Nambu-Goldstone Composite Higgs(es)

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Based on:
DC, Redi, Tesi, JHEP 1204 (2012) 042
Barducci et al, JHEP 1304 (2013) 152, JHEP 1309 (2013) 047, JHEP 1607(2016) 068
Agugliaro, Antipin, Becciolini, DC, Redi, Phys.Rev.D95 (2017)
DC, Delle Rose, Moretti, Yagyu, 1803.01865

New Frontiers in Theoretical Physics
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Motivations and Outline

- ☑ The 125 GeV Higgs-like signal observed at the LHC could not be the "fundamental" Standard Model Higgs

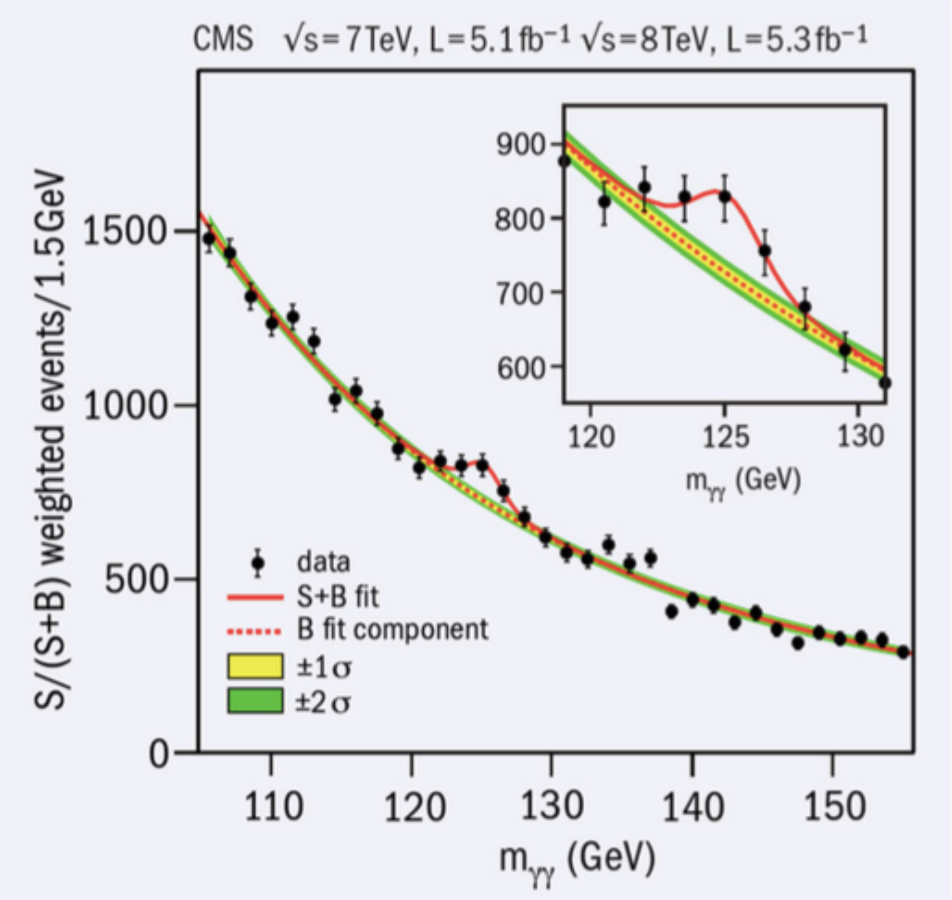
- ☑ From a theoretical point of view the SM is unsatisfactory. Explore BSM solutions: Higgs as a pseudo Nambu-Goldstone boson (pNGB) from a strong dynamics provides an elegant solution for naturalness

- ☑ Minimal realization: the 4-Dimensional Composite Higgs Model (4DCHM) describing also new fermion and vector composite resonances

- ☑ Ideal targets for the LHC program: could produce visible effects without conflict with indirect bounds (scenario more fine-tuned to escape the LHC scrutiny, but not too much)

- ☑ More than one composite Higgs ? Two examples: a composite pNGB realisation of a 2HDM (see *Delle Rose talk*); a composite pNGB doublet which mixes with the elementary Higgs = Partially Composite Higgs

We found the Higgs boson



- ☑ Is it the SM Higgs ?
- ☑ Is it an elementary/composite particle ?
- ☑ Is it natural ?
- ☑ Is it unique ?
- ☑ Is it the first supersymmetric particle ever observed ?
- ☑ Is it really responsible for the masses of all the elementary particles ?
- ☑ Is it a portal to a hidden world ?

Why Beyond the Standard Model ?

Is Naturalness a good guideline?

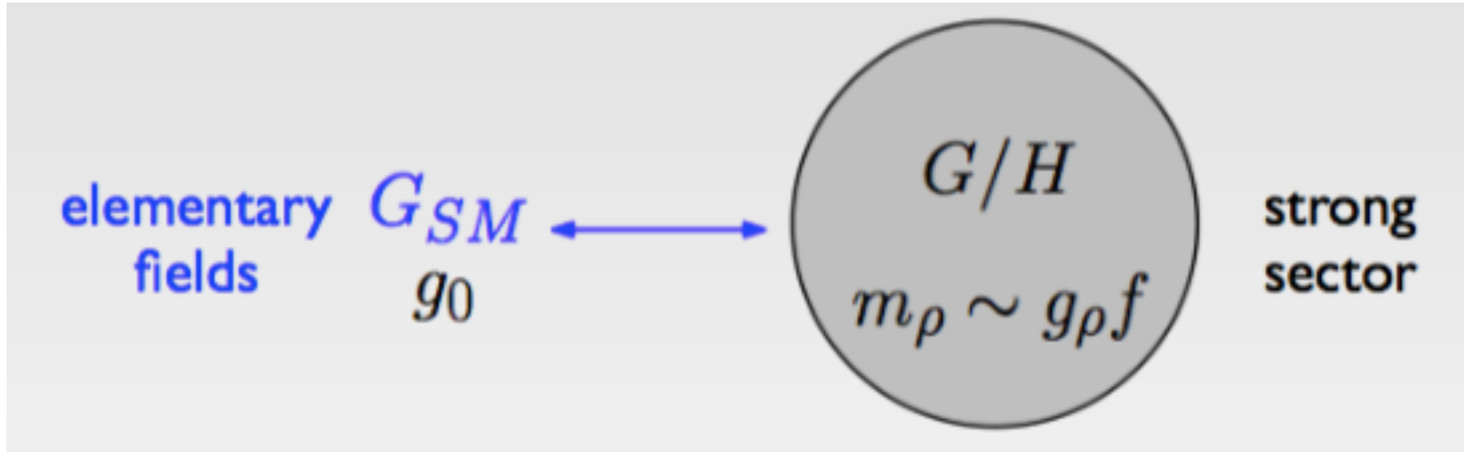
$\sim \Lambda^2 H^\dagger H$

In the SM, Higgs is not naturally light.

New paradigms...

- Supersymmetry
- Strong dynamics near the TeV scale
  - Technicolor
  - Extra Dimension
  - Higgsless
  - Composite Higgs Models

Higgs as a Composite Pseudo Goldstone Boson



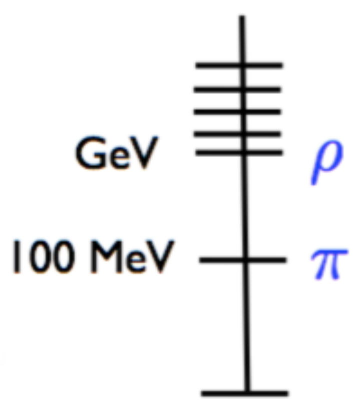
The basic idea

- Higgs as Goldstone Boson of G/H in a **strong** sector

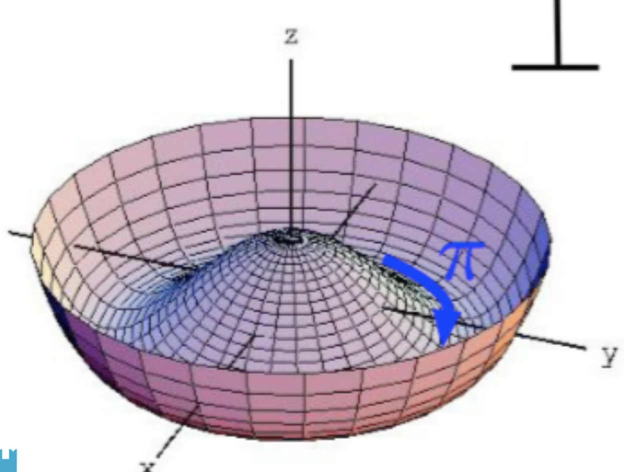
(Georgi, Kaplan '80s)

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

Spectrum:



Are Pseudo-Goldstone bosons (PGB)

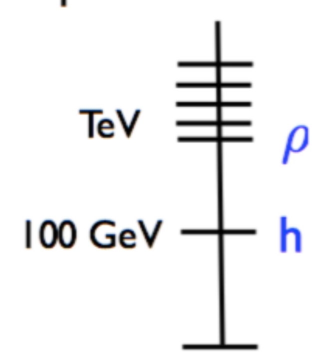


Mass protected by the global QCD symmetry!

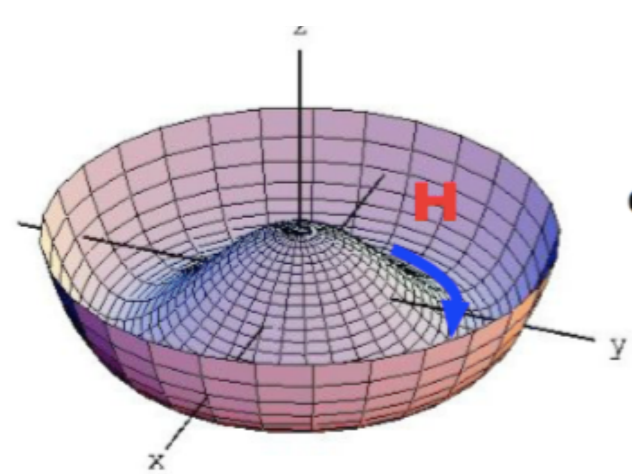
$\pi \to \pi + \alpha$

→ 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:



Pseudo-Goldstone bosons (PGB)



e.g. SO(5) → SO(4)

4 Goldstones

⬇

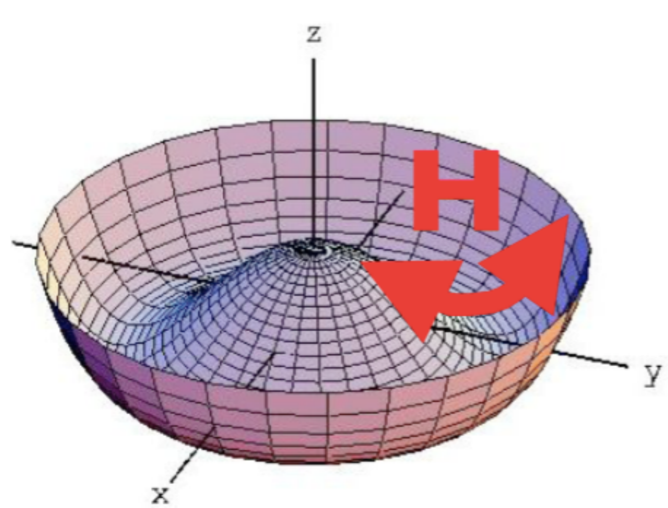
Higgs doublet

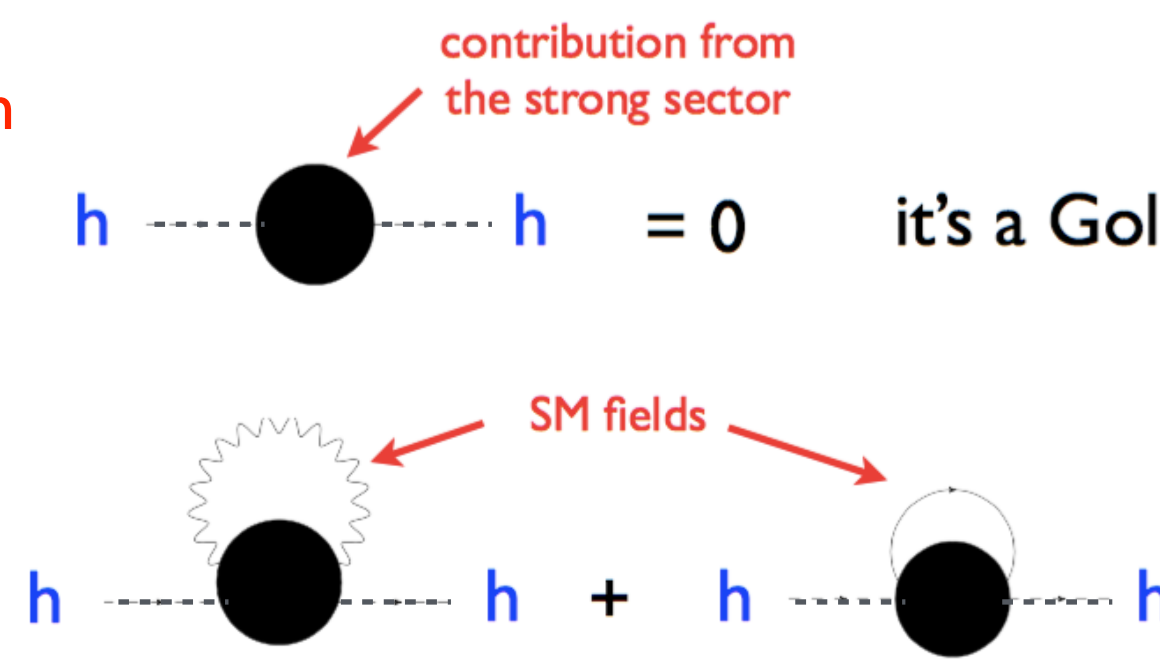
Higgs as a Composite Pseudo Goldstone Boson

How to get an Higgs mass?

- G is only an approximate global symmetry $g_0 \rightarrow V(h)$

SM-field couplings to the strong sector break the global G
SM loop effects → EWSB minimum





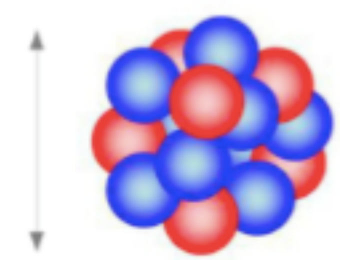
it's a Goldstone

- EWSB as in the SM
- And the hierarchy problem?

no Higgs mass term at tree level

$$\rightarrow \delta m_h^2 \sim \frac{g_0^2}{16\pi^2}\Lambda_{com}^2$$

$l \sim 1/\Lambda_{com}$



Characteristics of a Composite pNGB Higgs

It is not a true (SM-like) Higgs...

$$\mathcal{L} = \frac{1}{2}(\partial_\mu h)^2 + V(h) + \frac{v^2}{4}\mathrm{Tr}\big[(D_\mu\Sigma)^\dagger(D^\mu\Sigma)\big]\left(1 + 2a\frac{h}{v} + b\frac{h^2}{v^2} + \cdots\right)$$

$$-\frac{v}{\sqrt{2}}\sum_{i,j}(\bar{u}^i_L \bar{d}^i_L)\,\Sigma\begin{pmatrix}\lambda^u_{ij}u^j_R\\ \lambda^d_{ij}d^j_R\end{pmatrix}\left(1 + c\frac{h}{v} + \cdots\right) + \mathcal{L}_{SM,\not{h}}$$

$$\Sigma = e^{i\frac{\sigma^a\chi^a}{v}}$$

- SM Higgs for a $a = b = c = 1$
- GB Higgs $a = \sqrt{1 - v^2/f^2},\ b = 1 - 2\ v^2/f^2$ SM limit $f \to \infty$
- Composite Higgs only partly unitarizes WW scattering $A(s,t,u) \sim \frac{s+t}{f^2}$
- Technicolor limit $f = v$

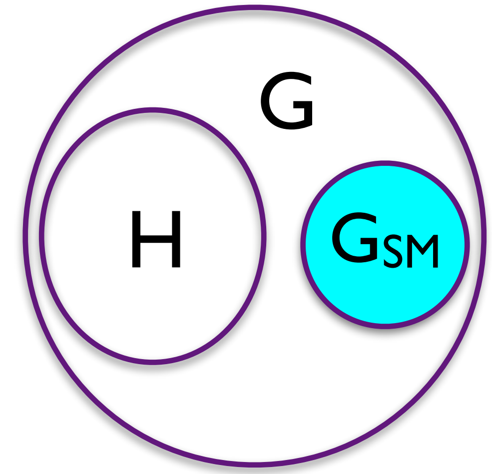
v = EW scale

f = compositeness scale

Composite Higgs Models vs Technicolor

1. $G \supset G_{SM}$
   $H \not\supset G_{SM}$

Technicolor



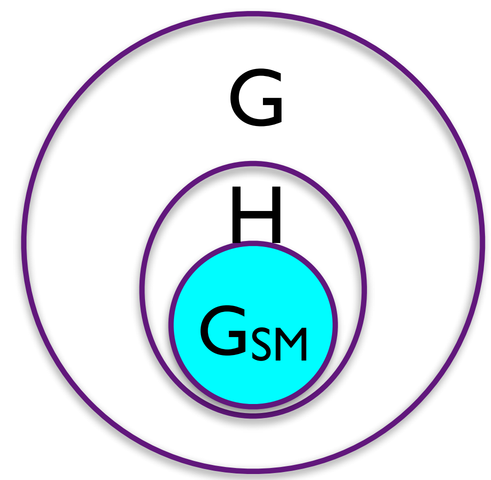
The condensate necessarily breaks G_{SM}

The Higgs can be played by a composite scalar resonance

No explanation for its small mass and its couplings to SM states are not expected to be SM-like

Large corrections to the EW precision measurements

2. $G \to H \supset G_{SM}$

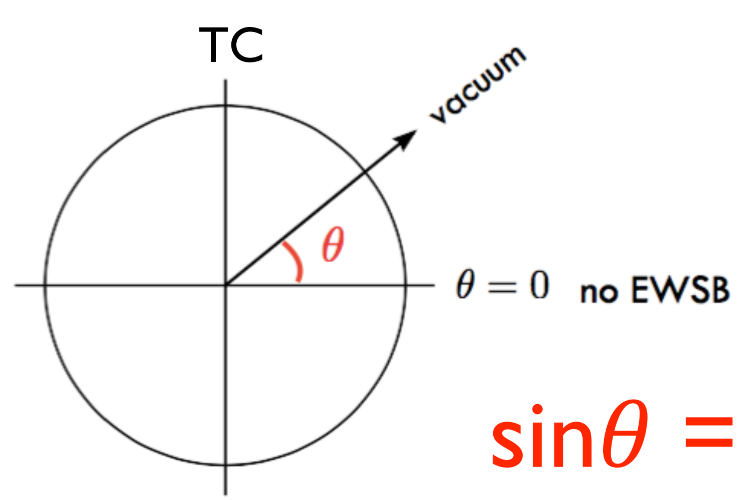


G/H contains a $SU(2)_L$ doublet (composite Higgs)

Vacuum misalignment depends on weak external interactions which can trigger EWSB

The pNGB Higgs mass is smaller than the compositeness scale

The EWSB by strong dynamics depends on the alignment of the vacuum in the global flavour space



small θ : little hierarchy between the EW scale v and the compositeness scale f

$$\sin\theta = v/f$$

Composite Higgs Models

From now on, composite=pseudo-Goldstone

How to construct a *complete* Composite Higgs Model?

- $G/H \supset \mathbf{4}$, $G_{SM} \subset H$
- Computable Higgs mass: finite 1-loop effective potential
- Need for composite resonances!
- Not too large tuning $\quad \xi = \frac{v^2}{f^2}, \quad v = 246 \text{ GeV}, \quad f \sim 1 \text{ TeV}$

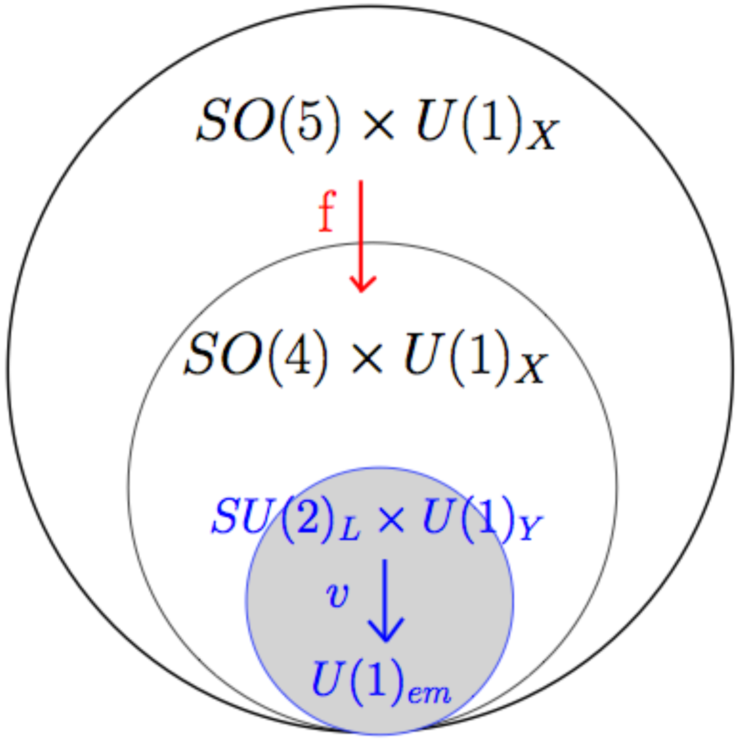
MINIMAL MODEL with $SU(2)_C$

Agashe, Contino, Pomarol (hep-ph/0412089)

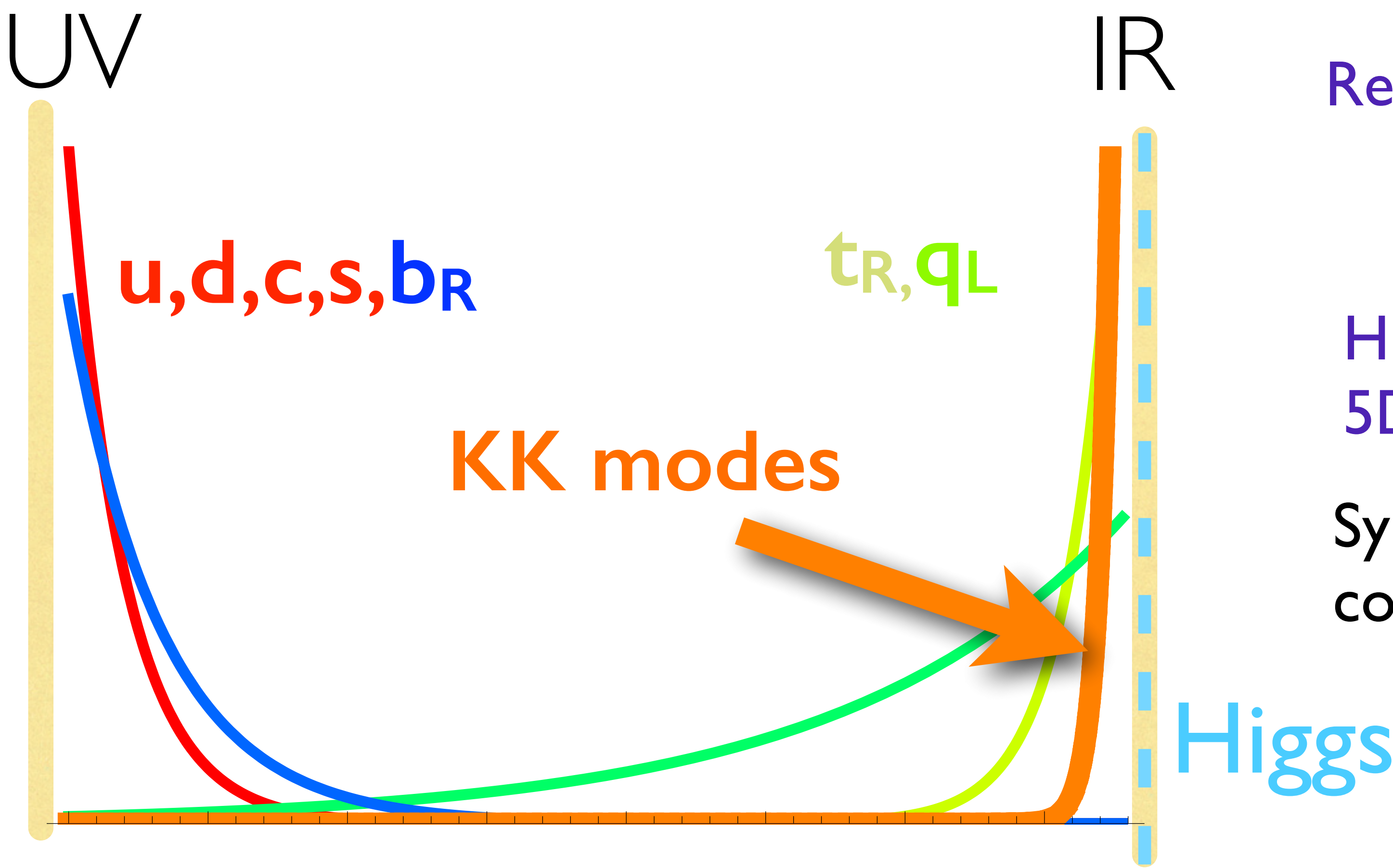
MCHM5

$$\frac{SO(5)}{SU(2)_L \times SU(2)_R} \quad \to \quad \text{GB: } (\mathbf{2}, \mathbf{2})$$

$$\text{Higgs} = \text{pseudo-GB}$$
$$(m_h \ll m_\rho)$$



Composite Higgs Models in 5D



Realised by Randall-Sundrum scenario

$$ds^2 = e^{-2kry}(-dt^2 + dx^2) + dy^2$$

H is the fifth component (A_5) of the 5D gauge field

Symmetry breaking by boundary conditions

resonances = ∞ (KK modes)

Compositeness degree ~ localisation toward the IR brane

Through AdS/CFT correspondence 5D models are dual to 4D strongly coupled theories

Composite physics is largely independent on the 5D bulk
→ only the lowest modes are relevant

➡ Go for an **effective 4D description** with one level of resonances

Explicit Models in 4D

Elementary Sector		Strong Sector
$A_\mu, \psi \in SU(2) \times U(1)_Y$	$\mathcal{L}_{\text{mix}} = g_0 A_\mu J^\mu_\rho + \Delta \bar{\psi} \Psi$	$\rho_\mu, \Psi \in G_{\text{strong}}$
$g_0 < 1$		$m_\rho,\ 1 < g_\rho < 4\pi$

4D Effective descriptions:

- Simplified model (two sectors without GB) Contino, Kramer, Son, Sundrum '07
- General low-energy effective description of a GB Higgs (CCWZ) Giudice, Grojean, Pomarol, Rattazzi '07
- Add the lightest composite resonance Contino et al.'11 De Simone et al. '13; Grojean et al. '13

Discrete models: Panico, Wulzer '11; DC, Redi,Tesi '12

- Deconstruction of a 5D model
- Description of the composite degrees of freedom accessible at the LHC
- Calculability

How to break G/H and add spin-1 resonances

Low-energy Lagrangian determined by the symmetries: CCWZ procedure

Consider the σ-models Ω_1 and Ω_2 $(\Phi_2 = \Omega_2 \phi_0)$ respectively,

$$\frac{G_L \times G_R}{G_{L+R}} \quad \text{and} \quad \frac{G}{H}$$

...and *gauge* $(G_R \times G)_{diag}$ " hidden local symmetry "

$$\mathcal{L} = \frac{f_1^2}{4} \mathrm{Tr} \left| D_\mu \Omega_1 \right|^2 + \frac{f_2^2}{2} (D_\mu \Phi_2)^T D^\mu \Phi_2 - \frac{1}{4 g_\rho^2} \rho^A_{\mu\nu} \rho^{A\mu\nu}$$

new spin-1 resonances $\rho_\mu \in Adj[G]$

$$D_\mu \Omega_1 = \partial_\mu \Omega_1 - i A_\mu \Omega_1 + i \Omega_1 \rho_\mu,$$
$$D_\mu \Phi_2 = \partial_\mu \Phi_2 - i \rho_\mu \Phi_2$$

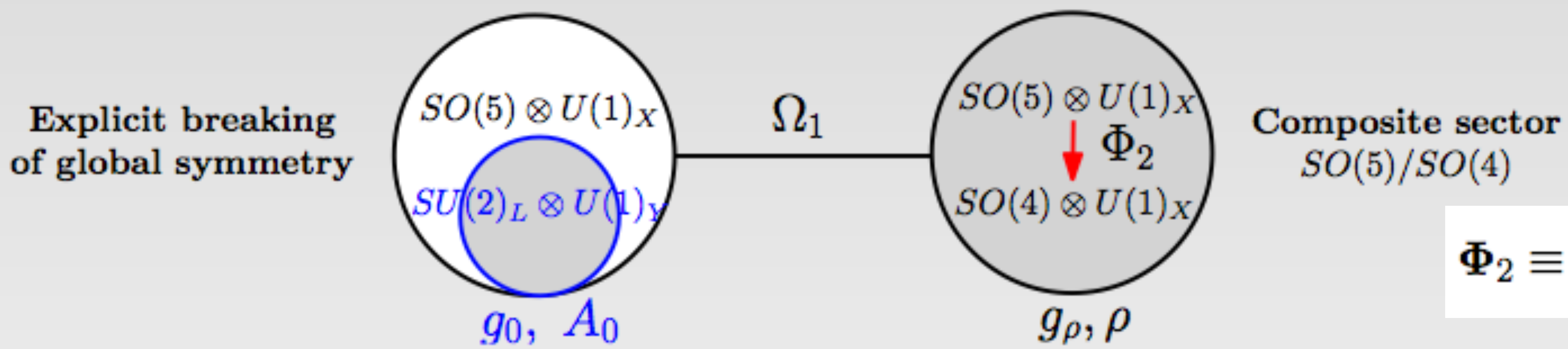
$$\Omega_n = e^{i \frac{f}{f_n^2} h^{\hat{a}} T^{\hat{a}}}$$

- Resonances in H and G/H (as vector/axial QCD mesons)
- G_L non-linear global symmetry, H unbroken one. GB field $\Phi = \Omega_1 \Phi_2$
- Kinetic terms for $A_\mu \in G_{SM}$ fix the model

external sources for the composite sector

4DCHM = Minimal 4D realization of MCHM5

DC, Redi, Tesi '12 Agashe, Contino, Pomarol '04



$\Phi_2 \equiv \Omega_2\varphi_0\ ,\ \ \varphi_0^i = \delta_5^i\ ,$

$$\mathcal{L}_{\rm ele} = -\frac{1}{4}A^a_{\mu\nu}A^a_{\mu\nu} - \frac{1}{4}B_{\mu\nu}B_{\mu\nu}$$

unitary gauge for the ρ

$$\mathcal{L}_{\rm comp} = -\frac{1}{4}\rho^A_{\mu\nu}\rho^A_{\mu\nu} + \frac{1}{2}m_\rho^2\rho^a_\mu\rho^a_\mu + \frac{1}{2}m_{a_1}^2\rho^{\hat a}_\mu\rho^{\hat a}_\mu + |\partial_\mu H - i g_\rho \rho_\mu H|^2 + \text{nl terms...}$$

$$\mathcal{L}_{\rm mix} = \frac{1}{2}m_\rho^2\frac{g_0^2}{g_\rho^2}A_\mu^2 - m_\rho^2\frac{g_0}{g_\rho}A_\mu\rho_\mu + (\partial^\mu H^\dagger A_\mu H)\ \text{nl terms...}$$

$$H = \begin{pmatrix} h_2 + i h_1 \\ h_4 - i h_3 \end{pmatrix}$$

- Non linear structure ↔ GB Higgs → $\Omega_1\Omega_2\varphi_0 = e^{\,i\Pi/f}\varphi_0 = \frac{1}{h}\sin\frac{h}{f}\left(h_1, h_2, h_3, h_4, h\cot\frac{h}{f}\right)$ $\quad h\equiv\sqrt{h^{\hat a}h^{\hat a}}$
- GB decay constant

$$f^2 = \frac{f_1^2 f_2^2}{f_1^2 + f_2^2}$$

- Composite spectrum → new spin-1 resonances: 5 Z' + 3 W'

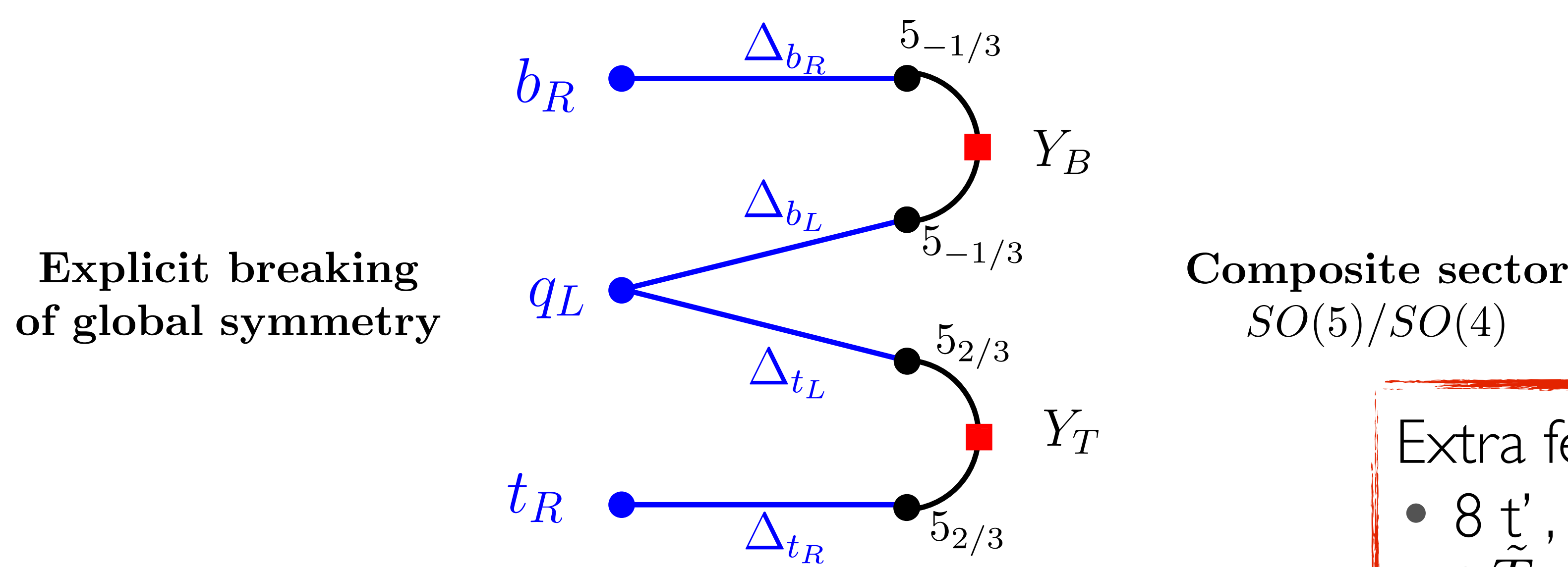
$$SO(4) \to m_\rho^2 = \frac{g_\rho^2 f_1^2}{2}, \qquad \frac{SO(5)}{SO(4)} \to m_{a_1}^2 = \frac{g_\rho^2(f_1^2 + f_2^2)}{2}$$

Fermion sector: which representation?

A phenomenolgical choice (protecting $Zb\bar{b}$) — Agashe, Contino, da Rold, Pomarol '06

$$\mathbf{5}_{2/3} = \underbrace{\mathbf{2}_{1/6}}_{q_L} \oplus \mathbf{2}_{7/6} \oplus \underbrace{\mathbf{1}_{2/3}}_{u_R}, \quad \mathbf{5}_{-1/3} = \mathbf{2}_{5/6} \oplus \underbrace{\mathbf{2}_{1/6}}_{q_L} \oplus \underbrace{\mathbf{1}_{-1/3}}_{d_R}, \quad Y = T_{3R} + X$$

4DCHM: four extra fermions in 5 reps of SO(5) -- minimum for UV finite effective potential



Extra fermions:
- 8 t', 8 b' $Q_{em} = 2/3, -1/3$
- 2 $\tilde{T}$, 2 $\tilde{B}$ $Q_{em} = 5/3, -4/3$

$$\mathcal{L}_{\rm 4DCHM} = \mathcal{L}^{el}_{fermions}$$
$$+ \Delta_{t_L} \bar{q}^{el}_L \Omega_1 \Psi_T + \Delta_{t_R} \bar{t}^{el}_R \Omega_1 \Psi_{\tilde{T}} + h.c.$$
$$+ \bar{\Psi}_T (i \not{D}^\rho - m_T) \Psi_T + \bar{\Psi}_{\tilde{T}} (i \not{D}^\rho - m_{\tilde{T}}) \Psi_{\tilde{T}}$$
$$- Y_T \bar{\Psi}_{T,L} \Phi_2^T \Phi_2 \Psi_{\tilde{T},R} - m_{Y_T} \bar{\Psi}_{T,L} \Psi_{\tilde{T},R} + h.c.$$
$$+ (T \to B)$$

→ Explicit SO(5) breaking

→ Composite physics SO(5)/SO(4)

Partial compositeness: 3rd generation quarks only

Strong sector: resonances + Higgs bound state

→ Extra particle content:
- Spin 1 resonances
- Spin 1/2 resonances

Spectrum :

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

m_T

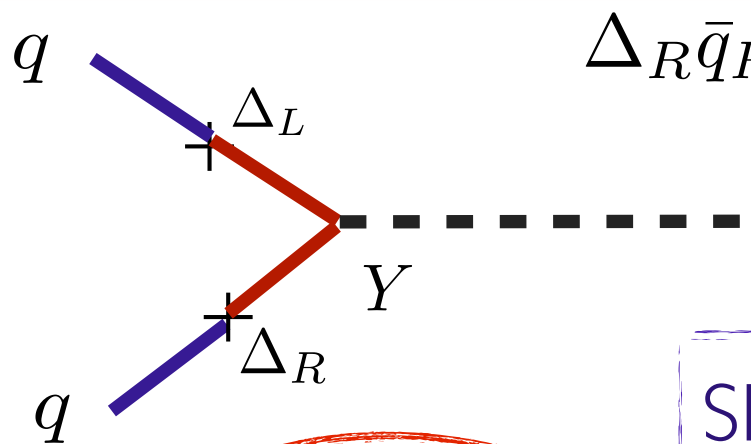
$m_h = 125\,\mathrm{GeV}$ } v

$m_W = 80\,\mathrm{GeV}$

0

g_ρ = strong coupling

Linear elementary-composite couplings (partial compositeness)



$$\Delta_R \bar{q}_R \mathcal{O}_L + \Delta_L \bar{q}_L \mathcal{O}_R + Y \bar{\mathcal{O}}_L H \mathcal{O}_R$$

$$y_{SM} = \epsilon_L \cdot Y \cdot \epsilon_R \qquad \epsilon = \frac{\Delta}{m_Q}$$

SM hierarchies are generated by the mixings:
light quarks elementary, top strongly composite

$$m_t \sim \frac{v}{\sqrt{2}} \frac{\Delta_{t_L}}{m_T} \frac{\Delta_{t_R}}{m_{\tilde{T}}} \frac{Y_T}{f}$$

top Yukawa coupling

What is the nature of the top quark?

Is it a heavy quark or an ordinary quark?

Does composite Higgs imply composite top?

☑ The top quark is the heaviest particle of the SM. Its coupling to the Higgs is the largest of any particle. No justification within the SM (nor for a light Higgs)

Search for an explanation outside the SM

☑ Higgs boson is composite

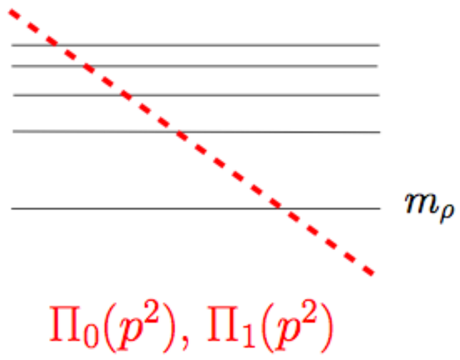
New interactions at the TeV scale bind the Higgs constituents. This is compatible with a Higgs light and weakly coupled if the Higgs is a pseudo Nambu-Goldstone Boson

☑ Compositeness of the Higgs can bring compositeness of the top quark (here realized by the partial compositeness hypothesis) and the prediction of extra particles: vector-like fermions and new vector resonances Z',W'

And the Higgs mass?

$\Delta_{t_{L,R}},\ \Delta_{b_{L,R}},\ g_0, g_{0Y}$ break the global G symmetry

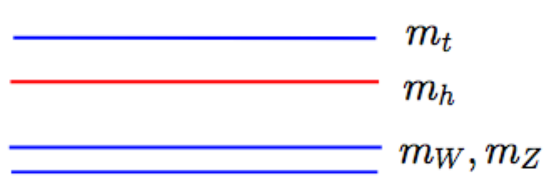
Quantum loops generate V(h)



Integrate out the composite sector and get a low-energy Lagrangian with form-factors

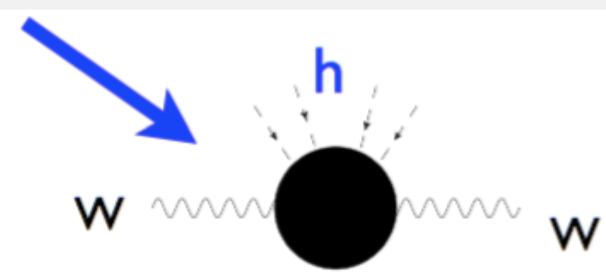
Agashe, Contino, Pomarol '04

Gauge Sector



$$\mathcal{L} = \frac{P^T_{\mu\nu}}{2}\left[\left(\Pi_0(p) + \frac{s_h^2}{4}\Pi_1(p)\right)A^a_\mu A^a_\nu + \left(\Pi_B(p) + \frac{s_h^2}{4}\Pi_1(p)\right)B_\mu B_\nu + 2s_h^2\,\Pi_1(p)\,\widehat{H}^\dagger T^a_L Y \widehat{H}\,A^a_\mu B_\nu\right], \qquad s_h^2 = \sin^2\frac{h}{f}$$

- $\Pi_i(p)$ form factors of the composite sector



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

from m_W^2 and $\Pi_1(0) = f^2$

EW scale

$$v^2 = f^2\sin^2\frac{\langle h\rangle}{f}$$

- SM couplings

$$\frac{1}{g^2} = -\Pi_0'(0) = \frac{1}{g_0^2} + \frac{1}{g_\rho^2}$$

$$\frac{1}{g'^2} = -\Pi_B'(0) = \frac{1}{g_{0Y}^2} + \frac{1}{g_\rho^2} + \frac{1}{g_{\rho X}^2}$$

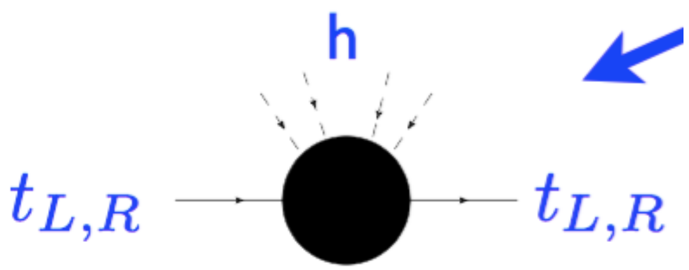
And the Higgs mass?

analogously with fermions (here only top): **(Contino, Da Rold, Pomarol '06)**

$$\mathcal{L}_{\rm eff}^{ferm} = \bar{q}_L \not{p} \left(\Pi_0^q(p^2) + \frac{1}{2} s_h^2 \Pi_1^q(p^2) \hat{H}_c \hat{H}_c^\dagger \right) q_L + \bar{t}_R \not{p} \left(\Pi_0^t(p^2) + \frac{1}{2} s_h^2 \Pi_1^t(p^2) \right) t_R$$

$$+ \frac{s_h c_h}{\sqrt{2}} M_1^t(p^2)\ \bar{q}_L \hat{H}_c t_R + \text{h.c.}$$

strong sector contribution in the h-background



top Yukawa coupling

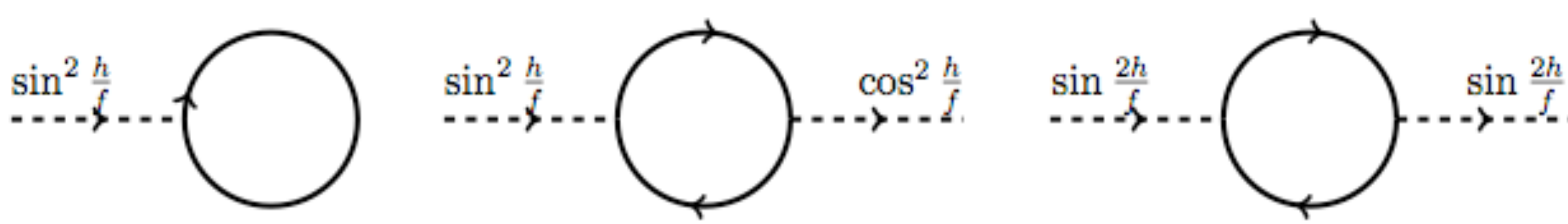
$$m_t \simeq \frac{1}{\sqrt{2}} \frac{\Delta_{tL}}{m_T} \frac{\Delta_{tR}}{m_{\tilde{T}}} \frac{Y_T}{f} v \equiv \frac{1}{\sqrt{2}} y_t\ v$$

Coleman-Weinberg effective potential generated at 1-loop

$$V(h)_{gauge} = \frac{9}{2} \int \frac{d^4p}{(2\pi)^4} \ln \left[1 + \frac{1}{4} \frac{\Pi_1(p^2)}{\Pi_0(p^2)} \sin^2 \frac{h}{f} \right] \approx \int \frac{d^4p}{(2\pi)^4} \frac{9\Pi_1}{8\Pi_0} \sin^2 \frac{h}{f}$$

$$V(h)_{fermions} \approx -N_c \int \frac{d^4p}{(2\pi)^4} \left[\frac{\Pi_1^{q_1}}{\Pi_0^q} + \frac{\Pi_1^u}{\Pi_0^u} \right] \sin^2 \frac{h}{f} + N_c \int \frac{d^4p}{(2\pi)^4} \left[\frac{(M_1^u)^2}{p^2 \Pi_0^q \Pi_0^u} \right] \sin^2 \frac{h}{f} \cos^2 \frac{h}{f}$$

triggers the EWSB



UV finite in the 4DCHM

Coleman-Weinberg effective potential generated at 1-loop

$$V(h) \approx \alpha\, s_h^2 - \beta\, s_h^2 c_h^2$$

EWSB $\longrightarrow$ $\langle s_h \rangle = \dfrac{v}{f} = \sqrt{\dfrac{\beta - \alpha}{2\beta}} \neq 0$

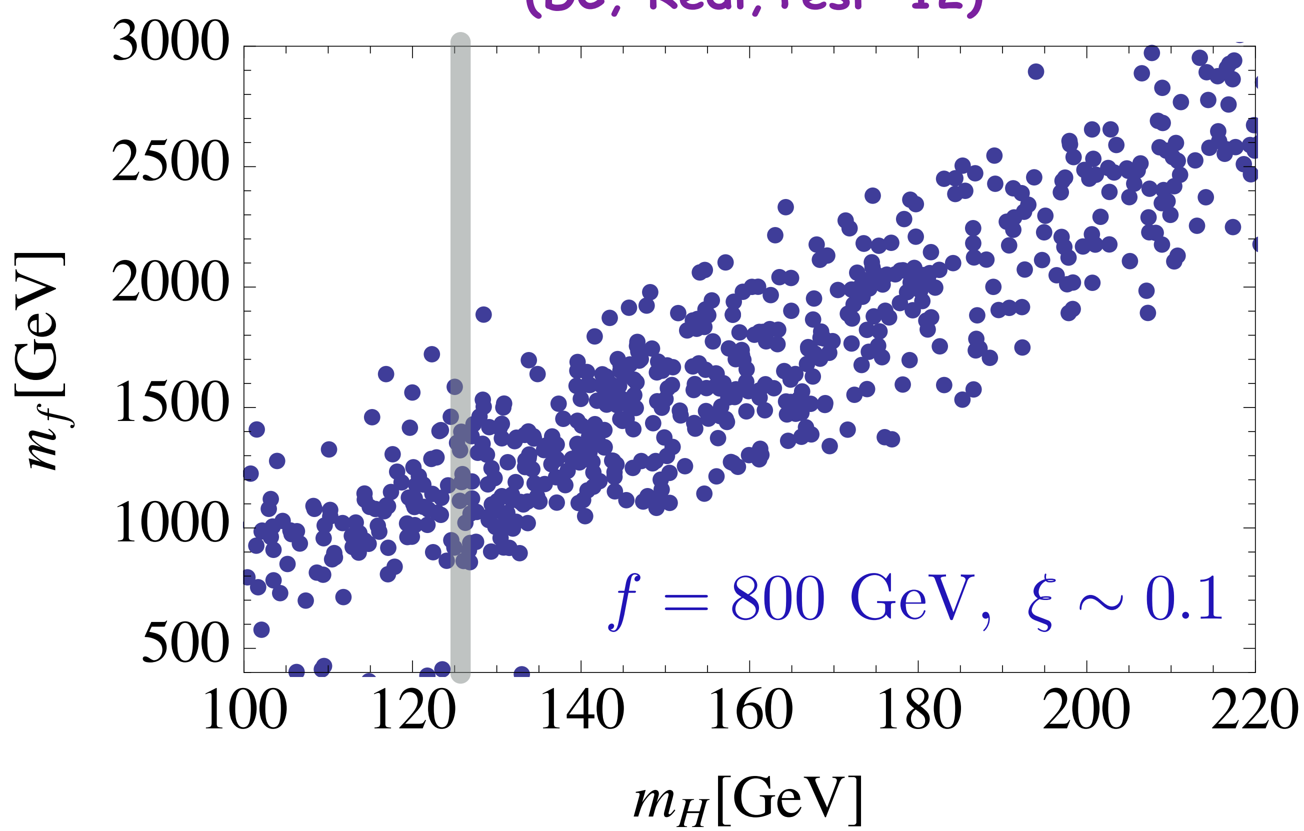
lightest extra-fermion mass

Higgs mass $\quad m_H^2 \simeq \dfrac{8\beta v^2}{f^4} \sim 0.3\, y_t \dfrac{m_f}{f} v$

top Yukawa coupling

Correlation with the lightest extra-fermion mass

(DC, Redi, Tesi '12)



125 GeV Higgs asks for light (in the TeV region) fermionic partners ➞ we are still in the ballpark with LHC bounds

Heaviest extra-fermions require a larger f value and a larger tuning

Tuning

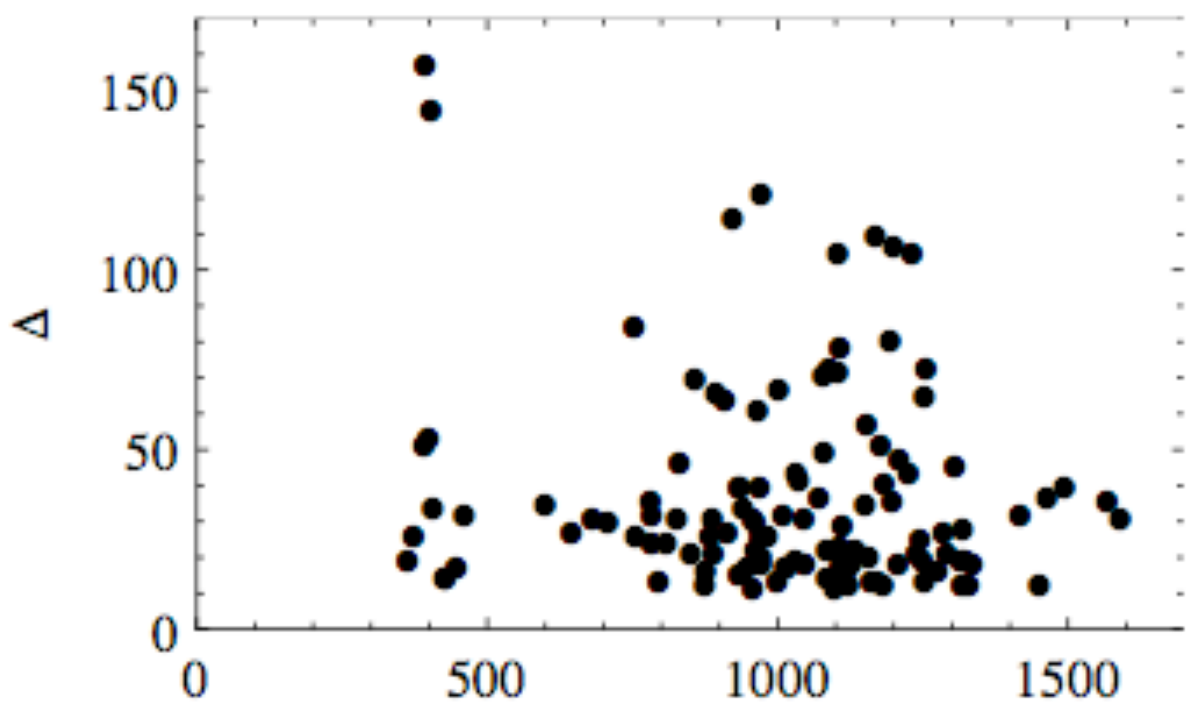
The Higgs potential generically has its minimum for <h> ~ f
For the phenomenological success of the model <h> ~246GeV i.e. $\xi = \left(\frac{v}{f}\right)^2 = \sin^2\frac{\langle h\rangle}{f} < 1$
This requires some cancellations → TUNING

$$\Delta = \mathrm{Max_i}\left|\frac{\partial \log m_Z}{\partial \log x_i}\right|$$

The tuning depends on the structure of the Higgs potential i.e. the fermionic repr. and the size of the fermionic couplings

The minimal tuning is $\Delta_{min} \sim 1/\xi$

An additional amount of tuning comes from the requirement $\alpha \lesssim \beta$ in the potential



m_{lightest} (GeV) = mass of the lightest extra-fermion

SO(5) → SO(4) with fermions in **5** rep.
and f = 800 GeV (ξ =0.1)
i.e. $\Delta_{min} \sim 10$

$$\Delta_{avg} \sim 30$$

(Panico, Redi, Tesi, Wulzer '12)

Composite Higgs and Flavour

In SM, the Yukawa interactions are the only source of the fermion masses

$$y_{ij}\bar{f}_{L_i}Hf_{R_j} = \frac{y_{ij}v}{\sqrt{2}}\bar{f}_{L_i}f_{R_j} + \frac{y_{ij}}{\sqrt{2}}h\bar{f}_{L_i}f_{R_j}$$

mass

higgs-fermion interactions

both matrices are simultaneously diagonalizable

⇓ ⇓ ⇓

no tree-level Flavor Changing Current induced by the Higgs

In the presence of **higher-dimensional operators** the SM fermion masses can be misaligned in flavour space with the Yukawa couplings → Higgs-mediated FCNC

$$y_{ij}\left(1 + c_{ij}\frac{|H|^2}{f^2}\right)\bar{f}_{L_i}Hf_{R_j} = \frac{y_{ij}v}{\sqrt{2}}\left(1 + c_{ij}\frac{v^2}{2f^2}\right)\bar{f}_{L_i}f_{R_j} + \left(1 + 3c_{ij}\frac{v^2}{2f^2}\right)\frac{y_{ij}}{\sqrt{2}}h\bar{f}_{L_i}f_{R_j}$$

In the case of a pNGB Higgs the shift symmetry forces an alignment of the fermion mass terms with their Yukawa couplings at leading order in the fermion degree of compositeness

BONUS

$$y_{ij}(1 + c_{ij}\frac{|H|^2}{f^2} + \cdots)\bar{f}_{Li}Hf_{Rj} \to y_{ij}\bar{f}_{Li}P(\Sigma)f_{Rj}$$

$$\Sigma = e^{iH/f}$$

$P(\Sigma)$ is a polynomial containing all the non-linearities → Flavour violation occurs only through the derivative operators ~ bounds coming from loops as in the SM

(Agashe, Contino '09)

Extra-fermions and Flavour

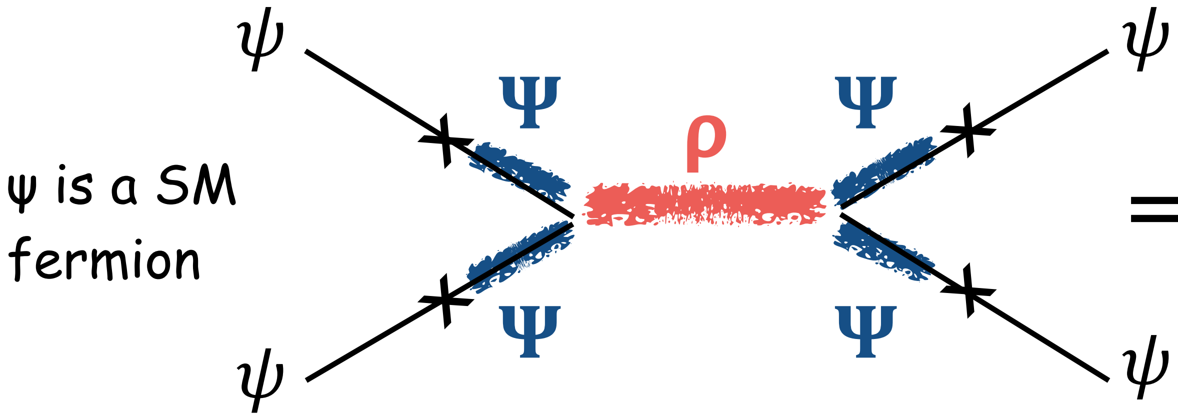
partial compositeness = general framework to generate the SM fermion masses and couplings

To construct a complete model we need to implement the SM structure with 3-families

$$\mathcal{L}_{mixing} = \Delta_L^{ij} \bar{\psi}_L^i \mathcal{O}_R^j + \Delta_R^{ij} \bar{\psi}_R^i \mathcal{O}_L^j \qquad \Delta_{L,R}^{ij} = \lambda_{L,R}^{ij} f$$

NON TRIVIAL TASK to ensure the suppression of flavour violating effects

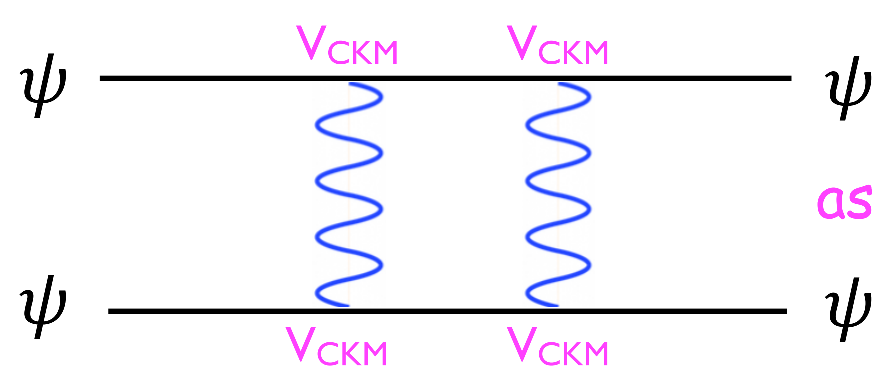
Four-fermion operators are generated integrating out the composite fermions and vectors



$$\Rightarrow \quad \frac{x_{ijkl}}{f^2} \psi_i \psi_j \psi_k \psi_l$$

They can mediate FCNC at tree-level if the flavour coefficients $x^{ijkl} \sim (\lambda\lambda)^{ij} (\lambda\lambda)^{kl}$ are generic

These effects are suppressed if a partial alignment of λ^{ij} with the CKM matrix is realised



as in the SM

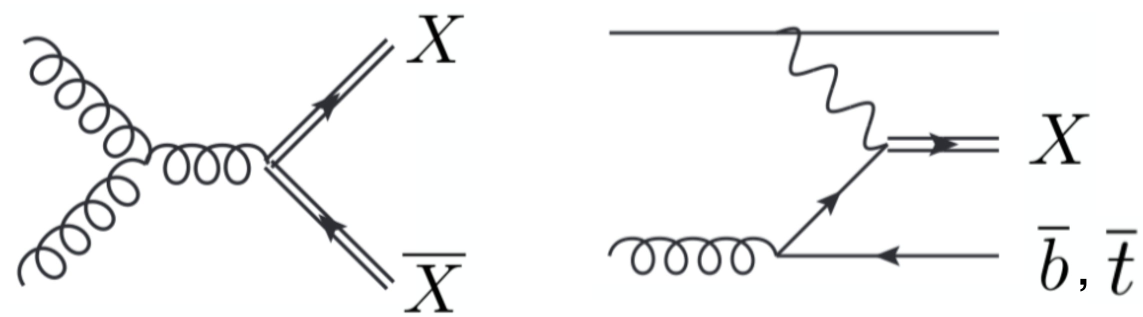
(Redi, Weiler 11; Barbieri et al. 12)

Indirect / Direct bounds on the 4DCHM and signals at the LHC and Future Colliders

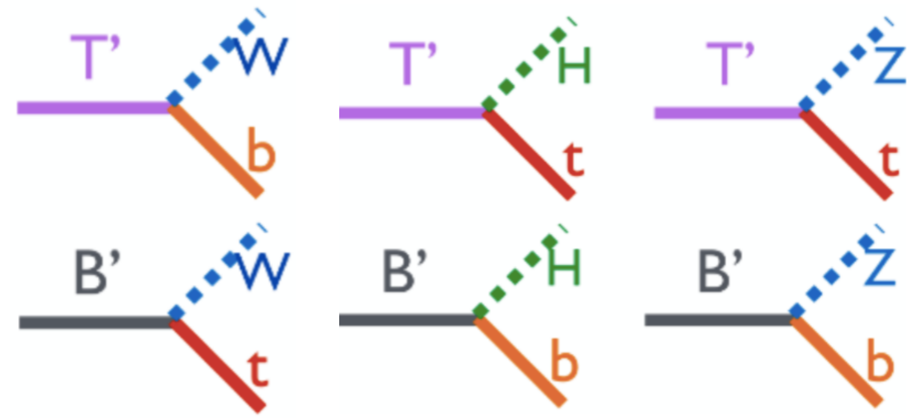
Composite fermions with charges 2/3,-1/3, 5/3,-4/3

Bounds from multiple topology searches: pair production (model independent) and associated single production (depends on the couplings)

- Production:

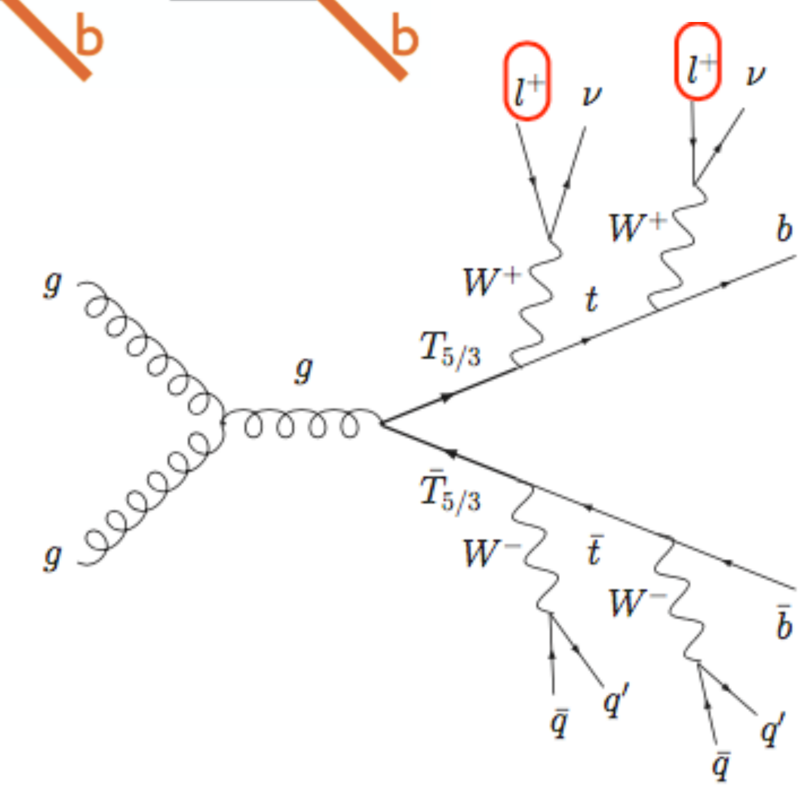


- Decays:

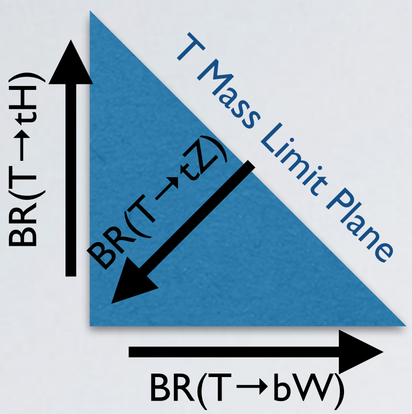


- Multi-lepton signatures:

Ex: $T_{5/3}$ pair production and decay in Wt leading to same sign di-leptons in the final state

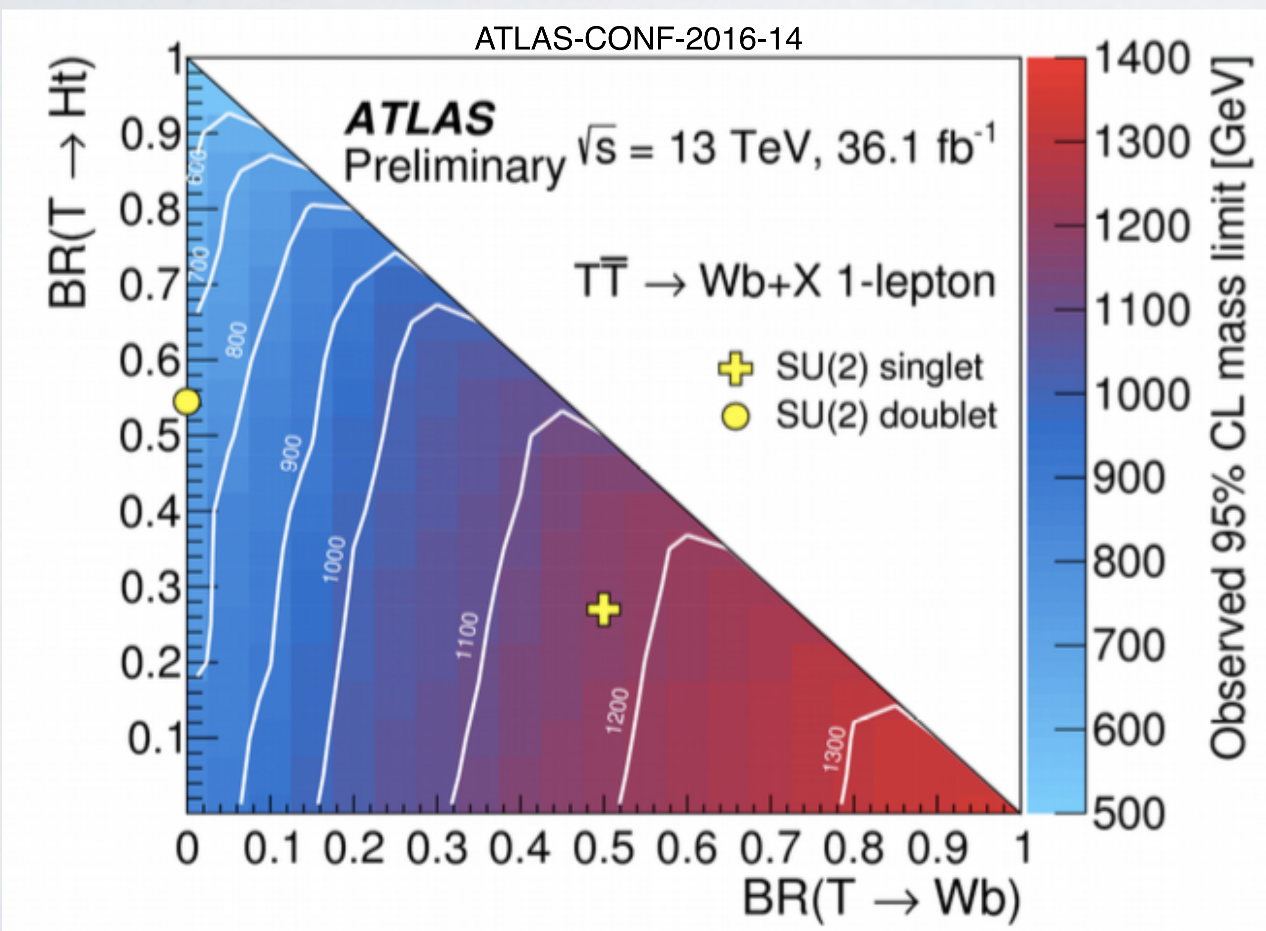


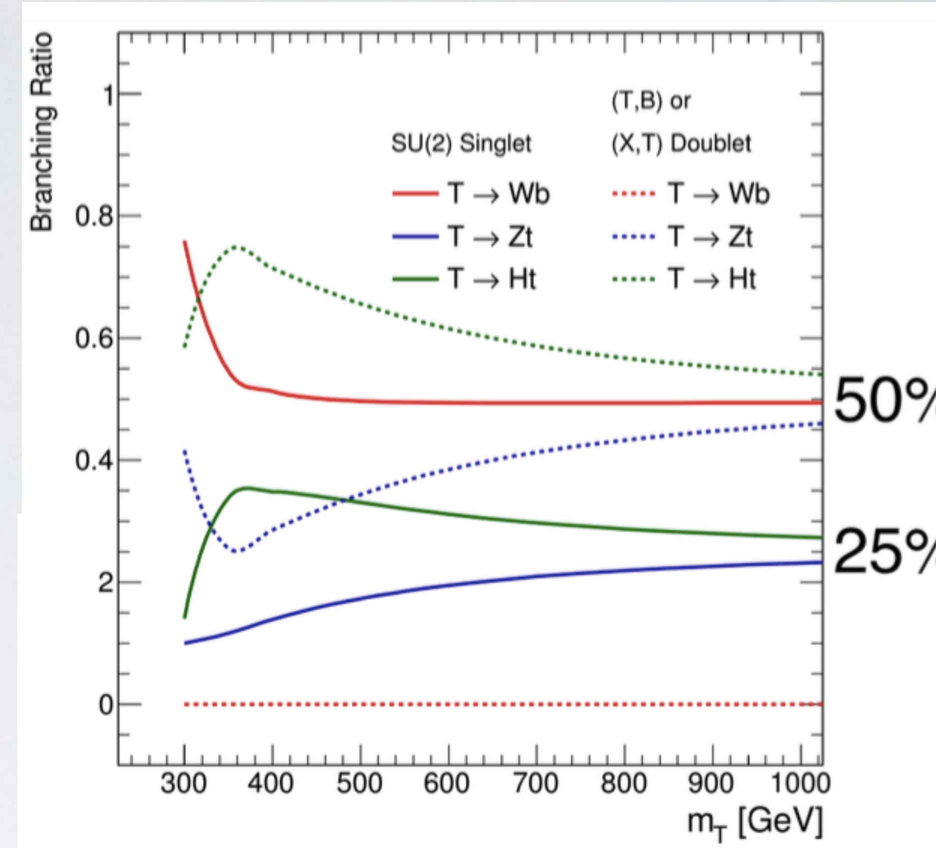
Lower bounds on the partners of the 3rd generation quarks by direct searches



Pair production searches set σ x BR limits depending on the extra-fermion mass and on the assumption for the BR

M. Narain talk, LFC17 ECT Sept.2017*





$5_{2/3}=(2,2)_{2/3}+(1,1)_{2/3}$

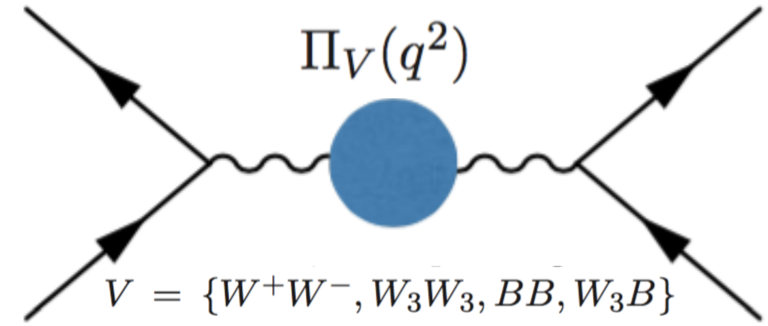
$$(\mathbf{2},\mathbf{2})_{2/3} = \begin{pmatrix} T & T_{\frac{5}{3}} \\ B & T_{\frac{2}{3}} \end{pmatrix}$$

$T_{5/3}=X$ $B_{-4/3}=Y$

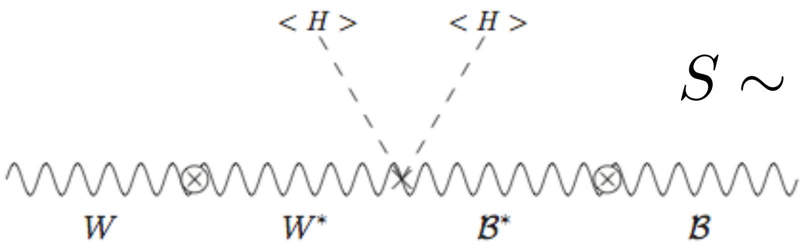
- Significantly improved limits (Run1)
  - $m_{T/Y}$(Wb=100%) > 1350 (782) GeV
  - m_T (singlet) > 1170 GeV
  - $m_{B/X}$ (Wt=100%) > 1250 GeV
  - m_B(singlet) > 1180 GeV
- Not very much improvement with 300/3000 fb-1

m_T(Wb=50%) > 1-1.2 TeV

Electro-Weak Precision Tests



- S-parameter ~ $\Pi'_{W_3B}(0)$

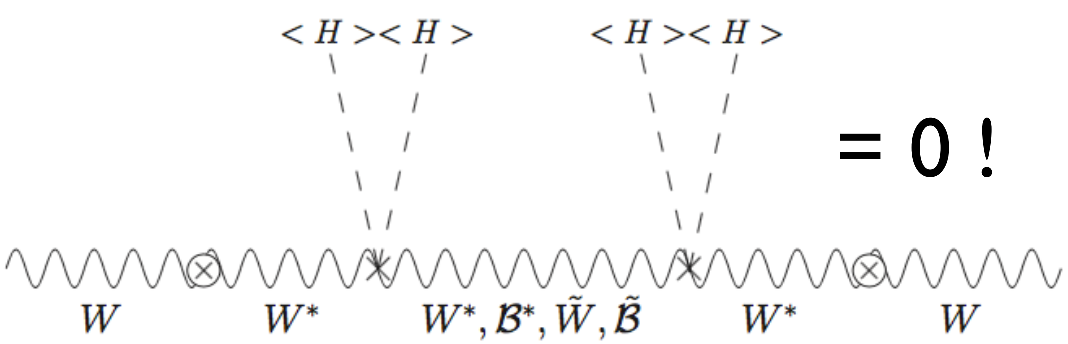


$$S \sim 4\pi v^2 \left(\frac{1}{m_\rho^2} + \frac{1}{m_{a_1}^2} \right)$$

$S \in [-0.1, 0.2] \longrightarrow m_\rho \geq 2 \text{ TeV}$

LHC competitive with LEP

- T-parameter ~ $\Pi_{W_3W_3}(0) - \Pi_{W^+W^-}(0)$ $\quad T \in [-0.1, 0.2]$



= 0 !

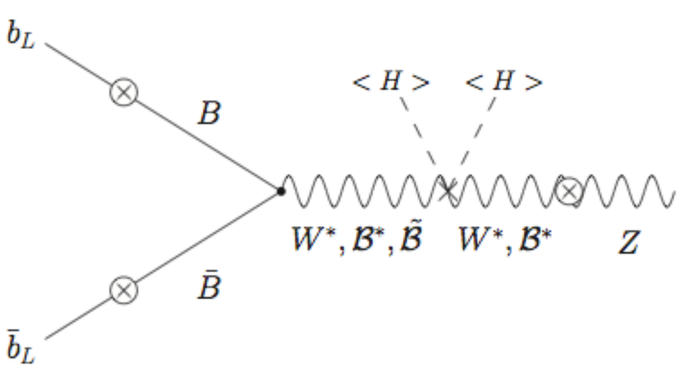
no tree-level due to $SU(2)_L \times SU(2)_R$ custodial symmetry of the composite gauge sector

1-loop contribution mainly from the extra-fermion sector (Contino, Kramer, Son, Sundrum '11)

- Non-universal corrections: Zb_Lb_L coupling

In the 4DCHM the choice of the fermion repr. prevents large corrections (as they are in Zt_Lt_L)

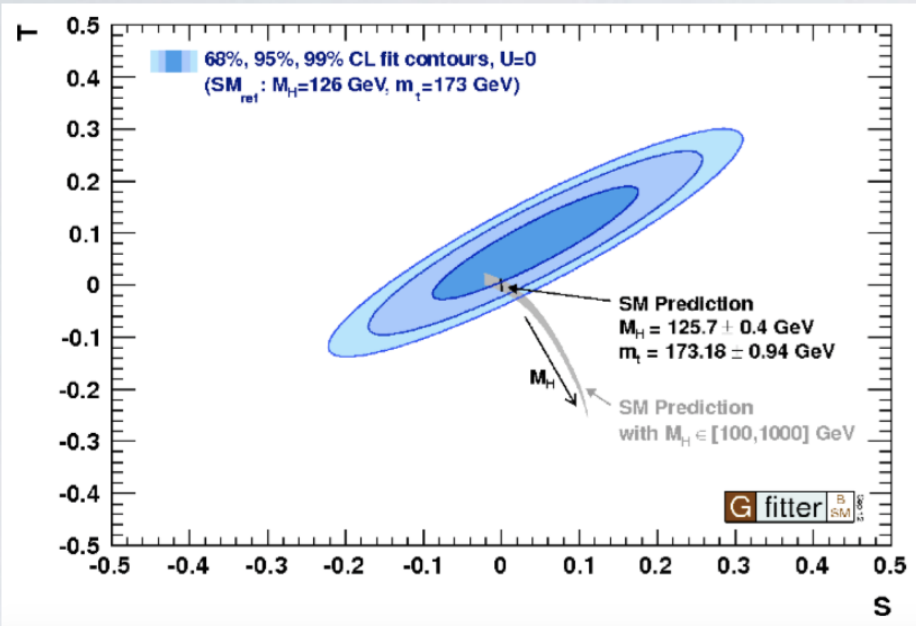
(Agashe, Contino, Da Rold, Pomarol '06, DC, Redi, Tesi, '12)



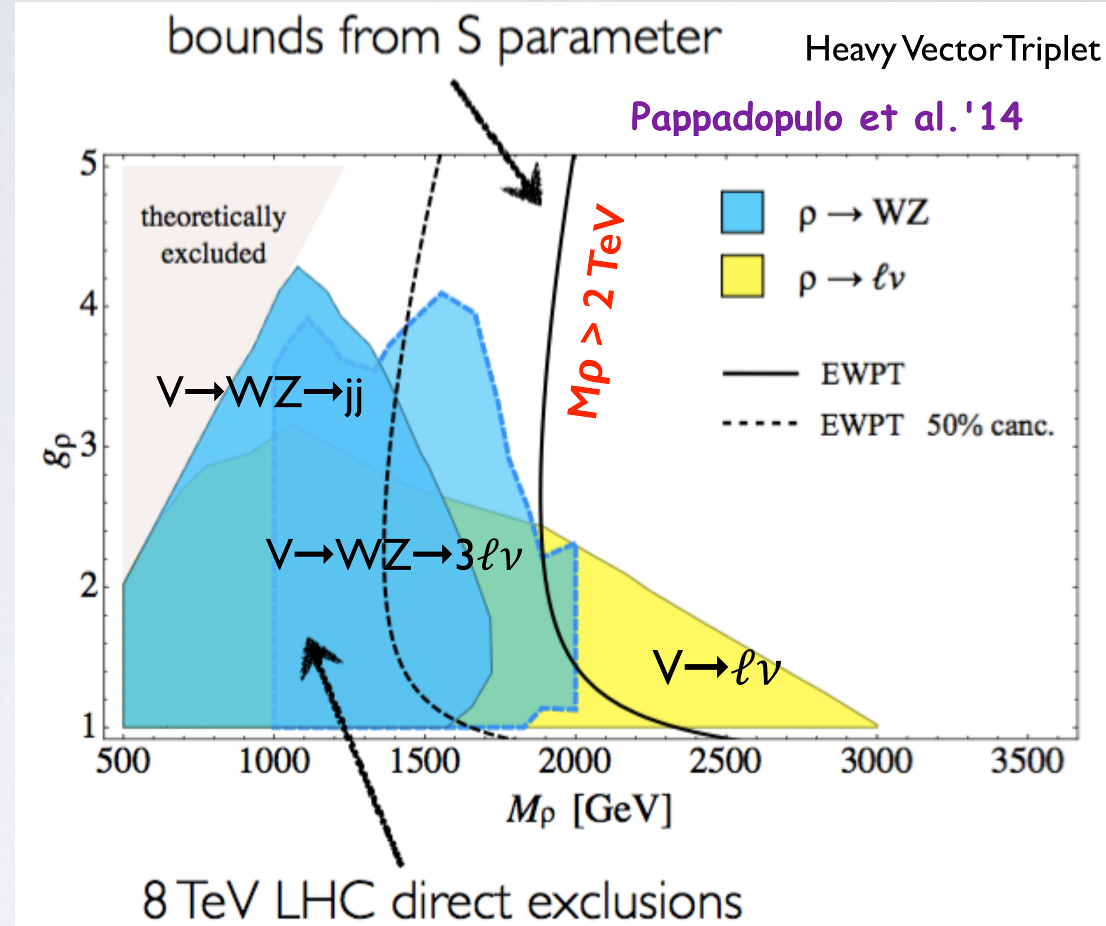
$$\frac{\delta g_{bL}}{g_{bL}^{SM}} \sim \epsilon_L^2 \frac{f^2}{m_B^2} \frac{v^2}{m_\rho^2}\Big|_{\max} \sim 10^{-3}$$

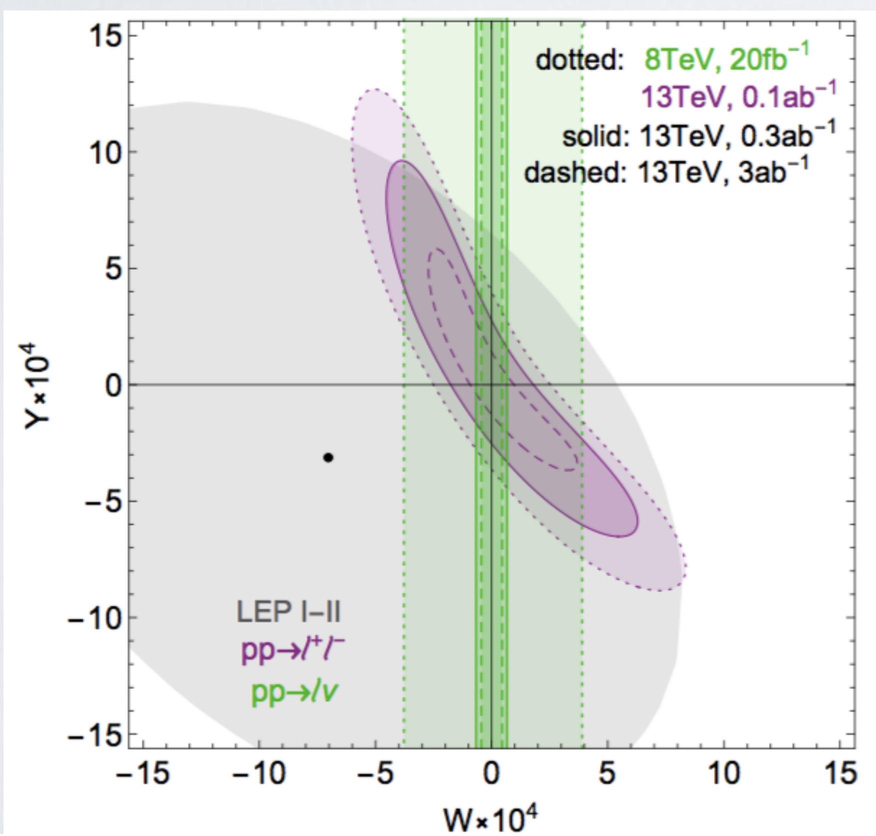
size comparable with the current bounds (can be lower il mB>>f)

Bounds from the Oblique Parameters S,T,W,Y



(S,T) →





(W,Y) →

LHC better than LEP in W,Y determination

$$W \sim \Pi''_{W_3 W_3}(0) \qquad Y \sim \Pi''_{BB}(0)$$

Associated to new structure in the vector channel

WARNING

Attention should be paid in translating the accuracy on the "tail" parameters W,Y to bounds on the (M_V,g_V) plane

The tails can reserve surprises (depletion of events)

(Accomando et al.'16, Alioli at al.'17)

HL-LHC bounds: $|W| < 0.045 \times 10^{-3}, \ |Y| < 0.08 \times 10^{-3}$

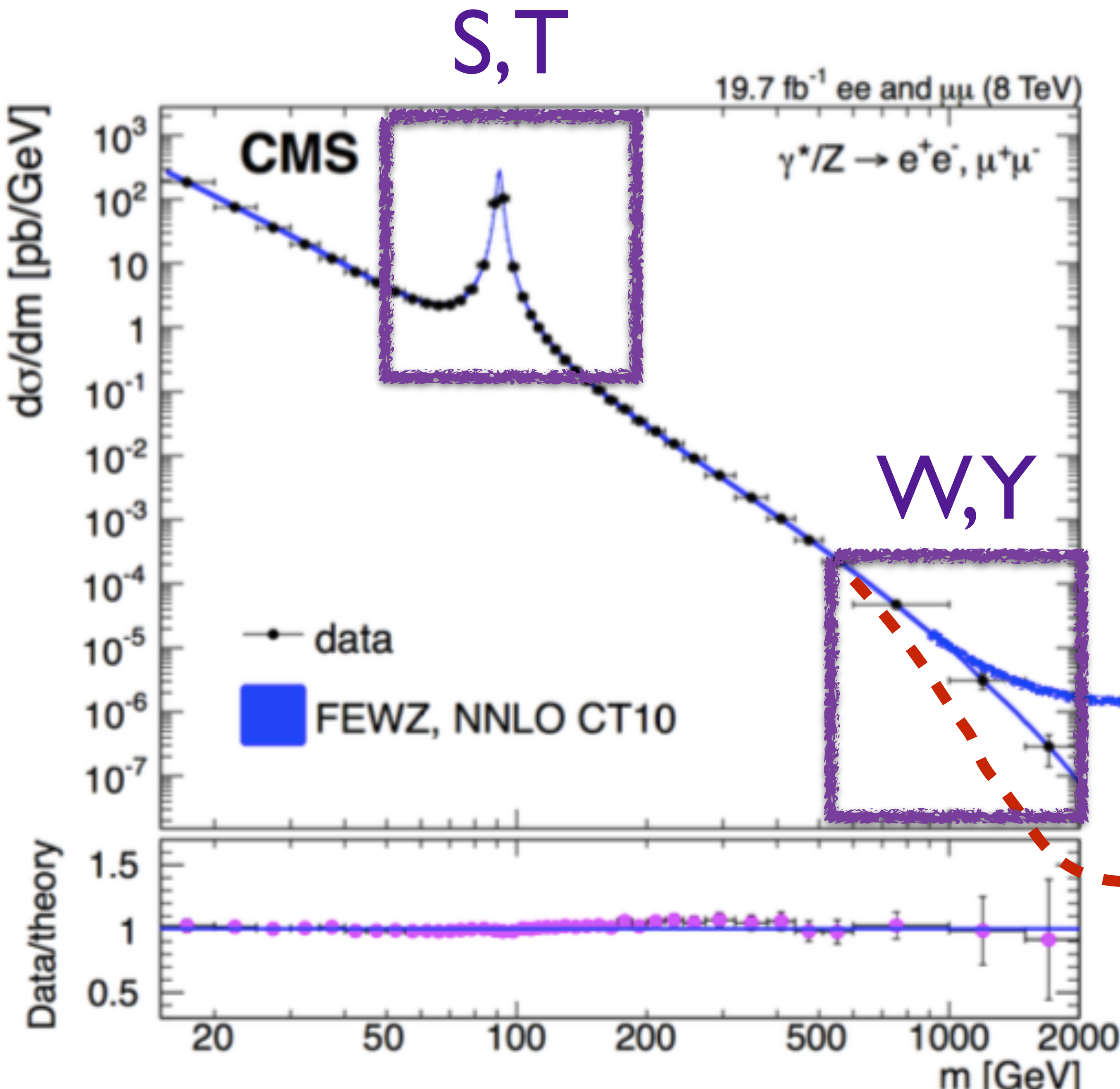
(Farina et al.'17')

a model independent analyses can fail

Can new physics be hiding in tails?

(Farina talk HL-LHC Workshop '17)

The tails can reserve surprises

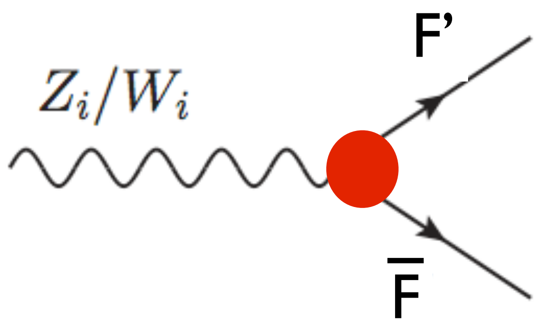


Large-width Z's can cause a depletion of events due to the interference with the SM gauge bosons

$pp \to \gamma, Z, (Z's) \to l^+l^-$

DY signal at the LHC
di-lepton invariant mass distribution

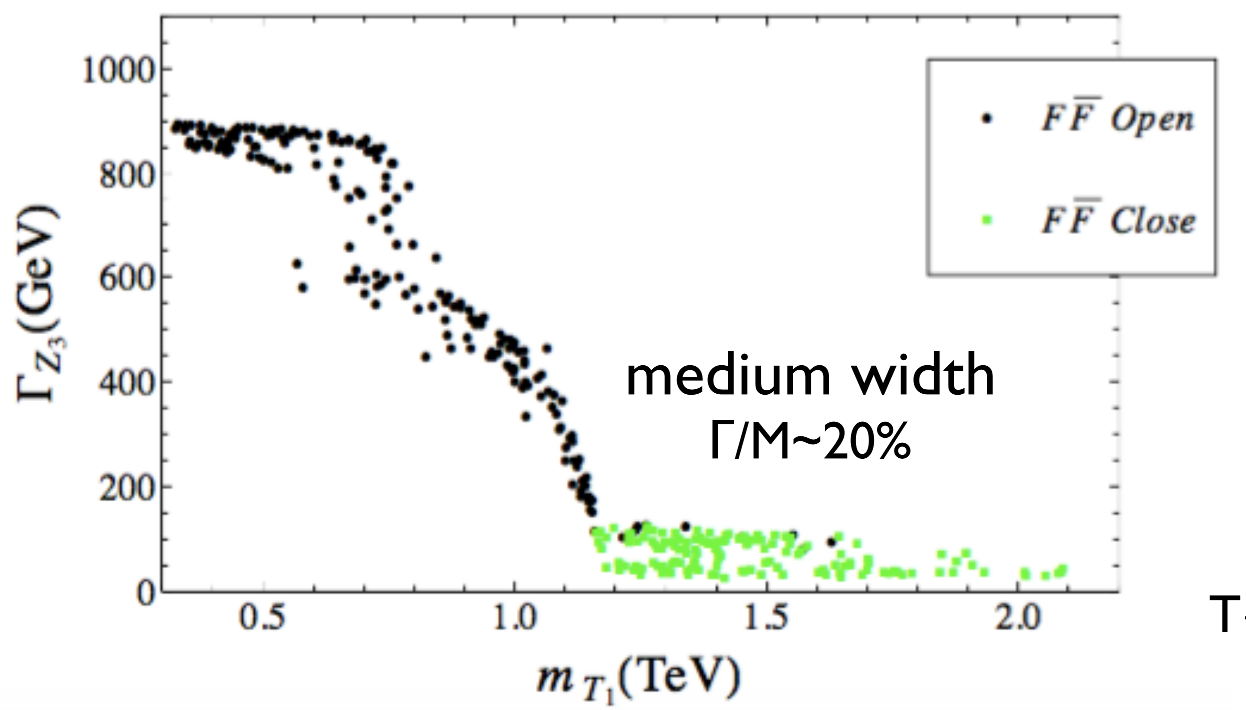
Large number of extra-fermions strongly coupled to W'and Z'



Widths of Z' and W'

Two possible extreme situations

- $M_{Z'/W'} < 2m_{t'/b'} \rightarrow$ Small width ($< 100\,GeV$)
- $M_{Z'/W'} > 2m_{t'/b'} \rightarrow$ Large width ($\Gamma_{Z_i/W_i} \simeq mass/2$)



f=1.2 TeV g*= 1.8
MZ_3=2.3TeV

T_1 = lights extra-fermion

Three ingredients to be taken into account for extracting the sensitivity from DY processes:

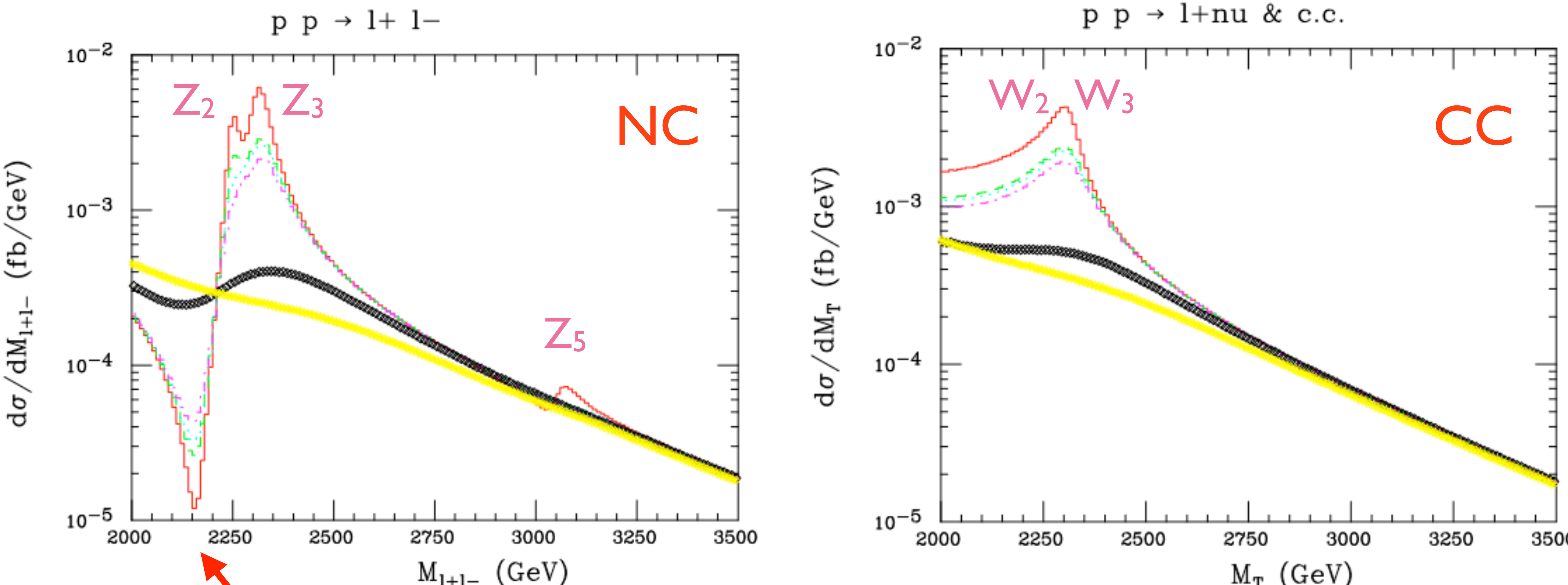
- ☑ finite widths of the new massive vectors (large width if $Z' \to \bar{T}T$)
- ☑ multi-Z' signal, typical of CHMs
- ☑ interference effects

→ small width is mandatory for leptonic DY processes

Drell-Yan signals from the 4DCHM at the LHC

Differential distributions in the lepton invariant mass (left) and transverse mass (right) for different choices of the Z' (left) and W' (right) widths

$\Gamma/M \sim$ 2% (red); 3%(green, cyan); 4% (magenta) ; 20% (black); > 40% (yellow)



Large width Z' and W' could escape the detection at the LHC in leptonic DY processes

Notice the very pronounced dip before the peaks due to the interference (much more pronounced for multi-Z' signal)
optimised cut are necessary to extract the significance of the signal events

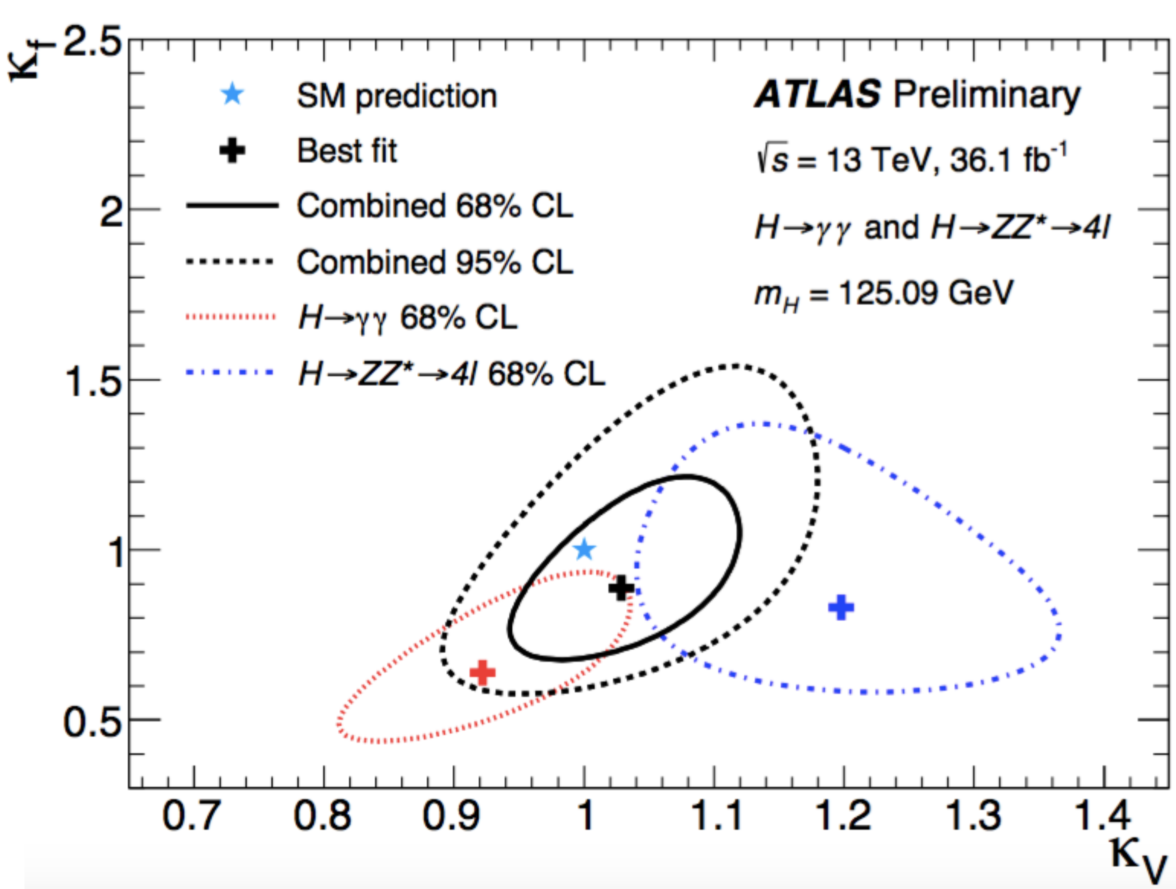
Composite pNGB Higgs couplings

- Higgs couplings dictated by symmetries (as in QCD chiral Lagrangian)
- For SO(5)/SO(4) $\quad g_{HVV} = g^{SM}_{HVV}\sqrt{1-\xi};\ g_{Hff} = g^{SM}_{Hff}\dfrac{(1-2\xi)}{\sqrt{1-\xi}}$

$\xi = v^2/f^2$ f =decay constant of the PNGB Higgs

- Small deviations in the $H\gamma\gamma$ and Hgg couplings due to the Goldstone nature of the Higgs (shift symmetry)

Facing the data: What we have learned from LHC Run2?



$= \dfrac{g_{hVV}}{g^{SM}_{hVV}}$

New results with 36 fb^{-1} of 13 TeV data

couplings h→bb, h→ττ directly measured

couplings still constrained at ~20% level

Bounds on Higgs compositeness from Higgs coupling measurements and EWPO Fit

CMS Projection for precision of Higgs coupling measurement

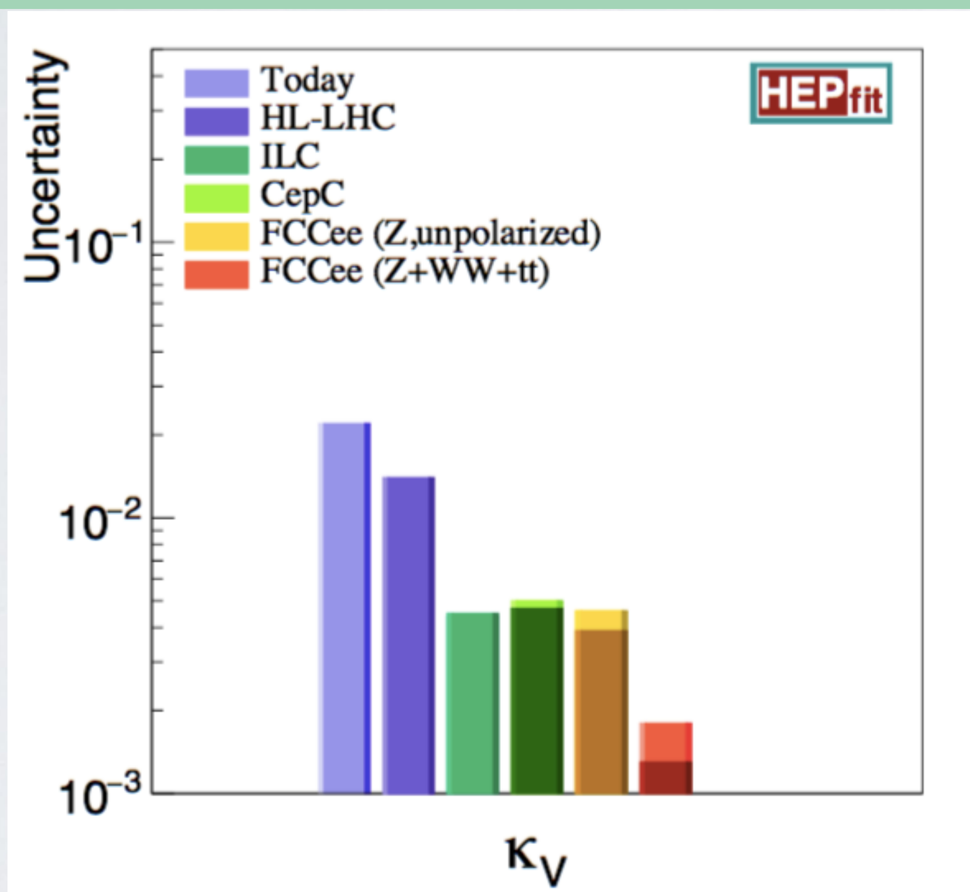
L (fb^{-1})	κ_γ	κ_W	κ_Z	κ_g	κ_b	κ_t	κ_τ
300	[5,7]	[4,6]	[4,6]	[6,8]	[10,13]	[14,15]	[6,8]
3000	[2,5]	[2,5]	[2,4]	[3,5]	[4,7]	[7,10]	[2,5]

CMS Note 13-002

$$\kappa_X = \frac{g_{hXX}}{g_{hXX}^{\rm SM}}$$

factor 2-3 improvement from HL-LHC

The sensitivity increases by combining with the EWPO fit



light shaded areas consider the effects of theoretical uncertainty

J.De Blas et al.1611.05354

Future proposed e^+e^- machines have a rich experimental program of (sub)percent precision

Bounds on the compositeness scale

Ex. in SO(5)/SO(4) $\quad \frac{g_{hVV}}{g_{hVV}^{\rm SM}} = \sqrt{1-\xi}$

ξ < 0.03 after HL-LHC
ξ < 0.008 after ILC/CepC
ξ < 0.002 after FCC-ee

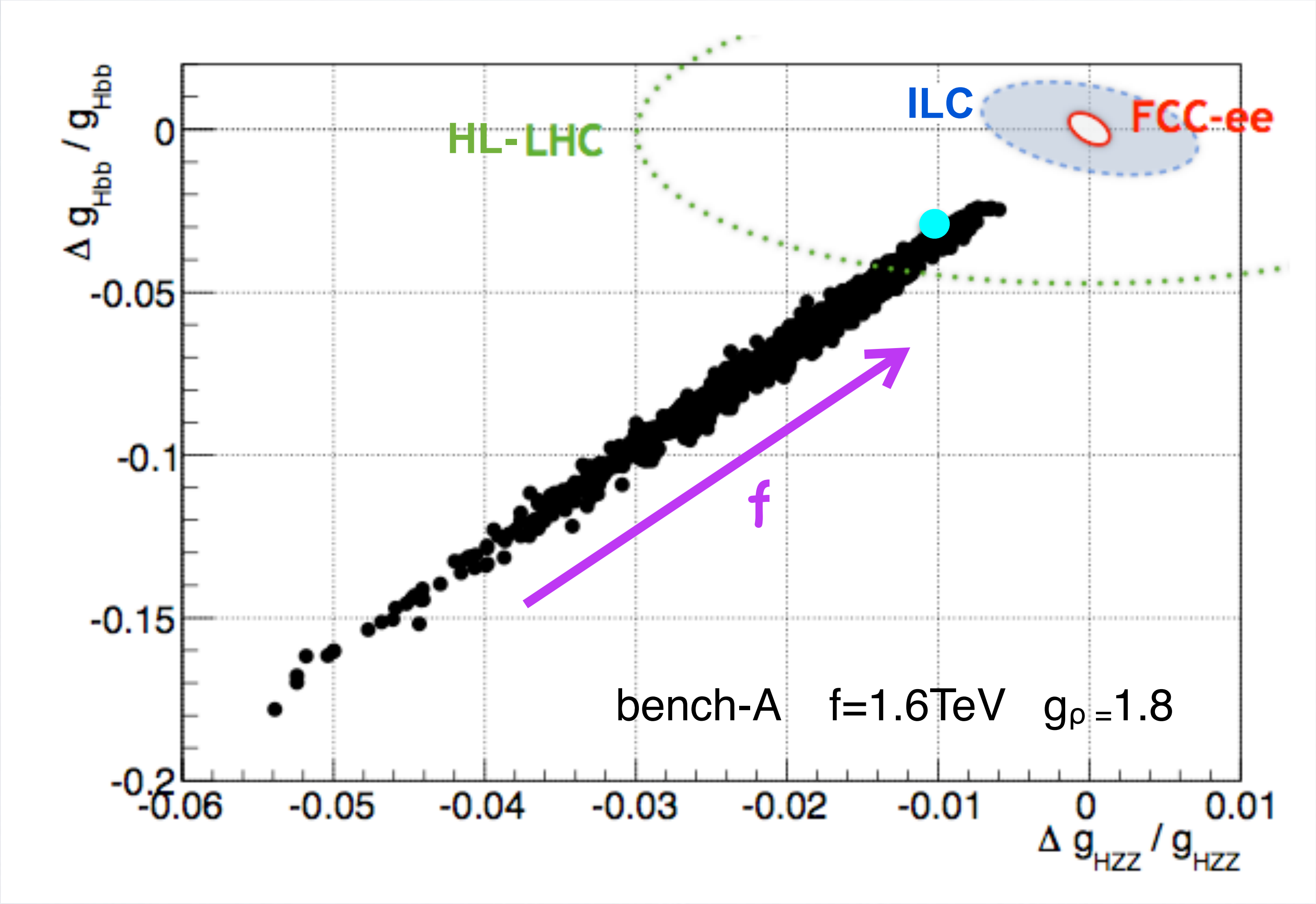
$$\xi = \frac{v^2}{f^2}$$

f > 5-6 TeV

4DCHM : Higgs coupling deviations

Deviations for HZZ and Hbb couplings in the 4DCHM compared with the relative precision expected at HL-LHC, ILC, FCC-ee

Barducci et al. JHEP 1309(2013)047
Janot PoS EPS HEP2015,333 (2015)



f = compositeness scale

$0.75 \leq f\ (\mathrm{TeV}) \leq 1.6$

g_ρ = strong coupling

$1.5 \leq g_\rho \leq 3$

scan over the 4DCHM fermion parameters

$$\frac{g_{HZZ}}{g^{SM}_{HZZ}} \sim \sqrt{1-\xi}$$

$$\frac{g_{Hbb}}{g^{SM}_{Hbb}} \sim \frac{1-2\xi}{\sqrt{1-\xi}}$$

$$\xi = \frac{v^2}{f^2}$$

4DCHM black points: $M_{Z'} \sim f g_\rho > 2$ TeV and M_T >800GeV, $M_{5/3}$ >900GeV

FCC-ee will be able to discover bench-A with a 10σ significance!!

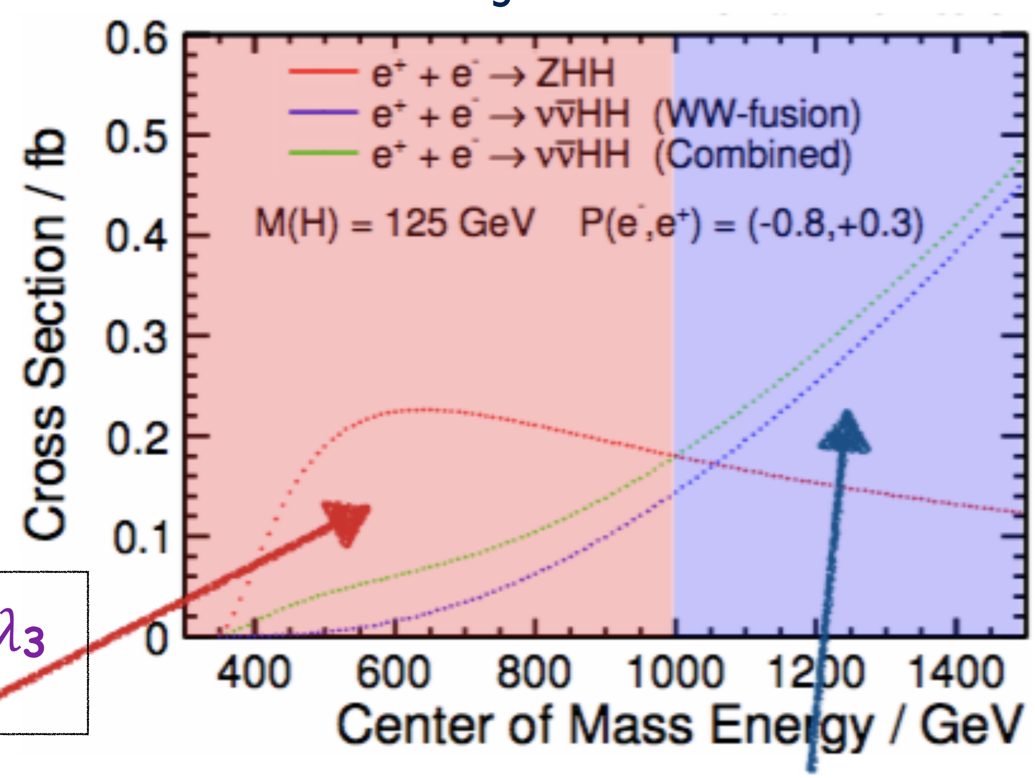
The Higgs self-interactions (a "portal" to strong dynamics?)

Measuring the Higgs self-interactions is a test of the Higgs potential

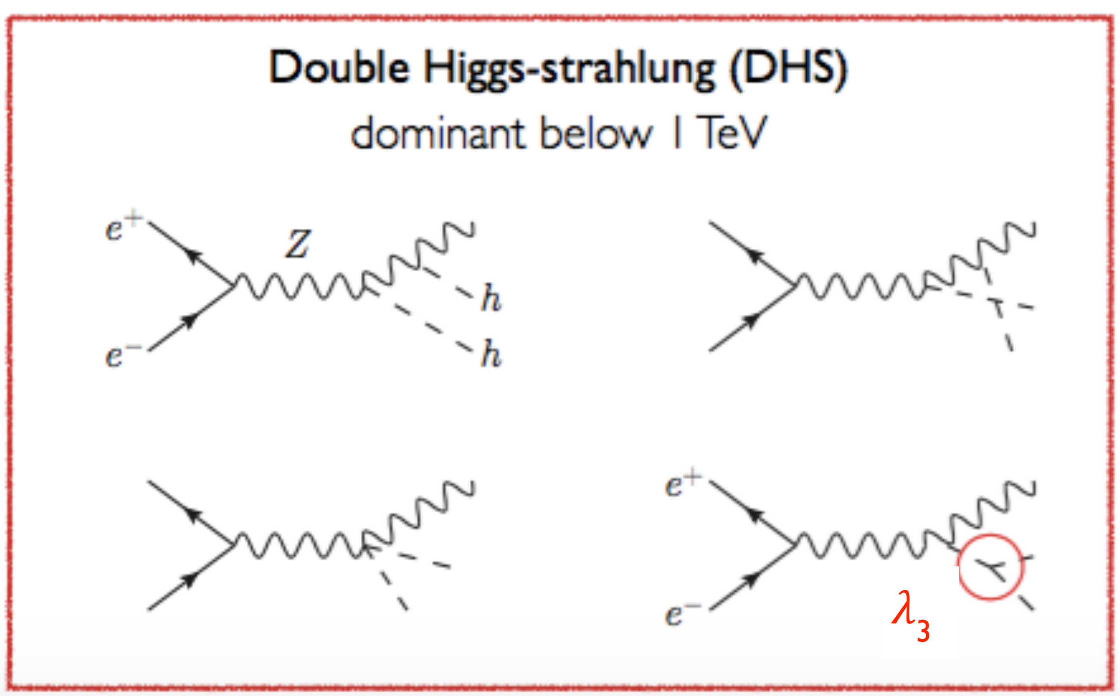
Limited precision at LHC due to small statistics: $\lambda_3 \in [0, 2]$ at 1σ

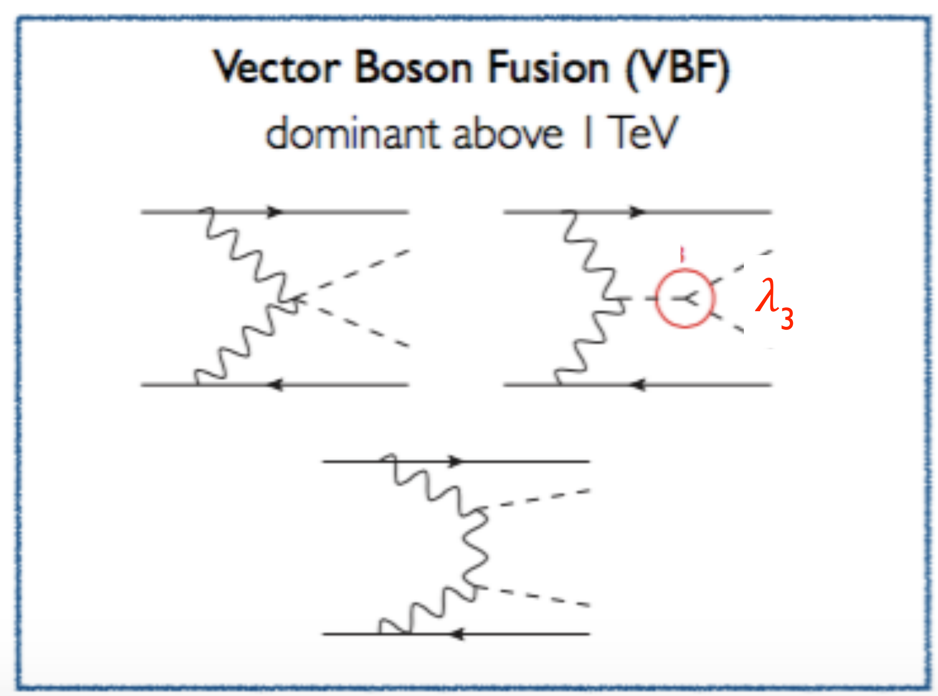
At e^+e^- colliders λ_3 is accessible
mainly in HH production
(it is also a probe of the Higgs strong interactions at high energy)

Two main channels
ZHH and $\nu\nu$HH



combined fit ILC+CLIC can reach ~20% on $\delta\lambda_3$
(Panico talk, CLIC Workshop '17)



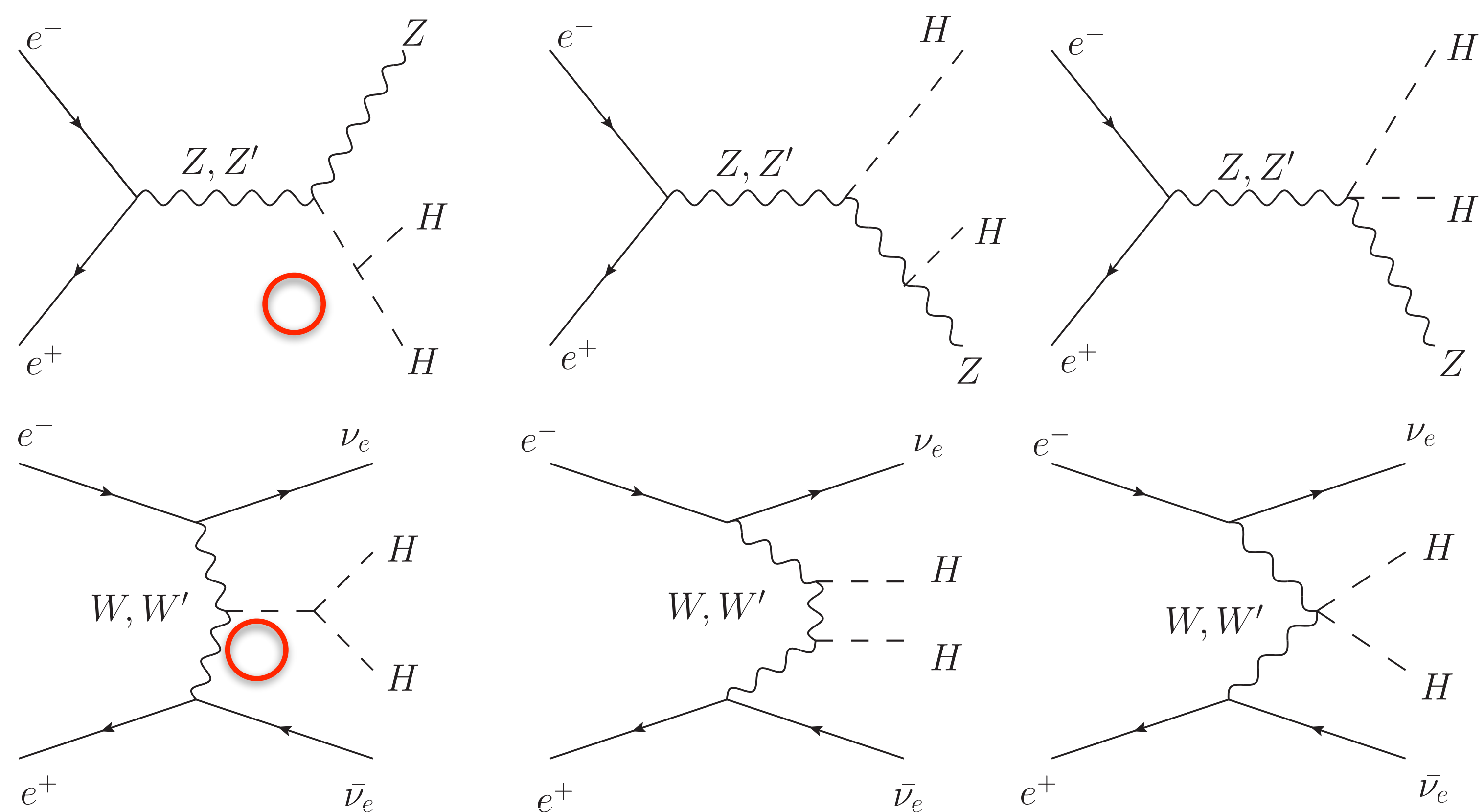


The triple Higgs self-coupling in the 4DCHM

In the 4DCHM the coupling modifications are not the only NP ingredient: W' and Z' exchanges affect the double Higgs production processes (both DHS and VBF)

at the leading order:

$$\lambda = \frac{3m_H^2}{v}\frac{1-2\frac{v^2}{f^2}}{\sqrt{1-\frac{v^2}{f^2}}} = \lambda_{SM}\frac{1-2\xi}{\sqrt{1-\xi}}$$



For realistic choices of the 4DCHM parameters, "effective" deviations in λ are at level of some 10% (comparable with the bounds from ILC+CLIC) (Barducci, DC, Moretti, Pruna, '11)

LHC will not be able to exclude CHM's even after the HL stage !!

Extended Composite Higgs Models

Models with a larger Higgs structure with respect to the SM have been proposed —> 2HDMs offer a rich phenomenology in EW and flavour physics

Look for a pNGB realization of extended Higgs scenarios

The structure of the Higgs sector is determined by the coset G/H

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

Doublet + Singlet

Gripaios et al.09; Redi,Tesi 12

Two Doublets

Mrazek et al.11

Bertuzzo et al.13

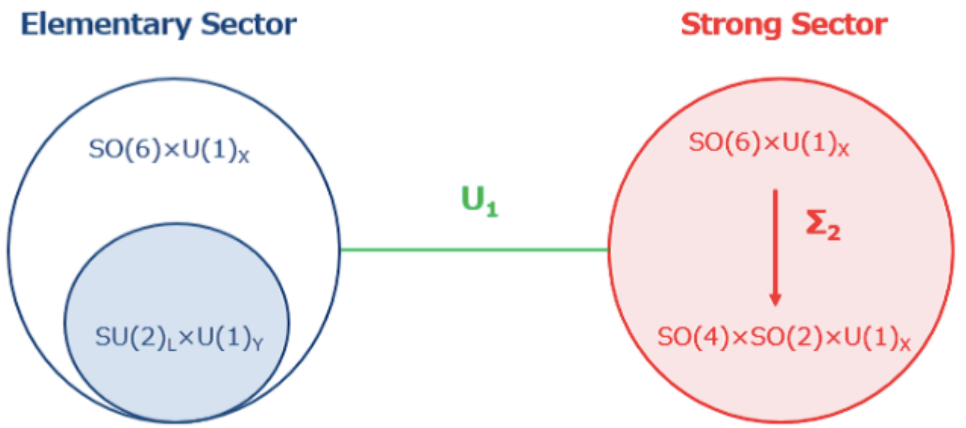
DC et al. 16; 18

SU(5) →SU(4) x U(1)

New players in the game

Composite 2-Higgs Doublet Models

J.Mrazek et al.11; DC,Moretti,Yagyu,Yildirim 16, DC,Delle Rose,Moretti,Yagyu 1803.01865



- EWSB is driven by 2 Higgs doublets as pNGBs of SO(6)/SO(4)xSO(2). The unbroken group contains the custodial SO(4)
- The construction of effective theory follows the same steps of the minimal 4DCHM
- Crucial is the presence of discrete symmetries in addition to the custodial SO(4) to control the T-parameter and to protect from Higgs-mediated FCNC
- Besides CP, one can impose a C_2 discrete symmetry (J.Mrazek et al.11) which distinguishes the 2 Higgs doublets (analogous of Z_2 in elementary 2HDM)
- If C_2 is not a symmetry of the strong sector, alignment conditions on the strong Yukawa couplings must be imposed to suppress FCNC (composite version of the Aligned 2HDM)

2-Higgs Doublets as pNGBs

Delle Rose, DC, Moretti, Yagyu 1803.01865; +Tesi in preparation

see Delle Rose talk this afternoon

- Use the 2-site construction to write the GB's interactions with the SM fields, the new spin-1 resonances in the adj. of $SO(6)xU(1)_X$ and new fermions in the **6** of SO(6)

- Integrate out the heavy degrees of freedom to derive the Coleman-Weinberg effective potential

- Up to the 4th order in the GB fields, the potential depends on 3 dimensionful mass parameters (m_{11}, m_{22} and m_{12}) and 7 dimensionless couplings λ_i ($i = 1, . ., 7$).
  In the C2HDM they **are not free but determined by the parameters of the strong sector:**

$$f, g_\rho, \underbrace{Y_1, Y_2}_{\text{Yukawas}}, \underbrace{\Delta_L, \Delta_R}_{\text{linear mixings}}, \underbrace{M_\psi, M_{12}}_{\text{heavy fermion mass parameters}}$$

(partial compositeness for the top)

- Impose the potential to be minimum for $v^2 = v_1^2 + v_2^2 = (246 \text{ GeV})^2$
- Impose $120 < m_h(\text{GeV}) < 130$
- Impose $165 < m_{top}(\text{GeV}) < 170$

2-Higgs Doublets as pNGBs

WE GOT SOLUTIONS !

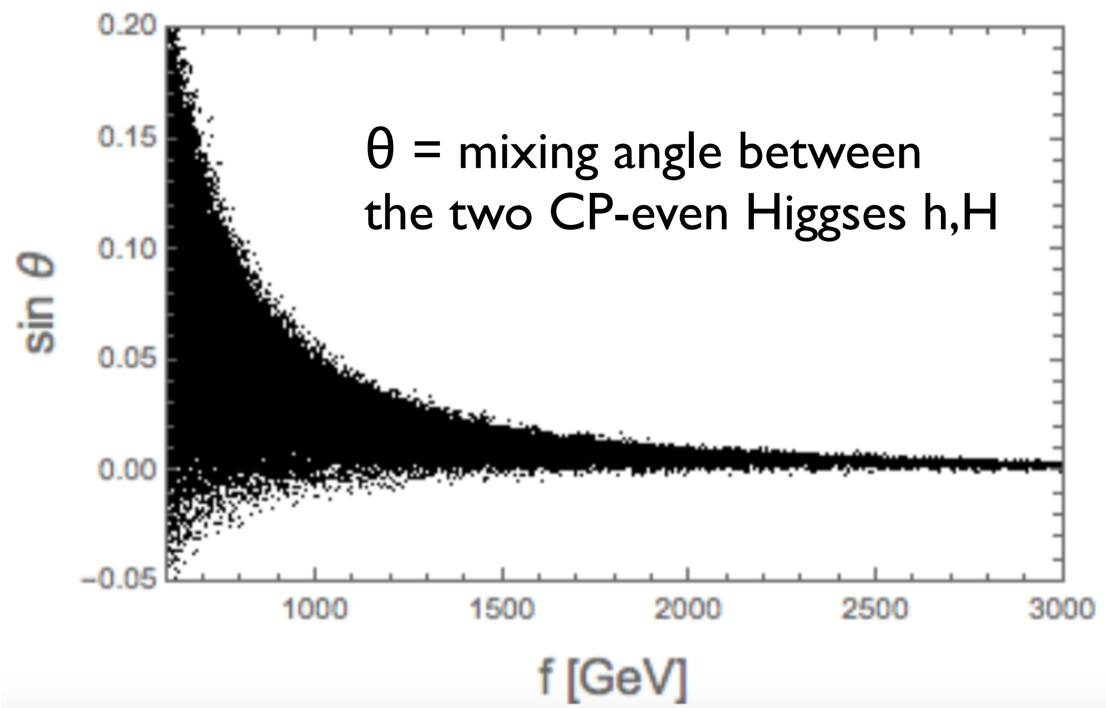
A realistic Aligned 2HDM can be realized in a Composite scenario

- CP , ~~Z_2~~
- The vanishing of the two tadpoles of the CP-even Higgs bosons requires tuning which is larger for large f (as expected)
- The requirement to reconstruct the experimental values of m_h and m_{top} selects values for the fermion sector parameters which are in the f range

$$m_{\text{top}} \sim \frac{v}{\sqrt{2}} \frac{\Delta_L}{m_Q} \frac{\Delta_R}{m_T} \frac{-Y_1 c_\beta + Y_2 s_\beta}{f}$$

$m_{Q,T}$ ~ heavy fermion masses

$\tan\beta = v_2/v_1$



$f \to \infty$ SM limit

H decouples and $h \to h^{SM}$

more results → Delle Rose talk

Strong dynamics beyond the hierarchy problem

Kilic,Okui,Sundrum '10, Antipin,Redi '15: Agugliaro et al '17

- Enlarge gauge dynamics to explain missing experimental facts (ex. Dark Matter, Baryogenesis) but *maintain* the SM paradigm
- Postulate new confining gauge dynamics G_{HC} (hyper color) with new fermions Q vectorial under G_{SM} and charged under G_{HC}
- The fermion condensate <QQ> breaks G→H and preserves G_{SM}

SM including elementary Higgs H couples to the strong sector with renormalizable couplings:

$$\mathcal{L} = \mathcal{L}_{\rm SM} + \bar{Q}_i(i\gamma^\mu D_\mu - m_i)Q_i + [H\bar{Q}_i(y^L_{ij}P_L + y^R_{ij}P_R)Q_j + {\rm h.c.}] + \cdots$$

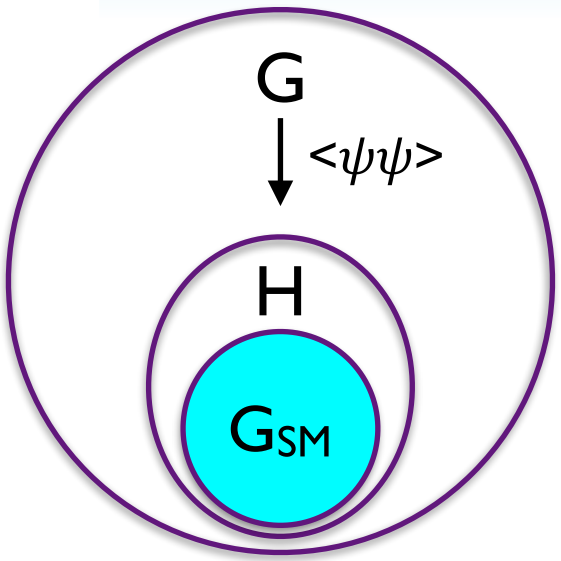
why ? possible candidate for UV completion of CHMs

Very weak bounds: automatic Minimal Flavour Violation, no need for partial fermion compositeness, Precision Tests ok, weak bounds on the overall scale m_ρ

Interesting phenomenology: Dark Matter candidates as composite states (stable due to accidental symmetries), plausible signatures for LHC and cosmology, partially composite Higgs, new light pion states

Partially Composite Higgs

Antipin,Redi '15, Agugliaro et al '17, Barducci et al. in preparation



G/H contains an $SU(2)_L$ doublet (composite Higgs K)

The strong sector does not break G_{SM} $\langle \psi_i \psi_j^c \rangle = -g_\rho f^3 \delta_{ij}$

vacuum misalignment from the mixing ϵ with the elementary Higgs H → <K> ~ ϵ<H> Kaplan,Georgi,'84

$$H\bar{Q}_i(y^L_{ij}P_L + y^R_{ij}P_R)Q_j \longrightarrow (y_L - y_R)m_\rho f\, HK + \dots$$

Yukawas

$$M^2 = \begin{pmatrix} m_H^2 & \epsilon m_K^2 \\ \epsilon^* m_K^2 & m_K^2 \end{pmatrix} \qquad \epsilon \sim (y_L - y_R)\frac{m_\rho f}{m_K^2}$$

Higgs compositeness controlled by the mixing: ϵ<1 Higgs ~ elementary

Corrections to EWPO and to Higgs couplings suppressed for small mixing:

$$\hat{S} \sim \frac{m_W^2}{m_\rho^2}\epsilon^2 \qquad \hat{T} \sim \frac{v^2}{f^2}\epsilon^4 \qquad \frac{\delta g_{hVV}}{g_{hVV}} = -|\epsilon|^2 \frac{m_h^4}{2m_K^4} - c_K|\epsilon|^4 \frac{v^2}{f^2}$$

$\epsilon \to 0$ $h \to h_{SM}$

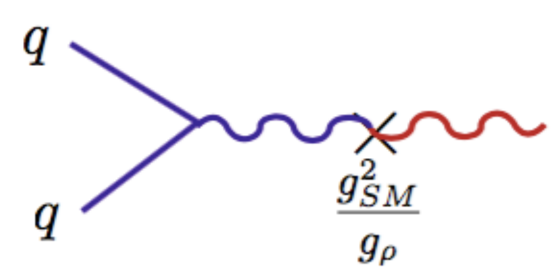
Collider Signatures of Partially Composite Higgs

Kilic, Okui, Sundrum '10, Barducci et al. in preparation

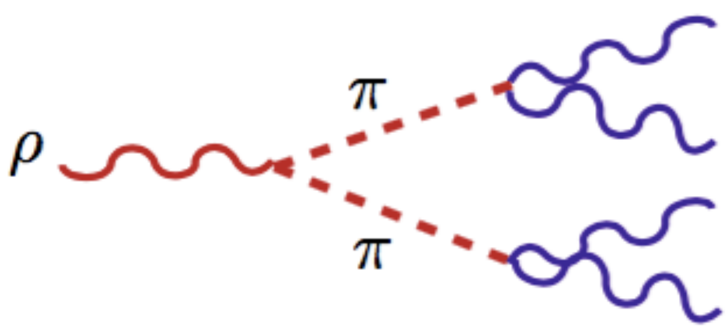
pseudo-Goldstone bosons and heavy vectors with SM charges

Ex: L+N model, the condensate breaks SU(3)xSU(3)→ SU(3) producing 8 GBs : K, π, η
the phenomenology is determined in terms of the fundamental description

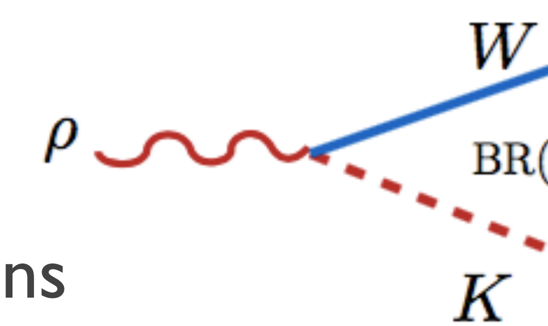
Heavy vectors mix with SM gauge bosons



$m_\rho \sim g_\rho f$



decay to pions and back to SM gauge bosons through anomalies. Also ρ→WK but suppressed if ϵ<1



$\mathrm{BR}(\rho \to KW) \sim \epsilon^2$

Pions can also be produced through SM interactions

$$pp \to W^\pm \to \pi_3^\pm \pi_3^0 \to 3\gamma + W^\pm$$

Interesting phenomenology for the LHC

Best bound from CDF

$$m_K > 230\,\mathrm{GeV}$$

Conclusions

☑ Higgs as a Nambu-Goldstone Boson is a compelling possibility for stabilising the EW scale

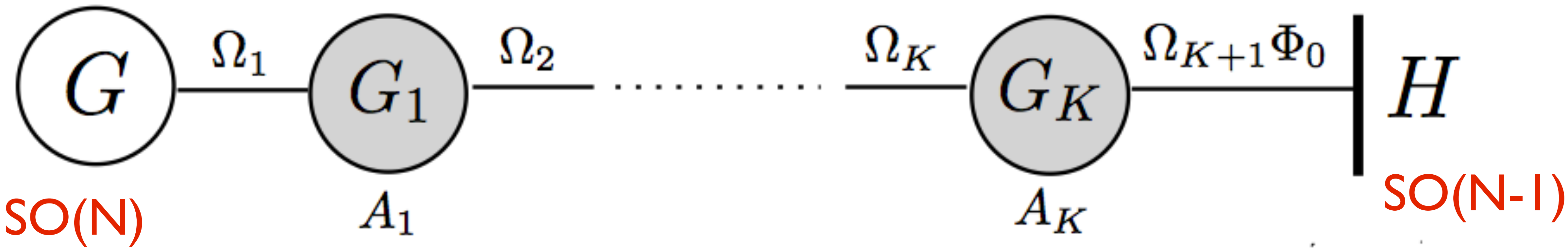
☑ Realistic scenarios can be built and analysed with the full spectrum including new particles

Waiting for BSM signals

Let’s continue in exploring new (but also old) ideas to explain what the SM fails to explain

BACKUP SLIDES

K copies $\longrightarrow$ moose model



$$\Omega_i \to g_{i-1}\,\Omega_i\,g_i^\dagger\,, \quad \Omega_{K+1} \to g_K\,\Omega_{K+1}\,h^\dagger$$

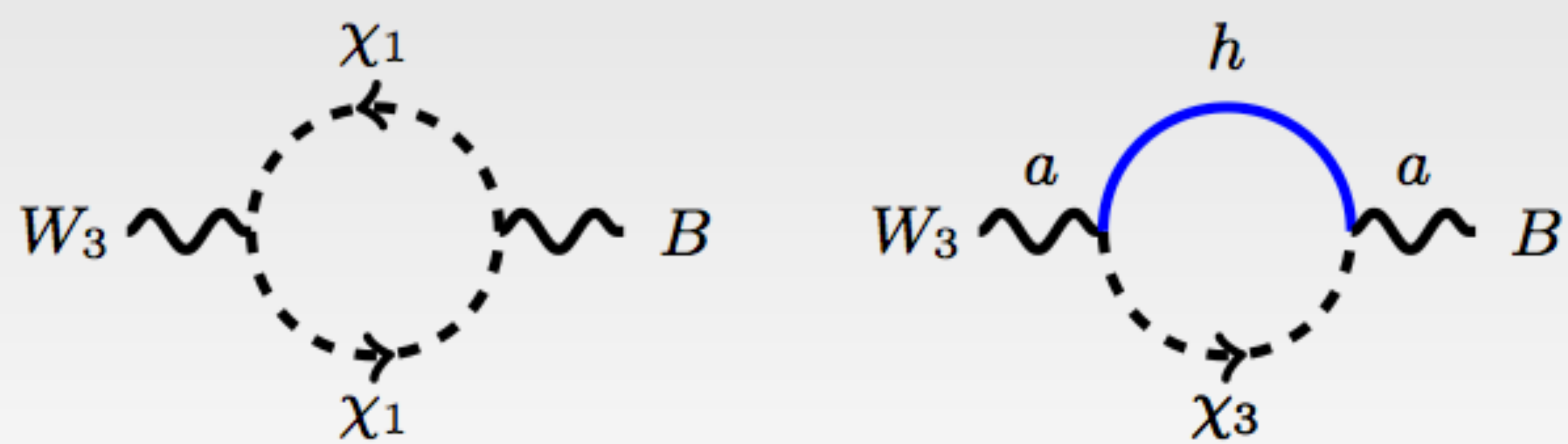
$$\text{GBs}: \quad U(\Pi) = \Omega_1 \ldots \Omega_{K+1}$$

K massive spin-1 resonances $+$ $SO(N)/SO(N-1)$ GBs

nearest neighbour interactions : $K \to \infty$ $\Rightarrow$ 5D theory

$\log \Lambda^2$-contributions to S and T

Reduced coupling to WW.



$$S = \frac{1}{12\pi}(1 - a^2)\log\left(\frac{\Lambda^2}{m_H^2}\right)$$

$$T = -\frac{3}{16\pi c_W^2}(1 - a^2)\log\left(\frac{\Lambda^2}{m_H^2}\right)$$

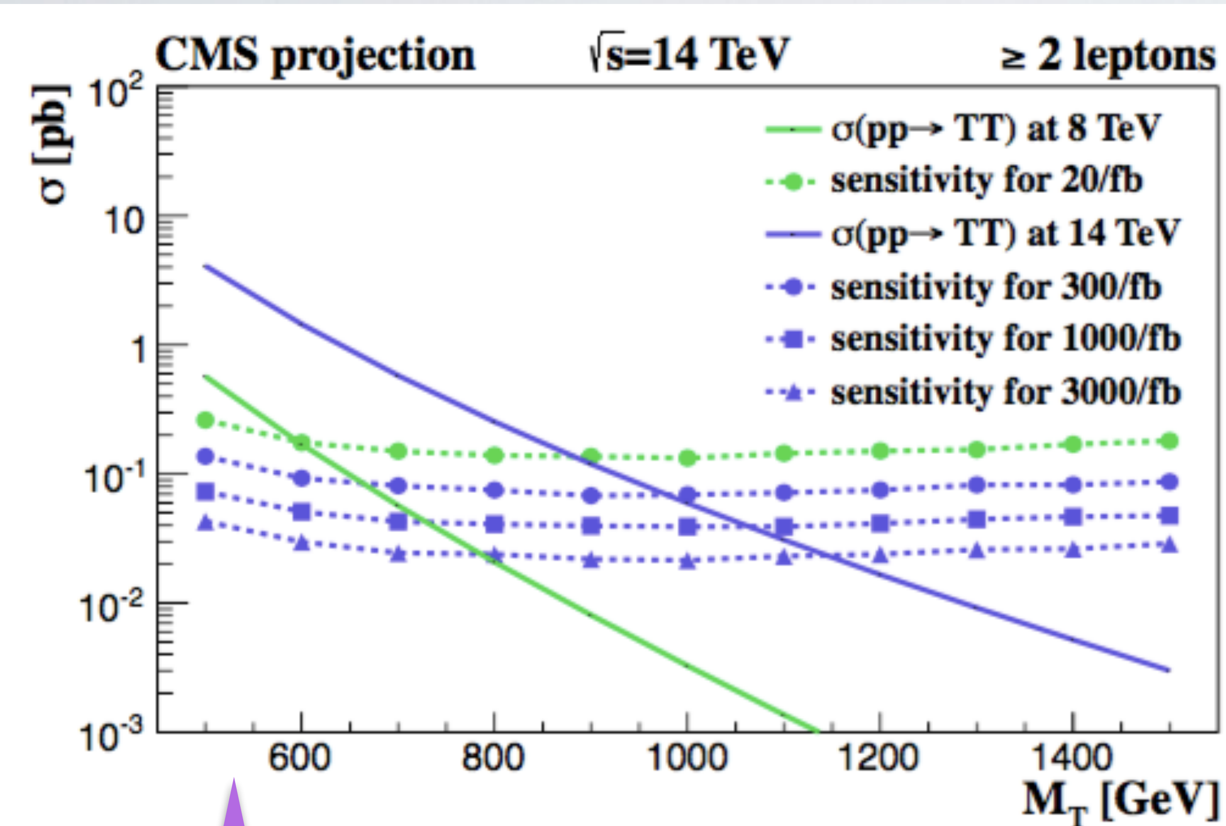
In other words

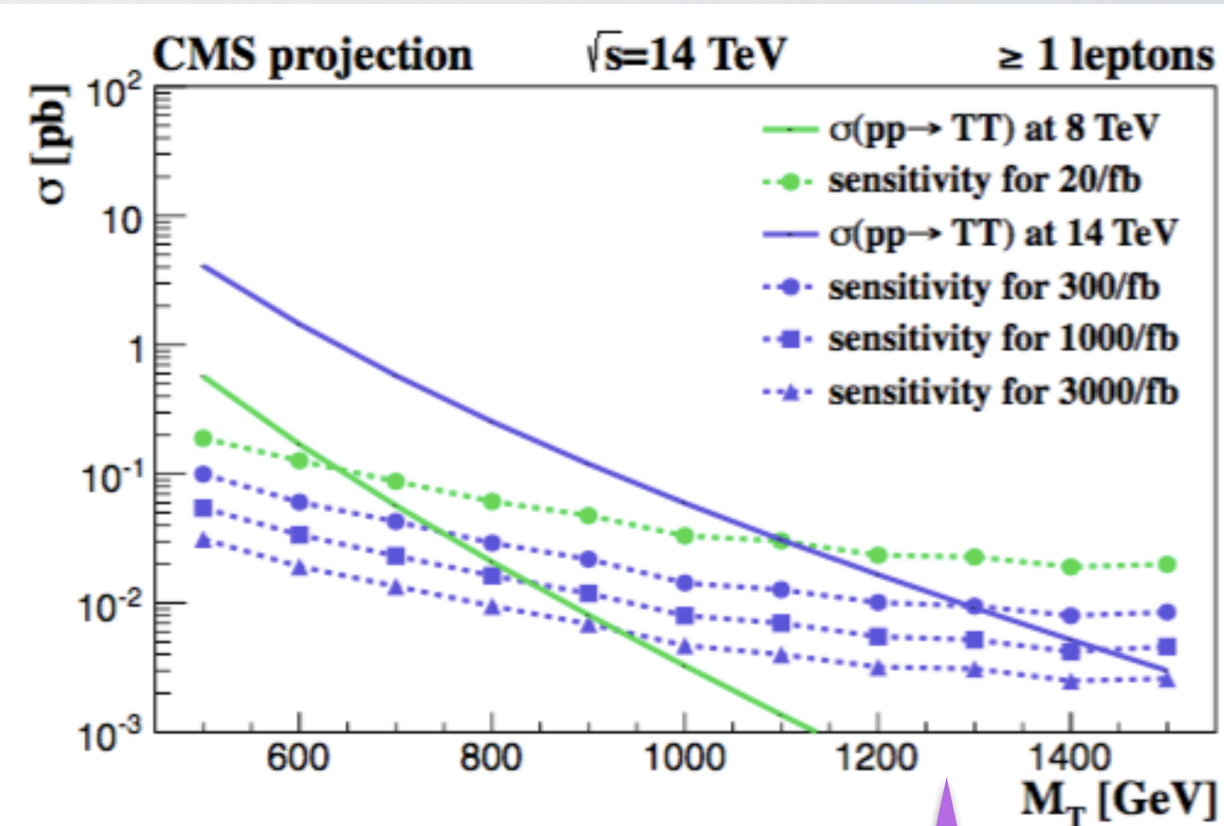
$$m_H \to m_H^{\text{eff}} = m_H \left(\frac{\Lambda}{m_H}\right)^{1-a^2}$$

Search for Heavy Vector-Like Charge 2/3 Quarks

Projection at 14 TeV with 300 / 1000/ 3000 fb^{-1}

BRs: 50% / 25% / 25% to bW / Zt / tH





Expected sensitivity for a T quark pair production signal

multilepton channel

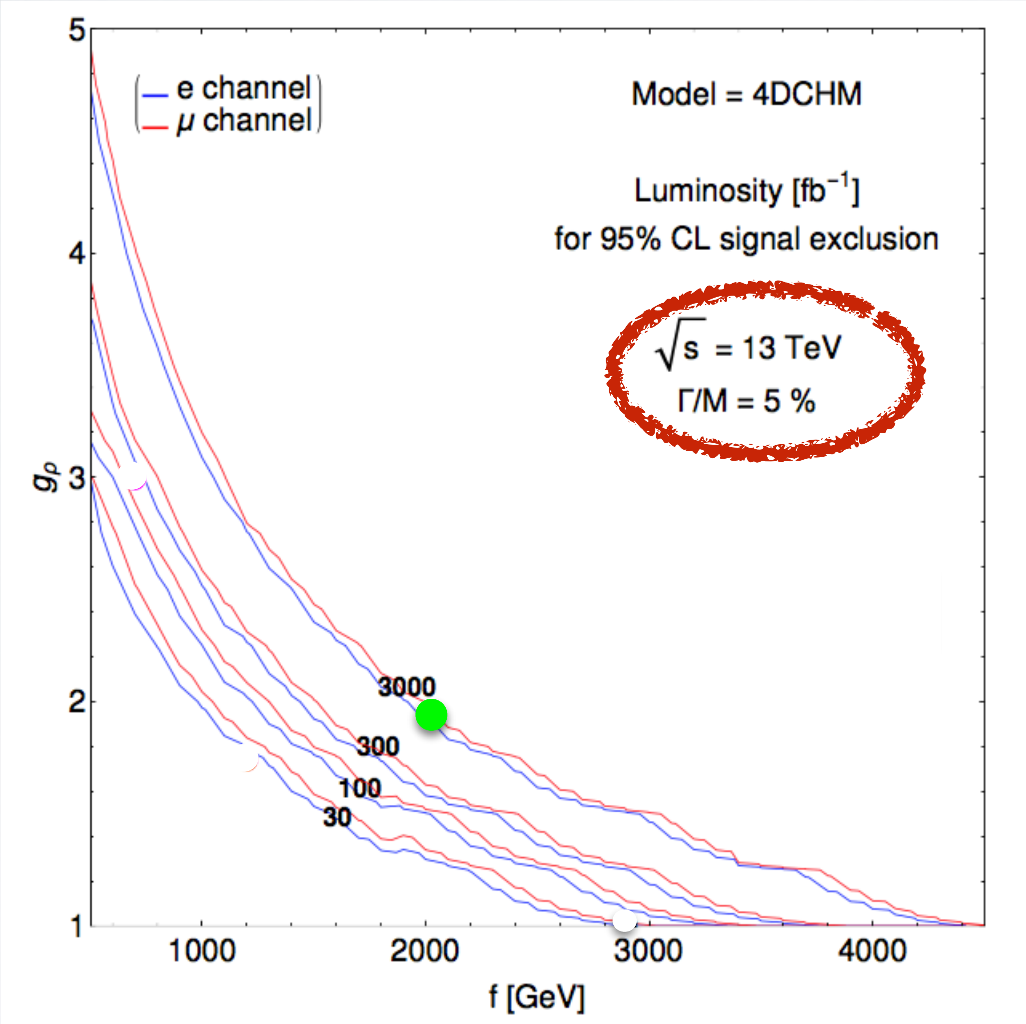
all channels combined

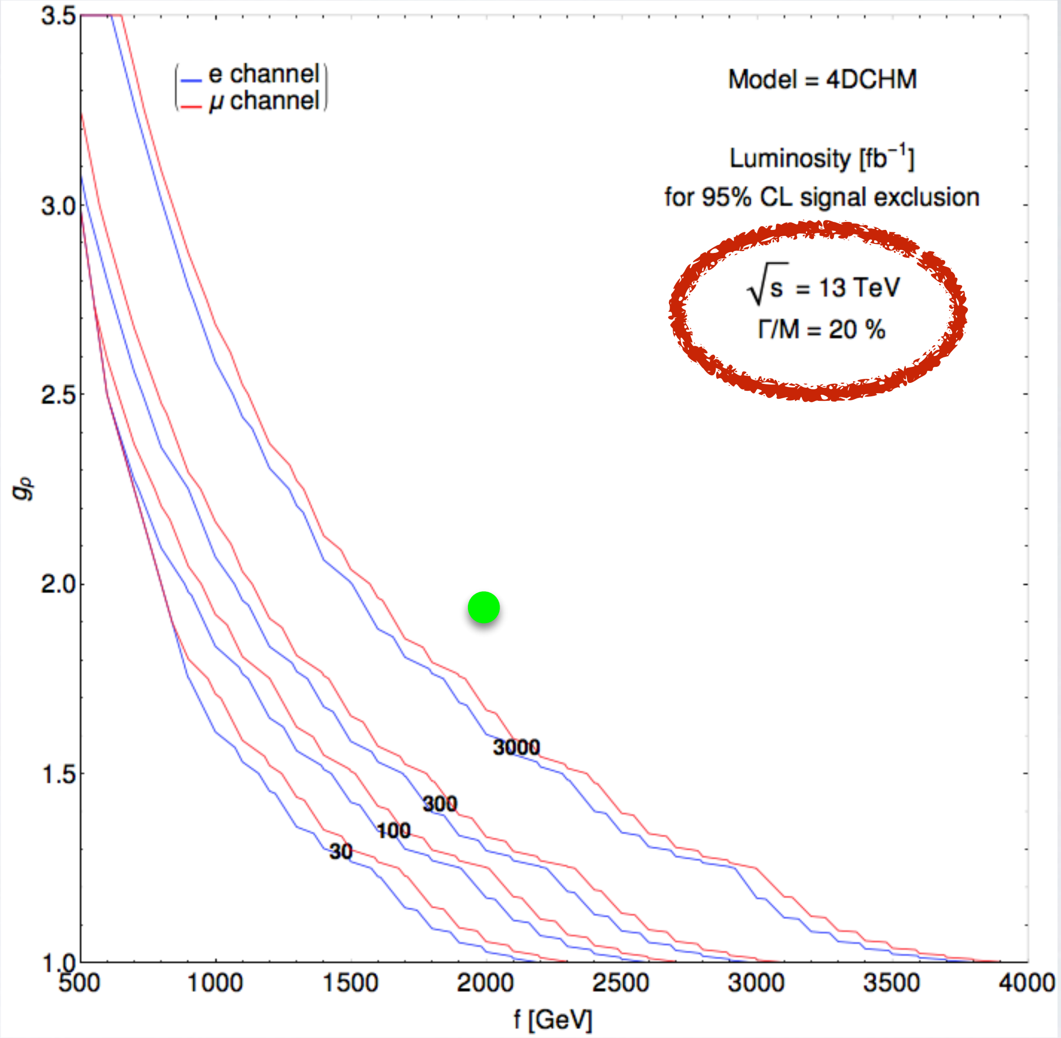
$T_{2/3}$ quarks with mass below 1(1.2)TeV could be discovered with 300(3000)fb^{-1}
1.3(1.5)TeV with all channels combined

CMS Note-13-002 - 1307.7135

Calculating significance, neutral DY channel at the LHC-13TeV

Accomando et al.JHEP1607(1016)068





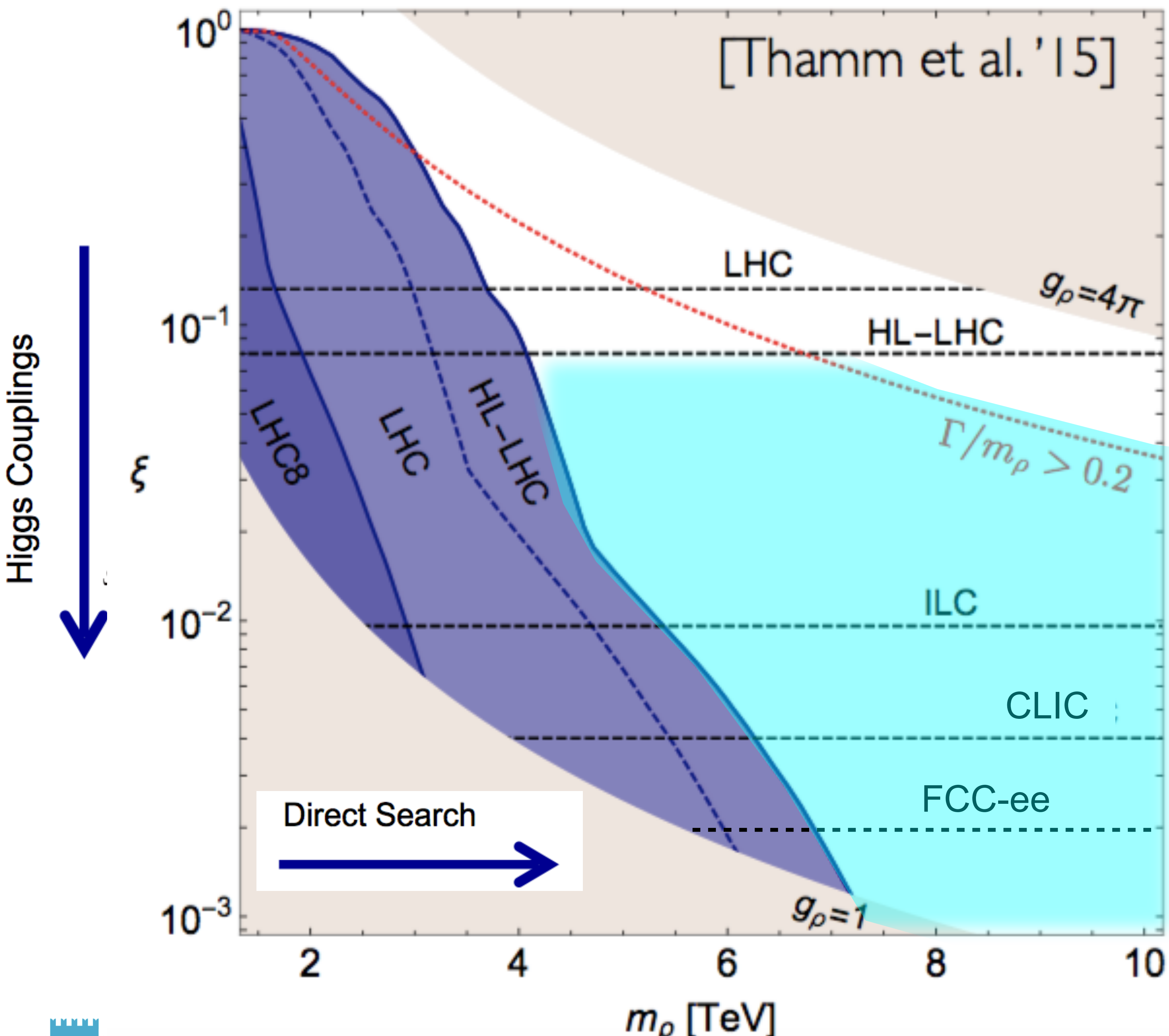
Projected 95%CL exclusion limits within the 4DCHM with $\Gamma/M=5\%$ and $\Gamma/M=20\%$ for electron/muon channel and different integrated luminosity values

Events within the crossing point (where the signal intersects the SM expectation) and $M_{Z3}+3\Gamma_{Z3}$
(model dependent optimization)

Ex. g_ρ =2 and f=2TeV ● is at the border of the exclusion limit for HL-LHC if $\Gamma/M=5\%$ but it is still allowed if $\Gamma/M=20\%$

Complementarity between Direct Searches and Indirect Measurements

General parametrization of the pNGB Higgs couplings: low-energy effective Lagrangian with one triplet spin-1 extra resonances $m_\rho = f\, g_\rho$, narrow width Γ_ρ



Indirect bounds, mainly from Higgs coupling modification, set an upper bound on ξ

$$\frac{g_{hVV}}{g_{h_{SM}VV}} = \sqrt{1-\xi} \qquad \xi = \frac{v^2}{f^2}$$

To the sensitivity on ξ it corresponds a reach on the compositeness scale $\Lambda=4\pi f$ (Ex. Λ=30-40 TeV @ILC)

Direct bounds from $pp \to l^+l^-$ and $pp \to WZ \to 3l+\nu$

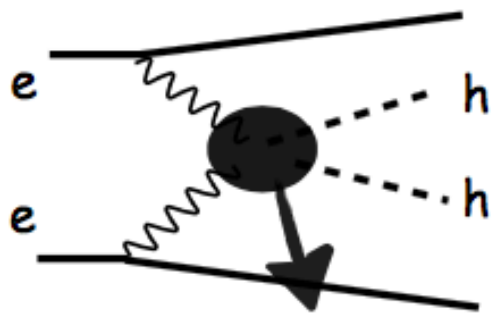
After HL-LHC the blue region will still be available (may be a larger region → interference and large-width, here not taken into account, substantially affect the direct search bounds)

VVHH: probe of Higgs strong interactions

Grojean talk, LCWS14

in the SM, the Higgs is essential to prevent strong interactions in EWSB sector

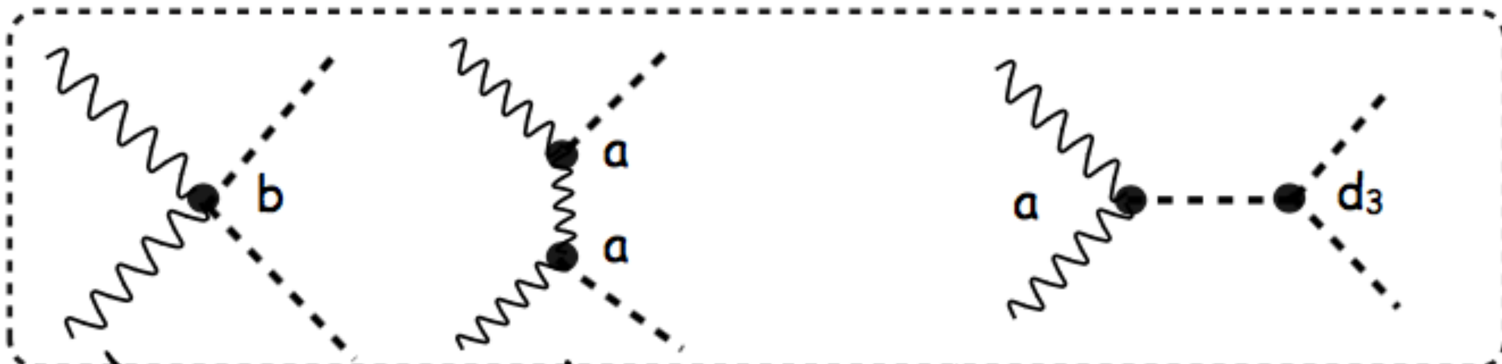
(e.g. WW scattering)



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

SM: $a=b=d_3=d_4=1$

$$V(h) = \frac{1}{2}m_h^2h^2 + d_3\frac{1}{6}\left(\frac{3m_h^2}{v}\right)h^3 + d_4\frac{1}{24}\left(\frac{3m_h^2}{v^2}\right)h^4 + \dots$$



$$\mathcal{A} \underset{s\,\gg m_W^2}{\sim} (b-a^2)\,\frac{4s}{v^2}$$

$$\mathcal{A} \underset{s\,\sim 4m_h^2}{\sim} {\rm cst.} + 3ad_3\frac{m_h^2}{v^2}$$

asymptotic behavior
sensitive to strong interaction

threshold effect
anomalous coupling'

VV→HH is difficult (impossible) at FCC-ee/ILC$_{500GeV}$

An e^+e^- collider with $\sqrt{s}$ = 0.5-1 TeV can reach a precision of ~20% on b through the double Higgs-strahlung process

Contino, Grojean, Pappadopulo, Rattazzi, Thamm '13