



# New Results on Searches for Heavy and Excited Quarks in CMS

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On Behalf of the CMS Collaboration

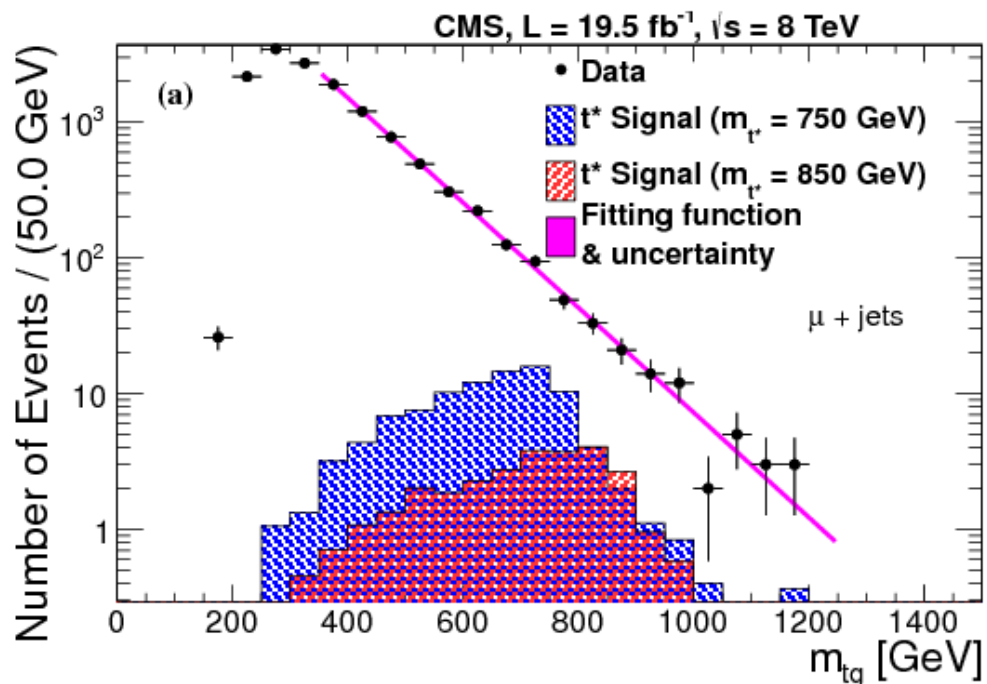
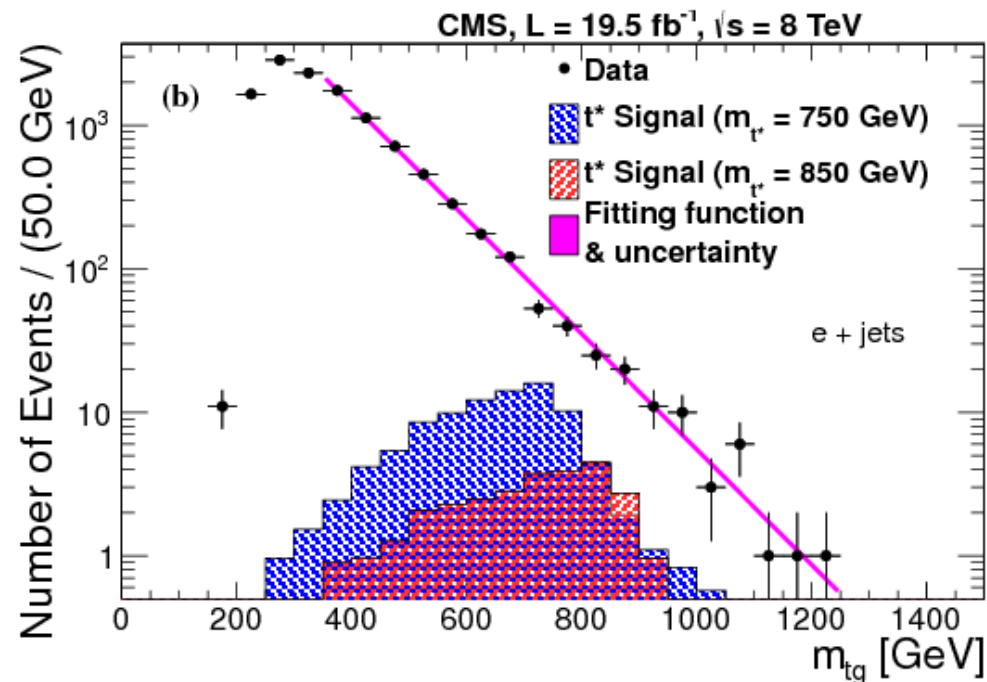
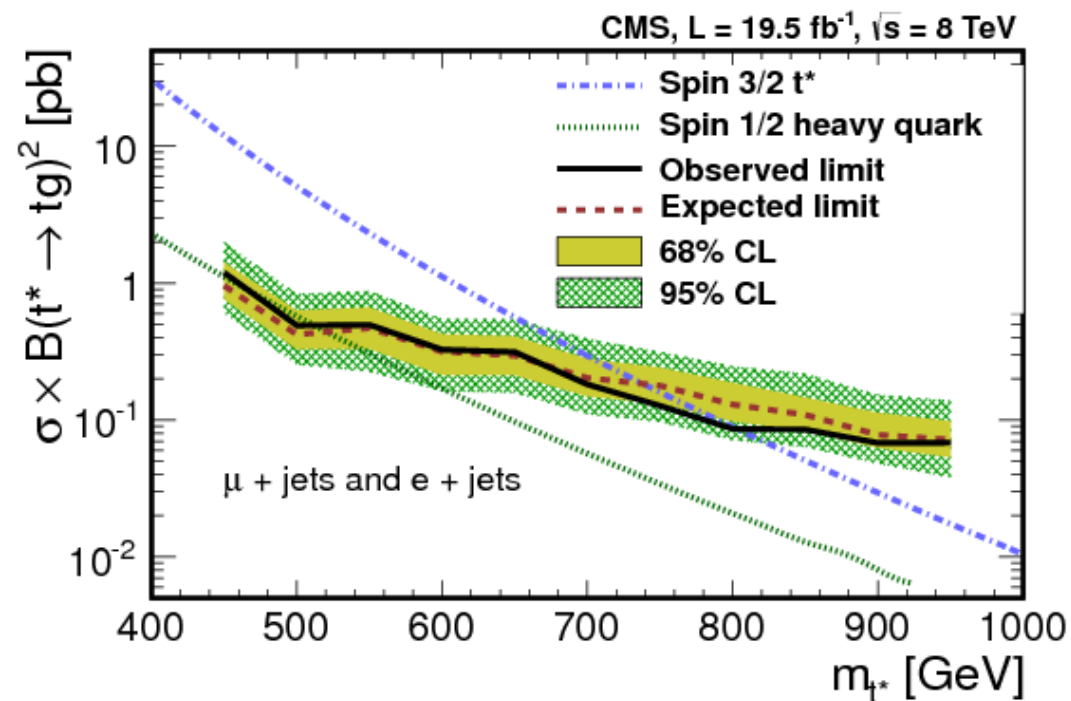
- Heavy and excited quarks are interesting because they appear in popular BSM models:
  - GUT, extradimension, composite top, . . .
- Vector-like quarks
  - Couplings to  $W, Z$  are symmetric or “vector-like”
    - Both left and right chiralities have the same representation under  $SU(2)$
  - Appear in several models to cancel radiative divergences in the Higgs sector (Little Higgs/ Composite Higgs)
- Excited Quarks
  - Consistent with SM Higgs production
  - Found in string realizations of the RS model

- Excited top quarks
  - In semileptonic (JHEP **06** 2013) and dileptonic (B2G-12-008) final states
- Search for vector-like tops:
  - Hadronic final state (B2G-14-002)
  - In  $tH$  where  $H \rightarrow \gamma\gamma$  (B2G-14-003)
  - Leptonic and semileptonic final states (PLB **729** 2014)
    - Decaying via  $bW$ ,  $tH$ , and  $tZ$
- Search for vector-like b-quarks:
  - Hadronic final state (B2G-14-001)
  - In semileptonic final state (B2G-12-019)
    - Decaying to  $tW$ ,  $bH$ , and  $bZ$
  - In  $bZ$  dilepton final state (B2G-12-021)
  - In  $tW$  same-sign lepton final state (B2G-12-020)
  - In multi-leptonic final states (B2G-13-003)
    - Decaying to  $tW$ ,  $bH$ , and  $bZ$

All results use  
data at  $\sqrt{s} = 8$  TeV  
from the LHC

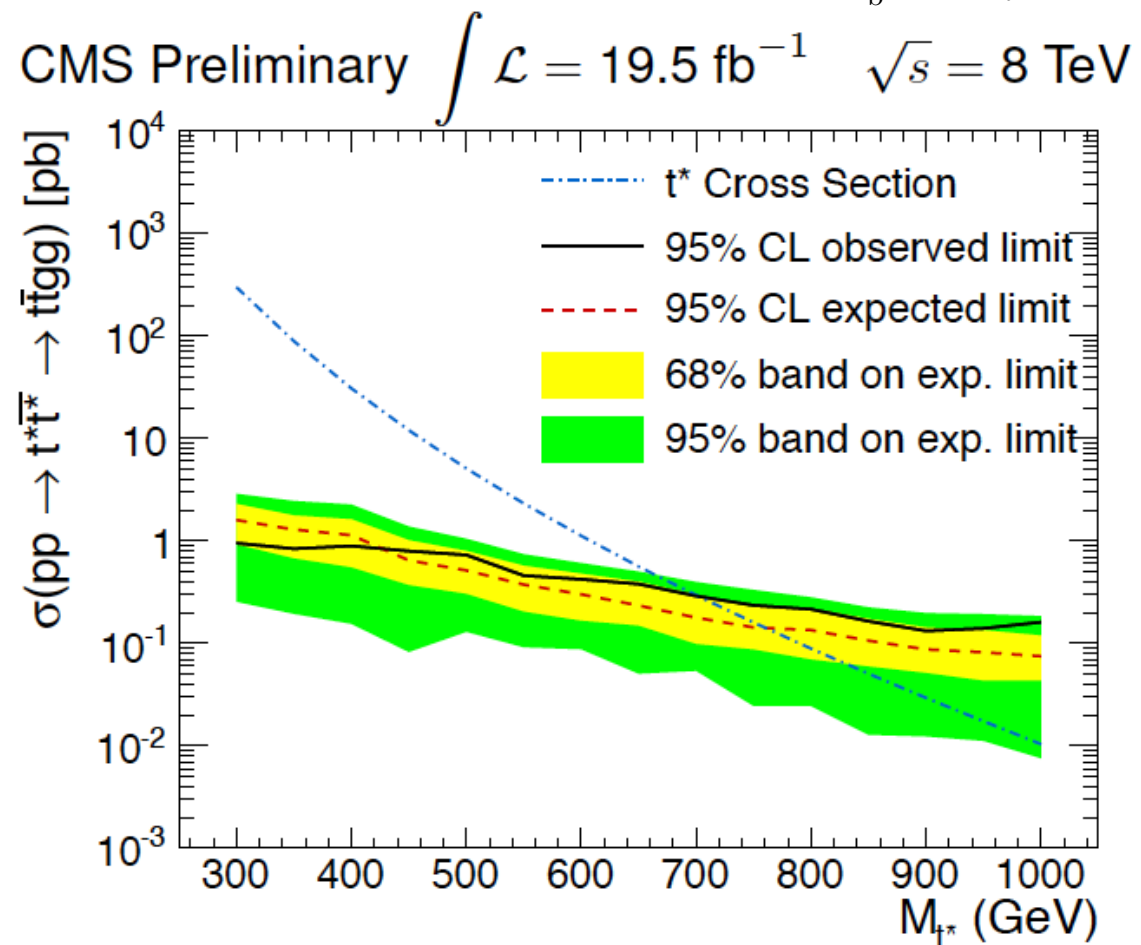
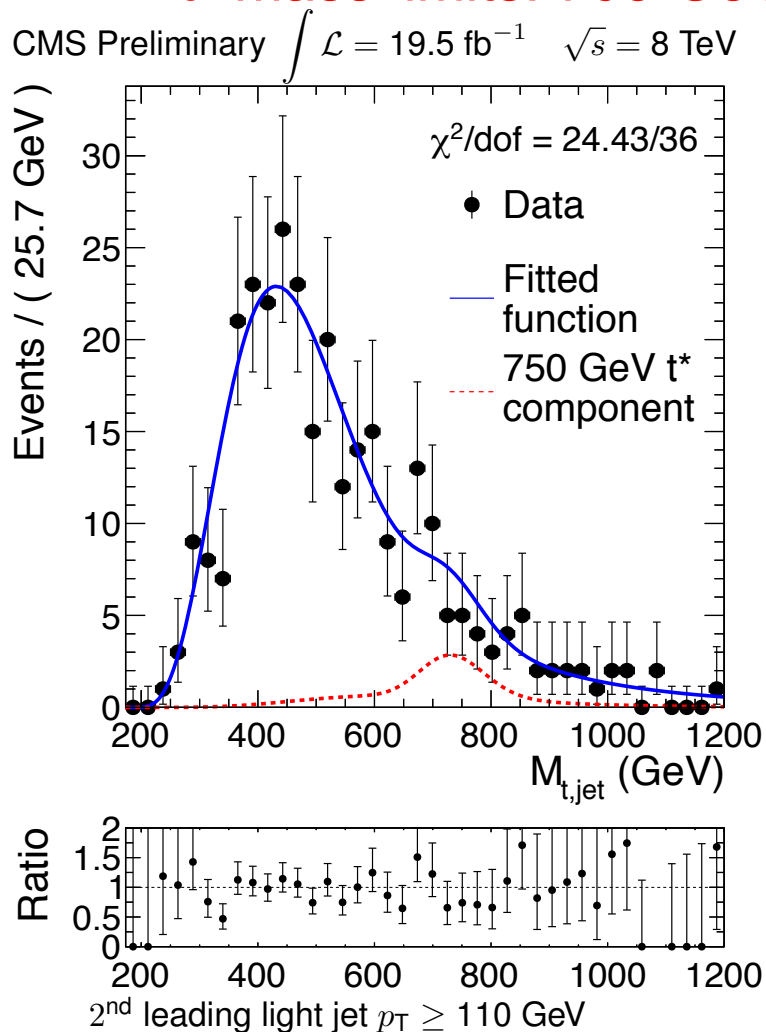
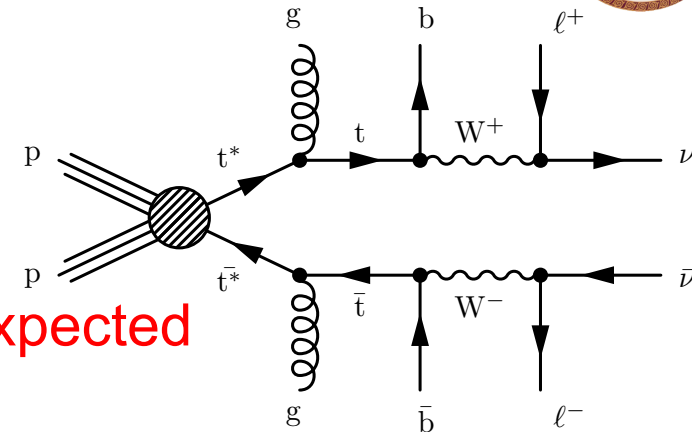
[https://twiki.cern.ch/twiki/bin/view/CMSPublic/PhysicsResultsB2G#Published\\_Results\\_2012\\_Run](https://twiki.cern.ch/twiki/bin/view/CMSPublic/PhysicsResultsB2G#Published_Results_2012_Run)

- $t^* \rightarrow t g$  in single lepton final states
  - Do not rely on simulation of bkgd
- Isolation lepton +  $\geq 6$  jets
  - Background fit of mass spectrum  
–  $m(l\nu_{bg}) = m(qq_{bg})$

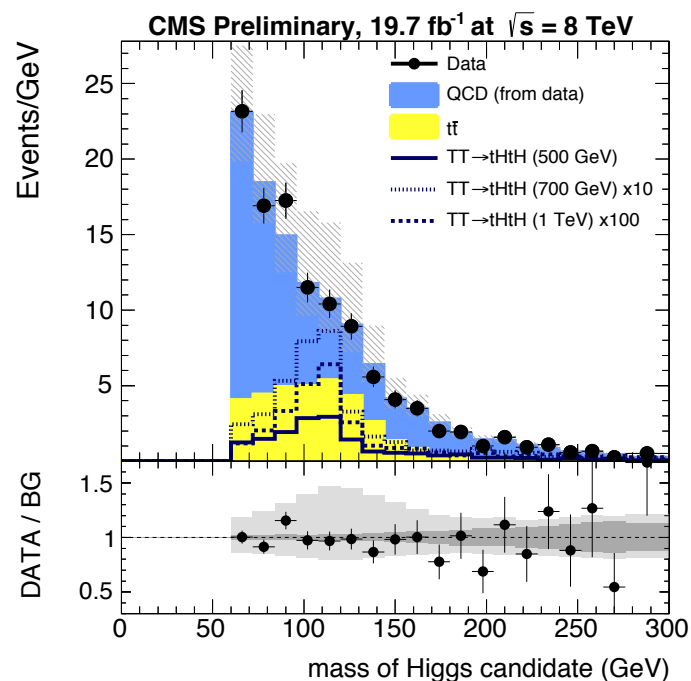
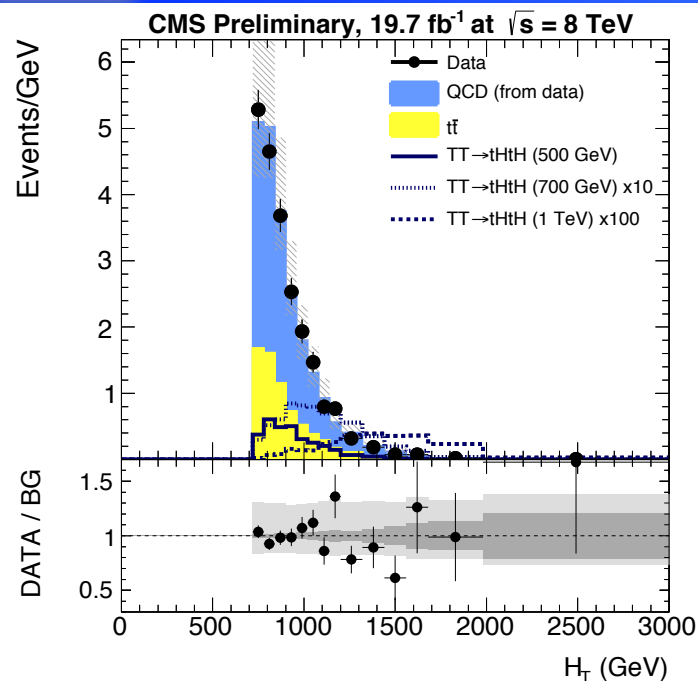


- $t^* \rightarrow t g$  in dilepton final states

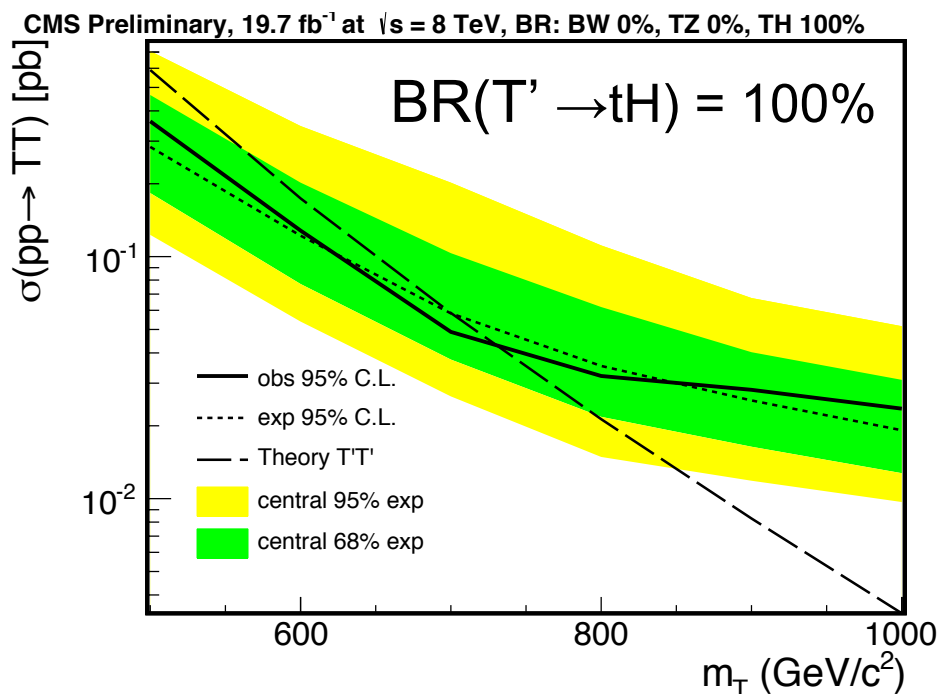
- 2 b-jets, 2 lights jets
- background fit of jet  $p_T$  distribution
- $t^*$  mass limits: 703 GeV observed, 763 GeV expected



# $T' \rightarrow tH, tZ, \text{ or } bW$



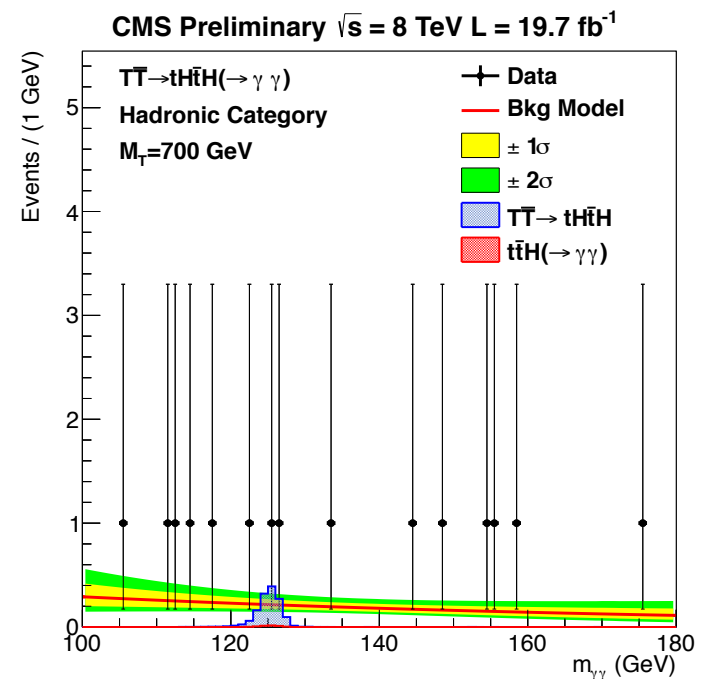
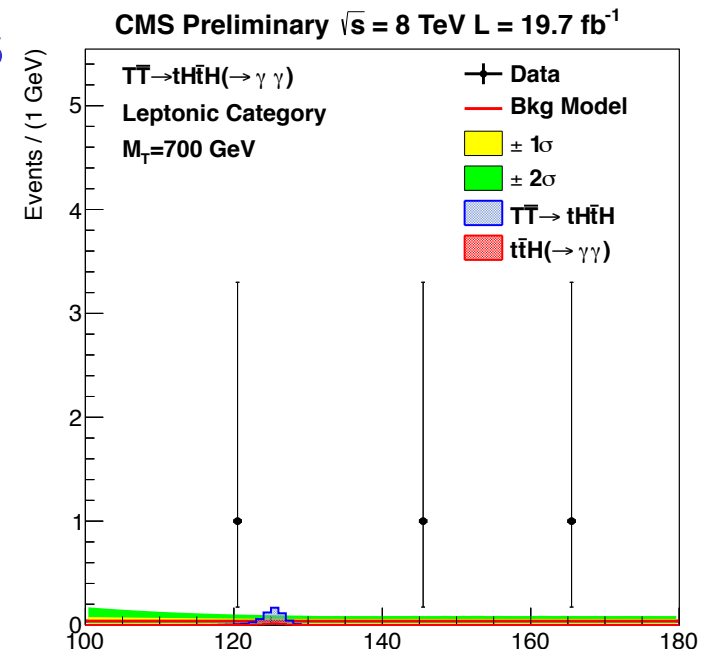
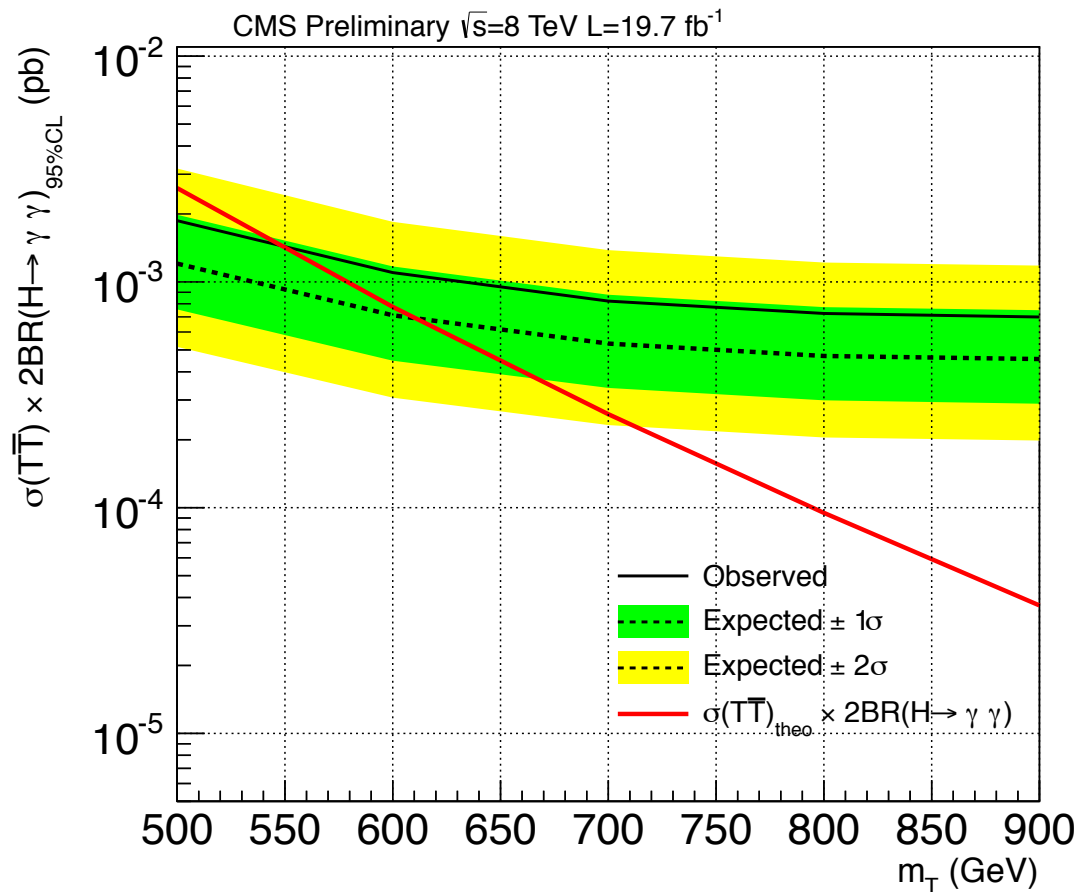
- Optimized for  $T' \rightarrow tH$ ,
  - Top decays via  $Wb$  in all hadronic final state,  $Higgs \rightarrow b\bar{b}$
- Uses jet substructure methods
  - Top-tagging and Higgs-tagging used to resolve substructure of boosted jets
- Single and Multi Higgs-tagged bins
- Background fit on likelihood discriminant based on  $H_T$  and  $m_H$



- Search for vector-like top quark partners produced in association with Higgs bosons in the diphoton final state

- T' mass limit:**

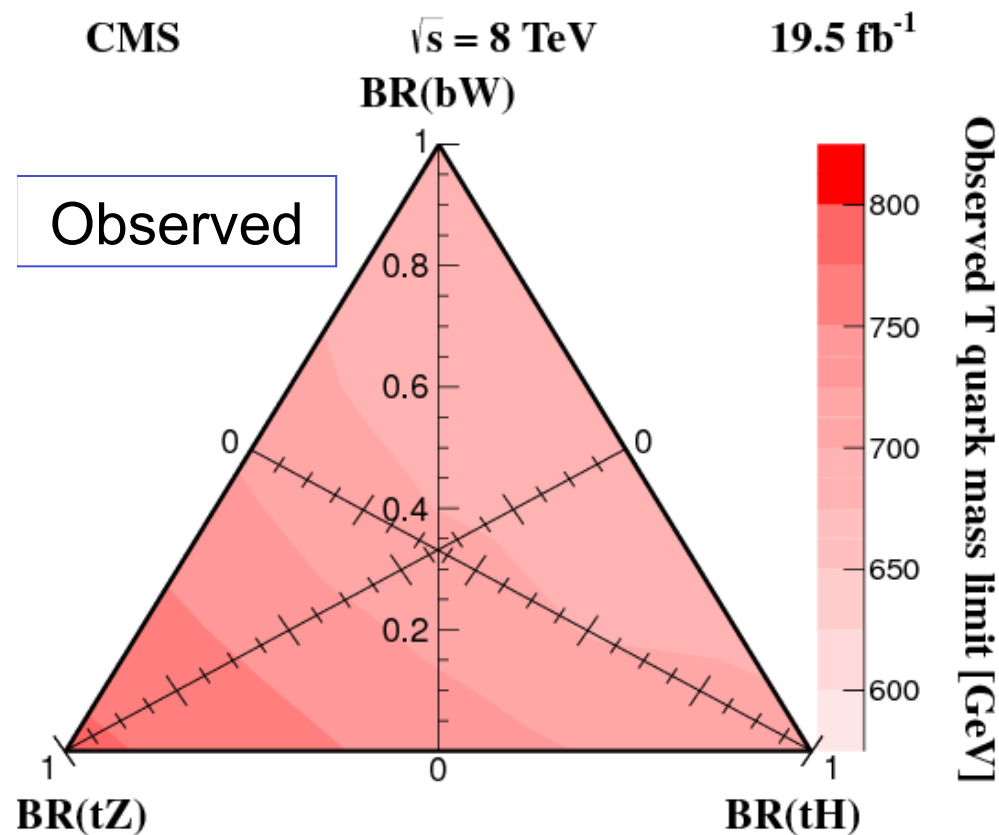
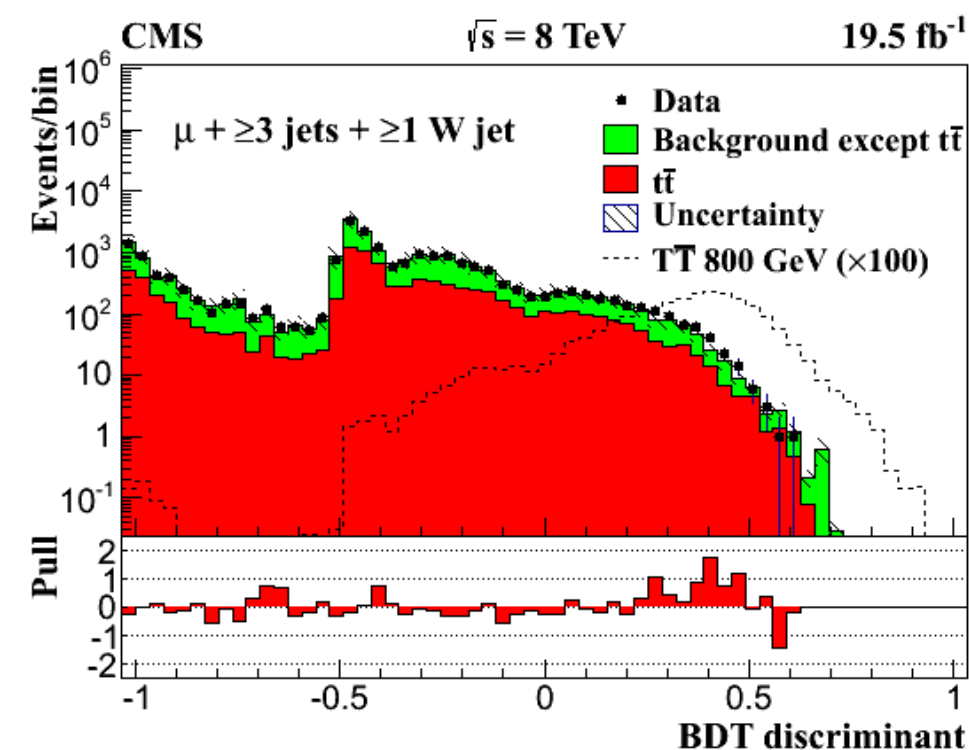
- 540 GeV observed, 607 GeV expected





# Vector-like Tops where final state has lepton(s)

- Inclusive  $T' \rightarrow bW$ ,  $tZ$ , and  $tH$  search where at least one of the  $W$  decays leptonically
  - Single lepton, opposite sign dilepton, same sign dilepton, trilepton
  - Jet substructure methods used for highly boosted  $t$ ,  $W$ , and  $Z$ 
    - CMS top-tagger and Boosted  $W$ -tagging
  - Background fit of BDT discriminant





# Search for $B' \rightarrow bH$

- Pair of heavy vector-like b-quarks decaying into Higgs and b-quark

- Higgs  $\rightarrow bb$  using boosted Higgs jet-tagging

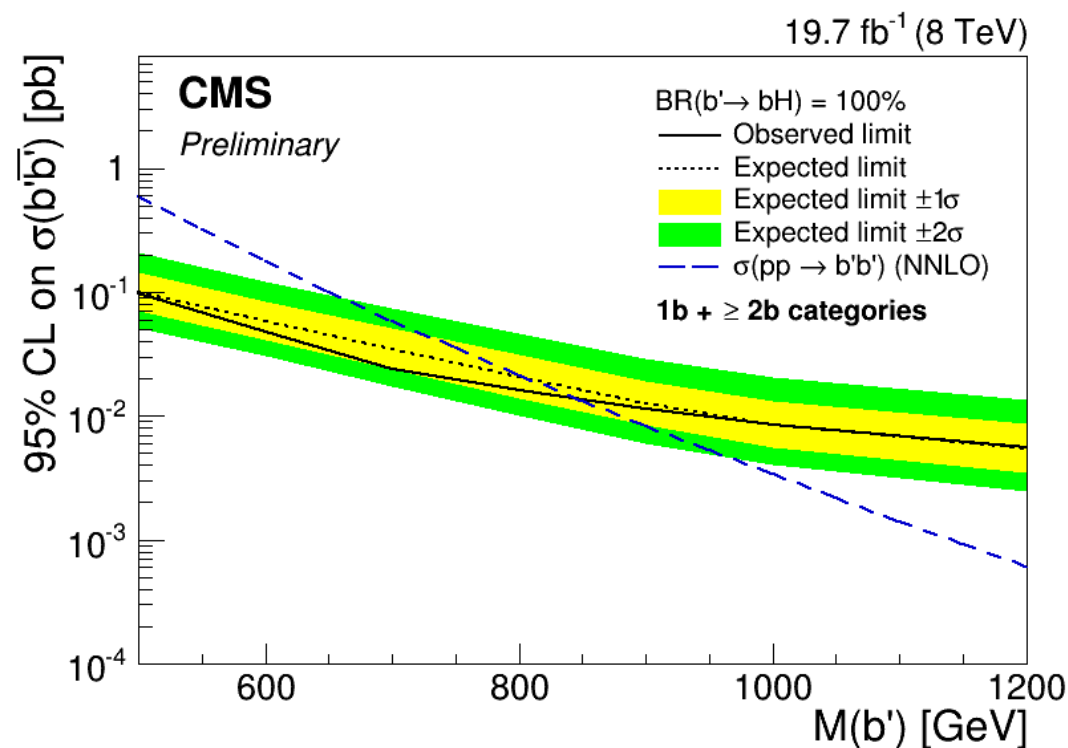
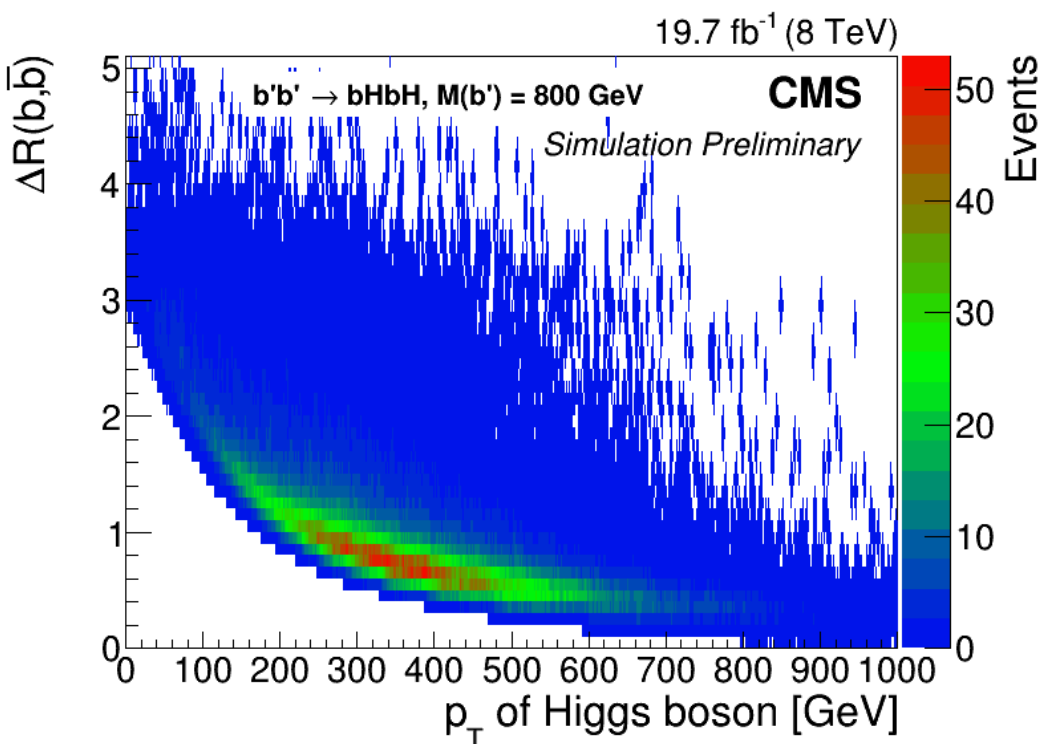
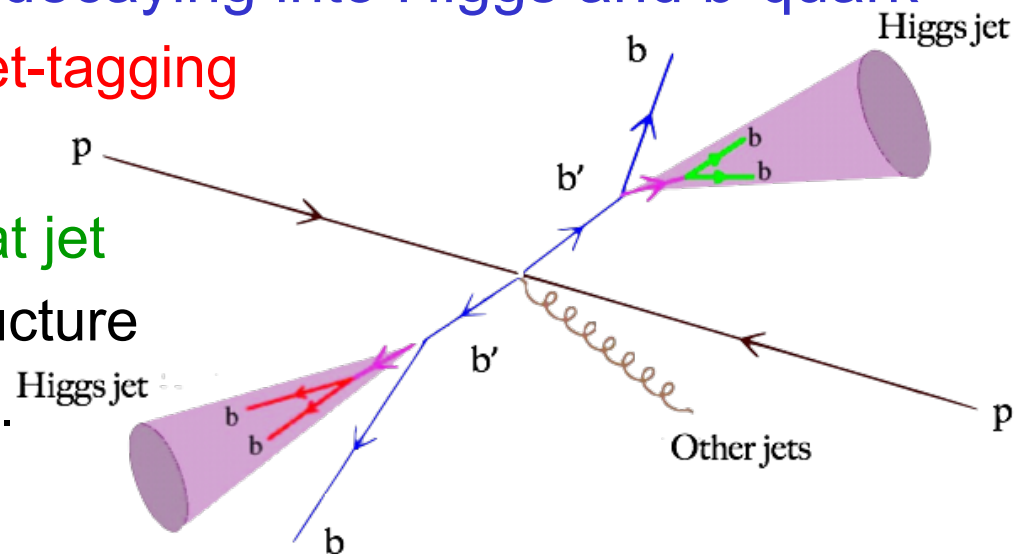
- Higgs is highly boosted

- $H \rightarrow bb$  reconstructed as one fat jet

- Identified using jet substructure

- Both subjets are b-tagged.

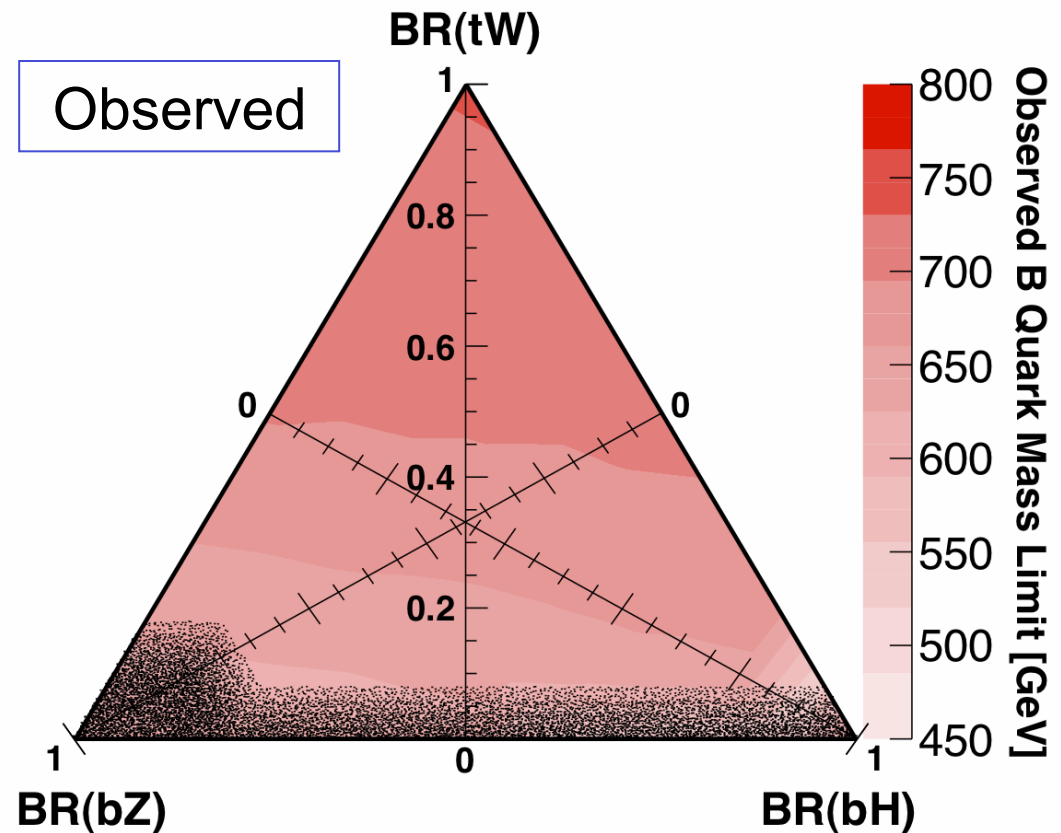
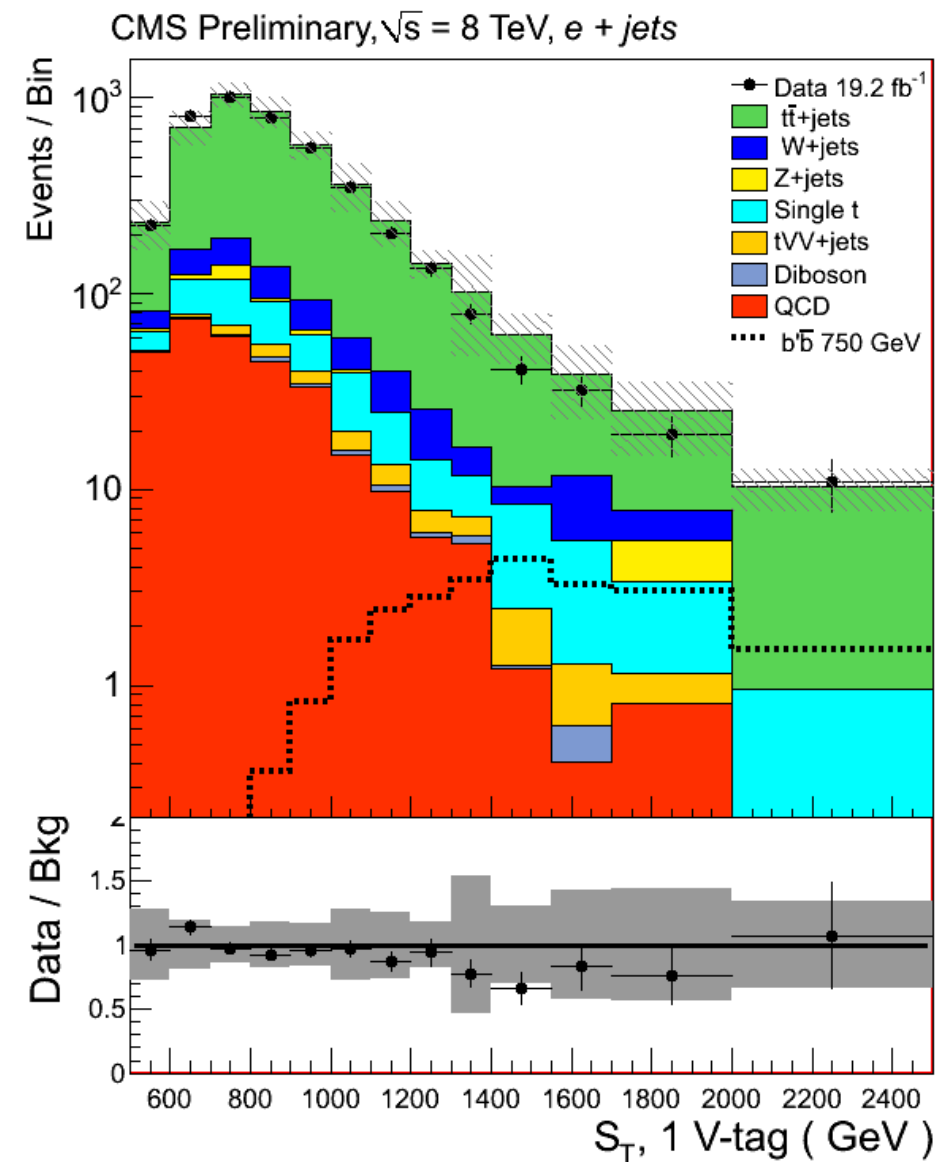
- Additional b-tagged jet required



- Pair-produced vector-like quarks in lepton + jets final state

- B'  $\rightarrow$  tW, bZ, and bH with final states containing one electron or one muon
- Fit  $S_T$  to measure the deviation between simulation and data

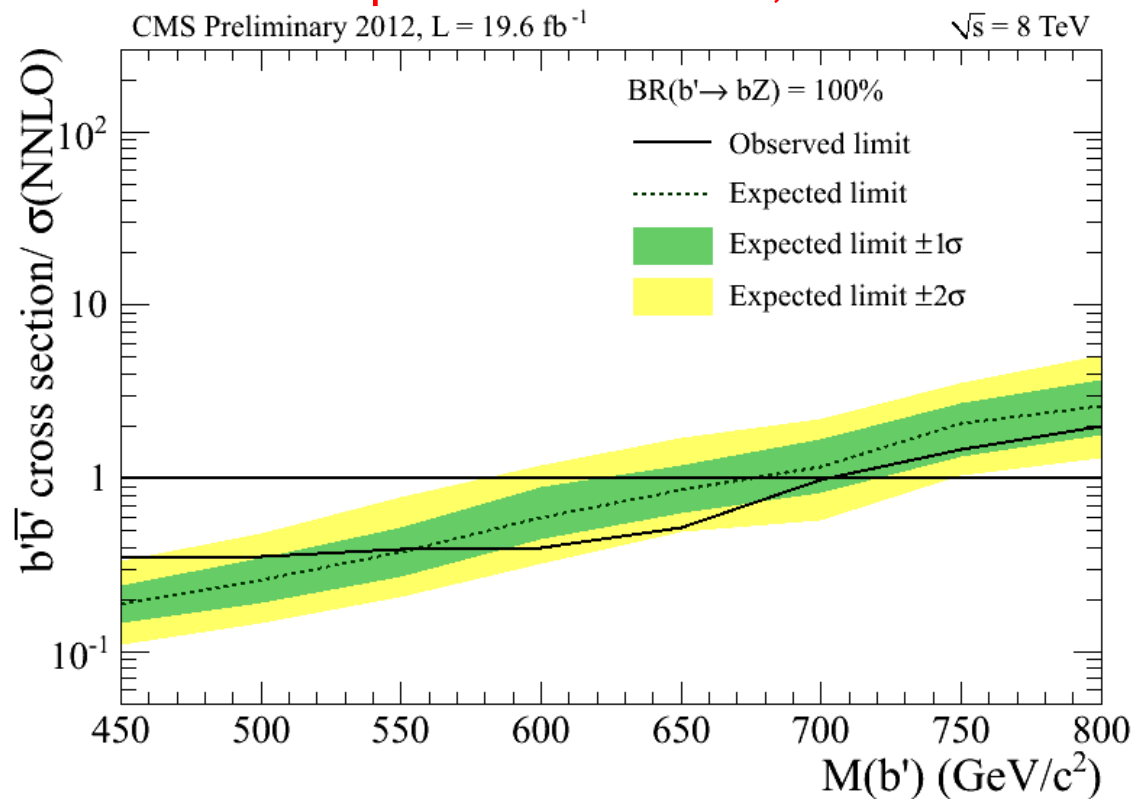
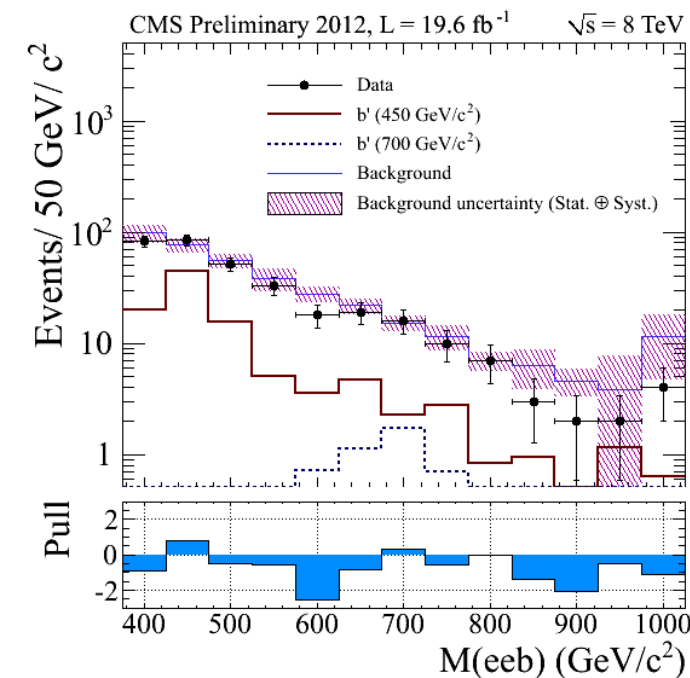
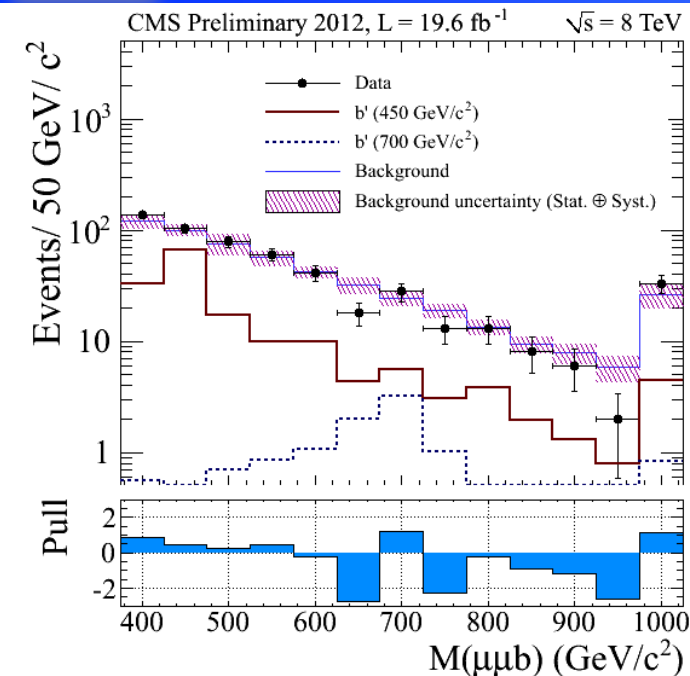
CMS Preliminary

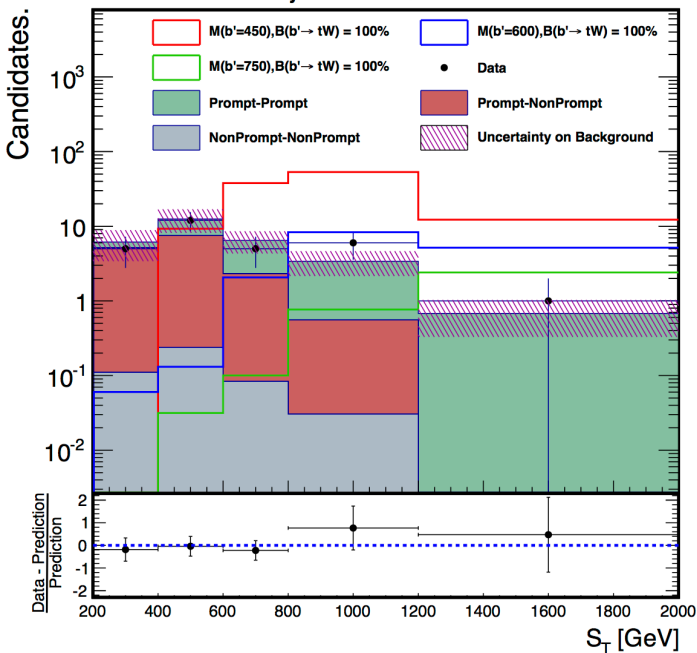
19.8 fb<sup>-1</sup>,  $\sqrt{s} = 8$  TeV

# $B' \rightarrow bZ$ dilepton

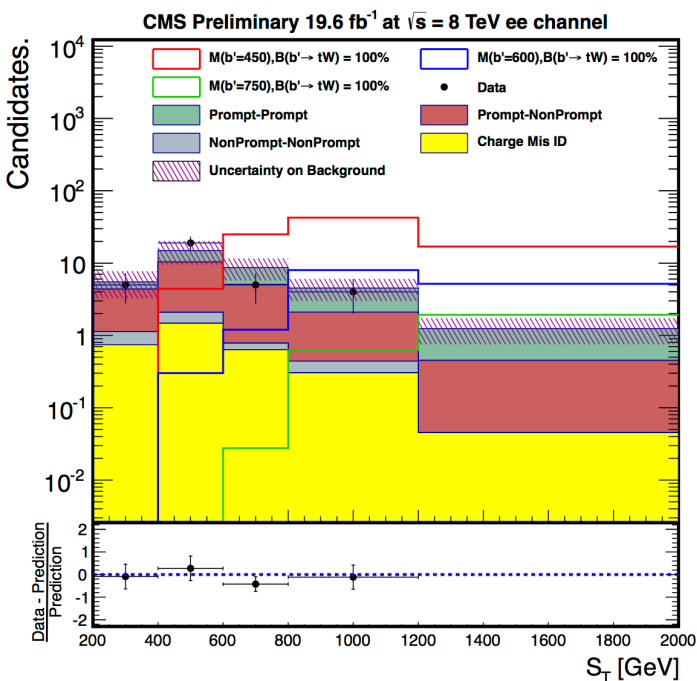
Search for pair-produced vector-like quarks of charge  $-1/3$  in dilepton+jets final state in pp collisions at  $\sqrt{s} = 8$  TeV

- One  $B'$  forced to decay to  $bZ$
- Other  $B'$  can decay to  $tW$  or  $bZ$ 
  - At least one  $Z \rightarrow ll$  per event
- Mass limit: Expected: 680 GeV, Observed: 700 GeV





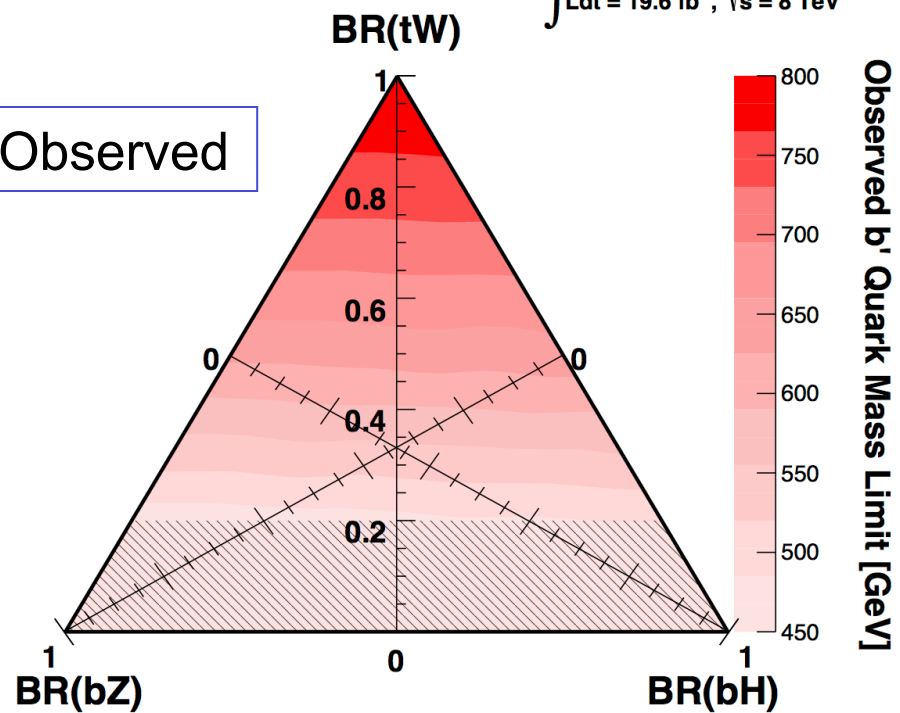
- $B' \rightarrow tW$ ,  $bH$ , and  $bZ$  with final states containing  $\mu^\pm\mu^\pm$ ,  $e^\pm e^\pm$ , or  $e^\pm\mu^\pm$
- Background fit to  $S_T$  distribution
- Data-driven methods used to estimate charge mis-identification and non-prompt leptons identified as prompt



**CMS Preliminary**

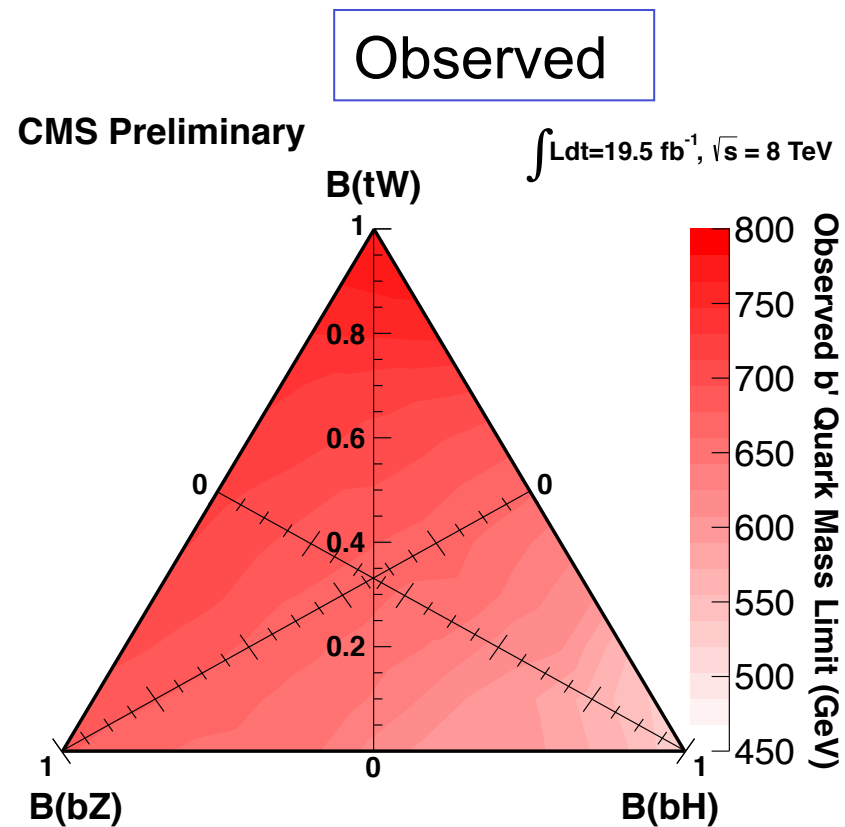
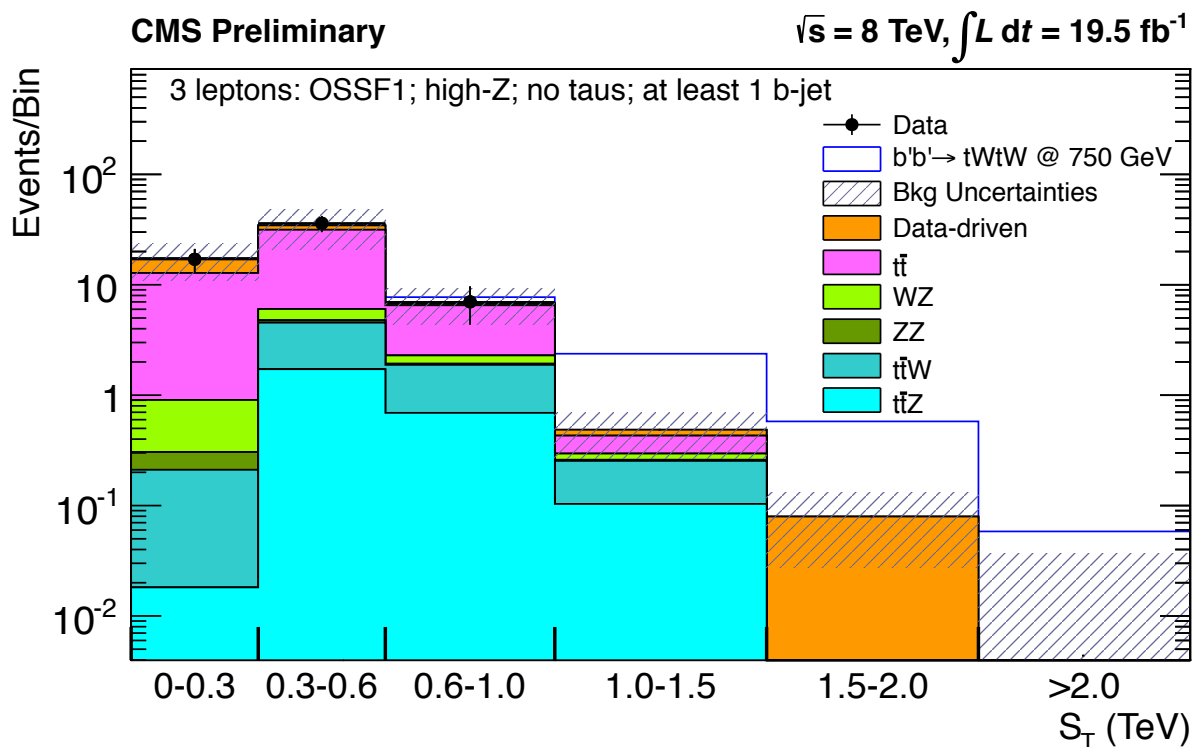
$\int \mathcal{L} dt = 19.6 \text{ fb}^{-1}$ ,  $\sqrt{s} = 8 \text{ TeV}$

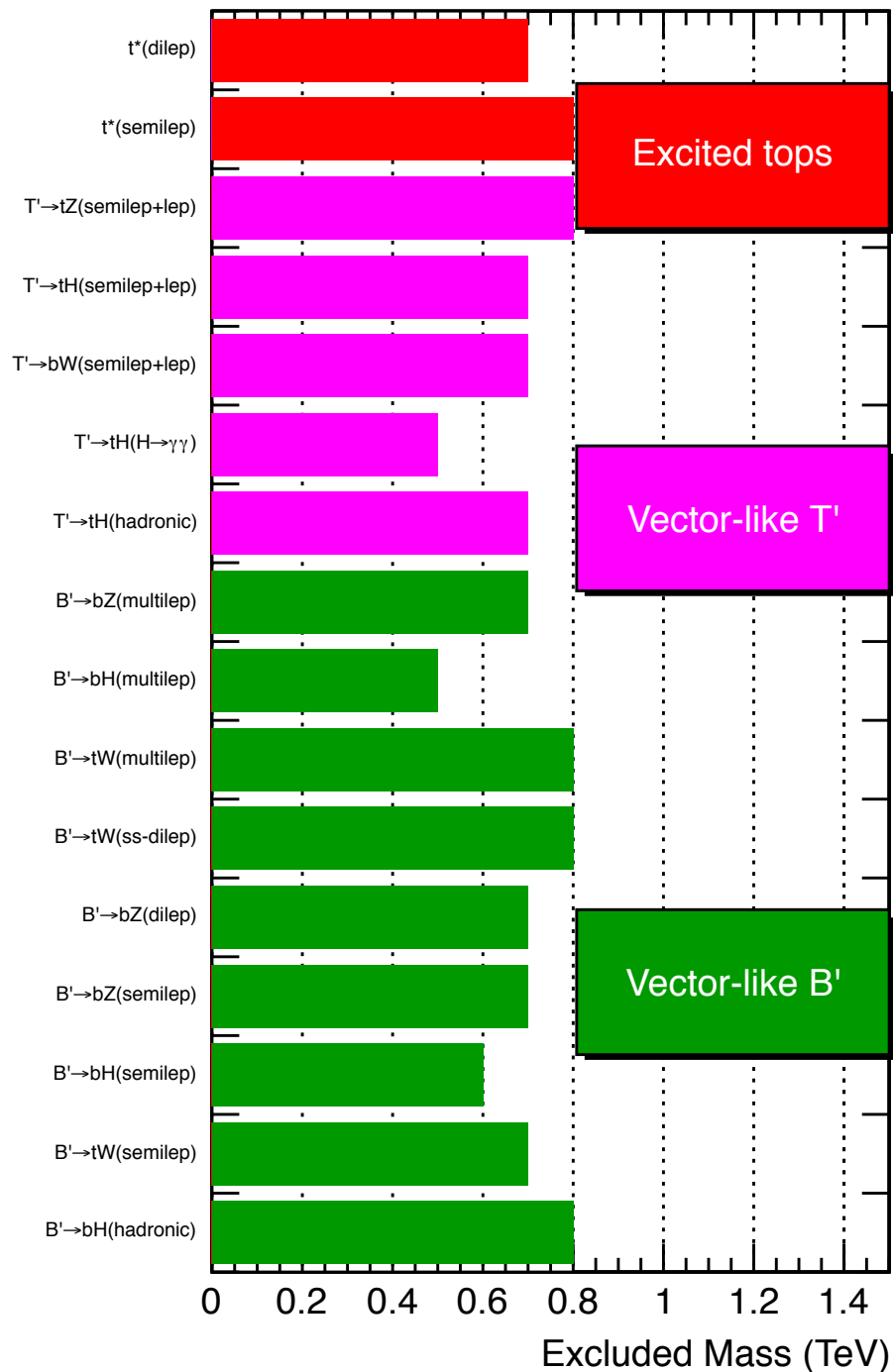
Observed



# B' in multilepton final state

- Search for Vector-Like b' Pair Production with Multilepton Final States in pp collisions at  $\sqrt{s} = 8$  TeV
  - B'  $\rightarrow$  tW, bZ, and bH where all branching ratios are considered
  - Events are categorized by the number of opposite-sign same-flavor pairs
  - Fit  $S_T$  to measure the deviation between simulation and data
  - B' mass limit: 520 to 785 GeV observed





CMS Searches for  
Heavy and Excited  
Quarks  
95% CL Exclusions  
(TeV)

Assumes 100% BR  
on each line

- CMS completed a robust and extensive probe of heavy and excited quarks at 8 TeV
  - Legacy combinations and a few other analyses still to come
- While no new particles were found at 8 TeV, advanced analysis techniques make CMS well prepared to probe this sector at  $\sqrt{s} = 13$  TeV
  - Boosted analyses become very interesting at 13 TeV





Thank you