Theory of (non-SUSY) Beyond the Standard Model

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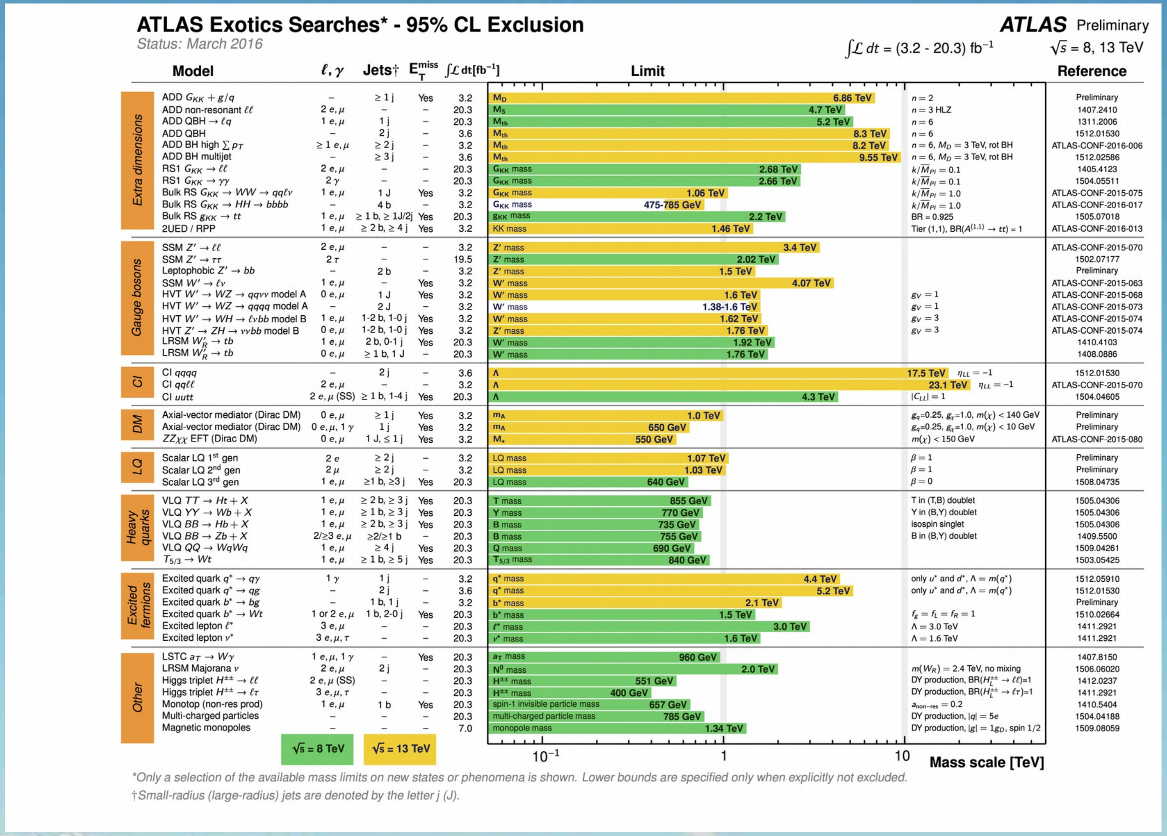
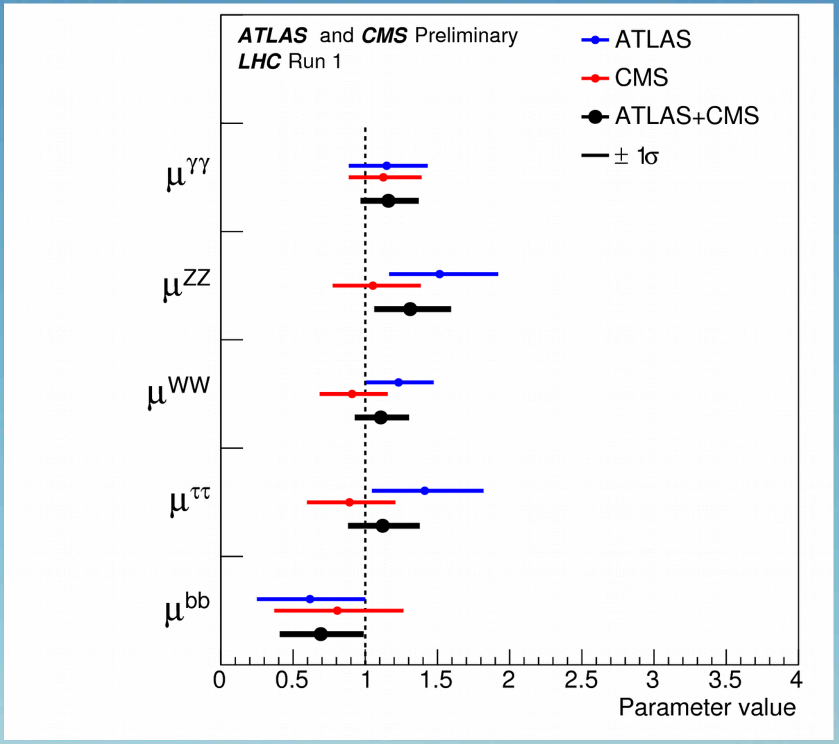
What's new? (in non-SUSY BSM)

- We have data

SM





What's new? (in non-SUSY BSM)

SM

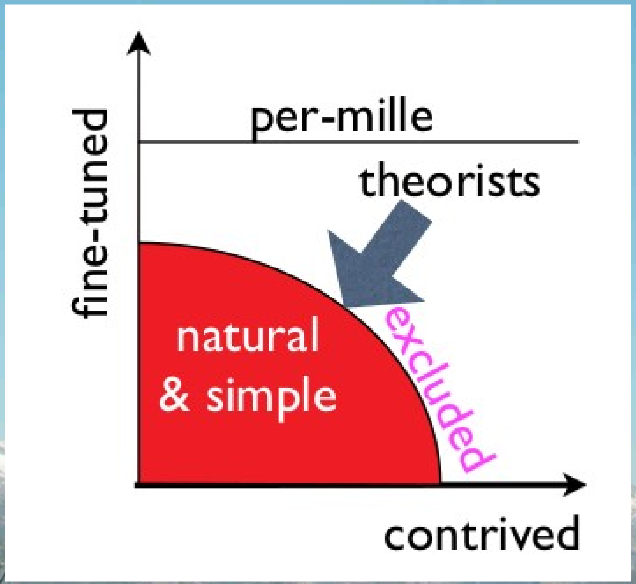
- We have data
- The decade of 2000’s was extremelly rich in model-building ideas, driven mainly by naturalness (main reason to expect new physics at the LHC)
- Now that we have LHC data at 8 and 13 TeV it’s time to confront these ideas with experimental data
- The stringent experimental constraints (direct searches, Higgs couplings) on many extensions on the SM creates some tension with natural models

What's new? (in non-SUSY BSM)

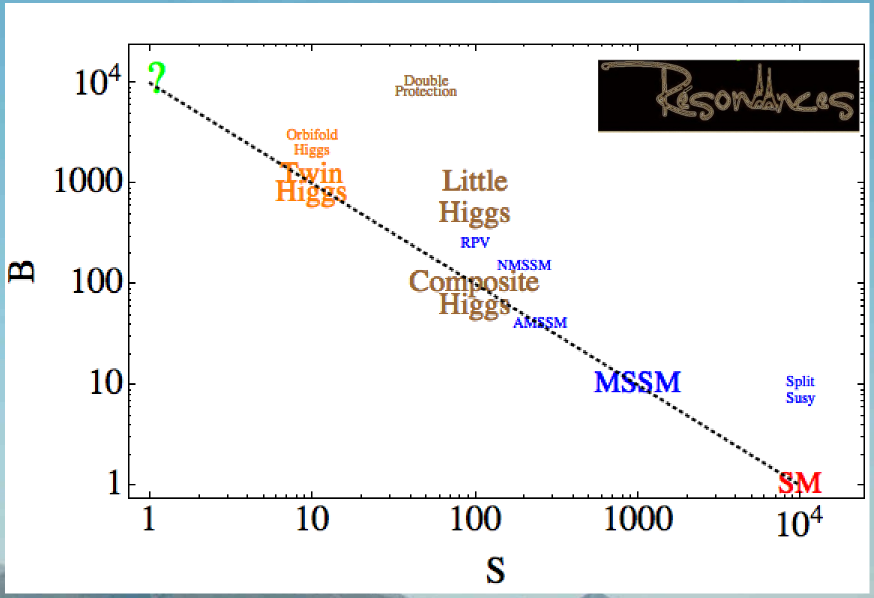
SM

- We have data
- More and more stringent bounds on the masses of new particles imply either more special (fine-tuned) or more baroque (~~complicated~~ rich) models

H. Murayama, Nobel Symposium on LHC results



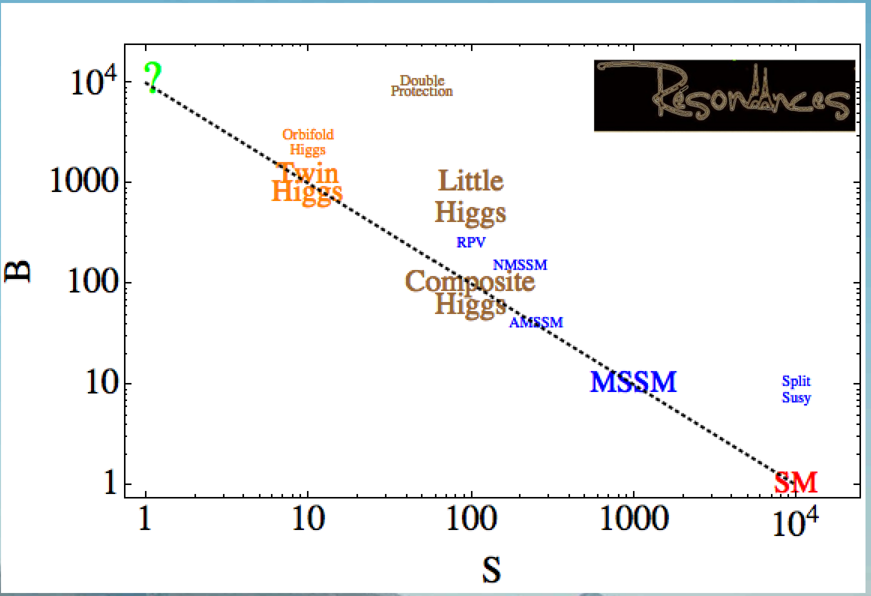
But beware that baroqueness is achieved by symmetries



What's new? (in non-SUSY BSM)

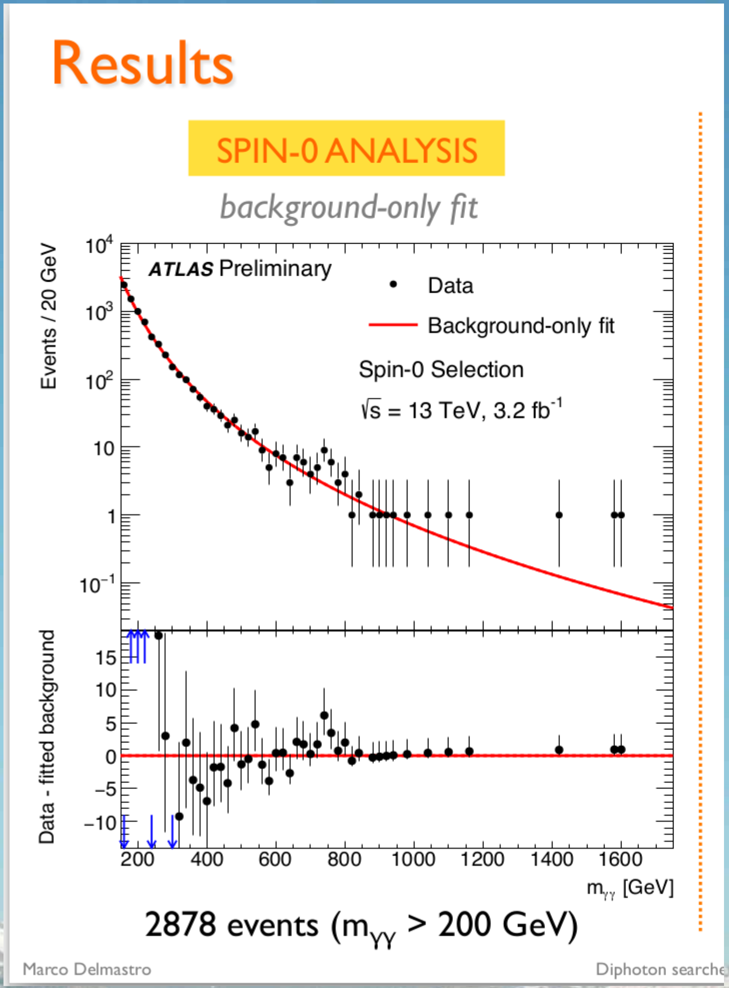
SM

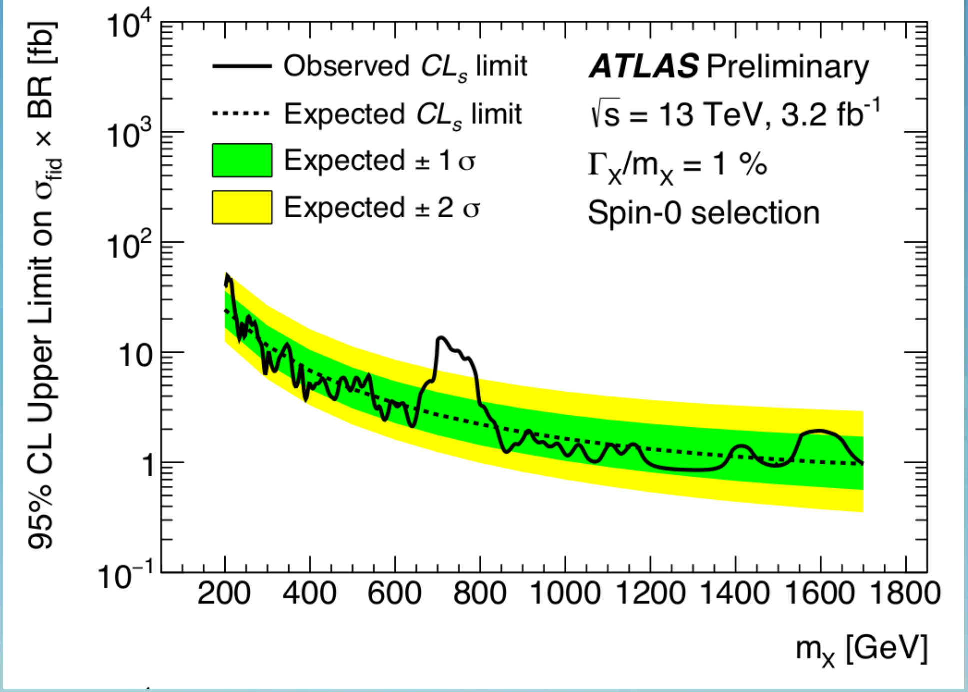
- We have data
- More and more stringent bounds on the masses of new particles imply either more special (fine-tuned) or more baroque (~~complicated~~ rich) models
- B and S imply different experimental strategies:
  - Larger S: keep looking (and hope you have kinematical reach)
  - Larger B: try new strategies (expect cancellations, new channels, unexpected behaviour, ...)



What's new? (in non-SUSY BSM)

- … and we have data





What's new? (in non-SUSY BSM)

- … and we have data
- Reported anomalies trigger the wild imagination of theorists
- It might be just a statistical fluctuation or the discovery of the century but it is an excellent model-building exercise (and a lot of fun!) finding possible explanations to the excesses

The Gold Rush: [INSPIRES][list]

Date	papers
16 Dec	10
25 Dec	101
1 Jan	137
1 Feb	212
1 Mar	263
1 Apr	?

Strumia, Moriond 2016

Outline

- Non-SUSY approaches to naturalness:
  - Composite pNGB Higgs:
    - Fine-tuning and baroqueness
    - Phenomenological implications
  - Increasing elusiveness: neutral naturalness
  - No new TeV particles: cosmologial relaxation
- Explaining anomalies: 750 diphoton
- Conclusions

Naturalness as guiding principle

- Naturalness problem: the mass of an elementary scalar is a relevant operator not (obviously) protected by any symmetry (it is quadratically sensitive to any UV new physics)

- It is difficult to understand the scale of EWSB unless some new structure appears around the TeV scale (within LHC reach) [counter example later]

- Currently tested tuning is not yet dramatic

$$\frac{\delta m_H^2}{m_H^2} \sim \frac{\Lambda^2}{4\pi^2 m_H^2} \leq \Delta \Rightarrow \Lambda \lesssim \text{few}\ \sqrt{\Delta}\, m_H \sim \ \text{few} \begin{cases} 1\ \text{TeV},\ 0.01\ \text{tuning} \\ 3\ \text{TeV},\ 0.001\ \text{tuning} \end{cases}$$

Crude estimate

Naturalness as guiding principle

- Naturalness is still a good guiding principle:
  - Tuning still at the ~ per-cent level
  - It is the main argument for new physics at the LHC (dark matter, baryon asymmetry, flavor, …, could be related to TeV physics or not)
  - Increasing the degree of baroqueness changes the collider phenomenology (cancelations imposed by symmetries, elusive new physics)

The Higgs as a composite pNGB

- Is the Higgs boson the first elementary scalar observed in Nature?
- Known examples of SSB and/or light scalars involve composite scalars:
  - Superconductivity: electron (Cooper) pairs condense due to their interactions with the phonons in a crystal
  - Pions are composite pNGB of chiral symmetry breaking
- Maybe the Higgs is also a composite state of a new strongly interacting theory?

The Higgs as a composite pNGB

- A naturally light composite Higgs: Ingredients
  - H as a pNGB: Georgi, Kaplan '80, ...
    - A new strongly coupled sector condenses at a scale f~TeV spontaneously breaking a global symmetry: H is the NGB of the breaking
    - Why NGB? To generate its potential from a weakly coupled sector (that breaks explicitly the global symmetry)

$$\delta m_H^2 \sim \frac{g^2}{16\pi^4} M^2$$

Weak coupling

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    - Why NGB? To generate its potential from a weakly coupled sector (that breaks explicitly the global symmetry)
    - $v = f \sin(\langle h \rangle / f)$
    - $\xi \equiv \frac{v^2}{f^2}$ parameterizes deviations of Higgs couplings (and minimal fine-tuning)

The Higgs as a composite pNGB

- Realistic example: Minimal Composite Higgs Model
  - $SO(5)/SO(4) \times P_{LR}$ Agashe, Contino, (Da Rold), Pomarol '05 ('06)
    - Custodial protection of T and $Zb_L\overline{b_L}$ [$SO(4) \sim SU(2)_L \times SU(2)_R$]
    - 4 NGB transforming as a 4 of SO(4) [just like the SM Higgs]
    - Explicit symmetry breaking by weak gauging (SM) and Yukawa couplings (mainly top)

$$V[H] = -\alpha f^2 \sin^2(H/f) + \beta f^2 \sin^4(H/f)$$

$$\xi = \alpha/(2\beta) \qquad m_H^2 = 8\xi(1-\xi)\beta$$

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- α and β depend on the fermion quantum numbers:
  - $\alpha_{5\oplus 5} \sim \frac{N_c}{16\pi^2}\lambda_t^2 m_\rho^2$ $\quad \beta_{5\oplus 5} \sim \frac{N_c}{16\pi^2}\lambda_t^4 f^2$ $\quad \Delta_{5\oplus 5} \sim \frac{m_\rho^2}{\lambda_t^2 f^2}\frac{1}{2\xi}$
  - $\alpha_{14\oplus 1} \sim \beta_{14\oplus 1} \sim \frac{N_c}{16\pi^2}\lambda_t^2 m_\rho^2$ $\quad \Delta_{14\oplus 1} \sim \frac{1}{2\xi}$

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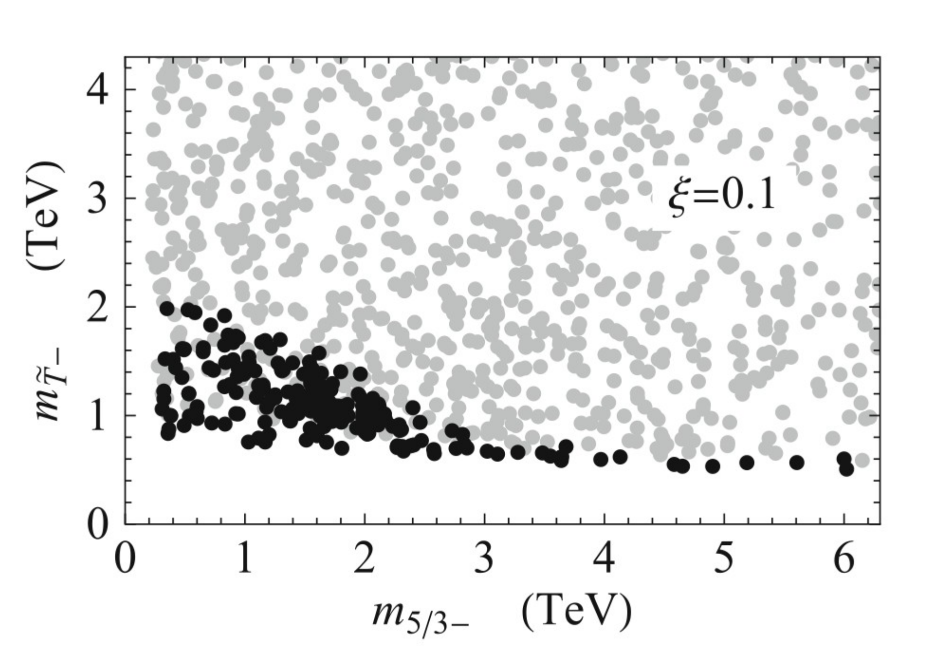
  - The Higgs mass also imposes constraints (on the masses of fermionic resonances) $\frac{m_H}{m_t} \sim \sqrt{\frac{N_c}{2\pi^2}} \frac{M_\psi}{f}$



But also alternatives with no light top partners: lepton partners contribution to Higgs potential [Carmona, Goertz '13]

The Higgs as a composite pNGB

- How baroque is it? Not bad. Fermion resonances:

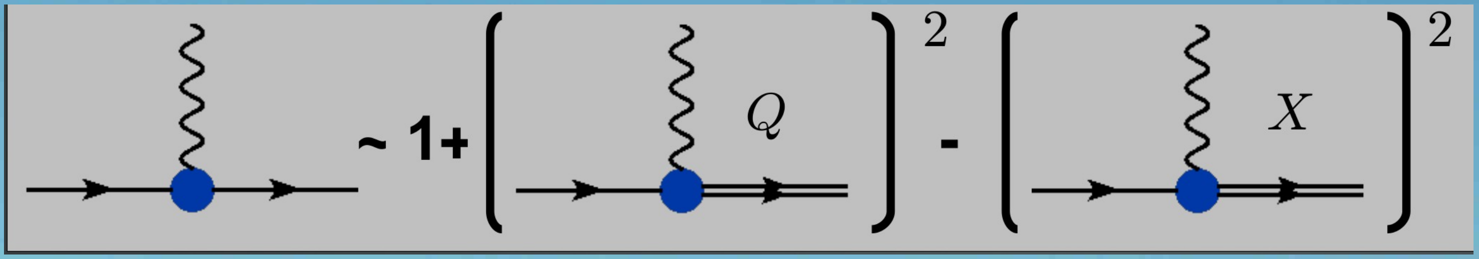
$$5_{\frac{2}{3}} \sim (2,2)_{\frac{2}{3}} \oplus (1,1)_{\frac{2}{3}} \sim 2_{\frac{1}{6}} \oplus 2_{\frac{7}{6}} \oplus 1_{\frac{2}{3}}$$

$$\begin{pmatrix} T \\ B \end{pmatrix} \quad \begin{pmatrix} X_{\frac{5}{3}} \\ T' \end{pmatrix} \quad \tilde{T}$$

- Not “just new vector-like quarks” (they come with a rich structure)
  - Cancellations are natural (large mixings allowed)
  - Large contributions to certain observables not only allowed but sometimes needed
  - Many new particles with large couplings (unusual behaviour)

The Higgs as a composite pNGB

- Not “just new vector-like quarks”
  - Cancellations are natural (large mixings allowed)
  - $\begin{pmatrix} T \\ B \end{pmatrix}$ $\begin{pmatrix} X_{\frac{5}{3}} \\ T' \end{pmatrix}$ mix with u_R in a custodially symmetric way



$$1 + \left(\frac{\lambda_Q v}{M_Q}\right)^2 - \left(\frac{\lambda_X v}{M_X}\right)^2$$

  - Large mixing with valence quarks implies huge single production cross sections: excellent reach

Atre et al (JS) ’09, ’11
ATLAS-CONF-2012-137

The Higgs as a composite pNGB

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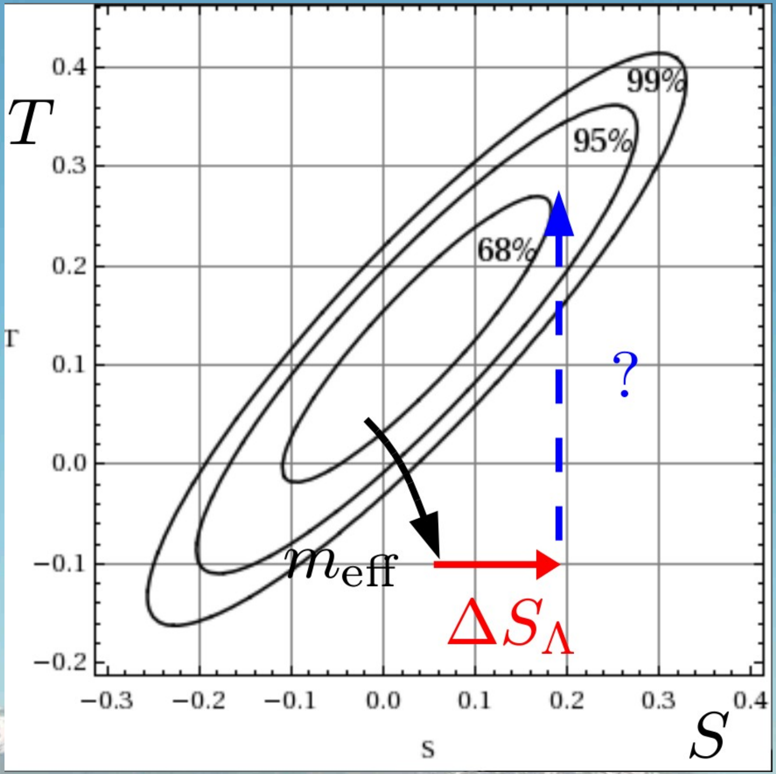
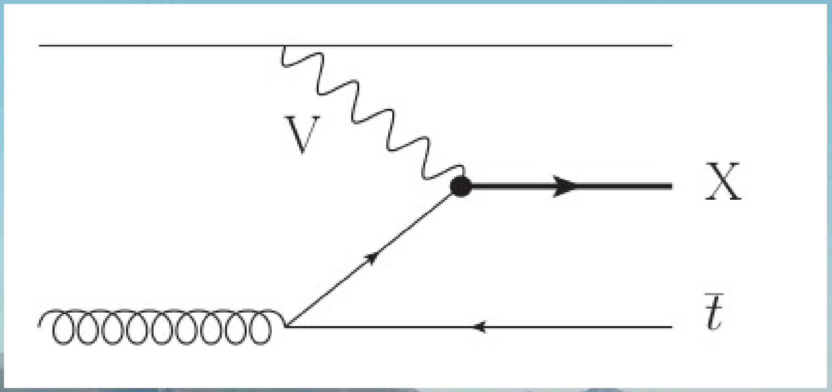


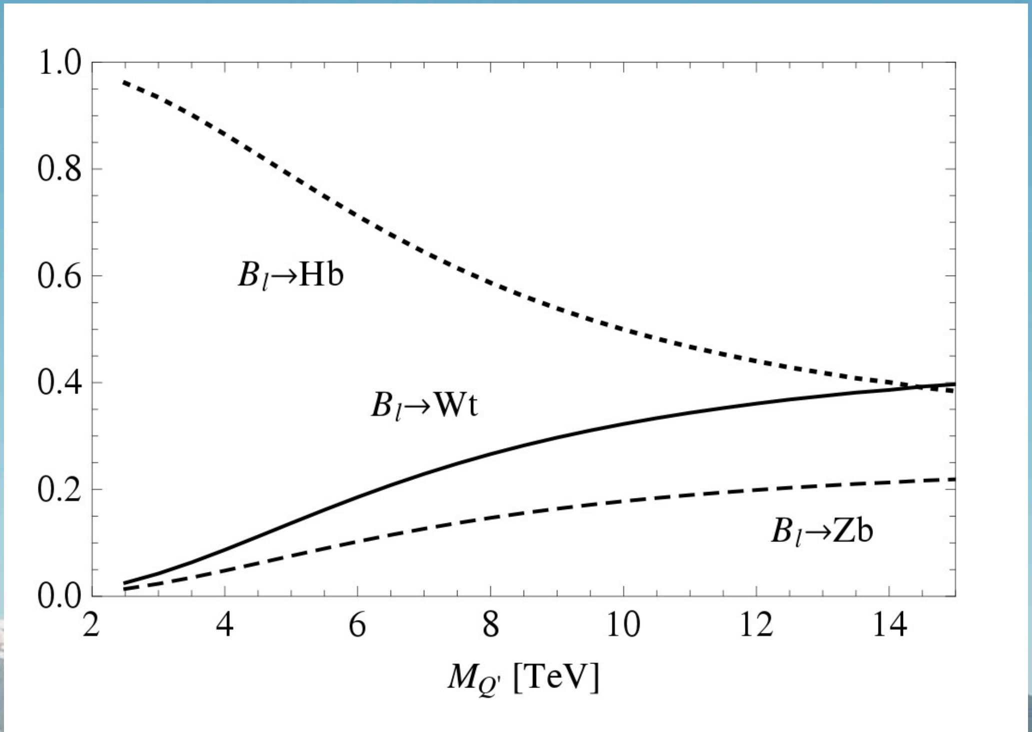
- Contributions to T and Zbb strongly correlated

  Carena, Pont n, JS, Wagner ’06, ’07
  Anastasiou, Furlan, JS ’09
- Large mixing: single production relevant



The Higgs as a composite pNGB

- Not “just new vector-like quarks”
  - Many new particles with large couplings (unusual behaviour)
    - Large mixing with heavier particles (beyond the LHC reach) can dramatically change the behaviour

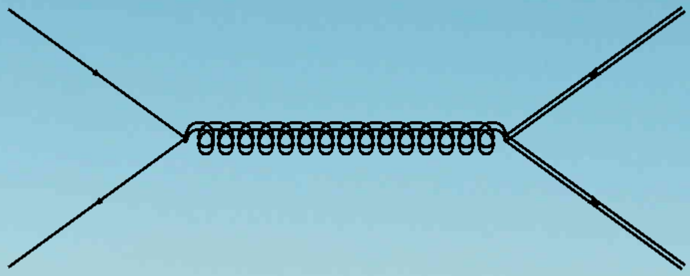


Chala, JS ’13

$$M_{B_l} = 1\ \text{TeV}$$

The Higgs as a composite pNGB

- Not “just new vector-like quarks”
  - Many new particles with large couplings (unusual behaviour)
    - Pair-production of VLQ can be mediated by new particles (heavy gluon): no longer model-independent.
    - Current searches assume QCD production. Are we sensitive to the different kinematics? Not yet (maybe with boosted techniques)



The Higgs as a composite pNGB

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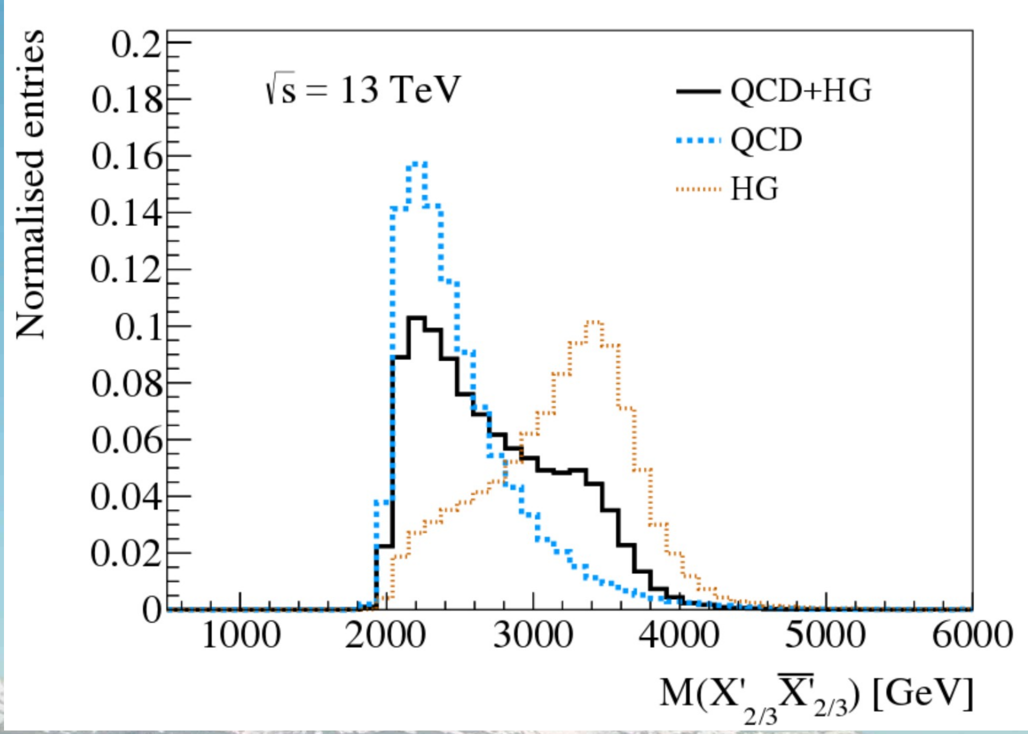

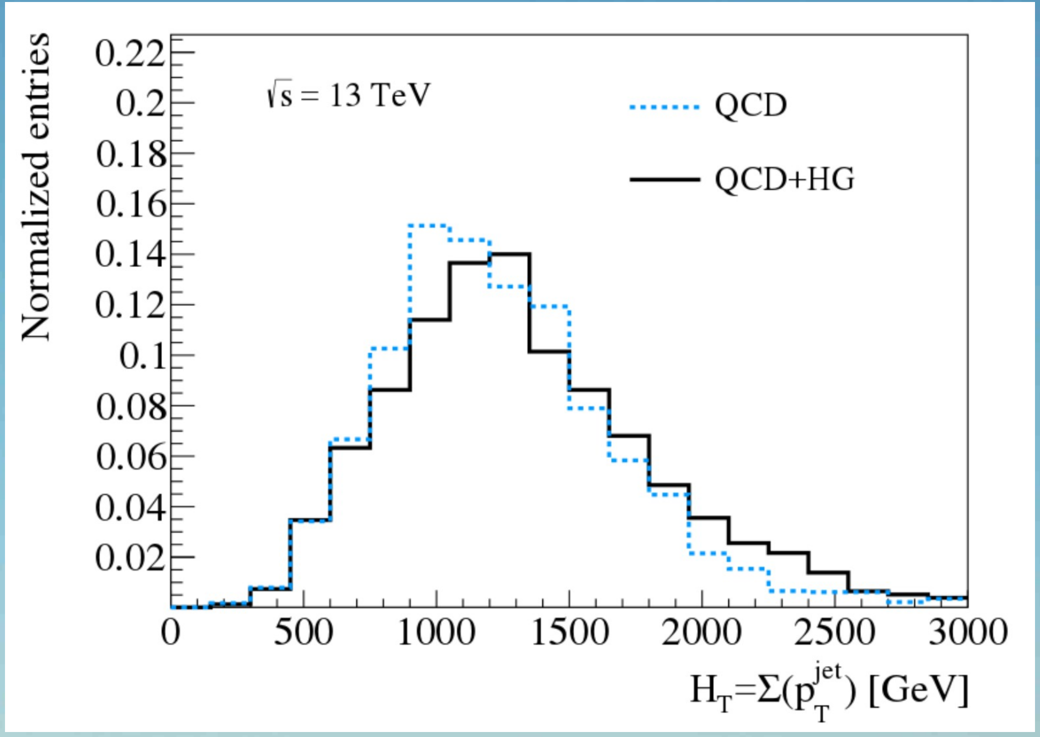

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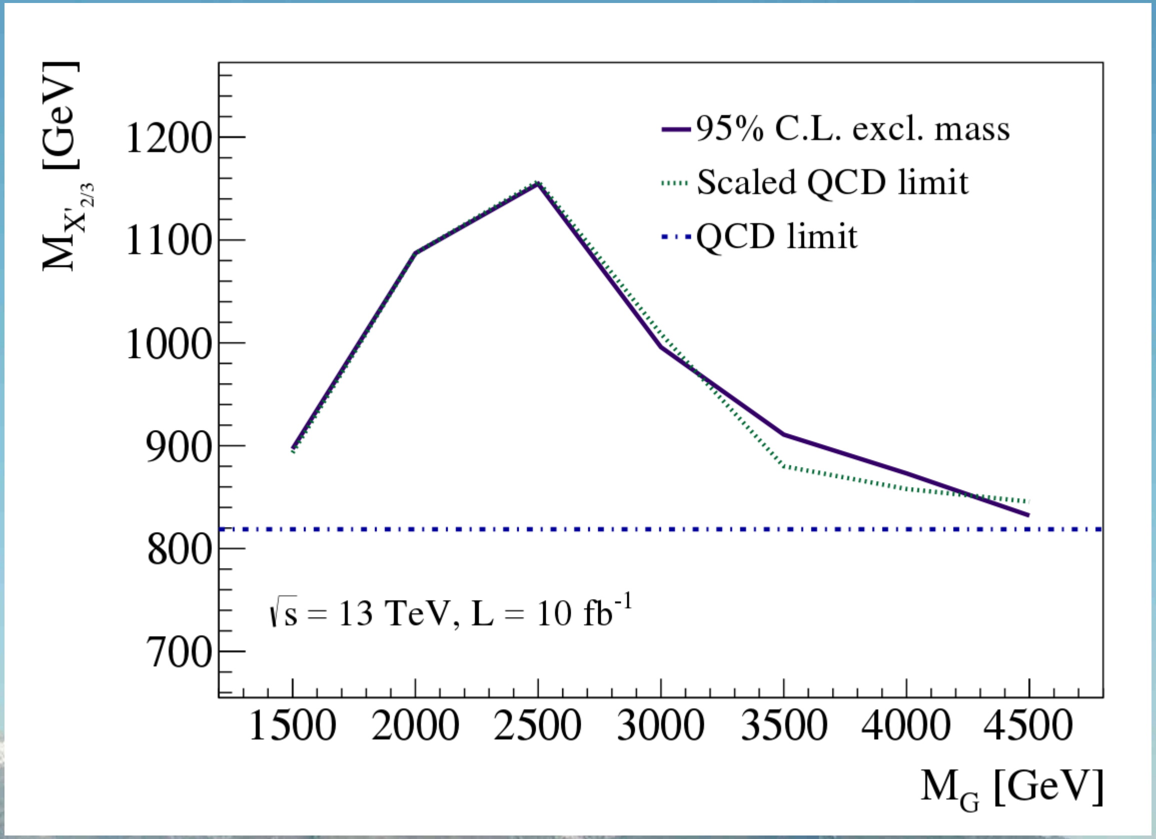
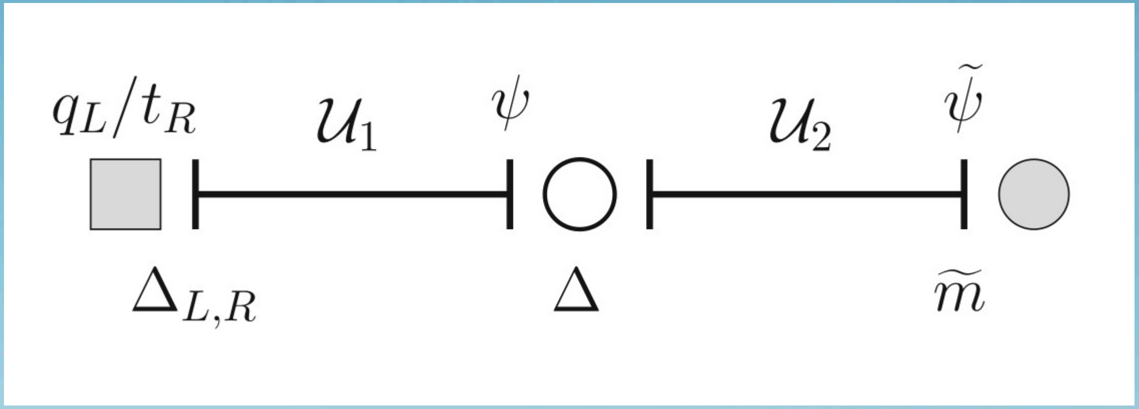


Beyond the MCHM

- Can we do better?
  - One loop quadratic divergencies can be totally cancelled if the global symmetry is explicitly broken only when two different couplings are different from zero (collective symmetry breaking a la Little Higgs)



  - Potential fully calculable in terms of low energy spectrum

Beyond the MCHM

- Uncolored top partners? Neutral naturalness

  Chacko, Goh, Harnik ’06

  - So far the particles regulating the quadratic divergencies are charged under the SM (top partners are colored) and are therefore easy to produce at the LHC
  - If the SM is doubled, the Higgs is the pNGB of a global symmetry that contains both copies and there is a Z_2 symmetry exchanging the two copies, the partners are charged under the (dark) copy SM but not under the SM
  - SM-neutral parters difficult to produce at the LHC:
    - Effects on Higgs couplings

      Craig, Katz, Strassler, Sundrum ’15
    - Possible displaced vertices and hidden-valley pheno

Naturalness without TeV particles?

Graham, Kaplan, Rajendran '15

- Can we go even further and have a natural theory with no new particles at the TeV? Cosmological relaxation
    - Higgs mass at its natural (cut-off) value
    - Field-dependent contribution to the Higgs mass scans different values during inflation
    - When the Higgs mass becomes negative, it triggers a potential for the new field that freezes and stops the scanning
    - Replace the Higgs mass with a (small) parameter that is technically natural (stable under radiative corrections).

Natural without TeV particles?

Graham, Kaplan, Rajendran '15

- Can we go even further and have a natural theory with no new particles at the TeV? Cosmological relaxation.

$$V(h,\phi) = -\frac{\Lambda h^2}{2}\left(1 - g\frac{\phi}{\Lambda}\right) + g\Lambda^3\phi + \epsilon\Lambda_c^3 h\cos(\phi/f)$$

- $\phi > \Lambda/g \Rightarrow \langle h \rangle = 0$
- ϕ slow rolls during inflation (g<<1), scaning h mass
- When $\phi \leq \Lambda/g \Rightarrow \langle h \rangle \neq 0$ and the last term induces a potential for ϕ , which stops rolling (and therefore the scan)

Natural without TeV particles?

- Can we go even further and have a natural theory with no new particles at the TeV? Cosmological relaxation.

$$V(h,\phi) = -\frac{\Lambda h^2}{2}\left(1 - g\frac{\phi}{\Lambda}\right) + g\Lambda^3\phi + \epsilon\Lambda_c^3 h\cos(\phi/f)$$

- Simplest option: ϕ QCD axion (problems with θ_{QCD})
- Alternative: change last term to $\epsilon\Lambda_c^2 h^2\cos(\phi/f)$
  - Λ_c not related to QCD but this term is not radiatively stable
  - Can be made natural by introducing a second relaxation field

Natural without TeV particles?

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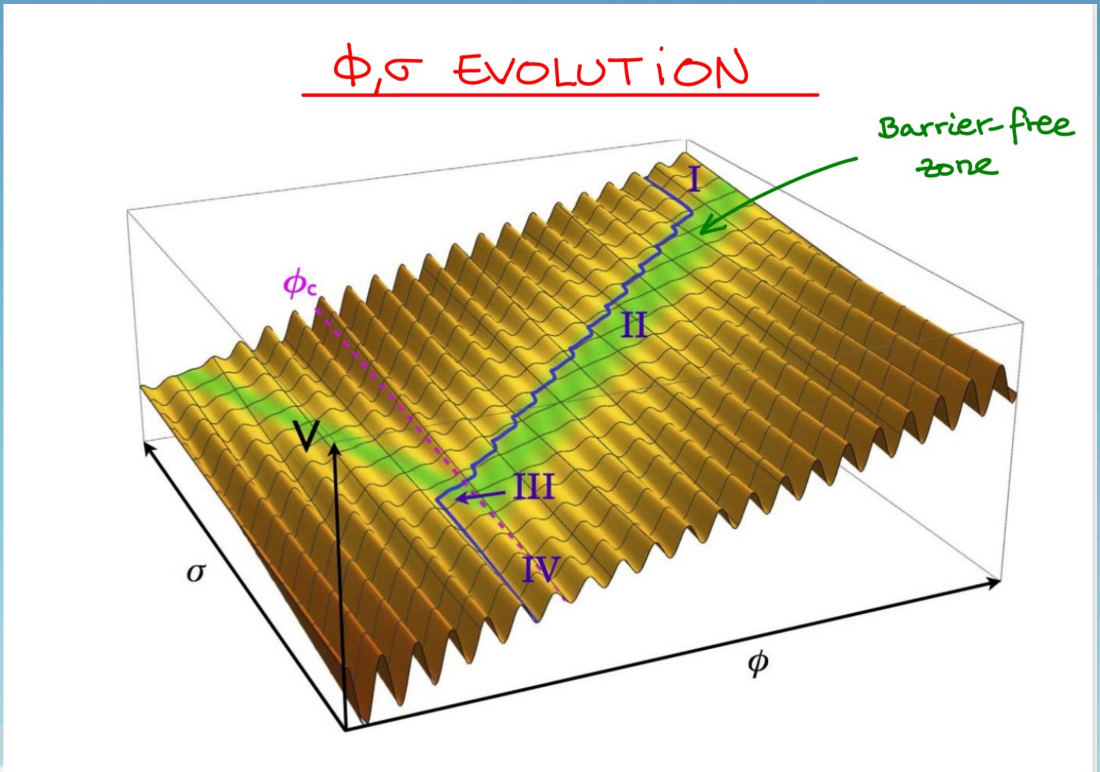


$$\Lambda \lesssim 10^6 \ \text{TeV}$$

- Only particles below Λ: ϕ, σ

$$m_\phi \in [10^{-20}, 10^2] \ \text{GeV}$$

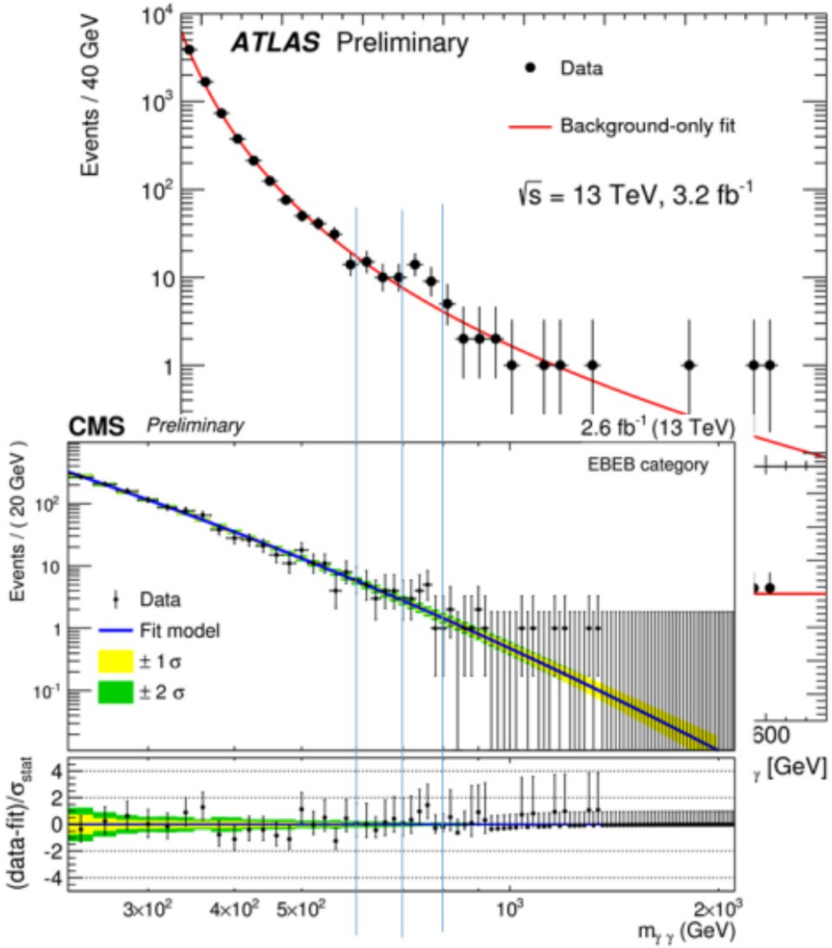
$$m_\sigma \in [10^{-45}, 10^{-2}] \ \text{GeV}$$

- Very suppressed couplings to SM: no collider signatures
- Possible axion-like DM candidates

Espinosa, Grojean, Panico, Pomarol, Pujol s, Servant '15

- Let’s change gears

First LHC data at 13 TeV



$\gamma\gamma$ peak around 750 GeV over flatland

$\sigma(pp \to \gamma\gamma)$	CMS	ATLAS
8 TeV	(0.5 ± 0.6) fb	(0.4 ± 0.8) fb
13 TeV	(6 ± 3) fb	(10 ± 3) fb

Theoretically clean.
Experimentally simple.

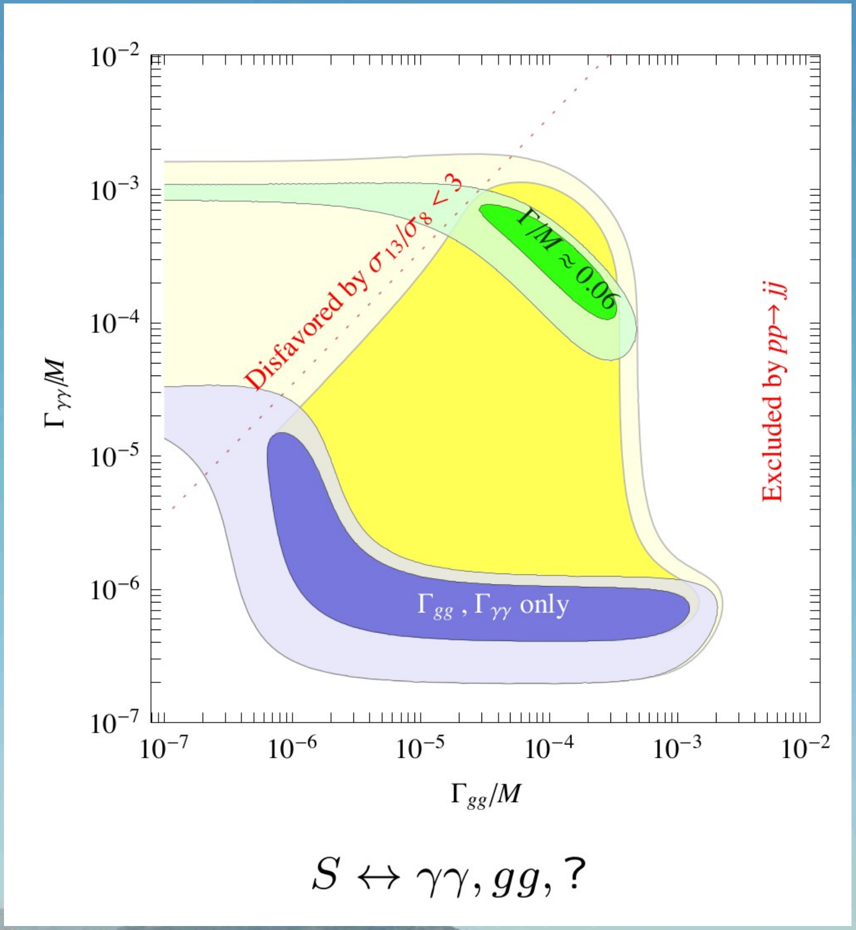
ATLAS prefers large width $\Gamma/M \sim 0.06$.
CMS prefers narrow width.

$\gamma\gamma$ not accompanied by hard extras.

Strumia, Moriond EW 2016

How can it be generated?

- The large enhancement from 8 to 13 TeV favours production via gg, $b\bar{b}$, $s\bar{s}$, $c\bar{c}$
- Assume gg production:



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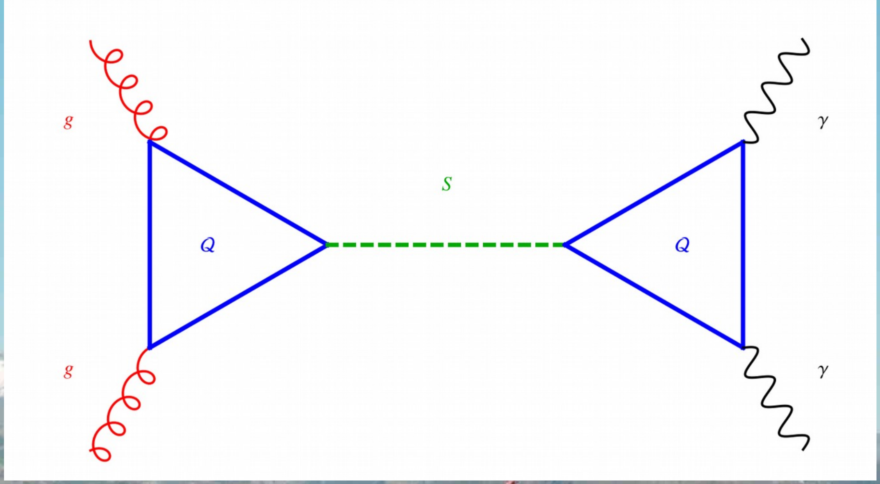
- The large enhancement from 8 to 13 TeV favours production via gg, $b\bar{b}$, $s\bar{s}$, $c\bar{c}$
- Assume gg production
- Easy to implement: new particles induce effective couplings at loop level (correlations with other channels)



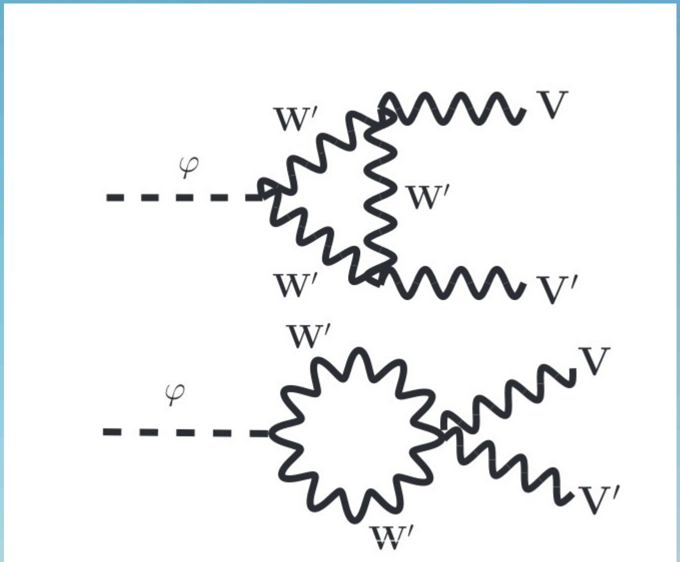
New vector-like quarks and leptons or new scalars normally used

New vectors also possible

How can it be generated?

- New vectors and the diphoton anomaly. The 750 GeV scalar can be the Higgs of a new broken gauge symmetry: the new vectors can induce the required couplings

Blas, JS, Vega-Morales ’15



Example: color octet with electric charge 1 and order one coupling reproduces with observed excess (with narrow width)

How can it be generated?

- New vectors and the diphoton anomaly. The 750 GeV scalar can be the Higgs of a new broken gauge symmetry: the new vectors can induce the required couplings
- It might be even possible to reproduce other reported anomalies like the ~ 2 TeV diboson and the $t\bar{t}$ forward-backward asymmetry
- Large width difficult to generate at the loop level (but not new Landau poles from vectors)

Conclusions

- Naturalness is still a good guiding principle for new physics at the LHC
- Pressure from null experimental results motivate more baroque models: new approach to collider searches
  - Cancellations possible (expected)
  - Rich spectra with unexpected features (large mixing, non-conventional decay or production channels, …)
- Reported anomalies have to be explained without contradicting other searches: diphoton is a good place for an anomaly to show up