Searches for Vector-like Quarks

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Outline

- Overview of Vector-like Quarks
- Pair Production @ 13 TeV

ATLAS
Ht+X (1-lepton) [ATLAS-CONF-2016-013]
Zt+X (1-lepton) [ATLAS-CONF-2016-007]
SS+b-jets [ATLAS-CONF-2016-032]

CMS
TT (1-lepton) [B2G-15-002]
XX (dilepton/1-lepton) [B2G-15-006]

NEW

- Single Production @ 13 TeV

CMS
T→Ht (1-lepton) [BTG-15-008]
T→Ht (0-lepton) [BTG-16-005]

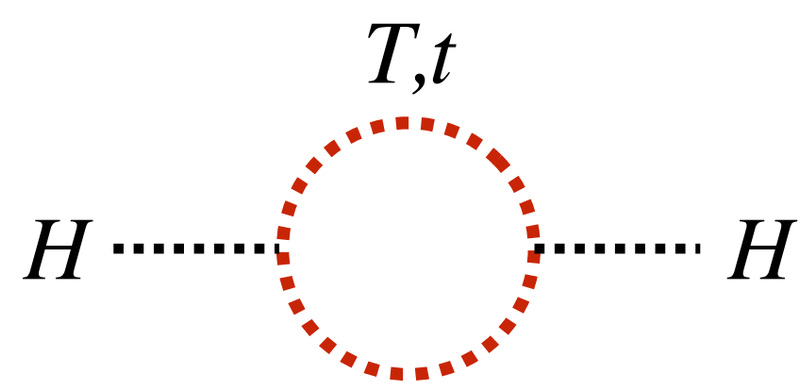
NEW

- Conclusions

Introduction

- Vector-like Quarks (VLQs) are heavy non-chiral quarks with symmetric left- and right-handed couplings to SM particles
  - Simplest colored fermion extra generation allowed by data
  - Couple to SM particles through Yukawa interactions
    - Modify SM couplings to Z,W,H
- Very common in many extensions to the SM (little higgs, composite higgs, warped or extra dimensions, …)

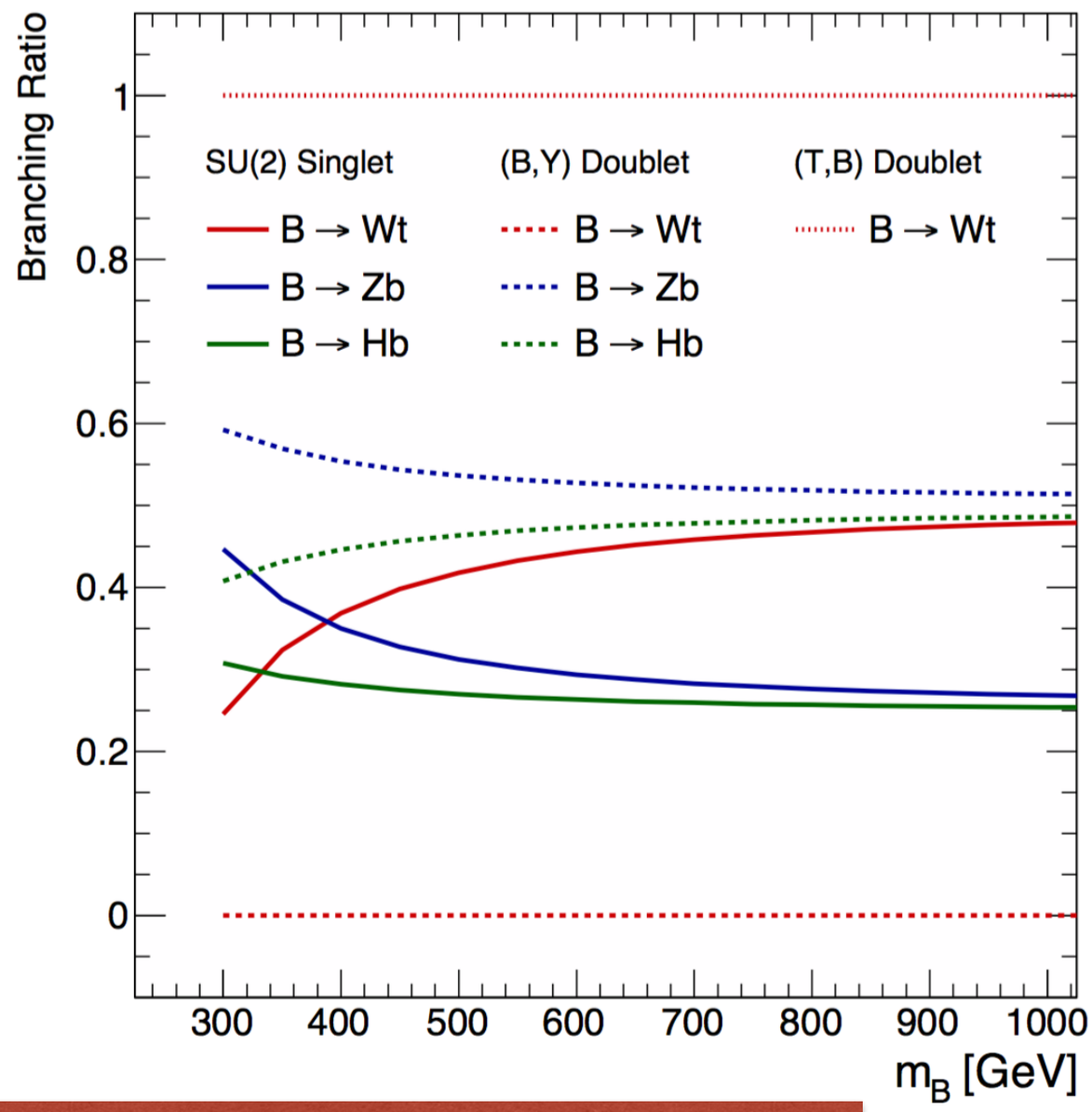
Singlets	Doublets	Triplets
$T_{L,R}$	$(X,T)_{L,R}$	$(X,T,B)_{L,R}$
$B_{L,R}$	$(T,B)_{L,R}$	$(T,B,Y)_{L,R}$
	$(B,Y)_{L,R}$	

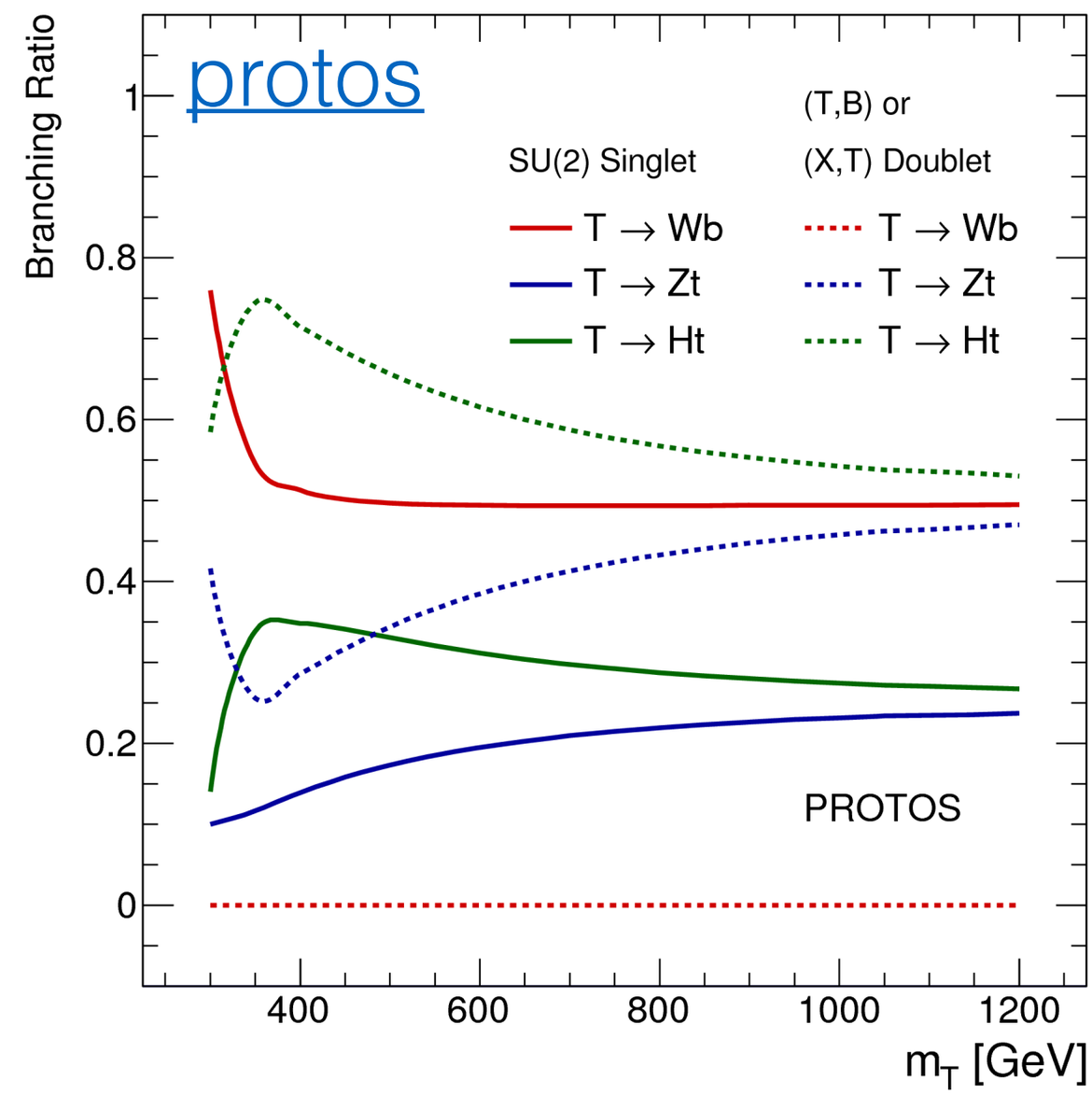


Alternative to SUSY that renders the Higgs natural!

VLQs at the LHC

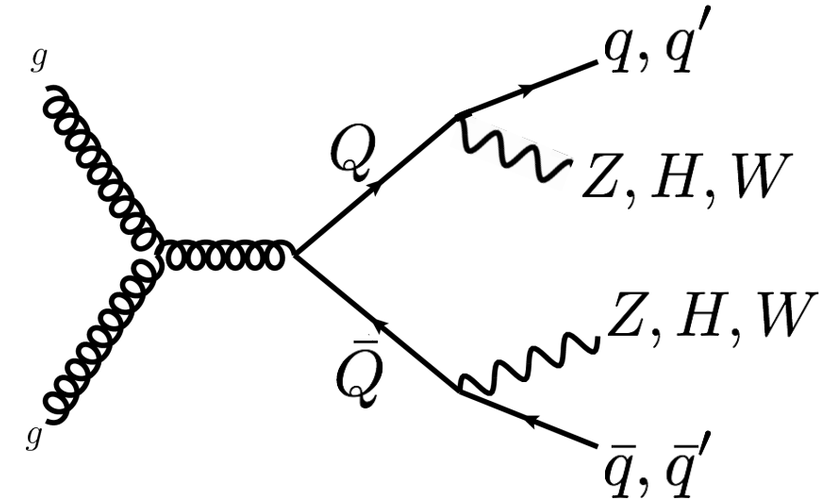
- VLQ decays produce rich final states:
  - **boosted hadronic decays**: Build jets with a larger radius parameter (R≥0.8) and apply jet substructure techniques to identify W/Z/H/tops
  - **boosted leptonic decays**: single, SS/OS high-p_T leptons (e/μ)



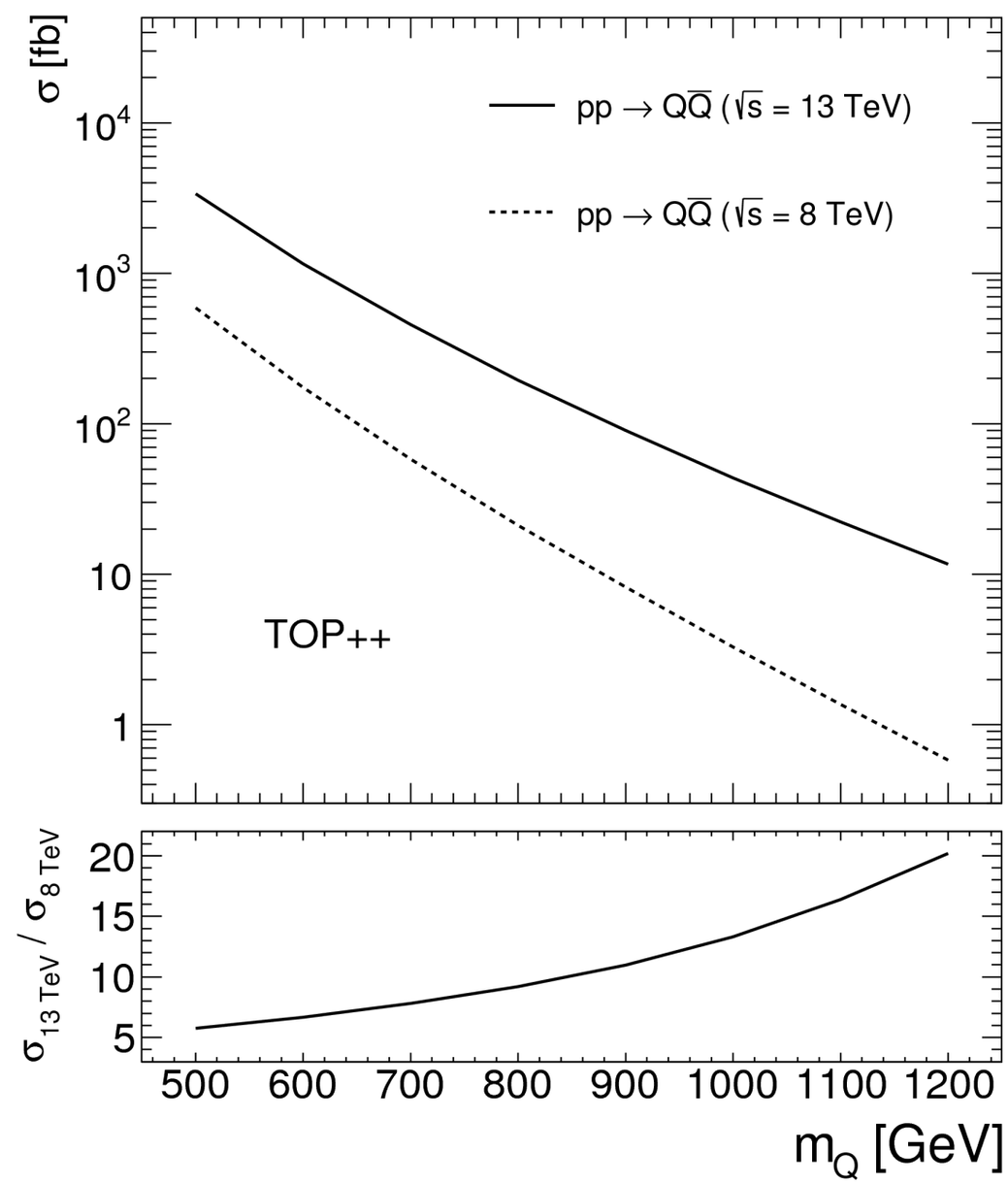


*BRs free parameters of the model

Pair Production

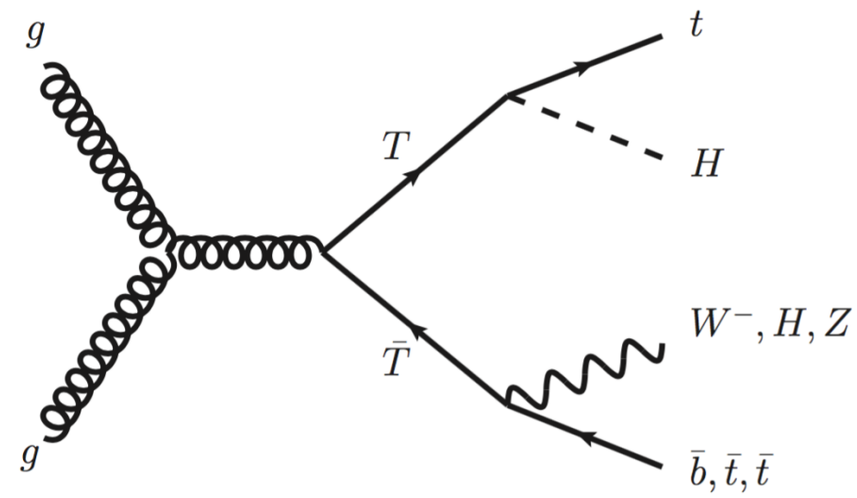


- Pair produced VLQ is generally model independent (via strong interaction)
- Cross Section depends on the VLQ mass
  - Independent of EW charges and couplings
- Large increase in cross section between 8 and 13 TeV



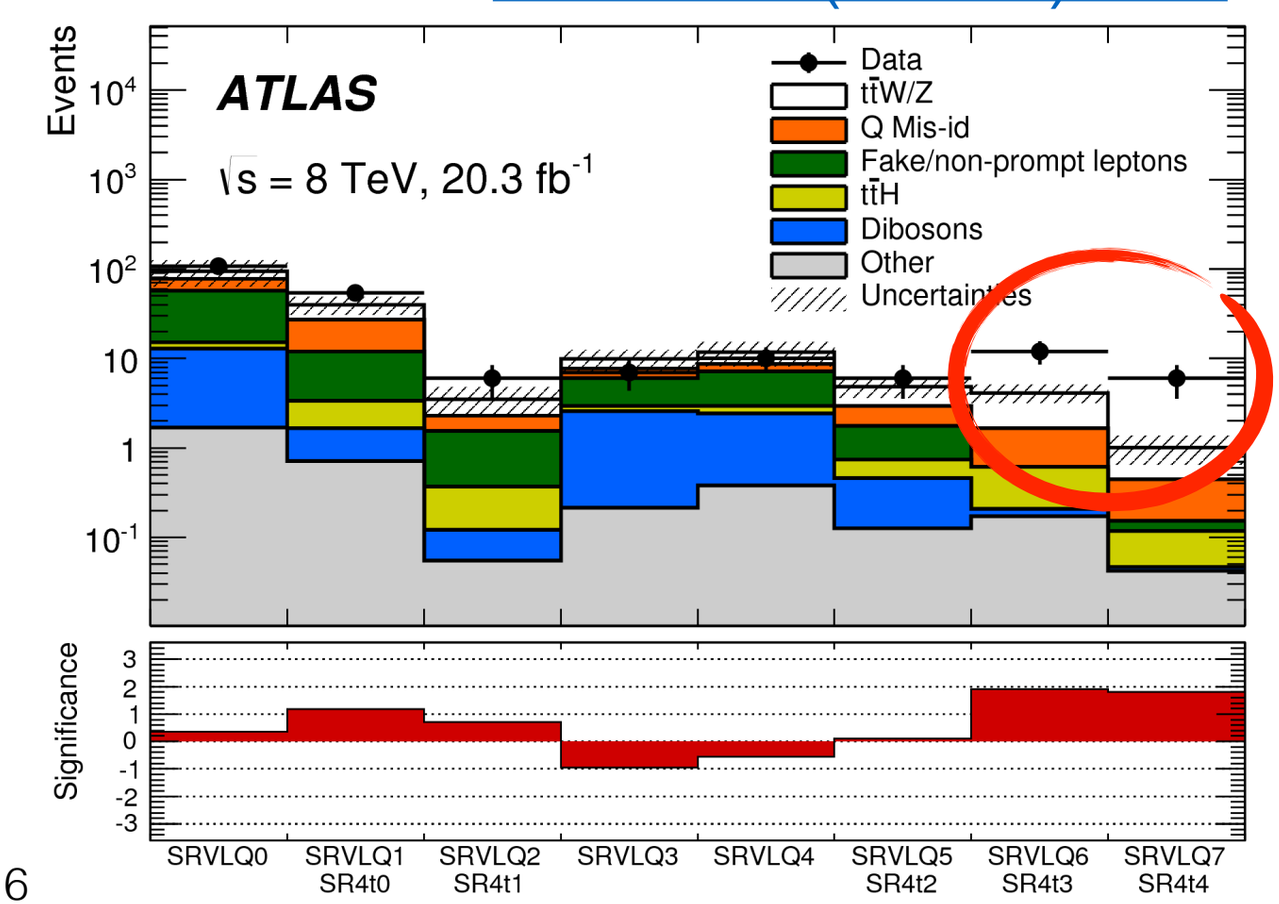
SS+b-jets

ATLAS-CONF-2016-032



- Clean detector signature: $\ell^\pm\ell^\pm/3\ell$ + b-jets
  - Cut & Count analysis
- At 8 TeV, discrepancy in signal regions 6 & 7 (~2σ)
- For initial run2 analysis, replicate steps of 8 TeV analysis to check if discrepancy still exists

run1: JHEP10(2015)150



SS+b-jets

ATLAS-CONF-2016-032

- Consider events with:
  - Leading 3 leptons:

dilepton	trilepton
2/3 leptons are “tight” & SS	All 3 leptons are “tight”
ee, eμ, μμ	eee, eeμ, eμμ, μμμ

  - large MET, multiple (b-tagged) jets, high H_T (sum of all jet and lepton p_T)

- Dominant Backgrounds
  - Non-prompt/fake lepton
  - Charge mis-ID

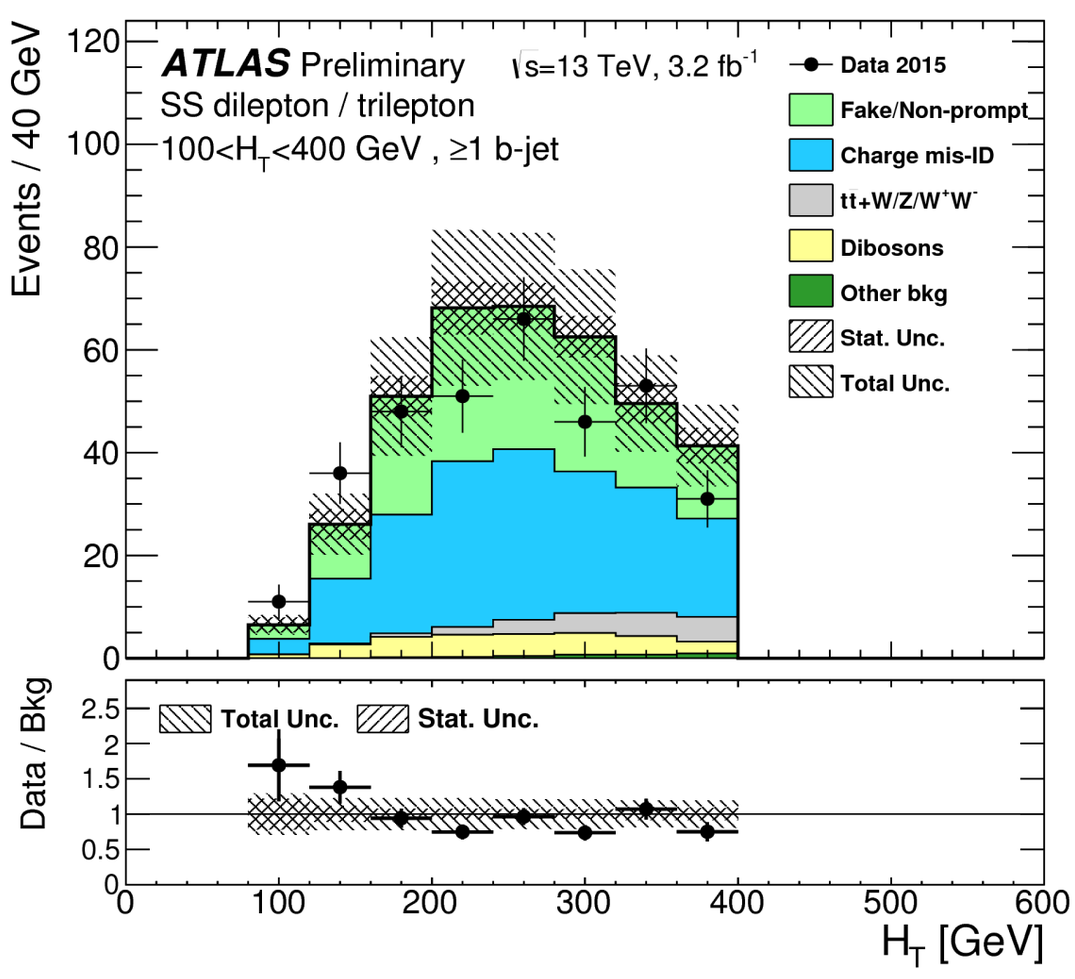
  } estimate from data

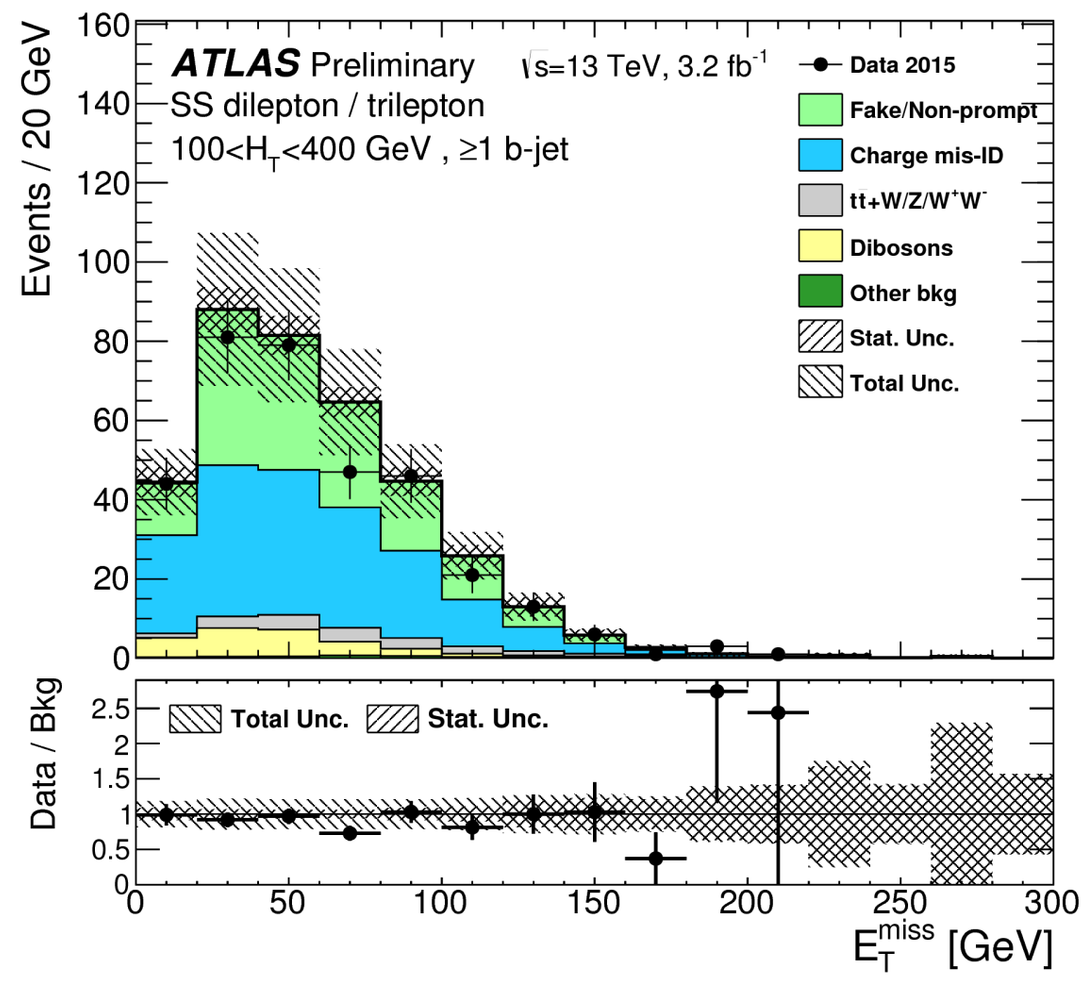
  - SM background (ttbar+V/H, diboson) :: estimate from MC

SS+b-jets

ATLAS-CONF-2016-032

- Estimate lepton non-prompt/fakes background using the Matrix Method with a likelihood approach
- Estimate charge mis-ID using Z→*ee* events to obtain the charge mis-measurement rate. Use OS selection similar to SR to estimate the number of charge mis-ID events in SR





SS+b-jets

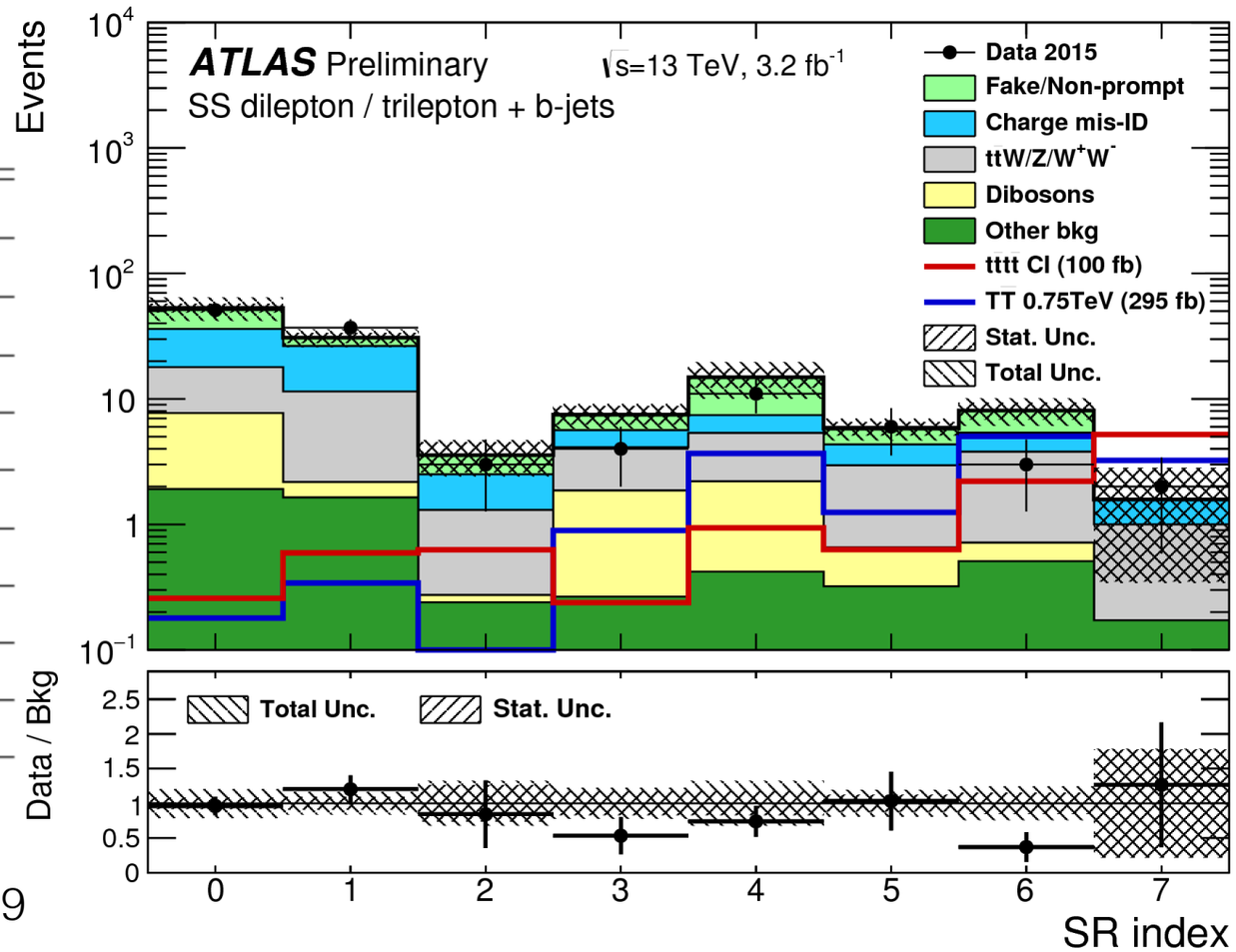
ATLAS-CONF-2016-032

- Dominant systematic uncertainties from cross sections and the fakes & charge mis-ID estimates

Source	Signal region							
	SR0	SR1	SR2	SR3	SR4	SR5	SR6	SR7
Cross section	8	11	26	13	9	27	23	57
Jet energy scale	1	1	3	1	1	3	2	4
Jet energy resolution	<1	2	2	2	< 1	1	<1	3
b-tagging efficiency	1	2	5	3	1	2	2	7
Luminosity	1	1	1	1	1	1	1	1
Fake/non-prompt leptons	17	7	15	13	26	13	17	17
Charge misID	8	3	7	5	3	6	5	8

Uncertainty in % on total background

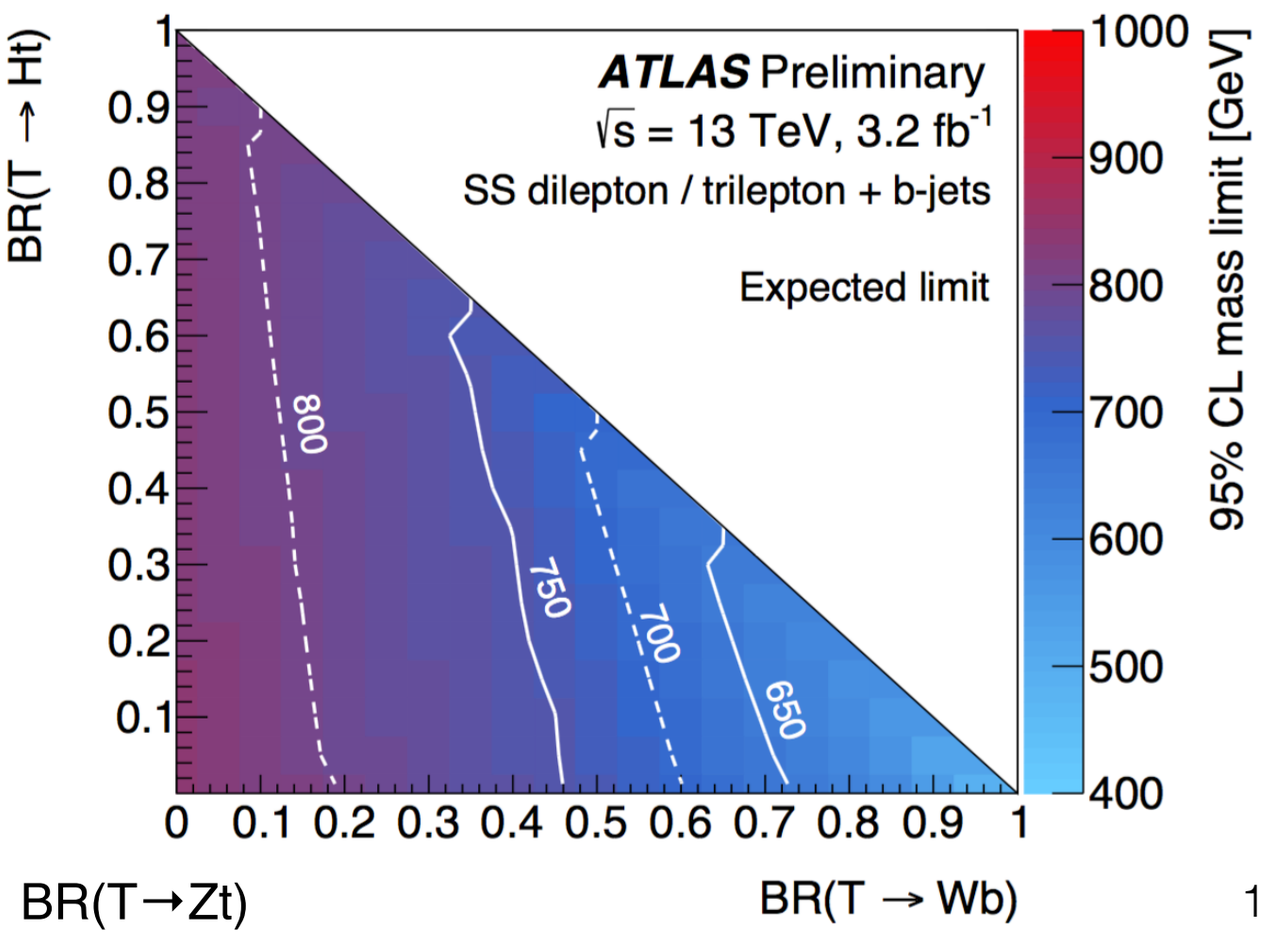
Definition			Name
$e^{\pm}e^{\pm} + e^{\pm}\mu^{\pm} + \mu^{\pm}\mu^{\pm} + eee + ee\mu + e\mu\mu + \mu\mu\mu$, $N_{\text{jets}} \geq 2$			
$400 < H_{\text{T}} < 700$ GeV	$N_b = 1$	$E_{\text{T}}^{\text{miss}} > 40$ GeV	SR0
	$N_b = 2$		SR1
	$N_b \geq 3$		SR2
$H_{\text{T}} \geq 700$ GeV	$N_b = 1$	$40 < E_{\text{T}}^{\text{miss}} < 100$ GeV	SR3
		$E_{\text{T}}^{\text{miss}} \geq 100$ GeV	SR4
	$N_b = 2$	$40 < E_{\text{T}}^{\text{miss}} < 100$ GeV	SR5
		$E_{\text{T}}^{\text{miss}} \geq 100$ GeV	SR6
	$N_b \geq 3$	$E_{\text{T}}^{\text{miss}} > 40$ GeV	SR7

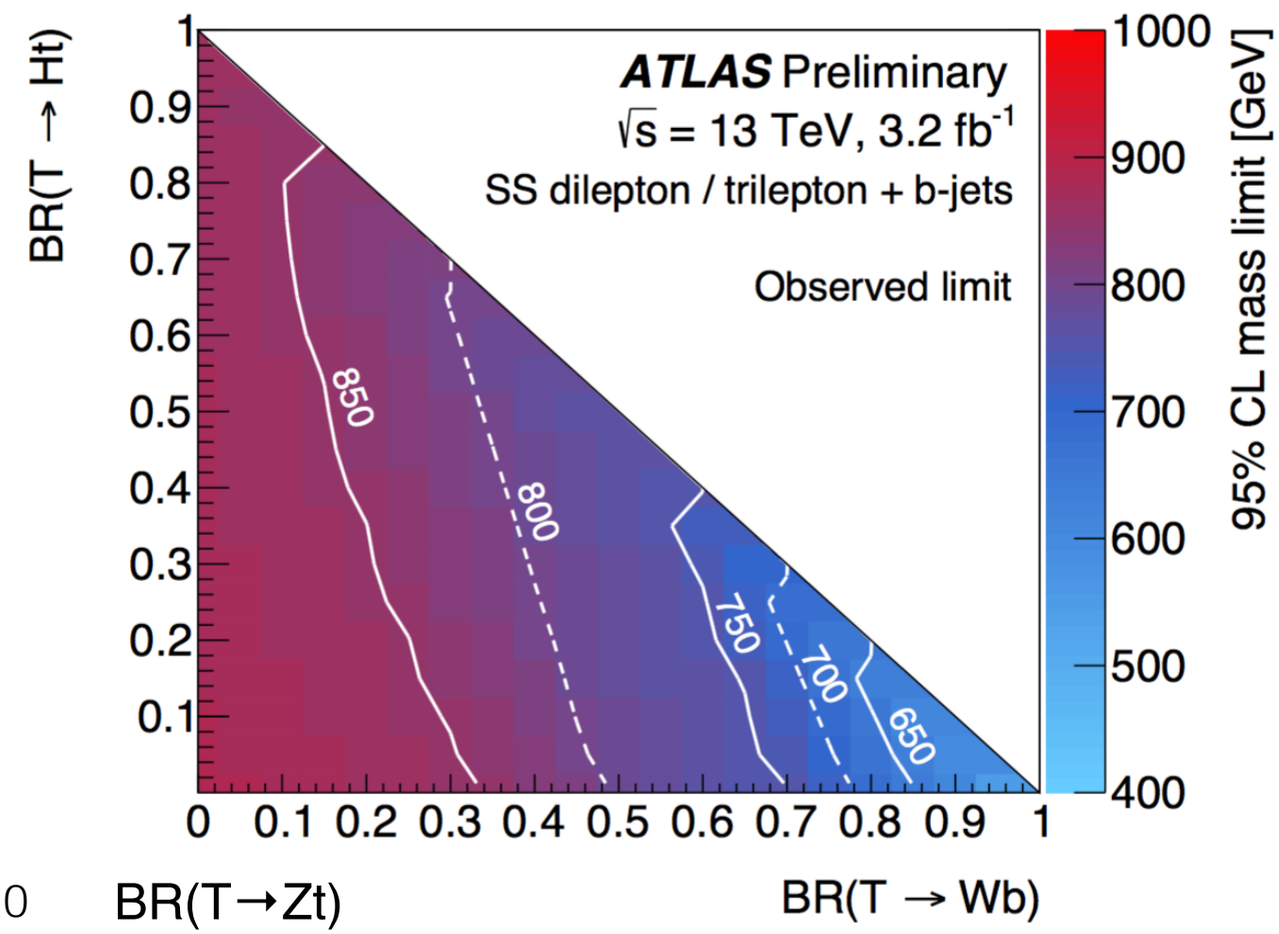


SS+b-jets

ATLAS-CONF-2016-032

- Likelihood fit applied to all 8 signal regions, where each region treated as a cut-and-count experiment, to extract limits on T, B, and T(5/3)

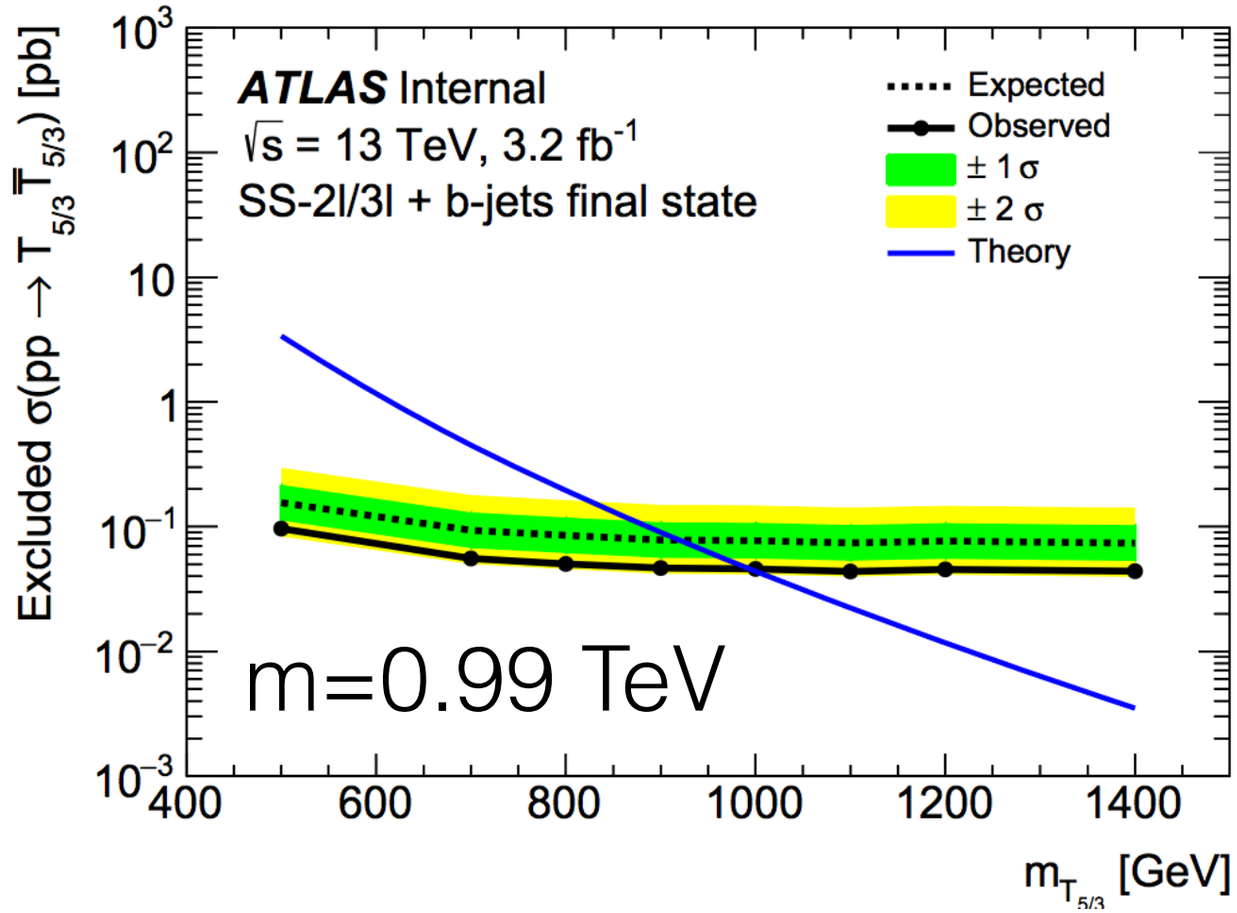


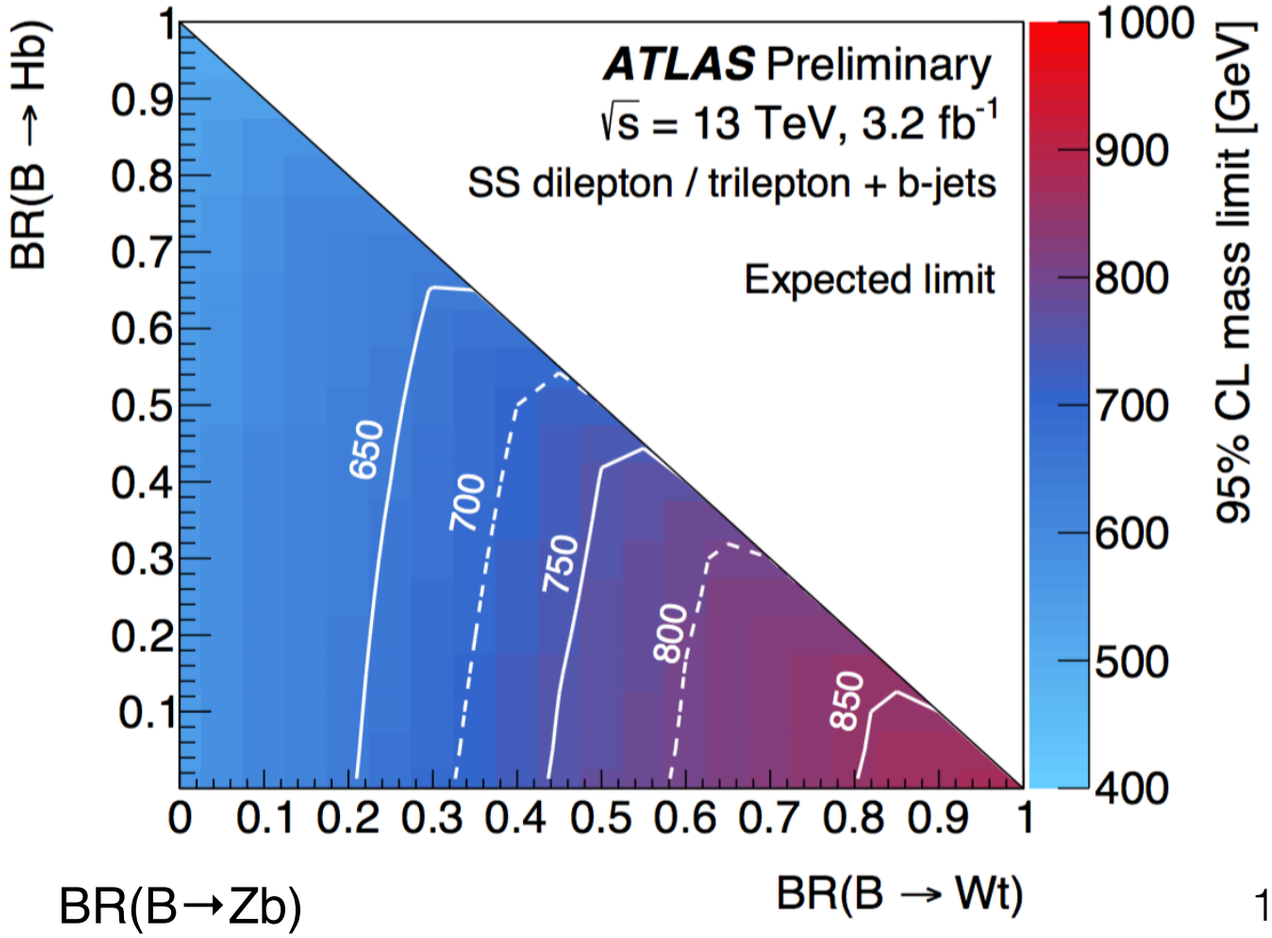


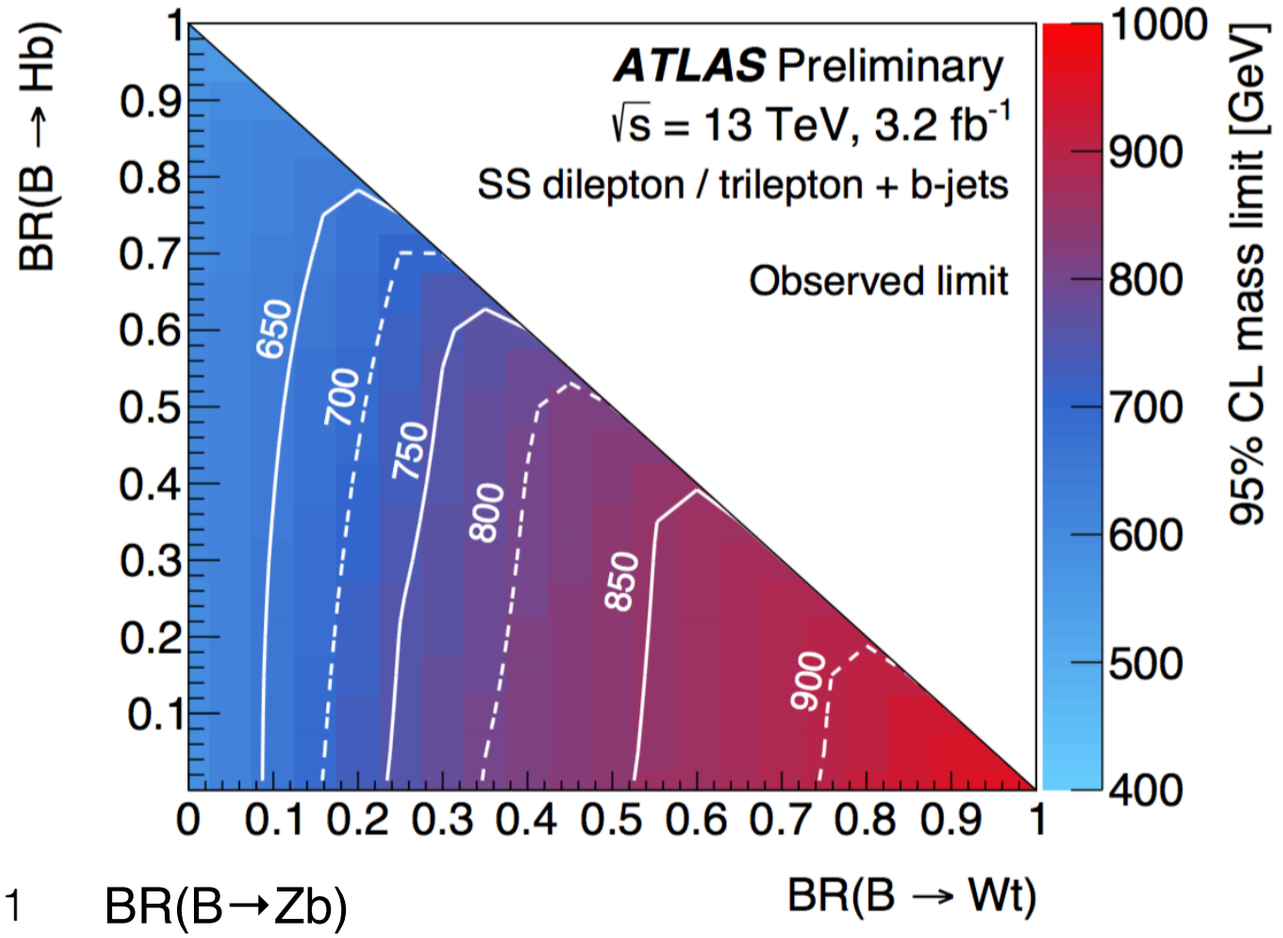
SS+b-jets

ATLAS-CONF-2016-032

- For T(5/3) and BR(B→Wt)=1, limits near 1 TeV are observed.



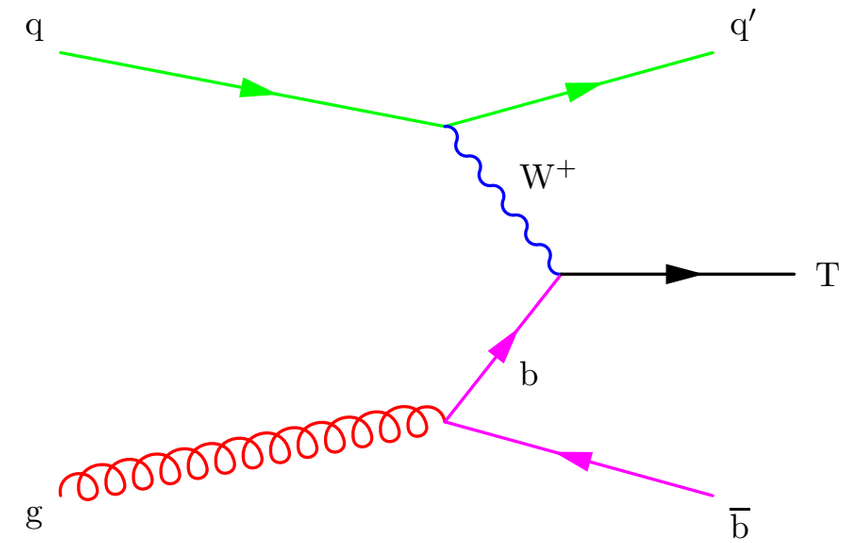




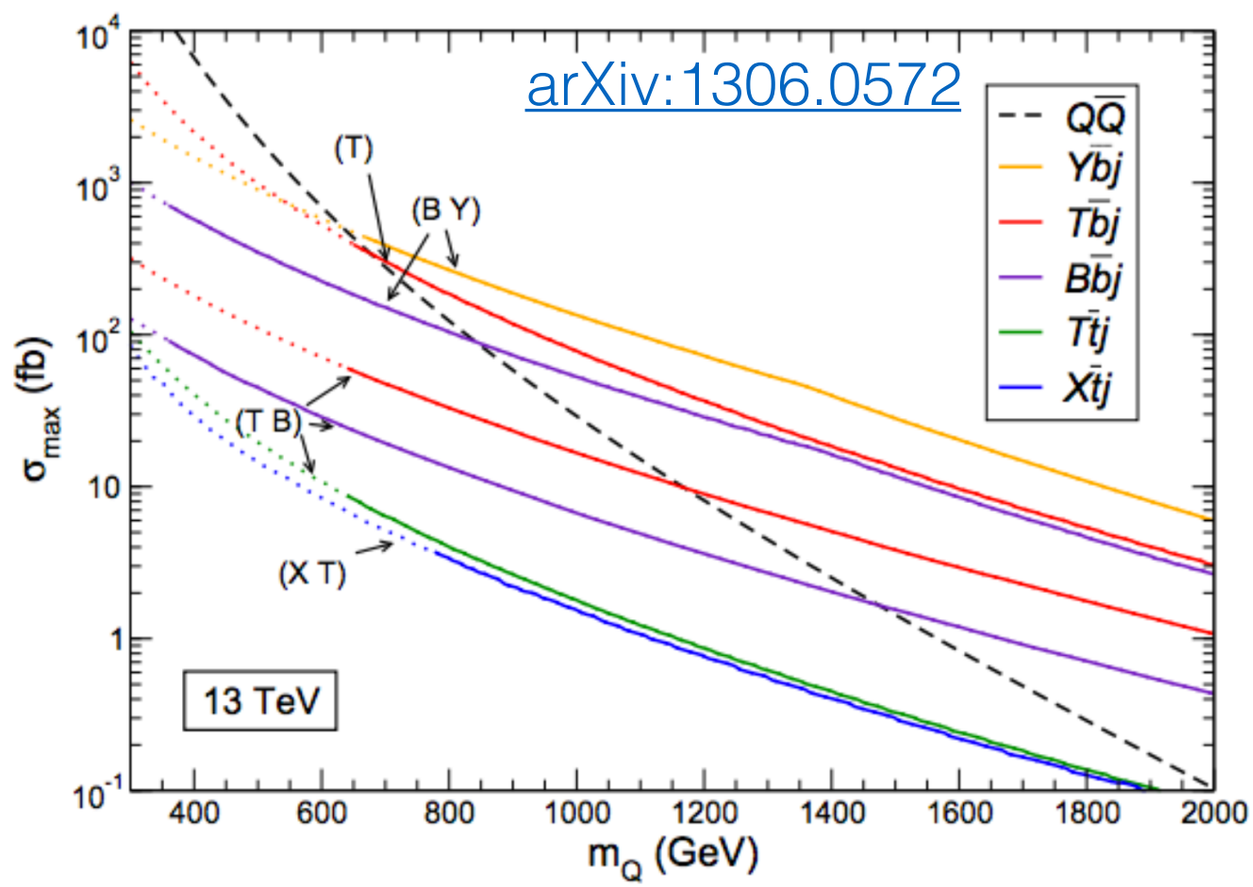
BR(B→Zb)

BR(B→Zb)

Single Production



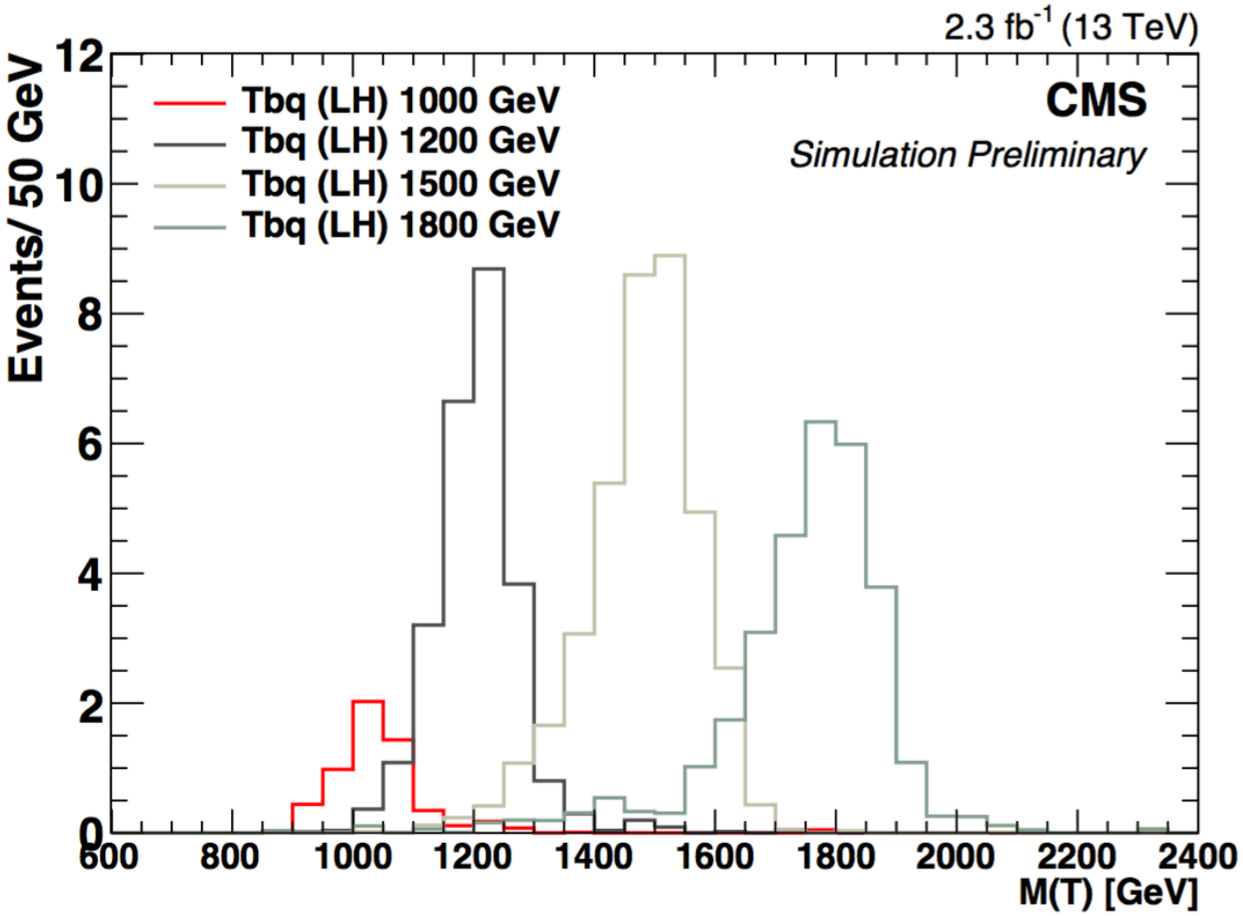
- At large VLQ masses, single production becomes the dominant mode of production
  - Given current limits, single production is important to search for in run2
- Mediated by EW interaction
- Sensitive to mixings and VLQ mass



T→Ht→All-Had

B2G-16-005

- Interested in events with high-p_T hadronically-decaying boosted Higgs and boosted top-quark with large H_T (sum of all small-radius jet p_T; p_T>30 GeV, |η|<5.0)
  - Before applying Higgs/top tagging, H_T is re-weighted to improve Data/Prediction agreement
- To discriminate against the QCD background, jet substructure techniques are applied using anti-k_T R=0.8 jets:
  - Boosted Higgs (p_T>300 GeV):
    - Pruned jet mass 105–135 GeV
    - 2 b-tagged subjets from softdrop algorithm
    - τ_{21}<0.6 (2-pronged decay)
  - Boosted top-quark (p_T>400 GeV):
    - softdrop mass 110–210 GeV
    - ≥1 b-tagged subjets
    - τ_{32}<0.54 (3-pronged decay)



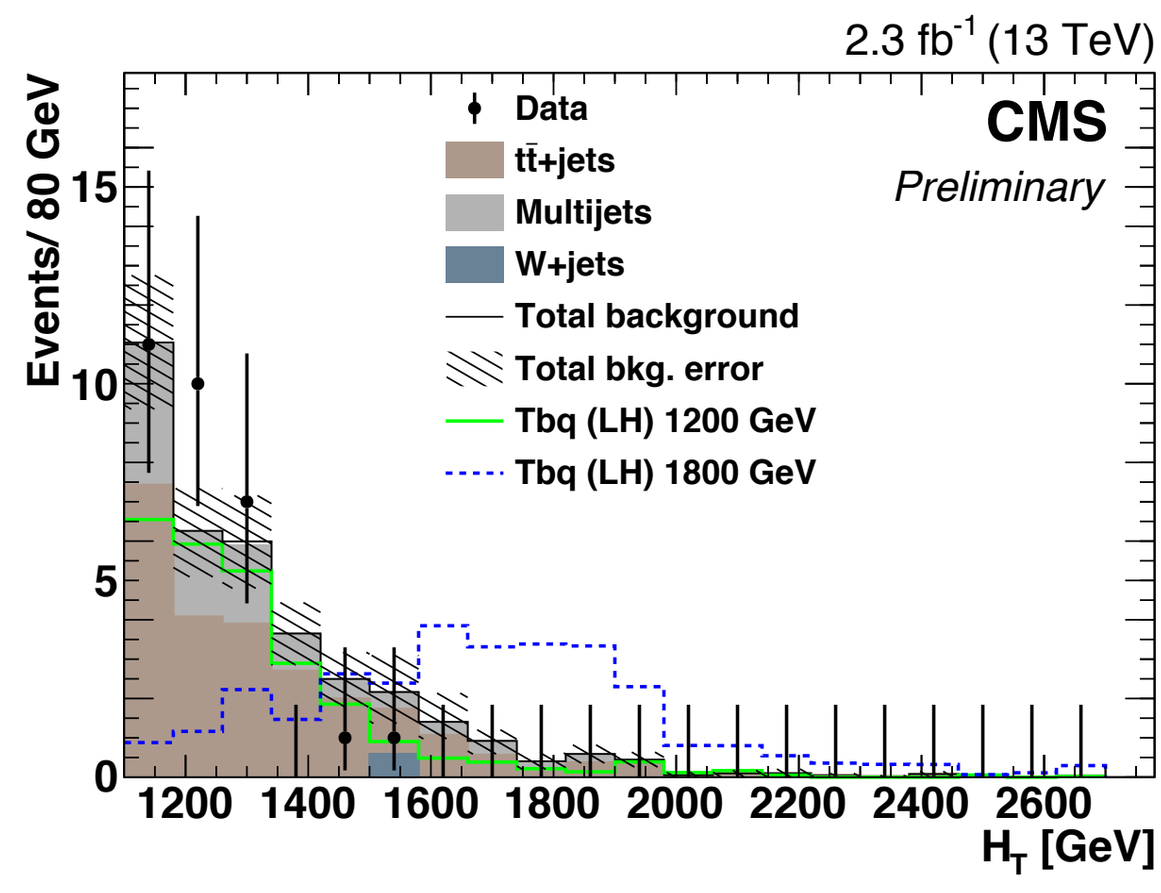
- Higgs and top-quark candidates (ΔR(H,t)>2.0) are combined to form VLQ candidate

T→Ht→All-Had

B2G-16-005

- Monte Carlo is used to estimate the ttbar+jets and W+jets background contributions
- Multi-jet background estimated from ABCD method
  - Shape of M(T) distribution in signal region also estimated using the shape from region B

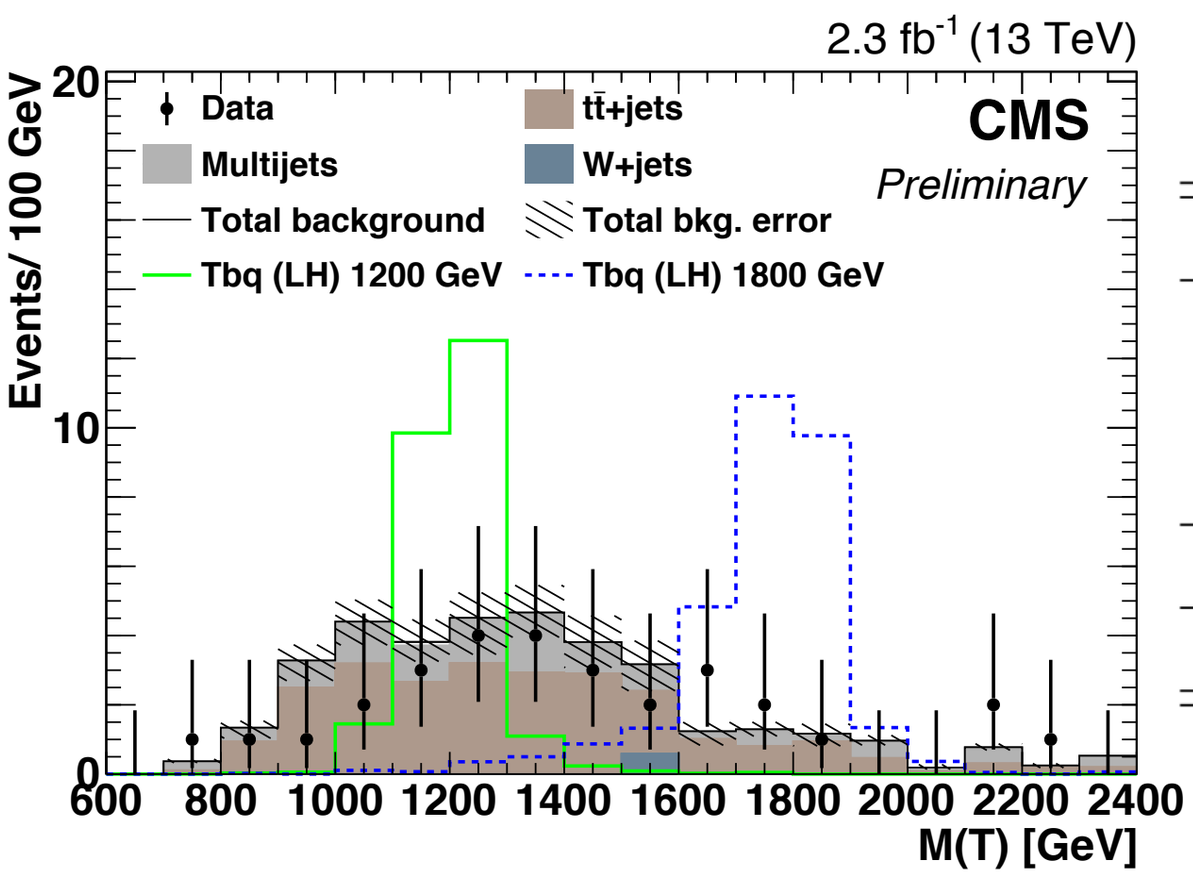
A 1 anti-Higgs 0 top tag	B 1 anti-Higgs 1 top tag
C 1 Higgs 0 top tag	D Signal Region



T→Ht→All-Had

B2G-16-005

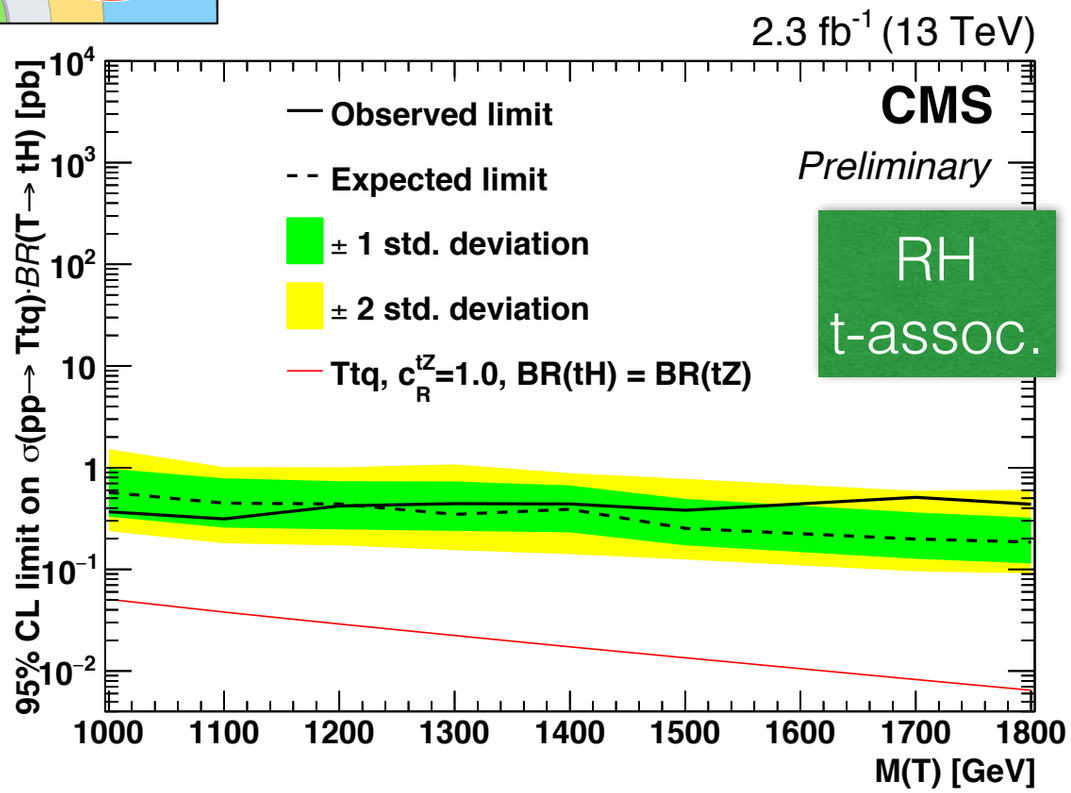
- Dominant systematic uncertainties originate from Higgs tagging SF (12.5%), jet mass (10%), top tagging SF (15-30%)
- No excess seen in the M(T) distribution → set limits on the production cross section of T produced with a b/top-quark in the Simplest Simplified Model framework
  - `singlet: BR(T→Wb):BR(T→Zt):BR(T→Ht) = 0.5 : 0.25 : 0.25`
  - `doublet: BR(T→Wb):BR(T→Zt):BR(T→Ht) = 0 : 0.5 : 0.5`

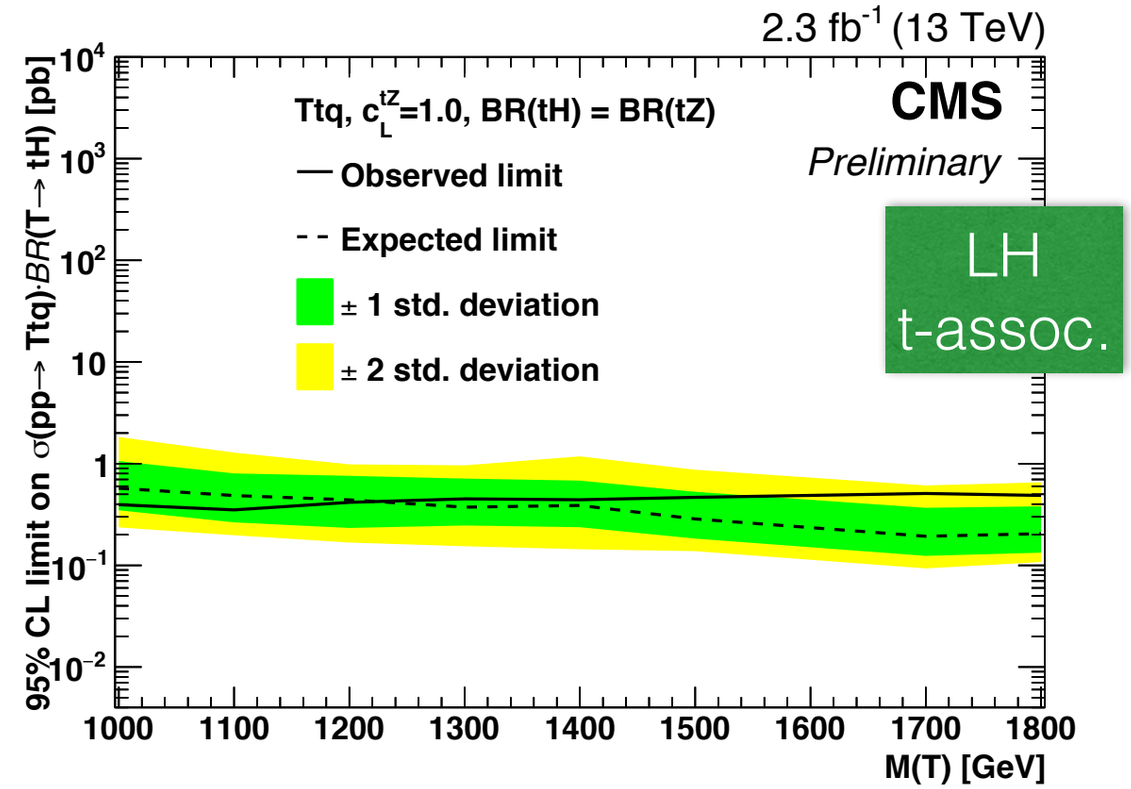


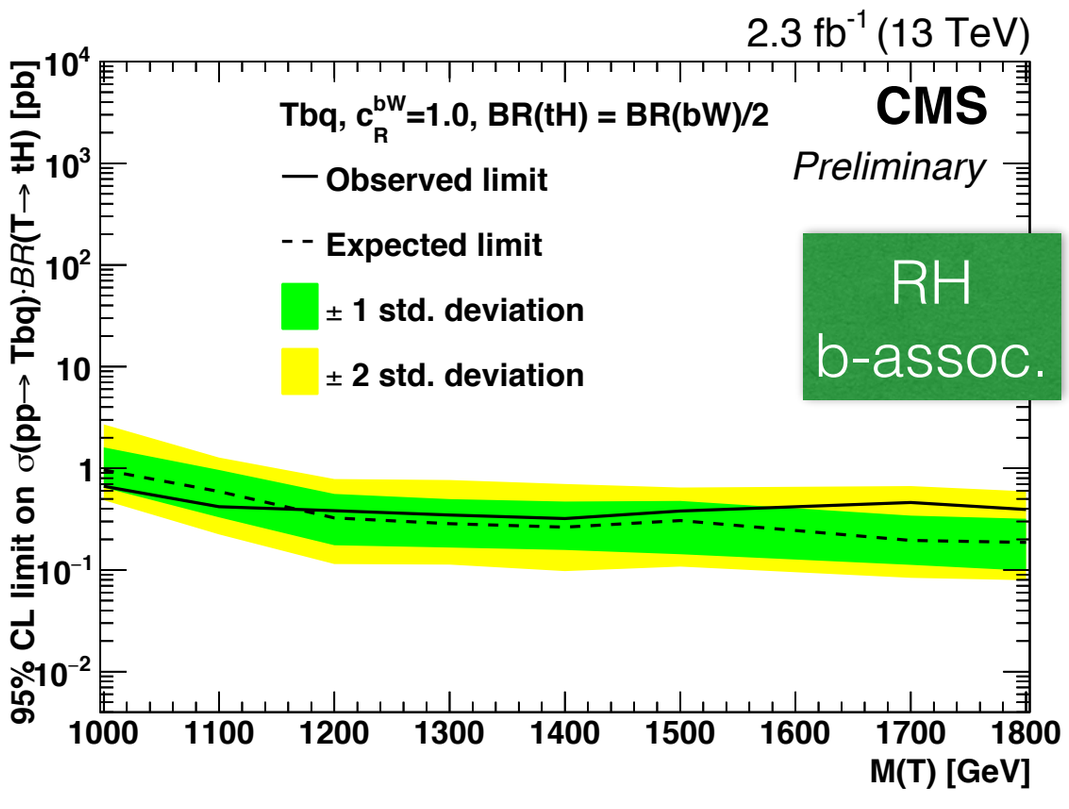
Process	Events
Estimated multijets (using data)	10.8 ± 5.5
Estimated $t\bar{t}$+jets (using MC)	24.3 ± 8.1
Estimated W+jets (using MC)	0.6 ± 0.6
Estimated total background	35.7 ± 5.6
Observed events	30

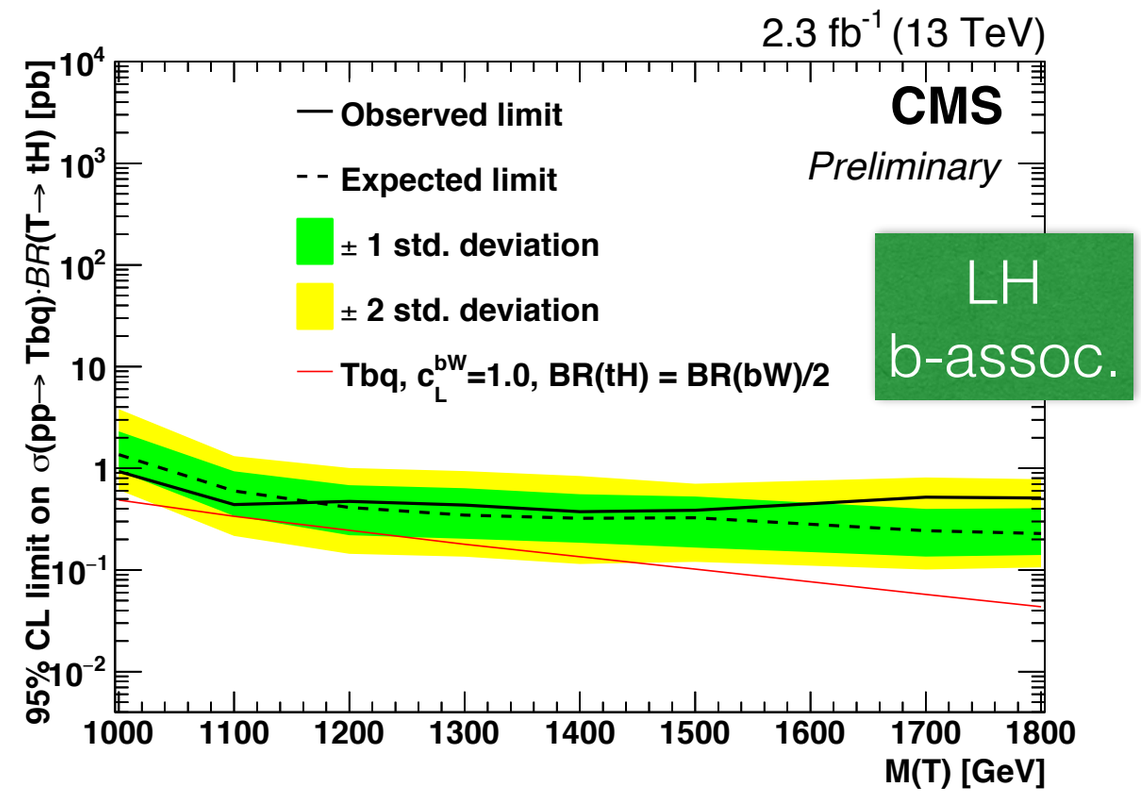
T→Ht→All-Had

B2G-16-005





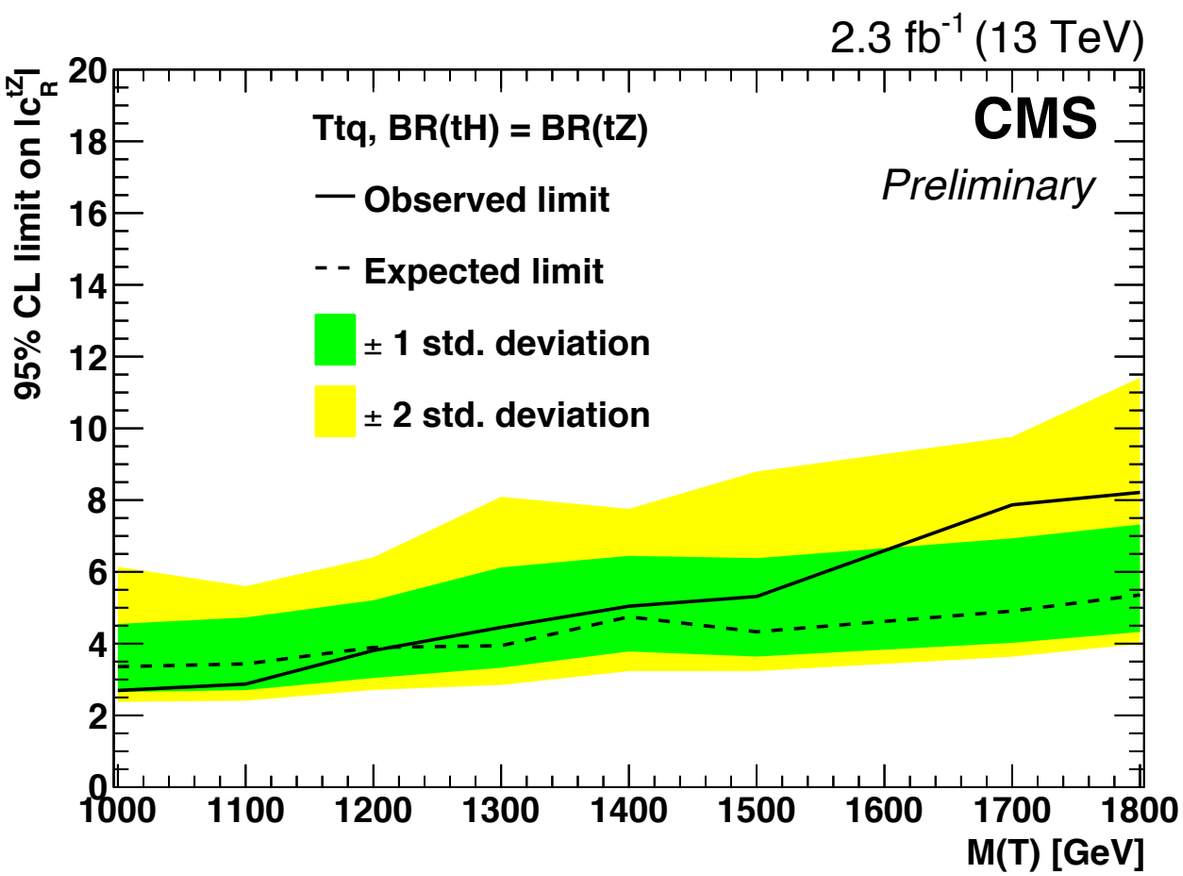


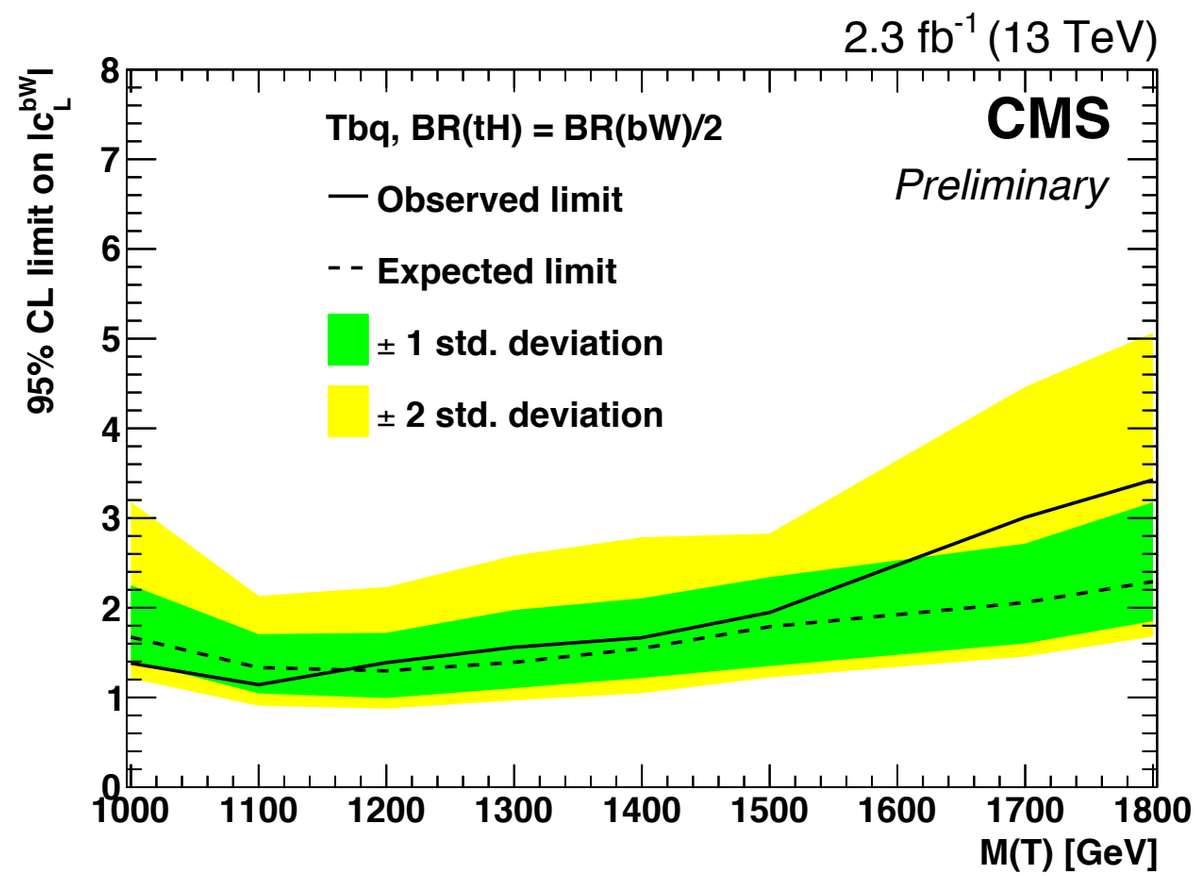


T→Ht→All-Had

B2G-16-005

- Given limits on σBR(T→Ht), exclusion limits are also set on the couplings for the singlet $c^{bW}(L)$ and doublet $c^{tZ}(R)$ scenarios
- Note: In the Simplest Simplified Model, no theoretical prediction of the RH singlet or LH doublet is possible





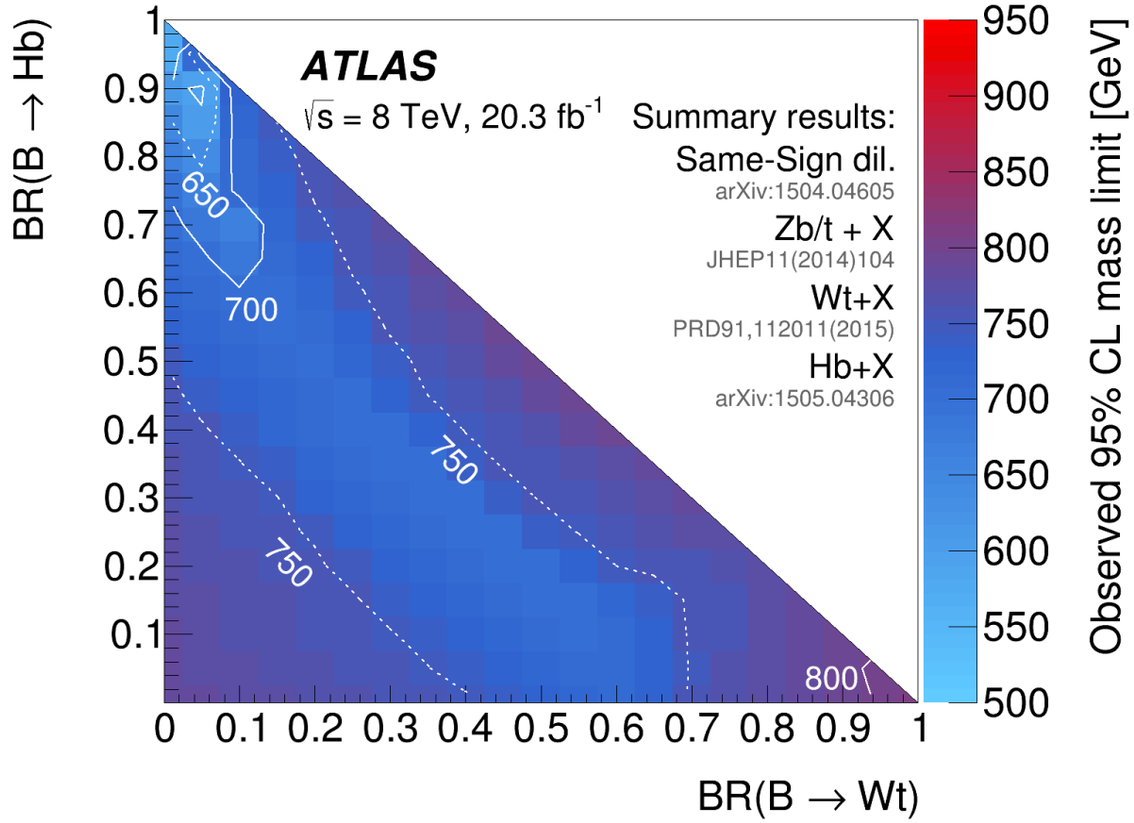
Public Results

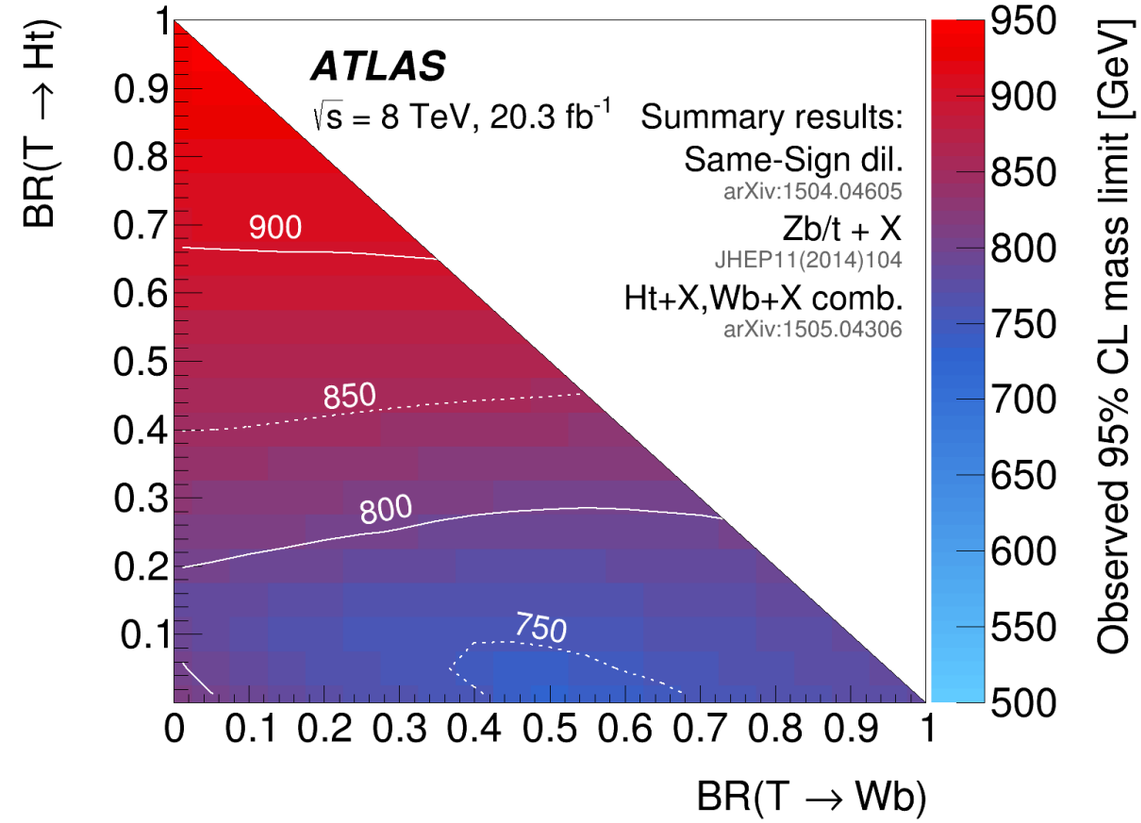
Conclusions

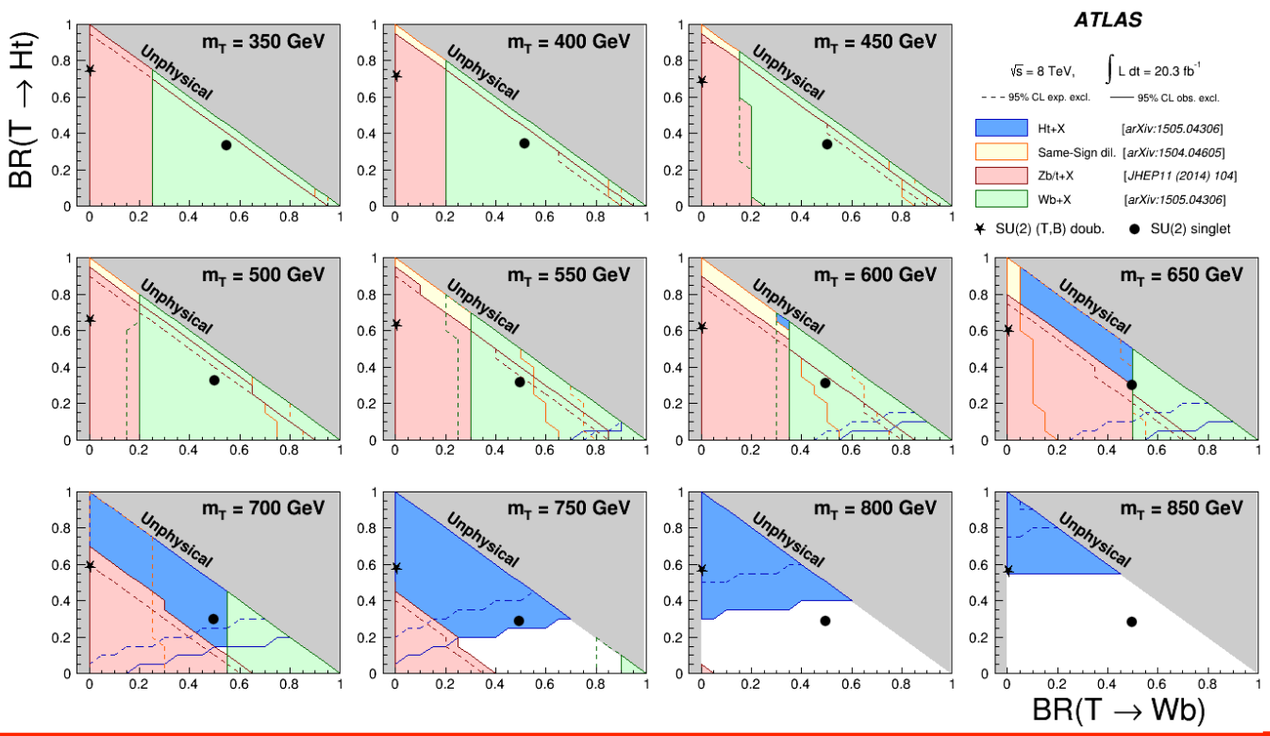
Public Results

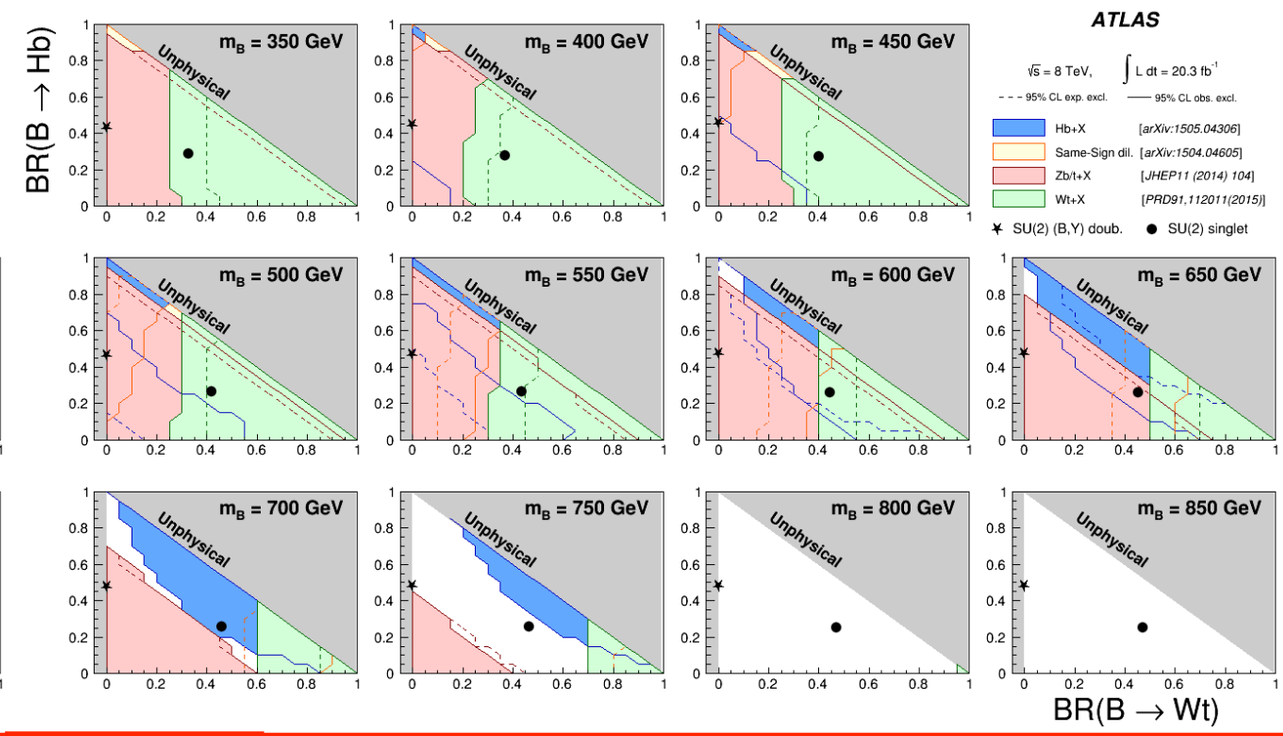
- VLQ searches allow experiments to cast a wide net and cover many different BSM models
- Given initial dataset for 13 TeV, many VLQ analyses able to surpass the limits from run1 results
- No significant excess observed in any analysis — all results are consistent with the SM
- Important results remain with the full 2016 dataset!

Backup



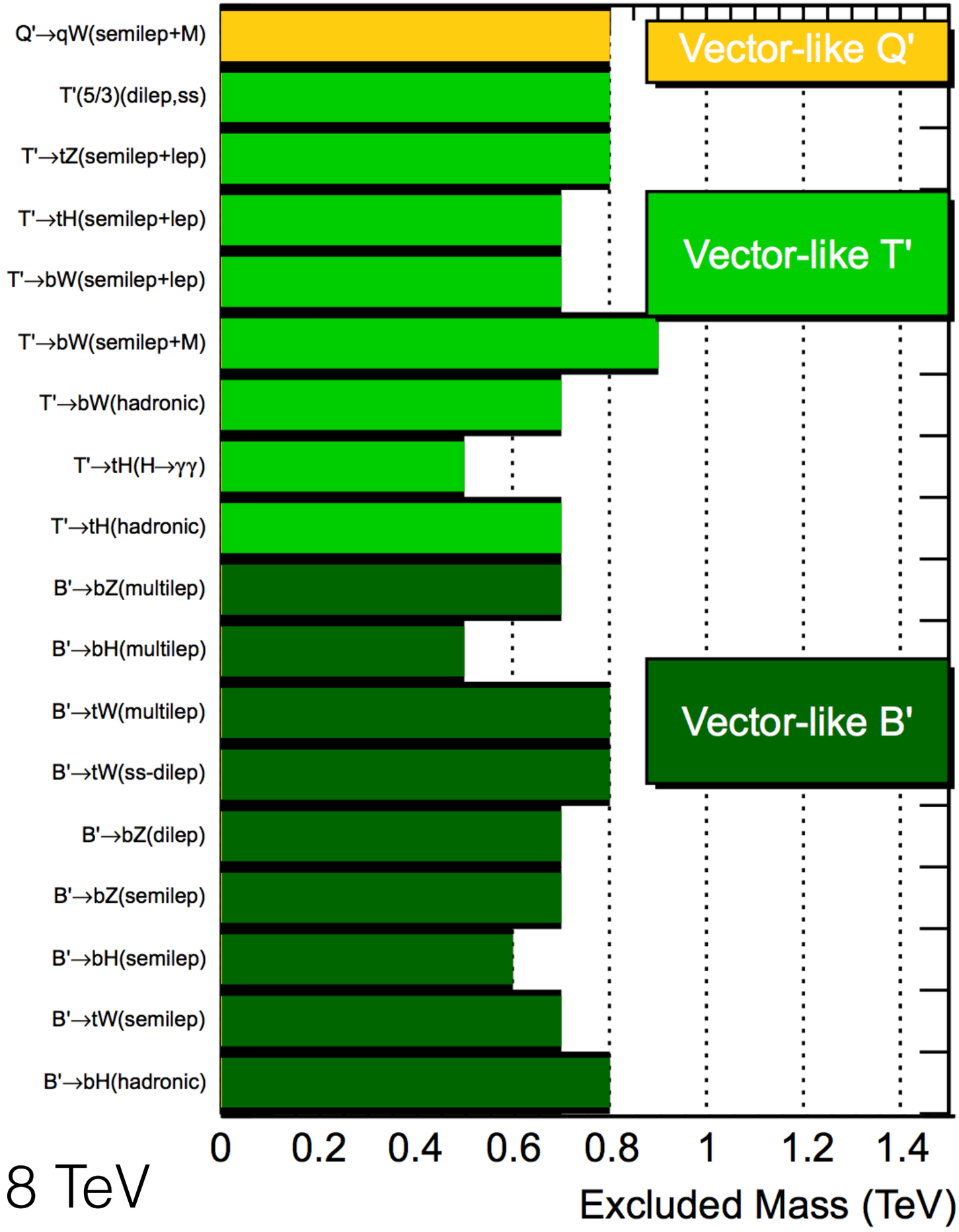






Heavy quarks	VLQ $TT \to Ht + X$	1 e, μ	$\geq$ 2 b, $\geq$ 3 j	1505.04306
	VLQ $YY \to Wb + X$	1 e, μ	$\geq$ 1 b, $\geq$ 3 j	1505.04306
	VLQ $BB \to Hb + X$	1 e, μ	$\geq$ 2 b, $\geq$ 3 j	1505.04306
	VLQ $BB \to Zb + X$	2/$\geq$3 e, μ	$\geq$2/$\geq$1 b	1409.5500
	VLQ $QQ \to WqWq$	1 e, μ	$\geq$ 4 j	1509.04261
	$T_{5/3} \to Wt$	1 e, μ	$\geq$ 1 b, $\geq$ 5 j	1503.05425

T mass	855 GeV
Y mass	770 GeV
B mass	735 GeV
B mass	755 GeV
Q mass	690 GeV
$T_{5/3}$ mass	840 GeV


Q'→qW(semilep+M)
T'(5/3)(dilep,ss)
T'→tZ(semilep+lep)
T'→tH(semilep+lep)
T'→bW(semilep+lep)
T'→bW(semilep+M)
T'→bW(hadronic)
T'→tH(H→γγ)
T'→tH(hadronic)
B'→bZ(multilep)
B'→bH(multilep)
B'→tW(multilep)
B'→tW(ss-dilep)
B'→bZ(dilep)
B'→bZ(semilep)
B'→bH(semilep)
B'→tW(semilep)
B'→bH(hadronic)
Vector-like Q'
Vector-like T'
Vector-like B'
0
0.2
0.4
0.6
0.8
1
1.2
1.4
Excluded Mass (TeV)

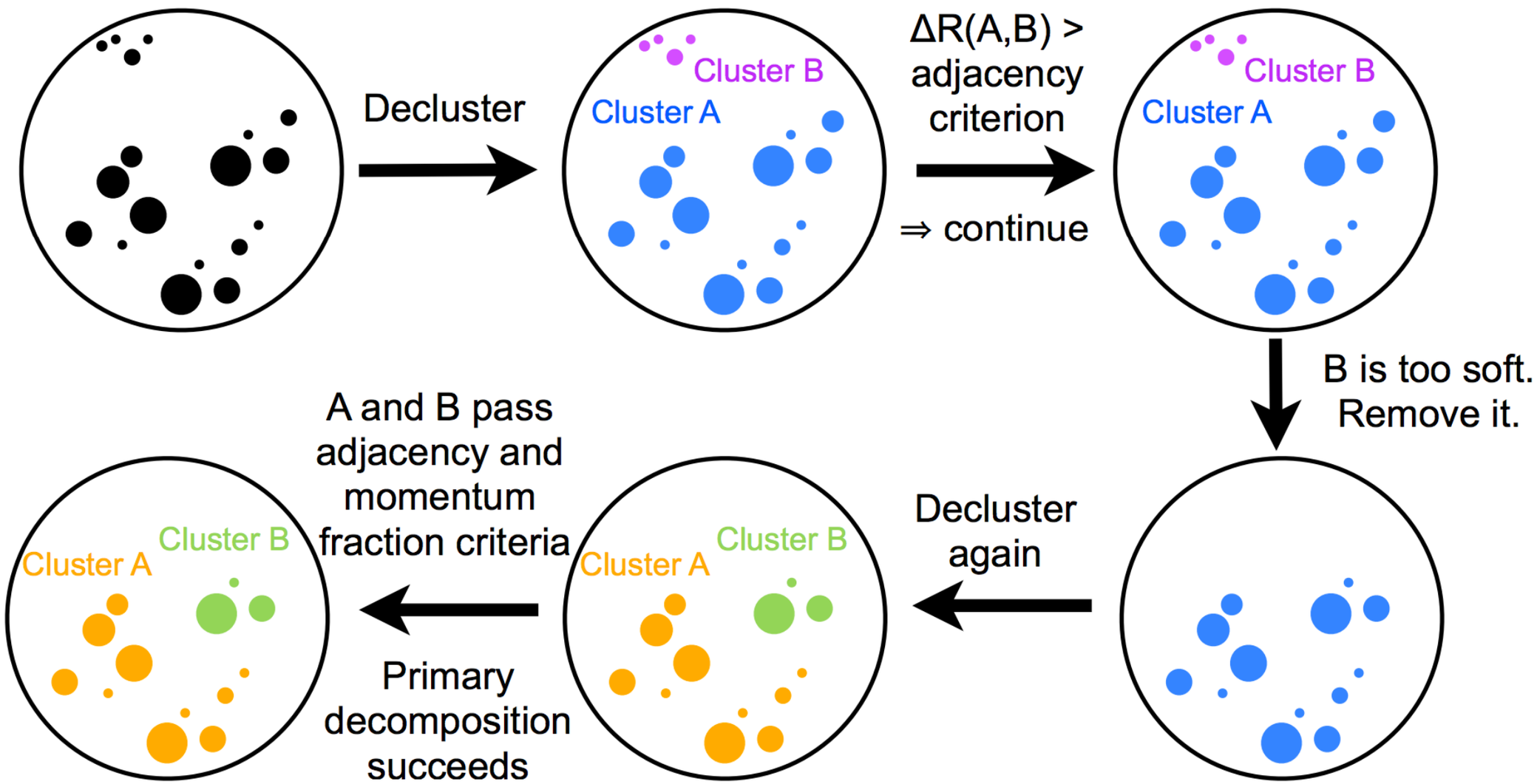
8 TeV

- Charge mis-ID calculated from ee events in the Z mass window, in bins of |η|,pT
- Obtain ε using a global likelihood fit

$$N_{ss}^{ij} = N^{ij}(\varepsilon_i(1-\varepsilon_j) + \varepsilon_j(1-\varepsilon_i))$$

$$w = \frac{\varepsilon_1 + \varepsilon_2 - 2\varepsilon_1\varepsilon_2}{1 - \varepsilon_1 - \varepsilon_2 + 2\varepsilon_1\varepsilon_2}$$

Event weight to calculate number of charge mis-ID events


Decluster
Cluster B
Cluster A
ΔR(A,B) >
adjacency
criterion
⇒ continue
Cluster B
Cluster A
B is too soft.
Remove it.
Decluster
again
Cluster A
Cluster B
Primary
decomposition
succeeds
A and B pass
adjacency and
momentum
fraction criteria
Cluster A
Cluster B