Boosted and off-shell Higgs in gluon fusion

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SUSY 2014

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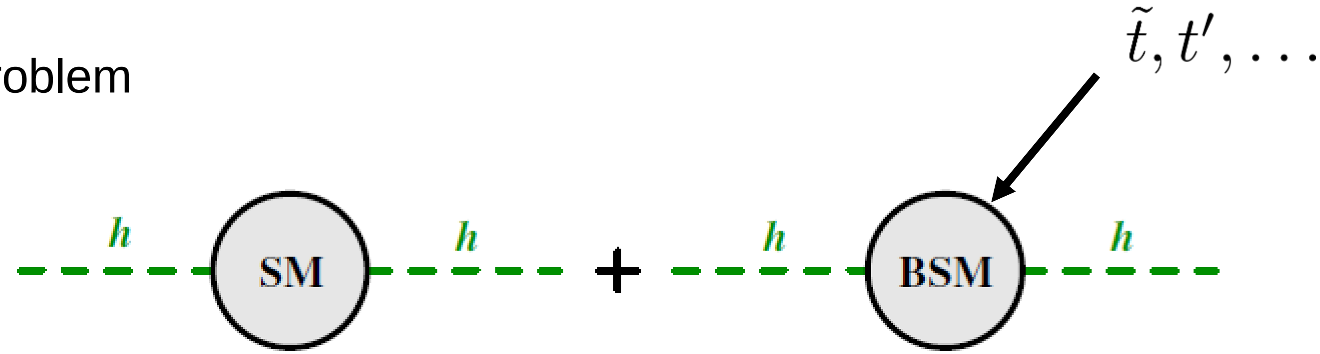
based on

1312.3317 (JHEP) *with Grojean, Schlaffer and Weiler*

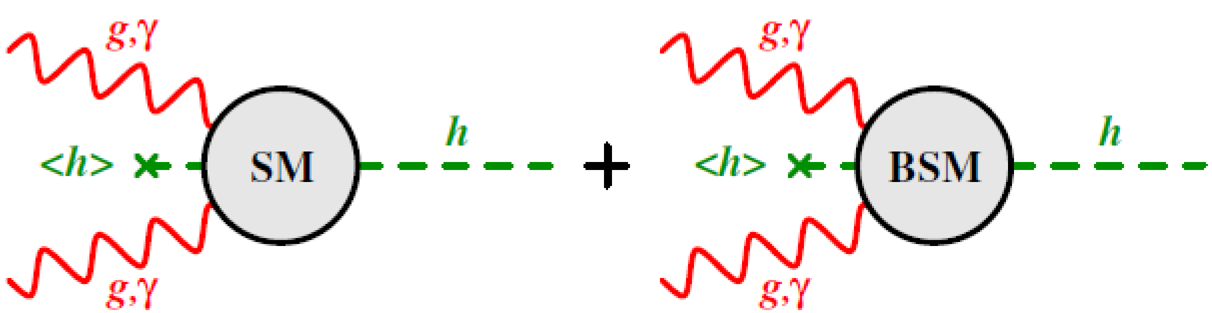
1406.6338 *with Azatov, Grojean and Paul*

Introduction

Hierarchy problem



new states charged
under color and EM



Expect deviations in couplings of Higgs to gluons and photons

e.g. **Low, Rattazzi, Vichi, 0907.5413,**
Arvanitaki and Villadoro, 1112.4835

Higgs production via gluon fusion

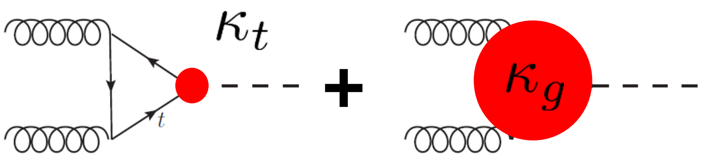
- Consider parameterization

loops of new states: stops, top partners…

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

- For **inclusive production**,

$$\mathcal{M}(gg \to h) \;=$$



(in terms of dimension-6 operators:

$$\mathcal{L}_6 \;=\; c_y \frac{y_t}{v^2} H^\dagger H \overline{q}_L \widetilde{H} t_R + \text{h.c.} + \; c_g \frac{\alpha_s}{12\pi v^2} H^\dagger H G^A_{\mu\nu} G^{\mu\nu\,A}$$

$$\Rightarrow \quad \kappa_t = 1 - \text{Re}\, c_y \,, \qquad \kappa_g = c_g$$

)

Higgs production via gluon fusion

- Consider parameterization

loops of new states: stops, top partners…

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

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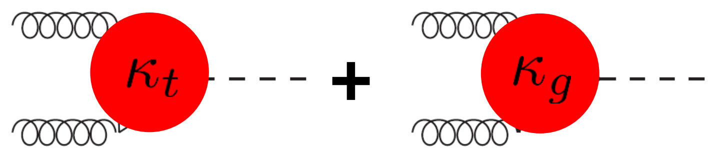


also effectively seen as point-like interaction!

$$(\hat{s} = m_h^2)$$

$$\mu_{\rm incl} = \frac{\sigma(pp\to h+X)}{\sigma(pp\to h+X)_{\rm SM}} \simeq (\kappa_t + \kappa_g)^2$$

degeneracy between ‘long-distance’ and ‘short-distance’ contributions

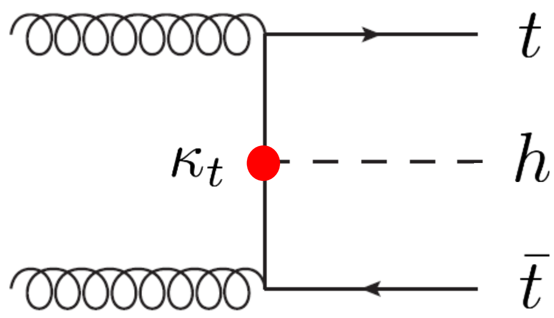
In the SM:

m_H(GeV)	$\frac{\sigma_{NLO}(m_t)}{\sigma_{NLO}(m_t\to\infty)}$
125	1.061
150	1.093
200	1.185

$$\mathcal{M}_{m_t} \simeq \mathcal{M}_\infty \left(1 + \frac{7}{30}\frac{m_h^2}{4m_t^2}\right)$$

How to break the degeneracy in the future?

Look at Higgs production in association with tops:



However, this is a difficult channel.

e.g. Snowmass Higgs report, 1310.8361

Expected accuracy on κ_t at HL-LHC is ~ 10%

Worthwhile to explore alternatives:

- boosted Higgs: $pp \to h + j$
- off-shell Higgs: $pp \to h^* \to ZZ$

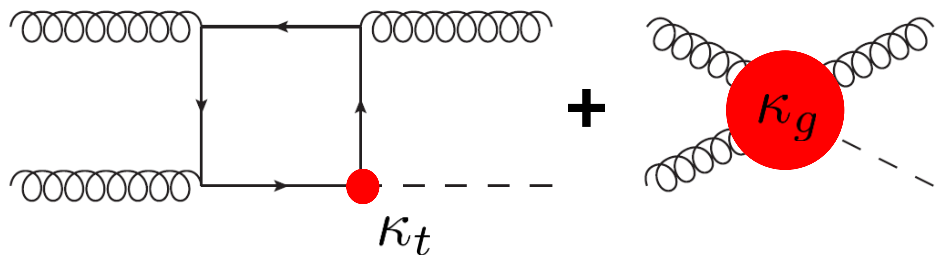
1. Boosted Higgs

Boosted Higgs in gluon fusion

see also Harlander et al., 1308.2225
Banfi et al., 1308.4771
Azatov and Paul, 1309.5273

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 degeneracy as in inclusive rate

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

different combination of couplings

$p_T^{\min}$ [GeV]	$\sigma^{\rm SM}_{p_T^{\min}}$ [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

Combining low and high p_T resolves long-distance *vs* short-distance physics

Estimate of measurement: $h \to \tau\tau$

To break the degeneracy in (κ_t, κ_g) plane, **combine** measurements of inclusive and boosted rates

For boosted measurement, to reduce theory uncertainty use ratio

$$\mathcal{R} = \frac{\sigma(p_T > 650\,\mathrm{GeV})}{\sigma(p_T > 150\,\mathrm{GeV})}$$

NB: QCD-NLO corrections to Higgs p_T spectrum are **not known yet** for finite m_t

Assume decay $h \to \tau\tau$, take efficiencies from ‘ditau-jet tagging’ (theory) analysis of Katz et al. (**1011.4523**),

$$\epsilon_{\mathrm{tot}} = \mathrm{BR}(h \to \tau\tau) \left(\sum_{i \in \tau_\ell\tau_\ell, \tau_\ell\tau_h, \tau_h\tau_h} \mathrm{BR}(\tau\tau \to i)\, \epsilon_i \right) \simeq 2 \times 10^{-2}$$

Only a first estimate. More realistic collider study in **Schlaffer et al., 1405.4295**

Breaking the degeneracy

Combine measurements using simple procedure (no backgrounds):

$$\chi^2(\kappa_t, \kappa_g) = \left(\frac{\mathcal{R}(\kappa_t,\kappa_g) - \mathcal{R}^*}{\delta \mathcal{R}} \right)^2 + \left(\frac{\mu_{\rm incl}(\kappa_t,\kappa_g) - \mu^*_{\rm incl}}{\delta \mu_{\rm incl}} \right)^2$$

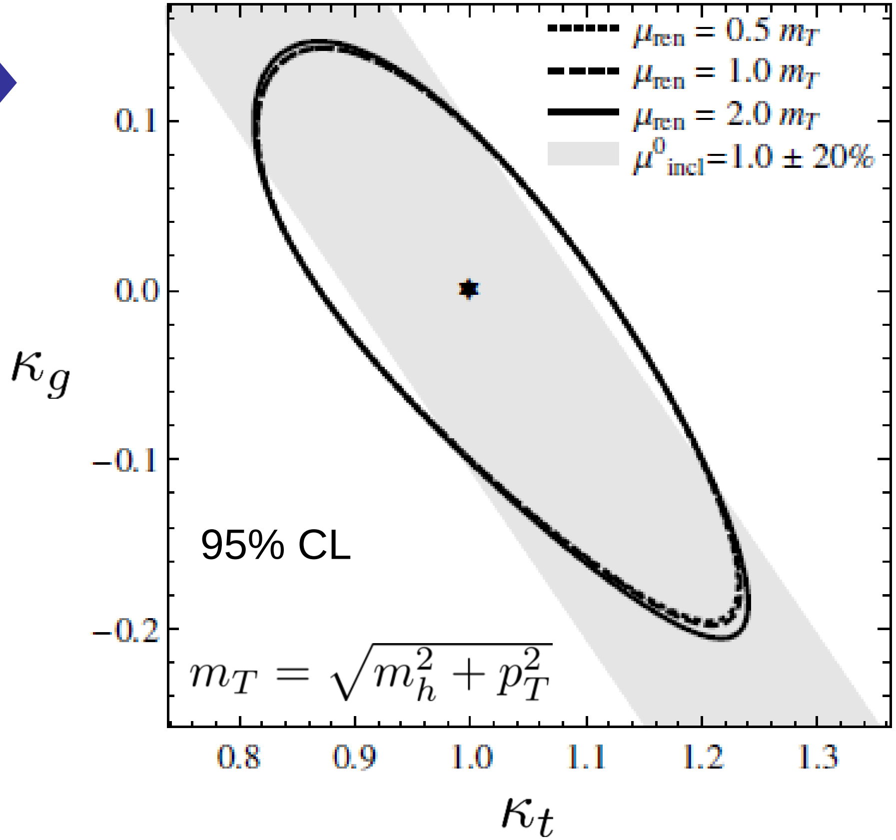
assume 10% syst uncertainty **+** stat uncertainty on $N_{\rm events}^{p_T > 650\,{\rm GeV}}$

$$\sqrt{s} = 14\,{\rm TeV}, \quad 3000\,{\rm fb}^{-1}$$

degeneracy broken

$$\mathcal{R} = \frac{\sigma(p_T > 650\,{\rm GeV})}{\sigma(p_T > 150\,{\rm GeV})}$$

$$\mu_{\rm incl} = \frac{\sigma(pp \to h + X)}{\sigma(pp \to h + X)_{\rm SM}} \simeq (\kappa_t + \kappa_g)^2$$



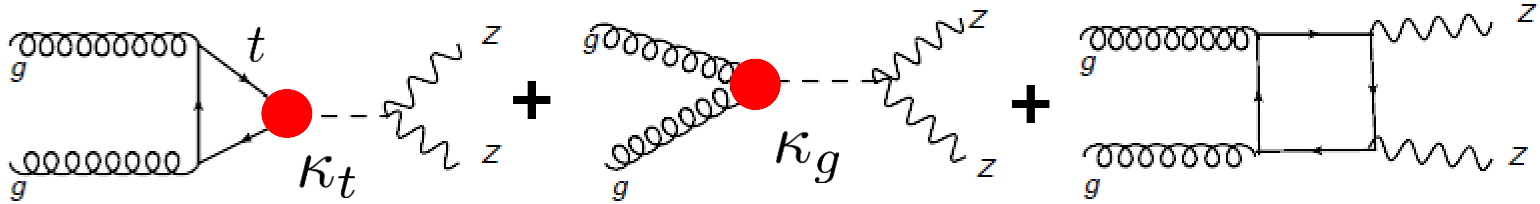
2. Off-shell Higgs

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

Assume:

- No invisible Higgs decay width
- Higher-dimensional operators modifying Higgs couplings:

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



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

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

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

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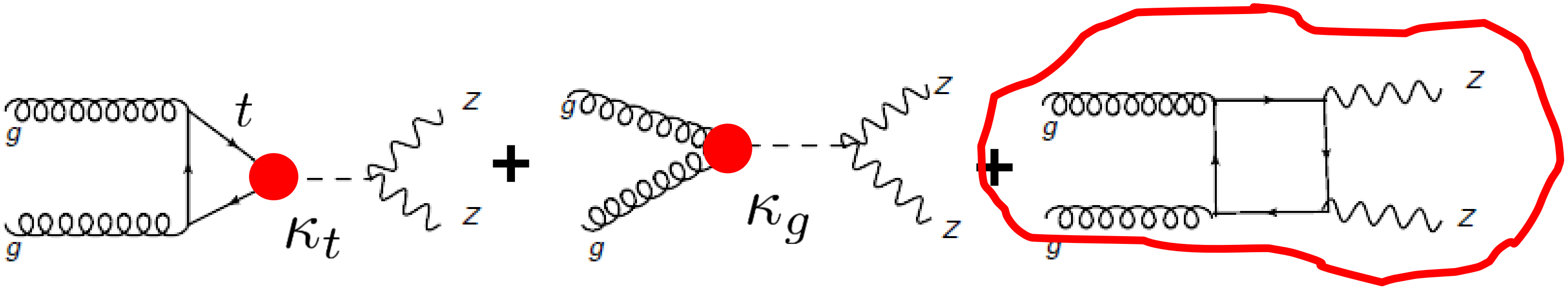

NB: known only at LO!

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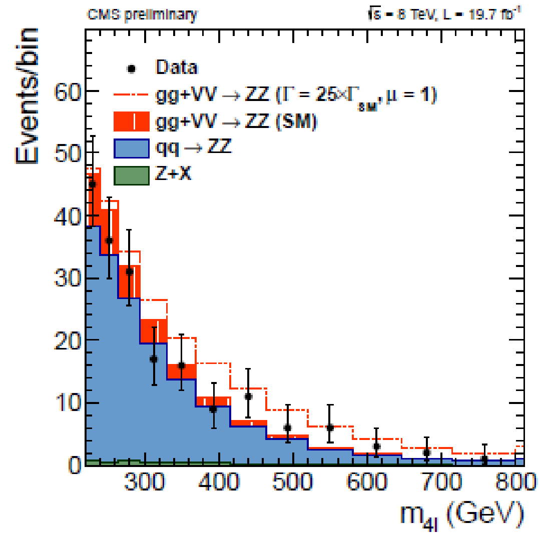
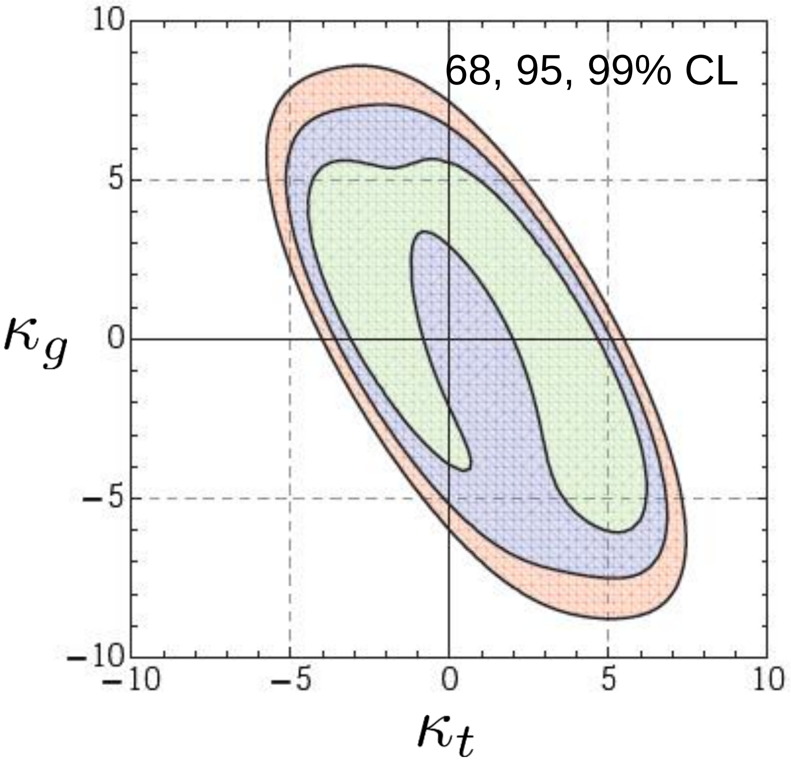
➡ **Region of large *VV* mass discriminates between the two couplings**

8 TeV data: CMS 4*l*

- 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)

CMS PAS - HIG - 14 - 002





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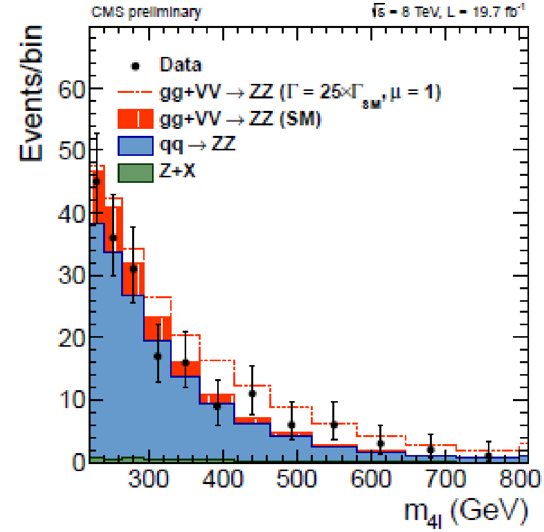
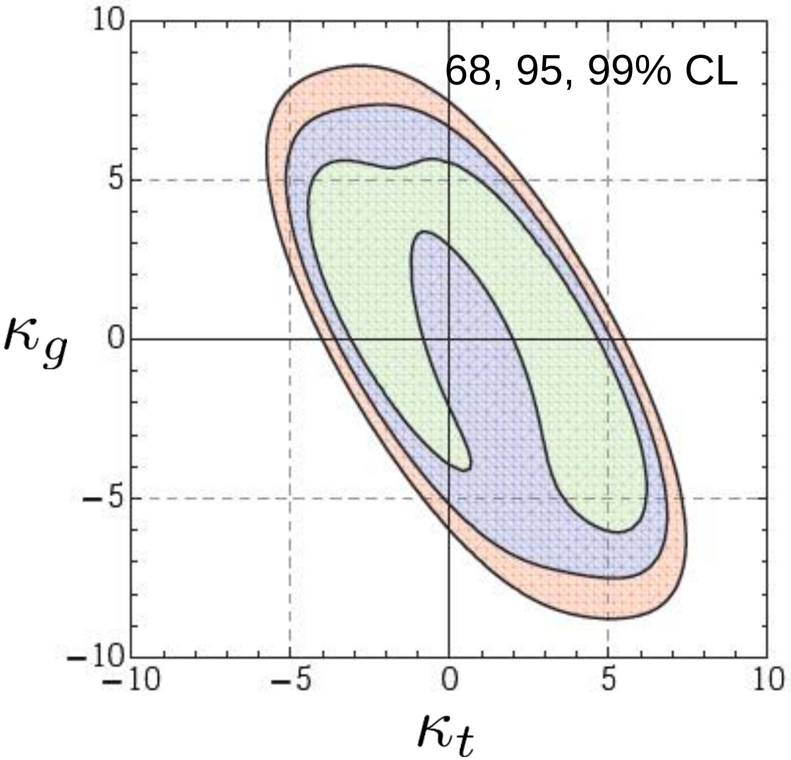
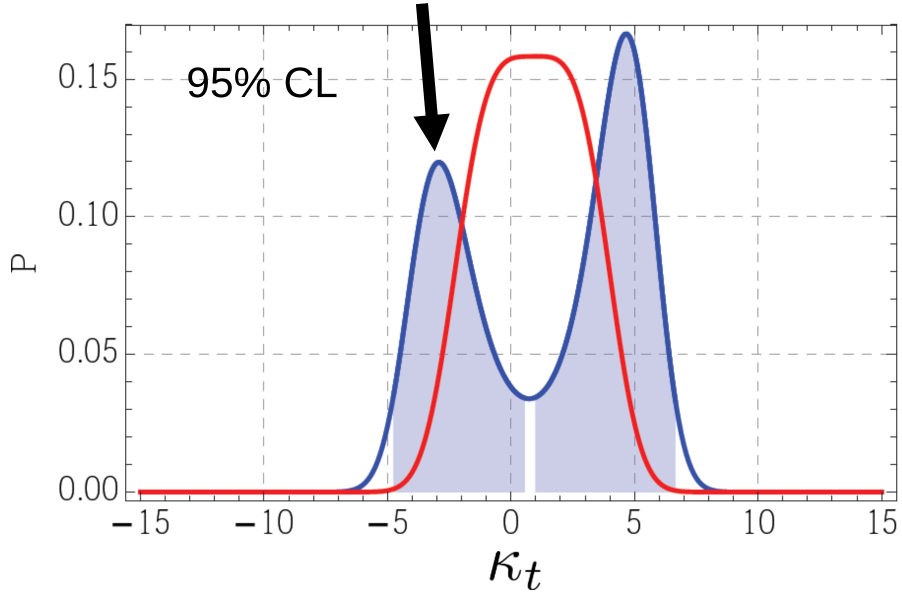




Assuming $\kappa_t + \kappa_g = 1$



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

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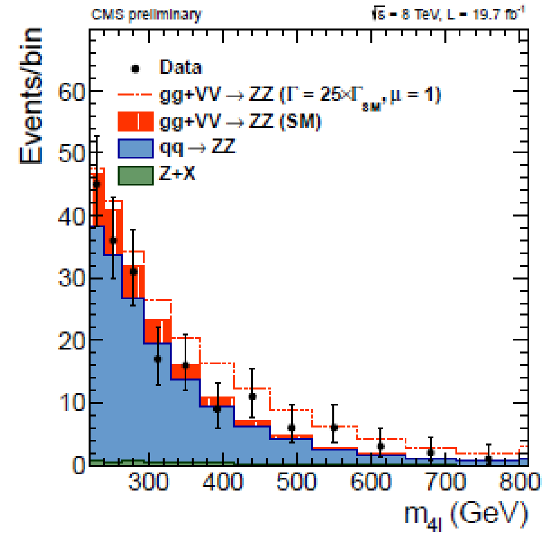

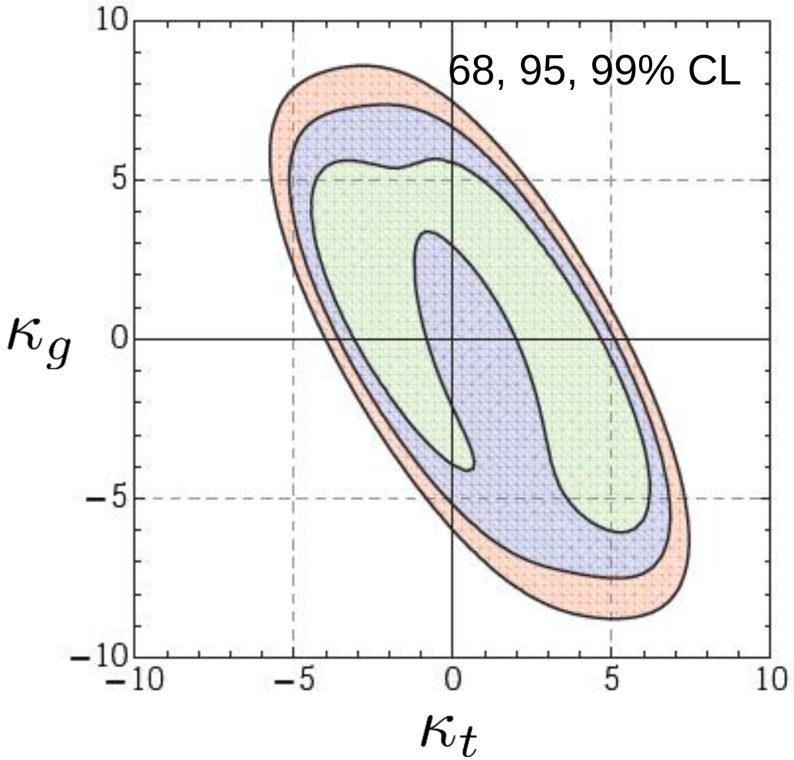

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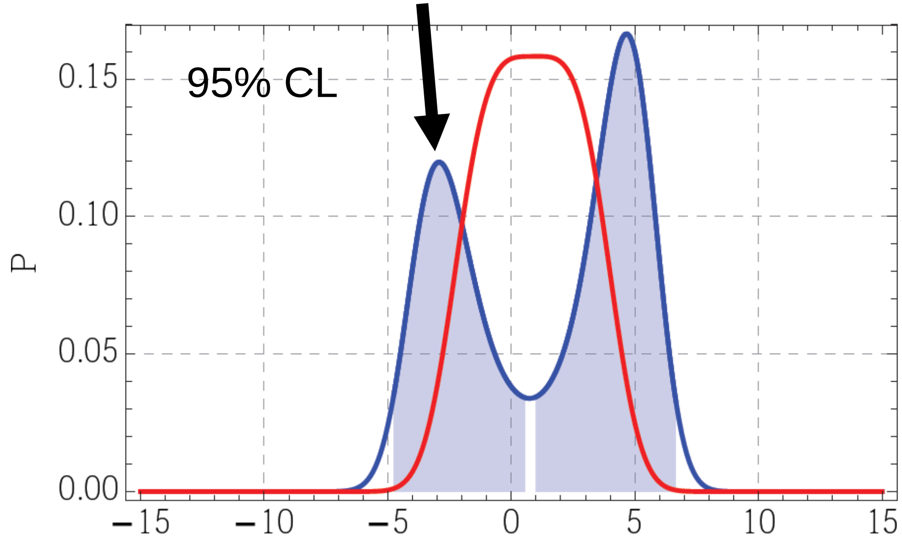


$$\kappa_t \in [-4.7, 0.5] \cup [1, 6.7]$$

Comparable to direct bounds from *tth*!

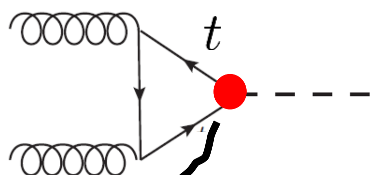
3. Applications

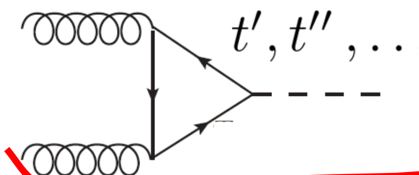
a) Higgs as a composite pseudo-Goldstone boson

b) Supersymmetry

The Higgs as a composite p-NGB

- A naturally light Higgs wants light top partners: colored fermions with mass below the TeV **e.g. Matsedonskyi et al., Pomarol et al. 2012**
- Important effects in hgg loop could be expected
- However, it turns out that loops of resonances cancel out exactly against corrections to $ht\bar{t}$ coupling **Falkowski 2007; Low & Vichi; Azatov & Galloway, ES et al.**

$\mathcal{M}(gg \to h) =$ 

$+$ 

$\sim \kappa_g$

they cancel out!

(MCHM$_5$)

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

$$\frac{g_{hgg}}{g_{hgg}^{\rm SM}} = \kappa_t + \kappa_g = \frac{1}{\sqrt{1-v^2/f^2}}\left[1 - 2\frac{v^2}{f^2}\right]$$

insensitive to top partners

The Higgs as a composite p-NGB

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Composite Higgs models are prime example where it is crucial to pin down κ_t and κ_g separately

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

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insensitive to top partners

3. Applications

a) Higgs as a composite pseudo-Goldstone boson

b) Supersymmetry

Supersymmetry

Top + stops give

$$\frac{\sigma(pp\to h+X)}{\sigma(pp\to h+X)_{\rm SM}} = (1+\Delta_t)^2$$

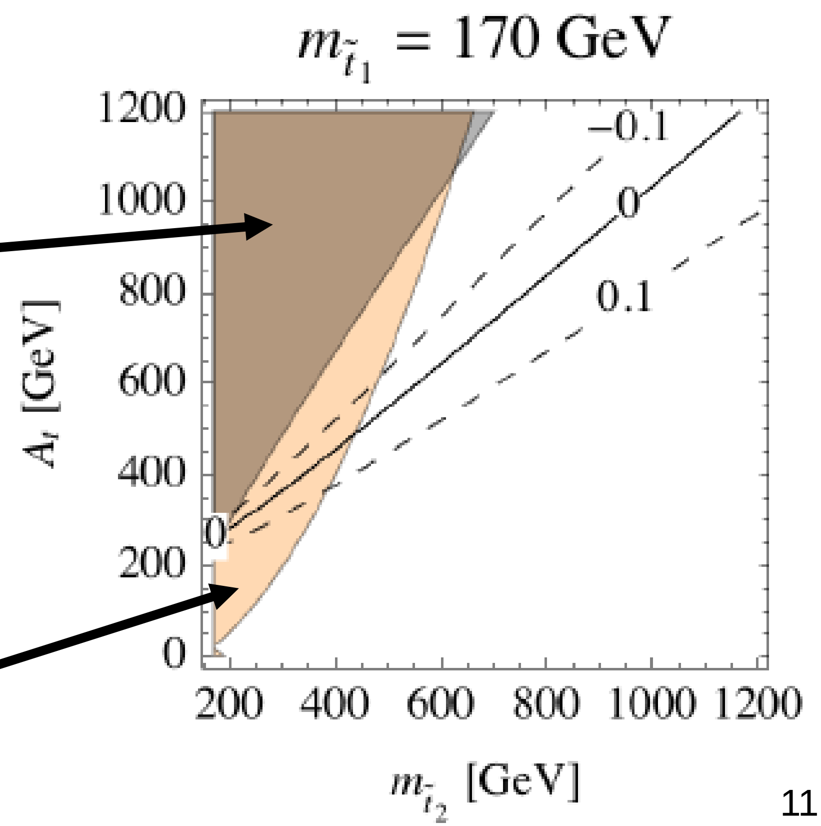
$$\Delta_t \simeq \frac{m_t^2}{4}\left(\frac{1}{m_{\tilde{t}_1}^2}+\frac{1}{m_{\tilde{t}_2}^2}-\frac{(A_t-\mu/\tan\beta)^2}{m_{\tilde{t}_1}^2\, m_{\tilde{t}_2}^2}\right)$$

'Flat direction' for large enough A_t

electric charge and color breaking vacua

$$A_t^2+3\mu^2 \lesssim 3\,(m_{\tilde{t}_1}^2+m_{\tilde{t}_2}^2)$$

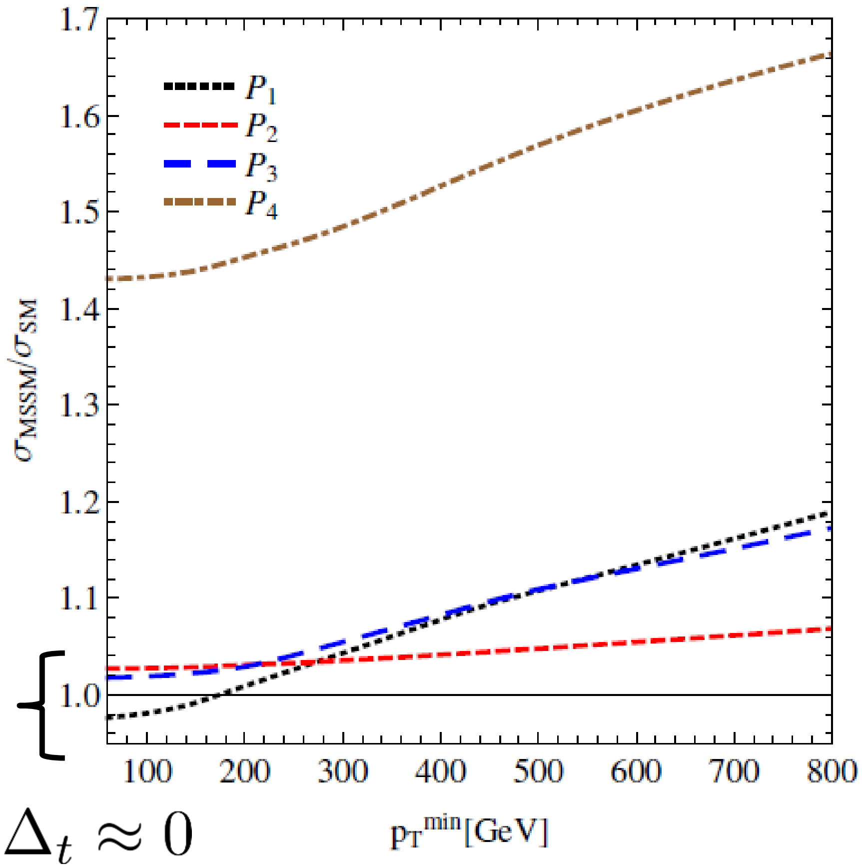
e.g. Kusenko et al., 1996



real soft masses

Supersymmetry /2

- Such light stops may or may not be excluded by direct LHC searches, depending on assumptions on spectra (e.g., neutralino mass)
- Still, it is interesting to ask whether boosted Higgs can be sensitive to light and mixed stops, **independently of assumptions on decay**



Point	$m_{\tilde{t}_1}$ [GeV]	$m_{\tilde{t}_2}$ [GeV]	A_t [GeV]	Δ_t
P_1	171	440	490	0.0026
P_2	192	1224	1220	0.013
P_3	226	484	532	0.015
P_4	226	484	0	0.18

boosted Higgs breaks degeneracy

Summary

- Inclusive Higgs production cannot discriminate top *vs* new physics contributions to the ggh vertex
- **Boosted** and **off-shell Higgs** probe $\hat{s} \gg m_t^2$, so can resolve the degeneracy. Alternatives to $t\bar{t}h$ channel.
- In both cases, need for more precise theoretical predictions:
  - Higgs p_T spectrum in gluon fusion at NLO with finite m_t
  - Box contribution to $gg \to ZZ$ at NLO

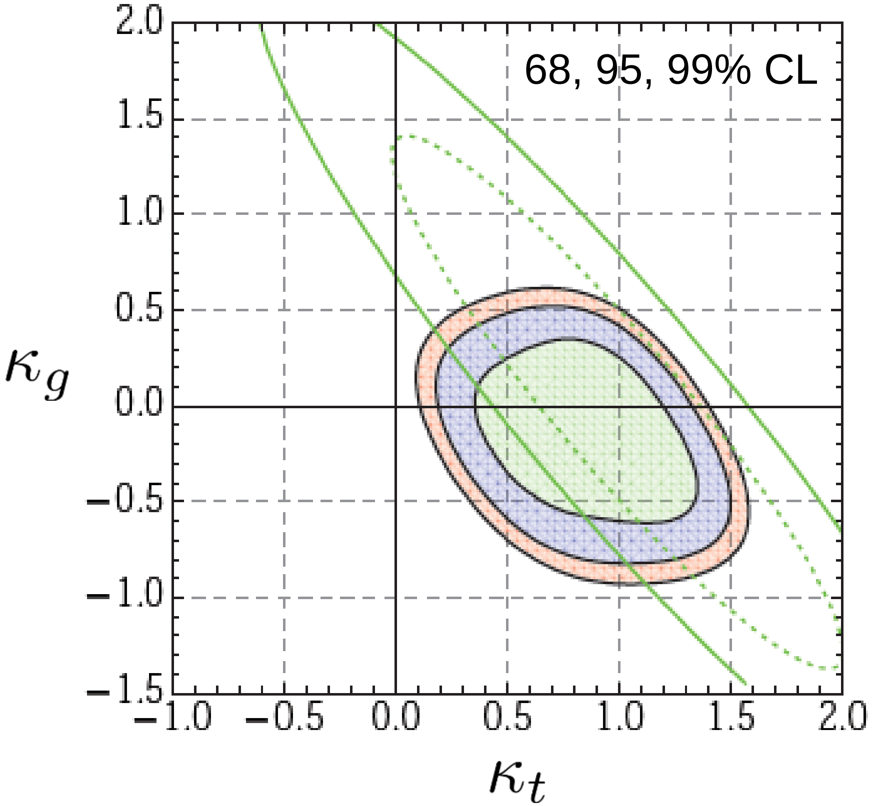
(two-loop diagrams with massive top in the internal lines)

- Resolving the degeneracy is not just an academic question.

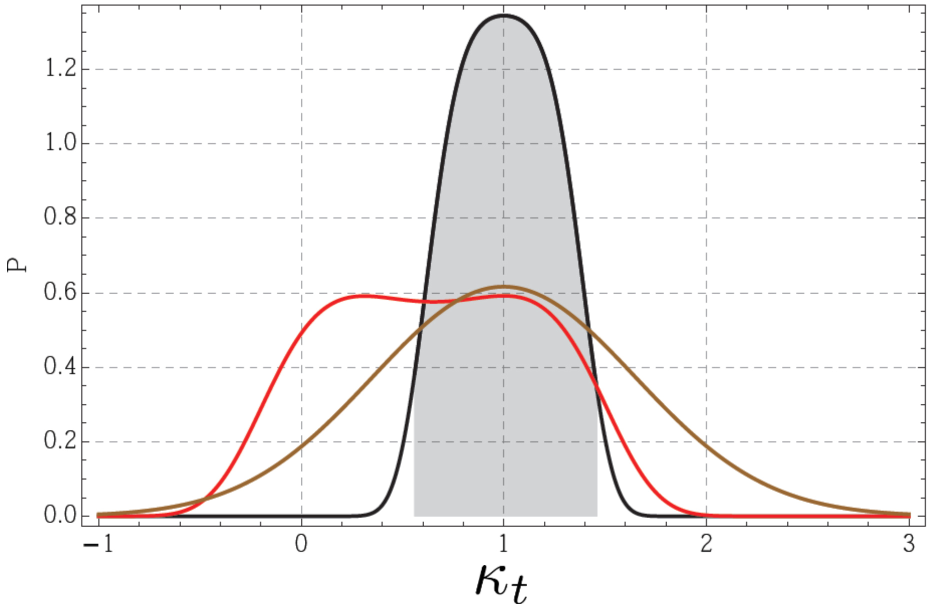
Application is very interesting in models of pseudo-Goldstone Higgs: inclusive rate is insensitive to fermionic resonances, boosted Higgs can resolve them. Relevant also for light and mixed stops in SUSY.

Backup

14 TeV, 3000 fb^{-1} results (MCFM)



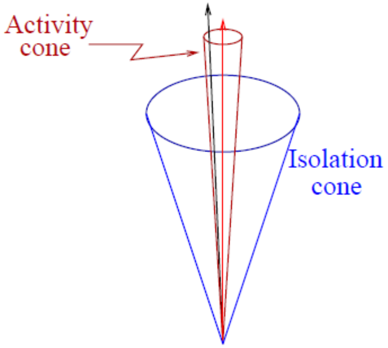
assuming $\kappa_t + \kappa_g = 1$



$$95\% \ : \quad \kappa_t \in [0.56, 1.46]$$

(will improve with MELA)

‘Ditau-jet’ tagging

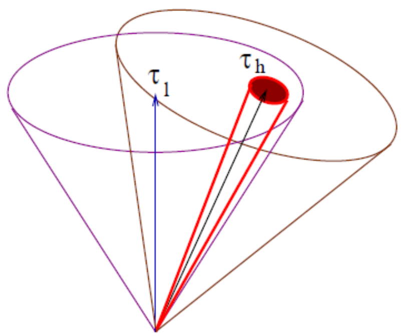


For $p_T = 650\,\mathrm{GeV}$, the taus have typical angular separation

$\Delta R \sim 2m_h/p_T \sim 0.4$ ➡ single tau-tag fails

Introduce ‘mutual isolation’.

For example, for **semi-leptonic** ditaus:

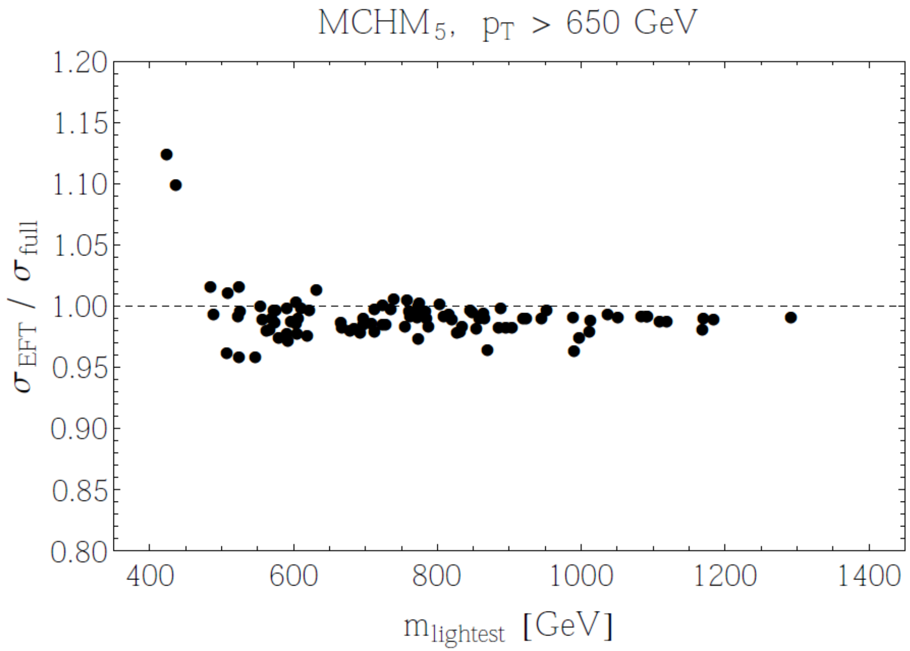


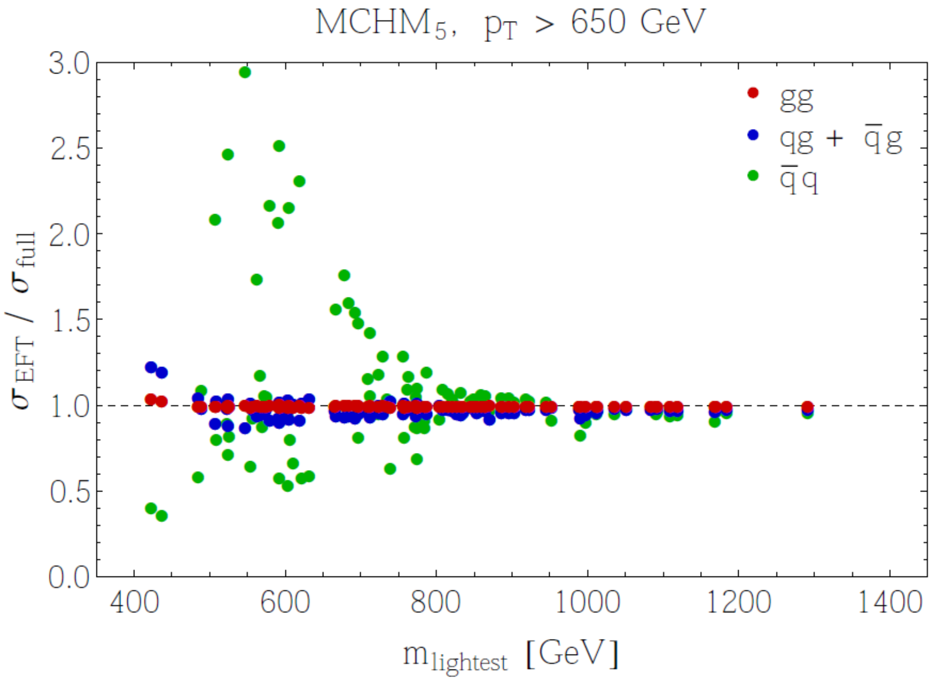
- find a lepton which fails isolation within $\Delta R = 0.4$ cone
- find hardest hadronic track inside cone
- draw small (0.07) tau-candidate cone around this track
- check if lepton passes isolation when removing
  the tau candidate (use only tracker + EM calo)
- if lepton passes, apply standard hadronic tau-tag, ignoring lepton for requirement of tau isolation.

Similarly for two hadronic taus.

See **Katz, Son and Tweedie, Phys.Rev. D83, 2011 (1011.4523)**

Validity of EFT

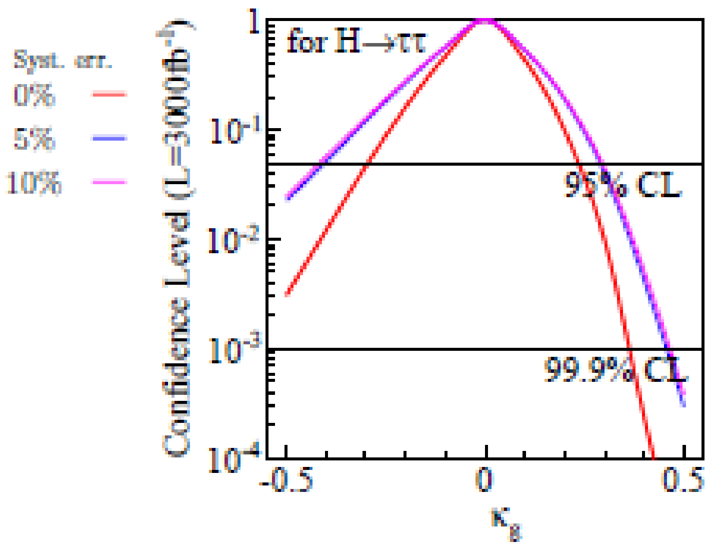




Boosted Higgs shapes

1405.4295

- Collider analysis focusing on $h \to 2\ell + \mathrm{MET}$ via $h \to \tau\tau, WW^*$ and taking into account backgrounds
- Large boost improves the collinear approximation for Higgs mass reconstruction in $h \to \tau\tau$ mode, which does better compared to $h \to WW^*$
- Estimate of capability to distinguish non-SM couplings in presence of backgrounds: assume $\kappa_t + \kappa_g = 1$



- assuming 0% syst. uncertainty, at 95% CL

$$-0.29 < \kappa_g < 0.24$$

- assuming 10% systematics,

$$-0.4 < \kappa_g < 0.3$$

Very boosted Higgs: 14 vs 100 TeV collider

$\sqrt{s}$ [TeV]	$p_T^{\min}$ [GeV]	$\sigma^{SM}_{p_T^{\min}}$ [fb]	δ	ϵ	$gg,\ qg$ [%]	$\tilde{\gamma} \cdot 10^2$	$\tilde{\delta}$	$\tilde{\epsilon}$
14	100	2180	0.0031	0.031	67, 31	2.6	0.033	0.031
	150	837	0.070	0.13	66, 32	1.7	0.094	0.13
	200	351	0.20	0.30	65, 34	0.28	0.22	0.30
	250	157	0.39	0.56	63, 36	0.20	0.41	0.56
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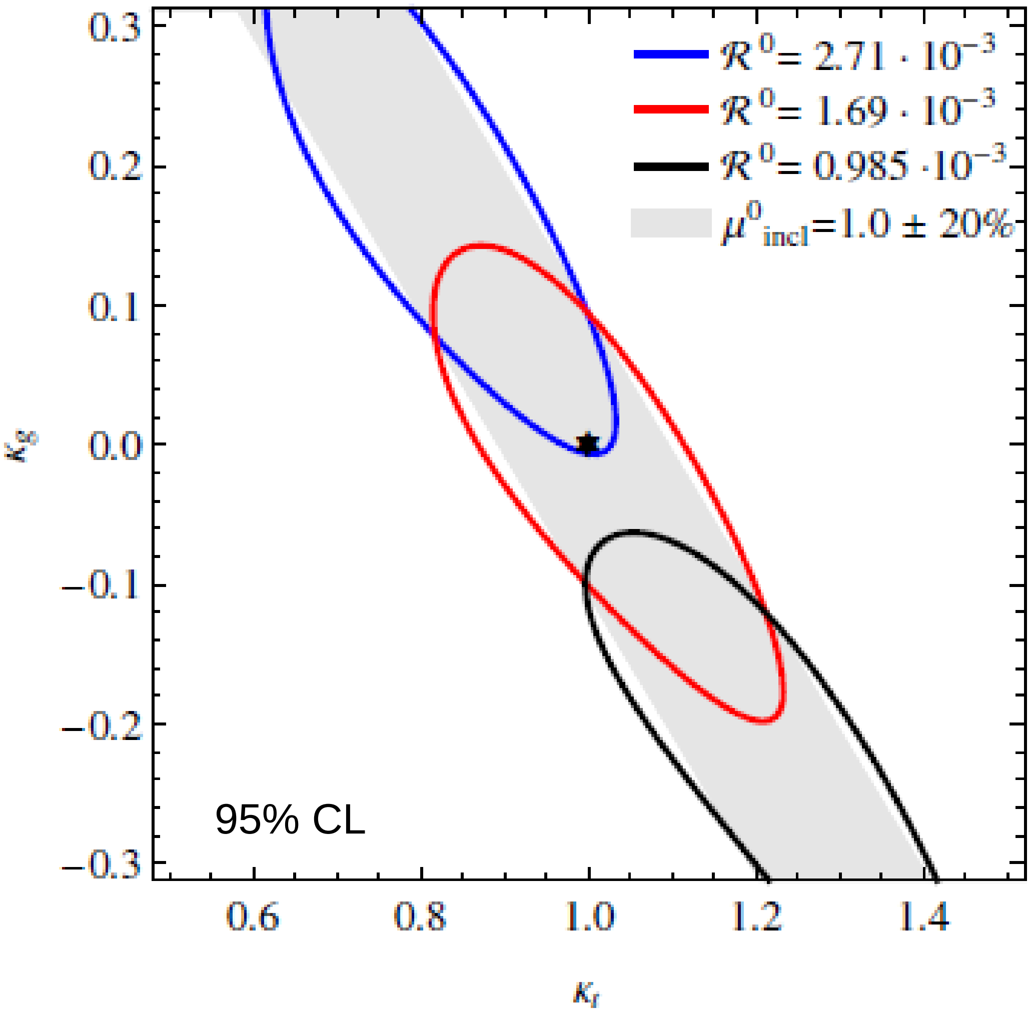
	350	37.7	0.85	1.3	58, 41	2.2	0.91	1.3
	400	19.9	1.1	1.7	56, 43	3.4	1.2	1.7
	450	10.9	1.4	2.3	54, 45	4.6	1.5	2.3
	500	6.24	1.7	2.9	52, 47	5.6	1.8	2.9
	550	3.68	2.0	3.6	50, 49	6.5	2.2	3.6
	600	2.22	2.3	4.4	48, 51	7.3	2.5	4.4
	650	1.38	2.6	5.2	46, 53	7.9	2.9	5.2
	700	0.871	3.0	6.2	45, 54	8.4	3.2	6.2
	750	0.562	3.3	7.2	43, 56	8.8	3.6	7.2
	800	0.368	3.7	8.4	42, 57	9.1	3.9	8.4
100	500	964	1.8	3.1	72, 28	5.0	1.9	3.1
	2000	1.01	14	78	56, 43	7.0	15	78

The rate is ~150 times bigger at a 100 TeV machine!
However, experimental conditions very different. Need separate study

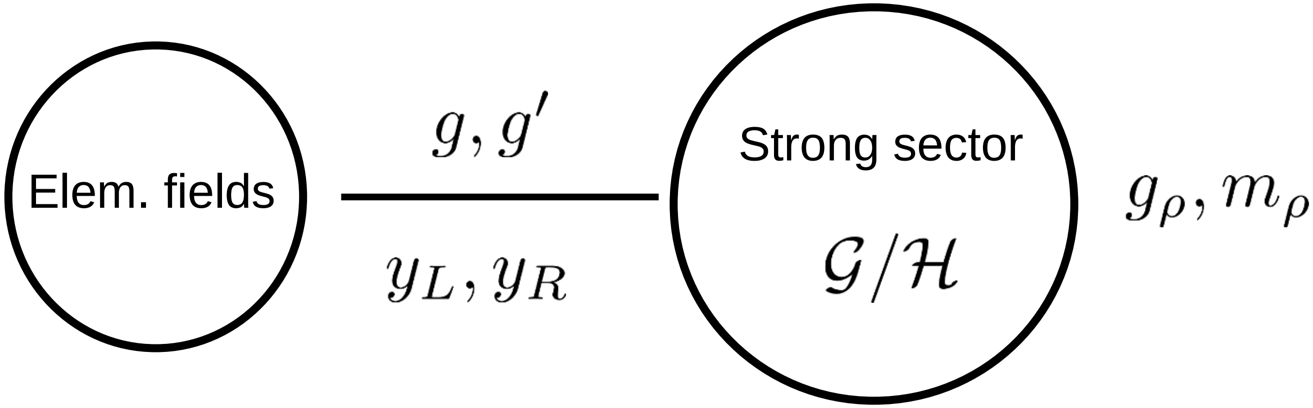
Breaking the degeneracy /2

blue	$\kappa_g = 0.2,\ \kappa_t = 0.8$
red	$\kappa_g = 0,\ \kappa_t = 1$
black	$\kappa_g = -0.2,\ \kappa_t = 1.2$



$$\mu_{\rm incl} = \frac{\sigma(pp\to h+X)}{\sigma(pp\to h+X)_{\rm SM}} \simeq (\kappa_t + \kappa_g)^2$$

The Higgs as a composite p-NGB



- Differently from Technicolor, strong sector does not break EW symmetry directly, but delivers as NGB the Higgs doublet *H.* This in turn acquires a (radiative) potential, and breaks EW symmetry
- Higgs doublet *H* emerges as fully composite pNGB, while SM vectors 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, and similarly for right-handed quarks **Kaplan, 1991**
- So all physical states are *partially composite*

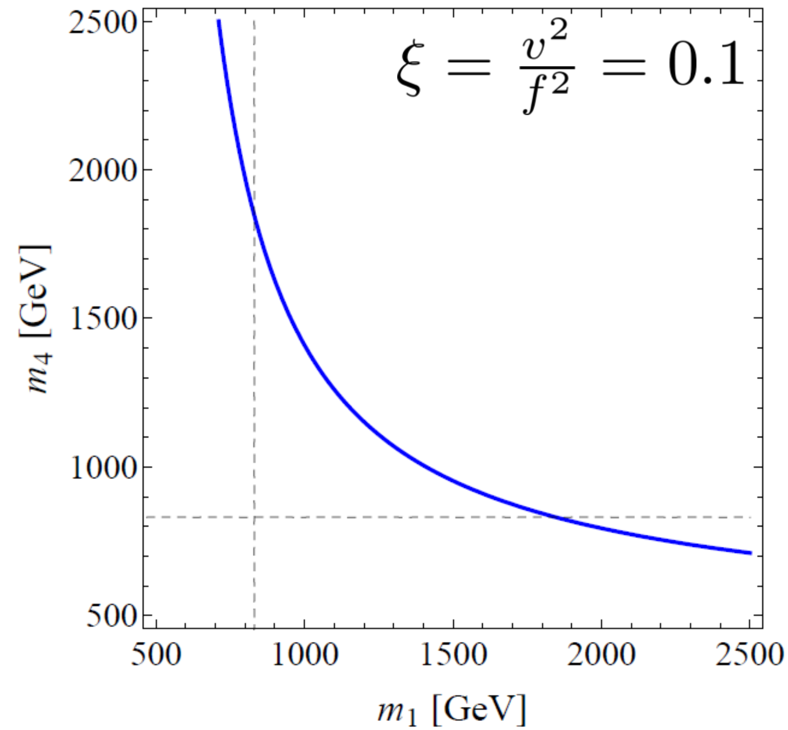
A light Higgs wants light top partners

- Largest breaking of global symmetry associated with top quark
  ➡ Higgs potential typically dominated by loops of top + "top partners"
- Connection between Higgs mass and mass of resonances: e.g., for $\mathcal{G}/\mathcal{H} = SO(5)/SO(4)$ and $q_L, t_R \sim \mathbf{5} = \mathbf{4} \oplus \mathbf{1}$ (MCHM$_5$)

$$m_h^2 \simeq \frac{N_c}{\pi^2} \frac{m_t^2}{f^2} \frac{m_1^2 m_4^2}{m_4^2 - m_1^2} \log \frac{m_4^2}{m_1^2}$$

- For not too large f (mild tuning), at least one resonance multiplet must be light
- Example: for $f \sim 800\,\mathrm{GeV}$ find

$$m_{\text{lightest}} \lesssim 1.2\,\mathrm{TeV}$$



e.g. Matsedonskyi et al., 1204.6333; Pomarol et al., 1205.6434

Insensitivity to top partners of inclusive rate

- The cancellation is general, and follows from partial compositeness structure:

Montull, Riva, ES, Torre, 2013

$$\kappa_t + \kappa_g = v \left(\frac{\partial}{\partial h} \log \det \mathcal{M}_t(h) \right)_{\langle h \rangle}$$

$$\mathcal{L}^t_{\text{mass}} = -\left(\bar{t}_L \quad \overline{\mathbf{C}}_L \right) \overbrace{\begin{pmatrix} 0 & \mathbf{y}_L^T(h) \\ \mathbf{y}_R(h) & \mathbf{M}_c \end{pmatrix}}^{\mathcal{M}_t(h)} \begin{pmatrix} t_R \\ \mathbf{C}_R \end{pmatrix} + \text{h.c.}$$

$$\det \mathcal{M}_t(h) = m_t^0(h) \times \det \mathbf{M}_c \implies \boxed{\kappa_t + \kappa_g = v \left(\frac{\partial}{\partial h} \log m_t^0(h) \right)_{\langle h \rangle}}$$

where m_t^0 is the top mass

Azatov and Galloway, 2011

- In most viable models, m_t^0 generated by *only one SO(4) invariant*

MCHM$_5$ $\quad m_t^0 \propto U_{Ii} (\hat{Q}^\dagger_{t_L})_I (\hat{Q}_{t_R})_J U_{Ji} \sim \sin 2h/f \implies \kappa_t + \kappa_g = \frac{1-2\xi}{\sqrt{1-\xi}}$

Boosted Higgs resolves top partners

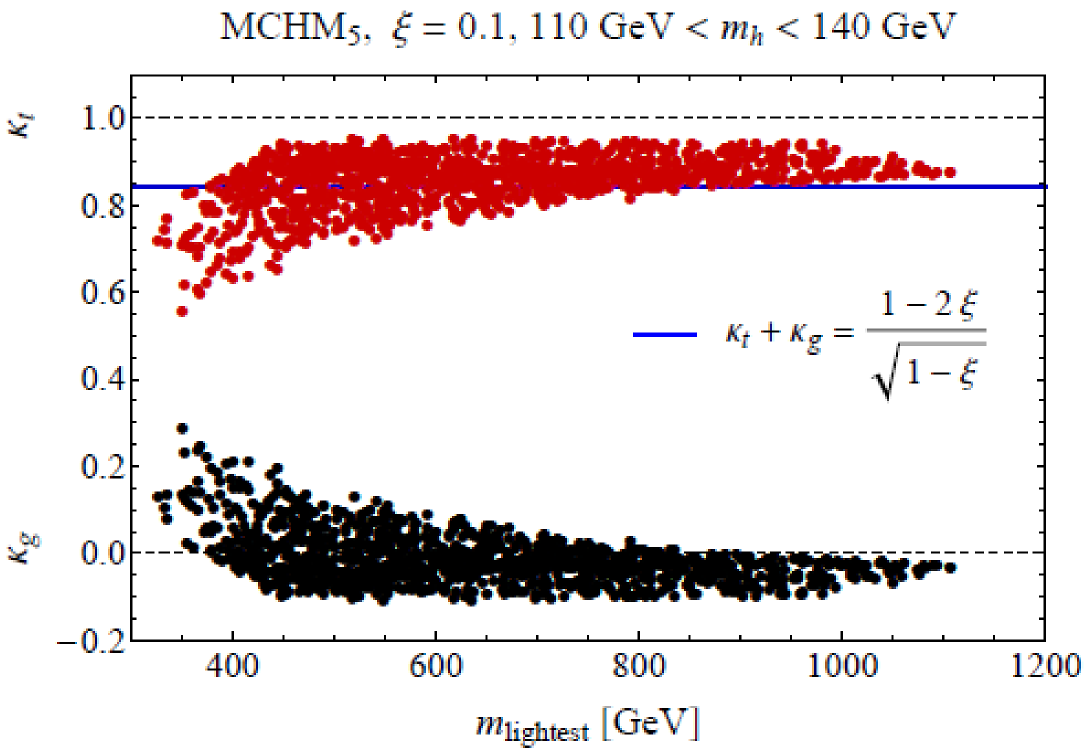
Consider two-site version of MCHM$_5$: $\psi = (\psi_4, \psi_1)^T$ is complete **5** of composites,

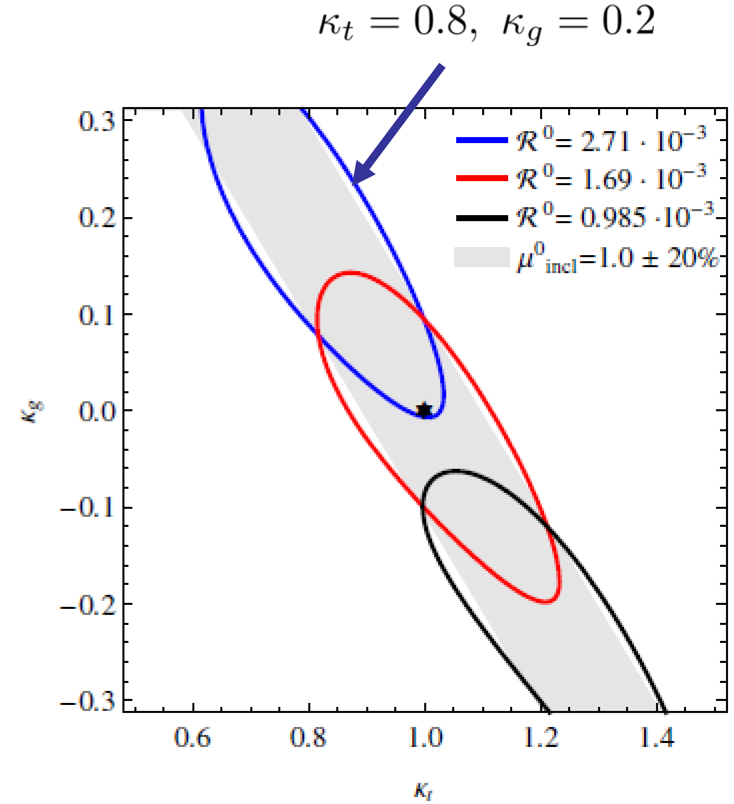
$$\mathcal{L}_f = i\bar{q}_L \not{D} q_L + i\bar{t}_R \not{D} t_R + i\bar{\psi}\not{D}\psi - m_4\overline{\psi}_4\psi_4 - m_1\overline{\psi}_1\psi_1$$
$$- \left(y_L \overline{\mathcal{Q}}_L U^T \psi_R + y_R \overline{\psi}_L U \mathcal{Q}_R + \text{h.c.}\right),$$

Higgs potential has the form

$V(h) \simeq \alpha \sin^2(h/f) + \beta \sin^4(h/f)$, with α divergent and β finite

→ can predict the Higgs mass (not the VEV)





EFT validity

- Current bounds are weak, no interpretation in terms of EFT.

  With increasing precision, important to check validity of the expansion.
- Our analysis neglects dim-8 operators, e.g. corrections to box diagrams

$$c_8 \frac{g_s^2}{16\pi^2 v^4} G_{\mu\nu} G^{\mu\nu} (D_\lambda H)^\dagger D^\lambda H$$

- Fully model-independent results include only interference of dim-6

  operators with SM: **'linear'** analysis, valid up to scale

$$\sqrt{\hat{s}} \sim \sqrt{\frac{c_y\,,\,c_g}{c_8}}\, v$$

  (e.g. for fermionic top partner, ~ mass of the resonance).
- Stronger bounds obtained retaining also terms ~ (dim-6)^2 :

  'nonlinear' analysis, valid provided

$$c_{y,g}^2 \gg c_8$$

  So applicability of the nonlinear bound is model-dependent.

Very boosted Higgs in gluon fusion

Ennio Salvioni

UC Davis

SUSY 2014

University of Manchester

July 25, 2014

based on

1312.3317 (JHEP) *with Grojean, Schlaffer and Weiler*

1406.6338 *with Azatov, Grojean and Paul*