Higgs (related) physics at the 13 TeV LHC

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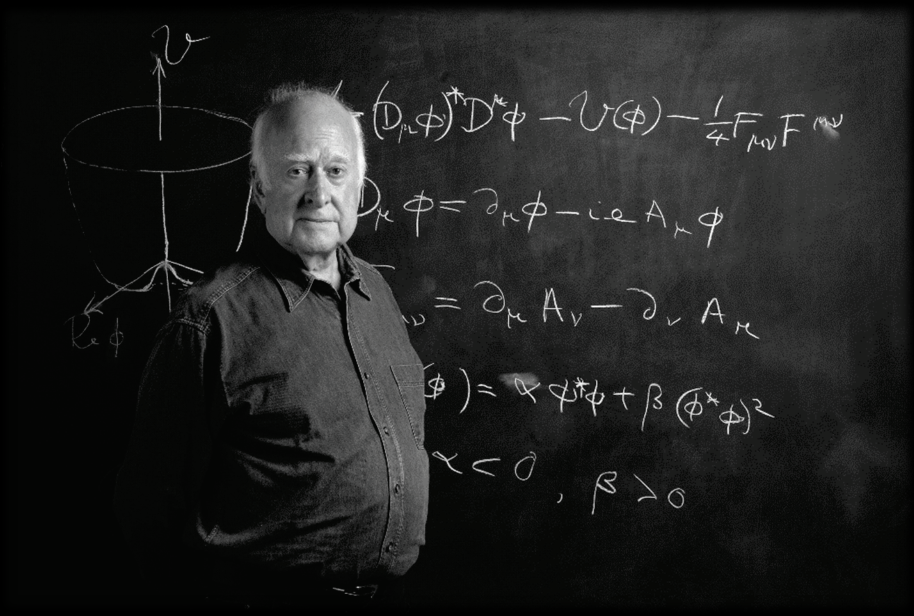


Enigmass, Nov. 28, 2014

Outline

- Main lesson from LHC run 1: $m_h = 125\,\mathrm{GeV}$
  $\rightarrow$ SM could rule up to $M_{\mathrm{Planck}} \sim 10^{19}\,\mathrm{GeV}$

- Why this is not the end of the story?
  $\rightarrow$ light Higgs boson needs new TeV-scale physics

- Some critical tests for LHC run 2+

Morale from LHC run 1:

A 125GeV Higgs boson restores unitarity

Standard Model w/out the Higgs

- nlσ-model of EW symmetry breaking: $v = \left(\sqrt{2}G_F\right)^{-1/2}$

$$\mathcal{L}_{\mathrm{SM}-h} = \mathcal{L}_{\mathrm{gauge}} + \frac{v^2}{4}\mathrm{Tr} D_\mu \Sigma^\dagger D^\mu \Sigma$$

W/Z masses

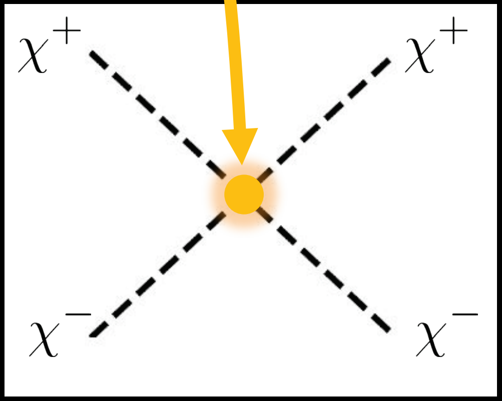
$$-\frac{v}{\sqrt{2}}\bar{q}\Sigma\left(y_u u + y_d d\right) + \mathrm{h.c.}$$

fermion masses

$\Sigma = e^{\frac{i}{v}\sigma^a \chi^a(x)}$ = Goldstone matrix

$$\chi^a \to \chi^a + \frac{v}{2}\left[\theta^a_L(x) - \delta^a_3 \theta_Y(x)\right]$$

$W_L^+ W_L^- \to W_L^+ W_L^-$ violates (perturbative) unitarity at $E \sim 4\pi v$



$\sim \dfrac{E^2}{v^2}$

[strongly coupled]

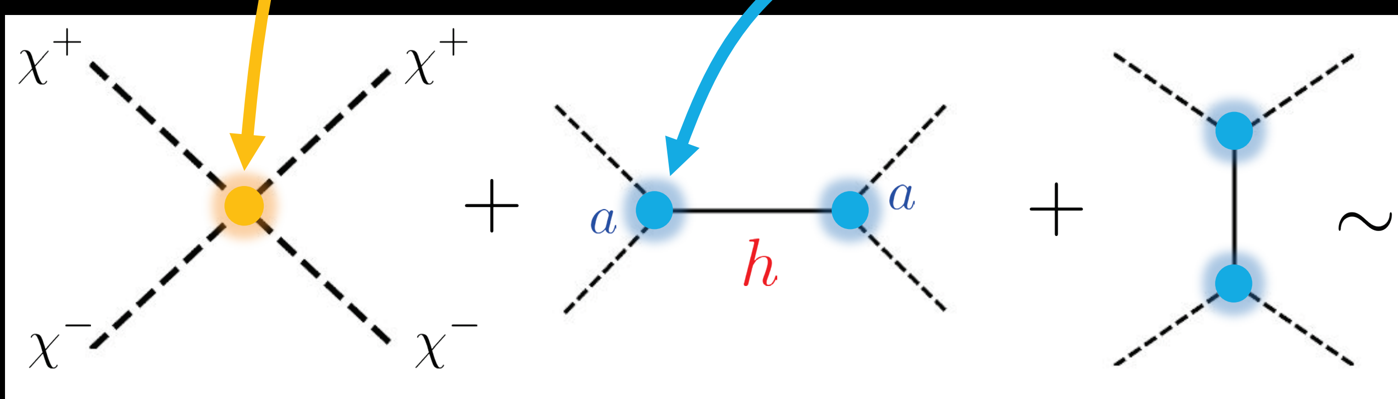
Standard Model w/ a Higgs

- adding a scalar singlet h:

$$\mathcal{L}_{\overline{\mathrm{SM}}} = \mathcal{L}_{\mathrm{gauge}} + \frac{1}{2}\left[(\partial_\mu h)^2 - m_h^2 h^2\right] + \frac{v^2}{4}\mathrm{Tr}\, D_\mu \Sigma^\dagger D^\mu \Sigma \left(1 + 2a\frac{h}{v} + b\frac{h^2}{v^2} + \cdots\right)$$

$$-\frac{v}{\sqrt{2}}\bar{q}\Sigma\left(1 + c\frac{h}{v} + \cdots\right)(y_u u + y_d d) + \mathrm{h.c.}$$

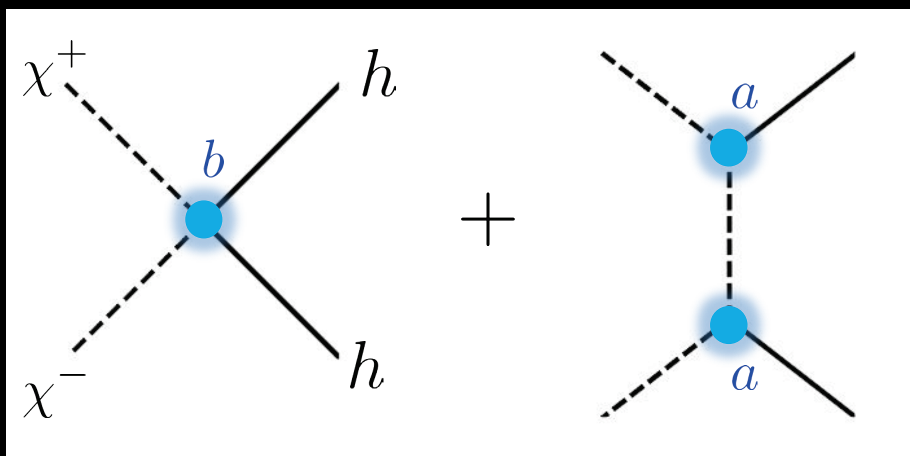
assuming $m_h \ll 4\pi v \sim 1\,\mathrm{TeV}$



$$\sim \frac{E^2}{v^2}\left(1 - a^2\right)$$

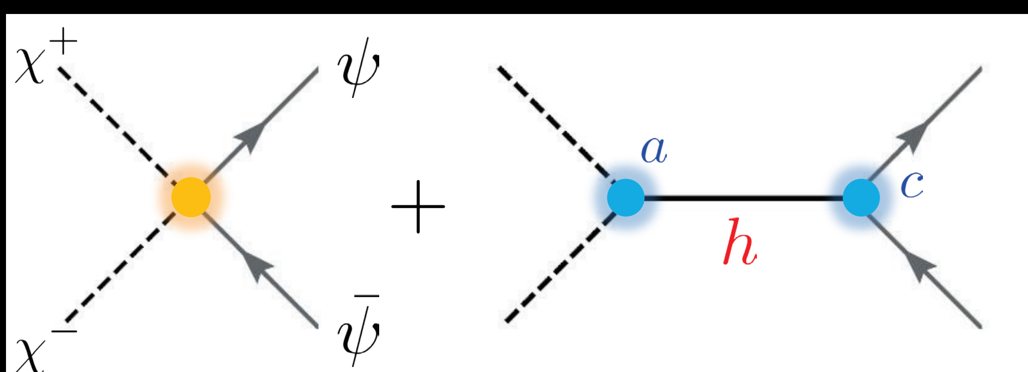
Standard Model w/ a Higgs

- other channels where unitarity is at stake:



$$\sim \frac{E^2}{v^2}\left(b - a^2\right)$$

$\hookrightarrow b \simeq a^2 \simeq 1$



$$\sim \frac{m_\psi E}{v^2}\left(1 - ac\right)$$

$\hookrightarrow c \simeq 1$

Pre-LHC one billion € question:

- What restores unitarity in the EW sector?

1. strong dynamics → *e.g.* technicolor theories

2. light scalar exchange w/ $a \simeq b \simeq c \simeq 1$

Pre-LHC one billion € question:

- What restores unitarity in the EW sector?

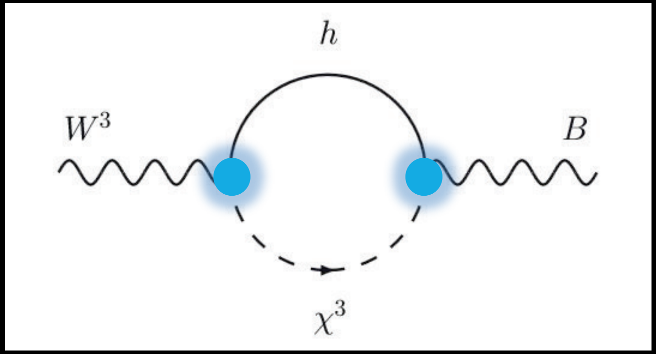
1. strong dynamics → *e.g.* technicolor theories

2. light scalar exchange w/ $a \simeq b \simeq c \simeq 1$

already favored
by EW precision LEP data

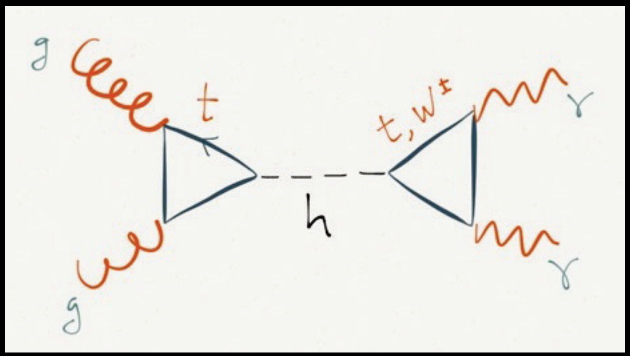
$m_h \sim \mathcal{O}(100\,\mathrm{GeV})$

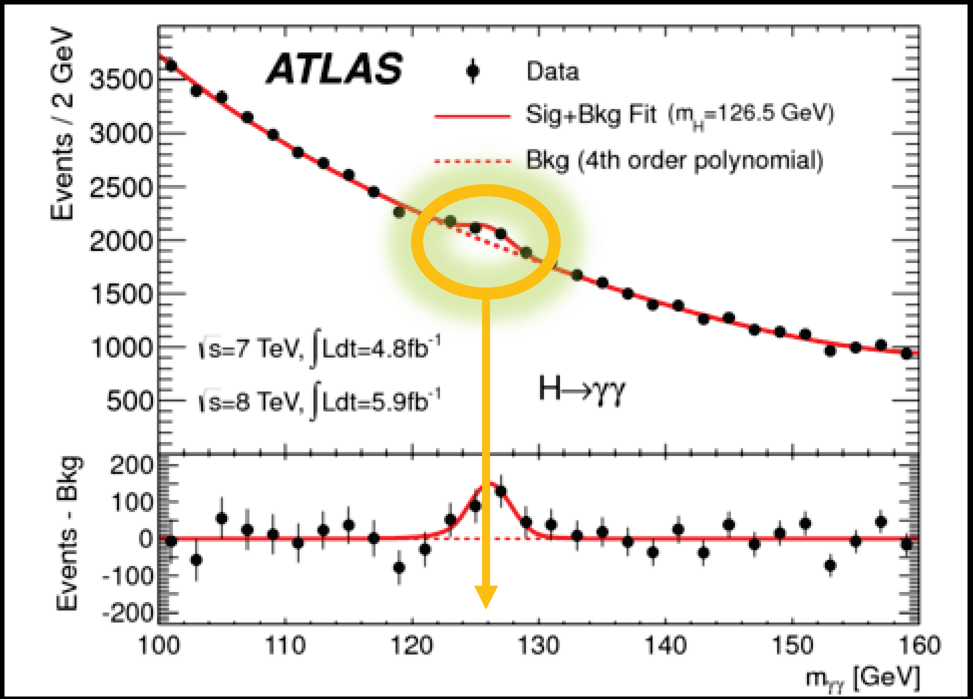
$|1-a| \simeq \text{few} \times 10^{-2}$



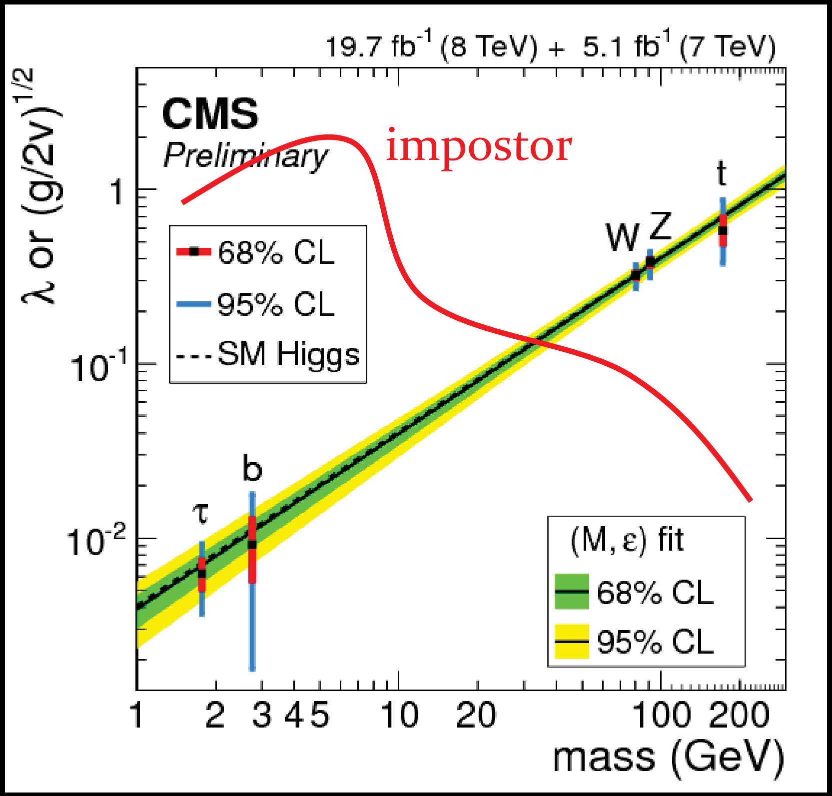
(First?) LHC great success

e.g.





$m_h \simeq 126\,\mathrm{GeV}$



Higgs couplings indeed roughly scale like masses

[Nature is weak]

The Standard Model Higgs

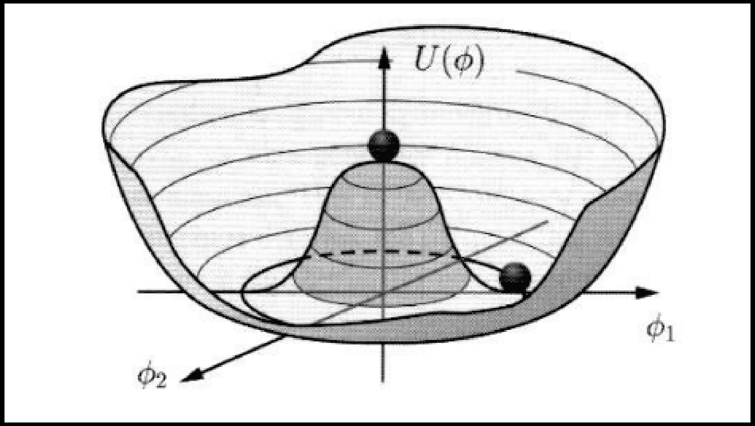
- SM is **defined** by $a = b = c = 1$, it's an **ideal** description, unitary up to arbitralily high energies

$$\mathcal{L}_{\rm SM} = \mathcal{L}_{\rm gauge} + |D_\mu H|^2 - V(H) - \left[\bar{q}\left(y_u \tilde{H} u + y_d H d\right) + \text{h.c.}\right]$$

h part of an $\mathrm{SU}(2)_L$ doublet:

$$H = e^{\frac{i}{v}\sigma^a \chi^a} \begin{pmatrix} 0 \\ \frac{v+h}{\sqrt{2}} \end{pmatrix}$$

$$V(H) = m^2 H^\dagger H + \lambda \left(H^\dagger H\right)^2$$

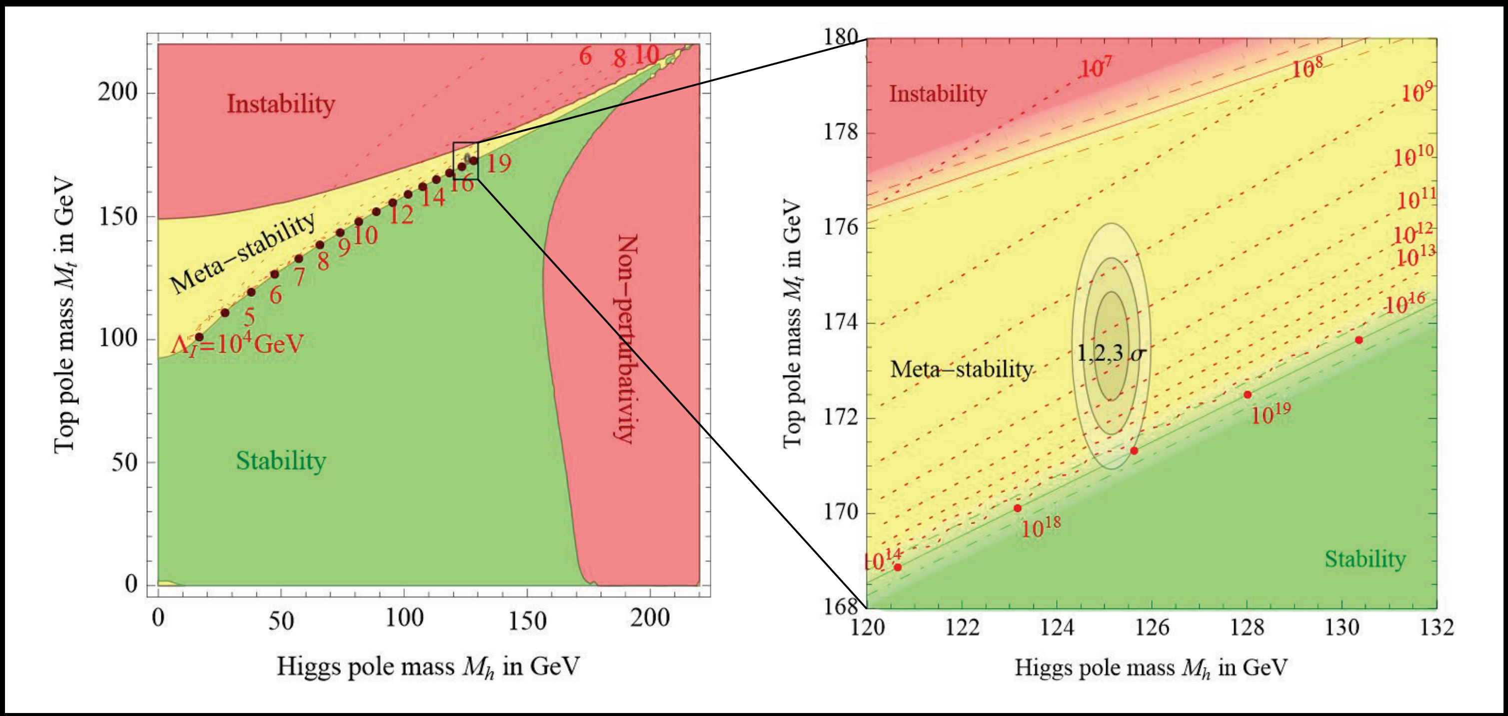


Taking $m^2 < 0 \rightarrow$ EWSB

$$v = \sqrt{\frac{-m^2}{\lambda}} \qquad m_h = \sqrt{2\lambda} v$$

The SM until the Planck scale?

- SM «phase diagram»:



$$\beta_\lambda = \frac{d\lambda}{d\log\mu} = \frac{1}{16\pi^2}\left[-6y_t^4 + 12y_t^2\lambda^2 + 24\lambda^2 + \text{gauge}\right] + \text{2loops} + \text{3loops} + \cdots$$

Why then extend the SM?

Are there chances to discover something new at the LHC?

Advocated SM shortcomings:

- neutrino mass: $\frac{y_\nu}{M}\overline{l^c}\widetilde{H}^*\widetilde{H}l \quad \rightarrow \quad \frac{1}{2}m_\nu \nu^T \nu$

  [accidental SM sym.]

- baryon asymmetry: $\frac{1}{M^2}q^c q q^c l$

- dark matter: fermion singlet $\rightarrow \frac{1}{M_{\mathrm{Pl}}^{n\geq 1}}\mathcal{O}_{\mathrm{DM}}\mathcal{O}_{\mathrm{SM}}$

- flavor hierarchies: marginal $y \quad \rightarrow$ no scale

$\rightarrow$ *none favors **low energy** extensions of the SM*

The SM issues

- Strong CP problem:

fine-tuning [no scale]

no n-EDM $\rightarrow$ $\theta_{\text{phys}} = \theta_{\text{QCD}} + \arg\det m_q \lesssim 10^{-10}$

- Higgs mass problem:

$$m^2_{\text{phys}} = m^2 + \frac{\alpha_{\text{SM}}}{4\pi} M^2 \simeq -\mathcal{O}(m_W^2)$$

$V(H) = m^2 H^\dagger H + \lambda \left(H^\dagger H\right)^2$

fine-tuning if $M \gg m_W$

- SM merely accounts for EWSB, not an explanation

Why $m^2_{\text{phys}} < 0$ *?*

Fine-tuning for dummies

Two possibilities:

- $\sim 10^{23}$ air molecules conspire to move upwards long enough to balance the gravitational pull of the Earth..

= short/long distance fine-tuning

- *There is a trick!* a hidden structure warrants stability

HEP most burning question:

What is the structure stabilizing $m^2 H^\dagger H$ *?*

The absolute main goal of LHC run2+ is to provide (elements of) an answer

New physics best contenders

- Supersymmetry: $m^2 H^\dagger H \leftrightarrow m\overline{\psi}_H \psi_H$

$$\delta m \propto m\left(a + b\log\frac{M}{m}\right)$$ from chiral symmetry

[e- mass]

- Composite pseudo-NGB Higgs: $H \to H + \text{cst}$

$$m^2 = \epsilon^2 \frac{\alpha_{\text{SM}}}{4\pi} M^2$$ $\epsilon =$ small shift sym. breaking

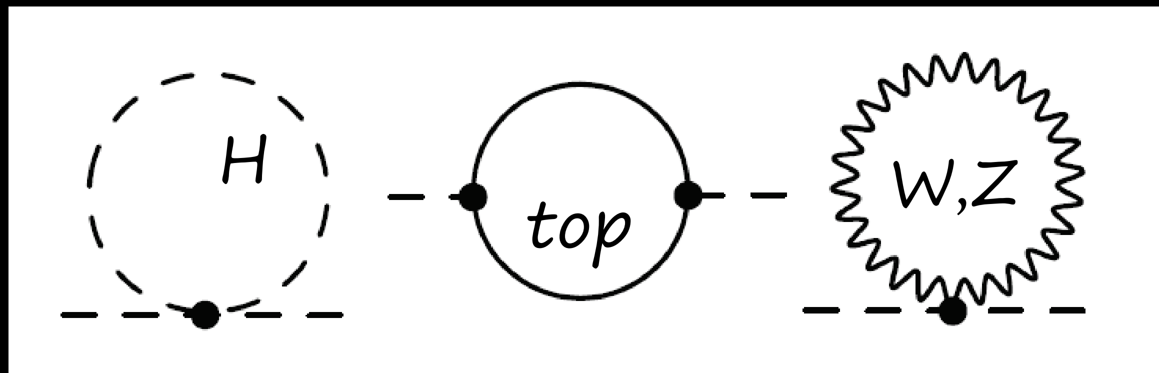
[pion mass]

(• Twin Higgs: $m^2(H_A^\dagger H_A + H_B^\dagger H_B)$ is SU(4) inv.)

The new physics natural scale:

[SM hint]

$$\delta m^2\Big|_{\rm SM} \simeq$$



$$\sim \frac{\Lambda^2}{16\pi^2}\left[6\lambda - 6y_t^2 + \frac{1}{4}\left(9g^2 + 3g'^2\right)\right] \sim \mathcal{O}(m_W^2)$$

$\Lambda_H \sim 1\,\mathrm{TeV}$
Higgs partners

$\Lambda_t \sim 400\,\mathrm{GeV}$
top partners

$\Lambda_W \sim 1\,\mathrm{TeV}$
gauge partners

($y_b \simeq 0.017 \rightarrow$ bottom partners at $\Lambda_b \sim 25\,\mathrm{TeV}$)

Searching for new physics at run 2:

Some important avenues

Two complementary approaches

- «energy» frontier:

  on-shell partner production

  $\to$ top partners

  ($\to$ W/Z partners)

- «intensity» frontier:

  precision measurements $\to$ h couplings

Two complementary approaches

- «energy» frontier:

  on-shell partner production

  $\rightarrow$ top partners

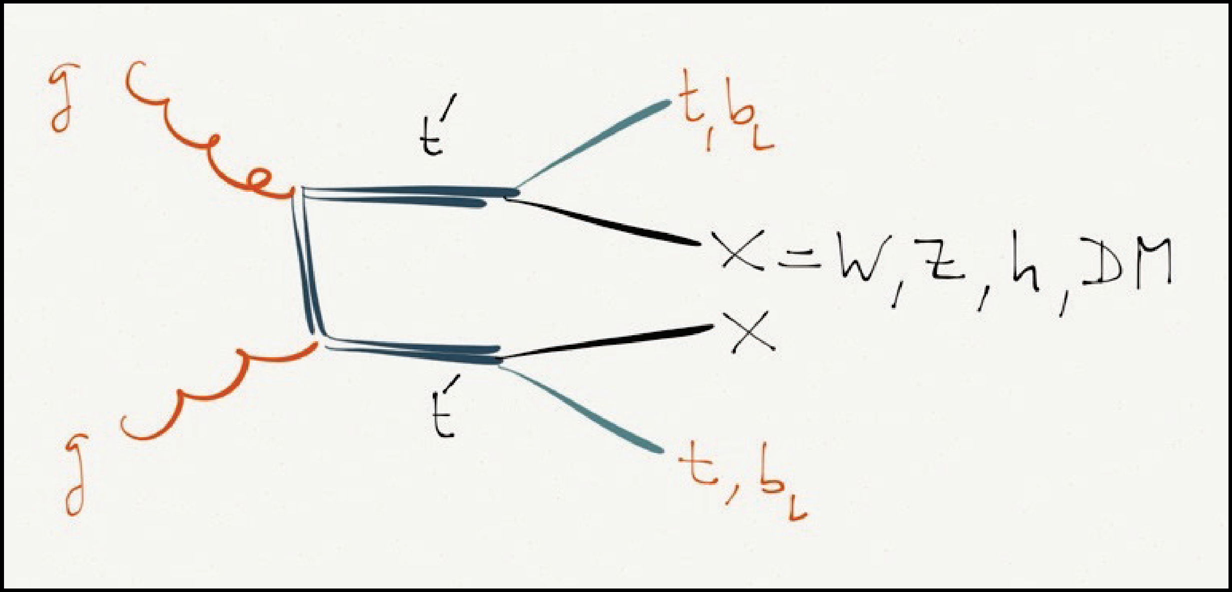
  ($\rightarrow$ W/Z partners)

- «intensity» frontier:

  precision measurements $\rightarrow$ h couplings

Direct searches of top partners

- $[T_{\rm QCD}, T_{\rm new}] = 0$ → colored top partners*
- secluded 3rd gen. → *t'* = mass-eigenstates



→ large visible signals at the LHC

counter example: twin Higgs

Top partner searches at LHC run1

- SUSY:

«MET-bound»:

$m_{\tilde{t}} \gtrsim 670\,\mathrm{GeV}$

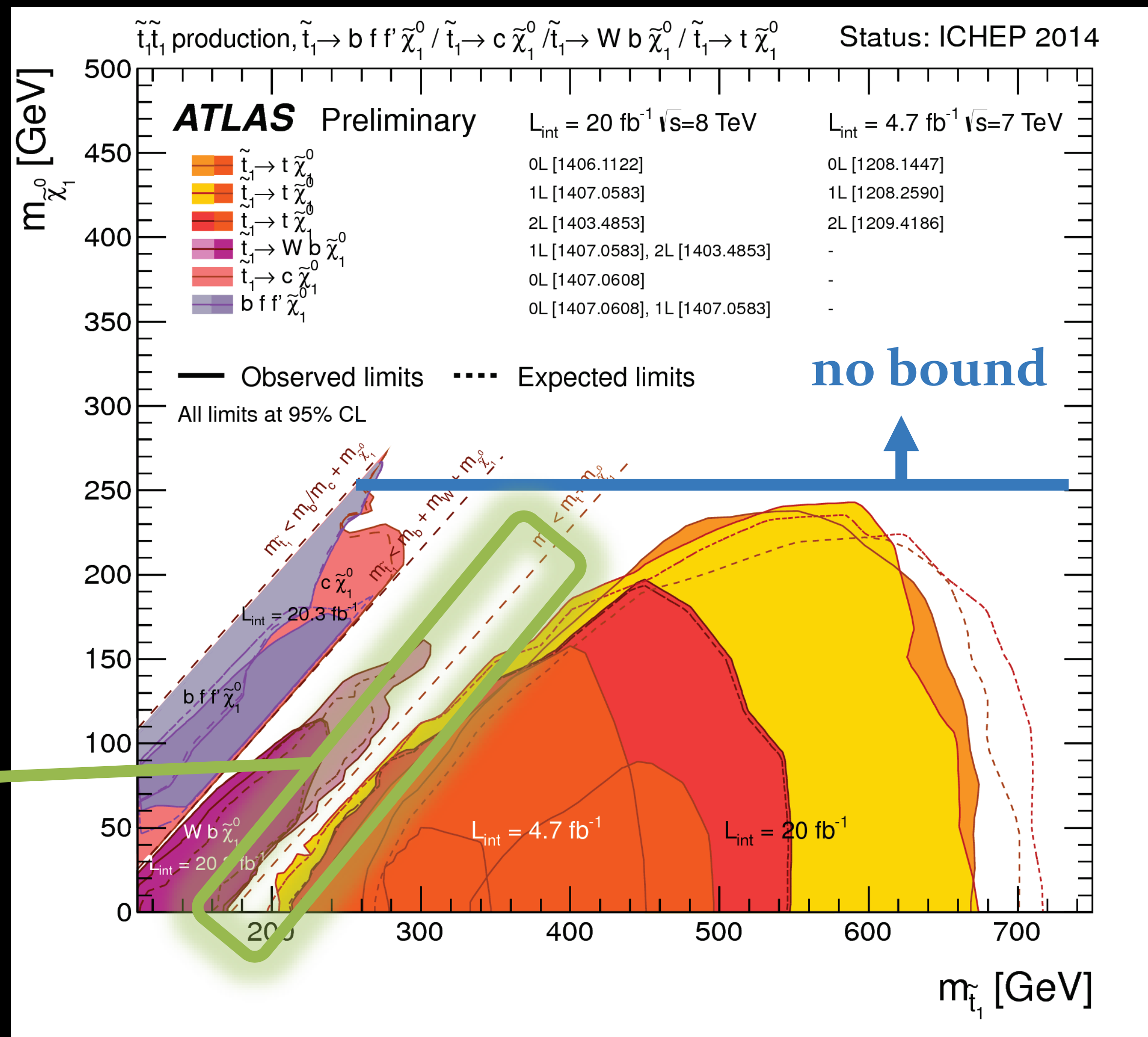
↓

$\mathcal{O}(10\%)$ fine-tuning

«stealth» region

(small MET)

spin-spin correlation
top pair cross-section



Top partner searches at LHC run1

- CHiggs:

2ssl-bound:

$$m_{T_{5/3}} \gtrsim 800\,\text{GeV}$$

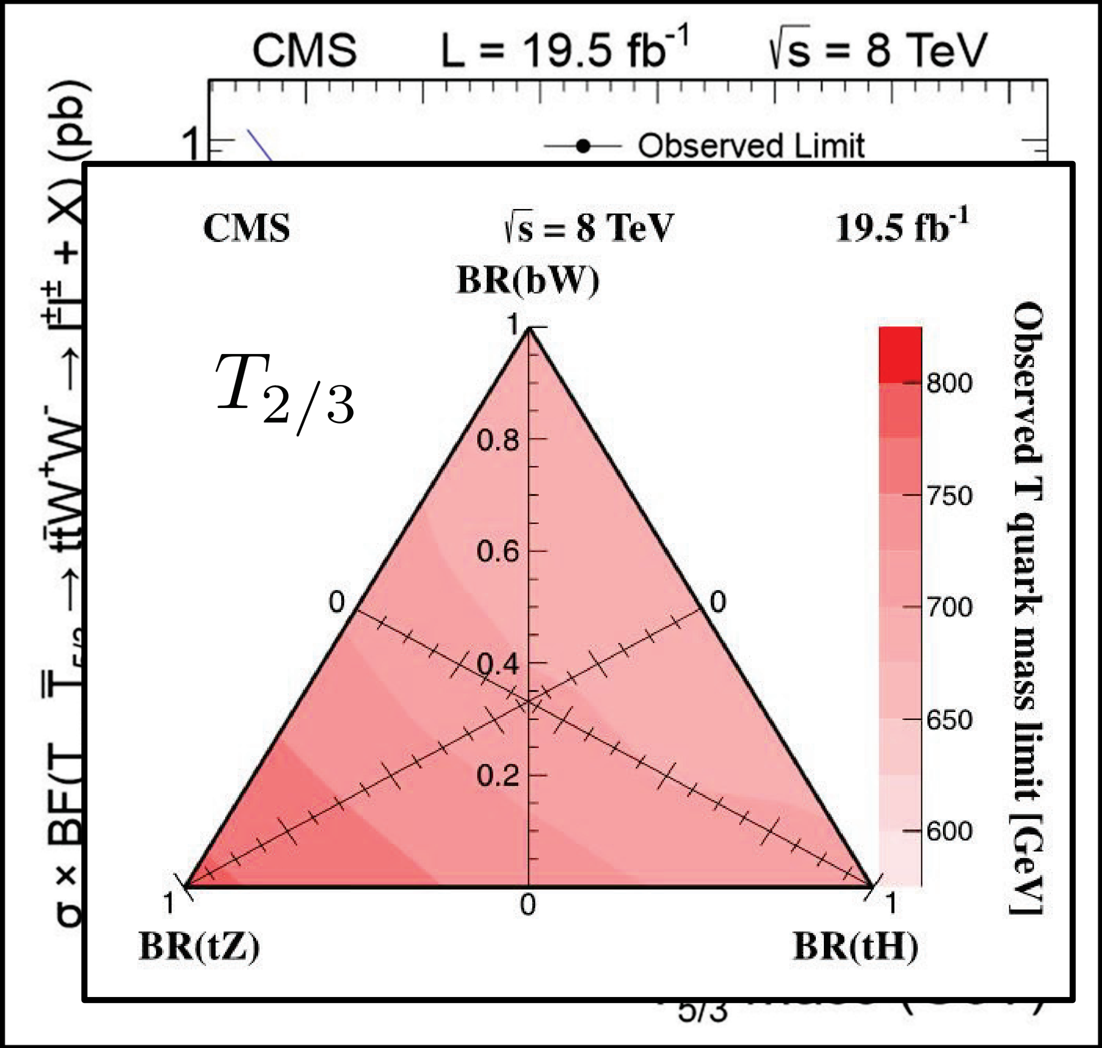
Q=2/3-bound:

$$m_{T_{2/3}} \gtrsim 690\,\text{GeV}$$

↓

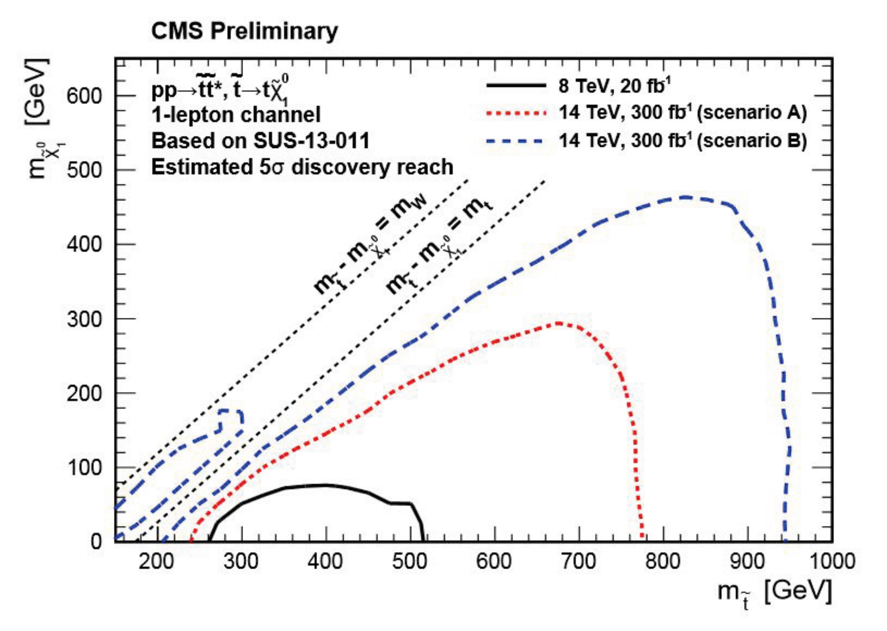
$\mathcal{O}(10\%)$ *fine-tuning*

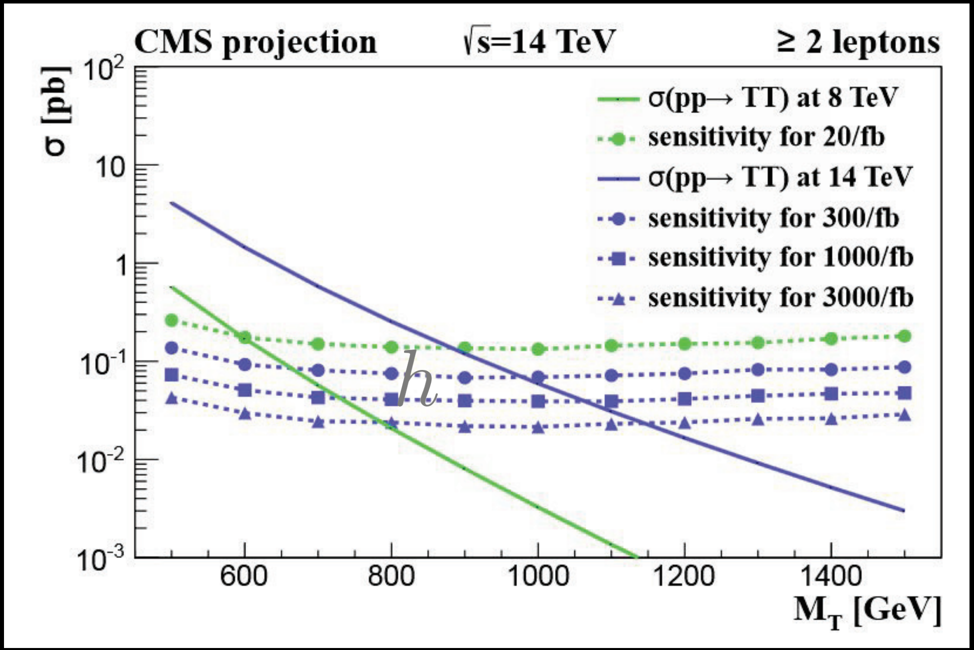
more robust than SUSY,
assumes model independent
QCD pair production,



Top partner searches summary:

- 8TeV run mildly pressures EW naturalness
- discovery reach @13/14TeV runs:





[+ closing the stealthy gaps]

[+ single production]

Two complementary approaches

- «energy» frontier:

    on-shell partner production

    $\rightarrow$ top partners

    ($\rightarrow$ W/Z partners)

- «intensity» frontier:

    precision measurements $\rightarrow h$ couplings

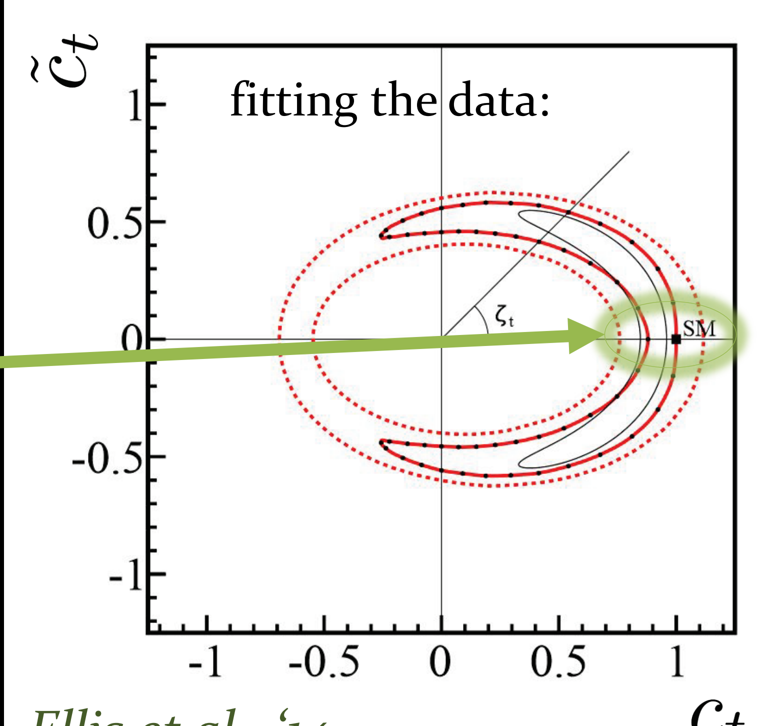
Higgs coupling to top quarks

- most important, direct window on naturalness
- contrary to common lore, not accessible in $\sigma^{\text{incl.}}_{pp\to h}$

$$-\frac{m_t}{v} h\bar{t}\,(c_t + i\gamma_5 \tilde{c}_t)\, t$$

e-EDM: $\tilde{c}_t \lesssim 10^{-2}$

LHC1 favors $c_t \simeq c_t^{\text{SM}} = 1$



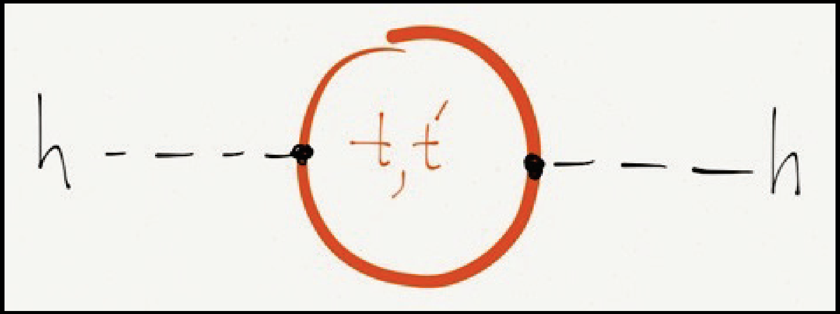
Ellis et al., '14

Brod-Haisch-Zupan, '13

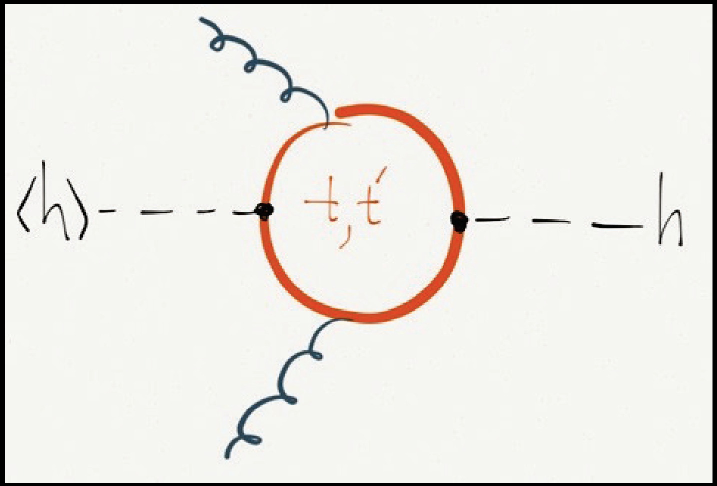
However, it does not include potential top partner loops...

Naturalness predicts: *Low-Rattazzi-Vichi, '09*

- If $[T_{\rm QCD}, T_{\rm new}] = 0$, the cancellation in



persists in



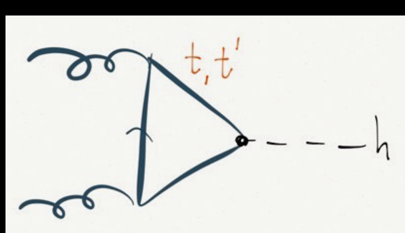
Higgs coupling to top quarks

- $m_{t'} \gg m_h \;\; \rightarrow$ EFT for partners: $-c_g \dfrac{h}{4v} G^a_{\mu\nu} G^{\mu\nu a}$

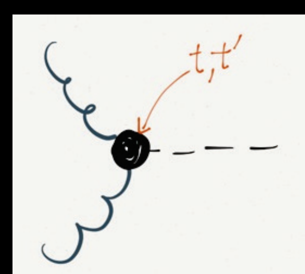
- $\sigma^{\text{incl.}}_{pp\to h}$ could be BSM driven
- only probes $c_g + \dfrac{\alpha_s}{3\pi} c_t$

Falkowski et al. '12

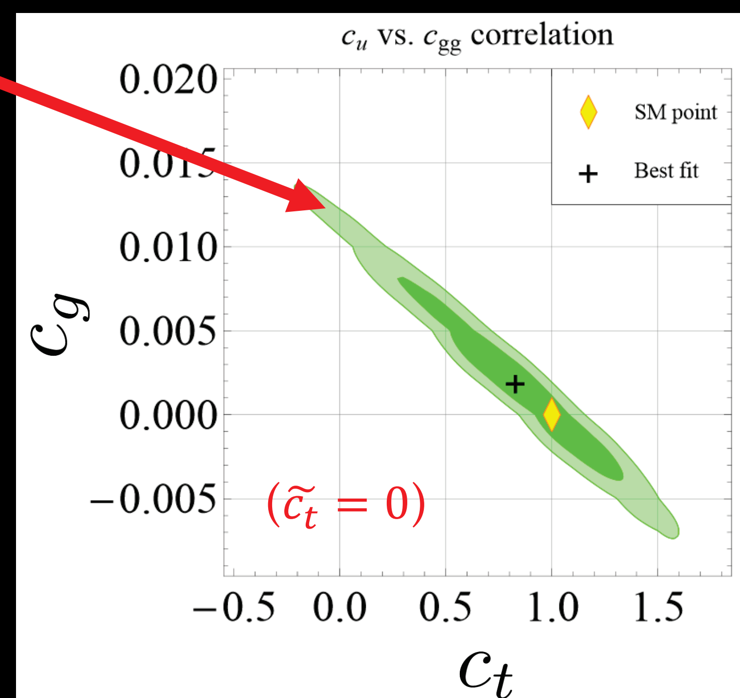
latest results from Belúsca-Maïto RPP2014



$\rightarrow$



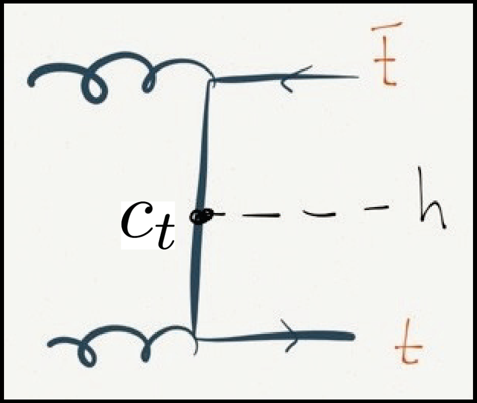
$m_{t,t'} \gg m_h$



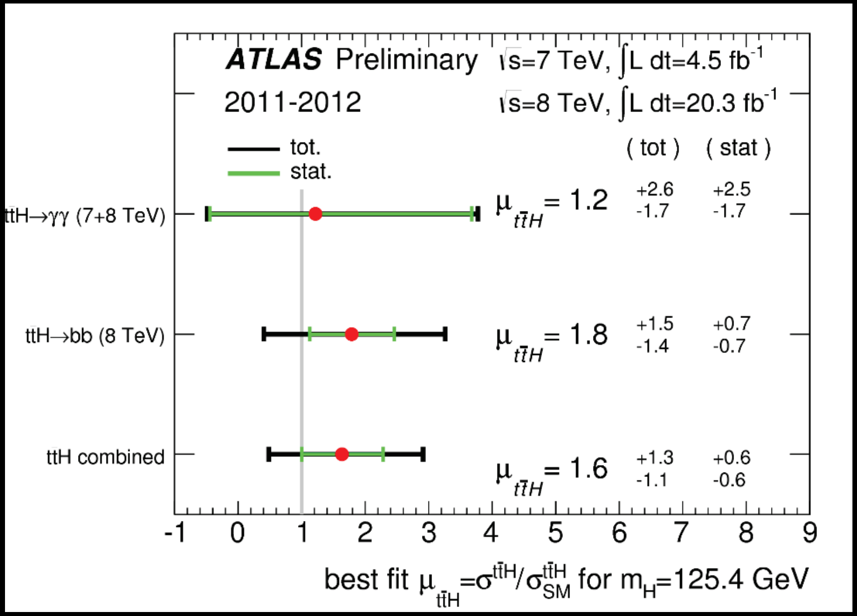
[can't resolve short/long distance]

Higgs coupling to top quarks

- $\sigma_{pp \to t\bar{t}+h}$ is a cleaner (tree-level) probe of c_t



but small signal (PDFs..)
+ large background



@8TeV : $0.6 \lesssim |c_t| \lesssim 1.7$

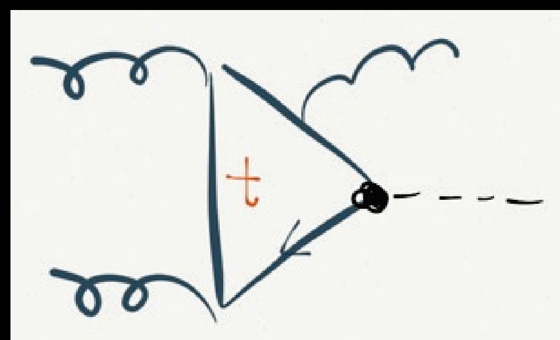
- HL-LHC lumi=3/ab

$$|c_t| \simeq 1 \pm \mathcal{O}(10\%)$$

Higgs coupling to top quarks

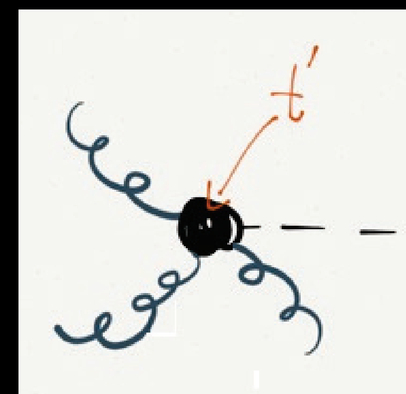
- alternate channel: boosted Higgs production

$\sigma_{pp\to h+j} = \Big($



long distance

$+$



short distance

$\Big)^2$

$p_T^h \gtrsim m_t$

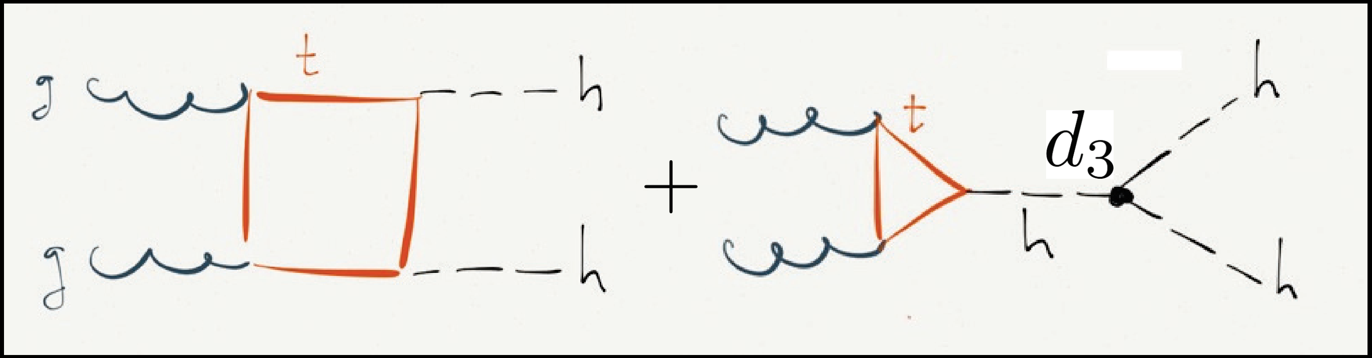
- optimistic estimate at HL-LHC:

$$|c_t| = 1 \pm \mathcal{O}(20\%)$$

Grojean-Salvioni-Schlaffer-Weiler '13
Banfi-Martin-Sanz '13
Buschmann-Englert-Goncalves-Plehn-Spannowsky '14

Higgs self-coupling

- test of the SM shape of $V(H)$
- only probe of $(H^\dagger H)^3$ operator
- LHC-access only through $\sigma_{pp\to hh}$



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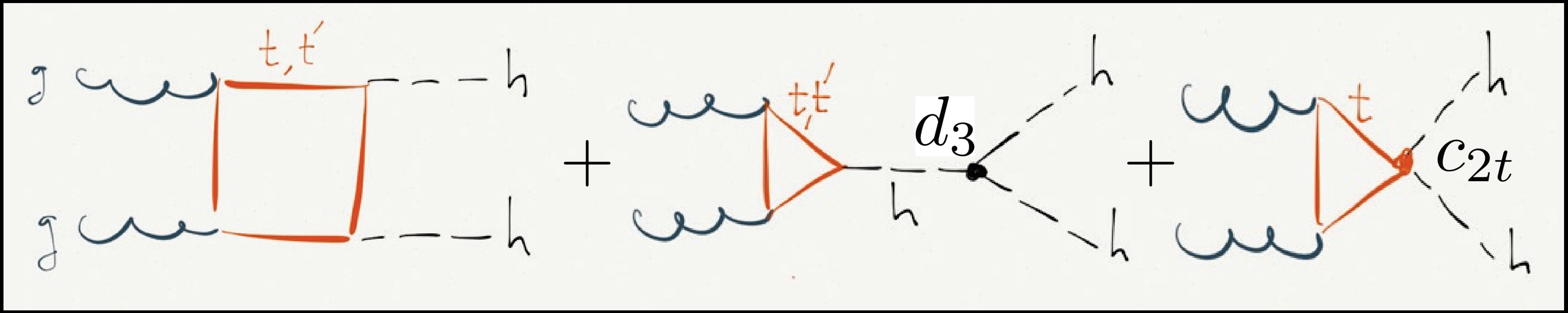


- polution from compositeness, partner loops
- remotely related to naturalness...

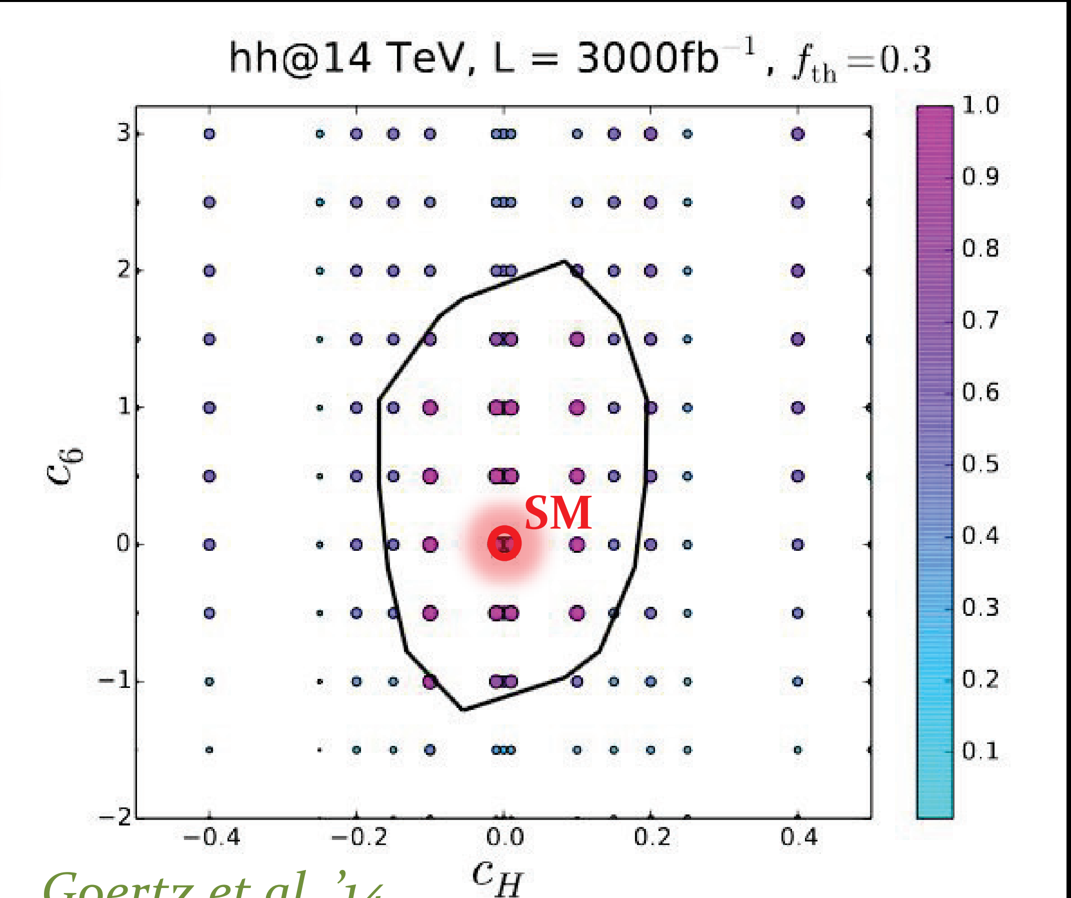
Higgs self-coupling

- HL-LHC (marginalizing over partner loops):

$$d_3 = \frac{3m_h^2}{v}\left(1 - \frac{3c_H}{2} + c_6\right)$$

$$\frac{1}{2}\left(\partial_\mu(H^\dagger H)\right)^2 \quad (H^\dagger H)^3$$

difficult to resolve at LHC



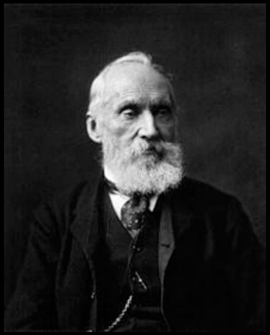
Goertz et al. '14

Conclusions

Take home

- SM w/ 125GeV Higgs = consistent description of EWSB up to $E \gg m_W$ $(M_{\rm Pl}?)$

- Present situation ressembles early XXe:



"There is nothing new to be discovered in physics now. All that remains is more and more precise measurement."

Lord Kelvin, 1900

- Let's not repeat Kelvin's mistake.

"I don't know the future.

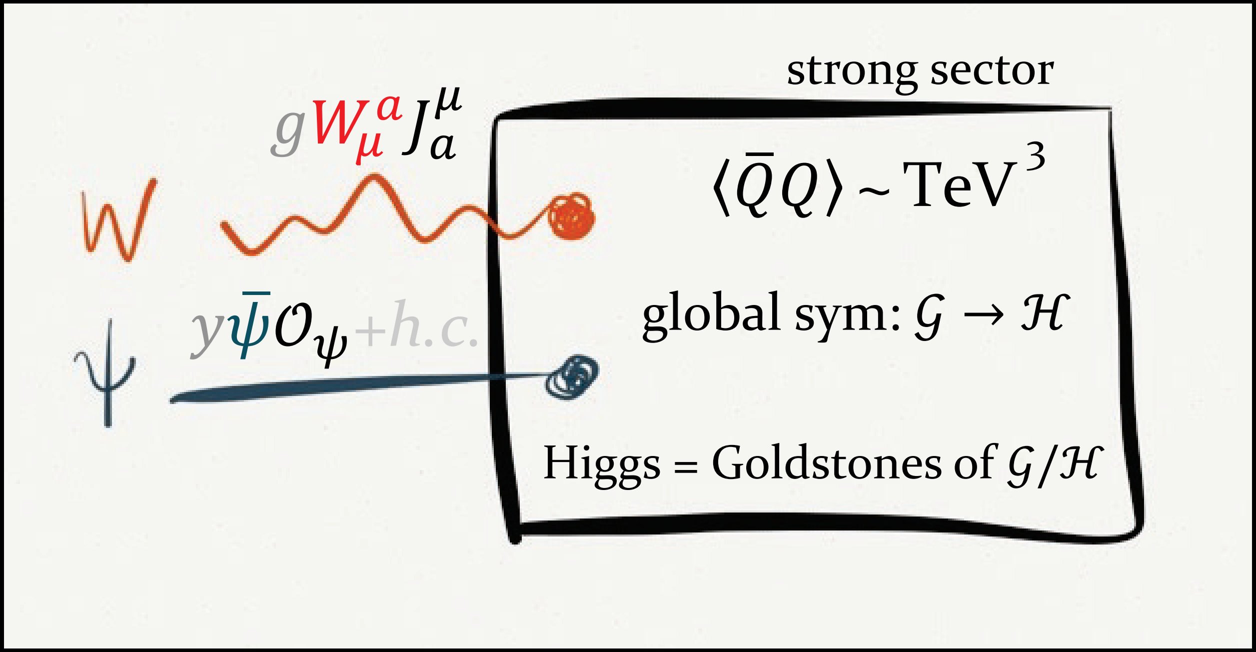
I didn't come here to tell you how this is going to end. I came here to tell how it's going to begin."

a late XXe american philosopher

Hopefully, the LHC is at the dawn of great discoveries

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_{top}):

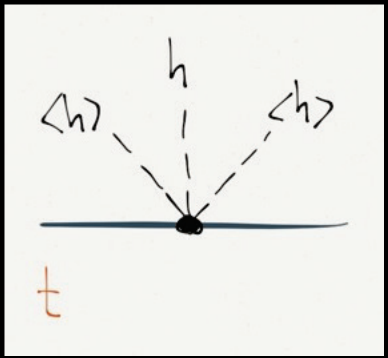
$$c_t = \frac{1 - \mathrm{n}\xi}{\sqrt{1-\xi}} + \delta c_t^{\psi}$$

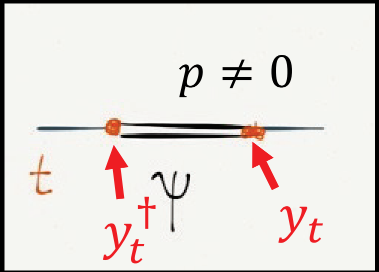
n = positive integer

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

H compositeness (< 0)

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





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

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