Composite Higgs

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MC4BSM

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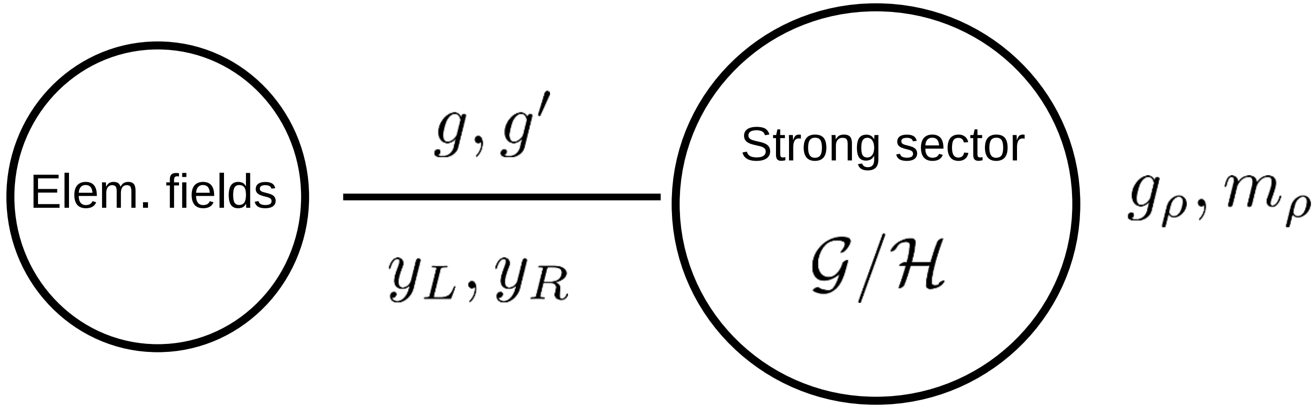
The Higgs as a composite p-NGB



- Global symmetry breaking in the strong sector delivers as NGB the Higgs doublet *H*
- *H* emerges as fully composite pNGB, while transverse gauge and fermions are introduced as external, elementary fields
- Vectors coupled to strong sector by gauging $SU(2)_L \times U(1)_Y \subset \mathcal{H}$

  ⇒ linear couplings to currents $\mathcal{L}^g_{UV} = g_{el} W^{el}_\mu J^\mu_{cmp}$
- Similarly for fermions: write $\mathcal{L}^f_{UV} = y_L \overline{q}_L \mathcal{O}$ with $\mathcal{O}$ fermionic composite operator, same for right-handed quarks
- All physical states are *partially composite*

The Higgs as a composite p-NGB

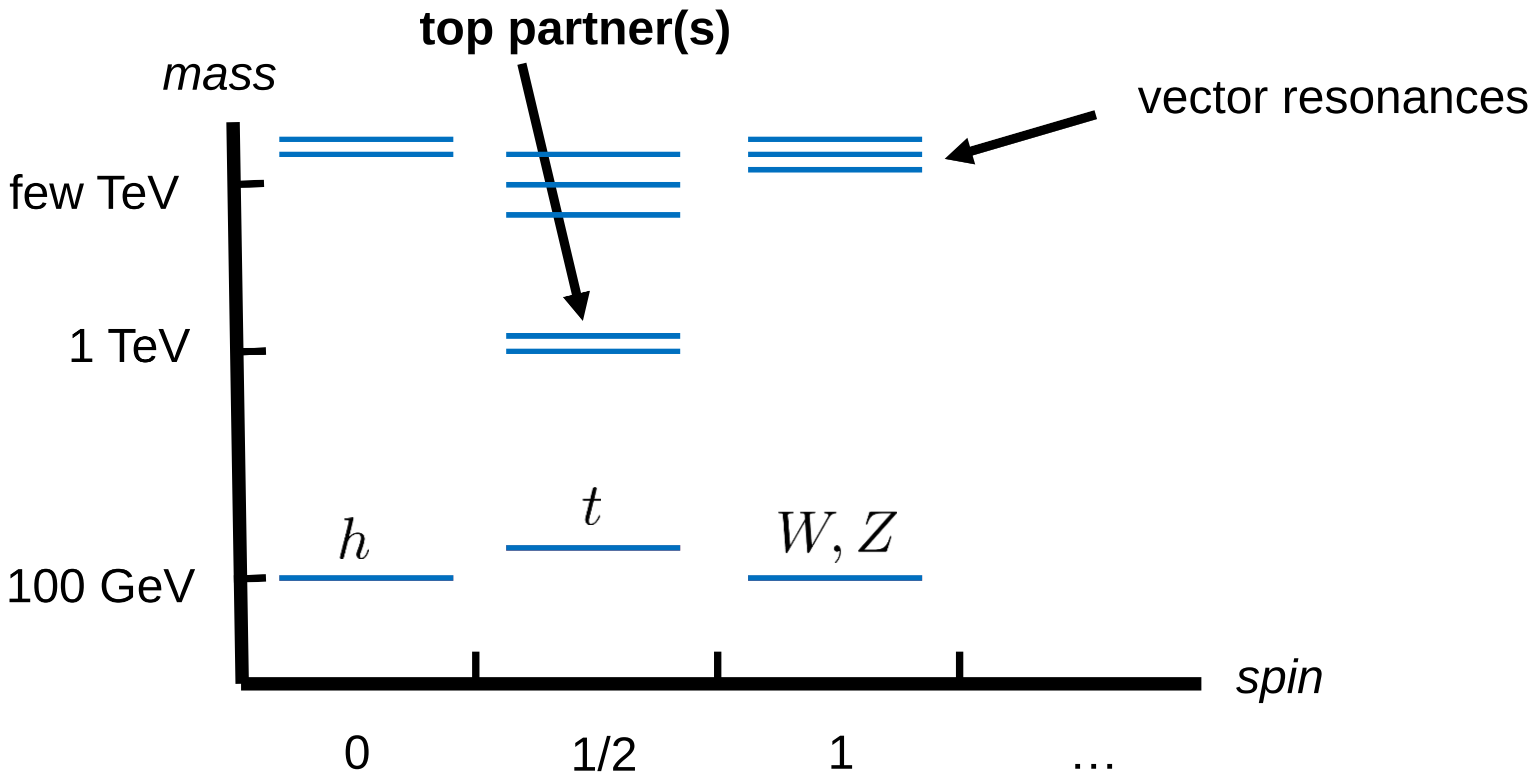
- SM fermion masses $m_f \sim g_\rho \frac{y_L}{g_\rho} \frac{y_R}{g_\rho} v$ ⇒ for flavor-anarchic strong sector, light quarks mostly elementary; third generation can be sizably composite

- Only breaking of the global symmetry comes from couplings to elementary states ⇒ radiative Higgs potential, form essentially dictated by structure of linear mixings

  Naive expectation is $v \sim f$, need to tune to obtain $v \ll f$ as required by data. Minimum tuning scales as $\frac{v^2}{f^2}$

- Moderate tuning + light Higgs imply that at least some fermionic resonances (‘top partners’) have to be light

Sketch of the minimal spectrum



Plan

- Direct searches for top partners

- Higgs coupling measurements after run I

- Exploiting differential distributions to probe Higgs couplings in new ways:
  - Boosted Higgs
  - Off-shell Higgs
  - Double *h* production

- What if the Higgs is coupled to technicolor? ‘Induced EWSB’

Plan

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- I apologize in advance for the **many** topics I am not covering here.

  For example: flavor, vector resonances, top seesaw models, little Higgs, twin composite Higgs, …

Direct searches for top partners

- Top partners come in complete multiplets of unbroken global symmetry.

  For minimal choice SO(5)/SO(4), reasonable to expect a **1** or a **4** of

$$SO(4) \sim SU(2)_L \times SU(2)_R$$

- Phenomenology determined by the lightest multiplet ➡ simplified models

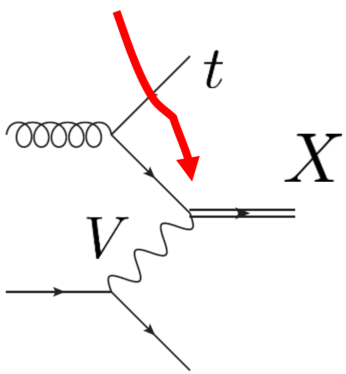
  (taking into account Goldstone nature of the Higgs)

- For example for the **4**,

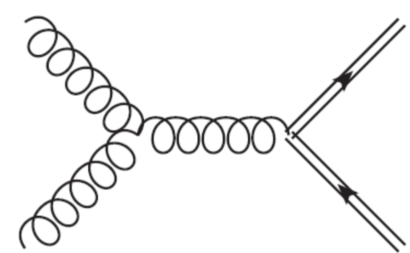
Contino, Kramer, Son, Sundrum 2006, Contino & Servant 2008, Mrazek & Wulzer 2009, De Simone, Matsedonskyi, Rattazzi, Wulzer 2012

$$\mathcal{L}_{\mathbf{4}_5} = (\text{kin. terms}) - M_\Psi \bar{\Psi}\Psi$$
$$+ \left[i c_1 \overline{\Psi}_{R\,i} \gamma^\mu d^i_\mu t_R + y f (\overline{Q}_L)^I U_{Ii} \Psi^i_R + y c_2 (\overline{Q}_L)^I U_{I5} t_R + \text{h.c.} \right]$$

single production



QCD pair production

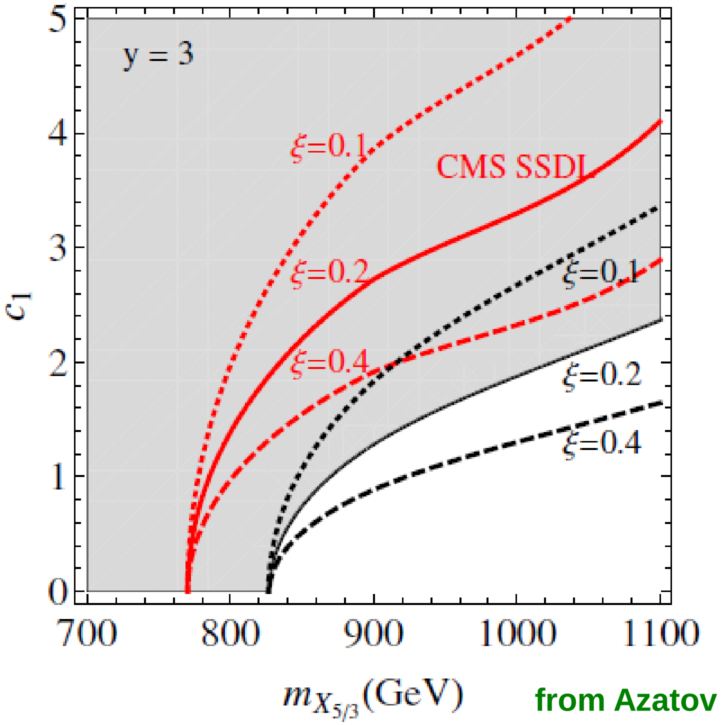


Direct searches for top partners

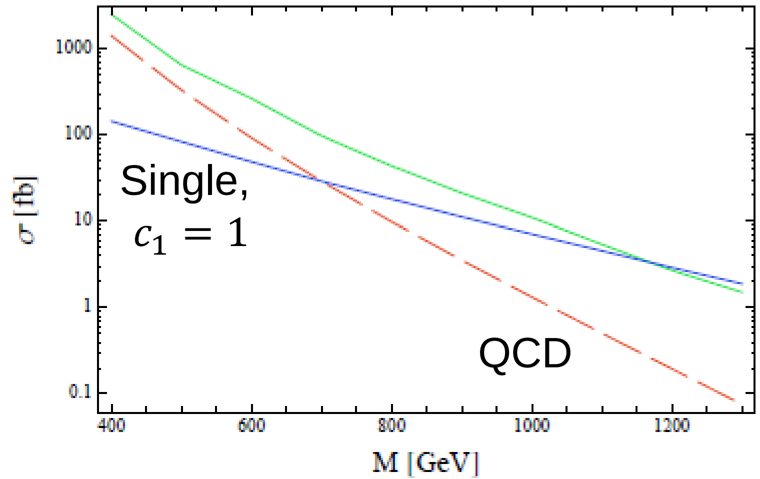
- The $X_{5/3}$ cannot mix with the SM fermions and is the lightest top partner

  It decays only into *tW*

8 TeV searches tailored to pair production, but sensitive also to single production



from Azatov et al. 2013



from De Simone et al. 2012

Run II reach: ~1.5 TeV from pair production, perhaps above 2 TeV including single production + hadronic final states

e.g. lepton + fat jet for $t\bar{t}Wj$ topology

Backovic et al. 2014

Simplified model at work

Matsedonskyi, Panico, Wulzer 2014

- The phenomenology of $X_{5/3}$ is described by just

$$\mathcal{L} = \frac{g}{2} c_R \overline{X}_{5/3R} \gamma^\mu t_R W^+_\mu + \text{h.c.} - M_X \overline{X}_{5/3} X_{5/3}$$

- Production cross sections

$$\sigma_{\text{pair}}(M_X)\,, \qquad \sigma_{\text{sing}} = c_R^2\, \sigma_{\text{sing}}(M_X)$$

- For a given search, efficiencies depend on M_X and chirality of coupling (assuming narrow resonances).

  Computed using MC (FeynRules-MG5-Pythia)

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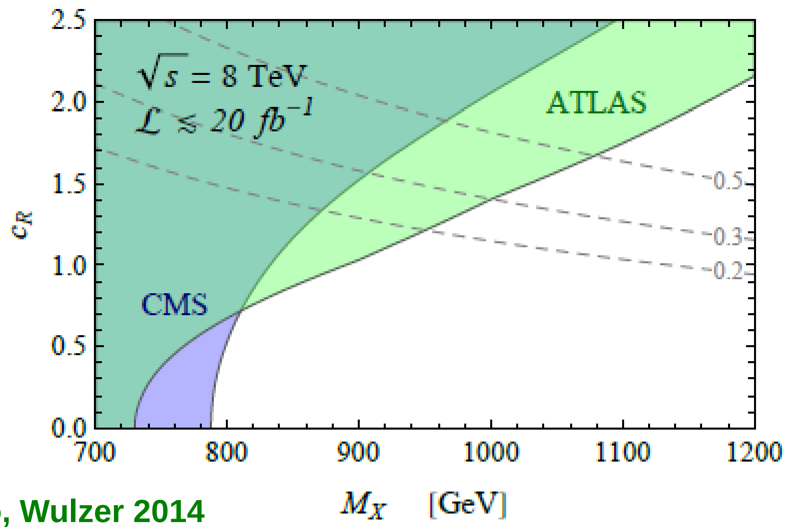
CMS-PAS-B2G-12-012, ATLAS-CONF-2013-051

Same-sign leptons analyses:

- CMS: require $N(\text{constituents}) \geq 5$, sensitivity to single production small
- ATLAS: require ≥ 2 jets, efficiencies for single and pair production comparable



from Matsedonskyi, Panico, Wulzer 2014

Effective Lagrangian for pNGB Higgs

- Given scale of new physics $m_\rho \sim g_\rho f$, leading effects from operators with extra Higgses, suppressed by $1/f$ while extra derivatives $\sim 1/m_\rho$

$$\frac{1}{f^2}\left[c_H \partial_\mu |H|^2 \partial^\mu |H|^2 - c_6 \lambda (H^\dagger H)^3 + c_y y_f H^\dagger H \overline{f}_L H f_R\right]$$

Higgs trilinear coupling

Higgs coupling to gauge bosons

$$\kappa_V = 1 - c_H \frac{v^2}{f^2}$$

Higgs coupling to fermions

$$\kappa_f = 1 - (c_H + c_y)\frac{v^2}{f^2}$$

- $c_i \sim O(1)$ are model-dependent, minimal example

$$\mathcal{G}/\mathcal{H} = SO(5)/SO(4) \implies c_H = \frac{1}{2}$$

Giudice et al. 2007

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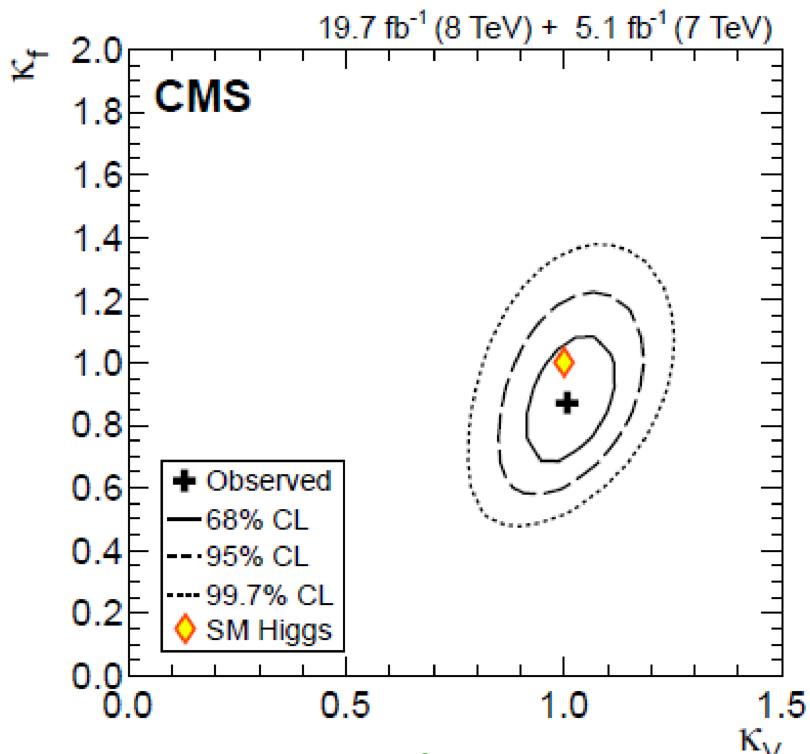
Higgs coupling to gauge bosons

$$\kappa_V = 1 - \frac{1}{2}\frac{v^2}{f^2}$$



from 1412.8662

- Higgs couplings measurements are directly testing the (minimum) tuning

$$\sim \frac{v^2}{f^2}$$

hgg and *hγγ* couplings

- Contribution of resonances to loop-induced couplings encoded by ops. of the form $H^\dagger H F_{\mu\nu} F^{\mu\nu}$: they break shift symmetry, suppressed by $\left(\frac{g_{\rm SM}}{g_\rho}\right)^2$, subleading at strong coupling

Giudice et al. 2007

- However, $m_h = 125$ GeV implies relatively light and more weakly coupled top partners, for example

$$m_h \sim \frac{\sqrt{N_c}}{\pi} m_t \frac{m_4}{f}$$

m_4 is the mass of the lightest top partner

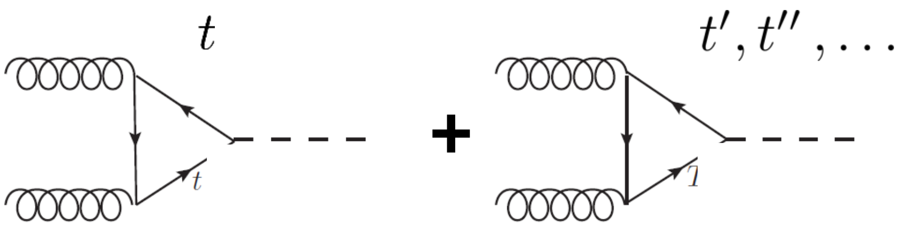
$f \sim 800$ GeV ⇒ $m_4 \lesssim 1.2$ TeV

Matsedonskyi et al.;
Pomarol et al.; Panico et al. 2012

hgg and *hγγ* couplings

- Naively, the effects of light top partners should be important
- However, it turns out that loops of resonances cancel out *exactly* against corrections to $ht\bar{t}$ coupling (follows from LET + symmetry argument)

Falkowski 2007, Low & Vichi 2010,
Azatov & Galloway, 2011, Montull, Riva, ES, Torre 2013



$$\frac{g_{hgg}}{g_{hgg}^{\mathrm{SM}}} = 1 - \frac{3}{2}\frac{v^2}{f^2}$$

no sign of the scale of top partners

- Important to separate the $ht\bar{t}$ coupling from the loops: each of them alone **does** carry info on top partners

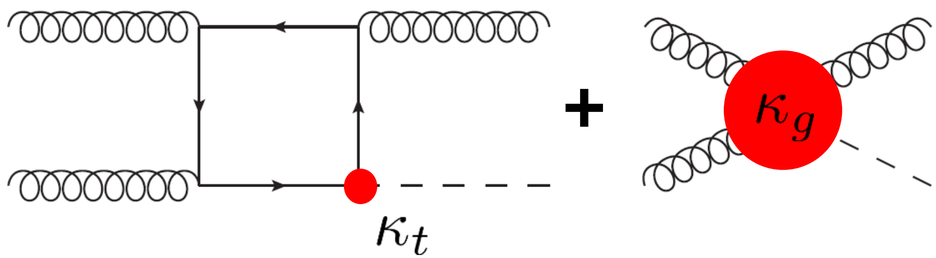
$$\kappa_t = 1 - \frac{3}{2}\frac{v^2}{f^2} + \frac{v^2}{f^2}\left(\frac{1}{m_1^2} - \frac{1}{m_4^2}\right)\left(y_R^2 - \frac{y_L^2}{2}\right) + O(\epsilon^4)$$

Higgs production at high p_T

Harlander et al.; Banfi et al.; Azatov & Paul; Grojean, ES, Schlaffer, Weiler 2013

Higgs recoiling against a large p_T jet

$$\mathcal{M}(gg \to gh) \sim$$



for $p_T \gg m_t$, resolve the top loop

same dependence as in inclusive rate

$$\frac{\sigma_{p_T^{\min}}(\kappa_t, \kappa_g)}{\sigma^{SM}_{p_T^{\min}}} = (\kappa_t + \kappa_g)^2 + \delta\, \kappa_t \kappa_g + \epsilon\, \kappa_g^2$$

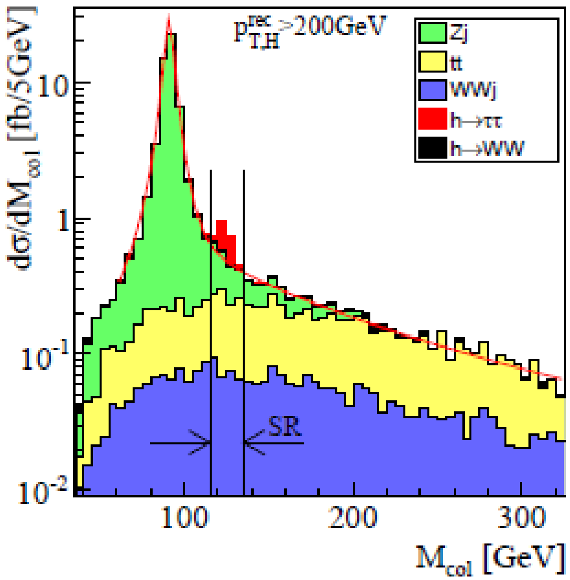
resolve short-distance ***vs*** long-distance

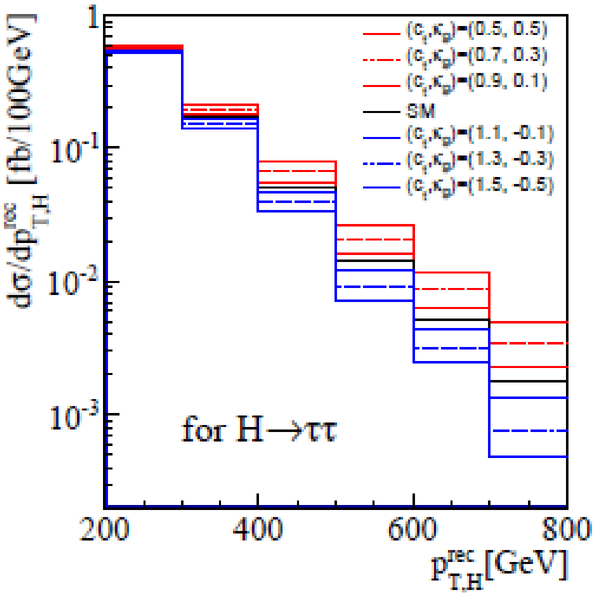
$p_T^{\min}$ [GeV]	$\sigma^{SM}_{p_T^{\min}}$ [fb]	δ	ϵ
100	2180	0.0031	0.031
150	837	0.070	0.13
200	351	0.20	0.30
250	157	0.39	0.56
300	74.9	0.61	0.89
350	37.7	0.85	1.3
400	19.9	1.1	1.7
450	10.9	1.4	2.3
500	6.24	1.7	2.9
550	3.68	2.0	3.6
600	2.22	2.3	4.4
650	1.38	2.6	5.2
700	0.871	3.0	6.2

Boosted Higgs analysis

- Select decay $h \to \tau\tau \to \ell\ell + \mathrm{MET}$

  (at large p_T, good Higgs mass reconstruction by assuming collinear approximation)





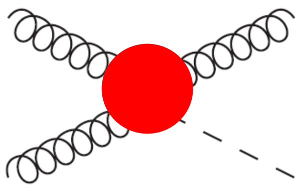
from Schlaffer et al. 2014

can achieve $S/B \sim 0.4$

Generating h + jet(s)

- Strategy: generate h + jet using HEFT model in MadGraph5,

  and reweight events by



$$\frac{|\mathcal{M}(\kappa_t,\kappa_g)|^2}{|\mathcal{M}(0,1)|^2}$$

- Generation soon automated with ‘LoopInduced’ upgrade of MG5 

  talk by Olivier, this morning

- Full matrix element, with top mass dependence, known only at LO in QCD

  Within HEFT, very recent computation up to NNLO

  Boughezal et al. 2015

Generating *h* + jet(s)

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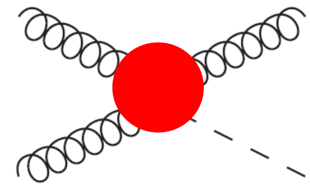


- Will become automated with ‘LoopInduced’ upgrade of MG5

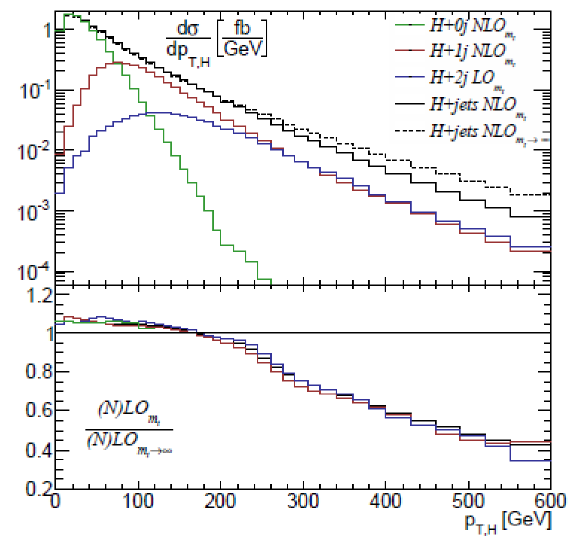
- Full matrix element, with top mass dependence, known only at LO in QCD

  Within HEFT, very recent computation up to NNLO

- The 2-jet bin also has discriminating power:

  NLO-merging up to 2 jets, with loop reweighting

  at LO within SHERPA

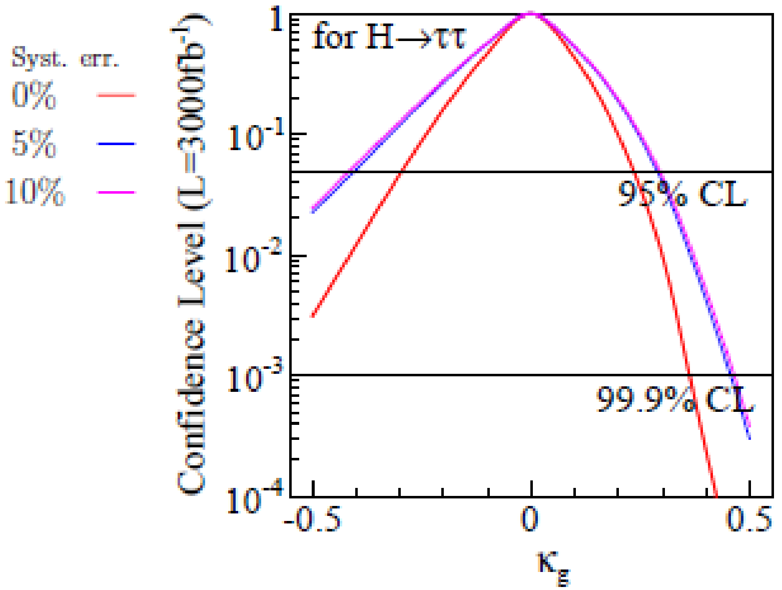


from Buschmann et al. 2014

Boosted Higgs analysis

$(\kappa_t + \kappa_g = 1)$

- Approach complementary to direct measurement of top Yukawa in $t\bar{t}h$

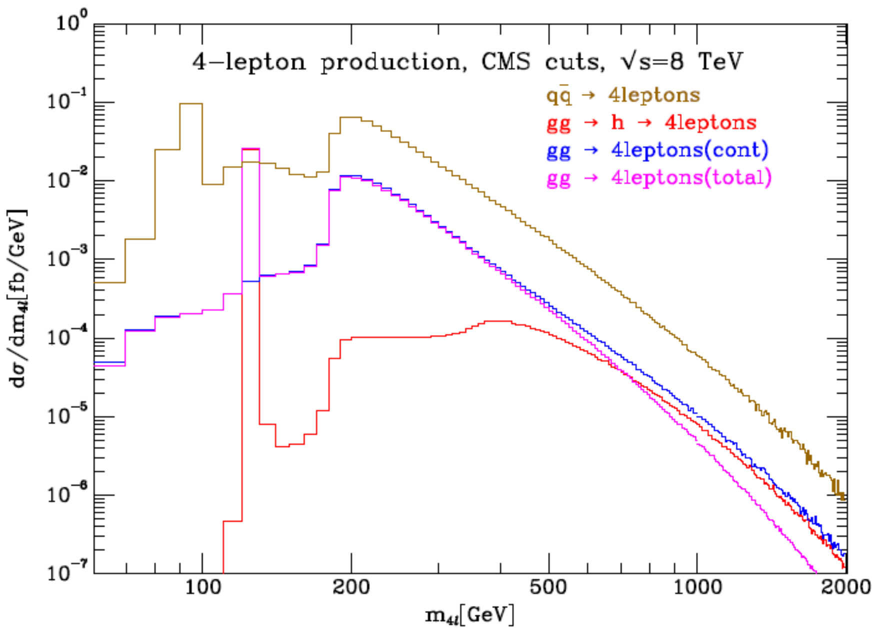


from Schlaffer et al. 2014

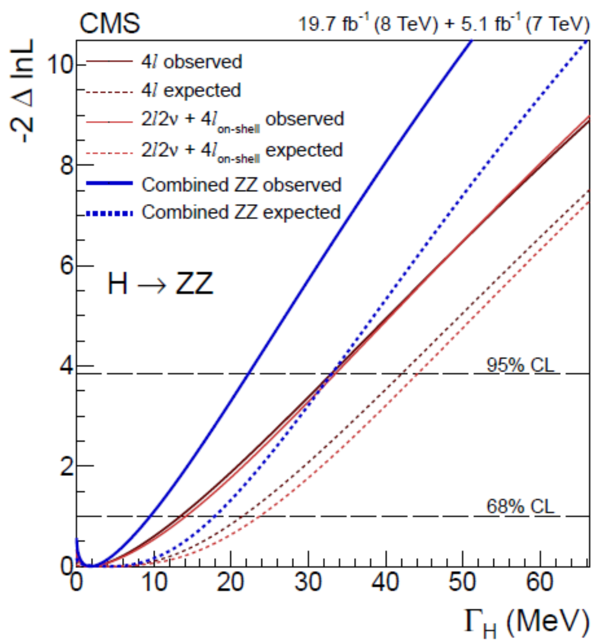
- Room for improvement:
  - Computation of SM Higgs p_T spectrum at full NLO (i.e. retaining the top mass dependence) to reduce systematics
  - Other Higgs decay channels: $h \to b\bar{b}$?
    At large boost, fight against dijets… playground for jet substructure

Off-shell Higgs in $gg \to ZZ \to 4l$

- Combination of on- and off-shell Higgs measurement proposed as indirect test of the Higgs total width **Caola & Melnikov, 2013**



from Campbell et al. 2013 (Kauer & Passarino 2012)

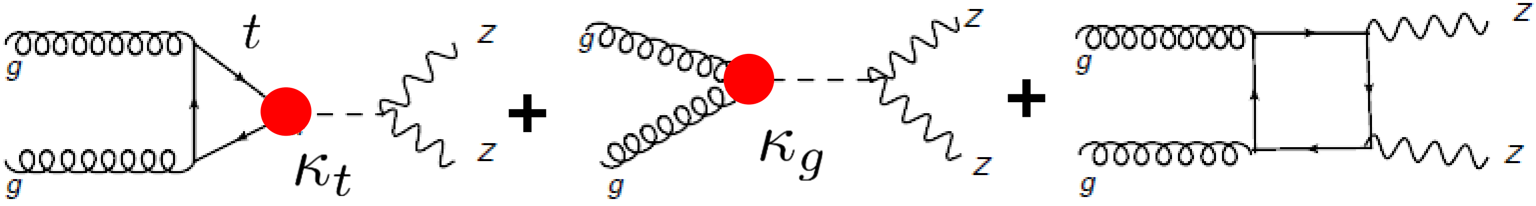


from 1405.3455

- Cannot be interpreted in these terms if NP contributes directly to the *hgg* loop.
- But can be rephrased as coupling measurement, resolve top *vs* NP loop (similar to boosted Higgs) **Azatov et al., Cacciapaglia et al. 2014**

High-mass $gg \to VV$ constrains Higgs couplings

$$\mathcal{L} = -\kappa_t \frac{m_t}{v} \bar{t} t h + \kappa_g \frac{\alpha_s}{12\pi} \frac{h}{v} G_{\mu\nu} G^{\mu\nu}$$



$$\mathcal{M}_{gg\to ZZ} \quad = \quad \kappa_t \mathcal{M}_{\kappa_t} + \kappa_g \mathcal{M}_{\kappa_g} + \mathcal{M}_{\text{background}}$$

$$\mathcal{M}_{\kappa_t} \sim \frac{m_t^2}{m_Z^2} \log^2 \frac{\hat{s}}{m_t^2} \qquad\qquad \mathcal{M}_{\kappa_g} \sim \frac{\hat{s}}{m_Z^2}$$

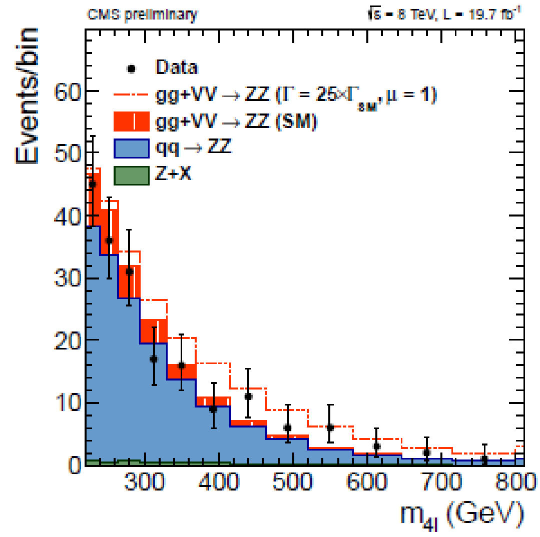
Region of large *VV* mass discriminates between the two couplings

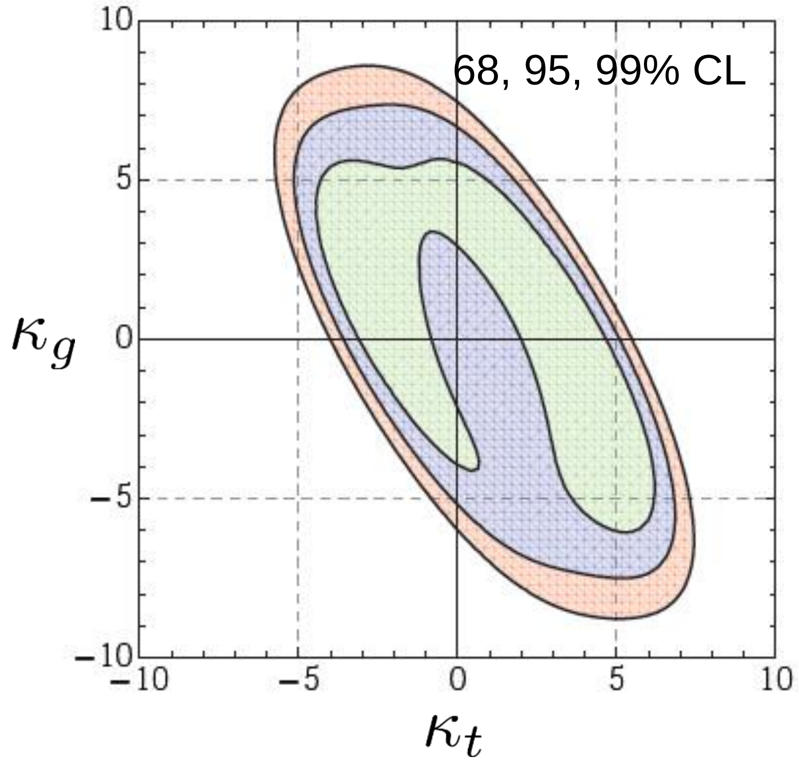
Azatov, Grojean, Paul, ES 2014

8 TeV data: CMS 4*l*

CMS PAS - HIG - 14 - 002

- Use MCFM to extract $\frac{d\sigma}{dm_{4l}}(\kappa_t, \kappa_g)$
- Take $q\bar{q}$ background and observed yields from CMS' first analysis (cut and count, **no MELA**)





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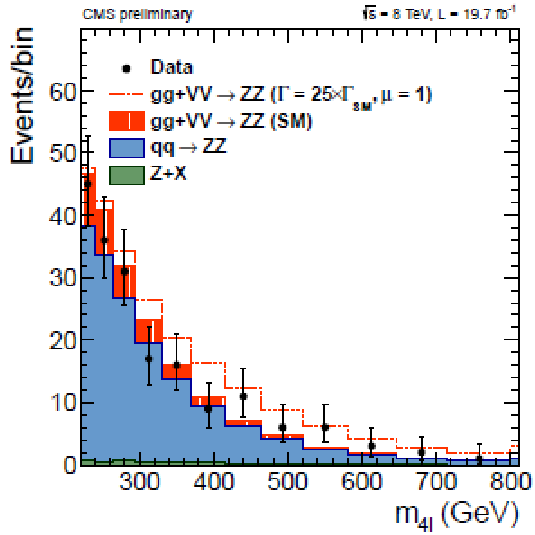
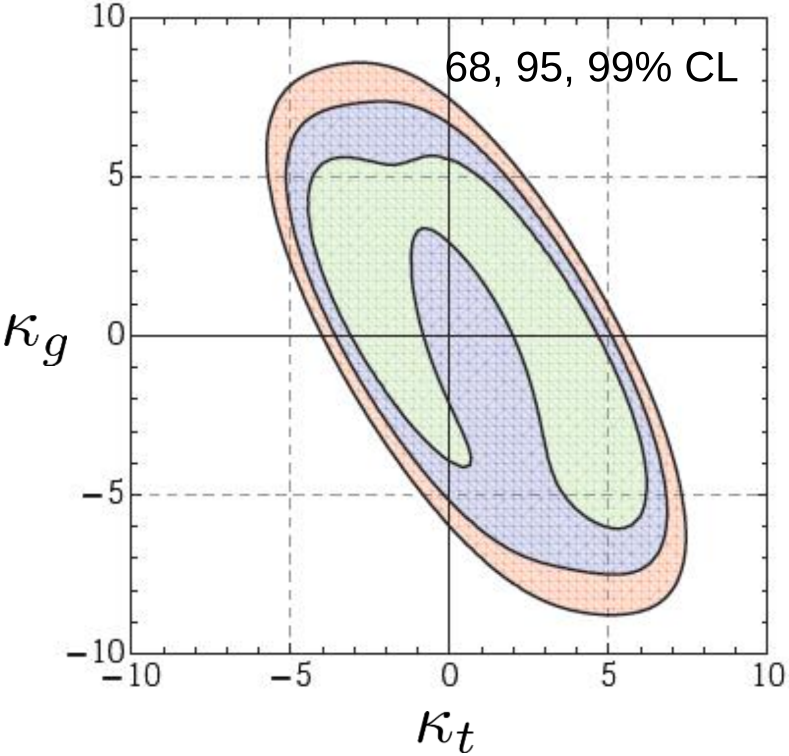
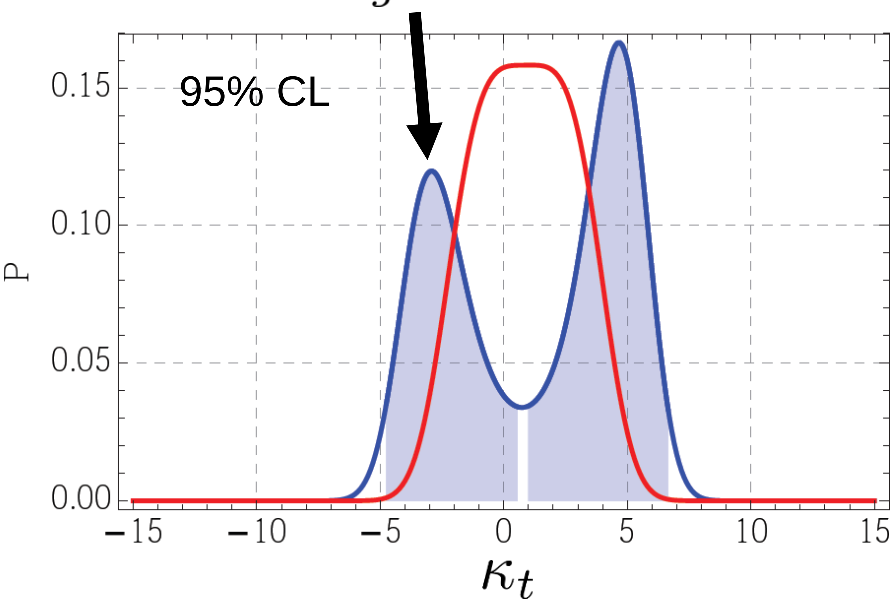




Assuming $\kappa_t + \kappa_g = 1$



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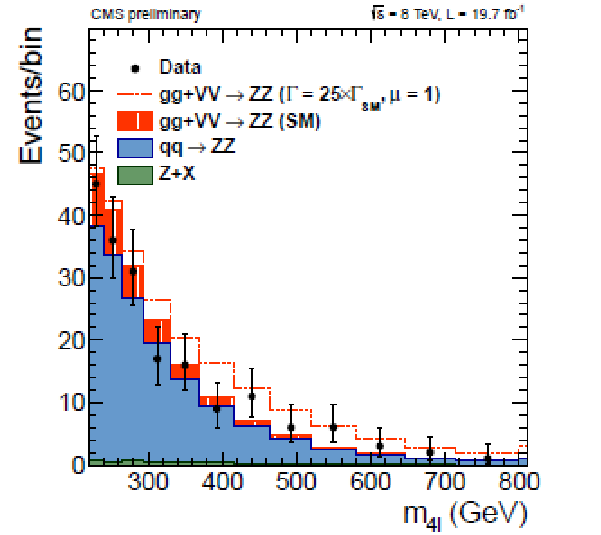
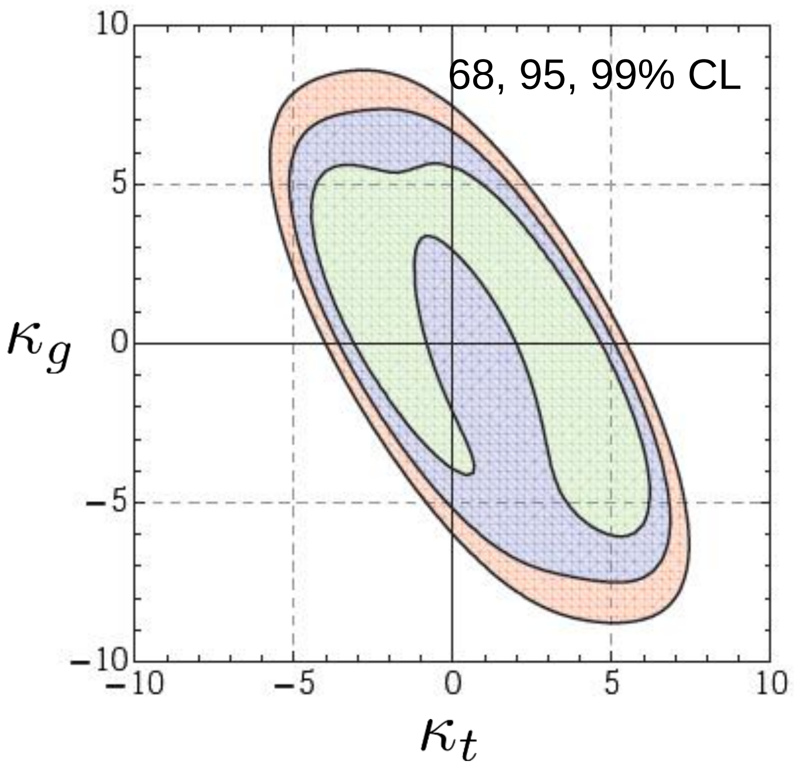
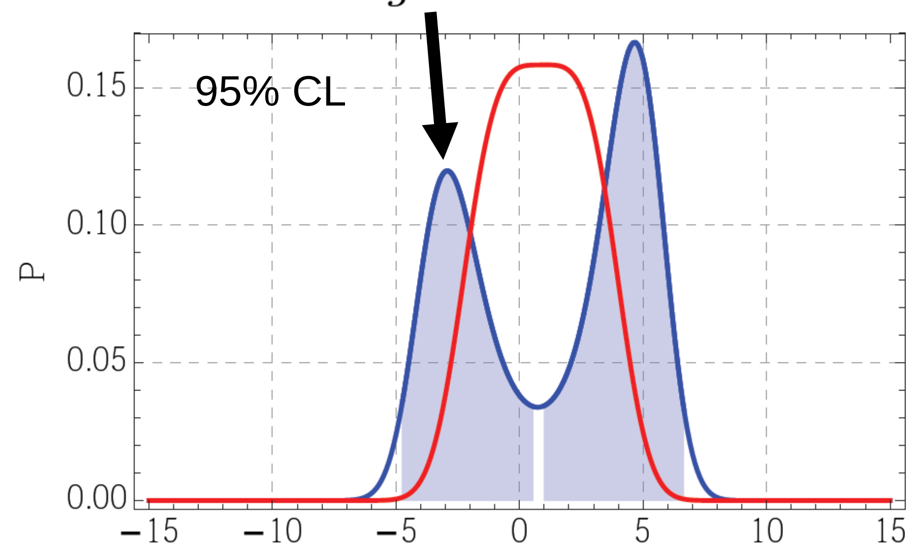




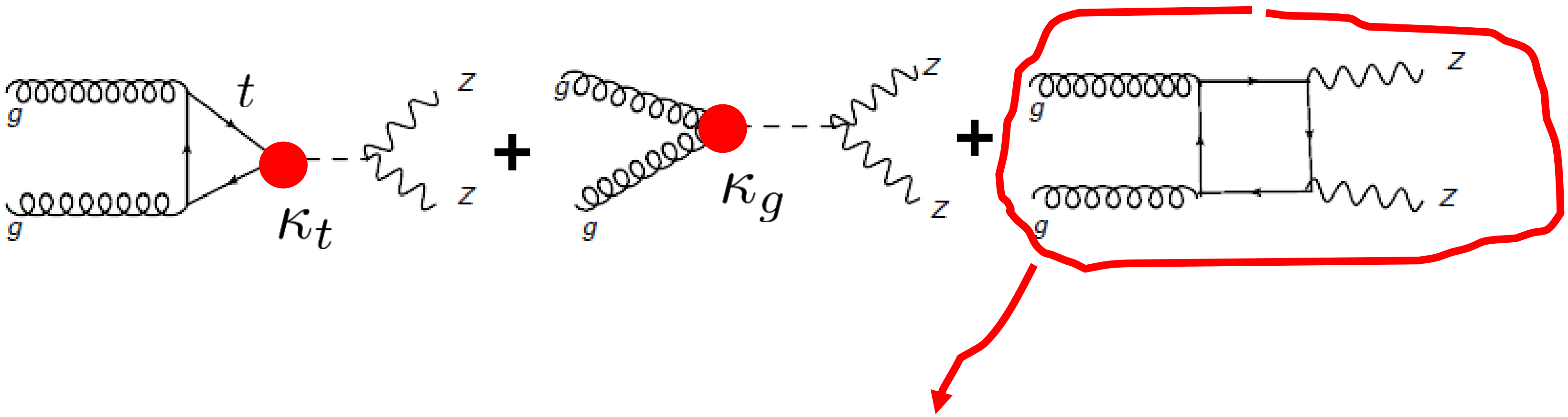
Assuming $\kappa_t + \kappa_g = 1$



$\kappa_t \in [-4.7, 0.5] \cup [1, 6.7]$

Comparable to direct bounds from *tth*

Off-shell Higgs: background prediction

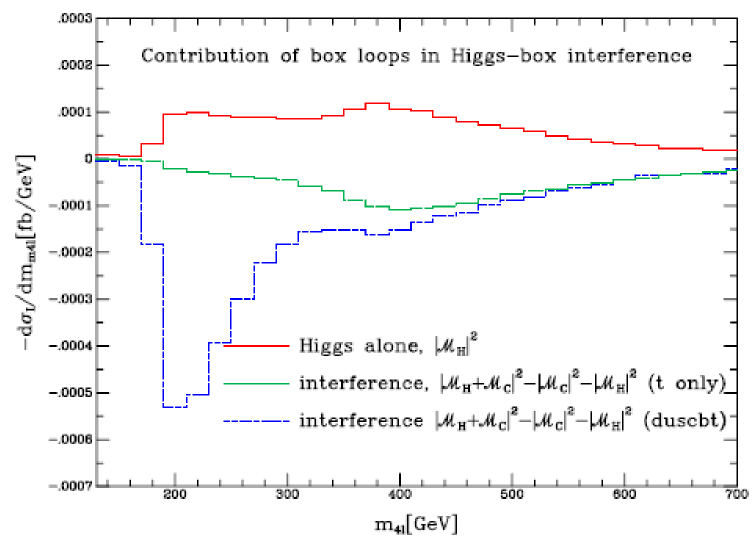


- Box contribution is known only at LO in QCD. This gives large uncertainty on the interference term (estimated ~30%).

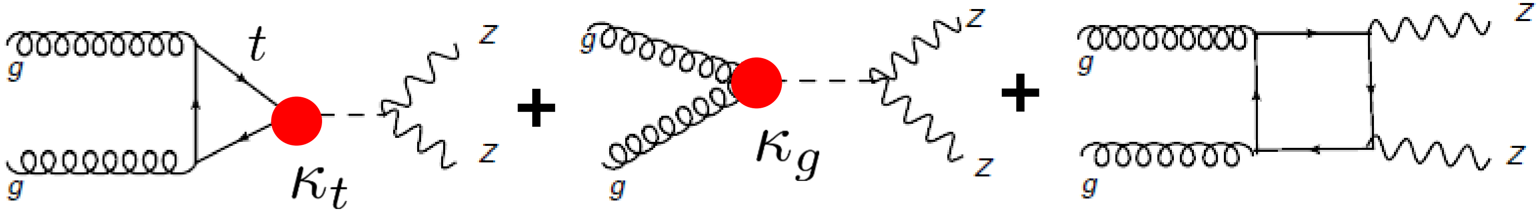
NB: 2-loop with top internal lines is needed for NLO

from talk by K. Ellis, 2014

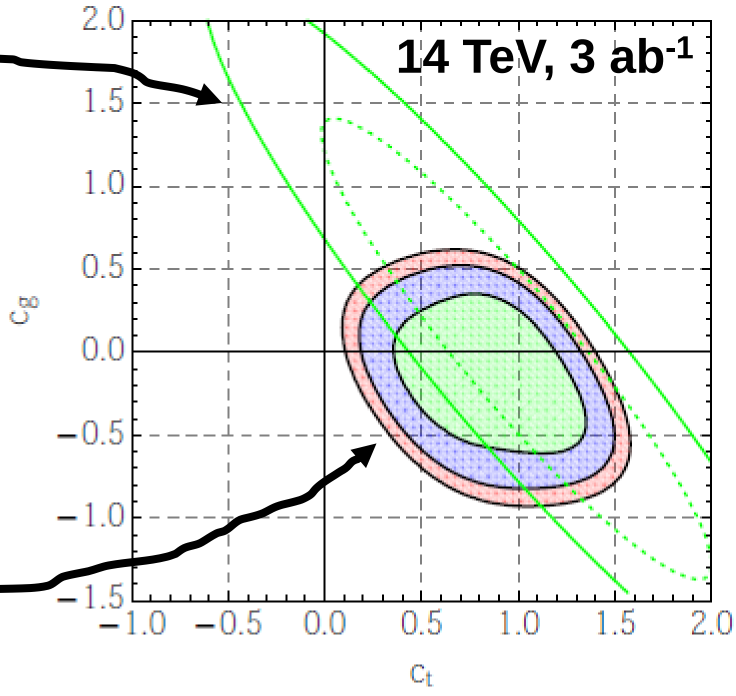
$$\mathcal{M}_{\text{box}} \sim \frac{m_t^2}{m_Z^2} \log^2 \frac{\hat{s}}{m_t^2}$$



Off-shell Higgs: EFT validity



Consistent EFT treatment: retain only interference of NP with SM amplitude



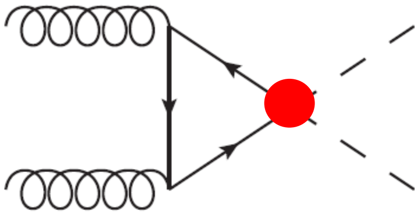
Keeping NP^2 terms

Double Higgs production

- Double Higgs production especially interesting as a test of nonlinear effects, in particular of $t\bar{t}hh$ coupling

$$c_{2t} = -\left(c_H + \frac{3}{2}c_y\right)\frac{v^2}{f^2} = -2\frac{v^2}{f^2}$$

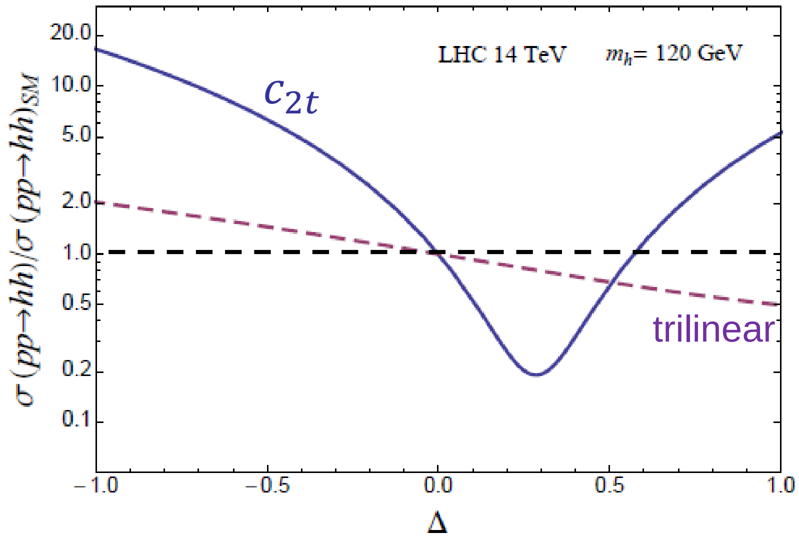
MCHM5



- This diagram leads to a large enhancement of the cross section if $c_{2t} < 0$

Groeber & Muehlleitner 2010

- Sensitivity much better than for Higgs trilinear

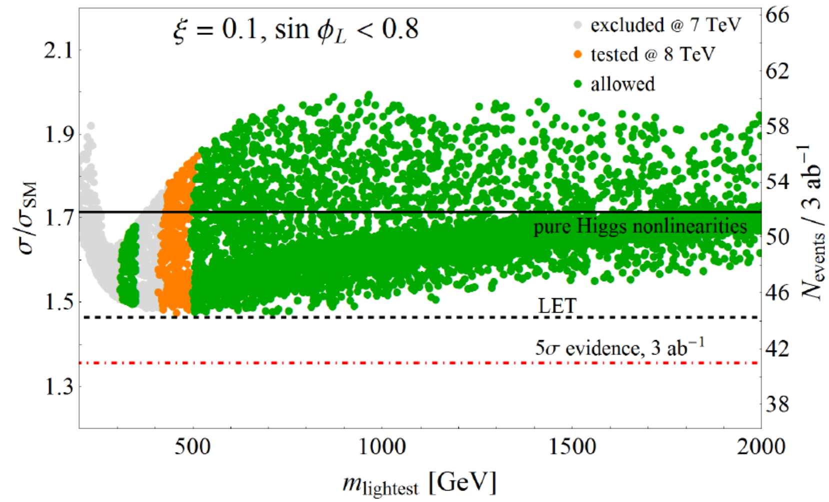


from Contino et al. 2012

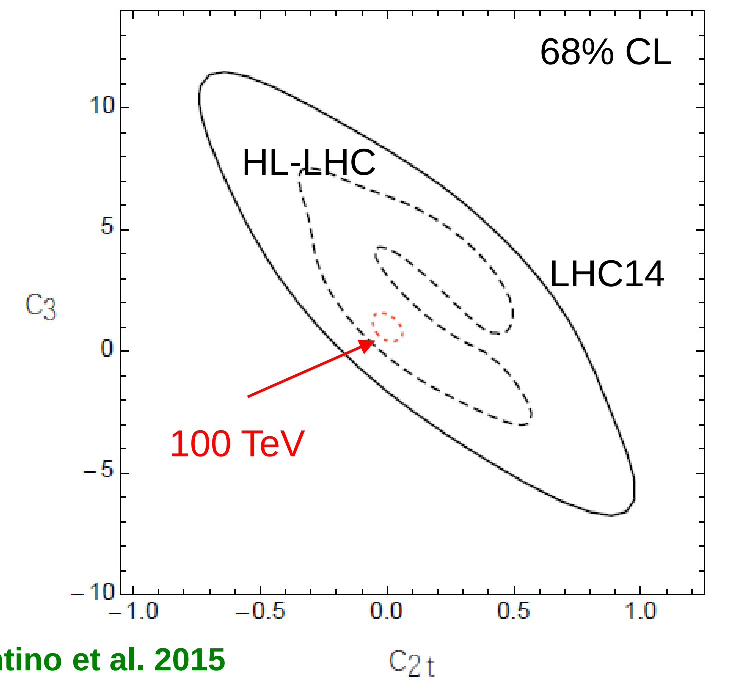
Double Higgs production

- Full computation in MCHM confirms enhancement
  (sensitivity to top partner spectrum is interesting but mild, ±15%)

Gillioz, Groeber, Grojean, Muehlleitner, ES 2012



- However, recent careful analysis in *bbγγ* channel is more pessimistic than previous work, ~50% determination of $t\bar{t}hh$ coupling at HL-LHC
- *Much* worse for Higgs trilinear, need FCC energies



from Contino et al. 2015

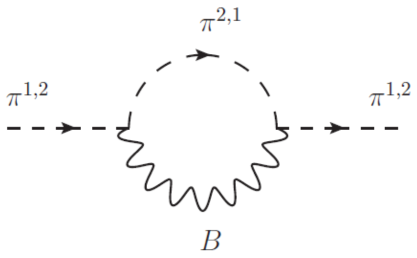
Electroweak precision tests

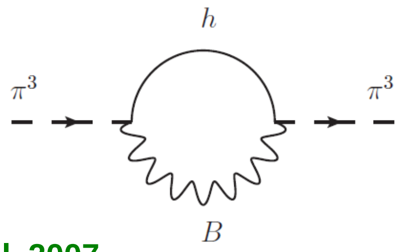
- Unavoidable contributions are

IR, due to modified *hVV* couplings

$$\Delta\hat{T} = -\frac{g'^2}{32\pi^2}\xi \log\frac{m_\rho}{m_h}$$

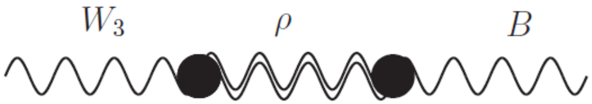
$$\Delta\hat{S} = +\frac{g^2}{96\pi^2}\xi \log\frac{m_\rho}{m_h}$$





UV

$$\Delta\hat{S} = \frac{m_W^2}{m_\rho^2}$$



Barbieri et al. 2007

Electroweak precision tests

- Unavoidable contributions are

IR, due to modified *hVV* couplings

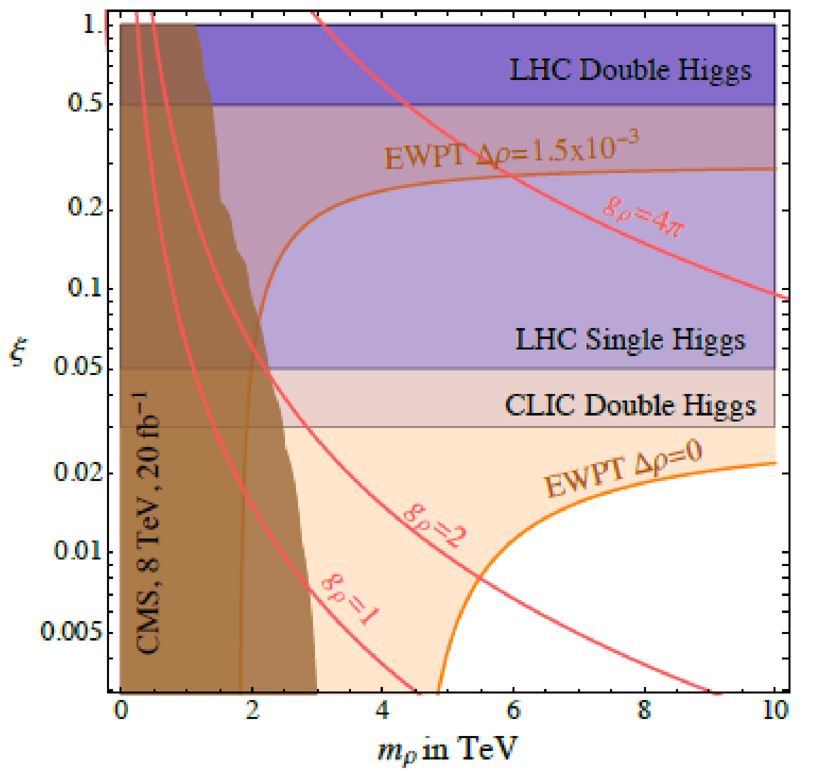
$$\Delta\hat{T} = -\frac{g'^2}{32\pi^2}\xi\log\frac{m_\rho}{m_h}$$

$$\Delta\hat{S} = +\frac{g^2}{96\pi^2}\xi\log\frac{m_\rho}{m_h}$$

UV

$$\Delta\hat{S} = \frac{m_W^2}{m_\rho^2}$$

from Contino et al. 2013



- Without extra contributions,

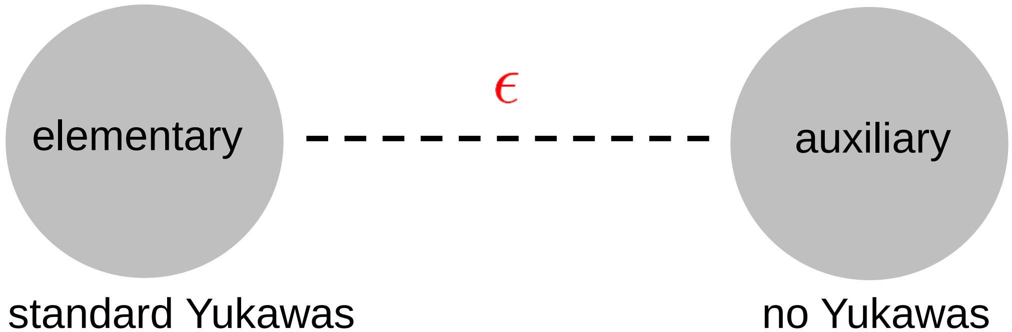
$$\xi < 0.02$$

- Extra positive T relaxes constraint strongly, and is possible in concrete models

Grojean et al. 2013

Induced EWSB

- Different approach: the Higgs is elementary, hierarchy problem solved by SUSY
- New (possibly strongly coupled) ‘auxiliary’ sector that breaks electroweak



Carone, Erlich, Tan 2006
Kagan 2008
Gherghetta, Pomarol 2011
Azatov, Galloway, Luty 2011, Galloway, Luty, Tsai, Zhao 2013

$$V \sim m_H^2 \, |H|^2 - \epsilon \, (H^\dagger \Sigma + \text{h.c.}) \qquad \Sigma = e^{i\frac{\Pi}{f}} \begin{pmatrix} 0 \\ f \end{pmatrix}$$

$\epsilon \neq 0$ ⇒

$$V(h) \simeq \tfrac{1}{2} m_H^2 h^2 - \epsilon f h$$

$$\langle h \rangle = \frac{\epsilon}{m_H^2} f \equiv v_H \,, \qquad m_H \simeq 125 \text{ GeV}$$

$$m_f = \frac{y_f}{\sqrt{2}} v_H \,, \qquad \sqrt{v_H^2 + f^2} \simeq 246 \text{ GeV}$$

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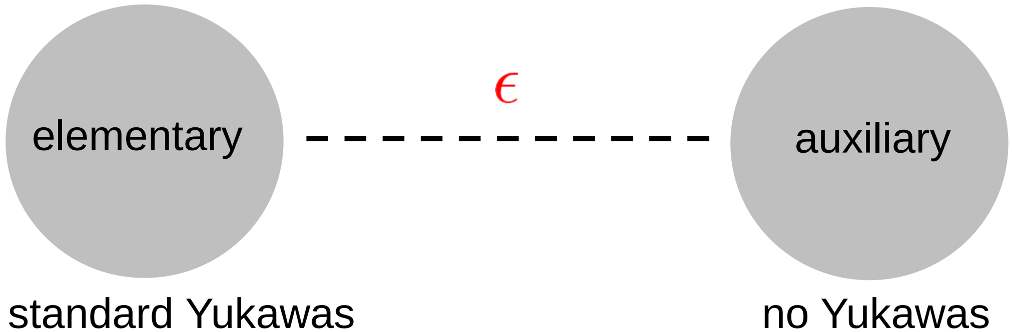

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EWSB from an induced tadpole

$$\langle h \rangle = \frac{\epsilon}{m_H^2} f \equiv v_H \, , \qquad m_H \simeq 125 \text{ GeV}$$

$$m_f = \frac{y_f}{\sqrt{2}} v_H \, , \qquad \sqrt{v_H^2 + f^2} \simeq 246 \text{ GeV}$$

Induced EWSB

- Tadpole potential naturally explains a 125 GeV mass for the Higgs, solving the 'too light *h*' problem in SUSY

- Higgs is elementary, but longitudinal *W* and *Z* are mixtures of elementary and composite d.o.f.

$$\begin{pmatrix} G^0 \\ A^0 \end{pmatrix} = (1/v) \begin{pmatrix} v_H & f \\ -f & v_H \end{pmatrix} \begin{pmatrix} \pi_0 \\ a_0 \end{pmatrix}$$

elementary (π_0)

'composite' (a_0)

- Light physical triplet of scalars,

$$m_{A^0} = m_{H^\pm} \simeq \frac{v}{f} m_h$$

Induced EWSB

- Potential dominated by quadratic + tadpole terms, higher order interactions are strongly suppressed

$$V_{\text{eff}}(h) \simeq \frac{1}{2} m_H^2 h^2 - \epsilon f h \left[1 + \left(\frac{\epsilon}{m_{\text{aux}}^2} \frac{v_H}{f} \right) \frac{h}{v_H} - \frac{1}{2} \left(\frac{\epsilon}{m_{\text{aux}}^2} \frac{v_H}{f} \right)^2 \frac{h^2}{v_H^2} + \ldots \right]$$

$$\frac{\epsilon}{m_{\text{aux}}^2} \ll 1 \qquad\qquad m_{\text{aux}}^2 \sim \lambda_\Sigma f^2 \,, \qquad \lambda_\Sigma \gg 1$$

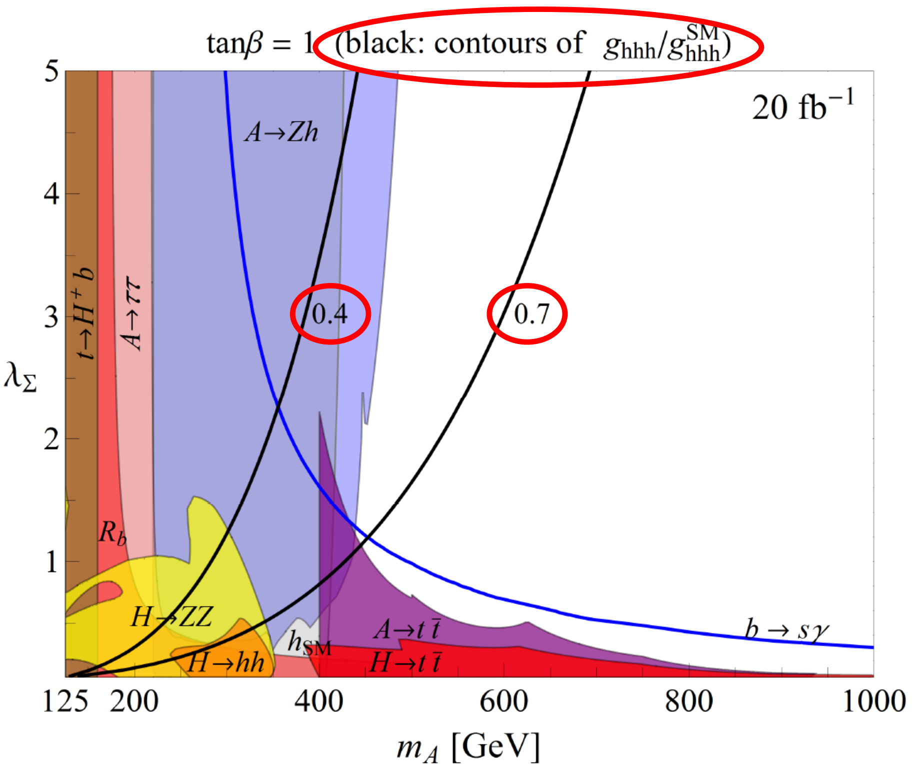
- **Singles out Higgs trilinear as parametrically largest deviation from SM**

Induced EWSB in double *h*

- Potential dominated by quadratic + tadpole terms, higher order interactions are strongly suppressed

$$g_{hhh} < g_{hhh}^{\mathrm{SM}} \quad \Rightarrow \quad \sigma(gg \to hh) > \sigma(gg \to hh)_{\mathrm{SM}}$$

- A value ~ half of the SM compatible with all 8 TeV bounds



Chang, Galloway, Luty, ES, Tsai 2014

Summary

- Direct searches for top partners are a crucial test of composite Higgs models. Including single production important for run II.

- New info will be available from measurements of Higgs distributions:

  - Boosted Higgs complementary to $t\bar{t}h$ in discriminating top Yukawa vs NP loops
  - Interpretation of off-shell Higgs measurement as constraint on Higgs total width is limited, but opportunity for coupling measurement
  - Double *h* production can test nonlinearities, e.g. $t\bar{t}hh$ coupling

- Induced EWSB is rather different approach: elementary (SUSY) Higgs coupled to technicolor sector. EWSB from induced tadpole, h^3 coupling is the largest deviation from SM