Recent Vector-like Quark Searches at the CMS Experiment

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on behalf of the CMS Collaboration

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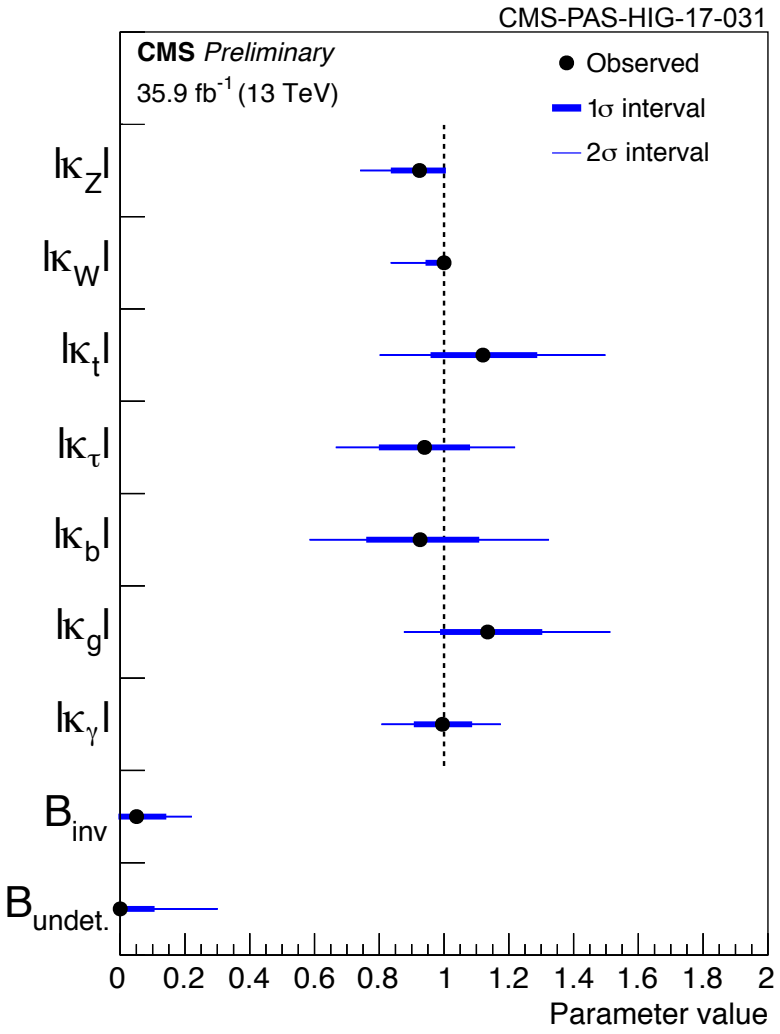
Introduction

- Higgs boson cross section measurements strongly constrain a chiral 4th generation of quarks
  - Interact via Yukawa couplings; would cause deviation
  - We are still left with the hierarchy problem!

- **Vector-like quarks (VLQ)** escape these constraints and provide a feasible solution
  - Present in many extensions to the SM (little-Higgs, extra dimensions, e.g.)
  - Left- and right-handed components transform equally under SU(2) ('vector')
  - Can be produced with high rates at LHC energies!

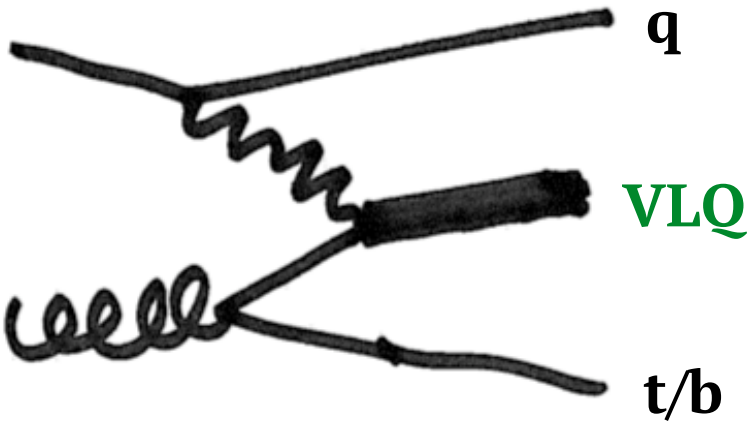


- t/b partners denoted T/B (singlets)
  - Can also have exotic charges in doublets or triplets
    - ($X_{5/3}$ T), (B $Y_{4/3}$), (X T B), (T B Y)

VLQ Phenomenology

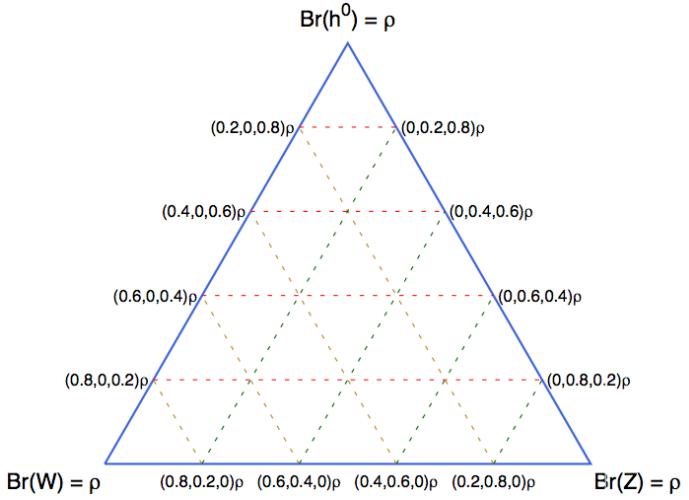
- **Pair production**
  - Through strong interaction
  - “Model independent”

- **Single production**
  - Electroweak interaction
  - Associated with forward jets
  - Can probe couplings to SM quarks



- Decays
  - T → bW, tH, tZ
  - B → tW, bH, bZ
  - Other decays to u/d/s/c quarks possible but expected to be suppressed

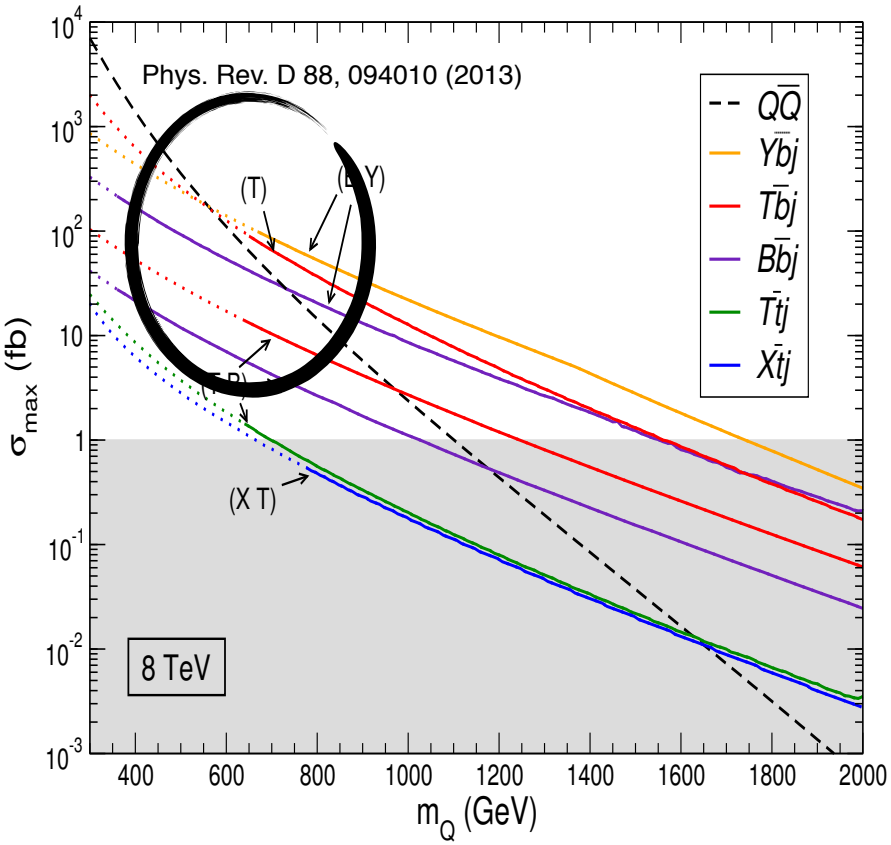
- Singlet scenario: 50% bW, 25% tH, 25% tZ
- Doublet scenario: 50% tH, 50% tZ

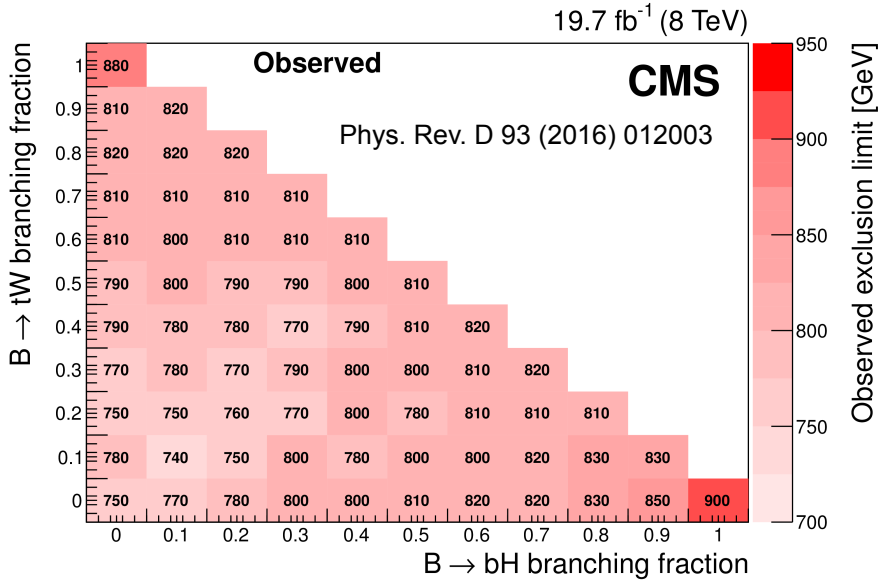


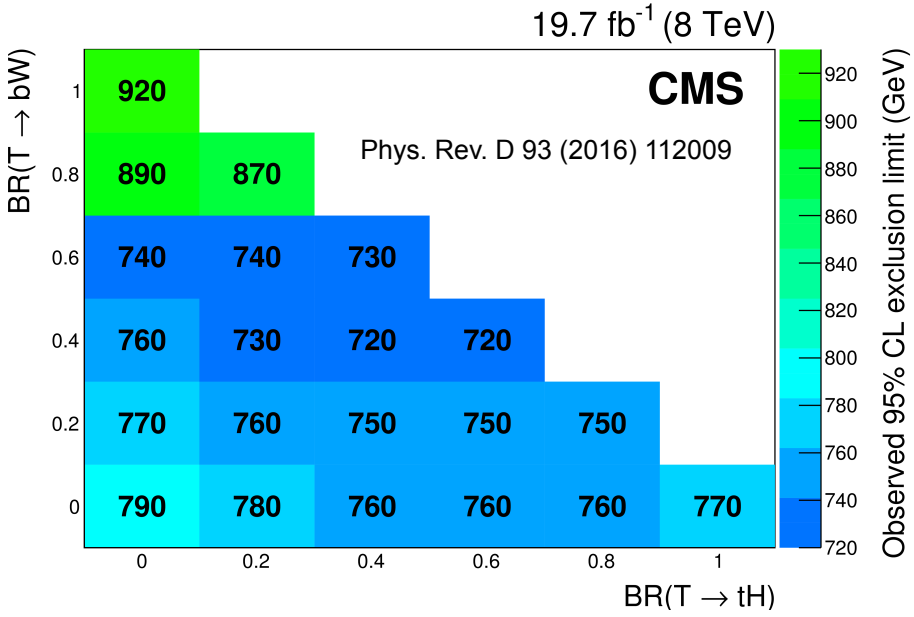
JHEP06(2017)095

Setting the Stage

- Emphasis on pair production in Run 1
- Mass exclusions range from ~700 to ~900 GeV depending on BR
  - Combination of many channels

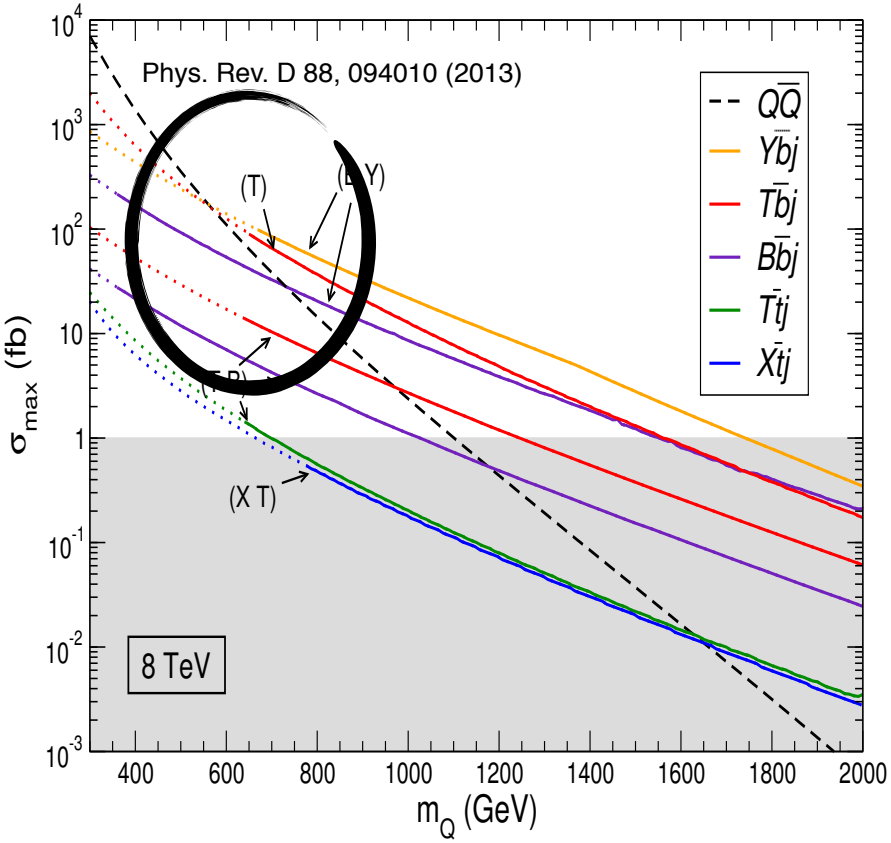


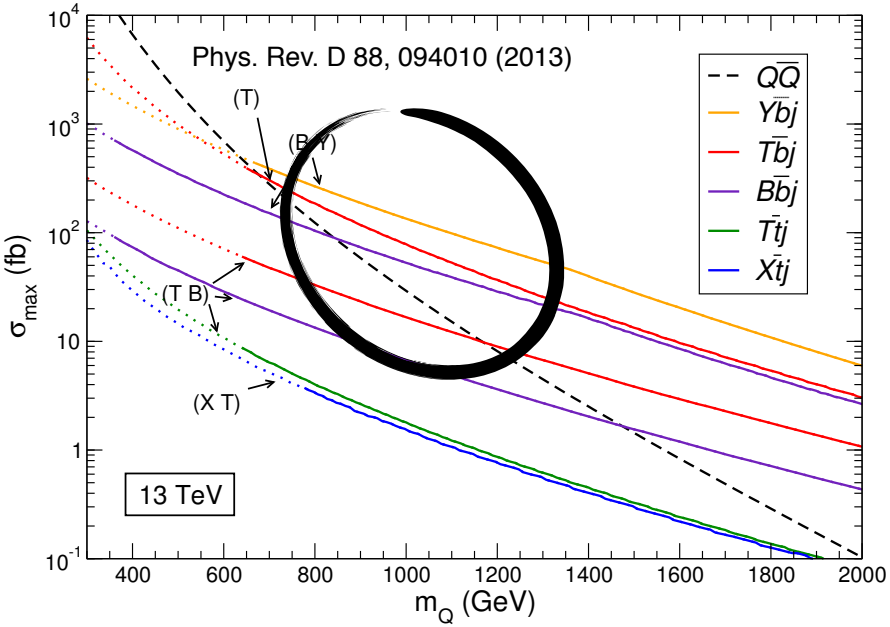




Setting the Stage

- Emphasis on pair production in Run 1
- Single production cross sections greatly benefit from increase in LHC energy
- With VLQ masses in the ~TeV range, decay products become more boosted
  - Dependence on jet substructure techniques to reconstruct merged W, Z, H, t with large-radius (anti-k_T R = 0.8) jets



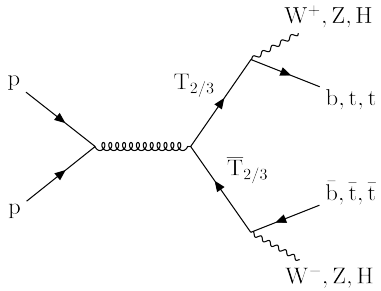


Recent CMS Analyses

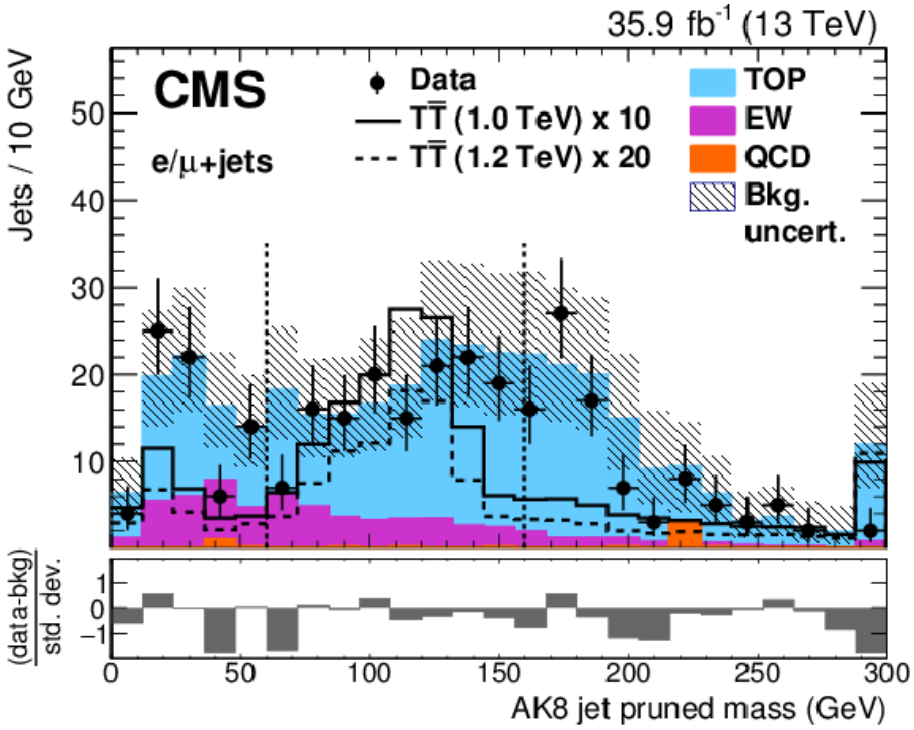
Search for TT/BB with leptons

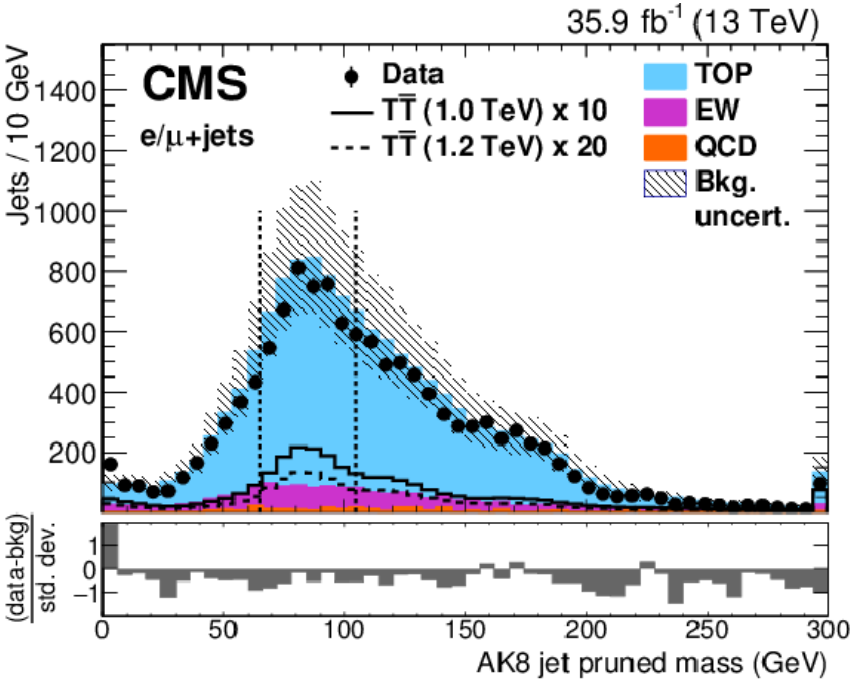
B2G-17-011
arXiv:1805.04758 [Sub. to JHEP]

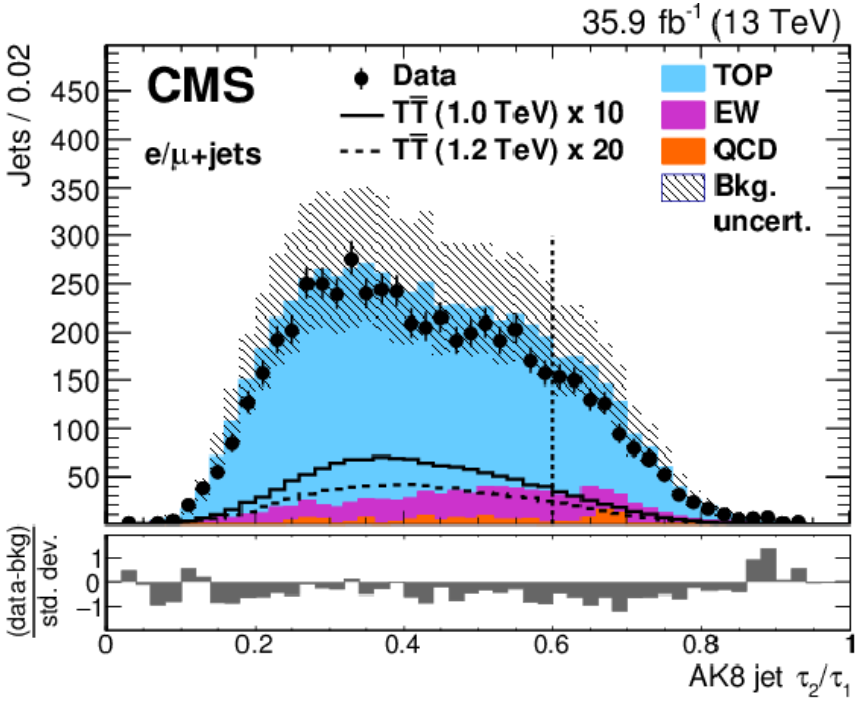
- Combine lepton selection with identification of highly-boosted W/H to enhance S:B



- Reliant on jet substructure variables
  - Groomed mass
  - N-subjettiness
  - Subjet b-tagging



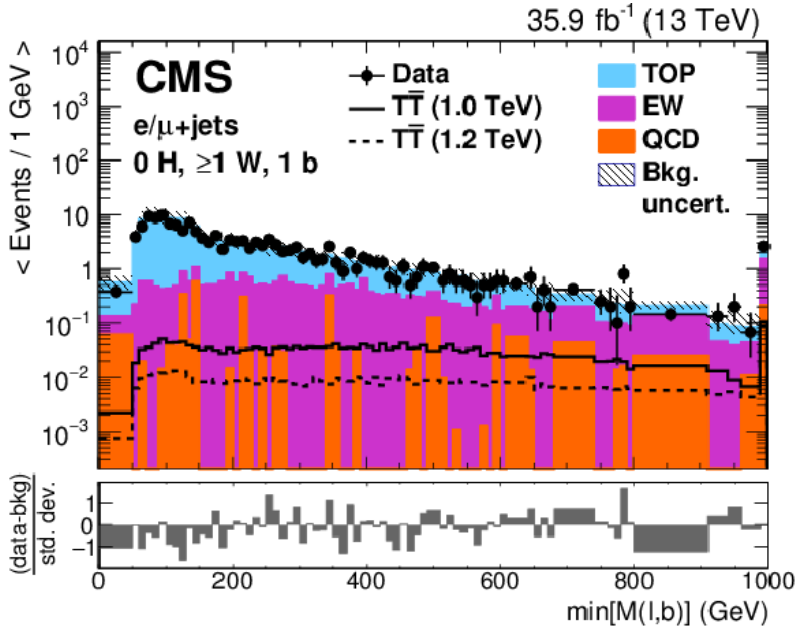


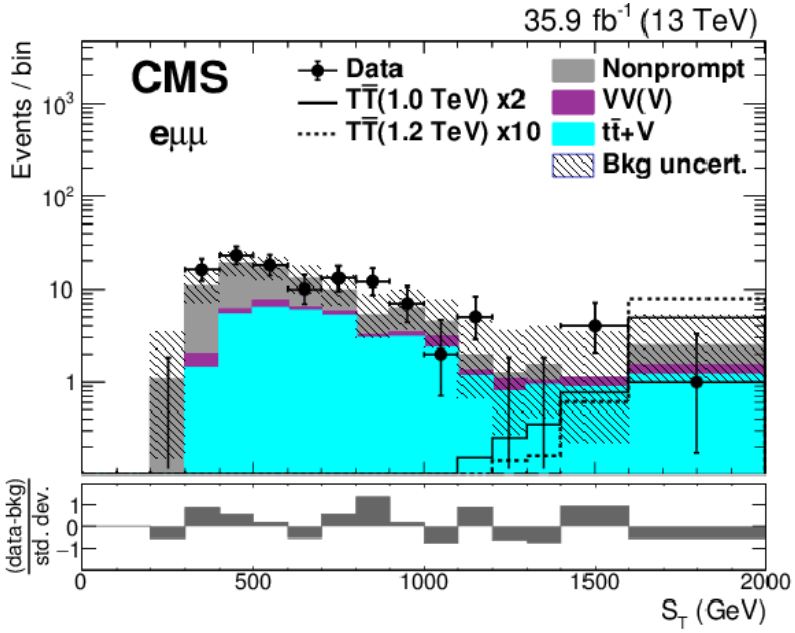


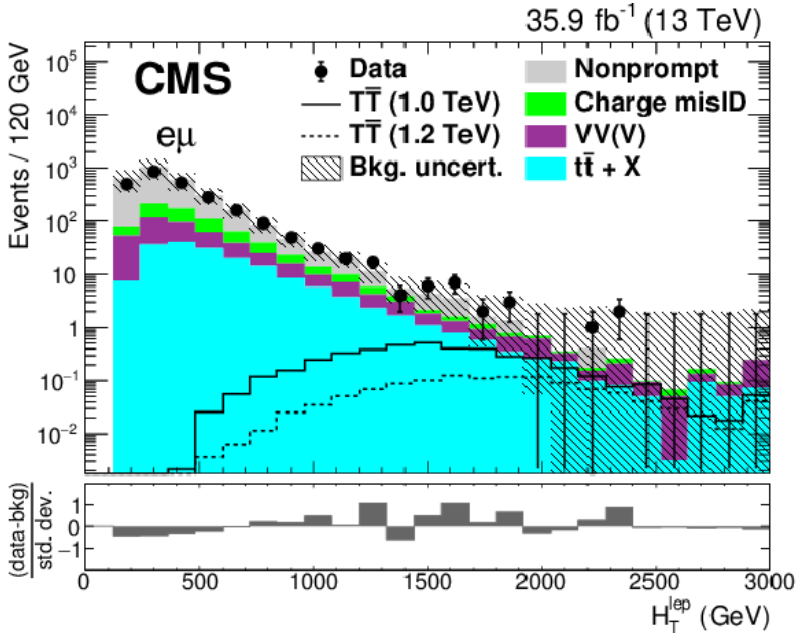
Search for TT/BB with leptons

B2G-17-011
arXiv:1805.04758 [Sub. to JHEP]

- Inclusive search with several analysis categories
  - Differing strategies to discriminate signal from background
- **Single lepton + jets**
  - Divide events based on number of W/H/b tags
  - Use min[M(l,b)] or S_T to discriminate
- **Same-sign dilepton**
  - Account for charge-misID background
  - Counting experiment performed
- **Trilepton**
  - Main background due to non-prompt leptons
  - Use S_T to discriminate





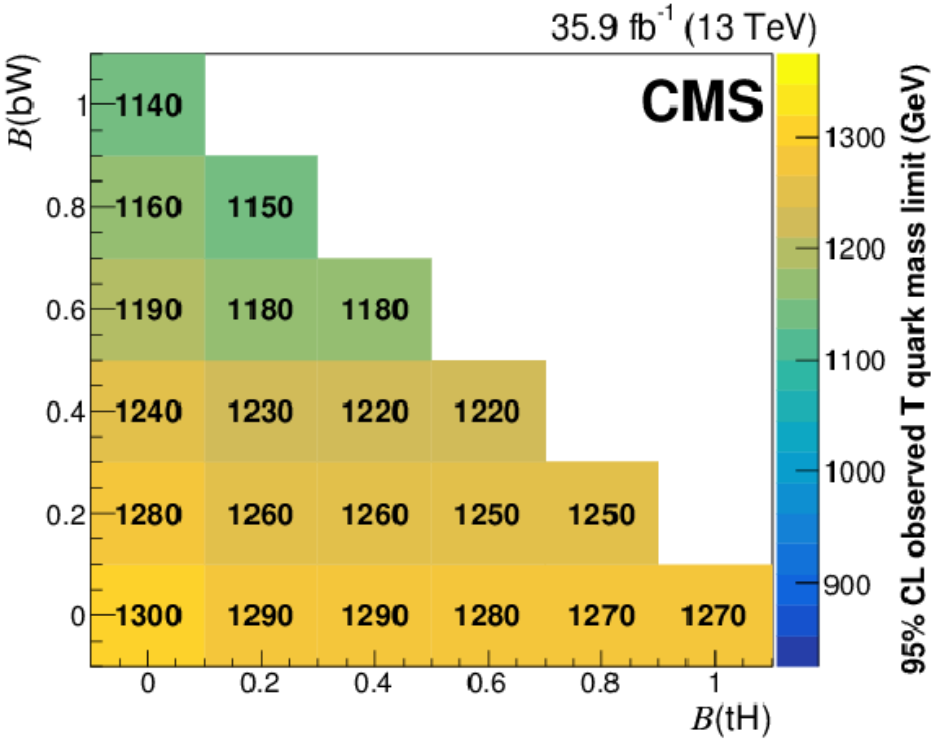


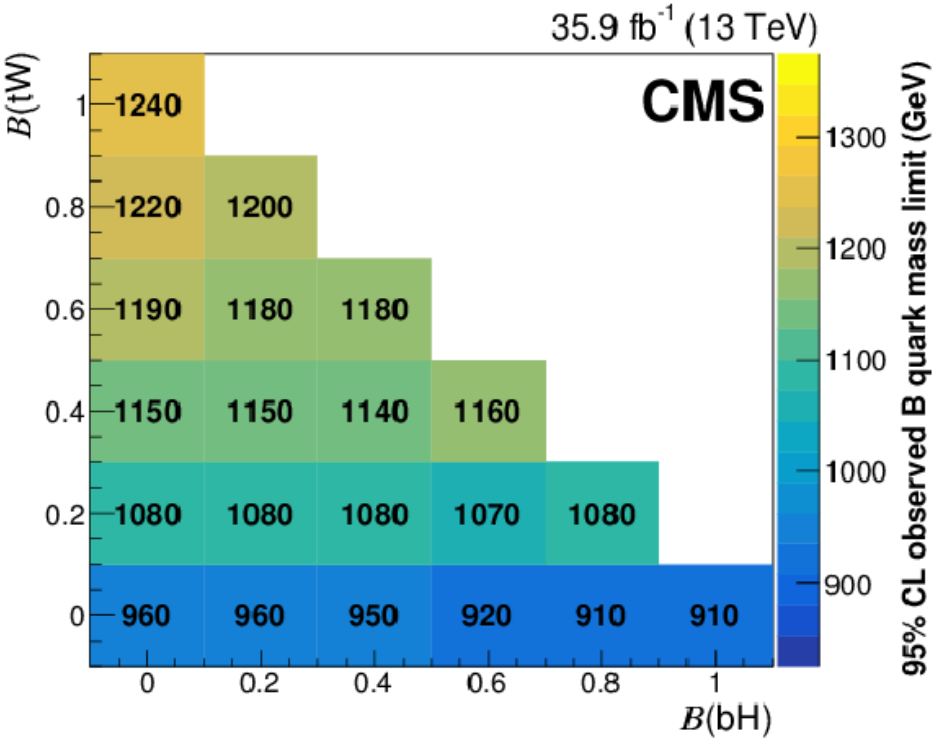
Search for TT/BB with leptons

B2G-17-011
arXiv:1805.04758 [Sub. to JHEP]

- Scan over T/B branching fractions
  - Mass exclusions range from 910 — 1300 GeV

- Singlet scenario:
  - m_T > 1.2 TeV (1.16 TeV exp), m_B > 1.17 TeV (1.13 TeV exp)
- Doublet scenario:
  - m_T > 1.28 TeV (1.24 TeV exp), m_B > 0.94 TeV (0.92 TeV exp)



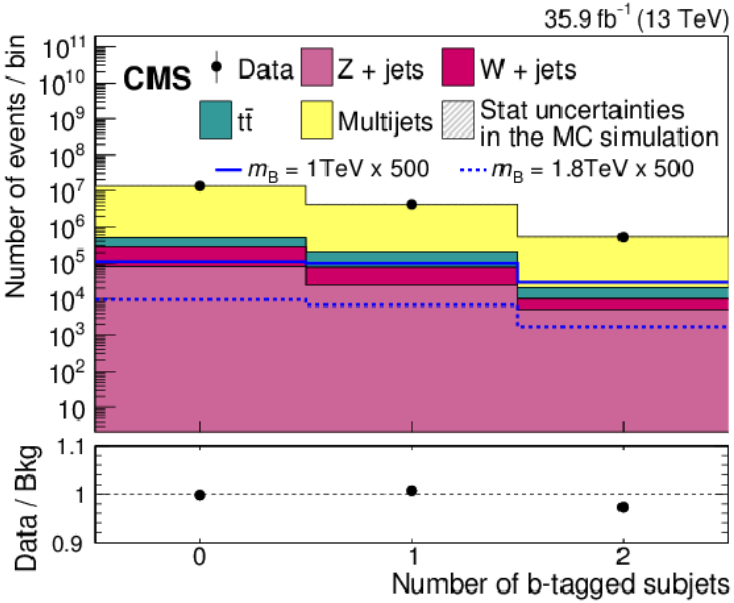


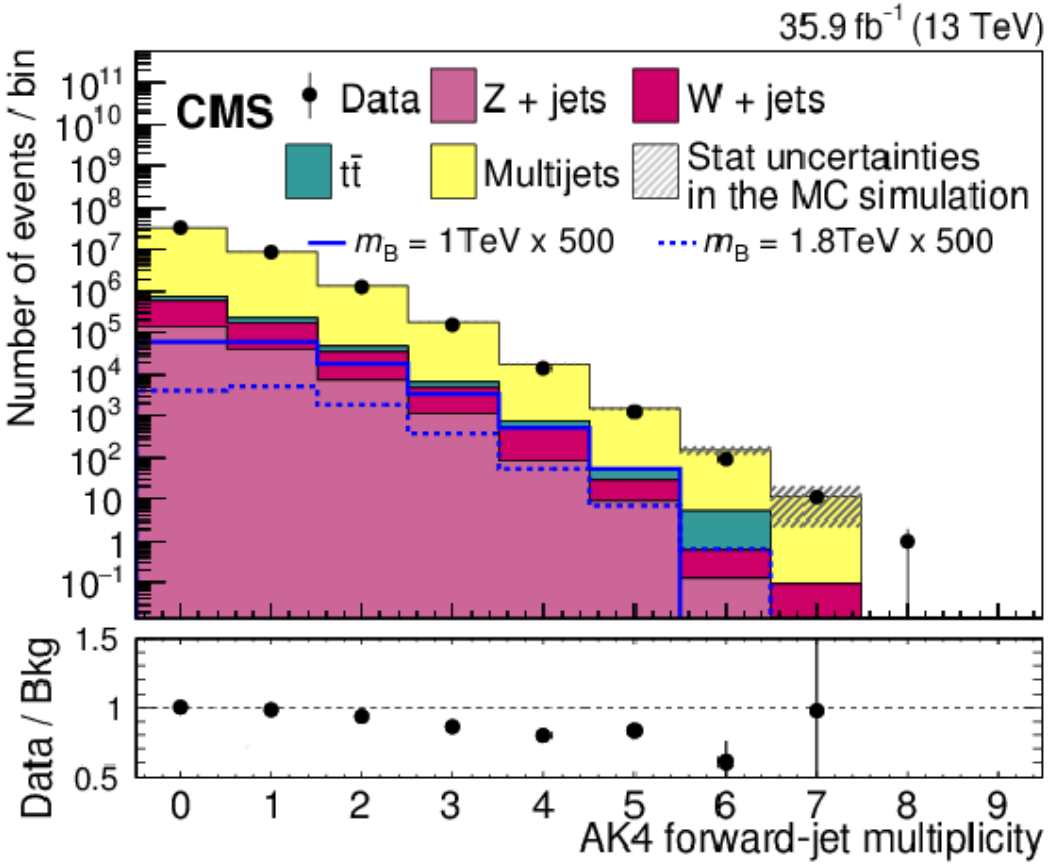
- Big improvement over Run 1 results!

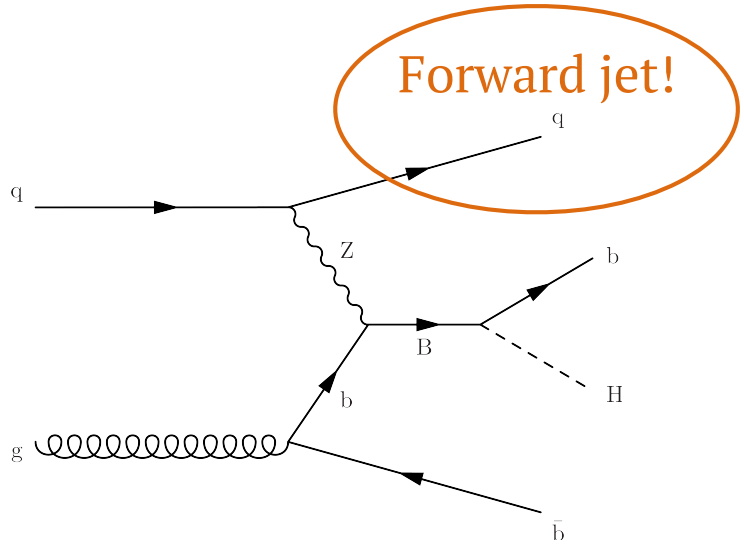
Search for B in bH channel

B2G-17-009
JHEP 06 (2018) 031

- Targeting single B production with bH decay mode
  - Identify merged Higgs jet with b-tagged subjets, mass
- Require forward jet to enhance signal purity



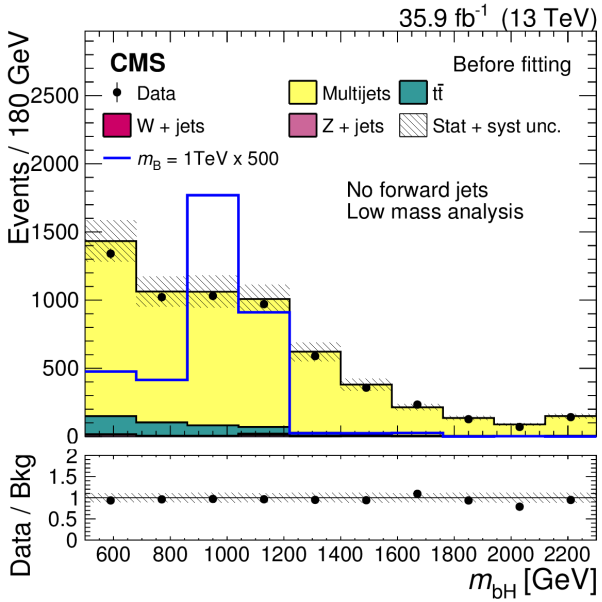


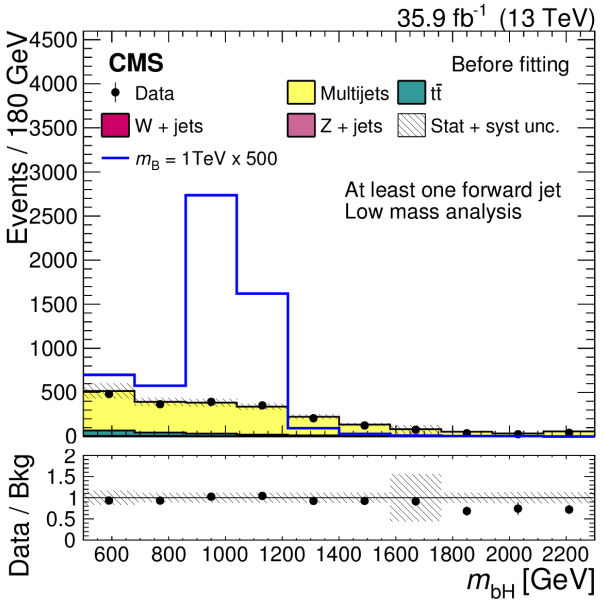


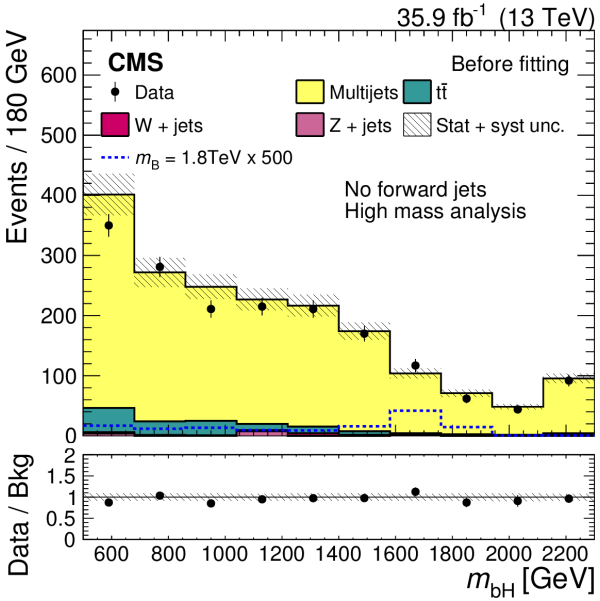
Search for B in bH channel

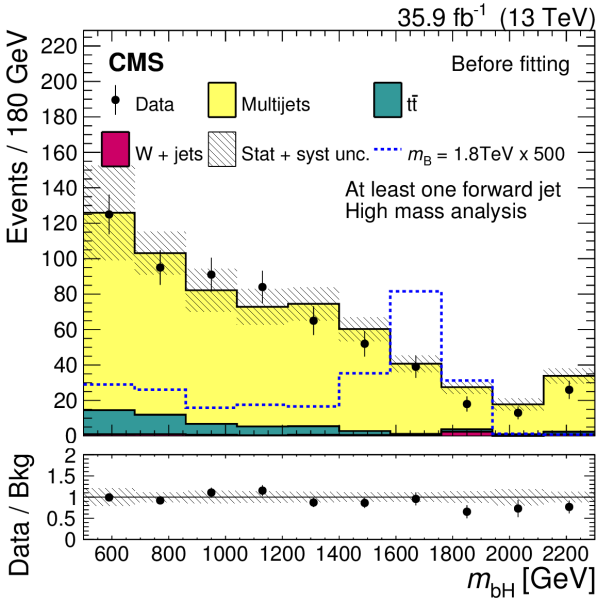
B2G-17-009
JHEP 06 (2018) 031

- Divide events based on number of forward jets; high/low mass strategy (based on H_T)
- QCD multijet production is dominant background
  - Estimated via ABCD method with sidebands of H-jet mass, subjet b-tags
- Mass of b+H-jet used to fully reconstruct B







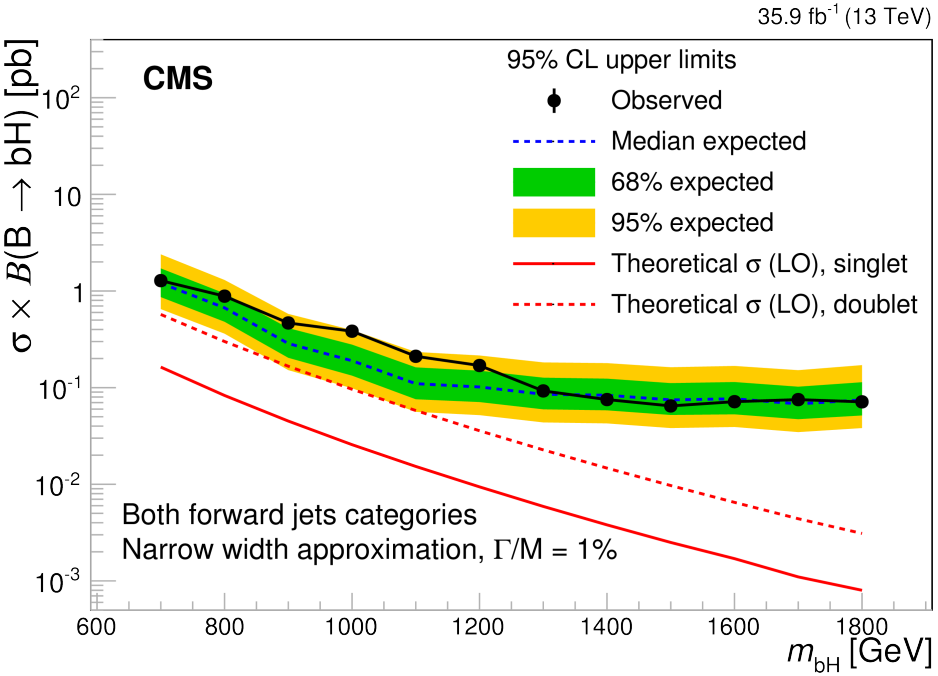


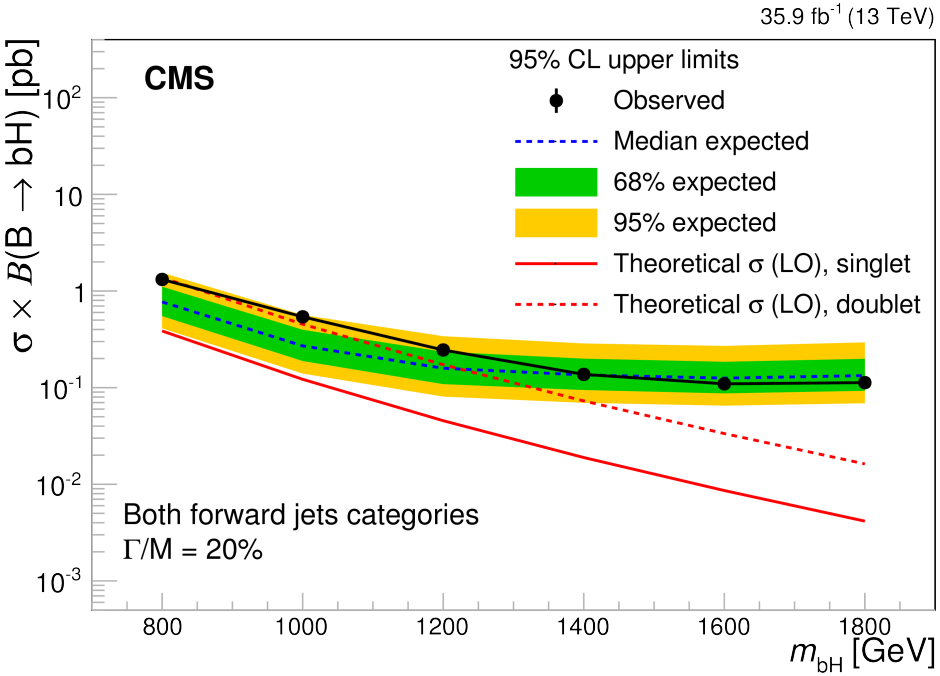
Search for B in bH channel

B2G-17-009
JHEP 06 (2018) 031

- m_{bH} is used to extract limits on the bBq cross section
  - Ranging from 1.28 — 0.07 pb for m_B from 700 — 1800 GeV

- Results are also interpreted assuming non-negligible VLQ resonance width
  - First such analysis to do so
  - Cross-section limits comparable to narrow width approximation
  - Theory expectation changes dramatically



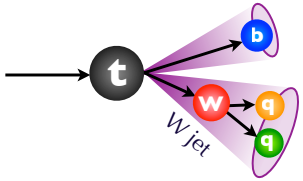


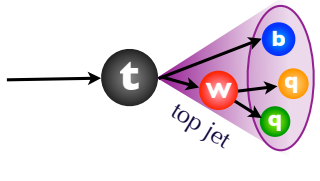
Search for T in tZ channel

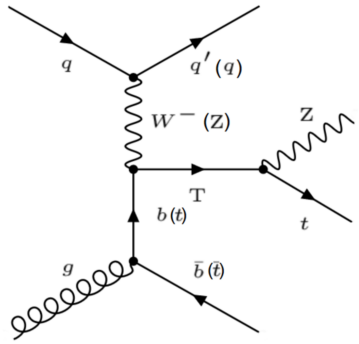
B2G-17-007
PLB 781 (2018) 574

- Target final states with leptonic Z decay and hadronic top decay
  - Divide events based on:
    - Z lepton flavor
    - Number of forward jets
    - Top decay topology

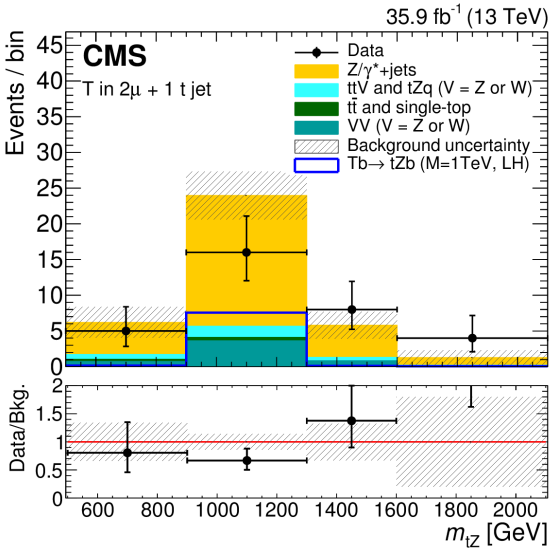
Category	Z boson	t quark	N(forward jets)	$\Delta R(\ell,\ell)$	$m_{j1,j2}$
1	two muons	fully merged	$\geq$0	<1.4	—
2	two electrons	fully merged	$\geq$0	<1.4	—
3	two muons	partially merged	0	<0.6	—
4	two muons	partially merged	$\geq$1	<0.6	—
5	two electrons	partially merged	0	<0.6	—
6	two electrons	partially merged	$\geq$1	<0.6	—
7	two muons	resolved	0	<0.6	<200 GeV
8	two muons	resolved	$\geq$1	<0.6	<200 GeV
9	two electrons	resolved	0	<0.6	<200 GeV
10	two electrons	resolved	$\geq$1	<0.6	<200 GeV

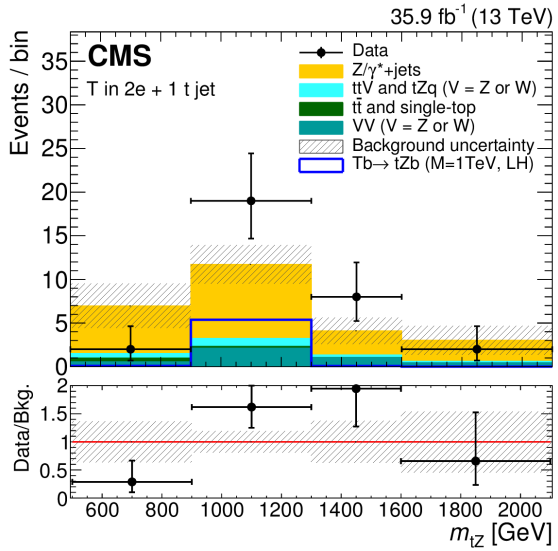


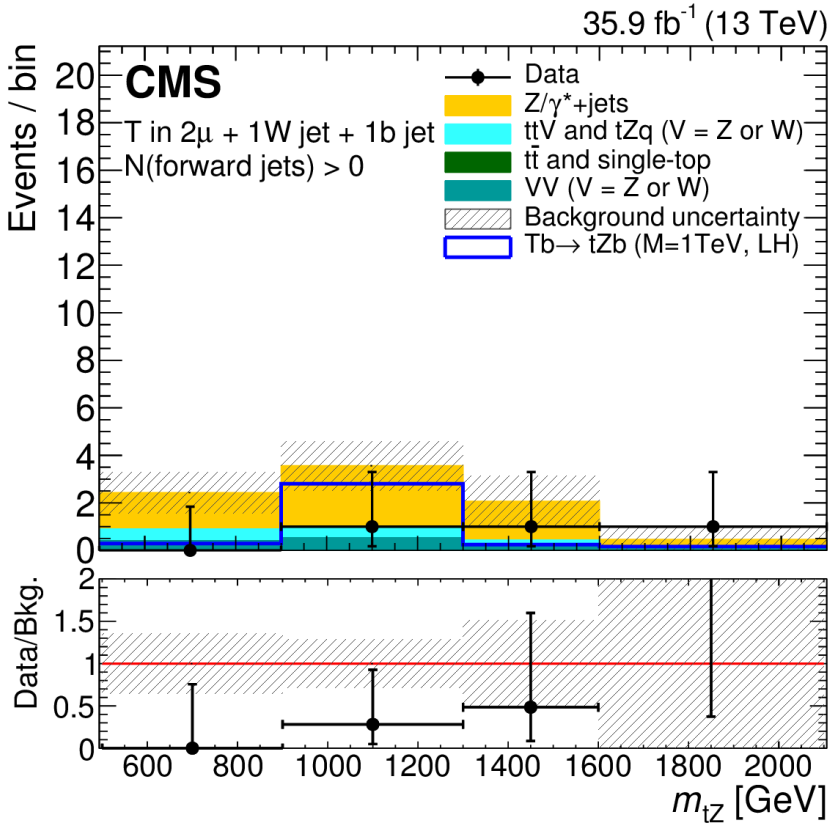




- Reconstructed tZ mass used to discriminate signal



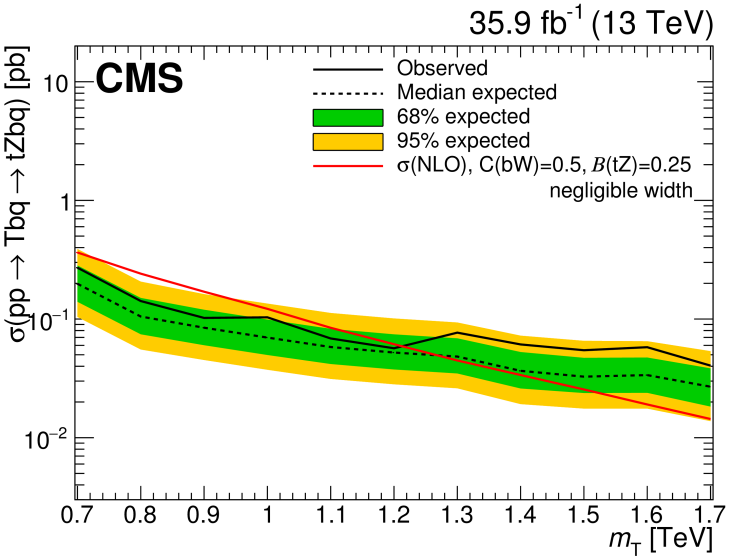


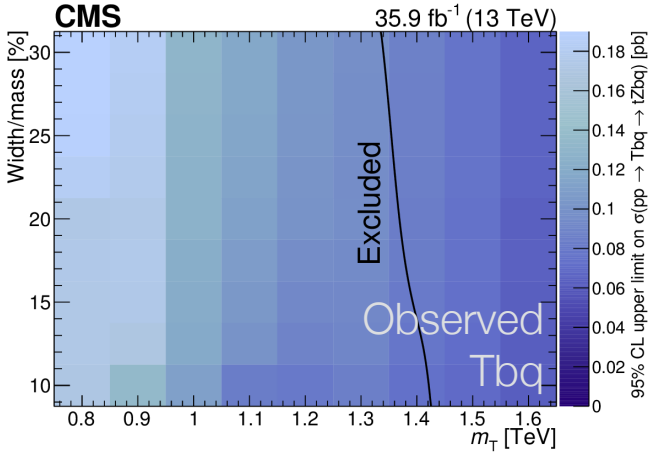


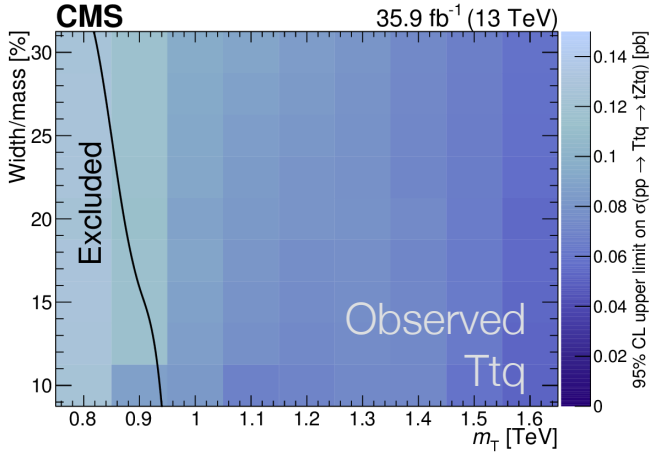
Search for T in tZ channel

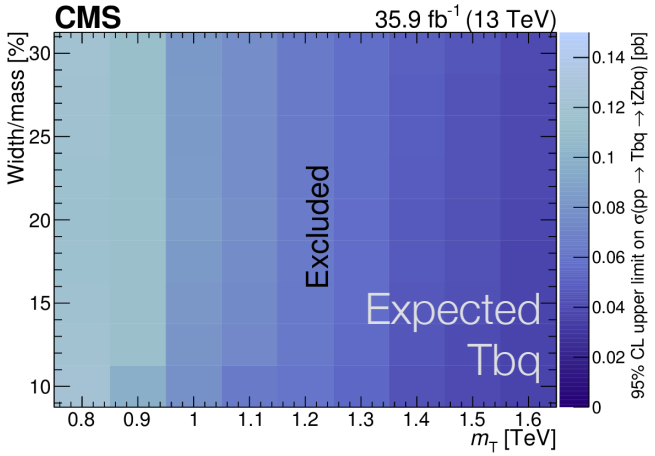
B2G-17-007
PLB 781 (2018) 574

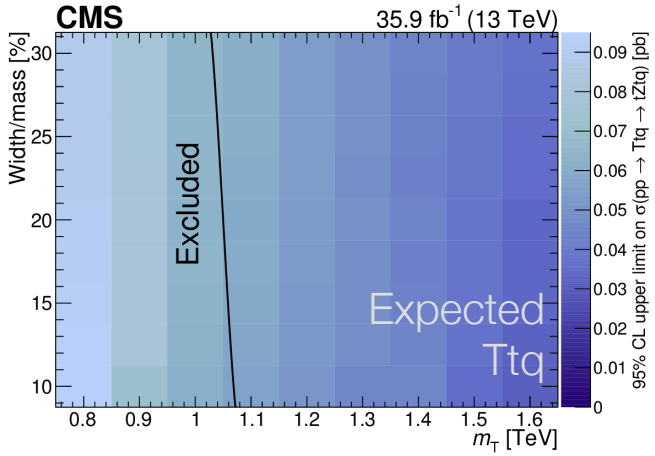
- Exclude narrow-width singlet T below 1.2 TeV
  - Results also interpreted in finite width scenarios (10% — 30%)
    - Depends on production in association with b or t











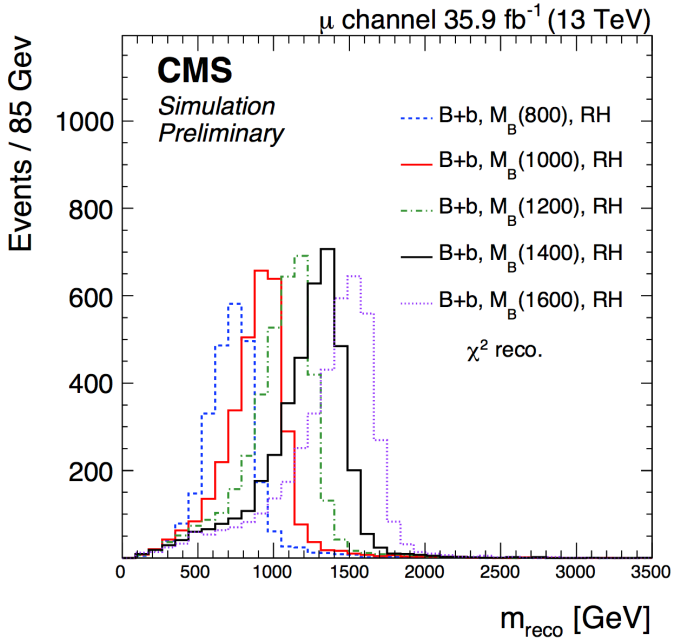
Search for B in tW channel

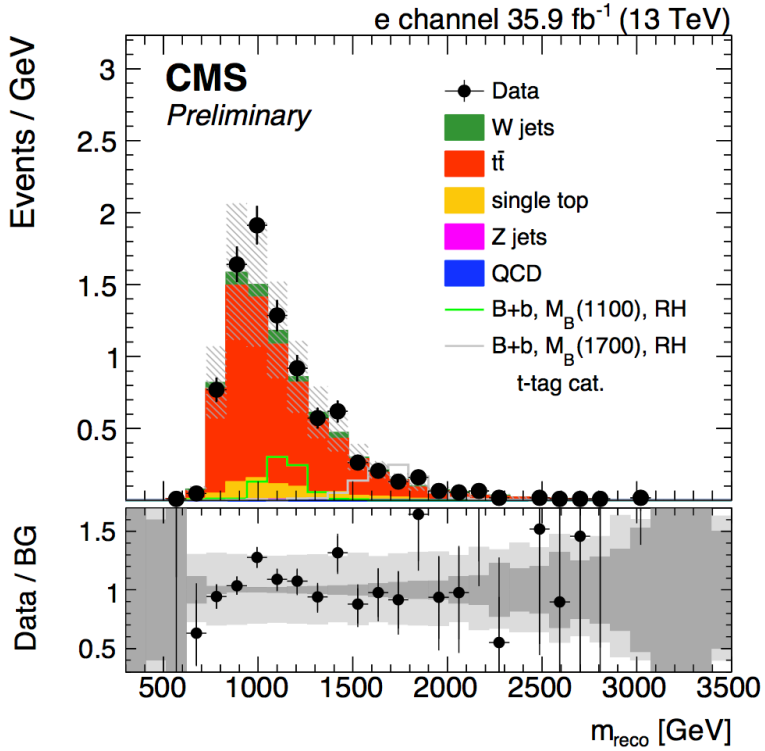
B2G-17-018

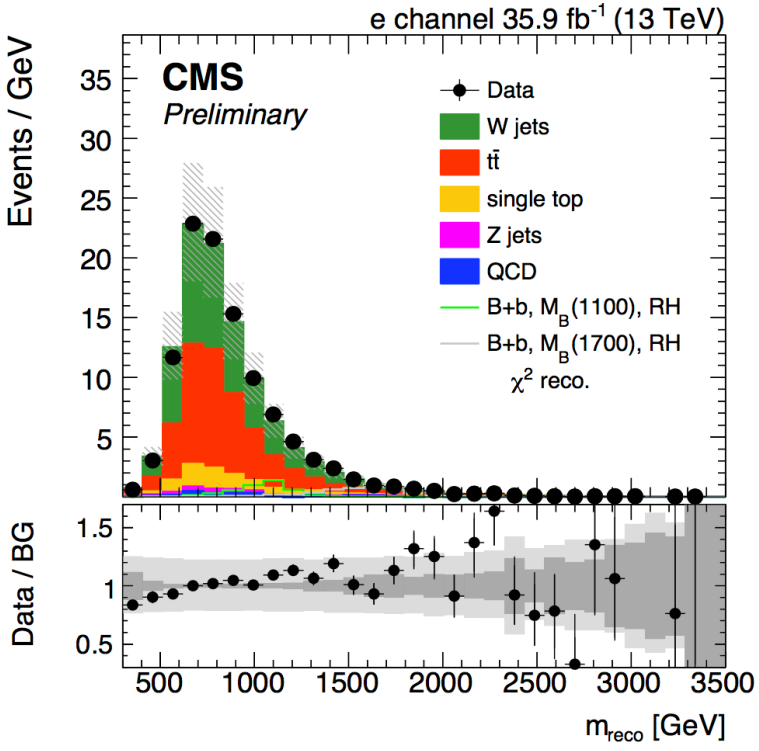
- Final state includes single electron/muon + (forward) jets
  - Large-radius jets used to identify boosted top/W
  - Divide events based on number of boosted top/W, b-jet multiplicity

- Mass of B is reconstructed from top jet + leptonic W
  - χ^2 method used in case of other channels by assigning objects to top/W reconstruction

$$\chi^2 = \frac{(m_t - \overline{m}_t)^2}{\sigma_t^2} + \frac{(m_W - \overline{m}_W)^2}{\sigma_W^2} + \frac{(\Delta R(t,W) - \pi)^2}{\sigma_{\Delta R}^2} + \frac{(p_{T,W}/p_{T,t} - 1)^2}{\sigma_{p_T}^2}$$



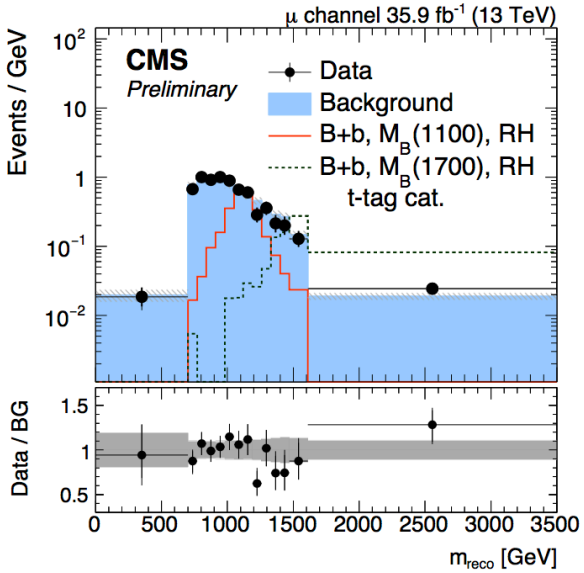




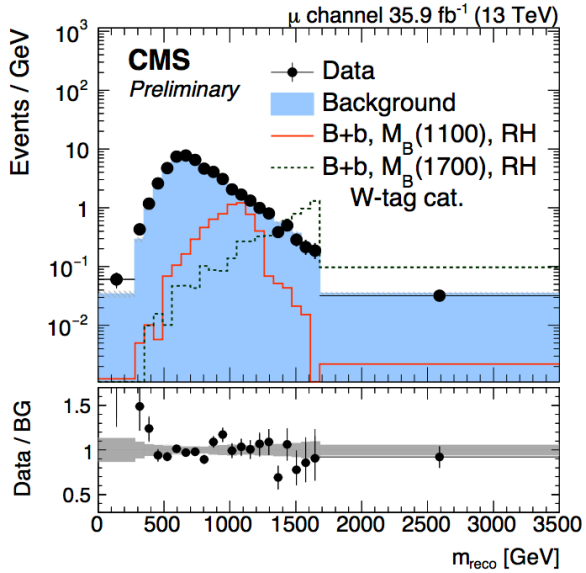
Search for B in tW channel

- Signal region requires at least one forward jet
  - Inverted to define background-enriched control region
  - Extrapolate shape from CR to SR

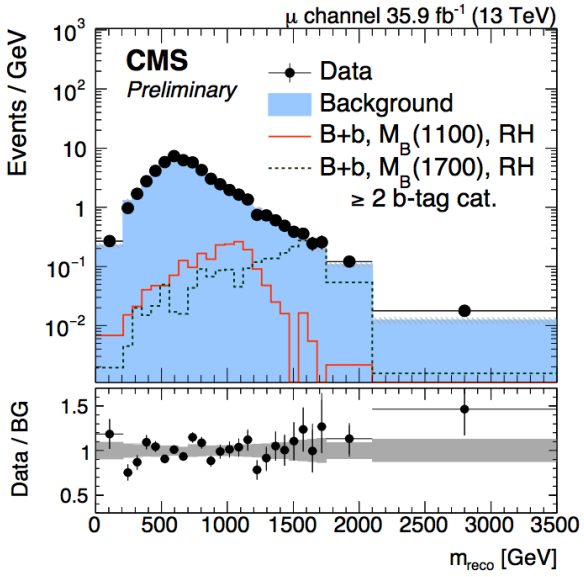
Top tag



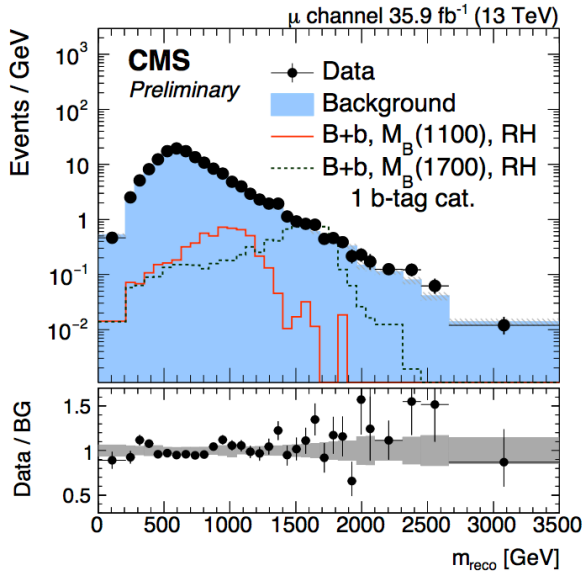
W tag



>= 2 b tag



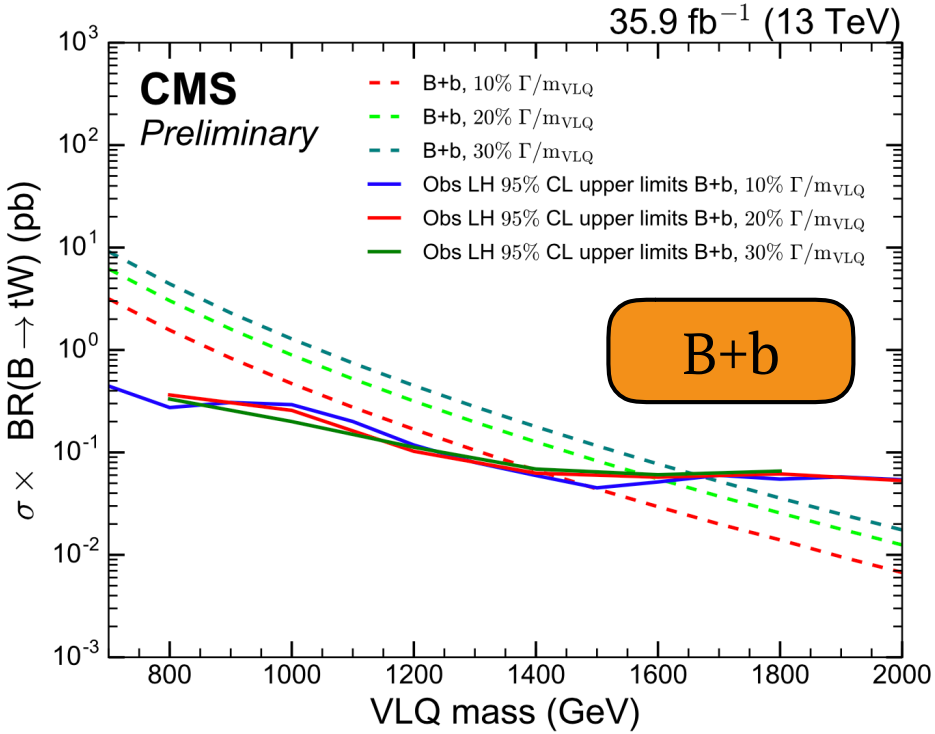
1 b tag

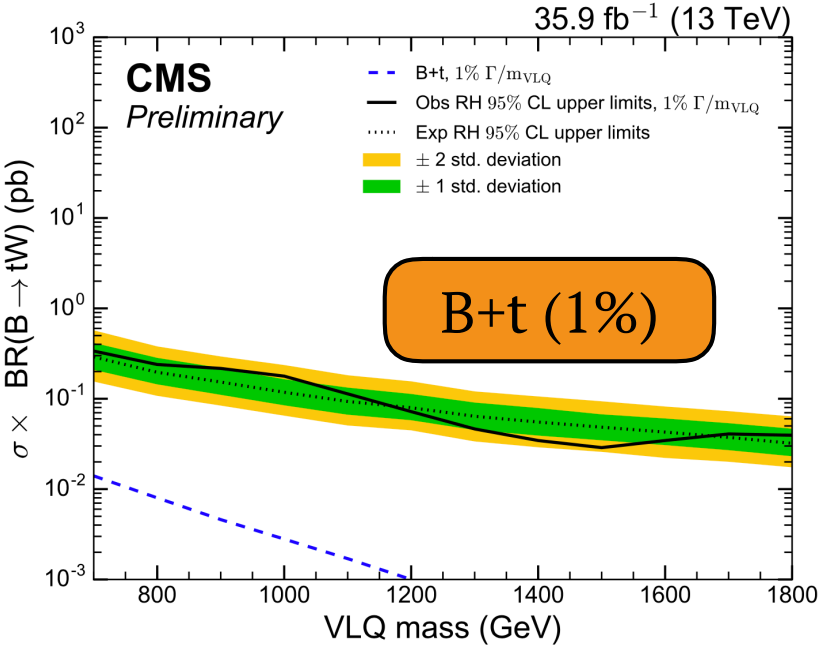


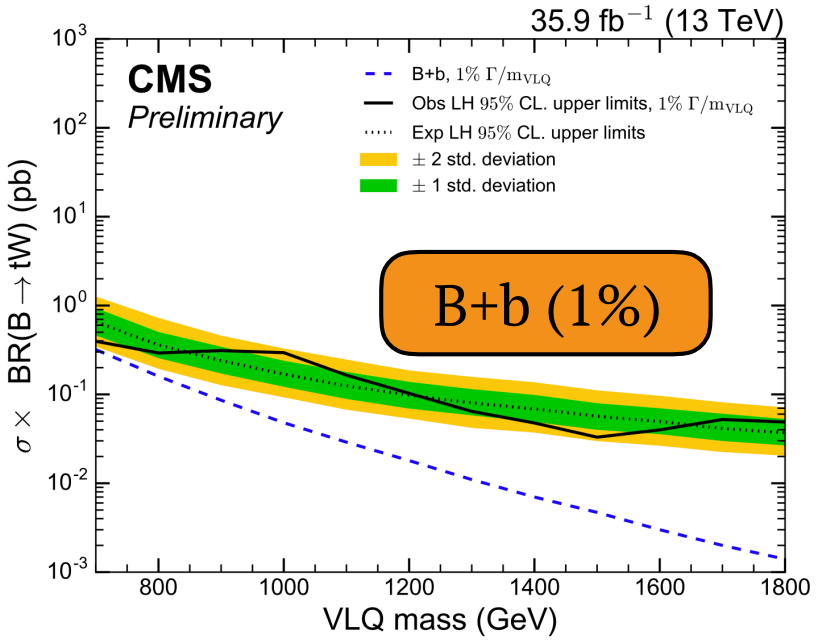
Search for B in tW channel

B2G-17-018

- Sensitive to both B and $X_{5/3}$ production
- Set limits on B+b, B+t production
  - LH and RH couplings
  - 1%-30% widths considered
- Cross section limits below 0.3 pb for range of B/X masses!

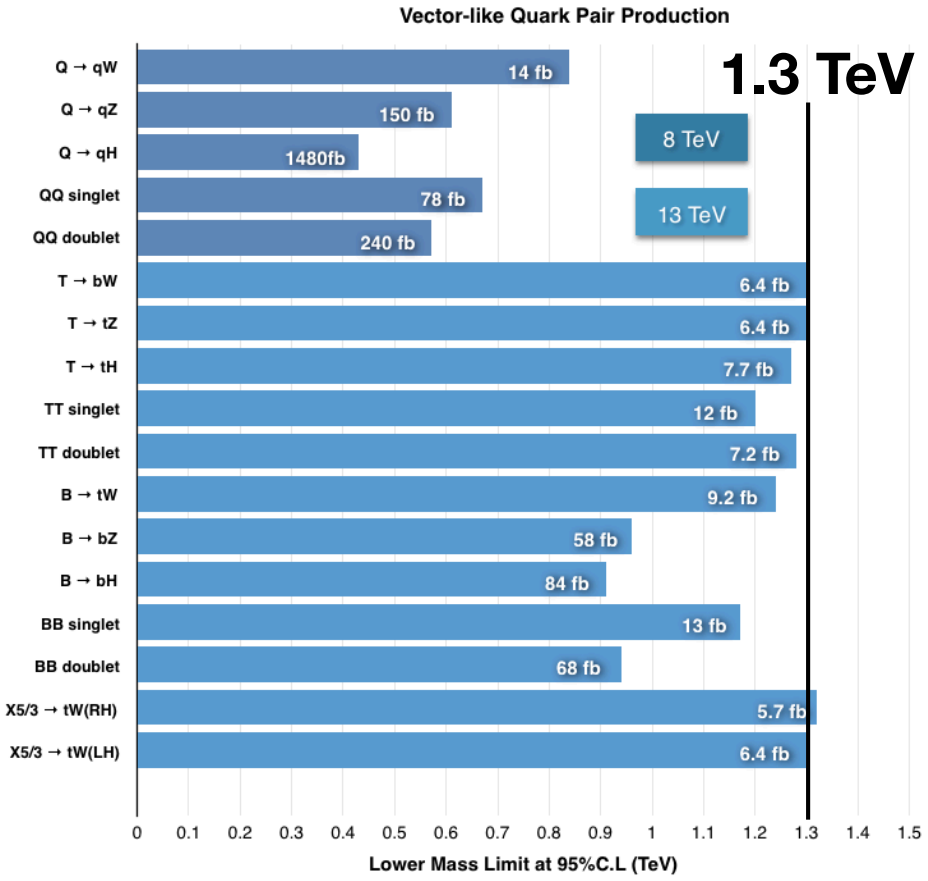


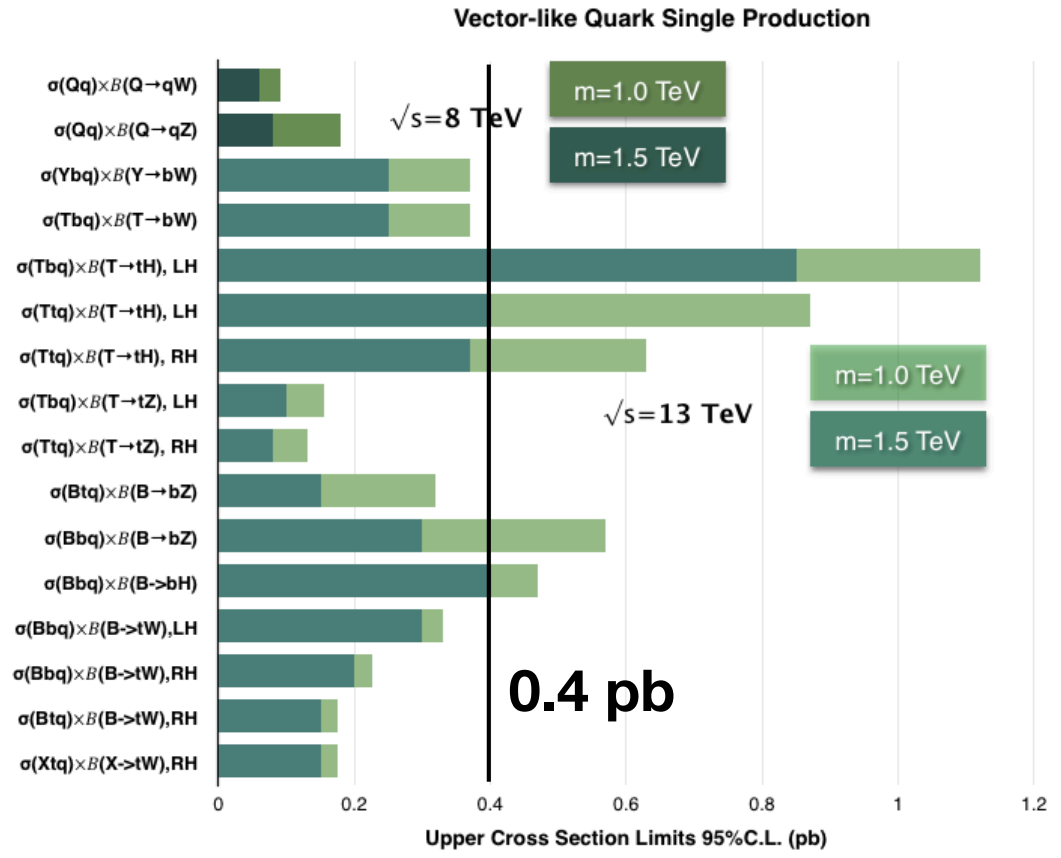




Summary

- Many more results available that could not be covered here
- CMS has an extensive program of VLQ searches
  - Single and pair production
  - Standard and exotic charges
  - Light quark couplings
- Most analyses based on 2016 dataset [~36 fb^{-1}] are public
  - Benefit from increase in energy from Run 1 to Run 2
  - Mass exclusions up to~1.3 TeV
  - Single VLQ production cross sections probed to < 1 pb!





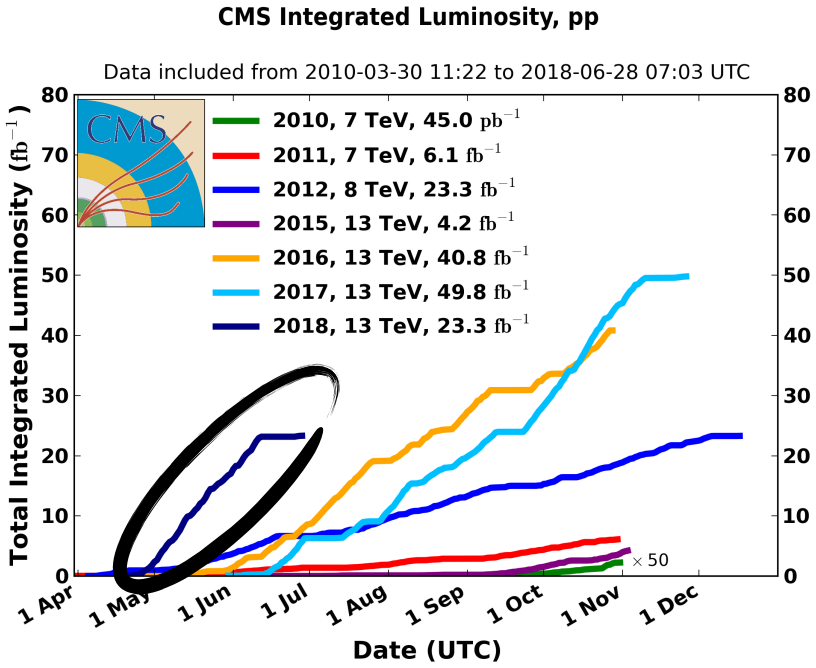
Conclusions / Outlook

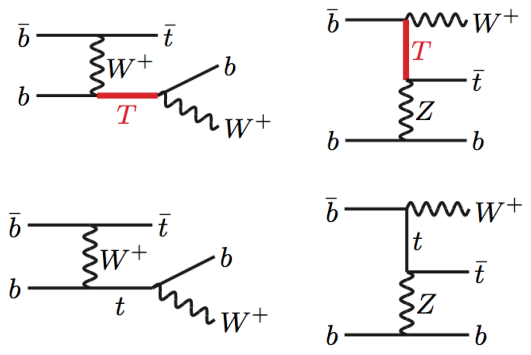
- The search for VLQ signatures continues
  - Strong limits
  - No sign of new physics yet

- After 2018, will have ~3-4x more data
  - Perform **statistical combinations**
  - **New techniques** will improve sensitivity
    - Jet substructure algorithms
    - Improvements in b-tagging

  - Continue to **improve theory interpretation**
    - Finite widths affect couplings affect branching fractions
    - NLO / Interference effects to be included
      - Can modify existing exclusions!

  - Signatures in combination with **other models**
    - Z' → tT, W' → tB, e.g. (see CMS talk by K. Nash)





arXiv:1805.06402

- **Stay tuned for more interesting VLQ search results from CMS!**

http://cms-results.web.cern.ch/cms-results/public-results/preliminary-results/B2G/index.html
http://cms-results.web.cern.ch/cms-results/public-results/publications/B2G/index.html