tth : theory top/higgs

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October 2nd 2014

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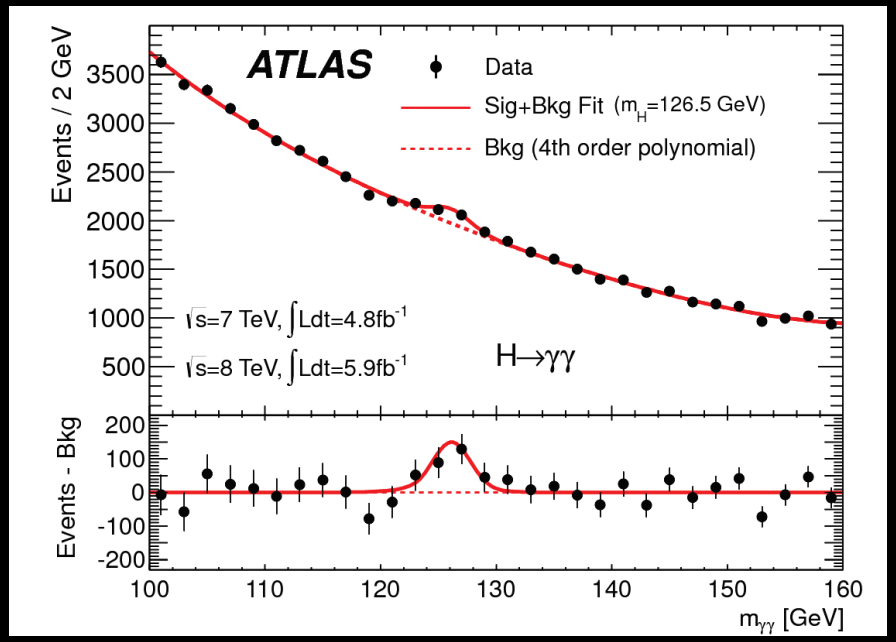
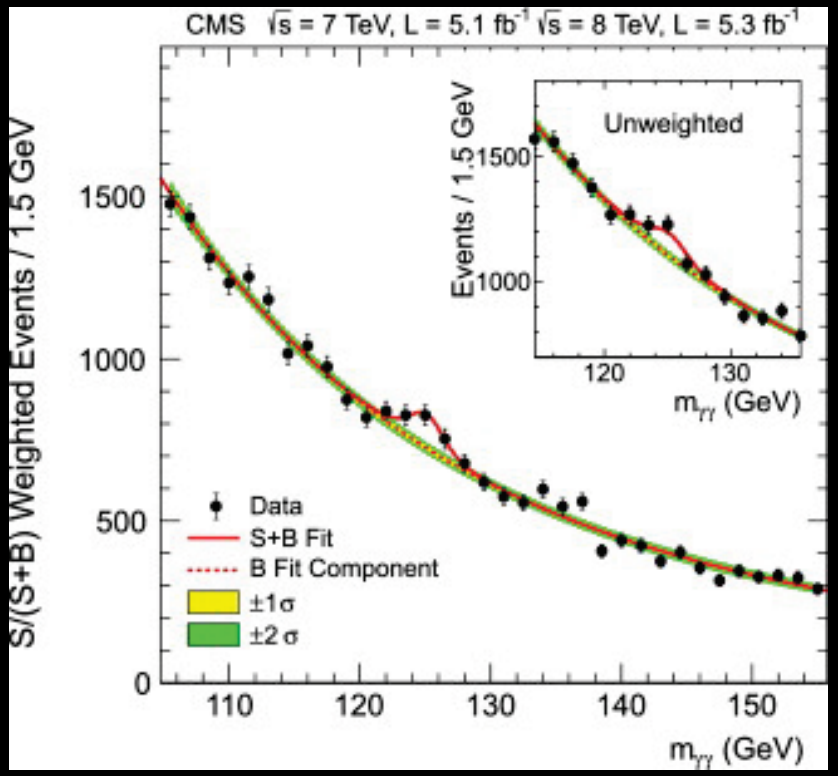
Outline

- top/higgs coupling is the next big step:
  - Higgs perspective, unique probe on naturalness
- What we learned so far about top/higgs coupling
  - Inclusive Higgs production
  - (EDMs)
- top coupling to composite PGB Higgs
  - Unveil existence/structure of top partners
- Complementary probes at LHC13/14
  - tt+Higgs
  - Higgs + hard jet production

Higgs perspective

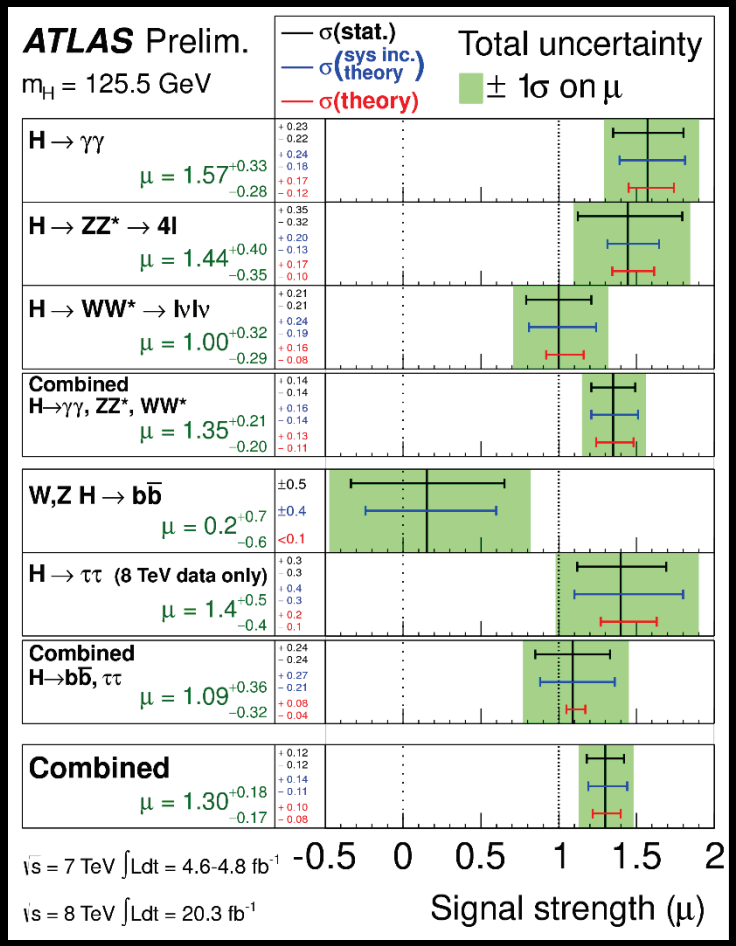
There is another light scalar in Nature:

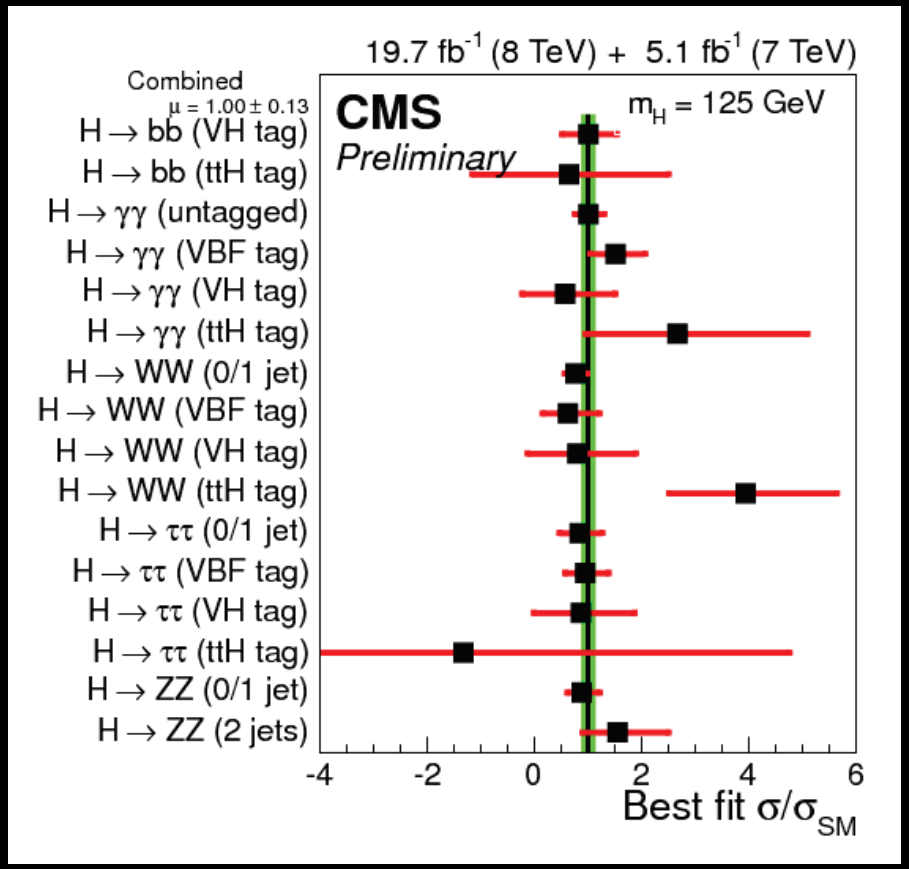




ATLAS, *Phys. Lett. B 716 (2012)*
CMS, *Phys. Lett. B 716 (2012)*

which ressembles the long sought SM Higgs:

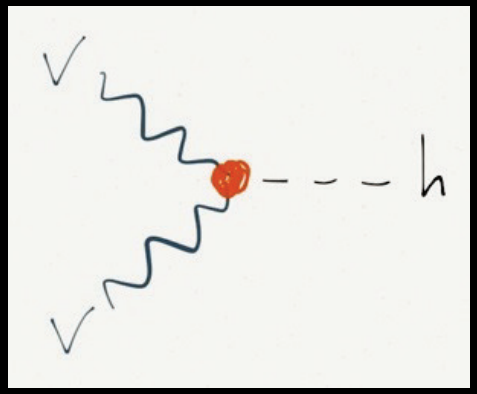




ATLAS-CONF-2014-009

CMS-PAS-HIG-14-009

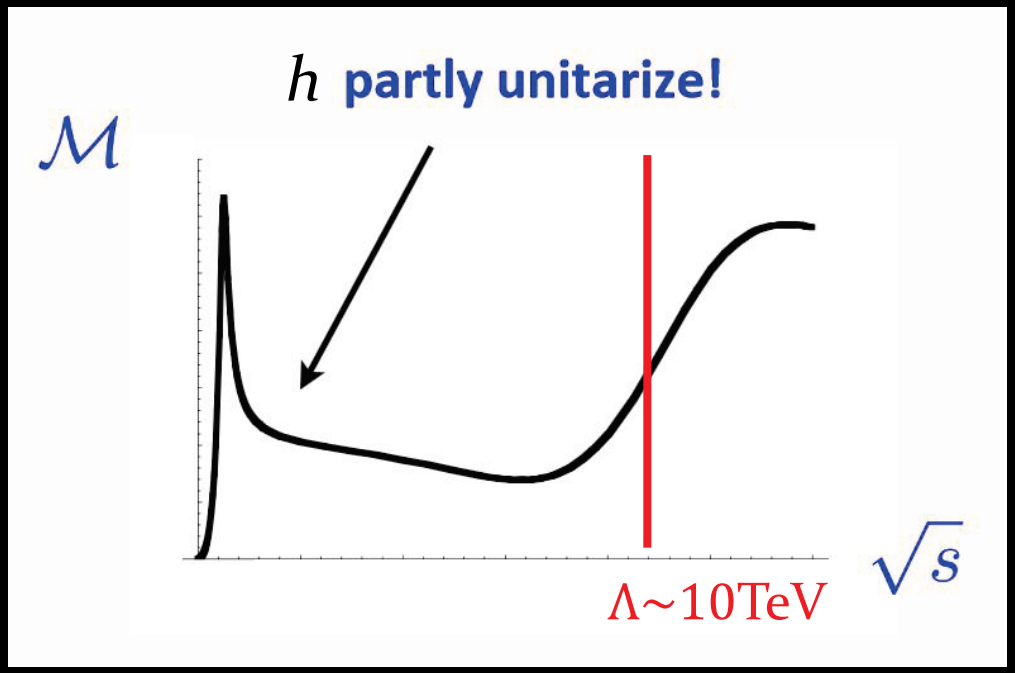
This Higgs unitarizes $W_L W_L$ scattering:



$$= 2\frac{m_V^2}{v} c_V \,, \qquad (v \approx 246\text{GeV})$$

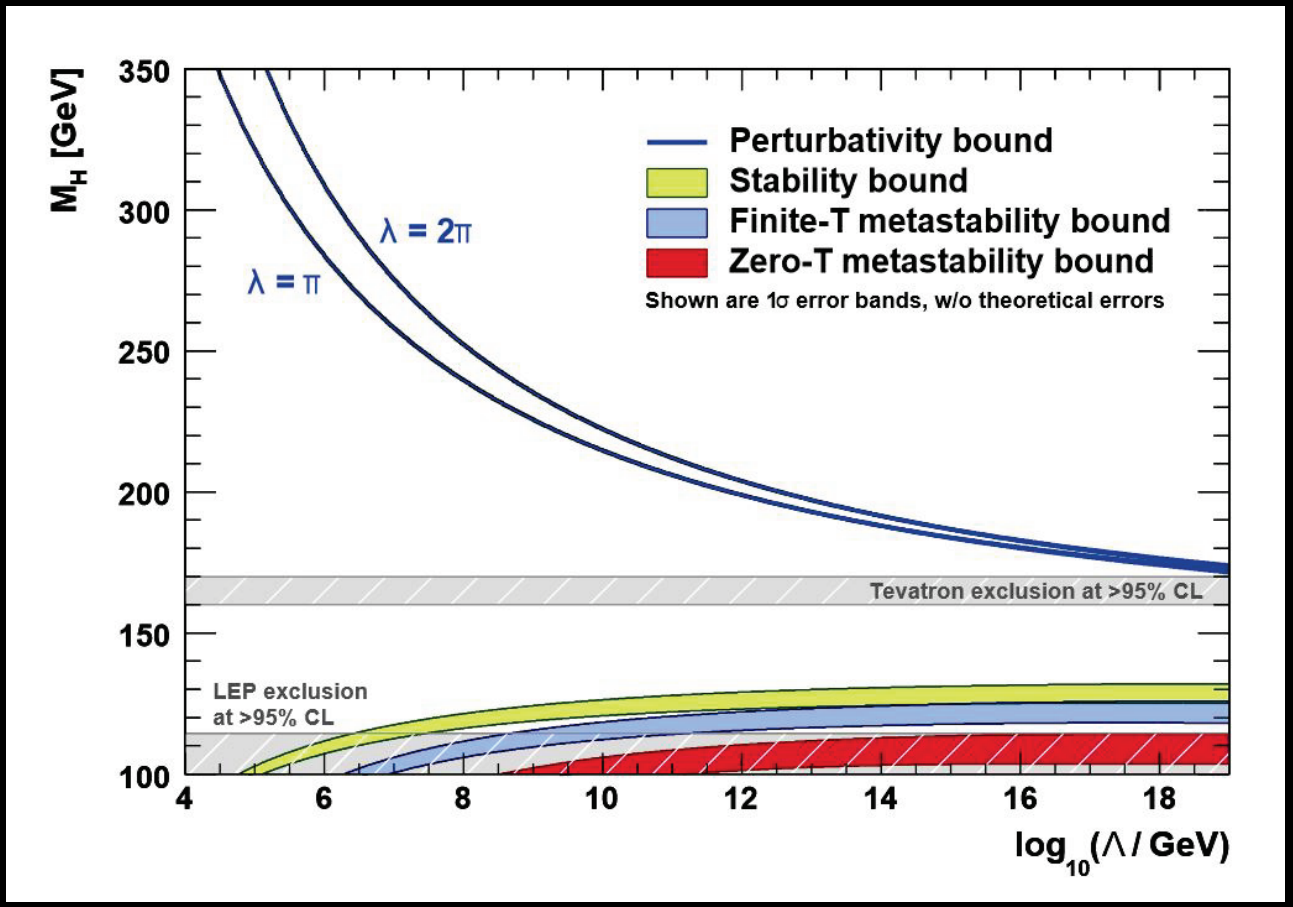
$$c_V = 1.04 \pm 0.03$$ *global fit to LHC+LEP*

e.g. Falkowski-Riva-Urbano, *'13*



$$\Lambda \sim \frac{4\pi v}{\sqrt{|1 - c_V^2|}}$$

The most stricking new input: $m_h \approx 125\text{GeV}$



Higgs quartic (λ) is strongly coupled below M_{Planck}

Vacuum stability lost below M_{Planck}

Ellis et al, *Phys. Lett. B 679 (2009)*

Both scenarios need BSM before gravity becomes relevant

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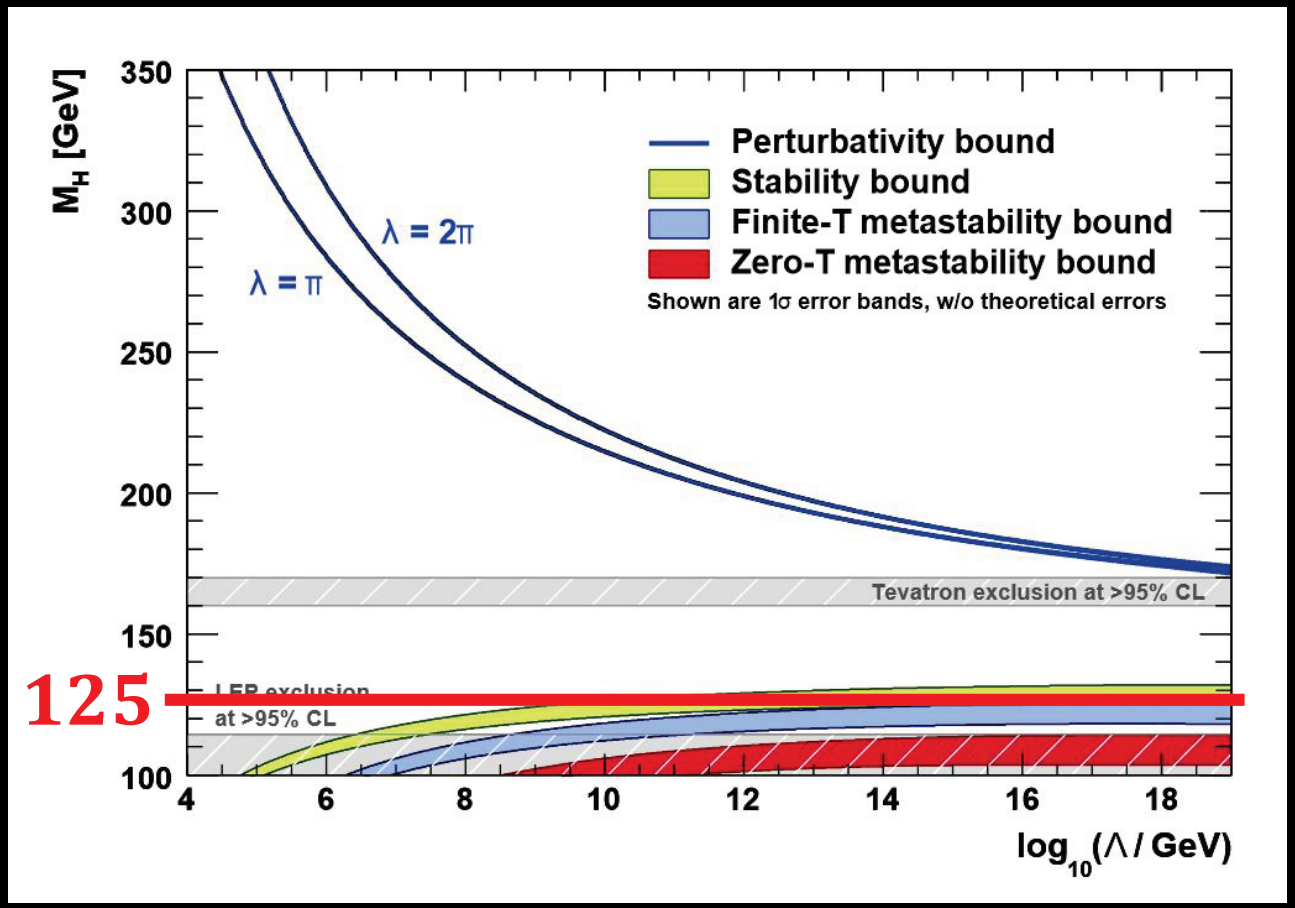


Higgs quartic (λ) is strongly coupled below M_{Planck}

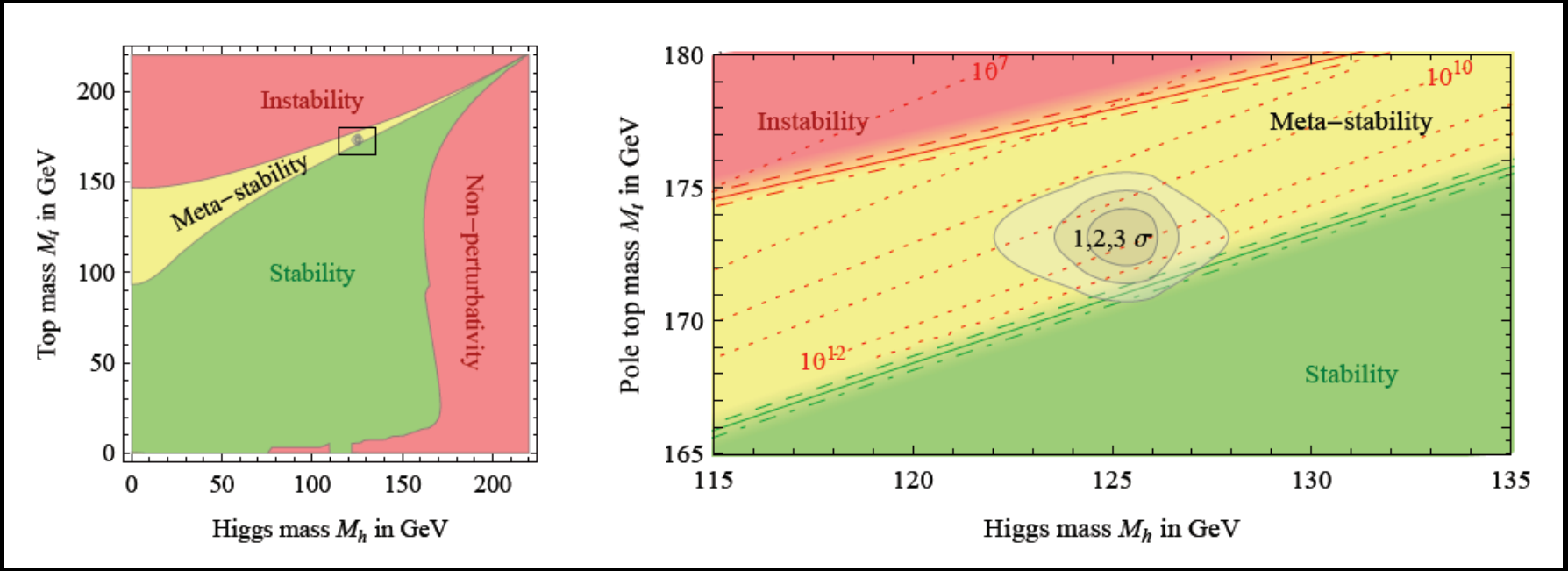
Vacuum stability lost below M_{Planck}

Ellis et al, *Phys. Lett. B 679 (2009)*

There remains a case for the SM valid up to gravity scale!!

Where we stand leans on knowing precisely m_{top}:

→ Hoang's talk



Degrassi et al. '12

$m_{\text{top}} = 173.34 \pm 0.76$ GeV

LHC+Tevatron average, arXiv:1403.4427

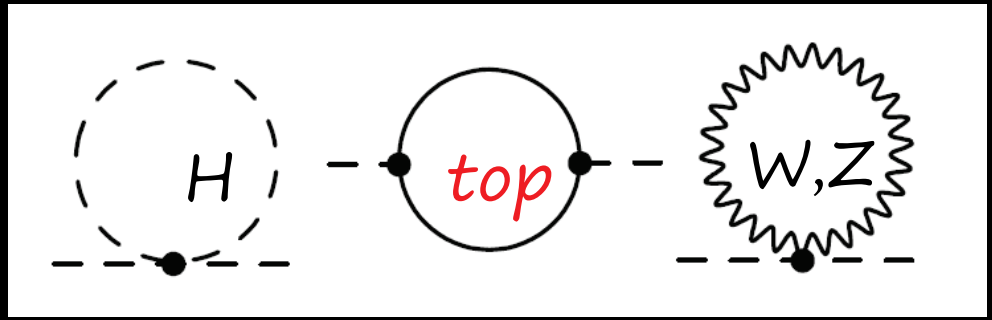
Central value favors meta-stability ($\Lambda \sim 10^{11}$ GeV), w/ lifetime $\sim 10^{100}$ yrs

Why going beyond the SM?

Top quark = SM destabilizing agent

- SM w/Higgs is a complete theory of EWSB (up to 10^{19}GeV?)
- But it is highly unnatural, ie. sensitive to UV dynamics:

$$\delta m_h^2 =$$



$$\sim -\frac{3Y_{\text{top}}^2}{8\pi^2}\Lambda^2$$

if $\Lambda \gg$ o(TeV) $\rightarrow$ *Hierarchy problem*

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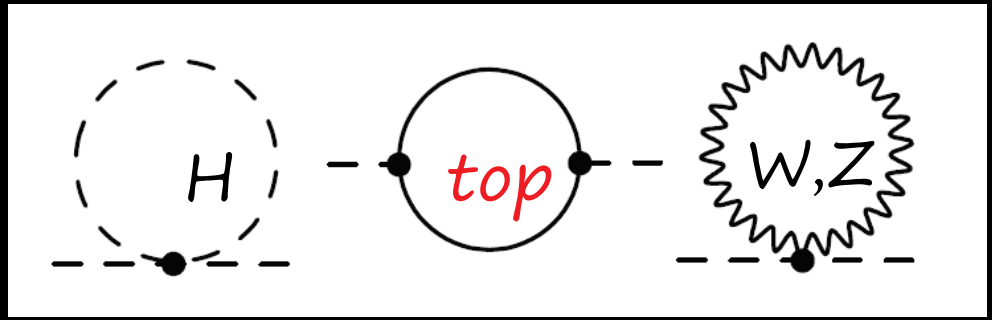
$$\delta m_h^2 =$$ 

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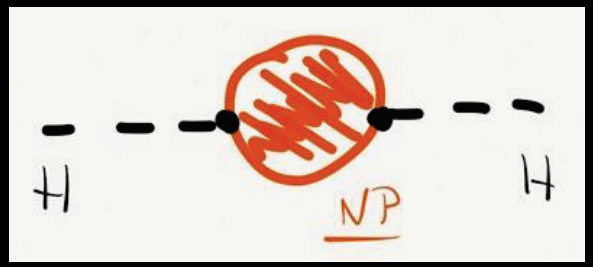
$+$ 

= *log*(Λ) or *finite*

- $\mathcal{O}$(TeV) New Physics needed to stabilize the 125GeV Higgs

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

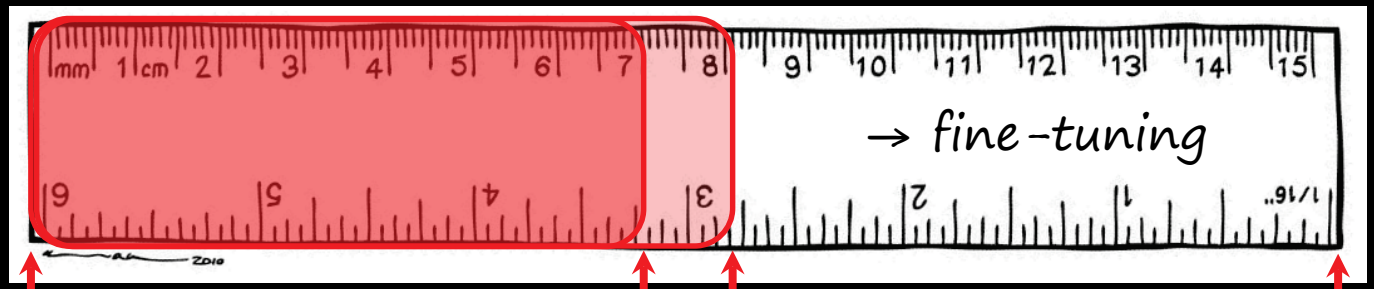
$$\psi \sim \begin{pmatrix} t \\ t' \end{pmatrix}$$

Since [SUSY/global sym, QCD]=0,
top partners are colored*
→ *large production cross-sections at hadron colliders*

* known counter example: *twin-Higgs*
Chacko-Goh-Harnik '05

Naturalness at LHC:

LHC naturalness ruler* :



natural weak scale
$m_{t'}$ ≈400GeV

SUSY stop search
$m_{\tilde{t}}$ ≈ 700GeV
Composite $T_{5/3}$ search
m_T ≈ 800GeV

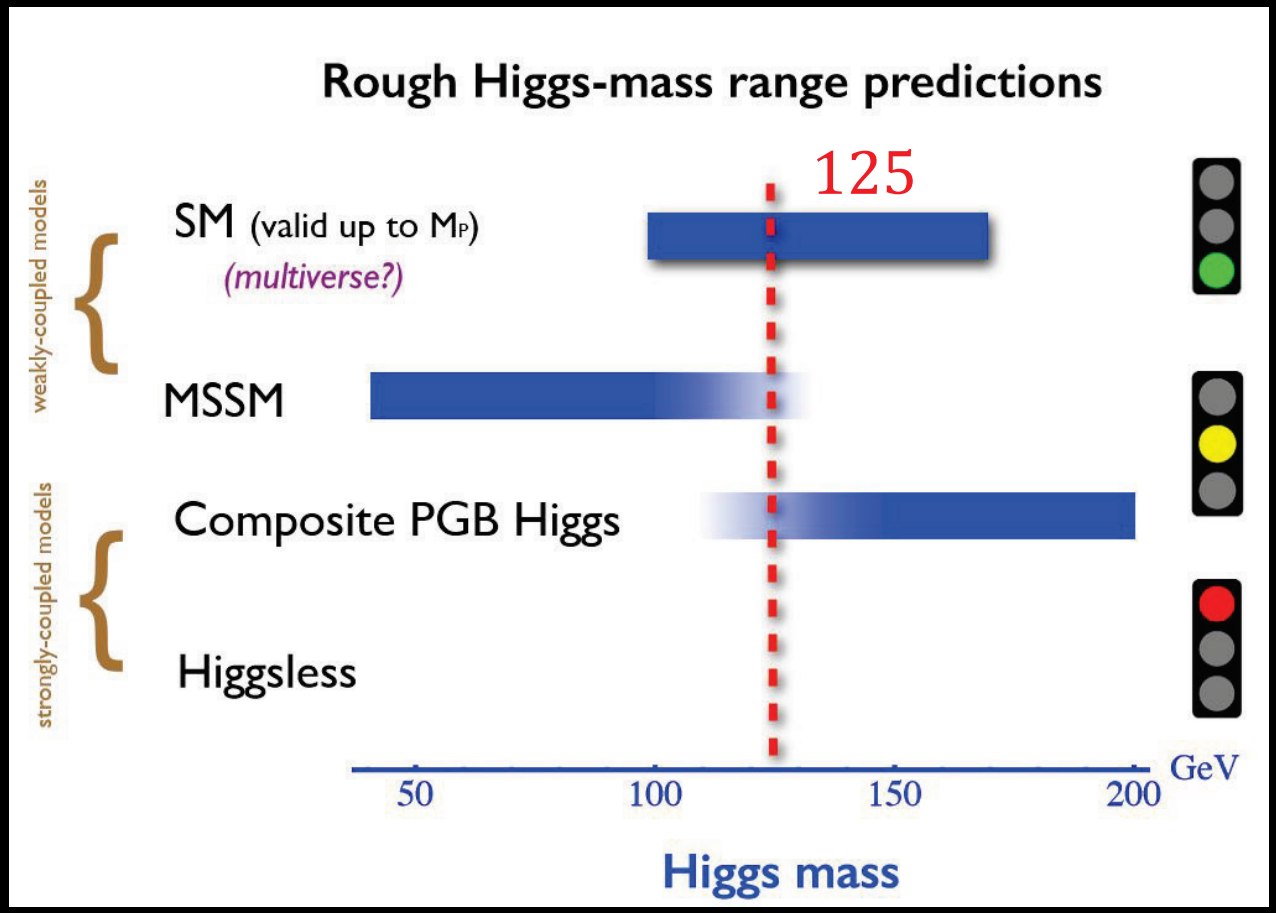
~10%

~1%

end of LHC14
$m_{t'}$ ≈ 2TeV

After LHC1, fine-tuning ~O(10%)
→ naturalness is under pressure

$m_h \approx 125$GeV does not favor any BSM paradigm



Courtesy of A. Pomarol, ESHEP 2014

→ *measuring top/Higgs coupling is the next big step!*

What we already know of top/Higgs coupling?

Effective top/Higgs parameterization

- BSM scale $\gg m_h, m_{\text{top}} \rightarrow$ EFT

$$-\mathcal{L} = x_{ij}\,\overline{Q_i} H u_j + \lambda_{ij}\,\overline{Q_i} H^3 u_j + hc. \qquad (\lambda \propto 1/\Lambda^2)$$

$$= m_i \bar{u}_i u_i + h\bar{u}_i[\mathrm{Re}(y_{ij}) + i\gamma_5 \mathrm{Im}(y_{ij})]u_j$$

$$y_{ij} = \frac{m_i}{v}\delta_{ij} + 2\tilde{\lambda}_{ij}v^2$$

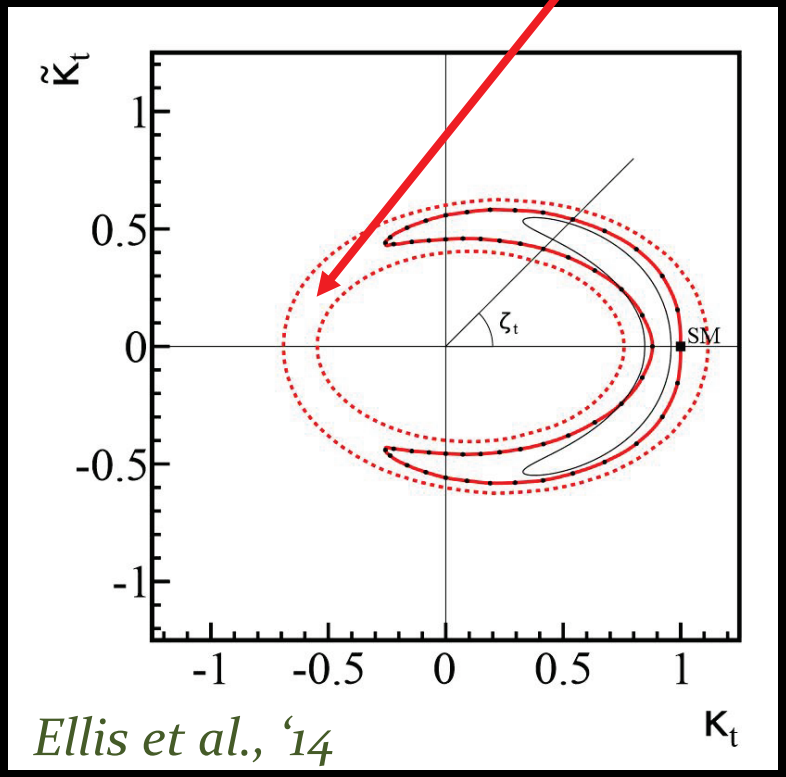
SM *BSM*

- $[x, \lambda] \neq 0 \rightarrow$ FCNC Higgs decays, *e.g.* t→hc → Goldouzian's talk
- $\arg(x/\lambda) \neq 0 \rightarrow$ CP violation (*e.g.* EDMs)
- Let's assume here: $-\frac{m_t}{v} h\bar{t}[c_t + i\gamma_5 \tilde{c}_t]t$

SM:
$c_t = 1$
$\tilde{c}_t = 0$

Inclusive Higgs production @LHC1

Higgs rates are only sensitive to $c_t^2 + \frac{9}{4}\tilde{c}_t^{\,2}$, except for $h \to \gamma\gamma$ whose top/W interference disfavors $c_t < 0$



Ellis et al., '14

Brod-Haisch-Zupan, '13

- CP-odd term $|\tilde{c}_t| \leq 0.5$

(e-EDM Barr-Zee diagram: $|\tilde{c}_t| \leq 0.01$)

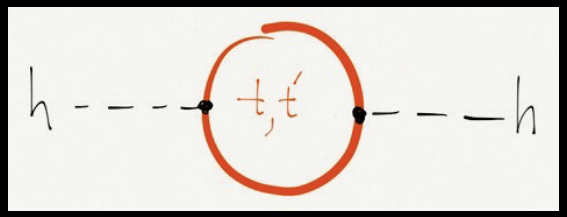
- if $\tilde{c}_t = 0$, indirect evidence for $c_t \approx 1$

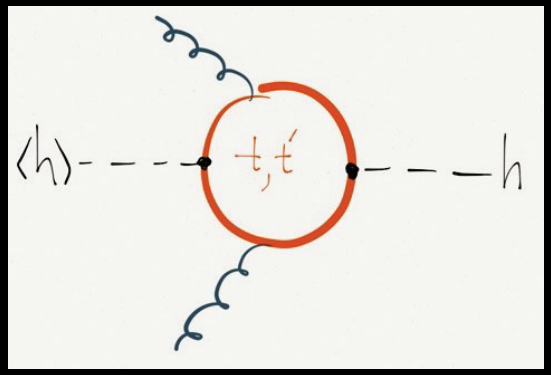
BUT, be careful, it assumes no other states, *e.g.* top partners

Inclusive Higgs production @LHC1

Naturalness predicts:

If [new symmetry, QCD]=0,

the cancellation in 

typically persists in 

!

ggh tends to be reduced by top partners.

Low-Rattazzi-Vichi, '09

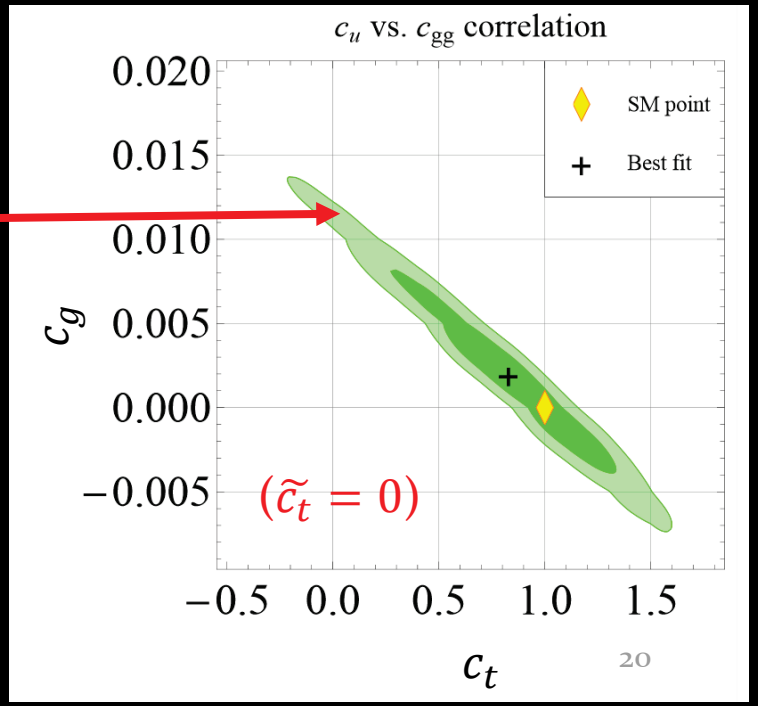
Inclusive Higgs production @LHC1

- top partner scale $\gg m_h, m_{\text{top}} \rightarrow$ EFT : $-c_g \frac{h}{4v} G^a_{\mu\nu} G^{\mu\nu a}$

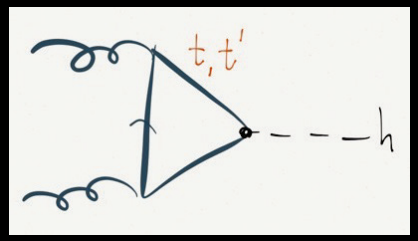
- Global fit constraint on c_t/c_g plane:

$c_V = 1.04^{+0.02}_{-0.02}$, $c_t = 1.30^{+0.10}_{-0.30}$, $c_d = 0.93^{+0.18}_{-0.15}$, $c_l = 1.16^{+0.17}_{-0.15}$,
$c_g = -0.0016^{+0.0022}_{-0.0037}$, $c_{\gamma\gamma} = 0.00059^{+0.00078}_{-0.00078}$, $c_{Z\gamma} = -0.001^{+0.020}_{-0.039}$

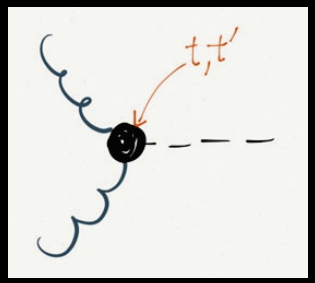
Falkowski et al. '12
latest results from Belúsca-Maïto RPP2014



- c_t is only poorly determined
- ggh could be 100% BSM-driven!
- Only $|c_g + \frac{\alpha_s}{3\pi} c_t|^2$ constrained:



$m_h \ll m_{\text{top}}, m_{t'}$

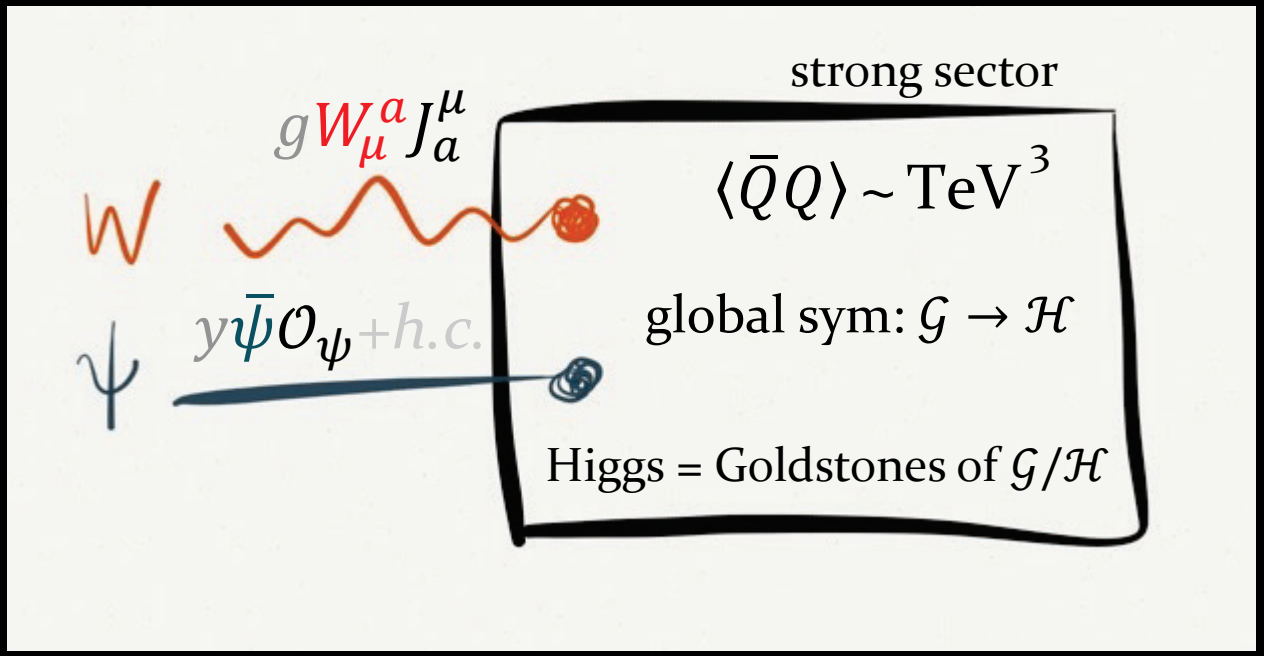


New physics* predictions
for tth coupling

* not SUSY, → Kats' talk

Composite PGB Higgs:

- Add a new strong interaction with "techni-quarks" Q



- Higgs mass protected by global (shift) symmetry: $H \to H + a$

- elementary top acquires mass through linear mixing

Top coupling to composite PGB Higgs:

- Minimal model: G/H = SO(5)/SO(4)
- Composite top partners come in 5,10,14… irreps of SO(5)
- they mix w/ elementary top to trigger EWSB ($+m_{\text{top}}$):

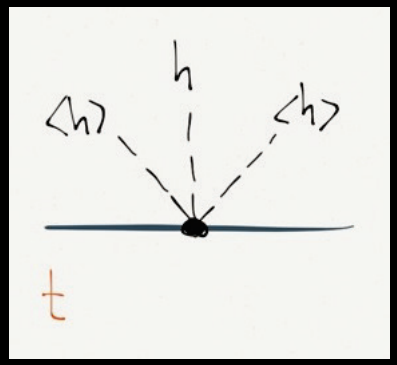
$$c_t = \frac{1 - n\xi}{\sqrt{1-\xi}} + \delta c_t^{\psi}$$

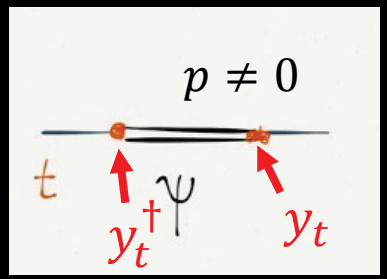
H compositeness (< 0)

t/t' mixing ($\leqslant 0$)

n = positive integer

$$\xi = \frac{v^2}{f^2} \leq 0.3 \text{ (LEP)}$$



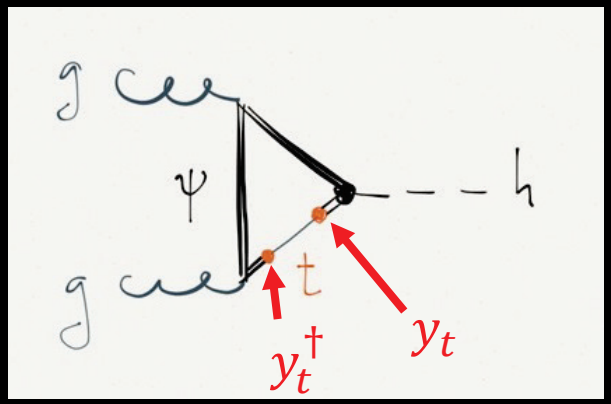


$$\delta c_t^{\psi} \propto y^2_{t_L, t_R}$$

$$\left(g_{hWW} = \sqrt{1-\xi}\, g^{\text{SM}}_{hWW} \right)$$

Gluon fusion in composite PGB Higgs:

- Top partners also contribute directly to ggh loop:



$$\rightarrow c_g = -\frac{\alpha_s}{3\pi}\delta c_t^{\psi}$$

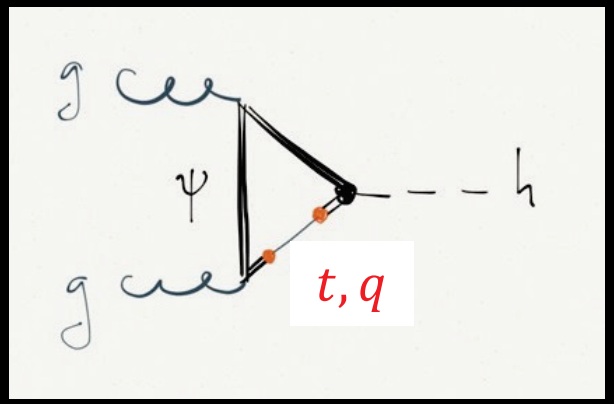
- inclusive single $h \propto \left| c_g + \frac{\alpha_s}{3\pi} c_t \right|^2 = F(\xi) < 1$!

→ top partner effects accidentally cancel out due to peculiar linear mixing structure of CHMs.

Falkowski '08, Azatov-Galloway '11

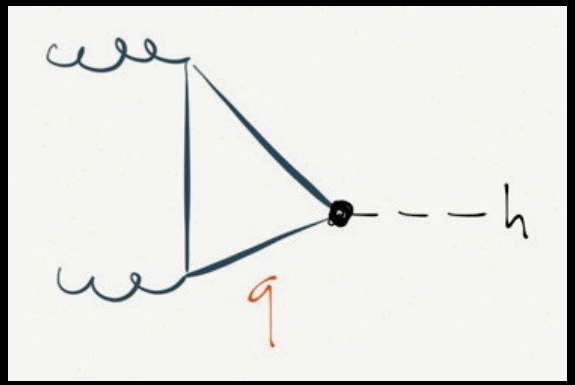
Gluon fusion in composite PGB Higgs:

- inclusive single h could still appear SM-like
  if more quark flavors are composite (flavor sym?)



$$\rightarrow c_g = -\frac{\alpha_s}{3\pi}\left(\delta c_t^{\psi} + \delta c_q^{\psi}\right)$$

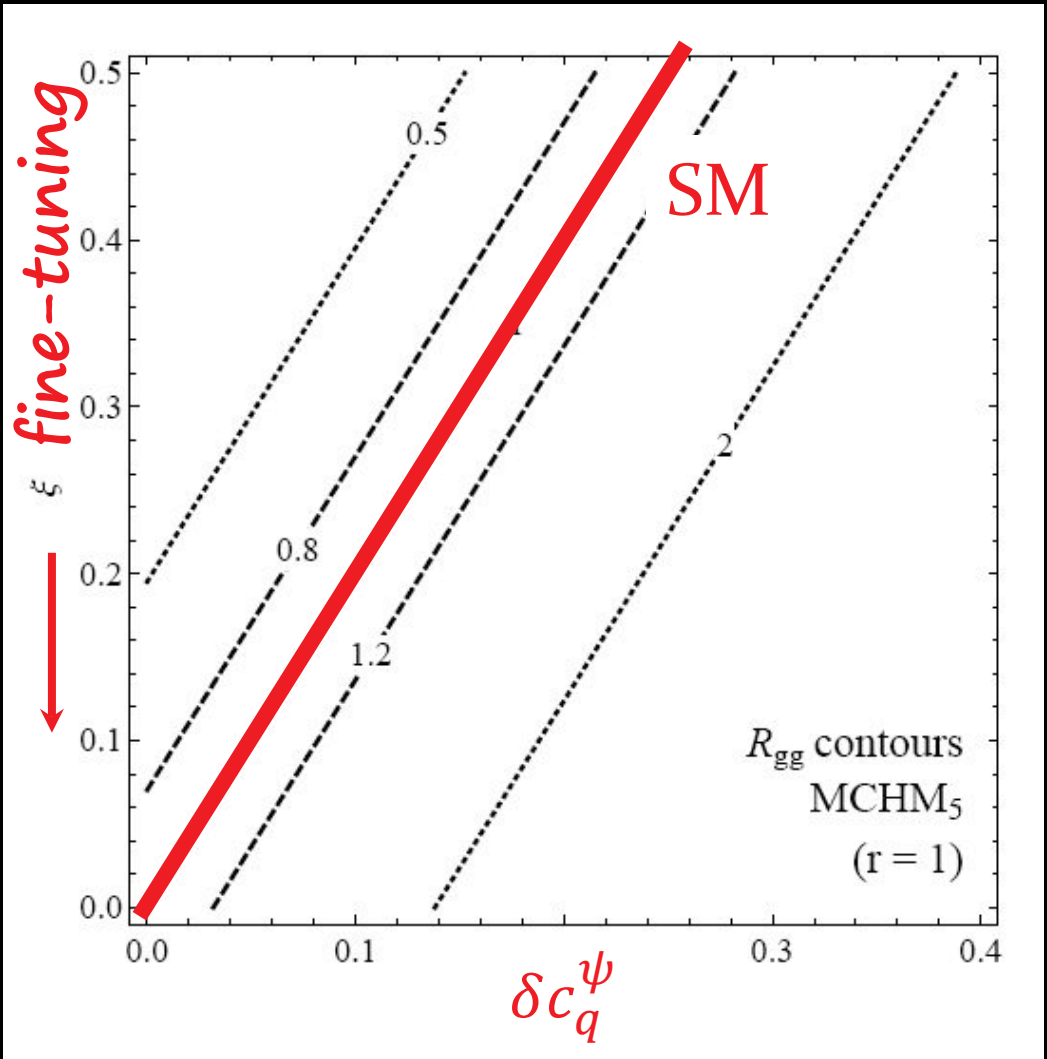
$$\delta c_q^{\psi} \approx \mathcal{O}(y_q^2)$$



$$\propto m_q^2$$

CD-Grojean-Perez '13

Gluon fusion in composite PGB Higgs:



Fine-tuning $\propto \xi^{-1}$

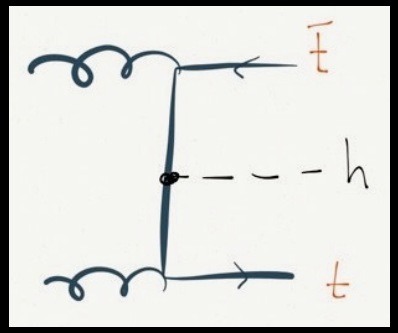
light q (charm?) partners could ease tension between naturalness (large ξ) and SM-like h production

CD-Grojean-Perez, '13

tt+h production @LHC

Cleanest probe of c_t: $pp \to tt + h$

- tree-level dominated, not polluted by partner loops

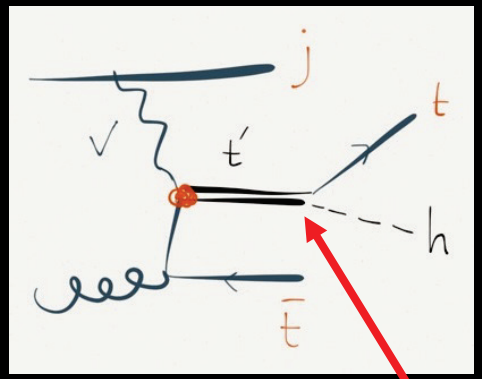


but rare events + large backgrounds

$\text{SM} : \sigma_{tth}^{8\text{TeV}} \approx 127\text{fb}$

$\to$ challenging channel @LHC

(



on-shell partner : $m_{t'} > 600\text{GeV}$

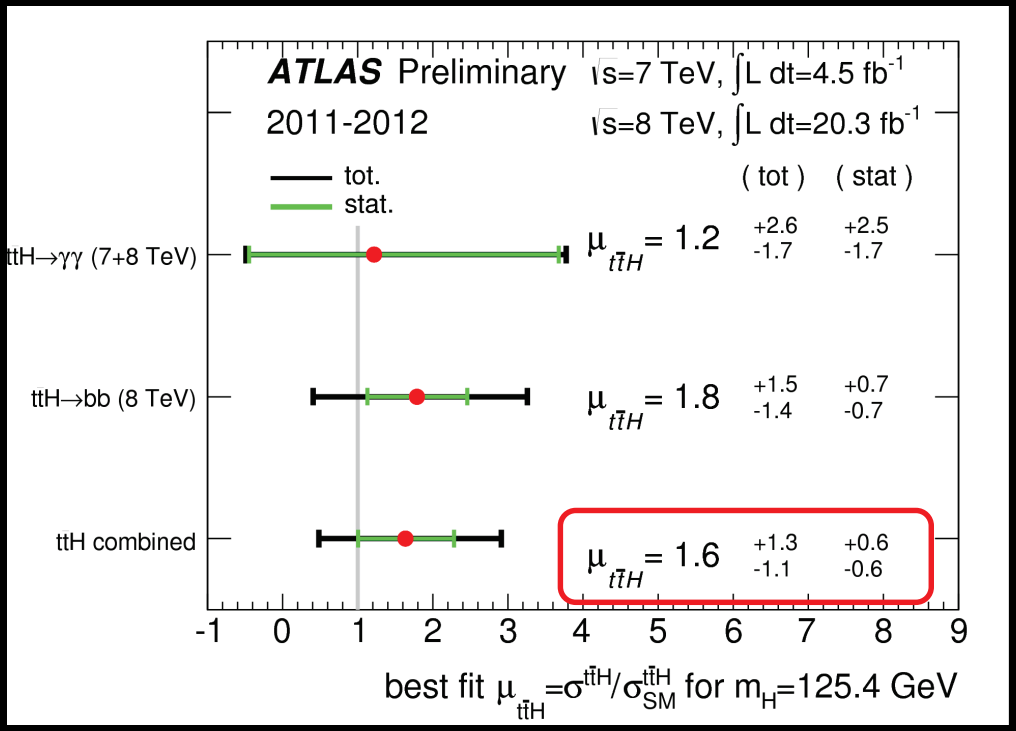
$\delta\sigma_{tth}^{8\text{TeV}} < o(10\text{fb})^*$

)

$Br_{t' \to th} \approx 25\%$

*estimated from:
DeSimone-Matsedonskyi-Rattazzi-Wulzer, '12

tt+h status after LHC1:



ATLAS-CONF-2014-043

ttH Channel	$\mu = \sigma/\sigma_{SM}$ ($m_H = 125.7$ GeV)
$\gamma\gamma$	$-0.2^{+2.4}_{-1.9}$
$b\bar{b}$	$+1.0^{+1.9}_{-2.0}$
$\tau\tau$	$-1.4^{+6.3}_{-5.5}$
4l	$-4.8^{+5.0}_{-1.2}$
3l	$+2.7^{+2.2}_{-1.8}$
Same-sign 2l	$+5.3^{+2.2}_{-1.8}$
Combined	$+2.5^{+1.1}_{-1.0}$

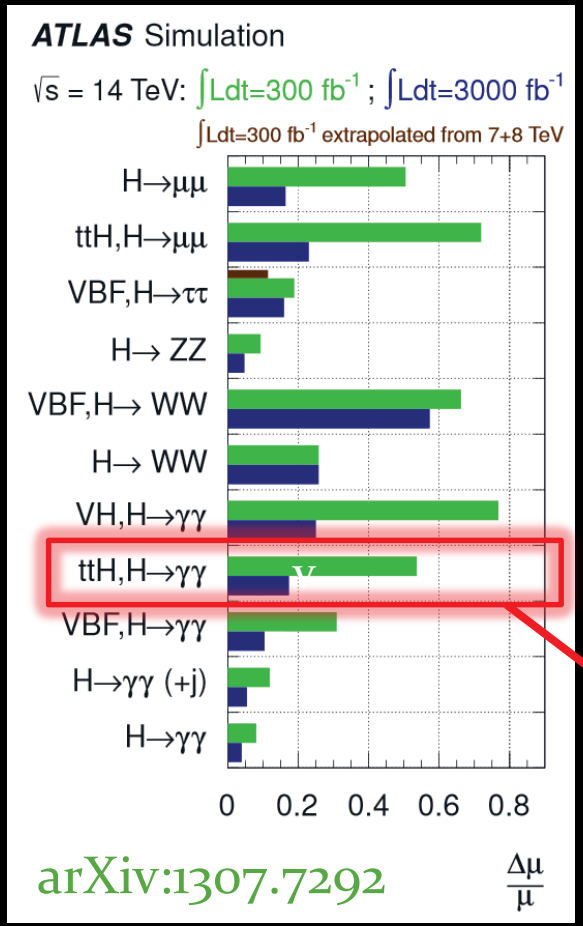
CMS-HIG-13-029

→ sensitivity close to SM prediction

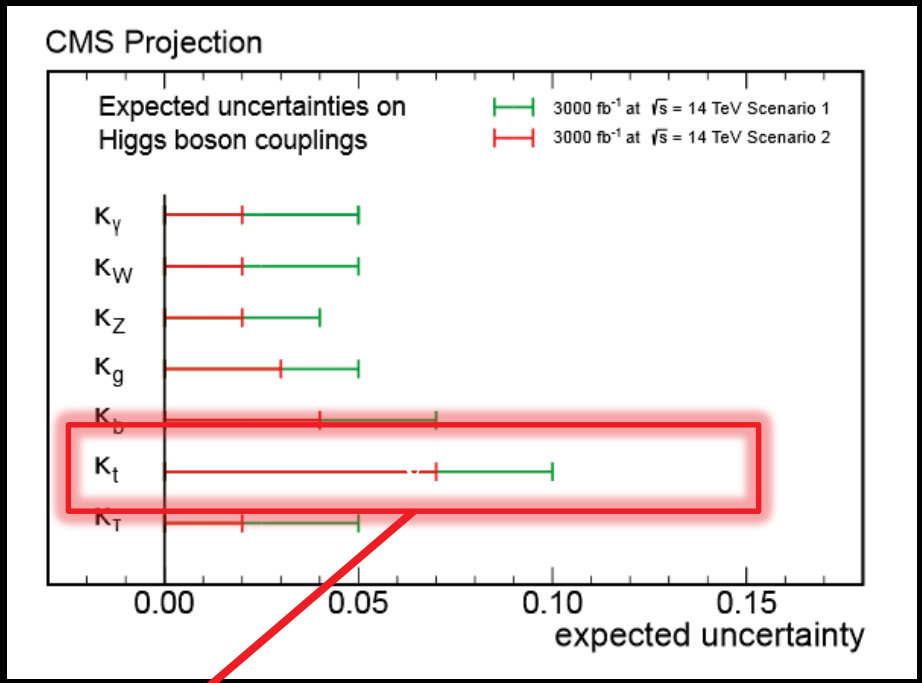
tt+h prospects at 13/14TeV

- cross-section more sensitive to pdfs fall: $\sigma_{tth}^{14\text{TeV}} \approx 4.6 \times \sigma_{tth}^{8\text{TeV}}$

$(\sigma_h^{14\text{TeV}} \approx 2.6 \times \sigma_h^{8\text{TeV}})$



arXiv:1307.7292

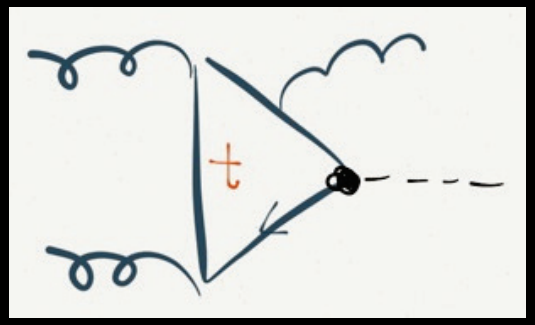


$\Delta c_t/c_t \approx 10\%$ by ~2030

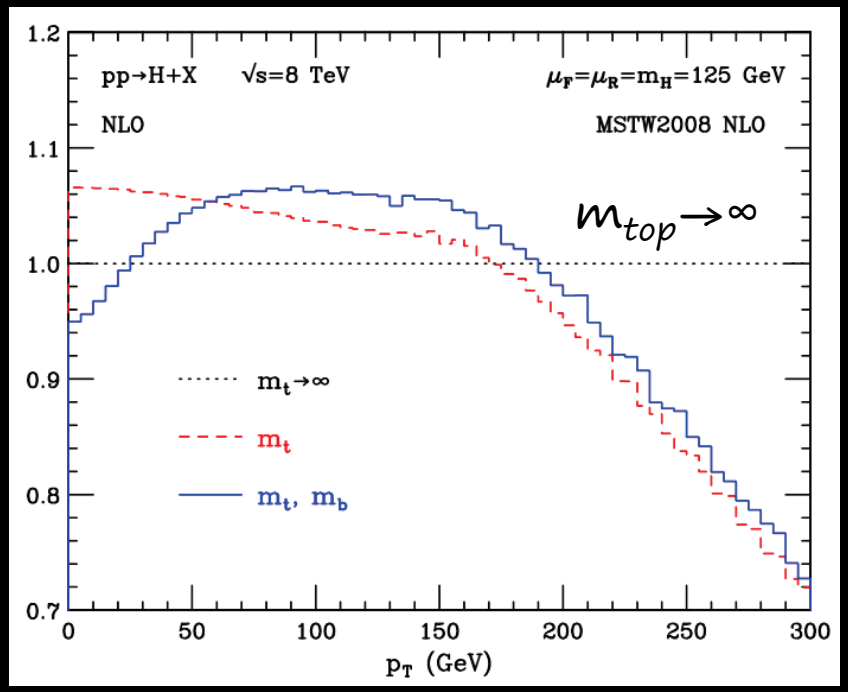
(ILC: ~5%)

Complementary probes of the top/Higgs coupling

Very boosted Higgs production:



for $p_T^{\text{Higgs}} > m_{\text{top}}$, the top loop is no longer point-like



Grazzini-Sargsyan '13

EFT (ie. LET) breaks down, more operators needed beyond $hG^a_{\mu\nu}G^{\mu\nu a}$

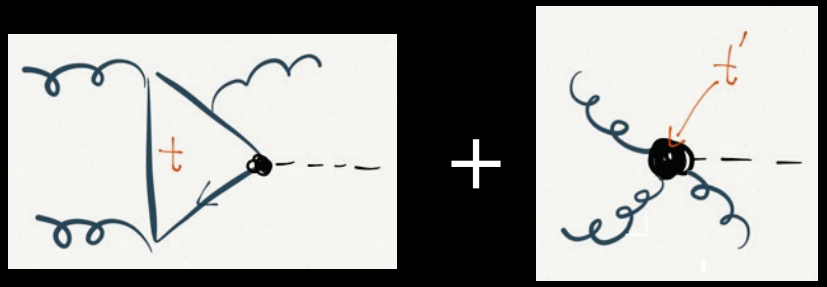
$e.g.\ (\partial^2 h)G^a_{\mu\nu}G^{\mu\nu a}$

....

Very boosted Higgs production:

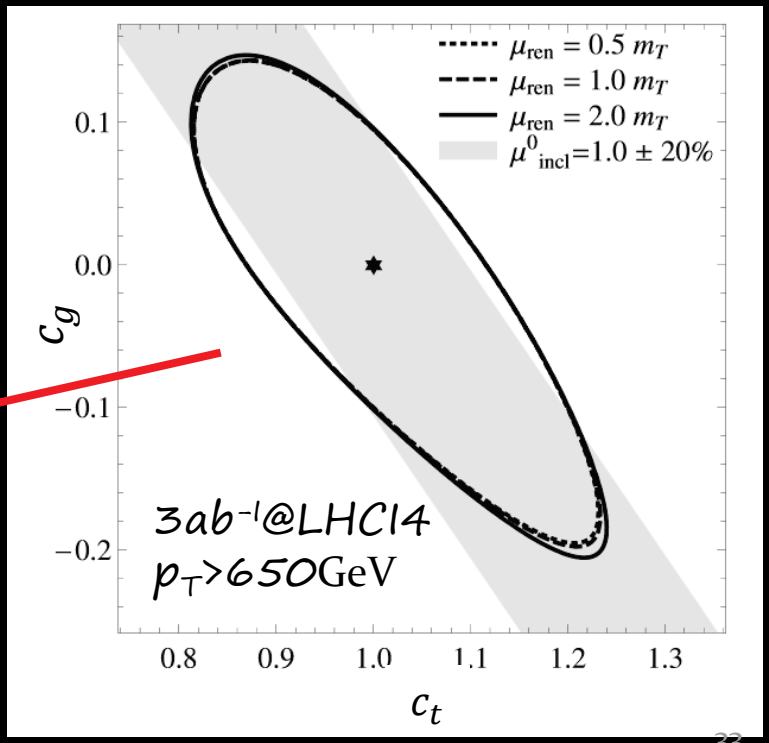
Grojean-Salvioni-Schlaffer-Weiler *'13*
see also Banfi-Martin-Sanz '13

requiring $p_T^{\text{Higgs}} > m_{\text{top}}$ resolves the top loop
and lift up the degeneracy w/ partners



$\Delta c_t/c_t \approx 20\%$

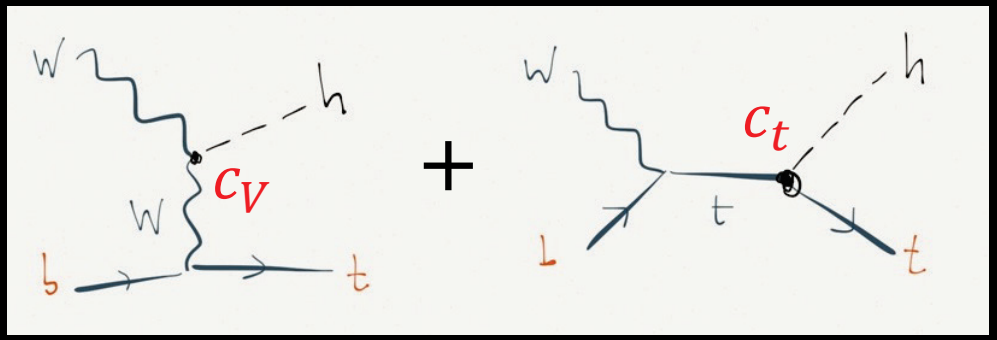
same ballpark as tt+h channel

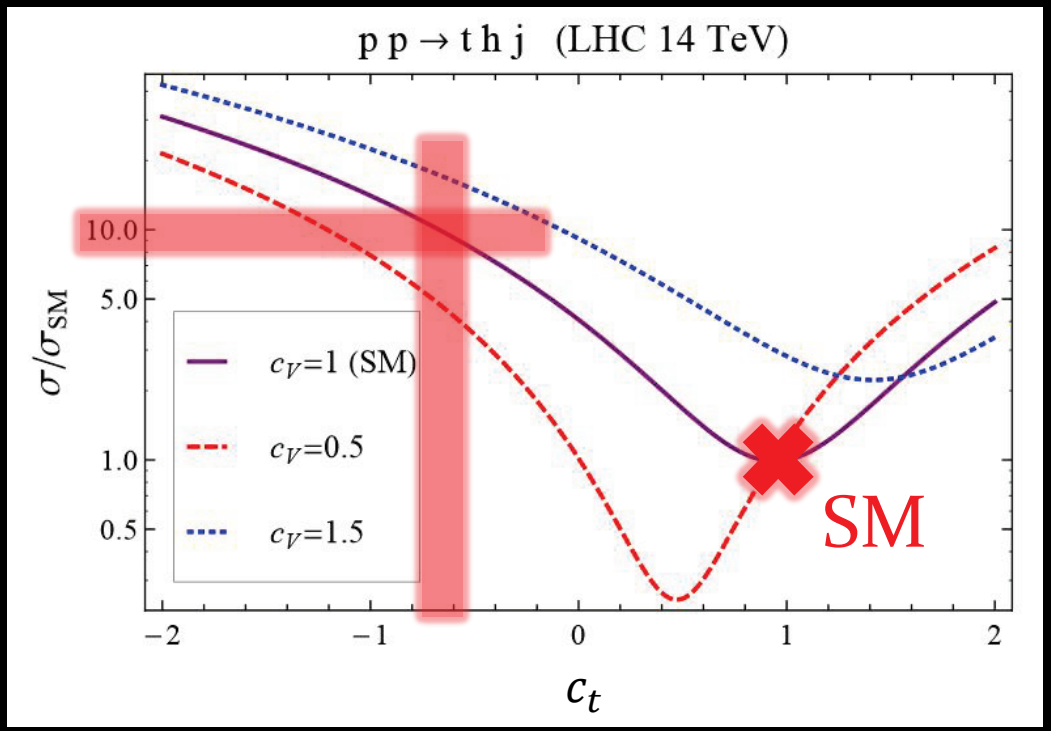


Single top + Higgs production:

Farina-Grojean-Maltoni-Salvioni-Thamm '12
Biswas-Gabrielli-Mele '12

Sensitive probe of $c_t < 0$,
due to large interference:



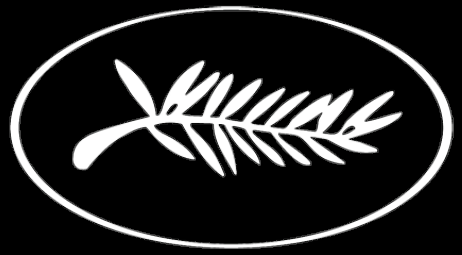


o(10) enhancement
relative to SM!

(SM : $\sigma_{thj}^{14\text{TeV}} \approx 88\text{fb}$)

Conclusions

Take home:

- top/higgs coupling = 

  = most important coupling to measure

  → directly probes naturalness*

- tt+h = cleanest (tree-level) probe, but challenging

- complementary channels will help unveiling top partner presence + spectrum, properties…

* in contrast with *e.g.* higgs self-interactions…