Top/Higgs coupling

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Outline

- top + Higgs in the SM → near-criticality
- top + Higgs naturalness → BSM near the TeV scale
- LHC probes of the top-Higgs coupling

Q: why top quark is so special?

A: because it's heavy!

see A.Weiler's talk

- *experimentally:* heavy top does not hadronize $\Gamma_{top} \gg \Lambda_{QCD}$
  - measure top spin → spin-spin correlation in t-tbar
  - measure top chirality if boosted from BSM decay

    is new physics more coupled to t_L or t_R?

- *theoretically:* heavy top destabilizes the weak scale

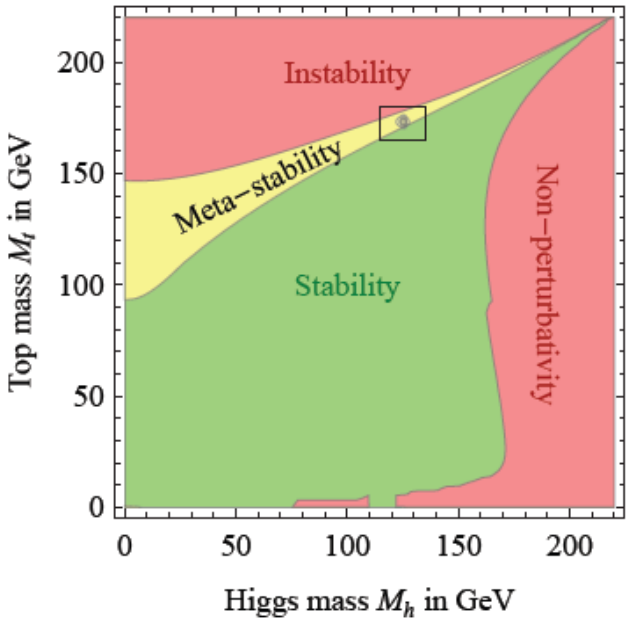
both features have common origin:
top couples with $o(1)$ strength
to electroweak symmetry breaking sector

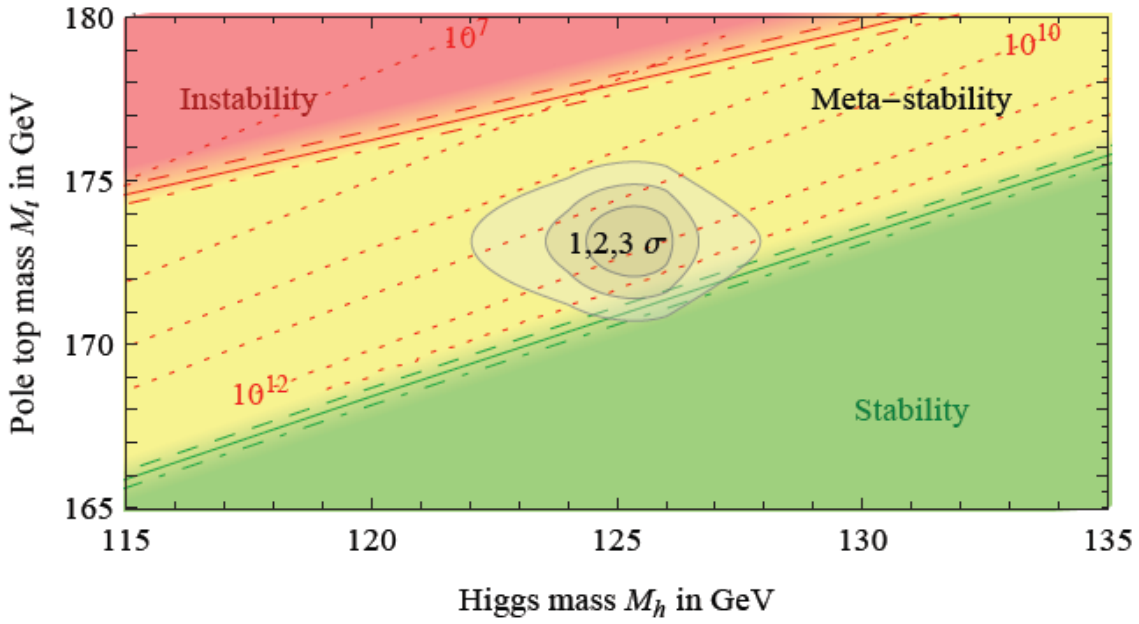
Top and Higgs in the SM

Top+Higgs near-criticality:

assume SM valid up to very high energies $E \gg m_Z$:

Degrassi et al. '12

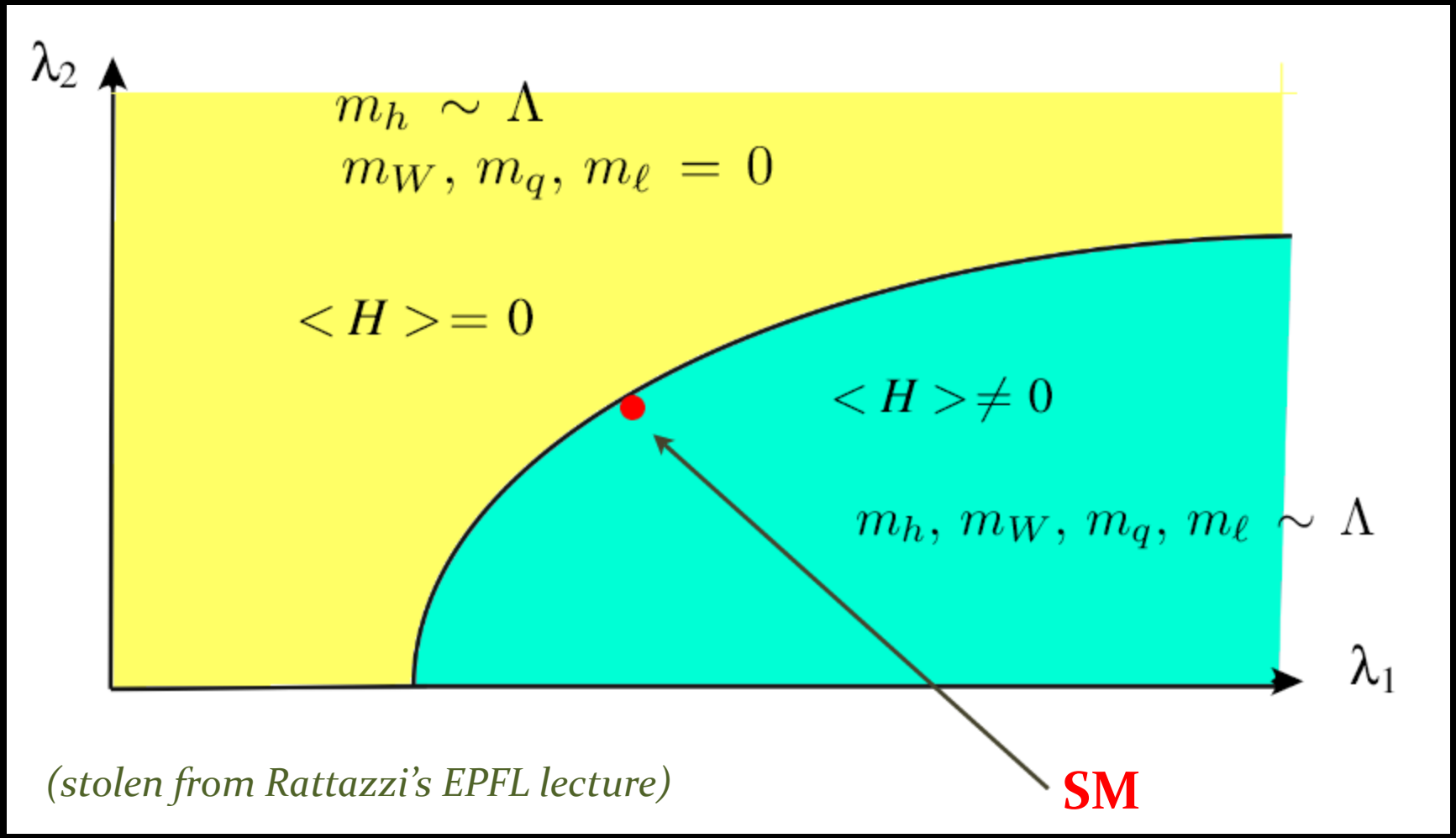




Higgs quartic turns negative at $\Lambda \approx 10^{11}$GeV: $d\lambda/d\log\mu \propto -N_c\, y_t^4/16\pi^2$

had y_{top} been ~3% larger, we would not be here...

another well-known Higgs near-criticality:



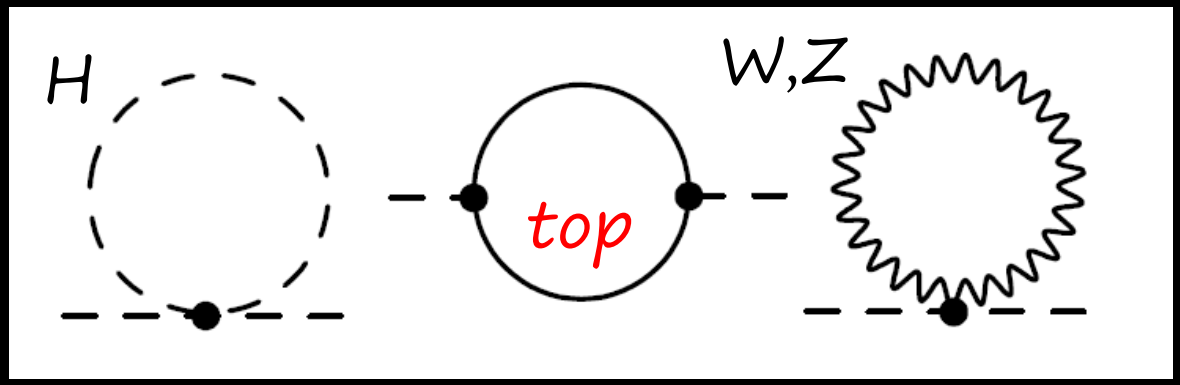
(stolen from Rattazzi's EPFL lecture)

$V(h)=m^2h^2+\lambda h^4$

a sketch of the hierarchy problem

Top, Higgs and naturalness

Q: what makes the observed SM-like Higgs so light?

$\delta m^2 =$ 

$\sim \frac{\Lambda^2}{16\pi^2}$

What's Λ? natural theory if $\delta m^2 \sim m^2 \rightarrow \Lambda \sim$ TeV

If nothing but gravity $\rightarrow \Lambda = M_{Pl} \sim 10^{19}$ GeV = *hierarchy problem*

2 ***new physics*** paths:

- $\Lambda \sim M_{Pl}$ but there's a new symmetry above the TeV scale
  e.g. supersymmetry
- SM fields couple to a new strong dynamics with $\Lambda \sim$ TeV
  e.g. composite Higgs models

be it weakly or strongly coupled,
natural BSM theories have
top partners < 1 TeV
to soften the UV sensitivity of the Higgs mass

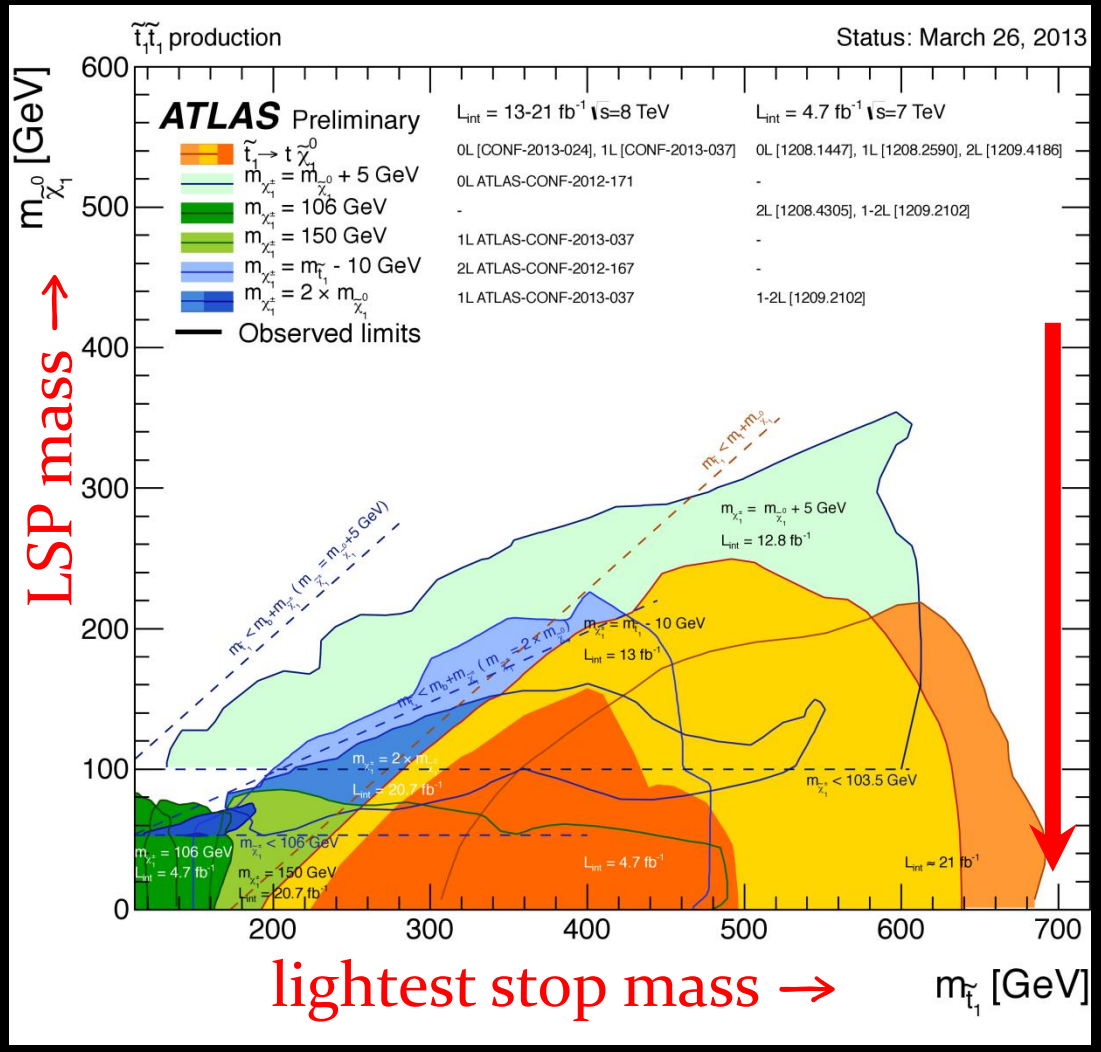
SUSY → light stops

Barbieri-Giudice '88,..., Papucci-Ruderman-Weiler '11

current limits are rather strong:

$m_{stop} > \sim 700 GeV$

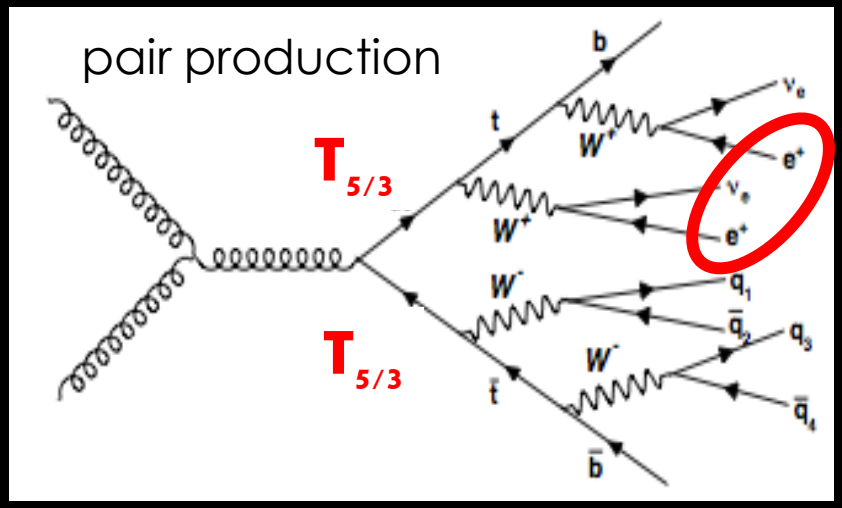
unless *e.g.* spectrum is compressed $m_{stop} \sim m_{top}$

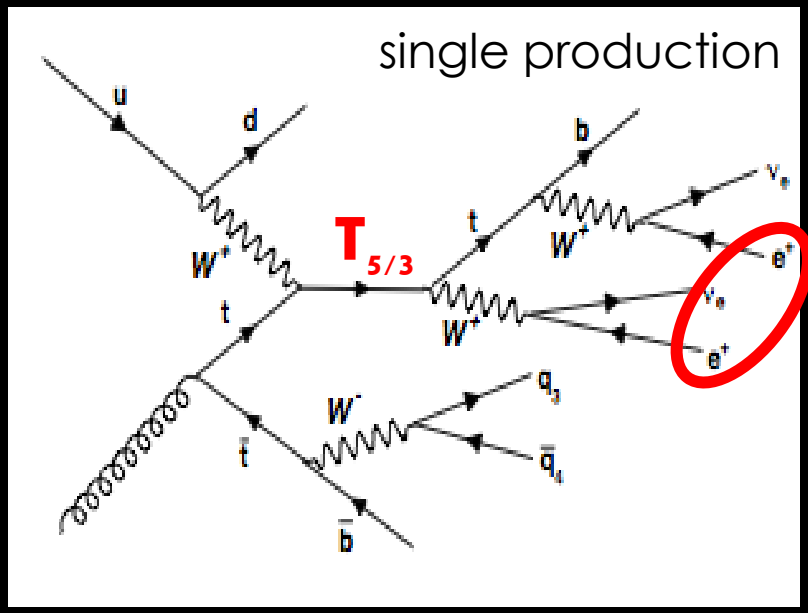


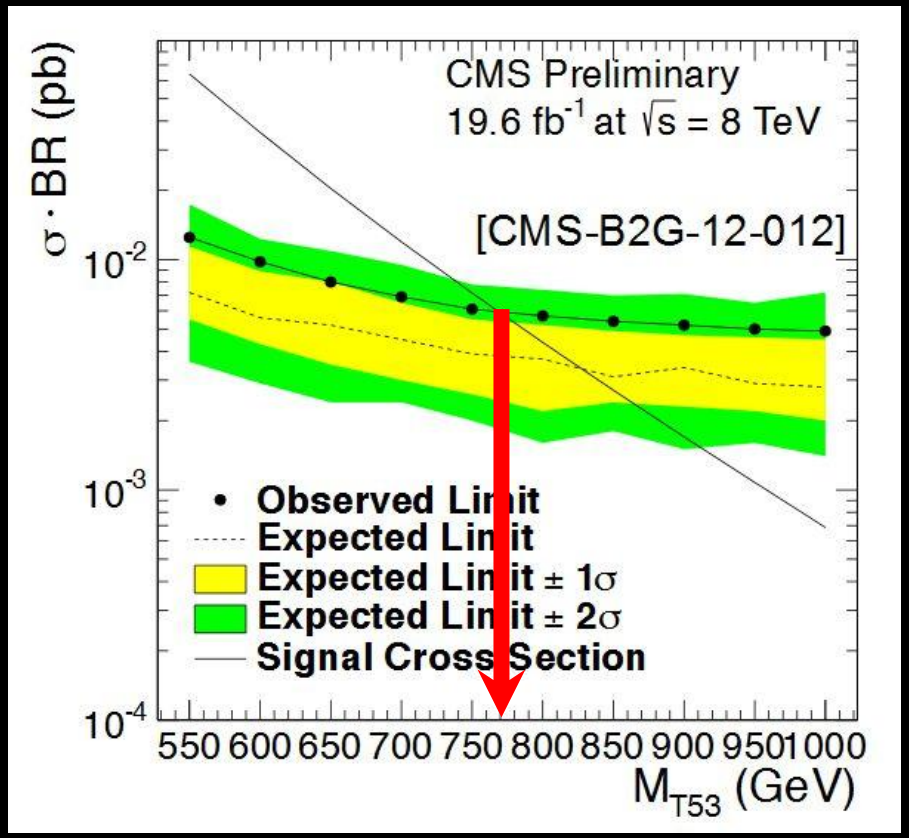
composite pGB Higgs models → cleanest signal = $T_{5/3}$

Contino-Servant '08, Mrazek-Wulzer '09, Rattazzi et al. '12

vector-like quark (Q=5/3)
« custodial » partner of top







$m_{T5/3} > \sim 770$ GeV

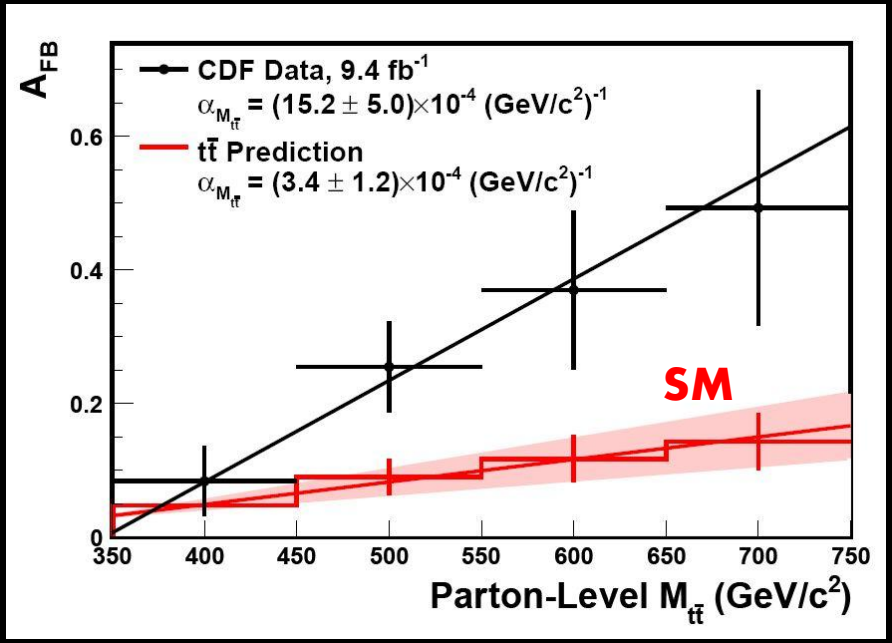
taken from Stelzer @HCP'12

A_{FB} at the Tevatron:

see S.Westhoff's talk

"tops fly forward, even more at higher energies"

CDF 1211.1003



A_{FB} from hard top physics:

CD-Gedalia-Hochberg -Perez-Soreq '11
(see also Degrande et al. '10)

Λ_{NP}>TeV : $\mathcal{L}_{top} = \mathcal{L}_{SM} + \mathcal{L}_{d=6}$

operators relevant to $q\bar{q} \to t\bar{t}$ transition @high m_{tt}

above 450GeV $q \simeq u$ as luminosity ratio $d\bar{d}/u\bar{u} \lesssim 20\%$

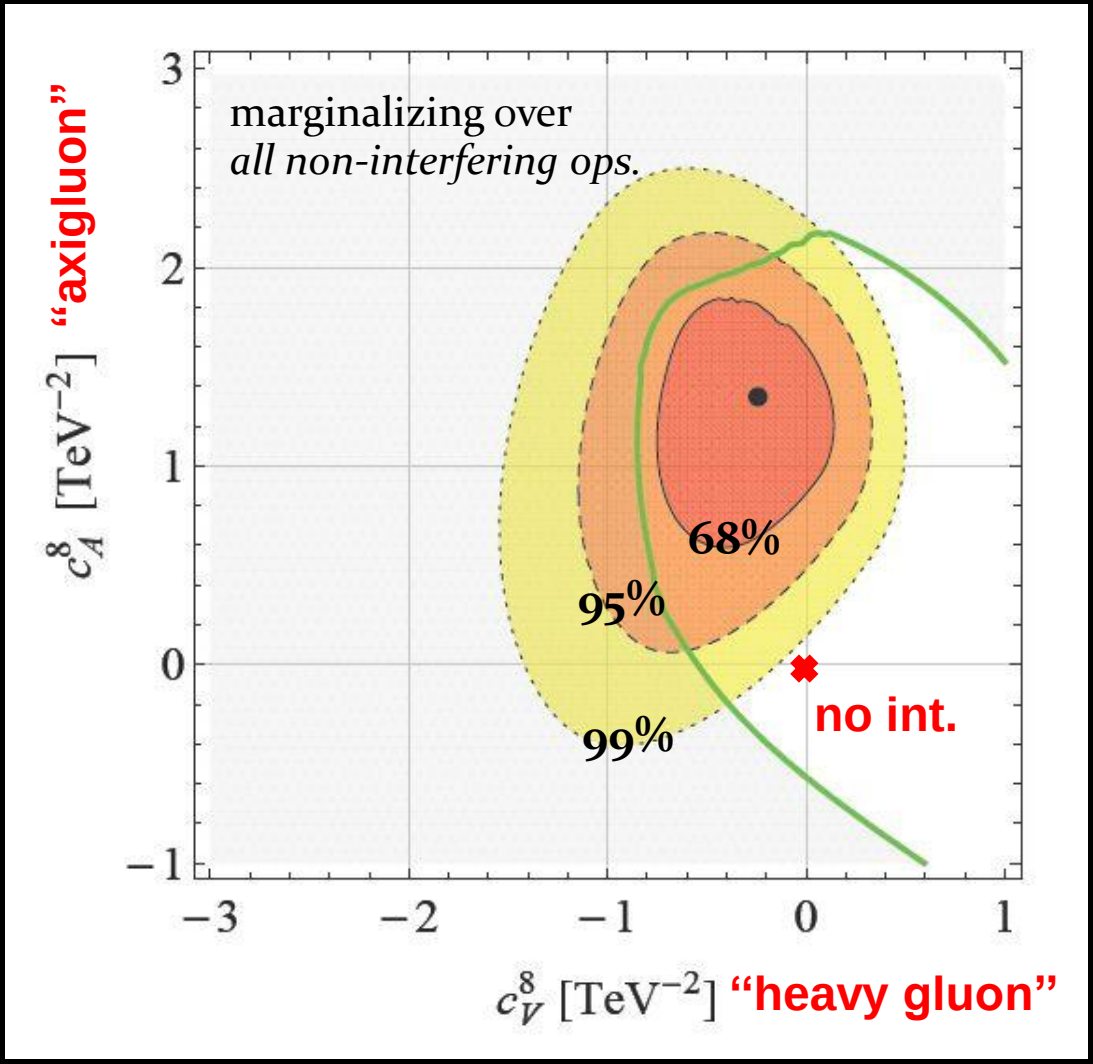
$\mathcal{L}_{d=6} \supset$

$$\mathcal{O}_A^8 = (\bar{u}\gamma_\mu\gamma^5 T^a u)(\bar{t}\gamma^\mu\gamma^5 T^a t)\,,$$
$$\mathcal{O}_V^8 = (\bar{u}\gamma_\mu T^a u)(\bar{t}\gamma^\mu T^a t)\,.$$

interfere w/QCD prodution

fitting the ttbar data:

CD-Gedalia-Hochberg-Soreq '12



fitting the ttbar data:

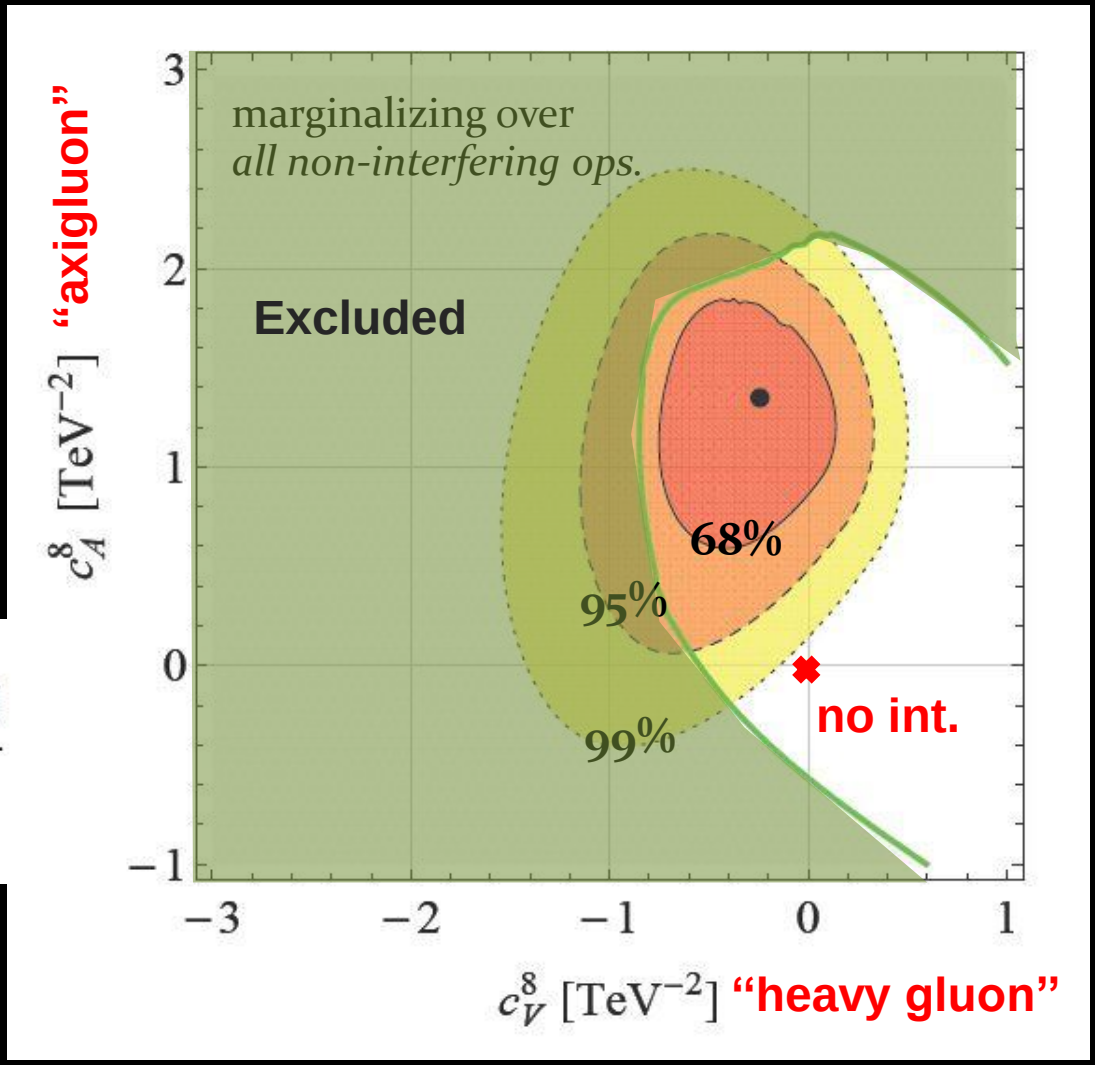
CD-Gedalia-Hochberg-Soreq '12

CMS measured integrated tail in all hadronic ttbar:

$$S = \frac{\int_{m_{t\bar{t}}>1\,\mathrm{TeV}/c^2} \frac{d\sigma_{SM+NP}}{dm_{t\bar{t}}} dm_{t\bar{t}}}{\int_{m_{t\bar{t}}>1\,\mathrm{TeV}/c^2} \frac{d\sigma_{SM}}{dm_{t\bar{t}}} dm_{t\bar{t}}}$$

$S < 2.6$ @95%CL LHC7

arxiv:1204.2488



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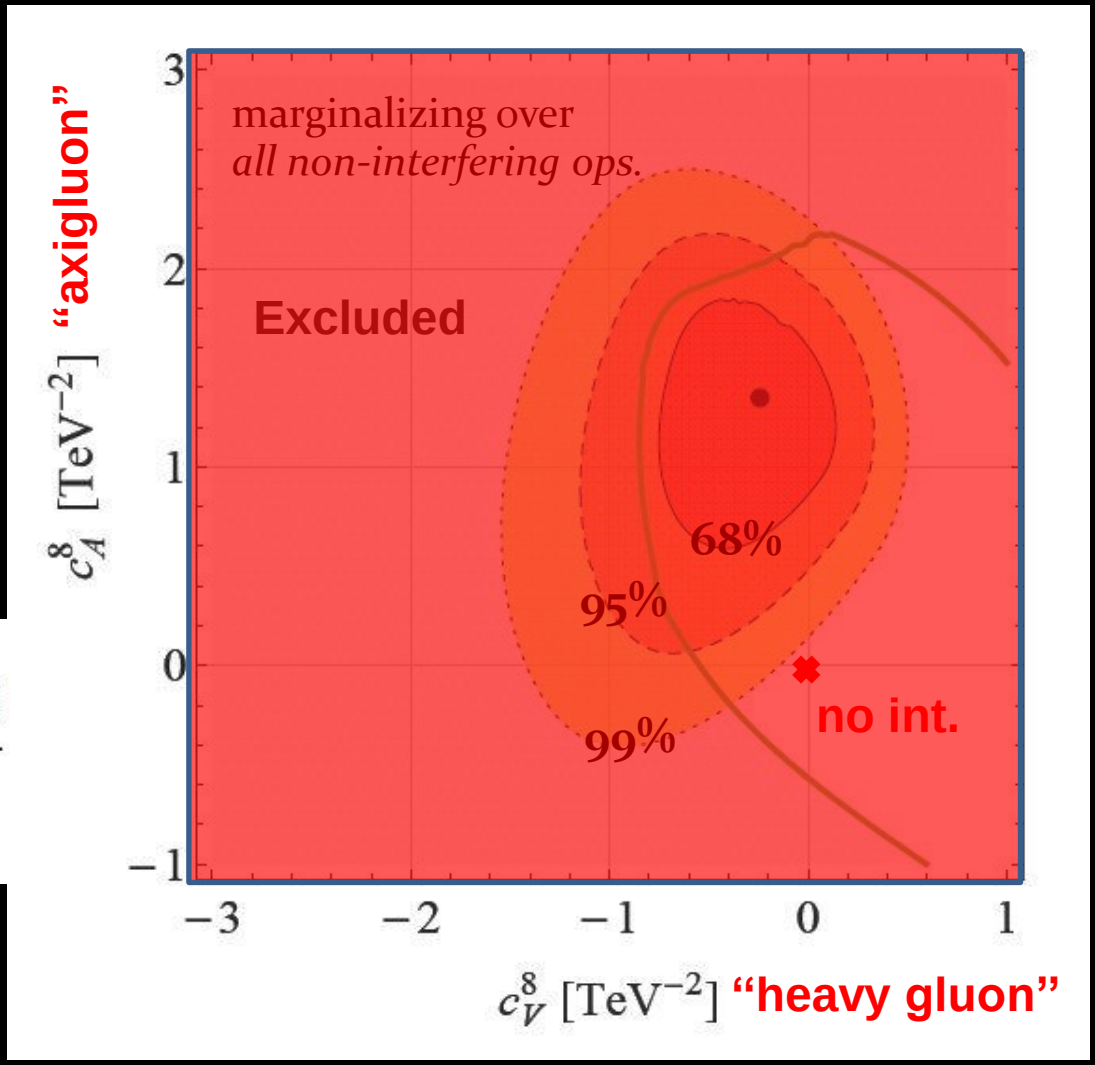
$S < 1.2$ @95%CL LHC8

arxiv:1309.2030



if true, heavy scale explanations for top A_{FB} are most likely excluded

$$\mathcal{S} = \frac{\int_{m_{t\bar{t}}>1\,\mathrm{TeV}/c^2} \frac{d\sigma_{SM+NP}}{dm_{t\bar{t}}} dm_{t\bar{t}}}{\int_{m_{t\bar{t}}>1\,\mathrm{TeV}/c^2} \frac{d\sigma_{SM}}{dm_{t\bar{t}}} dm_{t\bar{t}}}$$

$S < 1.2$ @95%CL LHC8

arxiv:1309.2030

bound approved by factor ~8

Q: is the tail cross section under control down to the 20% level?

what about PDFs, EW Sudakov or syst.?

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Measuring the top-Higgs coupling

Higgs EFT:

e.g. Falkowski-Riva-Urbano '12

$$\mathcal{L} = \frac{1}{2}\partial_\mu h\,\partial^\mu h - \frac{1}{2}m_h^2 h^2 - c_3\,\frac{1}{6}\left(\frac{3m_h^2}{v}\right)h^3 + \dots$$

$$+ m_W^2\,W_\mu^+ W^{-\mu}\left(1 + 2c_W\,\frac{h}{v} + \dots\right) + \frac{1}{2}m_Z^2\,Z_\mu Z^\mu\left(1 + 2c_Z\,\frac{h}{v} + \dots\right)$$

$$- \sum_{\psi=u,d,l} m_{\psi^{(i)}}\,\bar{\psi}^{(i)}\psi^{(i)}\left(1 + c_\psi\frac{h}{v} + \dots\right) + \dots$$

h = $SU(2)_{L+R}$ (custodial) singlet

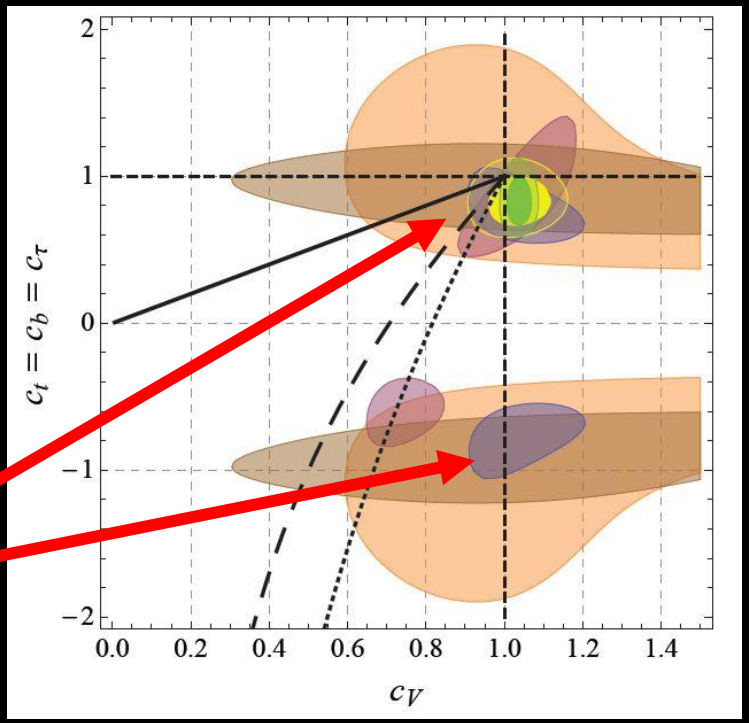
custodial symmetry → $c_Z = c_W = c_V$

SM limit → all $c_i = 1$

sign($c_t c_V$) is not fixed *a priori*

hard to resolve from rates

only $h\gamma\gamma$ is sensitive



Higgs EFT continued:

best fit + 68% confidence intervals:
(from Higgs rates + EWPTs)

$$c_V = 1.04 \pm 0.03, \quad c_t = 1.1^{+0.9}_{-3.0} \quad c_b = 1.06^{+0.30}_{-0.23}, \quad c_\tau = 1.04 \pm 0.22$$

$$\left(c_{gg} = -0.002 \pm 0.036, \quad c_{\gamma\gamma} = 0.0011^{+0.0019}_{-0.0028}, \quad c_{Z\gamma} = 0.000^{+0.019}_{-0.035}\right)$$

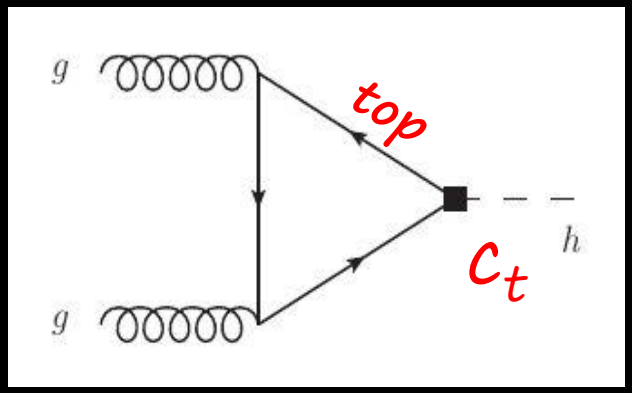
∂^2 - order cpl's: $\mathcal{L}_{(2)} = -\frac{h}{4v}\left[2c_{WW}W^\dagger_{\mu\nu}W^{\mu\nu} + c_{ZZ}Z_{\mu\nu}Z^{\mu\nu} + 2c_{Z\gamma}A_{\mu\nu}Z^{\mu\nu} + c_{\gamma\gamma}A_{\mu\nu}A^{\mu\nu} - c_{gg}G^a_{\mu\nu}G^{a,\mu\nu}\right]$,

SM-like top-Higgs coupling favored,
but deviations are poorly constrained...

...because of an almost "flat direction": $\sigma_{gg\to h} \propto \left|c_{gg} + \frac{\alpha_s c_t}{3\pi}\right|^2$

Higgs production as a probe of the top sector:

$\mathcal{M}_{gg\to h}$ =



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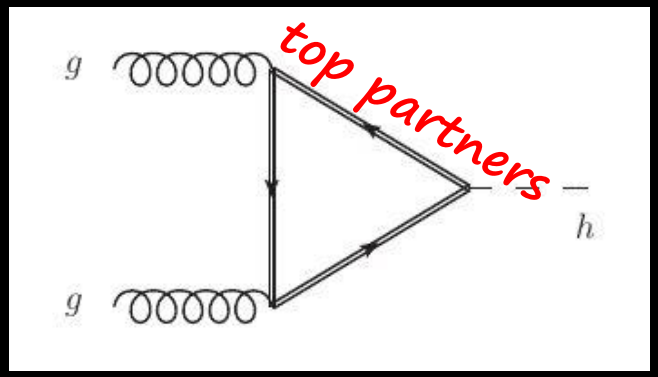


in composite pNGB Higgs: top partners mix with top $c_t = 1+\delta c_t$

yet in minimal constructions *e.g.* MCHM5,10

δc_t + partner's loop = 0 → cannot separate modified top Yukawa (long distance) from top partner loop (short distance)

Falkowski '08, Azatov-Galloway '10

easy to understand from Higgs low-E Theorem: Shifman et al. '78

$$\mathcal{M}_{gg\to h} \propto \left(\frac{\partial}{\partial \log H} \log\det \mathcal{M}^2(H) \right)_{H=v}$$

typically in CHM:

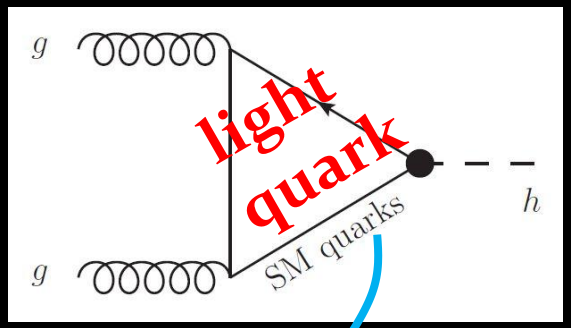
$\det M \propto f(H) \times P(M_T, y_t, \ldots)$

sensitivity to existence of light quark partners:

CD-Grojean-Perez '13

(yet, not necessarily requested by naturalness)

$M_{gg\to h}$ =



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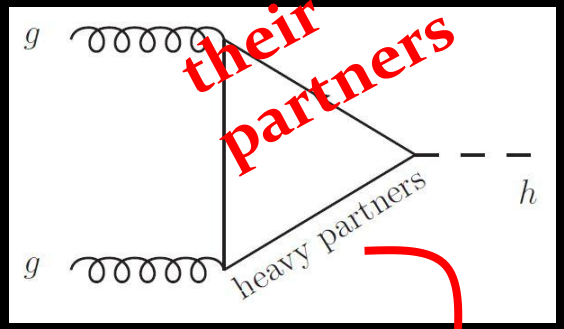
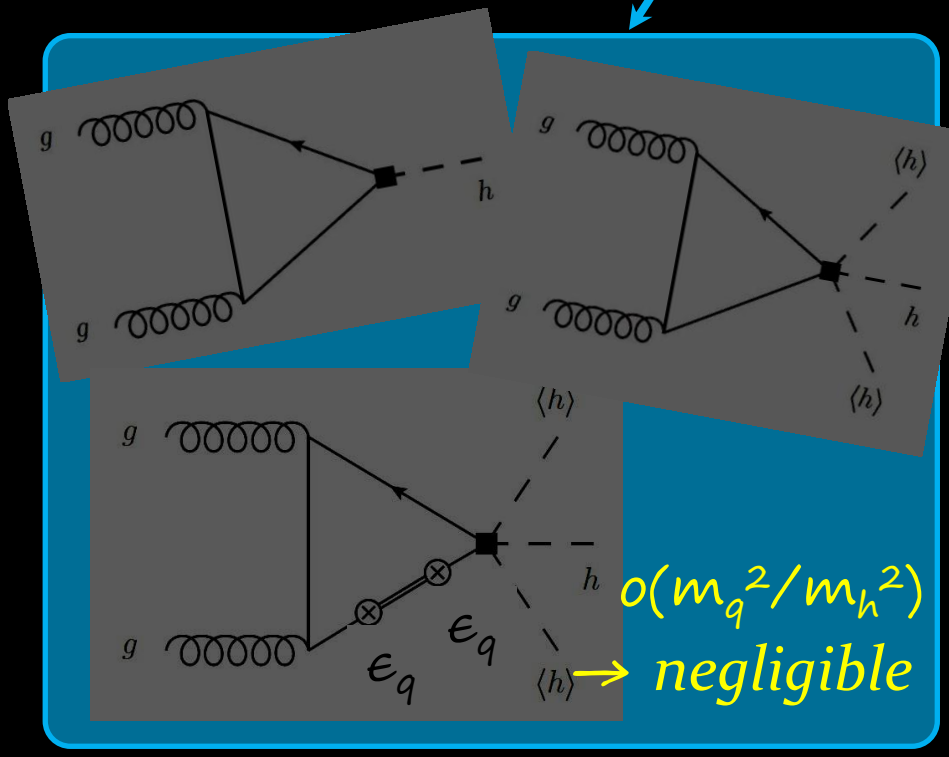
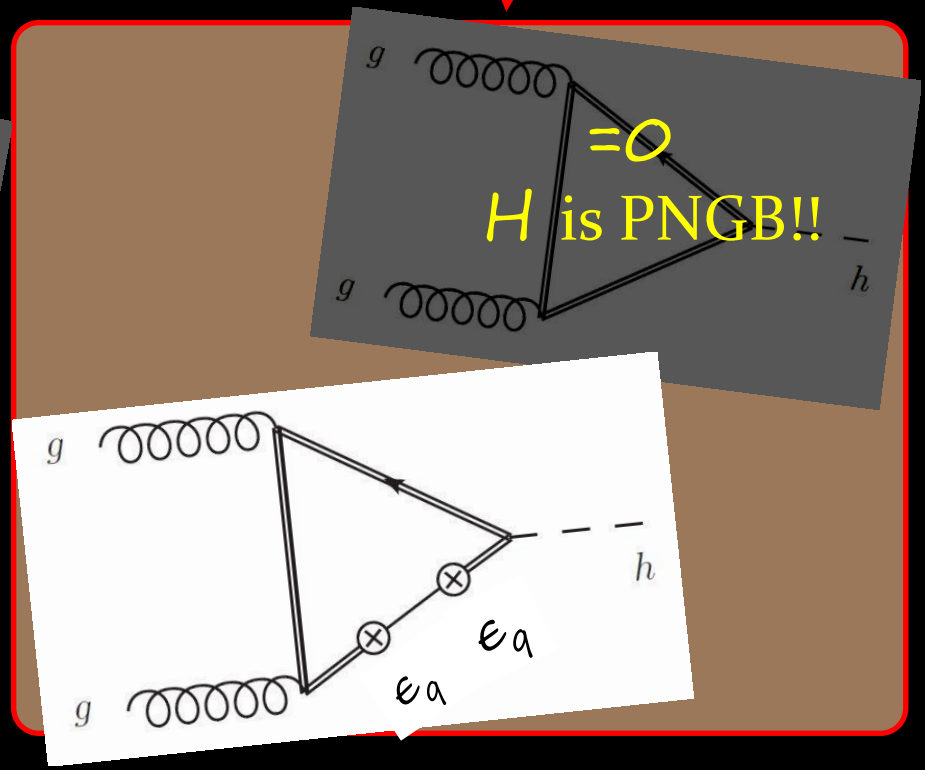






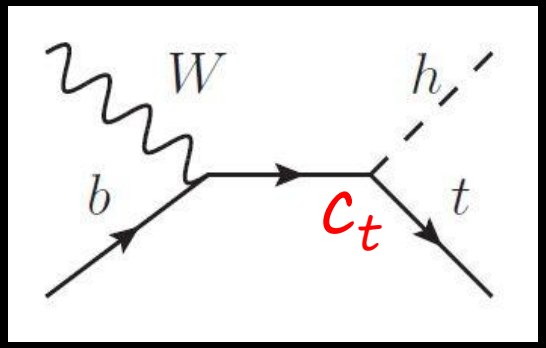
Ideally, one could look at t-tbar+h, but bkgd-challenged now...

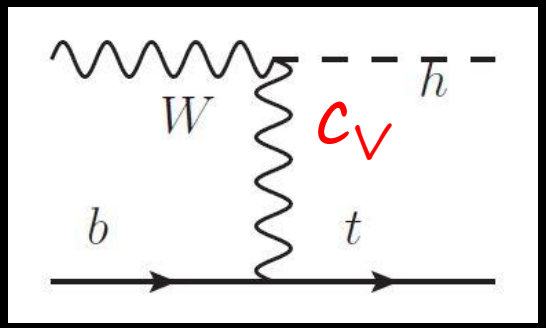
yet: $|c_t| \lesssim \begin{matrix} 2.3 \\ 2.4 \end{matrix}$ **ATLAS-CONF-2013-080** (with h→$\gamma\gamma$)
CMS-HIG-12-035 (with h→$b\bar{b}$)

it might be better to first look at single top + h production

Farina-Grojean-Maltoni-Salvioni-Thamm '12

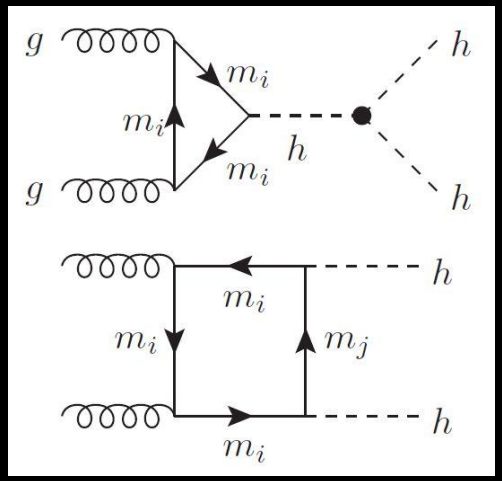
higher sensitivity to BSM due to strong cancellation in the amp'





$$\frac{|A_W - A_t|^2}{|A_W + A_t|^2} \approx 13 \rightarrow O(10) \text{ enhancement expected for } c_t = -1$$
in $\sigma_{pp\to thj}$ @8&14TeV

some handle on top parners in double Higgs production:



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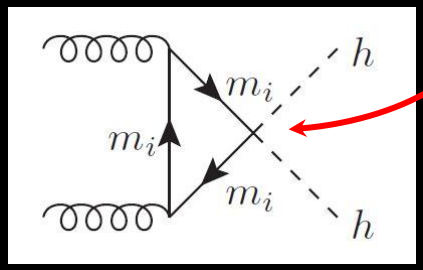


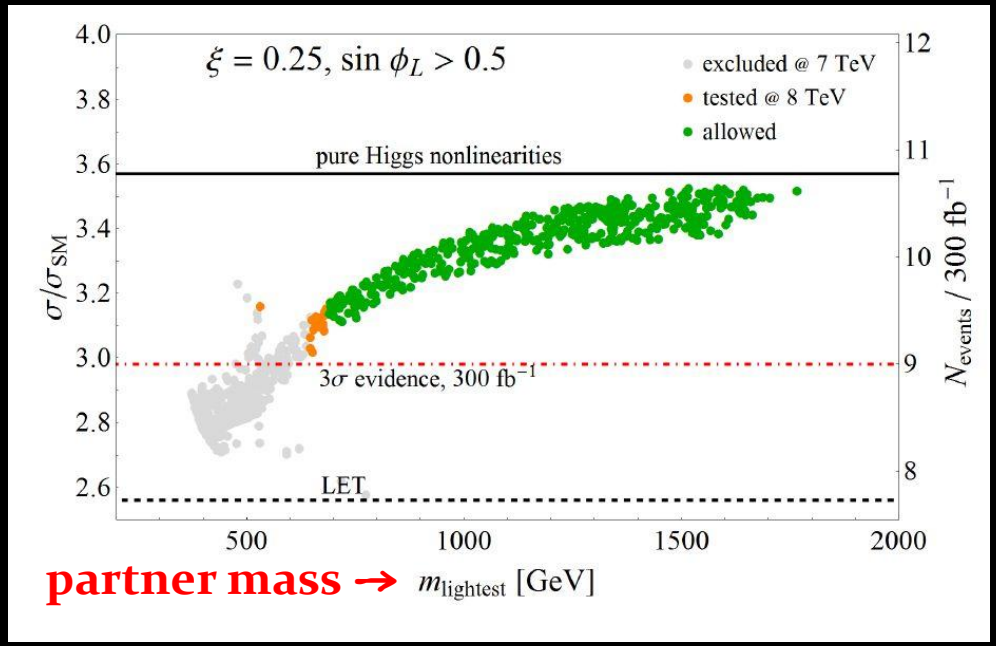
from pNGB Higgs non-linearity

yields large enhancement w/out partners

Contino-Grojean-Moretti-Piccinini-Rattazzi '10

adding top partners →

Gillioz-Grober-Grojean -Muhlleitner-Salvioni '12

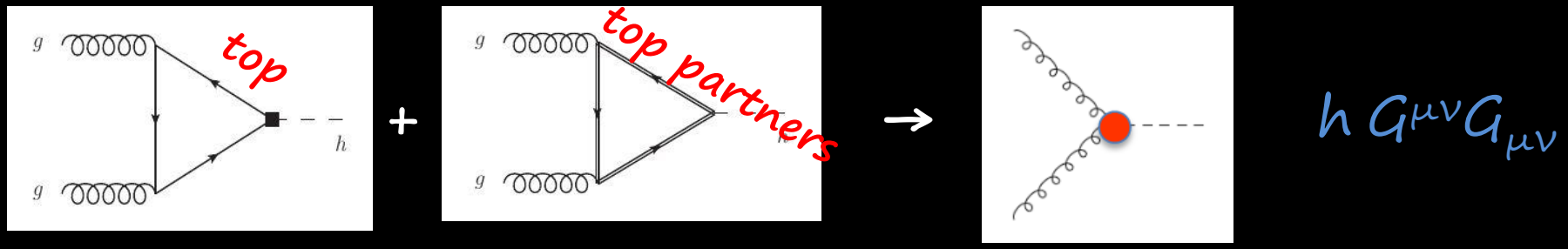


another handle on top parners in Higgs + high-p_T jet production:

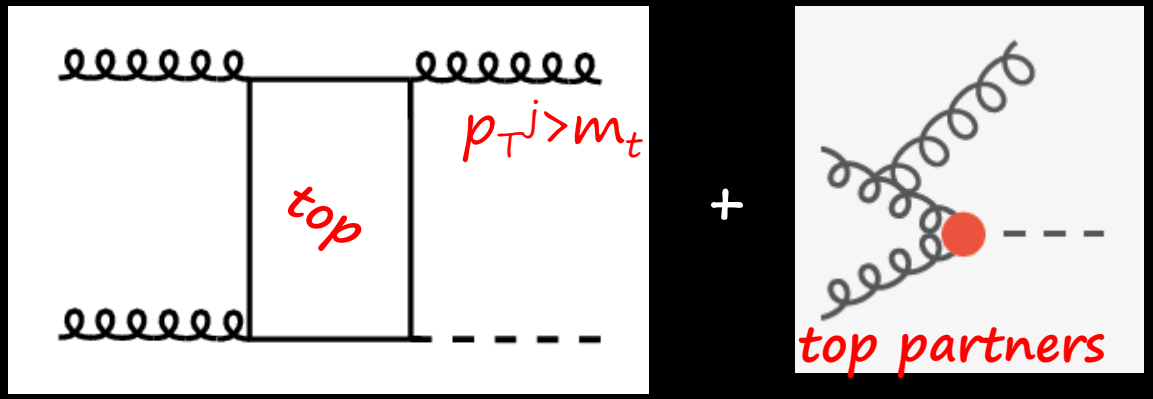
see A.Weiler's talk

Banfi-Martin-Sanz '13
Grojean-Salvioni-Schlaffer-Weiler *in prep'*
Spannowsky-Takeuchi-Wymant *in prep'*

can't resolve top+H coupling inclusively $m_h \ll m_{top}, M_T$



way-out: introduce a new hard scale $m_{top} \ll$ jet $p_T \ll M_T$



EFT breaks down, need to integrate the top in

Conclusions

- top/Higgs coupling is driving several fundamental phenomena, its o(1) value *(at the very least)*:
  - destabilizes the EW scale (hierarchy pb, leads to BSM physics @TeV)
  - destabilizes our vacuum (if SM valid up to E>>mZ)
  - controls Higgs production (which led to H discovery @LHC)

- yet its measurement is very challenging EXP-wise:
  - unprobed in inclusive H production (can't separate it from short distance)
  - ttH channel suffers from large background
  - perhaps tH and HH can shed some light
  - H+jet is an interesting complementary channel

which situation are we in?