Very boosted Higgs in gluon fusion

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UC Davis

LHC Lunch

October 30, 2013

based on work to appear with:

C.Grojean, M.Schlaffer and A.Weiler

Introduction (of self)

- *Undergraduate and Master’s in* ***Padova (Italy)****.*
- *Ph.D. formally granted from Padova, but have been at* ***CERN*** *almost all the time, advisor C.Grojean.*

  Research on pheno of composite Higgs models: Higgs physics, searches for resonances (‘top partners’, heavy vectors)

Introduction (of self)

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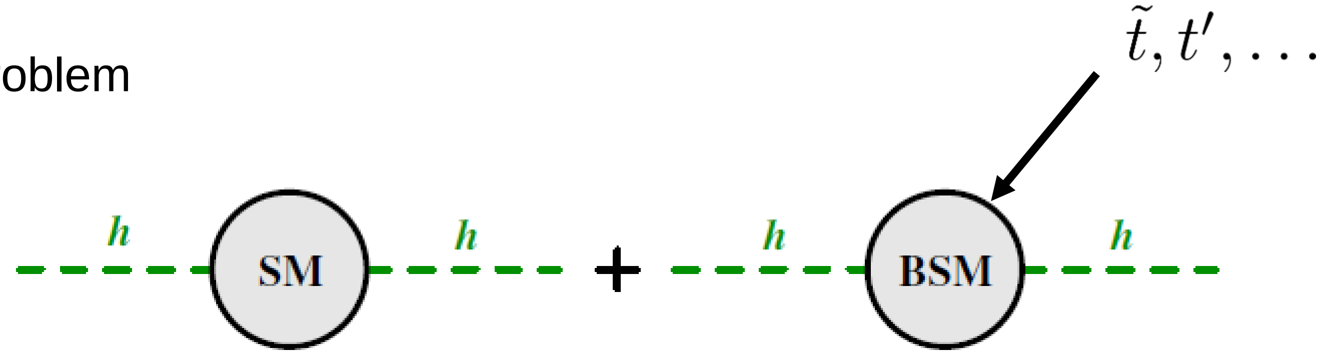
Research on pheno of composite Higgs models: Higgs physics, searches for resonances ('top partners', heavy vectors)

Highlight: celebrating the Higgs discovery

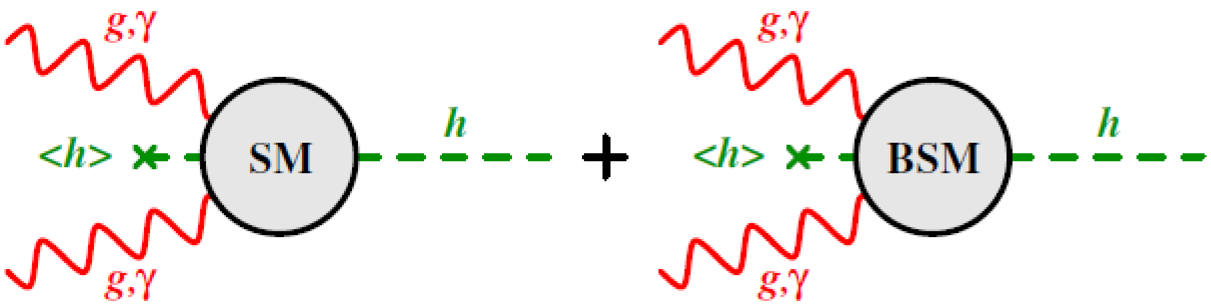
Course de la Marmite, Geneva, December 1st, 2012 (2nd prize for best group costume!)

Introduction of talk

Hierarchy problem



new states charged
under color and EM



Expect deviations in $hgg,\ h\gamma\gamma$ couplings

_e.g._ Low, Rattazzi, Vichi, 0907.5413,
Arvanitaki and Villadoro, 1112.4835

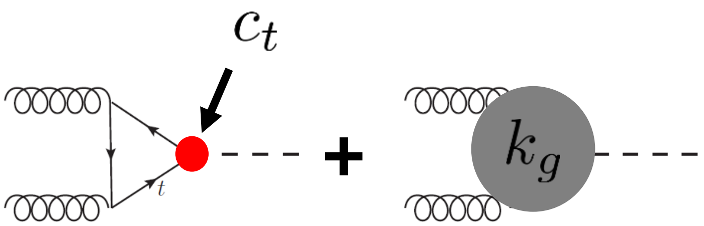
Higgs production via gluon fusion

- Consider parameterization

$$\mathcal{L} = -c_t \frac{m_t}{v} h t \bar{t} + \overbrace{k_g \frac{\alpha_s}{12\pi} \frac{h}{v} G^A_{\mu\nu} G^{A\,\mu\nu}}^{\text{loops of new states}}$$

- For **inclusive production**,

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



(in terms of dimension-6 operators:

$$\mathcal{L} = \mathcal{L}_{\rm SM} + \frac{c_H}{2\Lambda^2} \partial_\mu (H^\dagger H) \partial^\mu (H^\dagger H) + c_y \frac{y_t}{\Lambda^2} H^\dagger H \bar{q}_L \widetilde{H} t_R + \text{h.c.}$$
$$+\; c_g \frac{\alpha_s}{12\pi\Lambda^2} H^\dagger H G^A_{\mu\nu} G^{\mu\nu\,A}$$

➡ $c_t = 1 - \left(\frac{c_H}{2} + c_y\right) \frac{v^2}{\Lambda^2}\,, \qquad k_g = c_g \frac{v^2}{\Lambda^2}$)

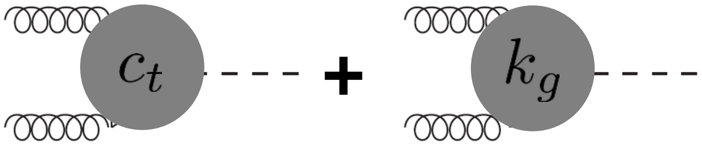
Higgs production via gluon fusion

- Consider parameterization

$$\mathcal{L} = -c_t \frac{m_t}{v} h t\bar{t} + \overbrace{k_g \frac{\alpha_s}{12\pi} \frac{h}{v} G^A_{\mu\nu} G^{A\,\mu\nu}}^{\text{loops of new states}}$$

- For **inclusive production**,

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



also effectively seen as point-like interaction!

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

➡ $$\mu_{\text{incl}} = \frac{\sigma(pp \to h)}{\sigma(pp \to h)_{\text{SM}}} \simeq (c_t + k_g)^2$$

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

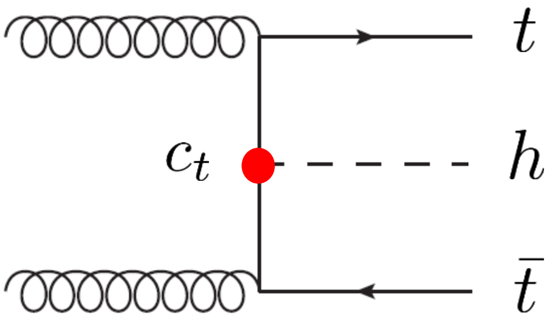
In the SM:

$m_H(\text{GeV})$	$\frac{\sigma_{NLO}(m_t)}{\sigma_{NLO}(m_t \to \infty)}$
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:



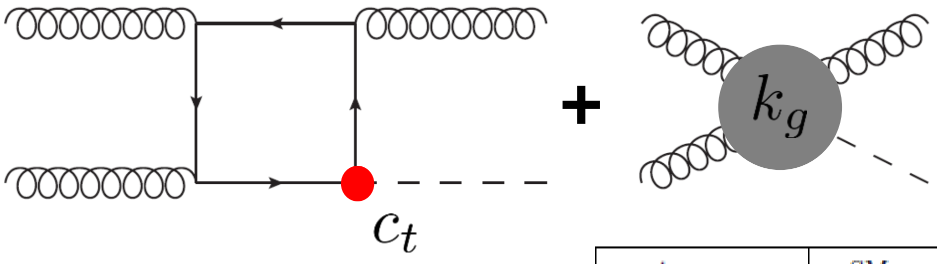
Here I’ll discuss another possibility: (**very) boosted Higgs in gluon fusion**

$$pp \to h + j$$

Very boosted Higgs in gluon fusion

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

$$\frac{\sigma_{p_T^{\min}}(c_t, k_g)}{\sigma^{\rm SM}_{p_T^{\min}}} = (c_t + k_g)^2 + c_t k_g\, \delta + k_g^2\, \theta$$

resolve short-distance *vs* long-distance

p_T^{min} [GeV]	$\sigma^{\rm SM}_{p_T^{min}}$ [fb]	δ	θ
100	2200	0.016	0.023
150	840	0.069	0.13
200	350	0.20	0.31
250	160	0.39	0.56
300	75	0.61	0.89
350	38	0.86	1.3
400	20	1.1	1.8
450	11	1.4	2.3
500	6.3	1.7	2.9
550	3.7	2.0	3.6
600	2.2	2.3	4.4
650	1.4	2.6	5.2
700	0.87	3.0	6.2

see also Azatov and Paul, 1309.5273

Estimate of measurement

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

For boosted measurement, use ratio

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

to reduce theory uncertainty (QCD-NLO corrections to Higgs p_T spectrum are not known for finite m_t)

Assume decay $h \to \tau\tau$, take efficiencies from ‘ditau-jet tagging’ analysis of Katz et al. (1011.4523), based on ‘mutual isolation’ of objects

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

(only first estimate; detailed study in other channels is in progress)

Breaking the degeneracy

Combine measurements using simple procedure:

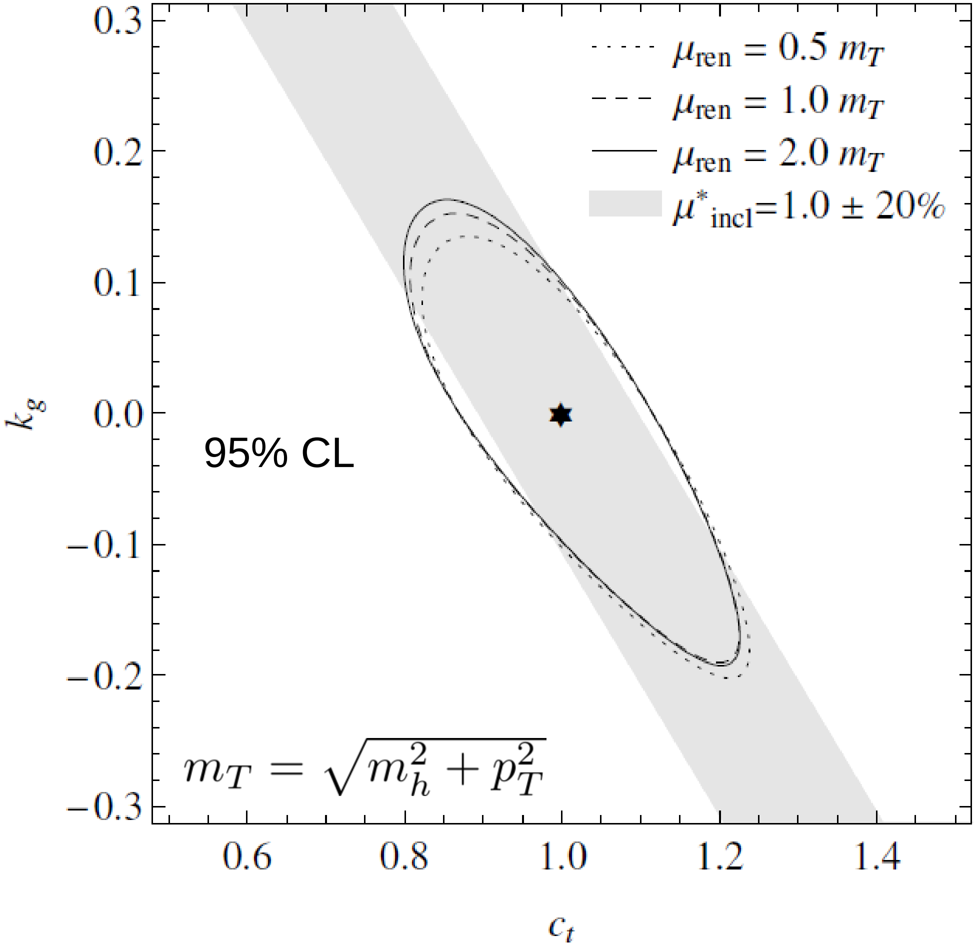
$$\chi^2(c_t, k_g) = \left(\frac{\mathcal{R}(c_t,k_g)-\mathcal{R}^*}{\delta\mathcal{R}}\right)^2 + \left(\frac{\mu_{\mathrm{incl}}(c_t,k_g)-\mu^*_{\mathrm{incl}}}{\delta\mu_{\mathrm{incl}}}\right)^2$$

assuming 10% syst uncertainty

on all measurements **+** stat uncertainty

on $N_{\mathrm{events}}^{p_T>650\,\mathrm{GeV}},\ N_{\mathrm{events}}^{p_T>150\,\mathrm{GeV}}$

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



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

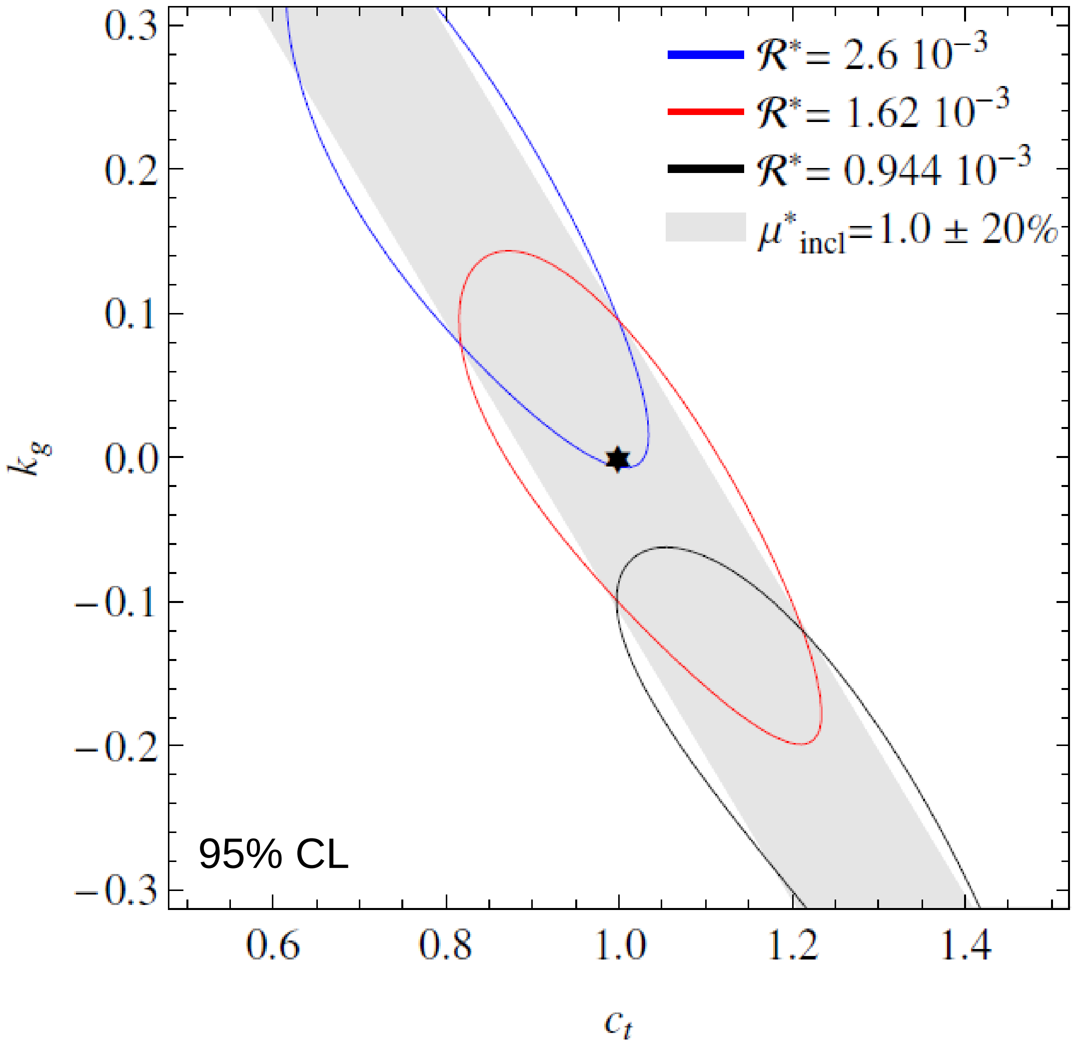
$$\mu_{\mathrm{incl}} = \frac{\sigma(pp\to h+X)}{\sigma(pp\to h+X)_{\mathrm{SM}}} \simeq (c_t + k_g)^2$$

Breaking the degeneracy /2

blue $k_g = 0.2,\ c_t = 0.8$

red $k_g = 0,\ c_t = 1$

black $k_g = -0.2,\ c_t = 1.2$



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

Explicit models

1) Higgs as a composite pseudo-Goldstone boson

2) Supersymmetry

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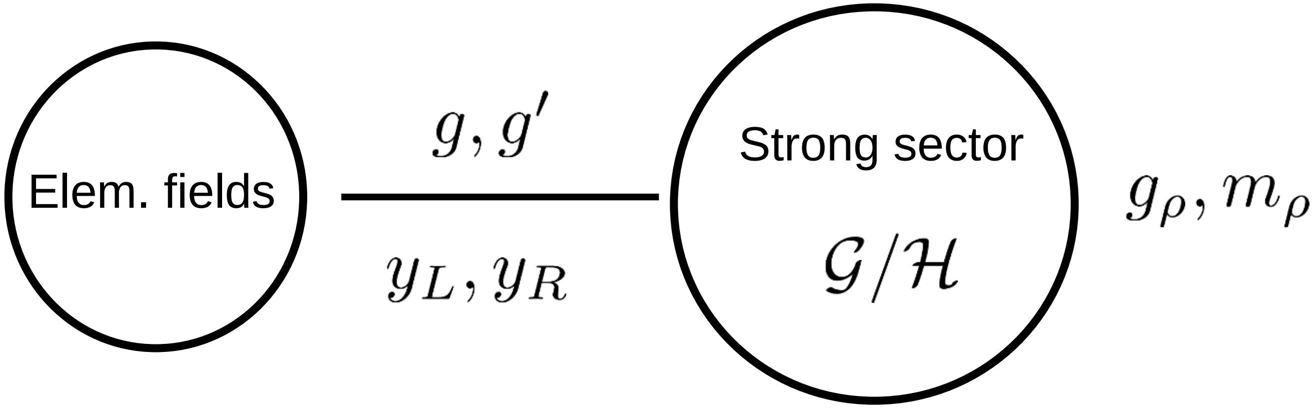
The Higgs as a composite p-NGB



- 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 $SU(2)_L \times U(1)_Y \subset \mathcal{H}$

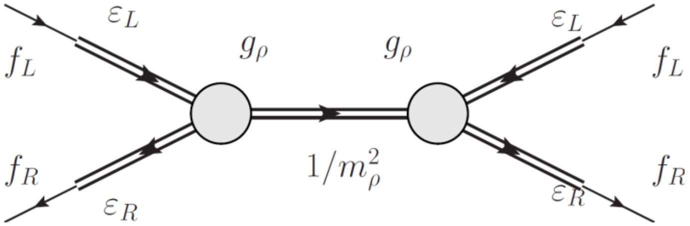
  ➡ linear couplings to currents $\mathcal{L}^g_{UV} = g_{el} W^{el}_\mu J^\mu_{cmp}$
- Similarly for fermions: write $\mathcal{L}^f_{UV} = y_L \bar{q}_L \mathcal{O}$ with $\mathcal{O}$ fermionic composite operator, and similarly for right-handed quarks

Kaplan, 1991

- So all physical states are *partially composite*

The Higgs as a composite p-NGB/2

- SM fermion mass $m_f \sim g_\rho \frac{y_L}{g_\rho}\frac{y_R}{g_\rho} v$ ⇒ for flavor-anarchic strong sector, light quarks mostly elementary; third generation sizably composite
- Partial compositeness gives an attractive flavor picture: "RS-GIM" mechanism, FCNC's suppressed by small mixings: $\left(\epsilon_{L,R} = \frac{y_{L,R}}{g_\rho}\right)$



$$\sim \epsilon_L^i \epsilon_R^j \epsilon_L^k \epsilon_R^l \frac{g_\rho^2}{m_\rho^2}\left(\bar{f}_L^i f_R^j \bar{f}_L^k f_R^l\right) ,$$

(some tension remains, in particular in Kaon mixing)

Csaki, Falkowski and Weiler, 0804.1954

- Only breaking of the global symmetry comes from couplings to elementary states ⇒ one-loop Higgs potential, form essentially dictated by structure of linear mixings
- Naive expectation is $v \sim f \equiv m_\rho/g_\rho$; need mild tuning to obtain $v \ll f$, as required by the S parameter: $\widehat{S} \sim m_W^2/m_\rho^2$
$v^2/f^2 \sim 0.1$ is enough (tuning of ~10%)

A light Higgs wants light top partners

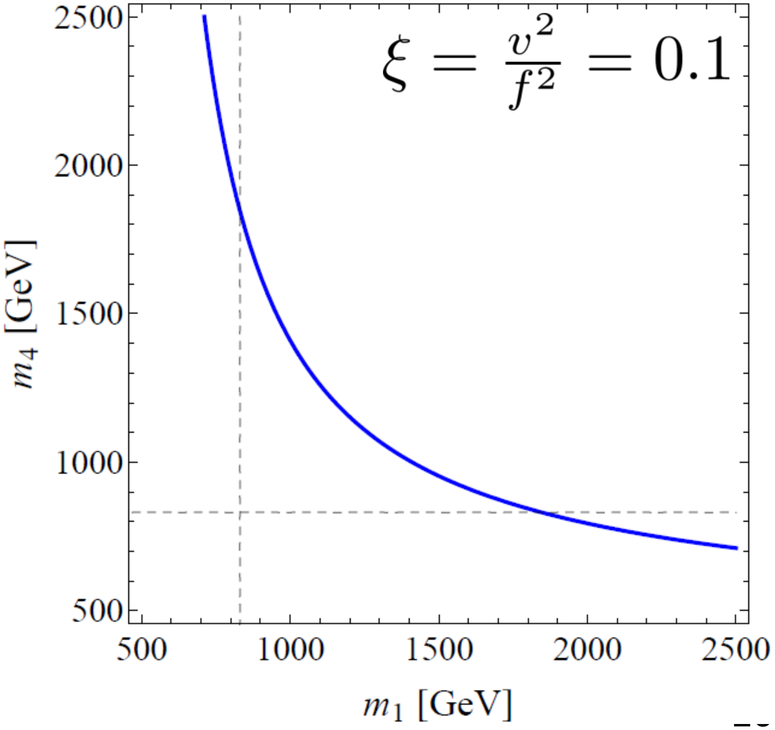
- Largest breaking of global symmetry associated with top quark

  ➡ Higgs potential typically dominated by loops of top + "top partners"

- Connection between Higgs mass and mass of resonances: e.g., for $\mathcal{G}/\mathcal{H} = SO(5)/SO(4)$ (MCHM) and $q_L, t_R \sim \mathbf{5} = \mathbf{4} \oplus \mathbf{1}$

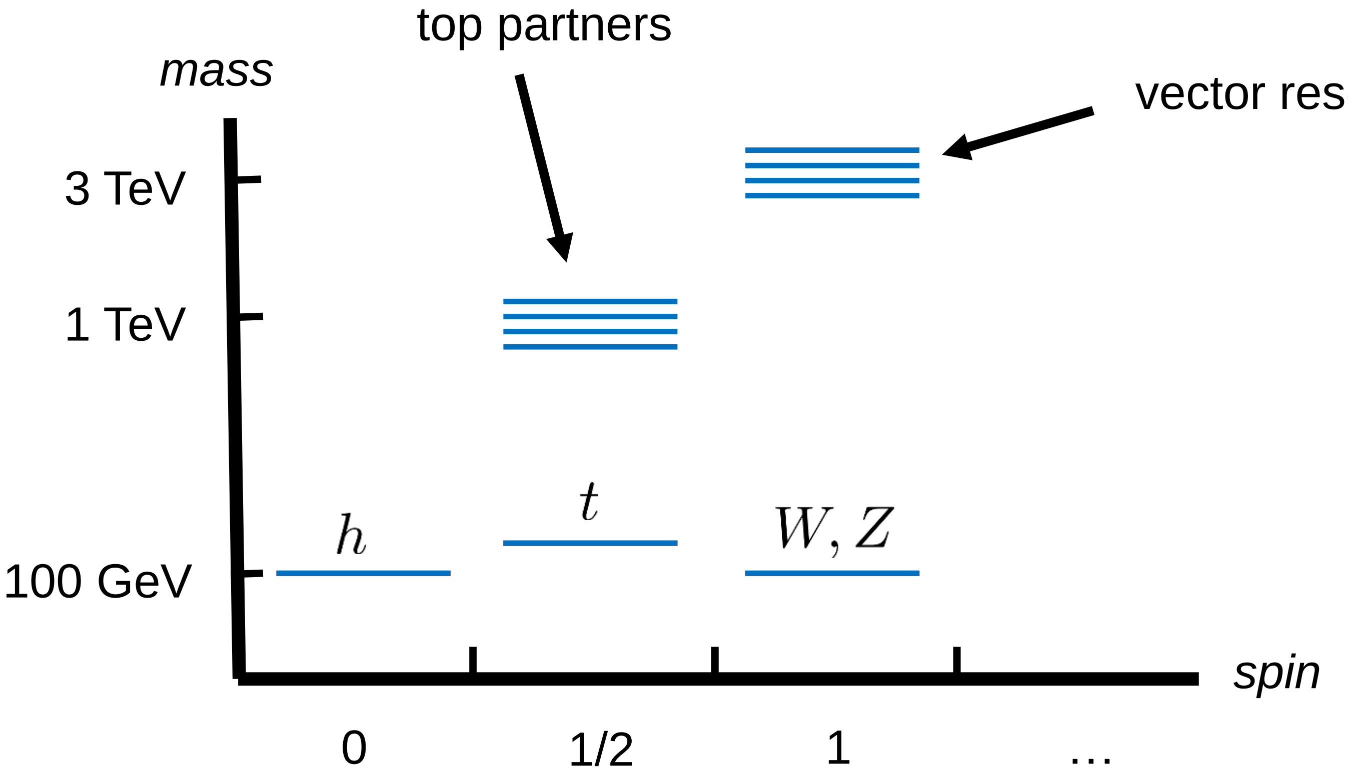
$$m_h^2 \simeq \frac{N_c}{\pi^2}\frac{m_t^2}{f^2}\frac{m_1^2 m_4^2}{m_4^2 - m_1^2}\log\frac{m_4^2}{m_1^2}$$

- For not too large f (mild tuning), at least one resonance multiplet must be light
- Example: for $f \sim 800\,\mathrm{GeV}$ find $m_{\mathrm{lightest}} \lesssim 1.2\,\mathrm{TeV}$



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

Sketch of the expected spectrum



Loop-induced Higgs couplings

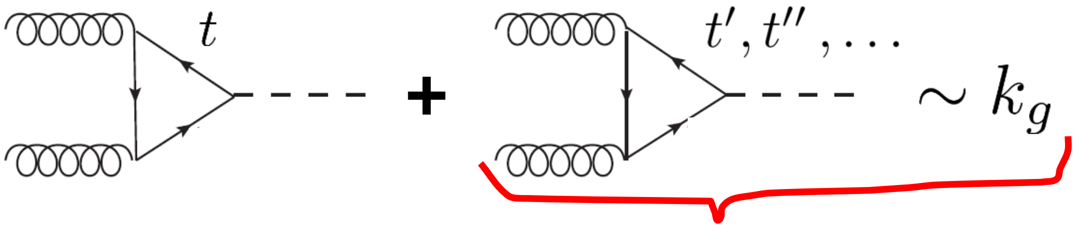
- Contribution of resonances to loop-induced couplings encoded by ops. of the form $H^\dagger H G^A_{\mu\nu} G^{\mu\nu\, A}$: break shift symmetry, extra-suppressed by powers of $g_{\rm SM}/g_\rho$.

Giudice et al., hep-ph/0703164

- Naively, for light top partners ($g_\rho \sim g_{\rm SM}$) effects should be important.
- However, it turns out that loops of resonances cancel out against corrections to $ht\bar{t}$ coupling

Falkowski, 0711.0828; Low & Vichi, 1010.2753
Azatov & Galloway, 1110.5646

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



$\sim k_g$

- MCHM$_5$:

$$c_t = \frac{1}{\sqrt{1-\xi}}\left[1 - 2\xi + \overbrace{\xi(1-\xi)\left(\frac{1}{m_1^2} - \frac{1}{m_4^2}\right)\left(y_R^2 - \frac{y_L^2}{2}\right) + O(\epsilon^4)}^{\text{they cancel out at all orders in } \epsilon}\right]$$

$$\Rightarrow \boxed{\frac{g_{hgg}}{g_{hgg}^{\rm SM}} = c_t + k_g = \frac{1}{\sqrt{1-\xi}}\left[1 - 2\xi\right]}$$

insensitive to top partners

Insensitivity to top partners of inclusive rate

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

Montull, Riva, ES, Torre, 2013

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

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

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

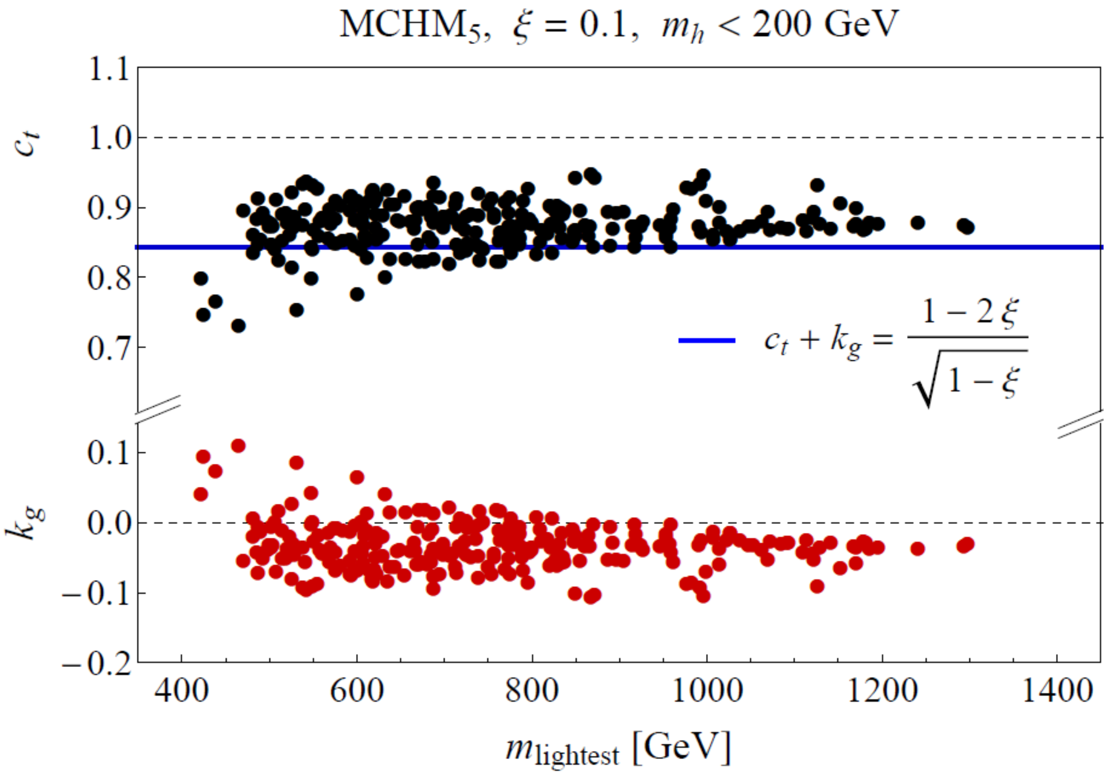
where m_t^0 is the top mass

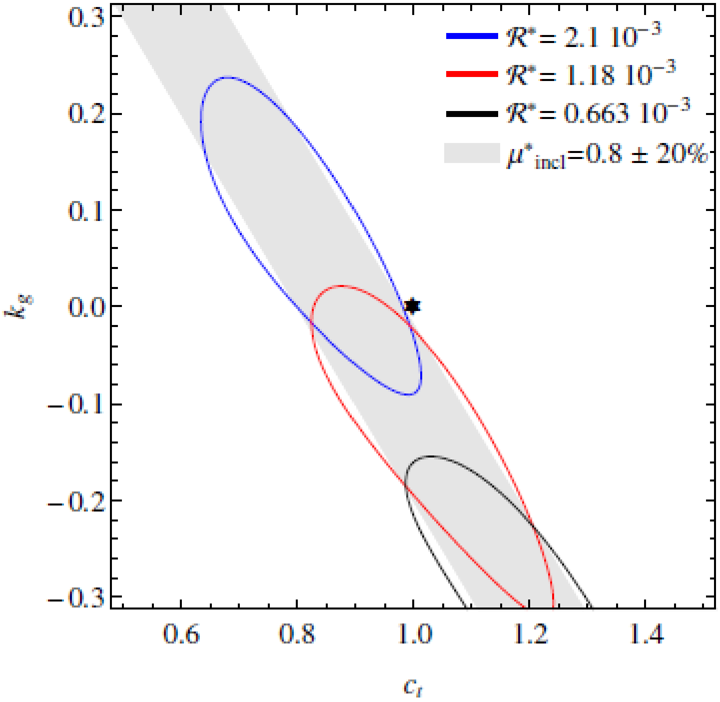
Azatov and Galloway, 2011

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

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

Boosted Higgs resolves top partners





$$k_g = \xi \sin^2\theta_R \left(\frac{m_1^2 - m_4^2}{m_4^2}\right) + O(\sin^2\theta_L)\,,$$

Delaunay et al., 2013

Explicit models

1) Higgs as a composite pseudo-Goldstone boson

2) Supersymmetry

Supersymmetry

Top + stops give

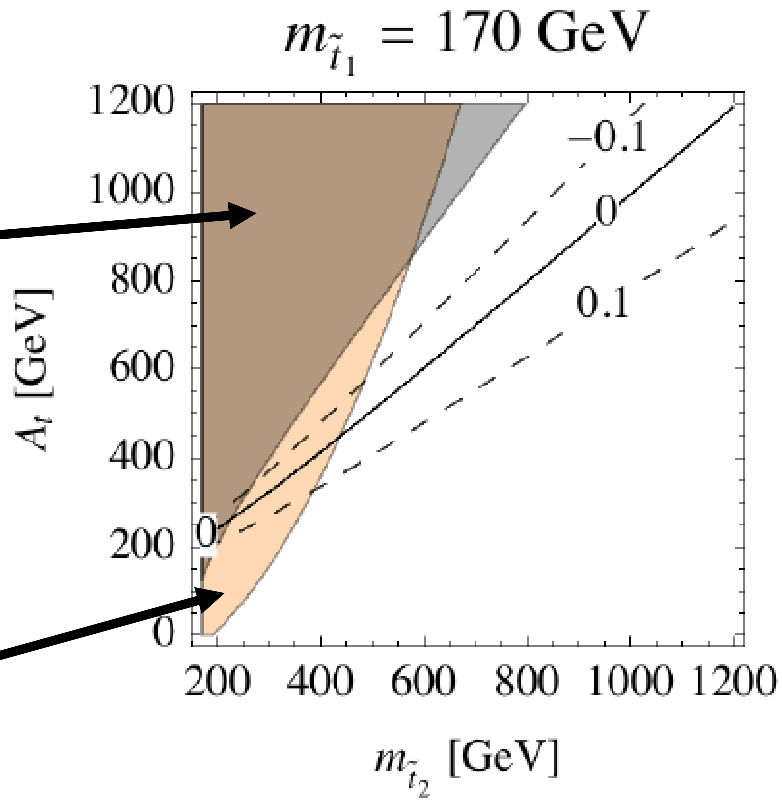
$$\frac{\sigma(pp\to h)}{\sigma(pp\to h)_{\rm SM}} = (1+\Delta_t)^2$$

$$\Delta_t \simeq \frac{m_t^2}{4}\left(\frac{1}{m_{\tilde t_1}^2}+\frac{1}{m_{\tilde t_2}^2}-\frac{(A_t-\mu/\tan\beta)^2}{m_{\tilde t_1}^2\, m_{\tilde t_2}^2}\right)$$

Flat direction for large enough A_t

electric charge and color breaking vacua

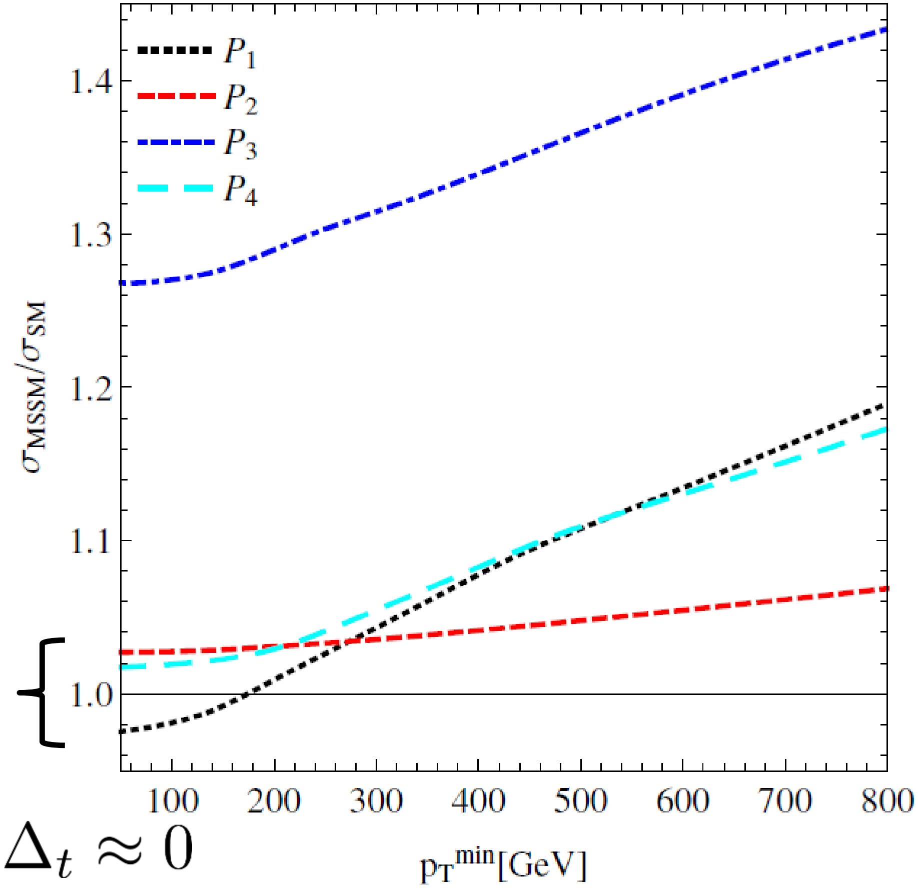
$$A_t^2+3\mu^2 \lesssim a\,(m_{\tilde t_1}^2+m_{\tilde t_2}^2)$$



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



$\Delta_t \approx 0$

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	259	1212	0	0.12
P_4	226	484	532	0.015

boosted Higgs breaks degeneracy

Conclusions

- Degeneracy between long-distance and short-distance contribution in inclusive Higgs production rate
- Boosted regime in gluon fusion can resolve the degeneracy.

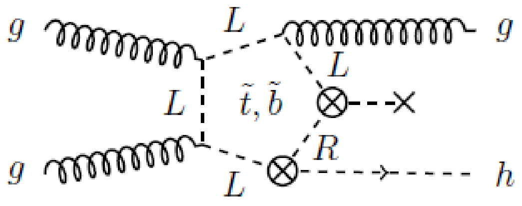
  Interesting complement to ‘standard’ process $pp \to t\bar{t}h$

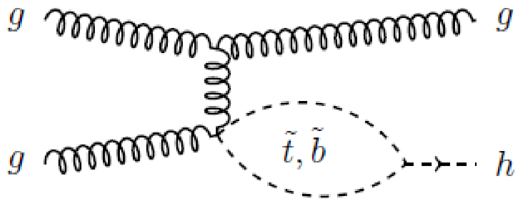
- We looked at $h \to \tau\tau$ decay channel just as a first estimate.

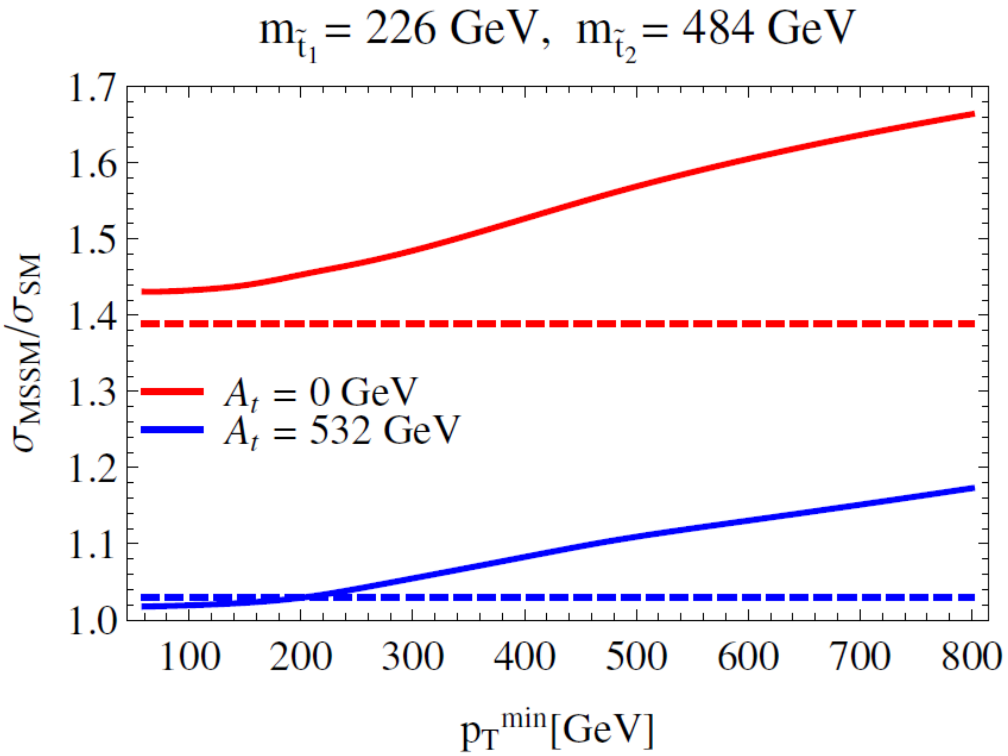
  Detailed study of phenomenology is in progress.

- Application is particularly interesting in models where the Higgs is a composite pseudo-Goldstone: inclusive rate is insensitive to resonances, boosted Higgs can resolve them
- Works also for light and mixed stops in SUSY.

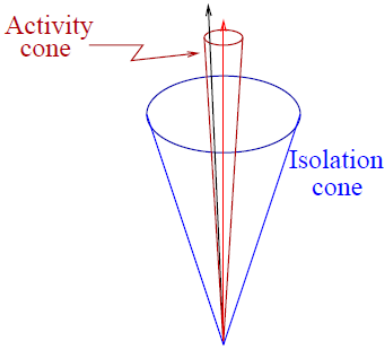
Backup


g
L
g
L
L
$\tilde{t}, \tilde{b}$
L
R
g
L
h


g
g
g
$\tilde{t}, \tilde{b}$
h


$m_{\tilde{t}_1} = 226$ GeV, $m_{\tilde{t}_2} = 484$ GeV
$\sigma_{\mathrm{MSSM}}/\sigma_{\mathrm{SM}}$
1.7
1.6
1.5
1.4
1.3
1.2
1.1
1.0
$A_t = 0$ GeV
$A_t = 532$ GeV
100
200
300
400
500
600
700
800
p_T^{min}[GeV]

‘Ditau-jet’ tagging

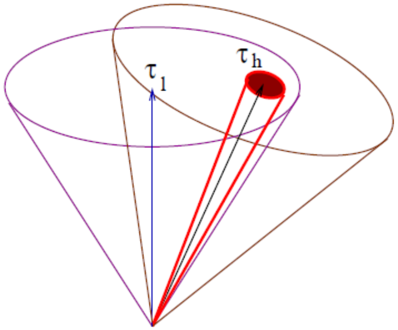


For $p_T = 650\,\mathrm{GeV}$, the taus have typical angular separation

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

Introduce ‘mutual isolation’.

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

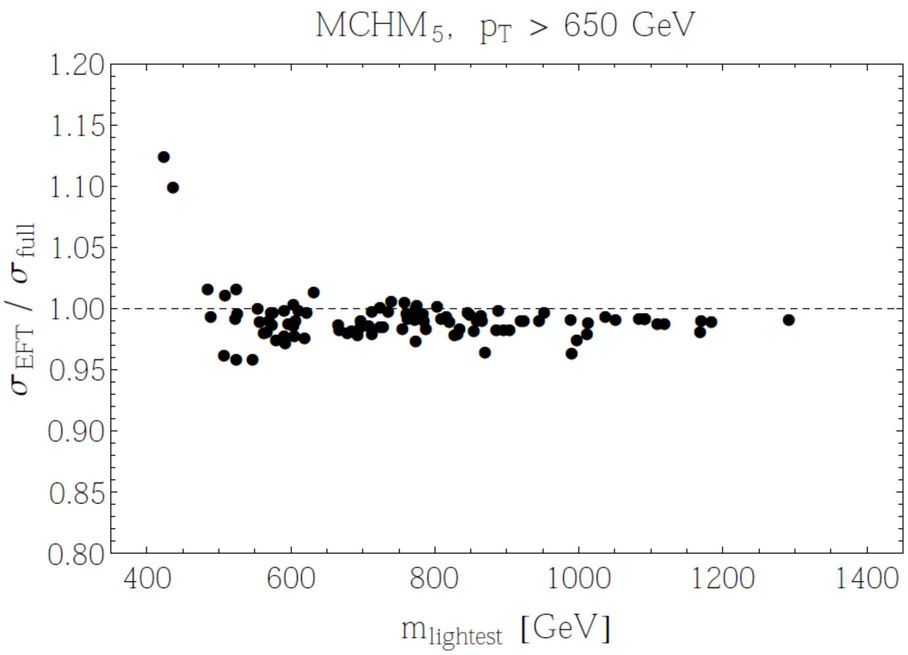


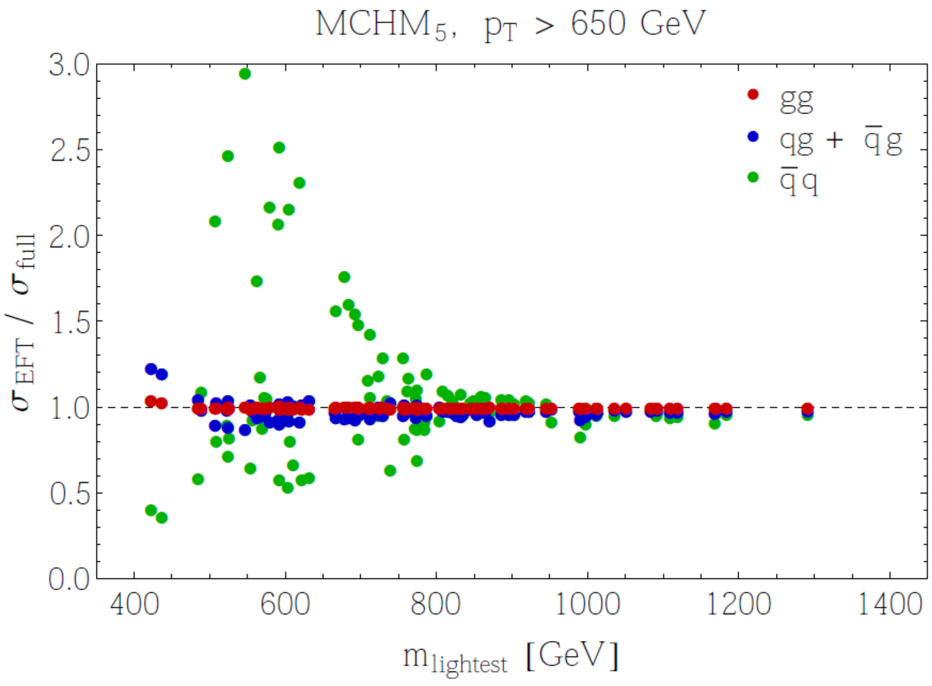
- find a lepton which fails isolation within $\Delta R = 0.4$ cone
- find hardest hadronic track inside cone
- draw small (0.07) tau-candidate cone around this track
- check if lepton passes isolation when removing the tau candidate (use only tracker + EM calo)
- if lepton passes, apply standard hadronic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





Gluon fusion in the MCHM, summary

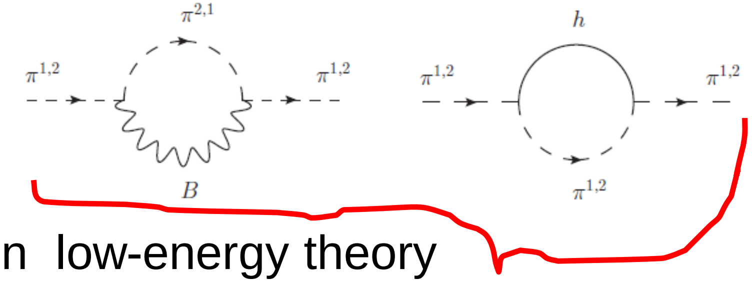
$$c_g^{(t)} = 1 - \Delta_g^{(t)}(y_r/y_{r'})\,\xi + \mathcal{O}(\xi^2)$$

$$y_r \equiv \sum_{i=1}^{n_r} \frac{F^L_{r(i)} F^R_{r(i)}}{M_{r(i)}}$$

$Q_L \setminus Q_R$	**1**	**5**	**10**	**14**
5	$1/2$	$3/2$	$1/2$	$\frac{5}{2}\,\frac{1-\frac{24}{25}\frac{y_1}{y_4}}{1-\frac{4}{5}\frac{y_1}{y_4}}$
10	$\times$	$1/2$	$3/2$	$3/2$
14	$3/2$	$\frac{9}{2}\,\frac{1-\frac{10}{9}\frac{y_1}{y_4}}{1-2\frac{y_1}{y_4}}$	$3/2$	$\frac{11}{2}\,\frac{1-\frac{64}{55}\frac{y_1}{y_4}-\frac{6}{11}\frac{y_9}{y_4}}{1-\frac{8}{5}\frac{y_1}{y_4}}$

Montull, Riva, ES, Torre, 2013

Electroweak precision tests



BSM contributions to ϵ_i, ϵ_b parameters:

- Modified coupling of the Higgs to gauge bosons

➡ contribution to $\epsilon_{1,3} \sim \widehat{T}, \widehat{S}$ calculable within low-energy theory

$$\Delta\epsilon_3^{\mathrm{IR}} = \frac{\alpha}{24\pi \sin^2\theta_W}(1-a^2)\log\frac{\Lambda}{m_h}\,, \qquad \Delta\epsilon_1^{\mathrm{IR}} = -\frac{3\,\alpha}{8\pi\cos^2\theta_W}(1-a^2)\log\frac{\Lambda}{m_h}$$

Barbieri et al., 0706.0432

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

$$\Delta\epsilon_3^{\mathrm{UV}} \simeq \frac{m_W^2}{m_\rho^2}$$

- 1-loop contributions to T

and $\epsilon_b \sim Z\text{-}b_L\text{-}\bar{b}_L$ from heavy fermions

Notice that 1-loop contribution to *S* is also important in general, see Matsedonskyi et al., 1306.4655

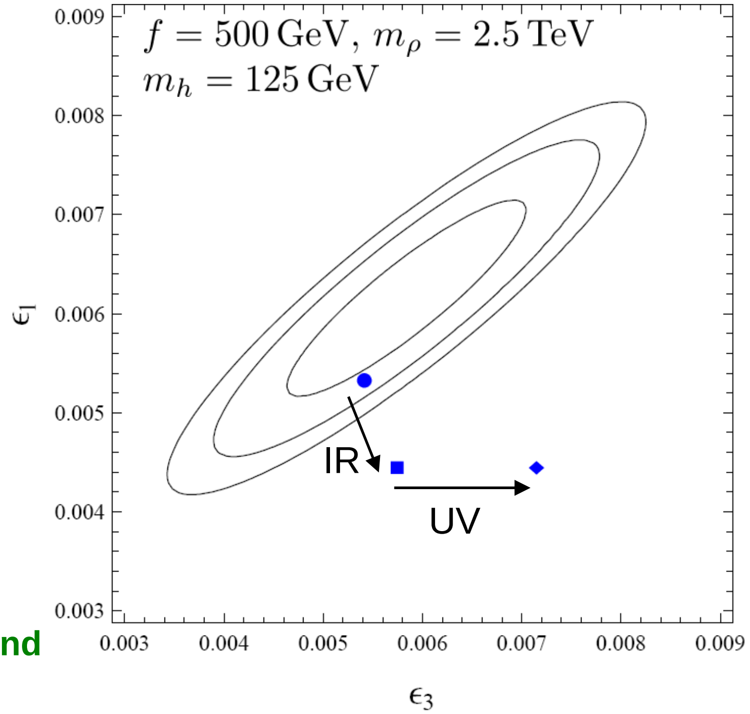
In general need a **positive contribution to** T

to get back into the ellipse, but at the same time

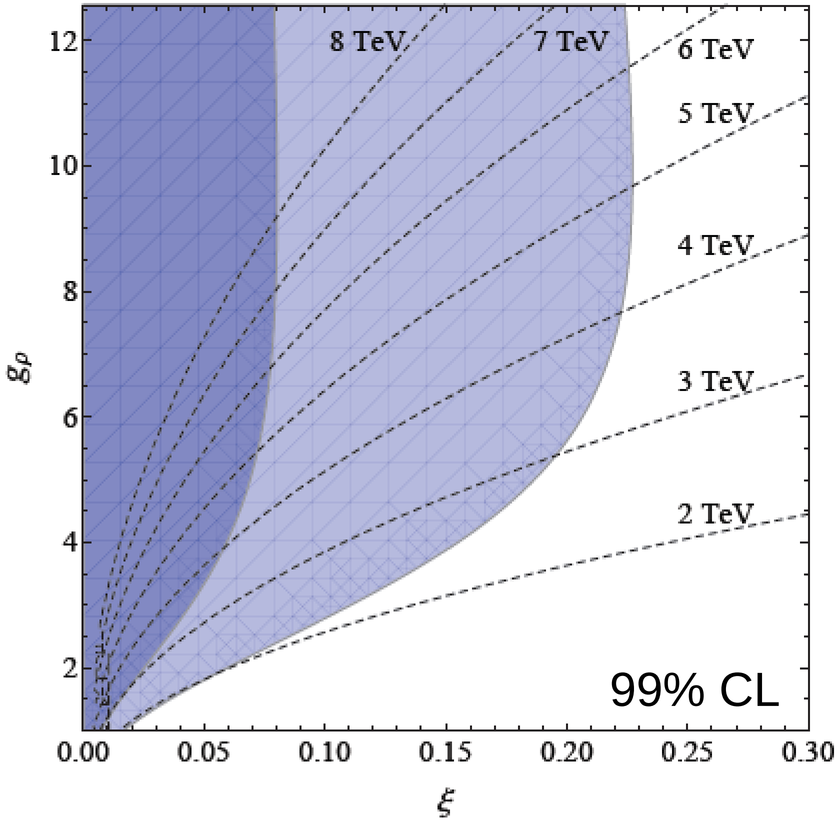
need to control correction to ϵ_b

➡ non-trivial interplay

Gillioz, 0806.3450
Anastasiou, Furlan and Santiago, 0901.2117



Electroweak precision tests /2



$$a = \sqrt{1-\xi}, \quad \Lambda = m_\rho = g_\rho v/\sqrt{\xi}$$

light blue: region allowed assuming an extra $\Delta\widehat{T} = +10^{-3}$