# Beyond the Higgs

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# Higgs = "raison d'être" of LHC

- ~500 physics papers over the last 5 years have an introduction starting like
  > "The main goal of the LHC is to unveil the mechanism of electroweak symmetry breaking",
  > "How the electroweak gauge symmetry is spontaneously broken is one of the most urgent and challenging questions before particle physics."
- ~9000 papers in Spires contain "Higgs" in their title
- ~3x10$^6$ references in google
- ... no Nobel prize (so far)

**Reasons of a success**

- last missing piece of the SM?
- at the origin of the masses of elementary particles?
- unitarization of WW scattering amplitudes?
- screening of gauge boson self-energies?

# Why do we need to go beyond the SM Higgs?

1. unsuccessful searches for a Higgs boson

2. EW precision data:
   - consistency with a light Higgs
   - strong constraints on anything else

'legacy of last 20 years of expts.'

⇒ we have to live with either
fine-tuning in parameter space
or
larger theory space ⇐

# The source of the Goldstone's

symmetry breaking: new phase with more degrees of freedom

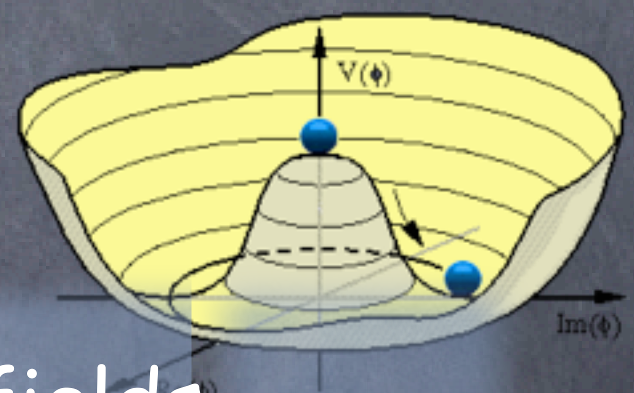
massive $W^{\pm}$, Z: 3 physical polarizations=eaten Goldstone bosons $\frac{SU(2)_L \times SU(2)_R}{SU(2)_V}$

$\Rrightarrow$ Where are these Goldstone's coming from? $\Lleftarrow$

what is the sector responsible for the breaking $SU(2)_L \times SU(2)_R$ to $SU(2)_V$?

with which dynamics? with which interactions to the SM particles?

common lore: from a scalar Higgs doublet




$$H = \begin{pmatrix} h^+ \\ h^0 \end{pmatrix}$$

Higgs doublet = 4 real scalar fields

3 eaten Goldstone bosons

One physical degree of freedom the Higgs boson

# The source of the Goldstone's

symmetry breaking: new phase with more degrees of freedom

massive $W^\pm$, Z: 3 physical polarizations=eaten Goldstone bosons $\frac{SU(2)_L \times SU(2)_R}{SU(2)_V}$

⇛ Where are these Goldstone's coming from? ⇚

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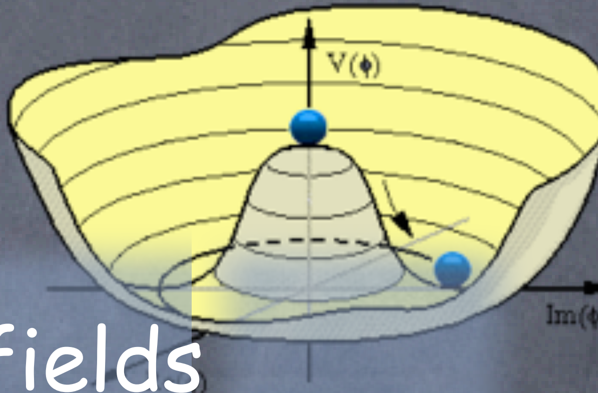
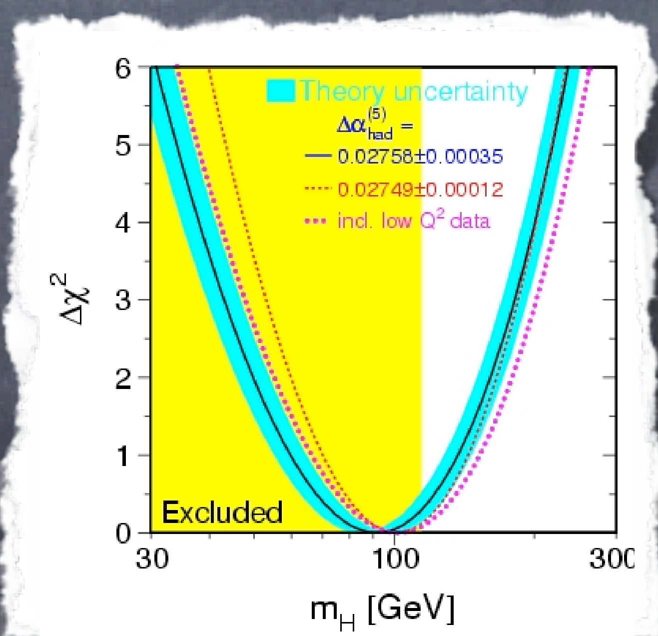


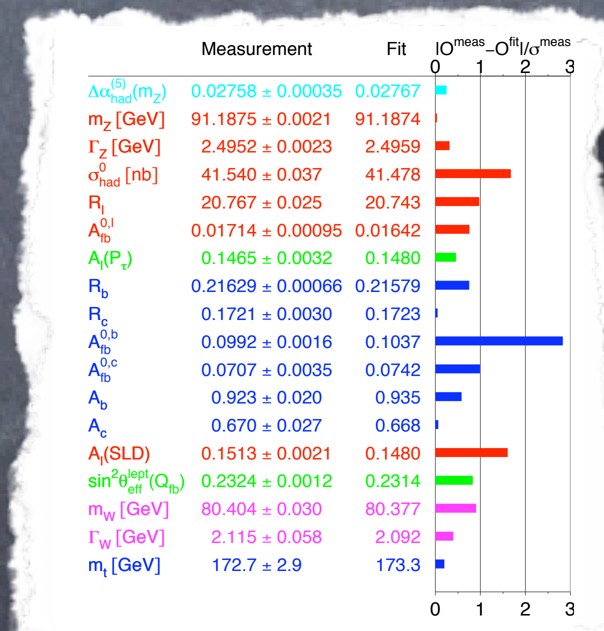

$$H = \begin{pmatrix} h^+ \\ h^0 \end{pmatrix}$$

Higgs doublet = 4 real scalar fields

Good agreement with EW data

(doublet ⇔ $\rho$=1)



| | Measurement | Fit | $\lvert O^{meas}-O^{fit}\rvert/\sigma^{meas}$ |
|---|---|---|---|
| $\Delta\alpha_{had}^{(5)}(m_Z)$ | 0.02758 ± 0.00035 | 0.02767 | |
| $m_Z$ [GeV] | 91.1875 ± 0.0021 | 91.1874 | |
| $\Gamma_Z$ [GeV] | 2.4952 ± 0.0023 | 2.4959 | |
| $\sigma_{had}^0$ [nb] | 41.540 ± 0.037 | 41.478 | |
| $R_l$ | 20.767 ± 0.025 | 20.743 | |
| $A_{fb}^{0,l}$ | 0.01714 ± 0.00095 | 0.01642 | |
| $A_l(P_\tau)$ | 0.1465 ± 0.0032 | 0.1480 | |
| $R_b$ | 0.21629 ± 0.00066 | 0.21579 | |
| $R_c$ | 0.1721 ± 0.0030 | 0.1723 | |
| $A_{fb}^{0,b}$ | 0.0992 ± 0.0016 | 0.1037 | |
| $A_{fb}^{0,c}$ | 0.0707 ± 0.0035 | 0.0742 | |
| $A_b$ | 0.923 ± 0.020 | 0.935 | |
| $A_c$ | 0.670 ± 0.027 | 0.668 | |
| $A_l$(SLD) | 0.1513 ± 0.0021 | 0.1480 | |
| $\sin^2\theta_{eff}^{lept}(Q_{fb})$ | 0.2324 ± 0.0012 | 0.2314 | |
| $m_W$ [GeV] | 80.404 ± 0.030 | 80.377 | |
| $\Gamma_W$ [GeV] | 2.115 ± 0.058 | 2.092 | |
| $m_t$ [GeV] | 172.7 ± 2.9 | 173.3 | |

But the Higgs hasn't been seen yet...

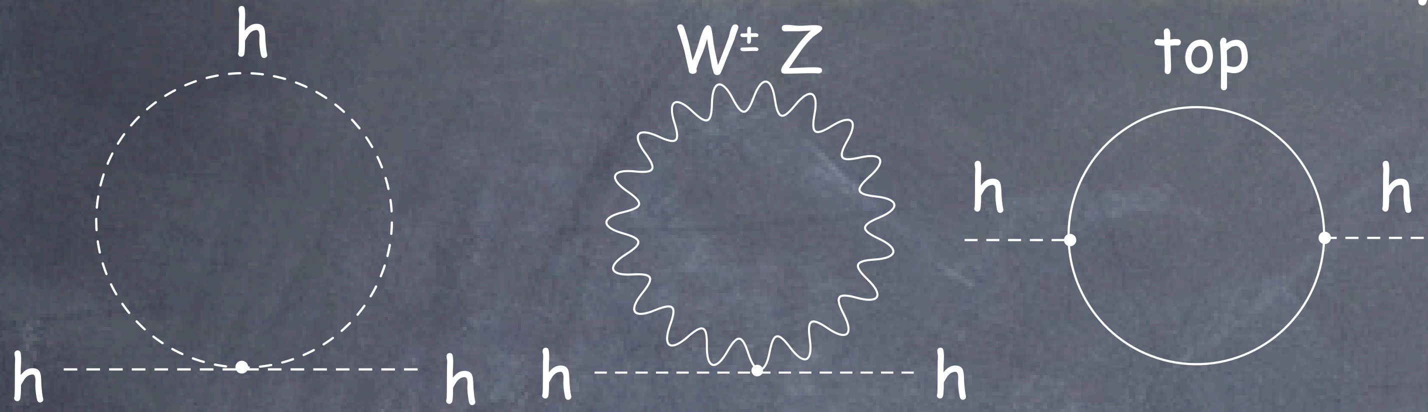
"Myth or fact?"

How close to reality is the SM Higgs boson?

# New physics: hierarchy pb @ flavor

# The hierarchy problem

need new degrees of freedom to cancel $\Lambda^2$ divergences
and ensure the stability of the weak scale




$$m_H^2 \sim m_0^2 - (115\ \mathrm{GeV})^2 \left(\frac{\Lambda}{400\ \mathrm{GeV}}\right)^2$$

1 add a sym. such that a Higgs mass is forbidden until this sym. is broken

- supersymmetry [Witten, '81]
- gauge-Higgs unification [Manton, '79, Hosotani '83]
- Higgs as a pseudo Nambu-Goldstone boson [Georgi-Kaplan, '84]

2 lower the UV scale

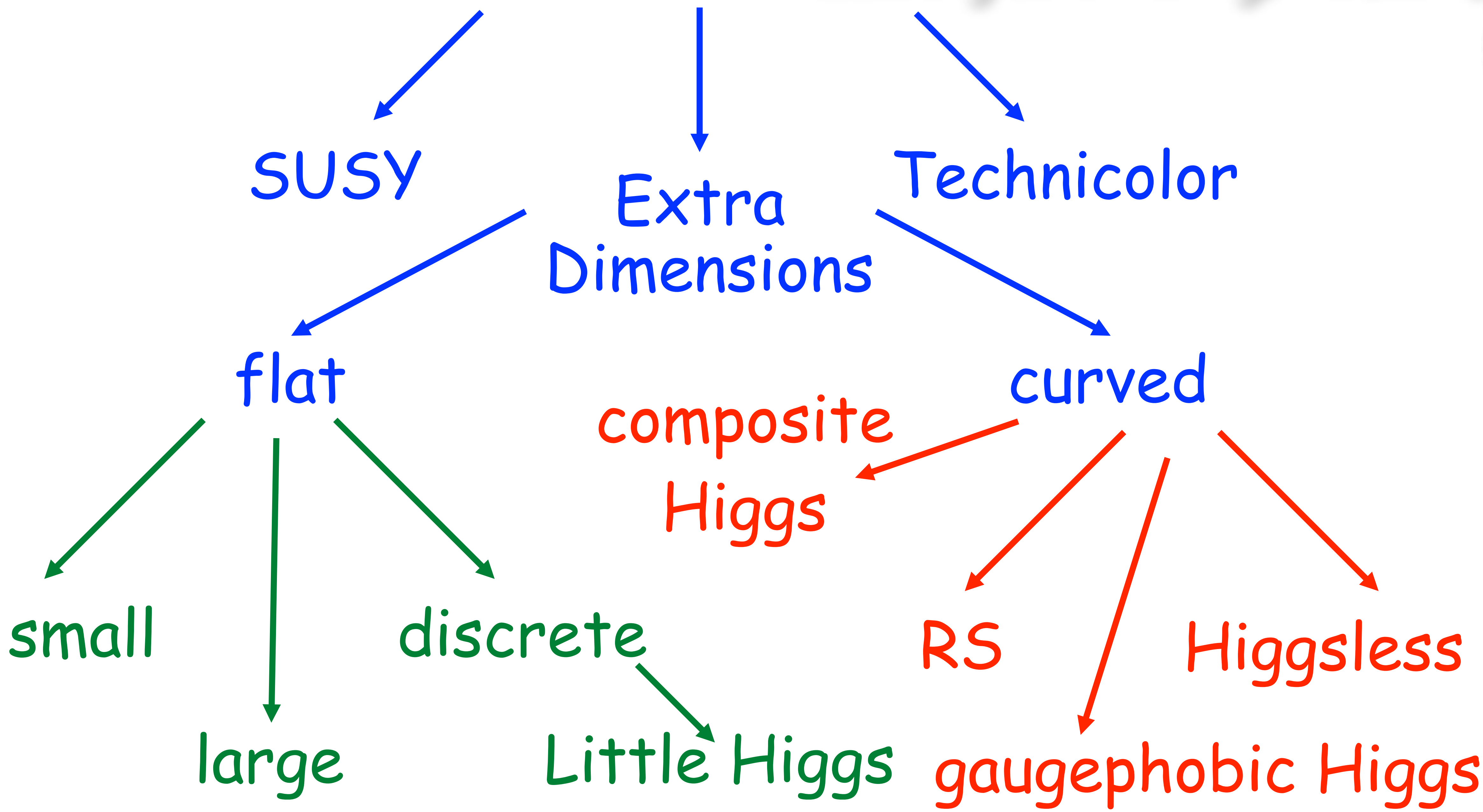
- large extra-dimension [Arkani-Hamed-Dimopoulos-Dvali, '98]
- $10^{32}$ species [Dvali '07]

3 remove the Higgs

- technicolor [Weinberg '79, Susskind '79]

# Hierarchy Problem Now

*According to J. Terning, MC4BSM4*



# Hierarchy problem vs flavor: tension

## Clash of Scales

**Higgs sector**

$\Lambda < 3\text{-}4$ TeV

?

**Flavor**

$\Lambda > 10^{4\div5}$ TeV

the higher the scale of new physics, the more fine-tuned the Higgs, the less likely a discovery at LHC

**Weak** | **Strong**

### SM & al.

H = elem. scalar: dim=1

$$\Lambda^2 \, |H|^2$$

sick when $\Lambda \to \infty$

$$y_{ij} \, H q_i \bar{q}_j \ \& \ \frac{1}{\Lambda^2} (q_i \bar{q}_j q_k \bar{q}_l)$$

fine when $\Lambda \to \infty$

### Technicolor

H=<q$\bar{q}$>: dim=3

$$\frac{1}{\Lambda^2} |H|^2$$

fine when $\Lambda \to \infty$

$$\frac{1}{\Lambda^2} H q_i \bar{q}_j \ \& \ \frac{1}{\Lambda^2} (q_i \bar{q}_j q_k \bar{q}_l)$$

sick when $\Lambda \to \infty$

# Hierarchy problem vs flavor: lesson?

Clash of Scales

**Higgs sector**

$\Lambda$ < 3-4 TeV

?

**Flavor**

$\Lambda$ > $10^{4÷5}$ TeV

Is flavor telling us anything about the solution to the hierarchy problem?

**Weak**

SM & al.

H = elem. scalar: dim=1

$$\Lambda^2 |H|^2$$

sick when $\Lambda \to \infty$

$$y_{ij}\, H q_i \bar{q}_j \;\;\&\;\; \frac{1}{\Lambda^2}(q_i \bar{q}_j q_k \bar{q}_l)$$

fine when $\Lambda \to \infty$

**conformal TC**

dim $_H$ = 1 but dim $_{|H|^2}$ = 4

would solve both pbs

but it seems impossible to realize

[Luty-Okui '04, Rattazzi et al '08]

**Strong**

Technicolor

H=<q$\bar{q}$>: dim=3

$$\frac{1}{\Lambda^2}|H|^2$$

fine when $\Lambda \to \infty$

$$\frac{1}{\Lambda^2} H q_i \bar{q}_j \;\;\&\;\; \frac{1}{\Lambda^2}(q_i \bar{q}_j q_k \bar{q}_l)$$

sick when $\Lambda \to \infty$

# Hierarchy problem vs flavor: lesson?

Clash of Scales

Higgs sector

$\Lambda < 3\text{-}4$ TeV

?

Flavor

$\Lambda > 10^{4\div 5}$ TeV

Is flavor telling us anything about the solution to the hierarchy problem?

Weak

SM & al.

H = elem. scalar: dim=1

$\Lambda^2 |H|^2$

sick when $\Lambda \to \infty$

$y_{ij}\, H q_i \bar{q}_j$ & $\frac{1}{\Lambda^2}(q_i \bar{q}_j q_k \bar{q}_l)$

fine when $\Lambda \to \infty$

1

conformal TC

2 [Kaplan '91]

partial compositeness

mixing elem. and composite fermions

dim $q_{R,L}$=3/2, dim $\mathcal{O}_{R,L}$=$d_{R,L}$

$$\frac{q_L \mathcal{O}_R}{\Lambda_R^{d_R-5/2}} + \frac{q_R \mathcal{O}_L}{\Lambda_L^{d_R-5/2}} + \frac{\mathcal{O}_L \mathcal{O}_R}{\Lambda^{d_L+d_R-4}}$$

$d_{R,L} \approx 5/2$ solves the flavor pb

Strong

Technicolor

$H=\langle q\bar{q}\rangle$: dim=3

$\frac{1}{\Lambda^2}|H|^2$

fine when $\Lambda \to \infty$

$\frac{1}{\Lambda^2} H q_i \bar{q}_j$ & $\frac{1}{\Lambda^2}(q_i \bar{q}_j q_k \bar{q}_l)$

sick when $\Lambda \to \infty$

# Partial compositeness: fermion masses

**partial compositeness**

mixing elem. and composite fermions

dim $q_{R,L}$=3/2, dim $\mathcal{O}_{R,L}$=$d_{R,L}$

$$\frac{q_L \mathcal{O}_R}{\Lambda_R^{d_R-5/2}} + \frac{q_R \mathcal{O}_L}{\Lambda_L^{d_R-5/2}} + \frac{\mathcal{O}_L \mathcal{O}_R}{\Lambda^{d_L+d_R-4}}$$

integrating out heavy fields

amount of compositeness $f_{q_{L,R}}$

$$\frac{\Lambda_R \Lambda_L}{\Lambda} \left(\frac{\Lambda}{\Lambda_R}\right)^{d_R} \left(\frac{\Lambda}{\Lambda_L}\right)^{d_L} q_L q_R$$

1. fermion mass hierarchy easily generated by small diff. in anomalous dims
2. alignment mixing angles/masses is also explained

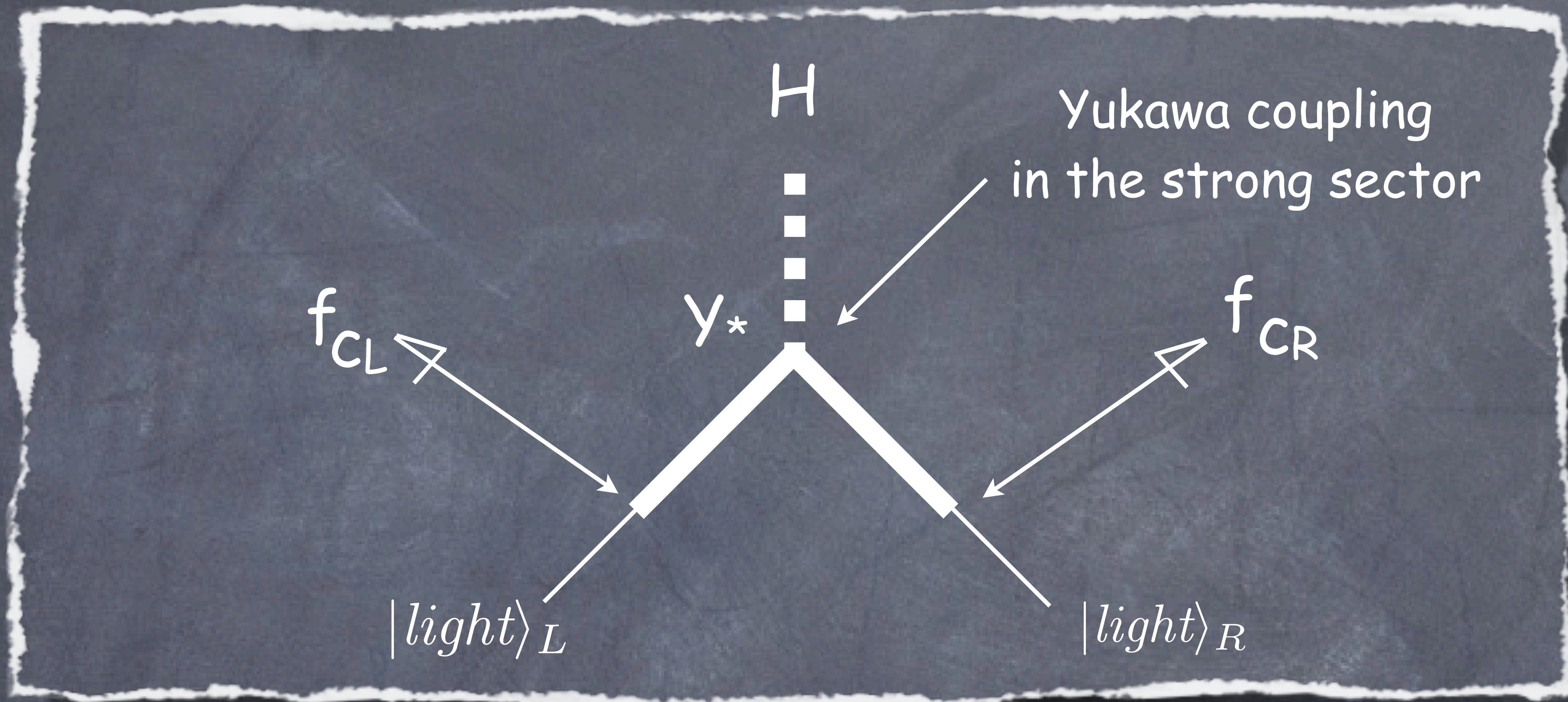
$$V_{CKM} \sim \begin{pmatrix} 1 & \lambda & \lambda^3 \\ \lambda & 1 & \lambda^2 \\ \lambda^3 & \lambda^2 & 1 \end{pmatrix}$$

$$m_{u_i} \propto f_{q_i} f_{u_i} \qquad m_{d_i} \propto f_{q_i} f_{d_i}$$

$$V_{CKM}^{ij} \sim f_{q_i}/f_{q_j}$$

# Partial Compositeness: fermion masses

Higgs part of the strong sector: it couples only to composite fermions




when the Higgs gets a vev, the light dof will acquire a mass prop. to

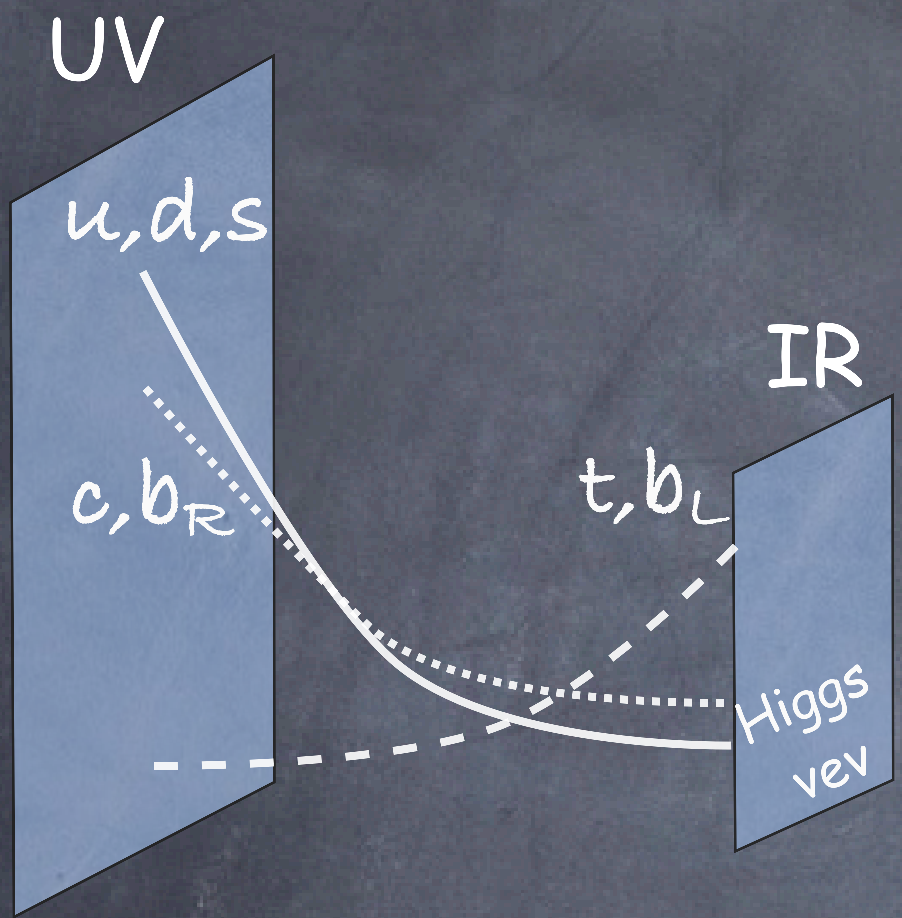
$$Y^{eff} = Y_\star f_{c_L} f_{c_R}$$

Yukawa hierarchy comes from the hierarchy of compositeness

the lighter the fermion, the less coupled to the strong sector

# Partial compositeness: xdim realization

[Grossman and Neubert, '00]
[Gherghetta and Pomarol, '00]
[Huber, '03]




fermion zero-mode has an exponential profile in the bulk

$$\chi(z) = \frac{f_c}{\sqrt{R'}} \left(\frac{z}{R}\right)^2 \left(\frac{z}{R'}\right)^{-c}$$

$f_c$ is the "value" of wavefct. on the IR:

$$f_c = \sqrt{\frac{1-2c}{1-(R/R')^{1-2c}}}$$

c < 1/2: heavy fermion

$$f_c \sim \mathcal{O}(1)$$

c > 1/2: light fermion

$$f_c \sim (R/R')^{c-1/2} \ll 1$$

light fermion exponentially localized on the UV brane

➲ overlap with Higgs vev on the IR tiny

➲ exponentially small 4D mass

UV localized fermion=elementary

IR localized fermion=composite

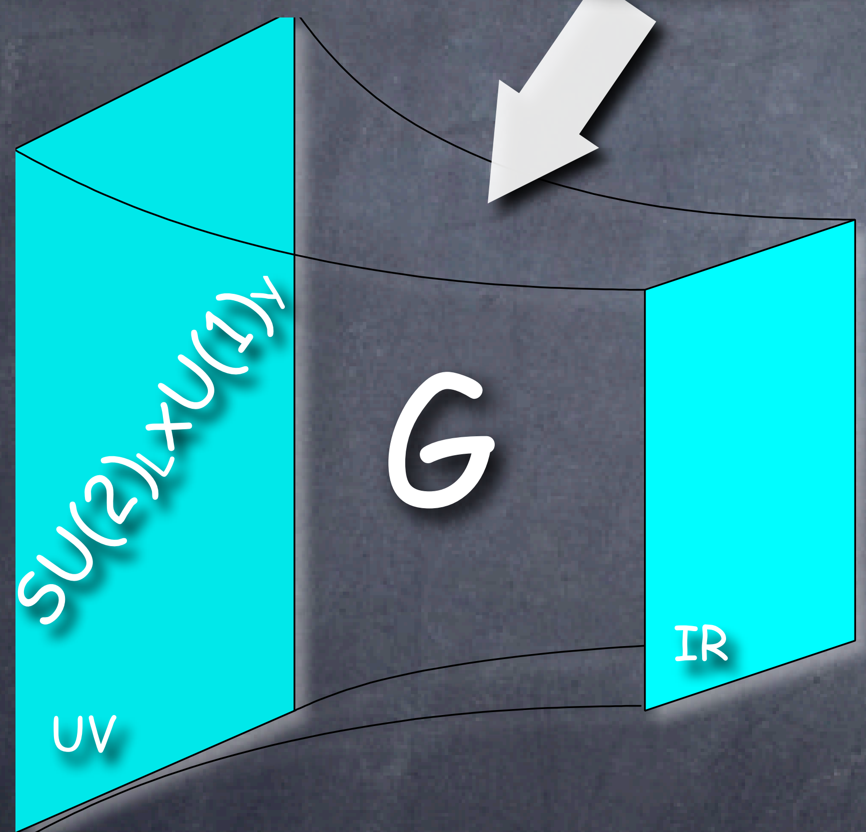
5D models=weakly coupled dual of 4D strongly models

# Holographic Models of EWSB

Bulk gauge fields: [Pomarol, '00]
Holographic technicolor=Higgsless: [Csaki et al., '03
Holographic composite Higgs: [Agashe et al., '04]

Gauge fields + fermions in the bulk

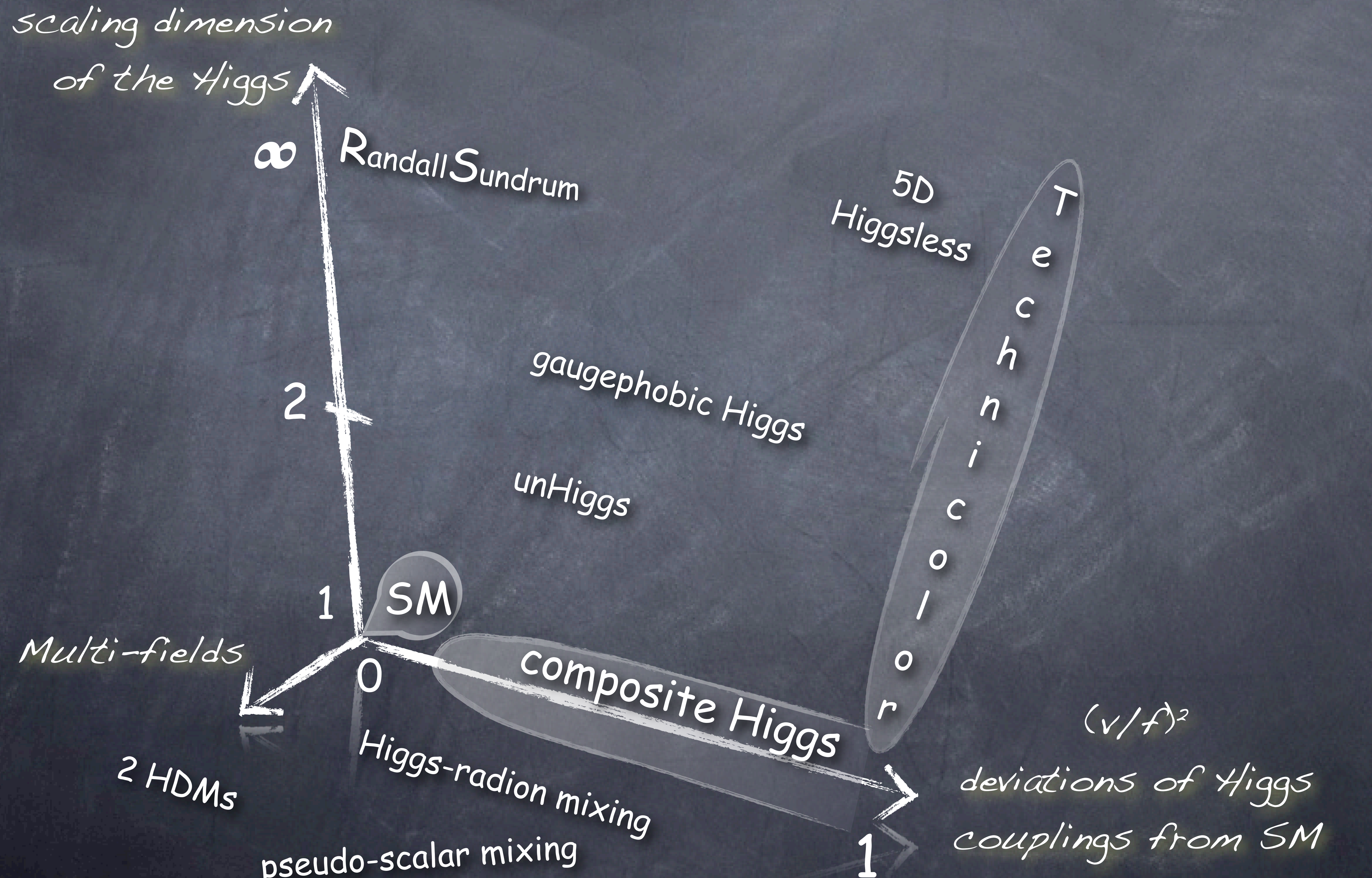
Higgs on the IR brane
or
Gauge breaking by boundary conditions




$G=SU(2)_L \times SU(2)_R \times U(1)_{B-L}$
$G=SO(5) \times U(1)_X$
$G=SO(6) \times U(1)_X$

- UV completion: log running of gauge couplings
- Custodial symmetry from bulk $SU(2)_R$

# A multi-dimensional deformation of the SM



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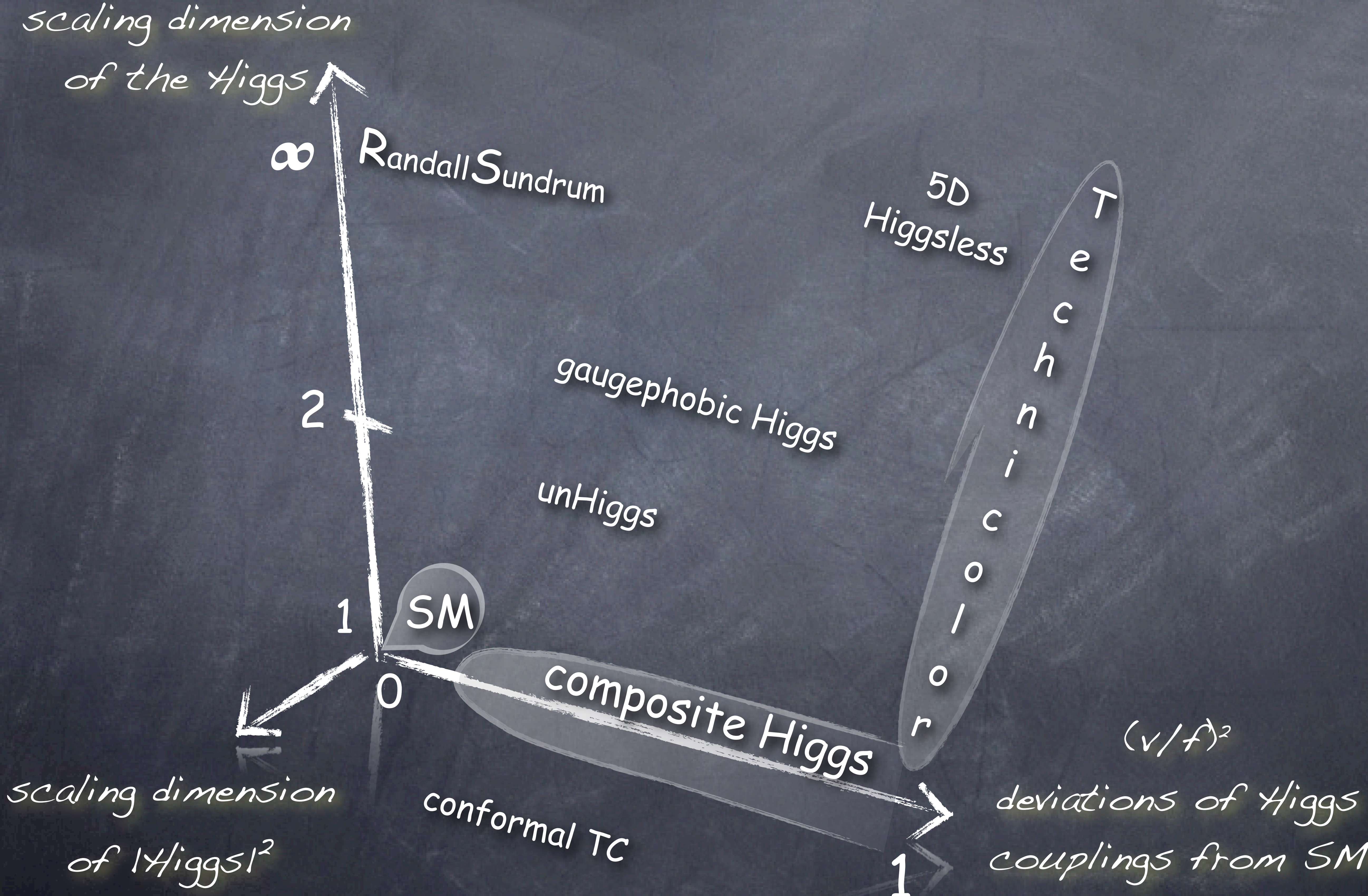
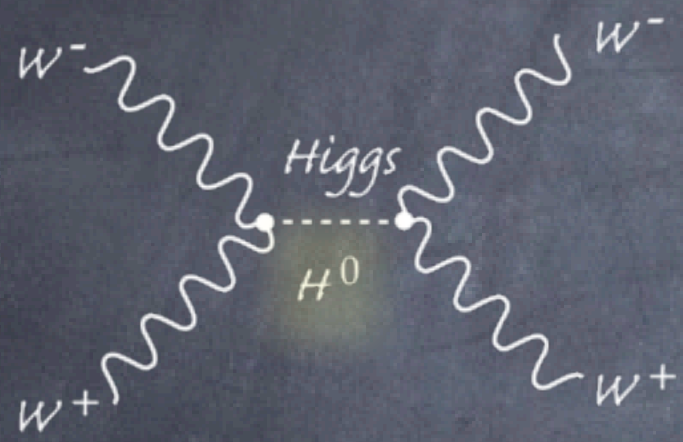


# SM Higgs as a peculiar scalar resonance

A single scalar degree of freedom with no charge under $SU(2)_L \times U(1)_Y$

$$\mathcal{L}_{\rm EWSB} = a\,\frac{v}{2}\,h\,{\rm Tr}\left(D_\mu\Sigma^\dagger D_\mu\Sigma\right) + b\,\frac{1}{4}\,h^2\,{\rm Tr}\left(D_\mu\Sigma^\dagger D_\mu\Sigma\right)$$

'a' and 'b' are arbitrary free couplings




$$\mathcal{A} = \frac{1}{v^2}\left(s - \frac{a^2\,s^2}{s-m_h^2}\right)$$

growth cancelled for

a = 1

restoration of

perturbative unitarity

For $b = a^2$: perturbative unitarity also maintained in inelastic channels

## 'a=1' & 'b=1' define the SM Higgs

$$\mathcal{L}_{\rm mass} + \mathcal{L}_{\rm EWSB}$$ can be rewritten as $$D_\mu H^\dagger D_\mu H$$

$$H = \frac{1}{\sqrt{2}}\, e^{i\sigma^a\pi^a/v}\begin{pmatrix} 0 \\ v+h \end{pmatrix}$$

$h$ and $\pi^a$ (ie $W_L$ and $Z_L$) combine to form a linear representation of $SU(2)_L \times U(1)_Y$

**Higgs properties depend on a single unknown parameter ($m_H$)**

# Continuous interpolation between SM and TC

$$\xi = \frac{v^2}{f^2} = \frac{(\text{weak scale})^2}{(\text{strong coupling scale})^2}$$

$\xi = 0$

**SM limit**

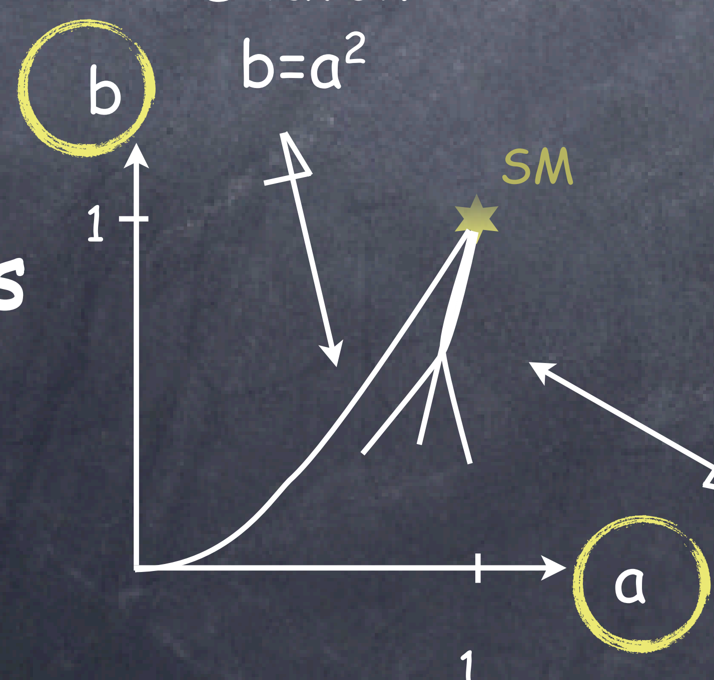
all resonances of strong sector, except the Higgs, decouple

$\xi = 1$

**Technicolor limit**

Higgs decouple from SM; vector resonances like in TC

Dilaton
b=a²



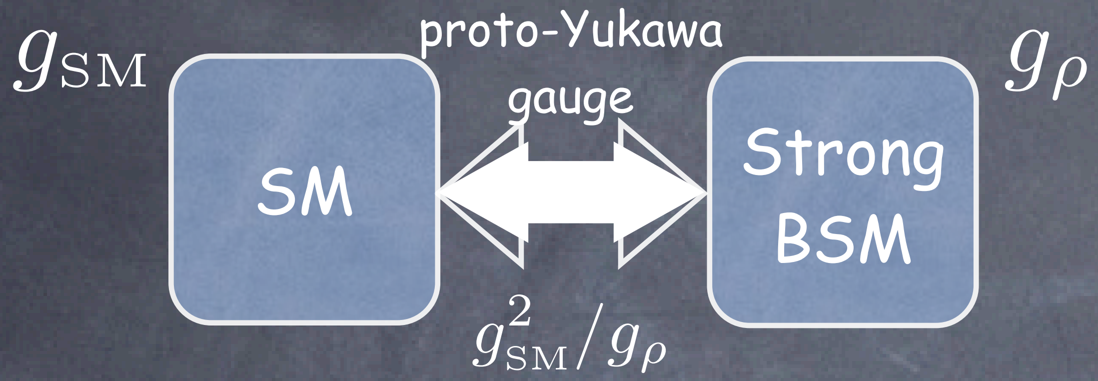

Composite Higgs
vs.
SM Higgs
Dilaton

$$\mathcal{L}_{\rm EWSB} = \left( a\,\frac{v}{2}\,h \;+ b\,\frac{1}{4}\,h^2 \right) {\rm Tr}\left(D_\mu \Sigma^\dagger D_\mu \Sigma\right)$$

Composite Higgs
universal behavior for large f
a=1-v/2f  b=1-2v/f

# How to obtain a light composite Higgs?

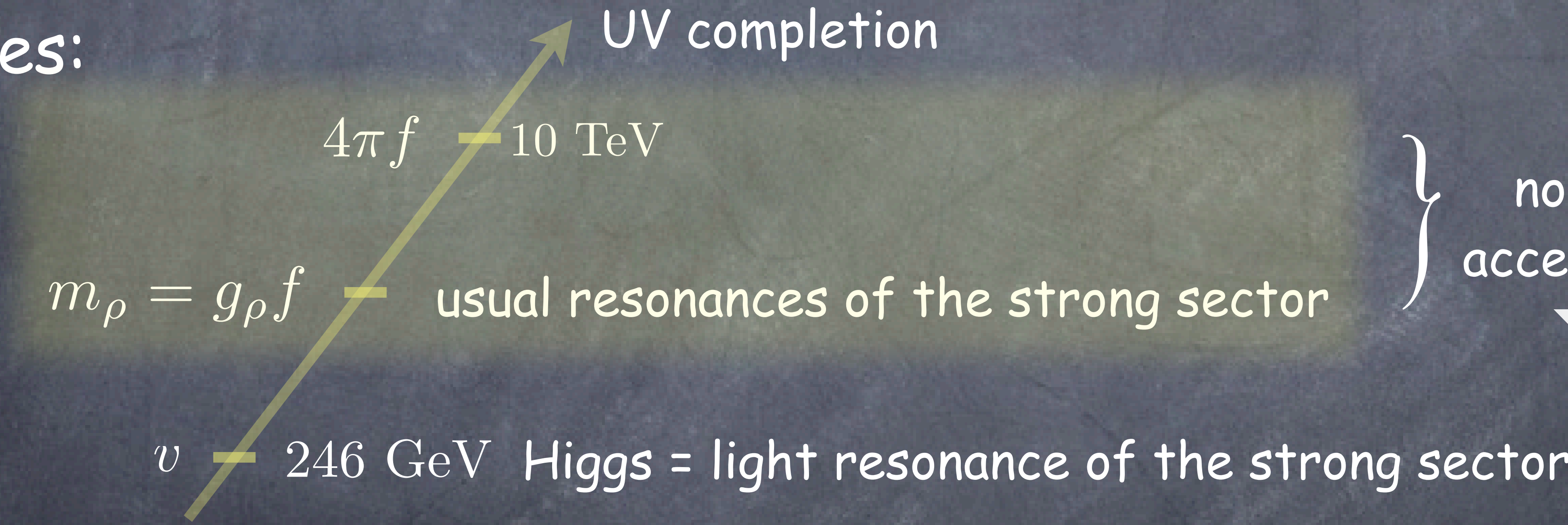
## Higgs=Pseudo-Goldstone boson of the strong sector




$m_{\rm Higgs}$=0 when $g_{\rm SM}$=0

global symmetry → $G/H$ ← residual global symmetry

3 scales:




} not directly accessible to LC

indirect probes

strong sector broadly characterized by 2 parameters

$m_\rho$ = mass of the resonances

$g_\rho$ = coupling of the strong sector or decay cst of strong sector $f = \frac{m_\rho}{g_\rho}$

# What distinguishes a composite Higgs?

Giudice, Grojean, Pomarol, Rattazzi '07

$$\mathcal{L} \supset \frac{c_H}{2f^2}\,\partial^\mu\left(|H|^2\right)\partial_\mu\left(|H|^2\right) \qquad c_H \sim \mathcal{O}(1)$$

$$U = e^{i\begin{pmatrix} & H/f \\ H^\dagger/f & \end{pmatrix}} U_0$$

$$f^2\,\mathrm{tr}\left(\partial_\mu U^\dagger \partial^\mu U\right) = |\partial_\mu H|^2 + \frac{\sharp}{f^2}\left(\partial|H|^2\right)^2 + \frac{\sharp}{f^2}|H|^2\,|\partial H|^2 + \frac{\sharp}{f^2}\left|H^\dagger \partial H\right|^2$$

# Anomalous Higgs Couplings

Giudice, Grojean, Pomarol, Rattazzi '07

$$\mathcal{L} \supset \frac{c_H}{2f^2}\, \partial^\mu \left(|H|^2\right) \partial_\mu \left(|H|^2\right) \qquad c_H \sim \mathcal{O}(1)$$

$$H = \begin{pmatrix} 0 \\ \frac{v+h}{\sqrt{2}} \end{pmatrix} \Longrightarrow \mathcal{L} = \frac{1}{2}\left(1 + c_H \frac{v^2}{f^2}\right) (\partial^\mu h)^2 + \ldots$$

Modified Higgs propagator ~ Higgs couplings rescaled by $\frac{1}{\sqrt{1 + c_H \frac{v^2}{f^2}}} \sim 1 - c_H \frac{v^2}{2f^2} \equiv 1 - \xi/2$

# SILH Effective Lagrangian

(strongly-interacting light Higgs)

Giudice, Grojean, Pomarol, Rattazzi '07

- extra Higgs leg: $H/f$
- extra derivative: $\partial/m_\rho$

## Genuine strong operators (sensitive to the scale f)

$$\frac{c_H}{2f^2}\left(\partial_\mu\left(|H|^2\right)\right)^2 \qquad \frac{c_T}{2f^2}\left(H^\dagger \overleftrightarrow{D^\mu} H\right)^2 \qquad \frac{c_y y_f}{f^2}|H|^2 \bar{f}_L H f_R + \text{h.c.} \qquad \frac{c_6\lambda}{f^2}|H|^6$$

custodial breaking

## Form factor operators (sensitive to the scale $m_\rho$)

$$\frac{ic_W}{2m_\rho^2}\left(H^\dagger\sigma^i \overleftrightarrow{D^\mu} H\right)\left(D^\nu W_{\mu\nu}\right)^i \qquad \frac{ic_B}{2m_\rho^2}\left(H^\dagger \overleftrightarrow{D^\mu} H\right)\left(\partial^\nu B_{\mu\nu}\right)$$

$$\frac{ic_{HW}}{m_\rho^2}\frac{g_\rho^2}{16\pi^2}(D^\mu H)^\dagger\sigma^i(D^\nu H)W^i_{\mu\nu} \qquad \frac{ic_{HB}}{m_\rho^2}\frac{g_\rho^2}{16\pi^2}(D^\mu H)^\dagger(D^\nu H)B_{\mu\nu}$$

minimal coupling: $h\to\gamma Z$

loop-suppressed strong dynamics

$$\frac{c_\gamma}{m_\rho^2}\frac{g_\rho^2}{16\pi^2}\frac{g^2}{g_\rho^2}H^\dagger H B_{\mu\nu}B^{\mu\nu} \qquad \frac{c_g}{m_\rho^2}\frac{g_\rho^2}{16\pi^2}\frac{y_t^2}{g_\rho^2}H^\dagger H G^a_{\mu\nu}G^{a\mu\nu}$$

Goldstone sym.

# EWPT constraints

$$\hat{T} = c_T \frac{v^2}{f^2} \Longrightarrow |c_T \frac{v^2}{f^2}| < 2 \times 10^{-3}$$

removed by custodial symmetry

$$\hat{S} = (c_W + c_B) \frac{m_W^2}{m_\rho^2} \Longrightarrow m_\rho \geq (c_W + c_B)^{1/2}\ 2.5\ \text{TeV}$$

There are also some 1-loop IR effects

Barbieri, Bellazzini, Rychkov, Varagnolo '07

$$\hat{S}, \hat{T} = a \log m_h + b$$

modified Higgs couplings to matter

$$\hat{S}, \hat{T} = a \left( (1 - c_H \xi) \log m_h + c_H \xi \log \Lambda \right) + b$$

effective Higgs mass

$$m_h^{\mathit{eff}} = m_h \left( \frac{\Lambda}{m_h} \right)^{c_H v^2/f^2} > m_h$$

LEPII, for $m_h$~115 GeV: $c_H v^2/f^2 < 1/3 \sim 1/2$

IR effects can be cancelled by heavy fermions (model dependent)

# Flavor Constraints

$$\left(1+\frac{c_{ij}|H|^2}{f^2}\right) y_{ij}\bar{f}_{Li}Hf_{Rj} = \left(1+\frac{c_{ij}v^2}{2f^2}\right)\frac{y_{ij}v}{\sqrt{2}}\bar{f}_{Li}f_{Rj}$$

$$+\left(1+\frac{3c_{ij}v^2}{2f^2}\right)\frac{y_{ij}}{\sqrt{2}}h\bar{f}_{Li}f_{Rj}$$

mass terms

Higgs fermion interactions

mass and interaction matrices are not diagonalizable simultaneously if $c_{ij}$ are arbitrary

$\Rrightarrow$ FCNC

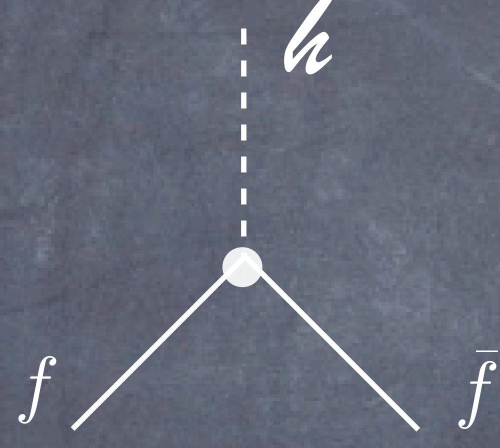
SILH: $c_y$ is flavor universal

$\Rrightarrow$ Minimal flavor violation built in

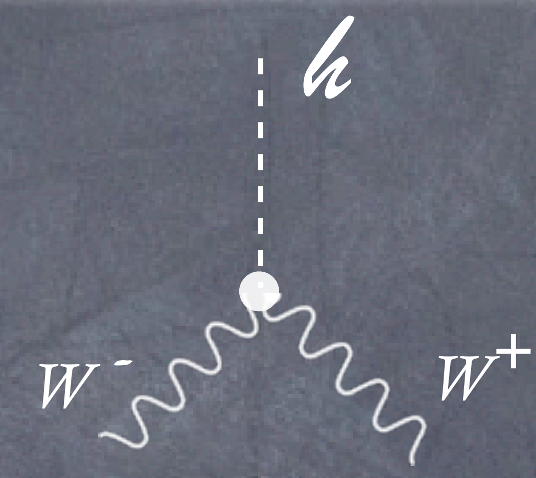
# Higgs anomalous couplings

## Lagrangian in unitary gauge

$$\mathcal{L} = \mathcal{L}_{\rm SM} + \left( -\frac{m_H^2}{2v}(c_6 - 3c_H/2)h^3 + \frac{m_f}{v}\bar{f}f(c_y + c_H/2)h - c_H\frac{m_W^2}{v}hW_\mu^+W^{-\mu} - c_H\frac{m_Z^2}{v}hZ_\mu Z^\mu \right)\frac{v^2}{f^2} + \ldots$$




$$g_{SM}\left(1 - (c_y + c_H/2)v^2/f^2\right)$$




$$g_{SM}\left(1 - c_H v^2/f^2\right)$$

$$\Gamma\left(h \to f\bar{f}\right)_{\rm SILH} = \Gamma\left(h \to f\bar{f}\right)_{\rm SM}\left[1 - (2c_y + c_H)\, v^2/f^2\right]$$

$$\Gamma\left(h \to gg\right)_{\rm SILH} = \Gamma\left(h \to gg\right)_{\rm SM}\left[1 - (2c_y + c_H)\, v^2/f^2\right]$$

Note: same Lorentz structure as in SM. Not true anymore if form factor ops. are included

# Higgs anomalous couplings for large v/f

The SILH Lagrangian is an expansion for small v/f
The 5D MCHM gives a completion for large v/f

$$m_W^2 = \frac{1}{4} g^2 f^2 \sin^2 v/f \quad \Rrightarrow \quad g_{hWW} = \sqrt{1-\xi}\, g_{hWW}^{\rm SM}$$

MCHM4

Fermions embedded in spinorial of SO(5)

$$m_f = M \sin v/f$$

$$\Downarrow$$

$$g_{hff} = \sqrt{1-\xi}\, g_{hff}^{\rm SM}$$

universal shift of the couplings
no modifications of BRs

MCHM5

Fermions embedded in 5+10 of SO(5)

$$m_f = M \sin 2v/f$$

$$\Downarrow$$

$$g_{hff} = \frac{1-2\xi}{\sqrt{1-\xi}}\, g_{hff}^{\rm SM}$$

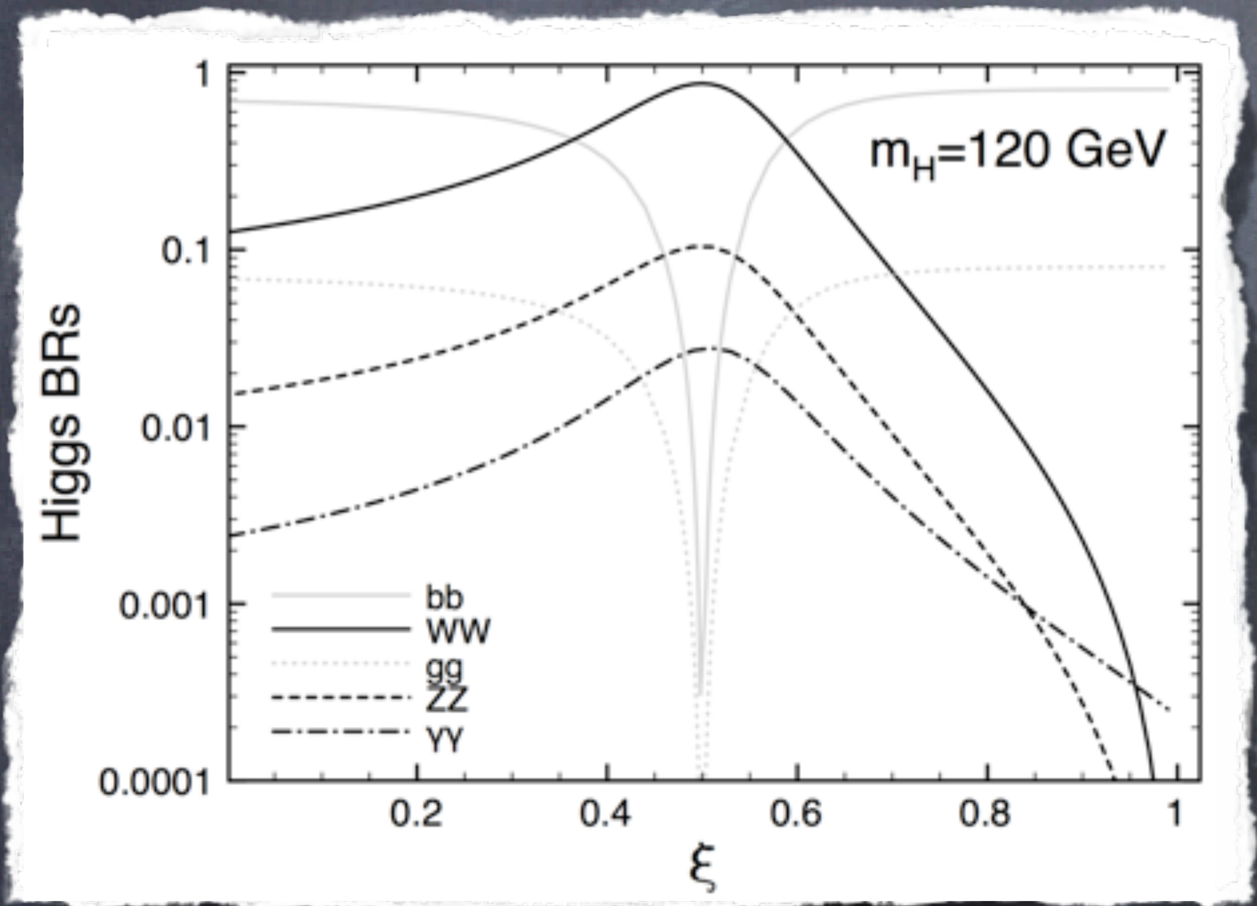
BRs now depends on v/f

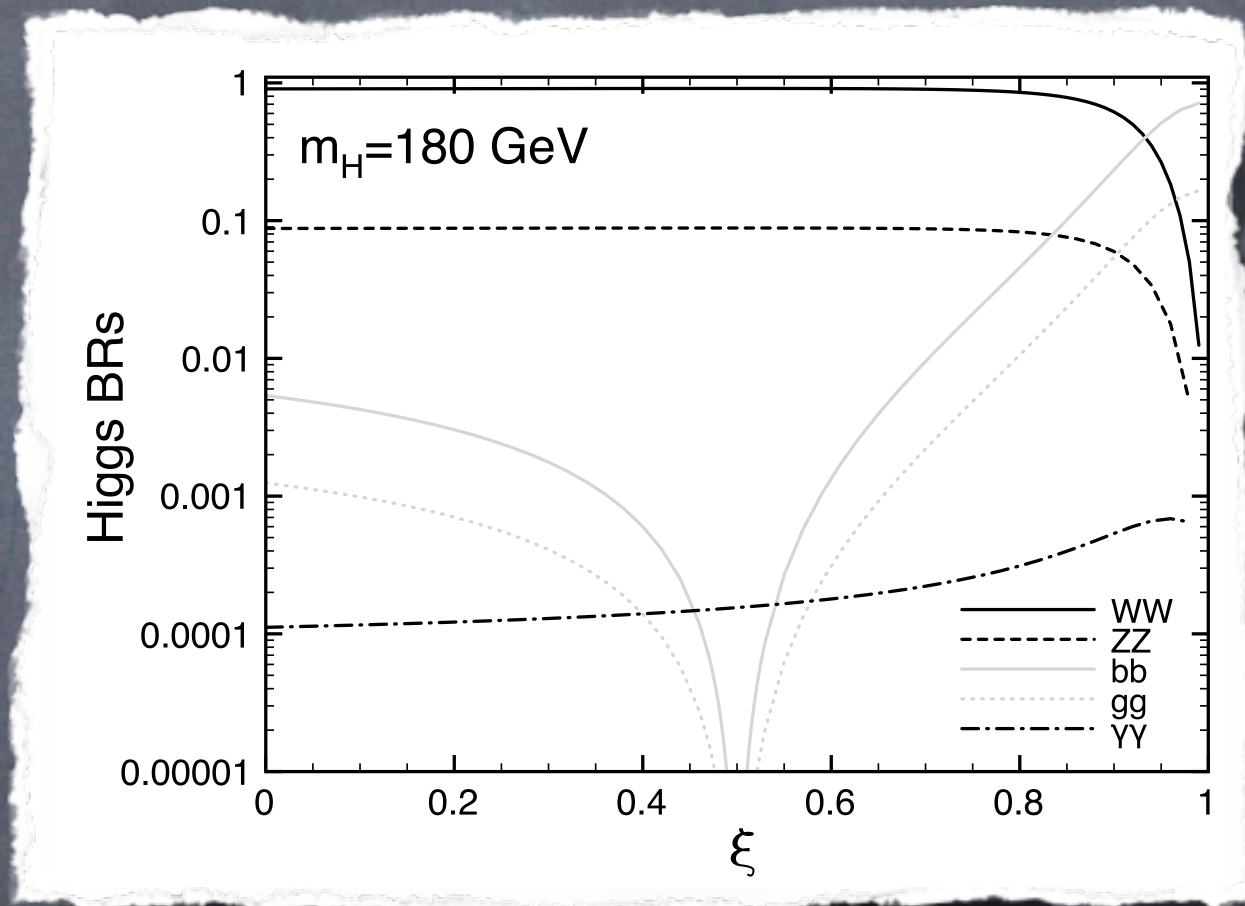
$$(\ \xi = v^2/f^2\ )$$

# Higgs BRs

MCHM5

Fermions embedded in 5+10 of SO(5)



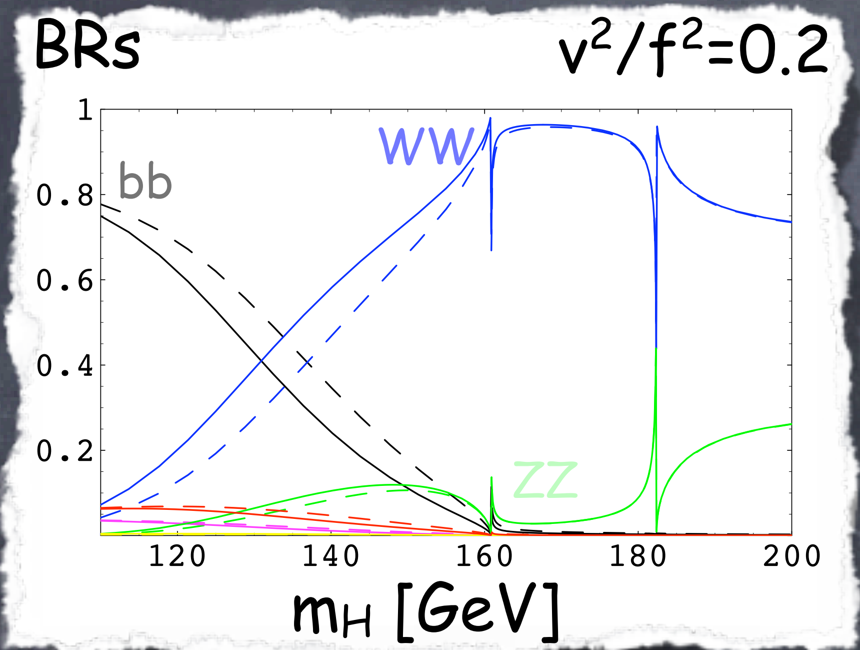

h→WW can dominate even for low Higgs mass

BRs remain SM like except for very large values of v/f

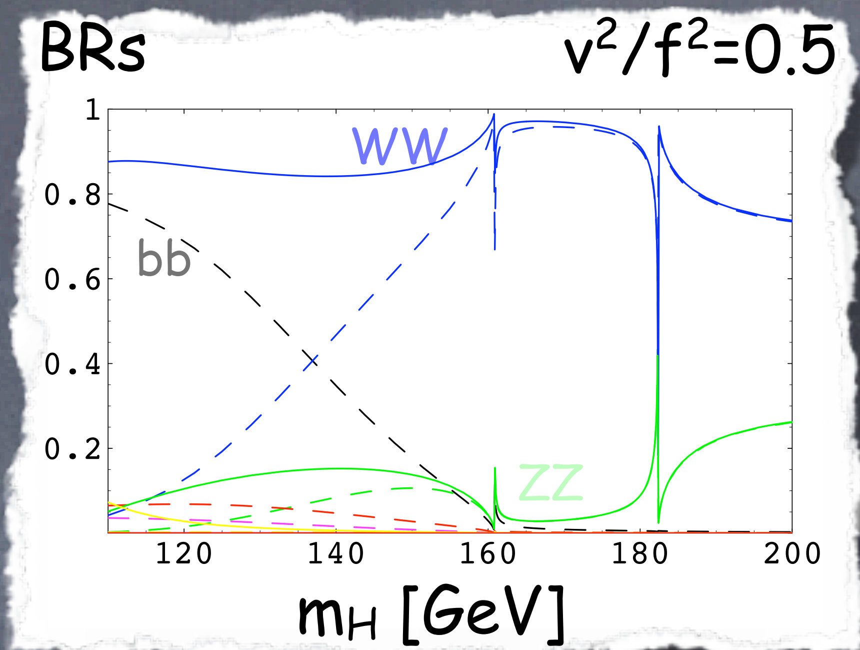
# Higgs BRs and total width

## Fermions embedded in 5+10 of SO(5)

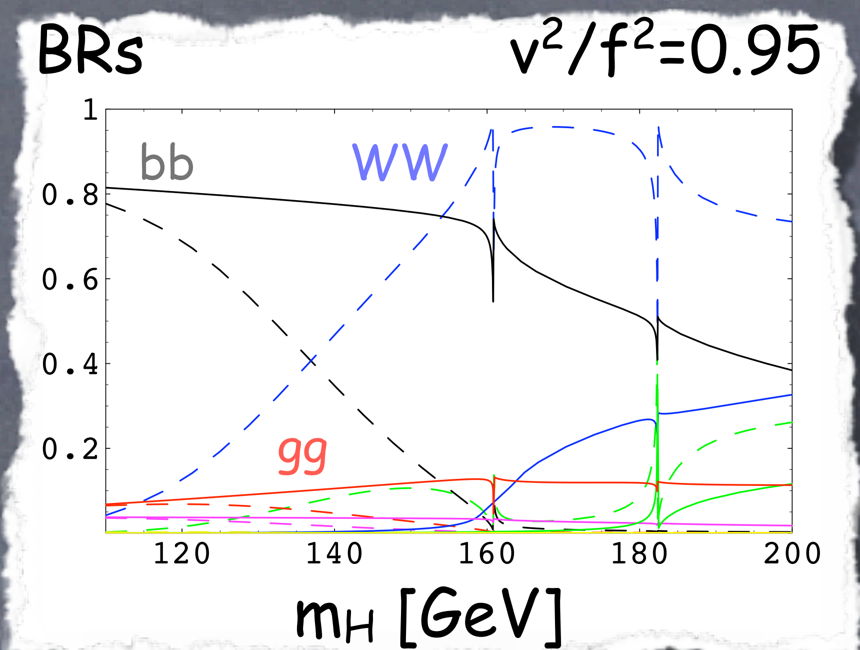
MCHM5




slight modifications

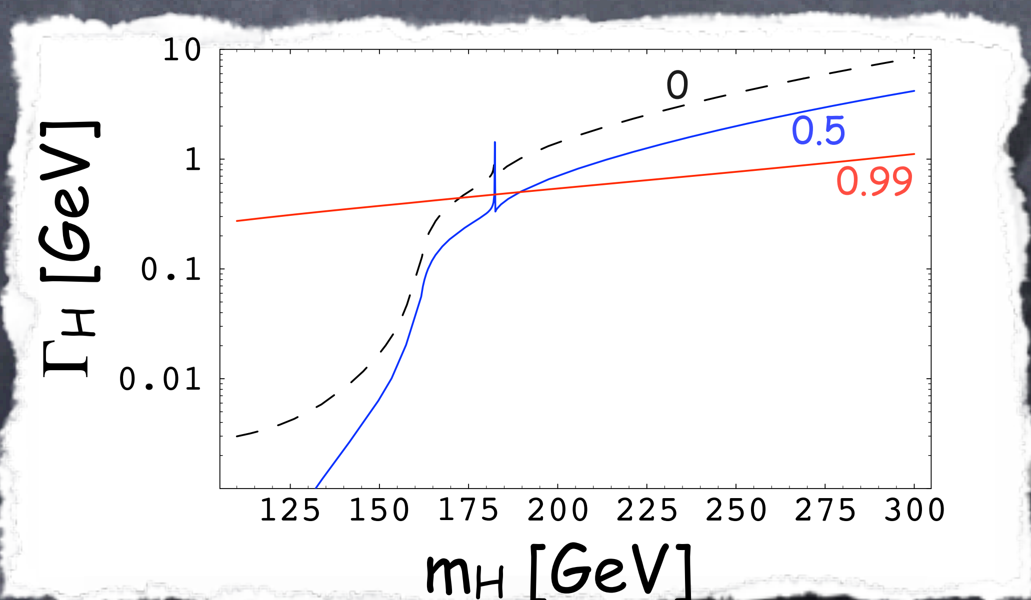



suppress bb




suppress WW

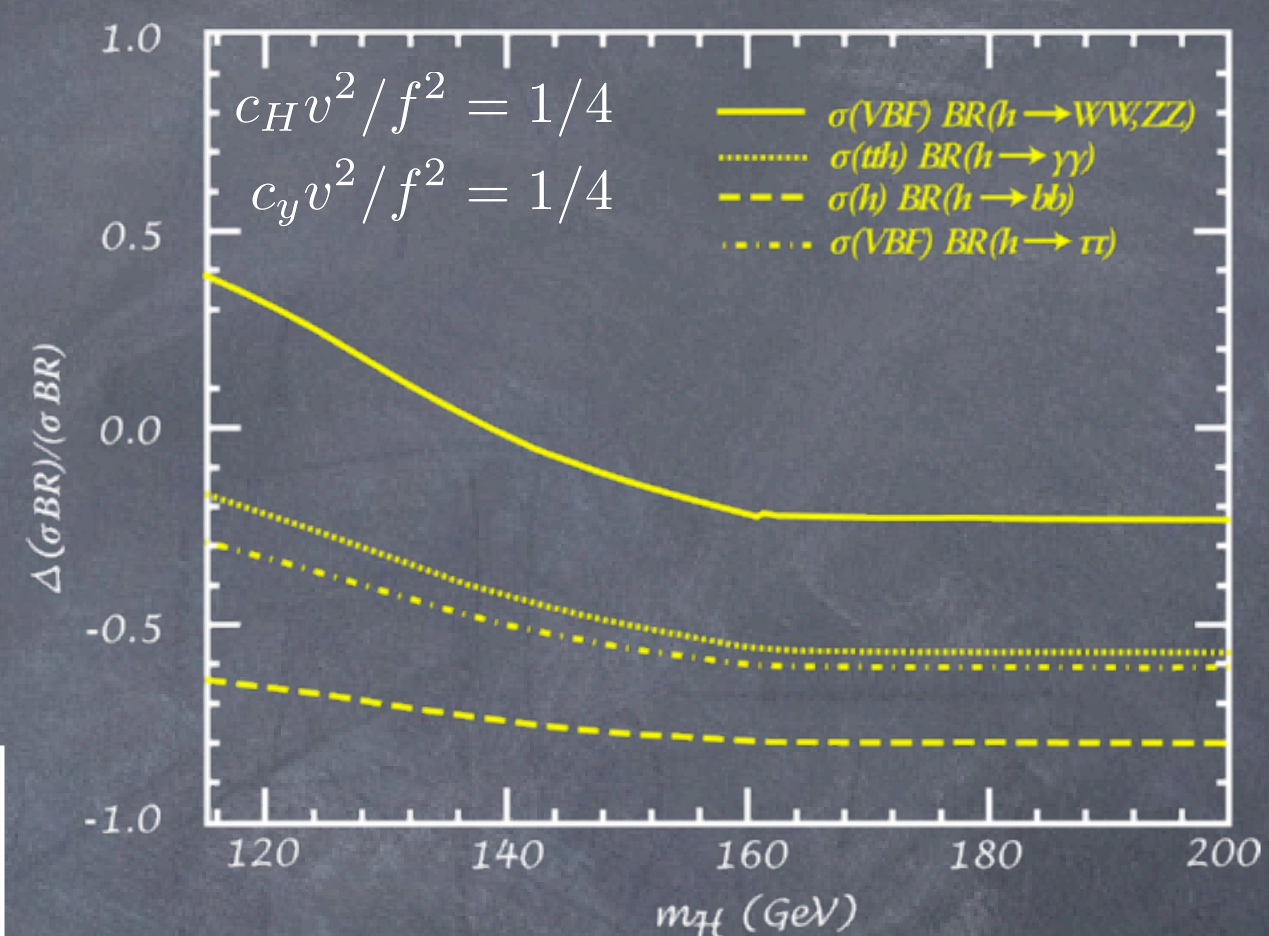
## Higgs total width



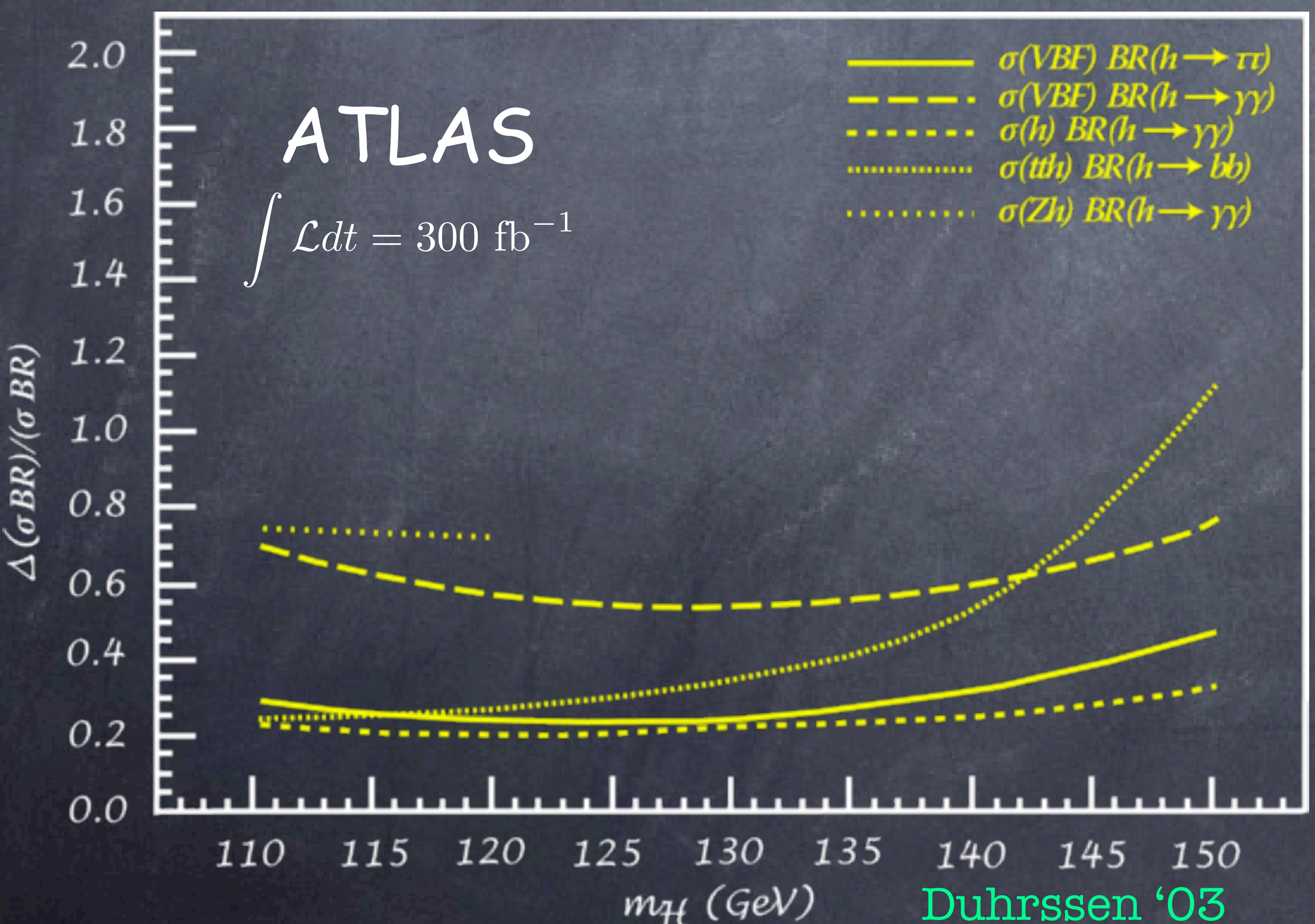
# Higgs anomalous couplings @ LHC

$$\Gamma\left(h \to f\bar{f}\right)_{\rm SILH} = \Gamma\left(h \to f\bar{f}\right)_{\rm SM}\left[1-\left(2c_y + c_H\right)v^2/f^2\right]$$

$$\Gamma\left(h \to gg\right)_{\rm SILH} = \Gamma\left(h \to gg\right)_{\rm SM}\left[1-\left(2c_y + c_H\right)v^2/f^2\right]$$




observable @ LHC?




Duhrssen '03

LHC can measure

$$c_H \frac{v^2}{f^2},\quad c_y \frac{v^2}{f^2}$$

up to 0.2-0.4

i.e. $4\pi f \sim 5-7$ TeV

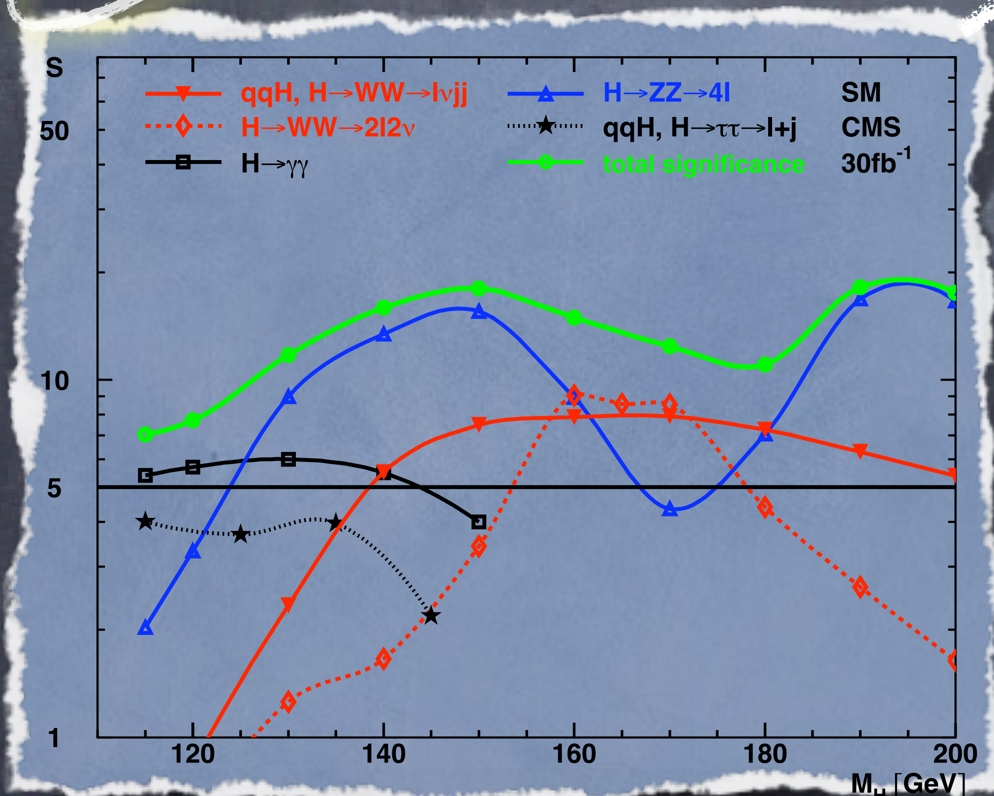
(ILC could go to few % ie test composite Higgs up to $4\pi f \sim 30$ TeV)

# Composite Higgs search @ LHC

Espinosa, Grojean, Muehlleitner '10

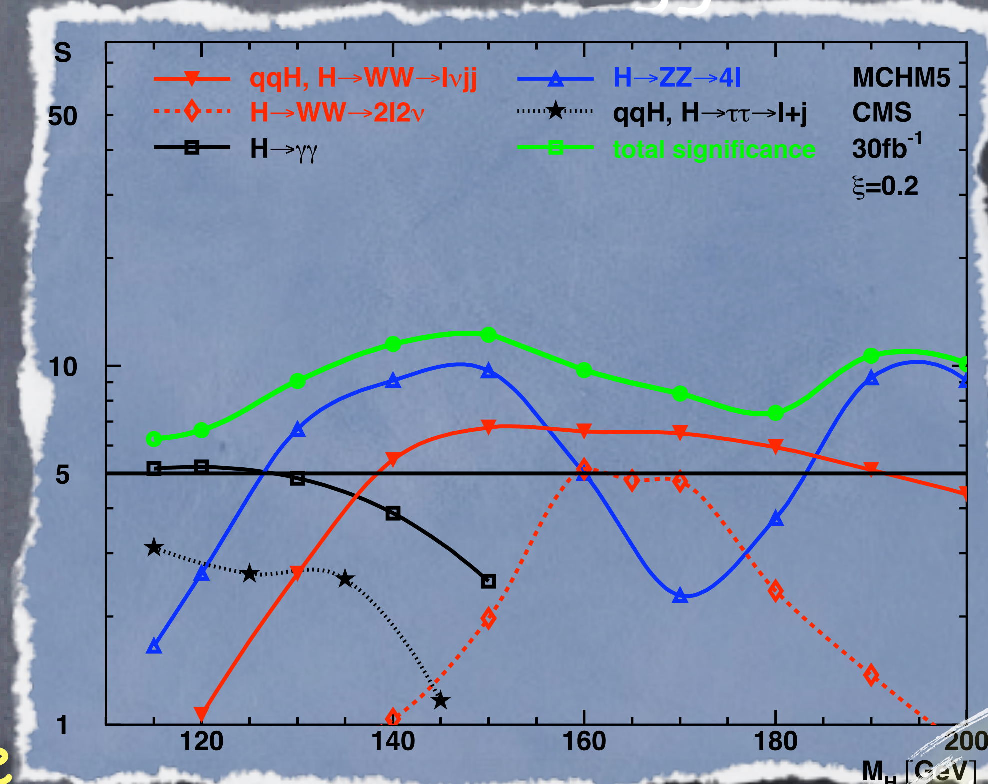
the modification of Higgs couplings and BRs affects the Higgs search

SM



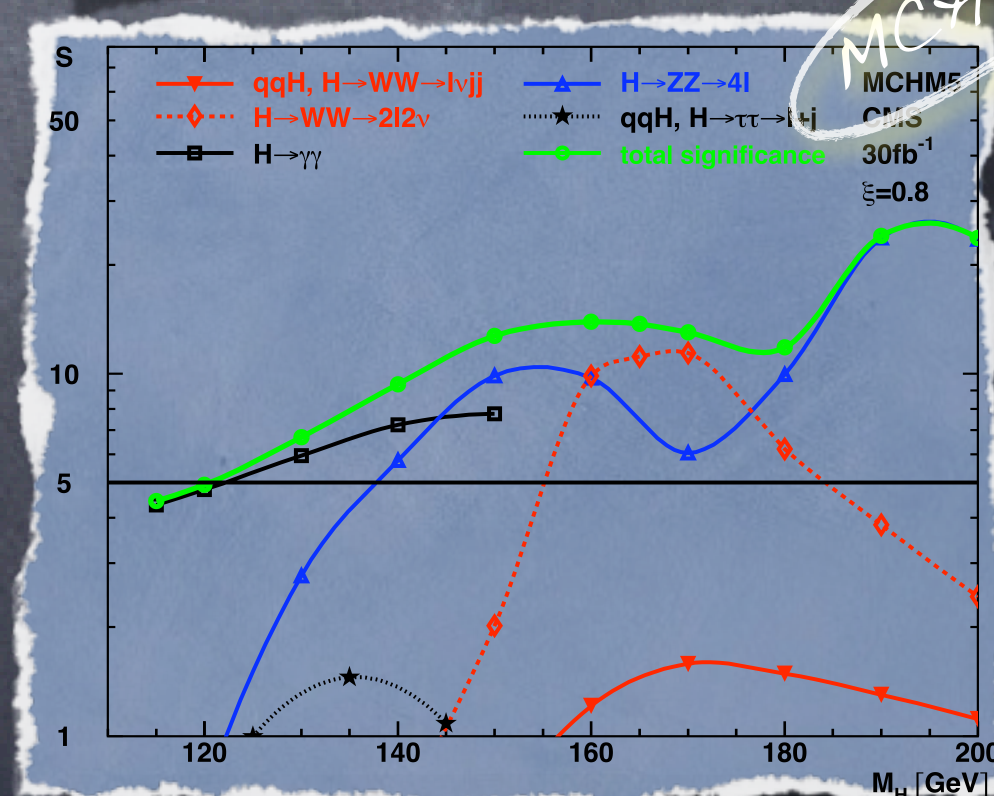

large

compositeness scale




signal significance for L=30/fb

MCHM5



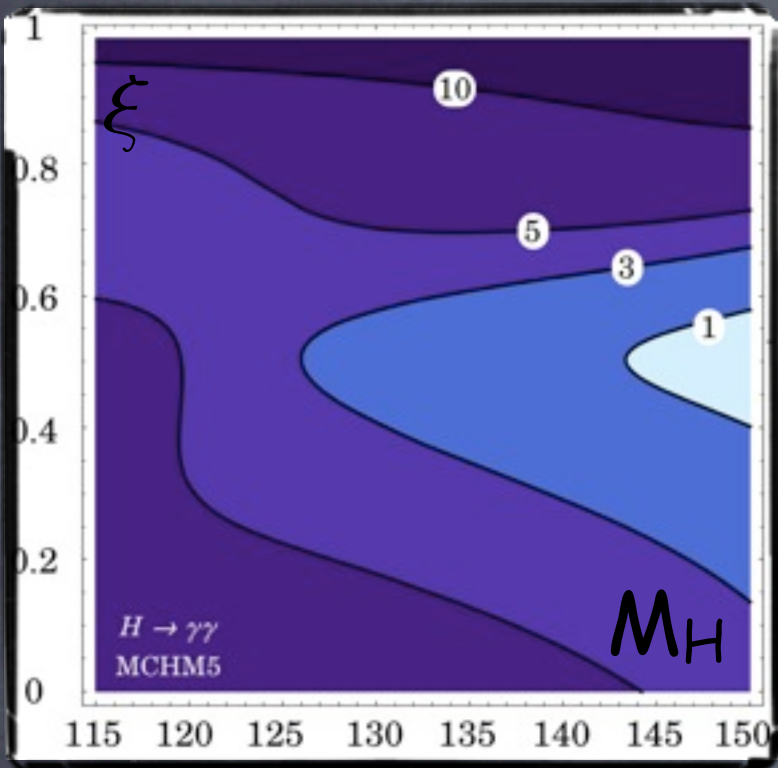

small

compositeness scale

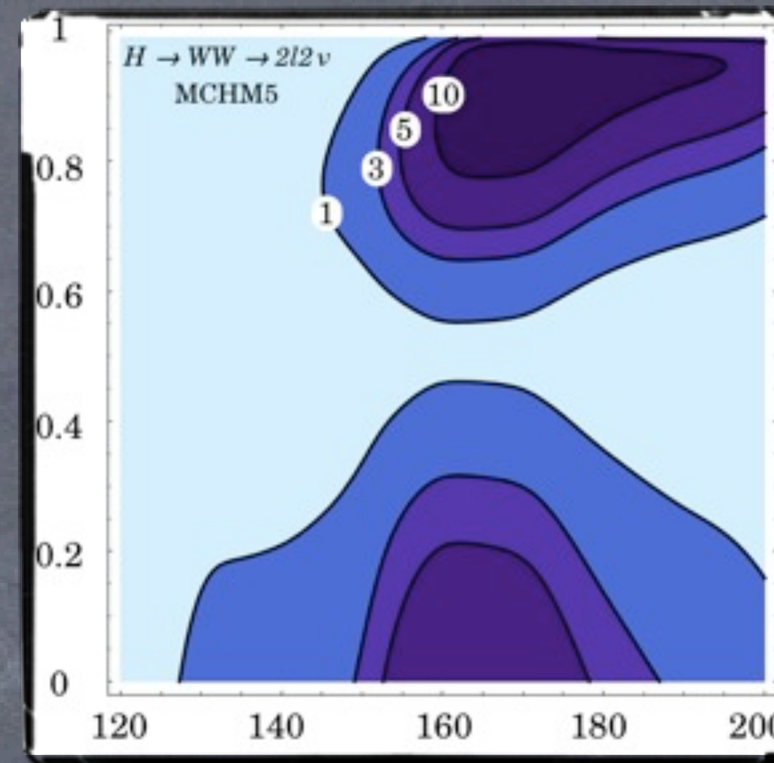
# Composite Higgs search @ LHC

Espinosa, Grojean, Muehlleitner '10

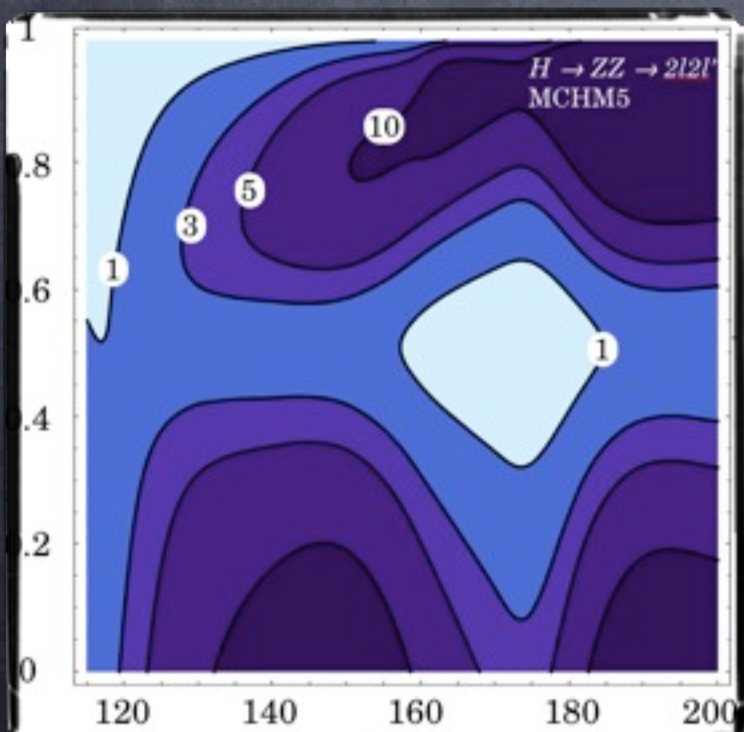
the modification of Higgs couplings and BRs affects the Higgs search

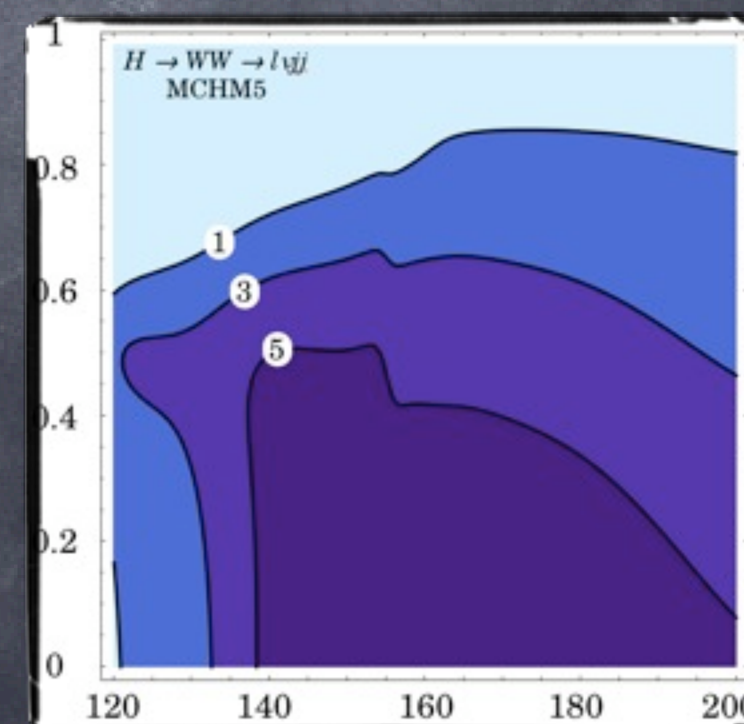



MCHM5




contour lines of signal significance for L=30/fb in the ($\xi$,$M_H$) plane

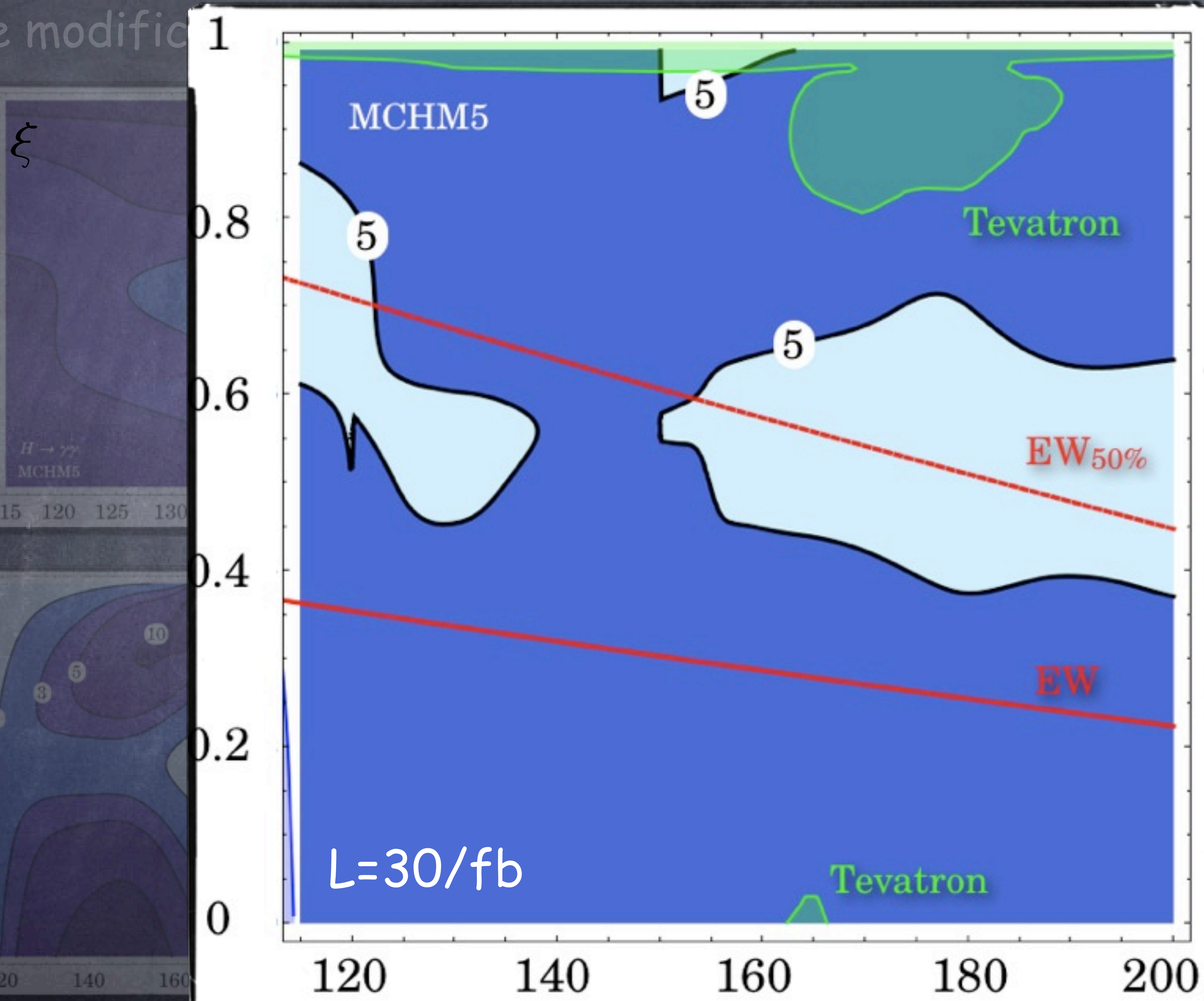



(neglect effects from heavy resonances)

# Composite Higgs search @ LHC

Espinosa, Grojean, Muehlleitner '10



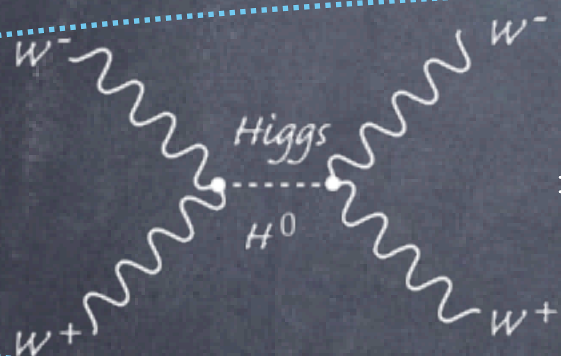
# Strong WW scattering

Giudice, Grojean, Pomarol, Rattazzi '07

$$\mathcal{L} \supset \frac{c_H}{2f^2} \partial^\mu \left(|H|^2\right) \partial_\mu \left(|H|^2\right) \qquad c_H \sim \mathcal{O}(1)$$

$$H = \begin{pmatrix} 0 \\ \frac{v+h}{\sqrt{2}} \end{pmatrix} \Longrightarrow \mathcal{L} = \frac{1}{2}\left(1 + c_H \frac{v^2}{f^2}\right)(\partial^\mu h)^2 + \ldots$$

Modified Higgs propagator $\sim$ Higgs couplings rescaled by $\frac{1}{\sqrt{1+c_H \frac{v^2}{f^2}}} \sim 1 - c_H \frac{v^2}{2f^2} \equiv 1 - \xi/2$




$$= -(1-\xi) g^2 \frac{E^2}{M_W^2}$$

no exact cancellation of the growing amplitudes

Even with a light Higgs, growing amplitudes (at least up to $m_\rho$)

$$\mathcal{A}\left(W_L^a W_L^b \to W_L^c W_L^d\right) = \mathcal{A}(s,t,u)\delta^{ab}\delta^{cd} + \mathcal{A}(t,s,u)\delta^{ac}\delta^{bd} + \mathcal{A}(u,t,s)\delta^{ad}\delta^{bc}$$

$$\mathcal{A}_{\mathrm{LET}}(s,t,u) = \frac{s}{v^2} \Longrightarrow \mathcal{A}_\xi = \xi\, \mathcal{A}_{\mathrm{LET}}$$

LET=SM-Higgs

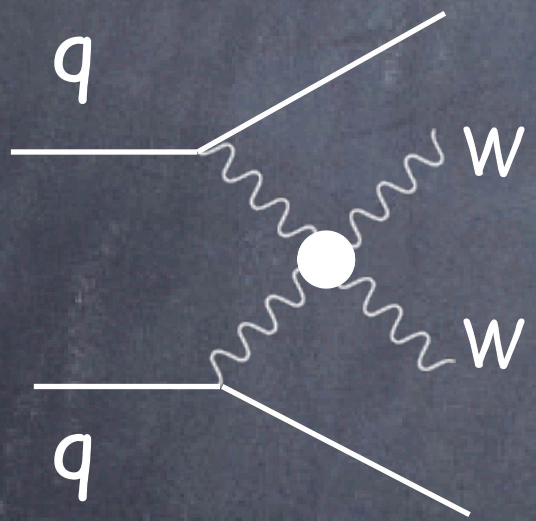
# Strong WW scattering @ LHC

Even with a light Higgs, growing amplitudes (at least up to $m_\rho$)

$$\mathcal{A}\left(Z_L^0 Z_L^0 \to W_L^+ W_L^-\right) = \mathcal{A}\left(W_L^+ W_L^- \to Z_L^0 Z_L^0\right) = -\mathcal{A}\left(W_L^\pm W_L^\pm \to W_L^\pm W_L^\pm\right) = \frac{c_H s}{f^2}$$

$$\mathcal{A}\left(W^\pm Z_L^0 \to W^\pm Z_L^0\right) = \frac{c_H t}{f^2}, \quad \mathcal{A}\left(W_L^+ W_L^- \to W_L^+ W_L^-\right) = \frac{c_H (s+t)}{f^2}$$

$$\mathcal{A}\left(Z_L^0 Z_L^0 \to Z_L^0 Z_L^0\right) = 0$$




$$\sigma\left(pp \to V_L V_L X\right)_\xi = \xi^2 \, \sigma\left(pp \to V_L V_L X\right)_{\mathrm{LET}}$$

leptonic vector decay channels

forward jet-tag, back-to-back lepton, central jet-veto

| | LET($\xi = 1$) | SM bckg |
|---|---|---|
| $ZZ$ | 4.5 | 2.1 |
| $W^+W^-$ | 15.0 | 36 |
| $W^\pm Z$ | 9.6 | 14.7 |
| $W^\pm W^\pm$ | 39 | 11.1 |

$\mathcal{L} = 300\,\mathrm{fb}^{-1}$

Bagger et al '95
Butterworth et al. '02

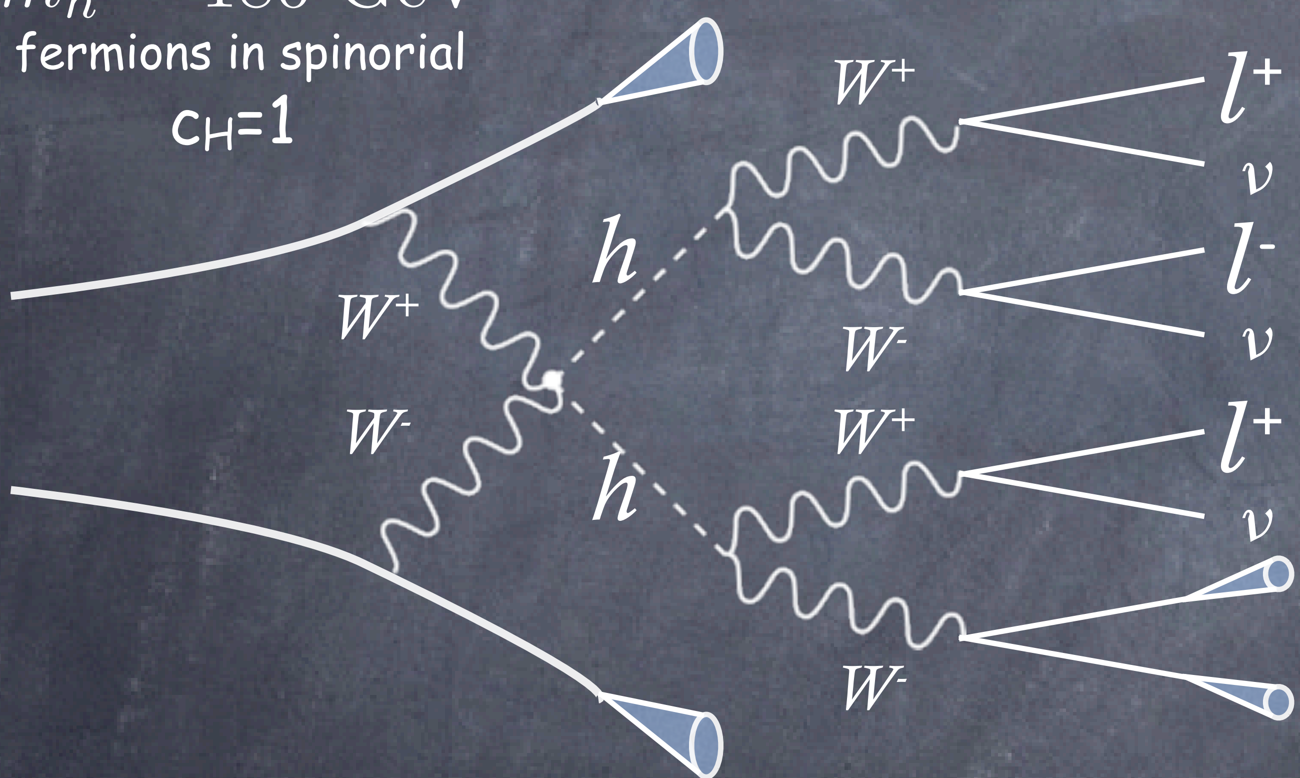
# Strong Higgs production: (3L+jets) analysis

Contino, Grojean, Moretti, Piccinini, Rattazzi '10

strong boson scattering ⇔ strong Higgs production

$$\mathcal{A}\left(Z_L^0 Z_L^0 \to hh\right) = \mathcal{A}\left(W_L^+ W_L^- \to hh\right) = \frac{c_H s}{f^2}$$

$m_h = 180$ GeV
fermions in spinorial
$c_H$=1




acceptance cuts

| jets | leptons |
|---|---|
| $p_T \geq 30$ GeV | $p_T \geq 20$ GeV |
| $\delta R_{jj} > 0.7$ | $\delta R_{lj(ll)} > 0.4(0.2)$ |
| $\lvert\eta_j\rvert \leq 5$ | $\lvert\eta_j\rvert \leq 2.4$ |

Dominant backgrounds: W$ll$4j, $t\bar{t}$W2j, $t\bar{t}$2W(j), 3W4j...

forward jet-tag, back-to-back lepton, central jet-veto

| $v/f$ | 1 | $\sqrt{.8}$ | $\sqrt{.5}$ |
|---|---|---|---|
| significance (300 fb$^{-1}$) | 4.0 | 2.9 | 1.3 |
| luminosity for 5$\sigma$ | 450 | 850 | 3500 |

⇚ good motivation to SLHC

# Conclusions

EW interactions need Goldstone bosons to provide mass to W, Z

⇓ ⇓ ⇓ ⇓ ⇓ ⇓

EW interactions also need a UV moderator/new physics

to unitarize WW scattering amplitude

We'll need another Gargamelle experiment

to discover the still missing neutral current of the SM: the Higgs

weak NC ⇔ gauge principle

Higgs NC ⇔ ?

**LHC is prepared to discover the "Higgs"**

collaboration EXP-TH is important to make sure

e.g. that no unexpected physics (unparticle, hidden valleys) is missed (triggers, cuts...)

**Should not forget that the LHC will be a (quark) top machine**

and there are many reasons to believe that the top is an important agent of the Fermi scale

“The Higgs mechanism is just a reincarnation of the Communist Party: it controls the masses”

attributed to Lenin by L. Álvarez-Gaumé
(according to G. Giudice)