Vector Like Quarks and where to Find them

A case study by ...

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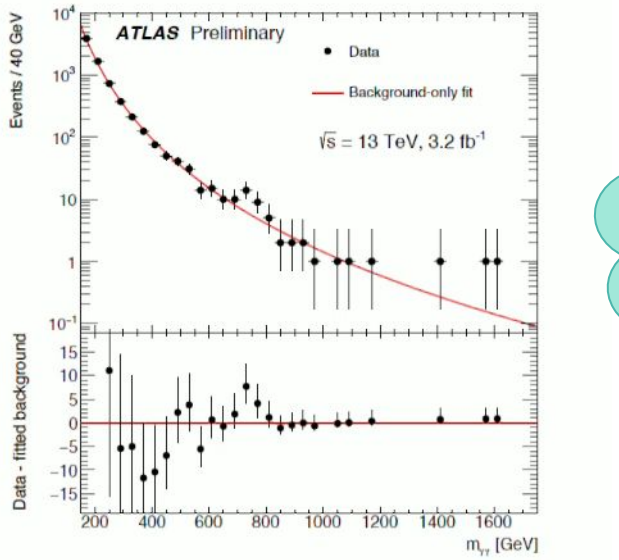
SSI

The Question

Searches for vector -like quarks (VLQ) at the LHC usually assume that they decay via mixing with the Standard Model (SM) quarks of the 3rd generation.

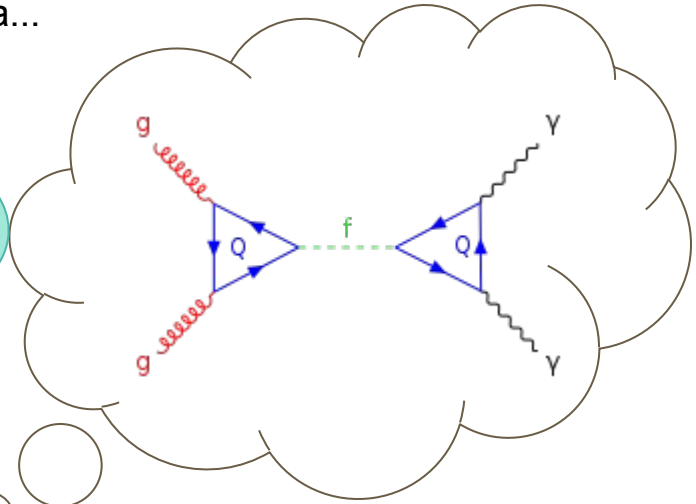
Part a)
How would such searches be altered if they decayed instead to the 1st generation? Estimate the corresponding search reaches in this case by employing the results of the existing searches performed by ATLAS & CMS.

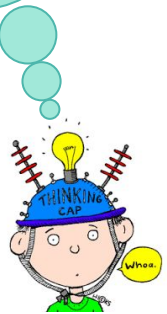
Lets say its 2015 December...



You have a ‘totally original’ idea...

I bet no one else is thinking about this…. I’m so clever!





What type of quarks?

- VLQs to escape Higgs Yukawa problems, Anomalies
- What are the current detector bounds?
- Let me open PDG
- Experimental results available only for VLQs decaying into 3rd generation
- What about the ones that couple preferentially to the light quarks?

VLQ Introduction

- Vector Like quarks arise in many extensions of the SM
  - For GUT example refer to Nate Craig's talk
- $\Delta\mathcal{L} = M_Q\bar{Q}Q$ mass-term with $\bar{Q}$ and Q having the same SU(2) quantum numbers, hence gauge invariant bare mass allowed
- From minimality point of view: heavy quarks gaining mass entirely from higgs will affect ggf. hence ruled out.
- Next simplest bare mass / mass from SU(2) singlet sector
- Anomaly Free
- Cannot be stable from cosmology considerations
- Decay to SM quarks to shed color and electric charge

Current status

- Most searches assume decays to 3rd generation
- Motivated by solutions to the hierarchy problem

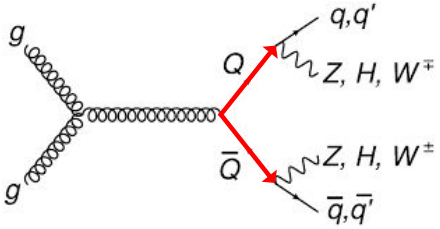
  viz. Little Higgs/Composite Higgs theories etc
- Decay to qZ, qW or qH where q = { t, b }
- Easy to trigger and isolate: better limits
- Assumption made: BR(qZ) + BR(qW) + BR(qH) = 1. (Refer to Nate Craig's talk)

Heavy quark phobic VLQs

- **Challenge:** Decay to qW, qZ or qH hence cannot use b or top tagging for light quarks in the decay chain
- This makes looking for them a bit more subtle

Production mechanisms

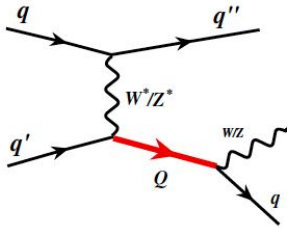
- Pair Production



- Model Independent production cross section
- Phase space suppressed for high quark masses

We limit ourselves to Pair Production here

- Single Production



- Cross section dependent on qQ coupling (constraints from flavor physics and Electroweak precision tests)
- Smaller phase space penalty for large Q

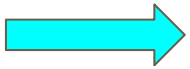
For a study refer to 1102.1987

Single Production

- Production depends on qQW coupling.
- Expect small qQW coupling from theory prejudices
  - Mixing typically occurs because of EWSB
  - Hence mixing angle ~ v/f
- qQW couplings constrained from flavor and EW bounds
- arXiv: 1102.1987 constrains mT from single production. Predicts poor limits if
  - (qQW/qqW)^2 < 0.04

Pair Production Strategy

There are no existing experimental limits specifically for VLQ pair → light jets

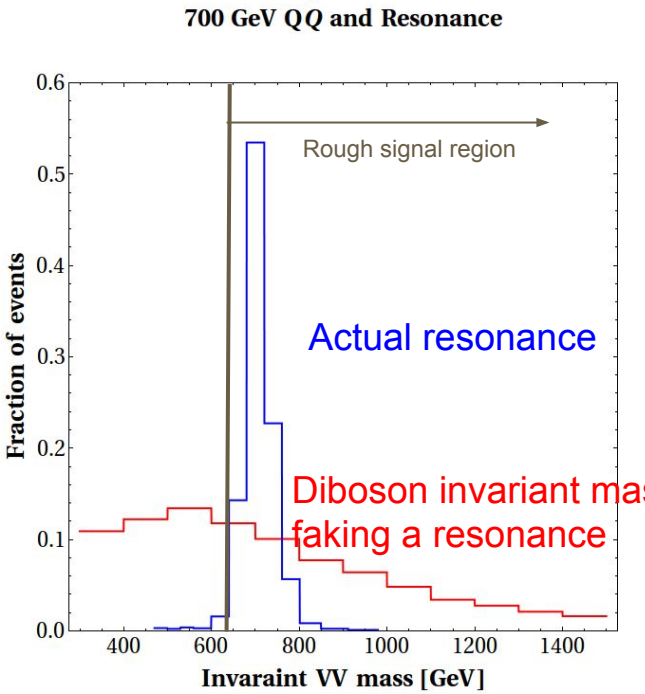
 Project from related searches!

Since VLQ pair gives two boosted bosons(W/Z/H)+jets, we can project from diboson resonance searches.

- Lower limits on $\sigma \propto L^{-½}$
- Can project from known 13 TeV results
- Modified signal efficiency for different search strategies

Faking Heavy Resonance

The invariant mass of VV is on average Q mass, assuming Q pairs are produced near threshold.



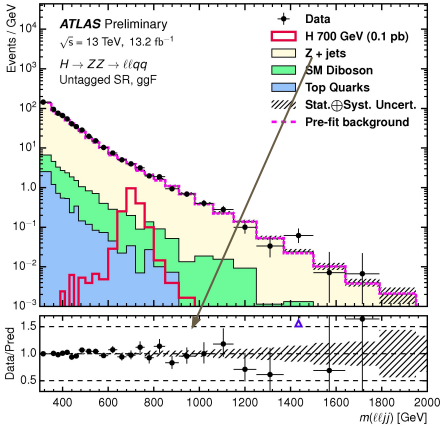
~54% events > 600 GeV

~43% events > 700 GeV

Taking a universal 30% efficiency for QQbar faking a heavy resonance

Future experiments can do better by putting cuts on extra jets.

e.g. ZZ resonance from CONF-2016-082



Existing 8 TeV result on qWqW final state

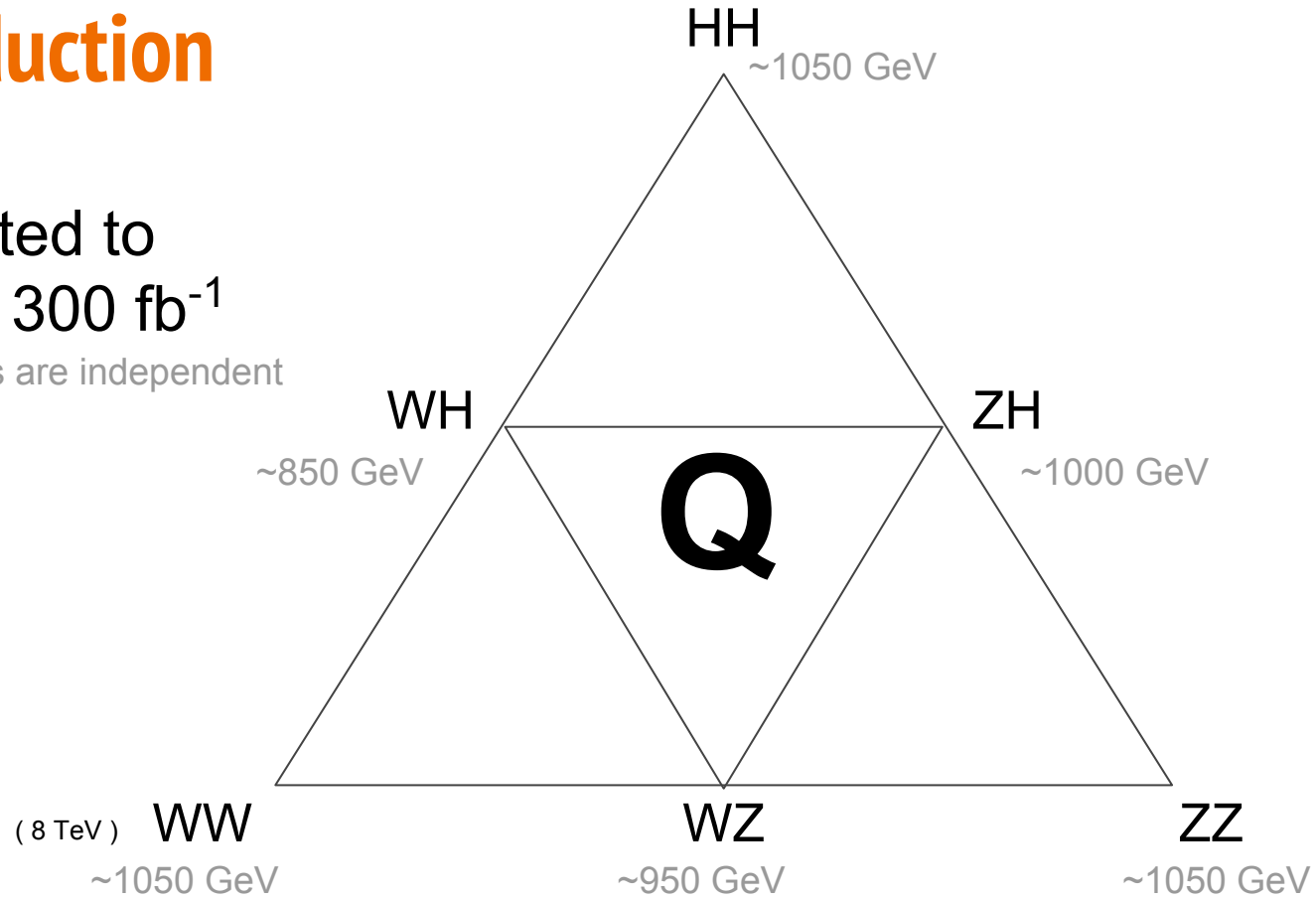
It is non-trivial to estimate the exclusion limit change from 8 TeV to 13 TeV.
Therefore for qWqW final state, we only projected the luminosity
("8 TeV 300fb^{-1}" result)

The result is roughly consistent with WW resonance search projection.

Pair Production

projected to
13 TeV, 300 fb^{-1}

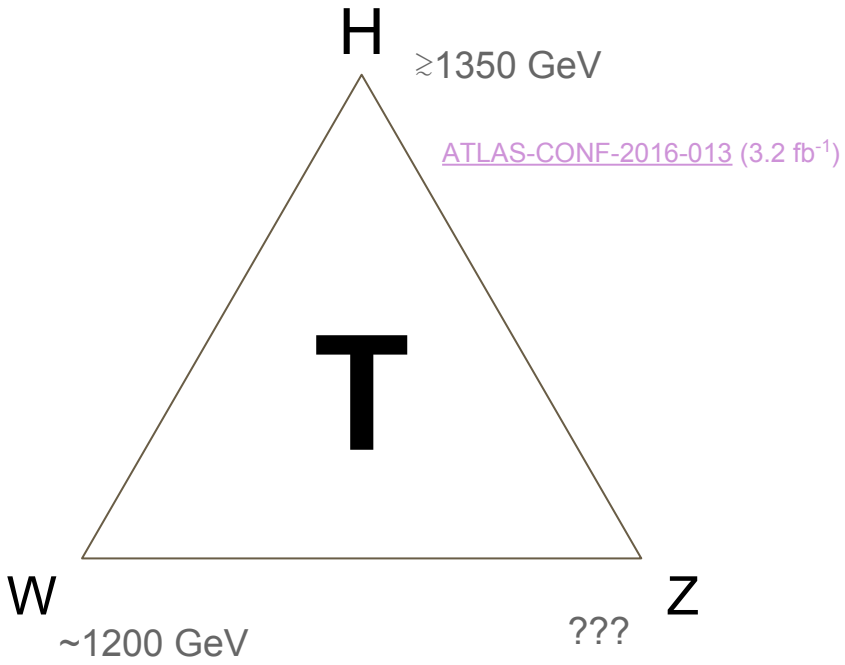
N.B. Mixed decays are independent



Pair Production (3rd Gen)

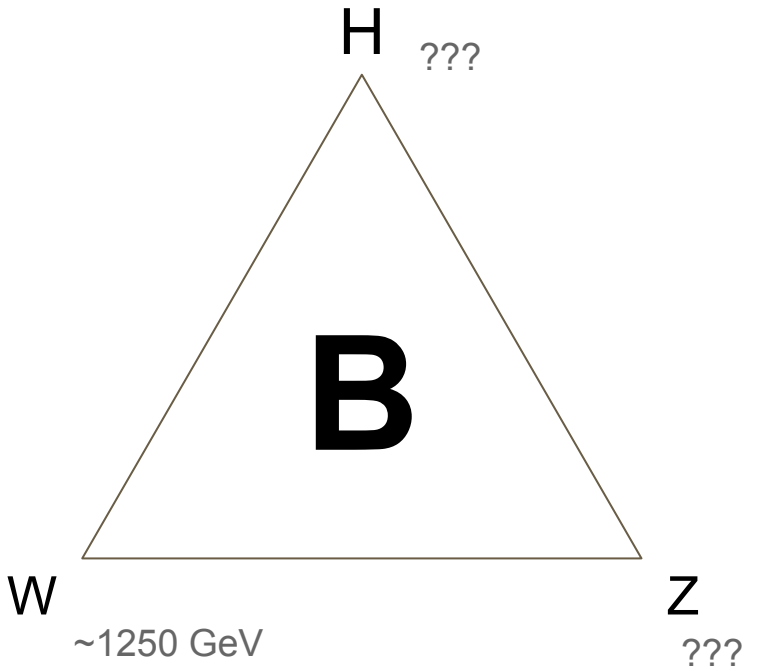
13 TeV, 300 fb^{-1}

??? = No Public 13 TeV Results to Extrapolate



ATLAS-CONF-2016-013 (3.2 fb^{-1})

B2G-16-002 (2.3 fb^{-1})



ATLAS-CONF-2016-032 (3.2 fb^{-1})

Opening up a 4th decay channel for heavy tops(T)

Searches for vector -like quarks (VLQ) at the LHC usually assume that they decay via mixing with the Standard Model (SM) quarks of the 3rd generation.

Part b)

VLQ searches also assume that these particles only decay into W, Z or Higgs final states so that the sum of the corresponding branching fractions is unity and this is used in combining the search results. How would this combination of results change if this strong assumption were to be dropped, e.g., there was a fourth possible final state?

4th decay channel (qW+qH+qZ < 1)

- If T has a parity(t) then cannot decay only to SM
- T → t+X where X is the Ltp
- Very similar to a stop search with R-parity: involves MET

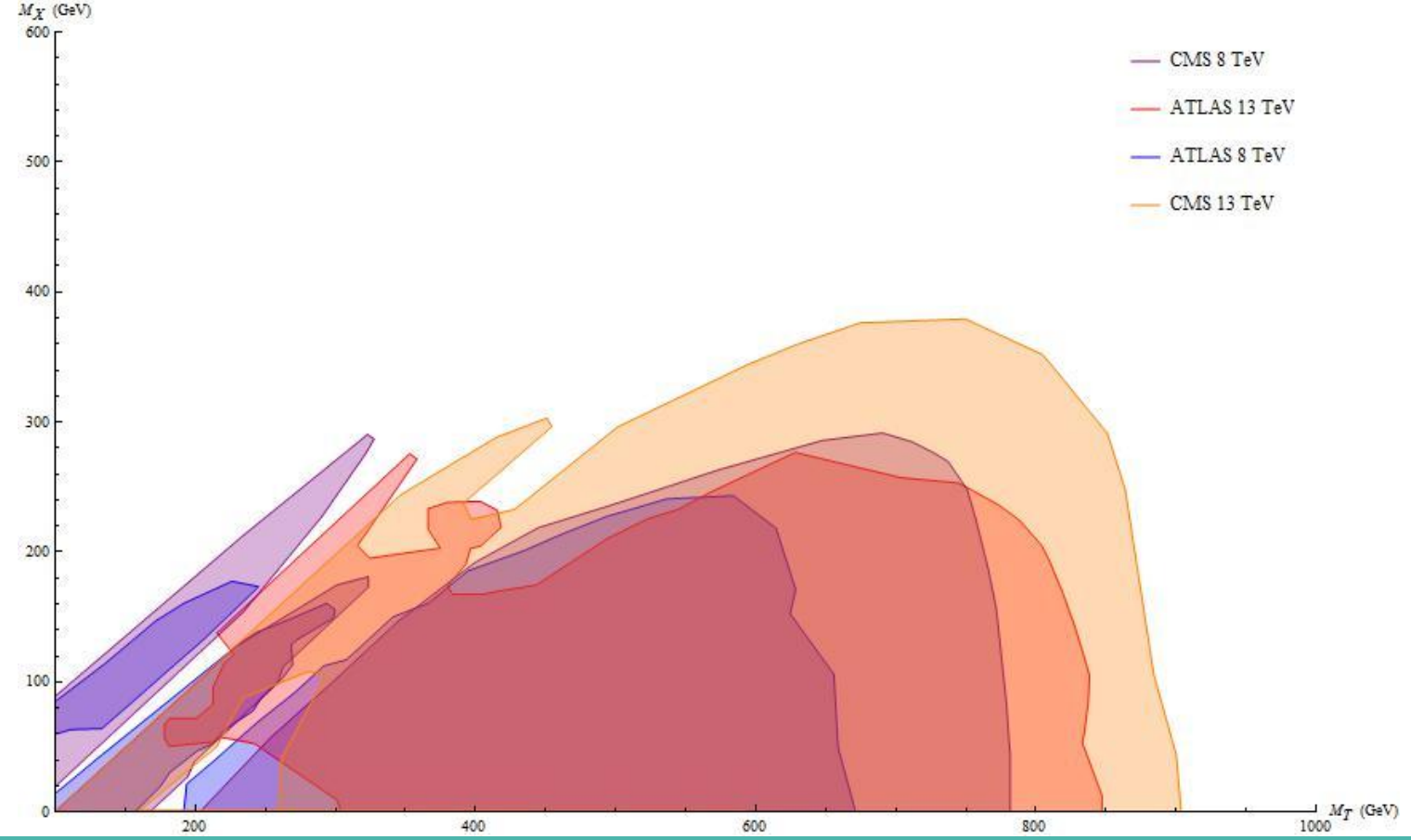
Refer to arXiv:1506.05130

For Ltp idea

Heavy Jet + MET (exact t-parity)

- Stop searches (bosons) have the same signature.
- Heavy quark production approx 9 times larger than stop production for the same mass.
- Heavy quark decay efficiencies lag stop specific efficiencies (source: arXiv:1506.05130)
- We need detector efficiencies to account for this accurately.
  We conservatively (*lackadaisically*?) assume they cancel.
- However placing cuts with fermions in mind can improve this situation hence heavy quark limits can get much better than stop limits for exact t(R)-parity.

Constraints from Stop Searches



Can we do better than this?

Yaay! more model building

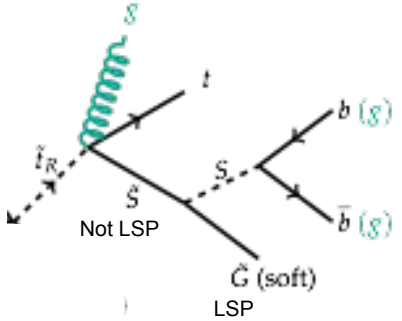
Approx t parity or ...

- Approx t parity: $T \rightarrow t+X, X \rightarrow t\bar{t}$ or $b\bar{b}$ or jj
  - Look for $t\,\bar{t}$+4b or $t\,\bar{t}$+4j or 6 tops
- Keep t-parity but build complicated hidden sector: new Ltp
  - $X \longrightarrow Y+Z$ with X and Y almost degenerate and Z the new Ltp.
  - Rehashing ideas already used in...

Stealth SUSY

- Invented to hide SUSY without violating R-parity
- New extended Stealth sector, Gravitino is the LSP
- Decay chains have almost-degenerate masses.
- Reduces MET hence difficult to trigger
- Increases Jet Multiplicity
- If extra jets are not heavy, limits are worse than even RPV stop scenarios

Stealth stop decay topology



4th decay channel (Stealth scenarios)

Model	Signature	Reinterpreted Search	Limits [GeV]
Approx t-parity/hidden valley : X->jj	2t+4j	Refers to tt Xsec measurements as: 1511.04716[ATLAS] ATLAS-CONF-2016-040 …...	Does not exist
X->bb	2t+4b	Reinterpret from 1311.6736,1404.2500[CMS] 1407.0600,1605.09318[ATLAS]	500
X->tt	6t	Does not exist - for reinterpretation: 1405.6119	700
Long lived X	displaced vertex search	1504.03634 [ATLAS]	~700 (optimized cτ)

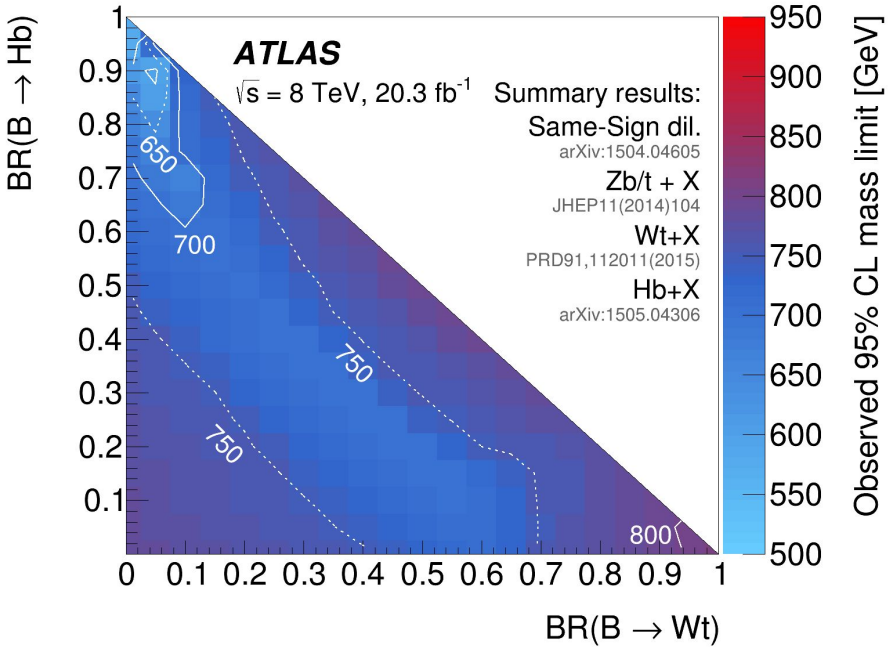
Note: these limits are actually for stealth susy stops/gluinos with the same decay final states

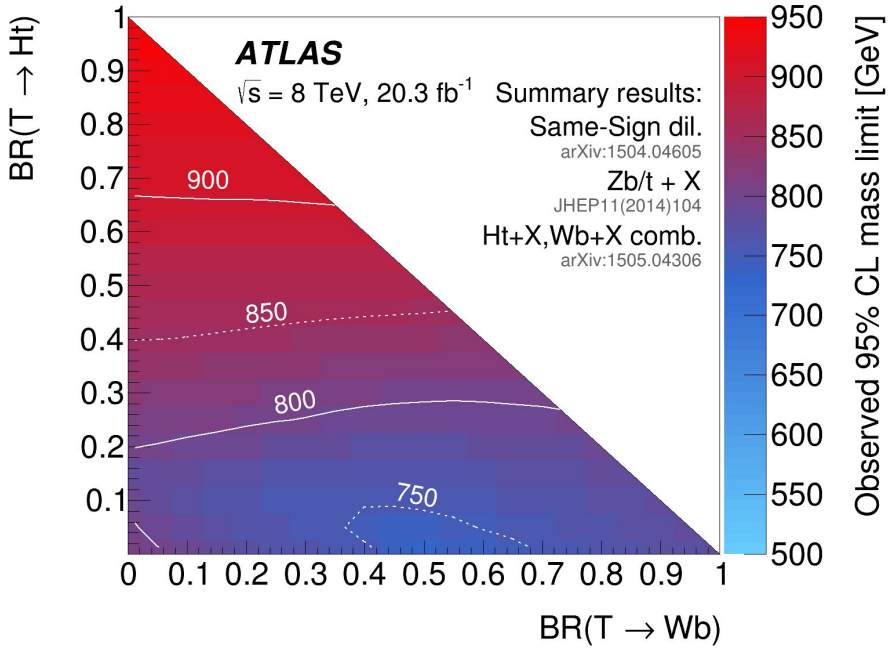
Conclusion

- 3rd-gen phobic VLQs have no current searches
- Our proposal involves faked diboson resonant searches
- With 300 fb^{-1} data we expect to push model-agnostic VLQ limits to a TeV
- Well…. not that agnostic
- We open new search channels with hidden valley model building
- In certain perverse cases no known model limits exist because of SM top background

Backup

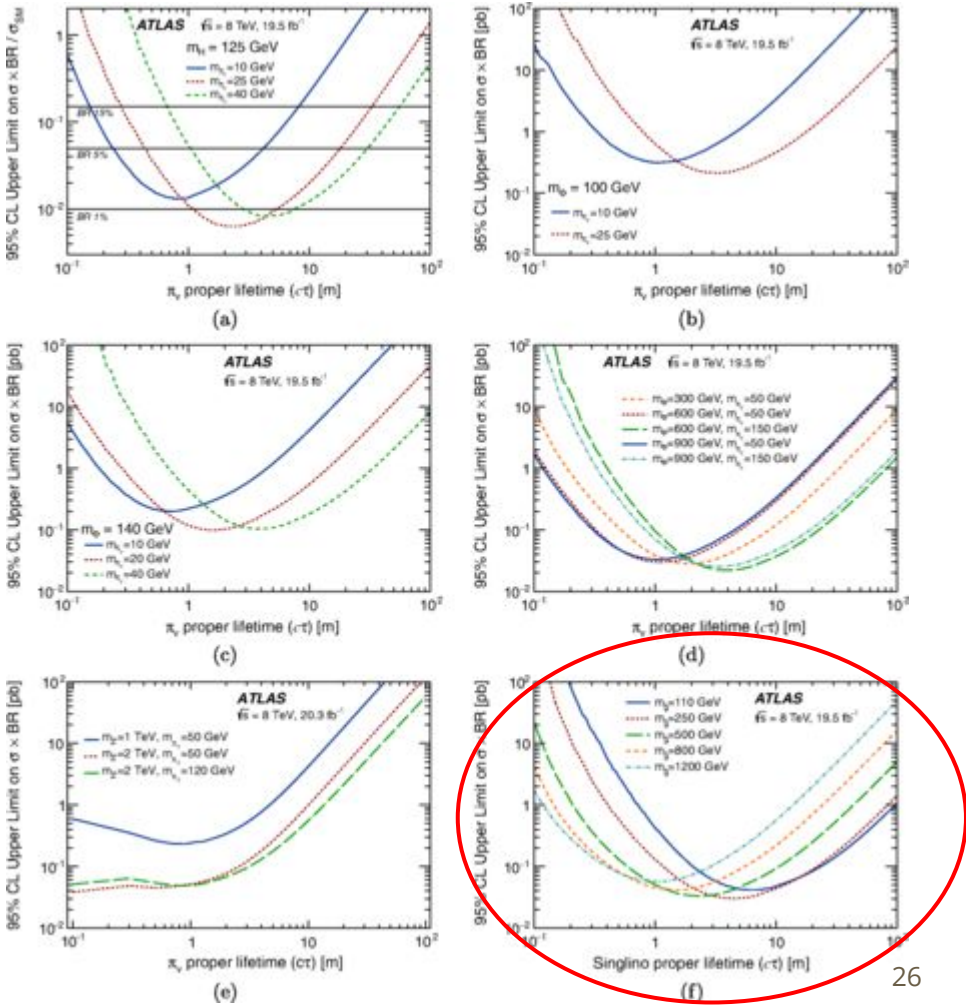
8 TeV limits on 3rd Gen. VLQ





Displaced Vertex

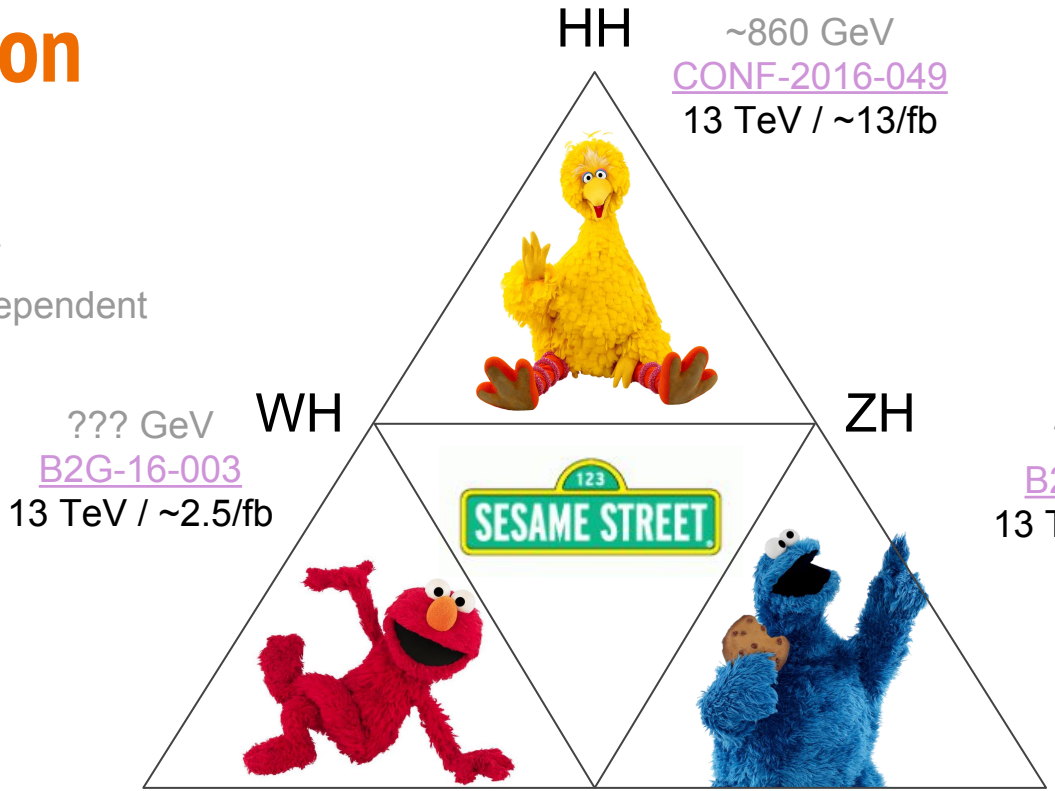
- The displaced vertex search is sensitive to cτ of the long lived X. In the stealth SUSY search, optimized cτ gives ≲ 0.1 pb limit for various gluino masses. (20 fb^{-1})
- Assuming the limit is controlled by signal instead of background
- Assuming similar efficiency from 8 TeV to 13 TeV



Pair Production

Current limits

N.B. Mixed decays are independent



~860 GeV
CONF-2016-049
13 TeV / ~13/fb

??? GeV
B2G-16-003
13 TeV / ~2.5/fb

??? GeV
B2G-16-003
13 TeV / ~2.5/fb

??? GeV
CONF-2016-082
13 TeV / ~13/fb

800 GeV
B2G-12-017
8 TeV / ~20/fb

??? GeV
CONF-2016-082
13 TeV / ~13/fb