ONE-LOOP EW CONSTRAINTS IN COMPOSITE HIGGS MODELS

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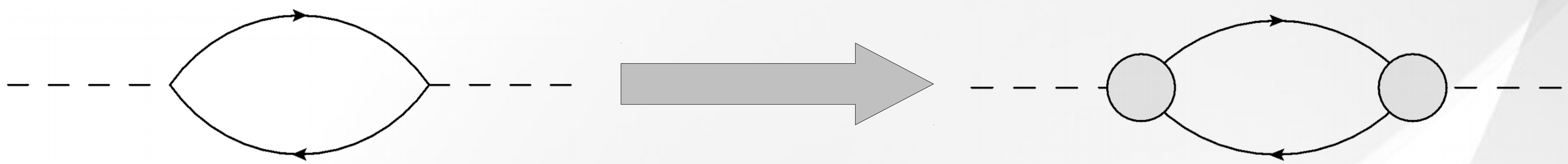
OUTLINE

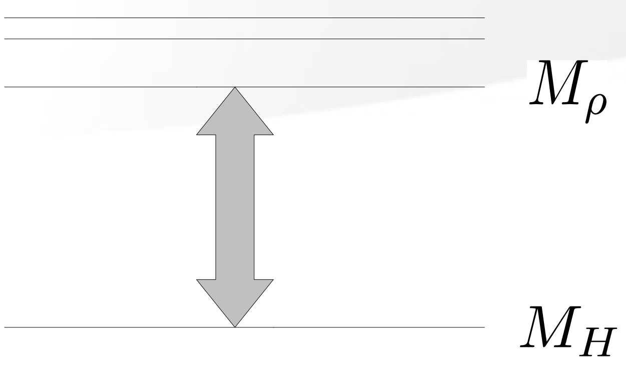
- Composite Higgs models and EWPT
- Minimal SO(5)→SO(4) Model
- UV extension (resonances)
- EWPO test

STRONG EWSB: COMPOSITE HIGGS MODELS

- A heavy (~TeV) strong sector triggers the EWSB: the Higgs Boson is **composite**



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



$$M_H = 126\, GeV$$

$$M_\rho \gtrsim TeV$$

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

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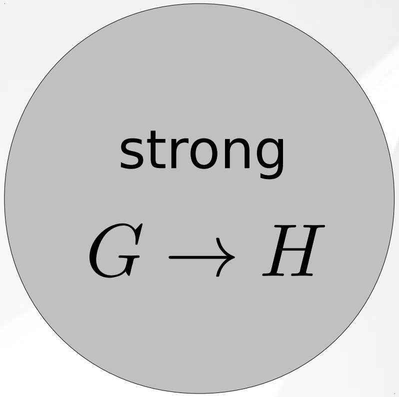

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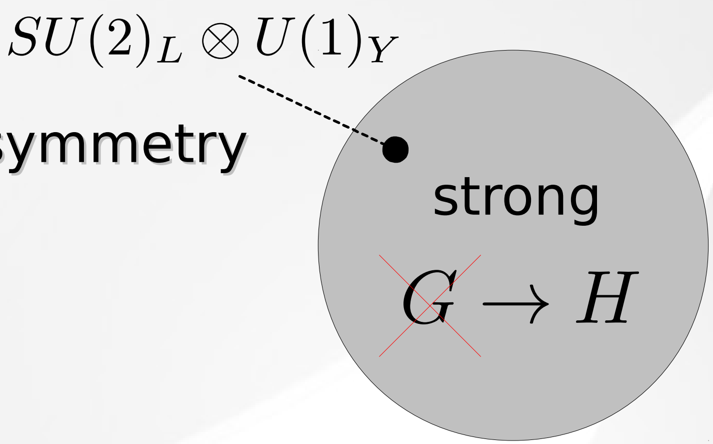

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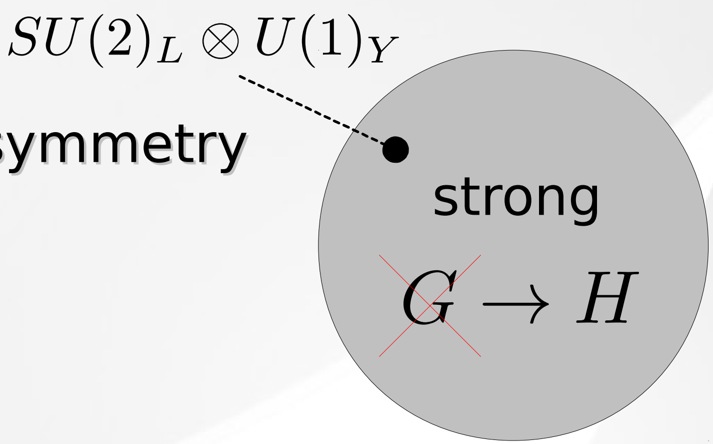
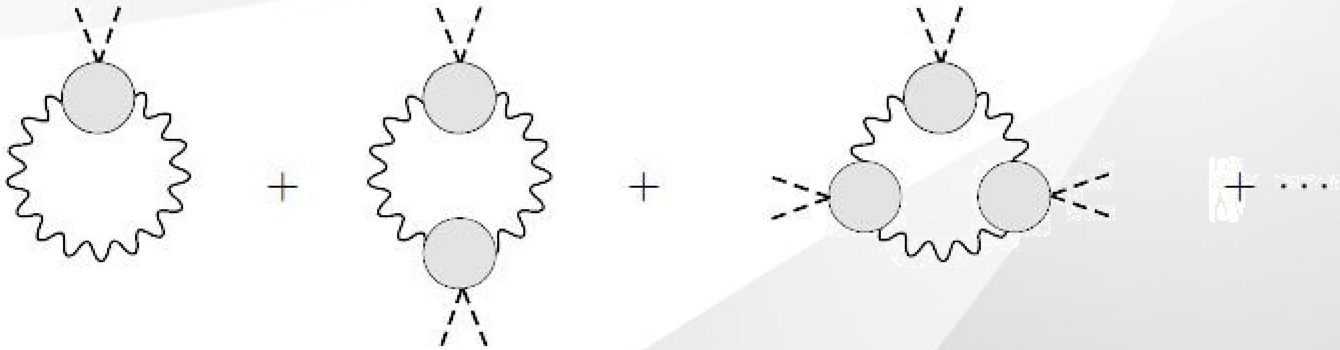


  - EFT for NGB Higgs: spontaneous symmetry breaking G → H at a scale f > v
  - Couple SM linearly to the strong sector ⇒ explicit breaking of G
  - A Higgs Potential is generated at one loop ⇒ Higgs mass, EWSB



STRONG EWSB: COMPOSITE HIGGS MODELS

- EFT for the Higgs as a NGB ⇒ Nonlinear Sigma model ⇒ **Non-standard Higgs couplings**

- Experimental signatures:
  - Direct: measure Higgs couplings, discover resonances
  - Indirect: EWPT ⟸

Universal contributions to EWPO

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

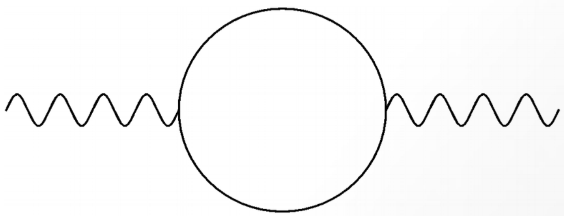
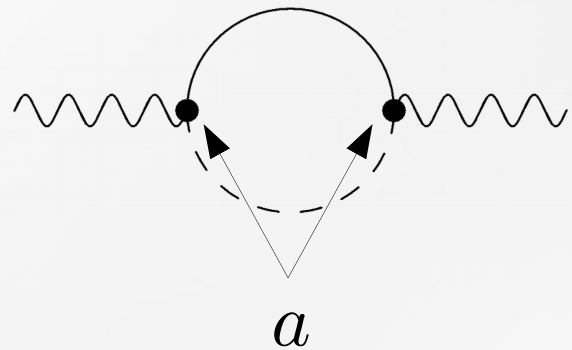
$$\epsilon_3 = \frac{c}{s} F'_{3B}\left(M_Z^2\right) + c^2\left(F_{\gamma\gamma}(0) - F_{\gamma\gamma}\left(M_Z^2\right)\right) - c^2 M_Z^2 F'_{ZZ}\left(M_Z^2\right)$$

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

[Altarelli, Barbieri, Caravaglios, 1993]

STRONG EWSB: COMPOSITE HIGGS MODELS

- Non-standard coupling effect on EWPO

$\epsilon_3 \supset$  + 

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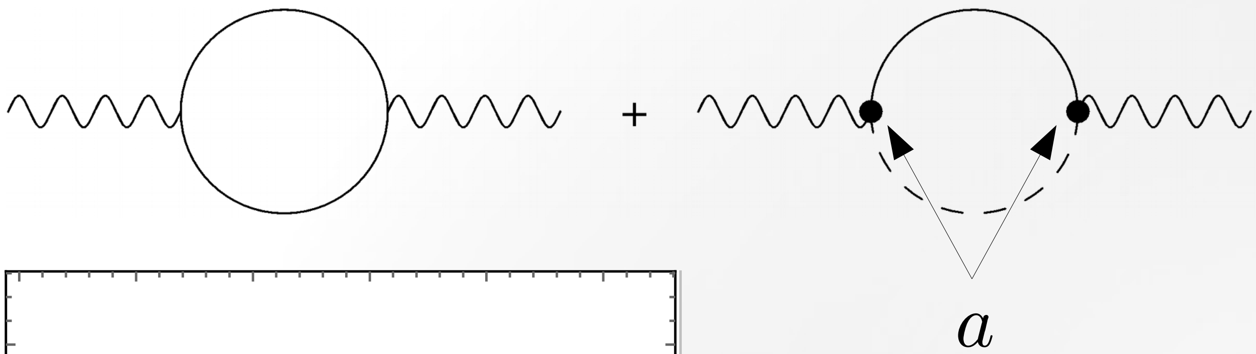
$\epsilon_3 \supset$ 

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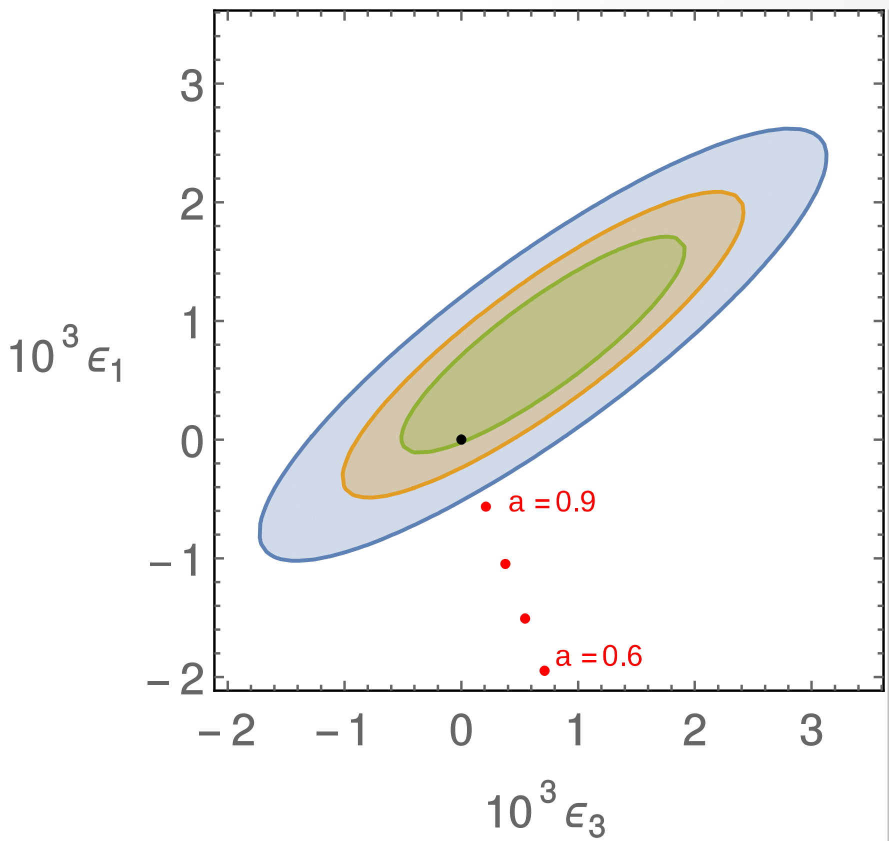
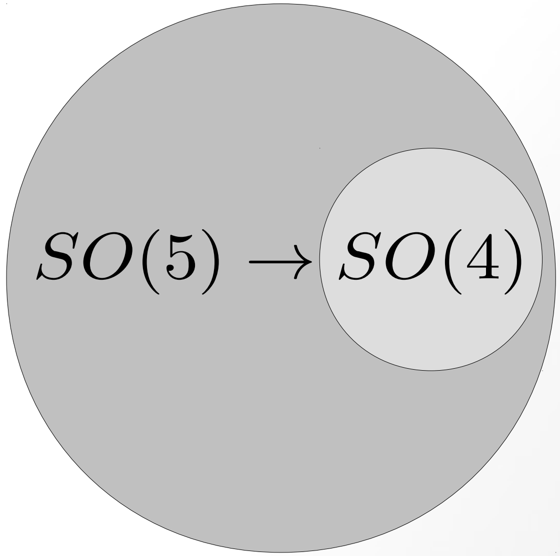


- Same effect for ε_1
- Fine tuning (~5-10%) on a required!
- **<u>Investigate resonances contribution</u>** to see if this picture can be improved or not

SO(5) → SO(4) MINIMAL COMPOSITE HIGGS MODEL

- SO(5) → SO(4) ⇒ 4 NGBs



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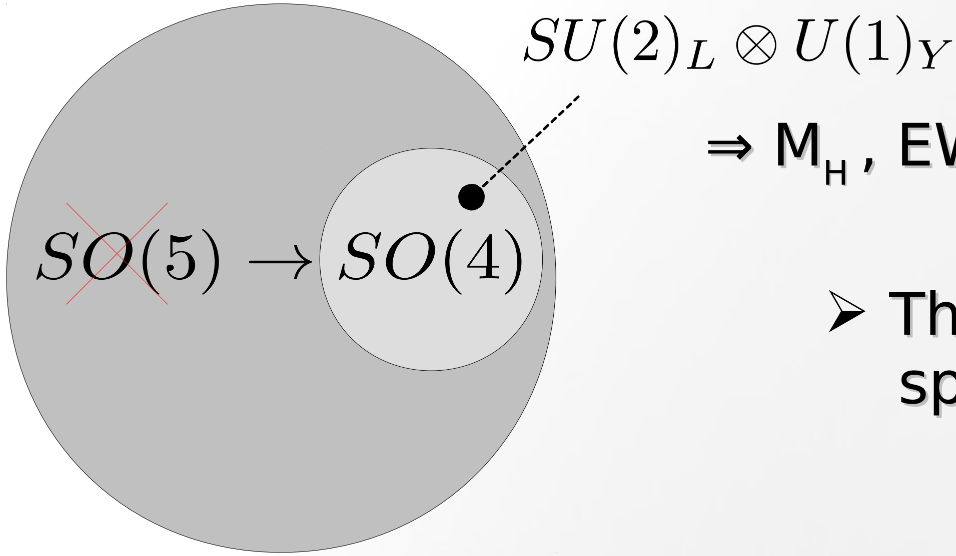

⇒ M_H, EWSB ⇒ 3 NGBs eaten by $W^{\pm}$, Z

- The Higgs is left in the spectrum as a massive pNGB

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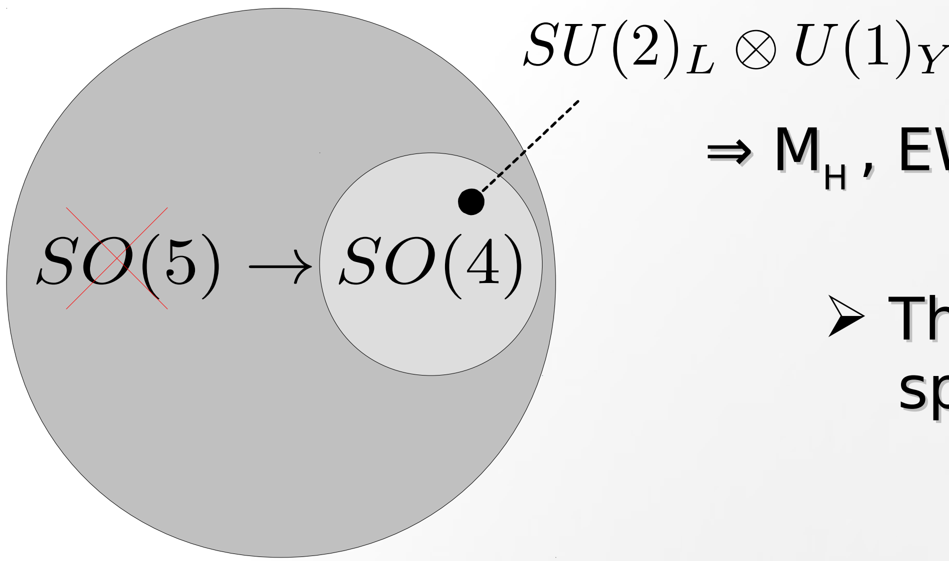

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- SO(5) → SO(4) breaking: scale f
- EWSB breaking: scale v

$$\xi = \left(\frac{v}{f}\right)^2$$

Separation of scales

- Resonances mass: $M_\rho \simeq g_\rho f$
- Decoupling: $\xi \rightarrow 0$

SO(5) → SO(4) MINIMAL COMPOSITE HIGGS MODEL

- CCWZ: natural formalism for spontaneusly broken effective theories, chiral (derivative) expansion is built-in.

[Callan, Coleman, Wess, Zumino, 1977]

- Building blocks:

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

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

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

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

$$h \in SO(4)$$

$d_\mu,\ E_\mu$ ⟷ 1 derivative

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

SO(5) → SO(4) MINIMAL COMPOSITE HIGGS MODEL

- Two-derivatives lagrangian: $\mathcal{L}_{(2)} = \frac{f^2}{4} Tr\left[d^\mu d_\mu\right] \supset \frac{1}{2}\partial_\mu \pi^a \partial^\mu \pi^a + \ldots$

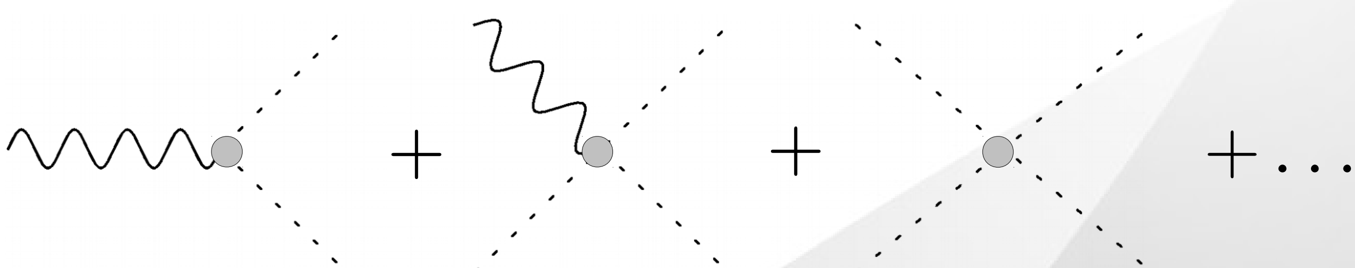
- Manually account for the one-loop generated ESWB: introduce a vev for $\pi_4 \leftrightarrow H$.

$$\pi_4 \to \pi_4 + \langle \pi \rangle \quad \Longrightarrow \quad \mathcal{L}_{(2)} \supset \frac{1}{2}\left(\frac{1}{2} g f \sin\left(\frac{\langle \pi \rangle}{f}\right)\right)^2 \left(W_\mu^a - \delta^{a3} B_\mu\right)^2$$

Usual mass term

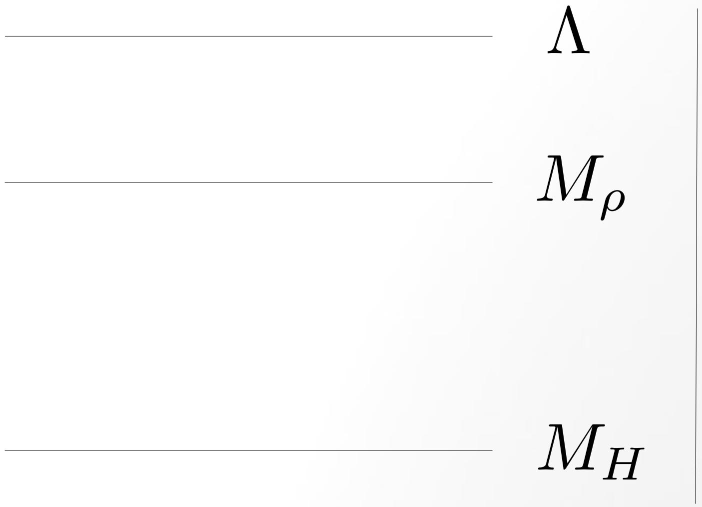
$$\Longrightarrow \quad \sin\left(\frac{\langle \pi \rangle}{f}\right) = \frac{v}{f} = \sqrt{\xi}$$

- Infinite interaction terms with rescaled couplings: $a = \sqrt{1-\xi}$



VECTOR RESONANCES LAGRANGIAN

➢ Introduce a single resonance much lighter than the others

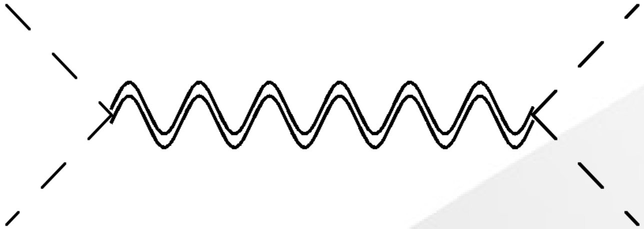


➢ Constrain its coupling strenghts $\{g_\rho^i\}$ with the following:

$$g_\rho^i\,(\Lambda) \sim g^* \equiv \frac{\Lambda}{f}\,(< 4\pi)$$

➢ Partial UV completion of ππ scattering amplitude (PUVC)

[Contino, Marzocca, Pappadopulo, Rattazzi, 2011]



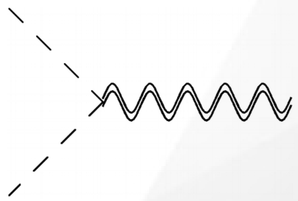
VECTOR RESONANCES LAGRANGIAN

- Our choice will be a **vector resonance living in a (3,1)⊕(1,3) of SU(2)⊗SU(2)** (=SO(4)).

$$\rho_\mu^{(L/R)} = \rho_\mu^{(L/R)a} T^{(L/R)a} \qquad \rho_\mu \xrightarrow[g \in SO(5)]{} h(x)\rho_\mu h^\dagger(x) - ih\partial_\mu h^\dagger$$

- Minimal lagrangian:

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

Mass + interactions:  $+\dots$

- Interactions regolated by $a_\rho \equiv \dfrac{M_\rho}{g_\rho f}$

- PUVC: $a_\rho \sim 1$

VECTOR RESONANCES LAGRANGIAN

- Another relevant operator (tree-level contribution to S):

$$\alpha_2 Tr\left[\rho^{\mu\nu} f_{\mu\nu}\right] \qquad \left(f^{\mu\nu} = e^{-i\pi^a T^{\hat{a}}} F^{\mu\nu} e^{i\pi^a T^{\hat{a}}}\right)$$

- Describes a coupling between the composite and the elementary sector

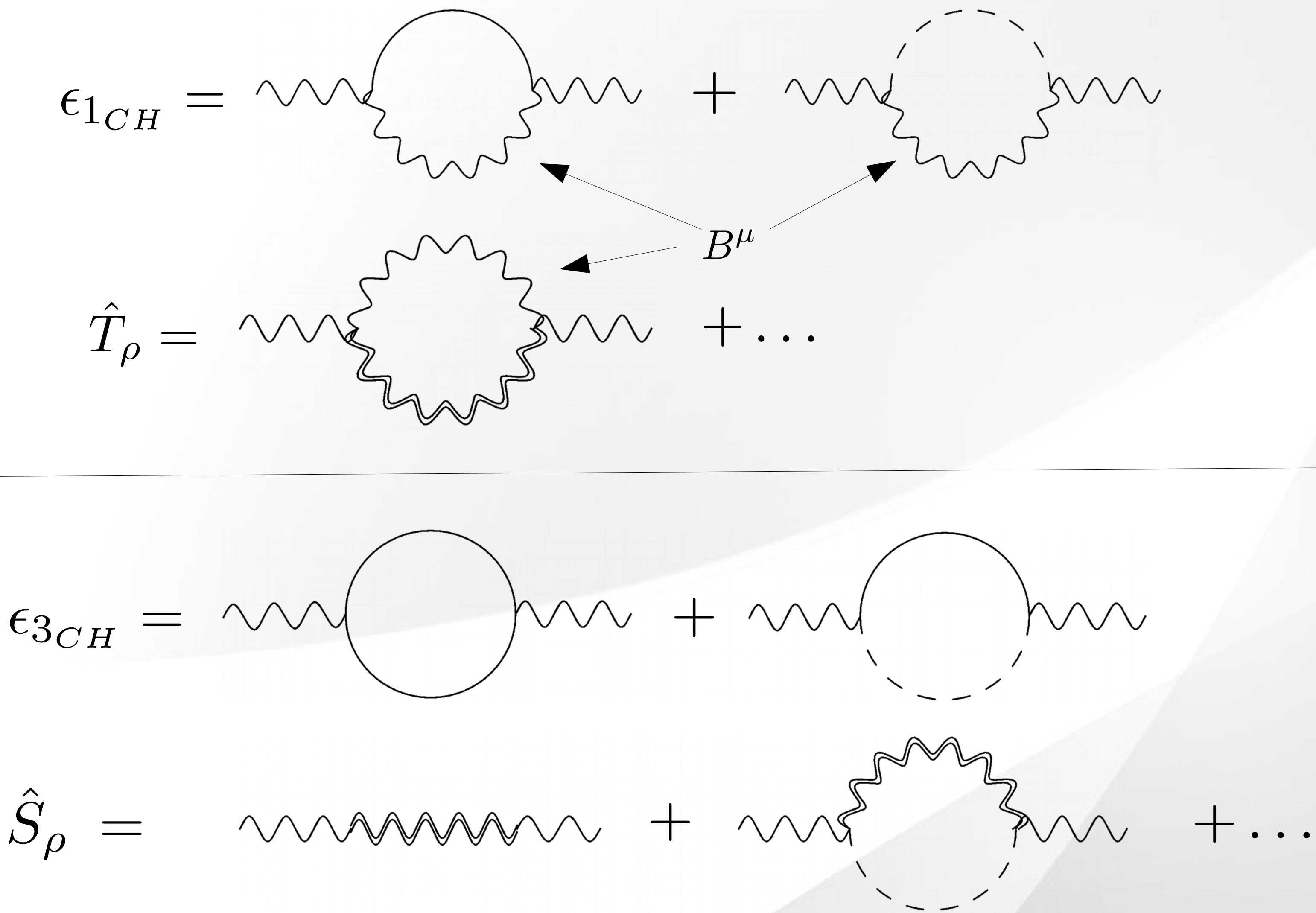
- PUVC does not apply here

- Can only impose, by positivity of the $SU(2)_L$ spectral density:

$$\alpha_2 \lesssim \frac{1}{g_\rho^2}$$

CALCULATION OF EW OBSERVABLES

- Some diagrams:



CALCULATION OF EW OBSERVABLES

- Final expressions for the case of a single ρ_L ($=\rho_R$) ($\varepsilon_i = \varepsilon_i^{(SM)} + \Delta\varepsilon_i$):

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

$$\Delta\epsilon_1 = -\frac{3g'^2}{32\pi^2}\xi\left[\log\left(\frac{\Lambda}{M_Z}\right) + f_1\left(\frac{M_H^2}{M_Z^2}\right)\right] + \frac{3g'^2}{32\pi^2}\xi\frac{3}{4}a_\rho^2\left[\log\left(\frac{\Lambda}{M_\rho}\right) + \frac{3}{4}\right]$$

Composite Higgs contribution (full ε_i)

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

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

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Resonance contribution
(Heavy physics T, S)

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<0

>0 (spectral density)

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PARAMETER SPACE CONSTRAINTS

- Set $\alpha_2 = 0$

- Four independent parameters: ξ, M_ρ, Λ, a_ρ

- Fix:

$$\Lambda = \Lambda_{MAX} = 4\pi f = \frac{4\pi v}{\sqrt{\xi}}$$

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- Constrain (ξ, M_ρ) @ 99% CL

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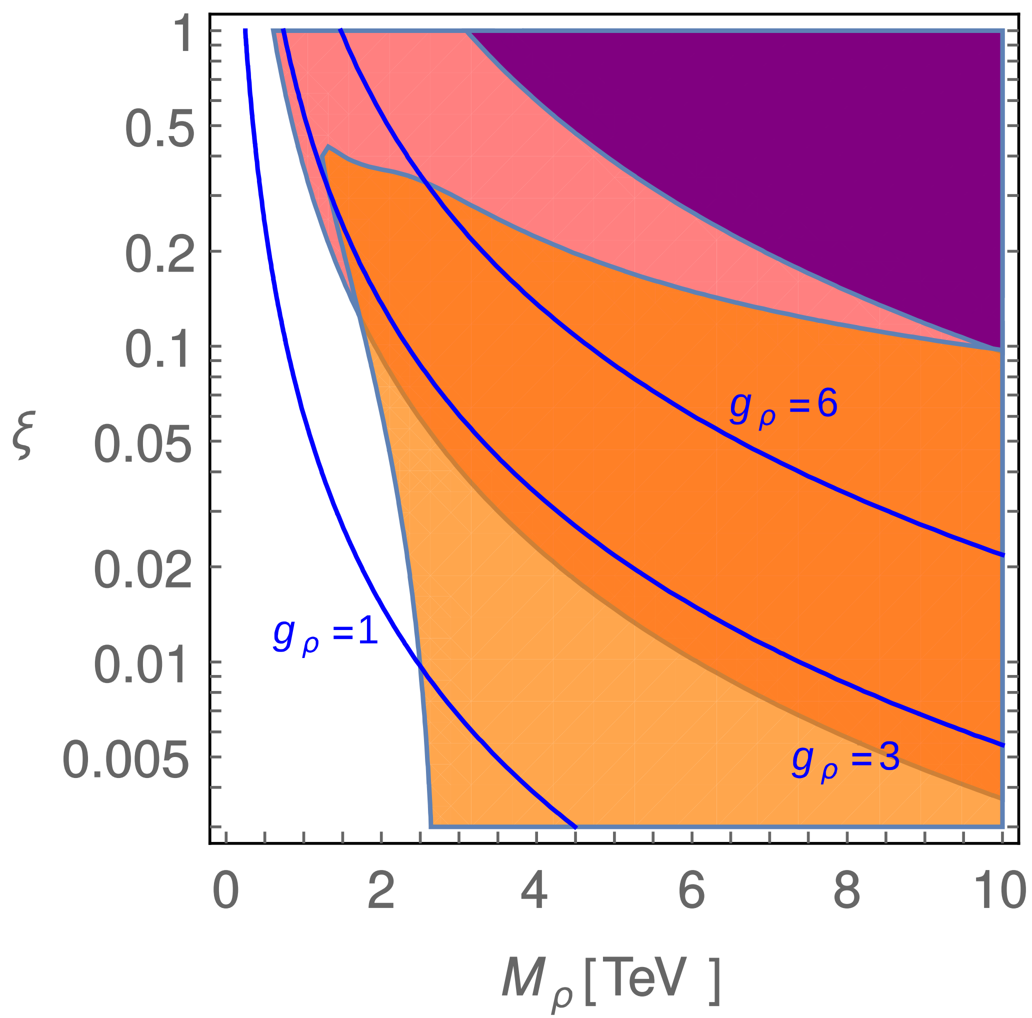

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EWPT allowed

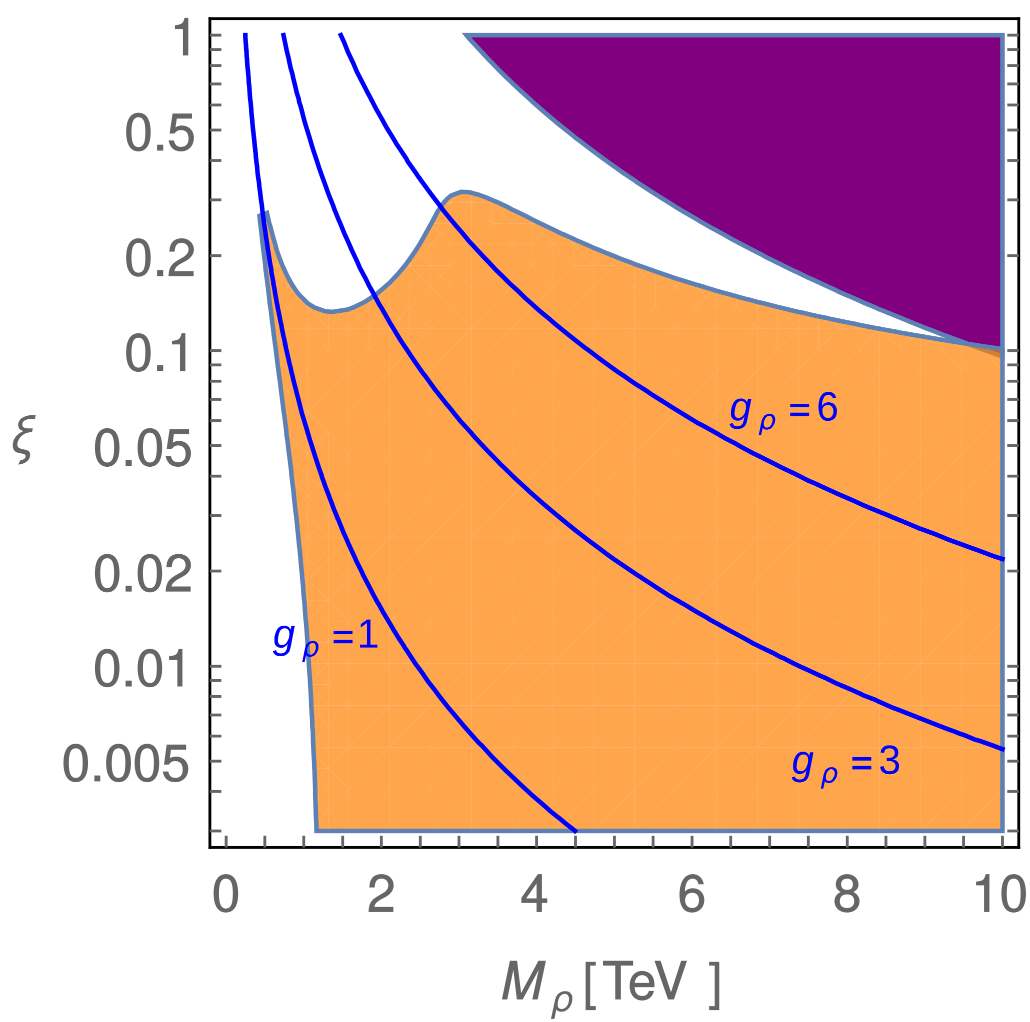
$M_\rho > \Lambda$

$|S_{loop}| > |S_{tree}|$

PARAMETER SPACE CONSTRAINTS

- Set 80% cancellation of S_{tree}:

$$\alpha_2 = 1/5 g_\rho^2$$



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$M_\rho > \Lambda$

TO DO

- Include fermion resonances (almost done):

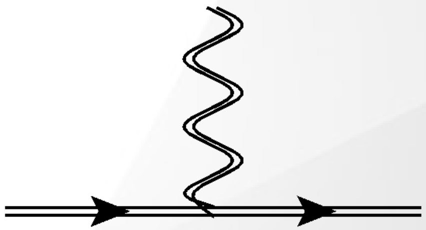
  - Light fermions ($\lesssim$TeV) needed for the Higgs potential

  - $\hat{T}\big|_{ferm} > 0$

    [Grojean, Matsedonskyi, Panico, 2013]

  - Vector + fermions: new strongly-coupled interactions (effects on S, $Zb\bar{b}$)

$$\Psi \in SO(5) \quad \Rightarrow \quad c_L \bar{\Psi} \gamma^\mu \left(\rho_\mu - E_\mu\right) \Psi \quad \Rightarrow$$



- Combine with direct searches constraints