Shedding light on the Higgs' identity through subleading production channels

Ennio Salvioni

CERN *and* ***University of Padova***

LAPTh, Annecy

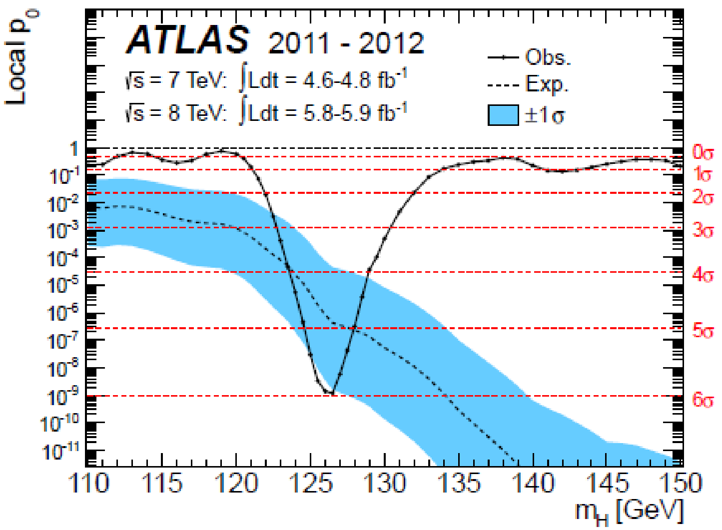
December 6, 2012

based on

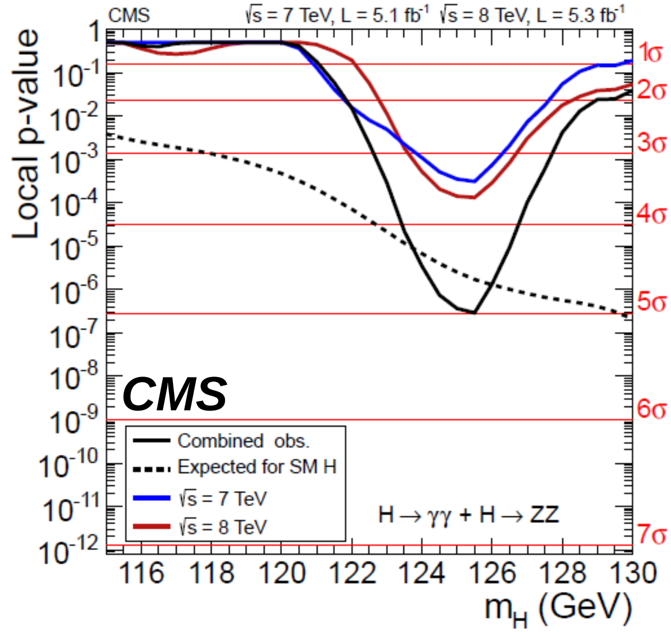
arXiv:**1211.3736**, with Farina, Grojean, Maltoni and Thamm

arXiv:**1206.7120** (JHEP), with Gillioz, Gröber, Grojean and Mühlleitner

2012 is *annus mirabilis* of particle physics



July 4th: a new particle discovered



… celebrations still going on!

Course de la Marmite,
Genève, December 1st

Introduction

- After discovery, determining the couplings of the new resonance is a crucial task: any deviations from the standard values would signal new physics.
- So far, most information comes from processes that proceed at loop level

  ➡ tree-level Higgs couplings not unambiguously identified.
- Important to investigate other channels, in particular those with real tops in final state: $t\bar{t}h$ is the main example.
- Here I am going to discuss another, subleading, process of this kind: **single top + Higgs associated production**, which can resolve the current ambiguity in the sign of the top Yukawa (potentially already with 2012 data).
- Also important to identify processes that are indirectly sensitive to new physics: in the second part of the talk I discuss $\boldsymbol{gg \to hh}$, which is strongly affected by non-linear Higgs couplings typical of strongly coupled EWSB.

  This process is also sensitive to light (< TeV) fermionic resonances, expected from naturalness arguments.

Part I

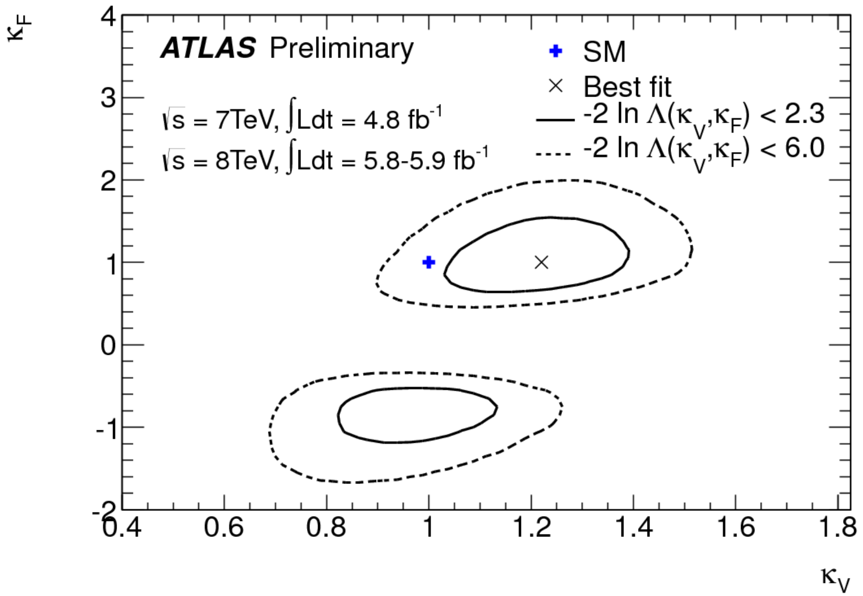
th production

as a probe of

the sign of the top Yukawa

(arXiv:1211.3736)

Ambiguity in the sign of the top Yukawa



$$\kappa_V \equiv c_V = g_{hVV}/g_{hVV}^{\rm SM}$$

$$\kappa_F \equiv c_F = g_{hf\bar{f}}/g_{hf\bar{f}}^{\rm SM}$$

ATLAS-CONF-2012-127

- Current data show an ambiguity in the sign of c_F. Exact degeneracy $c_F \to -c_F$ broken only by $h \to \gamma\gamma$, where *W* and top loops interfere.

- Looking only at $\gamma\gamma$, if a 'true' signal (c_V^t, c_F^t) is assumed, then in addition to $(c_V, c_F) = (c_V^t, c_F^t)$ there is another point giving the same event yields:

$$c_V = c_V^t \left| \frac{1.26 c_V^t - 0.26 c_F^t}{1.26 c_V^t + 0.26 c_F^t} \right| , \qquad c_F = -c_F^t \left| \frac{1.26 c_V^t - 0.26 c_F^t}{1.26 c_V^t + 0.26 c_F^t} \right|$$

Injecting the SM as true signal, one gets $(c_V, c_F) = (0.66, -0.66)$

- Including all other channels and real data, obtain plot as the one shown above.

A closer look at the degeneracy

- How do we get the solution with negative c_F for the $\gamma\gamma$ rates?
- Defining

$$\mu = \frac{\sigma \times \mathrm{BR}}{[\sigma \times \mathrm{BR}]_{\mathrm{SM}}}$$

then for the inclusive, VBF and associated production one has

$$\mu_{incl} \sim (1.26 c_V - 0.26 c_F)^2 \,, \qquad \mu_{VBF} \sim \mu_{ass\,prod} \sim c_V^2 \frac{(1.26 c_V - 0.26 c_F)^2}{c_F^2}$$

which admit the 2 solutions written before.

Recall

$$\Gamma(h \to \gamma\gamma)/\Gamma(h \to \gamma\gamma)_{\mathrm{SM}} \simeq (\underbrace{1.26 c_V}_{W\text{ loop}} - \underbrace{0.26 c_F}_{\text{top loop}})^2$$

- **How to break the degeneracy?** Azatov et al., 1204.4817

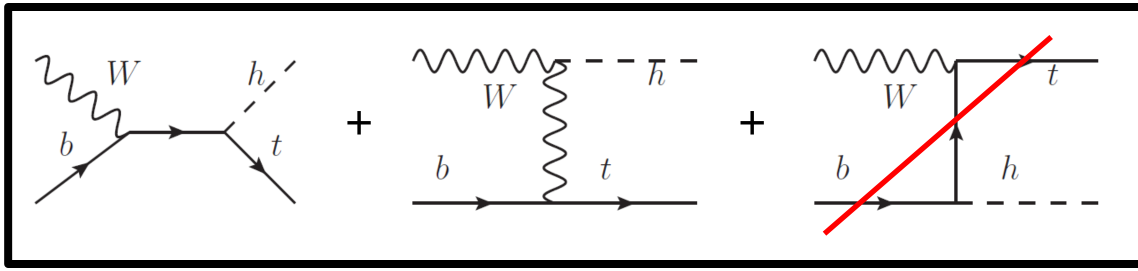
Combine $\gamma\gamma$ and $ZZ \to 4\ell$ channels, but not easy: with full 2012 data, ATLAS + CMS, solution with $c_F < 0$ can be disfavored but not excluded

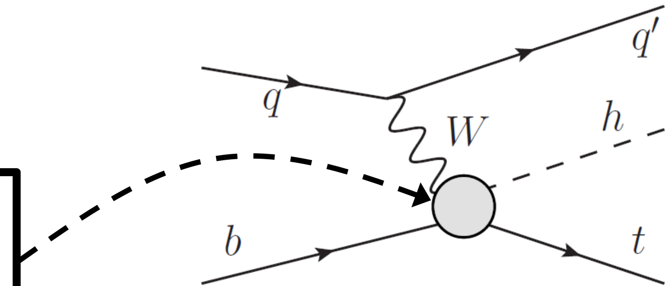
➡ need larger luminosity and/or new ingredients in existing analyses.

This motivates looking for other processes.

(t-channel) single top and Higgs associated production

- The ‘core’ process is the scattering $Wb \to th$





- In the SM, almost exact cancellation of the two (large) pieces, *s*- and *t*-channel

  ➡ **for non-standard (c_V, c_F) , enhancement of the cross section**

- At LHC, initial *W* is spacelike. But at high energies, ‘effective *W* approximation’ : factorize process in emission of on-shell *W* and subsequent hard scattering with bottom ➡ study $Wb \to th$ with on-shell *W* to get a qualitative understanding

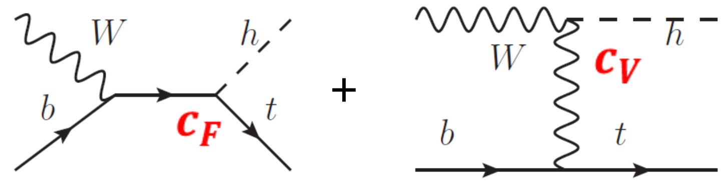
Tait and Yuan, hep-ph/0007298
Maltoni et al., hep-ph/0106293
Barger et al., 0911.1556

$Wb \to th$ scattering

- In the hard-scattering regime $s, -t, -u \gg m_t^2, m_W^2, m_h^2$ the amplitude is

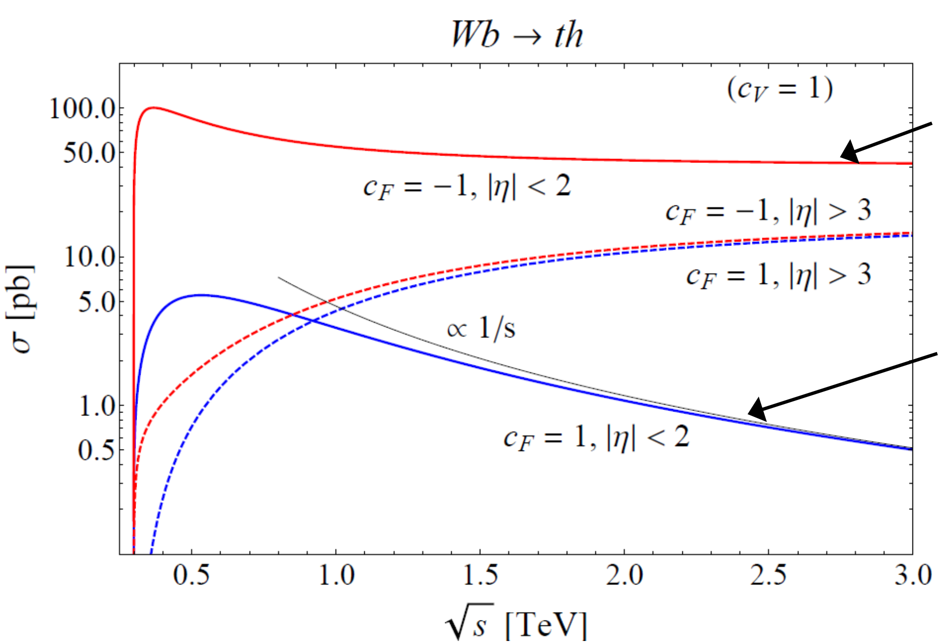
$$\mathcal{A} \sim \frac{g}{\sqrt{2}} \left[(-c_F + c_V) \frac{m_t \sqrt{s}}{m_W v} e^{i\varphi} \sqrt{-t/s} + \text{finite terms} \right] ,$$

where 'finite' = not growing with s .



Thus when $c_V \neq c_F$ the amplitude grows with energy like $\sqrt{s}$, and

the cross section is **enhanced** compared to the SM



- For $c_V = -c_F$, amplitude grows like $\sqrt{s}$, cross section is $\sim \text{const}$
- For $c_V = c_F$, amplitude is constant at large s , cross section goes as $\sim 1/s$

VERY LARGE (>10) ENHANCEMENT

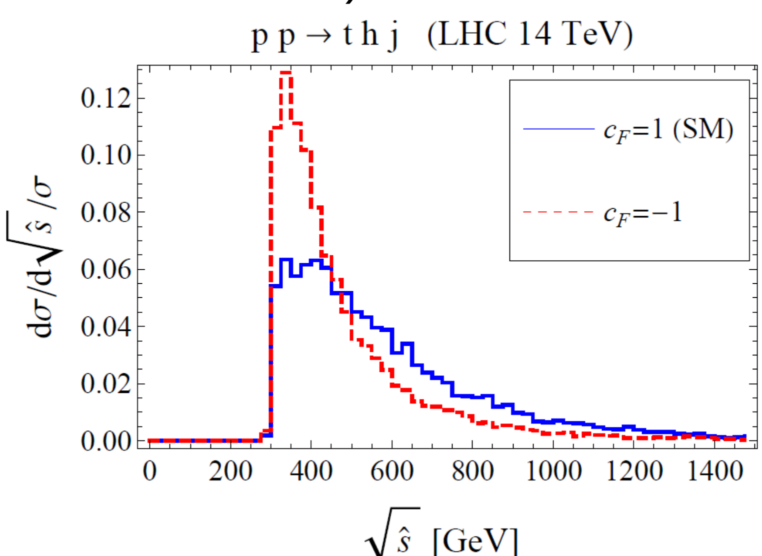
Perturbative unitarity breakdown

- Amplitude growing with energy ➡ perturbative unitarity is lost at some UV scale Λ. Find *s*-wave amplitude

$$a_0 = \frac{1}{24\sqrt{2}\pi}(c_V - c_F)\frac{g m_t \sqrt{s}}{m_W v} e^{i\varphi} \quad \overset{|a_0|<1}{\Longrightarrow} \quad \boxed{\Lambda \simeq 12\sqrt{2}\pi \frac{v^2}{m_t |c_F - c_V|}}$$

- For $c_V = -c_F = 1$, the cutoff is 9.3 TeV. Should we worry about sensitivity to UV physics?

- Look at distribution of th invariant mass in LHC events (after convolution with PDFs):

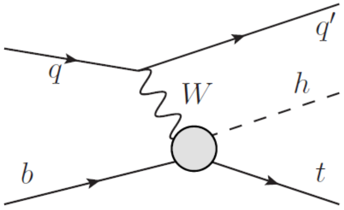


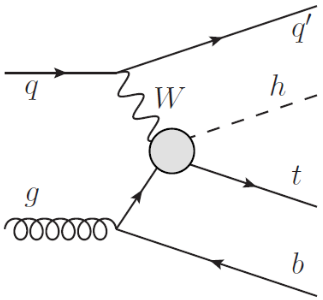
Contribution of region $\sqrt{\hat{s}} > 1\,\mathrm{TeV}$ is negligible, so our **perturbative computations can be safely trusted**.

Also, relative contribution from large $\sqrt{\hat{s}}$ is *larger* in the SM (see behavior of *Wb* → *th* cross section)

Single top + Higgs at the LHC

inclusive



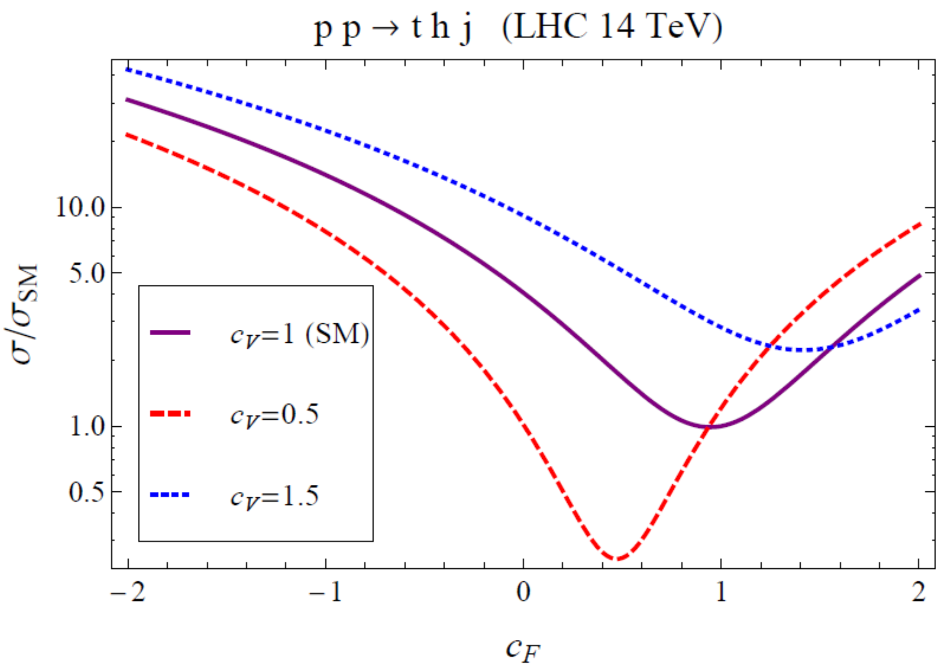


extra *b* in tagging region

5-flavor scheme

	$\sigma(pp \to thj)$ [fb]		$\sigma(pp \to thjb)$ [fb]	
	$c_F = 1$	$c_F = -1$	$c_F = 1$	$c_F = -1$
8 TeV	17.4	252.7	5.4	79.2
14 TeV	80.4	1042	26.9	363.5

$(p_T^b > 25\,\mathrm{GeV},\ |\eta^b| < 2.5)$



- Enhancement for flipped top Yukawa is 13 ÷ 15!

  ➡ worth looking into a detailed pheno analysis.

Parton-level analysis

ATLAS-CONF-2012-135
CMS PAS HIG-12-025

- Consider decay $h \to b\bar{b}$: final states

for h →γγ , see Biswas et al., 1211.0499

$$pp \to thj \to 3b + 1\,\text{forward jet} + \ell + E_T^{miss}$$

$$pp \to thjb \to 4b + 1\,\text{forward jet} + \ell + E_T^{miss}$$

are similar to those already studied by ATLAS and CMS in $t\bar{t}h$ searches.

➡ **full exp. analysis should be possible in very near future**

- Use MadGraph 5, jets defined at parton level with smearing of p_T following

$$\frac{\sigma(p_T)}{p_T} = \frac{a}{p_T} \oplus \frac{b}{\sqrt{p_T}} \oplus c\,, \qquad a = 2,\ b = 0.7,\ c = 0.06$$

(roughly compatible with ATLAS jet energy res).

- Acceptance cuts (no cut on missing energy):

Cut	$p_T^b >$	$p_T^\ell >$	$p_T^j >$	$\|\eta^{b,\ell}\| <$	$\|\eta^j\| <$	$\Delta R_{ij} >$
Value	25 GeV	25 GeV	30 GeV	2.5	5	0.4

- Assume *b*-tagging performance: $\epsilon_b = 0.7,\ \epsilon_c = 0.2,\ \epsilon_j \approx 0.008$

(cuts and *b*-tag numbers follow those of ATLAS $t\bar{t}h$ analysis)

3 *b* final state

- Signature: $pp \to thj \to 3b + 1\,\text{forward jet} + \ell + E_T^{miss}$
- Main backgrounds are
  - $t\bar{t}, \quad \bar{t} \to bcs$ with *c* mistagged as *b*
  - $t\bar{t}j, \quad \bar{t} \to bcs$ with *c* mistagged as *b* and *s* missed
- Cuts:
  - $m(bbj) > 270\,\text{GeV}$ kills $t\bar{t}$ (for which *bbj* all come from a hadronic top)

    NB: we assume 100% efficiency for reconstruction of semileptonic top, in all signal and backgrounds. So *b* from its decay always identified.
  - $|\eta^j| > 1.7$ reduces $t\bar{t}j$ a bit.

8 TeV

	Signal		Backgrounds				
Cuts	$c_F = 1$	$c_F = -1$	Total	tZj	$tb\bar{b}j$	$t\bar{t}$	$t\bar{t}j$
Acceptance Cuts + ϵ	0.18	2.88	600.81	0.61	1.01	456.40	142.80
$\lvert m_{bb} - m_h\rvert < 15$ GeV	0.15	2.55	245.95	0.02	0.11	184.2	61.65
$m_{bbj} > 270$ GeV	0.10	2.02	31.78	0.01	0.08	0.	30.68
$\lvert\eta^j\rvert > 1.7$	0.08	1.70	17.98	0.01	0.06	0.	17.24
Events at $25\,\text{fb}^{-1}$	1.9	42.5	449.4				

- Exclusion at 25 fb^{-1} , $c_F = -1$: ~2.2 σ at 8 TeV, ~4 σ at 14 TeV.

4 *b* final state

Maltoni et al., hep-ph/0106293

- Requiring an extra *b* helps suppressing the backgrounds: signature

$$pp \to thjb \to 4b + 1\,\text{forward jet} + \ell + E_T^{miss}$$

- Main backgrounds:
  - $t\bar{t}b\bar{b},\ \bar{t} \to bjj$ where one jet is missed
  - $t\bar{t}b\bar{b},\ \bar{t} \to bcs$ where the *c* is mistagged and one physical *b* missed
  - $t\bar{t}j,\ \bar{t} \to bcs$ with both *c* and *s* mistagged
- Cuts:
  - $\min m(bb) > 110\,\text{GeV}$ kills $t\bar{t}j$, where mistagged *c*+*s* come from *W*
  - $\min m(bj) > 180\,\text{GeV}$ suppresses $t\bar{t}b\bar{b}$, for which one *b*+*j* pair comes from top decay ➡ $m(bj) < \sqrt{m_t^2 - m_W^2} \sim 150\,\text{GeV}$

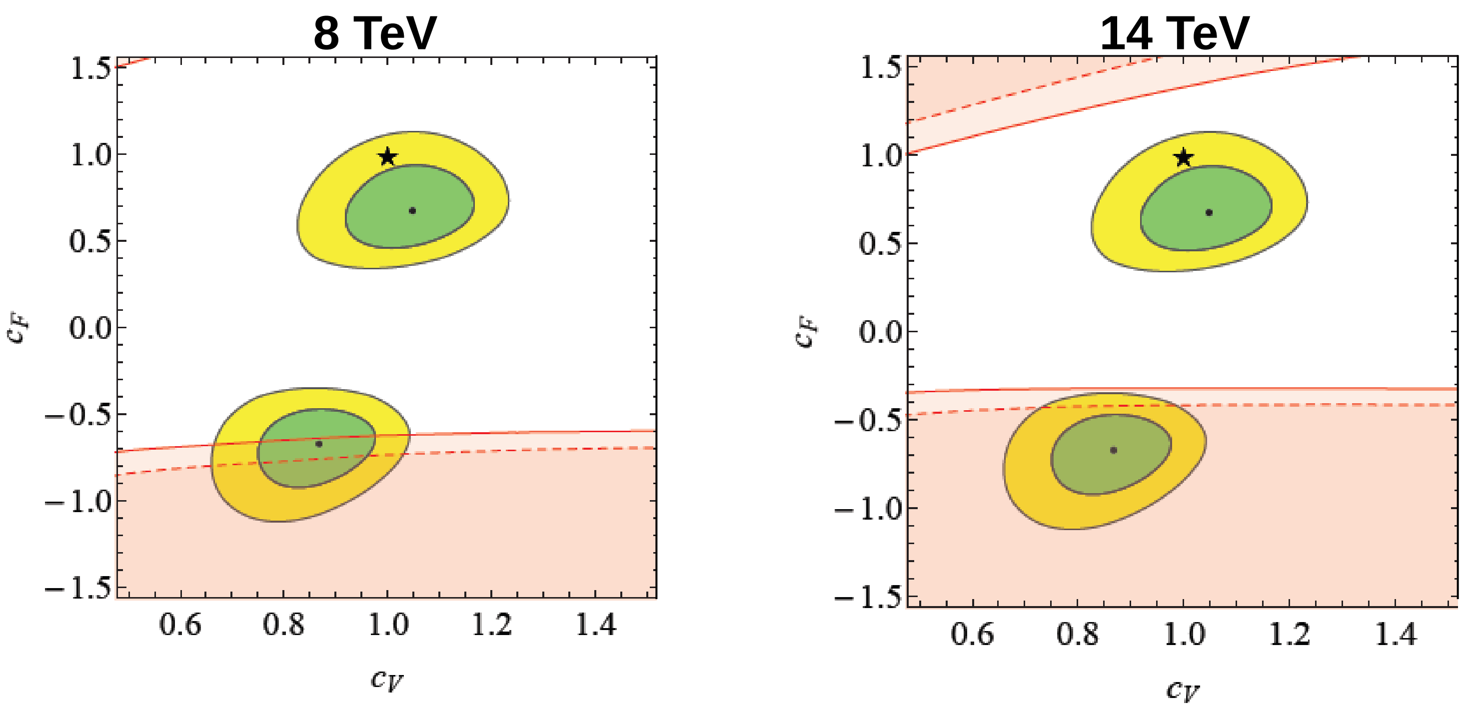
8 TeV

	Signal		Backgrounds					
Cuts	$c_F = 1$	$c_F = -1$	Total	$tZ\bar{b}j$	$tb\bar{b}\bar{b}j$	$t\bar{t}b\bar{b}$	$t\bar{t}b\bar{b}\ (mis)$	$t\bar{t}j$
Acceptance Cuts + ϵ	0.043	0.63	7.81	0.11	0.26	2.66	2.25	2.54
$\lvert m_{bb} - m_h \rvert < 15$ GeV	0.039	0.58	4.06	0.03	0.08	0.94	1.29	1.71
min $m_{bb} > 110$ GeV	0.023	0.30	0.67	0.002	0.015	0.20	0.44	0.
min $m_{bj} > 180$ GeV	0.008	0.15	0.014	0.	0.007	0.002	0.004	0.
Events at 25 fb^{-1}	0.2	3.8	0.4					

- Exclusion at 25 fb^{-1}, $c_F = -1$: ~2.4 σ at 8 TeV, ~6 σ at 14 TeV.

Implications on Higgs couplings

- Compare reach of our analysis (3*b* and 4*b* combined*)* to results of Higgs searches in 'standard' channels: assuming **universal** rescaling of Higgs couplings to fermions, $c_F = c_t = c_b = c_\tau = c_c$



- Solid and dashed lines are for 25 fb^{-1} and 50 fb^{-1}.

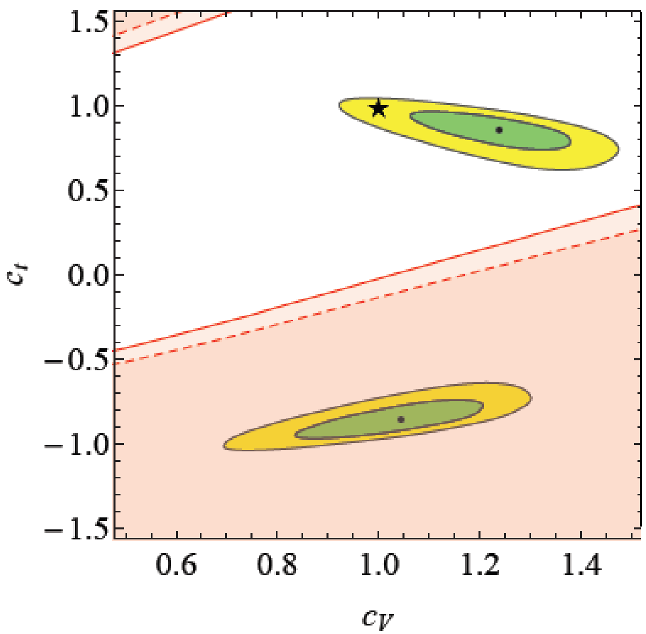
  Higgs data after ICHEP 2012 (*only illustrative!*)
- Interesting sensitivity already with ~25 fb^{-1} at 8 TeV
- Degeneracy removed completely with ~50 fb^{-1} at 14 TeV.

Implications on Higgs couplings/2

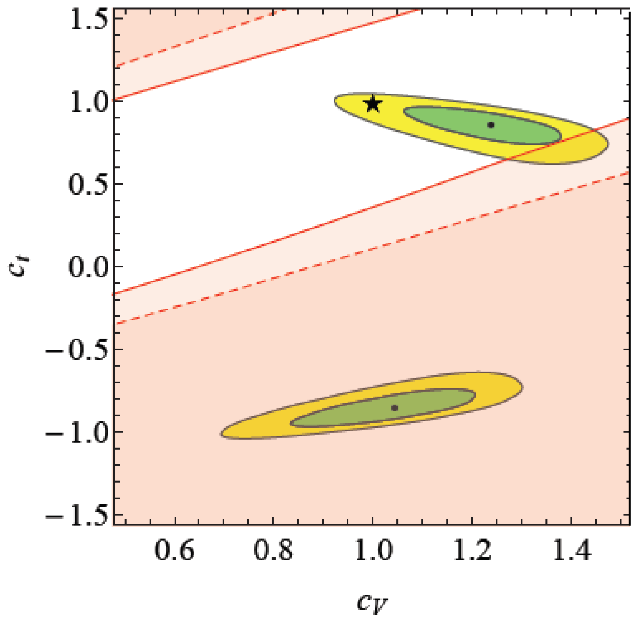
- Now assuming only c_t is rescaled, while $c_b = c_\tau = c_c = 1$

  $\Rightarrow$ $\Gamma(h \to b\bar{b}) = \Gamma(h \to b\bar{b})_{\rm SM}$

8 TeV



14 TeV



- Solid and dashed lines are for 25 fb^{-1} and 50 fb^{-1}.

  Higgs data after ICHEP 2012 (*only illustrative!*)

- Much better reach, because $\mathrm{BR}(h \to b\bar{b})$ is always sizable

  $\Rightarrow$ can exclude completely negative c_t region with 25 fb^{-1} at 8 TeV

Summary of Part I

- Single top + Higgs associated production can lift the current degeneracy in the sign of the top Yukawa: very large (>10) enhancement of rate for ‘flipped’ sign.
- For nonstandard couplings amplitude grows with energy, but cutoff is ~10 TeV

  ➡ perturbative computation fully trustable.
- Selecting decay of the Higgs into $b\bar{b}$, final states

$$pp \to thj \to 3b + 1\,\text{forward jet} + \ell + E_T^{miss}$$
$$pp \to thjb \to 4b + 1\,\text{forward jet} + \ell + E_T^{miss}$$

  similar to those of $t\bar{t}h$ analysis already done by ATLAS and CMS.
- We find interesting sensitivity already at 8 TeV. *O(*30) fb^{-1} at 14 TeV can lift the degeneracy completely.
- **We think the full experimental analysis can be done very soon!**

Part II

$gg \rightarrow hh$

in Composite Higgs models

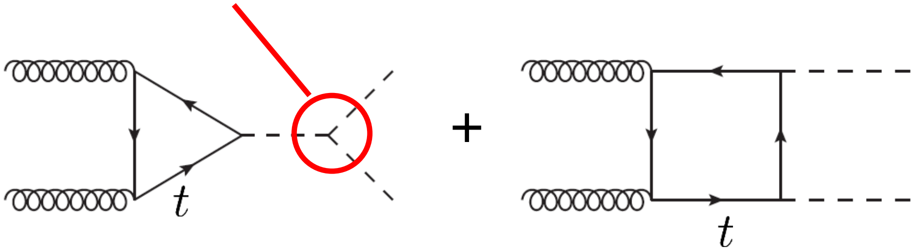
(arXiv:1206.7120, JHEP)

Introduction: why is *gg* → *hh* interesting?

- Gluon fusion $gg \to h,\, hh$ is the dominant mechanism for Higgs production at LHC.
- In the SM, amplitudes mediated by top loops.

  Measurement of Higgs self-coupling, long history of studies (still ongoing).

SM



- Experimentally very challenging signal for $m_h = 125\,\mathrm{GeV}$:

  best final state $hh \to \gamma\gamma b\bar{b}$, ***at least O(100) fb^{-1} at LHC14 needed*** to probe it in BSM with enhanced cross section (in the SM, even larger luminosity).

Baur et al., hep-ph/0310056
Groeber et al., 1012.1562

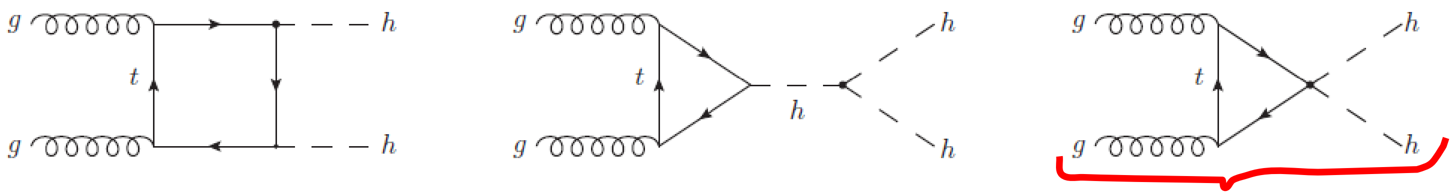
$gg \to hh$ in Composite Higgs models

- If the Higgs is composite, its couplings are modified from the standard ones:

  effective chiral Lagrangian

$$\mathcal{L} = \frac{1}{2}(\partial_\mu h)^2 - V(h) + \frac{v^2}{4}\mathrm{Tr}\left[(D_\mu \Sigma)^\dagger D^\mu \Sigma\right]\left(1 + 2\,c_V\,\frac{h}{v} + \dots\right)$$
$$- \frac{v}{\sqrt{2}}\,(\bar{u}_L^i \bar{d}_L^i)\,\Sigma\left[1 + c_F\,\frac{h}{v} + c_{2F}\,\frac{h^2}{v^2} + \dots\right]\begin{pmatrix} y_{ij}^u\, u_R^j \\ y_{ij}^d\, d_R^j \end{pmatrix} + \mathrm{h.c.} + \mathcal{L}^{(4)}, \quad \text{with}$$
$$V(h) = \frac{1}{2}\,m_h^2\,h^2 + d_3\left(\frac{m_h^2}{2v}\right)h^3 + \dots\,,$$
$$\mathcal{L}^{(4)} = \frac{g_s^2}{48\pi^2}G^{\mu\nu\,a}G_{\mu\nu}^a\left(k_g\frac{h}{v} + \frac{1}{2}k_{2g}\frac{h^2}{v^2} + \dots\right) + \frac{e^2}{32\pi^2}F_{\mu\nu}F^{\mu\nu}\left(k_\gamma\frac{h}{v} + \dots\right),$$

- Parameter c_{2F} controls nonlinear $t\bar{t}hh$ interaction, which vanishes in the SM



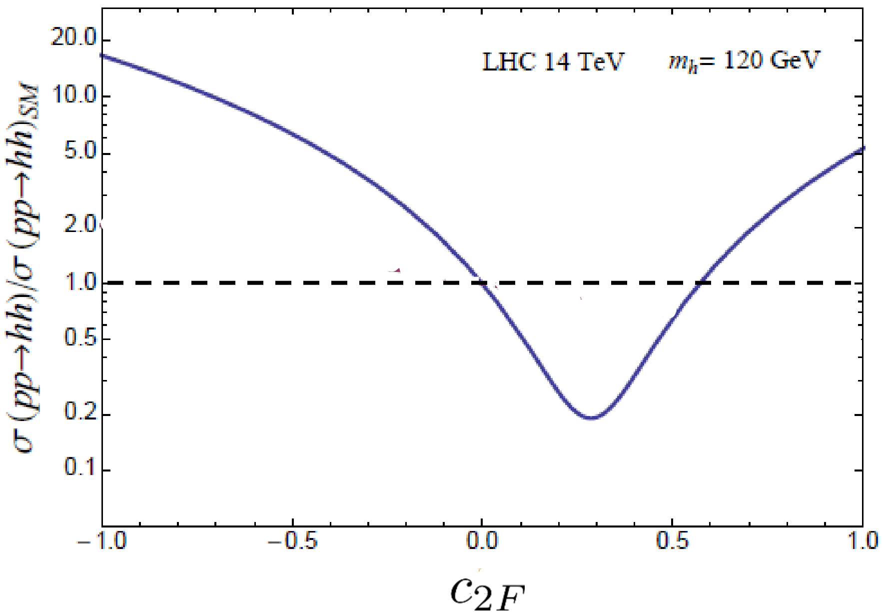
new!

this new diagram can lead to a **large enhancement** of the *gg* → *hh* rate!

Groeber et al., 1012.1562

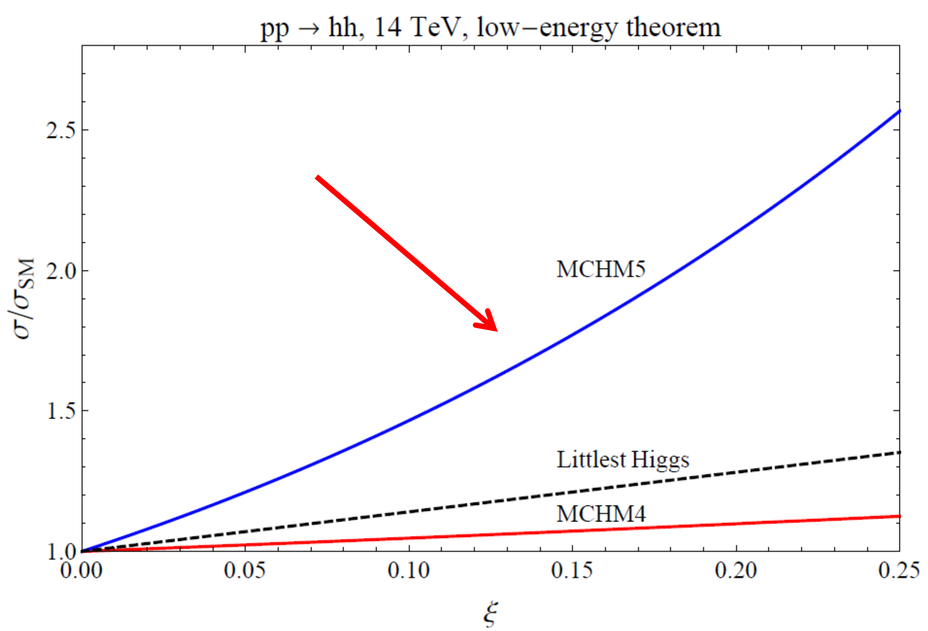
$gg \to hh$ in Composite Higgs models/2

adapted from Contino et al., 1205.5444



- Large enhancement possible, in particular for $c_{2F} < 0$

- Interestingly, in the simple minimal model ‘MCHM 5’ this is realized: one has $c_{2F} = -2\xi = -2(v^2/f^2)$ and a sizable enhancement of the cross section!
- For $\xi \leq 0.25$, model can be compatible with EW data and direct searches



Including the effect of fermionic resonances

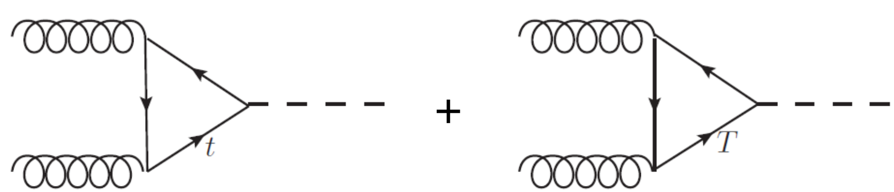
- In composite Higgs models, fermionic resonances are expected (‘top partners’)
- Their masses are related to the Higgs mass (Higgs potential generated at loop level) $\Rightarrow$ from naturalness can obtain *upper bound* on the mass of the lightest resonance, e.g.

$$m_T \lesssim 700\,\mathrm{GeV} \left(\frac{f}{500\,\mathrm{GeV}}\right) \left(\frac{m_h}{125\,\mathrm{GeV}}\right)$$

- **Must be light**, their effects in loop-induced processes could be sizable
- Look at $gg \to h,\ hh$ as ways to obtain indirect information on resonances, in addition to direct searches.

- Single production most relevant, but in most known models $\sigma(gg \to h)$ only depends on the overall scale of the strong sector, and **not on the masses of resonances.**

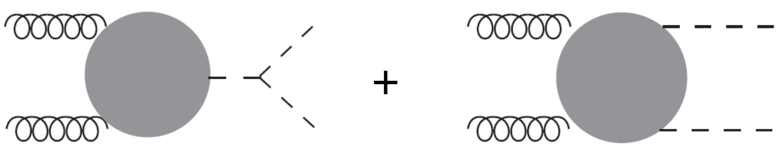
- Nontrivial result (not true e.g. in SUSY!), follows from a cancellation between correction to top Yukawa and loops of resonances:



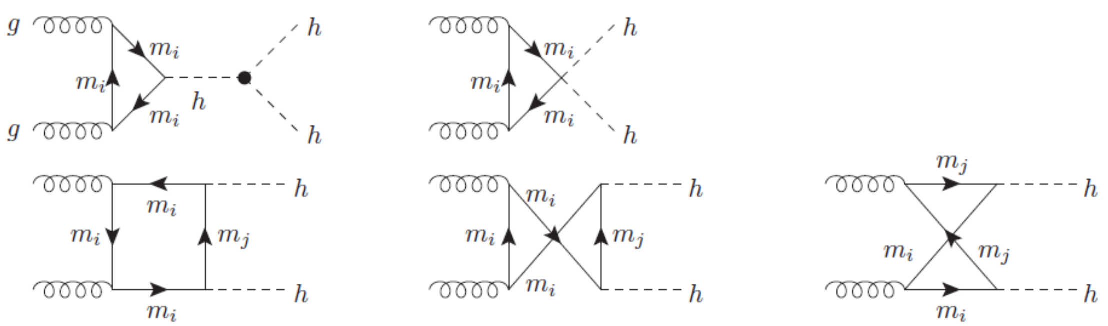
Falkowski, 0711.0828
Azatov et al., 1110.5646

Effects of resonances in *gg* → *hh*

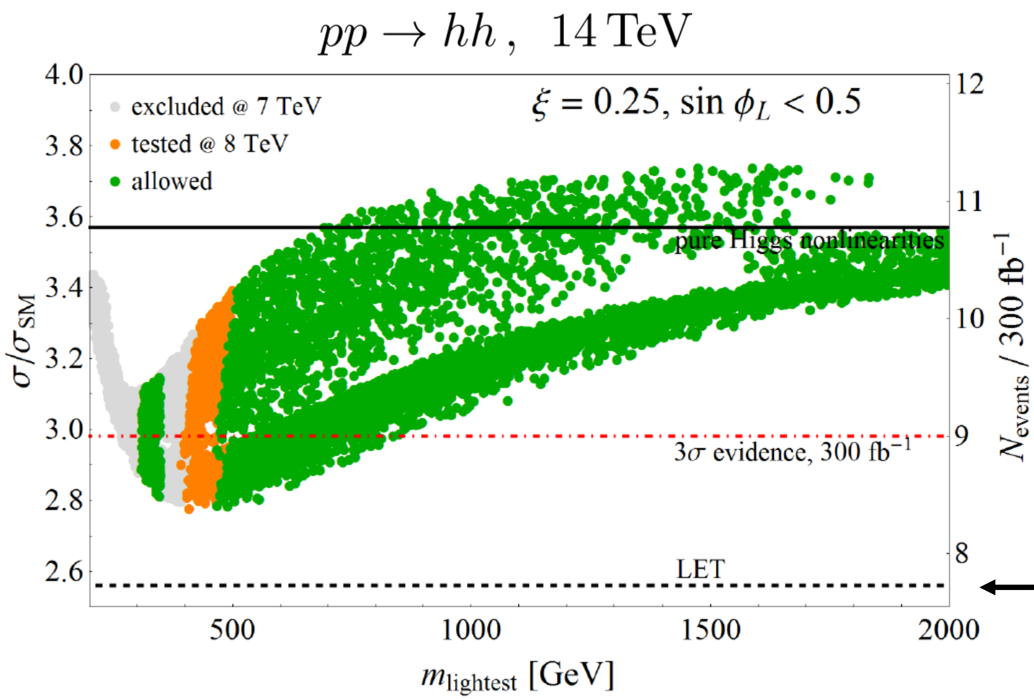
- Thus $gg \to h$ is not sensitive to resonances ➡ look at $gg \to hh$
- Simplest way to compute it, in any model, is via the Higgs Low-Energy Theorem. Find insensitivity to resonances.



- However, LET is only a first approximation in double Higgs production, and corrections are sizable in general.
- Choose a specific, simple model: MCHM5, where $gg \to hh$ is enhanced (seen before).
- Full 1-loop computation with top + 3 resonances in the loops



Double Higgs production in MCHM



Points are exact cross section:

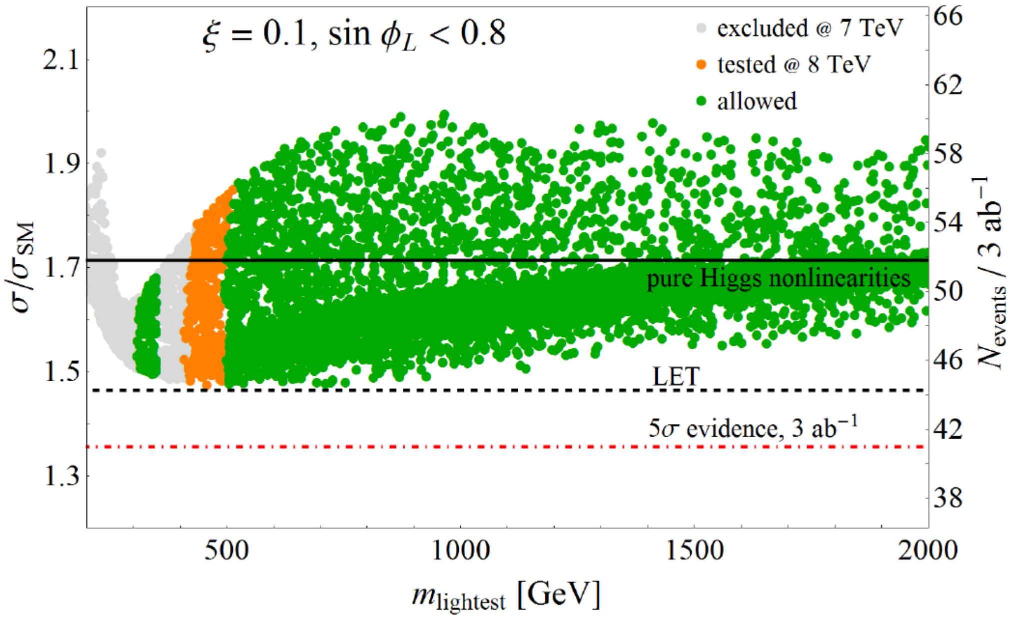
- All points pass EWPT at 99% CL
- Color code depending on point surviving (or not) LHC&Tevatron searches for heavy fermions

Dashed line is low-energy theorem result

- We find **some sensitivity to the masses of resonances**, cross section is *less enhanced* for very light top partner.

  ➡ could get indirect information on top partners from measurement of double Higgs production.

Double Higgs production in MCHM (2)



- Best final state for Higgs pair production at LHC, for a light Higgs, is $hh \to b\bar{b}\gamma\gamma$
- We follow the analysis of **Baur et al., hep-ph/0310056**

  roughly estimate the number of events at LHC14 by computing

  $\sigma(pp \to hh) \times \mathrm{BR}(hh \to b\bar{b}\gamma\gamma)$ and multiplying times the efficiency of cuts *for the SM*

  ($\epsilon \simeq 7\%$)
- QCD K-factor is 1.9; require 1 *b*-tag
- Take background estimate of Baur et al. (likely conservative):

  3σ evidence at LHC for $\xi = 0.25$, 5σ discovery at SuperLHC even for $\xi = 0.1$

***see also* Contino et al., 1205.5444**

Summary of Part II

- Double Higgs production in gluon fusion is sensitive to the non-linear Higgs coupling $t\bar{t}hh$, which is present if the Higgs is a composite state.
- A sizable enhancement of the cross section (up to more than factor 3) can be obtained in a simple, minimal CH model ➡ better prospects at LHC14

- Higgs production in gluon fusion is a priori sensitive to new colored resonances (top partners). However, due to a cancellation, in single production the sensitivity is negligible.
- We performed for the first time a full computation of $gg \to hh$ including resonances, and found some sensitivity to their spectrum ➡ hope to get indirect information on the new states from measurement of hh production.

Backup

Strongly Interacting Light Higgs (SILH) Lagrangian

Giudice et al., hep-ph/0703164

- Higgs doublet H results from a new strong interaction broadly described by the mass of composite states m_ρ and their self-coupling g_ρ.

$(f \equiv m_\rho / g_\rho)$

- At scales $E \ll m_\rho$, deviations from the SM described by

$$\mathcal{L}_{\text{SILH}} = \frac{c_H}{2f^2}\partial^\mu (H^\dagger H)\partial_\mu (H^\dagger H) + \frac{c_r}{2f^2} H^\dagger H (D_\mu H)^\dagger (D^\mu H) - \frac{c_6 \lambda}{f^2}(H^\dagger H)^3$$
$$+ \left(\frac{c_y y_f}{f^2} H^\dagger H \bar{f}_L H f_R + \text{h.c.}\right) + c_g \frac{g_s^2}{16\pi^2}\frac{y_f^2}{m_\rho^2} H^\dagger H G^a_{\mu\nu} G^{a\,\mu\nu} + \frac{c_T}{2f^2}\left(H^\dagger \overleftrightarrow{D^\mu} H\right)^2 + \ldots$$

- Operator $\propto c_r$ can be eliminated at order $1/f^2$ by field redefinition

$$H \to H + a(H^\dagger H) H$$

$$c_H \to c_H + 2a\,, \qquad c_r \to c_r + 4a\,, \qquad c_6 \to c_6 + 4a\,, \qquad c_y \to c_y - a$$

(choose $a = -c_r/4$). Instead we keep it (“natural” basis for nlσm has $c_r \neq 0$).

- Operator $\propto c_T$ shifts mass of the *Z*, breaking custodial symmetry:

$$\hat{T} = c_T v^2/f^2 \qquad (\rho = 1 + \hat{T})$$

but does not contribute to processes discussed in this talk.

Strongly Interacting Light Higgs (SILH) Lagrangian (2)

- Higgs doublet H results from a new strong interaction broadly described by the mass of composite states m_ρ and their self-coupling g_ρ.

$(f \equiv m_\rho / g_\rho)$

- At scales $E \ll m_\rho$, deviations from the SM described by

$$\mathcal{L}_{\mathrm{SILH}} = \frac{c_H}{2f^2}\partial^\mu (H^\dagger H)\partial_\mu (H^\dagger H) + \frac{c_r}{2f^2} H^\dagger H (D_\mu H)^\dagger (D^\mu H) - \frac{c_6 \lambda}{f^2}(H^\dagger H)^3$$
$$+ \left(\frac{c_y y_f}{f^2} H^\dagger H \bar{f}_L H f_R + \mathrm{h.c.}\right) + c_g \frac{g_s^2}{16\pi^2}\frac{y_f^2}{m_\rho^2} H^\dagger H G^a_{\mu\nu} G^{a\,\mu\nu} + \cancel{\frac{c_T}{2f^2}\left(H^\dagger \overleftrightarrow{D^\mu} H\right)^2} + \ldots$$

- From now on, we work in unitary gauge: $H \to \begin{pmatrix} 0 \\ H/\sqrt{2} \end{pmatrix}$
- c_r corrects the mass of the *W* :

$$\mathcal{L}_{W\,mass} = \frac{g^2 \langle H \rangle^2}{4}\left(1 + \frac{c_r}{4}\frac{\langle H \rangle^2}{f^2}\right) W^+ W^- \quad \Rightarrow \quad v^2 = \langle H \rangle^2 \left(1 + \frac{c_r}{4}\frac{\langle H \rangle^2}{f^2}\right)$$

- Non-canonical kinetic term for the Higgs (including derivative interactions):

$$\Delta\mathcal{L}_{h\,kin} = \frac{1}{2f^2}\left(c_H + \frac{c_r}{4}\right)(\langle H \rangle + h)^2 \partial_\mu h \partial^\mu h\,,$$

eliminated by non-linear rescaling

$$h \to h - \frac{1}{2}\frac{v^2}{f^2}\left(c_H + \frac{c_r}{4}\right)\left(h + \frac{h^2}{v} + \frac{h^3}{3v^2}\right)$$

Higgs couplings to gluons via the low-energy theorem

Ellis et al., NPB 1976
Shifman et al., SJNP 1979

- Heavy colored particle getting some of its mass from EWSB, $m(H)$
- For $m_h \ll m$, can integrate the particle out and write effective Lagrangian: leading term in $1/m$ will read $F(H) G^a_{\mu\nu} G^{\mu\nu\, a}$.
- Fix the function $F(H)$: treat H as background field, then $m(H)$ is a threshold for the running of QCD gauge coupling

$$\mathcal{L}_{eff} = -\frac{1}{4 g^2_{eff}(\mu, H)} G^a_{\mu\nu} G^{a\,\mu\nu}, \qquad \frac{1}{g^2_{eff}(\mu, H)} = \frac{1}{g_s^2(\Lambda)} - \frac{b_{UV}}{8\pi^2} \log\frac{\Lambda}{\mu} - \delta b \frac{1}{8\pi^2} \log\frac{m(H)}{\mu}$$

- For Dirac fermions $\delta b = 2/3$ $\Rightarrow$ $\mathcal{L}_{eff} = \sum_f \frac{g_s^2}{96\pi^2} G^a_{\mu\nu} G^{a\,\mu\nu} \log m_f^2(H)$

field-dependent mass of fermion *f*

and expanding get $(H = \langle H \rangle + h)$

$$\mathcal{L}_{h^n gg} = \frac{g_s^2}{96\pi^2} G^a_{\mu\nu} G^{a\,\mu\nu} \left[A_1 h + \frac{1}{2} A_2 h^2 + \ldots \right]$$

$$A_n \equiv \left(\frac{\partial^n}{\partial H^n} \log\det \mathcal{M}^\dagger(H) \mathcal{M}(H) \right)_{\langle H \rangle}$$

heavy fermion mass matrix

hgg coupling

- Linear term in *h*

$$\mathcal{L}_{hgg} = \frac{g_s^2}{48\pi^2} G^a_{\mu\nu} G^{a\,\mu\nu} \frac{h}{\langle H \rangle} \left(\frac{1}{2} \frac{\partial}{\partial \log H} \log \det \mathcal{M}^\dagger(H) \mathcal{M}(H) \right)_{\langle H \rangle}$$

- Now taking into account that $v^2 = \langle H \rangle^2 \left(1 + c_r v^2/4f^2\right)$

and the (nonlinear) rescaling needed to make the Higgs kin term canonical

$$h \to h \left(1 - \frac{v^2}{2f^2}\left(c_H + \frac{c_r}{4}\right)\right) + \mathcal{O}(h^2)$$

$$\mathcal{L}_{hgg} = \frac{g_s^2}{48\pi^2} G^a_{\mu\nu} G^{a\,\mu\nu} \frac{h}{v} \left[\underbrace{\frac{1}{2} \left(\frac{\partial}{\partial \log H} \log \det \mathcal{M}^\dagger(H) \mathcal{M}(H) \right)_{H=v}}_{= \; 1 - c_y \frac{v^2}{f^2} + 3 c_g y_t^2 \frac{v^2}{f^2}} - \frac{c_H}{2} \frac{v^2}{f^2} \right]$$

Note that

correction to top Yukawa

loops of top partners

Low, Rattazzi and Vichi, 0907.5413
Low and Vichi, 1010.2753

- SM: only top loop $m_t(H) = \frac{y_t H}{\sqrt{2}} \Longrightarrow \mathcal{L}_{h^n gg} = \frac{g_s^2}{48\pi^2} G^a_{\mu\nu} G^{a\,\mu\nu} \log\left(1 + \frac{h}{v}\right)$

In composite Higgs models, typically one or more top partners are present

hgg coupling in specific models

- In many popular models (both composite and Little Higgs), the gluon fusion cross section depends only on $\xi \equiv v^2/f^2$, and is **independent of the couplings and masses of the heavy fermions**

Falkowski, 0711.0828
Low and Vichi, 1010.2753

- Remarkable result (not true in other cases, e.g. SUSY), it happens because the determinant of fermion mass matrix has the form

Azatov and Galloway, 1110.5646

$$\det \mathcal{M}^\dagger(H)\mathcal{M}(H) = F(H/f) \times \underbrace{P(\lambda_i, M_i, f)}_{\text{independent of } H}$$

so taking $\frac{\partial}{\partial H} \log\left[F(H/f) \times P\right]$ the dependence on P cancels!

- Example: $SO(5)/SO(4)$ with composite fermions in a **5** (fundamental)

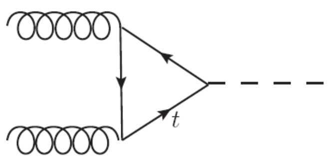
$$\det \mathcal{M}^\dagger(H)\mathcal{M}(H) = \sin^2(2H/f) \times P(y, M_0, f, \ldots)$$

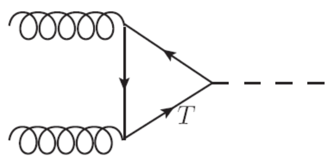
- Independence of spectrum is exactly true in the infinite fermion mass approximation

$\longleftrightarrow$ low-energy theorem. *Corrections due to higher orders in* $1/m_f$ *?*

Finite fermion mass corrections

- Simple case: **one top partner**. Parameterize mass eigenvalues as





$$m_t(H) = \frac{y_t H}{\sqrt{2}} \left(1 - c_y \frac{H^2}{2f^2}\right)$$
$$m_T(H) = \lambda_T f \left(1 + a_T \frac{H^2}{2f^2}\right)$$

Low-energy theorem gives the leading coupling:

$$\lambda_{hgg}/\lambda_{hgg}^{SM} = 1 + (a_T - c_y)\frac{v^2}{f^2} \qquad\qquad (c_H = 0)$$

but also, top Yukawa is $(m_t/v)\left(1 - c_y \frac{v^2}{f^2}\right)$ ➡ compute first correction in $1/m_t^2$

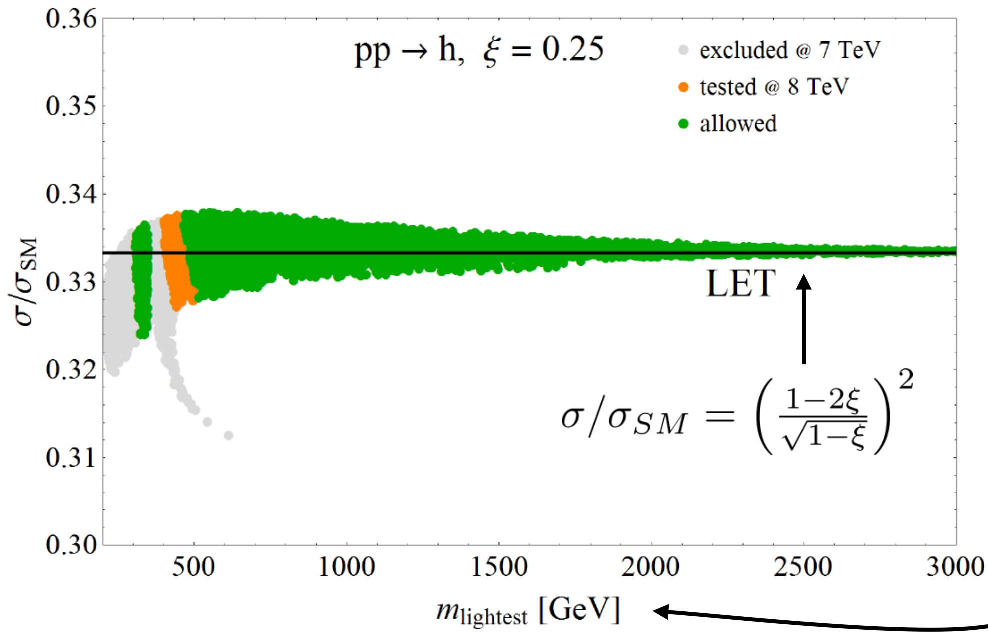
$$\lambda_{hgg}/\lambda_{hgg}^{SM} = 1 + (a_T - c_y)\frac{v^2}{f^2} + \frac{7}{120}\frac{m_h^2}{m_t^2}\left(1 - c_y \frac{v^2}{f^2}\right) + \ldots$$

- Now $c_y = c_y^{(\sigma)} + y_t^2/\lambda_T^2\,,\ \ a_T = y_t^2/\lambda_T^2$ so sensitivity to spectrum is, for light partner $(\lambda_T \sim y_t)$

$$\frac{\delta\sigma(gg\to h)}{\sigma(gg\to h)_{SM}} \sim \frac{7}{60}\frac{m_h^2}{m_t^2}\xi = 0.06\,\xi$$

Finite mass corrections: a full computation

- Take specific model: $SO(5)/SO(4)$ with 1 multiplet of composite fermions in fundamental representation
- Top sector has 4 states: top + 3 partners
- Full numerical result, including all fermions and mass dependence:



Note the sizable suppression compared to the SM!

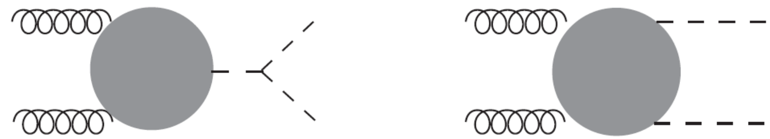
…but BRs enhanced

mass of lightest new fermion

- Corrections to LET very small as estimated: $\delta\sigma/\sigma_{SM} \sim (0.06\,\xi) \sim 0.015$
- **For single production, low-energy theorem gives excellent approximation, for any spectrum of extra fermions.**

Higgs pair production via LET

- Now we consider $gg \to hh$, dominant mechanism for Higgs pair production at LHC
- Apply low-energy theorem:



see also
Pierce, Thaler, Wang
hep-ph/0609049

- Effective *hhgg* vertex

$$\mathcal{L}_{hhgg} = \frac{g_s^2}{96\pi^2} G^a_{\mu\nu} G^{a\,\mu\nu} \frac{h^2}{v^2} \left\{ \overbrace{\frac{1}{2}\left[\left(\frac{\partial^2}{\partial(\log H)^2} - \frac{\partial}{\partial \log H}\right) \log\det \mathcal{M}^2(H)\right]_{H=v}}^{= \, -1 - c_y \frac{v^2}{f^2} + 3c_g y_t^2 \frac{v^2}{f^2}} - \frac{c_r}{4}\frac{v^2}{f^2} \right\}$$

- Correction to the Higgs self-coupling $\lambda_{hhh}/\lambda_{hhh}^{SM} = 1 + \left(c_6 - \frac{c_r}{4} - \frac{3}{2}c_H\right)\frac{v^2}{f^2}$
- Amplitude

$$\mathcal{A}_{let}\left(gg \to hh\right) = \frac{\alpha_s}{3\pi v^2} \delta^{ab} (p_1^\nu p_2^\mu - p_1 \cdot p_2 g^{\mu\nu})\, C(\hat{s})$$

$$\boxed{C(\hat{s}) = \frac{3m_h^2}{\hat{s}-m_h^2}\left(1 - \xi(c_y - c_6 + 2c_H + \frac{c_r}{4} - 3c_g \frac{y_t^2}{g_\rho^2})\right) - \left(1 + \xi(c_y + \frac{c_r}{4} - 3c_g \frac{y_t^2}{g_\rho^2})\right)}$$

reparam invariant

- Partonic cross section

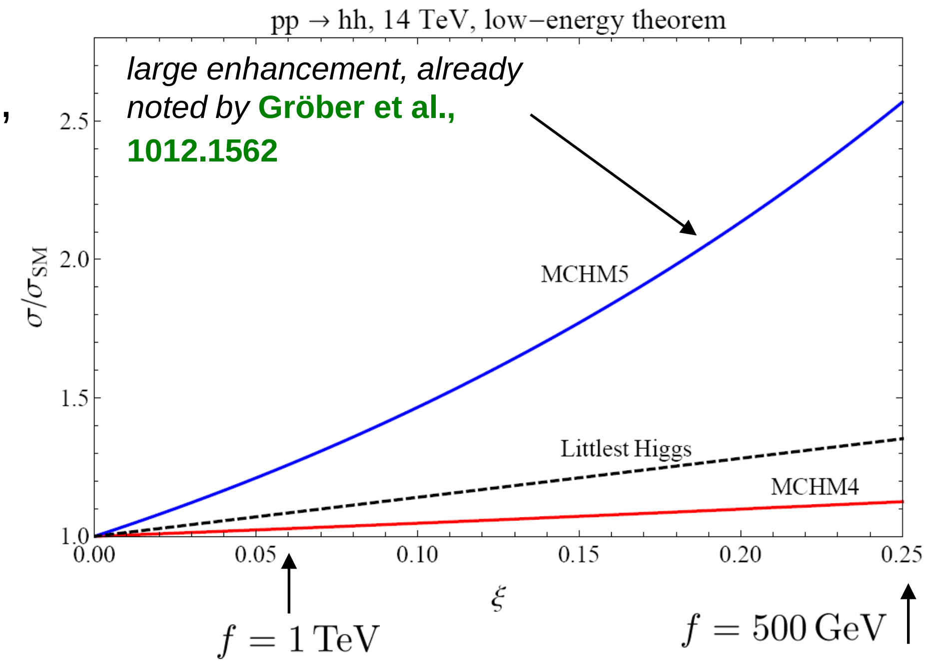
$$\hat{\sigma}_{gg\to hh} = \frac{G_F^2 \alpha_s^2(\mu)\hat{s}}{128(2\pi)^3} \frac{1}{9} \sqrt{1 - \frac{4m_h^2}{\hat{s}}}\, C^2(\hat{s})$$

- Hadronic cross section

$$\sigma = \int_{4m_h^2/s}^1 d\tau \overbrace{\int_\tau^1 \frac{dx}{x} f_{g/P}(x,Q) f_{g/P}(\tau/x,Q)}^{\text{gluon luminosity}} \hat{\sigma}_{gg\to hh}(\tau s)$$

Some examples

- SILH formalism applies to wide class of models, e.g. Little Higgs and "holographic" composite Higgs models
- MCHM5 has 3 top partners, MCHM4 has 2, Littlest Higgs has 1
- As in single Higgs production, in most popular models dependence **only on** $\xi = v^2/f^2$ and *not* on the details of fermion resonances.



- These results hold in the infinite fermion mass limit. *What about finite mass effects?*
- For $gg \to hh$ in the SM, low-energy theorem gives total cross section accurate at ~20 % for $m_h \leq 200\,\mathrm{GeV}$ (however, produces incorrect kinematic distributions)
- Take for example corrections $\sim \hat{s}/4m_t^2$: given that $\hat{s} \geq 4m_h^2$, a priori they can be large.

Minimal composite Higgs model

Agashe et al., hep-ph/0412089

- Higgs as a pseudo-Goldstone boson of spontaneous symmetry breaking $\mathcal{G}/\mathcal{H}$

  ⇒ explain "Little Hierarchy" between EW scale and scale of new strong sector.

- Minimal choice containing custodial symmetry (needed to protect ρ parameter)

  is $SO(5)/SO(4)$, giving four GBs in a **4** of $SO(4) \sim SU(2)_L \times SU(2)_R$

- Goldstones are described in terms of the field

$$\Sigma = \Sigma_0 e^{\Pi/f}\,, \qquad \Pi = -i\sqrt{2}\,T^{\hat{a}} h^{\hat{a}}\,, \qquad \Sigma_0 = (\,0\,,\,0\,,\,0\,,\,0\,,\,1\,)$$

$$\Sigma = \frac{\sin(h/f)}{h}\left(h_1, \quad h_2, \quad h_3, \quad h_4, \quad h\,\mathrm{cotan}(h/f)\right)\,, \qquad h = \sqrt{\sum_{\hat{a}} h_{\hat{a}}^2}$$

and the two-derivative Lagrangian is $\mathcal{L} = \frac{f^2}{2}(D_\mu \Sigma)(D^\mu \Sigma)^T$

$$\left(D_\mu \Sigma = \partial_\mu \Sigma + i g\, W_\mu^a \Sigma T_L^a + i g'\, B_\mu \Sigma T_R^3\right)$$

- Can write in unitary gauge

$$\Sigma = \left(0, \quad 0, \quad \sin(H/f), \quad 0, \quad \cos(H/f)\right)$$

  where H is the Higgs field (with $\langle H \rangle \neq 0$).

Minimal composite Higgs model (2)

- *W* mass is $m_W^2 = \frac{g^2 f^2}{4} \sin^2(\langle H \rangle / f)$ $\Rightarrow$ $f^2 \sin^2(\langle H \rangle / f) = v^2 \simeq (246\,\mathrm{GeV})^2$

- Fermion hypercharges require an extra $U(1)_X$, which remains unbroken since $\Sigma \sim \mathbf{5}_0$ under $SO(5) \times U(1)_X$.

- SM fermions acquire a mass by *mixing linearly* with composite states, which are the only ones who couple directly to the (comp.) Higgs: **partial compositeness**
- So we need to introduce vector-like fermions with right quantum numbers to mix with $q_L = (t_L \;\; b_L)^T$ and t_R, and to have “proto-Yukawa” interactions with the Higgs.
- We introduce one multiplet of fermionic resonances, transforming as a complete $\psi \sim \mathbf{5}_{2/3}$.
  With this choice, no tree-level correction to the Z-b-$\bar{b}$ coupling is generated (this does not happen with the spinorial $\mathbf{4}_{1/6}$).

Agashe et al., hep-ph/0605341

Partial compositeness Lagrangian

- Composite multiplet can be written as:

  Under $SU(2)_L \times SU(2)_R$,

$$\psi = \frac{1}{\sqrt{2}} \begin{pmatrix} B - X^{5/3} \\ -i(B + X^{5/3}) \\ T + X^{2/3} \\ i(T - X^{2/3}) \\ \sqrt{2}\tilde{T} \end{pmatrix}$$

$$\mathbf{5} \sim \underbrace{(\mathbf{2},\mathbf{2})}_{Q,\;X} \oplus \underbrace{(\mathbf{1},\mathbf{1})}_{\tilde{T}}$$

$$Q = \begin{pmatrix} T \\ B \end{pmatrix} , \quad X = \begin{pmatrix} X^{5/3} \\ X^{2/3} \end{pmatrix}$$

peculiar of **5** representation, contains a charge 5/3 fermion

- Q has the EW quantum numbers of q_L , while $\tilde{T}$ of t_R
- Minimal Lagrangian:

$$\begin{aligned} \mathcal{L}_f =\ & i\bar{q}_L \not{D} q_L + i\bar{t}_R \not{D} t_R + i\bar{b}_R \not{D} b_R + i\bar{\psi}_L \not{D} \psi_L + i\bar{\psi}_R \not{D} \psi_R \\ & - y f (\bar{\psi}_L \Sigma^T)(\Sigma \psi_R) - M_0 \bar{\psi}_L \psi_R + \mathrm{h.c.} \\ & - \Delta_L \bar{q}_L Q_R - \Delta_R \bar{\tilde{T}}_L t_R + \mathrm{h.c.} \end{aligned}$$

composite
"proto-Yukawa",
$SO(5)$ invariant

elementary/composite mixings
break global symmetry

- Notice that there is no composite with quantum numbers of b_R

no mass for the bottom is generated (need for ex. a $\mathbf{5}_{-1/3}$)

Fermion masses

- Diagonalization of masses is simple for $v = 0 \;\; (\Sigma = \Sigma_0)$: rotate

$$\begin{pmatrix} q_L \\ Q_L \end{pmatrix} \to \begin{pmatrix} \cos\phi_L & \sin\phi_L \\ -\sin\phi_L & \cos\phi_L \end{pmatrix} \begin{pmatrix} q_L \\ Q_L \end{pmatrix} , \qquad \tan\phi_L = \frac{\Delta_L}{M_0}$$

$$\begin{pmatrix} t_R \\ \tilde{T}_R \end{pmatrix} \to \begin{pmatrix} \cos\phi_R & \sin\phi_R \\ -\sin\phi_R & \cos\phi_R \end{pmatrix} \begin{pmatrix} t_R \\ \tilde{T}_R \end{pmatrix} , \qquad \tan\phi_R = \frac{\Delta_R}{M_0 + yf}$$

- **SM states are a linear combination of *elementary* and *composite* states**

  $\phi_{L,R}$ parameterize the degree of compositeness of $t_{L,R}$

- In this limit the top is massless, and composites have masses

$$M_Q = \frac{M_0}{c_L} , \qquad M_X = M_0 , \qquad M_{\tilde{T}} = \frac{yf + M_0}{c_R}$$

- Turning on EWSB, top becomes massive via mixing of $t_{L,R}$ with composites:

$$m_t = y \sin\phi_L \sin\phi_R \frac{v}{\sqrt{2}} \left(1 + \mathcal{O}(\xi)\right)$$

- After setting the top mass to exp value, model fully described by 4 parameters:

$$\xi \equiv v^2/f^2 , \quad \phi_L , \quad \phi_R , \quad R = (M_0 + yf)/M_0$$

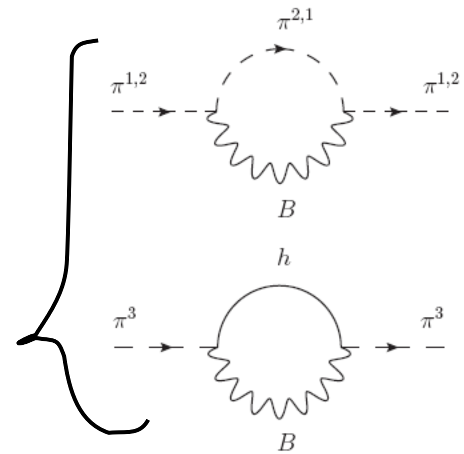
Electroweak precision tests

Three beyond-SM contributions to ϵ_i, ϵ_b parameters:

- Modified coupling of the Higgs to gauge bosons

➡ log divergence in $\epsilon_{1,3} \sim T, S$

$$\Delta\epsilon_3^{\mathrm{IR}} = \frac{\alpha(M_Z)}{48\pi \sin^2\theta_W}\xi \log\left(\frac{m_\rho^2}{m_h^2}\right), \qquad \Delta\epsilon_1^{\mathrm{IR}} = -\frac{3\,\alpha(M_Z)}{16\pi \cos^2\theta_W}\xi \log\left(\frac{m_\rho^2}{m_h^2}\right)$$



Barbieri et al., 0706.0432

- UV contribution to S from tree-level exchange of spin-1 resonances

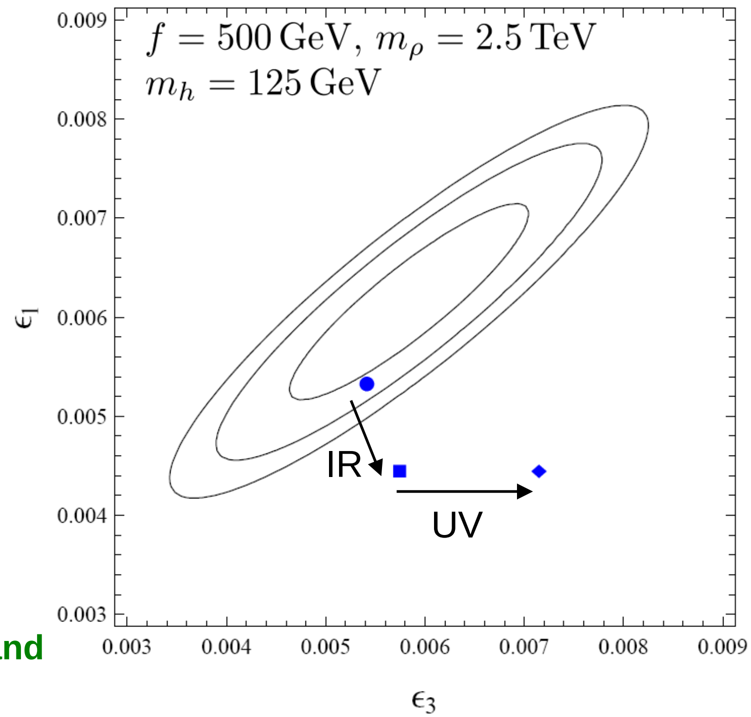
$$\Delta\epsilon_3^{\mathrm{UV}} = \frac{m_W^2}{m_\rho^2}\left(1+\frac{m_\rho^2}{m_a^2}\right) \simeq 1.36\frac{m_W^2}{m_\rho^2}$$

- 1-loop contributions to T and $\epsilon_b \sim Z\text{-}b_L\text{-}\bar{b}_L$ from heavy fermions

In general need a **positive contribution to** T to get back into the ellipse, but at the same time need to control correction to ϵ_b

➡ non-trivial interplay!

Gillioz, 0806.3450
Anastasiou, Furlan and Santiago, 0901.2117



Electroweak precision tests (2)

Perform numerical analysis, allowing $1.5\,\mathrm{TeV} < m_\rho < 4\pi f$

For largish ξ , **two regions** satisfying the constraints are found:

1) Singlet $\tilde{T}$ lighter than rest of the spectrum: it contributes positively to T and to ϵ_b . In this region $\sin\phi_L < 0.5$, so t_R has sizable degree of compositeness.

2) Large $\sin\phi_L$ ➡ t_L largely composite, doublet $X = (X^{5/3}, X^{2/3})$ is light. Intricated interplay of contributions to EW parameters.

light Q = 5/3 state ➡ strong bounds from LHC, see later

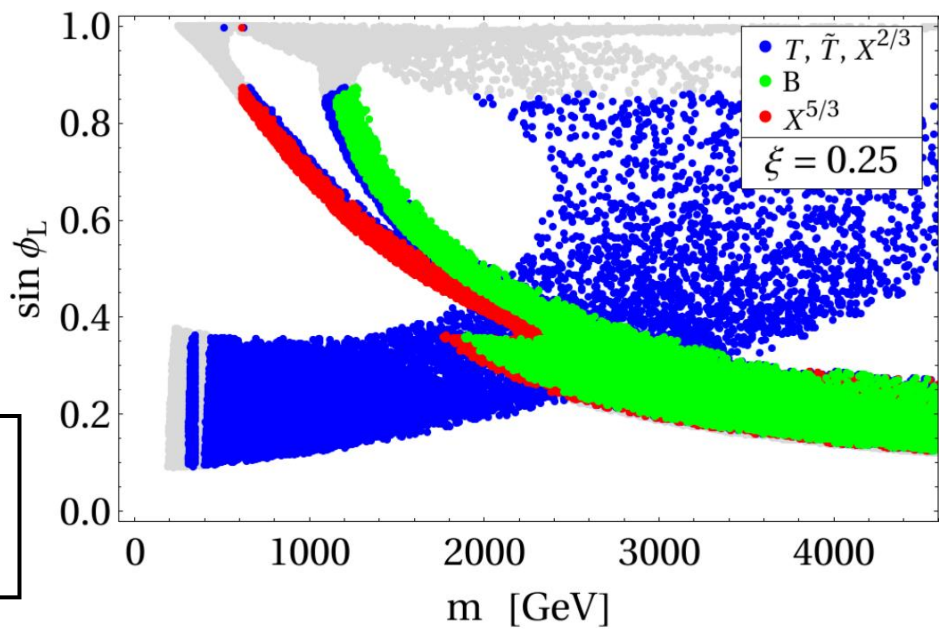
- *Note that a light Higgs requires at least one light fermionic resonance:*

$$m_Q \lesssim 700\,\mathrm{GeV}\left(\frac{f}{500\,\mathrm{GeV}}\right)\left(\frac{m_h}{125\,\mathrm{GeV}}\right)$$

see for example

Pomarol and Riva, 1205.6434

blue	Q = 2/3
red	Q = 5/3
green	Q = -1/3

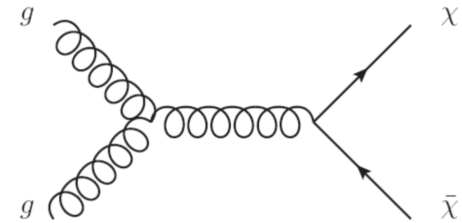


Bounds from collider searches

- Searches for heavy fermions at Tevatron&LHC put constraints on the model:

  pair production via QCD, decay into 3rd gen fermions

  and Goldstones: leading order BRs



$$\mathrm{BR}(\tilde{T} \to Wb) = \frac{1}{2}\,, \qquad \mathrm{BR}(\tilde{T} \to Zt) = \mathrm{BR}(\tilde{T} \to ht) = \frac{1}{4}\,;$$

$$\mathrm{BR}(X^{2/3} \to Zt) = \mathrm{BR}(X^{2/3} \to ht) = \frac{1}{2}\,, \qquad \mathrm{BR}(X^{5/3} \to Wt) = 1$$

from Yukawas, using Goldstone equivalence theorem

- Exp searches in final states $WbWb\,,\ ZtZt\,,\ WtWt$

- Region of composite t_L (large $\sin\phi_L$) is already strongly constrained:

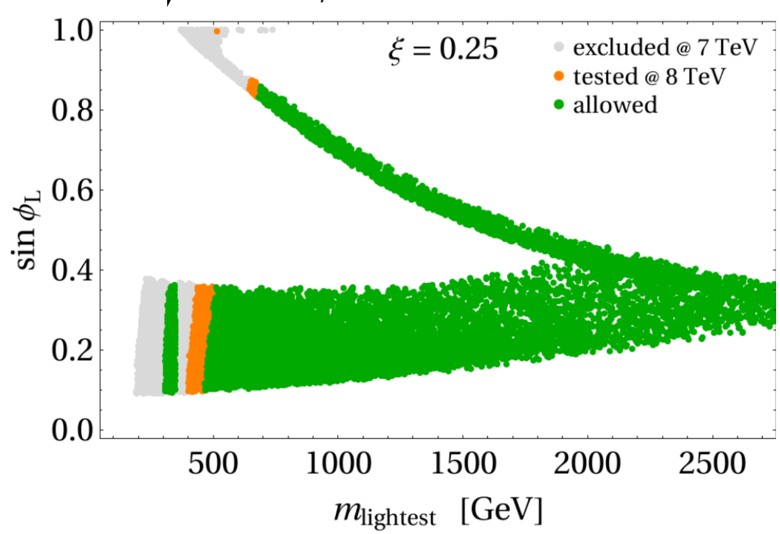
  $X^{5/3}$ is light and decays with BR = 1 into tW ➡ $m_{5/3} > 600\,\mathrm{GeV}$

  and thus $\sin\phi_L < 0.8$

- Region of composite t_R less constrained:

  $\tilde{T}$ is light, strongest bound from $WbWb$

  channel ➡ $m_{\tilde{T}} > 400\,\mathrm{GeV}$



Contino and Servant, 0801.1679
Aguilar-Saavedra, 0907.3155,
Dissertori et al., 1005.4414

An example: Littlest Higgs

- quark doublet q_L , new vector-like pair of singlets $\tilde{T}_{L,R}$ to implement collective breaking

$$-\mathcal{L}_Y = \frac{\lambda_1}{2} f\, \bar{t}_R \epsilon_{ijk}\epsilon_{ab}\chi_i\Sigma_{ja}\Sigma_{kb} + \lambda_2 f \bar{\tilde{T}}_R \tilde{T}_L + \text{h.c.} \qquad \chi = \begin{pmatrix} b_L \\ t_L \\ \tilde{T}_L \end{pmatrix}$$

- Diagonalize mass matrix and find:

$$m_t(H) = \frac{\lambda_1\lambda_2}{\sqrt{\lambda_1^2+\lambda_2^2}} H \left(1 - \frac{H^2}{3f^2} + \frac{H^2}{2f^2}\frac{\lambda_1^2\lambda_2^2}{(\lambda_1^2+\lambda_2^2)^2}\right)$$

$$m_T(H) = f\sqrt{\lambda_1^2+\lambda_2^2}\left(1 - \frac{H^2}{2f^2}\frac{\lambda_1^2\lambda_2^2}{(\lambda_1^2+\lambda_2^2)^2}\right).$$

that is

$$c_y = \frac{2}{3} - \frac{\lambda_1^2\lambda_2^2}{(\lambda_1^2+\lambda_2^2)^2} \qquad a_T = -\frac{\lambda_1^2\lambda_2^2}{(\lambda_1^2+\lambda_2^2)^2} \quad \Rightarrow \quad a_T - c_y = -2/3$$

- Notice that the cancellation is **not** fixed by the absence of quadratic divergences in Higgs mass:

$$\left[\text{Tr}\mathcal{M}^2(H)\right]_{H^2} = \left[m_t^2(H) + m_T^2(H)\right]_{H^2} = 0$$

$$\Downarrow$$

$$a_T = -y_t^2/(2\lambda_T^2)$$ but this argument does not fix c_y

Collider bounds

exp.	search	L [fb^{-1}]	range in M_ψ [GeV]	ref.
CMS [50]	$WbWb$ (1 lepton)	4.7	$[400, 625]$	CMS-PAS-EXO-11-099
	$WbWb$ (2 leptons)	5.0	$[350, 600]$	arXiv:1203.5410
	$WtWt$	1.14	$[350, 550]$	CMS-PAS-EXO-11-036
	$WtWt$	4.9	$[450, 650]$	arXiv:1204.1088
	$ZtZt$	1.14	$[250, 550]$	arXiv:1109.4985
ATLAS [51]	$WbWb$	1.04	$[250, 500]$	arXiv:1202.3076
	$WqWq$	1.04	$[300, 500]$	arXiv:1202.3389
	$WtWt$ (1 lepton)	1.04	$[300, 600]$	arXiv:1202.6540
	$WtWt$ (2 leptons)	1.04	$[300, 600]$	arXiv:1202.5520
CDF [52]	$WbWb$	5.6	$[180, 500]$	arXiv:1107.3875
	$WtWt$	4.8	$[260, 425]$	arXiv:1101.5728

Table 3: List of experimental searches for pair-produced heavy fermions that we included in our analysis of collider constraints.

$h\gamma\gamma$ coupling

- Contributions from fermion loops and *W* loop.

Another SILH operator is relevant: $\mathcal{O}_\gamma = c_\gamma \frac{g'^2}{16\pi^2 f^2} \frac{g^2}{g_\rho^2} H^\dagger H B_{\mu\nu} B^{\mu\nu}$

- Applying the LET obtain ($m_h \ll m_t, m_W$)

$$\mathcal{L}_{eff} = \frac{e^2}{16\pi^2} F_{\mu\nu} F^{\mu\nu} \left(\sum_f Q_f^2 \log m_f^2(H) - \frac{7}{4} \log m_W^2(H) \right)$$

and linear term in *h* reads

$$\mathcal{L}_{h\gamma\gamma} = \frac{e^2}{32\pi^2} F_{\mu\nu} F^{\mu\nu} \frac{h}{v} \left[4Q_t^2 \left(\frac{1}{2} \left(\frac{\partial}{\partial \log H} \log \det \mathcal{M}^2(H) \right)_{H=v} - \frac{c_H}{2} \xi \right) \right.$$
$$\left. - J_\gamma(4m_W^2/m_h^2) \left(1 + \xi \left(\frac{c_r}{4} - \frac{c_H}{2} \right) \right) \right]$$

full result for *W* loop

valid for $m_h \ll m_t$.

$$J_\gamma \simeq 8.3 \, (m_h = 125 \, \mathrm{GeV})$$

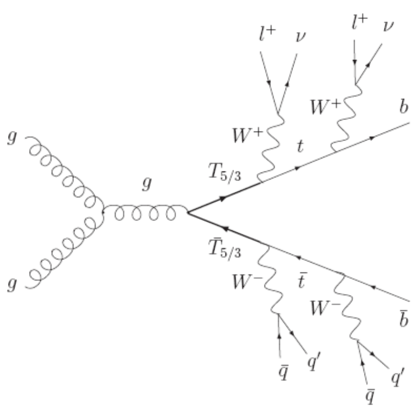
$$\text{for } m_h \lesssim 2m_W \longrightarrow J_\gamma(\infty) = 7 = 22/3 - 1/3$$

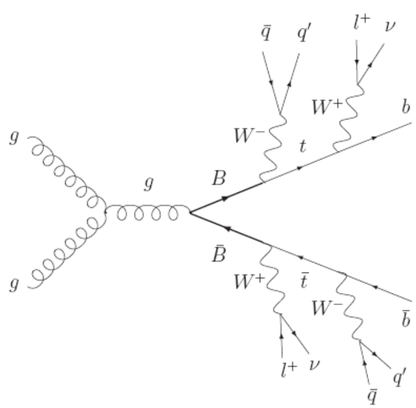
transverse, equal to gauge contribution to $SU(2)_L$ beta function

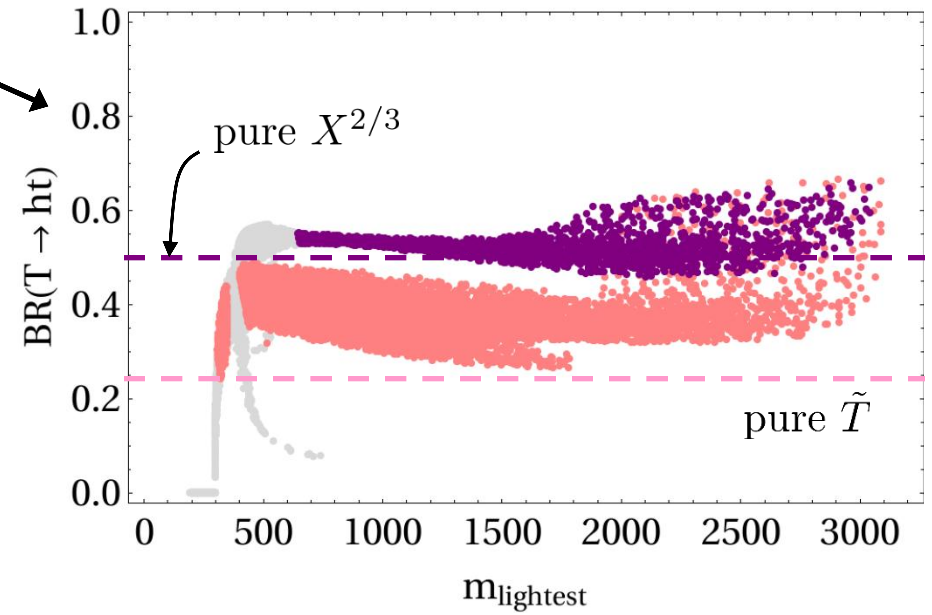
longitudinal (Goldstones)

Bounds from collider searches (2)

- We diagonalize top mass matrix numerically (keeping all orders in ξ), and compute couplings in unitary gauge: sizable corrections to LO predictions in some regions of parameter space

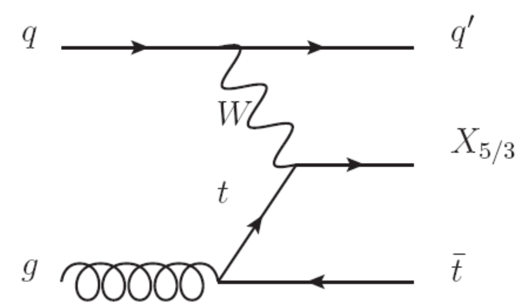






- Exp searches in $WtWt$ final state designed for heavy bottom, but apply also to $X^{5/3}$, despite different spatial configurations (only cuts on single objects applied).

- Also single production relevant, but no relevant searches published by experiments yet



Mrazek and Wulzer, 0909.3977