Composite Higgs Models and Fermionic Top Partners

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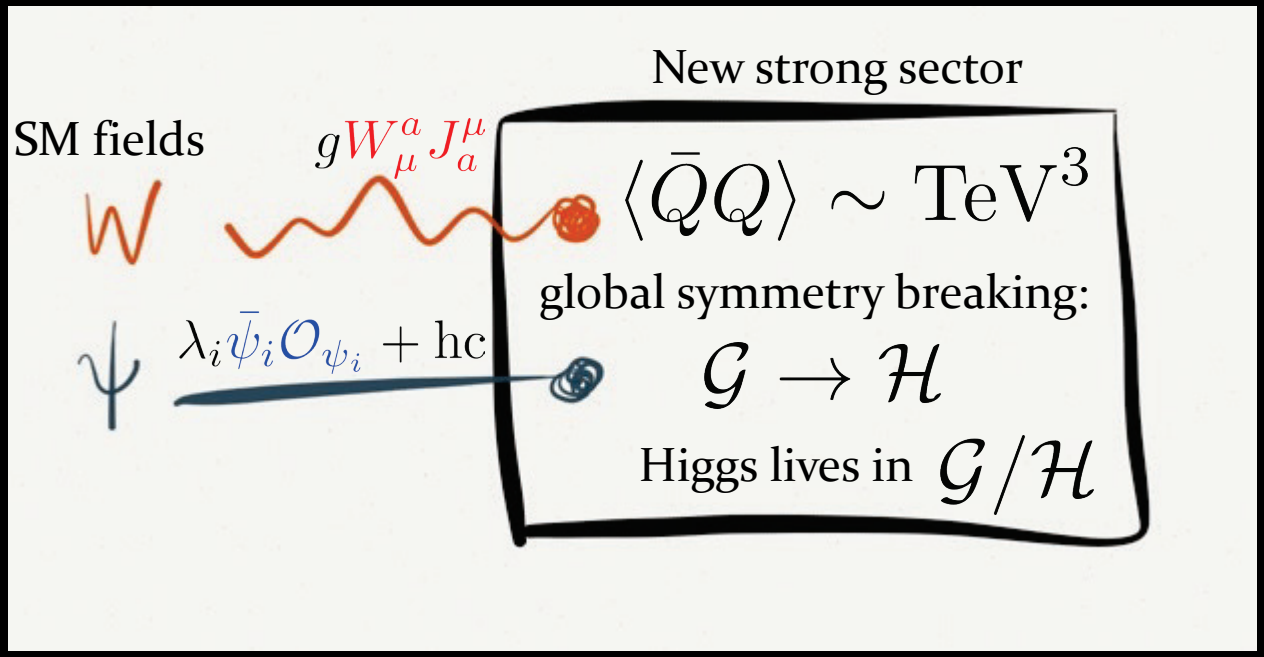
Outline

1. Main features of CHMs
2. Colliders hunting grounds + LHC8 results
3. LHC run 2 prospects

Features of a

Composite Higgs

Composite Higgs in a nutshell



Higgs is a pNGB and naturally light Georgi-Kaplan '84

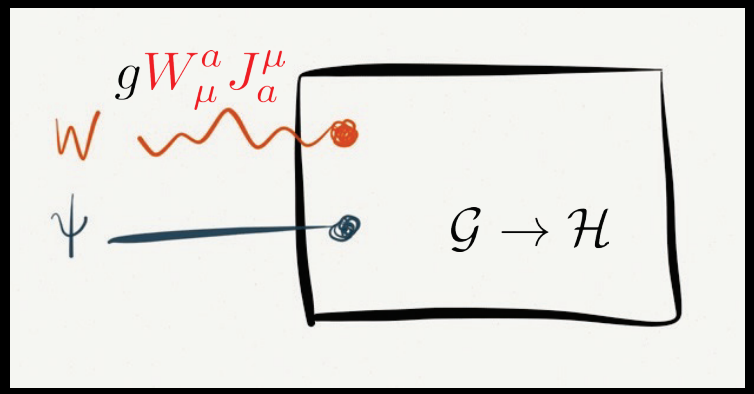
Higgs induced in a controlable way: $m_H^2 \sim \epsilon \Lambda^2$ $\quad \Lambda \sim \mathrm{TeV}$, $\epsilon \ll 1$

Minimal model w/ custodial symmetry: $H \in SO(5)/SO(4)$

Agashe-Contino-Pomarol '04

Composite Higgs in a nutshell

- EWSB through vacuum misalignment

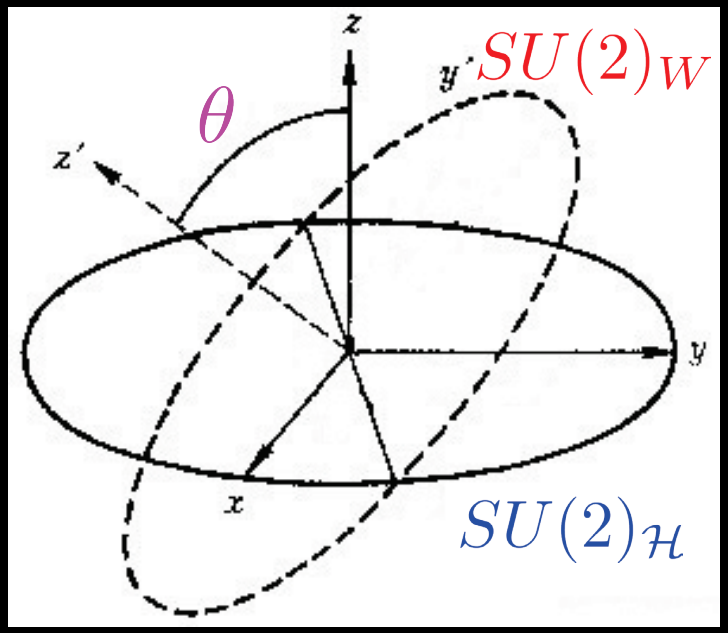


If $SU(2)_W$ not aligned with $SU(2)$ contained in $\mathcal{H}$, then $\mathcal{G} \to \mathcal{H}$ breaking at scale f induces EWSB.

$$v = f \sin\theta$$

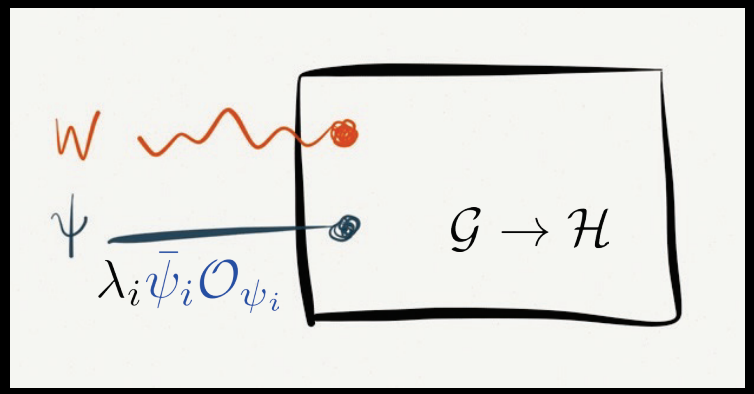
Generically, $v \sim f$

$$\left(\xi \equiv v^2/f^2\right)$$



Composite Higgs in a nutshell

- Fermion masses from partial compositeness: Kaplan '91



Below the cutoff, $\mathcal{O}_{\psi_i}$ interpolate to composite resonances, *linearly* mixed with the elecmentary ψ_i

$$\psi_i^{\rm SM} = \cos\theta_i \psi_i + \sin\theta_i \Psi_i$$

degree of compositeness

$$\left(\sin\theta_i \sim \epsilon_i \equiv \frac{\lambda_i}{g_\rho f}\right)$$

$$m_{\psi^{\rm SM}} \sim v \epsilon_L g_\rho \epsilon_R$$

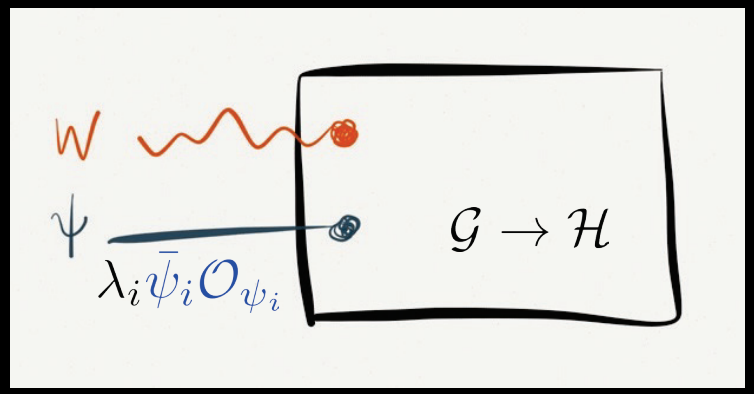
Generically, light fermions are ~elementary, while top is ~composite $\epsilon_{t_L, t_R, b_L} \sim \mathcal{O}(1)$

(For fully composite t_R, gauge unification as good as in SUSY)

Agashe-Contino-Sundrum '0

Composite Higgs in a nutshell

- EWSB from top compositeness: Agashe-Contino-Pomarol '04



ψ_i form *incomplete* irreps of $\mathcal{H}$, so λ_i breaks $\mathcal{H}$ *explicitly*, inducing a potential à la Coleman-Weinberg

$$V \sim \alpha \sin^2 \frac{\langle h \rangle}{f} + \beta \sin^4 \frac{\langle h \rangle}{f}$$

for $\begin{matrix} \mathcal{O}_{q_L} \sim \mathbf{5} \\ \mathcal{O}_{t_R} \sim \mathbf{5} \end{matrix}$, $\alpha \propto \lambda^2$, $\beta \propto \lambda^4$ hence FT$\sim \epsilon^2 \xi$ «double tuning»

instead for $\begin{matrix} \mathcal{O}_{q_L} \sim \mathbf{14} \\ \mathcal{O}_{t_R} \sim \mathbf{1} \end{matrix}$, $\alpha \sim \beta \propto \lambda^2$ so FT$\sim \xi$ «minimal tuning»

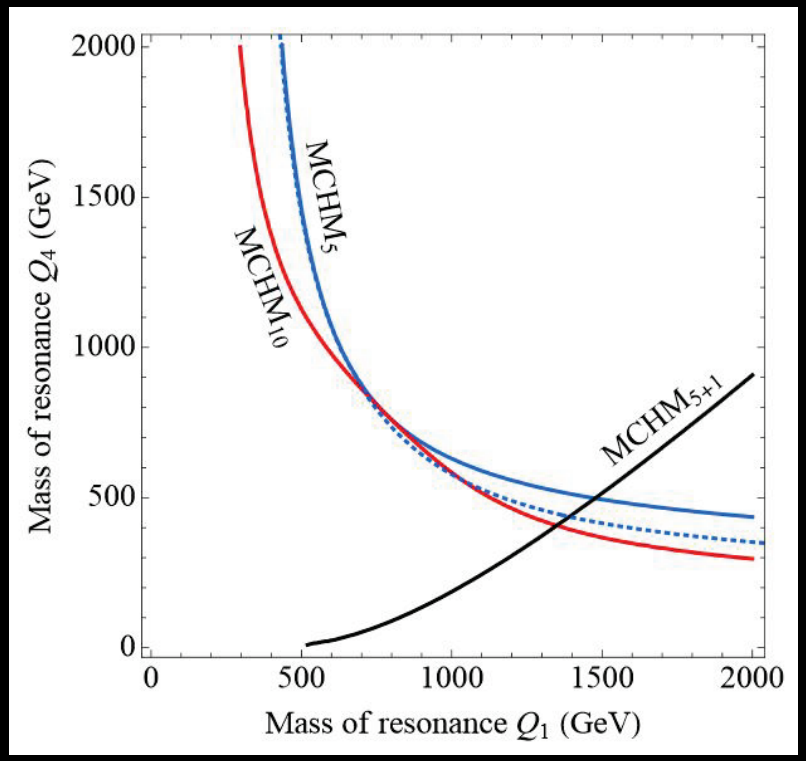
Panico-Redi-Tesi-Wulzer '13

Composite Higgs in a nutshell

- Light top partners for a light composite Higgs*:

Using Weinberg's sum rules for *e.g.* $\mathbf{5}+\mathbf{5}$ MCHM:

$$m_h^2 \simeq \frac{N_c m_t^2}{\pi^2 f^2} \frac{m_{Q_4}^2 m_{Q_1}^2}{m_{Q_1}^2 - m_{Q_4}^2} \log \frac{m_{Q_1}^2}{m_{Q_4}^2}$$



Generically, there's a light partner:

$$m_Q \lesssim 1\,\mathrm{TeV}$$

Pomarol-Riva '12

*see also Matsedonskyi-Panico-Wulzer '12

Composite Higgs'
hunting grounds at colliders

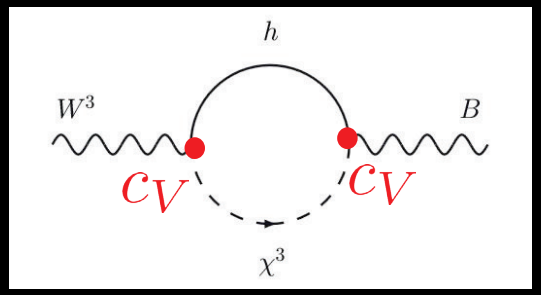
Composite Higgs hunting grounds

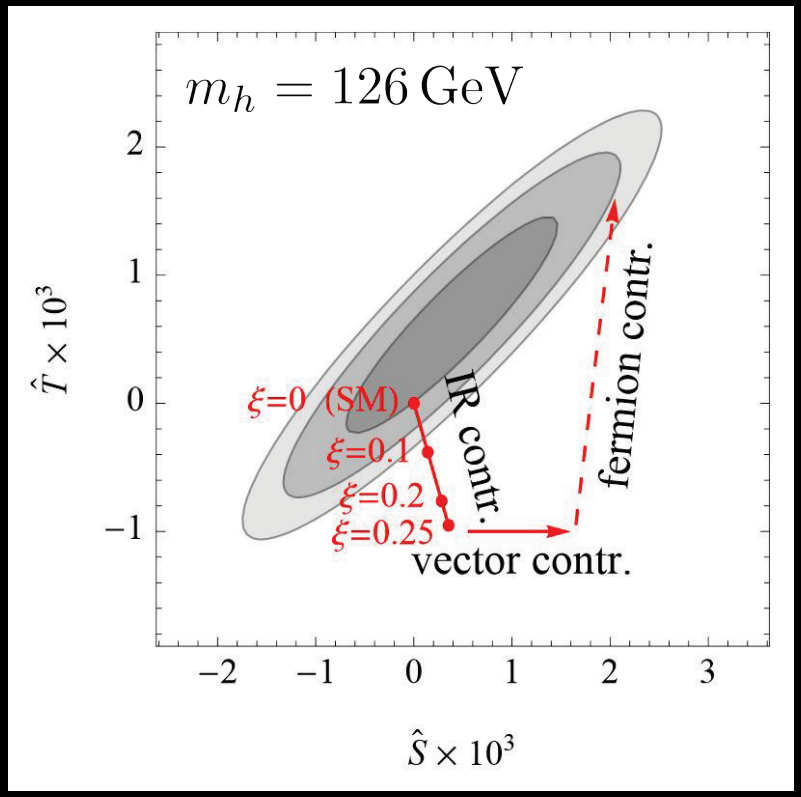
- LEP EW precision measurements:

  Higgs-to-VV reduced:

$$c_V = \sqrt{1-\xi}$$

  leading to oblique shifts:





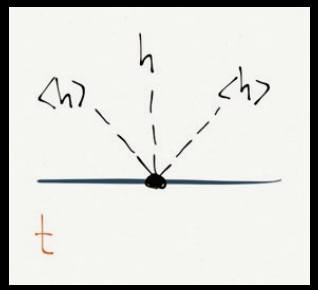
roughly $\xi \lesssim 0.1$

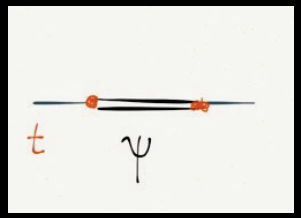
or $f \gtrsim 800\,\mathrm{GeV}$

Grojean-Matsedonskyi-Panico '12

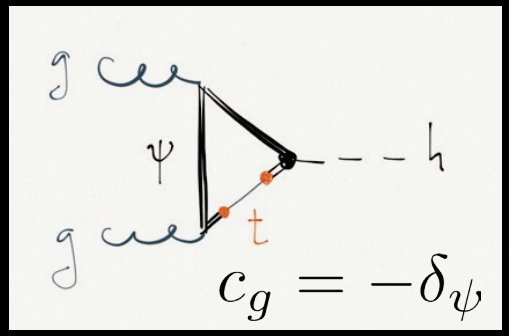
Composite Higgs hunting grounds

- LHC Higgs measurements:
  - Higgs-to-$t\bar{t}$ coupling: $$c_t = \frac{1 - n\xi}{\sqrt{1-\xi}} + \delta_\psi$$





  - Higgs production: $$\mathcal{O}_g = \frac{\alpha_s}{12\pi v} h (G^a_{\mu\nu})^2$$



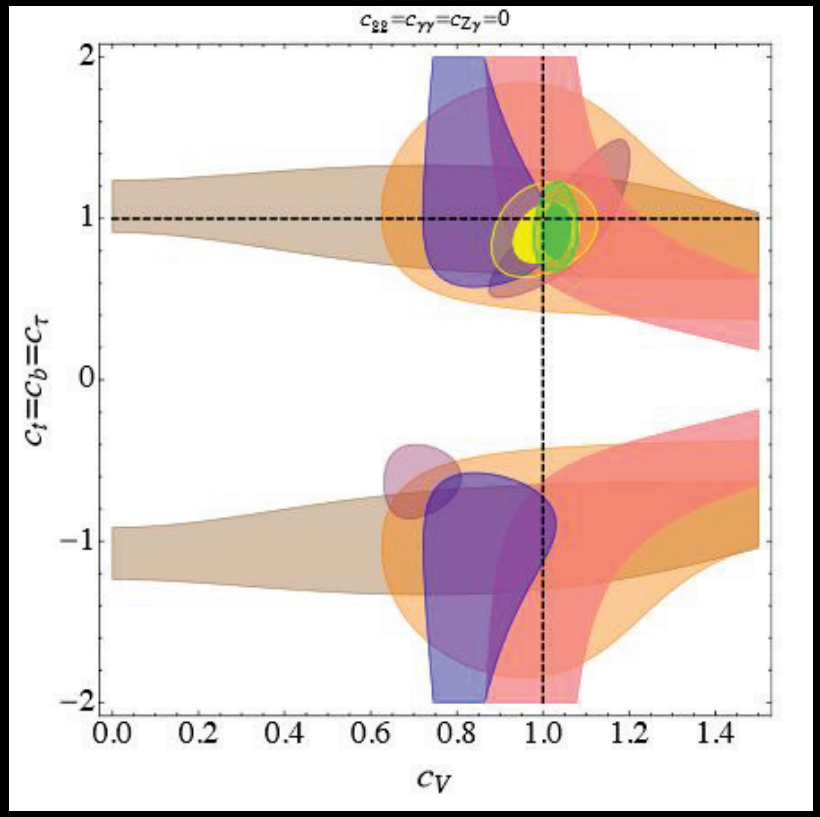
top partner accidentally cancel out

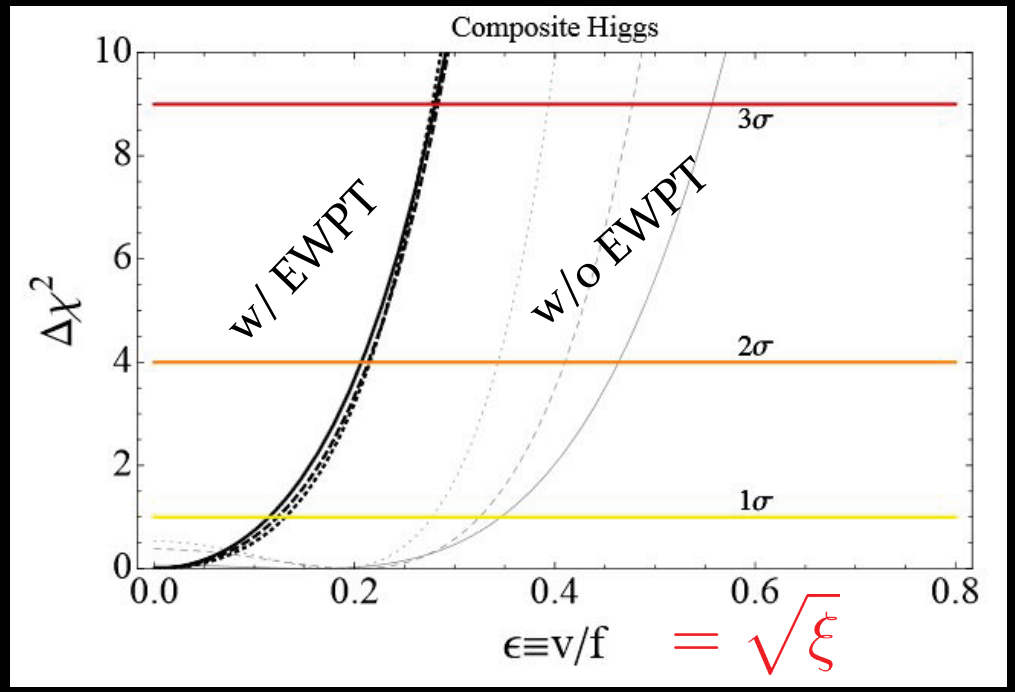
$$\sigma_{gg\to h} \propto |c_t + c_g|^2 \sim F(\xi) < 0$$

Falkowski '08, Azatov-Galloway '11
Low-Rattazzi-Vicchi '09

Composite Higgs hunting grounds

- Global fits to Higgs data: Falkowski-Riva-Urbano '13

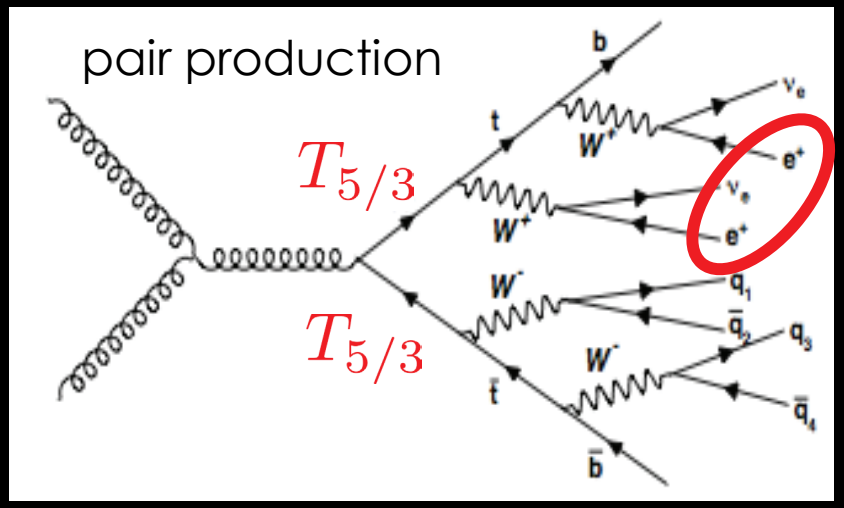


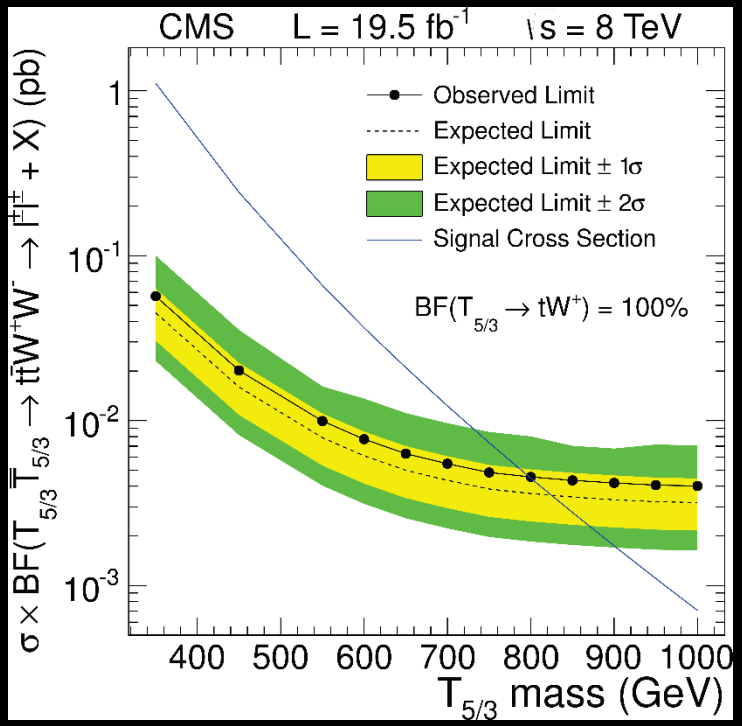


Composite Higgs hunting grounds

- Top partner searches:
  - exotic charges $\longrightarrow$ SS dilepton

$$\mathbf{5} = \mathbf{4} + \mathbf{1} \in T_{5/3}$$
$$\mathbf{14} = \mathbf{9} + \mathbf{4} + \mathbf{1} \in T_{5/3}, T_{8/3}$$





$$m_{T_{5/3}} \gtrsim 800\,\text{GeV} \qquad (95\%\text{CL})$$

(stronger limit for $\mathbf{9}$: $m_{T_{8/3}} \gtrsim 940\,\text{GeV}$)

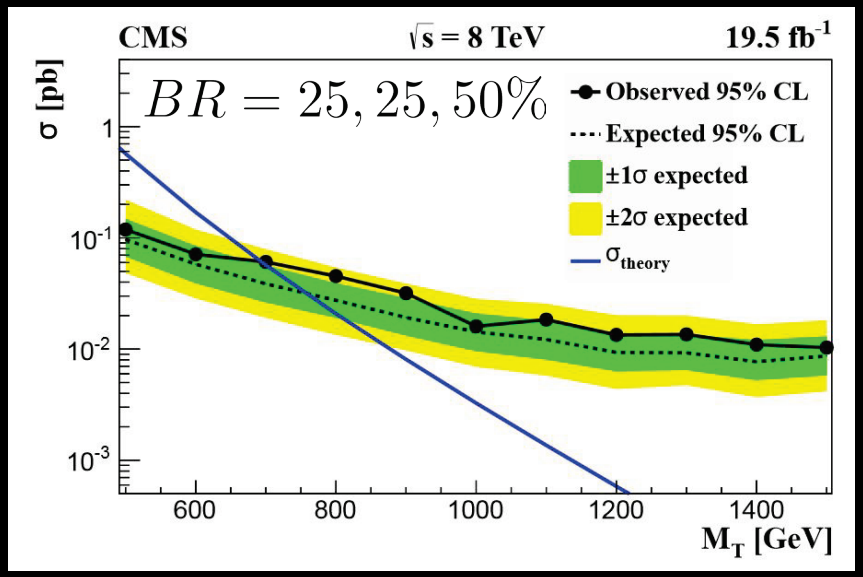
Matsedonskyi-Riva-Vantalon '14

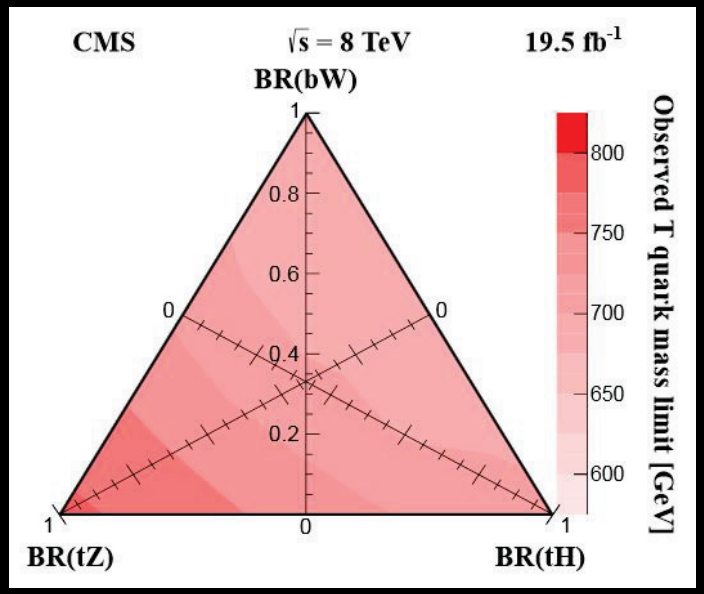
Composite Higgs hunting grounds

- Top partner searches:
  - top-like charge

$$T_{2/3} \to tZ, th, bW$$

$$\mathbf{5} = \mathbf{4} + \mathbf{1}$$
$$\mathbf{14} = \mathbf{9} + \mathbf{4} + \mathbf{1}$$





weakest limit:

$$m_{T_{2/3}} \gtrsim 687\,\mathrm{GeV}$$

LHC8 implications

- LEP lesson reinforced: $\mathcal{O}(10\%)$ fine-tuning needed

  minimal FT in models with top partners in $\mathbf{14}$ of SO(4)

$$f \gtrsim 800\,\mathrm{GeV}$$

- Top partners might not be colored after all:
  - Neutral naturalness, twin-CH?

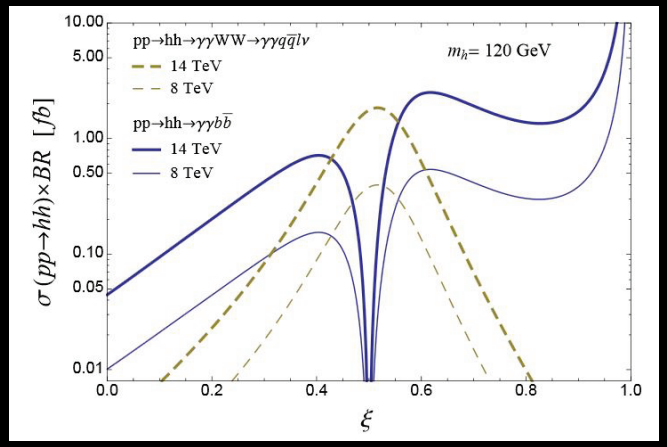
Chacko-Harnik '06
Rattazzi et al. '15
Tesi et al. '15

What's up
for LHC13?

Unexplored channels

- $h \to Z\gamma$: $\mathcal{O}(1)$ deviation possible Azatov-Contino-DiIura-Galloway '13
- double Higgs production:

Contino et al. '10
Gillioz et al. '12
Contino et al. '12



$\mathcal{O}(1)$ deviation also possible

- $pp \to t\bar{t} + h$
- Higgs+hard jet: challenging, resolve $c_t - c_g$?

Banf-Martin-Sanz '13
Grojean-Salvioni-Schlaffer-Weiler '13
Spannowsky et al. '13

More exotic signatures

If other SM fermions are composite:

- top FCNC decays: $BR(t \to cZ) \sim 10^{-5}\,,\ BR(t \to ch) \sim 10^{-6}$

  Azatov-Panico-Perez-Soreq '14

- $h \to c\bar{c}$ and $pp \to h + c$:

  Delaunay-Golling-Perez-Soreq '13
  Perez et al. '15
  Goertz-Isidori '15

  $y_{c\bar{c}}$ could be as large as $y_{b\bar{b}}$

- light generation partners: $pp \to QQ \to VVjj, hhjj$

$m_{C_{2/3}} \gtrsim 400\,\mathrm{GeV}$

Delaunay et al. '13
Flacke et al. '13

charm tagging?

Non-minimal top partner decays

Suppress canonical tZ, th, bW by opening new decay

- Next-to-minimal models: $SO(6)/SO(5) \in H + \eta$

Gripaios-Pomarol-Riva-Serra '09

pseudoscalar singlet

(some) partners have significant BR into $T_{2/3} \to t\eta$

Serra '15

(see also Anandakrishnan et al. '15)

- Flavored naturalness: (see Blanke et al. '13 for SUSY)

add non-trivial flavor mixing leading to significant

$T_{2/3} \to cZ, ch, sW$ or $T_{5/3} \to cW$

Blanke-Delaunay-Martin-Perez 'in progress

Concluding remarks

Conclusions

- Composite pNGB Higgs remains an attractive solution to weak scale naturalness
- LEP+LHC8 imply a generic fine-tuning of 10%, comparable to natural SUSY.
- Still many possibilities for unveiling compositeness at run 2+

- Three scenarios:
  - Canonical top partners are around LHC13 corner: Wait and see.
  - Non-minimal models are realized, more subtle decays: Work harder.
  - Naturalness, but uncolored ("neutral") partners: Work very hard (ILC?)