Beyond 3 quark generations

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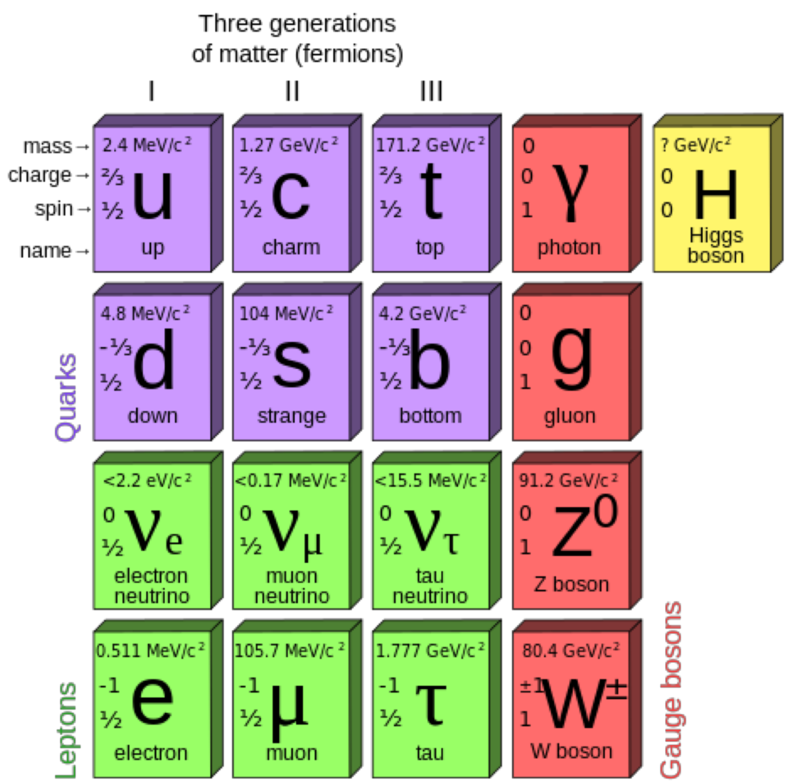
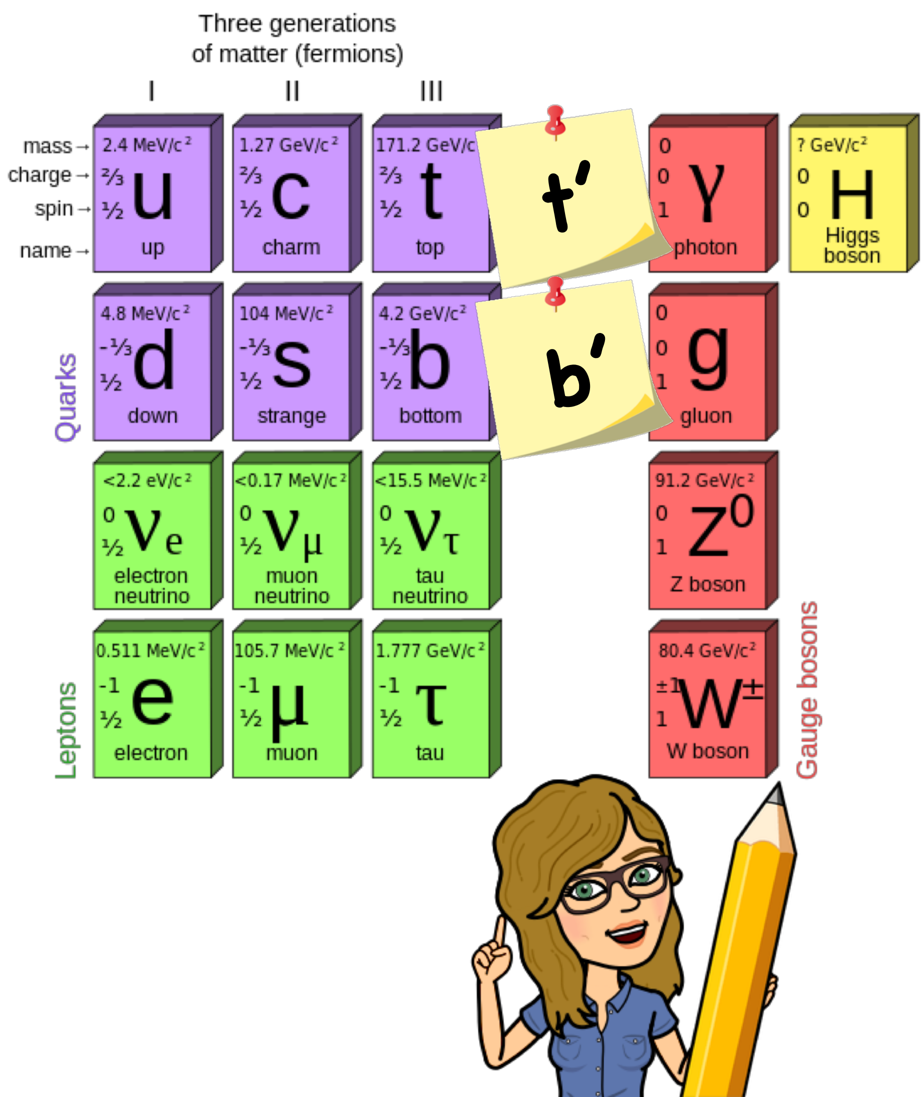
290e – February 27, 2019

Introduction



- In the Standard Model, have 3 generations of quarks
  - Spin ½
  - Electric charge +2/3 or -1/3
  - Color triplets
  - L-handed weak isospin doublet + R-handed singlet

The simplest extension



- Add a pair of quarks that ***interact just like the others***
- Since we haven't seen them yet, they must have ***high mass***

Implications of heavy quarks

- Heavy quarks b'/t' can be directly produced at high enough $\sqrt{s}$
  - 🙂 Possibility for direct searches at colliders
- Everywhere we sum over quarks, we now have extra terms for b' and t' that we know how to calculate
  - 🙂 Can derive indirect constraints if masses are too high for direct detection

Implications of heavy quarks

- Mixing between b'/t' and known quarks
  - 🙂 Decays to known quarks tell us what final states to search for
  - 🙂 Possible new source of CP violation
  - 🙁 Could create issues with CKM matrix unitarity
    (I'm going to ignore this)

Direct searches

- A quick search of ATLAS and CMS results on 4th generation quarks gives:
  - ATLAS search at 7 TeV for 4th generation d-type quarks
  - ATLAS search at 7 TeV for pair production of a new quark decaying to Z+b
  - ATLAS search at 7 TeV for 4th generation d-type quarks decaying to 1 lepton + hadronically decaying W
  - CMS search at 7 TeV for 4th generation u-type quarks with a lepton in the final state

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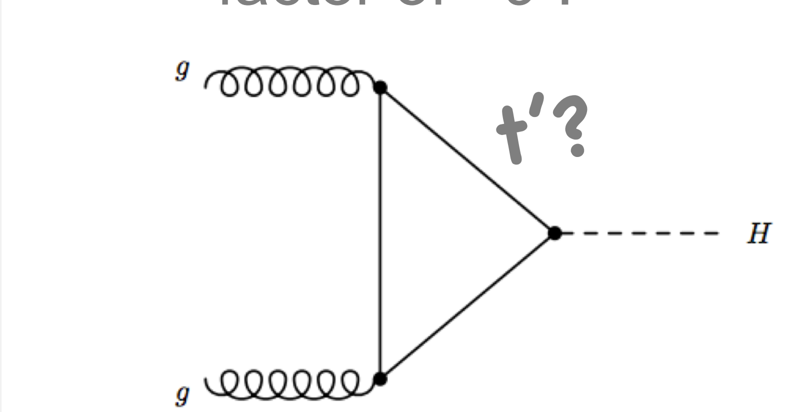
Haven't we made progress on this since Run 1?

Indirect constraints

- Everywhere we sum over quarks, we now have extra terms for b' and t'
- Example: cross section of Higgs production via gluon-gluon fusion (ggF)
  - Presence of b'/t' increases this cross section by a factor of ~9 !



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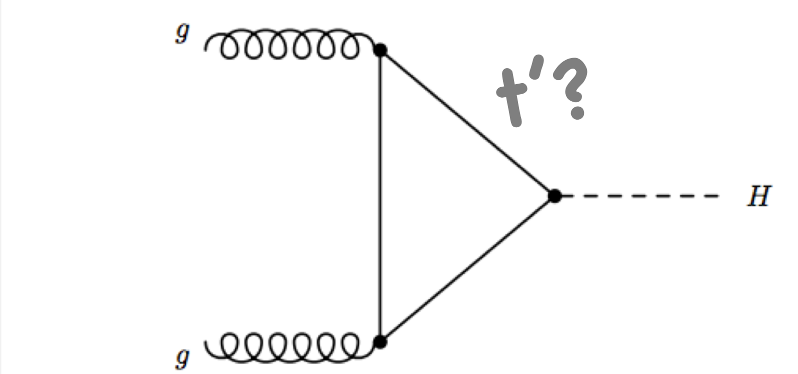
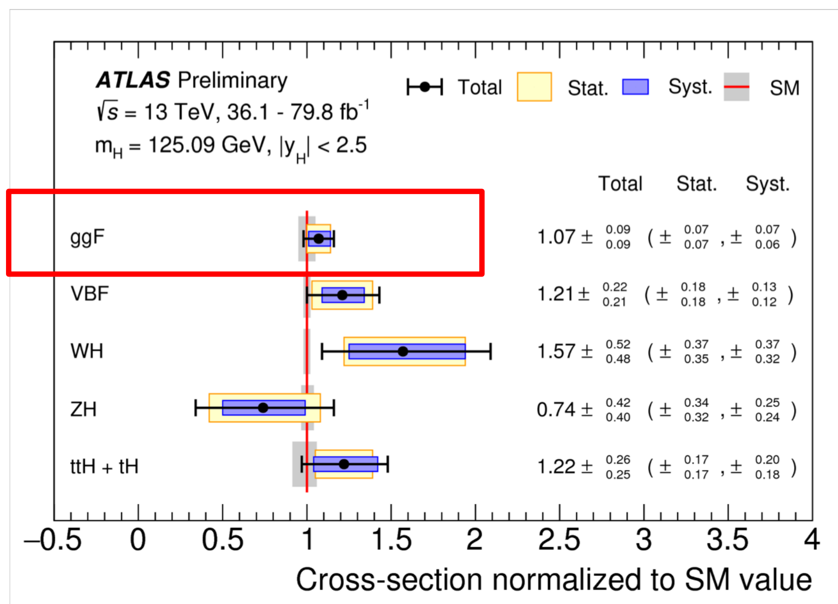
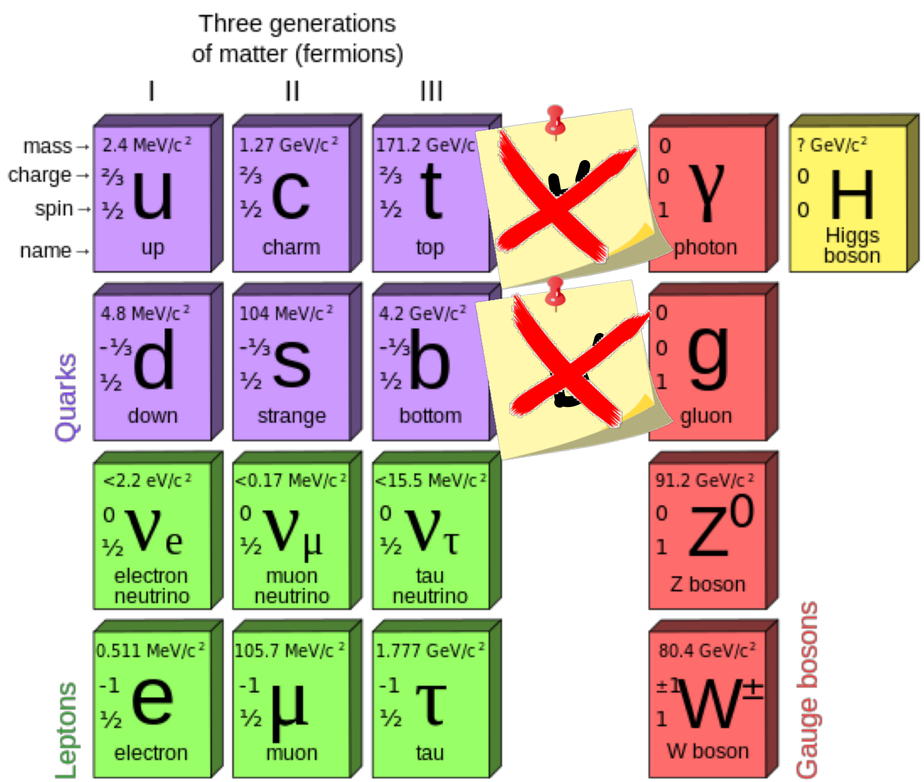


Higgs measurements strongly disfavor this



Adjusting the model



- How to introduce 4^{th} generation quarks in a way that is compatible with experiments?
- Solution: alter the form of the Higgs-quark couplings for 4^{th} generation

Quark couplings to Higgs

- For fermions, can generate mass and Higgs coupling terms with a Yukawa term:

$$\mathcal{L}_{\text{Yukawa}}(\phi, \psi) = -g\bar{\psi}\phi\psi$$

  - ttH and H(bb) observations indicate that this describes Higgs coupling to t, b
- This form is convenient, but ***not required*** by the Higgs mechanism

Vector-like quarks (VLQ)

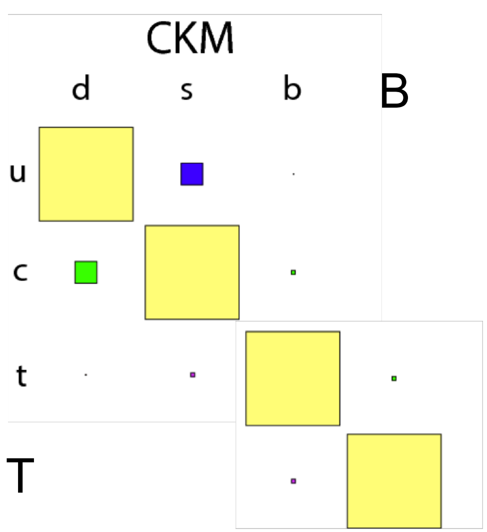
- They are quarks: spin ½, electric charge +2/3 or -1/3, color triplets
- They are vector-like: R- and L-handed have the same EW quantum numbers
  - Mass and Higgs coupling terms cannot have the same structure as known quarks
  - EW singlets, doublets, triplets are allowed

Implications of VLQs

- 🙂 VLQs B, T can be directly produced at high enough $\sqrt{s}$
- 🙂 Mixing with known quarks is retained
  – Decays to SM final states
  – Possibility for new source of CP violation
- Mass and Higgs coupling terms cannot have the same structure as known quarks
  - 🙂 Indirect constraints are loosened, e.g. on ggF

Direct VLQ searches

- VLQ are assumed to decay mostly to 3rd generation quarks
- Branching ratios depend on VLQ masses and mixing parameters



$$T \rightarrow Ht \text{ or } Zt \text{ or } Wb$$

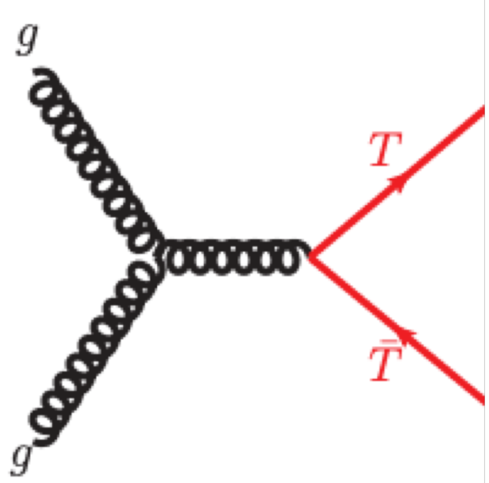
$$B \rightarrow Hb \text{ or } Zb \text{ or } Wt$$

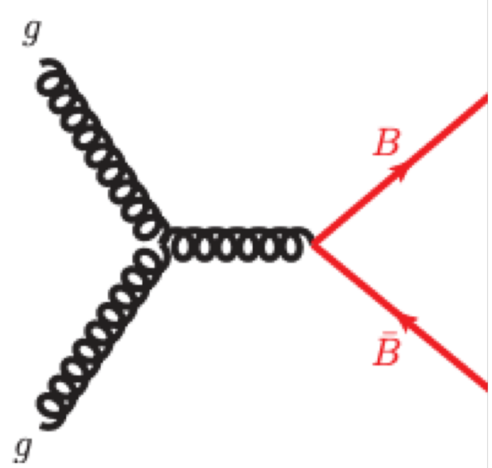
Branching ratios add up to 1.0

Possible extension:
allow decays to non-SM particles

VLQ pair-production

- At high enough $\sqrt{s}$, VLQ (B/T) cross section is dominated by QCD pair-production
  - At the LHC, this holds for VLQs with mass up to ~1 TeV
- Pair-production cross section depends on the VLQ mass (not mixing parameters)





VLQ pair-production

- 2018 ATLAS paper combines many VLQ searches targeting different decays
- Main backgrounds: top-antitop pair production, vector boson + jets

Analysis	$T\bar{T}$ decay	$B\bar{B}$ decay
$H(bb)t+X$ [16]	$HtH\bar{t}$	-
$W(\ell\nu)b+X$ [17]	$WbW\bar{b}$	-
$W(\ell\nu)t+X$ [18]	-	$WtW\bar{t}$
$Z(\nu\nu)t+X$ [19]	$ZtZ\bar{t}$	-
$Z(\ell\ell)t/b+X$ [20]	$ZtZ\bar{t}$	$ZbZ\bar{b}$
Tril./s.s. dilepton [21]	$HtH\bar{t}$	$WtW\bar{t}$
Fully hadronic [22]	$HtH\bar{t}$	$HbH\bar{b}$

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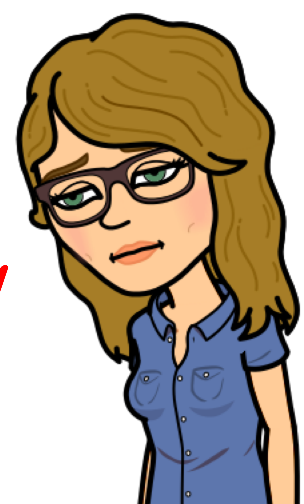
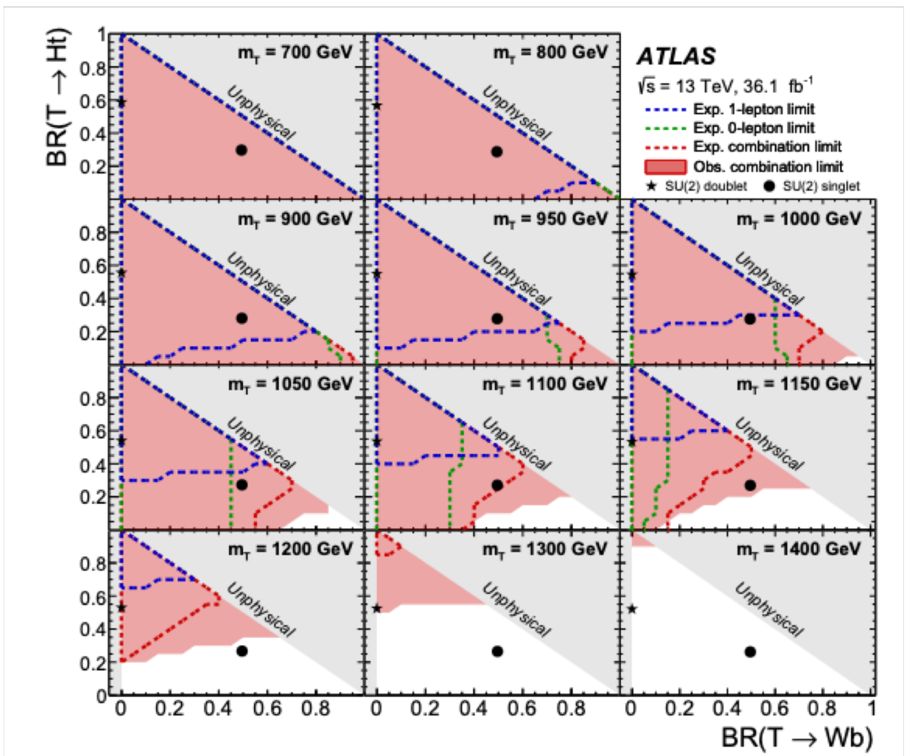
No VLQ observation in any channel



VLQ pair-production

- Sensitivity depends on VLQ mass and branching ratios



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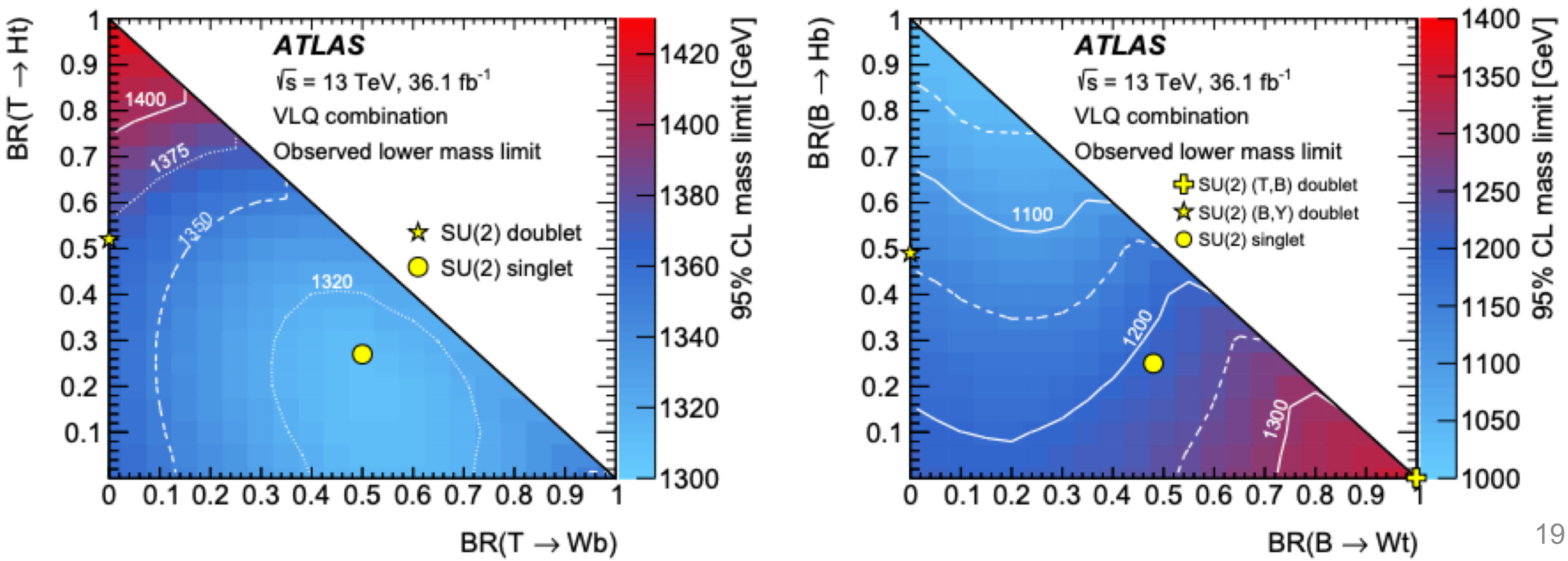
- H(bb)t + X is most sensitive to Ht final state
- Sensitivity is worse at high m_T

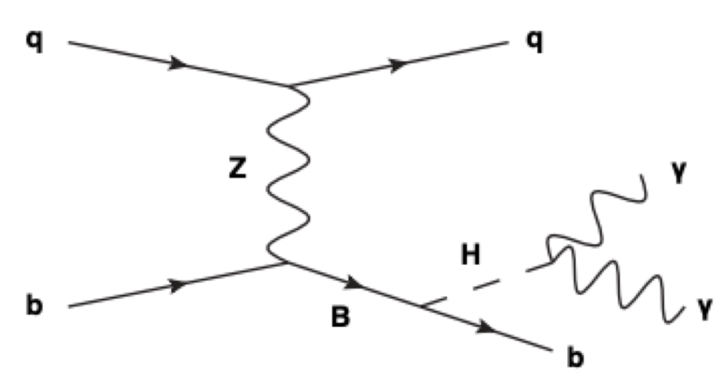
VLQ pair-production

- Combined limits are set on T and B as a function of BR and mass
  - T singlet excluded at 95% CL for $m_T < 1.3$ TeV, B singlet for $m_B < 1.2$ TeV



VLQ single-production

- Pair production of heavy VLQs limited by √s
  - Starts to apply at VLQ mass ~1 TeV. Already reaching this with current limits!
- Consider single T/B production through electroweak coupling to W, Z, H
  - Cross section depends on VLQ masses ***and mixing parameters***
- Example: 2018 ATLAS search for single B to H(ɣɣ)b



VLQ single-production

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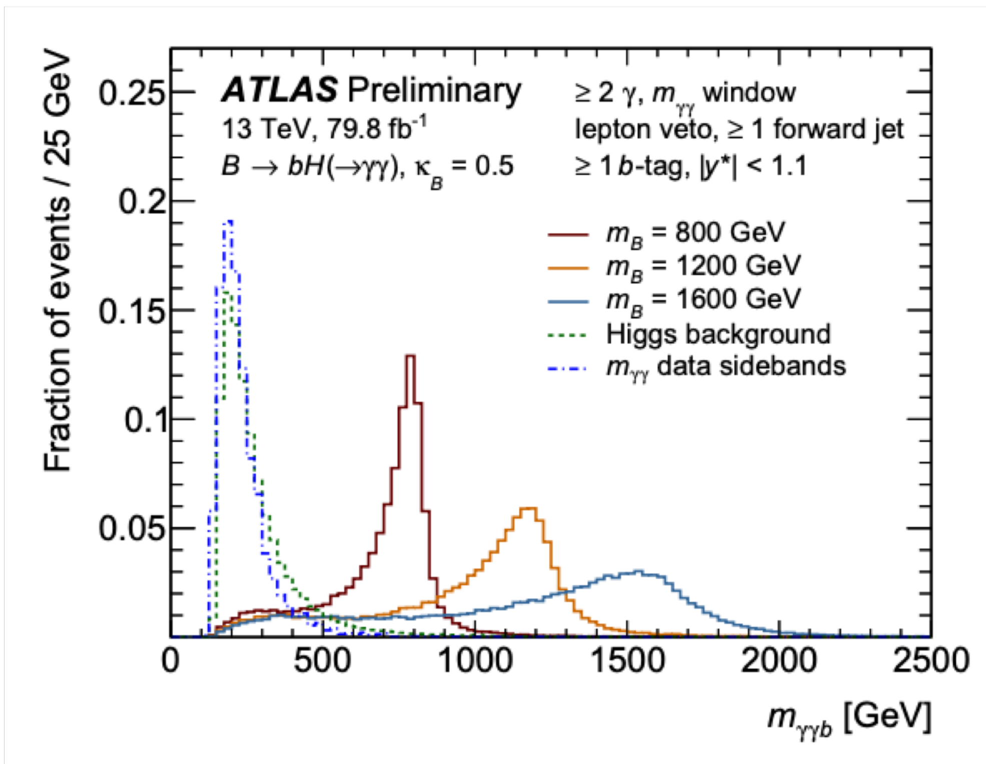
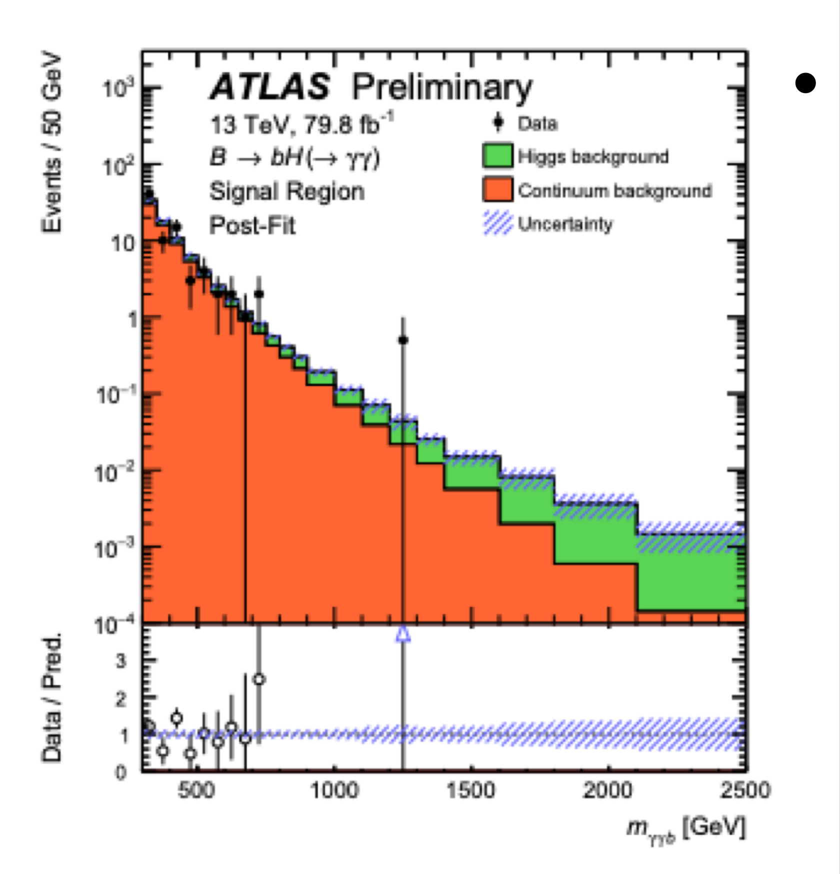


- Require 2 photons with $m_{\gamma\gamma}$ ~ 125 GeV
- Require 1 b-jet, 1 light forward jet, no leptons
- Clean channel with smooth background
- B signal shows up as a resonance in $m_{\gamma\gamma b}$

VLQ single-production

- 2018 ATLAS search for single B to H(γγ)b
- ***No VLQ observation***



- Assuming b-B coupling of 0.5, doublet model (B,Y) is excluded at 95% CL up to 1210 GeV
  - Compare to the combined exclusion on the same model of 1150 GeV!

Summary

- 4^{th} generation quarks with Yukawa couplings to Higgs are strongly disfavored
- VLQs are a very viable model of 4^{th} generation quarks!
  - VLQ pair production is an active search area at the LHC
  - Single VLQ production extends mass reach, but requires assumptions on couplings
  - Many final states remain to be explored!

Main resources

- 2009 "Beyond the 3-generation SM in the LHC era" Workshop
- 2013 theory review
- ATLAS and CMS public results pages (exotics)
- 2018 ATLAS VLQ combination
- 2018 ATLAS VLQ H(bb) + X
- 2018 ATLAS VLQ H(γγ)b + X