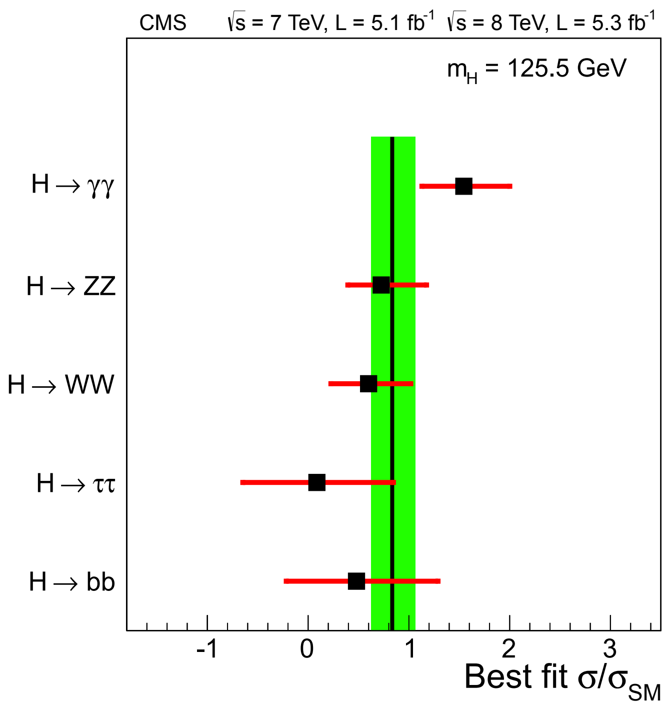
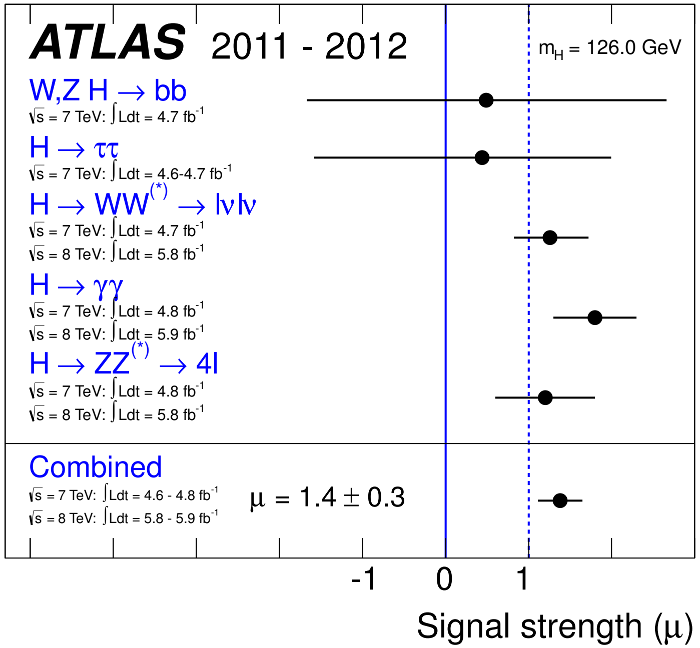
Implications of a 125 GeV Composite Higgs

Alex Pomarol, UAB *(Barcelona)*

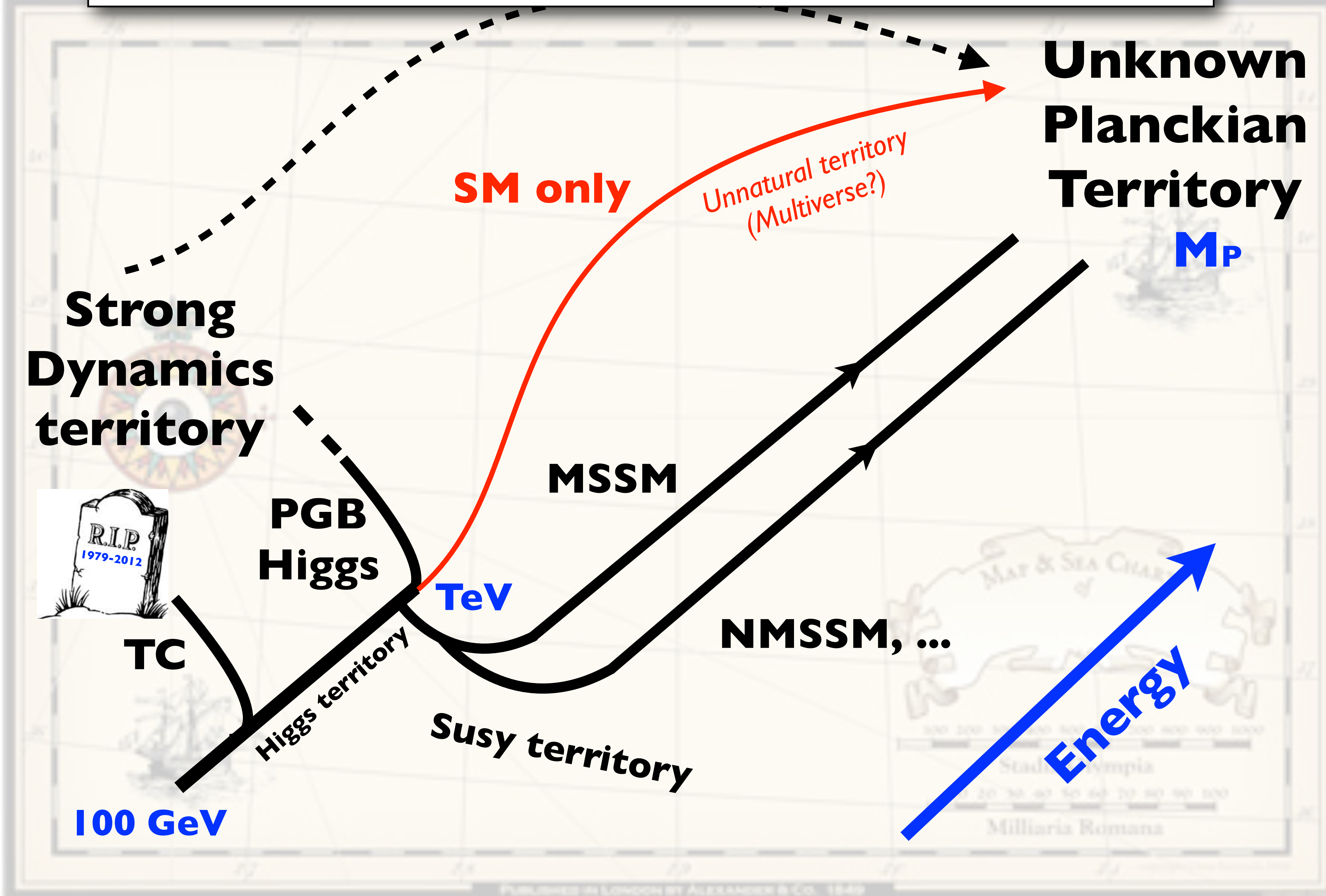
A 125 GeV Higgs-like state has been discovered





with no significant deviations from a SM Higgs!

Road Map of possible BSM scenarios



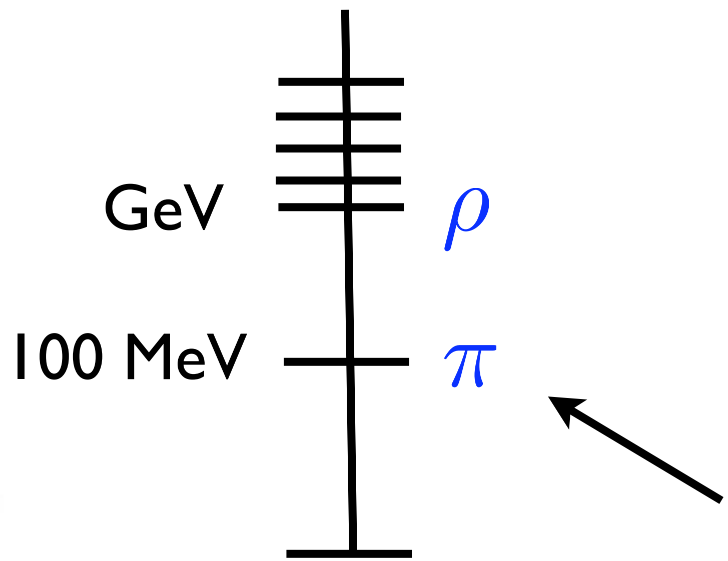
Purpose of my talk here:

How well this
recently discovered
125 GeV Higgs
fit in
Composite Higgs Models ?

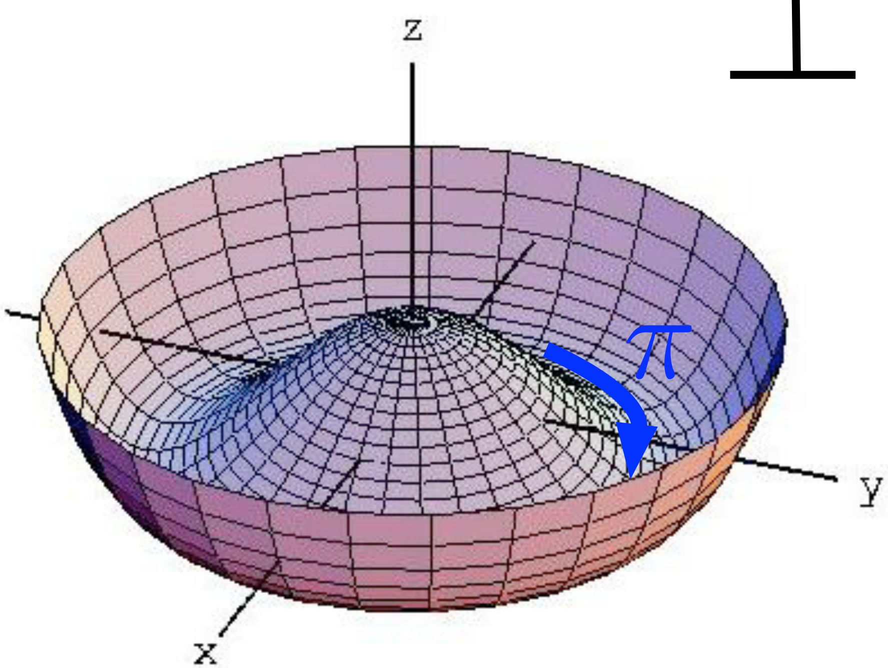
Composite PGB Higgs

inspired by QCD where one observes
that the (pseudo) scalar are the lightest states

Spectrum:



Are Pseudo-Goldstone
bosons (PGB)

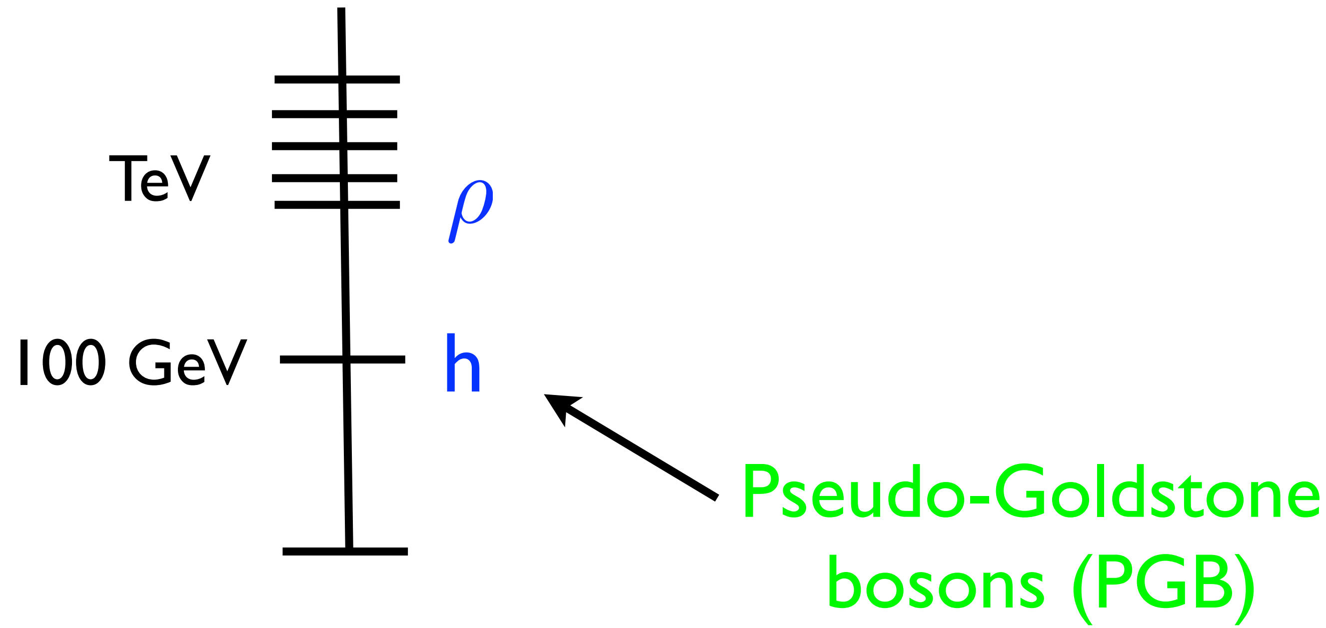


Mass protected by the
global QCD symmetry!

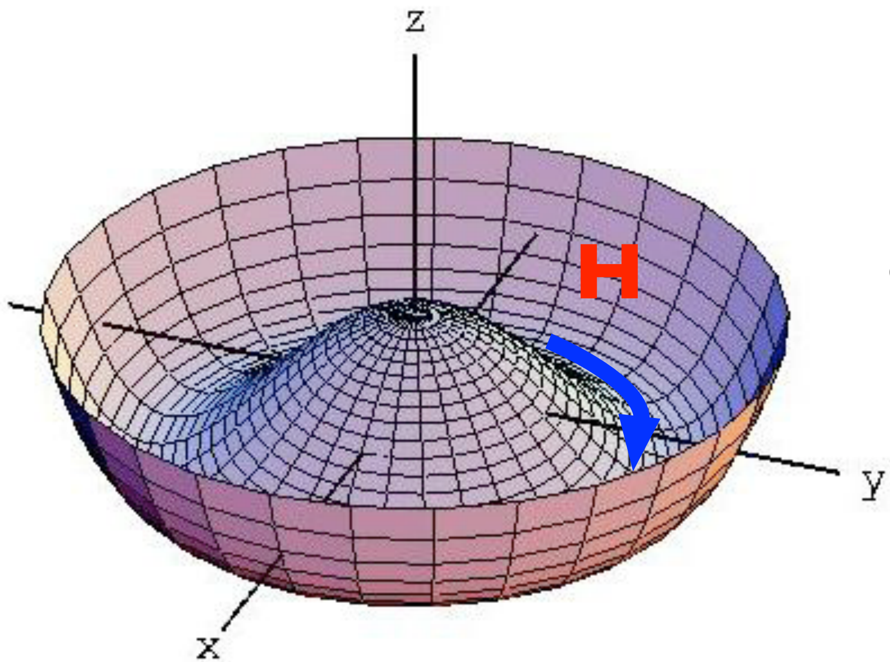
$$\pi \to \pi + \alpha$$

→ **Can the light Higgs be a kind of a pion from a new strong sector?**

We'd like the spectrum of the new strong sector to be:



Potential from some new strong dynamics at the TeV:



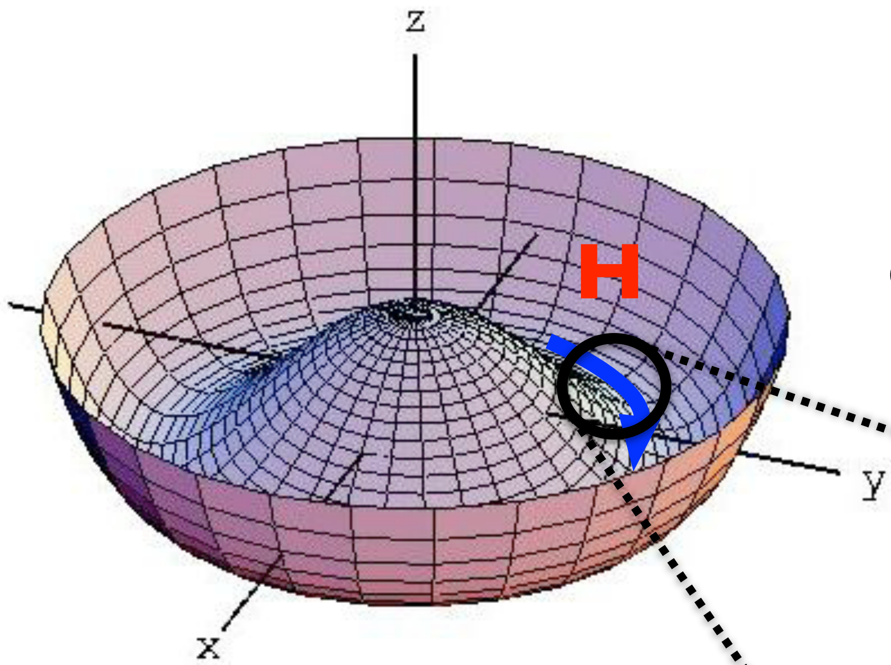
e.g. SO(5) → SO(4)

4 Goldstones

⇓

Higgs doublet

Potential from some new strong dynamics at the TeV:



e.g. $SO(5) \rightarrow SO(4)$

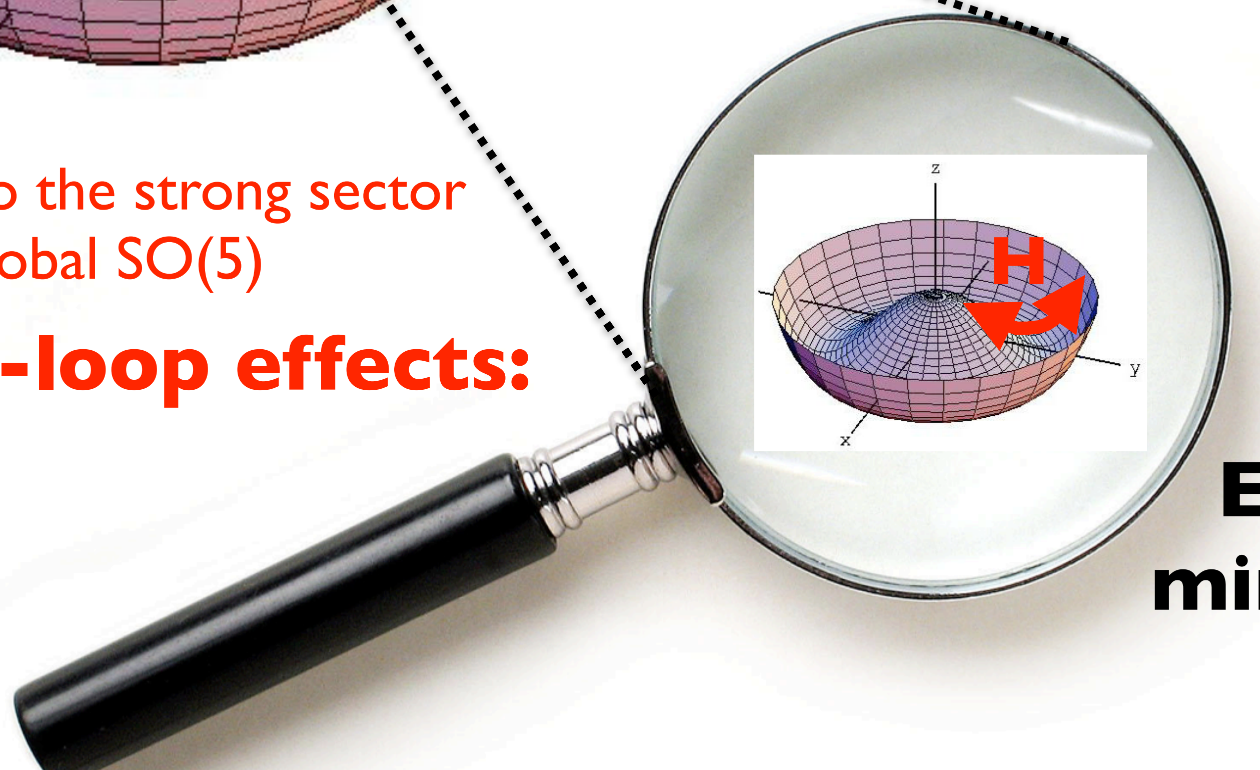
4 Goldstones

$\Downarrow$

Higgs doublet

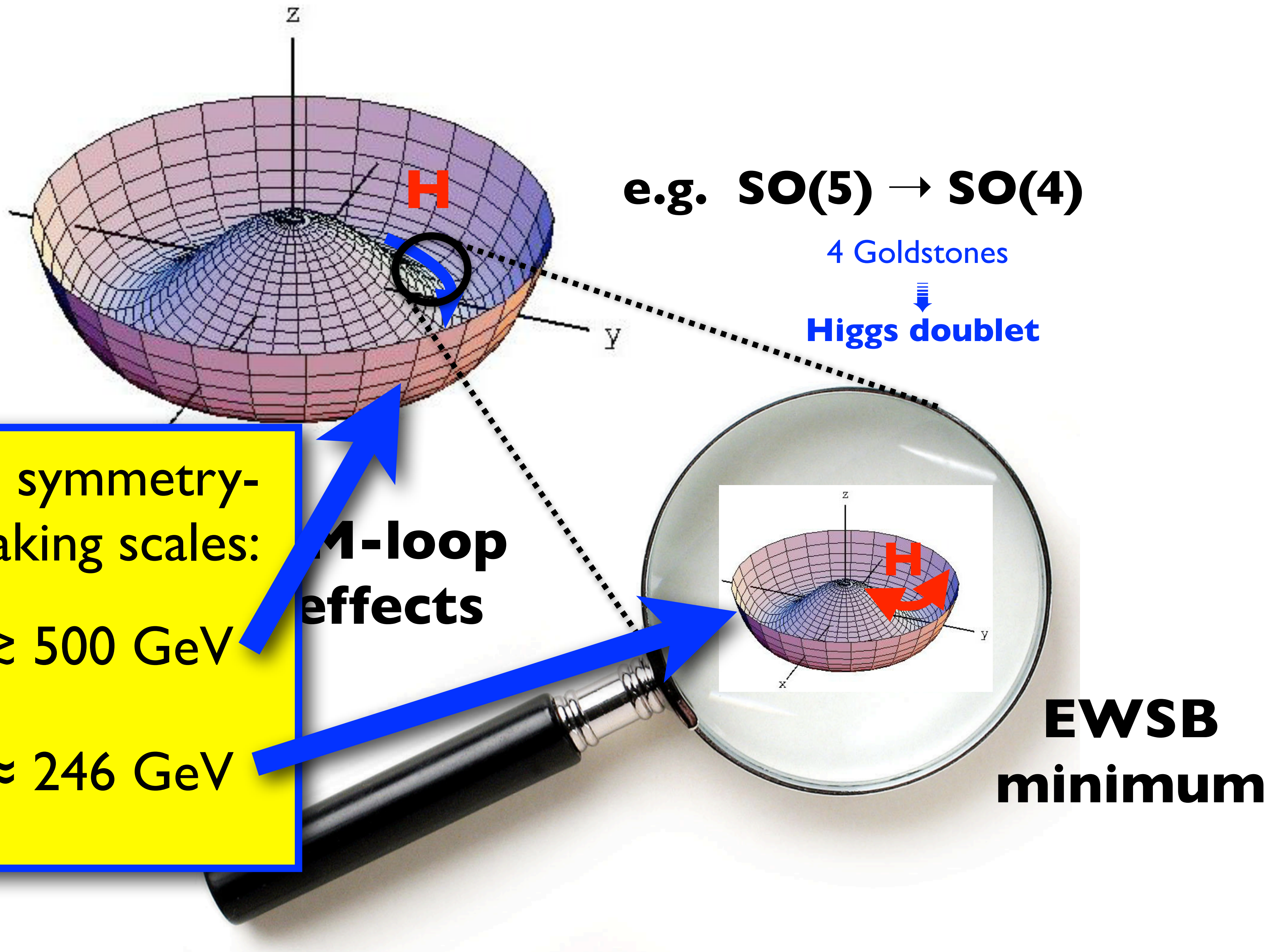
SM-field couplings to the strong sector
break the global SO(5)

SM-loop effects:



EWSB minimum

Potential from some new strong dynamics at the TeV:



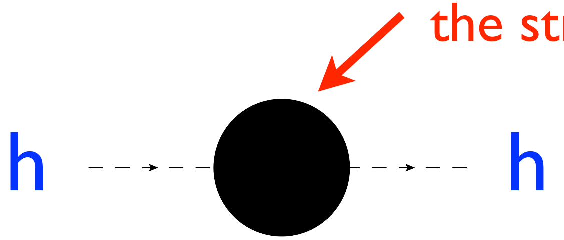
two symmetry-breaking scales:

$f \gtrsim 500$ GeV

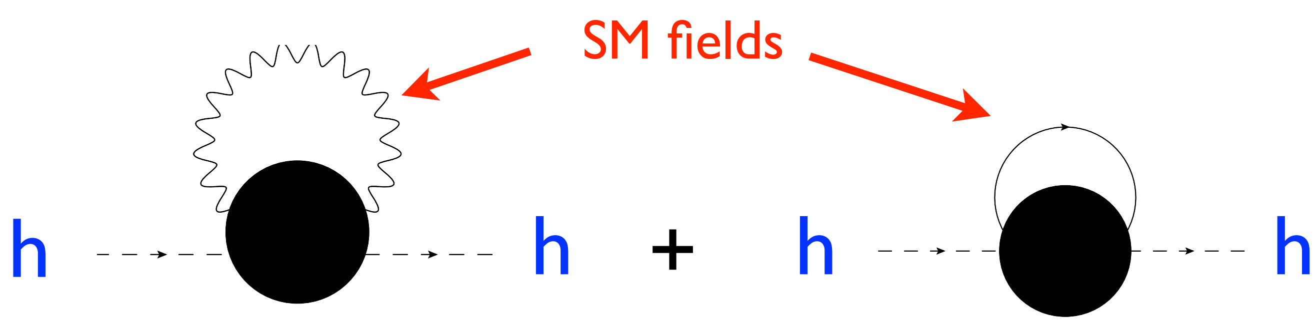
$v \approx 246$ GeV

Higgs Mass

contribution from
the strong sector



= 0 it's a Goldstone



$$\hookrightarrow \quad V(h) = \frac{g_{SM}^2 m_\rho^2}{16\pi^2} h^2 + \cdots$$

Difficult to get predictions
due to the intractable
strong dynamics**!**

A possibility to move forward has been to use the...

AdS/CFT approach

Strongly-coupled systems
in the Large N_c
Large $\lambda \equiv g^2 N_c$

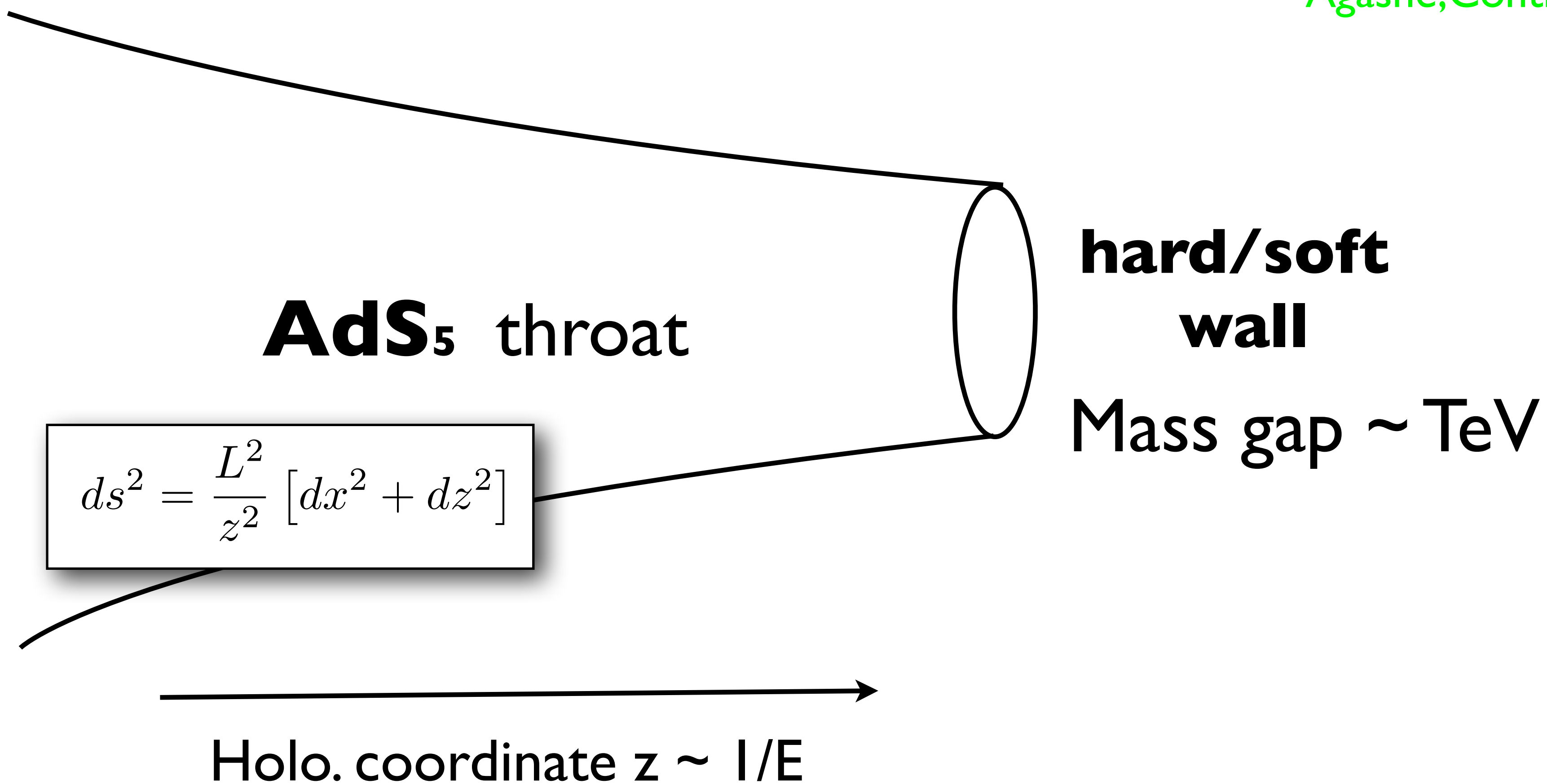
→

Weakly-coupled Gravitational systems in higher-dimensions

Very **useful** to derive properties of **composite states** from studying weakly-coupled fields in warped extra-dimensional models

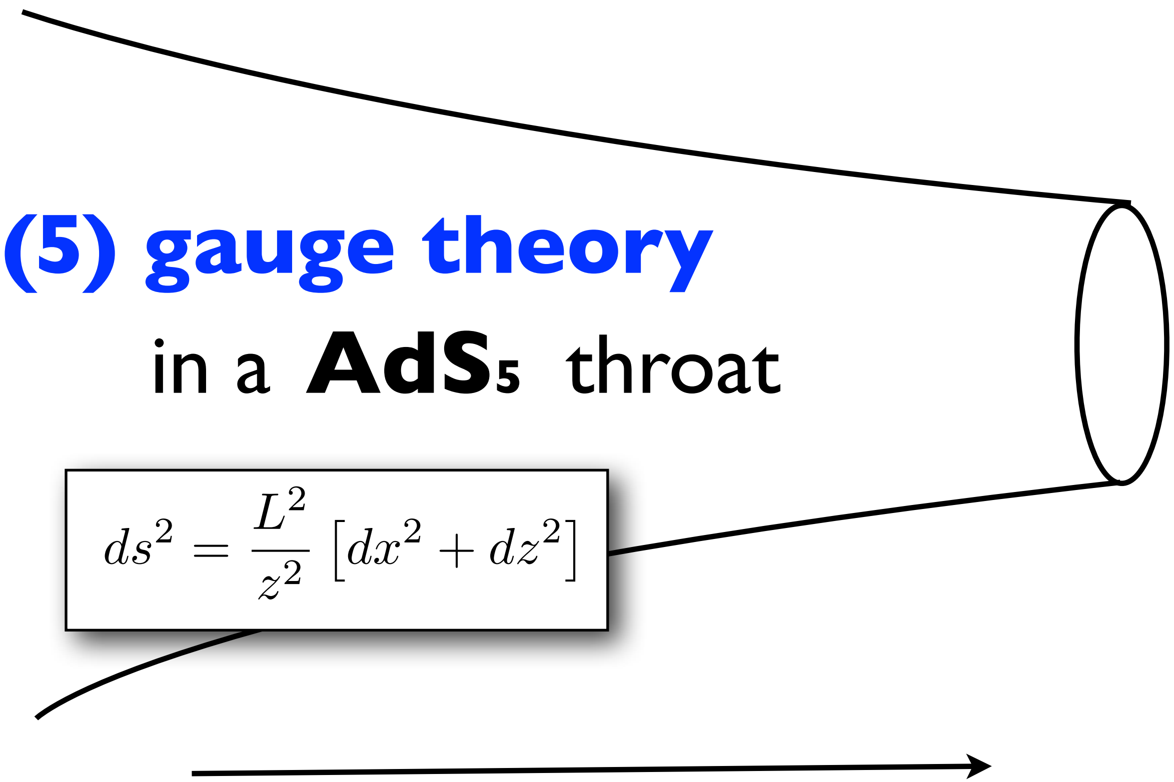
Holographic composite PGB Higgs model

Agashe, Contino, A.P.



Holographic composite PGB Higgs model

Agashe, Contino, A.P.



SO(5) gauge theory

in a **AdS₅** throat

$$ds^2 = \frac{L^2}{z^2}\left[dx^2 + dz^2\right]$$

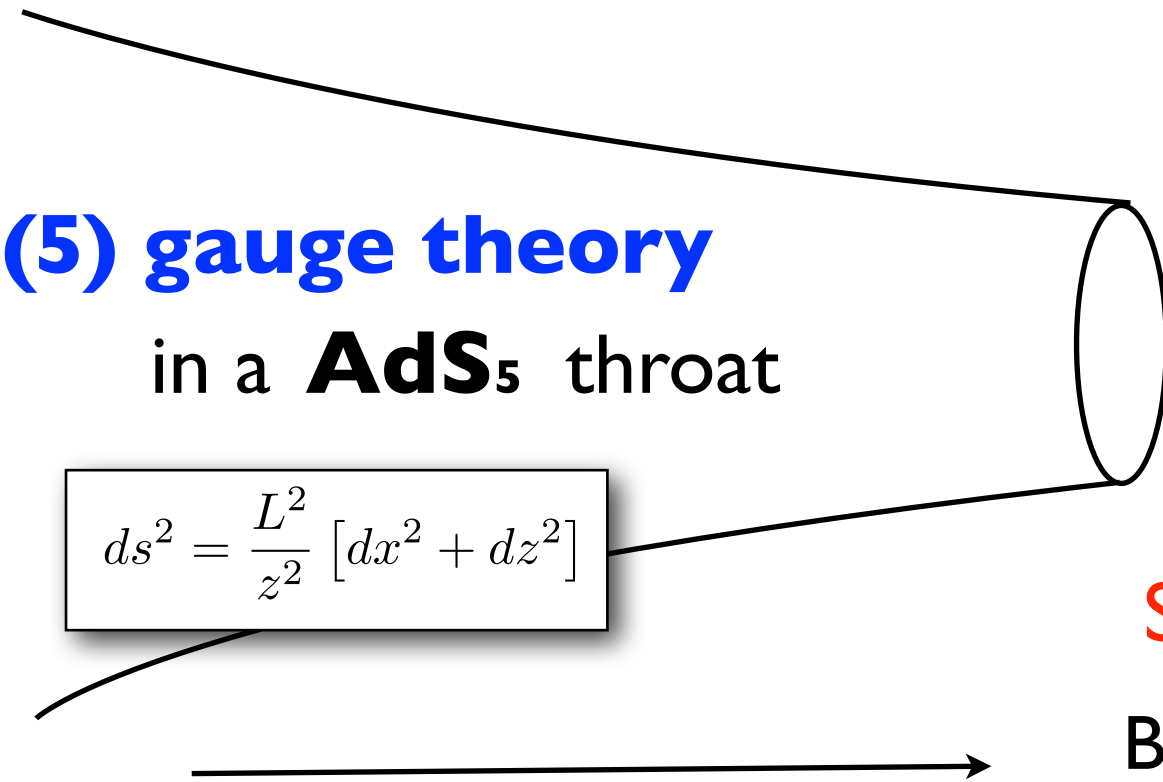
hard/soft wall

Mass gap ~ TeV

Holo. coordinate z ~ 1/E

Holographic composite PGB Higgs model

Agashe,Contino,A.P.



SO(5) gauge theory

in a **AdS₅** throat

$$ds^2 = \frac{L^2}{z^2}\left[dx^2 + dz^2\right]$$

Holo. coordinate z ~ 1/E

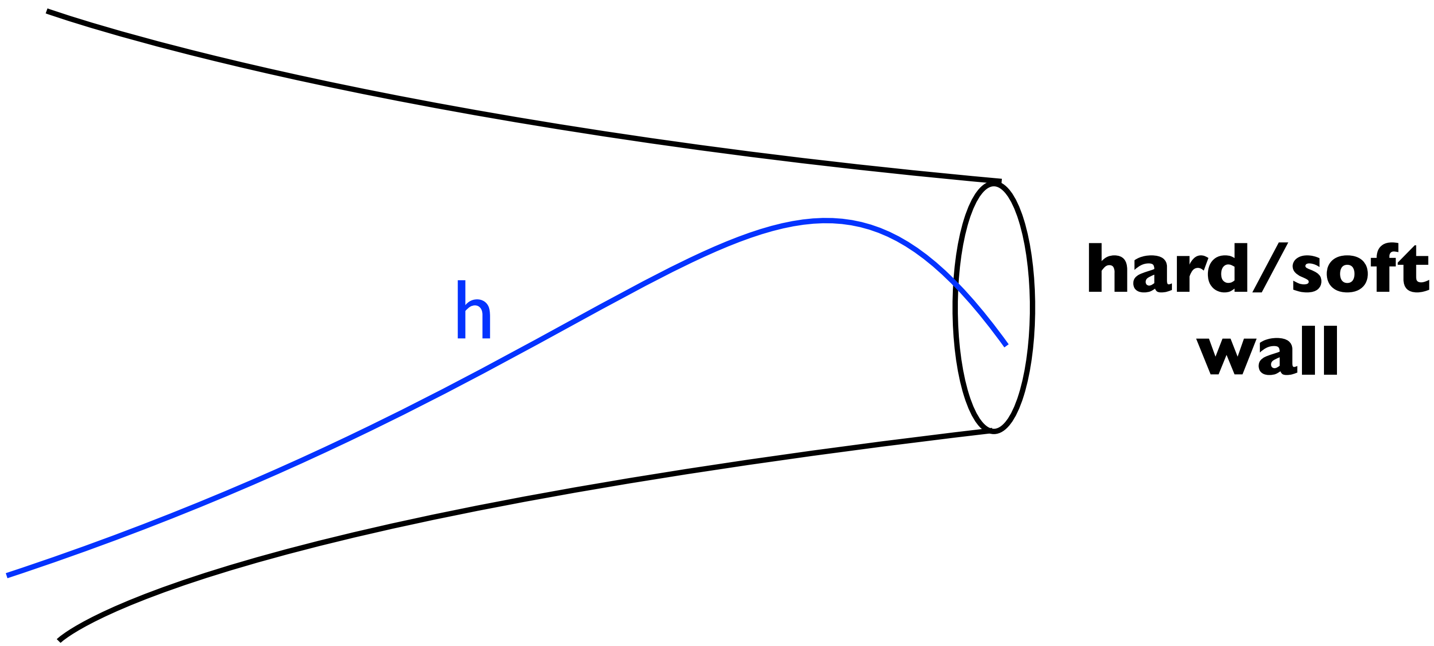
hard/soft wall

Mass gap ~ TeV

Symmetry : **SO(4)**

Breaking of symmetry by boundary conditions

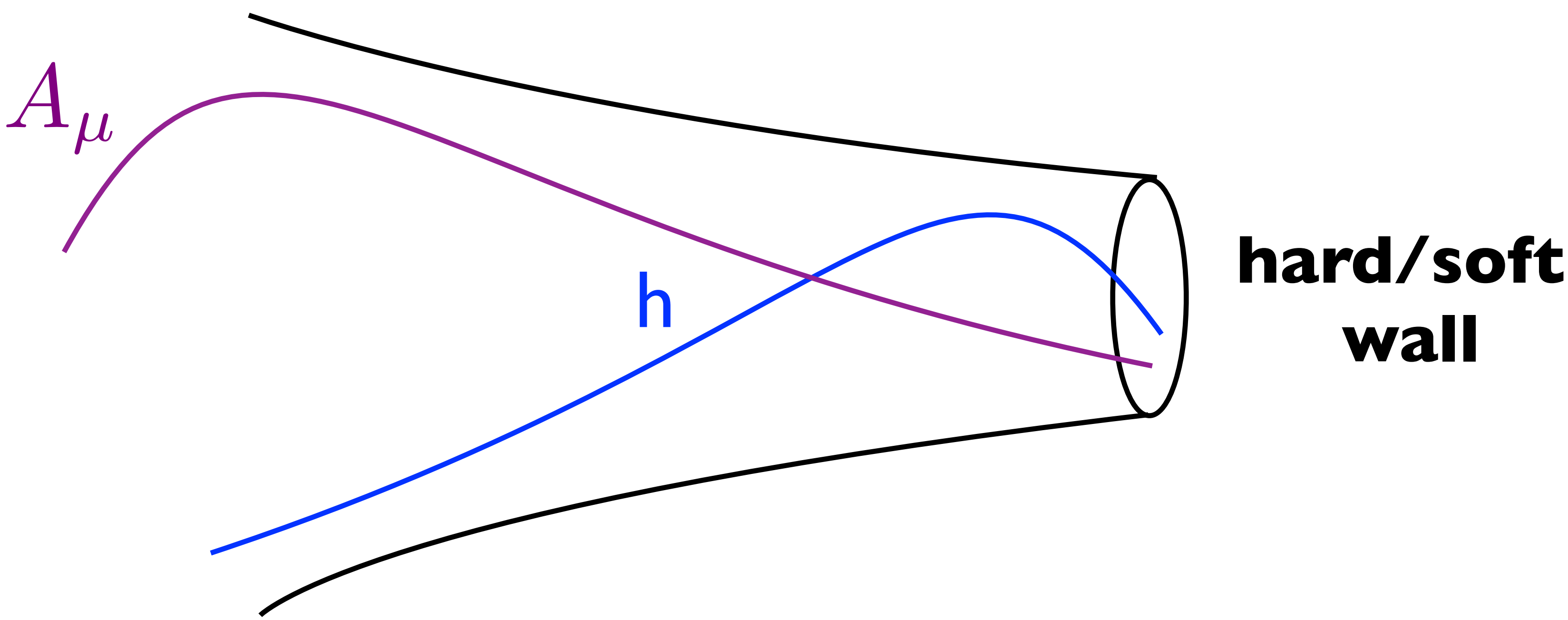
Massless Spectrum



Higgs = 5th component
of the SO(5)/SO(4) gauge bosons
(Gauge-Higgs unification, Hosotani Mechanism,...)

➥ Normalizable modes = **Composite**

Massless Spectrum



A_μ: **SO(4)**~SU(2)xSU(2) Gauge Bosons

➥ Non-normalizable modes

= External states

= Some of them dynamical (SU(2))

Achieve, as in Randall-Sundrum models, by a brane at z~0

What about fermions?
(Main difficulty in composite models)

The fermionic sector: We have to choose the bulk symmetry representation of the fermions and b.c. giving only the 4D massless spectrum of the SM

Up-quark sector: $\mathbf{5}_{2/3}$ of $\mathrm{SO}(5)\times\mathrm{U}(1)_X$.

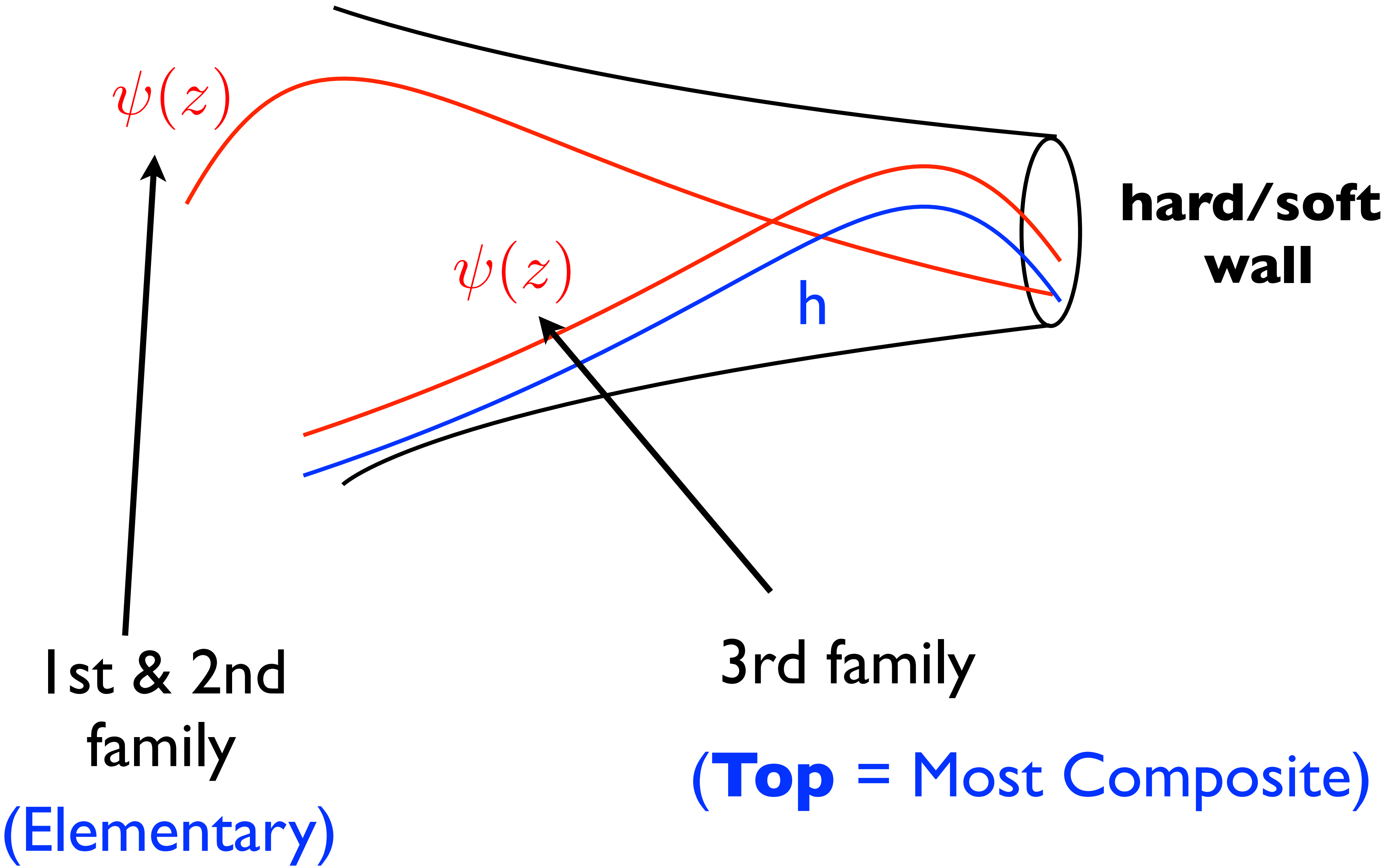
$$\xi_q = (\Psi_{q\,L}\ ,\Psi_{q\,R}) = \begin{bmatrix} (\mathbf{2},\mathbf{2})^{\mathbf{q}}_{\mathbf{L}} = \begin{bmatrix} q'_L(-+) \\ q_L(++) \end{bmatrix} & , & (\mathbf{2},\mathbf{2})^{\mathbf{q}}_{\mathbf{R}} = \begin{bmatrix} q'_R(+-) \\ q_R(--) \end{bmatrix} \\ (\mathbf{1},\mathbf{1})^{\mathbf{q}}_{\mathbf{L}}(--) & , & (\mathbf{1},\mathbf{1})^{\mathbf{q}}_{\mathbf{R}}(++) \end{bmatrix}$$

$$\xi_u = (\Psi_{u\,L}\ ,\Psi_{u\,R}) = \begin{bmatrix} (\mathbf{2},\mathbf{2})^{\mathbf{u}}_{\mathbf{L}}(+-) & , & (\mathbf{2},\mathbf{2})^{\mathbf{u}}_{\mathbf{R}}(-+) \\ (\mathbf{1},\mathbf{1})^{\mathbf{u}}_{\mathbf{L}}(-+) & , & (\mathbf{1},\mathbf{1})^{\mathbf{u}}_{\mathbf{R}}(+-) \end{bmatrix},$$

IR-bound. mass:

$$\widetilde{m}_u\,\overline{(\mathbf{2},\mathbf{2})}^{\mathbf{q}}_{\mathbf{L}}(\mathbf{2},\mathbf{2})^{\mathbf{u}}_{\mathbf{R}} + \widetilde{M}_u\,\overline{(\mathbf{1},\mathbf{1})}^{\mathbf{q}}_{\mathbf{R}}(\mathbf{1},\mathbf{1})^{\mathbf{u}}_{\mathbf{L}} + h.c.$$

Simple geometric approach to fermion masses



4D CFT Interpretation

Contino,AP

SM fermions Ψ are linearly coupled to a CFT operator:

$$\mathcal{L} = \lambda\,\Psi \cdot \mathcal{O}_\Psi + \mathcal{L}_{\rm CFT}$$

$$\mathrm{Dim}[\mathcal{O}_\Psi] = \frac{3}{2} + |M_\Psi + \frac{1}{2}|$$

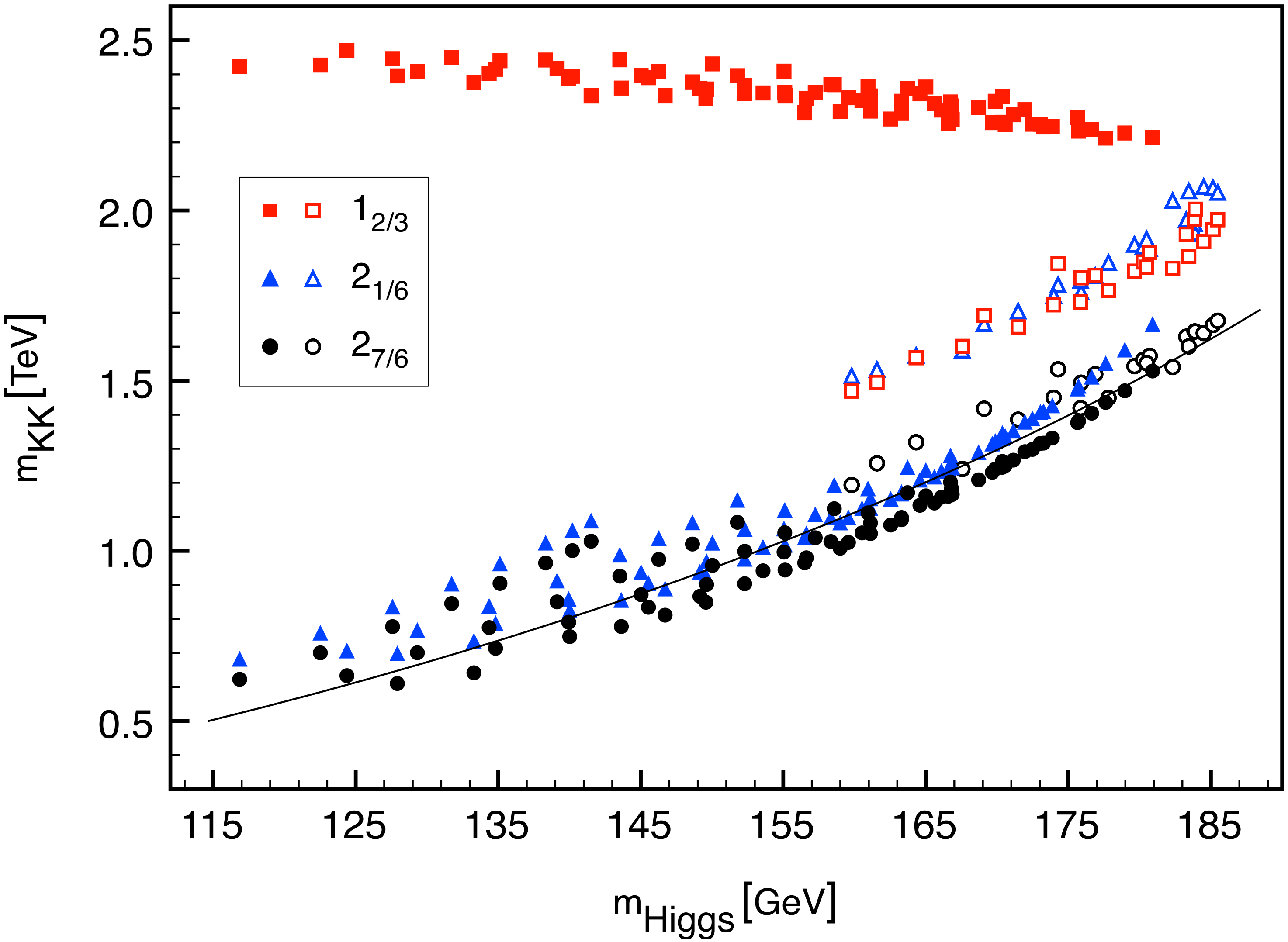
5D mass

$$M_\Psi \geq 1/2 \rightarrow \gamma_\lambda \geq 0$$ Irrelevant coupling

$$|M_\Psi| < 1/2 \rightarrow \gamma_\lambda < 0$$ Relevant coupling

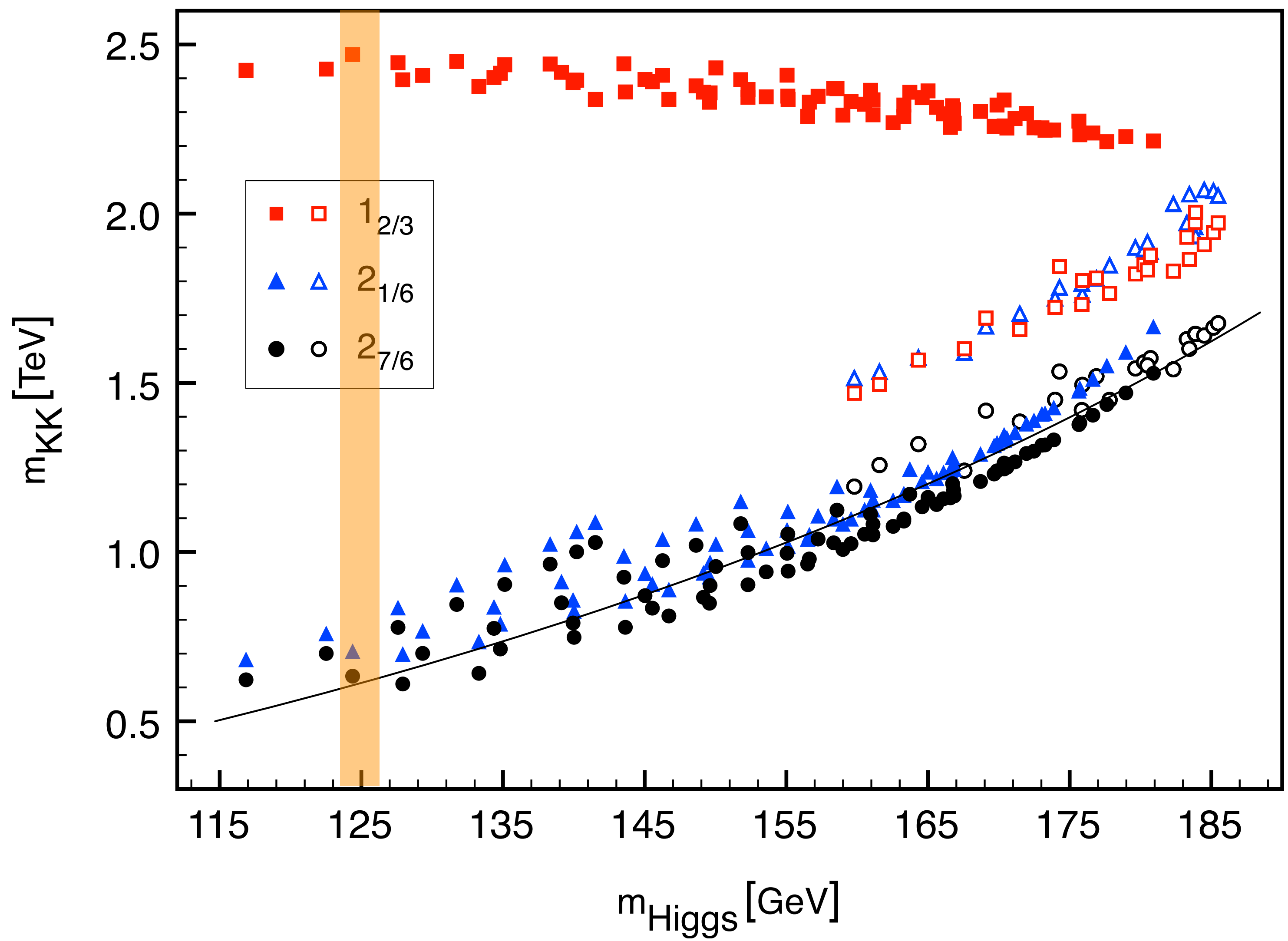
$m_\rho = 2.5$ TeV , $f = 500$ GeV

Contino,DaRold,AP 07



$m_\rho = 2.5$ TeV , $f = 500$ GeV

Contino, DaRold, AP 07



For a 125 GeV Higgs, the fermionic **resonances** of the top are lighter ~ 600 GeV

Why this correlation?

$$m_h^2 \sim \frac{N_c}{\pi^2}\frac{m_t^2}{f^2}m_Q^2 \sim (125\ \mathrm{GeV})^2\left(\frac{m_Q}{700\ \mathrm{GeV}}\right)^2$$

But why the model can accommodate light resonances?

Is it natural?

Why this correlation?

$$m_h^2 \sim \frac{N_c}{\pi^2}\frac{m_t^2}{f^2} m_Q^2 \sim (125\ \mathrm{GeV})^2 \left(\frac{m_Q}{700\ \mathrm{GeV}}\right)^2$$

But why the model can accommodate light resonances?

Is it natural? ***Yes***

AdS/CFT dictionary: $\mathrm{Dim}[\mathcal{O}_\Psi] = \frac{3}{2} + |M_\Psi + \frac{1}{2}|$

$$M_\Psi = -1/2 \quad \rightarrow \quad \mathrm{Dim}[\mathcal{O}_\Psi] = 3/2$$

5D mass:
free parameter

becomes a free field ~ decouple from the CFT

➥ in this limit, new light states

Why this correlation?

$$m_h^2 \sim \frac{N_c}{\pi^2}\frac{m_t^2}{f^2}m_Q^2 \sim (125\ \mathrm{GeV})^2\left(\frac{m_Q}{700\ \mathrm{GeV}}\right)^2$$

But why the model can accommodate light resonances?

Is it natural? ***Yes***

The more we localize the top towards the IR boundary,
the more composite it is

If fully composite, it must come in full reps of SO(5):
➥ there must be extra massless partners

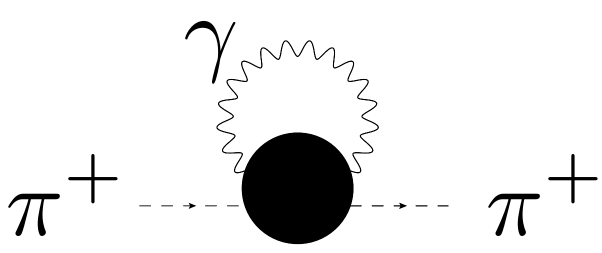
Simpler derivation of the connection:
Light Higgs - Light Resonance

Simpler derivation of the connection:
Light Higgs - Light Resonance

- Deconstruction: Matsedonskyi,Panico,Wulzer; Redi,Tesi 12
- "Weinberg Sum Rules": Marzocca,Serone,Shu; AP, Riva 12

  ➥ As Das,Guralnik,Mathur,Low,Young 67
  for the charged pion mass:

$$m^2_{\pi^+} - m^2_{\pi^0} \simeq \frac{3\alpha}{2\pi} m^2_\rho \log 2 \simeq (37\ \mathrm{MeV})^2$$



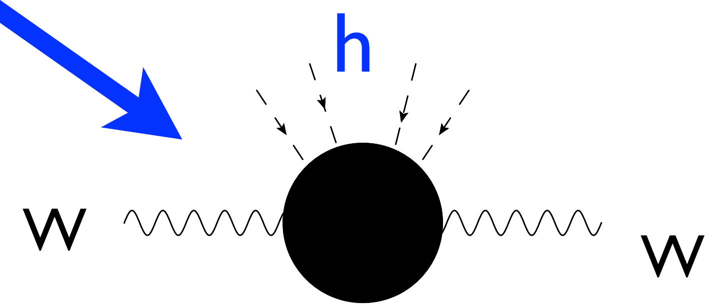
Exp. $(35\ \mathrm{MeV})^2$

quite successful!

Higgs potential

Gauge contribution (limit g'=0):

$$V(h) = \frac{9}{2}\int \frac{d^4p}{(2\pi)^4}\,\log \Pi_W$$



Encode the strong-sector contribution
to the gauge propagator
in the h-background

$$\Pi_W \simeq \frac{p^2}{g^2} + \frac{\sin^2 h/f}{2}\left[\langle J_{\hat a} J_{\hat a}\rangle - \langle J_a J_a\rangle\right]$$

Broken and **Conserved**
current-current correlators of the strong sector

Easy derivation using **spurion techniques**:

$$\mathcal{L} = \mathcal{L}_{\rm strong} + \mathcal{L}_{\rm SM} + J^{\mu}_{\rm strong} W_{\mu}$$

promote them
to an SO(5) rep:
$A_\mu \in$ **10=6+4**

The most general SO(5) invariant action as a function of A_μ after integrating out the strong sector:

$$\mathcal{L}_{\rm eff} = \frac{1}{2} P_{\mu\nu} \Big[\Pi_0(p)\, {\rm Tr}\big[A^\mu A^\nu\big] + \Pi_1(p)\, \Sigma A^\mu A^\nu \Sigma^T \Big] + \mathcal{O}(A^3)$$

parametrizes
the coset SO(5)/SO(4)
(equivalent SO(4) vacuums)

$$\Sigma = \Sigma_0 e^{\Pi/f_\pi} \ , \qquad \Sigma_0 = (0,0,0,0,1)$$

$$\mathcal{L}_{\rm eff} = \frac{1}{2} P_{\mu\nu} \Big[\Pi_0(p)\, \mathrm{Tr}\big[A^\mu A^\nu\big] + \Pi_1(p)\, \Sigma A^\mu A^\nu \Sigma^T \Big] + \mathcal{O}(A^3)$$

$$A^\mu = W^\mu$$

$$\langle \Sigma \rangle = (0,0,0,\sin h/f, \cos h/f)$$

$$\langle \Sigma \rangle = (0,0,0,0,1)$$

$$\Pi_W = \Pi_0 + \frac{\Pi_1}{4} \sin^2 \frac{h}{f}$$

$$\Pi_a = \langle J_a J_a \rangle = \Pi_0$$

$$\Pi_{\hat a} = \langle J_{\hat a} J_{\hat a} \rangle = \Pi_0 + \frac{1}{2} \Pi_1$$

$$\Pi_0 \simeq \frac{p^2}{g^2}$$

$$\Pi_W \simeq \frac{p^2}{g^2} + \frac{\sin^2 h/f}{2} \left[\langle J_{\hat a} J_{\hat a} \rangle - \langle J_a J_a \rangle \right]$$

Higgs Mass from Weinberg Sum Rules

Gauge contribution:

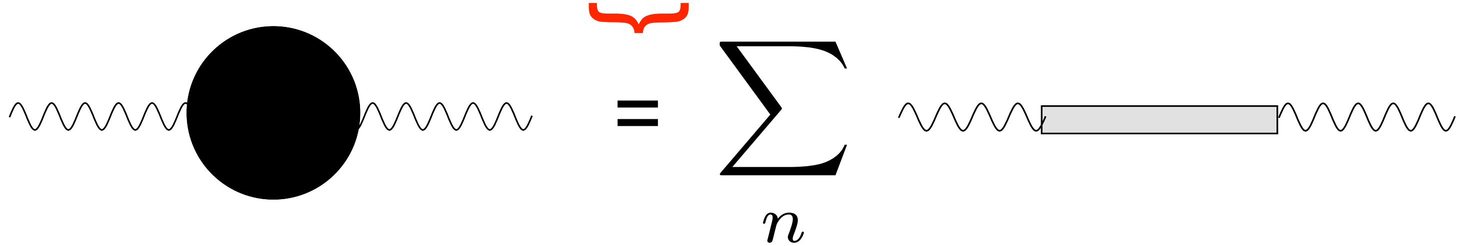
$$V(h) = \frac{9}{2}\int \frac{d^4p}{(2\pi)^4}\,\log \Pi_W \;=\; \frac{1}{2}m_h^2 h^2 + \cdots$$

$$\Rightarrow \quad m_h^2 \simeq \frac{9g^2}{2f^2}\int \frac{d^4p}{(2\pi)^4}\,\frac{\Pi_1(p)}{p^2}$$

$$\Pi_1 = 2\left[\langle J_{\hat a} J_{\hat a}\rangle - \langle J_a J_a\rangle\right] = f^2 + 2p^2\sum_n^{\infty}\frac{F_{a_n}^2}{p^2+m_{a_n}^2} - 2p^2\sum_n^{\infty}\frac{F_{\rho_n}^2}{p^2+m_{\rho_n}^2}$$

Euclidean momentum

Large N



$$F_{a_n} = \langle 0|J_{\hat a}|a_n\rangle \qquad a_n \in \mathbf{4} \text{ of SO(4)}$$

$$F_{\rho_n} = \langle 0|J_a|\rho_n\rangle \qquad \rho_n \in \mathbf{6}$$

Higgs Mass from Weinberg Sum Rules

Gauge contribution:

$$V(h)=\frac{9}{2}\int\frac{d^4p}{(2\pi)^4}\,\log\Pi_W\;=\frac{1}{2}m_h^2h^2+\cdots$$

$$\Rightarrow\quad m_h^2\simeq\frac{9g^2}{2f^2}\int\frac{d^4p}{(2\pi)^4}\frac{\Pi_1(p)}{p^2}$$

$$\Pi_1=2\left[\langle J_{\hat a}J_{\hat a}\rangle-\langle J_aJ_a\rangle\right]=f^2+2p^2\sum_n^\infty\frac{F_{a_n}^2}{p^2+m_{a_n}^2}-2p^2\sum_n^\infty\frac{F_{\rho_n}^2}{p^2+m_{\rho_n}^2}$$

Procedure:

1) Demand convergence of the integral:

$$\lim_{p^2\to\infty}\Pi_1(p)=0\ ,\qquad\qquad \lim_{p^2\to\infty}p^2\Pi_1(p)=0\ ,$$ "Weinberg Sum Rules"

Higgs Mass from Weinberg Sum Rules

Gauge contribution:

$$V(h) = \frac{9}{2}\int \frac{d^4p}{(2\pi)^4} \log \Pi_W \;=\; \frac{1}{2} m_h^2 h^2 + \cdots$$

$$\Rightarrow \quad m_h^2 \simeq \frac{9g^2}{2f^2}\int \frac{d^4p}{(2\pi)^4}\frac{\Pi_1(p)}{p^2}$$

$$\Pi_1 = 2\left[\langle J_{\hat a} J_{\hat a}\rangle - \langle J_a J_a\rangle\right] = f^2 + 2p^2 \sum_n^\infty \frac{F^2_{a_n}}{p^2 + m^2_{a_n}} - 2p^2 \sum_n^\infty \frac{F^2_{\rho_n}}{p^2+m^2_{\rho_n}}$$

Procedure:

1) Demand convergence of the integral:

$$\lim_{p^2\to\infty} \Pi_1(p) = 0\ , \qquad \lim_{p^2\to\infty} p^2 \Pi_1(p) = 0$$

"Weinberg Sum Rules"

$$\left[\langle J_{\hat a} J_{\hat a}\rangle - \langle J_a J_a\rangle\right] \sim \frac{\langle \mathcal{O}\rangle}{p^{d-2}} + \cdots$$

Just from the OPE at large p

$d = \mathrm{Dim}[\mathcal{O}]$

$\Rightarrow$ symmetry breaking operator

$\Rightarrow$ WSR = demand d>4

Higgs Mass from Weinberg Sum Rules

Gauge contribution:

$$V(h) = \frac{9}{2}\int \frac{d^4p}{(2\pi)^4}\,\log \Pi_W \;=\; \frac{1}{2} m_h^2 h^2 + \cdots$$

$$\Rightarrow \quad m_h^2 \simeq \frac{9g^2}{2f^2}\int \frac{d^4p}{(2\pi)^4}\frac{\Pi_1(p)}{p^2}$$

$$\Pi_1 = 2\left[\langle J_{\hat a} J_{\hat a}\rangle - \langle J_a J_a\rangle\right] = f^2 + 2p^2\sum_n^\infty \frac{F_{a_n}^2}{p^2 + m_{a_n}^2} - 2p^2 \sum_n^\infty \frac{F_{\rho_n}^2}{p^2+m_{\rho_n}^2}$$

Procedure:

1) Demand convergence of the integral:

$$\lim_{p^2\to\infty} \Pi_1(p) = 0\,, \qquad \lim_{p^2\to\infty} p^2\Pi_1(p) = 0\,;$$

"Weinberg Sum Rules"

Just from the OPE at large p

e.g. in QCD:

$$\Pi_{LR}(p) = \Pi_V - \Pi_A \to \langle q\bar q\rangle^2/p^4$$

Higgs Mass from Weinberg Sum Rules

Gauge contribution:

$$V(h) = \frac{9}{2}\int \frac{d^4p}{(2\pi)^4}\, \log \Pi_W \;=\; \frac{1}{2} m_h^2 h^2 + \cdots$$

$$\Rightarrow \quad m_h^2 \simeq \frac{9g^2}{2f^2}\int \frac{d^4p}{(2\pi)^4}\frac{\Pi_1(p)}{p^2}$$

$$\Pi_1 = 2\left[\langle J_{\hat{a}} J_{\hat{a}}\rangle - \langle J_a J_a\rangle\right] = f^2 + 2p^2 \sum_n^{\infty} \frac{F_{a_n}^2}{p^2 + m_{a_n}^2} - 2p^2 \sum_n^{\infty} \frac{F_{\rho_n}^2}{p^2 + m_{\rho_n}^2}$$

Procedure:

1) Demand convergence of the integral:

$$\lim_{p^2\to\infty} \Pi_1(p) = 0 \,, \qquad \lim_{p^2\to\infty} p^2\Pi_1(p) = 0$$ "Weinberg Sum Rules"

2) The Correlators are dominated by the lowest resonances (minimal number to satisfy WSR)

Result: two resonances needed: ρ and a_1

$$\Pi_1(p) = \frac{f^2 m_\rho^2 m_{a_1}^2}{(p^2 + m_\rho^2)(p^2 + m_{a_1}^2)}$$

$$\Rightarrow \quad m_h^2 \simeq \frac{9 g^2 m_\rho^2 m_{a_1}^2}{64\pi^2 (m_{a_1}^2 - m_\rho^2)} \log\left(\frac{m_{a_1}^2}{m_\rho^2}\right)$$

Similar result as the electromagnetic contribution to the charged pion mass

Similarly, for the top contribution...

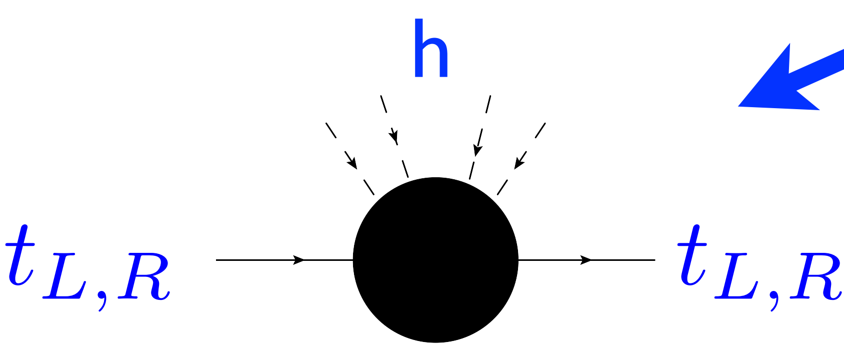
$$\mathcal{L} = \mathcal{L}_{\text{strong}} + \mathcal{L}_{\text{SM}} + J^{\mu}_{\text{strong}} W_{\mu} + \mathcal{O}_{\text{strong}} \cdot \psi_{\text{SM}}$$

we must specify which rep of SO(5)

$$\text{MCHM}_5 \;\equiv\; \text{Rep}[\mathcal{O}] = 5$$

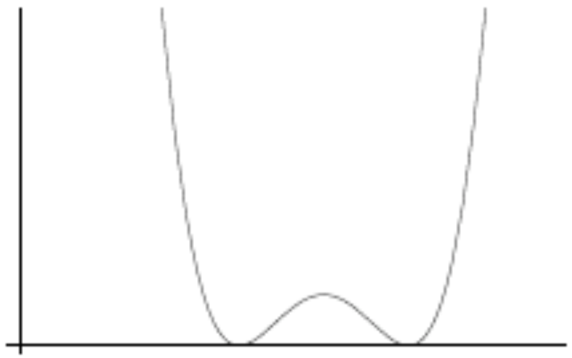
Top contribution to the Higgs potential:

$$V(h) = -2N_c \int \frac{d^4p}{(2\pi)^4} \log\left[-p^2\left(\Pi^{t_L}\Pi^{t_R}\right) - |\Pi^{t_L t_R}|^2\right]$$



Encode the strong sector contribution
to the top propagator
in the h-background

$$V(h) = -2N_c \int \frac{d^4p}{(2\pi)^4} \log\left[-p^2\left(\Pi^{t_L}\Pi^{t_R}\right) - |\Pi^{t_L t_R}|^2\right]$$



$$= -m^2h^2 + \lambda_h h^4 + \cdots$$

Triggers EWSB!

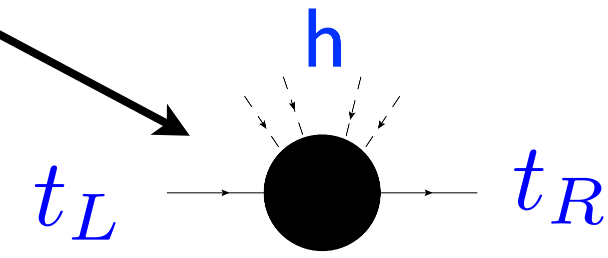
Higgs mass contribution:

$$m_h^2 \simeq \frac{8N_c v^2}{f^4} \int \frac{d^4p}{(2\pi)^4} \left[\frac{|M_1^t|^2}{p^2} + \frac{1}{4} \left(\Pi_1^{t_L}\right)^2 + \left(\Pi_1^{t_R}\right)^2 \right]$$

Higgs mass contribution:

$$m_h^2 \simeq \frac{8N_c v^2}{f^4}\int \frac{d^4p}{(2\pi)^4}\left[\frac{|M_1^t|^2}{p^2}+\frac{1}{4}\left(\Pi_1^{t_L}\right)^2+\left(\Pi_1^{t_R}\right)^2\right]$$

responsible of the top mass



$$\left\{\begin{array}{l}\Pi_1^{t_L}(p)=\Pi^L_{Q_1}(p)-\Pi^L_{Q_4}(p)\,,\\ \Pi_1^{t_R}(p)=\Pi^R_{Q_1}(p)-\Pi^R_{Q_4}(p)\,,\\ M_1^t(p)=M_{Q_1}(p)-M_{Q_4}(p)\,.\end{array}\right.$$

$\hookrightarrow$ fermion-fermion correlators

5=4+1 of SO(4):

$Q_1 \in \mathbf{1}$

$Q_4 \in \mathbf{4}$

Large N: $\Pi^L_{Q_4}(p)=\sum_n \frac{|F^L_{Q_4^{(n)}}|^2}{p^2+m^2_{Q_4^{(n)}}}\,,\qquad \Pi^L_{Q_1}(p)=\sum_n \frac{|F^L_{Q_1^{(n)}}|^2}{p^2+m^2_{Q_1^{(n)}}}\,,$

similarly for $\Pi^R_{Q_{4,1}}$ with the replacement $L\to R$, while

$$M_{Q_4}(p)=\sum_n \frac{F^L_{Q_4^{(n)}}F^{R*}_{Q_4^{(n)}}m_{Q_4^{(n)}}}{p^2+m^2_{Q_4^{(n)}}}\,,\qquad M_{Q_1}(p)=\sum_n \frac{F^L_{Q_1^{(n)}}F^{R*}_{Q_1^{(n)}}m_{Q_1^{(n)}}}{p^2+m^2_{Q_1^{(n)}}}\,.$$

Demanding again WSR:

$$\lim_{p\to\infty} M_1^t(p) \;=\; 0$$

$$\lim_{p\to\infty} p^n \Pi_1^{t_{L,R}}(p) = 0 \; (n = 0, 2)$$

... being fulfilled with the minimal set of resonances, two in this case, Q_1 and Q_4:

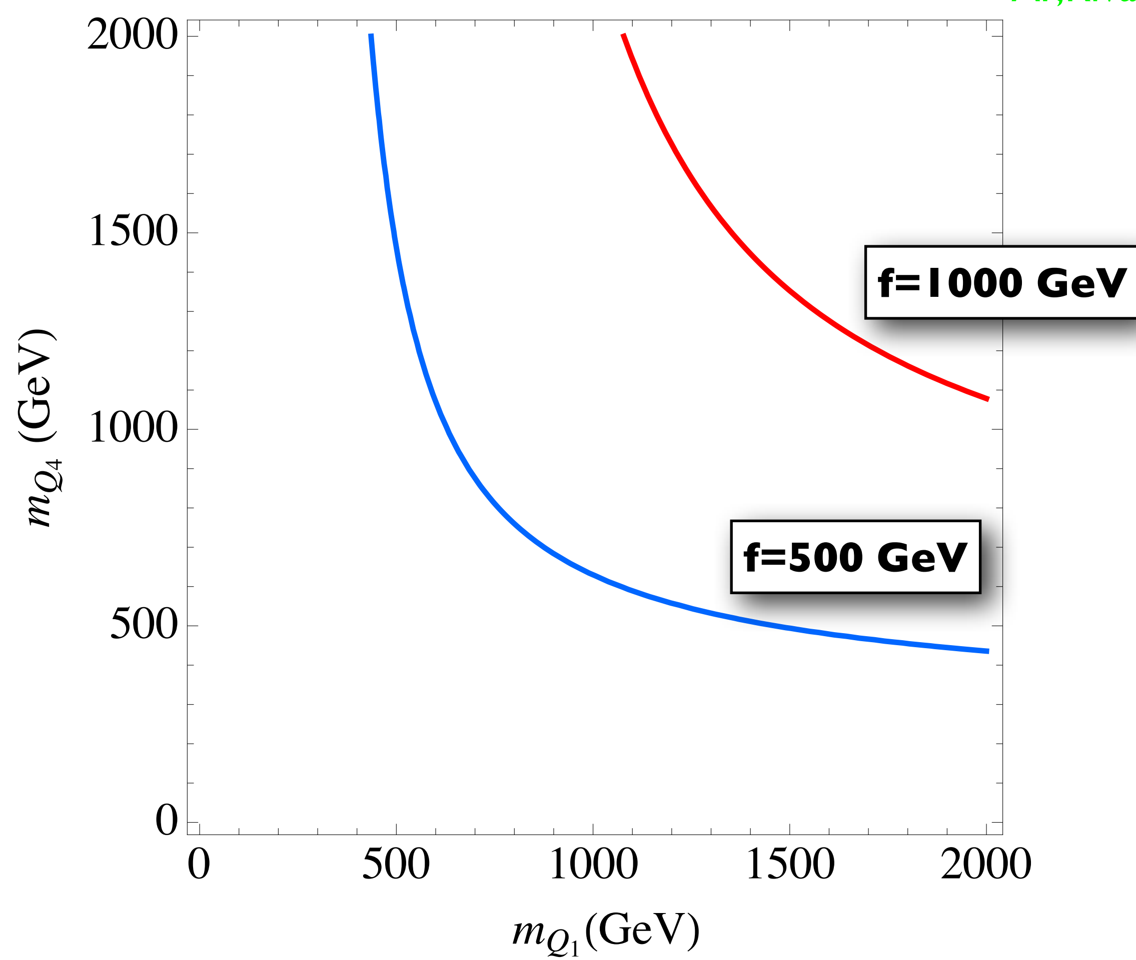
$$\begin{aligned} \Pi_1^{t_{L,R}} &= |F_{Q_4}^{L,R}|^2 \frac{(m_{Q_4}^2 - m_{Q_1}^2)}{(p^2 + m_{Q_4}^2)(p^2 + m_{Q_1}^2)} \;, \\ M_1^t(p) &= |F_{Q_4}^{L} F_{Q_4}^{R*}| \frac{m_{Q_4} m_{Q_1} (m_{Q_4} - m_{Q_1} e^{i\theta})}{(p^2 + m_{Q_4}^2)(p^2 + m_{Q_1}^2)} \left(1 + \frac{p^2}{m_{Q_4} m_{Q_1}} \frac{m_{Q_1} - m_{Q_4} e^{i\theta}}{m_{Q_4} - m_{Q_1} e^{i\theta}}\right) \end{aligned}$$

WSR + Minimal set of resonances (Q_1 and Q_4) + proper EWSB

$$m_h^2 \simeq \frac{N_c}{\pi^2}\left[\frac{m_t^2}{f^2}\frac{m_{Q_4}^2 m_{Q_1}^2}{m_{Q_1}^2 - m_{Q_4}^2}\log\left(\frac{m_{Q_1}^2}{m_{Q_4}^2}\right)\right]$$

AP,Riva 12

For a 125 GeV Higgs:



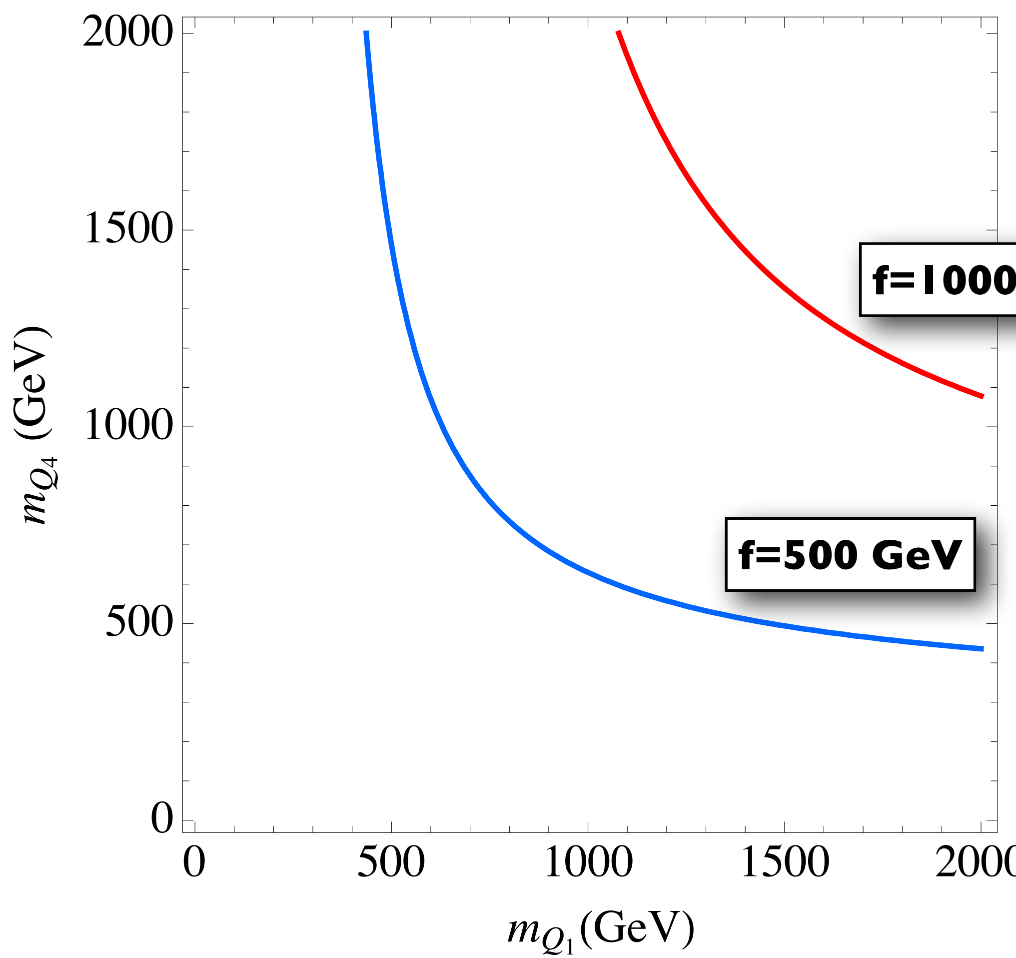
WSR + Minimal set of resonances (Q_1 and Q_4)

+ proper EWSB

$$m_h^2 \simeq \frac{N_c}{\pi^2}\left[\frac{m_t^2}{f^2}\frac{m_{Q_4}^2 m_{Q_1}^2}{m_{Q_1}^2 - m_{Q_4}^2}\log\left(\frac{m_{Q_1}^2}{m_{Q_4}^2}\right)\right]$$

AP,Riva 12

For a 125 GeV Higgs:



Fermionic resonances below 700 GeV

What about other representations?

$$\mathcal{L} = \mathcal{L}_{\rm strong} + \mathcal{L}_{\rm SM} + J^{\mu}_{\rm strong} W_{\mu} + \mathcal{O}_{\rm strong} \cdot \psi_{\rm SM}$$

$$\mathrm{MCHM}_{10} \;\equiv\; \mathrm{Rep}[\mathcal{O}] = 10$$

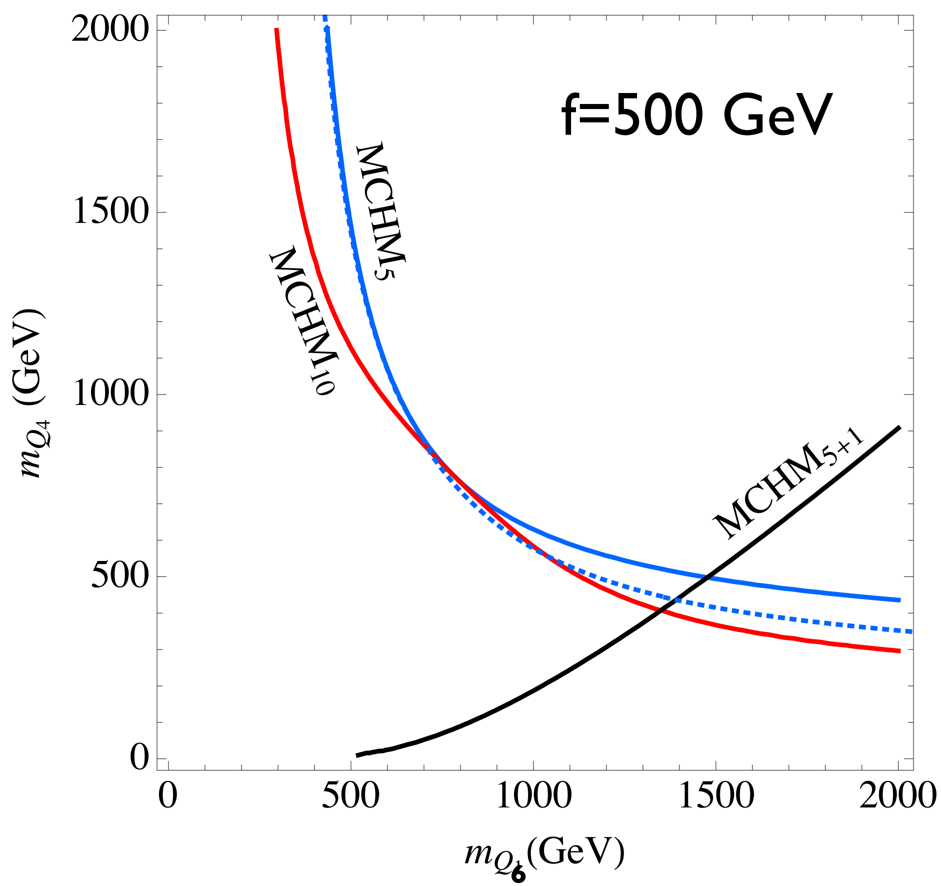
10=4+6 under SO(4)

What about other representations?

$$\mathcal{L} = \mathcal{L}_{\rm strong} + \mathcal{L}_{\rm SM} + J^{\mu}_{\rm strong} W_\mu + \mathcal{O}_{\rm strong} \cdot \psi_{\rm SM}$$

$$\mathrm{MCHM}_{10} \equiv \mathrm{Rep}[\mathcal{O}] = 10$$

Demanding
WSR with minimal set
of resonances (Q_1 and Q_6)
+ proper EWSB:



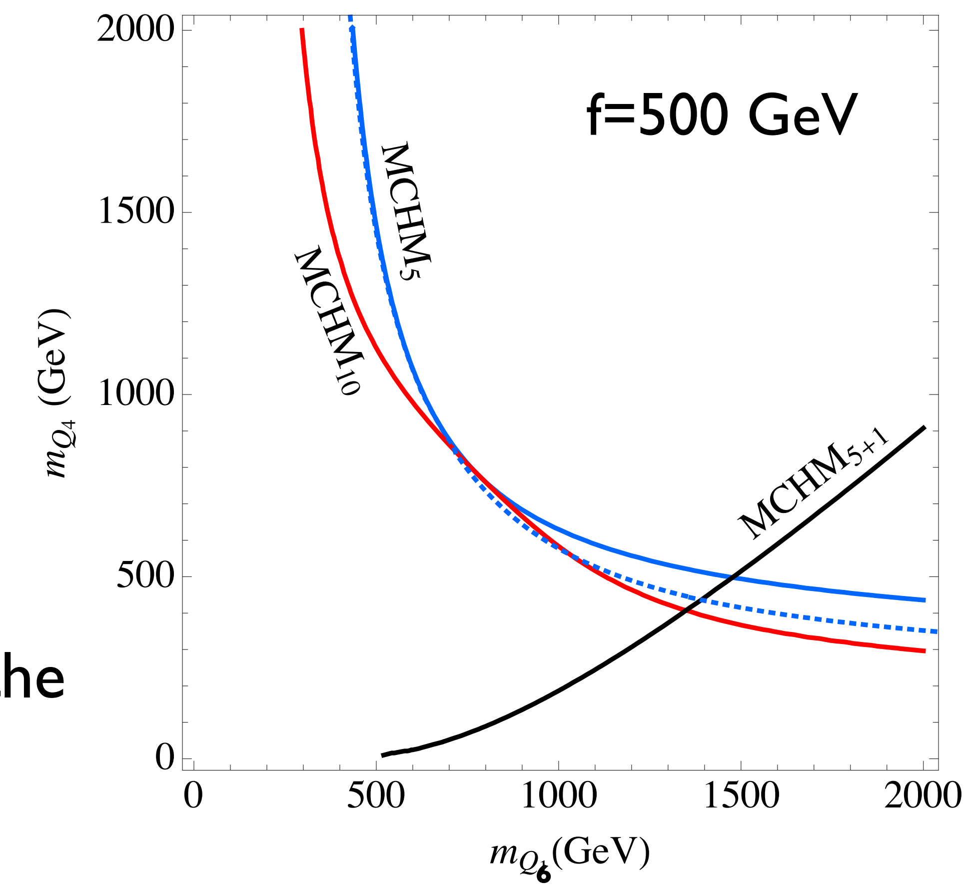
AP,Riva 12

What about other representations?

$$\mathcal{L} = \mathcal{L}_{\rm strong} + \mathcal{L}_{\rm SM} + J^{\mu}_{\rm strong} W_{\mu} + \mathcal{O}_{\rm strong} \cdot \psi_{\rm SM}$$

$$\mathrm{MCHM}_{10} \equiv \mathrm{Rep}[\mathcal{O}] = 10$$

Demanding
WSR with minimal set
of resonances (Q_1 and Q_6)
+ proper EWSB:



In most of the models
always an upper bound on the
resonance mass < TeV,
but exceptions exist!

AP,Riva 12

If the 125 GeV Higgs is composite...

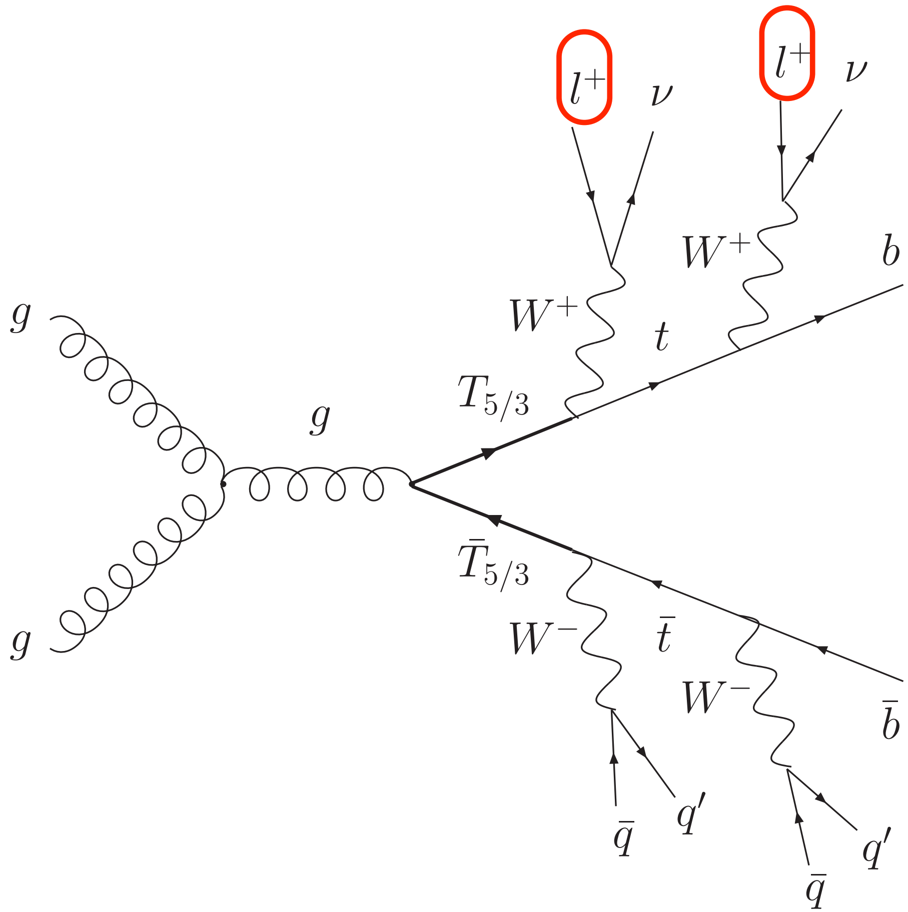
we must find at the LHC

color vector-like fermions in the **4** or **1** rep. of SO(4):

EM charges: 5/3,2/3,-1/3

Color vector-like fermions with charge 5/3:

If this fermion is light, it can be double produced:

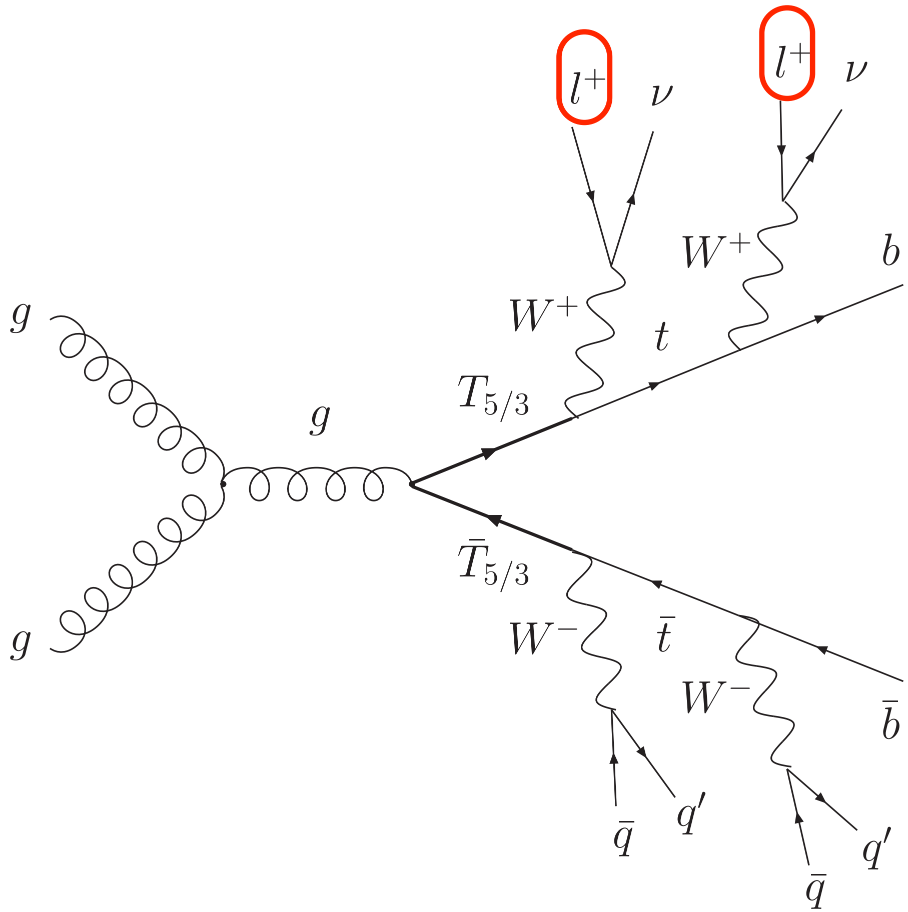


same-sign di-leptons

Contino,Servant
Mrazek, Wulzer
Aguilar-Saavedra,
Dissertori, Furlan,Moorgat,Nef

Color vector-like fermions with charge 5/3:

If this fermion is light, it can be double produced:



same-sign di-leptons

ATLAS-CONF-2012-130:

$$M_{T_{5/3}} \gtrsim 700 \text{ GeV}$$

Contino,Servant
Mrazek, Wulzer
Aguilar-Saavedra,
Dissertori, Furlan,Moorgat,Nef

Higgs couplings

Composite PGB Higgs couplings

Couplings dictated by symmetries (as in the QCD chiral Lagrangian)

Giudice,Grojean,AP,Rattazzi 07
AP,Riva 12

$$\frac{g_{hWW}}{g_{hWW}^{\rm SM}} = \sqrt{1-\frac{v^2}{f^2}}$$

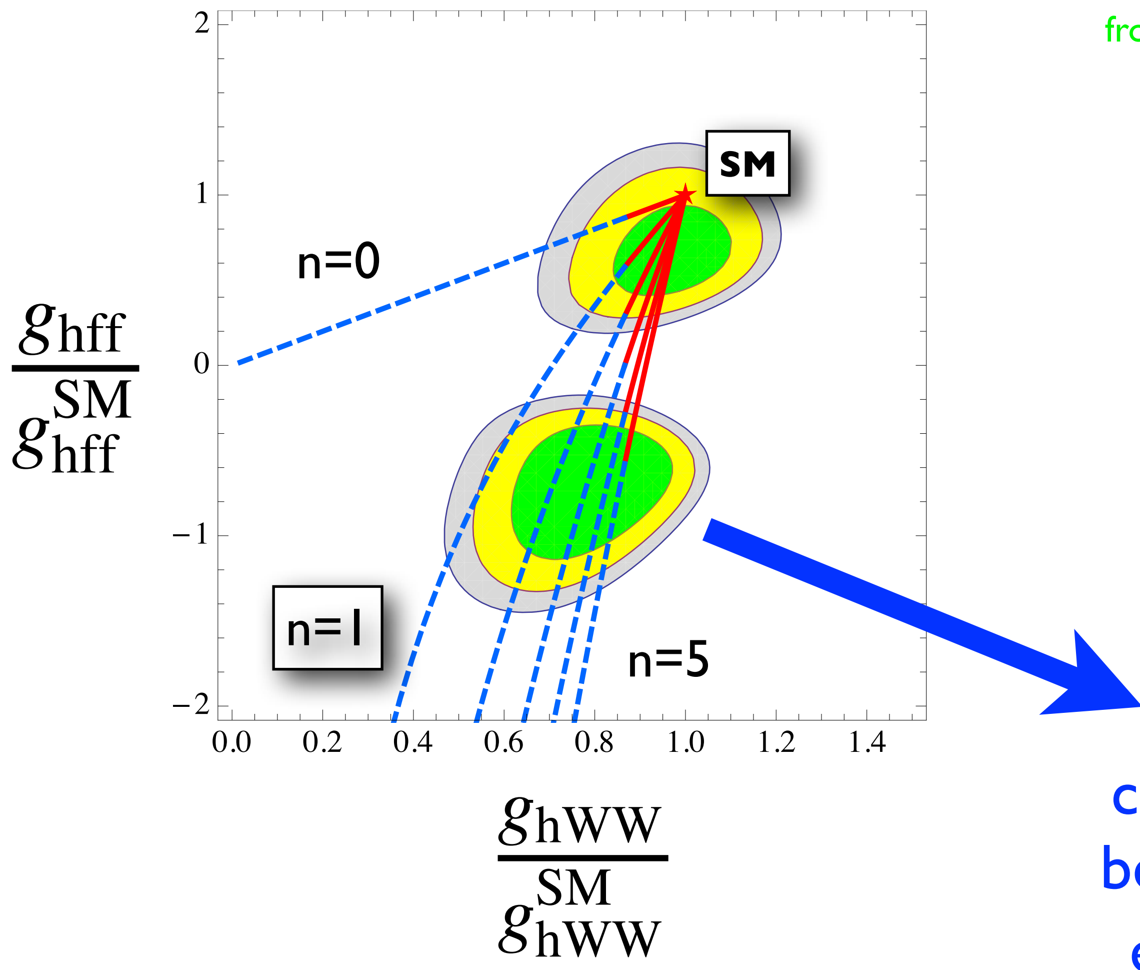
f = Decay-constant of the PGB Higgs

$$\frac{g_{hff}}{g_{hff}^{\rm SM}} = \frac{1-(1+n)\frac{v^2}{f^2}}{\sqrt{1-\frac{v^2}{f^2}}}$$

$$n = 0, 1, 2, \dots$$

$\mathrm{MCHM}_{5,10}$

small deviations on the h$\gamma\gamma$(gg)-coupling due to the Goldstone nature of the Higgs



from, e.g., Montull,Riva
arXiv:1207.1716

Allowed area where constructive interference between top and W loops enhances the $\gamma\gamma$ channel

Fit slightly better than the SM!

Other symmetry-breaking patterns $G \to H$:

G	H	PGB
SO(5)	SO(4)	4=(2,2)
SO(6)	SO(5)	5=(2,2)+(1,1)
	O(4)xO(2)	8=(2,2)+(2,2)
SO(7)	SO(6)	6=(2,2)+(1,1)+(1,1)
	G_2	7=(1,3)+(2,2)
...	...	...

Other symmetry-breaking patterns G→H:

G	H	PGB
SO(5)	SO(4)	4=(2,2)
SO(6)	SO(5)	5=(2,2)+(1,1)
	O(4)xO(2)	8=(2,2)+(2,2)
SO(7)	SO(6)	6=(2,2)+(1,1)+(1,1)
	G_2	7=(1,3)+(2,2)
...	...	...

One doublet
+ Singlet

Gripaios, AP, Riva, Serra

SB of minimal TC:
Just by replacing
$SU(3)_c$ by $SU(2)_c$

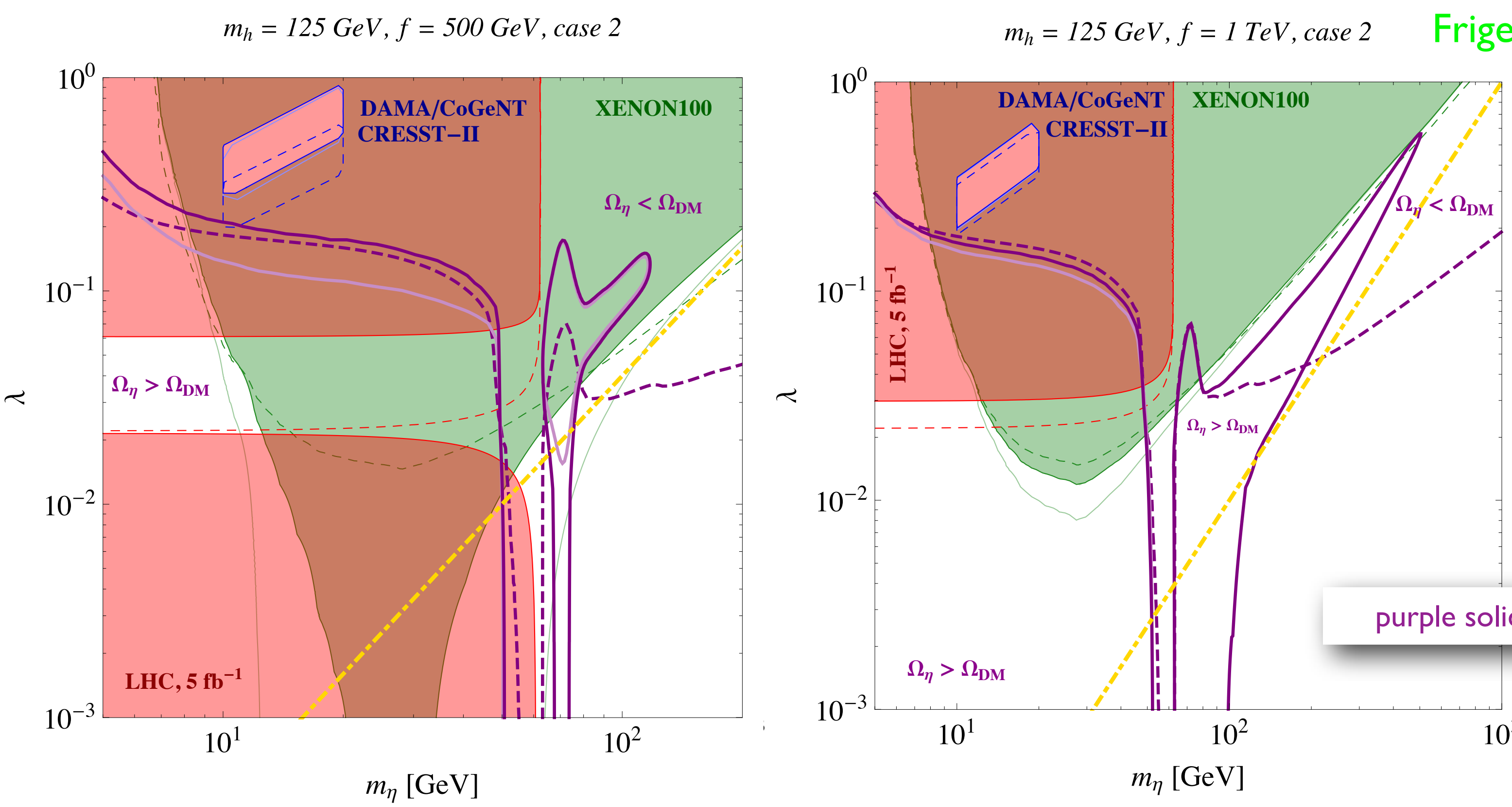
Galloway, Evans, Luty, Tacchi 10

If SO(6)→SO(5) breaking pattern: Doublet h +Singlet η

New player in the game:

- Mass of eta very model-dependent: depends on how the SO(2) ⊂ SO(6) is explicitly broken
- If extra parity $\eta \to -\eta$ (e.g. if O(6)): η can be Dark Matter !

Frigerio,AP,Riva,Urbano 12



purple solid line: proper relic density

Main impact in Higgs physics:

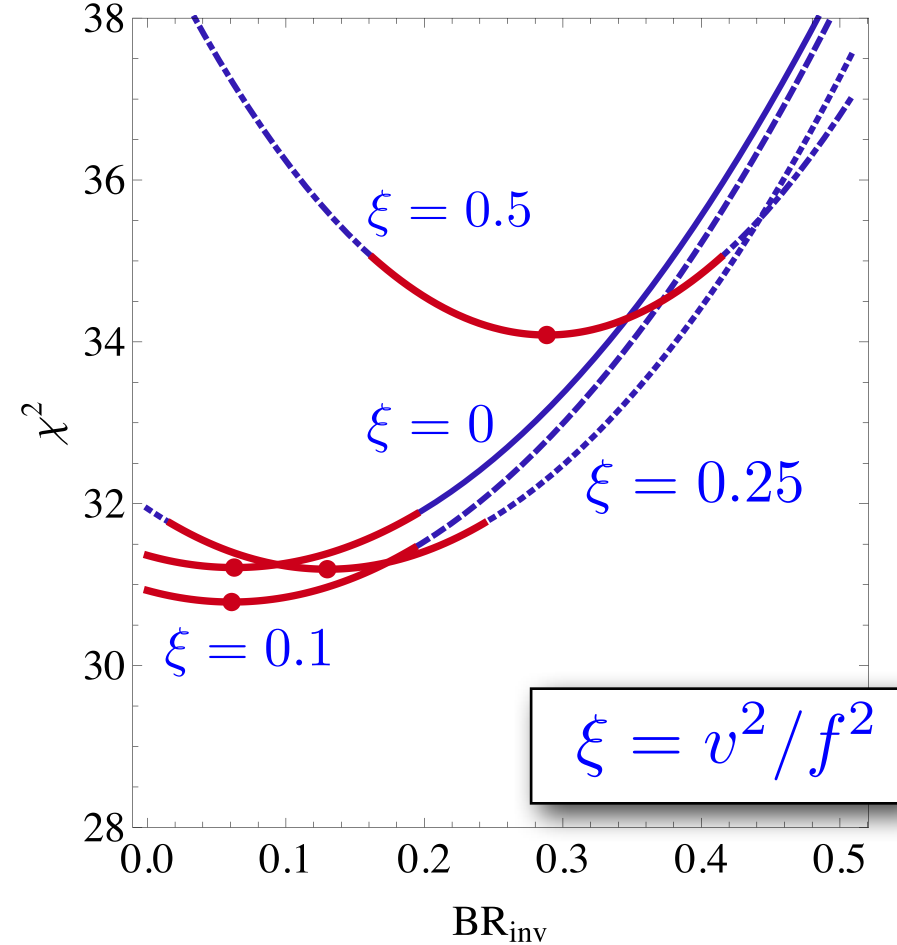
If lighter than h, possibility for an "invisible" decay width for h:

$$h \to \eta\eta$$

If not stable:

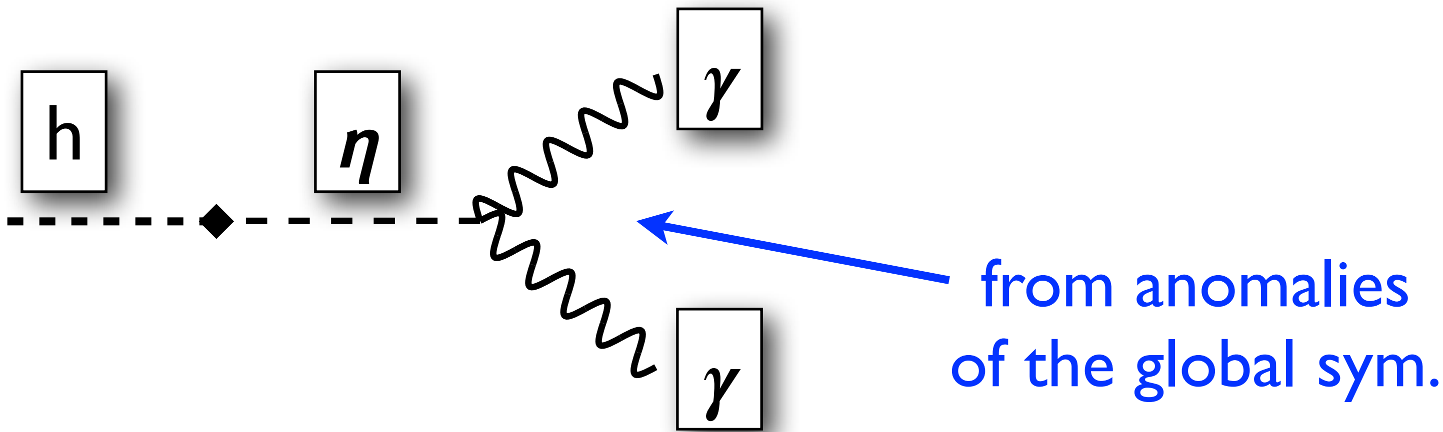
$$h \to \eta\eta \to b\bar{b}b\bar{b}$$

from, e.g., Montull,Riva
arXiv:1207.1716

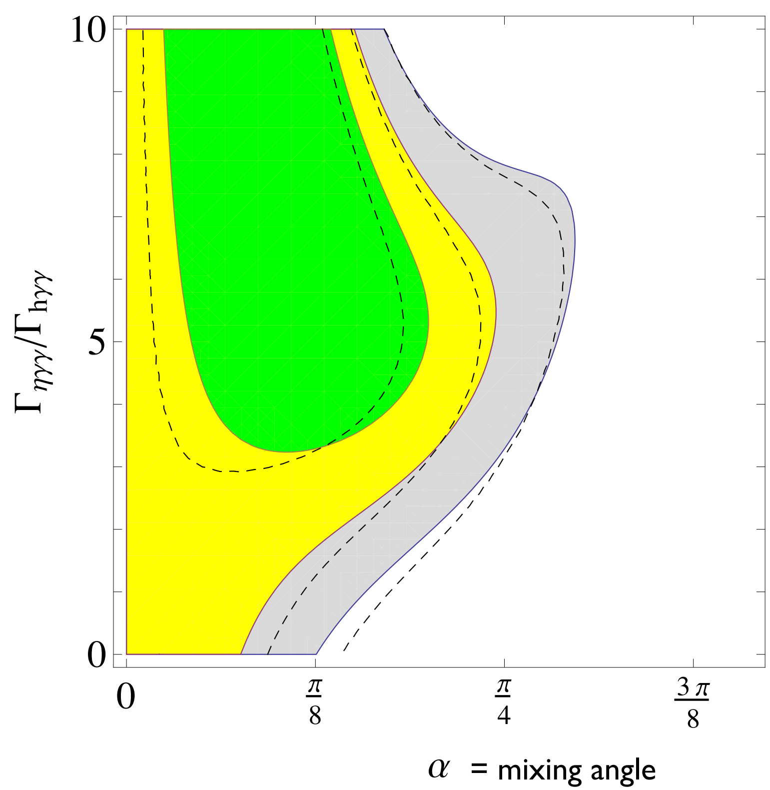


Not disfavored!

If h and eta mix, possible enhancement of the decay to $\gamma\gamma$



It can improve the fit!



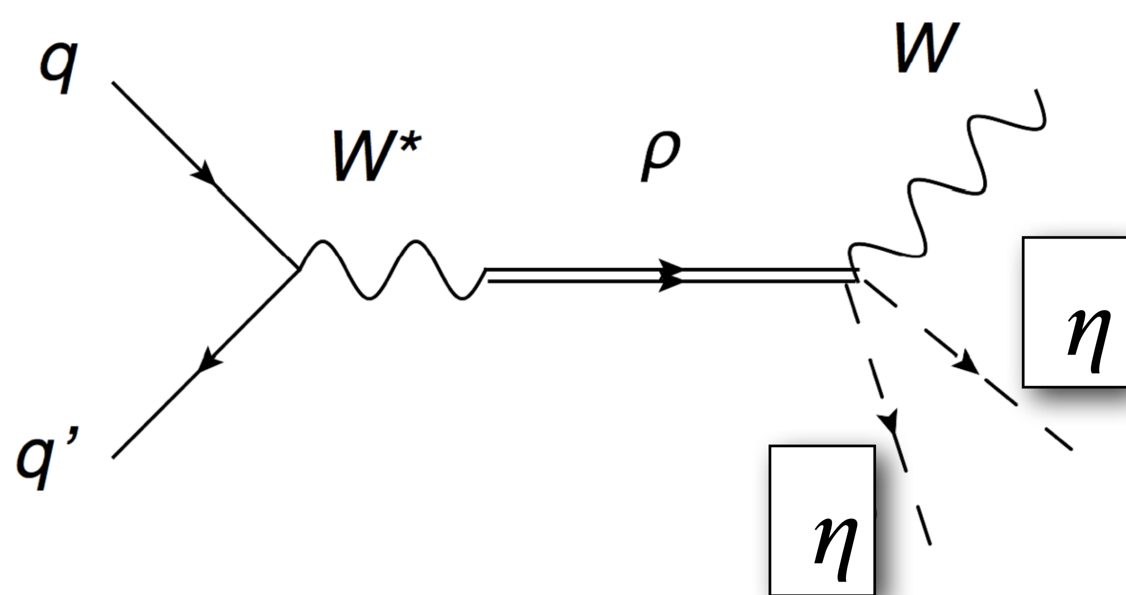
from, e.g., Montull,Riva
arXiv:1207.1716

Possible ways to "see" eta (if DM) at the LHC:

- Searches with Monojets+Missing E_T:

$$qq \rightarrow \eta\,\eta + \mathrm{Gluons}$$

- In heavy resonances decays:



Conclusions

Nature has chosen a light Higgs for EWSB:

- Composite Higgs as a PGB a natural possibility
  (Higgs mass at the loop level)

- A 125 GeV composite Higgs **implies** either from AdS/CFT, Weinberg Sum rules, deconstructed models:

  Fermionic colored vector-like **resonances**
  (either Q_{EM}=5/3,2/3,-1/3) with masses can be
  ~ 700 GeV

- It gives clear predictions for the Higgs couplings and their deviations from the SM

Hope to see them at the LHC !