Probing New Physics from the Top

Cédric Delaunay

LAPTh, Annecy-le-Vieux, France

Outline

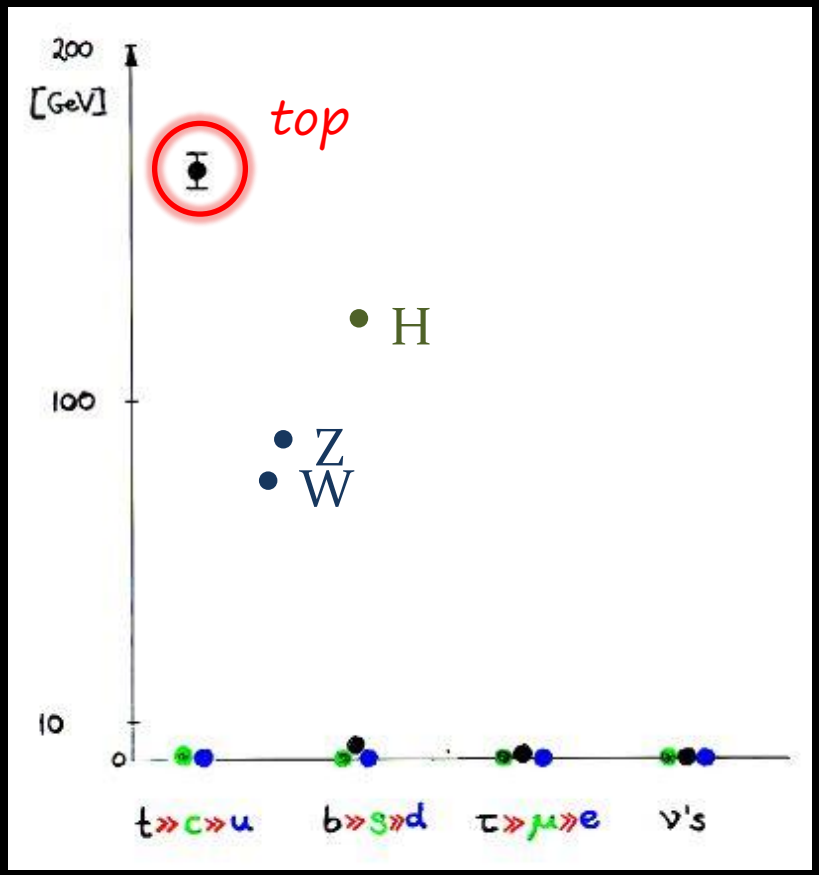
- Top is a weak-scale destabilizer in the SM

- Top as the lightest state of a BSM «top sector»
  → Direct searches of colored states decaying into top

- New physics in Top properties:
  → Top pair production at hadron colliders
  → Top-Higgs signals
  → Top FCNC decays *(if BSM flavor structure non-trivial)*

Top quark in the SM

heavy top quark is special:



[adapted from Weiler top2013]

- *experimentally:*

  heavy top does not hadronize

  $\Gamma_{top} >> \Lambda_{QCD}$

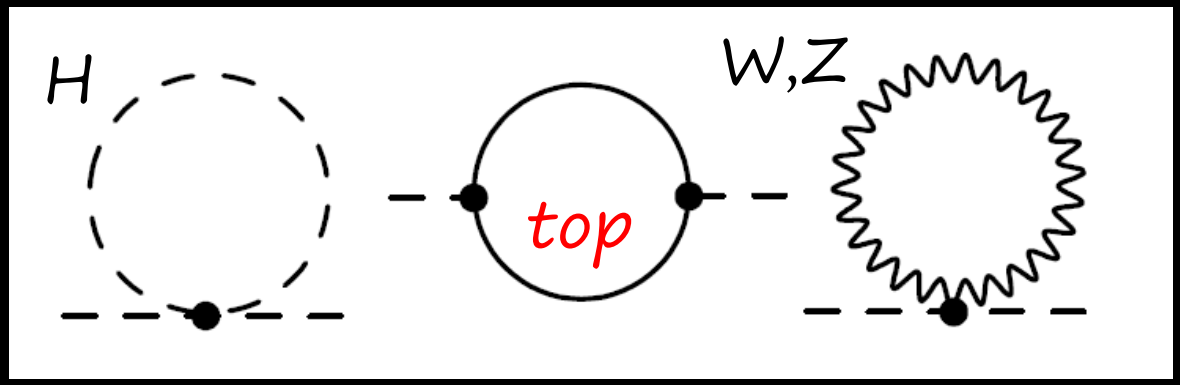
- *theoretically:*

  heavy top destabilizes

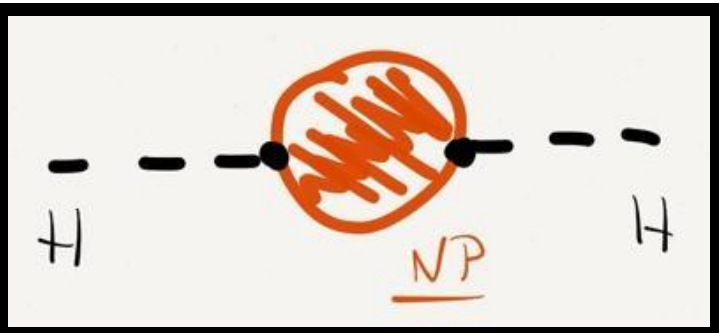
  the weak scale

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

SM Higgs is unaturally light:

$\delta m^2 =$ 

$\sim \Lambda^2$

$+$ 

$= \log(\Lambda)$ or *finite*

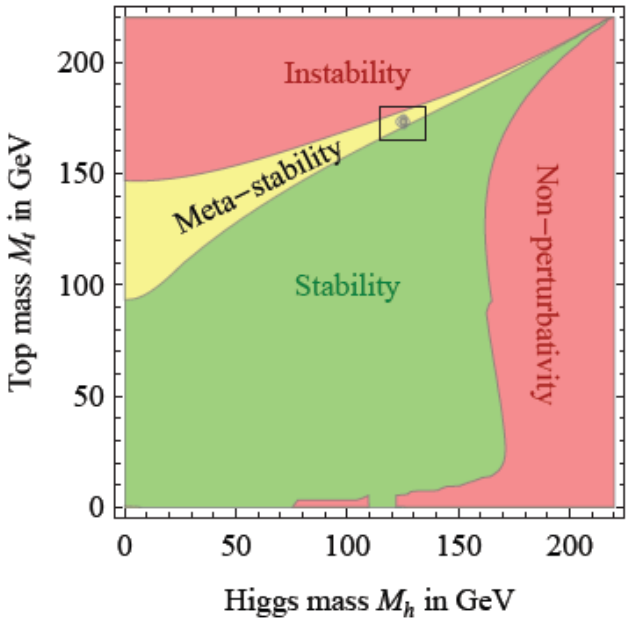
Nature's natural → $\Lambda \sim$ TeV 2 ***new physics*** paths:

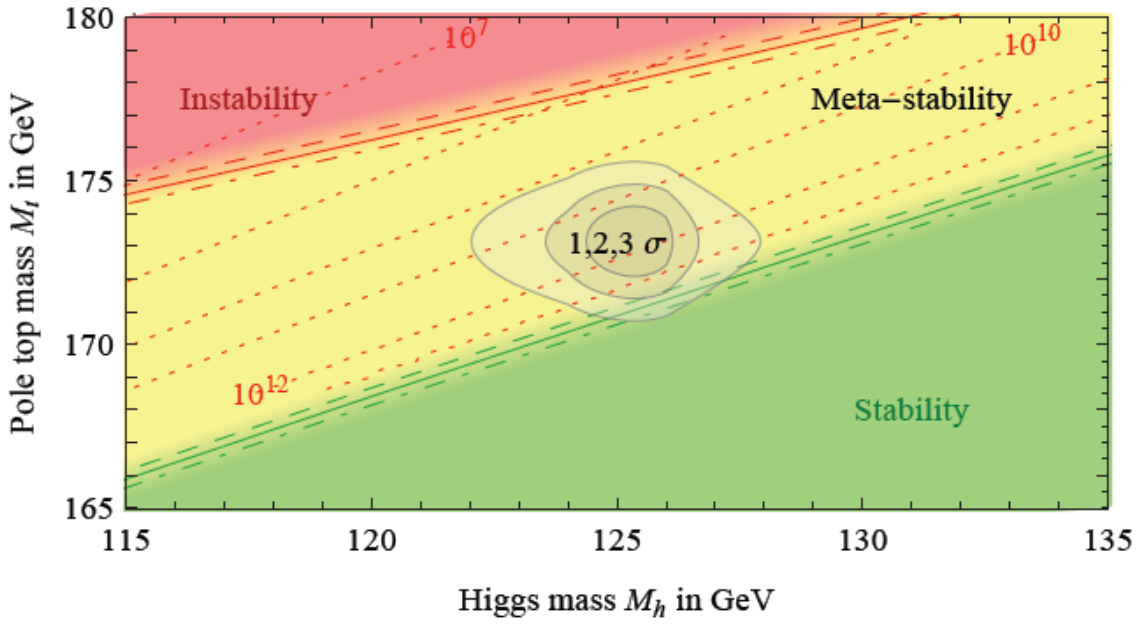
- $\Lambda \sim M_{Pl}$ but new symmetry kicks in at the TeV scale
  e.g. supersymmetry
- SM fields couple to a new strong dynamics with $\Lambda \sim$ TeV
  e.g. composite PGB Higgs models

SM top as a destabilizing agent, part 2:

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

Degrassi et al. '12

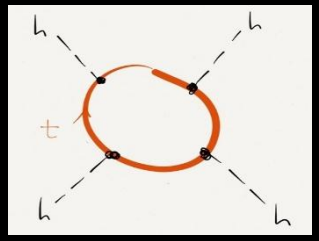


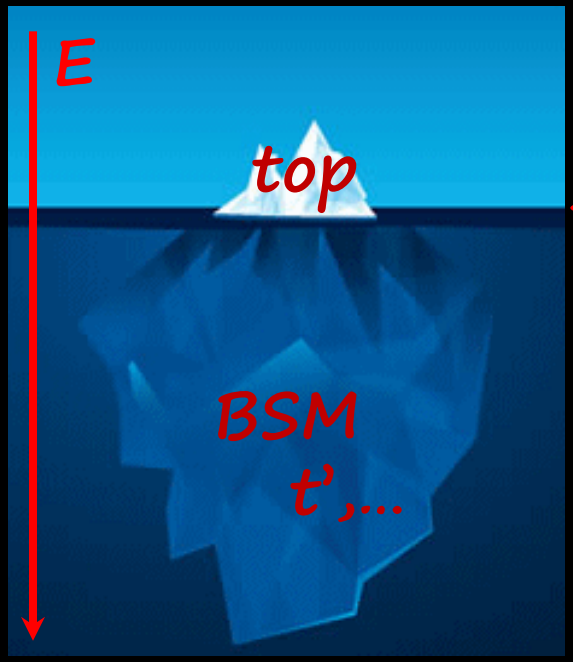


Higgs quartic turns negative at $\Lambda \approx 10^{11}$GeV: $d\lambda/d\log\mu \approx -N_c y_t^4/8\pi^2$

Dirac stat.

had m_{top} been ~3% larger,
we would not have been here!





Naturalness predicts a top quark sector

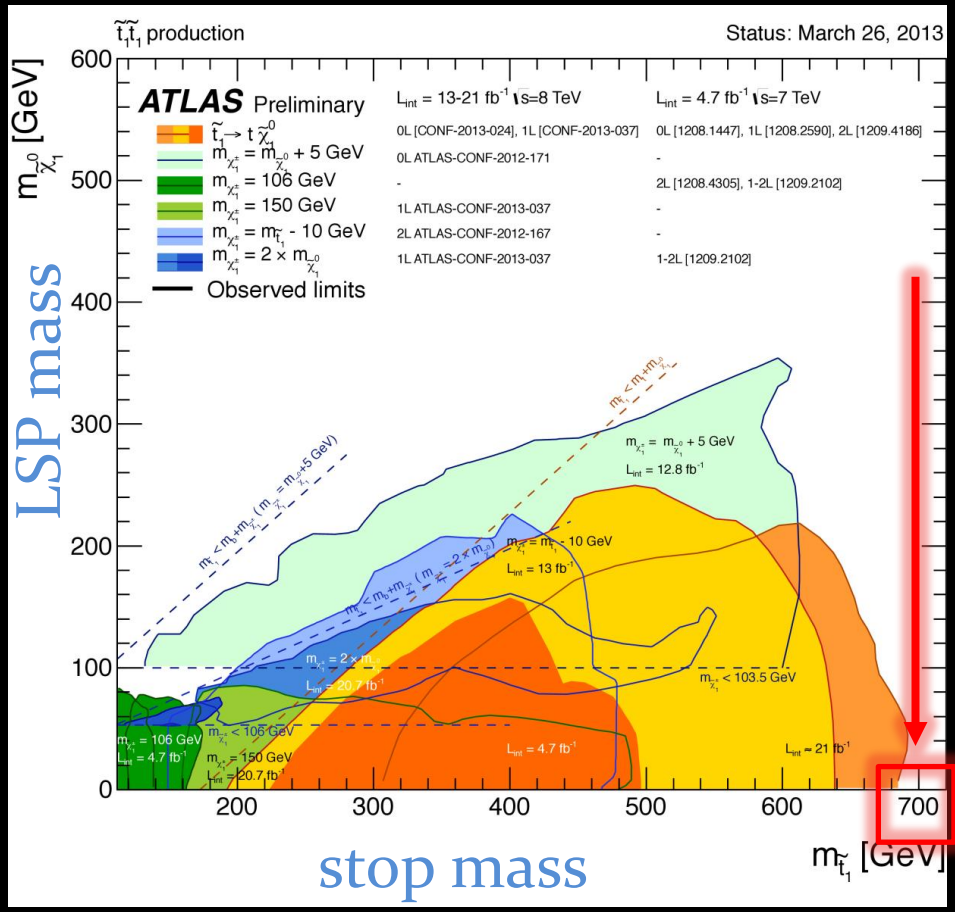
be it weakly or strongly coupled,
natural BSM theories have
top partners $< o(1\ TeV)$
to soften the UV sensitivity of the Higgs mass

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

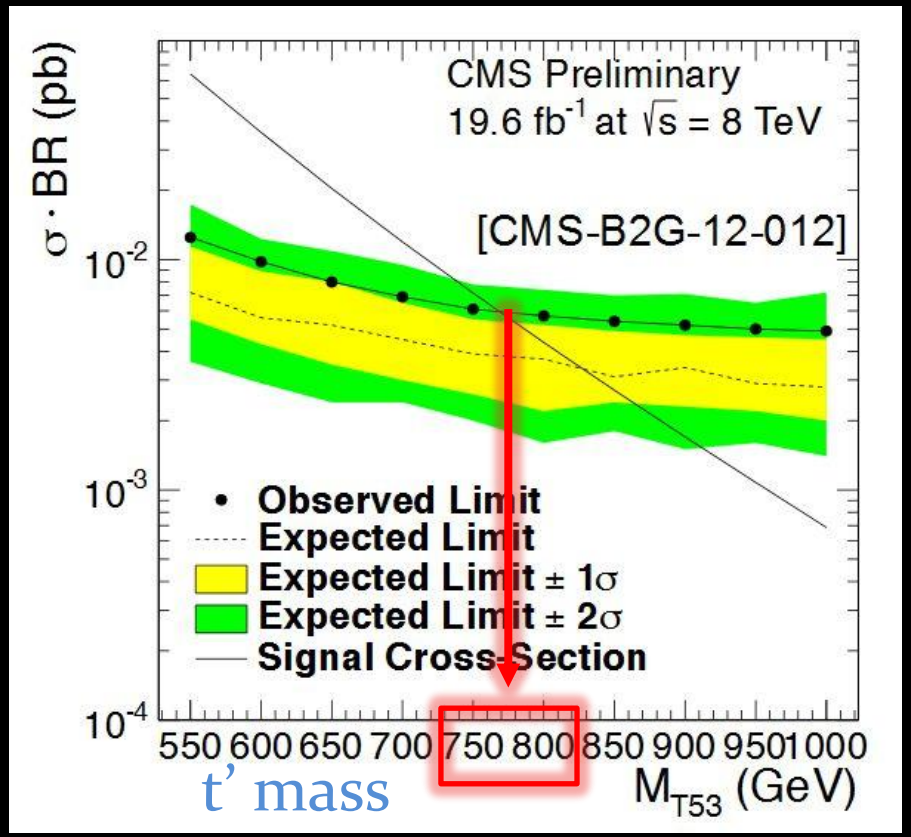
Since [SUSY/global sym, QCD]=0,
top partners are colored*
→ *large production cross-sections at hadron colliders*

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

If 3rd generation is secluded from the 1st two (as in the SM),
top partners decays dominantly to top quarks
→ *significant bounds from LHC*

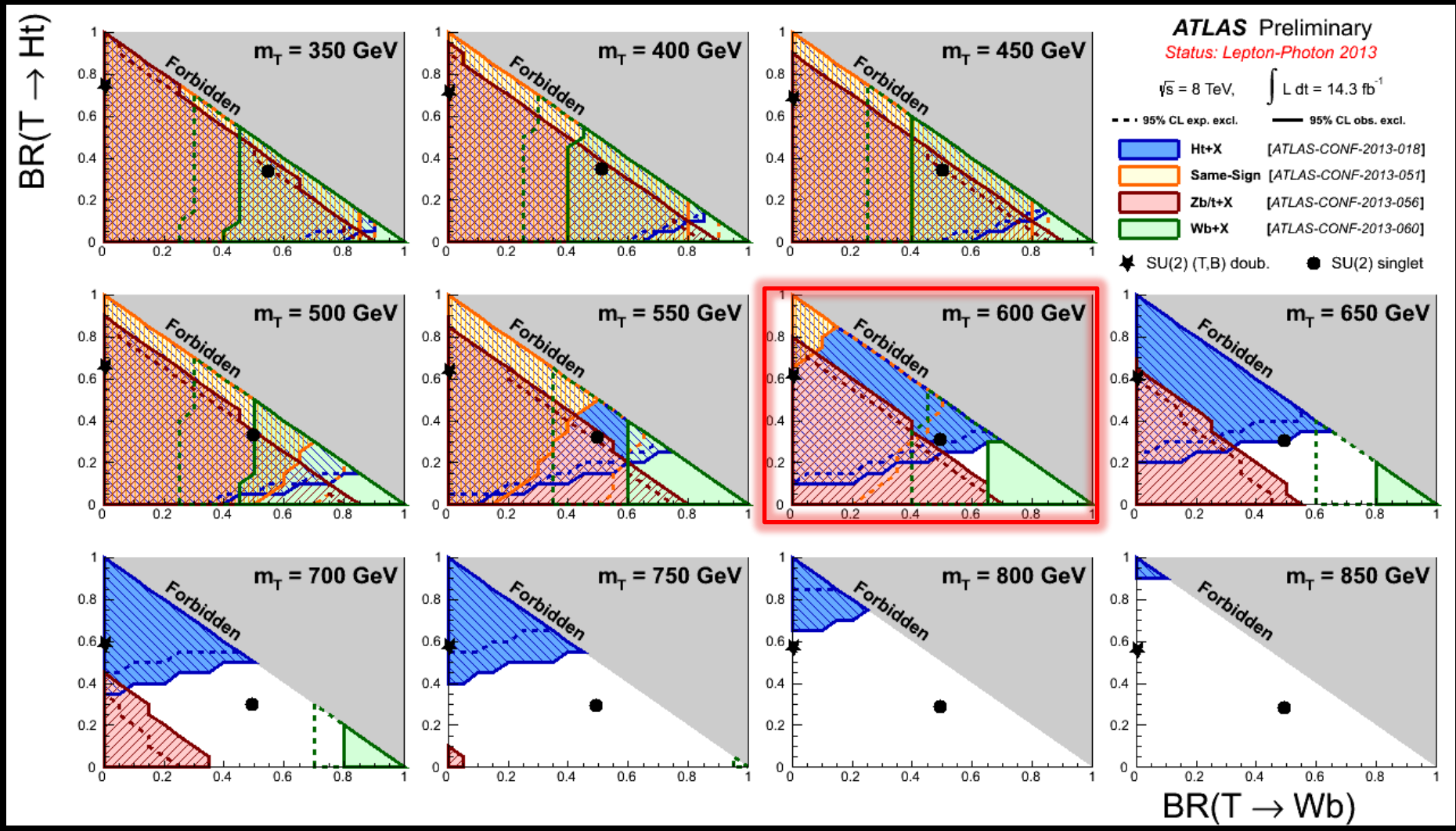


supersymmetry



composite PGB Higgs models

also significant bounds on Q=2/3 vector-like t'



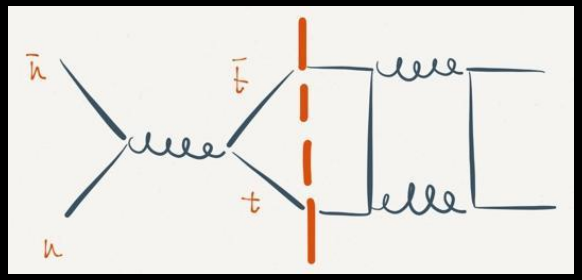
Naturalness is currently under siege!

Traces of new physics
in top quark properties

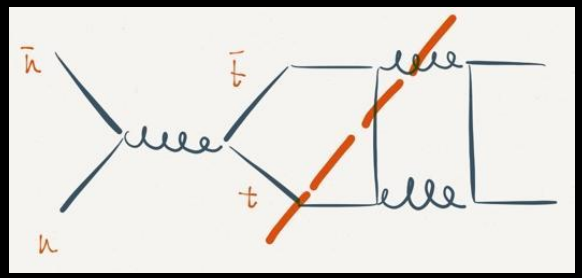
new physics in top-related SM processes:*

**non-comprehensive list*

- top pair production, anomalous FB asymmetries:



+

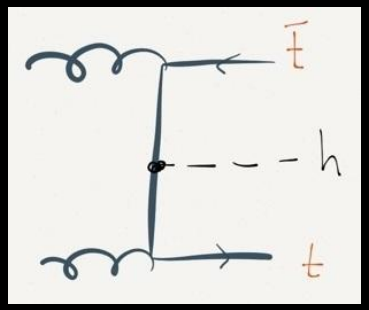


$= + O(\alpha_s^3)$

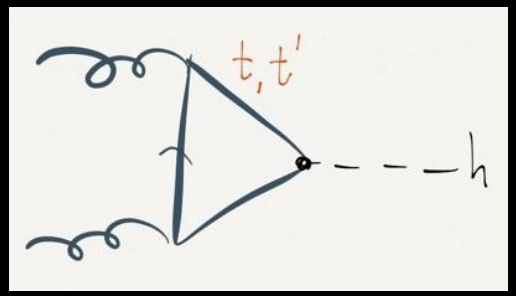
Kühn-Rodrigo '99

$+\infty$ $\quad\quad$ $-\infty$

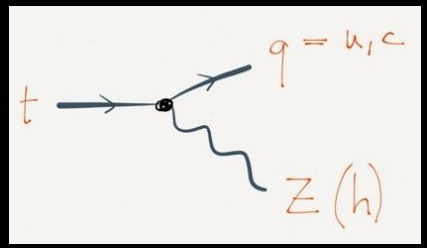
- top-Higgs coupling

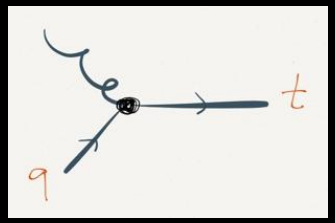


Vs.



- top FCNC decays



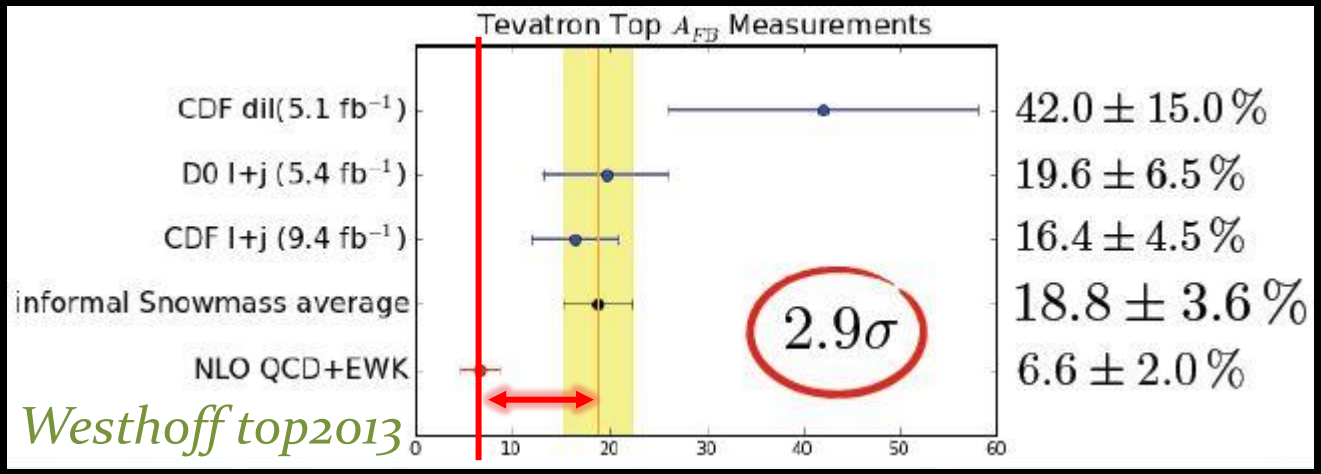


$BR(t \to qV) \sim 10^{-12} - 10^{-17}$

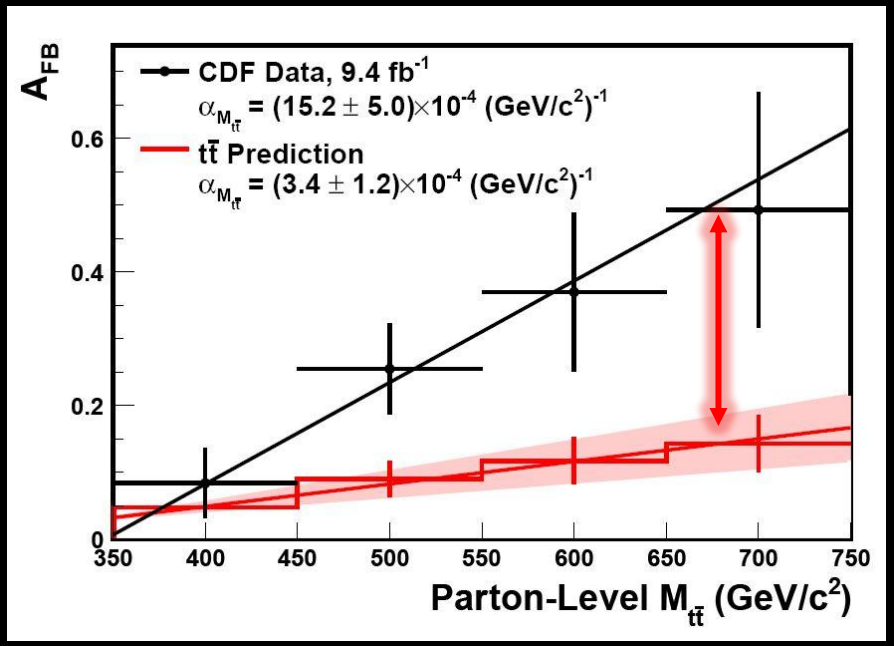
$V = \gamma, Z, g$
$q = u, c$

Forward-backward asymmetry
in top pair production

top quarks flew forward at Tevatron:



Westhoff top2013



[CDF 1211.1003]

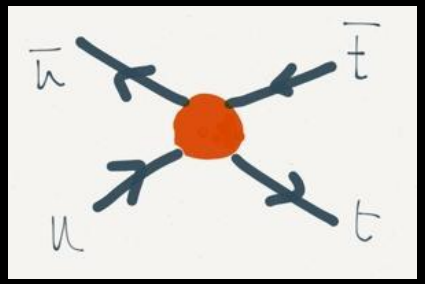
Perhaps just higher order QCD effect
(A_{FB} only known at LO)

Caveat:

if A_{FB} is BSM driven,
new physics must somehow
couple sizably to up quark,
which is *at odd with naturalness*

going forward or backward with new physics explanations?

- top EFT: *[Blum et al. PRD '11] [Degrande et al. JHEP '10]*



vs.

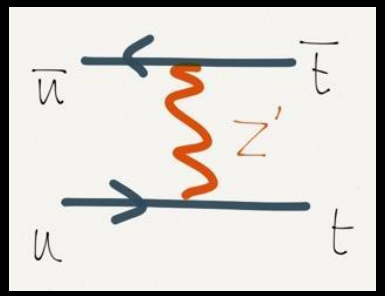
$$\mathcal{S} = \frac{\int_{m_{t\bar{t}}>1\,\mathrm{TeV}/c^2} \frac{d\sigma_{SM+NP}}{dm_{t\bar{t}}} dm_{t\bar{t}}}{\int_{m_{t\bar{t}}>1\,\mathrm{TeV}/c^2} \frac{d\sigma_{SM}}{dm_{t\bar{t}}} dm_{t\bar{t}}}$$

<1.2 @2σ

[CMS:1309.2030]

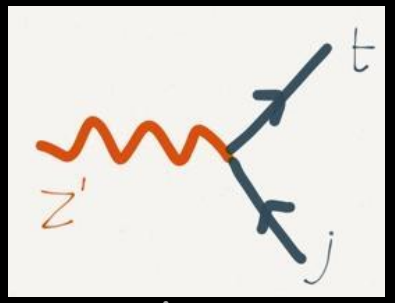
Λ< 8TeV

- t-channel Z': *[Jung-Pierce-Wells PRD '11] [Grinstein et al. PRL '11]*



$m_{Z'} \approx O(200\,GeV)$

vs.



Ok!

top-jet resonance

- light axigluons *[Tavares-Schmaltz PRD '11]*

$m_G \approx 400\,GeV$

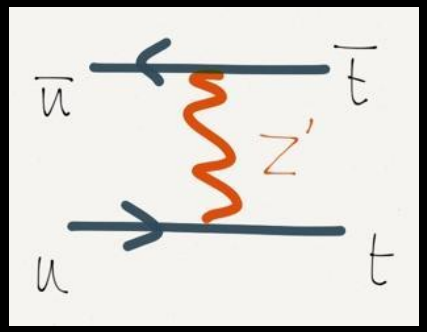
vs.

Ok!

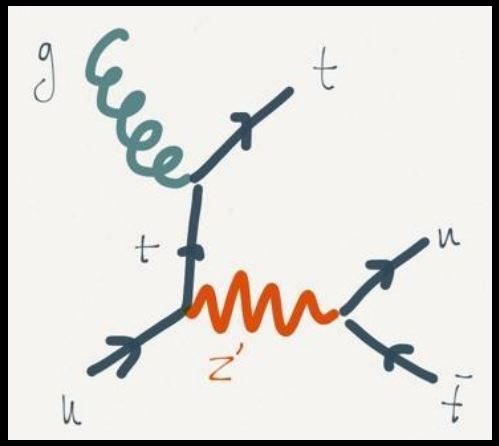
dijet resonance

reconciling large A_{FB} with SM-like A_C:

- t channel Z' + associates: *[Drobnak et al. PRD '12]*



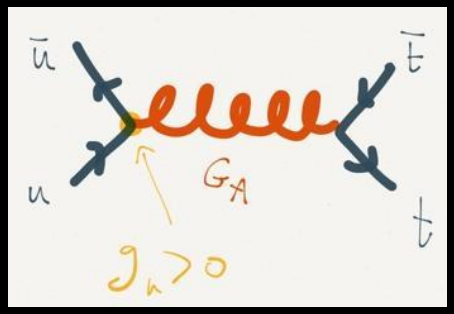
→ $A_{FB}>0$, $A_C>0$ +



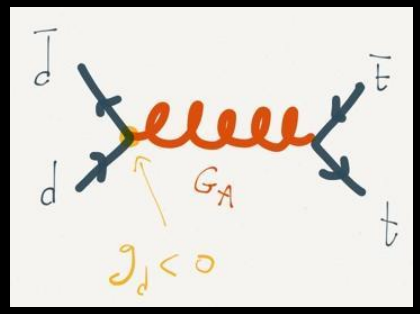
→ $A_{FB}\sim 0$, $A_C<0$

→ large A_{FB}, $A_C \approx 0$

- light axigluons coupled to *u*+*d*: *[Drobnak-Kamenik-Zupan '12]*



+



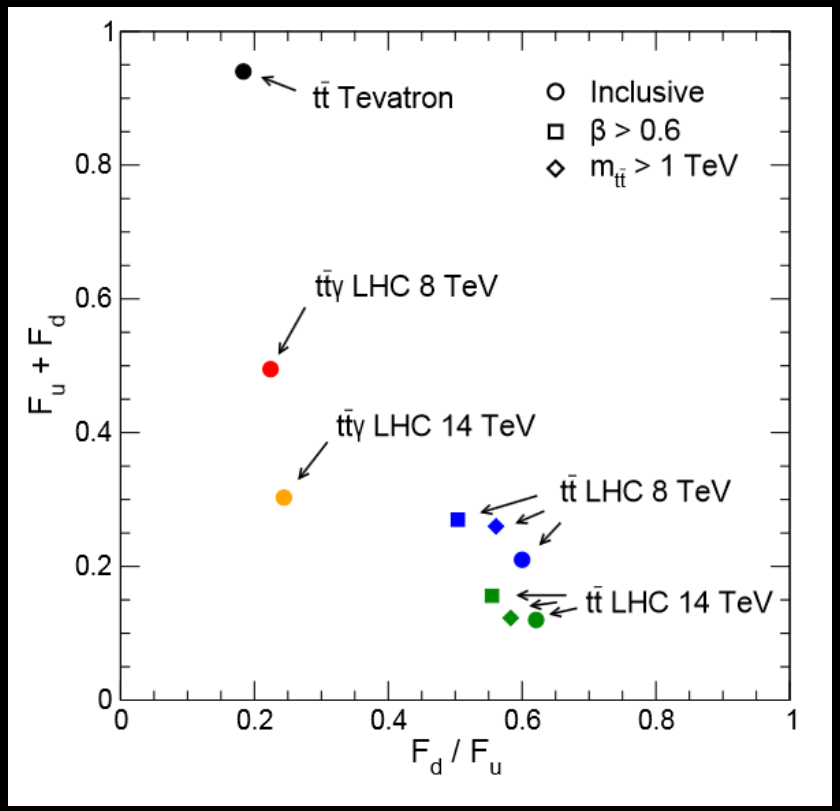
Tevatron/LHC probe
u-PDF and d-PDF at different x's

→ large A_{FB}, $A_C \approx <0$

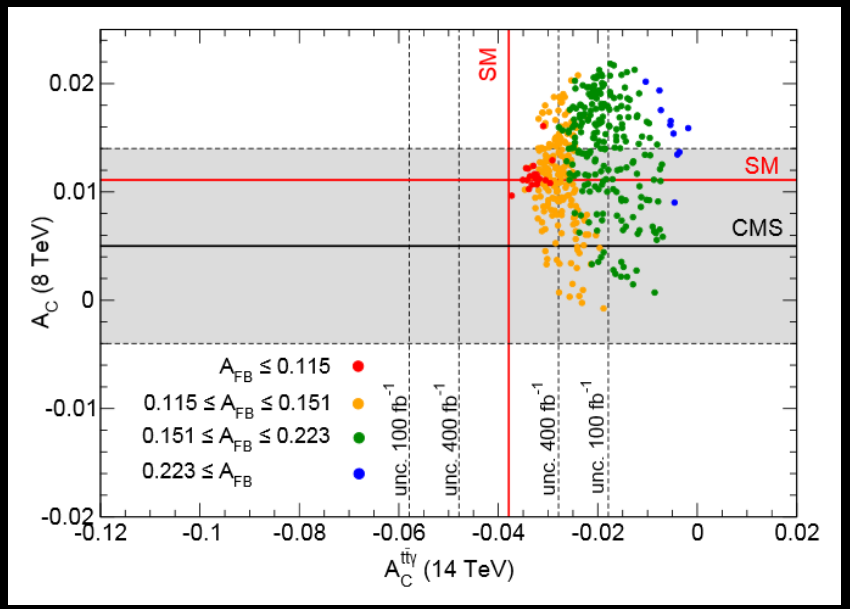
lower sensitivity to cancellations between diagrams in ttγ:

[Aguilar-Saveedra et al. 1402.3598]

- LHC cross-sections down by α
- but increased sensitivity to «Tevatron-like» kinematics



for light axigluon:



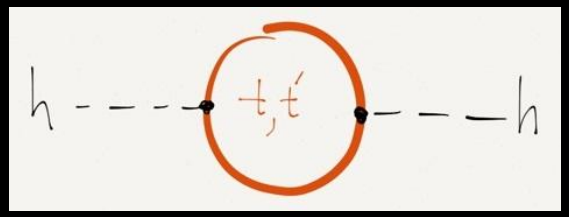
possible to test A_{FB} models at LHC14 with ~400/fb

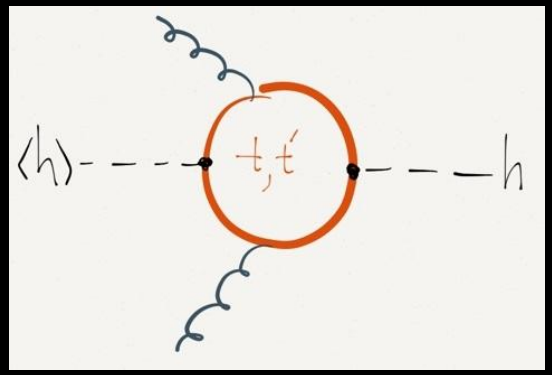
Higgs coupling to top pairs

H production cross-sections tend to be reduced by top partners:

Low-Rattazzi-Vichi '09

If [SUSY/global sym, QCD]=0,

the cancellation in 

typically persists in 

!

top-Higgs coupling from inclusive H production cross-section:

- Effective Higgs couplings to SM:

$$\mathcal{L}_{(0)} = \frac{h}{v}\left[c_V\left(2m_W^2 W_\mu^\dagger W^\mu + m_Z^2 Z_\mu Z^\mu\right) - c_t \sum_{f=u,c,t} m_f \bar{f} f - c_b \sum_{f=d,s,b} m_f \bar{f} f - c_\tau \sum_{f=e,\mu,\tau} m_f \bar{f} f\right]$$

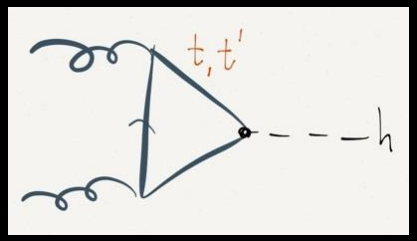
$$\mathcal{L}_{(2)} = -\frac{h}{4v}\left[2c_{WW} W_{\mu\nu}^\dagger W^{\mu\nu} + c_{ZZ} Z_{\mu\nu} Z^{\mu\nu} + 2c_{Z\gamma} A_{\mu\nu} Z^{\mu\nu} + c_{\gamma\gamma} A_{\mu\nu} A^{\mu\nu} - c_{gg} G^a_{\mu\nu} G^{a,\mu\nu}\right]$$

fit to all LHC run 1 Higgs data + LEP:

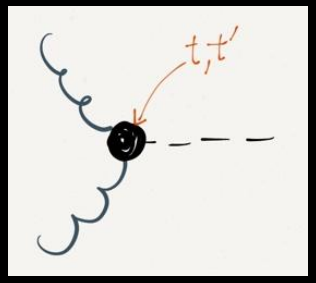
$$c_V = 1.04^{+0.02}_{-0.02}, \quad c_u = 1.30^{+0.10}_{-0.30}, \quad c_d = 0.93^{+0.18}_{-0.15}, \quad c_l = 1.16^{+0.17}_{-0.15},$$
$$c_{gg} = -0.0016^{+0.0022}_{-0.0037}, \quad c_{\gamma\gamma} = 0.00059^{+0.00078}_{-0.00078}, \quad c_{Z\gamma} = -0.001^{+0.020}_{-0.039}$$

inclusive Higgs production only constrains:

$$\sigma_{gg\to h} \propto \left| c_{gg} + \frac{\alpha_s c_t}{3\pi} \right|^2$$



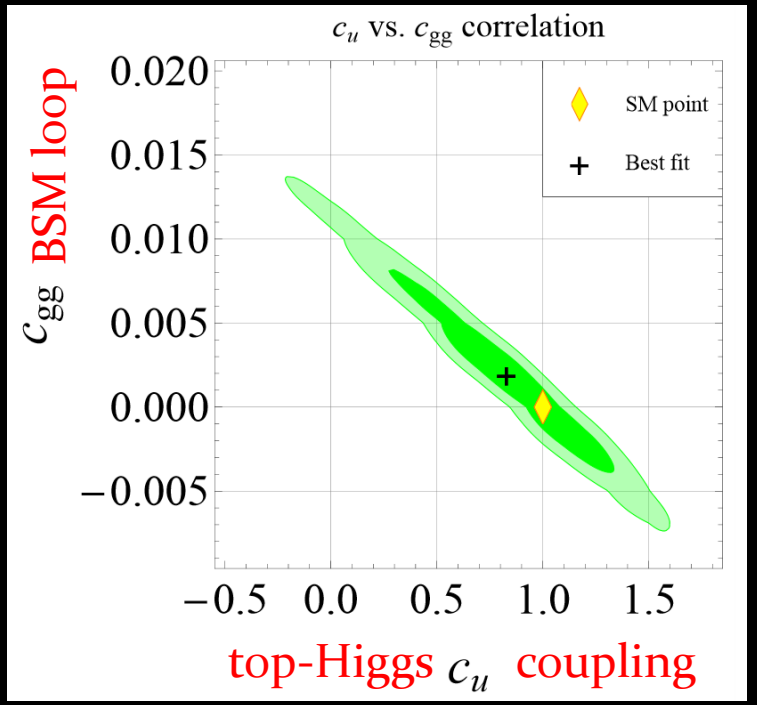
$m_h \ll m_{t,t'}$



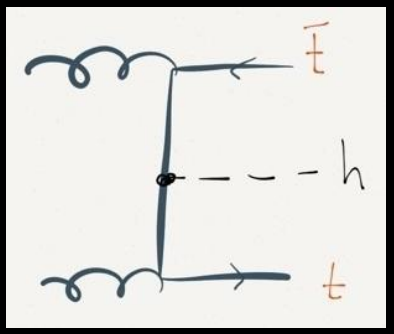
(flat direction weakly lifted by tth)

Falkowski et al. '12

latest results from Belúsca-Maïto RPP2014



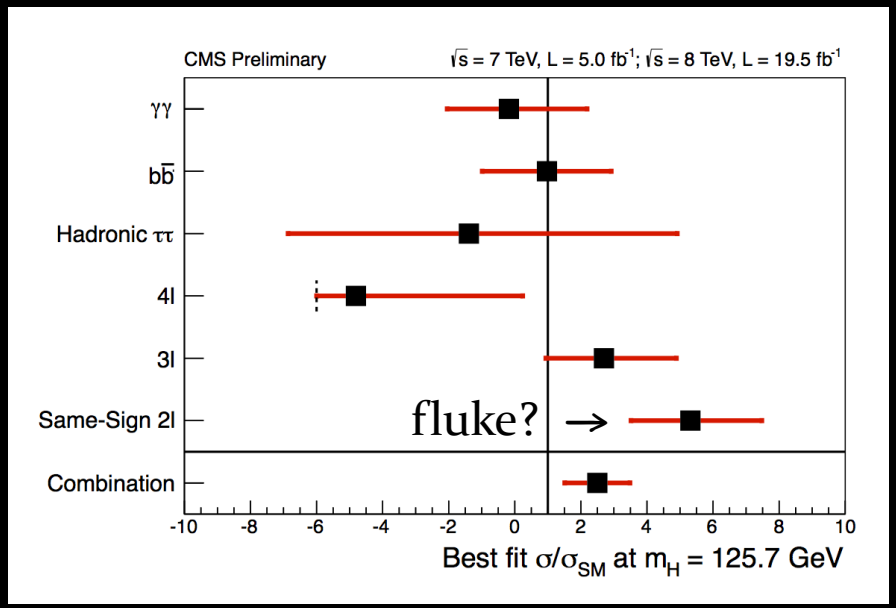
Extracting the top-Higgs coupling:



- Higgs production in association with top pairs:

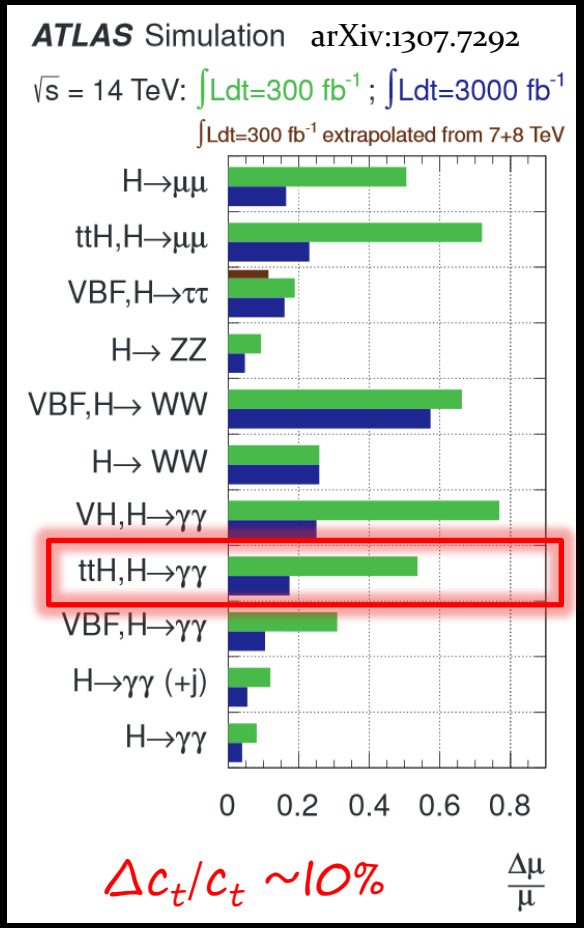
small cross-section + large bkgd = harder to probe channel

CMS combination: $\mu = 2.5 \pm 1$



ATLAS limit: $|c_t| < 2.3$ @95%C.L.

ATLAS-CONF-2013-080



$\Delta c_t / c_t \sim 10\%$

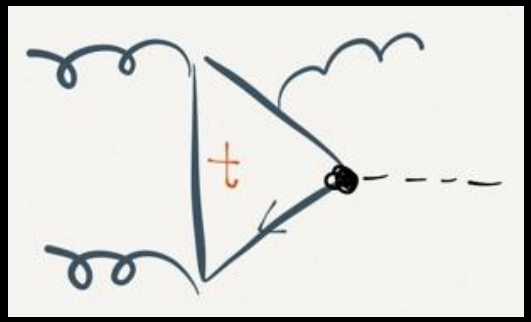
High-lumi LHC prospects →

Extracting the top-Higgs coupling:

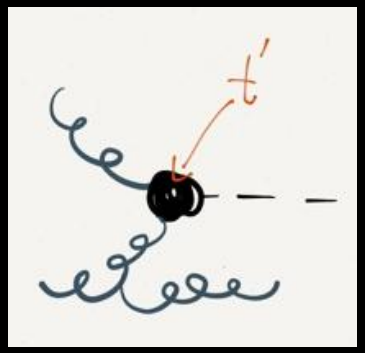
Grojean-Salvioni-Schlaffer-Weiler *'13*
see also Banfi-Martin-Sanz '13

- Very boosted Higgs production:

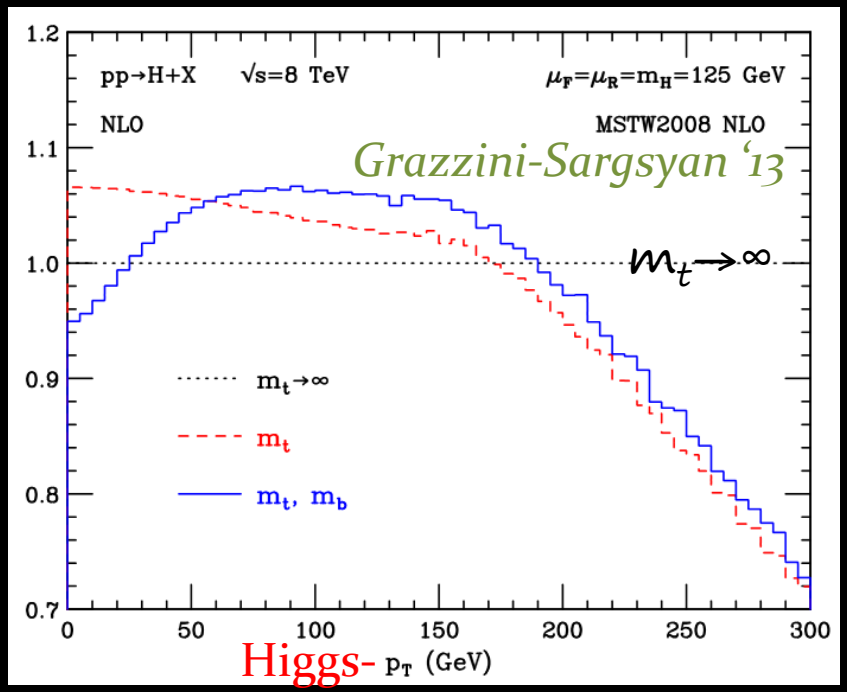
idea = introduce a new hard scale to resolve the top loop

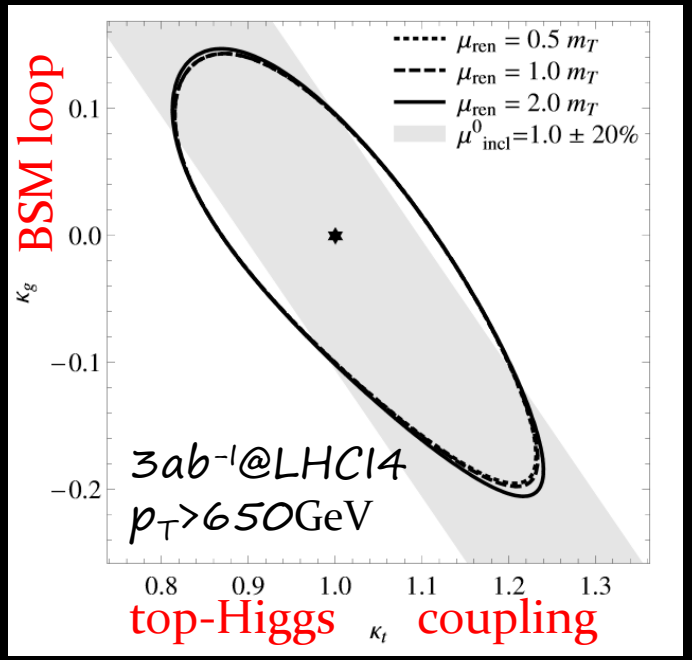


+



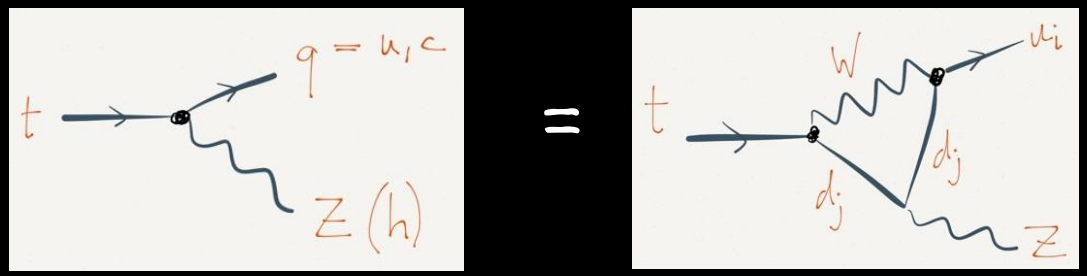
$m_t << p_T^{jet} << m_{t'}$





FCNC decays of top quarks

top FCNC widths are tiny in the SM:



loop+GIM suppressed

$BR(t \to qZ) \sim 10^{-12} - 10^{-14}$

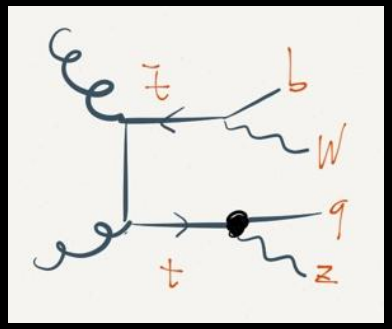
but tqZ could be $\sim 10^{-4}$ in BSM

not connected to naturalness *a priori*, yet worth checking

2 ways to probe top FCNC:

- in decays:

flavor blind
(c-tagging?)



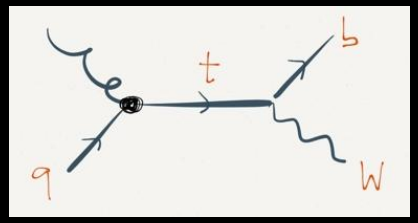
7TeV 2.1/fb ATLAS: $BR(t \to qZ) < 0.7\%$ arXiv:1206.0257

8TeV 21/fb CMS: $BR(t \to qZ) < 0.05\%$ arXiv:1312.4194

ATLAS projection for HL-LHC $\sim 10^{-5}$

- in single top production:

mostly q=u



8TeV ATLAS: $BR(t \to ug) < 3 \times 10^{-5}$

$BR(t \to cg) < 2 \times 10^{-4}$

ATLAS-CONF-23013-063

Summary

- SM-like Higgs is unlikely to be a complete answer to the EW symmetry breaking puzzle

- If BSM exists near the TeV scale, top quark dynamics should signicantly deviate from SM

- many handles available experimentally:
  → direct searches of top-partners
  → top pair production at hadron colliders (A_{FB}?)
  → top-Higgs signals (pin down tth at LHC14)
  → top FCNC decays *(if BSM flavor structure non-trivial)*
  → other fishing probes: EDMs from top-CPV

which situation are we in?