

Search for vector-like quarks at CMS



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Outline

- Recent results on the searches for vector-like quarks (VLQ) at the CMS detector at the LHC
 - Based on LHC Run 2 (13 TeV) collision data
 - First results on full Run 2 dataset
- All public results on VLQ searches at CMS can be accessed from the Beyond-Two-Generations Group public web page
 - <https://twiki.cern.ch/twiki/bin/view/CMSPublic/PhysicsResultsB2G>

Vector-like quarks (VLQ)

Spin $\frac{1}{2}$ fermions predicted by several extensions of the Standard Model (SM)

- *Left- and right-handed components behave the same under the SM symmetry group*
- *Vector current couplings to the weak gauge bosons*
- *VLQ mass may arise from non-Yukawa coupling terms*

Type	Charge
T	+2/3
B	-1/3
X	+5/3
Y	-4/3

<i>SU(2) multiplets</i>	
Singlets	T, B
Doublets	(T, B), (X, T), (B, Y)
Triplets	(X, T, B), (T, B, Y)

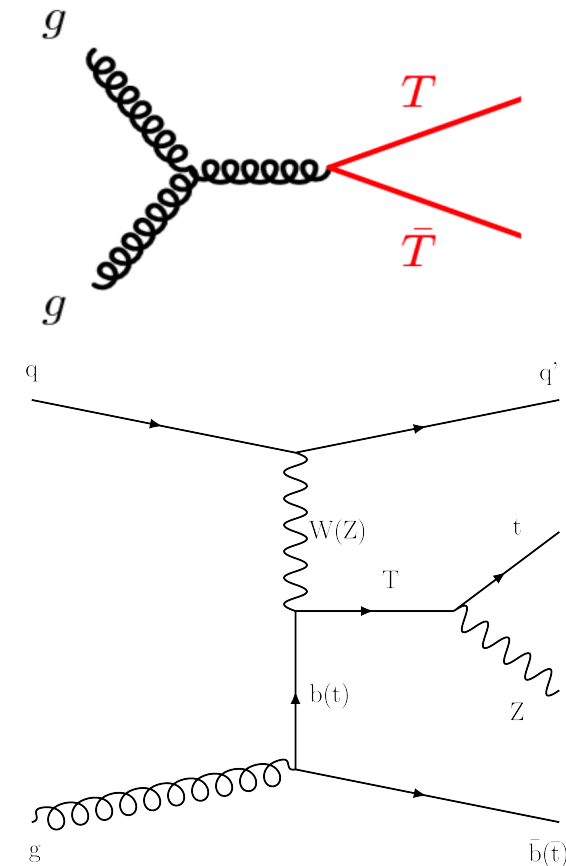
VLQ production at LHC and decay

Pair production

- Strong interaction processes
- Model independent cross section, depending on VLQ mass
- **Cross section suppressed for large VLQ mass**

Single production

- Electroweak processes
- Cross section depending on VLQ mass and (model dependent) coupling to SM particles
- **Models foresee preferential mixing with 3rd generation SM quarks**



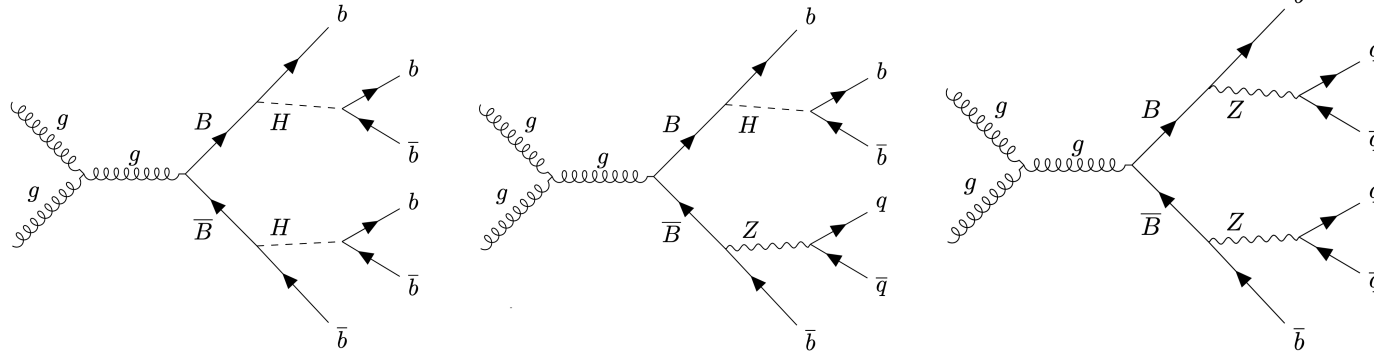
Type	Decay channels
T	tZ, tH, bW
B	bZ, bH, tW
X	tW
Y	bW

Branching ratios (BR) depending on VLQ mass and model (multiplet configuration, couplings to SM quarks)

BB → fully hadronic

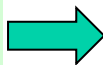
PRD 102 (2020) 112004
B2G-19-005

Targeting bH and bZ decay channels

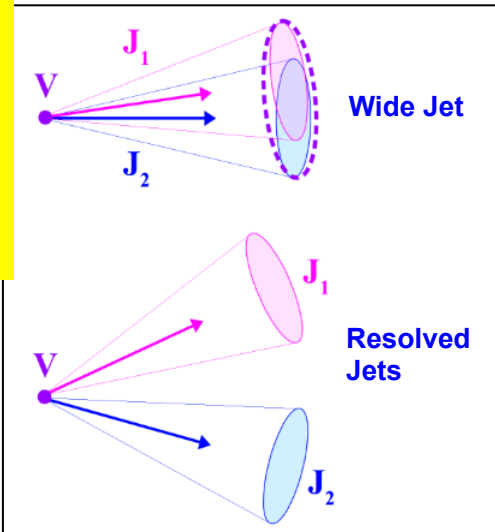


First full Run 2
(137 fb⁻¹) result for
pair production!

Investigated $m_B > 1$ TeV mass range
- boosted regime of B decay products:
jets from boson decays may overlap



Large radius jet ("wide jet") reconstruction + jet substructure techniques to identify boosted bosons (H/Z tagging)



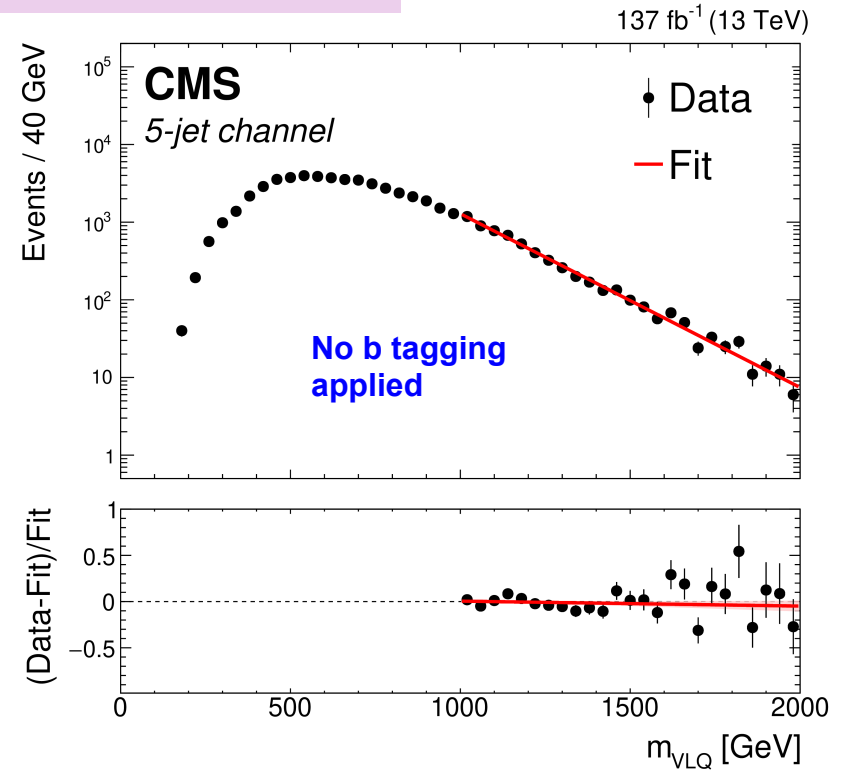
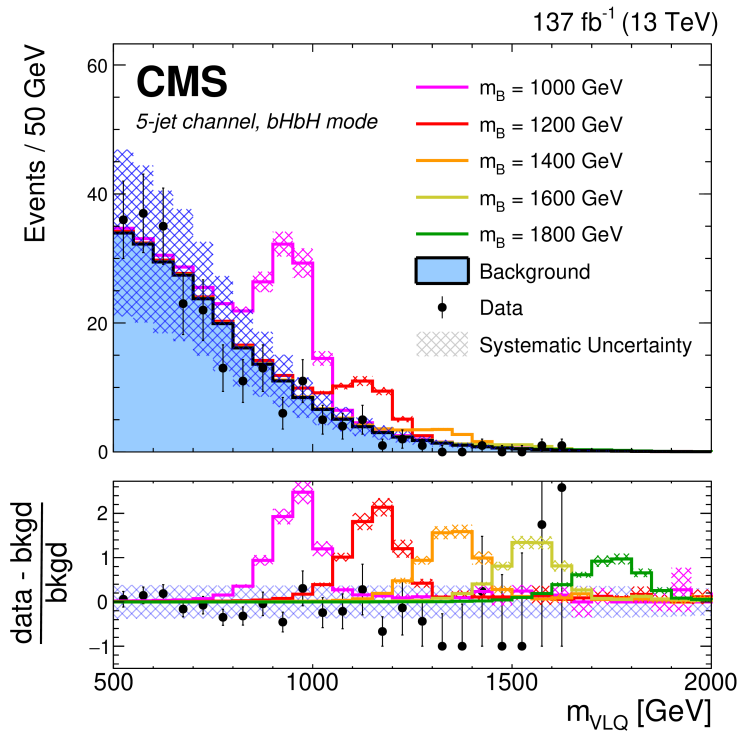
Signal selection strategy
- 6 high p_T jets in the final state
- $H_T > 1350$ GeV
- b -tagging of jets
Reconstruction of the decay chain and event assignment to a certain final state: χ^2 -like metrics

9 event categories defined according to number and type of reconstructed jets and final state assignment

BB → fully hadronic

Main background: QCD multijets, determined from data

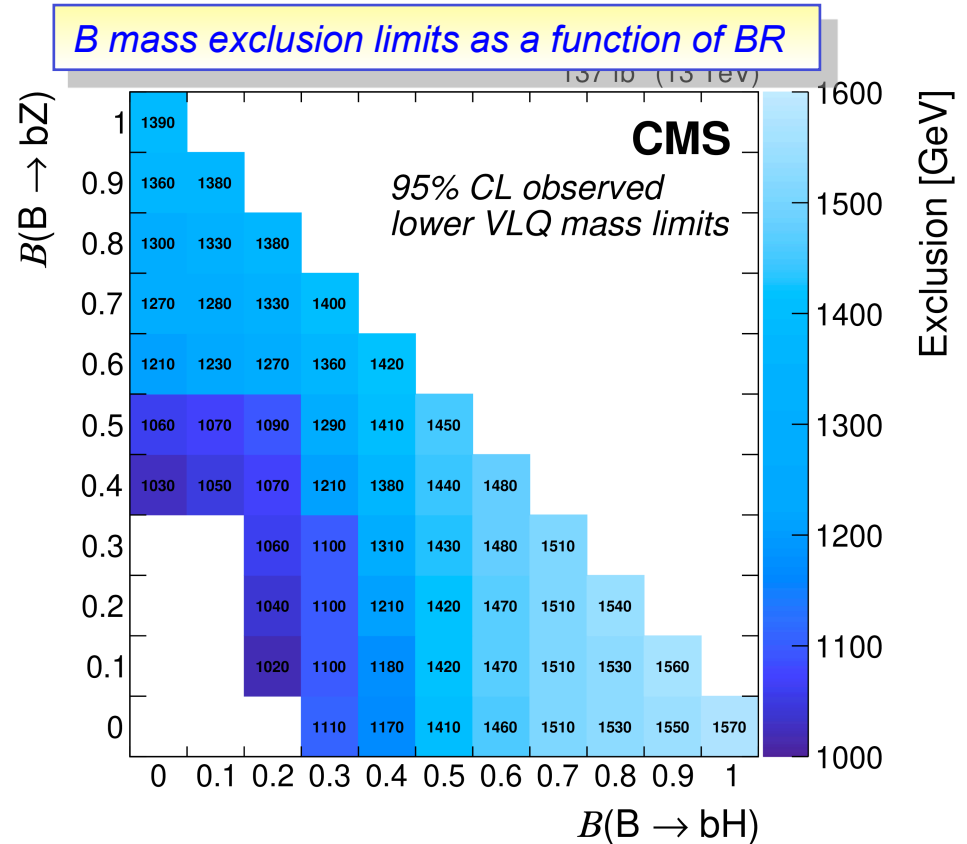
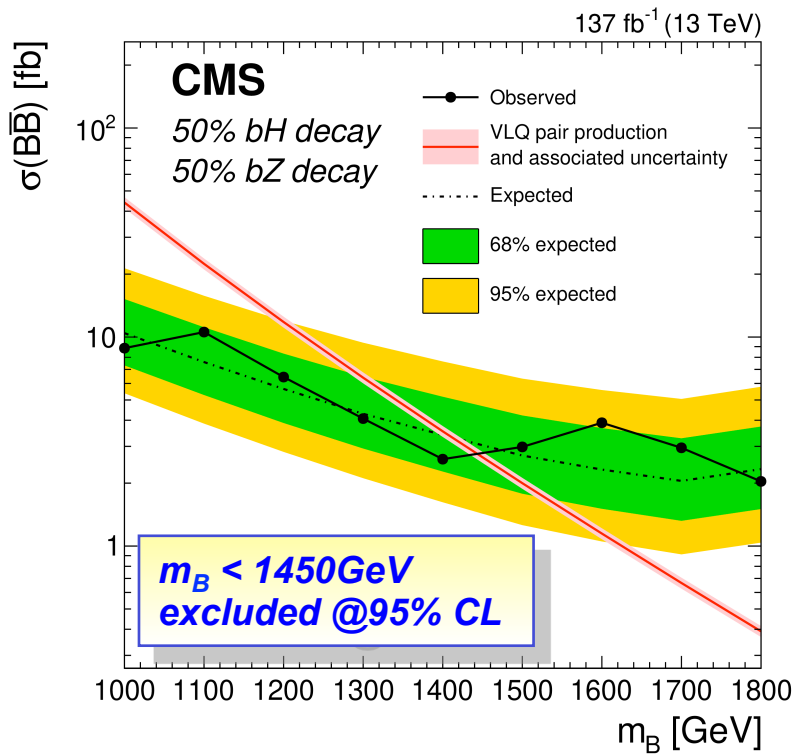
- Exponential fit to B mass distribution before b tagging requirement
- Rate of background jets passing b tagging requirements (background jets tagged fraction) estimated from low m_{VLQ} sideband region
- Background tagged fraction propagated to high mass using a high chi2 control region



No significant excess of data with respect to the expected background observed

BB → fully hadronic

95% CL upper limits on cross section as a function of B mass and BR of bZ and bH decay channels

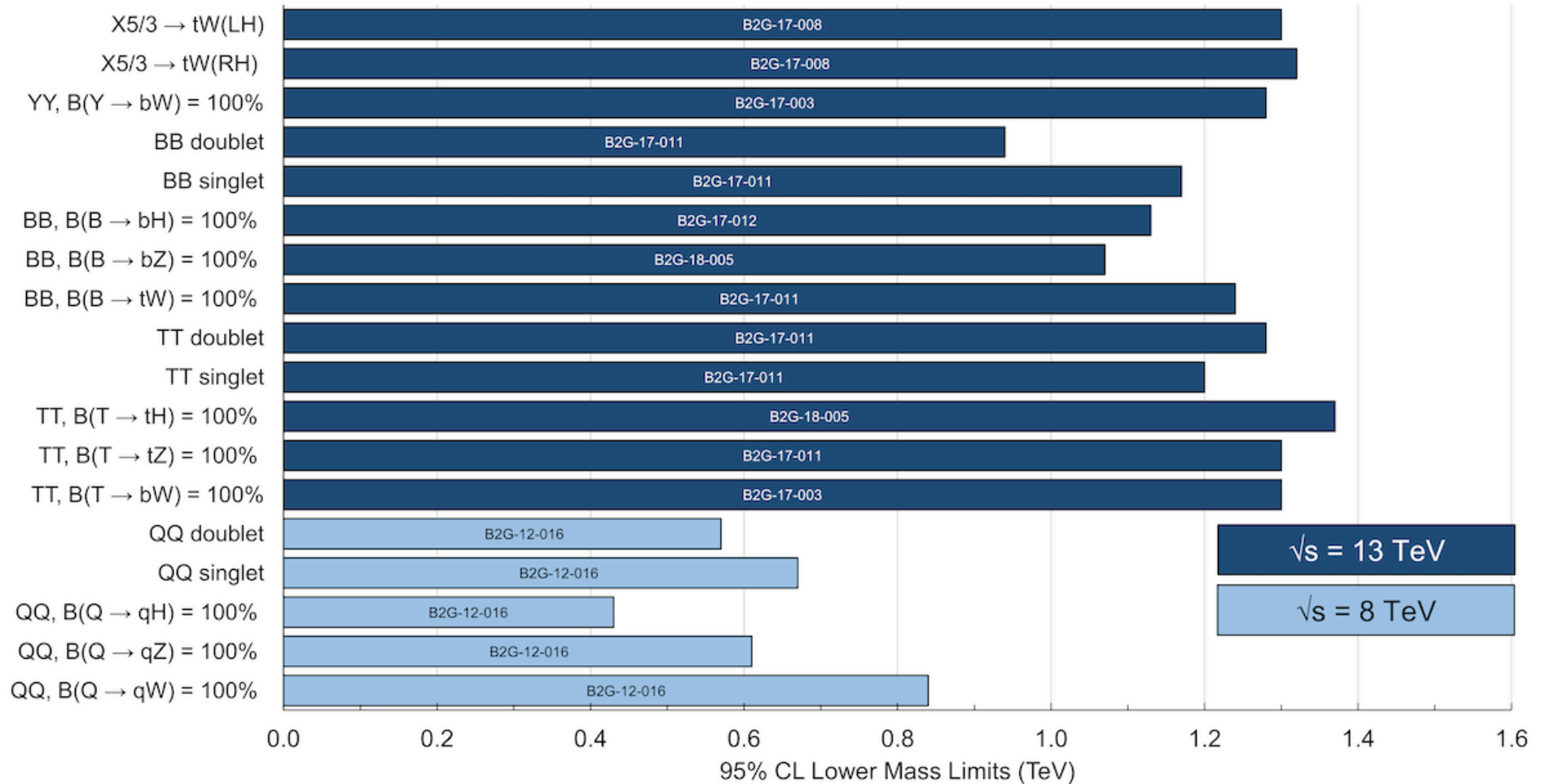


Improved B mass exclusion limits w.r.t. to previous results

Summary on pair production searches

Summary before B2G-19-005

Vector-like quark pair production

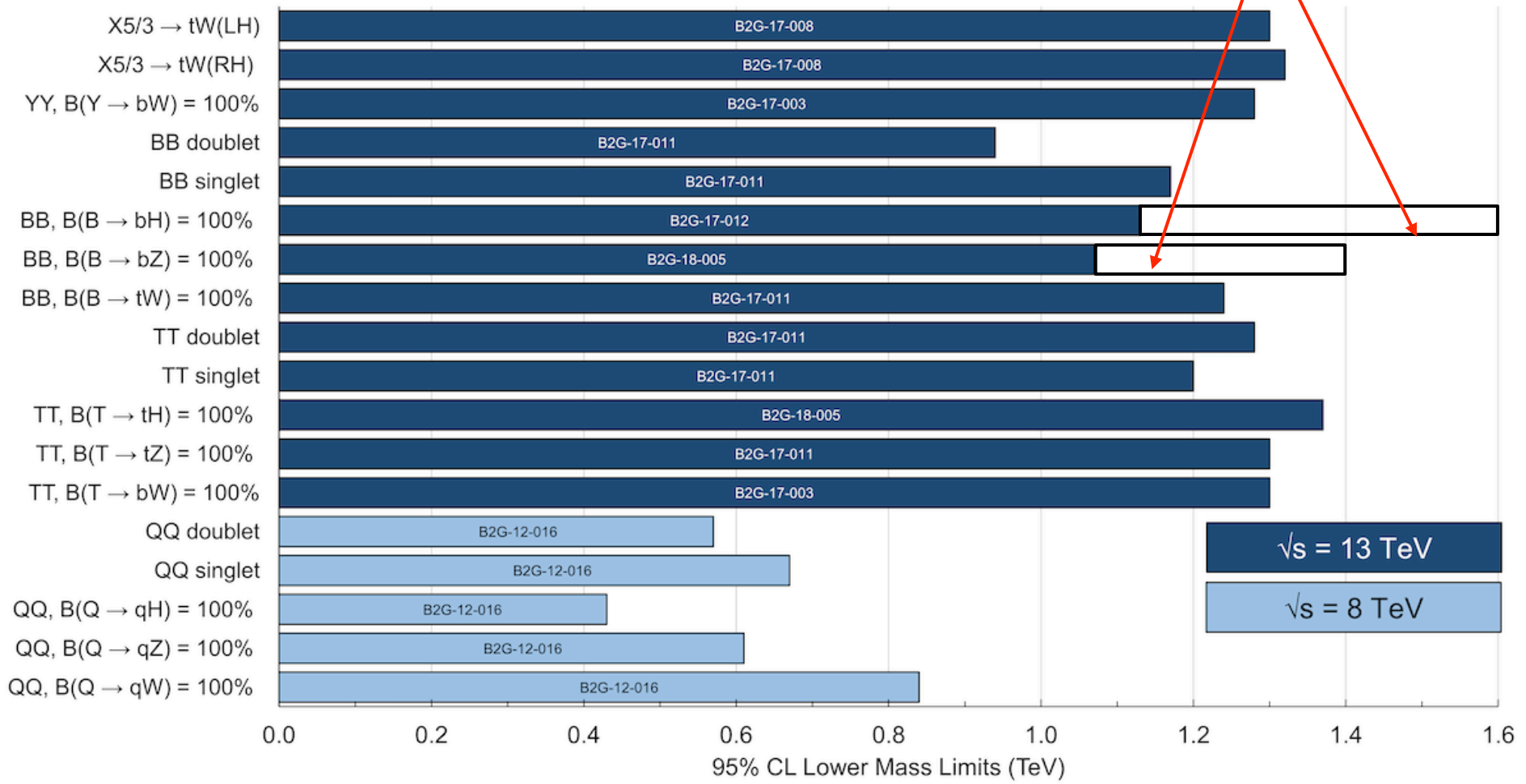


Summary on pair production searches

New mass ranges excluded by BB fully hadronic (full Run2)

Vector-like quark pair production

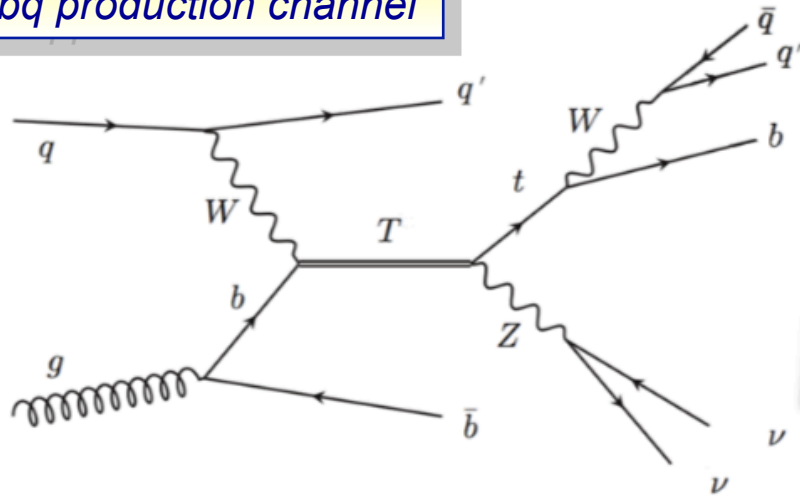
B2G-19-005



Single $T \rightarrow tZ$

Tbq production channel

PAS B2G-19-004



Final state:

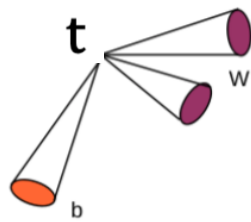
- Hadronic top decay
- Z in $\nu\nu$ (MET)

First full Run 2 result for single production!

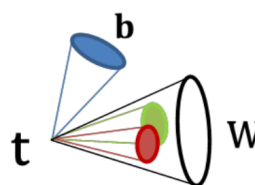
Large range of T masses investigated: [600, 1800] GeV

- Different boost regimes of top \rightarrow employ 3 algorithms to reconstruct the top candidate

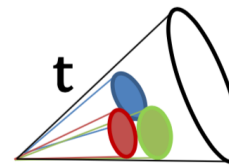
Resolved topology



Partially-merged topology



Merged topology



Top boost \rightarrow

Single $T \rightarrow tZ$

Signal selection strategy

- MET > 200 GeV
- Lepton veto
- $\min(\Delta\phi_{\text{MET, Jets}}) > 0.6$
- Jet from top decay is b-tagged

6 event categories depending on topology of reconstructed top candidate and presence of reconstructed forward jets

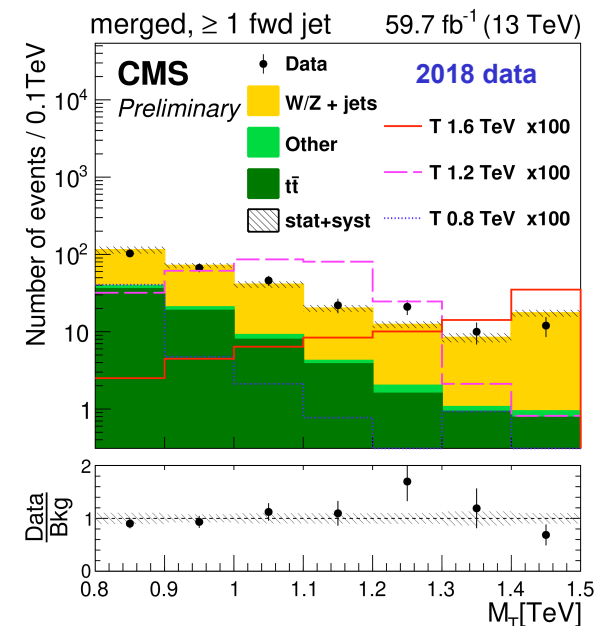
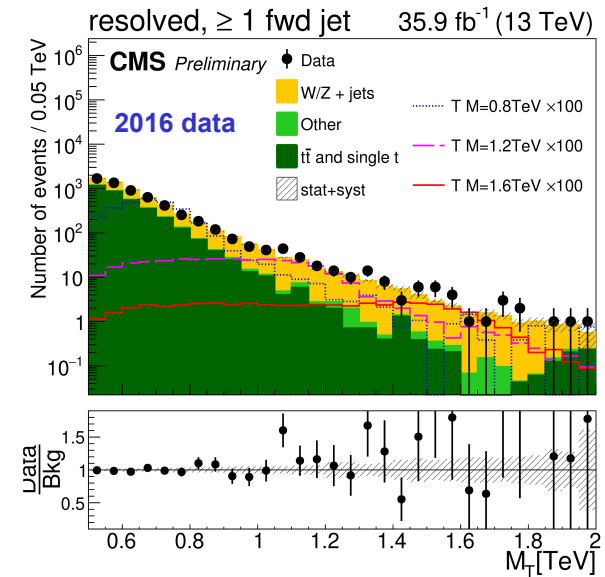
Signal extraction: simultaneous fit to transverse mass of the top and MET system in each category

$$M_T = \sqrt{2p_T^t p_T^{\text{miss}} (1 - \cos \Delta\phi_{t, \vec{p}_T^{\text{miss}}})}$$

Main backgrounds in signal region: $t\bar{t}$, V +jets ($V=W, Z$)

Data driven method to determine M_T distribution in signal region for the main backgrounds

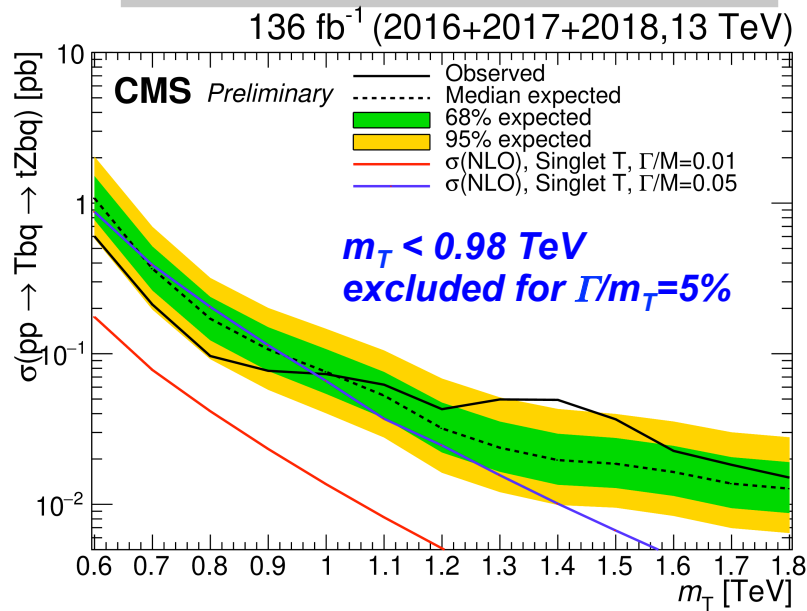
- Correction factors to simulation extracted from specific control regions



Single $T \rightarrow tZ$

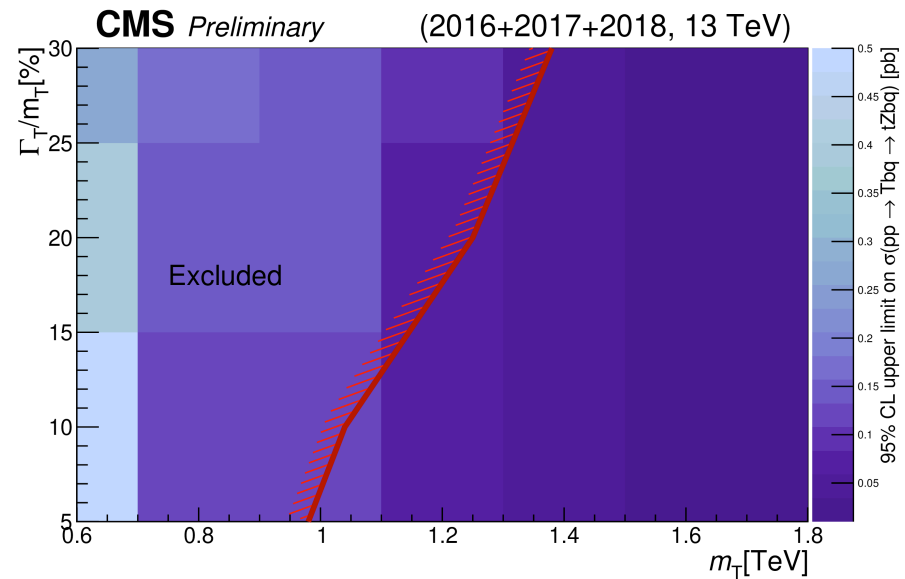
95% CL limits on cross section $\times BR(T \rightarrow tZ)$, assuming Tbq production channel (major production mode for a singlet T)

T resonance of negligible width



Local excess of 2.4σ for $m_T = 1.4 \text{ TeV}$ (driven by an excess in data observed in resolved category)

Limits as a function of mass and resonance width

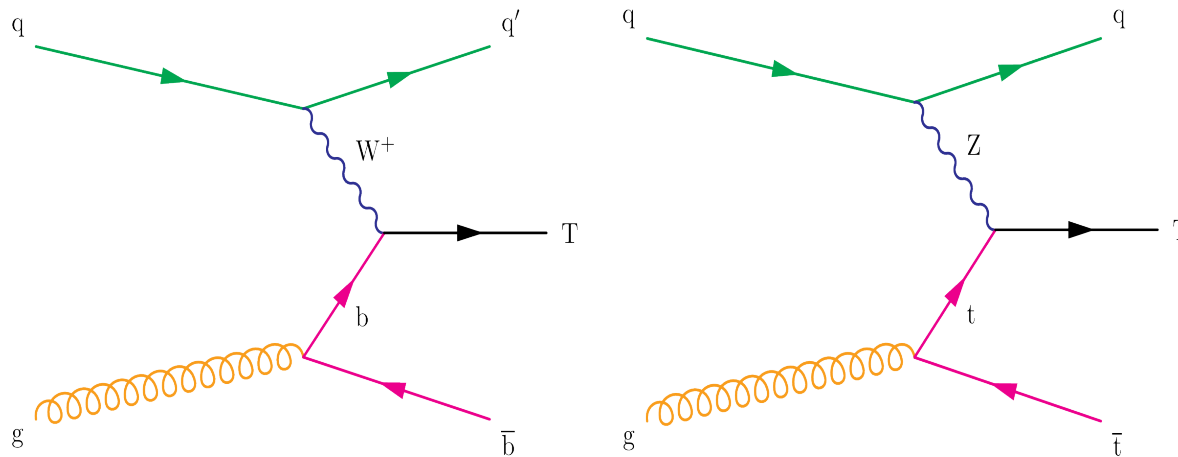


$m_T < 1.4 \text{ TeV}$ excluded for $\Gamma/m_T=30\%$

Single $T \rightarrow tX$ ($X=H, Z$) fully hadronic

JHEP 01 (2020) 036
B2G-18-003

Tbq and Ttq production channels



*Based on 2016
dataset (36 fb^{-1})*

*Final state characterized
by up to 7 (Tbq) or 9
(Ttq) jets*

Two analyses developed, targeting two VLQ mass ranges:

- *Low mass: 0.6 – 1.2 TeV*
- *High mass: > 1 TeV*

Main backgrounds: QCD, ttbar

Single $T \rightarrow tX$ ($X=H, Z$) fully hadronic

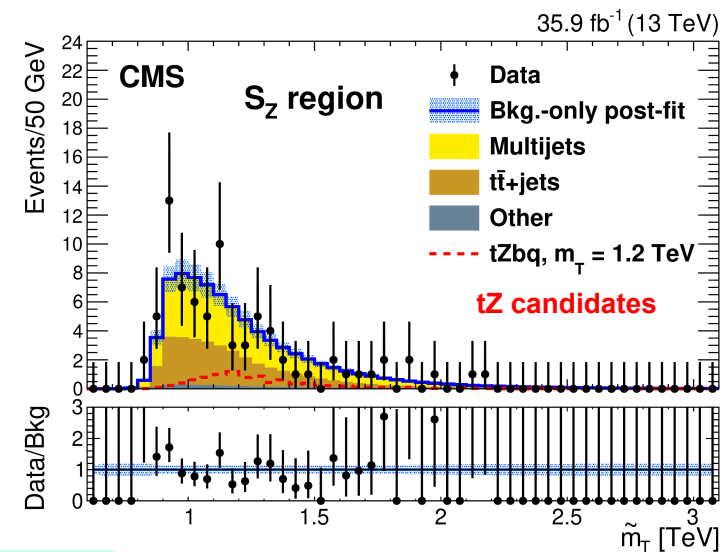
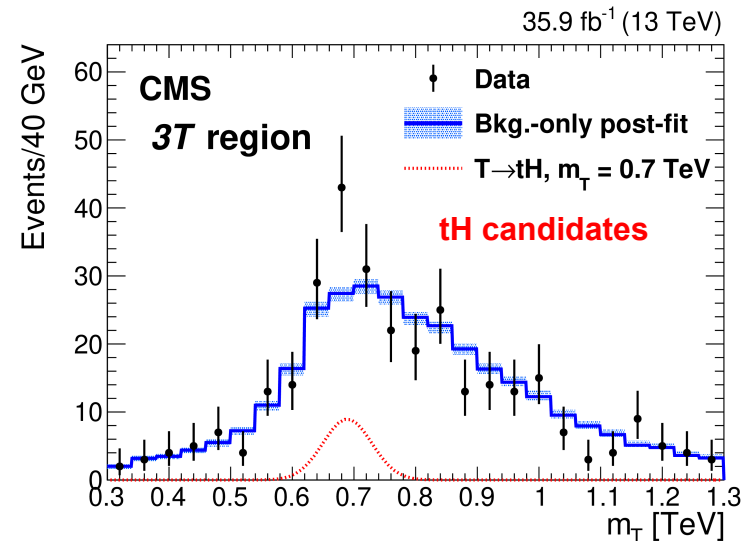
Low mass analysis

- 5 resolved jets from T decay
- Chi2-based sorting algorithm to assign jets to top / W / H / Z decay
- Signal and control regions based on the b tagging of the jets

High mass analysis

- top and H/Z from T decay reconstructed as wide jets passing top and H/Z tagging criteria
- b-tagging requirements applied to subjects of wide jets
- Six mutually exclusive control regions to predict the shape and rate of background from data

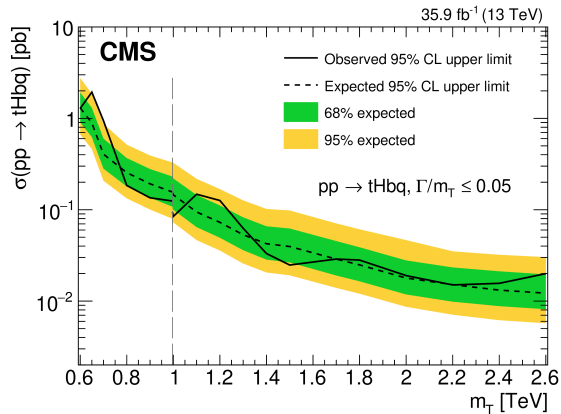
Signal extraction from simultaneous fit to the T candidate invariant mass in the signal and control regions



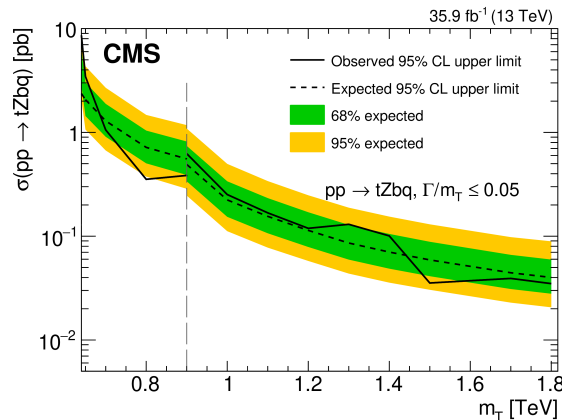
Single $T \rightarrow tX$ ($X=H, Z$) fully hadronic

95% CL limits on cross section \times BR for each channel and their sum for Γ/m_T up to 30%

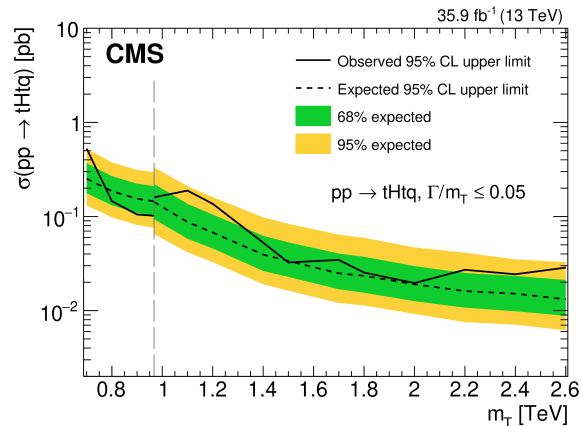
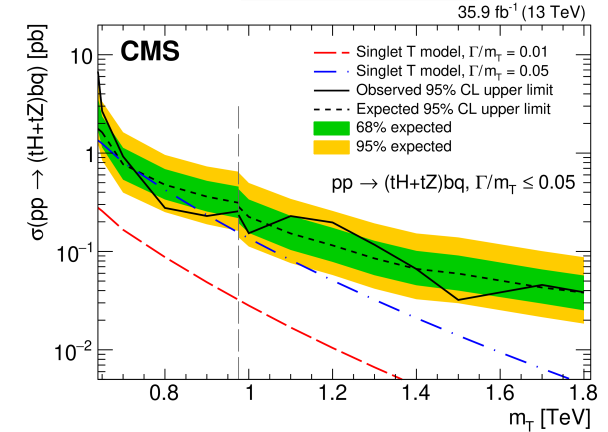
$T \rightarrow tH$ only limits



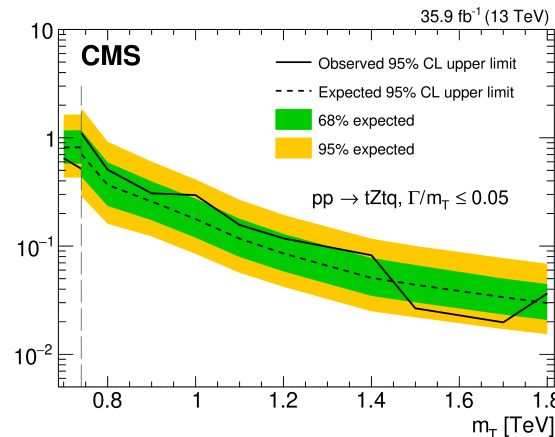
$T \rightarrow tZ$ only limits



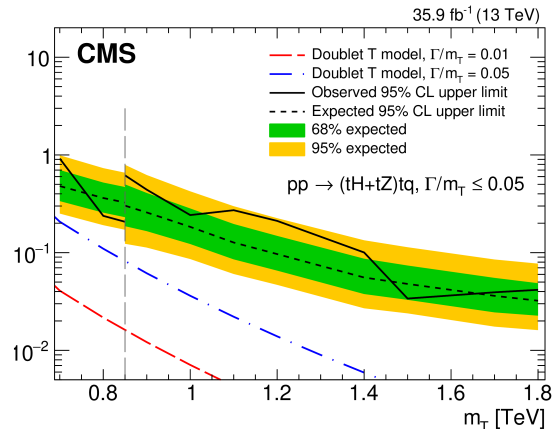
$tH+tZ$ limits



Strongest limits for $T \rightarrow tH$ searches



Limits competitive with other $T \rightarrow tZ$ searches



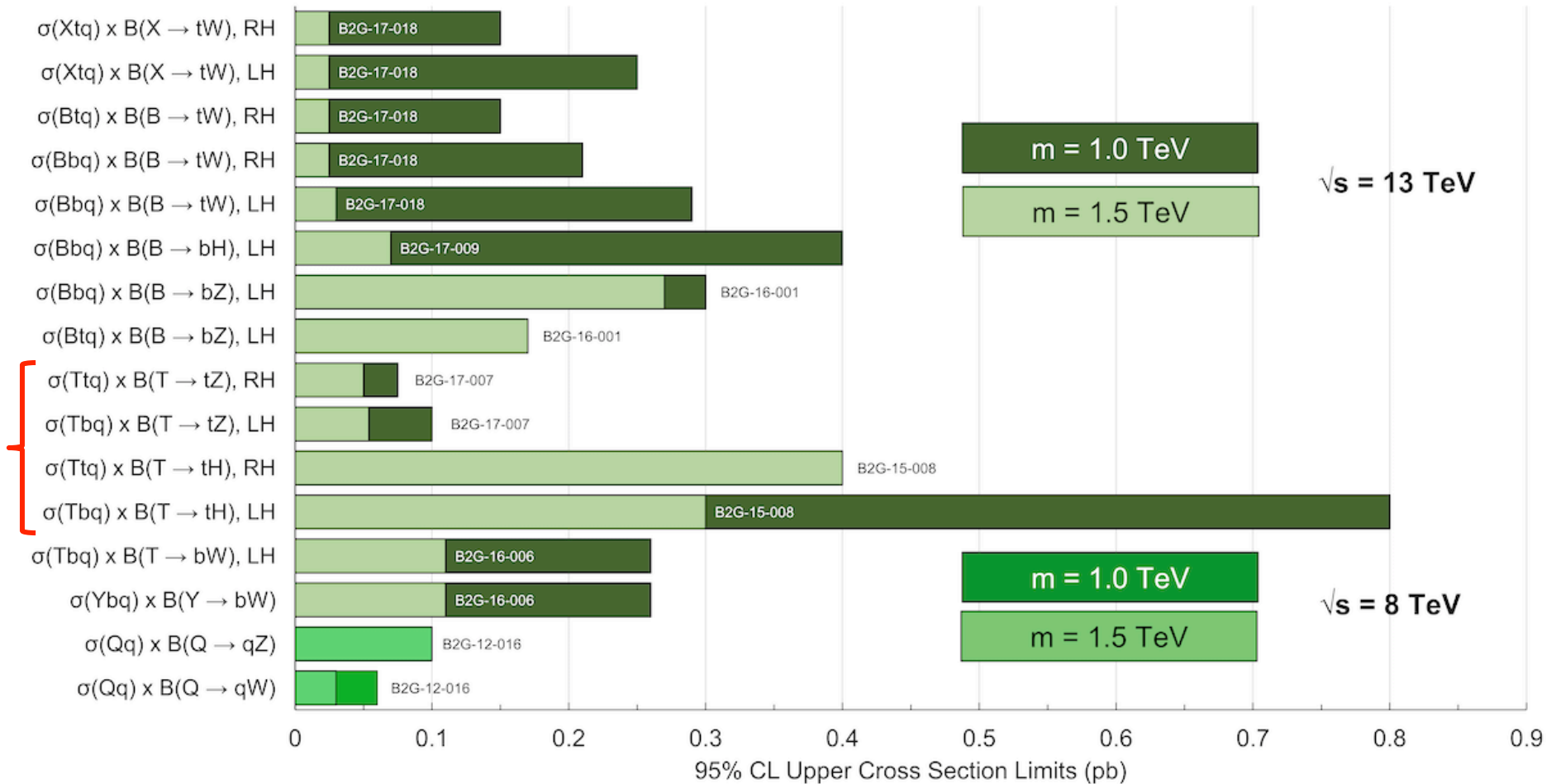
Masses in the range from 0.7 to 1 TeV are excluded for a singlet T model

No range of masses excluded for a doublet T model (Ttq production)

Summary on single production searches

Summary before B2G-18-003, B2G-19-004

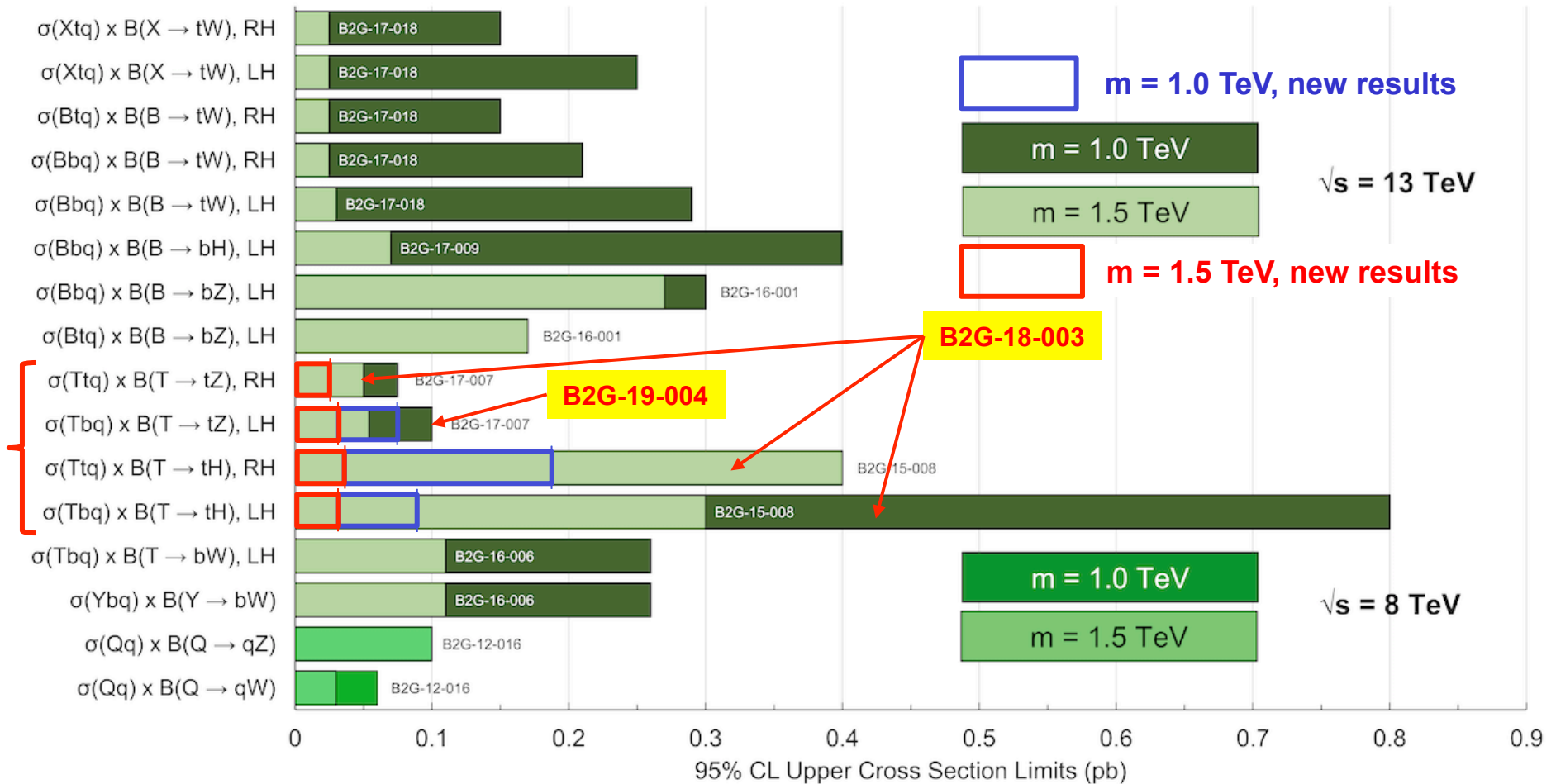
Vector-like quark single production



Summary on single production searches

New upper limits from full Run 2 $T \rightarrow tZ$ and fully hadronic $T \rightarrow tH$ analyses

Vector-like quark single production



Conclusions

- Presented recent results on the searches for VLQs at CMS based on LHC Run 2 data
 - First results on full Run 2 dataset ($\sim 137 \text{ fb}^{-1}$)
- No evidence of VLQs so far
 - Pair production searches providing stringent exclusion limits on VLQ mass
 - Single production searches setting stringent constraints using common benchmark models
- Stay tuned
 - More results from full Run 2 dataset to come
 - New Run 3 starting next year will provide additional data to search for VLQs