Dark Matter and the Fermi Scale from Strong Interactions

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to appear with O. Antipin, A. Strumia and G. Villadoro

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Strong dynamics is a very plausible possibility for BSM.

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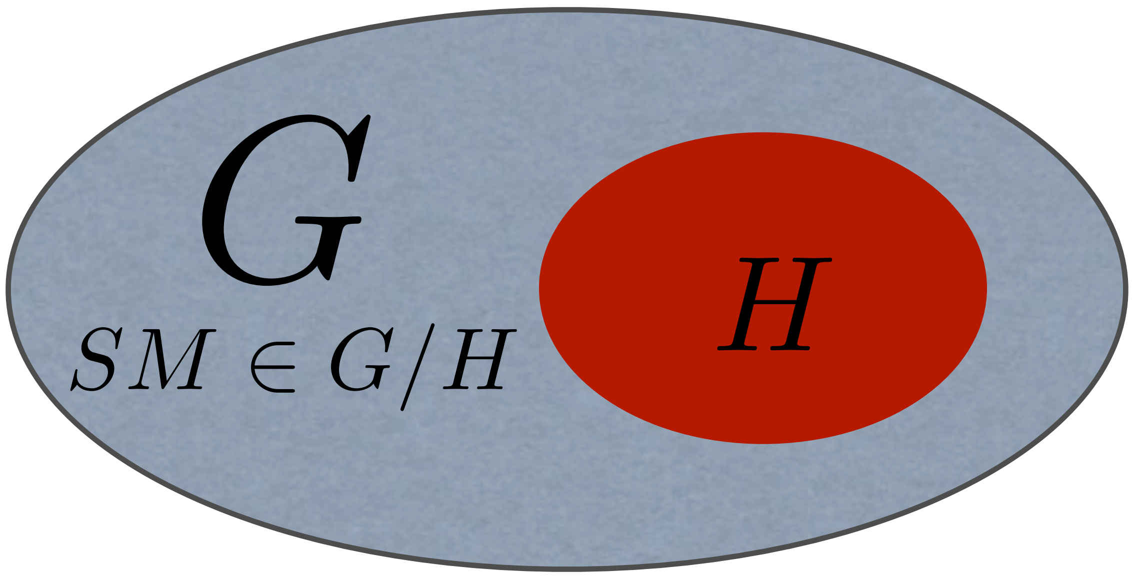
In origin it was technicolor:



$$f = v$$

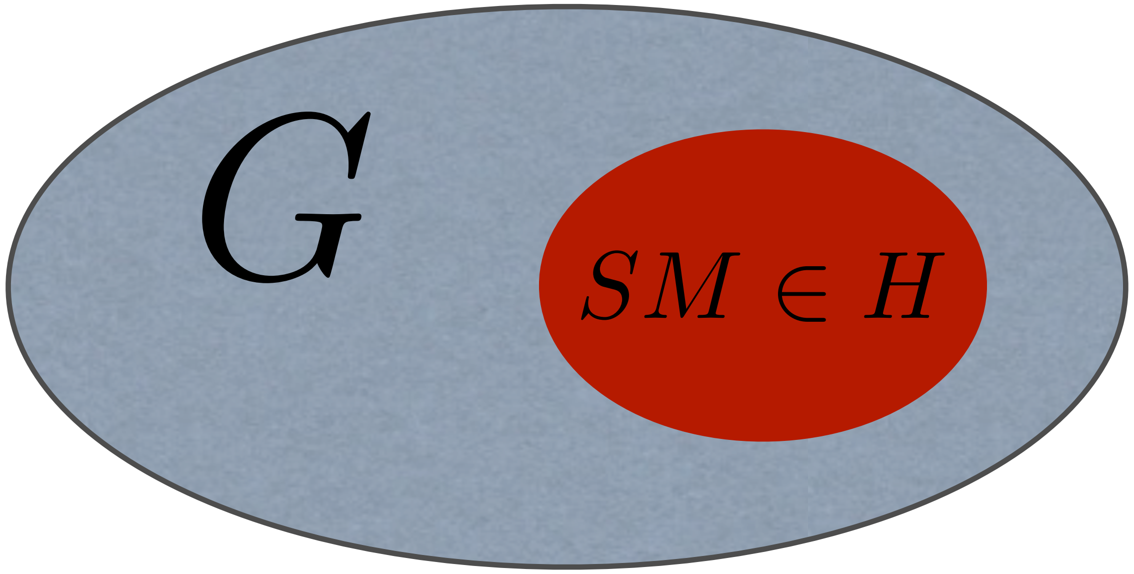
Completely natural theory. No need for the Higgs scalar.

Already in trouble before LHC, now dead.

Next it was the composite Higgs.

Georgi, Kaplan '80s

Higgs could be an approximate GB



$$m_\rho = g_\rho f$$

Ex:

Agashe , Contino, Pomarol, '04

$$\frac{SO(5)}{SO(4)} \xrightarrow{f > v} \mathrm{GB} = 4$$

Electro-weak scale determined by vacuum alignment.

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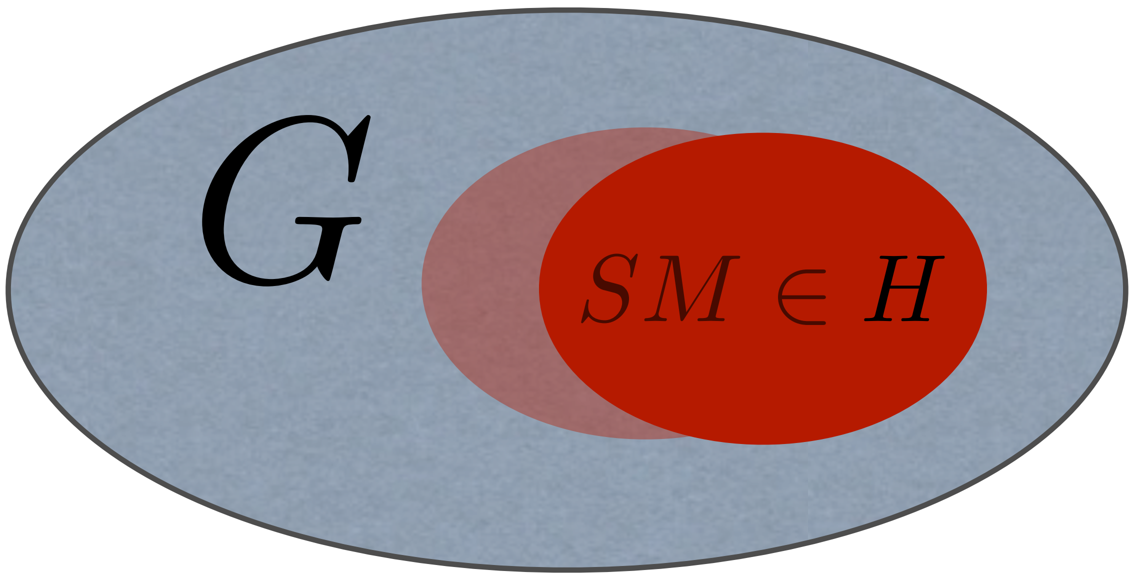

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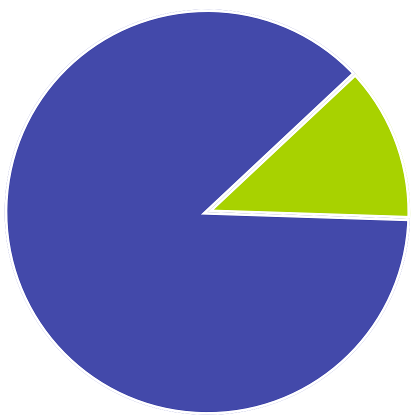
Deviations from SM: $\mathcal{O}\left(\frac{v^2}{f^2}\right)$

Higgs is an angle,



$0 < h < 2\pi f \longrightarrow \text{TUNING} \propto \frac{f^2}{v^2}$

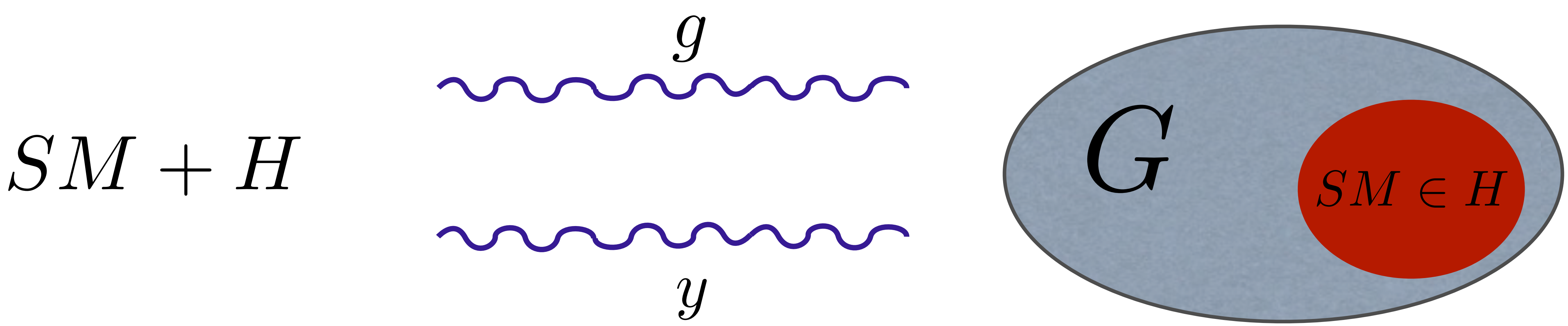
Small Tuning $f < TeV$

- Natural models are constrained by flavor, precision tests and now LHC.

- Hard to construct UV theories.
Typically postulate effective theories with correct features.

Electro-weak preserving strong sector

Kilic, Okui, Sundrum '09



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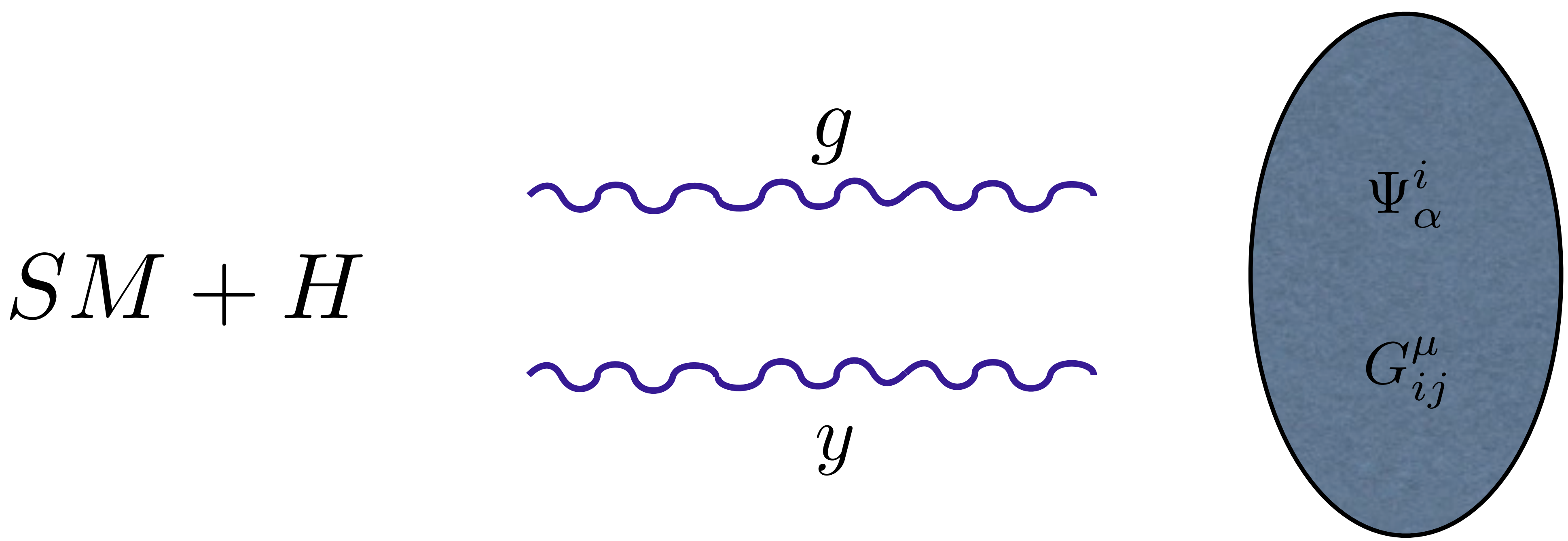

Higgs is elementary and couples to strong dynamics with renormalizable couplings.

$$\mathcal{L} = \mathcal{L}_{SM} - \frac{1}{4\, g_{TC}} G^a_{\mu\nu} G^{a\,\mu\nu} + i\bar{\Psi}\gamma_\mu(\partial_\mu - iA_\mu - iG_\mu)\Psi$$

Very weak bounds:

- Automatic MFV
- Precision tests ok
- LHC: $m_\rho > 1 - 2\,\mathrm{TeV}$

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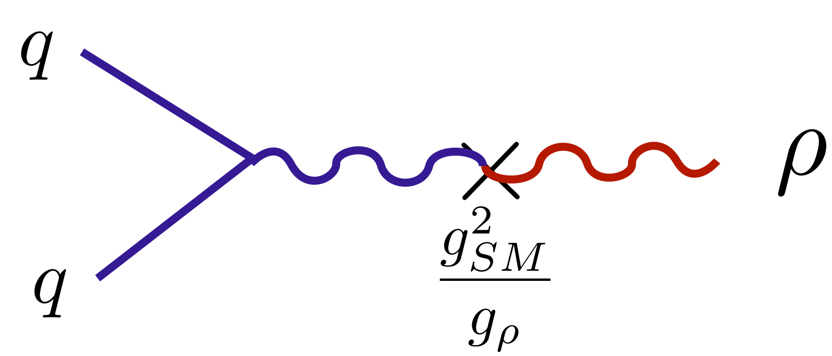
Interesting phenomenology:

- Plausible at LHC13
- Automatic dark matter candidates
- Can generate the electro-weak scale
- Simple UV models

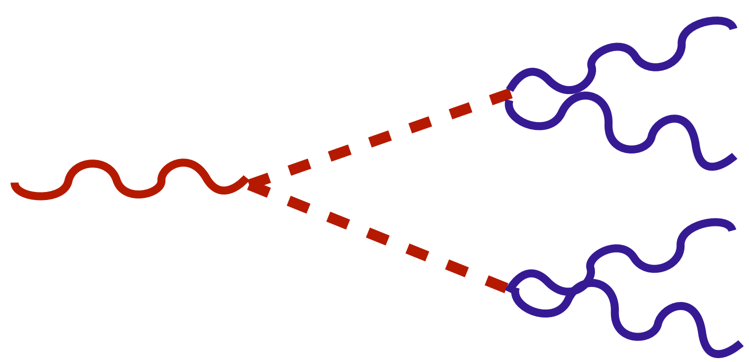
COLLIDER SIGNATURES

Kilic, Okui, Sundrum '09

Vector resonances with SM quantum numbers predicted



Decay to hidden pions and back to SM gauge bosons,



Pions can also be stable or long lived.

- **Models**

SU(n) gauge theory with NF flavors.
Techni-quarks are vectorial with respect to SM.

Fermions	SM	$SU(n)_{\mathrm{TC}}$
Ψ_L	$\sum_i r_i$	n
Ψ_R	$\sum_i \bar{r}_i$	$\bar{n}$

$$\sum_i d[r_i] = N_F$$

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Spontaneous symmetry breaking respects electro-weak.
Massless Goldstone bosons:

$$\frac{SU(N_F)\times SU(N_F)}{SU(N_F)}$$

$$\mathrm{Adj}[SU(N_F)] = \mathrm{Adj}[SM] + R(\pi)$$

Charged pions acquire positive mass from gauge interactions

$$m_\pi^2 \approx \frac{3\,g_2^2}{(4\pi)^2} J(J+1) m_\rho^2$$

These models have automatic dark matter candidates:

- **Baryons**

$$m_B \sim N m_\rho$$

Baryons are products of n quarks symmetric in flavor and spin(“eightfold way”).

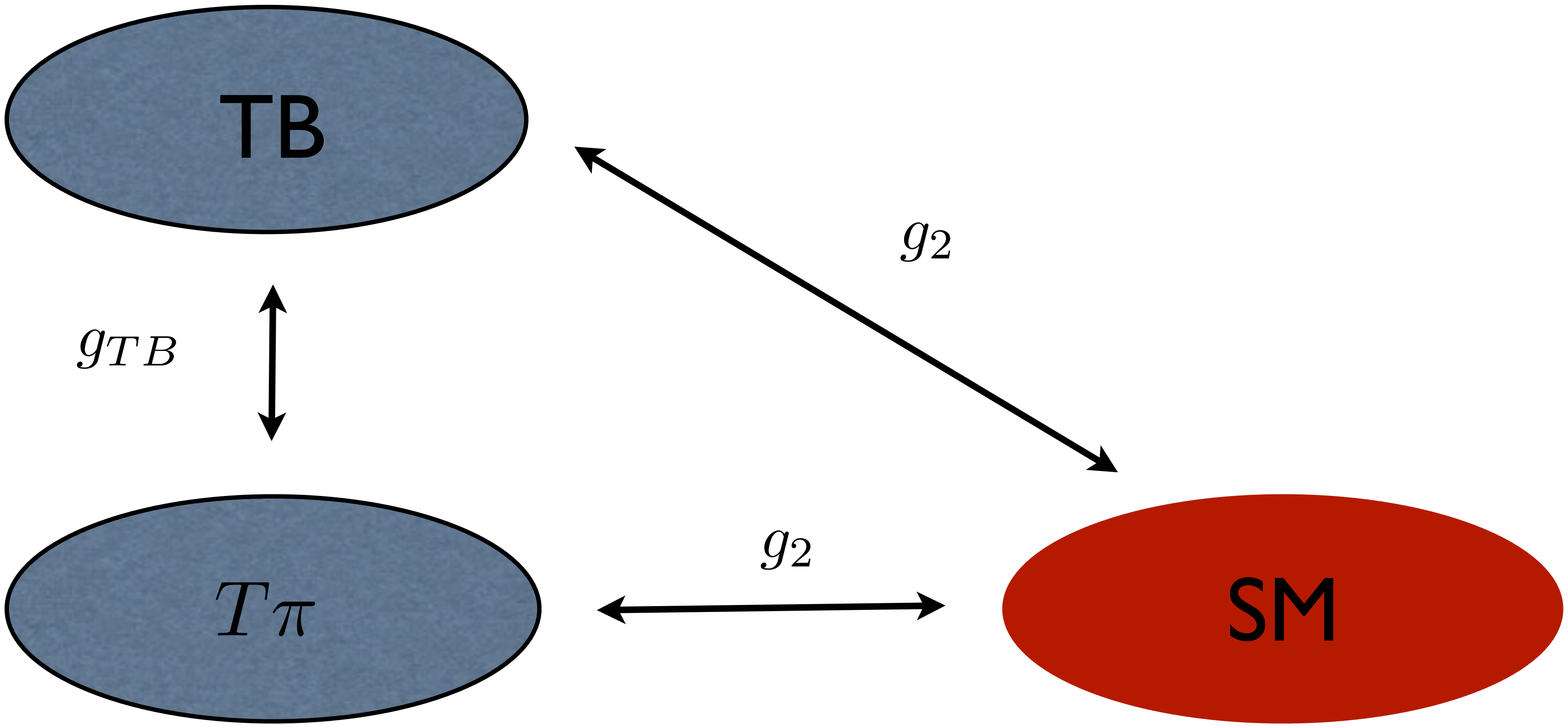
Lightest multiplet has minimum spin among reps.

$n = 3$

$n = 4$

Each multiplet is further split by SM interactions. Technibaryon DM requires I=0,1 and Y=0.

Baryons-anti-baryon annihilate mostly into pions



$$\langle \sigma_{B\bar{B}}^{ANN} v \rangle \sim \frac{4\pi}{m_B^2}$$

THERMAL ABUNDANCE

$$m_B \sim 50 - 100 \, \text{TeV}$$

- **Pions**

Bai, Hill '10

Pions can be stable due to G-parity:

$$\psi \to S\,\psi^C$$

$$W^a_\mu J^a \to W^a_\mu J^a$$

$$S^\dagger J^a S = -J^{a*}$$

$$A^a t^a \to A^a(-t^a)^*$$

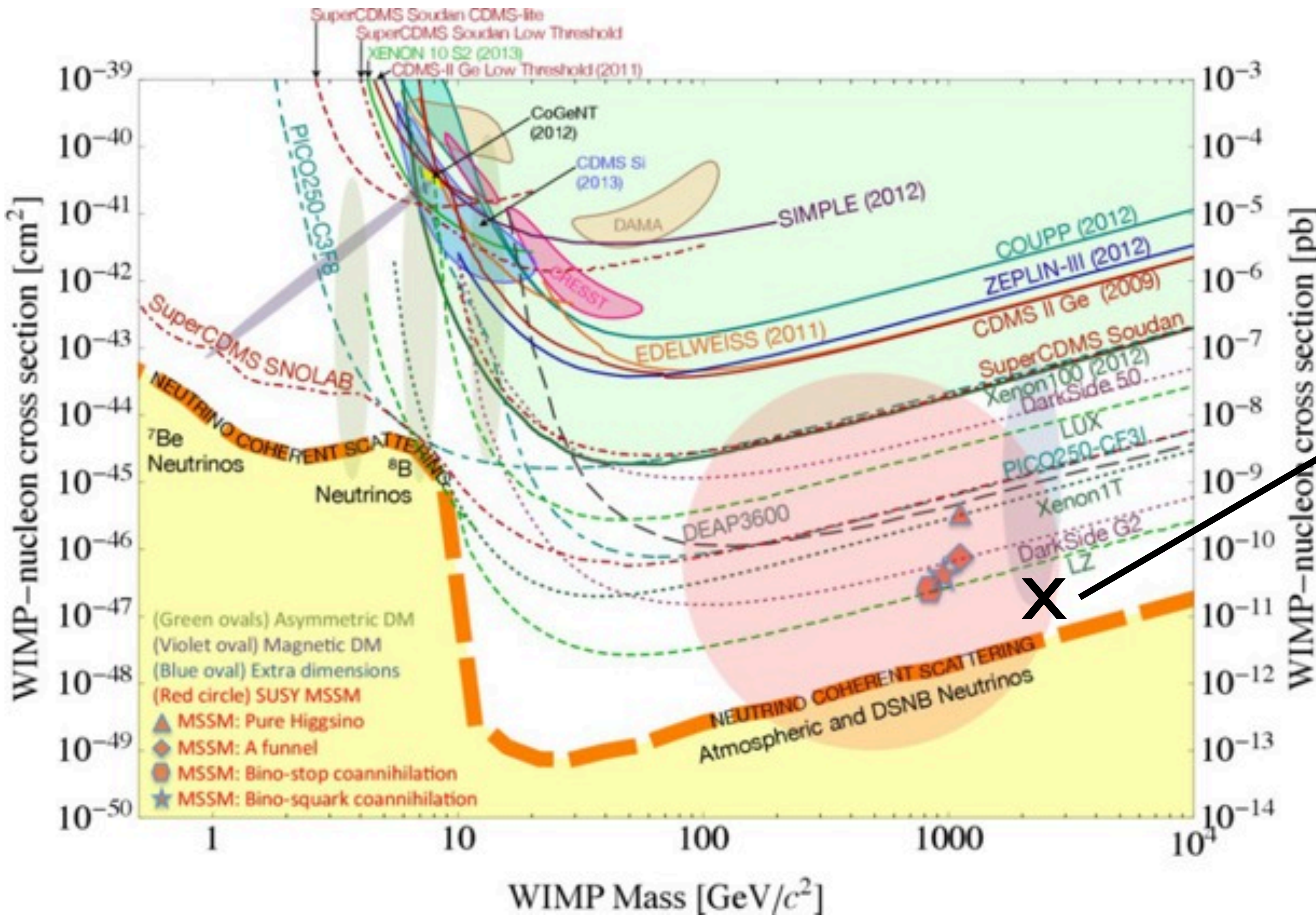
$$\Pi^J \to (-1)^J \Pi^J$$

Triplet is stable. Behaves as minimal dark matter.

Strumia, Cirelli '05

$$m_{J=1} \sim 2.5\,\mathrm{TeV}$$

$$\sigma_{SI} = 0.12 \pm 0.03 \times 10^{-46}\,\mathrm{cm}^2$$



pion triplet

Dipole interactions:

$$\frac{1}{4\,m_B}\bar{B}\sigma_{\mu\nu}(g_M + i g_E \gamma_5) B\ F_{\mu\nu}$$

$$\frac{d\sigma}{dE_R} \approx \frac{e^2 Z^2}{16\pi\, m_B^2\, E_R}\left(g_M^2 + \frac{g_E^2}{v^2}\right) \longrightarrow g_M^2 + 8\times 10^6 g_E^2 < \left(\frac{m_B}{5.8\,\mathrm{TeV}}\right)^3$$

$$n = N_F = 3$$

Pions and lightest baryons are adjoint of SU(3).

Rescale QCD:

$$\frac{m_B}{m_\rho} \approx 1.3 \qquad \frac{m_\pi}{m_\rho} \approx 0.1\,\sqrt{J(J+1)}$$

Technibaryon thermal abundance:

$$\sigma_{p\bar{p}}^{QCD} \sim 100\,\mathrm{GeV}^{-2} \longrightarrow \frac{\Omega_{DM}}{\Omega_{DM}^c} \sim \left(\frac{M_B}{200\,\mathrm{TeV}}\right)^2$$

- $SU(2)_L \subset SU(3)_F$

$$\mathbf{8} = \mathbf{3} + \mathbf{5}$$

Scalar triplet is stable and is dominant dark matter.

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- $SU(2)_L \times U(1)_Y \subset SU(3)_F$

$$3 = 2_{\frac{1}{2}} + 1_{-1}$$

Same as QCD quantum numbers.

$$\mathbf{8} = \mathbf{2}(\mathrm{p}, \mathrm{n}) + \mathbf{3}(\Sigma^{\pm,0}) + \mathbf{2}(\Xi^0, \Xi^-) + \mathbf{1}(\Lambda_0)$$

$$\mathbf{8} = \mathbf{2}(\mathrm{K}^0, \mathrm{K}^+) + \mathbf{3}(\pi^{\pm,0}) + \mathbf{2}(K^-, \bar{K}^0) + \mathbf{1}(\eta)$$

Quantum numbers allow for Yukawa interactions.
Singlet GB acquires mass and triplet decays.

Dark matter is a technibaryon.

DM summary (mQ=0):

number of techni-flavors	Yukawa	$N_{\rm TC}=3$ TCb	$N_{\rm TC}=3$ TCπ	$N_{\rm TC}=4$ TCb	$N_{\rm TC}=4$ TCπ	
$N_F=2$		2	3	1	3	under TC-flavor SU(2)
model 1: $Q=2_{Y=0}$	0	charged	3	1	3	DM, under $\mathrm{SU}(2)_L$
$N_F=3$		8	8	$\bar{6}$	8	under TC-flavor SU(3)
model 1: $Q=1_Y+2_{Y'}$	1	1	no	1	no	DM, under $\mathrm{SU}(2)_L$
model 2: $Q=3_{Y=0}$	0	3	3	1	3	DM, under $\mathrm{SU}(2)_L$
$N_F=4$		$\overline{20}$	15	$20'$	15	under TC-flavor SU(4)
model 1: $Q=4_{Y=0}$	0	charged	3	1	3	DM, under $\mathrm{SU}(2)_L$

With single SU(2) reps DM has two components.

The model with 2+1 allows for Yukawa interactions.
This gives mass to the singlet and breaks G-parity.
Dark matter is a singlet baryon.

DYNAMICAL GENERATION OF THE WEAK SCALE

Assumption: the fundamental theory has no scales.

Practically discard uncalculable quadratic divergences.
SM is natural ("finite naturalness"):

Farina, Pappadopulo, Strumia, '14

$$\delta m_h^2 \sim -\frac{3\, y_t^2}{(4\pi)^2} m_h^2 \log \frac{m_t^2}{\mu^2}$$

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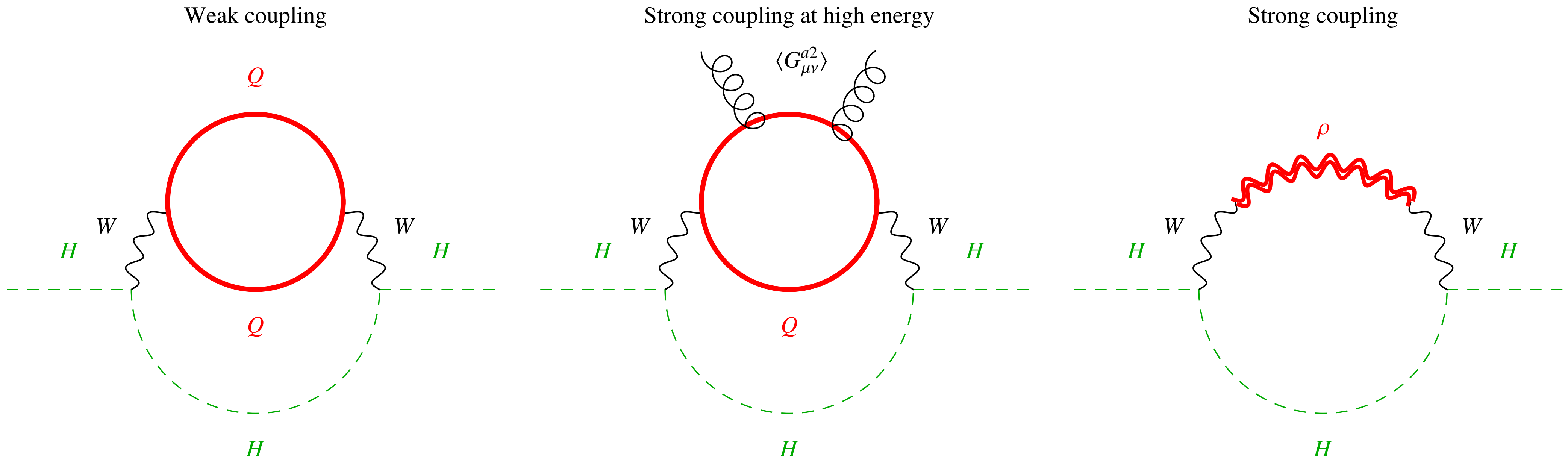
With no masses electro-weak scale determined by the confinement scale of strong sector.
Gauge (Yukawa) interactions trigger electro-weak symmetry breaking:

$$m_h \sim \alpha_2 f$$

- **Gauge Interactions**



Strong dynamics modifies SM propagators

$$G^{VV}_{\mu\nu}(q) = -i\frac{\eta_{\mu\nu}}{q^2}(1+g_2^2\Pi_{VV}(q^2)) + i\xi_V\frac{q_\mu q_\nu}{q^2}$$

$$i\int d^4x\, e^{iq\cdot x}\langle 0|\mathrm{T}J^a_\mu(x)J^b_\nu(0)|0\rangle \equiv \delta^{ab}(q^2 g_{\mu\nu} - q_\mu q_\nu)\Pi_{VV}(q^2)$$

Higgs mass:

$$\Delta m^2 = \frac{9g_2^4}{4(4\pi)^2}\int dQ^2\Pi_{VV}(-Q^2)$$

Contributions is finite. OPE:

$$\Pi_{VV}(q^2) \overset{q^2 \gg \Lambda_{\rm TC}^2}{\simeq} c_1(q^2) + c_2(q^2)\langle 0|m_Q Q_L Q_R|0\rangle + c_3(q^2)\langle 0|\frac{\alpha_{\rm TC}}{4\pi} G_{\mu\nu}^{A2}|0\rangle + \cdots$$

$$c_1 = C\frac{\alpha_2}{3\pi}\ln(-q^2) + \cdots \qquad\qquad c_3 = -C'\frac{g_2^2}{3q^4}$$

$$\Delta m^2|_{\rm UV} \simeq -\frac{3C' g_2^4}{4(4\pi)^2}\langle 0|\frac{\alpha_{\rm TC}}{4\pi} G_{\mu\nu}^{A2}|0\rangle \int_{Q^2_{\rm min}}^{\infty} \frac{dQ^2}{Q^4} \qquad \left(\text{in QCD} \quad \langle 0|\frac{\alpha_s}{4\pi} G_{\mu\nu}^{A2}|0\rangle = 0.03\,{\rm GeV}^4\right)$$

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Sign is negative:

$$\frac{\partial \Delta m^2}{\partial \Lambda_{\rm TC}^2} = \frac{9g_2^4}{4(4\pi)^2}\int dQ^2 \frac{\partial \Pi_{VV}}{\partial \Lambda_{\rm TC}^2} = -\frac{9g_2^4}{4(4\pi)^2}\int dQ^2 \frac{Q^2}{\Lambda_{TC}^2}\frac{\partial \Pi_{VV}}{\partial Q^2}$$

$$= \frac{9g_2^4}{4(4\pi)^2}\int dQ^2 \frac{1}{\pi}\frac{Q^2}{\Lambda_{TC}^2}\int_0^{\infty} ds \frac{{\rm Im}\,\Pi_{VV}(s)}{(s+Q^2)^2} < 0$$

Estimate:

$$\Pi_{VV}(q^2) = \frac{f^2}{(q^2 - m_\rho^2)}$$

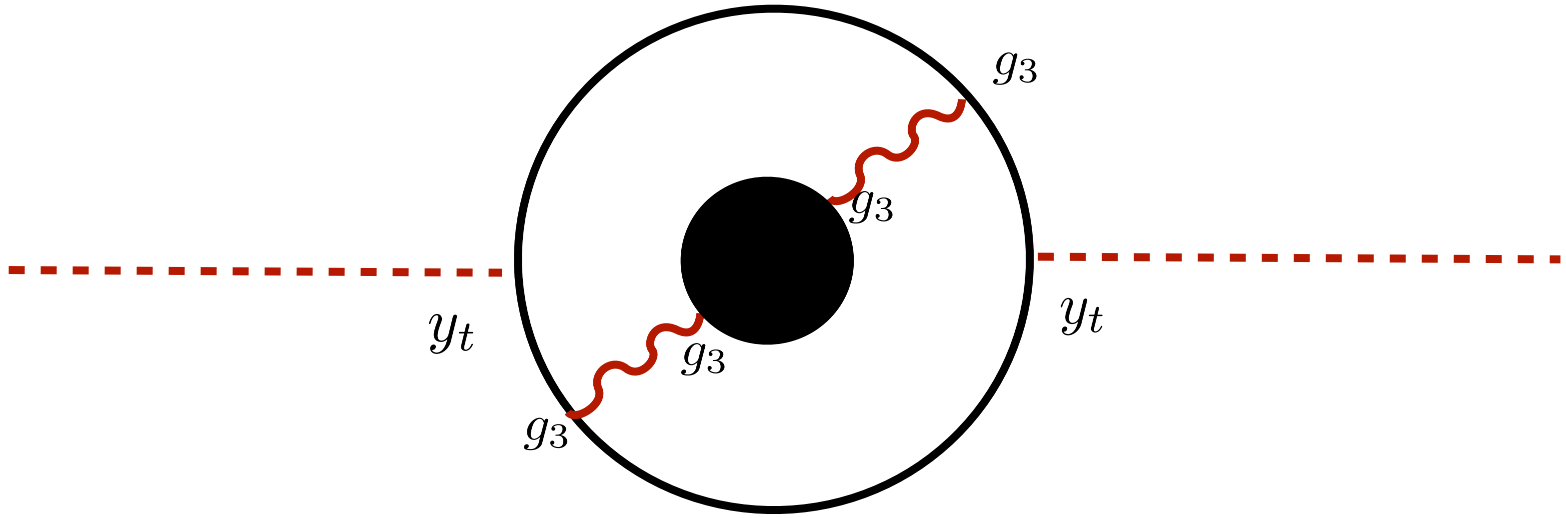
$$\Delta m^2 \approx -\frac{9g_2^4}{4(4\pi)^2} \int dQ^2 \frac{f^2}{(Q^2 + m_\rho^2)} \sim -\alpha_2^2 f^2$$

We obtain the following scales

$$f \sim \frac{m_H}{\alpha_2} \sim \text{few} \times \text{TeV}$$

$$m_\pi \sim 2\,\text{TeV}, \qquad m_\rho \sim 20\,\text{TeV}, \qquad m_B \sim 50\,\text{TeV}$$

- **3-loops**



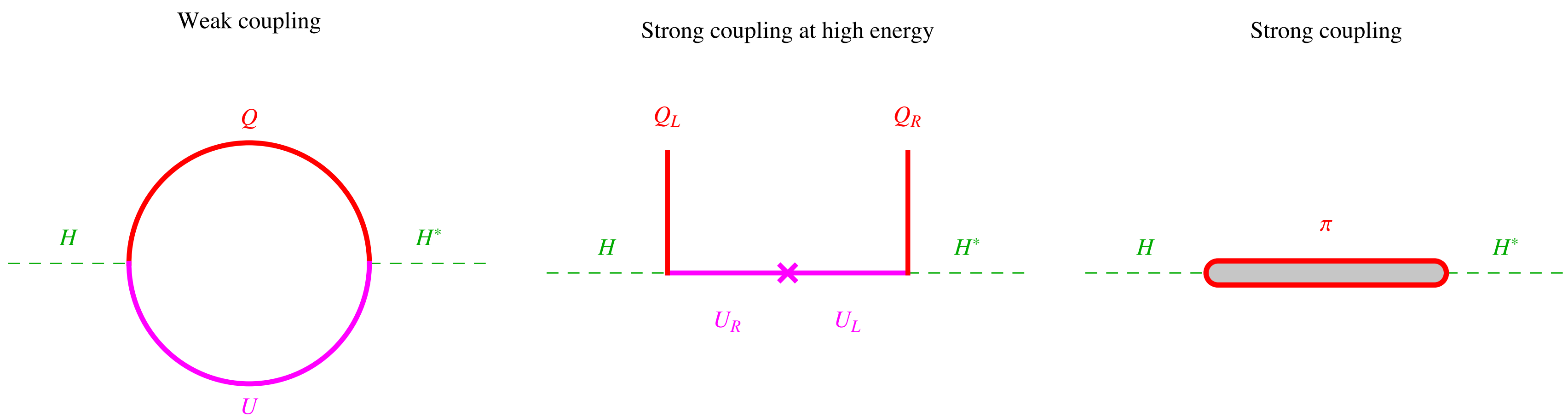
Positive Higgs mass:

$$\Delta m^2 = -\frac{64 y_t^2 g_3^4}{(4\pi)^4} \int dQ^2 \Pi_{GG}(-Q^2) \sim \frac{y_t^2 g_3^4}{(4\pi)^4} f^2$$

Gravitational corrections can be related to 2-point function of energy momentum tensor

$$\Delta m^2 \sim \frac{y_t^2 m_\rho^4 f^2}{(4\pi)^4 M_p^4}$$

- **Yukawa Interactions**



$$yHQ_LQ_R$$

Chiral lagrangian,

$$y\,\frac{N}{(4\pi)^2}m_\rho^3\mathrm{Tr}[HU]$$

2 Higgs doublets mix:

$$\begin{array}{c} \\ \pi \\ H \end{array} \begin{array}{cc} \pi^* & H^* \\ \left(\begin{array}{cc} (\mathcal{O}(g^2) \pm \mathcal{O}(y^2)) m_\rho^2/(4\pi)^2 & \mathcal{O}(y) m_\rho^2 \sqrt{N}/(4\pi) \\ \mathcal{O}(y) m_\rho^2 \sqrt{N}/(4\pi) & -\mathcal{O}(y^2)) m_\rho^2 N/(4\pi)^2 \end{array} \right) \end{array}$$

Mixing induces negative Higgs mass

$$\Delta m^2 \approx -\frac{y^2\, N}{(4\pi)^2} \frac{m_\rho^4}{m_\pi^2}$$

1-loop effective potential:

$$\frac{y^2}{(4\pi)^2} m_\rho^2 f^2 \sum_a \mathrm{Tr}[T^a U] \mathrm{Tr}[T^a U^\dagger]$$

$$\sim \frac{y^2}{(4\pi)^2} m_\rho^2 \left(\pi^{*2} + \pi^{*2} \frac{\eta^2}{f^2} + \dots \right)$$

CONCLUSIONS

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- Within finite naturalness electro-weak symmetry breaking could be induced from the technicolor dynamical scale. Scales and signs roughly work out.

Pions decompose under SM as,

$$\mathrm{Adj}_{SU(N_F)} = \sum_{i=1}^{K} r_i \times \sum_{i=1}^{K} \bar{r}_i - 1$$

K-1 singlets remain massless.
One combination anomalous under the SM,

$$\frac{e^2}{(4\pi)^2 f}\eta F\tilde{F}$$

Effectively behaves as weak scale axion. Excluded unless other sources of symmetry breaking included.

Simplest models contain 1 irreducible rep.