\mathcal{L}_\rho \supset \frac{1}{2} \frac{M_\rho^2}{g_\rho^2} \text{Tr} \left[ (\rho^\mu - E^\mu)^2 \right] \supset M_\rho^2 \frac{g}{g_\rho} \rho_\mu^a W^{\mu a}$$

- Mixing is small and can be treated as a vertex
- Relevant four-derivative operators (additional tree-level contribution to  $\Delta\epsilon_3$ ):

$$\alpha_2 r \text{Tr} \left[ \rho_{\mu\nu}^r f^{\mu\nu} \right] \quad \left( f^{\mu\nu} = e^{-i\pi^a T^{\hat{a}}} F^{\mu\nu} e^{i\pi^a T^{\hat{a}}} \right)$$

# CALCULATION OF EW OBSERVABLES

➤ Some diagrams:

$$\epsilon_1 = \text{[Diagram 1]} + \text{[Diagram 2]} + \text{[Diagram 3]} + \dots$$

The diagram shows the calculation of  $\epsilon_1$  as a sum of Feynman diagrams. The first row contains two diagrams: the first has a solid circle with a wavy line on the left and a wavy line on the right, and a wavy line with a jagged edge on the bottom; the second has a dashed circle with a wavy line on the left and a wavy line on the right, and a wavy line with a jagged edge on the bottom. The second row contains a third diagram: a wavy line with a jagged edge on the left and a wavy line with a jagged edge on the right, and a wavy line with a jagged edge on the bottom. Arrows point from a central  $B^\mu$  label to the jagged edges of the three diagrams. Ellipses follow the last diagram.

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$$\epsilon_3 = \text{[Diagram 4]} + \text{[Diagram 5]} + \text{[Diagram 6]} + \text{[Diagram 7]} + \dots$$

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# CALCULATION OF EW OBSERVABLES

➤ Final expressions for the case of a single  $\rho$ :

$$\Delta\epsilon_1 = -\frac{3g'^2}{32\pi^2}\xi \left[ \log\left(\frac{\Lambda}{M_Z}\right) + f_1\left(\frac{M_H^2}{M_Z^2}\right) \right] \quad \left( a_\rho \equiv \frac{M_\rho}{g_\rho f} \right)$$

IR Composite Higgs boson contribution

$$\Delta\epsilon_3 = \frac{g^2}{96\pi^2}\xi \left[ \log\left(\frac{\Lambda}{M_Z}\right) + f_3\left(\frac{M_H^2}{M_Z^2}\right) \right]$$

$$+ \frac{3g'^2}{32\pi^2}\xi \frac{3}{4} a_\rho^2 \left[ \log\left(\frac{\Lambda}{M_\rho}\right) + \frac{3}{4} \right]$$

$$+ g^2 \xi \left( \frac{1}{4g_\rho^2} - \alpha_2 \right) - \frac{g^2}{96\pi^2}\xi \left[ \frac{3}{4} (a_\rho^2 + 28) \log\left(\frac{\Lambda}{M_{\rho L}}\right) + \frac{41}{16} a_\rho^2 + 1 \right]$$



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UV Resonance contribution

$$+g^2\xi \left( \frac{1}{4g_\rho^2} - \alpha_2 \right) - \frac{g^2}{96\pi^2}\xi \left[ \frac{3}{4} (a_\rho^2 + 28) \log\left(\frac{\Lambda}{M_{\rho L}}\right) + \frac{41}{16} a_\rho^2 + 1 \right]$$

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$\left( a_\rho \equiv \frac{M_\rho}{g_\rho f} \right)$

$\uparrow$   
 $< 0$

$\uparrow$   
 $> 0$

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$< 0$



Any  
sign

$$\rightarrow \left[ +g^2\xi \left( \frac{1}{4g_\rho^2} - \alpha_2 \right) - \frac{g^2}{96\pi^2}\xi \left[ \frac{3}{4} (a_\rho^2 + 28) \log\left(\frac{\Lambda}{M_{\rho L}}\right) + \frac{41}{16} a_\rho^2 + 1 \right] \right]$$

# PARAMETER SPACE CONSTRAINTS

- Fix parameters:

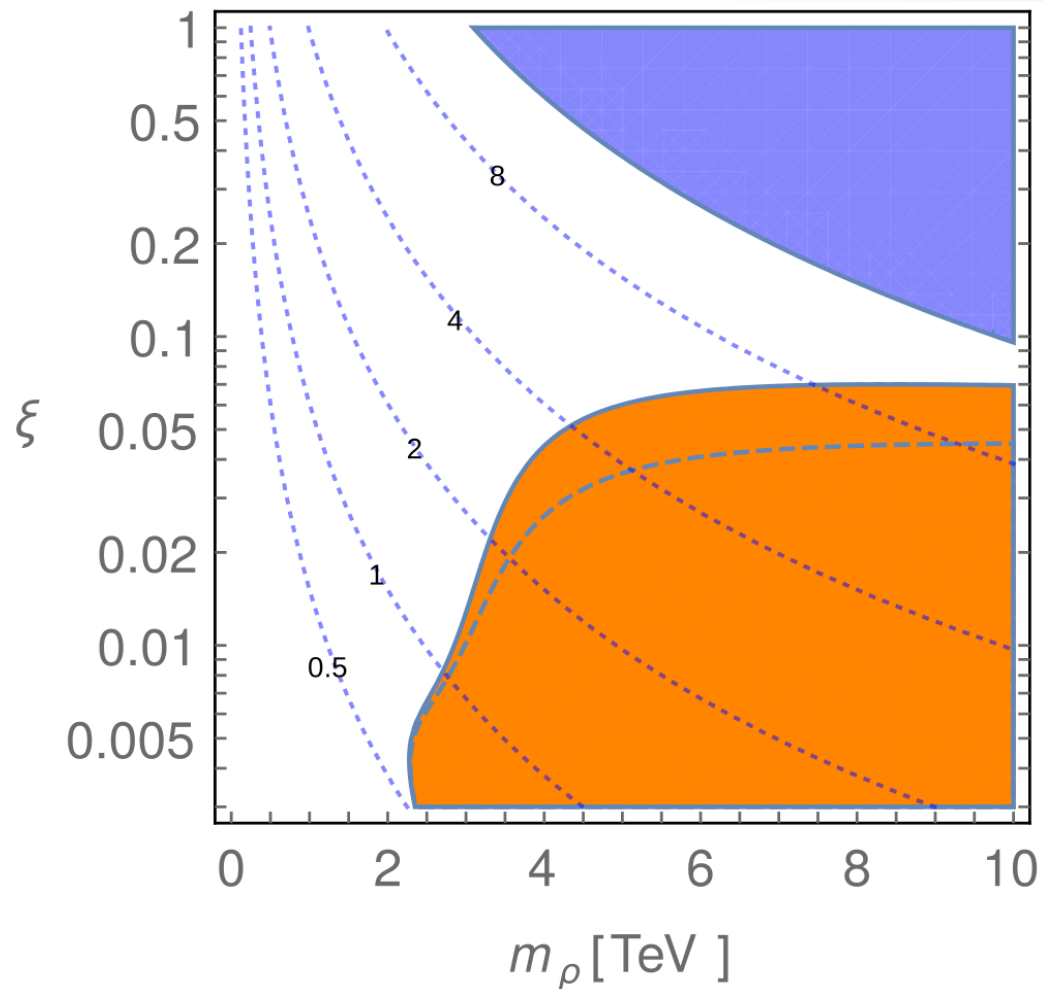
$$\alpha_2 = 0$$

$$a_\rho = 1$$

$$\Lambda = 3M_\rho$$

- Constrain  $(\xi, M_\rho)$  @ 95% CL
-

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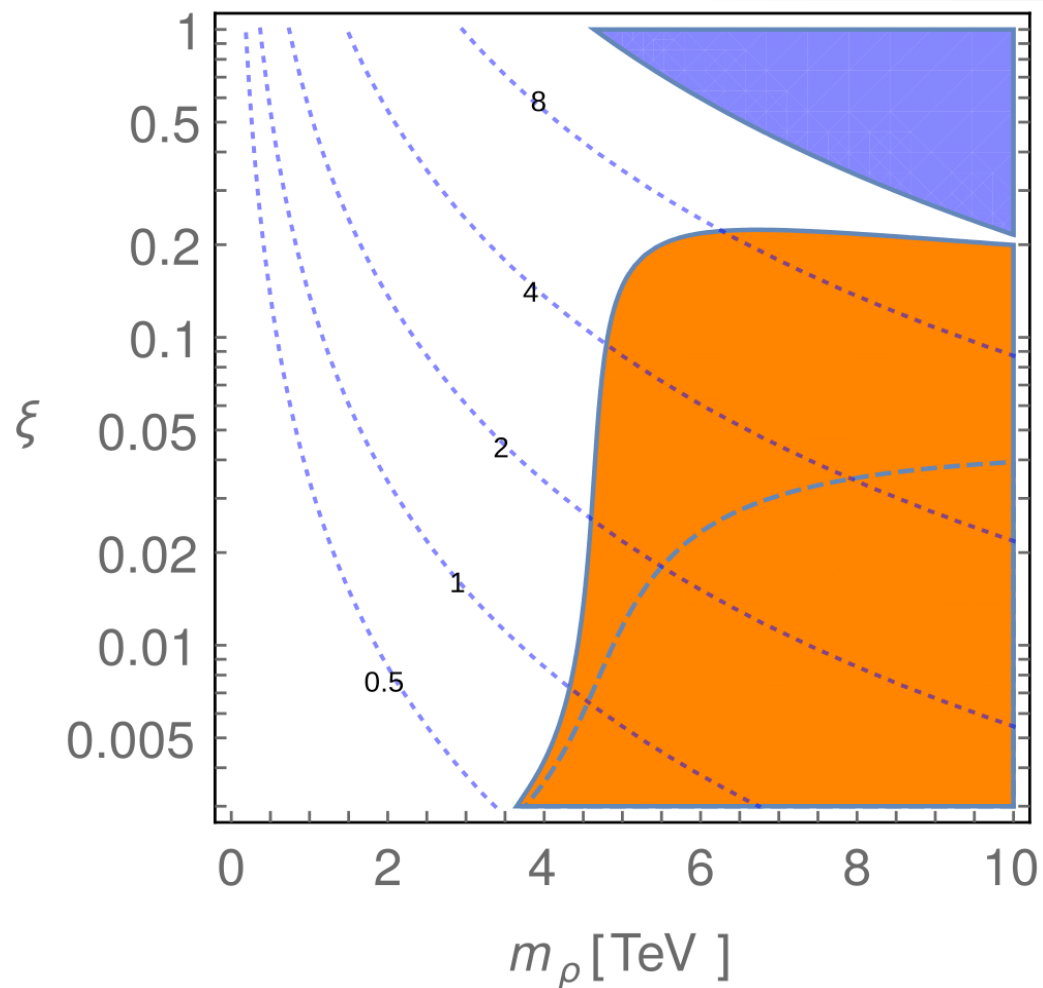
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⊖ IR + tree level  $\rho$

■ IR + one loop  $\rho$

■  $g_\rho > 4\pi$

# PARAMETER SPACE CONSTRAINTS



➤ Fix parameters:

$$\alpha_2 = 0$$

$$a_\rho = 1.5$$

$$\Lambda = 3M_\rho$$

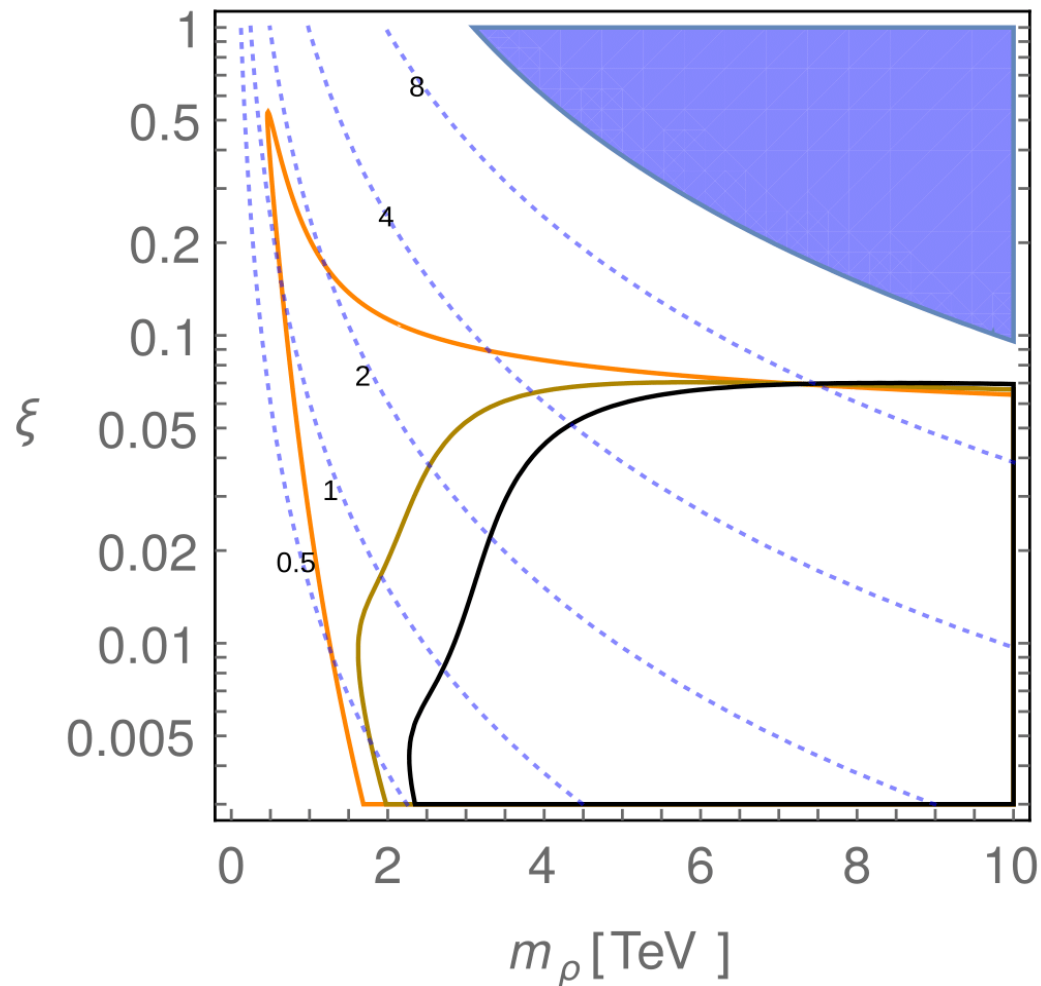
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➤ Fix parameters:

$$\alpha_2 = 0, 1/8g_\rho^2, 1/4g_\rho^2$$

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➤ Constrain  $(\xi, M_\rho)$  @ 95% CL

■  $\alpha_2 = 0$

■  $\alpha_2 = 1/8g_\rho^2$

■  $\alpha_2 = 1/4g_\rho^2$

# TO DO (ALMOST DONE)

- Aim at a first “complete” description of EWPT in composite Higgs
  - Vector resonances
  - Fermionic resonances
- Include many constraints
  - Oblique EWPO
  - $Z\bar{b}b$  coupling
  - Higgs potential
  - Top mass
  - Z mass

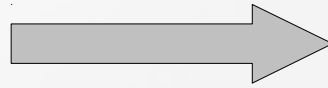
D. Ghosh, M. Salvarezza, F. Senia, L. Silvestrini, *in preparation*



# CCWZ LAGRANGIAN FOR SO(5) → SO(4)

➤ CCWZ: natural formalism for spontaneously broken effective theories, chiral expansion is built-in.

• Global G invariance



• Local H invariance

[Callan, Coleman, Wess, Zumino, 1977]

➤ Building blocks:

$$d_\mu = d_\mu^a T^{\hat{a}} = T^{\hat{a}} \left[ \frac{\sqrt{2}}{f} \partial_\mu \pi^a + \frac{1}{f\sqrt{2}} \epsilon^{abc} \pi^b (W_\mu^c + \delta^{c3} B_\mu) + \dots \right]$$

$$E_\mu = E_\mu^a T^a = T^a \left[ \frac{1}{2f^2} (\epsilon^{abc} \pi^b \partial_\mu \pi^c + \pi^a \partial_\mu \pi^4 - \pi^4 \partial_\mu \pi^a) + W_\mu^a + \dots \right]$$

$$d_\mu \xrightarrow{g \in SO(5)} h(x) d_\mu h^\dagger(x)$$

$$h \in SO(4)$$

$$E_\mu \xrightarrow{g \in SO(5)} h(x) d_\mu h^\dagger(x) - ih \partial_\mu h^\dagger$$

$$\mathcal{L} = \mathcal{L}(d_\mu, E_\mu)$$

$$d_\mu, E_\mu \longleftrightarrow \mathbf{1 \text{ derivative}}$$